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# Coverings of Laura Algebras: the Standard Case

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## Abstract

In this paper, we study the covering theory of lura algebras. We prove that if a connected lura algebra is standard (that is, it is not quasi-tilted of canonical type and its connecting components are standard), then this algebra has nice Galois coverings associated to the coverings of the connecting component. As a consequence, we show that the first Hochschild cohomology group of a standard lura algebra vanishes if and only if it has no proper Galois coverings.

## Introduction

The Hochschild cohomology groups are interesting invariants of associative algebras. In this paper, we are interested in the first group, which can be thought of as the group of classes of outer derivations of the algebra. In [42, §3, Pb. 1], Skowroński has related the vanishing of the first Hochschild cohomology group  $\mathrm{HH}^1(A)$  of an algebra (with coefficients in the bimodule  ${}_A A_A$ ) to the simple connectedness of  $A$ . A basic connected finite dimensional algebra over an algebraically closed field  $k$  is called *simply connected* if has no proper Galois covering or, equivalently, if the fundamental group (in the sense of [36]) of any presentation is trivial. In particular, Skowroński has conjectured that a tame triangular algebra  $A$  is simply connected if and only if  $\mathrm{HH}^1(A) = 0$ . Since then, this equivalence has been shown for several classes of algebras not necessarily tame or triangular. Thus, for instance, it has been proved for standard representation-finite algebras [15], for piecewise hereditary algebras [34] and for weakly shod algebras [32] (see also [6]).

Here, we study this conjecture for lura algebras. These are defined as follows. Let  $\mathrm{mod} A$  be the category of finitely generated right  $A$ -modules, and  $\mathrm{ind} A$  be a full subcategory consisting of exactly one representative of each isomorphism class of indecomposable  $A$ -modules. We define the *left part*  $\mathcal{L}_A$  of  $\mathrm{mod} A$  to be the full subcategory of  $\mathrm{ind} A$  consisting of those modules whose predecessors have projective dimension at most one, and we define its *right part*  $\mathcal{R}_A$  dually. These classes were introduced in [28] in order to study the module categories of quasi-tilted algebras. Following [3, 44], we say that  $A$  is *lura* provided  $\mathrm{ind} A \setminus (\mathcal{L}_A \cup \mathcal{R}_A)$  has only finitely many objects. Thus, any representation-finite algebra, any quasi-tilted algebra or any weakly shod algebra is lura. The class of lura algebras has been studied in [3, 4, 5, 7, 8, 23, 44]. Here, we concentrate on the conjecture that a lura algebra  $A$  is simply connected if and only if  $\mathrm{HH}^1(A) = 0$ .

One approach to this conjecture, already used in [33, 34], is to use the covering theory of lura algebras. Covering theory was introduced by Gabriel and his school (see [14, 25, 38], for instance) and consists in replacing an algebra by a locally bounded category, called its covering, which is sometimes easier to study. In the case of lura algebras, a non-quasi-tilted lura algebra  $A$  has a unique faithful non-semiregular Auslander-Reiten component which is *quasi-directed* (that is, it is generalised standard and almost all its modules are directed). This component is called the *connecting component* (see [3]) of the lura algebra, in analogy to the connecting components of tilted algebras. Thus, any lura algebra which is not quasi-tilted of canonical type has at least one, and at most two, connecting components (actually, it has two if and only if the algebra is concealed). If, in particular,  $A$  is representation-finite, then its connecting component coincides with the whole Auslander-Reiten quiver. We say that a lura algebra  $A$  which is not quasi-tilted of canonical type is *standard* provided its connecting components are all standard (it is known from [40] that the connecting components of a concealed algebra are standard). This generalises the notion of standard representation-finite algebra (see [14]). Several classes of lura algebras are standard, notably all tilted algebras or all weakly shod algebras. Our first main theorem says that the universal covering of the connecting component induces a covering of the algebra.

**Theorem A.** *Let  $A$  be lura and not quasi-tilted of canonical type. There exists a connected locally bounded  $k$ -category  $\tilde{A}$  and a covering functor  $F: \tilde{A} \rightarrow A$  whose fibres are in bijection with the fundamental group  $\pi_1(\Gamma)$  of the connecting component  $\Gamma$ . If moreover  $A$  is standard, then  $F$  is a Galois covering with group  $\pi_1(\Gamma)$ .*

Note that if  $A$  is concealed, then the fundamental groups of its two connecting components, which are postprojective and preinjective respectively, are isomorphic.

In order to prove Theorem A, we need to consider a more general situation. Namely, we first consider an Auslander-Reiten component of an algebra, which contains a left section (in the sense of [1]). We then show that to the universal cover of that component corresponds a covering of its support with nice properties. Applying this result to the connecting component of a lura algebra yields the required covering.

By the theorem, if  $A$  is standard, then we are able to work with the Galois coverings which are notably easier to handle than covering functors. We prove that if  $A$  is a standard lura algebra, then any Galois covering of the connecting component of  $A$  induces a Galois covering of  $A$  itself, with the same group. This allows us to prove our second main theorem, which settles the conjecture for the case of standard lura algebras.

**Theorem B.** *Let  $A$  be a standard lura algebra, and  $\Gamma$  its connecting component(s). The following are equivalent:*

- (a)  $A$  is simply connected.
- (b)  $\mathrm{HH}^1(A) = 0$ .
- (c)  $\Gamma$  is simply connected.
- (d) The orbit graph  $\mathcal{O}(\Gamma)$  is a tree.

Moreover, if these conditions are verified, then  $A$  is weakly shod.

If one drops the standard condition, then the above theorem may fail. Indeed, there are examples of non-standard representation-finite algebras which are simply connected and with non-zero first Hochschild cohomology group (see [14, 15], or below). However, some implications are still true in Theorem B without assuming standardness. Indeed, we always have: (c) and (d) are equivalent and (c) implies (a) and (b).

In our final section, we consider the case of special biserial lura algebras which have been characterised in [23], and we prove that the conjecture holds in this case also, although we do not know whether they are standard or not.

Our paper is organised as follows. After a short preliminary section, we prove a few preparatory lemmata on covering functors in Section 2. In Section 3, we give examples of standard lura algebras. Section 4 is devoted to properties of tilting modules which are in the image of the push-down functor associated to a covering functor. In Section 5 we study the coverings of Auslander-Reiten components having left sections. The proof of Theorem A occupies Section 6. We then concentrate on the case of Galois coverings in Section 7, which leads to the proof of Theorem B in Section 8. Finally, Section 9 deals with the special biserial case.

## 1 Preliminaries

### Categories and modules

Throughout this paper,  $k$  denotes a fixed algebraically closed field. All our categories are locally bounded  $k$ -categories, in the sense of [14, 2.1]. We assume that all locally bounded  $k$ -categories are small and that all functors are  $k$ -linear (the categories of finite dimensional modules and their bounded derived categories are skeletally small).

Let  $F: \mathcal{E} \rightarrow \mathcal{B}$  be a  $k$ -linear functor and let  $G$  be a group acting on  $\mathcal{E}$  and  $\mathcal{B}$  by automorphisms. Then  $F$  is called  $G$ -equivariant if  $F \circ g = g \circ F$  for every  $g \in G$ .

A basic finite dimensional algebra  $A$  can be considered equivalently as a locally bounded  $k$ -category as follows: we fix a complete set  $\{e_1, \dots, e_n\}$  of primitive orthogonal idempotents, then the object set of  $A$  is the set  $\{e_1, \dots, e_n\}$  and the morphisms space from  $e_i$  to  $e_j$  is  $e_j A e_i$ . The composition of morphisms is induced by the multiplication in  $A$ .

Let  $\mathcal{C}$  be a locally bounded  $k$ -category. We denote by  $\mathcal{C}_o$  its object class. A *right  $\mathcal{C}$ -module*  $M$  is a  $k$ -linear functor  $M: \mathcal{C}^{op} \rightarrow \mathrm{MOD} k$ , where  $\mathrm{MOD} k$  is the category of  $k$ -vector spaces. We write  $\mathrm{MOD} \mathcal{C}$  for the category of  $\mathcal{C}$ -modules and  $\mathrm{mod} \mathcal{C}$  for the full subcategory of the *finite dimensional*  $\mathcal{C}$ -modules, that is, those modules  $M$  such that  $\sum_{x \in \mathcal{C}_o} \dim M(x) < \infty$ . If  $\mathcal{A}$  is a subcategory of  $\mathrm{MOD} \mathcal{C}$ , we use the notation  $X \in \mathcal{A}$  to express that  $X$  is an object in  $\mathcal{A}$ . For every  $x \in \mathcal{C}_o$ , the indecomposable projective  $\mathcal{C}$ -module associated to  $x$  is  $\mathcal{C}(-, x)$ . The standard duality  $\mathrm{Hom}_k(-, k)$  is denoted by  $D$ . Let  $M$  be a  $\mathcal{C}$ -module. If  $\mathcal{B}$  is a full subcategory of  $\mathcal{C}$ , then  $M|_{\mathcal{B}}$  denotes the induced  $\mathcal{B}$ -module. If  $\mathcal{X}$  is a subcategory of  $\mathrm{mod} \mathcal{C}$ , then the  $\mathcal{X}$ -module  $\mathrm{Hom}_{\mathcal{C}}(-, M)|_{\mathcal{X}}$  is denoted by  $\mathrm{Hom}_{\mathcal{C}}(\mathcal{X}, M)$ . Also,  $\mathrm{Hom}_{\mathcal{C}}(M, \mathcal{C})$  denotes the  $\mathcal{C}^{op}$ -module  $\mathrm{Hom}_{\mathcal{C}}(M, \bigoplus_{x \in \mathcal{C}_o} \mathcal{C}(-, x))$  (if  $A = \mathcal{C}$  is a finite dimensional algebra, this is just the left  $A$ -module  $\mathrm{Hom}_A(M, A)$ ).

We let  $\mathrm{ind} \mathcal{C}$  be a full subcategory of  $\mathrm{mod} \mathcal{C}$  consisting of a complete set of representatives of the isomorphism classes of the indecomposable  $\mathcal{C}$ -modules. We write  $\mathrm{proj} \mathcal{C}$  and  $\mathrm{inj} \mathcal{C}$  for the full subcategories of  $\mathrm{ind} \mathcal{C}$  of projective and injective modules, respectively. Whenever we speak about an indecomposable  $\mathcal{C}$ -module, we always mean that it belongs to  $\mathrm{ind} \mathcal{C}$ .

For a full subcategory  $\mathcal{A}$  of  $\mathrm{mod} \mathcal{C}$ , we denote by  $\mathrm{add} \mathcal{A}$  the full subcategory of  $\mathrm{mod} \mathcal{C}$  with objects the direct sums of summands of modules in  $\mathcal{A}$ . If  $M$  is a module, then  $\mathrm{add} M$  denotes  $\mathrm{add} \{M\}$ .

The Auslander-Reiten translations of  $\mathrm{mod} \mathcal{C}$  are denoted by  $\tau_{\mathcal{C}} = D \mathrm{Tr}$  and  $\tau_{\mathcal{C}}^{-1} = \mathrm{Tr} D$ . The Auslander-Reiten quiver of  $\mathcal{C}$  is denoted by  $\Gamma(\mathrm{mod} \mathcal{C})$ . For a component  $\Gamma$  of  $\Gamma(\mathrm{mod} \mathcal{C})$ , we denote by  $\mathcal{O}(\Gamma)$  its orbit graph

(see [14, 4.2], its definition is recalled in Section 8 below). It is *non-semiregular* if it contains both an injective and a projective module. It is *faithful* if its *annihilator*  $\text{Ann } \Gamma = \bigcap_{X \in \Gamma} \text{Ann } X$  is zero. Following [43], a component of  $\Gamma$  is *generalised standard* if  $\text{rad}^\infty(X, Y) = 0$  for every  $X, Y \in \Gamma$ . It is *standard* if there exists an isomorphism of  $k$ -categories  $k(\Gamma) \xrightarrow{\sim} \text{ind } \Gamma$  which extends the identity on vertices, and which maps meshes to almost split sequences. Let  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  be a morphism of translation quivers. Let  $\mathcal{X}$  be a full convex subquiver of  $\tilde{\Gamma}$ . We let  $k(\mathcal{X})$  be the full subcategory of  $k(\tilde{\Gamma})$  with objects the vertices in  $\mathcal{X}$ . Following [14, 3.1], a functor  $p: k(\mathcal{X}) \rightarrow \text{ind } \Gamma$  is called *well-behaved* (with respect to  $\pi$ ) if the following conditions are satisfied:

1.  $p(X) = \pi(X)$  for every  $X \in \mathcal{X}$ .
2. Let  $X \in \mathcal{X}$ . Let  $(u_i: Z_i \rightarrow X)_{i=1, \dots, t}$  be all the arrows in  $\mathcal{X}$  ending at  $X$  (or  $(v_j: X \rightarrow Y_j)_{j=1, \dots, s}$  be all the arrows in  $\mathcal{X}$  starting from  $X$ ), then the morphism  $[p(u_1) \ \dots \ p(u_t)] : \bigoplus_{i=1}^t p(Z_i) \rightarrow p(X)$  (or  $[p(v_1) \ \dots \ p(v_s)]^t : p(X) \rightarrow \bigoplus_{j=1}^s p(Y_j)$ , respectively) is irreducible.
3. Let  $X \in \tilde{\Gamma}$  be non projective. Let  $(u_i: \tau X \rightarrow E_i)_{i=1, \dots, s}$  (or  $(v_i: E_i \rightarrow X)_{i=1, \dots, s}$ ) be all the arrows in  $\tilde{\Gamma}$  starting from  $\tau X$  (or ending at  $X$ , respectively). If the mesh in  $\tilde{\Gamma}$  ending at  $X$  is contained in  $\mathcal{X}$ , then  $\sum_{i=1}^s p(g_i)p(f_i) = 0$ .

Conditions 2 and 3 above imply that if a mesh in  $\tilde{\Gamma}$  is contained in  $\mathcal{X}$ , then  $p$  maps this mesh to an almost split sequence.

For more notions and results on modules, we refer the reader to [9, 10]. For a reminder on coverings and fundamental groups of translation quivers, we refer the reader to [14, §1].

## Paths

Let  $\mathcal{C}$  be a locally bounded  $k$ -category. Given  $X, Y \in \text{ind } \mathcal{C}$ , a *path*  $X \rightsquigarrow Y$  from  $X$  to  $Y$  in  $\text{ind } \mathcal{C}$  is a sequence of non-zero morphisms:

$$(\star) \quad X = X_0 \xrightarrow{f_1} X_1 \rightarrow \dots \rightarrow X_{t-1} \xrightarrow{f_t} X_t = Y \quad (t \geq 0)$$

where  $X_i \in \text{ind } \mathcal{C}$  for all  $i$ . We then say that  $X$  is a *predecessor* of  $Y$  and that  $Y$  is a *successor* of  $X$ . A path from  $X$  to  $X$  involving at least one non-isomorphism is a *cycle*. A module  $X \in \text{ind } \mathcal{C}$  which lies on no cycle is *directed*. If each  $f_i$  in  $(\star)$  is irreducible, we say that  $(\star)$  is a *path of irreducible morphisms* or a *path in  $\Gamma(\text{mod } \mathcal{C})$* . A path  $(\star)$  of irreducible morphisms is *sectional* if  $\tau_{\mathcal{C}} X_{i+1} \neq X_{i-1}$  for all  $i$  with  $0 < i < t$ .

An indecomposable module  $M \in \mathcal{L}_A$  is *Ext-injective* in  $\text{add } \mathcal{L}_A$  if  $\text{Ext}_A^1(-, M)|_{\mathcal{L}_A} = 0$  (see [11]). This is the case if and only if  $\tau_A^{-1} M \notin \mathcal{L}_A$ .

The endomorphism algebra of the direct sum of the indecomposable projective modules lying in  $\mathcal{L}_A$  is called the *left support* of  $A$ . If  $A$  is *laura*, then its left support is a product of tilted algebras (see [5, 4.4, 5.1]).

An algebra  $A$  is *weakly shod* if the length of any path in  $\text{ind } A$  from an injective to a projective is bounded [20]. Also,  $A$  is *quasi-tilted* if its global dimension  $\text{gl.dim } A$  is at most two and  $\text{ind } A = \mathcal{L}_A \cup \mathcal{R}_A$ , see [28].

## 2 Preliminaries on covering functors

We recall some notions on covering functors. A  $k$ -linear functor  $F: \mathcal{E} \rightarrow \mathcal{B}$  is a *covering functor* if (see [14, 3.1]):

1.  $F^{-1}(x) \neq \emptyset$  for every  $x \in \mathcal{B}_o$ .
2. For every  $x, y \in \mathcal{E}_o$ , the two following  $k$ -linear maps are bijective:

$$\bigoplus_{F(y')=F(y)} \mathcal{E}(x, y') \rightarrow \mathcal{B}(F(x), F(y)), \quad \text{and} \quad \bigoplus_{F(x')=F(x)} \mathcal{E}(x', y) \rightarrow \mathcal{B}(F(x), F(y)) .$$

Following [25, § 3],  $F$  is a *Galois covering with group  $G$*  if there exists a group morphism  $G \rightarrow \text{Aut}(\mathcal{C})$  such that  $G$  acts freely on  $\mathcal{E}_o$ ,  $F \circ g = F$  for every  $g \in G$  and the functor  $\mathcal{E}/G \rightarrow \mathcal{B}$  induced by  $F$  is an isomorphism. We refer the reader to [25, 3.1] for the definition of  $\mathcal{E}/G$ . Galois coverings are covering functors.

If  $F: \mathcal{E} \rightarrow \mathcal{B}$  is a covering functor, then  $F$  defines an adjoint pair  $(F_\lambda, F_*)$  of functors  $F_\lambda: \text{MOD } \mathcal{E} \rightarrow \text{MOD } \mathcal{B}$  and  $F_*: \text{MOD } \mathcal{B} \rightarrow \text{MOD } \mathcal{E}$  (see [14, 3.2]). The functor  $F_*$  is called the *pull-up functor* and  $F_\lambda$  is called the *push-down functor*. We recall briefly their construction: If  $M \in \text{MOD } \mathcal{B}$ , then  $F_* M = M \circ F^{op}$ ; if  $M \in \text{MOD } \mathcal{E}$ , then  $F_\lambda M$  is the  $\mathcal{B}$ -module such that  $F_\lambda M(x) = \bigoplus_{F(\tilde{x})=x} M(\tilde{x})$ , for every  $x \in \mathcal{B}_o$ . Both  $F_\lambda$  and  $F_*$  are exact.

Let  $F: \mathcal{E} \rightarrow \mathcal{B}$  be a covering functor between locally bounded  $k$ -categories. We prove a few facts relative to  $F$ . Some of these are easy to prove in case  $F$  is a Galois covering. However, in general, the proofs are more complicated. This can be explained simply by the following fact:  $F^{op}: \mathcal{E}^{op} \rightarrow \mathcal{B}^{op}$  is also a covering functor, and  $D F_\lambda^{op} \simeq F_\lambda D$  if  $F$  is Galois. However, this isomorphism no longer exists in the general case of covering functors (see [14, 3.4], for instance).

As a motivation for the results in this section, we start with the following proposition which is essential in our paper. It is mainly due to Riedtmann (see [38, 2.2]). In the sequel, we use it without further reference.

**Proposition 2.1.** *Let  $A$  be a basic finite dimensional algebra. Let  $\Gamma$  be a component of  $\Gamma(\text{mod } A)$ . Let  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  be the universal Galois covering of translation quivers. Then there exists a well-behaved functor  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$ . If, moreover,  $\Gamma$  is generalised standard then  $p$  is a covering functor.*

**Proof:** The functor  $p$  was first constructed in [38, 2.2] for the stable part of the Auslander-Reiten quiver of a self-injective representation-finite algebra. The covering property was proved in [38, 2.3] under the same setting. The construction of  $p$  was generalised to any Auslander-Reiten component in [14, 3.1]. Finally, it is easy to check that the arguments given in [38, 2.3] to prove that  $p$  is a covering functor apply to the case of generalised standard components. ■

The results of this section will be applied to covering functors as in 2.1. We now turn to the general situation where  $F: \mathcal{E} \rightarrow \mathcal{B}$  is a covering functor between locally bounded  $k$ -categories.

Since  $F_\lambda$  and  $F$  are exact, we still have an adjunction at the level of derived categories. Here and in the sequel,  $\mathcal{D}(\text{MOD } \mathcal{E})$  and  $\mathcal{D}^b(\text{mod } \mathcal{E})$  denote the derived category of  $\mathcal{E}$ -modules and the bounded derived category of finite dimensional  $\mathcal{E}$ -modules, respectively. The following lemma is immediate. For a background on derived categories, we refer the reader to [26, Chap. III].

**Lemma 2.2.**  *$F_\lambda$  and  $F$  induce an adjoint pair  $(F_\lambda, F)$  of exact functors:*

$$\mathcal{D}(\text{MOD } \mathcal{E}) \xrightleftharpoons[F]{F_\lambda} \mathcal{D}(\text{MOD } \mathcal{B}) .$$

Moreover  $F_\lambda(\mathcal{D}^b(\text{mod } \mathcal{E})) \subseteq \mathcal{D}^b(\text{mod } \mathcal{B})$ . ■

Let  $x \in \mathcal{E}_o$ . By condition 2 in the definition of a covering functor,  $F$  induces a canonical isomorphism  $F_\lambda(\mathcal{E}(-, x)) \xrightarrow{\sim} \mathcal{B}(-, F(x))$  of  $\mathcal{B}$ -modules (see [14, 3.2]). In the sequel, we always identify these two modules by means of this isomorphism. Using this identification we get the following result.

**Lemma 2.3.** *Let  $M \in \mathcal{D}(\text{MOD } \mathcal{E})$ . Then  $F_\lambda$  induces two linear maps for every  $x \in \mathcal{B}_o$ :*

$$\bigoplus_{F(\tilde{x})=x} \mathcal{D}(\text{MOD } \mathcal{E})(M, \mathcal{E}(-, \tilde{x})) \rightarrow \mathcal{D}(\text{MOD } \mathcal{B})(F_\lambda M, \mathcal{B}(-, x)) ,$$

$$\text{and } \bigoplus_{F(\tilde{x})=x} \mathcal{D}(\text{MOD } \mathcal{E})(\mathcal{E}(-, \tilde{x}), M) \rightarrow \mathcal{D}(\text{MOD } \mathcal{B})(\mathcal{B}(-, x), F_\lambda M) .$$

These maps are functorial in  $M$ , and they are bijective if  $M$  is quasi-isomorphic to a bounded complex of finite dimensional projective modules (for example, if  $\text{gl.dim } \mathcal{E} < \infty$  and  $M \in \text{mod } \mathcal{E}$ ).

**Proof:** Let  $\varphi_M$  be the first map. If  $M = P[l]$  where  $l \neq 0$  and  $P$  is a projective  $\mathcal{E}$ -module, then  $\varphi_M$  is bijective (because  $\text{Ext}_{\mathcal{E}}^{-l}(P, \mathcal{E}(-, \tilde{x})) = 0$ ). Also, if  $M$  is an indecomposable projective  $\mathcal{E}$ -module, then  $\varphi_M$  is bijective (because  $F$  is a covering functor). Finally, if  $M \rightarrow M' \rightarrow M'' \rightarrow M[1]$  is a triangle in  $\mathcal{D}(\text{MOD } \mathcal{E})$ , then  $\varphi_M, \varphi_{M'}$  and  $\varphi_{M''}$  are bijective as soon as two of them are so. Consequently,  $\varphi_M$  is bijective if  $M$  is quasi-isomorphic to a bounded complex of finite dimensional projective  $\mathcal{E}$ -modules. The second map is handled similarly. ■

It is not always true that  $F_\lambda$  commutes with the Auslander-Reiten translation. However, we have the following.

**Lemma 2.4.** *Let  $X \in \text{ind } \mathcal{E}$  be such that  $F_\lambda X \in \text{ind } \mathcal{B}$  and  $\text{pd } X < \infty$ . Then  $\dim \tau_{\mathcal{E}} X = \dim \tau_{\mathcal{B}} F_\lambda X$ .*

**Proof:** Let  $X \in \text{mod } \mathcal{E}$  be any module. Let  $P_1 \rightarrow P_0 \rightarrow X \rightarrow 0$  be a minimal projective presentation in  $\text{mod } \mathcal{E}$ . By [14, 3.2], we deduce that  $F_\lambda P_1 \rightarrow F_\lambda P_0 \rightarrow F_\lambda X \rightarrow 0$  is a minimal projective presentation in  $\text{mod } \mathcal{B}$ . So we have exact sequences in  $\text{mod } \mathcal{E}^{op}$  and  $\text{mod } \mathcal{B}^{op}$ , respectively:

$$0 \rightarrow \text{Hom}_{\mathcal{E}}(X, \mathcal{E}) \rightarrow \text{Hom}_{\mathcal{E}}(P_0, \mathcal{E}) \rightarrow \text{Hom}_{\mathcal{E}}(P_1, \mathcal{E}) \rightarrow \text{Tr}_{\mathcal{E}} X \rightarrow 0 ,$$

$$\text{and } 0 \rightarrow \text{Hom}_{\mathcal{B}}(F_\lambda X, \mathcal{B}) \rightarrow \text{Hom}_{\mathcal{B}}(F_\lambda P_0, \mathcal{B}) \rightarrow \text{Hom}_{\mathcal{B}}(F_\lambda P_1, \mathcal{B}) \rightarrow \text{Tr}_{\mathcal{B}} F_\lambda X \rightarrow 0 ,$$

Let  $X \in \text{mod } \mathcal{E}$  be of finite projective dimension, thus quasi-isomorphic to a bounded complex of finite dimensional projective  $\mathcal{E}$ -modules. The bijections of 2.3 imply that  $\dim \text{Hom}_{\mathcal{E}}(X, \mathcal{E}) = \sum_{x \in \mathcal{E}_o} \dim \text{Hom}_{\mathcal{E}}(X, \mathcal{E}(-, x)) =$

$\sum_{x \in \mathcal{B}_o} \dim \text{Hom}_{\mathcal{B}}(X, \mathcal{B}(-, x)) = \dim \text{Hom}_{\mathcal{B}}(F_\lambda X, \mathcal{B})$ . Using the above exact sequences, we deduce that  $\dim \text{Tr}_{\mathcal{E}} X = \dim \text{Tr}_{\mathcal{B}} F_\lambda X$ . Whence the lemma in case  $X$  and  $F_\lambda X$  are indecomposable. ■

### 3 Standard lura algebras

In this section, our objective is to derive sufficient conditions for a lura algebra to be standard. Weakly shod algebras are particular cases of lura algebras. It is proved in [20, § 4] that if  $A$  is weakly shod and not quasi-tilted, then  $A$  can be written as a one-point extension  $A = B[M]$  such that the connecting component of  $A$  can be recovered from  $M$  and from the connecting components of  $B$ . This motivates the following definition.

**Definition 3.1.** Let  $A$  be a connected lura algebra which is not quasi-tilted of canonical type. An indecomposable projective  $A$ -module  $P$  lying in the connecting component  $\Gamma$  is a *maximal projective* if it has an injective predecessor and no projective proper successor in  $\text{ind } A$ . Furthermore,  $A$  is a *maximal extension* of  $B$  if there exists a maximal projective  $P = eA$  such that  $B = (1 - e)A(1 - e)$  and  $A = B[M]$ , where  $M = \text{rad } P$ .

By definition, a maximal projective belongs to  $\mathcal{R}_A$ . In particular, by [6, 2.2], it is directed. The notions of *minimal injective* or *maximal coextension* are defined dually. If  $A$  is a tilted algebra which is the endomorphism algebra of a regular tilting module, then it has neither maximal projective, nor minimal injective (see [41]).

**Proposition 3.2.** Let  $A = B[M]$  be a maximal extension. Then  $B$  is a product of lura algebras not quasi-tilted of canonical type. Moreover, if every connecting component of  $B$  is standard, then so is  $A$ .

**Proof:** Let  $P_m \in \text{ind } A$  be the maximal projective such that  $\text{rad } P_m = M$  and denote by  $\Gamma$  the component of  $\Gamma(\text{mod } A)$  in which  $P_m$  lies. So  $P_m \in \mathcal{R}_A \cap \Gamma$ . In particular,  $P_m$  is directed. Note that every proper predecessor of  $P_m$  is an indecomposable  $B$ -module.

Let us prove the first assertion. If it is false, then a connected component  $B'$  of  $B$  is quasi-tilted of canonical type. Since  $A$  is connected, at least one indecomposable summand  $M'$  of  $M$  lies in  $\text{ind } B'$ . Assume first that  $M'$  is not directed. In particular,  $M' \in \Gamma$  implies that  $M' \notin \mathcal{L}_A \cup \mathcal{R}_A$ . Therefore there is a non-sectional path  $M' \rightsquigarrow P$  in  $\text{ind } A$  with  $P$  projective. If  $P = P_m$ , then there exists a non-sectional path  $M' \rightsquigarrow M''$  with  $M''$  an indecomposable summand of  $M = \text{rad } P_m$ . This is impossible because  $P_m$  is directed (see [29, Thm. 1 of § 2]). So  $P \neq P_m$ . By maximality of  $P_m$ , the path  $M' \rightsquigarrow P$  is a non-sectional path in  $\text{ind } B'$  ending at a projective. So  $M' \notin \mathcal{R}_{B'}$ . On the other hand,  $M' \notin \mathcal{L}_A$  means that there exists a non-sectional path  $I \rightsquigarrow M'$  in  $\text{ind } A$ , where  $I$  is injective. By maximality of  $P_m$ , this is a non-sectional path in  $\text{ind } B'$ . For the same reason, we have  $\text{Hom}_A(P_m, I) = 0$ , so that  $I$  is injective as a  $B'$ -module. So  $M' \notin \mathcal{L}_{B'} \cup \mathcal{R}_{B'}$ . This is impossible because  $B'$  is quasi-tilted. Therefore  $M'$  is directed. Since  $B'$  is quasi-tilted of canonical type, the component  $\Gamma'$  of  $\Gamma(\text{mod } B')$  containing  $M'$  is either the unique postprojective or the unique preinjective component (see [35, Prop. 4.3]). Assume that  $\Gamma'$  is the unique postprojective component of  $\Gamma(\text{mod } B')$ . Then  $\Gamma' \subseteq \mathcal{L}_{B'} \setminus \mathcal{R}_{B'}$  (see [21, 5.2]). In particular, there exists a non-sectional path  $M' \rightsquigarrow P$  in  $\text{ind } B'$  with  $P$  projective. Since  $P_m$  is maximal, this is also a non-sectional path in  $\text{ind } A$ . Since  $P$  is projective and since  $M' \in \Gamma$ , we deduce that  $P \in \Gamma$  and that the path is refinable to a non-sectional path in  $\Gamma(\text{mod } A)$  and therefore in  $\Gamma(\text{mod } B')$  because  $P_m$  is maximal. Consequently,  $M'$  lies in the postprojective component  $\Gamma'$  of  $\Gamma(\text{mod } B')$  and is the starting point of a non-sectional path in  $\Gamma(\text{mod } B')$  ending at a projective. This is absurd. If  $\Gamma'$  is the unique preinjective component of  $\Gamma(\text{mod } B')$ , then, using dual arguments, we also get a contradiction. Thus,  $B'$  cannot be quasi-tilted of canonical type.

Now, we assume that every connected component of  $B$  is standard, and prove that  $A$  is standard. Later, in 5.7, we shall see that if  $A$  is tilted then all its connecting components are standard. So we assume that  $A$  is not tilted. Let  $\Gamma$  be the connecting component of  $\Gamma(\text{mod } A)$  and  $\Gamma'$  be the disjoint union of the connecting components of the Auslander-Reiten quivers of the components of  $B$ . We compare  $\Gamma$  and  $\Gamma'$ . More precisely, let  $\mathcal{X}$  be the full subquiver of  $\Gamma$  with vertices those modules which are not successors of  $P_m$ . So  $\mathcal{X}$  is a full subquiver of  $\Gamma(\text{mod } B)$  stable under predecessors in  $\Gamma(\text{mod } B)$ , and it contains  $\Gamma \setminus \mathcal{R}_A$ . We claim that  $\mathcal{X}$  is contained in  $\Gamma'$ . For this purpose, we prove a series of assertions.

(a) **The left supports of  $A$  and  $B$  coincide.** Indeed, we have  $\mathcal{L}_A \cap \text{ind } B \subseteq \mathcal{L}_B$  (see [4, 2.1]). On the other hand, if  $P \in \text{ind } B$  is a projective not lying in  $\mathcal{L}_A$ , then there is a non-sectional path  $I \rightsquigarrow P$  in  $\text{ind } A$  with  $I$  injective. Since  $P_m$  is maximal, this is a non-sectional path in  $\text{ind } B$ . For the same reason,  $\text{Hom}_A(P_m, I) = 0$ , so that  $I$  is injective as a  $B$ -module. So  $P \notin \mathcal{L}_B$ . Thus  $A$  and  $B$  have the same left support.

(b) **Let  $P \neq P_m$  be a projective lying in  $\Gamma$ . Then  $P \in \Gamma'$ .** Indeed, if there exists a path  $I \rightsquigarrow P$  in  $\Gamma$  with  $I$  injective, then the maximality of  $P_m$  implies that this path lies entirely in  $\text{ind } B$  and starts from an injective  $B$ -module. So  $P \in \Gamma'$ . If there is no such path, then  $P \in \mathcal{L}_A \cap \Gamma$ . So  $P$  lies in a connecting component of one of the components of the left support of  $A$ , which is also the left support of  $B$ . From [3, 5.4], we deduce that  $P$  lies in  $\Gamma'$ .

(c) **Let  $X \in \mathcal{X}$ . There exists  $m \geq 0$  such that  $\tau_A^m X \in \Gamma'$ .** By assumption on  $X$ , we have  $\tau_B X = \tau_A X$ . Assume first that  $\tau_A^m X = P$  for some  $m \geq 0$  and some projective  $P$ . So  $P \neq P_m$ . From (b), we get that  $P \in \Gamma'$ . Now assume that  $X$  is left stable and non-periodic. If  $X \in \mathcal{R}_A$ , there exists  $l \geq 0$  such that  $\tau_A^l X$  is Ext-projective in  $\mathcal{R}_A$ . Since  $X$  is left stable, we deduce that  $\tau_A^{l+1} X \in \Gamma \setminus \mathcal{R}_A$ . So we can assume that  $X \in \Gamma \setminus \mathcal{R}_A$ . Since  $A$  is lura, there exists  $m$  such that  $\tau_A^m X \in \Gamma \cap \mathcal{L}_A$ . So  $\tau_A^m X$  lies in one of the connecting components of the left support of  $A$ . So  $\tau_A^m X \in \Gamma'$  because the left supports of  $A$  and  $B$  are equal. Finally, assume that  $X$  is periodic.

Then there exists a projective module  $P \in \Gamma$ , a periodic direct summand  $Y$  of  $\text{rad}P$ , and a path  $Y \rightsquigarrow X$  in  $\Gamma \backslash \mathcal{R}_A$ , and therefore in  $\Gamma(\text{mod } B)$ . Since  $Y$  is periodic, then  $P \neq P_m$  (otherwise  $P_m$  would be a proper successor of itself). Since  $P \in \Gamma'$ , we have  $Y \in \Gamma'$  and therefore  $X \in \Gamma'$ .

**(d)  $\mathcal{X}$  is contained in  $\Gamma'$ .** Indeed, we already know that  $\mathcal{X}$  is a full subquiver of  $\Gamma(\text{mod } B)$ . Also, we proved that for every  $X \in \mathcal{X}$ , there exists  $m \geq 0$  such that  $\tau_A^m X = \tau_B^m X \in \Gamma'$ . So  $\mathcal{X}$  is contained in  $\Gamma'$ .

We now show that  $\Gamma$  is standard. By hypothesis, there exists a well-behaved functor  $\varphi: k(\Gamma') \rightarrow \text{ind } \Gamma'$ . Since  $\mathcal{X}$  is a full subquiver of  $\Gamma'$  stable under predecessors in  $\Gamma(\text{mod } B)$ , there exists a well-behaved functor  $\psi: k(\mathcal{Y}) \rightarrow \text{ind } \Gamma$  where  $\mathcal{Y}$  is a full subquiver of  $\Gamma$  such that:

1.  $\mathcal{Y}$  contains  $\mathcal{X}$ .
2.  $\mathcal{Y}$  is stable under predecessors in  $\Gamma(\text{mod } A)$ .
3.  $\psi$  and  $\varphi$  coincide on  $\mathcal{X}$ .
4.  $\mathcal{Y}$  is maximal for these properties.

We wish to show that  $\mathcal{Y} = \Gamma$ . Assume that  $\mathcal{Y} \neq \Gamma$ . Since  $\mathcal{Y}$  contains  $\mathcal{X}$ , it contains  $\Gamma \backslash \mathcal{R}_A$ , so there exists a source  $X$  in  $\Gamma \backslash \mathcal{Y}$ . If  $X$  is projective, then  $X = P_m$ . So  $\psi$  is defined on every indecomposable summand  $Y$  of  $\text{rad}P_m$ . We set  $\psi(X) = P_m$ . Let  $\alpha_1: X_1 \rightarrow P_m, \dots, \alpha_t: X_t \rightarrow P_m$  be the arrows ending at  $X$ . Then  $X_1 \oplus \dots \oplus X_t = \text{rad}P_m$ , and we let  $\psi(\alpha_i)$  be the inclusion  $X_i \hookrightarrow P_m$ . If  $X$  is not projective, then the mesh ending at  $X$  has the following shape:

$$\begin{array}{ccccc} & & X_1 & & \\ & \nearrow^{u_1} & & \searrow_{v_1} & \\ \tau_A X & & & & X \\ & \searrow_{u_n} & \vdots & \nearrow_{v_n} & \\ & & X_n & & \end{array} \quad (\star)$$

Since  $X$  is a source of  $\Gamma \backslash \mathcal{Y}$ , then  $\psi$  is already defined on the full subquiver of the mesh consisting of all vertices except  $X$ . In particular, the following map is right minimal almost split:

$$[\psi(u_1) \quad \dots \quad \psi(u_n)]^t : \tau_A X \rightarrow X_1 \oplus \dots \oplus X_n.$$

We let  $\psi(X) = X$ , and  $[\psi(v_1) \quad \dots \quad \psi(v_n)] : X_1 \oplus \dots \oplus X_n \rightarrow X$  be the cokernel of the above map. This construction is inspired from [14, 3.1, Ex. b]. Clearly, this construction contradicts the maximality of  $\mathcal{Y}$ . So  $\mathcal{Y} = \Gamma$  and there exists a well-behaved functor  $\psi: k(\Gamma) \rightarrow \text{ind } \Gamma$  which is the identity on objects. The arguments in the proof of [14, 5.1] show that this is an isomorphism. So  $\Gamma$  is standard.  $\blacksquare$

**Corollary 3.3.** *Let  $A$  be a weakly shod algebra not quasi-tilted of canonical type, then  $A$  is standard.*

**Proof:** By [6, 3.3], there exists a sequence of full convex subcategories

$$C = A_0 \subsetneq A_1 \subsetneq \dots \subsetneq A_m = A$$

with  $C$  tilted and, for each  $i \geq 0$ , the algebra  $A_{i+1}$  is a maximal extension of  $A_i$ . The result follows from 3.2 and induction because  $C$  is standard (see 5.7 below).  $\blacksquare$

The preceding result motivates the following definition, inspired from [6, 2.3].

**Definition 3.4.** Let  $A$  be a lura algebra. We say that  $A$  admits a *maximal filtration* if there exists a sequence

$$C = A_0 \subsetneq A_1 \subsetneq \dots \subsetneq A_m = A \quad (f)$$

of full convex subcategories with  $C$  a product of representation-finite algebras and, for each  $i \geq 0$ , the algebra  $A_{i+1}$  is a maximal extension, or a maximal coextension, of  $A_i$ .

**Corollary 3.5.** *Let  $A$  be a lura algebra admitting a maximal filtration (f):*

- (a) *If  $C$  is a product of standard representation-finite algebras, then  $A$  is standard.*
- (b) *If the Auslander-Reiten quiver of every connected component of  $C$  is simply connected, then  $A$  is standard.*
- (c) *If  $\text{HH}^1(A) = 0$ , then  $A$  is standard.*

**Proof:** Statement (a) follows directly from 3.2.

(b) This follows from 3.2 and the fact that if a representation-finite connected algebra  $C$  has vanishing first Hochschild cohomology group  $\text{HH}^1(C)$ , or equivalently, if its Auslander-Reiten quiver is simply connected, then  $C$  is standard [15, 4.2].

(c) We use induction on the length  $m$  of a maximal filtration. If  $m = 0$ , then  $A$  is representation-finite and the result follows from [15, 4.2]. Now assume that  $m \geq 1$  and that the statement holds for algebras admitting maximal filtrations of length less than  $m$ . Without loss of generality, we may assume that  $A = A_{m-1}[M]$  is a maximal extension. We claim that  $\text{Ext}_{A_{m-1}}^1(M, M) = 0$ . Indeed, if this is not the case, then there exists

an indecomposable summand  $N$  of  $M$  such that  $\text{Ext}_{A_{m-1}}^1(M, N) \neq 0$ . Write  $M \simeq N \oplus N'$  and let  $P$  be the indecomposable projective such that  $M = \text{rad} P$ . Then  $N'$  is a submodule of  $P$  and  $L = P/N'$  is indecomposable. By [28, III.2.2, (a)] we have  $\text{id} L \geq 2$ . But this contradicts the fact that  $L \in \mathcal{R}_A$  because it is a successor of the maximal projective  $P$ . So  $\text{Ext}_{A_{m-1}}^1(M, M) = 0$ . Applying [27, 5.3], the exact sequence

$$\text{HH}^1(A) \rightarrow \text{HH}^1(A_{m-1}) \rightarrow \text{Ext}_{A_{m-1}}^1(M, M) .$$

yields  $\text{HH}^1(A_{m-1}) = 0$ . By the induction hypothesis,  $A_{m-1}$  is standard. By 3.2, so is  $A$ .  $\blacksquare$

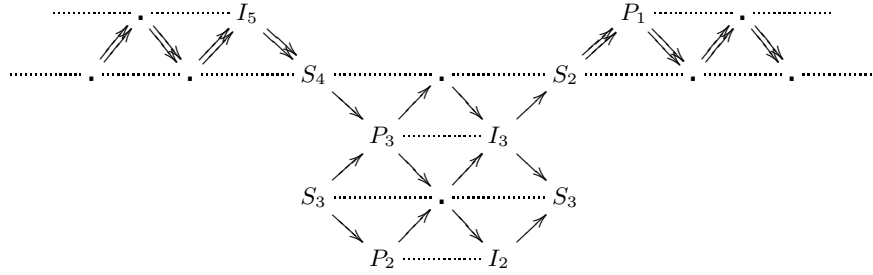
*Examples 3.6.* (a) Let  $A$  be the radical-square zero algebra given by the quiver

$$1 \begin{array}{c} \leftarrow \\ \rightarrow \end{array} 2 \begin{array}{c} \leftarrow \\ \rightarrow \end{array} 3 \begin{array}{c} \leftarrow \\ \rightarrow \end{array} 4 \begin{array}{c} \leftarrow \\ \rightarrow \end{array} 5 .$$

This is a lura algebra (see [3, 2.3]). Here and in the sequel, we denote by  $P_x$ ,  $I_x$  and  $S_x$  the indecomposable projective, the indecomposable injective, and the simple corresponding to the vertex  $x$ , respectively. It is easily seen that  $P_5$  is maximal projective and  $I_1$  is minimal injective. Letting  $C$  be the representation-finite full convex subcategory with objects  $\{2, 3, 4\}$  we see that

$$C \subsetneq [S_2 \oplus S_2]C \subsetneq A$$

is a maximal filtration. Since  $C$  is standard, so is  $A$ . The connecting component is drawn below:



where the two copies of  $S_3$  are identified.

- (b) Let  $B, C$  be products of standard lura algebras, and  $A$  an articulation of  $B, C$  (in the sense of [24]). Then  $A$  is lura not quasi-tilted of canonical type (see *loc. cit.*). Using the description of the connecting component of  $A$  (see [24, 3.9]) it is easy to check that  $A$  is standard.

The section motivates the following questions.

**Problem 1.** Which lura algebras admit maximal filtrations?

**Problem 2.** Assume that  $A$  is a lura algebra which does not admit a maximal filtration. If  $\text{HH}^1(A) = 0$ , do we have that  $A$  is standard?

## 4 Tilting modules of the first kind with respect to covering functors

For tilting theory, we refer to [9]. Let  $B$  be a product of tilted algebras and  $n$  be the rank of its Grothendieck group. In [34, Cor. 4.5], it is proved that tilting modules are of the first kind with respect to any Galois covering of  $B$ . More precisely, let  $F: \tilde{B} \rightarrow B$  be a Galois covering with group  $G$ , where  $\tilde{B}$  is locally bounded. Denote by  $\mathcal{T}$  the class of complexes  $T \in \mathcal{D}^b(\text{mod } B)$  such that:

1.  $T$  is multiplicity-free and has  $n$  indecomposable summands.
2.  $\mathcal{D}^b(\text{mod } B)(T, T[i]) = 0$  for every  $i \geq 1$  (so  $T$  is a *silting complex* in the sense of [30]).
3.  $T$  generates the triangulated category  $\mathcal{D}^b(\text{mod } B)$ .

Any multiplicity-free tilting module lies in  $\mathcal{T}$ . It was proved in [34, § 4] that for any  $T \in \mathcal{T}$  and for any indecomposable summand  $X$  of  $T$ , there exists  $\tilde{X} \in \mathcal{D}^b(\text{mod } \tilde{B})$  such that:

1.  $F_\lambda \tilde{X} \simeq X$ .
2.  ${}^g \tilde{X} \not\simeq {}^h \tilde{X}$  for  $g \neq h$ .
3. If  $Y \in \mathcal{D}^b(\text{mod } \tilde{B})$  is such that  $F_\lambda Y \simeq X$ , then  $Y \simeq {}^g \tilde{X}$  for some  $g \in G$ .

Given  $T \in \mathcal{T}$  and an indecomposable summand  $X$  of  $T$ , we fix  $\tilde{X} \in \mathcal{D}^b(\text{mod } \tilde{B})$  arbitrarily such that  $F_\lambda \tilde{X} \simeq X$ .

For later reference, we recall some facts on the objects  $\tilde{X}$  when  $T$  is a tilting module. The following result was proved in [34, Lem. 3.7].

**Lemma 4.1.** Let  $F: \tilde{B} \rightarrow B$  be a Galois covering with group  $G$ . Let  $T \in \text{mod } B$  be a multiplicity-free tilting module. Let  $T = T_1 \oplus \dots \oplus T_n$  be an indecomposable decomposition. For every  $i$ , there exists  $\tilde{T}_i \in \text{ind } \tilde{B}$  such that  $F_\lambda \tilde{T}_i = T_i$ . Moreover:

- (a)  ${}^g \tilde{T}_i \not\simeq {}^h \tilde{T}_j$  for  $(g, i) \neq (h, j)$ .
- (b)  $\text{pd } \tilde{T}_i \leq 1$  for every  $i$ .
- (c)  $\text{Ext}_{\tilde{B}}^1({}^g \tilde{T}_i, {}^h \tilde{T}_j) = 0$  for every  $g, h, i, j$ .
- (d) For every indecomposable projective  $\tilde{B}$ -module  $P$ , there exists an exact sequence  $0 \rightarrow P \rightarrow T^{(1)} \rightarrow T^{(2)} \rightarrow 0$  with  $T^{(1)}, T^{(2)}$  in  $\text{add } \{{}^g \tilde{T}_i \mid g \in G, i \in \{1, \dots, n\}\}$ .

■

We shall use similar facts about covering functors which need not be Galois. Therefore we prove the following result.

**Proposition 4.2.** Let  $F: \tilde{B} \rightarrow B$  be a Galois covering with group  $G$ , where  $\tilde{B}$  is locally bounded. With the above setting, let  $p: \tilde{B} \rightarrow B$  be a covering functor such that  $F(x) = p(x)$  for every  $x \in \tilde{B}_0$ . Let  $T \in \mathcal{T}$  and  $X$  be an indecomposable summand of  $T$ . Then:

- (a) There exists an isomorphism  $p_\lambda({}^g \tilde{X}) \xrightarrow{\sim} X$ , for every  $g \in G$ .
- (b) If  $M \in \mathcal{D}^b(\text{mod } \tilde{B})$  is such that  $p_\lambda M \simeq X$ , then  $M \simeq {}^g \tilde{X}$  for some  $g \in G$ .
- (c) For every  $M \in \mathcal{D}^b(\text{mod } \tilde{B})$ , the following maps induced by  $p_\lambda$  and by the isomorphisms of (a) are linear bijections:

$$\begin{aligned} \varphi_{X,M}: \bigoplus_{g \in G} \mathcal{D}^b(\text{mod } \tilde{B})({}^g \tilde{X}, M) &\xrightarrow{\sim} \mathcal{D}^b(\text{mod } B)(X, p_\lambda M), \\ \text{and } \psi_{X,M}: \bigoplus_{g \in G} \mathcal{D}^b(\text{mod } \tilde{B})(M, {}^g \tilde{X}) &\xrightarrow{\sim} \mathcal{D}^b(\text{mod } B)(p_\lambda M, X). \end{aligned}$$

In order to prove the proposition, we need the following lemma. In case  $p$  a Galois covering, the lemma was proved in [34, Lems. 4.2, 4.3] (see also [33, Lems. 3.2, 3.3]). For simplicity, we write  $\text{Hom}(X, Y)$  for the space of morphisms in the derived category.

**Lemma 4.3.** Let  $T, T' \in \mathcal{T}$  be such that 4.2 holds true for  $T$  and for  $T'$ . Consider a triangle in  $\mathcal{D}^b(\text{mod } B)$ :

$$X \rightarrow X'_1 \oplus \dots \oplus X'_t \rightarrow Y \rightarrow X[1], \quad (\Delta)$$

where  $X \in \text{add } T$  and  $X'_1, \dots, X'_t$  are indecomposable summands of  $T'$ . Assume that  $\text{Hom}(Y, X'_i[1]) = 0$  for all  $i$  (we do not assume that  $Y \in \text{add } T$  or  $Y \in \text{add } T'$ ). Then for every  $g \in G$ , there exist  $\tilde{Y} \in \mathcal{D}^b(\text{mod } \tilde{B})$  and  $g_1, \dots, g_t \in G$  such that the triangle  $\Delta$  is isomorphic to the image under  $p_\lambda$  of a triangle in  $\mathcal{D}^b(\text{mod } \tilde{B})$  as follows:

$${}^g \tilde{X} \rightarrow {}^{g_1} \tilde{X}'_1 \oplus \dots \oplus {}^{g_t} \tilde{X}'_t \rightarrow \tilde{Y} \rightarrow {}^g \tilde{X}[1].$$

Dually, consider a triangle in  $\mathcal{D}^b(\text{mod } B)$ :

$$Y \rightarrow X'_1 \oplus \dots \oplus X'_t \rightarrow X \rightarrow Y[1], \quad (\Delta')$$

where  $X \in \text{add } T$  and  $X'_1, \dots, X'_t$  are indecomposable summands of  $T'$ . Assume that  $\text{Hom}(X'_i, Y[1]) = 0$  for all  $i$ . Then for every  $g \in G$ , there exist  $\tilde{Y} \in \mathcal{D}^b(\text{mod } \tilde{B})$  and  $g_1, \dots, g_t \in G$  such that the triangle  $\Delta'$  is isomorphic to the image under  $p_\lambda$  of a triangle in  $\mathcal{D}^b(\text{mod } \tilde{B})$  as follows:

$$\tilde{Y} \rightarrow {}^{g_1} \tilde{X}'_1 \oplus \dots \oplus {}^{g_t} \tilde{X}'_t \rightarrow {}^g \tilde{X} \rightarrow \tilde{Y}[1].$$

**Proof:** The proofs of [34, Lems. 4.2, 4.3] use the following key property of a Galois covering  $F: \tilde{B} \rightarrow B$  with group  $G$ . Given  $L, M \in \mathcal{D}^b(\text{mod } \tilde{B})$ , the two following linear maps induced by  $F_\lambda$  are bijective:

$$\bigoplus_{g \in G} \text{Hom}({}^g L, M) \xrightarrow{\sim} \text{Hom}(F_\lambda L, F_\lambda M) \text{ and } \bigoplus_{g \in G} \text{Hom}(L, {}^g M) \xrightarrow{\sim} \text{Hom}(F_\lambda L, F_\lambda M).$$

Of course, these bijections no longer exist for a covering functor which is not Galois. However, using our hypothesis that 4.2 holds true for  $T$  and for  $T'$ , it is easy to check that the proofs of [34, Lems. 4.2, 4.3] still work in the present case. Whence the lemma. ■

**Proof of 4.2:** We proceed in several steps.

**Step 1: If  $T = B$ , then 4.2 holds true.** The following facts are direct consequences of the definition of a covering functor (see also [14, 3.2]):

1.  $Y \in \mathcal{D}^b(\text{mod } \tilde{B})$  is a projective module if and only if  $p_\lambda Y$  is a projective module.
2.  $p_\lambda(\tilde{B}(-, x)) \simeq F_\lambda(\tilde{B}(-, x)) \simeq B(-, F(x)) = B(-, p(x))$  for every  $x \in \tilde{B}_o$ .
3.  ${}^g\tilde{B}(-, x) = \tilde{B}(-, gx)$  for every  $x \in \tilde{B}_o$  and every  $g \in G$ .

Therefore 4.2 holds true for  $T = B$ .

Given an object  $X$  in a triangulated category, we write  $\langle X \rangle$  for the smallest full subcategory containing  $X$  which is stable under sums, summands and shifts (in both directions).

**Step 2: If  $T, T' \in \mathcal{T}$  are such that  $T' \in \langle T \rangle$ , then 4.2 holds true for  $T$  if and only if it does for  $T'$ .** This follows directly from the compatibility of  $p_\lambda$  with the shift.

For the next step, we consider the following situation. Assume that  $T, T' \in \mathcal{T}$  are such that:

1.  $T = M \oplus \overline{T}$ , where  $M$  is indecomposable.
2.  $T' = M' \oplus \overline{T}$ , where  $M'$  is indecomposable.
3. There exists a non-split triangle  $\Delta : M \xrightarrow{u} E \xrightarrow{v} M' \rightarrow M[1]$  where  $u$  is a left minimal  $\text{add } \overline{T}$ -approximation and  $v$  is a right minimal  $\text{add } \overline{T}$ -approximation.

**Step 3: If  $T, T' \in \mathcal{T}$  are as above, then 4.2 holds true for  $T$  if and only if it does for  $T'$ .** We prove that the condition is necessary. Clearly it suffices to prove that the assertions (a), (b), and (c) of 4.2 are true for  $M'$ . For simplicity, we identify  $p_\lambda({}^g\tilde{X})$  and  $X$  via the isomorphism used to define  $\varphi_{X,-}$  and  $\psi_{X,-}$  for every indecomposable summand  $X$  of  $T$  and  $g \in G$ .

Fix an indecomposable decomposition  $E = \bigoplus_{i=1}^t E_i$ . Recall from [34, Lem. 4.4] that  $\Delta$  is isomorphic to the image under  $F_\lambda$  of a triangle  $\tilde{\Delta}$  in  $\mathcal{D}^b(\text{mod } \tilde{B})$ :

$$\tilde{M} \xrightarrow{\tilde{u}} \bigoplus_{i=1}^t {}^{g_i}\tilde{E}_i \xrightarrow{\tilde{v}} {}^{g_0}\tilde{M}' \rightarrow \tilde{M}[1], \quad (\tilde{\Delta})$$

for some  $g_0, g_1, \dots, g_t \in G$ . Moreover,  $\tilde{u}$  is a left minimal  $\text{add } \mathcal{X}$ -approximation and  $\tilde{v}$  is a right minimal  $\text{add } \mathcal{X}'$ -approximation, where  $\mathcal{X}$  and  $\mathcal{X}'$  are the following full subcategories of  $\mathcal{D}^b(\text{mod } \tilde{B})$ :

- $\mathcal{X} = \{{}^g\tilde{X} \mid g \in G, X \text{ an indecomposable summand of } T \text{ and } {}^g\tilde{X} \not\cong \tilde{M}\}.$
- $\mathcal{X}' = \{{}^g\tilde{X} \mid g \in G, X \text{ an indecomposable summand of } T' \text{ and } {}^g\tilde{X} \not\cong \tilde{M}'\}.$

Fix  $g \in G$ . Since 4.2 holds for  $T$ , we may apply 4.3 to construct a triangle  $\tilde{\Delta}' : {}^g\tilde{M} \xrightarrow{\tilde{u}'} \bigoplus_{i=1}^t {}^{g'_i}\tilde{E}_i \xrightarrow{\tilde{v}'} Z_g \rightarrow {}^g\tilde{M}[1]$  whose image under  $p_\lambda$  is isomorphic to  $\Delta$ . In particular,  $p_\lambda(Z_g) \simeq M'$ . For simplicity, we assume that  $\Delta$  is equal to the image of  $\tilde{\Delta}$  under  $p_\lambda$ , and we set  $\tilde{E}' = \bigoplus_{i=1}^t {}^{g'_i}\tilde{E}_i$ . Let us prove that  $Z_g \simeq {}^{g_0}\tilde{M}'$ . It suffices to prove that  $\tilde{\Delta}'$  and  ${}^g\tilde{\Delta}$  are isomorphic. For this purpose, we only need to prove that  $\tilde{u}'$  is a left minimal  $\text{add } {}^g\mathcal{X}$ -approximation. Let  $f : {}^g\tilde{M} \rightarrow {}^{g'}\tilde{Y}$ , where  $Y$  is an indecomposable summand of  $T$  such that  ${}^{g'}\tilde{Y} \in {}^g\mathcal{X}$ . Since  $\varphi_{M, \tilde{M}}$  is bijective and since  $\text{End}(M) = k$ , we have  $Y \in \text{add } \overline{T}$ . So we have a factorisation by  $u = p_\lambda(\tilde{u}')$ :

$$\begin{array}{ccc} M & \xrightarrow{u} & E \\ & \searrow p_\lambda(f) & \downarrow f' \\ & & Y \end{array} .$$

Since  $\psi_{Y, \tilde{E}_i}$  is bijective for every  $i$ , we have  $f' = \sum_{h \in G} p_\lambda(f'_h)$ , where  $(f'_h)_h \in \bigoplus_{h \in G} \text{Hom}(\tilde{E}, {}^h\tilde{Y})$ . So  $p_\lambda(f - f'_g, \tilde{u}') - \sum_{h \neq g'} p_\lambda(f'_h \tilde{u}') = 0$ . Using 4.2, we get  $f = f'_g, \tilde{u}'$ . Hence  $\tilde{u}'$  is a left  $\text{add } {}^g\mathcal{X}$ -approximation. On the other hand,  $\tilde{u}'$  is left minimal because  $u = p_\lambda(\tilde{u}')$  is left minimal and  $p_\lambda$  is exact. As explained above, these facts imply that  $Z_g \simeq {}^{g_0}\tilde{M}'$ . So  $p_\lambda({}^g\tilde{M}') \simeq M'$ , for every  $g \in G$ .

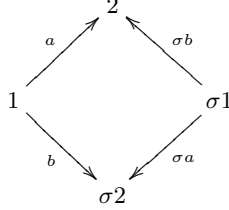
Let  $Y \in \mathcal{D}^b(\text{mod } \tilde{B})$ . Using the triangles  ${}^g\tilde{\Delta}$  ( $g \in G$ ) and using that 4.2 holds true for  $T$ , the maps  $\varphi_{M', Y}$  and  $\psi_{M', Y}$  are bijective (recall that  $\text{Hom}$ -functors are cohomological).

Finally, if  $Y \in \mathcal{D}^b(\text{mod } \tilde{B})$ , and if  $f : p_\lambda Y \rightarrow M'$  is an isomorphism, then  $f = \sum_{g \in G} p_\lambda(f_g)$  with  $(f_g)_g \in \bigoplus_{g \in G} \text{Hom}(Y, {}^g\tilde{M}')$ . Since  $p_\lambda Y$  and  $M'$  are indecomposable, there exists  $g_1 \in G$  such that  $p_\lambda(f_{g_1})$  is an isomorphism. Since  $p_\lambda$  is exact, we deduce that  $f_{g_1} : Y \rightarrow {}^{g_1}\tilde{M}'$  is an isomorphism. This finishes the proof of the

assertion: 4.2 holds true for  $T'$  if it holds true for  $T$ . The converse implication is proved using similar arguments.

**Step 4: If  $T \in \mathcal{T}$ , then 4.2 holds true.** This follows directly from the three preceding steps, and from [34, Prop. 3.6].  $\blacksquare$

*Example 4.4.* Let  $B = kQ$  be the path algebra of the Kronecker quiver  $1 \begin{smallmatrix} \xrightarrow{a} \\ \xrightarrow{b} \end{smallmatrix} 2$ . There is a Galois covering  $F: \tilde{B} \rightarrow B$  with group  $\mathbb{Z}/2\mathbb{Z} = \{1, \sigma\}$ , where  $\tilde{B} = k\tilde{Q}$  is the path algebra of the following quiver:



and where  $F$  is the functor such that  $F(\sigma^i \alpha) = \alpha$  for every arrow  $\alpha$  and every  $i \in \{0, 1\}$ . On the other hand, there is a covering functor  $p: B' \rightarrow B$  such that  $p(a) = p(\sigma b) = b$ ,  $p(a) = a$  and  $p(\sigma a) = a + b$ . The module  $T = e_2 B \oplus \tau_B^{-1}(e_1 B)$  is tilting. One checks easily that  $F_\lambda(e_2 \tilde{B}) = e_2 B$ ,  $F_\lambda(\tau_{\tilde{B}}^{-1}(e_1 \tilde{B})) = \tau_B^{-1}(e_1 B)$  and that  $p_\lambda(e_2 \tilde{B}) \simeq e_2 B$ ,  $p_\lambda(\tau_{\tilde{B}}^{-1}(e_1 \tilde{B})) \simeq \tau_B^{-1}(e_1 B)$ .

## 5 Coverings of left sections

Let  $A$  be a basic finite dimensional  $k$ -algebra,  $\Gamma$  a component of  $\Gamma(\mathbf{mod} A)$ ,  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  the universal cover of translation quivers and  $p: k(\tilde{\Gamma}) \rightarrow \mathbf{ind} \Gamma$  a well-behaved covering functor. A *left section* (see [1, 2.1]) in  $\Gamma$  is a full subquiver  $\Sigma$  such that:  $\Sigma$  is acyclic; it is convex in  $\Gamma$ ; and, for any  $x \in \Gamma$ , predecessor in  $\Gamma$  of some  $y \in \Sigma$ , there exists a unique  $n \geq 0$  such that  $\tau^{-n} x \in \Sigma$ . Assume that  $\Sigma$  is a left section in  $\Gamma$  and let  $B = A/\mathbf{Ann} \Sigma$ . In this section, we construct a covering functor  $F: \tilde{B} \rightarrow B$  associated to  $p$  and we construct a functor  $\varphi: k(\tilde{\Gamma}) \rightarrow \mathbf{mod} \tilde{B}$ . Both  $F$  and  $\varphi$  are essential in the proofs of Theorems A and B.

By [1, Thm. A], the algebra  $B$  is a full convex subcategory of  $A$  and a product of tilted algebras and the components of  $\Sigma$  form complete slices of the components of  $B$ . So we assume that  $Q$  is a finite quiver with no oriented cycle and  $T \in \mathbf{mod} kQ$  is a tilting module such that  $B = \mathbf{End}_{kQ}(T)$ . Any module  $X \in \mathbf{mod} B$  defines the  $\Sigma$ -module  $\mathbf{Hom}_B(\Sigma, X)$  which, as a functor, assigns the vector space  $\mathbf{Hom}_B(E, X)$  to the object  $E$  of  $\Sigma$ . By the above properties of  $B$ , the map  $x \mapsto \mathbf{Hom}_{kQ}(T, D(kQe_x))$  defines an isomorphism of  $k$ -categories  $kQ \xrightarrow{\sim} \Sigma$ . We denote by  $\Gamma_{\leq \Sigma}$  the full subquiver of  $\Gamma$  generated by all the predecessors of  $\Sigma$  in  $\Gamma$ .

### The covering of the left section $\Sigma$

Let  $\tilde{\Sigma}$  be the full subcategory of  $k(\tilde{\Gamma})$  whose objects are the points  $x \in k(\tilde{\Gamma})$  such that  $p(x) \in \Sigma$ . Therefore  $p: k(\tilde{\Gamma}) \rightarrow \mathbf{ind} \Gamma$  induces a covering functor  $p: \tilde{\Sigma} \rightarrow \Sigma$ . Note that  $\tilde{\Sigma}$  and  $\tilde{\Gamma}_{\leq \tilde{\Sigma}}$  are stable under  $\pi_1(\Gamma)$ , as subquivers of  $\tilde{\Gamma}$ . Since  $\Sigma$  is hereditary, so is  $\tilde{\Sigma}$ . Therefore we have  $\tilde{\Sigma} = k\tilde{Q}$  for some quiver  $\tilde{Q}$ . In particular, the isomorphism  $kQ \xrightarrow{\sim} \Sigma$  and the covering functor  $p: \tilde{\Sigma} \rightarrow \Sigma$  defines a covering functor  $q: k\tilde{Q} \rightarrow kQ$ .

### The covering functor of $B$

Since  $\pi$  and  $p$  coincide on vertices,  $\pi$  induces a Galois covering of quivers  $\pi: \tilde{Q} \rightarrow Q$  with group  $\pi_1(\Gamma)$ . We write  $\pi: k\tilde{Q} \rightarrow kQ$  for the induced Galois covering with group  $\pi_1(\Gamma)$ . Note that  $\tilde{Q}$  is a disjoint union of copies of the universal cover of  $Q$  because  $\tilde{\Gamma}$  is simply connected. Also, remark that thanks to the Galois covering  $\pi: \tilde{Q} \rightarrow Q$  there is an action of  $\pi_1(\Gamma)$  on  $\mathbf{mod} k\tilde{Q}$ . Let  $T = T_1 \oplus \dots \oplus T_n$  be an indecomposable decomposition and  $\tilde{B}$  be the full subcategory of  $\mathbf{mod} k\tilde{Q}$  with objects the modules  ${}^g \tilde{T}_i$  (with  $i \in \{1, \dots, n\}$ ,  $g \in \pi_1(\Gamma)$ , see 4.3).

**Lemma 5.1.** *The  $k$ -category  $\tilde{B}$  is locally bounded. The push-down functor  $p_\lambda: \mathbf{mod} k\tilde{Q} \rightarrow \mathbf{mod} kQ$  induces a covering functor:*

$$\begin{aligned} F: \quad \tilde{B} &\rightarrow B \\ {}^g \tilde{T}_i &\mapsto T_i = p_\lambda({}^g \tilde{T}_i) \end{aligned}$$

Moreover, if  $p: k(\tilde{\Gamma}) \rightarrow \mathbf{ind} \Gamma$  is a Galois covering with group  $\pi_1(\Gamma)$ , then so is  $F$ .

**Proof:** We apply the results of the preceding section to the covering functor  $q: k\tilde{Q} \rightarrow kQ$  and the Galois covering  $\pi: k\tilde{Q} \rightarrow kQ$ . The first assertion follows from 4.1 and 4.2, and the second follows from 4.2. Finally, the last

assertion was proved in [33, Lem. 2.2]. ■

We also have a Galois covering  $\tilde{B} \rightarrow B$  induced by the push-down  $\pi_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$  (see [33, Lem. 2.2]). In particular, the covering functor  $F: \tilde{B} \rightarrow B$  and the Galois covering  $\tilde{B} \rightarrow B$  coincide on objects. Therefore we may apply the results of the preceding section to  $F$ .

In the sequel, we write  $\tilde{T}$  for the  $k\tilde{Q}$ -module  $\bigoplus \{ {}^g \tilde{T}_i \mid i \in \{1, \dots, n\}, g \in \pi_1(\Gamma) \}$ . Although  $\tilde{T}$  is not necessarily finite dimensional, it follows from 4.2 that it induces a well-defined functor:

$$\text{Hom}_{k\tilde{Q}}(\tilde{T}, -): \text{mod } k\tilde{Q} \rightarrow \text{mod } \tilde{B}.$$

More precisely, if  $X \in \text{mod } k\tilde{Q}$ , then  $\text{Hom}_{k\tilde{Q}}(\tilde{T}, X)$  is the  $\tilde{B}$ -module defined by  ${}^g \tilde{T}_i \mapsto \text{Hom}_{k\tilde{Q}}({}^g \tilde{T}_i, X)$ . In particular, an object  $x$  in  $\tilde{\Sigma} = k\tilde{Q}$  defines the injective  $k\tilde{Q}$ -module  $D(k\tilde{Q}(x, -))$  which gives rise to the  $\tilde{B}$ -module  $\text{Hom}_{k\tilde{Q}}(\tilde{T}, D(k\tilde{Q}(x, -)))$ . Therefore every  $\tilde{B}$ -module  $X$  defines a  $\tilde{\Sigma}$ -module:

$$\begin{aligned} \tilde{\Sigma}^{\text{op}} &\rightarrow \text{mod } k \\ x &\mapsto \text{Hom}_{\tilde{B}}(\text{Hom}_{k\tilde{Q}}(\tilde{T}, D(k\tilde{Q}(x, -))), X) \end{aligned}.$$

For reasons that will become clear later, this module is denoted by  $\text{Hom}_{\tilde{B}}(\tilde{\Sigma}, X)$ . This way, we get a functor  $\text{Hom}_{\tilde{B}}(\tilde{\Sigma}, -): \text{mod } \tilde{B} \rightarrow \text{mod } \tilde{\Sigma}$ . We need the following result for later reference.

**Lemma 5.2.** *The following diagram commutes up to isomorphism of functors:*

$$\begin{array}{ccccc} \text{mod } k\tilde{Q} & \xrightarrow{\text{Hom}_{k\tilde{Q}}(\tilde{T}, -)} & \text{mod } \tilde{B} & \xrightarrow{\text{Hom}_{\tilde{B}}(\tilde{\Sigma}, -)} & \text{mod } \tilde{\Sigma} \\ q_\lambda \downarrow & & \downarrow F_\lambda & & \downarrow p_\lambda \\ \text{mod } kQ & \xrightarrow{\text{Hom}_{kQ}(T, -)} & \text{mod } B & \xrightarrow{\text{Hom}_B(\Sigma, -)} & \text{mod } \Sigma \end{array}.$$

Moreover:

- (a) *The two top horizontal arrows are  $\pi_1(\Gamma)$ -equivariant.*
- (b) *If  $\theta: \text{mod } kQ \rightarrow \text{mod } \Sigma$  (or  $\tilde{\theta}: \text{mod } k\tilde{Q} \rightarrow \text{mod } \tilde{\Sigma}$ ) denotes the composition of the two bottom (or top) horizontal arrows, then it induces an equivalence from the full subcategory of injective  $kQ$ -modules (or injective  $k\tilde{Q}$ -modules) to the full subcategory of projective  $\Sigma$ -modules (or projective  $\tilde{\Sigma}$ -modules, respectively).*
- (c) *Let  $\tilde{\alpha}: \tilde{I} \rightarrow \tilde{J}$  be a surjective morphism between injective  $k\tilde{Q}$ -modules. Let  $\alpha: I \rightarrow J$  be equal to  $q_\lambda(\tilde{\alpha})$ . Then  $F_\lambda$  maps the connecting morphism  $\text{Hom}_{k\tilde{Q}}(\tilde{T}, \tilde{J}) \rightarrow \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{\alpha})$  to the connecting morphism  $\text{Hom}_{kQ}(T, J) \rightarrow \text{Ext}_{kQ}^1(T, \text{Ker } \alpha)$ .*

**Proof:** The commutativity is an easy exercise on covering functors, and left to the reader.

- (a) This assertion follows from a direct computation.
- (b) We know from tilting theory that  $\theta$  induces an equivalence (see [9, Chap. VIII Thm. 3.5]):

$$\begin{aligned} \Phi: \text{inj } kQ &\rightarrow \text{proj } \Sigma \\ I &\mapsto \text{Hom}_B(\Sigma, \text{Hom}_{kQ}(T, I)) \end{aligned}.$$

Let  $I \in \text{inj } k\tilde{Q}$ . Then  $p_\lambda \tilde{\theta}(I) = \theta q_\lambda(I)$ . Moreover,  $q_\lambda$  maps indecomposable injective  $k\tilde{Q}$ -modules to indecomposable injective  $kQ$ -modules (see 4.2). So  $p_\lambda \tilde{\theta}(I)$  is indecomposable projective, and therefore so is  $\tilde{\theta}(I)$  (see [14, 3.2]). Consequently,  $\tilde{\theta}$  induces the following functor:

$$\begin{aligned} \Psi: \text{inj } k\tilde{Q} &\rightarrow \text{proj } \tilde{\Sigma} \\ I &\mapsto \text{Hom}_{\tilde{B}}(\tilde{\Sigma}, \text{Hom}_{k\tilde{Q}}(\tilde{T}, I)) \end{aligned}.$$

So we have a commutative diagram:

$$\begin{array}{ccc} \text{inj } k\tilde{Q} & \xrightarrow{\Psi} & \text{proj } \tilde{\Sigma} \\ q_\lambda \downarrow & & \downarrow p_\lambda \\ \text{inj } kQ & \xrightarrow{\Phi} & \text{proj } \Sigma \end{array}.$$

In this diagram,  $p_\lambda$ ,  $q_\lambda$  and  $\Phi$  are faithful. Hence, so is  $\Psi$ . Let  $I, J \in \text{inj } k\tilde{Q}$  and let  $f: \Psi(I) \rightarrow \Psi(J)$ . Let  $h: q_\lambda I \rightarrow q_\lambda J$  be such that  $\Phi(h) = p_\lambda(f)$ . Using 4.2, we have  $h = \sum_{g \in \pi_1(\Gamma)} q_\lambda(h_g)$ , where  $(h_g)_g \in \bigoplus_{g \in \pi_1(\Gamma)} \text{Hom}_{k\tilde{Q}}(\tilde{T}, {}^g \tilde{J})$ .

So  $p_\lambda(f) = \sum_{g \in G} p_\lambda \Psi(h_g)$ . Using 4.2 again, we deduce that  $f = \Psi(h_1)$ . So  $\Psi$  is full. Finally, we know from the preceding section that  $q_\lambda: \text{inj } k\tilde{Q} \rightarrow \text{inj } kQ$  is dense. Also, so is  $p_\lambda: \text{proj } \tilde{\Sigma} \rightarrow \text{proj } \Sigma$  (see [14, 3.2], for instance). Since  $\Phi$  is an equivalence, we deduce that  $\Psi$  is dense. Therefore  $\Psi$  is an equivalence.

(c) The push-down functors  $q_\lambda$  and  $F_\lambda$  are exact. So we have a commutative diagram up to isomorphism:

$$\begin{array}{ccc} \mathcal{D}^b(\text{mod } k\tilde{Q}) & \xrightarrow{\text{RHom}_{k\tilde{Q}}(\tilde{T}, -)} & \mathcal{D}^b(\text{mod } \tilde{B}) \\ q_\lambda \downarrow & & \downarrow F_\lambda \\ \mathcal{D}^b(\text{mod } kQ) & \xrightarrow{\text{RHom}_{kQ}(T, -)} & \mathcal{D}^b(\text{mod } B) \end{array} \quad .$$

The statement follows from this diagram. ■

We now wish to construct a functor  $\varphi: k(\tilde{\Gamma}) \rightarrow \text{mod } \tilde{B}$ . We proceed in several steps:

1. Define a functor  $\varphi_0: k(\tilde{\Gamma}_{\leq \tilde{\Sigma}}) \rightarrow \text{mod } \tilde{B}$  where  $k(\tilde{\Gamma}_{\leq \tilde{\Sigma}})$  denotes the full subcategory of  $k(\tilde{\Gamma})$  with objects the vertices in  $\tilde{\Gamma}_{\leq \tilde{\Sigma}}$ .
2. Define  $\varphi$  on objects, so that it coincides with  $\varphi_0$  on predecessors of  $\tilde{\Sigma}$ .
3. Define  $\varphi$  on morphisms, so that it extends  $\varphi_0$ .

**The functor  $\varphi_0: k(\tilde{\Gamma}_{\leq \tilde{\Sigma}}) \rightarrow \text{mod } \tilde{B}$**

Before constructing  $\varphi_0$ , we prove the following lemma. In the case of a Galois covering whose group acts freely on indecomposables, a corresponding result was proved in [25, 3.6]. We know that  $p: \tilde{\Sigma} \rightarrow \Sigma$  and  $F: \tilde{B} \rightarrow B$  are covering functors, and that the latter coincides on objects with a Galois covering  $\tilde{B} \rightarrow B$  with group  $\pi_1(\Gamma)$ . Finally, if  $X \in \text{ind } B$  is a summand of a tilting  $B$ -module, then  $\tilde{X} \in \text{ind } \tilde{B}$  is a module such that  $p_\lambda(\tilde{X}) \simeq X$  (see 4.2).

**Lemma 5.3.** *Let  $X \in \Gamma_{\leq \Sigma}$  and  $g_0 \in \pi_1(\Gamma)$ . If  $\tilde{u}: \tilde{E} \rightarrow {}^{g_0}\tilde{X}$  is right minimal almost split, then so is  $p_\lambda \tilde{u}: p_\lambda \tilde{E} \rightarrow X$ . Consequently,  $p_\lambda \tau_{\tilde{B}}({}^{g_0}\tilde{X}) \simeq \tau_B X$  if  $X$  is not projective.*

**Proof:** Notice that  $X$  is an indecomposable summand of some tilting  $B$ -module. So we may apply the results of 4.2. If  $X$  is projective, the assertion follows from [14, 3.2]. So we assume that  $X$ , and therefore  ${}^{g_0}\tilde{X}$ , are not projective. Let  $u: E \rightarrow X$  be right minimal almost split and  $E = E_1 \oplus \dots \oplus E_t$  an indecomposable decomposition. Since  $\Gamma_{\leq \Sigma}$  has no oriented cycle (see [1, 2.2]), we have  $\text{Ext}_B^1(E, \tau_B X) = 0$ . Also, the linear map  $\bigoplus_{g \in \pi_1(\Gamma)} \text{Hom}_{\tilde{B}}({}^g \tilde{E}_i, {}^{g_0}\tilde{X}) \rightarrow \text{Hom}_B(E_i, X)$  is bijective, for every  $i$  (see 4.2). Therefore we apply 4.3 to the exact

sequence  $0 \rightarrow \tau_B X \rightarrow E \xrightarrow{u} X \rightarrow 0$ : There exist  $g_1, \dots, g_t \in G$  and morphisms  $\tilde{u}_i: {}^{g_i}\tilde{E}_i \rightarrow {}^{g_0}\tilde{X}$  ( $i \in \{1, \dots, t\}$ ) fitting into a commutative diagram whose vertical arrow on the left is an isomorphism:

$$\begin{array}{ccc} E & \xrightarrow{p_\lambda[\tilde{u}_1, \dots, \tilde{u}_t]} & X \\ \sim \downarrow & & \parallel \\ E & \xrightarrow{u} & X \end{array} \quad .$$

We identify  $u$  and  $p_\lambda[\tilde{u}_1, \dots, \tilde{u}_t]$  via this diagram. Let  $i \in \{1, \dots, n\}$ . Then  $\tilde{u}_i: {}^{g_i}\tilde{E}_i \rightarrow {}^{g_0}\tilde{X}$  is not a retraction because  ${}^{g_i}\tilde{E}_i$  and  ${}^{g_0}\tilde{X}$  are non-isomorphic indecomposable modules. So  $\tilde{u}_i$  factors through  $\tilde{u}$ , for every  $i$ . Applying  $p_\lambda$  to each factorisation shows that  $u$  factors through  $p_\lambda(\tilde{u})$ . On the other hand,  $p_\lambda \tilde{u}$  is not a retraction because  $X$  is not a direct summand of  $E$ . So  $p_\lambda(\tilde{u})$  factors through  $u$ . The right minimality of  $u$  implies that the morphism  $u$  is a direct summand of  $p_\lambda(\tilde{u})$ . Finally, the following equality follows from 2.4:

$$\dim \text{Ker } u = \dim \tau_B X = \dim \tau_B p_\lambda {}^{g_0}\tilde{X} = \dim p_\lambda \tau_{\tilde{B}} {}^{g_0}\tilde{X} = \dim \text{Ker } p_\lambda(\tilde{u}) \quad .$$

So  $p_\lambda(\tilde{u})$  and  $u$  are isomorphic, and  $p_\lambda(\tilde{u})$  is right minimal almost split. ■

Thanks to the preceding lemma, we can construct a functor  $\varphi_0: k(\tilde{\Gamma}_{\leq \tilde{\Sigma}}) \rightarrow \text{ind } \tilde{B}$ .

**Lemma 5.4.** *There exists a full and faithful functor,  $\pi_1(\Gamma)$ -equivariant on vertices  $\varphi_0: k(\tilde{\Gamma}_{\leq \tilde{\Sigma}}) \rightarrow \text{ind } \tilde{B}$ . This functor maps arrows in  $\tilde{\Gamma}_{\leq \tilde{\Sigma}}$  to irreducible maps, and meshes to almost split sequences. Moreover, it commutes with the translations and it extends the canonical functor  $\tilde{\Sigma} \rightarrow \text{ind } \tilde{B}$  defined on the objects by*

$x \mapsto \text{Hom}_{k\tilde{Q}}(\tilde{T}, D(k\tilde{Q}(x, -)))$ . Finally, the following diagram is commutative up to isomorphism of functors:

$$\begin{array}{ccc} k(\tilde{\Gamma}_{\leq \tilde{\Sigma}}) & \xrightarrow{\varphi_0} & \text{ind } \tilde{B} \\ p \downarrow & & \downarrow F_\lambda \\ \text{ind } (\Gamma_{\leq \Sigma}) & \hookrightarrow & \text{ind } B \end{array}$$

**Proof: Step 1:** Clearly there is a functor  $\varphi_0: \tilde{\Sigma} \rightarrow \text{mod } \tilde{B}$  given by  $\tilde{x} \mapsto \text{Hom}_{k\tilde{Q}}(\tilde{T}, D(k\tilde{Q}(\tilde{x}, -)))$ . Note that  $\tilde{\Sigma}$  (or  $\Sigma$ ) is naturally equivalent to the full subcategory of  $\text{mod } k\tilde{Q}$  (or  $\text{mod } kQ$ , respectively), consisting of the indecomposable injective modules. Therefore 5.2 shows that this functor is full and faithful, and that the following diagram commutes up to isomorphism:

$$\begin{array}{ccc} \tilde{\Sigma} & \xrightarrow{\varphi_0} & \text{ind } \tilde{B} \\ p \downarrow & & \downarrow F_\lambda \\ \Sigma & \hookrightarrow & \text{ind } B \end{array} .$$

Note that  $\varphi_0(M)$  is indecomposable for every  $M$  because so is  $F_\lambda \varphi_0(M) = p(M)$ . The functor  $\varphi_0: \tilde{\Sigma} \rightarrow \text{ind } \tilde{B}$  is  $\pi_1(\Gamma)$ -equivariant: Indeed, for every  $g \in \pi_1(\Gamma)$ , and every  $\tilde{x} \in \tilde{Q}_0$ , we have the following equalities:

$$\varphi_0(g\tilde{x}) = \text{Hom}_{k\tilde{Q}}(\tilde{T}, D(k\tilde{Q}(g\tilde{x}, -))) = \text{Hom}_{k\tilde{Q}}(\tilde{T}, {}^g D(k\tilde{Q}(\tilde{x}, -))) = {}^g \text{Hom}_{k\tilde{Q}}(\tilde{T}, D(k\tilde{Q}(\tilde{x}, -))) = {}^g \varphi_0(\tilde{x}) .$$

**Step 2:** If  $M \in k(\tilde{\Gamma}_{\leq \tilde{\Sigma}})$ , there exists a unique  $n \in \mathbb{N}$  such that  $\tau^{-n}M \in \tilde{\Sigma}$ . Let  $\varphi_0(M)$  be the  $\tilde{B}$ -module:

$$\varphi_0(M) = \tau_B^n \varphi_0(\tau^{-n}M) .$$

It follows from 5.3 that  $F_\lambda \varphi_0(M) = p(M)$ . Also  $\varphi_0({}^g M) = {}^g \varphi_0(M)$  for every  $g \in \pi_1(\Gamma)$  and for every vertex  $M$  because  $\tau$  commutes with the action of  $\pi_1(\Gamma)$ .

**Step 3:** In order to define  $\varphi_0$  on morphisms, we construct inductively a sequence of  $\pi_1(\Gamma)$ -invariant left sections  $\tilde{\Sigma}_i$  of  $\tilde{\Gamma}$  such that  $\tilde{\Sigma}_0 = \tilde{\Sigma}$ , such that  $\tilde{\Sigma}_{i+1} \setminus \tilde{\Sigma}_i$  consists of the  $\pi_1(\Gamma)$ -orbit of a vertex, and such that, if  $\bigcup_{t=1}^i \tilde{\Sigma}_t$  denotes the full subcategory of the path category  $k\tilde{\Gamma}$  whose vertices are given by those of  $\tilde{\Sigma}_0, \dots, \tilde{\Sigma}_i$ , then  $k\tilde{\Gamma}_{\leq \tilde{\Sigma}} = \bigcup_{i \geq 0} \tilde{\Sigma}_i$ . Each inductive step defines a functor  $\varphi_0: \bigcup_{t=1}^i \tilde{\Sigma}_t \rightarrow \text{ind } \tilde{B}$  which maps arrows to irreducible maps and extends the constructions of the two preceding steps. This functor makes the following diagram commute:

$$\begin{array}{ccc} \bigcup_{t=1}^i \tilde{\Sigma}_t & \xrightarrow{\varphi_0} & \text{ind } \tilde{B} \\ \downarrow p & & \downarrow F_\lambda \\ \text{ind } (\Gamma_{\leq \Sigma}) & \hookrightarrow & \text{ind } B \end{array} ,$$

where the vertical arrow on the left is naturally induced by  $p$ . Assume that  $\varphi_0: \bigcup_{t=1}^i \tilde{\Sigma}_t \rightarrow \text{ind } \tilde{B}$  has been defined for some  $i \geq 0$ . Since  $\tilde{\Sigma}_i$  is acyclic, it has a sink. Assume first that all sinks are projective. Let  $P$  be a projective sink, and let  $\tilde{\Sigma}_{i+1}$  be equal to  $\tilde{\Sigma}_i \setminus \{ {}^g P \mid g \in \pi_1(\Gamma) \}$ ; then,  $\tilde{\Sigma}_{i+1}$  is a left section, and there is a unique  $\varphi_0: \bigcup_{t=0}^{i+1} \tilde{\Sigma}_t \rightarrow \text{ind } \tilde{B}$  satisfying the required conditions. Assume that there is a non projective sink  $M$  in  $\tilde{\Sigma}_i$ . Then there exists a mesh in  $\tilde{\Gamma}$ :

$$\begin{array}{ccccc} & & N_1 & & \\ & \nearrow v_1 & & \searrow u_1 & \\ \tau M & & \vdots & & M \\ & \searrow v_s & & \nearrow u_s & \\ & & N_s & & \end{array} ,$$

and  $M, N_1, \dots, N_s \in \tilde{\Sigma}_i$  because  $M \in \tilde{\Sigma}_i$  is a sink. In particular,  $\varphi_0(u_j)$  is defined, and  $F_\lambda \varphi_0(u_j) = p(u_j)|_B$  for every  $j$ . For simplicity, we write  $\varphi_0(u)$  for  $[\varphi_0(u_1) \dots \varphi_0(u_s)]$  and  $p(u)$  for  $[p(u_1) \dots p(u_s)]$ . Then  $\varphi_0(u)$  is right minimal almost split in  $\text{mod } \tilde{B}$ : Indeed, there exists a right minimal almost split morphism  $L \xrightarrow{w} \varphi_0(M)$ . Since  $\varphi_0(u): \bigoplus_j \varphi_0(N_j) \rightarrow \varphi_0(M)$  is not a retraction (because each  $\varphi_0(u_j)$  is an irreducible morphism, by

the induction hypothesis), there exists a morphism  $w': \bigoplus_j \varphi_0(N_j) \rightarrow L$  such that  $\varphi_0(u) = ww'$ ; applying  $F_\lambda$ , we have  $F_\lambda \varphi_0(u) = F_\lambda(w)F_\lambda(w')$ ; but now  $F_\lambda \varphi_0(u) = p(u)|_B$  is right minimal almost split by construction, and so is  $F_\lambda(w)$  (see 5.3); hence,  $F_\lambda(w')$  is an isomorphism and therefore so is  $w'$  because  $F_\lambda$  is exact. We let  $[\varphi_0(v_1) \ \dots \ \varphi_0(v_s)]^t : \varphi_0(\tau M) \rightarrow \bigoplus_{j=1}^s \varphi_0(N_j)$  be the kernel of  $\varphi_0(u)$ . For simplicity, we write  $\varphi_0(v)$  for  $[\varphi_0(v_1) \ \dots \ \varphi_0(v_s)]^t$  and  $p(v)$  for  $[p(v_1) \ \dots \ p(v_s)]^t$ . We let  $\tilde{\Sigma}_{i+1} = \left( \tilde{\Sigma}_i \setminus \{ {}^g M \mid g \in \pi_1(\Gamma) \} \right) \cup \{ {}^g \tau M \mid g \in \pi_1(\Gamma) \}$ . Clearly,  $\tilde{\Sigma}_{i+1}$  is a left section. We now show that we may assume  $\varphi_0(v)$  to be taken such that  $F_\lambda \varphi_0(v) = p(u)|_B$ . Indeed, the commutative diagram with exact rows:

$$\begin{array}{ccccccc} 0 & \longrightarrow & F_\lambda \varphi_0(\tau M) & \xrightarrow{F_\lambda \varphi_0(v)} & F_\lambda \varphi_0 \left( \bigoplus_{j=1}^s N_j \right) & \xrightarrow{F_\lambda \varphi_0(u)} & F_\lambda \varphi_0(M) \longrightarrow 0 \\ & & & & \parallel & & \parallel \\ 0 & \longrightarrow & p(\tau M)|_B & \xrightarrow{p(v)|_B} & p \left( \bigoplus_{j=1}^s N_j \right)_{|B} & \xrightarrow{p(u)|_B} & p(M)|_B \longrightarrow 0 \end{array}$$

shows that there exists an isomorphism  $F_\lambda \varphi_0(\tau M) \rightarrow p(\tau M)|_B$  which makes the left square commute. Since  $F_\lambda \varphi_0(\tau M) = p(\tau M)|_B$  is a brick (because it belongs to  $\tilde{\Gamma}_{\leq \tilde{\Sigma}}$ ), this isomorphism is the multiplication by a non-zero constant  $c$ . Hence,  $p(v)|_B = c F_\lambda \varphi_0(v)$ . Replacing  $\varphi_0(v)$  by  $c \varphi_0(v)$  does the trick. Thus, we have defined  $\varphi_0: \bigcup_{t=1}^{i+1} \tilde{\Sigma}_t \rightarrow \text{ind } \tilde{B}$ . It is clear that the required conditions are satisfied. This induction shows that there is a functor  $\varphi_0: k\tilde{\Gamma}_{\leq \tilde{\Sigma}} \rightarrow \text{ind } \tilde{B}$  mapping arrows to irreducible maps and meshes to almost split sequences, and such that the following diagram commutes:

$$\begin{array}{ccc} k\tilde{\Gamma}_{\leq \tilde{\Sigma}} & \xrightarrow{\varphi_0} & \text{ind } \tilde{B} \\ \downarrow & & \downarrow F_\lambda \\ \text{ind } \Gamma_{\leq \Sigma} & \hookrightarrow & \text{ind } B \end{array},$$

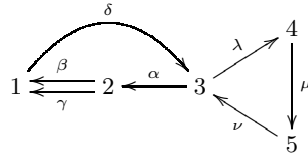
where the vertical arrow on the left is induced by  $p$ . Since  $F_\lambda$  is faithful,  $\varphi_0$  induces a functor  $\varphi_0: k(\tilde{\Gamma}_{\leq \tilde{\Sigma}}) \rightarrow \text{ind } \tilde{B}$ . It is now clear that this functor satisfies the conditions of the lemma.  $\blacksquare$

It was shown in [1, 3.2] that the existence of a left section  $\Sigma$  in an Auslander-Reiten component  $\Gamma$  implies that  $\Gamma_{\leq \Sigma}$  is generalised standard. We now prove that it is standard.

**Corollary 5.5.** *Let  $A$  be a finite dimensional  $k$ -algebra and  $\Gamma$  be a component of  $\Gamma(\text{mod } A)$  having a left section  $\Sigma$ . Then  $\Gamma_{\leq \Sigma}$  is standard.*

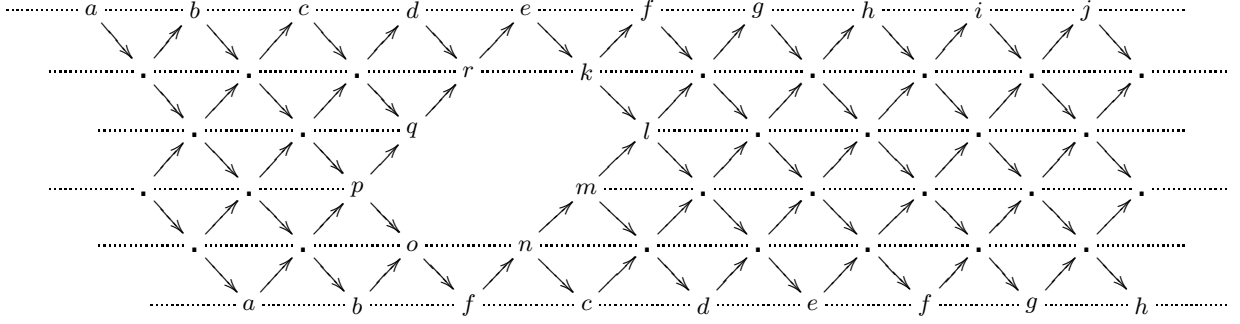
**Proof:** Let  $B = A/\text{Ann } \Sigma$ . Then  $B$  is a product of tilted algebras and the components of  $\Sigma$  form complete slices for the components of  $B$ . Let  $\Gamma'$  be the union of the components of  $\Gamma(\text{mod } B)$  intersecting  $\Sigma$ . The arguments of the proof of 5.4 show that there exists a full and faithful functor  $k(\Gamma'_{\leq \Sigma}) \rightarrow \text{ind } \Gamma'_{\leq \Sigma}$  extending the identity on vertices. So  $\Gamma_{\leq \Sigma} = \Gamma'_{\leq \Sigma}$  is standard.  $\blacksquare$

*Example 5.6.* Let  $A$  be the cluster-tilted algebra of type  $\tilde{A}$  given by the quiver

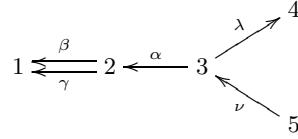


and the potential  $w = \delta\beta\alpha + \nu\mu\lambda$  (or, equivalently, by the relations  $\beta\alpha = 0$ ,  $\delta\beta = 0$ ,  $\alpha\delta = 0$ ,  $\mu\lambda = 0$ ,  $\nu\mu = 0$

and  $\lambda\nu = 0$ ). Then the transjective component  $\Gamma$  of  $\Gamma(\text{mod } A)$  is of the form



where the vertices with the same label are identified. Then  $\Gamma$  admits a left section  $\Sigma = \{e, r, q, p, o, f\}$  and  $B = A/\text{Ann } \Sigma$  is the algebra given by the quiver:



with the inherited relations. As we have seen,  $\Gamma_{\leq \Sigma}$  is standard (and generalised standard) while, clearly,  $\Gamma$  itself is not.

The following corollary seems to be well-known. However we have been unable to find a reference.

**Corollary 5.7.** *Let  $B$  be a tilted algebra and  $\Gamma$  be a connecting component of  $B$ . Then  $\Gamma$  is standard.*

**Proof:** If  $B$  is concealed, this follows from [40, 2.4 (11) p. 80]. Assume that  $B$  is not concealed. So  $\Gamma$  is the unique connecting component of  $B$ . Let  $\Sigma$  be a complete slice in  $\Gamma$ . As observed in 5.5, we have a full and faithful functor  $k(\Gamma_{\leq \Sigma}) \rightarrow \text{ind } \Gamma$  extending the identity on vertices. A dual construction extends this functor to a full and faithful functor  $k(\Gamma) \rightarrow \text{ind } \Gamma$  extending the identity on vertices. So  $\Gamma$  is standard. ■

From now on, we identify  $\tilde{\Sigma}$  to a full subcategory of  $\text{mod } \tilde{B}$  by means of  $\varphi_0$ .

### Construction of $\varphi$ on objects

We prove that for any  $M \in \tilde{\Gamma}$ , there exists  $\varphi(M) \in \text{mod } \tilde{B}$  whose image under  $F_\lambda: \text{mod } \tilde{B} \rightarrow \text{mod } B$  coincides with  $p(M)|_B$ , in such a way that  $\varphi({}^g M) = {}^g \varphi(M)$ , for every  $g \in \pi_1(\Gamma)$ . We define  $\mathcal{L}_\Sigma$  to be the full subcategory of  $\text{ind } B$  which consists of the predecessors of the complete slice  $\Sigma$ . Also a *minimal add  $\mathcal{L}_\Sigma$ -presentation* of a module  $R$  is a sequence of morphisms:

$$E_1 \rightarrow E_2 \rightarrow R$$

where the morphism on the right is a minimal  $\text{add } \mathcal{L}_\Sigma$ -approximation and the one on the left is a minimal  $\text{add } \mathcal{L}_\Sigma$ -approximation of its kernel. Before constructing  $\varphi(M)$ , we prove two lemmata.

**Lemma 5.8.** *Let  $R \in \text{mod } B$  be a module with no direct summand in  $\mathcal{L}_\Sigma$ . There exists an exact sequence in  $\text{mod } B$ , which is a minimal  $\text{add } \mathcal{L}_\Sigma$ -presentation:*

$$0 \rightarrow E_1 \rightarrow E_2 \rightarrow R \rightarrow 0 \quad (\star)$$

with  $E_1, E_2 \in \text{add } \Sigma$ . Moreover, the functor  $\text{Hom}_{kQ}(T, -)$  induces a bijection between the class of all such exact sequences, and the class of minimal injective copresentations:

$$0 \rightarrow \text{Tor}_1^B(R, T) \rightarrow I_1 \rightarrow I_2 \rightarrow 0 \quad .$$

Finally, there is an isomorphism in  $\text{mod } B$ :

$$R \simeq \text{Ext}_{kQ}^1(T, \text{Tor}_1^B(R, T)) \quad .$$

**Proof:** Let  $\mathcal{X}(T)$  be the torsion class induced by  $T$  in  $\text{mod } B$ . So  $R$  lies in  $\mathcal{X}(T)$  and has no direct summand in  $\Sigma$ . Therefore  $R$  is the epimorphic image of a module in  $\text{add } \Sigma$ . The first assertion then follows from [8, 2.2, (d)].

Let  $f: I_1 \rightarrow I_2$  be the morphism between injective  $kQ$ -modules such that  $\text{Hom}_{kQ}(T, f)$  is equal to the morphism  $E_1 \rightarrow E_2$  in  $(\star)$ . Because of the Brenner-Butler Theorem (see [9, Chap. VI, Thm. 3.8, p.207]), the functor  $-\otimes_B T$  applied to  $(\star)$  yields an injective copresentation in  $\text{mod } kQ$ :

$$0 \rightarrow \text{Tor}_1^B(R, T) \rightarrow I_1 \rightarrow I_2 \rightarrow 0 \quad .$$

The minimality of this copresentation follows from the minimality of  $E_2 \rightarrow R$ . With these arguments, it is straightforward to check that there is a well-defined bijection which carries the equivalence class of the exact sequence  $0 \rightarrow E_1 \rightarrow E_2 \rightarrow R \rightarrow 0$  to the equivalence class of the exact sequence  $0 \rightarrow \text{Tor}_1^B(R, T) \rightarrow I_1 \rightarrow I_2 \rightarrow 0$ .

The last assertion follows from the Brenner-Butler Theorem and from the fact that  $R \in \mathcal{X}(T)$ .  $\blacksquare$

**Lemma 5.9.** *add  $\mathcal{L}_\Sigma$  is contravariantly finite in  $\text{mod } A$ . Therefore if  $X \in \Gamma \backslash \mathcal{L}_\Sigma$ , then  $X|_B$  lies in the torsion class induced by  $T$  in  $\text{mod } B$ .*

**Proof:** By [1, Thm. B], the algebra  $B$  is the endomorphism algebra of the indecomposable projective  $A$ -modules lying in  $\mathcal{L}_\Sigma$ . In particular, a projective  $B$ -module is projective as an  $A$ -module so that the projective dimensions in  $\text{mod } A$  and in  $\text{mod } B$  coincide on  $\mathcal{L}_\Sigma$ . Also, by [1, Thm. B], all modules in  $\mathcal{L}_\Sigma$  have projective dimension at most one as  $B$ -modules. Therefore  $\mathcal{L}_\Sigma \subseteq \mathcal{L}_A$ . Moreover,  $\bigoplus \Sigma$  is sincere as a  $B$ -module. Hence, [1, 8.2] implies that  $\text{add } \mathcal{L}_\Sigma$  is contravariantly finite in  $\text{mod } A$ . Let  $X \in \Gamma \backslash \mathcal{L}_\Sigma$ . Let  $P \twoheadrightarrow M|_B$  be the projective cover in  $\text{mod } B$ . As noticed above, we have  $P \in \text{add } \mathcal{L}_\Sigma$ . Therefore  $P \twoheadrightarrow M|_B$  factors through  $\text{add } \Sigma$ . Thus,  $X$  lies in the torsion class.  $\blacksquare$

**Lemma 5.10.** *There exists a map  $\varphi: \tilde{\Gamma}_o \rightarrow \text{mod } \tilde{B}$  extending  $\varphi_0$ , and such that  $F_\lambda(\varphi(M)) = p(M)|_B$ , for every  $M \in \tilde{\Gamma}$ . Moreover,  $\varphi({}^g M) = {}^g \varphi(M)$  for every  $g \in \pi_1(\Gamma)$  and  $M \in \tilde{\Gamma}$ .*

**Proof:** Note that  $\varphi$  is already defined on  $\tilde{\Gamma}_{\leq \Sigma}$  because of 5.4. Let  $M \in \tilde{\Gamma} \backslash \tilde{\Gamma}_{\leq \Sigma}$ . Then  $p(M) \in \Gamma \backslash \Gamma_{\leq \Sigma} = \Gamma \backslash \mathcal{L}_\Sigma$ . By 5.9, the module  $p(M)|_B$  lies in the torsion class induced by  $T$  in  $\text{mod } B$ . So there is a decomposition in  $\text{mod } B$ :

$$p(M)|_B = R \oplus E ,$$

where  $E \in \text{add } \Sigma$  and  $R$  has no indecomposable summand in  $\mathcal{L}_\Sigma$ . Also, fix a decomposition in  $\text{mod } \tilde{\Sigma}$ :

$$k(\tilde{\Gamma})(\tilde{\Sigma}, M) = \tilde{R} \oplus \tilde{P} ,$$

where  $\tilde{P}$  is projective and maximal for this property. Let  $\tilde{E} \in \text{add } \tilde{\Sigma}$  be such that  $\tilde{P} = k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E})$ .

We claim that  $p_\lambda: \text{mod } \tilde{\Sigma} \rightarrow \text{mod } \Sigma$  maps  $\tilde{R}$  and  $\tilde{P}$  to  $\text{Hom}_B(\Sigma, R)$  and  $\text{Hom}_B(\Sigma, E)$  respectively. Indeed, since  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$  is a covering functor inducing  $p: \tilde{\Sigma} \rightarrow \Sigma$ , the image of  $k(\tilde{\Gamma})(\tilde{\Sigma}, M)$  under  $p_\lambda: \text{mod } \tilde{\Sigma} \rightarrow \text{mod } \Sigma$  is  $\text{Hom}_B(\Sigma, p(M))$ . Moreover, the decomposition  $p(M)|_B = R \oplus E$  in  $\text{mod } B$  gives a decomposition  $\text{Hom}_B(\Sigma, p(M)) = \text{Hom}_B(\Sigma, R) \oplus \text{Hom}_B(\Sigma, E)$  in  $\text{mod } \Sigma$  where  $\text{Hom}_B(\Sigma, E)$  is projective and  $\text{Hom}_B(\Sigma, R)$  has no non-zero projective direct summand. The claim then follows from [14, 3.2].

In order to prove that  $R$  is the image of a  $\tilde{B}$ -module under  $F_\lambda$ , we consider a minimal projective presentation in  $\text{mod } \tilde{\Sigma}$ :

$$0 \rightarrow \tilde{P}_1 \rightarrow \tilde{P}_2 \rightarrow \tilde{R} \rightarrow 0 .$$

Then there exists a morphism  $\tilde{f}: \tilde{I}_1 \rightarrow \tilde{I}_2$  between injective  $k\tilde{Q}$ -modules such that the morphism  $\tilde{P}_1 \rightarrow \tilde{P}_2$  equals  $\tilde{\theta}(\tilde{f})$  (here  $\tilde{\theta}$  is as in 5.2). Let  $f: I_1 \rightarrow I_2$  be the image of  $\tilde{f}$  under  $q_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$ . Hence, the image of  $\text{Ker } \tilde{f}$  under  $q_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$  is  $\text{Ker } f$ . Let  $P_1 \rightarrow P_2$  be the image of  $\tilde{\theta}(\tilde{f})$  under the same functor. Therefore the commutativity of the diagram in 5.2 gives a minimal projective presentation in  $\text{mod } \Sigma$ :

$$0 \rightarrow P_1 \rightarrow P_2 \rightarrow \text{Hom}_B(\Sigma, R) \rightarrow 0 .$$

On the other hand, 5.2 shows that  $P_1 \rightarrow P_2$  is equal to the following morphism in  $\text{mod } \Sigma$ :

$$\text{Hom}_B(\Sigma, \text{Hom}_{kQ}(T, I_1)) \xrightarrow{\text{Hom}_B(\Sigma, \text{Hom}_{kQ}(T, f))} \text{Hom}_B(\Sigma, \text{Hom}_{kQ}(T, I_2)) .$$

Therefore we have a minimal  $\text{add } \mathcal{L}_\Sigma$ -presentation:

$$\text{Hom}_{kQ}(T, I_1) \xrightarrow{\text{Hom}_{kQ}(T, f)} \text{Hom}_{kQ}(T, I_2) \rightarrow R ,$$

Because of 5.8, the sequence  $0 \rightarrow \text{Hom}_{kQ}(T, I_1) \rightarrow \text{Hom}_{kQ}(T, I_2) \rightarrow R \rightarrow 0$  is exact and  $\text{Ker } f = \text{Tor}_1^B(R, T)$ . In other words,  $q_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$  maps  $\text{Ker } \tilde{f}$  to  $\text{Tor}_1^B(R, T)$ . Using 5.8 and the last diagram in the proof of 5.2, we get  $F_\lambda(\text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f})) = R$ .

We give an explicit construction of  $\varphi$ . Let  $M \in k(\tilde{\Gamma})$ . We fix a minimal projective presentation in  $\text{mod } \tilde{\Sigma}$ :

$$0 \rightarrow \tilde{P}_1 \xrightarrow{\tilde{u}} \tilde{P}_2 \rightarrow \tilde{R} \rightarrow 0 ,$$

and fix injective  $k\tilde{Q}$ -modules  $\tilde{I}_1$  and  $\tilde{I}_2$ , together with a morphism  $\tilde{f}: \tilde{I}_1 \rightarrow \tilde{I}_2$  such that  $\tilde{u} = \tilde{\theta}(\tilde{f})$ . Then we let  $\varphi(M)$  be the following  $\tilde{B}$ -module:

$$\varphi(M) = \varphi_0(\tilde{E}) \oplus \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}) .$$

Where  $\varphi_0(\tilde{E}) = \varphi_0(\tilde{E}_1) \oplus \dots \oplus \varphi_0(\tilde{E}_s)$  if  $\tilde{E} = \tilde{E}_1 \oplus \dots \oplus \tilde{E}_s$  with  $\tilde{E}_1, \dots, \tilde{E}_s \in \tilde{\Sigma}$ . This finishes the construction of the map  $\varphi: \tilde{\Gamma}_o \rightarrow \mathbf{mod} \tilde{B}$ . We now prove the  $\pi_1(\Gamma)$ -equivariance property. Let  $M \in k(\tilde{\Gamma})$  be a vertex and let  $g \in \pi_1(\Gamma)$ . We keep the above notation  $\tilde{R}, \tilde{E}$ , etc. introduced for  $M$ , and we adopt the dashed notation  $\tilde{R}', \tilde{E}'$ , etc. for the corresponding objects associated to  ${}^g M$ . We have  $k(\tilde{\Gamma})(\tilde{\Sigma}, {}^g M) = {}^g k(\tilde{\Gamma})(\tilde{\Sigma}, M)$ . Indeed, the  $\tilde{\Sigma}$ -modules  $k(\tilde{\Gamma})(\tilde{\Sigma}, {}^g M)$  and  ${}^g k(\tilde{\Gamma})(\tilde{\Sigma}, M)$  are given by the functors  $X \mapsto k(\tilde{\Gamma})(X, {}^g M)$  and  $X \mapsto k(\tilde{\Gamma})({}^{g^{-1}} X, M)$  from  $\tilde{\Sigma}^{op}$  to  $\mathbf{mod} k$ , respectively. These two functors coincide because  $\pi_1(\Gamma)$  acts on  $k(\tilde{\Gamma})$ . Hence,  $\tilde{E}' = {}^g \tilde{E}$  and  $\tilde{R}' = {}^g \tilde{R}$ . Therefore any minimal projective presentation of  $\tilde{R}'$  in  $\mathbf{mod} \tilde{\Sigma}$  is obtained from a minimal projective presentation of  $\tilde{R}$  by applying  $g$ . Since, moreover,  $\tilde{\theta}$  is  $\pi_1(\Gamma)$ -equivariant (see 5.2), we deduce that  $\tilde{f}' = {}^g \tilde{f}$ . Finally, the  $\pi_1(\Gamma)$ -action on  $\mathbf{mod} k\tilde{Q}$  implies, as above, that  $\mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, \mathrm{Ker} {}^g \tilde{f}) = \mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, {}^g \mathrm{Ker} \tilde{f}) = {}^g \mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, \mathrm{Ker} \tilde{f})$ . From the construction of  $\varphi$ , we get  $\varphi({}^g M) = {}^g \varphi(M)$ . ■

### Construction of $\varphi$ on morphisms

We complete the construction of  $\varphi$  by proving the following lemma.

**Lemma 5.11.** *Let  $u: M \rightarrow N$  be a morphism in  $k(\tilde{\Gamma})$ . Then there exists a unique morphism  $\varphi(u): \varphi(M) \rightarrow \varphi(N)$  in  $\mathbf{mod} \tilde{B}$ , such that  $F_\lambda(\varphi(u)) = p(u)|_B$ .*

**Proof:** Since  $F_\lambda$  is exact, it is faithful so the morphism  $\varphi(u)$  is unique. We prove the existence. By 5.4, we have constructed  $\varphi(u) = \varphi_0(u)$  in case  $N \in \tilde{\Gamma}_{\leq \tilde{\Sigma}}$ . So we may assume that  $N \in \tilde{\Gamma} \setminus \tilde{\Gamma}_{\leq \tilde{\Sigma}}$ . Since any path in  $\tilde{\Gamma}$  from a vertex in  $\tilde{\Gamma}_{\leq \tilde{\Sigma}}$  to  $N$  has a vertex in  $\tilde{\Sigma}$ , we may also assume that  $M \in (\tilde{\Gamma} \setminus \tilde{\Gamma}_{\leq \tilde{\Sigma}}) \cup \tilde{\Sigma}$ . Notice that the functor  $\varphi_0: k(\tilde{\Gamma}_{\leq \tilde{\Sigma}}) \rightarrow \mathbf{mod} \tilde{B}$  naturally extends to a unique functor  $\varphi_0: \mathbf{add}(k(\tilde{\Gamma}_{\leq \tilde{\Sigma}})) \rightarrow \mathbf{mod} \tilde{B}$ , such that the following diagram is commutative:

$$\begin{array}{ccc} \mathbf{add}(k(\tilde{\Gamma}_{\leq \tilde{\Sigma}})) & \xrightarrow{\varphi_0} & \mathbf{mod} \tilde{B} \\ \downarrow \text{add } p & & \downarrow F_\lambda \\ \mathbf{add}(\mathrm{ind} \Gamma_{\leq \Sigma}) & \xrightarrow{\quad} & \mathbf{mod} B \end{array} .$$

Let us fix decompositions in  $\mathbf{mod} \tilde{\Sigma}$  as in the proof of 5.10:

$$k(\tilde{\Gamma})(\tilde{\Sigma}, M) = \tilde{P} \oplus \tilde{R}, \quad \text{and} \quad k(\tilde{\Gamma})(\tilde{\Sigma}, N) = \tilde{P}' \oplus \tilde{R}' ,$$

where  $\tilde{P}, \tilde{P}'$  are projective and  $\tilde{R}, \tilde{R}'$  have no non-zero projective direct summand. We let  $\tilde{E}, \tilde{E}' \in \mathbf{add} \tilde{\Sigma}$  be such that  $\tilde{P} = k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E})$  and  $\tilde{P}' = k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E}')$ , respectively. Therefore the morphism  $k(\tilde{\Gamma})(\tilde{\Sigma}, u)$  can be written as:

$$k(\tilde{\Gamma})(\tilde{\Sigma}, u) = \begin{bmatrix} \tilde{u}_1 & 0 \\ \tilde{u}_2 & \tilde{u}_3 \end{bmatrix} : k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E}) \oplus \tilde{R} \rightarrow k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E}') \oplus \tilde{R}' .$$

Similarly, we fix decompositions in  $\mathbf{mod} B$ :

$$p(M)|_B = E \oplus R, \quad p(N)|_B = E' \oplus R' ,$$

where  $E, E' \in \mathbf{add} \Sigma$ , and  $R, R'$  have no direct summand in  $\Sigma$ . As above, the morphism  $p(u)|_B$  decomposes as:

$$p(u)|_B = \begin{bmatrix} u_1 & 0 \\ u_2 & u_3 \end{bmatrix} : E \oplus R \rightarrow E' \oplus R' .$$

Recall from the proof of 5.10 that  $p_\lambda: \mathbf{mod} \tilde{\Sigma} \rightarrow \mathbf{mod} \Sigma$  maps  $k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E})$ ,  $\tilde{R}$ ,  $k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E}')$  and  $\tilde{R}'$  to  $\mathrm{Hom}_B(\Sigma, E)$ ,  $\mathrm{Hom}_B(\Sigma, R)$ ,  $\mathrm{Hom}_B(\Sigma, E')$  and  $\mathrm{Hom}_B(\Sigma, R')$ , respectively. As a consequence, it maps  $\tilde{u}_i$  to  $\mathrm{Hom}_B(\Sigma, u_i)$ , for every  $i$ . As in the proof of 5.10, we have morphisms  $\tilde{f}: \tilde{I}_1 \rightarrow \tilde{I}_2$  and  $\tilde{f}': \tilde{I}_1' \rightarrow \tilde{I}_2'$  between injective  $k\tilde{Q}$ -modules such that there exist minimal projective presentations in  $\mathbf{mod} \tilde{\Sigma}$ :

$$\tilde{\theta}(\tilde{I}_1) \xrightarrow{\tilde{\theta}(\tilde{f})} \tilde{\theta}(\tilde{I}_2) \rightarrow \tilde{R} \rightarrow 0 \quad \text{and} \quad \tilde{\theta}(\tilde{I}_1') \xrightarrow{\tilde{\theta}(\tilde{f}')} \tilde{\theta}(\tilde{I}_2') \rightarrow \tilde{R}' \rightarrow 0 .$$

With these notations, we have:

$$\varphi(M) = \varphi_0(\tilde{E}) \oplus \mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, \mathrm{Ker} \tilde{f}) \quad \text{and} \quad \varphi(N) = \varphi_0(\tilde{E}') \oplus \mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, \mathrm{Ker} \tilde{f}') .$$

Also, if  $M \in \tilde{\Sigma}$ , then  $\tilde{f} = 0$ , so  $\varphi(M) = \varphi_0(\tilde{E})$ .

It suffices to prove that each of  $u_1, u_2, u_3$  is the image under  $F_\lambda$  of some morphism  $\varphi_0(\tilde{E}) \rightarrow \varphi_0(\tilde{E}')$ ,  $\varphi_0(\tilde{E}) \rightarrow \mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, \mathrm{Ker} \tilde{f}')$  and  $\mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, \mathrm{Ker} \tilde{f}) \rightarrow \mathrm{Ext}_{k\tilde{Q}}^1(\tilde{T}, \mathrm{Ker} \tilde{f}')$  respectively. Clearly  $u_1: k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E}) \rightarrow k(\tilde{\Gamma})(\tilde{\Sigma}, \tilde{E}')$  is induced by a morphism  $\tilde{E} \rightarrow \tilde{E}'$  in  $\mathbf{add} \tilde{\Sigma}$ . This and 5.4 imply that  $u_1$  is the image under  $F_\lambda$  of a morphism

$\varphi_0(\tilde{E}) \rightarrow \varphi_0(\tilde{E}')$ . We now prove that  $u_2$  is the image under  $F_\lambda$  of a morphism  $\varphi_0(\tilde{E}) \rightarrow \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}')$ . Let  $f': I'_1 \rightarrow I'_2$  be the image of  $\tilde{f}': \tilde{I}'_1 \rightarrow \tilde{I}'_2$  under  $q_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$ . Therefore we have a minimal projective presentation in  $\text{mod } \Sigma$  (see 5.2):

$$0 \rightarrow \theta(I'_1) \xrightarrow{\theta(f')} \theta(I'_2) \rightarrow \text{Hom}_B(\Sigma, R') \rightarrow 0 ,$$

together with a minimal injective copresentation in  $\text{mod } kQ$ :

$$0 \rightarrow \text{Tor}_1^B(R', T) \rightarrow I'_1 \xrightarrow{f'} I'_2 \rightarrow 0 .$$

Recall that  $\text{Tor}_1^B(R', T)$  is equal to the image of  $\text{Ker } \tilde{f}'$  under  $q_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$ . Therefore we have an exact sequence in  $\text{mod } B$ , which is also a minimal  $\text{add } \mathcal{L}_\Sigma$ -presentation:

$$0 \rightarrow \text{Hom}_{kQ}(T, I'_1) \rightarrow \text{Hom}_{kQ}(T, I'_2) \xrightarrow{v} R' \rightarrow 0 ,$$

where the morphism  $v$  is such that  $\text{Hom}_B(\Sigma, v)$  is the image of  $\tilde{v}: \tilde{\theta}(\tilde{I}'_2) \rightarrow \tilde{R}'$  under  $p_\lambda: \text{mod } \tilde{\Sigma} \rightarrow \text{mod } \Sigma$  (see the diagram in 5.2). The projective cover  $\tilde{v}$  of  $\tilde{R}'$  in  $\text{mod } \tilde{\Sigma}$  yields a morphism  $\tilde{\delta}: \tilde{I} \rightarrow \tilde{I}'_2$  in  $\text{mod } k\tilde{Q}$ , where  $\tilde{I}$  is the injective  $k\tilde{Q}$ -module such that  $\tilde{P} = \tilde{\theta}(\tilde{I})$ , and such that the following diagram of  $\text{mod } \tilde{\Sigma}$  is commutative:

$$\begin{array}{ccc} & \tilde{P} & \\ \tilde{\theta}(\tilde{\delta}) \swarrow & \downarrow \tilde{u}_2 & \\ \tilde{\theta}(\tilde{I}'_2) & \xrightarrow{\tilde{v}} & \tilde{R}' \end{array} .$$

Therefore if  $\delta: I \rightarrow I'_2$  denotes the image of  $\tilde{\delta}: \tilde{I} \rightarrow \tilde{I}'_2$  under  $q_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$ , then  $\text{Hom}_B(\Sigma, u_2)$  equals the composition  $\theta(I) \xrightarrow{\theta(\delta)} \theta(I'_2) \xrightarrow{\text{Hom}_B(\Sigma, v)} \text{Hom}_B(\Sigma, R')$ . This is an equality of morphisms in  $\text{mod } \Sigma$ , hence, of morphisms between contravariant functors from  $\text{add } \Sigma$  to  $\text{mod } k$ . Applying this equality to  $E$  yields that  $u_2$  equals the composition  $E \xrightarrow{\text{Hom}_{kQ}(T, \delta)} \text{Hom}_{kQ}(T, I'_2) \xrightarrow{v} R'$ . On the other hand, the morphism:

$$\text{Hom}_{kQ}(T, I'_2) \xrightarrow{v} R' = \text{Ext}_{kQ}^1(T, \text{Ker } f')$$

is the connecting morphism of the sequence resulting from the application of  $\text{Hom}_{kQ}(T, -)$  to the exact sequence  $0 \rightarrow \text{Ker } f' \rightarrow I'_1 \xrightarrow{f'} I'_2 \rightarrow 0$ . Therefore 5.2 implies that  $v$  equals the image under  $F_\lambda$  of the connecting morphism of the sequence resulting from the application of  $\text{Hom}_{k\tilde{Q}}(\tilde{T}, -)$  to the exact sequence

$$0 \rightarrow \text{Ker } \tilde{f}' \rightarrow \tilde{I}'_1 \rightarrow \tilde{I}'_2 \rightarrow 0 . \text{ Consequently, } u_2 \text{ equals the image under } F_\lambda \text{ of the composition } \varphi_0(\tilde{E}) \xrightarrow{\text{Hom}_{k\tilde{Q}}(\tilde{T}, \delta)} \varphi_0(\text{Hom}_{kQ}(\tilde{T}, \tilde{I}'_2)) \rightarrow \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}').$$

It only remains to prove that  $u_3: R \rightarrow R'$  equals the image under  $F_\lambda$  of a morphism  $\text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}) \rightarrow \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}')$  in  $\text{mod } \tilde{B}$ . Using the projective presentations of  $\tilde{R}$  and  $\tilde{R}'$ , we find morphisms  $\tilde{\alpha}: \tilde{I}_2 \rightarrow \tilde{I}'_2$  and  $\tilde{\beta}: \tilde{I}_1 \rightarrow \tilde{I}'_1$  such that the following diagram is commutative:

$$\begin{array}{ccccccc} 0 & \longrightarrow & \tilde{\theta}(\tilde{I}_1) & \xrightarrow{\tilde{\theta}(\tilde{f})} & \tilde{\theta}(\tilde{I}_2) & \longrightarrow & \tilde{R} \longrightarrow 0 \\ & & \downarrow \tilde{\theta}(\tilde{\beta}) & & \downarrow \tilde{\theta}(\tilde{\alpha}) & & \downarrow \tilde{u}_3 \\ 0 & \longrightarrow & \tilde{\theta}(\tilde{I}'_1) & \xrightarrow{\tilde{\theta}(\tilde{f}')} & \tilde{\theta}(\tilde{I}'_2) & \longrightarrow & \tilde{R}' \longrightarrow 0 \end{array} .$$

Therefore there exists a morphism  $\tilde{\gamma}: \text{Ker } \tilde{f} \rightarrow \text{Ker } \tilde{f}'$  making the following diagram in  $\text{mod } k\tilde{Q}$  commute:

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Ker } \tilde{f} & \longrightarrow & \tilde{I}_1 & \xrightarrow{\tilde{f}} & \tilde{I}_2 \longrightarrow 0 \\ & & \downarrow \tilde{\gamma} & & \downarrow \tilde{\beta} & & \downarrow \tilde{\alpha} \\ 0 & \longrightarrow & \text{Ker } \tilde{f}' & \longrightarrow & \tilde{I}'_1 & \xrightarrow{\tilde{f}'} & \tilde{I}'_2 \longrightarrow 0 \end{array} .$$

We claim that the image of  $\text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \tilde{\gamma}): \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}) \rightarrow \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}')$  under  $F_\lambda$  is equal to  $u_3$ . Indeed, let  $\alpha, \beta, \gamma$  be the respective images of  $\tilde{\alpha}, \tilde{\beta}, \tilde{\gamma}$  under  $q_\lambda: \text{mod } k\tilde{Q} \rightarrow \text{mod } kQ$ . Then the image of  $\text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \tilde{\gamma})$  under  $F_\lambda$  is equal to (see 5.2):

$$\text{Ext}_{kQ}^1(T, \gamma): \text{Ext}_{kQ}^1(T, \text{Ker } f) \rightarrow \text{Ext}_{kQ}^1(T, \text{Ker } f') .$$

On the other hand, we have two commutative diagrams in  $\text{mod } kQ$  and  $\text{mod } \tilde{B}$  respectively:

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Ker } f = \text{Tor}_1^B(R, T) & \longrightarrow & I_1 & \longrightarrow & I_2 \longrightarrow 0 \\ & & \gamma \downarrow & & \beta \downarrow & & \alpha \downarrow \\ 0 & \longrightarrow & \text{Ker } f' = \text{Tor}_1^B(R', T) & \longrightarrow & I'_1 & \longrightarrow & I'_2 \longrightarrow 0 \end{array}, \text{ and}$$

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Hom}_{kQ}(T, I_1) & \longrightarrow & \text{Hom}_{kQ}(T, I_2) & \longrightarrow & R \longrightarrow 0 \\ & & \text{Hom}_{kQ}(T, \beta) \downarrow & & \text{Hom}_{kQ}(T, \alpha) \downarrow & & u_3 \downarrow \\ 0 & \longrightarrow & \text{Hom}_{kQ}(T, I'_1) & \longrightarrow & \text{Hom}_{kQ}(T, I'_2) & \longrightarrow & R' \longrightarrow 0 \end{array},$$

from which it is straightforward to check that  $u_3: R \rightarrow R'$  coincides with  $\text{Ext}_{kQ}^1(T, \gamma)$ . Thus,  $u_3$  is equal to the image under  $F_\lambda$  of the morphism  $\text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \tilde{\gamma}): \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}) \rightarrow \text{Ext}_{k\tilde{Q}}^1(\tilde{T}, \text{Ker } \tilde{f}')$ . This completes the proof. ■

We summarise our results in the following theorem.

**Theorem 5.12.** *Let  $A$  be a finite dimensional  $k$ -algebra and  $\Gamma$  be a component of  $\Gamma(\text{mod } A)$  containing a left section  $\Sigma$ . Let  $B = A/\text{Ann } \Sigma$  and  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  be the universal cover of translation quivers. To a well-behaved covering functor  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$  corresponds a covering  $F: \tilde{B} \rightarrow B$  with  $\tilde{B}$  locally bounded and a functor  $\varphi: k(\tilde{\Gamma}) \rightarrow \text{mod } \tilde{B}$  which is  $\pi_1(\Gamma)$ -equivariant on vertices and makes the following diagram commute:*

$$\begin{array}{ccc} k(\tilde{\Gamma}) & \xrightarrow{\varphi} & \text{mod } \tilde{B} \\ p \downarrow & & \downarrow F_\lambda \\ \text{ind } \Gamma & \xrightarrow{\text{Hom}_A(B, -)} & \text{mod } B \end{array}.$$

**Proof:** The functor  $\varphi$  is constructed as above. The  $\pi_1(\Gamma)$ -equivariance follows from 5.10 and 5.11. ■

**Corollary 5.13.** *If  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$  is a Galois covering (with respect to the action of  $\pi_1(\Gamma)$  on  $k(\tilde{\Gamma})$ ), then the functor  $\varphi: k(\tilde{\Gamma}) \rightarrow \text{mod } \tilde{B}$  of the preceding theorem is  $\pi_1(\Gamma)$ -equivariant.*

**Proof:** We already know that  $\varphi$  is  $\pi_1(\Gamma)$ -equivariant on objects. Note also that  $F: \tilde{B} \rightarrow B$  is a Galois covering with group  $\pi_1(\Gamma)$  (see 5.1). Let  $f: M \rightarrow N$  be a morphism in  $k(\tilde{\Gamma})$ , and  $g \in \pi_1(\Gamma)$ . Then  $\varphi({}^g f): \varphi({}^g M) \rightarrow \varphi({}^g N)$  and  ${}^g \varphi(f): {}^g \varphi(M) \rightarrow {}^g \varphi(N)$  are two morphisms in  $\text{mod } \tilde{B}$  such that  $F_\lambda(\varphi({}^g f)) = p({}^g f)|_B = p(f)|_B = F_\lambda({}^g \varphi(f))$  (recall that  $F_\lambda = F_\lambda \circ g$  for every  $g \in \pi_1(\Gamma)$  because it is the push-down functor of a Galois covering with group  $\pi_1(\Gamma)$ ). So we deduce that  $\varphi({}^g f) = {}^g \varphi(f)$ . ■

## 6 The main theorem

The aim of this section is to prove Theorem A. Thus we assume that  $A$  is a connected lura algebra, not quasi-tilted of canonical type. For simplicity, we assume that  $A$  is not concealed. We use the following notation:

- $\Gamma$  is the connecting component of  $\Gamma(\text{mod } A)$ , and  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  is the universal cover of translation quivers (if  $A$  is concealed, we may equivalently choose  $\Gamma$  to be the unique postprojective component or the unique preinjective component).
- $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$  is a well-behaved covering functor. If  $\Gamma$  is standard, we assume that  $p$  equals the composition of  $k(\pi): k(\tilde{\Gamma}) \rightarrow k(\Gamma)$  with some isomorphism  $k(\Gamma) \xrightarrow{\sim} \text{ind } \Gamma$ , so that  $p$  is a Galois covering with group  $\pi_1(\Gamma)$ .
- $\Sigma$  is the full subcategory of  $\text{ind } \Gamma$  whose objects are the Ext-injective objects in  $\mathcal{L}_A$ .
- $B$  is the left support of  $A$ .

We know from [5, 4.4, 5.1] that the algebra  $B$  is a product of tilted algebras. Without loss of generality, we assume that:

- $B = \text{End}_{kQ}(T)$ , where  $T = T_1 \oplus \dots \oplus T_n$  is a multiplicity-free tilting  $kQ$ -module ( $T_i \in \text{ind } kQ$ ).

-  $\Sigma$  is the full subcategory of  $\mathbf{mod} B$  with objects the modules of the form  $\mathbf{Hom}_{kQ}(T, D(kQe_x))$ ,  $x \in Q_0$ .

It follows from [1, 2.1 Ex. b] that  $\Sigma$  is a left section of  $\Gamma$ . So we may apply 5.12. The proof of Theorem A is done in the following steps: We first construct a locally bounded  $k$ -category  $\tilde{A}$  endowed with a free  $\pi_1(\Gamma)$ -action in case  $A$  is standard; then construct a covering functor  $F: \tilde{A} \rightarrow A$  extending the functor  $F: \tilde{B} \rightarrow B$  of 5.12 and satisfying the conditions of the theorem; we also construct a functor  $\Phi: k(\tilde{\Gamma}) \rightarrow \mathbf{mod} \tilde{A}$  which extends the functor  $\varphi: k(\tilde{\Gamma}) \rightarrow \mathbf{mod} \tilde{B}$  of 5.12 and is essential in the study of the Galois coverings of standard lura algebras; and finally we prove Theorem A.

### The category $\tilde{A}$

We need some notation. Let  $C$  be the full subcategory of  $\mathbf{ind} A$  with objects the indecomposable projective  $A$ -modules not in  $\mathcal{L}_A$ . So  $C$  is a full subcategory of  $\mathbf{ind} \Gamma$ . Let  $\tilde{C}$  be the full subcategory  $p^{-1}(C)$ , so that  $p$  induces a covering functor  $\tilde{C} \rightarrow C$ . Note that if  $A$  is standard and  $p$  is Galois with group  $\pi_1(\Gamma)$ , then  $p: \tilde{C} \rightarrow C$  is a Galois covering with group  $\pi_1(\Gamma)$ . For every  $x \in \tilde{B}_o$ , let  $\tilde{P}_x$  be the corresponding indecomposable projective  $\tilde{B}$ -module. Also,  $P_x \in \mathbf{mod} B$  denotes the indecomposable projective  $B$ -module associated to an object  $x \in B_o$ . We define the  $\tilde{C} - \tilde{B}$ -bimodule  $\tilde{M}$  to be the functor  $\tilde{C} \times \tilde{B}^{op} \rightarrow \mathbf{mod} k$  such that for every  $\tilde{P} \in \tilde{C}_o$  and  $x \in \tilde{B}_o$

$${}_{\tilde{P}}\tilde{M}_x = \mathbf{Hom}_{\tilde{B}}(\tilde{P}_x, \varphi(\tilde{P})) ,$$

with obvious actions of  $\tilde{C}$  (using  $\varphi$ ) and  $\tilde{B}$ . We need the following technical lemma.

**Lemma 6.1.** *Let  $X \in \tilde{\Gamma}$ . Let  $p(X)|_B = X_1^{l_1} \oplus \dots \oplus X_t^{l_t}$  be an indecomposable decomposition in  $\mathbf{mod} B$  with  $X_1, \dots, X_t$  pairwise non isomorphic. Then  $X_1, \dots, X_t \in \mathbf{ind} B \cap \Gamma$ , and they are direct summands of tilting  $B$ -modules. If  $N \in \mathbf{ind} \tilde{B}$  is a summand of  $\varphi(X)$ , then there exist  $i \in \{1, \dots, t\}$  and  $g \in \pi_1(\Gamma)$  such that  $N \simeq {}^g\tilde{X}_i$ .*

**Proof:** By the proof of 5.10, the two first assertions are true. Therefore we apply 4.2 to the modules  $X_1, \dots, X_t$ . Up to a renumbering, we may assume that  $\mathbf{Hom}_B(X_i, X_j) = 0$  if  $i < j$ . Now  $F_\lambda N$  is a direct summand of  $p(X)|_B$ . So there exist indices  $1 \leq i_1 < i_2 < \dots < i_t \leq t$  such that  $F_\lambda N \simeq X_{i_1} \oplus \dots \oplus X_{i_t}$ . In particular, there is a section  $s: X_{i_1} \rightarrow F_\lambda N$  which defines a split triangle in  $\mathcal{D}^b(\mathbf{mod} B)$ :

$$M \rightarrow X_{i_1} \xrightarrow{s} F_\lambda N \rightarrow M[1] ,$$

where  $M = \bigoplus_{j \geq 2} X_{i_j}[-1]$ . In particular, we have  $\mathcal{D}^b(\mathbf{mod} B)(X_{i_1}, M[1]) = \mathbf{Hom}_B(X_{i_1}, \bigoplus_{j \geq 2} X_{i_j}) = 0$ . This and the isomorphisms of 4.2 (applied to  $X_{i_1}$  which is an indecomposable summand of a tilting  $B$ -module) show that 4.3 applies here. So, there exist  $g \in \pi_1(\Gamma)$ , a morphism  $\tilde{s}: {}^g\tilde{X}_{i_1} \rightarrow N$  (in  $\mathcal{D}^b(\mathbf{mod} \tilde{B})$ , and actually in  $\mathbf{mod} \tilde{B}$ ), and a commutative diagram:

$$\begin{array}{ccc} X_{i_1} & \xrightarrow{F_\lambda \tilde{s}} & F_\lambda N \\ \sim \downarrow & & \downarrow \sim \\ X_{i_1} & \xrightarrow{s} & F_\lambda N \end{array} ,$$

where the vertical arrows are isomorphisms. This allows the identification  $s = F_\lambda \tilde{s}$ . We claim that  $\tilde{s}$  is a section. For this purpose, we complete  $\tilde{s}$  into a triangle  ${}^g\tilde{X}_{i_1} \xrightarrow{\tilde{s}} N \rightarrow N' \xrightarrow{f} {}^g\tilde{X}_{i_1}$  in  $\mathcal{D}^b(\tilde{B})$ . Since  $F_\lambda: \mathcal{D}^b(\mathbf{mod} \tilde{B}) \rightarrow \mathcal{D}^b(\mathbf{mod} B)$  is exact, we deduce a triangle  $X_{i_1} \xrightarrow{s} F_\lambda N \rightarrow F_\lambda N' \xrightarrow{F_\lambda f} X_{i_1}[1]$  in  $\mathcal{D}^b(\mathbf{mod} B)$ . Since  $s$  is a section, this triangle splits, that is  $F_\lambda f = 0$ . The bijections of 4.2 imply that  $f = 0$ , that is,  $\tilde{s}$  is a section. Since  $N$  is indecomposable, we get  $N \simeq {}^g\tilde{X}_{i_1}$ . ■

The following lemma defines  $\tilde{A}$  and its  $\pi_1(\Gamma)$ -action in case  $A$  is standard.

**Lemma 6.2.** *Let  $\tilde{A} = \begin{bmatrix} \tilde{B} & 0 \\ \tilde{M} & \tilde{C} \end{bmatrix}$ . Then  $\tilde{A}$  is locally bounded and  $\pi_1(\Gamma)$  acts freely on  $\tilde{A}$  if  $A$  is standard.*

**Proof:** We know that  $\tilde{B}$  and  $\tilde{C}$  are locally bounded. Let  $P \in \tilde{C}_o$ . We have the bijection of 4.2:

$$\bigoplus_{\tilde{x} \in \tilde{B}_o} \mathbf{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, \varphi(\tilde{P})) \xrightarrow{\sim} \bigoplus_{x \in B_o} \mathbf{Hom}_B(P_x, p(\tilde{P})|_B) . \quad (i)$$

Since the right hand-side is finite dimensional, then so is  $\bigoplus_{\tilde{x} \in \tilde{B}_o} {}_{\tilde{P}}\tilde{M}_{\tilde{x}}$ , for every  $\tilde{P} \in \tilde{C}_o$ .

Now let  $P \in \tilde{C}_o$ , let  $\tilde{x} \in \tilde{B}_o$ , and let us prove that  $\bigoplus_{p(P')=p(P)} \mathbf{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, \varphi(P'))$  is finite dimensional. By definition of  $p$ , we have  $p^{-1}(p(P)) = \{{}^g P \mid g \in \pi_1(\Gamma)\}$ . Also, we know from 5.12 that  $\varphi$  is  $\pi_1(\Gamma)$ -equivariant on objects. Therefore:

$$\bigoplus_{p(P')=p(P)} \mathbf{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, \varphi(P')) = \bigoplus_{g \in \pi_1(\Gamma)} \mathbf{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, {}^g \varphi(P)) . \quad (ii)$$

Moreover, 6.1 shows that there exist modules  $X_1, \dots, X_t \in \text{ind } B$  which are direct summands of tilting  $B$ -modules and there exist  $g_1, \dots, g_t$  such that  $\varphi(P) = \bigoplus_{i=1}^t {}^{g_i} \tilde{X}_i$ . By applying 4.2 to each  $X_i$ , we get a bijection of vector spaces:

$$\bigoplus_{g \in \pi_1(\Gamma)} \text{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, {}^g \varphi(P)) \simeq \text{Hom}_B(P_{F(\tilde{x})}, F_\lambda \varphi(P)) . \quad (\text{iii})$$

From (ii) and (iii) we infer that  $\bigoplus_{p(P')=p(P)} \text{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, \varphi(P'))$  is finite dimensional for every  $\tilde{x} \in \tilde{B}_o$  and  $P \in \tilde{C}_o$ .

This shows that  $\tilde{A}$  is locally bounded.

Assume now that  $A$  is standard and that  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$  is a Galois covering with group  $\pi_1(\Gamma)$ . Let us define a free  $\pi_1(\Gamma)$ -action on  $\tilde{A}$ . We already have a free  $\pi_1(\Gamma)$ -action on  $\tilde{B}$  and on  $\tilde{C}$ . Also, for every  $\tilde{x} \in \tilde{B}_o$ ,  $\tilde{P} \in \tilde{C}_o$  and  $g \in \pi_1(\Gamma)$ , we have an isomorphism of vector spaces:

$${}_{\tilde{P}} \tilde{M}_{\tilde{x}} = \text{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, \varphi(P)) \xrightarrow{\sim} {}_{g\tilde{P}} \tilde{M}_{g\tilde{x}} = \text{Hom}_{\tilde{B}}({}^g \tilde{P}_{\tilde{x}}, \varphi({}^g \tilde{P})) \quad (\star)$$

given by the  $\pi_1(\Gamma)$ -action on  $\text{mod } \tilde{B}$  (recall that  $\varphi$  is  $\pi_1(\Gamma)$ -equivariant on objects, and that  $\tilde{P}_{g\tilde{x}} = {}^g \tilde{P}_{\tilde{x}}$ ). We define the action of  $g$  on morphisms of  $\tilde{A}$  lying in  $\tilde{M}$  using this isomorphism. Since  $\pi_1(\Gamma)$  acts on  $\text{mod } \tilde{B}$ , this defines a  $\pi_1(\Gamma)$ -action on  $\tilde{A}$ , that is,  $g(vu) = g(v)g(u)$  whenever  $u$  and  $v$  are composable morphisms in  $\tilde{A}$ . Moreover,  $\pi_1(\Gamma)$  acts freely on objects in  $\tilde{B}$  and in  $\tilde{C}$ . So we have a free  $\pi_1(\Gamma)$ -action on  $\tilde{A}$ . ■

**The functor  $F: \tilde{A} \rightarrow A$**

**Lemma 6.3.** *There exists a covering functor  $F: \tilde{A} \rightarrow A$  extending  $F: \tilde{B} \rightarrow B$ . If moreover  $A$  is standard, then  $F$  can be taken to be Galois with group  $\pi_1(\Gamma)$ .*

**Proof:** Note that  $A = \begin{bmatrix} B & 0 \\ M & C \end{bmatrix}$  where  $M$  is the  $C - B$ -bimodule such that  ${}_P M_x = \text{Hom}_B(P_x, P|_B)$  for every  $P \in C_o$  and  $x \in B_o$ . Let us define  $F: \tilde{A} \rightarrow A$  as follows:

- $F|_{\tilde{B}}$  coincides with the functor  $F: \tilde{B} \rightarrow B$ .
- $F|_{\tilde{C}}$  coincides with  $p: \tilde{C} \rightarrow C$ .
- Let  $x \in \tilde{B}_o$  and  $\tilde{P} \in \tilde{C}_o$ , then  $F: {}_{\tilde{P}} \tilde{M}_x \rightarrow {}_{F(\tilde{P})} M_{F(x)}$  is the following map induced by  $F_\lambda$ :

$$\text{Hom}_{\tilde{B}}(\tilde{P}_x, \varphi(\tilde{P})) \rightarrow \text{Hom}_B(P_{F(x)}, p(\tilde{P})|_B) .$$

Since  $F_\lambda: \text{mod } \tilde{B} \rightarrow \text{mod } B$  is a functor and  $F_\lambda \varphi = p(-)|_B$  (see 5.12), we have defined a functor  $F: \tilde{A} \rightarrow A$ . Let us prove that  $F: \tilde{A} \rightarrow A$  is a covering functor. Since  $F: \tilde{B} \rightarrow B$  and  $p: \tilde{C} \rightarrow C$  are covering functors, the bijections (i), (iii) in the proof of 6.2 show that for any  $\tilde{a} \in \tilde{B}_o$  and any  $\tilde{P} \in \tilde{C}_o$ , the two following maps induced by  $F_\lambda$  are isomorphisms:

$$\begin{aligned} \bigoplus_{F(\tilde{x})=F(\tilde{a})} \text{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{x}}, \varphi(\tilde{P})) &\rightarrow \text{Hom}_B(P_{F(\tilde{a})}, p(\tilde{P})|_B) , \\ \bigoplus_{p(\tilde{Q})=p(\tilde{P})} \text{Hom}_{\tilde{B}}(\tilde{P}_{\tilde{a}}, \varphi(\tilde{Q})) &\rightarrow \text{Hom}_B(P_{F(\tilde{a})}, p(\tilde{Q})|_B) . \end{aligned}$$

So  $F$  is a covering functor. Assume now that  $A$  is standard. We may suppose that  $p$  is a Galois covering with group  $\pi_1(\Gamma)$ . By 6.2, there is a free  $\pi_1(\Gamma)$ -action on  $\tilde{A}$ . Moreover,  $F: \tilde{B} \rightarrow B$ , and therefore  $F_\lambda: \text{mod } \tilde{B} \rightarrow \text{mod } B$ , are  $\pi_1(\Gamma)$ -equivariant, and so is  $p: \tilde{C} \rightarrow C$ , because it restricts the Galois covering  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$ . Therefore  $F: \tilde{A} \rightarrow A$  is  $\pi_1(\Gamma)$ -equivariant. Finally, the fibres of  $F: \tilde{A} \rightarrow A$  on objects are the  $\pi_1(\Gamma)$ -orbits in  $\tilde{A}_o$  because  $F: \tilde{B} \rightarrow B$  and  $p: \tilde{C} \rightarrow C$  are Galois coverings. Since  $F: \tilde{A} \rightarrow A$  is a covering functor, this implies that it is also a Galois covering with group  $\pi_1(\Gamma)$  (see for instance the proof of [31, Prop. 6.1.37]). ■

**The functor  $\Phi: k(\tilde{\Gamma}) \rightarrow \text{mod } \tilde{A}$**

Recall that an  $\tilde{A}$ -module is a triple  $(K, L, f)$  where  $K \in \text{mod } \tilde{B}$ ,  $L \in \text{mod } \tilde{C}$  and  $f: L \otimes_{\tilde{C}} \tilde{M} \rightarrow K$  is a morphism of  $\tilde{B}$ -modules. Let  $\psi: k(\tilde{\Gamma}) \rightarrow \text{mod } \tilde{C}$  be the functor:

$$\psi: X \mapsto k(\tilde{\Gamma})(\tilde{C}, X) .$$

Clearly, it is  $\pi_1(\Gamma)$ -equivariant. Let  $L \in k(\tilde{\Gamma})$ . Then  $\psi(L) \otimes_{\tilde{C}} \tilde{M}$  is the  $\tilde{B}$ -module whose value at  $x \in \tilde{B}_o$  equals:

$$\left( \psi(L) \otimes_{\tilde{C}} \tilde{M} \right) (x) = \left( \bigoplus_{\tilde{P} \in \tilde{C}_o} k(\tilde{\Gamma})(\tilde{P}, L) \otimes_k \text{Hom}_{\tilde{B}}(\tilde{P}_x, \varphi(\tilde{P})) \right) / N ,$$

where  $N$  is the following subspace:

$$N = \left\langle f f' \otimes u - f \otimes \varphi(f') u \mid f \in k(\tilde{\Gamma})(\tilde{P}, L), f' \in k(\tilde{\Gamma})(\tilde{P}', \tilde{P}), u \in \text{Hom}_{\tilde{B}}(\tilde{P}_x, \varphi(\tilde{P})) , \text{ for every } \tilde{P}, \tilde{P}' \in \tilde{C}_o \right\rangle .$$

For every  $x \in \tilde{B}_o$  and  $\tilde{P} \in \tilde{C}_o$ , we have a  $k$ -linear map:

$$\begin{aligned} \eta_{L,x,P}: \quad k(\tilde{\Gamma})(\tilde{P}, L) \otimes_k \text{Hom}_{\tilde{B}}(\tilde{P}_x, \varphi(\tilde{P})) &\rightarrow \text{Hom}_{\tilde{B}}(\tilde{P}_x, \varphi(L)) = \varphi(L)(x) \\ f \otimes u &\mapsto \varphi(f) u \end{aligned} .$$

It is not difficult to check that the family of maps  $(\eta_{L,x,\tilde{P}})_{L,x,\tilde{P}}$  defines a functorial morphism:

$$\eta: \psi(-) \otimes_{\tilde{C}} \tilde{M} \rightarrow \varphi .$$

Moreover, if  $\varphi$  is  $\pi_1(\Gamma)$ -equivariant, then  $\eta$  is  $\pi_1(\Gamma)$ -equivariant. We let  $\Phi: k(\tilde{\Gamma}) \rightarrow \text{mod } \tilde{A}$  be the following functor:

$$\Phi: L \mapsto (\varphi(L), \psi(L), \eta_L) .$$

### The main theorem

Our Theorem A follows directly from the following result.

**Theorem 6.4.** *Let  $A$  be laura and not quasi-tilted of canonical type. Let  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  be the universal cover of the connecting component  $\Gamma$ . There exists a covering functor  $F: \tilde{A} \rightarrow A$ , and a commutative diagram:*

$$\begin{array}{ccc} k(\tilde{\Gamma}) & \xrightarrow{\Phi} & \text{mod } \tilde{A} \\ p \downarrow & & \downarrow F_\lambda \\ \text{ind } \Gamma & \xrightarrow{\quad} & \text{mod } A \end{array} ,$$

where  $p$  is a well-behaved covering functor, and  $\Phi$  is faithful. If, moreover,  $A$  is standard, then  $F$  and  $p$  may be assumed to be Galois coverings with group  $\pi_1(\Gamma)$ , and  $\Phi$  is then  $\pi_1(\Gamma)$ -equivariant and full.

**Proof:** Let  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$  be a well-behaved covering functor. The commutativity of the shown diagram follows from the one of 5.12 and from the one of the diagram:

$$\begin{array}{ccc} k(\tilde{\Gamma}) & \xrightarrow{\psi} & \text{mod } \tilde{C} \\ p \downarrow & & \downarrow p_\lambda \\ \text{ind } \Gamma & \xrightarrow{X \mapsto \text{Hom}_A(C, X)} & \text{mod } C \end{array} ,$$

Since  $F_\lambda \Phi = p$  and  $p$  is faithful, then  $\Phi$  is faithful. Therefore  $\Phi(k(\tilde{\Gamma}))$  is contained in a connected component  $\Omega$  of  $\text{mod } \tilde{A}$ .

We now prove that  $\tilde{A}$  is connected. Let  $x \in \tilde{A}_o$  and  $Q_x$  be the corresponding indecomposable projective  $\tilde{A}$ -module. If  $\tilde{F}_\lambda Q_x \in C_o$ , then, by construction,  $Q_x$  lies in the image of  $\Phi$ , so that  $Q_x \in \Omega$ . If  $\tilde{F}_\lambda Q_x \notin C_o$ , then  $F(x) \in B_o$  and  $x \in \tilde{B}_o$ . In this case, there is a non-zero morphism  $u: P_{F(x)} = \tilde{F}_\lambda Q_x \rightarrow E$  in  $\text{mod } \tilde{B}$ , where  $E \in \Sigma$ . Fix  $\tilde{E} \in p^{-1}(E)$  so that  $F_\lambda \Phi(\tilde{E}) = E$ . Since  $u$  is non-zero, 4.2 implies that there is a non-zero morphism  $Q_x \rightarrow {}^g \varphi(\tilde{E}) = \Phi({}^g \tilde{E})$  in  $\text{mod } \tilde{B}$  (recall that  $\varphi$  is  $\pi_1(\Gamma)$ -equivariant on vertices). So  $Q_x \in \Omega$ , and  $\Omega$  contains all the indecomposable projective  $\tilde{A}$ -modules. This proves that  $\tilde{A}$  is connected.

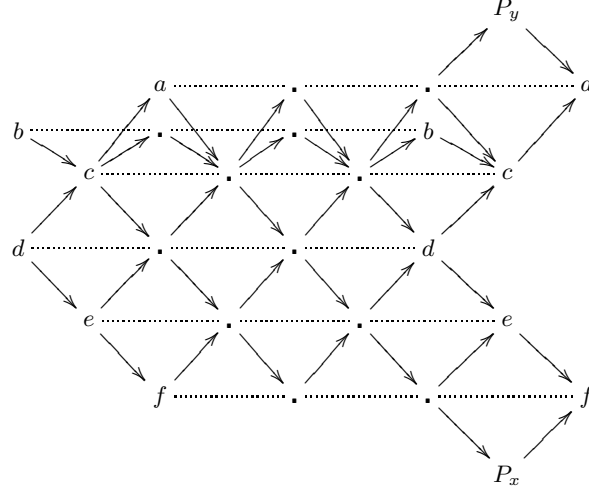
It remains to prove that if  $A$  is standard, then  $\Phi$  is full and  $\pi_1(\Gamma)$ -equivariant, and  $F$  is Galois with group  $\pi_1(\Gamma)$ . In case  $A$  is standard, we suppose that  $p: k(\tilde{\Gamma}) \rightarrow \text{ind } \Gamma$  is Galois with group  $\pi_1(\Gamma)$ . Therefore  $\varphi$  is  $\pi_1(\Gamma)$ -equivariant (see 5.13) and so is  $\eta$ . Hence,  $\Phi$  is  $\pi_1(\Gamma)$ -equivariant. Also,  $F$  is a Galois covering because of 6.3. We prove that  $\Phi$  is full. Given a morphism  $f: \Phi(L) \rightarrow \Phi(N)$ , there exists  $(f_g)_g \in \bigoplus_{g \in \pi_1(\Gamma)} \text{Hom}_{k(\Gamma)}(L, {}^g N)$  such that  $F_\lambda(f) = \sum_g p(f_g)$  (because  $p$  is Galois). So  $F_\lambda(f - \Phi(f_1)) = \sum_{g \neq 1} F_\lambda(\Phi(f_g)) = 0$ . Since  $F$  is Galois with group  $\pi_1(\Gamma)$  and since  $\Phi$  is  $\pi_1(\Gamma)$ -equivariant, we get  $f = \Phi(f_1)$ . So  $\Phi$  is full and the theorem is proved. ■

The following example due to Riedtmann shows that  $F$  needs not be a Galois covering.

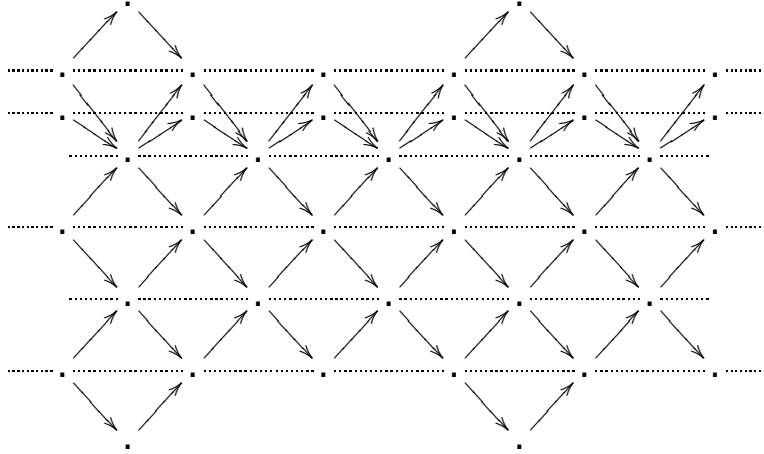
*Example 6.5.* Assume that  $\text{char}(k) = 2$  and let  $A$  be given by the bound quiver (see [14, §7, Ex. 14 bis] and [39]):

$$x \begin{array}{c} \xrightarrow{\sigma} \\ \xleftarrow{\delta} \end{array} y \begin{array}{c} \circlearrowleft \\ \circlearrowright \end{array} \rho, \quad \rho^4 = 0, \quad \rho^2 = \delta\sigma, \quad \sigma\delta = \sigma\rho\delta.$$

Then  $A$  is representation-finite and not standard, with the following Auslander-Reiten quiver:



where the two copies of  $a, b, c, d, e$  and  $f$ , respectively, are identified. Here,  $\pi_1(\Gamma) \simeq \mathbb{Z}$  and  $\tilde{\Gamma}$  is as follows:



Therefore  $\tilde{A}$  is the locally bounded  $k$ -category, given by the following bound quiver:

$$\begin{array}{ccccccc} \cdots & y_{i-1} & \xrightarrow{\quad} & y_i & \xrightarrow{\quad} & y_{i+1} & \xrightarrow{\quad} & y_{i+2} & \cdots \\ & \searrow & & \nearrow & \searrow & & \nearrow & & \\ \cdots & x_{i-1} & & x_i & & x_{i+1} & & x_{i+2} & \cdots \end{array}$$

$$\delta_{i+1}\sigma_i = \rho_{i+1}\rho_i, \quad \sigma_{i+1}\delta_i = 0, \text{ for all } i,$$

where  $\sigma_i$ ,  $\delta_i$  and  $\rho_i$  denote the arrows  $y_i \rightarrow x_{i+1}$ ,  $x_i \rightarrow y_{i+1}$ , and  $y_i \rightarrow y_{i+1}$ , respectively. Now the covering functor  $F: \tilde{A} \rightarrow A$  is as follows:

1.  $F(\rho_i) = \rho$  for every  $i$ ,
2.  $F(\sigma_i) = \sigma$  for every  $i \equiv 0, 1 \pmod{4}$ ,
3.  $F(\sigma_i) = \sigma + \sigma\rho$  for every  $i \equiv 2, 3 \pmod{4}$ ,
4.  $F(\delta_i) = \delta$  for every  $i \equiv 1, 3 \pmod{4}$ ,
5.  $F(\delta_i) = \delta + \rho\delta$ , for every  $i \equiv 0, 2 \pmod{4}$ .

Obviously,  $F$  is a covering functor which is not Galois. Actually, one can easily check that  $A$  is simply connected, that is, the fundamental group (in the sense of [36]) of any presentation of  $A$  is trivial. Hence,  $A$  has no proper Galois covering by a locally bounded and connected  $k$ -category.

The following corollary is a particular case of our main theorem. We state it for later purposes.

**Corollary 6.6.** *Let  $A$  be a standard lura algebra and let  $\Gamma$  be its connecting component. There exists a Galois covering  $F: \tilde{A} \rightarrow A$  with group  $\pi_1(\Gamma)$  together with a commutative diagram:*

$$\begin{array}{ccc} k(\tilde{\Gamma}) & \xrightarrow{\Phi} & \text{mod } \tilde{A} \\ k(\pi) \downarrow & & \downarrow F_\lambda \\ k(\Gamma) & \xrightarrow{\subset} & \text{mod } A \end{array},$$

where  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  is the universal cover and where  $\Phi$  is full, faithful and  $\pi_1(\Gamma)$ -equivariant. ■

We pose the following problems.

**Problem 3.** Does there exists a combinatorial characterisation of standardness for lura algebras (as happens for representation-finite algebras, see [13])?

**Problem 4.** Let  $A$  be left supported algebra. Is it possible to construct a covering  $\tilde{A} \rightarrow A$  associated to the universal coverings of the components of  $\Gamma(\text{mod } A)$  containing the Ext-injective modules of  $\mathcal{L}_A$ ?

## 7 Galois coverings of the connecting component

**Theorem 7.1.** *Let  $A$  be a standard lura algebra, and  $p: \Gamma' \rightarrow \Gamma$  be a Galois covering with group  $G$  of its connecting component. Then there exists a Galois covering  $F': A' \rightarrow A$  with group  $G$ , where  $A'$  is connected and locally bounded. Moreover, there exists a commutative diagram:*

$$\begin{array}{ccc} k(\Gamma') & \xrightarrow{\Phi'} & \text{mod } A' \\ k(p) \downarrow & & \downarrow F'_\lambda \\ k(\Gamma) & \xrightarrow{j} & \text{mod } A \end{array},$$

where  $\Phi'$  is full, faithful and  $G$ -equivariant.

**Proof:** Since  $A$  is standard, there exists a full and faithful functor  $j: k(\Gamma) \hookrightarrow \text{ind } A$  with image  $\text{ind } \Gamma$ , and which maps meshes to almost split sequences. Let  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  be the universal cover. Then there exists a normal subgroup  $H \triangleleft \pi_1(\Gamma)$  such that  $\tilde{\Gamma}/H \simeq \Gamma'$  and  $G \simeq \pi_1(\Gamma)/H$ , and such that under these identifications, the following diagram commutes:

$$\begin{array}{ccc} \tilde{\Gamma} & & \\ \pi \downarrow & \searrow q & \\ & \tilde{\Gamma}/H = \Gamma' & \\ & \swarrow p & \\ \Gamma & & \end{array},$$

where  $q$  is the projection. These identifications imply that  $p: \Gamma' \rightarrow \Gamma$  is induced by  $\pi: \tilde{\Gamma} \rightarrow \Gamma$  by factoring out by  $H$ . By 6.6, there exist a Galois covering  $F: \tilde{A} \rightarrow A$  with group  $\pi_1(\Gamma)$  and a commutative diagram:

$$\begin{array}{ccc} k(\tilde{\Gamma}) & \xrightarrow{\Phi} & \text{mod } \tilde{A} \\ k(\pi) \downarrow & & \downarrow F_\lambda \\ k(\Gamma) & \xrightarrow{j} & \text{mod } A \end{array},$$

where  $\Phi$  is full, faithful and  $\pi_1(\Gamma)$ -equivariant. Setting  $A' = \tilde{A}/H$ , we deduce a Galois covering  $F': A' \rightarrow A$  with group  $G$ , making the following diagram commute:

$$\begin{array}{ccc} \tilde{A} & & \\ \downarrow F & \searrow F'' & \\ & \tilde{A}/H = A' & \\ & \swarrow F' & \\ A & & \end{array},$$

where  $F''$  is the natural projection (and  $F'$  is deduced from  $F$  by factoring out by  $H$ ). Therefore we have a commutative diagram of solid arrows:

$$\begin{array}{ccccc} k(\tilde{\Gamma}) & \xrightarrow{\Phi} & \text{mod } \tilde{A} & & \\ \downarrow k(\pi) & \searrow k(q) & \downarrow F_\lambda & \searrow F'_\lambda & \\ & k(\Gamma') & \cdots \xrightarrow{\Phi'} & \text{mod } A' & \\ & \swarrow k(p) & \downarrow j & \swarrow F'_\lambda & \\ k(\Gamma) & \xrightarrow{j} & \text{mod } A & & \end{array}.$$

We prove the existence of the dotted arrow  $\Phi'$  such that  $\Phi' k(q) = F'_\lambda F''_\lambda \Phi$ . For this purpose, recall that  $k(q)$  is a Galois covering with group  $H$ . Hence, it suffices to prove that  $F'_\lambda F''_\lambda \Phi$  is  $H$ -invariant. Indeed, we have  $F'_\lambda F''_\lambda = \Phi' h = F'_\lambda h \Phi' = F'_\lambda \Phi'$ , for every  $h \in H$ , because  $\Phi$  is  $\pi_1(\Gamma)$ -equivariant and  $F''$  is a Galois covering with group  $H$ . Now, we prove that the whole diagram commutes. We have:

$$(F'_\lambda \Phi') k(q) = F'_\lambda F''_\lambda \Phi = F_\lambda \Phi = j k(\pi) = j k(p) k(q),$$

hence,  $F'_\lambda \Phi' = j k(p)$ . We prove next that  $\Phi'$  is full and faithful. Let  $f: X \rightarrow Y$  be a morphism in  $k(\Gamma')$  such that  $\Phi'(f) = 0$ . Fix  $\tilde{X}, \tilde{Y} \in k(\tilde{\Gamma})$  such that  $q(\tilde{X}) = X$  and  $q(\tilde{Y}) = Y$ . Since  $k(q)$  is Galois with group  $H$ , there exists  $(f_h)_{h \in H} \in \bigoplus_{h \in H} k(\tilde{\Gamma})(\tilde{X}, {}^h \tilde{Y})$  such that  $\sum_{h \in H} k(q)(f_h) = f$ . The commutativity of the diagram gives:

$$0 = \sum_{h \in H} F'_\lambda F''_\lambda (\Phi(f_h)),$$

where  $(\Phi(f_h))_{h \in H} \in \bigoplus_{h \in H} \text{Hom}_{\tilde{A}}(\Phi(\tilde{X}), {}^h \Phi(\tilde{Y}))$  (recall that  $\Phi$  is  $\pi_1(\Gamma)$ -equivariant). Since  $F'': \tilde{A} \rightarrow A'$  is Galois with group  $H$ , we deduce that  $\Phi(f_h) = 0$  for every  $h \in H$ , so that  $f_h = 0$  for every  $h \in H$ , because  $\Phi$  is faithful. Thus,  $f = \sum_{h \in H} k(q)(f_h) = 0$  and  $\Phi'$  is faithful. Let  $X, Y \in k(\Gamma')$  and  $u: \Phi'(X) \rightarrow \Phi'(Y)$  be a morphism in  $\text{mod } A'$ , and fix  $\tilde{X}, \tilde{Y} \in k(\tilde{\Gamma})$  as above. In particular, we have  $\Phi'(X) = F'_\lambda F''_\lambda(\Phi(\tilde{X}))$  and  $\Phi'(Y) = F'_\lambda F''_\lambda(\Phi(\tilde{Y}))$ . Therefore there exists  $(\tilde{u}_h)_{h \in H} \in \bigoplus_{h \in H} \text{Hom}_{\tilde{A}}(\Phi(\tilde{X}), {}^h \Phi(\tilde{Y}))$  such that  $u = \sum_{h \in H} F'_\lambda F''_\lambda(\tilde{u}_h)$ . Since  $\Phi'$  is  $\pi_1(\Gamma)$ -equivariant, we have  $\text{Hom}_{\tilde{A}}(\Phi'(\tilde{X}), {}^h \Phi'(\tilde{Y})) = \text{Hom}_{\tilde{A}}(\Phi'(\tilde{X}), \Phi'({}^h \tilde{Y}))$ , for every  $h \in H$ . Using the fullness of  $\Phi'$ , we find  $(\tilde{f}_h)_{h \in H} \in \bigoplus_{h \in H} k(\tilde{\Gamma})(\tilde{X}, {}^h \tilde{Y})$  such that  $\tilde{u}_h = \Phi(\tilde{f}_h)$  for every  $h \in H$ . Since  $k(q)$  is Galois with group  $H$ , we deduce that  $\sum_{h \in H} k(q)(\tilde{f}_h) \in k(\Gamma)(X, Y)$ . Moreover, we have:

$$\Phi' \left( \sum_{h \in H} k(q)(\tilde{f}_h) \right) = \sum_{h \in H} F'_\lambda F''_\lambda \Phi(\tilde{f}_h) = \sum_{h \in H} F'_\lambda \tilde{u}_h = u,$$

whence the fullness of  $\Phi'$ . To finish, it remains to prove that  $\Phi'$  is  $G$ -equivariant. Let  $g \in H$  be the residual class of  $\sigma \in \pi_1(\Gamma)$  modulo  $H$ . We need to prove that  $\Phi' \circ g = g \circ \Phi'$ . We have  $\Phi' \circ g \circ k(q) = \Phi' \circ k(q) \circ \sigma$ , because  $q: \tilde{\Gamma} \rightarrow \Gamma' = \tilde{\Gamma}/H$  is the canonical projection. Hence,  $\Phi' \circ g \circ k(q) = F'_\lambda F''_\lambda \circ \sigma \circ \Phi$ , because  $F'_\lambda F''_\lambda \circ \Phi = \Phi' \circ k(q)$ , and  $\Phi$  is  $\pi_1(\Gamma)$ -equivariant. Since  $F'_\lambda F''_\lambda \circ \sigma = g \circ F'_\lambda F''_\lambda$  (because  $F''$  is deduced from  $F$  by factoring out by  $H$ ), we have  $\Phi' \circ g \circ k(q) = g \circ F'_\lambda F''_\lambda \circ \Phi = g \circ \Phi' \circ k(q)$ , and so  $\Phi' \circ g = g \circ \Phi'$ . The proof is complete. ■

**Corollary 7.2.** *In the situation of Theorem 7.1, the full subquiver  $\Omega$  of  $\Gamma(\mathbf{mod} A')$  with vertex set equal to  $\{X \in \mathbf{ind} A' \mid F'_\lambda X \in \Gamma\}$  is a faithful and generalised standard component of  $\Gamma(\mathbf{mod} A')$ , isomorphic, as a translation quiver, to  $\Gamma'$ . Moreover, there exists a Galois covering of translation quivers  $\Gamma' \rightarrow \Gamma$  with group  $G$  extending the map  $X \mapsto F'_\lambda X$ .*

**Proof:** Since  $F'_\lambda \Phi = j k(p)$ , the module  $\Phi(X)$  is indecomposable and lies in  $\Omega$ , for every  $X \in \Gamma'$ . On the other hand if  $X \in \Omega$ , there exists  $X' \in \Gamma'$  such that  $F'_\lambda X = k(p)(X')$ . Therefore  $F'_\lambda X = F'_\lambda \Phi(X')$ . Since  $X$  and  $\Phi(X')$  are indecomposable, there exists  $g \in G$  such that  $X = {}^g \Phi(X') = \Phi({}^g X') \in \Phi(\Gamma')$ . Thus, we have shown that:

(i)  $\Omega$  coincides with the full subquiver of  $\Gamma(\mathbf{mod} A')$  with set of vertices  $\{\Phi(X) \mid X \in \Gamma'\}$ .

Let  $X \xrightarrow{u} Y$  be an arrow in  $\Gamma'$ . Since  $F'_\lambda \Phi = j k(p)$ , then  $F'_\lambda \Phi(u)$  is an irreducible morphism between indecomposable  $A$ -modules. Using [32, Lem. 2.1], we deduce that  $\Phi(u)$  is irreducible. This proves that:

(ii) The full subquiver of  $\Gamma(\mathbf{mod} A')$  with set of vertices  $\{\Phi(X) \mid X \in \Gamma'\}$  is contained in a connected component of  $\Gamma(\mathbf{mod} A')$ .

Combining (i), (ii) and [32, Lem. 2.3], we deduce that  $\Omega$  is a component of  $\Gamma(\mathbf{mod} A')$ . The same lemma shows that  $\Omega$  is faithful and generalised standard because so is  $\Gamma$ .

Let us prove that  $\Phi'$  induces an isomorphism between  $\Gamma'$  and  $\Omega$ . Since  $q: \tilde{\Gamma} \rightarrow \Gamma'$  is surjective on vertices and  $F''_\lambda \Phi = \Phi' k(q)$ , we know that every  $X \in \Omega$  lies in the image of  $F''_\lambda$ . Also,  $k(q)$  and  $\Phi$  commute with the translation, and so does  $F''_\lambda$  (see [32, Lem. 2.1]). Hence  $\Phi'$  commutes with the translation. Finally  $k(q)$  maps meshes to meshes, and  $\Phi$  maps meshes to almost split sequences. So  $\Phi'$  maps meshes to almost split sequences (see [32, Lem. 2.2]). Therefore there exists a morphism of translation quivers  $\Gamma' \rightarrow \Omega$  extending the map  $X \mapsto \Phi'(X)$  on vertices. Since it is a bijection on vertices, we deduce that it is an isomorphism  $\Gamma' \xrightarrow{\sim} \Omega$ .

Finally, the stabiliser  $G_X = \{g \in G \mid {}^g X \simeq X\}$  of  $X$  is trivial, for every  $X \in \Omega$  because  $G$  acts freely on  $\Gamma'$  and  $\Phi'$  is  $G$ -equivariant. Therefore there exists a Galois covering of translation quivers  $\Omega \rightarrow \Gamma$  with group  $G$  and extending the map  $X \mapsto F'_\lambda(X)$  (see [25, 3.6]). ■

**Corollary 7.3.** *In the situation of Theorem 7.1, if  $G$  is finite, then  $A'$  is a finite dimensional standard lura algebra.*

**Proof:** Since  $G$  is finite,  $A'$  is finite dimensional. By the preceding corollary,  $\Gamma'$  is generalised standard and faithful. Since  $\Gamma$  has only finitely many isomorphism classes of indecomposable modules lying on oriented cycles, the same is true for  $\Gamma'$ . Therefore  $\Gamma'$  is quasi-directed and faithful. Applying [37, 3.1] (or [45, Thm. 2]) shows that  $A'$  is a lura algebra with  $\Gamma'$  as a connecting component. Finally, the full and faithful functor  $\Phi': k(\Gamma') \rightarrow \mathbf{mod} A'$  with image equal to  $\mathbf{ind} \Gamma'$  shows that  $\Gamma'$  is standard, that is,  $A'$  is standard. ■

*Remark 7.4.* The above corollary may be compared with [7, Thm. 1.2] and [32, Thm. 3]. Indeed, if  $A'$  is a finite dimensional algebra endowed with the free action of a (necessarily finite) group  $G$ , then the category  $A/G$  and the skew-group algebra  $A[G]$  are Morita equivalent.

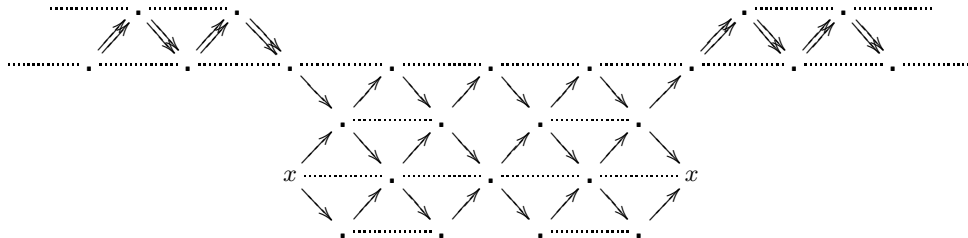
We end this section with the following corollary:

**Corollary 7.5.** *In the situation of Theorem 7.1, if  $G$  is finite, then:*

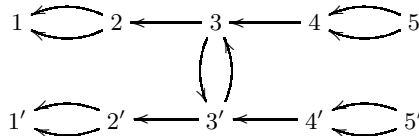
- (a)  *$A$  is tame if and only if  $A'$  is tame.*
- (b)  *$A$  is wild if and only if  $A'$  is wild.*

**Proof:** This follows from Theorem 7.1 and from [3, 5.3, (b)]. ■

*Example 7.6.* Consider the algebra  $A$  of 3.6, (a). The connecting component  $\Gamma$  admits a Galois covering with group  $\mathbb{Z}/2\mathbb{Z}$  by the following translation quiver:



where the two copies of  $x$  are identified. With our construction, we get a Galois covering  $F: A' \rightarrow A$  with group  $\mathbb{Z}/2\mathbb{Z}$ , where  $A'$  is the radical square zero algebra with the following quiver:



Note that both  $A$  and  $A'$  are tame.

## 8 Proof of Theorem B

We recall the definition of the orbit graph  $\mathcal{O}(\Gamma)$  (see [14, 4.2]). Given a vertex  $x \in \Gamma$ , its  $\tau$  orbit  $x^\tau$  is the set  $\{y \in \Gamma \mid y = \tau^l x, \text{ for some } l \in \mathbb{Z}\}$ . Also, we fix a polarisation  $\sigma$  in  $\Gamma$ . Recall that the periodic components of  $\Gamma$  are defined as follows. Consider the full translation subquiver of  $\Gamma$  with vertices the periodic vertices in  $\Gamma$ . To this subquiver, add a new arrow  $x \rightarrow \tau x$  for every vertex  $x$ . A *periodic component* of  $\Gamma$  is a connected component of the obtained quiver. Then:

1. The orbit graph  $\mathcal{O}(\Gamma)$  has as vertices the periodic components of  $\Gamma$  and the  $\tau$ -orbits of the non-periodic vertices.
2. For each periodic component, there is a loop attached to the associated vertex in  $\mathcal{O}(\Gamma)$ .
3. Let  $u^\sigma$  be the  $\sigma$ -orbit of an arrow  $u: x \rightarrow y$ . If both  $x$  and  $y$  are non-periodic, an edge is attached between  $x^\tau$  and  $y^\tau$ . If  $x$  (or  $y$ ) is non-periodic and  $y$  (or  $x$ ) is periodic, then an edge is attached between  $x^\tau$  (or  $y^\tau$ ) and the vertex associated to the periodic component containing  $y$  (or  $x$ , respectively). Otherwise, there is no arrow associated to  $u^\sigma$ .

By [14, 4.2], the fundamental group of the orbit graph  $\mathcal{O}(\Gamma)$  is isomorphic to  $\pi_1(\Gamma)$ .

Throughout this section, we assume that  $A$  is standard lura, having  $\Gamma$  as its connecting component. We use the following two lemmata:

**Lemma 8.1.** *If  $\mathcal{O}(\Gamma)$  is a tree, then  $A$  is weakly shod.*

**Proof:** If  $\mathcal{O}(\Gamma)$  is a tree, then  $\Gamma$  is simply connected (see [14, 4.1 and 4.2]). In particular,  $\Gamma$  has no oriented cycle. So  $A$  is weakly shod. ■

**Lemma 8.2.** *Let  $A$  be a (non necessarily connected) lura algebra which is not quasi-tilted of canonical type. If the orbit graph of any connecting component is a tree, then  $A$  is simply connected and  $\mathrm{HH}^1(A) = 0$ .*

**Proof:** This follows from the preceding lemma and from [32, Cor. 2]. ■

We now prove Theorem B whose statement we recall for convenience.

**Theorem B.** *Let  $A$  be a standard lura algebra, and  $\Gamma$  its connecting component(s). The following are equivalent:*

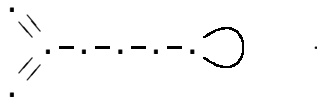
- (a)  $A$  is simply connected.
- (b)  $\mathrm{HH}^1(A) = 0$ .
- (c)  $\Gamma$  is simply connected.
- (d) The orbit graph  $\mathcal{O}(\Gamma)$  is a tree.

Moreover, if these conditions are verified, then  $A$  is weakly shod.

**Proof:** By [14, 4.1, 4.2] and the above lemma, (c) and (d) are equivalent and imply (a) and (b). If  $A$  is simply connected, then 6.6 implies that  $\pi_1(\Gamma) = 1$ . So (a) implies (c). Finally, assume that  $\mathrm{HH}^1(A) = 0$ . By 6.6, the algebra  $A$  admits a Galois covering with group  $\pi_1(\Gamma)$ . This group is free because of [14, 4.2]. On the other hand, the rank of  $\pi_1(\Gamma)$  is less than or equal to  $\dim \mathrm{HH}^1(A)$  because of [18, Thm. 4.1]. Therefore  $\pi_1(\Gamma) = 1$ . So (b) implies (c). So the conditions are equivalent, and they imply that  $A$  is weakly shod by 8.1. ■

We illustrate Theorem B on the following examples. In particular, note that this theorem does not necessarily hold true if one drops the standard condition.

*Example 8.3.* (a) Let  $A$  be as in 3.6, (a). Then  $A$  clearly admits a Galois covering with group a free group of rank 3 by a locally bounded  $k$ -category. It is given by the universal cover of the underlying graph of the ordinary quiver. So  $A$  is not simply connected. The orbit graph  $\mathcal{O}(\Gamma)$  of the connecting component  $\Gamma$  is as follows:



Its fundamental group is free of rank 3. A straightforward computation shows that  $\dim \mathrm{HH}^1(A) = 7$  (see also [19, Thm. 1]).

- (b) Let  $A$  be as in 6.5. As already noticed,  $A$  is a simply connected representation-finite algebra. Also, it is not standard. The orbit graph of its Auslander-Reiten quiver is as follows:

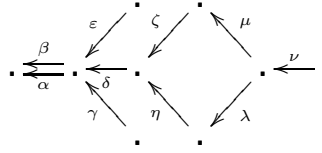


Finally,  $A$  admits the following outer derivation, yielding a non-zero element in  $\mathrm{HH}^1(A)$  (see [15, 4.2])

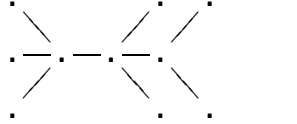
$$d: \begin{array}{ccc} A & \rightarrow & A \\ \sigma, \delta & \mapsto & 0 \\ \rho & \mapsto & \rho^3 \end{array}.$$

This example shows that Theorem B may fail if one drops the standard condition. Note that the definition of simple connectedness used in [15, 4.3] differs slightly from ours: In *loc. cit.*, as in [14, § 6], a representation-finite algebra is called simply connected if its Auslander-Reiten quiver is simply connected.

- (c) Let  $A$  be the algebra given by the quiver:



bound by the relations  $\beta\epsilon = 0$ ,  $\alpha\gamma = 0$ ,  $\beta\delta = \alpha\delta$ ,  $\delta\zeta = 0$ ,  $\delta\eta = 0$ ,  $\zeta\mu = \eta\lambda$ ,  $\zeta\mu\nu = 0$ . Then  $A$  is laura. Actually, it is right glued in the sense of [2, 3.1]. The orbit graph  $\mathcal{O}(\Gamma)$  of its connecting component  $\Gamma$  is as follows:



It is a tree. Also,  $A$  is clearly simply connected, and it is not hard to see that  $\mathrm{HH}^1(A) = 0$  using, for instance, Happel's long exact sequence (see [27, 5.3]).

We pose the following problem.

**Problem 5.** Let  $A$  be a non-standard laura algebra. How can the vanishing of  $\mathrm{HH}^1(A)$  be expressed in terms of topological properties of  $A$ ?

## 9 Special biserial laura algebras

Throughout this section, we fix a laura algebra  $A = kQ/I$ , where  $(Q, I)$  is special biserial. This class of algebras is characterised in [23]. As we shall see, Theorem B holds true for  $A'$ . In the following proposition, we consider a specific kind of Galois covering of  $A$ : Given a Galois covering of bound quivers  $(\overline{Q}, \overline{I}) \rightarrow (Q, I)$  with group  $G$  (in the sense of [16]), we consider the induced Galois covering  $\overline{A} = k\overline{Q}/\overline{I} \rightarrow A$  with group  $G$ .

**Proposition 9.1.** *Let  $A = kQ/I$  be as above. Let  $(\overline{Q}, \overline{I}) \rightarrow (Q, I)$  be a Galois covering of bound quivers with group  $G$  (with  $\overline{Q}$  connected). Let  $F: \overline{A} = k\overline{Q}/\overline{I} \rightarrow A$  be the induced Galois covering with group  $G$ . Then there exists a Galois covering of translation quivers  $\overline{\Gamma} \rightarrow \Gamma$  with group  $G$ , extending the map  $X \mapsto F_\lambda X$ , where  $\overline{\Gamma}$  is the full translation subquiver of  $\Gamma(\mathrm{mod} \overline{A})$  with set of objects equal to  $\{X \in \mathrm{ind} \mathcal{C} \mid F_\lambda X \in \Gamma\} \subseteq \Gamma(\mathrm{mod} \mathcal{C})$ . Moreover,  $\overline{\Gamma}$  is a component of  $\Gamma(\mathrm{mod} \overline{A})$ .*

**Proof:** We only need to prove the two following facts:

1. If  $X \in \Gamma$ , then there exists  $\overline{X} \in \mathrm{ind} \overline{A}$  such that  $F_\lambda \overline{X} = X$ , and  $\overline{X} \neq {}^g \overline{X}$  for every  $g \in G \setminus \{1\}$ .
2. The full subquiver  $\overline{\Gamma}$  of  $\Gamma(\mathrm{mod} \overline{A})$  is a component.

Since  $\Gamma$  has modules which are not  $\tau_A$ -invariant, all modules in  $\Gamma$  are string modules. Let  $\gamma$  be a string in  $Q$ . Since  $(\overline{Q}, \overline{I}) \rightarrow (Q, I)$  is a covering of bound quivers, there exists a string  $\overline{\gamma}$  in  $\overline{Q}$  whose image under  $Q' \rightarrow Q$  is equal to  $\gamma$ . Therefore if we write  $M(\gamma)$  for the corresponding string module, then  $F_\lambda(M(\overline{\gamma})) = M(\gamma)$ , and  ${}^g M(\overline{\gamma}) = M({}^g \overline{\gamma})$ , so that  $G_{M(\overline{\gamma})} = 1$ . This proves the first assertion. Also, by [25, 3.6], there exists a Galois covering of translation quivers  $\overline{\Gamma} \rightarrow \Gamma$  extending the map  $X \mapsto F_\lambda X$ .

There remains to prove that  $\overline{\Gamma}$  is a connected component of  $\Gamma(\mathrm{mod} \overline{A})$ . By [32, Prop. 2.3],  $\overline{\Gamma} \subseteq \Gamma(\mathrm{mod} \overline{A})$  is a union of components of  $\Gamma(\mathrm{mod} \overline{A})$ . Let  $T_1, \dots, T_n$  be the (pairwise distinct) modules of  $\Gamma$  which are either

Ext-injectives of  $\mathcal{L}_A$  or projective modules not in  $\mathcal{L}_A$ . Because of [5, 4.2, 4.4], the module  $T = T_1 \oplus \dots \oplus T_n$  is a tilting  $A$ -module. Let  $\mathcal{T}$  be the full subcategory of  $\text{ind } \overline{A}$  with set of vertices equal to:

$$\{X \in \overline{\Gamma} \mid F_\lambda X \in \{T_1, \dots, T_n\}\} .$$

Let us prove that  $\mathcal{T}$  is connected. Let  $P \in \text{ind } \overline{A}$  be projective. There is an exact sequence  $0 \rightarrow F_\lambda P \rightarrow T^{(1)} \rightarrow T^{(2)} \rightarrow 0$  in  $\text{mod } A$ , with  $T^{(1)}, T^{(2)} \in \text{add } T$ . Since  $\text{Ext}_A^1(T^{(2)}, T^{(1)}) = 0$ , 4.3 yields an exact sequence in  $\text{mod } \overline{A}$ :

$$0 \rightarrow P \rightarrow X_P^{(1)} \rightarrow X_P^{(2)} \rightarrow 0 , \quad (\Delta_P)$$

with  $X^{(1)}, X^{(2)} \in \text{add } T$ . Note that  $\text{pd } X \leq 1$  for every  $X \in \mathcal{T}$  because  $F_\lambda$  is exact. So:

- $\mathcal{T} \subseteq \mathcal{K}^b(\text{proj } \overline{A})$ , where  $\mathcal{K}^b$  stands for the homotopy category of bounded complexes.
- The exact sequences  $\Delta_P$ , for  $P \in \text{ind } \overline{A}$  projective, show that  $\mathcal{T}$  generates  $\mathcal{K}^b(\text{proj } \overline{A})$ , as a triangulated category.

Now,  $\mathcal{K}^b(\text{proj } \overline{A})$  is connected because so is  $\overline{A}$ . So  $\mathcal{T}$  is connected. On the other hand, [32, Prop. 2.3] shows that  $\text{rad}^\infty(X, Y) = 0$  for every  $X, Y \in \overline{\Gamma}$ , because the same property holds for  $\Gamma$ . Therefore there exists a connected component  $\Omega$  of  $\overline{\Gamma}$  containing all the modules in  $\mathcal{T}$ . Since  $G$  acts transitively on the connected components of  $\overline{\Gamma}$  (thanks to the Galois covering  $\overline{\Gamma} \rightarrow \Gamma$ ) we deduce that  $\overline{\Gamma} = \Omega$ . So  $\overline{\Gamma}$  is a component. ■

Before proving our next lemma, we state the characterisation of [23] of those special biserial algebras which are lura. Given a special biserial quiver  $(Q, I)$ , consider a walk in  $Q$ :

$$\gamma = \rho \omega_1 \omega_2 \omega_3 \rho'$$

such that the following conditions are satisfied:

1.  $\rho$  and  $\rho'$  are paths lying in  $I$ ,
2.  $\omega_2$  is a cyclic walk, that is, its source and target are equal, and
3.  $\omega_1 \omega_2 \omega_3$  is a string, that is, it contains neither a path lying in  $I$ , nor the formal inverse of a path lying in  $I$ .

Then  $\gamma$  is called an *intertwined double-zero* if for every  $n \geq 1$ , the walk  $\omega_1 \omega_2^n \omega_3$  is a string. This combinatorial configuration was defined by Dionne in [23] and called DOZE for short.

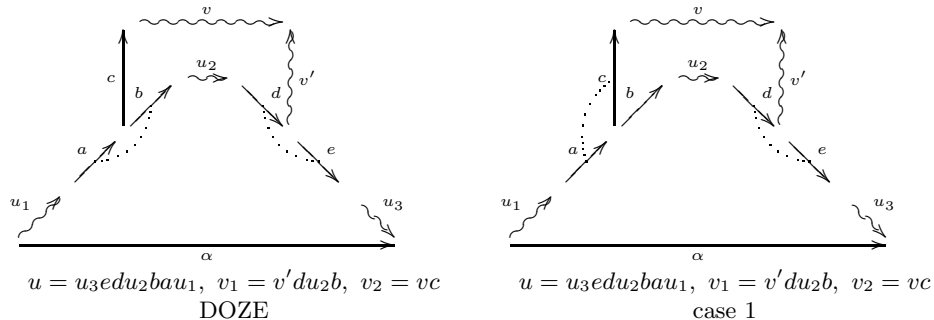
**Theorem 9.2.** *see [23] Let  $(Q, I)$  be a special biserial quiver. Then  $kQ/I$  is a lura algebra if and only if there is no DOZE in  $(Q, I)$ .*

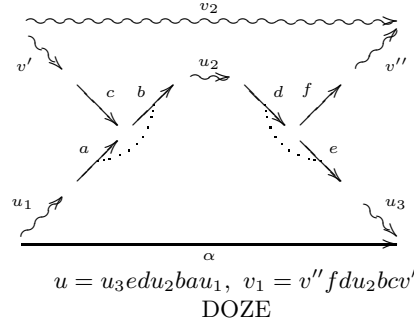
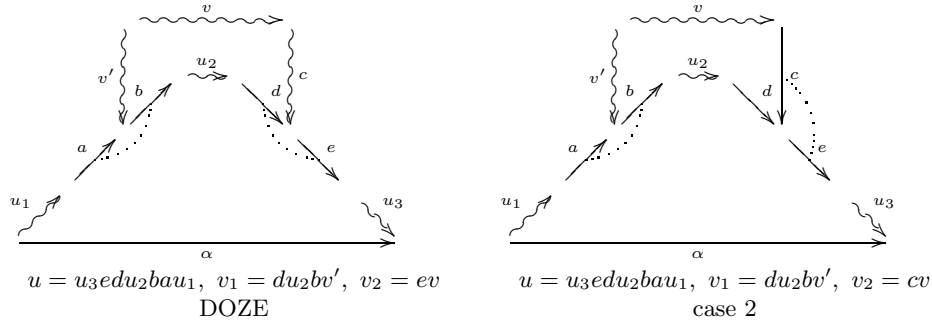
If we let  $(\overline{Q}, \overline{I}) \rightarrow (Q, I)$  be the universal cover (see [36]), then we get a Galois covering  $F: \overline{A} \rightarrow A$  with group  $\pi_1(Q, I)$ . Later, we prove that  $F$  coincides with the covering functor given by our main result. For this purpose, we need the following lemma. Recall that given an arrow  $\alpha: x \rightarrow y$  in a quiver  $Q$ , a path  $u = \beta_1 \dots \beta_s$  from  $x$  to  $y$  distinct from  $\alpha$  is called a *bypass*.

**Lemma 9.3.** *Let  $\sim$  be the homotopy relation defined by  $(Q, I)$  (as in [36]). Then  $\alpha \not\sim u$  for every bypass  $u$  of  $\alpha$  in  $Q$ .*

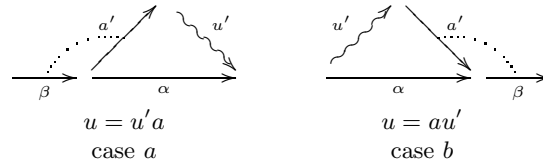
**Proof of 9.3:** We proceed by contradiction and assume that  $\alpha \sim u$  for some bypass  $u$  of  $\alpha$ . Thus,  $\alpha$  appears in a path belonging to a binomial relation, and the same holds for at least one arrow of  $u$  (with a binomial relation which needs not be the same as the one for  $\alpha$ ).

**Assume first that  $u$  is not an arrow.** Let  $v_1 - t v_2$  be a binomial relation such that  $v_1, v_2$  are paths, and  $v_1$  and  $u$  share at least one arrow. Assume that neither  $v_1$  is contained in  $u$ , nor  $u$  is contained in  $v_1$ . Then one can see that  $(Q, I)$  contains one of the following five bound quivers, where the monomial relations (denoted by dotted lines) are due to the fact that  $(Q, I)$  is special biserial, and where the symbol  $\rightsquigarrow$  denotes a path:

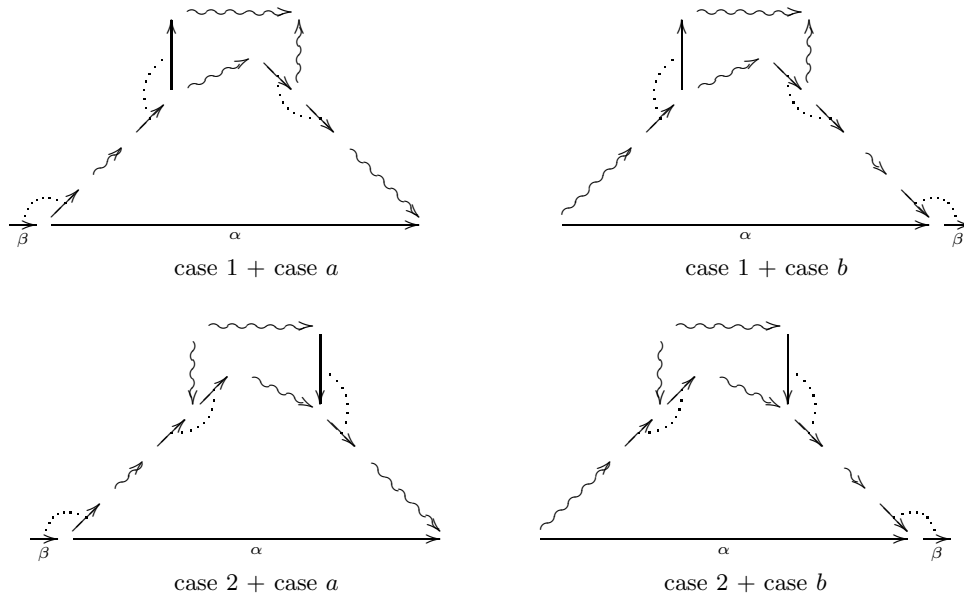




We have specified the cases which obviously contain a DOZE. These cases cannot appear because  $A$  is *laura*. So only cases 1 and 2 are possible. Now,  $\alpha$  also appears in a binomial relation: There exists an arrow  $\beta$  such that  $\beta\alpha$  or  $\alpha\beta$  is a subpath of a path appearing in a binomial relation (and, in particular, we have  $\beta\alpha \notin I$  or  $\alpha\beta \notin I$ , respectively). Thus  $(Q, I)$  also contains a bound subquiver of one of the following two shapes:

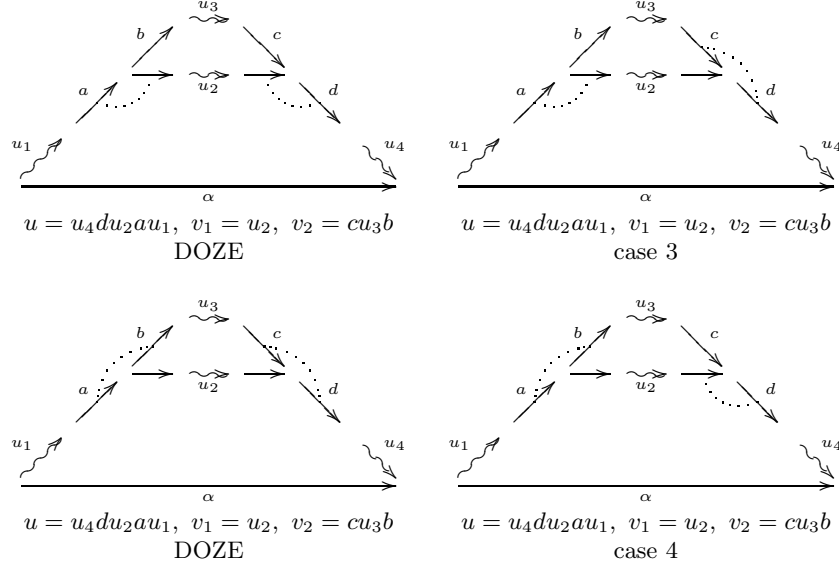


According to the cases 1, 2, a and b, we deduce that  $(Q, I)$  contains one of the following bound quivers:

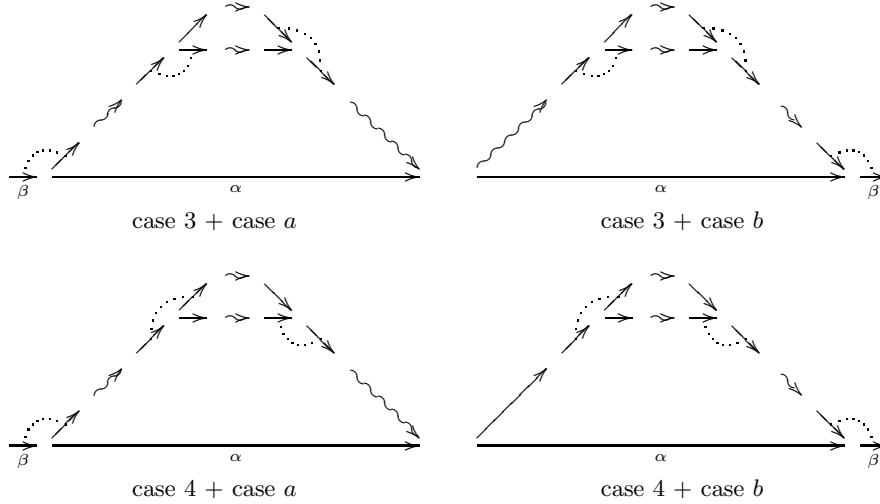


Obviously,  $(Q, I)$  contains a DOZE in each of the above four cases, whereas  $A$  is *laura*. This contradiction shows that  $v_1$  is contained in  $u$ , or  $u$  is contained in  $v_1$ . Now, assume that  $v_1$  is contained in  $u$ . So  $(Q, I)$  contains one

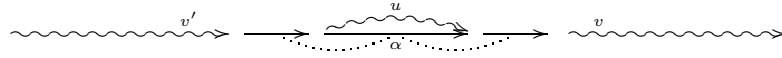
of the following four bound quivers:



Again, the cases specified with "DOZE" contain a DOZE. So only cases 3 and 4 are possible. If we combine these two cases with  $a$  and  $b$ , we find that  $(Q, I)$  contains one of the following four bound quivers:



Therefore  $(Q, I)$  contains a DOZE in each case, whereas  $A$  is laura. This contradiction shows that  $u$  is necessarily contained in  $v_1$ . Remark that since  $v_1, v_2 \notin I$ , since no vertex of  $Q$  is the source (or the target) of three arrows, and since  $(Q, I)$  contains no DOZE, we necessarily have  $v_1 = vu_1v'$ , with  $v, v'$  two non-trivial paths. Consequently,  $(Q, I)$  contains a DOZE, because  $v_1 \notin I$ :

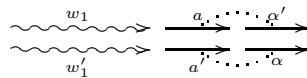


This is absurd. Therefore  $u$  is necessarily an arrow.

**We now assume that  $u = \alpha'$  is an arrow:**  $x \xrightarrow[\alpha']{\alpha} y$ . Let  $r = v_1 - t v_2$  and  $r' = v'_1 - t' v'_2$  be binomial relations such that  $\alpha$  and  $\alpha'$  are contained in  $v_1$  and  $v'_1$ , respectively. We assume first that  $r$  ends at  $y$ . Since  $(Q, I)$  is special biserial, we have:

- $v_1 = \alpha a w_1$ , with  $a \in Q_1$  and  $w_1$  a path.
- $v'_1 = \alpha' a' w'_1$ , with  $a' \in Q_1$  and  $w'_1$  a path.

Therefore  $(Q, I)$  contains the following bound quiver:





**Proof:** The quasi-tilted case was settled in [34, Cor. 2]. So we assume that  $A$  is not quasi-tilted. We therefore write  $F: \tilde{A} \rightarrow A$  for the covering functor given by our main theorem. Recall that (c) and (d) are equivalent (see [14, § 4]). Let  $(Q, I)$  be a special biserial quiver such that  $A \simeq kQ/I$ . According to 9.6, we denote by  $r$  the rank of the free group  $\pi_1(Q, I)$ . We write  $F': \bar{A} \rightarrow A$  for the Galois covering with group  $\pi_1(Q, I)$  induced by the presentation  $A \simeq kQ/I$ . Recall that  $F'$  defines an injective linear map  $\text{Hom}(\pi_1(Q, I), k^+) \hookrightarrow \text{HH}^1(A)$  (see [22, Cor. 3]). In particular, we have  $\dim \text{HH}^1(A) \geq r$ .

If  $\text{HH}^1(A) = 0$  then  $r = 0$ . So  $\pi_1(Q, I)$  is trivial.

If  $A$  is simply connected, then  $\pi_1(Q, I)$  is trivial and  $F': \bar{A} \rightarrow A$  is an isomorphism (see [31, Rem. 6.1.5]). So,  $A$  is constricted because of 9.3. Now [31, Prop. 6.2.27] shows that the covering functor  $F: \tilde{A} \rightarrow A$  is induced by a covering  $(Q', I') \rightarrow (Q, I)$  of bound quivers. Since  $\pi_1(Q, I)$  is trivial, this covering is trivial, that is,  $(Q', I') \rightarrow (Q, I)$  is an isomorphism (see [36]). In other words, we have  $\tilde{A} \simeq A$  and, therefore,  $\tilde{\Gamma} \simeq \Gamma$ . In particular,  $A$  is weakly shod (see 8.1).

Thus, any of the hypotheses (a), (b), (c) or (d) implies that  $A$  is weakly shod. The equivalence between these conditions is therefore given by [32, Cor. 2]. ■

We end this section with the following problem.

**Problem 6.** Assume that  $A$  is lura special biserial. Is it standard?

## Acknowledgements

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