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# DOUBLY-RESONANT SADDLE-NODES IN $(\mathbb{C}^3, 0)$ AND THE FIXED SINGULARITY AT INFINITY IN THE PAINLEVÉ EQUATIONS. PART III: LOCAL ANALYTIC CLASSIFICATION

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ABSTRACT. In this work which follows directly [Bit16b, Bit16c], we consider analytic singular vector fields in  $\mathbb{C}^3$  with an isolated and doubly-resonant singularity of saddle-node type at the origin. Such vector fields come from irregular two-dimensional differential systems with two opposite non-zero eigenvalues, and appear for instance when studying the irregular singularity at infinity in Painlevé equations  $(P_j)_{j=I\dots V}$ , for generic values of the parameters. Under suitable assumptions, we provide an analytic classification under the action of fibered diffeomorphisms, based on the study of the *Stokes diffeomorphisms* obtained by comparing consecutive sectorial normalizing maps *à la* Martinet-Ramis / Stolovitch [MR82, MR83, Sto96]. These normalizing maps over sectorial domains are obtained in the main theorem of [Bit16c], which is analogous to the classical one due to Hukuhara-Kimura-Matuda [HKM61] for saddle-nodes in  $\mathbb{C}^2$ . We also prove that these maps are in fact the Gevrey-1 sums of the formal normalizing map, the existence of which has been proved in [Bit16b].

## 1. INTRODUCTION

As in [Bit16b, Bit16c], we consider (germs of) singular vector fields  $Y$  in  $\mathbb{C}^3$  which can be written in appropriate coordinates  $(x, \mathbf{y}) := (x, y_1, y_2)$  as

$$(1.1) \quad Y = x^2 \frac{\partial}{\partial x} + \left( -\lambda y_1 + F_1(x, \mathbf{y}) \right) \frac{\partial}{\partial y_1} + \left( \lambda y_2 + F_2(x, \mathbf{y}) \right) \frac{\partial}{\partial y_2} ,$$

where  $\lambda \in \mathbb{C}^*$  and  $F_1, F_2$  are germs of holomorphic function in  $(\mathbb{C}^3, 0)$  of homogeneous valuation (order) at least two. They represent irregular two-dimensional differential systems having two opposite non-zero eigenvalues and a vanishing third eigenvalue. These we call doubly-resonant vector fields of saddle-node type (or simply **doubly-resonant saddle-nodes**). For a historical context, a presentation of the main motivations (the study of the irregular singularity at infinity in Painlevé equations  $(P_j)_{j=I\dots V}$ ), and a review of some results linked with this study, we refer to [Bit16b].

Several authors studied the problem of convergence of formal transformations putting vector fields as in (1.1) into “normal forms”. Shimomura, improving on a result of Iwano [Iwa80], shows in [Shi83] that analytic doubly-resonant saddle-nodes satisfying more restrictive conditions are conjugate (formally and over sectors) to vector fields of the form

$$x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x) y_2 \frac{\partial}{\partial y_2}$$

*via* a diffeomorphism whose coefficients have asymptotic expansions as  $x \rightarrow 0$  in sectors of opening greater than  $\pi$ .

Stolovitch then generalized this result to any dimension in [Sto96]. More precisely, Stolovitch’s work offers an analytic classification of vector fields in  $\mathbb{C}^{n+1}$  with an irregular singular point, without further hypothesis on eventual additional resonance relations between eigenvalues of the linear part. However, as Iwano and Shimomura did, he needed to impose other assumptions, among which the

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*Key words and phrases.* Painlevé equations, singular vector field, irregular singularity, resonant singularity, analytic classification, Stokes diffeomorphisms.

condition that the restriction of the vector field to the invariant hypersurface  $\{x = 0\}$  is a linear vector field. In [BDM08], the authors obtain a *Gevrey-1 summable* “normal form”, though not as simple as Stolovitch’s one and not unique *a priori*, but for more general kind of vector field with one zero eigenvalue. However, the same assumption on hypersurface  $\{x = 0\}$  is required (the restriction is a linear vector field). Yet from [Yos85] (and later [Bit16b]) stems the fact that this condition is not met in the case of Painlevé equations  $(P_j)_{j=I\dots V}$ .

In comparison, we merely ask here that this restriction be orbitally linearizable (see Definition 1.6), *i.e.* the foliation induced by  $Y$  on  $\{x = 0\}$  (and not the vector field  $Y|_{\{x=0\}}$  itself) be linearizable. The fact that this condition is fulfilled by the singularities of Painlevé equations formerly described is well-known. As discussed in Remark 1.16, this more general context also introduces new phenomena and technical difficulties as compared to prior classification results.

### 1.1. Scope of the paper.

The action of local analytic / formal diffeomorphisms  $\Psi$  fixing the origin on local holomorphic vector fields  $Y$  of type (1.1) by change of coordinates is given by

$$\Psi_* Y := (D\Psi.Y) \circ \Psi^{-1} .$$

In [Bit16b] we performed the formal classification of such vector fields by exhibiting an explicit universal family of vector fields for the action of formal changes of coordinates at 0 (called a family of normal forms). Such a result seems currently out of reach in the analytic category: it is unlikely that an explicit universal family for the action of local analytic changes of coordinates be described anytime soon. If we want to describe the space of equivalent classes (of germs of a doubly-resonant saddle-node under local analytic changes of coordinates) with same formal normal form, we therefore need to find a complete set of invariants which is of a different nature. We call **moduli space** this quotient space and give it a (non-trivial) presentation based on functional invariants *à la* Martinet-Ramis [MR82, MR83].

In this paper we will therefore present only the  $x$ -fibered local analytic classification for vector fields of the form (1.1), with some additional assumptions detailed further down (see Definitions 1.1, 1.2 and 1.6). Importantly, these hypothesis are met in the case of Painlevé equations mentioned above. The full analytic classification (under the action of all local diffeomorphisms, not necessarily  $x$ -fibered) will be done in a forthcoming work.

In [Bit16c], we have proved the existence of analytic sectorial normalizing maps (over a pair of opposite “wide” sectors of opening greater than  $\pi$  whose union covers a full punctured neighborhood of  $\{x = 0\}$ ). Then we attach to each vector field a complete set of invariants given as transition maps (over “narrow” sectors of opening less than  $\pi$ ) between the sectorial normalizing maps. Although this viewpoint has become classical since the work of Martinet and Ramis, and has latter been generalized by Stolovitch as already mentioned, our approach has a more geometric flavor (for instance, we perform a precise study of the Stokes diffeomorphisms in the *space of leaves*).

As a by-product, we deduce that the normalizing sectorial diffeomorphisms of [Bit16c] are Gevrey-1 asymptotic to the normalizing formal power series of [Bit16b], retrospectively proving their 1-summability. When the vector field additionally supports a symplectic transverse structure (which is again the case of Painlevé equations) we prove a theorem of analytic classification under the action of *transversally symplectic* diffeomorphisms.

### 1.2. Definitions and previous results.

To state our main results we need to introduce some notations and nomenclature.

- For  $n \in \mathbb{N}_{>0}$ , we denote by  $(\mathbb{C}^n, 0)$  an (arbitrary small) open neighborhood of the origin in  $\mathbb{C}^n$ .
- We denote by  $\mathbb{C}\{x, \mathbf{y}\}$ , with  $\mathbf{y} = (y_1, y_2)$ , the  $\mathbb{C}$ -algebra of germs of holomorphic functions at the origin of  $\mathbb{C}^3$ , and by  $\mathbb{C}\{x, \mathbf{y}\}^\times$  the group of invertible elements for the multiplication (also called units), *i.e.* elements  $U$  such that  $U(0) \neq 0$ .

- $\chi(\mathbb{C}^3, 0)$  is the Lie algebra of germs of singular holomorphic vector fields at the origin  $\mathbb{C}^3$ . Any vector field in  $\chi(\mathbb{C}^3, 0)$  can be written as

$$Y = b(x, y_1, y_2) \frac{\partial}{\partial x} + b_1(x, y_1, y_2) \frac{\partial}{\partial y_1} + b_2(x, y_1, y_2) \frac{\partial}{\partial y_2}$$

with  $b, b_1, b_2 \in \mathbb{C}\{x, y_1, y_2\}$  vanishing at the origin.

- $\text{Diff}(\mathbb{C}^3, 0)$  is the group of germs of holomorphic diffeomorphisms fixing the origin of  $\mathbb{C}^3$ . It acts on  $\chi(\mathbb{C}^3, 0)$  by conjugacy: for all

$$(\Phi, Y) \in \text{Diff}(\mathbb{C}^3, 0) \times \chi(\mathbb{C}^3, 0)$$

we define the push-forward of  $Y$  by  $\Phi$  by

$$(1.2) \quad \Phi_*(Y) := (D\Phi \cdot Y) \circ \Phi^{-1} \quad ,$$

where  $D\Phi$  is the Jacobian matrix of  $\Phi$ .

- $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0)$  is the subgroup of  $\text{Diff}(\mathbb{C}^3, 0)$  of fibered diffeomorphisms preserving the  $x$ -coordinate, *i.e.* of the form  $(x, \mathbf{y}) \mapsto (x, \phi(x, \mathbf{y}))$ .
- We denote by  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  the subgroup of  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0)$  formed by diffeomorphisms tangent to the identity.

All these concepts have *formal* analogues, where we only suppose that the objects are defined with formal power series, not necessarily convergent near the origin.

**Definition 1.1.** A **diagonal doubly-resonant saddle-node** is a vector field  $Y \in \chi(\mathbb{C}^3, 0)$  of the form

$$(1.3) \quad Y = x^2 \frac{\partial}{\partial x} + \left( -\lambda y_1 + F_1(x, \mathbf{y}) \right) \frac{\partial}{\partial y_1} + \left( \lambda y_2 + F_2(x, \mathbf{y}) \right) \frac{\partial}{\partial y_2} \quad ,$$

with  $\lambda \in \mathbb{C}^*$  and  $F_1, F_2 \in \mathbb{C}\{x, \mathbf{y}\}$  of order at least two. We denote by  $\mathcal{SN}_{\text{diag}}$  the set of such vector fields.

Based on this expression, and considering the expansion

$$F_j(x, \mathbf{y}) = \sum_{\mathbf{k}=(k_0, k_1, k_2)} F_{j, \mathbf{k}} x^{k_0} y_1^{k_1} y_2^{k_2}$$

for  $j = 1, 2$ , we state:

**Definition 1.2.** The **residue** of  $Y \in \mathcal{SN}_{\text{diag}}$  as in (1.3) is the complex number

$$\text{res}(Y) := F_{1, (1, 1, 0)} + F_{2, (1, 0, 1)} \quad .$$

We say that  $Y$  is **non-degenerate** (*resp.* **strictly non-degenerate**) if  $\text{res}(Y) \notin \mathbb{Q}_{\leq 0}$  (*resp.*  $\Re(\text{res}(Y)) > 0$ ).

*Remark 1.3.* It is obvious that there is an action of  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  on  $\mathcal{SN}_{\text{diag}}$ . The residue is an invariant of each orbit of  $\mathcal{SN}_{\text{fib}}$  under the action of  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  by conjugacy (it is actually invariant by formal conjugacies, see[Bit16b]).

The main result of [Bit16b] can now be stated as follows:

**Theorem 1.4.** [Bit16b] *Let  $Y \in \mathcal{SN}_{\text{diag}}$  be non-degenerate. Then there exists a unique formal fibered diffeomorphism  $\hat{\Phi}$  tangent to the identity such that:*

$$(1.4) \quad \begin{aligned} \hat{\Phi}_*(Y) &= x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x + c_1(y_1 y_2)) y_1 \frac{\partial}{\partial y_1} \\ &+ (\lambda + a_2 x + c_2(y_1 y_2)) y_2 \frac{\partial}{\partial y_2} \quad , \end{aligned}$$

where  $\lambda \in \mathbb{C}^*$ ,  $c_1, c_2 \in v\mathbb{C}[[v]]$  are formal power series in  $v = y_1 y_2$  without constant term and  $a_1, a_2 \in \mathbb{C}$  are such that  $a_1 + a_2 = \text{res}(Y) \in \mathbb{C} \setminus \mathbb{Q}_{\leq 0}$ .

**Definition 1.5.** The vector field obtained in (1.4) is called the **formal normal form** of  $Y$ . The formal fibered diffeomorphism  $\hat{\Phi}$  is called the **formal normalizing map** of  $Y$ .

The above result is valid for formal objects, without considering problems of convergence. The main result in [Bit16c] states that this formal normalizing map is analytic in sectorial domains, under some additional assumptions that we are now going to precise.

**Definition 1.6.**

- We say that a germ of a vector field  $X$  in  $(\mathbb{C}^2, 0)$  is **orbitally linear** if

$$X = U(\mathbf{y}) \left( \lambda_1 y_1 \frac{\partial}{\partial y_1} + \lambda_2 y_2 \frac{\partial}{\partial y_2} \right),$$

for some  $U(\mathbf{y}) \in \mathbb{C}\{\mathbf{y}\}^\times$  and  $(\lambda_1, \lambda_2) \in \mathbb{C}^2$ .

- We say that a germ of vector field  $X$  in  $(\mathbb{C}^2, 0)$  is analytically (*resp.* formally) **orbitally linearizable** if  $X$  is analytically (*resp.* formally) conjugate to an orbitally linear vector field.
- We say that a diagonal doubly-resonant saddle-node  $Y \in \mathcal{SN}_{\text{diag}}$  is **div-integrable** if  $Y|_{\{x=0\}} \in \chi(\mathbb{C}^2, 0)$  is (analytically) orbitally linearizable.

*Remark 1.7.* Alternatively we could say that the foliation associated to  $Y|_{\{x=0\}}$  is linearizable. Since  $Y|_{\{x=0\}}$  is analytic at the origin of  $\mathbb{C}^2$  and has two opposite eigenvalues, it follows from a classical result of Brjuno (see [Mar81]), that  $Y|_{\{x=0\}}$  is analytically orbitally linearizable if and only if it is formally orbitally linearizable.

**Definition 1.8.** We denote by  $\mathcal{SN}_{\text{diag},0}$  the set of strictly non-degenerate diagonal doubly-resonant saddle-nodes which are div-integrable.

The main result of [Bit16c] can now be stated (we refer to section 2. for precise definitions on weak 1-summability).

**Theorem 1.9.** [Bit16c] *Let  $Y \in \mathcal{SN}_{\text{diag},0}$  and let  $\hat{\Phi}$  (given by Theorem 1.4) be the unique formal fibered diffeomorphism tangent to the identity such that*

$$\begin{aligned} \hat{\Phi}_*(Y) &= x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x + c_1(y_1 y_2)) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x + c_2(y_1 y_2)) y_2 \frac{\partial}{\partial y_2} \\ &=: Y_{\text{norm}}, \end{aligned}$$

where  $\lambda \neq 0$  and  $c_1(v), c_2(v) \in v\mathbb{C}[[v]]$  are formal power series without constant term. Then:

- (1) the normal form  $Y_{\text{norm}}$  is analytic (i.e.  $c_1, c_2 \in \mathbb{C}\{v\}$ ), and it also is div-integrable, i.e.  $c_1 + c_2 = 0$ ;
- (2) the formal normalizing map  $\hat{\Phi}$  is weakly 1-summable in every direction  $\theta \neq \arg(\pm\lambda)$ ;
- (3) there exist analytic sectorial fibered diffeomorphisms  $\Phi_+$  and  $\Phi_-$ , (asymptotically) tangent to the identity, defined in sectorial domains of the form  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively, where

$$\begin{aligned} S_+ &:= \left\{ x \in \mathbb{C} \mid 0 < |x| < r \text{ and } \left| \arg\left(\frac{x}{i\lambda}\right) \right| < \frac{\pi}{2} + \epsilon \right\} \\ S_- &:= \left\{ x \in \mathbb{C} \mid 0 < |x| < r \text{ and } \left| \arg\left(\frac{-x}{i\lambda}\right) \right| < \frac{\pi}{2} + \epsilon \right\} \end{aligned}$$

(for any  $\epsilon \in ]0, \frac{\pi}{2}[$  and some  $r > 0$  small enough), which admit  $\hat{\Phi}$  as weak Gevrey-1 asymptotic expansion in these respective domains, and which conjugate  $Y$  to  $Y_{\text{norm}}$ . Moreover  $\Phi_+$  and  $\Phi_-$  are the unique such germs of analytic functions in sectorial domains (see Definition 2.2).

**Definition 1.10.** We call  $\Phi_+$  and  $\Phi_-$  the **sectorial normalizing maps** of  $Y \in \mathcal{SN}_{\text{diag},0}$ .

They are the weak 1-sums of  $\hat{\Phi}$  along the respective directions  $\arg(i\lambda)$  and  $\arg(-i\lambda)$ . Notice that  $\Phi_+$  and  $\Phi_-$  are *germs of analytic sectorial fibered diffeomorphisms*, i.e. they are of the form

$$\begin{aligned} \Phi_+ : S_+ \times (\mathbb{C}^2, 0) &\longrightarrow S_+ \times (\mathbb{C}^2, 0) \\ (x, \mathbf{y}) &\longmapsto (x, \Phi_{+,1}(x, \mathbf{y}), \Phi_{+,2}(x, \mathbf{y})) \end{aligned}$$

and

$$\begin{aligned} \Phi_- : S_- \times (\mathbb{C}^2, 0) &\longrightarrow S_- \times (\mathbb{C}^2, 0) \\ (x, \mathbf{y}) &\longmapsto (x, \Phi_{-,1}(x, \mathbf{y}), \Phi_{-,2}(x, \mathbf{y})) \end{aligned}$$

(see section 2. for a precise definition of *germ of analytic sectorial fibered diffeomorphism*). The fact that they are also *(asymptotically) tangent to the identity* means that we have:

$$\Phi_{\pm}(x, \mathbf{y}) = \text{Id} + \text{O}\left(\|(x, \mathbf{y})\|^2\right).$$

Another result proved in [Bit16c], is that the uniqueness of the sectorial normalizing maps holds in fact under weaker assumptions.

**Proposition 1.11.** *Let  $\varphi_+$  and  $\varphi_-$  be two germs of sectorial fibered diffeomorphisms in  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively, where  $S_+$  and  $S_-$  are as in Theorem 1.9, which are (asymptotically) tangent to the identity and such that*

$$(\varphi_{\pm})_*(Y) = Y_{\text{norm}}.$$

*Then, they necessarily coincide with the weak 1-sums  $\Phi_+$  and  $\Phi_-$  defined above.*

### 1.3. Main results.

The first main result of this paper is the following.

**Theorem 1.12.** *Let  $Y \in \mathcal{SN}_{\text{diag},0}$  and let  $\hat{\Phi}$  (given by Theorem 1.4) be the unique formal fibered diffeomorphism tangent to the identity such that*

$$\begin{aligned} \hat{\Phi}_*(Y) &= x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x - c(y_1 y_2)) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x + c(y_1 y_2)) y_2 \frac{\partial}{\partial y_2} \\ &=: Y_{\text{norm}}, \end{aligned}$$

*where  $\lambda \neq 0$  and  $c(v) \in v\mathbb{C}\{v\}$ . Then  $\hat{\Phi}$  is 1-summable (with respect to  $x$ ) in every direction  $\theta \neq \arg(\pm\lambda)$ , and  $\Phi_+, \Phi_-$  in Theorem 1.9 are the 1-sums of  $\hat{\Phi}$  in directions  $\arg(i\lambda), \arg(-i\lambda)$  respectively.*

Since two analytically conjugate vector fields are also formally conjugate, we fix now a normal form

$$Y_{\text{norm}} = x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x - c(v)) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x + c(v)) y_2 \frac{\partial}{\partial y_2},$$

with  $\lambda \in \mathbb{C}^*$ ,  $\Re(a_1 + a_2) > 0$  and  $c \in v\mathbb{C}\{v\}$  vanishing at the origin.

**Definition 1.13.** We denote by  $[Y_{\text{norm}}]$  the set of germs of holomorphic doubly-resonant saddle-nodes in  $(\mathbb{C}^3, 0)$  which are formally conjugate to  $Y_{\text{norm}}$  by formal fibered diffeomorphisms tangent to the identity, and denote by  $[Y_{\text{norm}}] / \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  the set of orbits of the elements in this set under the action of  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$ .

According to Theorem 1.9, to any  $Y \in [Y_{\text{norm}}]$  we can associate two sectorial normalizing maps  $\Phi_+, \Phi_-$ , which can in fact extend analytically in domains  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$ , where  $S_{\pm}$  is an asymptotic sector in the direction  $\arg(\pm i\lambda)$  with opening  $2\pi$  (see Definition 2.3):

$$(S_+, S_-) \in \mathcal{AS}_{\arg(i\lambda), 2\pi} \times \mathcal{AS}_{\arg(-i\lambda), 2\pi}.$$

Then, we consider two germs of sectorial fibered diffeomorphisms  $\Phi_{\lambda}, \Phi_{-\lambda}$  analytic in  $S_{\lambda}, S_{-\lambda}$ , with

$$\begin{aligned} (1.5) \quad S_{\lambda} &:= S_+ \cap S_- \cap \left\{ \Re\left(\frac{x}{\lambda}\right) > 0 \right\} \in \mathcal{AS}_{\arg(\lambda), \pi} \\ S_{-\lambda} &:= S_+ \cap S_- \cap \left\{ \Re\left(\frac{x}{\lambda}\right) < 0 \right\} \in \mathcal{AS}_{\arg(-\lambda), \pi}, \end{aligned}$$

defined by:

$$\begin{cases} \Phi_\lambda := (\Phi_+ \circ \Phi_-^{-1})|_{S_\lambda \times (\mathbb{C}^2, 0)} \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\text{arg}(\lambda), \epsilon}; \text{Id}) & , \forall \epsilon \in [0, \pi[ \\ \Phi_{-\lambda} := (\Phi_- \circ \Phi_+^{-1})|_{S_{-\lambda} \times (\mathbb{C}^2, 0)} \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\text{arg}(-\lambda), \epsilon}; \text{Id}) & , \forall \epsilon \in [0, \pi[ . \end{cases}$$

Notice that  $\Phi_\lambda, \Phi_{-\lambda}$  are *isotropies* of  $Y_{\text{norm}}$ , *i.e.* they satisfy:

$$(\Phi_{\pm\lambda})_*(Y_{\text{norm}}) = Y_{\text{norm}} .$$

**Definition 1.14.** With the above notations, we define  $\Lambda_\lambda(Y_{\text{norm}})$  (*resp.*  $\Lambda_{-\lambda}(Y_{\text{norm}})$ ) as the group of germs of sectorial fibered isotropies of  $Y_{\text{norm}}$ , tangent to the identity, and admitting the identity as Gevrey-1 asymptotic expansion (see Definition 2.4) in sectorial domains of the form  $S_\lambda \times (\mathbb{C}^2, 0)$  (*resp.*  $S_{-\lambda} \times (\mathbb{C}^2, 0)$ ), with  $S_{\pm\lambda} \in \mathcal{AS}_{\text{arg}(\pm\lambda), \pi}$ .

The two sectorial isotropies  $\Phi_\lambda$  and  $\Phi_{-\lambda}$  defined above are called the **Stokes diffeomorphisms** associate to  $Y \in [Y_{\text{norm}}]$ .

Our second main result gives the moduli space for the analytic classification that we are looking for.

**Theorem 1.15.** *The map*

$$\begin{aligned} [Y_{\text{norm}}] / \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id}) &\longrightarrow \Lambda_\lambda(Y_{\text{norm}}) \times \Lambda_{-\lambda}(Y_{\text{norm}}) \\ Y &\longmapsto (\Phi_\lambda, \Phi_{-\lambda}) \end{aligned}$$

*is well-defined and bijective.*

In particular, the result states that Stokes diffeomorphisms only depend on the class of  $Y \in [Y_{\text{norm}}]$  in the quotient  $[Y_{\text{norm}}] / \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$ . We will give a description of this set of invariants in terms of power series in the *space of leaves* in section 4.

*Remark 1.16.* In [Bit16c] we have proved a theorem of sectorial normalizing map analogous to the classical one due to Hukuhara-Kimura-Matuda for saddle-nodes in  $(\mathbb{C}^2, 0)$  [HKM61], generalized later by Stolovitch in any dimension in [Sto96]. Unlike the method based on a fixed point theorem used by these authors, we have used a more geometric approach (following the works of Teyssier [Tey03, Tey04]) based on the resolution of an homological equation, by integrating a well chosen 1-form along asymptotic paths. This latter approach turned out to be more efficient to deal with the fact that  $Y_{\{x=0\}}$  is not necessarily linearizable. Indeed, if we try to adapt the proof of [Sto96], one of the first new main difficulties is that in the irregular systems that needs to be solved by a fixed point method (for instance equation (2.7) in the cited paper), the non-linear terms would not be divisible by the independent variable (*i.e.* the time) in our situation. This would complicate the different estimates that are done later in the cited work. This was the first main new phenomena we have met.

In contrast to a result of [Bit16c] which states that the only sectorial isotropy (tangent to the identity) of the normal form over wide sectors (of opening  $> \pi$ ) is the identity, we will see here that the situation is rather different over sector with narrow opening. In order to prove both Theorems 1.12 and 1.15, we will show that the Stokes diffeomorphisms  $\Phi_\lambda$  and  $\Phi_{-\lambda}$  obtained from the germs of sectorial normalizing maps  $\Phi_+$  and  $\Phi_-$ , admit the identity as Gevrey-1 asymptotic expansion. In the cited reference we were only able to establish that fact with a weaker notion of Gevrey-1 expansion. The main difficulty is to prove that such a sectorial isotropy of  $Y_{\text{norm}}$  over the “narrow” sectors described above is necessarily exponentially close to the identity (see Proposition 3.5). This will be done *via* a detailed analysis of these maps in the space of leaves (see Definition 4.4). In fact, this is the second main new difficulties we have met, which is due to the presence of the “resonant” term

$$\frac{c_m (y_1 y_2)^m \log(x)}{x}$$

in the exponential expression of the first integrals of the vector field (see (4.1)). In [Sto96], similar computations are done in subsection 3.4.1. In this part of the paper, infinitely many irregular differential equations appear when identifying terms of same homogeneous degree. The fact that  $Y_{\{x=0\}}$  is linear implies that these differential equations are all linear and independent of each others (*i.e.* they

are not mixed together). In our situation, this is not the case and then more complicated. Using a “non-abelian” version of the Ramis-Sibuya theorem due to Martinet and Ramis [MR82], we prove both sectorial normalizing maps  $\Phi_+$  and  $\Phi_-$  admit the formal normalizing map  $\hat{\Phi}$  as Gevrey-1 asymptotic expansion in the corresponding sectorial domains. This establishes the Gevrey-1 summability of  $\hat{\Phi}$ .

#### 1.4. The transversally Hamiltonian case.

In order to motivate the following definition, we refer to [Bit16c] where the study of the Painlevé case is performed.

**Definition 1.17.** Consider the rational 1-form

$$\omega := \frac{dy_1 \wedge dy_2}{x}.$$

We say that vector field  $Y$  is **transversally Hamiltonian** (with respect to  $\omega$  and  $dx$ ) if

$$\mathcal{L}_Y(dx) \in \langle dx \rangle \quad \text{and} \quad \mathcal{L}_Y(\omega) \in \langle dx \rangle.$$

For any open sector  $S \subset \mathbb{C}^*$ , we say that a germ of sectorial fibered diffeomorphism  $\Phi$  in  $S \times (\mathbb{C}^2, 0)$  is **transversally symplectic** (with respect to  $\omega$  and  $dx$ ) if

$$\Phi^*(\omega) \in \omega + \langle dx \rangle$$

(here  $\Phi^*(\omega)$  denotes the pull-back of  $\omega$  by  $\Phi$ ).

We denote by  $\text{Diff}_\omega(\mathbb{C}^3, 0; \text{Id})$  the group of transversally symplectic diffeomorphisms which are tangent to the identity.

*Remark 1.18.* A fibered sectorial diffeomorphism  $\Phi$  is transversally symplectic if and only if  $\det(D\Phi) = 1$ .

**Definition 1.19.** A **transversally Hamiltonian doubly-resonant saddle-node** is a transversally Hamiltonian vector field which is conjugate, *via* a (fibered) transversally symplectic diffeomorphism, to one of the form

$$Y = x^2 \frac{\partial}{\partial x} + \left( -\lambda y_1 + F_1(x, \mathbf{y}) \right) \frac{\partial}{\partial y_1} + \left( \lambda y_2 + F_2(x, \mathbf{y}) \right) \frac{\partial}{\partial y_2},$$

with  $\lambda \in \mathbb{C}^*$  and  $F_1, F_2$  analytic in  $(\mathbb{C}^3, 0)$  and of order at least 2.

Notice that a transversally Hamiltonian doubly-resonant saddle-node is necessarily strictly non-degenerate (since its residue is always equal to 1), and also div-integrable (see section 3).

We recall the second main result from [Bit16b].

**Theorem 1.20.** [Bit16b]

*Let  $Y$  be a diagonal doubly-resonant saddle-node which is transversally Hamiltonian. Then, there exists a unique formal fibered transversally symplectic diffeomorphism  $\hat{\Phi}$  tangent to identity such that:*

$$\begin{aligned} \hat{\Phi}_*(Y) &= x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x - c(y_1 y_2)) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x + c(y_1 y_2)) y_2 \frac{\partial}{\partial y_2} \\ (1.6) \quad &=: Y_{\text{norm}}, \end{aligned}$$

where  $\lambda \in \mathbb{C}^*$ ,  $c(v) \in v\mathbb{C}[[v]]$  a formal power series in  $v = y_1 y_2$  without constant term and  $a_1, a_2 \in \mathbb{C}$  are such that  $a_1 + a_2 = 1$ .

The second main result in [Bit16c] is the following.

**Theorem 1.21.** *Let  $Y$  be a transversally Hamiltonian doubly-resonant saddle-node. Let  $\hat{\Phi}$  be the unique formal normalizing map given by Theorem 1.20. Then the associate sectorial normalizing maps  $\Phi_+$  and  $\Phi_-$  given by Theorem 1.9 are also transversally symplectic.*



Let us fix a normal form  $Y_{\text{norm}}$  as in Theorem 1.21, and consider two sectorial domains  $S_\lambda \times (\mathbb{C}^2, 0)$  and  $S_{-\lambda} \times (\mathbb{C}^2, 0)$  as in (1.5). Then, the Stokes diffeomorphisms  $(\Phi_\lambda, \Phi_{-\lambda})$  defined in the previous subsection as

$$\begin{cases} \Phi_\lambda := (\Phi_+ \circ \Phi_-^{-1})|_{S_\lambda \times (\mathbb{C}^2, 0)} \\ \Phi_{-\lambda} := (\Phi_- \circ \Phi_+^{-1})|_{S_{-\lambda} \times (\mathbb{C}^2, 0)} \end{cases} ,$$

are also transversally symplectic.

**Definition 1.22.** We denote by  $\Lambda_\lambda^\omega(Y_{\text{norm}})$  (*resp.*  $\Lambda_{-\lambda}^\omega(Y_{\text{norm}})$ ) the group of germs of sectorial fibered isotropies of  $Y_{\text{norm}}$ , admitting the identity as Gevrey-1 asymptotic expansion in sectorial domains of the form  $S_\lambda \times (\mathbb{C}^2, 0)$  (*resp.*  $S_{-\lambda} \times (\mathbb{C}^2, 0)$ ), and which are transversally symplectic.

Let us denote by  $[Y_{\text{norm}}]_\omega$  the set of germs of vector fields which are formally conjugate to  $Y_{\text{norm}}$  *via* (formal) transversally symplectic diffeomorphisms tangent to the identity. As a consequence of Theorems (1.15) and (1.21), we can now state our third main result:

**Theorem 1.23.** *The map*

$$\begin{aligned} [Y_{\text{norm}}]_\omega / \text{Diff}_\omega(\mathbb{C}^3, 0; \text{Id}) &\longrightarrow \Lambda_\lambda^\omega(Y_{\text{norm}}) \times \Lambda_{-\lambda}^\omega(Y_{\text{norm}}) \\ Y &\longmapsto (\Phi_\lambda, \Phi_{-\lambda}) \end{aligned}$$

*is a well-defined bijection.*

## 1.5. Outline of the paper.

In section 2, we recall the different tools, notations and nomenclature we will need regarding asymptotic expansion, Gevrey-1 series, 1-summability and sectorial germs.

In section 3, we prove the main theorems presented above, assuming the Proposition 3.5 holds.

In section 4, we prove the key Proposition 3.5 by studying the automorphisms of the space of leaves.

In section 5, we give a description of the moduli space in Theorem 1.15 in terms of power series in the space of leaves, and present some applications.

In section 6, we present a generalization of Theorem 1.15 where we study the action of  $\text{Diff}(\mathbb{C}^3, 0)$  instead of  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0)$ .

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## 2. BACKGROUND

We refer the reader to [MR82], [Mal95] and [RS93] for a general and detailed introduction to the theory of asymptotic expansion, Gevrey series and summability (see also [Sto96] for a useful discussion of these concepts). We refer more precisely to [Bit16c] when it comes to the notion of *weak 1-summability*.

We call  $x \in \mathbb{C}$  the *independent* variable and  $\mathbf{y} := (y_1, \dots, y_n) \in \mathbb{C}^n$ ,  $n \in \mathbb{N}$ , the *dependent* variables. As usual we define  $\mathbf{y}^{\mathbf{k}} := y_1^{k_1} \dots y_n^{k_n}$  for  $\mathbf{k} = (k_1, \dots, k_n) \in \mathbb{N}^n$ , and  $|\mathbf{k}| = k_1 + \dots + k_n$ . The notions of asymptotic expansion, Gevrey series and 1-summability presented here are always considered with respect to the independent variable  $x$  living in (open) sectors

$$S(r, \alpha, \beta) = \{x \in \mathbb{C} \mid 0 < |x| < r \text{ and } \alpha < \arg(x) < \beta\} ,$$

the dependent variable  $\mathbf{y}$  belonging to poly-discs

$$\mathbf{D}(\mathbf{0}, \mathbf{r}) := \{\mathbf{y} = (y_1, \dots, y_n) \in \mathbb{C}^n \mid |y_1| < r_1, \dots, |y_n| < r_n\} ,$$

of poly-radius  $\mathbf{r} = (r_1, \dots, r_n) \in (\mathbb{R}_{>0})^n$ . Given an open subset  $\mathcal{U} \subset \mathbb{C}^{n+1}$ , we denote by  $\mathcal{O}(\mathcal{U})$  the algebra of holomorphic function in  $\mathcal{U}$ .

### 2.1. Sectorial germs.

Let  $\theta \in \mathbb{R}$ ,  $\eta \in \mathbb{R}_{\geq 0}$  and  $n \in \mathbb{N}$ .

**Definition 2.1.** (1) An *x-sectorial neighborhood* (or simply *sectorial neighborhood*) of the origin (in  $\mathbb{C}^{n+1}$ ) in the direction  $\theta$  with opening  $\eta$  is an open set  $\mathcal{S} \subset \mathbb{C}^{n+1}$  such that

$$\mathcal{S} \supset S\left(r, \theta - \frac{\eta}{2} - \epsilon, \theta + \frac{\eta}{2} + \epsilon\right) \times \mathbf{D}(\mathbf{0}, \mathbf{r})$$

for some  $r > 0$ ,  $\mathbf{r} \in (\mathbb{R}_{>0})^n$  and  $\epsilon > 0$ . We denote by  $(\mathcal{S}_{\theta, \eta}, \leq)$  the directed set formed by all such neighborhoods, equipped with the order relation

$$S_1 \leq S_2 \iff S_1 \supset S_2 .$$

(2) The algebra of *germs of holomorphic functions in a sectorial neighborhood of the origin in the direction  $\theta$  with opening  $\eta$*  is the direct limit

$$\mathcal{O}(\mathcal{S}_{\theta, \eta}) := \varinjlim \mathcal{O}(\mathcal{S})$$

with respect to the directed system defined by  $\{\mathcal{O}(\mathcal{S}) : \mathcal{S} \in \mathcal{S}_{\theta, \eta}\}$ .

We now give the definition of a (*germ of a*) *sectorial diffeomorphism*.

**Definition 2.2.** (1) Given an element  $\mathcal{S} \in \mathcal{S}_{\theta, \eta}$ , we denote by  $\text{Diff}_{\text{fib}}(\mathcal{S}, \text{Id})$  the set of holomorphic diffeomorphisms of the form

$$\begin{aligned} \Phi : \mathcal{S} &\rightarrow \Phi(\mathcal{S}) \\ (x, \mathbf{y}) &\mapsto (x, \phi_1(x, \mathbf{y}), \phi_2(x, \mathbf{y})) , \end{aligned}$$

such that  $\Phi(x, \mathbf{y}) - \text{Id}(x, \mathbf{y}) = \mathcal{O}(\|x, \mathbf{y}\|^2)$ , as  $(x, \mathbf{y}) \rightarrow (0, \mathbf{0})$  in  $\mathcal{S}$ .<sup>1</sup>

- (2) The set of germs of (fibered) sectorial diffeomorphisms in the direction  $\theta$  with opening  $\eta$ , tangent to the identity, is the direct limit

$$\text{Diff}_{\text{fib}}(\mathcal{S}_{\theta, \eta}; \text{Id}) := \varinjlim \text{Diff}_{\text{fib}}(\mathcal{S}, \text{Id})$$

with respect to the directed system defined by  $\{\text{Diff}_{\text{fib}}(\mathcal{S}, \text{Id}) : \mathcal{S} \in \mathcal{S}_{\theta, \eta}\}$ . We equip  $\text{Diff}_{\text{fib}}(\mathcal{S}_{\theta, \eta}; \text{Id})$  of a group structure as follows: given two germs  $\Phi, \Psi \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\theta, \eta}; \text{Id})$  we chose corresponding representatives  $\Phi_0 \in \text{Diff}_{\text{fib}}(\mathcal{S}, \text{Id})$  and  $\Psi_0 \in \text{Diff}_{\text{fib}}(\mathcal{T}, \text{Id})$  with  $\mathcal{S}, \mathcal{T} \in \mathcal{S}_{\theta, \eta}$  such that  $\mathcal{T} \subset \Phi_0(\mathcal{S})$  and let  $\Psi \circ \Phi$  be the germ defined by  $\Psi_0 \circ \Phi_0$ .<sup>2</sup>

We will also need the notion of *asymptotic sectors*.

**Definition 2.3.** An (open) asymptotic sector of the origin in the direction  $\theta$  and with opening  $\eta$  is an open set  $S \subset \mathbb{C}$  such that

$$S \in \bigcap_{0 \leq \eta' < \eta} \mathcal{S}_{\theta, \eta'} .$$

We denote by  $\mathcal{AS}_{\theta, \eta}$  the set of all such (open) asymptotic sectors.

## 2.2. Gevrey-1 power series and 1-summability.

In this subsection we fix a formal power series

$$\hat{f}(x, \mathbf{y}) = \sum_{k \geq 0} f_k(\mathbf{y}) x^k = \sum_{(j_0, \mathbf{j}) \in \mathbb{N}^{n+1}} f_{j_0, \mathbf{j}} x^{j_0} \mathbf{y}^{\mathbf{j}} \in \mathbb{C}[[x, \mathbf{y}]] .$$

### Definition 2.4.

- An analytic (and bounded) function  $f$  in a sectorial domain  $S(r, \alpha, \beta) \times \mathbf{D}(\mathbf{0}, \mathbf{r})$  admits  $\hat{f}$  as *Gevrey-1 asymptotic expansion* in this domain, if for all closed sub-sector  $S' \subset S(r, \alpha, \beta)$ , there exists  $A, C > 0$  such that:

$$\left| f(x, \mathbf{y}) - \sum_{k=0}^{N-1} f_k(\mathbf{y}) x^k \right| \leq AC^N (N!) |x|^N$$

for all  $N \in \mathbb{N}$  and  $(x, \mathbf{y}) \in S' \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ .

- A formal power series  $\hat{f} \in \mathbb{C}[[x, \mathbf{y}]]$  is 1-summable in the direction  $\theta$  if and only if there exists a germ of a sectorial holomorphic function  $f_\theta \in \mathcal{O}(\mathcal{S}_{\theta, \pi})$  which admits  $\hat{f}$  as Gevrey-1 asymptotic expansion in some  $S \in \mathcal{S}_{\theta, \pi}$ .

*Remark 2.5.* In the definition above,  $f_\theta$  is unique (as a germ in  $\mathcal{O}(\mathcal{S}_{\theta, \pi})$ ), and is called the *1-sum of  $\hat{f}$  in the direction  $\theta$* .

**Lemma 2.6.** The set  $\Sigma_\theta \subset \mathbb{C}[[x, \mathbf{y}]]$  of 1-summable power series in the direction  $\theta$  is an algebra closed under differentiation. Moreover the map

$$\begin{aligned} \Sigma_\theta &\longrightarrow \mathcal{O}(\mathcal{S}_{\theta, \pi}) \\ \hat{f} &\longmapsto f_\theta \end{aligned}$$

is an injective morphism of differential algebras.

**Proposition 2.7.** Let  $\hat{\Phi}(x, \mathbf{y}) \in \mathbb{C}[[x, \mathbf{y}]]$  be 1-summable in directions  $\theta$  and  $\theta - \pi$ , and let  $\Phi_+(x, \mathbf{y})$  and  $\Phi_-(x, \mathbf{y})$  be its 1-sums directions  $\theta$  and  $\theta - \pi$  respectively. Let also  $\hat{f}_1(x, \mathbf{z}), \dots, \hat{f}_n(x, \mathbf{z})$  be 1-summable in directions  $\theta, \theta - \pi$ , and  $f_{1,+}, \dots, f_{n,+}$ , and  $f_{1,-}, \dots, f_{n,-}$  be their 1-sums in directions  $\theta$  and  $\theta - \pi$  respectively. Assume that

$$(2.1) \quad \hat{f}_j(0, \mathbf{0}) = 0, \text{ for all } j = 1, \dots, n .$$

<sup>1</sup>This condition implies in particular that  $\Phi(\mathcal{S}) \in \mathcal{S}_{\theta, \eta}$ .

<sup>2</sup>One can prove that this definition is independent of the choice of the representatives

Then

$$\hat{\Psi}(x, \mathbf{z}) := \hat{\Phi}\left(x, \hat{f}_1(x, \mathbf{z}), \dots, \hat{f}_n(x, \mathbf{z})\right)$$

is 1-summable in directions  $\theta, \theta - \pi$ , and its 1-sum in the corresponding direction is

$$\Psi_{\pm}(x, \mathbf{z}) := \Phi_{\pm}(x, f_{1,\pm}(x, \mathbf{z}), \dots, f_{n,\pm}(x, \mathbf{z})) \quad ,$$

which is a germ of a sectorial holomorphic function in directions  $\theta$  and  $\theta - \pi$ .

*Proof.* See [Bit16b]. □

Consider  $\hat{Y}$  a formal singular vector field at the origin and a formal fibered diffeomorphism  $\hat{\varphi} : (x, \mathbf{y}) \mapsto (x, \hat{\varphi}(x, \mathbf{y}))$ . Assume that both  $\hat{Y}$  and  $\hat{\varphi}$  are 1-summable in directions  $\theta$  and  $\theta - \pi$ , for some  $\theta \in \mathbb{R}$ , and denote by  $Y_+, Y_-$  (resp.  $\varphi_+, \varphi_-$ ) their 1-sums in directions  $\theta$  and  $\theta - \pi$  respectively. As a consequence of Proposition 2.7 and Lemma 2.6, we can state the following:

**Corollary 2.8.** *Under the assumptions above,  $\hat{\varphi}_*(\hat{Y})$  is 1-summable in both directions  $\theta$  and  $\theta - \pi$ , and its 1-sums in these directions are  $\varphi_+(Y_+)$  and  $\varphi_-(Y_-)$  respectively.*

### 2.3. An important result by Martinet and Ramis.

We are going to make an essential use of an isomorphism theorem proved in [MR82]. This result is of paramount importance in the present paper since it will be a key tool in the proofs of both Theorems 1.9 and 1.15 (see section 3).

Let us consider two open asymptotic sectors  $\mathcal{S}$  and  $\mathcal{S}'$  at the origin in directions  $\theta$  and  $\theta - \pi$  respectively, both of opening  $\pi$ :

$$\begin{aligned} \mathcal{S} &\in \mathcal{AS}_{\theta, \pi} \\ \mathcal{S}' &\in \mathcal{AS}_{\theta - \pi, \pi} \end{aligned}$$

(see Definition 2.3). In this particular setting, the cited theorem can be stated as follows.

**Theorem 2.9.** [MR82, Théorème 5.2.1] *Consider a pair of germs of sectorial diffeomorphisms*

$$(\varphi, \varphi') \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\theta, 0}; \text{Id}) \times \text{Diff}_{\text{fib}}(\mathcal{S}_{\theta - \pi, 0}; \text{Id})$$

such that  $\varphi$  and  $\varphi'$  extend analytically and admit the identity as Gevrey-1 asymptotic expansion in  $S \times (\mathbb{C}^2, 0)$  and  $S' \times (\mathbb{C}^2, 0)$  respectively. Then, there exists a pair  $(\phi_+, \phi_-)$  of germs of sectorial fibered diffeomorphisms

$$(\phi_+, \phi_-) \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\theta + \frac{\pi}{2}, \eta}; \text{Id}) \times \text{Diff}_{\text{fib}}(\mathcal{S}_{\theta - \frac{\pi}{2}, \eta}; \text{Id})$$

with  $\eta \in ]\pi, 2\pi[$ , which extend analytically in  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively, for some  $S_+ \in \mathcal{AS}_{\theta + \frac{\pi}{2}, 2\pi}$  and  $S_- \in \mathcal{AS}_{\theta - \frac{\pi}{2}, 2\pi}$ , such that:

$$\begin{cases} \phi_+ \circ (\phi_-)^{-1}|_{S_+ \times (\mathbb{C}^2, 0)} = \varphi \\ \phi_+ \circ (\phi_-)^{-1}|_{S' \times (\mathbb{C}^2, 0)} = \varphi' \end{cases} .$$

There also exists a formal diffeomorphism  $\hat{\phi}$  which is tangent to the identity, such that  $\phi_+$  and  $\phi_-$  both admit  $\hat{\phi}$  as Gevrey-1 asymptotic expansion in  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively.

In particular, in the theorem above  $\hat{\phi}$  is 1-summable in every direction except  $\theta$  and  $\theta - \pi$ , and its 1-sums in directions  $\theta + \frac{\pi}{2}$  and  $\theta - \frac{\pi}{2}$  respectively are  $\phi_+$  and  $\phi_-$ . For future use, we are going to prove a “transversally symplectic” version of the above theorem.

**Corollary 2.10.** *With the assumptions and notations of Theorem 2.9, if  $\varphi$  and  $\varphi'$  both are transversally symplectic (see Definition 1.17), then there exists a germ of an analytic fibered diffeomorphism  $\psi \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  (tangent to the identity), such that*

$$\sigma_+ := \phi_+ \circ \psi \quad \text{and} \quad \sigma_- := \phi_- \circ \psi$$

both are transversally symplectic. Moreover we also have:

$$\begin{cases} \sigma_+ \circ (\sigma_-)^{-1}|_{S \times (\mathbb{C}^2, 0)} = \varphi \\ \sigma_+ \circ (\sigma_-)^{-1}|_{S' \times (\mathbb{C}^2, 0)} = \varphi' \end{cases} .$$

*Proof.* We recall that for any germ  $\varphi$  of a sectorial fibered diffeomorphism which is tangent to the identity,  $\varphi$  is transversally symplectic if and only if  $\det(D\varphi) = 1$ .

First of all, let us show that

$$\det(D\phi_+) = \det(D\phi_-) \text{ in } (S_+ \cap S_-) \times (\mathbb{C}^2, 0) .$$

Since  $\phi_+$  and  $\phi_-$  both are sectorial fibered diffeomorphism which are tangent to the identity and transversally symplectic, then

$$\det\left(\phi_+ \circ (\phi_-)^{-1}|_{(S_+ \cap S_-) \times (\mathbb{C}^2, 0)}\right) = 1 .$$

The *chain rule* implies immediately that

$$\det(D\phi_+) = \det(D\phi_-) \text{ in } (S_+ \cap S_-) \times (\mathbb{C}^2, 0) .$$

Thus, this equality allows us to define (thanks to the Riemann's Theorem of removable singularities) a germ of analytic function  $f \in \mathcal{O}(\mathbb{C}^3, 0)$ . Notice that  $f(0, 0, 0) = 1$  because  $\phi_+$  and  $\phi_-$  are tangent to the identity. Now, let us look for an element  $\psi \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  of the form

$$(2.2) \quad \psi : (x, y_1, y_2) \mapsto (x, \psi_1(x, \mathbf{y}), y_2)$$

such that

$$\sigma_+ := \phi_+ \circ \psi \text{ and } \sigma_- := \phi_- \circ \psi$$

both be transversally symplectic. An easy computation gives:

$$\det(\sigma_{\pm}) = (\det(D\phi_{\pm}) \circ \psi) \det(D\psi) = 1$$

*i.e.*

$$(f \circ \psi) \det(D\psi) = 1 .$$

According to (2.2), we must have:

$$(2.3) \quad (f \circ \psi) \frac{\partial \psi_1}{\partial y_1} = 1 .$$

Let us define

$$F(x, y_1, y_2) := \int_0^{y_1} f(x, z, y_2) dz ,$$

so that (2.3) can be integrated as

$$F \circ \psi = y_1 + h(x, y_2) ,$$

for some  $h \in \mathbb{C}\{x, y_2\}$ . Notice that

$$\frac{\partial F}{\partial y_1}(0, 0, 0) = 1$$

since  $f(0, 0, 0) = 1$ . Let us chose  $h = 0$ . Then, we have to solve

$$F \circ \psi = y_1 ,$$

with unknown  $\psi \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  as in (2.3). If we define

$$\Phi : (x, \mathbf{y}) \mapsto (x, F(x, \mathbf{y}), y_2) ,$$

the latter problem is equivalent to find  $\psi$  as above such that:

$$\Phi \circ \psi = \text{Id} .$$

Since  $D\Phi_0 = \text{Id}$ , the inverse function theorem gives us the existence of the germ  $\psi = \Phi^{-1} \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$ .  $\square$

#### 2.4. 1-summability implies weakly 1-summability.

Any function  $f(x, \mathbf{y})$  analytic in a domain  $\mathcal{U} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ , where  $\mathcal{U} \subset \mathbb{C}$  is open, and bounded in any domain  $\mathcal{U} \times \overline{\mathbf{D}}(\mathbf{0}, \mathbf{r}')$  with  $r'_1 < r_1, \dots, r'_n < r_n$ , can be written

$$(2.4) \quad f(x, \mathbf{y}) = \sum_{\mathbf{j} \in \mathbb{N}^n} F_{\mathbf{j}}(x) \mathbf{y}^{\mathbf{j}} \quad ,$$

where for all  $\mathbf{j} \in \mathbb{N}^n$ ,  $F_{\mathbf{j}}$  is analytic and bounded on  $\mathcal{U}$ , and defined *via* the Cauchy formula:

$$F_{\mathbf{j}}(x) = \frac{1}{(2i\pi)^n} \int_{|z_1|=r'_1} \dots \int_{|z_n|=r'_n} \frac{f(x, \mathbf{z})}{(z_1)^{j_1+1} \dots (z_n)^{j_n+1}} dz_n \dots dz_1 \quad .$$

Notice that the convergence of the series above is uniform on every compact with respect to  $x$  and  $\mathbf{y}$ .

In the same way, any formal power series  $\hat{f}(x, \mathbf{y}) \in \mathbb{C}[[x, \mathbf{y}]]$  can be written as

$$\hat{f}(x, \mathbf{y}) = \sum_{\mathbf{j} \in \mathbb{N}^n} \hat{F}_{\mathbf{j}}(x) \mathbf{y}^{\mathbf{j}} \quad .$$

We present here a weaker notion of 1-summability that we will also need.

#### Definition 2.11.

- A function

$$f(x, \mathbf{y}) = \sum_{\mathbf{j} \in \mathbb{N}^n} F_{\mathbf{j}}(x) \mathbf{y}^{\mathbf{j}}$$

analytic and bounded in a domain  $S(r, \alpha, \beta) \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ , admits  $\hat{f}$  as **weak Gevrey-1 asymptotic expansion** in  $x \in S(r, \alpha, \beta)$ , if for all  $\mathbf{j} \in \mathbb{N}^n$ ,  $F_{\mathbf{j}}$  admits  $\hat{F}_{\mathbf{j}}$  as Gevrey-1 asymptotic expansion in  $S(r, \alpha, \beta)$ .

- The formal power series  $\hat{f}$  is said to be **weakly 1-summable in the direction**  $\theta \in \mathbb{R}$ , if the following conditions hold:
  - for all  $\mathbf{j} \in \mathbb{N}^n$ ,  $\hat{F}_{\mathbf{j}}(x) \in \mathbb{C}[[x]]$  is 1-summable in the direction  $\theta$ , whose 1-sum in the direction  $\theta$  is denoted by  $F_{\mathbf{j}}$ ;
  - the series  $f_{\theta}(x, \mathbf{y}) := \sum_{\mathbf{j} \in \mathbb{N}^n} F_{\mathbf{j}}(x) \mathbf{y}^{\mathbf{j}}$  defines a germ of a sectorial holomorphic function in a domain of the form

$$S\left(r, \theta - \frac{\pi}{2} - \epsilon, \theta + \frac{\pi}{2} + \epsilon\right) \times \mathbf{D}(\mathbf{0}, \mathbf{r}) \quad .$$

In this case,  $f_{\theta}(x, \mathbf{y})$  is called **the weak 1-sum of  $\hat{f}$  in the direction  $\theta$** .

The following proposition is an analogue of Proposition 2.7 for weak 1-summable formal power series, with the a stronger condition instead of (2.1).

#### Proposition 2.12. *Let*

$$\hat{\Phi}(x, \mathbf{z}) = \sum_{\mathbf{j} \in \mathbb{N}^n} \hat{\Phi}_{\mathbf{j}}(x) \mathbf{z}^{\mathbf{j}} \in \mathbb{C}[[x, \mathbf{y}]]$$

and

$$\hat{f}^{(k)}(x, \mathbf{y}) = \sum_{\mathbf{j} \in \mathbb{N}^n} \hat{F}_{\mathbf{j}}^{(k)}(x) \mathbf{y}^{\mathbf{j}} \in \mathbb{C}[[x, \mathbf{y}]] \quad ,$$

for  $k = 1, \dots, n$ , be  $n+1$  formal power series which are weakly 1-summable in directions  $\theta$  and  $\theta - \pi$ , and let us denote by  $\hat{\Phi}_+, f_+^{(1)}, \dots, f_+^{(n)}$  (resp.  $\hat{\Phi}_-, f_-^{(1)}, \dots, f_-^{(n)}$ ) their respective weak 1-sums in the direction  $\theta$  (resp.  $\theta - \pi$ ). Assume that  $\hat{F}_{\mathbf{0}}^{(k)} = 0$  for all  $k = 1, \dots, n$ . Then,

$$\hat{\Psi}(x, \mathbf{y}) := \hat{\Phi}\left(x, \hat{f}^{(1)}(x, \mathbf{y}), \dots, \hat{f}^{(n)}(x, \mathbf{y})\right)$$

is weakly 1-summable directions  $\theta$  and  $\theta - \pi$ , and its 1-sum in the corresponding direction is

$$\Psi_{\pm}(x, \mathbf{y}) = \Phi_{\pm}\left(x, f_{\pm}^{(1)}(x, \mathbf{y}), \dots, f_{\pm}^{(n)}(x, \mathbf{y})\right) \quad ,$$

which is a germ of a sectorial holomorphic function in the direction  $\theta$  (resp.  $\theta - \pi$ ) with opening  $\pi$ .

*Proof.* See [Bit16c]. □

As proved in [Bit16c], the next corollary gives the link between 1-summability in some direction and weak 1-summability in the same direction (we refer to [Bit16c], Definition 2.8, or to [MR82], section IV, for a definition of the norm  $\|\cdot\|_{\lambda,\theta,\delta,\rho}$  associate to the space of 1-summable formal power series in the direction  $\theta$ ).

**Corollary 2.13.** *Let*

$$\hat{f}(x, \mathbf{y}) = \sum_{\mathbf{j} \in \mathbb{N}^n} \hat{F}_{\mathbf{j}}(x) \mathbf{y}^{\mathbf{j}} \in \mathbb{C}[[x, \mathbf{y}]]$$

*be a formal power series. Then,  $\hat{f}$  is 1-summable in the direction  $\theta \in \mathbb{R}$ , of 1-sum  $f \in \mathcal{O}(\mathcal{S}_{\theta,\pi})$ , if and only if the following two conditions hold:*

- *$\hat{f}$  is weakly 1-summable in the direction  $\theta$ , i.e. there exists  $\lambda, \delta, \rho$  such that  $\forall \mathbf{j} \in \mathbb{N}^n$ ,  $\|\hat{F}_{\mathbf{j}}\|_{\lambda,\theta,\delta,\rho} < \infty$*
- *the power series  $\sum_{\mathbf{j} \in \mathbb{N}^n} \|\hat{F}_{\mathbf{j}}\|_{\lambda,\theta,\delta,\rho} \mathbf{y}^{\mathbf{j}}$  is convergent in some polydisc  $\mathbf{D}(\mathbf{0}, \mathbf{r})$ .*

*Proof.* See [Bit16c]. □

### 3. PROOFS OF THE MAIN THEOREMS

The aim of this section is to prove the main results of this paper, assuming Proposition 3.5 below holds.

#### 3.1. Analytic invariants: Stokes diffeomorphisms.

From now on, we fix a normal form

$$Y_{\text{norm}} = x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x - c(y_1 y_2)) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x + c(y_1 y_2)) y_2 \frac{\partial}{\partial y_2},$$

with  $\lambda \in \mathbb{C}^*$ ,  $\Re(a_1 + a_2) > 0$  and  $c \in v\mathbb{C}\{y\}$  vanishing at the origin. We denote by  $[Y_{\text{norm}}]$  the set of germs of holomorphic doubly-resonant saddle-nodes in  $(\mathbb{C}^3, 0)$ , formally conjugate to  $Y_{\text{norm}}$  by formal fibered diffeomorphisms tangent to the identity. We refer the reader to Definition 2.1 for notions relating to sectors.

#### Definition 3.1.

- We define  $\text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\theta,\eta}; \text{Id})$ , for all  $\theta \in \mathbb{R}$  and  $\eta \in [0, 2\pi]$ , as the group of germs of sectorial fibered isotropies of  $Y_{\text{norm}}$  in sectorial domains in  $\mathcal{S}_{\theta,\eta}$  (see Definition 2.3), which are tangent to the identity.
- We define  $\Lambda_{\lambda}^{(\text{weak})}(Y_{\text{norm}})$  (*resp.*  $\Lambda_{-\lambda}^{(\text{weak})}(Y_{\text{norm}})$ ) as the group of germs of sectorial fibered isotropies of  $Y_{\text{norm}}$ , admitting the identity as **weak** Gevrey-1 asymptotic expansion in sectorial domains of the form  $S_{\lambda} \times (\mathbb{C}^2, 0)$  (*resp.*  $S_{-\lambda} \times (\mathbb{C}^2, 0)$ ), where:

$$\begin{aligned} S_{\lambda} &\in \mathcal{AS}_{\arg(\lambda),\pi} \\ S_{-\lambda} &\in \mathcal{AS}_{\arg(-\lambda),\pi} \end{aligned}$$

(see Definition 2.3).

We recall the notations given in the introduction: we have defined  $\Lambda_{\lambda}(Y_{\text{norm}})$  (*resp.*  $\Lambda_{-\lambda}(Y_{\text{norm}})$ ) as the group of germs of sectorial fibered isotropies of  $Y_{\text{norm}}$ , admitting the identity as Gevrey-1 asymptotic expansion in sectorial domains of the form  $S_{\lambda} \times (\mathbb{C}^2, 0)$  (*resp.*  $S_{-\lambda} \times (\mathbb{C}^2, 0)$ ). It is clear that we have:

$$\Lambda_{\pm\lambda}(Y_{\text{norm}}) \subset \Lambda_{\pm\lambda}^{(\text{weak})}(Y_{\text{norm}}) \subset \text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\arg(\pm\lambda),\eta}; \text{Id}), \quad \forall \eta \in ]0, \pi[.$$

According to Theorem 1.9, to any  $Y \in [Y_{\text{norm}}]$ , we can associate a pair of germs of sectorial fibered isotropies in  $S_\lambda \times (\mathbb{C}^2, 0)$  and  $S_{-\lambda} \times (\mathbb{C}^2, 0)$  respectively, denoted by  $(\Phi_\lambda, \Phi_{-\lambda})$ :

$$\begin{cases} \Phi_\lambda := (\Phi_+ \circ \Phi_-^{-1})|_{S_\lambda \times (\mathbb{C}^2, 0)} \in \text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\text{arg}(\lambda), \eta}; \text{Id}) & , \forall \eta \in ]0, \pi[ \\ \Phi_{-\lambda} := (\Phi_- \circ \Phi_+^{-1})|_{S_{-\lambda} \times (\mathbb{C}^2, 0)} \in \text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\text{arg}(-\lambda), \eta}; \text{Id}) & , \forall \eta \in ]0, \pi[ \end{cases} ,$$

where  $(\Phi_+, \Phi_-)$  is the pair of the sectorial normalizing maps given by Theorem 1.9.

**Proposition 3.2.** *For any given  $\eta \in ]0, \pi[$  the map*

$$\begin{aligned} [Y_{\text{norm}}] &\longrightarrow \text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\text{arg}(\lambda), \eta}; \text{Id}) \times \text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\text{arg}(-\lambda), \eta}; \text{Id}) \\ Y &\longmapsto (\Phi_\lambda, \Phi_{-\lambda}) \end{aligned} ,$$

actually ranges in  $\Lambda_\lambda^{(\text{weak})}(Y_{\text{norm}}) \times \Lambda_{-\lambda}^{(\text{weak})}(Y_{\text{norm}})$ .

*Proof.* The fact that the sectorial normalizing maps  $\Phi_+, \Phi_-$  given by Theorem 1.9 both conjugate  $Y \in [Y_{\text{norm}}]$  to  $Y_{\text{norm}}$  in the corresponding sectorial domains proves that the arrow above is well-defined, with values in  $\text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\text{arg}(\lambda), \eta}; \text{Id}) \times \text{Isot}_{\text{fib}}(Y; \mathcal{S}_{\text{arg}(-\lambda), \eta}; \text{Id})$ , for all  $\eta \in ]0, \pi[$ . The fact that  $\Phi_{\pm\lambda}$  admits the identity as weak Gevrey-1 asymptotic expansion in  $S_{\pm\lambda} \times (\mathbb{C}^2, 0)$  comes from the fact that  $\Phi_+$  and  $\Phi_-$  admits the same weak Gevrey-1 asymptotic expansion in  $S_\lambda \times (\mathbb{C}^2, 0)$  and  $S_{-\lambda} \times (\mathbb{C}^2, 0)$ , and from Proposition 2.12.  $\square$

The subgroup  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id}) \subset \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0)$  formed by fibered diffeomorphisms tangent to the identity acts naturally on  $[Y_{\text{norm}}]$  by conjugacy. Now we show that the uniqueness of germs of sectorial normalizing maps  $(\Phi_+, \Phi_-)$  implies that the Stokes diffeomorphisms  $(\Phi_\lambda, \Phi_{-\lambda})$  of a vector field  $Y \in [Y_{\text{norm}}]$  is invariant under the action of  $\text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$ . Furthermore, this map is one-to-one.

**Proposition 3.3.** *The map*

$$\begin{aligned} [Y_{\text{norm}}] &\longrightarrow \Lambda_\lambda^{(\text{weak})}(Y_{\text{norm}}) \times \Lambda_{-\lambda}^{(\text{weak})}(Y_{\text{norm}}) \\ Y &\longmapsto (\Phi_\lambda, \Phi_{-\lambda}) \end{aligned}$$

factorizes through a one-to-one map

$$\begin{aligned} [Y_{\text{norm}}] / \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id}) &\longrightarrow \Lambda_\lambda^{(\text{weak})}(Y_{\text{norm}}) \times \Lambda_{-\lambda}^{(\text{weak})}(Y_{\text{norm}}) \\ Y &\longmapsto (\Phi_\lambda, \Phi_{-\lambda}) \end{aligned} .$$

*Remark 3.4.* This very result means that the Stokes diffeomorphisms encode completely the class of  $Y$  in the quotient  $[Y_{\text{norm}}] / \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  as they separate conjugacy classes.

*Proof.* First of all, let us prove that the latter map is well-defined. Let  $Y, \tilde{Y} \in [Y_{\text{norm}}]$  and  $\Theta \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  be such that  $\Theta_*(Y) = \tilde{Y}$ . We denote by  $\Phi_\pm$  (*resp.*  $\tilde{\Phi}_\pm$ ) the sectorial normalizing maps of  $Y$  (*resp.*  $\tilde{Y}$ ), and  $(\Phi_\lambda, \Phi_{-\lambda})$  (*resp.*  $(\tilde{\Phi}_\lambda, \tilde{\Phi}_{-\lambda})$ ) the Stokes diffeomorphisms of  $Y$  (*resp.*  $\tilde{Y}$ ).

By assumption,  $\tilde{\Phi}_\pm \circ \Theta$  is also a germ of a sectorial fibered normalization of  $Y$  in  $S_\pm \times (\mathbb{C}^2, 0)$ , which is tangent to the identity. Thus, according to the uniqueness statement in Theorem 1.9:

$$\Phi_\pm = \tilde{\Phi}_\pm \circ \Theta .$$

Consequently, in  $S_{\pm\lambda} \times (\mathbb{C}^2, 0)$  we have

$$\begin{aligned} \Phi_\lambda &= (\Phi_+ \circ \Phi_-^{-1})|_{S_\lambda \times (\mathbb{C}^2, 0)} \\ &= \tilde{\Phi}_+ \circ \Theta \circ \Theta^{-1} \circ \tilde{\Phi}_- \\ &= \tilde{\Phi}_\lambda \end{aligned} ,$$



and similarly

$$\begin{aligned}\Phi_{-\lambda} &= (\Phi_- \circ \Phi_+^{-1})|_{S_{-\lambda} \times (\mathbb{C}^2, 0)} \\ &= \tilde{\Phi}_- \circ \Theta \circ \Theta^{-1} \circ (\tilde{\Phi}_+)^{-1} \\ &= \tilde{\Phi}_{-\lambda} .\end{aligned}$$

Let us prove that the map is one-to-one. Let  $Y, \tilde{Y} \in [Y_{\text{norm}}]$  share the same Stokes diffeomorphisms  $(\Phi_\lambda, \Phi_{-\lambda})$ . We denote by  $\Phi_\pm$  (*resp.*  $\tilde{\Phi}_\pm$ ) the germ of a sectorial fibered normalizing map of  $Y$  (*resp.*  $\tilde{Y}$ )  $S_\pm \times (\mathbb{C}^2, 0)$ . We have:

$$\begin{cases} \Phi_+ \circ (\Phi_-)^{-1} = \Phi_\lambda = \tilde{\Phi}_+ \circ (\tilde{\Phi}_-)^{-1} & \text{in } S_\lambda \times (\mathbb{C}^2, 0) \\ \Phi_- \circ (\Phi_+)^{-1} = \Phi_{-\lambda} = \tilde{\Phi}_- \circ (\tilde{\Phi}_+)^{-1} & \text{in } S_{-\lambda} \times (\mathbb{C}^2, 0) . \end{cases}$$

Thus:

$$\begin{cases} (\tilde{\Phi}_+)^{-1} \circ \Phi_+ = (\tilde{\Phi}_-)^{-1} \circ \Phi_- & \text{in } S_\lambda \times (\mathbb{C}^2, 0) \\ (\tilde{\Phi}_+)^{-1} \circ \Phi_+ = (\tilde{\Phi}_-)^{-1} \circ \Phi_- & \text{in } S_{-\lambda} \times (\mathbb{C}^2, 0) . \end{cases}$$

We can then define a map  $\varphi$  analytic in a domain of the form  $(D(0, r) \setminus \{0\}) \times \mathbf{D}(\mathbf{0}, \mathbf{r})$  by setting:

$$\begin{cases} \varphi|_{S_+} = (\tilde{\Phi}_+)^{-1} \circ \Phi_+ & \text{in } S_+ \\ \varphi|_{S_-} = (\tilde{\Phi}_-)^{-1} \circ \Phi_- & \text{in } S_- . \end{cases}$$

This map is analytic and bounded in  $(D(0, r) \setminus \{0\}) \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ , and the Riemann singularity theorem tells us that this map can be analytically extended to the entire poly-disc  $D(0, r) \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ . As a conclusion,  $\varphi \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$ ,  $\Phi_\pm = \tilde{\Phi}_\pm \circ \varphi$  and  $\varphi_*(Y) = \tilde{Y}$ .  $\square$

### 3.2. Proof of Theorem 1.12: 1-summability of the formal normalization.

We fix a normal form

$$Y_{\text{norm}} = x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x - c(y_1 y_2)) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x + c(y_1 y_2)) y_2 \frac{\partial}{\partial y_2} ,$$

with  $\lambda \in \mathbb{C}^*$ ,  $\Re(a_1 + a_2) > 0$  and  $c \in v\mathbb{C}\{v\}$  vanishing at the origin. In section 4 we will prove the following result.

**Proposition 3.5.** *Any  $\psi \in \Lambda_{\pm\lambda}^{(\text{weak})}(Y_{\text{norm}})$  admits the identity as Gevrey-1 asymptotic expansion in  $S_{\pm\lambda} \times (\mathbb{C}^2, 0)$ . In other words:*

$$\Lambda_{\pm\lambda}^{(\text{weak})}(Y_{\text{norm}}) = \Lambda_{\pm\lambda}(Y_{\text{norm}}) .$$

As a first consequence of Proposition 3.5, we obtain Theorem 1.12 which states that the formal normalizing map from [Bit16b] is in fact 1-summable.

*Proof of Theorem 1.12.*

Let us consider the unique germs of a sectorial normalizing map  $\Phi_+$  and  $\Phi_-$  in  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively, and their associated Stokes diffeomorphisms:

$$\begin{cases} \Phi_\lambda = (\Phi_+ \circ \Phi_-^{-1})|_{S_\lambda \times (\mathbb{C}^2, 0)} \in \Lambda_\lambda^{(\text{weak})}(Y_{\text{norm}}) \\ \Phi_{-\lambda} = (\Phi_- \circ \Phi_+^{-1})|_{S_{-\lambda} \times (\mathbb{C}^2, 0)} \in \Lambda_{-\lambda}^{(\text{weak})}(Y_{\text{norm}}) . \end{cases}$$

According to Proposition 3.5,

$$\Lambda_{\pm\lambda}^{(\text{weak})}(Y_{\text{norm}}) = \Lambda_{\pm\lambda}(Y_{\text{norm}}) ,$$

so that  $\Phi_\lambda$  and  $\Phi_{-\lambda}$  both admit the identity as Gevrey-1 asymptotic expansion, in  $S_\lambda \times (\mathbb{C}^2, 0)$  and  $S_{-\lambda} \times (\mathbb{C}^2, 0)$  respectively. Then, Theorem 2.9 gives the existence of

$$(\phi_+, \phi_-) \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\arg(i\lambda), \eta}; \text{Id}) \times \text{Diff}_{\text{fib}}(\mathcal{S}_{\arg(-i\lambda), \eta}; \text{Id})$$

for all  $\eta \in ]\pi, 2\pi[$ , such that:

$$\begin{cases} \phi_+ \circ (\phi_-)^{-1}|_{S_\lambda \times (\mathbb{C}^2, 0)} = \Phi_\lambda \\ \phi_- \circ (\phi_+)^{-1}|_{S_{-\lambda} \times (\mathbb{C}^2, 0)} = \Phi_{-\lambda} \end{cases},$$

and the existence of a formal diffeomorphism  $\hat{\phi}$  which is tangent to the identity, such that  $\phi_+$  and  $\phi_-$  both admit  $\hat{\phi}$  as Gevrey-1 asymptotic expansion in  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively. In particular, we have:

$$\left( (\Phi_+)^{-1} \circ \phi_+ \right)|_{(S_\lambda \cup S_{-\lambda}) \times (\mathbb{C}^2, 0)} = \left( (\Phi_-)^{-1} \circ \phi_- \right)|_{(S_\lambda \cup S_{-\lambda}) \times (\mathbb{C}^2, 0)}.$$

This proves that the function  $\Phi$  defined by  $(\Phi_+)^{-1} \circ \phi_+$  in  $S_+ \times (\mathbb{C}^2, 0)$  and by  $(\Phi_-)^{-1} \circ \phi_-$  in  $S_- \times (\mathbb{C}^2, 0)$  is well-defined and analytic in  $D(0, r) \setminus \{0\} \times \mathbf{D}(0, \mathbf{r})$ . Since it is also bounded, it can be extended to an analytic map  $\Phi$  in  $D(0, r) \times \mathbf{D}(0, \mathbf{r})$  by Riemann's theorem. Hence:

$$\begin{cases} \phi_+ = \Phi_+ \circ \Phi \\ \phi_- = \Phi_- \circ \Phi \end{cases}.$$

In particular, by composition,  $\Phi_+$  and  $\Phi_-$  both admit  $\hat{\phi} \circ \Phi^{-1}$  as Gevrey-1 asymptotic expansion in  $S_\lambda \times (\mathbb{C}^2, 0)$  and  $S_{-\lambda} \times (\mathbb{C}^2, 0)$  respectively. Since  $\Phi_+$  and  $\Phi_-$  conjugates  $Y$  to  $Y_{\text{norm}}$  and since the notion of asymptotic expansion commutes with the partial derivative operators, the formal diffeomorphism  $\hat{\phi} \circ \Phi^{-1}$  formally conjugates  $Y$  to  $Y_{\text{norm}}$ . Finally, notice that  $\hat{\phi} \circ \Phi^{-1}$  is necessarily tangent to the identity. Hence, by uniqueness of the formal normalizing map given by Theorem 1.4, we deduce that  $\hat{\phi} \circ \Phi^{-1} = \hat{\Phi}$ , the unique formal normalizing map tangent to the identity.  $\square$

### 3.3. Proofs of Theorems 1.15 and 1.23.

Let us now present the proofs of Theorems 1.15 and 1.23, assuming Proposition 3.5.

#### 3.3.1. Proof of Theorem 1.15.

*Proof of Theorem 1.15.*  $\square$

Propositions 3.3, together with Proposition 3.5, tell us that the considered map is well-defined and one-to-one. It remains to prove that this map is onto. Let

$$\begin{cases} \Phi_\lambda \in \Lambda_\lambda(Y_{\text{norm}}) \\ \Phi_{-\lambda} \in \Lambda_{-\lambda}(Y_{\text{norm}}) \end{cases}.$$

According to Theorem 2.9, there exists

$$(\phi_+, \phi_-) \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\arg(i\lambda), \eta}; \text{Id}) \times \text{Diff}_{\text{fib}}(\mathcal{S}_{\arg(-i\lambda), \eta}; \text{Id})$$

with  $\eta \in ]\pi, 2\pi[$ , which extend analytically to  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively, such that:

$$\phi_\pm \circ (\phi_\mp)^{-1}|_{S_{\pm\lambda} \times (\mathbb{C}^2, 0)} = \Phi_{\pm\lambda}$$

and there also exists a formal diffeomorphism  $\hat{\phi}$  which is tangent to the identity, such that  $\phi_\pm$  both admit  $\hat{\phi}$  as asymptotic expansion in  $S_\pm \times (\mathbb{C}^2, 0)$ . Let us consider the two germs of sectorial vector fields obtained as

$$Y_\pm := (\phi_\pm^{-1})_*(Y_{\text{norm}})$$

In particular, since  $\hat{\phi}$  is the Gevrey-1 asymptotic expansion of  $\phi_{\pm}$ , the vector fields  $Y_{\pm}$  both admit  $(\hat{\phi})_*(Y_{\text{norm}})$  as Gevrey-1 asymptotic expansion. The fact that  $\phi_+ \circ (\phi_-)^{-1}$  is an isotropy of  $Y_{\text{norm}}$  implies immediately that  $Y_+ = Y_-$  on

$$(S_+ \cap S_-) \times (\mathbb{C}^2, 0) = (S_{\lambda} \cup S_{-\lambda}) \times (\mathbb{C}^2, 0) .$$

Then, the vector field  $Y$ , which coincides with  $Y_{\pm}$  in  $S_{\pm} \times (\mathbb{C}^2, 0)$ , defines a germ of analytic vector field in  $(\mathbb{C}^3, 0)$  by Riemann's theorem. By construction,  $Y \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})_*(Y_{\text{norm}})$  and admits  $(\Phi_{\lambda}, \Phi_{-\lambda})$  as Stokes diffeomorphisms.

### 3.3.2. Proof of Theorem 1.23.

In a similar way, we prove now Theorem 1.23.

#### Proof of Theorem 1.23.

Let  $Y_{\text{norm}} \in \mathcal{SN}_{\text{diag}, 0}$  be a normal form which is also transversally symplectic. We refer to subsection 1.4 for the notations. It is clear from Theorems 1.15 and 1.21 that the mapping is well-defined and one-to-one. It remains to prove that it is also onto. Let

$$\begin{cases} \Phi_{\lambda} \in \Lambda_{\lambda}^{\omega}(Y_{\text{norm}}) \\ \Phi_{-\lambda} \in \Lambda_{-\lambda}^{\omega}(Y_{\text{norm}}) \end{cases} .$$

Since  $\Lambda_{\lambda}^{\omega}(Y_{\text{norm}}) \subset \Lambda_{\lambda}(Y_{\text{norm}})$  and  $\Lambda_{-\lambda}^{\omega}(Y_{\text{norm}}) \subset \Lambda_{-\lambda}(Y_{\text{norm}})$ , according to Theorem 2.9 there exists

$$(\phi_+, \phi_-) \in \text{Diff}_{\text{fib}}(\mathcal{S}_{\text{arg}(i\lambda), \eta}; \text{Id}) \times \text{Diff}_{\text{fib}}(\mathcal{S}_{\text{arg}(-i\lambda), \eta}; \text{Id})$$

with  $\eta \in ]\pi, 2\pi[$ , which extend analytically in  $S_+ \times (\mathbb{C}^2, 0)$  and  $S_- \times (\mathbb{C}^2, 0)$  respectively, such that:

$$\phi_{\pm} \circ (\phi_{\mp})^{-1}|_{S_{\pm\lambda} \times (\mathbb{C}^2, 0)} = \Phi_{\pm\lambda}$$

and there also exists a formal diffeomorphism  $\hat{\phi}$  which is tangent to the identity, such that  $\phi_{\pm}$  both admit  $\hat{\phi}$  as Gevrey-1 asymptotic expansion in  $S_{\pm} \times (\mathbb{C}^2, 0)$ . According to Corollary 2.10, there exists a germ of an analytic fibered diffeomorphism  $\psi \in \text{Diff}_{\text{fib}}(\mathbb{C}^3, 0, \text{Id})$  (tangent to the identity), such that

$$\sigma_{\pm} := \phi_{\pm} \circ \psi$$

both are transversally symplectic. Then, we have:

$$\sigma_{\pm} \circ (\Psi_{\mp})^{-1}|_{S_{\pm\lambda} \times (\mathbb{C}^2, 0)} = \Phi_{\pm\lambda} .$$

The end of the proof goes exactly as at the end of the proof of the previous theorem.  $\square$

## 4. SECTORIAL ISOTROPIES AND SPACE OF LEAVES: PROOF OF PROPOSITION 3.5

A normal form

$$Y_{\text{norm}} = x^2 \frac{\partial}{\partial x} + (-\lambda + a_1 x - c(y_1 y_2)) y_1 \frac{\partial}{\partial y_1} + (\lambda + a_2 x + c(y_1 y_2)) y_2 \frac{\partial}{\partial y_2}$$

is fixed for some  $\lambda \in \mathbb{C}^*$ ,  $\Re(a_1 + a_2) > 0$  and  $c \in v\mathbb{C}\{v\}$  (vanishing at the origin). The aim of this section is to prove Proposition 3.5 stated in Section 3.

Let us denote  $a := \text{res}(Y_{\text{norm}}) = a_1 + a_2$ ,  $m := \frac{1}{a}$  and

$$c(v) = \sum_{k=1}^{+\infty} c_k v^k .$$

If  $m \notin \mathbb{N}_{>0}$ , we set  $c_m := 0$ . We also define the following power series

$$\tilde{c}(v) = m \sum_{k \neq m} \frac{c_k}{k - m} v^k ,$$

and we notice that  $\tilde{c}(v) \in v\mathbb{C}\{v\}$ .

#### 4.1. Sectorial first integrals and the space of leaves.

In a sectorial neighborhood of the origin of the form  $S_\lambda \times (\mathbb{C}^2, 0)$  (resp.  $S_{-\lambda} \times (\mathbb{C}^2, 0)$ ), with  $S_{\pm\lambda} \in \mathcal{S}_{\arg(\pm\lambda), \epsilon}$  and  $\epsilon \in ]0, \pi[$ , we can give three first integrals of  $Y_{\text{norm}}$  which are analytic in the considered domain. Let us start with the following proposition.

**Proposition 4.1.** *The following quantities are first integrals of  $Y_{\text{norm}}$ , analytic in  $S_{\pm\lambda} \times (\mathbb{C}^2, 0)$ :*

$$(4.1) \quad \begin{cases} w_{\pm\lambda} := \frac{y_1 y_2}{x^a} \\ h_{1, \pm\lambda}(x, \mathbf{y}) := y_1 \exp\left(\frac{-\lambda}{x} + \frac{c_m (y_1 y_2)^m \log(x)}{x} + \frac{\tilde{c}(y_1 y_2)}{x}\right) x^{-a_1} \\ h_{2, \pm\lambda}(x, \mathbf{y}) := y_2 \exp\left(\frac{\lambda}{x} - \frac{c_m (y_1 y_2)^m \log(x)}{x} - \frac{\tilde{c}(y_1 y_2)}{x}\right) x^{-a_2} \end{cases}$$

(we fix here a branch of the logarithm analytic in  $S_{\pm\lambda}$ , and we write simply  $h_j$  and  $w$  instead of  $h_{j, \pm\lambda}$  and  $w_{\pm\lambda}$  respectively, if there is no ambiguity on the sector  $S_{\pm\lambda}$ ).

Moreover, we have the relation:

$$h_1 h_2 = w .$$

*Proof.* It is an elementary computation. □

*Remark 4.2.* In other words, in a sectorial domain, we can parametrize a leaf (which is not in  $\{x = 0\}$ ) of the foliation associated to  $Y_{\text{norm}}$  by:

$$(4.2) \quad \begin{cases} y_1(x) = h_1 \exp\left(\frac{\lambda}{x} - c_m (h_1 h_2)^m \log(x) - \frac{\tilde{c}(h_1 h_2 x^a)}{x}\right) x^{a_1} \\ y_2(x) = h_2 \exp\left(-\frac{\lambda}{x} + c_m (h_1 h_2)^m \log(x) + \frac{\tilde{c}(h_1 h_2 x^a)}{x}\right) x^{a_2} \end{cases} \\ (h_1, h_2) \in \mathbb{C}^2 .$$

**Corollary 4.3.** *The map*

$$\begin{aligned} \mathcal{H}_{\pm\lambda} : S_{\pm\lambda} \times (\mathbb{C}^2, 0) &\rightarrow S_{\pm\lambda} \times \mathbb{C}^2 \\ (x, \mathbf{y}) &\mapsto (x, h_{1, \pm\lambda}(x, \mathbf{y}), h_{2, \pm\lambda}(x, \mathbf{y})) , \end{aligned}$$

(where  $h_{1, \pm\lambda}, h_{2, \pm\lambda}$  are defined in (4.1)) is a sectorial germ of a fibered analytic map in  $S_{\pm\lambda} \times (\mathbb{C}^2, 0)$ , which is into. Moreover, there exists an open neighborhood of the origin in  $\mathbb{C}^2$ , denoted by  $\Gamma_{\pm\lambda} \subset \mathbb{C}^2$ , such that

$$\mathcal{H}_{\pm\lambda}(S_{\pm\lambda} \times (\mathbb{C}^2, 0)) = S_{\pm\lambda} \times \Gamma_{\pm\lambda} .$$

In particular,  $\mathcal{H}_{\pm}$  induces a fibered biholomorphism

$$S_{\pm\lambda} \times (\mathbb{C}^2, 0) \xrightarrow{\mathcal{H}_{\pm\lambda}} S_{\pm\lambda} \times \Gamma_{\pm\lambda}$$

which conjugates  $Y_{\text{norm}}$  to  $x^2 \frac{\partial}{\partial x}$ , i.e.

$$(\mathcal{H}_{\pm\lambda})_*(Y_{\text{norm}}) = x^2 \frac{\partial}{\partial x} .$$

**Definition 4.4.** We call  $\Gamma_{\pm\lambda}$  **the space of leaves of  $Y_{\text{norm}}$  in  $S_{\pm\lambda} \times (\mathbb{C}^2, 0)$ .**

*Remark 4.5.* The set  $\Gamma_{\pm\lambda}$  depends on the choice of the neighborhood  $(\mathbb{C}^2, 0)$ , but also on the choice of the sectorial neighborhood  $S_{\pm\lambda} \in \mathcal{S}_{\arg(\pm\lambda), \epsilon}$ .

#### 4.2. Sectorial isotropies in the space of leaves.

Now, we consider a germ of a sectorial isotropy  $\psi_{\pm\lambda} \in \Lambda_{\pm\lambda}^{(\text{weak})}(Y_{\text{norm}})$  and we denote by  $\Gamma'_{\pm\lambda}$  the (germ of an) open subset of  $\mathbb{C}^2$  such that:

$$\mathcal{H}_{\pm\lambda} \circ \psi_{\pm} (S_{\pm\lambda} \times (\mathbb{C}^2, 0)) = S_{\pm\lambda} \times \Gamma'_{\pm\lambda} .$$

**Proposition 4.6.** *With the notations and assumptions above, the map*

$$\Psi_{\pm\lambda} := \mathcal{H}_{\pm\lambda} \circ \psi_{\pm} \circ \mathcal{H}_{\pm\lambda}^{-1} : S_{\pm\lambda} \times \Gamma_{\pm\lambda} \longrightarrow S_{\pm\lambda} \times \Gamma'_{\pm\lambda}$$

*is a sectorial germ of a fibered biholomorphism from  $S_{\pm\lambda} \times \Gamma_{\pm\lambda}$  to  $S_{\pm\lambda} \times \Gamma'_{\pm\lambda}$ , which is of the form:*

$$\Psi_{\pm\lambda} (x, h_1, h_2) = (x, \Psi_{1,\pm\lambda}(h_1, h_2), \Psi_{2,\pm\lambda}(h_1, h_2)) .$$

*In particular,  $\Psi_{1,\pm\lambda}$  and  $\Psi_{2,\pm\lambda}$  are analytic and depend only on  $(h_1, h_2) \in \Gamma_{\pm\lambda}$ , while  $\Psi_{\pm\lambda}$  induces a biholomorphism (still written  $\Psi_{\pm\lambda}$ ):*

$$\begin{aligned} \Psi_{\pm\lambda} : \Gamma_{\pm\lambda} &\rightarrow \Gamma'_{\pm\lambda} \\ (h_1, h_2) &\mapsto (\Psi_{1,\pm\lambda}(h_1, h_2), \Psi_{2,\pm\lambda}(h_1, h_2)) . \end{aligned}$$

*Proof.* We only have to prove that  $\Psi_{1,\pm\lambda}$  and  $\Psi_{2,\pm\lambda}$  depend only on  $(h_1, h_2) \in \Gamma_{\pm\lambda}$ . By assumption,  $\Psi_{\pm\lambda}$  is an isotropy of  $x^2 \frac{\partial}{\partial x}$ :

$$(\Psi_{\pm\lambda})_* \left( x^2 \frac{\partial}{\partial x} \right) = x^2 \frac{\partial}{\partial x} .$$

We immediately obtain:

$$\frac{\partial \Psi_{1,\pm\lambda}}{\partial x} = \frac{\partial \Psi_{2,\pm\lambda}}{\partial x} = 0 .$$

□

In the space of leaves  $\Gamma_{\pm\lambda}$  equipped with coordinates  $(h_1, h_2)$ , we denote by  $w$  the product of  $h_1$  and  $h_2$ :

$$w(h_1, h_2) := h_1 h_2 .$$

We define the two following quantities:

$$(4.3) \quad \begin{cases} f_1(x, w) := \exp\left(\frac{\lambda}{x} - c_m w^m \log(x) - \frac{\tilde{c}(wx^a)}{x}\right) x^{a_1} \\ f_2(x, w) := \exp\left(-\frac{\lambda}{x} + c_m w^m \log(x) + \frac{\tilde{c}(wx^a)}{x}\right) x^{a_2} \end{cases} ,$$

such that the leaves of the foliations are parametrized by:

$$\begin{cases} y_1(x) = h_1 f_1(x, h_1 h_2) \\ y_2(x) = h_2 f_2(x, h_1 h_2) \end{cases} , (h_1, h_2) \in \mathbb{C}^2 .$$

Notice that:

$$f_1(x, w) f_2(x, w) = x^a .$$

Moreover, one checks immediately the following statement.

**Fact 4.7.** *For all  $w \in \mathbb{C}$ :*

$$\begin{cases} \lim_{\substack{x \rightarrow 0 \\ x \in S_\lambda}} |f_1(x, w)| = \lim_{\substack{x \rightarrow 0 \\ x \in S_{-\lambda}}} |f_2(x, w)| = +\infty \\ \lim_{\substack{x \rightarrow 0 \\ x \in S_{-\lambda}}} |f_1(x, w)| = \lim_{\substack{x \rightarrow 0 \\ x \in S_\lambda}} |f_2(x, w)| = 0 \end{cases} .$$

Using notations of Proposition 4.6, we also assume from now on that  $(\mathbb{C}^2, 0) = \mathbf{D}(\mathbf{0}, \mathbf{r})$ , with  $\mathbf{r} = (r_1, r_2) \in (\mathbb{R}_{>0})^2$  and  $r_1, r_2 > 0$  small enough so that

$$\psi_{\pm\lambda}(S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})) \subset S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r}')$$

for some  $\mathbf{r}' = (r'_1, r'_2) \in (\mathbb{R}_{>0})^2$ . Let us now define in a general way the following set associated to the sector  $S_{\pm\lambda}$  and to a polydisc  $\mathbf{D}(\mathbf{0}, \tilde{\mathbf{r}})$ , with  $\tilde{\mathbf{r}} := (\tilde{r}_1, \tilde{r}_2)$ .

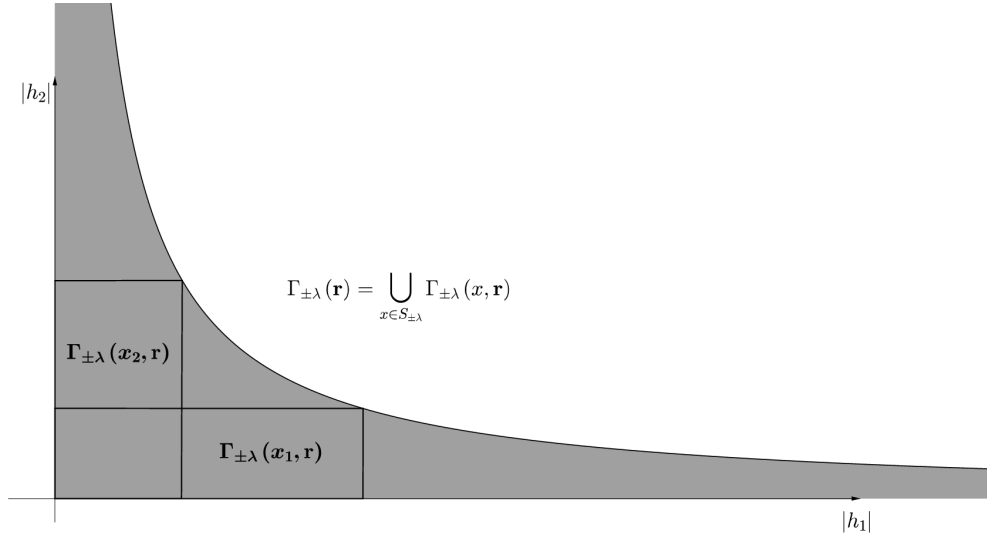


FIGURE 4.1. Representation of the space of leaves in terms of  $|h_1|$  and  $|h_2|$  when  $c = 0$ : in this case, it is a *Reinhardt domain* (cf. [Hor73]).

**Definition 4.8.** For all  $x \in S_{\pm\lambda}$  et  $\tilde{\mathbf{r}} := (\tilde{r}_1, \tilde{r}_2) \in (\mathbb{R}_{>0})^2$ , we define

$$\Gamma_{\pm\lambda}(x, \tilde{\mathbf{r}}) := \left\{ (h_1, h_2) \in \mathbb{C}^2 \mid |h_j| \leq \frac{\tilde{r}_j}{|f_j(x, h_1 h_2)|}, \text{ for } j \in \{1, 2\} \right\}.$$

We also consider the:

$$\begin{aligned} \Gamma_{\pm\lambda}(\tilde{\mathbf{r}}) &:= \bigcup_{x \in S_{\pm\lambda}} \Gamma_{\pm\lambda}(x, \tilde{\mathbf{r}}) \\ &= \left\{ (h_1, h_2) \in \mathbb{C}^2 \mid \exists x \in S_{\pm\lambda} \text{ s.t. } |h_j| \leq \frac{\tilde{r}_j}{|f_j(x, h_1 h_2)|}, \text{ for } j \in \{1, 2\} \right\} \end{aligned}$$

(cf. figure 4.1).

Since we assume now that  $(\mathbb{C}^2, 0) = \mathbf{D}(\mathbf{0}, \mathbf{r})$ , then we have:

$$\Gamma_{\pm\lambda} = \Gamma_{\pm\lambda}(\mathbf{r}),$$

and

$$\Gamma'_{\pm\lambda} \subset \Gamma_{\pm\lambda}(\mathbf{r}').$$

*Remark 4.9.*

- (1) It is important to notice that the particular form of  $\Psi_{\pm\lambda}$  implies that the image of any fiber

$$\{x = x_0\} \times \Gamma_{\pm\lambda}(x_0, \mathbf{r})$$

by  $\Psi_{\pm\lambda}$  is included in a fiber of the form

$$\{x = x_0\} \times \Gamma_{\pm\lambda}(x_0, \mathbf{r}').$$

- (2) If  $(h_1, h_2) \in \Gamma_{\pm\lambda}(x, \mathbf{r})$ , then

$$|h_1 h_2| < \frac{r_1 r_2}{|x^a|}.$$

- (3) As  $(h_1, h_2) \in \Gamma_{\pm\lambda}$  varies the values of  $w = h_1 h_2$  cover the whole  $\mathbb{C}$ .

### 4.3. Action on the resonant monomial in the space of leaves.

Let us study the the action of  $\Psi_{\pm\lambda}$  on the resonant monomial  $w = h_1 h_2$  in the space of leaves.

**Lemma 4.10.** *We consider a biholomorphism*

$$\begin{aligned} \Psi_{\pm\lambda} : \Gamma_{\pm\lambda} &\xrightarrow{\sim} \Gamma'_{\pm\lambda} \\ (h_1, h_2) &\mapsto (\Psi_{1,\pm}(h_1, h_2), \Psi_{2,\pm}(h_1, h_2)) , \end{aligned}$$

such that for all  $x \in S_{\pm\lambda}$ , we have

$$\Psi_{\pm\lambda}(\Gamma_{\pm\lambda}(x_0, \mathbf{r})) \subset \Gamma_{\pm\lambda}(x_0, \mathbf{r}') .$$

We also define  $\Psi_{w,\pm\lambda} := \Psi_{1,\pm\lambda}\Psi_{2,\pm\lambda}$ . Then, for all  $n \in \mathbb{N}$ , there exists entire (i.e. analytic over  $\mathbb{C}$ ) functions  $\Psi_{w,\lambda,n}$  and  $\Psi_{w,-\lambda,n}$  such that

$$\begin{cases} \Psi_{w,\lambda}(h_1, h_2) = \sum_{n \geq 0} \Psi_{w,\lambda,n}(h_1 h_2) h_1^n \\ \Psi_{w,-\lambda}(h_1, h_2) = \sum_{n \geq 0} \Psi_{w,-\lambda,n}(h_1 h_2) h_2^n \end{cases} .$$

Moreover, the series above uniformly converge (for the sup-norm) in every subset of  $\Gamma_{\pm\lambda}$  of the form  $\Gamma_{\pm\lambda}(\tilde{\mathbf{r}})$ , with  $\tilde{\mathbf{r}} := (\tilde{r}_1 \tilde{r}_2)$  and

$$0 < \tilde{r}_j < r_j \quad , \quad j \in \{1, 2\}$$

(cf. Definition 4.8). More precisely, for all  $\tilde{r}_1, \tilde{r}_2, \delta > 0$  such that

$$0 < \tilde{r}_j + \delta < r_j \quad , \quad j \in \{1, 2\}$$

for all  $x \in S_{\pm\lambda}$  and  $w \in \mathbb{C}$  we have

$$|wx^a| \leq \tilde{r}_1 \tilde{r}_2 \implies \begin{cases} |\Psi_{w,\lambda,n}(w)| \leq \frac{r'_1 r'_2}{|x^a|} \left| \frac{f_1(x,w)}{\tilde{r}_1 + \delta} \right|^n \\ |\Psi_{w,-\lambda,n}(w)| \leq \frac{r'_1 r'_2}{|x^a|} \left| \frac{f_2(x,w)}{\tilde{r}_2 + \delta} \right|^n \end{cases} , \quad \forall n \geq 0 .$$

*Proof.* Let us give the proof for  $\Psi_{w,\lambda}, \Psi_{1,\lambda}$  and  $\Psi_{2,\lambda}$  in  $\Gamma_\lambda$  (the same proof applies also for  $\Psi_{w,-\lambda}$  in  $\Gamma_{-\lambda}$  by exchanging the role played by  $h_1$  and  $h_2$ ). We fix some  $0 < \tilde{r}_j < r_j, j \in \{1, 2\}$ , and  $\delta > 0$  such that

$$0 < \tilde{r}_j + \delta < r_j \quad , \quad j \in \{1, 2\} .$$

For a fixed value  $w \in \mathbb{C}$ , we consider the restriction of  $\Psi_{w,\lambda}$  to the hypersurface  $M_w := \{h_1 h_2 = w\} \cap \Gamma_\lambda$ : this restriction is analytic in  $M_w$ . The map

$$\varphi_w : h_1 \mapsto \Psi_{w,\lambda} \left( h_1, \frac{w}{h_1} \right)$$

is analytic in

$$M_{w,1} := \bigcup_{\substack{x \in S_\lambda \\ |wx^a| < r_1 r_2}} \Omega_{x,w} ,$$

where for all  $x \in S_\lambda$  with  $|wx^a| < r_1 r_2$ , the set  $\Omega_{x,w}$  is the following annulus:

$$\Omega_{x,w} := \left\{ h_1 \in \mathbb{C} \mid \left| \frac{w f_2(x,w)}{r_2} \right| < |h_1| < \left| \frac{r_1}{f_1(x,w)} \right| \right\} .$$

In particular,  $\varphi_w$  admits a Laurent expansion

$$\varphi_w(h_1) = \Psi_{w,+} \left( h_1, \frac{w}{h_1} \right) = \sum_{n \geq -L} \Psi_{w,+,n}(w) h_1^n$$

in every annulus  $\Omega_{x,w}$ , with  $x \in S_\lambda$  such that  $|wx^a| < r_1 r_2$ . Moreover for all  $x \in S_\lambda$  such that  $|wx^a| < r_1 r_2$ , Cauchy's formula gives

$$\Psi_{w,\lambda,n}(w) = \frac{1}{2i\pi} \oint_{\gamma(x,w)} \frac{\Psi_{w,\lambda} \left( h_1, \frac{w}{h_1} \right)}{h_1^{n+1}} dh_1 , \quad \text{for all } n \in \mathbb{Z} ,$$

where  $\gamma(x, w)$  is any circle (oriented positively) centered at the origin with a radius  $\rho(x, w)$  satisfying

$$\left| \frac{wf_2(x, w)}{r_2} \right| < \rho(x, w) < \left| \frac{r_1}{f_1(x, w)} \right|.$$

If  $|wx^a| < (\tilde{r}_1 + \delta)(\tilde{r}_2 + \delta)$ , we can take for instance

$$\rho(x, w) = \left| \frac{\tilde{r}_1 + \delta}{f_1(x, w)} \right|.$$

Therefore, for all  $x \in S_\lambda$  and all  $w \in \mathbb{C}$  such that  $|wx^a| \leq \tilde{r}_1\tilde{r}_2$ , for all  $\xi \in \mathbb{C}$  with  $|\xi| < \delta$ , we also have:

$$\Psi_{w, \lambda, n}(w + \xi) = \frac{1}{2i\pi} \oint_{\gamma(x, w)} \frac{\Psi_{w, \lambda} \left( h_1, \frac{w + \xi}{h_1} \right)}{h_1^{n+1}} dh_1, \text{ for all } n \in \mathbb{Z},$$

where  $\gamma(x, w)$  is the same circle (of radius  $\rho(x, w) = \left| \frac{\tilde{r}_1 + \delta}{f_1(x, w)} \right|$ ) for all  $|\xi| < \delta$ . Moreover, since for all  $x \in S_\lambda$ , we have

$$\Psi_\lambda(\Gamma_\lambda(x, \mathbf{r})) \subset \Gamma_\lambda(x, \mathbf{r}'),$$

and since for all  $(h'_1, h'_2) \in \Gamma_\lambda(x, \mathbf{r}')$  we have

$$|h'_1 h'_2| \leq \frac{r'_1 r'_2}{|x^a|},$$

then for all  $x \in S_\lambda$  and  $w \in \mathbb{C}$  such that  $|wx^a| \leq \tilde{r}_1\tilde{r}_2$ , the following inequality holds for all  $h_1$  with  $|h_1| < \frac{r_1}{f_1(x, w)}$ :

$$\left| \Psi_{w, \lambda} \left( h_1, \frac{w}{h_1} \right) \right| < \frac{r'_1 r'_2}{|x^a|}.$$

The well-known theorem regarding integrals depending analytically on a parameter asserts that for all  $n \in \mathbb{Z}$  the mapping  $\Psi_{w, \lambda, n}$  is analytic near any point  $w \in \mathbb{C}$ . Hence, it is an entire function (*i.e.* analytic over  $\mathbb{C}$ ). Moreover, the inequality above and the Cauchy's formula together imply that for all  $n \in \mathbb{Z}$  and for all  $(x, w) \in S_\lambda \times \mathbb{C}$  such that  $|wx^a| \leq \tilde{r}_1\tilde{r}_2$ , we have:

$$|\Psi_{w, \lambda, n}(w)| < \frac{r'_1 r'_2}{|x^a| \rho(x, w)^n} = \frac{r'_1 r'_2}{|x^a|} \left| \frac{f_1(x, w)}{\tilde{r}_1 + \delta} \right|^n.$$

According to Fact 4.7, for a fixed value  $w \in \mathbb{C}$ , if  $n < 0$ , the right hand-side tends to 0 as  $x$  tends to 0 in  $S_\lambda$ . This implies in particular that  $\Psi_{w, \lambda, n} = 0$  for all  $n < 0$ . Consequently:

$$\Psi_{w, \lambda} \left( h_1, \frac{w}{h_1} \right) = \sum_{n \geq 0} \Psi_{w, \lambda, n}(w) h_1^n.$$

Moreover, for all  $w \in \mathbb{C}$  the series converges normally in every domain of the form

$$\Omega_{x, w} := \left\{ h_1 \in \mathbb{C} \mid |h_1| \leq \left| \frac{\tilde{r}_1}{f_1(x, w)} \right| \right\}, \text{ for all } x \in S_\lambda, 0 < \tilde{r}_1 < r_1,$$

since the Laurent expansion's range is  $n \geq 0$ . This actually means that the series converges normally in an entire neighborhood of the origin in  $\mathbb{C}$ . In particular, for all fixed  $w \in \mathbb{C}$ , the map

$$h_1 \mapsto \Psi_{w, \lambda} \left( h_1, \frac{w}{h_1} \right) = \sum_{n \geq 0} \Psi_{w, \lambda, n}(w) h_1^n$$

is analytic in a neighborhood of the origin. Finally, the series

$$\Psi_{w, \lambda}(h_1, h_2) = \sum_{n \geq 0} \Psi_{w, \lambda, n}(h_1 h_2) h_1^n$$

converges normally, and hence its sum is analytic in every domain of the form  $\Gamma_\lambda(\tilde{\mathbf{r}})$ , with  $0 < \tilde{r}_1 < r_1$  and  $0 < \tilde{r}_2 < r_2$ .  $\square$



#### 4.4. Action on the resonant monomial.

Since  $\psi_{\pm\lambda} \in \Lambda_{\pm\lambda}^{(\text{weak})}(Y_{\text{norm}})$ , the mapping  $\psi_{\pm\lambda}$  is of the form

$$\psi_{\pm\lambda}(x, \mathbf{y}) = (x, \psi_{1,\pm\lambda}(x, \mathbf{y}), \psi_{2,\pm\lambda}(x, \mathbf{y})) ,$$

with  $\psi_{1,\pm\lambda}, \psi_{2,\pm\lambda}$  analytic and bounded in  $S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ . Moreover, by assumption  $\psi_{\pm\lambda}$  admits the identity as weak Gevrey-1 asymptotic expansion, *i.e.* we have a normally convergent expansion:

$$\psi_{i,\pm\lambda}(x, \mathbf{y}) = y_i + \sum_{\mathbf{k} \in \mathbb{N}^2} \psi_{i,\pm\lambda,\mathbf{k}}(x) \mathbf{y}^{\mathbf{k}} ,$$

where  $\psi_{i,\pm\lambda,\mathbf{k}}$  is holomorphic in  $S_{\pm\lambda}$  and admits 0 as Gevrey-1 asymptotic expansion, for  $i = 1, 2$  and all  $\mathbf{k} = (k_1, k_2) \in \mathbb{N}^2$ .

**Lemma 4.11.** *With the notations and assumptions above, let us define  $\psi_{v,\pm\lambda} := \psi_{1,\pm\lambda}\psi_{2,\pm\lambda}$ . Then  $\psi_{v,\lambda}$  and  $\psi_{v,-\lambda}$  can be expanded as the series*

$$\begin{cases} \psi_{v,\lambda}(x, \mathbf{y}) = y_1 y_2 + x^a \sum_{n \geq 1} \Psi_{w,\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \left( \frac{y_1}{f_1 \left( x, \frac{y_1 y_2}{x^a} \right)} \right)^n \\ \psi_{v,-\lambda}(x, \mathbf{y}) = y_1 y_2 + x^a \sum_{n \geq 1} \Psi_{w,-\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \left( \frac{y_2}{f_2 \left( x, \frac{y_1 y_2}{x^a} \right)} \right)^n \end{cases}$$

which are normally convergent in every subset of  $S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$  of the form  $S_{\pm\lambda} \times \overline{\mathbf{D}}(\mathbf{0}, \tilde{\mathbf{r}})$ , where  $\overline{\mathbf{D}}(\mathbf{0}, \tilde{\mathbf{r}})$  is a closed poly-disc with  $\tilde{\mathbf{r}} = (\tilde{r}_1, \tilde{r}_2)$  such that

$$0 < \tilde{r}_j < r_j \quad , \quad j \in \{1, 2\} .$$

Here  $\Psi_{w,\lambda,n}$  and  $\Psi_{w,-\lambda,n}$ , for  $n \in \mathbb{N}$ , are the ones appearing in Lemma 4.10. Moreover, for all closed sub-sector  $S' \subset S_{\pm\lambda}$  and for all closed poly-disc  $\overline{\mathbf{D}} \subset \mathbf{D}(\mathbf{0}, \mathbf{r})$ , there exists  $A, B > 0$  such that:

$$|\psi_{v,\pm\lambda}(x, y_1, y_2) - y_1 y_2| \leq A \exp\left(-\frac{B}{|x|}\right) , \quad \forall (x, \mathbf{y}) \in S' \times \overline{\mathbf{D}} .$$

In particular,  $\psi_{v,\pm\lambda}$  admits  $y_1 y_2$  as Gevrey-1 asymptotic expansion in  $S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ .

*Proof.* By definition, we have

$$\Psi_{\pm\lambda} \circ \mathcal{H}_{\pm\lambda} = \mathcal{H}_{\pm\lambda} \circ \psi_{\pm\lambda} .$$

In particular, for all  $(x, \mathbf{y}) \in S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ :

$$\Psi_{w,\pm} \left( x, \frac{y_1}{f_1 \left( x, \frac{y_1 y_2}{x^a} \right)}, \frac{y_2}{f_2 \left( x, \frac{y_1 y_2}{x^a} \right)} \right) = \frac{\psi_{v,\pm}(x, y_1, y_2)}{x^a} .$$

Thus, according to Lemma 4.10 we have:

$$(4.4) \quad \begin{cases} \psi_{v,\lambda}(x, \mathbf{y}) = x^a \sum_{n \geq 0} \Psi_{w,\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \left( \frac{y_1}{f_1 \left( x, \frac{y_1 y_2}{x^a} \right)} \right)^n \\ \psi_{v,-\lambda}(x, \mathbf{y}) = x^a \sum_{n \geq 0} \Psi_{w,-\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \left( \frac{y_2}{f_2 \left( x, \frac{y_1 y_2}{x^a} \right)} \right)^n \end{cases} .$$

Besides we know that  $\psi_{v,\pm\lambda}$  admits  $y_1 y_2$  as weak Gevrey-1 asymptotic expansion in  $S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ :

$$(4.5) \quad \psi_{v,\pm\lambda}(x, y_1, y_2) = y_1 y_2 + \sum_{\mathbf{k} \in \mathbb{N}^2} \psi_{v,\pm\lambda,\mathbf{k}}(x) \mathbf{y}^{\mathbf{k}} ,$$

where for all  $\mathbf{k} = (k_1, k_2) \in \mathbb{N}^2$  the mapping  $\psi_{v,\pm\lambda,\mathbf{k}}$  is holomorphic in  $S_{\pm\lambda}$  and admits 0 as Gevrey-1 asymptotic expansion. Let us compare both expressions of  $\psi_{v,\pm\lambda}$  above. Looking at monomials  $\mathbf{y}^{\mathbf{k}}$

with  $k_1 = k_2$  in (4.5), and at terms corresponding to  $n = 0$  on the right-hand side of (4.4), we must have for all  $x \in S_{\pm\lambda}$  and  $v \in \mathbb{C}$  with  $|v| < r_1 r_2$ :

$$v + \sum_{k \geq 0} \psi_{v,\lambda,\mathbf{k}(k,k)}(x) v^k = x^a \Psi_{w,\lambda,0} \left( \frac{v}{x^a} \right).$$

Since  $\Psi_{w,\pm\lambda,0}$  is analytic in  $\mathbb{C}$ , there exists  $(\alpha_{\pm\lambda,k})_{k \in \mathbb{N}} \subset \mathbb{C}$  such that

$$\Psi_{w,\pm\lambda,0} \left( \frac{v}{x^a} \right) = \sum_{k \geq 0} \alpha_{\pm\lambda,k} \left( \frac{v}{x^a} \right)^k.$$

This can only happen if  $\alpha_{\pm\lambda,k} = 0$  whenever  $k \neq 1$ , for  $\psi_{v,\pm\lambda,\mathbf{k}}$  is holomorphic in  $S_{\pm\lambda}$  and admits 0 as Gevrey-1 asymptotic expansion. A further immediate identification yields

$$\Psi_{v,\pm\lambda,0}(w) = w.$$

Thus

$$\begin{cases} \psi_{v,\lambda}(x, \mathbf{y}) = y_1 y_2 + x^a \sum_{n \geq 1} \Psi_{w,\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \left( \frac{y_1}{f_1 \left( x, \frac{y_1 y_2}{x^a} \right)} \right)^n \\ \psi_{v,-\lambda}(x, \mathbf{y}) = y_1 y_2 + x^a \sum_{n \geq 1} \Psi_{w,-\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \left( \frac{y_2}{f_2 \left( x, \frac{y_1 y_2}{x^a} \right)} \right)^n \end{cases}.$$

Let us prove that  $\psi_{v,\pm\lambda}$  admits  $y_1 y_2$  as Gevrey-1 asymptotic expansion in  $S_{\pm\lambda} \times (\mathbb{C}^2, 0)$ . We have to show that  $|\psi_{v,\pm\lambda}(x, y_1, y_2) - y_1 y_2|$  is exponentially small with respect to  $x \in S_{\pm\lambda}$ , uniformly in  $\mathbf{y} \in \mathbf{D}(\mathbf{0}, \mathbf{r})$ . As for the previous lemma, we perform the proof for  $\psi_{v,\lambda}$  only (the same proof applies for  $\psi_{v,-\lambda}$  by exchanging  $y_1$  and  $y_2$ ).

From the computations above we derive

$$|\psi_{v,\lambda}(x, y_1, y_2) - y_1 y_2| \leq \sum_{n \geq 1} \left| x^a \Psi_{w,\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \left( \frac{y_1}{f_1 \left( x, \frac{y_1 y_2}{x^a} \right)} \right)^n \right|.$$

Let us fix  $\tilde{r}_1, \tilde{r}_2, \delta > 0$  in such a way that

$$0 < \tilde{r}_j + \delta < r_j, \quad j \in \{1, 2\}.$$

Let us take  $|x|, |y_1|$  and  $|y_2|$  small enough so that

$$2x \in S_\lambda$$

and

$$|y_1 y_2| < \frac{\tilde{r}_1 \tilde{r}_2}{|2^a|} < r_1 r_2.$$

According to Lemma 4.10, for all  $\tilde{x} \in S_\lambda$  and all  $w \in \mathbb{C}$ :

$$|w \tilde{x}^a| \leq \tilde{r}_1 \tilde{r}_2 \implies |\Psi_{w,\lambda,n}(w)| \leq \frac{r'_1 r'_2}{|\tilde{x}^a|} \left| \frac{f_1(\tilde{x}, w)}{\tilde{r}_1 + \delta} \right|^n.$$

In particular for  $\tilde{x} = 2x$  and  $w = \frac{y_1 y_2}{x^a}$  we derive  $|w \tilde{x}^a| < \tilde{r}_1 \tilde{r}_2$ , from which we conclude

$$\left| \Psi_{w,\lambda,n} \left( \frac{y_1 y_2}{x^a} \right) \right| \leq \frac{r'_1 r'_2}{|2^a x^a|} \left| \frac{f_1 \left( 2x, \frac{y_1 y_2}{x^a} \right)}{\tilde{r}_1 + \delta} \right|^n.$$

Consequently, for all  $(x, y_1, y_2) \in S_\lambda \times \mathbf{D}(\mathbf{0}, \tilde{\mathbf{r}})$  with

$$\begin{cases} 2x \in S_\lambda \\ |y_1 y_2| < \frac{\tilde{r}_1 \tilde{r}_2}{|2^a|} < r_1 r_2 \end{cases},$$

we have

$$\begin{aligned} |\psi_{v,\lambda}(x, y_1, y_2) - y_1 y_2| &\leq \sum_{n \geq 1} \left| x^a \frac{r'_1 r'_2}{2^a x^a} \left( \frac{f_1(2x, \frac{y_1 y_2}{x^a})}{\tilde{r}_1 + \delta} \right)^n \left( \frac{y_1}{f_1(x, \frac{y_1 y_2}{x^a})} \right)^n \right| \\ &\leq \frac{r'_1 r'_2}{|2^a|} \sum_{n \geq 1} \left| \left( \frac{y_1}{\tilde{r}_1 + \delta} \right)^n \left( \frac{f_1(2x, \frac{y_1 y_2}{x^a})}{f_1(x, \frac{y_1 y_2}{x^a})} \right)^n \right|. \end{aligned}$$

Since  $\tilde{c}(v)$  is the germ of an analytic function near the origin which is null at the origin, we can take  $r_1, r_2 > 0$  small enough in order that for all closed sub-sector  $S' \subset S_\lambda$ , for all  $\tilde{r}_1 \in ]0, r_1[$  and  $\tilde{r}_2 \in ]0, r_2[$ , there exist  $A, B > 0$  satisfying:

$$(x, y_1, y_2) \in S' \times \mathbf{D}(\mathbf{0}, \tilde{\mathbf{r}}) \implies |\psi_{v,\lambda}(x, y_1, y_2) - y_1 y_2| A \exp\left(-\frac{B}{|x|}\right).$$

Let us prove this. We need here to estimate the quantity:

$$\left| \frac{f_1(2x, \frac{y_1 y_2}{x^a})}{f_1(x, \frac{y_1 y_2}{x^a})} \right| = \left| 2^{a_1} \exp\left(-\frac{\lambda}{2x} - c_m \frac{(y_1 y_2)^m}{x} \log(2) - \frac{\tilde{c}(y_1 y_2 2^a)}{2x} + \frac{\tilde{c}(y_1 y_2)}{x}\right) \right|.$$

On only have to deal with the case where  $x \in S'$  is such that  $2x \in S'$  (otherwise,  $x$  is “far from the origin”, and we conclude without difficulty). We have:

$$(x, y_1, y_2) \in S' \times \mathbf{D}(\mathbf{0}, \tilde{\mathbf{r}}) \text{ et } 2x \in S' \implies \left| \frac{f_1(2x, \frac{y_1 y_2}{x^a})}{f_1(x, \frac{y_1 y_2}{x^a})} \right| \leq |2^{a_1}| \exp\left(-\frac{B}{|x|}\right) < 1.$$

Hence

$$\begin{aligned} |\psi_{v,\lambda}(x, y_1, y_2) - y_1 y_2| &\leq \frac{r'_1 r'_2}{|2^a|} \sum_{n \geq 1} \left| \frac{2^{a_1} y_1}{\tilde{r}_1 + \delta} \exp\left(-\frac{B}{|x|}\right) \right|^n \\ &\leq \frac{r'_1 r'_2}{|2^a|} \frac{\left| \frac{2^{a_1} y_1}{\tilde{r}_1 + \delta} \exp\left(-\frac{B}{|x|}\right) \right|}{1 - \left| \frac{2^{a_1} y_1}{\tilde{r}_1 + \delta} \exp\left(-\frac{B}{|x|}\right) \right|} \\ &\leq A \exp\left(-\frac{B}{|x|}\right), \end{aligned}$$

for a convenient  $A > 0$ . □

The latter lemma implies  $\Psi_{v,\pm\lambda,0}(w) = w$ , having for consequence the next result.

**Corollary 4.12.** *For all closed sub-sector  $S' \subset S_{\pm\lambda}$  and for all  $\tilde{r}_1 \in ]0, r_1[$  and  $\tilde{r}_2 \in ]0, r_2[$ , there exists  $A, B > 0$  such that for all  $x \in S'$ :*

$$\left. \begin{aligned} |h_1| &\leq \frac{\tilde{r}_1}{|f_1(x, h_1 h_2)|} \\ |h_2| &\leq \frac{\tilde{r}_2}{|f_2(x, h_1 h_2)|} \end{aligned} \right\} \implies |\Psi_{w,\pm}(x, h_1, h_2) - h_1 h_2| \leq \frac{A \exp\left(-\frac{B}{|x|}\right)}{|x^a|}.$$

In particular, there exists  $C > 0$  such that:

$$\left. \begin{aligned} |h_1| &\leq \frac{\tilde{r}_1}{|f_1(x, h_1 h_2)|} \\ |h_2| &\leq \frac{\tilde{r}_2}{|f_2(x, h_1 h_2)|} \end{aligned} \right\} \implies \frac{\left| \exp\left(c_m (h_1 h_2)^m \log(x) + \frac{\tilde{c}(x^a (h_1 h_2)^m)}{x}\right) \right|}{\left| \exp\left(c_m (\Psi_w(x, h_1, h_2))^m \log(x) + \frac{\tilde{c}(x^a (\Psi_w(x, h_1, h_2))^m)}{x}\right) \right|} < C.$$

#### 4.5. Power series expansion of sectorial isotropies in the space of leaves.

Now, we give a power series expansion of  $\Psi_{1,\pm\lambda}$  and  $\Psi_{2,\pm\lambda}$  in the space of leaves. Let us introduce the following notations:

$$\begin{cases} N(1, +) := N(2, -) := 1 \\ N(1, -) := N(2, +) := -1 \end{cases} .$$

**Lemma 4.13.** *With the notations and assumptions above, there exists entire functions (i.e. analytic over  $\mathbb{C}$ ) denoted by  $\Psi_{j,\pm\lambda,n}$ ,  $j \in \{1, 2\}$ ,  $n \geq N(j, \pm)$ , such that for  $j \in \{1, 2\}$ :*

$$\begin{cases} \Psi_{j,\lambda}(h_1, h_2) = \sum_{n \geq N(j,+)} \Psi_{j,\lambda,n}(h_1 h_2) h_1^n \\ \Psi_{j,-\lambda}(h_1, h_2) = \sum_{n \geq N(j,-)} \Psi_{j,\lambda,n}(h_1 h_2) h_2^n \end{cases} .$$

These series converge normally in every subset of  $\Gamma_{\pm\lambda}$  of the form  $\Gamma_{\pm\lambda}(\tilde{\mathbf{r}})$  with  $0 < \tilde{r}_1 < r_1$  and  $0 < \tilde{r}_2 < r_2$  (cf. Definition 4.8). More precisely, for all  $\tilde{r}_1, \tilde{r}_2, \delta > 0$  such that

$$0 < \tilde{r}_j + \delta < r_j, \quad j \in \{1, 2\}$$

there exists  $C > 0$  such that for all  $x \in S_{\pm\lambda}$  and for all  $w \in \mathbb{C}$ , we have:

$$|wx^a| \leq \tilde{r}_1 \tilde{r}_2 \implies \begin{cases} |\Psi_{1,\lambda,n}(w)| < Cr'_1 \frac{|f_1(x, w)|^{n-1}}{(\tilde{r}_1 + \delta)^n}, & n \geq 1 \\ |\Psi_{2,\lambda,n}(w)| < \frac{Cr'_2}{|x^a|} \frac{|f_1(x, w)|^{n+1}}{(\tilde{r}_1 + \delta)^n}, & n \geq -1 \\ |\Psi_{1,-\lambda,n}(w)| < \frac{Cr'_1}{|x^a|} \frac{|f_2(x, w)|^{n+1}}{(\tilde{r}_2 + \delta)^n}, & n \geq -1 \\ |\Psi_{2,-\lambda,n}(w)| < Cr'_2 \frac{|f_2(x, w)|^{n-1}}{(\tilde{r}_2 + \delta)^n}, & n \geq 1. \end{cases}$$

Moreover:

$$\Psi_{1,-\lambda,-1}(0) = \Psi_{2,\lambda,-1}(0) = 0 .$$

*Proof.* We use the same notations as in the proof of Lemma 4.10, and as usual, we give the proof only for  $\Psi_\lambda$  (the proof for  $\Psi_{-\lambda}$  is analogous, by exchanging the role played by  $h_1$  and  $h_2$ ). For fixed  $w \in \mathbb{C}$ , the maps

$$\varphi_1 : h_1 \mapsto \Psi_{1,\lambda} \left( h_1, \frac{w}{h_1} \right)$$

and

$$\varphi_2 : h_1 \mapsto \Psi_{2,\lambda} \left( h_1, \frac{w}{h_1} \right)$$

are analytic in

$$M_{w,1} = \bigcup_{\substack{x \in S_\lambda \\ |wx^a| < r_1 r_2}} \Omega_{x,w}$$

(see the proof of Lemma 4.10). In particular,  $\varphi_1$  and  $\varphi_2$  admit Laurent expansions

$$\begin{cases} \varphi_1(h_1) = \Psi_{1,\lambda} \left( h_1, \frac{w}{h_1} \right) = \sum_{n \geq -L_1} \Psi_{1,\lambda,n}(w) h_1^n \\ \varphi_2(h_1) = \Psi_{2,\lambda} \left( h_1, \frac{w}{h_1} \right) = \sum_{n \geq -L_2} \Psi_{2,\lambda,n}(w) h_1^n \end{cases}$$

in every annulus  $\Omega_{x,w}$ , with  $x \in S_\lambda$  such that  $|wx^a| < r_1 r_2$ . Using the same method as in the proof of Lemma 4.10, we prove without additional difficulties that for all  $n \in \mathbb{Z}$ ,  $\Psi_{1,\lambda,n}$  and  $\Psi_{2,\lambda,n}$  are analytic

in any point  $w \in \mathbb{C}$ , and thus are entire functions (*i.e.* analytic over  $\mathbb{C}$ ). Moreover, we also show in the same way as earlier that for all  $\tilde{r}_1, \tilde{r}_2, \delta > 0$  with

$$0 < \tilde{r}_j + \delta < r_j, \quad j \in \{1, 2\},$$

for all  $n \in \mathbb{Z}$  and for all  $(x, w) \in S_\lambda \times \mathbb{C}$  such that  $|wx^a| \leq \tilde{r}_1 \tilde{r}_2$ , we have:

$$\begin{cases} |\Psi_{1,\lambda,n}(w)| < \frac{r'_1}{\left| f_1 \left( x, \Psi_{w,\lambda} \left( x, h_1, \frac{w}{h_1} \right) \right) \right|} \left| \frac{f_1(x, w)}{\tilde{r}_1 + \delta} \right|^n \\ |\Psi_{2,\lambda,n}(w)| < \frac{r'_2}{\left| f_2 \left( x, \Psi_{w,\lambda} \left( x, h_1, \frac{w}{h_1} \right) \right) \right|} \left| \frac{f_1(x, w)}{\tilde{r}_1 + \delta} \right|^n \end{cases}.$$

According to Corollary 4.12, there exists  $C > 0$  such that for all  $(x, w) \in S_\lambda \times \mathbb{C}$  with  $|wx^a| \leq \tilde{r}_1 \tilde{r}_2$ , we have:

$$\begin{cases} |\Psi_{1,\lambda,n}(w)| < Cr'_1 \frac{|f_1(x, w)|^{n-1}}{(\tilde{r}_1 + \delta)^n} \\ |\Psi_{2,\lambda,n}(w)| < \frac{Cr'_2 |f_1(x, w)|^{n+1}}{|x^a| (\tilde{r}_1 + \delta)^n} \end{cases}.$$

According to the statement in Fact 4.7, for a fixed value  $w \in \mathbb{C}$ , if we look at the limit as  $x$  tends to 0 in  $S_\lambda$  of the right hand-sides above we deduce that:

$$\begin{cases} |\Psi_{1,\lambda,n}(w)| = 0, \quad \forall n \leq 0 \\ |\Psi_{2,\lambda,n}(w)| = 0, \quad \forall n \leq -2. \end{cases}$$

Consequently:

$$\begin{cases} \Psi_{1,\lambda}(h_1, h_2) = \sum_{n \geq 1} \Psi_{1,\lambda,n}(h_1 h_2) h_1^n \\ \Psi_{2,\lambda}(h_1, h_2) = \sum_{n \geq -1} \Psi_{2,\lambda,n}(h_1 h_2) h_1^n \end{cases}.$$

These function series converges normally (and are analytic) in every domain of the form  $\Gamma_\lambda(\tilde{\mathbf{r}})$  with  $\tilde{\mathbf{r}} := (\tilde{r}_1, \tilde{r}_2)$  and

$$0 < \tilde{r}_j + \delta < r_j, \quad j \in \{1, 2\}$$

(*cf.* Definition 4.8). Moreover, for any fixed value of  $h_2$ , on the one hand the function series

$$h_1 \mapsto \Psi_{2,\lambda}(h_1, h_2) = \sum_{n \geq -1} \Psi_{2,\lambda,n}(h_1 h_2) h_1^n$$

is analytic in a punctured disc, since

$$|f_2(x, h_1, h_2)| \xrightarrow[x \in S_\lambda]{x \rightarrow 0} 0,$$

and on the other hand, we already know that the function  $h_1 \mapsto \Psi_{2,\lambda}(h_1, h_2)$  is analytic in a neighborhood of the origin. Thus, we must have  $\Psi_{2,\lambda,-1}(0) = 0$ .  $\square$

#### 4.6. Sectorial isotropies: proof of Proposition 3.5.

The following lemma is a more precise version of Proposition 3.5. We recall the notations:

$$\begin{cases} N(1, +) = N(2, -) = 1 \\ N(1, -) = N(2, +) = -1 \end{cases}.$$

**Lemma 4.14.** *With the notations and assumptions above, we consider  $\psi_{\pm\lambda} \in \Lambda_{\pm\lambda}^{(\text{weak})}(Y_{\text{norm}})$ , with*

$$\psi_{\pm\lambda}(x, \mathbf{y}) = (x, \psi_{1,\pm\lambda}(x, \mathbf{y}), \psi_{2,\pm\lambda}(x, \mathbf{y})) .$$

Then, for  $i \in \{1, 2\}$ ,  $\psi_{i,\lambda}$  and  $\psi_{i,-\lambda}$  can be written as power series as follows:

$$\begin{cases} \psi_{i,\lambda}(x, \mathbf{y}) = y_i + f_i\left(x, \frac{\psi_{v,\lambda}(x, \mathbf{y})}{x^a}\right) \sum_{n \geq N(i,+)+1} \Psi_{i,\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_1}{f_1\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^n \\ \psi_{i,-\lambda}(x, \mathbf{y}) = y_i + f_i\left(x, \frac{\psi_{v,-\lambda}(x, \mathbf{y})}{x^a}\right) \sum_{n \geq N(i,-)+1} \Psi_{i,-\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_2}{f_2\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^n \end{cases} .$$

which are normally convergent in every subset of  $S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$  of the form  $S_{\pm\lambda} \times \overline{\mathbf{D}}(\mathbf{0}, \tilde{\mathbf{r}})$ , where  $\overline{\mathbf{D}}(\mathbf{0}, \tilde{\mathbf{r}})$  is a closed poly-disc with  $\tilde{\mathbf{r}} = (\tilde{r}_1, \tilde{r}_2)$  such that

$$0 < \tilde{r}_j < r_j \quad , \quad j \in \{1, 2\} .$$

Here  $\Psi_{i,\lambda,n}$ ,  $\Psi_{i,-\lambda,n}$  (for  $i = 1, 2$  and  $n \in \mathbb{N}$ ) are given in Lemma 4.13. Moreover, for all closed sub-sector  $S' \subset S_{\pm\lambda}$  and for all closed poly-disc  $\overline{\mathbf{D}} \subset \mathbf{D}(\mathbf{0}, \mathbf{r})$ , there exists  $A, B > 0$  such that for  $j = 1, 2$ :

$$|\psi_{j,\pm\lambda}(x, y_1, y_2) - y_j| \leq A \exp\left(-\frac{B}{|x|}\right) , \quad \forall (x, \mathbf{y}) \in S' \times \overline{\mathbf{D}} .$$

As a consequence,  $\psi_{j,\pm\lambda}$  admits  $y_j$  as Gevrey-1 asymptotic expansion in  $S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ .

*Remark 4.15.* In particular,  $\Psi_{1,\lambda,1}(w) = \Psi_{2,-\lambda,1}(w) = 1$  and  $\Psi_{1,-\lambda,-1}(w) = \Psi_{2,\lambda,-1}(w) = w$ .

*Proof.* By definition, we have

$$\Psi_{\pm\lambda} \circ \mathcal{H}_{\pm\lambda} = \mathcal{H}_{\pm\lambda} \circ \psi_{\pm} .$$

In particular, for  $j = 1, 2$  and all  $(x, \mathbf{y}) \in S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ :

$$\Psi_{j,\pm\lambda}\left(x, \frac{y_1}{f_1\left(x, \frac{y_1 y_2}{x^a}\right)}, \frac{y_2}{f_2\left(x, \frac{y_1 y_2}{x^a}\right)}\right) = \frac{\psi_{j,\pm\lambda}(x, y_1, y_2)}{f_j\left(x, \frac{\psi_{v,\pm}(x, y_1, y_2)}{x^a}\right)} .$$

Thus, according to Lemma 4.13 we have for  $i = 1, 2$ :

$$(4.6) \quad \begin{cases} \psi_{i,\lambda}(x, \mathbf{y}) = f_i\left(x, \frac{\psi_{v,\lambda}(x, \mathbf{y})}{x^a}\right) \sum_{n \geq N(i,+)} \Psi_{i,\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_1}{f_1\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^n \\ \psi_{i,-\lambda}(x, \mathbf{y}) = f_i\left(x, \frac{\psi_{v,-\lambda}(x, \mathbf{y})}{x^a}\right) \sum_{n \geq N(i,-)} \Psi_{i,-\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_2}{f_2\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^n \end{cases} ,$$

and these series are normally convergent (and then define analytic functions) in any domain of the form  $S' \times \overline{\mathbf{D}}(\mathbf{0}, \tilde{\mathbf{r}})$ , where  $S'$  is a closed sub-sector of  $S_{\pm\lambda}$  and  $\overline{\mathbf{D}}(\mathbf{0}, \tilde{\mathbf{r}})$  is a closed poly-disc with  $\tilde{\mathbf{r}} = (\tilde{r}_1, \tilde{r}_2)$  such that

$$0 < \tilde{r}_j < r_j \quad , \quad j \in \{1, 2\} .$$

Let us compare the different expressions of  $\psi_{j,\pm\lambda}$ ,  $j = 1, 2$ . We know that  $\psi_{j,\pm\lambda}(x, y_1, y_2)$  admits  $y_j$  as weak Gevrey-1 asymptotic expansion in  $S_{\pm\lambda} \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ . Thus, we can write:

$$\psi_{j,\pm\lambda}(x, y_1, y_2) = y_j + \sum_{\mathbf{k} \in \mathbb{N}^2} \psi_{j,\pm\lambda,\mathbf{k}}(x) \mathbf{y}^{\mathbf{k}} ,$$

where for all  $\mathbf{k} = (k_1, k_2) \in \mathbb{N}^2$ ,  $\psi_{j,\pm\lambda,\mathbf{k}}$  is analytic in  $S_{\pm\lambda}$  and admits 0 as Gevrey-1 asymptotic expansion. As usual, let us deal with the case of  $\psi_{1,\lambda}$  and  $\psi_{2,\lambda}$  (the other one being similar by exchanging  $y_1$  and  $y_2$ ).

According to the expressions given by Lemmas 4.10 and 4.13, we can be more precise on the index sets in the sums above:

$$(4.7) \quad \begin{cases} \psi_{1,\lambda}(x, y_1, y_2) = y_1 + \sum_{\substack{\mathbf{k}=(k_1, k_2) \in \mathbb{N}^2 \\ k_1 \geq k_2+1}} \psi_{1,\lambda,\mathbf{k}}(x) y_1^{k_1} y_2^{k_2} \\ \psi_{2,\lambda}(x, y_1, y_2) = y_2 + \sum_{\substack{\mathbf{k}=(k_1, k_2) \in \mathbb{N}^2 \\ k_1 \geq k_2}} \psi_{2,\lambda,\mathbf{k}}(x) y_1^{k_1} y_2^{k_2} \end{cases} .$$

Let us deal with  $\psi_{1,\lambda}$  (a similar proof holds for  $\psi_{2,\lambda}$ ). Looking at terms for  $n = 1$  in (4.6) and at monomials terms  $\mathbf{y}^{\mathbf{k}}$  such that  $k_1 \leq k_2 + 1$  in (4.7), we must have for all  $x \in S_\lambda$ ,  $y_1, y_2 \in \mathbb{C}$  with  $|y_1| < r_1$ ,  $|y_2| < r_2$ :

$$1 + \sum_{k \geq 0} \psi_{1,\lambda,(k+1,k)}(x) y_1^k y_2^k = \frac{f_1\left(x, \frac{\psi_{v,\lambda}(x,\mathbf{y})}{x^a}\right)}{f_1\left(x, \frac{y_1 y_2}{x^z}\right)} \Psi_{1,\lambda,1}\left(\frac{y_1 y_2}{x^a}\right).$$

According to Lemma 4.11 and Corollary 4.12, we have:

$$\begin{aligned} \frac{f_1\left(x, \frac{\psi_{v,\lambda}(x,\mathbf{y})}{x^a}\right)}{f_1\left(x, \frac{y_1 y_2}{x^z}\right)} &= 1 + \sum_{j_1 \geq j_2 + 1 \geq 1} F_{j_1, j_2}(x) y_1^{j_1} y_2^{j_2} \\ &= 1 + \underset{\substack{\mathbf{O} \\ (x,\mathbf{y}) \rightarrow 0 \\ (x,\mathbf{y}) \in S_\lambda \times \mathbf{D}(\mathbf{0},\mathbf{r})}}{(|y_1|)}, \end{aligned}$$

for some analytic and bounded functions  $F_{j_1, j_2}(x)$ ,  $j_1 \geq j_2$ . As in the proof of Lemma 4.11, using the fact that  $\psi_\lambda$  admits the identity as weak Gevrey-1 asymptotic expansion, we deduce that  $\Psi_{1,\lambda,1}(w) = 1$ , and then:

$$\begin{aligned} \psi_{1,\lambda}(x, \mathbf{y}) &= y_1 + f_1\left(x, \frac{\psi_{v,\lambda}(x,\mathbf{y})}{x^a}\right) \sum_{n \geq 2} \Psi_{1,\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_1}{f_1\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^n \\ &= y_1 + \sum_{\substack{\mathbf{k}=(k_1, k_2) \in \mathbb{N}^2 \\ k_1 \geq k_2 + 2}} \psi_{1,\lambda,\mathbf{k}}(x) y_1^{k_1} y_2^{k_2}. \end{aligned}$$

It remains to show that  $\psi_{1,\lambda}$  admits  $y_1$  as Gevrey-1 asymptotic expansion in  $S_\lambda \times \mathbf{D}(\mathbf{0}, \mathbf{r})$ . From the computations above, we deduce:

$$|\psi_{1,\lambda}(x, y_1, y_2) - y_1| \leq \sum_{n \geq 2} \left| \Psi_{1,\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_1}{f_1\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^{n-1} \frac{f_1\left(x, \frac{\psi_{v,\lambda}(x,\mathbf{y})}{x^a}\right)}{f_1\left(x, \frac{y_1 y_2}{x^a}\right)} y_1 \right|.$$

Using Lemma 4.13, Corollary 4.12 and the same method as at the end of the proof of Lemma 4.11, we can show the following: we can take  $r_1, r_2 > 0$  small enough such that for all closed sub-sector  $S'$  of  $S_\lambda$  for all  $\tilde{r}_1 \in ]0, r_1[$  and  $\tilde{r}_2 \in ]0, r_2[$ , there exists  $A, B > 0$  satisfying:

$$(x, y_1, y_2) \in S' \times \mathbf{D}(\mathbf{0}, \tilde{\mathbf{r}}) \implies |\psi_{1,\lambda}(x, y_1, y_2) - y_1| \leq A \exp\left(-\frac{B}{|x|}\right).$$

A similar proof holds for  $\psi_{2,\lambda}, \psi_{2,-\lambda}$  and  $\psi_{1,-\lambda}$ .  $\square$

*Remark 4.16.* It should be noticed that in the expressions

$$\begin{cases} \psi_{1,\lambda}(x, \mathbf{y}) = y_1 + f_1\left(x, \frac{\psi_{v,\lambda}(x,\mathbf{y})}{x^a}\right) \sum_{n \geq 2} \Psi_{1,\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_1}{f_1\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^n \\ \psi_{1,-\lambda}(x, \mathbf{y}) = y_1 + f_1\left(x, \frac{\psi_{v,-\lambda}(x,\mathbf{y})}{x^a}\right) \sum_{n \geq 0} \Psi_{1,-\lambda,n}\left(\frac{y_1 y_2}{x^a}\right) \left(\frac{y_2}{f_2\left(x, \frac{y_1 y_2}{x^a}\right)}\right)^n \end{cases}$$

given by Lemma 4.14, the expansion of  $\psi_{1,\lambda}$  with respect to  $\mathbf{y} = (y_1, y_2)$  starts with a term of order 1, namely  $y_1$ , followed by terms of order at least 2, while in the expansion of  $\psi_{1,-\lambda}$ , the term of lowest order is a constant, namely  $\Psi_{1,-\lambda,0}(0)$ . Similarly, the expansion of  $\psi_{2,-\lambda}$  (with respect to  $\mathbf{y} = (y_1, y_2)$ ) starts with  $y_2$ , while the expansion of  $\psi_{1,-\lambda}$  starts with the constant  $\Psi_{2,\lambda,0}(0)$ .

## 5. DESCRIPTION OF THE MODULI SPACE AND SOME APPLICATIONS

From Lemmas 4.13 and 4.14, we can give a description of the moduli space  $\Lambda_\lambda(Y_{\text{norm}}) \times \Lambda_{-\lambda}(Y_{\text{norm}})$  of a fixed analytic normal form  $Y_{\text{norm}}$ .

### 5.1. A power series presentation of the moduli space.

We use the notations introduced in section 4. We denote by  $\mathcal{O}(\mathbb{C})$  the set of entire functions, *i.e.* of functions holomorphic in  $\mathbb{C}$ . We consider the functions  $f_1$  and  $f_2$  defined in (4.3) and introduce four subsets of  $(\mathcal{O}(\mathbb{C}))^{\mathbb{N}}$ , denoted by  $\mathcal{E}_{1,\lambda}(Y_{\text{norm}})$ ,  $\mathcal{E}_{2,\lambda}(Y_{\text{norm}})$ ,  $\mathcal{E}_{1,-\lambda}(Y_{\text{norm}})$  and  $\mathcal{E}_{2,-\lambda}(Y_{\text{norm}})$ , defined as follows. On remind the notations

$$\begin{cases} N(1,+) = N(2,-) = 1 \\ N(1,-) = N(2,+) = -1 \end{cases} .$$

**Definition 5.1.** For  $j \in \{1, 2\}$ , a sequence  $(\psi_n(w))_{n \geq N(j,\pm)+1} \in (\mathcal{O}(\mathbb{C}))^{\mathbb{N}}$  belongs to  $\mathcal{E}_{j,\pm\lambda}(Y_{\text{norm}})$  if there exists an open polydisc  $\mathbf{D}(\mathbf{0}, \mathbf{r})$  and an open asymptotic sector

$$S_{\pm\lambda} \in \mathcal{AS}_{\arg(\pm\lambda), 2\pi}$$

such that for all  $\tilde{r}_1, \tilde{r}_2, \delta > 0$  with

$$0 < \tilde{r}_i + \delta < r_i \quad , \quad i \in \{1, 2\}$$

there exists  $C > 0$  such that for all  $x \in S_\lambda$  (*resp.*  $x \in S_{-\lambda}$ ) and for all  $w \in \mathbb{C}$ :

$$|wx^a| \leq \tilde{r}_1 \tilde{r}_2 \implies \begin{cases} |\psi_n(w)| < C \frac{|f_1(x, w)|^{n-1}}{(\tilde{r}_1 + \delta)^n} , \forall n \geq 2, & \text{if } (\psi_n(w))_{n \geq 2} \in \mathcal{E}_{1,\lambda}(Y_{\text{norm}}) \\ |\psi_n(w)| < \frac{C}{|x^a|} \frac{|f_1(x, w)|^{n+1}}{(\tilde{r}_1 + \delta)^n} , \forall n \geq 0, & \text{if } (\psi_n(w))_{n \geq 2} \in \mathcal{E}_{2,\lambda}(Y_{\text{norm}}) \\ |\psi_n(w)| < \frac{C}{|x^a|} \frac{|f_2(x, w)|^{n+1}}{(\tilde{r}_2 + \delta)^n} , \forall n \geq 0, & \text{if } (\psi_n(w))_{n \geq 2} \in \mathcal{E}_{1,-\lambda}(Y_{\text{norm}}) \\ |\psi_n(w)| < C \frac{|f_2(x, w)|^{n-1}}{(\tilde{r}_2 + \delta)^n} , \forall n \geq 2, & \text{if } (\psi_n(w))_{n \geq 2} \in \mathcal{E}_{2,-\lambda}(Y_{\text{norm}}) . \end{cases}$$

As explained in section 4, we can associate to any pair

$$(\psi_\lambda, \psi_{-\lambda}) \in \Lambda_\lambda(Y_{\text{norm}}) \times \Lambda_{-\lambda}(Y_{\text{norm}})$$

two germs of sectorial biholomorphisms of the space of leaves corresponding to each “narrow” sector, which we denote by  $\Psi_\lambda$  and  $\Psi_{-\lambda}$ , defined by:

$$(5.1) \quad \Psi_{\pm\lambda} := \mathcal{H}_{\pm\lambda} \circ \psi_{\pm\lambda} \circ \mathcal{H}_{\pm\lambda}^{-1} ,$$

where  $\mathcal{H}_{\pm\lambda}$  is given by Corollary 4.3. According to Lemmas 4.13 and 4.14, if we write  $\Psi_{\pm\lambda} = (x, \Psi_{1,\pm\lambda}, \Psi_{2,\pm\lambda})$ , then for  $j = 1, 2$  we have:

$$(5.2) \quad \begin{aligned} \Psi_{j,\lambda}(h_1, h_2) &= h_j + \sum_{n \geq N(j,+)+1} \Psi_{j,\lambda,n}(h_1 h_2) h_1^n \\ \Psi_{j,-\lambda}(h_1, h_2) &= h_j + \sum_{n \geq N(j,-)+1} \Psi_{j,-\lambda,n}(h_1 h_2) h_2^n \end{aligned}$$

$(\Psi_{j,\pm\lambda,n})_n \in \mathcal{E}_{j,\pm\lambda}$ . Conversely, given  $(\Psi_{j,\pm\lambda})_n \in \mathcal{E}_{j,\pm\lambda}$  for  $j = 1, 2$ , the estimates made in section 4 show that

$$\psi_{\pm\lambda} := \mathcal{H}_{\pm\lambda}^{-1} \circ \Psi_{\pm\lambda} \circ \mathcal{H}_{\pm\lambda} ,$$

where  $\Psi_{\pm\lambda}(x, \mathbf{h}) = (x, \Psi_{1,\pm\lambda}(\mathbf{h}), \Psi_{2,\pm\lambda}(\mathbf{h}))$ , belongs to  $\Lambda_{\pm\lambda}(Y_{\text{norm}})$ . Consequently, we can state:

**Proposition 5.2.** *We have the following bijections:*

$$\begin{aligned} \Lambda_\lambda(Y_{\text{norm}}) &\xrightarrow{\sim} \mathcal{E}_{1,\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,\lambda}(Y_{\text{norm}}) \\ \psi_\lambda &\mapsto (\Psi_{1,\lambda}, \Psi_{2,\lambda}) \end{aligned}$$

and

$$\begin{aligned} \Lambda_{-\lambda}(Y_{\text{norm}}) &\xrightarrow{\sim} \mathcal{E}_{1,-\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,-\lambda}(Y_{\text{norm}}) \\ \psi_{-\lambda} &\mapsto (\Psi_{1,-\lambda}, \Psi_{2,-\lambda}) \end{aligned}$$



(we identify here  $\Psi_{\pm\lambda}(x, \mathbf{h}) = (x, \Psi_{1,\pm\lambda}(\mathbf{h}), \Psi_{2,\pm\lambda}(\mathbf{h}))$  with  $(\Psi_{1,\pm\lambda}(\mathbf{h}), \Psi_{2,\pm\lambda}(\mathbf{h}))$ ).

### 5.2. Analytic invariant varieties and two-dimensional saddle-nodes.

We can give a necessary and sufficient condition for the existence of analytic invariant varieties in terms of the moduli space described above.

We recall that for any vector field  $Y \in [Y_{\text{norm}}]$  as in (1.1) (cf. Definition 1.13), there always exist three formal invariant varieties:  $\mathcal{C} = \{(y_1, y_2) = (g_1(x), g_2(x))\}$ ,  $\mathcal{H}_1 = \{y_1 = f_1(x, y_2)\}$  and  $\mathcal{H}_2 = \{y_2 = f_2(x, y_1)\}$ , where  $g_1, g_2, f_1, f_2$  are formal power series with null constant term. The first one is classically called the *center variety*, and we have  $\mathcal{C} = \mathcal{H}_1 \cap \mathcal{H}_2$ . If  $Y = Y_{\text{norm}}$ , then:

$$\begin{cases} \mathcal{C} = \{y_1 = y_2 = 0\} \\ \mathcal{H}_1 = \{y_1 = 0\} \\ \mathcal{H}_2 = \{y_2 = 0\} \end{cases} .$$

**Proposition 5.3.** *Let  $Y \in [Y_{\text{norm}}]$  and  $(\Phi_\lambda, \Phi_{-\lambda}) \in \Lambda_\lambda(Y_{\text{norm}}) \times \Lambda_{-\lambda}(Y_{\text{norm}})$  be its Stokes diffeomorphisms. We consider  $\Psi_\pm = \mathcal{H}_{\pm\lambda} \circ \Phi_{\pm\lambda} \circ \mathcal{H}_{\pm\lambda}^{-1}$  as above. Then:*

- (1) *the center variety  $\mathcal{C}$  is convergent (analytic in the origin) if and only if  $\Psi_{2,\lambda,0}(0) = \Psi_{1,-\lambda,0}(0) = 0$ ;*
- (2) *the invariant hypersurface  $\mathcal{H}_1$  is convergent (analytic in the origin) if and only if for all  $n \geq 0$ , we have  $\Psi_{1,-\lambda,n}(0) = 0$ ;*
- (3) *the invariant hypersurface  $\mathcal{H}_2$  is convergent (analytic in the origin) if and only if for all  $n \geq 0$ , we have  $\Psi_{2,\lambda,n}(0) = 0$ .*

*Proof.* It is a direct consequence of the power series representation (5.2) of the Stokes diffeomorphisms  $(\Phi_\lambda, \Phi_{-\lambda})$ . Let us explain item 2. (the same arguments hold for 1. and 3. with minor adaptation). The fact that  $\Psi_{1,-\lambda,n}(0) = 0$  for all  $n \geq 0$  means that  $\Psi_{1,-\lambda}$  is divisible by  $h_1$ . Equivalently, both  $\Phi_{1,\lambda}$  and  $\Phi_{1,-\lambda}$  are divisible by  $y_1$ , so that the analytic hypersurface  $\{y_1 = 0\}$  has the same pre-image by the sectorial normalizing maps  $\Phi_+$  and  $\Phi_-$ . These pre-images glue together in order to define an analytic invariant hypersurface  $\mathcal{H}_1$ .  $\square$

Notice that if we consider the restriction of a formal normal form  $Y_{\text{norm}}$  to one of the formal invariant hypersurfaces, we obtain precisely the normal form for two-dimensional saddle-nodes as given in [MR82]. When one of these hypersurfaces is convergent (*i.e.* analytic), we recover the Martinet-Ramis invariants by restriction to this hypersurface, as we present below.

**Proposition 5.4.** *Suppose that the formal invariant hypersurface  $\mathcal{H}_1$  is convergent (*i.e.* analytic in the origin). Then, the Martinet-Ramis invariants for the saddle-node  $Y|_{\mathcal{H}_1}$  are given by:*

$$\begin{cases} \Psi_{2,\lambda}(0, h_2) = h_2 + \Psi_{2,\lambda,0}(0) \in \text{Aff}(\mathbb{C}) \\ \Psi_{2,-\lambda}(0, h_2) = h_2 + \sum_{n \geq 2} \Psi_{2,-\lambda,n}(0) h_2^n \in \text{Diff}(\mathbb{C}, 0). \end{cases}$$

Similar result holds for the hypersurface  $\mathcal{H}_2$ .

### 5.3. The transversally symplectic case and quasi-linear Stokes phenomena in the first Painlevé equation.

Let us now focus on the transversally symplectic case studied in Theorem 1.23. Let  $Y_{\text{norm}} \in \mathcal{SN}_{\text{diag},0}$  be transversally symplectic (*i.e.* its residue is  $\text{res}(Y_{\text{norm}}) = 1$ ). Using the notations introduced in paragraph 5.1, we define the following sets:

$$\begin{aligned} (\mathcal{E}_{1,\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,\lambda}(Y_{\text{norm}}))_\omega &:= \left\{ \begin{array}{l} \Psi_\lambda = (\Psi_{1,\lambda}, \Psi_{2,\lambda}) \in \mathcal{E}_{1,\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,\lambda}(Y_{\text{norm}}) \\ \text{such that: } \det(D\Psi_\lambda) = 1 \end{array} \right\} \\ (\mathcal{E}_{1,-\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,-\lambda}(Y_{\text{norm}}))_\omega &:= \left\{ \begin{array}{l} \Psi_{-\lambda} = (\Psi_{1,-\lambda}, \Psi_{2,-\lambda}) \in \mathcal{E}_{1,-\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,-\lambda}(Y_{\text{norm}}) \\ \text{such that: } \det(D\Psi_{-\lambda}) = 1 \end{array} \right\}. \end{aligned}$$

According to Proposition 5.2, the map

$$\begin{aligned} \Lambda_{\pm\lambda}(Y_{\text{norm}}) &\longrightarrow \mathcal{E}_{1,\pm\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,\pm\lambda}(Y_{\text{norm}}) \\ \psi_{\pm\lambda} &\mapsto \Psi_{\pm\lambda} := \mathcal{H}_{\pm\lambda} \circ \psi_{\pm\lambda} \circ \mathcal{H}_{\pm\lambda}^{-1} \end{aligned}$$

given in (5.1) is a bijection (we identify here  $\Psi_{\pm\lambda}(x, \mathbf{h}) = (x, \Psi_{1,\pm\lambda}(\mathbf{h}), \Psi_{2,\pm\lambda}(\mathbf{h}))$  with  $(\Psi_{1,\pm\lambda}(\mathbf{h}), \Psi_{2,\pm\lambda}(\mathbf{h}))$ ). An easy computation based on (4.1) gives:

$$(\mathcal{H}_{\pm\lambda}^{-1})^* \left( \frac{dy_1 \wedge dy_2}{x} \right) = dh_1 \wedge dh_2 + \langle dx \rangle .$$

This means in particular that  $\psi_{\pm\lambda}$  is transversally symplectic with respect to  $\omega = \frac{dy_1 \wedge dy_2}{x}$ , *i.e.*

$$(\psi_{\pm\lambda})^*(\omega) = \omega + \langle dx \rangle ,$$

if and only if  $\Psi_{\pm\lambda} = (\Psi_{1,\pm\lambda}, \Psi_{2,\pm\lambda})$  preserves the standard symplectic form  $dh_1 \wedge dh_2$  in the space of leaves, *i.e.*  $\det(D\Psi_{\pm\lambda}) = 1$ . In other words:

**Proposition 5.5.** *We have the following bijections:*

$$\begin{aligned} \Lambda_{\lambda}^{\omega}(Y_{\text{norm}}) &\xrightarrow{\sim} (\mathcal{E}_{1,\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,\lambda}(Y_{\text{norm}}))_{\omega} \\ \psi_{\lambda} &\mapsto (\Psi_{1,\lambda}, \Psi_{2,\lambda}) \end{aligned}$$

and

$$\begin{aligned} \Lambda_{-\lambda}^{\omega}(Y_{\text{norm}}) &\xrightarrow{\sim} (\mathcal{E}_{1,-\lambda}(Y_{\text{norm}}) \times \mathcal{E}_{2,-\lambda}(Y_{\text{norm}}))_{\omega} \\ \psi_{-\lambda} &\mapsto (\Psi_{1,-\lambda}, \Psi_{2,-\lambda}) \end{aligned}$$

(we identify here  $\Psi_{\pm\lambda}(x, \mathbf{h}) = (x, \Psi_{1,\pm\lambda}(\mathbf{h}), \Psi_{2,\pm\lambda}(\mathbf{h}))$  with  $(\Psi_{1,\pm\lambda}(\mathbf{h}), \Psi_{2,\pm\lambda}(\mathbf{h}))$ ).

#### 5.4. Quasi-linear Stokes phenomena in the first Painlevé equation.

In [Bit16a], we link the study of *quasi-linear Stokes phenomena* (see [Kap04] for the first Painlevé equation) to our Stokes diffeomorphisms. For instance, in the case of the first Painlevé equation, we show that the quasi-linear Stokes phenomena formula found by Kapaev in [Kap04] allows to compute the terms  $\Psi_{2,\lambda,0}(0)$  and  $\Psi_{1,-\lambda,0}(0)$  in (5.2). More precisely, elementary computations (using Kapaev's connection formula) give:

$$\Psi_{2,\lambda,0}(0) = i\Psi_{1,-\lambda,0}(0) = \frac{e^{\frac{i\pi}{8}}}{\sqrt{\pi}} 2^{\frac{3}{8}} 3^{\frac{1}{8}} .$$

Moreover, our description of the Stokes diffeomorphisms implies a more precise estimate of the order of the remaining terms in Kapaev's formula. In a forthcoming paper, we will use the study of some *non-linear Stokes phenomena* for the second Painlevé equations (see *e.g.* [CM82]) in order to compute coefficients of the  $\Psi_{i,\pm\lambda}$ 's.

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