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Gold-Catalyzed Enantioselective Functionalizations of Indoles

Pierre Milcendeau,^{a,§} Nazarii Sabat,^{a,§} Angélique Ferry*^{b,c} and Xavier Guinchart*^a

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Gold catalysis and indole chemistry are two mature and prolific fields. The gold-catalyzed functionalization of indoles has produced numerous results and paved the way for novel strategies in the building of molecular complexity. However -and curiously- though enantioselective gold catalysis is now a well-established field, it has been relatively little applied to the modification of indoles. This review exhaustively highlights the enantioselective gold-catalyzed examples of the functionalization of indoles in order to highlight the strengths and limitations of the method.

1. Introduction

The indole heterocycle holds a special place in heterocyclic chemistry. Discovered and characterized more than 150 years ago by Baeyer,¹ the interest in this heterocycle has never decreased, probably because of its prominence in natural products and biologically active compounds.²⁻⁸ Its reactivity and the rich chemistry developed around the indole ring are also crucial to understand its popularity in the scientific community and all the efforts directed toward its synthesis and functionalization.⁵⁻¹⁰¹¹ Over the past 20 years, the field of homogeneous gold catalysis exploded, resulting in a paradigm shift on the retrosynthetic analyses, especially in the field of carbon-heteroatom bond formation.¹²⁻¹⁷ With a careful work on the ligand design, enantioselective gold catalysis rapidly became possible and efficient –though difficulties linked to the linear geometry of gold complexes and outer-sphere mechanisms are still not fully overcome.¹⁸⁻²³ Not surprisingly, these two worlds –indole chemistry and gold catalysis- met quickly after chemist's eyes opened on the catalytic abilities of gold complexes in homogeneous catalysis. This led to vibrant and intense creativity in the field of indole synthesis,²⁴ modification, functionalization, mostly because of the unique nucleophilicity of indoles combined with the ability of Au(I) complexes to activate a number of unsaturated bonds.²⁵ However, the ratio of enantioselective/non-enantioselective gold-catalyzed functionalization remains quite low, demonstrating that enantioselective gold-catalysis is still challenging in indole chemistry. In this review, we present the established results in the field of enantioselective indole functionalization, focusing on gold catalysis in order to highlight the strength and weaknesses of the area. The papers discussed

are restricted to enantioselective reactions in which a bond is created between the indole and an electrophile with the concomitant formation of a stereogenic center. Papers where the indole ring is a non-reacting substituent of a scaffold, even in enantioselective gold catalysis, are not included. For each example, the focus will be given on the nature of the catalysts, the ligand design and the mechanisms when relevant.

2. Reactions with unsaturated functions

Most of the literature related to the field is dominated by the use of unsaturated functions as the electrophilic partner. Triple bonds, alkenes, allenes, olefins are all suitably activated by the gold complex and are a source of important structural complexity.

2.1 Triple Bonds

2.1.1. Alkynes

Gold complexes possess a high affinity for alkyne π -bonds, allowing a selective activation in complex molecular structures. This particularity makes alkynes probably the most used electrophiles in gold catalysis. Gold-catalyzed functionalization of indole heterocycles tethered to alkynes is an attractive and well-developed field.²⁶ However, reactions involving indoles and alkynes upon enantioselective gold-catalysis are scarce.

One of the first examples of enantioselective gold-catalyzed functionalization for the synthesis of polycyclic indoles was demonstrated by Bandini in 2012 (Scheme 1).²⁷ Indoles tethered to alkyne functions are known to undergo gold-catalyzed spirocyclizations²⁸⁻³⁶ with concomitant indole dearomatization. Compounds **1** (X= NTs or diester moiety) undergo hydroindolination of the carbon-carbon triple bond followed by iminium trapping of the alkenyl-gold intermediate. This process leads to the formation of 6/5-fused dihydropyranylidolines **2** and 5/7-fused furoindolines **3** in high chemo- and regioselectivities. A range of chiral C₂-symmetrical bis-phosphine ligands was tested in the cascade reaction by *in situ* generation of cationic binuclear gold complexes. Optimal

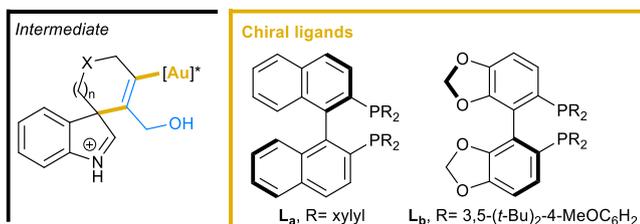
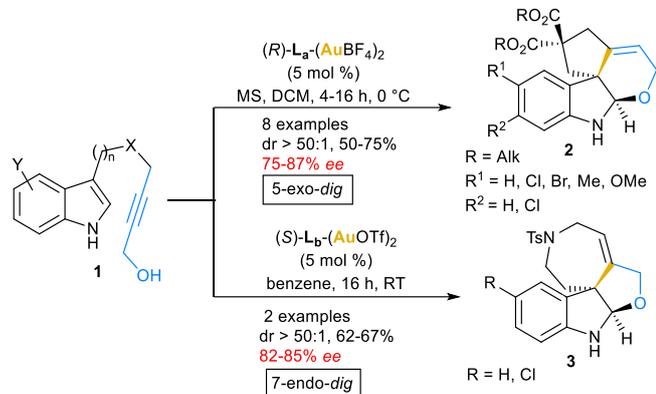
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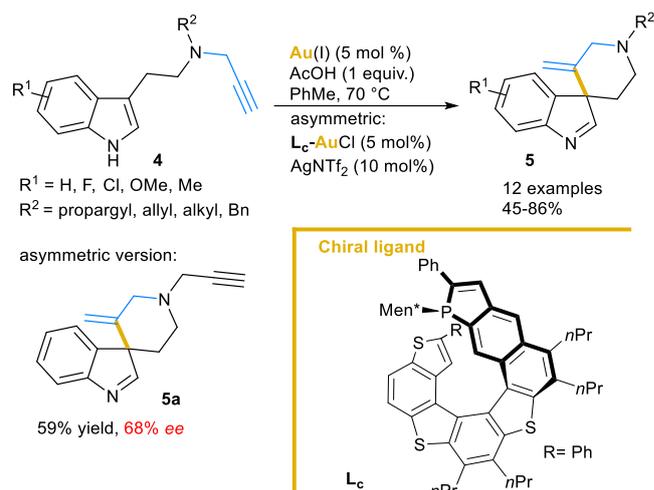
[§] These authors contributed equally.

conditions for the synthesis of tetracyclic furoindolines **2** were achieved by the use of 5 mol% of (*R*)-xylylBINAP(AuBF₄)₂ complex with exclusive 5-*exo-dig* regiochemistry, excellent diastereoselectivities (*dr* > 50:1) and enantioselectivities (*ee* = 75–87%). Further expansion to tryptamine-derived propargyl alcohols led to the preferential formation of furoindolines **3** via 7-*endo-dig* regiochemical pathway using chiral (*S*)-DTBM-SEGPHOS(AuOTf)₂ complex in good yields and enantioselectivities (*ee* = 82–85%).



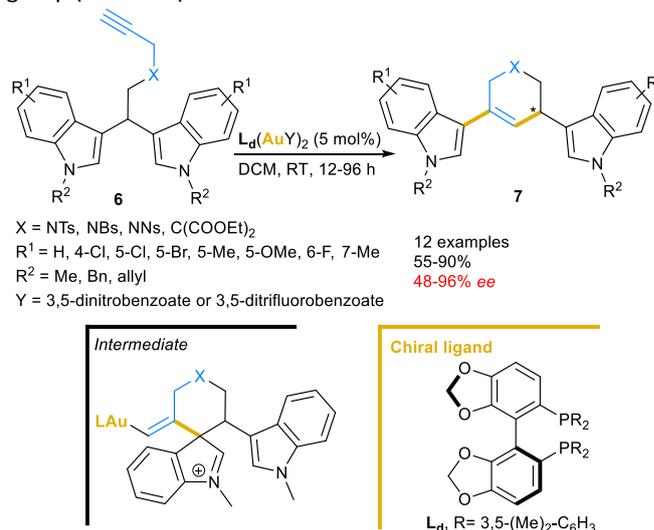
Scheme 1. Intramolecular spirocyclizations of indoles tethered to alkyne function with nucleophilic trapping of the imine.

Interestingly, however, the control of the enantioselectivity is much more difficult when the alkyne is not disubstituted. In 2017, our group developed a gold(I)-catalyzed cyclization of readily available *N*-propargyl tryptamines **4** using 5 mol% of [JohnPhosAuMeCN]SbF₆ catalyst for the synthesis of spiroindolenines **5** (Scheme 2).³⁷ The asymmetric version of this reaction was studied using a range of chiral ligands. The use of chiral [Ph-HelPhosS] ligand L_c previously developed in our group³⁸ showed the best result providing the desired spiroindolenine product **5a** in 59% yield and 68% *ee* (62% *ee* using [(*R*)-DTBM-BIPHEP(AuNTf₂)₂]. Though moderate, this is still the first example of this class of challenging asymmetric spirocyclization under gold catalysis.



Scheme 2. Intramolecular cyclization of *N*-propargyl tryptamines.

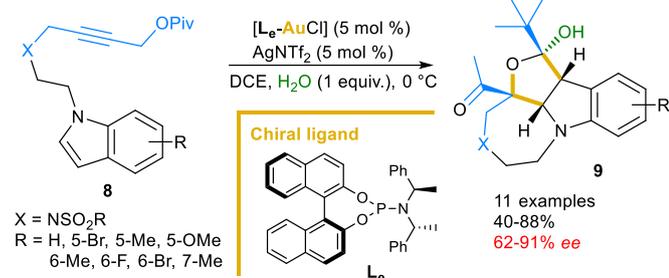
Shi *et al.*³⁹ reported in 2015 an elegant gold(I)-catalyzed cycloisomerization of 1,1-bis(indolyl)-5-alkynes **6** in regio- and enantioselective manner (Scheme 3). A series of bis(indole) alkaloids **7** were obtained through a 6-*endo-dig* cyclization/*pseudo* 1,5-migration sequence. This reaction was shown to be working perfectly with the 2.5 mol% of [Me₄tBuXPhosAu]SbF₆ gold complex in toluene, providing racemic products **7** up to 99% yield after 10 minutes of reaction time at room temperature. The enantioselective version of this reaction using (*R*)-DM-SEGPHOS L_d as the chiral ligand together with 3,5-dinitrobenzoate (DBN) or 3,5-di(trifluoromethyl)benzoate (DTfB) as the counterion, lead to moderate to good *ee* values. Noteworthy, substrates **6** with *N*-R linker connected to the propargyl group demonstrated better tolerance (*ee* = 60–96%) than the substrate with a gem-diester group (*ee* = 48%).



Scheme 3. Synthesis of bis(indole) alkaloids by intramolecular cycloisomerization.

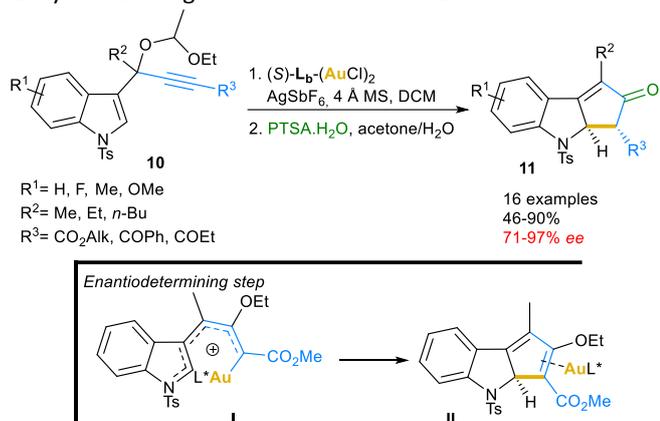
Another efficient enantioselective synthesis of highly-functionalized polycyclic indolines **9** featuring four contiguous stereocenters was described by Shi the next year (Scheme 4).⁴⁰ Interestingly, in this work, the alkyne functionality was linked to

the indolic nitrogen and not to the C3 or C2 carbons. This resulted in a new type of 5/7-fused polycyclic compounds **9** connected through the nitrogen atom. With the racemic cyclization conditions of indolyl propargylic esters **8** in hand, the authors developed the asymmetric version using Feringa phosphoramidate **L_e** as the best chiral ligand, leading to 80-91% *ee* values. The complex mechanism for this cascade cyclization reaction involves a 1,2-acyloxy migration and a [3+2] cycloaddition as key steps.



Scheme 4. Intramolecular cascade cyclization route to polycyclic indolines.

In 2015, Toste reported the access to enantioenriched cyclopenta[*b*]indoles **11** by the first gold-catalyzed dearomative Rautenstrauch rearrangement of propargyl acetates **10** using (*S*)-DTBM-SEGPHOS(AuSbF₆)₂ (Scheme 5).⁴¹ The enantioselectivity was well controlled by the chiral ligand during the imino-Nazarov cyclization of intermediate **I** to the next intermediate **II**. After de-coordination of gold and hydrolysis, the desired cyclopenta[*b*]indoles **11** were obtained in good 71-97% yields and high enantioselectivities 71-97% *ee*.

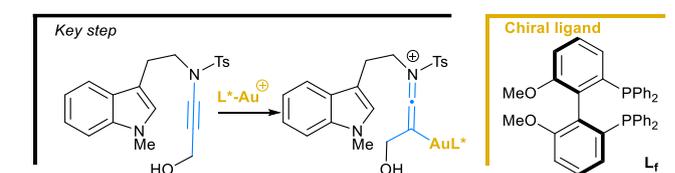
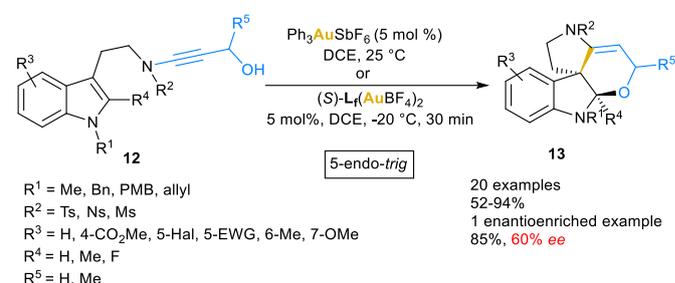


Scheme 5. Intramolecular dearomative Rautenstrauch rearrangement of indolyl propargyl acetates.

2.1.2. Ynamides

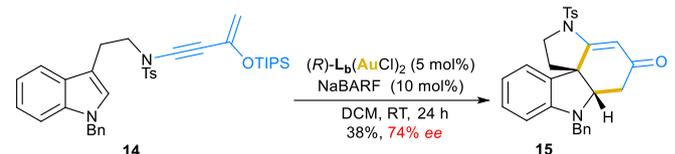
Ynamides are another kind of highly electron-rich triple bonds that are easily activated by gold-complexes. Following previous work of Bandini with propargylic alcohols, Gong and Yang reported the gold-catalyzed intramolecular cyclization of ynamides **12**. This reaction proceeds *via* an intramolecular trapping of the intermediate iminium by the alcohol providing 6/5-fused pyrrolidinoindolines **13** in 52-94% yields (Scheme 6).⁴² A number of chiral ligands were tested, leading to the

identification of (*S*)-Ph-MeO-BIPHEP **L_f** as the best chiral ligand, providing the enantioenriched product **13** in a moderate 60% *ee*. This shows that discrimination of one of the geometries of the keteneiminium by chiral ligand during the coordination of starting ynamide with the chiral gold complex is not an easy task. Surprisingly, the non-bulky ligand **L_f** was the best one here, whereas the same ligand with phenyl groups was unsuccessful in most enantioselective gold-catalyzed processes.



Scheme 6. Intramolecular cyclizations of ynamides to tetracyclic indolines.

Recently, Ohno *et al.*⁴³ developed the asymmetric synthesis of pyrrolo[2,3-*d*]carbazole core **15** of aspidosperma alkaloids based on a gold-catalyzed cascade reaction of ynamide with silyl enol ether **14** as the terminal nucleophile (Scheme 7). The optimal conditions using 5 mol% of (*R*)-DTMB-SEGPHOS(AuCl)₂ chiral complex and sodium tetrakis[3,5-bis(trifluoromethyl)phenyl]borate (NaBARF) led to moderate 38% yield but provided ready access to the synthetic intermediate **15** of vindorosine alkaloid with good enantioselectivity (74% *ee*).



Scheme 7. Intramolecular cascade reaction of indolyl ynamide to pyrrolo[2,3-*d*]carbazole.

2.2 Allenes and related unsaturated functions

Allenes figure among the most used electrophilic partners in gold catalysis,⁴⁴ and their reactions with indoles have been particularly studied²⁵ both in an inter- and intramolecular manner. With their axial chirality and various coordination modes, allenes have met particular success in enantioselective Au(I)-catalysis.

2.2.1. Intermolecular reactions with allenes

Following the precursor reports of Widenhoefer in 2009,⁴⁵ Che *et al.* developed the intermolecular reactions of indoles **16** with symmetrical allenes **17**. The best conditions used (*S*)-Ph-MeO-BIPHEP **L_g** and AuCl as the chiral binuclear gold(I) phosphine complexes, displaying intramolecular Au(I)-Au(I) interactions in combination with silver salt (Scheme 8).⁴⁶ Diverse di-aryl-allenes **17** were used leading to high yields (up to 90%) but only

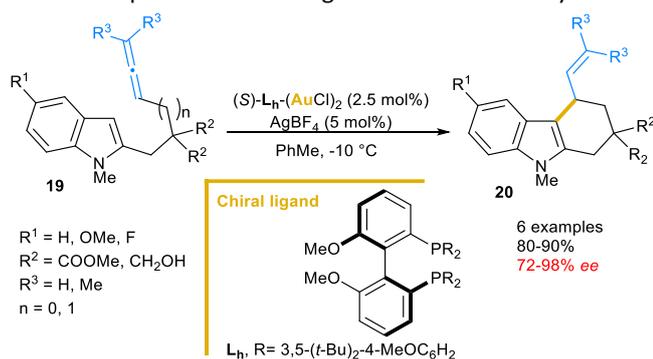
with moderate enantioselectivities (up to 63% *ee*) of the *E*-isomer as the sole products **18**. The presence of *ortho*-substituents on the aryl ring on allenes resulted in a significant decrease in the yield and the enantioselectivity. Similarly, the electron-withdrawing group on these aryl rings are detrimental in the enantiocontrol. Allenes substituted with alkyl groups were unsuccessful in these conditions. This rare example of intermolecular enantioselective reaction with allenes reveals the high challenge associated with the stereocontrol in this reaction, despite a thorough chiral ligand screening. The authors showed in this reaction that Au-Au interaction in the catalyst appear crucial to the enantiodiscrimination since more flexible binuclear digold complexes with no Au-Au interaction showed lower *ee* values.



Scheme 8. Intermolecular hydroarylation of allenes with indoles.

2.2.2. Intramolecular reactions with allenes

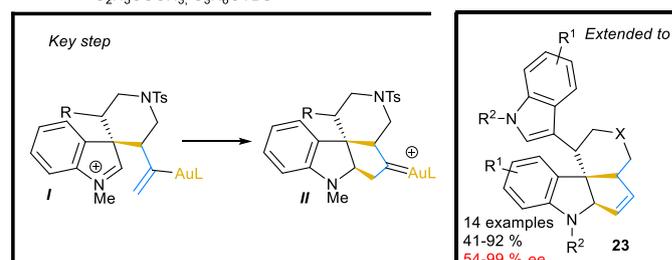
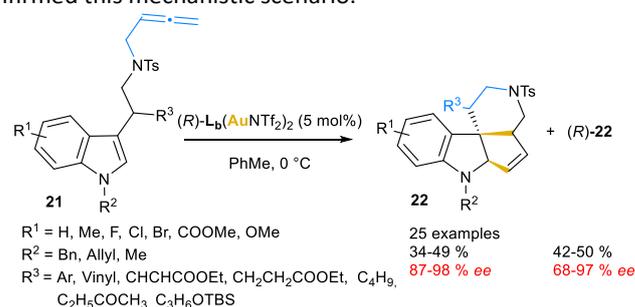
When the allene is tethered to the indole, gold activation triggers an intramolecular cyclization, which is usually more favorable for the enantioinduction. Widenhoefer's group developed in 2006 the first reactions between indoles and allenes using a catalytic amount of AuCl and a silver salt.⁴⁷ The enantioselective version was then reported using the AuCl complex of (*S*)-DTBM-MeO-BIPHEP **L_h** and AgBF₄ (Scheme 9).⁴⁸ Diverse 2-allenyl indoles **19** were used leading to high (80-90 %) yields of products **20** with moderate to high enantioselectivities (60-98 % *ee*). The presence of an electron-withdrawing group at R² seems required to ensure a good enantioselectivity.



Scheme 9. Intramolecular cyclization of 2-allenyl indoles.

When the allene function is in a 1,6-relationship with the nucleophilic indole ring, spirocyclization can occur. In 2019, Shi *et al.* have reported kinetic resolutions from racemic *N*-homoallenyl tryptamines **21** to form spirofused complex polycyclic indole **22** (Scheme 10).⁴⁹ The (*R*)-DTBM-SEGPHOS gold complex **L_b**-(AuCl)₂ coordinates preferentially to the (*S*)-

configured isomer, to give a tetracyclic compound, while the (*R*) isomer is left alone and sees its enantiomeric excess rising. With this methodology, two different targets can be accessed starting from one racemic compound, with good yields (maximum 50 % for each compound) and good *ee* values. The same group extended this reactivity to the desymmetrization of allenyl bisindole **23** with the same catalyst in 2019 (Scheme 10).⁵⁰ Because of the symmetry of the starting material, high yields can be obtained *via* this desymmetrization. Alternative linkers have been investigated, but tryptamine derivatives seem to be preferred for those kinds of reactions. Noteworthy, these reactions do not work with non *N*-substituted indoles. The reactions evolve through intermediate **I** after the first cyclization, and the iminium is then trapped by the vinylgold intermediate forming gold carbene **II** (Scheme 10). A combination of deuterium labeling and DFT calculations confirmed this mechanistic scenario.



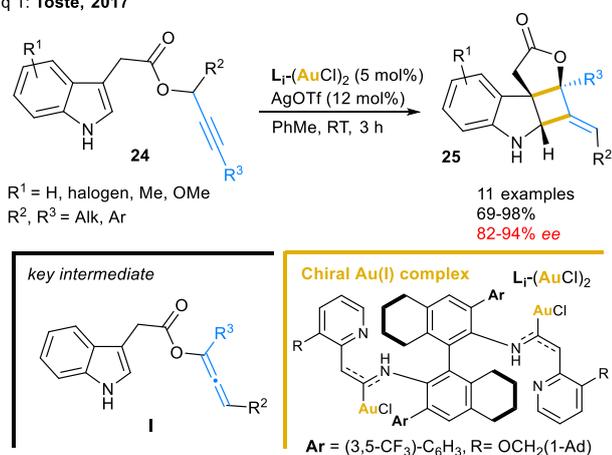
Scheme 10. Kinetic resolutions of racemic *N*-homoallenyl tryptamines.

In 2017, the Toste group established the enantioselective version⁵¹ of a tandem rearrangement/cyclization process initially developed by Zhang (Scheme 11, eq. 1).⁵² The process initiates from indole propargyl esters **24** that rearrange to the allenyl ester **I** *via* a 3,3-sigmatropic rearrangement promoted by the Au(I) complex. The allene function, hence generated *in situ* undergoes a [2+2] cyclization to the polycyclic indoles **25**. In this work, Toste reported a method to analyse the independent structural features of acyclic diaminocarbenes (ADC) ligands, allowing to correlate and predict mathematical models of enantioselectivity. Based on that, the best catalyst was found to be the chiral acyclic diaminocarbene gold complex **L_i**. The scope of reaction was then tested on a series of propargylic esters **24** to show a good level of substituent tolerance providing the 2,3-indoline-fused cyclobutanes **25** in 69-98% yields and 82-94% *ee* values.

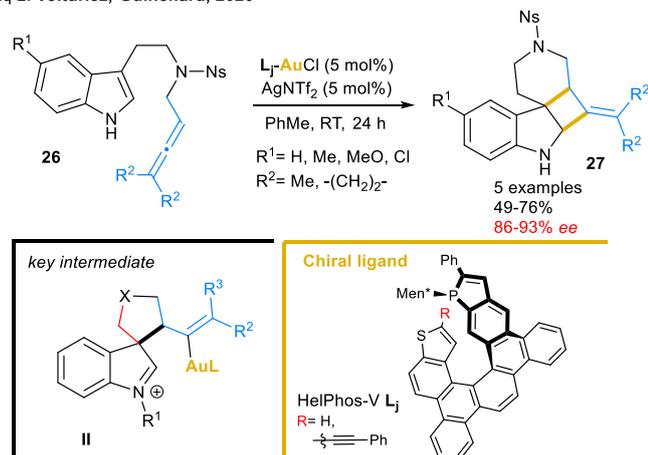
Very recently, our group reported that *N*-homoallenyl tryptamines **26** behave the same as intermediates allenes generated in Toste's system,⁵¹ leading to spirofused compounds

27 (Scheme 11, eq. 2).⁵³ Newly designed HelPhos chiral ligands L_j were used as their chiral gold complexes ensuring high enantioselectivities in a range of compounds. Interestingly, the replacement of the unsubstituted catalyst ($R = H$) by an alkyne substitution ($R = -C\equiv C-Ph$) led to an increase of the enantioselectivities, as previously observed in other enantioselective gold-catalyzed processes.⁵⁴ The vinylgold key intermediate **II** is common to our work and Toste's report and traps the iminium function. Interestingly, the iminium is trapped here by the carbon bearing the gold atom, as opposed to previous work of Shi for which the similar intermediates evolved through the formation of a carbene and finally the generation of a five-membered ring (See Scheme 10, key step).⁵⁵ Interestingly too, monosubstituted allenes were not suitable in neither of these reactions, though it was working well in Shi's work. This may be linked to the fact that the indole has to be *N*-substituted in Shi's work, to ensure sufficient electrophilicity of the intermediate iminium.

Eq 1: Toste, 2017



Eq 2: Voituriez, Guinchar, 2020



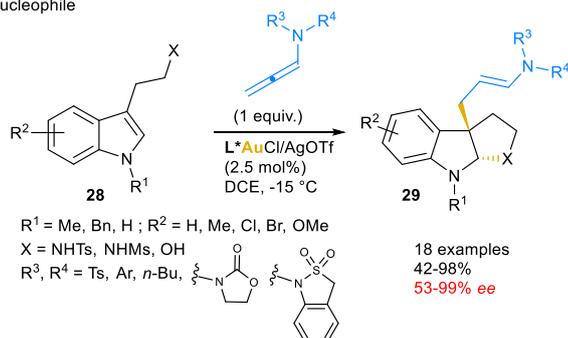
Scheme 11. Formation of cyclobutane-fused polycyclic indoles derivatives *via* [2+2] cyclizations.

2.2.3. Allenamides

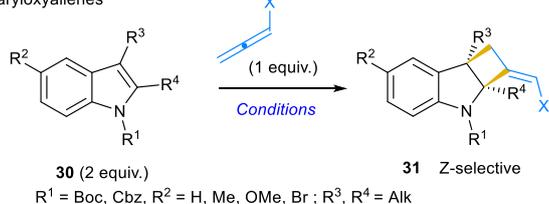
In 2015, Chen *et al.* extended the hydroarylation reactivity to the asymmetric gold-catalyzed annulation of tryptamines or tryptols **28** with allenamides, which furnished pyrroloindolines, and furoindolines **29** with moderate to excellent *ee*'s (Scheme

12, eq. 1).⁵⁶ The enantioselectivity was here controlled by two different BINOL derived phosphoramidite ligands L_k and L_l , depending on the substrate. The same year, Bandini *et al.* showed that 2,3-disubstituted indoles and allenamides undergo a [2+2]-cycloaddition process.⁵⁷ This process is favored by the use of an electron-rich phosphine on the gold complex and the presence of an EWG at the *N*(1) position (Boc, Cbz), enhancing the electrophilicity of the iminium intermediate. These two parameters prevent the protodeauration process and allow the formation of the *cis* methylene 2,3-cyclobutane-fused indolines **31** bearing two quaternary stereocenters and possessing a (*Z*) *exo* carbon-carbon double bond. The use of chiral (*R*)-DTBM-SEGPHOS ligand L_b coordinated-gold complex in the presence of AgNTf₂ as activator furnished **31** in modest to excellent *ee*'s (Scheme 12, conditions A). In the presence of allenamides, the same chiral catalyst enabled the enantioselective formation of **31** with excellent diastereo- and enantioselectivities (*dr*>20:1, *ee*'s up to 99%) with the (*Z*)-configuration for the exocyclic double bond (Scheme 12, conditions B).⁵⁸ Allenamides usually presented a higher reactivity than aryloxyallenes. DFT calculations evidenced for a two-step process, namely the dearomative C-C bond formation (being rate-determining step) followed by the formation of the cyclobutane ring. Recently, Chen *et al.* developed a series of axially chiral gold complexes L_m possessing a bis-triazole-type scaffold and showed that this new class of chiral Au(I) complex does not have aurophilic interactions.⁵⁹ These catalysts were applied in the enantioselective [2+2]-cycloaddition of 2,3-dimethylindole with allenamide leading, however, to moderate enantiomeric excess (Scheme 12, conditions C).

Eq. 1: **Chen 2015**, addition to allenamides with trapping by external nucleophile



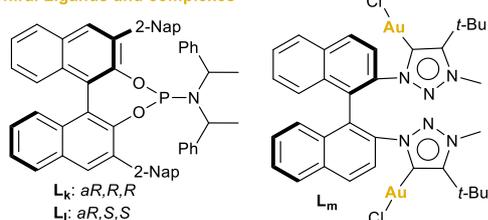
Eq. 2: Formal [2+2] cycloaddition processes with allenamides and aryloxyallenes



Bandini 2015: (R)-L_B-(AuCl)₂ **Chen 2018:** L_m (2.5 mol%), AgSbF₆ (5 mol%)

A	B	C
X = OAr	X = NRR'	X = NRR'
6 examples	17 examples	2 examples
32-74%, dr > 20:1	41-96%, dr > 20:1	70%
64-95% ee	81-99% ee	64% ee

Chiral Ligands and complexes



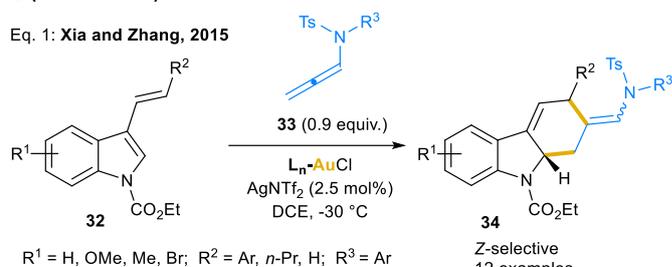
Scheme 12. Intermolecular reactivities of indoles with allenamides/aryloxyallenes.

In 2013, Vicente and Rossi extended this methodology in a racemic manner to 2-vinylindoles.⁶⁰ When the Gagosz catalyst⁶¹ Ph₃PAuNTf₂ was used with *N*-methyl or *N*-H 2-vinylindoles, the classical hydroarylation process occurs. However, with EWG on the indole nitrogen, the intermediate iminium becomes more electrophilic, driving a gold-catalyzed [4+2] cycloaddition to form tetrahydrocarbazoles derivatives. Xia and Zhang next developed enantioselective version of this [4+2]-cycloaddition between *N*-(carbamoyl)-3-vinylindoles **32** and allenamides **33** using a chiral H₈-BINOL-derived phosphoramidite ligand (Scheme 13, eq. 1).⁶² Various tetrahydrocarbazoles **34** could be obtained in good to excellent yields with a (*Z*)-selectivity up to 14:1 and excellent ee's.

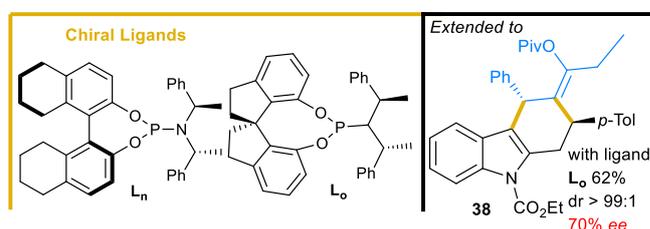
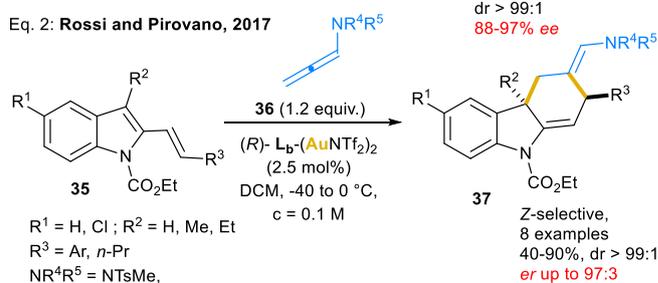
In 2017, Rossi and Pirovano *et al.* developed a variant of this enantioselective cycloaddition between 2-vinylindoles **35** and allenamides **36**,⁶³ using (*R*)-DTBM-SEGPHOS **L_B** as the chiral ligand. Diverse 2-vinylindoles **35** bearing both EWG and EDG were successfully transformed in these conditions leading to the corresponding products **37** with good ee's (Scheme 13, eq. 2) as the (*Z*)-isomers only. A low temperature (-40 °C), as well as the excess of allenamide partners, were key parameters in the

optimization process. However, the presence of alkyl substitution on a vinyl part is deleterious on the enantioselectivity, but the reaction tolerated C3-substituents such as hydrogen, methyl or ethyl. These conditions could then be applied to 3-vinylindoles furnishing the corresponding carbazoles **37** in excellent yield (80-97%) and good ee (76-98%) on four examples but as a mixture of (*Z*) and (*E*) isomers (not shown). Finally, in 2016, Rossi and Pirovano preliminary reported the enantioselective version of a new cyclization leading to compound **38** in good yield and a 70% ee using ligand **L_o** (Scheme 13).⁶⁴

Eq. 1: **Xia and Zhang, 2015**

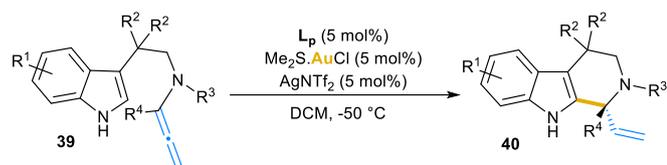


Eq. 2: **Rossi and Pirovano, 2017**



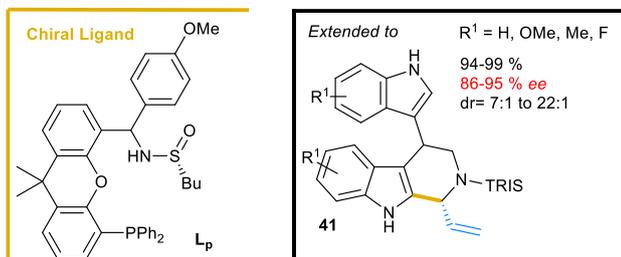
Scheme 13. Cycloaddition between vinylindoles and allenamides.

This methodology was then extended to the isomeric 3-allenyl indoles, particularly on tryptamine derivatives **39** by Zhang *et al.* in 2017 (Scheme 14).⁶⁵ During this work, a chiral bifunctional sulfonamide monoposphine ligand **L_p** was used. Nosyl and tosyl R³ groups led to good enantioselectivities (>77 % ee), but the TRIS group was the one that showed the best ee. With this group, the substitution of the indole has been studied, leading to high yields (> 90 %) and enantioselectivities (> 86% ee). Unfortunately, it was also shown that substitution of the allenamide (R⁴ ≠ H) led to low enantioselectivity. Interestingly, the desymmetrization reaction of bisindole starting materials has been studied and led to high ee's and diastereoselectivities for compounds **41** (See scheme 14). These approaches provide an interesting alternative to classical enantioselective strategies to access chiral tetrahydro-β-carbolines, for which organocatalysis is not so efficient as far as 1-vinyl-TH-β-Cs are concerned.⁶⁶⁻⁶⁸



R¹ = H, OR, Alk, Ph, F, Br
 R² = H, Me
 R³ = Ts, Ns, Ms, TRIS, Ar
 R⁴ = H

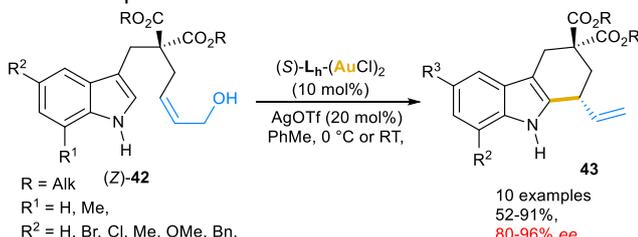
23 examples
 88-99%
 77-97% ee



Scheme 14. Synthesis of chiral tetrahydro- β -carbolines via intramolecular cyclization of indoles to allenamides.

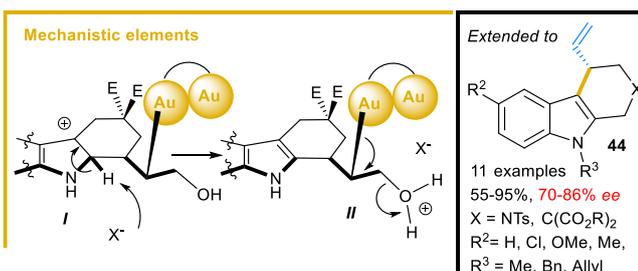
2.3 Allylic alcohols

Bandini *et al.* showed the reactivity of π -activated alcohols in the first enantioselective gold-catalyzed intramolecular Friedel-Crafts alkylation of indoles.^{69, 70} Starting from (*Z*)-**42** (Scheme 15), this transformation allowed the formation of enantioenriched 1-vinyltetrahydrocarbazoles **43** using the C2-symmetric biphasic (S)-DTBM-MeO-BIPHEP **L_h** chiral ligand. The triflate gold-counterion appeared to be crucial to obtain the optimal reactivity and stereoselectivity. These conditions tolerate a wide range of electron-withdrawing and -donating functional groups on the indole ring. Tricyclic compounds **43** were then obtained in good yields and high enantiomeric excesses. The (*Z*)-configuration of the C=C bond of the acyclic precursor is necessary to observe the described reactivity. Using isomeric starting material, the authors could access 4-vinyltetrahydrocarbazoles or 4-vinyltetrahydro- β -carbolines **44** with good enantioselectivities. DFT computations suggested that the mechanism of these transformations involves a single-site interaction mode involving a monogold-activation leading to intermediate **I**, for which the rearomatization is the rate-limiting step, combined then with a Brønsted acid assisted β -hydroxy elimination process from **II**.⁷¹



R = Alk (*Z*)-**42**
 R¹ = H, Me,
 R² = H, Br, Cl, Me, OMe, Bn.

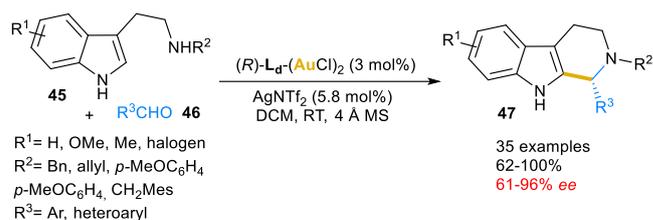
10 examples
 52-91%
 80-96% ee



Scheme 15. Access to 4-vinyltetrahydrocarbazoles by intramolecular Friedel-Crafts alkylation.

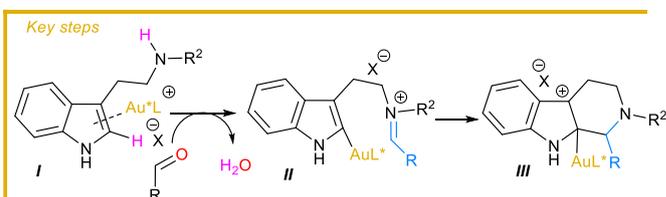
2.4 Pictet-Spengler Reactions

Recently, our group reported that tryptamines **45** and aldehydes **46** undergo enantioselective Pictet-Spengler reactions in the presence of a chiral gold-complex to form tetrahydro- β -carbolines **47** (Scheme 16).⁷² Screening of chiral ligands revealed that (*R*)-DM-SEGPHOS **L_d** Au(I) complex led to the best enantioselectivities, ranging mostly from 72 to 96% ee. The nature of the R² group proved crucial to obtain the highest enantioselectivities. The reaction, though efficient, was, however, limited to the use of aromatic aldehydes. This reactivity is somewhat unexpected for Au(I) complexes that are weak Lewis acids, despite the precedence of both Au(III) and Au(I)-catalyzed non-enantioselective reactions.^{73, 74, 75} The mechanistic hypothesis explains how the iminium can be formed while the reaction is performed in the strict absence of any acidic proton. It relies on the auration of the indole ring generating intermediate **I**, from the reaction of the tryptamine gold-complex **I** with the aldehyde followed by the dehydration of the intermediate hemiaminal. Once formed, intermediate **II** is nucleophilic enough to trap the iminium species to reach intermediate **III**, that deaureate to release the final product.



R¹ = H, OMe, Me, halogen
 R² = Bn, allyl, *p*-MeOC₆H₄,
p-MeOC₆H₄, CH₂Mes
 R³ = Ar, heteroaryl

35 examples
 62-100%
 61-96% ee



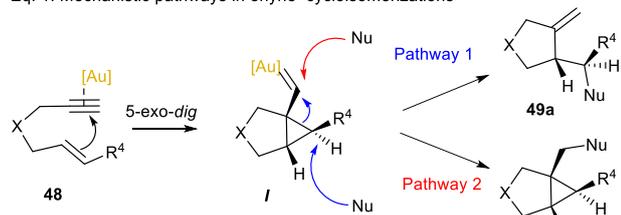
Scheme 16. Gold-catalyzed enantioselective Pictet-Spengler reactions.

3. Reactions involving indoles as an external nucleophile

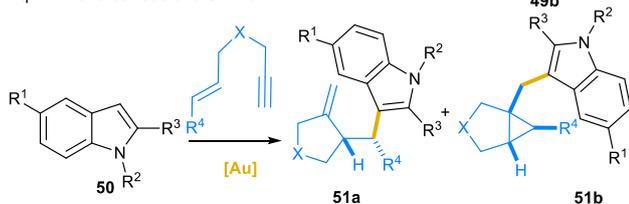
Since the rise of homogeneous gold catalysis in the first decade of the century, cycloisomerizations have been one of the major class of reactions to be studied in details.⁷⁶⁻⁷⁸ Those reactions are of infinite richness in terms of structural complexity since they combine in general two unsaturated arms. In a number of reactions, the late stage of the mechanistic pattern involves the formation of a carbocation that can be trapped by a nucleophile. With its exceptionally high nucleophilicity, the indole ring is very often used as a randomly assayed nucleophile in a vast number of reactions in organic synthesis, including in cycloisomerizations. In particular, over the last decade, the indole trapping of electrophilic gold carbenes species formed by reaction with 1,6-enynes was largely explored. In 2007,

Echavarren showed that the activation of 1,6-enyne substrates **48** by cationic gold(I) complexes generated, *via* a 5-*exo-dig* cyclization (Scheme 17, eq. 1), a cyclopropyl gold carbene intermediate **I** which could be attacked by electron-rich arenes such as indoles in two different sites namely the cyclopropane (Pathway 1) and the carbene (Pathway 2), followed by rearomatization of the indole and protodemetalation. Most of the tested catalysts lead to compounds **49a** as the major products (Pathway 1). On the contrary, bulky NHC-Au complexes favor the formation of **49b** (Pathway 2).^{79, 80, 81, 82} The first enantioselective version of this reaction was reported by Michelet *et al.* using (*R*)-DTBM-MeO-BIPHEP-(AuCl)₂ complex combined to silver salt under mild conditions (Scheme 17, eq. 2, conditions A),^{83, 84} leading to **51a** as single *anti* diastereoisomers in good to excellent enantiomeric excesses. The authors suggested that both the cyclization and the addition of the nucleophile may be concerted. Michelet, Toullec and Mézailles reported later⁸⁵ alternative conditions using undecagold clusters bearing chiral phosphine ligands **L_f** or BINAP and best conditions resulted in 99% yield and 44% *ee* of a member of series of compound **51a** (X= C(CO₂Me)₂, R¹= R³= H, R²= Me, R⁴= Ph), which was comparable to the previously reported result⁸³ (91% yield, 45% *ee*, Scheme 17, eq. 2, conditions A). Later, Shi *et al.* proposed new axially chiral NHC gold complex **L_q** catalyzing the formation of **51a** in good yields and with excellent diastereoisomeric ratios but with moderate to good enantioselectivities (Scheme 17, eq. 2, conditions B).⁸⁶

Eq. 1: Mechanistic pathways in enyne cyclizations



Eq. 2: Michelet 2009 and Shi 2011

**Conditions A:**

(*R*)-L_h-(AuCl)₂ (3 mol%), AgOTf (6 mol%), Et₂O, RT, 15-20 h
8 examples, 37-99%, **51a/51b** = >99/1

36-95% *ee*

R¹= H, R²= H, Me;

R³= H, Ph; R⁴= Ph, Ar, (Me)₂

X= C(CO₂R)₂, C(SO₂Ph)₂, O

Conditions B:

L_q-Au(I)/AgSbF₆ (5 mol%)

DCE, 25 °C, 24 h

27 examples, 40-90%, **51a/51b** = >99/1

dr 9:1- >99:1

2-66% *ee*

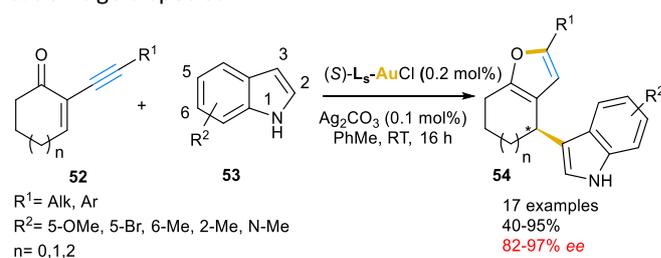
R¹=H, Br; R²= Me, Bn, Boc;

R³= H, Me; R⁴= Ar

X= NBs, NNs, NTs, NSO₂Ar

Scheme 17. Cycloisomerizations of enynes in the presence of indoles.

Recently, our group reported on the enantioselective cycloisomerization of 2-alkynyl-enones **52** in the presence of a range of nucleophiles, including indoles **53** (Scheme 18).⁸⁷ This reaction, initially developed by Larock with AuCl₃ as the catalyst, could be performed with newly designed chiral gold phosphoric acid **L_s** as the precatalyst, activated *in situ* by silver carbonate. With this, a range of ketones **52** and indoles **53** were used to generate enantioenriched furanes **54** in excellent yields and enantioselectivities at only 0.2 mol% catalyst loading. The key intermediate in the process is the carbocation **I**, which is stabilized by the chiral phosphate, which hinders one of the sides of the carbocation. In this ligand design, this is the first time the chiral counterion is intramolecularly linked to the cationic gold species.^{88, 89}



R¹= Alk, Ar

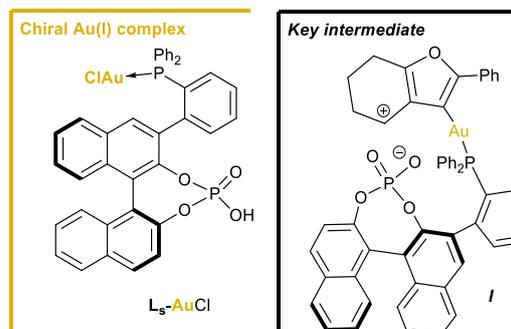
R²= 5-OMe, 5-Br, 6-Me, 2-Me, N-Me

n= 0,1,2

17 examples

40-95%

82-97% *ee*



Scheme 18. Cycloisomerization of 2-alkynyl-enones with indoles.

4. Miscellaneous

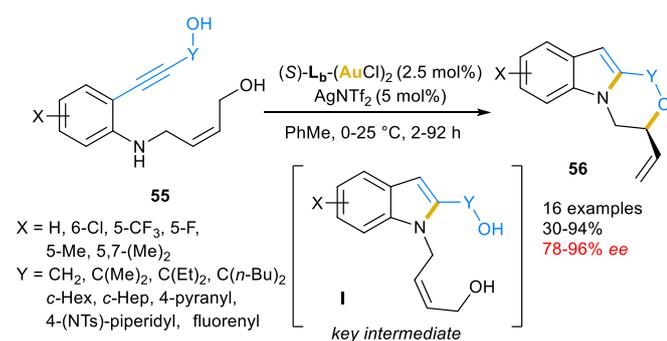
In this brief section, some papers and approaches at the border of the scope of this review are presented, either because the indole is not functionalized or because the gold catalyst is not the source of enantioselectivity in the process.

4.1 Reaction with the indole being formed *in situ*

Gold complexes are not only used to trigger a nucleophilic reaction of the indole but are also able to generate the indole ring *in situ* from aniline precursors. In the following examples, the indole ring is generated *in situ* in the course of an enantioselective functionalization, but the indole itself is not further functionalized.

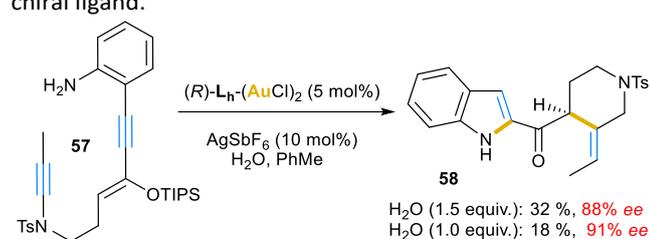
Inspired by previous work on the racemic synthesis of oxazinoindoles starting from the corresponding *ortho*-alkynylaniline diols,⁹⁰ Bandini's group developed in 2013 the asymmetric methodology to access highly enantioenriched oxazino[4,3- α]indoles **56** starting from *ortho*-alkynylaniline allyl diols **55** and using (*S*)-DTBM-SEGPHOS **L_b** as the chiral ligand (Scheme 19).⁹¹ The reaction path goes through the *in situ* formation of

intermediate **I** that further undergoes stereoselective alkoxylation to provide the corresponding products **56**.



Scheme 19. Access to oxazino-indoles from alkyne-alkenyl aniline-type substrates.

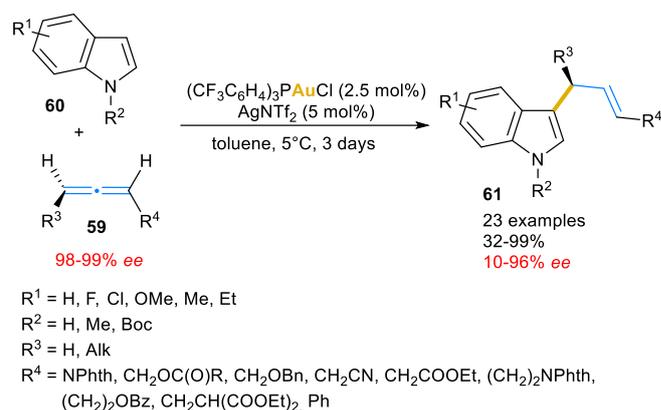
Ohno *et al.* reported in 2016 the total synthesis of (+)-conolidine using an enantioselective gold-catalyzed formation of the indole ring **58** combined with the addition of a silyl enol ether to a triple bond **57** (Scheme 20).⁹² After optimization, they were able to obtain indole **58** in low to moderated yields but high enantiomeric excess using (*R*)-DTBM-MeO-BIPHEP **L_h** as the chiral ligand.



Scheme 20. Formation of functionalized indoles from enyne substrates.

4.2. Chirality conversion

Following on Che's report that indoles intermolecularly react with symmetrical allenes,⁴⁶ Lee *et al.* reported in 2018 an alternative approach using an enantiomerically pure allene **59** and an achiral gold catalyst, relying on the axial to central chirality conversion (Scheme 21).^{93, 94} They designed the allenes with an electron-withdrawing group to prevent racemization. They showed that indoles **60** and these allenes **59** react to generate compounds **61** with good regioselectivities (induced by the EWG). Despite the severe loss of the stereochemical information in some cases, conversion percentages (defined as the *ee* of **61**/*ee* of **59**) were high in most examples.



Scheme 21. Hydroarylation between indoles and enantiomerically pure allenes.

Conclusions

Recent progress on the design of chiral gold complexes have lately enabled efficient enantioselective functionalization of indoles by many intramolecular and intermolecular strategies. This review shows the big efforts made by the scientific community to improve ligand design, to extend the scope of given reactivities, but also to better understand the associated mechanisms. Despite these actual progresses, a large number of well-known reactions developed in non enantioselective catalysis are underrepresented or even absent of the bibliographic picture. Firstly, it is clearly visible that intramolecular pathways dominate the literature. Some representative electrophiles have even no –or poorly efficient– intermolecular examples so far. For example, enantioselective intermolecular additions of indoles to allenes are scarce, which witnesses the challenge associated to this transformation. On the contrary, reactions involving highly reactive alkynyl-type electrophiles or allenamides are more documented. The linear geometry of gold complexes, making more challenging the stereocontrol of the process, forces to a careful design of the ligand to have excellent enantiocontrol. Here again, it is clear that reaction involving monosubstituted alkynes are highly challenging.

Given the small number of enantioselective processes that have been reported, enantioselective gold-catalysis applied to indole scaffolds has not revealed all its secrets and thus leaves huge horizons opened to the creativity of organic chemists.

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Notes and references

- 1 A. Baeyer, *Liebigs Ann.*, 1866, **140**, 295-296.
- 2 R. J. Sundberg, *The chemistry of indoles*, Academic Press New York, London, 1970.

- 3 S. E. O'Connor and J. J. Maresh, *Nat. Prod. Rep.*, 2006, **23**, 532-547.
- 4 S. Lakhdar, M. Westermaier, F. Terrier, R. Goumont, T. Boubaker, A. R. Ofial and H. Mayr, *J. Org. Chem.*, 2006, **71**, 9088-9095.
- 5 G. Bartoli, G. Bencivenni and R. Dalpozzo, *Chem. Soc. Rev.*, 2010, **39**, 4449-4465.
- 6 R. Dalpozzo, *Chem. Soc. Rev.*, 2015, **44**, 742-778.
- 7 S. Cacchi and G. Fabrizi, *Chem. Rev.*, 2005, **105**, 2873-2920.
- 8 S. Cacchi and G. Fabrizi, *Chem. Rev.*, 2011, **111**, PR215-PR283.
- 9 M. Inman and C. J. Moody, *Chem. Sci.*, 2013, **4**, 29-41.
- 10 M. Bandini and A. Eichholzer, *Angew. Chem. Int. Ed.*, 2009, **48**, 9608-9644.
- 11 J.-B. Chen and Y.-X. Jia, *Org. Biomol. Chem.*, 2017, **15**, 3550-3567.
- 12 A. S. K. Hashmi and G. J. Hutchings, *Angew. Chem. Int. Ed.*, 2006, **45**, 7896-7936.
- 13 A. Fürstner and P. W. Davies, *Angew. Chem. Int. Ed.*, 2007, **46**, 3410-3449.
- 14 N. Krause, V. Belting, C. Deutsch, J. Erdsack, H.-T. Fan, B. Gockel, A. Hoffmann-Roeder, N. Morita and F. Volz, *Pure Appl. Chem.*, 2008, **80**, 1063-1069.
- 15 M. H. Vilhelmsen and A. S. K. Hashmi, in *PATAI'S Chemistry of Functional Groups*, John Wiley & Sons, Ltd, 2009, DOI: 10.1002/9780470682531.pat0800.
- 16 I. Braun, A. M. Asiri and A. S. K. Hashmi, *ACS Catal.*, 2013, **3**, 1902-1907.
- 17 B. Ranieri, I. Escofet and A. M. Echavarren, *Org. Biomol. Chem.*, 2015, **13**, 7103-7118.
- 18 R. A. Widenhoefer, *Chem. Eur. J.*, 2008, **14**, 5382-5391.
- 19 A. S. K. Hashmi, M. Hamzic, F. Rominger and J. W. Bats, *Chem. Eur. J.*, 2009, **15**, 13318-13322.
- 20 S. Sengupta and X. Shi, *ChemCatChem*, 2010, **2**, 609-619.
- 21 A. Pradal, P. Y. Toullec and V. Michelet, *Synthesis*, 2011, 1501-1514.
- 22 G. Cera and M. Bandini, *Isr. J. Chem.*, 2013, **53**, 848-855.
- 23 W. Zi and D. F. Toste, *Chem. Soc. Rev.*, 2016, **45**, 4567-4589.
- 24 F. Pan, C. Shu and L.-W. Ye, *Org. Biomol. Chem.*, 2016, **14**, 9456-9465.
- 25 V. Pirovano, *Eur. J. Org. Chem.*, 2018, **2018**, 1925-1945.
- 26 M. Bandini, *Chem. Soc. Rev.*, 2011, **40**, 1358-1367.
- 27 G. Cera, M. Chiarucci, A. Mazzanti, M. Mancinelli and M. Bandini, *Org. Lett.*, 2012, **14**, 1350-1353.
- 28 C. Ferrer and A. M. Echavarren, *Angew. Chem. Int. Ed.*, 2006, **45**, 1105-1109.
- 29 C. Ferrer, C. H. M. Amijs and A. M. Echavarren, *Chem. Eur. J.*, 2007, **13**, 1358-1373.
- 30 M. Jia, G. Cera, D. Perrotta, M. Monari and M. Bandini, *Chem. Eur. J.*, 2014, **20**, 9875-9878.
- 31 V. Magné, F. Blanchard, A. Marinetti, A. Voituriez and X. Guinchard, *Adv. Synth. Catal.*, 2016, **358**, 3355-3361.
- 32 V. Magné, P. Retailleau, A. Marinetti, A. Voituriez and X. Guinchard, *Molbank*, 2018, M985.
- 33 N. Glinsky-Olivier, P. Retailleau and X. Guinchard, *Eur. J. Org. Chem.*, 2018, 5823.
- 34 W. Xu, W. Wang and X. Wang, *Angew. Chem. Int. Ed.*, 2015, **54**, 9546-9549.
- 35 L. Zhang, Y. Wang, Z.-J. Yao, S. Wang and Z.-X. Yu, *J. Am. Chem. Soc.*, 2015, **137**, 13290-13300.
- 36 N. Sabat, F. Soualmia, P. Retailleau, A. Benjdia, O. Berteau and X. Guinchard, *Org. Lett.*, 2020, **22**, 4344-4349.
- 37 V. Magné, A. Marinetti, V. Gandon, A. Voituriez and X. Guinchard, *Adv. Synth. Catal.*, 2017, **359**, 4036-4042.
- 38 P. Aillard, A. Voituriez, D. Dova, S. Cauteruccio, E. Licandro and A. Marinetti, *Chem. Eur. J.*, 2014, **20**, 12373-12376.
- 39 L. Huang, H.-B. Yang, D.-H. Zhang, Z. Zhang, X.-Y. Tang, Q. Xu and M. Shi, *Angew. Chem. Int. Ed.*, 2013, **52**, 6767-6771.
- 40 J.-M. Yang, P.-H. Li, Y. Wei, X.-Y. Tang and M. Shi, *Chem. Commun.*, 2016, **52**, 346-349.
- 41 W. Zi, H. Wu and F. D. Toste, *J. Am. Chem. Soc.*, 2015, **137**, 3225-3228.
- 42 N. Zheng, Y.-Y. Chang, L.-J. Zhang, J.-X. Gong and Z. Yang, *Chem. Asian J.*, 2016, **11**, 371-375.
- 43 J. Matsuoka, H. Kumagai, S. Inuki, S. Oishi and H. Ohno, *J. Org. Chem.*, 2019, **84**, 9358-9363.
- 44 W. Yang and A. S. K. Hashmi, *Chem. Soc. Rev.*, 2014, **43**, 2941-2955.
- 45 K. L. Toups, G. T. Liu and R. A. Widenhoefer, *J. Organomet. Chem.*, 2009, **694**, 571-575.
- 46 M.-Z. Wang, C.-Y. Zhou, Z. Guo, E. L.-M. Wong, M.-K. Wong and C.-M. Che, *Chem. Asian J.*, 2011, **6**, 812-824.
- 47 Z. Zhang, C. Liu, R. E. Kinder, X. Han, H. Qian and R. A. Widenhoefer, *J. Am. Chem. Soc.*, 2006, **128**, 9066-9073.
- 48 C. Liu and R. A. Widenhoefer, *Org. Lett.*, 2007, **9**, 1935-1938.
- 49 Y.-Y. Zhang, Y. Wei and M. Shi, *Chem. Commun.*, 2019, **55**, 4210-4213.
- 50 Y.-Y. Zhang, Y. Wei and M. Shi, *Org. Lett.*, 2019, **21**, 8250-8255.
- 51 Z. L. Niemeyer, S. Pindi, D. A. Khrakovsky, C. N. Kuzniewski, C. M. Hong, L. A. Joyce, M. S. Sigman and F. D. Toste, *J. Am. Chem. Soc.*, 2017, **139**, 12943-12946.
- 52 L. Zhang, *J. Am. Chem. Soc.*, 2005, **127**, 16804-16805.
- 53 V. Magné, Y. Sanogo, C. S. Demmer, P. Retailleau, A. Marinetti, X. Guinchard and A. Voituriez, *ACS Catal.*, 2020, DOI 10.1021/acscatal.0c01819.
- 54 P. Aillard, D. Dova, V. Magne, P. Retailleau, S. Cauteruccio, E. Licandro, A. Voituriez and A. Marinetti, *Chem. Commun.*, 2016, **52**, 10984-10987.
- 55 R. Fang, Z. Feng, A. M. Kirillov and L. Yang, *Organometallics*, 2020, **39**, 1782-1789.
- 56 Z.-Q. Shen, X.-X. Li, J.-W. Shi, B.-L. Chen and Z. Chen, *Tetrahedron Lett.*, 2015, **56**, 4080-4083.
- 57 R. Ocello, A. De Nisi, M. Jia, Q.-Q. Yang, M. Monari, P. Giacinto, A. Bottoni, G. P. Miscione and M. Bandini, *Chem. Eur. J.*, 2015, **21**, 18445-18453.
- 58 M. Jia, M. Monari, Q.-Q. Yang and M. Bandini, *Chem. Commun.*, 2015, **51**, 2320-2323.
- 59 W. Huang, Y.-C. Zhang, R. Jin, B.-L. Chen and Z. Chen, *Organometallics*, 2018, **37**, 3196-3209.
- 60 V. Pirovano, L. Decataldo, E. Rossi and R. Vicente, *Chem. Commun.*, 2013, **49**, 3594-3596.
- 61 N. Mézailles, L. Ricard and F. Gagosz, *Org. Lett.*, 2005, **7**, 4133-4136.
- 62 Y. Wang, P. Zhang, Y. Liu, F. Xia and J. Zhang, *Chem. Sci.*, 2015, **6**, 5564-5570.
- 63 V. Pirovano, M. Borri, G. Abbiati, S. Rizzato and E. Rossi, *Adv. Synth. Catal.*, 2017, **359**, 1912-1918.
- 64 V. Pirovano, E. Arpini, M. Dell'Acqua, R. Vicente, G. Abbiati and E. Rossi, *Adv. Synth. Catal.*, 2016, **358**, 403-409.
- 65 Y. Wang, P. Zhang, X. Di, Q. Dai, Z. M. Zhang and J. Zhang, *Angew. Chem. Int. Ed.*, 2017, **56**, 15905-15909.
- 66 N. Glinsky-Olivier and X. Guinchard, *Synthesis*, 2017, **49**, 2605-2620.
- 67 R. Dalpozzo, *Molecules*, 2016, **21**, 699.
- 68 C. Ingallina, I. D'Acquarica, G. Delle Monache, F. Ghirga, D. Quaglio, P. Ghirga, S. Berardozi, V. Markovic and B. Botta, *Curr. Pharm. Des.*, 2016, **22**, 1808-1850.
- 69 M. Bandini and A. Eichholzer, *Angew. Chem. Int. Ed.*, 2009, **48**, 9533-9537.

- 70 M. Bandini, A. Gualandi, M. Monari, A. Romaniello, D. Savoia and M. Tragni, *J. Organomet. Chem.*, 2011, **696**, 338-347.
- 71 M. Bandini, A. Bottoni, M. Chiarucci, G. Cera and G. P. Miscione, *J. Am. Chem. Soc.*, 2012, **134**, 20690-20700.
- 72 N. Glinsky-Olivier, S. Yang, P. Retailleau, V. Gandon and X. Guinchard, *Org. Lett.*, 2019, **21**, 9446-9451.
- 73 B. V. Subba Reddy, M. Swain, S. M. Reddy, J. S. Yadav and B. Sridhar, *J. Org. Chem.*, 2012, **77**, 11355-11361.
- 74 S. W. Youn, *J. Org. Chem.*, 2006, **71**, 2521-2523.
- 75 V. Gobé, P. Retailleau and X. Guinchard, *Chem. Eur. J.*, 2015, **21**, 17587-17590.
- 76 M. Marín-Luna, O. Nieto Faza and C. Silva López, *Front. Chem.*, 2019, **7**.
- 77 Y.-C. Lee and K. Kumar, *Isr. J. Chem.*, 2018, **58**, 531-556.
- 78 A. Marinetti, H. Jullien and A. Voituriez, *Chem. Soc. Rev.*, 2012, **41**, 4884-4908.
- 79 C. H. M. Amijs, C. Ferrer and A. M. Echavarren, *Chem. Commun.*, 2007, 698-700.
- 80 C. H. M. Amijs, V. López-Carrillo, M. Raducan, P. Pérez-Galán, C. Ferrer and A. M. Echavarren, *J. Org. Chem.*, 2008, **73**, 7721-7730.
- 81 H. Seo, B. P. Roberts, K. A. Abboud, K. M. Merz and S. Hong, *Org. Lett.*, 2010, **12**, 4860-4863.
- 82 P. de Frémont, H. Clavier, V. Rosa, T. Avilés and P. Braunstein, *Organometallics*, 2011, **30**, 2241-2251.
- 83 C.-M. Chao, M. R. Vitale, P. Y. Toullec, J.-P. Genêt and V. Michelet, *Chem. Eur. J.*, 2009, **15**, 1319-1323.
- 84 A. Pradal, C.-M. Chao, M. R. Vitale, P. Y. Toullec and V. Michelet, *Tetrahedron*, 2011, **67**, 4371-4377.
- 85 E. S. Andreiadis, M. R. Vitale, N. Mézailles, X. Le Goff, P. Le Floch, P. Y. Toullec and V. Michelet, *Dalton Trans.*, 2010, **39**, 10608-10616.
- 86 J. Yang, R. Zhang, W. Wang, Z. Zhang and M. Shi, *Tetrahedron: Asymmetry*, 2011, **22**, 2029-2038.
- 87 Z. Zhang, V. Smal, P. Retailleau, A. Voituriez, G. Frison, A. Marinetti and X. Guinchard, *J. Am. Chem. Soc.*, 2020, **142**, 3797-3805.
- 88 S. M. Inamdar, A. Konala and N. T. Patil, *Chem. Commun.*, 2014, **50**, 15124-15135.
- 89 C. C. J. Loh and D. Enders, *Chem. Eur. J.*, 2012, **18**, 10212-10225.
- 90 M. Chiarucci, E. Matteucci, G. Cera, G. Fabrizi and M. Bandini, *Chem. Asian J.*, 2013, **8**, 1776-1779.
- 91 M. Chiarucci, R. Mocchi, L.-D. Syntrivanis, G. Cera, A. Mazzanti and M. Bandini, *Angew. Chem. Int. Ed.*, 2013, **52**, 10850-10853.
- 92 S. Naoe, Y. Yoshida, S. Oishi, N. Fujii and H. Ohno, *J. Org. Chem.*, 2016, **81**, 5690-5698.
- 93 D. R. Sutherland, L. Kinsman, S. M. Angiolini, G. M. Rosair and A.-L. Lee, *Chem. Eur. J.*, 2018, **24**, 7002-7009.
- 94 For a review dealing on chirality transfer and memory of chirality in gold-catalyzed processes, see: N. T. Patil, *Chem. Asian J.*, 2012, **7**, 2186-2194.