Research Statement

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I shall be describing my main research line on *Global Lie theory*, my secondary research line on *foliations and Picard-Lefschetz theory* and my *other research interests*, this including my publications, work in progress and research lines to be pursued in the future.

1 Global Lie theory

Lie theory is one of the most fundamental subjects in mathematics. It is deeply linked to every branch of geometry, for symmetries of geometric structures are in most cases encoded by Lie groups. Moreover, spaces intimately related to Lie groups play a prominent role in important areas of geometry: this is the case for example of symmetric and homogeneous spaces in Riemannian geometry, coadjoint orbits in symplectic geometry and the coadjoint representation in Poisson geometry.

My current research addresses global aspects of the relation between symplectic groupoids and Poisson structures and their interaction with various geometries. This amounts to a very broad generalization of the relation between the symplectic geometry of the cotangent bundle of a compact Lie groupoid and the Poisson geometry of its coadjoint representation. A large number of topics -some of them seemingly unrelated- are coming together in my research, interacting in a most exciting way, and opening many avenues to be explored. The list includes:

- Poisson geometry and symplectic lie groupoids.
- Lie groupoids and regular resolutions.
- Integral affine geometry.
- Nielsen realization problem and moduli of K3 surfaces.
- Homotopy theory of diffeomorphism groups of compact coadjoint orbits.
- Chern Weyl theory, equivariant cohomology and Schubert calculus.

1.1 Poisson geometry and Lie groupoids

A Poisson structure on a manifold makes precise the notion of a possibly singular foliation by symplectic leaves, the latter being the submanifolds to which Hamiltonian vector fields are tangent. Poisson geometry is an old subject which goes back to the discovery of Poisson brackets [52]. It has had a rapid development in its last decades due to strong connections among others with deformation quantization theory [6], singularity theory [56], completely integrable systems [19] and generalized complex geometry [25]. It is this many links what makes nowadays Poisson geometry a central subject and what explains why advances in Poisson geometry are bound to have deep impact in a number of different areas.

In sharp contrast with symplectic geometry, the flexibility of Poisson structures prevents the existence of a rich general theory which applies in a satisfactory manner, more so when it comes to global or semi-local questions: invariants such as Poisson cohomology [55] and the obstruction to the existence of integrable systems realizing regular Poisson manifolds [15] are hardly computable; semi local normal form theorems only apply in very particular situations [14]; there is no satisfactory deformation theory.

Clarifying the existence of a class of Poisson manifolds rigid enough to possess a rich general theory is a capital problem. My research is proving that the class of Poisson manifolds of compact type (henceforth PCMT) solves such fundamental question. It is laying both a powerful general theory [10, 11, 12] and methods to construct PMCT [13]. The novelty and key feature in my approach is the use of Lie groupoids and a blend of tools coming from integral affine geometry, singularity theory, complex geometry, foliation theory, algebraic topology, Chern Weyl theory, equivariant cohomology and Schubert calculus.

Lie groupoids -generalizations of Lie groups formalizing the notion of partial symmetry- appear in the picture because a Poisson structure on a manifold defines a Lie algebroid structure on its cotangent bundle. Not all Lie algebroids integrate into a Lie groupoid [8, 9]. If the Lie algebroid of a Poisson structure is integrable, the maximal or canonical integration carries a multiplicative symplectic structure [9]; for example the linear Poisson structure on the dual of the Lie algebra of a Lie group G is integrable, and its canonical symplectic integration is $(T^*G, d\lambda)$, where G is the 1-connected Lie group integrating the given Lie algebra, and $d\lambda$ is the canonical symplectic 2-form on a cotangent bundle.

A PMCT is defined as an integrable Poisson manifold whose canonical Lie groupoid is compact (and Hausdorff). While the definition of PMCT is simple, their study falls into the very challenging problem of relating global properties of Lie groupoids to global properties of their Lie algebroids, an area in which I have already made contributions [39].

Seen from a different perspective my research addresses foundational questions for a multiplicative version of symplectic topology: drawing global consequences for a compact Lie groupoid from the existence of a multiplicative symplectic form (obstructions), and providing explicit constructions of compact Lie groupoids endowed with multiplicative symplectic structures. These results and the many tools needed to prove them will have important consequences in many fields.

1.2 Lie groupoids and regular resolutions

Lie groupoids appear often in classification of geometric structures, when it is important to know not only when two objects are equivalent, but in how many ways they are equivalent. The manifold of objects of a Lie groupoid carries a (possibly singular) characteristic foliation, each leaf being a connected component of objects in the same equivalent class. It is of great importance to have as much information as possible on the leaf space of a Lie groupoid.

Of course, this task is easier if the Lie groupoid is regular, meaning that the characteristic foliation is a regular foliation.

A proper Lie groupoid is the generalization of a proper group action of a Lie group on a manifold. Another aspect of my current research is the introduction for any proper symplectic groupoid $\mathcal{G} \rightrightarrows M$ of a regular resolution [13]. This is by definition a proper regular (presymplectic) Lie groupoid mapping onto $\mathcal{G} \rightrightarrows M$ diffeomorphically over the regular part, and inducing a homeomorphism of leaf spaces. In other words, it can be understood as a resolution of singularities of the leaf space $M/\mathcal{G}$. More generally, in [13] for any proper Lie groupoid $\mathcal{H} \rightrightarrows Y$ a canonical partial regular resolution is constructed (a global version of the Weyl's covering theorem [18]). This partial resolution induces a homeomorphism of leaf spaces and has a minimality property, so it should be understood as the proper Lie groupoid with the least singular characteristic foliation and leaf space $Y/\mathcal{H}$.

Certainly, this construction should become a fundamental tool for the study of proper Lie groupoids. More specifically, I will be addressing possible applications to quantization of proper Lie groupoids and complex analogs of the construction (which should extend the Grothendieck simultaneous resolution).

1.3 Integral affine geometry

An integral affine structure on a manifold is given by an atlas whose changes of coordinates are integral affine transformations, meaning that the linear part of the affine transformation must have integer coefficients. After a period of intense activity and important results [21, 22, 23], the interest in (integral) affine structures receded mostly because of the difficulty in proving the main conjectures in the field, the Auslander and the Markus conjectures on the structure of the fundamental group and the developing map on an affine manifold.

Any Lagrangian torus fibration induces an integral affine structure on its base [17]. Integral Poisson structures enter in Poisson geometry in a similar fashion: If a regular Poisson manifold is integrated by a regular symplectic Lie groupoid with compact (source) fibers, then its leaf space admits the structure of an integral affine orbifold [58]. An important consequence of the existence of the regular resolution [13], is that the leaf space of a Poisson manifold integrated by a symplectic Lie groupoid with compact fibers is always an integral affine manifold [11], despite the characteristic foliation being singular.

The role of integral affine geometry is crucial in my study of PMCT, since it is the unique geometric tool which allows us to go from semilocal to global considerations [11].

In the other direction, Lie groupoids are the right framework for integral affine geometry, since they permit to reformulate the whole theory in a global manner (without choices). I shall be addressing the application of the Lie groupoid viewpoint to (integral) affine geometry.

1.4 Nielsen realization problem and moduli of K3 surfaces

The Nielsen realization problem in its more general form, asks for when a given closed manifold F there exists over a given subgroup of the mapping class group $\mathrm{Diff(F)}/\mathrm{Diff(F)}^0$ -or more generally over a subgroup of automorphisms of the cohomology ring- a right inverse to the map from the group of diffeomorphisms to the mapping class group (respectively the group of automorphism of the cohomology ring). A famous result of Kerchoff [34] states that for a closed surface any finite group of the mapping class group admits a lift to the group of diffeomorphisms. Later, Morita [49] showed that a right inverse does not exist over the whole mapping class group, since it is obstructed by certain characteristic classes.

When F is the 4-manifold underlying a K3 surface, a result in the spirit of Morita [20], asserts that there is no right inverse from the mapping class group of a K3 surface to the group of diffeomorphisms. Making extensive use of the refined moduli space of marked K3 surfaces [3], I have constructed right inverses over subgroups of the group of automorphism of the cohomology ring of a K3 surface [12]. The relation with my research in Poisson geometry, is that those right inverses give rise to fibrations $K3 \hookrightarrow M \to B$ over an integral affine tori with fiber the K3, and the fibers are nothing but the leaves of the characteristic foliation of a Poisson structure of compact type that can be constructed on M.

These families of K3 are very different from the known ones in complex geometry, since the cohomology class of the real part of the holomorphic symplectic structure varies from fiber to fiber (and the base B is compact). I will be addressing the existence of other interesting structures in these families, such as Riemannian metrics or generalized complex structures.

1.5 Homotopy theory of diffeomorphism groups of compact coadjoint orbits

In the theory of PMCT, homogeneous bundles over symplectic manifold are of great importance, since a semi-local normal form asserts that these spaces are the building blocks of PMCT [10]. The simplest non-trivial case is that of homogeneous bundles over the 2-sphere. It is natural to investigate how many of these building blocks we have. In other words, given G a compact, connected semisimple Lie group and $\mathcal{O}$ a coadjoint orbit, it is important to know whether for different principal G bundles the associated bundles with fiber $\mathcal{O}$ are different or not. And one can ask whether they are different as Hamiltonian bundles or just as bundles. Since a principal G bundle over the sphere can be identified with a homotopy class in $\pi_1(G)$, the question is whether the natural maps

$$\pi_1(G) \to \pi_1(\mathrm{Ham}(\mathcal{O}, \omega_{\mathcal{O}})), \tag{1}$$

$\omega_{\mathcal{O}}$ the Konstant-Kirillov-Souriau symplectic form, and

$$\pi_1(G) \to \pi_1(\mathrm{Diff}(\mathcal{O})), \tag{2}$$

are injective. The question on the injectivity of (1) was raised by Weinstein [57], and answered in the positive [50] (see also [7]).

Observe that the analysis of the injectivity of (2) is important in several areas of mathematics. For Poisson geometry because of the aforementioned study of building blocks of PMCT. For symplectic geometry because a central problem in the field is to understand how the group of Hamiltonian diffeomorphism sits inside other classical groups. For topology because groups of diffeomorphisms of closed manifold are Hilbert manifolds, and therefore much of their topological properties are controlled by their homotopy theory.

When G is a classical group I have shown that (2) is injective [46], and I expect the injectivity to hold for all compact, connected semisimple Lie groups.

1.6 Chern Weyl theory, equivariant cohomology and Schubert calculus

Perhaps the most classical algebraic invariant to distinguish spaces is cohomology (homology). In my research on homogeneous bundles over the 2-sphere, cohomology with integral coefficients is the tool to distinguish the trivial bundle $S^2 \times \mathcal{O}$ with fiber a coadjoint orbit of a compact, connected, semisimple Lie groupoid, from the associated bundle Y coming from a twisted principal G-bundle.

More precisely, the use of Wang long exact sequence exhibits the integral cohomology ring of Y as an extension of the integral cohomology ring of the flag variety $\mathcal{O}$ by itself, the latter viewed as an $H^*(\mathcal{O};\mathbb{Z})$ module.

Chern-Weyl theory appears when we pass to rational coefficients, since the Chern-Weyl homomorphism (Borel homomorphism) identifies the rational cohomology of Y with the rational cohomology of the trivial bundle [27]. Hence the problem is a fine one, since we must distinguish spaces whose rational cohomology is identical by carefully comparing their integral cohomology. This comparison is delicate, since already for flag varieties the Borel homomorphism cannot quite describe the integral cohomology [5, 54]. Therefore methods from Schubert calculus are being extended from flag varieties [4] to our more general setting of homogeneous fibrations over the 2-sphere. Together with localization techniques in equivariant cohomology, they are the main tools for the delicate computations we are carrying out [46].

Part of the previous strategy does extend to study the torsion part of $\pi_1(\mathrm{Diff}(F))$, where F is a closed orientable manifold whose cohomology ring is concentrated in even dimensions, and satisfies the strong Lefschetz property. I intend to explore such generalization.

2 Foliations and Picard-Lefschetz theory

There is no Morse theory for foliations. As a result most of the constructions of differential topology cannot be carried to foliations.

The analog of Morse theory for complex projective manifolds is Picard-Lefschetz theory. Very much as a Morse function on a compact manifold furnishes a CW complex decomposition of the manifold, a Lefschetz pencil structure on a projective manifold presents it (possibly after a blow up) as a family of codimension one subvarieties over the complex projective line.

My research on foliation theory is centered about codimension 1 foliations $(M, \mathcal{F})$ which admit a closed 2-form making each leaf symplectic, referred to as 2-calibrated foliations. These are in particular Poisson manifolds, but of a very special kind. A very important feature is that there is a Picard-Lefschetz theory for them [37] and therefore some constructions of differential topology can be carried out. The topics which arise in my research on foliations include:

- Approximately holomorphic geometry.
- Gluing techniques for Poisson and related structures.

General codimension one foliations do not posses "submanifolds", these defined as submanifolds inheriting a codimension one foliation (transverse to the foliation). Picard-Lefschetz theory provides submanifolds for our class of

2-calibrated foliations, and most surprisingly these submanifolds capture the topology of the leaf space $(M, \mathcal{F})$ [37].

The leaf space of a foliation $(M, \mathcal{F})$ is the leaf space of its holonomy groupoid [48]. My current research [44] aims at proving that the submanifolds provided by Picard-Lefschetz theory capture not just the leaf space of $(M, \mathcal{F})$, but the transverse geometry of the foliation. In other words, the injection of the submanifold in M should provide an essential equivalence between the corresponding holonomy groupoids.

2.1 Approximately holomorphic geometry for symplectic and related structures

In recent years there has been an enormous success in the study of closed symplectic manifolds using approximately holomorphic methods. These methods -introduced by S. Donaldson in 1996 [16]- amount to treating symplectic manifolds as generalizations of Kähler manifolds. It is convenient to think of a symplectic manifold -once a compatible almost complex structure J has been fixed- as a Kähler manifold (X, J, ω) for which the integrability condition for J has been dropped. Assuming $[\omega]$ to be an integral class, and very much as in a Hodge manifold, there is an associated very ample complex line bundle. Of course in general there will not be J-holomorphic sections, but nevertheless it is possible to find sequences of sections which asymptotically behave as J-holomorphic ones. Moreover, among them it is possible to find linear systems with suitable genericity conditions. In particular one can construct sections transverse to the zero section to produce symplectic submanifolds, rank one generic linear systems to introduce an analog of Picard-Lefschetz theory, etc.

I have done research to extend approximately holomorphic theory to odd dimensional versions of symplectic geometry: these include contact structures, the codimension one foliations referred to in the previous section, and more generally manifolds with a closed 2-forms and a codimension one distribution which is symplectic with respect to the 2-form ("2-calibrated structures").

My work in approximately holomorphic geometry includes: A proof of the existence of contact submanifolds of closed contact manifolds [32], a generalization of the famous Giroux' open book decompositions in contact geometry to 2-calibrated structures [35], a construction of contact embeddings of closed contact manifolds endowed Giroux' open book decompositions, in standard contact spheres endowed with the standard linear open book decompositions [41], an extension of Picard-Lefschetz theory and the construction of generic linear systems of any rank to 2-calibrated manifolds [30, 31, 38] and the construction of generic linear systems for projective CR manifolds (CR manifolds embedded in complex projective space) of hypersurface type [40].

2.2 Gluing techniques for Poisson and related structures

In manifold theory one can produce a new manifold by giving two manifolds with boundary, and an isotopy class of diffeomorphisms of the boundary. Surgeries are instances of this construction: one starts with an n-manifold and an embedded (k-1)-sphere with framed trivial normal bundle. A small tubular neighborhood of the sphere is drilled out to produce a manifold with boundary. The second manifold is the k-handle $D^k \times D^{n-k}$; the gluing map between the boundaries is determined by the chosen framing [24]. These gluing procedures, most notably surgeries, have been shown to be extremely useful to describe the topology of higher dimensional manifolds, i.e those with dimensions bigger or equal than five.

For a given geometric structure without local invariants it is a relevant problem to explore which gluing constructions are compatible with it. The absence of local invariants is often reflected in the large size of the group of symmetries of the structure, and in the existence of normal forms around certain kinds of submanifolds. Therefore one may be able to isotope the gluing diffeomorphism into morphisms of the structure. The consequence is that new manifolds carrying such type of structure can be produced, and in some situations with control over some of their topological invariants.

I have adapted to Poisson geometry Gompf's normal connected sum of symplectic manifolds [29], proving in particular that any finitely presented group is the fundamental group of a 5-dimensional regular Poisson manifold with 4-dimensional symplectic leaves. I have also introduced a couple of surgeries for 2-calibrated foliations to show that this class of foliations is large enough. The surgeries are an analog of the normal connected sum and a Lagrangian or generalized Dehn surgery, the latter very much related to the monodromies around critical points arising from Picard-Lefschetz theory [37].

Very recently, the 5-sphere has been shown to admit a regular Poisson structure with 4-dimensional symplectic leaves [47], and with characteristic foliation one of Lawson's foliations. This constructions raises very natural questions which I plan to explore. Namely, whether there is an alternative construction of such Poisson structure using the surgeries the generalized Dehn surgery introduced in [37], and how to generalize the construction to higher dimensional spheres.

Another aspect of generalized Dehn surgery which I will be exploring, is its use to build new examples of 4-dimensional b-symplectic with prescribed hypersurface of non-symplectic points [26].

3 Other research interest

Apart from my main and secondary research lines, I have conducted research in the following fields:

3.1 Symplectic and locally conformal symplectic geometry

A question I have been interested in is momentum maps for Hamiltonian actions. In [33], I showed that for a closed symplectic manifold whose symplectic form is integral, all integrable Hamiltonian systems with compact symmetry group exhibit asymptotically polynomial integrability. That is, the momentum map can be uniformly approximated by polynomials.

Very important symplectic manifolds are constructed by infinite dimensional symplectic reduction. The first example is the space of flat connections on G-bundles over Riemann surfaces [1]; another important example, closer my research, is the construction of symplectic groupoids of integrable Poisson manifolds [9]. More generally, there is a whole philosophy advocating the use of "standard" constructions in symplectic and Riemannian geometry, to approach very important and difficult problems in Kahler geometry. In [42], I noticed that a very simple construction in symplectic geometry, namely that around a fixed point of a Hamiltonian action the linearized action is Hamiltonian with momentum map the quadratic expansion of the momentum map for the action, extends to the Frechet setting. In this way, and using work on the symplectic geometry of non-linear Grassmannian of symplectic submanifolds of a symplectic manifold [28], I gave a conceptual explanation of a well known momentum map for the action of the Lie algebra of Hamiltonian vector fields of a closed integral symplectic manifold on the space of sections of its prequantum line bundle.

A locally conformal symplectic structure on a manifold is given by a non-degenerate 2-form which locally is conformal to a closed 2-form. These structures were first introduced in the complex setting, since there were non-Kahler surfaces such as the Hopf manifolds, which had natural Hermitian metrics locally conformal to Kahler ones. A fundamental result in symplectic geometry is the theorem of Tischler and Gromov on the existence of symplectic embeddings of integral closed symplectic manifolds on projective space (the analog of Kodaira's embedding theorem). In [45], I have proved an analog in the locally conformal setting of Tischler and Gromov embedding theorem. Using the appropriate version of Moser's theorem [2], I have related my construction with work of Ornea and Verbitsky on embeddings of an appropriate class of locally conformal Kahler manifolds on linear Hopf manifolds [51].

3.2 Non-degenerate vector fields of top degree

On a compact manifold volume forms are classified by their total volume. Dually, a similar classification holds for no-where vanishing top degree multivector fields. The next interesting class of top degree multivector fields are those vanishing transversely. In dimension two, this is the class of topologically stable Poisson structures introduced and classified in [53]. In [36] I extended the results in [53] and classified multivector fields vanishing transversely.

3.3 Convexity in complex geometry

Convexity of a bounded domain Ω of Euclidean space is an affine notion, and two approaches are possible: a global or synthetic one in which the intersection of $\overline{\Omega}$ with any affine line is asked to be either empty of connected, and an infinitesimal or analytical one which assumes $\partial\Omega$ to be a C^2-hypersurface, and requires its Euclidean shape operator to be definite positive at every point. Convexity can be generalized to the complex setting in two different ways, according to whether we want it to be a complex analytic or a complex affine property. In the first case the appropriate notion is that of (Levi) pseudoconvexity. In the second case the correct notion is $\mathbb{C}$-convexity: a bounded connected open subset $\Omega \subset \mathbb{C}^N$ is $\mathbb{C}$-convex if the intersection of $\overline{\Omega}$ with any complex affine line is either empty or 1-connected; the infinitesimal approach asks the restriction of the Euclidean shape operator to the subspace of complex tangencies $J(T_x\partial\Omega) \cap T_x\partial\Omega$ to be positive definite. The novelty in [43] is the study of strict $\mathbb{C}$-convex domains using the differential geometry of the complex Gauss map, rather than the classical methods of 1-variable complex analysis (Riemann mapping theorem).

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