

Project Title Non-commutative analysis and geometry: actions of quantum groups and noncommutative manifolds.

Aims and Background

Broad Aim This proposal covers a novel viewpoint on non-commutative (analogies of) Riemannian manifolds and their study through recently developed methods in non-commutative analysis. It aims bringing together an international team of experts **I have not seen any experts mentioned in the application below** with a new approach to fundamental and long-standing problems in geometry **such as** and harmonic analysis **such as**.

There exist two approaches to the study of Riemannian manifolds: the classical one underlying the whole of classical differential geometry (which treats manifold X as a locally Euclidean space) and the modern one introduced by Connes (which treats manifold as a spectral triple). A spectral triple consists of $*$ -algebra \mathcal{A} represented on a Hilbert space H and an unbounded self-adjoint operator D on H and satisfying a few properties spelt out below in General Background. Connes' beautiful idea [8] allowing to compare both theories may be described as follows: let $\mathcal{A} = C^\infty(X)$ be the algebra of all smooth functions on X , let $H = L_2\Omega(X)$ be the Hilbert space of all square-integrable forms on X and let D be a Hodge-Dirac operator on H (see e.g. [2]). A fundamental Connes Reconstruction Theorem [10] tells us that so-defined spectral triple captures all the geometric information about a manifold X available from the classical approach. This result confirms the efficacy of this new approach based on spectral triples.

Classical Riemannian manifolds are often equipped with a Lie group action. For instance, if X is the real sphere \mathbb{S}^{n-1} , then an orthogonal group $SO(n)$ acts on it by rotations. Moreover, rotations are exactly those automorphisms of the sphere which commute with Laplace-Beltrami operator Δ_g (see the definition in General Background below). If, in general, a Lie group G acts on a manifold X , then one wants to take this action into account by constructing a Laplace-type or a Dirac-type operator compatible with this action. A natural way to achieve this objective is to request that the Dirac-type operator featuring in the definition of the spectral triple commutes with the action of the group (see e.g. construction of Dirac operator on the sphere given in [22]).

In the noncommutative realm, when we move from classical manifolds to noncommutative ones and replace the commutative algebra $\mathcal{A} = C^\infty(X)$ with a noncommutative C^* or pre- C^* -algebra \mathcal{A} we usually have an action of a given Lie group (or even quantum group) on \mathcal{A} . This noncommutative analogue of the property "the operator D commutes with a group action" is called an *equivariance property*. If, for example, our quantum group is a q -deformation of a classical Lie group, then we require D to commute with q -deformed left regular representation of the group. Precisely this setting opens an avenue of marrying deep ideas of noncommutative geometry with penetrating methods of noncommutative analysis, which lay at the heart of this proposal.

The main idea of our proposal consists in the new method of studying of non-commutative manifolds which are equipped with a natural action of (quantum) group action. The CI will investigate actions of groups (more broadly, quantum groups) on noncommutative manifolds using novel methods recently developed in non-commutative analysis with his immediate participation. The program which we outline below will benefit to both Non-commutative Geometry and Non-commutative Analysis. In particular, our proposal envisages a strong contribution to a grand program started by Connes-Tretkoff [17] concerning curvature and higher order smooth invariants and suggests a completely different perspective on Connes Reconstruction Theorem. Simultaneously with quantum groups actions we shall introduce and study an equivariant Dirac operator on a variety of noncommutative manifolds which captures both the geometric information about the manifold and the quantum group, thus adding new features to the latter theorem. More importantly, endowing Connes Reconstruction Theorem with these new features will make it amenable for a vast generalization of this theorem suitable for non-commutative manifolds admitting equivariance property for actions of quantum groups.

General Background Operator algebras provide a natural edifice to many areas of classical and modern Mathematics. They also play a paramount role in the present proposal. A particular role is played by the class of C^* -algebras (uniformly closed $*$ -subalgebras in the $*$ -algebra $B(H)$ of all bounded operators on a Hilbert space H) and that of von Neumann algebras (weakly closed $*$ -subalgebras in $B(H)$). The topological requirements imposed on these algebras make them a suitable foundation for developing noncommutative analysis.

The starting point of noncommutative geometry can be traced back to the Gelfand-Naimark theorem which delivers a duality between category of locally compact topological spaces and that of commutative C^* -algebras. Briefly speaking, it allows to express numerous topological properties of underlying spaces in the language of C^* -algebras. This theorem can be viewed as an anti-equivalence between the category of locally compact Hausdorff spaces and the category of commutative C^* -algebras. The correspondence anti-equivalence is given by the map $X \rightarrow C_0(X)$, where $C_0(X)$ is the algebra of all continuous functions which vanish at infinity. This may be interpreted as the statement that all the information about a space is actually encoded in the algebra of continuous functions on it. Thus one may think of noncommutative C^* -algebras as noncommutative topological spaces and attempts to apply topological methods to understand these algebras are well justified.

Another fundamental result due to von Neumann and Segal provides a duality between category of measure spaces and that of commutative von Neumann algebras. This fact provided impetus to view a classical measure theory as a part of von Neumann algebras theory and further develop noncommutative integration theory.

A conventional wisdom suggests further analogies between classical and quantum worlds. While topology and measure theory were supplied with natural quantum counter-parts yet in 1950s, the geometrical developments were lacking until 1980's. In fact, starting from von Neumann himself, a number of researchers tried to find a quantum analogue of geometry (that is, to construct a functor from useful geometric categories to treatable quantum categories), however the success of their attempts was questionable.

Let us now briefly review the foundational features of the classical differential geometry. We start with the notion of a Riemannian manifold which is its pillar. Usually, a manifold is defined as a topological space in which every point admits a neighborhood which is homeomorphic to Euclidean space. A manifold (denoted further by X) equipped with a smooth metric tensor (denoted further by g) is called Riemannian.

So far, the most successful attempt to quantise the notion of Riemannian manifold is due to Connes who introduced the notion of a spectral triple and promoted it as an analogue of Riemannian manifold and further as a convenient vehicle for new (noncommutative) differential geometry comprising closed Riemannian manifolds as a very special example.

We say that (\mathcal{A}, H, D) is a spectral triple if

1. $\pi : \mathcal{A} \rightarrow B(H)$ is a representation of the $*$ -algebra \mathcal{A} on the separable Hilbert space H .
2. D is a self-adjoint unbounded operator on H .
3. for every $a \in \mathcal{A}$, the commutator is bounded.
4. for every $a \in \mathcal{A}$, the operator $\pi(a)(D + i)^{-1}$ is compact.
5. if, for every $a \in \mathcal{A}$, singular values of the operator $\pi(a)(D + i)^{-1}$ decrease as $k^{-\frac{1}{d}}$, the spectral triple is called d -dimensional.

With every Riemannian manifold X , one can associate a spectral triple (\mathcal{A}, H, D) as follows: (i) \mathcal{A} is the algebra $C^\infty(X)$ of all smooth functions on X ; (ii) H is the Hilbert space $L_2\Omega(X)$ of all square-integrable forms on X ; (iii) D is the Hodge-Dirac operator D (see e.g. [2]) on $L_2\Omega(X)$. It is folklore (at least for compact manifolds) that the just constructed spectral triple (\mathcal{A}, H, D) is d -dimensional, where $d = \dim(X)$ (by Garding inequality [30] this assertion does not depend on the choice of metric tensor; hence, one can choose a special metric tensor which makes verification of this claim straightforward).

As we already stated earlier, the celebrated Reconstruction Theorem due to Connes [10] stipulates that every spectral triple with commutative \mathcal{A} (satisfying a few natural conditions) comes from a d -dimensional Riemannian manifold X . Thus it makes good sense to think of spectral triples as noncommutative manifolds. We wholeheartedly adopt this point of view in this proposal and shall develop it much further.

Hodge-Dirac operator D is a convenient tool to identify and describe the isometries of the manifold X . If $\gamma : X \rightarrow X$ is an isometry and if $U : L_2\Omega(X) \rightarrow L_2\Omega(X)$ is the composition operator (with γ), then (i) U is unitary on $L_2\Omega(X)$; (ii) U preserves $\pi(\mathcal{A})$ (that is, $U^{-1}\pi(\mathcal{A})U = \pi(\mathcal{A})$); (iii) U commutes with D . Conversely, every diffeomorphism $\gamma : X \rightarrow X$ which commutes with D is an isometry. This simple but revealing result can be found in [23].

As is typical in applications to harmonic analysis [23] and mathematical physics [20], manifolds are equipped with isometric action of Lie groups. Moreover, most examples of the manifolds which are of serious interest and importance in applications are actually homogeneous spaces of some Lie group (e.g., the sphere \mathbb{S}^{n-1} is a homogeneous space of the Lie group $SO(n)$). In such a situation, it does not make sense to consider manifold alone, but rather only a manifold equipped with an isometric group action. We propose to investigate spectral triples which arise from action of Lie group (or some other group-like object like quantum group) on a manifold (including, of course, non-commutative manifolds as a prime source of inspiration for our proposal).

Group-like objects which are most suitable for this role are quantum groups, whose theory was developing since early 1980's. The theory of quantum groups has its origin in attempts to find a good duality theorem, analogous to Pontryagin duality theorem, for general locally compact non-Abelian groups. In late 1980's, Woronowicz developed a general theory of compact quantum groups and developed a Peter-Weyl theory for them. One of the main examples in Woronowicz's theory is the quantum group $SU_q(n)$ (a natural q -deformation of the compact Lie group $SU(n)$).

The rich interplay between Lie groups and differential geometry naturally raises the question of understanding the interaction between quantum groups and noncommutative geometry. Papers [5], [27] (among many others) attempt to put quantum groups within the framework of Non-commutative Geometry. These attempts drew serious attention of Alain Connes (see [6]) who developed further results by Chakraborty and Pal [5]. Our proposal is in fact partly motivated by these developments.

In this project, we aim to construct spectral triples for certain quantum groups (e.g. compact quantum groups like $SU_q(n)$ and $SO_q(n)$ as well as non-compact quantum groups like $SL_q(n)$) and their homogeneous spaces, to investigate the validity of major results in Non-commutative Geometry (such as Connes Character

Formula) for these examples and to compute numerically those topological invariants (such as their K -theory) which follow from these results.

We complete this Section by explaining another very popular option, allowing to supply a spectral triple with a natural (semi)-group action, that is an action of the heat semi-group associated with a Hodge-Laplace operator. If (X, g) is a Riemannian manifold, then $-D^2$ is a Hodge-Laplace operator (denoted further by Δ_g) and its component acting on 0 order forms is Laplace-Beltrami operator (also denoted by Δ_g) [30]. Heat semi-group is now defined by the formula

$$t \rightarrow e^{t\Delta_g}, \quad t > 0.$$

If X is compact, then resolvent of Laplace-Beltrami operator Δ_g is compact. Hence, $e^{t\Delta_g}$ is compact for $t > 0$. In fact, it happens that $e^{t\Delta_g}$ belongs to the trace class for $t > 0$.

In the seminal work [33], Weyl proved that

$$\lim_{t \downarrow 0} (4\pi t)^{\frac{d}{2}} \text{Tr}(e^{t\Delta_g}) = \text{Vol}(X), \quad t \downarrow 0. \quad (1)$$

After Weyl's work, it became an established custom to measure various geometric (and often topological) quantities associated with Riemannian manifold X in terms of heat semi-group expansion $t \rightarrow e^{t\Delta_g}$, $t > 0$. A mere existence of such expansion is a famous Minakshisundaram-Plejel theorem (among all approaches to that theorem, the most readable one is given in [30]; even though Theorem 3.24 there concerns only a special case $f = 1$, the proof of the formula stated below in general case is very similar).

For every $f \in C^\infty(X)$, Minakshisundaram-Plejel theorem asserts an existence of an asymptotic expansion

$$\text{Tr}(M_f e^{t\Delta_g}) \approx (4\pi t)^{-\frac{d}{2}} \cdot \sum_{n \geq 0} a_n(f) t^n, \quad t \downarrow 0. \quad (2)$$

Here, d is the dimension of X and $M_f : L_2(X) \rightarrow L_2(X)$ is a multiplication operator. Moreover, there exist functions $A_k \in C^\infty(X)$ such that

$$a_k(f) = \int_X A_k \cdot f d\text{vol}_g, \quad (3)$$

where vol_g is the standard volume element on X given in local coordinates by the formula

$$d\text{vol}_g = (\det(g))^{\frac{1}{2}}(x) dx.$$

As follows from (1), $A_0 = 1$. Further computations (see e.g. Proposition 3.29 in [30]) show that

$$A_1 = \frac{1}{6} R,$$

where R is the scalar curvature. In particular, $a_1(1)$ is the Einstein-Hilbert action (see e.g. [8]).

Note that a_0 extends to a normal state h on $L_\infty(X)$ by the obvious formula

$$h(f) = \int_X f d\text{vol}_g, \quad f \in L_\infty(X).$$

Equation (3) can be re-written as

$$a_k(f) = h(A_k \cdot f), \quad f \in C^\infty(X).$$

DIMA!! Where are subheadings? You must finish General Background somewhere and somehow and move to next Sections!!

One of the *primary targets* of this project is finding a suitable extension of Minakshisundaram-Plejel theorem (and, consequently, Weyl theorem — see formula (1)) for a vast class of non-commutative manifolds (such as non-commutative tori with generic, non-flat, metric tensor). This grand program began in [17] (published only in 2011, but the main concepts and techniques were developed yet in 90's), where special 2-dimensional non-commutative manifolds (conformal deformations of a flat non-commutative torus) were considered. The authors of [17] proved that Euler characteristic of such manifold is 0 by means of Gauss-Bonnet theorem (recall that the classical Gauss-Bonnet theorem asserts that Euler characteristic of the 2-dimensional Riemannian manifold equals to the average of its scalar curvature). Subsequently, the scalar curvature (for the conformal deformation of the 2-dimensional non-commutative torus) was explicitly computed in [15] and [19] and, later, the term a_2 (the first place where the Riemann curvature tensor manifests itself beyond the scalar curvature) was further computed in [12] (intermediate computations include about a million terms!). Below, we briefly restate the whole programme as it can be surmised from in [17].

For a given d -dimensional spectral triple (\mathcal{A}, H, D) , the steps needed to be done in the program are as follows (for brevity we omit π from the formulae below):

1. to prove a non-commutative version of Weyl theorem, that is, to find a normal state h on \mathcal{A}'' such that

$$\mathrm{Tr}(xe^{-tD^2}) \approx (4\pi t)^{-\frac{d}{2}} h(x), \quad t \downarrow 0, \quad (4)$$

for every $x \in \mathcal{A}''$;

2. to prove a non-commutative version of Minakshisundaram-Plejel theorem or, equivalently, to verify that following strong generalization of (2) holds

$$\mathrm{Tr}(xe^{-tD^2}) \approx (4\pi t)^{-\frac{d}{2}} \sum_{n \geq 0} a_n(x) t^n, \quad t \downarrow 0,$$

for every $x \in \mathcal{A}''$;

3. to verify the normality of coefficients as in (3) with respect to the volume state, i.e., to show that

$$a_k(x) = h(xA_k), \quad x \in \mathcal{A}'',$$

for every $k \geq 0$ and for some $A_k \in \mathcal{A}''$;

4. to compute A_k explicitly.

When this mission is accomplished, one can *define* a scalar curvature of a non-commutative manifold by setting $R = 6A_1$.

We acknowledge that this program sets reasonable objectives but we claim that the tools based on pseudo-differential calculus in various guises applied up-to-date to accomplish it have been inadequate. Our main technical innovation which we bring here is based on the novel Double Operator Integration technique developed by CI recently in close collaboration with Alain Connes and Fedor Sukochev. The particular integral representations (see Approach to Aims 1,2,3 below) arose in [16] when geometric measures on Julia sets were recovered by means of the singular traces. They form the core contribution of UNSW team (including the CI) to [16].

One of the fundamental tools in noncommutative geometry is the Chern character. The Connes Character Formula (also known as the Hochschild character theorem) provides an expression for the class of the Chern character in Hochschild cohomology, and it is an important tool in the computation of the Chern character. The formula has been applied to many areas of noncommutative geometry and its applications: such as the local index formula [14], the spectral characterisation of manifolds [10] and recent work in mathematical physics [11]. We point out to its applications in [10] as particularly relevant to the theme of this application.

In its original formulation, [7], the Character Formula is stated as follows: Let (\mathcal{A}, H, D) be a p -dimensional compact spectral triple with (possibly trivial) grading Γ . By the definition of a spectral triple, for all $a \in \mathcal{A}$ the commutator $[D, a]$ has an extension to a bounded operator $\partial(a)$ on H . Assume for simplicity that $\ker(D) = \{0\}$ and set $F = \mathrm{sgn}(D)$. For all $a \in \mathcal{A}$ the commutator $[F, a]$ is a compact operator in the weak Schatten ideal $\mathcal{L}_{p,\infty}$ (see e.g. [8, 26]).

Consider the following two linear maps on the algebraic tensor power $\mathcal{A}^{\otimes(p+1)}$, defined on an elementary tensor $c = a_0 \otimes a_1 \otimes \cdots \otimes a_p \in \mathcal{A}^{\otimes(p+1)}$ by setting

$$\mathrm{Ch}(c) := \frac{1}{2} \mathrm{Tr}(\Gamma F[F, a_0][F, a_1] \cdots [F, a_p]), \quad \Omega(c) := \Gamma a_0 \partial a_1 \partial a_2 \cdots \partial a_p.$$

Then the Connes Character Formula states that if c is a Hochschild cycle then

$$\mathrm{Tr}_\omega(\Omega(c)(1 + D^2)^{-p/2}) = \mathrm{Ch}(c)$$

for every Dixmier trace Tr_ω . In other words, the multilinear maps Ch and $c \mapsto \mathrm{Tr}_\omega(\Omega(c)(1 + D^2)^{-p/2})$ define the same class in Hochschild cohomology. We mention, in passing, that the generality of the result just stated was achieved fairly recently by the CI and his co-authors, see [4].

There has been great interest in generalising the tools and results of noncommutative geometry to the “non-compact” (i.e., non-unital) setting. The definition of a spectral triple associated to a non-unital algebra originates with Connes [9], was furthered by the work of Rennie [29] and Gayral, Gracia-Bondía, Iochum, Schücker and Varilly [21]. Earlier, similar ideas appeared in the work of Baaj and Julg [1]. Additional contributions to this area were made by Carey, Gayral, Rennie and Sukochev [3]. The conventional definition of a non-compact spectral triple is to replace the condition that $(1 + D^2)^{-1/2}$ be compact with the assumption that for all $a \in \mathcal{A}$ the operator $a(1 + D^2)^{-1/2}$ is compact. This raises an important question: is the Connes Character Formula true for locally compact spectral triples? This question was suggested to the CI by Professor Connes himself during Shanghai conference celebrating 70-th anniversary of A. Connes (Fudan University). During lengthy discussions covering substantial range of topics of importance in non-commutative geometry, Professor Connes, in particular had emphasized to the CI that such an extension could be an excellent starting point for several new directions

in non-commutative geometry. Here are two such directions. Firstly, the Connes Character Formula plays an important role in the reconstruction theorem for closed Riemannian manifolds, and it is natural to expect that its extension would play a similar role for locally compact Riemannian manifolds. Secondly, developing suitable new techniques needed for a self-contained theory of locally compact spectral triples should also open an avenue for treating the case of noncommutative manifolds with boundary, in particular punctured manifolds. This suggestion by Professor Connes has been taken seriously by the CI and preliminary work in this direction has already brought substantial fruits. Firstly, jointly with Professor Sukochev, the CI has achieved a substantial progress in treating locally compact spectral triples using novel analytic methods (this work has not yet been published). Secondly, in the ground-breaking manuscript co-authored by Professor Connes and the CI (and a number of collaborators from UNSW) the new approach to spectral triples involving *symmetric, non-self-adjoint* operators has been proposed [13]. This is precisely the required tools allowing to develop new theory for non-commutative Riemannian manifolds with boundary. This development indicate the importance and timeliness of the present proposal which is already achieved a serious progress and leads to a unified theory of locally compact manifolds with boundary and incomplete manifolds. We emphasize that the progress achieved involves joint work with luminaries like Alain Connes, and local top experts in noncommutative analysis and geometry like Alan Carey, Adam Rennie and Fedor Sukochev.

Specific aims There are 7 specific aims.

Aim 1: Investigate when Chern character provides an asymptotic expansion for the heat semi-group. More precisely, when

$$\mathrm{Tr}(\Omega(c)e^{-s^2D^2}) = \mathrm{Ch}(c)s^{-p} + O(s^{1-p}), \quad s \downarrow 0, \quad (5)$$

for every Hochschild cycle $c \in \mathcal{A}^{\otimes(p+1)}$? This aim is in "high completion status" due to the yet unpublished joint work with Fedor Sukochev. We need, however, to substantially revise and strengthen that work and take into account serious connections with Local Index Formula as in [3, 14] ignored in the first version.

Aim 2: Aim 1 above is closely related (albeit, not equivalent) to the question about analyticity of a suitable ζ -function. The latter is an analytic function defined by the formula

$$z \rightarrow \mathrm{Tr}(\Omega(c)(1 + D^2)^{-\frac{z}{2}}), \quad \Re(z) > p.$$

We aim to find an analytic extension to the half-plane $\Re(z) > p - 1$ so that

$$\lim_{z \rightarrow p} (z - p) \mathrm{Tr}(\Omega(c)(1 + D^2)^{-\frac{z}{2}}) = p \mathrm{Ch}(c).$$

Aim 3: The purpose of the Connes Character Formula is to compute the Hochschild class of the Chern character by a "local" formula, which is customarily stated in terms of singular traces on the ideal $\mathcal{L}_{1,\infty}$ ($\mathcal{L}_{1,\infty}$ is the principal ideal in $B(H)$ generated by an operator with singular values $(\frac{1}{k})_{k \geq 1}$). Here, trace $\varphi : \mathcal{L}_{1,\infty} \rightarrow \mathbb{C}$ is a unitarily invariant linear functional; it can be seen from CI's results in [26] that such a functional is automatically singular. Show that

$$\varphi(\Omega(c)(1 + D^2)^{-\frac{p}{2}}) = \mathrm{Ch}(c). \quad (6)$$

for every (normalised) trace φ on $\mathcal{L}_{1,\infty}$ and for every Hochschild cycle $c \in \mathcal{A}^{\otimes(p+1)}$. Equivalently, show that

$$\sum_{k=0}^n \lambda(k, \Omega(c)(1 + D^2)^{-p/2}) = \mathrm{Ch}(c) \log(n) + O(1), \quad n \rightarrow \infty.$$

Here, $\lambda(k, T)$ means the k -th eigenvalue (counted with algebraic multiplicity) of a compact operator T .

Aims 2 and 3 are intimately connected with Aim 1, however, the amount of analytical complications which arise when one navigates between formulas stated in all three aims is enormous and requires a very careful treatment and certainly warrants a separation of these aims.

Aim 4: Introduce a generic (i.e., not necessarily a conformal deformation of a flat one) Laplace-Beltrami operator Δ on the non-commutative torus and non-commutative Euclidean space. Prove a non-commutative version of Minakshisundaram-Pleijel theorem (for these manifolds) as outlined above.

Aim 4, in turn, depends on Aims 1 and 2, or rather on the technical instruments which are to be developed to deal with those aims in full generality.

Aim 5: Compute explicitly the curvature for a generic Riemannian metric on the non-commutative torus and non-commutative Euclidean space.

This aim, if achieved (and we are in a very strong position to do so) amounts to completion of the program started by [5, 6, 27].

Aim 6: Construct a spectral triple (possibly, twisted one) on quantum groups (like $SU_q(n)$) and on their homogeneous spaces (like Podleś sphere). Previous attempts [5] suffer from "dimension drop" pathology (that is, spectral dimension differs from cohomological one). We aim to have an equivariance property for the Dirac operator in a way that prevents "dimension drop" pathology.

Aim 7: Design a version of Connes Character Formula for the above spectral triples which recovers a non-trivial cocycle.

Generally speaking, the development of noncommutative geometry and its applications is hindered by the paucity of non-trivial examples demonstrating its richness and ability to *compute* quantities of geometric significance for (genuine) noncommutative manifolds. This direction of study also involves top class practitioners of Noncommutative Analysis and Quantum Probability such as Marius Junge (University of Illinois) and Nigel Higson (Penn State University). The CI is in regular contact with both (they both are to visit UNSW in 2019) and this collaboration is to continue unabated.

Future Fellowship Candidate

The proposed research deals with subtle issues concerning axioms of free probability theory and the notions paramount for the development of Non-commutative Analysis. The CI is well prepared to attack this important problem: during 2015–2018, the candidate held an ARC DECRA titled "New concept of independence in non-commutative probability theory" and achieved deep results which substantially improved understanding of the theory, its problems and approaches. An acknowledgement of this assertion can be seen from the CI's paper [24] published in *Advances in Mathematics*. In this publication a long standing problem about non-commutative analogue of the Poisson process (defying efforts of top experts in the area) has been resolved. In the process of work on these deep problems, CI has acquired his ideas concerning the notion of non-commutative manifolds. Furthermore, the candidate has also established strong research collaboration with a number of world leading experts in the area (including a genuine legend of modern mathematics Professor Alain Connes). The collaboration with Professor Connes has yielded recently publications [16] containing important results in Non-commutative Geometry based on the theory of singular traces (this theory was largely developed in CI's works and CI co-authored the world first monograph [26] on the subject). It should be pointed out that Professor Connes is very enthusiastic about the suggested direction of research and this strong endorsement from the world leading expert and his on-going commitment to the joint research efforts is a strong acknowledgement that the candidate has the capacity to undertake the proposed research.

The CI is currently employed as UNSW Scientia Fellow (75% research load, 25 % teaching load). CI plans to spend 100% of his research time on this project. CI also teaches high-level courses for UNSW best students, who will be recruited to do the research related to this project.

Project quality and innovation

Significance The problems to be considered are fundamental and are at the forefront of the modern Non-commutative Analysis and are of substantial importance for Noncommutative Geometry. The complete resolution of Aims 1-7 will be important for development of both disciplines, especially for Non-commutative Geometry. This is a mature project with an experienced CI who has already made significant progress and with a star-line of current and potential collaborators (Connes, Junge, Higson, Ponge, Carey, Rennie, Sukochev). Other researchers actively work in the field, so this is becoming a very competitive area of investigation, however, we are in the unique vaulting position to achieve success in the next four years.

Approach to specific aims Here we describe methods in our possession which we are going to employ in order to resolve the problems stated above.

Approach to Aim 1: Our computations show, for a chain $c = a_0 \otimes \cdots \otimes a_p \in \mathcal{A}^{\otimes(p+1)}$, that

$$\text{Ch}(c) := \frac{1}{2} \text{Tr}(\Gamma F[F, a_0][F, a_1] \cdots [F, a_p] e^{-s^2 D^2}) + O(s), \quad s \downarrow 0.$$

It seems plausible that Hochschild cochain on the right hand side is cohomologous to the one in the left hand side in (5). In fact, we have already made initial computations confirming this guess in the already mentioned unpublished joint work with Professor Sukochev.

Approach to Aim 2: The ζ -function, whose analyticity should be proved in Aim 1 is of the shape $z \rightarrow \text{Tr}(CB^z)$. We have $C = AC$ (hence $C = A^z C$) for a suitable A and, therefore,

$$\text{Tr}(CB^z) = \text{Tr}(CB^z A^z).$$

It is desirable to replace $B^z A^z$ with $(A^{\frac{1}{2}} B A^{\frac{1}{2}})^z$. For this purpose, we use the integral representation

$$B^z A^z - (A^{\frac{1}{2}} B A^{\frac{1}{2}})^z = T_z(0) - \int_{\mathbb{R}} T_z(s) \widehat{g}_z(s) ds,$$

where $(s, z) \rightarrow \widehat{g}_z(s)$ is a sufficiently good scalar-valued function and where

$$T_z(s) = B^{z-1+is} [B A^{\frac{1}{2}}, A^{z-\frac{1}{2}+is}] Y^{-is} + B^{is} [B A^{\frac{1}{2}}, A^{\frac{1}{2}+is}] Y^{z-1-is}.$$

By using Double Operator Integration technique as developed in [28], we aim to prove analyticity of the right hand side and, hence, of the left hand side. The application of this techniques is our trump card and the joint

work with Professor Connes [16], in which we have completed the work started by such giants as Connes and Sullivan, and which left dormant for more than 20 years, until our new techniques was brought to bear on that problem is an explanation to such unbridled optimism.

Approach to Aim 3: Having established analyticity of the function

$$z \rightarrow \text{Tr}(C(A^{\frac{1}{2}}BA^{\frac{1}{2}})^z), \quad \Re(z) > p-1,$$

with simple pole at $z = p$, we expect that methods from [31] will lead us to the formula

$$\varphi(CA^{\frac{1}{2}}BA^{\frac{1}{2}}) = \frac{1}{p} \lim_{z \rightarrow p} (z-p) \text{Tr}(C(A^{\frac{1}{2}}BA^{\frac{1}{2}})^z)$$

for every (normalised) trace on $\mathcal{L}_{1,\infty}$. We shall draw on the the deep theory of singular traces and its connections with operator ζ -functions which the CI (with various collaborators) has been developing since 2009 [26, 31]. The CI is in the unique position to apply numerous and well-developed techniques from that theory in order to achieve this aim.

Approach to Aim 4: The very definition of Laplace-Beltrami operator, involves a determinant of a matrix-valued function. On matrices, determinant is defined as (practically unique) homomorphism into a field of scalars. On matrix-valued functions, it is defined pointwise.

However, on a non-coimmutative manifold, matrix-valued function is replaced with a matrix whose entries belong to a von Neumann algebra. Though a surrogate notion of determinant (due to Fuglede and Kadison) exists for such matrices, our computations show an inconsistency in the formula (4) above. That is, instead of the volume state, a different functional appears on the right hand side of (4).

We propose to sacrifice the property "determinant is homomorphism" for being able to perform computations making the formula (4) consistent with the definition of Laplace-Beltrami operator. Precisely, we set

$$G^{-\frac{1}{2}} = (\det(g_{ij}))^{-\frac{1}{2}} \stackrel{def}{=} \pi^{-\frac{d}{2}} \int_{\mathbb{R}^d} e^{-\sum_{i,j} g_{ij} t_i t_j} dt.$$

Now, define the volume state h by setting $h(x) = \tau(xG^{\frac{1}{2}})$ and consider an inner product $(x, y) \rightarrow h(xy^*)$ on the non-commutative torus. Define Laplace-Beltrami operator by the formula

$$-\Delta_g x = M_{G^{-\frac{1}{2}}} \sum_{i,j=1}^d D_i M_{G^{\frac{1}{4}}(g^{-1})_{ij} G^{\frac{1}{4}}} D_j x.$$

Our computations show that so-defined operator is self-adjoint (and positive) and that formula (4) becomes consistent. It should be also stated that this particular problem has been discussed in depth with Professor Raphael Ponge, who is to take part time position on ARC funded grant (with CI Fedor Sukochev) in UNSW for the next few years. Professor Ponge (who is a former PhD student of Alain Connes and a top class expert in noncommutative differential geometry) is actively involved in the discussions with CI concerning this plan of action. Again, our preliminary discussion with Raphael as well as with PhD student at UNSW, Edward McDonald, make us confident that this aim is achievable. The presense of Professor Ponge at UNSW will be a bonus and will strengthen the cooperation between him, the CI and McDonald, which the CI has already initiated.

Approach to Aim 5: In the special case of conformal deformation, Laplace-Beltrami operator is (unitarily equivalent to) $M_h \Delta M_h$, where Δ is the flat Laplacian. According to the asymptotics in Aim 3, the function

$$z \rightarrow \text{Tr}(M_x(-M_h \Delta M_h)^{-z})$$

admits an analytic extension with at most simple poles at $z = \frac{d}{2}, \frac{d}{2} - 1, \dots$. The curvature term is provided (for $d > 2$) by the residue of this function at the point $\frac{d}{2} - 1$. Our function has a shape

$$z \rightarrow \text{Tr}(C(A^{\frac{1}{2}}BA^{\frac{1}{2}})^z).$$

It is desirable to replace $(A^{\frac{1}{2}}BA^{\frac{1}{2}})^z$ with $B^z A^z$. Here, we propose to use an integral representation similar to (but more complicated than) the one specified in the Approach to Aim 2. Again, despite numerous technical setbacks which are encountered by anyone who tries to perform the step outlined above, we are confident that our novel double operator integration techniques is the "magic wand" which will open this serious technical problem for successful resolution.

In the case of general metric tensor, formulae become much harder and more investigation is required.

Approach to Aim 6: Spectral triple constructed in [5] is equivariant and its spectral dimension is 3. However, every 3-cocycle is cohomologous to 0 and, therefore, homological dimension is strictly less than 3.

We expect that the reason of this phenomenon is the wrong choice of q -deformed left regular representation. Our aim is to find a suitable q -deformation which make spectral triple to be equivariant, 3-dimensional and,

at the same time allow certain 3-cocycles to be non-trivial. Natural candidate for such a 3-cocycle is the Hochschild class of the Chern Character. Successful resolution of Aims 1,2,3 will deliver the required technical tools to determine the "correct representation" and such cocycles.

Approach to Aim 7: It is extremely probable that ordinary spectral triples in this setting should be replaced by twisted ones (when commutator is unbounded, but twisted commutator is bounded). At the moment, no satisfactory theory is available which allows to derive Connes Character formula for such triples. The only attempt is made in [18]. However, we expect that a combination of approaches from [18] and [4] would yield (at least a germ of) such a theory.

The expected results and timeframe Below we schedule the tasks for the next 4 years.

Character formula via heat semi-group, year 1. Method proposed in [4] seems more reliable than approaches in [22]. This method provides a cluster of mutually cohomologous Hochschild cocycles. Key obstruction is that in our setting the corresponding cocycles are not exactly cohomologous. Hence, it is necessary to measure how far the cocycles in this cluster are from being cohomologous to each other. This requires certain commutator estimates to be developed during the first year.

Character formula via ζ -function residue, year 1. Strong empirical evidence suggests the equivalence of Aims 1 and 2. Namely, the more is known about poles of the ζ -function, the better asymptotic for the heat semi-group can be derived. In reality, the situation is not 100% clear — it looks like no information about the poles outside of the real line can be acquired from the heat semi-group asymptotic. We expect, however, that one-side implication is correct, that is Aim 2 should actually follow from Aim 1.

Character formula via singular traces, year 2. Previous tailor-made approaches [3] are not sufficiently strong to derive Connes Character formula in its full glory. The first task in Aim 3 is to build a theoretical framework which allows to derive (6) from the formulae in Aims 1 and 2. We expect the integral representations specified in the Approach to Aim 3 (see above) to form a core of this framework. Precise conditions under which the methodology works well are yet unknown and one needs an honest theoretical investigation of the limitations of the methodology.

Minakshisundaram-Plejel theorem for non-commutative manifolds, year 3. We expect that Laplace-Beltrami operator introduced in Approach to Aim 4 (see above) is compatible with heat semi-group asymptotic up to terms of arbitrarily high order. One needs to investigate conditions under which such an asymptotic exists.

Computation of the curvature term, year 3. We plan to refine methods in [25] by involving Double and Multiple Operator Integrals.

Equivariant Dirac operator on quantum groups, year 4.

Feasibility and Strategic Alignment The CI has already demonstrated his capacity to make significant, original and innovative contributions to wide range of Non-commutative Analysis and Non-commutative Geometry. He has co-authored the very first monograph on singular traces [26], which has albeit in embryonic form, some necessary components to attack Aim 3. The project presents a realistic timeframe as seen from above. Confidence in the feasibility is enhanced by the following:

1. The CI has already demonstrated his research credentials in the field of Noncommutative Analysis. His numerous papers in this area are published in the highly ranked journals like Crelle's Journal, Advances in Mathematics, Journal of Functional Analysis.
2. The CI wrote a number of publications in the field of Mathematical Physics. For example, paper [32] is published in prestigious journal Communications in Mathematical Physics.
3. The CI has co-authored a number of publications in the field of Classical Analysis.
4. The CI has authored a research monograph [26] jointly written with S. Lord and F. Sukochev. The substantial portion of this monograph describes CI's contribution to the field of Non-commutative Geometry and related parts of Quantised Calculus. At the moment, second edition of the book is in preparation.
5. The CI can rely on support and expert advice from the members of the Noncommutative Analysis group at UNSW (M. Cowling, I. Doust, D. Potapov, F. Sukochev).

It should also be pointed out that some parts of the current proposal have been thoroughly discussed with Professor Alain Connes (Fields medalist) who is the originator of (and leading expert in) Non-commutative Geometry. Professor Connes strongly and enthusiastically endorsed the ideas and methods underlying this proposal and the approach.

Benefit and collaboration

The CI expects the project to produce significant results and to publish them in the most reputed journals. In addition, the CI expects the project to be beneficial in the following ways.

- a. Enhance the scale and focus of research in the Strategic Research Priorities. The current project is directed towards the development of skills and knowledge and is well-aligned with the part "Deliver skills for the new economy" (Lifting Productivity and Economic Growth) in the Strategic Research Priorities. **THERE IS NO SUCH PART IN SRP!!! WHAT TO DO?**

b. Enhance international collaboration in research. The CI is collaborating with highly-distinguished international experts (Alain Connes, Kenneth Dykema, Nigel Higson, Marius Junge). This collaboration already resulted in a number of papers in prestigious journals. Involvement of the mathematicians of such a calibre would be beneficial not only for this project, but for all the mathematical research in UNSW.

c. Improve the international competitiveness of Australian research. The area of free probability is the cutting edge research in the modern probability theory. This proposal is on par with efforts of top world experts in the area and thus enhances the Australian position in research.

Communication of results

Management of data UNSW has implemented a data storage solution for every stage in the life cycle of a research project. The data management plan for the project will be established using UNSW's resources when applicable. Data will be archived using UNSW's Long-term Data archive (or other archive mechanism as applicable). Data will be made discoverable by registration on discipline-specific registries and indexation services.

References

- [1] Baaj, S., Julg, P. *Théorie bivariante de Kasparov et opérateurs non bornés dans les C^* -modules hilbertiens*. C. R. Acad. Sci. Paris Sér. I Math. **296** (1983), no. 21, 875–878.
- [2] Berline N., Getzler E., Vergne M. *Heat kernels and Dirac operators*. Grundlehren der Mathematischen Wissenschaften, **298**. Springer-Verlag, Berlin, 1992.
- [3] Carey A., Gayral V., Rennie A., Sukochev F. *Integration on locally compact noncommutative spaces*. J. Funct. Anal. **263** (2012), no. 2, 383–414; Carey A., Gayral V., Rennie A., Sukochev F. *Index theory for locally compact noncommutative geometries*. Mem. Amer. Math. Soc. **231** (2014), no. 1085, vi+130 pp.
- [4] Carey A., Rennie A., Sukochev F., Zanin D. *Universal measurability and the Hochschild class of the Chern character*. J. Spectr. Theory **6** (2016), no. 1, 1–41.
- [5] Chakraborty P., Pal A. *Equivariant spectral triples on the quantum $SU(2)$ group*. K-Theory **28** (2003), no. 2, 107–126; Chakraborty P., Pal A. *Spectral triples and associated Connes-de Rham complex for the quantum $SU(2)$ and the quantum sphere*. Comm. Math. Phys. **240** (2003), no. 3, 447–456.
- [6] Connes A. *Cyclic cohomology, quantum group symmetries and the local index formula for $SU_q(2)$* . J. Inst. Math. Jussieu **3** (2004), no. 1, 17–68.
- [7] Connes A. *Geometry from the spectral point of view*. Lett. Math. Phys., **34** (3) 203–238, 1995.
- [8] Connes A. *Noncommutative geometry*. Academic Press, Inc., San Diego, CA, 1994.
- [9] Connes A., *Noncommutative geometry and reality*. J. Math. Phys. **36** (1995), 6194–6231.
- [10] Connes A. *On the spectral characterization of manifolds*. J. Noncommut. Geom. **7** (2013), no. 1, 1–82.
- [11] Chamseddine, A., Connes, A., Mukhanov, V. *Quanta of geometry: noncommutative aspects*. Phys. Rev. Lett. **114** (2015), no. 9, 091302, 5pp.
- [12] Connes A., Fathizadeh F. *The term a_4 in the heat kernel expansion of noncommutative tori*. arXiv:1611.09815
- [13] Connes A., Levitina G., McDonald E., Sukochev F., Zanin D. *Noncommutative Geometry for Symmetric Non-Self-Adjoint Operators*. arXiv:1808.01772
- [14] Connes A., Moscovici H. *The local index formula in noncommutative geometry*. Geom. Funct. Anal. **5** (1995), no. 2, 174–243.
- [15] Connes A., Moscovici H. *Modular curvature for noncommutative two-tori*. J. Amer. Math. Soc. **27** (2014), no. 3, 639–684.
- [16] Connes A., Sukochev F., Zanin D. *Trace theorem for quasi-Fuchsian groups*. Mat. Sb. **208** (2017); Connes A., McDonald E., Sukochev F., Zanin D. *Conformal trace theorem for Julia sets of quadratic polynomials*. Ergodic Theory Dyn. Syst. Published online: 04 December 2017. <https://doi.org/10.1017/etds.2017.124>
- [17] Connes A., Tretkoff P. *The Gauss-Bonnet theorem for the noncommutative two torus*. Noncommutative geometry, arithmetic, and related topics, 141–158, Johns Hopkins Univ. Press, Baltimore, MD, 2011.
- [18] Fathizadeh F., Khalkhali M. *Twisted spectral triples and Connes' character formula*. Perspectives on noncommutative geometry, 79–101, Fields Inst. Commun., **61**, Amer. Math. Soc., Providence, RI, 2011.
- [19] Fathizadeh F., Khalkhali M. *Scalar curvature for the noncommutative two torus*. J. Noncommut. Geom. **7** (2013), no. 4, 1145–1183; Fathizadeh F., Khalkhali M. *Scalar curvature for noncommutative four-tori*. J. Noncommut. Geom. **9** (2015), no. 2, 473–503.
- [20] di Francesco P., Mathieu P., Senechal D. *Conformal Field Theory*. Springer-Verlag, New York, 1997.
- [21] Gayral V., Gracia-Bondia J., Iochum B., Schücker T., Varilly J. *Moyal planes are spectral triples*. Comm. Math. Phys. **246** (2004), no. 3, 569–623.
- [22] Gracia-Bondia J., Varilly J., Figueroa H. *Elements of noncommutative geometry*. Birkhäuser Advanced Texts: Basler Lehrbücher. Birkhäuser Boston, Inc., Boston, MA, 2001.
- [23] Helgason S., *Differential geometry, Lie groups, and symmetric spaces*. Graduate Studies in Mathematics, **34**. American Mathematical Society, Providence, RI, 2001.

- [24] Junge M., Sukochev F., Zanin D. *Embeddings of operator ideals into L_p -spaces on finite von Neumann algebras*. Adv. Math. **312** (2017), 473–546.
- [25] Lesch M. *Divided differences in noncommutative geometry: rearrangement lemma, functional calculus and expansional formula*. J. Noncommut. Geom. **11** (2017), no. 1, 193–223.
- [26] Lord S., Sukochev F., Zanin D. *Singular traces. Theory and applications*. De Gruyter Studies in Mathematics, **46**. De Gruyter, Berlin, 2013.
- [27] Neshveyev S., Tuset L. *The Dirac operator on compact quantum groups*. J. Reine Angew. Math. **641** (2010), 1–20; Dabrowski L., Landi G., Sitarz A., van Suijlekom W., Varilly J. *The Dirac operator on $SU_q(2)$* . Comm. Math. Phys. **259** (2005), no. 3, 729–759.
- [28] Potapov D., Sukochev F. *Operator-Lipschitz functions in Schatten-von Neumann classes*. Acta Math. **207** (2011), no. 2, 375–389; Potapov D., Sukochev F. *Unbounded Fredholm modules and double operator integrals*. J. Reine Angew. Math. **626** (2009), 159–185.
- [29] Rennie A. *Smoothness and locality for nonunital spectral triples*. K-Theory **28** (2003), no. 2, 127–165; Rennie A. *Summability for nonunital spectral triples*. K-Theory **31** (2004), no. 1, 71–100.
- [30] Rosenberg S. *The Laplacian on a Riemannian manifold. An introduction to analysis on manifolds*. London Mathematical Society Student Texts, **31**. Cambridge University Press, Cambridge, 1997.
- [31] Sukochev F., Usachev A., Zanin D. *Singular traces and residues of the ζ -function*. Indiana U. Math. J., **66** (2017), no. 4, 1107–1144.
- [32] Sukochev F., Zanin D. *Connes integration formula for the noncommutative plane*. Comm. Math. Phys. **359** (2018), no. 2, 449–466.
- [33] Weyl H. *Das asymptotische Verteilungsgesetz der Eigenwerte linearer partieller Differentialgleichungen (mit einer Anwendung auf die Theorie der Hohlraumstrahlung)*. Math. Ann. **71** (1912), no. 4, 441–479.