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# ABSTRACTS

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## Special Session 185 : Multiscale Analysis: Geometry and Evolution Problems (mSPACE)

Organizer(s): Delio Mugnolo , Leonard Monsaingeon , Matthias Neumann

**Introduction:** Multiscale systems, where complex dynamics emerge from interactions across multiple spatial and temporal scales, are ubiquitous in nature, technology, and society. The recently approved COST Action mSPACE (CA24122) aims to establish a rigorous mathematical framework for the analysis of such systems, with particular emphasis on large-scale and long-time behavior in discrete, continuous, and hybrid models. By combining geometric and stochastic perspectives, mSPACE addresses fundamental challenges arising in linear and nonlinear models, network transport phenomena, and biological systems. Core mathematical tools include discrete calculus, asymptotic analysis, spectral geometry, gradient flows, and optimal transport. A prominent application area is materials science, where multiscale modeling and microstructure optimization naturally arise, illustrating how abstract theory can inform practical design. More broadly, mSPACE seeks to bridge fundamental analysis with real-world modeling challenges. This special session will showcase recent advances connected to the themes of the Action, bringing together theoretical developments, modeling approaches, and applications, and aims to foster interaction between the multiscale analysis community and applied researchers.

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### Eigenbranches of elliptic operators in singularly perturbed problems

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**Schedule:** July 10 10:30-11:00      Room 311

**Laura Abatangelo**

Politecnico di Milano, Italy

**Abstract:**

We consider eigenproblems for elliptic operators in bounded domains, namely the Dirichlet Laplacian. Suppose to perturb the problem in one of the following ways: removing a small hole from the interior of the domain, attaching a thin tube at a boundary point, disrupting the Dirichlet boundary condition with a Neumann condition in a small part of the boundary. In all these cases the operator's spectrum is stable and eigenvalues can be continued as the perturbation parameter tends to zero. We can prove the sharp asymptotic behavior of eigenbranches which will strongly rely on the local behavior of the limit eigenfunctions at the perturbation point.

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### On open book analogs of quantum graphs

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**Schedule:** July 9 13:30-14:00     Room 311

**Setenay Akduman**

Izmir Democracy University, Turkey

**Co-Author(s):** none

**Abstract:**

Quantum graphs have long served as effective models for thin structures. In various applications, however, such as photonic crystals and dynamical systems, one encounters stratified structures that naturally motivate higher-dimensional analogs of graph-like models. This leads to the study of ``open book`` type geometries, where multiple smooth ``pages`` meet transversely along a common ``binding``. Such structures can be viewed as higher-dimensional stratified varieties equipped with differential operators. This talk develops a mathematical framework for quantum open books and defines the associated differential operators. After introducing metric open book structures, we formulate natural junction conditions and identify a subclass of gluing data that ensures the Fredholm property under suitable ellipticity assumptions. We also determine conditions guaranteeing self-adjointness of the corresponding operator, in relation to well-known results from quantum graph theory. From a broader perspective, these structures provide a multiscale modeling framework, in which lower-dimensional singular sets may appear as geometric interfaces between higher-dimensional components. This viewpoint connects the analysis of quantum open books with current developments in multiscale systems, particularly in settings where geometric, spectral, and analytic features interact across different dimensions. We also discuss several directions for future research.

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### On the Lumpability of Dynamical Systems

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**Schedule:** July 10 9:00-9:30     Room 311

**Fatihcan M. Atay**

Bilkent University, Turkey

**Co-Author(s):** Fatihcan M. Atay

**Abstract:**

Multiscale systems often exhibit distinct yet related dynamical characteristics across different scales. One approach to exploring the relationship between dynamics at various spatial scales is through the concept of lumpability. This talk deals with exact lumpability of dynamical systems, namely the possibility of projecting the dynamics onto a smaller state space in which a self-contained dynamical description exists. This projection is also referred to as lumping, aggregation, or reduction in different contexts. We consider systems whose evolution is governed by bounded or unbounded linear operators on Banach spaces and derive conditions for lumpability in the language of semigroup theory. We further extend these results to nonlinear systems on finite-dimensional manifolds. Finally, we discuss lumpability within the framework of networks.

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### limits of time-changed degenerate semigroups & applications

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**Schedule:** July 10 11:00-11:30     Room 311

**Ali BenAmor**

University of Sousse, high school for transport and logistics, Tunisia

**Abstract:**

For a given standard process and a sequence of measures converging vaguely to a final measure, under some assumptions, we establish convergence of the sequence of the semigroups and the resolvents of the corresponding time changed-processes. Some applications are given: convergence of solutions of evolution equations and convergence of finite time distributions, as well as weak convergence of the related processes.

### on the $p$ -Wasserstein barycenter: behaviours and regularity properties

**Schedule:** July 9 9:30-10:00      Room 311

**Camilla Brizzi**

Technical University of Munich (TUM), Germany

**Co-Author(s):** Gero Friesecke, Tobias Ried, Lorenzo Portinale

**Abstract:**

The talk is about the barycenters of  $N$  probability measures with respect to the  $p$ -Wasserstein metric ( $p > 1$ ), which generalizes the notion of Wasserstein barycenters for  $p = 2$ , introduced by Agueh and Carlier. Providing a natural way to interpolate probability measures and computing a representative summary of input datasets, they are useful tools in data science, statistics, and image processing. This is a highly nonlinear problem but it can be rewritten as an equivalent multi-marginal optimal transport problem, paying with a (a priori) high dimension. Here we show that thanks to a new technique based on the geometric properties of the support of the optimal plan, the  $p$ -Wasserstein barycenters of absolutely continuous marginals are unique and absolutely continuous. This implies that the optimal MMOT plan is unique and can be parametrized as a graph over any marginal space (with a consequent dimension reduction). Some finer integrability properties of the density of the barycenter are also discussed. We present also some examples in one dimension, with emphasis on the statistical meaning of the  $p$ -Wasserstein barycenters and on the two natural limits  $p \rightarrow 1$  and  $p \rightarrow \infty$ . This is based on joint works with G. Friesecke and T. Ried and L. Portinale.

### Bi-Continuous semigroups for flows on infinite networks

**Schedule:** July 10 11:30-12:00      Room 311

**Christian Budde**

University of the Free State, So Africa

**Co-Author(s):** Marjeta Kramar Fijavz

**Abstract:**

In this talk we investigate transport processes on infinite metric graphs with non-constant velocities and matrix boundary conditions in the  $\mathcal{L}^\infty$ -setting. We apply the theory of bi-continuous operator semigroups to obtain well-posedness of the problem under different assumptions on the velocities and for general stochastic matrices appearing in the boundary conditions. This is joint work with Marjeta Kramar Fijavz (Ljubljana, Slovenia).

### Concentration phenomena of self-attention dynamics

**Schedule:** July 9 14:00-14:30      Room 311

**Leon Bungert**

University of Wuerzburg, Germany

**Co-Author(s):** Albert Alcalde, Konstantin Riedl, Tim Roith

**Abstract:**

In this talk I will speak about concentration phenomena of self-attention transformers in the regimes of infinitely many layers and tokens. The dynamics are described by the Fokker–Planck equation  $\partial_t \rho_t^\beta(x) = -\operatorname{div}(\rho_t^\beta(x) P_x V_{\beta}[\rho_t^\beta](x))$ ,  $\rho_t^\beta(x) \geq 0$ ,  $(t,x) \in [0,T] \times \mathbb{S}^{d-1}$ , where  $\mathbb{S}^{d-1} := \{x \in \mathbb{R}^d, |x|=1\}$  is the sphere in  $\mathbb{R}^d$ ,  $T>0$  is a time horizon,  $P_x: \mathbb{R}^d \rightarrow \mathbb{R}^d$ ,  $y \mapsto y - \langle x, y \rangle x$  is the projection onto  $T_x \mathbb{S}^{d-1}$ , and  $V_{\beta}[\rho_t^\beta](x) := \frac{\int_{\mathbb{S}^{d-1}} e^{\beta \langle x, y \rangle} \rho_t^\beta(y) dy}{\int_{\mathbb{S}^{d-1}} e^{\beta \langle x, y \rangle} dy}$  involves the inverse heat parameter  $\beta>0$ . The matrices  $V, B \in \mathbb{R}^{d \times d}$  contain learned parameters and are assumed to be constant in time. It is known that for  $\beta \rightarrow \infty$  solutions of the Fokker–Planck equation converge to solutions of a linear PDE, the solutions of which concentrate as  $T \rightarrow \infty$  on the dominating eigendirections of the matrix  $VB^{\top}$ . In our work we will quantify these results by exploiting a striking similarity between self-attention dynamics and the so-called polarized consensus-based optimization (CBO) method for global optimization. Using a CBO-inspired analysis we give explicit bounds for the Wasserstein-2 distance of the solution of the Fokker–Planck equation and a suitable target measure. The proof relies on an application of a quantitative Laplace principle to  $\mathbb{S}^{d-1}$  as well as a Lyapunov-type analysis for the time asymptotics. Our result sheds more light on the interior dynamics of self-attention transformers and might help identify reduced effective models.

### Non-uniqueness of normalized ground states for nonlinear Schrödinger equations

**Schedule:** July 9 16:30-17:00      Room 311

**Simone Dovetta**

Politecnico di Torino, Italy

**Abstract:**

The talk discusses general non-uniqueness results for normalized ground states of nonlinear Schrödinger equations with power nonlinearity. Basically, we show that, when in the  $L^2$ -subcritical regime ground states exist at every mass, for nonlinearity powers close to the  $L^2$ -critical exponent there is at least one value of the mass for which ground states are non-unique. As a consequence, whenever such non-uniqueness occurs there exist action ground states that are not normalized ground states. These results have been obtained both when the problem is set on metric graphs (compact and non-compact) and when it is posed on polygons with homogeneous Neumann boundary conditions.

### Graph approximation for nonlocal interaction equations

**Schedule:** July 9 14:30-15:00      Room 311

**Antonio Esposito**

University of L'Aquila, Italy

**Abstract:**

In this talk I will discuss the connection between nonlocal dynamics on graphs and the corresponding local counterparts in the underlying Euclidean space. Equations on graphs have been recently introduced in applications to data science and social dynamics, among others. Starting from the nonlocal interaction equation on graphs, we can obtain a class of nonlocal interaction equations with the presence of tensor-mobility encoding the information on the localised graph. This talk is based on joint works with G. Heinze, F. Patacchini, A. Schlichting, and D. Slepcev.

### On the stability of the JKO operator under different notions of convexity.

**Schedule:** July 9 17:00-17:30      Room 311

**Sara Farinelli**

University of Genova, Italy

**Co-Author(s):** Di Marino, Naldi

**Abstract:**

Given a metric space  $(X, d)$  and a functional  $\mathcal{F}$  defined on it, a relevant role in the theory of gradient flows associated with  $\mathcal{F}$  is played by the proximity operator  $P_{\mathcal{F}}(x) = \arg\min_y \left\{ \frac{1}{2} d^2(x, y) + \mathcal{F}(y) \right\}$ . In the setting of the Wasserstein space, that is  $(X, d) = (P_2(\mathbb{R}^d), W_2)$ , the proximity operator is often called JKO operator. Motivated from the fact that if  $(X, d)$  is a Hilbert space then  $x \mapsto P_{\mathcal{F}}(x)$  is non-expansive when  $\mathcal{F}$  is convex, the non-expansivity of the JKO operator has been a topic of investigation. It has been proved recently by Cavagnari-Savare-Sodini that if  $\mathcal{F}$  is totally convex then non-expansivity holds. Various partial results are present in literature assuming weaker notions of convexity. In this talk we review these contributions and we present some generalizations under the assumption that  $\mathcal{F}$  is convex on generalized geodesics. This is based on a joint work in preparation with Di Marino and Naldi.

### Critical lack of detailed balance in stochastic kinetic proofreading models

**Schedule:** July 8 16:30-17:00      Room 311

**Eugenia Franco**

University of Bonn, Germany

**Co-Author(s):** J.J.L. Velázquez

**Abstract:**

In this talk, I will discuss the role of the lack of detailed balance in a class of stochastic kinetic proofreading models. Kinetic proofreading systems were proposed by Hopfield and Ninio in the 70s in order to explain the way in which receptors can distinguish between different ligands with a low error rate. This ability is referred to as specificity. It was already suggested by Hopfield that in order to achieve high specificity, the system must spend energy, hence it should not satisfy the detailed balance property. We prove the existence of a critical amount of lack of detailed balance that kinetic proofreading models must have in order to have strong specificity.

### Effective transmission through a thin heterogeneous layer via EDP-convergence

**Schedule:** July 9 17:30-18:00    Room 311

**Gianna Goetzmann**

University of Augsburg, Germany

**Co-Author(s):** Lucas M. Fix, Malte A. Peter, Jan-F. Pietschmann

**Abstract:**

We study the asymptotic behavior of a Fokker--Planck system in a domain consisting of two bulk regions connected by periodically arranged channels within a thin heterogeneous layer. Both the layer thickness and the distance between the channels scale with  $\varepsilon \ll 1$ . The system admits a gradient flow formulation with respect to the Boltzmann entropy functional defined on the space of probability measures. Using the notion of EDP-convergence, which is based on the energy--dissipation principle, we aim to derive an effective transmission model in the limit  $\varepsilon \rightarrow 0$ .

### On the asymptotic behavior of the spectral gap for discrete Schrödinger operators

**Schedule:** July 10 12:00-12:30    Room 311

**Matthias Hofmann**

FernUniversität in Hagen, Germany

**Co-Author(s):** Joachim Kerner, Maximilian Pechmann

**Abstract:**

We investigate the asymptotic behavior of the spectral gap of a class of discrete Schrödinger operators defined on a path graph in the limit of infinite volume. We confirmed recent results and generalized them to a larger class of potentials using entirely different methods. Notably, we also resolved a conjecture previously proposed in this context, which yields new insights into the rate at which the spectral gap tends to zero as the volume increases. This is joint work with Joachim Kerner (FernUniversität in Hagen) and Maximilian Pechmann (Tennessee Technology University).

### The dynamic Schrödinger problem on metric graphs

**Schedule:** July 10 13:30-14:00    Room 311

**Juliane Krautz**

University of Augsburg, Germany

**Co-Author(s):** Jan-F. Pietschmann

**Abstract:**

We study the dynamic formulation of the Schrödinger problem on metric graphs. Using the direct method of calculus of variations, we show existence of minimizers and investigate the connection to dynamic optimal transport. A particular focus lies on the analysis of  $\Gamma$ -convergence between both problems for vanishing diffusive effects.

### Asymptotic Analysis of a Biharmonic Steklov Problem on Thin Domains

**Schedule:** July 8 17:30-18:00      Room 311

**Pier Domenico Lamberti**

University of Padova, Italy

**Co-Author(s):** Bauyrzhan Derbissaly

**Abstract:**

We analyze the asymptotic behavior of eigenvalues and eigenfunctions for a biharmonic Steklov problem on a thin domain in  $\mathbb{R}^n$  collapsing to a segment. In dimension  $n=2$ , the model describes vibrations of a thin elastic plate with mass concentrated on part of the boundary. The problem depends on a parameter  $\sigma$ , representing the Poisson ratio, which plays a key role in the limiting process. As the thickness vanishes, we derive the limit problem and show that the resulting operator exhibits a nontrivial distortion depending on both  $\sigma$  and the space dimension  $n$ . Based on a joint work with Bauyrzhan Derbissaly.

### Fractal Inverse Problems: The Crucial Role of Scaling

**Schedule:** July 8 17:00-17:30      Room 311

**Maria Rosaria Lancia**

Sapienza Università di Roma, Italy

**Co-Author(s):** Simone Creo, Gianluca Mola, Silvia Romanelli

**Abstract:**

This paper investigates the well-posedness and approximation of inverse problems formulated on highly irregular spatial domains, including those with fractal boundaries. The primary objective is the identification of a constant diffusivity parameter,  $\alpha_* > 0$ , within an abstract parabolic Cauchy problem. This identification relies on a quadratic overdetermining condition, which requires measuring the  $L^2$ -norm of the solution's energy at a fixed measuring time-instant  $T > 0$ . To address the geometric complexities inherent to irregular domains, we introduce a sequence of approximating direct and inverse problems defined on smoother, more regular spatial domains. The rigorous convergence of these approximations to the exact solution of the original inverse problem is established through the Mosco convergence of the associated Dirichlet energy forms. Crucially, appropriate scaling is fundamental in proving this Mosco convergence of the energies, precisely because there is a jump of dimension when passing from the regular approximating domains to the highly irregular or fractal limit geometry. Finally, we will also address the case of a fractional-in-time inverse problem, demonstrating the versatility of the proposed mathematical framework.

### Probing the influence of topological and geometric disorder on the spectrum of the differential Laplacian operator on networks

**Schedule:** July 9 18:00-18:30      Room 311

**Jeremy L Marzuola**

University of North Carolina, USA

**Co-Author(s):** Charles Maher and Katherine Newhall



**Abstract:**

Metric networks are network-shaped, one-dimensional structures on which one can solve differential equations to simulate a wide range of physical systems including conjugated molecules, photonic crystals, quantum mechanics in waveguide networks, and acoustic metamaterials. More concretely, a metric network is a network whose edges are each assigned a notion of length and a coordinate describing position. One can then define function spaces and differential operators on these objects to model the aforementioned systems. Recent software advancements have made it feasible to analyze partial differential equations on large, compact metric networks with a vast array of structures. Here, we generate compact metric network structures using the spatial tessellations of two-dimensional hyperuniform point patterns, which have suppressed large-scale density fluctuations relative to typical disordered point patterns. This choice of structure is inspired by the exotic physical properties of network materials with these structures in other contexts. Then, we characterize the eigenvalue spectrum structure of the differential Laplace operator on these networks. In particular, we find that gaps can form in the eigenvalue spectra of these networks whose widths increase when the distribution of edge lengths is narrow and as the number of triangular faces increases. Importantly, many of the structures we consider are realizable in Euclidean space, meaning they are well-suited for practical applications in, e.g., metamaterial design. This work can thus be used to inform the design of metric network-based systems with spectral gaps with tunable widths and locations.

### Multiscale approaches in optimal control

**Schedule:** July 9 18:30-19:00      Room 311

**Idriss Mazari-Fouquer**

CEREMADE, Paris Dauphine University PSL, France

**Abstract:**

We report on recent progress in using oscillatory techniques to derive point wise and geometric properties in optimal control theory, in particular to derive the bang-bang property in parabolic models.

### Quantitative converge for displacement monotone Mean Field Games of controls

**Schedule:** July 9 15:00-15:30      Room 311

**Alpar R Meszaros**

Durham University, England

**Abstract:**

In this talk we present some recent results about quantitative convergence of Nash equilibria (both open and closed loop) of a general class of N-player stochastic differential games, when agents interact through the empirical measure supported on both states and controls. Our analysis is based on a careful comparison between open and closed loop Nash equilibria, and the mean field Nash equilibrium. A particular challenge is to understand the properties of an additional fixed point map and to obtain dimension-free estimates as N increases to infinity. Our quantitative analysis does not impose implicit assumptions on the fixed point map nor uses the master equation, but it relies on displacement monotonicity techniques. The talk will be based on joint works with Joe Jackson (University of Chicago).

### Replicator dynamics as the large population limit of a discrete Moran process

**Schedule:** July 10 9:30-10:00      Room 311

**Marco Morandotti**

Politecnico di Torino, Italy

**Co-Author(s):** Gianluca Orlando

**Abstract:**

The replicator dynamics accomplishes the task of modelling the evolution of strategies in a population by subjecting the probability of reproduction to their fitness: The higher the fitness, the higher the chance of being selected to reproduce. Yet, the criterion followed by individual agents to select their strategies is latent in the replicator equation, which describes the continuous-time evolution of the proportions of strategies in an averaged fashion. In this talk, we provide a mathematical framework to derive the replicator equation as a mean-field limit of a discrete stochastic process modelling this evolutionary mechanism from the point of view of individual agents and their pairwise interactions. In this context, the classical Moran process is a prototypical example of discrete stochastic process that models natural selection in finite populations with two strategies (alleles, in biology) competing for dominance. We study the mean-field limit of a generalised Moran process as the number of agents diverges and we show that, in the weak selection regime, it converges to the replicator dynamics.

### Regularity by duality for minimising movements with nonlinear mobility

**Schedule:** July 9 8:30-9:00      Room 311

**Lorenzo Portinale**

Universita' di Milano statale, Italy

**Co-Author(s):** Emanuela Radici, Simone di Marino

**Abstract:**

In this talk, we discuss conservation laws that can be written as gradient flows with respect to a Wasserstein distance with nonlinear mobility. In particular, we discuss ideas for inferring regularity estimates for time-discretisation schemes using two important tools: (dynamical) duality and comparison principles.

### Westervelt Boundary Value Problems on Domains With Non-Lipschitz Boundaries

**Schedule:** July 9 15:30-16:00      Room 311

**Anna Rozanova-Pierrat**

CentraleSup'elec, University Paris-Saclay, France

**Co-Author(s):** A. Dekkers, M.Hinz, A. Teplyaev

**Abstract:**

We obtain the global on-time well-posedness of the Robin type boundary valued problem for the Westervelt equation on a bounded domain with a non-Lipschitz boundary. The obtained weak solutions are considered in the domain of Laplacian and thus are more regular than  $H^1$ . The irregularity of the boundary does not allow the usual  $H^2$ -regularity. In the framework of uniform domains in  $\mathbb{R}^2$  or  $\mathbb{R}^3$  we also validate the approximation of the solution of the Westervelt equation on a fractal domain by the solutions on the prefractals using the Mosco convergence of the corresponding variational forms. We consider the shape optimization problem for this ultrasound wave propagation model to minimize the system's total acoustic energy by the shape of the boundary for fixed source and initial data. For the Robin boundary, modeling the reflection, we prove the existence of an optimal shape realizing the infimum of the acoustic energy in a class of Lipschitz boundaries. Using its relaxation on the uniform class of domains, we prove the existence of an optimal shape realizing the minimum.

### Spectral Flow and Eigenvalue Comparison for Schrodinger Operators on Metric Graphs

**Schedule:** July 10 14:00-14:30      Room 311

**Gilad Sofer**

Technion - Israel Institute of Technology, Israel

**Co-Author(s):** Ram Band, Marina Prokhorova

**Abstract:**

When comparing the spectra of two self-adjoint operators, it is often useful to compare their eigenvalue counting functions. A well-known result in this direction for Schrodinger operators on metric graphs is known as Dirichlet-Neumann bracketing, which essentially states that the eigenvalue counting functions of the Dirichlet and Neumann Laplacians differ by at most the size of the boundary. This can be seen as a manifestation of how local boundary conditions influence global spectral quantities. The goal of this talk is to introduce a useful tool for such comparison results, known as the spectral flow, which is a topological invariant associated with one-parameter families of self-adjoint operators. In this setting, the parameter can be interpreted as a continuous change of boundary conditions or coupling along the graph. We show that for Schrodinger operators on metric graphs, the spectral flow can be effectively computed using the associated scattering matrices. We then present several applications, in the form of generalized nodal index theorems and eigenvalue interlacing results, which quantify how spectral data evolves under these changes. The talk is based on joint work with Ram Band and Marina Prokhorova.

### Censored subordinate Brownian motion

**Schedule:** July 9 9:00-9:30      Room 311

**Vanja Wagner**

University of Zagreb, Croatia

**Abstract:**

Let  $D \subset \mathbb{R}^d$ , be an open  $d$ -set, and  $L$  a nonlocal operator of the form  $L = -\phi(-\Delta)$ , where  $\phi: (0, \infty) \rightarrow (0, \infty)$  is a complete Bernstein function. The operator  $L$  is a generator for the subordinate Brownian motion, with the Laplace exponent  $\phi$  of the subordinator, and admits the following singular integral form 
$$Lu(x) = \int_{\mathbb{R}^d} (u(y) - u(x)) j(|y-x|) dy, \quad u \in C_c^2(\mathbb{R}^d),$$
 where  $j: (0, \infty) \rightarrow (0, \infty)$  is the corresponding radially decreasing Lévy density. In this talk, we revisit the regional subordinate Laplacian on  $D$ , i.e. the nonlocal operator of the form 
$$L_D u(x) = \int_D (u(y) - u(x)) j(|y-x|) dy, \quad u \in C_c^2(D),$$
 and two associated strong Markov processes on  $\overline{D}$  -- the censored and resurrected subordinate Brownian motions on  $D$ . Specifically, we discuss the pathwise behaviour of these processes and give conditions under which they are equivalent.

## Panarchy: From Theory to Measurement

**Schedule:** July 10 8:30-9:00      Room 311

**Hannah HZ Zoller**

Stockholm Resilience Centre, Sweden

**Abstract:**

Multiscale analysis is a key aspect of complexity science. An established conceptual framework grounded in resilience science is provided by L. H. Gunderson's and C. S. Holling's *Panarchy* heuristic (2002), which envisions a complex system as a nested set of cyclic processes, hierarchically structured across spatiotemporal scales. Originally formulated for socio-ecological systems, this model has been rapidly adopted across scientific disciplines, including biology, economics, and politics. However, to date, corresponding studies have been almost exclusively of qualitative nature. An integral quantitative approach to panarchies would require the identification of relevant operating scales, the assessment of adaptive cycles within scales, and the estimation of information flow across scales. Current quantitative approaches cover only individual aspects, leveraging established measures rooted in spectral analysis, information theory, and network analysis (Angeler et al. 2023). In this talk, we review the recent development and consider potential future pathways.