STRUCTURES | NEWS

STRUCTURES CLUSTER OF EXCELLENCE

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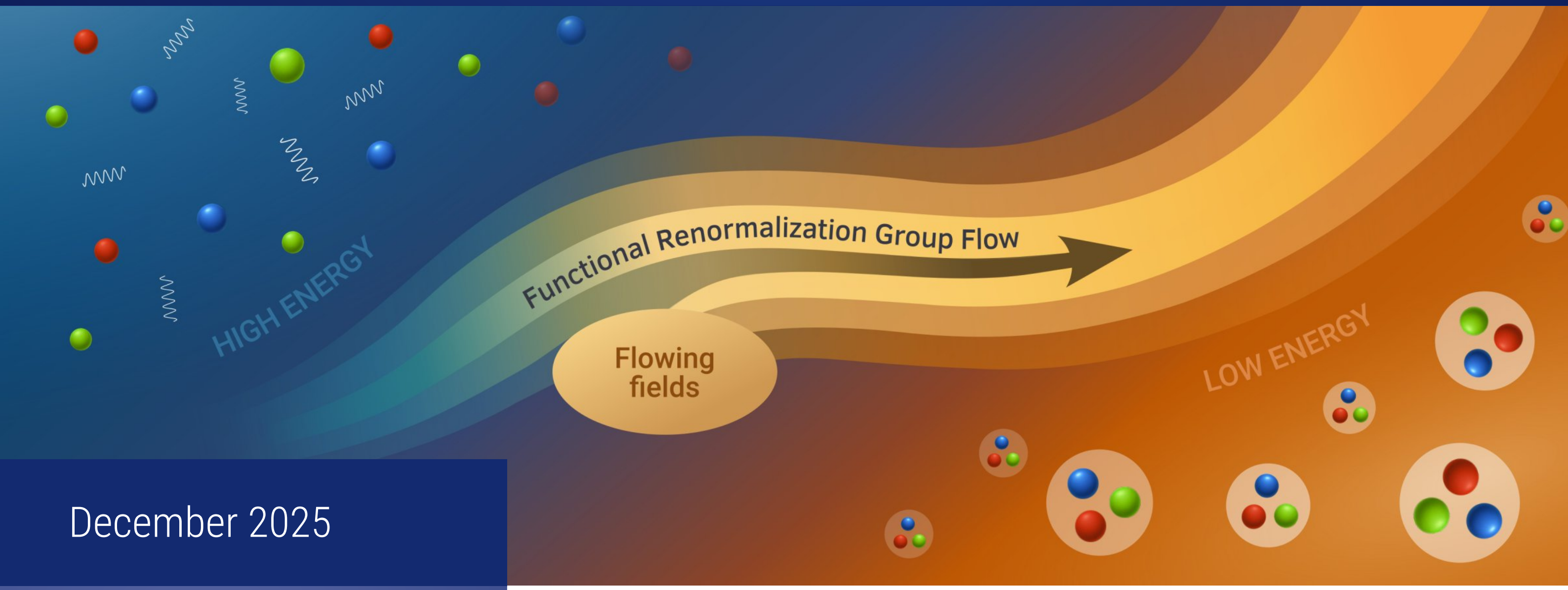

December 2025

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Upcoming

- **STRUCTURES Jour Fixe**:
  - **Dec 12:** STRUCTURES Christmas party
  - **Jan 16:** Victor Ksoll
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  - **Jan 21:** Sebastian Will
- **Lecture Series:** *Basics of Quantum Gravity*. Jan 19 – Oct 2, 2026

Happy Holidays!

We wish everyone happy holidays and a serene close to the year! We thank all members, colleagues and friends for their outstanding commitment!

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RESEARCH

A New Map for Emergence: Physics-Informed Renormalization Group Flows

Physics faces some of its hardest questions when studying systems with many interacting parts. Out of this complexity – whether in ultracold atomic gases or the early universe – simple and universal laws may emerge at larger scales. To understand how such behaviour arises, physicists use a method known as the *functional renormalization group (fRG)*. The fRG tracks how a system's equations evolve with scale – a process known as its *flow*.

Applying the fRG, however, can be challenging. Expansion schemes may fail or become inefficient when the relevant degrees of freedom change with scale, as is the case for strongly correlated systems. For instance, while quarks and gluons are the "right vocabulary" at high energies, at lower energies it is more useful to work in terms of hadrons – composite states of quarks bound by the strong force. Accommodating such emergent degrees of freedom is therefore of crucial interest.

In a new study, STRUCTURES members Friederike Ihssen and Jan Pawlowski introduce *physics-informed renormalization group flows (PIRG)*, a generalization of the fRG that lets the theory adjust its own description as the scale changes. Instead of studying a system in fixed variables, PIRG allows for scale-dependent redefinitions of the fields, treating them as part of the flow. This active change of fields throughout the flow allows *e.g.* for a systematic and dynamic identification of relevant degrees of freedom, and makes expansions more efficient by ensuring they are performed in the variables best suited to physics at each stage.

As a proof of principle, the authors apply PIRGs to scalar $O(N)$ field theories – simple model systems that contain symmetry breaking and phase transitions. They show that the novel freedom introduced by PIRG can be used for improving expansion schemes, but also to simplify the technical task of computing the RG flow itself, while maintaining access to physical observables.

By combining conceptual adaptability with computational efficiency, PIRG offers a versatile framework for exploring strongly correlated quantum matter, phase transitions, and complex many-body dynamics.

Original Publication:

Ihssen, F. and Pawlowski, J. M., "Physics-informed renormalisation group flows", *Annals of Physics*, vol. 481, Art. no. 170177, Elsevier, 2025. doi:10.1016/j.aop.2025.170177.

RESEARCH

Bridging Worlds of Quantum Matter: Longstanding Quasiparticle Puzzle Solved

When a single particle moves inside a sea of many others, their mutual interactions can give rise to new collective behaviours, such as the formation of so-called *quasi-particles*. These emergent forms of matter display properties of individual particles even though they arise from the coordinated motion of many particles, acting together as if they were a single one.

An important example is the *Fermi polaron*, which forms when an impurity is introduced into a sea of *fermions* – particles such as electrons that obey what is known as *Pauli exclusion principle*. Like a pebble dropped into calm water, the impurity perturbs its surrounding, forming a particle-like pattern: the polaron. Polarons serve as a cornerstone for understanding novel quantum materials and ultracold atomic gases.

For years, however, physicists have faced a fundamental puzzle about the formation of Fermi polarons: how can their quasi-particle nature coexist with a phenomenon known as the *Anderson orthogonality catastrophe*? The latter is a theoretical prediction stating that if the impurity is made so heavy that it becomes effectively immobile, it should instead completely disrupt its environment.

A new study by Xin Chen, Eugen Dizer, Emilio Ramos Rodríguez, and Richard Schmidt – three of whom are members of STRUCTURES – resolves this long-standing question. The researchers developed a unified theory that smoothly connects the two seemingly contradictory regimes. The key insight lies in the impurity's unavoidable response to changes in the environment, which softens the disturbance it causes. In particular, when the surrounding medium adjusts, an impurity with finite mass cannot remain at rest: even if its net momentum is zero, it must recoil as the medium reorganizes. This creates what physicists refer to as an *energy gap* – a small energy cost for disturbing the medium. As a result of this gap, the impurity and its neighbouring particles can develop a smooth, coordinated motion, forming a well-defined quasi-particle. In contrast, if the impurity becomes heavier, it can respond less to its surrounding, and the medium reacts more strongly – until, in the extreme limit of an immobile impurity, the quasiparticle nature ultimately breaks down.

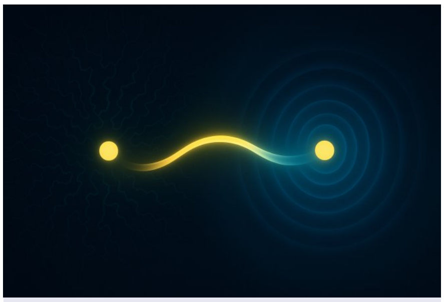

Image generated with AI assistance.

Illustration of the transition from a static impurity (left) that disrupts its environment completely, to a mobile impurity (right) whose motion restores order through the emergence of a quasiparticle.

This mechanism explains how quasi-particles emerge from an otherwise "gap-less" medium and reveals the microscopic origin of the observed transition between polarons and molecules. The new theory provides a simple yet powerful description of interacting quantum systems, with broad implications for ultracold-atom experiments, novel atomically thin semiconductors, and future studies of strongly correlated matter.

Original Publication:

Chen, X., Dizer, E., Rodríguez, E. R., and Schmidt, R., "Mass-Gap Description of Heavy Impurities in Fermi Gases", *Phys. Rev. Lett.*, vol. 135, no. 19, Art. no. 193401, APS, 2025. doi:10.1103/h2f7-dhjh.

EVENTS

GTML 2025: Connecting Geometry, Topology, and Machine Learning

The *Workshop on Geometry, Topology, and Machine Learning (GTML 2025)*, jointly organized by the Max Planck Institute for Mathematics in the Sciences (MPI-MiS Leipzig) and the STRUCTURES Cluster of Excellence took place from October 11-14. It marked the first event of this scale to unite the research communities of geometry, topology, and machine learning. The workshop, which attracted 132 participants, provided a unique platform for researchers to explore the fundamental role of geometric and topological methods in understanding data structures and developing rigorous frameworks for machine learning. It fostered deep scientific exchange and created valuable opportunities to identify new connections and build bridges between traditionally separate fields.

The scientific programme featured 10 keynote lectures and 20 expert presentations from leading researchers worldwide. A special highlight of the workshop were the *Lightning Sessions*, designed specifically for early-career researchers. These rapid-format presentations created a dynamic space for young scientists to share ideas, showcase ongoing work, and expand their professional networks. Short papers will be published as a special edition of the

Image credit: MPI-MiS.

PMLR (Proceedings of Machine Learning Research) series, ensuring continued visibility of the scientific contributions beyond the event itself. The organizing committee included STRUCTURES members Michael Bleher, Freya Jensen and Levin Maier, as well as Diaaeldin Taha and Anna Wienhard from MPI-MiS.

STRUCTURES COMMUNITY

We Are STRUCTURES

In our newsletter we regularly present short interviews with three randomly picked members of the *Young Researchers Convent (YRC)*, a subgroup of STRUCTURES that brings together the early-career researchers of our scientific community. For this newsletter edition, we interviewed León-Alexander Hühn, Pedro G.S. Fernandes and Jingqian Gou:

Interview with León-Alexander Hühn:

León-Alexander Hühn - PhD student at ZAH, *Dullemond group*

What are you working on?
I perform 3D hydrodynamics simulations of protoplanetary disks, the birthplaces of planets. My recent work explores how these disks interact with the interstellar environment via the formation of material streamers, which deliver new solids for planet formation and impact the disk physics in various ways.

What fascinates you about your research?
The most interesting aspects of research in astrophysics are the unfathomable size and distance scales. Astronomical conditions are largely impossible to recreate on Earth, which necessitates studying fundamental questions about the Universe with very limited information – thereby putting special emphasis on numerical experiments.

What motivated you to enter science?
Physics, mathematics, and computer science were my favourite subjects back in high school, motivating me to pursue physics at the University level. Interesting talks and lectures led me to computational astrophysics.

How does one recognize you?
If you bring up topics related to Linux and Open Source Software in my general vicinity, chances are that you will notice me as I join the conversation. Otherwise, if you are trying to find me, a coffee machine is usually a good place to start looking.

Interview with Pedro G.S. Fernandes:

Pedro G.S. Fernandes Postdoc at ITP, *Eichhorn group*

What are you working on?
I'm investigating what happens at the centre of a black hole, specifically, how its singularity might be resolved, and, more broadly, whether Einstein's theory of General Relativity is truly the correct description of gravity.

What fascinates you about your research?
I'm fascinated by the fact that mathematics alone allows us to understand and even predict how the universe behaves. My work sits at the frontier of human knowledge about the fundamental laws of nature, and exploring that boundary feels incredibly profound.

What motivated you to enter science?
I've always been a deeply curious person. As a young person, hearing about the strange and beautiful ideas of quantum mechanics, relativity, and black holes, I couldn't help but want to learn more. That curiosity naturally led me into science.

How does one recognize you?
The simplest way is by looking at my photo. If that's not an option, I'm usually the guy at Philosophenweg 12 with messy hair, talking enthusiastically about black holes and football.

Interview with Jingqian Gou:

Jingqian Gou PhD student at ITP, *Heisenberg / Hebecker group*

What are you working on?
I'm working on two projects: approaching de Sitter vacua in type IIB string landscape with intricate Calabi-Yau topology, focusing on the strong-warping effect on non-perturbative corrections and moduli stabilization, and relating semi-classical effective models of black holes in loop quantum gravity (LQG) and hairy black hole solutions in modified gravity.

What fascinates you about your research?
Fundamental questions such as quantum gravity or a grand unified theory have always gripped my curiosity, the physical and mathematical richness of string theory and LQG also allow me to keep learning and improving to the largest extent. On the other hand, I'm willing to engage with different (even controversial) approaches at the same time, gradually forming my own opinions and intuitions in a reasoned and well-grounded way.

What motivated you to enter science?
The approaches of physics and mathematics have given me courage and strength to confront and explore the most profound and counter-intuitive aspects of the natural and logical worlds within my ordinary human life.

How does one recognize you?
A girl with black hair and glasses hanging around the string theorists at Philosophenweg 19 and Mathematikon.

INTERESTED IN JOINING THE YRC?
Any student (BSc, MSc, PhD) or postdoc whose work fits into the concept of STRUCTURES can apply for YRC membership. If your supervisor is a STRUCTURES member *or* your work is funded by STRUCTURES, you are *directly eligible* for membership in the YRC. Feel free to reach out anytime at: *structuresyrc(at)thphys.uni-heidelberg.de*. For more details, *visit https://structures.uni-heidelberg.de/YRC.php.*

MEMBER INTERVIEWS

STRUCTURES Asks: Hans Knüpfer

In this edition of our series *STRUCTURES Asks*, we interviewed Hans Knüpfer, professor of applied mathematics at the Institute for Mathematics (IMa). His research focuses on applied analysis, in particular on nonlinear partial differential equations and variational problems arising from physics. Beyond his work in STRUCTURES' Comprehensive Projects CP3 and CP4, Hans Knüpfer is also active in the local co-organization of the *Young African Mathematicians (YAM)* fellowship programme.

Interview with Hans Knüpfer:

What is the core focus of your research?
I am interested in models from materials science and fluid dynamics, which exhibit the formation of complex behaviours such as self-similar structures or the development of singularities. In particular, my work has been focused on ferromagnetic and elastic materials and free boundary problems in fluid dynamics.

How would you describe the role of applied analysis in enhancing our understanding of complex material behaviours?
Many real world systems can be described by continuum models, and in particular partial differential equations. In applied analysis we first investigate solvability of these models and the continuity of the solution operators in terms of the data. Usually, the models are too hard to solve explicitly. However, with tools from applied analysis we can often characterize the qualitative properties of the solutions, such as relevant asymptotics and related scaling laws.

What role does energy minimization play for pattern formation and self-organization in such systems?
Minimization principles are a universal feature in many systems. In complex materials the energy landscape is typically highly non-convex, which drives the complex behaviour of the system.

Shape memory alloys, after deformed, revert to their original shape when heated. Is there an energetic origin of this "ability to remember"?
Shape memory alloys have two modes to change their shape: A reversible elastic deformation and an irreversible elastic deformation. When a shape memory alloy is deformed in a low temperature state, only the elastic mode of deformation is active. When reheated they remember and return to their initial shape. Understanding the pathway of shape memory alloys requires understanding the underlying energetic structures.

Your work sits at the intersection of mathematics and physics. What do you find most rewarding about this interdisciplinary research?
The questions we ask in applied analysis are motivated by physical observations and conjectures. This connection between different disciplines is rewarding and stimulating in my research.

You are co-organizing STRUCTURES' participation in the Young African Mathematicians (YAM) programme, which offers

Prof. Hans Knüpfer
Institute for Mathematics (IMa)

early-career scientists from Africa fellowships at German excellence clusters. What are your takeaways on the programme and its impact?
YAM is a joint fellowship programme with Bonn, Berlin and Münster in collaboration with the African Institute for Mathematical Sciences (AIMS). We award one-year fellowships to recent master graduates from one of the AIMS institutes. It has been very rewarding to see the impact we could provide to these fellows, who either continued to pursue a Ph.D. in Europe or the U.S., or sometimes go back to their countries of origin to bring their experiences there.

If you could meet any historical figure over coffee or tea, who would it be, and what would you ask them?
I enjoyed reading the short stories of Mark Twain, as well as his travel diary A Tramp Abroad, where he also described his experiences in Heidelberg. Since he was a dedicated learner of German it would be fun to learn about his experiences here and his hate and love relationship with the German language.

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IMPRESSUM & CONTACT
Exzellenzcluster STRUCTURES
Universität Heidelberg
Philosophenweg 12 & Berliner Straße 47
D-69120 Heidelberg
office@structures.uni-heidelberg.de

Layout, editing & texts:
Sebastian Stapelberg, STRUCTURES Office,
Guest Authors and Speakers.