STRUCTURES | NEWS

STRUCTURES CLUSTER OF EXCELLENCE

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

July 2025

Emergent Order in Turbulent, Driven and Dynamic Worlds

Background image: Two-dimensional slice through a simulation of supersonic turbulence in the interstellar medium.
Image credit: James R. Beattie, Princeton University / CITA, U. Toronto, reproduced with kind permission.

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Upcoming

- **July 08 :** Machine Learning Galore!
- **July 11:** STRUCTURES Jour Fixe
- **July 14-18:** Workshop: Billiards and Quantitative Symplectic Geometry
- July 18: STRUCTURES Jour Fixe

Further upcoming events can be found on our website:

https://structures.uni-heidelberg.de

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RESEARCH

Scientists Map Hidden Structure of Magnetized Turbulence in Interstellar Space

World's largest simulation of magnetized turbulence reveals deviations from canonical models.

Groundbreaking simulations led by an international team of researchers, including STRUCTURES member Ralf Klessen (ZAH/IWR), have unveiled previously unknown details about turbulence in the magnetized environment of the *interstellar medium (ISM)*. This complex, turbulent plasma, composed of hot, electrically charged gas and dust between the stars in our galaxy, profoundly influences fundamental cosmic processes such as star formation and cosmic-ray transport. The new study, published in *Nature Astronomy*, utilized simulations with unprecedented grid resolutions to model highly compressible, magnetized turbulence akin to that occurring in the ISM.

A key finding is the discovery of two distinct, coexisting kinetic energy cascades within the turbulence – a process where kinetic energy flows from large to small scales within the turbulent ISM. The ISM can be envisioned as a fluid with swirling motions of various sizes, powered by energy often injected on large scales (*e.g.*, from exploding stars). According to the new simulations, this energy transfer happens in two separate ways depending on the scale of these motions. On the largest scales, where gas is moving faster than sound and magnetic fields are relatively weak, the transfer of energy can "jump" more directly across different sizes of swirls. However, on smaller scales, where gas moves slower than sound and is strongly influenced by magnetic fields, energy flows more gradually down through successive scales. This two-level process of energy dissipation is a significant departure from simpler, older models of turbulence. The team also discovered that energy stored in the magnetic field itself has its own unique way of cascading through these turbulent regions, in a pattern current theories do not fully explain.

These findings challenge fundamental theories of *magnetohydrodynamic (MHD) turbulence* and provide crucial insights into the properties of the ISM. In particular, they help to explain how turbulence affects the initial conditions for star formation.

Original Publication:

Beattie, J.R., Federrath, C., Klessen, R.S. et al. The spectrum of magnetized turbulence in the interstellar medium. Nat Astron, 2025. doi:10.1038/s41550-025-02551-5.

RESEARCH

Heidelberg Researchers Discover New Emergent Properties in a Driven Superfluid

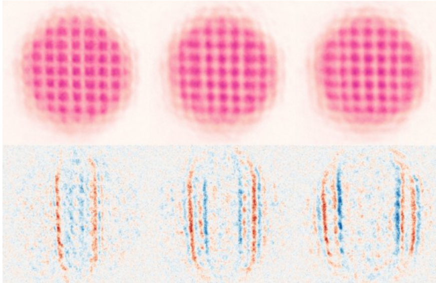
STRUCTURES researchers have uncovered supersolid-like sound modes in a far-from equilibrium quantum gas.

In a new study, experimental physicists from the Oberthaler group at *Kirchhoff Institute for Physics* have observed that spontaneously emerging patterns in driven *superfluids* exhibit properties characteristic of a rare state of matter known as a *supersolid*. Supersolids are unique because they simultaneously behave like a fluid that can flow without resistance (a *superfluid*) and a solid with a crystalline structure, meaning particles are both delocalized and arranged in a regular pattern. This duality results from breaking two fundamental symmetries: the *U(1) symmetry* associated with superfluidity and *translational symmetry* associated with the periodic structure. A key feature of supersolids is the presence of two distinct types of sound waves, or *sound modes*, connected to the two independently broken symmetries.

Driven systems, which are systems continuously supplied with energy, are of significant scientific interest because they can display unique properties distinct from those at equilibrium, sometimes leading to long-lived states with novel material characteristics. Although these systems are far from equilibrium, in certain cases they can produce ordered stationary states that share physical properties usually attributed to equilibrium systems. This enables the application of mathematical descriptions developed for equilibrium scenarios.

In superfluids, it is known that driving the interaction strength results in stable periodic density structures. However, no previous study has been performed on how sound waves propagate through these patterns. This work demonstrates that the theoretical framework of supersolids (developed for equilibrium systems) can be applied far from equilibrium (in the metastable patterned state), therefore uniting the study of pattern formation with that of supersolids.

The team studied a *Bose-Einstein condensate* of *potassium-39* atoms, periodically driven by modulating the atomic interaction strength, creating stable, periodic density patterns. By probing the state's response to disturbances, similar to how sound waves are used to study materials, they were able to excite and measure distinct sound modes in this driven quantum gas, whose analysis confirmed that this patterned state behaved like a one-dimensional supersolid, aligning with the hydrodynamic description of *superfluid smectics*, a state of matter that is the superfluid analogue of what is known as a *smectic-A liquid crystal phase*.



Wave packet propagating in a lattice pattern after locally disturbing the superfluid with energy pulses. The top panel shows the density distribution, while the bottom panel isolates the density perturbation by subtracting the density of the unperturbed system. (Image credit: Liebster et al. 2025)

This research, published in Nature Physics, reveals fundamental insights into driven quantum matter, demonstrating that the concept of supersolidity is useful for understanding dynamic and far-from-equilibrium states of matter. Moreover, it establishes the studied Bose-Einstein condensate as a promising platform for exploring other complex phenomena in patterned superfluids, such as *topological defects* or phase transitions out of equilibrium.

Original Publication:

Liebster, N., Sparn, M., Kath, E. et al. Supersolid-like sound modes in a driven quantum gas. Nat. Phys. (2025). doi:10.1038/s41567-025-02927-4.

RESEARCH

New Exploratory Projects – Eleventh EP Call

Five new Exploratory Projects (EPs) were selected for funding by the STRUCTURES Cluster of Excellence in 2025 as part of the eleventh EP call. Complementary to the Comprehensive Projects (CPs), the highly flexible format of EPs aims to drive innovation within the cluster.

EPs enable pursuing new ideas, creating new research directions, and establishing new links between scientific areas. Since 2019, more than 60 EPs have been selected, which have led to remarkable breakthroughs and plenty of activity in the cluster, freshening our research and bringing our community closer together.

The following new projects have been selected in 2025 by the Steering Board:

- **Tensor Models and Gravitational Universality Classes** – *Astrid Eichhorn, Razvan Gurau, Jan Pawlowski.*
- **Inferring Drivers in Non-Autonomous Astrophysical Dynamical Systems** – *Tobias Buck, Daniel Durstewitz, Hubert Klahr.*
- **Building an RG Quantum Simulator – Exploring Functional Renormalisation Group Flows Through Physics-Derived Regulators** – *Xin Chen, Selim Jochim, Richard Schmidt, Manfred Salmhofer, Maximilian Rieger.*
- **Building Fractional Quantum Hall States Atom-by-Atom** – *Selim Jochim, Richard Schmidt, Matthias Weidemüller, Maciej Gałka.*
- **Sampling in High Dimensions – Using Intrinsic Structures to Tame Complexity** – *Friederike Ihssen, Jan M. Pawlowski, Björn Malte Schäfer, Robert Scheichl.*

Congratulations!

TRAVELS

YRC Travels: Supporting Early Independence and Collaboration Around the Globe

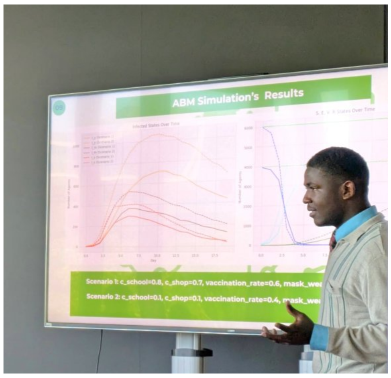
To support the independence of early-career researchers, STRUCTURES offers a certain budget for travels through the *Young Researchers Convent (YRC)*. This funding support has enabled many of our YRC members to attend scientific events ranging from workshops to large conferences, where they presented their work within STRUCTURES and engaged in vibrant exchanges. As a subgroup of STRUCTURES, the YRC brings together and bolsters early-career researchers of our scientific community in realizing their own projects.

This map shows a few of the locations (red markers) and scientific events that our YRC members visited with support by STRUCTURES YRC travel funding. These events range from schools and workshops to large conferences, where the researchers were able to present their research and engage in vibrant exchanges.

EVENTS

YAM Network Meeting 2025 in Heidelberg

On June 31 and July 01, STRUCTURES had the pleasure of welcoming *YAM* fellows and organizers from various German clusters of excellence to this year's *YAM network meeting* in Heidelberg. During the meeting, which took place at STRUCTURES' *Oberstübchen*, the YAM fellows presented and discussed their research, shared experiences and engaged in dialogue with peers and coordinators. In addition, two invited guests, Dr. Helke Hillebrand (*Graduate Academy Heidelberg*) and Dr. Patrick Wagner (*heiSKILLS Competence and Language Centre*) gave talks on career opportunities for mathematicians in Germany.



The programme was complemented by a campus tour, a guided walk through Heidelberg's Old Town, and several get-togethers. The two-day meeting fostered lively discussion, providing valuable insights and new connections.

The *Young African Mathematician Programme (YAM)* is a joint initiative between the five centres of the *African Institute for Mathematical Science (AIMS)* and four German clusters of excellence. It enables outstanding graduates of the AIMS Master Programme to spend an academic year at a German research cluster, performing their own research under supervision by a professor, and participating in a structured course programme. STRUCTURES is proud to have been a part of the YAM network since 2023, as part of its efforts to promote international cooperation, diversity and equity. The local YAM coordination team in Heidelberg consists of Prof. Hans Knüpfer, Dr. May-Britt Becker, Dr. Beate Sandler and the STRUCTURES Office team.

YAM Fellows from four German clusters of excellence: HCM Bonn, MATH+ Berlin, Mathematics Münster, and STRUCTURES Heidelberg.

STRUCTURES COLLEGE

STRUCTURES Jour Fixe Summer Term 2025

After a long break, the STRUCTURES Jour Fixe has resumed. The first talk, by Andrew Tolley on *causality and analyticity*, attracted more than 75 visitors (+ 10 remote guests).

The weekly Jour Fixe is the central meeting point of the STRUCTURES community. As a part of *STRUCTURES College*, it provides a forum and an environment for exchanging and discussing ideas. As such, it not only joins researchers from different scientific disciplines, but brings together both early-career and senior researchers.

A list of recent and upcoming Jour Fixe talks can be found at the following page on the STRUCTURES website:

STRUCTURES Jour Fixe
https://structures.uni-heidelberg.de/jour_fixe.php

STRUCTURES Jour Fixe Talk by Andrew Tolley.

WORKSHOPS

Schöntal Workshop 2025: Inverse Problems

We are delighted to announce this year's iteration of the Schöntal Discussion Workshop on *Inverse Problems*, taking place from 26th to 29th of August 2025 – once again in the tranquil and idyllic location of Schöntal Abbey. The Schöntal workshop aims to bring together early-career researchers from different scientific areas of STRUCTURES to engage in discussion over topics that go beyond the standard physics and mathematics curriculum. It especially aims at fostering vivid interdisciplinary scientific exchanges.

This year's overarching topic allows in particular interdisciplinary discussions between physicists, mathematicians and computer scientists without requiring specialized knowledge in advance. The sub-topics of the Workshop are:

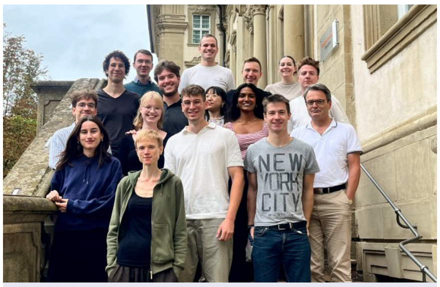
1. regularization and stability;
2. Bayesian methods and uncertainty quantification;
3. sampling and learning-based methods;
4. inverse problems in soft matter & liquid state theory.

This year's invited guests are professors Tristan Bereau and Jakob Zech.

This workshop is funded by STRUCTURES' Young Researchers Convent (YRC). This year's organizers are Rebecca Maria Kuntz, Carlos Pastor Marcos, Hannes Heisler, and Sander Hummerich.

Participation is free of charge for attendees from STRUCTURES. The registration is open until Monday, July 21 via the following link:

Schöntal Registration Form
https://structures.uni-heidelberg.de/events/schoental2025/register.php



Participants of the Schöntal Workshop 2024.

Schöntal Abbey (Image credit: Rosenzweig/Wikipedia)

YOUNG RESEARCHERS CONVENT

Any early-career researcher who works on research topics related to STRUCTURES can apply for a YRC membership. If you are supervised by a STRUCTURES member or funded by STRUCTURES, you are directly eligible.

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