STRUCTURES | NEWS

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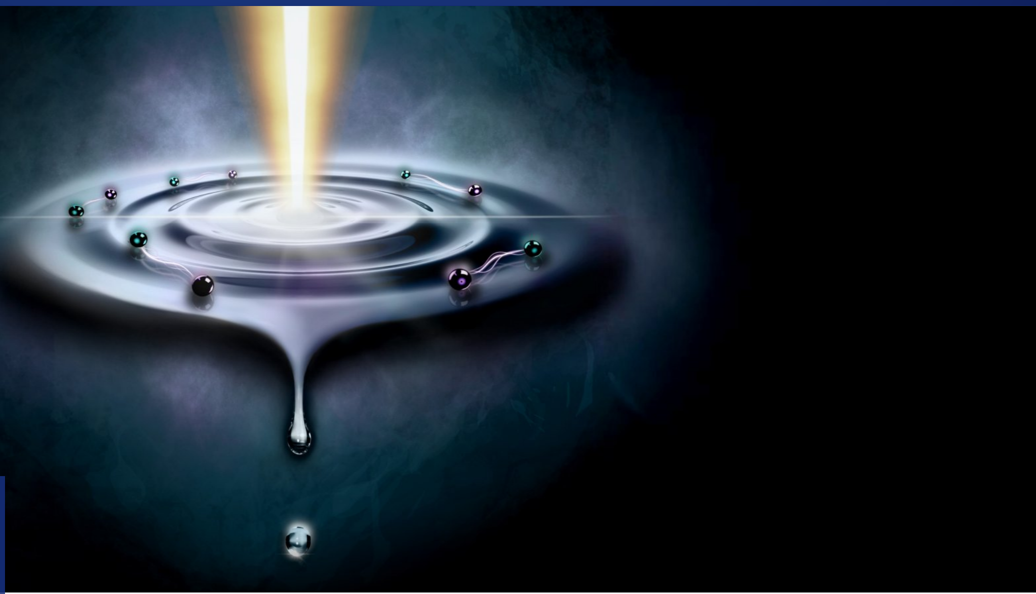

Illustration by Helene Hainzer (https://www.visual-scientist.com/)

April 2025

Contents

Upcoming

April 2-3: 10th DFG Interdisciplinary Symposium for Women in MINT
April 9: CQD Colloquium: Michal Heller
May 7: 3rd SIMPLAIX Workshop
May 9: STRUCTURES Jour Fixe

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RESEARCH

Building a Fluid Atom by Atom: Researchers Study Emergent Hydrodynamic Behaviour of a Few-Fermion System

How many particles does it take to form a fluid? A recent study led by STRUCTURES researchers reveals that fluid-like collective behaviour can emerge with as few as ten ultracold lithium atoms. Inspired by observations in high-energy nuclear collisions, where similar phenomena are seen in systems with only a few dozen constituents, the researchers explored the onset of collectivity in quantum systems.

By precisely controlling the number of atoms and the strength of their interactions, they observed "elliptic flow" – a striking inversion of the initial aspect ratio that is a hallmark of hydrodynamic behaviour. This phenomenon, typically associated with much larger systems, challenges the conventional understanding that elliptic flow requires vast numbers of particles.

The study not only challenges long-held assumptions but also provides access to observables that remain elusive in high-energy nuclear collisions. This interdisciplinary effort, combining advanced experiments and theoretical modelling, paves the way for a deeper understanding of collective phenomena in quantum systems and opens exciting new avenues for research at the interface of quantum physics and particle physics.

Original Publication

S. Brandstetter, P. Lunt, C. Heintze, G. Giacalone, L.H. Heyen, M. Gałka, K. Subramanian, M. Holten, P.M. Preiss, S. Floerchinger, S. Jochim, Nature Physics 2025, DOI:10.1038/s41567-024-02705-8.

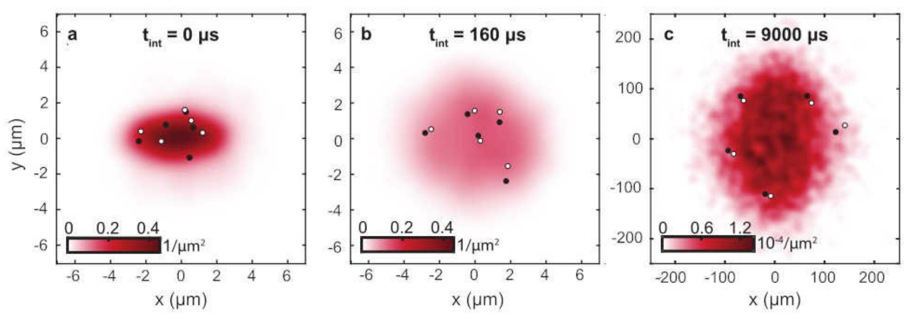


Fig. 1: Measured probability density distribution of ten atoms (black and white dots). The atoms start out with an elliptical shape that is inverted after a long interacting expansion time - a characteristic behaviour of fluids.

STRUCTURES COMMUNITY

Petra Schwer is New STRUCTURES Trust Professor

We are delighted to announce that Prof. Petra Schwer has been elected as a STRUCTURES Trust Professor by the Young Researchers Convent (YRC). Since 2024, Petra Schwer has been leading the research group *Geometry & Group Theory* at the *Institute for Mathematics (IMa)*. She joins the current team of Trust Professors, consisting of Lavinia Heisenberg (Theoretical Physics), Matthias Bartelmann (Theoretical Physics), and Ullrich Köthe (Scientific Computing), who have been reelected. Trust Professors play a crucial role insupporting early-career researchers by offering guidance, career advice and mediation in case of conflicts within research groups or with supervisors. Their goal is to foster a supportive and constructive research environment. Each year, the YRC elects four Trust Professors during their general assembly.

The YRC is a subgroup within the STRUCTURES Cluster of Excellence that connects, supports and represents the early-career researchers of our scientific community, including BSc, MSc, and PhD students, as well as postdoctoral researchers.

Petra Schwer, Professor at Institute for Mathematics (IMa)

We warmly congratulate Prof. Schwer on her election and thank all our Trust Professors for their commitment and support!

RESEARCH

`UM-Bridge`: Democratizing Uncertainty Quantification for Complex Systems

Uncertainty Quantification (UQ) is essential for reliable decision-making in safety-critical fields like engineering, environmental science, and public health, where precise risk assessment is vital. Advanced statistical tools simplify UQ workflows by separating algorithm development from domain-specific modelling. Yet, their integration with computationally demanding applications — such as PDE-based simulations in a high-performance computing (HPC) environment – remains a major barrier, limiting their widespread adoption in critical fields. To remove this barrier, an international research team led by a former young researcher from Heidelberg, Dr. Linus Seelinger (now KIT), and STRUCTURES member Robert Scheichl has developed `UM-Bridge`, a universal interface that allows to link an arbitrary UQ package to any relevant (potentially complex) computational model from applications. It is lightweight, using HTTP-protocols to map a set of input parameters to a set of outputs. `UM-Bridge` supports HPC scalability and containerized models for portability, and contains the first standardized UQ benchmark library for reproducible method comparisons. This enhances separation of concerns: instead of struggling with incompatible software, researchers can focus on their core expertise. The new software protocol thus removes barriers that have made uncertainty analysis a complex field, improving predictions, decisions, and ultimately, safety.

Original Publication:

Seelinger, L., Reinarz, A., Lykkegaard, M.B., (...), Scheichl, R., et al. Democratizing uncertainty quantification. Journal of Computational Physics 521, 113542 (2025).

RESEARCH

AL-RNNs: New Neural Networks Simplify Complex Dynamical Systems

Dynamical systems theory is key to understanding the behaviour of systems over time in science and engineering, often described through differential or recursive equations. However, nonlinear dynamical systems often defy straightforward analysis due to their complexity and chaotic behaviour.

A common way of simplification is to decompose these systems into multiple linear dynamical systems – so-called piecewise-linear (PWL) systems. However, crafting these representations manually is tedious, while inferring them from data often introduces unnecessary complexity.

A new interdisciplinary study by STRUCTURES researchers Manuel Brenner (ZI Mannheim & IWR), Christoph Hemmer (ZI Mannheim), Zahra Monfared (IWR), and Daniel Durstewitz (ZI Mannheim & IWR) introduces *Almost-Linear Recurrent Neural Networks (AL-RNNs)*. AL-RNNs learn minimal, topologically accurate PWL representations directly from time-series data. In their study, the researchers demonstrate that AL-RNNs can discover known minimal PWL representations for classical chaotic systems and generate interpretable symbolic encodings from complex real-world data. The study highlights the potential of AL-RNNs to make deep learning-based dynamical systems reconstruction more interpretable and tractable.

Original Publication:

Brenner, M., Hemmer, C.J., Monfared Z., Durstewitz D. Almost-Linear RNNs Yield Highly Interpretable Symbolic Codes in Dynamical Systems Reconstruction. Advances in Neural Information Processing Systems 37 (NeurIPS 2024).

Institute abbreviations:

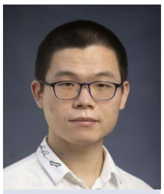
ZI = Central Institute of Mental Health, Mannheim, IWR = Interdisciplinary Center for Scientific Computing.

STRUCTURES COMMUNITY

We Are STRUCTURES

In every newsletter issue, we present short interviews with three randomly picked early-career researchers from the STRUCTURES *Young Researchers Convent (YRC)*. The YRC is a subgroup of the STRUCTURES Cluster of Excellence that brings together the early-career researchers of our scientific community. For this newsletter edition, we interviewed Boyuan Liu (Astrophysics), Finn Münnich (Mathematics) and Karina Koval (Scientific Computing):

Interview with Boyuan Liu:



Boyuan Liu
Postdoc at ZAH, *Mapelli group*

What are you working on?
I study the first generation of stars, galaxies, and black holes in the Universe using numerical simulations. My recent focus is the impact of binary stellar evolution on their properties and observational signatures, such as their formation history, chemical evolution, and emission of electromagnetic and gravitational waves.

What fascinates you about your research?
Theoretical research in astrophysics is fascinating because of the rich physics and phenomena involved across vast scales. Building physical models for such complex systems and the cosmos as a whole is a wonderful adventure of our intelligence.

How and when did you decide to pursue science?
My interest in physics was inspired by Stephen Hawking's books when I was in high school.

How does one recognize you?
If you see a cyclist at INF heading towards the north with a badminton racket, it is probably me.

Interview with Finn Münnich:

Finn Münnich
PhD student at IMa, *Marciniak-Czochra group*

What are you working on?
I am interested in the mathematical description of pattern formation arising from biological applications. The main focus of my research is to analyze the existence of stationary solutions and their stability.

What fascinates you about your research?
Many real-life phenomena can be explained through mathematical equations, where even simple models can lead to a rich variety of complex patterns. The process of uncovering the mechanisms behind these models is particularly interesting to me.

How and when did you decide to pursue science?
I have always loved math and solving problems, so studying mathematics felt like the logical choice, especially since my father also studied it.

How does one recognize you?
I am easily recognized by my long, thin braid, resembling a Padawan braid. Occasionally, you might spot me in the Mathematikon carrying a foam weapon (Pompfe) or a bike.

Interview with Karina Koval:

Karina Koval
Postdoc at IWR, *Herzog group* and *Scheichl group*

What are you working on?
I work on optimal experimental design for Bayesian inverse problems, focusing on the development of efficient computational methods for problems involving expensive forward models and infinite-dimensional unknown parameters.

What fascinates you about your research?
I enjoy my research because it combines various interesting topics, including optimization, statistics, numerical methods for partial differential equations, and reduced-order models. It also allows me to explore a wide range of application problems across different fields.

How and when did you decide to pursue science?
I chose to pursue science after taking classes with a few influential teachers in high school. That led me to engineering and, eventually, to mathematics.

How does one recognize you? *During the winter months, you'll probably hear me stomping around Mathematikon before you see me – my boots are pretty loud.*

Institute abbreviations:
ZAH = Centre for Astronomy Heidelberg,
IMa = Institute for Mathematics,
IWR = Interdisciplinary Center for Scientific Computing.

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.*

INTERVIEWS

STRUCTURES Asks: Agustin Moreno (Symplectic Working Group)

For this edition of *STRUCTURES Asks*, we interviewed Agustin Moreno, a Junior Professor in the *Symplectic Working Group* at the Institute for Mathematics' (IMA) *Research Station for Geometry & Dynamics*. His research centers on contact and symplectic topology, symplectic field theory, Hamiltonian dynamics, and their applications in celestial mechanics and space mission design. Before joining STRUCTURES, he was a Postdoctoral Member at Princeton's *Institute for Advanced Study*. Dr. Moreno has received significant grants and honours, including the *John Hawkes Scholarship*, the 2014 *Tripos Prize*, as well as a prestigious *Air Force Office of Scientific Research* grant, supporting his innovative work in symplectic dynamics.

Interview with Agustin Moreno:

Your research focuses on symplectic geometry. Can you briefly explain what this area is about?

Symplectic geometry is the study of the geometry of all possible phase-spaces for all those systems which arise in classical mechanics, i.e. *it is inherently connected to physics. (Editor's note: a phase-space represents all possible states of a system, defined by its variables, such as position and momentum.)*

How do physics and mathematics intersect and shape each other in your research?

What fascinates me is the connections to other fields, be it more theoretical (like mirror symmetry in string theory) or more practical (like astrodynamics). Some aspects of my work explore mostly the latter connections.

In 2021, a NASA engineer reached out to you regarding your work in symplectic geometry. How did this connection come about and what did it lead to?

Dayung Koh, a navigational engineer at JPL-NASA, needed mathematicians to help her with one of her papers concerning bifurcations. At the time, I had no experience with these, but she sent an email to me as I had just written a survey on the circular, restricted three-body problem, the same model she was using. After a lot of work with Urs Frauenfelder on board, we managed to create a collaboration that is still ongoing, and also includes Otto van Koert, Cengiz Aydin, and Bhanu Kumar. I believe that there is a lot to be explored at the intersection of symplectic geometry and astrodynamics.

How can interdisciplinary science best overcome initial barriers like differences in terminology?

I do not have a specific recipe to make this work, but in my experience, one needs to be patient and ask each other many questions, and explain all concepts carefully. Sometimes one is speaking about the same objects but with different names or from a different perspective, and putting the two approaches together is where the strength of an interdisciplinary collaboration lies in.

What sparked your interest in science? Do you have any advice for students?

I was always marvelled by the structure, not only of science itself, but also by how one does science. It is a very specific way of thinking that we scientists are trained in

Agustin Moreno, Junior Professor at the Institute for Mathematics (IMa)

(rational but also beautiful). My advice to students is to study as much as you can, in order to get a comprehensive as possible view of what scientists do and what we care about.

What interests or hobbies do you pursue outside of mathematics?

I can play the cello to a semi-professional standard, and I also like creative writing.

As a cellist, does mathematics influence your music or vice versa?

Not really, perhaps only in the rigorous approach, as, similar with science, there is a method and practice to studying (classical) music.

If you could meet a famous person in history over coffee, who would it be, and what would you ask them?

I would sit down with Milan Kundera, and ask him to criticize my writing.

If the three-body problem were a musical composition, what instruments would it be written for?

It would be written for a trio (cello = Earth, violin = Moon, piano = Sun).

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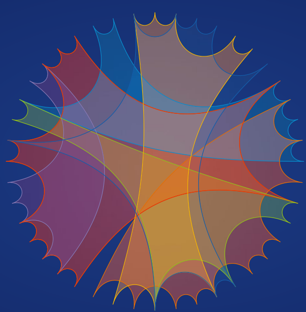
The production of this newsletter is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy EXC 2181/1 - 390900948 (the Heidelberg STRUCTURES Excellence Cluster).



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