STRUCTURES | NEWS

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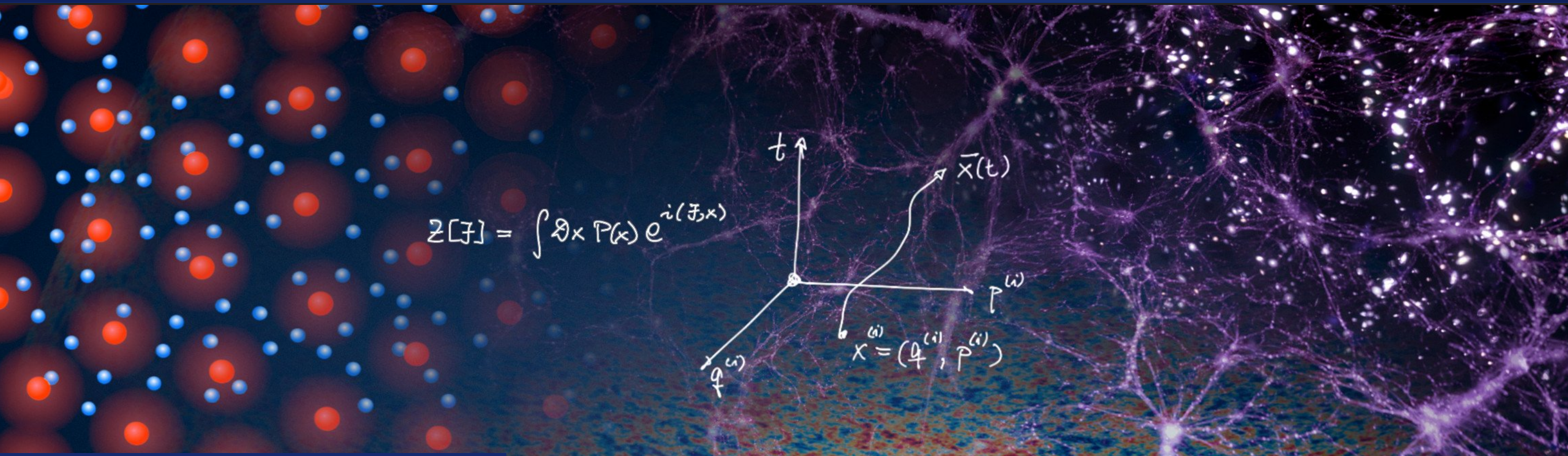

Kinetic Field Theory ▸ Project Report on p.2

A New Analytical Approach to Structure Formation in Ultracold Plasmas

Dec 2023

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Happy Holidays!

STRUCTURES wishes everyone happy and peaceful holidays! We thank our members, colleagues and everyone involved in STRUCTURES for their outstanding work and commitment, and all our readers for their interest in STRUCTURES and its activities!

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BRIEF UPDATE

KFT Reproduces Baryon Acoustic Oscillations

In cosmology, a key challenge is to understand how tiny initial density fluctuations gave rise to the presently observed cosmic structures. While linear structure growth is well understood, the non-linear phase of growth is complex and typically studied in large-scale numerical simulations. Kinetic Field Theory (KFT) offers an analytical description of structure formation that follows trajectories of classical point particles in phase space. Unlike standard perturbative approaches, KFT does not smooth velocity fields, enabling proper handling of multiple velocities where streams cross. Recently, STRUCTURES researchers have taken KFT a step further by including effects of pressure caused by interactions with photons. Applying a simplified model of these interactions to the early period in the cosmos when baryons and photons were tightly coupled, they were able to qualitatively reproduce the formation of baryon acoustic oscillations, a characteristic pattern in the matter power spectrum that offers important insights into the early cosmos.

Literature:

Kostyuk, I., Lilow, R., and Bartelmann, M., "Baryon-photon interactions in Resummed Kinetic Field Theory", *Journal of Cosmology and Astroparticle Physics*, 09(2023)032 (2023).

AWARDS & HONOURS

Congratulations to Anja Randecker and Felix Joos!

Anja Randecker

We congratulate **Anja Randecker (IMa)** on receiving the *Klaus-Georg and Sigrid Hengstberger Prize* for her outstanding research on infinite-type surfaces. Anja Randecker is principal investigator at *Research Station Geometry & Dynamics* and *Asymptotic Invariants & Limits of Groups & Spaces*, and is a founding member of the experimental geometry lab HEGL. For this newsletter, we interviewed her on page 4.

Felix Joos

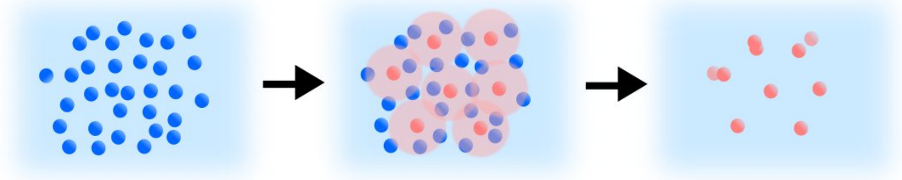
We congratulate **Felix Joos (IFI)** on receiving one of two *European Prizes in Combinatorics 2023* for his exceptional work related to asymptotic decomposition theorems. The award is considered one of the most prestigious prizes in combinatorics. Felix Joos leads the *Theoretical Computer Science & Discrete Mathematics Group*. For a portrait, we recommend reading his interview in the Oct 2022 newsletter.

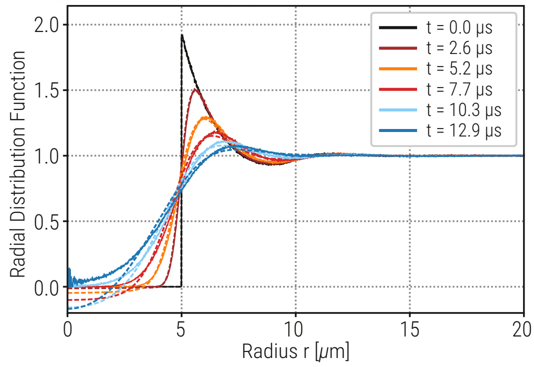
PROJECT REPORT

A New Analytical Approach to Structure Formation in Ultracold Plasmas

Invited Article by Elena Kozlikin (ITP)

Exploring the dynamics of correlated systems remains a formidable challenge across many fields ranging from cosmology to plasma physics. At the heart of this challenge lies the complexity arising due to the vast numbers of particles involved. Recent results in our project focusing on the evolution of ultracold, correlated many-body systems have unveiled new and interesting insights utilising the analytical framework of Kinetic Field Theory (KFT) [1].





Top: In order to avoid disorder-induced heating, ultracold plasmas can be produced by exciting the atoms into a Rydberg state first.

Left: The correlation function obtained with KFT (dashed curves) matches the results from molecular dynamics simulations (solid curves) up to very small scales during the evolution of the system. Here the correlation function is shown for different times. The anti-correlations introduced by the Rydberg blockade are shown in black at time $t = 0$.

The KFT formalism is based on the path-integral formulation for classical mechanics and has proven successful in describing structure formation in Dark Matter. In our recent project, we have extended the application of KFT to an ultracold many-body system created from an initially Rydberg-blockaded state, paving the way towards studying the dynamics of ultracold ion plasmas within the KFT framework.

Ultracold plasmas are particularly interesting because they offer access to the regime of strong coupling where the Coulomb interaction energy exceeds the kinetic energy of the ions. This allows us to explore properties of exotic phases of matter such as laser-induced plasmas, dense astrophysical plasmas or quark-gluon plasmas. Experiments, however, have shown that entering the strongly coupled regime is inhibited by disorder-induced heating which leads to a significant temperature increase during plasma formation. The amount of heating depends directly on the difference between the degree of correlation before and after ionisation. While neutral atoms are typically randomly distributed, Coulomb interactions between the ions will impose strong correlations after ionisation. One way to minimise disorder-induced heating is by introducing order, prior to ionisation. This can be achieved by producing the plasma from a Rydberg-blockaded neutral gas, since the anti-correlations imposed by the Rydberg-blockade resemble those induced by the Coulomb potential.

Using the analytical framework of KFT, we were able to quantify the amount of disorder-induced heating in an ultracold interacting system by computing the evolution of the correlation function and show that our analytical results match those of numerical simulations to a high degree. More interestingly, we observed that for certain choices of system parameters the effect can be reversed, leading to correlation cooling. Due to its numerical efficiency as compared to numerical simulations, a detailed study using KFT can help to constrain parameter spaces where disorder-induced heating is minimal in order to reach the regime of strong coupling. Furthermore, our results show that effects due to the discrete nature of the particle system have to be taken into account even at very high packing fractions in order to obtain correct correlation functions which agree with numerical simulations. This is an important finding, since most analytical methods are based on the hydrodynamic equations and require the assumption of a thermodynamic limit where the discrete nature of the many-particle system is neglected.

Literature:

1. E. Kozlikin, R. Lilow, M. Pauly, A. Schuckert, A. Salzinger, M. Bartelmann and M. Weidemüller, "Ultracold plasmas from strongly anti-correlated Rydberg gases in the Kinetic Field Theory formalism," submitted to SciPost Physics, [arXiv:2302.01807].

OUTREACH

Cosmology Question of the Week

Cosmology Question of the Week (www.ita.uni-heidelberg.de/~spirou/blog/) features a weekly appearing question in the area of cosmology, gravity, field theory and fundamental physics, curated by Björn Malte Schäfer. No matter if you're preparing for an exam, like to step up your physics game or want to discuss with your friends, CQW has you covered. There are already over 500 questions available, and Björn offers a bounty to the students of STRUCTURES for well-formulated sample solutions to be published on CQW - please enquire.

QUESTION OF THIS WEEK (DEC 13):

The wave equation for a scalar field, $\Box\varphi = 0$ is identical for a non-relativistic mechanical wave and for a relativistic wave, despite the fact that the classical wave is Galilei-covariant and the relativistic wave is Lorentz-covariant. Can this be?

STRUCTURES COMMUNITY

We Are STRUCTURES

In our newsletter we regularly introduce members of the *Young Researchers Convent (YRC)*, a subgroup of STRUCTURES that brings together students and postdocs. For this issue, we interviewed Johannes Meyer, Rebecca Kuntz and Enrique Fita Sanmartín:

Interview with Johannes Meyer:

Johannes Meyer
PhD student,
AG Klahr, MPIA

What are you working on?
I am developing my own implicit hydro code that will hopefully be useful in simulating hydrodynamical instabilities in the context of protoplanetary disks. Currently I am also exploring the formation processes of Asteroids and Kuiper Belt Objects with numerical techniques.

What is your area of expertise?
Implicit hydrodynamics but I like data analysis as well.

What is your connection to STRUCTURES?
I joined STRUCTURES through my supervisor Prof Hubert Klahr, who is a member. I love reading the STRUCTURES Blog, it's really cool to see the work in other fields explained simply.

What has been your greatest scientific success up to now?
Running my 10K line code and seeing it produce meaningful results for the first time was my personal high.

How does one recognize you?
I am constantly working on or thinking about my code. So if you meet a guy burning the midnight oil, thats probably me 🙂.

Interview with Rebecca Kuntz:

Rebecca Kuntz
MSc student, AG Schäfer, ARI/ZAH

What are you working on?
I am currently working on various aspects of Bayesian inference and information geometry. More specifically, my group and I employ concepts from statistical physics in order to implement a new Markov Chain Monte Carlo sampling algorithm. Apart from that, the focus of my thesis in particular lies on the generalization of the Fisher formalism to the inference of scalar functions.

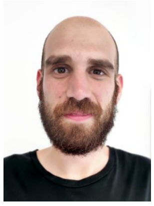
What is your area of expertise?
I would not consider myself an expert, but I spent a considerable amount of time in the past year learning about Bayesian statistics, inference and information theory.

What is your connection to STRUCTURES?
My thesis advisor Prof Björn Schäfer is a STRUCTURES member. Furthermore, I consider many members of the YRC to be my good friends. I also attended the YRC Schöntal Workshop, which was a great opportunity to learn about physics and have many meaningful conversations.

What has been your greatest scientific success up to now?
Working on two publications together with my group. I am very proud of the hard work we put in as a team in order to achieve this.

How does one recognize you?
If you find yourself at the second floor of Philosophenweg 12 and encounter a dark haired physicist with a fondness of long black skirts, it might just be me.

Interview with Enrique Fita Sanmartín:



Enrique F. Sanmartín
PhD student,
AG Hamprecht, IWR

What are you working on?
I am working on *spanning stable trees* for point clouds. Assuming these points follow a hidden structure described by a graph's spanning tree, my aim is to identify a robust spanning tree within the given point cloud. This tree should accurately represent the data and undergo only subtle changes when the points are slightly perturbed.

What is your area of expertise?
I do not consider myself an expert in any particular field, as every day I realize how much I am still unaware of. Nevertheless, I suppose I am relatively more knowledgeable about graphs than the average person.

What is your connection to STRUCTURES?
I am part of the CP6 comprehensive project *Networks and Machine Learning*.

What has been your greatest scientific success up to now?
The work I did during my MSc thesis. It focused on establishing a connection between two semi-supervised graph-based algorithms: the Watershed and Random Walker algorithms. Specifically, I demonstrated the equivalence between a probabilistic version of the Watershed and the Random Walker algorithm.

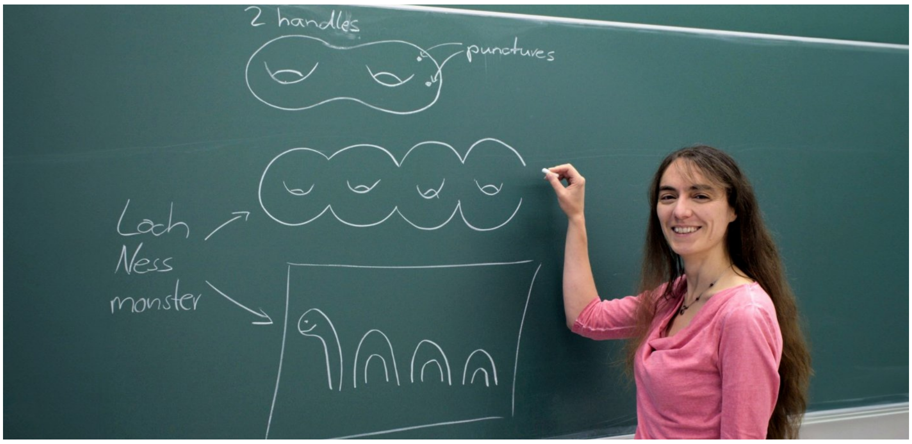
How does one recognize you?
I have often been noticed due to my reddish jacket, which apparently stands out. If you encounter someone wearing a reddish jacket who is also bald, I guess that's me.

JOIN THE YRC: Any student or postdoc whose work fits into the concept of STRUCTURES can apply for YRC membership. If your supervisor is a full STRUCTURES member or if your work is funded by STRUCTURES, you are directly eligible for membership in the YRC. For more information, see: *https://structures.uni-heidelberg.de/YRC.php*. You can ask questions or apply via mail anytime at: *structuresyrc(at)thphys.uni-heidelberg.de*

STRUCTURES INTERVIEWS

STRUCTURES Asks: Anja Randecker

In our newsletter, we regularly interview group leaders, members and guests. For this edition, we interviewed Anja Randecker, principal investigator at Research Station Geometry + Dynamics and in RTG2229 "Asymptotic Invariants and Limits of Groups and Spaces", a joined research training group with KIT as part of the HEiKa alliance. Anja Randecker is a founding member of the experimental geometry lab HEGL. Her research in the fields of geometry and surface dynamics has recently been honoured with the Hengstberger Prize.



Dr. Anja Randecker (IMa), principal investigator at GeoDyn and RTG2229

What are you working on, and what fascinates you about it?

I study the symmetries of surfaces. This is a topic where most members of STRUCTURES will have immediately a picture in mind, so it is easy to describe. However, despite its apparent simplicity, the questions within this field reach very deep, and that is what makes it fascinating.

Do you have a favourite type of geometric or topological structure?

I am particularly interested in surfaces of infinite type. Formally, we say that these are surfaces with infinitely generated fundamental group. To paint a picture for you: topologically, we classify surfaces by their number of handles (a cup has one, a pretzel has three) and punctures (like the valve in a tire). If one of these numbers is infinite, we have a surface of infinite type.

What is a topological *"Loch Ness Monster"*?

This is arguably the simplest surface of infinite type. It has infinitely many handles and you can imagine it as a bagel baked together with another bagel which is in turn baked together with another bagle which is in turn... As some of the theory of surfaces of infinite type is very recent, not even the symmetries of this Loch Ness monster are fully understood. The name, however, has been around for at least 40 years, appearing in an article of Phillips–Sullivan.

What is an open problem in your field?

If we take classical surfaces, those of finite type, there is a classification of the symmetries. The maps that realize these symmetries can be only of three different types, where the easiest is being periodic, that is, if we apply the map a couple of times in a row, we end up with the same surface as the one we started with.

For surfaces of infinite type, we do not have such a classification yet but the search has started.

How do you convey the beauty and significance of mathematics to students? Do you have any advice for teachers?

A picture says more than a thousand words... As a general approach to teaching, I think we should consider less conveying and more exploring. Making your own discovery will feel so much more beautiful and significant than facts told to you. And that's also an advice for mathematics teachers: spark the curiosity. Make students wonder about math. Give them the chance for discoveries.

What do you regard as important for promoting inclusivity in science?

To listen to the insights and advices of experts! We all have experiences and they should be heard. But if we have questions on how to do better, we should do the same as we do in research: ask the experts from the field.

Suppose you were gifted an additional 48 hours - how would you spend the time?

I'd bake several kilograms of Christmas cookies. And although I doubt that anyone would grant me such a gift soon - I'll still bake them this weekend. Loch Ness monsters have to wait for Monday morning.

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