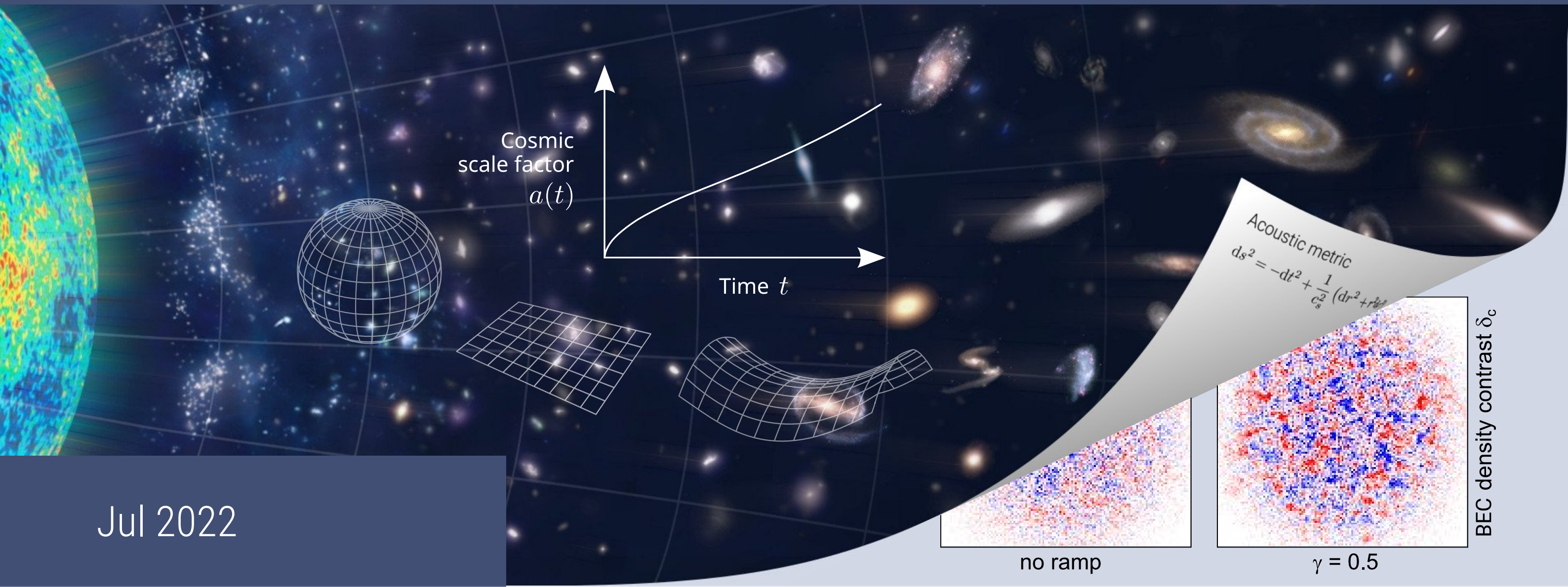
STRUCTURES | NEWS

STRUCTURES CLUSTER OF EXCELLENCE

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386



Jul 2022

Contents

Upcoming

STRUCTURES General Assembly: July 15, 1:30 pm

Celebrating the Poincaré Conjecture:

- **July 15, 3:30 pm:** Mathematical Lecture by Markus Banagl
- **July 22, 4:30 pm:** Public Lecture by Sebastian Hensel (in German) + Open HEGL

STRUCTURES Summer Party: July 15, 5 pm

More Information can be found on the STRUCTURES website.

STRUCTURES Short News

KIP & ITP PHYSICISTS STUDY QUANTUM ANALOGUE OF EXPANDING UNIVERSE

STRUCTURES scientists at Kirchhoff-Institute for Physics (KIP) and Institute for Theoretical Physics (ITP) have built and analysed an acoustic analogue of the universe in the lab using ultracold atoms. The phononic excitations in a Bose-Einstein condensate behave as a relativistic scalar field in an expanding & curved spacetime, allowing to study difficult-to-observe effects such as cosmological particle production. The researchers summarise their work in a report on page 2.

SIMPLAIX: BOOSTING MOLECULAR RESEARCH WITH SIMULATIONS & AI

The new SIMPLAIX collaboration, headed by Rebecca Wade and Frauke Gräter, brings together researchers from Heidelberg Institute for Theoretical Studies (HITS), Heidelberg University, and KIT, under participation of STRUCTURES members. The scientists will pool their unique expertise in multi-scale simulations and machine learning in order to bridge scales in simulating biomolecules and molecular materials.

MATHFEST: CELEBRATING THE POINCARÉ CONJECTURE

In July 2022, Heidelberg University (Mathematisches Institut, STRUCTURES & GeoDyn) organises a series of public events on the Poincaré Conjecture, one of the seven famous Millennium Prize problems – and the only one fully resolved so far. Several public lectures and a workshop will give an introduction to the subject as well as insights into exciting recent mathematical developments. The events are part of a nationwide Millennium Prize problem celebration. More information can be found at: https://mathfest.mathi.uni-heidelberg.de.

OPEN DOORS AT THE PARENT – CHILD OFFICES OF ISOQUANT & STRUCTURES

On May 18, special guests and members of both projects (Age 1-99) celebrated the opening of office space fully equipped to enable parents to work and take care of their kids simultaneously. To register or learn more about the parent-child offices "KIDS" by ISOQUANT and STRUCTURES, please visit: https://ekb.thphys.uni-heidelberg.de.

CP REPORT

From CP4: Simulating a Quantum Field in Curved and Expanding Spacetimes

Invited guest article by the Curved Spacetime Collaboration

Authors: Celia Viermann, Marius Sparn, Nikolas Liebster, Maurus Hans, Elinor Kath, Álvaro Parra-López, Mireia Tolosa-Simeón, Natalia Sánchez-Kuntz, Tobias Haas, Helmut Strobel, Stefan Floerchinger, Markus K. Oberthaler

When quantum fields experience spacetime curvature, many fascinating phenomena arise. This includes particle production, which occurs when the spacetime metric is explicitly time-dependent. One such metric is the Friedmann–Lemaître–Robertson-Walker (FLRW) metric,

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}u^2}{1-\kappa u^2} + u^2 \mathrm{d}\Omega^2\right), \quad (1)$$

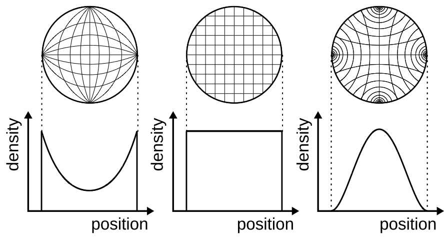


Fig. 1a: Density profiles realise spatial curvature

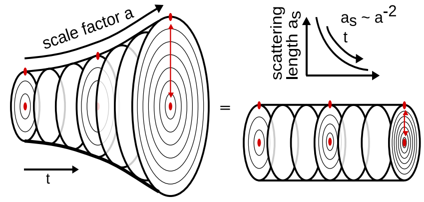


Fig. 1c: Expansion $a(t)$ generated by reducing the coupling

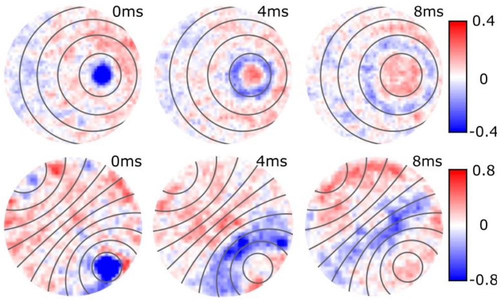


Fig. 1b: Propagation of phonon wave packet

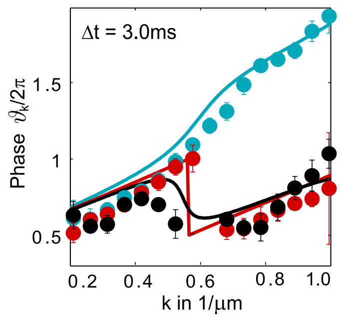


Fig. 1d: Phases of produced particles

which describes the homogeneity and isotropy of our universe on large scales. The scale factor $a(t)$ encodes the expansion history, while κ determines the spatial curvature.

Detecting cosmological particle production directly is an open challenge. However, there exist one-to-one mappings between massless relativistic particles in a flat FLRW universe and acoustic excitations (so-called phonons) in a Bose-Einstein condensate (BEC), providing the possibility to study this effect in the laboratory.

In [1], we have upgraded this analogy: engineering specific background density profiles for an ultracold atomic cloud in $d = 2+1$ spacetime dimensions allows us additionally to realise FLRW spacetimes with arbitrary spatial curvature κ (cf. Fig. 1a with spherical, flat and hyperbolic geometry from left to right). To benchmark the mapping, we analysed the propagation of a phononic wavepacket in a static universe, which should move along geodesics derived from Eq. 1 for given κ [2]. The successful implementation is shown in Fig. 1b (upper/lower row corresponds to hyperbolic/spherical geometry and the black lines are equidistant from the initial perturbation).

An expanding universe is realised by ramping down the interaction between the atoms in a time-dependent way (cf. Fig. 1c), which can be controlled independently of the spatial curvature. In this way, the causal speed of a moving signal is decreased, which is equivalent to a constant causal speed in an expanding space.

Signatures of particle production can be found in the correlations of the (temporal derivatives of the) quantum field at given instances of time. Experimentally, this can be quantified by measuring a suitably chosen density correlation function, such that the symmetries of the FLRW universe are preserved and the background density profile is subtracted. Applying a Hankel transform to this quantity gives access to the spectrum of quantum fluctuations in momentum space, which depends on the expansion history $a(t)$ and the initial mode population.

To clearly distinguish different expansion histories, especially accelerating or decelerating scenarios, we identified a feature robust against thermal fluctuations in the initial state: the phase Θ_k of the produced particles with wavenumber k, which is shown in Fig. 1d for expansions of different types [2]. The solid lines indicate theory predictions within the FLRW paradigm [1, 3], which are in quantitative agreement with experimental findings (dots).

To summarise, we established and confirmed a quantum field simulator for the dynamics of a scalar field in spatially curved FLRW universes in a BEC and thereby observed analogue cosmological particle production in agreement with our proposal.

Literature

1. M. Tolosa-Simeón, Á. Parra-López, N. Sánchez-Kuntz, T. Haas, C. Viermann, M. Sparn, N. Liebster, M. Hans, E. Kath, H. Strobel, M. K. Oberthaler, and S. Floerchinger, Curved and expanding spacetime geometries in Bose-Einstein condensates, arXiv:2202.10441 (2022)
2. C. Viermann, M. Sparn, N. Liebster, M. Hans, E. Kath, Á. Parra-López, M. Tolosa-Simeón, N. Sánchez-Kuntz, T. Haas, H. Strobel, S. Floerchinger, and M. K. Oberthaler, Quantum field simulator for dynamics in curved spacetime, arXiv:2202.10399 (2022)
3. N. Sánchez-Kuntz, A. Parra-López, M. Tolosa-Simeón, T. Haas, and S. Floerchinger, Scalar quantum fields in cosmologies with 2 + 1 spacetime dimensions, Phys. Rev. D 105, 105020 (2022)

STRUCTURES COMMUNITY

We Are STRUCTURES

In each newsletter, we introduce three members of the Young Researchers Convent (YRC) to you. For this edition, we interviewed Eileen Giesel (ZAH), Janne Frenz (MI) and Maximilian Kaiser (PI).

Interview with Eileen Giesel:

Eileen Giesel
PhD student, AG Schäfer, ZAH

What are you working on? In my PhD Thesis I am working on Intrinsic Alignment, which describes how galaxies align in tidal fields and is an important correction in gravitational lensing. I also work on the phenomenology of weak area metric lensing, where my work has some overlaps with Constructive Gravity.

What are you an expert for? Though I would not dare to call myself an expert, I feel quite knowledgeable in the fields mentioned above 😉. I also know a bunch about information geometry, and I am generally interested in how geometry helps to understand physics.

What is your connection to STRUCTURES? I am a member of the YRC working together with Prof. Björn Malte Schäfer.

How does one recognise you? My trademark is my excessive coffee and tea consumption and unusual working rhythm. If you see lights at Philosophenweg 12 late at night it is probably me still working at the office.

Interview with Janne Frenz:

Janne Frenz
MSc student, MI, in the process of orientation

What are you working on? Currently I am specialising in Lie groups and representation theory, algebraic number theory and algebraic topology. I am looking forward to exploring algebraic geometry starting next semester.

What was your greatest scientific success up to now? My BSc thesis and a programming project for visualising imaginary quadratic number fields by means of their geometric properties. Visualising abstract objects in this way was fun and inspiring. I can well imagine to continue with similar projects in the context of my MSc thesis.

What are you an expert for? Calling myself an expert is a lot for a master's student. I definitely want to continue working in computer assisted mathematics. Optimally, my work has something to do with the fields of algebraic geometry and group theory. Actually I went to a conference on group theory in Milan last month.

What is your connection to STRUCTURES? I learned about the YRC last summer and joined the cluster just recently. My interests overlap most with STRUCTURES' CP 7.

How does one recognise you? You will most likely recognise me by my loud laugh. My favorite description came from a fellow student: "You laugh like a video game boss."

Interview with Maximilian Kaiser:

Maximilian Kaiser
PhD student, AG Jochim, PI

What are you working on? Together with my colleague, Tobias Hammel, I am building a new apparatus for experiments and quantum simulations with ultracold fermionic Lithium. The machine has been named "Heidelberg Quantum Architecture" (HQA).

What are you an expert for? I committed my diploma thesis and now my Ph.D. to the field of ultracold quantum gases. So far, I had the opportunity to learn a lot about the technical aspects of trapping and cooling neutral atoms.

What is your connection to STRUCTURES? HQA is part of two projects in STRUCTURES: Within one project, CP4, we want to use our new experiment to learn more about the role of fundamental quantum properties (e.g. coherence and entanglement) in emergent many-body phenomena. The second project, CP5, aims at a physical connection between BrainScaleS and HQA to combine neuromorphic computing and ultracold quantum gases.

What was your greatest scientific success up to now? I built a laser system for trapping and reliably transporting cold neutral atoms over macroscopic distances of around 0.5 m as part of my diploma thesis.

#1 2022 YRC STRUCTURES CONFERENCE

Oct. 4–7 2022, Heidelberg
REGISTER NOW

Registration for the **YRC STRUCTURES Conference 2022** is now open.

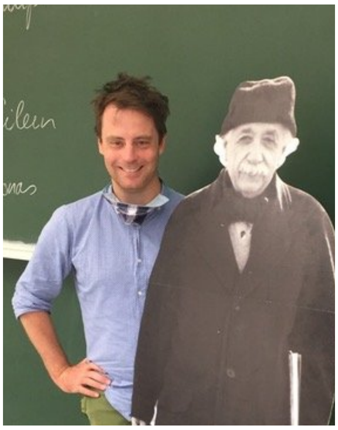
Make sure to register until **August 7** to present a talk or a poster, and until **September 7** to participate in the conference.

https://www.conferencecentral.org/webpage/view/20

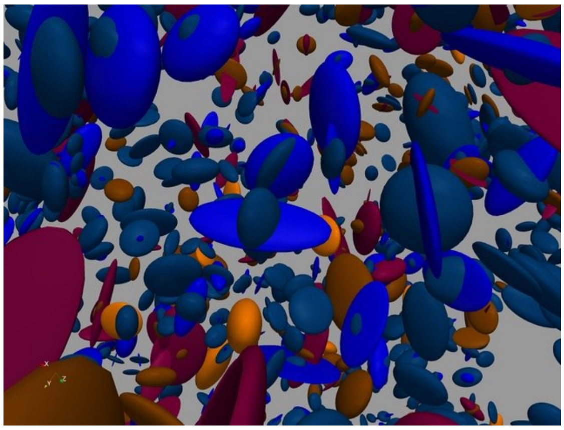
MEMBER INTERVIEWS

STRUCTURES Asks: Björn Malte Schäfer

In our newsletter, we regularly present interviews with STRUCTURES faculty members to give you the opportunity to get to know them a little better. For this edition, we interviewed Björn Malte Schäfer, professor for fundamental physics at the Center for Astronomy of Heidelberg University (ZAH), where he leads the Statistics & Cosmology group. Within STRUCTURES, he is leading EP 6.1: "Reconstructions of potentials with neural differential equations: applications to cosmic inflation and dark energy".



Björn Malte Schäfer (left), professor for fundamental physics at ZAH.



Visualisation of tidal gravitational fields acting on dark matter haloes in a cosmological simulation, one of Prof. Schäfer's research topics.

What are you working on and what fascinates you most about it? At the moment I am working on cosmic inference problems: how much information about fundamental physical ideas is contained in cosmological data and how one can extract that information from data. I am trying to develop methods that allow us to do that in strongly non-Gaussian statistics, using a new field of mathematics called information geometry.

What are the big unsolved questions underlying your research? There is of course the big question about dark matter, its relation to particle physics and its role in structure formation, as well as of dark energy and new gravitational phenomena on large scales. But what I find way more interesting is the question how complexity arises in cosmic structures and how fundamental theories are tested in astrophysical observations.

What surprises you most about the fundamental laws of physics (and their mathematical structure)? I find it surprising that we always gravitate towards geometry in our description of nature, and that geometric concepts are so successful, even in areas of physics where you might not expect them, for instance statistics.

What motivated you to study physics and to choose the field of cosmology? As a kid I read a book about the cosmic microwave background (*M. Rowan-Robinson: Ripples in the cosmos*) and I wanted to know more about it.

Do you have any advice for young researchers about choosing their career path? My advice would be to follow what interests you most, to deliver the best work that you can, and to continuously improve as scientists.

What profession other than yours would you like to attempt and why? There are two possibilities: I love marine biology and investigating marine life, in particular whales and sea lions. And I do like music, perhaps there's a parallel universe with me as a (mediocre, at best) piano player.

What is the future fate of the universe and its structures? That's a well-posed questions with a quantitative answer: dark energy will shut off structure formation and reduces the size of the observable universe, so that we can observe fewer and fewer structures, ultimately only the Local Group as a gravitationally bound object.

Imagine you get 48 extra hours as a present – what would you do with it? Work out a couple of integrals and practice piano: not necessarily in that order, though.

STRUCTURES ON THE WEB
https://structures.uni-heidelberg.de

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).

IMPRESSUM & CONTACT
Exzellenzcluster STRUCTURES
Universität Heidelberg
Berliner Straße 47
D-69120 Heidelberg

office@structures.uni-heidelberg.de

Text & Editing: STRUCTURES Office, Guest Authors, Spokespersons
Design, layout, cover picture: Sebastian Stapelberg