Titles and Abstracts

Hyper-Millennium project: a hyper cosmological simulation for the next generation of large-scale structure survey

Qi Guo
National Astronomical Observatories, N body simulation and structure formation

Dark matter and dark energy are among the most important cutting-edge sciences. Extensive global efforts have been dedicated to the large-scale structure evolution through projects like LSST, DESI, Euclid, PFS, and the Chinese space station optical survey. We have successfully completed a N-body cosmological simulation that traces 4 trillion particles from redshift 100 to the present day within a 2.5 Gpc/h box. The particle mass is 3.2 x 10^8 solar masses, meeting the requirements for the next generation of large-scale structure surveys. This simulation aids in understanding the systemic and statistical uncertainties involved in studying large-scale structure formation, including baryon acoustic oscillations, redshift distortion, weak lensing, high redshift AGNs and etc. In my presentation, I will delve into the details of the simulation and discuss advancements made in galaxy and AGN formation models.

Cosmology beyond the dark ages

David L. Wiltshire
University of Canterbury

For 25 years a standard model of cosmology has reigned in which most of the stuff in the universe is mysterious: 70% dark energy attributed to a cosmological constant, Λ, and 25% to cold dark matter particles. Their effects are only inferred gravitationally. However, standard cosmology does not use the full possibilities of Einstein's general relativity. For nearly 2 decades, I have been working on an alternative cosmology, the timescape, revisiting the foundations of Einstein's theory: the issues of quasilocal energy and angular momentum in a Universe with large complex structures. Quantitative predictions had to wait til the 2020s for observations to reach a precision to distinguish the timescape from the 100–year old Friedmann-Lemaˆıtre models, on which standard cosmology is based. With a huge variety of new data now pouring in, standard cosmology is increasingly challenged. But the timescape and related solutions are fitting well [1-4], offering new insights, new questions, and a potential change to our fundamental paradigm for the universe.

References

[1] A. Seifert, Z.G. Lane, M. Galoppo, R. Ridden-Harper and D.L. Wiltshire, "Supernovae evidence for foundational change to cosmological models." Mon. Not. R. Astr. Soc. Letters, 537 (2025) L55.
[2] Z.G. Lane, A. Seifert, R. Ridden-Harper and D.L. Wiltshire, "Cosmological foundations revisited with Pantheon+." Mon. Not. R. Astr. Soc. 536 (2025) 1752.
[3] M.J. Williams, H.J. Macpherson, D.L. Wiltshire and C. Stevens. "First investigation of void statistics in numerical relativity simulations." Mon. Not. R. Astr. Soc. 536 (2025) 2645.
[4] M. Galoppo and D.L. Wiltshire. "Exact solutions for differentially rotating galaxies in general relativity." arXiv:2406.14157 [gr-qc] (2024).

General Relativistic Galaxy Dynamics

Marco Galoppo
University of Canterbury

Conventionally the Newtonian limit of general relativity (GR) assumes an empty universe at spatial infinity. We demonstrate that for realistic isolated differentially rotating systems – disc galaxies – a new quasilocal Newtonian limit of GR is found to self-consistently couple gravitational energy and angular momentum. A modified Poisson equation is obtained, along with modifications to the equations of motions of the effective fluid elements. The results may have major implications for all gravitational physics on galactic and cosmological scales. We show that the phenomenology of collisionless dark matter for disc galaxies can be reproduced.

Gravitational waves from boson star mergers

Daniela Cors
University of Cambridge

We provide results of the gravitational-wave energy emitted by head-on collisions of equal-mass solitonic boson stars. Our numerical simulations span a two-dimensional parameter space, where a range of values for the central amplitude of the star is considered for different values of the solitonic constant. We report gravitational wave energies emitted by the merger of fluffy (less compact) boson stars that are up to an order of magnitude higher than those emitted by a binary black hole merger. The interplay between our control parameter - the distance separating the stars dictating the time of merger - and the multiple extrema present in the solitonic potentials considered, provide a surprisingly rich phenomenology. For certain values of the solitonic constant, the gravitational wave energy exhibits striking needle-sharp features across some range of central amplitudes, whilst in other regions of the parameter space it can drop discontinuously towards the value emitted by a binary black hole merger. An interpretation of all these results will be provided.

Nonlinear fluid dynamics near the Big Bang singularity

Florian Beyer
University of Otago

This talk investigates the nonlinear dynamics of relativistic fluid matter near the Big Bang singularity, moving beyond assumptions of spatial homogeneity and isotropy. Over the past decade, significant progress has been made in understanding these dynamics through advances in the mathematical theory of partial differential equations, though many questions remain unresolved. I will provide an overview of these developments, present recent results from my collaboration with Todd Oliynyk, and discuss open problems in the field.

Statistical Properties of Cosmological Density Fields and the Size of the Largest Structures

Francesco Sylos-Labini
Enrico Fermi Research Center

On cosmological scales, the distribution of galaxies raises critical questions, particularly regarding the existence of a definitive cut-off for the size of cosmic structures. Observations of the large-scale network of voids and filaments challenge the predictions of CDM models, which suggest that, on sufficiently large scales, the correlation function should become negative. This behavior implies a super-homogeneous distribution of matter, characterized by the suppression of long-wavelength density fluctuations compared to typical disordered systems, such as fluids or amorphous solids. Despite their significance, the super-homogeneous density fields predicted by CDM models remain underexplored and demand deeper theoretical and observational investigation. In particular, observational studies must aim to identify their signatures in galaxy surveys. Current data, however, reveal highly correlated galaxy structures—filaments and voids—that are challenging to reconcile with a super-homogeneous framework.

In this talk, I will review the principal scales of the standard CDM model, focusing on the homogeneity scale, which determines the distance at which gravitational dynamics adhere to linear evolution, and the scale at which the correlation function becomes negative, marking the transition from a homogeneous to a super-homogeneous distribution. I will then present an overview of the measurements of these length scales in redshift surveys and discuss the potential impact of new data from ongoing galaxy surveys, such as DESI and Euclid.

Numerical Relativity and Applications in Cosmology

Ulrich Sperhake
University of Cambridge

In this talk we provide a (in parts historically structured) overview of the methodology and developments in numerical relativity. We discuss the key challenges that have been overcome over the decades preceding the breakthroughs of the 2000s and how the codes have now matured into efficient toolboxes for exploring non-linear gravity phenomena across a wide range of key areas in contemporary physics. We discuss the specific considerations required for the numerical modeling of cosmological spacetimes, discuss where open challenges remain and review main applications and those issues that merit particular investigation in future work.

Noncompact n-dimensional Einstein spaces as attractors for the Einstein flow

Jinhua Wang
Xiamen University

We prove that along with the Einstein flow, any small perturbations of an $n(n \geq 4)$-dimensional, non-compact negative Einstein space with some "non-positive Weyl tensor" lead to a unique and global solution, and the solution will be attracted to a noncompact Einstein space that is close to the background one. The $n = 3$ case has been addressed in WangYuan, while in dimension $n \geq 4$, as we know, negative Einstein metrics in general have non-trivial moduli spaces. This fact is reflected on the structure of Einstein equations, which further indicates no decay for the spatial Weyl tensor. Furthermore, it is suggested in the proof that the mechanic preventing the metric from flowing back to the original Einstein metric lies in the non-decaying character of spatial Weyl tensor. In contrary to the compact case considered in Andersson-Moncrief, our proof is independent of the theory of infinitesimal Einstein deformations. Instead, we take advantage of the inherent geometric structures of Einstein equations and develop an approach of energy estimates for a hyperbolic system of Maxwell type.

The emergence of nonlinear Jeans-type instabilities for quasilinear wave equations

Chao Liu
Huazhong University of Science and Technology

This talk (see arXiv:2409.02516) contributes a key ingredient to the longstanding open problem of understanding the fully nonlinear version of Jeans instability. We establish a family of self-increasing blowup solutions for the following class of quasilinear wave equations that have not previously been studied:

$$\partial_t^2\varrho-\left(\frac{m^2\left(\partial_t\varrho\right)^2}{(1+\varrho)^2}+4\left(k-m^2\right)(1+\varrho)\right)\Delta\varrho=F\left(t,\varrho,\partial_\mu\varrho\right)$$

where F is given by

$$F\left(t,\varrho,\partial_\mu\varrho\right):=\underbrace{\frac{2}{3}\varrho(1+\varrho)}_{\text{(i) self-increasing}}\underbrace{-\frac{1}{3}\partial_t\varrho}_{\text{(ii) damping}}+\underbrace{\frac{4}{3}\frac{\left(\partial_t\varrho\right)^2}{1+\varrho}}_{\text{(iii) Riccati}}+\underbrace{\left(m^2\frac{\left(\partial_t\varrho\right)^2}{(1+\varrho)^2}+4\left(k-m^2\right)(1+\varrho)\right)q^i\partial_i\varrho-K^{ij}\partial_i\varrho\partial_j\varrho}_{\text{(iv) convection}}.$$

The result implies the solutions can attain arbitrarily large values over time, leading to self-increasing singularities at some future endpoints of null geodesics, provided the inhomogeneous perturbations of data are sufficiently small. This phenomenon is referred to as the nonlinear Jeans-type instability because this wave equation is closely related to the nonlinear version of the Jeans instability problem in the Euler-Poisson and Einstein-Euler systems, which characterizes the formation of nonlinear structures in the universe. The growth rate of ϱ is significantly faster than that of the solutions to the classical linearized Jeans instability.

The possible evidence of modification to gravity

Bin Hu
Beijing Normal University

In this talk, I will review 3 different observations: Hubble tension revealed by the cepheid distance observation; DESI year 1 baryonic acoustic oscillation result; ultra-massive early type galaxies discovered by James Webb Space Telescope. Combining the three observations, we might have the first convincing evidence for modification to gravity.

Aspects of Mathematical Cosmology

David Fajman
Vienna University

In this talk I will give an overview on results in the field of Mathematical Cosmology and an introduction to some aspects of the methods involved to obtain them. This concerns the Einstein equations and some particular classes of Einstein-matter systems.

Oppenheimer-Snyder type collapse for a collisionless gas

Håkan Andreasson
University of Gothenburg

In the seminal work by Oppenheimer and Snyder from 1939 it is shown that a homogeneous ball of dust undergoes gravitational collapse. This work has had an enormous impact on the field since it predicts the existence of black holes. In this talk I will show that the Oppenheimer-Snyder type collapse can be approximated arbitrary well by solutions to the Einstein-Vlasov system. It is crucial for the argument to work in Painlevé-Gullstrand coordinates rather than in comoving coordinates which is standard in the case of dust. Extensions of this result to the inhomogeneous case will also be discussed. In particular, there exist inhomogeneous data for dust which give rise to naked singularities and it is thus of great importance to understand the relation between the dust solutions and the solutions to the Einstein-Vlasov system in the context of the weak cosmic censorship conjecture. This is a joint work with Gerhard Rein.

Relativistic Nonlinear Dynamics in Structure Formation in ΛCDM

Marco Bruni
University of Portsmouth

In this talk I will give an overview of work on nonlinear structure formation in ΛCDM in the context of General Relativity (GR). Starting from briefly presenting a post-Friedmann approximation, I will show how gravito-magnetic effects (AKA frame-dragging) can be extracted from standard Newtonian N-body simulations, as well as from N-body simulations with GRAMSES, an approximate GR code. I will then present full-GR simulations of a toy-model "cosmic web" of over-densities, voids and filaments with the Einstein Toolkit fluid code, showing how the first shell-crossing at peaks of over-densities is very well predicted by the simple top hat model, while in the formation of the cosmic web a role is played by gravito-magnetism, especially around filaments.
In the last part of the talk I will illustrate some work in progress, some aimed at extending the work on frame-dragging on smaller galactic scales, some aimed at understanding to what extent relativistic effects can play a role during collapse and past the first shall crossing and virialization. I will conclude with an outline of possible future work.

Gravitational-wave standard sirens and implication for cosmology

Wen Zhao
University of Science and Technology of China

We introduction the basic idea of using gravitational-wave event as a new probe, i.e. the standard sirens, to measure various cosmological parameters. The advantage and disadvantage, the detection status, and the potential futures of different gravitational-wave sources will also be discussed.

How to Make a Black Hole

Xinliang An
National University of Singapore

Black holes are predicted by Einstein's theory of general relativity, and now we have ample observational evidence for their existence. However theoretically there are many unanswered questions about how black holes come into being. In this talk, we will prove that, through a nonlinear focusing effect, initially low-amplitude and diffused gravitational waves can give birth to a black hole formation in our universe.

Hyperboloidal compactification for wave equations on FLRW backgrounds

Alex Vañó Viñuales
University of Lisbon

This work is motivated by the study of the decay of a wave equation on flat and hyperbolic FLRW spacetimes with a time-dependent scale factor. Compactified hyperboloidal slices track wave packets until they leave the computational domain through future null infinity. The idea is to adapt the slices and compactification to account for the change in the spacetime's scale during the evolutions. This allows us to perform numerical simulations without a timelike outer boundary. I will show current results in spherical symmetry and how they enable the recovery of the decay rates obtained from evolutions on usual truncated Cauchy slices. Application of this hyperboloidal setup is also suitable for more general settings such as non-linear waves with self-interactions.
Joint work with Flavio Rossetti.

Wave Effects of Gravitational Waves

Jian-Hua He
Nanjing University, data analysis and simulation of cosmology

Wave effects are a crucial aspect of gravitational waves. When the wavelength of GWs is comparable to or greater than the Schwarzschild radius of an object, the propagation of gravitational waves no longer follows geometrical optics, and coherence and interference can occur. Despite their significance, studying these wave effects can be challenging due to their complexity.

In this talk, I will discuss numerical techniques for simulating these effects in the gravitational field of a Schwarzschild black hole. I will talk about the back-scattering effect of the interaction between GWs and the background curvature. Finally, I will discuss the potential detectability of these wave effects in aLIGO.

Non-Gaussianities and Primordial Black Holes

Shi Pi
Institute of Theoretical Physics, CAS

I will briefly review the recent progress in the non-Gaussian effect on the primordial black hole formation and the induced GWs.The most promising mechanism of generating PBHs is by the enhancement of power spectrum of the primordial curvature perturbation, which is usually accompanied by the the enhancement of non-Gaussianity that crucially changes the abundance of PBHs. I will show how non-Gaussianity is generated in single field inflation as well as in the curvaton scenario, and how to calculate PBH mass function with such non-Gaussianities. Non-Gaussianity only has mild effects on the induced gravitational waves (GWs), which gives robust predictions in the mHz and nHz GW experiments. I will also talk about the implications of the recently reported nHz GW signal, and the predictions in the space-borne interferometers.

Random sample generation for galaxy survey and sample variance correlation for distance ladder

Shao-Jiang Wang
Institute of Theoretical Physics, Chinese Academy of Sciences

In this talk, I will talk about two separate problems in galaxy surveys and distance ladders. For galaxy survey, the large-scale correlation signal is extracted with respect to the random samples, whose current generation process may inherit signal residuals and could be in principle removed with pure mathematical constructions. For distance ladder, the sample variance in measuring the Hubble constant could correlate to the local environment of distance indicators, which may reveal a non-trivial clue for new physics beyond the LCDM model.