Annual Report 2024
Jaan Einasto

1 Research

I participated in the study by Einasto et al. (2024) in all stages from preparation and discussion of data and polishing the final text.

I prepared second edition of the book "Dark Matter and Cosmic Web Story" (Einasto, 2024), which contains discussion of the development of these topics after the publication of the first edition of the book by Einasto (2014).

Following the request of World Scientific I prepared together with my collaborators Gert Hütsi, Istvan Szapudi and Peeter Tenjes a textbook Einasto et al. (2025). "Spinning the Cosmic Web" is a textbook on modern cosmology with an observational focus using only elementary calculus and statistics. Unlike previous titles that focus on linear cosmology at an undergraduate level, the present work will extend to non-linear phenomena, particularly emphasising the cosmic network of clusters connected with filaments and separated by walls, surrounding cosmic voids. For the first time, the intertwined processes on various scales, from the largest scales to the structure and emergence of the cosmic web and galaxies and their populations, will get their due. The observational approach facilitates including the often neglected formation and evolution of galaxies in dark matter halos, forming the cosmic web and crucial to understanding the interconnection between the observed galaxy distribution and the underlying dark matter structure – the bias.

After a short introduction to the contemporary cosmological paradigm in a historical context, we discuss the current observations of the Universe and its constituents. Further chapters will dive gradually into the non-linear process and the physics of the cosmic web. We have a few chapters presented in a dialogue form (like Platon). This would distinguish us from most physics books, although it takes up time, and it would be quite unconventional. Nevertheless, we could use that format to keep the readers mind on Cosmology. Dialogue form is most suited for topics where we need to show different sides of arguments.

The book is divided into ten chapters. The book's first half focuses on cosmic web, while the second half deals with galaxies and their evolution within the cosmic web. The classical view on cosmology was based on Lick galaxy counts, and is described quantitatively using the correlation function of galaxies. The growth of the modern view on cosmology is manifested by the understanding that dark matter and dark energy are important components of matter-energy content of the Universe, and that galaxies are not distributed randomly but form the cosmic web.

In 1960s new centres of theoretical cosmology were created in Princeton by Robert Dicke, in Cambridge by Dennis Sciama, and in Moscow by Yakov Zeldovich. Now processes in the Universe were studied as physical ones rather than purely mathematical. These theoretical developments were supported by observational studies, which led to the discovery of the presence of Dark Matter (DM) in the Universe, its web-like structure, and the inflation period in the evolution of the Universe. Concepts of DM, cosmic web and inflation were accepted by the cosmology community in 1980s. In late years of the 20th century rapid growth of the observational cosmology started, which included several 10-m class telescopes and numerous space observatories. This allowed to find observational evidence for the presence of dark energy, to measure redshifts of galaxies in large numbers, and to study early phases of the evolution of galaxies. A rapid growth of studies in various fields of cosmology followed. Galaxies born and evolve in the cosmic environment — the cosmic web. Formation and evolution of galaxies is influenced by the presence of DM. Thus the evolution of galaxies must be treated simultaneously with the evolution of the cosmic web. This book is an introduction to the complex problem: structure and evolution of galaxies in the cosmic web. We treat the problem primary from observational point of view. The evolution of galaxies and the cosmic web is difficult to observe directly. Thus observational data must be complemented by numerical simulations. We concentrate in this book to the discussion of the evolution of global properties of the web. The discussion of evolution of components of the web — galaxies and systems of galaxies, is done in the context of their environment in the web.

2 Conferences and popular talks

On 20 Feb. 2024 I had a report on my work in Barlova Coffee, and on 23. Feb. 2024 in Tartu University a discussion of my work was made in the program to celebrate my 95th birthday.

I participated in the Tartu-Tuorla workshop on cosmic web 06 - 08 May 2024 in Turku Universeity, where on 06 May the official presentation of the book "Dark Matter and Cosmic Web Story. Second Edition". took place.

On 1. Oct. 2024 the journal "Edasi" published an interview with me.

3 Scientific organisations, awards

I am member of the International Astronomical Union (1961), Estonian Academy of Sciences (1981), American Astronomical Society (1981), European Astronomical Society (1990), Academia Europaea (1990), Royal Astronomical Society (1994).

I have Estonian Science Prizes (1982, 1998, 2003, 2007), Gauss Professor of the Göttingen University (1993), The Estonian Order of the National Coat of Arms (1998), Marcel Grossmann Award (2009), honorary Doctor of Tartu University (2010), Viktor Ambartsumian International Prize (2012), Doctor Honoris Causa degree of the Turku University (2013), Gruber International Cosmology Award (2014), Estonian Academy of Sciences Harald Keres medal (2019), Tartu University great medal (2019)..

References

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Einasto, M., Einasto, J., Tenjes, P., Korhonen, S., Kipper, R., Tempel, E., Liivamägi, L. J., & Heinämäki, P. 2024, *Galaxy groups and clusters and their brightest galaxies within the cosmic web*, A&A, 681, A91

Januar 12, 2025

Annual report 2024

Manuel Hohmann

January 14, 2025

1 Research

1.1 Laboratory of Theoretical Physics

Global portraits of nonminimal inflation: Metric and Palatini formalism [JKS24] In this paper, we study the global phase space dynamics of single nonminimally coupled scalar field inflation models in the metric and Palatini formalisms. Working in the Jordan frame, we derive the scalar-tensor general field equations and flat Friedmann-Lemaître-Robertson-Walker cosmological equations and present the Palatini and metric equations in a common framework. We show that inflation is characterized by a "master" trajectory from a saddle-type de Sitter fixed point to a stable node fixed point, approximated by slow-roll conditions (presented for the first time in the Palatini formalism). We show that, despite different underlying equations, the fixed point structure and properties of many models are congruent in metric and Palatini formalisms, which explains their qualitative similarities and their suitability for driving inflation. On the other hand, the global phase portraits reveal how even models which predict the same values for observable perturbations differ, both to the extent of the phase space physically available to their trajectories, as well as their past asymptotic states. We also note how the slow-roll conditions tend to underestimate the end of inflationary accelerated expansion experienced by the true nonlinear "master" solution. The explicit examples we consider range from the metric and Palatini induced gravity quintic potential with a Coleman-Weinberg correction factor to Starobinsky, metric, and Palatini nonminimal Higgs, as well as second-order pole and several nontrivial Palatini models.

Schrödinger connections: from mathematical foundations towards Yano–Schrödinger cosmology [CAI24] Schrödinger connections are a special class of affine connections, which despite being metric incompatible, preserve length of vectors under autoparallel transport. In the present paper, we introduce a novel coordinate-free formulation of Schrödinger connections. After recasting their basic properties in the language of differential geometry, we show that Schrödinger connections can be realized through torsion, non-metricity, or both. We then calculate the curvature tensors of Yano–Schrödinger geometry and present the first explicit example of a non-static Einstein manifold with torsion. We generalize the Raychaudhuri and Sachs equations to the Schrödinger geometry. The length-preserving property of these connections enables us to construct a Lagrangian formulation of the Sachs equation. We also obtain an equation for cosmological distances. After this geometric analysis, we build gravitational theories based on Yano–Schrödinger geometry, using both a metric and a metric-affine approach. For the latter, we introduce a novel cosmological hyperfluid that will source the Schrödinger geometry. Finally, we construct simple cosmological models within these theories and compare our results with observational data as well as the ΛCDM model.

Weak equivalence principle and nonrelativistic limit of general dispersion relations [HPW24] We study the weak equivalence principle in the context of modified dispersion relations, a prevalent approach to quantum gravity phenomenology. We find that generic modified dispersion relations violate the weak equivalence principle. The acceleration in general depends on the mass of the test body, unless the Hamiltonian is either two-homogeneous in the test particles' 4-momenta or the corresponding Lagrangian differs from the homogeneous case by a total derivative only. The key ingredient of this calculation is a $3+1$ decomposition of the parametrization invariant relativistic test particle action derived from the dispersion relation. Additionally, we apply a perturbative expansion in the test particle's spatial velocity and the inverse speed of light. To quantify our result, we provide a general formula for the Eötvós factor of modified dispersion relations. As a specific example, we study the point-particle motion determined from the κ-Poincaré dispersion relation in the bicrossproduct basis. Comparing the ensuing non-vanishing Eötvós factor to recent data from the MICROSCOPE experiment, we obtain a bound of the model parameter $\hat{\Xi}^{-1} \geq 10^{15}\mathrm{GeV}/c^2$.

Cosmology of the complete quadratic metric-affine gravity [IP25] We study the cosmology of the complete quadratic (in torsion and nonmetricity) metric-affine gravity. Namely, we add to the scalar-curvature gravitational Lagrangian, the 17 independent quadratic (parity-even and parity-odd) torsion and nonmetricity invariants. Sticking to a homogeneous and isotropic Friedmann-Robertson-Walker spacetime and assuming a perfect hyperfluid source, we explore the new effects that torsion and nonmetricity bring into play. It is shown that the inclusion of these invariants offers rich phenomenology. In particular, some well-known examples of exotic matter like cosmic strings, domain walls, stiff matter, etc., emerge quite naturally as manifestations of the fluid's intrinsic structure (hypermomentum). By studying the extended Friedmann equations in the complete quadratic theory and isolating the various parts of the hypermomentum, we find a plethora of solutions with interesting features.

Statistical conformal Killing vector fields for FLRW space-time [PNI24] The classification of conformal Killing vector fields for FLRW space-time from Riemannian point of view was done by Maartens-Maharaj. In this paper, we introduce conformal Killing vector fields from a new point of view for the FLRW space-time. In particular, we consider three cases for the conformal factor. Then, it is shown that there exist nine conformal vector fields on FLRW in total, such that six of them are Killing and the rest being non-Killing conformal vector fields. Consequently, by recalling the concept of statistical conformal Killing vector fields introduced, we classify statistical structures whith repsect to which these vector fields are conformal Killing. We also obtain the form of affine connections that feature a vanishing Lie derivative with respect to these conformal Killing vector fields. Imposing the torsion-free and the Codazzi conditions on these connections, we study statistical structures on FLRW. Finally, for torsionful connections we study the vanishing of the Lie derivative of the torsion tensor with respect to these conformal Killing vector fields and derive the conditions under which this is valid.

Relativistic interacting fluids in cosmology [IJK24] Motivated by cosmological applications for interacting matters, an extension of the action functional for relativistic fluids is proposed to incorporate the physics of non-adiabatic processes and chemical reactions. The former are characterised by entropy growth, while the latter violate particle number conservation.The relevance of these physics is demonstrated in the contexts of self-interacting fluids, fluids interacting with scalar fields, and hyperhydrodynamical interactions with geometry. The possible cosmological applications range from early-universe phase transitions to astrophysical phenomena, and from matter creation inflationary alternatives to interacting dark sector alternatives to the ΛCDM model that aim to address its tensions.As an example of the latter, a single fluid model of a unified dark sector is presented. The simple action of the model features one field and one parameter, yet it can both reproduce the ΛCDM cosmology and predict new phenomenology.

A class of ghost-free theories in symmetric teleparallel geometry [BMBJJC$^+$24] Theories formulated in the arena of teleparallel geometries are generically plagued by ghost-like instabilities or other pathologies that are ultimately caused by the breaking of some symmetries. In this work, we construct a class of ghost-free theories based on a symmetry under Transverse Diffeomorphisms that is naturally realised in symmetric teleparallelism. We explicitly show their equivalence to a family of theories with an extra scalar field plus a global degree of freedom and how Horndeski theories and healthy couplings to matter fields can be readily accommodated.

Black holes in Lorentz gauge theory [KZ24] Black hole solutions are explored in the Lorentz gauge theory of gravity. The fields of the theory are the gauge potential in the adjoint and a scalar in the fundamental representation of the Lorentz group, a metric tensor then emerging as a composite field in a symmetry-broken phase. Three distinct such phases of the theory are considered. In an SO(3) phase, the fundamental field is identified with a generalised Painlevé-Gullstrand-Lemaître coordinate time. In the static spherically symmetric case it is a stealth scalar, and the general vacuum solution is then parameterised by two constants, one related to the black hole mass and the other to an observer. Also, formulations of pregeometric first order electromagnetism are considered in order to construct a consistent realisation of a charged black hole. In an $\mathrm{SO}(1,2)$ phase of the theory, the Schwarzschild solution is realised as a configuration wherein the fundamental field is real outside and imaginary inside the horizon. In this phase the field can be associated with an effective radial pressure resulting in additional singularities and asymptotic non-flatness. Finally, a symmetry-broken phase which would correspond to solutions in an alternative attempt at a Lorentz gauge theory is shown to be incompatible with black holes.

Crystallized white dwarf stars in scalar-tensor gravity [VWJD24] We study the effects of massive scalar-tensor theories on the internal properties, crystallization, and cooling process of white dwarf stars that might potentially solve observational tensions. We show that these modified gravity theories alter the inner structure of the star leading to sub-Chandrasekhar mass white dwarfs. This further results in a modification of Debye temperature, ion and electron specific heats. Finally, we find that the cooling process is significantly shortened in scalar-tensor theories leading to reduced cooling ages.

Extended Metric-Affine $f(R)$ Gravity with Dynamical Connection in Vacuum [Ios24] We extend the usual vacuum Metric-Affine $f(R)$ Gravity by supplementing it with all parity even quadratic invariants in torsion and non-metricity. As we show explicitly this supplementation drastically changes the status of the Theory which now propagates an additional scalar degree of freedom on top of the graviton. This scalar degree of freedom has a geometric origin as it relates to spacetime torsion and non-metricity. The resulting Theory can be written equivalently as a metric and torsionless Scalar-Tensor Theory whose potential and kinetic term coupling depend on the choice of the function $f(R)$ and the dimensionless parameters of the quadratic invariants respectively.

Friedmann cosmology with hyperfluids [AIJS24] In metric-affine gravity, both the gravitational and matter actions depend not just on the metric, but also on the independent affine connection. Thus matter can be modeled as a hyperfluid, characterized by both the energy-momentum and hypermomentum tensors. The latter is defined as the variation of the matter action with respect to the connection and it encodes extra (micro)properties of particles. For a homogeneous and isotropic universe, it was recently shown that the generic cosmological hypermomentum possesses five degrees of freedom: one in dilation, two in shear, and two in spin part. The aim of the current work is to present the first systematic study of the implications of this perfect hyperfluid on the universe with Friedmann-Lemaître-Robertson-Walker metric. We adopt a simple model with non-Riemannian Einstein-Hilbert gravitational action plus arbitrary hyperfluid matter, and solve analytically the cosmological equations for single and multiple component hypermomentum contributions using different assumptions about the equation of state. It is remarkable, that in a number of cases the forms of the time evolution of the Hubble function and energy density still coincide with their general relativity counterparts, only the respective indexes w_{eff} and w_ρ start to differ due to the hypermomentum corrections. The results and insights we obtained are very general and can assist in constructing interesting models to resolve the issues in standard cosmology.

Symmetric Teleparallel Connection and Spherical Solutions in Newer GR [HK24] In this article, we focus on symmetric teleparallel gravity, a modification of General Relativity where gravity is described by the non-metricity of an affine connection, whose curvature and torsion vanish. In these theories, the fundamental variables are the metric and an affine connection. Starting from the coincident gauge, a system of coordinates for which the affine connection coefficients vanish, we derive the most general connection for a spherically symmetric and stationary spacetime. We then derive the field equations in a specific class of symmetric teleparallel theories, the so-called Newer General Relativity. This theory is constructed from the five possible quadratic scalars of non-metricity. We find two families of vacuum solutions that correspond to some exotic objects and we study their properties. In particular, we investigate the possibility of having a traversable wormhole, we compute the Komar mass, we discuss the conditions for asymptotic flatness, the existence of singularities, the radial motion and bound orbits of particles around these objects, the light deflection as well as the causal structure of these spacetimes.

Euclidean teleparallel relativity and black hole partition functions [BJK24] The Euclidean path integral approach to quantum gravity is conventionally formulated in terms of the Einstein-Hilbert-York-Gibbons-Hawking action, which requires suitable subtractions to produce the correct black hole partition function. However, there is a unique, canonical teleparallel reformulation which reproduces the same results without subtractions or other ambiguities. This is verified in the case of a black hole with or without an electric or a magnetic charge and in a background with or without a cosmological constant. Further, it is conjectured that the results may be improved in a local prescription which reduces the canonical teleparallel action to a surface integral over the horizon.

Complete background cosmology of parity-even quadratic metric-affine gravity [DBI24] The cosmology of metric-affine gravity is studied for the general, parity preserving action quadratic in curvature, torsion and non-metricity. The model contains 27 a priori independent couplings in addition to the Einstein constant. Linear and higher order relations between the quadratic operators in a Friedmann–Lemaitre–Robertson–Walker spacetime are obtained, along with the modified Friedmann, torsion and non-metricity equations. Extra parameter constraints lead to two special branches of the model. Firstly, a branch is found in which the Riemannian spatial curvature (thought to be slightly closed or flat in the Lambda-CDM model of our Universe) is entirely screened from all the field equations, regardless of its true value. Secondly, an integrable branch is found which yields (anti) de Sitter expansion at late times. The particle spectra of these two branches are studied, and the need to eliminate higher-spin particles as well as ghosts and tachyons motivates further parameter constraints in each case. The most general model is also found which reproduces the exact Friedmann equations of general relativity. The full set of equations describing closed, open or flat cosmologies, for general parity-even quadratic metric-affine gravity, is made available for SymPy, Mathematica and Maple platforms.

1.2 Tartu Observatory

Galaxy groups and clusters and their brightest galaxies within the cosmic web [EET+24] The evolution of galaxy groups and the brightest group galaxies (BGGs) is influenced by their location in the cosmic web. Our aim is to combine data on galaxy groups, their BGGs, and their location in the cosmic web, to determine classes of groups and clusters, and to obtain a better understanding of their properties and evolution. Data on groups and their BGGs are based on the Sloan Digital Sky Survey DR10 MAIN spectroscopic galaxy sample in the redshift range $0.009 \leq z \leq 0.200$. We characterize the group environments by the luminosity–density field and their filament membership. We divide BGGs according to their star formation properties as quenched (Q), red star-forming galaxies (RSF), and blue star-forming galaxies (BSF). We apply multidimensional Gaussian mixture modelling to divide groups based on the properties of the groups, their BGGs, and their environments. We analyse the offset of BGGs with respect to the group centre, and the relation between the stellar velocity dispersion of BGGs $\sigma^{\star}$ and the group velocity dispersions σ_{v}. For comparison we also analyse the properties of single galaxies of different star formation properties in various environments. The galaxy groups in our sample can be divided into two main classes: high-luminosity rich groups and clusters, and low-luminosity poor groups with threshold luminosity $L_{gr}^{thr} = 15 \times 10^{10} h^{-2} L_{\odot}$ and total mass $M_{gr}^{thr} \approx 23 \times 10^{12} h^{-1} M_{\odot}$. The brightest galaxies in clusters and groups have different star formation properties. In rich groups and clusters ≈ 90 % of the BGGs are red quenched galaxies, while in poor groups only $\approx 40 - 60$ % of BGGs are red and quenched, and the rest of the BGGs are star-forming, either blue ($20 - 40$ % of BGGs) or red ($\sim$17% of BCGs). Rich groups and clusters are located in global high-density regions (superclusters) in filaments or filament outskirts, while poor groups reside everywhere in the cosmic web regardless of the global density (superclusters or voids). Clusters with quenched BGGs have higher luminosities and their BGGs are closer to the cluster centre than in clusters with star-forming BGGs. Groups of the same richness with red (quenched and star-forming) BGGs are more luminous, and they lie in higher global density environment than groups with blue star-forming BGGs. Our results suggest that the evolution of groups and clusters and their BGGs is related to their location in the cosmic web. We emphasize the role of global high-density regions–superclusters as a special environment for group growth. The processes that shape the properties of groups and their BGG are different and/or have different timescales in groups and clusters.

Identification of Superclusters and their Properties in the Sloan Digital Sky Survey [SBT+24] Superclusters are the largest massive structures in the cosmic web on tens to hundreds of megaparsecs (Mpc) scales. They are the largest assembly of galaxy clusters in the Universe. Apart from a few detailed studies of such structures, their evolutionary mechanism is still an open question. In order to address and answer the relevant questions, a statistically significant, large catalog of superclusters covering a wide range of redshifts and sky areas is essential. Here, we present a large catalog of 662 superclusters identified using a modified *Friends of Friends* algorithm applied on the WHL (Wen-Han-Liu) cluster catalog within a redshift range of $0.05 \leq z \leq 0.42$. We name the most massive supercluster at $z \sim 0.25$ as *Einasto Supercluster*. We find that the median mass of superclusters is $\sim 5.8 \times 10^{15}$ M$_{\odot}$ and median size ~ 65 Mpc. We find that the supercluster environment slightly affects the growth of clusters. We compare the properties of the observed superclusters with the mock superclusters extracted from the Horizon Run 4 cosmological simulation. The properties of superclusters in mocks and observations are in broad agreement. We find that the density contrast of a supercluster is correlated with its maximum extent with a power law index, $\alpha \sim -2$. The phase-space distribution of mock superclusters shows that, on average, $\sim 90\%$ part of a supercluster has a gravitational influence on its constituents. We also show mock halos' average number density and peculiar velocity profiles in and around the superclusters.

The miniJPAS survey: Maximising the photo-z accuracy from multi-survey datasets with probability conflation [HAL+24] We present a new method for obtaining photometric redshifts (photo-z) for sources observed by multiple photometric surveys using a combination (conflation) of the redshift probability distributions (PDZs) obtained independently from each survey. The conflation of the PDZs has several advantages over the usual method of modelling all the photometry together, including the modularity, speed, and accuracy of the results. Using a sample of galaxies with narrow-band photometry in 56 bands from J-PAS and deeper *grizy* photometry from the Hyper-SuprimeCam Subaru Strategic program (HSC-SSP), we show that PDZ conflation significantly improves photo-z accuracy compared to fitting all the photometry or using a weighted average of point estimates. The improvement over J-PAS alone is particularly strong for $i \gtrsim 22$ sources, which have low signal-to-noise ratios in the J-PAS bands. For the entire $i<22.5$ sample, we obtain a 64% (45%) increase in the number of sources with redshift errors $|\Delta z|<0.003$, a factor of 3.3 (1.9) decrease in the normalised median absolute deviation of the errors (σ_{NMAD}), and a factor of 3.2 (1.3) decrease in the outlier rate (η) compared to J-PAS (HSC-SSP) alone. The photo-z accuracy gains from combining the PDZs of J-PAS with a deeper broad-band survey such as HSC-SSP are equivalent to increasing the depth of J-PAS observations by ~1.2–1.5 magnitudes. These results demonstrate the potential of PDZ conflation and highlight the importance of including the full PDZs in photo-z catalogues.

Superbubbles as the source of dynamical friction: gas migration, stellar and dark matter contributions [KVN+24] The gas distribution in galaxies is smooth on large scales but is usually inhomogeneous as well as time-dependent on smaller scales. The time-dependence originates from processes such as cloud formation, their collisions and supernovae (SNe) explosions. The inhomogeneities in the matter distribution give rise to variations in the local galactic gravitational potential, which can contribute towards dynamically coupling the gas disk to the stellar and the dark matter (DM) components of the galaxy. Specifically, multiple supernovae occurring in young stellar clusters give rise to superbubbles (SB), which modify the local acceleration field and alter the energy and momentum of stars of DM particles traversing them, in broad analogy to the dynamical friction caused by a massive object. We aim to quantify how the acceleration field from SBs causes dynamical friction and contributes to the secular evolution of galaxies. In order to assess this, we construct the density modifications to the gas distribution that mimics a SB. By evaluating the acceleration field from these density modifications, we see how the momentum or angular momentum of the gas hosting the SBs changes when stars pass through the SB. Combining the effects of all the stars and SBs we, construct an empirical approximation formula for the momentum loss in homogeneous and isotropic cases. We find that the rate at which the gas disc loses its specific angular momentum via the above process is up to 4% per Gyr, which translates to under half of its original value over the lifetime of the disc. Finally, we studied how the dynamical coupling of the gas disk with the DM halo depends on assumptions on the halo kinematics (e.g. rotation) and found a 0.3% variation in the gas disc secular evolution between different DM kinematic models.

Archives of Photographic PLates for Astronomical USE (APPLAUSE). Digitisation of astronomical plates and their integration into the International Virtual Observatory [ETG+24] The Archives of Photographic PLates for Astronomical USE (APPLAUSE) project is aimed at digitising astronomical photographic plates from three major German plate collections, making them accessible through integration into the International Virtual Observatory (IVO). Photographic plates and related materials (logbooks, envelopes, etc.) were scanned with commercial flatbed scanners. Astrometric and photometric calibrations were carried out with the developed PyPlate software, using Gaia EDR3 data as a reference. The APPLAUSE data publication complies with IVO standards. The latest data release contains images and metadata from 27 plate collections from the partner institutes in Hamburg, Bamberg, and Potsdam, along with digitised archives provided by Tautenburg, Tartu, and Vatican observatories. Altogether, over two billion calibrated measurements extracted from about 70,000 direct photographic plates can readily be used to create long-term light curves. For instance, we constructed the historic light curve of the enigmatic dipping star KIC 8462852. We found no evidence of previously assumed variations on timescales of decades in our light curve. Potential uses of APPLAUSE images for transient sources can be appreciated by following the development of the nova shell of GK Per (1901) over time and the change in brightness of two extragalactic supernovae. The database holds about 10,000 spectral plates. We made use of objective prism plates to follow the temporal changes of Nova DN Gem through 1912 and 1913, highlighting an outburst in early 1913.

Search and analysis of giant radio galaxies with associated nuclei (SAGAN). IV. Interplay with the Supercluster environment [SD24] We investigated the prevalence of giant radio galaxies (GRGs), some of the largest structures powered by supermassive black holes, within supercluster environments, and the influence of such environments on their properties. Utilising two large catalogues of superclusters (401) and GRGs (1446), we established the existence of 77 GRGs (5.3%) residing in 64 superclusters (16%) within $0.05 \leq z \leq 0.42$. Among the 77 GRGs found in superclusters, we identified $\sim$70% as residing within galaxy clusters. Within the subset of GRGs not located in superclusters, which constitutes 94.7% of the sample, a mere 21% are associated with galaxy clusters, while the remaining majority are situated in sparser environments. We examined the influence of differing environments, such as cluster versus non-cluster and supercluster versus non-supercluster regions, on the size of GRGs, while also exploring the driving factors behind their overall growth. Our findings show that the largest GRGs ($\gtrsim$3 Mpc) grow in underdense environments beyond the confines of dense environments. Moreover, we show that $\sim$ 24% of 1446 GRGs reside in galaxy clusters. We conclude that GRGs preferentially grow in sparser regions of the cosmic web and have a significantly larger median size. Finally, we demonstrate the potential of GRGs as astrophysical probes with specific cases where GRGs, exhibiting polarised emissions and located behind superclusters (acting as natural Faraday screens), were used to estimate magnetic field strengths of the supercluster environment at sub-microgauss levels.

Dark Matter halo parameters from overheated exoplanets via Bayesian hierarchical inference [BKL+24] Dark Matter (DM) can become captured, deposit annihilation energy, and hence increase the heat flow in exoplanets and brown dwarfs. Detecting such a DM-induced heating in a population of exoplanets in the inner kpc of the Milky Way thus provides potential sensitivity to the galactic DM halo parameters. We develop a Bayesian Hierarchical Model to investigate the feasibility of DM discovery with exoplanets and examine future prospects to recover the spatial distribution of DM in the Milky Way. We reconstruct from mock exoplanet datasets observable parameters such as exoplanet age, temperature, mass, and location, together with DM halo parameters, for representative choices of measurement uncertainty and the number of exoplanets detected. We find that detection of $\mathcal{O}(100)$ exoplanets in the inner Galaxy can yield quantitative information on the galactic DM density profile, under the assumption of 10% measurement uncertainty. Even as few as $\mathcal{O}(10)$ exoplanets can deliver meaningful sensitivities if the DM density and inner slope are sufficiently large. http://github.com/mariabenitocst/exoplanets

Galaxy Spectra neural Network (GaSNet). II. Using deep learning for spectral classification and redshift predictions [ZNH+24] The size and complexity reached by the large sky spectroscopic surveys require efficient, accurate, and flexible automated tools for data analysis and science exploitation. We present the Galaxy Spectra Network/GaSNet-II, a supervised multinetwork deep learning tool for spectra classification and redshift prediction. GaSNet-II can be trained to identify a customized number of classes and optimize the redshift predictions. Redshift errors are determined via an ensemble/pseudo-Monte Carlo test obtained by randomizing the weights of the network-of-networks structure. As a demonstration of the capability of GaSNet-II, we use 260k Sloan Digital Sky Survey spectra from Data Release 16, separated into 13 classes including 140k galactic, and 120k extragalactic objects. GaSNet-II achieves 92.4 per cent average classification accuracy over the 13 classes and mean redshift errors of approximately 0.23 per cent for galaxies and 2.1 per cent for quasars. We further train/test the pipeline on a sample of 200k 4MOST (4-metre Multi-Object Spectroscopic Telescope) mock spectra and 21k publicly released DESI (Dark Energy Spectroscopic Instrument) spectra. On 4MOST mock data, we reach 93.4 per cent accuracy in 10-class classification and mean redshift error of 0.55 per cent for galaxies and 0.3 per cent for active galactic nuclei. On DESI data, we reach 96 per cent accuracy in (star/galaxy/quasar only) classification and mean redshift error of 2.8 per cent for galaxies and 4.8 per cent for quasars, despite the small sample size available. GaSNet-II can process ∼40k spectra in less than one minute, on a normal Desktop GPU. This makes the pipeline particularly suitable for real-time analyses and feedback loops for optimization of Stage-IV survey observations.

Dissecting a miniature universe: A multi-wavelength view of galaxy quenching in the Shapley supercluster [ATB+24] Multiple cluster systems, that is superclusters, contain large numbers of galaxies assembled in clusters interconnected by multi-scale filamentary networks. As such, superclusters are a smaller version of the cosmic web and can hence be considered as miniature universes. In addition to the galaxies, superclusters also contain gas, which is hot in the clusters and warmer in the filaments. Therefore, they are ideal laboratories to study the interplay between the galaxies and the gas. In this context, the Shapley supercluster (SSC) stands out since it hosts the highest number of galaxies in the local Universe with clusters interconnected by filaments. In addition, it is detected both in X-rays and via the thermal Sunyaev-Zel'dovich (tSZ) effect, making it ideal for a multi-wavelength study of the gas and galaxies. Applying for the first time a filament-finder based on graphs, T-REx, on a spectroscopic galaxy catalogue, we uncovered the 3D filamentary network in and around SSC. Simultaneously, we used a large sample of photometric galaxies with information on their star formation rates (SFRs) in order to investigate the quenching of star formation in the SSC environment which we define as a function of the gas distribution in the Planck tSZ map and the ROSAT X-ray map. With T-REx, we confirm filaments already observed in the distribution of galaxies of the SSC, and we detect new ones. We observe the quenching of star formation as a function of the gas contained in the SSC. We show a general trend of decreasing SFR where the tSZ and X-ray signals are the highest, within the high density environments of the SSC. Within these regions, we also observe a rapid decline in the number of star-forming galaxies, coinciding with an increasing number of transitioning and passive galaxies. Within the SSC filaments, the fraction of passive galaxies is larger than outside filaments, irrespective of the gas pressure. Our results suggest that the zone of influence of the SSC in which galaxies are pre-processed and quenched is well defined by the tSZ signal that combines the density and temperature of the environments.

AXES-SDSS: Comparison of SDSS galaxy groups with all-sky X-ray extended sources [DFL+24a, DFL+24b] We revisit the picture of X-ray emission of groups through the study of systematic differences in the optical properties of groups with and without X-ray emission and study the effect of large-scale density field on scaling relations. We present the identification of X-ray galaxy groups using a combination of RASS and SDSS data. We include new X-ray reanalysis of RASS, to include very extended (up to a size of half a degree) sources and account for differences in the limiting sensitivity towards compact and very extended X-ray emission. X-ray groups exhibit less scatter in the scaling relations and selecting the groups based on the extended X-ray emission leads to an additional scatter reduction. Most of the scatter for the optical groups is associated with a small (6%) fraction of outliers, primarily associated with low optical luminosity groups found in dense regions of the cosmic web. These groups are the primary candidates for being the contaminants in the optical group catalogues. Removing those groups from the optical group sample using optically measured properties only, leads to a substantial reduction in the scatter in the most scaling relations of the optical groups. We find a density dependence of both the X-ray and optical luminosity of groups, which we associate with the assembly bias.

AXES-2MRS: A new all-sky catalogue of extended X-ray galaxy groups [KFTM24a, KFTM24b] We present a new all-sky catalogue of X-ray detected groups (AXES-2MRS), based on the identification of large X-ray sources found in the ROSAT All-Sky Survey (RASS) with the Two Micron Redshift Survey (2MRS) Bayesian Group Catalogue. We study the basic properties of these galaxy groups to gain insights into the effect of different group selections on the properties. In addition to X-ray luminosity coming from shallow survey data of RASS, we have obtained detailed X-ray properties of the groups by matching the AXES-2MRS catalogue to archival X-ray observations by XMM-Newton and complemented this by adding the published XMM-Newton results on galaxy clusters in our catalogue. We analyse temperature and density to the lowest overdensity accessible by the data, obtaining hydrostatic mass estimates and comparing them to the velocity dispersions of the groups. We find a large spread in the central mass to virial mass ratios for galaxy groups in the XMM-Newton subsample. This can either indicate large non-thermal pressure of galaxy groups affecting our X-ray mass measurements, or the effect of a diversity of halo concentrations on X-ray properties of galaxy groups. Previous catalogues, based on detecting the peak of the X-ray emission preferentially sample the high-concentration groups, while our new catalogue includes many low-concentration groups.

Radiation Transport Simulations of Quasi-Periodic Eruptions from Star-Disk Collisions [VLM24] Periodic collisions between a star on an inclined orbit around a supermassive black hole and its accretion disk offers a promising explanation for X-ray "quasi-periodic eruptions" (QPEs). Each passage through the disk shocks and compresses gas ahead of the star, which subsequently re-expands above the disk as a quasi-spherical cloud. We present spherically symmetric Monte Carlo radiation transport simulations which follow the production of photons behind the radiation-mediated shock, Comptonization by hot electrons, and the eventual escape of the radiation through the expanding debris. Such one-dimension calculations are approximately justified for thin disks, through which the star of radius $R_\star$ passes faster than the shocked gas can flow around the star. For collision speeds $v_{\rm coll} \gtrsim 0.15c$ and disk surface densities $\Sigma \sim 10^3$ g cm^{-2} characteristic of those encountered by stellar orbits consistent with QPE recurrence times, the predicted transient light curves exhibit peak luminosities $\gtrsim 10^{42}$ erg s^{-1} and Comptonized quasi-thermal (Wien-like) spectra which peak at energies $h\nu \sim 100$ eV, broadly consistent with QPE properties. For these conditions, gas and radiation are out of equilibrium and the emission temperature is harder than the blackbody value due to inefficient photon production behind the shock. Alternatively, for higher disk densities and/or lower shock velocities, QPE emission could instead represent the comparatively brief phase shortly after shock break-out, though in this case the bulk of the radiation is thermalized and occurs in the ultraviolet instead of the X-ray band. In either scenario, reproducing the observed eruption properties (duration, luminosity, temperature) requires a large radius $R_\star \gtrsim 10R_\odot$, which may point to inflation of the star's atmosphere from repeated collisions.

CHANCES, The Chilean Cluster Galaxy Evolution Survey: selection and initial characterization of clusters and superclusters [SFH+24] CHANCES, the CHileAN Cluster galaxy Evolution Survey, will study the evolution of galaxies in and around ∼150 massive galaxy clusters, from the local universe out to z=0.45. CHANCES will use the new 4MOST Spectroscopic Survey Facility on the VISTA 4m telescope to obtain spectra for ∼500,000 galaxies with magnitudes $r_{\rm AB} < 20.5$, providing comprehensive spectroscopic coverage of each cluster out to $5r_{200}$. Its wide and deep scope will trace massive and dwarf galaxies from the surrounding filaments and groups to the cores of galaxy clusters, enabling the study of galaxy pre-processing and the role of the evolving environment on galaxy evolution. In this paper we present and characterize the sample of clusters and superclusters to be targeted by CHANCES. We used literature catalogues based on X-ray emission and Sunyaev-Zel'dovich effect to define the cluster sample in a homogeneous way, with attention to cluster mass and redshift, as well as the availability of ancillary data. We calibrated literature mass estimates from various surveys against each other and provide an initial mass estimate for each cluster, which we used to define the radial extent of the 4MOST coverage. We also present an initial assessment of the structure surrounding these clusters based on the redMaPPer red-sequence algorithm as a preview of some of the science CHANCES will enable.

Detecting clusters and groups of galaxies populating the local Universe in large optical spectroscopic surveys [MPD+24] Wide-field cosmological surveys provide hundreds of thousands of spectroscopically confirmed galaxy groups and clusters, valuable for tracing baryonic matter distribution. However, controlling systematics in identifying host dark matter halos and estimating their properties is crucial. We evaluate three group detection methods on a simulated dataset replicating the GAMA selection to understand systematics and selection effects. This is key for interpreting data from SDSS, GAMA, DESI, WAVES, and leveraging optical catalogues in the (X-ray) eROSITA era to quantify baryonic mass in galaxy groups. Using a lightcone from the Magneticum hydrodynamical simulation, we simulate a spectroscopic galaxy survey in the local Universe (down to $z < 0.2$ and stellar mass completeness $M_\star \geq 10^{9.8} M_\odot$). We assess completeness and contamination of reconstructed halo catalogues, evaluate membership accuracy, and analyse the halo mass recovery rate of group finders. All three group finders achieve high completeness ($> 80\%$) at group and cluster scales, confirming optical selection's suitability for dense regions. Contamination at low masses ($M_{200} < 10^{13} M_\odot$) arises from interlopers and fragmentation. Membership is at least 70% accurate above the group mass scale, but inaccuracies bias halo mass estimates using galaxy velocity dispersion. Alternative proxies, like total stellar luminosity or mass, yield more accurate halo masses. The cumulative luminosity function of galaxy members matches predictions, showing the group finders' accuracy in identifying galaxy populations. These results confirm the reliability and completeness of spectroscopic catalogues produced by state-of-the-art group finders. This supports studies requiring large spectroscopic samples of galaxy groups and clusters, as well as investigations into galaxy evolution across diverse environments.

The perils of stacking optically selected groups in eROSITA data. The Magneticum perspective [PMD+24] Hydrodynamical simulation predictions are often compared with observational data without fully accounting for systematics and biases specific to observational techniques. Using the magnetohydrodynamical simulation Magneticum, we generate mock eROSITA eRASS:4 data, combined with GAMA-like spectroscopic surveys and optically selected galaxy catalogs from the same light-cone, to analyze hot gas properties in galaxy groups via a stacking technique. This study aims to (i) incorporate observational systematics into predictions and (ii) evaluate the reliability of stacking techniques for determining average X-ray properties of galaxy groups. Our analysis provides X-ray emission predictions from Magneticum, including contributions from AGN, X-ray binaries (XRBs), and the Intra-Group Medium (IGM) as a function of halo mass, covering Milky Way (MW)-like groups to poor clusters. We find that AGN and XRBs dominate the X-ray surface brightness profiles of low-mass halos. The reliability of stacking techniques is tested by reproducing input X-ray surface brightness and electron density profiles, accounting for completeness and contamination of prior samples, miscentering of optical group centers, uncertainties in X-ray emissivity due to gas temperature and metallicity assumption, and systematics in halo mass proxies. The halo mass proxy emerges as the primary source of systematics, affecting X-ray surface brightness and scaling relations. We show that stacked X-ray luminosity-mass relations are flatter than input relations but consistent with observations. Additionally, the retrieved hot gas fraction-mass relation aligns well with observational data. These results highlight the need to account for systematic errors when comparing stacking techniques to other methods using different prior catalogs or predictions.

Wide Area VISTA Extra-galactic Survey (WAVES): unsupervised star-galaxy separation on the WAVES-Wide photometric input catalogue using UMAP and HDBSCAN [CBP+24] Star-galaxy separation is a crucial step in creating target catalogues for extragalactic spectroscopic surveys. A classifier biased towards inclusivity risks including high numbers of stars, wasting fibre hours, while a more conservative classifier might overlook galaxies, compromising completeness and hence survey objectives. To avoid bias introduced by a training set in supervised methods, we employ an unsupervised machine learning approach. Using photometry from the Wide Area VISTA Extragalactic Survey (WAVES)-Wide catalogue comprising nine-band $u - K_s$ data, we create a feature space with colours, fluxes, and apparent size information extracted by PROFOUND. We apply the non-linear dimensionality reduction method UMAP (Uniform Manifold Approximation and Projection) combined with the classifier HDBSCAN (Hierarchical Density-Based Spatial Clustering of Applications with Noise) to classify stars and galaxies. Our method is verified against a baseline colour and morphological method using a truth catalogue from Gaia, SDSS (Sloan Digital Sky Survey), GAMA (Galaxy And Mass Assembly), and DESI (Dark Energy Spectroscopic Instrument). We correctly identify 99.75 per cent of galaxies within the AB magnitude limit of $Z = 21.2$, with an F1 score of 0.9971 ± 0.0018 across the entire ground truth sample, compared to 0.9879 ± 0.0088 from the baseline method. Our method's higher purity (0.9967 ± 0.0021) compared to the baseline (0.9795 ± 0.0172) increases efficiency, identifying 11 per cent fewer galaxy or ambiguous sources, saving approximately 70 000 fibre hours on the 4MOST (4-m Multi-Object Spectroscopic Telescope) instrument. We achieve reliable classification statistics for challenging sources including quasars, compact galaxies, and low surface brightness galaxies, retrieving 92.7 per cent, 84.6 per cent, and 99.5 per cent of them, respectively. Angular clustering analysis validates our classifications, showing consistency with expected galaxy clustering, regardless of the baseline classification.

On the detection of stellar wakes in the Milky Way: a deep learning approach [PPB+24] Due to poor observational constraints on the low-mass end of the subhalo mass function, the detection of dark matter (DM) subhalos on sub-galactic scales would provide valuable information about the nature of DM. Stellar wakes, induced by passing DM subhalos, encode information about the mass of the inducing perturber and thus serve as an indirect probe for the DM substructure within the Milky Way (MW). Our aim is to assess the viability and performance of deep learning searches for stellar wakes in the Galactic stellar halo caused by DM subhalos of varying mass. We simulate massive objects (subhalos) moving through a homogeneous medium of DM and star particles, with phase-space parameters tailored to replicate the conditions of the Galaxy at a specific distance from the Galactic center. The simulation data is used to train deep neural networks with the purpose of inferring both the presence and mass of the moving perturber, and assess subhalo detectability in varying conditions of the Galactic stellar and DM halos. We find that our binary classifier is able to infer the presence of subhalos, showing non-trivial performance down to a subhalo mass of $5 \times 10^7\,\mathrm{M}_\odot$. We also find that our binary classifier is generalisable to datasets describing subhalo orbits at different Galactocentric distances. In a multiple-hypothesis case, we are able to discern between samples containing subhalos of different masses. Out of the phase-space observables available to us, we conclude that overdensity and velocity divergence are the most important features for subhalo detection performance.

J-PLUS: Tomographic analysis of galaxy angular density and redshift fluctuations in Data Release 3. Constraints on photo-z errors, linear bias, and peculiar velocities [HBv+24] The *Javalambre Photometric Local Universe Survey* (J-PLUS) is a *spectro-photometric* survey covering about 3,000 deg^2 in its third data release (DR3), and containing about 300,000 galaxies with high quality (*odds*> 0.8) photometric redshifts (hereafter photo-zs). We use this galaxy sample to conduct a tomographic study of the counts and redshift angular fluctuations under Gaussian shells sampling the redshift range $z \in [0.05, 0.25]$. We confront the angular power spectra of these observables measured under shells centered on 11 different redshifts with theoretical expectations derived from a linear Boltzmann code (`ARFCAMB`). Overall we find that J-PLUS DR3 data are well reproduced by our linear, simplistic model. We obtain that counts (or density) angular fluctuations (hereafter ADF) are very sensitive to the linear galaxy bias $b_g(z)$, although weakly sensitive to radial peculiar velocities of the galaxy field, while suffering from systematics residuals for $z > 0.15$. Angular redshift fluctuations (ARF), instead, show higher sensitivity to radial peculiar velocities and also higher sensitivity to the average uncertainty in photo-zs (σ_{Err}), with no obvious impact from systematics. For $z < 0.15$ both ADF and ARF agree on measuring a monotonically increasing linear bias varying from $b_g(z = 0.05) \simeq 0.9 \pm 0.06$ up to $b_g(z = 0.15) \simeq 1.5 \pm 0.05$, while, by first time, providing consistent measurements of $\sigma_{\mathrm{Err}}(z) \sim 0.014$ that are ~ 40 % higher than estimates from the photo-z code `LePhare`, ($\sigma_{\mathrm{Err}}^{\mathrm{LePhare}} = 0.010$). As expected, this photo-z uncertainty level prevents the detection of radial peculiar velocities in the modest volume sampled by J-PLUS DR3, although prospects for larger galaxy surveys of similar (and higher) photo-z precision are promising.

The J-PLUS collaboration. Additive versus multiplicative systematics in surveys of the large scale structure of the Universe [HAC+24] Observational and/or astrophysical systematics modulating the observed number of luminous tracers can constitute a major limitation in the cosmological exploitation of surveys of the large scale structure of the universe. Part of this limitation arises on top of our ignorance on how such systematics actually impact the observed galaxy/quasar fields. In this work we develop a generic, hybrid model for an arbitrary number of systematics that may modulate observations in both an additive and a multiplicative way. This model allows us devising a novel algorithm that addresses the identification and correction for either additive and/or multiplicative contaminants. We test this model on galaxy mocks and systematics templates inspired from data of the third data release of the *Javalambre Photometric Local Universe Survey* (J-PLUS). We find that our method clearly outperforms standard methods that assume either an additive or multiplicative character for all contaminants in scenarios where both characters are actually acting on the observed data. In simpler scenarios where only an additive or multiplicative imprint on observations is considered, our hybrid method does not lie far behind the corresponding simplified, additive/multiplicative methods. Nonetheless, in scenarios of mild/low impact of systematics, we find that our hybrid approach converges towards the standard method that assumes additive contamination, as predicted by our model describing systematics. Our methodology also allows for the estimation of biases induced by systematics residuals on different angular scales and under different observational configurations, although these predictions necessarily restrict to the subset of *known/identified* potential systematics, and say nothing about "unknown unknowns" possibly impacting the data.

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Black Holes and Gravitational Waves from Slow First-Order Phase Transitions [LTV24b] Slow first-order phase transitions generate large inhomogeneities that can lead to the formation of primordial black holes (PBHs). We show that the gravitational wave (GW) spectrum then consists of a primary component sourced by bubble collisions and a secondary one induced by large perturbations. The latter gives the dominant peak if $\beta/H_0 < 12$, impacting, in particular, the interpretation of the recent PTA data. The GW signal associated with a particular PBH population is stronger than in typical scenarios because of a negative non-Gaussianity of the perturbations and it has a distinguishable shape with two peaks.

The dark timbre of gravitational waves [UV24] Gravitational wave timbre, the relative amplitude and phase of the different harmonics, can change due to interactions with low-mass halos. We focus on binaries in the LISA range and find that the integrated lens effect of cold dark matter structures can be used to probe the existence of $M_{\rm v} \lesssim 10\, M_\odot$ halos if a single binary with eccentricity $e = 0.3 - 0.6$ is detected with a signal-to-noise ratio $100 - 10^4$.

Gravitational waves from first-order phase transitions in LISA: reconstruction pipeline and physics interpretation [CJL+24] We develop a tool for the analysis of stochastic gravitational wave backgrounds from cosmological first-order phase transitions with LISA: we initiate a template databank for these signals, prototype their searches, and forecast their reconstruction.The templates encompass the gravitational wave signals sourced by bubble collisions, sound waves and turbulence. Accounting for Galactic and extra-Galactic foregrounds, we forecast the region of the parameter space that LISA will reconstruct with better than $\sim 10\%$ accuracy, if certain experimental and theoretical uncertainties are solved by the time LISA flies.We illustrate the accuracy with which LISA can reconstruct the parameters on a few benchmark signals, both in terms of the template parameters and the phase transition ones.To show the impact of the forecasts on physics beyond the Standard Model, we map the reconstructed benchmark measurements into the parameter spaces of the singlet extension of the Standard Model and of the classically conformal invariant $\mathrm{U}(1)_{B-L}$ model.

Inflation and reheating in quadratic metric-affine gravity with derivative couplings [GKT24] Within the framework of metric-affine theories of gravity, where both the metric and connection are treated as independent variables, we consider actions quadratic in the Ricci scalar curvature coupled non-minimally to a scalar field through derivative couplings. Our analysis delves into the inflationary predictions, revealing their consistency with the latest observational constraints across a wide range of parameters. This compatibility permits adjustments such as an increase in the spectral index and a reduction in the tensor-to-scalar ratio. While we do not propose a specific reheating mechanism, our analysis demonstrates that within the quadratic model of inflation, the maximum reheating temperature can reach $\sim 3 \times 10^{15}$GeV.

Probing sterile neutrino freeze-in at stronger coupling [KLR24] The regime of dark matter (DM) freeze-in at stronger coupling interpolates between freeze-in and freeze-out. It relies on Boltzmann-suppressed dark matter production, implying that the Standard Model bath temperature never exceeds the dark matter mass. In this work, we study this regime in the context of sterile neutrino dark matter, which can be sufficiently long-lived for a tiny sterile-active mixing. The sterile neutrino is assumed to couple to a real singlet scalar, providing for a thermal production mechanism of the former. We find that DM mass can range from GeV to tens of TeV consistently with all the constraints. The most interesting aspect of the consequent freeze-in phenomenology is that the sterile neutrino dark matter can be probed efficiently by both direct detection experiments and invisible Higgs decay at the LHC.

Natural metric-affine inflation [RS24] We consider here natural inflation in the low energy (two-derivative) metric-affine theory containing only the minimal degrees of freedom in the inflationary sector, i.e. the massless graviton and the pseudo-Nambu-Goldstone boson (PNGB). This theory contains the Ricci-like and parity-odd Holst invariants together with non-minimal couplings between the PNGB and the above-mentioned invariants. The Palatini and Einstein-Cartan realizations of natural inflation are particular cases of our construction. Explicit models of this type featuring non-minimal couplings are shown to emerge from the microscopic dynamics of a QCD-like theory with an either sub-Planckian or trans-Planckian confining scale and that is renormalizable on Minkowski spacetime. Moreover, for these models, we find regions of the parameter space where the inflationary predictions agree with the most recent observations at the 2σ level. We find that in order to enter the 1σ region it is necessary (and sufficient) to have a finite value of the Barbero-Immirzi parameter and a sizable non-minimal coupling between the inflaton and the Holst invariant (with sign opposite to the Barbero-Immirzi parameter). Indeed, in this case the potential of the canonically normalized inflaton develops a plateau as shown analytically.

Consistency of JWST black hole observations with NANOGrav gravitational wave measurements [EFH+24] JWST observations have opened a new chapter in supermassive black hole (SMBH) studies, stimulating discussion of two puzzles: the abundance of high-z SMBHs and the fraction of dual active galactic nuclei (AGNs). We argue that the answers to these puzzles may be linked to an interpretation of the data on the nanohertz gravitational waves (GWs) discovered by NANOGrav and other pulsar timing arrays as SMBH binaries whose evolution is driven by interactions with their environments down to O(0.1 pc) separations. We show that the stellar mass-black hole mass correlations found in JWST data and in low-z inactive galaxies are similar, and present a global fit to these data, excluding low-z AGNs. Matching the NANOGrav and dual-AGN data requires that binary evolution due to environmental effects at separations below O(1 kpc) be rapid on cosmological timescales. According to this interpretation, the SMBHs in low-z AGNs are the tip of the iceberg of a local SMBH population in mainly inactive galaxies. This interpretation is consistent with the 'little red dots' observed with JWST being AGNs, and would favour the observability of GW signals from black hole binaries in LISA and decihertz GW detectors.Key words: quasars: supermassive black holes / cosmology: theory / early Universe

Formation of primordial black hole binaries and their merger rates [RVV24] We review the theory behind the formation of primordial black hole binaries and their merger rates. We consider the binary formation in the early and late Universe, emphasising the former as it gives the dominant contribution of the present primordial black hole merger rate. The binaries formed in the early Universe are highly eccentric so their interactions with other primordial black holes can significantly increase their coalescence times and thereby suppress the merger rate. We discuss in detail how the suppression of the merger rate arising from such interactions can be estimated and how such interactions lead to the formation of another, much harder, binary population that contributes to the present merger rate if more than 10% of dark matter consists of primordial black holes with a relatively narrow mass distribution. When the primordial abundance is below 1%, encounters between primordial black holes are unlikely and their effect on the merger rate becomes negligible.

Constraints on primordial black holes from LIGO-Virgo-KAGRA O3 events [ACIV+24] Primordial black holes (PBH) can efficiently form black hole binaries in the early universe. We update the resulting constraints on PBH abundance using data from the third observational run (O3) of LIGO-Virgo-KAGRA. To capture a wide range of PBH scenarios, we consider a variety of mass functions, including critical collapse in the QCD epoch and primordial non-Gaussianities. Applying hierarchical Bayesian analysis to a population of binaries consisting of primordial and astrophysical black holes, we find that, in every scenario, the PBHs can make up at most $f_{\rm PBH} \lesssim 10^{-3}$ of dark matter in the mass range $1 - 200 M_{\odot}$. The shape and strength of the constraints are not significantly affected by the type of non-Gaussianities, the modifications to the mass function during the QCD epoch, or the modelling of the astrophysical PBH population.

In Search of the Biggest Bangs since the Big Bang [EFUV24a] Many galaxies contain supermassive black holes (SMBHs), whose formation and history raise many puzzles. Pulsar timing arrays have recently discovered a low-frequency cosmological "hum" of gravitational waves that may be emitted by SMBH binary systems, and the JWST and other telescopes have discovered an unexpectedly large population of high-redshift SMBHs. We argue that these two discoveries may be linked, and that they may enhance the prospects for measuring gravitational waves emitted during the mergers of massive black holes, thereby opening the way towards resolving many puzzles about SMBHs as well as providing new opportunities to probe general relativity.

Generalized uncertainty principle and neutrino phenomenology [GKM24] Generalized uncertainty principles are effective changes to the Heisenberg uncertainty principle that emerge in several quantum gravity models. In the present letter, we study the consequences that two classes of these modifications yield on the physics of neutrinos. Besides analyzing the change in the oscillation probabilities that the generalized uncertainty principles entail, we assess their impact on the neutrino coherence length and their possible interpretation as non-standard neutrino interactions. Constraints cast by present and planned neutrino experiments on the generalized uncertainty principles parameters are also derived.

Eccentricity effects on the supermassive black hole gravitational wave background [RUVV24a] We studied how eccentricity affects the gravitational wave (GW) spectrum from supermassive black hole (SMBH) binaries. We developed a fast and accurate semi-analytic method for computing the GW spectra, the distribution for the spectral fluctuations and the correlations between different frequencies. As GW emission circularizes binaries, the suppression of the signal strength due to eccentricity is relevant for signals from wider binaries emitting at lower frequencies. Such a feature is present in the signal observed at pulsar timing arrays. We found that when orbital decay of the SMBH binaries is driven by GWs only, the shape of the observed signal preferred highly eccentric binaries $\langle e \rangle_{2\,\mathrm{nHz}} = 0.83^{+0.04}_{-0.05}$. However, when environmental effects were included, the initial eccentricity could be significantly lowered, yet the scenario with purely circular binaries was still mildly disfavored.

Interpreting DESI 2024 BAO: late-time dynamical dark energy or a local effect? [GHK+24] We perform fits to DESI, CMB and supernova data to understand the physical origin of the DESI hint for dynamical dark energy. We find that the linear parametrization of the equation of state w may guide to misleading interpretations, such as the hint for a phantom Universe, which are not preferred by the data. Instead, physical quintessence models fit the data well. Model-independently, present observations prefer deviations from the constant dark energy, $w = -1$, only at very low redshifts, $z < \mathcal{O}(0.1)$. We find that this result is driven by low-z supernova data. Therefore, either the fundamental properties of our Universe, characterised by the equation of state w and the Hubble parameter H, underwent dramatic changes very recently or, alternatively, we do not fully understand the systematics of our local Universe in a radius of about $300\,h^{-1}$Mpc.

Curbing PBHs with PTAs [IPRV24] Sizeable primordial curvature perturbations needed to seed a population of primordial black holes (PBHs) will be accompanied by a scalar-induced gravitational wave signal that can be detectable by pulsar timing arrays (PTA). We derive conservative bounds on the amplitude of the scalar power spectrum at the PTA frequencies and estimate the implied constraints on the PBH abundance. We show that only a small fraction of dark matter can consist of stellar mass PBHs when the abundance is calculated using threshold statistics. The strength and the shape of the constraint depend on the shape of the power spectrum and the nature of the non-Gaussianities. We find that constraints on the PBH abundance arise in the mass range $0.1 - 10^3\,M_\odot$, with the sub-solar mass range being constrained only for narrow curvature power spectra. These constraints are softened when positive non-Gaussianity is introduced and can be eliminated when $f_{\mathrm{NL}} \gtrsim 5$. On the other hand, if the PBH abundance is computed via the theory of peaks, the PTA constraints on PBHs are significantly relaxed, signalling once more the theoretical uncertainties in assessing the PBH abundance. We further discuss how strong positive non-Gaussianites can allow for heavy PBHs to potentially seed supermassive BHs.

Gravitational waves from inflation in LISA: reconstruction pipeline and physics interpretation [B+24] Various scenarios of cosmic inflation enhance the amplitude of the stochastic gravitational wave background (SGWB) at frequencies detectable by the LISA detector. We develop tools for a template-based analysis of the SGWB and introduce a template databank to describe well-motivated signals from inflation, prototype their template-based searches, and forecast their reconstruction with LISA. Specifically, we classify seven templates based on their signal frequency shape, and we identify representative fundamental physics models leading to them. By running a template-based analysis, we forecast the accuracy with which LISA can reconstruct the template parameters of representative benchmark signals, with and without galactic and extragalactic foregrounds. We identify the parameter regions that can be probed by LISA within each template. Finally, we investigate how our signal reconstructions shed light on fundamental physics models of inflation: we discuss their impact for measurements of *e.g.,* the couplings of inflationary axions to gauge fields; the graviton mass during inflation; the fluctuation seeds of primordial black holes; the consequences of excited states during inflation, and the presence of small-scale spectral features.

Irreducible cosmological backgrounds of a real scalar with a broken symmetry [DTV24] We explore the irreducible cosmological implications of a singlet real scalar field. Our focus is on theories with an approximate and spontaneously broken $\mathbb{Z}_2$ symmetry where quasi-stable domain walls can form at early times. This seemingly simple framework bears a wealth of phenomenological implications that can be tackled by means of different cosmological and astrophysical probes. We elucidate the connection between domain wall dynamics and the production of dark matter and gravitational waves. In particular, we identify three main benchmark scenarios. The gravitational wave signal observed by pulsar timing arrays can be generated by the domain walls if the mass of the singlet is $m_s \sim \mathrm{PeV}$. For lower masses, but with $m_s \gtrsim 10\,\mathrm{GeV}$, scalars produced in the annihilation of the domain walls can be dark matter with a distinctive feature in their power spectrum. Finally, the thermal bath provides an unavoidable source of unstable scalars via the freeze-in mechanism whose subsequent decays can be tested by their imprints on cosmological and terrestrial observables.

Gravitino Thermal Production, Dark Matter, and Reheating of the Universe [EGS24] We present a full one-loop calculation of the gravitino thermal production rate, beyond the so-called hard thermal loop approximation, using the corresponding thermal spectral functions in numerical form on both sides of the light cone. This framework requires a full numerical evaluation. We interpret our results within the framework of a general supergravity-based model, remaining agnostic about the specifics of supersymmetry breaking. In this context, assuming that gravitinos constitute the entirety of the dark matter in the Universe imposes strict constraints on the reheating temperature. For example, with a gluino mass at the current LHC limit, a maximum reheating temperature of $T_{\mathrm{reh}} \simeq 10^9\mathrm{GeV}$ is compatible with a gravitino mass of $m_{3/2} \simeq 1\mathrm{TeV}$. Additionally, with a reheating temperature an order of magnitude lower at $T_{\mathrm{reh}} \simeq 10^8\mathrm{GeV}$, the common gaugino mass $M_{1/2}$ can range from 2 to 4TeV within the same gravitino mass range. For much higher values of $M_{1/2}$, which are favored by current accelerator and cosmological data in the context of supersymmetric models, such as $M_{1/2} = 10\mathrm{TeV}$, and for $m_{3/2} \simeq 1\mathrm{TeV}$ the reheating temperature compatible with the gravitino dark matter scenario is $10^7\mathrm{GeV}$. If other dark matter particles are considered, the reheating temperature could be much lower.

Inflation in Weyl-invariant Einstein-Cartan gravity [GT24b] We consider Weyl-invariant quadratic Einstein-Cartan gravity coupled to a scalar field and study the inflationary behaviour of the coupled system of the scalar field and the pseudoscalar associated with the Holst invariant. We find that the model is characterized by effective single-field inflation occurring at small field values and analyze its predictions which are in comfortable agreement with existing observations for a range of parameter values.

Cosmic inflation in metric-affine gravity [GT24a] In the context of metric-affine gravity theories, where the metric and connection are independent, we examine actions involving quadratic terms in the Ricci scalar curvature and the Holst invariant. These actions are non-minimally coupled to a scalar field. We explore the behavior of the corresponding effective metric theory, which includes an extra dynamic pseudoscalar degree of freedom. Detailed analysis of inflationary predictions reveals compliance with recent observations across various parameters, potentially allowing a higher tensor-to-scalar ratio. The spectral index's direction of change varies based on parameter positioning.

What is the origin of the JWST SMBHs? [EFUV24b] We present a new semi-analytical model for the evolution of galaxies and supermassive black holes (SMBHs) that is based on the extended Press-Schechter formalism and phenomenological modelling of star formation. The model yields BH mass-stellar mass relations that reproduce both the JWST and pre-JWST observations. If the efficiency for BH mergers is high the JWST data prefer light seeds while the pre-JWST data prefers heavy seeds. The fit improves for a smaller merger efficiency, $O(0.1)$, for which both data prefer heavy seeds, while also accommodating the PTA GW background data.

$\tilde{\xi}$-attractors in metric-affine gravity [Rac24] We propose a new class of inflationary attractors in metric-affine gravity. Such class features a non-minimal coupling $\tilde{\xi}\,\Omega(\phi)$ with the Holst invariant $\tilde{\mathcal{R}}$ and an inflaton potential proportional to $\Omega(\phi)^2$. The attractor behaviour of the class takes place with two combined strong coupling limits. The first limit is realized at large $\tilde{\xi}$, which makes the theory equivalent to a $\tilde{\mathcal{R}}^2$ model. Then, the second limit considers a very small Barbero-Immirzi parameter which leads the inflationary predictions of the $\tilde{\mathcal{R}}^2$ model towards the ones of Starobinsky inflation. Because of the analogy with the renown ξ-attractors, we label this new class as $\tilde{\xi}$-attractors.

Thermalization effects on the dynamics of growing vacuum bubbles [KLV$^+$24] We study the evolution of growing vacuum bubbles. The bubble walls interact with the surrounding fluid and may, consequently, reach a terminal velocity. If the mean free path of the particles in the fluid is much shorter than the bubble wall thickness, the fluid is locally in thermal equilibrium and the wall's terminal velocity can be determined by entropy conservation. On the other hand, if local thermal equilibrium inside the wall cannot be maintained, the wall velocity can be estimated from the pressure impacted by ballistic particle dynamics at the wall. We find that the latter case leads to slightly slower bubble walls. Expectedly, we find the largest differences in the terminal velocity when the fluid is entirely ballistic. This observation indicates that the non-equilibrium effects inside walls are relevant. To study bubble evolution, we perform hydrodynamic lattice simulations in the case of local thermal equilibrium and N-body simulations in the ballistic case to investigate the dynamical effects during expansion. Both simulations show that even if a stationary solution exists in theory it may not be reached depending on the dynamics of the accelerating bubble walls.

Statistics of the supermassive black hole gravitational wave background anisotropy [RUVV24b] We study the statistical properties of the anisotropy in the gravitational wave (GW) background originating from supermassive black hole (SMBH) binaries. We derive the distribution of the GW anisotropy power spectrum coefficients, $C_{l\geq 1}/C_0$, in scenarios including environmental effects and eccentricities of the SMBH binaries. Although the mean of $C_{l\geq 1}/C_0$ is the same for all multipoles, we show that their distributions vary, with the low l distributions being the widest. We also find a strong correlation between spectral fluctuations and the anisotropy in the GW signal. We show that the GW anisotropy can break the degeneracy between the scenarios including environmental effects or eccentricity. In particular, we find that existing NANOGrav constraints on GW anisotropy begin to constrain SMBH scenarios with strong environmental effects.

Magnetic Anti-de Sitter Wormholes as seeds for Higgs Inflation [BGP24] We show how certain types of magnetic asymptotically Anti-de Sitter Euclidean wormholes can catalyze the onset of inflation. These wormholes can be embedded as saddle point solutions of General Relativity coupled to the Standard Model, the inflaton being identified with the Higgs particle. Our scenario is based on the assumption that the quantum effective potential for the Higgs turns negative at a certain high energy window, in line with current measured values for the Higgs and Top quark masses. Within our proposal, we can estimate various parameters and physical quantities of interest, in consistency with current observational bounds.

Black holes and gravitational waves from phase transitions in realistic models [LTV24a] We study realistic models predicting primordial black hole (PBH) formation from density fluctuations generated in a first-order phase transition. We show that the second-order correction in the expansion of the bubble nucleation rate is necessary for accurate predictions and quantify its impact on the abundance of PBHs and gravitational waves (GWs). We find that the distribution of the fluctuations becomes more Gaussian as the second-order term increases. Consequently, models that predict the same PBH abundances can produce different GW spectra.

Symmetry-breaking inflation in non-minimal metric-affine gravity [GR24] We study symmetry-breaking inflation within the framework of metric-affine gravity. By introducing a non-minimal coupling, $\beta(\phi)\tilde{\mathcal{R}}$, between the Holst invariant and the inflaton, both small-field and large-field inflationary predictions can be brought into agreement with the latest observational constraints. Remarkably, even for sub-Planckian vacuum expectation values, appropriately chosen values of $\beta(\phi)$ enable viable inflation, a scenario previously considered unattainable.

2 Conferences and public events

1. Tuorla-Tartu meeting 2024: Borderless Universe, 6-8 May 2024: http://sites.utu.fi/luma/tt2024-programme/
2. Metric-affine gravity 2024, 17-21 June 2024: http://geomgrav.fi.ut.ee/conf/maffgrav2024/
3. Dark Matter Week, 29 October - 5 November 2024: http://kosmos.ut.ee/en/content/dark-matter-week-celebrating-unseen-force

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1. Laur Järv (PhD, associate professor, head of Laboratory of Theoretical Physics)
2. Tomi Sebastian Koivisto (PhD, visiting professor)
3. María José Guzmán Monsalve (PhD, associate professor)
4. Manuel Hohmann (PhD, associate professor)
5. Piret Kuusk (DSc, associate professor)
6. Margus Saal (PhD, associate professor)
7. Damianos Iosifidis (PhD, scientist)
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9. Ilaria Andrei (MSc, junior scientist)
10. Ernest Michael Priidik Gallagher (MSc, junior scientist)
11. Vasiliki Karanasou (MSc, junior scientist)
12. Konstantinos Pallikaris (MSc, junior scientist)
13. Laxmipriya Pati (MSc, junior scientist)
14. Sofía Vidal (MSc, junior scientist)
15. Luxi Zheng (MSc, junior scientist)

3.2 Tartu Observatory

1. Elmo Tempel (PhD, Prof., head of Department of Physics of Galaxies and Cosmology);
2. Jaan Einasto (Prof. DSc, science consultant);
3. Maret Einasto, (DSc, associate professor);
4. Antti Tamm (PhD, associate professor);
5. Peeter Tenjes (DSc, associate professor);
6. Indrek Vurm (DSc, associate professor);
7. Rain Kipper (PhD, scientist);
8. Jaan Laur (PhD, scientist);
9. Juhan Liivamägi (PhD, scientist);
10. Taavi Tuvikene (PhD, scientist);
11. Moorits Mihkel Muru (PhD, scientist);
12. Maria Jose Benito (PhD, visiting scientist);
13. Shishir Sankhyayan (PhD, visiting scientist);
14. Divya Pandey (PhD, visiting scientist);
15. Luis Eduardo Suelves (PhD, visiting scientist);
16. Aikaterini Niovi Triantafyllaki (MSc, junior scientist);
17. Jad-Alexandru Mansour (MSc, junior scientist);
18. Mousumi Mahato (MSc, junior scientist);
19. Ninad Bhagwan Khobrekar (MSc, junior scientist);
20. Annaliina Sofia Aavik (MSc, junior scientist);
21. Zoe Rhiannon Jones (MSc, junior scientist);

3.3 National Institute for Chemical Physics and Biophysics

1. Martti Raidal (PhD, research professor, head of High Energy and Computational Physics group)
2. Tomi Sebastian Koivisto (PhD, senior researcher)
3. Luca Marzola (PhD, senior researcher)
4. Gert Hütsi (PhD, senior researcher)
5. Antonio Racioppi (PhD, senior researcher)
6. Hardi Veermäe (PhD, senior researcher)
7. Ville Vaskonen (PhD, senior researcher)
8. Carlo Marzo (PhD, researcher)
9. Ioannis Gialamas (PhD, researcher)
10. Alexandros Karam (PhD, researcher)
11. Niko Koivunen (PhD, researcher)

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