Annual Report 2023

Jaan Einasto
and Tartu Observatory cosmology group

1 Research

In this Section the work is described I made together with my collaborates. The work is described using Abstracts of papers and is divided into sections.

Einasto et al. (2023b): Jaan Einasto, Lauri-Juhan Liivamägi and Maret Einasto from Tartu Observatory published a study titled "The time evolution of bias" . To investigate the evolution of bias parameter with cosmic epoch authors used numerical simulations of the evolution of cosmic web. Authors calculated the time evolution of the bias parameter, starting from an early epoch where the universe was only several millions years old, to the present epoch where the universe is 13.8 billion years old. The study shows that during the evolution the bias parameter decreases. The basic result of the study indicates that the bias parameter depends on two factors: the higher is the fraction of matter in voids and the higher is the luminosity of galaxies, the larger is the bias parameter. The first evolutionary trend can be explained by the flow of matter from voids to galaxies. However, gravity cannot deplete voids completely, thus there is always some unclustered matter in voids, and the bias parameter of galaxies is always greater than unity, over the whole range of evolution epochs. Earlier investigations suggested that galaxies trace matter. The present study shows that the early belief explains only the dependence of the bias parameter on the luminosity of galaxies, but its dependence on void factor was not taken into account.

Einasto et al. (2023a): We quantify the evolution of matter and galaxy clustering in cosmological hydrodynam- ical simulations via correlation and bias functions of matter and galaxies. We use simulations TNG100 and TNG300 with epochs from $z = 5$ to $z = 0$. We calculate spatial correlation functions (CF) of galaxies, $\xi(r)$, for simulated galaxies and dark matter (DM) particles to characterise the evolving cosmic web. We find that bias parameters decrease during the evolution, confirming earlier results. Bias parameters of the lowest luminosity galaxies, b0, estimated from CFs are lower relative to CFs of particle density-limited clustered samples of DM. At low and medium luminosities, bias parameters of galaxies are equal, suggesting that dwarf galaxies reside in the same filamentary web as brighter galaxies. We find that bias parameters b0, estimated from CFs of clustered DM, agree with the expected values from the fraction of particles in the clustered population, $b = 1/F_c$. The cosmic web contains filamentary structures of various densities, and fractions of matter in the clustered and the unclustered populations are both less than unity. Thus the CF amplitude of the clustered matter is always higher than for all matter, i.e. bias parameter must be $b > 1$. Differences between CFs of galaxies and clustered DM suggest that these functions describe different properties of the cosmic web.

I participated in the study by Einasto et al. (2023c) in all stages from preparation and discussion of data and polishing the final text.

Following the request of World Scientific 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).

2 Conferences and popular talks

I participated in the Kavli Institute for Theoretical Physics program "The Cosmic Web: Connecting Galaxies to Cosmology at High and Low Redshift", coordinated by Joanne Cohn, Nick Kaiser, Christophe Pichon, and Dmitri Pogosyan. The whole program was from January 3, 2023 to May 17, 2023, I was invited to the program from January 23 to February 18, 2023. I participated in the associated KITP conference: "The Co-evolution of the Cosmic Web and Galaxies across Cosmic Time" and had on February 06 a talk "Time evolution of bias – applying different methods". I started a collaboration with Istvan Szapudi, which lead to the paper Einasto et al. (2023a).

In November 2023 I had several public talks, also a Press Release was made "Exploring the Evolution of the Cosmic Web ".

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)..

4 Research – Tartu Observatory cosmology group

In this Section the work is described done in Tartu Observatory cosmology group, in addition to the work described in Section 1. This overview is based on abstracts written by authors of respective papers.

4.1 Collection of new data

Taylor et al. (2023): The 4MOST Hemisphere Survey (4HS) will obtain uniform spectroscopy and redshifts for approximately six million galaxies over $\sim 2\pi$ steradians, and with high and unbiased completeness for $z < 0.15$. 4HS aims to 1) complete the map of mass and motion in the Local Volume, 2) map the influence of environment on galaxy evolution through overwhelming statistics, and 3) define the local ($z < 0.15$) galaxy reference sample for the era of LSST, Euclid, and ASKAP/MeerKAT/SKA. The result is a dataset with exceptional and long-lasting legacy value.

Hernán-Caballero et al. (2023a): 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 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 $i = 22$ sources, which have low signal- to-noise ratio 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 3.3 (1.9) decrease in the normalised median absolute deviation of the errors (σNMAD), and a factor 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 broadband 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.

Zhong et al. (2023) Large sky spectroscopic surveys have reached the scale of photometric surveys in terms of sample sizes and data complexity. These huge datasets require efficient, accurate, and flexible automated tools for data analysis and science exploitation. We present the Galaxy Spectra Network/GaSNet-II, a supervised multi-network 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 for classified objects in each of them. It also provides redshift errors, using a network-of-networks that reproduces a Monte Carlo test on each spectrum, by randomizing their weight initialization. As a demonstration of the capability of the deep learning pipeline, 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% average classification accuracy over the 13 classes (larger than 90% for the majority of them), and an average redshift error of approximately 0.23% for galaxies and 2.1% for quasars. We further train/test the same pipeline to classify spectra and predict redshifts for a sample of 200k 4MOST mock spectra and 21k publicly released DESI spectra. On 4MOST mock data, we reach 93.4% accuracy in 10-class classification and an average redshift error of 0.55% for galaxies and 0.3% for active galactic nuclei. On DESI data, we reach 96% accuracy in (star/galaxy/quasar only) classification and an average redshift error of 2.8% for galaxies and 4.8% for quasars, despite the small sample size available. GaSNet-II can process $\sim$ 40k spectra in less than one minute, on a normal Desktop GPU. This makes the pipeline particularly suitable for real-time analyses of Stage-IV survey observations and an ideal tool for feedback loops aimed at night-by-night survey strategy optimization.

HermanHernán-Caballero et al. (2023b): The Javalambre-Physics of the Accelerating Universe Astrophysical Survey (J-PAS) will observe approximately one-third of the northern sky with a set of 56 narrow-band filters using the dedicated 2.55 m Javalambre Survey Telescope (JST) at the Javalambre Astrophysical Observatory. Prior to the installation of the main camera, in order to demonstrate the scientific potential of J-PAS, two small surveys were performed with the single-CCD Pathfinder camera: miniJPAS (∼1 deg2 along the Extended Groth Strip), and J-NEP (0.3 deg2 around the JWST North Ecliptic Pole Time Domain Field), including all 56 J-PAS filters as well as u, g, r, and i. J-NEP is 0.5-1.0 mag deeper than miniJPAS, providing photometry for 24,618 r-band-detected sources and photometric redshifts (photo-z) for the 6662 sources with $r < 23$. In this paper, we describe the photometry and photo-z of J-NEP and demonstrate a new method for the removal of systematic offsets in the photometry based on the median colours of galaxies, which we call 'galaxy locus recalibration'. This method does not require spectroscopic observations except in a few reference pointings and, unlike previous methods, is directly applicable to the whole J-PAS survey. We use a spectroscopic sample of 787 galaxies to test the photo-z performance for J-NEP and in comparison to miniJPAS. We find that the deeper J-NEP observations result in a factor ∼1.5-2 decrease in σNMAD (a robust estimate of the standard deviation of the photo-z error) and η (the outlier rate) relative to mini-

JPAS for $r > 21.5$ sources, but no improvement in brighter ones, which is probably because of systematic uncertainties. We find the same relation between σNMAD and odds in J-NEP and miniJPAS, which suggests that we will be able to predict the σNMAD of any set of J-PAS sources from their odds distribution alone, with no need for additional spectroscopy to calibrate the relation. We explore the causes of photo-z outliers and find that colour-space degeneracy at low S/N, photometry artefacts, source blending, and exotic spectra are the most important factors.

Yuan et al. (2023): With a unique set of 54 overlapping narrow-band and two broader filters covering the entire optical range, the incoming Javalambre-Physics of the Accelerating Universe Astrophysical Survey (J-PAS) will provide a great opportunity for stellar physics and near-field cosmology. In this work, we use the miniJPAS data in 56 J-PAS filters and 4 complementary SDSS-like filters to explore and prove the potential of the J-PAS filter system in characterizing stars and deriving their atmospheric parameters. We obtain estimates for the effective temperature with a good precision (¡150 K) from spectral energy distribution fitting. We have constructed the metallicity-dependent stellar loci in 59 colours for the miniJPAS FGK dwarf stars, after correcting certain systematic errors in flat-fielding. The very blue colours, including uJAVA - r, J0378 - r, J0390 - r, uJPAS - r, show the strongest metallicity dependence, around 0.25 mag dex-1. The sensitivities decrease to about 0.1 mag dex$\sim$1 for the J0400 - r, J0410 - r, and J0420 - r colours. The locus fitting residuals show peaks at the J0390, J0430, J0510, and J0520 filters, suggesting that individual elemental abundances such as [Ca/Fe], [C/Fe], and [Mg/Fe] can also be determined from the J-PAS photometry. Via stellar loci, we have achieved a typical metallicity precision of 0.1 dex. The miniJPAS filters also demonstrate strong potential in discriminating dwarfs and giants, particularly the J0520 and J0510 filters. Our results demonstrate the power of the J-PAS filter system in stellar parameter determinations and the huge potential of the coming J-PAS survey in stellar and Galactic studies.

4.2 Cosmic web: structure of superclusters

Sankhyayan et al. (2023): 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 $5.8 \times 10^{15}\ M_{\odot}$ and median size $\sim\ \times 65$ 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.

Bag et al. (2023): Galaxy superclusters, the largest galaxy structures in the cosmic web, are formed due to the gravitational collapse (although they are not usually gravitationally bound). Their geometrical properties can shed light on the structure formation process on cosmological scales, hence on the fundamental properties of gravity itself. In this work we study the distributions of the shape, topology and morphology of the superclusters extracted from Sloan Digital Sky Survey Data Release 12 (SDSS DR12) main galaxy sample and defined in two different ways – using fixed and adaptive density threshold in the luminosity-density field. To assess the geometry and topology of each individual supercluster, we employ Minkowski functionals and Shapefinders, precisely calculated by the shape diagnostic tool SURFGEN2. Both supercluster samples produce similar shape distributions. Perhaps not surprisingly, most superclusters are spherical in shape with trivial topology. However, large superclusters with volumes $V \approx 10^4 Mpc^3$ are statistically found to be filamentary with non-zero genus values. The results, supercluster catalogues and shape distributions are publicly available.

4.3 Early Universe

Ellis et al. (2023c): The most conservative interpretation of the nHz stochastic gravitational wave background (SGWB) discovered by NANOGrav and other Pulsar Timing Array (PTA) Collaborations is astrophysical, namely that it originates from supermassive black hole (SMBH) binaries. However, alternative cosmological models have been proposed, including cosmic strings, phase transitions, domain walls, primordial fluctuations and "audible" axions. We perform a multi-model analysis (MMA) to compare how well these different hypotheses fit the NANOGrav data, both in isolation and in combination with SMBH binaries, and address the questions: Which interpretations fit the data best, and which are disfavoured? We also discuss experimental signatures that can help discriminate between different sources of the PTA GW signal, including fluctuations in the signal strength between frequency bins, individual sources and how the PTA signal extends to higher frequencies.

Ellis et al. (2023b): NANOGrav and other Pulsar Timing Arrays (PTAs) have discovered a common-spectrum process in the nHz range that may be due to gravitational waves (GWs): if so, they are likely to have been generated by black hole (BH) binaries with total masses $> 10^9 M_\odot$. Using the Extended Press-Schechter formalism to model the galactic halo mass function and a simple relation between the halo and BH masses suggests that these binaries have redshifts $z = \mathcal{O}(1)$ and mass ratios ≥ 10, and that the GW signal at frequencies above $\mathcal{O}(10)$ nHz may be dominated by relatively few binaries that could be distinguished experimentally and would yield observable circular polarization. Extrapolating the model to higher frequencies indicates that future GW detectors such as LISA and AEDGE could extend the PTA observations to lower BH masses $\geq 10^3 M_\odot$.

Ellis et al. (2023a): The NANOGrav Collaboration has recently announced evidence for nHz gravitational waves (GWs), in the form of a Hellings-Downs angular correlation in the common-spectrum process that had been observed previously by them and other Pulsar Timing Arrays (PTAs). We analyze the possibility that these GWs originate from binary supermassive black holes (SMBHs) with total masses $\geq 10^9 M_\odot$. The spectral index of the GW signal differs at 95 % CL from that predicted for binary evolution by GW emission alone, and we find $> 3\sigma$ evidence that environmental effects such as dynamical friction with gas, stars, and dark matter may be affecting the binary evolution. We estimate the required magnitude and spectrum of such environmental effects and comment on their possible implications for measurements of GWs at higher frequencies.

Hütsi et al. (2023): The James Webb Space Telescope has detected surprisingly luminous early galaxies that indicate a tension with the Λ cold dark matter. Motivated by scenarios including axion miniclusters or primordial black holes, we consider power-law modifications of the matter power spectrum. We show that the tension could be resolved if dark matter consists of 2×10^{-18} eV axions or if a fraction $fPBH > 0.005$ of dark matter is composed of compact heavy $4 \times 10^6 M_\odot$(fPBH/0.005)-1 structures such as primordial black hole clusters.

However, in both cases, the star formation efficiency needs to be significantly enhanced.

4.4 Structure of groups and clusters of galaxies

Einasto et al. (2023c): Our aim is to combine data on single galaxies, galaxy groups, their BGGs, and their location in the cosmic web, to determine classes of groups, 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. 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, and red and blue star-forming galaxies. We apply multidimensional Gaussian mixture modelling to divide groups based on their properties and environments. We analyse the offset of BGGs with respect to the group centre, and the relation between the stellar velocity dispersion of BGGs and the group velocity dispersions. We show that the 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 $L = 15 \times 10^{10} h^{-2} L_{\odot}$ and mass $M = 23 \times 10^{12} h^{-1} M_{\odot}$. In rich clusters approximately 90% of the BGGs are red and quenched galaxies, while in poor groups only 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 (17% of BCGs). Rich groups and clusters are located in global high-density regions in filaments or filament outskirts, while poor groups reside everywhere in the cosmic web. Our results suggest that group and cluster properties are modulated by their location in the cosmic web, but the properties of their BGGs are mostly determined by processes within group or cluster dark matter halo. We emphasize the role of superclusters as a special environment for group growth.

4.5 Statistical methods

Sorce et al. (2023): The peculiar velocities of galaxies can serve as excellent cosmological probes provided that the biases inherent to their measurements are contained prior to the start of any study. This paper proposes a new algorithm based on an object point process model whose probability density is built to statistically reduce the effects of Malmquist biases and uncertainties due to lognormal errors in radial peculiar velocity catalogs. More precisely, a simulated annealing algorithm allows for the probability density describing the point process model to be maximized. The resulting configurations are bias-minimized catalogs. We conducted tests on synthetic catalogs mimicking the second and third distance modulus catalogs of the Cosmicflows project from which peculiar velocity catalogs are derived. By reducing the local peculiar velocity variance in catalogs by an order of magnitude, the algorithm permits the recovery of the expected one, while preserving the small-scale velocity correlation. It also allows for the expected clustering to be retrieved. The algorithm was then applied to the observational catalogs. The large-scale structure reconstructed with the Wiener-filter technique applied to the bias-minimized observational catalogs matches that of the local cosmic web well, as supported by redshift surveys of local galaxies. These new bias-minimized versions of peculiar velocity catalogs can be used as a starting point for several studies, from plausible estimations of the most probable value for the Hubble constant, H0, to the production of simulations constrained to reproduce the local Universe.

Muru & Tempel (2023): Context. Filament finders are limited, among other things, by the abundance of spectroscopic redshift data. This limits the sky areas and depth where we can detect the filamentary network. Aims: As there are proportionally more photometric redshift data than spectroscopic, we aim to use data with photometric redshifts to improve and expand the areas where we can detect the large-scale structure of the Universe. The Bisous model is a filament finder that uses only the galaxy positions. We present a proof of concept, showing that the Bisous filament finder can improve the detected filamentary network with photometric redshift data. Methods: We created mock data from the MULTIDARK-GALAXIES catalogue. Galaxies with spectroscopic redshifts were given exact positions from the simulation. Galaxies with photometric redshifts were given uncertainties along one coordinate. The errors were generated with different Gaussian distributions for different samples. We sample the photometric galaxy positions for each Bisous run based on the uncertainty distribution. In some runs, the sampled positions are closer to the true positions and produce persistent filaments; other runs produce noise, which is suppressed in the post-processing. Results: There are three different types of samples: spectroscopic only, photometric only, and mixed samples of galaxies with photometric and spectroscopic redshifts. In photometric-only samples, the larger the uncertainty for photometric redshifts, the fewer filaments are detected, and the filaments strongly align along the line of sight. Using mixed samples improves the number of filaments detected and decreases the alignment bias of those filaments. The results are compared against the full spectroscopic sample. The recall for photometric-only samples depends heavily on the size of uncertainty and dropped close to 20%; for mixed samples, the recall stayed between 40% and 80%. The false discovery rate stayed below 5% in every sample tested in this work. Mixed samples showed better results than corresponding photometric-only or spectroscopic-only samples for every uncertainty size and number of spectroscopic galaxies in mixed samples. Conclusions: Mixed samples of galaxies with photometric and spectroscopic redshifts help us to improve and extend the large-scale structure further than possible with only spectroscopic samples. Although the uncertainty sizes tested in this work are smaller than those for the available photometric data, upcoming surveys, such as J-PAS, will achieve sufficiently small uncertainties to be useful for large-scale structure detection.

4.6 Simulations of the structure and evolution of the cosmic web

Tuominen et al. (2023): Context. The current observational status of the hot ($logT(K) > 5.5$) intergalactic medium (IGM) remains incomplete. While recent X-ray emission and Sunyaev-Zeldovich effect observations from stacking large numbers of Cosmic Web filaments have yielded statistically significant detections of this phase, direct statistically significant measurements of single objects remain scarce. The lack of such a sample currently prevents a robust analysis of the cosmic baryon content composed of the hot IGM, which would potentially help solve the cosmological missing baryons problem. Aims: In order to improve the observationally challenging search for the missing baryons, we utilise the theoretical avenue afforded by the EAGLE simulations. Our aim is to get insights into the metal enrichment of the Cosmic Web and the distribution of highly ionised metals in the IGM. Our goal is to aid in the planning of future X-ray observations of the hot intergalactic plasma. Methods: We detected the filamentary network by applying the Bisous formalism to galaxies in the EAGLE simulation. We characterised the spatial distributions of oxygen and O VII and studied their mass and volume filling fractions in the filaments. Since oxygen is formed in and expelled from galaxies, we also studied the surroundings of haloes. We used this information to construct maps of the O VII column density and determine the feasibility of detecting it via absorption with Athena X-IFU. Results: Within EAGLE, the oxygen and O VII number densities drop dramatically beyond the virial radii of haloes. In the most favourable scenario, the median extent of O VII above the Athena X-IFU detection limit is ≈ 700 kpc. Since galaxies are relatively far apart from one another, only $\sim$1% of the filament volumes are filled with O VII at high enough column densities to be detectable by X-IFU. The highly non-homogeneous distribution of the detectable O

VII complicates the usage of the measurements of the intergalactic O VII absorbers for tracing the missing baryons and estimating their contribution to the cosmic baryon budget. Instead, the detectable volumes form narrow and dense envelopes around haloes, while the rest of the O VII is diluted at low densities within the full filament volumes. This localised nature, in turn, results in a low chance ($\sim 10-20\%$ per sight line) of detecting intergalactic O VII with Athena X-IFU within the observational SDSS catalogue of nearby filaments. Fortunately, with deeper filament samples, such as those provided via the future 4MOST 4HS survey, the chances of intercepting an absorbing system are expected to increase up to a comfortable level of $\sim 50\%$ per sight line. Conclusions: Based on EAGLE results, targeting the Cosmic Web with Athena may only result in tip-of-the-iceberg detections of the intergalactic O VII, which is located in the galaxy outskirts. This would not be enough to conclusively solve the missing baryon problem. However, the projection of many filaments into a single line of sight will enable a useful X-ray observation strategy with Athena X-IFU for the hot cosmic baryon gas, reducing the amount of baryons still missing by up to $\sim$25%.

Vurm et al. (2023): Context. A substantial fraction of cosmic baryons is expected to hide in the form of diffuse warm-hot intergalactic medium (WHIM) at X-ray temperatures ($T = 10^5 - 10^7$ K). Due to the expected low density of WHIM, it has been very difficult to detect so far. A statistically significant sample of credible detections of the WHIM phase might help solve the problem of the missing cosmic baryons. While the majority of cosmic gas is approximately at rest inside the filaments of the Cosmic Web, the fraction of gas located close to galaxy clusters is falling towards them with substantial velocities. The infalling gas is influenced by the increasing density in the cluster vicinity and eventually undergoes a termination shock, which may boost its X-ray signal. Thus, the cluster outskirts are potential locations for improved detectability of the missing baryons. Aims: The primary goal of this work is to identify optimal locations of the enhanced X-ray emission and absorption, arising from the interaction of infalling filamentary gas with cluster material. Our further goal is to improve our understanding of the various physical processes affecting WHIM as it falls towards clusters of galaxies along the cosmic filaments. We aim to utilise this information for planning future X-ray observations of WHIM in cluster outskirts. Methods: We applied the DisPerSE filament finder to the galaxy distribution in the surroundings of a single Coma-like ($M200 \sim 10^{15.4} M_{\odot}$) simulated C-EAGLE cluster of galaxies. We characterised the distribution of the thermodynamic properties of the gas in such filaments and provided a physical interpretation for the results. This analysis serves as a proof of method to be applied to the full C-EAGLE sample in a future work. Results: We captured a large fraction ($\sim 50\%$) of the hot ($T > 10^{5.5}$ K) gas falling towards the cluster in the detected filaments in the cluster outskirts. The gas in the filaments is in approximate free fall all the way down to the radial distance of $\sim$2 r200 from the cluster. At smaller radii, the filament gas begins to slow down due to the increasing pressure of the ambient gas; approximately half of the filament gas nevertheless penetrates into the cluster before being decelerated. The deceleration is accompanied by the conversion of gas bulk kinetic energy into heat. As a result, the density and temperature of the gas in the filaments increase from the general Cosmic Web level of $\rho \sim 10\rho av$ (where ρav is the cosmic mean baryon density) and $T = 10^5 - 10^6 K$ at $r \sim 4$ r200 towards $\rho \sim 100\rho av$ and $T = 10^7 - 10^8$ K at the virial boundary of the very massive cluster studied in this paper. Conclusions: The detection of the cosmic filaments of galaxies around clusters may provide a practical observational avenue for locating the densest and hottest phase of the missing baryons.

Muru (2023): The Bisous model is a tool that uses stochastic methods to detect the network of galactic filaments. This model is explicitly developed to detect the structure from observational data, using only galaxy positions as input. This paper shows that the Bisous model gives reliable results and including photometric data improves the resulting filamentary network. We used MultiDark-Galaxies catalogue to create a mock with photometric redshifts and samples with different galaxy number densities. We found that the filaments detected with the Bisous model are reliable; 85% of the detected filaments are unchanged compared to results with more complete input data. Adding photometric data improves the fraction of galaxies in filaments. Using the confusion matrix technique, we found the false discovery rate to always be below 5% when using photometric data.

4.7 Structure and evolution of galaxies

Kipper et al. (2023) Context. Dynamical friction can be a valuable tool for inferring dark matter properties that are difficult to constrain by other methods. Most applications of dynamical friction calculations are concerned with the long-term angular momentum loss and orbital decay of the perturber within its host. This, however, assumes knowledge of the unknown initial conditions of the system. Aims. We advance an alternative methodology to infer the host properties from the perturber's shape distortions induced by the tides of the wake of dynamical friction, which we refer to as the tidal dynamical friction. Methods. As the shape distortions rely on the tidal field that has a predominantly local origin, we present a strategy to find the local wake by integrating the stellar orbits back in time along with the perturber, then removing the perturber's potential and re-integrating them back to the present. This provides perturbed and unperturbed coordinates and hence a change in coordinates, density, and acceleration fields, which yields the back-reaction experienced by the perturber. Results. The method successfully recovers the tidal field of the wake based on a comparison with N-body simulations. We show that similar to the tidal field itself, the noise and randomness of the dynamical friction force due to the finite number of stars is also dominated by regions close to the perturber. Stars near the perturber influence it more but are smaller in number, causing a high variance in the acceleration field. These fluctuations are intrinsic to dynamical friction. We show that a stellar density of $0.0014 M_{\odot} kpc^{-3}$ yields an inherent variance of 10% to the dynamical friction. Conclusions. The current method extends the family of dynamical friction methods that allow for the inference of host properties from tidal forces of the wake. It can be applied to specific galaxies, such as Magellanic Clouds, with Gaia data.

4.8 Structure of the Galaxy and Local Group

Newton et al. (2023) Ultradiffuse galaxies (UDGs) are attractive candidates to probe cosmological models and test theories of galaxy formation at low masses; however, they are difficult to detect because of their low surface brightness. In the Local Group a handful of UDGs have been found to date, most of which are satellites of the Milky Way and M31, and only two are isolated galaxies. It is unclear whether so few UDGs are expected. We address this by studying the population of UDGs formed in hydrodynamic constrained simulations of the Local Group from the HESTIA suite. For a Local Group with a total enclosed mass $M_{LG}(< 2.5 Mpc) = 8 \times 10^{12} M_{\odot}$, we predict that there are 12 ± 3 isolated UDGs (68% confidence) with stellar masses $10^6 \leq M^{\star}/M_{\odot} < 10^9$, and effective radii $R_e \geq 1.5$ kpc, within 2.5 Mpc of the Local Group, of which 2+2-1 (68% confidence) are detectable in the footprint of the Sloan Digital Sky Survey (SDSS). Accounting for survey incompleteness, we find that almost the entire population of UDGs in the Local Group field would be observable in a future all-sky survey with a depth similar to the SDSS, the Dark Energy Survey, or the Legacy Survey of Space and Time. Our results suggest that there is a population of UDGs in the Local Group awaiting discovery.

Khoperskov et al. (2023b): Theory suggests that mergers play an important role in shaping galactic discs and stellar haloes, which was observationally confirmed in the Milky Way (MW) thanks to Gaia data. In this work, aiming to probe the contribution of mergers to the in situ stellar halo formation, we analyse six M 31 and MW analogues from the HESTIA suite of cosmological hydrodynamical zoom-in simulations of the Local Group. We found that all the HESTIA galaxies experience between one to four mergers with stellar mass ratios between 0.2 and 1 relative to the host at the time of the merger. These significant mergers, with a single exception, happened 7 - 11 Gyr ago. The overall impact of the most massive mergers in HESTIA is clearly seen as a sharp increase in the orbital eccentricity (and a corresponding decrease in the rotational velocity V_{Ψ}) of pre-existing disc stars of the main progenitor, thus nicely reproducing the Splash-, Plume-like feature that was discovered in the MW. We do find a correlation between mergers and close pericentric passages of massive satellites and bursts of the star formation in the in situ component. Massive mergers sharply increase the disc velocity dispersion of the in situ stars; however, the latest significant merger often heats up the disc up to the numbers when the contribution of the previous ones is less prominent in the age-velocity dispersion relation. In HESTIA galaxies, the in situ halo is an important component of the inner stellar halo where its fraction is about 30 - 40%, while in the outer parts it typically does not exceed $\approx 5\%$ beyond 15 kpc from the galactic centre. The simulations suggest that this component of the stellar haloes continues to grow well after mergers conclude; however, the most significant contribution comes from stars that formed recently before the merger. The orbital analysis of the HESTIA galaxies suggests that wedges in $R_{max} - Z_{max}$ (apocentre - maximum height from the mid-plane) space are mainly populated by the stars born in between significant mergers.

Khoperskov et al. (2023c): Recent progress in understanding the assembly history of the Milky Way (MW) is driven by the tremendous amount of high-quality data delivered by Gaia (ESA), revealing a number of substructures potentially linked to several ancient accretion events. In this work we aim to explore the phase-space structure of accreted stars by analysing six M31/MW analogues from the HESTIA suite of cosmological hydrodynamics zoom-in simulations of the Local Group. We find that all HESTIA galaxies experience a few dozen mergers but only between one and four of those have stellar mass ratios ¿ 0.2, relative to the host at the time of the merger. Depending on the halo definition, the most massive merger contributes from 20% to 70% of the total stellar halo mass. Individual merger remnants show diverse density distributions at $z = 0$, significantly overlapping with each other and with the in situ stars in the $L_z - E, (V_R, V_{\Psi})$ and (R, v_{Ψ}) coordinates. Moreover, merger debris often shifts position in the$L_z - E$ space with cosmic time due to the galactic mass growth and the non-axisymmetry of the potential. In agreement with previous works, we show that even individual merger debris exhibit a number of distinct $L_z - E$ features. In the (VR, V_{Ψ}) plane, all HESTIA galaxies reveal radially hot, non-rotating or weakly counter-rotating, Gaia-Sausage-like features, which are the remnants of the most recent significant mergers. We find an age gradient in $L_z - E$ space for individual debris, where the youngest stars, formed in the inner regions of accreting systems, deposit to the innermost regions of the host galaxies. The bulk of these stars formed during the last stages of accretion, making it possible to use the stellar ages of the remnants to date the merger event. In action space $(Jr, Jz, J\Psi)$, merger debris do not appear as isolated substructures, but are instead scattered over a large parameter area and overlap with the in situ stars. We suggest that accreted stars can be best identified using $Jr > 0.2 - 0.3(10^4 kpckms^{-1})0.5$. We also introduce a new, purely kinematic space (Jz/Jr-orbital eccentricity), where different merger debris can be disentangled better from each other and from the in situ stars. Accreted stars have a broad distribution of eccentricities, peaking at $\epsilon \approx 0.6 - 0.9$, and their mean eccentricity tends to be smaller for systems accreted more recently.

Khoperskov et al. (2023a): Stellar chemical abundances and kinematics provide key information for recovering the assembly history of galaxies. In this work we explore the chemo-chrono-kinematics of accreted and in situ stellar populations, by analyzing six M31/Milky Way (MW) analogues from the HESTIA suite of cosmological hydrodynamics zoom-in simulations of the Local Group. We show that elemental abundances ([Fe/H], [Mg/Fe]) of merger debris in the stellar haloes are chemically distinct from the survived dwarf galaxies, in that they are $[\alpha/Fe]$-enhanced and have lower metallicity in the same stellar mass range. Therefore, mergers debris have abundances expected for stars originating from dwarfs that had their star formation activity quenched at early times. Accreted stellar haloes, including individual debris, reveal [Fe/H] and [Mg/Fe] gradients in the $E-L_z$ plane, with the most metal-rich, $[\alpha/Fe]$-poor stars, which have formed in the inner parts of the disrupted systems before the merger, contributing mainly to the central regions of the host galaxies. This results in negative metallicity gradients in the accreted components of stellar haloes at $z=0$, seen also for the individual merger debris. We suggest, therefore, that abundance measurements of halo stars in the inner MW will allow constraining better the parameters, such as the mass and merger time, of MW's most massive merger Gaia-Sausage-Enceladus. The metallicity distribution functions (MDFs) of the individual debris show several peaks and the majority of debris have lower metallicity than the in situ stars in the prograde part of the $E-L_z$ space. At the same time, non-rotating and retrograde accreted populations are very similar to the in situ stars in terms of [Fe/H] abundance. Prograde accreted stars show a prominent knee in the [Fe/H]-[Mg/Fe] plane, reaching up to solar [Mg/Fe], while retrograde stars typically contribute to the high-[Mg/Fe] sequence only. We find that the most metal-poor stars ($[Fe/H] \leq -1$) of the HESTIA galaxies exhibit net rotation up to 80 km s^{-1}, which is consistent with the Aurora population recently identified in the MW. At higher metallicities ($[Fe/H] \approx -0.5 \pm 0.1$) we detect a sharp transition (spin-up) from the turbulent phase to a regular disk-like rotation. Different merger debris appear similar in the [Fe/H]-[Mg/Fe] plane, thus making it difficult to identify individual events. However, combining a set of abundances, and especially stellar age, makes it possible to distinguish between different debris.

Kalberla & Haud (2023): Context. Dusty magnetized structures observable in the far-infrared (FIR) at high Galactic latitudes are ubiquitous and found to be closely related to H I filaments with coherent velocity structures. Aims: Considering dimensionless morphological characteristics based on Minkowski functionals, we determine the distribution of filamentarities $\mathcal{F}$ and aspect ratios $\mathcal{A}$ for these structures. Methods: Our data are based on Planck FIR and HI4PI H I observations. Filaments have previously been extracted by applying the Hessian operator. We trace individual filamentary structures along the plane of the sky and determine $\mathcal{A}$ and $\mathcal{F}$. Results: Filaments in the diffuse interstellar medium (ISM) are seldom isolated structures, but are rather part of a network of filaments with a well-defined, continuous distribution in $\mathcal{A}$ and $\mathcal{F}$. This distribution is self-replicating, and the merger or disruption of individual filamentary structures leads only to a repositioning of the filament in $\mathcal{A}$ and $\mathcal{F}$ without changing the course of the distribution. Conclusions: FIR and H I filaments identified at high Galactic latitudes are a close match to model expectations for narrow filaments with approximately constant widths. This distribution is continuous without clear upper limits on the observed aspect ratios. Filaments are associated with enhanced column densities of CO-dark H2. Radial velocities along the filaments are coherent and mostly linear with typical dispersions of $\Delta\nu LSR = 5.24$ km s^{-1}. The magnetic field strength in the diffuse turbulent ISM scales with hydrogen volume density as $B \approx nH0.58$. At high Galactic latitudes, we determine an average turbulent magnetic field strength of $\delta B \approx 5.3\ \mu G$ and an average mean strength of the magnetic field in the plane of the sky of $B_{POS} \approx 4.4\mu G$.

Põder et al. (2023): Aims: Our goal is to calculate the circular velocity curve of the Milky Way, along with corresponding uncertainties that quantify various sources of systematic uncertainty in a self-consistent manner. Methods: The observed rotational velocities are described as circular velocities minus the asymmetric drift. The latter is described by the radial axisymmetric Jeans equation. We thus reconstruct the circular velocity curve between Galactocentric distances from 5 kpc to 14 kpc using a Bayesian inference approach. The estimated error bars quantify uncertainties in the Sun's Galactocentric distance and the spatial-kinematic morphology of the tracer stars. As tracers, we used a sample of roughly 0.6 million stars on the red giant branch stars with six-dimensional phase-space coordinates from Gaia Data Release 3 (DR3). More than 99% of the sample is confined to a quarter of the stellar disc with mean radial, rotational, and vertical velocity dispersions of (35 ± 18) km s^{-1}, (25 ± 13) km s^{-1}, and (19 ± 9) km s^{-1}, respectively. Results: We find a circular velocity curve with a slope of0.4 ± 0.6 km s^{-1} kpc^{-1}, which is consistent with a flat curve within the uncertainties. We further estimate a circular velocity at the Sun's position of $v_c(R0) = 233 \pm 7$ km s^{-1} and that a region in the Sun's vicinity, characterised by a physical length scale of $\sim$1 kpc, moves with a bulk motion of $VLSR = 7 \pm 7$ km s^{-1}. Finally, we estimate that the dark matter (DM) mass within 14 kpc is $\log 10MDM(R < 14kpc)/M_{\odot} = (11.2 + 2.0 - 2.3)$ and the local spherically averaged DM density is $\rho DM(R_0) = (0.41 + 0.10 - 0.09)$ GeV cm^{-3} = (0.011+0.003-0.002) $M_{\odot}$pc^{-3}. In addition, the effect of biased distance estimates on our results is assessed.

4.9 High-energy astrophysics

Dabhade et al. (2023): Giant radio sources (GRSs) defined to $be > 0.7$ Mpc are the largest single objects in the Universe and can be associated with both galaxies (GRGs) and quasars (GRQs). They are important for understanding the evolution of radio galaxies and quasars whose sizes range from pc to Mpc scales and are also valuable probes of their environment. These radio-loud active galactic nuclei (RLAGN) interact with the interstellar medium of the host galaxy on small scales and the large-scale intracluster or intergalactic medium for the GRSs. With several new and sensitive surveys over the last few years, the number of known GRSs has increased many fold, which has led a resurgence of interest in the field. This review article summarises our current understanding of these sources based on nearly five decades of research, and discusses the importance of the Square Kilometer Array (SKA) in addressing some of the outstanding questions.

Acharyya et al. (2023): Superluminous supernovae (SLSNe) are a rare class of stellar explosions with luminosities $\sim 10 - 100$ times greater than ordinary core-collapse supernovae. One popular model to explain the enhanced optical output of hydrogen-poor (Type I) SLSNe invokes energy injection from a rapidly spinning magnetar. A prediction in this case is that high-energy gamma-rays, generated in the wind nebula of the magnetar, could escape through the expanding supernova ejecta at late times (months or more after optical peak). This paper presents a search for gamma-ray emission in the broad energy band from 100 MeV to 30 TeV from two Type I SLSNe, SN2015bn, and SN2017egm, using observations from Fermi-LAT and VERITAS. Although no gamma-ray emission was detected from either source, the derived upper limits approach the putative magnetar's spin-down luminosity. Prospects are explored for detecting very-high-energy (VHE; 100 GeV-100 TeV) emission from SLSNe-I with existing and planned facilities such as VERITAS and CTA.

4.10 Study of stellar evolution

Sokolovsky et al. (2023a): Lightcurves of many classical novae deviate from the canonical ”fast rise - smooth decline” pattern and display complex variability behavior. We present the first TESS-space-photometry-based investigation of this phenomenon. We use TESS Sector 41 full-frame images to extract a lightcurve of the slow Galactic nova V606 Vul that erupted nine days prior to the start of the TESS observations. The lightcurve covers the first of two major peaks of V606 Vul that was reached 19 days after the start of the eruption. The nova reached its brightest visual magnitude V=9.9 in its second peak 64 days after the eruption onset, following the completion of Sector 41 observations. To increase the confidence level of the extracted lightcurve, we performed the analysis using four different codes implementing the aperture photometry (Lightkurve, VaST) and image subtraction (TESSreduce, tequilan shots) and find good agreement between them. We performed ground-based photometric and spectroscopic monitoring to complement the TESS data. The TESS lightcurve reveals two features: periodic variations (0.12771d, 0.01mag average peak-to-peak amplitude) that disappeared when the source was within 1mag of peak optical brightness and a series of isolated mini-flares (with peak-to-peak amplitudes of up to 0.5mag) appearing at seemingly random times. We interpret the periodic variations as the result of azimuthal asymmetry of the photosphere engulfing the nova-hosting binary that was distorted by and rotating with the binary. Whereas we use spectra to associate the two major peaks in the nova lightcurve with distinct episodes of mass ejection, the origin of mini-flares remains elusive.

Sokolovsky et al. (2023b): Classical novae are shock-powered multiwavelength transients triggered by a thermonuclear runaway on an accreting white dwarf. V1674 Her is the fastest nova ever recorded (time to declined by two magnitudes is t2 = 1.1 d) that challenges our understanding of shock formation in novae. We investigate the physical mechanisms behind nova emission from GeV γ-rays to cm-band radio using coordinated Fermi-LAT, NuSTAR, Swift, and VLA observations supported by optical photometry. Fermi-LAT detected short-lived (18 h) 0.1-100 GeV emission from V1674 Her that appeared 6 h after the eruption began; this was at a level of $(1.6 \pm 0.4) \times 10^{-6}$ photons cm^{-2} s^{-1}. Eleven days later, simultaneous NuSTAR and Swift X-ray observations revealed optically thin thermal plasma shock-heated to kT shock ≈ 4 keV. The lack of a detectable 6.7 keV Fe K_α emission suggests super-solar CNO abundances. The radio emission from V1674 Her was consistent with thermal emission at early times and synchrotron at late times. The radio spectrum steeply rising with frequency may be a result of either free-free absorption of synchrotron and thermal emission by unshocked outer regions of the nova shell or the Razin-Tsytovich effect attenuating synchrotron emission in dense plasma. The development of the shock inside the ejecta is unaffected by the extraordinarily rapid evolution and the intermediate polar host of this nova.

Diesing et al. (2023): In 2021 August, the Fermi Large Area Telescope, H.E.S.S., and MAGIC detected GeV and TeV γ-ray emission from an outburst of recurrent nova RS Ophiuchi. This detection represents the first very high-energy γ-rays observed from a nova, and it opens a new window to study particle acceleration. Both H.E.S.S. and MAGIC described the observed γ-rays as arising from a single, external shock. In this paper, we perform detailed, multi-zone modeling of RS Ophiuchi’s 2021 outburst, including a self-consistent prescription for particle acceleration and magnetic field amplification. We demonstrate that, contrary to previous work, a single shock cannot simultaneously explain RS Ophiuchi’s GeV and TeV emission, in particular the spectral shape and distinct light-curve peaks. Instead, we put forward a model involving multiple shocks that reproduces the observed γ-ray spectrum and temporal evolution. The simultaneous appearance of multiple distinct velocity components in the nova optical spectrum over the first several days of the outburst supports the presence of distinct shocks, which may arise either from the strong latitudinal dependence of the density of the external circumbinary medium (e.g., in the binary equatorial plane versus the poles) or due to internal collisions within the white dwarf ejecta (which power the γ-ray emission in classical novae).

Liimets et al. (2023): Context. V838 Monocerotis is a peculiar binary that underwent an immense stellar explosion in 2002, leaving behind an expanding cool supergiant and a hot B3V companion. Five years after the outburst, the B3V companion disappeared from view, and has not returned to its original state. Aims: We investigate the changes in the light curve and spectral features to explain the behaviour of V838 Mon during the current long-lasting minimum. Methods: A monitoring campaign has been performed over the past 13 years with the Nordic Optical Telescope to obtain optical photometric and spectroscopic data. The datasets are used to analyse the temporal evolution of the spectral features and the spectral energy distribution, and to characterise the object. Results: Our photometric data show a steady brightening in all bands over the past 13 years, which is particularly prominent in the blue. This rise is also reflected in the spectra, showing a gradual relative increase in the continuum flux at shorter wavelengths. In addition, a slow brightening of the $H\alpha$ emission line starting in 2015 was detected. These changes might imply that the B3V companion is slowly reappearing. During the same time interval, our analysis reveals a considerable change in the observed colours of the object along with a steady decrease in the strength and width of molecular absorption bands in our low-resolution spectra. These changes suggest a rising temperature of the cool supergiant along with a weakening of its wind, most likely combined with a slow recovery of the secondary due to the evaporation of the dust and accretion of the material from the shell in which the hot companion is embedded. From our medium-resolution spectra, we find that the heliocentric radial velocity of the atomic absorption line of Ti I 6556.06 Åhas been stable for more than a decade. We propose that Ti I lines are tracing the velocity of the red supergiant in V838 Mon, and do not represent the infalling matter as previously stated.

5 List of collaborators

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December 27, 2023