Annual Report 2021

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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.

1.1 Fundamental problems of the cosmological paradigm

We investigate the evolution of the one-point probability distribution function (PDF) of the dark matter density field and the evolution of its moments for fluctuations that are Gaussian in the linear regime (Einasto et al., 2021c). We performed numerical simulations of the evolution of the cosmic web for the conventional ΛCDM model. The simulations covered a wide range of box sizes $L = 256 - 4000\ h^{-1}$ Mpc, mass, and force resolutions, and epochs from very early moments $z = 30$ to the present moment $z = 0$. We calculated density fields with various smoothing lengths to determine the dependence of the density field on the smoothing scale. We calculated the PDF and its moments variance, skewness, and kurtosis. We determined the dependence of these parameters on the evolutionary epoch z, on the smoothing length R_t, and on the rms deviation of the density field σ using a cubic-cell and top-hat smoothing with kernels $0.4 \leq R_t \leq 32\ h^{-1}$ Mpc. We focus on the third (skewness S) and fourth (kurtosis K) moments of the distribution functions: their dependence on the smoothing scale R_t, the amplitude of the fluctuations σ , and the redshift z. Moments S and K, calculated for density fields at different cosmic epochs and smoothed with various scales, characterise the evolution of different structures of the web. Moments calculated with small-scale smoothing ($R_t \approx (1-4)\ h^{-1}$ Mpc) characterise the evolution of the web on cluster-type scales. Moments found with strong smoothing ($R_t \gtrsim (5-15)\ h^{-1}$ Mpc) describe the evolution of the web on supercluster scales. During the evolution, the reduced skewness $S_3 = S/\sigma$ and reduced kurtosis $S_4 = K/\sigma^2$ present a complex behaviour: at a fixed redshift, curves of $S_3(\sigma)$ and $S_4(\sigma)$ steeply increase with σ at $\sigma \lesssim 1$ and then flatten out and become constant at $\sigma \gtrsim 2$. When we fixed the smoothing scale R_t, the curves at large σ started to gradually decline after reaching the maximum at $\sigma \approx 2$, . We provide accurate fits for the evolution of $S_{3,4}(\sigma, z)$. Skewness and kurtosis approach constant levels at early epochs $S_3(\sigma) \approx 3$ and $S_4(\sigma) \approx 15$. Most of the statistics of dark matter clustering (e.g. halo mass function or concentration-mass relation) are nearly universal: they mostly depend on the σ with a relatively modest correction to apparent dependence on the redshift. We find just the opposite for skewness and kurtosis: the dependence of the moments on the evolutionary epoch z and smoothing length R_t is very different. Together, they uniquely determine the evolution of $S_{3,4}(\sigma)$. The evolution of S_3 and S_4 cannot be described by current theoretical approximations. The often used lognormal distribution function for the PDF fails to even qualitatively explain the shape and evolution of S_3 and S_4.

Our goal is to find the relation between the two-point correlation functions (CFs) of projected and spatial density fields of galaxies in the context of the cosmic web (Einasto et al., 2021a). To investigate relations between spatial (3D) and projected (2D) CFs of galaxies we used density fields of two simulations: a Λ-dominated cold dark matter (LCDM) model with known particle data, and the Millennium simulation with know data on simulated galaxies. We compare 3D and 2D correlation functions. In the 2D case, we use samples of various thickness to find the dependence of 2D CFs on the thickness of samples. We also compare 3D CFs in real and redshift space. The dominant elements of the cosmic web are clusters and filaments, separated by voids filling most of the volume. In individual 2D sheets, the positions of clusters and filaments do not coincide. As a result, in projection, the clusters and filaments fill in 2D voids. This leads to a decrease in the amplitudes of CFs (and power spectra) in projection. For this reason, the amplitudes of 2D CFs are lower than the amplitudes of 3D correlation functions: the thicker the 2D sample, the greater the difference. Spatial CFs of galaxies contain valuable information about the geometrical properties of the cosmic web that cannot be found from projected CFs.

We investigate the evolution of superclusters and supercluster cocoons (basins of attraction), and the effect of cosmological parameters on the evolution(Einasto et al., 2021b). We performed numerical simulations of the evolution of the cosmic web for different cosmological models: the Λ cold dark matter (LCDM) model with a conventional value of the dark energy (DE) density, the open model OCDM with no DE, the standard SCDM model with no DE, and the hyper-DE HCDM model with an enhanced DE density value. We find ensembles of superclusters of these models for five evolutionary stages, corresponding to the present epoch $z = 0$, and to redshifts $z = 1,\ 3,\ 10,\ 30$. We used the diameters of the largest superclusters and the number of superclusters as percolation functions to describe the properties of the ensemble of superclusters in the cosmic web. We analysed the size and mass distribution of superclusters in models and in real samples based on the Sloan Digital Sky Survey (SDSS). In all models, the numbers and volumes of supercluster cocoons are independent of the cosmological epochs. The supercluster masses increase with time and the geometrical sizes in comoving coordinates decrease with time for all models. The LCDM, OCDM, and HCDM models have almost similar percolation parameters. This suggests that the essential parameter, which defines the evolution of superclusters, is the matter density. The DE density affects the growth of the amplitude of density perturbations and the growth of masses of superclusters, but significantly weaker. The HCDM model has the highest speed of the growth of the density fluctuation amplitude and the largest growth of supercluster masses during the evolution. The geometrical diameters and the numbers of HCDM superclusters at high threshold densities are larger than for the LCDM and OCDM superclusters. The SCDM model has about twice as many superclusters as other models, and the SCDM superclusters have smaller diameters and lower masses. We find that supercluster embryos form at very early cosmological epochs and that the evolution of superclusters occurs mainly inside their cocoons. The evolution of superclusters and their cocoons as derived from density fields agress well with the evolution found from velocity fields.

Jaan Einasto translated into English to Doctor of Sciences thesis Einasto (1972). A summary of the Thesis in English is available (Einasto, 2021). The Thesis was an attempt to combine data from three previously independent areas: the structure and kinematics of stellar populations of the Galaxy, photometric and dynamical models of galaxies, and models of the dynamical and physical evolution of galaxies. The Thesis was completed in November 1971 and defended in March 17, 1972 for the degree of Doctor of Science in astronomy and celestial mechanics. This synthesis was made with the goal to understand better the vast topic of the structure and evolution of galaxies.

The main results of the study can be divided into methodical and astronomical. The methodical results include: (i) extrapolation of the mass distribution function beyond the Sun's distance, and the determination of the circular velocity at the Sun's distance from the Galactic centre; (ii) conditions of physical correctness of models are developed, and the generalised exponential model is suggested; (iii) a method has been developed to construct spatial and hydrodynamical models of stellar systems, using a combination of observational data on populations, and data on physical evolution of populations.

The main astronomical results are: (i) spatial and hydrodynamical models of the Galaxy and the Andromeda galaxy M31 are elaborated in several approximations; (ii) the dynamical evolution of the Galaxy is reconstructed using kinematical characteristics of stellar populations of different ages; (iii) on the basis of stellar evolutionary tracks and star formation function, a theory of the evolution of galaxies is elaborated. The basic conclusion of the study is: *it was impossible to reproduce the observed rotation curves of galaxies with known stellar populations.*

2 Conferences and popular talks

In October 5 — 8 Tuorla-Tartu Cosmology Meeting 2021 "Interaction of the cosmic matter" took place. I had a talk on topic *Integral distribution functions of the cosmic web*. Maret Einasto had a talk *The Corona Borealis supercluster: connectivity, collapse, and evolution* (Einasto et al., 2021d).

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

Hernán-Caballero et al. (2021). MiniJPAS is a ~ 1 deg2 imaging survey of the AEGIS field in 60 bands, performed to demonstrate the scientific potential of the upcoming Javalambre-Physics of the Accelerating Universe Astrophysical Survey (J-PAS). Full coverage of the 3800-9100 Å range with 54 narrow-band filters, in combination with 6 optical broad-band filters, allows for extremely accurate photometric redshifts (photo-z), which, applied over areas of thousands of square degrees, will enable new applications of the photo-z technique, such as measurement of baryonic acoustic oscillations. In this paper we describe the method we used to obtain the photo-z that is included in the publicly available miniJPAS catalogue, and characterise the photo-z performance. We built photo-spectra with 100 Å resolution based on forced-aperture photometry corrected for point spread function. Systematic offsets in the photometry were corrected by applying magnitude shifts obtained through iterative fitting with stellar population synthesis models. We computed photo-z with a customised version of LEPHARE, using a set of templates that is optimised for the J-PAS filter-set. We analysed the accuracy of miniJPAS photo-z and their dependence on multiple quantities using a subsample of 5266 galaxies with spectroscopic redshifts from SDSS and DEEP, which we find to be representative of the whole r ¡ 23 miniJPAS sample. Formal 1σ uncertainties for the photo-z that are calculated with the $\Delta\chi 2$ method underestimate the actual redshift errors. The odds parameter has a stronger correlation with $|\Delta z|$ and accurately reproduces the probability of a redshift outlier ($|\Delta z| > 0.03$), regardless of the magnitude, redshift, or spectral type of the sources. We show that the two main summary statistics characterising the photo-z accuracy for a population of galaxies (σNMAD and η) can be predicted by the distribution of odds in this population, and we use this to estimate the statistics for the whole miniJPAS sample. At $r < 23$, there are ~ 17500 galaxies per deg2 with valid photo-z estimates, 4200 of which are expected to have $|\Delta z| < 0.003$. The typical error is $\sigma NMAD = 0.013$ with an outlier rate $\eta = 0.39$. The target photo-z accuracy σNMAD = 0.003 is achieved for odds ¿ 0.82 with $\eta = 0.05$, at the cost of decreasing the density of selected galaxies to $n \sim 5200 deg^2$ (2600 of which have $|\Delta z| < 0.003$).

López-Sanjuan et al. (2021). Aims: We present the photometric calibration of the twelve optical passbands for the Javalambre Photometric Local Universe Survey (J-PLUS) second data release (DR2), comprising 1088 pointings of two square degrees, and study the systematic impact of metallicity on the stellar locus technique. Methods: The [Fe/H] metallicity from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) for 146 184 high-quality calibration stars, defined with signal-to-noise ratio larger than ten in J-PLUS passbands and larger than three in Gaia parallax, was used to compute the metallicity-dependent stellar locus (ZSL). The initial homogenization of J-PLUS photometry, performed with a unique stellar locus, was refined by including the metallicity effect in colors via the ZSL. Results: The variation of the average metallicity along the Milky Way produces a systematic offset in J-PLUS calibration. This effect is well above 1% for the bluer passbands and amounts 0.07, 0.07, 0.05, 0.03, and 0.02 mag in u, J0378, J0395, J0410, and J0430, respectively. We modeled this effect with the Milky Way location of the J-PLUS pointing, also providing an updated calibration for those observations without LAMOST information. The estimated accuracy in the calibration after including the metallicity effect is at 1% for the bluer J-PLUS passbands and below for the rest. Conclusions: Photometric calibration with the stellar locus technique is prone to significant systematic bias in the Milky Way for passbands bluer than $\lambda = 4500\mathring{A}$. The calibration method for J-PLUS DR2 reaches 1-2% precision and 1% accuracy for 12 optical filters within an area of 2176 square degrees.

Bonoli et al. (2021). The Javalambre-Physics of the Accelerating Universe Astrophysical Survey (J-PAS) will scan thousands of square degrees of the northern sky with a unique set of 56 filters using the dedicated 2.55 m Javalambre Survey Telescope (JST) at the Javalambre Astrophysical Observatory. Prior to the installation of the main camera (4.2 deg2 field-of-view with 1.2 Gpixels), the JST was equipped with the JPAS-Pathfinder, a one CCD camera with a 0.3 deg2 field-of-view and plate scale of 0.23 arcsec pixel[1]. To demonstrate the scientific potential of J-PAS, the JPAS-Pathfinder camera was used to perform miniJPAS, a 1 deg2 survey of the AEGIS field (along the Extended Groth Strip). The field was observed with the 56 J-PAS filters, which include 54 narrow band (FWHM - 145 Å) and two broader filters extending to the UV and the near-infrared, complemented by the u, g, r, i SDSS broad band filters. In this miniJPAS survey overview paper, we present the miniJPAS data set (images and catalogs), as we highlight key aspects and applications of these unique spectro-photometric data and describe how to access the public data products. The data parameters reach depths of magAB = 22 - 23.5 in the 54 narrow band filters and up to 24 in the broader filters (5σ in a 3 min aperture). The miniJPAS primary catalog contains more than 64 000 sources detected in the r band and with matched photometry in all other bands. This catalog is 99% complete at r = 23.6 (r = 22.7) mag for point-like (extended) sources. We show that our photometric redshifts have an accuracy better than 1% for all sources up to r = 22.5, and a precision of $\leq 0.3\%$ for a subset consisting of about half of the sample. On this basis, we outline several scientific applications of our data, including the study of spatially-resolved stellar populations of nearby galaxies, the analysis of the large scale structure up to $z = 0.9$, and the detection of large numbers of clusters and groups. Sub-percent redshift precision can also be reached for quasars, allowing for the study of the large-scale structure to be pushed to $z > 2$. The miniJPAS survey demonstrates the capability of the J-PAS filter system to accurately characterize a broad variety of sources and paves the way for the upcoming arrival of J-PAS, which will multiply this data by three orders of magnitude.

González Delgado et al. (2021). The Javalambre-Physics of the Accelerating Universe Astrophysical Survey (J-PAS) will soon start imaging thousands of square degrees of the northern sky with its unique set of 56 filters (spectral resolution of $R \approx 60$). Before the arrival of the final instrument, we observed 1 deg2 on the AEGIS field with an interim camera with all the J-PAS filters. Taking advantage of these data, dubbed miniJPAS, we aim at proving the scientific potential of the J-PAS to derive the stellar population properties of galaxies via fitting codes for spectral energy distributions (SEDs), with the ultimate goal of performing galaxy evolution studies across cosmic time. One parametric (BaySeAGal) and three non-parametric (MUFFIT, AlStar, and TGASPEX) SED-fitting codes are used to constrain the stellar mass, age, metallicity, extinction, and rest-frame and dust-corrected (u - r) colours of a complete flux-limited sample (rSDSS$\leq$ 22.5 AB) of miniJPAS galaxies that extends up to $z = 1$. We generally find consistent results on the galaxy properties derived from the different codes, independently of the galaxy spectral type or redshift; this is remarkable considering that 25% of the J-spectra have signal-to-noise ratios (S/N) ≈ 3. For galaxies with S/N≥ 10, we estimate that the J-PAS photometric system will allow us to derive the stellar population properties of rest-frame (u - r) colour, stellar mass, extinction, and mass-weighted age with a precision of 0.04 ± 0.02 mag, 0.07 ± 0.03 dex, 0.2 ± 0.09 mag, and 0.16 ± 0.07 dex, respectively. This precision is equivalent to that obtained with spectroscopic surveys of similar S/N. By using the dust-corrected $(u - r)$ colour-mass diagram, a powerful proxy for characterizing galaxy populations, we find: (i) that the fraction of red and blue galaxies evolves with cosmic time, with red galaxies being 38% and -18% of the whole population at $z = 0.1$ and $z = 0.5$, respectively, and (ii) consistent results between codes for the average intrinsic (u - r) colour, stellar mass, age, and stellar metallicity of blue and red galaxies and their evolution up to $z = 1$. At all redshifts, the more massive galaxies belong to the red sequence, and these galaxies are typically older and more metal-rich than their counterparts in the blue cloud. Our results confirm that with J-PAS data we will be able to analyse large samples of galaxies up to $z = 1$, with galaxy stellar masses above log$(M_\star/M_\odot) \approx 8.9, 9.5$, and 9.9 at $z = 0.3$, 0.5, and 0.7, respectively. The star formation history of a complete sub-sample of galaxies selected at $z \approx 0.1$ with log$(M_\star/M_\odot)$ ¿ 8.3 constrains the cosmic evolution of the star formation rate density up to $z \approx 3$, in good agreement with results from cosmological surveys.

Baqui et al. (2021). Context. Future astrophysical surveys such as J-PAS will produce very large datasets, the so-called "big data", which will require the deployment of accurate and efficient machine-learning (ML) methods. In this work, we analyze the miniJPAS survey, which observed about 1 deg2 of the AEGIS field with 56 narrow-band filters and 4 ugri broad-band filters. The miniJPAS primary catalog contains approximately 64 000 objects in the r detection band (magAB≤ 24), with forced-photometry in all other filters. Aims: We discuss the classification of miniJPAS sources into extended (galaxies) and point-like (e.g., stars) objects, which is a step required for the subsequent scientific analyses. We aim at developing an ML classifier that is complementary to traditional tools that are based on explicit modeling. In particular, our goal is to release a value-added catalog with our best classification. Methods: In order to train and test our classifiers, we cross-matched the miniJPAS dataset with SDSS and HSC-SSP data, whose classification is trustworthy within the intervals $15 \leq r \leq 20$ and $18.5 \leq r \leq 23.5$, respectively. We trained and tested six different ML algorithms on the two cross-matched catalogs: K-nearest neighbors, decision trees, random forest (RF), artificial neural networks, extremely randomized trees (ERT), and an ensemble classifier. This last is a hybrid algorithm that combines artificial neural networks and RF with the J-PAS stellar and galactic loci classifier. As input for the ML algorithms we used the magnitudes from the 60 filters together with their errors, with and without the morphological parameters. We also used the mean point spread function in the r detection band for each pointing. Results: We find that the RF and ERT algorithms perform best in all scenarios. When the full magnitude range of $15 \leq r \leq 23.5$ is analyzed, we find an area under the curve AUC = 0.957 with RF when photometric information alone is used, and AUC = 0.986 with ERT when photometric and morphological information is used together. When morphological parameters are used, the full width at half maximum is the most important feature. When photometric information is used alone, we observe that broad bands are not necessarily more important than narrow bands, and errors (the width of the distribution) are as important as the measurements (central value of the distribution). In other words, it is apparently important to fully characterize the measurement. Conclusions: ML algorithms can compete with traditional star and galaxy classifiers; they outperform the latter at fainter magnitudes ($r \geq 21$). We use our best classifiers, with and without morphology, in order to produce a value-added catalog.

4.2 Early Universe

Hütsi et al. (2021c). We analyse the LIGO-Virgo data, including the recently released GWTC-2dataset, to test a hypothesis that the data contains more than one population of black holes. We perform a maximum likelihood analysis including a population of astrophysical black holes with a truncated power-law mass function whose merger rate follows from star formation rate, and a population of primordial black holes for which we consider log-normal and critical collapse mass functions. We find that primordial black holes alone are strongly disfavoured by the data, while the best fit is obtained for the template combining astrophysical and primordial merger rates. Alternatively, the data may hint towards two different astrophysical black hole populations. We also update the constraints on primordial black hole abundance from LIGO-Virgo observations finding that in the 2-400 mass range they must comprise less than 0.2% of dark matter.

Delle Rose et al. (2021). We consider the boosted dark matter solution of the XENON1T excess to constrain the framework through loop-generated processes. The interaction of the boosted dark matter component, which sources the signal, effectively couples the cold dark matter background to the electrons, making it potentially visible in the electron recoil searches. Similarly, once the radiative corrections due to the Standard Model are taken into account, dark matter also scatters on quarks and becomes observable in nuclear recoil measurements. By analysing these processes in a class of effective models built on vector and scalar couplings, we find that the current direct detection constraints exclude the upper mass range selected by the anomaly, especially if the boosted component is generated through dark matter annihilation.

Hütsi et al. (2021a). We show that the physical conditions which induce the Thakurta metric, recently studied by Bœhm *et al.* in the context of time-dependent black hole masses, correspond to a single accreting black hole in the entire Universe filled with isotropic non-interacting dust. In such a case, the physics of black hole accretion is not local but tied to the properties of the whole Universe. We show that radiation, primordial black holes or particle dark matter cannot produce the specific energy flux required for supporting the mass growth of Thakurta black holes. In particular, this solution does not apply to black hole binaries. We conclude that cosmological black holes and their mass growth cannot be described by the Thakurta metric, and thus existing constraints on the primordial black hole abundance from the LIGO-Virgo and the CMB measurements remain valid.

Vipp et al. (2021). We are approaching a new era to probe the 21-cm neutral hydrogen signal from the period of cosmic dawn. This signal offers a unique window to the virgin Universe, e.g., to study dark matter models with different small-scale behaviors. The EDGES Collaboration recently published the first results of the global 21-cm spectrum. We demonstrate that such a signal can be used to set, unlike most observations concerning dark matter, both lower and upper limits for the mass of dark matter particles. We study the 21-cm signal resulting from a simple warm dark matter model with a sharp-k window function calibrated for high redshifts. We tie the PopIII star formation to Lyman-alpha and radio background production. Using Markov Chain Monte Carlo to sample the parameter space, we find that to match the EDGES signal, a warm dark matter particle must have a mass of 7.3-3.3+1.6 keV at 68% confidence interval. This translates to 2.2-1.7+1.4×10-20 eV for fuzzy dark matter and 63-35+19 keV for Dodelson-Widrow sterile neutrinos. Cold dark matter is unable to reproduce the signal due to its slow structure growth.

Hütsi et al. (2021b). In this reply, we address the comment [arXiv:2105.14908] to our recent paper [arXiv:2105.09328], where we argued that the Thakurta metric does not describe cosmological black holes. We clarify that the mass growth of Thakurta black holes is due to an influx of energy (i.e. accretion), which, by definition, is not a feature of geometry. The conclusions of [arXiv:2105.09328] are independent of the interpretation of this energy flux. We show that the average energy density of primordial Thakurta black holes scales as a^2 and requires an unrealistic and fine-tuned energy transfer from a smooth dark matter component to the primordial black hole sector.

4.3 Cosmic web: structure of superclusters

Einasto et al. (2021d). Context. Rich superclusters of galaxies represent dynamically active environments in which galaxies and their systems form and evolve. Aims: We study the dynamical properties and connectivity of the richest galaxy clusters in the Corona Borealis (CB) supercluster and of the whole supercluster, and analyse star formation of galaxies in them with the aim to understand the evolution of the supercluster and the galaxies within it. We compare it with the supercluster SCl A2142. Methods: We used the luminosity-density field to determine the high-density cores of the CB. We identified the richest galaxy clusters in them and studied the dynamical state of the clusters, analysed their substructure, and studied the star formation properties of galaxies in them using normal mixture modelling and the projected phase space diagram. We determined filaments in the supercluster to analyse the connectivity of clusters. To understand the possible future evolution of the CB, we compared the mass distribution in it with predictions from the spherical collapse model and analysed the gravitational acceleration field in the CB. Results: The richest clusters in the high-density cores of the CB are the Abell clusters A2065, A2061 (together with A2067), A2089, and Gr2064. At a radius R30 around each cluster (corresponding to the density contrast $\Delta\rho \approx 30$), the galaxy distribution shows a minimum. The R30 values for individual clusters lie in the range of $3 - 6h^{-1}$ Mpc. The radii of the clusters (splashback radii) lie in the range of $R_{cl} \approx 2 - 3R_{vir}$. The projected phase space diagrams and the comparison with the spherical collapse model suggest that R30 regions have passed turnaround and are collapsing, forming infall regions around each cluster. Galaxies in the richest cluster of the CB, A2065, and in its infall region have on average younger stellar populations than other clusters and their environment. The cluster A2061 has the highest fraction of galaxies with very old stellar populations, similar to those in A2142. The number of long filaments that begin near clusters vary from one near A2089 to five near A2061. The total connectivity of these clusters (the number of infalling groups and filaments) varies from two to nine. Conclusions: During the future evolution, the clusters in the main part of the CB may merge and form one of the largest bound systems in the nearby Universe. Another part, with the cluster Gr2064, will form a separate system. Our study suggests that structures with a current characteristic density contrast $\Delta\rho \approx 30$ have passed turnaround and started to collapse at redshifts $z \approx 0.3 - 0.4$. The comparison of the number and properties of the most massive collapsing supercluster cores from observations and simulations may serve as a test for cosmological models.

4.4 Structure of clusters of galaxies

Ferragamo et al. (2021). We present the velocity dispersion and dynamical mass estimates for 270 galaxy clusters included in the first Planck Sunyaev-Zeldovich (SZ) source catalogue, the PSZ1. Part of the results presented here were achieved during a two-year observational program, the ITP, developed at the Roque de los Muchachos Observatory (La Palma, Spain). In the ITP we carried out a systematic optical follow-up campaign of all the 212 unidentified PSZ1 sources in the northern sky that have a declination above -15° and are without known counterparts at the time of the publication of the catalogue. We present for the first time the velocity dispersion and dynamical mass of 58 of these ITP PSZ1 clusters, plus 35 newly discovered clusters that are not associated with the PSZ1 catalogue. Using Sloan Digital Sky Survey (SDSS) archival data, we extend this sample, including 212 already confirmed PSZ1 clusters in the northern sky. Using a subset of 207 of these galaxy clusters, we constrained the MSZ – M_{dyn} scaling relation, finding a mass bias of $(1-B) = 0.83 \pm 0.07$ (stat) ± 0.02 (sys). We show that this value is consistent with other results in the literature that were obtained with different methods (X-ray, dynamical masses, or weak-lensing mass proxies). This result cannot dissolve the tension between primordial cosmic microwave background anisotropies and cluster number counts in the ΩM – σ_8 plane.

De Propris et al. (2021). We explore the persistence of the alignment of brightest cluster galaxies (BCGs) with their local environment. We find that a significant fraction of BCGs do not coincide with the centroid of the X-ray gas distribution and/or show peculiar velocities (they are not at rest with respect to the cluster mean). Despite this, we find that BCGs are generally aligned with the cluster mass distribution even when they have significant offsets from the X-ray centre and significant peculiar velocities. The large offsets are not consistent with simple theoretical models. To account for these observations BCGs must undergo mergers preferentially along their major axis, the main infall direction. Such BCGs may be oscillating within the cluster potential after having been displaced by mergers or collisions, or the dark matter halo itself may not yet be relaxed.

4.5 Cosmic web: structure of filaments

Wang et al. (2021b). Although structures in the Universe form on a wide variety of scales, from small dwarf galaxies to large super clusters, the generation of angular momentum across these scales is poorly understood. Here we investigate the possibility that filaments of galaxies—cylindrical tendrils of matter hundreds of millions of light years across—are themselves spinning. By stacking thousands of filaments together and examining the velocity of galaxies perpendicular to the filament's axis (via their redshift and blueshift), we find that these objects too display vortical motion consistent with rotation, making them the largest objects known to have angular momentum. The strength of the rotation signal is directly dependent on the viewing angle and the dynamical state of the filament. Filament rotation is more clearly detected when viewed edge-on. In addition, the more massive the haloes that sit at either end of the filaments, the more rotation is detected. These results signify that angular momentum can be generated on unexpectedly large scales.

Ganeshaiah Veena et al. (2021). We explore the evolution of halo spins in the cosmic web using a very large sample of dark matter haloes in the Lambda cold dark matter Planck-Millennium N-body simulation. We use the NEXUS+ multiscale formalism to identify the hierarchy of filaments and sheets of the cosmic web at several redshifts. We find that at all times the magnitude of halo spins correlates with the web environment, being largest in filaments, and, for the first time, we show that it also correlates with filament thickness as well as the angle between spin orientation and the spine of the host filament. For example, massive haloes in thick filaments spin faster than their counterparts in thin filaments, while for low-mass haloes the reverse is true. We have also studied the evolution of alignment between halo spin orientations and the preferential axes of filaments and sheets. The alignment varies with halo mass, with the spins of low-mass haloes being predominantly along the filament spine, while those of high-mass haloes being predominantly perpendicular to the filament spine. On average, for all halo masses, halo spins become more perpendicular to the filament spine at later times. At all redshifts, the spin alignment shows a considerable variation with filament thickness, with the halo mass corresponding to the transition from parallel to perpendicular alignment varying by more than one order of magnitude. The cosmic web environmental dependence of halo spin magnitude shows little evolution for $z \leq 2$ and is likely a consequence of the correlations in the initial conditions or high redshift effects.

Muru & Tempel (2021). Context. Recent years have given rise to numerous methods of detecting the cosmic web elements in the large-scale structure of the Universe. All of these methods describe more or less the same features, but each with its nuance. The Bisous filament finder is a stochastic tool for identifying the spines of filaments using galaxy positions. Aims: This work provides an analysis of how the galaxy number density of the input data affects the filaments detected with the Bisous model and gives estimates of the reliability of the method itself to assess the robustness of the results. Methods: We applied the Bisous filament finder to MultiDark-Galaxies data, using various magnitude cuts from the catalogue to study the effects of different galaxy number densities on the results and different parameters of the model. We compared the structures by the fraction of galaxies in filaments and the volume filled by filaments, and we analysed the similarities between the results from different cuts based on the overlap between detected filamentary structures. The filament finder was also applied to the exact same data 200 times with the same parameters to study the stochasticity of the results and the correlation between different runs was calculated. Results: Multiple samples show that galaxies in filaments have preferentially higher luminosity. We found that when a galaxy is in a filament there is a 97% chance that the same galaxy would be in a filament with even more complete input data and about 85% of filaments are persistent when detecting the filamentary network with higher-density input data. Lower galaxy number density inputs mean the Bisous model finds fewer filaments, but the filaments found are persistent even if we use more complete input data for the detection. We calculated the correlation coefficient between 200 Bisous runs on the exact same input, which is 0.98. Conclusions: This study confirms that increased number density of galaxies is important to obtain a more complete picture of the cosmic web. To overcome the limitation of the spectroscopic surveys, we will develop the Bisous model further to apply this tool to combined spectroscopic and narrow-band photometric redshift surveys, such as the J-PAS.

4.6 Cosmic web: missing baryons

Tuominen et al. (2021). Context. A significant fraction of the predicted baryons remain undetected in the local Universe. We adopted the common assumption that a large fraction of the missing baryons correspond to the hot (log T(K) = 5.5-7) phase of the warm-hot intergalactic medium (WHIM). We base our missing baryons search on the scenario whereby the WHIM has been heated up via accretion shocks and galactic outflows, and it is concentrated towards the filaments of the cosmic web. Aims: Our aim is to improve the observational search for the poorly detected hot WHIM. Methods: We detected the filamentary structure within the EAGLE hydrodynamical simulation by applying the Bisous formalism to the galaxy distribution. To test the reliability of our results, we used the MMF/NEXUS+ classification of the large-scale environment of the dark matter component in EAGLE. We then studied the spatio-thermal distribution of the hot baryons within the extracted filaments. Results: While the filaments occupy only 5% of the full simulation volume, the diffuse hot intergalactic medium in filaments amounts to 23%-25% of the total baryon budget, or 79%-87% of all the hot WHIM. The optimal filament sample, with a missing baryon mass fraction of 82%, is obtained by selecting Bisous filaments with a high galaxy luminosity density. For these filaments, we derived analytic formulae for the radial gas density and temperature profiles, consistent with recent Planck Sunyaev-Zeldovich and cosmic microwave background lensing observations within the central $r \approx 1$ Mpc. Conclusions: Results from the EAGLE simulation suggest that the missing baryons are strongly concentrated towards the filament axes. Since the filament finding methods used here are applicable to galaxy surveys, a large fraction of the missing baryons can be localised by focusing the observational efforts on the central 1 Mpc regions of the filaments. To optimise the observational signal, it is beneficial to focus on the filaments with the highest galaxy luminosity densities detected in the optical data.

Nevalainen et al. (2021). A fraction of the XMM-Newton/EPIC FOV is obscured by the dysfunctional (i.e. bad) pixels. The fraction varies between different EPIC instruments in a given observation. These complications affect the analysis of extended X-ray sources observed with XMM-Newton/EPIC and the consequent scientific interpretation of the results. For example, the accuracy of the widely used cosmological probe of the gas mass of clusters of galaxies depends on the accuracy of the procedure of removing the obscuration effect from the measured flux. The Science Analysis Software (SAS) includes an option for recovering the lost fraction of the flux measured by a primary instrument by utilising a supplementary image of the same source. The correction may be accurate if the supplementary image is minimally obscured at the locations of the bad pixels of the primary instrument. This can be achieved e.g. by using the observation-based MOS2 image for correcting the pn flux, or by using a synthetic model image. By utilising a sample of 27 galaxy cluster observations we evaluated the accuracy of the recovery method based on observed images, as implemented in SAS 18.0.0. We found that the accuracy of the recovered total flux in the 0.5-7.0 keV band in the full geometric area within the central r = 6 arcmin is better than 0.1% on average while in some individual cases the recovered flux may be uncertain by 1%.

4.7 Structure and evolution of galaxies

Kipper et al. (2021b). Matter distribution models of the Milky Way galaxy are usually stationary, although there are known to be wave-like perturbations in the disc at 10 per cent level of the total density. Modelling of the overall acceleration field by allowing non-equilibrium is a complicated task. We must learn to distinguish whether density enhancements are persistent or not by their nature. In this paper, we elaborate our orbital arc method to include the effects of massless perturbations and non-stationarities in the modelling. The method is tested by modelling of simulation data and shown to be valid. We apply the method to the Gaia Data Release 2 (DR2) data within a region of 0.5 kpc from the Sun and confirm that acceleration field in the solar neighbourhood has a perturbed nature - the phase-space density along the orbits of stars grow in the order of $h \leq 5$ per cent per Myr due to non-stationarity. This result is a temporally local value and can be used only within the time frame of a few Myr. An attempt to pinpoint the origin of the perturbation shows that the stars having larger absolute angular momentum are the main carriers of the local perturbation. As they are faster than the average thin disc star, they are either originating further away and are close in their pericentre or they are perturbed locally by a fast comoving perturber, such as gas disc inhomogeneities.

Wang et al. (2021a). Satellites are not randomly distributed around their central galaxies but show polar and planar structures. In this paper, we investigate the axis asymmetry or lopsidedness of satellite galaxy distributions around isolated galaxies in a hydrodynamic cosmological simulation. We find a statistically significant lopsided signal by studying the angular distribution of the satellite galaxies' projected positions around isolated central galaxies in a two-dimensional plane. The signal is dependent on galaxy mass, color, and large-scale environment. Satellites that inhabit low-mass blue hosts, or located further from the hosts, show the most lopsided signal. Galaxy systems with massive neighbors exhibit stronger lopsidedness. This satellite axis-asymmetry signal also decreases as the universe evolves. Our findings are in agreement with recent observational results and they provide a useful perspective for studying galaxy evolution, especially on the satellite accretion, internal evolution, and interaction with the cosmic large-scale structure.

4.8 Structure of the Galaxy and Local Group

Newton et al. (2021). The Local Group is a unique environment in which to study the astrophysics of galaxy formation. The proximity of the Milky Way and M31 causes a large fraction of the low-mass halo population to interact with more massive dark matter haloes, which increases their concentrations and strips them of gas and other material. Some low-mass haloes pass through the haloes of the Milky Way or M31 and are either ejected into the field or exchanged between the two primary hosts. We use high resolution gas-dynamical simulations to describe a new class of field halo that passed through the haloes of both the Milky Way and M31 at early times and is almost twice as concentrated as isolated field haloes. These 'Hermeian' haloes are distributed anisotropically at greater distances from the Local Group barycentre than the primary haloes and appear to cluster close to the Milky Way and M31 in projection. We show that some Hermeian haloes can host galaxies that are promising targets for indirect dark matter searches and are competitive with signals from other dwarf galaxies. Hermeian galaxies in the Local Group should be detectable by forthcoming wide-field imaging surveys.

Kipper et al. (2021a). Context. Galaxies can be classified as passive ellipticals or star-forming discs. Ellipticals dominate at the high end of the mass range, and therefore there must be a mechanism responsible for the quenching of star-forming galaxies. This could either be due to the secular processes linked to the mass and star formation of galaxies or to external processes linked to the surrounding environment. However, the contribution from these smooth and stochastic processes to galaxy quenching has yet to be quantified. Aims: In this paper, we analytically model the processes that govern galaxy evolution and quantify their contribution. The key advantage of our method is that we do not assume the strength of the contribution from any of these processes beforehand, but instead aim to find their efficiencies. We have specifically studied the effects of mass quenching, gas stripping, and mergers on galaxy quenching. Methods: To achieve this, we first assumed a set of differential equations that describe the processes that shape galaxy evolution. We then modelled the parameters of these equations by maximising likelihood. These equations describe the evolution of galaxies individually, but the parameters of the equations are constrained by matching the extrapolated intermediate-redshift galaxies with the low-redshift galaxy population. In this study, we modelled the processes that change star formation and stellar mass in massive galaxies from the GAMA survey between $z \approx 0.4$ and the present. Results: We identified and quantified the contributions from mass quenching, gas stripping, and mergers to galaxy quenching. By modelling mass quenching, we found that quenching begins for galaxies above a mass of 1010.2 $M_{\odot}$, but is dependent on the gas accretion rate before quenching. The quenching timescale is on average 1.2 Gyr and a closer look reveals support for the slow-then-rapid quenching scenario. The major merging rate of galaxies is about once per 10 Gyr, while the rate of ram pressure stripping is significantly higher. In galaxies with decreasing star formation, we show that star formation is lost to fast quenching mechanisms such as ram pressure stripping and is countered by mergers, at a rate of about 41% Gyr^{-1} and to mass quenching 49% Gyr^{-1}. Therefore, slow quenching mechanisms have a greater influence on galaxies in group or cluster environments than fast quenching mechanisms.

Kalberla et al. (2021). Context. H I filaments are closely related to dusty magnetized structures that are observable in the far infrared (FIR). Recently it was proposed that the coherence of oriented H I structures in velocity traces the line of sight magnetic field tangling. Aims: We study the velocity-dependent coherence between FIR emission at 857 GHz and H I on angular scales of 18'. Methods: We use HI4PI H I data and Planck FIR data and apply the Hessian operator to extract filaments. For coherence, we require that local orientation angles θ in the FIR at 857 GHz along the filaments be correlated with the H I. Results: We find some correlation for H I column densities at —vLSR— ¡ 50 km/s, but a tight agreement between FIR and H I orientation angles θ exists only in narrow velocity intervals of 1 km/s. Accordingly, we assign velocities to FIR filaments. Along the line of sight these H I structures show a high degree of the local alignment with θ, as well as in velocity space. Interpreting these aligned structures in analogy to the polarization of dust emission defines an H I polarization. We observe polarization fractions of up to 80%, with averages of 30%. Orientation angles θ along the filaments, projected perpendicular to the line of sight, are fluctuating systematically and allow a characteristic distribution of filament curvatures to be determined. Conclusions: Local H I and FIR filaments identified by the Hessian analysis are coherent structures with well-defined radial velocities. H I structures are also organized along the line of sight with a high degree of coherence. The observed bending of these structures in the plane of the sky is consistent with models for magnetic field curvatures induced by a Galactic small-scale turbulent dynamo.

4.9 High-energy astrophysics

Rabinowitz et al. (2021). Superluminous Supernovae (SLSNe) are a rare class of supernovae with luminosity 10-100 times greater than standard supernovae. It is still unknown exactly what powers SLSNe, though different models have been proposed for both Type I (hydrogen poor) and Type II (hydrogen rich) SLSNe, such as powering by a central engine (particularly Type

I) or interactions with circumstellar material. Studying emission from these objects can help constrain the models and provide a better understanding of what makes these supernovae so optically bright. This project studied high-energy gamma-ray emission (600 MeV to above 300 GeV) from two Type I SLSNe, SN2015bn and SN2017egm, by performing binned likelihood analyses of data from the Fermi-LAT, in support of a study of the same sources using data from VERITAS in the 200 GeV to 10 TeV energy range (Ribeiro, D., et al., 2020, BAAS, 52, 3). No gamma-ray emission was detected from either source in this energy range, but upper limits on flux and luminosity were derived. An analysis was also carried out on the recently-detected source SN2020jhm, and an update will be presented; also, prospects for future observations with existing or planned facilities will be outlined.

Ribeiro et al. (2021). The powering mechanism for the bright luminosity in Superluminous supernovae (SLSNe) is a still-unsettled question. The light curves of conventional core-collapse supernovae are primarily derived from the decay of Ni, while the presence of hydrogen in type II SLSNe spectra indicates interactions between circumstellar medium and the expanding ejecta. Alternatively, hydrogen-poor type I SLSNe may be powered by a central engine such as a highly magnetized pulsar, creating gamma rays that thermalize in the outflowing ejecta and power the bright optical emission. These gamma rays may escape the ejecta as the opacity drops, and become visible after several hundred days. In this talk, we report the search for gamma rays with VERITAS from two bright and nearby type I SLSNe, SN2015bn and SN2017egm, 133 and 670 days after explosion, respectively. We found no detections and report upper limits. We also report upper limits with Fermi-LAT for six-month bins after the explosion. We conclude by reporting the viability for future observation strategies by other ground-based gamma-ray telescopes. This work is presented on behalf of VERITAS Collaboration.

Vurm & Metzger (2021). Superluminous supernovae (SLSNe) are massive star explosions that are too luminous to be powered by traditional energy sources, such as the radioactive decay of 56Ni. Instead, they may be powered by a central engine, such as a millisecond pulsar or magnetar, whose relativistic wind inflates a nebula of high-energy particles and radiation behind the expanding supernova ejecta. We present three-dimensional Monte Carlo radiative transfer calculations of SLSNe that follow the production of high-energy emission in the nebula and its subsequent thermalization into optical radiation within the surrounding ejecta and, conversely, determine the gamma-ray emission that escapes the ejecta without thermalizing. We identify a novel mechanism by which yy pair creation in the upstream pulsar wind regulates the mean energy of particles entering the nebula over the first several years after the explosion, rendering our results on this timescale insensitive to the (uncertain) intrinsic wind pair multiplicity. To explain the observed late-time steepening of SLSN optical light curves as being the result of gamma-ray leakage, we find that the nebular magnetization must be very low, $\epsilon_B \leq 10^{-6} - 10^{-4}$, the more efficiently thermalized lower-energy synchrotron emission would overproduce the late-time (≥ 1 yr) optical radiation, inconsistent with observations. For magnetars to remain as viable contenders for powering SLSNe, we conclude that either magnetic dissipation in the wind/nebula is extremely efficient or the spin-down luminosity decays significantly faster than the canonical dipole rate t^{-2} in a way that coincidentally mimics gamma-ray escape.

Sokolovsky et al. (2021). Peaking at 3.7 mag on 2020 July 11, YZ Ret was the second-brightest nova of the decade. The nova's moderate proximity (2.7 kpc from Gaia) provided an opportunity to explore its multi-wavelength properties in great detail. Here we report on YZ Ret as part of a long-term project to identify the physical mechanisms responsible for high-energy emission in classical novae. We use simultaneous Fermi/LAT and NuSTAR observations complemented by XMM-Newton X-ray grating spectroscopy to probe the physical parameters of the shocked ejecta and the nova-hosting white dwarf. The XMM-Newton observations revealed a super-soft X-ray emission which is dominated by emission lines of CV, CVI, NVI, NVII, and OVIII rather than a blackbody-like continuum, suggesting CO-composition of the white dwarf in a high-inclination binary system. Fermi/LAT detected YZ Ret for 15 days with the gamma-ray spectrum best described by a power law with an exponential cut-off at 1.9 +/-0.6 GeV. In stark contrast with theoretical predictions and in keeping with previous NuSTAR observations of Fermi-detected classical novae (V5855 Sgr and V906 Car), the 3.5-78 keV X-ray emission is found to be two orders of magnitude fainter than the GeV emission. The X-ray emission observed by NuSTAR is consistent with a single-temperature thermal plasma. We detect no non-thermal tail of the GeV emission expected to extend down to the NuSTAR band. NuSTAR observations continue to challenge theories of high-energy emission from shocks in novae.

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