2022 Institute of Astronomy Summer Research Opportunity

Project Booklet

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Project 1 Spatial Curvature and time-delay cosmography: A forecast for the Vera Rubin Observatory

Supervisor: Dr Suhail Dhawan (sd919@cam.ac.uk)

Description

Measuring the spatial curvature of the Universe is of long-standing interest in cosmology. Determining the sign and value of the curvature density parameter is of great importance in relation to early universe inflationary paradigm and the eventual fate of the universe. While recent measurements from the cosmic microwave background (CMB) from Planck satellite provide extremely stringent constraints on its value pointing to a flat universe, the situation in the late universe is quite difference with an order of magnitude weaker constraints on curvature. Moreover, recent studies have also potentially suggested that the CMB indicates a non-flat universe, leading to a possible debate. Thus, it is imperative to have independent, high-fidelity constraints on spatial curvature from the late universe.

A promising route to achieve precise late universe estimates of the curvature density is via time-delay distances to multiply imaged, strongly lensed supernovae. Future transient facilities like the Rubin Observatory's legacy survey of space and time (LSST) will find hundreds of such events in its 10 year survey baseline (a few tens per year). this will be a rich dataset to measure curvature independent of the CMB. This project will involve forecasting constraints on curvature under various assumptions of the dark energy and with different combination of late universe probes complementary the time-delay lenses.

Skills recommended: prior knowledge of python will be helpful, any previos experience with MCMC sampling while advantageous is not mandatory.

References

1. Efstathiou G., Gratton S., 2020, MNRAS, 496, L91
2. Vagnozzi S. et al. 2020 (arXiv: 2010.02230)
3. Dhawan S. et al. 2020, MNRAS, 506, L1-5
4. Handley W., 2021, Phys. Rev. D, 103, L041301
5. Di Valentino E., Melchiorri A., Silk J., 2019, Nat. Astron., 4, 196

Project 2 Interior evolution of an exoplanet

Supervisors: Mr Marc Brouwers (mgb52@ast.cam.ac.uk) and Dr Amy Bonsor (abonsor@ast.cam.ac.uk)

Description

Stars throughout the universe are surrounded by planets of various kinds. These planets are often diverse and wonderous and efforts to characterize them are now fully underway.

In order to properly understand what planets are made of, we must understand how their interiors evolve. Recent work has shown that planets larger than Earth are expected to form with small central cores, surrounded by regions of rock in gaseous or supercritical form, likely mixed with hydrogen and helium. Temperatures can rise up to tens of thousands of degrees, making the deep interiors of larger exoplanets potentially hotter than the surface of the Sun. The nature of these interiors influences the radius and temperature of the planet that forms, and is crucial to understand.

In this project, we will model the cooling of a Naptune-like planet over Gyrs and study the evolution of its interior. We will account for the effects of a compositional gradient on its heat transport and study whether this can keep heat trapped inside. The modeling will consist of mathematical calculations, as well as more extensive numerical modeling in Python.

Project 3 Accretion onto a polluted white dwarf

Supervisors: Mr Marc Brouwers (mgb52@ast.cam.ac.uk) and Dr Amy Bonsor (abonsor@ast.cam.ac.uk)

Description

A significant fraction of white dwarfs – contracted stars that have evolved off the main sequence – show metal lines indicative of pollution with planetary material. Currently, it remains poorly understood how this material gets there. We hypothesize that accretion might begin with the tidal disruption of a scattered asteroid and the formation of a highly eccentric tidal debris disc. The debris would then collide and produce dust, which accretes onto the star.

In this project, we will model the infrared signature of such a dust disc around a white dwarf. We will expand on an existing numerical model to include dust circularization by gas drag and perform more detailed calculations with a radiative transfer code. These calculations will help to inform us what signatures we can expect from accretion and could help to validate or reject our current hypotheses. This project will consist of some mathematical modeling and more detailed computational work in Python.

Project 4 Constraining the mass distribution of the first stars with the Square Kilometre Array

Supervisors: Dr Anastasia Fialkov (afialkov@ast.cam.ac.uk) and Mr Thomas Gessey-Jones

Description

The first stars in the universe formed from the primordial mix of hydrogen and helium produced in the big bang. These stars hence contained no elements heavier than lithium, which leads to theoretical predictions that they should be much more massive and luminous than typical stars seen today. Unfortunately, forming so early in the universe puts these stars out of reach of conventional direct observation. The burgeoning field of 21-cm cosmology provides an alternative, instead focusing on observing the neutral hydrogen gas around the stars, via the absorption/emission of 21-cm wavelength photons by this gas. When the first stars form they heat and ionize the gas surrounding them and so cause spatial variations in the amount of 21-cm absorption/emission. Hence, observing these variations in the 21-cm signal from the early universe will provide an avenue for indirectly observing the enigmatic first stars, and potentially an opportunity to infer some of their properties.

In this summer project, you will explore the potential for constraining the mass distribution of the first stars using the upcoming square kilometre array (SKA). Initially, the project will consist of using a state of the art semi-numerical simulation code to predict the 21-cm signal that would result from different first-star mass distributions. Using these results, you will then compare the differences between the predicted signals to the noise levels anticipated for the SKA. From which you will quantify if, and to what extent, SKA observations will allow us to constrain the mass distribution of the first stars. The project will hence involve working at the frontiers of our understanding of the early universe and provide an opportunity to learn about the prospects for the new science we will learn from next-generation experiments. Through this project, you will also gain experience in using high-performance computing facilities. Some experience with Python and/or MATLAB is required.

Project 5 Constraining the mass of Neptune analogues based on debris disc inner edges

Supervisor: Dr Sebastián Marino (sm2132@ast.cam.ac.uk)

Description

Debris discs are a ubiquitous component of planetary systems. These discs are analogous to the asteroid and Kuiper belt in our Solar System, whose morphology has been shaped by planets. Today we know hundreds of these discs and a few tens have been imaged revealing their morphology, thus giving us a tool to search for the dynamical presence of exoplanets. A key feature of a disc is its inner edge since it is there where we expect to find Neptune analogues that truncated the disc in the past. However, although we have characterised the position and sharpness of the inner edge for many discs, we lack a relation to connect the edge properties with the characteristics of a putative planet. The aim of the project is to find a relationship between a planet's mass and the shape of the disc's inner edge. In order to do this, the student will run and analyse a series of N-body simulations of a planet interacting with a disc. Once that relation is found, the student will apply it to a sample of systems to constrain the mass of potential planets that truncated the discs in the past.

Project 6 Exploring Dark Matter models with 3pt correlation function of Lyman-alpha forest

Supervisor: Dr Vid Irsic (vi223@cam.ac.uk)

Description

For the last few decades increasing number of astrophysical observations have been used to detect dark matter (DM), the unknown particle responsible for 25% of the total matter energy density of the Universe today. On the frontier of those efforts are the observations of the Lyman-alpha forest -- a collection of absorption lines in the spectra of distant quasars, that are caused by Lyman-alpha transitions of the neutral hydrogen in the low-density, high-redshift intergalactic medium. The combination of DM particle mass and momentum distribution provides a natural scale below which different DM models suppress the amount of structure in the cosmic web. The unique sensitivity of the Lyman-alpha forest to this effect has been extensively used to put some of the strongest constraints to date on many different DM models (e.g. Warm Dark Matter, Fuzzy Dark Matter, etc.). The main statistical tool to measure the amount of structure in the Lyman-alpha forest has historically been 2pt correlation function, or power spectrum. However, recent studies suggest that the precision of power spectrum measurements have reached a point where only a little gain is achieved for a lot of effort in controlling systematic effects. As a result, additional statistical measures of the Lyman-alpha forest that go beyond 2pt correlations might provide a larger gain. This is further reinforced by the evidence that the Lyman-alpha field is highly non-Gaussian, suggesting that considerable amount of information is held in 3pt (and higher order) correlations. In this project, the student will estimate both the 2pt and 3pt correlations (power spectrum and bispectrum) of the Lyman-alpha field in high resolution simulations of the intergalactic medium. The simulations span a range of different DM models, thus allowing for an investigation into the sensitivity of such measurements to the DM properties, in particular on how much additional information on DM particle mass can be obtained by combining power spectrum and bispectrum measurements.

Due to computational nature of the project, some experience with UNIX and programming is advised. The student will be encouraged to analyze the data using C (through already existing analysis package), although scripting language such as python can also be used.

Project 7 Modelling the X-ray variability of ultra-soft narrow-line Seyfert 1 AGN

Supervisors: Dr Jiachen Jiang (jj447@cam.ac.uk) and Dr Michael Parker (mlparker@ast.cam.ac.uk)

Description

Narrow-line Seyfert 1 galaxies (NLS1s) are a unique class of Seyfert 1 galaxies. They are often found to show extreme properties in the X-ray band, such as very soft X-ray continuum emission and strong, variable soft excess emission. Their X-ray complexity is often explained by either the light-bending model in the vicinity of a black hole in the disk reflection scenario or variable absorption.

In this project, the student will study the origin of the soft excess emission and its variability in a sample of special NLS1s. Previous spectral studies suggest that the X-ray continuum of these sources is very soft and they are accreting around or a few times the Eddington limit. The student will learn 1) how to reduce XMM-Newton data and extract scientific products from raw data; 2) how to calculate RMS spectra; 3) the modelling of their RMS spectra based on different theories.

Project 8 Angular velocity distribution of Pop III stars

Supervisors: Dr Nina Sartorio (sartorio.nina@ast.cam.ac.uk) and Dr Anastasia Fialkov (afialkov@ast.cam.ac.uk)

Description

Population III stars were born out of the pristine gas soon after the Big Bang and shone light on a previously dark universe. Unfortunately, little is known about properties of these stars. One of their main properties is that they are expected to rotate much faster than an average star in the present-day Universe. Because rotation affects the evolution of the stars (Yoon er al 2012) as well as their capacity to interact with other stars (Sana, 2012), it is essential to have a correct prescription of rotation in simulations of star formation and population synthesis codes. However, most works done to date on population III stars ignore their rotation. This summer project will focus on taking the first step to include this essential variable into a population synthesis code binary_c.

In this summer project the student will develop a prescription for the distribution of angular velocity of population III stars based on hydrodynamic simulations reported in the literature. The student will implement this prescription in the population evolution code binary_c and test the results.

Project 9 21-cm signal with Fuzzy Dark Matter Cosmology

Supervisors: Dr Anastasia Fialkov (afialkov@ast.cam.ac.uk) and Mr Tibor Dome (td448@ast.cam.ac.uk)

Description

One of the most exciting ways to probe the Epoch of Reionisation (EoR) and Cosmic Dawn eras is via the redshifted 21 cm signal of hydrogen (Furlanetto et al. 2006; Pritchard & Loeb 2012). The 21 cm signal is expected to be observable as both emission and absorption by neutral hydrogen (HI) clouds, relative to the Cosmic Microwave Background (CMB). Recently, the EDGES collaboration claimed to have detected a 21 cm absorption profile centred at 78 megahertz in the sky-averaged spectrum (Bowman et al 2018), although this detection remains unconfirmed. In addition to testing astrophysics, this signal is a probe of cosmology, structure formation and the nature of dark matter.

In this summer project, the student will post-process intermediate-scale (10 and 40 cMpc/h boxes) simulations of cold dark matter (CDM) and fuzzy dark matter (FDM) run with hydrodynamical code AREPO. The student will generate high-redshift 21 cm maps. If time permits, a Generative Adversarial Neural Network (GAN) will be implemented to quickly generate 21 cm maps with the same statistical properties as those from computationally expensive AREPO simulations. Prerequisites: Some basic Python skills will come in handy.

Project 10 Unlocking the properties of dark matter: Using machine learning to identify the tiniest galaxies

Supervisor: Dr Alexandra Amon (alexandra.amon@ast.cam.ac.uk)

Description

Dark matter comprises 85% of the mass in the Universe. It exists everywhere, forming the scaffolding of the Universe, and without it, the galaxy we call home wouldn't exist. It is a cornerstone to our Standard Model of Cosmology, which remarkably describes a plethora of cosmological observations. Yet, we don't know *what* dark matter is: one of the biggest challenges in modern physics. To shed light on this dark entity, a compelling avenue is dwarf galaxies [1], like the Magellanic Clouds. Comprised of relatively high fractions of dark matter compared to 'normal' matter, these tiny galaxies provide mighty potential as a unique probe of the nature of dark matter [2].

Using data from the Dark Energy Survey, a training sample of dwarf galaxies with accurate redshifts and machine learning techniques, we will extract a candidate dwarf sample – potentially constituting the largest catalogue of these unique galaxies. We will measure the weak gravitational lensing signal of the dwarf galaxies – a first detection for the field. Due to the computational nature of this project, some experience using UNIX shells and python programming is advised.

References

1. Bullock & Boylan-Kolchin 2017: Small-Scale Challenges to the LCDM Paradigm
2. Simon 2019: The Faintest Dwarf Galaxies

Project 11 Quantum stability of a novel theory of gravity

Supervisor: Dr Will Barker (wb263@cam.ac.uk)

Description

Einstein's General Relativity (GR) remains the preferred effective theory of gravity as spacetime curvature, explaining the orbital precession of Mercury and solar bending of starlight while underpinning modern cosmology. However, GR does not explain dark matter or dark energy, while an alleged `Hubble tension' indicates that our Universe is expanding 10% faster than it should be. And of course, GR continues to stubbornly resist attempts at (complete) quantum reformulation.

We recently attracted some attention by proposing an alternative theory of gravity as a blend of spacetime torsion and curvature: this appears to provide a cosmological constant and alleviate the Hubble tension. Our Lagrangian is wildly different from that of GR, with a quantum structure suggestive of renormalisability. We believe the theory adopts a torsion vacuum expectation value (VEV) at a primordial epoch, on the back of which the good classical phenomena emerge. However, many quantum/classical aspects of this torsion VEV, and the violent early-Universe physics of its formation, remain shrouded in mystery...

The findings of the project may debunk our theory or, if we are lucky, propel it further into the spotlight of community interest. The student may wish to target one of several new fronts we are opening in our research campaign:

1) *Quantum stability and the infrared* -- This is an urgent question; we don't really know if the torsion VEV is stable against quantum fluctuations, as is the case for the Minkowski vacuum of GR. The student will apply well established effective field theory and ghost condensate techniques to characterise the infrared environment of the VEV. Extensions to the ultraviolet are of course welcome depending on expertise, though expected to be more challenging. A stable vacuum is quite a big deal, while convincing instabilities would seem to rule our theory out: either way this avenue promises high returns.

2) *Cosmological perturbation theory* -- There is a very well established theory dictating how cosmic density perturbations evolve under gravity, which supports GR to amazing precision based on tiny anisotropies in the cosmic microwave background and the clustering of matter on the grandest scales. The student will extract and characterise the classical perturbation equations (and perhaps convenient gauges) around the torsion VEV, matching against GR where possible. This also targets aspects of the infrared environment, but uses classical methods so does not require prior knowledge of QFT. Apart from offering a neat standalone stability test the perturbation theory will facilitate, in the long run (2023), sophisticated Monte Carlo tests against cosmological survey data: to this end a successful student would also have a stake in these future research way points.

3) *Primordial symmetry breaking* -- We imagine that the Big Bang left our gravity theory in a torsionless conformal phase, bathed in the standard model plasma. So how and when does the torsion VEV form in relation to the condensation of the Higgs field? Could this process have driven inflation, the violent expansion thought to have occurred in the very early Universe? A decaying deviation from the torsion VEV just after inflation can alleviate the Hubble tension: what physics sets this initial condition? The student may wish to merely explore these questions using the background cosmology equations, and there is a viable research-grade project at this level. However, depending on interest/experience in electroweak symmetry breaking or effective quantum theories of inflation, we may hope to propose a novel inflationary mechanism.

These topics are not exhaustive and are subject to shift as we study the theory throughout spring 2022.

References

1. For the history of our new theory, skim chapters 2-4/refs therein: https://wevbarker.com/assets/papers/Barker_PhDThesis.pdf
2. For an intro to spacetime torsion, skim the first three chapters: http://alpha.sinp.msu.ru/~panov/LibBooks/GRAV/Blagojevic_M.-Gravitation_and_gauge_symmetries(2002).pdf
3. For ghost condensates and the infrared analysis: https://arxiv.org/abs/hep-th/0312099
4. For more infrared techniques that will apply near the VEV: https://arxiv.org/abs/hep-th/9210046
5. The excellent Les Houches notes on effective field theories: https://arxiv.org/abs/1804.05863
6. For effective field theories of inflation: https://physics.mcmaster.ca/~cburgess/Notes/InflationEFTs.pdf
7. For an intro to cosmological perturbations: https://arxiv.org/abs/hep-th/0306071

Work environment

The student would ideally have a desk at the IoA, or neighbouring Kavli Institute for Cosmology, Cambridge (KICC). We have a small modified gravity nexus belonging to the Cavendish Astrophysics Group, comprising Professors Lasenby and Hobson and myself. The broader environment in the Kavli is dominated by theoretical, observational and statistical cosmologists. The student would be encouraged to take advantage of seminars and networking both at the Kavli and the CMS. There are also opportunities to liaise remotely with astroparticle theorists at CEICO in Prague and at the Instituut Lorentz in Leiden. We have free coffee.

Project 12 Revisiting the spin rate of the supermassive black hole in the radio-loud active galactic nucleus 4C74.26

Supervisors: Prof. Chris Reynolds (csr12@ast.cam.ac.uk) and Dr Dominic Walton

Description

The spin of a supermassive black hole (SMBH) is a window into how the black hole grew and also can be a powerful source of energy for driving relativistic jets. Over the past 15 years, we have developed and honed techniques for measuring the spin of the accreting SMBHs that we find at the hearts of active galactic nuclei (AGN) - these techniques are based on a careful examination of the X-ray spectrum (see Reynolds 2021). The intense X-ray emission that is released in the central regions of an AGN causes the inner accretion disk to emit a set of fluorescent emission lines, and the observed profile of those emission lines in the X-ray spectrum is strongly shaped by relativistic effects (Doppler shifts and gravitational redshifts) that in turn depend on spin. These processes can be modelled and then compared with the real spectra received from, for example, ESA's XMM-Newton observatory and NASA's NuSTAR observatory.

To date, we have measured or constrained the spin of over 30 SMBHs using these techniques. An interesting pattern is emerging. The low-mass SMBHs (with masses less than about 30 million solar masses) are almost all found to be spinning as fast as is permitted by General Relativity. For the more massive SMBHs, we start to find a population of more modestly spinning SMBHs. This in fact is in line with theoretical ideas for how SMBHs evolve (Bustamante & Springel 2019). The lower-mass SMBHs can easily realign themselves with the net angular momentum of accreting matter and hence always tend to get spun up by accretion. The more massive black holes, with their higher moments of inertia, cannot realign and hence accrete matter from random directions causing them to have lower net spin. In order to further test this picture, we need to measure the spin of the most massive black holes we can find.

The quasar 4C74.26 is one of the nearest (redshift $z=0.104$) powerful quasars that also possesses powerful relativistic jets. It is estimated to have a mass of 4 billion solar masses, making it one of the most massive SMBHs in the local Universe. It has been observed by a number of X-ray observatories including XMM-Newton and NuSTAR. Lohfink et al. (2017) has previously examined the spin rate of this black hole, but the limited datasets that were employed (just NuSTAR plus low signal-to-noise Swift/XRT data) plus the relative crudeness of the models that were available at that time prevented strong conclusions from being reached. In this project, we will take a fresh look at the highest-quality data for this AGN using the latest models. Our goal will be to examine the nature of the X-ray emission from the innermost parts of the accretion disk and, if possible, extract robust constraints on the spin of this massive SMBH.

References

1. Bustamante, S., Springel, V., 2019, Monthly Notices of the Royal Astronomical Society, 490, 4133
2. Lohfink A., et al., 2017, Astrophysical Journal, 841, 80
3. Reynolds, C.S., 2021, Annual Reviews of Astronomy and Astrophysics, 59, 117

Project 13 3d kinematics of star clusters in Gaia DR3

Supervisor: Dr Eugene Vasiliev (vasiliev@ast.cam.ac.uk)

Description

Gaia is a space telescope that maps out our Galaxy in exquisite detail, measuring the photometry, positions, parallaxes and proper motions for over a billion stars, and line-of-sight velocities for tens of millions stars. The upcoming third data release (DR3) scheduled for June 13th, among other things, will increase the number of stars with measured line-of-sight velocities nearly five-fold, producing by far the largest and most uniform spectroscopic dataset to date.

In this project, we will scrutinize a tiny fraction of this dataset -- stars in open and globular clusters within a few kpc from the Sun. For the brightest stars in a given cluster, we can measure 5 out of 6 phase-space coordinates (the distance to the entire cluster is also well constrained, but not the spread of distances within the cluster). In particular, the combination of proper motions in the sky plane and line-of-sight velocities allows us to map out the 3d kinematic structure of these systems: velocity anisotropy and rotation. Are younger clusters rotating faster or slower than older ones? Is their 3d rotation axis aligned with the Galactic disc? We will hopefully find answers to these and other related questions in the course of this project.