THESIS ABSTRACTS

The Structure of Extrasolar Planetesimal Belts in Images

By Yinuo Han

Solid bodies in the form of planets and planetesimal belts familiar to us in the Solar System are also a prevalent feature around other stars. Their great diversity highlights a lack of complete theories for how they formed, which is further complicated by observational challenges to understand their full architecture in the first place. Currently, our best observational constraints on the outer planetary system come from imaging the planetesimal belts that populate this region, known as debris discs. As planets dynamically interact with the disc throughout their formation and evolution, structures reflecting their history are imprinted on the disc. In this thesis, I develop systematic and unbiassed methods to recover the three-dimensional structure of debris discs from their images applicable to a versatile range of imaging modes. By removing assumptions on the functional form of the disc structure, this method provides unbiassed constraints on disc substructures with realistic uncertainties that enable us to interpret dynamical interactions shaping the planetary system. I apply this method to a sample of debris discs with resolved imaging to infer general three-dimensional structures of debris discs and their implications for planetary-system formation. For the archetypal edge-on debris disc of β Pictoris, for which multiple epochs of high-resolution mid-infrared and millimetre images are available, I model in detail its vertical structure for different grain sizes and any variations in azimuthal substructures across time, constraining dynamical scenarios that could be shaping the evolution of the system. The approaches developed in this work to model debris-disc structures from images will be important for interpreting upcoming observations with *ALMA*, *JWST*, and the next generation of observatories at high sensitivity and resolution. — *University of Cambridge; accepted 2024 August.*

Constraining Reionization: Evidence from 21-cm Limits Predictions for Fast Radio Bursts

By Stefan Heimersheim

In this thesis, I explore multiple constraints on the properties of early galaxies, the reionization history, and the global 21-cm signal. Specifically, I use upper limits on the 21-cm power spectrum measured by the *HERA* (*Hydrogen Epoch of Reionization Array*) interferometer, current and future measurements of the global 21-cm signal, and forecasts for high-redshift Fast Radio Bursts (FRBs).

Firstly, I examine the influence of cosmic reionization on FRBs. They are recently discovered extra-galactic sources of strong radio signals, and the dispersion measure of these signals is sensitive to the ionization state of the intergalactic medium. (This analysis has previously been done only for specific reionization models; I propose using a model-independent parameterization of reionization.) I employ synthetic data of future FRB measurements at high redshifts, $z > 5$, to show that (*i*) the model-independent method removes a significant bias in the inferred optical depth, and (*ii*) that the observation of high-z FRBs can facilitate direct and model-independent measurements of the reionization history and associated cosmological parameters.

Secondly, I use Bayesian methods for a model-independent parameterization of the sky-averaged 21-cm signal. One of the biggest challenges in that field is identifying the cosmological signal among other systematic contributions and foregrounds. In my work, I compare two model-independent methods to fit the 21-cm signal and to separate out the foregrounds: (*i*) a Gaussian process modelling the foreground-orthogonal component of the data, and (*ii*) a spline-based FlexKnot interpolation utilising Bayesian evidence to find the simplest signal (agnostic of its cosmological or systematic nature) that fits the data. I apply these methods to both a synthetic validation data set and the *EDGES* (*Experiment to Detect the Global EoR Signature*) observations. I find that both methods fully recover the foreground-orthogonal component of the signal and that the FlexKnot method is able to separate the signal from the foreground in the synthetic data. Using this novel analysis I discover a set of four different shapes that can explain the *EDGES* observations, only one of which resembles the originally reported absorption signal.

Finally, I derive constraints on the astrophysical properties of early galaxies using 21-cm power-spectrum observations from the *HERA* telescope. I derive a likelihood function to compare the data with cosmological models, develop a neural-network emulator to speed up the computation of those cosmological models, and analyse the measurements of two *HERA* data releases. I derive constraints on astrophysical parameters based on semi-numerical models, in particular focussing on models with non-standard radio backgrounds. The main constraint I find is that early galaxies cannot simultaneously produce low X-ray and high radio emissions, as such scenarios would produce a signal larger than the upper limits set by *HERA*. — *University of Cambridge; accepted 2024 January.*

Unveiling Fundamental Physics with High-Resolution X-Ray Spectroscopy of Active Galactic Nuclei

By Júlia M. Sisk-Reynés

This doctoral thesis explores the use of high-resolution spectroscopy of active galactic nuclei (AGNs) to probe fundamental physics. It focusses on the study of axion-like particles (ALPs) and the spin of supermassive black holes (SMBHs).

Chapter 1 starts with a review of black holes as mathematical and astronomical objects and provides an account of the knowledge of the physics of the accretion flow onto SMBHs in AGNs as revealed by X-ray observations of AGNs. This is followed with a discussion on the use of X-ray reflection spectroscopy as a probe of the spin of moderately accreting SMBHs, and the use of spin diagnostics to probe the growth of SMBHs over cosmic time-scales. Summaries of the Standard Models of cosmology (or the ΛCDM paradigm) and particle physics are provided. Evidence of the need for physics beyond the Standard Model