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

(BSM) is presented. This introductory chapter concludes by highlighting the role of ALPs as generic predictions in BSM theories and as compelling dark-matter candidates and is accompanied by a description of plausible techniques towards their detectability with astronomical sources.

Chapter 2 begins our discussion on astrophysical ALP searches by presenting the tightest bounds to date on the coupling of light ALPs to electromagnetism based on a spectral analysis of high-resolution archival *Chandra*/Grating observations of the luminous cluster-hosted quasar H 1821+643.

Chapter 3 provides an exploration of how the next-generation *Athena* X-ray flagship observatory will improve on the current most sensitive limits presented in Chapter 2. A promising technique to mitigate the effect of previously ignored systematic uncertainties is discussed. ALP projections from the *AXIS* probe-class concept proposed to NASA for a 2032 launch are also introduced.

The future of ALP searches with upcoming missions is encouraging due to advances in detector technology. These advances include improvements in effective area, spatial resolution, and spectral resolution when compared with current observatories. In future, probing light ALPs with observations of bright AGNs located at the centres of rich clusters may be the only plausible observational test of string theories and will complement the search for ALP dark matter at light ALP masses.

Chapter 4 presents the application of state-of-the-art X-ray reflection models on the *Chandra* spectral view of H 1821+643 introduced in Chapter 2, pointing out that its colossal, central SMBH is rotating at moderate speeds. This chapter concludes by presenting the observed population of SMBHs whose spin has been estimated from such models.

The observed population seems to feature two sub-populations: a population of low-mass SMBHs with maximal-to-extreme spins and a high-mass population of SMBHs whose spins cluster at moderate values. This notion is aligned with the predictions of semi-analytic and numerical models of hierarchical structure formation and black-hole evolution over cosmic time-scales. Therefore, assessing this hypothesis with Bayesian statistics may eventually help confirm what drives SMBH growth over cosmic time-scales and help distinguish between the relative importance of growth powered by coherent and incoherent accretion and SMBH–SMBH mergers.

Chapter 5 presents closing remarks and outlines possible future research directions. — *University of Cambridge; accepted 2024 July.*

Here and There

THE PANDEMIC WAS RESPONSIBLE FOR MORE THAN WE THOUGHT

A few weeks later, I flew to CERN for the first time after the pandemic had begun to present our results to the outside world. — *Space Oddities* (Picador). p. 193, 2024.