Scientific interests and future research plans

Introduction and summary: The last few decades have witnessed several rapid advances in the field of observational cosmology. Today, we have probes of the universe over a wide range of wavelengths from the radio to the gamma-ray bands, as well as – recently – in the gravitational wave regime. The wealth of observational data has led to the development of **precision cosmology**, whereby the cosmological parameters may be measured to unprecedented accuracy with the available data. The fact that all the independent observational constraints are consistent with the 'standard model' of theoretical cosmology, known as ΛCDM, is one of the most impressive successes of the theory.

However, the standard model of cosmology also leaves us with several challenging problems. About 70% of the present-day energy density of the universe is in the form of 'dark energy', which behaves like a smooth fluid having negative pressure, and leads to the accelerated expansion of the universe. This component is consistent with a cosmological constant term introduced in Einstein's equations. Another 25% is in the form of 'dark matter' – which does not interact with radiation, but participates in gravitational clustering. We do not have a physical understanding of (or laboratory evidence for) either of these two components, which together comprise about 95% of the present-day universe. Only the remaining approximately 5% of the energy density is in the form of ordinary matter (with a tiny amount in the form of radiation), whose physical properties are familiar to us.

A key aspect of observational cosmology consists of tracing the evolution of this ordinary matter (known as baryonic material) in the universe. Being directly accessible to observations, this component is especially important as a probe of dark matter and dark energy. Radiation decoupled from the neutral baryonic matter in the first major phase transition of the observable universe known as the **epoch of recombination**, which occurred about 300,000 years after the Big Bang when the universe was about 1000 times smaller than the present. This primordial radiation is observable today as the cosmic microwave background (CMB). Most of the baryonic material in the universe was (and is) in the diffuse plasma and gas between galaxies, known as the **intergalactic medium (IGM)**. At the end of the epoch of recombination, the baryonic matter in the universe was almost fully hydrogen, in its electrically neutral, gaseous form (known as neutral hydrogen, referred to as HI, as commonly done in the literature), with small ($\sim$ 10%) amounts of neutral helium and remained so (a period known as the **dark ages of the universe**) until the first stars and galaxies formed about a few hundred million years later. These luminous sources contributed ionizing photons and completed the *second major phase transition* in the observable universe known as *cosmic reionization*. In this process, the radiation from starlight was responsible for ionizing the hydrogen in the universe – and this period, which lasted for about a few hundred million years, is referred to as the **Cosmic Dawn**. Mapping the period between Cosmic Dawn and the present-day provides access to more than 90% of the Universe's baryonic (normal) matter, and unlocks almost all the information in cosmological baryons.

It is therefore obvious that a precise understanding of cosmology and fundamental physics in the future will come only through the study of the baryonic gas tracers of the Universe, the majority of which lie between the local universe probed by galaxy surveys, and the CMB surface of last scattering. This allows access to almost three orders of magnitude more information than currently available from the combination of galaxy surveys (which extend only to the edge of the local universe), and the CMB. In the last several years, a tremendous effort to revolutionise our understanding of cosmology from baryonic gas is bearing fruit. The neutral hydrogen of the intergalactic medium (at the epoch of Reionization and Cosmic Dawn) is chiefly probed using its 21 cm spin-flip transition, which manifests in the radio band. After reionization, neutral hydrogen exists in the form of dense clumps in galaxies, and extremely dense systems known as Lyman-limit systems and Damped Lyman-Alpha systems (DLAs). The carbon monoxide (CO) molecular abundance also offers exciting prospects for placing constraints on the global star-formation rate, which is observed to peak around 2 billion years after the Big Bang. The technique of intensity mapping (IM) has emerged as the powerful tool to explore this phase of the Universe by measuring the integrated emission from sources over a broad range of frequencies, providing a tomographic, or three-dimensional picture of the Universe. Notably, this is being complemented by large scale efforts to probe the first galaxies and black holes by using the combined power of the electromagnetic and gravitational wave bands. We are thus on the threshold of the richest available cosmological dataset in the coming years, facilitating the most precise constraints on theories of Fundamental Physics.

My research uses a unique combination of analytical, statistical and simulation tools suited to extract the maximum information from the multi-messenger data from the Cosmic Dawn to the present day. Through my collaborations with the Square Kilometre Array (SKA), the CO Mapping Array Pathfinder (COMAP), the Cosmic Visions 21 cm, GBT-Parkes, AtLAST, and the Murchinson Widefield Array (MWA), this will enable us to:

- develop a consolidated set of key astrophysical variables parametrising baryonic gas, by combining intensity mapping observations with galaxy survey data extending to the epoch of Reionization,
- couple this framework with gravitational wave observations to constrain the formation history and properties of the first black holes, and

- use the theoretical tools thus developed to obtain the best possible constraints on fundamental physics (dark matter, dark energy, theories of gravity and the Universe's earliest moments) using the largest observational datasets.

My research program is split into the following three broad themes, which can together achieve the above goals:

► **A holistic framework for cosmology with baryonic tracers – all the way up to Cosmic Dawn.**

Hydrogen is the most abundant element in the universe and as such, mapping the evolution of neutral hydrogen (HI) across cosmic time promises important insights into galaxy evolution, as well as theories of gravity and fundamental physics. In the post-reionization era of the Universe (the last 12 billion years; redshifts 0 to 5), HI exists chiefly inside galaxies.

Traditionally, galaxy surveys have been used as probes of the neutral hydrogen distribution (Zwaan et al., 2005a; Martin et al., 2010; Zwaan et al., 2005b) at late times. The limits of current radio facilities, however, hamper the detection of 21-cm in emission from normal galaxies at earlier times. At these epochs, the HI distribution has been studied via the identification of DLAs (e.g., Noterdaeme et al., 2012; Crighton et al., 2015; Zafar et al., 2013) — which are known to be the primary reservoirs of neutral hydrogen.

Intensity mapping with HI: A novel technique used to study HI evolution is known as *intensity mapping* (IM). In this technique, the large-scale distribution of a tracer (like HI) can be mapped without resolving the individual galaxies which host the tracer. Being faster and less expensive than galaxy surveys, IM has been a rapidly emerging cosmological probe over the last decade (e.g., Chang et al., 2010; Loeb & Wyithe, 2008; Anderson et al., 2018; Wolz et al., 2022). Since IM probes three dimensional volumes, it will access at least four orders of magnitude more modes of information than current surveys (Loeb & Zaldarriaga, 2004), dramatically improving the precision of cosmological measurements. Moreover, its wide redshift coverage helps break degeneracies between cosmological parameters, while its access to large scales allows the extraction of information about physics on the scale of the cosmological horizon (Karkare et al., 2022; Bernal & Kovetz, 2022; Kovetz et al., 2019).

Thus, the three main probes of HI over the last 12 billion years are galaxy emission surveys, intensity mapping experiments and DLA observations. Though there have been several studies (e.g., Bagla et al., 2010; Barnes & Haehnelt, 2014) that model these datasets separately, it is important to *unify* the data into a self-consistent framework that addresses both high- and low-redshift observations. Such a framework, which encapsulates the astrophysical information into a set of key physical parameters, is crucial to properly take into account the astrophysical uncertainties in order to use IM for constraining models of fundamental physics and cosmology.

I have been leading a research program aimed at filling this gap.

I have developed (Padmanabhan & Refregier, 2017) a data-driven halo model framework for the evolution of HI covering the past 12 billion years. This built upon my previous work analyzing the different datasets available (e.g. Padmanabhan et al., 2015a), and bringing together the models available in the literature (Padmanabhan et al., 2016). In a map of unresolved HI emission over a large area in the sky, the main quantity of interest is known as the *power spectrum*. Denoted by $P_{\mathrm{HI}}(k,z)$, it is a measure of the strength of intensity fluctuations as a function of wave number (k), and is sensitive to both the underlying cosmology as well as the astrophysics of HI in the galaxies. Incorporating all the available data into a consistent data-driven framework, as I did for the first time in Padmanabhan, Refregier & Amara (2017), allows us to precisely separate both these aspects and make predictions for future surveys (Padmanabhan, Refregier & Amara, 2019). *It is crucial to note that these astrophysical forecasts would not have been possible without the input from the halo model I developed and which can be refined further using all the available data.* Being highly versatile, this framework is being extensively used in the community to model and interpret 21 cm observations. The novel approach allows us to construct large statistical samples of mock galaxies, include the effects of many models, and impose the most realistic priors conveniently within a Fisher matrix analysis.

Recently, the MeerKAT collaboration released its *first ever autocorrelation results* of the 21 cm signal of neutral hydrogen, covering redshifts 0.32 and 0.44 (Paul et al., 2023). These results extend the previous ones down to an order of magnitude smaller scales, thanks to the power of interferometry. In Padmanabhan et al. (2023), we describe, for the first time, the analytical framework to include the effects of redshift-space distortions in the baryonic halo model power spectrum, and provide comparisons to the MeerKAT results.

This technique has an extremely wide applicability. There are also exciting prospects for making intensity maps of molecular lines, like the carbon monoxide (CO) line. CO behaves as a tracer of molecular hydrogen, which has no permanent dipole moment due to symmetry and thus no rotational transitions of its own. The CO line corresponding to the transition between rotational quantum numbers J and $J-1$ has a rest frequency of approximately $J \times 115.27$ GHz, making it an ideal target in the microwave regime. It is easy to separate the signal from contaminants due to its multiple emission lines (with different values of the angular momentum quantum number J) which have a well defined frequency relationship, a feature that is not available to other tracers. CO observations are very sensitive to the spatial distribution of star formation. Observations made using the Karl G. Jansky Very Large Array (JVLA) and the Atacama Large Millimeter Array (ALMA) have recently shown that line emission from the CO transitions will be bright even at high redshift, $z > 6$. The levels of foreground contamination in a CO survey are also much lower than for many other types of line intensity mapping, making it a promising target for ground-based observations.

I am a member of the CO Mapping Array Project (COMAP) collaboration[1], which aims to use CO intensity mapping to trace the global properties of galaxies across cosmic time back to the Epoch of Reionization.

In November 2021, the COMAP Pathfinder (whose science observations began in 2019 using the 10.4 metre Owens Valley Radio Observatory dish in the 26-34 GHz regime) released the *first direct 3D measurement* of the CO power spectrum on large scales (Cleary et al., 2022), nearly an order of magnitude improvement compared to the previous best measurement (Keating et al., 2020).

My research (Padmanabhan, 2018) had incorporated for the first time the different CO observational constraints in a consistent manner into a halo model framework. My analysis formed the basis of an updated model (Chung et al., 2022) developed by the COMAP team for the analysis and interpretation of their intensity mapping observations, allowing for stringent constraints on the evolution of the cosmic molecular gas density.

The gas distribution in galaxies and their environments is strongly connected to the physics of galaxy evolution. Comparing data-driven models to semi-analytical and hydrodynamical simulations – as we explored in Padmanabhan & Kulkarni (2017); Padmanabhan & Loeb (2020a) allows us to evaluate, for the first time from the data, the relative contribution of accretion and mergers to the evolution of the star formation history by developing baryonic merger trees, that form a basis for calibrating future simulations. This will shed light on several outstanding questions, such as:

- *What is the role of cold gas in star formation?*
- *What processes (known as 'feedback') lead to cessation of star formation in galaxies?*
- *Is there evidence for 'missing physics' in current hydrodynamical simulations of galaxy evolution?*

The synergy is greater than the sum of its parts. My future work will involve cross-correlating the galaxy and gas content data from the results of CO, HI and optical surveys, using the datasets from large- scale experiments like the DESI and Euclid, and the precursors of the SKA. This promises much more stringent constraints on the astrophysical and cosmological parameters than correlating galaxies with galaxies, as we showed for a Canadian Hydrogen Intensity Mapping Experiment (CHIME)-like survey cross-correlated with a Dark Energy Spectroscopic Instrument (DESI)-like Emission Line Galaxy (ELG) galaxy survey (Padmanabhan et al., 2020). Notably, this improvement occurs in spite of the fact that the redshift coverage of the cross-correlation is only about half that of the CHIME-like autocorrelation survey, illustrating that adding the galaxy survey information will significantly aid the interpretation of results from intensity mapping surveys.

► **What is the way forward for theoretical modelling of reionization?**

The epoch of *Cosmic Dawn*, where the first stars and galaxies were born, is often called the 'final frontier' of cosmological surveys to astronomers. It signals the start of cosmic reionization, the second major phase transition of nearly all the normal matter in the universe. Reionization is characterized by the development of ionized regions (known as 'bubbles') around the first luminous sources, and the end of reionization is marked by the complete overlap of these bubbles. The distribution of the bubble sizes leads to fluctuations in the HI density field, and thus in the signal observable with future 21 cm experiments. Hence, understanding the distribution of these ionized bubbles (e.g., as we did in Paranjape et al. (2016)) is crucial for modelling the observable signal. On the observational front, the SKA will be able to image these ionized bubbles at Cosmic Dawn – and the European Southern Observatory (ESO)'s facilities will provide constraints on the galaxies responsible for the ionization.

An outstanding question related to reionization is the origin and growth of the earliest black holes in the universe. Observations have revealed the presence of billion-solar-mass supermassive black holes (SMBHs) just hundreds of millions of years after the Big Bang, posing strong challenges to theoretical models of their formation. Two main

[1] http://comap.caltech.edu

parameters governing the fuelling and growth of SMBHs are (i) their Eddington ratio and (ii) their active lifetime of accretion, the latter of which makes the SMBH observable as a quasi-stellar object (QSO) or quasar.

Intermediate-mass black holes (IMBHs), with masses between a hundred and a million solar masses, are often referred to as the "missing-link" in black hole formation scenarios. An important fuelling mechanism for IMBHs are so-called tidal disruption events (TDEs), in which a star, passing too close to the black hole gets ripped apart by its gravity. We used the latest quasar abundance measurements and models of the TDE phenomenon, to find that TDEs could be a salient source fuelling IMBH at early times (Padmanabhan & Loeb, 2021b).

Furthermore, the properties of the earliest SMBHs can be well constrained through their gravitational wave emission detectable by the next-generation Laser Interferometer Space Antenna (LISA) instrument and the Square Kilometre Array Pulsar Timing Array (SKA PTA, Padmanabhan & Loeb (2020c, 2023). Particularly, for the most massive SMBHs (of 10 billion solar masses), we show that a *unique* quasar should be localisable by electromagnetic follow-up to the SKA detection. The presence of the black holes at the centres of high-redshift galaxies can be inferred from their radii of influence, which is found to be *directly resolvable* by current and upcoming telescopes (Padmanabhan & Loeb, 2020b) during the period of reionization.

Determining the relative contributions of luminous sources (galaxies and quasars) to reionization remains an open question in the field. We showed that tight constraints could be placed on the temperature evolution (Padmanabhan et al., 2015b) of the intergalactic medium, which is directly related to the contribution of quasars to reionization (Padmanabhan et al., 2014). Recently, some extremely luminous galaxies have been detected close to the epoch of reionization, some of which show evidence for so-called double-peaked line profiles in the Lyman-alpha line. This is rare among high-redshift galaxies (e.g., Gronke et al., 2020), as the increasing neutral fraction in the intergalactic medium (Hu et al., 2010) almost always leads to the resonant absorption of the blue wing of the line at these epochs. In our recent paper (Padmanabhan & Loeb, 2021a), we pointed out a novel scenario for the ionization zones around these galaxies being created by obscured quasars, whose intrinsic Lyman-alpha line is blocked by the effect of obscuration.

My invited review article on this topic, titled 'A multi-messenger view of Cosmic Dawn', for the Special Issue of the International Journal of Modern Physics D (IJMPD) was published in November 2021 (Padmanabhan, 2021).

There are very good prospects for investigating reionization using molecular lines. The CO molecular spectrum has a 'ladder' of states, and hence the CO 1-0 line from the epoch of Galaxy Assembly, $z \sim 2-3$, also contains a contribution from the CO 2-1 line from $z \sim 6-8$, the mid to late stages of reionization. One of my chief modelling aims with COMAP is to probe large-scale structure during the Epoch of Reionization. The subsequently planned phases of COMAP (COMAP-EoR and COMAP-ERA) involve cross-correlating the signal in two frequency bands to isolate the signal coming from the Epoch of Reionization. *I am a member of the modelling team* involved in this effort, whose latest forecasts predict a detection (Breysse et al., 2021) of the Reionization signal at high significance for the COMAP-EoR survey over $z \sim 6-8$. It allows us to place very tight constraints on the cosmic molecular gas density where there is a significant contribution from faint galaxies *that would otherwise be missed by current and future galaxy surveys*, re-iterating the unique ability of line intensity mapping to constrain the properties of the earliest galaxies.

In addition to the CO transitions, a particularly exciting frontier of recent research involves the lines of singly ionized carbon [CII] and doubly ionized oxygen [OIII]. In Padmanabhan (2019), I extended my data-driven halo model approach for CO to the [C II] (158 μm) line emission, for constraining early star formation history with various instrumental configurations, including the ALMA. This model has been extensively employed by the EXCLAIM (Experiment for Cryogenic Large-Aperture Intensity Mapping, a balloon based facility) for forecasting constraints on cosmology and astrophysics from intensity mapping at $z \sim 3$ (Pullen et al., 2022).

In Padmanabhan et al. (2022), we explored the potential of intensity mapping surveys in [CII] and [OIII] based on the EXCLAIM and the FYST (Fred Young Submillimetre Telesope, a ground-based facility) experiments, finding detection significances of several tens of sigma for a designed experiment aiming to unravel the properties of star-forming galaxies at the epoch of reionization. Such sub-millimetre experiments, in cross-correlation with the Murchinson Widefield Array (MWA), can leads to a significant detection of the 21 cm power spectrum at reionization (Padmanabhan, 2023). With the MWA collaboration, I envision novel project efforts synergizing future 21 cm surveys with observations of individual high-redshift galaxies from ALMA (selected in CO and [CII]), and the forthcoming AtLAST survey which I recently joined. A schematic summary of the constraints expected from current and future experiments is provided in Figure 1.

- **How can we extract fundamental physics from the Cosmic Dawn?**

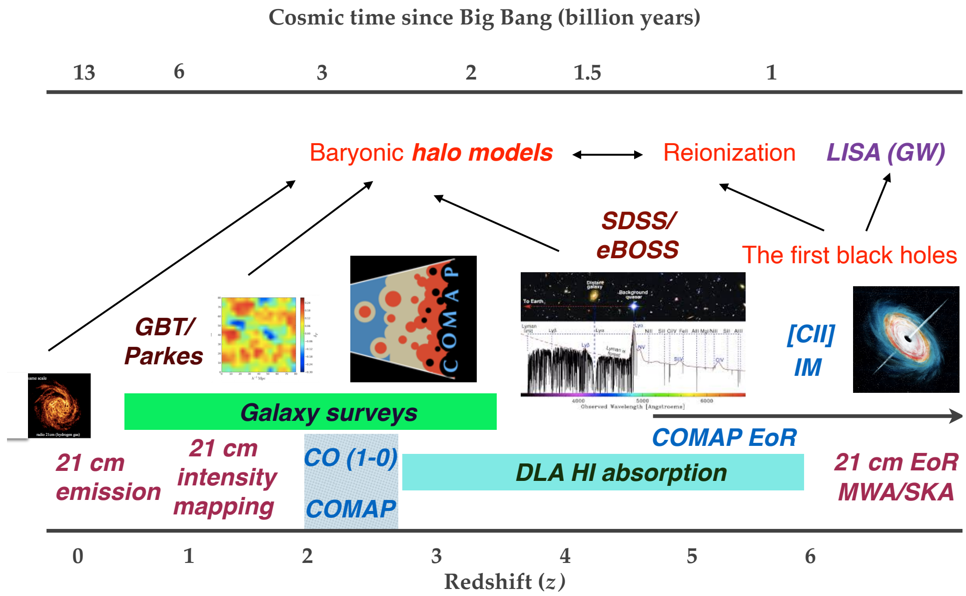

Figure 1: Summary of the redshift ranges constrained by the different types of observations.

Although the standard model of cosmology (i.e. ΛCDM), has become fairly well established over the last decade, from a theoretical point of view, several outstanding questions remain to be answered in the context of this model, of which the chief ones are: (i) the nature of dark matter, (ii) the nature of the late-time accelerated expansion of the cosmos, often attributed to dark energy, and (iii) the mechanism responsible for generating the primordial perturbations that led to structure formation, which is believed to be connected to an early inflationary epoch of the Universe.

We can use intensity mapping to answer fundamental physics questions about the nature of dark matter, dark energy and the Universe's earliest moments. In Padmanabhan et al. (2019), we examined the relative degradation in the precision of cosmological forecasts in the presence of astrophysics, on which realistic priors could be imposed from the HI halo model. In Camera & Padmanabhan (2020), we examined, for the first time, the complementary problem, viz. how much the uncertainty in our astrophysical knowledge causes a bias in the accuracy of cosmological measurements using the nested likelihoods framework. As a bonus, we found that this technique readily incorporates effects beyond the standard ΛCDM framework into the halo model - such as a non-zero primordial non-Gaussianity effect imprinted on the power spectrum (a stringent test of theories of inflation) as well as *deviations from Einstein's general relativity* on the largest scales.

The nature of dark matter (DM) also continues to be a mystery. One candidate for a significant fraction of DM are axions, which occur in many extensions of the standard model (Peccei & Quinn, 1977; Weinberg, 1978). In Bauer et al. (2021), we used my halo model to explore the effects of axion DM in the mass range of 10^{-32} to 10^{-22} eV on the 21 cm power spectrum at $z \leq 6$. For the first time, we were able to forecast the bounds on the axion fraction of DM in the presence of astrophysical and model uncertainties, achievable with upcoming facilities such as the SKA.

Having the formalism in place to model baryonic gas and galaxies up to the epoch of Cosmic Dawn, opens up the exciting possibility of realistically addressing fundamental physics questions from a thorough understanding of the astrophysics. This is crucial since an inadequate modelling of the astrophysics can indicate false inconsistencies in different data sets and lead us to incorrect conclusions, like e.g., new physics. Electromagnetic counterparts of the sources of gravitational waves from Pulsar Timing Arrays and LISA (e.g., Padmanabhan & Loeb, 2023, 2020c) promise independent measurements of cosmological parameters from the highest redshifts, which can, in turn, be confirmed by 21 cm surveys in the future. I *recently co-led* the SKA white paper on Fundamental Physics with the Square Kilometre Array (Weltman et al., 2020), which examines how the SKA will deliver unprecedented constraints that can transform our understanding of cosmology and astrophysics.

Measuring the dipole of the large-scale structure, traced, e.g., by galaxies, and its deviation from that of the Cosmic Microwave Background (CMB) is an important test of the isotropy of the universe and hence, the cosmological principle. Our recent work (Nadolny et al., 2021) shows that the intrinsic dipole may be disentangled from the kinematic dipole arising due to our motion, using a large catalog of radio sources such as with SKA-like surveys in the coming years. This important test of fundamental physics can thus be refined with future large datasets. I have also worked on the *weak lensing* of the CMB from gravitational waves (Padmanabhan et al., 2013; Pal et al., 2014) and large-scale structure in the universe.

As an aside from doing more observationally-oriented cosmology, I have also made an excursion into a fundamental physics problem during my research! My work with T. Padmanabhan provides a possible solution to the cosmological constant problem by relating it to the flow of cosmic information across the evolution of the universe (Padmanabhan & Padmanabhan, 2017)– which comes about naturally in the emergent paradigm of gravity (e.g., Padmanabhan & Padmanabhan, 2014). These ideas have received the Honorable mention at the Gravity Research Foundation awards for Essays on Gravitation three times, in 2013, 2016 and 2017.

To summarize, the time is ripe for using the wealth of observations being generated by cosmological surveys to address major unresolved questions in theoretical physics. Through my involvement in the collaborative teams, I hope to develop adequately detailed theoretical tools to extract astrophysics and physics constraints from these exciting measurements, especially at the epoch of Cosmic Dawn. I look forward to making substantial contributions to the observational efforts of the SKA and its pathfinders, with close connections to complementary observations with optical facilities and multi-messenger astronomy. A precise description of the astrophysics will place us in an extremely strong position to utilize cosmological observations to constrain fundamental physics, such as the nature of dark matter and dark energy, with a view towards connecting up with a quantum theory of gravity.

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