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Snowmass 2021 Cosmic Frontier 5 Topical Report
Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before

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EXECUTIVE SUMMARY

The early universe is a unique and powerful tool for fundamental science. From the validation of "Big Bang cosmology" to precision measurements of our cosmological model, studies of the early universe have transformed our understanding of high energy physics. This report summarizes the major themes arising from activities of the Snowmass CF5 working group. The envisioned timeframe is 2025-35 with an eye towards 2035–50.

The scientific goals fall broadly into two categories.

- The first category is the topic of inflation where the goals are to discover/constrain the amplitude of inflationary gravitational waves (r), make precision measurements of the shape of the primordial matter power spectrum and its gaussian/non-gaussian statistics, and to test for deviations from the scale invariant spectrum of inflationary gravitational waves.
- The second category is the discovery of new physics via precision measurements of relic radiation. In the Standard Model, the only relic radiation apart from photons is the Cosmic Neutrino Background, which has a precisely predicted energy density. Thus, measuring any signal that differs from the predicted CNB would be an unambiguous discovery of new physics.

The envisioned research activities for 2025–35 fall into two directions: major facilities and enabling capabilities. Major facilities for this decade will drive transformational impact through searches for r, primordial features and statistics, and searches for the stochastic background of primordial gravitational waves. These facilities include:

- constructing and operating the CMB-S4 experiment,
- operating and upgrading existing gravitational wave observatories (LIGO), and
- developing, constructing and operating a new Wide-Field Multi-Object Spectroscopic survey.

Research into enabling capabilities includes:

- Research into theory with a program that is aligned with the major facilities described above and encompasses a continuum of research including: theoretical model building, predicting and calculating new observable phenomena, modeling and simulating astrophysical and cosmological signals, and building analysis pipelines.

- Investing in new technologies to provide the needed technical foundation to execute the next major facilities in 2035+. These technologies include developing new CMB detectors and instrumentation; developing new technologies for future gravitational wave observatories (e.g. CBE); and developing technologies for long-wave intensity mapping surveys including 21-cm and mm-wave. This technology development will include fielding smaller-scale instruments to provide a staged approach to developing the needed technical maturity for executing a major survey in the next decade.

The research program described in this report is ambitious, which reflects the excitement and discovery potential of early universe studies.

1 Introduction

Fourteen billion years ago, the Universe began, generating particles and planting the seeds that would later develop into the galaxies and large scale structure we measure today. During the first fraction of a second, the Universe conducted most extreme high-energy physics experiment ever. That experiment provides us with a unique window on two important areas of interest: inflation and particle relics from the Hot Big Bang.

Inflation — The leading paradigm to describe the first moments is inflation, characterized by rapid, accelerated expansion at energies potential as high as the scale of grand unification. The violent expansion generates gravitational waves and imprints specific features in to the primordial density field. This report presents observational targets for three important signatures of inflation: primordial gravitational waves, primordial non-Gaussianity, and primordial features. If we detect these graviational waves, we will have indirectly observed quantum fluctuations in the spacetime metric and thus the quantum nature of gravity. We will have learned about high-energy physics more generally, for example, by constraining axion physics and moduli, the fields that control the shapes and sizes of the internal manifolds in string theory. In additional, primordial features and non-Gaussianity reveal the dynamics, particle content and interactions that govern the inflation epoch. Combining theoretical advances, new analysis techniques, and tremendous increases in raw sensitivity, upcoming and planned surveys offer the potential for dramatic discoveries about the nature of cosmic acceleration in the very early universe, and will probe physics on the smallest scales and at the highest energies.

Relic Radiation — Many well-motivated extensions of the Standard Model (SM) predict the existence of yet-unknown relic radiation (e.g. light species, gravitational waves, axions). The hunt it is more than a blind search. Many models that aim to explain the physics of the dark sector, address the strong CP problem, solve the hierarchy problem, and account for short baseline neutrino anomalies share a feature. Each contains new

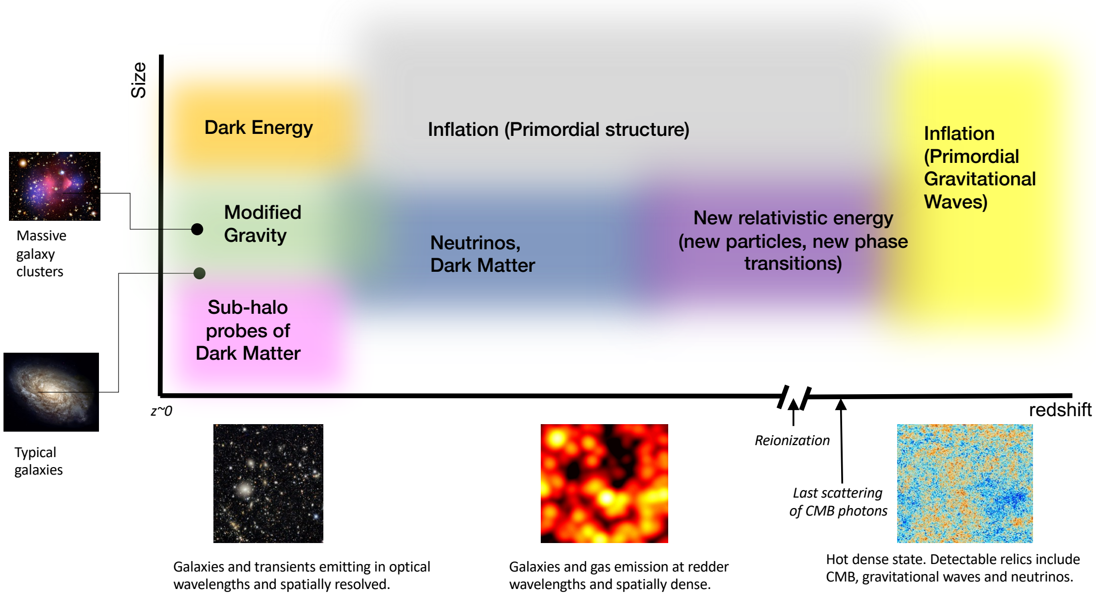

Figure 1: The nature of gravity, Dark Matter, inflation, and Dark Energy can be explored using cosmological surveys spanning different ranges in redshift (x-axis) and spatial scale (y-axis). Physics associated with the early universe (e.g. inflation and relics) can be explored with high redshift techniques (e.g. CMB, GWO) and large volume galaxy surveys.

light degrees of freedom that upcoming cosmological observations can detect or severely constrain. In addition, phase transitions associated with symmetry breaking at a variety of energy scales may generate gravitational waves measurable by next-generation observatories.

Measurements of inflation and light relics follow three broad classes of complementary observations: Cosmic Microwave Background (CMB) surveys, measurements by Gravitational Wave Observatories (GWOs), and Large Scale Structure (LSS) surveys. For inflationary gravitational waves in the nearer term, CMB measurements can detect the signature in the B-mode polarization power spectrum. In the longer term, GWOs can probe the waves directly and constrain or measure the gravitational-wave amplitude (a probe of inflation's energy scale) and shape of the spectrum (a probe of the particular inflationary model). Interactions during inflation leave evidence in the non-gaussianity of primordial fluctuations. The CMB records the two-dimensional projection of the fluctuations, while three-dimensional LSS surveys will likely deliver large improvements in the constraining power, in particular with optical galaxy surveys and line intensity mapping (in 21 cm or other lines). For early-Universe, light-relic particles outside the standard model, CMB and LSS measurements provide indirect probes via the shape of the power spectra. GWOs can directly probe a gravitational-wave component generated during phase transitions.

In the near term, we would target large surveys that are technically ready and have an established track-record of success: CMB (CMB-S4), LSS (DESI, LSST, WFMOS), and GWOs (LIGO/Virgo). This generation of experiments will make definitive measurements of or constraints on the amplitude of gravitational waves from inflation, and place interesting constraints on the abundance of light relics. In parallel with this large survey program is an R&D program advancing new technologies to further these goals beyond 2035, in particular in new measurements of LSS via line intensity mapping and next generation GWOs. In concert and aligned with this experimental program is a research program across theory, computing, and analysis.

2 Inflation

2.1 Introduction

The current leading scenario for the origin of structure in our Universe is cosmic inflation, a period of accelerated expansion prior to the hot big bang, as discussed in the dedicated Snowmass 2021 White Papers [1, 2], also see [3, 4]. Quantum fluctuations during inflation were blown up to large scales, and manifest as density perturbations in the hot particle plasma that followed – these perturbations are visible in the primordial power spectrum. Eventually, the density perturbations developed into the structure (galaxies, clusters of galaxies, the cosmic web) in the Universe today. If gravitational waves from inflation are measured in the CMB B-mode spectrum at the level achievable by CMB-S4, inflation would have occurred near the energy scale associated with grand unified theories, thus a detection would provide evidence for quantum gravity and new physics at energy scales far beyond the reach of any terrestrial collider experiment.

Inflation is defined by two fundamental properties. First, it is a period of of nearly exponential expansion, such that the expansion rate $H(t) = \dot{a}/a$ is nearly constant, $|\dot{H}| \ll H^2$. Second, inflation includes a physical degree of freedom that behaves a clock, effectively telling the universe when to end inflation. Like any clock, it is subject to errors from quantum fluctuations giving rise to the density fluctuations.

The physics of inflation is characterized by energy scales that are relevant for various physical processes, illustrated in Figure 2. In practice, what we observe are dimensionless ratios involving the Hubble scale during inflation, H, and these other physical scales. Measurements to date determine the scale of the background evolution f, which in the case of conventional slow roll inflation is given by speed of the background scalar field, $f^2 = |\dot{\phi}|$. The spectral tilt, n_s, encodes the time evolution of inflationary parameters such as $\epsilon \equiv -\dot{H}/H^2 \ll 1$.

Future probes of inflation can be roughly characterized by three new scales that are parameterized by the variables, $A_{\rm t}$, $f_{\rm NL}$ and $A_{\rm lin}$. The first parameter, $A_{\rm t}$, is the amplitude of primordial gravitational waves and is typically fixed in terms of H and the Planck scale, $M_{\rm pl}$,

$$A_t = \frac{1}{2\pi^2}\frac{4H(t_\star)^2}{M_{\rm pl}^2} \tag{1}$$

where $t_\star$ is a reference time (which is usually translated to a pivot scale $k_\star$ by $k_\star = a(t_\star)H(t_\star)$). This parameter is often expressed in terms of the tensor to scalar ratio, $r \equiv A_t/A_s$. In conventional slow-roll, $f^4 = -2M_{\rm pl}^2\dot{H} = \dot{\phi}^2$, $3H^2M_{\rm pl}^2 \approx V(\phi)$, and $r =$

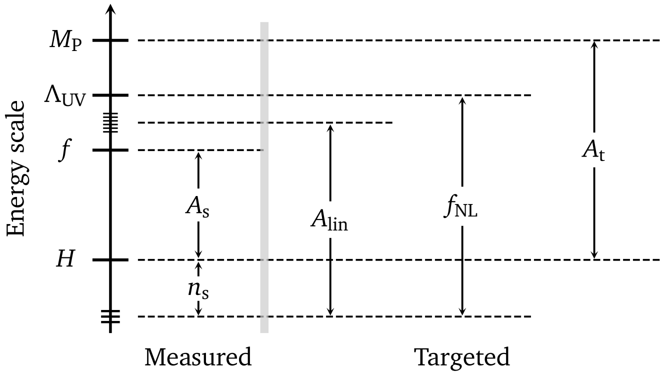

Figure 2: Energy scales relevant to inflation. Reproduced from [5].

$-16\dot{H}/H^2 = 16\epsilon$.

The second parameter, $f_{\rm NL}$, is the amplitude of primordial non-Gaussianity associated with a particular three-point function, or bispectrum. Non-Gaussianity is a direct reflection of the mechanism of inflation, particle content, and interactions during the inflationary era that can be inferred from the amplitude of the particular non-Gaussian 'shapes' in the bispectrum. Deviations from non-Gaussianity come in many shapes, and the amplitudes of three typical shapes are given by $f_{\rm NL}^{\rm loc}$ (local shape), $f_{\rm NL}^{\rm eq.}$ (equilateral shape), and $f_{\rm NL}^{\rm ortho.}$ (orthogonal shape), described in more detail below.

The third parameter, $A_{\rm lin}$, is a characteristic scale of features in the inflationary power spectrum (and/or higher point correlators). This is a signal of the breaking of scale invariance, which indicates that there is a characteristic time-scale associated with inflation beyond f. The precise form of the features encodes the physics responsible.

2.2 Observable – Amplitude of Primordial Gravitational Waves: $r \equiv \frac{A_{\rm t}}{A_{\rm s}}$

During inflation, quantum fluctuations were imprinted on all spatial scales in the Universe. These fluctuations seeded the density perturbations that developed into all the structure in the Universe today. While there are still viable alternative models for the early history of the Universe, the simplest models of inflation are exceptionally successful in describing the data.

Tantalizingly, the observed scale dependence of the amplitude of density perturbations has quantitative implications for the amplitude of primordial gravitational waves, commonly parameterized by r, the ratio of fluctuation power in gravitational waves to that in density perturbations. All inflation models that naturally explain the observed deviation from scale invariance and that also have a characteristic scale equal to or larger than the Planck scale predict $r \gtrsim 0.001$. The observed departure from scale invariance is a potentially important clue that strongly motivates exploring down to $r = 10^{-3}$.

For these simple models of inflation, the tensor to scalar ratio can be related to the energy scale of inflation:

$$V^{1/4} = 1.04 \times 10^{16}\ \text{GeV}\ \left(\frac{r}{0.01}\right)^{1/4} \tag{2}$$

This highlights that for a tensor-to-scalar ratio within reach of CMB observations, inflation would have occurred near the energy scale associated with grand unified theories, thus a detection would provide evidence for new physics at energy scales far beyond the reach of any terrestrial experiment. In addition, this is the power spectrum associated with quantum fluctuations in the metric. A detection of this signal would therefore provide evidence for quantum gravity.

2.2.1 Cosmic Microwave Background

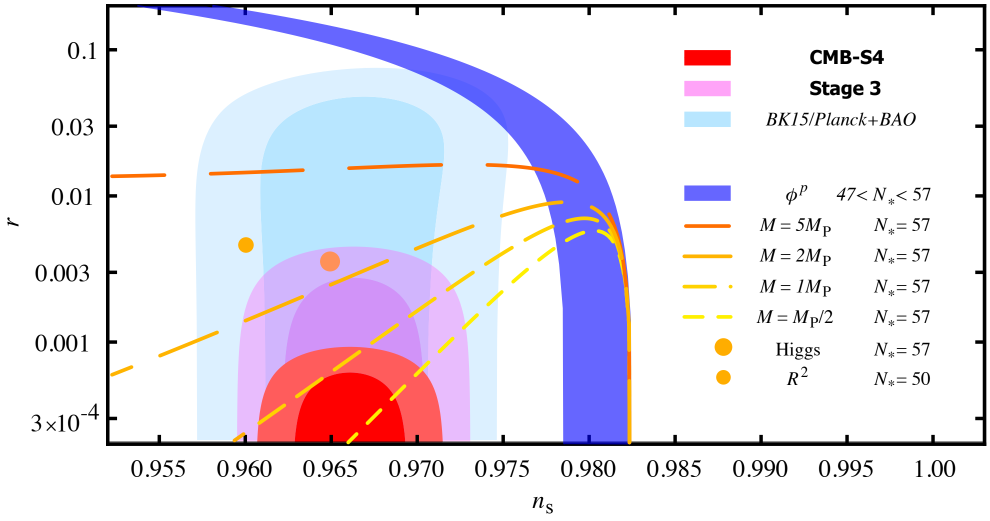

Figure 3: Forecasts and constraints on primordial gravitational waves from inflation, via measurements of the CMB B-mode polarization signal. The current best constraints from a combination of the BICEP2/Keck Array experiments and Planck is shown in light blue. Projected "Stage-3" constraints from the South Pole Observatory and Simons Observatory are shown in purple. The red region shows projected constraints for CMB-S4. The orange circles correspond to the Starobinsky model and Higgs inflation. The lines show classes of models that naturally explain the observed value of n_s with various "characteristic scales," M. The Planck scale plays an important role because the gravitational scale and the characteristic scale share a common origin. The number of e-folds, N_*, chosen for the figure corresponds to nearly instantaneous reheating, which leads to the smallest values for r for a given model.

Primordial gravitational waves (PWGs) from inflation leave an imprint in the temperature and polarization anisotropies. In particular, PGWs generate divergence-free (parity-odd) B-mode polarization and are the only source of B modes at recombination at linear order. As such, B modes of the CMB provide a unique window to PGWs [6, 7], typically targeting scales of $\theta \sim 1^\circ$ from the ground. Given the significance of the implications of a detection of PWGs, many current- and next-generation experiments are designed to go after this ‘B-mode signature’ in the CMB [8–16]. In the last $\sim$10 years, the uncertainty on r has tightened by about two orders of magnitude [8]. Looking forward, upcoming experiments such as the Simons Observatory [17] and South Pole Observatories [18, 19] are projected to cross an important threshold: $r < 0.01$, which is associated with monomial models and a super-Planckian excursion in field space that would provide strong evidence for the existence of an approximate shift symmetry in quantum gravity. However, to reach $r < 0.001$, which is associated with the simplest models of inflation that naturally predict the observed value of the scalar spectral index n_s and have a characteristic scale that exceeds the Planck scale requires an experiment the scale of CMB-S4, as shown in Figure 3.

2.2.2 Gravitational Wave Observatories

The successful direct detection of gravitational waves provides an exciting opportunity to consider direct detection of PGWs from inflation. Though the standard inflationary paradigm generally predicts PGW spectra that are nearly undetectable by GWOs, the existence of new physical processes during and/or after inflation could lead to significantly stronger high frequency signal that may be detectable by upcoming experiments (see Fig. 4). For example, scenarios in which the inflaton couples to a gauge field or the existence of a new pre-radiation dominated epoch with equations of state $1/3 \leq w \leq 1$ can lead to strongly blue-tilted PGW spectra and the existence of a new matter-dominated era with $w = 0$ or phase transitions during the inflationary epoch can lead to kinks and oscillatory features in the PGW spectrum.

The combination of CMB and GWO provides a complementary suite of measurements of inflationary PGWs and their spectrum. Though the favored focus of these observations is inflationary physics, we note that the combination of measurements are also probes of alternatives to the inflationary hypothesis. For example, the pre-Big Bang [28] model would generate a red PGW spectrum with additional power at higher frequencies within the design sensitivity of aLIGO/Virgo and/or LISA [29]; the ekpyrotic model [30] predicts a very blue PGW specturm with negligible gravitational waves on cosmological scales; the string gas cosmology [31, 32] predicts a slightly blue spectrum (compared to the slightly red spectrum generated by canonical inflation); and the matter bounce scenario [33, 34] would generate large gravitational waves, such that $r \sim 1$, which is a prediction in tension with current CMB measurements.

2.3 Observable – Interactions during Inflation: $f_{\rm NL}$

Quantum fluctuations of the inflaton or, equivalently, the scalar mode of the metric would change the amount of inflation that occurred in different parts of the universe, and thus correspond to a change in the physical energy densities from place to place. After reheating, these density perturbations grow and evolve as they re-enter the cosmic horizon. This gives rise to a primordial spectrum of fluctuations, $\zeta(\vec{k})$ where where $\vec{k}$ is a comoving wave-number, or the comoving scale of the fluctuations. In the simplest single-field inflationary models, these fluctuations only self-interact gravitationally, resulting in Gaussian statistics. Deviations from Gaussianity (primordial non-Gaussianity, or PNG), would

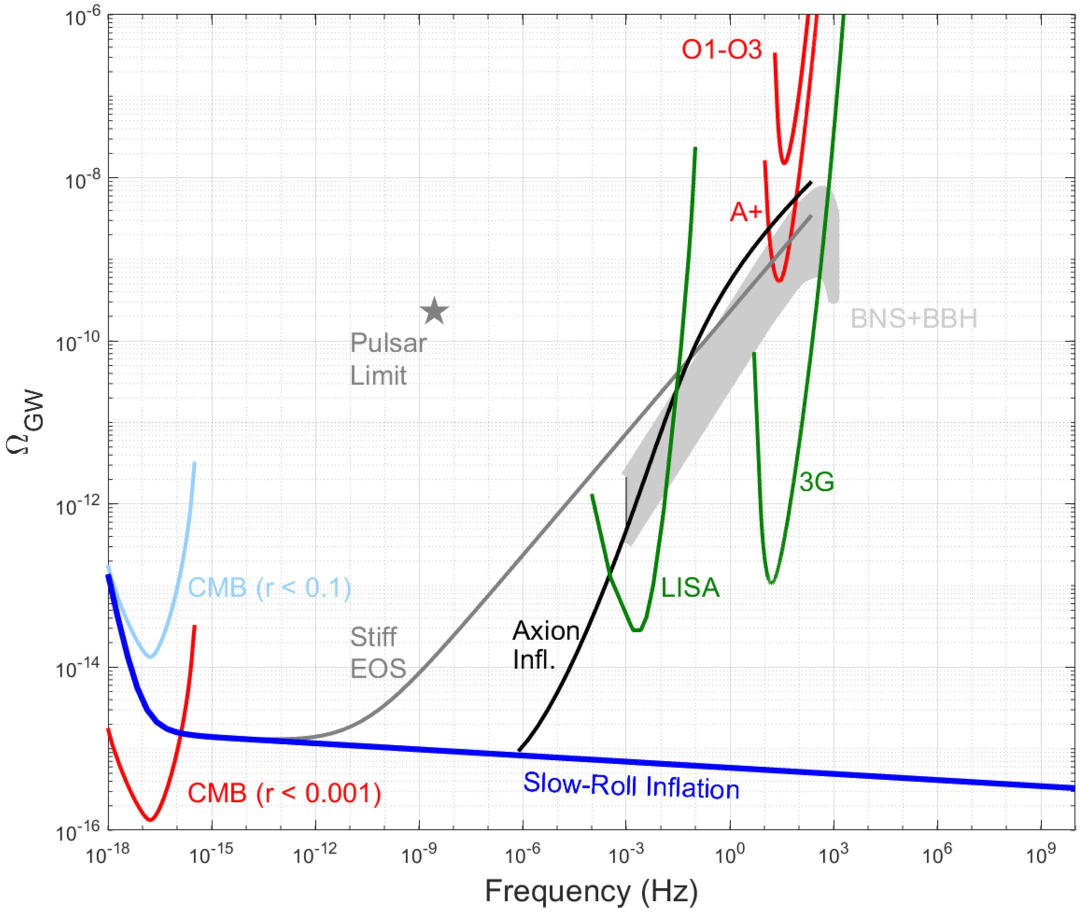

Figure 4: Landscape of gravitational wave cosmology. Experimental results include: O1-O3 LIGO-Virgo upper limits [20], CMB limits [21], and Parkes pulsar timing limit [21], as well as projected sensitivities of the third generation (3G) terrestrial GW detectors [22, 23], LISA [24] and CMB-S4. Theoretical models include examples of slow-roll inflation [25], Axion Inflation [26], hypothetical stiff equation of state in the early universe [27], and foregrounds due to binary black hole/neutron stars [20].

be evidence for additional interactions present in the early Universe. Measuring PNG will thus allow us to answer fundamental questions, such as: How did the background evolve and is it consistent with slow-roll inflation scenarios? Are there additional scalar fields at play during inflation? If so, how did they evolve and interact? Were there heavy fields ($\sim$ Hubble scale) present during inflation?

There are various measures of non-Gaussianity. We focus on the scalar three-point correlation function, the bispectrum. It has been the most studied and analyzed observable in the literature, because it often is the dominant non-Gaussian signature in weakly coupled models of inflation. For translational, rotational and scale-invariant perturbations,

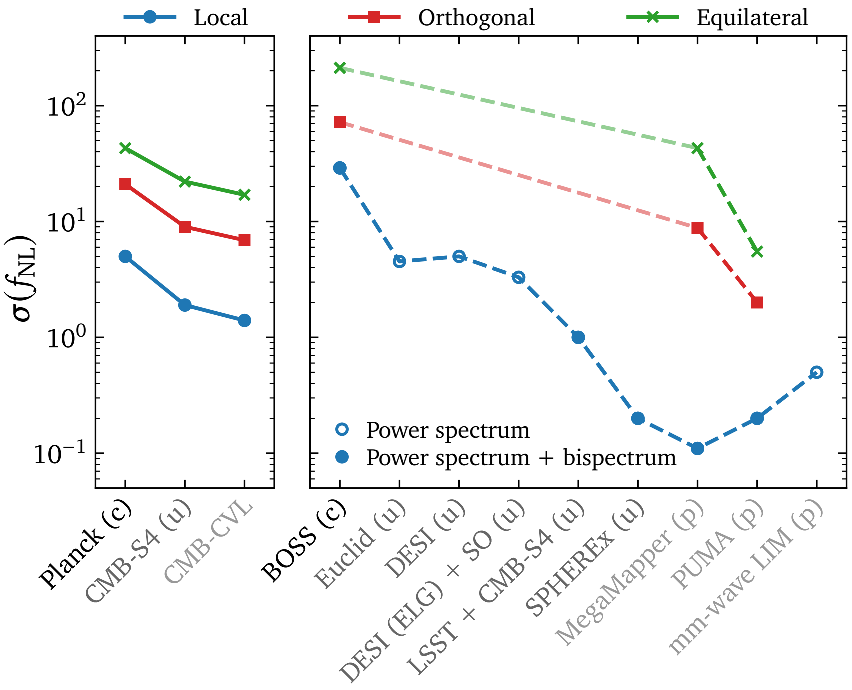

Figure 5: CMB and LSS forecasts and constraints on primordial non-Gaussianity. Reproduced from [5].

the bispectrum is:

$$\langle\zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3)\rangle \propto f_{\rm NL}^{\rm type}\delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)\frac{S^{\rm type}(k_1,k_2,k_3)}{k_1k_2k_3} \tag{3}$$

Here, $f_{\rm NL}$ parameterizes the size of PNG and the dimensionless shape function $S^{\rm type}$ controls the overall size of PNG as a function of the triangle formed by the momenta. The shape dependence encodes information about the specific dynamical mechanism that generated the non-Gaussian signal, thus serving as a discriminator between various inflationary models. Studies of various inflationary models have demonstrated several broad classes of scale invariant PNG with large, potentially detectable $f_{\rm NL}$. We list them below with emphasis on the physics that they probe:

- 'Local' non-Gaussianity and multi-field inflation ($f_{\rm NL}^{\rm loc}$): This is also defined by a large signal in the squeezed limit ($k_3 \to 0$). The single-field consistency conditions forbid any contribution in this region in the absence of extra particles; the squeezed limit is therefore an excellent probe of single- versus multi-field inflation. Non-Gaussian correlators of this type are particularly sensitive to the mass and spin of additional fields in addition to being a probe of light fields.
- Orthogonal non-Gaussianity ($f_{\rm NL}^{\rm ortho.}$): This is the flattened limit ($k_1 = 2k_2 = 2k_3$). Enhanced signal in the flattened limit is associated with excited states (with respect to the Bunch-Davis vacuum).

- 'Equilateral' non-Gaussianity and single field inflation ($f_{\mathrm{NL}}^{\mathrm{eq.}}$, where $k_1 \sim k_2 \sim k_3$): Both $f_{\mathrm{NL}}^{\mathrm{eq.}}$ and $f_{\mathrm{NL}}^{\mathrm{ortho.}}$ get large contributions from this region. This is typical of self-interactions of the inflaton and is often used as a test of canonical single-field slow-roll inflation which requires $f_{\mathrm{NL}}^{\mathrm{eq.}}, f_{\mathrm{NL}}^{\mathrm{ortho.}} < 1$. Interactions between the inflaton and heavy fields also contributes significantly in this region. A detection of equilateral non-Gaussianity without a large $f_{\mathrm{NL}}^{\mathrm{ortho.}}$ is a signal of the quantum origin of structure.

These three PNG bispectrum shape estimators provide a mechanism to use non-Gaussianity to characterize inflation. Because there are many more shapes that may test for non-Gaussian signatures, this bispectrum-based framing is a significant under-estimate of the opportunity from PNG measurements to probe inflation.

To measure the PNG, we note that these quantum fluctuations would change the amount of inflation that occurred in different parts of the universe, and thus correspond to a change in the physical energy densities from place to place. After reheating, these density perturbations grow and evolve as the re-enter the cosmic horizon. As a result, these fluctuations would eventually appear as temperature anisotropies in the CMB and also dictate where structure would preferentially form, leading to a connection between the primordial fluctuations and structure formation. The different components of the energy density and their fundamental interactions shape this subsequent evolution, giving rise (at linear order) to:

$$\delta_i(\vec{k}, z) = T_i(k, z)\zeta(\vec{k}) \tag{4}$$

where $\vec{k}$ is again comoving wave-number, $k = |\vec{k}|$, $\zeta(\vec{k})$ is the scalar metric fluctuation, $\delta(\vec{k}, i)$ is the density contrast of species i and $T_i(k, i)$ is its transfer function. As a result, any level of non-Gaussianity in the statistics of the primordial fluctuations ($\zeta(\vec{k})$) will be transferred to the maps of the cosmic microwave background and large-scale structure.

The best constraints on non-Gaussianity have come from the CMB, as shown in Figure 5, and CMB-S4 can improve on the f_{NL} parameters by a factor of a few before reaching a fundamental floor based on the number of modes available in the sky area available to the experiment. Because large scale structure surveys have access to three-dimensional volumes of modes, in principle they can significantly improve upon the CMB constraints, in particular for $f_{\mathrm{NL}}^{\mathrm{eq.}}$ and $f_{\mathrm{NL}}^{\mathrm{ortho.}}$. As a result, large scale structure surveys including 21cm intensity mapping (e.g. PUMA) and optical galaxy surveys (e.g. MegaMapper) expect to significantly improve upon the CMB. The power of these surveys are shown in Figure 5: the CMB essentially 'ends' on the left hand side, and future LSS surveys project dramatic improvements. Although they can access far more modes than are available in the CMB, these surveys observe the primordial power spectrum through a more complicated matter transfer function $T_m(k, z)$ that includes non-linear local gravitational effects. Non-linear effects become worse at lower redshift because there has been more time for structure to evolve based on its local gravitational environment, and at smaller scales where the local environment operates more efficiently, thus the limitations of LSS surveys at redshifts $z < 6$ will ultimately be related to the modeling of small scale non-linearities. LSS surveys at higher redshifts, where the signal is more pristine ($z > 10$, 'Dark Ages'), may be uniquely possible using 21 cm intensity mapping techniques but with more complex instrument requirements (such as deploying on the lunar surface to avoid human-generated radio frequency interference).

Local non-Gaussianity ($f_{\rm NL}^{\rm loc}$) and other shapes with a contribution in the squeezed limit are made easier to observe through their non-local effect on the formation of halos, namely scale-dependent bias. The halos essentially form in proportion to the Newtonian potential in a way that causes large changes to the power spectrum at small k (large distances), well away from the nonlinear regime. This effect can even be measured without cosmic variance, either from using multiple populations of halos or by cross correlating with the matter density inferred from gravitational lensing (e.g. CMB lensing). Forecasts show an order of magnitude or more improvement in $f_{\rm NL}^{\rm loc}$ is realistic for a number of surveys and could be enhanced by cross-correlations with the CMB-S4 lensing maps.

2.4 Observable – Inflationary Potential: $A_{\rm lin}$

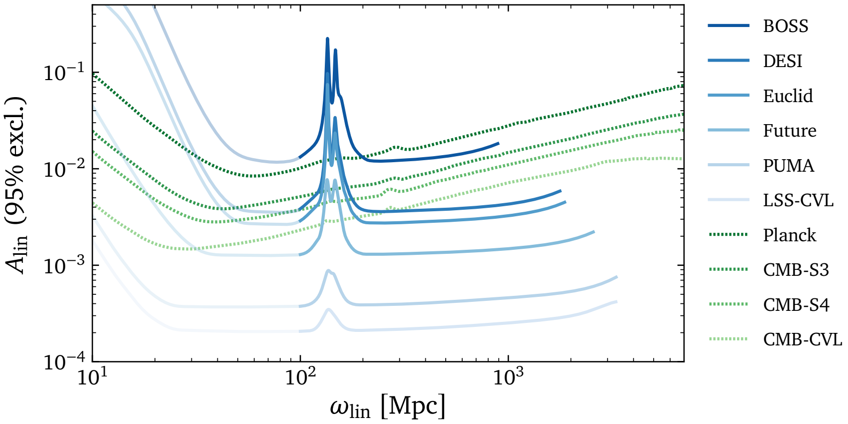

Figure 6: CMB and LSS forecasts and constraints on primordial features. Reproduced from [5].

A conventional picture of a slow-rolling scalar field on a flat potential is consistent with observations. In this context, the measurement of $n_s \simeq 0.97$ is consistent a mild time dependence of the inflationary background due to the slope of the potential. However, observations do not forbid more dramatic deviations of scale invariance that can arise from sharp or oscillatory features in the potential, particle production events, and more.

Like deviations from Gaussianity, departures from scale invariance can come in many forms. Observations of the CMB and LSS certainly forbid power laws for the power spectrum that are dramatically different from k^{-3} at cosmological scales. That still leaves three much less constrained possibilities (i) oscillatory features in the power spectrum (ii) power-law changes to the power spectrum on small scales and/or (iii) scale dependent non-Gaussian correlators.

Oscillatory features are a particularly well motivated target for several reasons. First, they arise naturally within a variety of microscopic models of inflation. The flatness of the potential required for successful inflation can be broken to a discrete symmetry by non-perturbative corrections. These periodic corrections to the potential give rise to logarithmically spaced oscillations in the power spectrum. Alternatively, particle production can give rise to linear oscillations. Phenomenologically, these features can also evade current constraints without hiding the signal in modes that will be difficult to measure. In fact, these signals are visible even on nonlinear scales, thus allowing for strong constraints from current and future galaxy surveys.

Although there is no specific theoretical target for these kinds of features, future observations can make dramatic improvements in sensitivity that present significant discovery potential. The forecasts are shown in Figure 6 for the amplitude of linear oscilations, $A_{\rm lin}$, in the matter or CMB power spectrum. We see that next generation large scale structure experiments like PUMA or Megamapper could improve on current constraints by up to a factor of 100. Furthermore, unlike other LSS signals from inflation, current analyses have already reached CMB sensitivity and produced constraints on $A_{\rm lin}$ at the level of these forecasts.

3 Relics of the Hot Big Bang

In addition to the direct inflationary signatures described in the section above, the early universe presents another avenue for exploring new fundamental physics through the measurement of relic radiation. In the simplest narrative of the early universe, the only relic radiation (apart from CMB photons) is the Cosmic Neutrino Background. Because the Standard Model precisely predicts this neutrino energy density, measurements of relic radiation from the early universe have tremendous potential— measuring any departure from the predicted neutrino background would be a clear sign of new physics.

The landscape for new physics is broad ranging from around $\mathcal{O}(1)$ MeV, which is constrained by Big Bang Nucleosynthesis (BBN), up to at least $\mathcal{O}(10^{16})$ GeV. For example, Standard Model extensions with new light degrees of freedom can lead to thermal relic radiation. A stochastic background of gravitational waves and its associated spectrum will carry the imprint of the pre-BBN eera, phase transitions in the early universe, and of any particle production associated with pre-heating/reheating. Similarly, axion-like particles generate additional relativistic degrees of freedom and potentially carry the imprint of the inflationary epoch. Measuring and constraining relic radiation from the early universe presents a unique tool for exploring high energy physics complementing collider-based approaches, which are sensitive to different energies and scales.

3.1 Light Relics

After reheating, all the components of the Standard Model were in equilibrium, likely at temperatures well above the weak scale, $T \gg 1$ TeV. At these enormous temperatures, any number of additional (beyond the Standard Model) particles could also have been in equilibrium with the Standard Model and would have been produced with number densities similar to that of the photons (or any other relativistic particle).

Particles and/or dark sectors that decouple from the Standard Model while they are relativistic will carry a large amount of entropy. For sufficiently heavy particle, $m \gg 1$ MeV, it is possible for these particles to decay back to the Standard Model while leaving little/no observational signature. In contrast, for $m < 1$ MeV, there will be a measurable

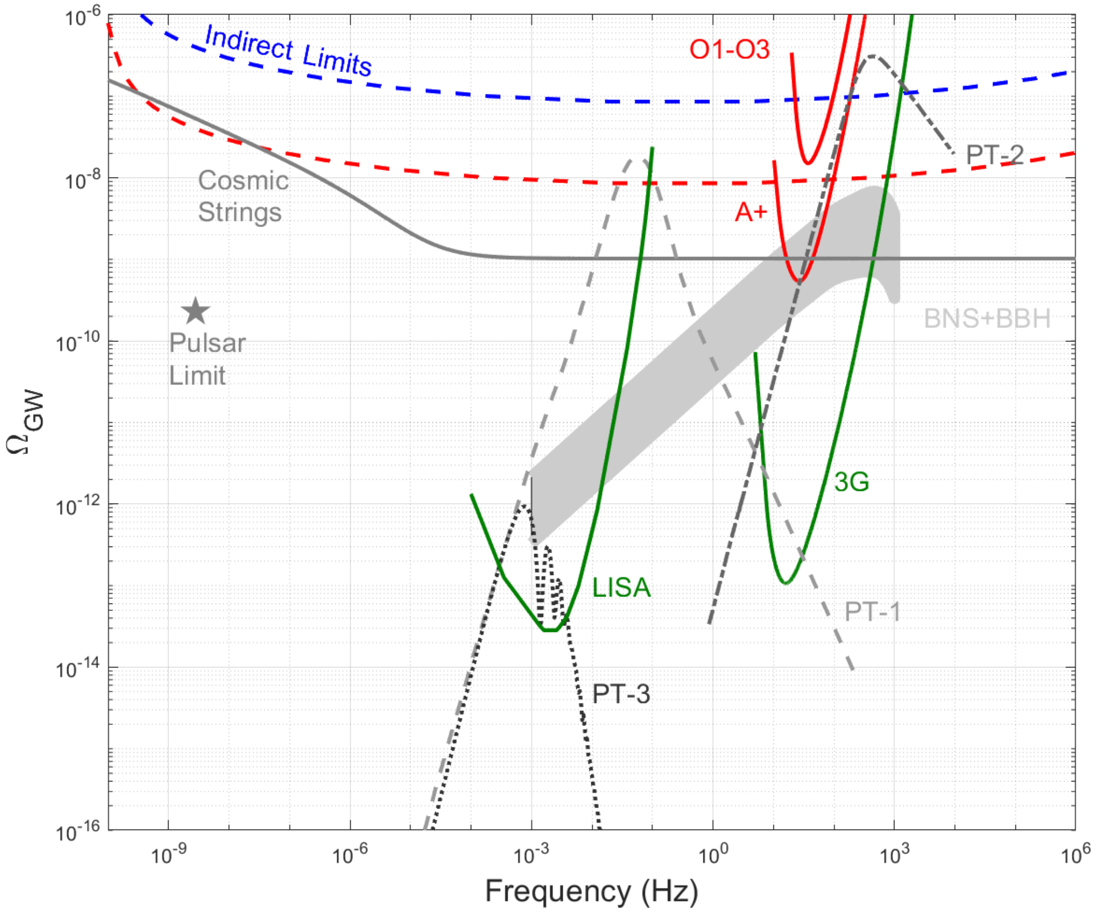

Figure 7: Same as Fig. 4, but focused on models of phase transitions and topological defects. Theoretical models include examples of first-order phase transitions (PT-1 [35], PT-2 [36], and PT-3 [37]), cosmic strings [38], and foregrounds due to binary black hole/neutron stars [20]. Also included is the indirect limits from big bang nucleosynthesis [21] and corresponding projections from CMB-S4.

impact on the amount of radiation in the universe. This is particularly straight-forward for light particles, $m \ll 1$ eV. Because light particle remain relativistic through recombination and contribute to the total amount of radiation, during radiation domination, in the same way as a neutrino.

It is conventional to define the total radiation density during this epoch as

$$\rho_r = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right) \tag{5}$$

such that $N_{\rm eff} \approx 3$ in the Standard Model (reflecting the 3 species of neutrinos). In detail, the energy density of neutrinos in the Standard model is equivalent to $N_{\rm eff} = 3.045$.

Additional light particles add to this energy density so that $N_{\rm eff} = 3.045 + \Delta N_{\rm eff}$, with $\Delta N_{\rm eff} > 0$. Because there is no way to ride these sectors of their entropy after decoupling from the Standard Model, their contribution to $\Delta N_{\rm eff}$ is determined by the number of degrees of freedom of the additional particle(s) and the entropy of the Standard Model at the temperature. These universal results are shown in Figure 8.

Current observations constrain $\Delta N_{\rm eff} < 0.3$ (95%), which probes individual particles decoupling during or after the QCD phase transition ($T_F \approx 100 MeV$). The next generation of cosmic surveys is poised to reach very exciting targets in $\Delta N_{\rm eff}$. CMB-S4 is expected to limit $\Delta N_{\rm eff} < 0.06$ (95 %) which would be sensitive to new particles with spin decoupling at $T_{\approx}100$ GeV and real scalars at 1 GeV, just prior to the QCD phase transition. The later is particularly important for axion-like particles coupling to heavy fermions, where CMB-S4 would be the most sensitive experimental or observational probe by orders of magnitude. Building off CMB-S4, more futuristic surveys like PUMA, LIM, Megamapper or high CMB-HD could reach the ambitious goal of excluding $\Delta N_{\rm eff} = 0.027$ at 95%, which would be sensitive to any particle that was in thermal equilibrium which the Standard Model at any time after reheating.

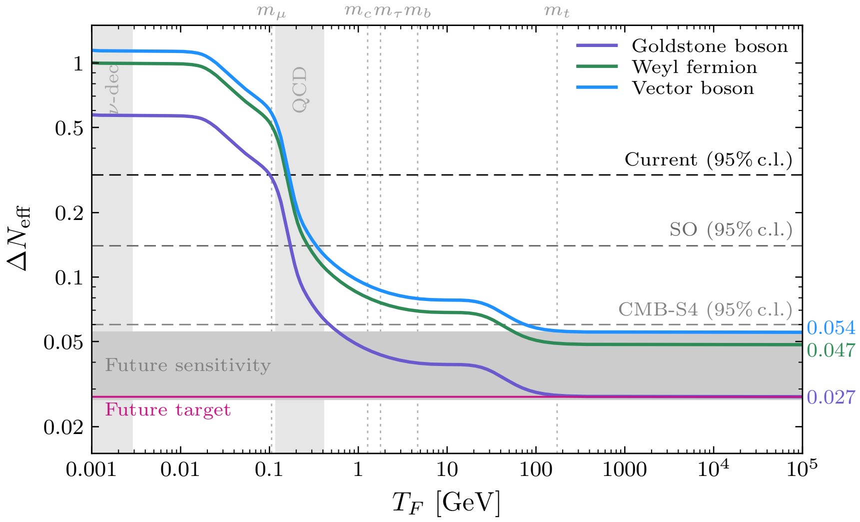

Figure 8: Contributions to $\Delta N_{\rm eff}$ light particle that decouple from the Standard Model at temperature $T_{\rm F}$, reproduced from [39].

More generally, cosmic surveys are sensitive to a wide range of well motivated targets through potential contributions to $N_{\rm eff}$ at recombination and/or suppression of small scale clustering at late times. Dark sectors of many varieties are motivated by solutions to the hierarchy problem, the Strong CP problem and the cosmological constant problem, and of course as models of dark matter. These dark sectors can include both very light ($m \ll eV$) and light-but-massive ($m \approx$ eV) relics. In some parameter regimes, these models correspond to changes to $N_{\rm eff}$ and $\sum m_\nu$. Somewhat heavier relics produce changes to the matter power spectrum that are similar to massive neutrinos but are distinguishable in principle.

3.2 Phase Transitions

First order phase transitions (FOPTs) in the early Universe produce gravitational waves and offer a unique way of probing particle physics models at energy scales otherwise inaccessible. Such phase transitions could occur at nearly any time during or after inflation, and the GW spectrum, with examples shown in Fig. 7, is sensitive to the shape of the effective potential, which depends on the symmetry breaking pattern and the particle content of the theory. This provides access to regions of parameter space unexplored so far in various extensions of the SM. Moreover, thermal phase transitions and weak transitions source GWs with different spectral shapes (see e.g. [40–45]), as illustrated in Fig. 7, allowing the possibility of reconstructing the conditions during and after the FOPT.

GWs from a strong FOPT have a plethora of motivations in the early universe. For instance, new states at the electroweak scale can catalyze a strongly first order electroweak phase transition [46–72] and large lepton asymmetries or different quark masses can make the QCD transition strong [73–76]. Beyond this, a strong transition can occur in multistep phase transitions[1] [82–87], B-L breaking [35, 88–95] (or B/L breaking [96]), flavour physics [97, 98], axions [36, 99, 100], GUT symmetry breaking chains [101–105], supersymmetry breaking [106–109], hidden sector involving scalars [110–114, 114–119], neutrino mass models [120–122] and confinement [123, 123–130].

Of particular interests are phase transitions associated with physics that can is also explored by current and upcoming collider experiments. A high priority topic is electroweak symmetry breaking (EWSB), which in the Standard Model with a 125 GeV Higgs boson, occurs via a smooth cross-over rather than a FOPT [131]. However, there are compelling theoretical arguments to expect new physics coupled to the SM Higgs not far from the TeV energy scale [46] (for example, light supersymmetric particles, such as stops or additional scalars in non minimal SUSY extensions, coupled to the SM Higgs). These new physical processes could alter the nature of the EWSB transition possibly making it a first order transition. The existence of such a transition is a necessary ingredient for electroweak baryogenesis [132–134] and could provide a source for observable gravitational radiation.

Another potential FOTP arises from spontaneous R-symmetry breaking [135] in viable SUSY models. A study [107] has investigated the conditions where this transition can be first order, leading to GWs, and demonstrated that the resulting GW spectrum covers the frequency range accessible to current and future GW detectors. Moreover, once the SUSY breaking mediation scheme is specified, the peak of the GW spectrum is correlated with the typical scale of the SM superpartners, and a visible GW signal would imply superpartners within reach of future colliders.

3.3 Topological Defects

Phase transitions associated with symmetry breaking generically result in topological defects [136] that could have different forms [137, 138]. Three types of topological defects have been shown to produce SGWB: domain walls [139–144], textures [145] and cosmic strings [38, 146–154]. In all cases the amplitude of the GW signal grows with the sym-

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[1] See Refs. [77–81] for the viability of a multistep phase transition

metry breaking scale, implying that topological defects are effective probes of high energy physics. Furthermore, topological defects can also arise in superstring theories [155–157], implying that GW experiments can provide a novel and powerful way to test string theory [158, 159].

Among these, cosmic strings have been studied the most extensively, either as global strings (e.g. in axion dark matter models where a U(1) is broken to a vacuum with a discrete symmetry [160]) or as local strings in symmetry breaking chains that result from SO(10) breaking to the SM [144]. Considering all possible spontaneous symmetry breaking patterns from the GUT down to the SM gauge group, it was shown [136] that cosmic string formation is unavoidable.

Here we briefly highlight the SGWB production by local cosmic strings (for a more extensive discussion, see [161] and references therein). Local strings with no internal structure can be described by the Nambu-Goto action, and are expected to quickly reach the scaling regime [137]. The predicted SGWB spectrum is then defined by the dimensionless power spectrum for a string loop of a given length and by the number density of loops, both of which are studied in theoretical and numerical modeling [147, 149, 162–169]. The resulting SGWB spectrum is roughly constant over many decades of frequency, assuming standard cosmological history [170]. Detection of the SGWB due to cosmic strings could therefore be used to test for any departures from a standard cosmological picture [171–173]: probe new equations of state of the early universe, probe new particle species, and probe (pre-)inflationary universe [161]. Indeed, searches for cosmic string SGWB have already been conducted, placing upper limits on the string tension $G\mu \lesssim 9.6 \times 10^{-9}$ by LIGO-Virgo [174], and $G\mu \lesssim 10^{-10}$ by pulsar timing arrays [175, 176]. NANOGrav has reported a possible hint of cosmic strings [177], although their observation may also be of instrumental origin. Future experiments covering a wide frequency range will further improve the sensitivity to GW signals from cosmic strings, including Einstein Telescope, Cosmic Explorer, AEDGE, DECIGO, BBO, μAres and Theia [178–183]. Cosmic string tension in the range of $G\mu \approx 10^{-16} - 10^{-15}$ or bigger could be detectable by LISA, with the galactic foreground affecting this limit more than the astrophysical background [170, 184].

3.4 Axion Like Particles

Axions or axion-like particles (ALPs) are pseudo Nambu-Goldstone bosons that result from spontaneous symmetry breaking. Originally introduced to solve the strong CP problem, axions solve the hierarchy problem, inflation naturalness and naturally arise in string theory as modulus fields from dimensional compactification (see [185] for a recent review of axions in cosmology). Axions are typically light, and impact cosmology both at early and late times. Late-time effects of $\simeq 10^{-22}$ eV ALPs include the suppression of clustering of dark matter and galaxies, while $m_a < 10^{-27}$ eV ALPs generate late-time acceleration and change the amplitude of the Integrated Sachs Wolf (ISW) plateau in the CMB [186–188]. In the early universe, ALPs behave as relativistic species and can be mapped onto potential deviations from the Standard Model value of $N_{\rm eff}$, with deviations $\Delta N_{\rm eff}$ expected to be within the measurement sensitivity of experiments like CMB Stage IV [189, 190].

If the axion symmetry-breaking occurs during inflation, ALPs would source isocurvature perturbations with an amplitude set by the energy scale of inflation, which also sets the amplitude of the tensor spectrum from GW [191, 192]. Upcoming polarization CMB measurements will constrain H_I while complementary constraints from the temperature spectrum constrain the contribution of ALPs to the total cosmic energy budget. For ALPs in the $10^{-25}\,\mathrm{eV} < m_a < 10^{-24}\,\mathrm{eV}$ mass range, current data allow a roughly 10% contribution of ALPs to the total dark matter budget, with around a 1% contribution to isocurvature and tensors. This will significantly improve in the coming decade with increases in sensitivity to CMB polarization. Alternatively, if the ULA U(1) symmetry is broken *after the end* of inflation, a white noise power spectrum of isocurvature would be produced. For these models, the expected sensitivity of experiments like CMB-S4 is to axions with masses as 'high' as 10^{-17} eV.

A background of oscillating ALPS with the standard $\frac{g_{a\gamma}}{4} aF\bar{F}$ coupling to photons leads to the rotation of linear polarization by ALP dark matter [185, 193–198]. It is the parity breaking associated with this coupling of a non-stationary background field to electromagnetism that generates this 'birefringence' for the propagation of opposite-helicity photons.

If the source of the cosmic birefringence is *spatially varying*, then the polarization rotation will be anisotropic across the sky [199, 200]. Many models of birefringence predict such anisotropies in the signal, or produce both an anisotropic and an isotropic birefringence signal. A measurement of anisotropic birefringence signal will strongly constrain these models[201]. While current bounds on the anisotropic CMB birefringence signal limit the axion-photon coupling to $g_{a\gamma} < 4.0 \times 10^{-2}/H_I$ [200], future CMB observations should tighten limits by a few orders of magnitude.

An added effect is the washing out of polarization at the last scattering surface due to the early-time oscillations of the axion field. This would lower the polarized fraction measured through the TE and EE cross power spectra compared to the standard prediction [199].

3.5 Observation

Relic radiation can be measured in one of two ways: direct interaction between the radiation on a detector, and indirectly through influencing other cosmological observables. The recent detection of GWs presents the tantalizing prospect of directly measuring relic GWs from the early universe. Current and upcoming GWOs could not only measure the energy density of relic GWs, but also the spectral density and perhaps even the spatial distribution. Gravitational and non-gravitational (e.g. axions, thermal relics, neutrinos) can also be measured through its impact on various cosmological observables. Relic radiation influences cosmological observables through its contribution to the scale of matter-radiation equality, which then changes the short wavelength modes of the matter power spectrum, and the phase of oscillations in the primordial photon-baryon fluid. Both of these signals can be observed via smaller-scale measurements of CMB and LSS. Though the search for new physics is often framed as searching for additional relativistic energy ($\Delta N_{\mathrm{eff}} > 0$), we note that it is permissible for new physics to result in ($\Delta N_{\mathrm{eff}} < 0$), which would carry significant implications for our understanding of neutrinos and our thermal history.

4 Facilities

All of the observable signals described above directly connect to new fundamental physics presenting an exciting opportunity for discovery. Robust detection and measurement of these signals is challenging requiring large facilities that employ sophisticated detector systems and technologies. Successful construction of these facilities requires that the selected technologies demonstrate an appropriate degree of technical readiness prior to implementation. This need for technical readiness shapes the experimental program for studies of the early universe.

In the next ten years (2025-35), the early universe experimental program has two major activities. The first is the construction and operation of large facilities that are technically ready. These facilities include the CMB-S4 project, a new OIR Wide-Field Multi-Object Spectrometer, and upgrades to the operating Advanced LIGO and Advanced Virgo observatories. The second major activity is technology R&D focused on advancing new technologies to be implemented in large facilities in the following decade (2035-). These technologies include new capabilities with line intensity mapping, new gravitational wave detection technologies, and new CMB instrumentation. In order to ensure sufficient technical maturity, this R&D activity must extend beyond technology development in the lab and requires fielding smaller scale experiments using these novel techniques.

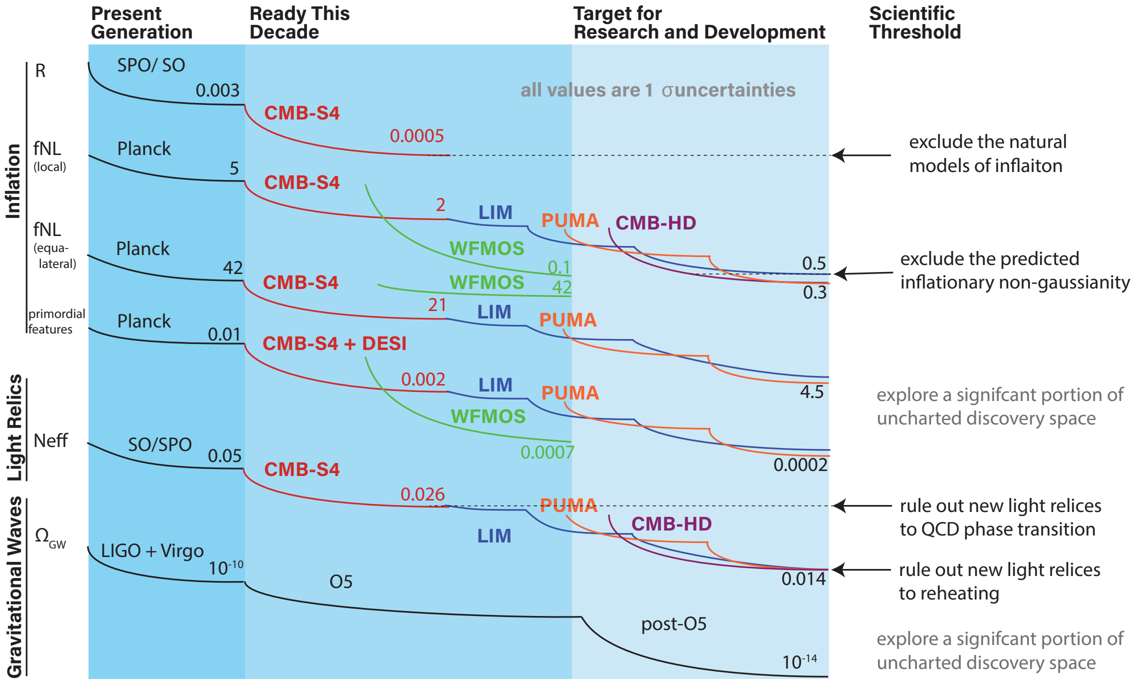

Figure 9: Cartoon illustrating the growing scientific reach of early universe facilities broken into experiments that are technically ready to begin operation in this decade (2025-2035) and more ambitious experiments requiring staged R&D to realize facilities in the next decade (2035-).

4.1 Large Facilities ready for construction and upgrade in 2025-35

The first major activity in 2025–35 is carrying out an early universe measurements with large facilities that are ready for operation in this decade. These include the CMB-S4 experiment, a new Wide-Field Multi-Object Spectrometer (WFMOS), and operations and upgrades to the currently running Gravitational Wave Observatories (GWOs). These facilities will target key scientific goals to realize substantial improvements in our understanding of new physics in the early universe.

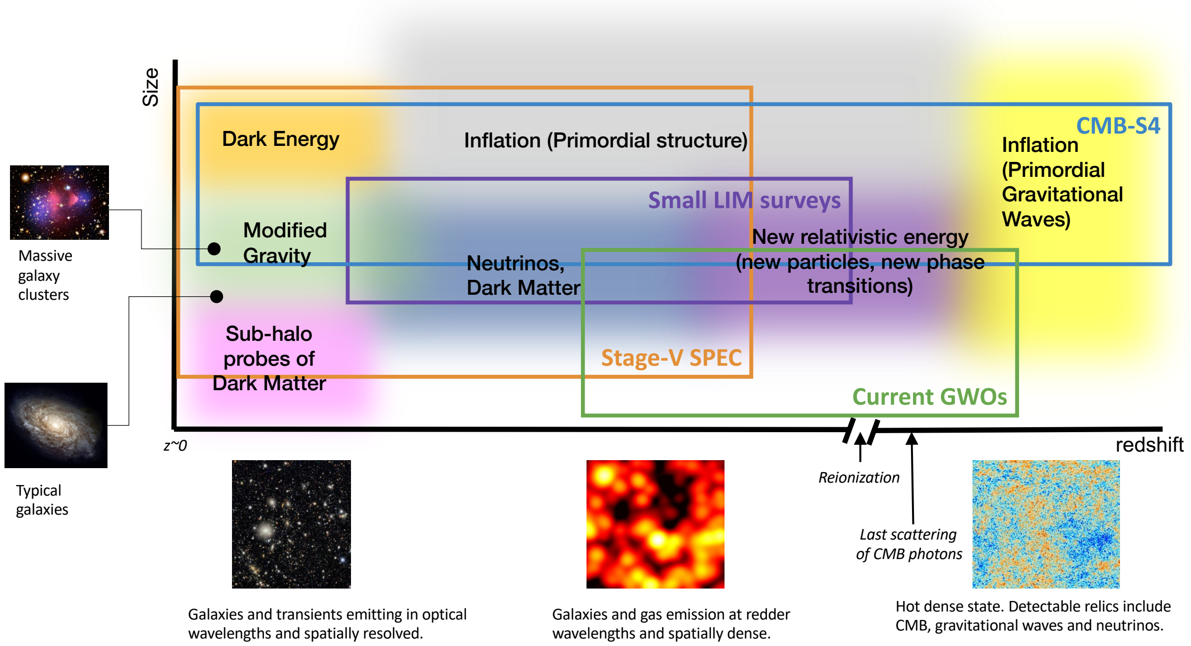

Figure 10: Landscape for Early Universe facilities operating during 2025–35 highlighting the overlapping and complementary approach to Early Universe science. The 2025–35 early universe science program includes three major facilities: CMB-S4, operating/upgrading existing GWOs, and a new Stage V spectroscopic facility. The 2025–35 decade will also develop new technology critical for future surveys including fielding of small-scale instruments (e.g. LIM) and invest in key theoretical research to provide the needed tools to analyze the data.

4.1.1 CMB-S4

CMB-S4 [202] is a “stage 4” cosmic microwave background project that plans to field multiple telescopes at the South Pole and in the Atacama, Chile.

Science goals. CMB-S4 has an enormously broad science case, including searches for primordial gravitational waves as predicted from inflation (detecting $r > 3 \times 10^{-3}$ at 5σ or limiting $r \leq 10^{-3}$ at 95% confidence if r is very small) and for the imprint of relic particles including neutrinos (measuring $\sigma_{N_{\rm eff}}$ with uncertainty ≤ 0.06 at 95% confidence). CMB-S4 will also offer unique insights into dark energy and tests of gravity on large scales, find large samples of high-redshift galaxy clusters, elucidate the role of baryonic feedback on galaxy formation and evolution, open a window onto the transient Universe at millimeter wavelengths, and explore objects the outer Solar System, among other investigations.

Instrument description. Current CMB-S4 plans call for 500,000 polarization-sensitive bolometers that measure the sky at frequencies from 20–280 GHz. The superconducting quantum interference device detectors will be read out using time-domain multiplexed electronics and will be distributed between a set of telescopes at two site: two 6-meter cross-Dragone reflecting telescopes in Chile, a 5-meter three-mirror-astigmatic reflecting telescope at the South Pole, and eighteen 0.5-meter refracting telescopes at the South Pole, grouped as triplets on six mounts, with each mount sharing a cryogenic system.

Technology status. The preliminary baseline design for CMB-S4 uses proven technology scaled up to much higher detector counts. The already-establish integrated project office has addressed the technical challenges of that scale-up with a detailed design and implementation plan that includes a full work-breakdown structure. The project office also maintains a register of risks and a detailed cost estimation plan. The preliminary, technology-limited project schedule contains nearly nine thousand milestones and catalogs the dependent relationships between them. A dedicated group within the project oversees the production of prototype detectors and leads the development of a unified detector fabrication plan that covers multiple fabrication sites.

4.1.2 Stage V spectroscopic facility

The upcoming Stage V spectroscopic facility will employ highly-multiplexed spectroscopy on a large telescope to deliver a spectroscopic galaxy survey complementing and building upon the currently operating photometric galaxy surveys (e.g. LSST/VRO).

Science goals. The overarching goal of the upcoming Stage V spectroscopic facility is implementing large-format spectroscopy to capitalize on the large-area images currently coming online. With spectroscopy providing a fundamental and complementary observable, such a facility will lead to a broad suite of scientific results encompassing astrophysics to cosmology. Of relevance to the US High Energy Program are substantial improvements in astrophysical studies of Dark Matter and advancing the exploration of Dark Energy. Of particular overlap with early universe science is precision measurements of the primordial power spectrum and its statistics, which is enabled by the large volume survey of over 100 M galaxies out to high redshifts.

Instrument description. A Stage V spectroscopic instrument consists of a 6-12 m Optical/IR telescope with a large (>5 deg) field-of-view. The instrument's massively multiplexed spectrometer consists of fiber-fed spectrographs multiplexed by >10,000 robotically positioned fibers.

Technology status. The spectroscopic survey technique is well developed with an established track record (e.g. eBOSS, DESI) making a Stave V spectrograph an instrument with high technical maturity. The only technologies requiring development are the compact fiber positioners and low-noise CCDs at long wavelengths. Several concepts are already under development (MSE, MegaMapper, SpecTel) and recently, the Astro2020 Decadal Survey identified highly multiplexed spectroscopy as a strategic priority and recommended that a major (MSRI-2 scale) investment could be made in a large, dedicated facility late in the coming decade.

4.1.3 Operating gravitational-wave observatories

The two Advanced LIGO detectors in the US and the Advanced Virgo detector in Italy were the first machines to directly observe gravitational-waves from binary merger events. Also operating, but in the early stages of commissioning, is the Japanese KAGRA detector.

Science goals. Originally built for enabling the first detection of gravitational waves, the primary science goal of current gravitational-wave observatories is to study the population of compact mergers, to look for other potential signals from pulsars or other sources, to study any potential deviations from general relativity, and to constrain gravitational-wave background radiation, see figure 4. GWs offer the unique possibility to probe the evolution of the universe within the first minute after the big bang, and the corresponding high-energy physics. (Roughly 1 minute after the big bang is when nucleosynthesis took place, of which we have observational evidence via the abundance of lightest nuclei.) During the first minute, the primordial plasma was opaque to both photons and neutrinos, so they cannot serve as messengers about this early epoch. Hence, GWs could tell us about inflation, possible additional phases of evolution (i.e. between inflation and radiation domination), phase transitions (multiple possibilities exist such as SUSY, QCD, electroweak and other transitions), and topological defects (cosmic strings, branes). Many of the proposed models (of inflation, particle physics etc) would result in the stochastic GW background that could be within reach of the upcoming terrestrial GW detectors (Voyager, Cosmic Explorer, Einstein Telescope, and even upgrades to LIGO/Virgo/KAGRA) as well as to LISA and perhaps to PTA.

Instrument description. The Advanced LIGO and Advanced Virgo observatories are ground-based, L-shaped laser interferometers of 4 km and 3 km respective arm length. They are currently undergoing a significant upgrade to their readout and quantum noise reduction system, as well as the low frequency thermal noise. The upgrades are referred to as ”A+” and ”Advanced Virgo+” respectively. Their next one-year observation run (O4) is expected to start at the beginning of 2023, followed by a 2.5-year run (O5) between 2025 and 2028 at the full upgrade sensitivity sensitivity - about twice the current sensitivity and corresponding to observing more than one binary merger per day. The Japanese KAGRA observatory is also commissioning their detector, planing to join the O5 run.

Technology status. Planing on possible post-O5 run observatory upgrades has started. Possible scenarios include detector upgrades that allow increasing the low frequency sensitivity, while at the same time testing technology for the next-generation observatories Cosmic Explorer in the US and Einstein Telescope in Europe.

4.2 R&D for future facilities

The second major activity in 2025-35 is technology R&D to deliver key technologies for future large surveys after 2035. The science discussed above illustrates that there is significant discovery potential beyond the reach of the CMB, LSS and GW facilities described earlier, but going beyond those ambitious projects requires developing new technology and achieving a sufficient level of technical readiness for implementation in a future large survey instrument. With this objective, technology R&D in 2025-35 will focus not only on advancing new instrumentation, but will require fielding new small-scale instruments to develop the needed experience with systems-level integration and systematics control.

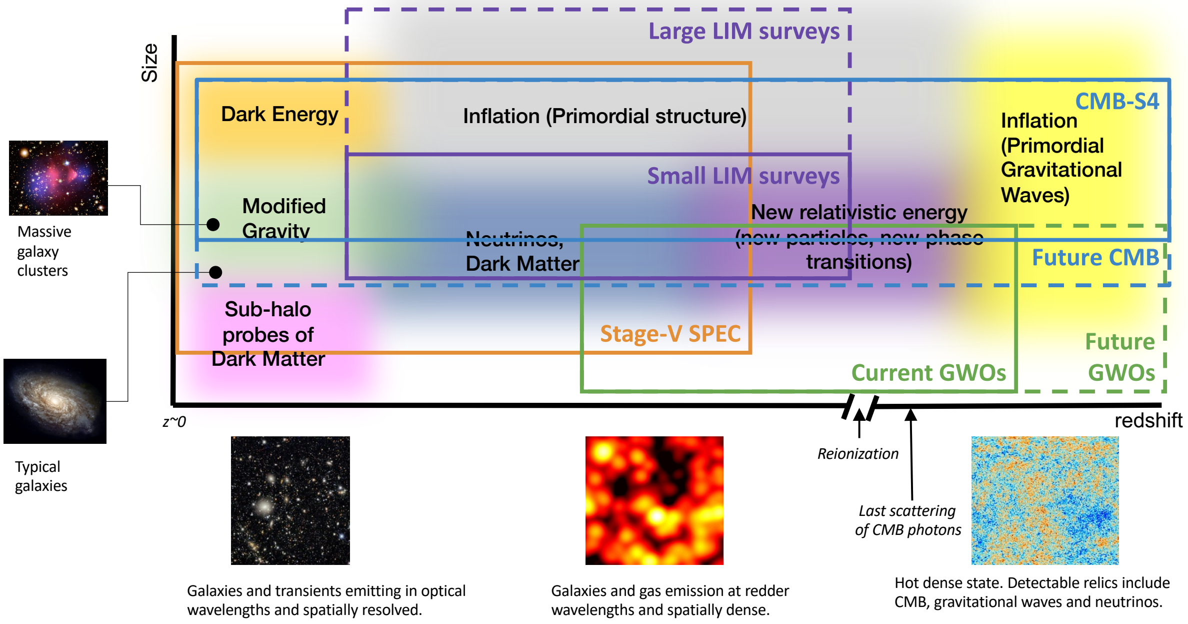

Figure 11: Potential landscape for early universe facilities post 2035 and the focus of technology R&D in 2025–35. The large-scale nature of these facilities and novel survey approach require that the 2025-35 development include fielding instruments to sufficiently advance the readiness of the new technologies for a large scale experiment.

4.2.1 R&D for future 21 cm line intensity mapping

Science goals Neutral hydrogen in the Universe emits 21 cm radiation across cosmic ages and hence forms a probe of structure starting from the earliest epoch after the CMB was formed. In particular:

Dark Ages – $150 \gtrsim z \gtrsim 20$ – The Dark Ages are prior to the formation of the first luminous sources are a particularly clean probe of a large number of modes [203–205] and thus may be used to detect features in the primordial power spectrum [206], PNG [207, 208], test statistical isotropy and homogeneity[209], enable measurements of the neutrino mass [205], constraints on the existence of warm dark matter [203], and exotic searches [210]. Although the instrumentation is challenging, the Decadal panel on Astronomy and Astrophysics 2020 has identified Dark Ages cosmology as the sole discovery area.

Cosmic Dawn and Reionization – $20 \gtrsim z \gtrsim 5.5$ – 21 cm emission traces the first luminous objects as they begin to form in this era. Measurements of velocity-induced acoustic oscillations [211–214] may provide standard rulers at high redshifts and enable precision measurements of the Hubble expansion rate [215].

High Redshift Galaxy Surveys – $z \lesssim 5$ – 21 cm observations at lower redshift form a measurement of large-scale structure through the redshift desert ($z \sim 1$–3) and beyond ($3 \lesssim z \lesssim 6$) where optical spectroscopy is challenging. These experiments target measurements of Dark Energy[216], particularly in the context of proposed explanations that have non-trivial time evolution of dark energy at $z \gtrsim 1$ (e.g., [217–219]); PNG[220, 221], features in the power spectrum[222, 223]; and may constrain the sum of the neutrino masses to otentially the number relativistic degrees of freedom and the sum of the neutrino masses $\lesssim 20\,\mathrm{meV}$ in combination with other probes[224, 225].

Instrument description Detections of the $\mathcal{O}$(100 mK) 21 cm signal from high redshift large scale structure requires high sensitivity on few-degree spatial scales on the sky and good redshift resolution ($\delta z/z \sim 10^{-3}$). As a result the instrumentation is driven towards many (hundreds to thousands) radio detectors built as an interferometer for high sensitivity to a wide variety of spatial scales. Because frequency maps directly to redshift of 21 cm emission, they also operate across a wide bandwidth for sensitivity to a wide redshift range, with many frequency channels commensurate with a spectroscopic survey. These arrays are physically large, with a digital correlator capable of processing many inputs and frequency channels. Future arrays designed for inflation science goals at redshifts $0.3 < z < 6$ will require a close-packed array of $> 10,000$ dishes at least 6 m in diameter [226, 227] across $\sim$ km scales. These future arrays will require us to overcome a few challenges:

Foreground removal – There is now $\sim$ 1 decade of experience using radio telescopes to measure cosmological neutral hydrogen in 'intensity mapping' mode, with detections of large scale structure in combination with optical surveys [228–234], limits on $\Omega_{\rm HI}$ [235], limits on IGM heating at high redshift [236], the 21 cm power spectrum [237–240], and a tension has appeared between results from different global experiments [241, 242]. Current results are limited by their ability to remove bright astrophysical foregrounds from galactic and extragalactic synchrotron emission[**? ?**]. Removing this foreground emission relies on differentiating the frequency dependence between the foregrounds and signal of interest [243–246] which requires good knowledge and control of the instrumental frequency response [247, 248].

Big Data from Large Arrays – The data sets resulting from these future arrays will need to be calibrated and processed in real-time to compress the data for transfer, storage, and analysis.

Technology R&D roadmap Taken together, overcoming these challenges will require a dedicated and phased R&D effort:

- Current generation experiments (e.g. CHIME, HERA, MWA): These experiments are actively pursuing calibration and analysis techniques, data compression, and RFI removal for their science goals. Their results will be critical for informing the design of future arrays.
- Near-term pathfinders (e.g. LuSEE night, CHORD, HIRAX): These experiments are working towards building a suite of simulations for instrument design. In particular, the individual telescopes comprising the array must be uniform to efficiently use current real-time gain stabilization algorithms which feeds back to manufacturing tolerances. Similarly, a flat bandpass response is necessary for foreground mitigation, and simulations are required to quantify the amount of bandpass variation allowed in the design. A uniform array allows efficient compression schemes for correlating the data and redundant array configurations provide the possibility of real-time gain stabilization with a sky model.
- R&D for future arrays: Instrument stability would be made more tractable if digitization could occur at or near the focus of the dish, however a high degree of shielding from the digitizer's radio frequency interference (RFI) would be necessary. LuSEE-Night is likely to act as the first demonstration of nearby digitization. Digitization near the dishes also requires excellent (better than 1 ps) timing between the array elements, and so timing must be distributed across a large footprint with a mechanism for precise timing corrections. In addition, 21 cm arrays find beam measurements challenging because they are designed to have broad beams with poor sensitivity to point sources, and are typically designed as transit telescopes (stationary, non-steerable) to reduce costs. New digital calibrators have been proposed for beam measurements from drones [249] and are being explored by LuSEE-Night as well.

4.2.2 R&D for future mm-wave LIM

Science goals Millimeter-wave line intensity mapping uses low angular resolution, spectroscopic observations of rest-frame far-IR atomic or molecular emission lines to trace large-scale structure [250]. Ground-based observations in the 80–310 GHz atmospheric window are sensitive to multiple CO rotational lines and the [CII] ionized carbon fine structure line originating from an extremely wide redshift range, $0 < z < 10$. A wide-field, high-sensitivity survey could therefore offer a valuable complement to galaxy surveys at $z \lesssim 2$ and a unique probe of higher redshifts. Such a survey would provide access to ultra-large scales and an unprecedented number of modes for testing primordial non-Gaussianity [251], constrain the expansion history in the matter-dominated regime and a wide array of dark energy and modified gravity models [252], and limit neutrino masses beyond the capability of current LSS surveys [253].

Instrument description The observational requirements of mm-wave LIM—high-sensitivity, low-systematics measurements of faint, diffuse structure over large areas of sky—are largely met by contemporary CMB experiments operating in the Atacama Desert or the South Pole. Instead of broadband detectors, however, the LIM measurement requires moderate-resolution spectroscopy ($R \gtrsim 300$) to resolve fluctuations along the line of sight. We envision a straightforward replacement of current or future CMB experiments (ACT, SPT, SO, CMB-S4) with focal planes of high-density, on-chip mm-wave spectrometers [254]. Millimeter-wave LIM surveys can be parametrized by *spectrometer-hours*, and generally become competitive with galaxy surveys in the $\sim 10^7$ spectrometer-hour range. Advances in technology (see below) should allow spectrometer counts in the thousands on typical high-throughput cryogenic CMB receivers, enabling the survey depths necessary for precision cosmology at high redshift.

Technology R&D roadmap Current approaches to mm-wave spectroscopy (diffraction gratings, Fourier Transform or Fabry-Perot spectroscopy, heterodyne detection) are difficult to scale to large spectrometer counts. *On-chip* spectroscopy, in which the detector and spectrometer are integrated on a silicon wafer, offers a natural path to maximizing the sensitivity of mm-wave detectors. However, while prototype on-chip spectrometers are now being demonstrated [255, 256], their spatial packing density is still significantly lower than CMB focal planes (primarily due to the physical extent of the spectrometer on the wafer). Innovation in focal plane geometry and layout will be key to enabling high-density close-packed arrays. Similarly, while on-chip spectrometers have demonstrated spectral resolution of $R \sim 300 - 500$, improving to $R \sim 1000$ would move LIM experiments into the regime of spectroscopic surveys and significantly improve science return and systematics mitigation. This requires development of new low-loss dielectric materials. Finally, spectroscopic pixels require significantly more detectors than their broadband counterparts. Readout development based on state-of-the-art FPGA platforms, such as the RF system-on-chip, promise to dramatically reduce overall readout costs to $1–2 per channel [257].

4.2.3 R&D for future high angular resolution CMB experiments

For CMB science, one proposed next-generation aim is to pursue much finer resolution in a wide-area survey. For example, the CMB-HD telescope [258], a concept under development by some members of the CMB community, targets $15'$ resolution at 150 GHz over 20,000 square degrees.

Science goals. The CMB-HD concept seeks to measure cosmic structure by mapping matter via gravitational lensing to $k \sim 10\,h\text{Mpc}^{-1}$ scales (thus probing dark matter physics) and mapping gas via the thermal and kinematic Sunyaev-Zeldovich effects. The survey's sensitivity would rule out or detect any light thermal relic in the early Universe and rule out or detect inflationary magnetic fields. Other science goals include constraints on axion-like particles, cosmic birefringence, the summed neutrino mass, dark energy, and a variety of astrophysical objects.

Instrument description. The envisioned CMB-HD design calls for a pair of off-axis Dragone telescopes with 30-m primary and 26-m secondary mirrors and image-correcting cold optics. The telescope focal planes will host 1.6 million detectors ($> 3\times$CMB-S4) in seven frequency bands from 30 GHz to 350 GHz. Each detector pixel will measure two frequencies and two linear polarizations.

Technology R&D roadmap. For CMB-HD, research and development efforts are required for the telescope, cryostat, detectors, and detector readout. The crossed Dragone optical configuration requires four ~ 30 m mirrors. Though this design is scaled-up from similar architectures employed by the Simons Observatory large-aperture telescope and CCAT-prime, the nearly 25x more massive mirrors along with more stringent pointing requirements present new challenges for telescope design. The mount for CMB-HD must bear much more weight. In order to achieve sufficient optical stability on a timescale of tens of seconds under thermal, gravitational, and wind forces while scanning, the mirror surface will likely require active shape correction such as a laser metrology system currently being explored by the GBT 100-m telescope. The conceptual design assumes horn-fed detectors, which at higher frequencies, will likely require new mulitplexing capabilities to realize the required pixel density. Potential technologies include new microwave-SQUID TES multiplexers currently being fielded by experiments like Simons Observatory or Microwave Kinetic Inductance Detectors (MKIDs) similar to technologies being developed for the MUSTANG-2 receiver on the GBT and the TolTEC reciever on the LMT at frequencies from 90 GHz to 270 GHz. Significant engineering effort is needed to develop the design and mature the project plan.

4.2.4 R&D for future Gravitational Wave observatories

The next generation of gravitational-wave observatories can explore a wide range of fundamental physics phenomena throughout the history of the universe. These phenomena include access to the universe's binary black hole population throughout cosmic time, to the universe's expansion history independent of the cosmic distance ladders, to stochastic gravitational-waves from early-universe phase transitions, to warped space-time in the strong-field and high-velocity limit, to the equation of state of nuclear matter at neutron star and post-merger densities, and to dark matter candidates through their interaction in extreme astrophysical environments or their interaction with the detector itself. [259]

Scaling the current gravitational-wave detector technology to the needs of the next generation of observatories Cosmic Explorer and Einstein Telescope requires research targeting improvements in squeezing and quantum metrology techniques, the production of large (320 kg) low-loss fused silica optics for test masses, optical coatings with reduced mechanical dissipation, and a low-cost ultra-high vacuum system. Accessing the scientifically interesting low-frequency band also requires improved active seismic isolation, including systems to subtract the direct Newtonian coupling of the seismic motion.

One possible upgrade for the Cosmic Explorer facilities is the technology currently being developed for the LIGO Voyager concept, consisting of a 2 micron laser and cryogenic silicon test masses. This approach would also require the production of large (320 kg) single crystal silicon test masses, a cryogenic cooling system with low vibrational coupling, and improved 2 um wavelength laser technology, particularly low-noise lasers and high quantum-efficiency photo diodes.

5 Theory and Analysis

Theoretical astrophysics and cosmological, modeling building and data analysis are increasingly important to progressing the cosmic frontier. As data becomes larger and more complex, theory and data analysis become critical parts of an experimental mission. In fact, all the facilities this report covers have in common foreground signal subtraction: foreground signature from dust for CMB, foreground contamination to the 21cm line, and Newtonian noise subtraction for GWO. The techniques and limitations in the other fields sounded remarkably similar.

To illustrate just one example of the importance of coupling the development of theory and analysis to that of experiment and observations, consider the measurement of primordial gravitational waves via CMB B-modes. Future surveys of these modes will be limited by galactic dust and gravitational lensing. Without the continued development of the theory and analytical techniques to model and/or remove these additional signals, it will be impossible to reach the potential of these surveys.

Sensitivity to fundamental physics in cosmological probes, as described above, are increasingly limited by astrophysics foregrounds rather then experimental noise. In many cases, there is no clear line distinguishing the theoretical contributions needed to achieve the goals of a specific survey and the broader activities of the theory community. A special feature of cosmic surveys is the dual role of astrophysical effects as a signal and a source of noise. The apparent foregrounds may themselves encode important information about the fundamental laws. For example, gravitational lensing decreases our sensitivity to parameters in the primary CMB, such as r and $N_{\rm eff}$, but is itself used to measure the sum of the neutrino masses, $\sum m_\nu$. These kinds of secondary signals have already been proven to be powerful cosmological probes in their own right.

In this section, we will highlight a few concrete examples where theoretical and analysis techniques are essential and require future investment.

5.1 From Theory to Observations

Fundamental Physics in Cosmic Surveys

The cosmological information from the next generation of surveys will increasingly arise from nonlinear structures at low-redshift, whether it comes in the form of CMB secondaries (lensing,SZ) or directly mapping galaxies or other tracers of nonlinear structure. Isolating the physics of inflation, dark matter, neutrinos, etc. from the physics of structure formation itself is essential to maximizing the scientific return from these surveys.

Both past, current and future analyses of these surveys have relied on theoretical insights to make this split possible. Famously, the use of the BAO as a probe of the expansion [260] of the universe arose from the understanding that the signal was robust to nonlinear corrections [261]. Fundamentally, the BAO signal is associated with the acoustic horizon at recombination that is vastly larger than the scale associated with nonlinearity. Related ideas have inspired the measurement of $N_{\rm eff}$ [262, 263] and primordial features [260] in LSS survey and play a critical role in these analyses that are needed to achieve the sensitivity outlined in this report. Less targeted analyses do not reproduce the same sensitivities because the usual split between the linear and nonlinear regimes would exclude modes that contain these signals.

The search for primordial non-Gaussianity in LSS surveys has also been driven by theoretical developments. Future constraints on local non-Gaussianity will be driven by LSS surveys (with the assistance of CMB lensing [264]) because of discovery of scale dependent bias [265]. Nonlinear structures, like galaxies, form differently in the presence of local non-Gaussianity and give rise to a signal at large distances that cannot arise from Newtonian physics. Further theoretical work showed how this same effect enables a measurement of $f_{\rm NL}^{\rm loc}$ without cosmic variance [266]. From understanding the space of inflationary models, it has also been understood that this is a unique signal of multi-field inflation [267] and the above analysis can be generalize to extract the mass and spin of these additional fields [268].

In contrast, the search for equilateral-type non-Gaussianity will depend crucially on continued theoretical developments in the next decade [269]. The equilateral bispectrum generated during inflation is highly degenerate with the bispectrum that arises from nonlinear effects and presents a serious challenge to these analyses. Analysis are further challenged by the presence of redshift space distortions and bulk flows. A number of theoretical techniques [270–272] have been developed to confront these challenges that use our fundamental understanding of both the inflationary physics and the nonlinear structure formation to try to disentangle these effects. In addition, there is reason to believe that the initial concerns arise by the correlation of the bispectra overstates the degeneracy in the maps that could be accessible with a number of new analysis techniques [273]. However, these ideas are still far from producing competitive results [274, 275] and continued investments in these theoretical tools is necessary to reach the observational aspirations of the community.

More generally, one broad appeal of mapping the universe on large scales is that the history of the universe and any forces that shaped its evolution will be encoded in these maps. As a result, the value of these surveys is expected to grow as new uses for these maps arise from theoretical progress.

Theoretical studies of FOPTs

Theoretical and numerical modelling of phase transitions is a very active area. Four parameters are critical for determining the GW production: the nucleation temperature T_*, the bubble wall velocity v_w, the FOPT's strength α and its inverse duration β. Multiple open questions are under investigation focused on estimating these parameters. First, a perturbative treatment of the finite temperature potential is known to breakdown. The central problem is that the expansion parameter at finite temperature involves a mode occupation which diverges when the mass vanishes [276]. Currently, only the technique of dimensional reduction [277, 278] performed at NLO using an $\hbar$ expansion provides a prescription to calculate thermodynamic parameters at $O(g^4)$ in a gauge independent way [51, 279]. This method is challenging to use and has been applied to benchmarks in very few models. Proposed alternatives to dimensional reduction [280, 281] are in need of further development and testing. Second, an accurate evaluation of the nucleation rate $\Gamma_{\rm nuc}$ and its evolution with temperature is critical for defining the characteristic time scales of the transition. For sufficiently fast transitions, T_* and β can be obtained by linearizing the rate near T_*. This breaks down for slow transitions, which can be of great phenomenological interest, where the next order corrections must be accounted for [282]. A number of other issues that affect the nucleation rate also require further study [161]. Third, the bubble wall speed can be calculated via different formalisms whose applicability depends on the relative strengths of the transition that determine whether the terminal speed will be only mildly relativistic or ultrarelativistic. This is also investigated by many authors [68, 161, 283–290].

In non-thermal transitions, the vacuum energy released in phase transitions can far exceed the surrounding radiation energy [291, 292]. Here the bubble expansion mode has two possibilities [293]: (i) strong detonation, where the wall reaches a terminal velocity due to balancing between the outward pressure and the friction, and GW production comes from a highly relativistic and concentrated fluid around the bubbles, and (ii) a runaway, where the wall continues to accelerate until it collides producing GWs [35]. Both scenarios are being investigated, e.g. through the bulk flow runaway model [294–296], and the sound shell detonation model [41, 297].

In addition, both purely hydrodynamic and magneto-hydrodynamic (MHD) turbulence are expected to source GWs [298]. Past analyses have evaluated the GW production using semi-analytical modelling [42, 43, 299–303]. Simulation-based approaches are also being pursued [44, 304–307].

GW-EM Correlations

Many SGWB models, astrophysical and cosmological, also yield predictions for other observables, such as the CMB, the distribution of galaxies across the sky and redshift, and the distribution of dark matter throughout the universe. It is therefore expected that cross-correlating the SGWB spatial structure with spatial structures in electromagnetic (EM) observables would enable new probes of the underlying physical models and of the earliest phases of the evolution of the universe [308–329]. Such spatial correlations can be studied in terms of the angular power spectrum:

$$D(\theta) = \langle \delta\Omega_{\rm GW}(\hat{e}_1, f), \delta X(\hat{e}_2) \rangle = \sum_{lm} \frac{2l+1}{4\pi} D_l(f) P_l(\cos\theta) \tag{6}$$

where $X(\hat{e}_2)$ describes an EM observation such as the CMB or galaxy count distribution in sky direction $\hat{e}_2$, $\Omega_{\rm GW}(\hat{e}_1, f)$ is the SGWB energy density normalized to the critical energy density in the universe at frequency f and direction $\hat{e}_1$, θ is the angle between the two sky directions $\hat{e}_1$ and $\hat{e}_2$, and P_l are Legendre polynomials. Predictions for the angular power spectrum can already be found in the literature. In the case of phase transitions, the PT would have nucleated at slightly different redshifts in different causally disconnected regions of the universe, giving rise to anisotropy in the SGWB. The SGWB angular structure would not be affected by interactions with the plasma (i.e. effects such as Silk damping and baryon acoustic oscillations are not relevant for GWs), resulting in a simple angular spectrum: $C_l^{\rm GW} \sim [l(l+1)]^{-1}$ [325]. Assuming the PT happened after inflation, the primordial density fluctuations that led to the CMB angular spectrum would also have been present during the PT, imprinting a SGWB anisotropy at least as large as the CMB anisotropy [325].

In the case of cosmic strings, the angular spectrum would depend on fundamental parameters of cosmic strings (string tension, reconnection probability), and on the network dynamics model. While the isotropic (monopole) component of this SGWB may be within reach of the advanced or 3G detectors [330], the anisotropy amplitudes are found to be $10^4 - 10^6$ times smaller than the isotropic component, depending on the string tension and network dynamics [309, 331]. This level of anisotropy may be within reach of the 3G detectors. Correlating the anisotropy of this SGWB with anisotropy in the CMB or large scale structure may reveal details about the formation and dynamics of the cosmic string network.

In the case of primordial black holes (PBH), cross correlating the sky-map of the SGWB due to binary black hole (BBH) signals with the sky-maps of galaxy distribution or dark matter distribution could provide additional insights on the origin of black holes [332–335]. In particular, PBH binaries are more likely to form in low-mass halos where typical velocities are smaller and binary formation through GW emission is more likely. On the other hand, stellar black holes are more likely to form binaries in more luminous galaxies (with more massive halos). Studying the correlations of the BBH SGWB anisotropy with distributuon of visible and dark matter on the sky can therefore be used to probe the origin of the BBH systems and their potential dark matter component.

Techniques for conducting GW-EM cross correlation studies are currently under development [336–338]. However, much more remains to be done in order to fully explore the potential of this approach: develop appropriate statistical formalisms for parameter estimation; systematic studies to understand the angular resolution of GW detector networks; development of theoretical models of SGWB-EM anisotropy correlation; studies delineating the astrophysical and cosmological components of the SGWB, and others.

5.2 Simulations and Analysis

Astrophysical modelling

Large-scale cosmological simulations are central to modelling astrophysical foregrounds and systematic effects. These simulations provide the testing suite to understand the interplay of these effects with the signals from gravitational waves. The challenges facing the simulation community include simulating large enough volumes to capture both large scale effects while still having resolution to reach low mass objects [339]. Relying too closely on sub-grid modelling can lead to biases in the foreground simulations, and an inability to distinguish new physics from foreground modelling [340, 341]. Similarly, accurate modelling of neutrino physics in terms of their impact on the clustering of matter (which in turn impacts the lensing power spectrum of the CMB, and is therefore degenerate with other parameters) may require a hybrid approach between hydrodynamical and N-body simulations, perturbative methods and improved sampling of the full six-dimensional neutrino phase space [342–344]. Another need for progress in simulations comes from $21\,\mathrm{cm}$ experiments. While the Dark Ages is relatively straightforward to simulate (often involving just linear physics), the later phases of the reionization and post-reionization universe are non-trivial. Reionization simulations require large dynamic ranges in scale, since the reionization is driven by the uncertain small-scale astrophysics of the first luminous sources, modulated by large scale cosmology. The post-reionization universe is arguably slightly simpler, but uncertainties still exist (such as the uncertainty in the halo mass to HI mass relation), which must be modeled or at least parametrized with enough flexibility. These large-volume and high-resolution simulations are not only required to model a cosmological effect itself. Estimates of the covariance matrix typically require many realizations of a given model to supplement any analytical estimates of the covariance. Here approximate methods and machine learning techniques prove useful. Finally, with cross correlations between multiple probes (e.g., $21\,\mathrm{cm}$ and galaxy surveys) being important both from a standpoint of science and from a standpoint of systematics, self-consistent simulations will be of crucial importance.

Data analysis pipeline development

As models become more and more complex, efficient sampling of parameter space for statistical inference becomes prohibitively slow with standard Monte Carlo sampling techniques. In some cases, a smaller number of high-quality simulations are produced and statistical ‘emulators’ are used to interpolate between nodes when sampling. Development of emulators that connect theories across a range of observables, and that include the foreground modelling described above are needed to integrate this theoretical framework into an experimental context.

Similarly, many of the current emulators have been built around models close to the ΛCDM paradigm, and on gravity-only simulations. Extending the model space and coupling the advances in hydrodynamical modelling with those in fundamental theory model-building will be key to ensuring that future observations are able to make contact with theory [339].

High performance computing requirements form an integral part of planning and costing for future cosmic experiments like CMB-S4 (which will have an estimated 70 TB/day or 800 MB/s data rate) or any $21\,\mathrm{cm}$ cosmology experiment (which already have such a data rate). Efficient pipeline development for signal processing and map-making of large volumes of data, foreground cleaning and parameter sampling will be needed to ensure processing of data in a timely manner for release to the community. Much of the algorithmic development of analysis pipelines and tools starts with individual researchers undergoing university-funded research. Supporting this research is critical to developing the tools and techniques needed to maximize scientific return on investment in experiment.

Shared tools and frameworks

Using bespoke software for individual experiments can lead to replication of analysis pipelines on common elements. While redundancy and independence of different groups is essential to reducing systematic experimental bias, development of common and shared tools for some parts of the analysis pipeline will lead to improvement in delivery of results. An example of efforts in this area is the Core Cosmology Library [345], a common library of cosmological observables given an input cosmological model. In particular this propagates the modelling of astrophysical uncertainties across probes, removing inconsistencies in approach linking fundamental physics to astrophysical uncertainties, which is of particular interest when cross-correlating different probes.

Coordination between groups and experiments in software development and theory support is critical to make the most of the observations planned for the coming decade. Several white papers submitted to this group report on the need for dedicated theory and simulation efforts e.g. to model the distribution of dark matter on astrophysical scales, to distinguish between dark matter physics and early universe models [346], 21-cm modelling for upcoming experiments [347] and to develop the tools and techniques for data mining of the large data sets that will be generated by upcoming facilities [348].

5.3 Astrophysical Foregrounds

CMB

The cosmic microwave background to date has provided our most precise measurement of cosmological parameters. As the next generation of surveys produces maps of increasing depth [349–351], the use of CMB data will require theoretical techniques that separate the primary CMB from a variety of secondary effects. CMB photons are gravitationally lensed by the intervening matter [352] and scattered [353] by ionized electrons. Ongoing theoretical work into the nature of these secondary effects has led to techniques to separate these various contributions to the CMB maps based on their statistical properties and frequency dependence. CMB secondaries thus give rise to new maps for the distribution of matter in the universe and the locations of high redshift galaxy clusters. From these secondaries, we gain new insights into the history of the universe and fundamental physics. CMB lensing with the next generation of cosmic surveys is a central tool in constraints on (and eventually, detection of) a non-zero sum of the neutrino masses [354] or the energy density in other hot relics [39].

Galactic foregrounds present an additional challenge to CMB measurements, particularly the constraints on r from polarization B-modes [355, 356]. Polarized dust emission in our galaxy contaminates our measurement of both E-modes and B-modes [357]. The amplitude of the dust B-mode at CMB frequencies is larger than the gravitational wave signals consistent with current limit. As a result, dust foregrounds must be removed from the maps in order to reach future r targets [358]. Our understanding of dust emission from first principle is insufficient for these purposes but has been bolstered by simulations [359, 360] and data-driven techniques [361, 362]. Continued research into the dust foregrounds and techniques to remove them will be essential for the success of surveys like the Simons Observatory [363], CMB-S4 [350] and CMB-HD [351].

21cm Foreground Removal

Foregrounds—and their interaction with the non-idealities of one's instrument—are arguably the chief obstacle in $21\,$cm cosmology. The challenge is in some ways greater than with the CMB, given that even the coolest parts of our Galaxy contain foregrounds that dwarf the cosmological signal by orders of magnitude. Compounding this problem is foreground modeling *uncertainty*, which is considerable given the lack of high-quality, all-sky maps at low frequencies. Further observations at relevant low-frequency bands will reduce this uncertainty, but this must be coupled with detailed studies of algorithms that incorporate knowledge of how foregrounds appear in the data when processed through instrumental systematics, as discussed in Section 4.2.1.

SGWB Foreground Removal

Since the detection of the first binary black hole merger in 2014, GW detectors have observed nearly 100 such events. With the increased sensitivity, the upcoming observation runs of Advanced LIGO, Advanced Virgo, and KAGRA are expected to yield one detection per day. The next (3rd) generation of GW detectors, Einstein Telescope and Cosmic Explorer, are expected to observe $10^5 - 10^6$ binary merger events per year. These signals will form astrophysical foreground masking the cosmological contributions to the SGWB.

Removal of this foreground is a significant challenge and the necessary technology currently does not exist. The first challenge is to enable parameter estimation of multiple merger signals overlapping in time (and in frequency) domain. At the moment, parameter estimation techniques rely on the assumption of a given time segment containing at most one binary merger. The second challenge is to remove the individually observed binary signals. This could be done by notching out the individually detected binary signals in time-frequency space, by subtracting the binary signals from the GW detector strain data [364–366], and by simultaneously fitting all binary signals along with the SGWB present in a given data segment [337, 367]. At the moment, none of these approaches have been developed to the point that their application to 3G GW detector data is possible.

6 Conclusion

Measurements of the early Universe have the potential to access physics at GUT scales and provide evidence for light relic particles, axions, phase transitions, and neutrinos. Physics at these scales can be measured through a few complementary probes: measurements of the Cosmic Microwave Background at large and small scales, gravitational wave observatories, and surveys of structure through cosmic time.

Measurements with the CMB and GWO seek to detect primordial gravitational waves. A measurement from CMB-S4 would allow a measurement or constraint on the amplitude of inflationary gravitational waves down to $r < 0.001$. If measured by CMB-S4, inflation would have occurred near the energy scale associated with grand unified theories, thus a detection would probe physics at $10^{16}\,$GeV energy scales and provide evidence for quantum gravity. GWOs can search for deviations of the primordial gravitational wave spectrum from the predicted scale invariant shape and constrain more exotic and complex inflationary scenarios. And, in combination, CMB and GWOs may also be used to identify or rule out alternatives to inflation.

The primordial power spectrum of quantum fluctuations generated during inflation can measure the interactions of the inflaton. Currently, the best constraints to-date come from the '2D' measurements available in the CMB, but these measurements have nearly reached their statistical limit. In principle, measurements in '3D' with large scale structure through cosmic time can dramatically improve these measurements. Measurements of Large scale structure have been incredibly successful using optical surveys of galaxies out to redshifts $z < 1$ and quasars at higher redshifts (SDSS, DESI). Future directions for this area include improved spectroscopic surveys, and "line intensity mapping" which holds promise for more easily reaching large volumes and the statistics necessary for inflationary constraints. In particular, using low angular resolution surveys to detect the 21 cm emission line from neutral hydrogen or rest-frame far-IR lines in the millimeter band, aggregated over many galaxies to increase signal-to-noise, can efficiently survey cosmic structure beyond the redshift reach of spectroscopic galaxy surveys. Due to the abundance of neutral hydrogen, 21 cm surveys have access to the entire redshift range from $(150 \gtrsim z \gtrsim 0)$, with varying astrophysics and instrumentation challenges at play. Millimeter-wave measurements can similarly probe structure from $10 \gtrsim z \gtrsim 0$ with different foreground and measurement challenges, and take advantage of decades of experience with similar instrumentation from the CMB community. Measurements at the highest redshifts in this range are an incredibly clean probe of the primordial power spectrum but are quite challenging, while taking full advantage of all scales at redshifts $5.5 < z < 2$ will require additional modelling into the non-linear structure formation regime. However, even if the non-linear structure ultimately limits a measurement of non-Gaussian features from LSS, measurements from a high-redshift survey constrain the expansion history of the Universe and hence Dark Energy (see CF4), including 21 cm measurements of Cosmic Dawn and Reionization which can serve as clean standard rulers at high redshifts—even in the presence of the astrophysics of Cosmic Dawn. This would enable precision measurements of the Hubble expansion rate [211–215], and measurements at lower redshifts, $z < 5.5$, from a galaxy survey for constraints on the expansion history and Dark Energy.

We strongly recommend that we take advantage of the unique physics possible in CF5 to build a program of experiments and R&D:

- Support upcoming and ongoing efforts in the CMB, GWO, and optical surveys of galaxies

- Support theory and analysis required to take advantage of combined surveys, large data sets, and model-building required to exploit the full physics available in these measurements (including accessing non-linear scales and foreground removal). This also includes research in theory required to explore where these measurements lie in fundamental particle physics.

- Explore R&D for future experiments that have capabilities beyond the 2030-era experiments, including 21cm and mm-waveLIM, CMB measurements, and GWOs.

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