FEEDBACK & DISCUSSION

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

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[1]Topical Group Convener

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EXECUTIVE SUMMARY

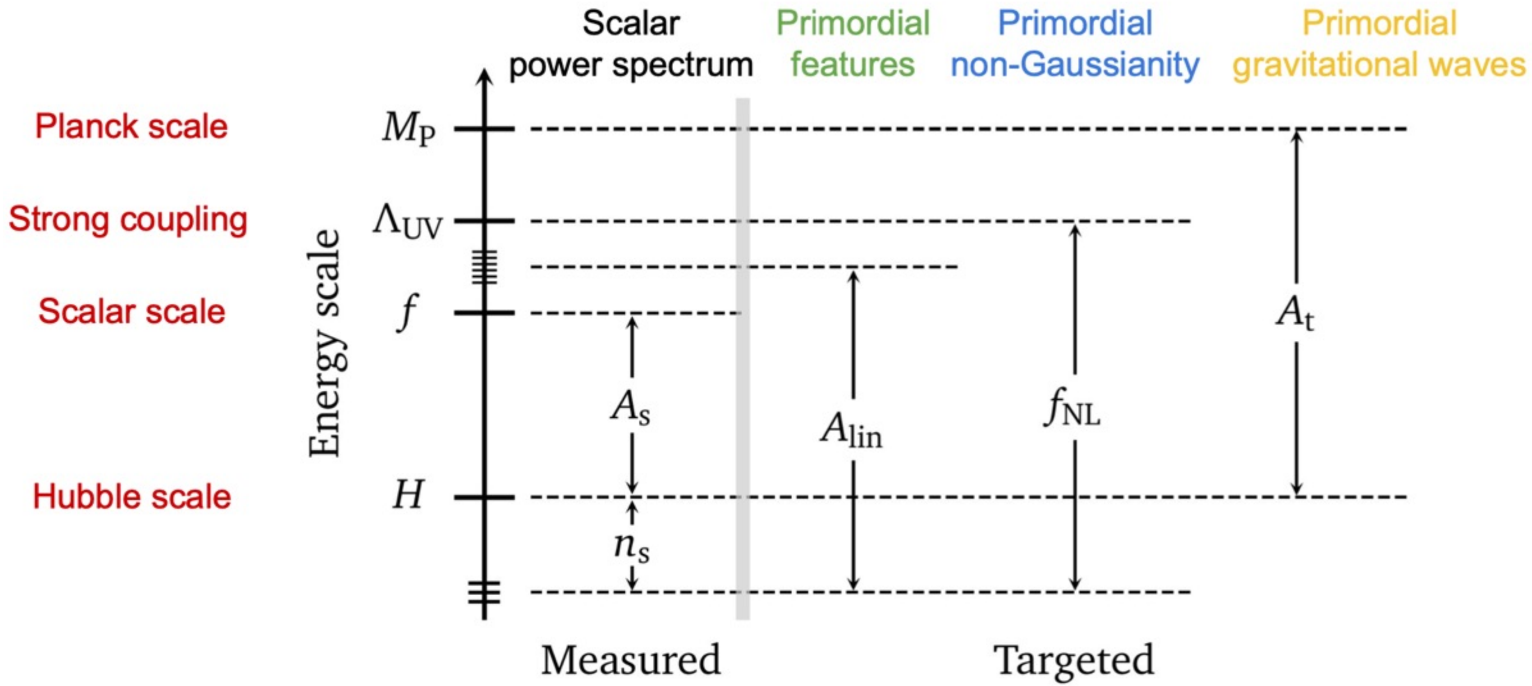
Targeting this decade (~2025-35) with and eye towards 2050

- Scientific themes
  - Inflation: explore, constrain, discover physics beyond A_s and n_s
    - Tensor perturbations, non-Gaussianity, deviations from scale invariance
  - Relic radiation: constrain and discover physics beyond cosmic microwave and neutrino backgrounds
    - Light relics, new phases, neutrino physics
- Major facilities
  - CMB-S4, Current GWOs, new Stage-V Spectroscopic survey
- Enabling capabilities
  - Theory aligned w/ facility science: model building, predicting and calculating new observable phenomena, modeling and simulating astrophysical and cosmological signals, and building analysis pipelines.
  - Instrumentation to enable next-decade facilities (CMB, GWO, LSS via 21-cm & CO/CII Intensity Mapping) through fielding small experiments.

SCIENTIFIC THEMES:
INFLATION AND RELIC RADIATION

INFLATION

Beyond A_s and n_s



→ Access to new energy scales and detailed dynamics of inflation.

arXiv:2203.08128

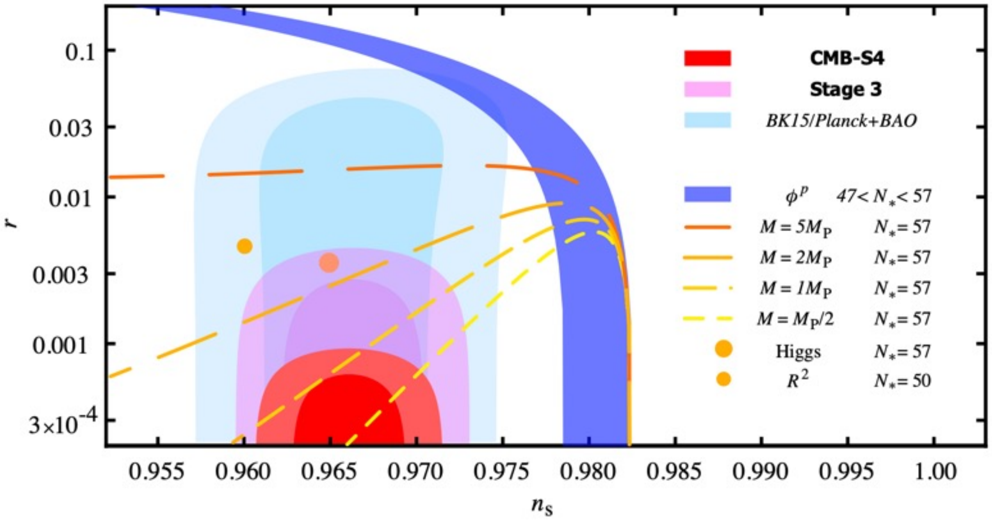
INFLATION

Beyond A_s and n_s

- Primordial GWs
  - Sourced by inflation, amplitude is related to energy scale, constrains distance traveled by inflaton
  - Detection would offer glimpse of quantum gravity?
  - Active area of theoretical research. Non-detection constrains model space.
- Non-Gaussianity
  - Robust probe of inflationary interactions (number of light degrees of freedom, curvature self-interactions)
  - Active area of theoretical research (cosmological collider physics, connections to Standard Model of particle physics, non-perturbative techniques for rare-but-large fluctuations, ...)
- Features in primordial spectra
  - Generic in broad classes of models beyond simplest. New energy scales.
  - Ubiquitous when connecting inflationary modeling to fundamental physics

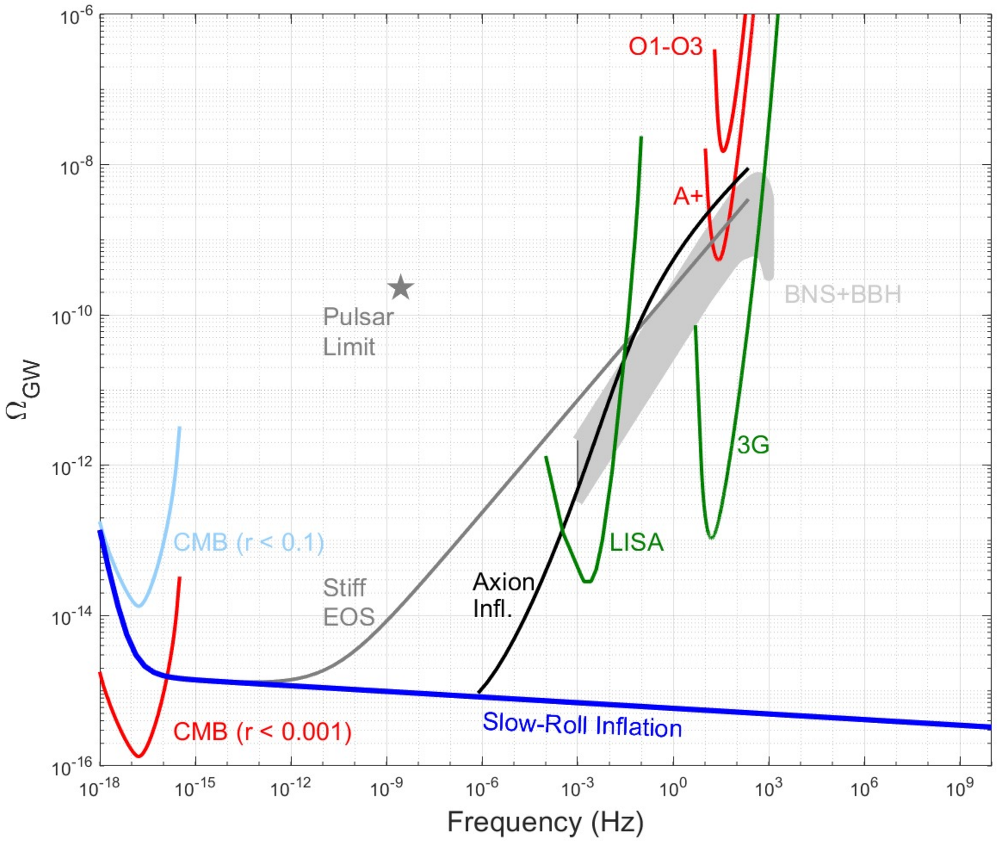
PRIMORDIAL GWS

- $r \gtrsim 0.01$
  - Super-Planckian inflaton field excursion,
  - Evidence for approximate shift symmetry in quantum gravity.
- $r \gtrsim 0.001$
  - Evidence for the simplest models of inflation which naturally predict observed n_s and have a characteristic scale > M_P.
- $r \lesssim 0.001$
  - Vast restriction of inflationary model space



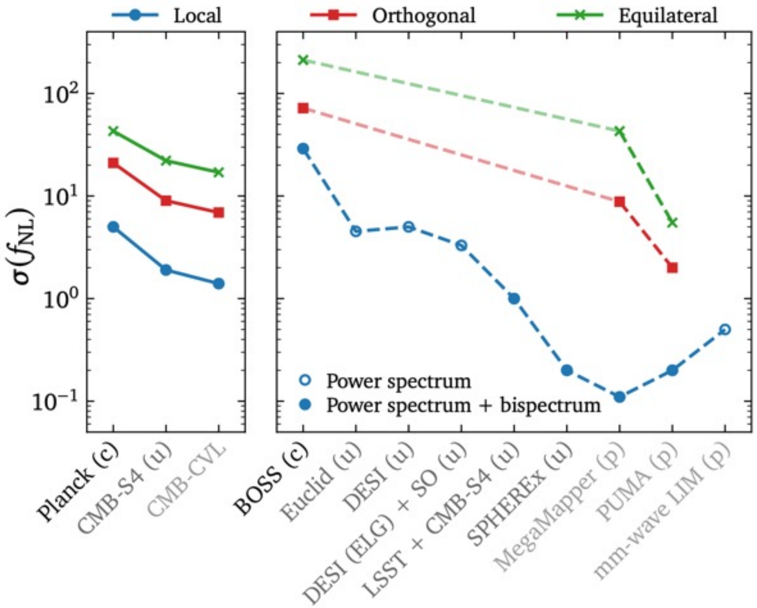
PRIMORDIAL GWS

- Simple inflation models predict scale invariant GW spectrum
  - Out of reach of envisioned instruments
- Richer physics can modify PGW spectrum
  - Potentially detectable with GWOs as SGWB
  - Multiple observations constrain amplitude and spectrum



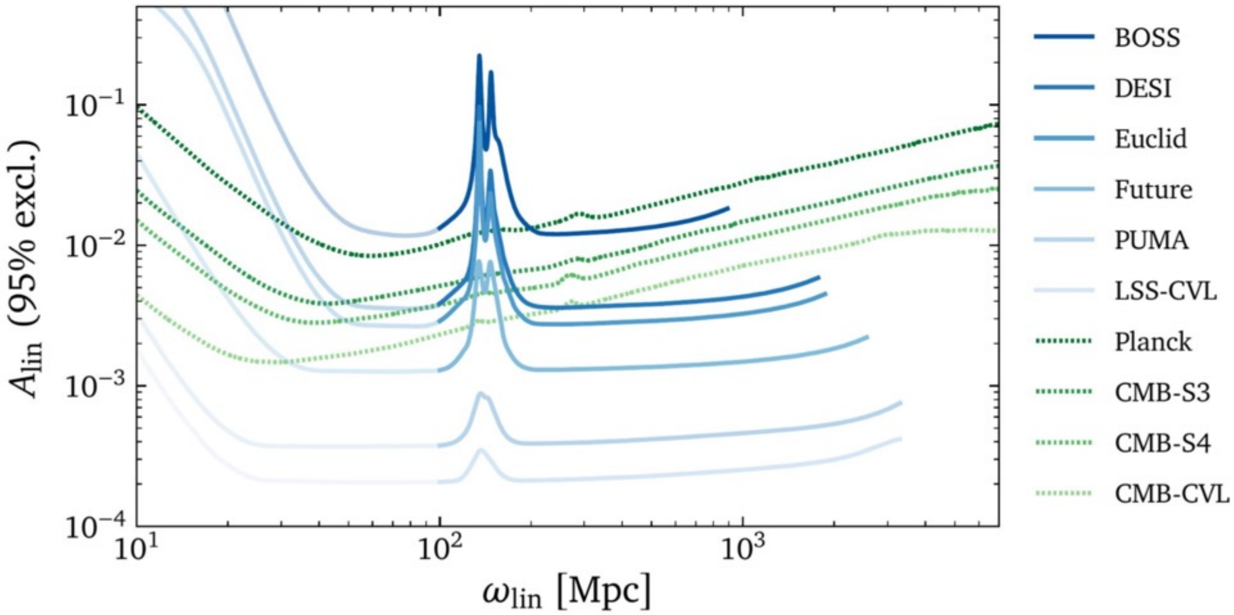
NON-GAUSSIANITY

- $f_{NL}^{local} \gtrsim 1$
  – Differentiate models with extra light species during/after inflation.
- $f_{NL}^{equil,\ ortho} \gtrsim 1$
  – Inflaton likely has subluminal sound speed,
  – Constrain the symmetry breaking patterns of inflation.
- Detailed shape information:
  – Detect new particles mediating self-interactions & particle spectroscopy.
- Non-detection:
  – Constrain large classes of models,
  – Point to favored directions in “theory



PRIMORDIAL FEATURES

- Improve constraints by more than an order of magnitude



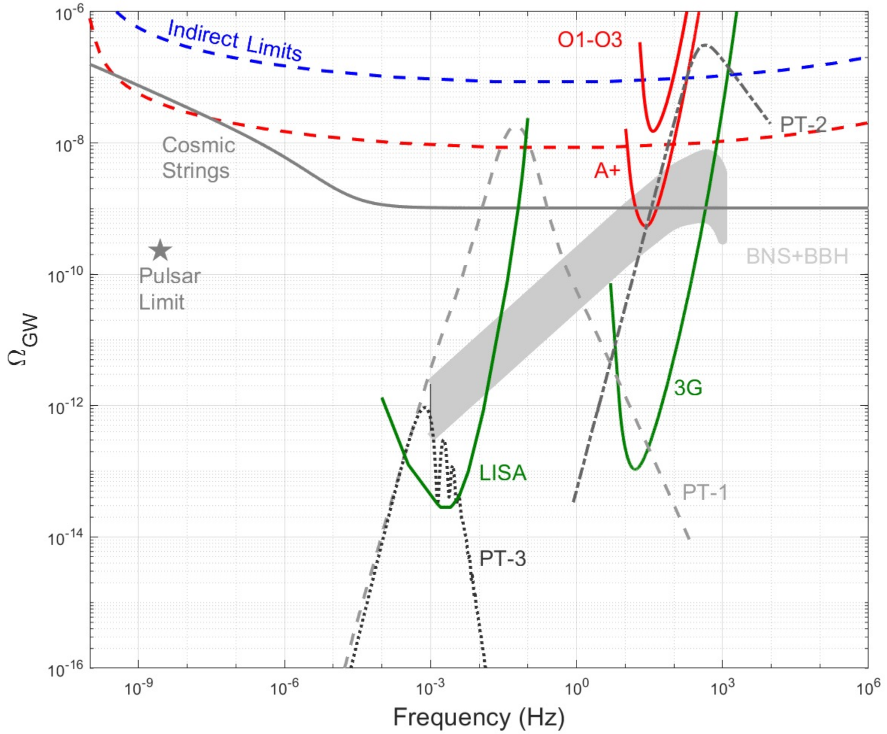
RELIC RADIATION

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

- "Hot Big Bang" + SM
  - Only relics nuclei, CMB, CNB (and CDM, which isn't SM…)
  - Predicted CNB energy density is $N_{\rm eff} = 3.045$
  - Detection of any departure from this predicted energy content is direct evidence of new physics

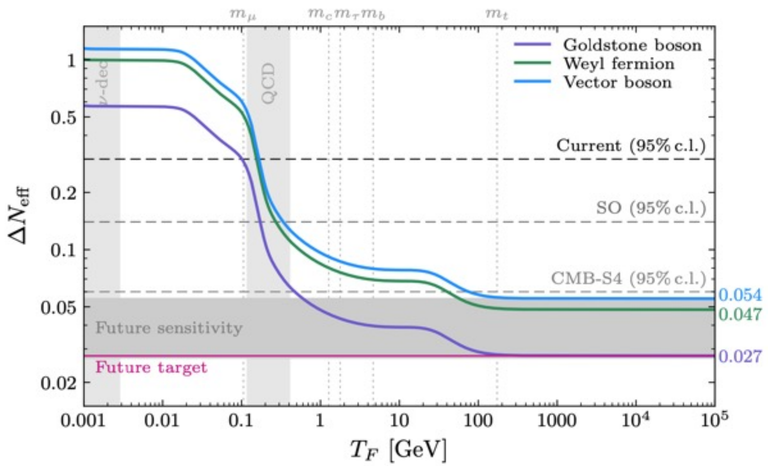
RELIC GWS

- First Order Phase Transitions
  - QCD transition, multi-step phase transitions, B-L breaking, flavour physics, axions, GUT symmetry breaking chains, supersymmetry breaking, hidden sector involving scalars, neutrino mass models, confinement
  - New physics making EWSB a FOPT complements collider searches
- Topological defects
  - domain walls, textures, cosmic strings

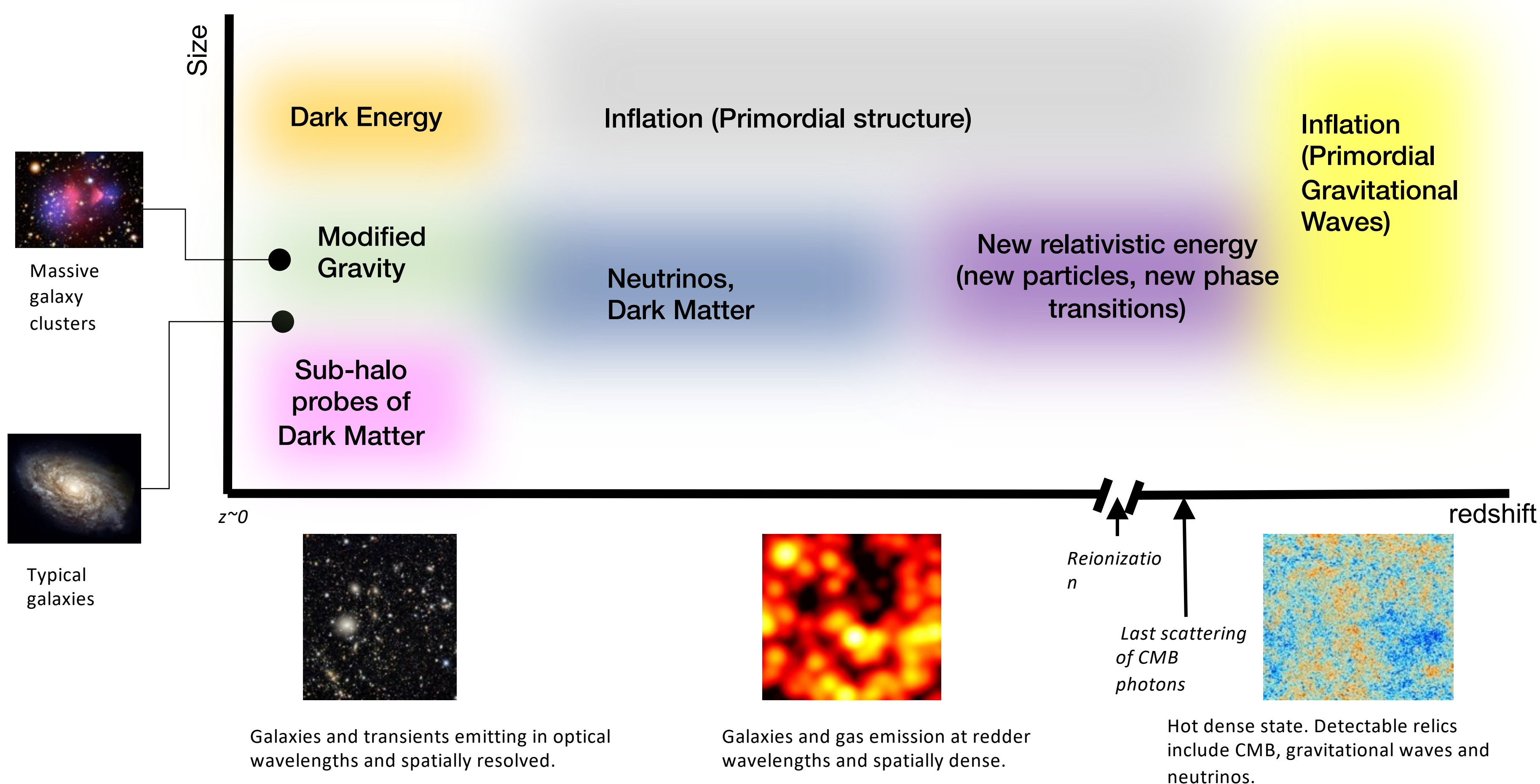


RELIC PARTICLES

- New physics that addresses hierarchy problem, Strong CP problem, cosmological constant problem, dark matter
  - Often include degrees of freedom that decouple in early universe
  - ΔN_{eff}, small scale clustering
- Axions & ALPs
  - solve the strong CP problem, the hierarchy problem, inflation naturalness
  - naturally arise in string theory as modulus fields from dimensional compactification
  - ΔN_{eff}, small scale clustering, isocurvature perturbations, birefrigence

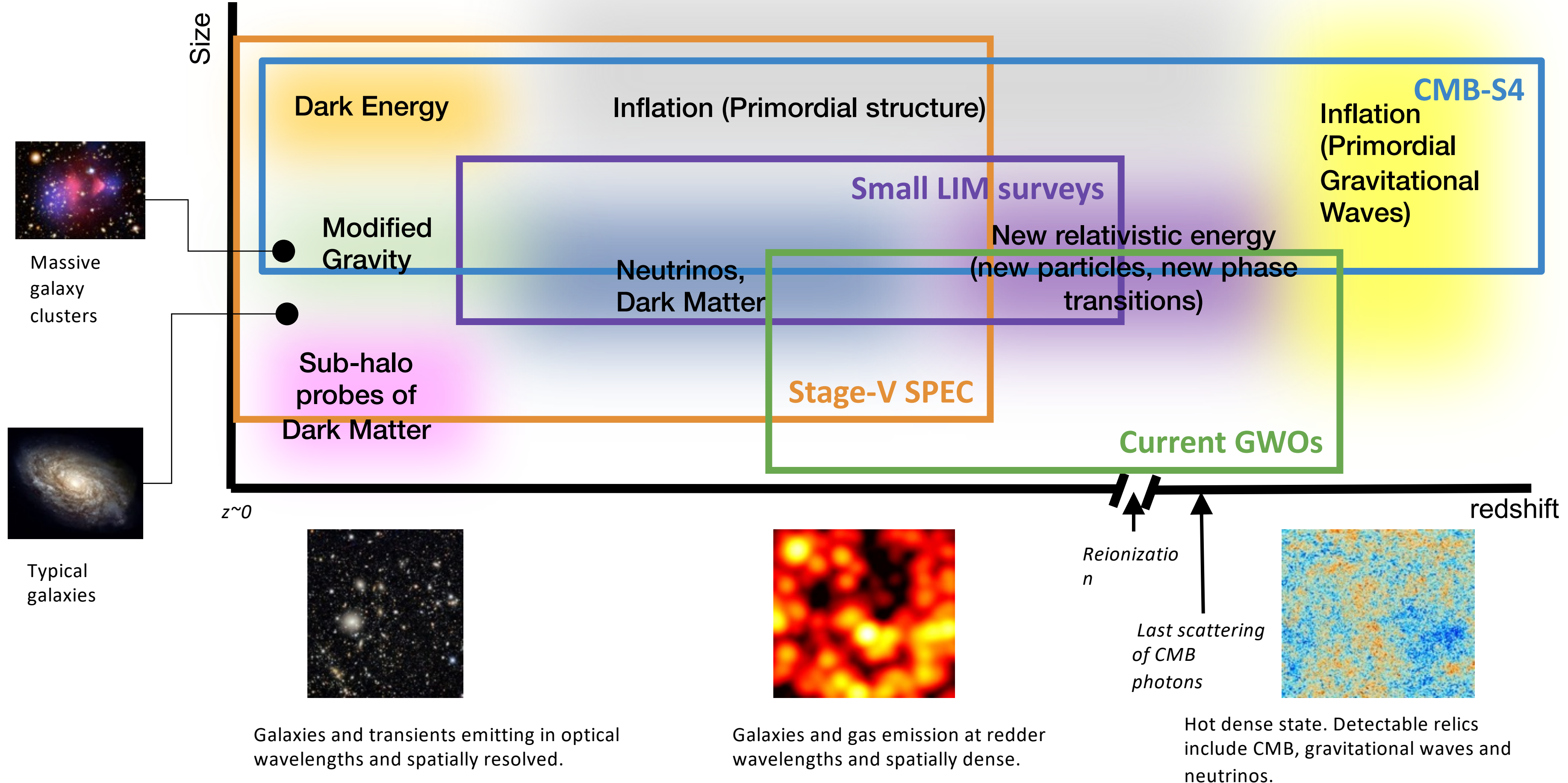


MAJOR FACILITIES



Size
Dark Energy
Inflation (Primordial structure)
Inflation (Primordial Gravitational Waves)
Modified Gravity
Neutrinos, Dark Matter
New relativistic energy (new particles, new phase transitions)
Sub-halo probes of Dark Matter
Massive galaxy clusters
Typical galaxies
z~0
redshift
Reionizatio n
Last scattering of CMB photons
Galaxies and transients emitting in optical wavelengths and spatially resolved.
Galaxies and gas emission at redder wavelengths and spatially dense.
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

This decade…


Size
Dark Energy
Inflation (Primordial structure)
CMB-S4
Inflation (Primordial Gravitational Waves)
Small LIM surveys
Modified Gravity
Massive galaxy clusters
New relativistic energy (new particles, new phase transitions)
Neutrinos, Dark Matter
Sub-halo probes of Dark Matter
Stage-V SPEC
Current GWOs
Typical galaxies
z~0
redshift
Reionization
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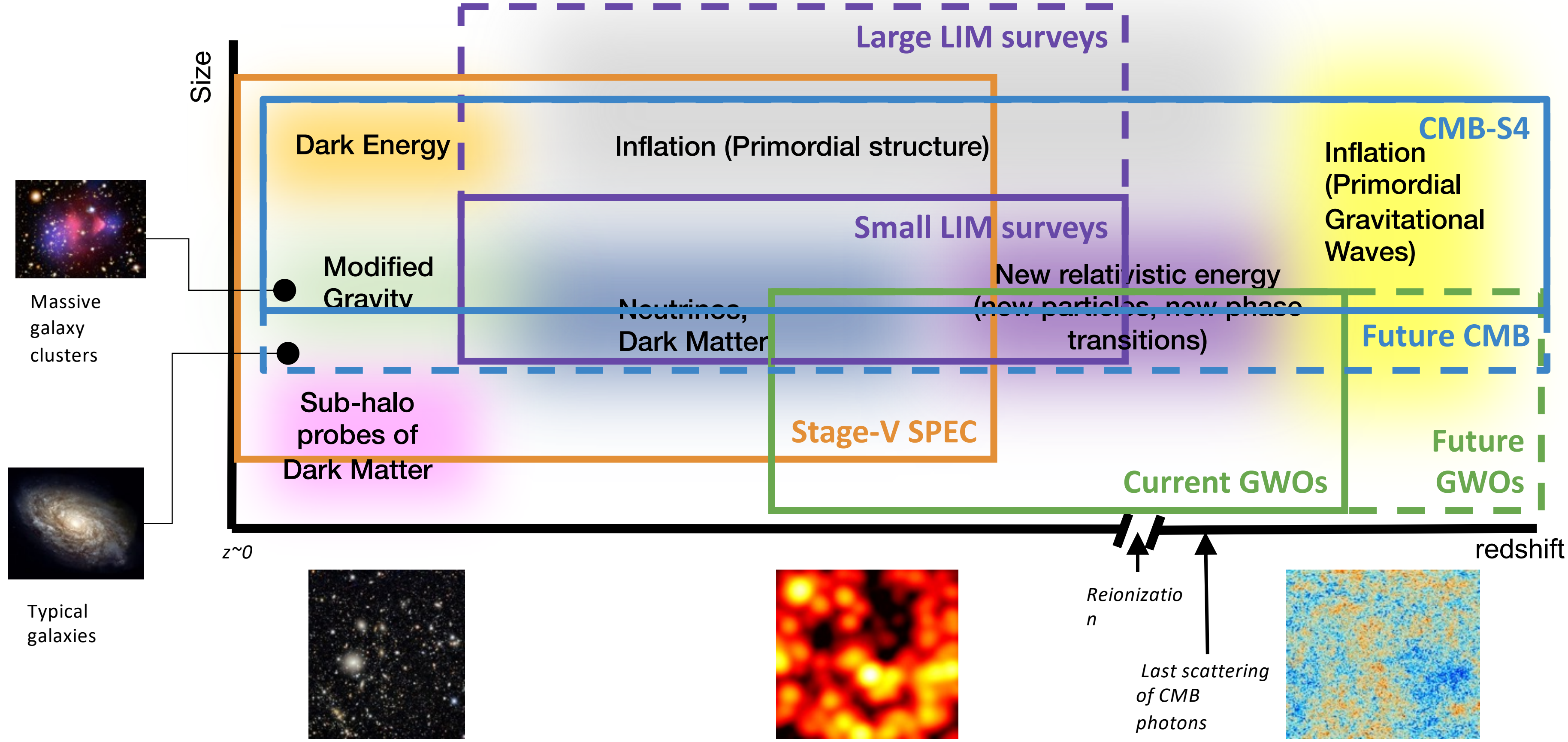
… eye towards the next decade



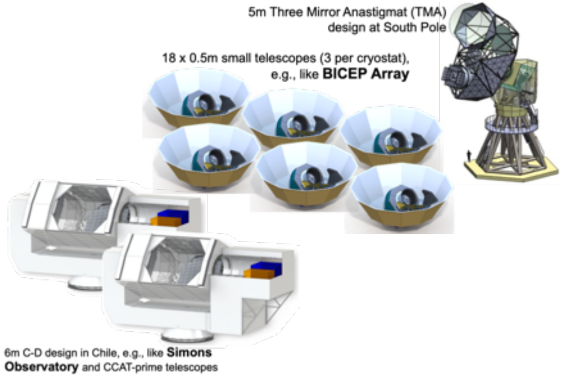
Galaxies and transients emitting in optical wavelengths and spatially resolved.

Galaxies and gas emission at redder wavelengths and spatially dense.

Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

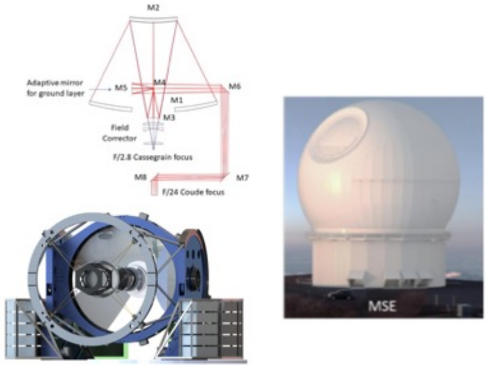
EARLY UNIVERSE FACILITIES IN THIS DECADE

CMB-S4



- Search for inflationary GWs (A_t)
- Measure primordial spectrum (A_{lin}, f_{NL})
- Measure relic radiation

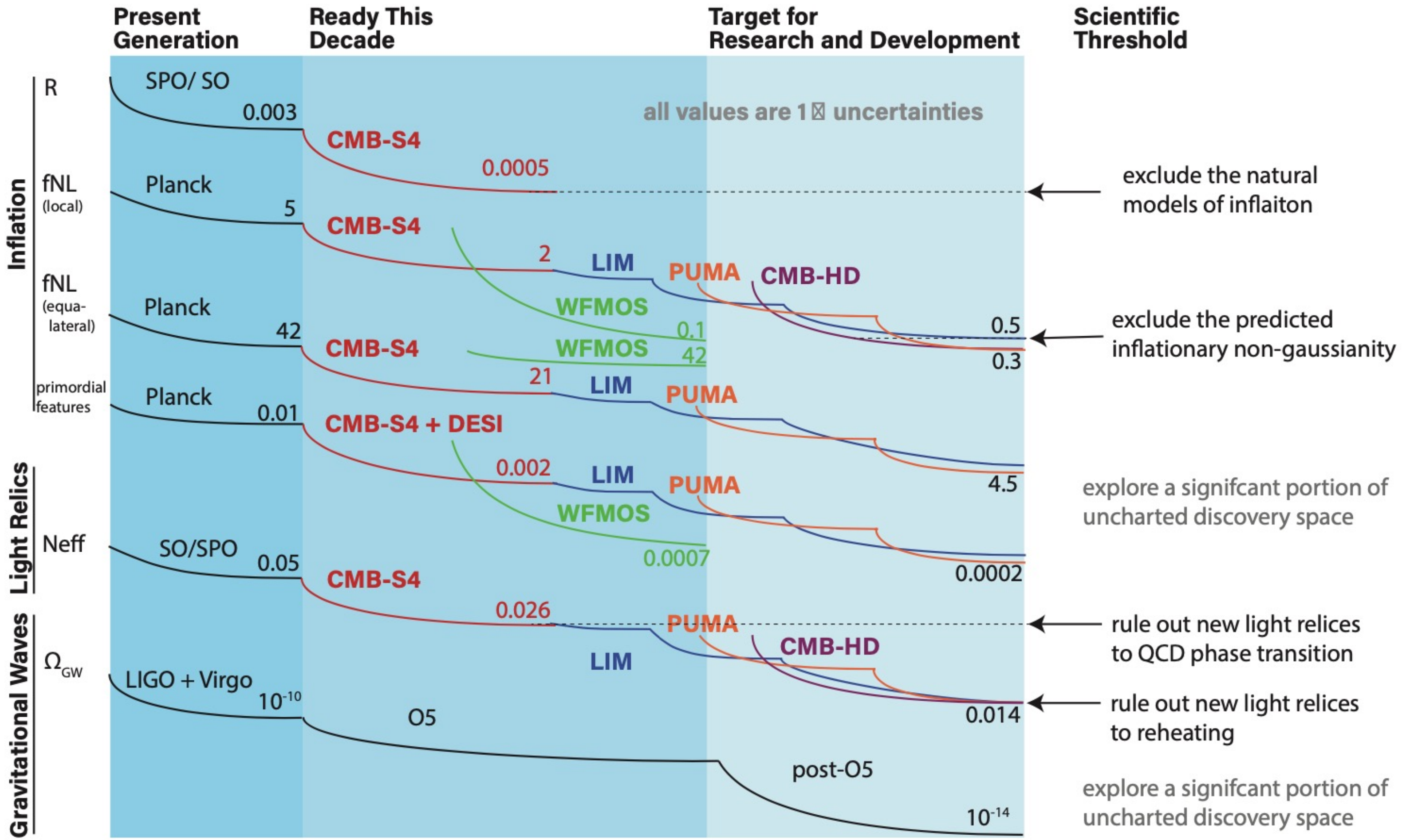
Stage-V spec.



- Measure primordial spectrum (A_{lin}, f_{NL})
- Measure relic radiation
- Measure more modes than CMB

LIGO/VIRGO/KAGRA

- Search for non-scale invariant inflationary GWs
- Measure relic GWs from new physics



Present Generation
Ready This Decade
Target for Research and Development
Scientific Threshold
Inflation
Light Relics
Gravitational Waves
R
fNL (local)
fNL (equa-lateral)
primordial features
Neff
Ω_{GW}
SPO/ SO
0.003
CMB-S4
0.0005
all values are 1⊠ uncertainties
exclude the natural models of inflaiton
Planck
5
CMB-S4
2
LIM
PUMA
CMB-HD
WFMOS
0.1
0.5
0.3
exclude the predicted inflationary non-gaussianity
Planck
42
CMB-S4
WFMOS
42
21
LIM
PUMA
Planck
0.01
CMB-S4 + DESI
0.002
LIM
PUMA
WFMOS
4.5
explore a signifcant portion of uncharted discovery space
0.0007
0.0002
SO/SPO
0.05
CMB-S4
0.026
PUMA
CMB-HD
LIM
rule out new light relices to QCD phase transition
0.014
rule out new light relices to reheating
LIGO + Virgo
10^{-10}
O5
post-O5
10^{-14}
explore a signifcant portion of uncharted discovery space

ENABLING CAPABILITIES

THEORY

Some examples (not comprehensive)

- Fundamental theoretical insights about models and observables
  - Historical e.g.: theory of CMB acoustic oscillation framework, BAO
  - E.g.: research into non-gaussianity (evading CVL? Ortho and equi bispectra?)
  - E.g.: research into phase transitions, GW-CMB correlations.
- Foreground modeling
  - Dust (CMB polarization), galactic emission (21-cm), line confusion (mm-wave LIM), binary mergers (SGWB)
- Simulations
  - Astrophysical modeling (large range of scales, cross correlation, error estimation)
  - Pipeline development (signal processing, map-making of large volumes of data, foreground cleaning, parameter sampling)
  - Coordinated development of shared tools vs bespoke software

INSTRUMENTATION

Develop the foundation for facilities in the following decade

- CMB: increased detector density (at high frequency), large optics for higher angular resolution
- 21-cm: calibration/stability, digitization & timing, RFI shielding & removal, real time signal processing
- Mm-wave LIM: large focal planes of on-chip spectrometers, increase pixel packing density, increase spectroscopic resolving power, reduce readout cost
- GWO: improvements in squeezing and quantum metrology techniques, production of large (320 kg) low-loss fused silica optics for test masses, optical coatings with reduced mechanical dissipation, low-cost ultra-high vacuum system, improved active seismic isolation
- Requires more than lab demonstrations, fielding new technology (e.g. smaller pathfinder experiments, staged development) is critical
  - Develop integrated systems
  - Mature understanding of experiment operations and systematics

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