FEEDBACK & DISCUSSION

Argonne NATIONAL LABORATORY 75 1946–2021

CF5. DARK ENERGY AND COSMIC ACCELERATION: COSMIC DAWN AND BEFORE

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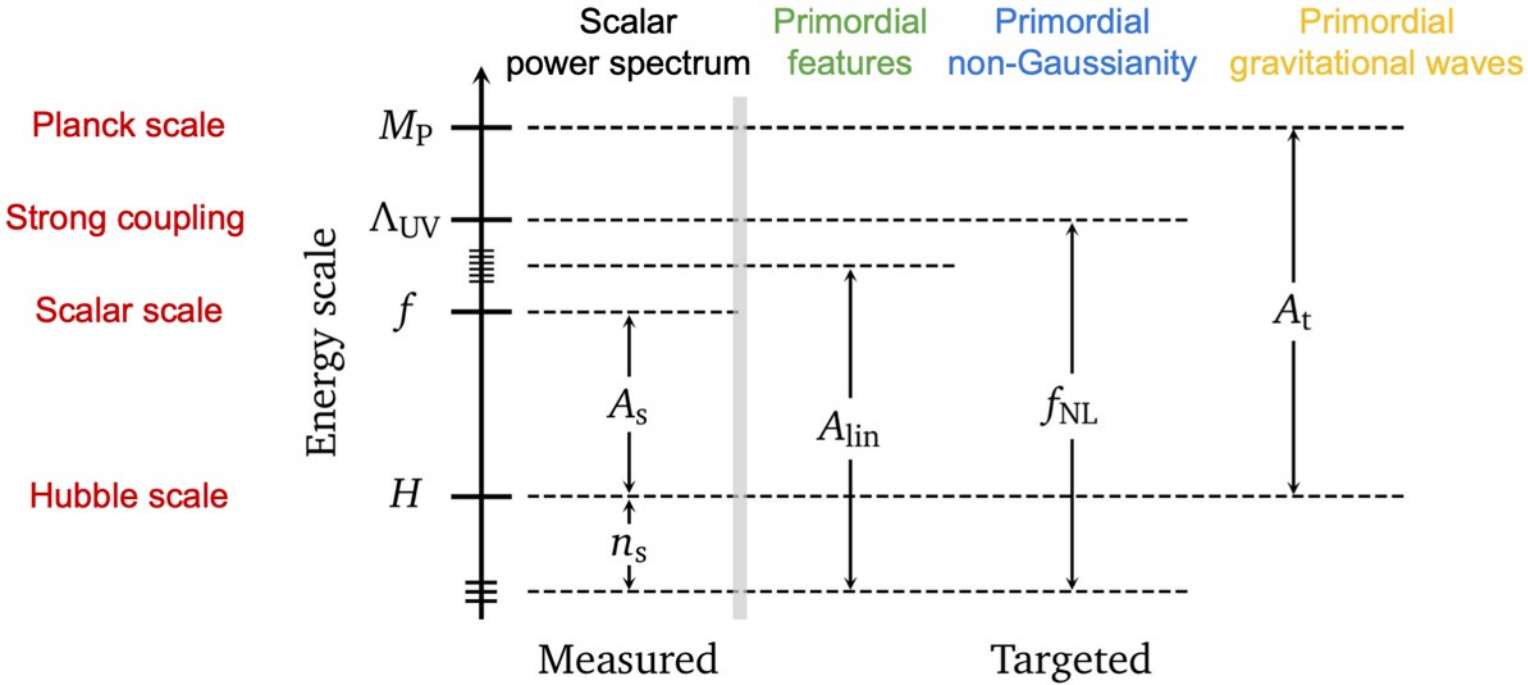
[1]Topical Group Convener

July 19, 2022; Seattle, WA

SCIENTIFIC THEMES:
INFLATION
NEW PARTICLES, INTERACTIONS, AND PHASES

INFLATION

Beyond A_s and n_s



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

arXiv:2203.08128

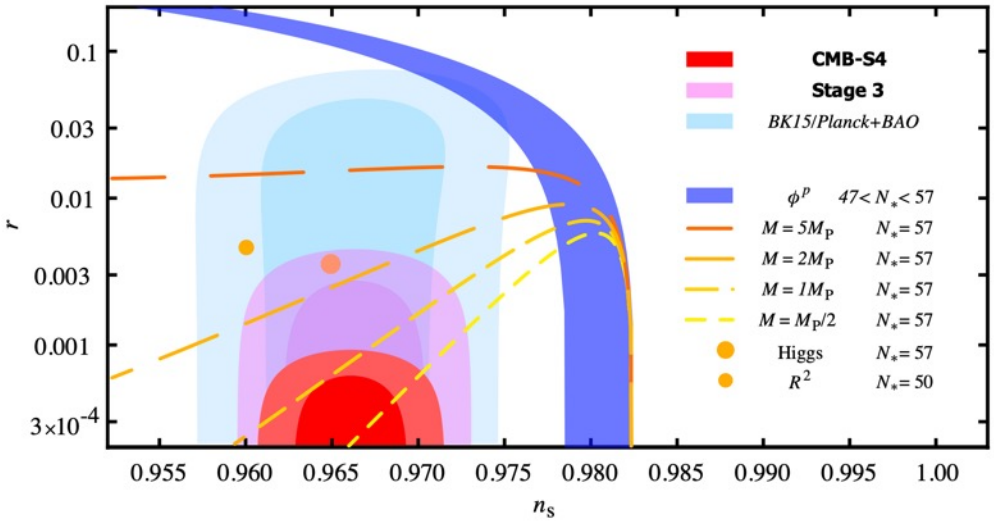
INFLATION

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

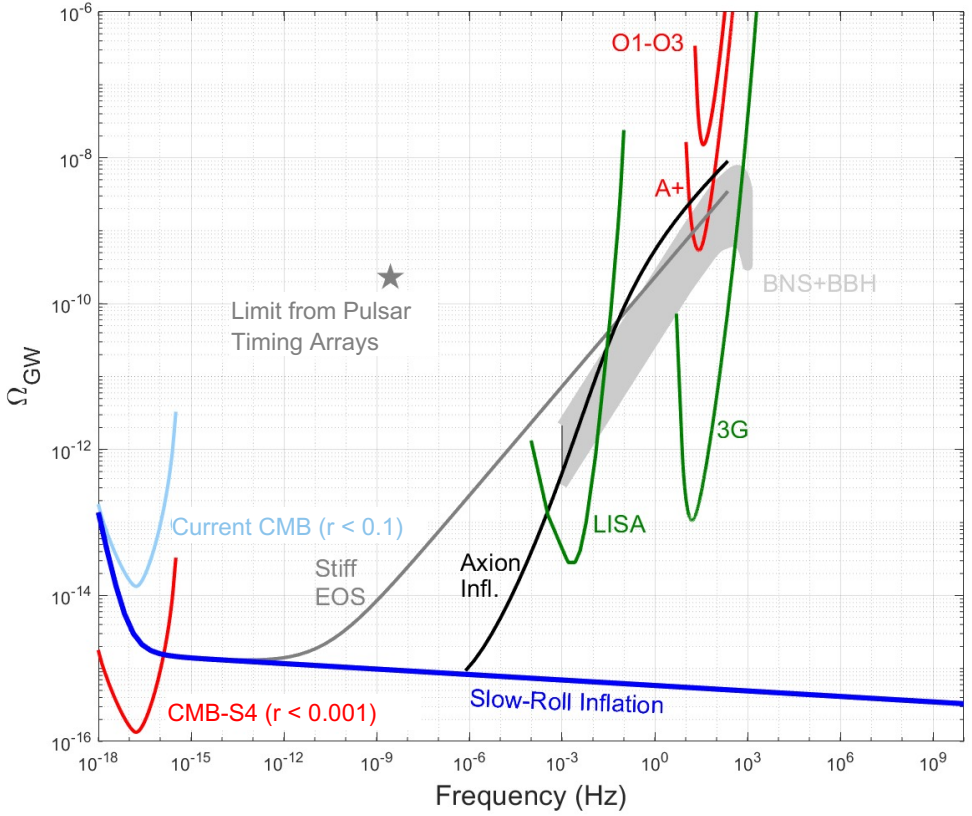
PRIMORDIAL GWS

- $r \gtrsim 0.01$
  - 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

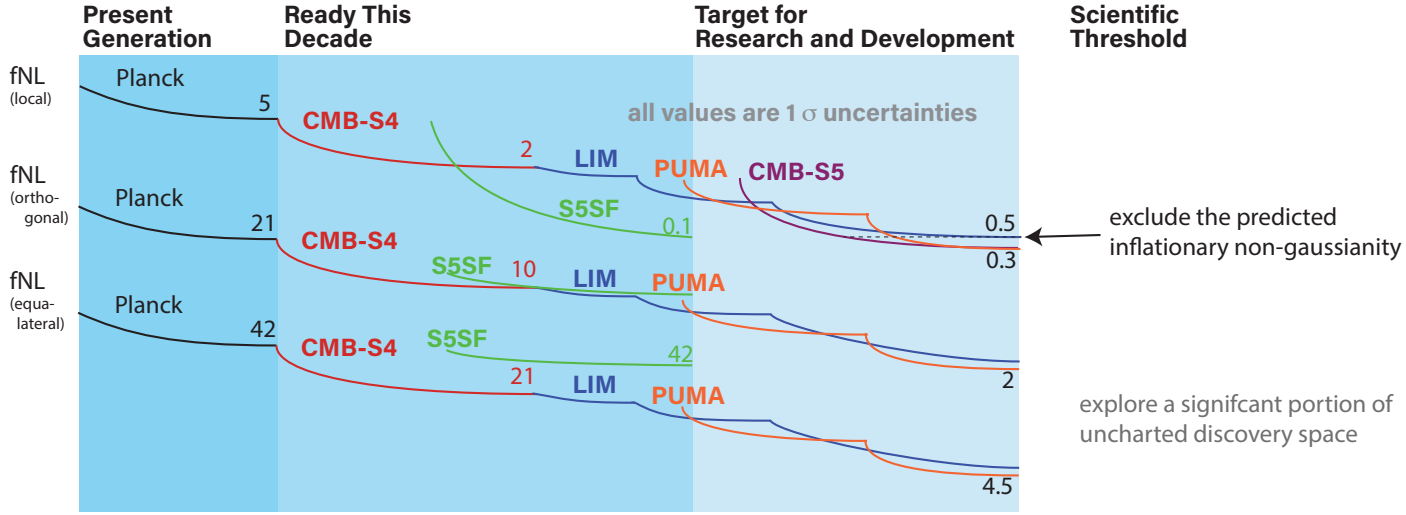


MEASURE THE SPECTRUM OF PRIMORDIAL GWS

- CMB-S4 + GWs can constrain amplitude and spectrum
  - Prediction from simple slow roll is scale invariant spectrum
  - Deviation from scale invariance is potentially detectable by CMB-S4+GWs
  - Would point to new physics associated w/ inflation



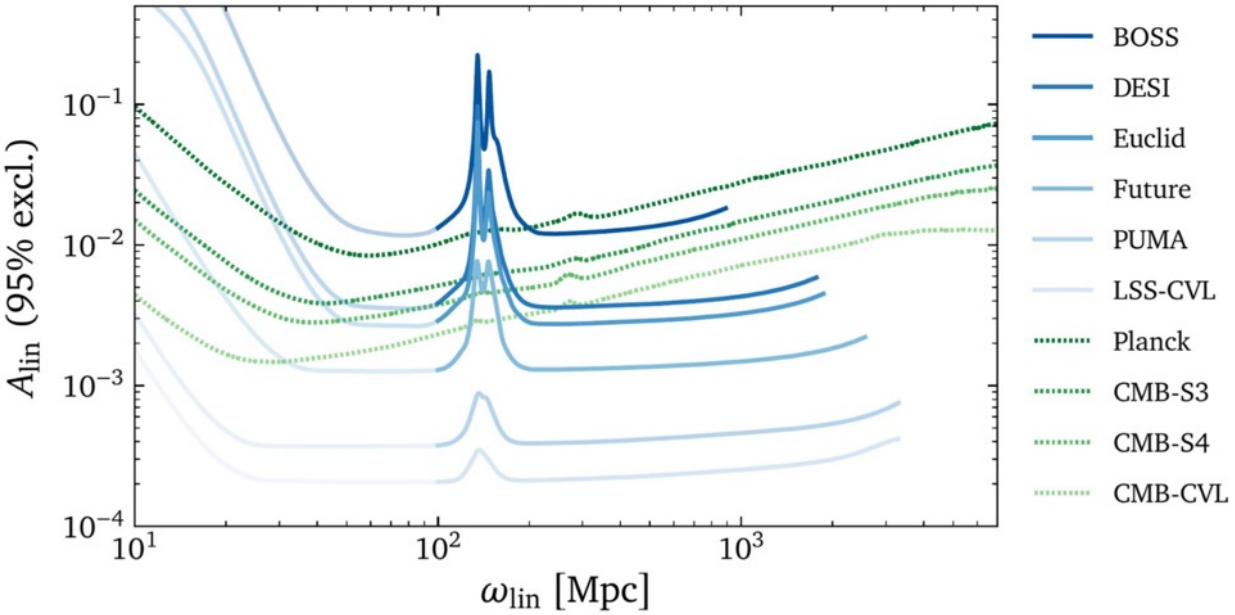
NON-GAUSSIANITY



- $f_{NL}^{local} \gtrsim 1$: 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

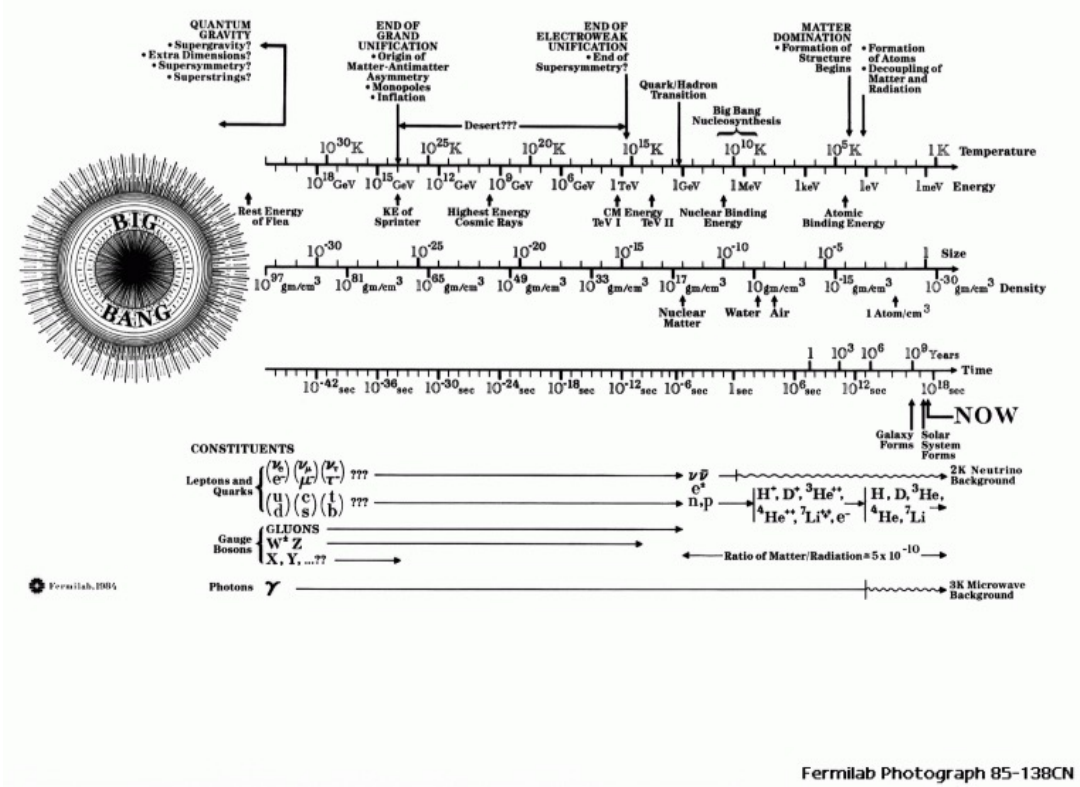
PRIMORDIAL FEATURES

- Improve constraints by more than an order of magnitude



SCIENTIFIC THEMES:
INFLATION
NEW PARTICLES, INTERACTIONS, AND PHASES

NEW PARTICLES, INTERACTIONS, AND PHASES



Fermilab Photograph 85-138CN

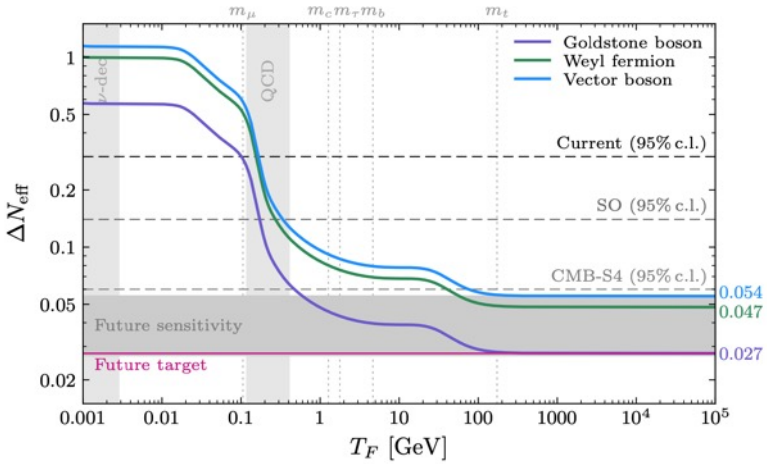
"Hot Big Bang" + SM

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

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

NEW PARTICLES, INTERACTIONS, AND PHASES

- New physics that addresses hierarchy problem, Strong CP problem, cosmological constant problem, dark matter
  - Often include degrees of freedom that decouple in early universe
  - $\Delta N_{\rm eff}$, 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
  - $\Delta N_{\rm eff}$, small scale clustering, isocurvature perturbations, birefringence



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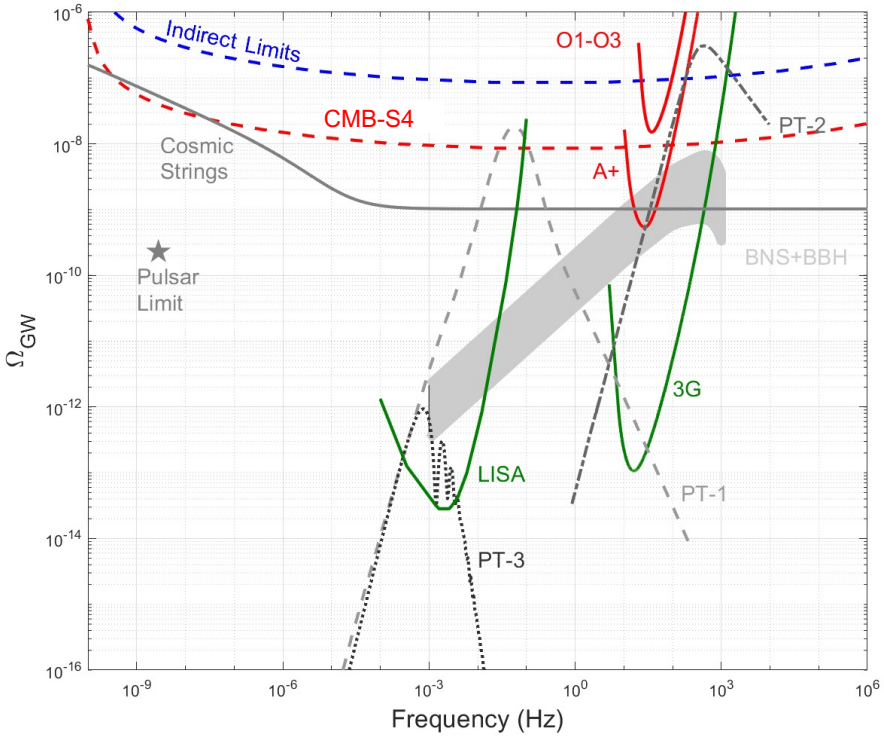
NEW PARTICLES, INTERACTIONS, AND PHASES

- 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



MAJOR FACILITIES

Massive galaxy clusters

Typical galaxies

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

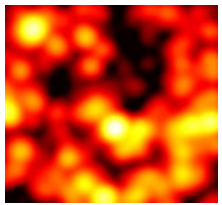
z~0

redshift

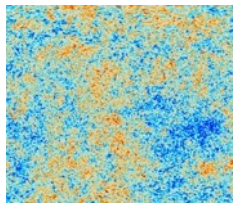
Reionizatio n

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.



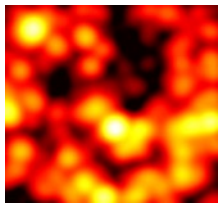
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

This decade…

Massive galaxy clusters

Typical galaxies

Galaxies and transients emitting in optical wavelengths and spatially resolved.



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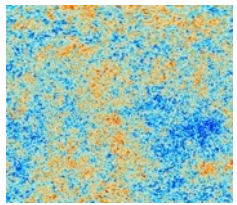


Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

Size

Dark Energy

Inflation (Primordial structure)

CMB-S4

Inflation (Primordial Gravitational Waves)

Small LIM surveys

Modified Gravity

New relativistic energy (new particles, new phase transitions)

Neutrinos, Dark Matter

Sub-halo probes of Dark Matter

Stage-V SPEC

Current GWOs

z~0

redshift

Reionization

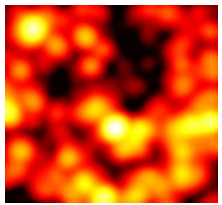
Last scattering of CMB photons

… eye towards the next decade

Massive galaxy clusters

Typical galaxies

Galaxies and transients emitting in optical wavelengths and spatially resolved.



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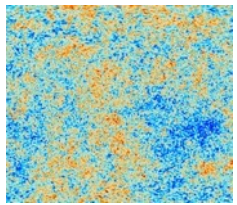


Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

Size

Large LIM surveys

Dark Energy

Inflation (Primordial structure)

CMB-S4

Inflation (Primordial Gravitational Waves)

Small LIM surveys

Modified Gravity

Neutrinos, Dark Matter

New relativistic energy (new particles, new phase transitions)

Future CMB

Sub-halo probes of Dark Matter

Stage-V SPEC

Future GWOs

Current GWOs

z~0

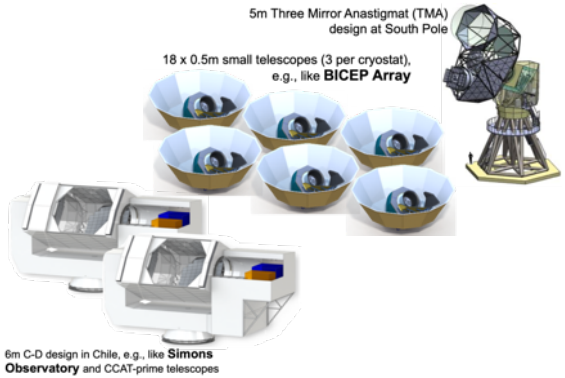
redshift

Reionization

Last scattering of CMB photons

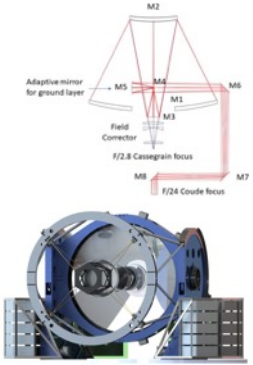
EARLY UNIVERSE FACILITIES IN THIS DECADE

CMB-S4



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

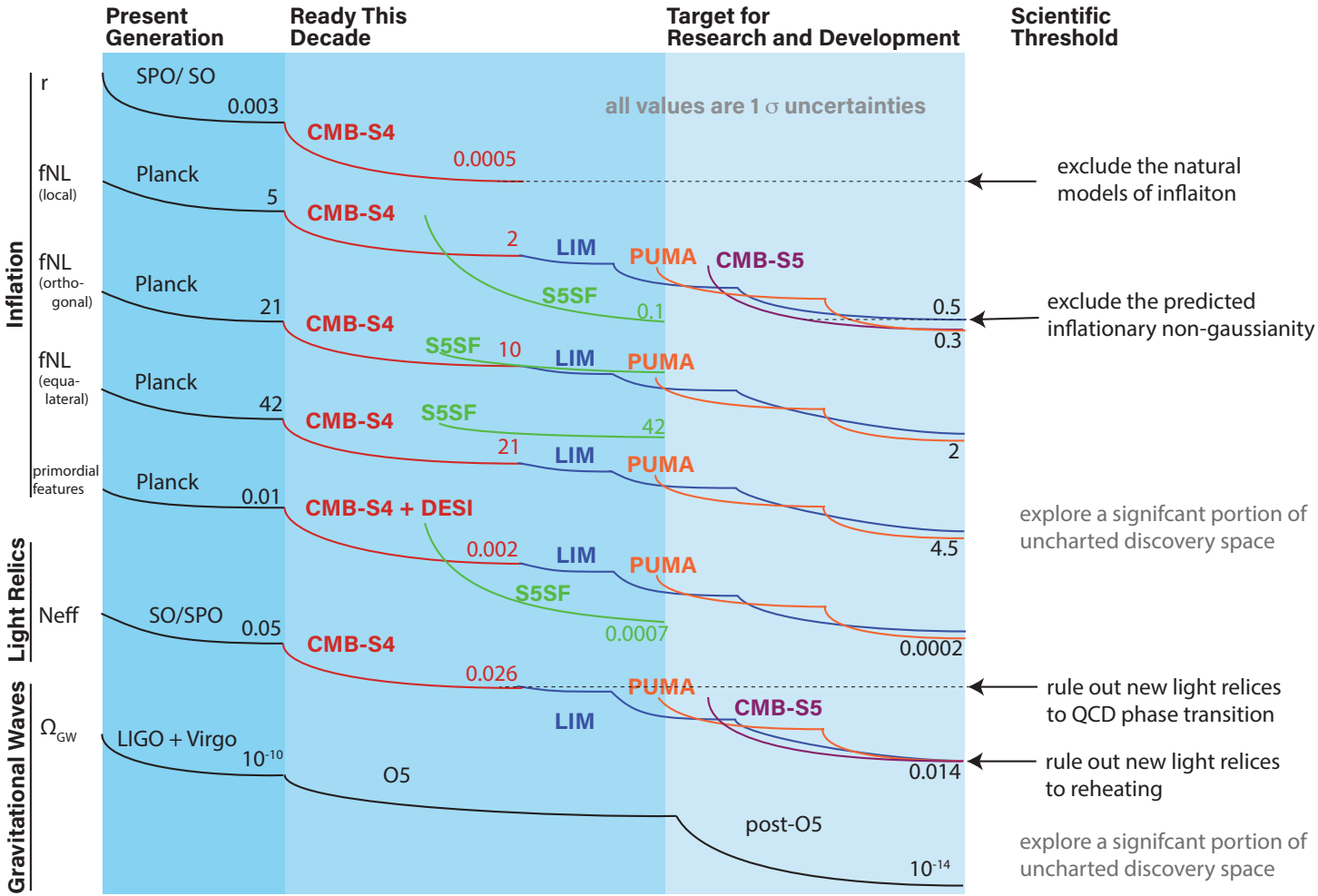
Stage-V Spec Facility



- 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
all values are 1 σ uncertainties
Inflation
r
SPO/ SO
0.003
CMB-S4
0.0005
fNL (local)
Planck
5
CMB-S4
2
LIM
PUMA
CMB-S5
S5SF
0.1
0.5
0.3
fNL (ortho-gonal)
Planck
21
CMB-S4
S5SF
10
LIM
PUMA
fNL (equa-lateral)
Planck
42
CMB-S4
S5SF
42
21
LIM
PUMA
2
primordial features
Planck
0.01
CMB-S4 + DESI
0.002
LIM
PUMA
4.5
Light Relics
Neff
SO/SPO
0.05
CMB-S4
S5SF
0.0007
0.0002
0.026
PUMA
LIM
CMB-S5
Gravitational Waves
Ω_{GW}
LIGO + Virgo
10^{-10}
O5
post-O5
0.014
10^{-14}
exclude the natural models of inflaiton
exclude the predicted inflationary non-gaussianity
explore a signifcant portion of uncharted discovery space
rule out new light relices to QCD phase transition
rule out new light relices to reheating
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**
  - Critical to field new technology (e.g. smaller experiments, staged development)
    - Develop integrated systems
    - Mature understanding of experiment operations and systematics

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
  - New particles, interactions, and phases:
    - Light relics, phase transitions, neutrino physics
- Major facilities
  - Carry out CMB-S4 (recommended by last P5).
  - Participate in GW facilities and their upgrades. Take advantage of this new probe of the early universe.
  - Carry out a Stage-V Spectroscopic survey. We are ready.
- Enabling capabilities
  - Theory: model building, phenomenology, modeling and simulating astrophysical and cosmological signals, and building analysis pipelines.
  - Instrumentation to enable next-decade facilities (CMB, GWO, 21-cm & CO/CII Intensity Mapping) through fielding smaller experiments.