Inflation: Theory and Observations

Benjamin Wallisch
(with Guilherme Pimentel and Kimmy Wu)

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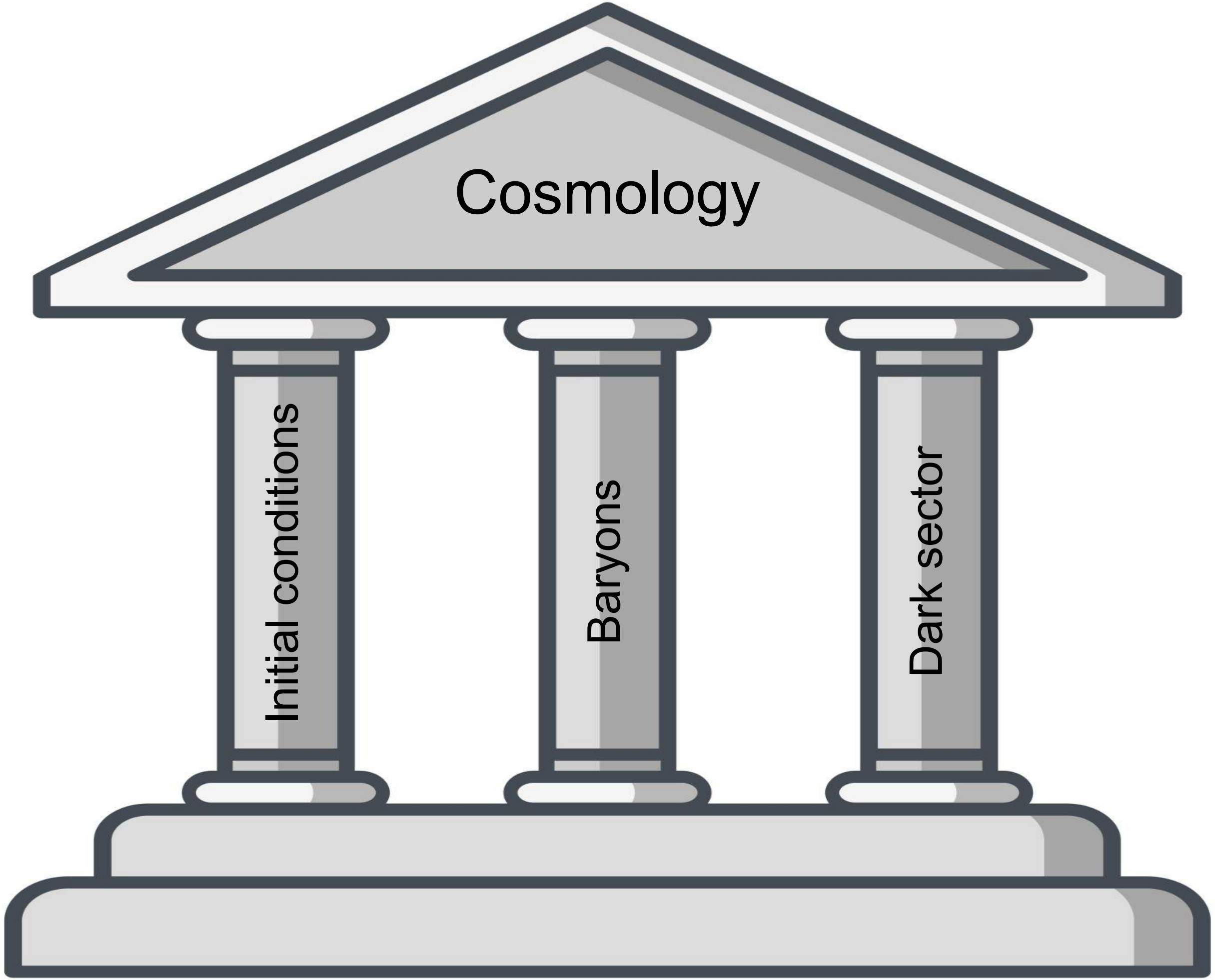
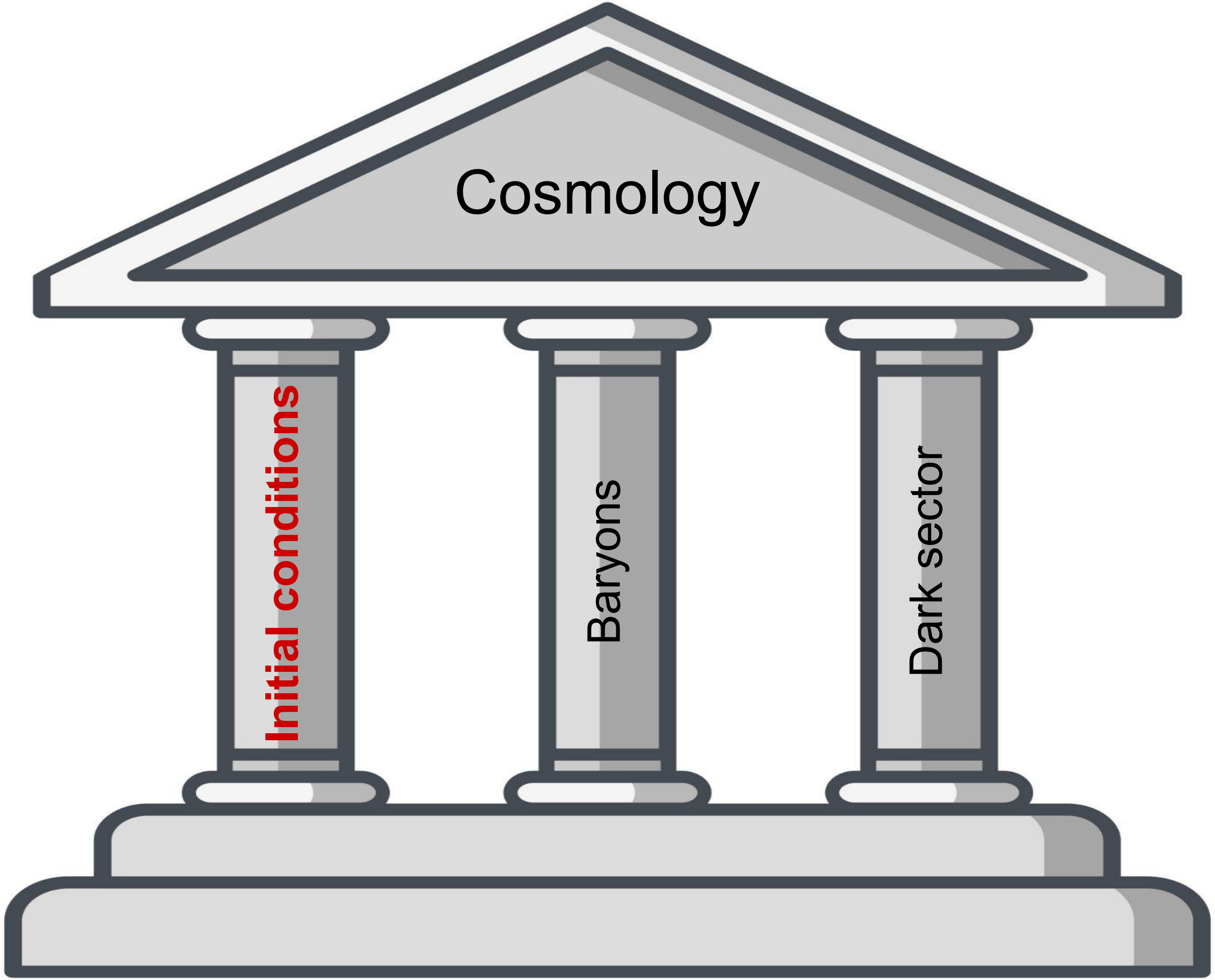


Vecteezy



Vecteezy

Initial Conditions and Inflation

- Initial conditions provide the seeds for structure formation.
  → Matter and radiation trace the earliest phase of the universe.

- Primordial density fluctuations are inferred from observations as Gaussian and almost scale-invariant.
  → Power-law power spectrum characterized by $A_{\rm s}$ and $n_{\rm s}$.
  → Two of the seven cosmological parameters of ΛCDM.

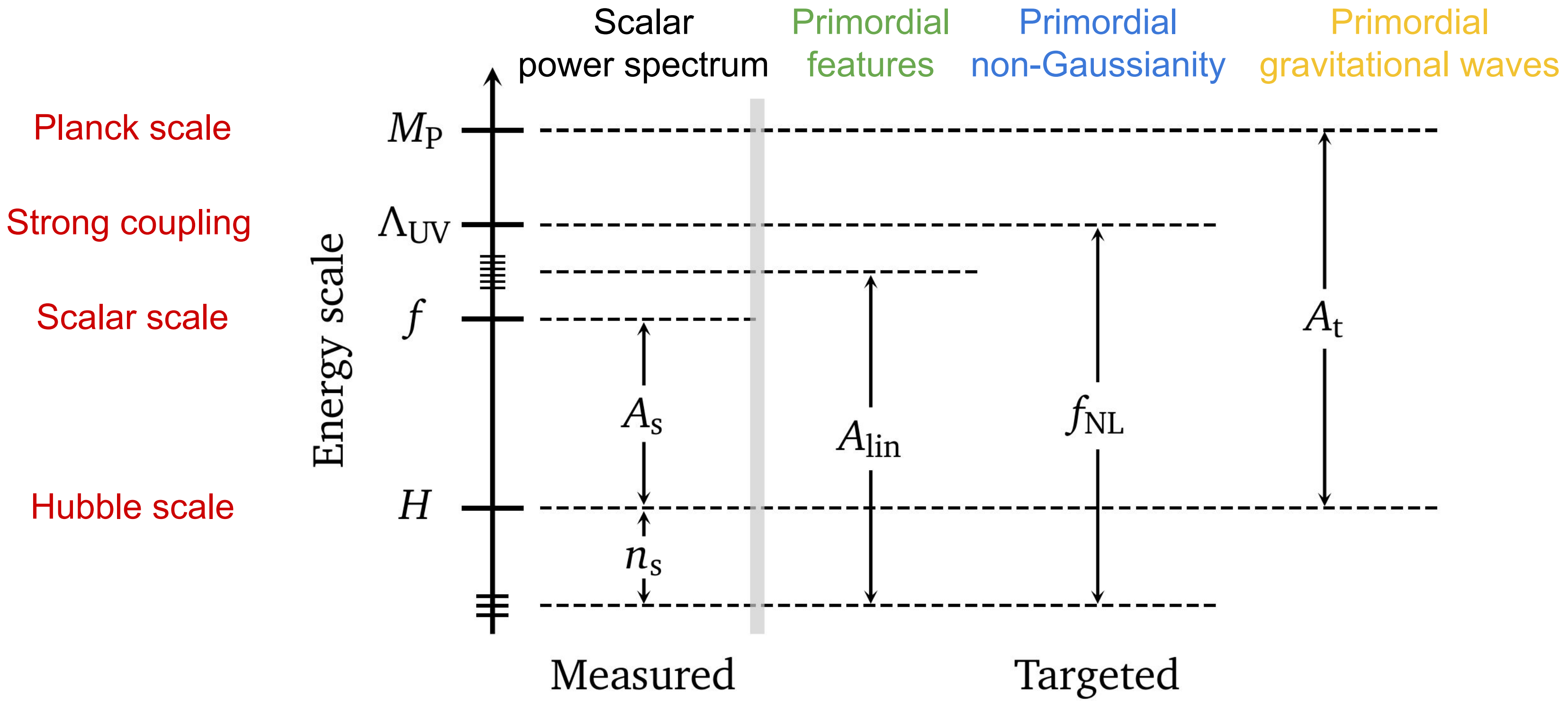
- Powerful theoretical ideas & exquisitely precise observations + major advances in modeling and data analysis.
  → Probe initial fluctuations beyond $A_{\rm s}$ and $n_{\rm s}$.

Simple Imprints of New Physics Predicted by Inflation

- Primordial gravitational waves: tensor fluctuations of the metric,
- Primordial non-Gaussianity: small deviations from Gaussianity,
- Primordial features: new scales breaking scale invariance.

There are many other potential signatures of inflation! We focus on these due to their theoretical breadth and observational accessibility.

Simple Imprints of New Physics Predicted by Inflation

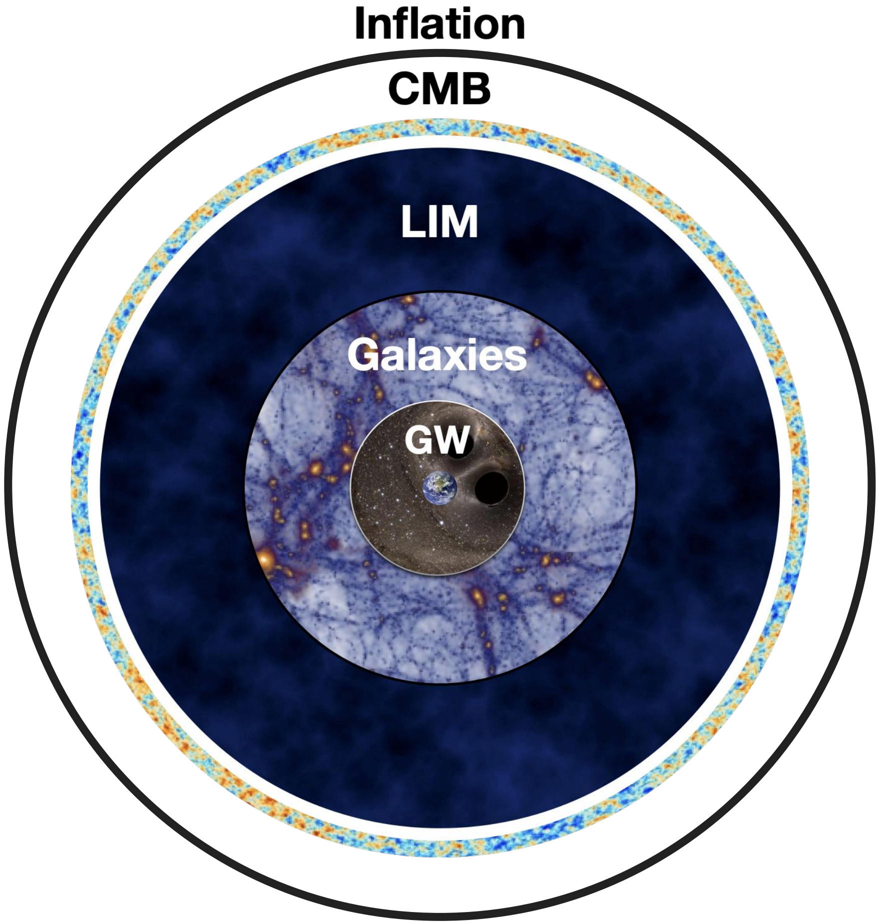


→ Access to new energy scales and detailed dynamics of inflation.

arXiv:2203.08128

Host of Observational Probes

- Cosmic microwave background (CMB)
  - Anisotropies,
  - Spectral distortions;
- Large-scale structure (LSS)
  - Galaxy surveys,
  - Line intensity mapping;
- Gravitational wave background (GWB)
  - Direct observations,
  - Indirect observations.



G. Pimentel

Current Observational Status

- Primordial gravitational waves:
  CMB B-modes measured by BICEP/Keck+Planck: $r < 0.035$ (95% C.L.).
- Primordial non-Gaussianity:
  CMB bispectrum from Planck: $f_{\rm NL}^{\rm local} = -0.9 \pm 5.1, \;\; f_{\rm NL}^{\rm equil} = -26 \pm 47, \;\; \ldots$
- Primordial features:
  CMB (Planck) and LSS (BOSS): deviations from scale invariance < 1%.

$\longrightarrow$ CMB drives the current sensitivity.
$\longrightarrow$ LSS will be crucial in the future.
$\longrightarrow$ GWB and spectral distortions will be complementary.

Primordial Gravitational Waves

Theoretical Background

- Inflation sources quantum fluctuations, esp. scalar & tensor metric fluctuations.
  $\rightarrow$ Tensor fluctuations are primordial gravitational waves.
- Observation of a non-zero tensor amplitude (~ tensor-to-scalar ratio r).
  $\rightarrow$ Glimpse of quantum gravity at work.
- In simple models:
  $\rightarrow$ Related to energy scale of inflation,
  $\rightarrow$ Constrains distance traversed by the inflaton.
- Ongoing theoretical exploration.

Theoretical Targets

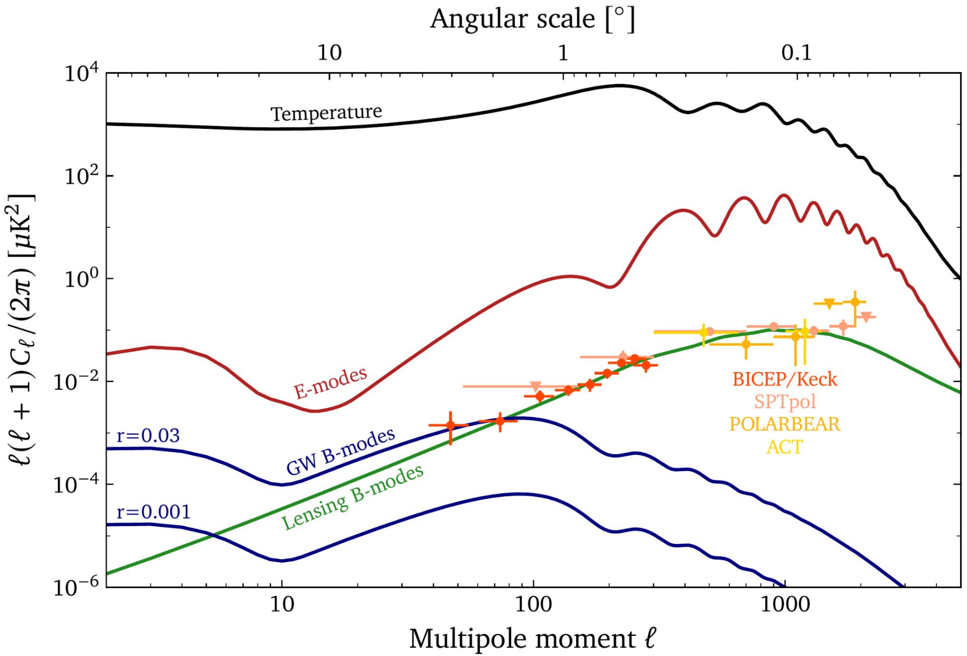
- $r \gtrsim 0.01$:
  → Super-Planckian inflaton field excursion,
  → Evidence for approximate shift symmetry in quantum gravity.

- $r \gtrsim 0.001$:
  → Evidence for the simplest models of inflation which naturally predict observed n_s and have a characteristic scale $> M_\mathrm{P}$.
  (cf. Starobinsky's R^2 inflation, Higgs inflation, α-attractors, …).

- Non-detection:
  → Vast restriction of inflationary model space,
  → Still insights into physics at very high scales.

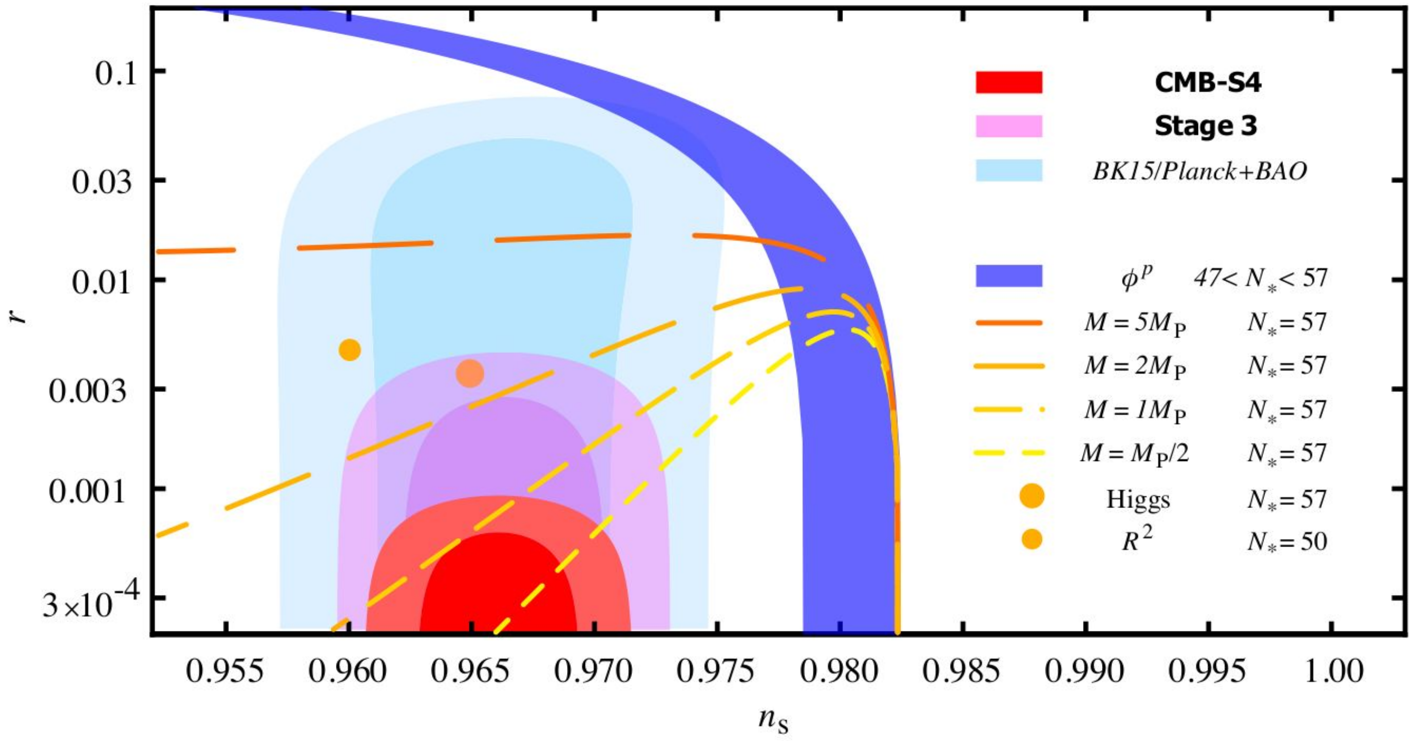
CMB B-Mode Observations Drive Sensitivity

Posted B-Mode Sensitivity to r			
Experiment	**arxiv post**	**Bands [GHz]**	**σ(r)**
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	95, 150 + WP	0.024
ABS	1801.01218	150	0.7
Planck	1807.06209	30...353	~0.2
BK15 + WP	1810.05216	95,150,220+WP	0.020
Polarbear	1910.02608	150 + P	0.3
SPTpol	1910.05748	95 + 150	0.22
Planck/Tristram	2010.01139	30...353	0.07
SPIDER	2103.13334	95 + 150	0.13
BK18 + WP	2110.00483	95,150,220+WP	0.009
Polarbear	2203.02495	150 + P	~0.16



- Small-aperture telescopes at the South Pole are leading observational constraints (BICEP/Keck).

Future CMB Experiments Will Detect or Rule Out Targets



arXiv:2203.08128 (adapted)

Observational Requirements

- Ultra-deep CMB survey (CMB-S4)
  → Essential for driving constraints, detections and reaching targets.
- CMB satellite (e.g. LiteBird, PICO)
  → Complementary to ground-based, in particular also for foregrounds.
- Challenges of CMB B-mode measurements:
  – Weak gravitational lensing,
  – Astrophysical foregrounds on large and small scales.
  → Need work on simulations, modeling, analysis, dust observations, etc.
- Futuristic LSS probes (via cosmic shear, 21cm polarization, polarized SZ, …).
- Complementary measurements on smaller scales from direct observations of the stochastic gravitational wave background (LIGO/Virgo/KAGRA, LISA, …).

Primordial Non-Gaussianity

Theoretical Background

- Deviations from Gaussianity are necessarily present, even in simplest models.
- Robust probe of interactions during inflation and unique dynamical information (beyond the free propagation of curvature fluctuations).
- Simplest statistical measure: primordial bispectrum (three-point function),
  $\rightarrow$ three "basic" shapes:
  – Local: new light degrees of freedom correlate large and small scales,
  – Equilateral & orthogonal: probe curvature self-interactions.
- Ongoing theoretical exploration
  (e.g. cosmological collider physics, connections to Standard Model of particle physics, non-perturbative techniques for rare-but-large fluctuations, …).

Theoretical Targets

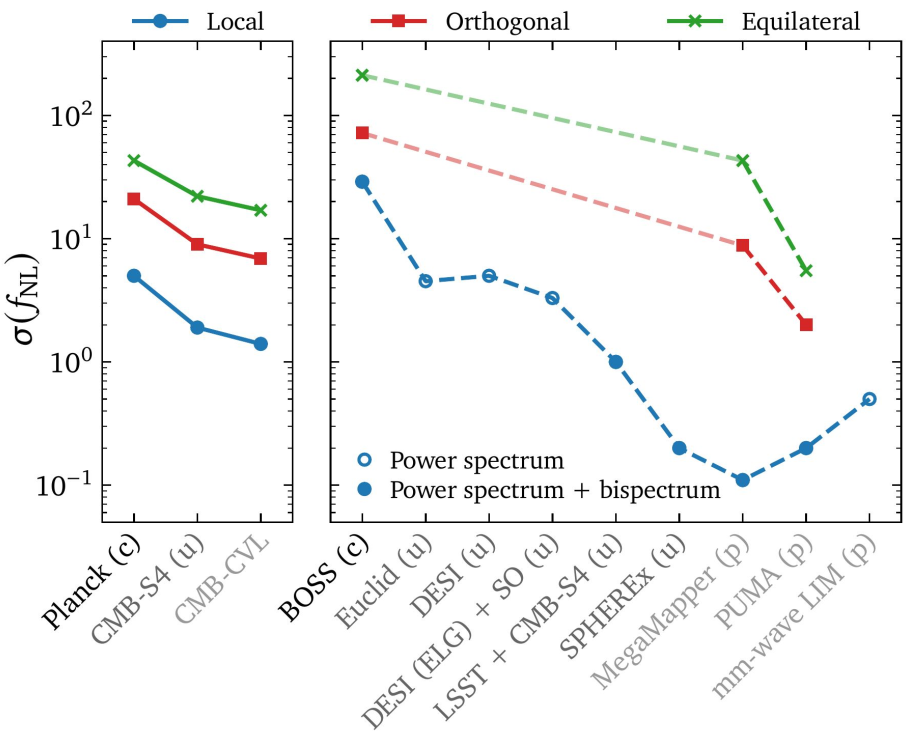
- $f_{\rm NL}^{\rm local} \gtrsim 1$:
  $\longrightarrow$ Differentiate models with extra light species during/after inflation.
- $f_{\rm NL}^{\rm equil,ortho} \gtrsim 1$:
  $\longrightarrow$ Inflaton likely has subluminal sound speed,
  $\longrightarrow$ Constrain the symmetry breaking patterns of inflation.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

CMB and LSS Observations Drive Sensitivity

- Measure as many primordial modes as possible.
- CMB anisotropy bispectra have been leading the constraints (Planck).
- LSS power spectrum & bispectrum (BOSS).
  → Power spectrum: scale-dependent bias from local non-Gaussianity,
  → Bispectrum: theoretical progress now allows measurement.
- Various cross-correlations:
  – Primary CMB anisotropies,
  – LSS probes (including multi-tracer),
  – Gravitational waves.
  – CMB spectral distortions,
  – Secondary CMB signals,

Future LSS Surveys Required for Achieving Targets

- CMB constraints will improve.
- LSS surveys are crucial for important improvements.
- Targets only achievable with:
  - High-redshift galaxy surveys,
  - Line intensity mapping.



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Observational Requirements

- CMB experiments covering low and high multipoles (e.g. CMB-S4).
  → Important to constrain/detect many different shapes.
- High-redshift galaxy surveys and line intensity mapping experiments (e.g. MegaMapper, PUMA and mm-wave LIM).
  → Measure large cosmic volumes to extract all available modes.
- Challenges:
  – Mitigate systematic errors on large scales,
  – Reliably extract more modes on small scales.

  → Need work on classifying shapes, modeling the late-time observables, simulations of the non-Gaussian universe, efficient analysis techniques, …

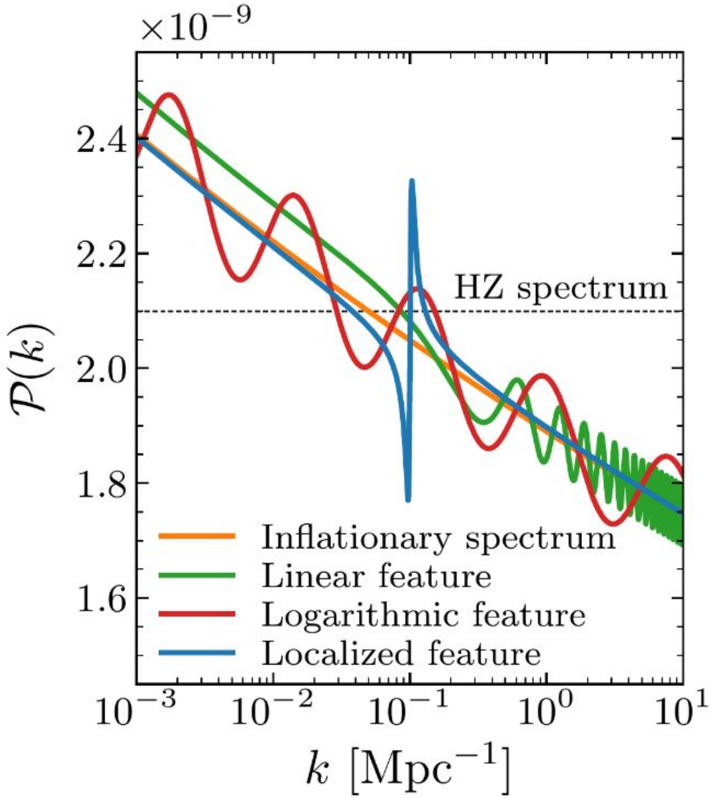
Primordial Features

Theoretical Background

- Primordial dynamics may exhibit a significant departure from scale invariance:
  → Generic in broad classes of models beyond simplest,
  → New energy scales during inflation.

- Ubiquitous when connecting inflationary modeling to fundamental physics.

- Strongly scale-dependent deviations from minimal power-law power spectrum:
  → Oscillatory and/or localized imprints in momentum space.



Theoretical Targets

- Two main classes:
  – Sharp features: momentary departure of evolution from attractor,
  – Resonant features: periodic oscillation around attractor solution.

- Correlated signals in power spectrum and higher-point spectra.

- No useful theoretical priors on scale/amplitude of primordial features:
  → Origin: lack of our understanding of fundamental physics,
  → Cover as much of parameter and model space as possible.

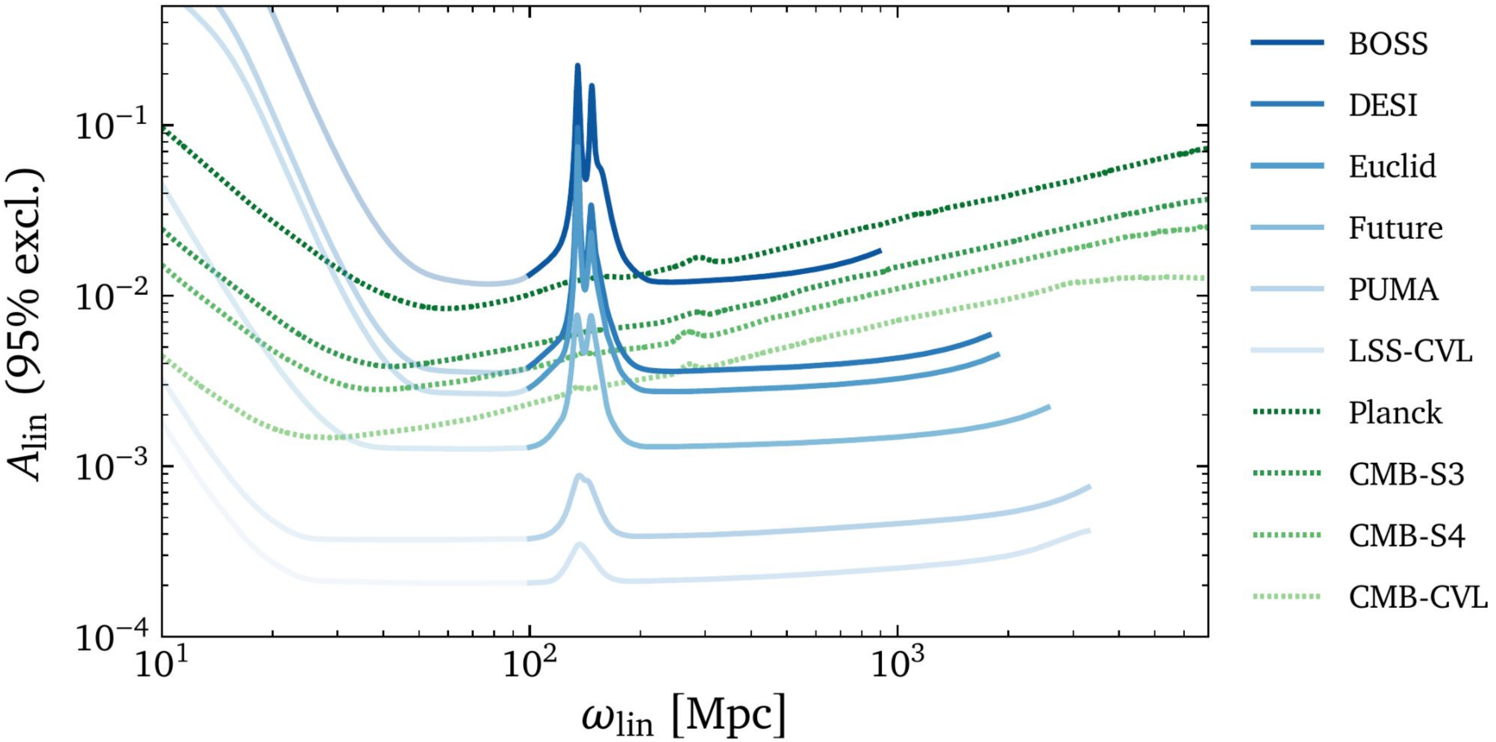
CMB and LSS Observations Drive Sensitivity

- CMB anisotropies have been leading the constraining power (Planck):
  → Template searches and non-parametric reconstruction,
  → Power spectrum and polyspectra searches,
  → No significant detections.

- LSS searches have recently become more sensitive (BOSS):
  → Exploit easier separation of the primordial signal from late-time effects,
  → Three-dimensional density field,
  → Upper limits of 1% relative to scalar amplitude.

- CMB spectral distortions provide complementary constraints (COBE FIRAS) on large features on small scales, as will future GWB measurements.

Future LSS Surveys Required for Decisive Improvements



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Observational Requirements

- CMB experiments covering all, especially high multipoles (e.g. CMB-S4).
- High-redshift galaxy surveys and line intensity mapping experiments (e.g. MegaMapper, PUMA and mm-wave LIM).
  → Measure large cosmic volumes to extract all available modes.
- Complemented by spectral distortions (e.g. PIXIE) and future GWB (e.g. LISA).
  → Constrain large features on very small scales.
- Challenges:
  – Reliably extract/reconstruct more modes on small scales,
  – Efficient data analysis techniques,
  – Advance GWB modeling and extraction.

Conclusions

CF4, 5 & 6

- Strong theoretical foundation and many new exciting ongoing developments.

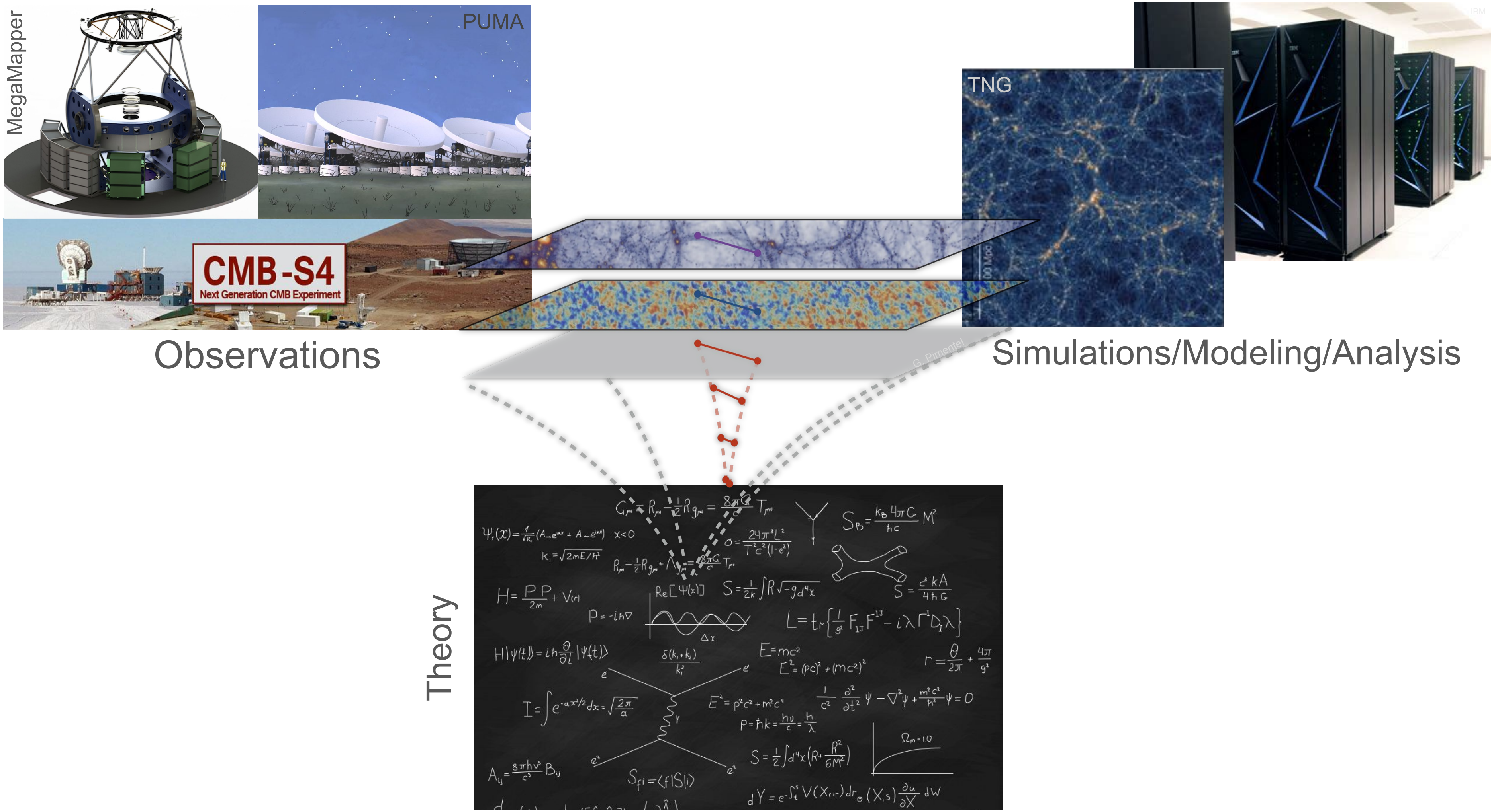
- Now is the time to plan for the next generation of inflationary observations:
  – Cosmic microwave background anisotropies, → CMB-S4
  – Galaxy surveys, → MegaMapper
  – Line intensity mapping, → PUMA/mm-wave LIM
  – Complementary: gravitational waves & CMB spectral distortions.

  → Measure as many primordial modes as possible.

- Dedicated analysis, modeling and simulation efforts are essential.

- Important targets are within reach with upcoming and proposed facilities.

- Even without any detections:
  – Severe restriction of the vast landscape of models,
  – Powerful lessons about the primordial universe & high-energy physics.


MegaMapper
PUMA
CMB-S4
Next Generation CMB Experiment
TNG
G. Pimentel
Observations
Simulations/Modeling/Analysis
Theory

The future for inflationary cosmology is very bright,
with clear directions for further
theoretical and observational explorations!

Thank you!