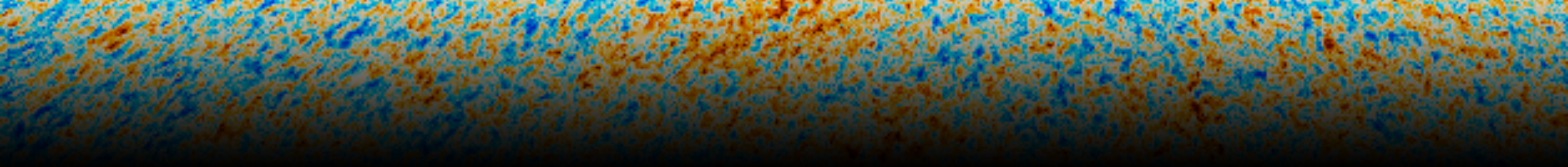


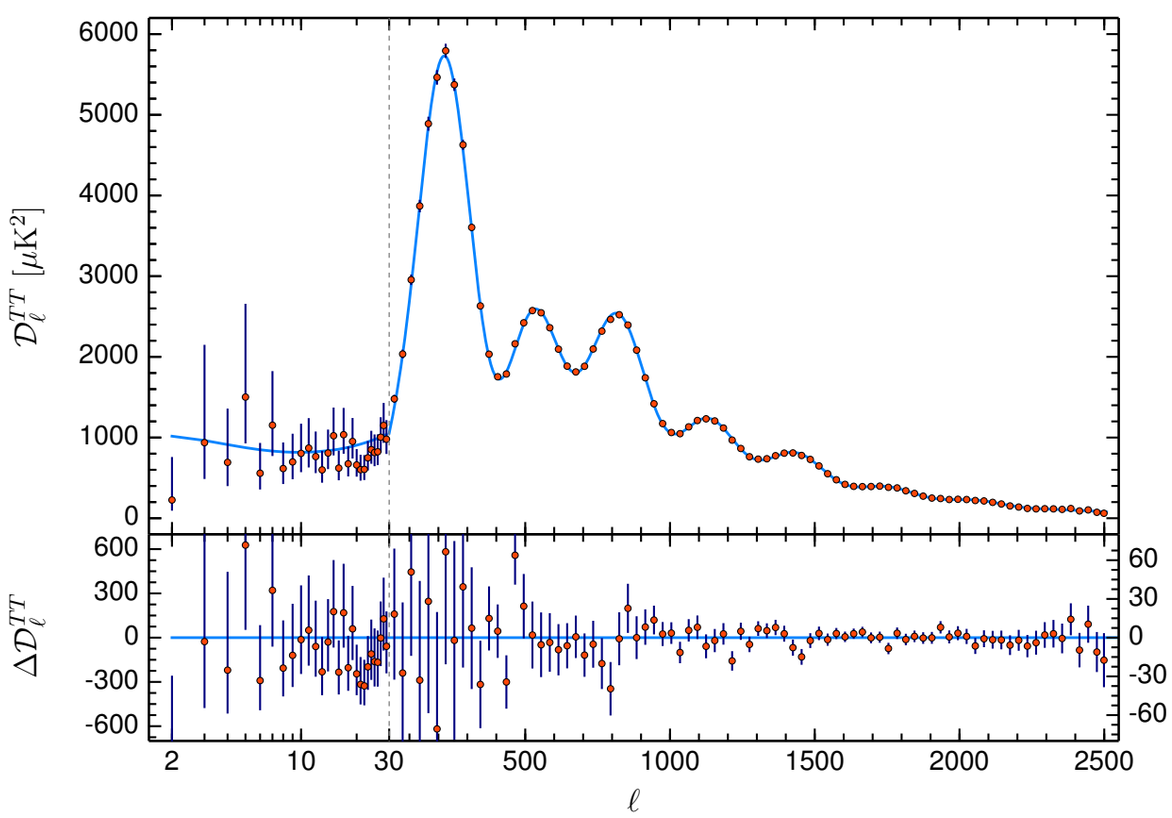
Searching for Primordial Gravitational Waves with CMB-S4

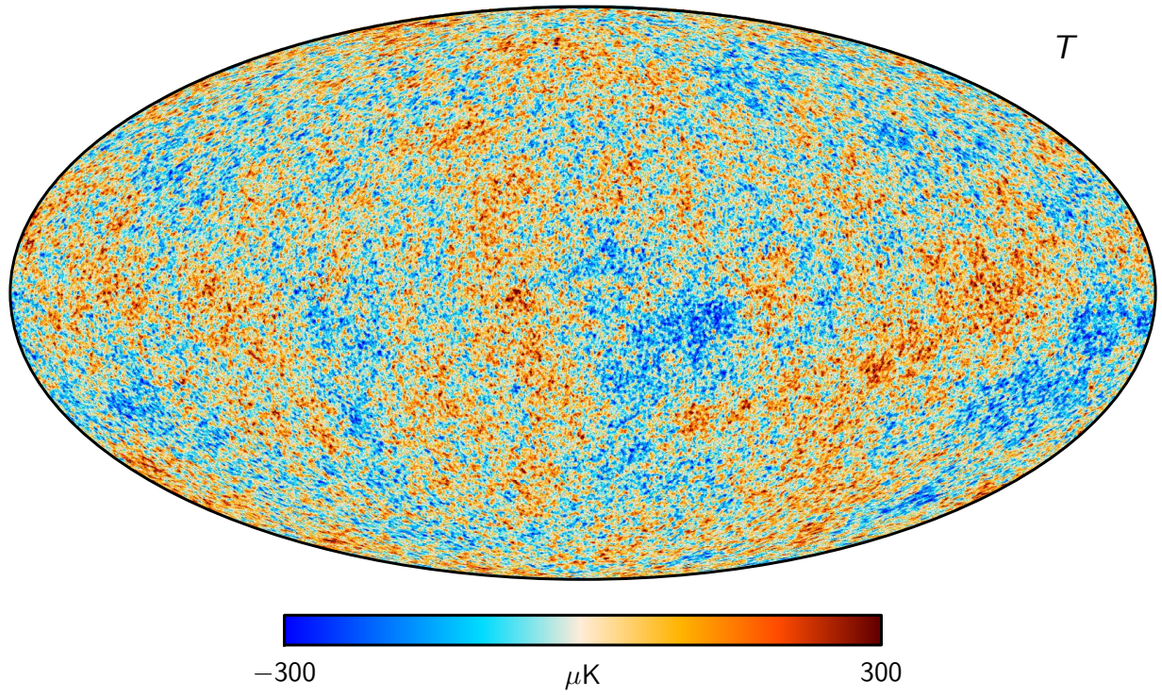
Raphael Flauger

Gravitational Waves Probes of

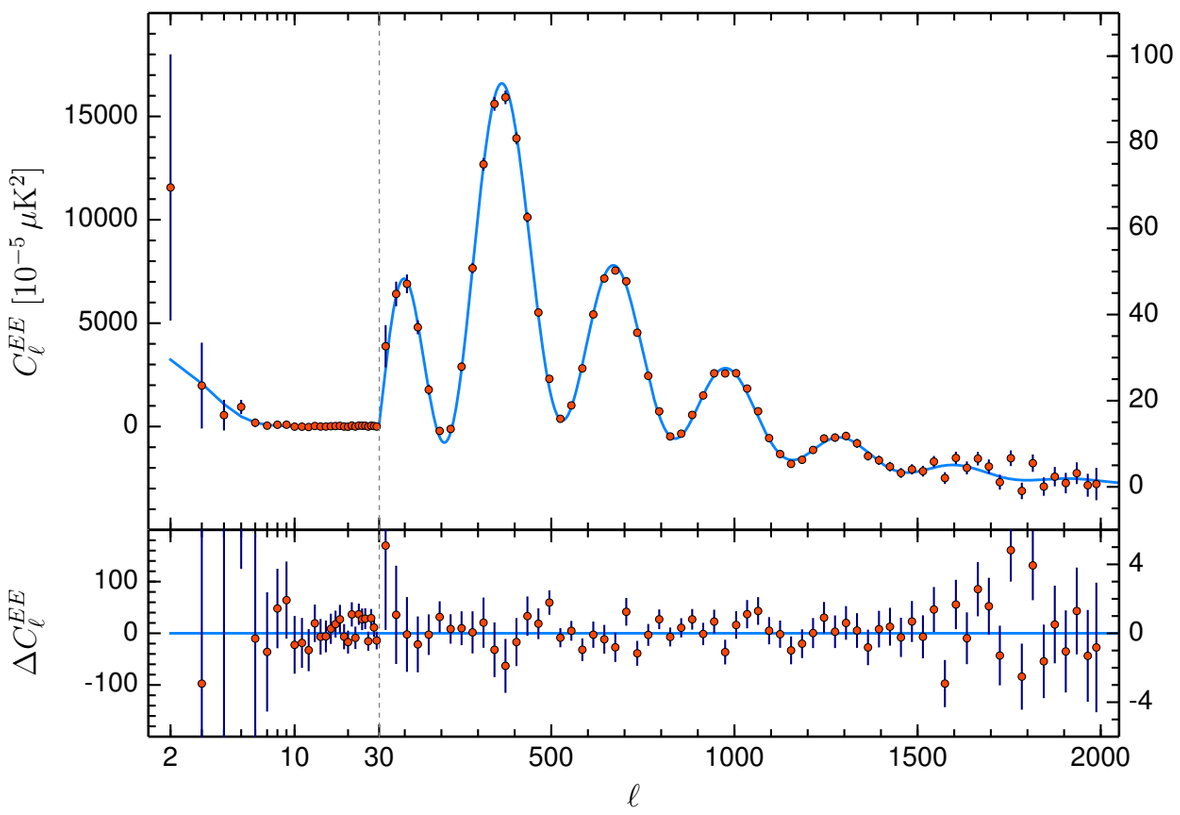
Physics Beyond Standard Model, July, 16 2021

Planck's measurements of the CMB



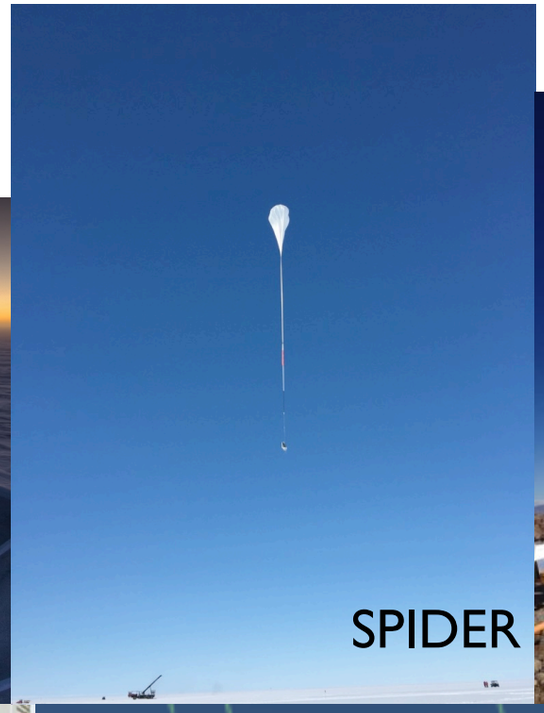


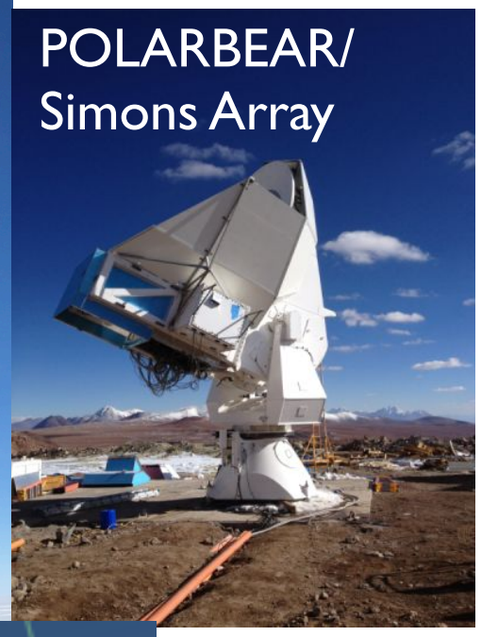
tightly constrained departures from LCDM model and established that the early Universe is remarkably simple.

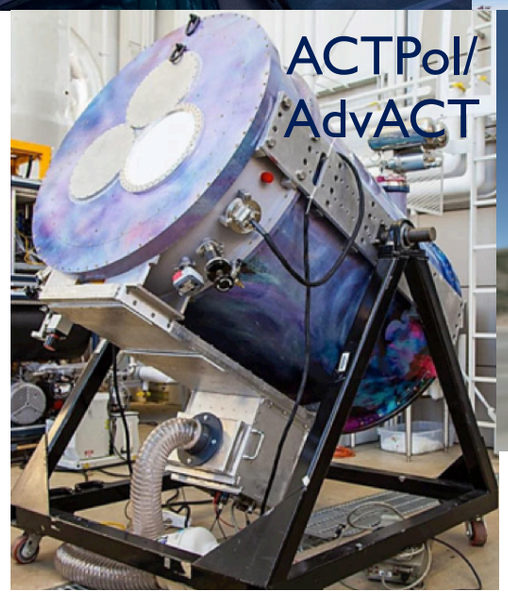


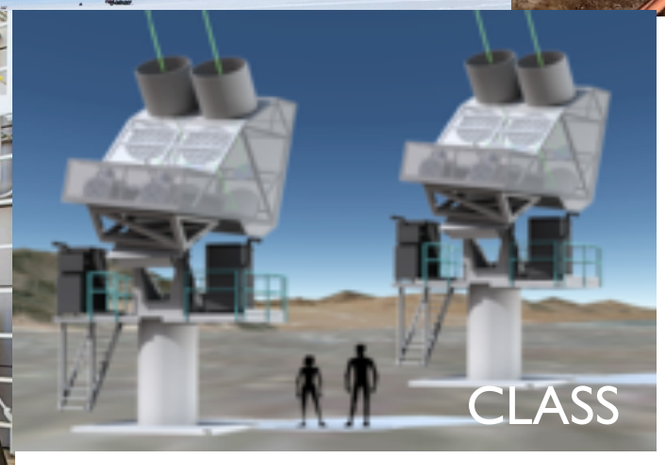
Current Experiments

Stage III: now

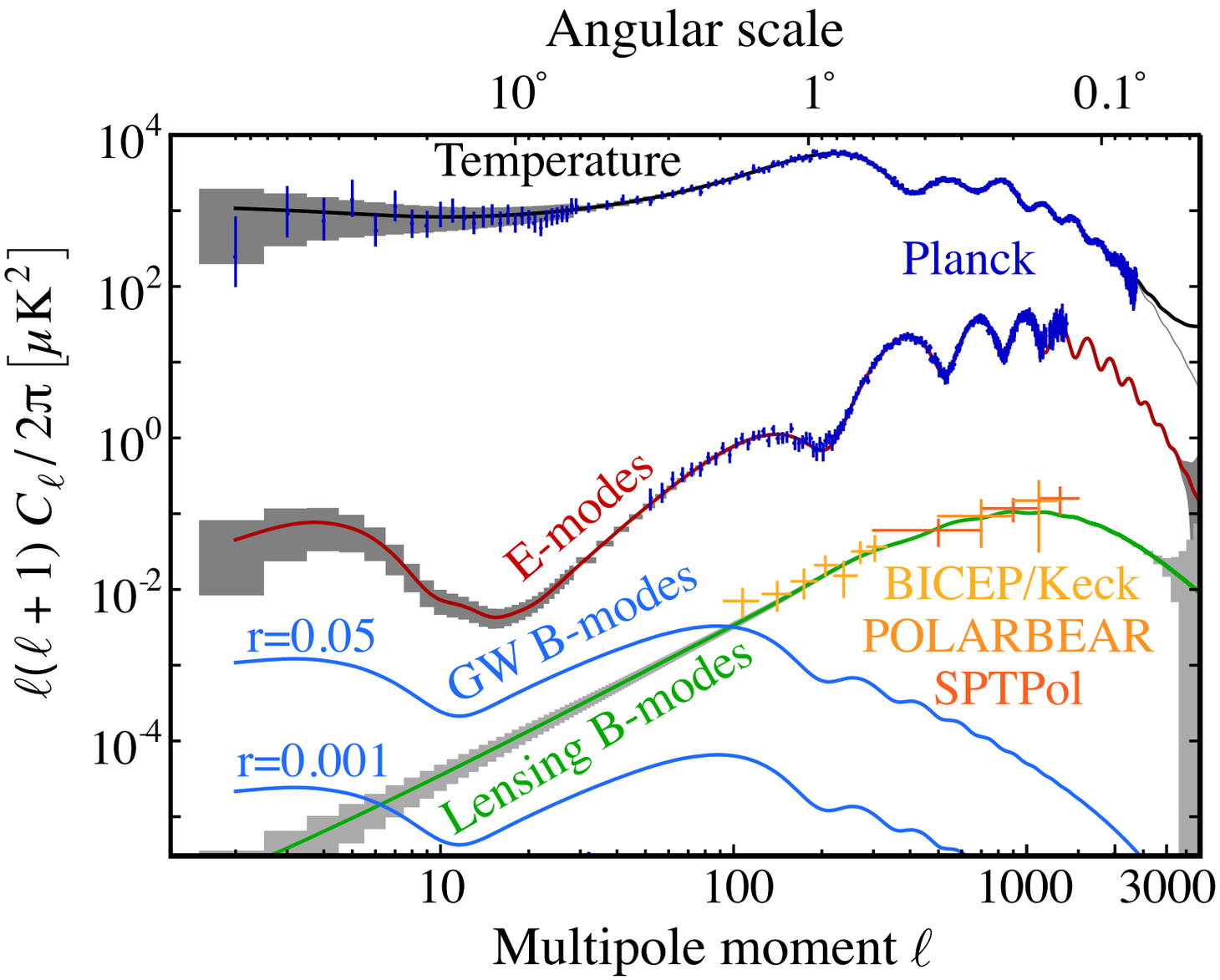








Era of CMB Polarization

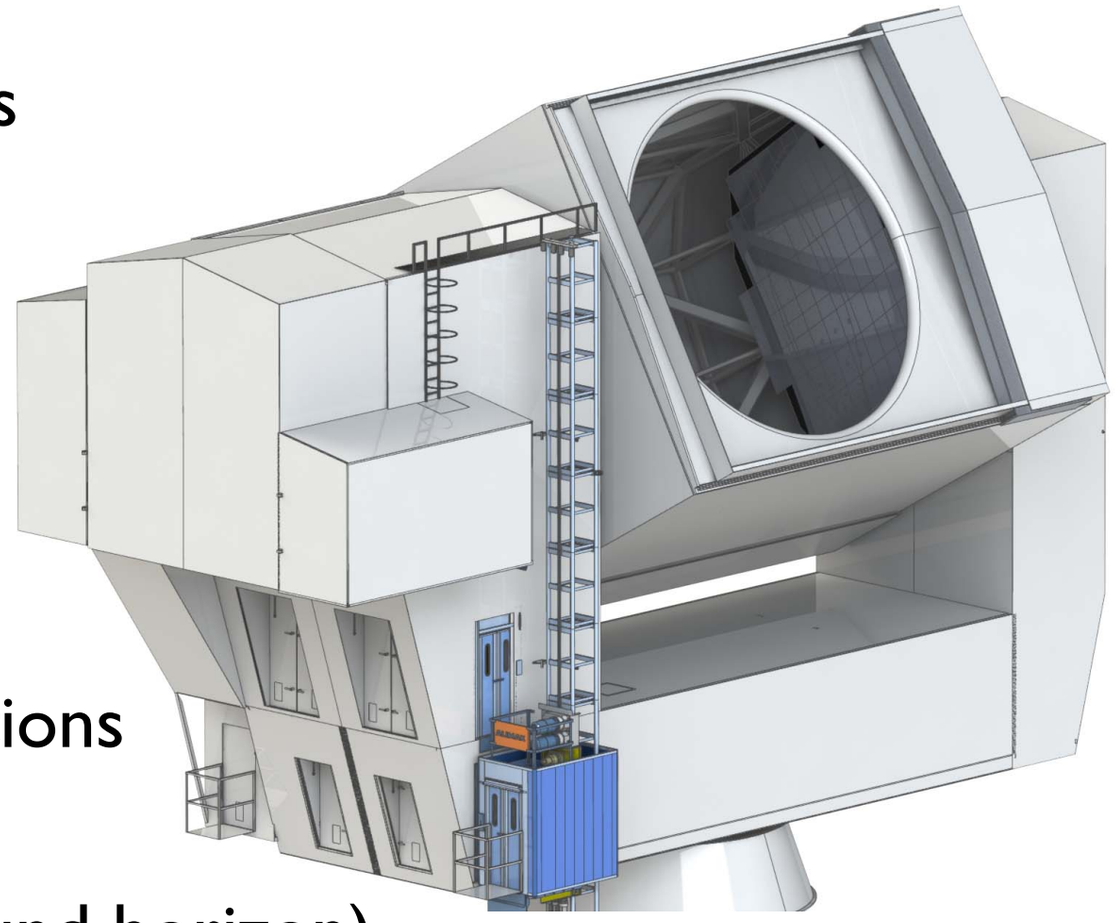


Invaluable information about both astro- and particle physics remains to be extracted from CMB polarization.

Small scale polarization

constrains

- number of relativistic species
- sum of neutrino masses
- dark matter properties
- dark energy properties
- statistical properties of primordial density perturbations
- Hubble parameter (through angular scale of sound horizon)
- proposed solutions to the tension
- …



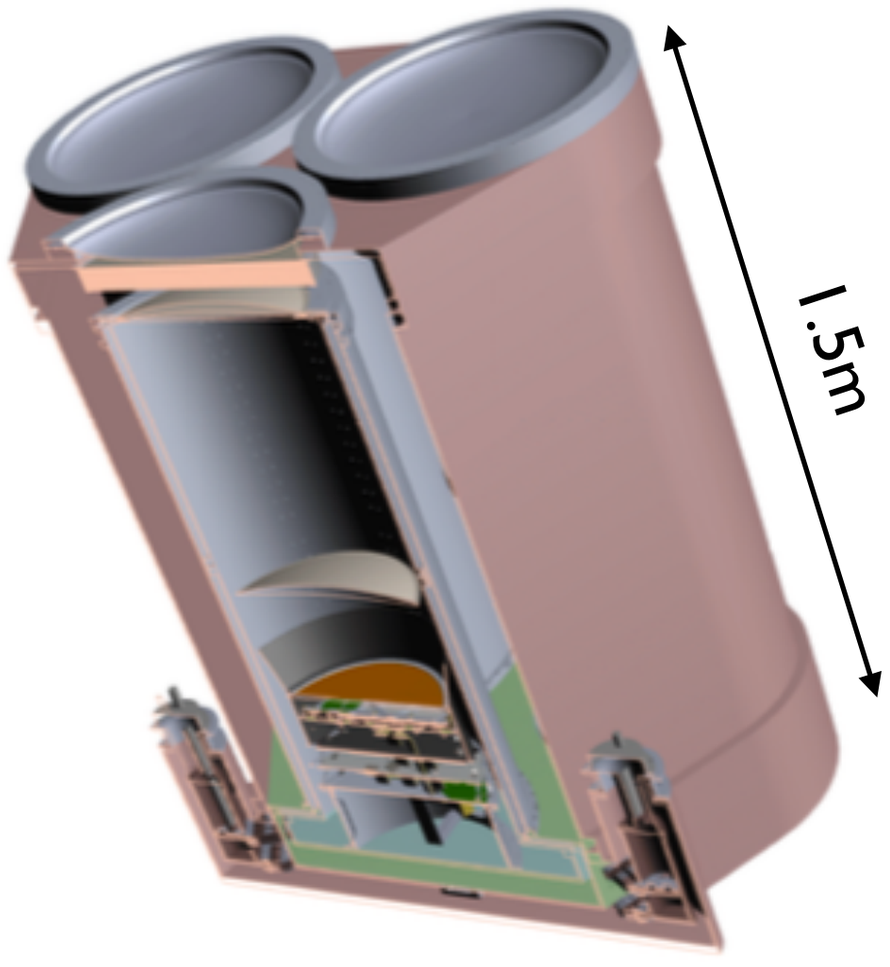
Degree scale polarization

is a sensitive probe of primordial gravitational waves

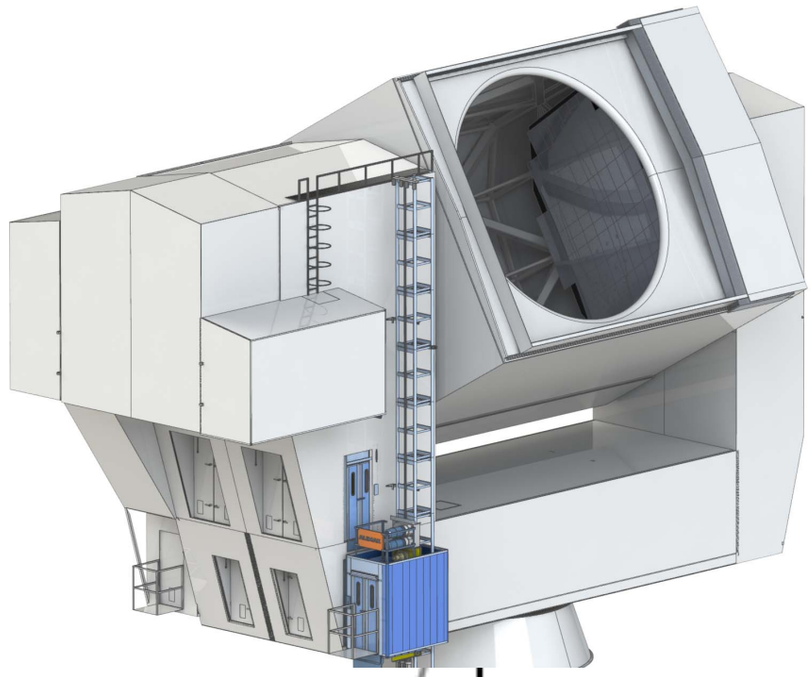
- Primordial gravitational waves are a pristine relic of the early universe.

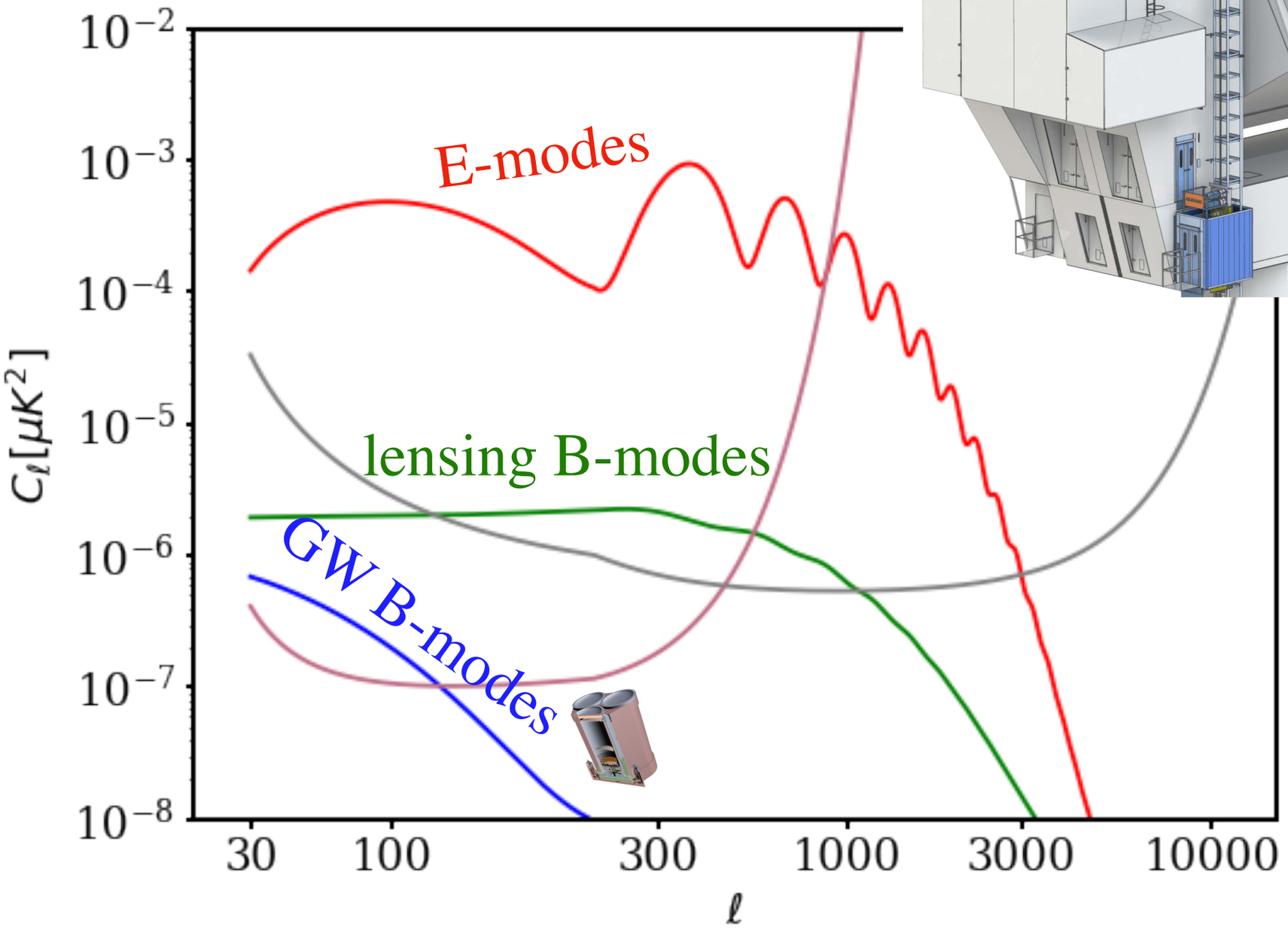
- For the simplest models of inflation the imprint on the polarization of the CMB is our only way to detect them in the near future.

- These gravitational waves are statistically independent from density perturbations and a detection would provide a new window onto the early universe.

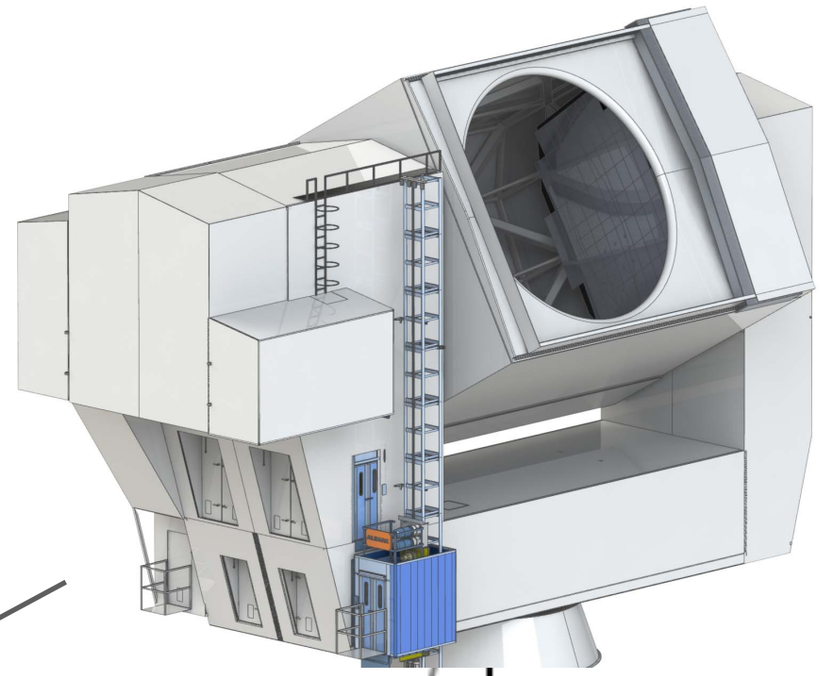


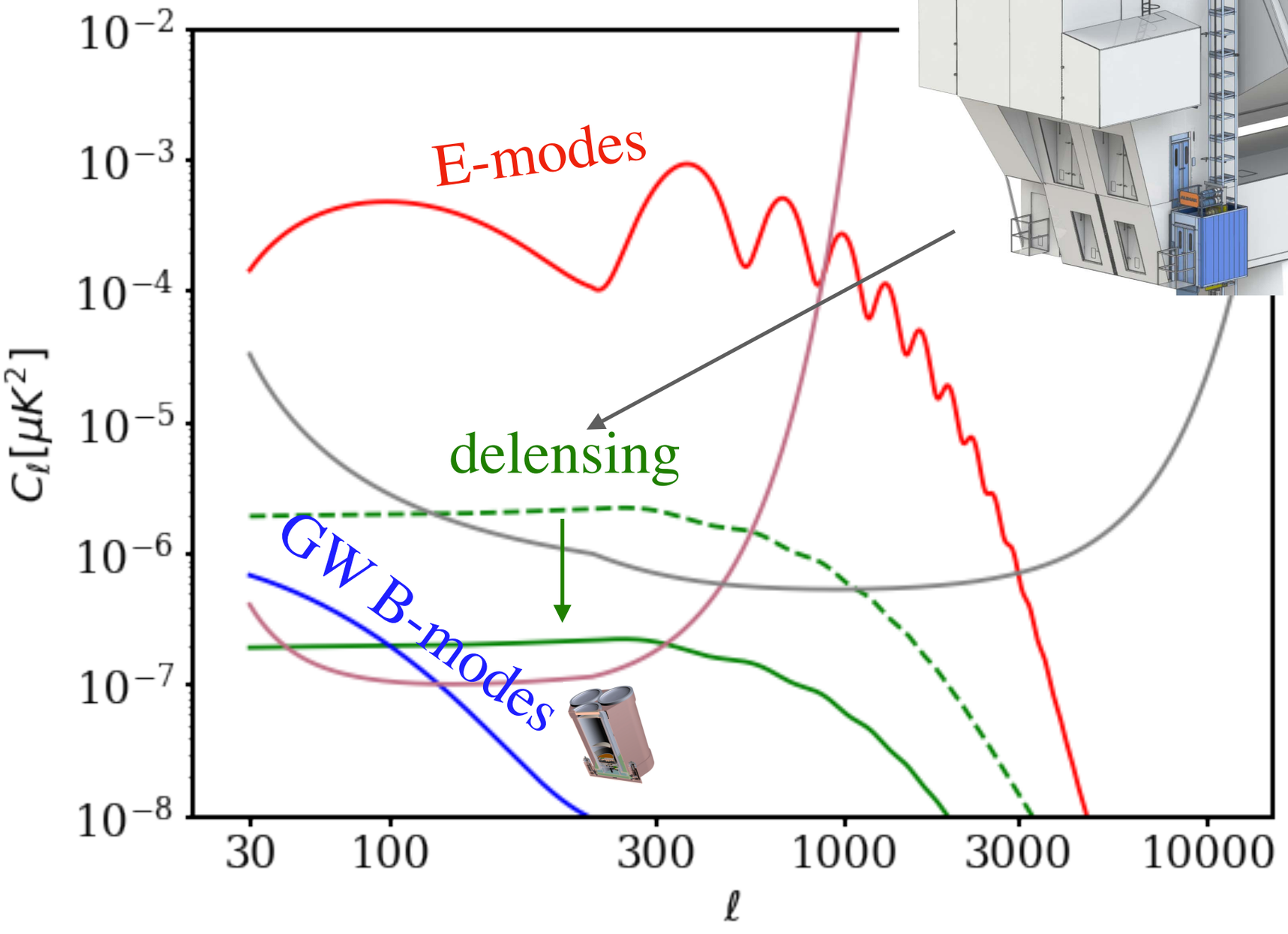
Degree and small scale polarization





Degree and small scale polarization





South Pole Observatory

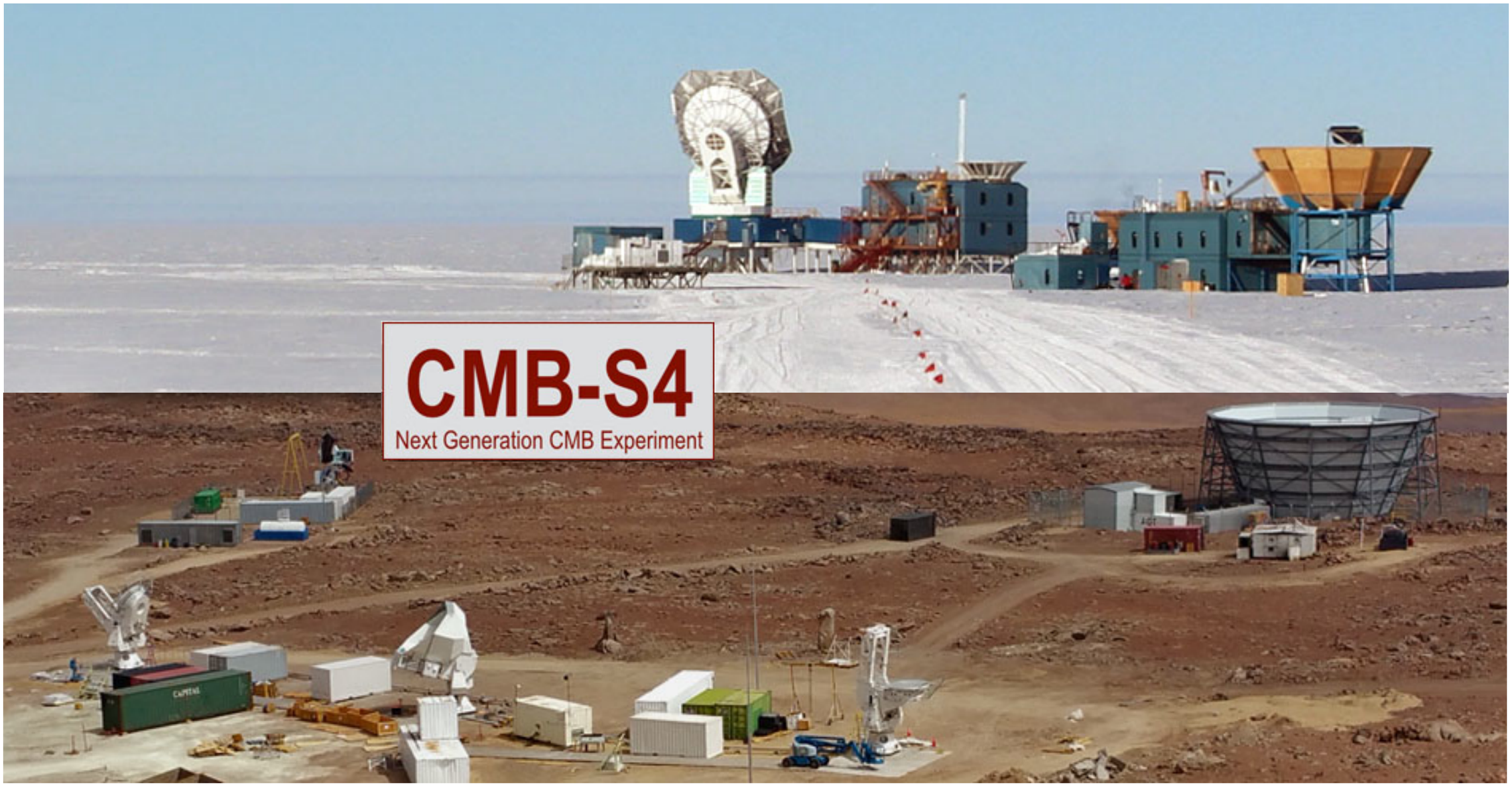
Stage III.5: 2021-2024

Simons Observatory

Stage III.5: 2021-2028

CMB-S4

Expected: 2028-2035



Inflation

The simplest system leading to a sufficiently long phase of accelerated expansion (that ends) is

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R$$
$$- \int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + V(\phi)\right)$$

with $M_P^2\left(\frac{V'}{V}\right)^2 \ll 1$ and $M_P^2\left|\frac{V''}{V}\right| \ll 1$ somewhere

If the scalar field is nearly homogeneous, and at a position in field space such that the potential energy dominates its energy density, this leads to nearly exponential expansion.

Inflation

The simplest models of inflation predict

- primordial fluctuations that are
  - well approximated by a power law (with exponent $n_{\rm s} - 1$)
  - nearly scale invariant ($n_{\rm s} - 1 \approx 0$)
  - dominated by density fluctuations with subdominant contribution from gravitational waves
  - close to Gaussian
  - adiabatic
- a universe that is spatially flat

consistent with observations

Expectations

Taking the observed value of the spectral index seriously, one might expect

$$n_s(\mathcal{N}) - 1 = -\frac{p+1}{\mathcal{N}}$$

In general (provided $\epsilon = -\dot{H}/H^2 \ll 1$)

$$\frac{d\ln\epsilon}{d\mathcal{N}} - (n_{\rm s}(\mathcal{N}) - 1) - 2\epsilon = 0$$

or

$$\epsilon(\mathcal{N}) = \frac{p}{2\mathcal{N}}\frac{1}{1 \pm (\mathcal{N}/\mathcal{N}_{\rm eq})^p}$$

with integration constant $\mathcal{N}_{\rm eq}$, which we might expect to be O(1) .

Expectations

Away from special period $\mathcal{N} \approx \mathcal{N}_{\rm eq}$, one of the terms dominates.

Monomial models

$$\epsilon(\mathcal{N}) = \frac{p}{2\mathcal{N}}$$

or (during inflation) $$V(\phi) = \mu^{4-2p}\phi^{2p}$$

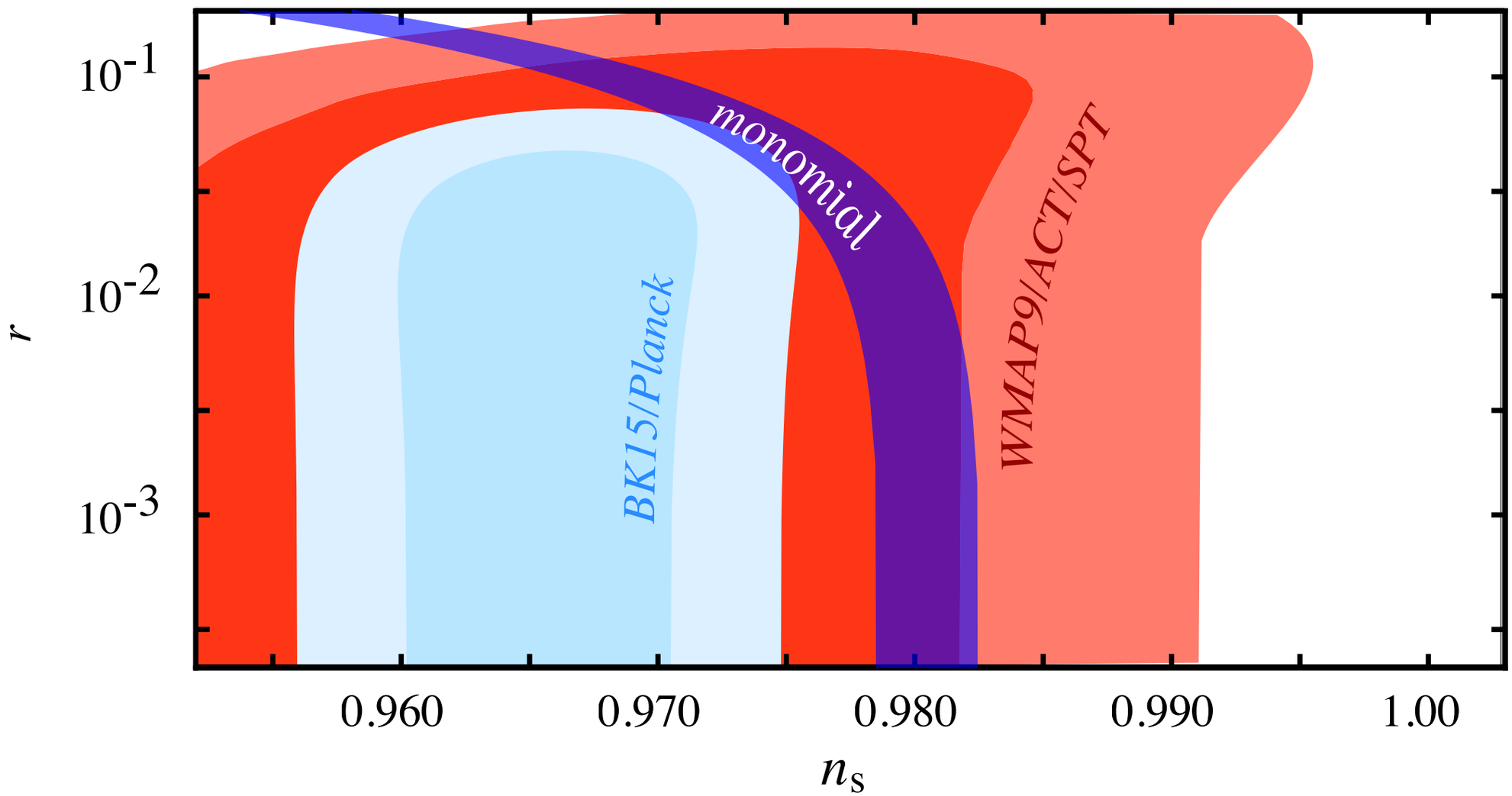
Plateau and hilltop models

$$\epsilon(\mathcal{N}) = \frac{p}{2\mathcal{N}}\left(\frac{\mathcal{N}_{\rm eq}}{\mathcal{N}}\right)^{p}$$

or (during inflation) $$V(\phi) \approx V_0\left[1-\left(\frac{\phi}{\Lambda}\right)^{\frac{2p}{p-1}}\right]$$

Expectations

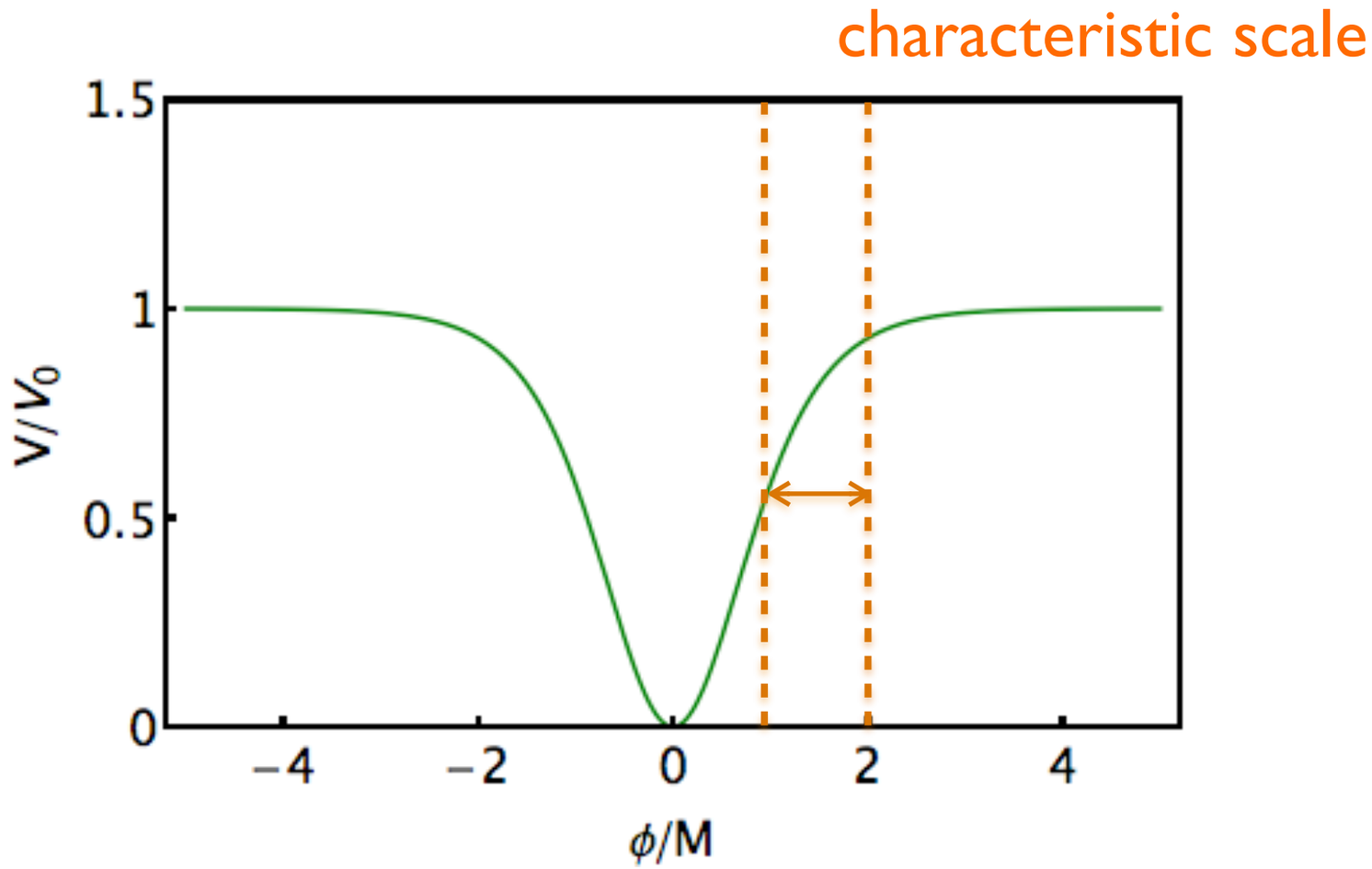
Monomial models



are about to be excluded by current data.

Expectations

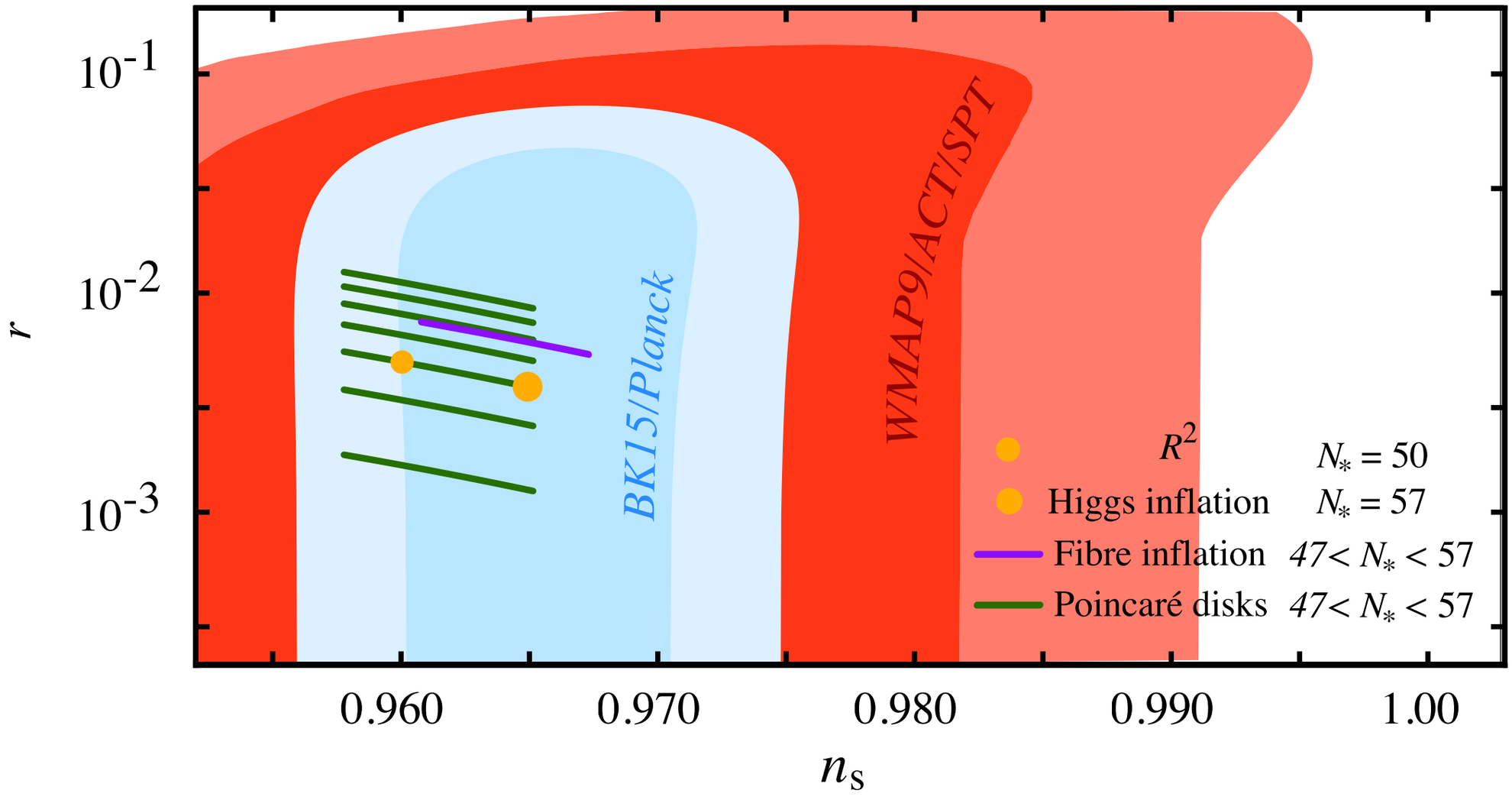
The plateau and hilltop models come with a characteristic scale over which the potential departs from a constant.



The integration constant is given by $\mathcal{N}_{\rm eq} = \dfrac{p}{4}\left(\dfrac{M}{M_P}\right)^2$.

Expectations

In many models, $M \approx M_P$ because they have a common origin.



all within reach of CMB-S4

CMB-S4

CMB-S4 goal (for primordial gravitational waves)

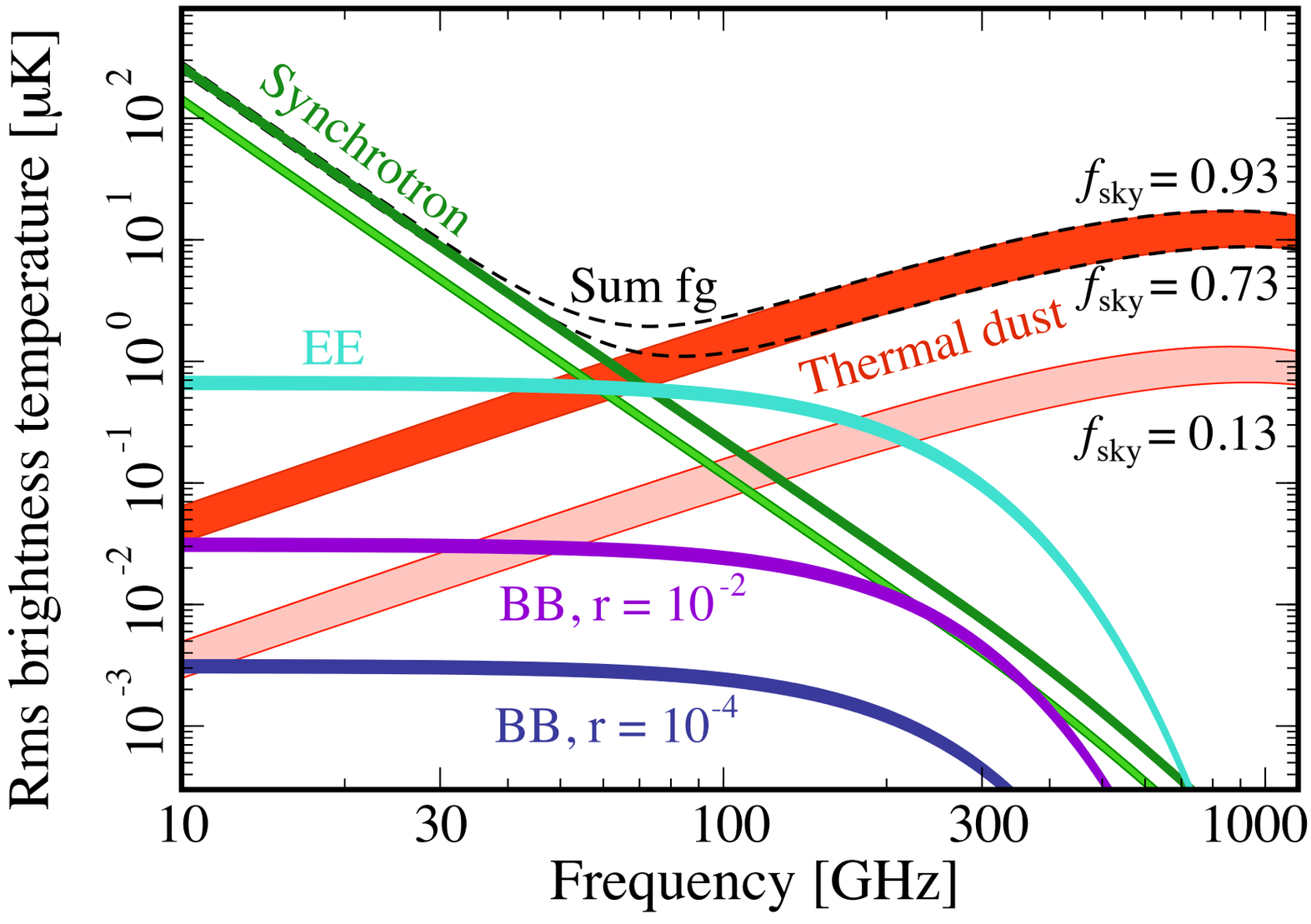
Robust detection of primordial gravitational waves
or upper limit $r < 0.001$ at 95%CL

(Main) challenges

- Weak gravitational lensing of the CMB by intervening matter converts E- to B-modes and data must be delensed.
- Galactic foregrounds generate B-modes and must be removed

Challenge: Foregrounds

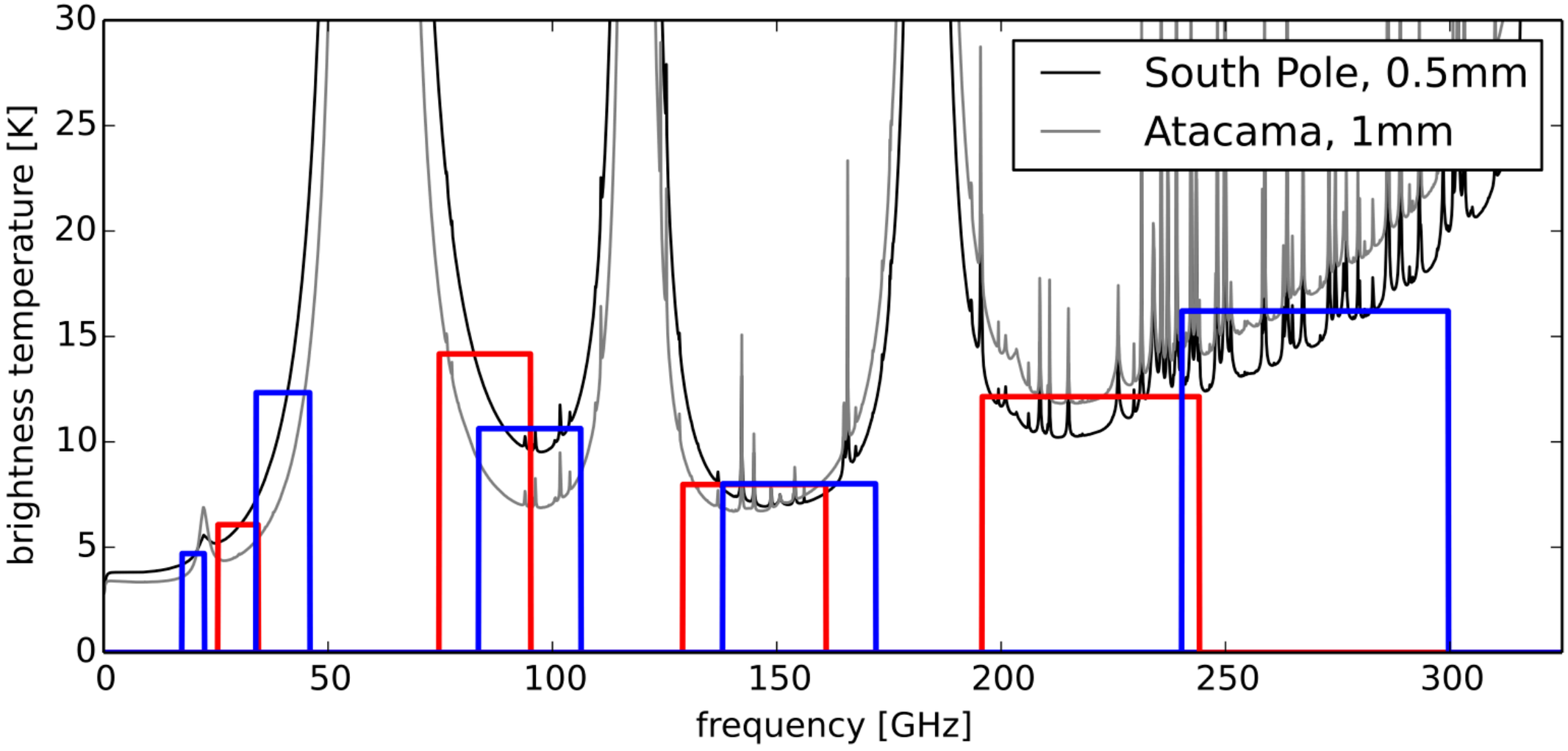
We measure degree-scale polarization of the microwave sky, not of the CMB directly.



Multifrequency degree-scale polarization measurements are needed to remove foregrounds.

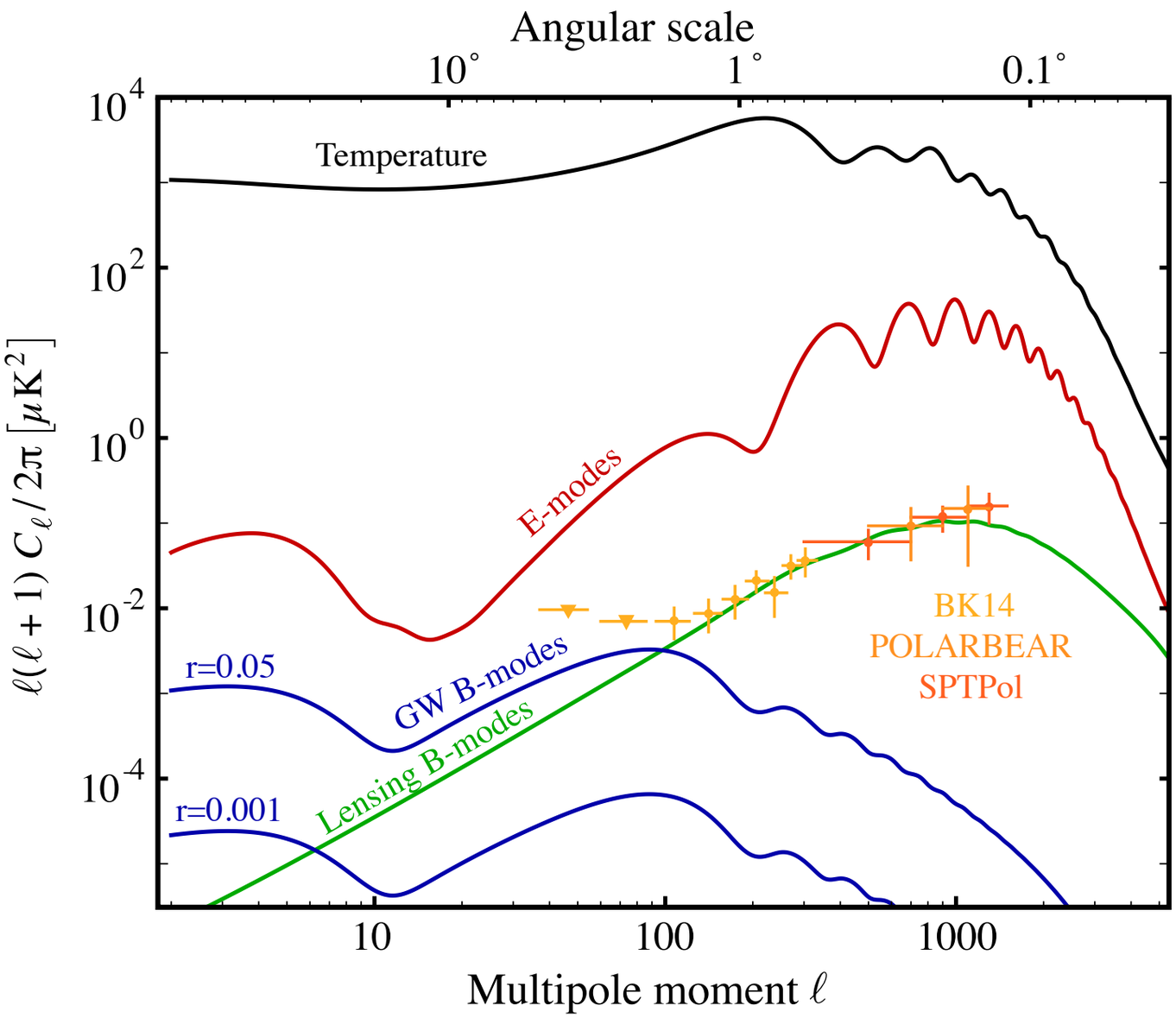
Challenge: Foregrounds

For ground-based experiments, the atmosphere limits the possible frequency coverage.



This makes it natural to target the cleanest regions.

Challenge: Lensing B-modes

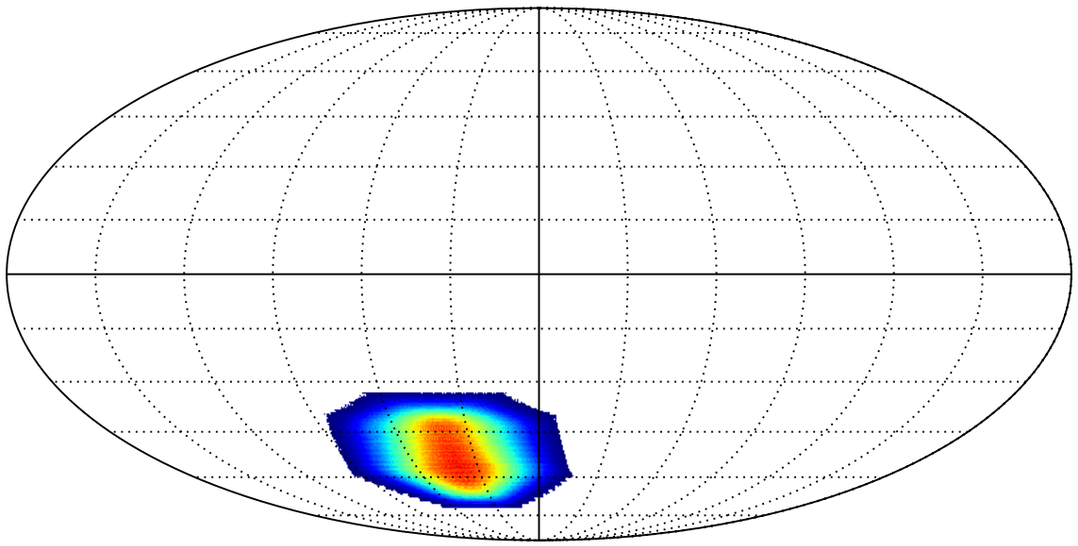


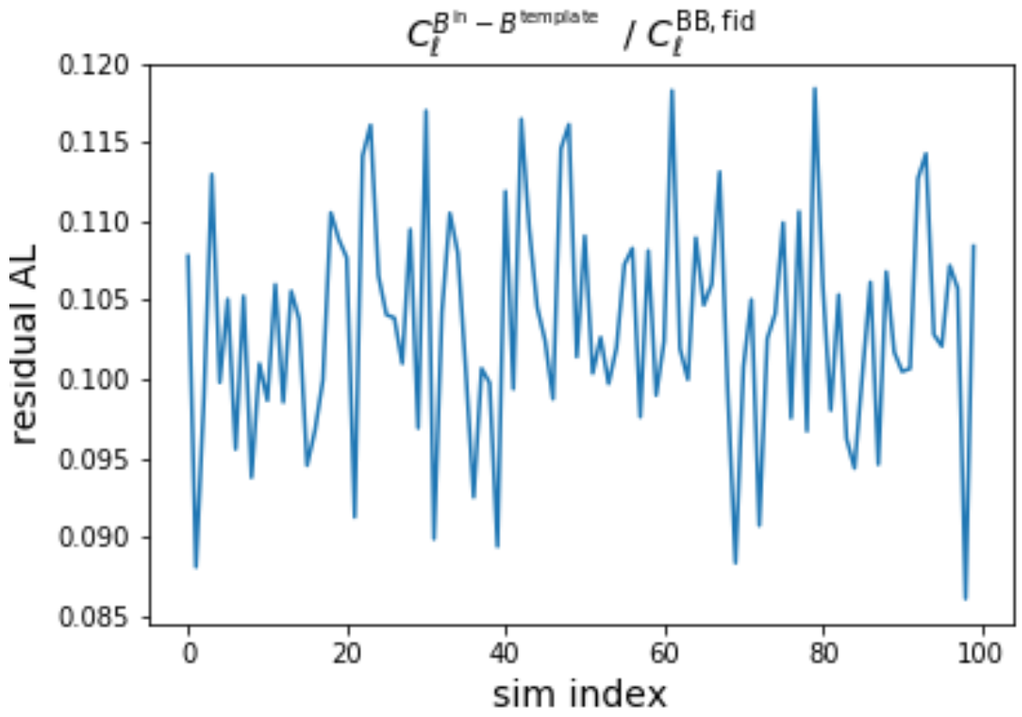
Lensing B-modes introduce an effective floor at 5μK-arcmin.

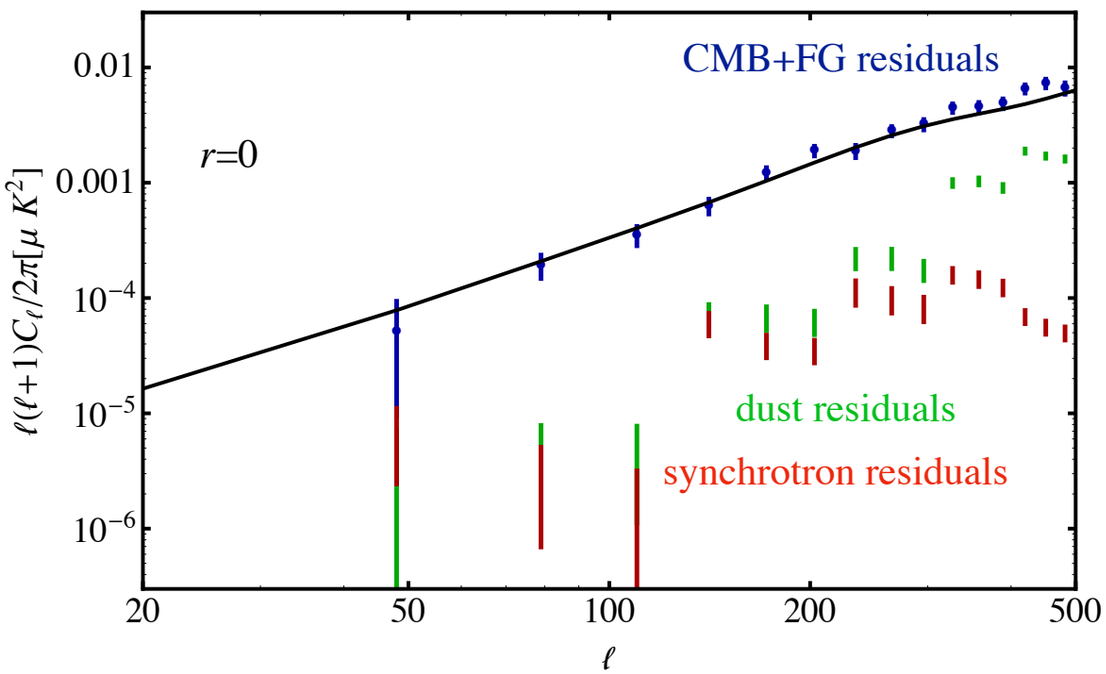
Going beyond this floor for degree-scale measurements requires high resolution polarization data to "delens".

Validation

We can "observe" the sky with this configuration and validate its performance on simulations on a suite of foreground models.

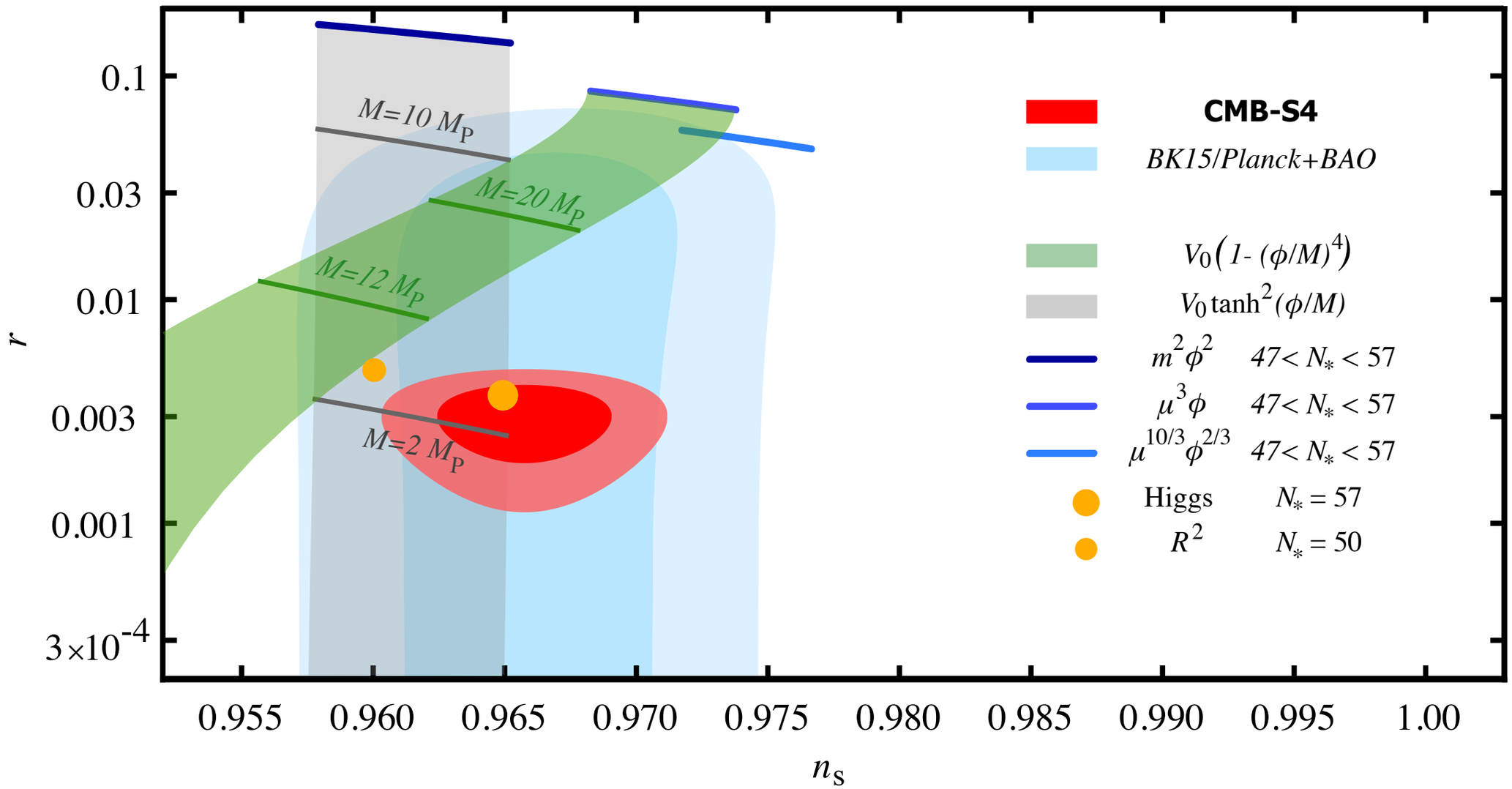






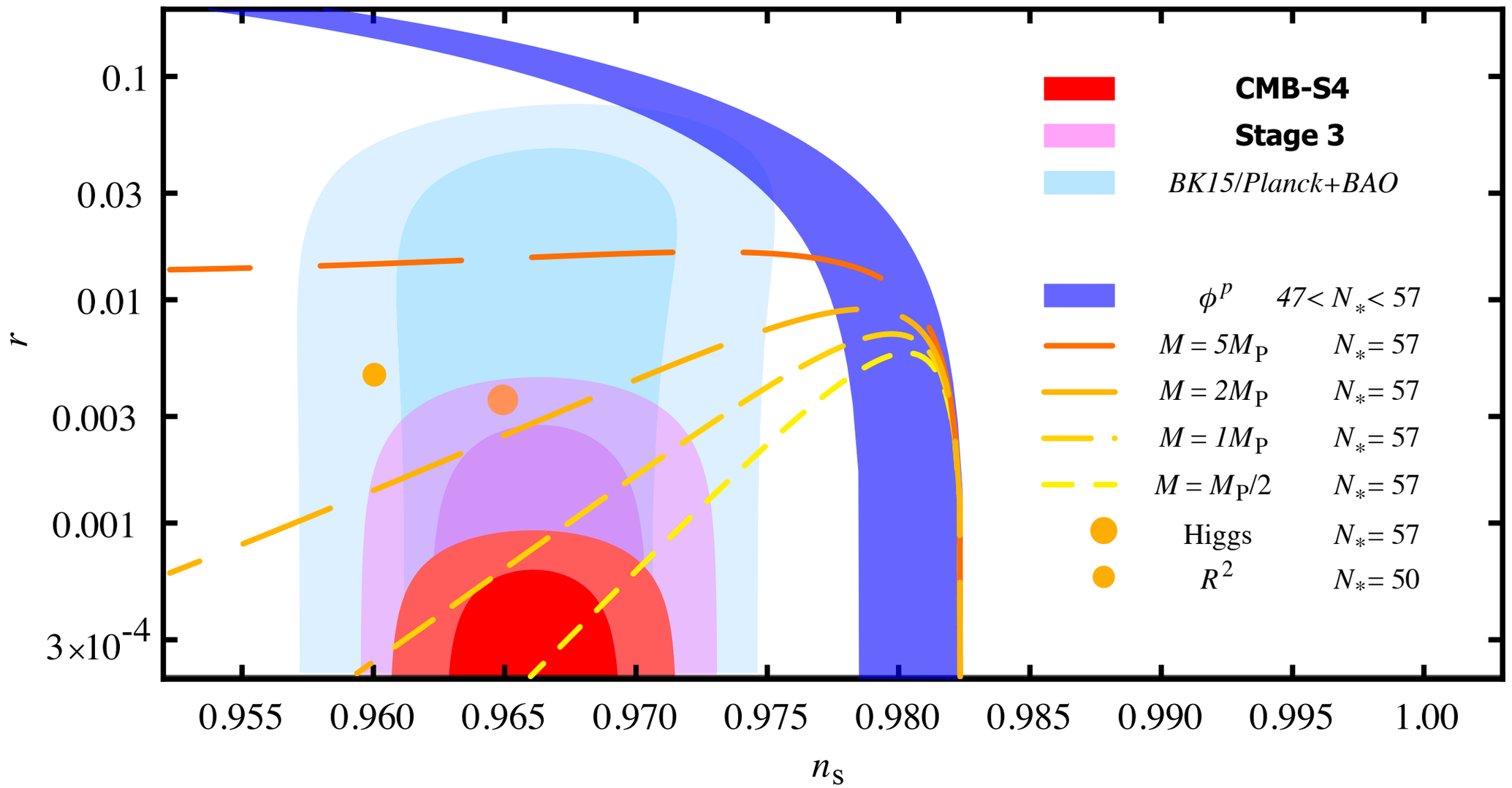
CMB-S4

Detection

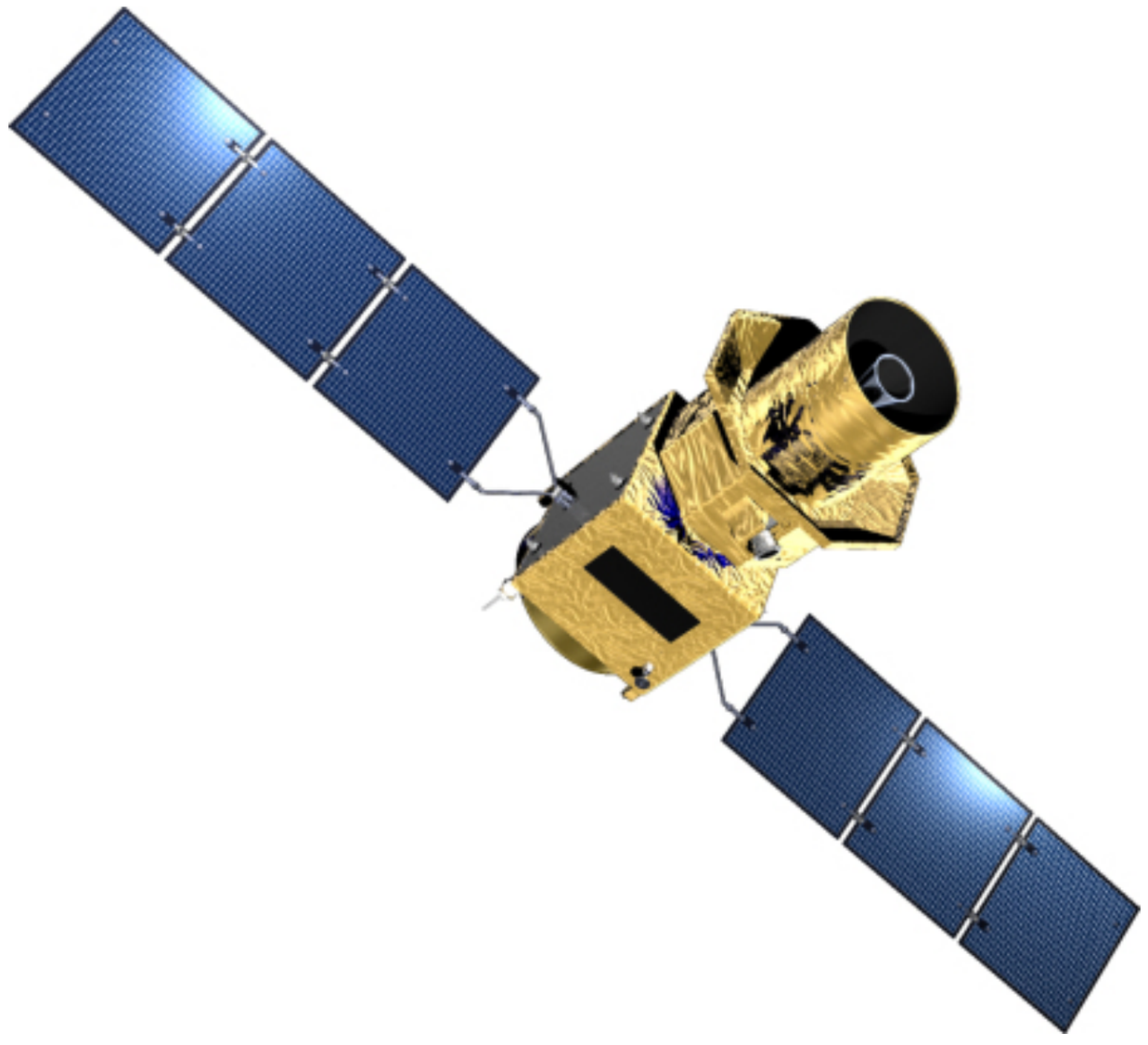


CMB-S4

Expected upper limits



LiteBIRD

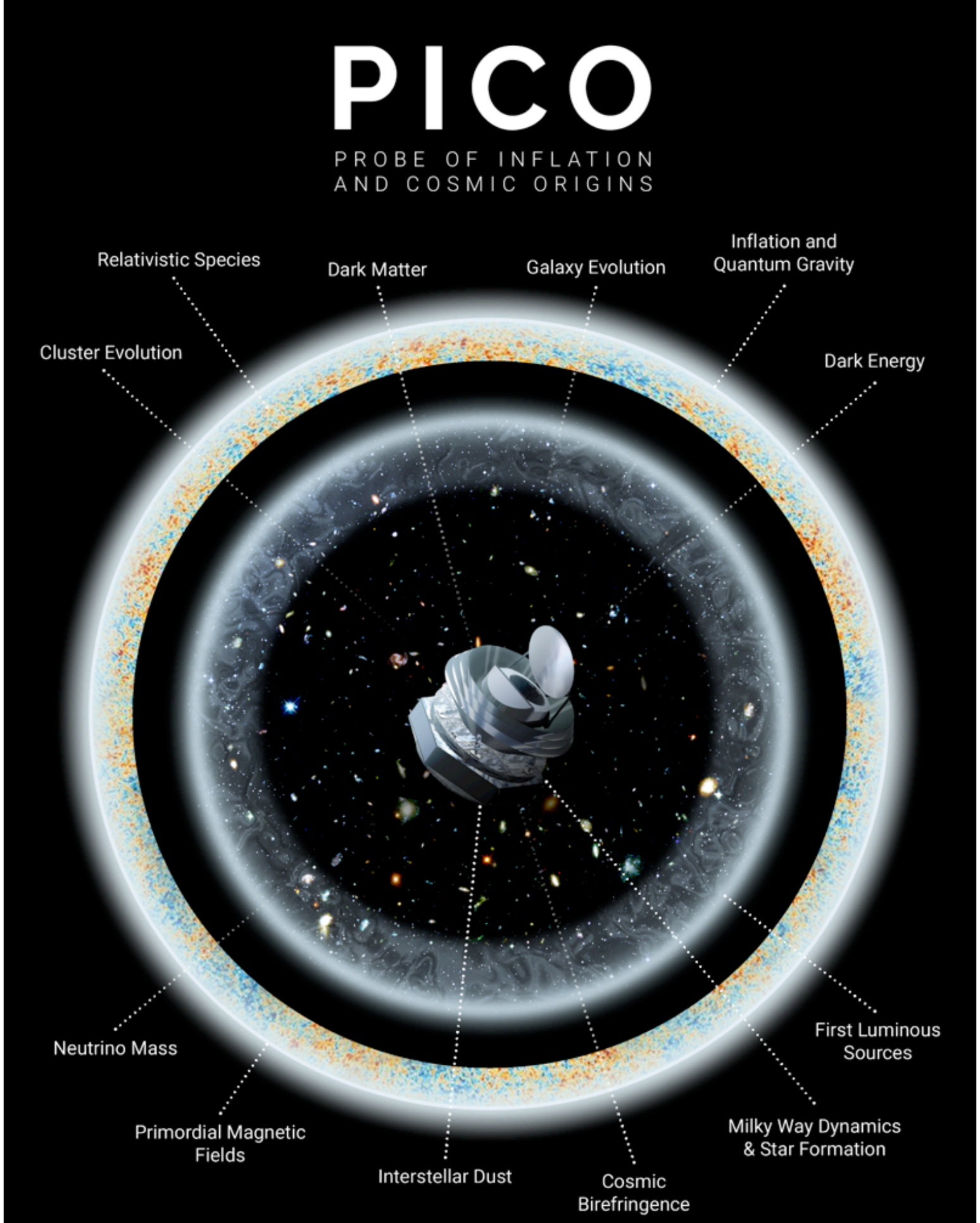


Selected by JAXA in 2019

Launch in 2028

PICO

PROBE OF INFLATION
AND COSMIC ORIGINS



Conclusions

- The CMB has provided us with invaluable information about the early universe for 56 years and will continue to do so for at least another decade.
- CMB-S4 is exquisitely sensitive to gravitational waves present at recombination.
- Gravitational waves present at recombination are a pristine relic of the primordial universe.
- Either a detection of, or an upper limit on, the amount of gravitational waves with CMB-S4 will provide invaluable information about the primordial universe.
- To achieve the science goals, unprecedented control over delensing, foregrounds, and instrumental systematics is required, but so far simulations indicate that both foregrounds and lensing can be controlled at the required levels.

Thank you