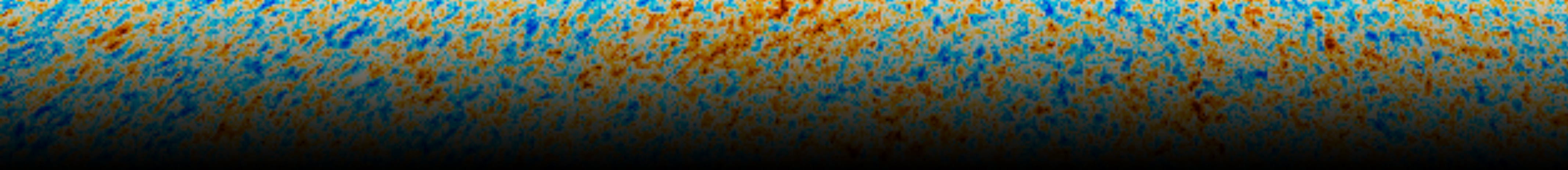
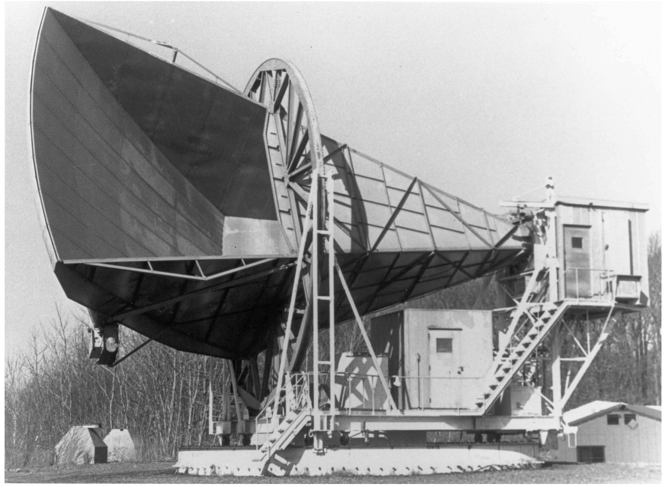


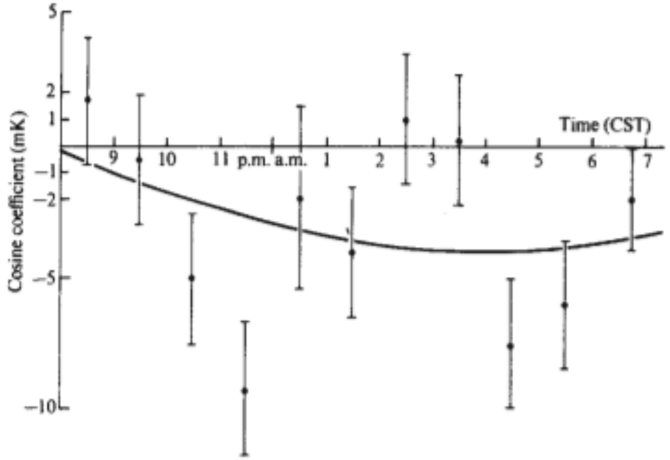
Future CMB Experiments and Impact for Fundamental Physics

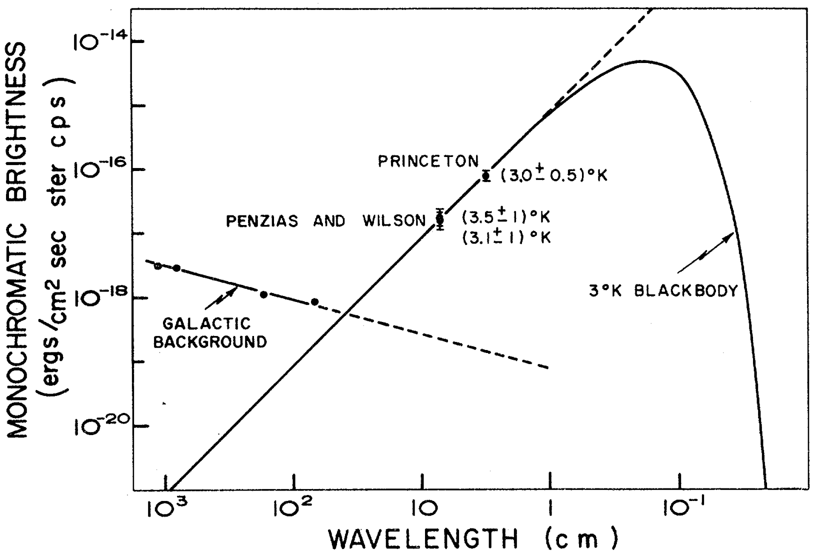
Raphael Flauger

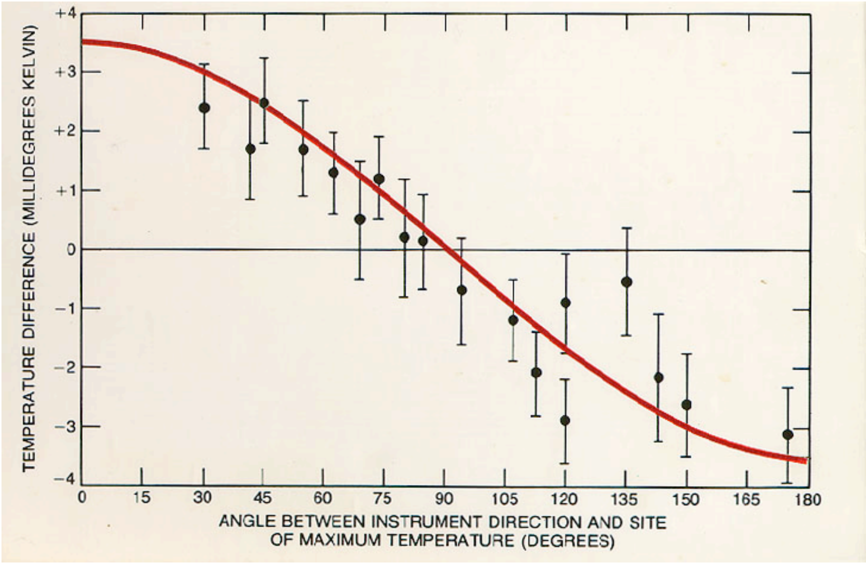
Fundamental Physics of the Cosmos, DESY, Hamburg, September, 28 2017

Past Experiments

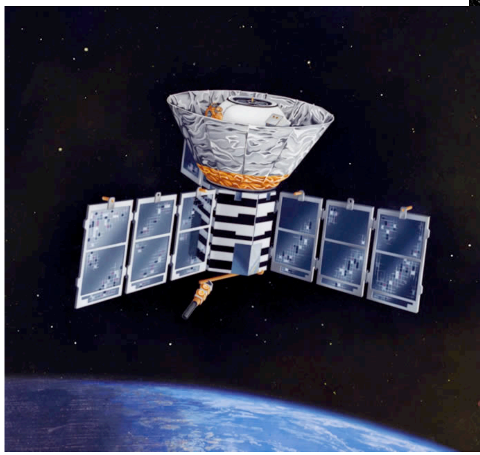


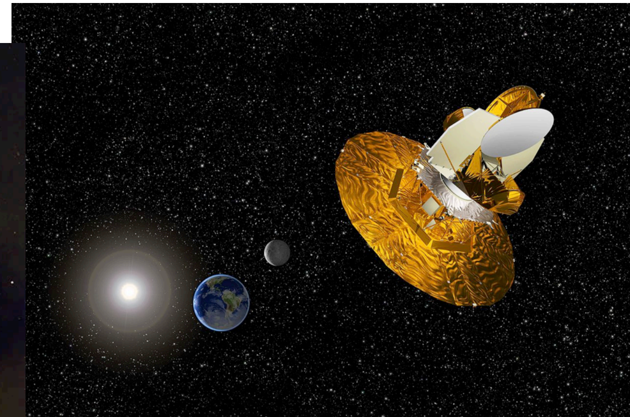


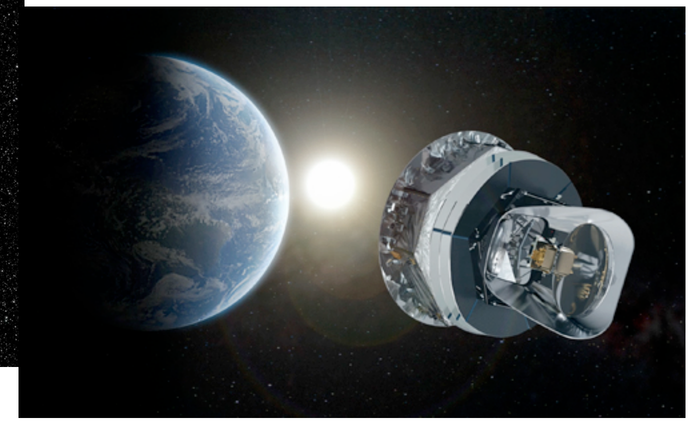


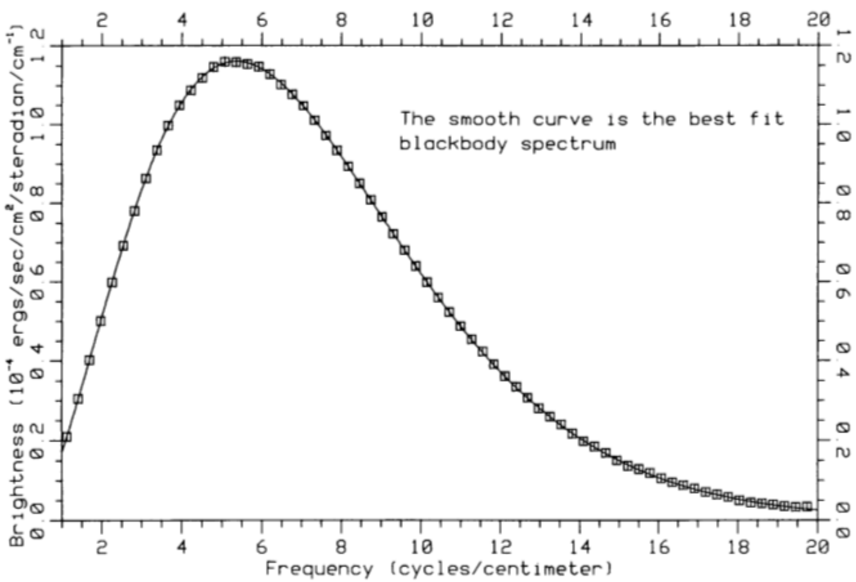


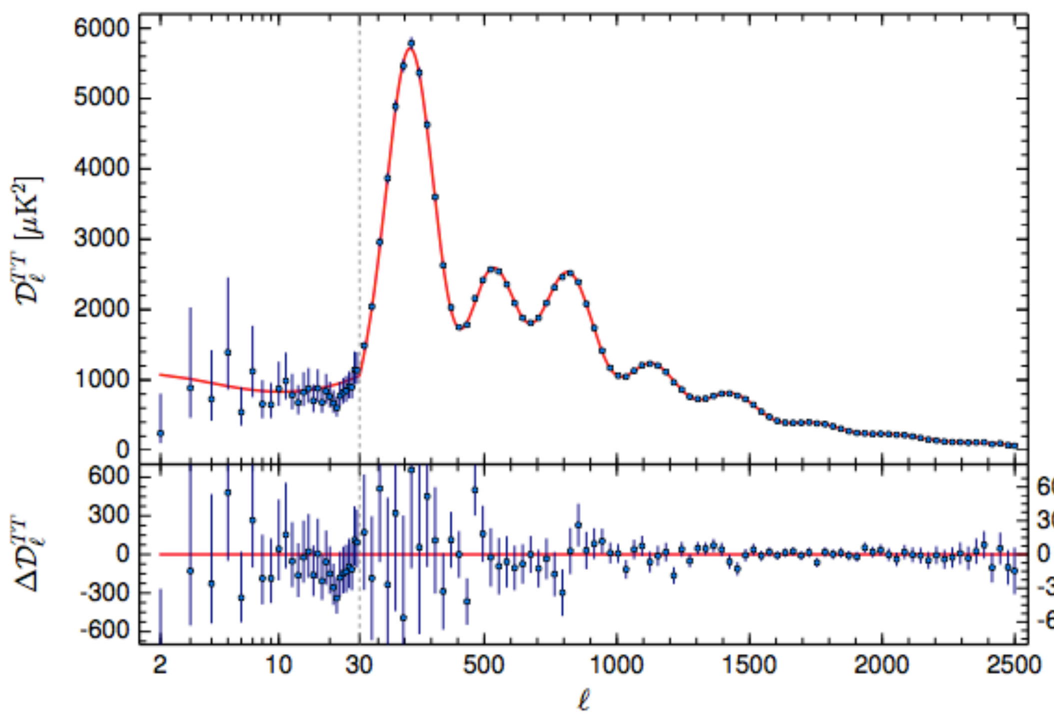
Past Experiments











Past Experiments

Measurements of the CMB have taught us a great deal about the early universe

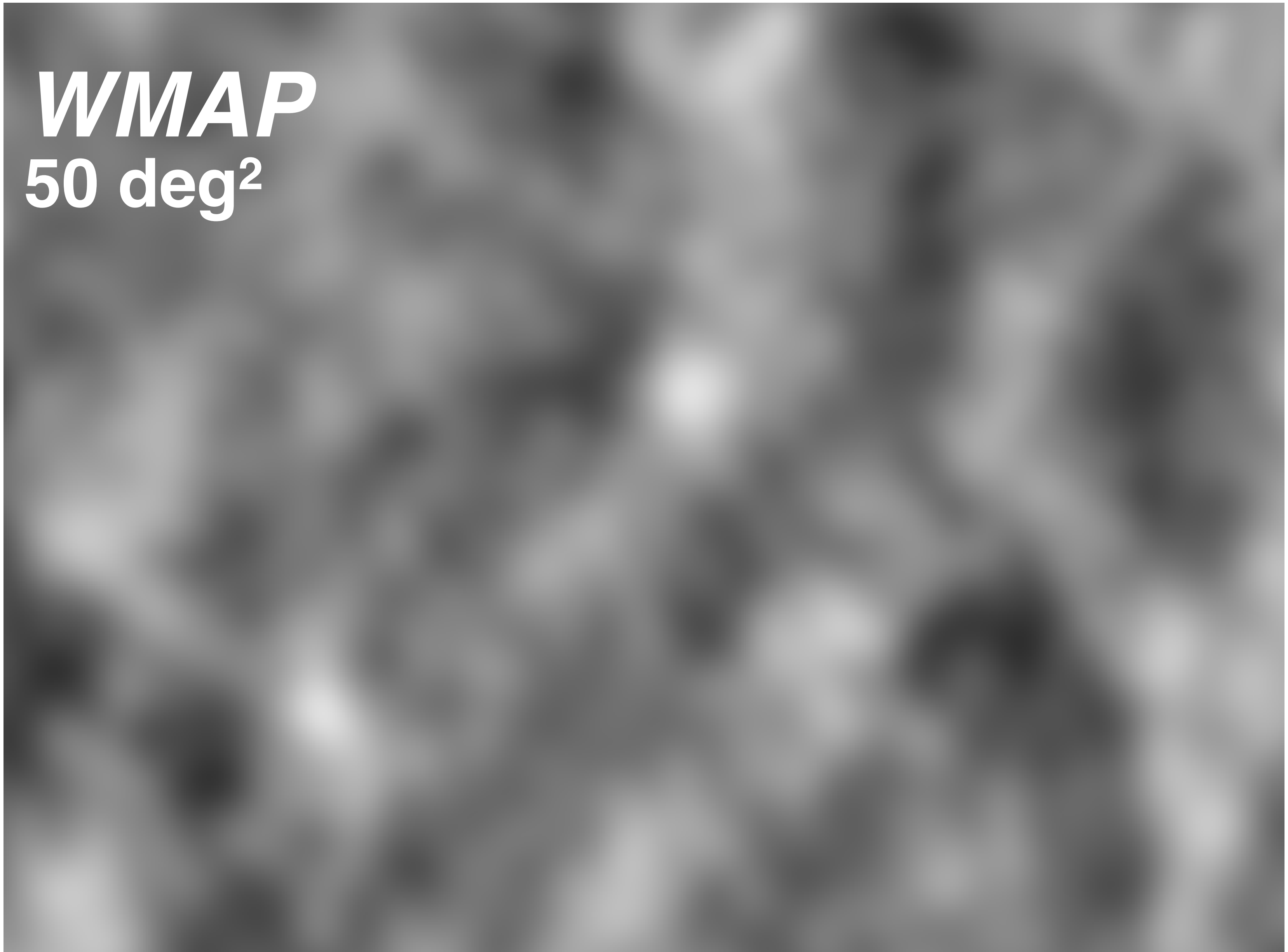
- Hot big bang
- Age and composition of the universe
- Adiabatic, nearly scale invariant, Gaussian perturbations
- Non-baryonic dark matter
- ...

Past Experiments

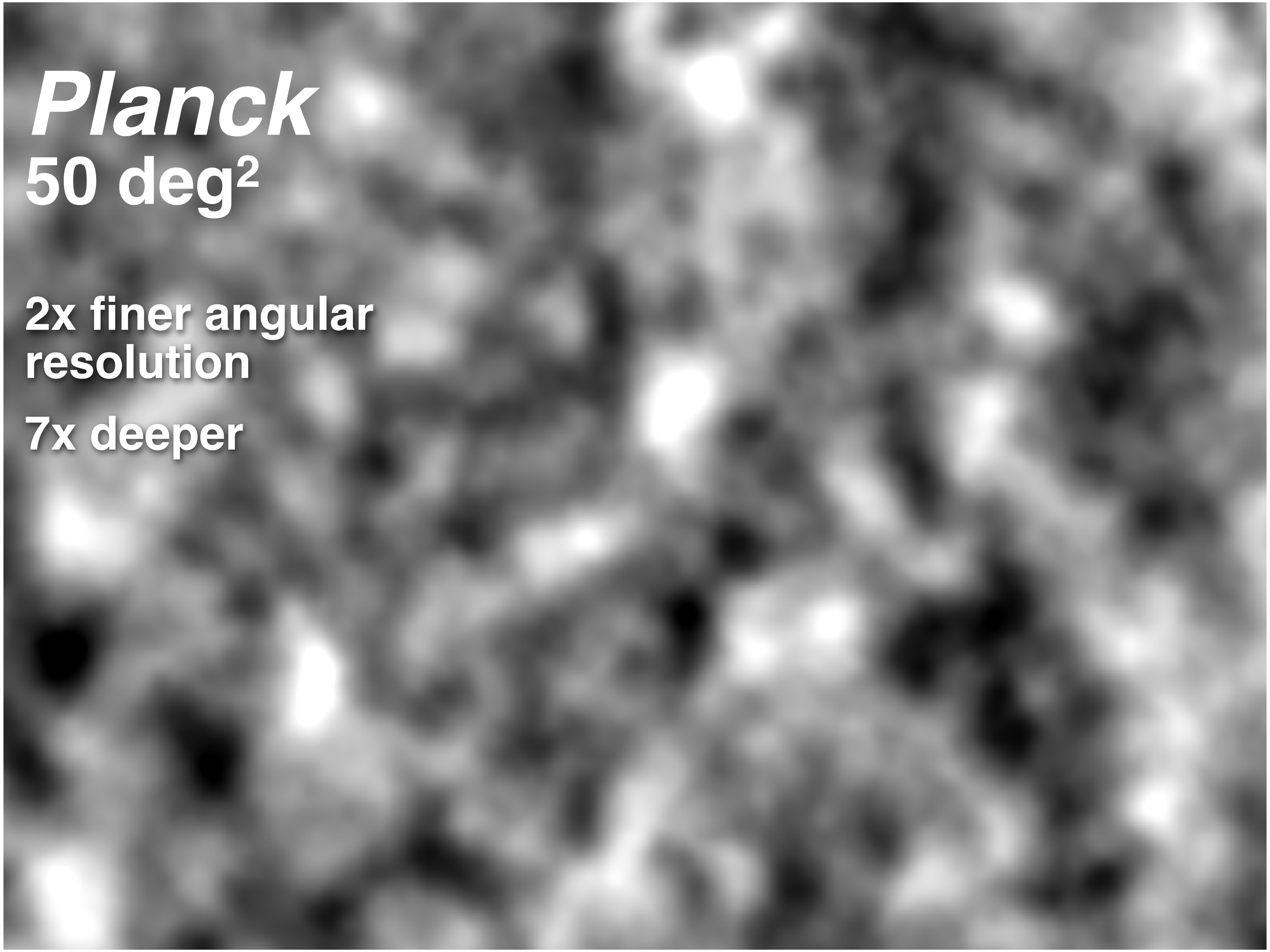
Primary temperature anisotropies have been measured as well as possible, and we are entering a new era that will explore

- Polarization of the CMB
- Secondary anisotropies in temperature and polarization
- Frequency spectrum of the CMB

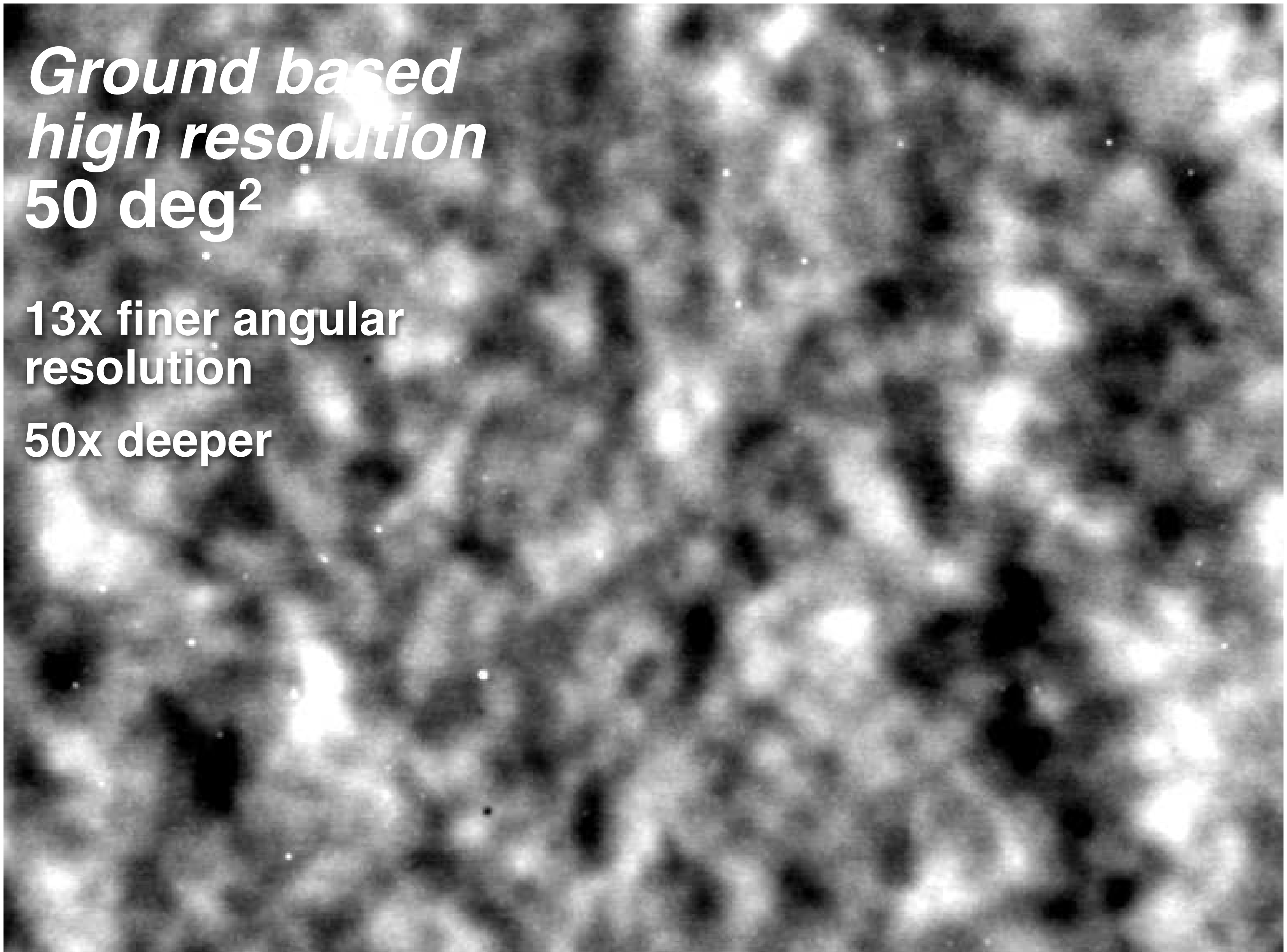
Past Experiments



Past Experiments

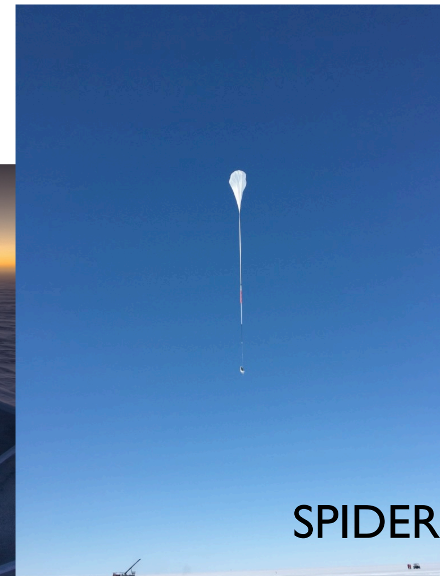


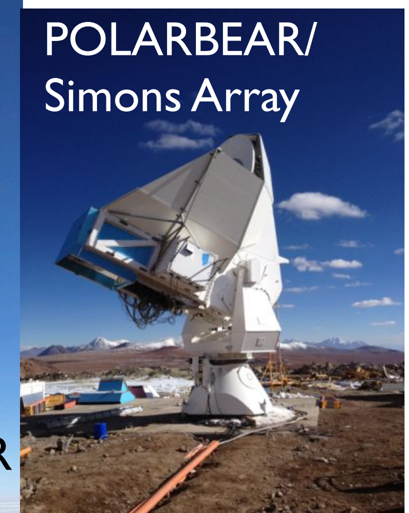
Past Experiments



Current Experiments

Stage III: now-2020





Future Experiments

Stage III.5: soon-2020

http://simonsobservatory.org

- A five year, $45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.
- Merger of the ACT and POLARBEAR/Simons Array teams.
- Tentative plans include:
  - Major site infrastructure
  - Technology development (detectors, optics, cameras)
  - Demonstration of new high throughput telescopes.
  - CMB-S4 class receivers with partially filled focal planes.
  - Data analysis

Future Experiments

Stage IV: 2020-2030

Potentially Space Missions

LiteBIRD, CMB Probe?

CMB-S4

Joint effort of entire US CMB community

September 2015 Collaboration Workshop
University of Michigan

March 2016 Collaboration Workshop
LBNL

September 2016 Collaboration Workshop
University of Chicago

CMB-S4 Science Book (http://www.cmbs4.org)

March 2017 Collaboration Workshop
SLAC

August 2017 Collaboration Workshop
Harvard University

CDT

Julian Borrill	LBNL
John Carlstrom	Chicago
Tom Crawford	Chicago
Mark Devlin	Penn
Jo Dunkley	Princeton
Raphael Flauger	UCSD
Brenna Flaugher	FNAL
Shaul Hanany	U Minnesota
Kent Irwin	Stanford/SLAC
Bill Jones	Princeton
Brian Keating	UCSD
John Kovac	Harvard
Akito Kusaka	LBNL
Charles Lawrence (Chair)	JPL
Adrian Lee	Berkeley/LBNL
Jeff McMahon	Michigan
Mike Niemack	Cornell
Steve Padin	Chicago
Clem Pryke	Minnesota
Suzanne Staggs	Princeton
Ed Wollack	GSFC

CMB-S4 Science Goals

Driving the design

- Primordial gravitational waves
- Light relics

Free science

- Neutrino mass measurement
- Measurement of evolution of cosmic structure
- ...

CMB-S4 Science Goals

The science goals most relevant to the high energy community are

- Detect primordial gravitational waves or place an upper limit $r < 0.001$ at 95%CL
- Measure $N_{\rm eff}$ with a precision of $\sigma(N_{\rm eff}) \approx 0.03$
- Determine the sum of neutrino masses at $\geq 2\sigma$ even for the minimum value allowed for the normal hierarchy (58 meV)

CMB-S4

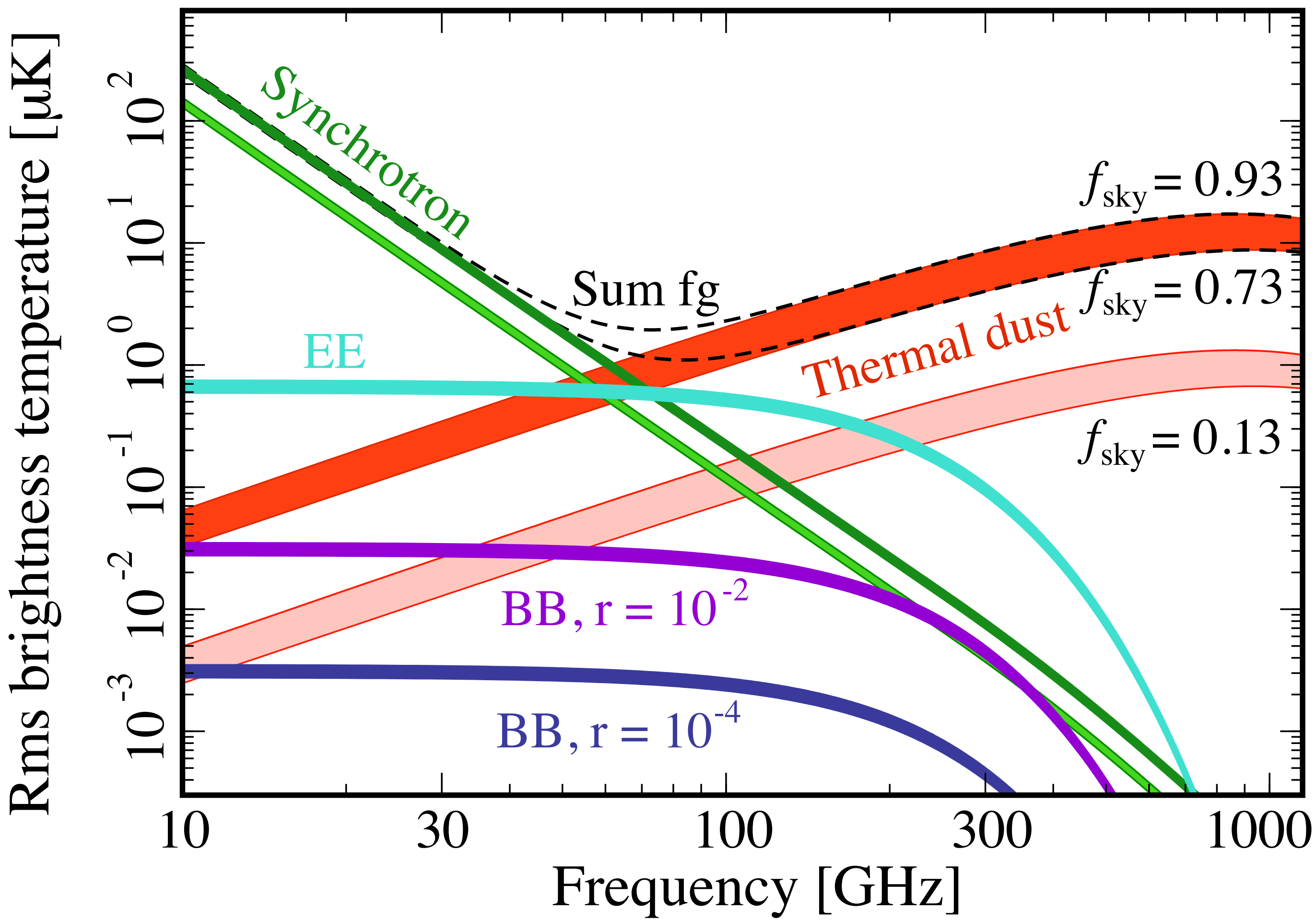
CMB-S4 will be a single experiment and collaboration at two sites (South pole and Atacama)

- deep survey on small patch (or patches) for primordial B-mode search
- wide survey for measurement of effective number of relativistic degrees of freedom, neutrino mass, growth of structure, ...

Primordial B-modes

- Seemingly straightforward because at linear order scalar perturbations do not generate B-modes.
- However, weak gravitational lensing of the CMB by intervening matter converts E- to B-modes
- Galactic foregrounds generate B-modes

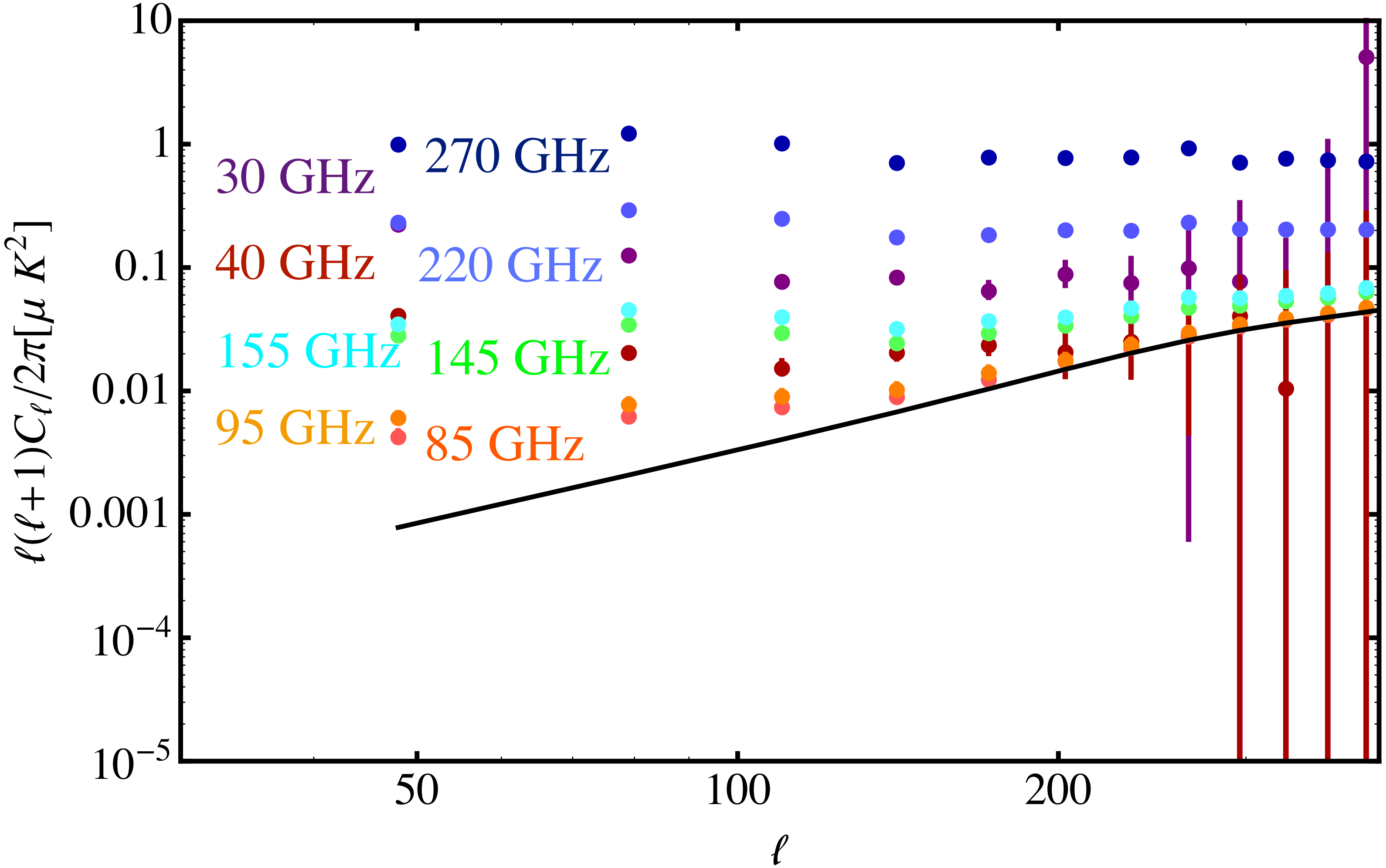
Primordial B-modes



We cannot avoid foregrounds anywhere in the sky at any frequency

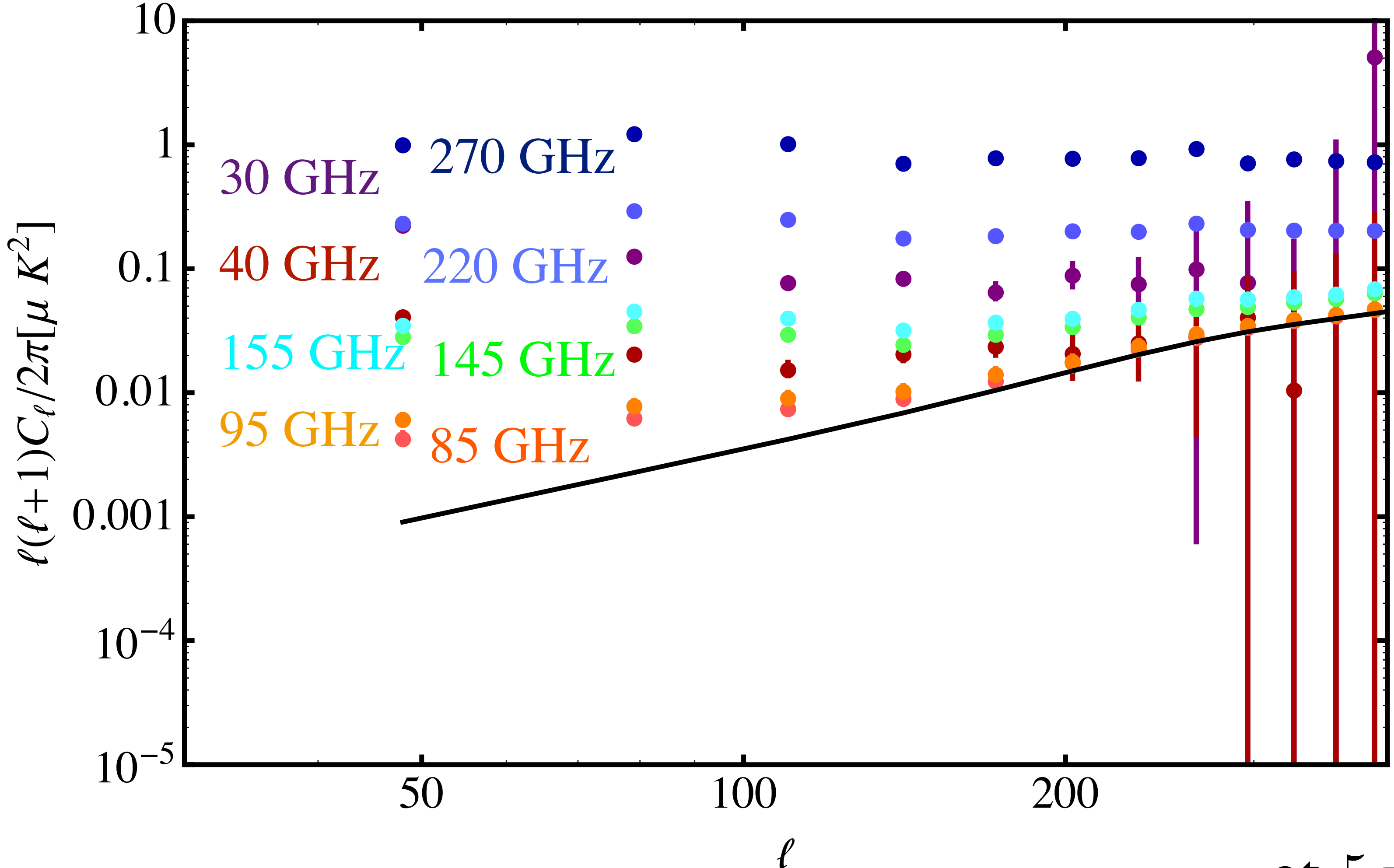
Primordial B-modes

The challenge is to use maps with auto-spectra shown below to tell the difference between (r=0)...



Primordial B-modes

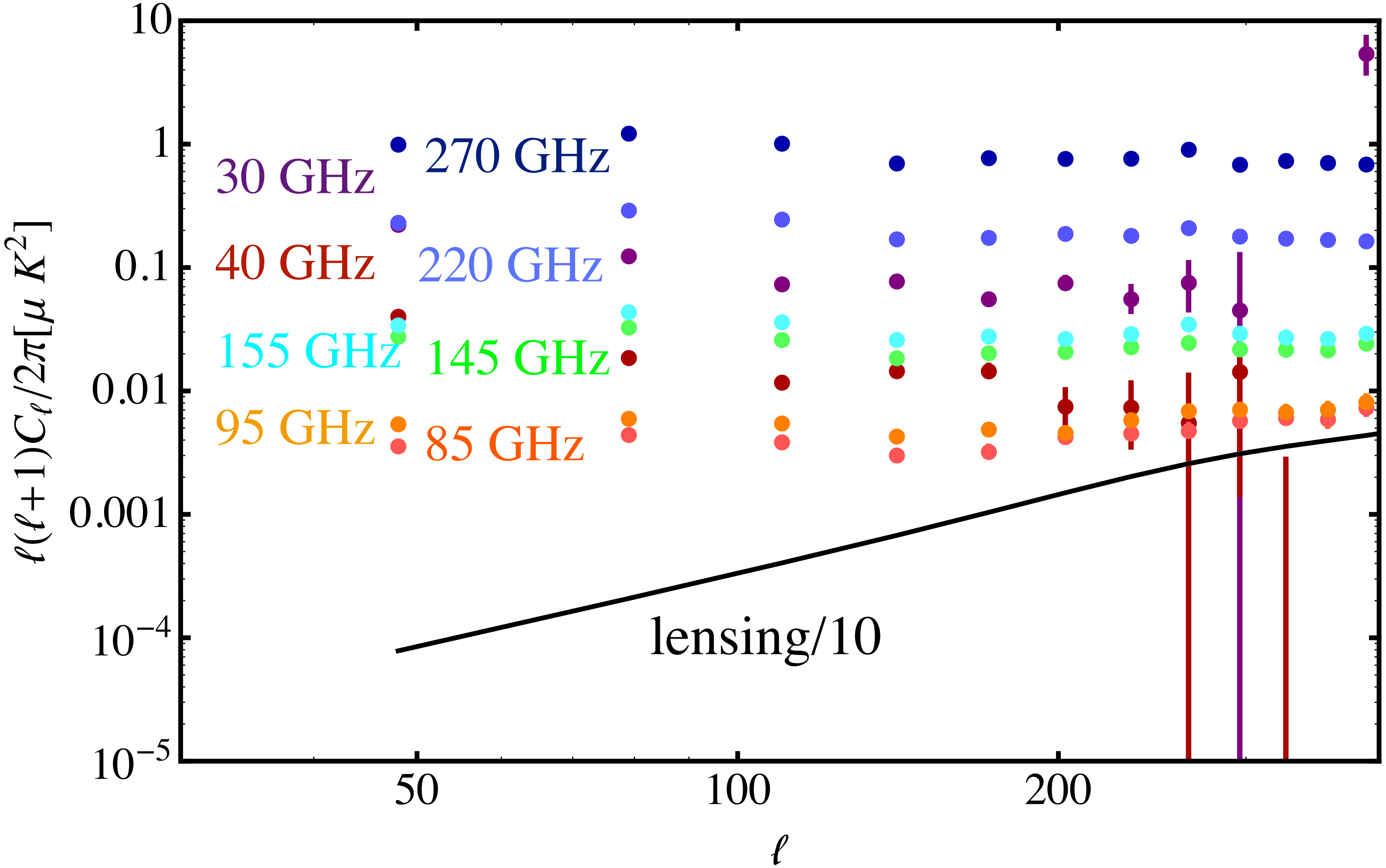
and (r=0.003)...



at 5σ

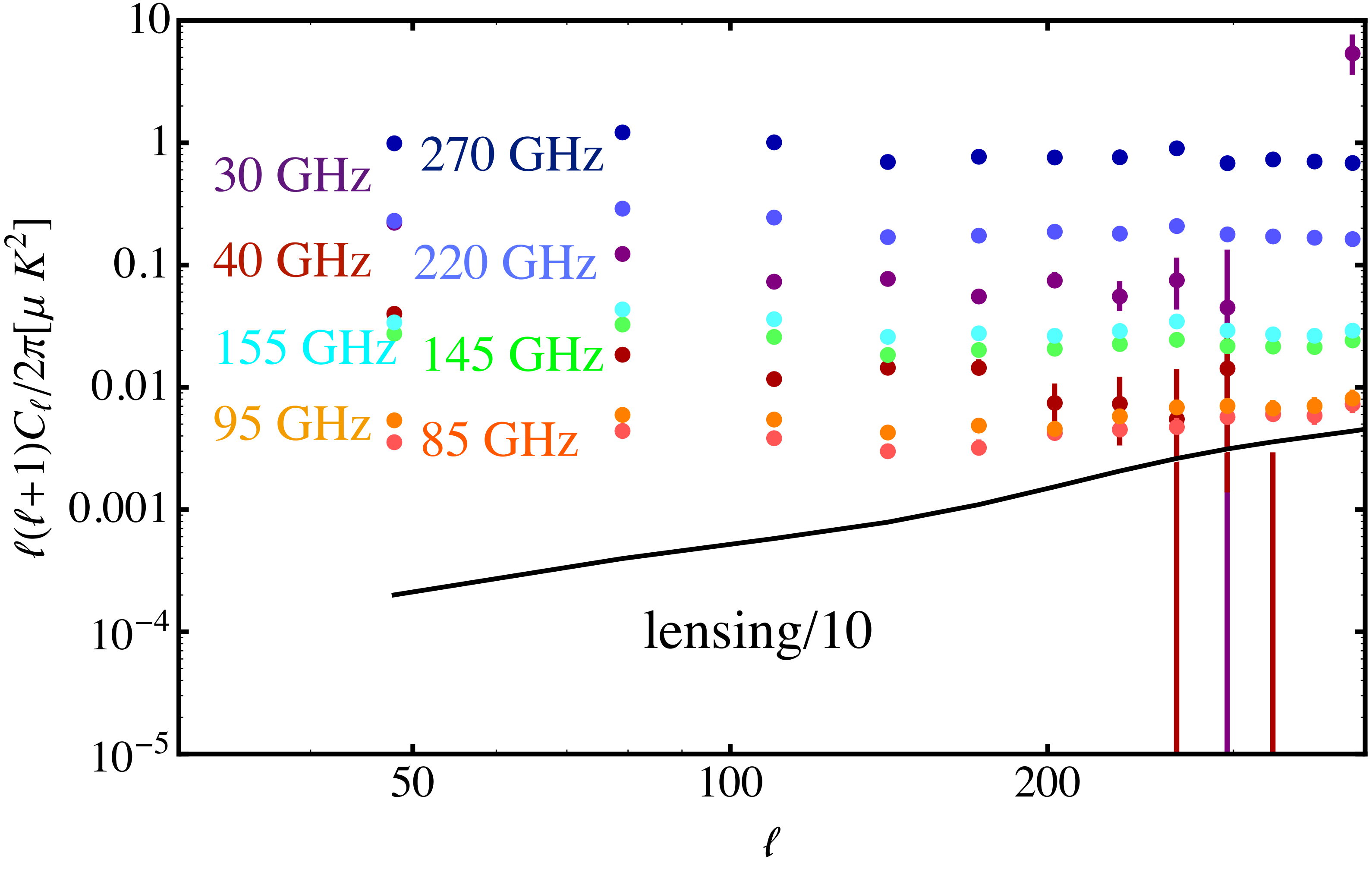
Primordial B-modes

Lensing B-modes can be partially removed through precise measurements of the lensing potential and E-modes



Primordial B-modes

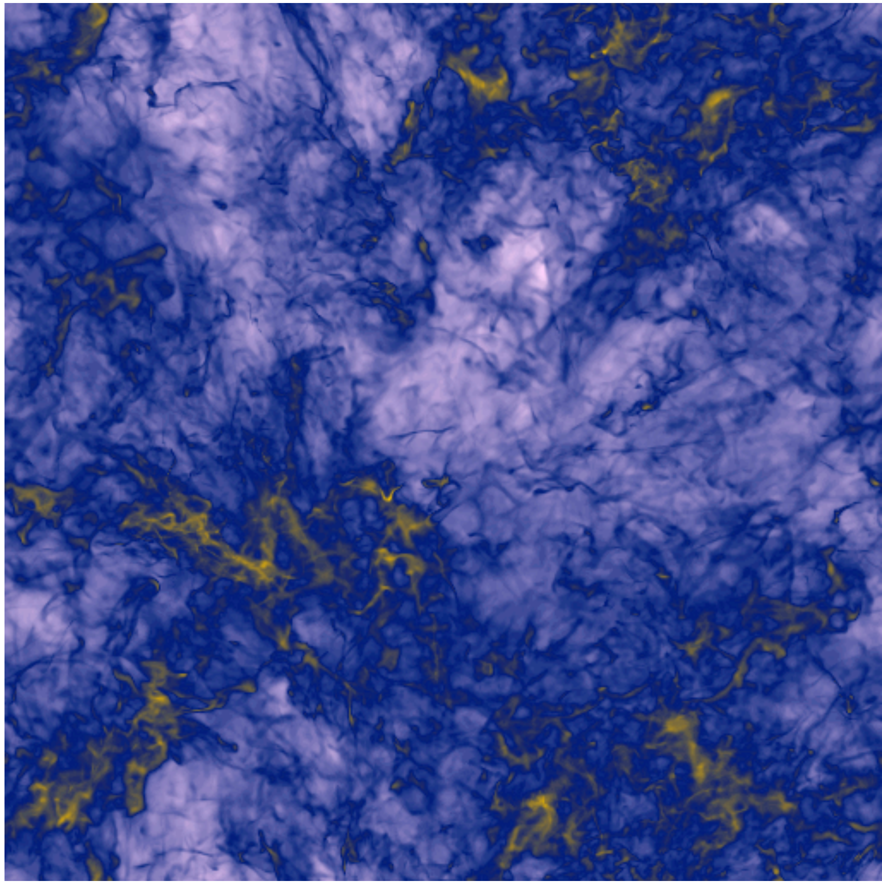
r=0.003



Primordial B-modes

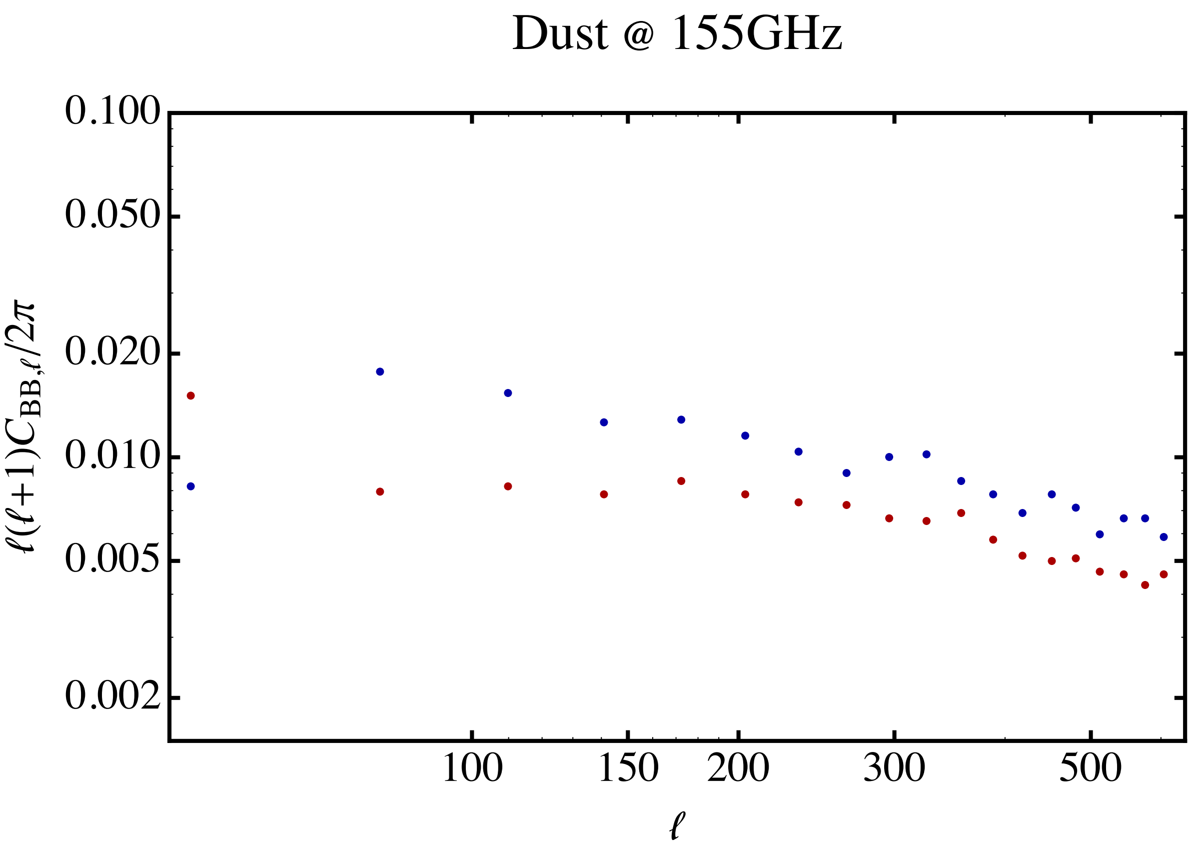
Models based on MHD simulations

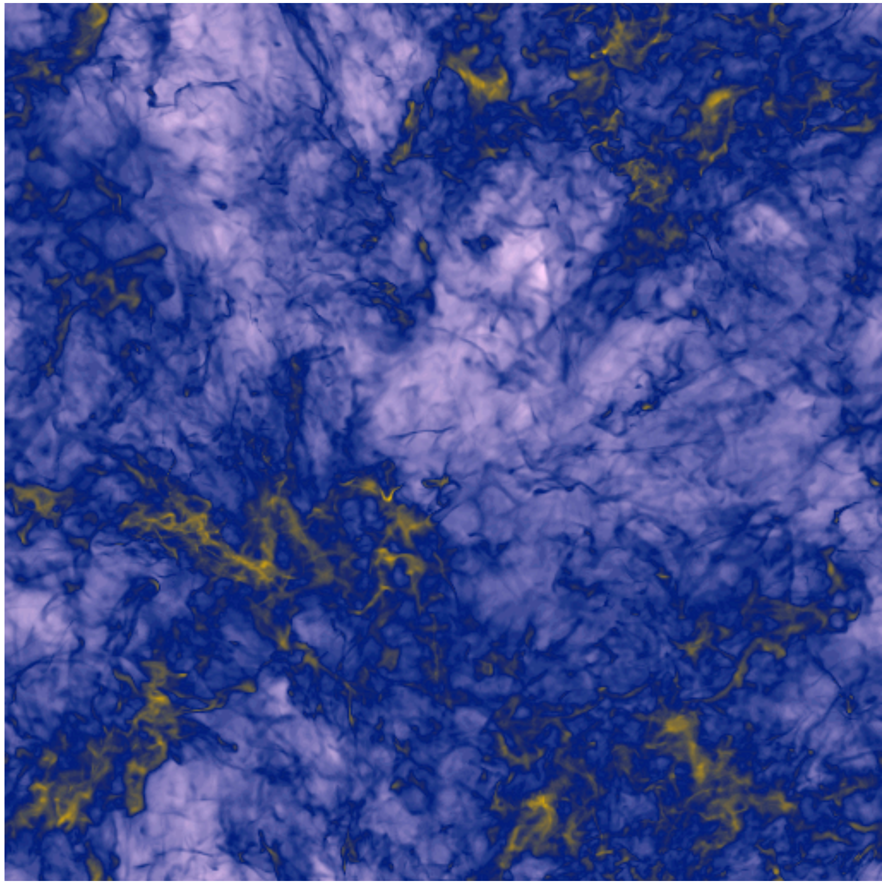
- assume constant dust-to-gas ratio to include dust (not necessary)
- assume energy spectrum of electrons to include synchrotron



Primordial B-modes

Models based on MHD simulations

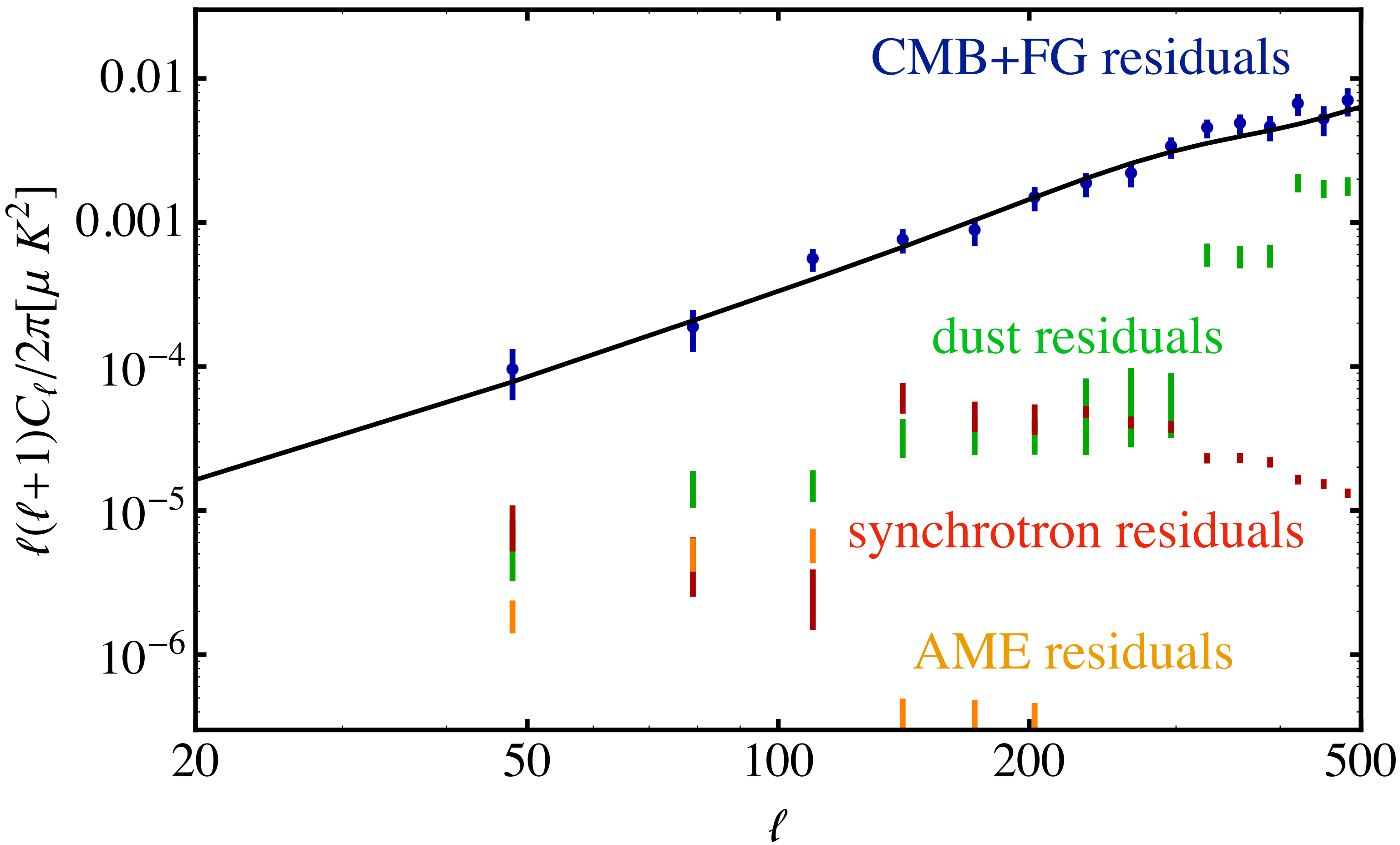




- Correctly reproduce E/B ratio, TE correlations, scale dependence

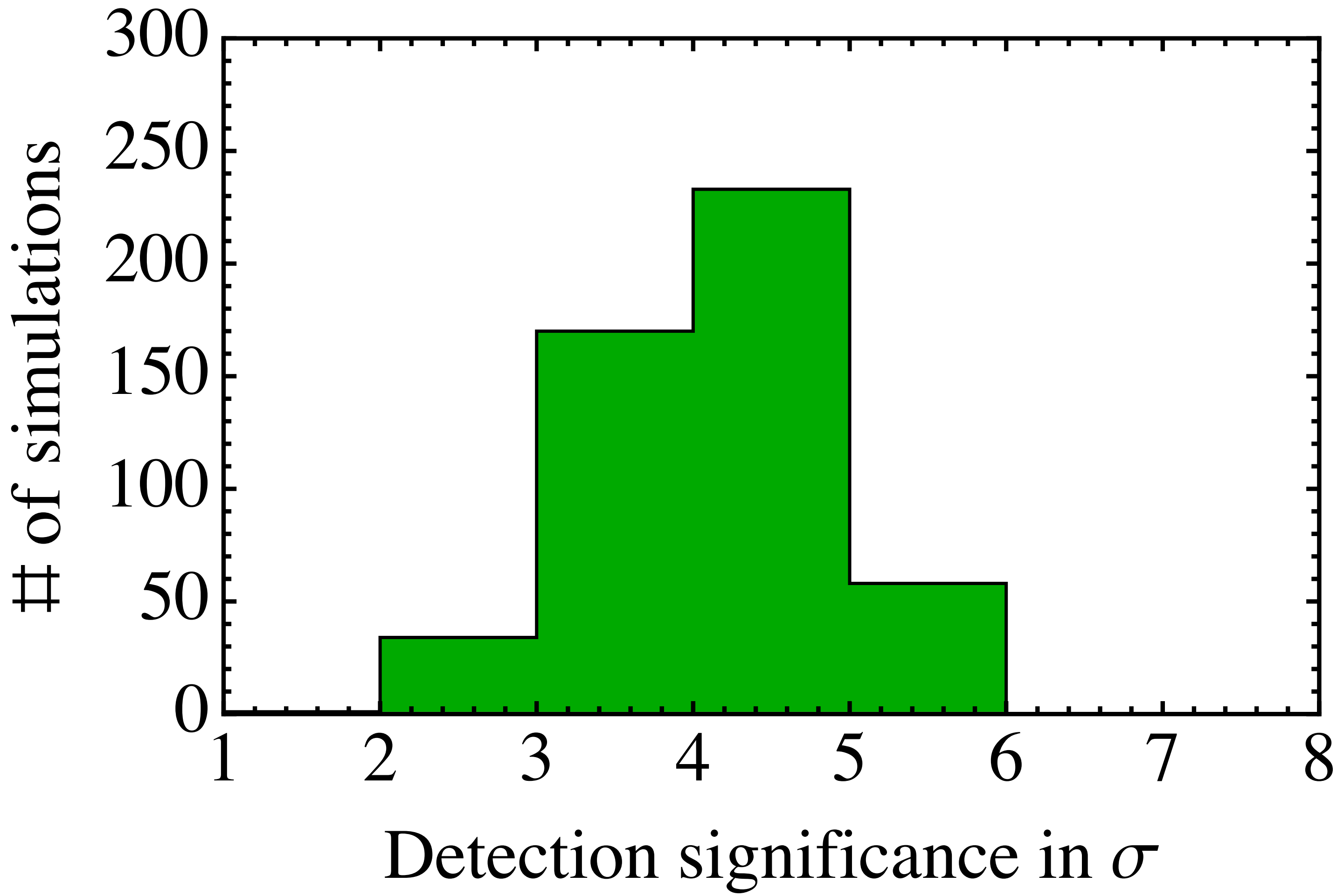
Primordial B-modes

Foreground cleaned spectrum and foreground residuals from simulation



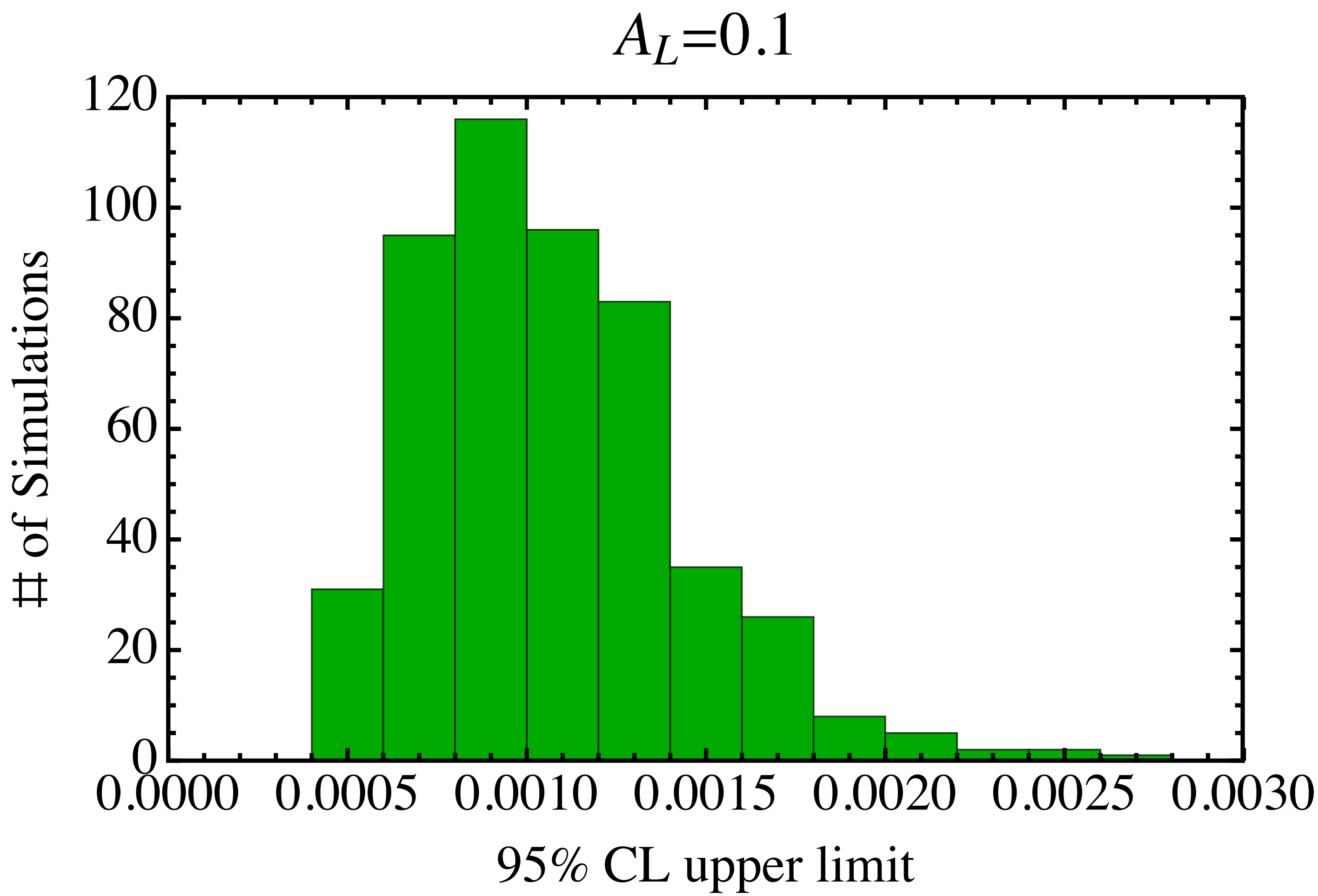
Primordial B-modes

Detection significance for r=0.003 (after 4 years)



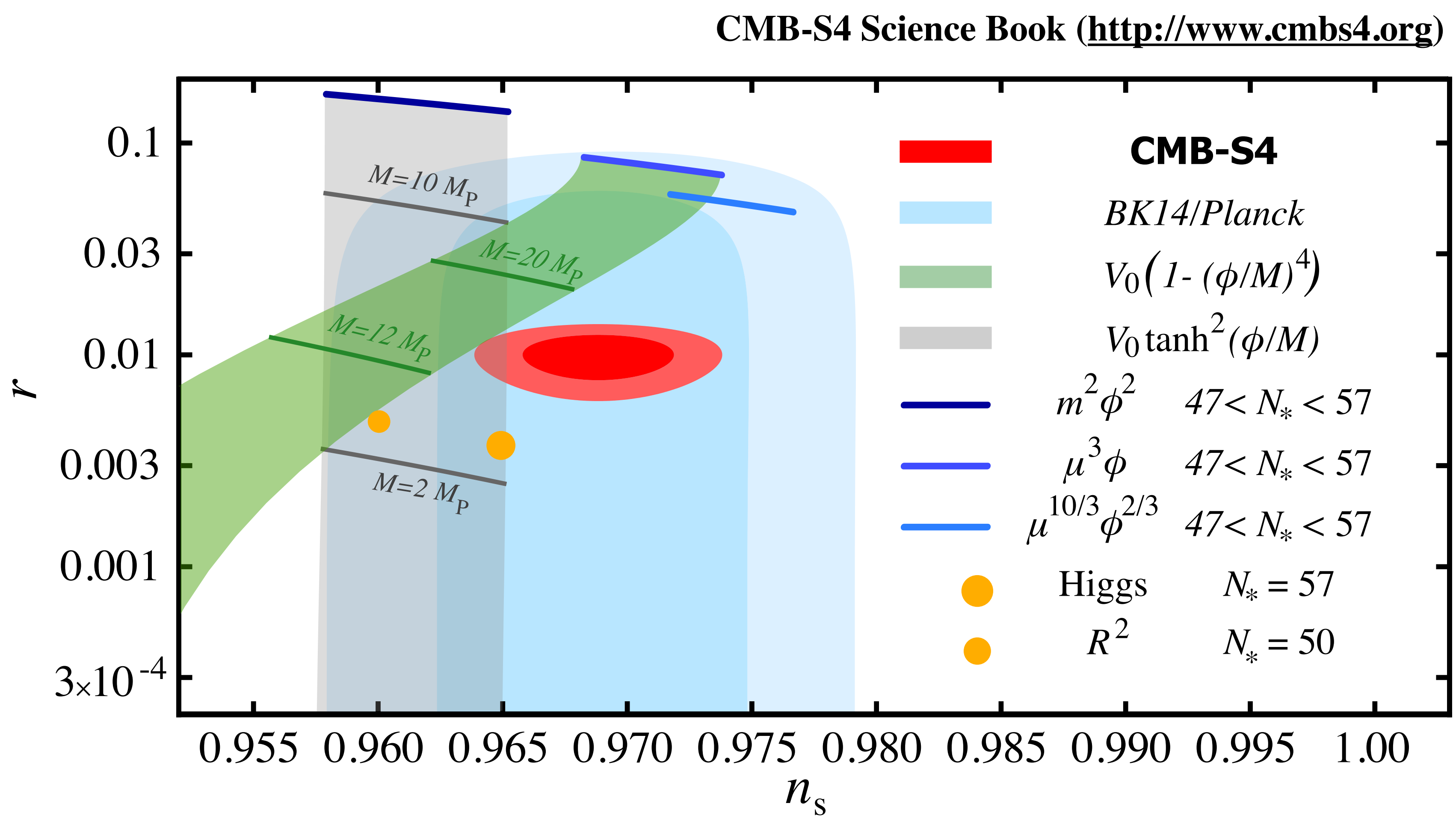
Primordial B-modes

95% CL upper limits



Primordial B-modes

CMB-S4 would detect r=0.01 at high significance



Primordial B-modes

Even an upper limit from CMB-S4 is interesting

If the inflationary model naturally explains the observed value of the spectral index, i.e.

$$n_{\mathrm{s}}(\mathcal{N}) - 1 = -\frac{p+1}{\mathcal{N}}$$

then the inflationary part of the potential is either

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

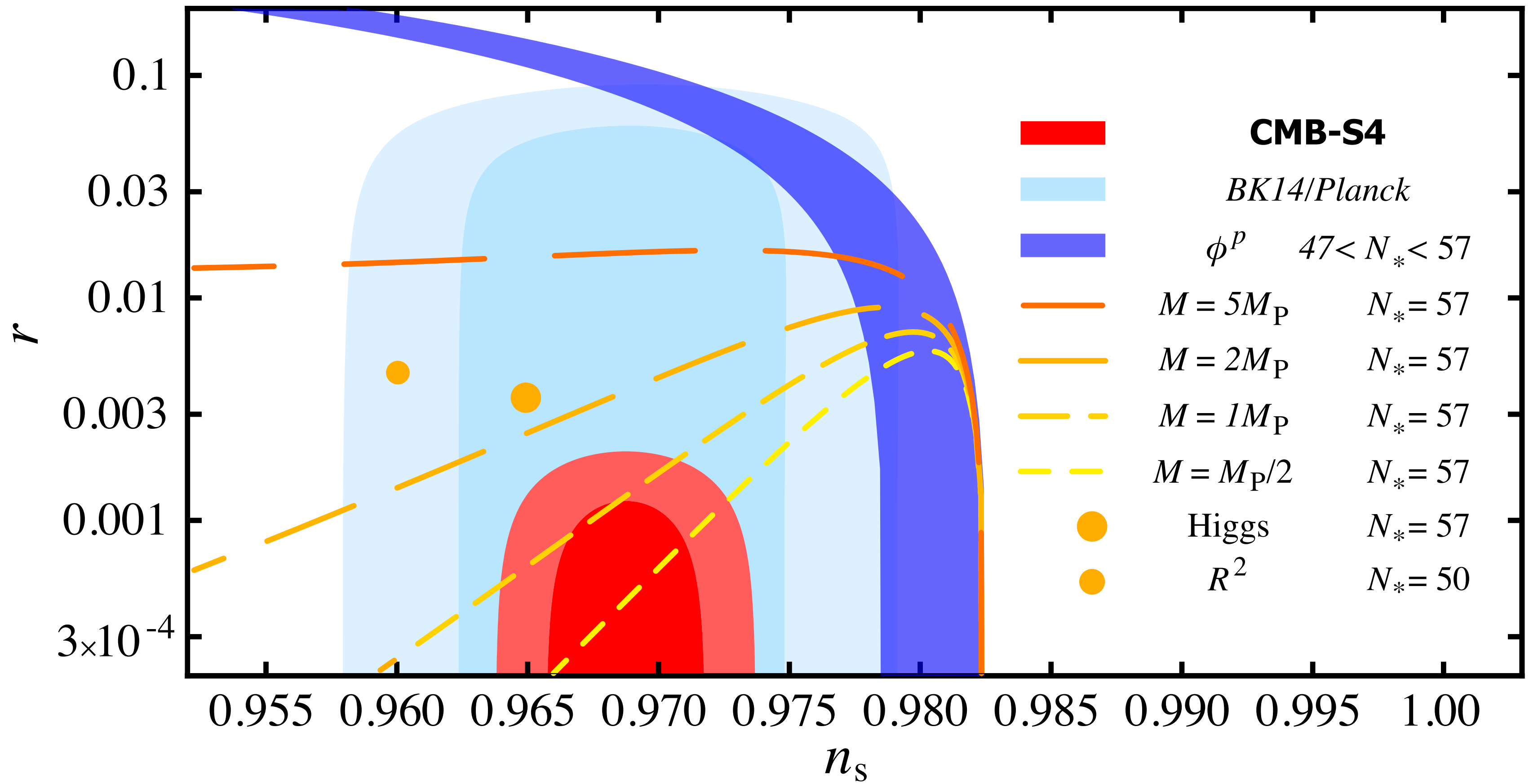
or

$$V(\phi) = V_0 \exp\left[-\left(\frac{\phi}{\Lambda}\right)^{\frac{2p}{p-1}}\right] \qquad (p \neq 1)$$

The characteristic scale in latter case is $M = \Lambda \frac{|1-p|}{p}$

Primordial B-modes

CMB-S4 Science Book (http://www.cmbs4.org)



An upper limit with CMB-S4 would disfavor all models of inflation that naturally explain n_s with super-Planckian characteristic scale M

Light Relics

Light Relic

Particle that is stable on cosmological time scales and light enough to be relativistic at recombination

Contribute to the energy density in radiation

$$\rho_{\rm rad} = \frac{\pi^2 k_{\rm B}^4}{15\hbar^3 c^3}\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] T_\gamma^4$$

Defined so that $N_{\rm eff} = 1$ for a fermion that decouples just before electron-positron freeze-out.

Light Relics

Light Relic

QED corrections and the fact that neutrinos are not fully decoupled when electrons and positrons annihilate imply

$$N_{\rm eff} = 1.015$$

for each flavor of active neutrinos

$N_{\rm eff} = 3.045$ in the Standard Model

Current constraint (from Planck)

$$N_{\rm eff} = 3.15 \pm 0.23$$

Light Relics

The earlier particles decouple, the smaller their contribution to $N_{\rm eff}$, so one may think of bounds on $N_{\rm eff}$ as bounds on the decoupling temperature

Planck:	$T_d > 80\,\mathrm{MeV}$	$\sigma(N_{\rm eff}) \approx 0.2$
Stage 3:	$T_d > 180\,\mathrm{MeV}$	$\sigma(N_{\rm eff}) \approx 0.06$
CMB-S4:	$T_d > 800\,\mathrm{MeV}$	$\sigma(N_{\rm eff}) \approx 0.03$

(bounds on spin-0 particles)

CMB-S4 has the potential to exclude spin-1 relics even if they decoupled right after reheating, spin-1/2 to 80 GeV.

Light Relics

These numbers assume only standard model and light relics are relevant.

Affected if additional states annihilate into standard model particles after decoupling, but this is highly constrained by LHC.

Additionally constrains

- Decay of moduli
- Weakly coupled particles produced through kinetic mixing
- any departure from the standard thermal history

Conclusions

- Cosmological observations allow us to test our ideas about the early universe
- Many experiments are already taking data, many will soon come online and will constrain light relics, neutrinos, dark matter, ...
- The next decade or two will be eventful and should provide us with a much better understanding of the early universe.

Thank you