From the CMB
to the Very Early Universe

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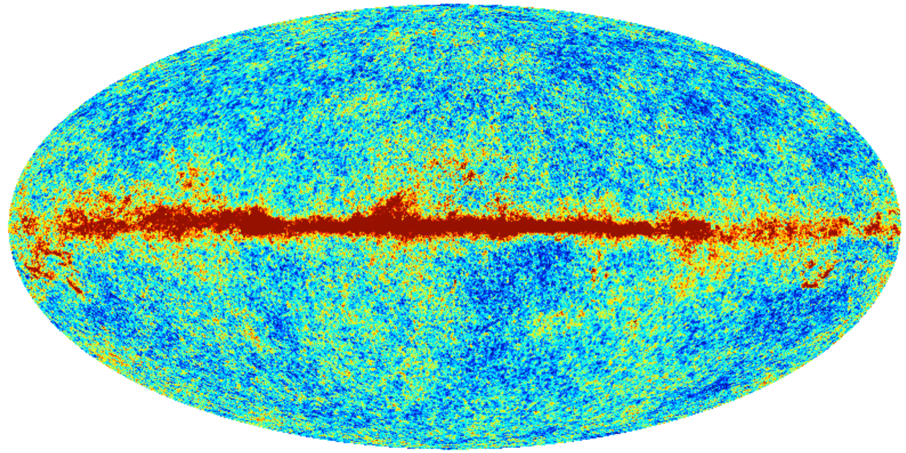
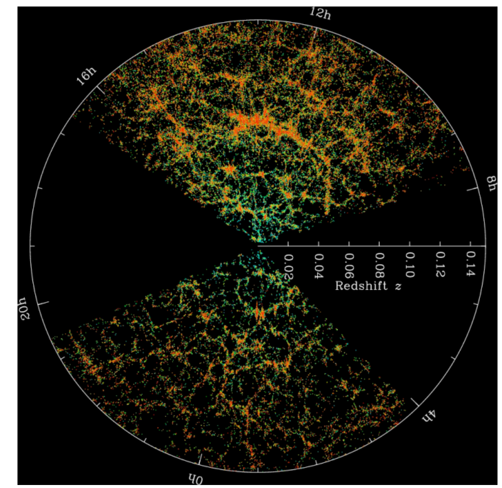
SoCal BSM Meeting 2017, Riverside, April 2, 2017





Observations of supernovae, cosmic microwave background, and galaxy redshift surveys are in good agreement with the simple six-parameter LCDM model.

Parameter Constraints

Parameter constraints from Planck temperature data

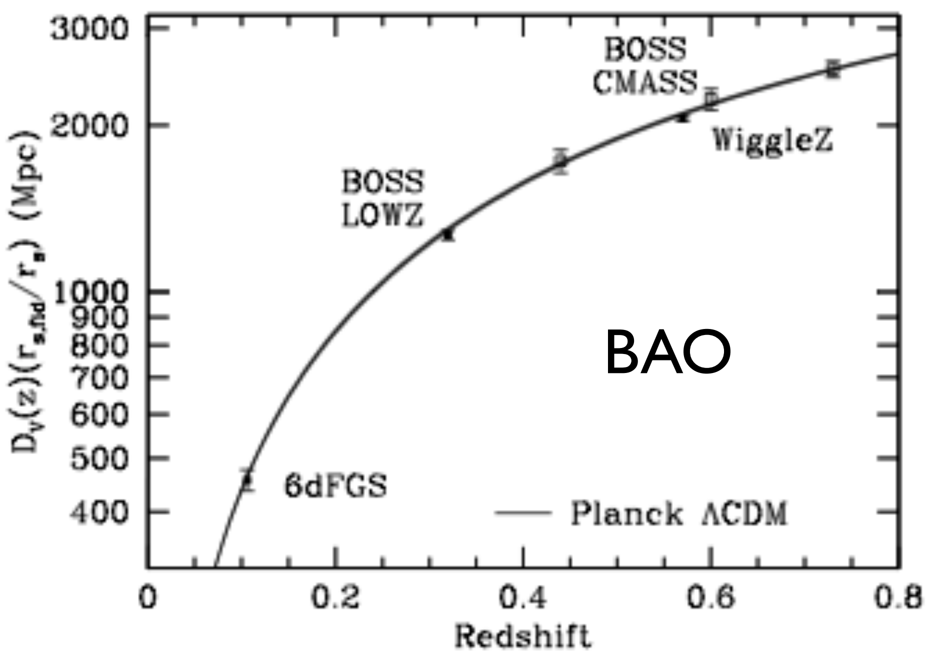
Parameter	*Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

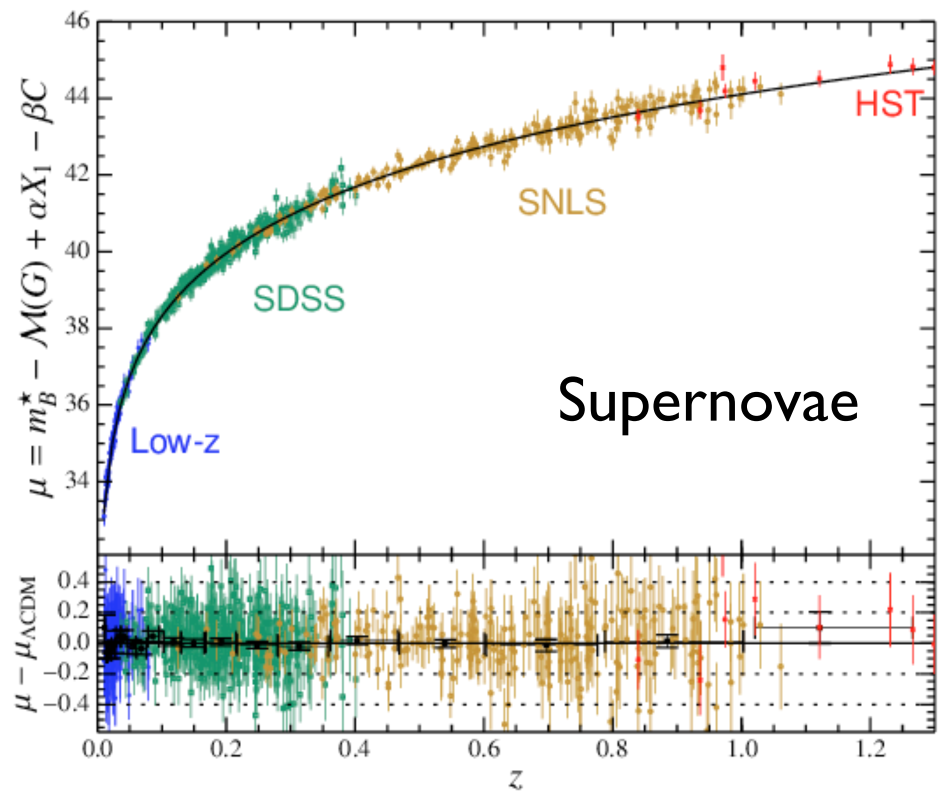
LCDM

In addition, LCDM is consistent with low redshift large-scale structure* and supernova data

(Anderson et al. 2013)

(Betoule et al. 2014)



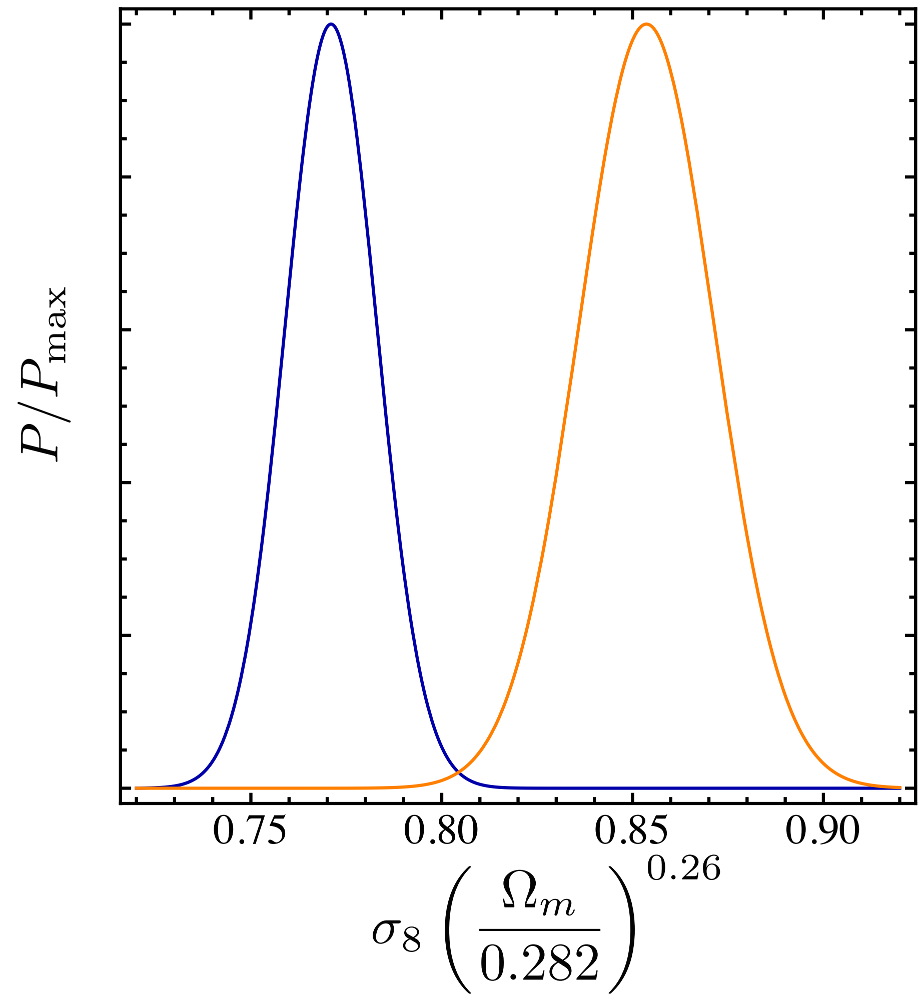


* on small scales baryonic feedback should be understood better to assess whether there are departures from LCDM

Clustering

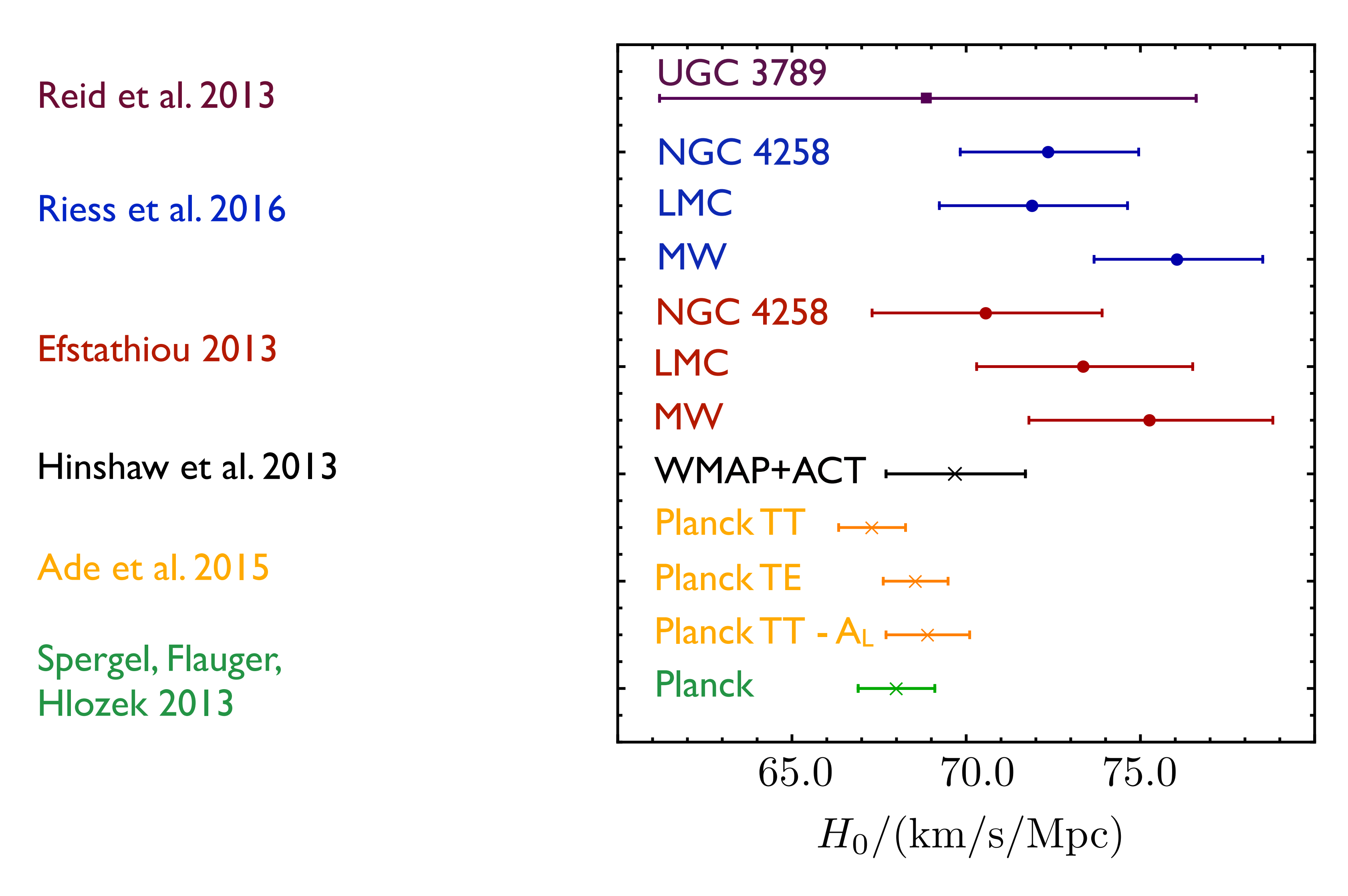
tSZ power spectrum
(Hill, Spergel 2013)

Planck 2015 TT+lowP
Paper XIII



- similar tensions exist between the Planck TT data and a number of other low redshift observations

The Hubble Constant



Primordial Perturbations

Measurements of the CMB have taught us that the primordial perturbations

- existed before the hot big bang
- are nearly scale invariant
- are very close to Gaussian
- are adiabatic

What generated them?

Primordial Perturbations

Assuming general relativity, the primordial perturbations were either generated during accelerated expansion (inflation) or decelerated contraction followed by a bounce.

- How did inflation begin?

Assuming inflation took place, what can we learn about it beyond n_s and $\Delta^2_{\mathcal{R}}$?

- What is the energy scale of inflation?
- How far did the field travel?
- Are there additional light degrees of freedom?
- What is the propagation speed of the inflaton quanta?

tensor modes

non-Gaussianity

Energy Scale of Inflation

In addition to the nearly scale invariant density perturbations we observe, inflation also predicts a nearly scale invariant spectrum of gravitational waves

$$\Delta_h^2(k) = \frac{2H^2(t_k)}{\pi^2}$$

A measurement of the tensor contribution would provide a direct measurement of the expansion rate of the universe during inflation, as well as the energy scale

$$V_{\rm inf}^{1/4} = 1.04 \times 10^{16}\, GeV \left(\frac{r}{0.01}\right)^{1/4}$$

with $\qquad r = \dfrac{\Delta_h^2}{\Delta_{\mathcal{R}}^2}$

Field Range

For r>0.01 the inflaton must have moved over a super-Planckian distance in field space. **(Lyth; Turner)**

Possible Solution:

Use a field with a shift symmetry and break the shift symmetry in a controlled way.

e.g. Linde's chaotic inflation

$$V(\phi) = \frac{1}{2}m^2\phi^2 \qquad \text{with} \qquad m \ll M_p$$

or natural inflation

Freese, Frieman, Olinto, PRL 65 (1990)

$$V(\phi) = \Lambda^4\left[1 + \cos\left(\frac{\phi}{f}\right)\right] \qquad \text{with} \qquad f \gtrsim M_p$$

Field Range

In field theory we may simply postulate such a symmetry, but it is not obvious that such shift symmetries exist in a theory of quantum gravity.

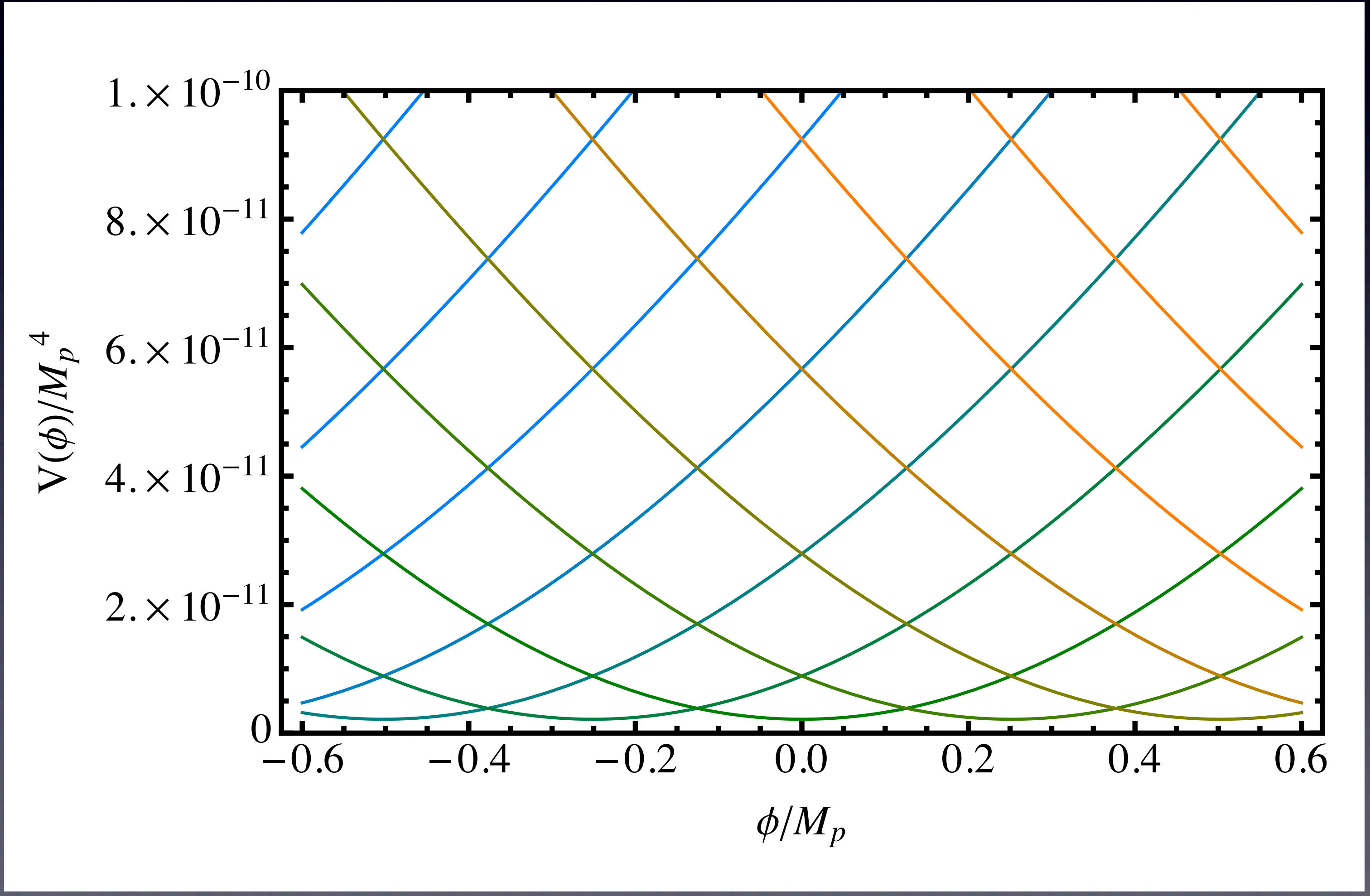
In fact, the most naive implementation of an axion with $f \gtrsim M_p$ seems hard to realize string theory.

This motivates the search for a no-go theorem, or a systematic study of large field models of in quantum gravity/string theory

So far there is no systematic study, of models but a number of lamp posts

Axion Monodromy Inflation

One mechanism that allows super-Planckian excursions with sub-Planckian f is monodromy



Axion Monodromy Inflation

Monodromy occurs in various contexts

- in non-Abelian gauge theories
- in string theory
  - in the presence of branes
  - in the presence of fluxes

Axion Monodromy Inflation

Branes

For definiteness consider a D5-brane wrapping a two-cycle $\Sigma^{(2)}$ of size $L\sqrt{\alpha'}$.

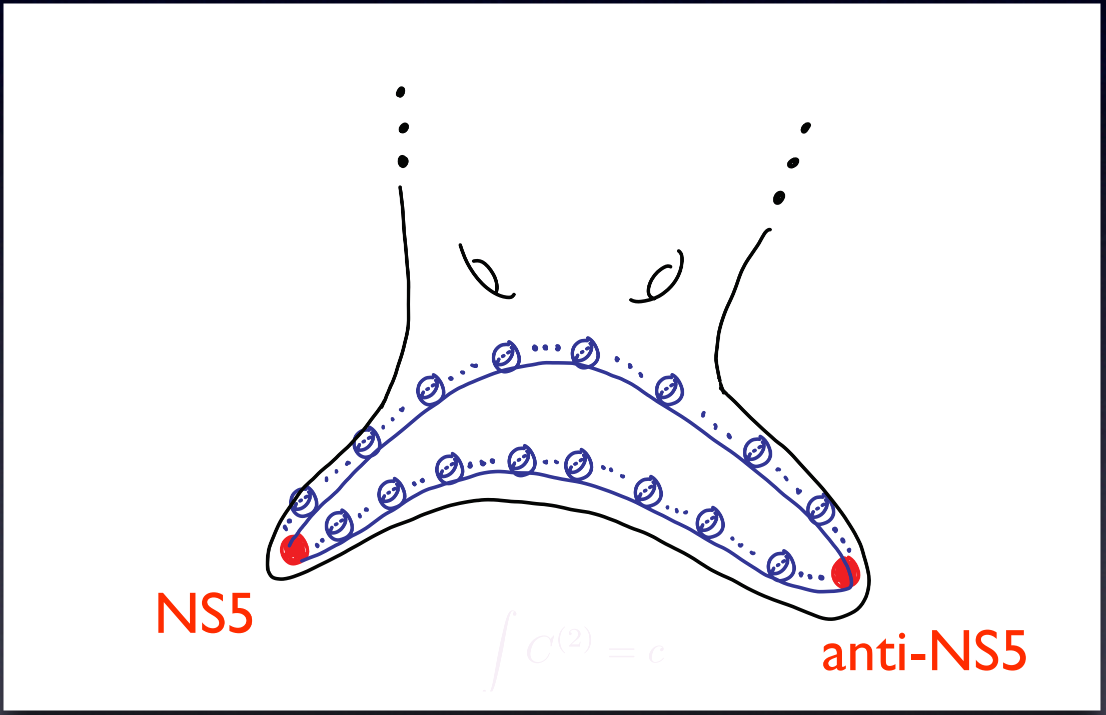
$$S_{\mathrm{DBI}} = -\frac{1}{(2\pi)^5 {\alpha'}^3 g_s} \int d^6\xi \sqrt{det(-\varphi^*(G+B))}$$

$$\supset -\frac{\epsilon}{(2\pi)^5 {\alpha'}^2 g_s} \int d^4x \sqrt{{}^{(4)}g} \sqrt{L^4 + b^2}$$

The basic mechanism is very generic, stabilizing moduli at high enough scales is challenging.

Axion Monodromy Inflation

Comic version of axion monodromy inflation



Axion Monodromy Inflation

The original axion monodromy model is one example of a larger class of models with potentials

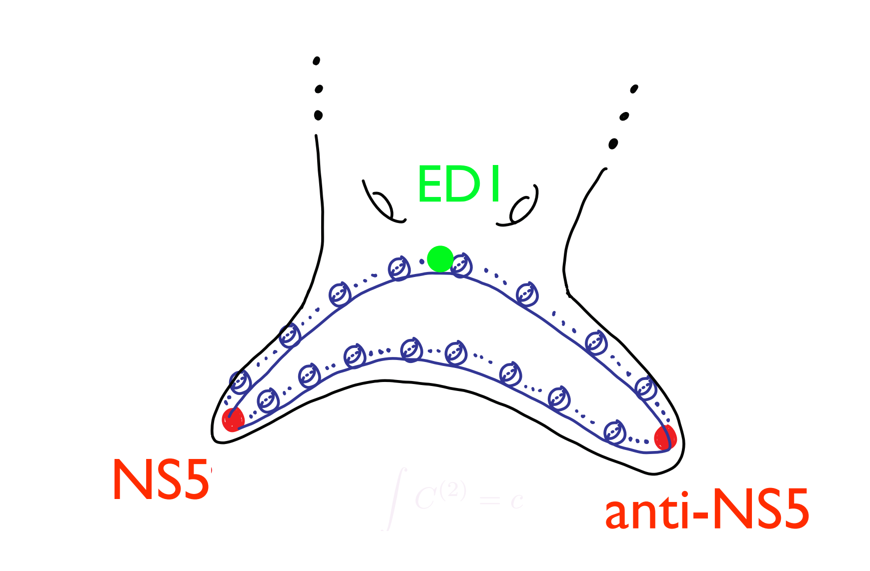
$$V(\phi) = \mu^{4-p}\phi^p$$

so far with $\qquad p = \frac{2}{3}, 1, \frac{4}{3}, 2, 3$

A robust prediction of these models is an imprint of gravitational waves in the CMB that is observably large

Axion Monodromy Inflation

These models may lead to additional signatures



Instanton corrections may lead to oscillatory contributions to the potential.

$$V(\phi) = \mu^3 \phi + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

These lead to oscillations in the power spectrum that can be searched for.

Axion Monodromy Inflation

In general the decay constant and amplitude may themselves depend on the inflaton

$$V(\phi) = \mu^{4-p}\phi^p + \Lambda(\phi)^4 \cos\left(\frac{\phi_0}{f_0}\left(\frac{\phi}{\phi_0}\right)^{1+p_f} + \Delta\varphi\right)$$

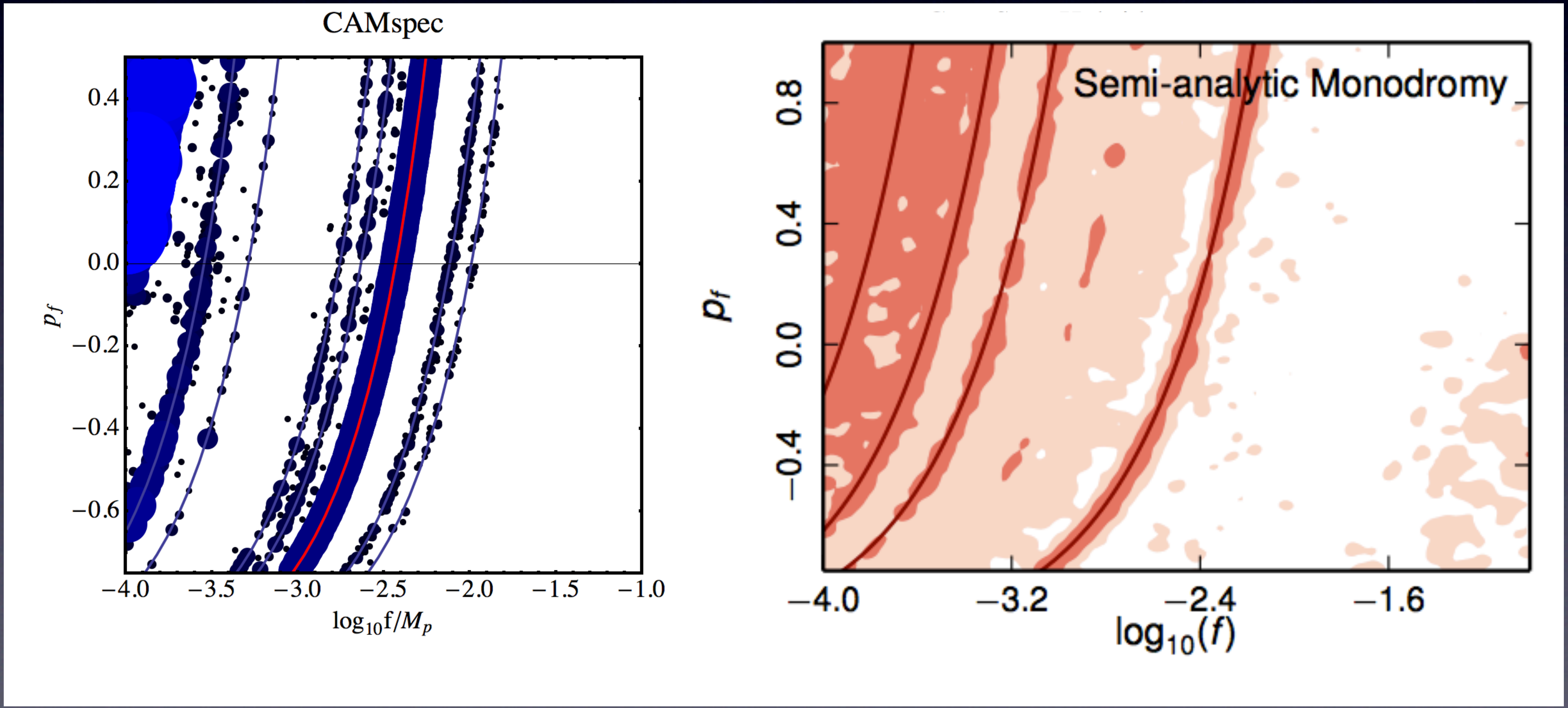
This leads to a power spectrum of the form

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}\left(\frac{k}{k_\star}\right)^{n_s-1}\left(1 + \delta n_s \cos\left[\frac{\phi_0}{\tilde{f}}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1} + \Delta\tilde{\varphi}\right]\right)$$

$$\delta n_s = 3b\left(\frac{2\pi}{\alpha}\right)^{1/2} \qquad \text{with} \qquad \alpha = (1+p_f)\frac{\phi_0}{2fN_0}\left(\frac{\sqrt{2pN_0}}{\phi_0}\right)^{1+p_f}$$

Axion Monodromy Inflation

Search for oscillations with drifting period in Planck nominal mission data and full mission data



Axion Monodromy Inflation

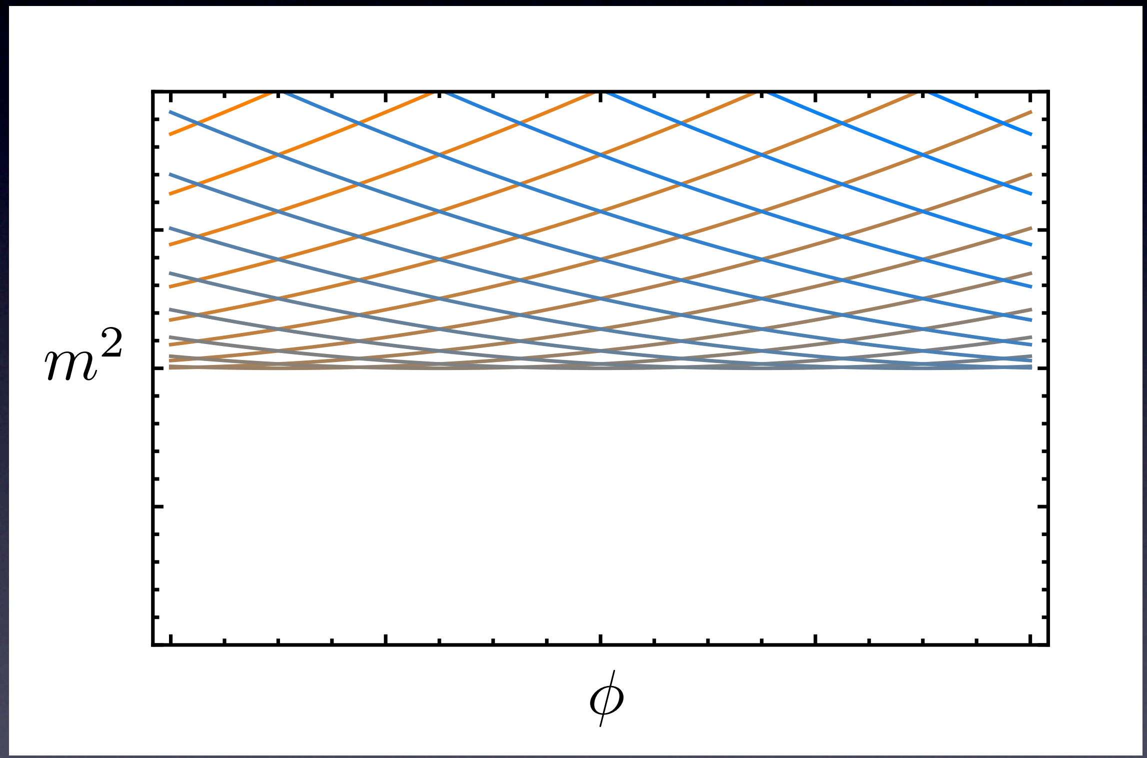
Improvement of the fit over ΛCDM: $\Delta\chi^2 = 18$

Expectation based on simulations in the absence of a signal: $\Delta\chi^2 = 16.5 \pm 3.5$

As of now there is no evidence for such oscillations in the primordial power spectrum.

Axion Monodromy Inflation

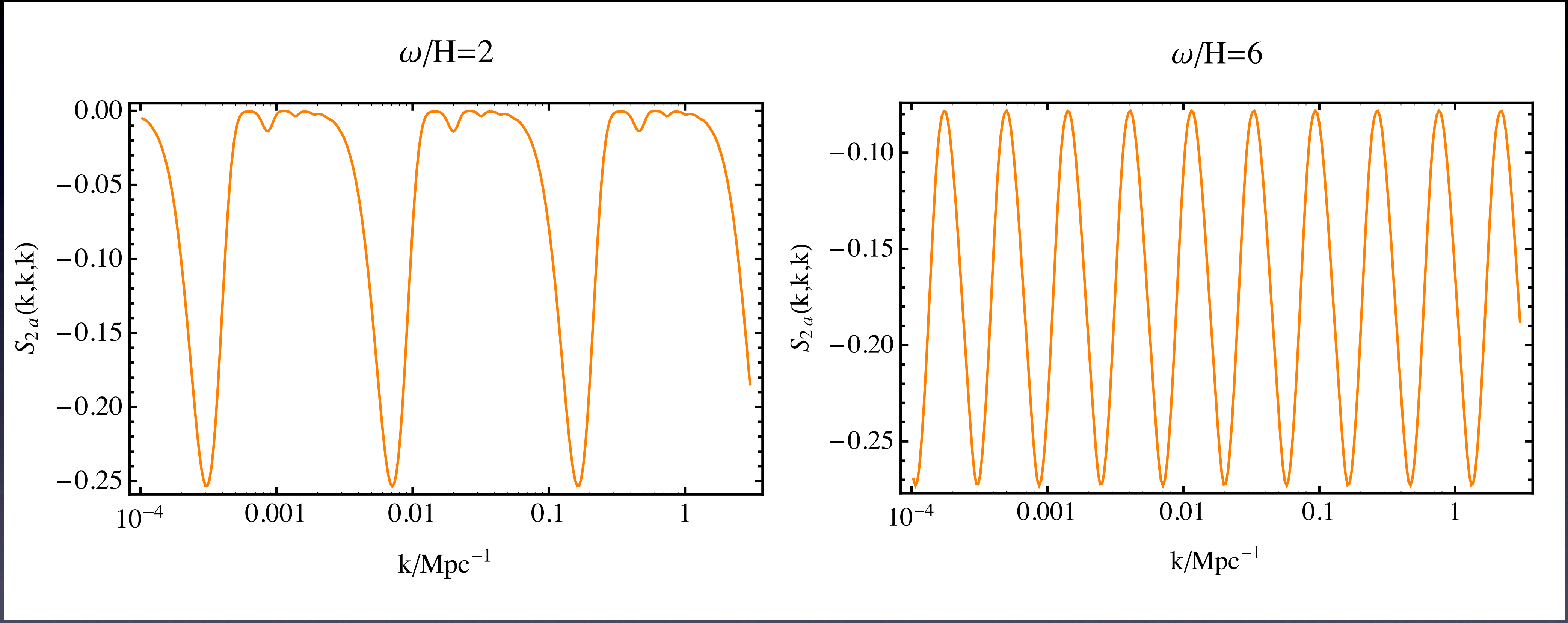
Monodromy in the spectrum $m_n^2 \approx \mu^2 + g^2(\phi - \phi_n)^2$



Leads to periodic bursts of particle/string production, which source perturbations in the inflaton large enough to be detectable even if the states are never light $\mu \gtrsim \dot{\phi}^{\frac{1}{2}}$.

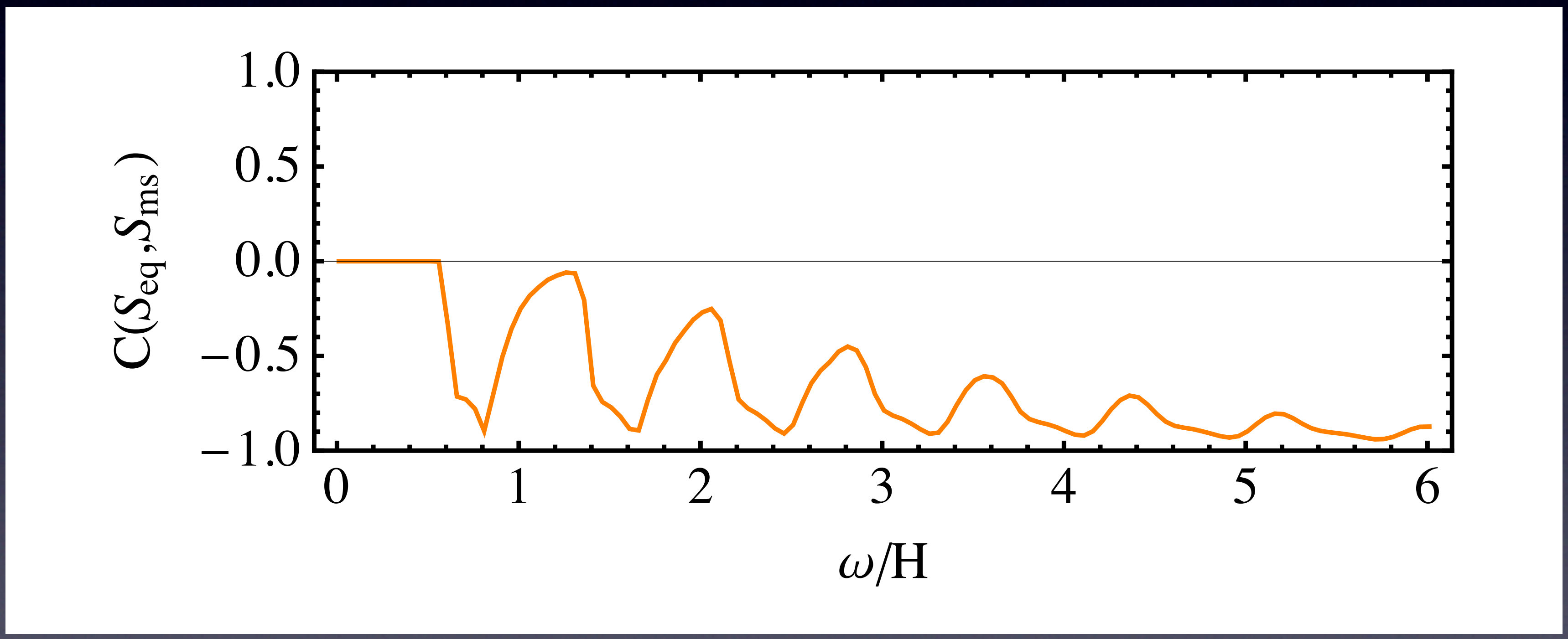
Axion Monodromy Inflation

Resulting bispectrum for particle production



Axion Monodromy Inflation

Overlap with existing shapes is small at least for some range of frequencies



Axion Monodromy Inflation

Modulated moduli masses

Moduli dependence of the potential

$$V(\phi, \chi) = \mu^3 \phi + \Lambda^4(\chi) \cos\left(\frac{\phi}{f}\right) + V(\chi)$$

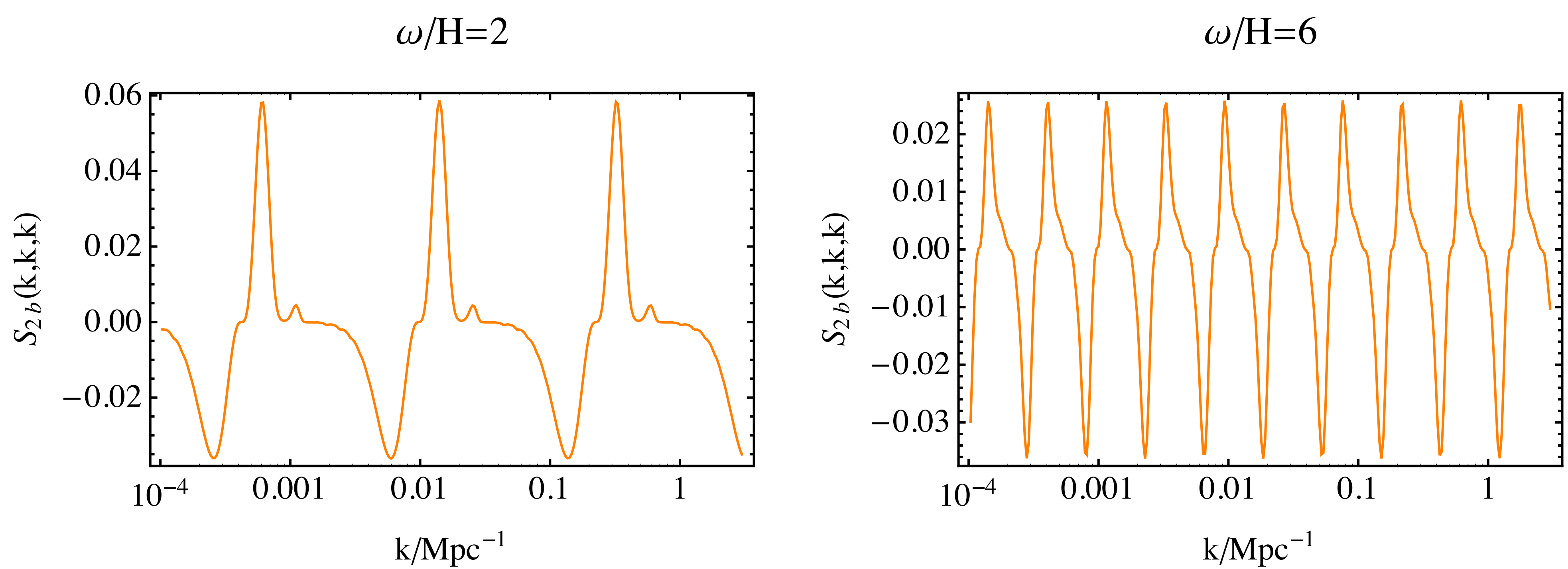
leads to modulated masses for moduli

$$m^2 \approx \mu^2 + g^2 f^2 \cos\left(\frac{\phi}{f}\right)$$

Again leads to periodic bursts of particle production, which source perturbations in the inflaton large enough to be detectable even if the states are never light $\mu \gtrsim \dot{\phi}^{\frac{1}{2}}$.

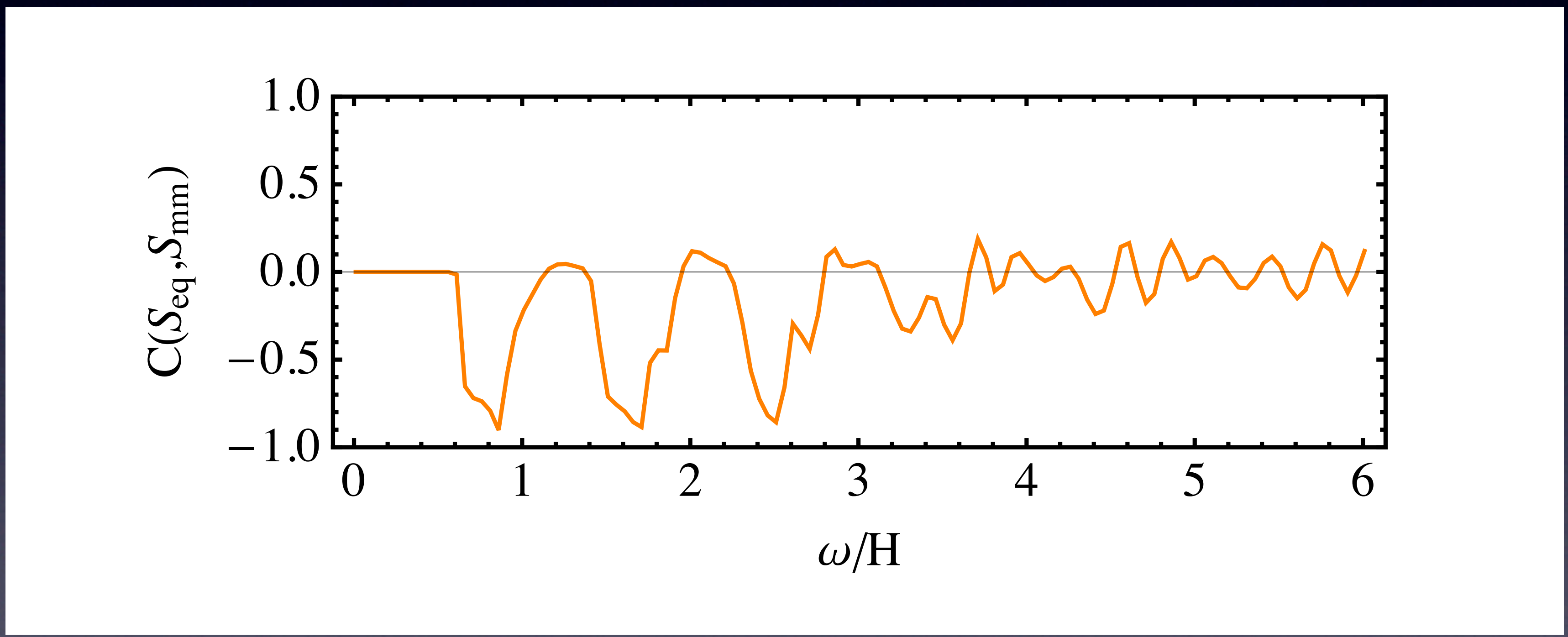
Axion Monodromy Inflation

Resulting bispectrum



Axion Monodromy Inflation

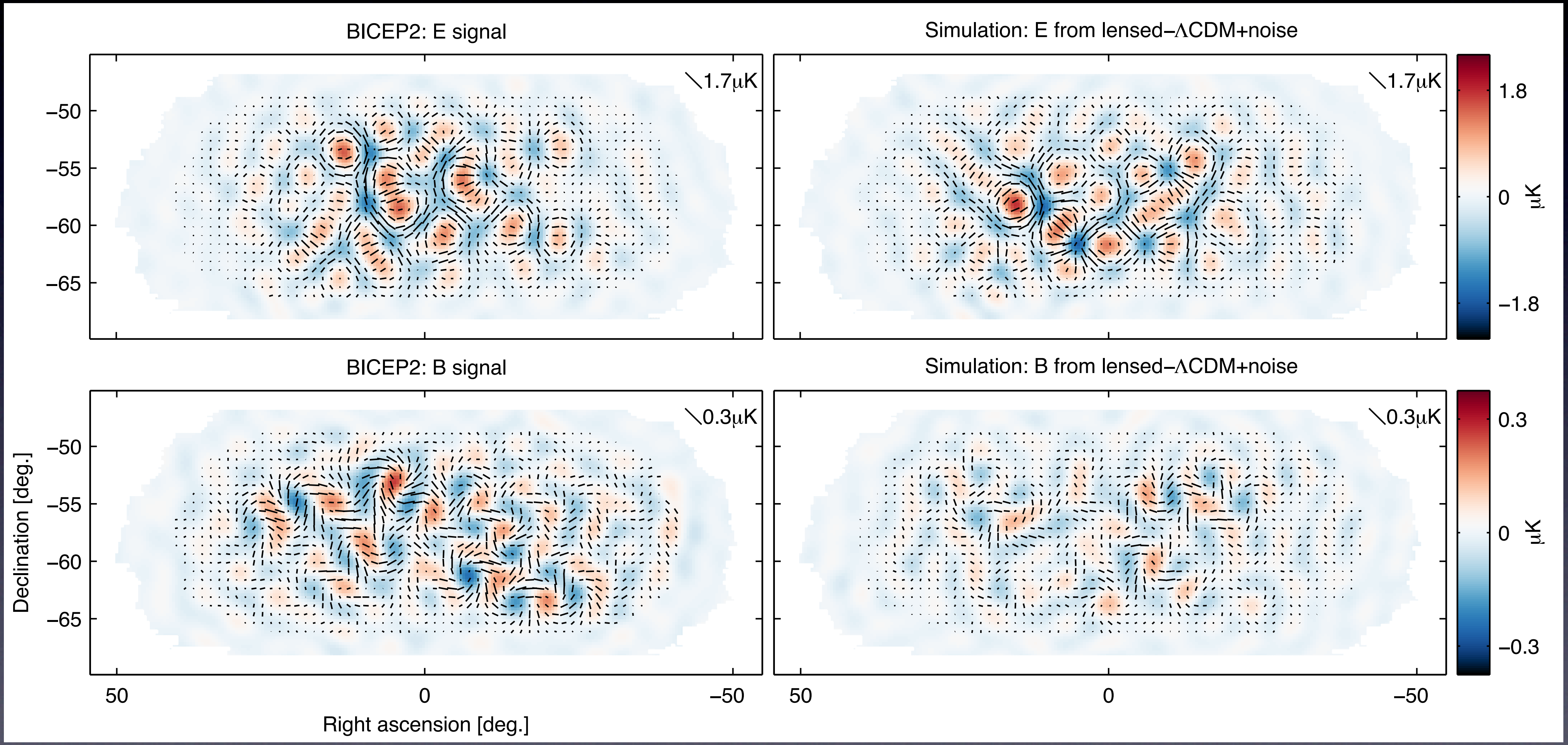
Overlap with existing shapes is small for a wide range of frequencies.



These periodic signatures that have not yet been searched for but this is work in progress.

Experimental Constraints on r

BICEP2 polarization data

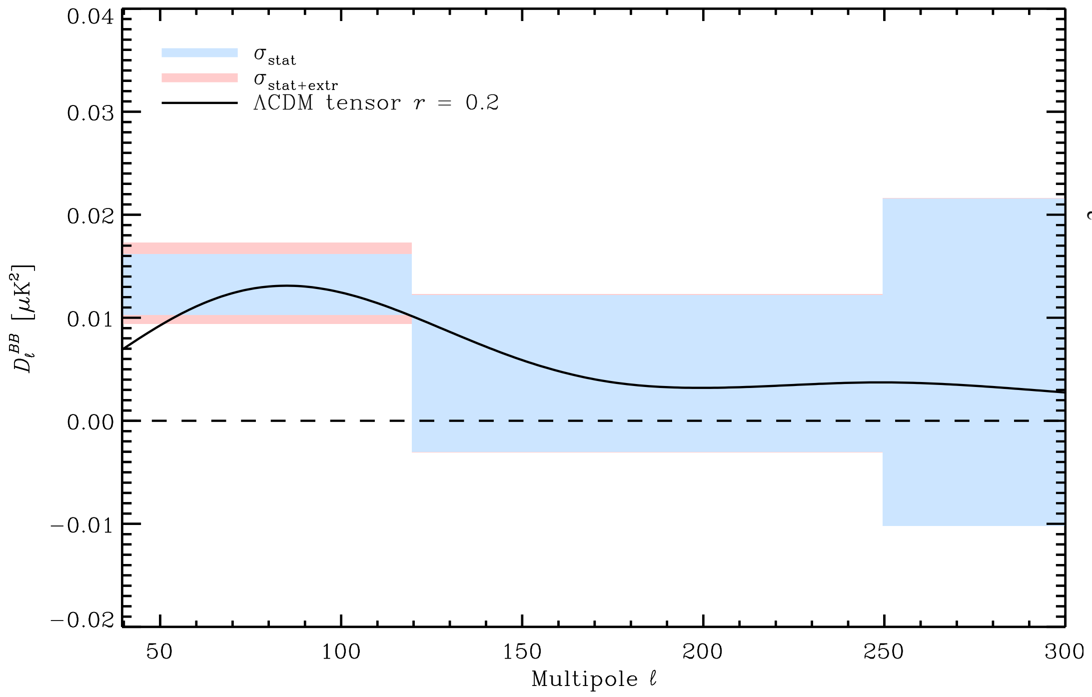


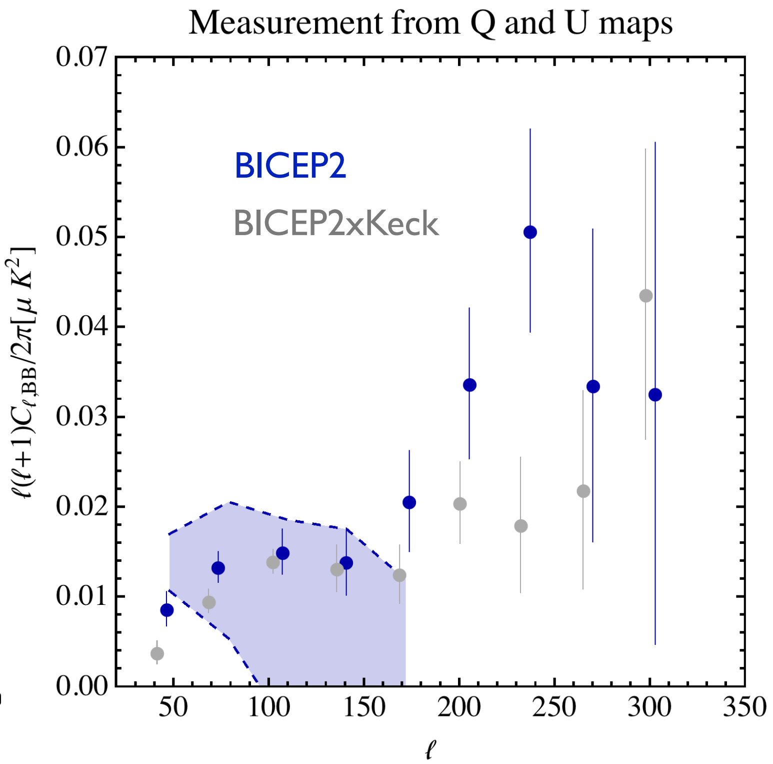
Noise level: 87 nK deg - the deepest map at 150 GHz of this patch of sky

(Planck noise level: few μK deg)

Experimental Constraints on r

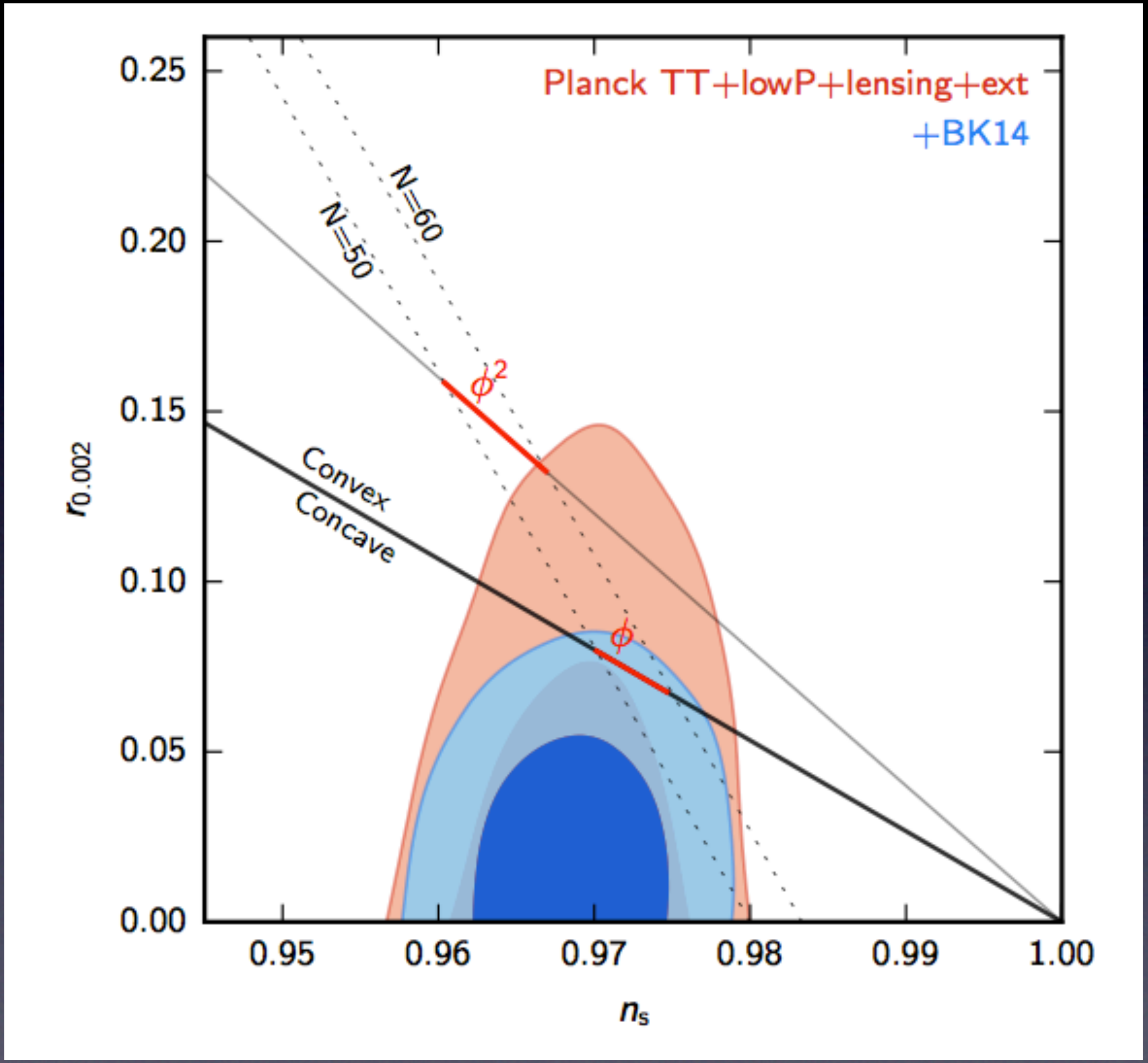
- measurement of BB in the BICEP2 region at 353 GHz rescaled to 150 GHz





$$D_\ell^{BB} = 1.32\times 10^{-2}\,\mu\mathrm{K}^2_{\rm CMB}$$

Experimental Constraints on r



$$V_{\rm inf}^{1/4} < 1.7 \times 10^{16}\, GeV$$

Experimental Progress on r

With the current data, we can constrain r with

- the tensor contribution to the temperature anisotropies on large angular scales
- the B-mode polarization generated by tensors.

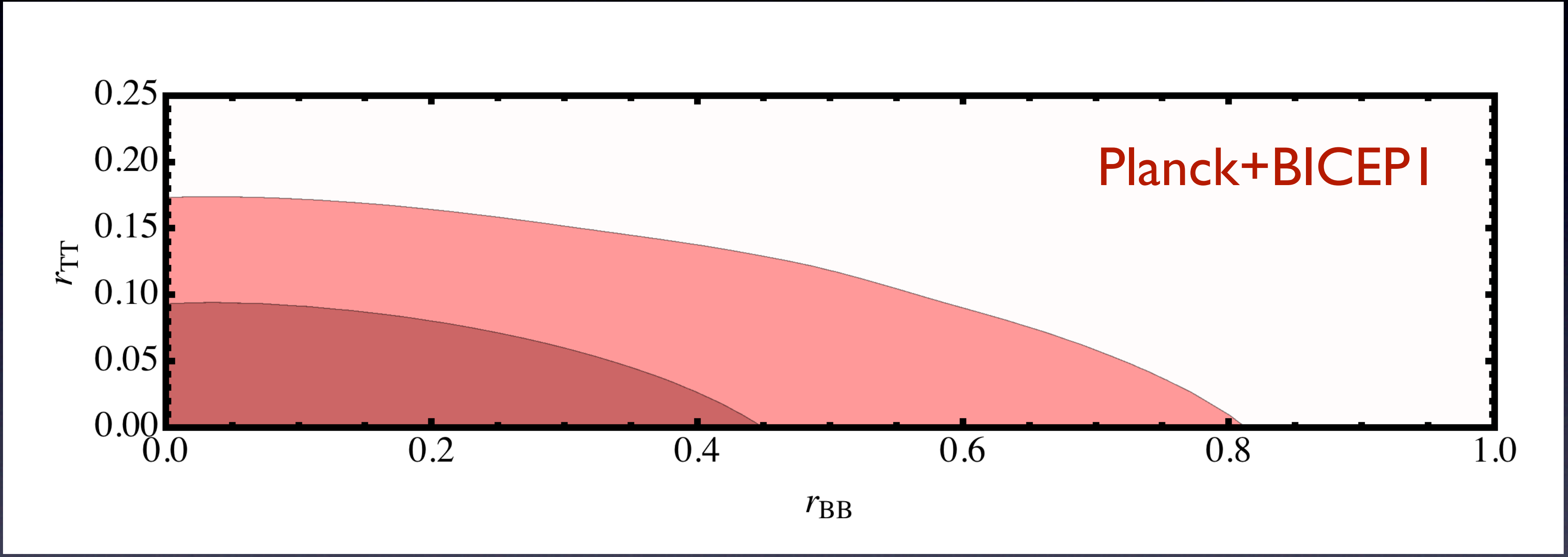
The two likelihood are essentially independent

$$\mathcal{L}(r_{TT}, r_{BB}) = \mathcal{L}_{TT}(r_{TT})\mathcal{L}_{BB}(r_{BB})$$

Typically we talk about $\mathcal{L}(r, r)$

Experimental Progress on r

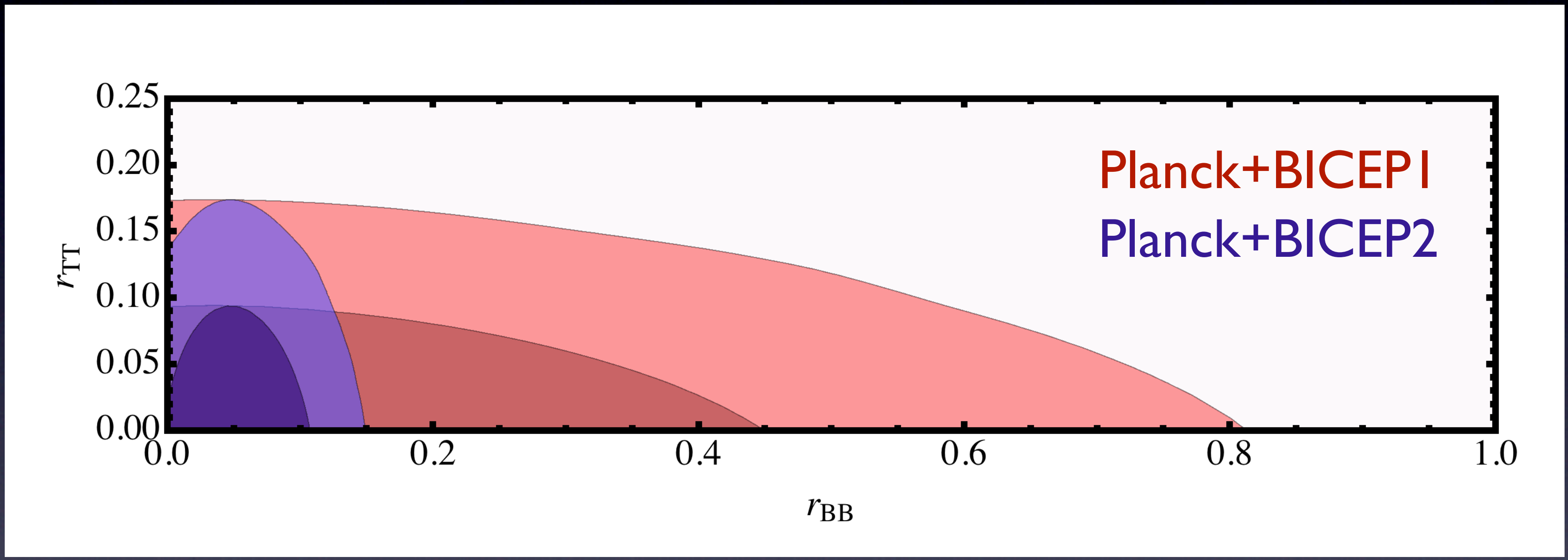
$\mathcal{L}(r_{TT}, r_{BB})$ before March



Constraint dominated by temperature data

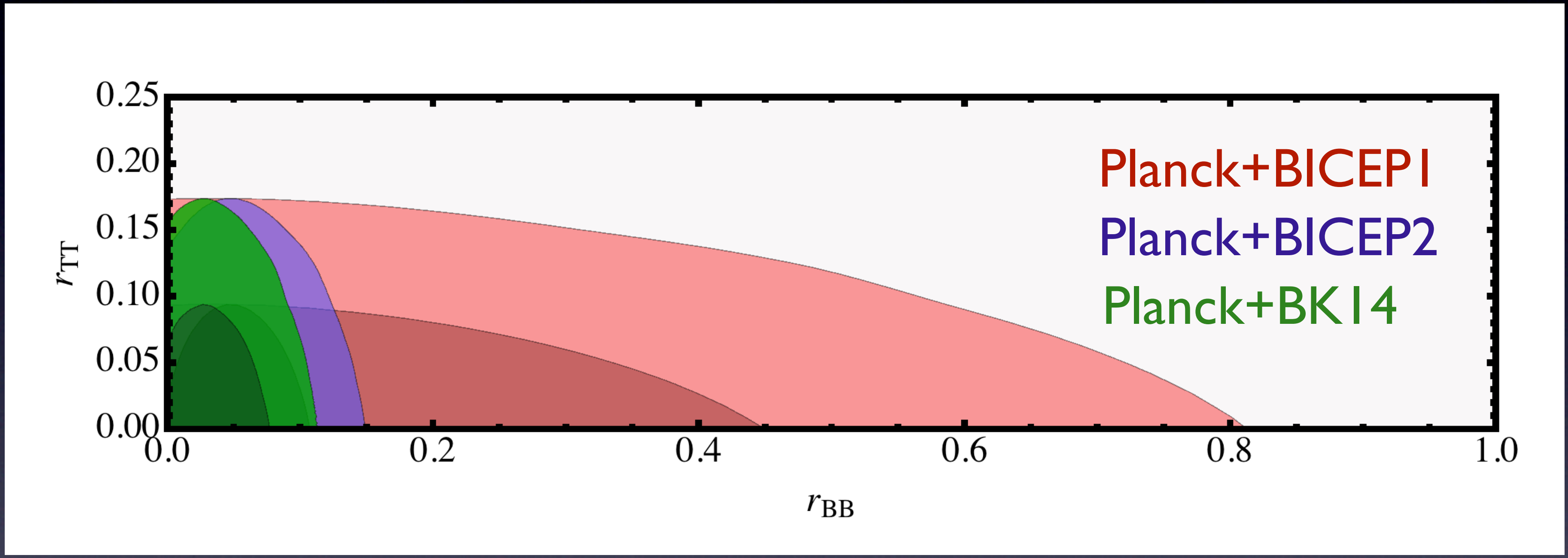
Experimental Progress on r

$\mathcal{L}(r_{TT}, r_{BB})$ after BICEP2



Experimental Progress on r

$\mathcal{L}(r_{TT}, r_{BB})$ after BICEP2



Constraint from polarization data comparable to constraint from temperature and will soon be significantly stronger.

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, PIXIE

Inflation 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

CMB-S4

The science goals most relevant to high energy physics are

- Detect primordial gravitational waves or place an upper limit of $r < 0.001$ 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

These science goals roughly imply it will

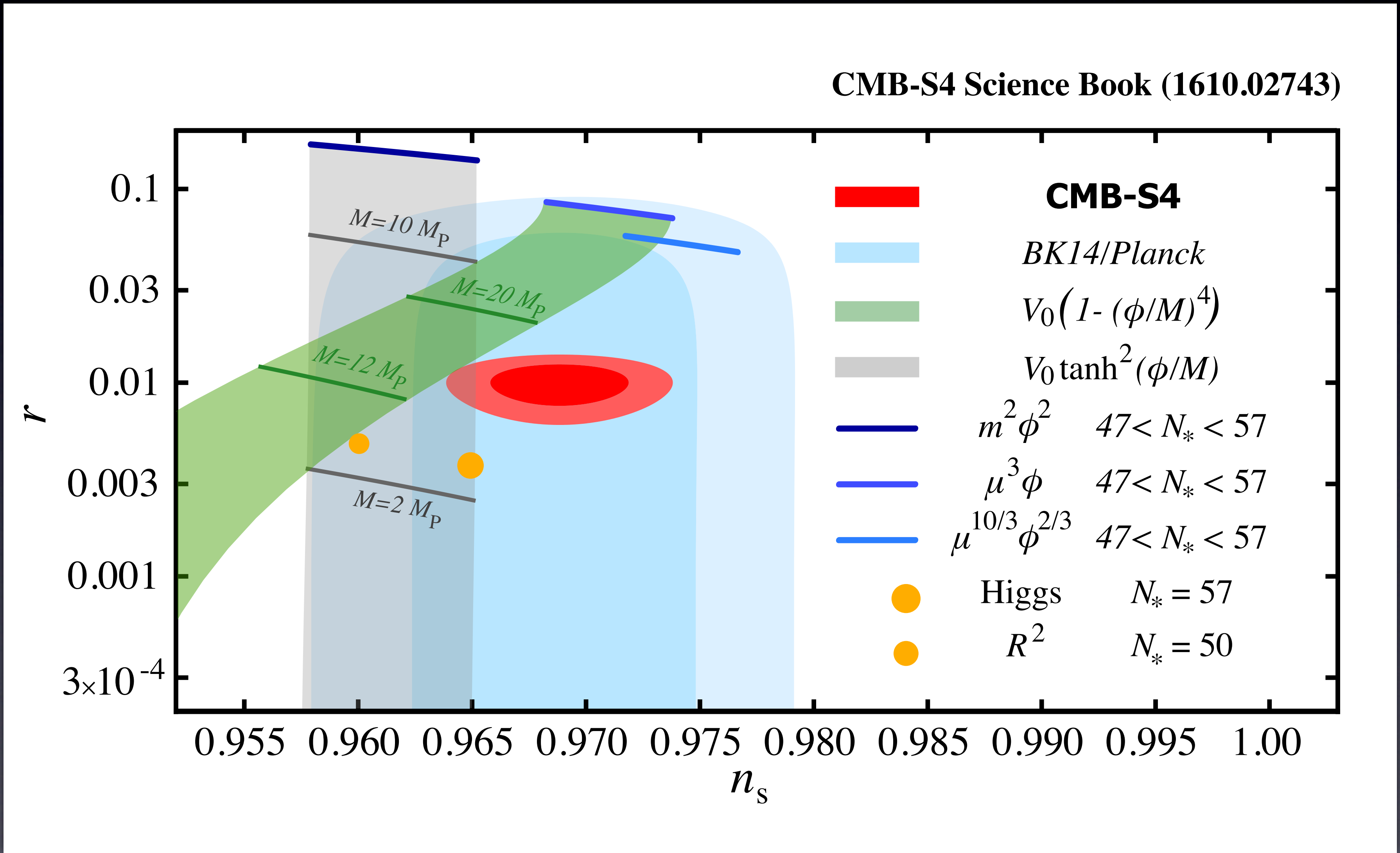
- cover a large fraction of the sky (>70%)
- have $1 - 3\mathrm{arcmin}$ resolution
- have a noise level of $1 - 3\mu\mathrm{Karcmin}$

Such an experiment will also place tight constraints on

- light thermal dark matter
- axions
- cosmic strings, primordial magnetic fields, ...

Future Experiments

CMB-S4 could detect r=0.01 at high significance



Future Experiments

Even an upper limit from CMB-S4 is interesting

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

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

then the inflationary part of the potential is either

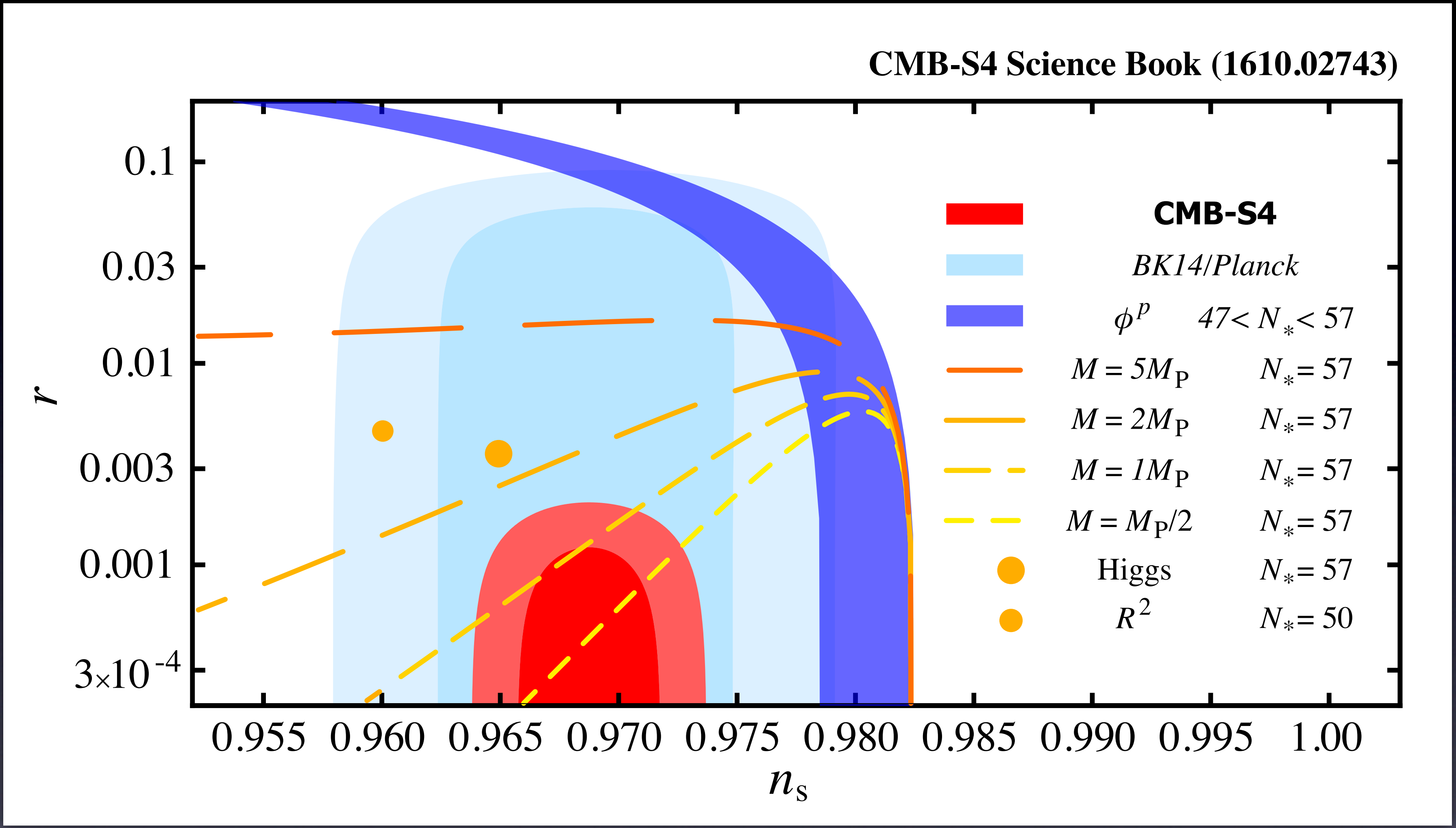
$$V(\phi) = \mu^{4-2p}\phi^{2p}$$

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 $M = \Lambda\dfrac{|1-p|}{p}$

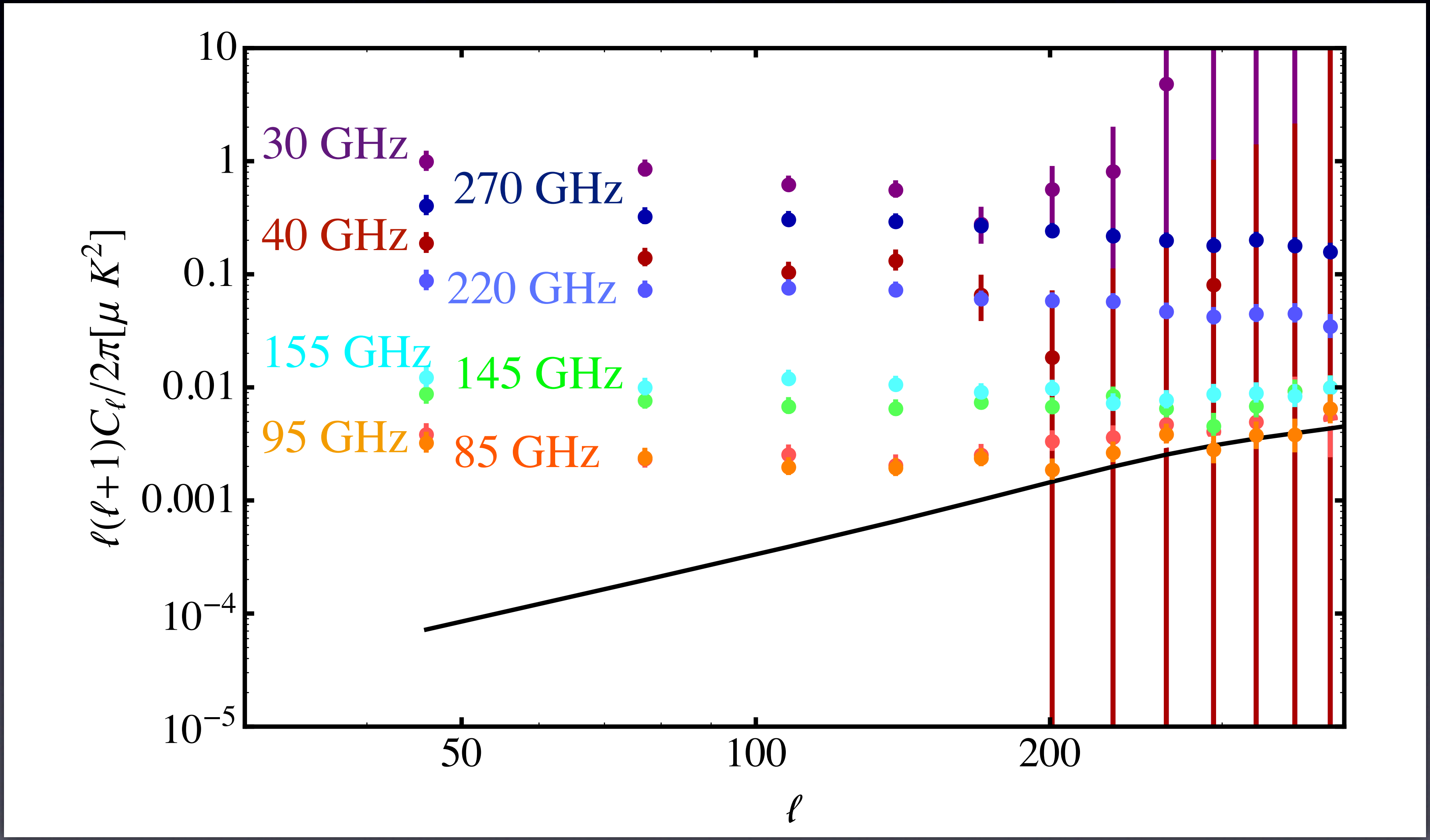
Future Experiments



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

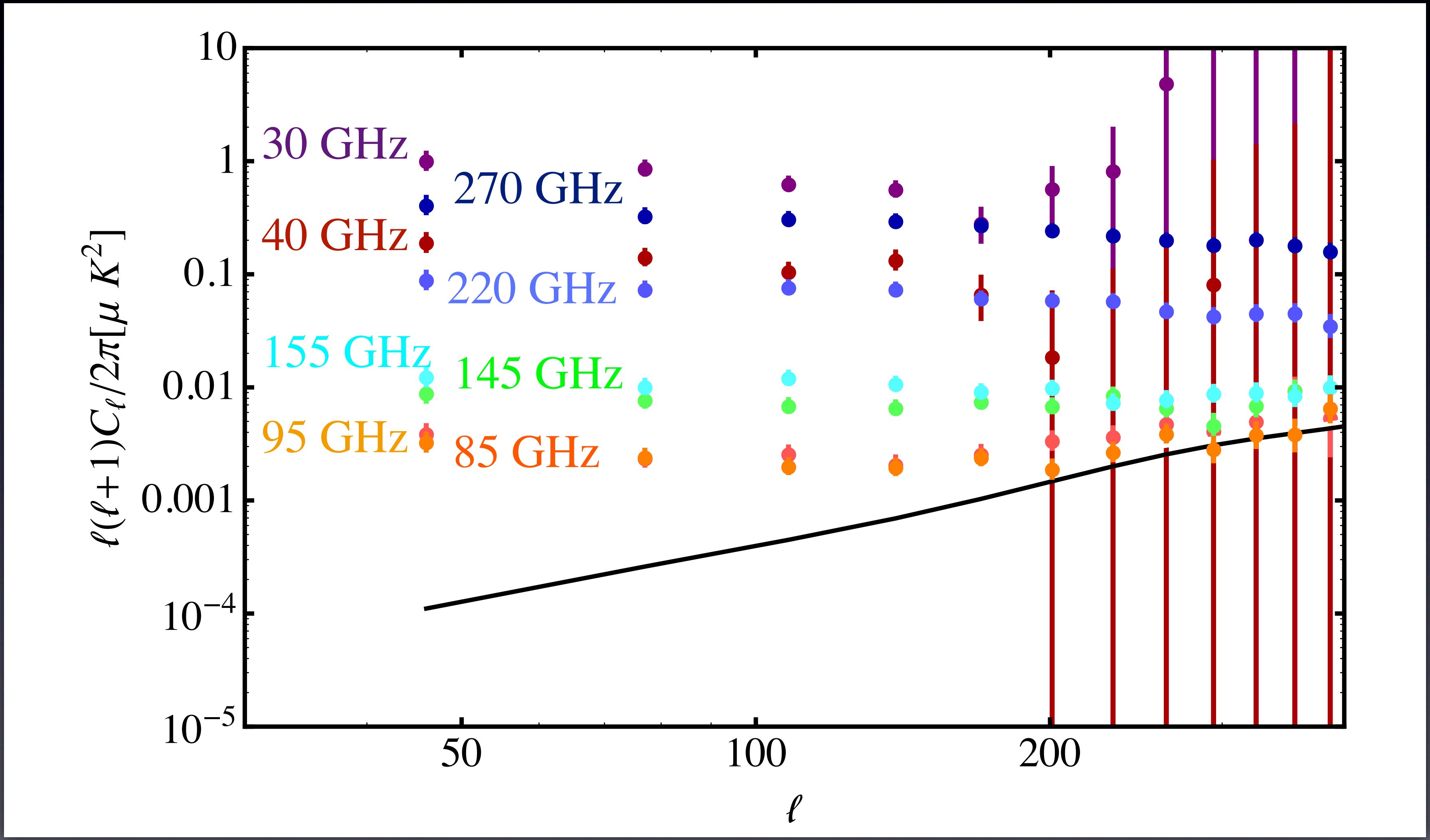
Primordial B-modes

The challenge is to use maps with auto-spectra shown below to tell the difference between...



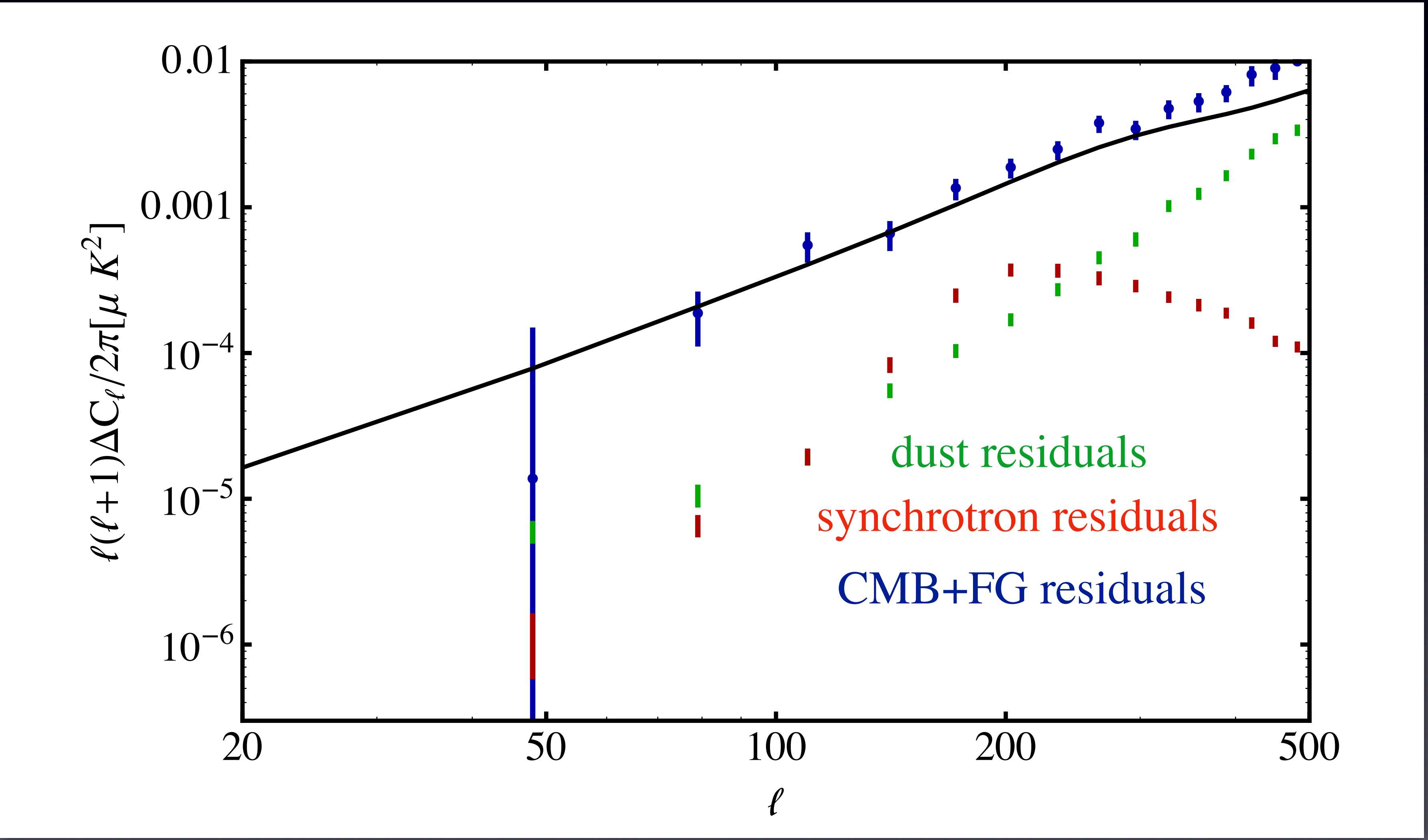
Primordial B-modes

and...

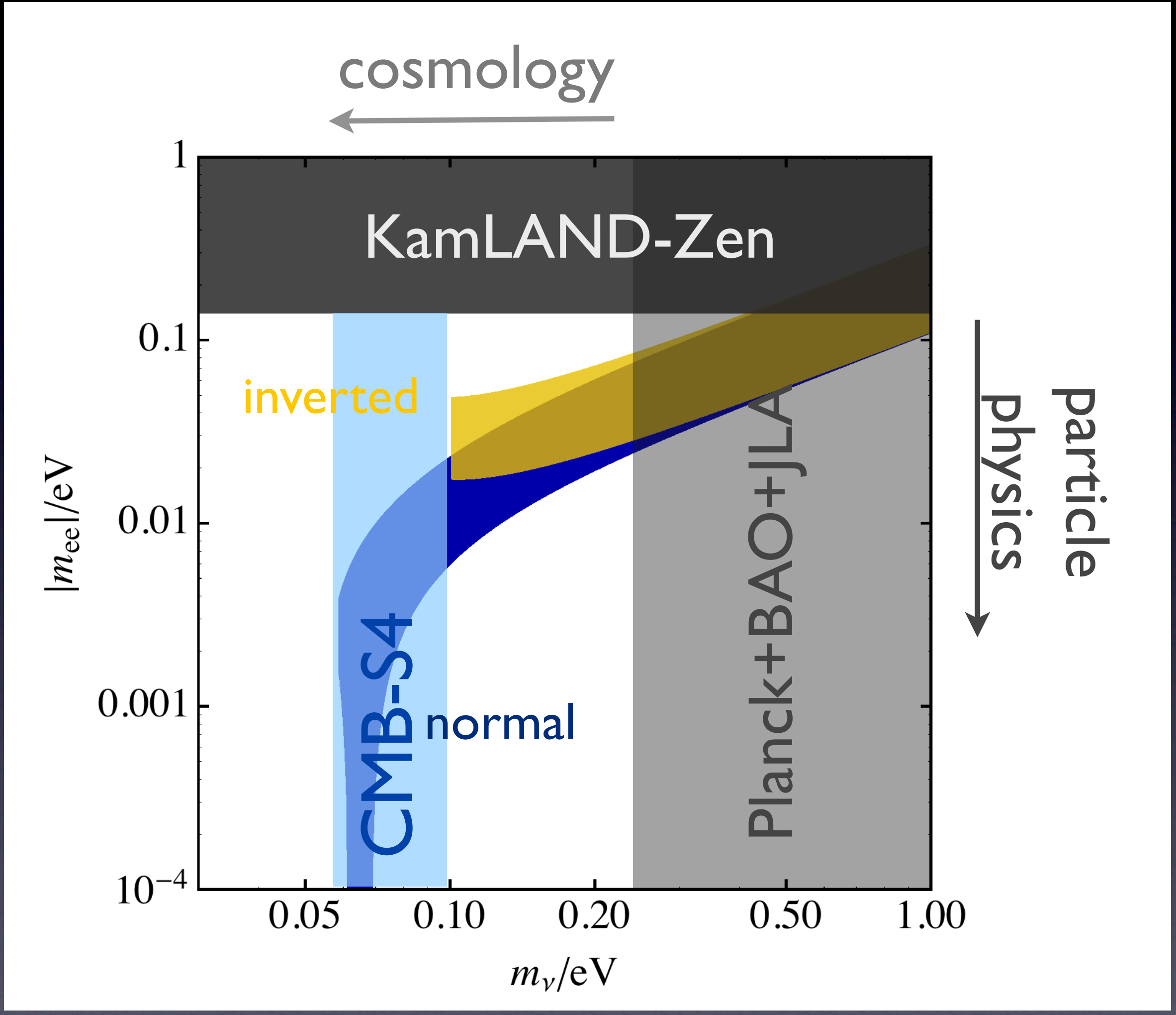


Primordial B-modes

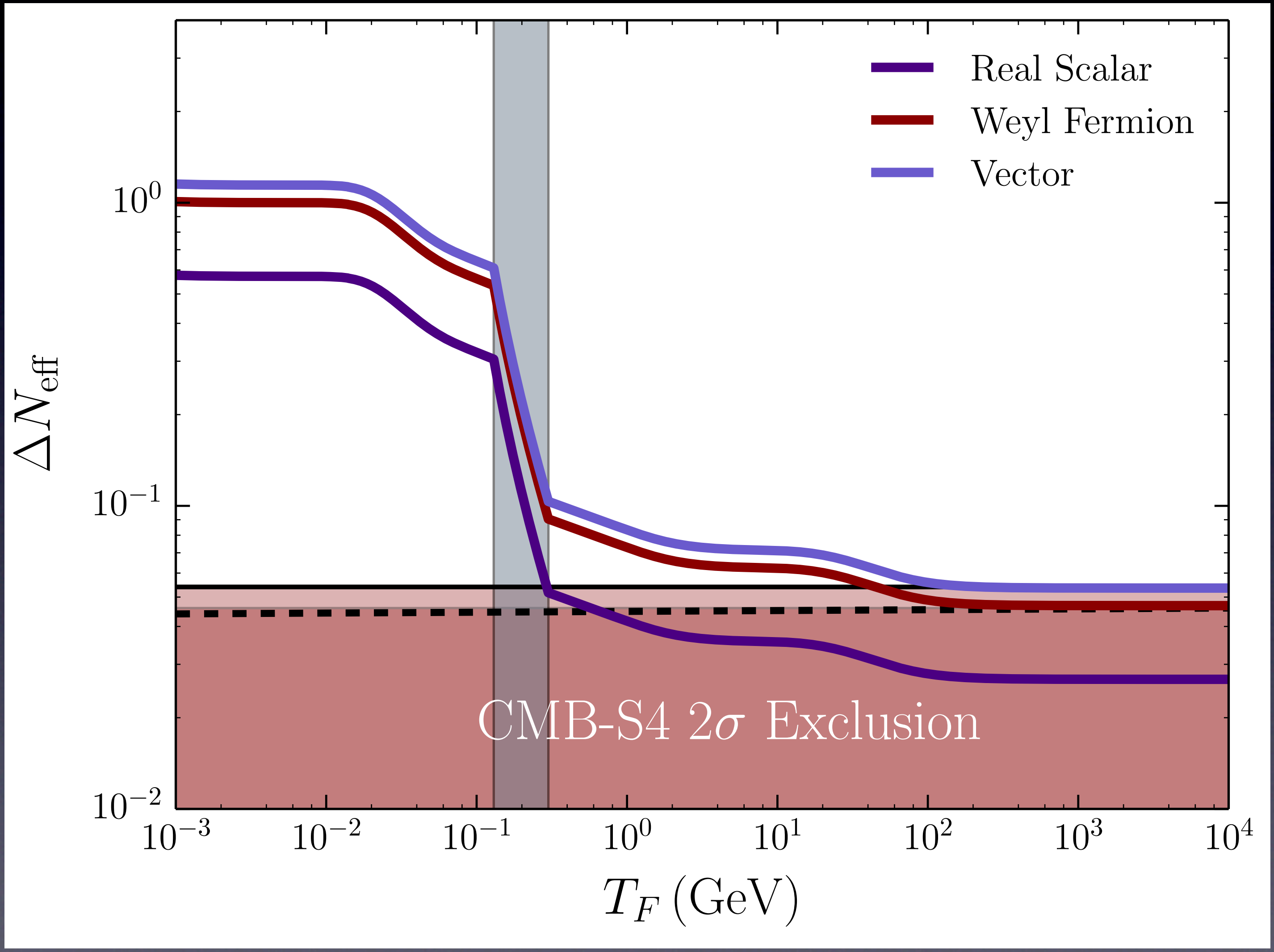
Foreground cleaned spectrum and foreground residuals based on simulation for representative configuration



Neutrino Mass



N_{eff}



Real Scalar
Weyl Fermion
Vector
$\Delta N_{\rm eff}$
10^0
10^{-1}
10^{-2}
CMB-S4 2σ Exclusion
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
T_F (GeV)

Conclusions

- The LCDM model with inflationary spectrum of perturbations is consistent with all current cosmological data.
- Small "tensions" exist, but at a level where they might be caused by systematic effects.
- The CMB will continue to provide valuable information about primordial gravitational waves, neutrino masses, the number of effective relativistic degrees of freedom, dark matter, and the early universe.
- Stringy inflation models continue to provide a way to generate new ideas and motivate new searches.
- With some luck we may detect stringy features or B-modes and learn more about the very early universe.

Thank you