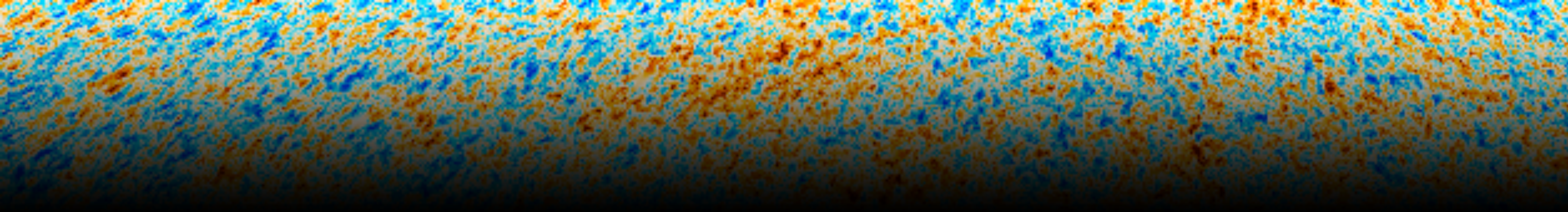


Did $m^2\phi^2$ bite the dust?

A closer look at n_s and r

Raphael Flauger

Cosmology with the CMB and its Polarization, University of Minnesota, January 15, 2015

The Cosmic Microwave Background

The Cosmic Microwave Background

Observations of the CMB have taught us that the primordial perturbations

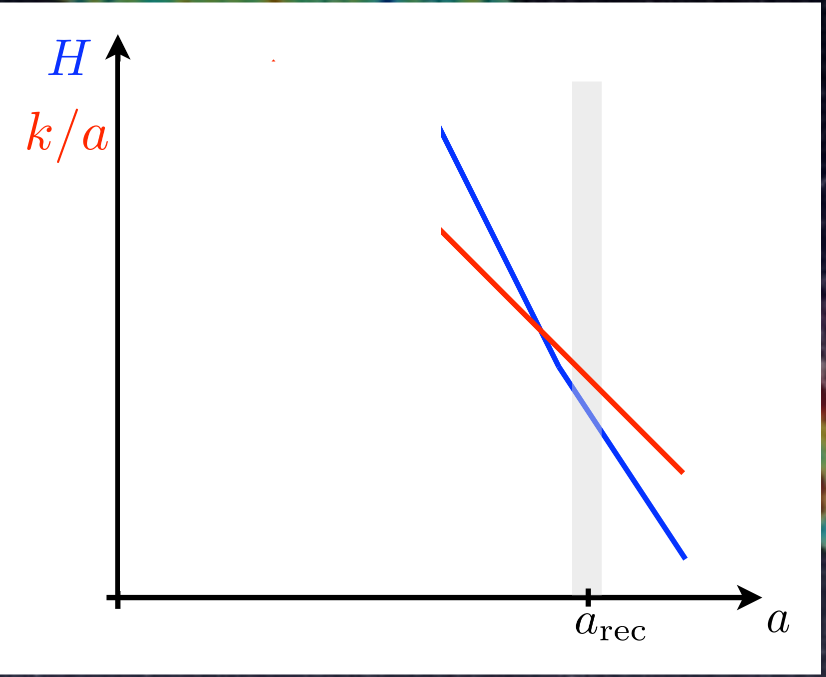
- existed before the hot big bang
- are nearly scale invariant
- are very close to Gaussian
- are adiabatic

What generated them?

Generating Primordial Perturbations

The system of equations describing the early universe contains two important scales k/a and H.

To generate the perturbations causally, they cannot have been outside the horizon very early on, requiring a phase with



$$\frac{d}{dt}\left(\frac{k}{a|H|}\right) < 0 \qquad \text{(inflation or bounce)}$$

Inflation

The simplest system leading to a phase of inflation (that ends) is

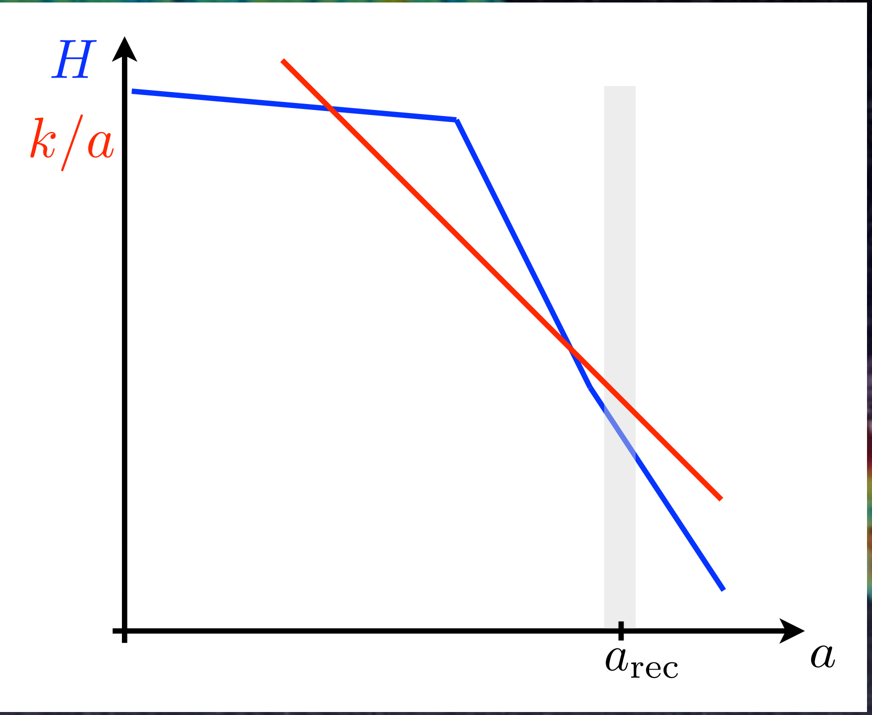
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,R$$

$$-\int d^4x\sqrt{-g}\,\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}m^2\phi^2\right)$$

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 perturbations are generated as quantum fluctuations deep inside the horizon, and eventually exit the horizon.



Outside the horizon, a quantity $\mathcal{R}$ is conserved.

This sets the initial conditions for the equations describing the universe from a few keV to the present.

We observe the density perturbations in the plasma at recombination that were seeded by the inflationary perturbations.

Inflation

For standard single field slow-roll inflation, the primordial spectrum of scalar perturbations is

$$\Delta^2_{\mathcal{R}}(k) = \frac{H^2(t_k)}{8\pi^2\epsilon(t_k)} \approx \Delta^2_{\mathcal{R}} \left(\frac{k}{k_*}\right)^{n_s-1}$$

with $\quad n_s = 1 - 4\epsilon_* - 2\delta_*$

and $\quad \epsilon = -\frac{\dot{H}}{H^2} \qquad \delta = \frac{\ddot{H}}{2H\dot{H}}$

in agreement with observations.

Inflation

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 scalar modes, 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

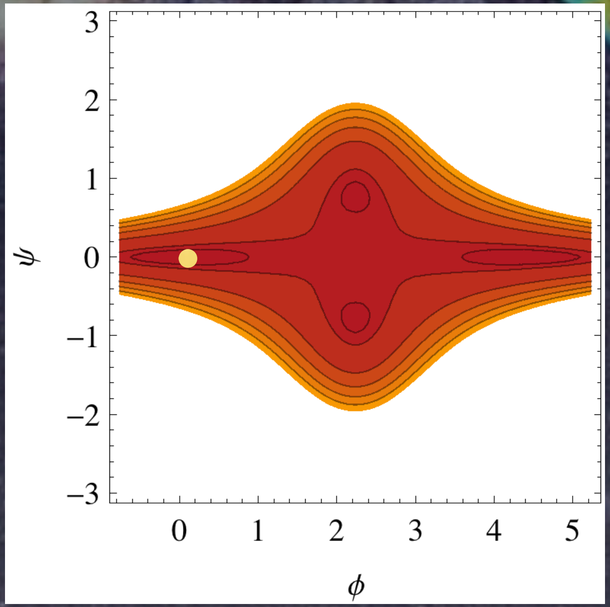
$$V_{\inf}^{1/4} = 1.06 \times 10^{16}\, GeV \left(\frac{r}{0.01}\right)^{1/4}$$

The Field Range

- For r>0.01 the inflaton must have moved over a super-Planckian distance in field space. **(Lyth, Turner)**
- Motion of the scalar field over super-Planckian distances is hard to control in an effective field theory

$$V(\phi) = V_0 + \frac{1}{2}m^2\phi^2 + \frac{1}{3}\mu\phi^3 + \frac{1}{4}\lambda\phi^4 + \phi^4 \sum_{n=1}^{\infty} c_n \left(\phi/\Lambda\right)^n$$

$$(\Lambda < M_p)$$



The Field Range

Possible Solution:

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

e.g. Linde's chaotic inflation with

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

natural inflation

Freese, Frieman, Olinto, PRL 65 (1990)

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

The Field Range

In field theory we may simply postulate such a symmetry, but it is far from 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.

Banks, Dine, Fox, Gorbatov hep-th/0303252

(However, see
Kim, Nilles, Peloso hep-ph/0409138, Bachlechner, Long, McAllister 1412.1093)

This motivates a systematic study of large field models of inflation in quantum gravity/string theory

Axion Monodromy Inflation

Consider string theory on $M \times X$

Axions arise from integrating gauge potentials over non-trivial cycles in the compactification manifold.

$$b_I(x) = \int_{\Sigma_I^{(2)}} B$$

$$c_\alpha(x) = \int_{\Sigma_\alpha^{(p)}} C^{(p)}$$

where $\Sigma_\alpha^{(p)}$ is an element of an integral basis of $H_p(X, \mathbb{Z})$

Inspection of the vertex operator for $b_I(x)$ reveals that these fields possess a shift symmetry to all orders in string perturbation theory.

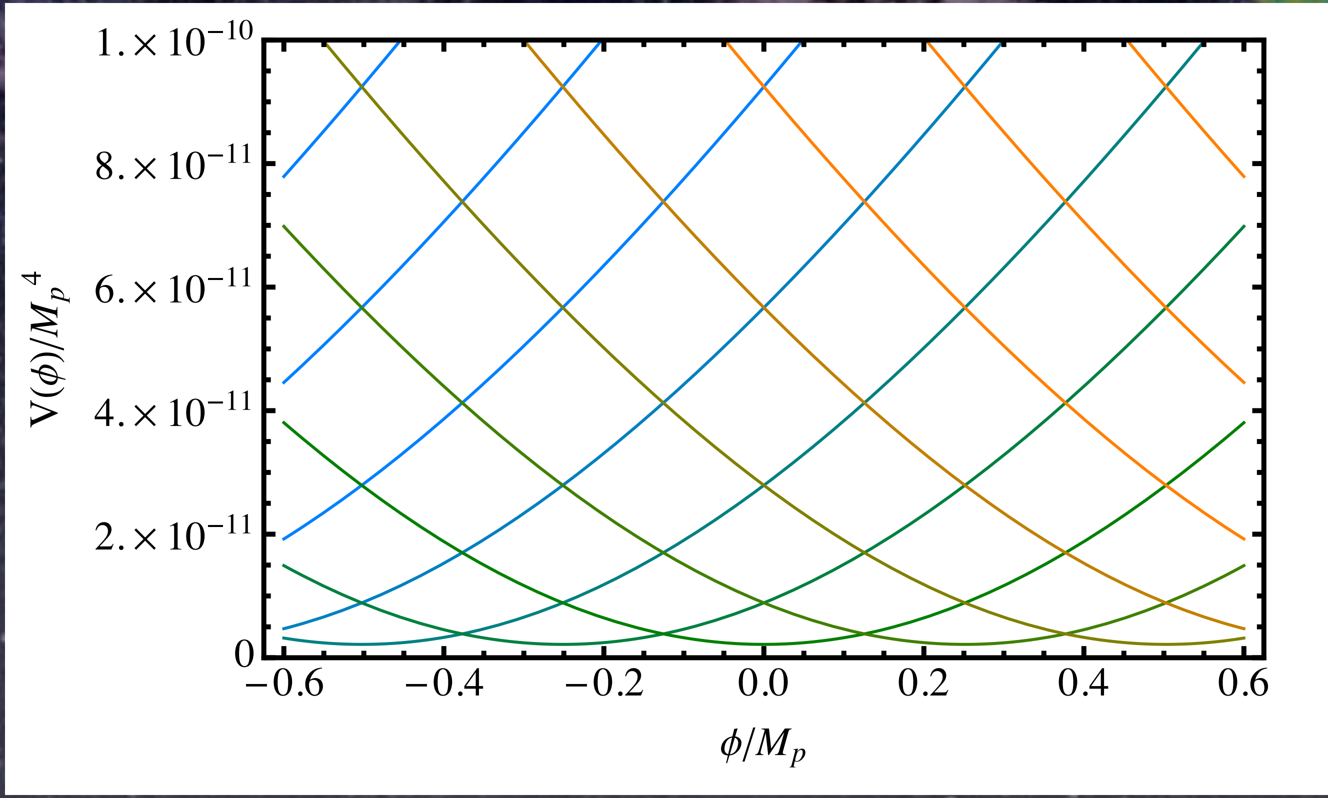
Axion Monodromy Inflation

The corresponding canonically normalized scalar fields are periodic with period $2\pi f$, with typically $f \lesssim 0.1 M_p$.

Axion Monodromy Inflation

The corresponding canonically normalized scalar fields are periodic with period $2\pi f$, with typically $f \lesssim 0.1 M_p$.

One way to achieve super-Planckian excursions 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

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

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

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

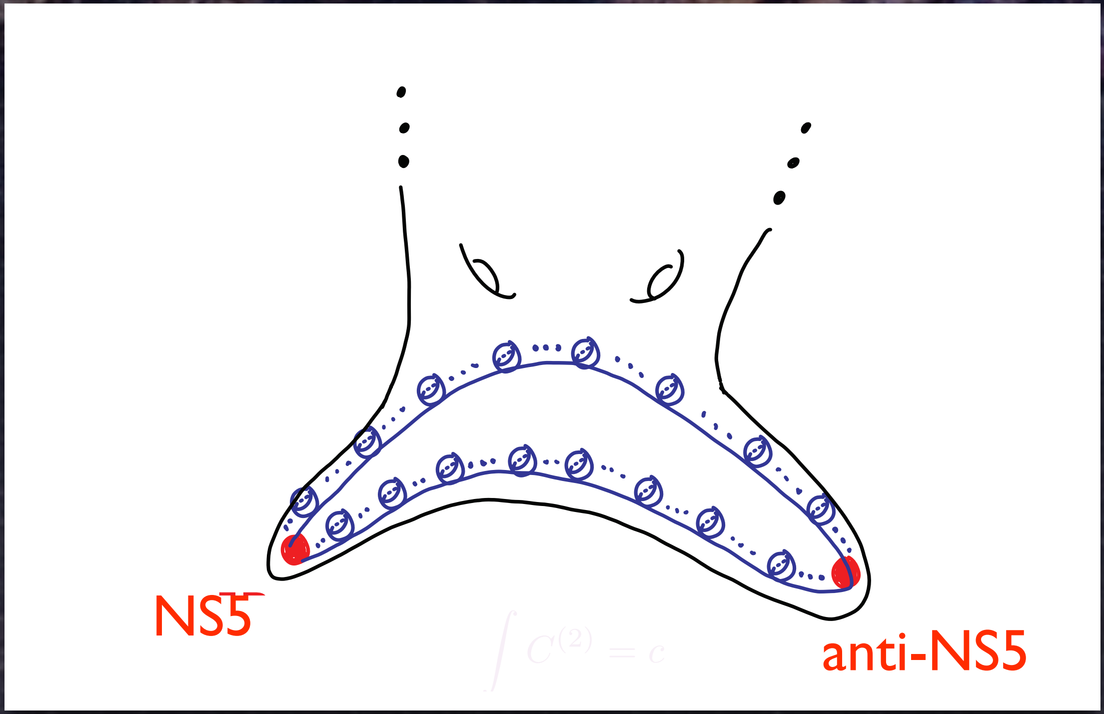
For large field values in terms of the canonically normalized fields the potential then becomes

$$V(\phi) \approx \mu^3 \phi$$

Axion Monodromy Inflation

<u>Basic setup</u>

- Type IIB orientifolds with O3/O7
- Stabilize the moduli a la KKLT



Axion Monodromy Inflation

This is just one example of a larger class of models with potentials

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

so far with

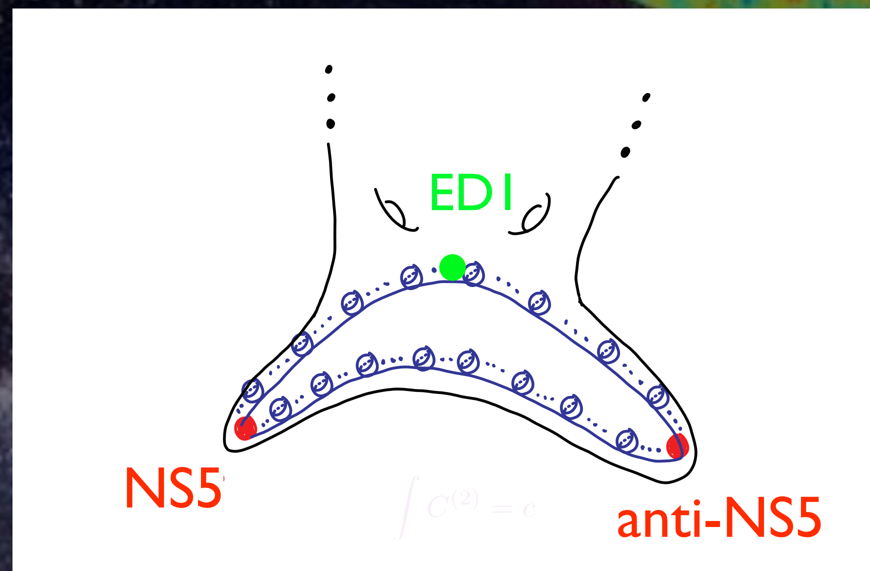
$$p = \frac{2}{3}, 1, \frac{4}{3}, 2, 3$$

(see Alexander's talk)

Even though one can arrange p=2, would we believe any of this if we found that the data was consistent with $m^2\phi^2$?

Axion Monodromy Inflation

Indeed the models make additional predictions



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 the larger class of models they are of the form

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

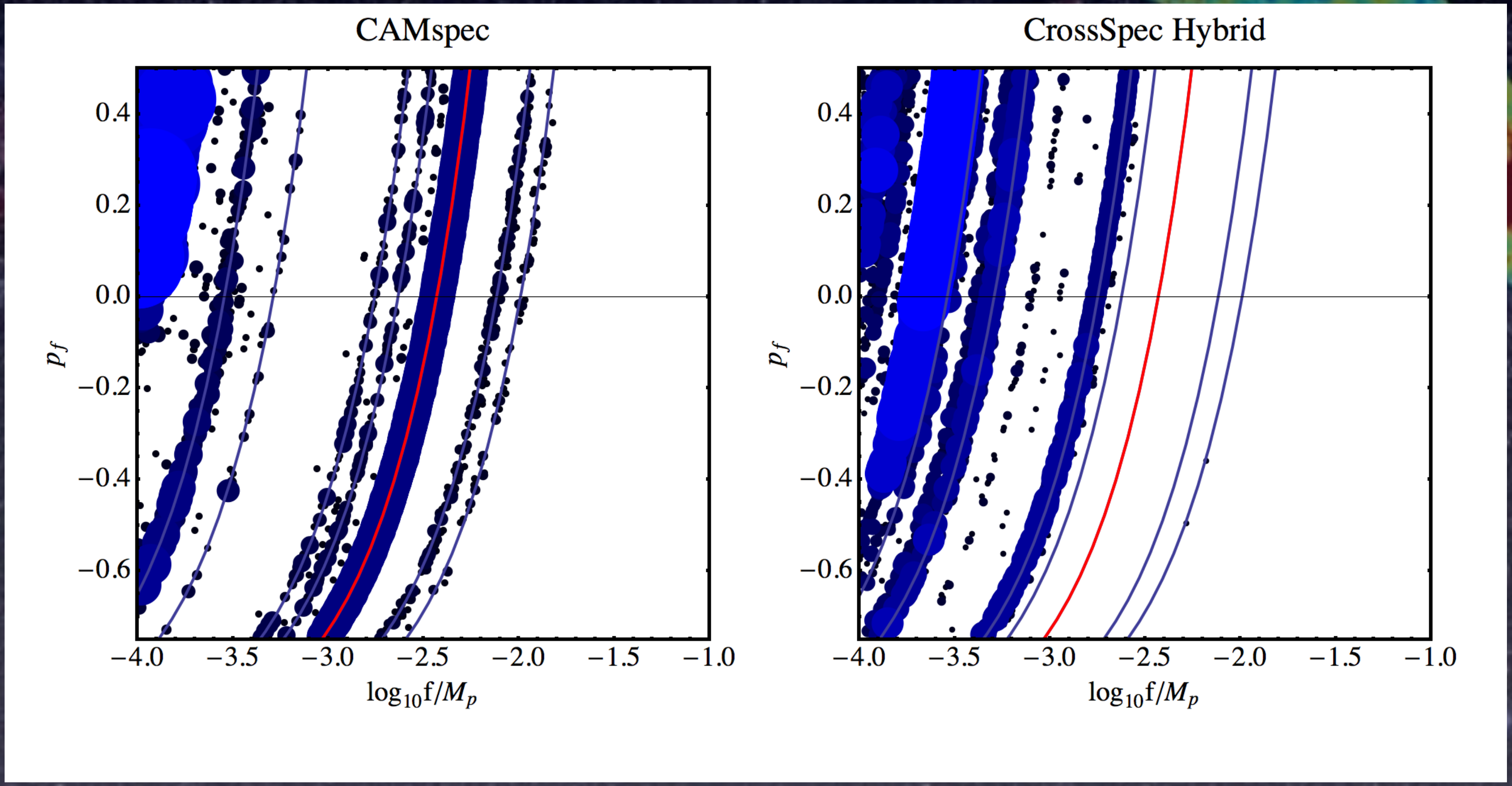
This can be shown to lead to a power spectrum of the form

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

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

Axion Monodromy Inflation

Search for oscillations with drifting period in Planck nominal mission data



Axion Monodromy Inflation

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

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

One should keep in mind that not the entire parameter space was searched and more work is required, but as of now there is no evidence for oscillations in the primordial power spectrum.

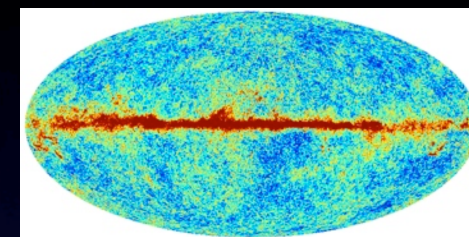
The amplitude is very model dependent, and a non-detection does not rule out these models, but it means for now* we are stuck with n_s and r.

(*) LSS may some day dramatically improve the constraints

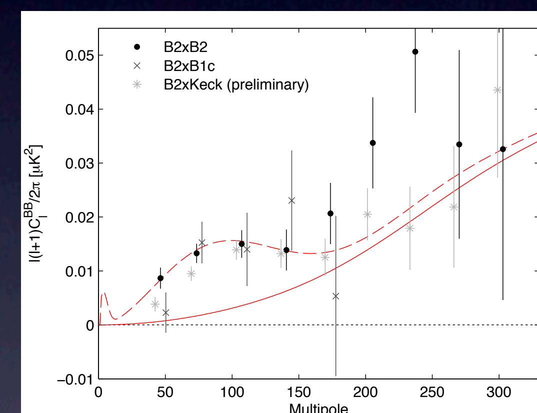
A closer look at n_s and r

Using

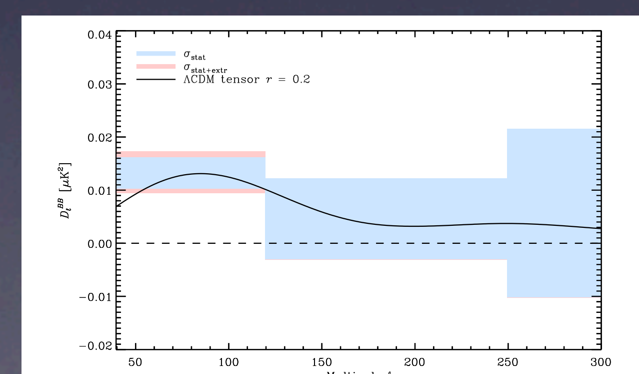
- Planck temperature anisotropies



- BICEP2 BB power spectrum

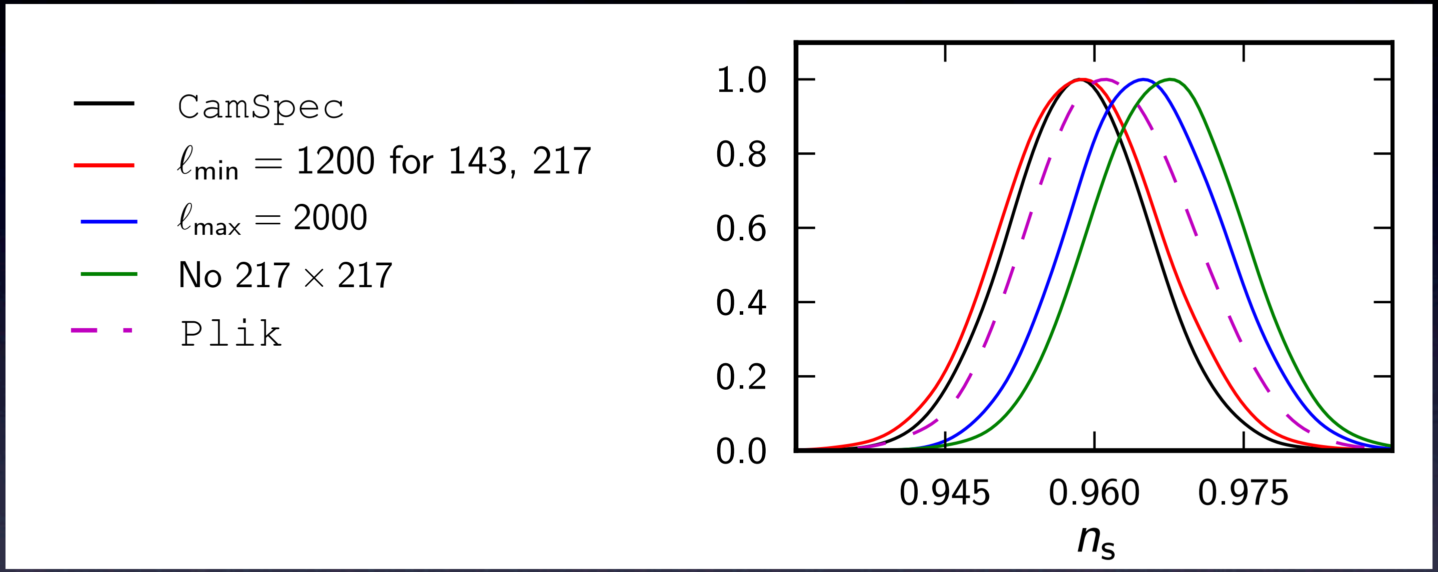


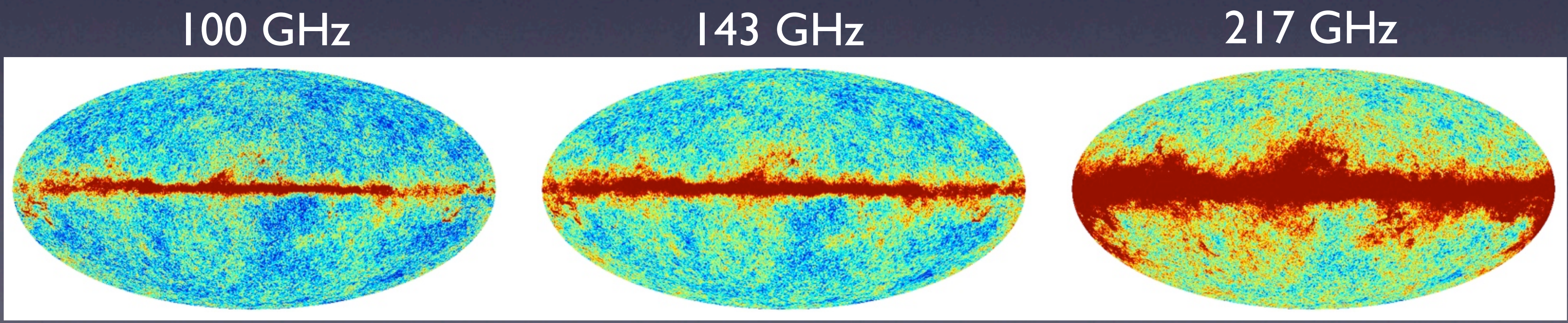
- Planck 353 GHz BB power spectrum



A closer look at n_s

(Planck XVI)





A closer look at n_s

Is 217x217 consistent with the other frequencies?

Use Planck covariance matrix to compute

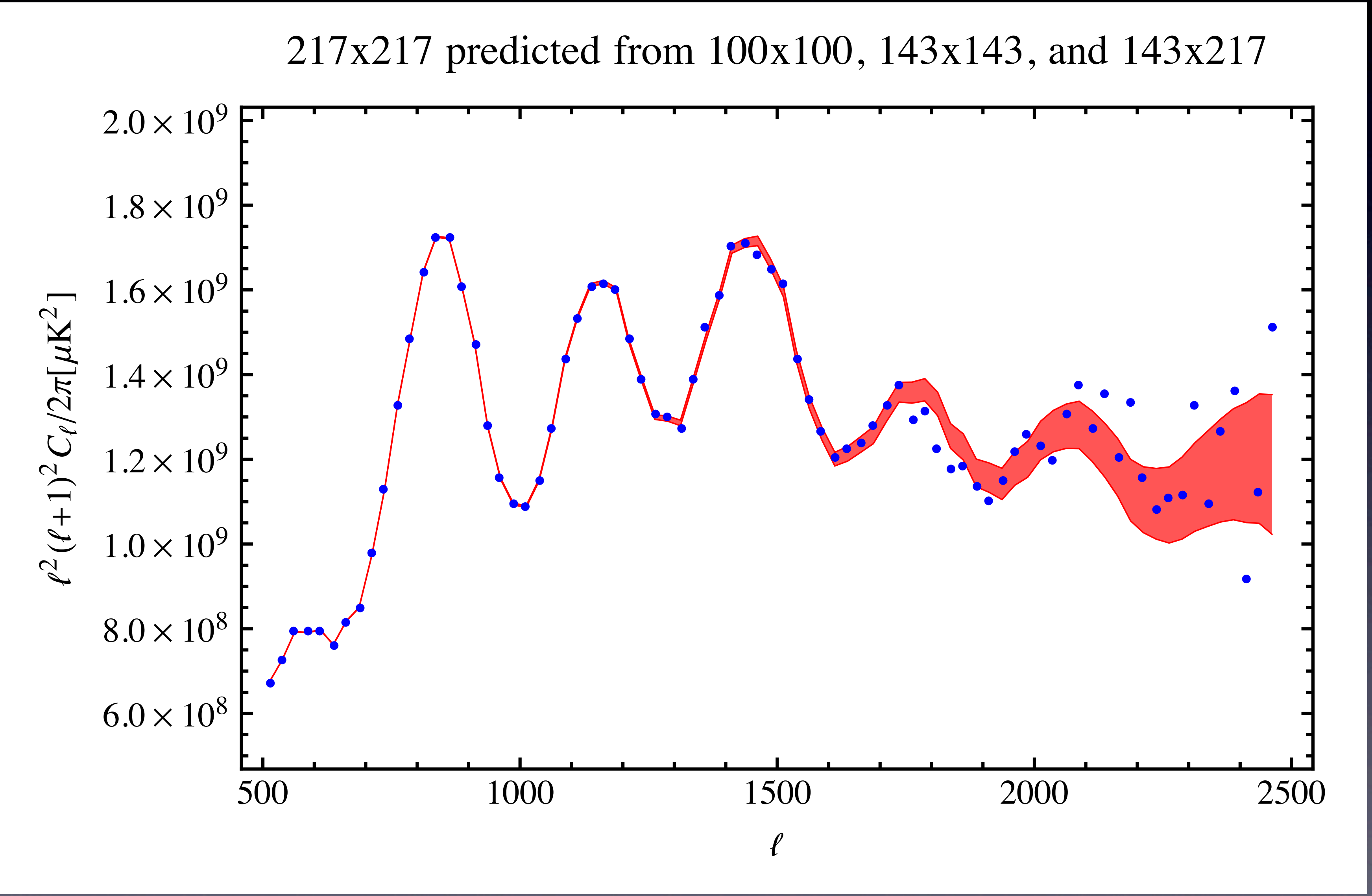
$$P(C_\ell^{217\times217}|\{C_\ell^{100\times100}, C_\ell^{143\times143}, C_\ell^{143\times217}\})$$

and $\langle C_\ell^{217\times217} \rangle_{\{C_\ell^{100\times100}, C_\ell^{143\times143}, C_\ell^{143\times217}\}}$

to predict the spectrum

A closer look at n_s

Predicted versus measured 217x217 spectrum

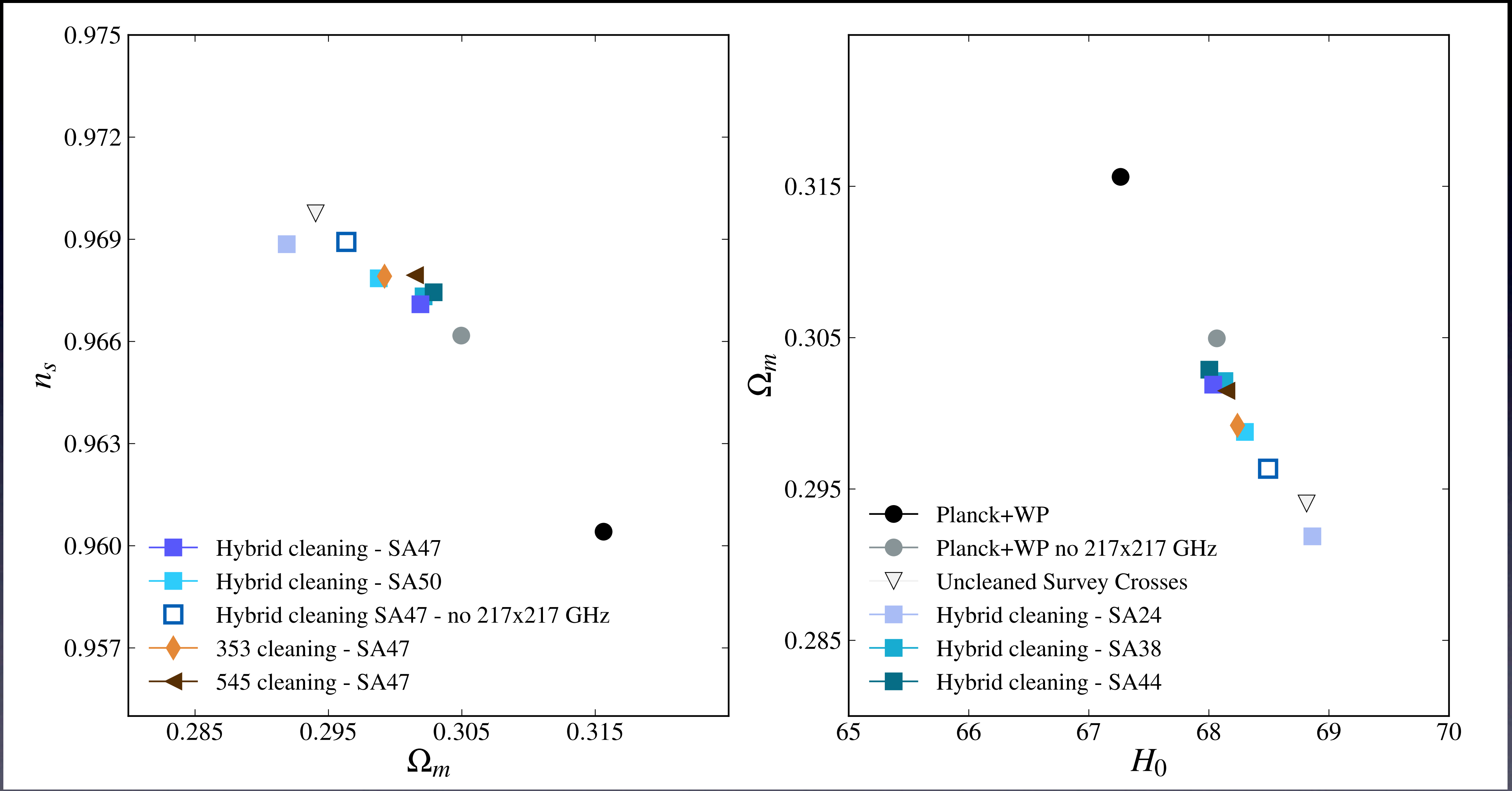


A closer look at n_s

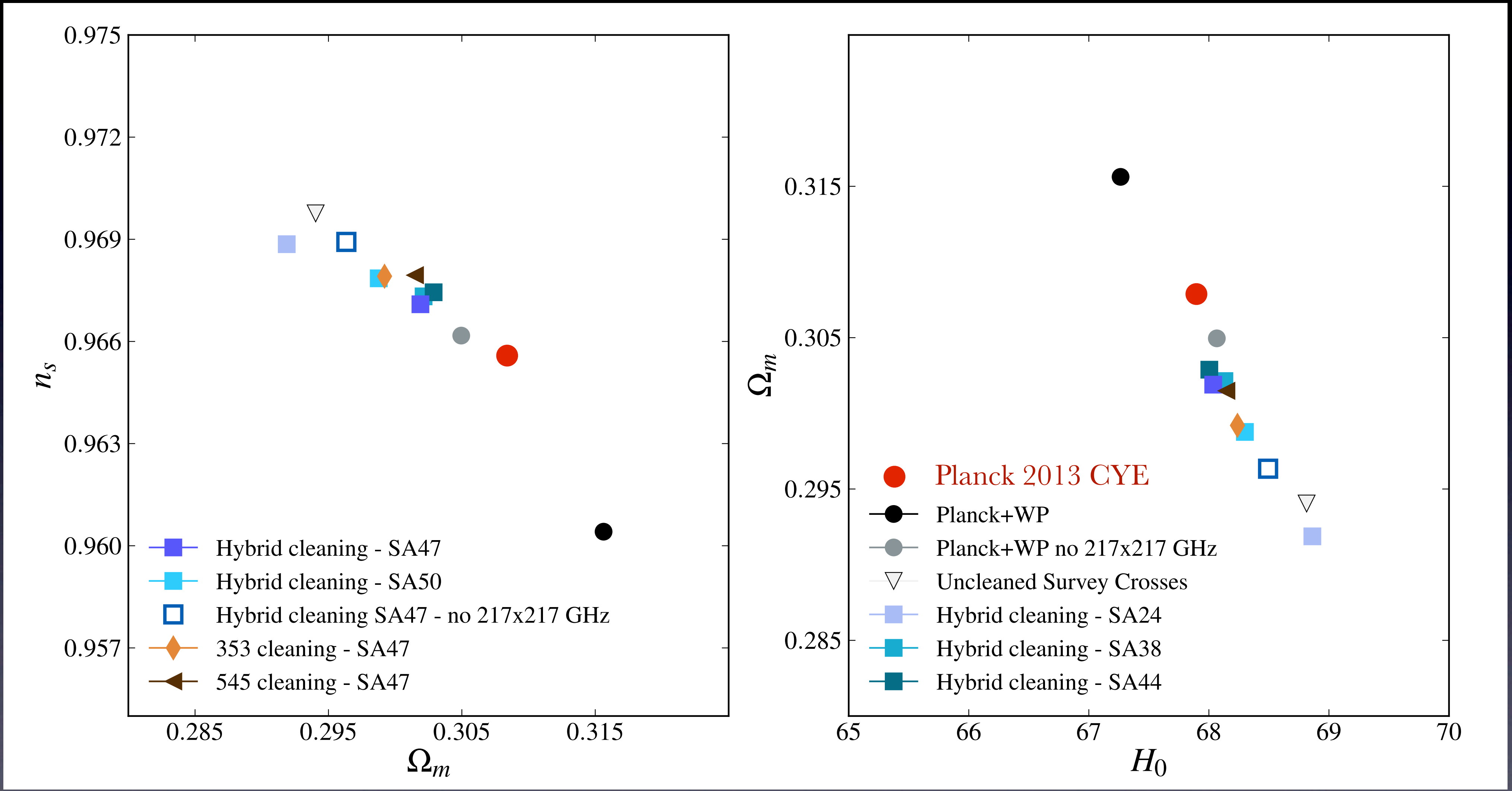
In our reanalysis

- We use survey cross spectra rather than detector set spectra
- We have used various cleaning procedures and a range of masks to test for stability
- We have performed the analysis with the same treatment of foregrounds as Planck (but for survey cross-spectra)
- We do not find strong dependence on mask or treatment of foregrounds

A closer look at n_s



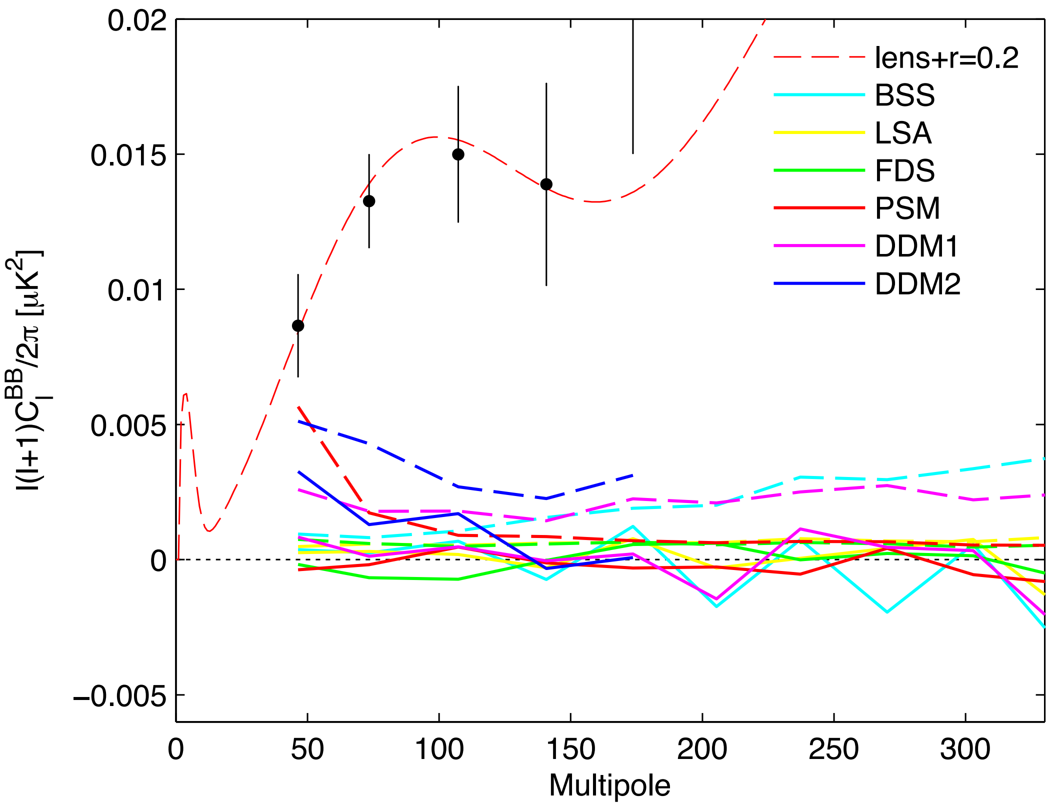
A closer look at n_s

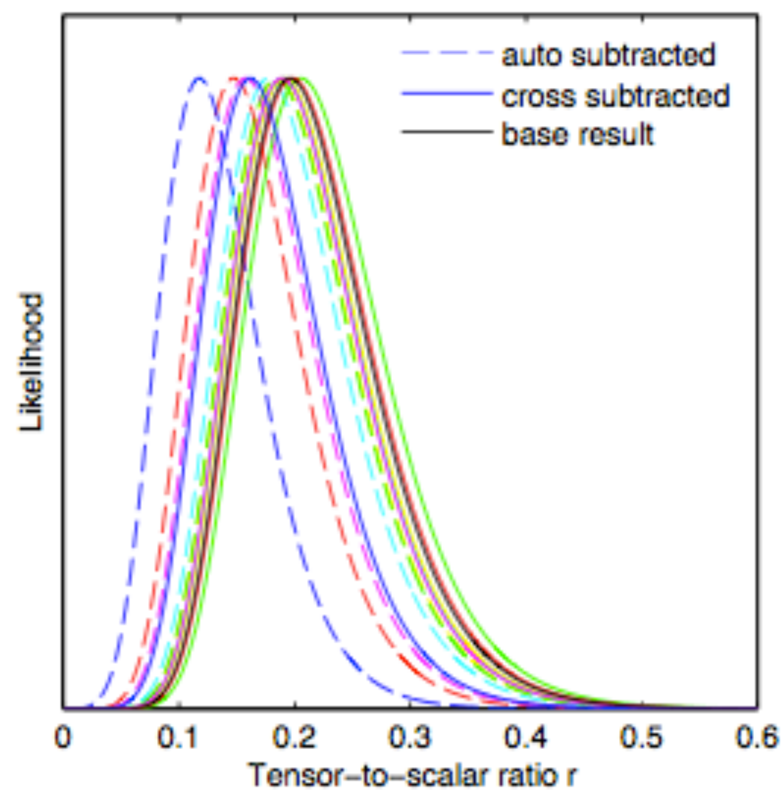


With the new prior on the optical depth we find, e.g.

$$n_s = 0.9651 \pm 0.0066 \qquad H_0 = 67.45 \pm 1.07$$

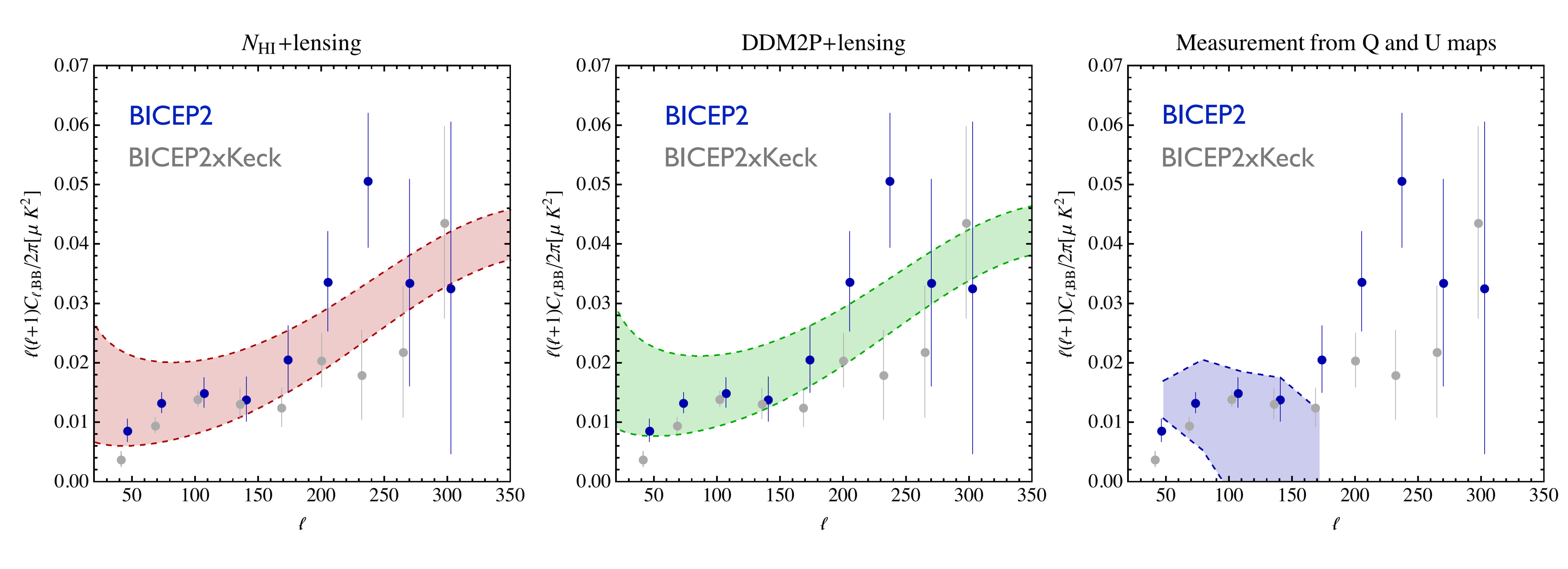
A closer look at r





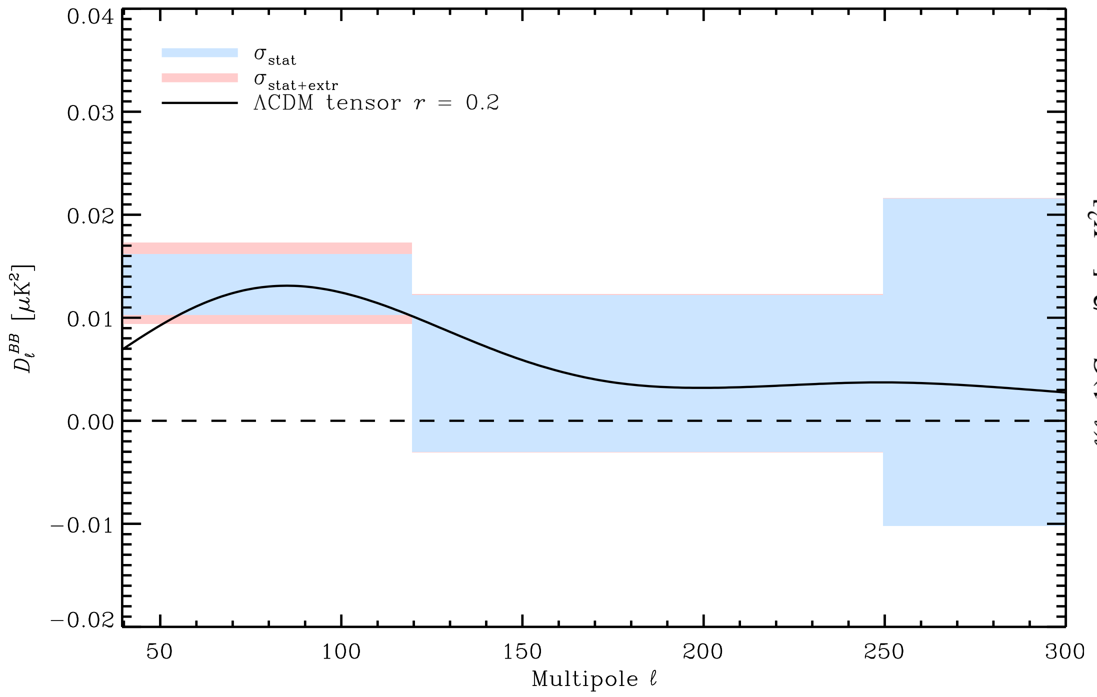
A closer look at r

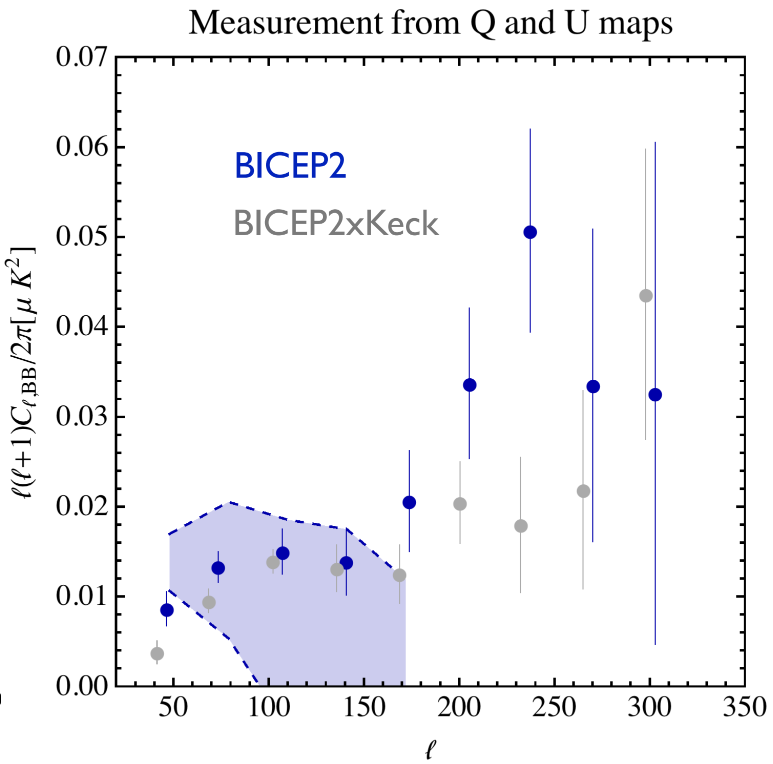
Foreground models made in collaboration with David Spergel, Colin Hill, and Aurelien Fraisse



A closer look at r

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





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

Joint Likelihood

TT and BB is essentially independent so that the likelihoods factorize.

BICEP2 and Planck 353 GHz are not independent and we need a joint likelihood.

$$\mathcal{L}(C^{th}_{\rm CMB}, C^{th}_{\rm dust}|C_i^{(B)}) \propto \exp\left[-\frac{1}{2}\frac{\tilde{\Delta}^{(P)2}}{\sigma^2_{P\,\rm eff}}\right]\mathcal{L}_{\rm BICEP}(C^{th}_{\rm CMB}, C^{th}_{\rm dust}|C_i^{(B)})$$

with

$$\tilde{\Delta}^{(P)} = (C^{(P)} - C_{\rm dust}) - \Delta_i^{(B)}\mathcal{C}^{-1}_{ij}\mathcal{C}_j$$

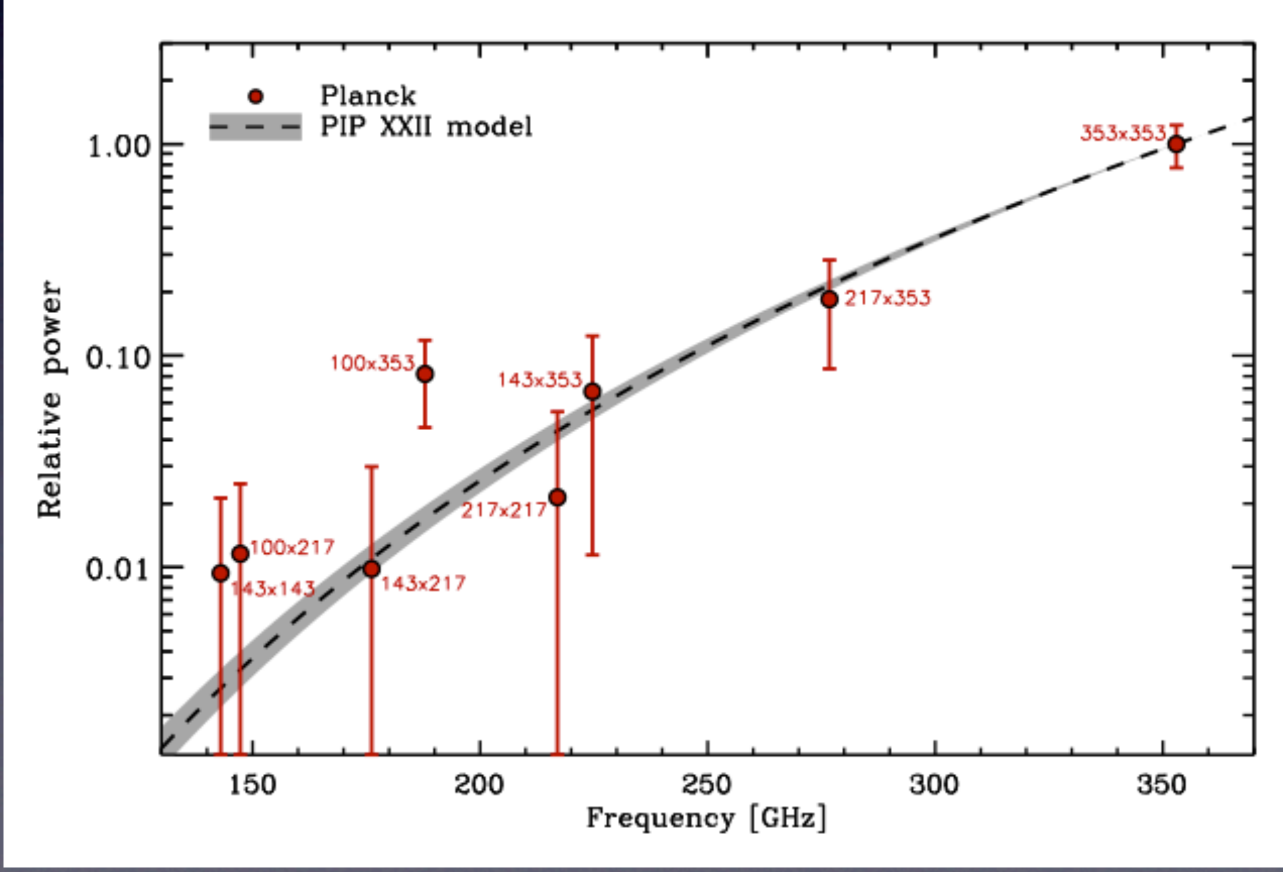
$$\Delta_i^{(B)} = C_i^{(B)} - C_{{\rm dust}\,i} - C_{{\rm CMB}\,i}$$

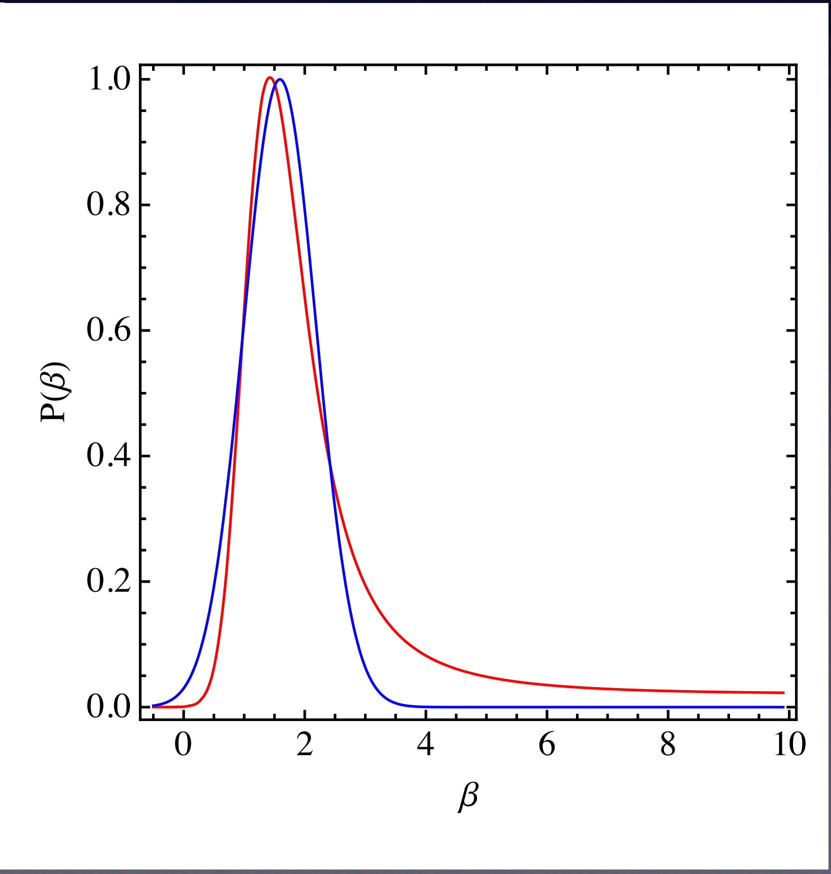
$$\sigma^2_{P\,\rm eff} = \mathcal{C}_P - \mathcal{C}_i\mathcal{C}^{-1}_{ij}\mathcal{C}_i$$

Frequency dependence

The Planck 353 GHz measurement must be rescaled to 150 GHz, and the uncertainty in the rescaling must be included.

$$\mathcal{L}(\beta_{\rm dust}, C^{th}_{\rm CMB}, C^{th}_{\rm dust} | C^{(B)}_i, C^{(P)})$$





A closer look at n_s and r

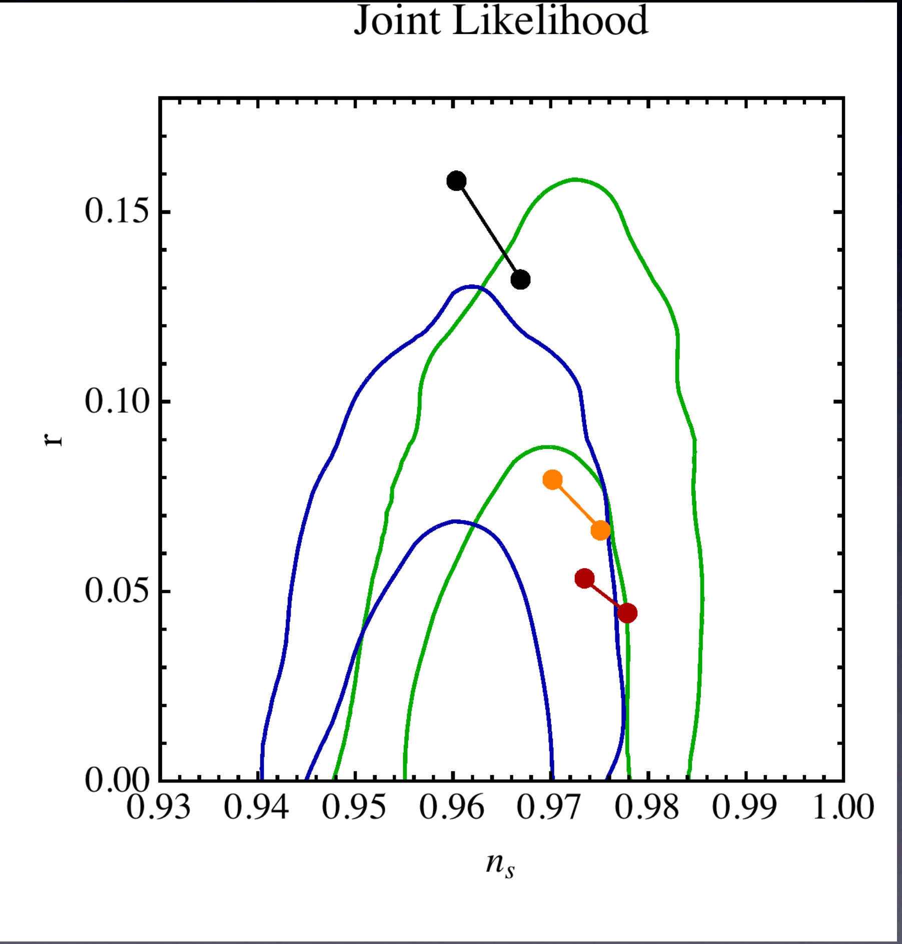
Assuming only frequency information in the patch

CAMspec

$r < 0.10$ at $95\% \, CL$

hybrid cleaning

$r < 0.12$ at $95\% \, CL$



Experimental Progress

With the current data, we can constrain r by

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

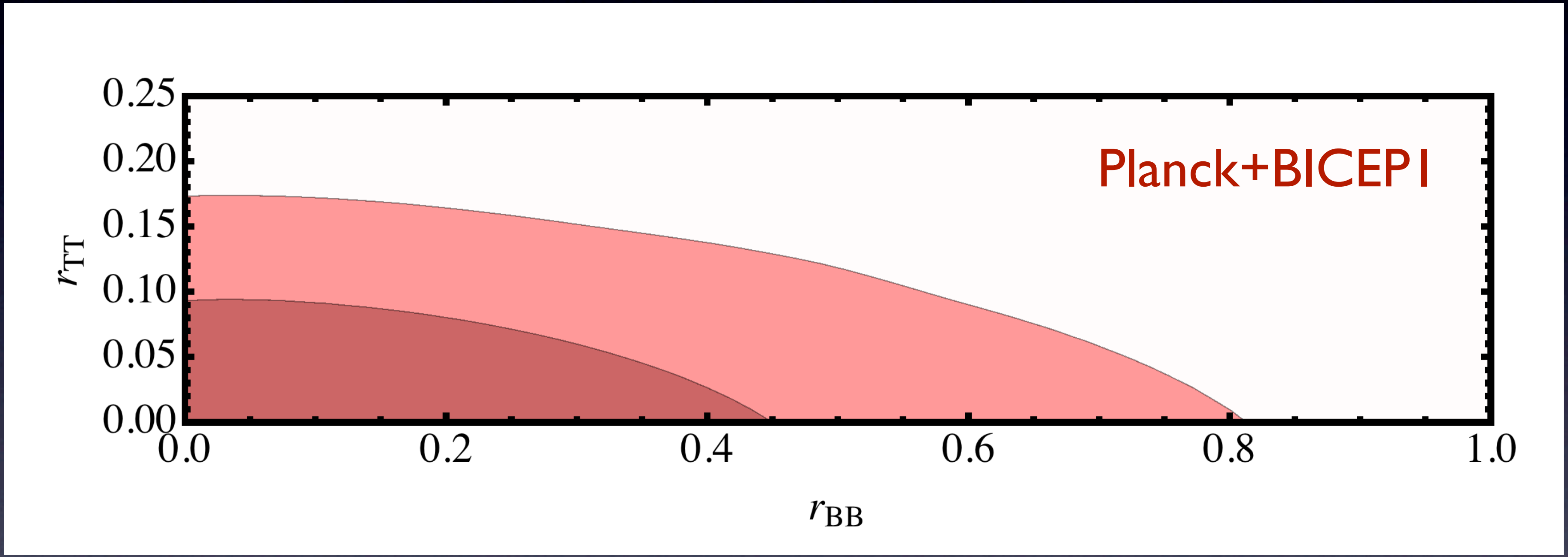
The two likelihood are essentially independent

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

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

Experimental Progress

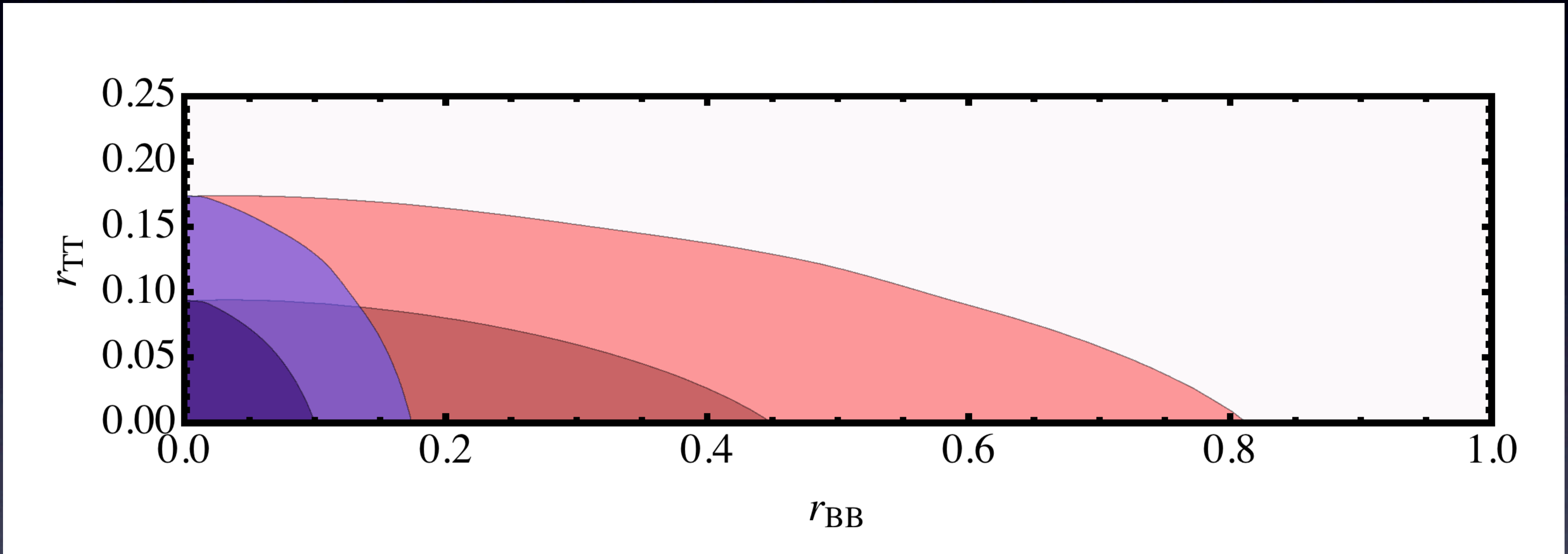
$\mathcal{L}(r_{TT}, r_{BB})$ before March



Constraint dominated by temperature data

Experimental Progress

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



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

Conclusions

- The BICEP2 BB power spectrum combined with Planck 353 GHz BB power spectrum in the BICEP region, and the Planck power spectrum of temperature anisotropies provide no evidence for primordial gravitational waves
- The simplest model of inflation is currently disfavored at 2-3 σ depending on the likelihood used for the temperature data, suggesting the existence of a second parameter in the inflationary model.
- Inclusion of cross-spectra between Planck and BICEP as well as the Keck Array 95 GHz data will soon tell us if the simplest model of inflation is relevant to our universe.

Conclusions

- Over the course of the decade we will find out if we are lucky enough that the CMB contains valuable information about quantum gravity or string theory
- Until then, we (theorists) should work harder to understand our theories at the relevant energy scales

Thank you