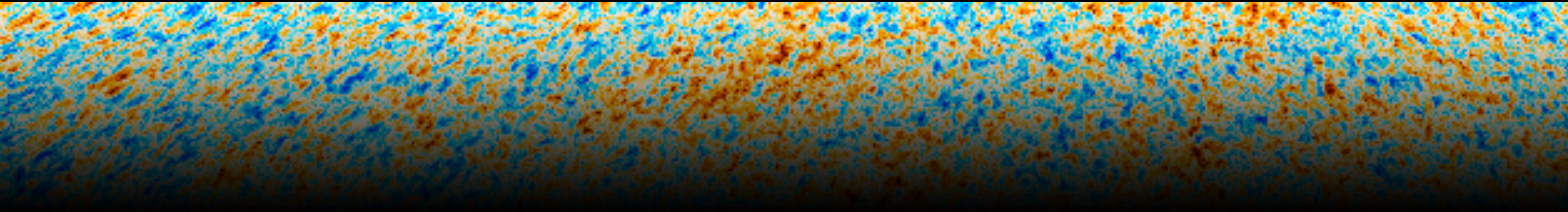
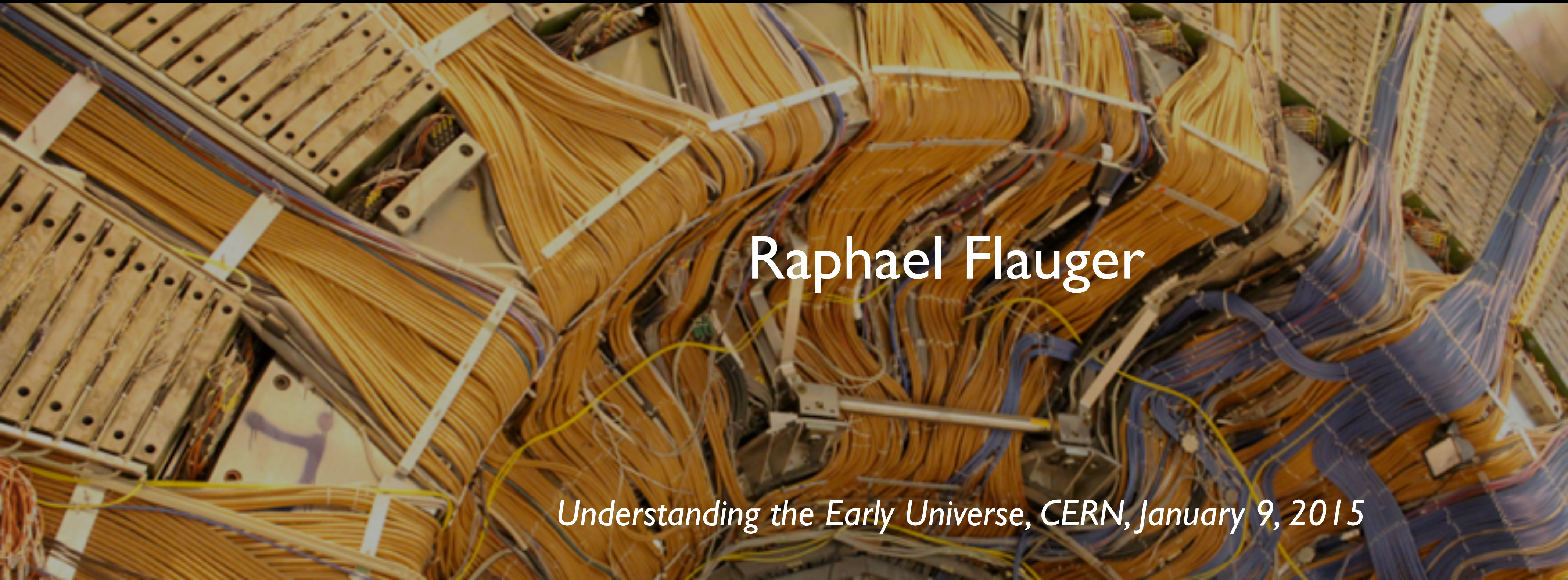


Did $m^2\phi^2$ bite the dust?

A closer look at n_s and r



Raphael Flauger

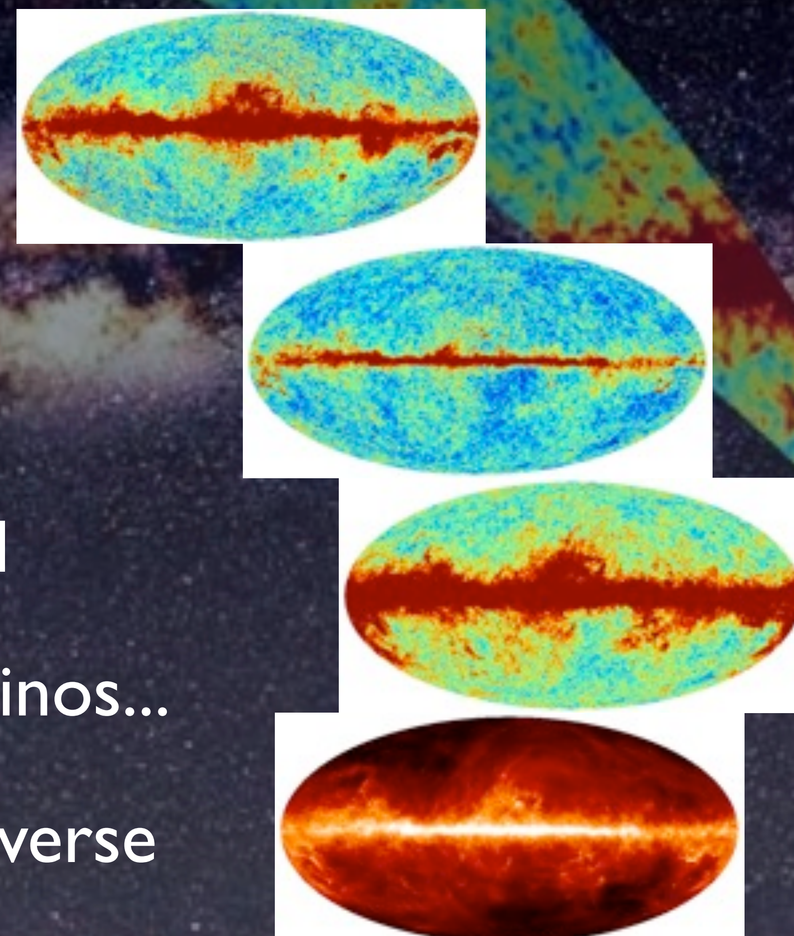
Understanding the Early Universe, CERN, January 9, 2015

The Cosmic Microwave Background

The Cosmic Microwave Background

CMB data consists of sky maps at different microwave frequencies and contains information about

- properties of dust
- magnetic fields in our galaxy
- reionization
- parameters of the LCDM model
- properties of dark matter, neutrinos...
- the earliest moments of our universe



The Cosmic Microwave Background

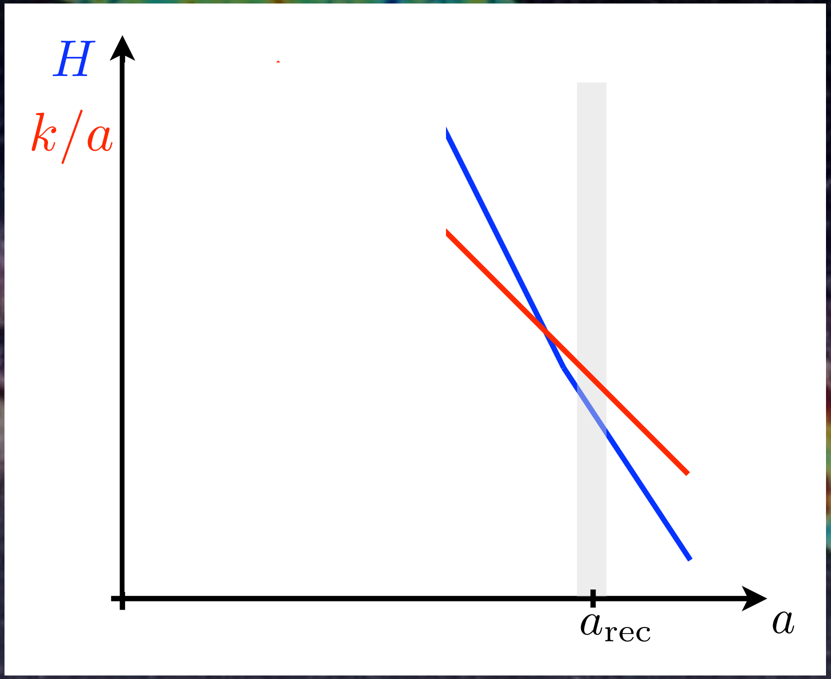
Observations of the CMB have taught us that the primordial perturbations

- 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

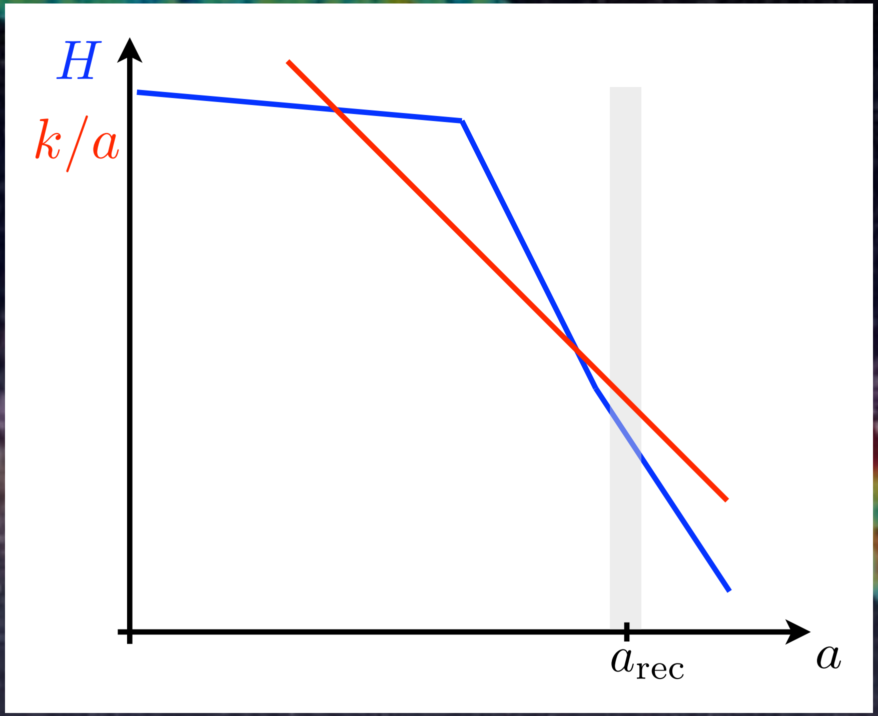
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,R$$

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

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 $\Delta_{\mathcal{R}}^2$?

- 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!

The Friedmann equation then tells us the energy scale.

Energy Scale of Inflation

Whether primordial gravitational waves are observable depends on the tensor-to-scalar ratio

$$r = \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2}$$

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

We expect that r~0.001 can be reached over the next decade.

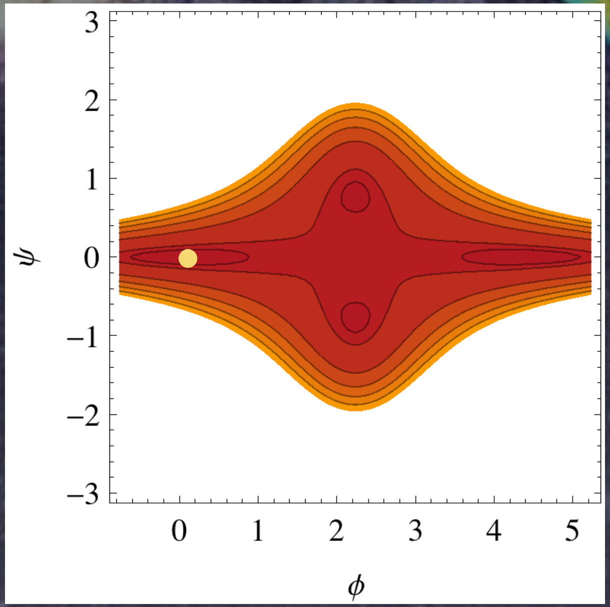
The Field Range

- 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

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

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

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 $f \gtrsim M_p$ seem hard to realize string theory.

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

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.

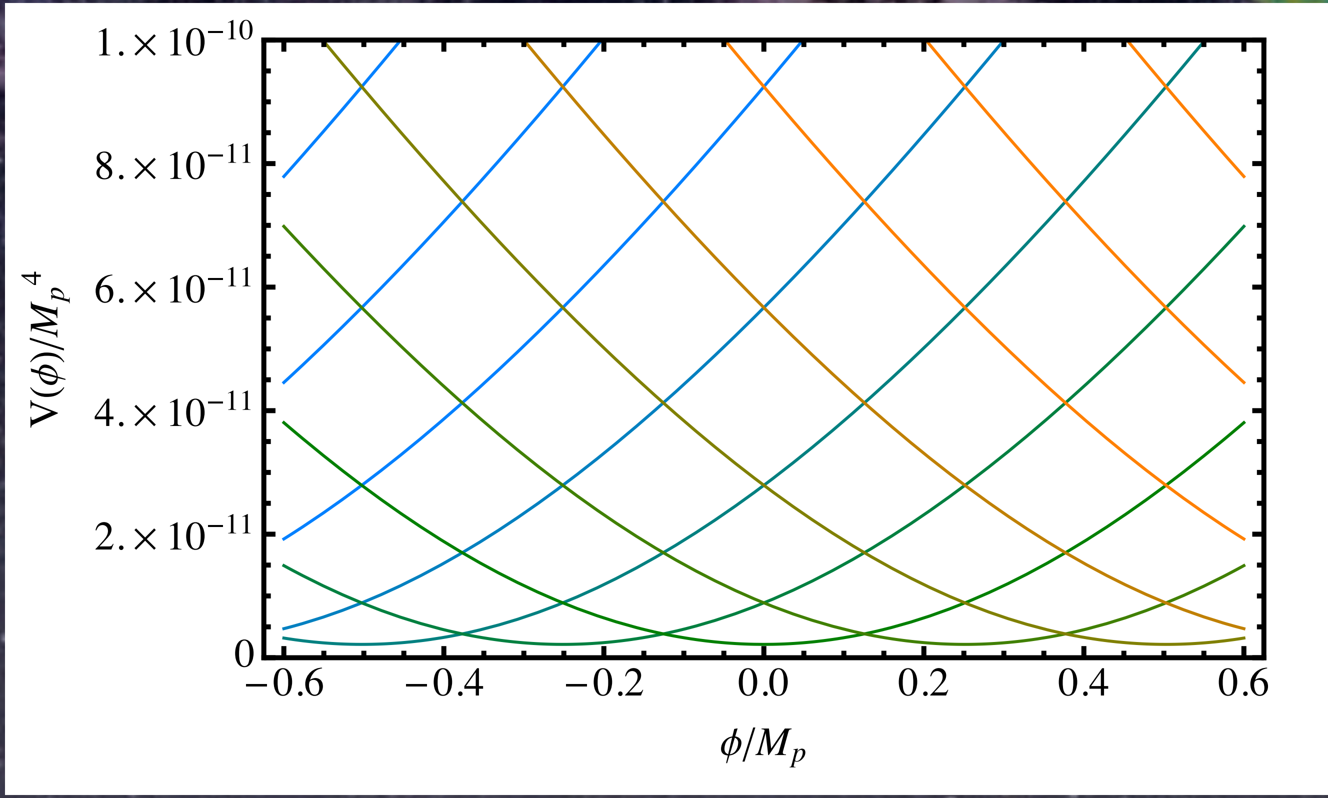
Axion Monodromy Inflation

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

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

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

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

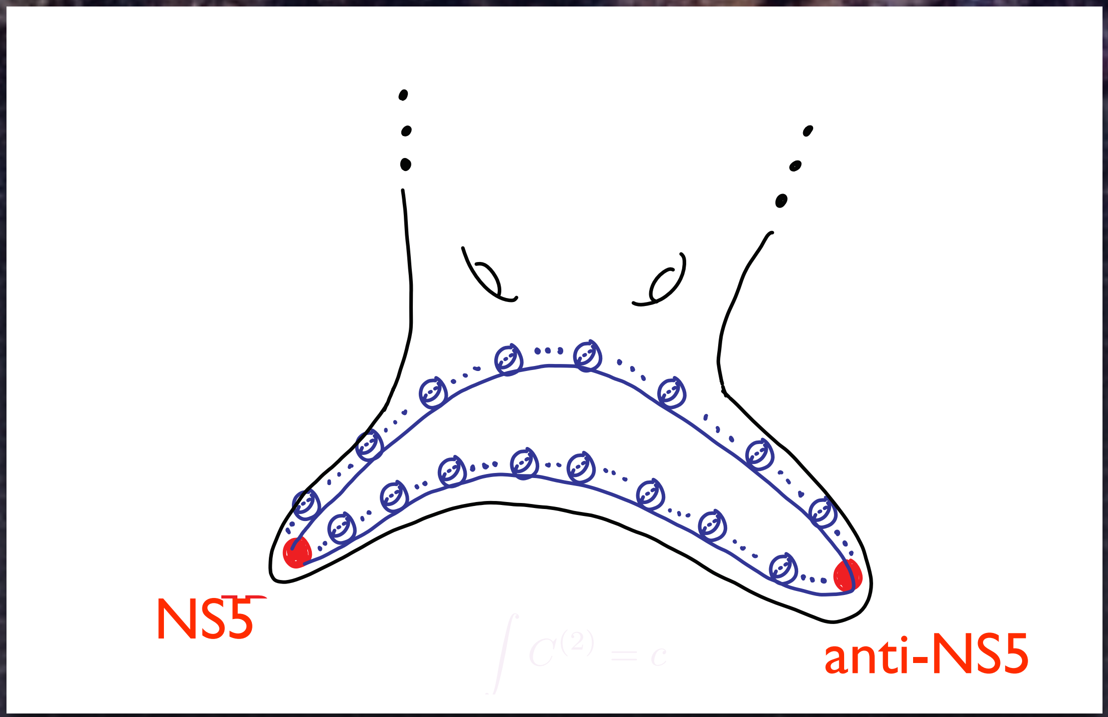
For large field values in terms of the canonically normalized fields the potential then becomes

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

Axion Monodromy Inflation

Basic setup

- 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

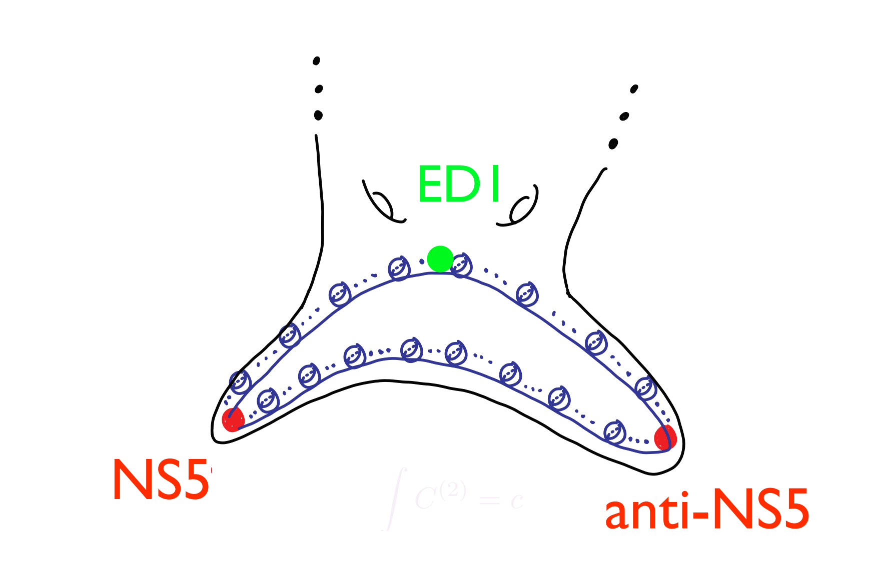
$$p = \tfrac{2}{3}, 1, \tfrac{4}{3}, 2, 3$$

(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

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

(see Alexander's talk)

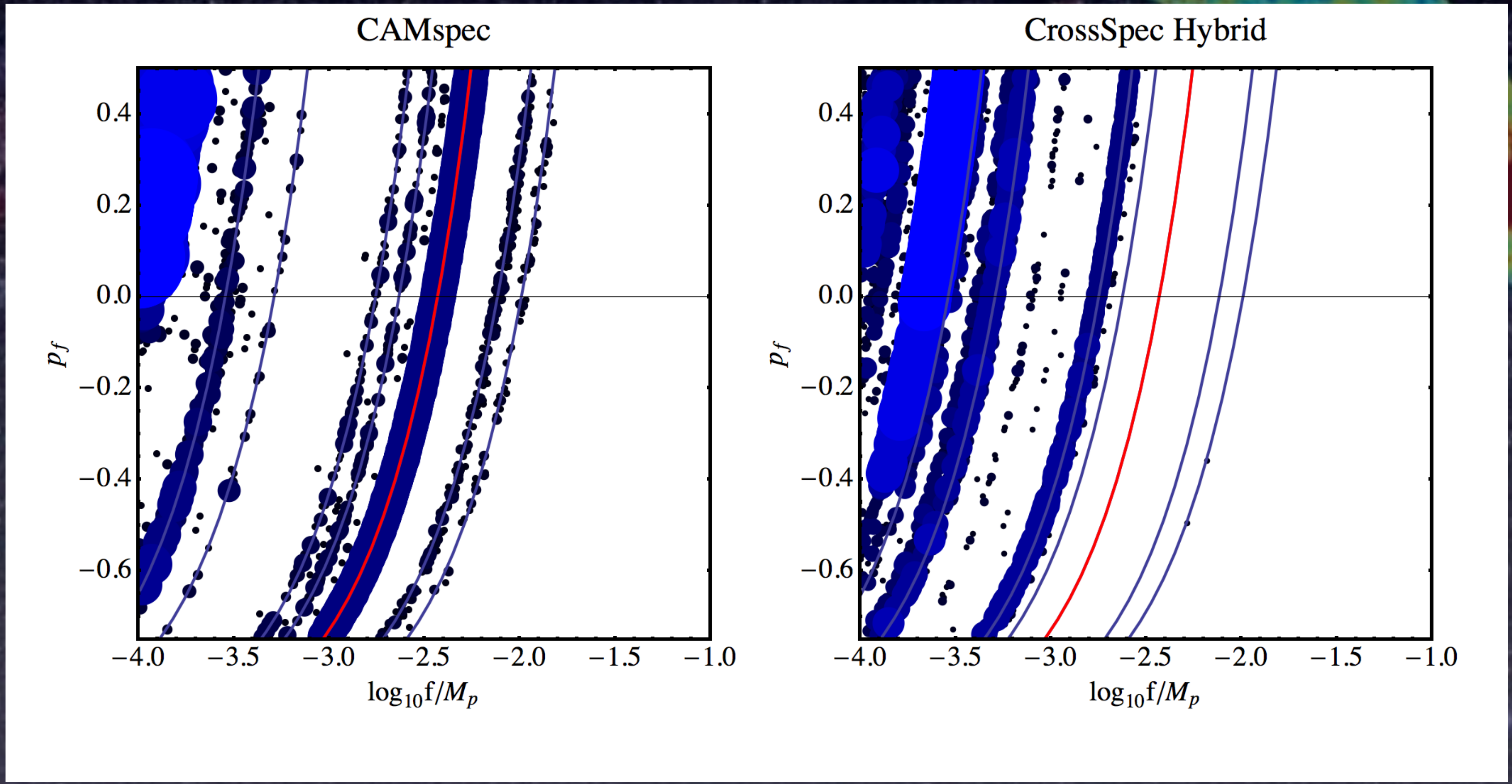
This can be shown to lead to a power spectrum of the form

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

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

Axion Monodromy Inflation

Search for oscillations with drifting period in Planck nominal mission data



Axion Monodromy Inflation

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

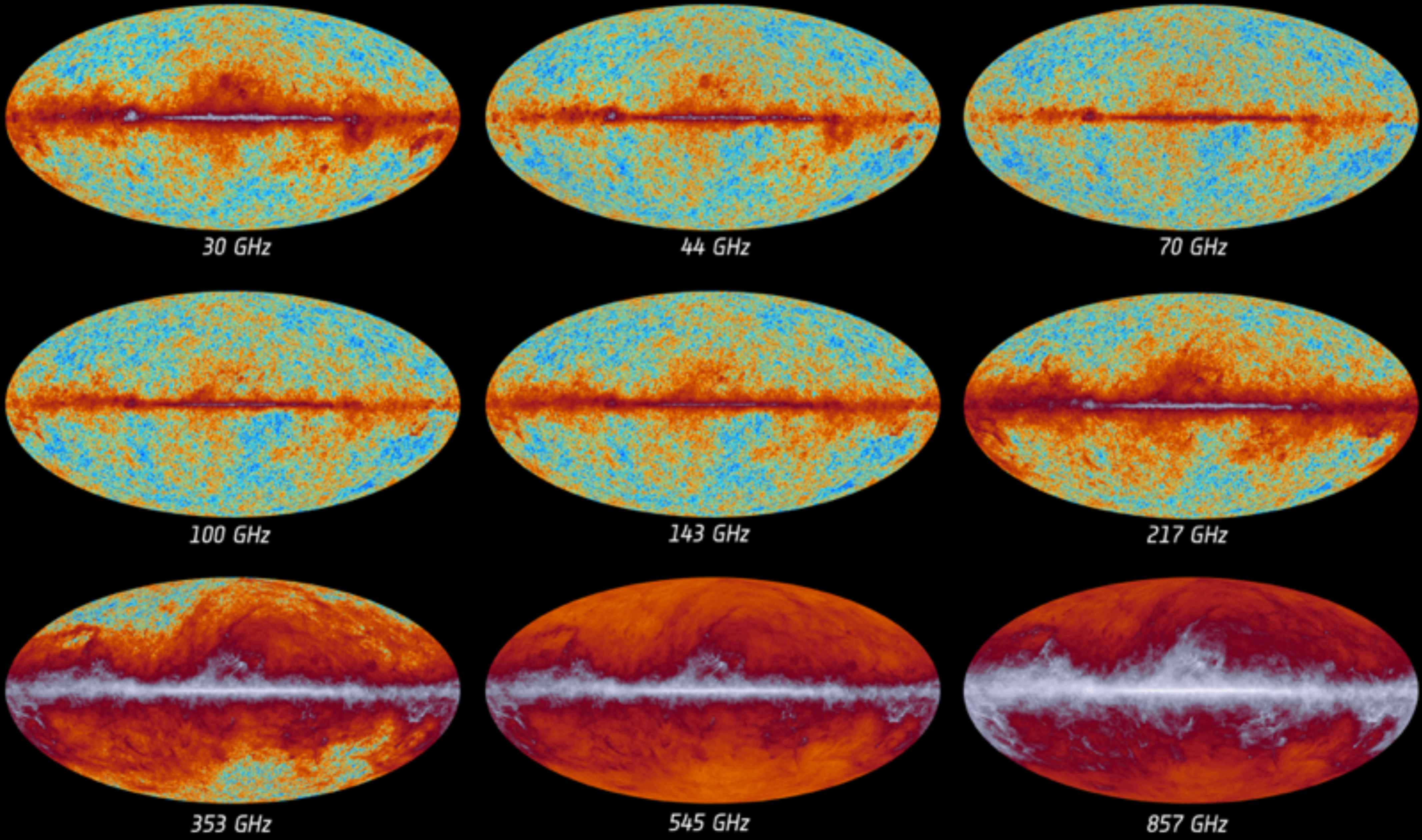
Expectation based on simulations in the absence of a signal: $\Delta\chi^2 = 16.5 \pm 3.5$

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.

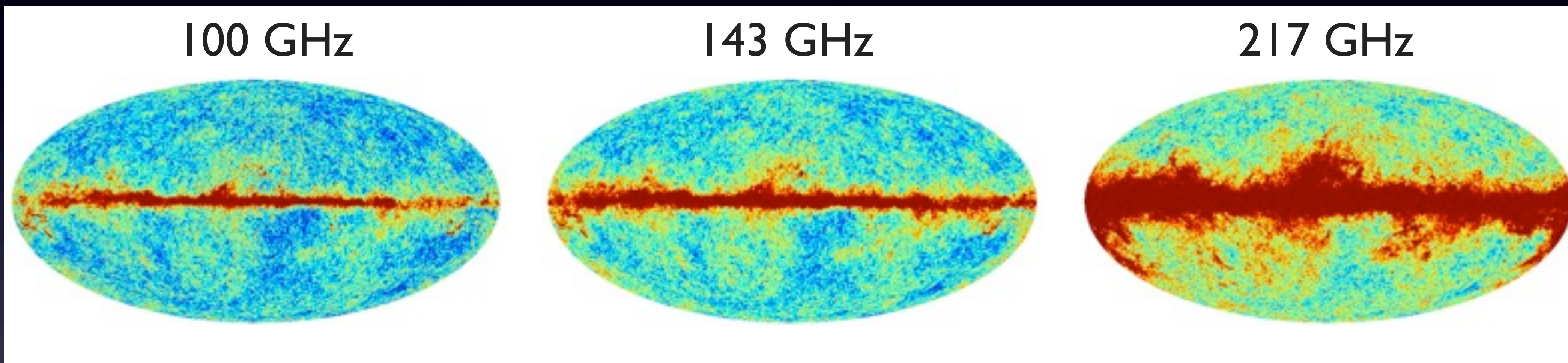
(*) understanding LSS would dramatically improve the constraints

Planck Angular Power Spectrum of Temperature Anisotropies



Planck Power Spectrum

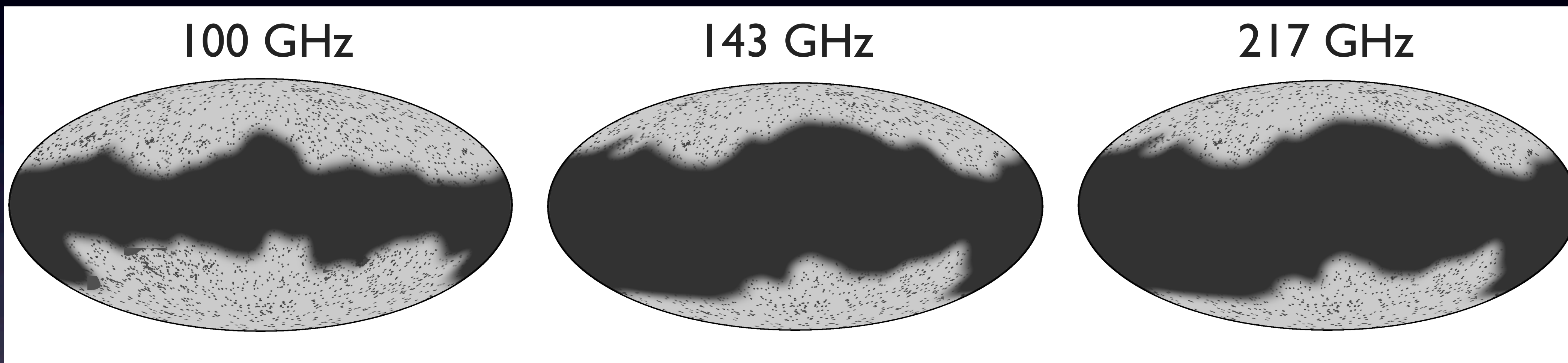
For $\ell > 50$ Planck likelihood function (CAMspec) relies on



- 100x100 detector set spectra up to $\ell = 1200$
- 143x143 detector set spectra up up to $\ell = 2000$
- 143x217 and 217x217 $\ell = 500$ up to $\ell = 2500$

Planck Power Spectrum

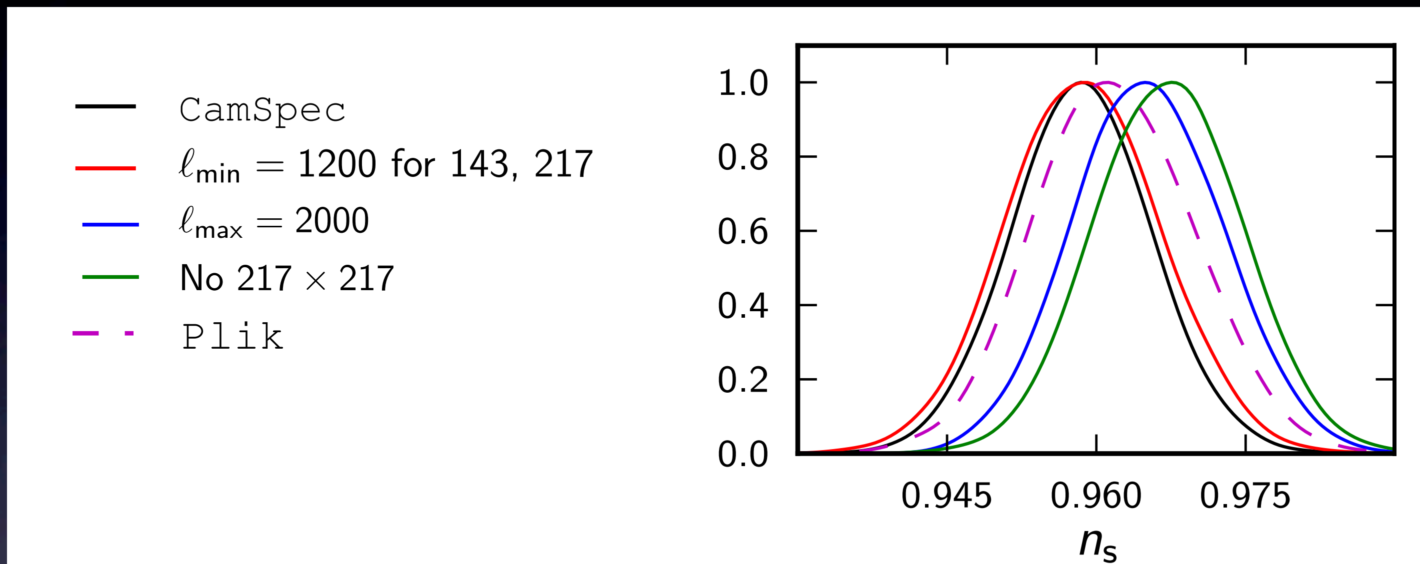
- masks for galactic and point source emission



- template subtraction for diffuse galactic emission for 143 and 217 GHz spectra
- model for extragalactic foregrounds
- analytic, Gaussian approximation for covariance matrix

Motivation for Reanalysis

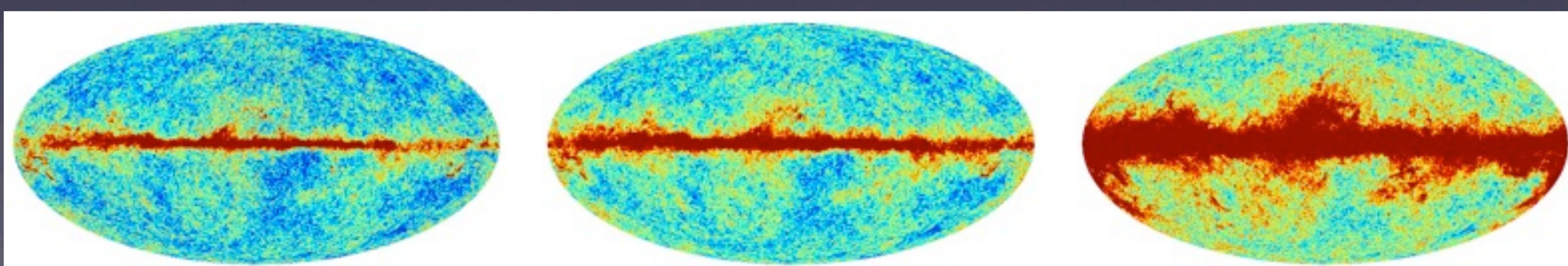
(Planck XVI)



100 GHz

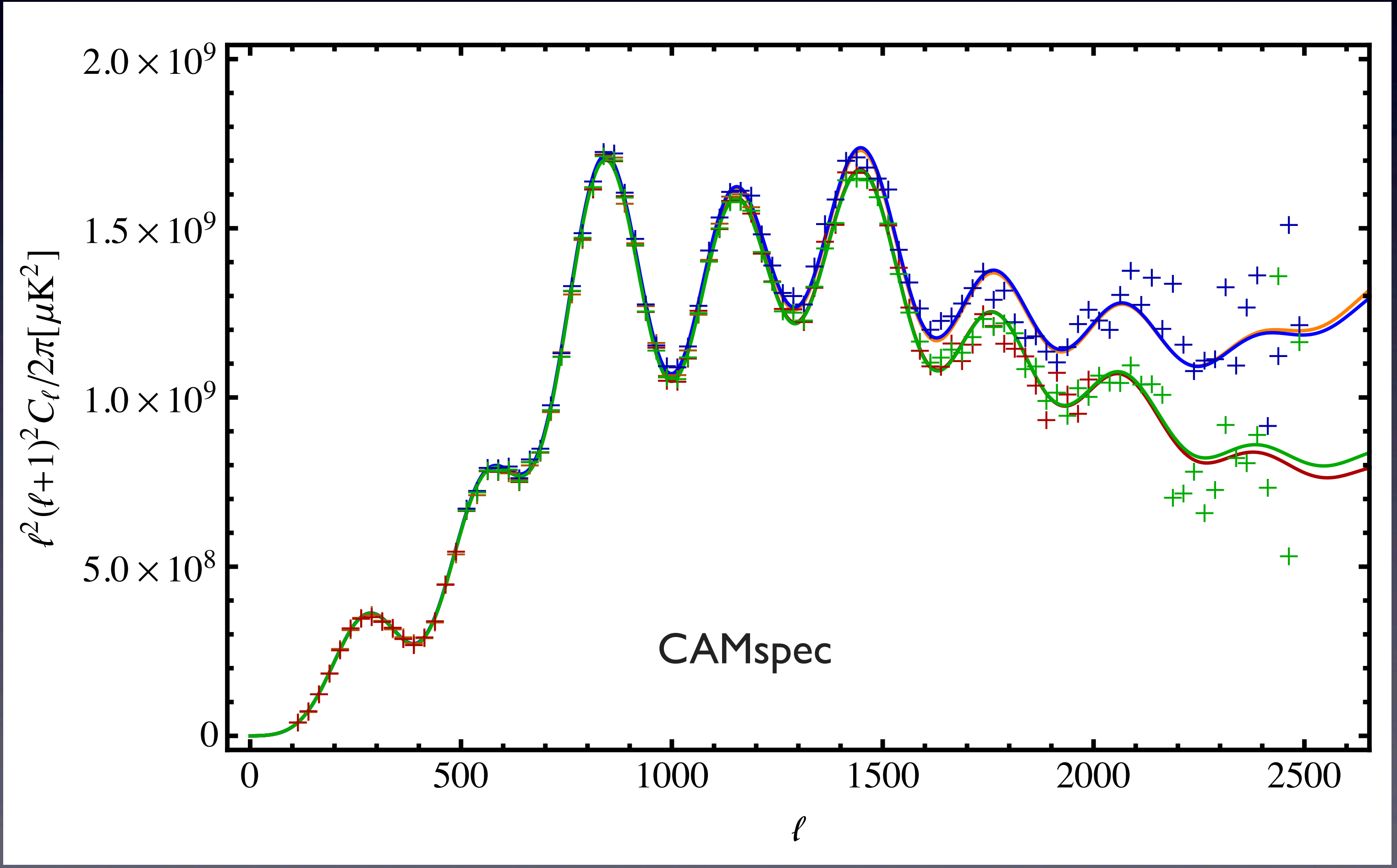
143 GHz

217 GHz



Motivation for Reanalysis

- The 217x217 foreground contribution is significant
- 217x217 shows a dip around $\ell \approx 1800$

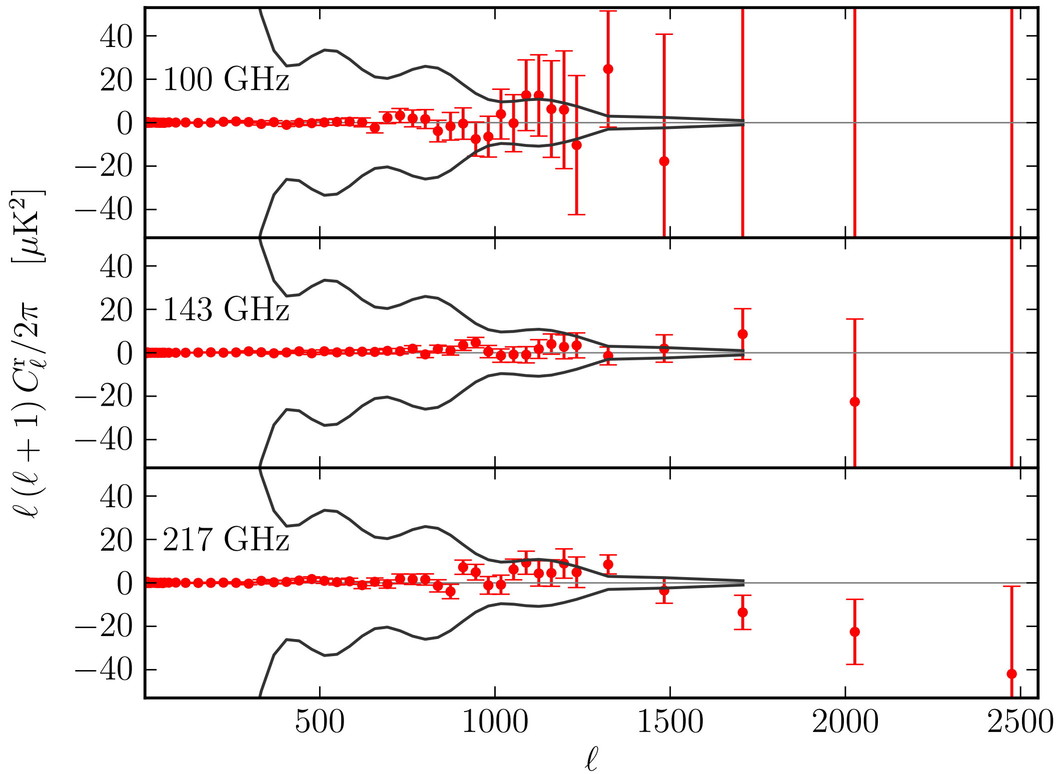


Motivation for Reanalysis

Null-tests provide additional motivation to take a closer look

(Paper VI)

survey 2 - survey 1



In addition to the 217-ds1 × 217-ds2 cross spectrum shown in Fig. 29, only two other cross-spectra fail this test, namely 217-1 × 217-ds2 and 217-1 × 217-3.

Motivation for Reanalysis

Is 217x217 consistent with the other frequencies?

Use Planck covariance matrix to compute

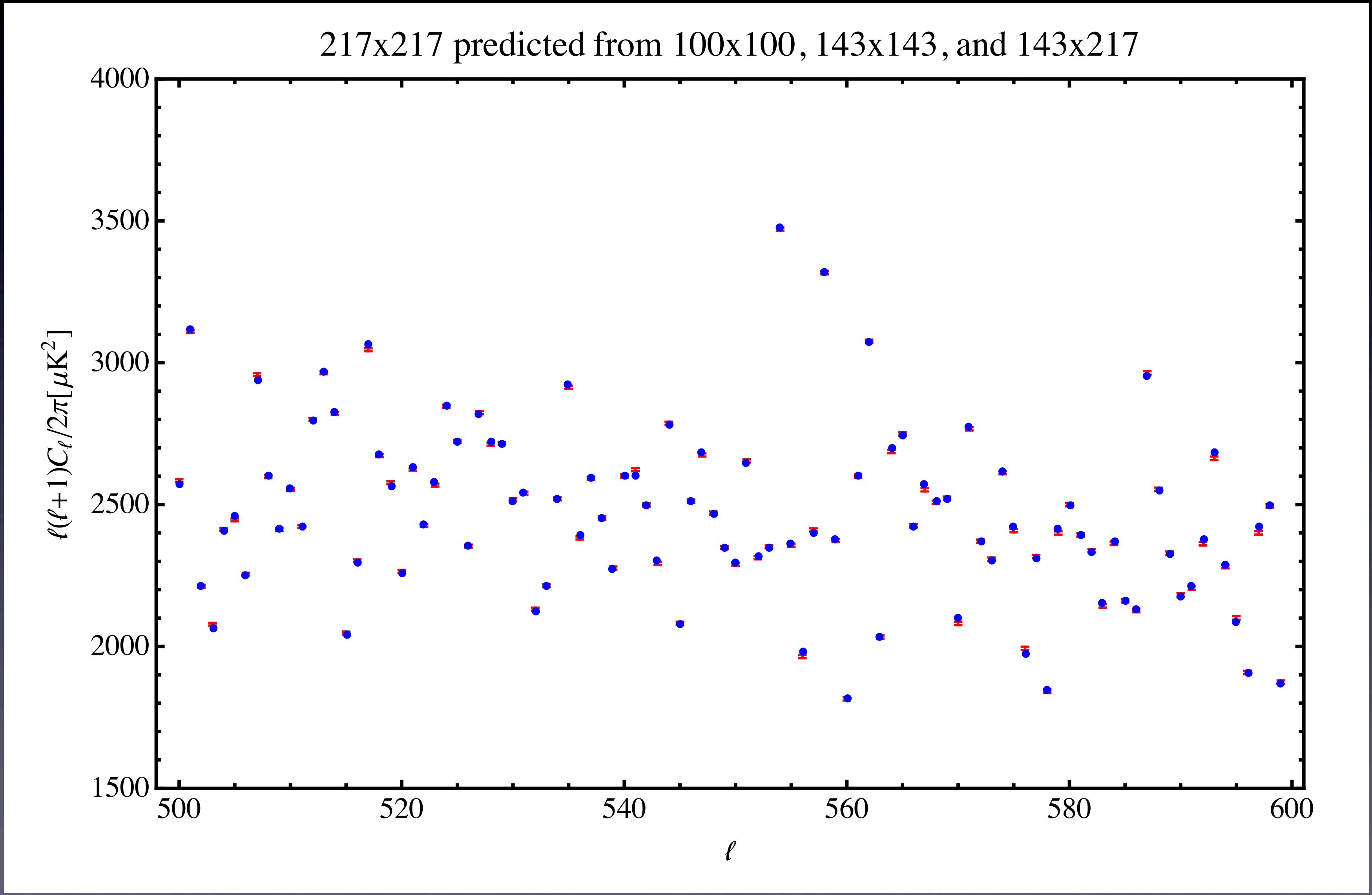
$$P(C_\ell^{217\times 217} | \{C_\ell^{100\times 100}, C_\ell^{143\times 143}, C_\ell^{143\times 217}\})$$

and $\langle C_\ell^{217\times 217} \rangle_{\{C_\ell^{100\times 100}, C_\ell^{143\times 143}, C_\ell^{143\times 217}\}}$

to predict the spectrum

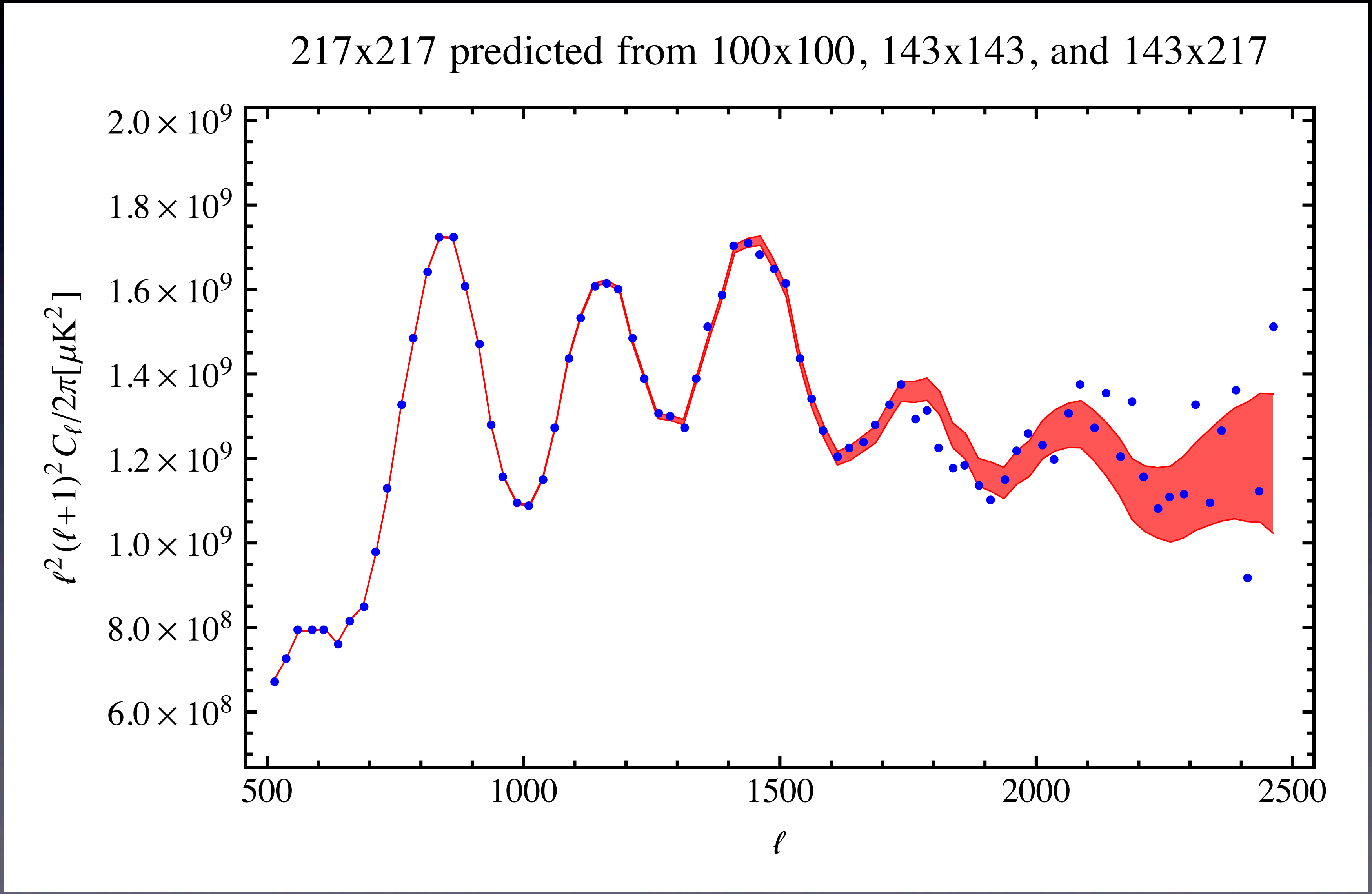
Motivation for Reanalysis

Predicted versus measured 217x217 spectrum



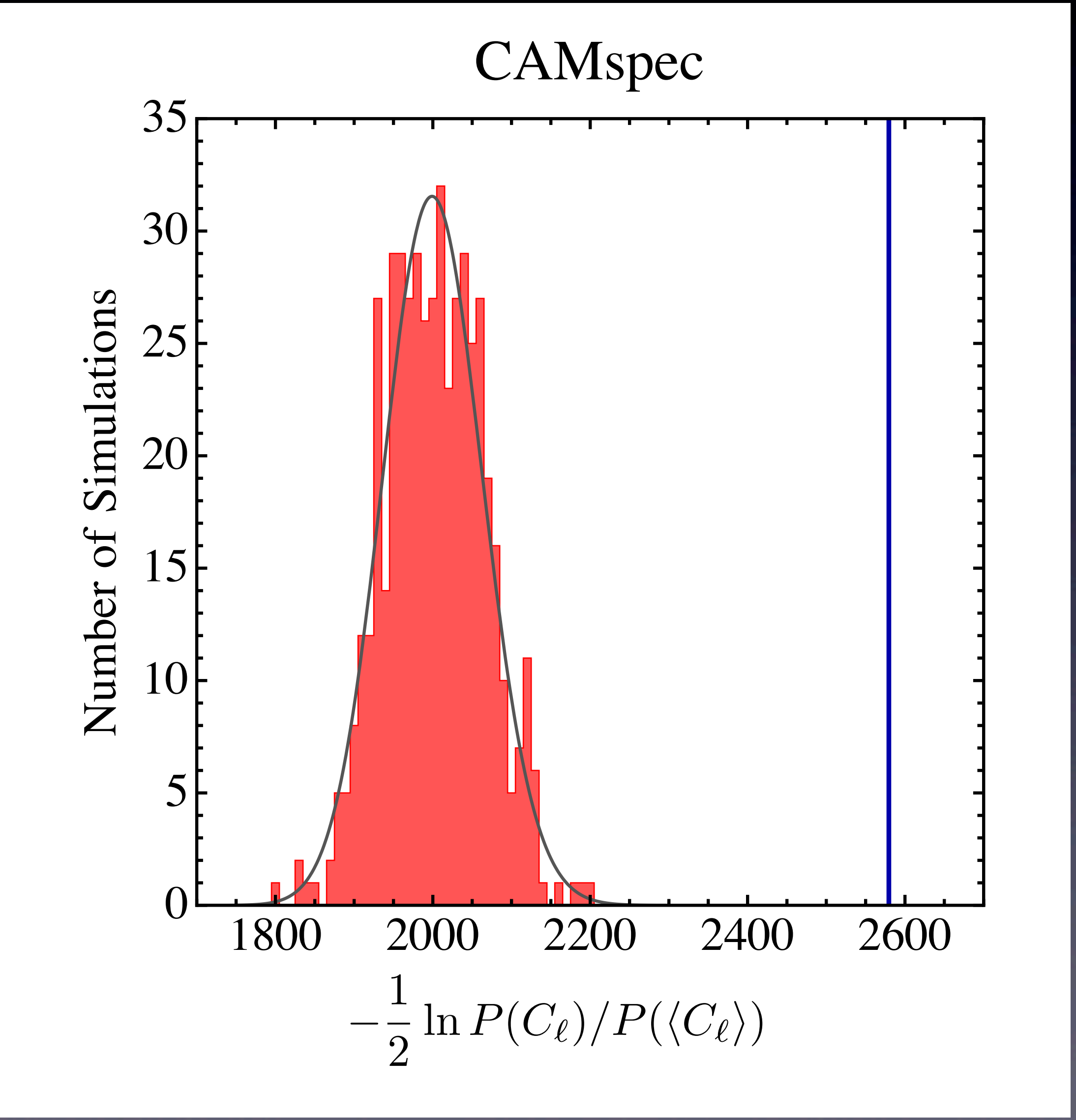
Motivation for Reanalysis

Predicted versus measured 217x217 spectrum



Motivation for Reanalysis

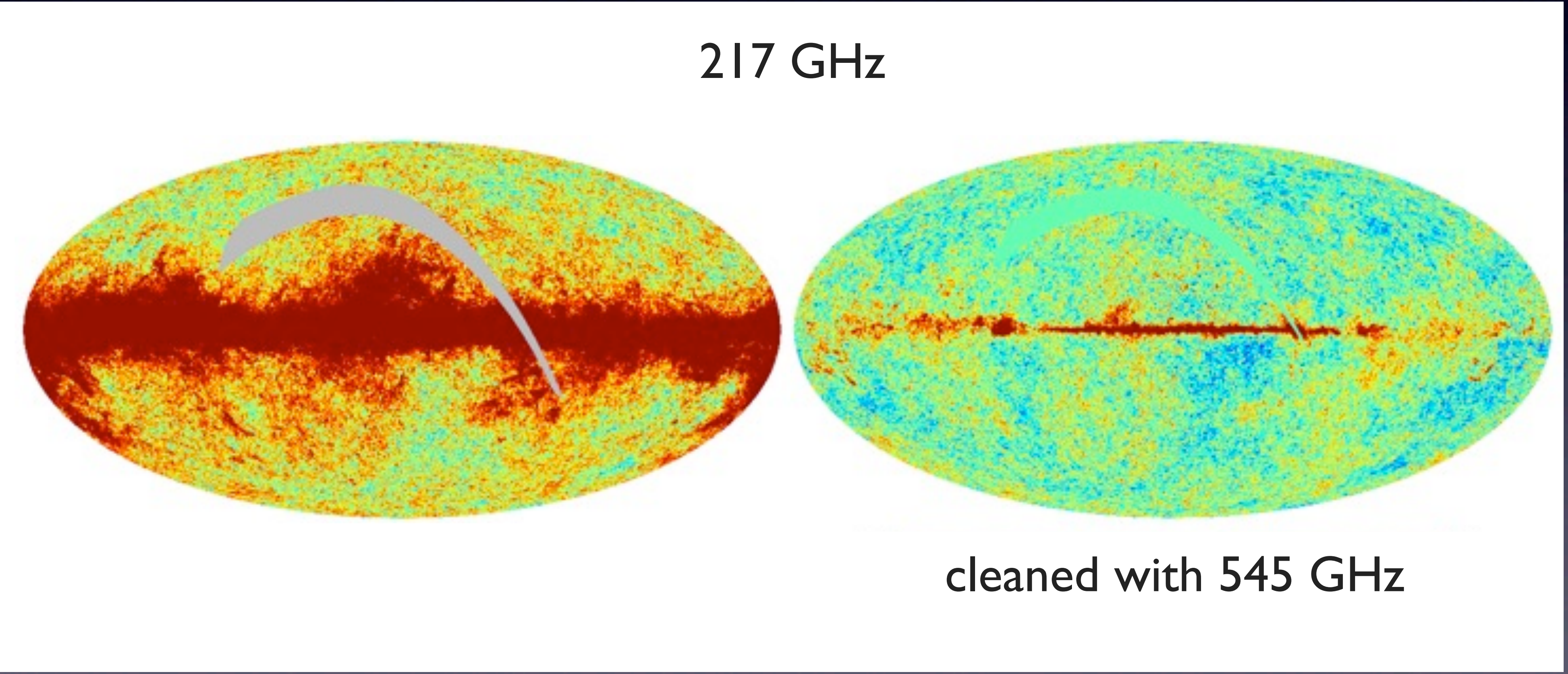
Predicted versus measured 217x217 spectrum



Analysis

This motivated us to

- clean the spectra (with 353 and/or 545 GHz)



Analysis

This motivated us to

- clean the spectra (with 353 and/or 545 GHz)

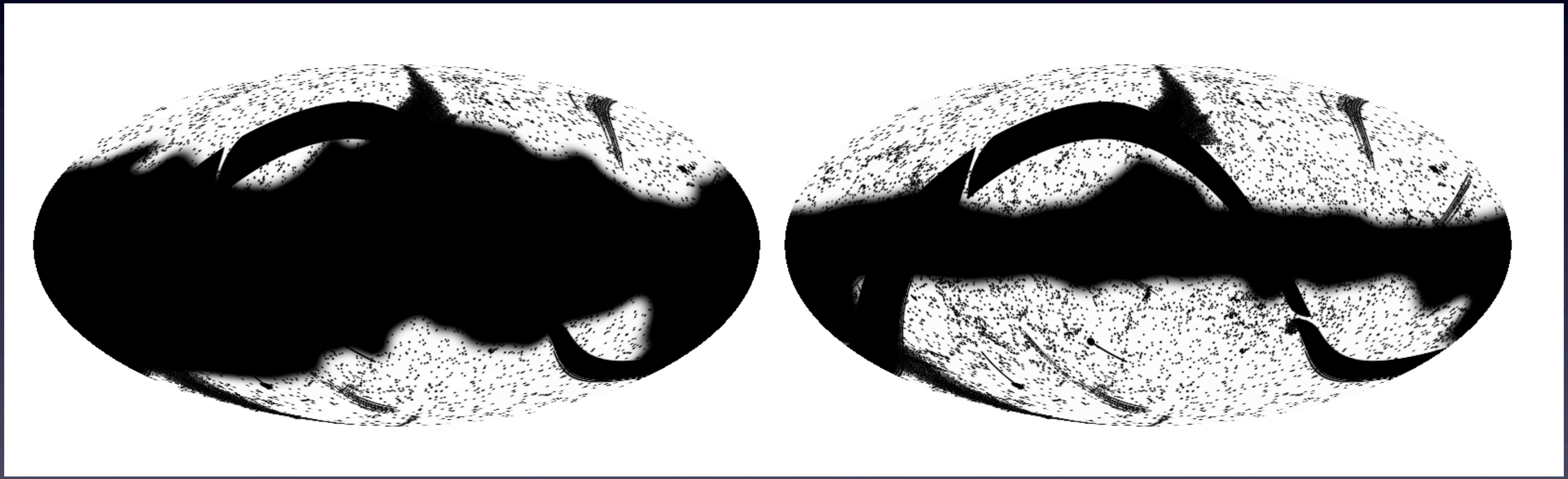
Note that we use survey maps rather than detector sets (because detector set maps are not public)

For the covariance matrix, we use the same approximations as in CAMspec. We need to specify

- the masks
- the noise
- the cleaning procedure

Analysis

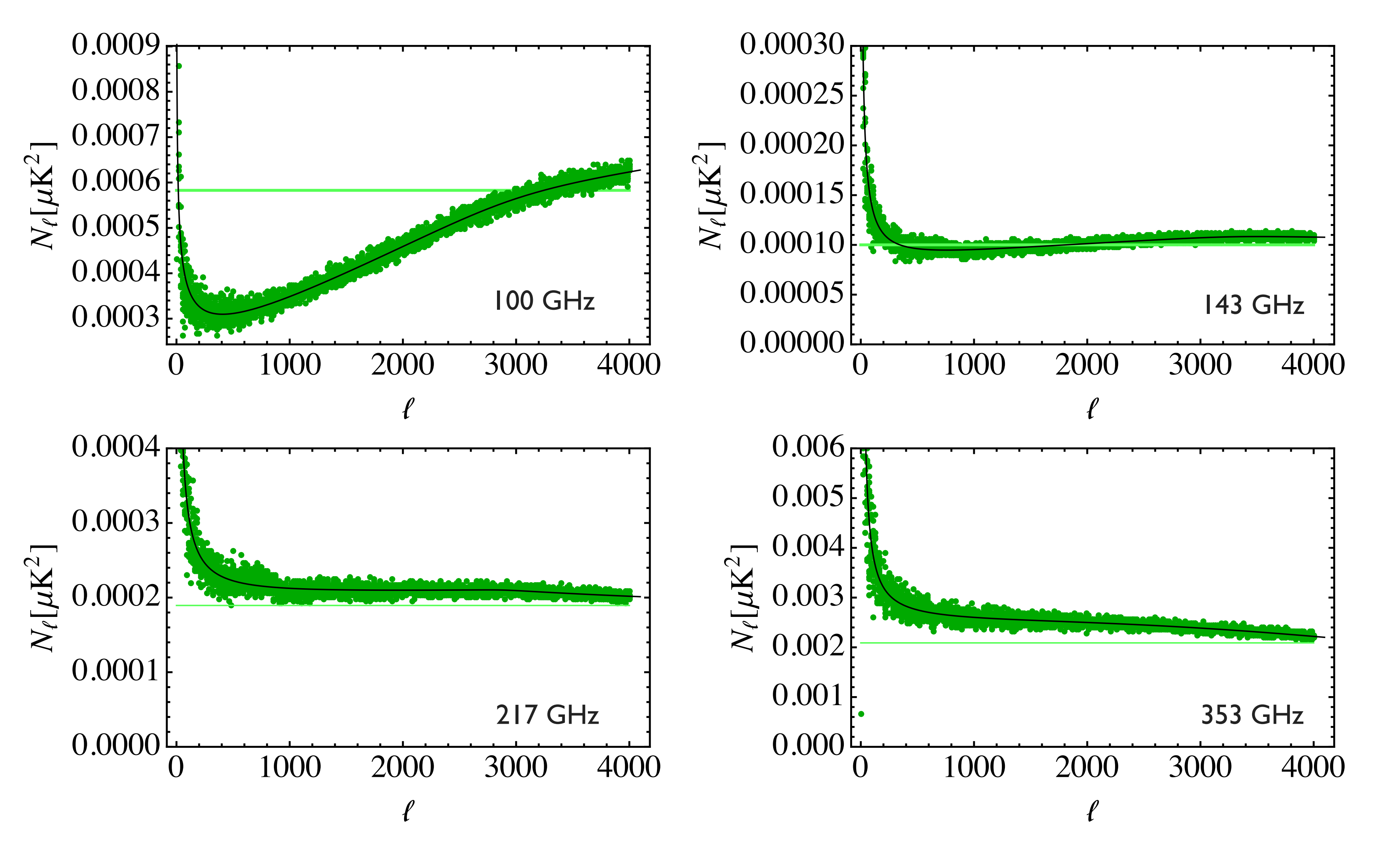
The masks



Cleaning allows us to use significantly more of the sky.

Analysis

Noise from survey differences

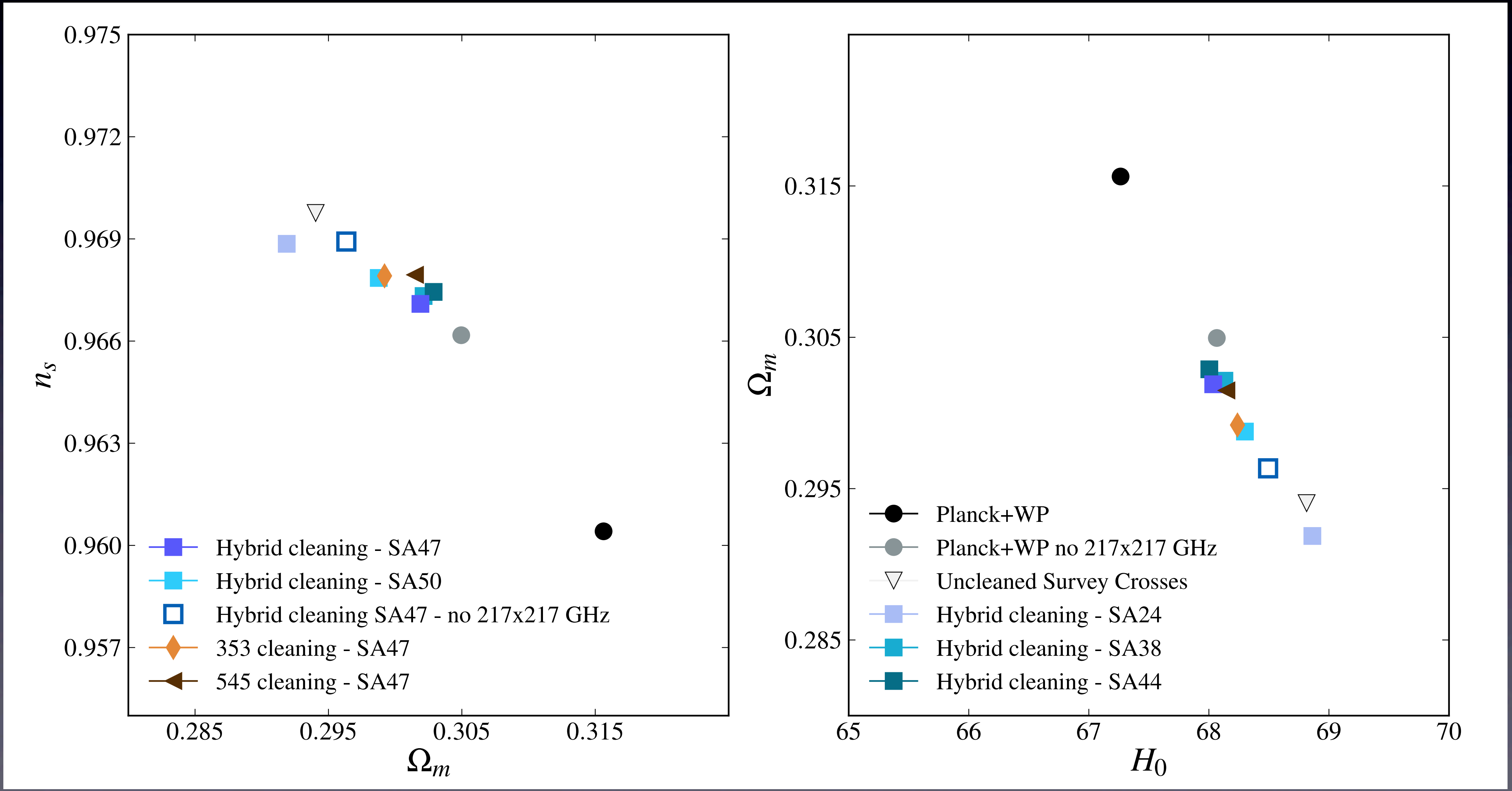


Analysis

The cleaning procedure

- 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 maps
- We do not find strong dependence on mask or treatment of foregrounds

Analysis

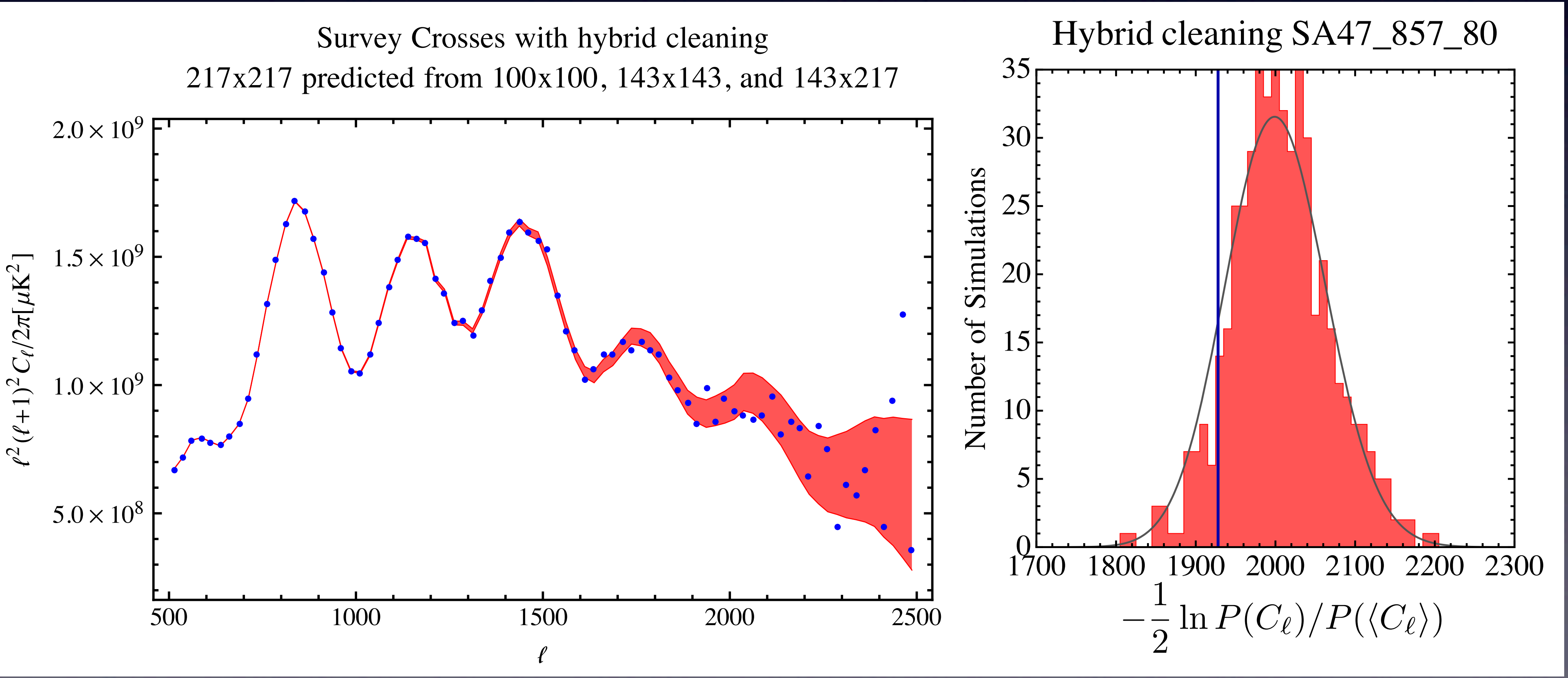


0.975
0.972
0.969
0.966
0.963
0.960
0.957
n_s
0.285
0.295
0.305
0.315
Ω_m
Hybrid cleaning - SA47
Hybrid cleaning - SA50
Hybrid cleaning SA47 - no 217x217 GHz
353 cleaning - SA47
545 cleaning - SA47
0.315
0.305
0.295
0.285
Ω_m
65
66
67
68
69
70
H_0
Planck+WP
Planck+WP no 217x217 GHz
Uncleaned Survey Crosses
Hybrid cleaning - SA24
Hybrid cleaning - SA38
Hybrid cleaning - SA44

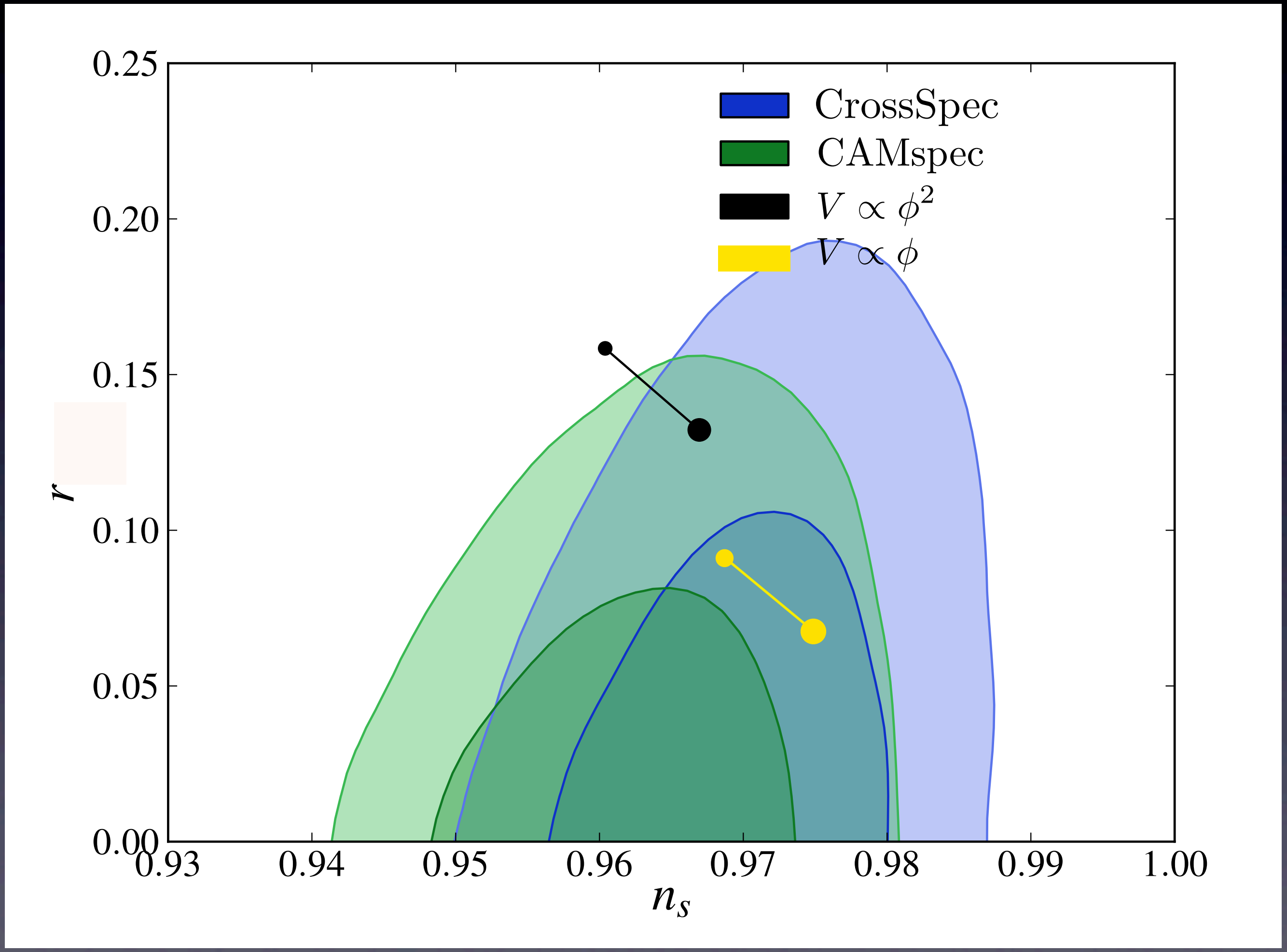
Analysis

Lessons:

- The Planck 2013 foreground model works well
- 217x217 spectra from survey crosses are less affected by systematics and cause smaller shifts than for detector sets



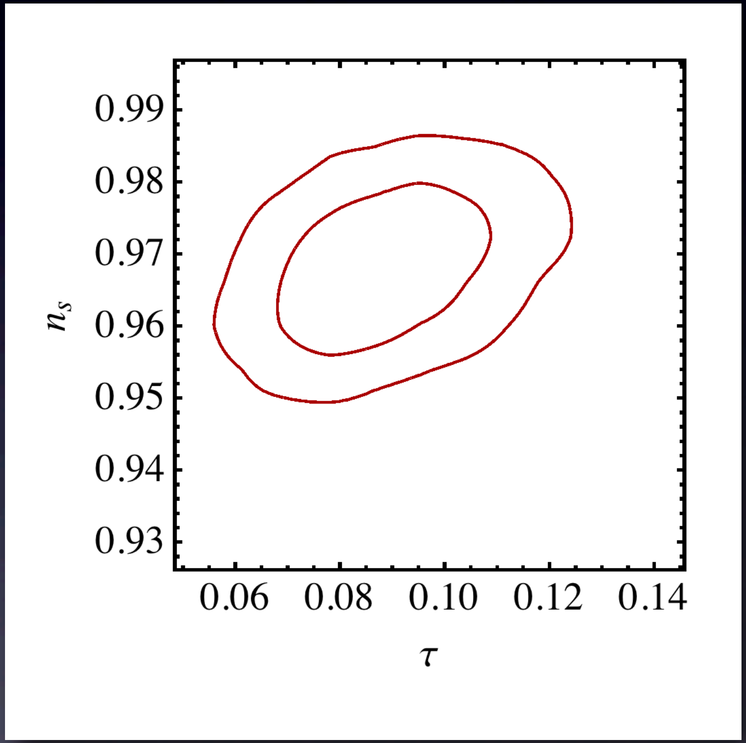
Analysis



0.25
0.20
0.15
0.10
0.05
0.00
r
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00
n_s
CrossSpec
CAMspec
$V \propto \phi^2$
$V \propto \phi$

Comments on Optical Depth

When discussing the spectral index, one should remember a degeneracy with the optical depth

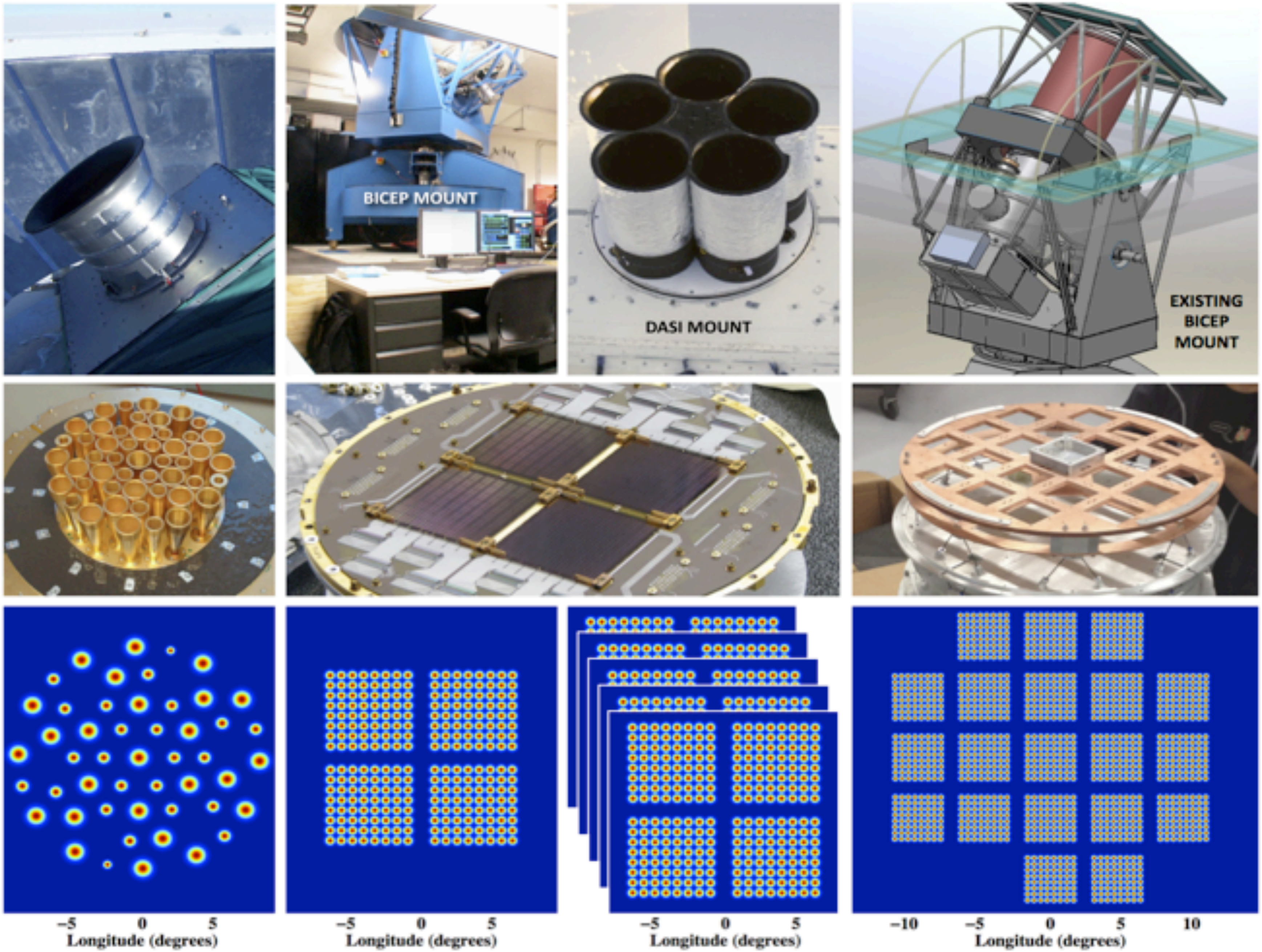


With the new prior on the optical depth we find

$$n_s = 0.9657 \pm 0.0066$$

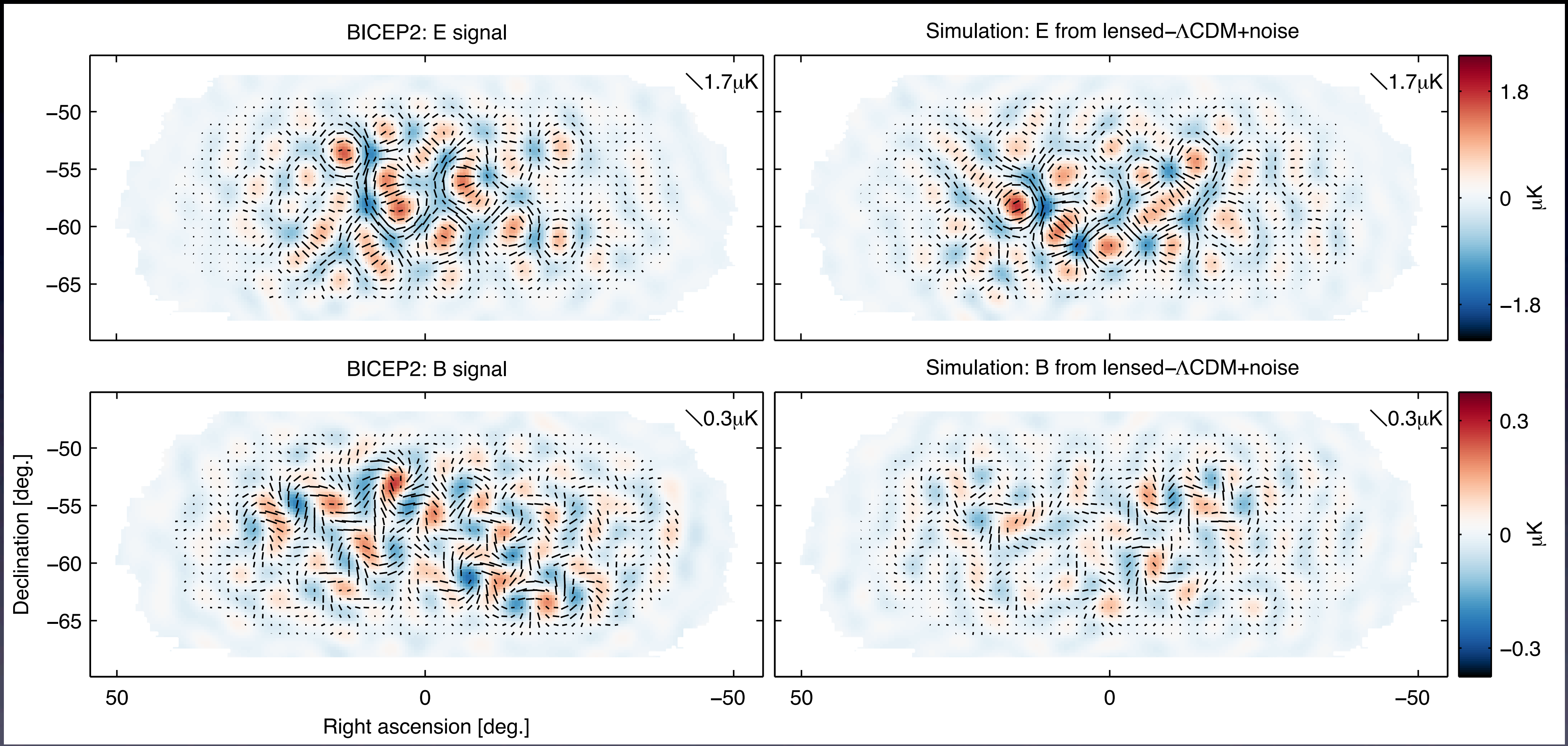
BICEP2

BICEP1 (2006-2008) | **BICEP2 (2010-2012)** | **Keck Array (2011-2016)** | **BICEP3 (2015-2016)**



98 NTDs (95/150 GHz)	512 TESs (150 GHz)	2560 TESs (150 GHz)	2560 TESs (95 GHz)
0.93°/0.60° FWHM	0.52° FWHM		0.37° FWHM
18° FOV	17° FOV		26° FOV
44 m² deg² AΩ	44 m² deg² AΩ	222 m² deg² AΩ	502 m² deg² AΩ optical throughput

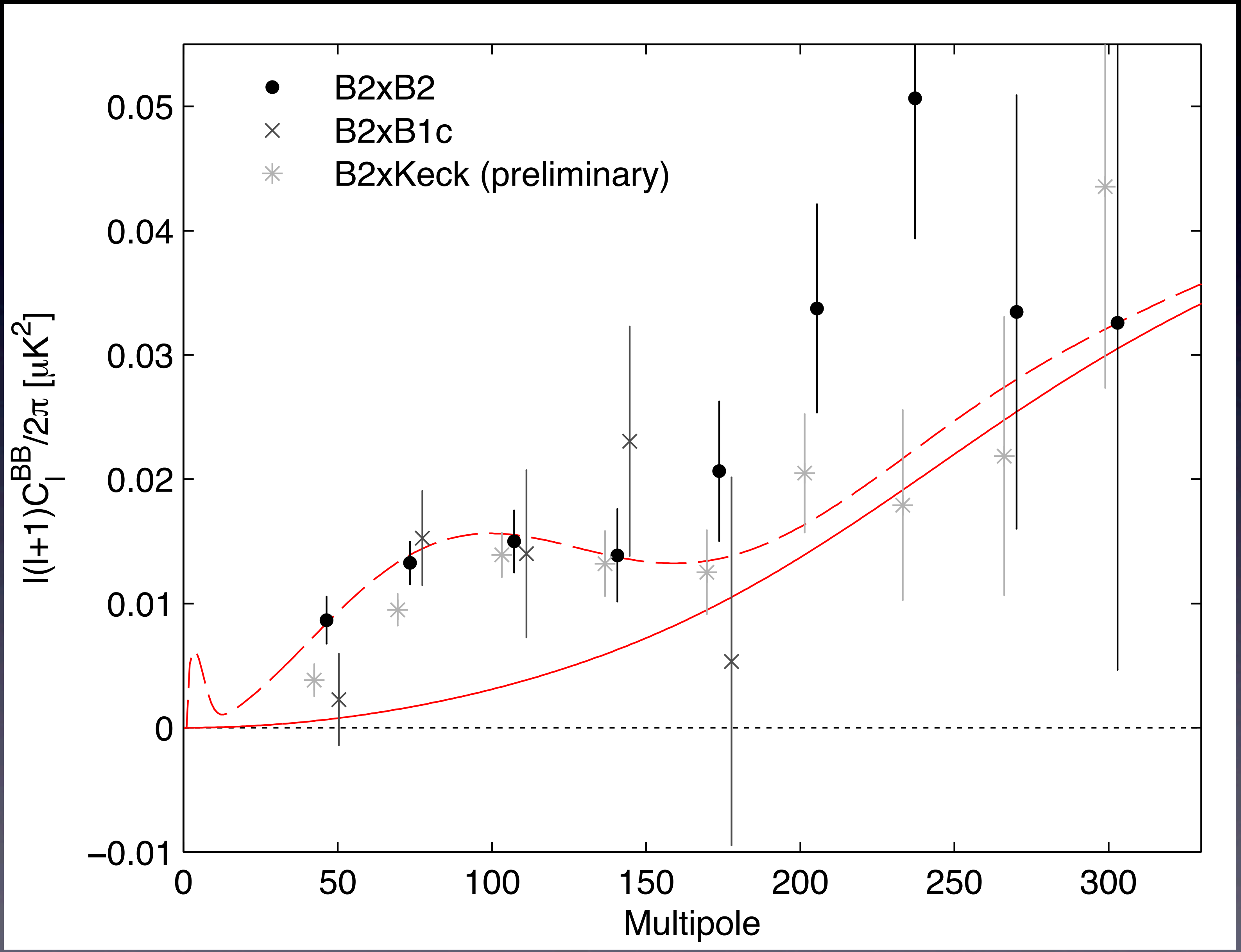
BICEP2 Polarization Data



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

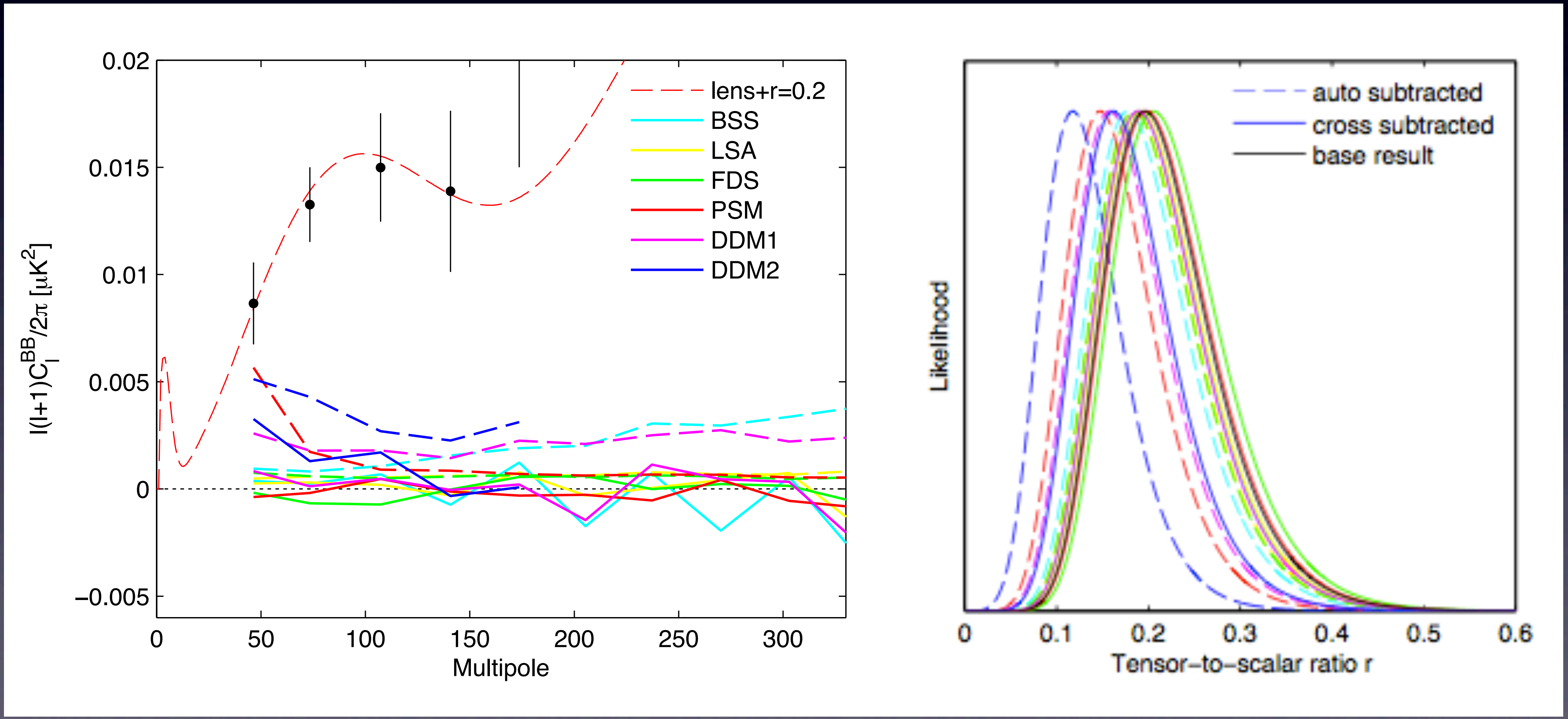
(Planck noise level: few μK deg)

BICEP2 Polarization Data



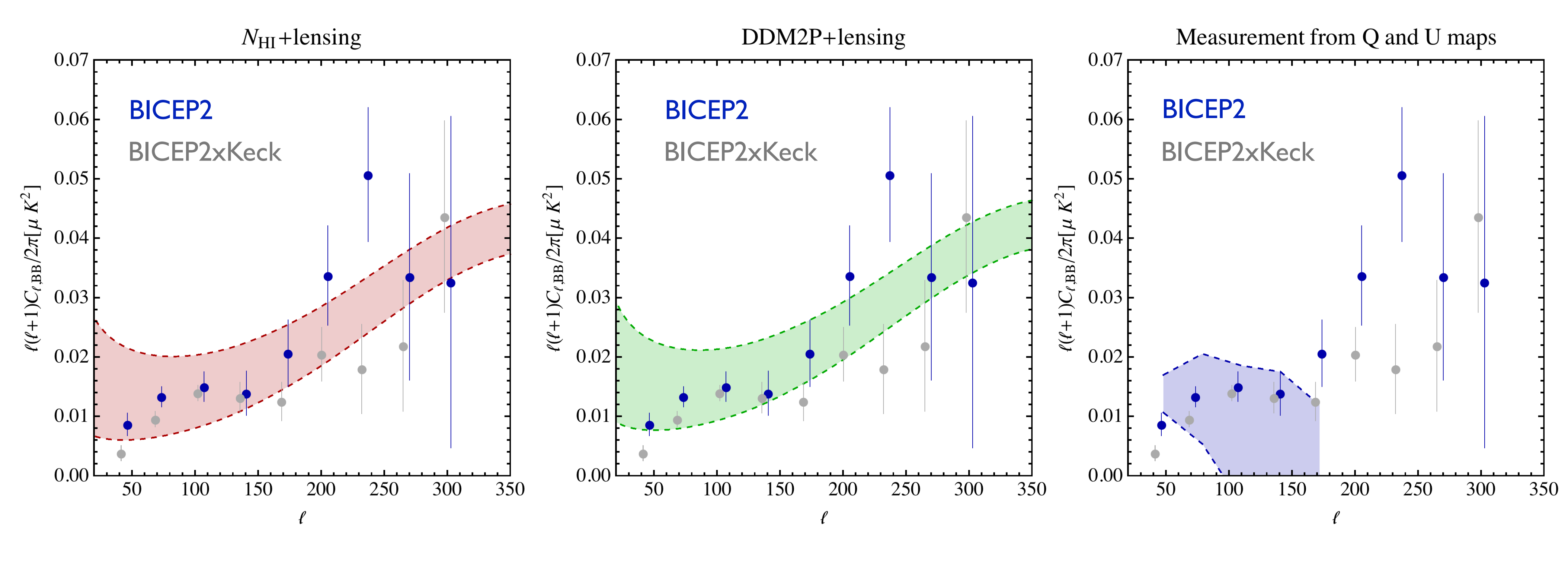
BICEP2 Polarization Data

Foreground models initially presented by BICEP



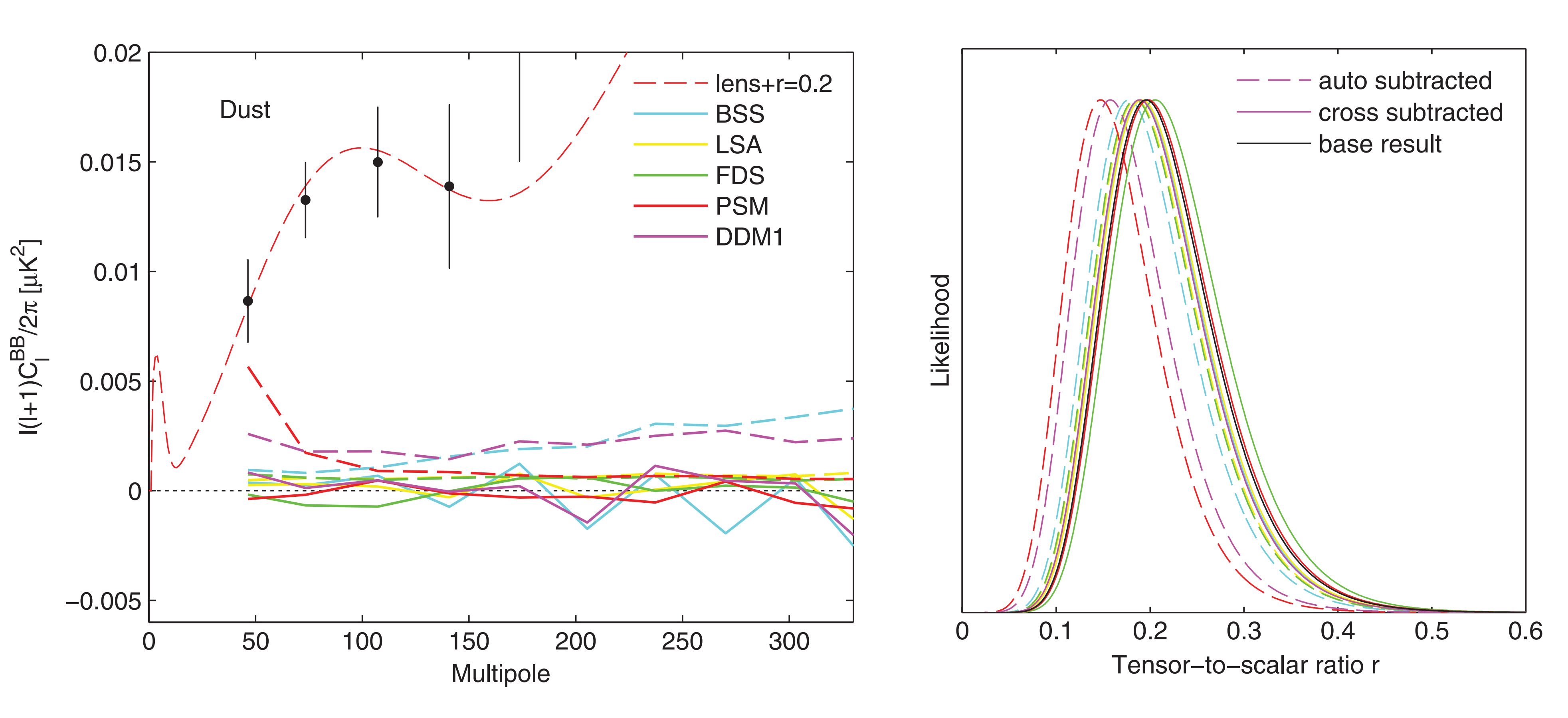
BICEP2 Polarization Data

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



BICEP2 Polarization Data

As a result, in the published version the figure changed to



Note on foreground models

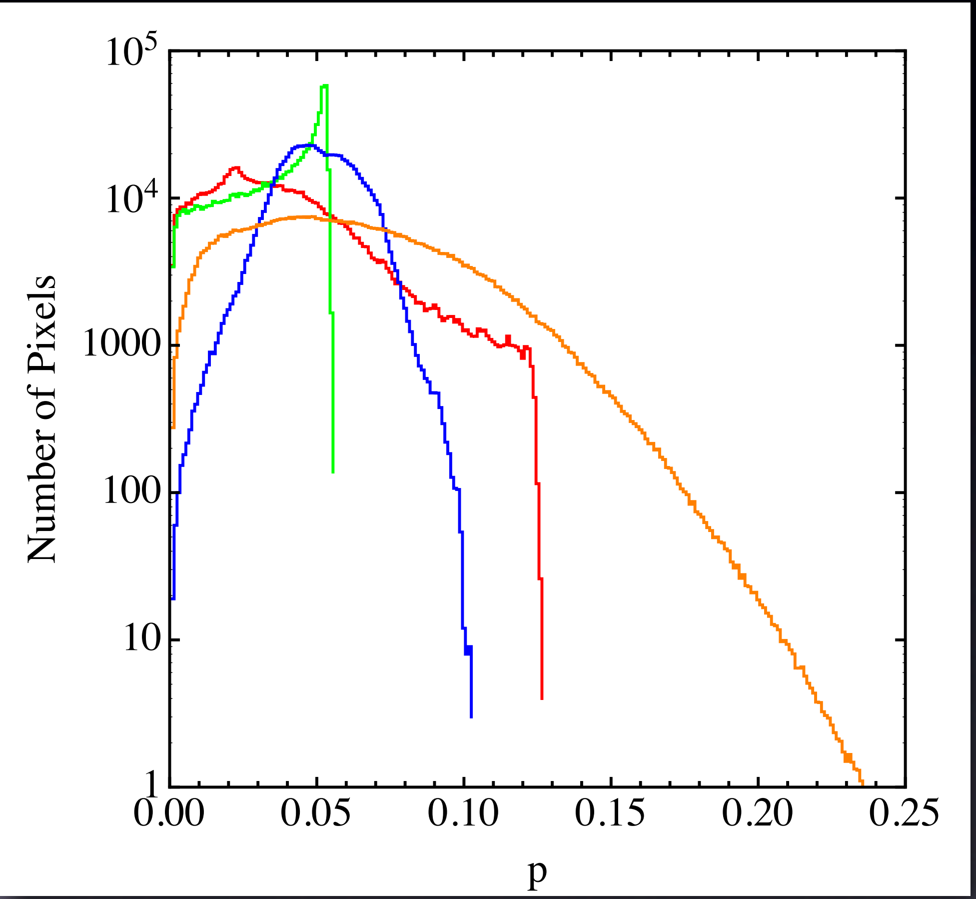
Models for polarized foreground need three ingredients, typically

- Intensity map
- Polarization fraction*
- Polarization angles

$$Q(\hat{n}) = p(\hat{n})I(\hat{n})\cos(\psi(\hat{n}))$$

$$U(\hat{n}) = p(\hat{n})I(\hat{n})\sin(\psi(\hat{n}))$$

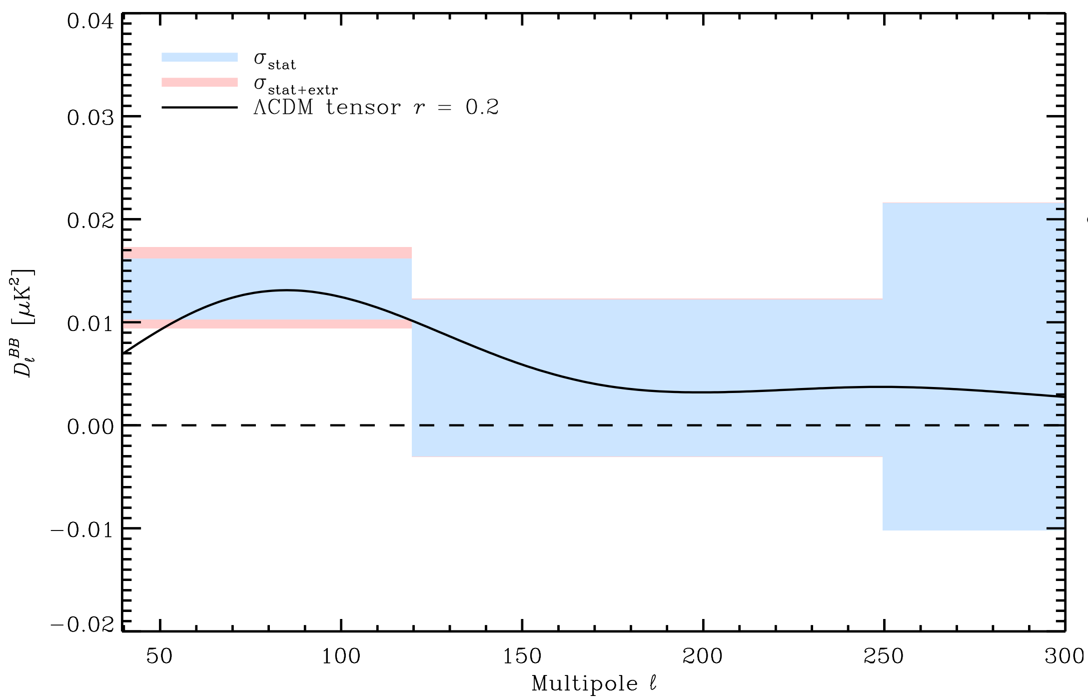
*Until measured, the average polarization fraction is essentially a free parameter

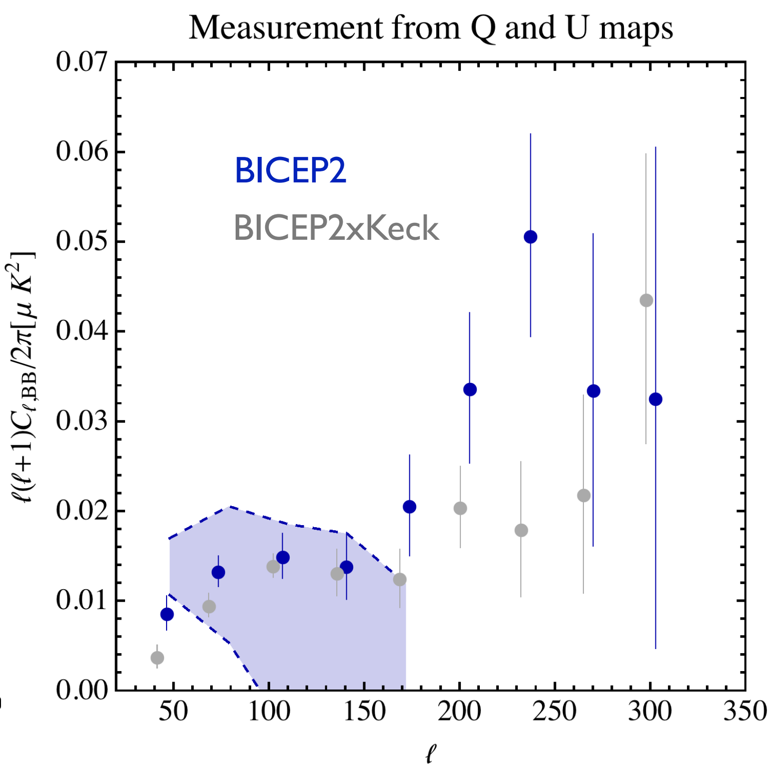


The real sky does not look like LSA, BSS, or PSM models

Planck 353 GHz Polarization Data

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





$$D_\ell^{BB} = 1.32\times10^{-2}\,\mu\mathrm{K}^2_{\mathrm{CMB}}$$

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.

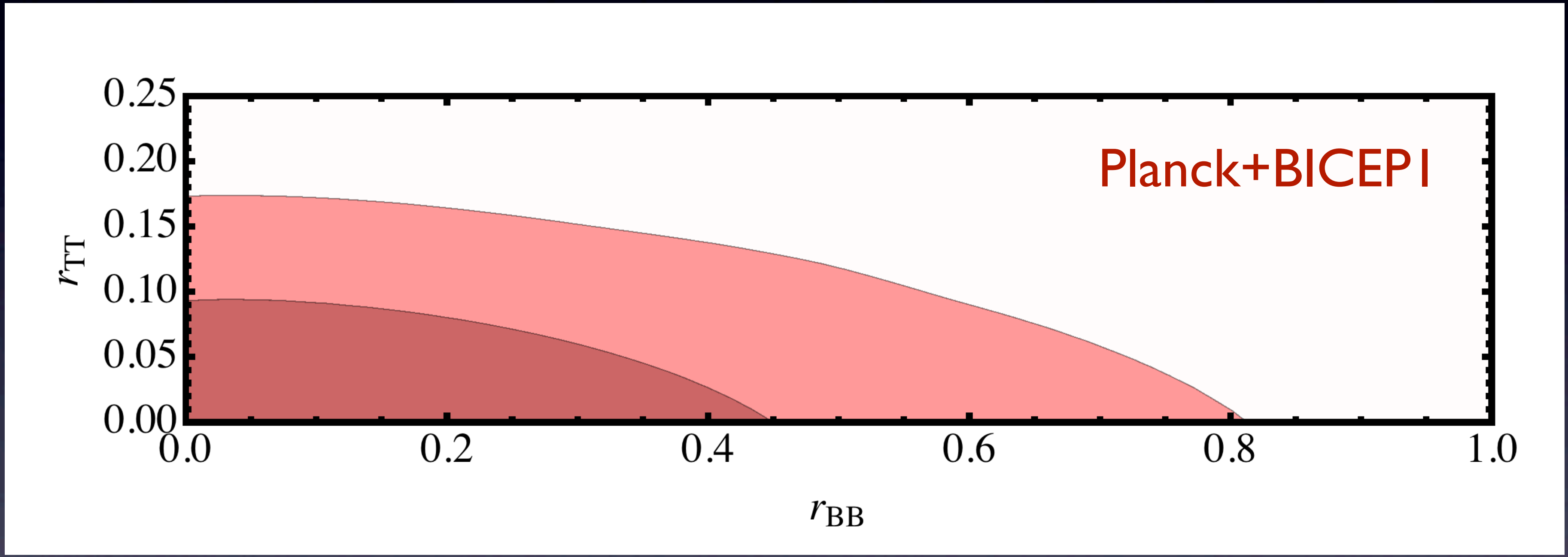
The two likelihood are essentially independent

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

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

Experimental Progress

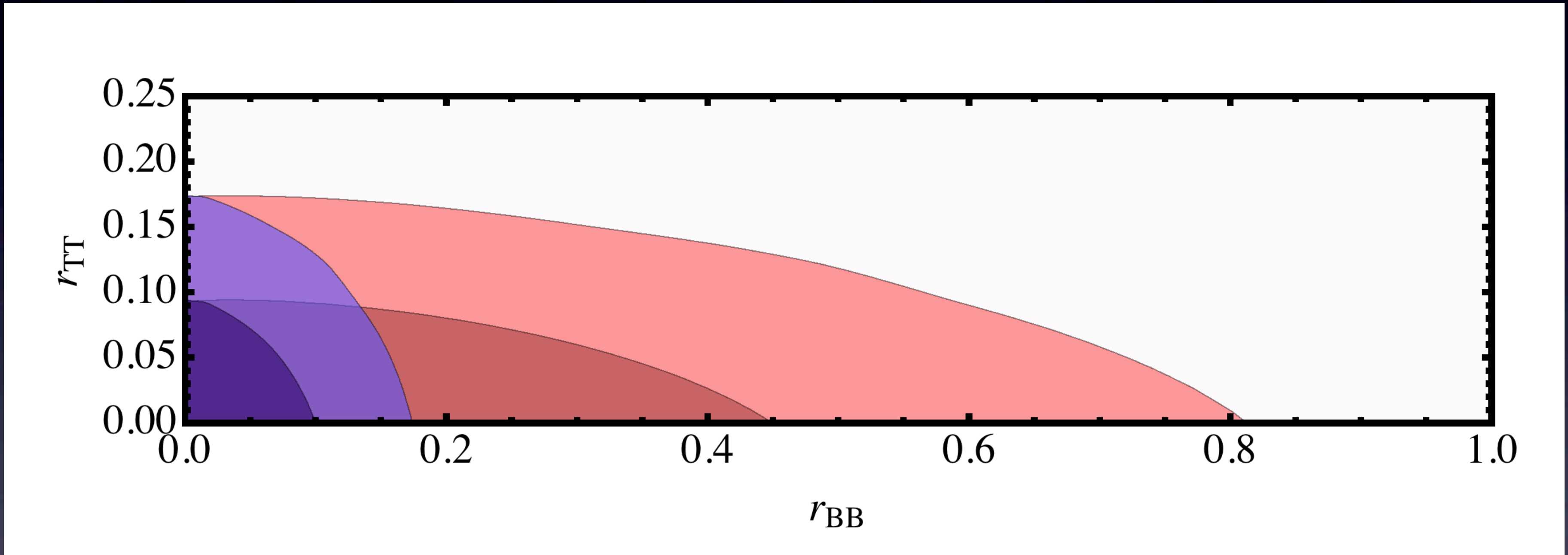
$\mathcal{L}(r_{TT}, r_{BB})$ before March



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 (r~0.001 in a decade)

Joint Analysis

I will combine

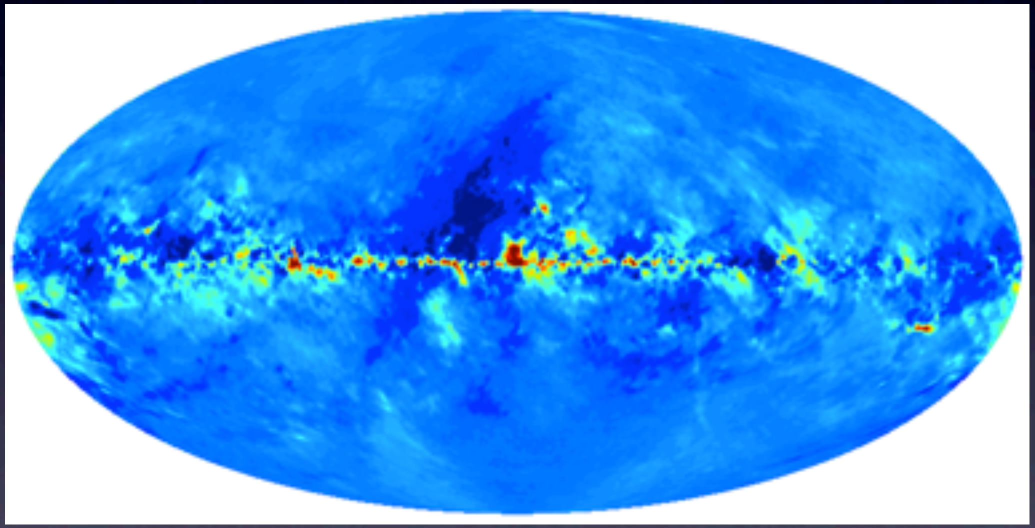
- BICEP2 BB power spectrum
- Planck 353 GHz BB power spectrum
- Planck temperature anisotropies

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

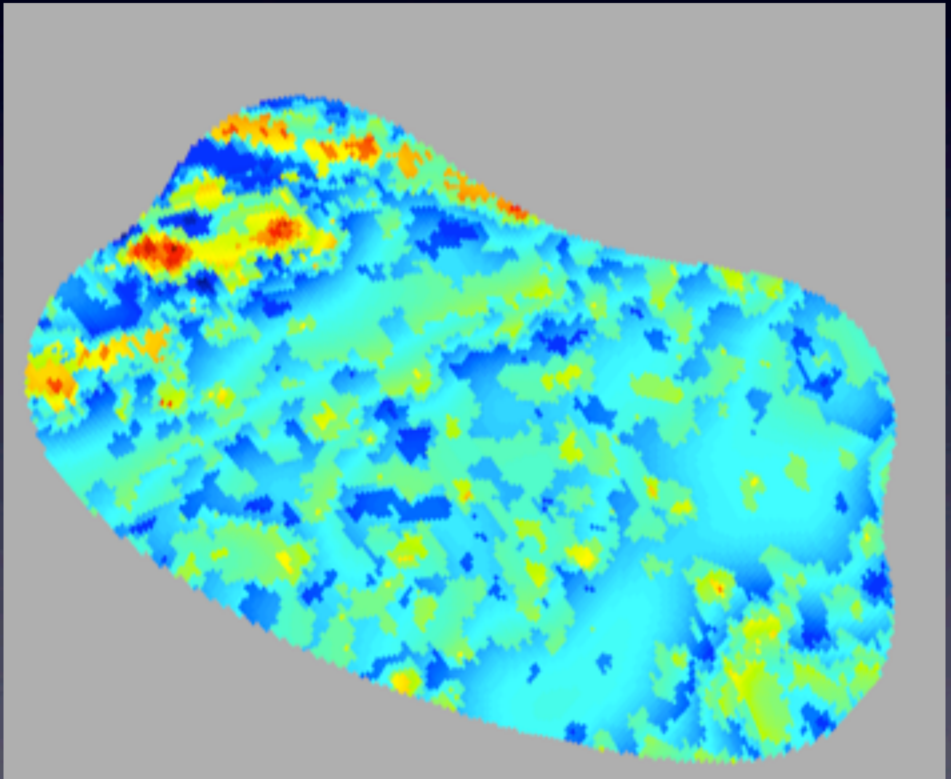
BICEP2 and Planck 353 GHz are not independent and we need a joint likelihood.

Joint Analysis

Ideally, one should include the cross spectrum between BICEP2 and Planck as well as additional Planck polarization data, but these are not public.



I will not include the cross-spectra from the digitized maps because of their obvious shortcomings



filtered

Joint Analysis

For simplicity consider a Gaussian approximation to the likelihood

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

$$\exp\left[-\frac{1}{2}(\Delta^{(P)}\,\Delta^{(B)})\begin{pmatrix} \mathcal{C}_P & \mathcal{C}_i \\ \mathcal{C}_i & \mathcal{C}_{ij} \end{pmatrix}^{-1}\begin{pmatrix} \Delta^{(P)} \\ \Delta^{(B)} \end{pmatrix}\right]$$

$$\Delta^{(P)} = C^{(P)} - C_{\mathrm{dust}}$$

$$\Delta^B_i = C^{(B)}_i - C_{\mathrm{dust}\,i} - C_{\mathrm{CMB}\,i}$$

Joint Analysis

We can write this as

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

or

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

with

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

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

Joint Analysis

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

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

(accounting for both Planck and BICEP color corrections)

I will show results either

- assuming the patch is typical
- or using only information inside the patch

Joint Analysis

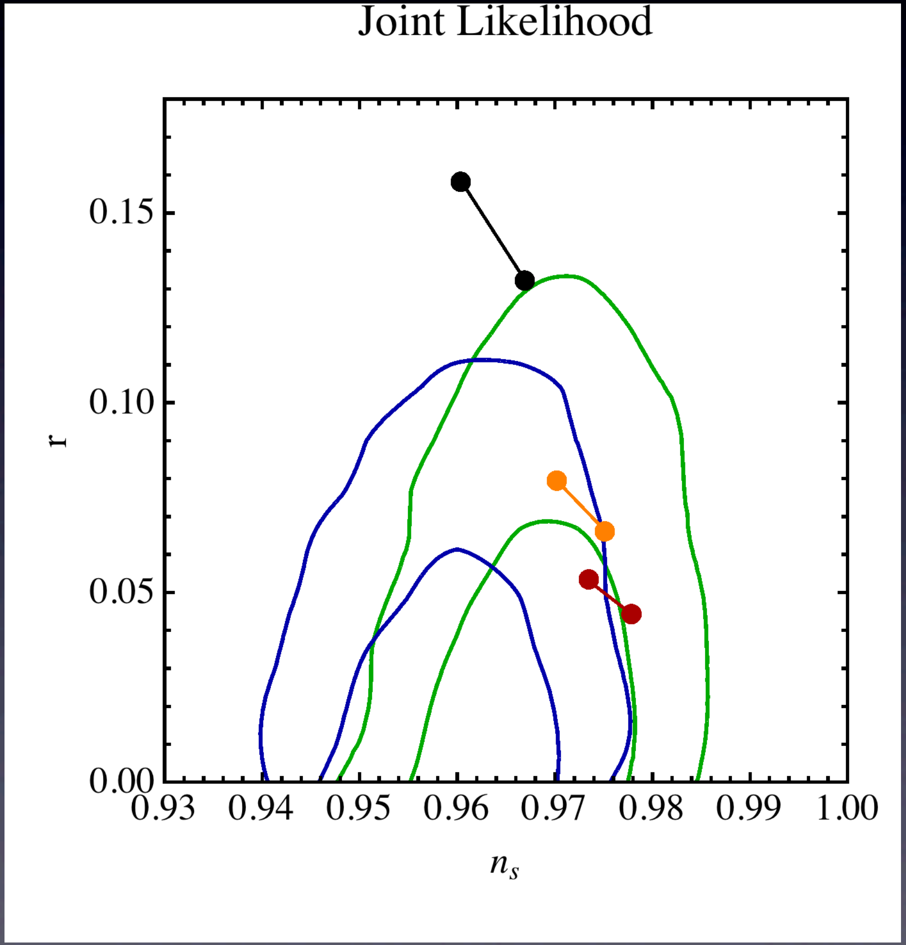
If the patch is typical

CAMspec

$r < 0.09$ at $95\% \, CL$

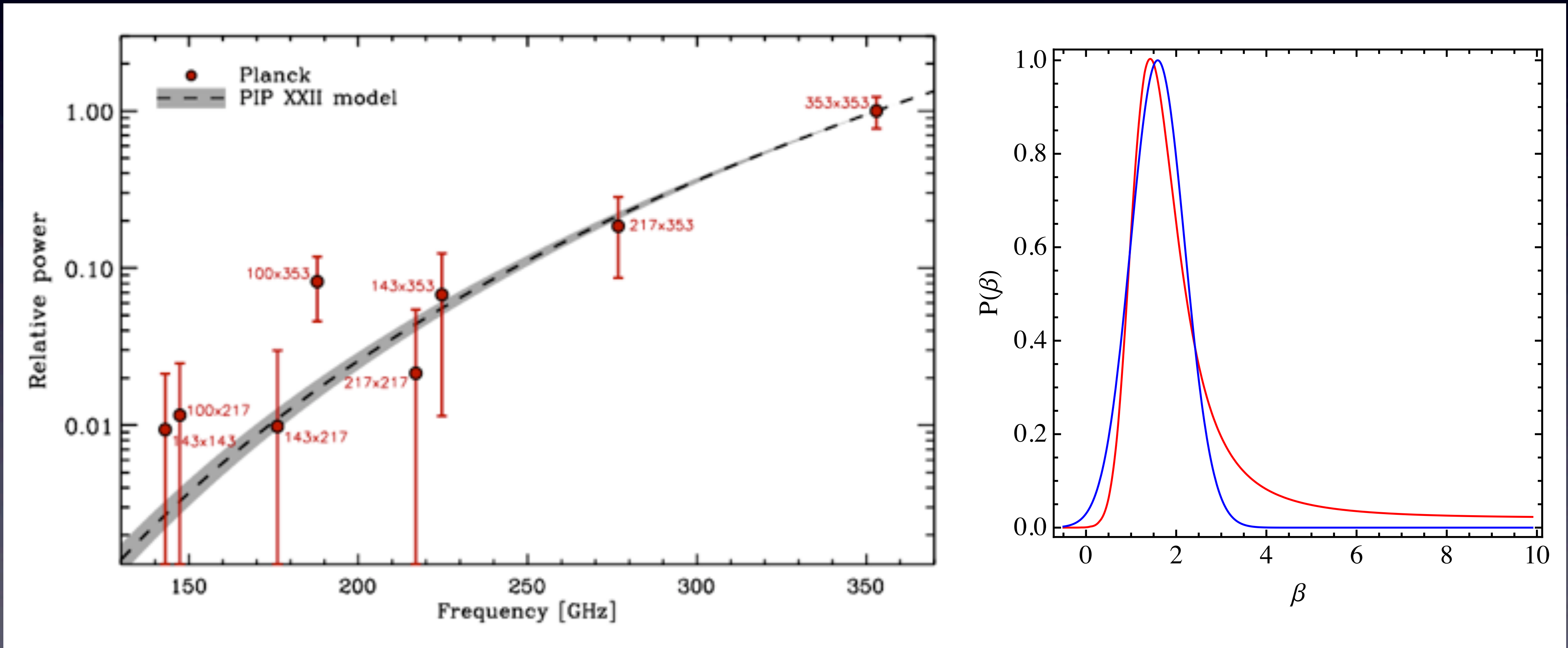
hybrid cleaning

$r < 0.11$ at $95\% \, CL$



Joint Analysis

Frequency information in the patch (Fig. 10 in Planck XXX)



Joint Analysis

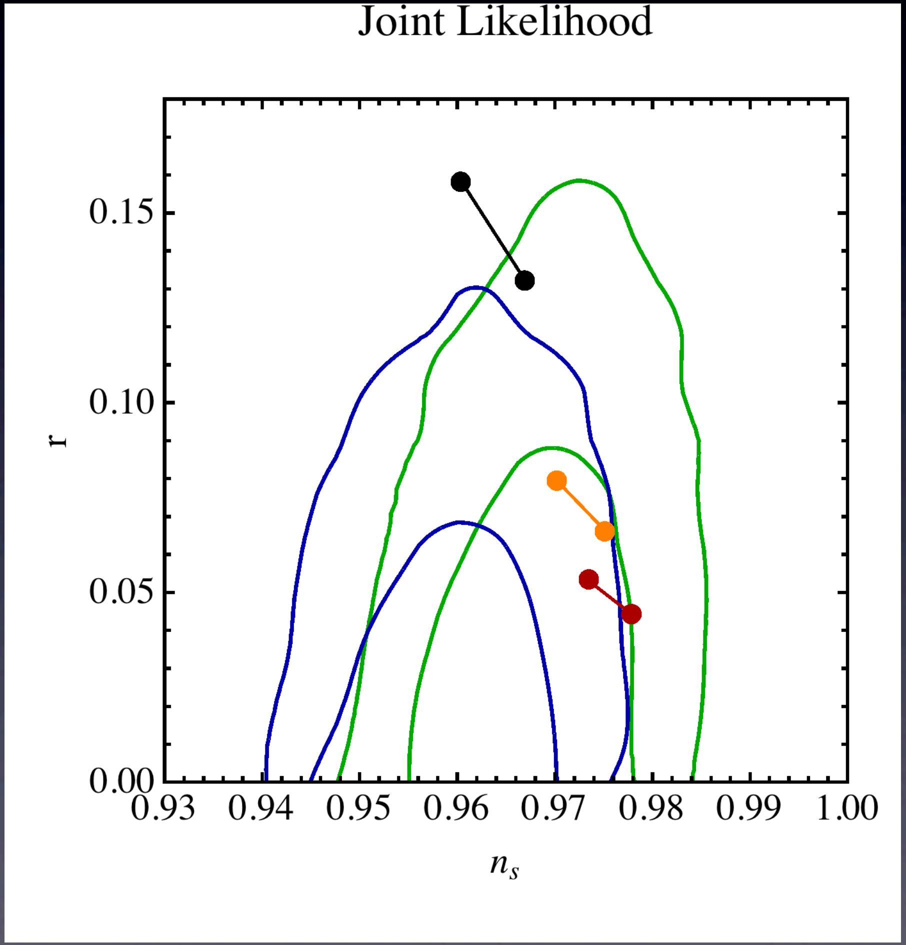
Assuming only frequency information in the patch

CAMspec

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

hybrid cleaning

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



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.
- Inclusion of cross-spectra between Planck and BICEP as well as Keck Array 100 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 should have a good idea whether we are lucky enough that the CMB contains valuable information about quantum gravity or string theory
- Until then, we should work harder to understand our theories at the relevant energy scales

Thank you