Planck, BICEP, and the Early Universe

Raphael Flauger

KICP Colloquium, Chicago, December 2, 2015

CMB@50

COSMIC BLACK-BODY RADIATION*

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965

Palmer Physical Laboratory
Princeton, New Jersey

measurement of excess antenna temperature and interpretation in terms of CMB published in July 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

A. A. Penzias
R. W. Wilson

May 13, 1965

Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

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Spectrum

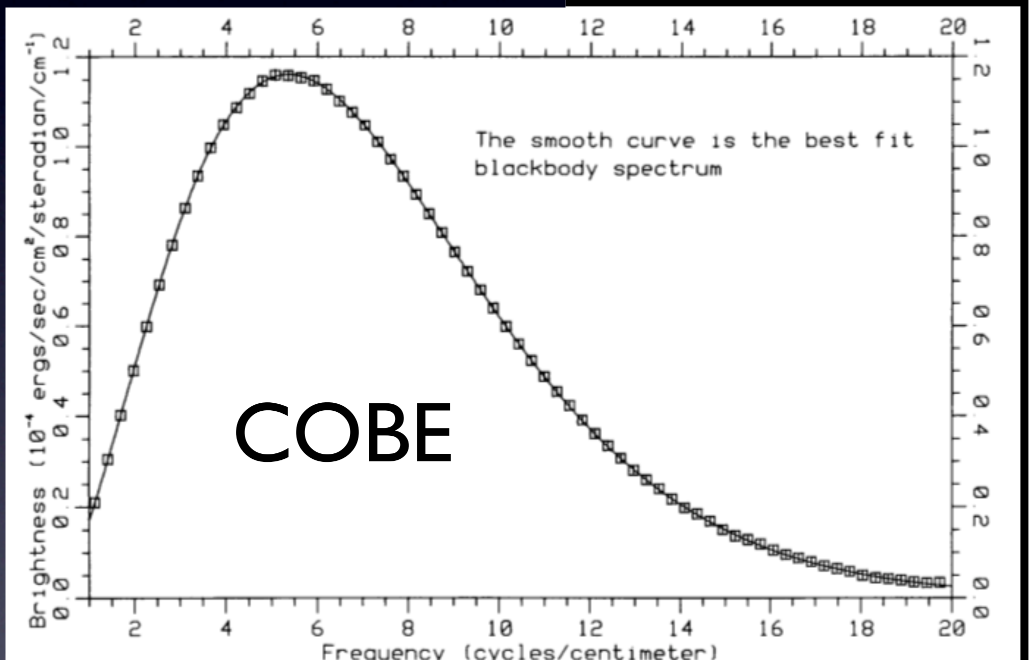
VOLUME 65, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JULY 1990

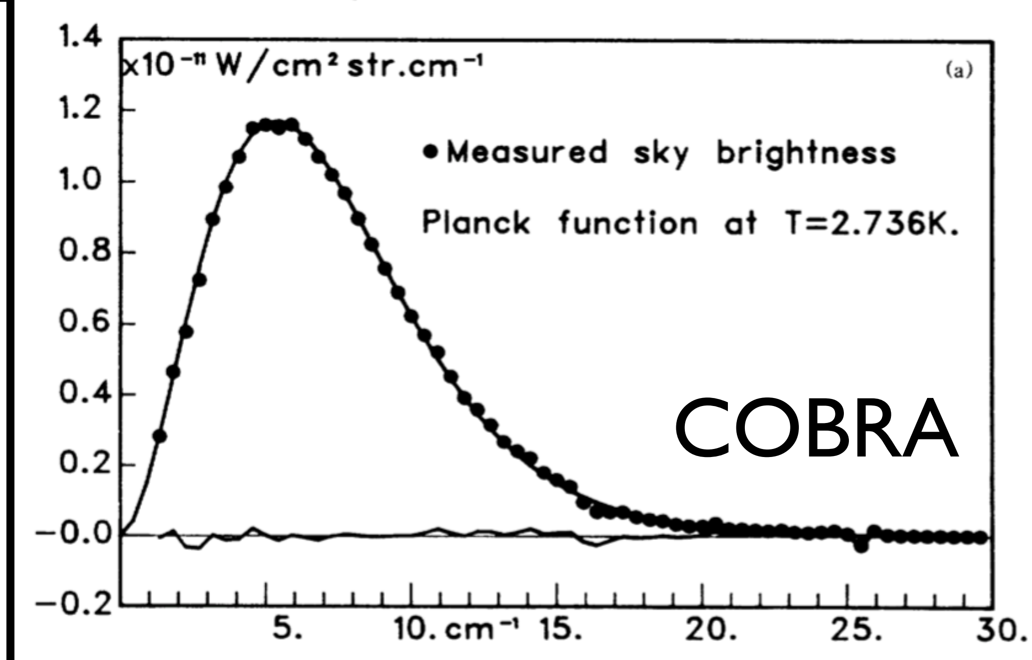
Rocket Measurement of the Cosmic-Background-Radiation mm-Wave Spectrum

H. P. Gush, M. Halpern, and E. H. Wishnow

Department of Physics, University of British Columbia, Vancouver, Canada V6T 2A6

(Received 10 May 1990)





A PRELIMINARY MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COSMIC BACKGROUND EXPLORER* (*COBE*)[1] SATELLITE

J. C. MATHER,[2] E. S. CHENG,[2] R. E. EPLEE, JR.,[3] R. B. ISAACMAN,[3] S. S. MEYER,[4] R. A. SHAFER,[2] R. WEISS,[4] E. L. WRIGHT,[5] C. L. BENNETT, N. W. BOGGESS,[2] E. DWEK,[2] S. GULKIS,[6] M. G. HAUSER,[2] M. JANSSEN,[6] T. KELSALL,[2] P. M. LUBIN,[7] S. H. MOSELEY, JR.,[2] T. L. MURDOCK,[8] R. F. SILVERBERG,[2] G. F. SMOOT,[9] AND D. T. WILKINSON[10]

Received 1990 January 16; accepted 1990 February 19

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Dipole

Velocity of the Earth with Respect to the Cosmic Background Radiation

E. K. Conklin

Radio Astronomy Institute,
Stanford University,
Stanford, California.

Received March 17, 1969.

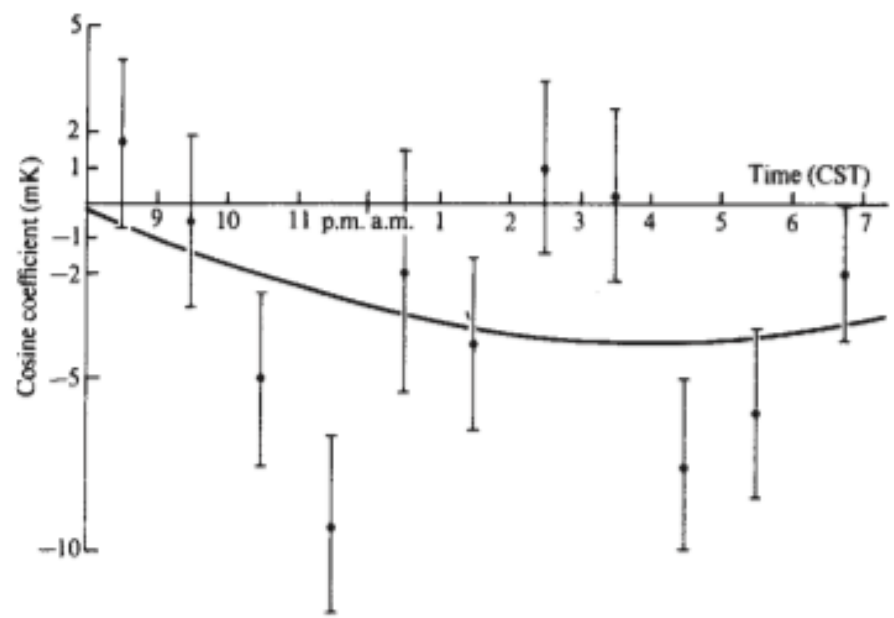
Isotropy of the 3 K Background

3.2 ± 0.8 mK

Paul S. Henry*

Joseph Henry Laboratories,
Department of Physics,
Princeton University,
Princeton, New Jersey 08540

Received May 17, 1971.



(Planck 2015: 3.3645 ± 0.0020 mK)

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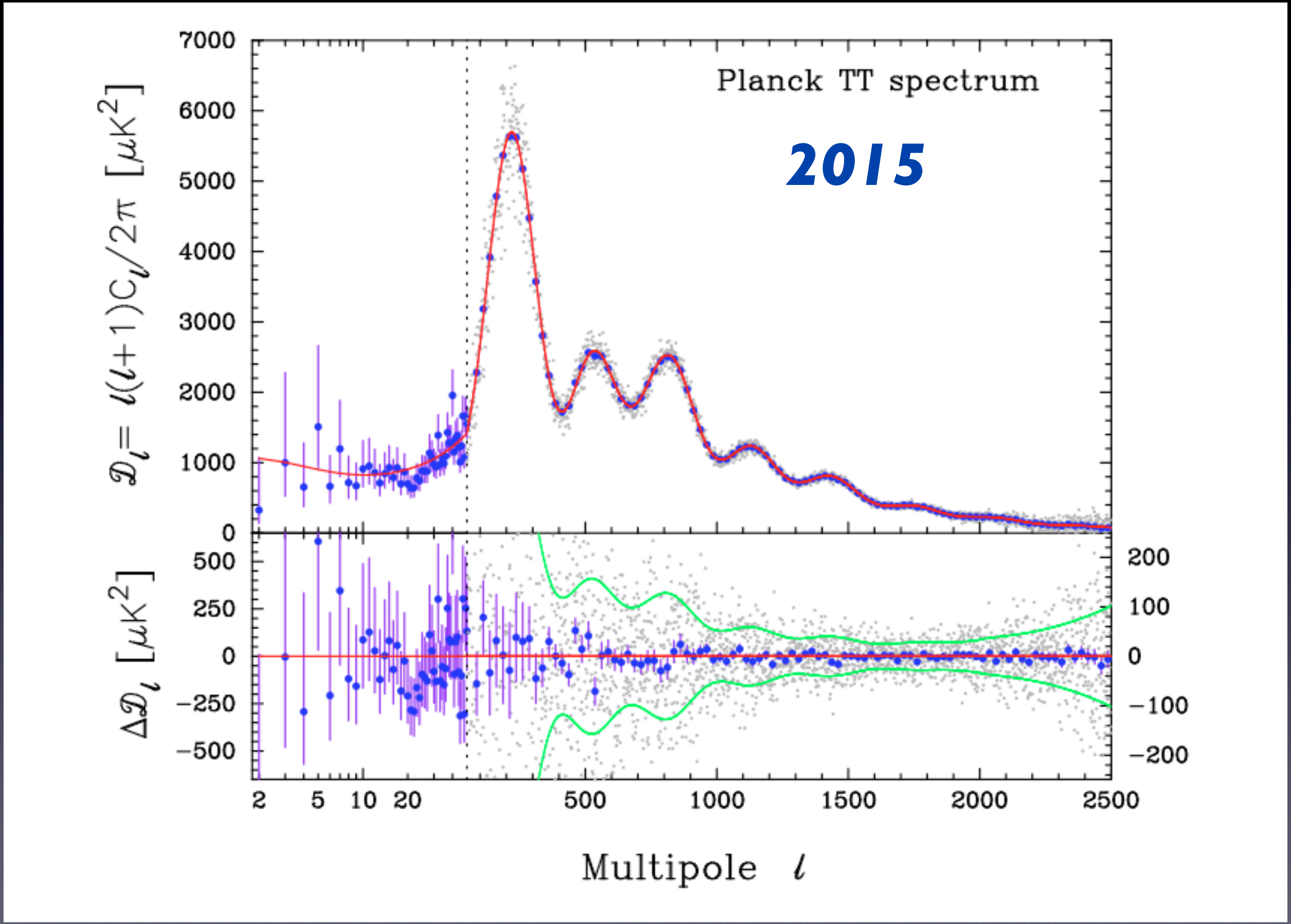


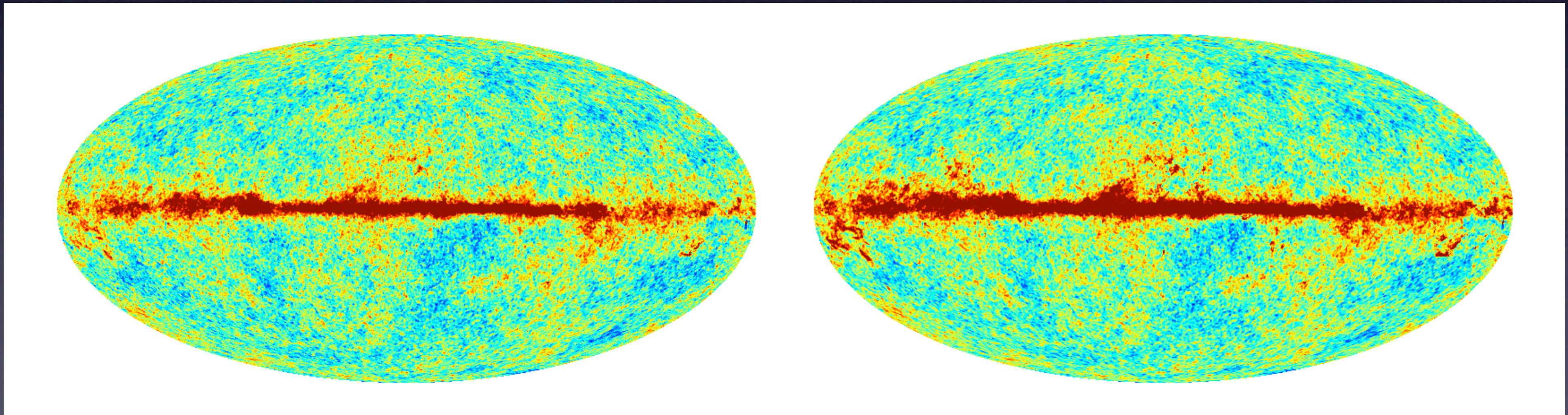
Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500
Multipole ℓ

Planck & WMAP

- Planck and WMAP temperature data agree very well at WMAP resolution

WMAP 94 GHz

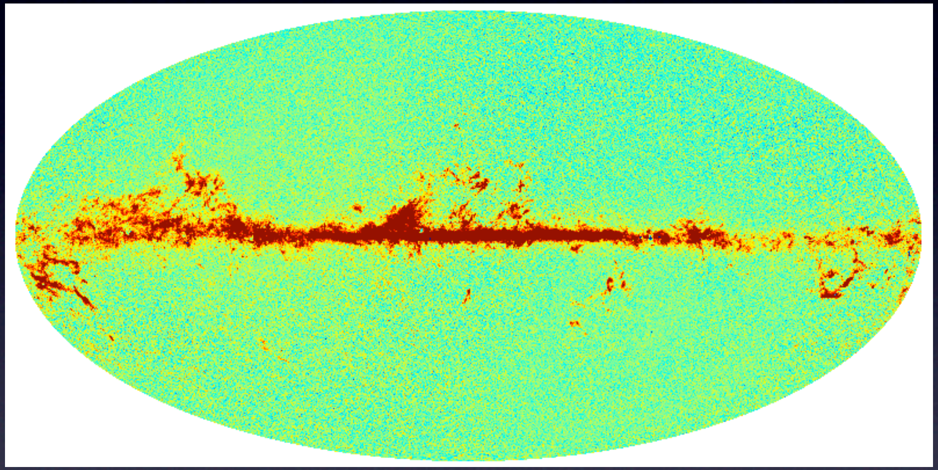
Planck 100 GHz



(N_{side}=512)

Planck & WMAP

Planck 100 GHz
- WMAP 94 GHz =

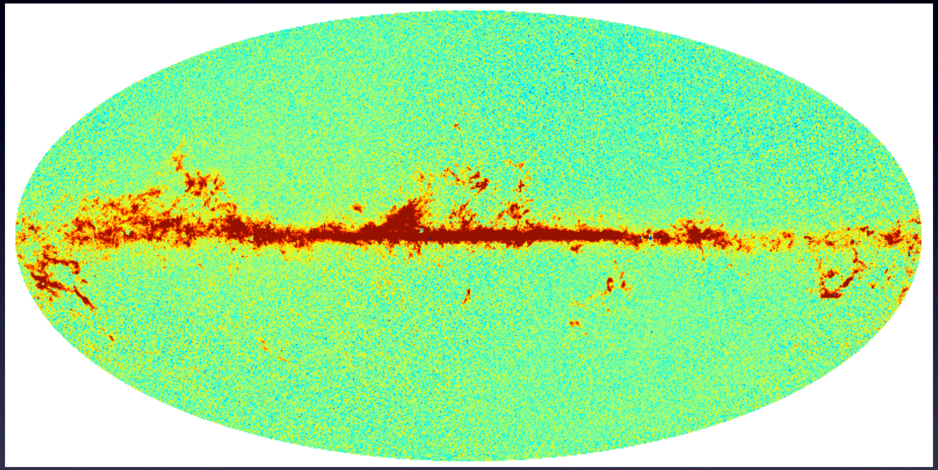


Planck & WMAP

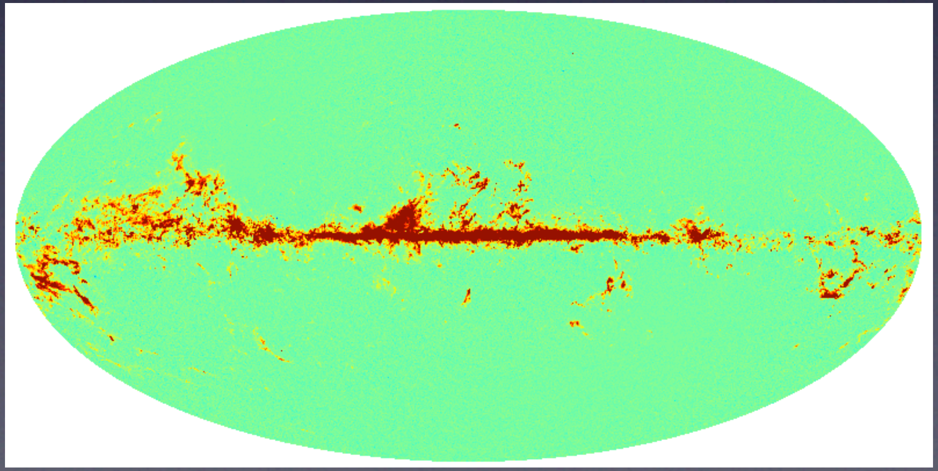
The small but visible difference is due to a CO emission line

Planck 100 GHz

- WMAP 94 GHz =



vs Planck CO$(1-0)$ map

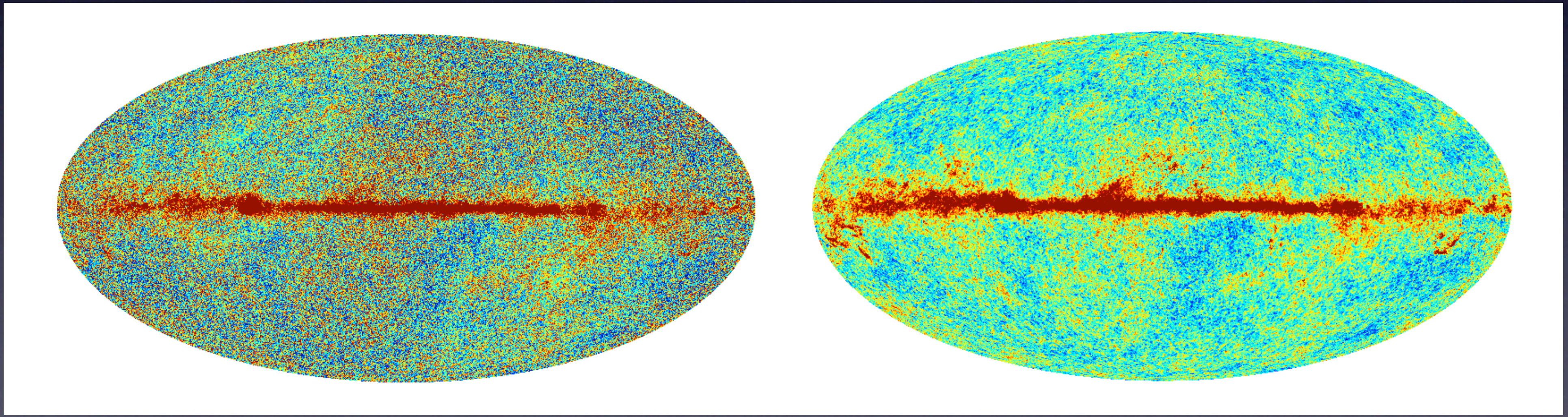


Planck & WMAP

- Planck and WMAP temperature data agrees very well at WMAP resolution
- Planck is much more powerful

WMAP 94 GHz

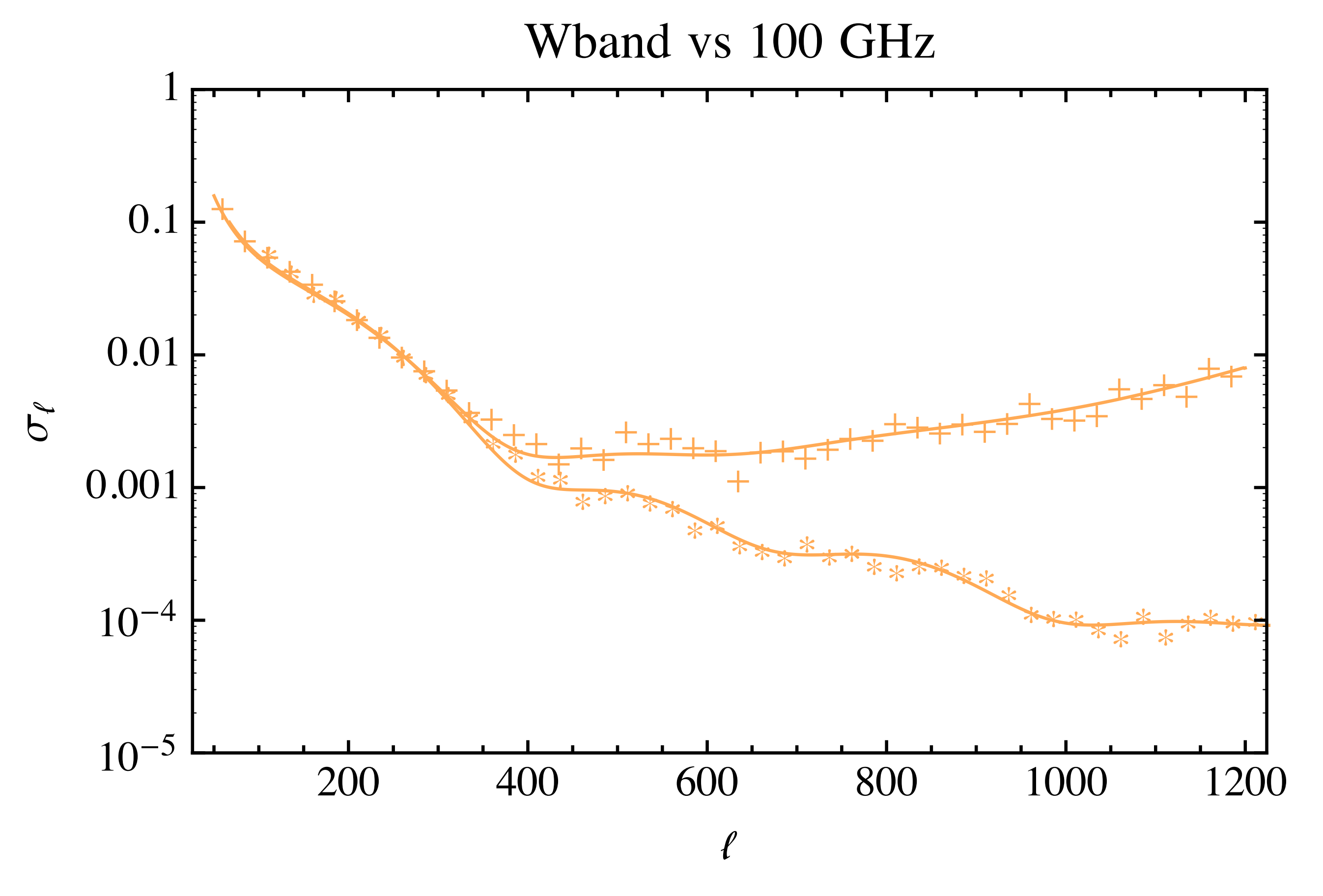
Planck 100 GHz



(N_{side}=1024)

Planck & WMAP

- Planck and WMAP temperature data agrees very well at WMAP resolution
- Planck is much more powerful



LCDM

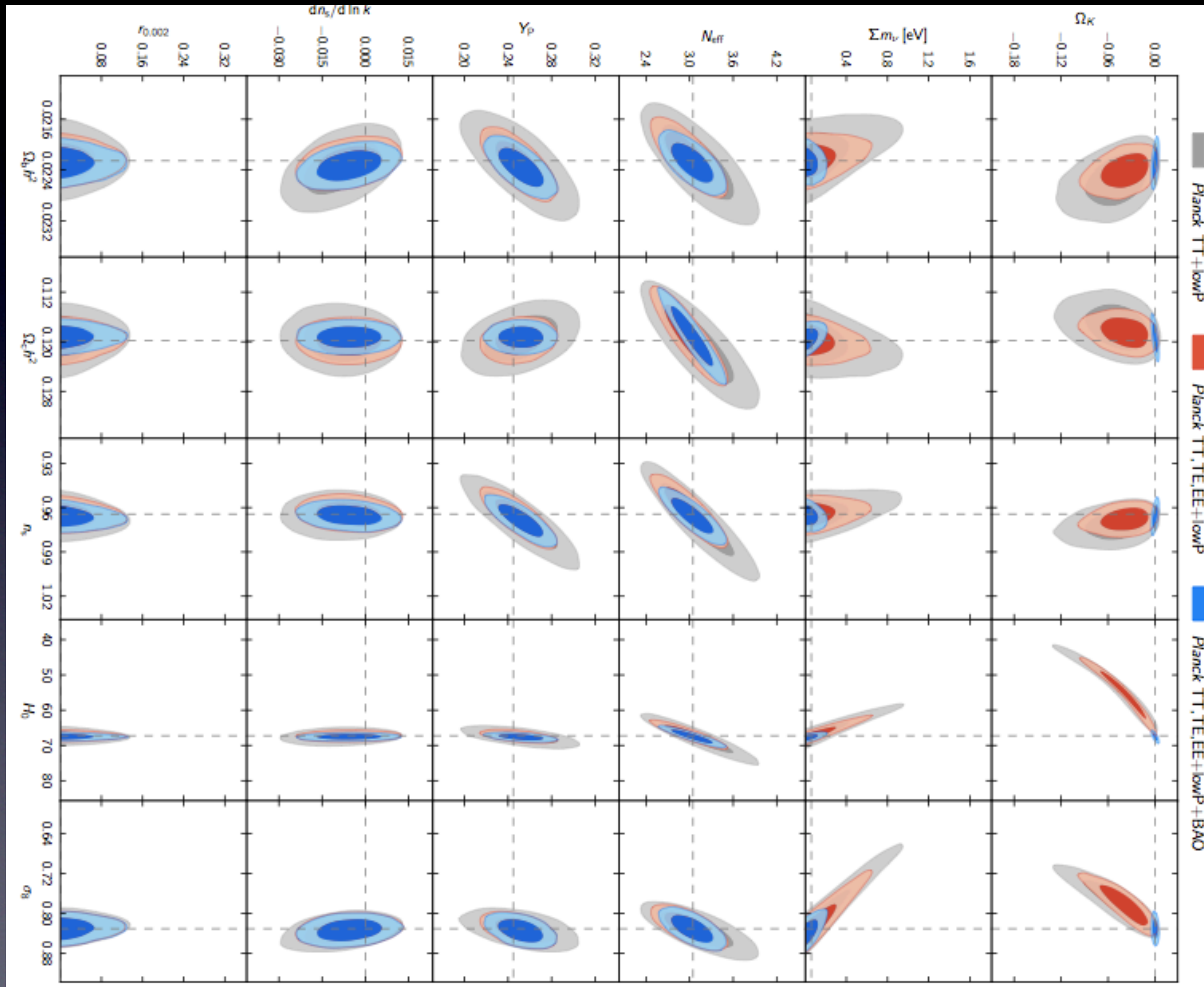
The early universe is remarkably simple and the CMB temperature data is in good agreement with the six-parameter LCDM model.

(Ade et al. 2015)

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

* the sum of the neutrino masses is kept fixed at 0.06 eV

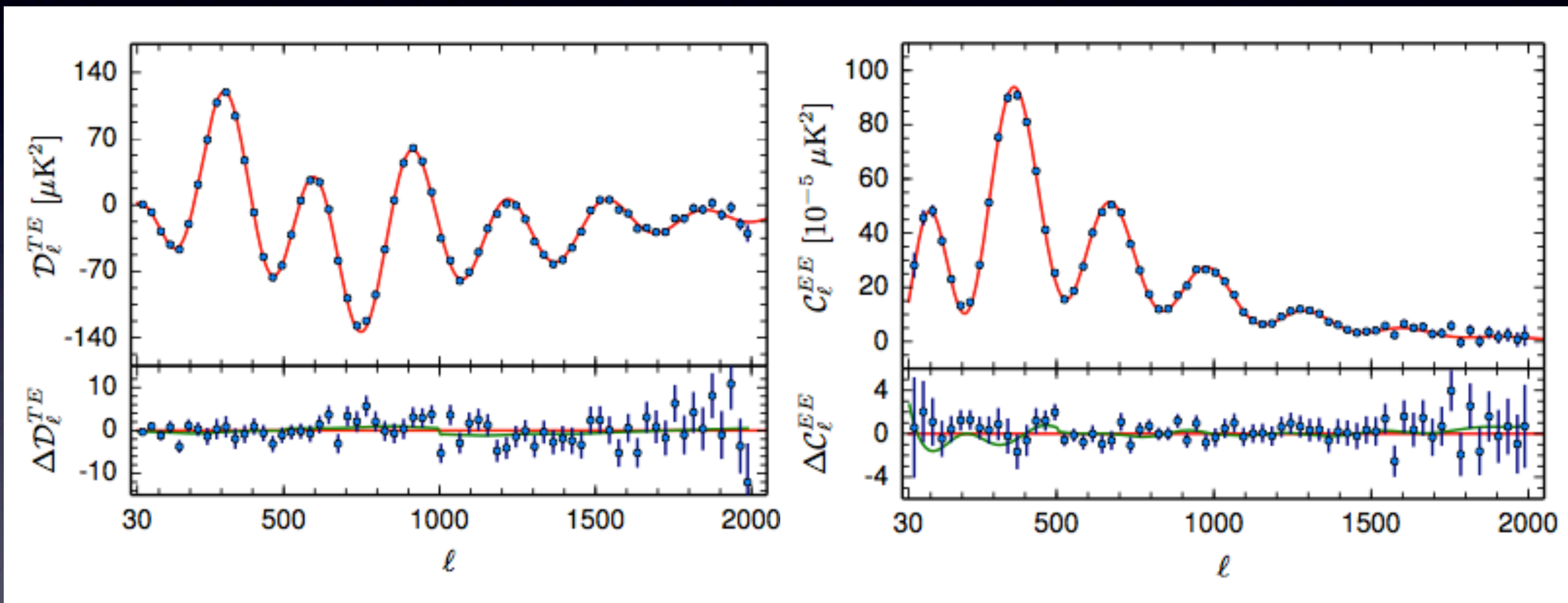
LCDM+X



(Ade et al. 2015)

LCDM

In the context of LCDM, we can predict the TE and EE angular power spectra and compare with the Planck measurements



(Ade et al. 2015)

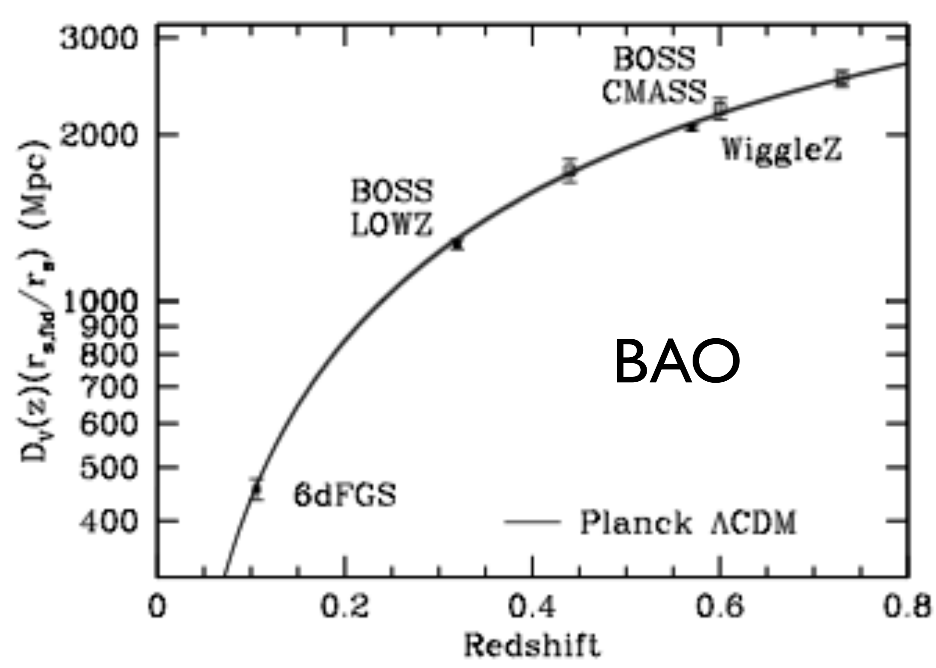
(systematics remain to be understood)

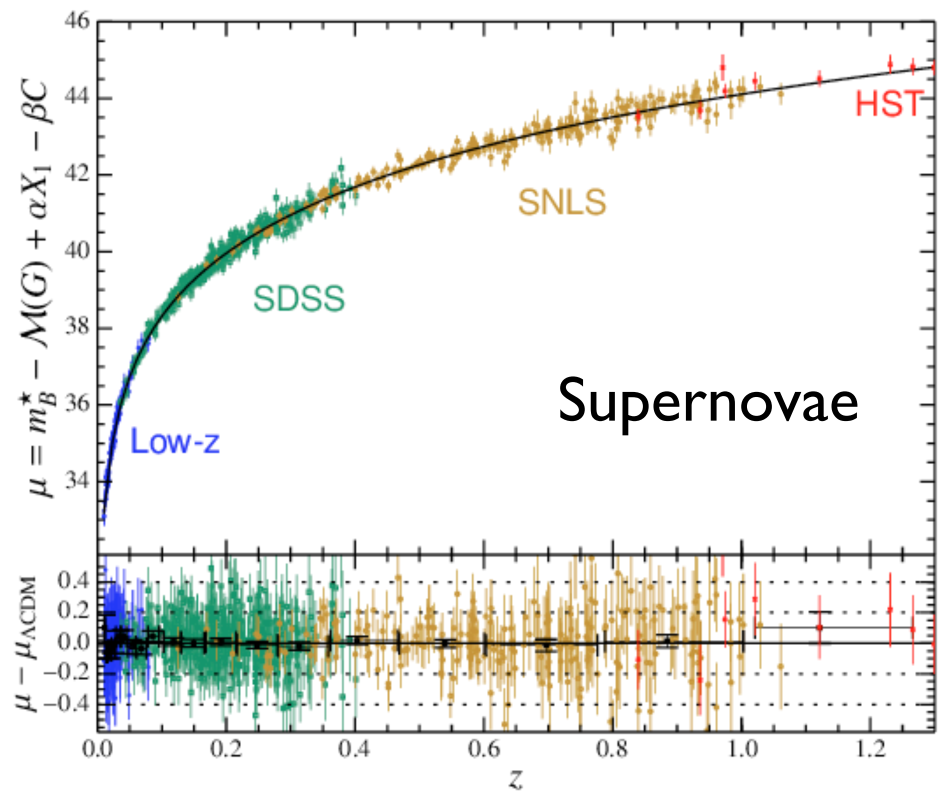
LCDM

In addition, LCDM is consistent with all 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

Parameter Constraints

Parameter constraints from TT

Parameter	2013N(DS)	2015F(CHM)	2015F(CHM) (Plik)
$100\theta_{MC}$	1.04131 ± 0.00063	1.04094 ± 0.00048	1.04086 ± 0.00048
$\Omega_b h^2$	0.02205 ± 0.00028	0.02225 ± 0.00023	0.02222 ± 0.00023
$\Omega_c h^2$	0.1199 ± 0.0027	0.1194 ± 0.0022	0.1199 ± 0.0022
H_0	67.3 ± 1.2	67.48 ± 0.98	67.26 ± 0.98
n_s	0.9603 ± 0.0073	0.9682 ± 0.0062	0.9652 ± 0.0062
Ω_m	0.315 ± 0.017	0.313 ± 0.013	0.316 ± 0.014
σ_8	0.829 ± 0.012	0.829 ± 0.015	0.830 ± 0.015
τ	0.089 ± 0.013	0.079 ± 0.019	0.078 ± 0.019
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.875 ± 0.014	1.881 ± 0.014

- Good consistency between 2013 and 2015 parameters

Parameter Constraints

Parameter constraints from TT

Parameter	2013N(DS)	2015F(CHM)	2015F(CHM) (Plik)
$100\theta_{MC}$	1.04131 ± 0.00063	1.04094 ± 0.00048	1.04086 ± 0.00048
$\Omega_b h^2$	0.02205 ± 0.00028	0.02225 ± 0.00023	0.02222 ± 0.00023
$\Omega_c h^2$	0.1199 ± 0.0027	0.1194 ± 0.0022	0.1199 ± 0.0022
H_0	67.3 ± 1.2	67.48 ± 0.98	67.26 ± 0.98
n_s	0.9603 ± 0.0073	0.9682 ± 0.0062	0.9652 ± 0.0062
Ω_m	0.315 ± 0.017	0.313 ± 0.013	0.316 ± 0.014
σ_8	0.829 ± 0.012	0.829 ± 0.015	0.830 ± 0.015
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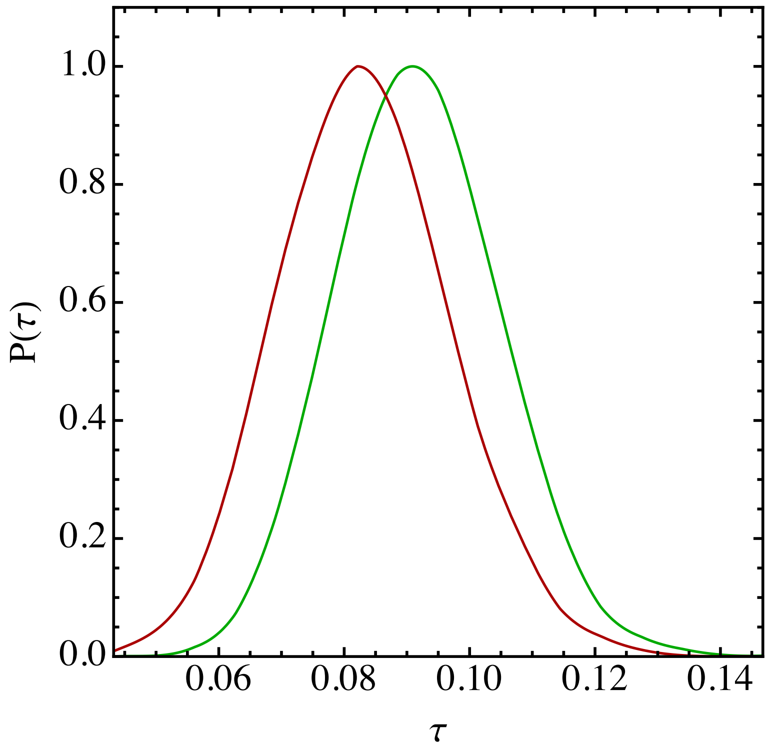
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.875 ± 0.014	1.881 ± 0.014

- The optical depth is one exception. It has shifted due to dust polarization data at 353 GHz

Parameter Constraints

Shift in optical depth for WMAP due to 353 GHz data



low-ℓ polarization data

Ka, Q,V cleaned with K-band and WMAP dust model, then coadded

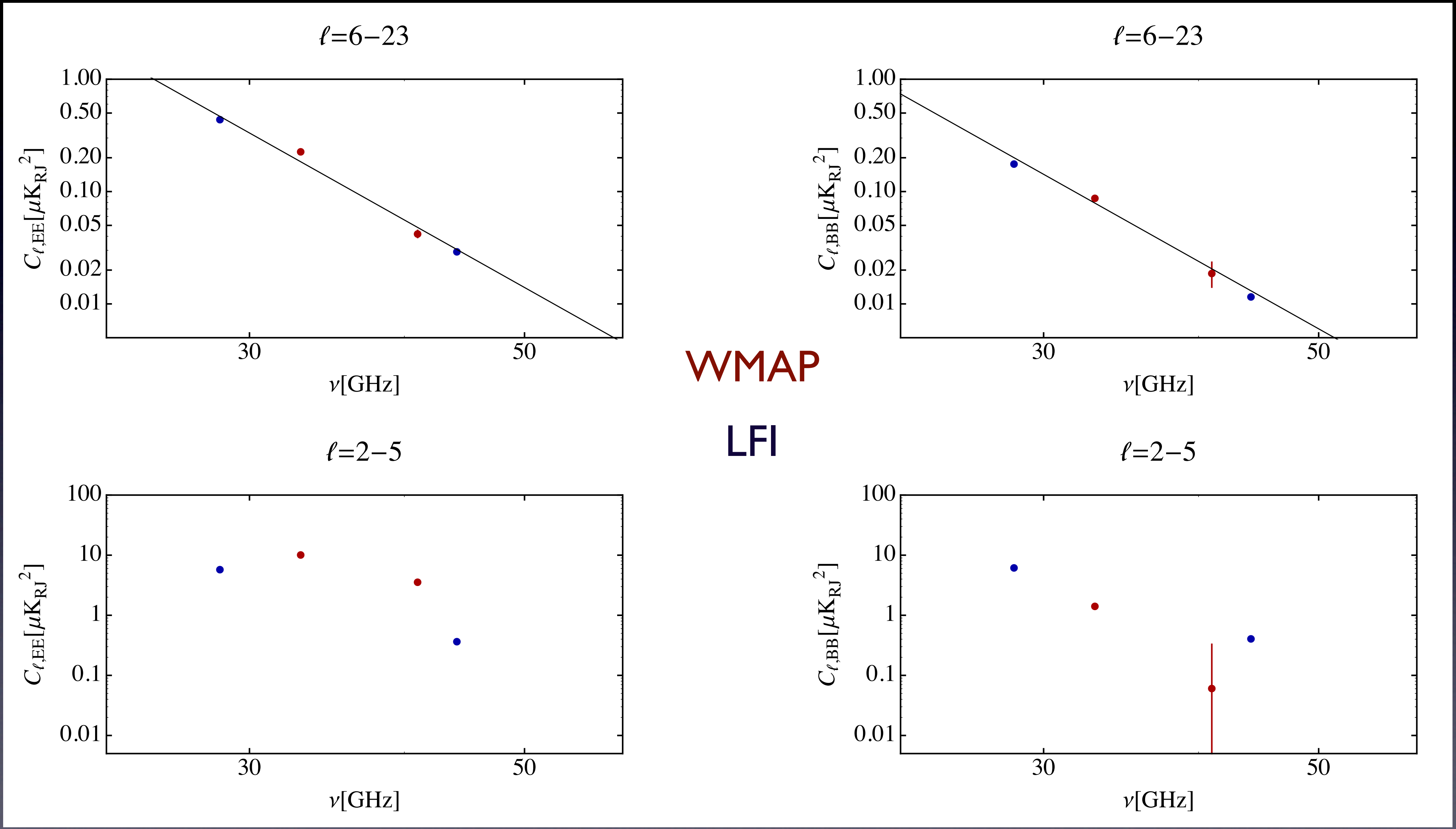
Ka, Q,V cleaned with K-band and 353 GHz data, then coadded

high-ℓ temperature data

hybrid-cleaned cross-halfmission spectra

- Most parameters are degenerate with τ.
  The old measurement of optical depth would have led to ~0.5σ shifts in parameters.

Parameter Constraints



LFI and WMAP polarization currently do not agree on large scales

Parameter Constraints

Parameter constraints from TT

Parameter	2013N(DS)	2015F(CHM)	2015F(CHM) (Plik)
$100\theta_{MC}$	1.04131 ± 0.00063	1.04094 ± 0.00048	1.04086 ± 0.00048
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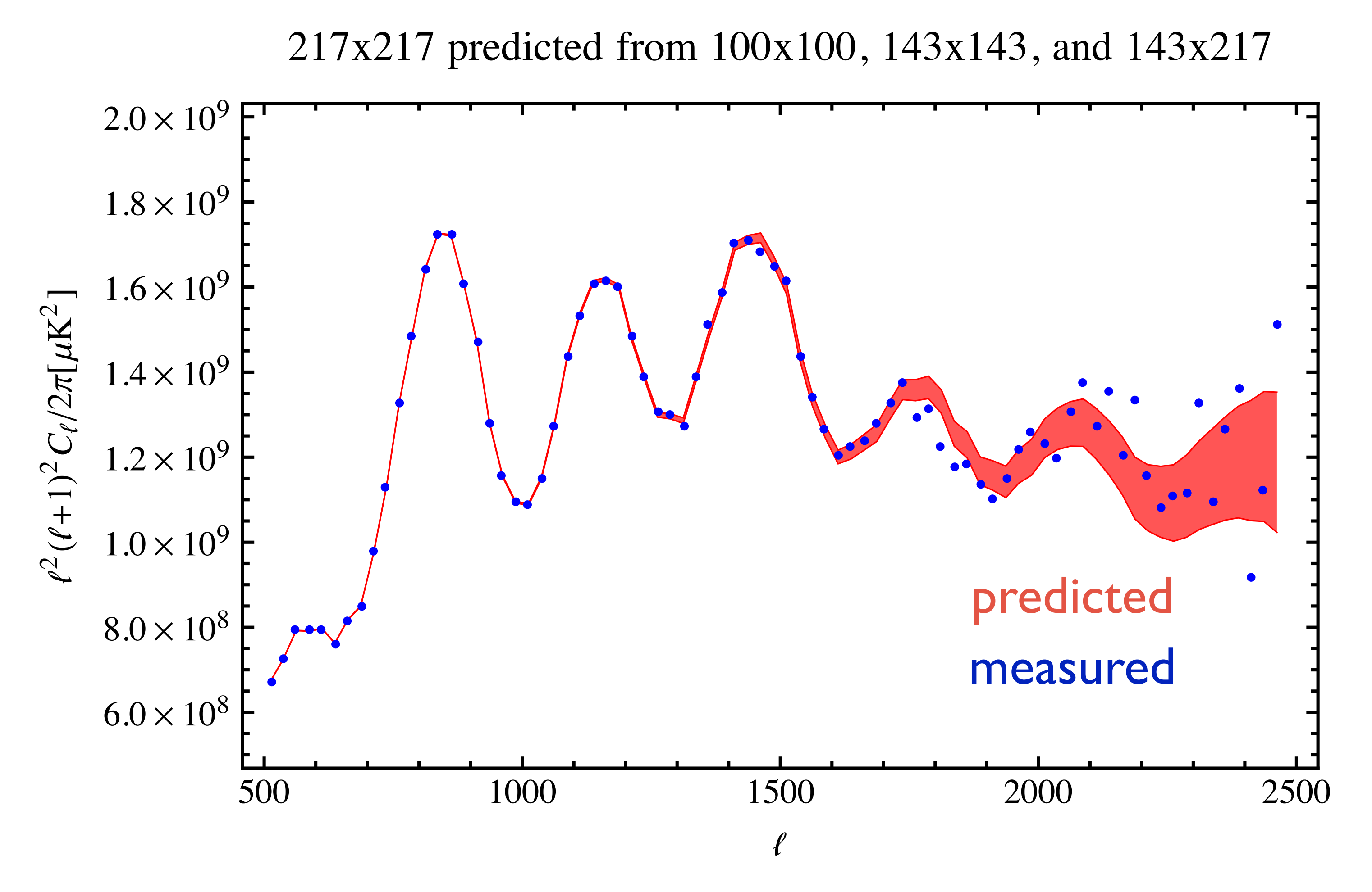
$\Omega_c h^2$	0.1199 ± 0.0027	0.1194 ± 0.0022	0.1199 ± 0.0022
H_0	67.3 ± 1.2	67.48 ± 0.98	67.26 ± 0.98
n_s	0.9603 ± 0.0073	0.9682 ± 0.0062	0.9652 ± 0.0062
Ω_m	0.315 ± 0.017	0.313 ± 0.013	0.316 ± 0.014
σ_8	0.829 ± 0.012	0.829 ± 0.015	0.830 ± 0.015
τ	0.089 ± 0.013	0.079 ± 0.019	0.078 ± 0.019
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.875 ± 0.014	1.881 ± 0.014

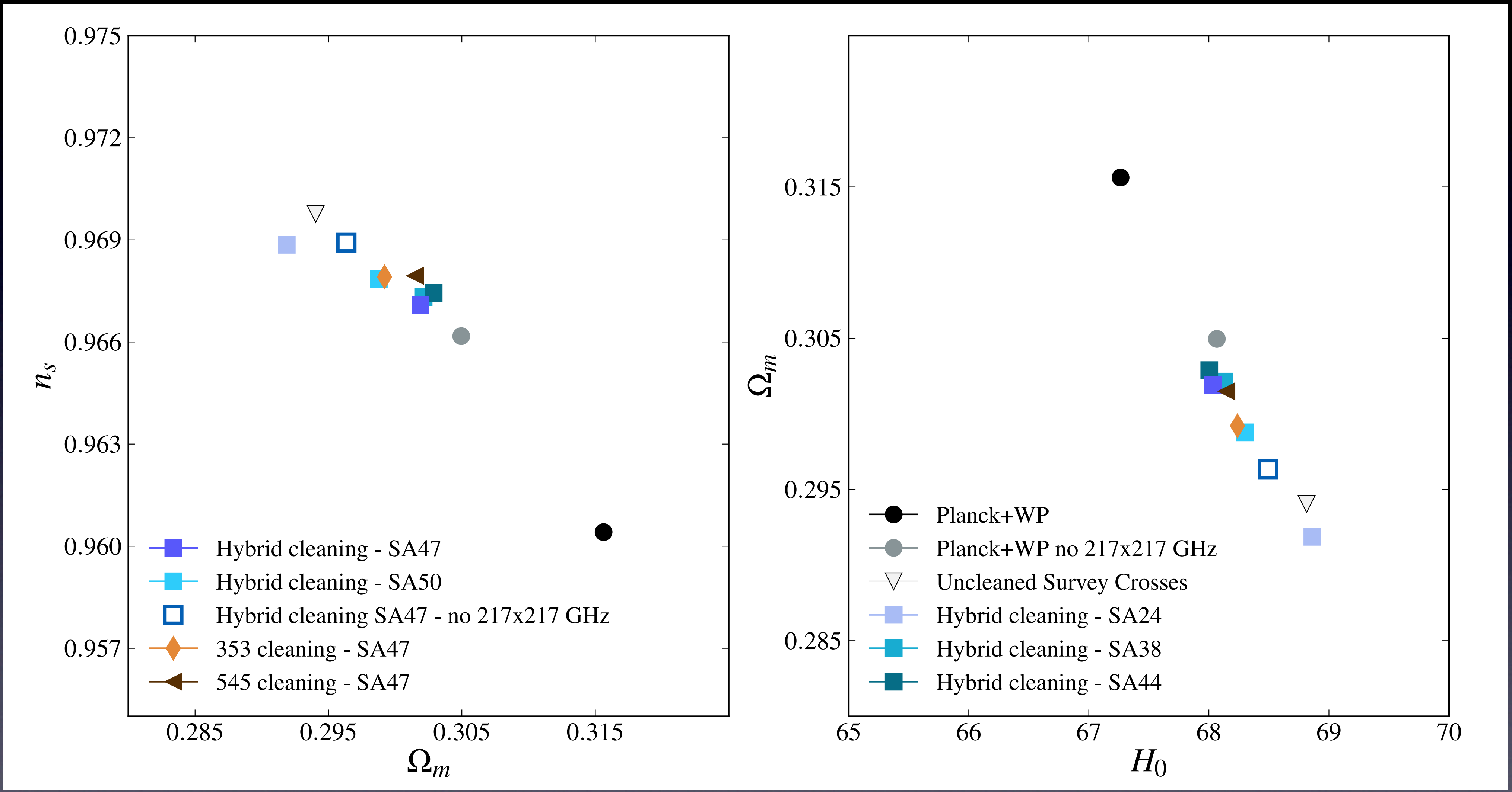
- The scalar spectral index has shifted between 2013 and 2015
- much of the shift in the spectral index between 2013 and 2015 can be traced to systematics in 2013 217 GHz detector set spectra.

Parameter Constraints

Parameter constraints from TT

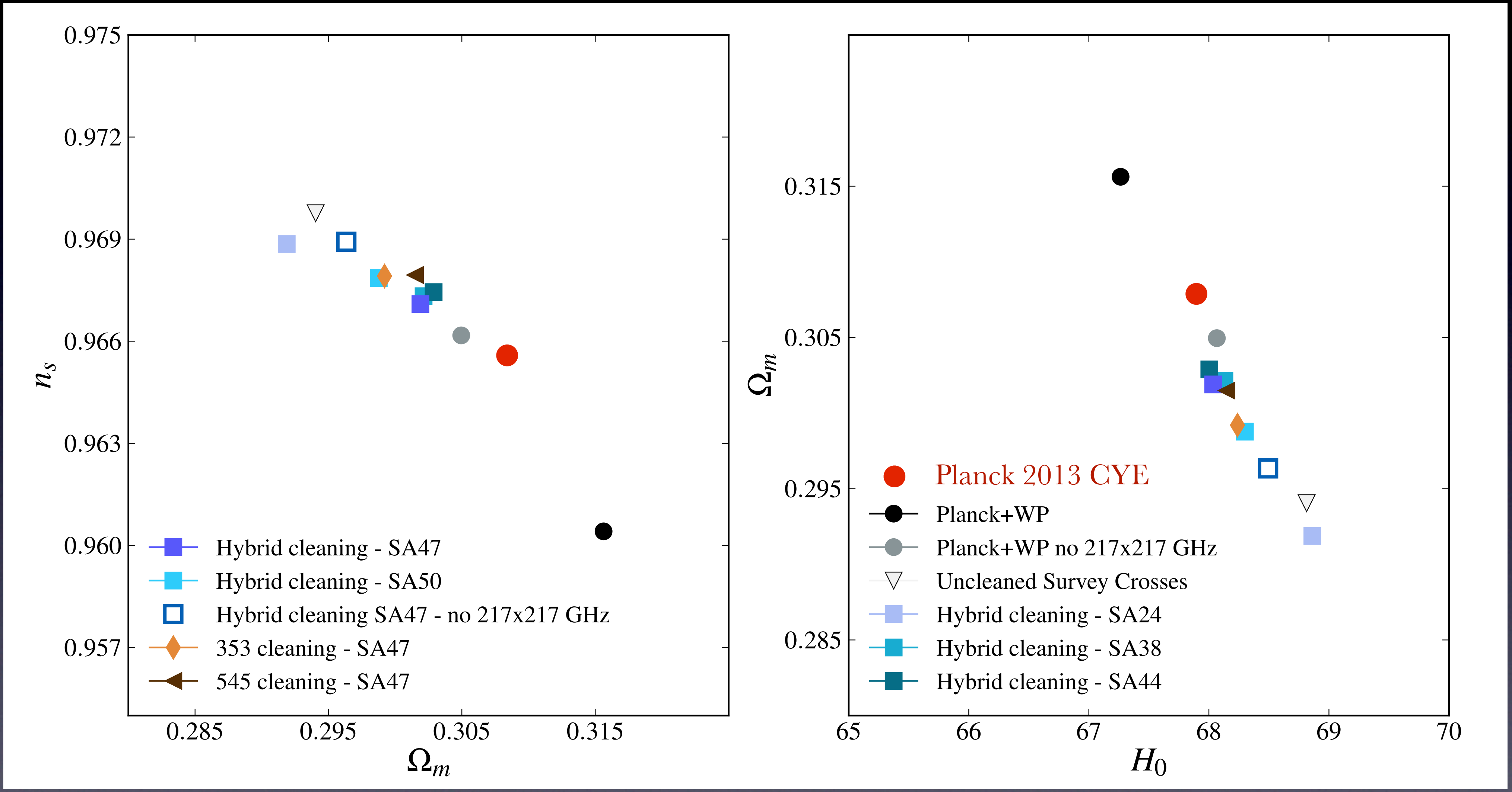


Analysis



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



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 2013 CYE
Planck+WP
Planck+WP no 217x217 GHz
Uncleaned Survey Crosses
Hybrid cleaning - SA24
Hybrid cleaning - SA38
Hybrid cleaning - SA44

Parameter Constraints

Parameter constraints from TT

Parameter	2015F(CHM)	2015F(CHM) (Plik)
$100\theta_{MC}$	1.04094 ± 0.00048	1.04086 ± 0.00048
$\Omega_b h^2$	0.02225 ± 0.00023	0.02222 ± 0.00023
$\Omega_c h^2$	0.1194 ± 0.0022	0.1199 ± 0.0022
H_0	67.48 ± 0.98	67.26 ± 0.98
n_s	0.9682 ± 0.0062	0.9652 ± 0.0062
Ω_m	0.313 ± 0.013	0.316 ± 0.014
σ_8	0.829 ± 0.015	0.830 ± 0.015
τ	0.079 ± 0.019	0.078 ± 0.019
$10^9 A_s e^{-2\tau}$	1.875 ± 0.014	1.881 ± 0.014

- CAMspec and Plik disagree on spectral index by ~0.5 σ.

Parameter Constraints

Parameter constraints from TT

Parameter		2015F(CHM) (Plik)	2015F(CHM)	
A^{tSZ}_{143}	. . . .	5.2 ± 1.9	$3.2^{+1.4}_{-2.6}$	(-1.0σ)
A^{CIB}_{217}	. . . .	63.9 ± 6.6	46 ± 7	(-2.7σ)
A^{kSZ}	. . . .	< 4.46	$5.2^{+3.6}_{-2.5}$	$(+0.7\sigma)$
c_{100}	. . . .	0.99788 ± 0.00078	0.99678 ± 0.00097	(-1.4σ)
c_{217}	. . . .	0.9959 ± 0.0015	0.9972 ± 0.0018	$(+0.9\sigma)$
n_s	. . . .	0.9655 ± 0.0062	0.9682 ± 0.0062	$(+0.4\sigma)$
Y_P	. . . .	0.24532 ± 0.00010	0.244922 ± 0.000099	(-3.9σ)

- also disagreement on calibration and foreground parameters
- CAMspec tSZ and CIB(+PS) amplitude in good agreement with ACT/SPT

Parameter Constraints

Parameter constraints from TE, EE

Parameter	*Planck* TT+lowP	*Planck* TE+lowP	*Planck* EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$
$\ln(10^{10}A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027

- The polarization data is still preliminary but leads to cosmological parameters consistent with those from TT

Parameter Constraints

Parameter constraints from TE, EE

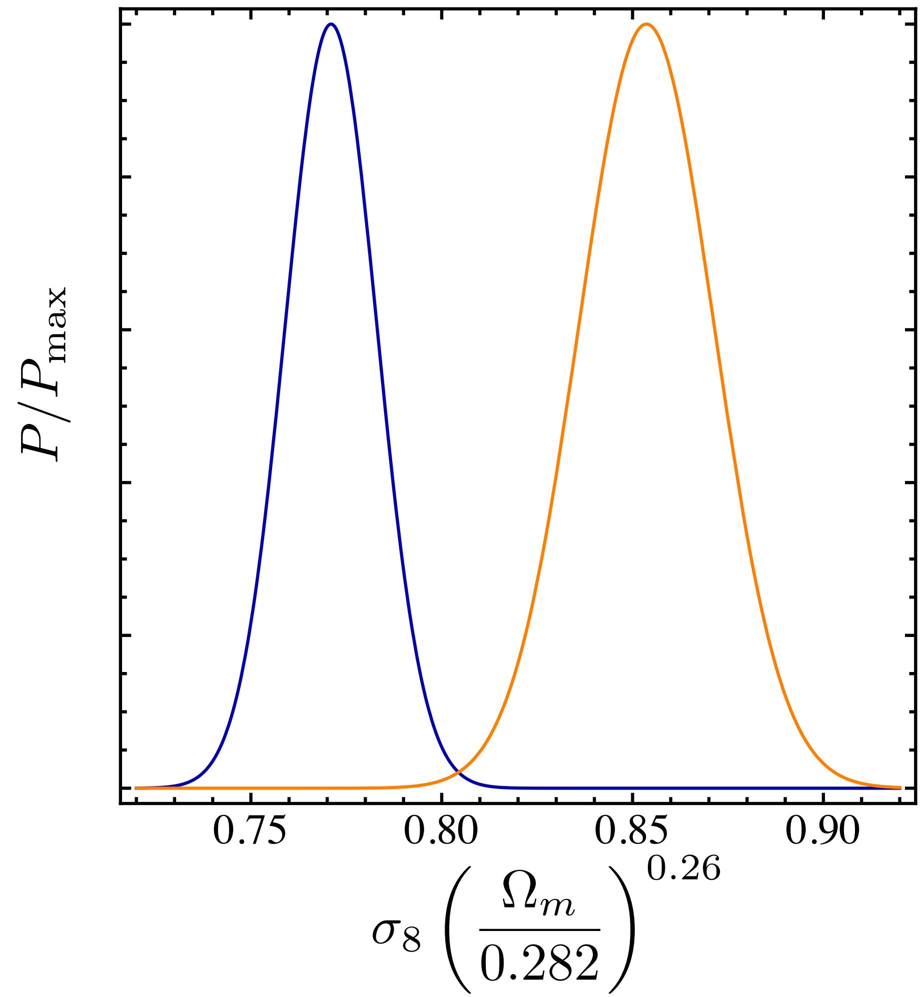
Parameter	*Planck* TT+lowP	*Planck* TE+lowP	*Planck* EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027

- Although consistent with TT, the polarization data favors lower matter density Ω_m and σ_8.

Clustering

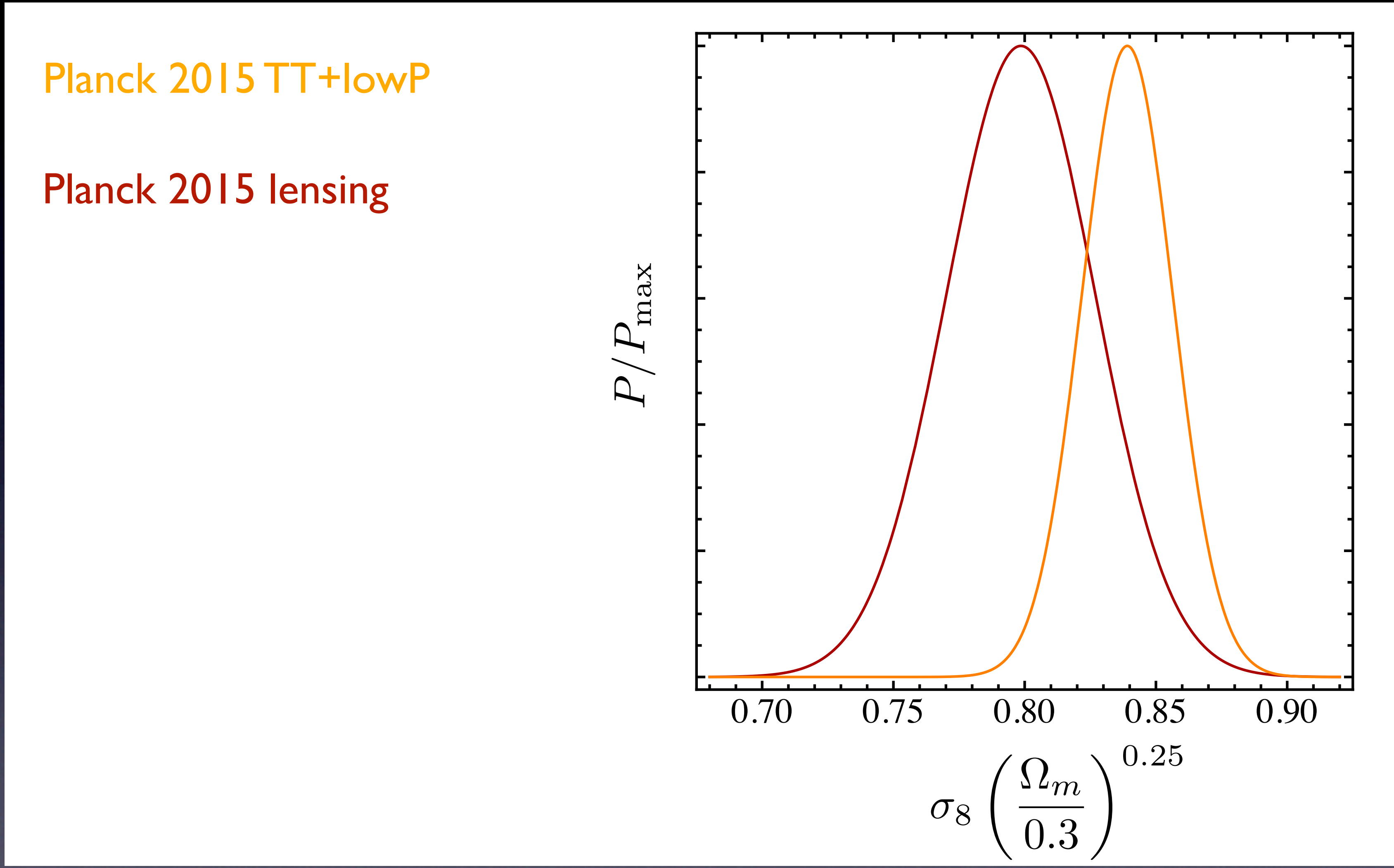
tSZ power spectrum
(Hill, Spergel 2013)

Planck 2015 TT+lowP
Paper XIII



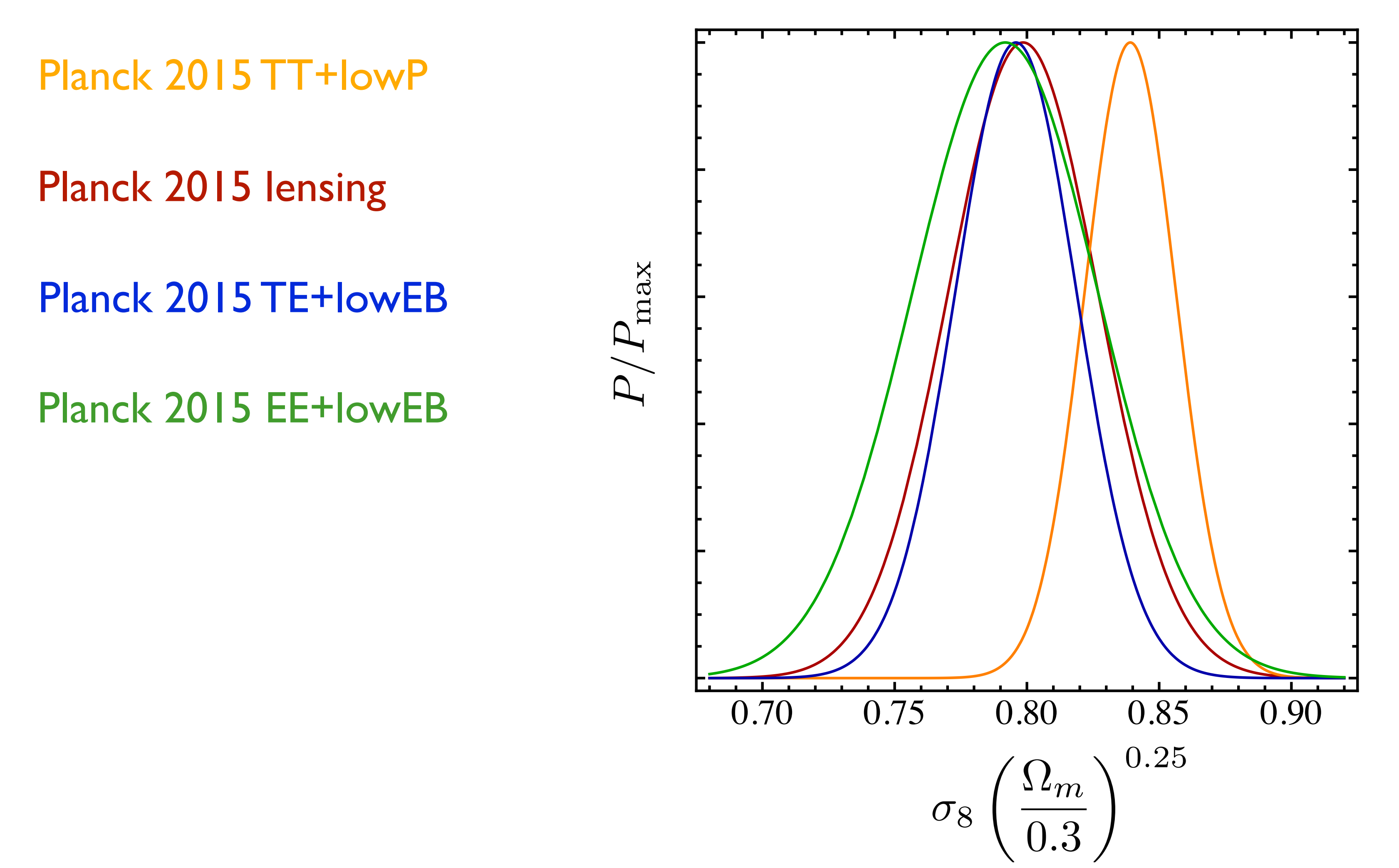
- similar tensions exist between the Planck TT data and a number of other low redshift observations

Clustering



- A milder tension also exists between Planck lensing and cosmology predicted by Planck TT

Clustering



- however, both Planck TE and Planck EE cosmologies in excellent agreement with Planck lensing

Parameter Constraints

Parameter constraints from TT marginalized over A_L and TE

Parameter	*Planck* TT + lowP − A_L	*Planck* TE + lowEB
$\Omega_b h^2$	0.02262 ± 0.00029	0.02233 ± 0.00025
$\Omega_c h^2$	0.1166 ± 0.0025	0.1169 ± 0.0021
$100\theta_{MC}$	1.04137 ± 0.00053	1.04126 ± 0.00050
τ	0.059 ± 0.021	0.055 ± 0.020
$\ln(10^{10} A_s)$	3.046 ± 0.041	3.026 ± 0.044
n_s	0.9740 ± 0.0073	0.975 ± 0.011
H_0	68.9 ± 1.2	68.55 ± 0.93
Ω_m	$0.295^{+0.015}_{-0.016}$	0.298 ± 0.012
σ_8	0.802 ± 0.018	0.797 ± 0.019
$10^9 A_s e^{-2\tau}$	1.868 ± 0.015	1.849 ± 0.027
$\mathbf{A_L}$	$1.224^{+0.096}_{-0.11}$	1

- The TT power spectrum data favors ~2σ higher A_L than expected theoretically or observed in lensing power spectrum.

Parameter Constraints

Parameter constraints from TT marginalized over A_L and TE

Parameter	*Planck* TT + lowP − A_L	*Planck* TE + lowEB
$\Omega_b h^2$	0.02262 ± 0.00029	0.02233 ± 0.00025
$\Omega_c h^2$	0.1166 ± 0.0025	0.1169 ± 0.0021
$100\theta_{MC}$	1.04137 ± 0.00053	1.04126 ± 0.00050
τ	0.059 ± 0.021	0.055 ± 0.020
$\ln(10^{10} A_s)$	3.046 ± 0.041	3.026 ± 0.044
n_s	0.9740 ± 0.0073	0.975 ± 0.011
H_0	68.9 ± 1.2	68.55 ± 0.93
Ω_m	$0.295^{+0.015}_{-0.016}$	0.298 ± 0.012
σ_8	0.802 ± 0.018	0.797 ± 0.019
$10^9 A_s e^{-2\tau}$	1.868 ± 0.015	1.849 ± 0.027
$\mathbf{A_L}$	$1.224^{+0.096}_{-0.11}$	1

- Marginalization over A_L leads to higher value of Hubble parameter, lower value of matter density Ω_m and σ_8, and better agreement with polarization.

The Hubble Constant

Reid et al. 2013

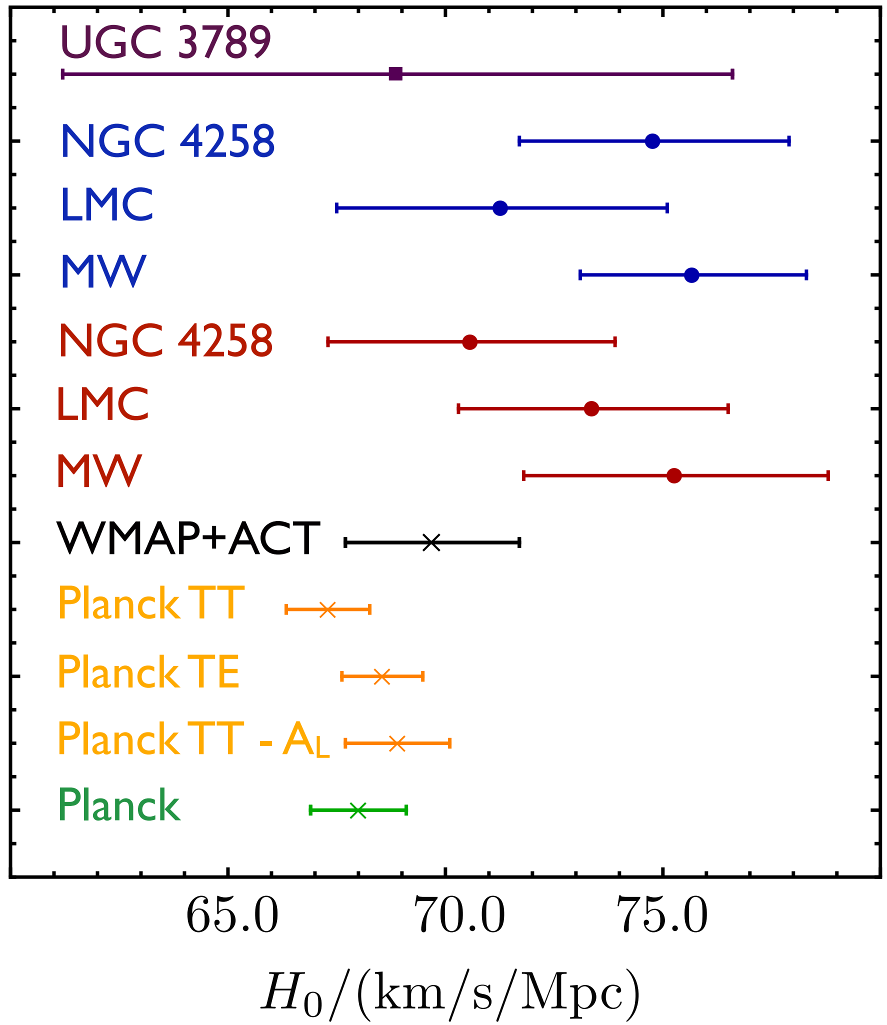
Riess et al. 2011

Efstathiou 2013

Hinshaw et al. 2013

Ade et al. 2015

Spergel, Flauger, Hlozek 2013



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?

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

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

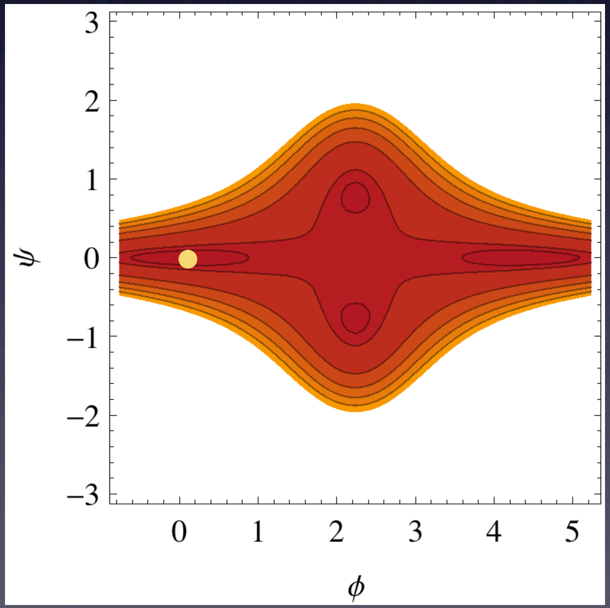
with $$r = \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2}$$

Field Range

- For r>0.01 the inflaton must have moved over a super-Planckian distance in field space. **(Lyth 1996)**
- Motion of the scalar field over super-Planckian distances is hard to control in an effective field theory

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

$$(\Lambda < M_p)$$



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)

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

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

Arkani-Hamed, Motl, Nicolis, Vafa hep-th/0601001

more recently

Rudelius 1503.00795

Brown, Cotrell, Shiu, Soler 1503.04783, 1504.00659

Heidenreich, Reece, Rudelius 1506.03447, 1509.06374

Bachlechner, Long, McAllister 1412.1093, 1503.07853

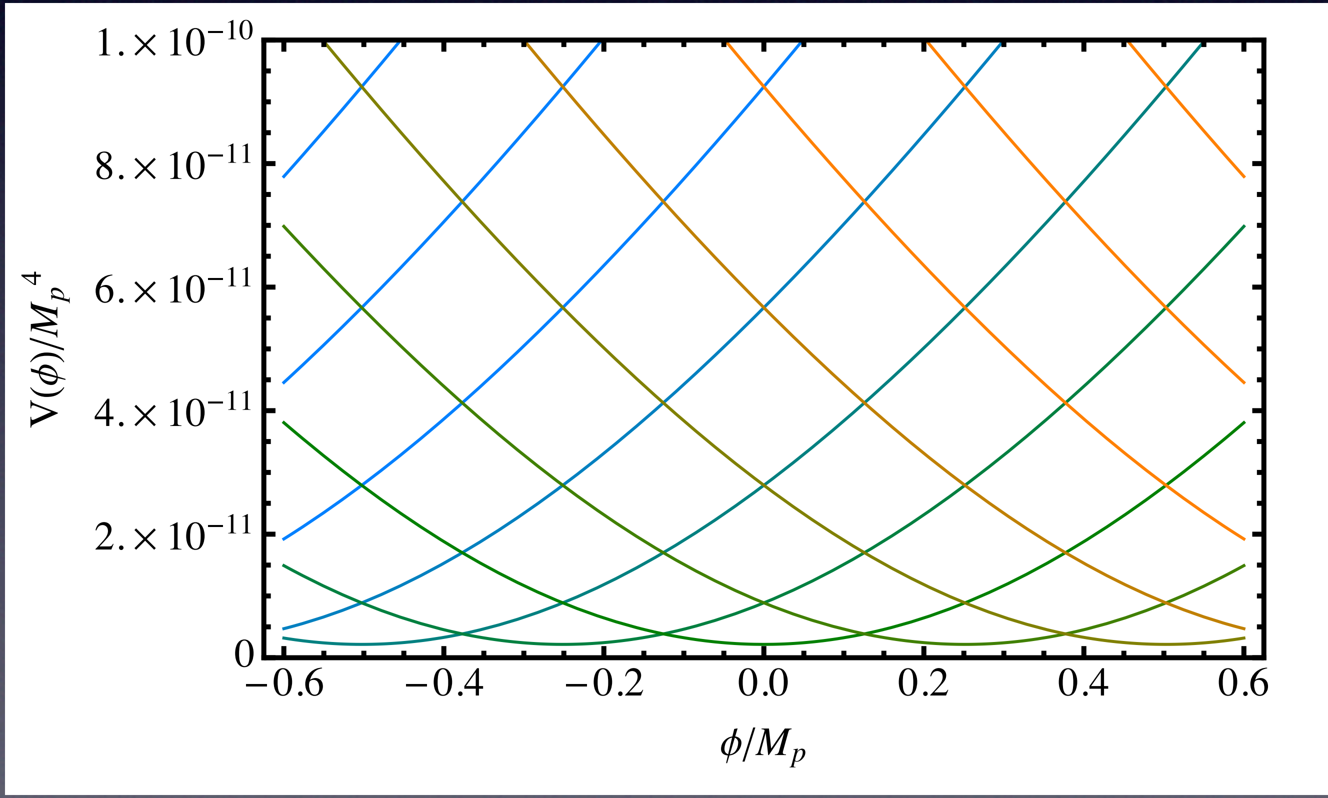
...

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

Axion Monodromy Inflation

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

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



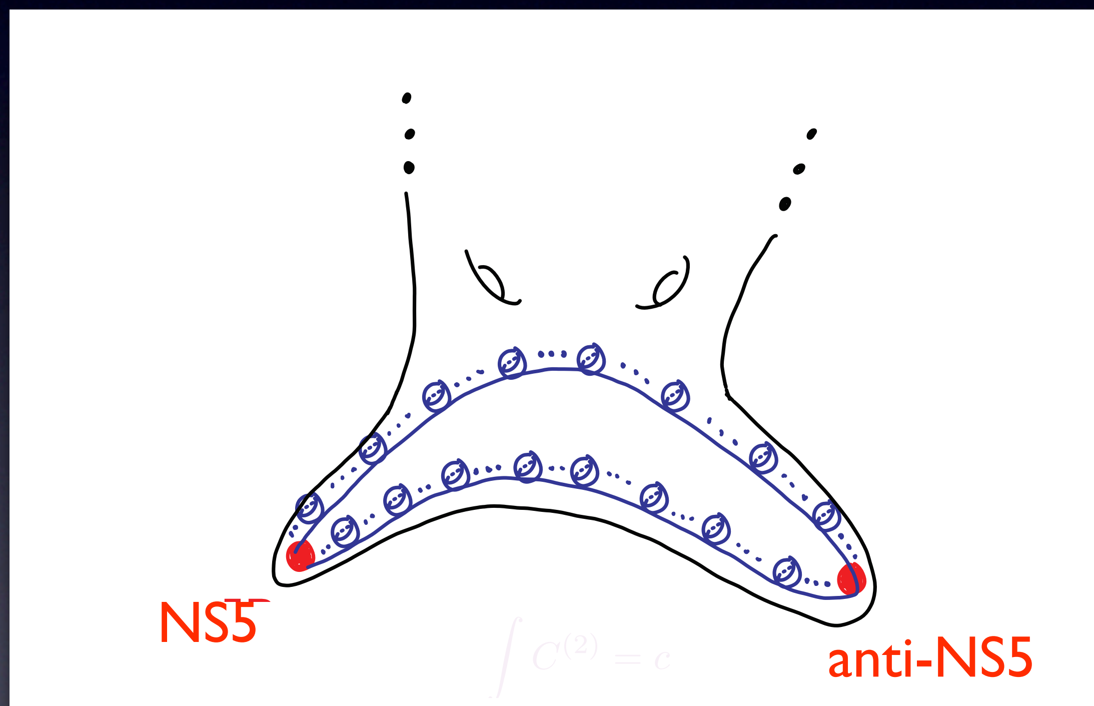
Axion Monodromy Inflation

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

Comic version of axion monodromy inflation



Axion Monodromy Inflation

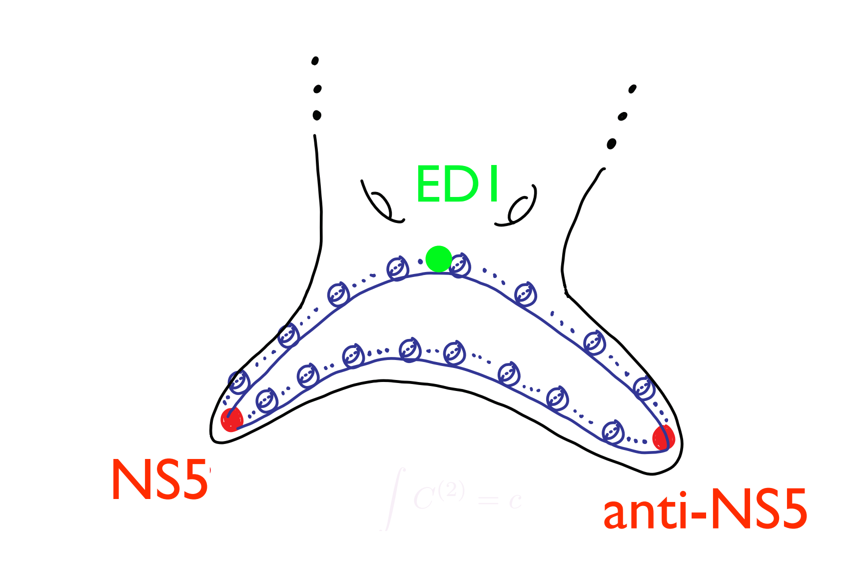
The original axion monodromy model is just one example of a larger class of models with potentials

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

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

Axion Monodromy Inflation

These models often 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

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

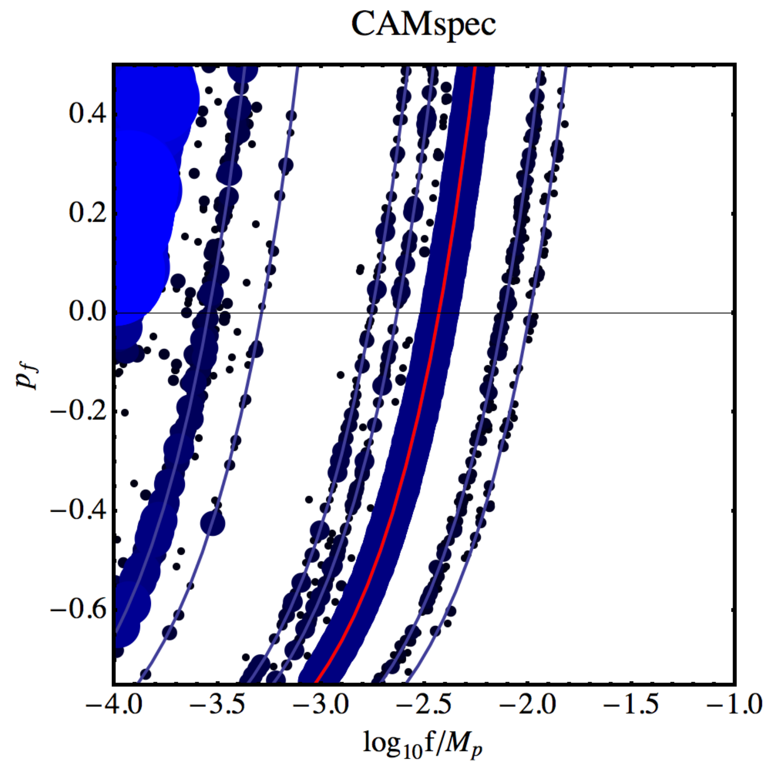
This can be shown to lead to a power spectrum of the form

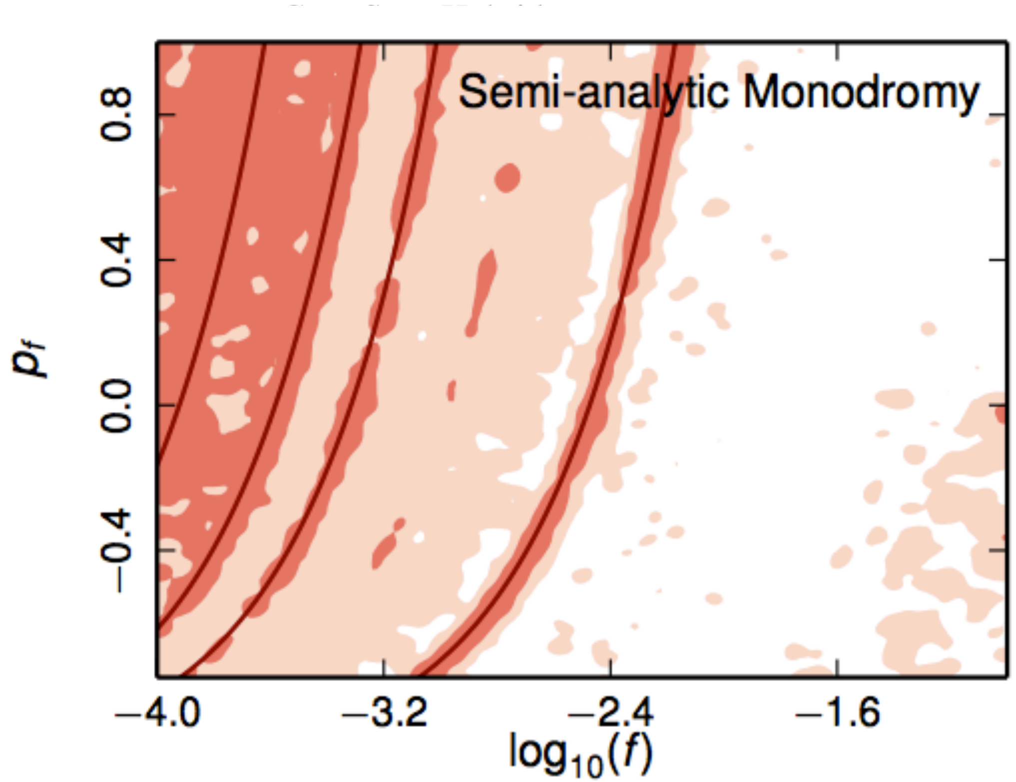
$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}\left(\frac{k}{k_\star}\right)^{n_s-1}\left(1 + \delta n_s \cos\left[\frac{\phi_0}{\tilde{f}}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1} + \Delta\tilde{\varphi}\right]\right)$$

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

Axion Monodromy Inflation

Search for oscillations with drifting period in Planck nominal mission data 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: $\Delta\chi^2 = 16.5 \pm 3.5$

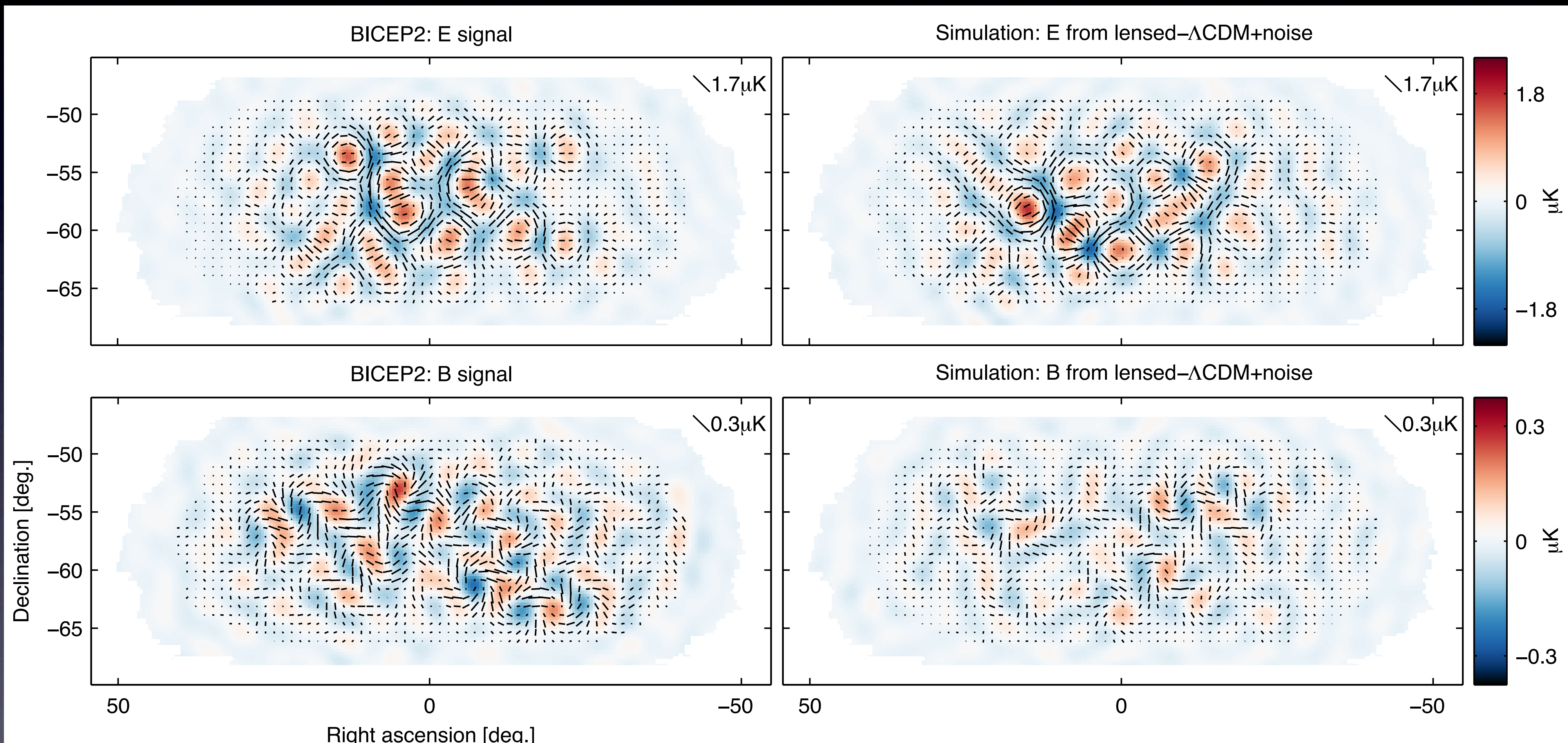
One should keep in mind that not the entire parameter space was searched and more work is required, but as of now there is no evidence for oscillations in the primordial power spectrum.

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

Experimental Constraints on r

BICEP2 polarization data

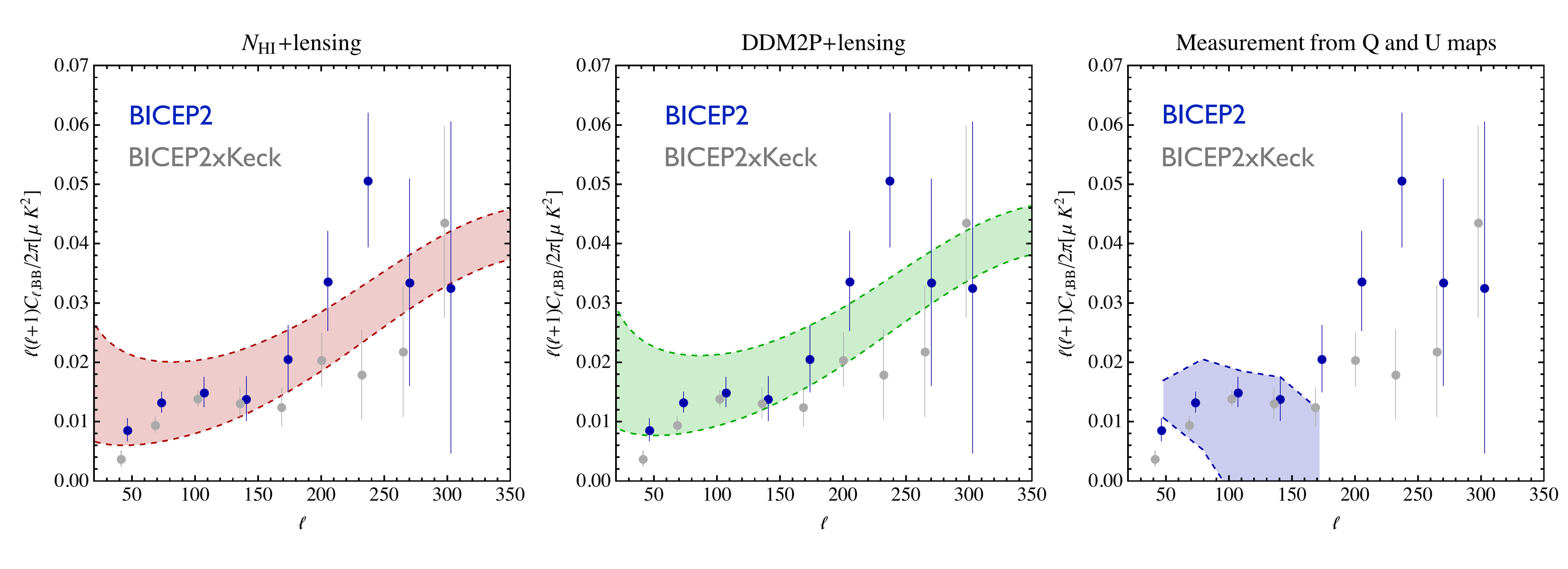


Noise level: 87 nK deg - the deepest map at 150 GHz of this patch of sky

(Planck noise level: few μK deg)

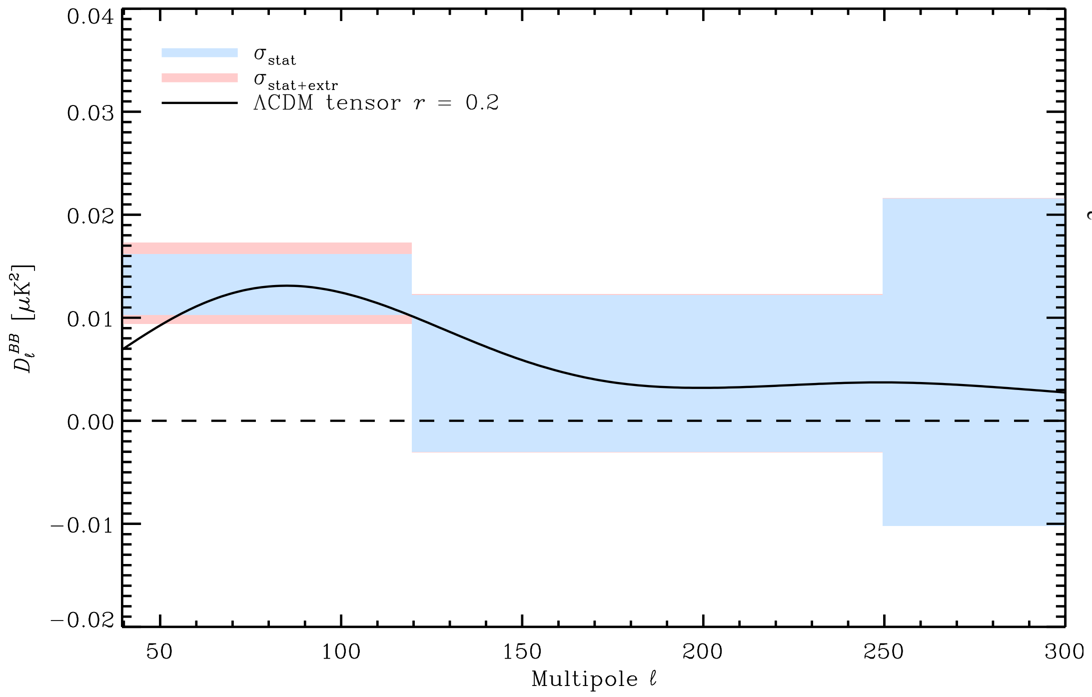
Experimental Constraints on r

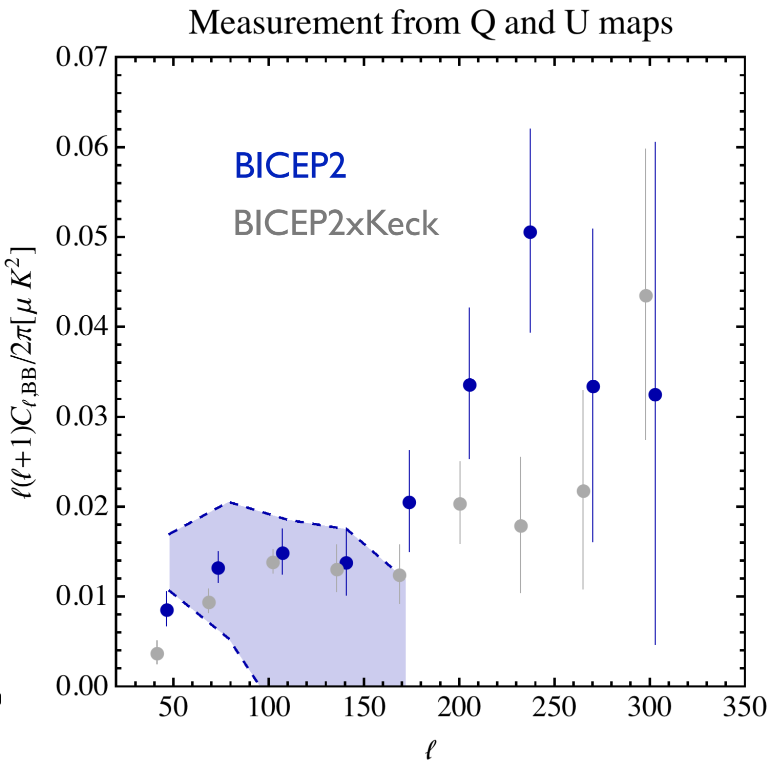
Foreground models made in collaboration with David Spergel, Colin Hill, and Aurelien Fraisse



Experimental Constraints on r

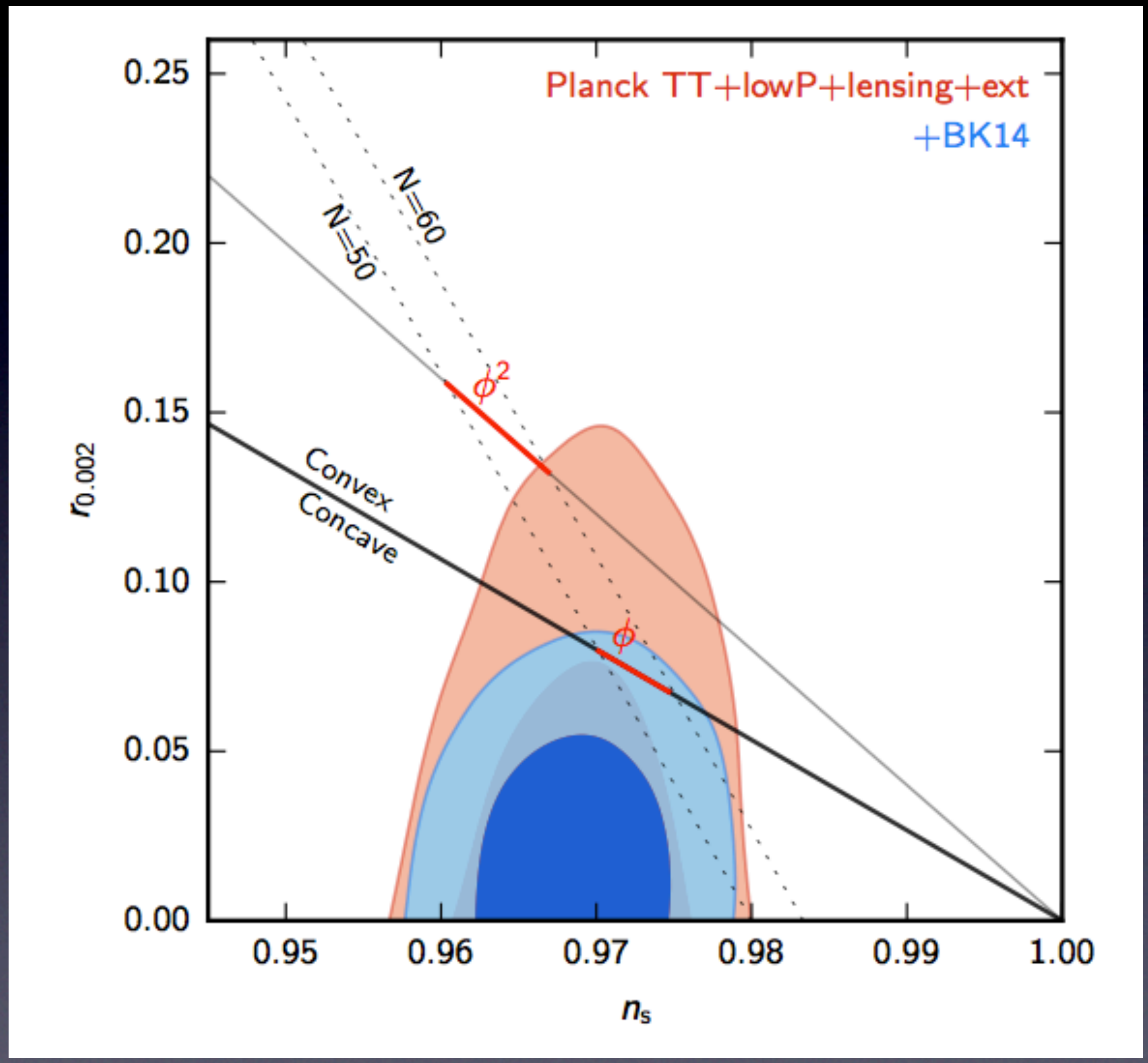
- measurement of BB in the BICEP2 region at 353 GHz rescaled to 150 GHz





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

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.

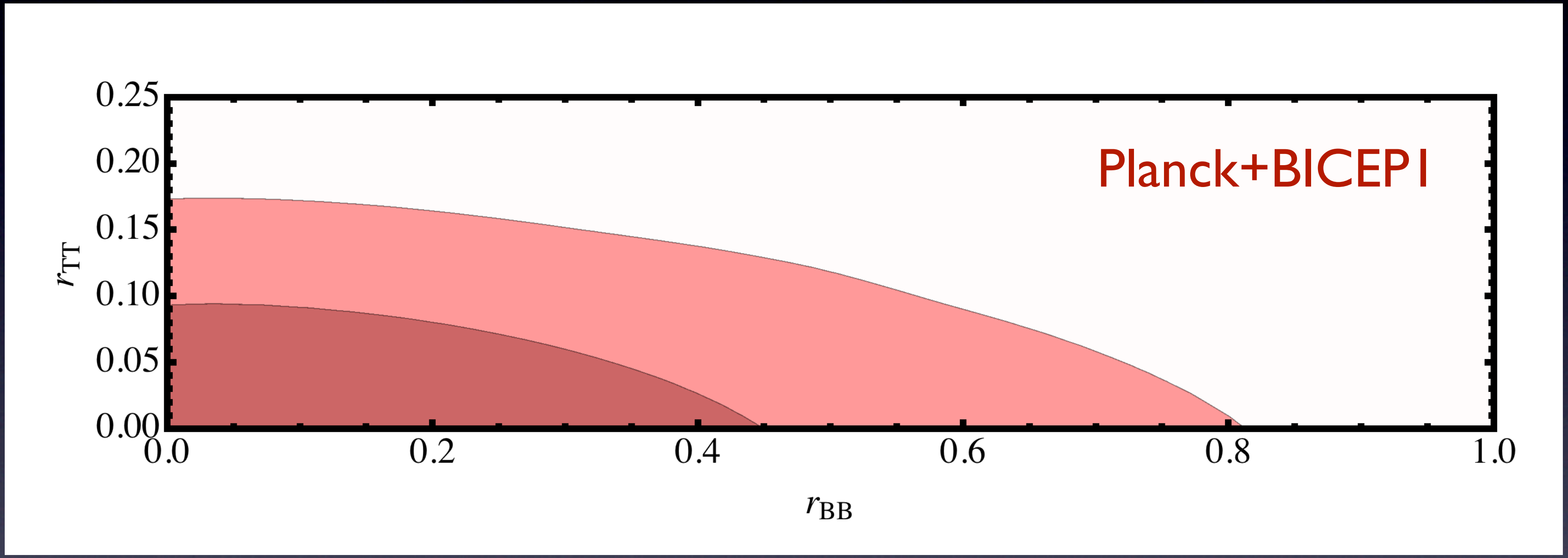
The two likelihood are essentially independent

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

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

Experimental Progress on r

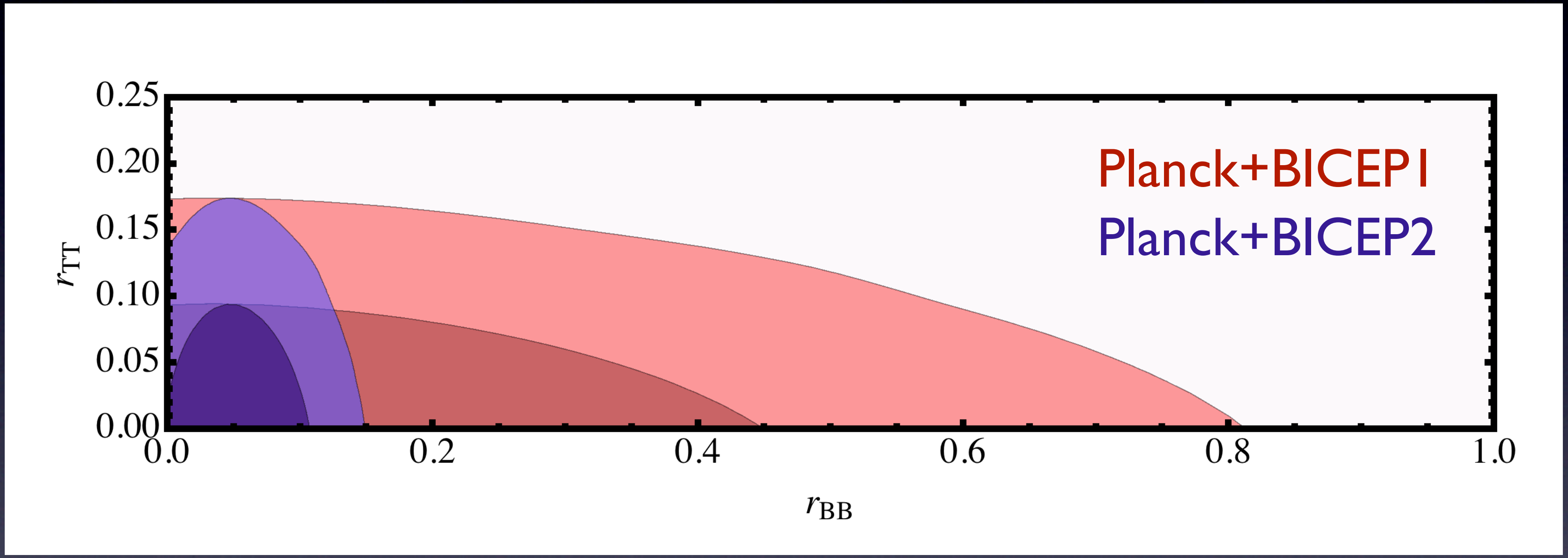
$\mathcal{L}(r_{TT}, r_{BB})$ before March



Constraint dominated by temperature data

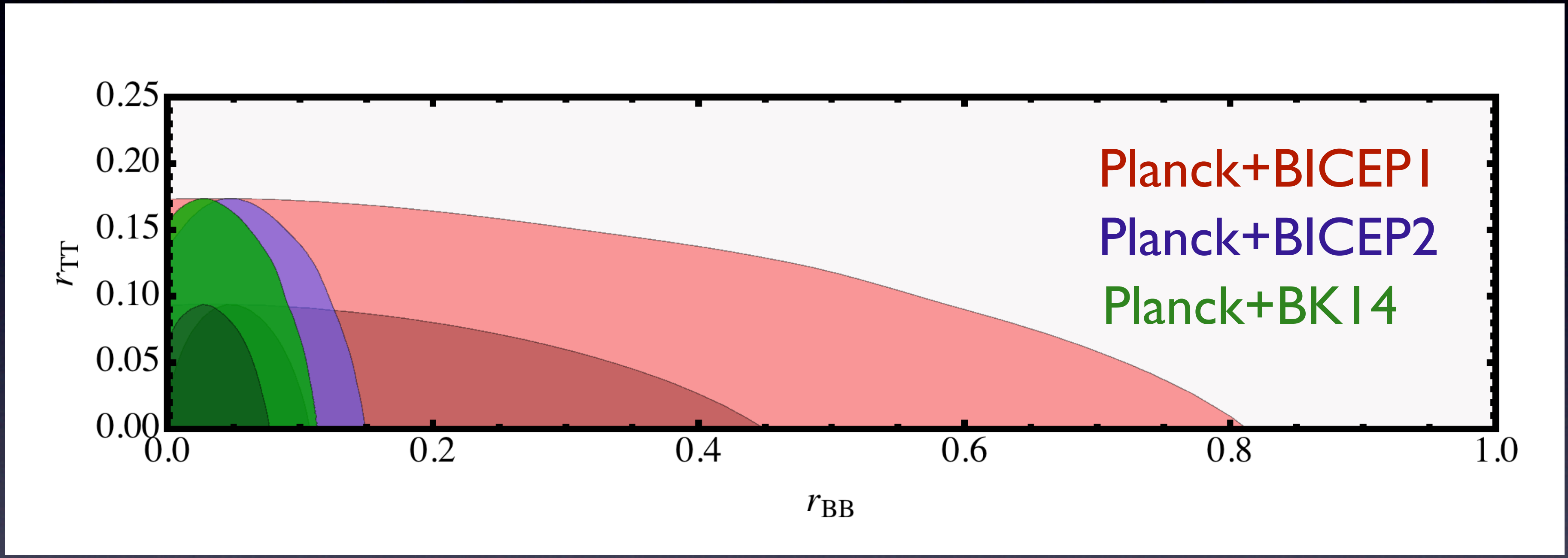
Experimental Progress on r

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

Experimental Progress on r

ongoing and upcoming:

Ground: BICEP2, Keck Array, BICEP3, SPTPol/SPT3G, ACTPol/AdvACT, ABS, CLASS, POLARBEAR/Simons Array, C-BASS, QUIJOTE, B-Machine,...

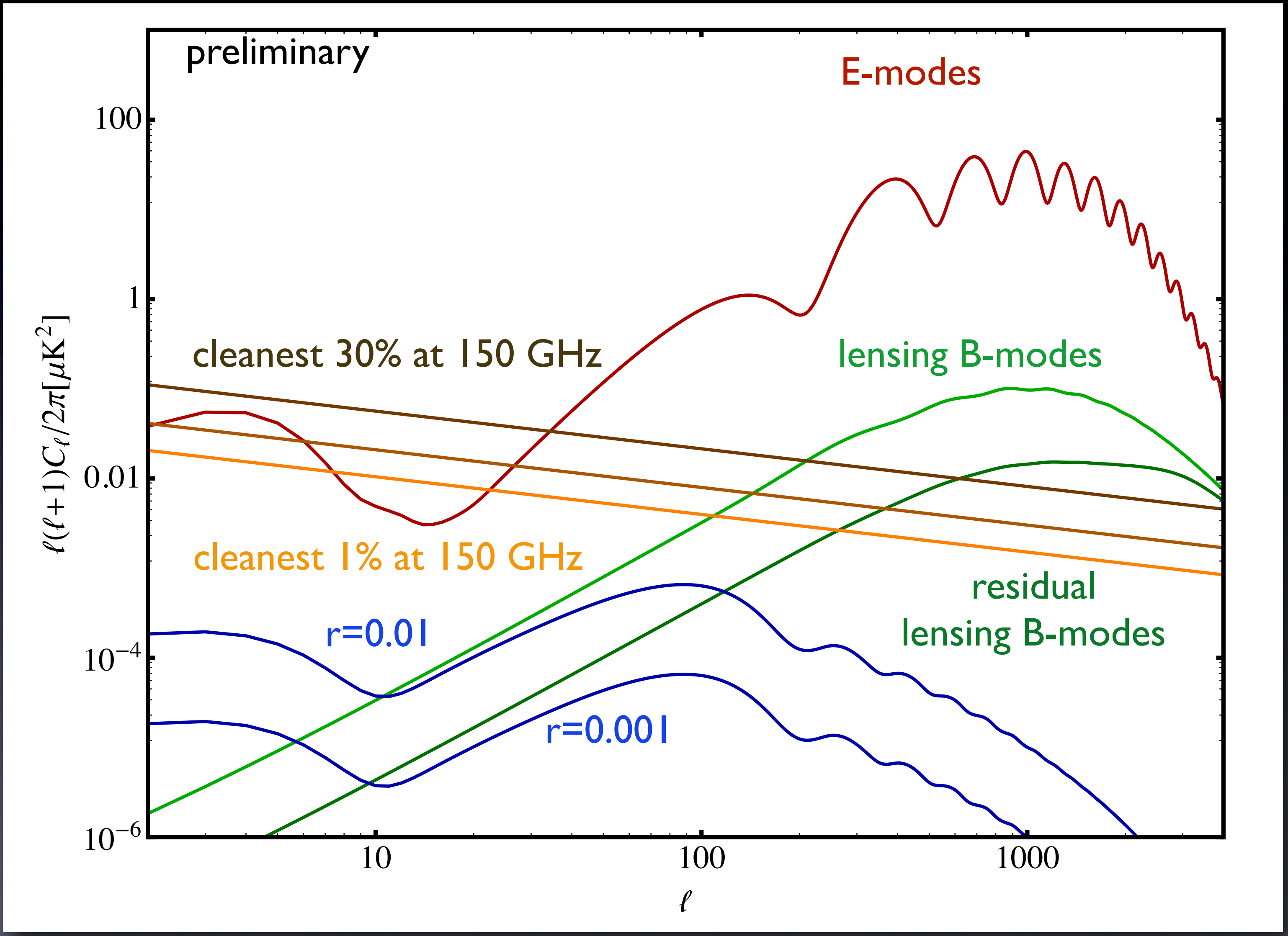
Balloon: EBEX, SPIDER, PIPER

future (>5 years)

Ground: CMB Stage IV

Satellite: LiteBIRD, PIXIE,...

Experimental Progress on r

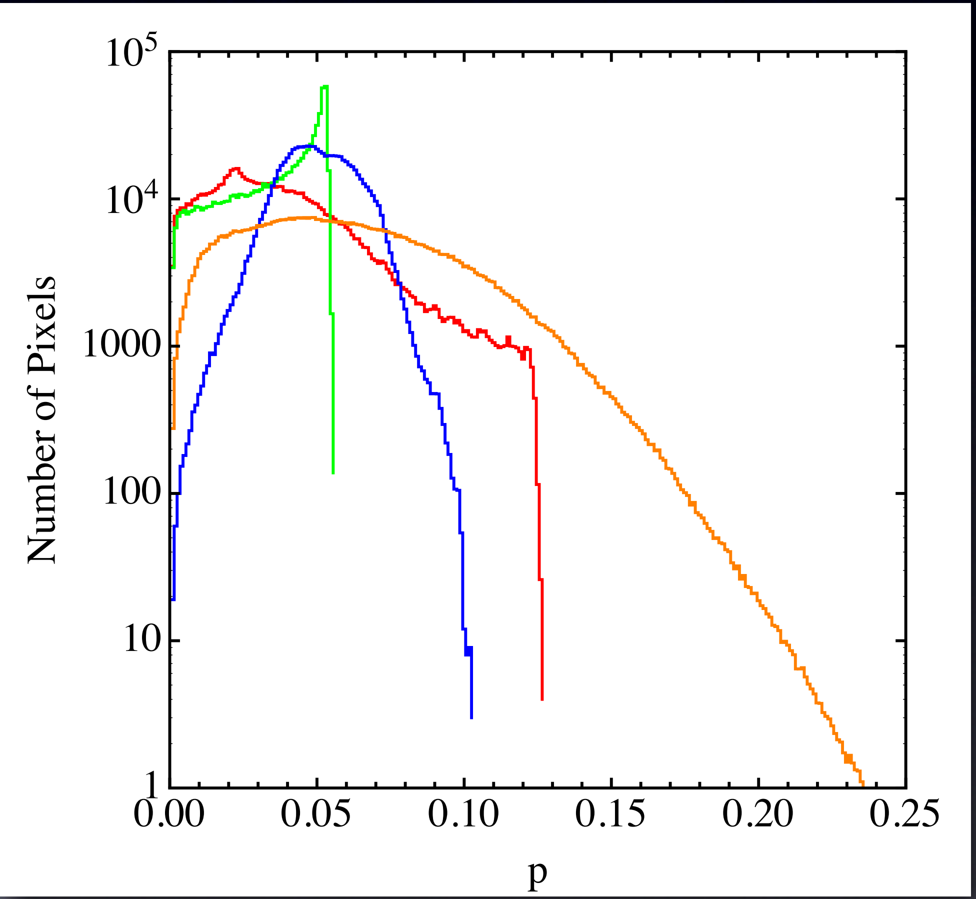


Experimental Progress on r

Forecasting exactly how well it can do is difficult given our current level of understanding of foregrounds.

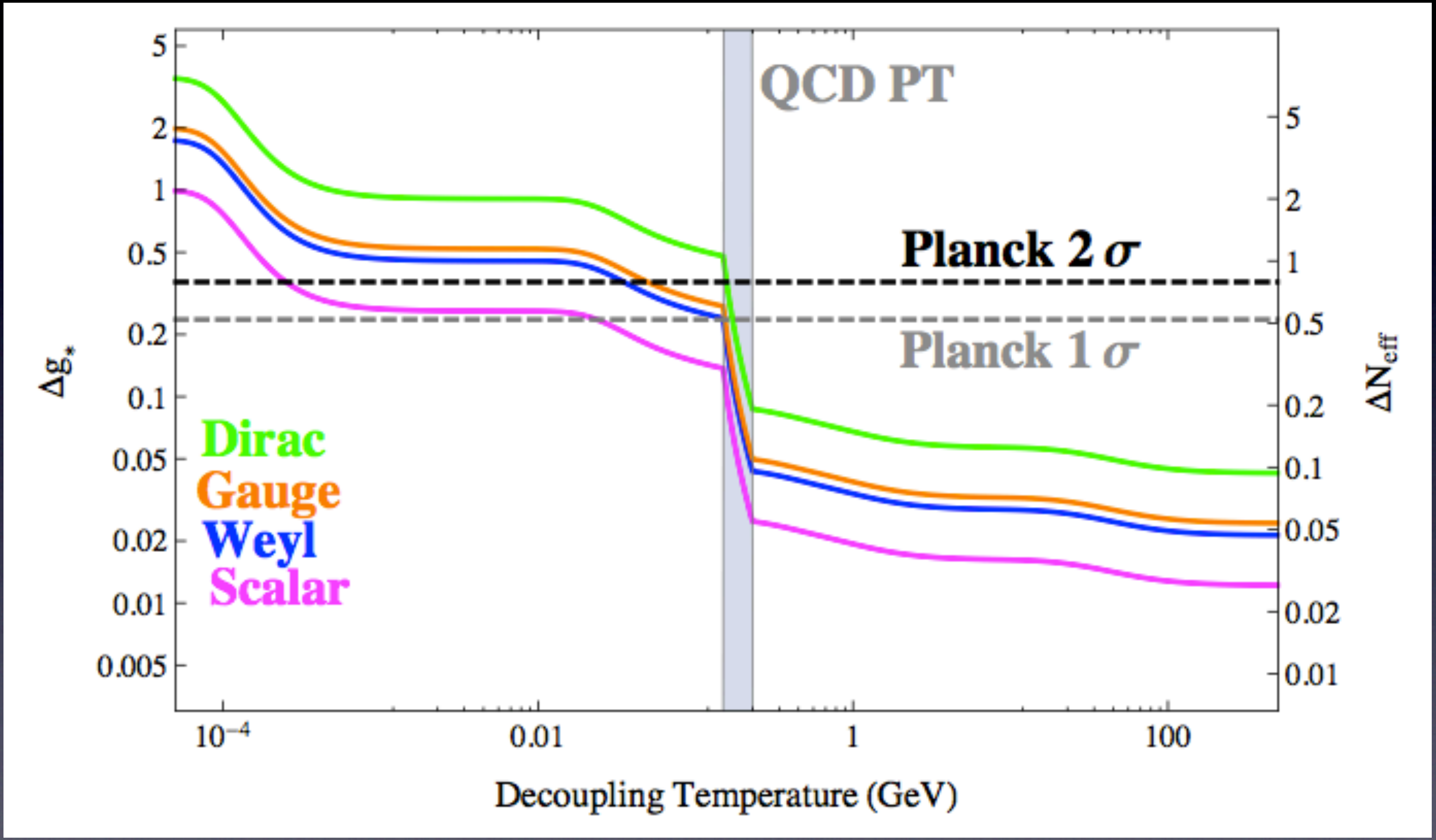
Models for polarized foreground need three ingredients, typically

- Intensity map
- Polarization fraction
- Polarization angles



Planck helps on large scales at frequencies 150 GHz and up.

$N_{\rm eff}$



$\sigma_{\rm CMBS4}(N_{\rm eff}) \approx 0.02$

Brust, Kaplan, Walters 1303.5079

Conclusions

- The LCDM model with inflationary spectrum of perturbations is consistent with all current cosmological data.
- The CMB will continue to provide valuable information about primordial gravitational waves, neutrino masses, the number of effective relativistic degrees of freedom, dark matter, ...
- Large scale structure surveys will provide a useful counter part
- The next decade should be very interesting in cosmology

Thank you