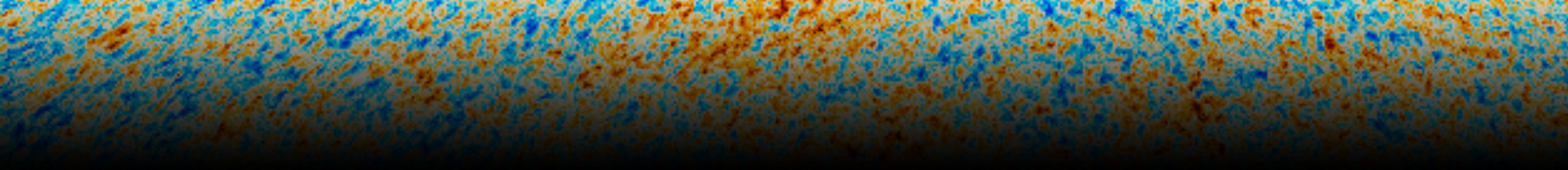


Implications of CMB Observations

Raphael Flauger

SUSY 2015, Lake Tahoe, CA, August 26, 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

CMB@50

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.

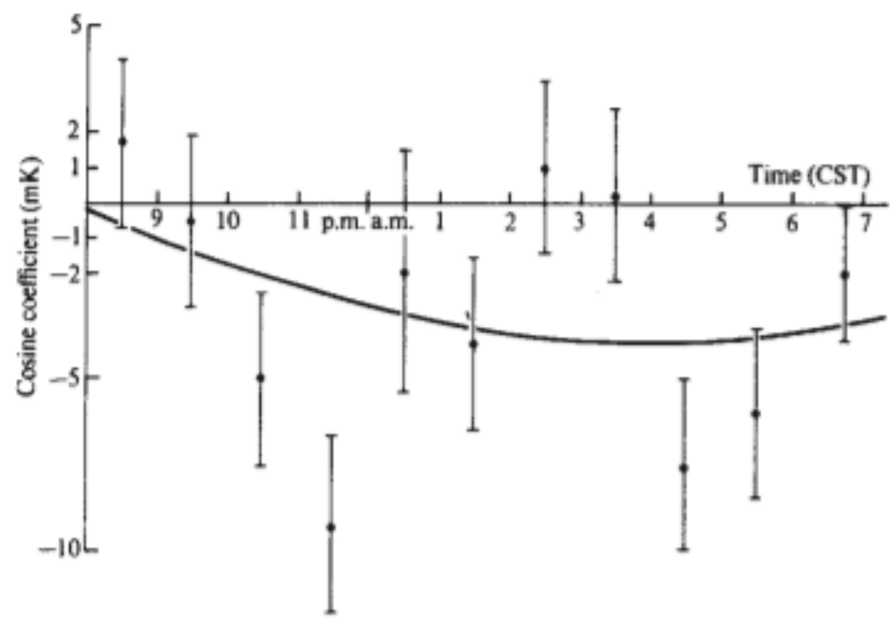
Isotropy of the 3 K Background

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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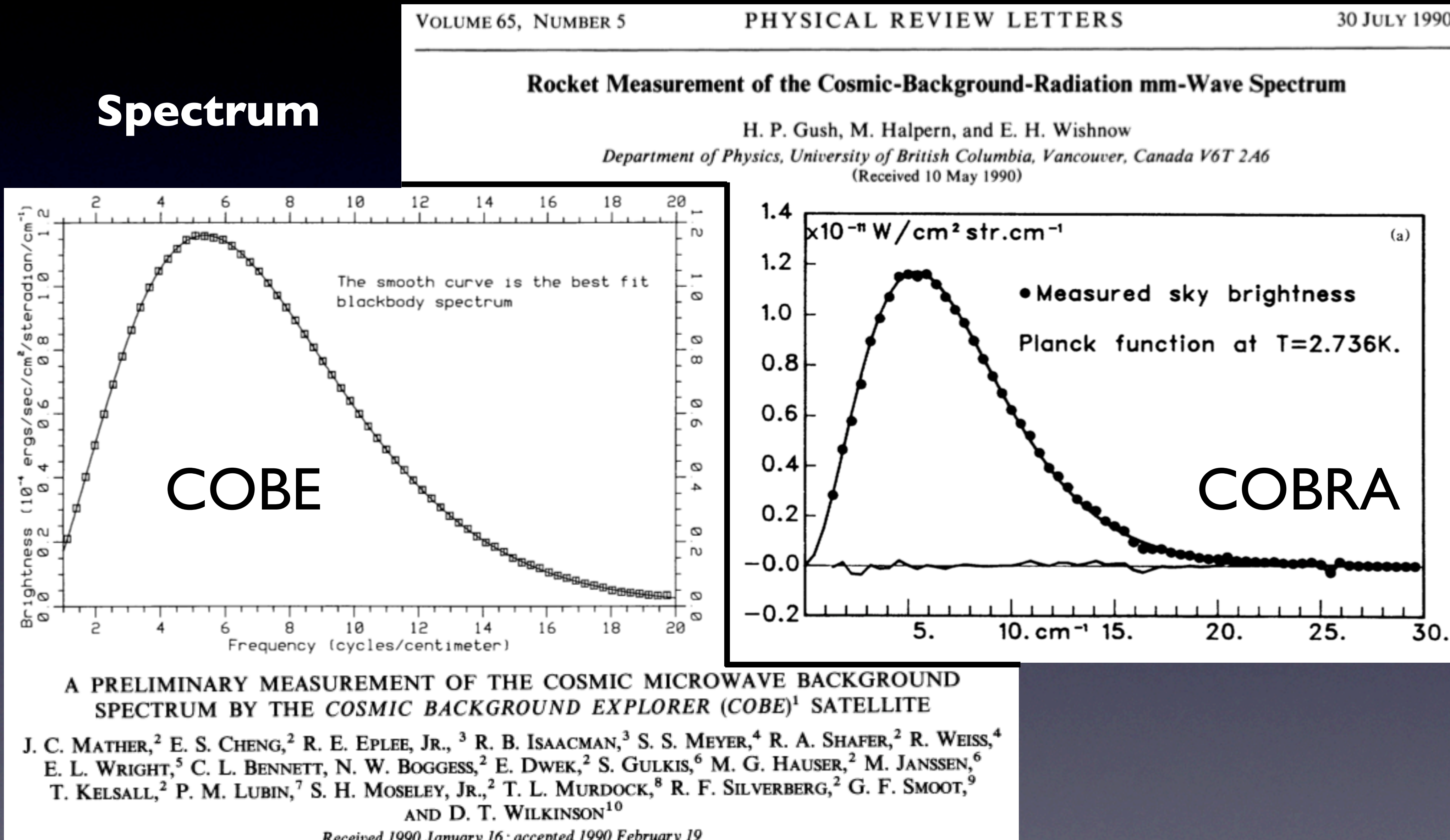
Spectrum


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

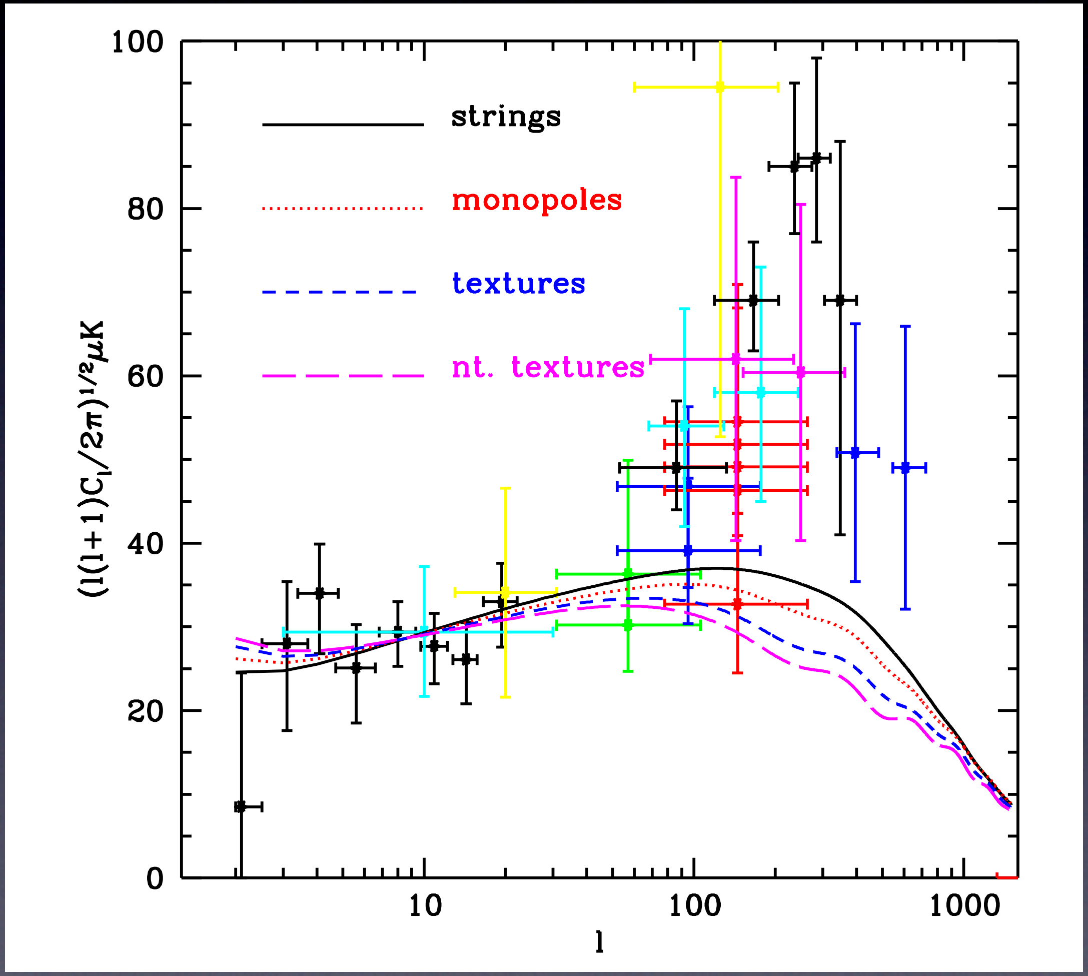
J. C. MATHER,[2] E. S. CHENG,[2] R. E. EPLEE, JR.,[3] R. B. ISAACMAN,[3] S. S. MEYER,[4] R. A. SHAFER,[2] R. WEISS,[4] E. L. WRIGHT,[5] C. L. BENNETT, N. W. BOGGESS,[2] E. DWEK,[2] S. GULKIS,[6] M. G. HAUSER,[2] M. JANSSEN,[6] T. KELSALL,[2] P. M. LUBIN,[7] S. H. MOSELEY, JR.,[2] T. L. MURDOCK,[8] R.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

Received 1990 January 16; accepted 1990 February 19

CMB@50

(Pen, Seljak, Turok 1997)

Angular Power Spectrum



Until ca. 1997 data was consistent with defects (such as strings) generating the primordial perturbations.

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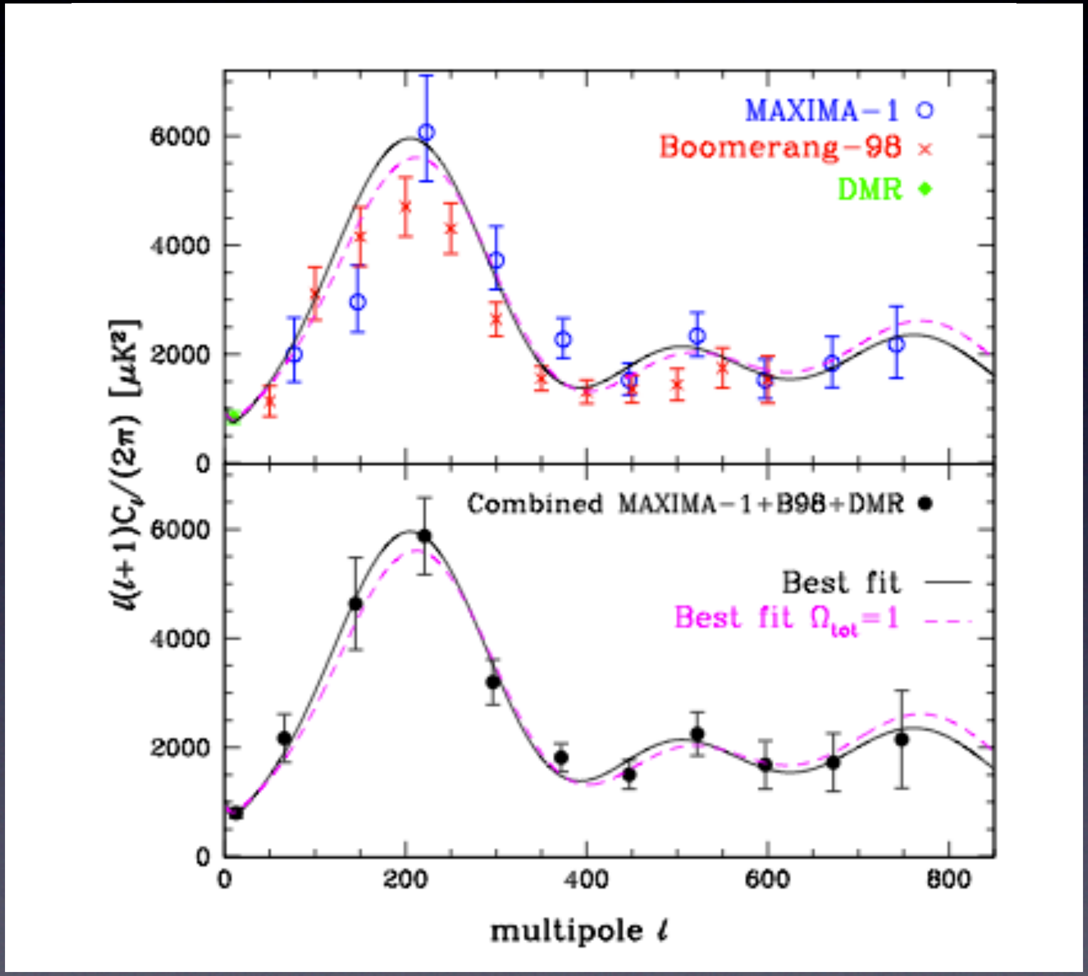
(Jaffe et al. 2001)

Angular Power Spectrum



Shortly after it became clear that defects were not the dominant source of primordial perturbations.

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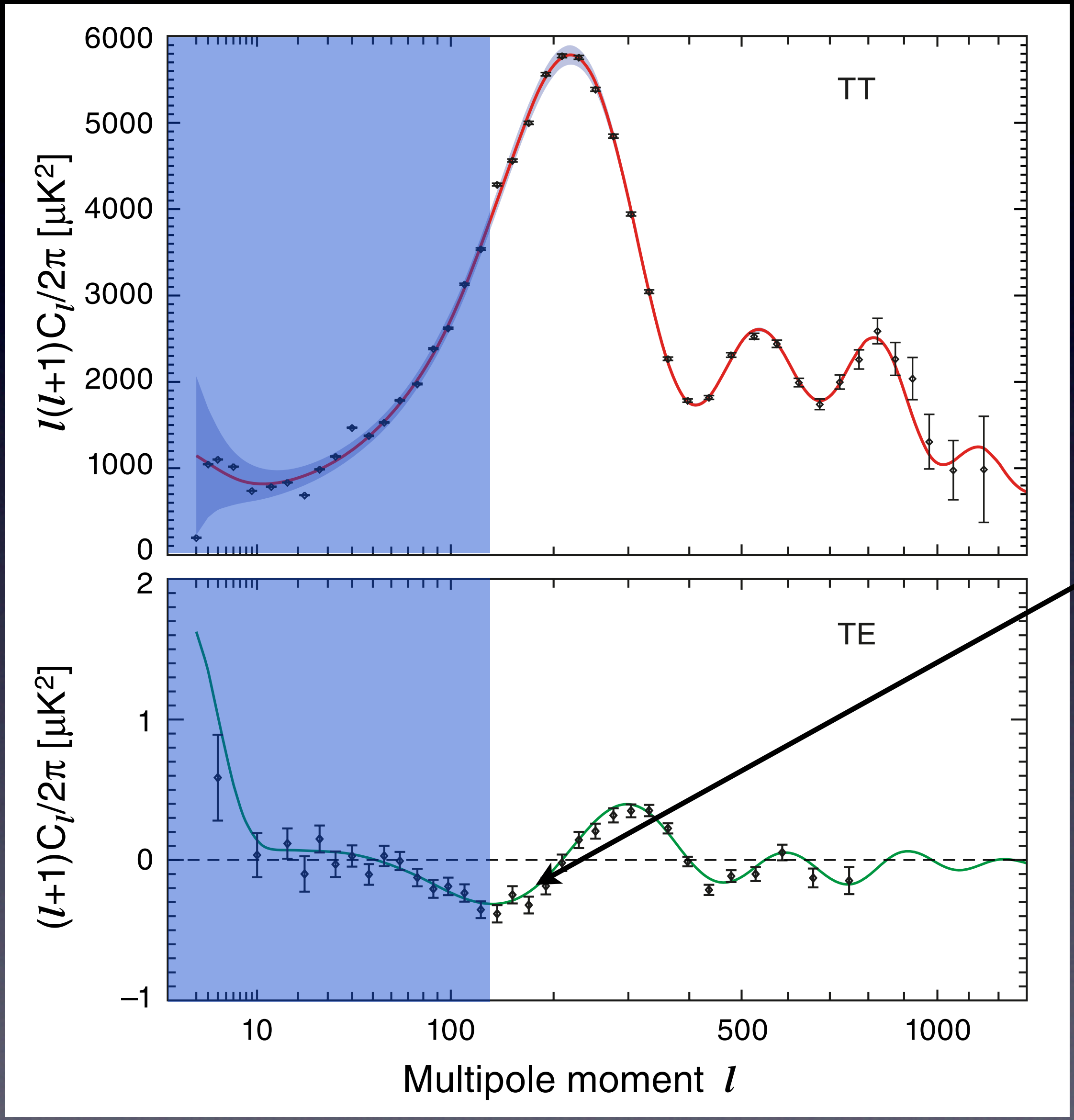

Perturbations exist on scales larger than the Hubble radius at recombination.

Implies these perturbations already existed at recombination

Together with General Relativity it means they existed before the hot big bang!

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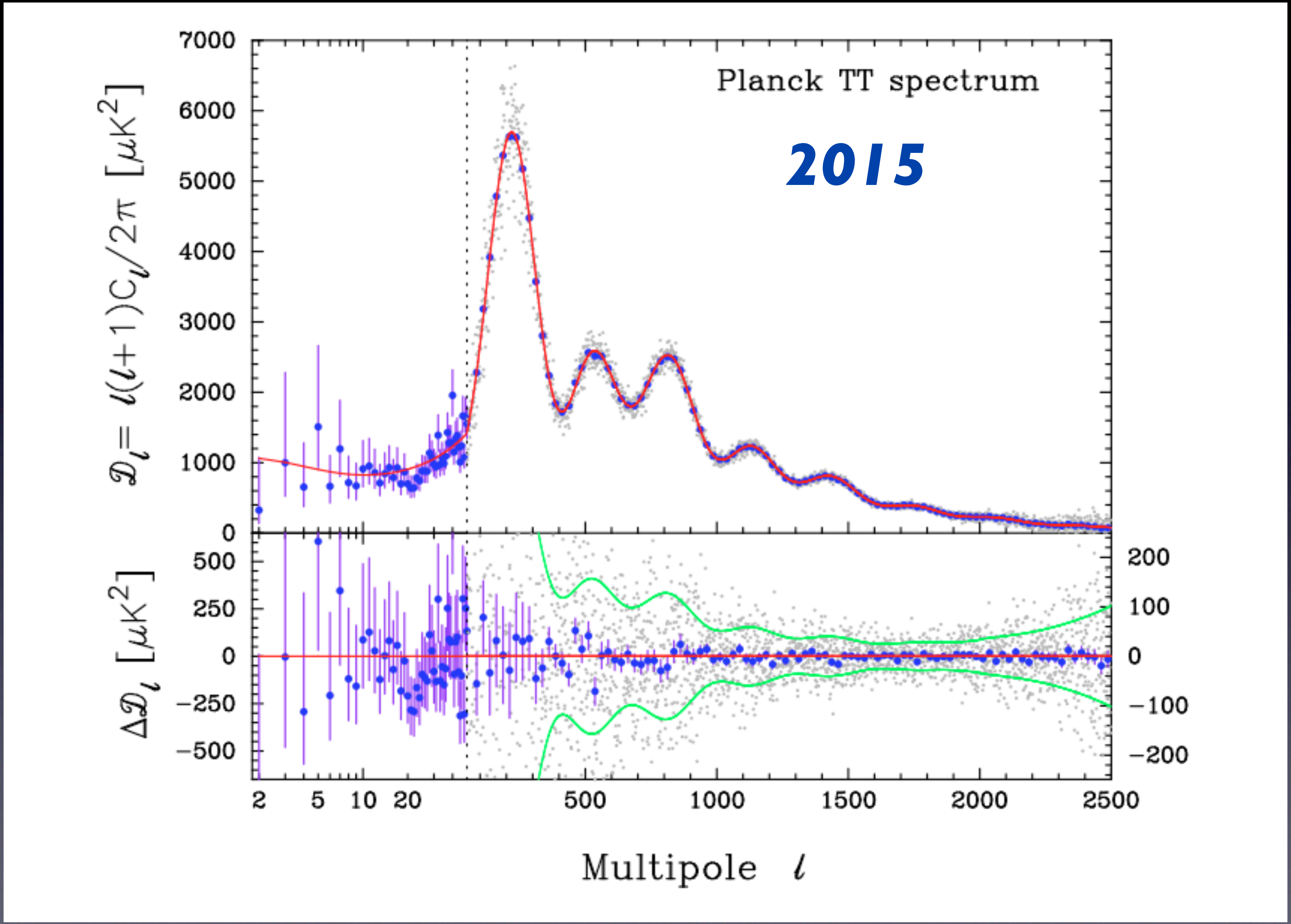
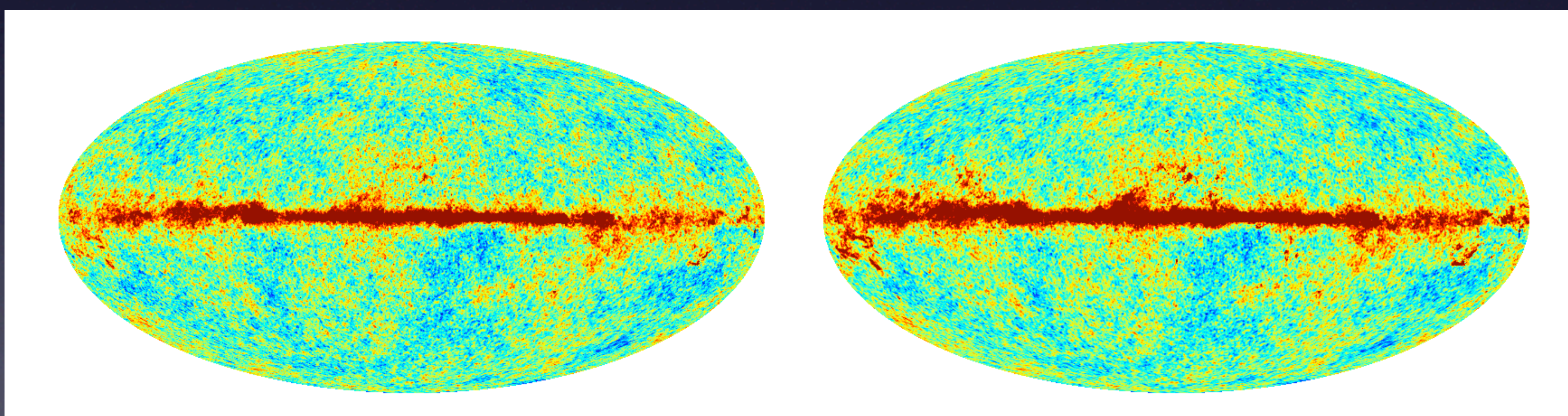


Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500
Multipole ℓ

Planck & WMAP

- Planck agrees very well with WMAP at WMAP resolution

WMAP 94 GHz Planck 100 GHz

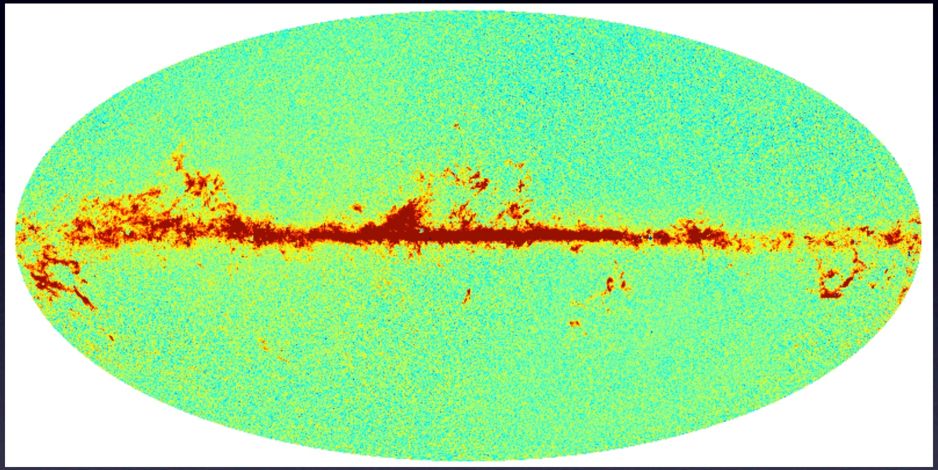


(N_{side}=512)

Planck & WMAP

Planck 100 GHz

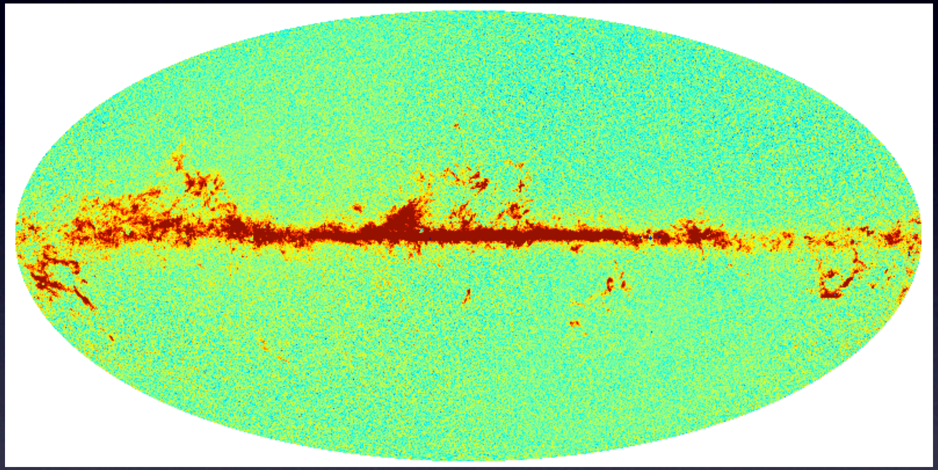
- WMAP 94 GHz =



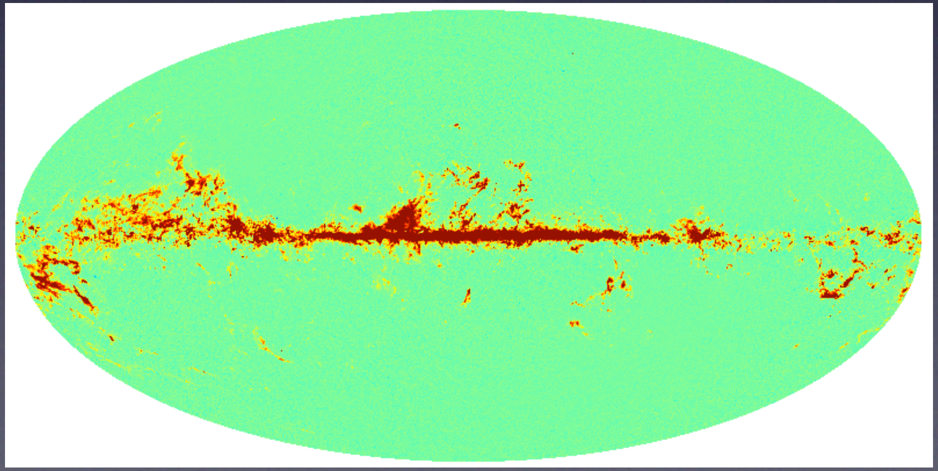
Planck & WMAP

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

Planck 100 GHz
- WMAP 94 GHz =



vs Planck CO$(1-0)$ map

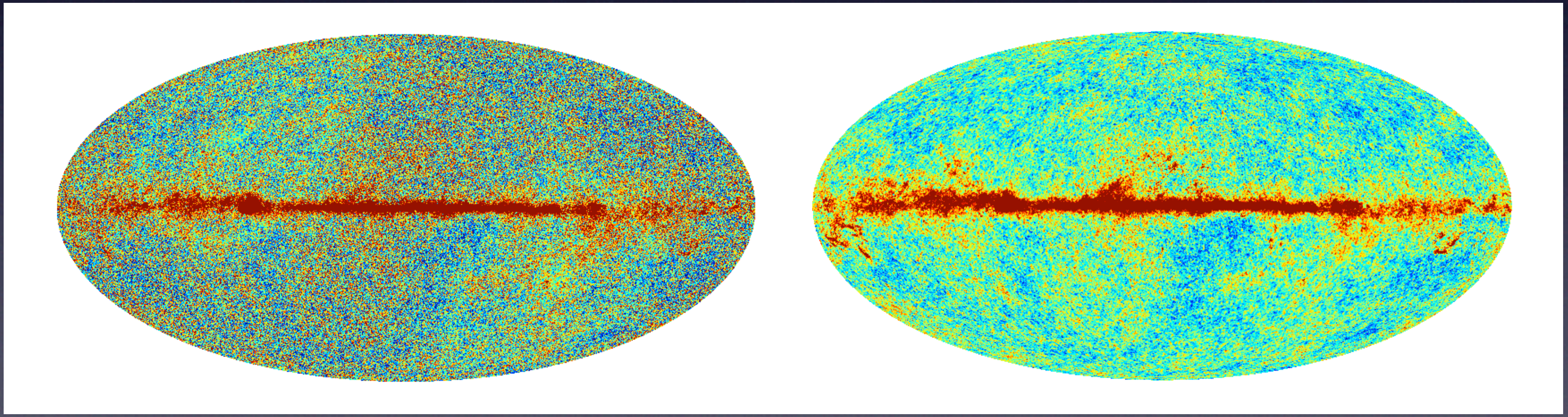


Planck & WMAP

- Planck agrees very well with WMAP at WMAP resolution
- but is much more powerful

WMAP 94 GHz

Planck 100 GHz



(N_{side}=1024)

LCDM

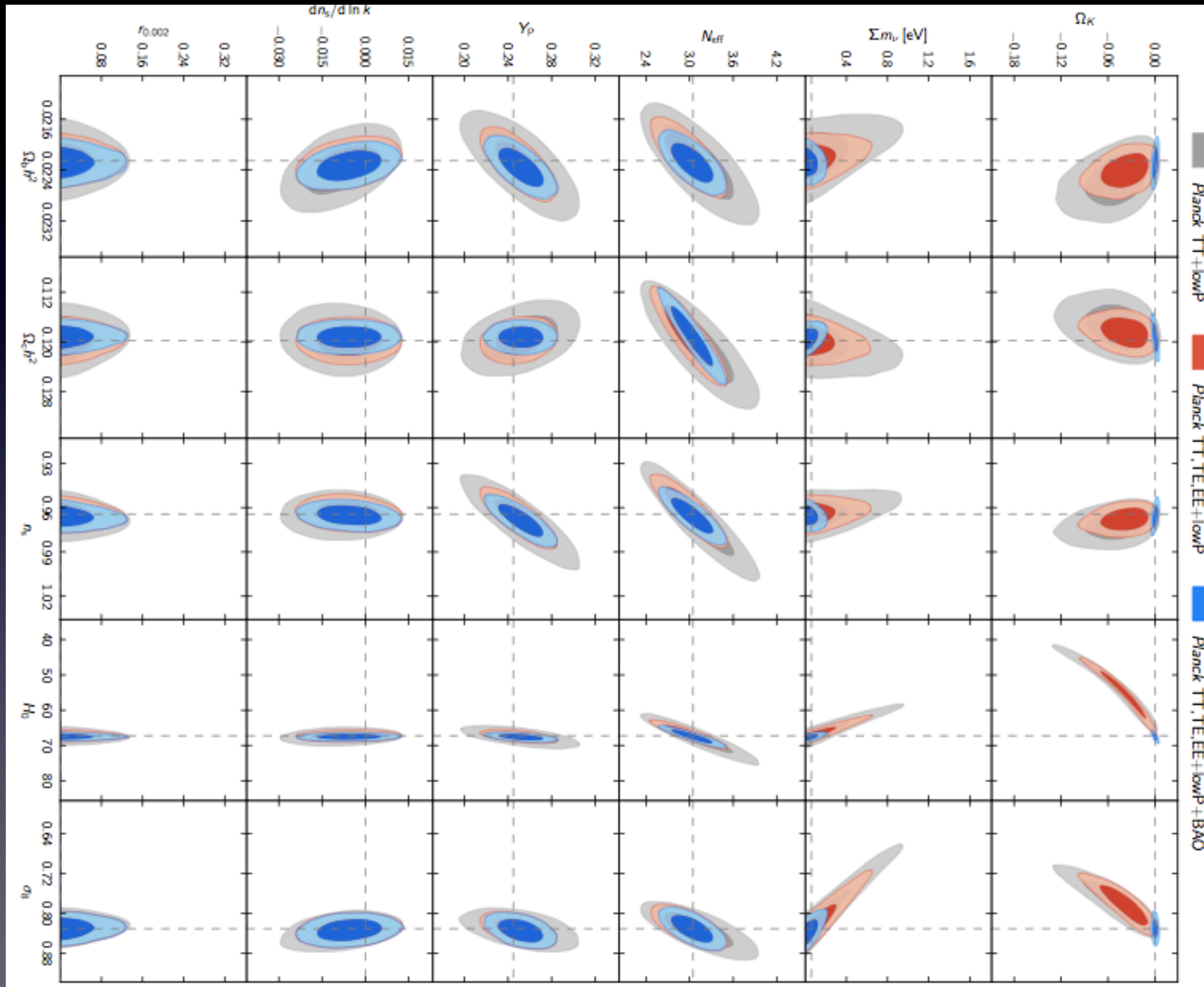
We have learned that the early universe is remarkably simple and the CMB temperature data is in good agreement with the six-parameter LCDM model.

(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

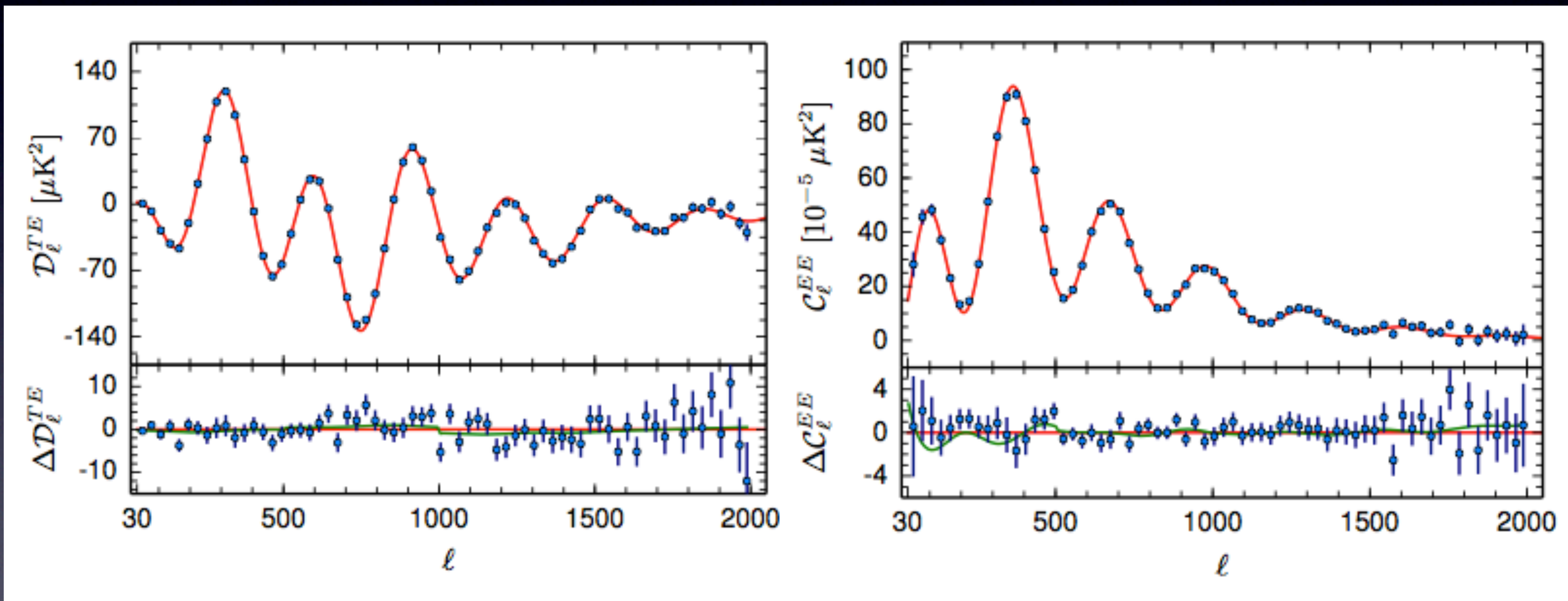
LCDM+X



(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



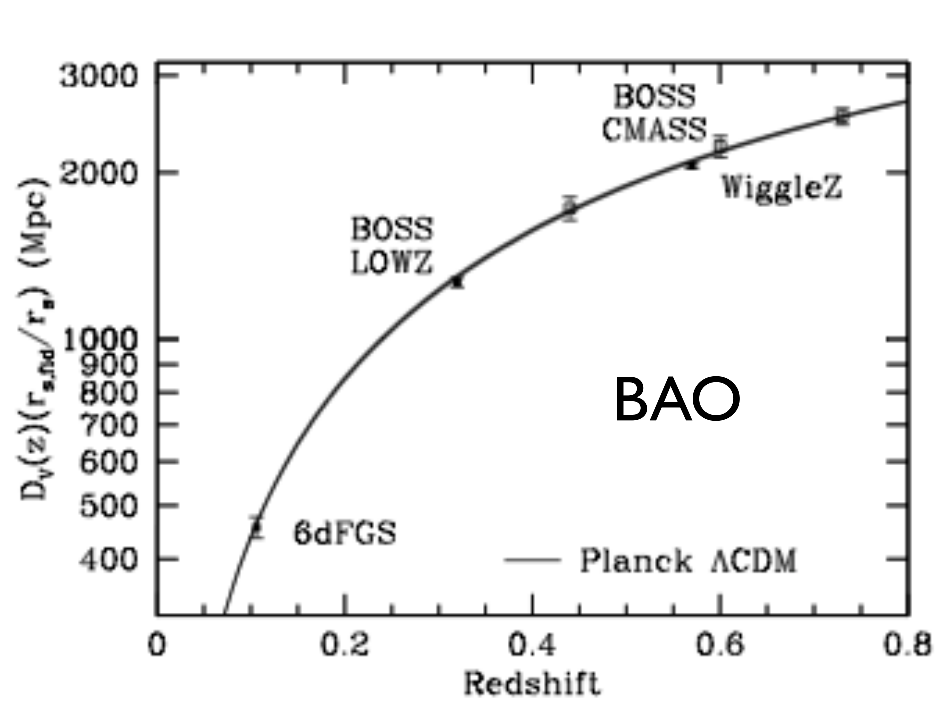
(Ade et al. 2015)

(systematics remain to be understood)

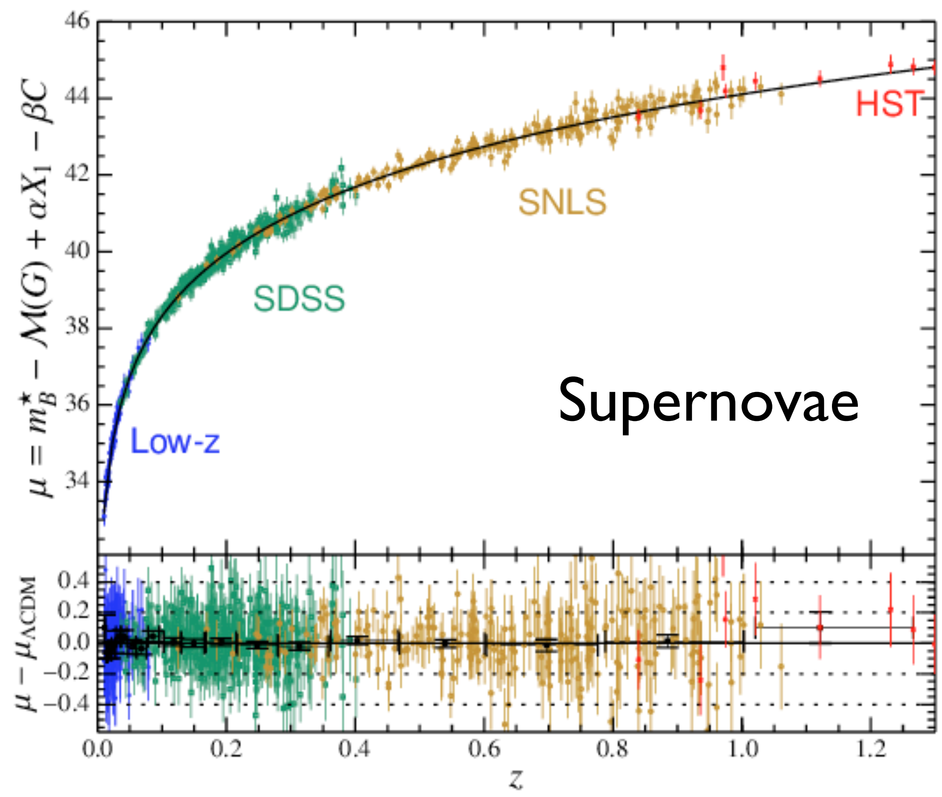
LCDM

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

LCDM

LCDM describes our universe remarkably well on large scales, but raises many questions

- What is dark energy?
- What is dark matter?
- What is the origin of the baryon asymmetry?
- What is the neutrino mass scale and hierarchy?
- What is the origin of neutrino mass?
- What generated the primordial perturbations?

Generating Primordial Perturbations

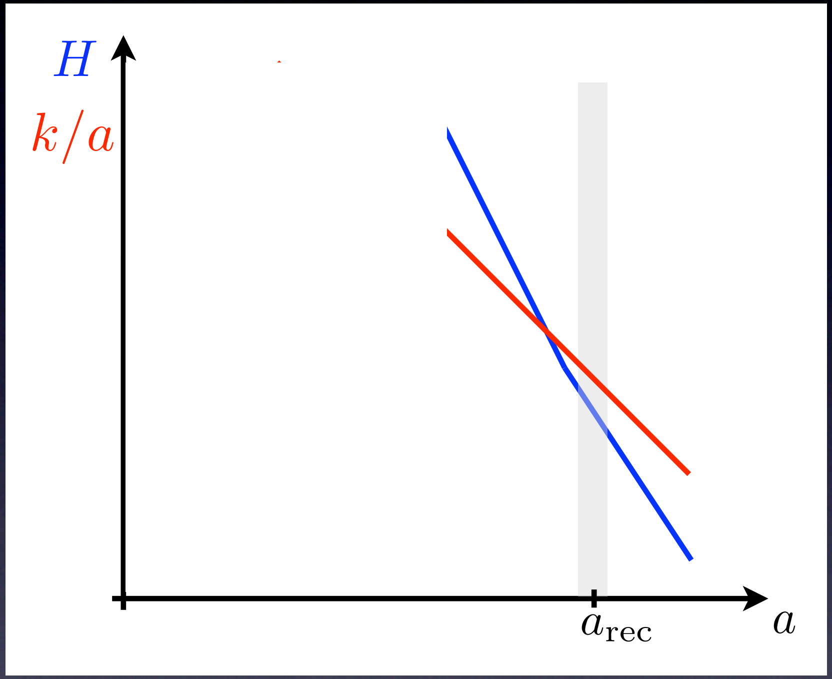
Measurements of the CMB have taught us that the primordial perturbations

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

but 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

$$\frac{d}{dt}\left(\frac{k}{a|H|}\right) < 0$$

(inflation or bounce)

Inflation

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

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

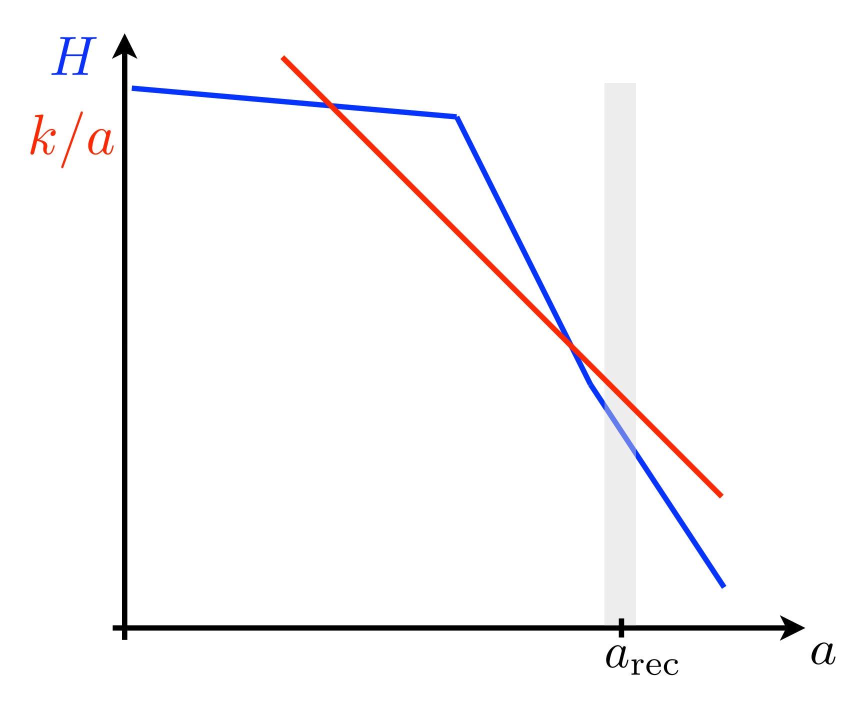
$$-\int d^4x\sqrt{-g}\;\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}m^2\phi^2\right)$$

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

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

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

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

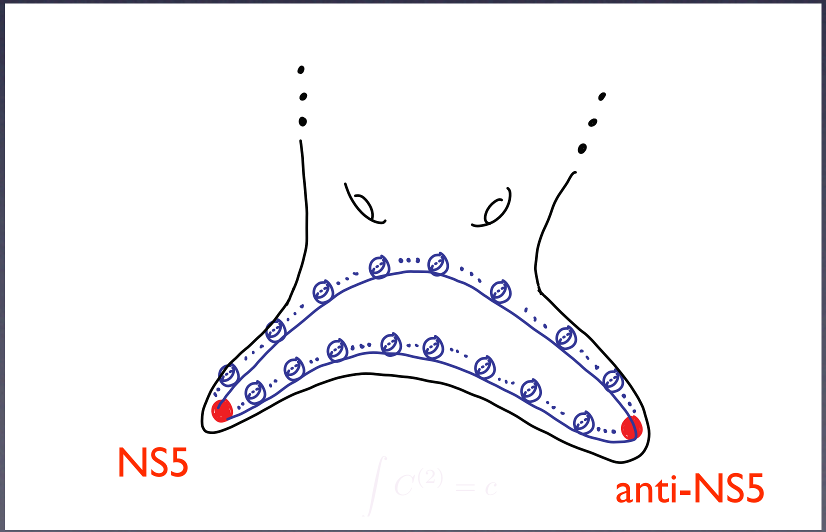
with $$r = \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2}$$

Field Range

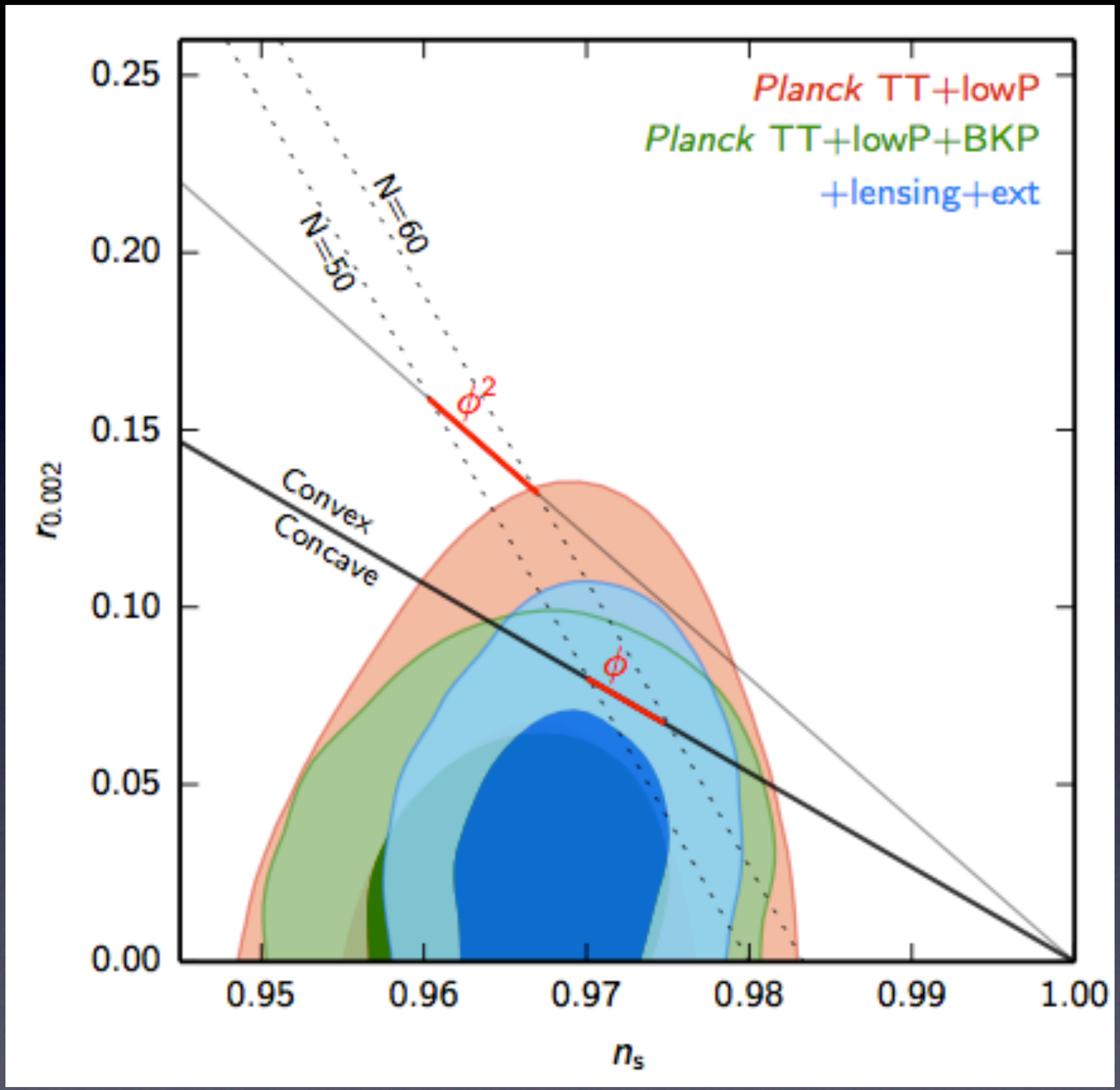
- For r>0.01 the inflaton must have moved over a super-Planckian distance in field space. **(Lyth 1996)**

$$\Delta\phi \approx \Delta N \sqrt{\frac{r}{8}} M_p \approx \sqrt{\frac{r}{0.01}} M_p$$

- This suggest a systematic study in the context of string theory.



Experimental Constraints on r



$$V_{\rm inf}^{1/4} < 1.8 \times 10^{16}\, GeV$$

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.

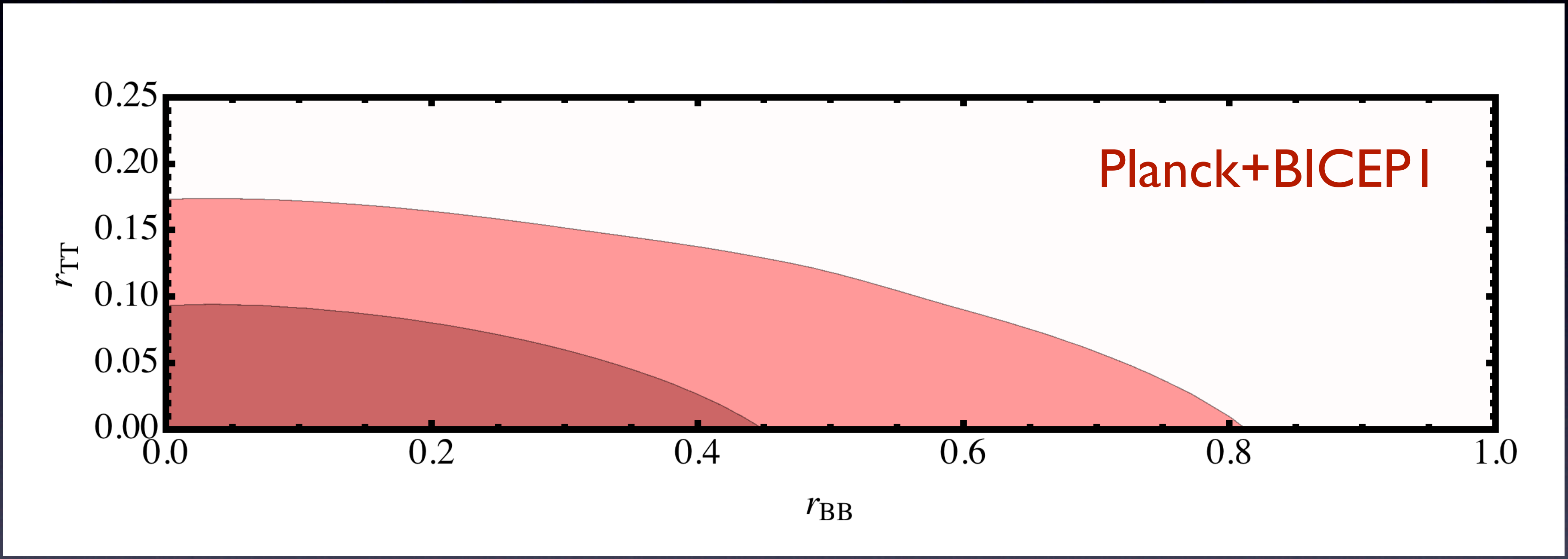
The two likelihood are essentially independent

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

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

Experimental Progress on r

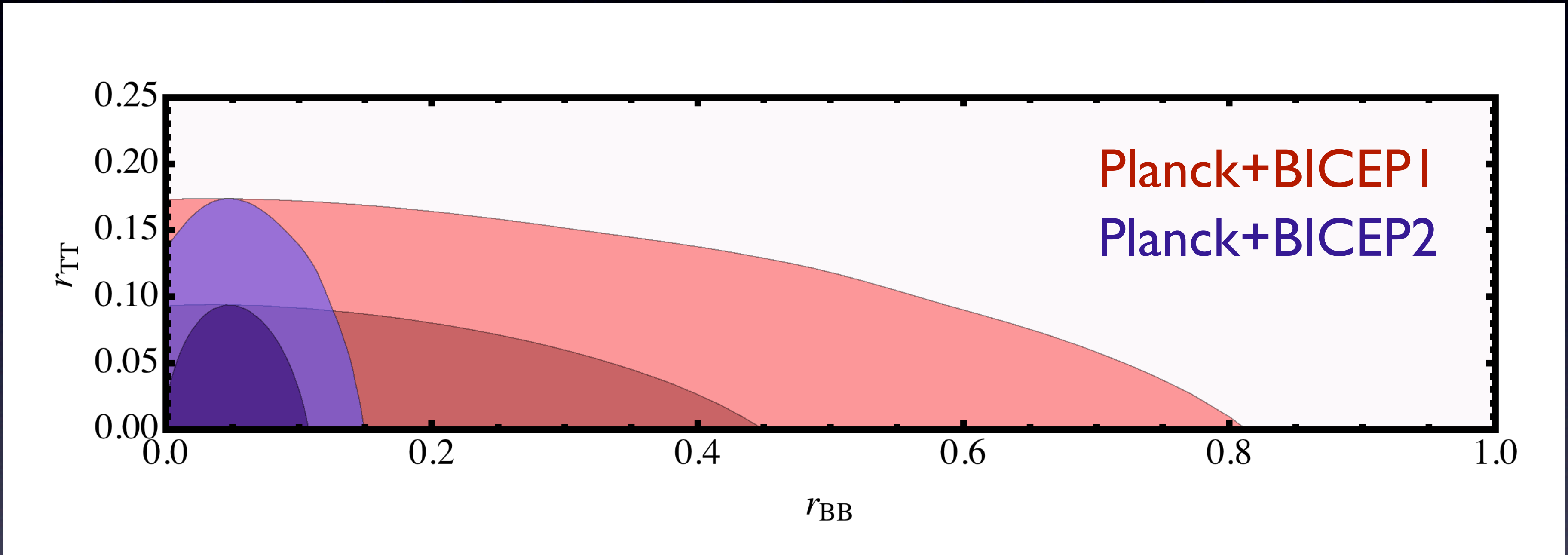
$\mathcal{L}(r_{TT}, r_{BB})$ before March



Constraint dominated by temperature data

Experimental Progress on r

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



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,...

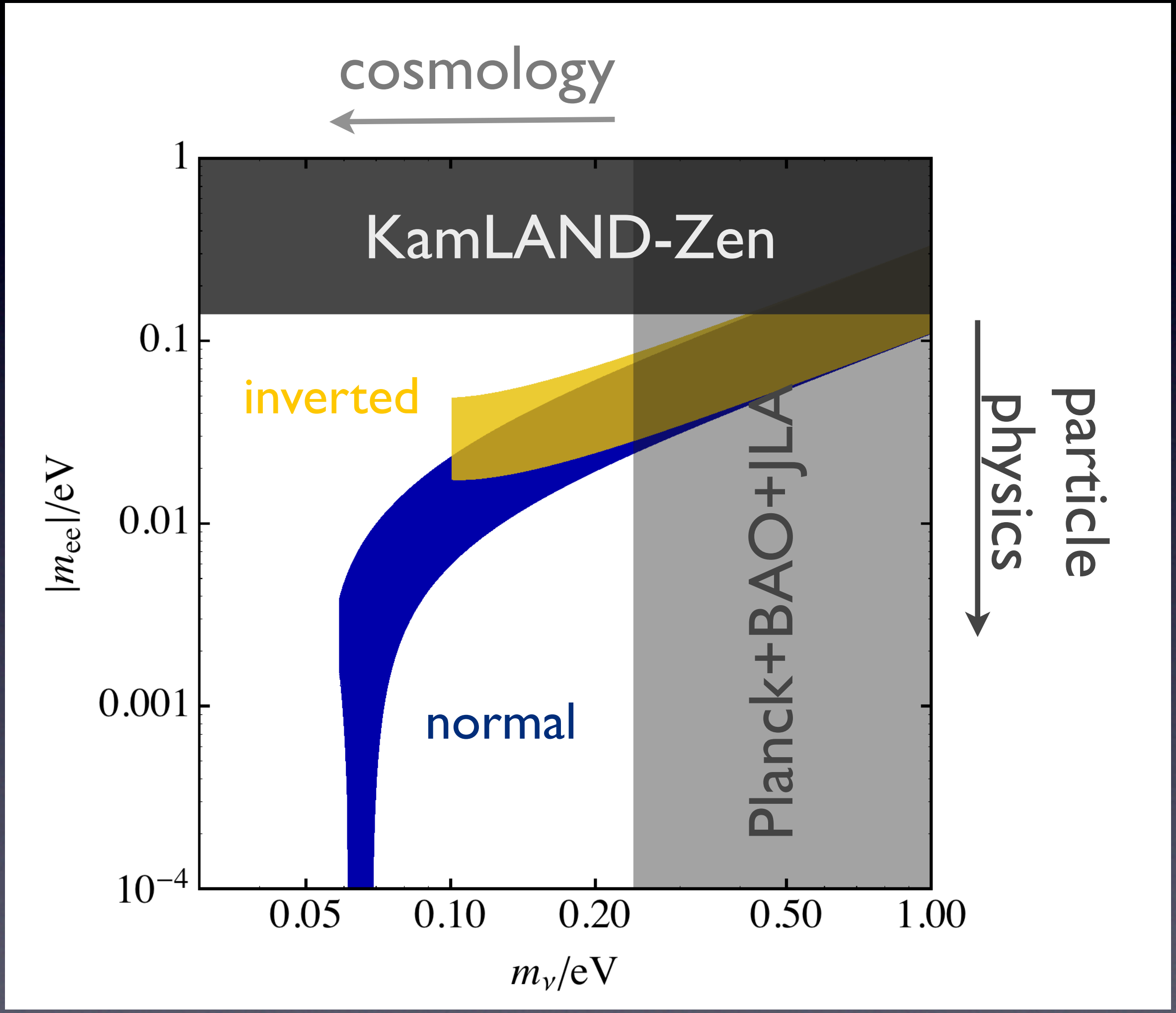
Primordial Non-Gaussianity

Shape and method	$f_{\rm NL}$(KSW) Independent	$f_{\rm NL}$(KSW) ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

- No evidence for departures from Gaussianity in standard LEO shapes (but possible hints for oscillatory shapes?)
- Some room for improvement with E-mode polarization, but significant progress will rely on large scale structure surveys

Neutrinos

The race for neutrino mass and hierarchy



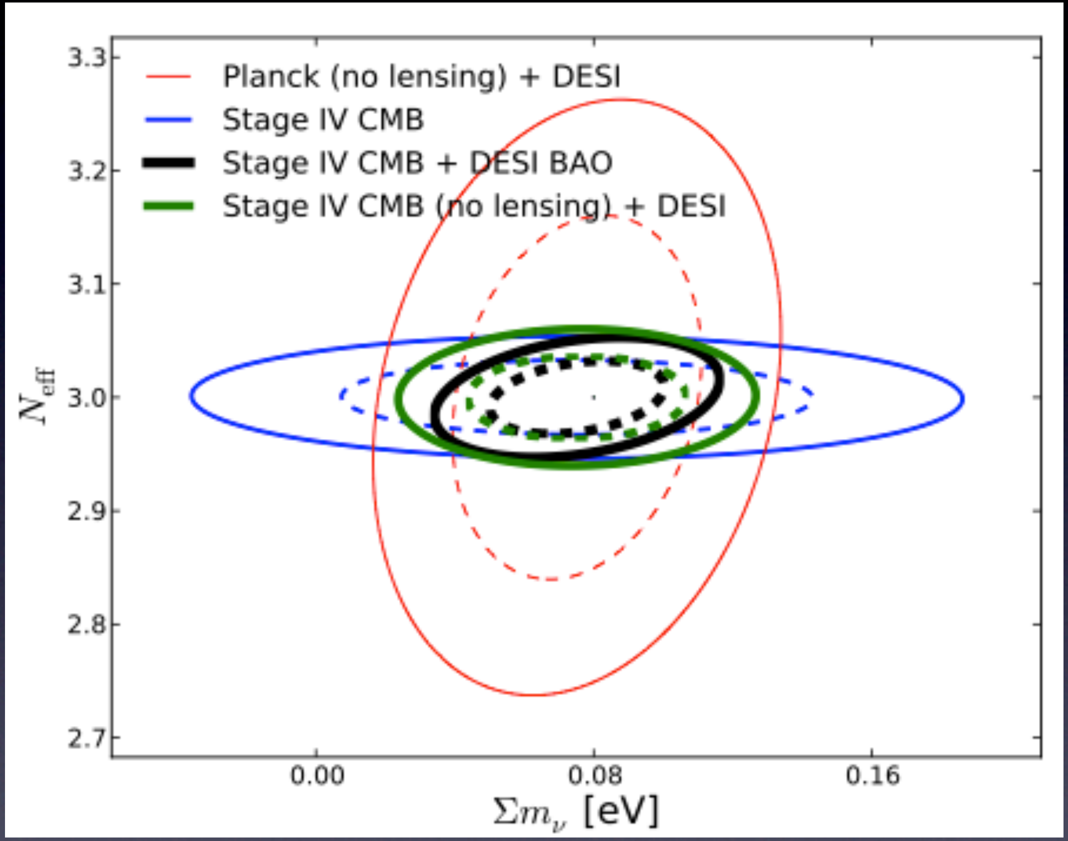
Neutrino Mass

Forecasts

Cosmology

e.g. CMB Stage IV+DESI

$\sigma(m_\nu) \sim 0.016\, eV$



KATRIN $m(\nu_e) < 0.2\, eV$ at $90\%\, C.L.$

Conclusions

- The LCDM model with inflationary spectrum of perturbations is consistent with all current cosmological data.
- The standard model is consistent with all current particle physics data.
- Many open questions in both cosmology and particle physics remain, some of which will require a joint effort of the two communities.
- The CMB will continue to provide valuable information about primordial gravitational waves, neutrino masses, the number of effective relativistic degrees of freedom, dark matter, ...

Thank you