The Particle Physics Cosmology Connection
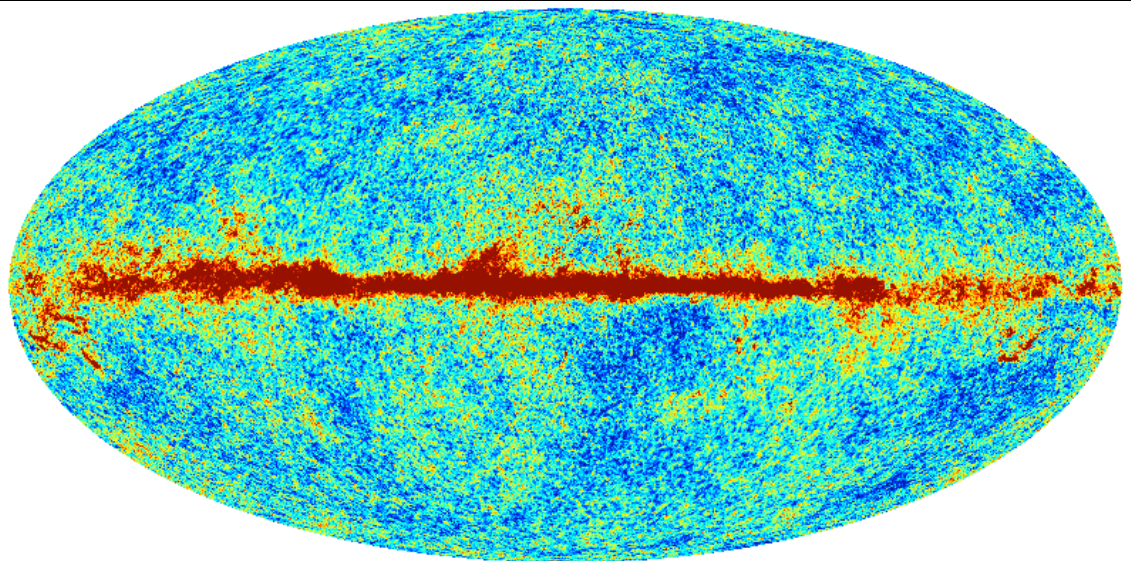
Raphael Flauger
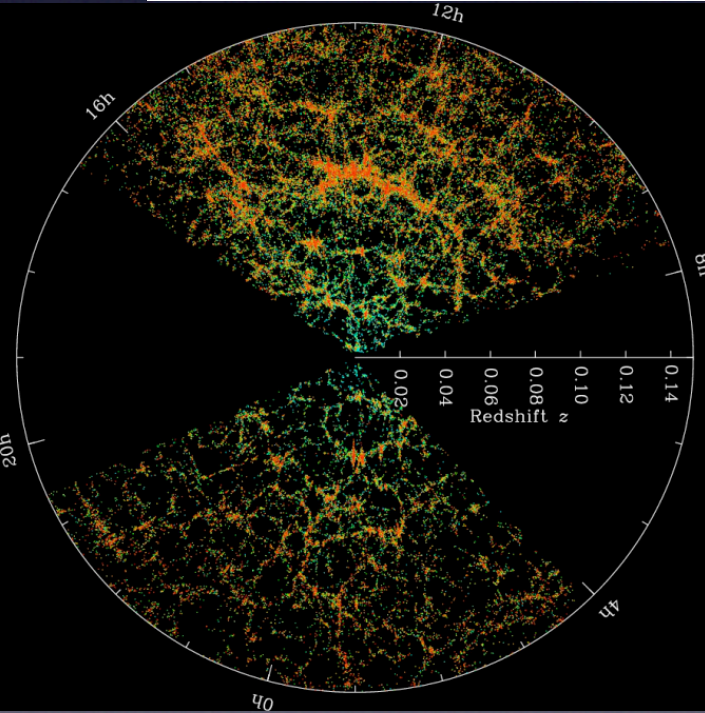
EPS Meeting 2015, Vienna, Austria, July 25, 2015

Cosmology

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

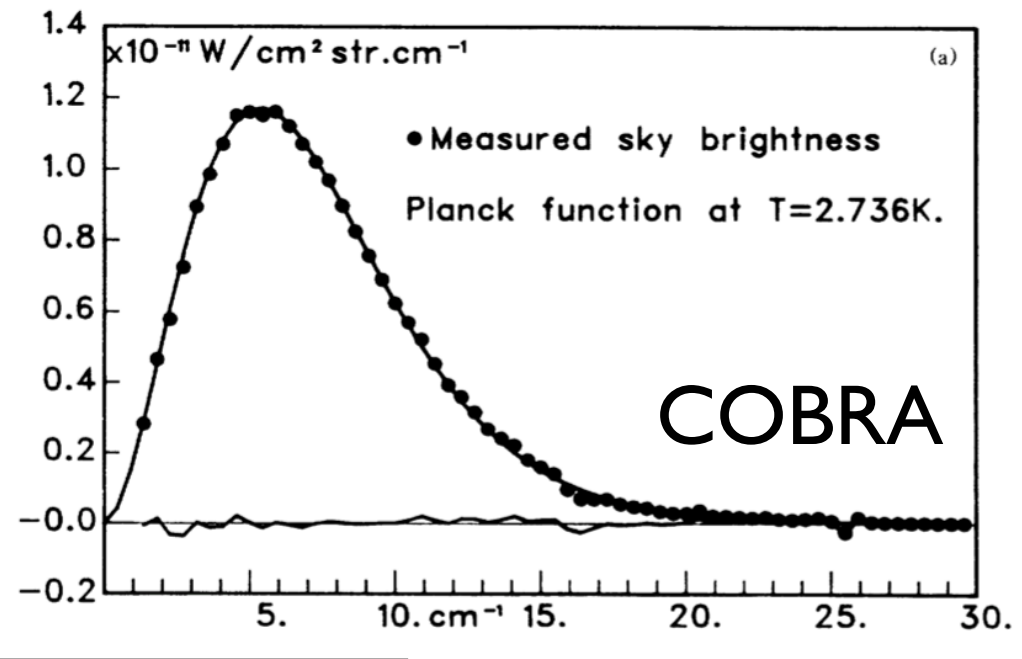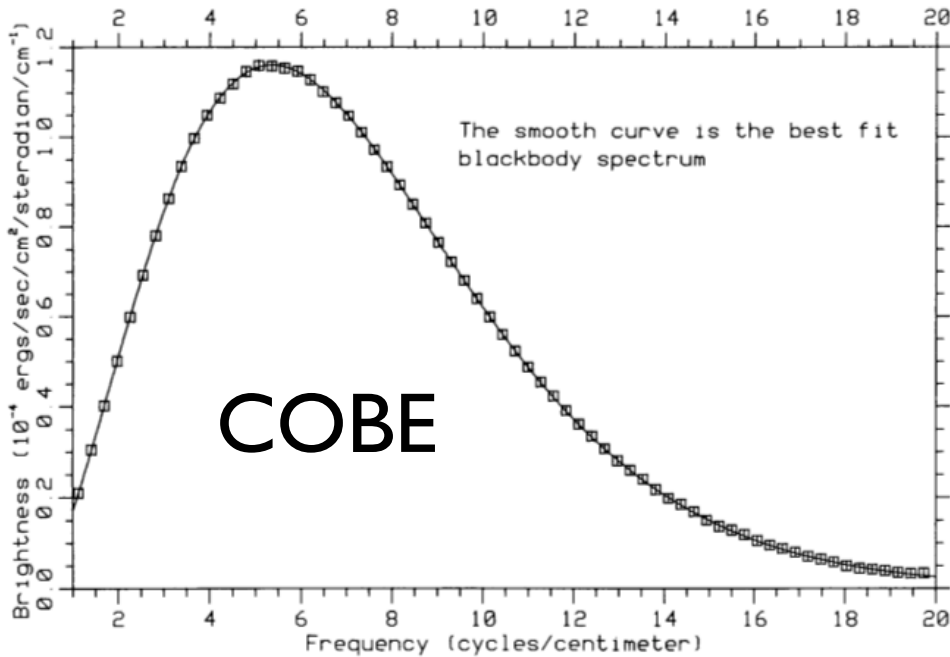## Rocket Measurement of the Cosmic-Background-Radiation mm-Wave Spectrum

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

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

(Received 10 May 1990)

The smooth curve is the best fit blackbody spectrum

COBE

• Measured sky brightness

Planck function at T=2.736K.

COBRA

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]
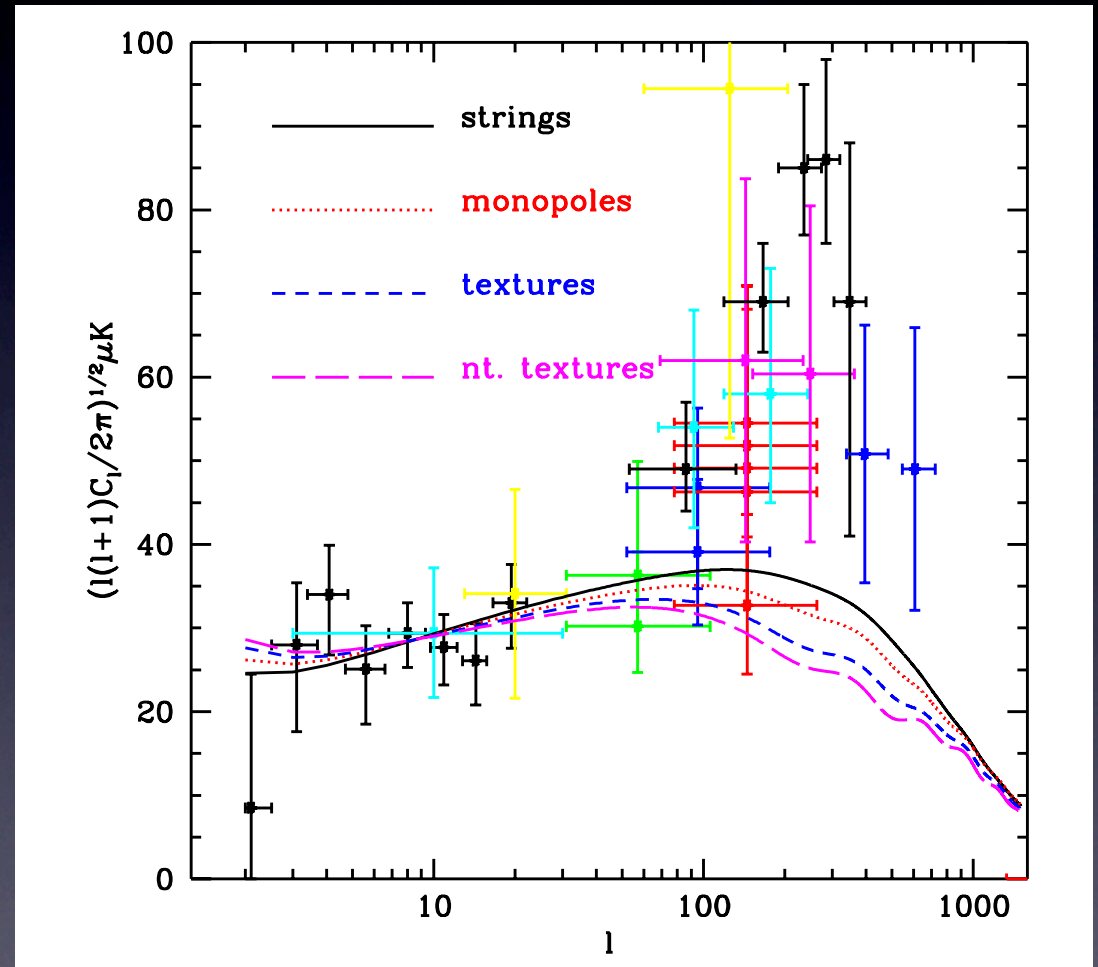AND D. T. WILKINSON[10]

Received 1990 January 16; accepted 1990 February 19

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(Pen, Seljak, Turok 1997)

Angular Power Spectrum

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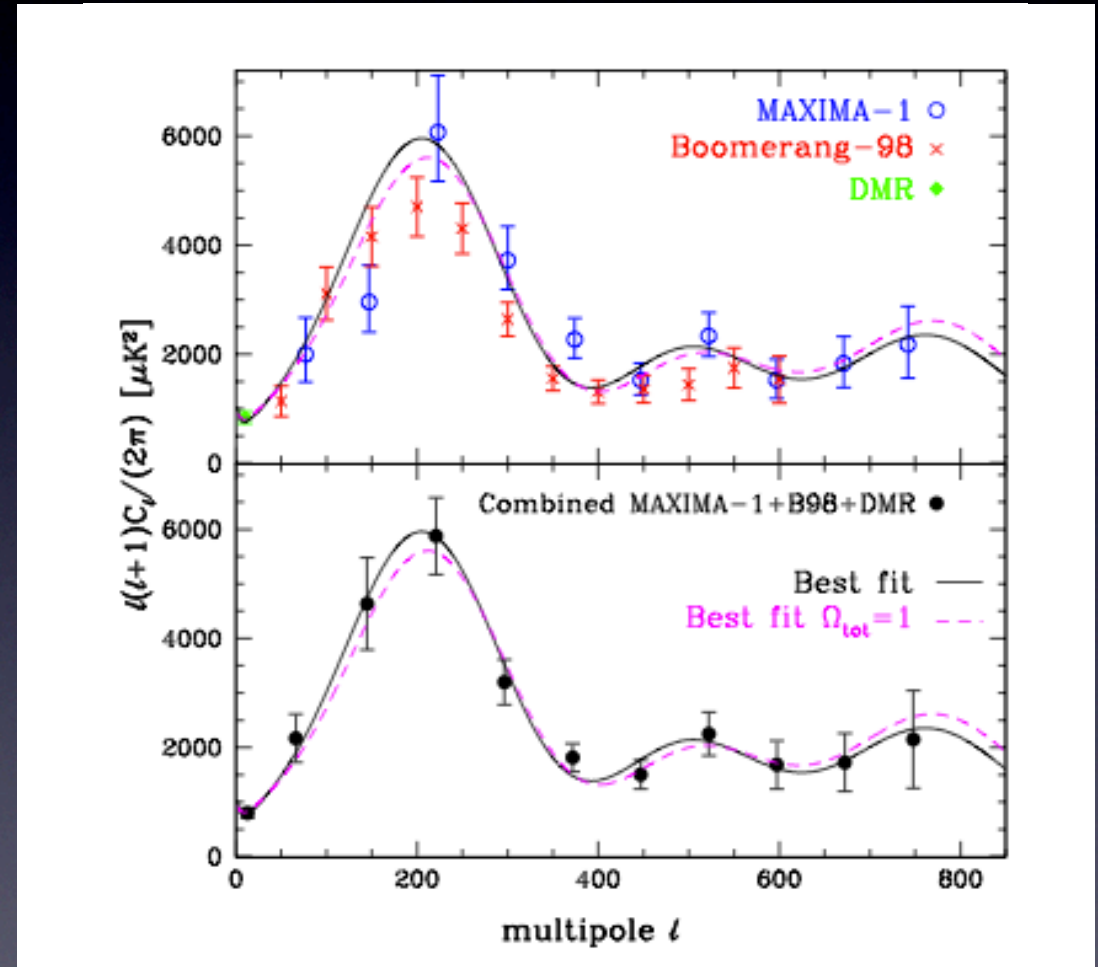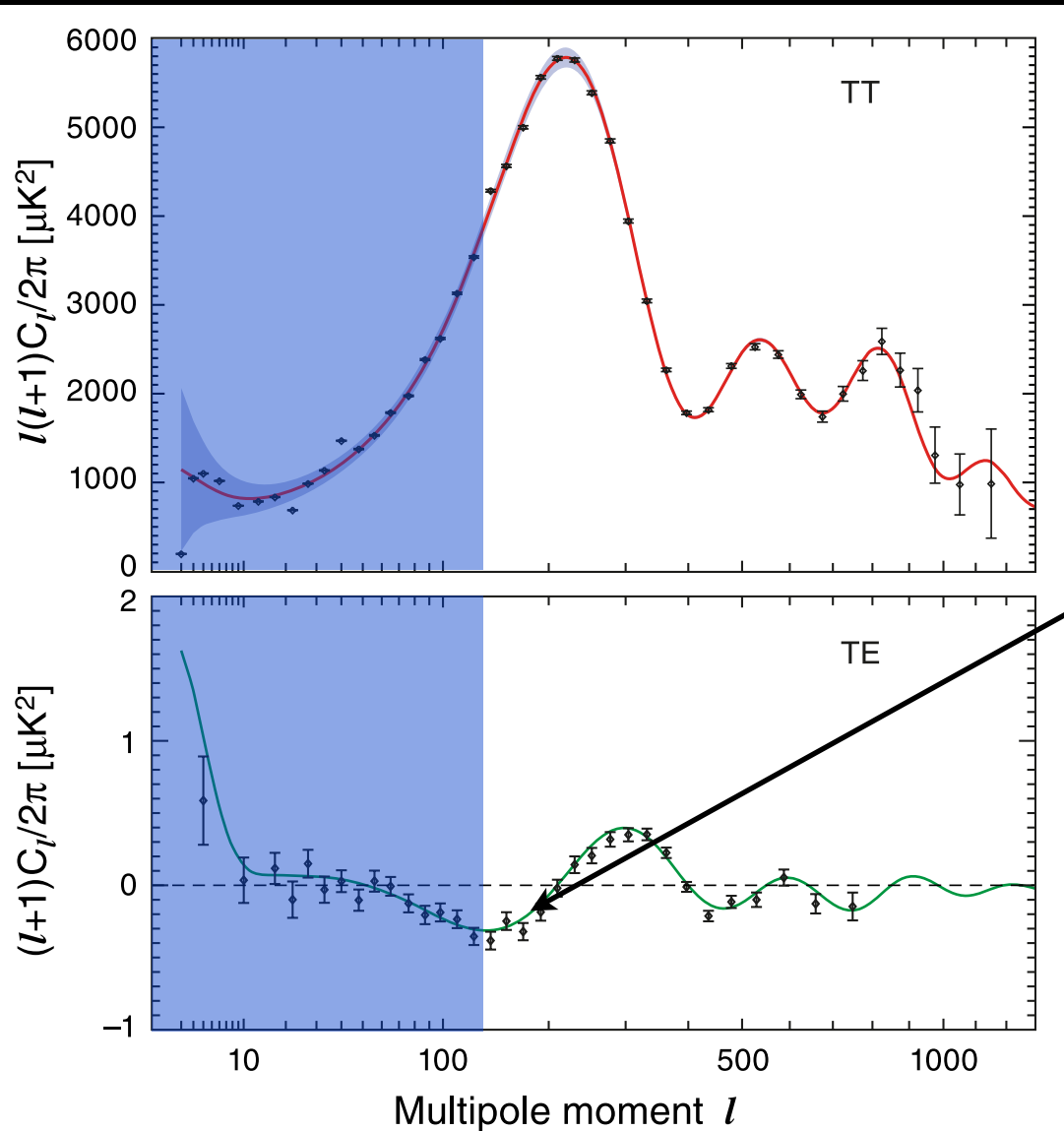
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Angular Power Spectrum

Shortly after it became clear that defects were not the dominant source of primordial perturbations.
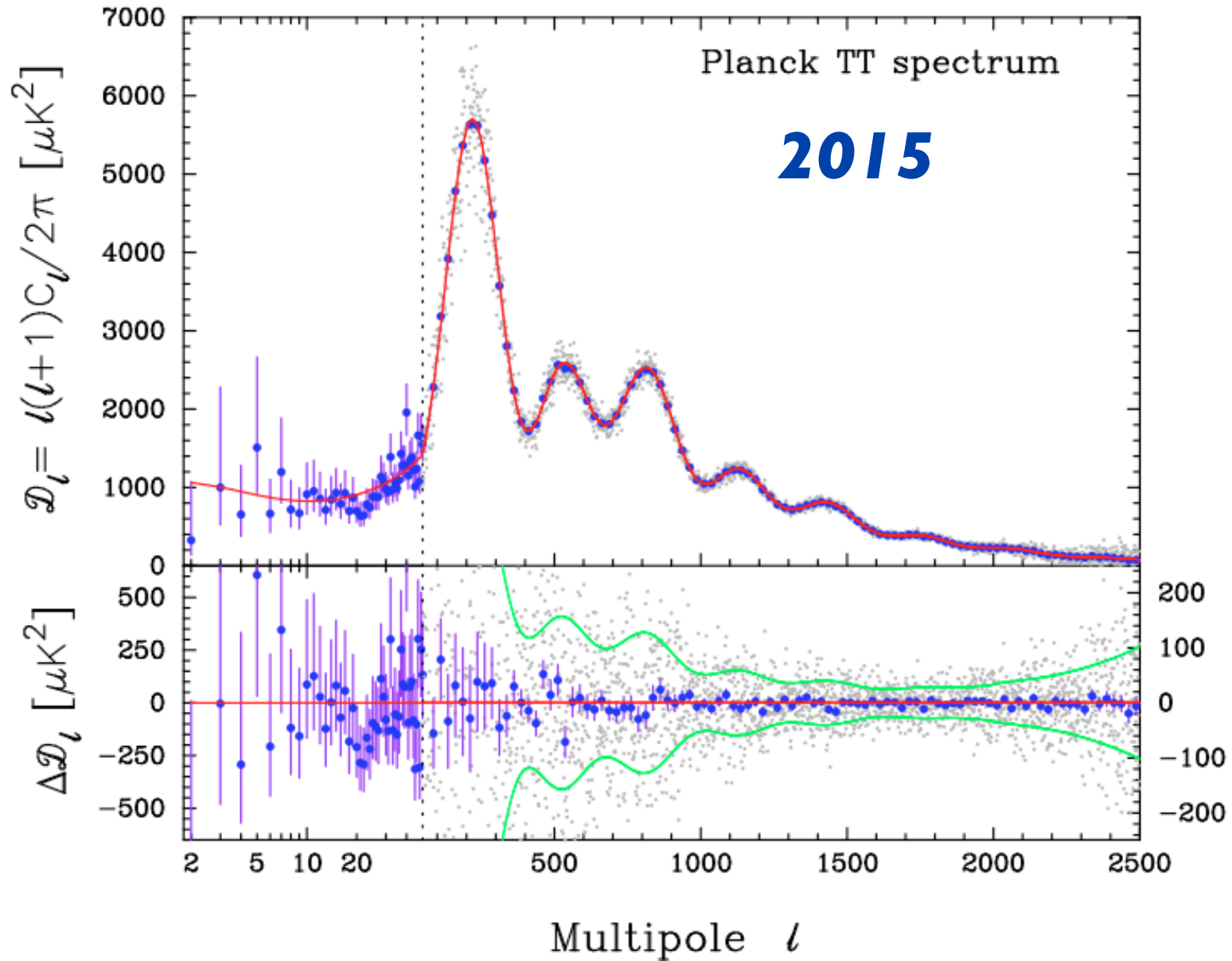
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Perturbations exist on scales larger than the Hubble radius at recombination.

Implies these perturbations already existed at recombination

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

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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.

- dark energy

$$\Omega_\Lambda = 0.685 \pm 0.013$$

- dark matter

$$\Omega_c h^2 = 0.1197 \pm 0.0022$$

- baryonic matter

$$\Omega_b h^2 = 0.02222 \pm 0.00023$$

- optical depth

$$\tau = 0.078 \pm 0.019$$

- amplitude of primordial density perturbations

$$\Delta_\mathcal{R}^2 = (2.189^{+0.076}_{-0.085}) \times 10^{-9}$$

- spectral index of primordial density perturbations

$$n_s = 0.9655 \pm 0.0062$$

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

LCDM

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$$\Omega_c h^2 = 0.1197 \pm 0.0022$$

60σ detection of dark matter

(85σ after inclusion of CMB lensing)

LCDM

Von Neumann: "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."

LCDM

Von Neumann: "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."

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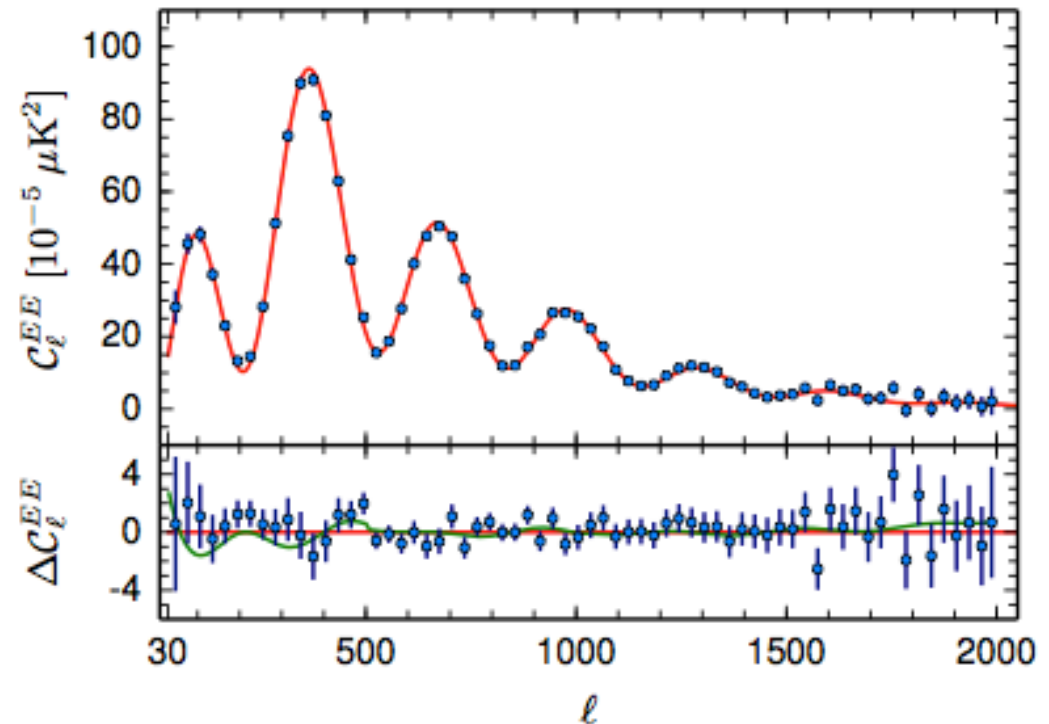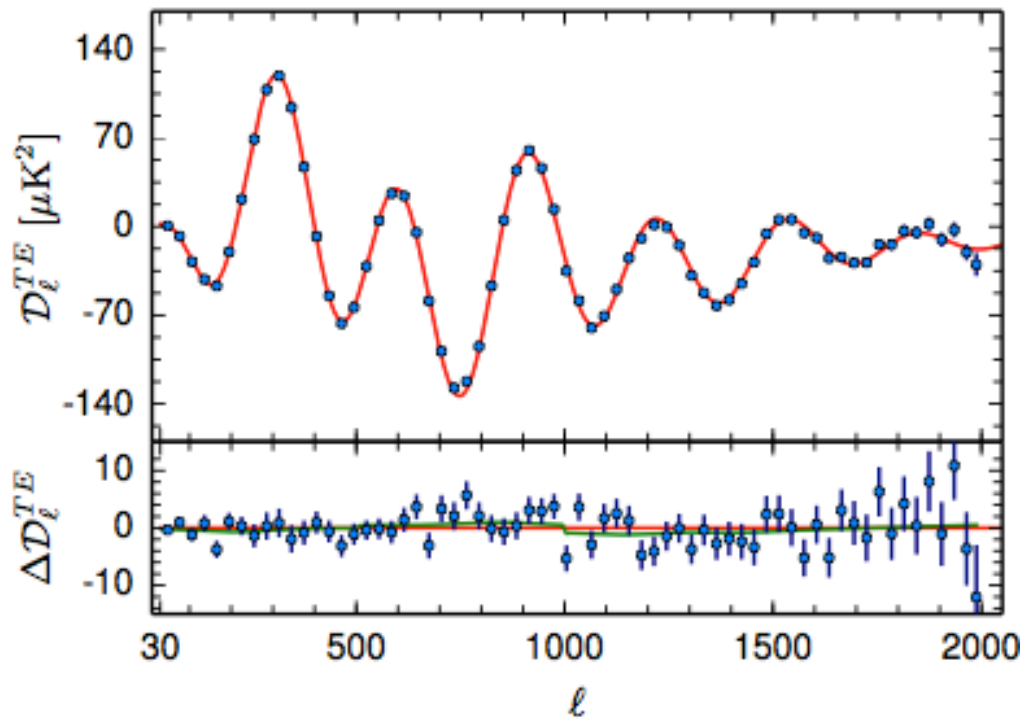
LCDM

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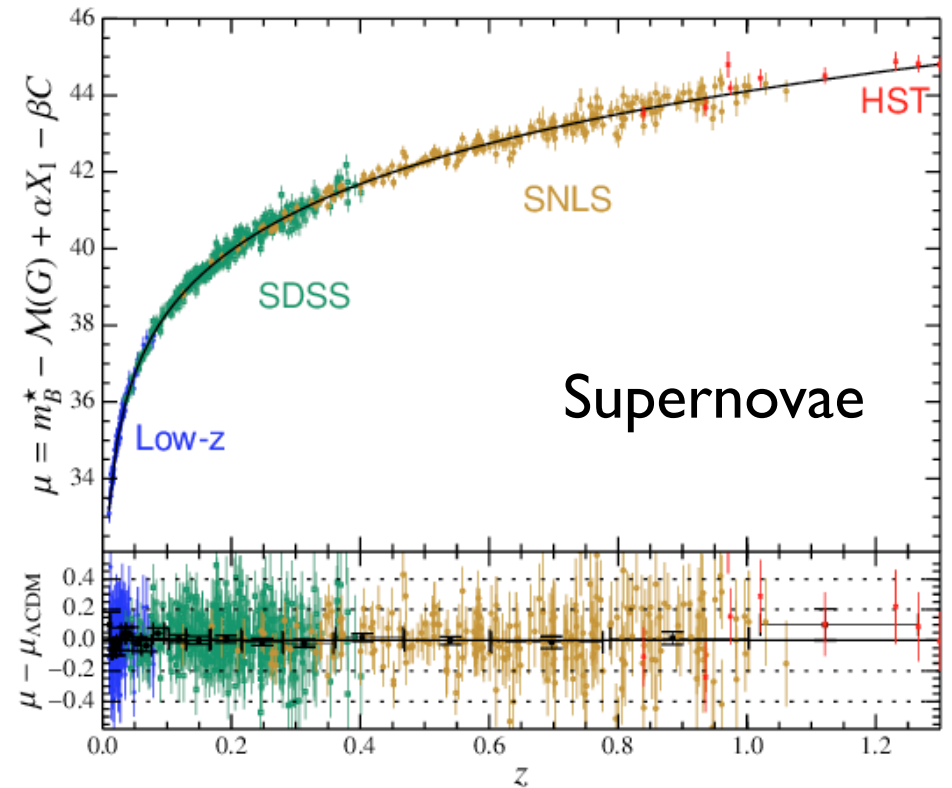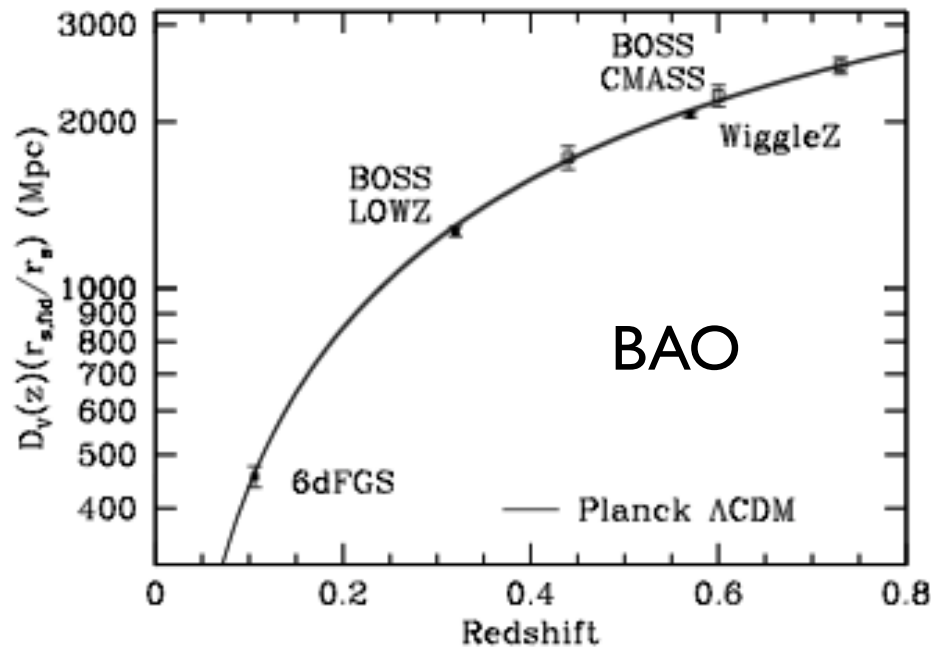
LCDM

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 and the Standard Model

LCDM provides a remarkably successful description of our universe on large scales

LCDM and the Standard Model

LCDM provides a remarkably successful description of our universe on large scales

Similarly, the standard model provides a remarkably successful description of our universe on small scales

LCDM and the Standard Model

Comparison of the standard model and LCDM 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 does the recent Higgs discovery imply for cosmology?

- 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
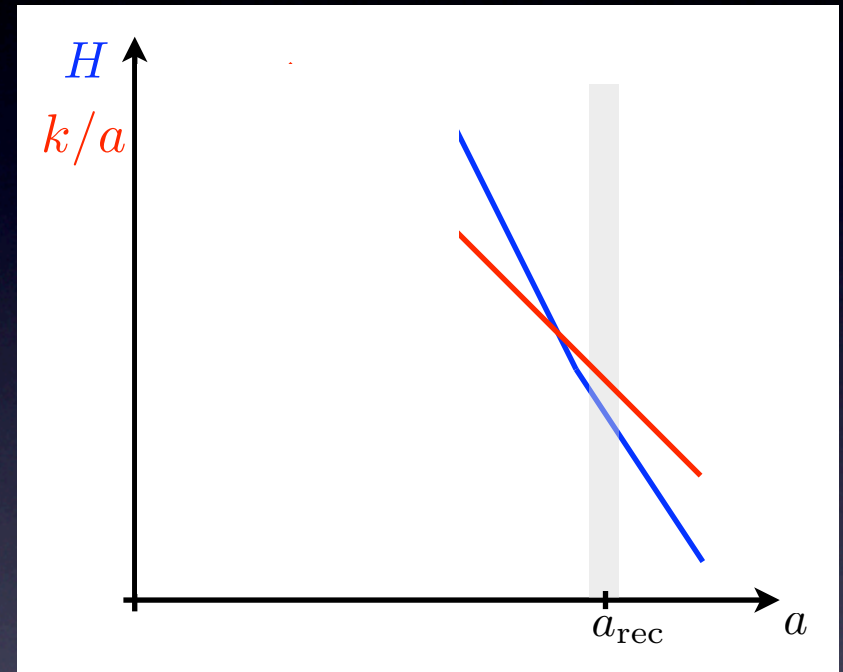
- are adiabatic

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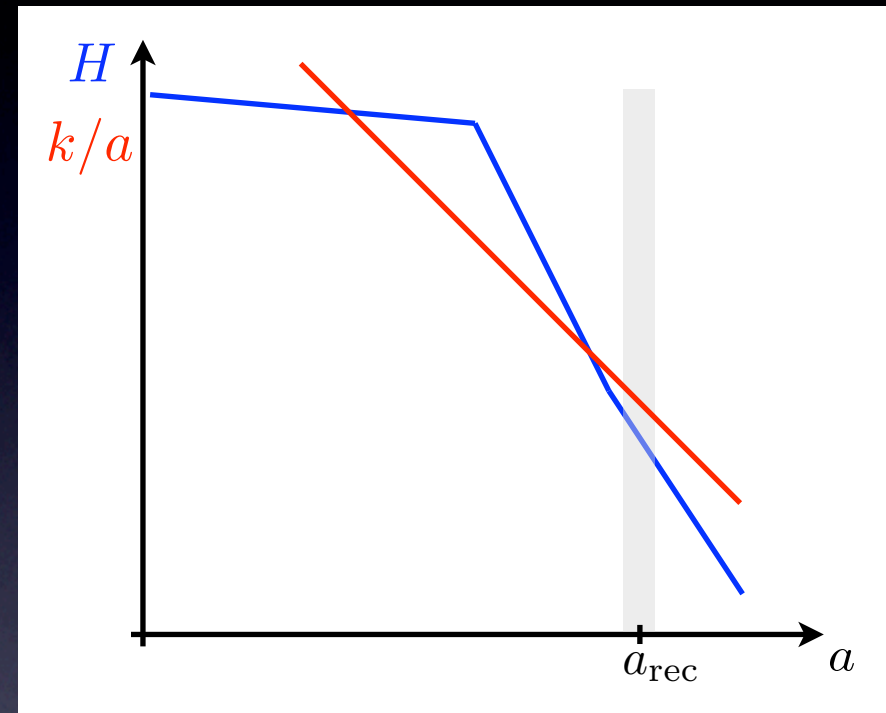
This sets the initial conditions for the equations describing the universe from a few keV to the present.

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

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

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

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

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, as well as the energy scale

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

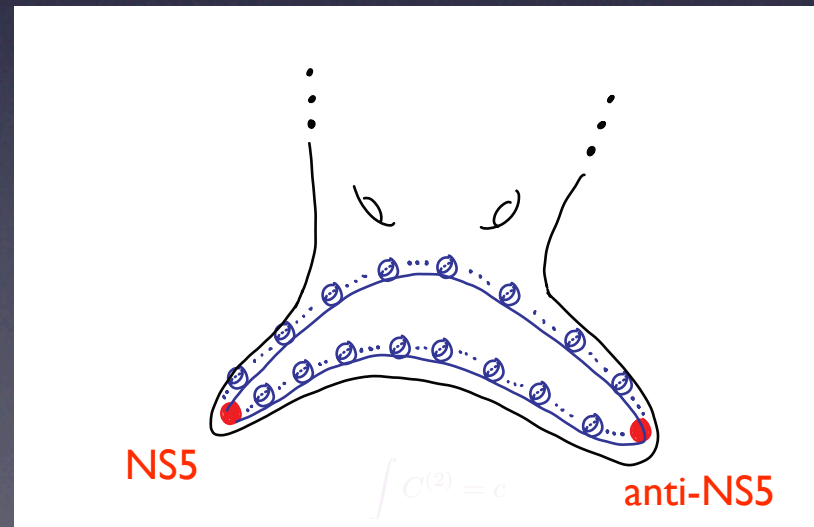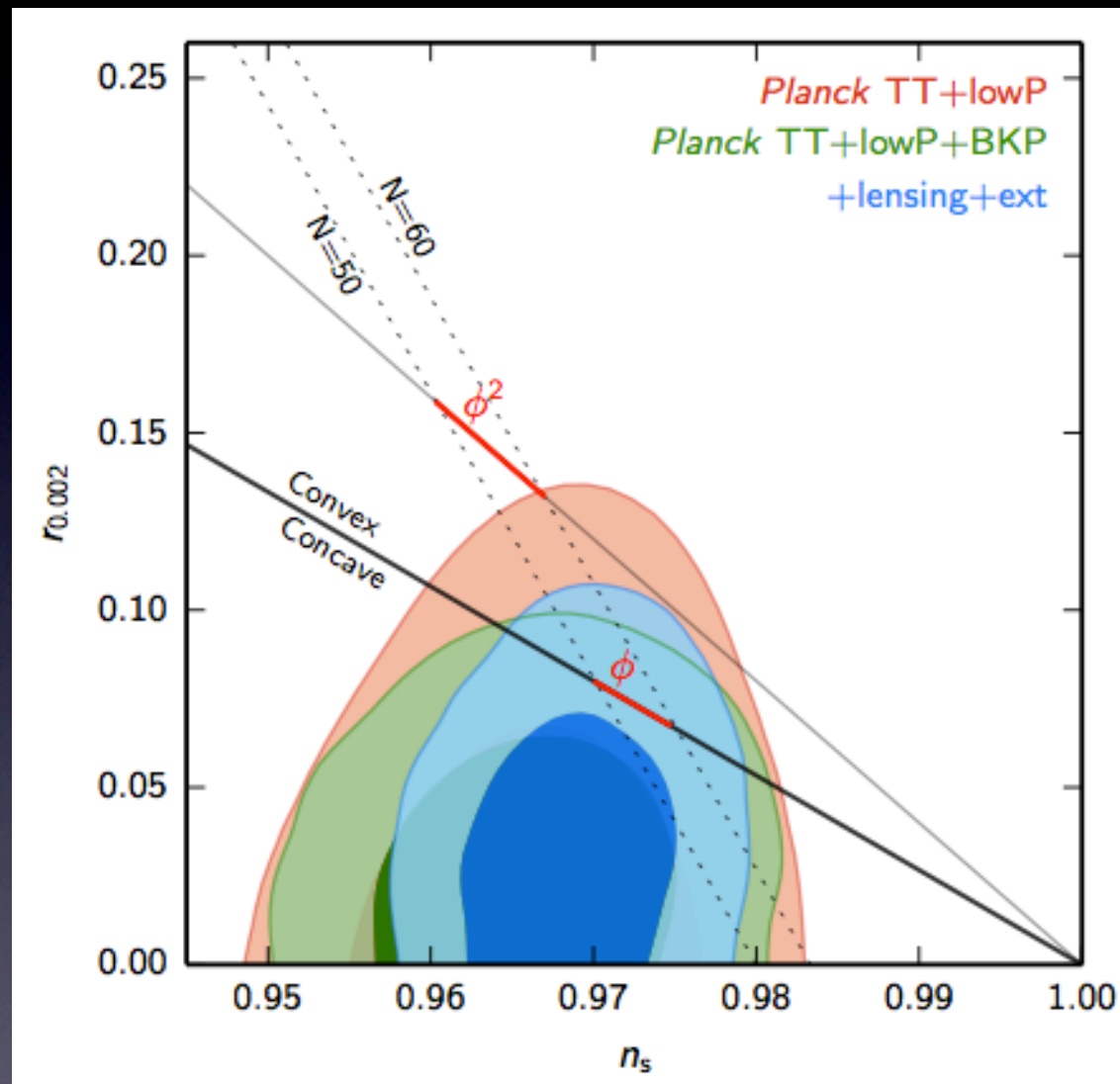with $\qquad r = \dfrac{\Delta_h^2}{\Delta_{\mathcal{R}}^2}$

Field Range

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

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

Experimental Progress on r

With the current data, we can constrain r by

- the tensor contribution to the temperature anisotropies on large angular scales

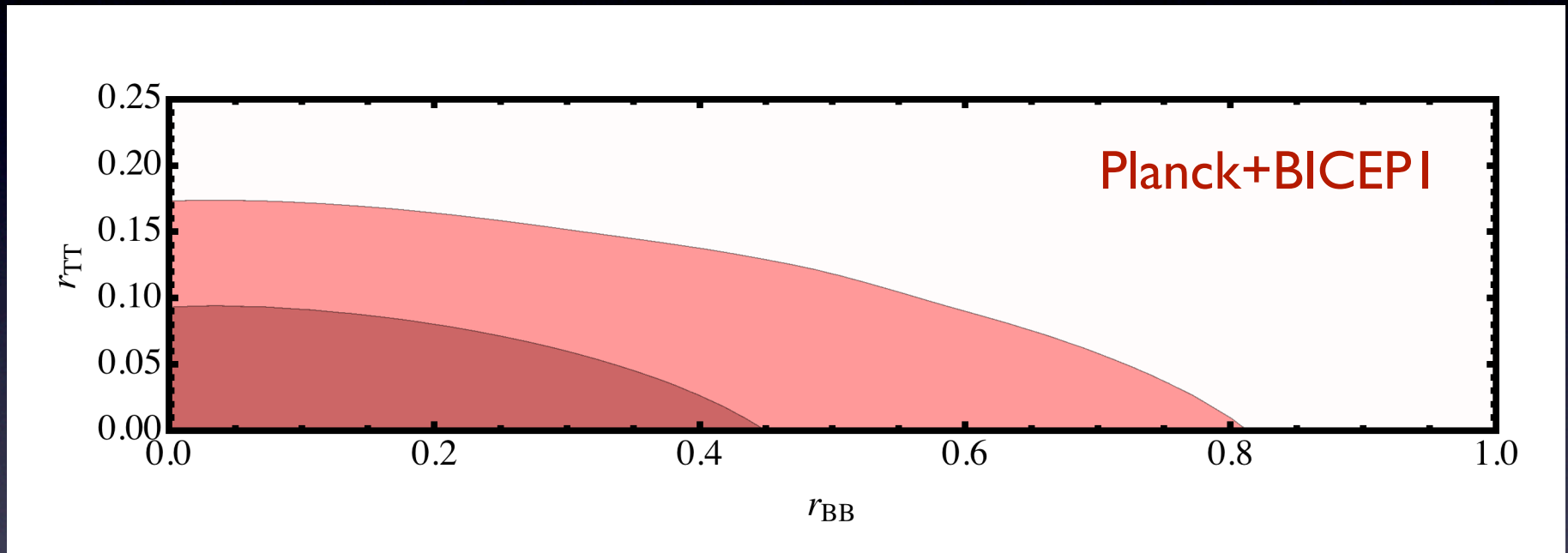- the B-mode polarization generated by tensors.

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 $\mathcal{L}(r, r)$
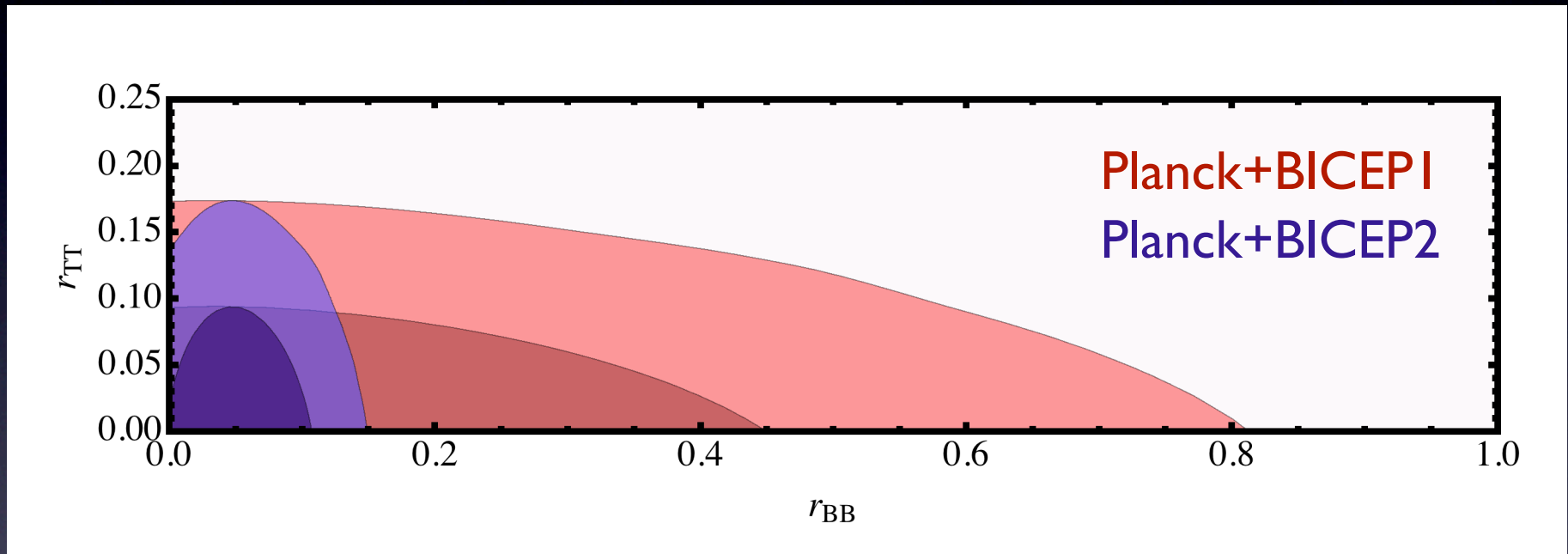
Experimental Progress on r

$\mathcal{L}(r_{TT}, r_{BB})$ 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
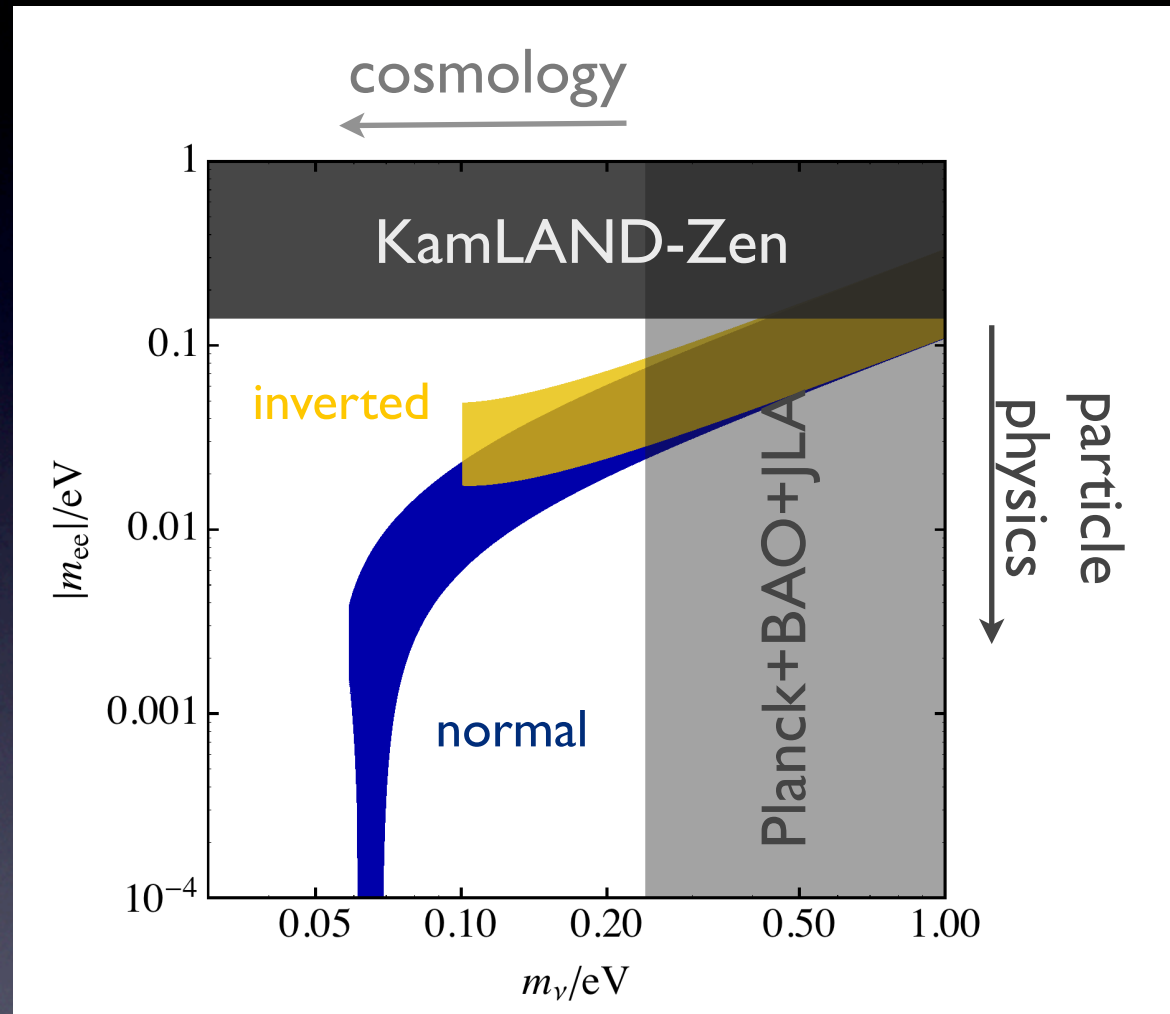
Balloon: EBEX, SPIDER, PIPER

future (>5 years)

Ground: CMB Stage IV

Satellite: LiteBIRD, PIXIE,...

Neutrinos

The race for neutrino mass and hierarchy

see also constraints from:

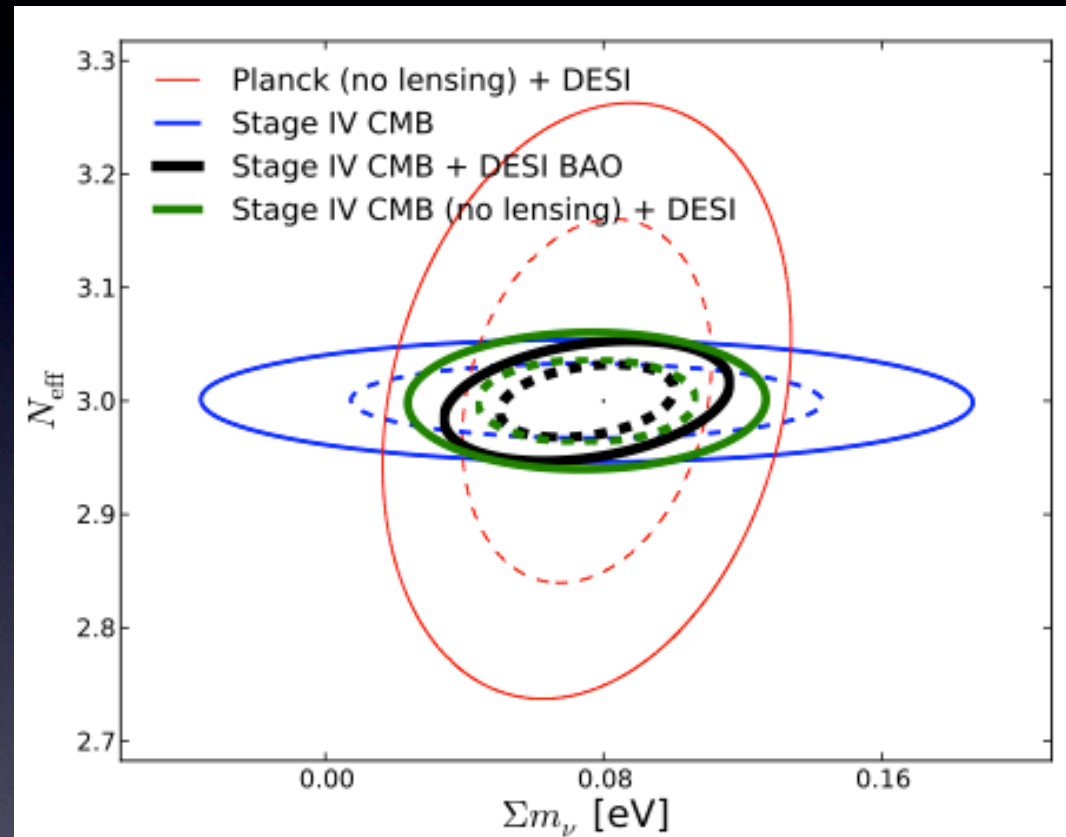CUORE0+Cuoricino, GERDA, HdM, IGEX, NEMO3

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 $90\%\,C.L.$

Dark Matter

See other sessions for nice talks on constraints on dark matter from indirect and direct detection.

Dark Energy

Depending on the theorist, dark energy is either the one of the biggest problems in particle physics, or no problem at all.

We should probe it experimentally with large scale structure surveys and supernovae

ongoing and upcoming:

  BOSS, DES, HETDEX, PAU, J-PAS

future (>5 years)

  DESI, LSST, Euclid, WFIRST

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.

- Nevertheless, many open questions in both cosmology and particle physics remain, some of which will require a joint effort of the two communities.

- We will hear more about them in the remaining talks of this session.

Thank you