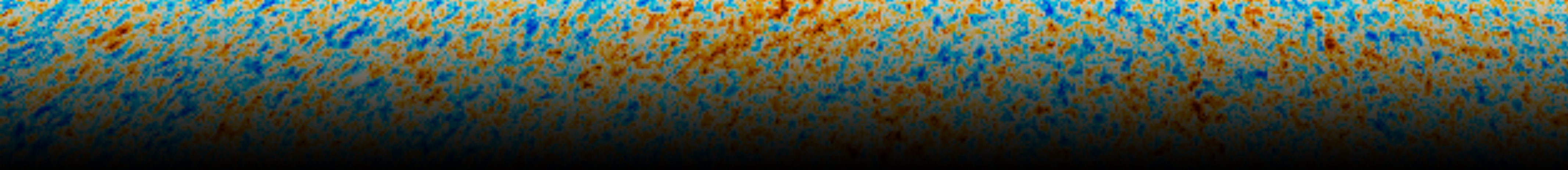


Implications of CMB Observations for Particle Physics

Raphael Flauger

From the LHC to Dark Matter and Beyond, Aspen, CO, March 23, 2017

Introduction

Measurements of the CMB have come a long way,

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

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

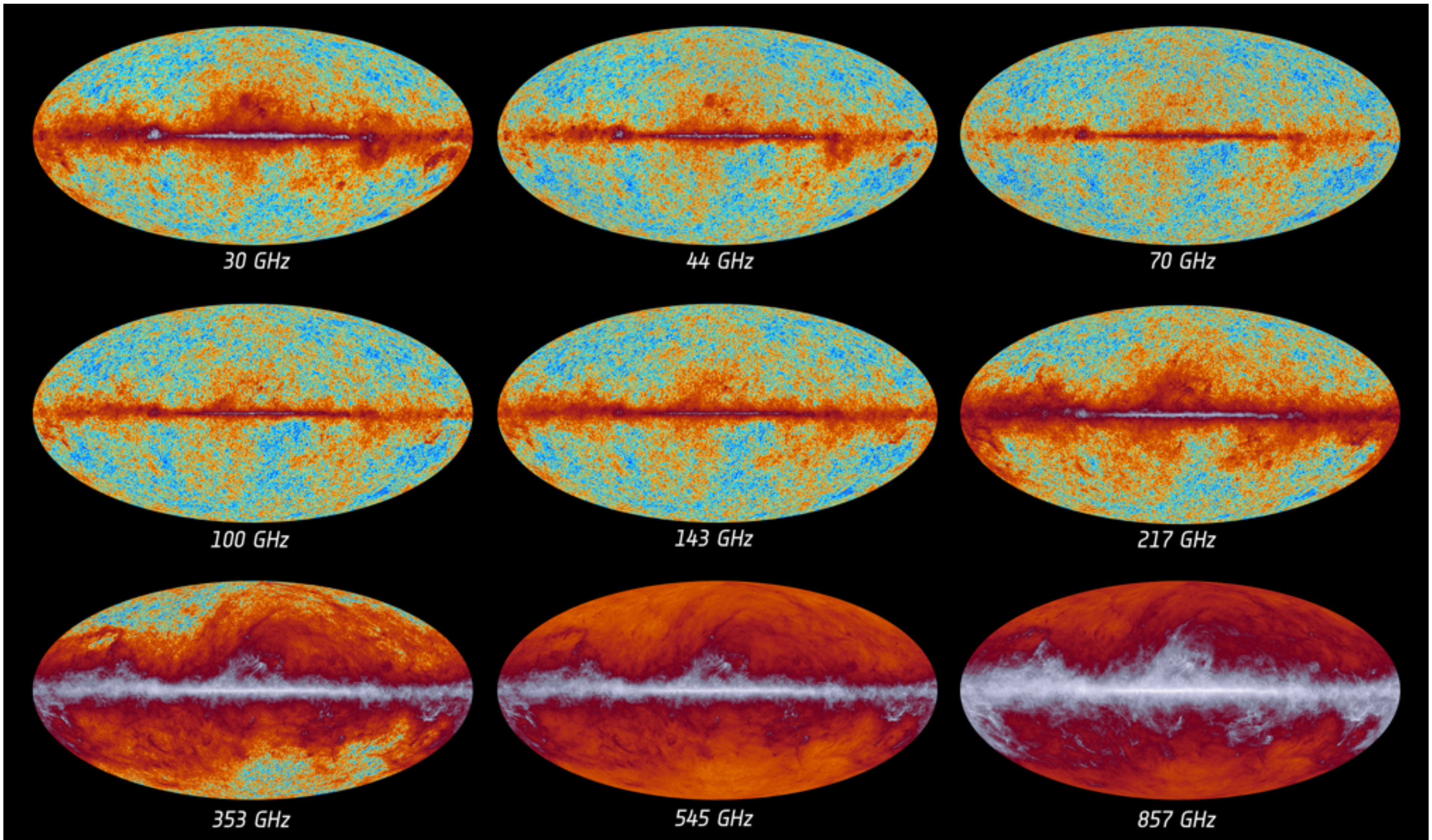
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

A. A. Penzias
R. W. Wilson

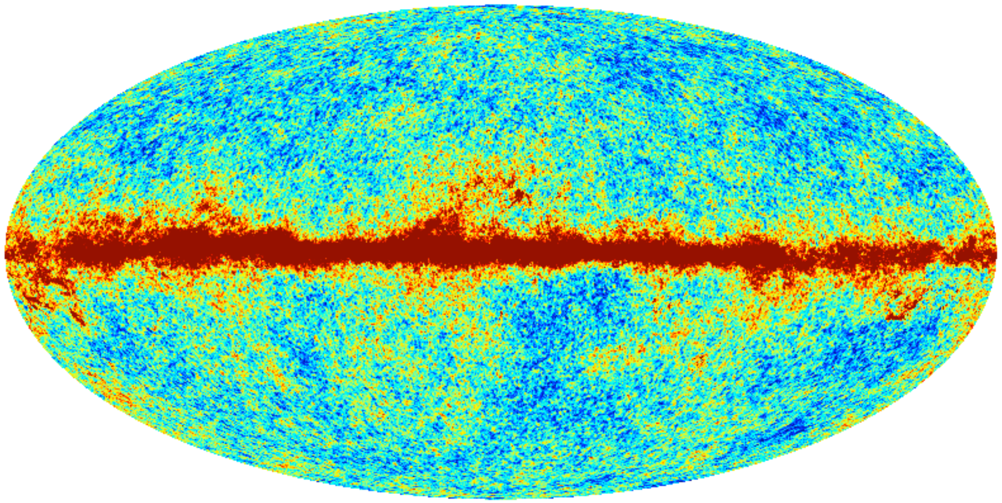
May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

Introduction

... to Planck's beautiful all sky maps



Introduction

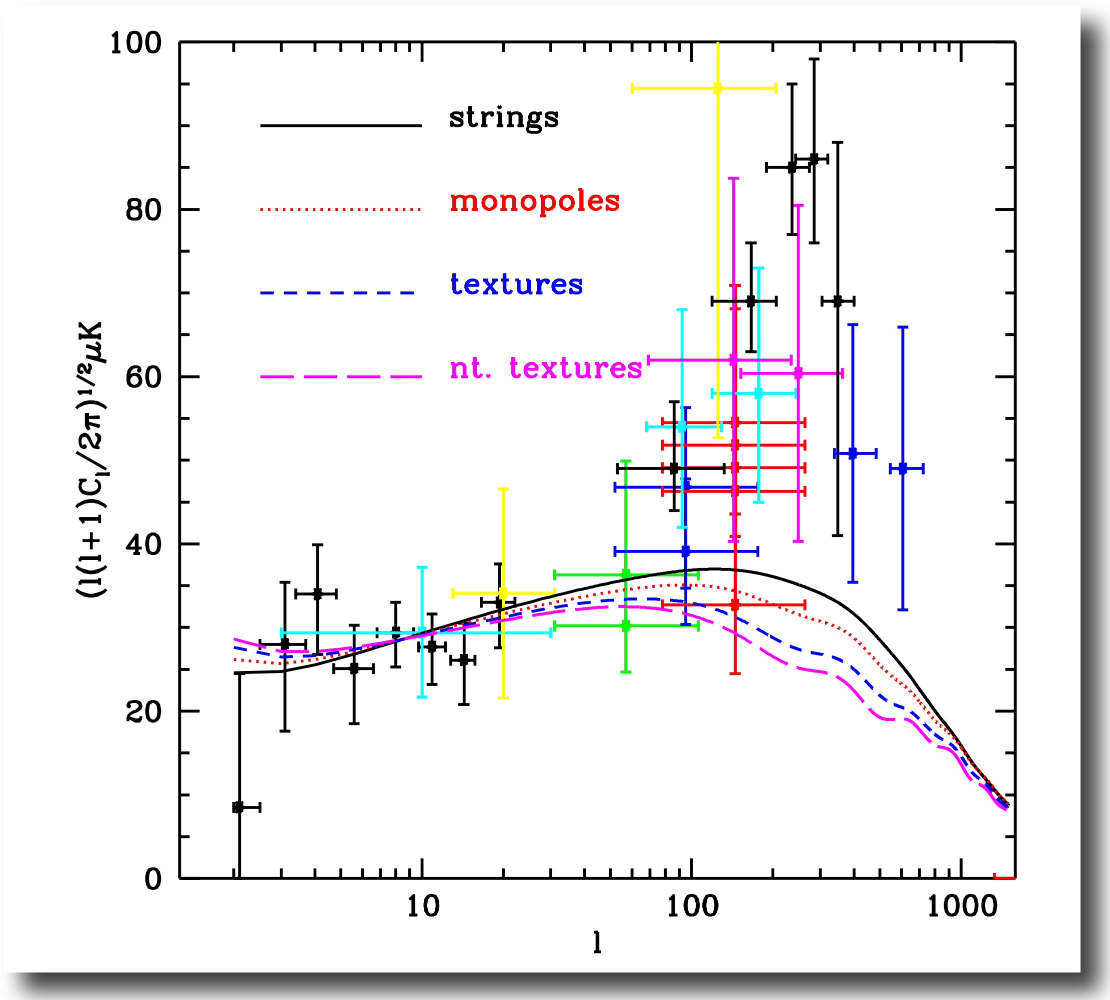


$$a^{\rm obs}_{T,\ell m} = \int d^2\hat{n}\; Y_\ell^{m\,*}(\hat{n})\Delta T(\hat{n})$$

$$C^{\rm obs}_{TT,\ell} \equiv \frac{1}{2\ell+1}\sum_m \left|a^{\rm obs}_{T,\ell\,m}\right|^2$$

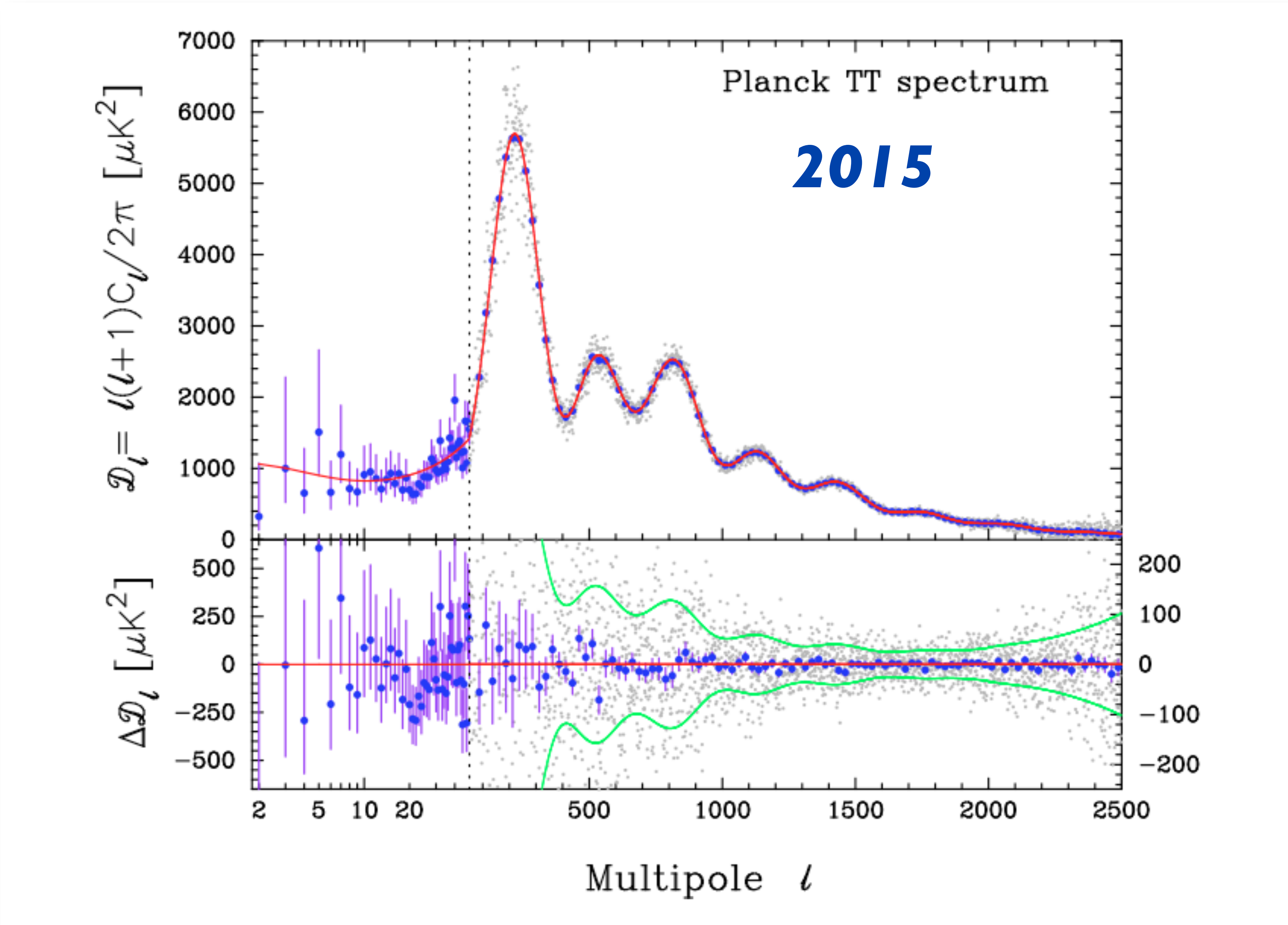
Introduction

Angular power spectrum measurements ca. 1997



(Pen, Seljak, Turok 1997)

Introduction



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

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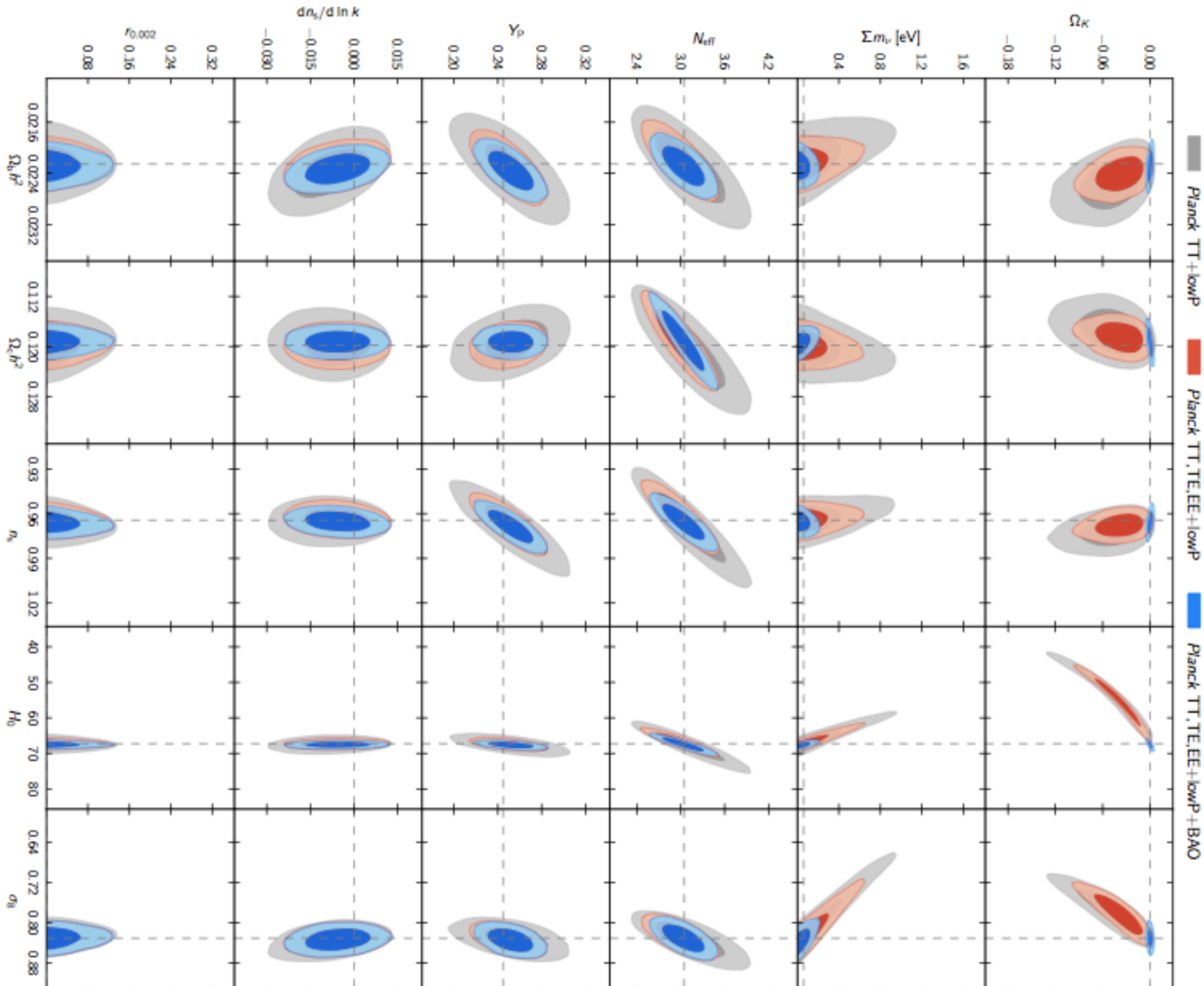
54 σ detection of non-baryonic dark matter

(85 σ with polarization)

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

LCDM+X

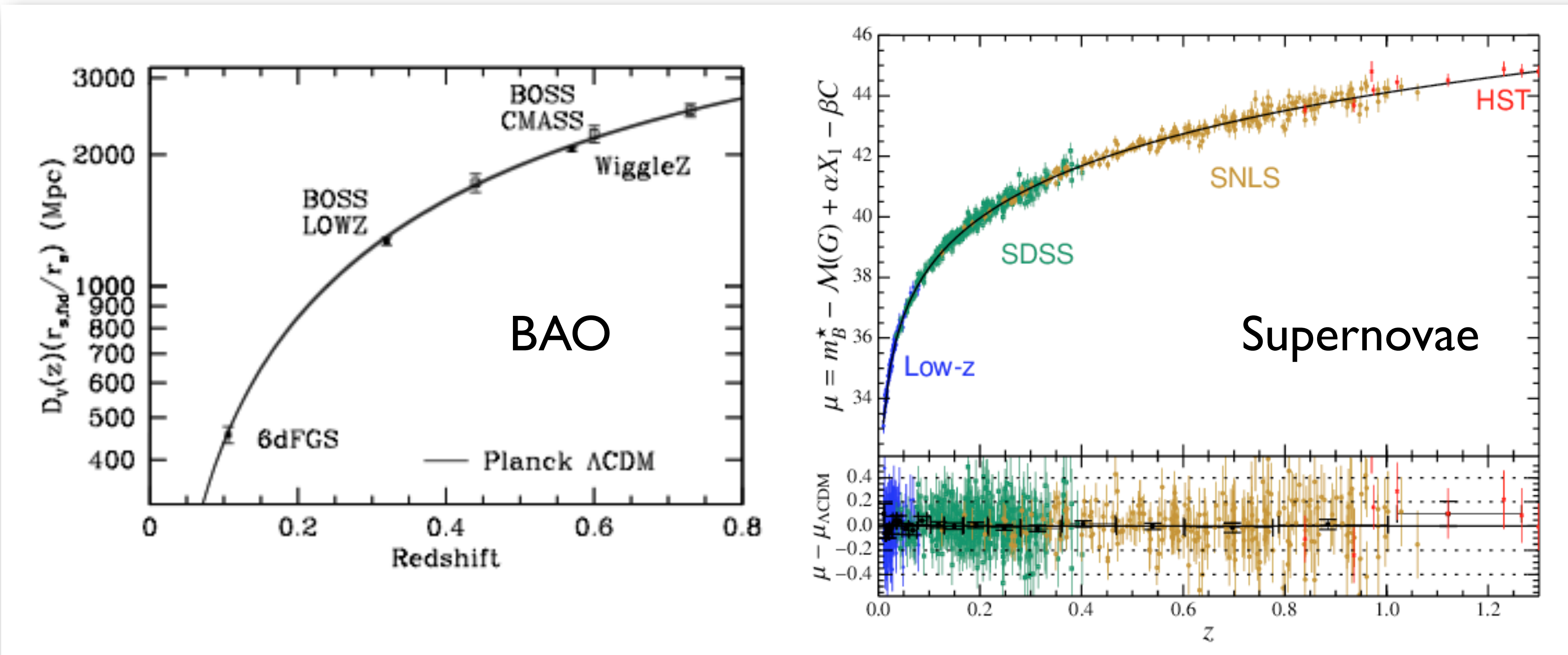


(Ade et al. 2015)

LCDM

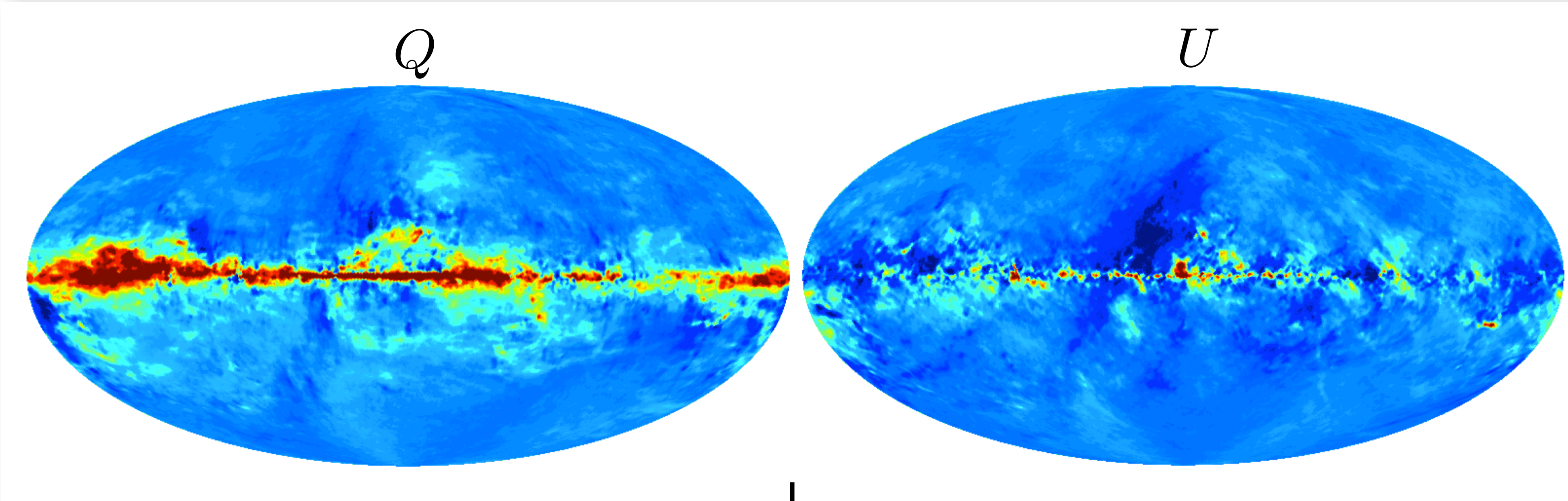
In addition, LCDM is consistent with all low redshift large-scale structure* and supernova data

(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

Polarization



$$a_{P,\ell m} = \int d^2\hat{n}\ {}_2Y_\ell^{m*}(\hat{n})\,(Q(\hat{n}) + iU(\hat{n}))$$

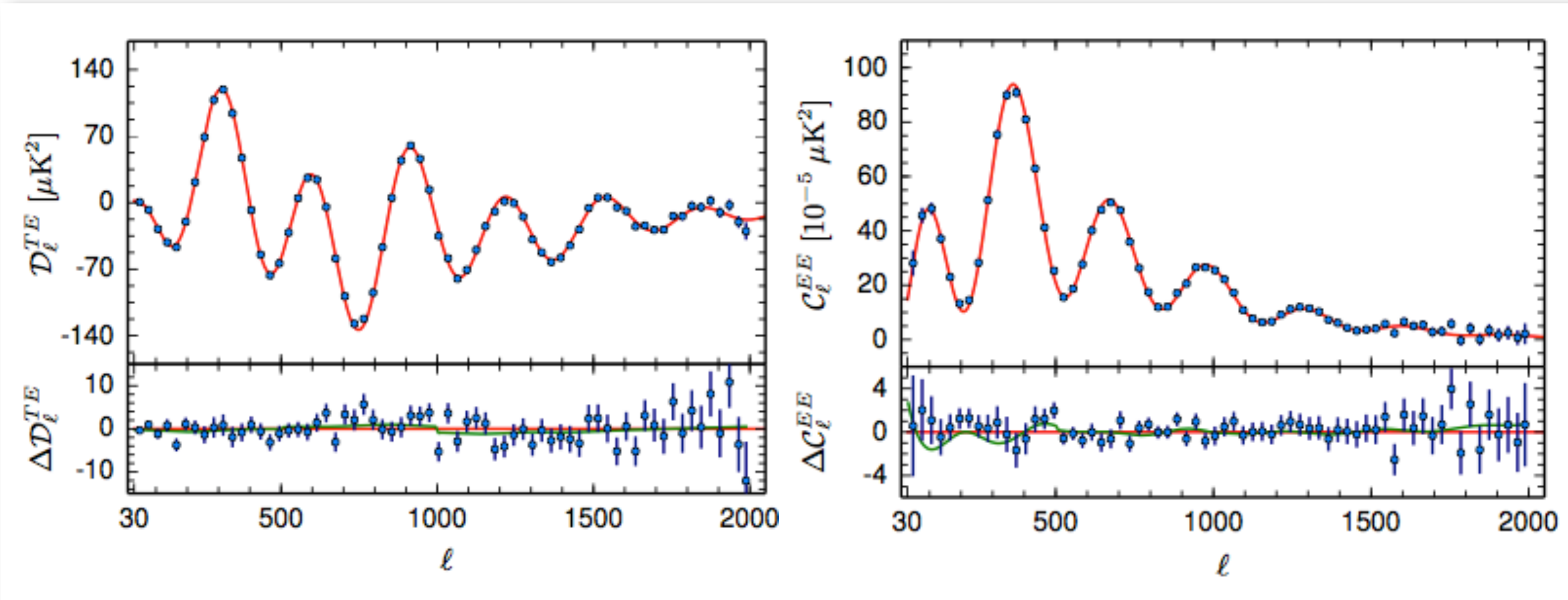
$$a_{E,\ell\, m} \equiv -(a_{P,\ell\, m} + a^*_{P,\ell\, -m})/2$$

$$a_{B,\ell\, m} \equiv i(a_{P,\ell\, m} - a^*_{P,\ell\, -m})/2$$

$$C_{TE,\ell}, C_{EE,\ell}, C_{BB,\ell}$$

LCDM

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



(systematics remain to be understood)

(Ade et al. 2015)

LCDM

- Overall LCDM is remarkably consistent with CMB, large scale structure and supernova data, but there are small tensions.

- The cosmology derived from Planck angular power spectra predicts slightly stronger clustering σ_8 than observed in low redshift data (e.g. tSZ, weak lensing,...).

- The value of the Hubble parameter inferred from CMB data is lower than the supernova measurement by around 3σ.

- The low redshift measurements are challenging for several reasons, and it will take new data to understand if these are statistical fluctuations, caused by residual systematics, or first hints of new physics.

Current Experiments

Stage III: now-2020

Future Experiments

Stage III.5: soon-2020

http://simonsobservatory.org

- A five year, $45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.
- Merger of the ACT and POLARBEAR/Simons Array teams.
- Tentative plans include:
  - Major site infrastructure
  - Technology development (detectors, optics, cameras)
  - Demonstration of new high throughput telescopes.
  - CMB-S4 class receivers with partially filled focal planes.
  - Data analysis

BERKELEY LAB CONICYT Ministerio de Educación HEISING-SIMONS FOUNDATION NSF Penn University of Pennsylvania PRINCETON UNIVERSITY SIMONS FOUNDATION

Future Experiments

Stage IV: 2020-2030

Potentially Space Missions

LiteBIRD, PIXIE

CMB-S4

Joint effort of entire US CMB community

September 2015 Collaboration Workshop
University of Michigan

March 2016 Collaboration Workshop
LBNL

September 2016 Collaboration Workshop
University of Chicago

CMB-S4 Science Book (http://www.cmbs4.org)

March 2017 Collaboration Workshop
SLAC

CMB-S4

The science goals most relevant to the high energy community are

- Detect primordial gravitational waves or place an upper limit $r < 0.001$ at 95%CL

  on the tensor-to-scalar ratio $r = \dfrac{\Delta_h^2}{\Delta_{\mathcal{R}}^2}$

- Measure $N_{\rm eff}$ with a precision of $\sigma(N_{\rm eff}) \approx 0.03$

- Determine the sum of neutrino masses at $\geq 2\sigma$ even for the minimum value allowed for the normal hierarchy (58 meV)

CMB-S4

These science goals roughly imply it will

- cover a large fraction of the sky (>70%)
- have $1 - 3\mathrm{arcmin}$ resolution
- have a noise level of $1 - 3\mu\mathrm{Karcmin}$

Such an experiment will also place tight constraints on

- light thermal dark matter
- axions
- cosmic strings, primordial magnetic fields, ...

Primordial B-modes

- At linear order scalar perturbations do not generate B-modes.
- At higher order weak gravitational lensing of the CMB by intervening matter converts E- to B-modes
- The lensing contribution is well understood and can be removed (at least partially).
- Detection of excess B-modes would provide a new window on the early universe

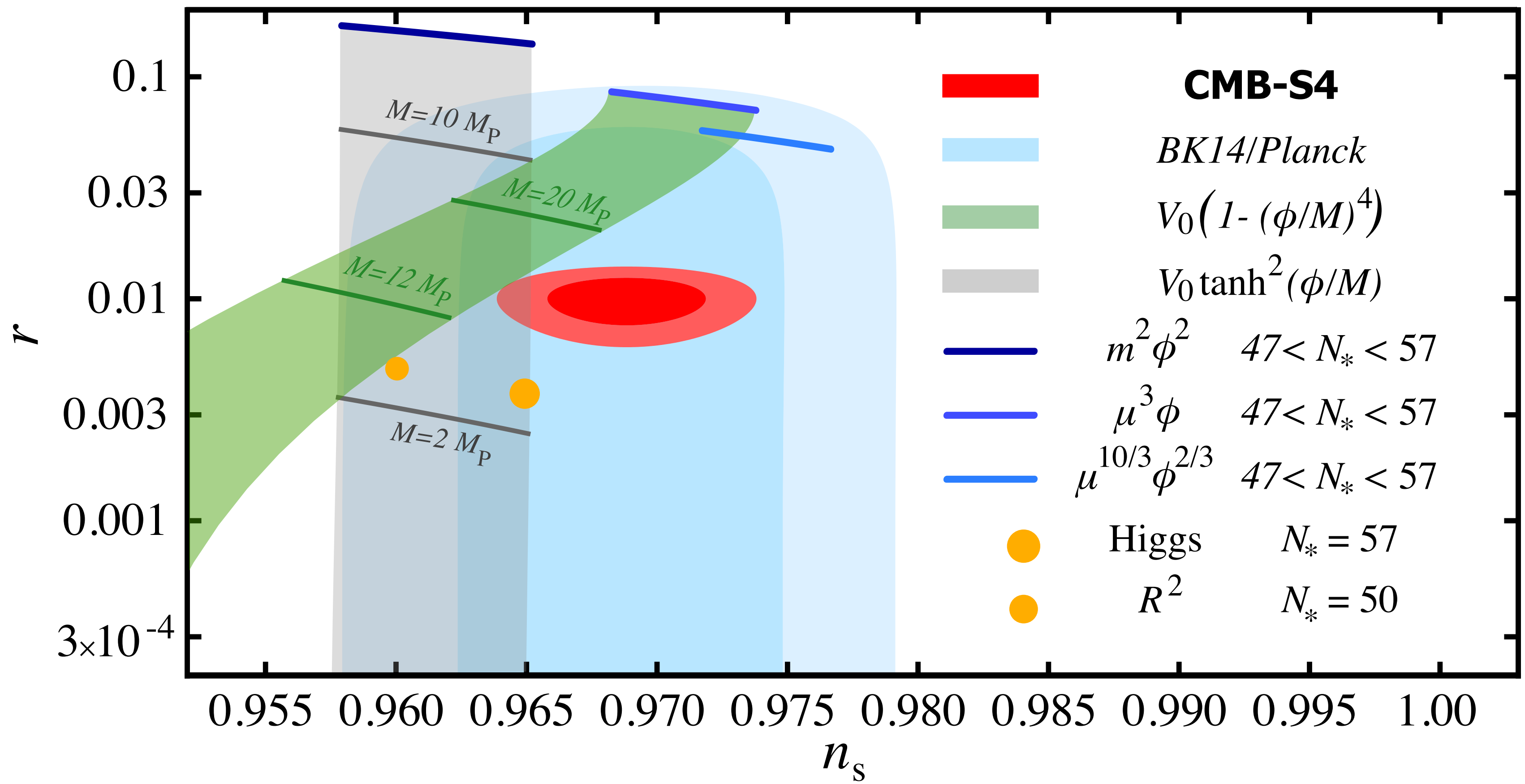
In the context of inflation it would measure the Hubble rate and via the Friedmann equation

$$V_{\rm inf}^{1/4} = 1.04 \times 10^{16}\,{\rm GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

Primordial B-modes

CMB-S4 could detect r=0.01 at high significance

CMB-S4 Science Book (http://www.cmbs4.org)



Primordial B-modes

Even an upper limit from CMB-S4 is interesting

If the inflationary model naturally explains the observed value of the spectral index, i.e.

$$n_{\rm s}(\mathcal{N}) - 1 = -\frac{p+1}{\mathcal{N}}$$

then the inflationary part of the potential is either

$$V(\phi) = \mu^{4-2p}\phi^{2p}$$

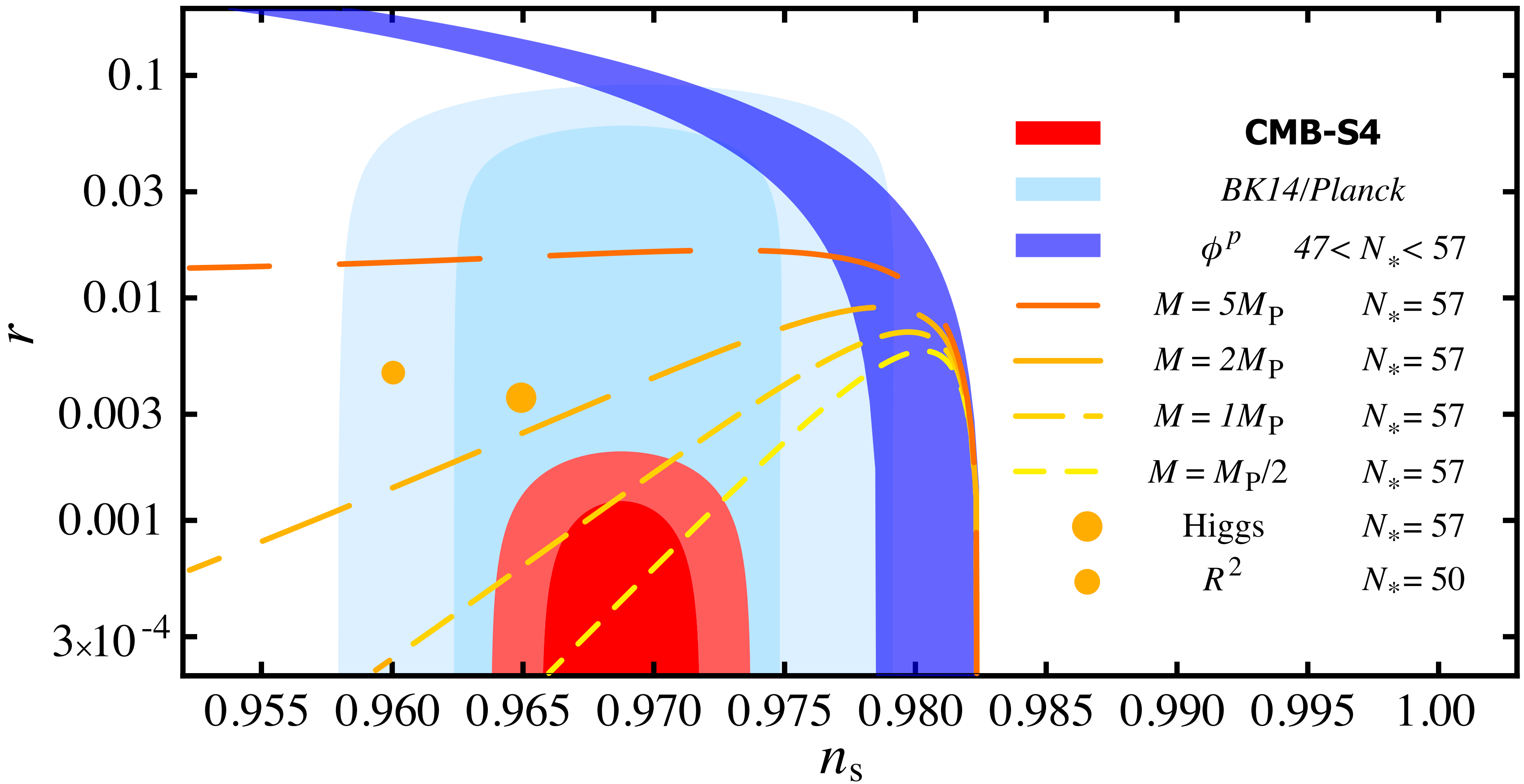
or

$$V(\phi) = V_0 \exp\left[-\left(\frac{\phi}{\Lambda}\right)^{\frac{2p}{p-1}}\right] \qquad (p \neq 1)$$

The characteristic scale in latter case is $M = \Lambda\dfrac{|1-p|}{p}$

Primordial B-modes

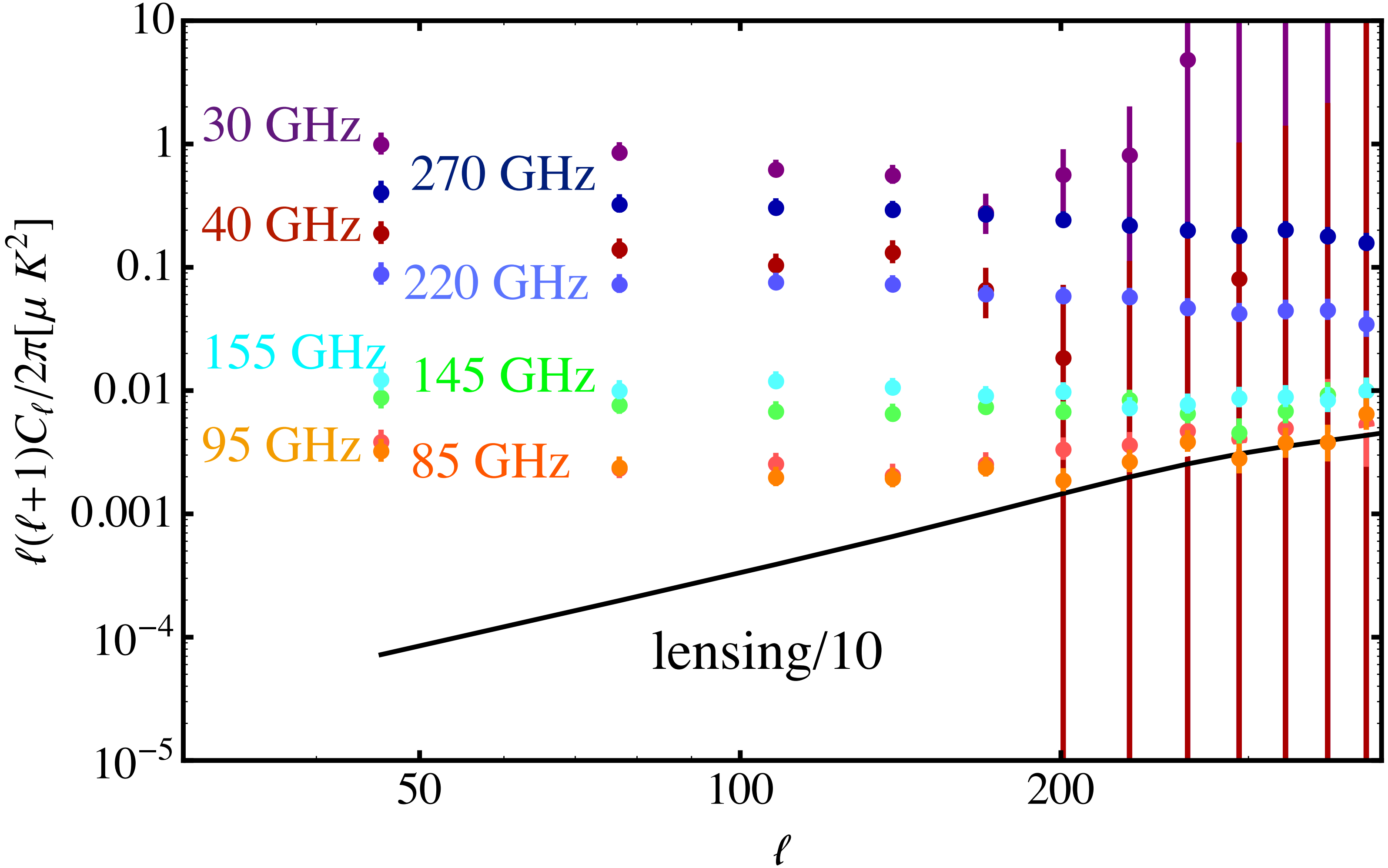
CMB-S4 Science Book (http://www.cmbs4.org)



An upper limit with CMB-S4 would disfavor all models of inflation that naturally explain n_s with super-Planckian characteristic scale M

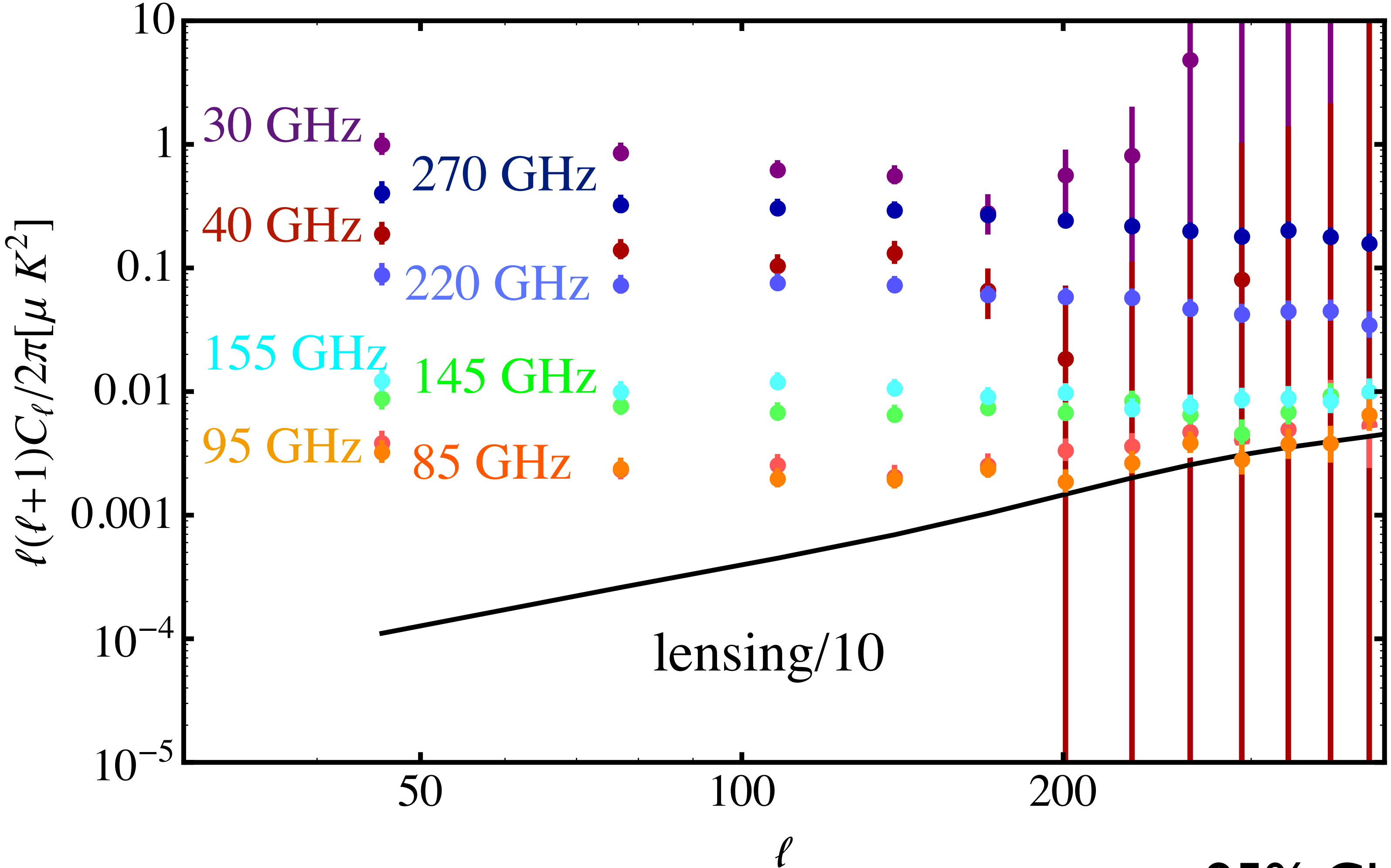
Primordial B-modes

The challenge is to use maps with auto-spectra shown below to tell the difference between...



Primordial B-modes

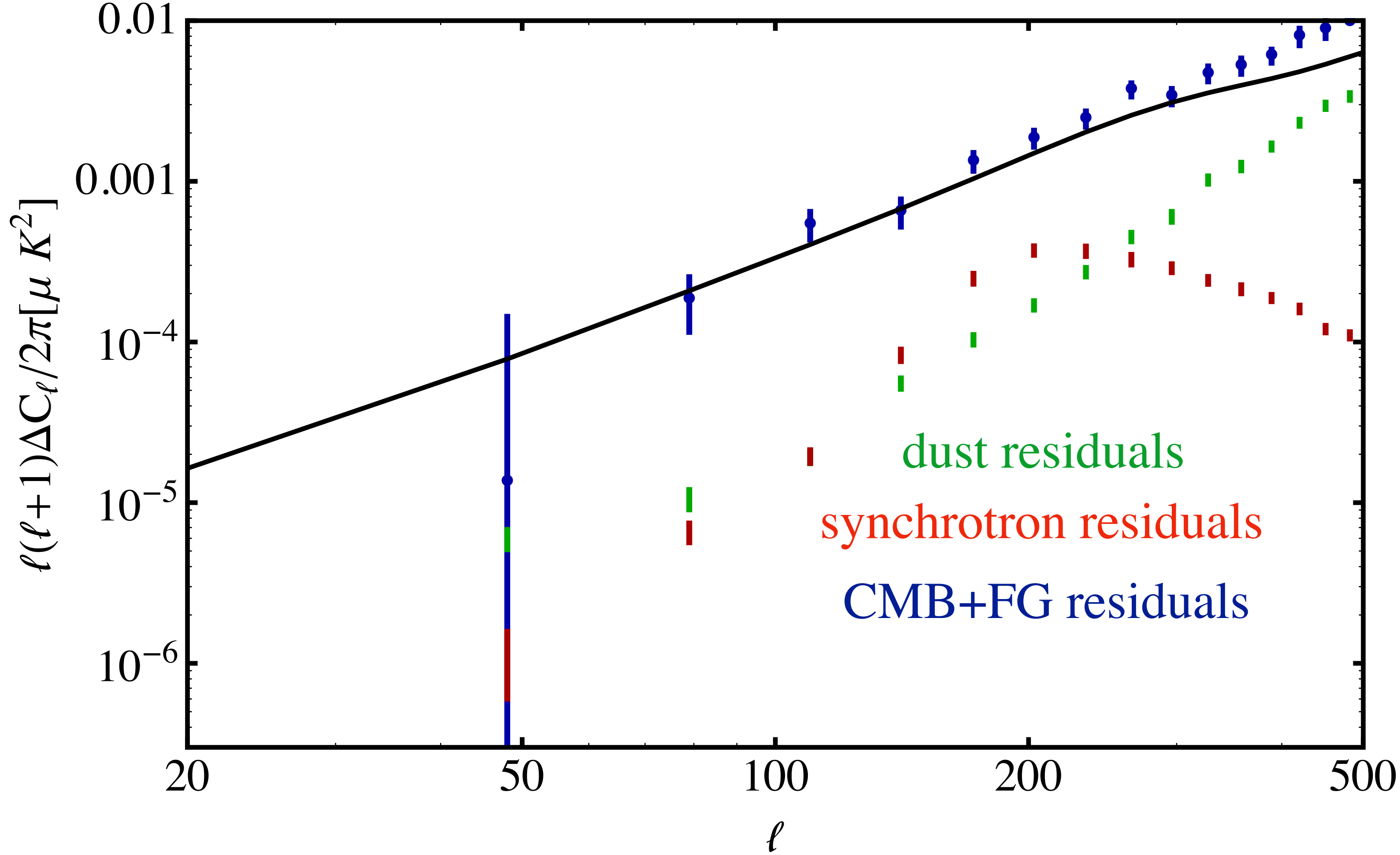
and...



at 95% CL

Primordial B-modes

Foreground cleaned spectrum and foreground residuals based on simulation for representative configuration



Light Relics

Light Relic

Particle that is stable on cosmological time scales and light enough to be relativistic at recombination

Contribute to the energy density in radiation

$$\rho_{\rm rad} = \frac{\pi^2 k_{\rm B}^4}{15\hbar^3 c^3}\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] T_\gamma^4$$

with $N_{\rm eff} = 3.046$ in the Standard Model

Light Relics

The CMB is predominantly sensitive to N_{eff} through

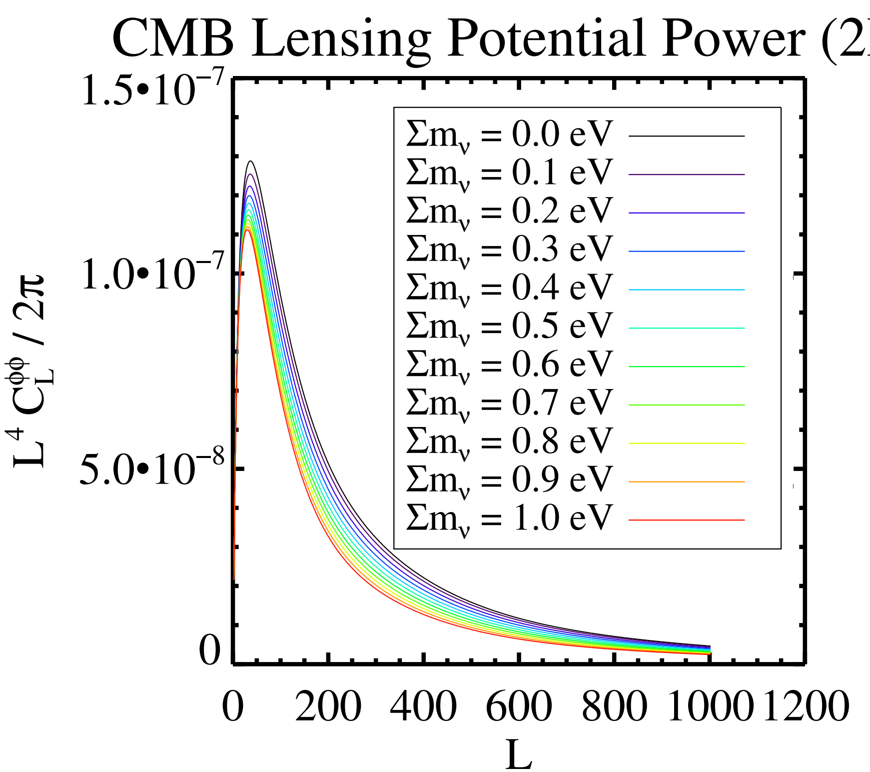
- the damping tail
- and phase of accoustic oscillations

A detection of $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - 3.046 \neq 0$ would indicate physics beyond the Standard Model or a non-standard cosmology.

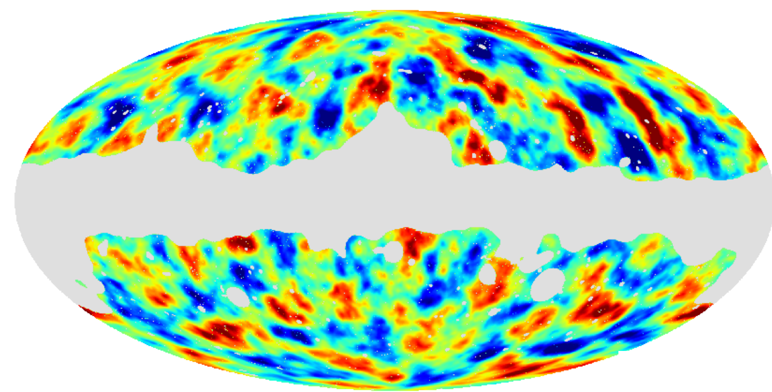
See Daniel Green's talk for details

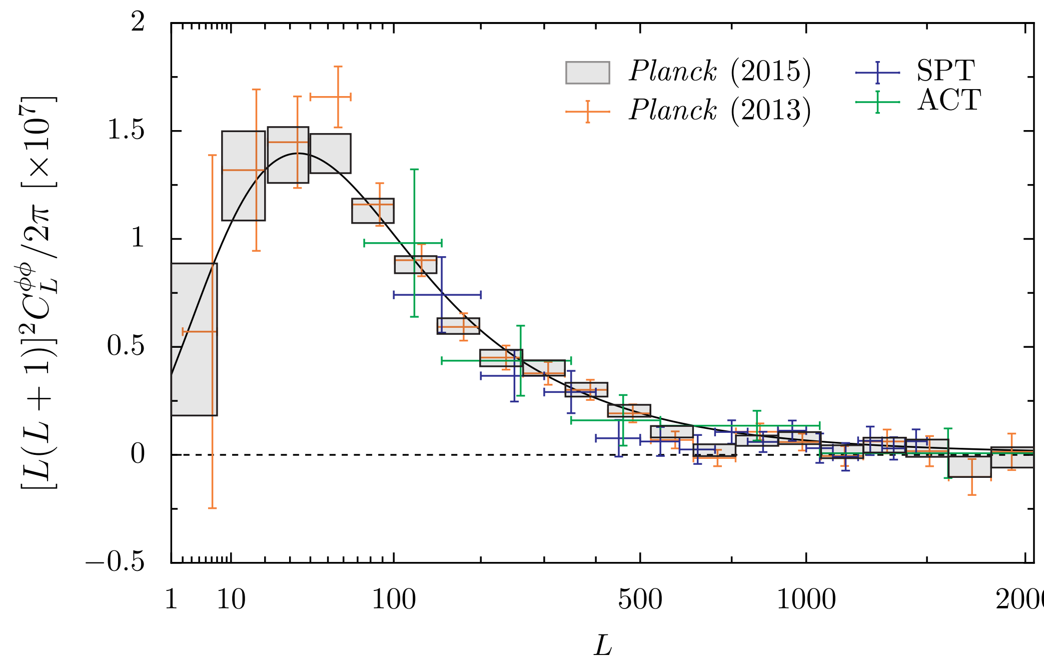
Neutrino Mass

The CMB is predominantly sensitive to neutrino mass through the early integrated Sachs-Wolfe effect and through weak lensing lensing of the CMB



CMB-S4 Science Book (http://www.cmbs4.org)

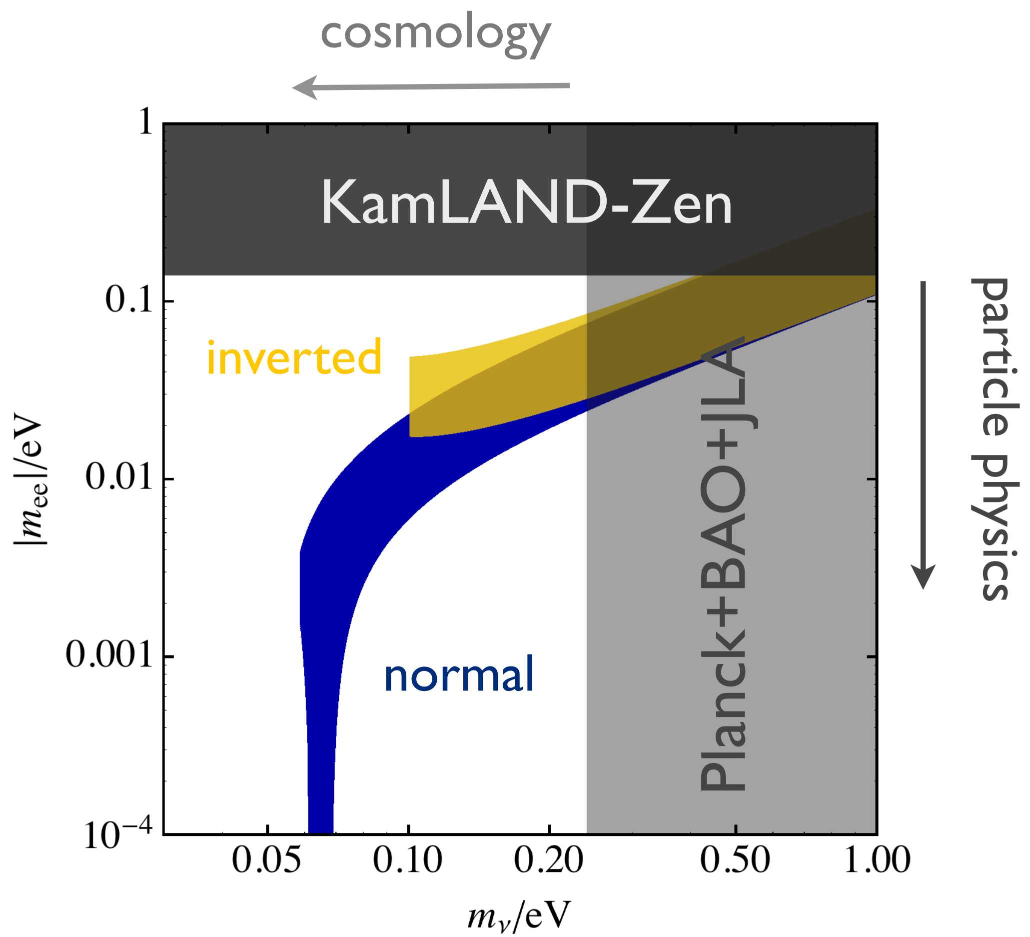




Neutrino Mass

Completely complementary to lab experiments

Current:

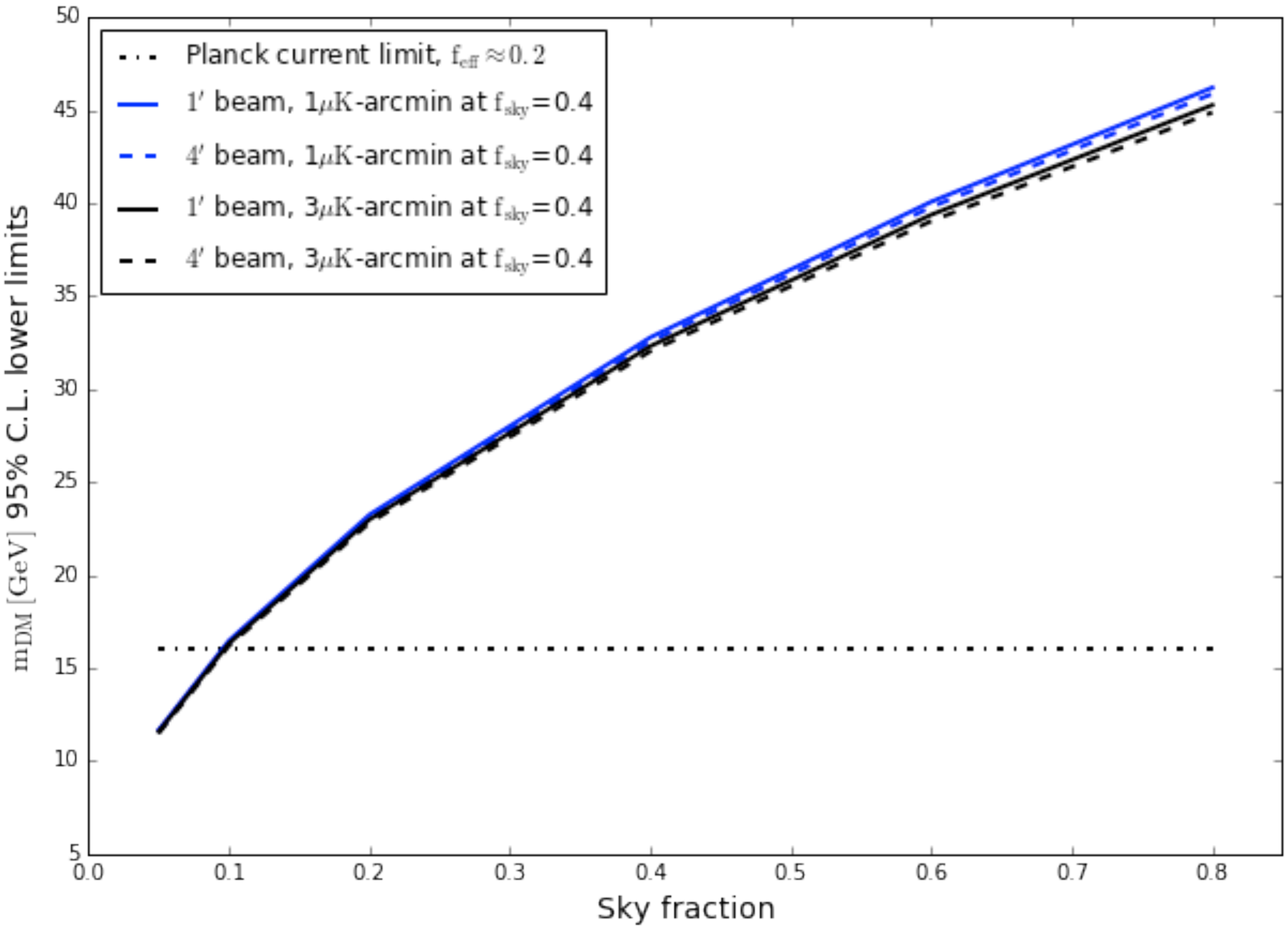


DESI+CMB-S4: $\sigma(m_\nu) \approx 0.02\,\mathrm{eV}$

3σ measurement even for normal hierarchy

Dark Matter

CMB-S4 Science Book (http://www.cmbs4.org)



(only applies to s-wave annihilation)

Conclusions

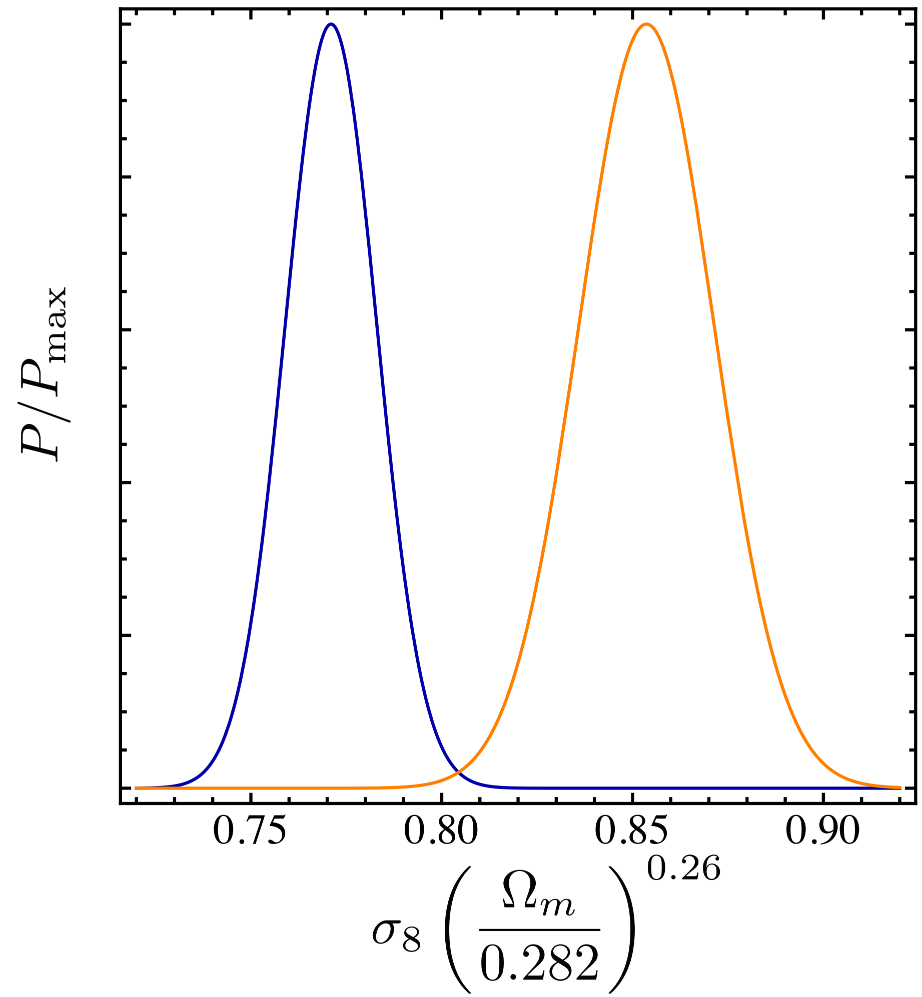
- Our understanding of the early universe has improved significantly over the past two decades
- Although there are small tensions, all data remains consistent with the simple LCDM model
- Many experiments are already taking data, many will soon come online and will constrain light relics, neutrinos, dark matter, ...
- The next decade will be eventful and we should continue to learn a lot about the early universe and particle physics from CMB (as well as other cosmological) experiments

Thank you

Clustering

tSZ power spectrum
(Hill, Spergel 2013)

Planck 2015 TT+lowP
Paper XIII

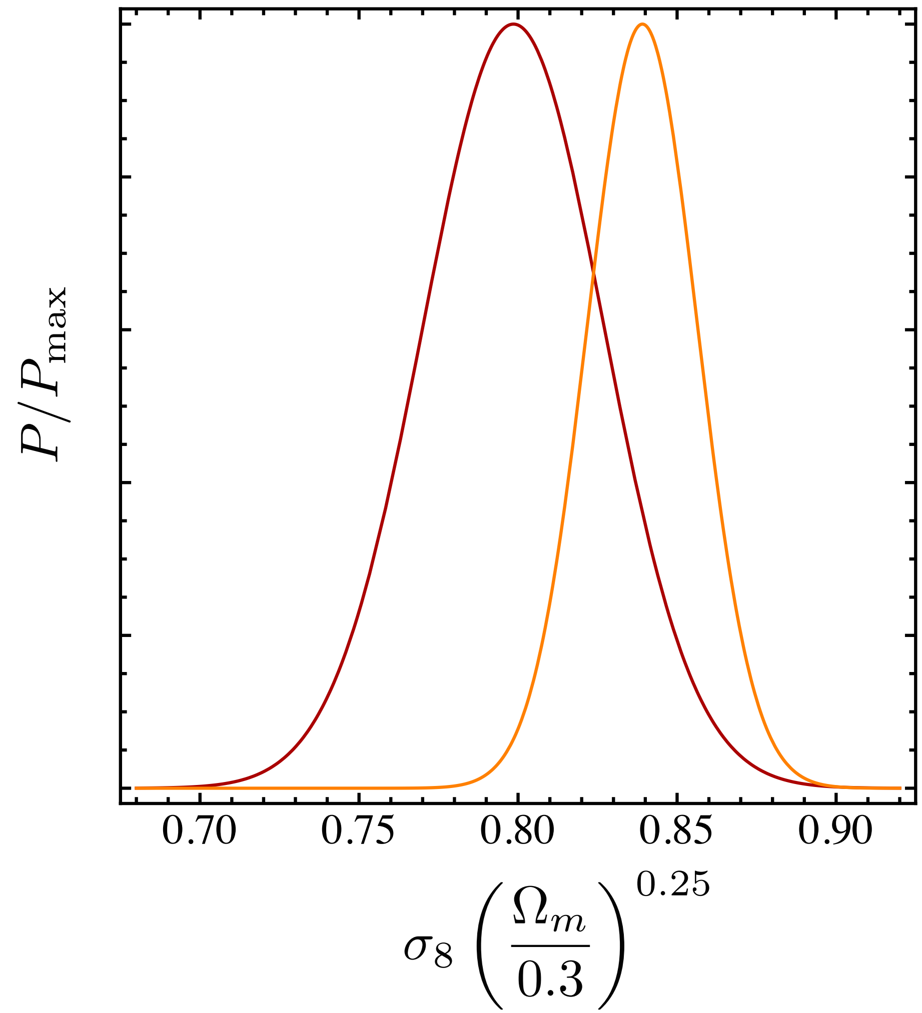


- Small tensions exist between the Planck TT data and a number of low redshift observations

Clustering

Planck 2015 TT+lowP

Planck 2015 lensing



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

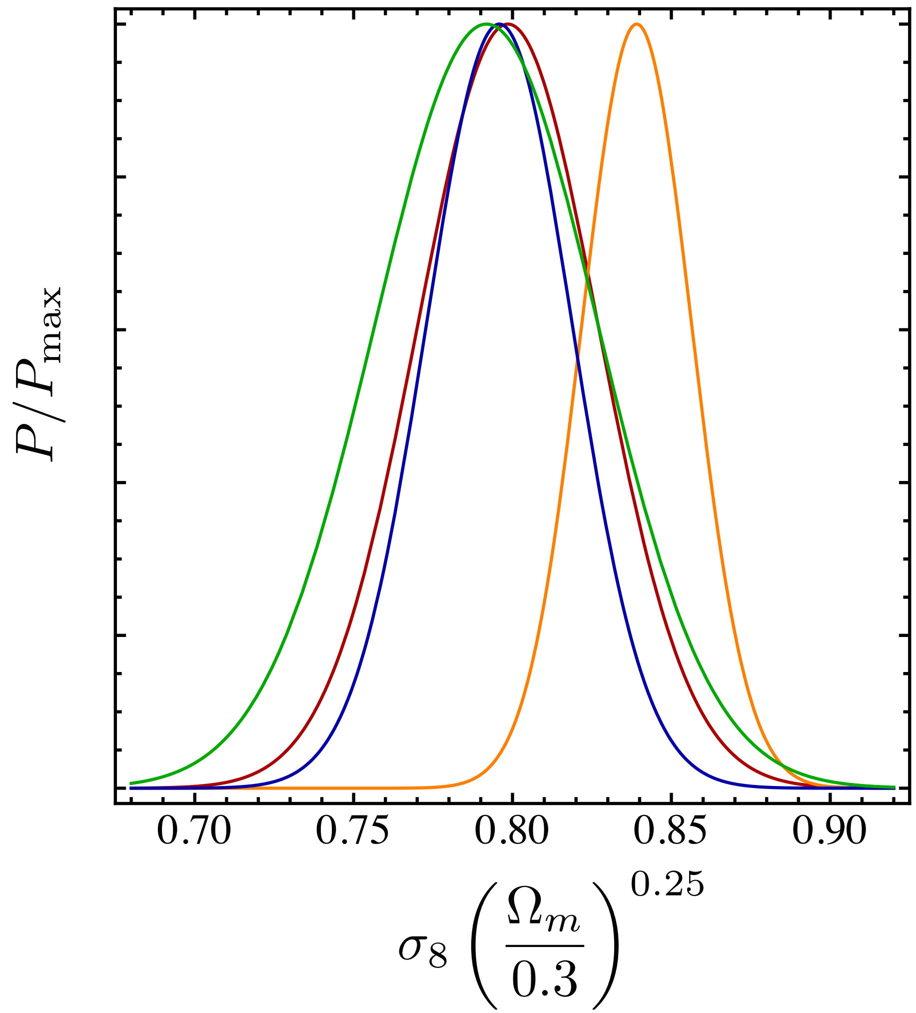
Clustering

Planck 2015 TT+lowP

Planck 2015 lensing

Planck 2015 TE+lowEB

Planck 2015 EE+lowEB



- Both Planck TE and Planck EE cosmologies in excellent agreement with Planck lensing

The Hubble Constant

Reid et al. 2013

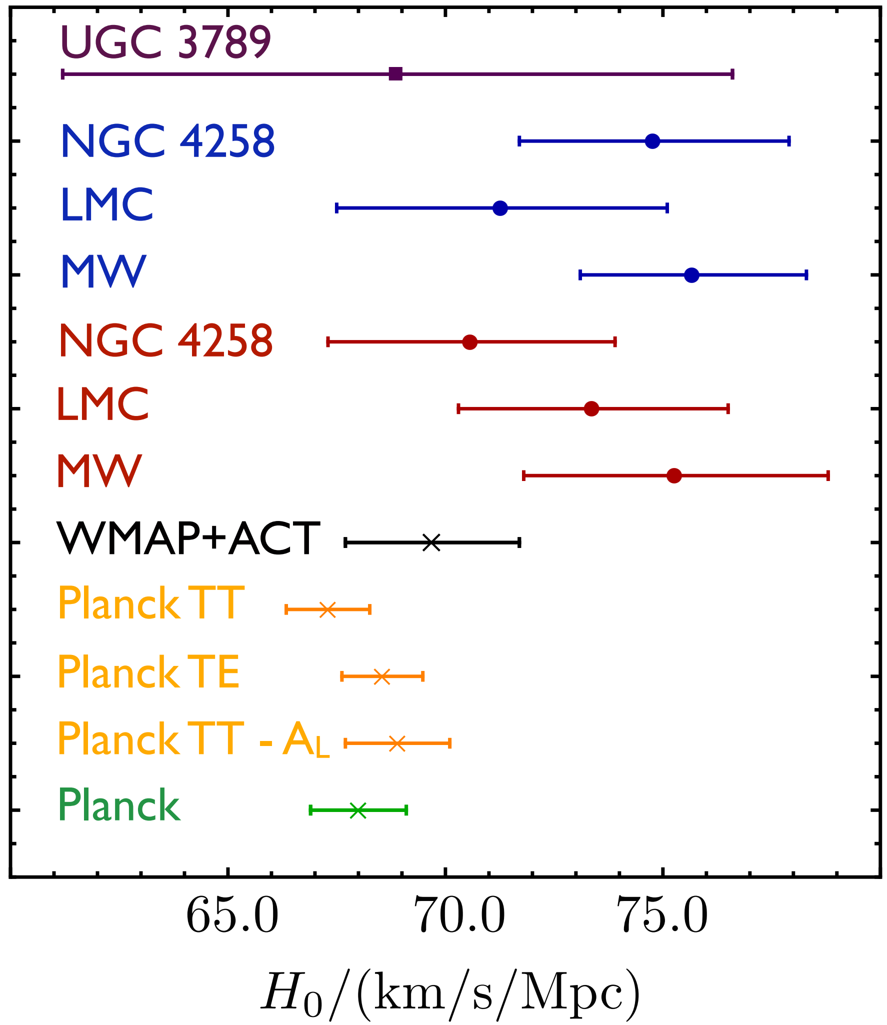
Riess et al. 2011

Efstathiou 2013

Hinshaw et al. 2013

Ade et al. 2015

Spergel, Flauger, Hlozek 2013



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