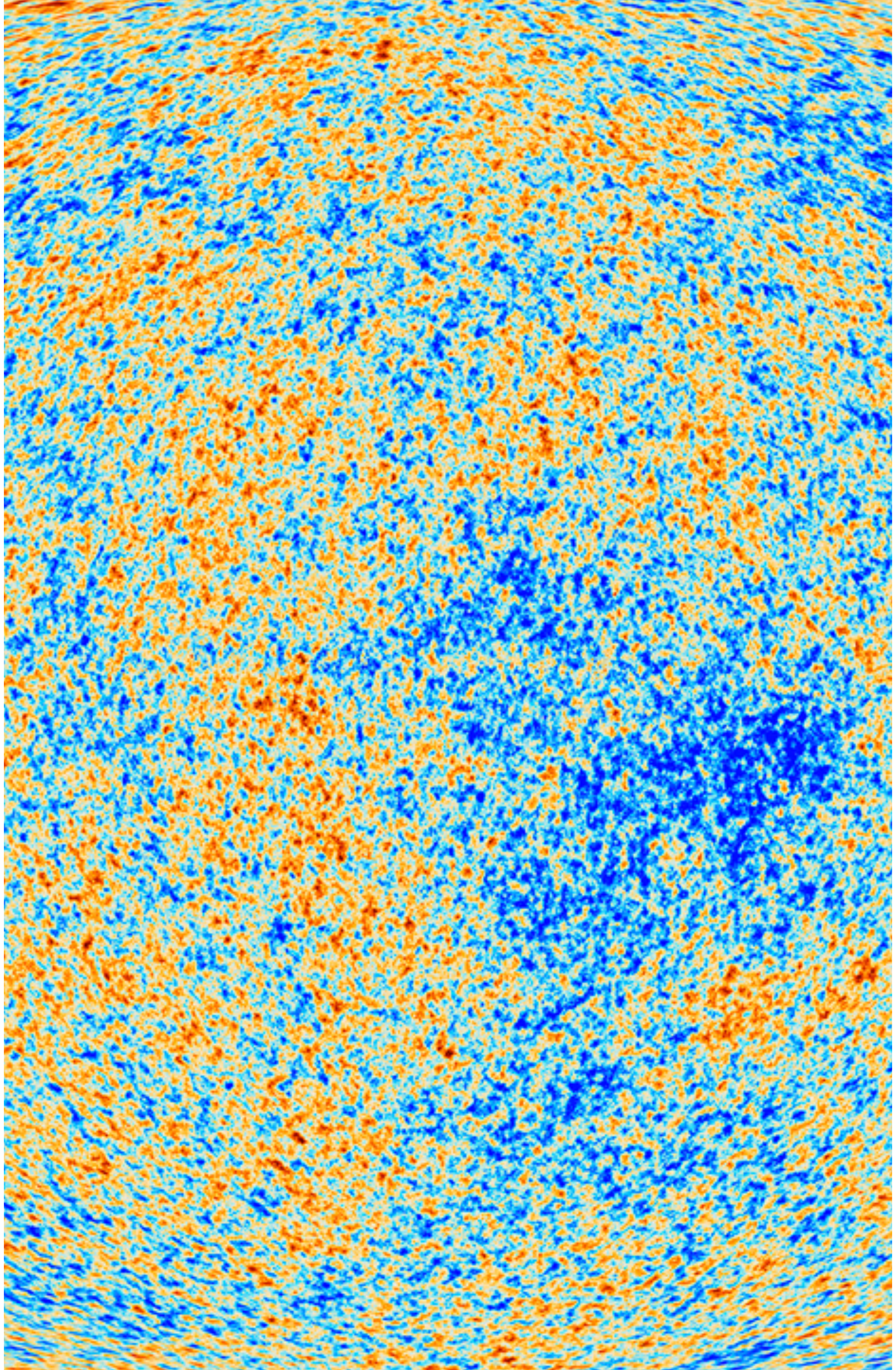


Critical interpretation of Planck results

Jo Dunkley
University of Oxford

5/11/2015

esa

planck

cnes

agenzia spaziale italiana

NASA

CNRS

DTU Space
National Space Institute

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science & Technology Facilities Council

CSIC
Consejo Superior de Investigaciones Científicas

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

Aalto University

APC

California Institute of Technology

ioa

Kavli Institute for Cosmology Cambridge KICC

Cavendish Astrophysics

University of Cambridge

Cardiff University Prifysgol Caerdydd

irfu cea saclay

cea energie atomique • energies alternatives

CESR

CITA–ICAT

CNRS IN2P3 Les deux infinis

ipac Infrared Processing and Analysis Center

Helsinki Institute of Physics

Instituto de Astrofísica de Canarias IAC

IFCA Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

Néel institut

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

ISDC Data Centre for Astrophysics

JPL

LAL Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris LERMA

LPSC Grenoble Laboratoire de Physique Subatomique et de Cosmologie

The University of Manchester

MilliLab

Max-Planck-Institut für Astrophysik

NUI Maynooth

INAF Osservatorio Astronomico di Padova

University of Oxford

Dipartimento di Fisica Sapienza Università di Roma

Science & Technology Facilities Council Rutherford Appleton Laboratory

Università degli Studi di Roma Tor Vergata

Osservatorio Astronomico Trieste

UBC

UC Universidad de Cantabria

UCSB

SISSA

Stanford University

ALMA

ESO

US University of Sussex

esa

University of Helsinki

Universitas Oslonensis

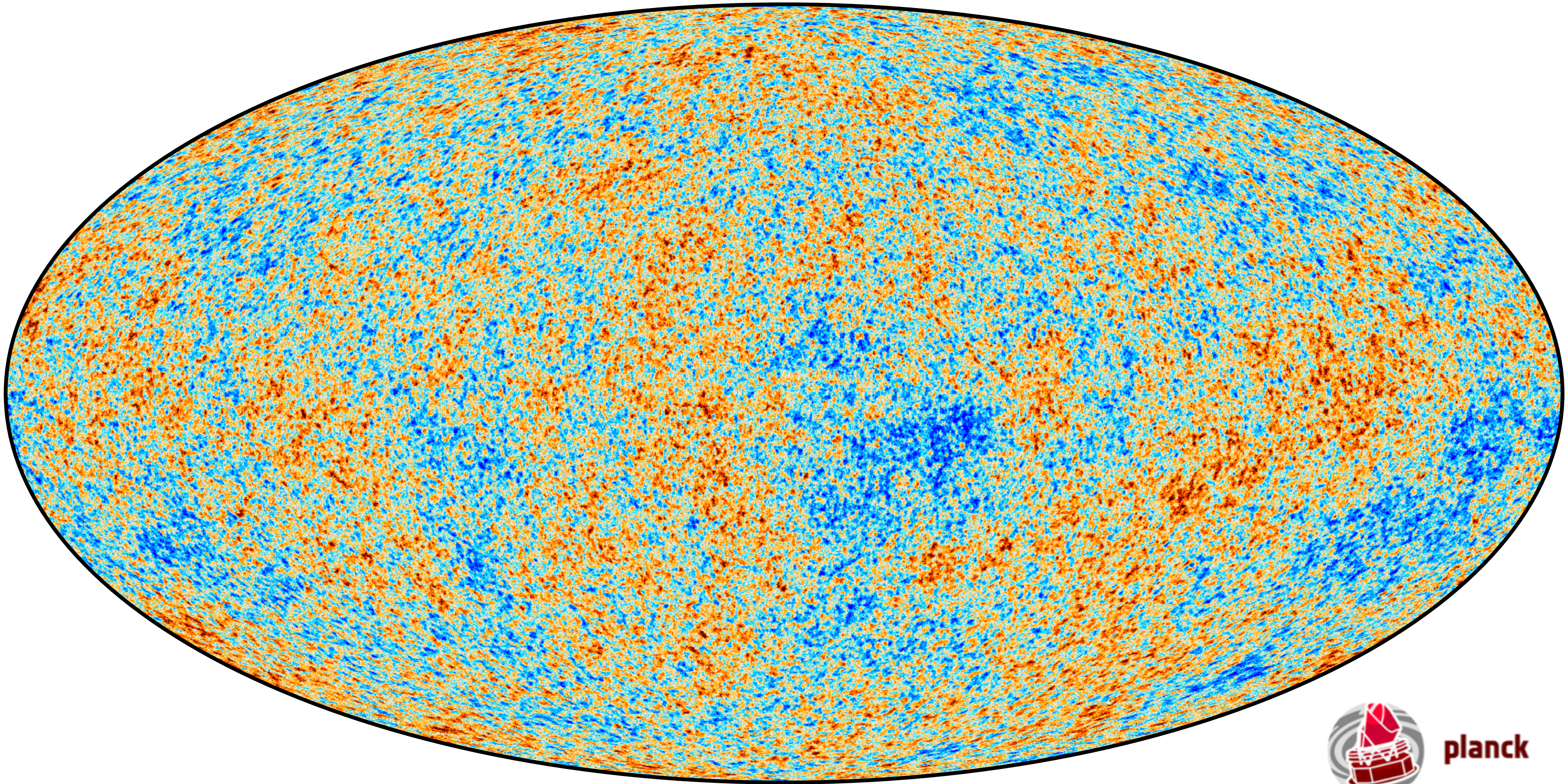
Université de Genève

University of Toronto

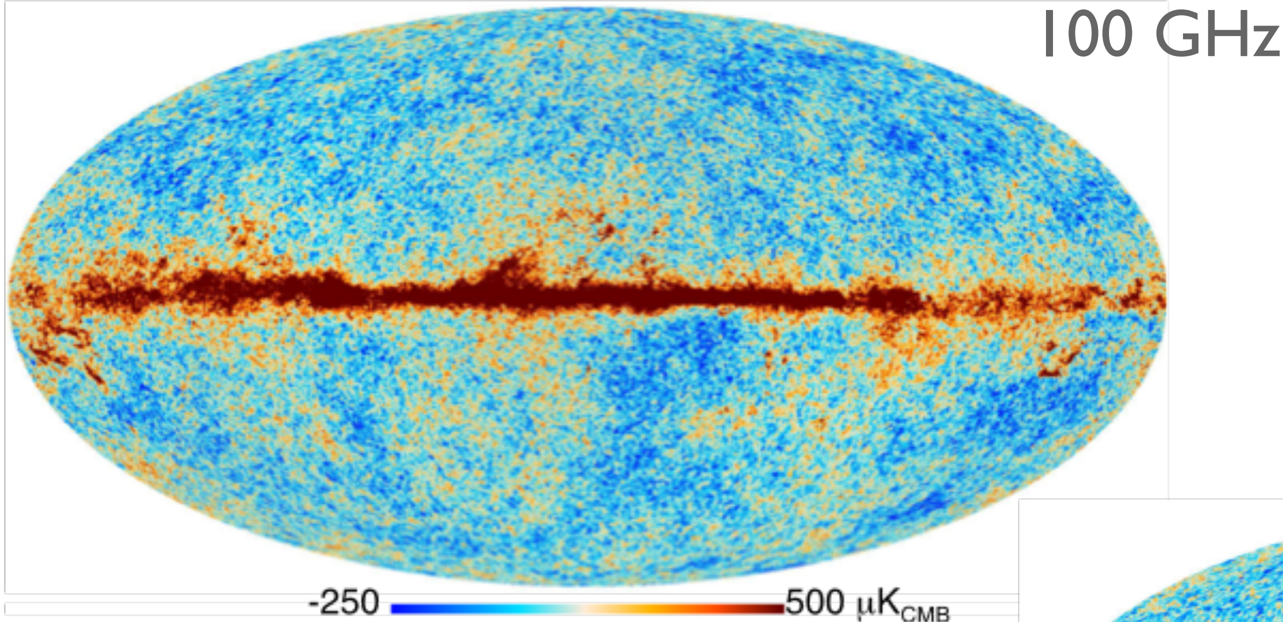
Université de Paris-Sud XI

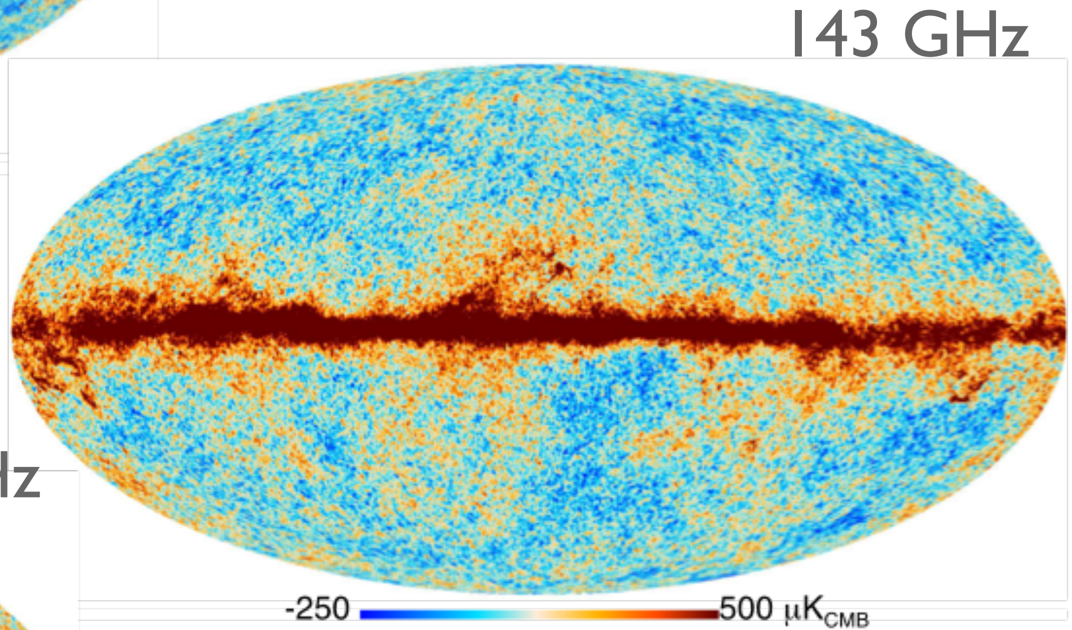
asdc ASI Science Data Center

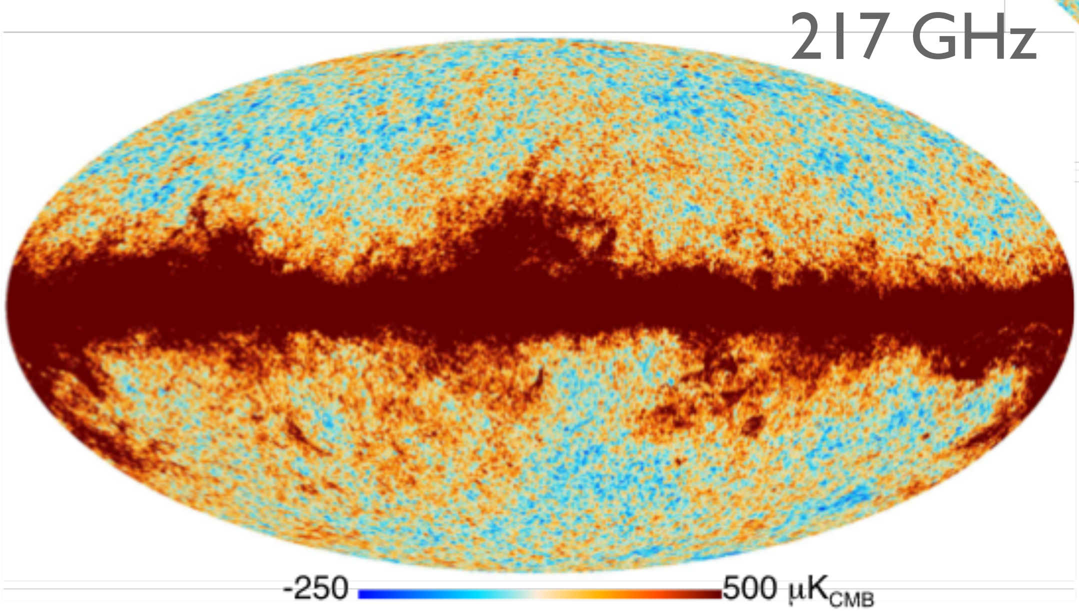
Istituto di Scienza e Tecnologie dell'Informazione "A. Faedo"



Planck Collaboration 2015

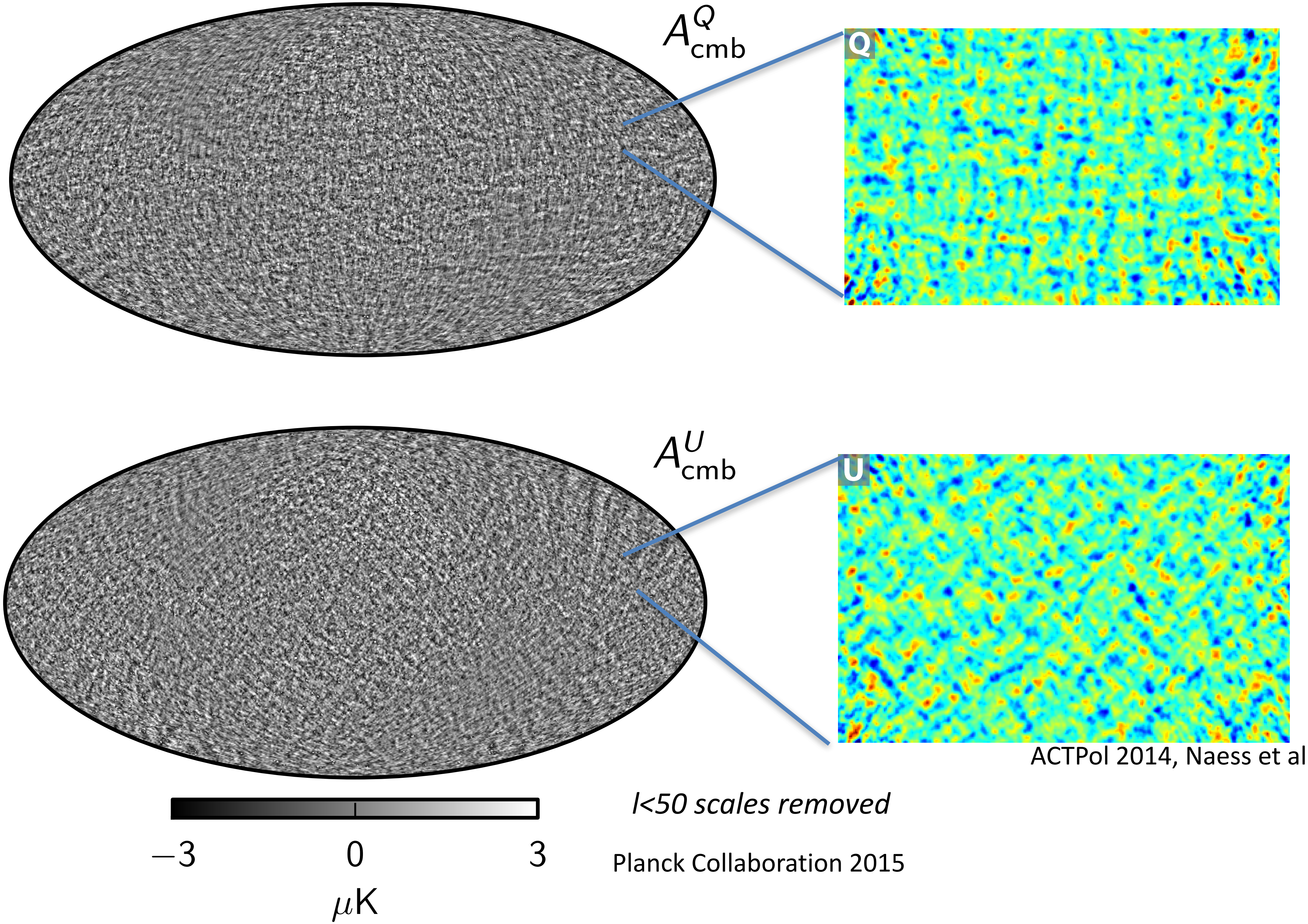




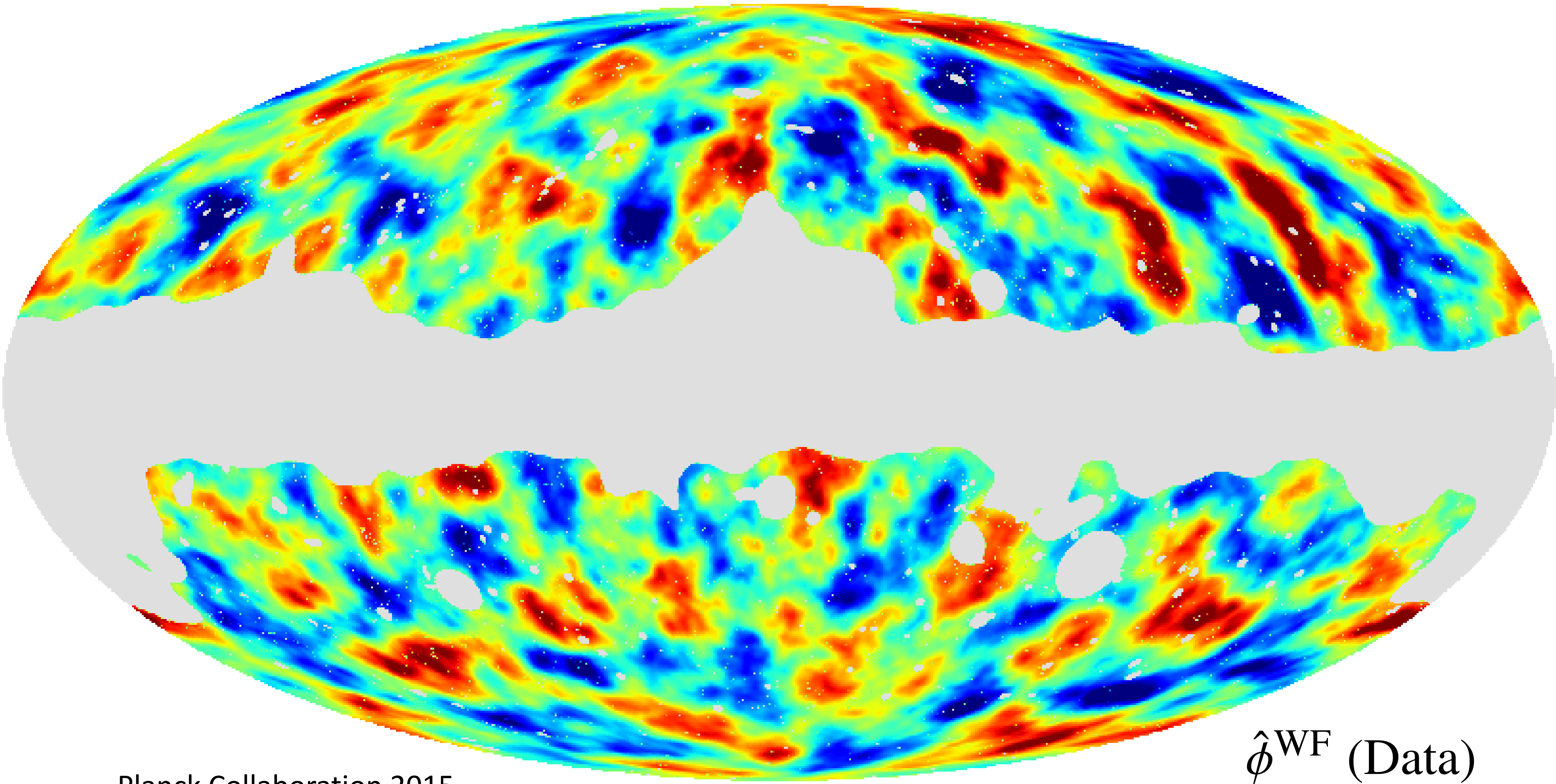


Plus 6 other wavelengths

Polarization anisotropy



Lensing potential, phi



Planck Collaboration 2015

$$T(n) = \tilde{T}(n + \nabla\phi)$$

$$\propto T(\boldsymbol{\ell})T^*(\boldsymbol{L}-\boldsymbol{\ell})$$

What are the geometry and contents of the universe?

What are the properties of the dark sector?

Did inflation happen/what are the initial conditions?

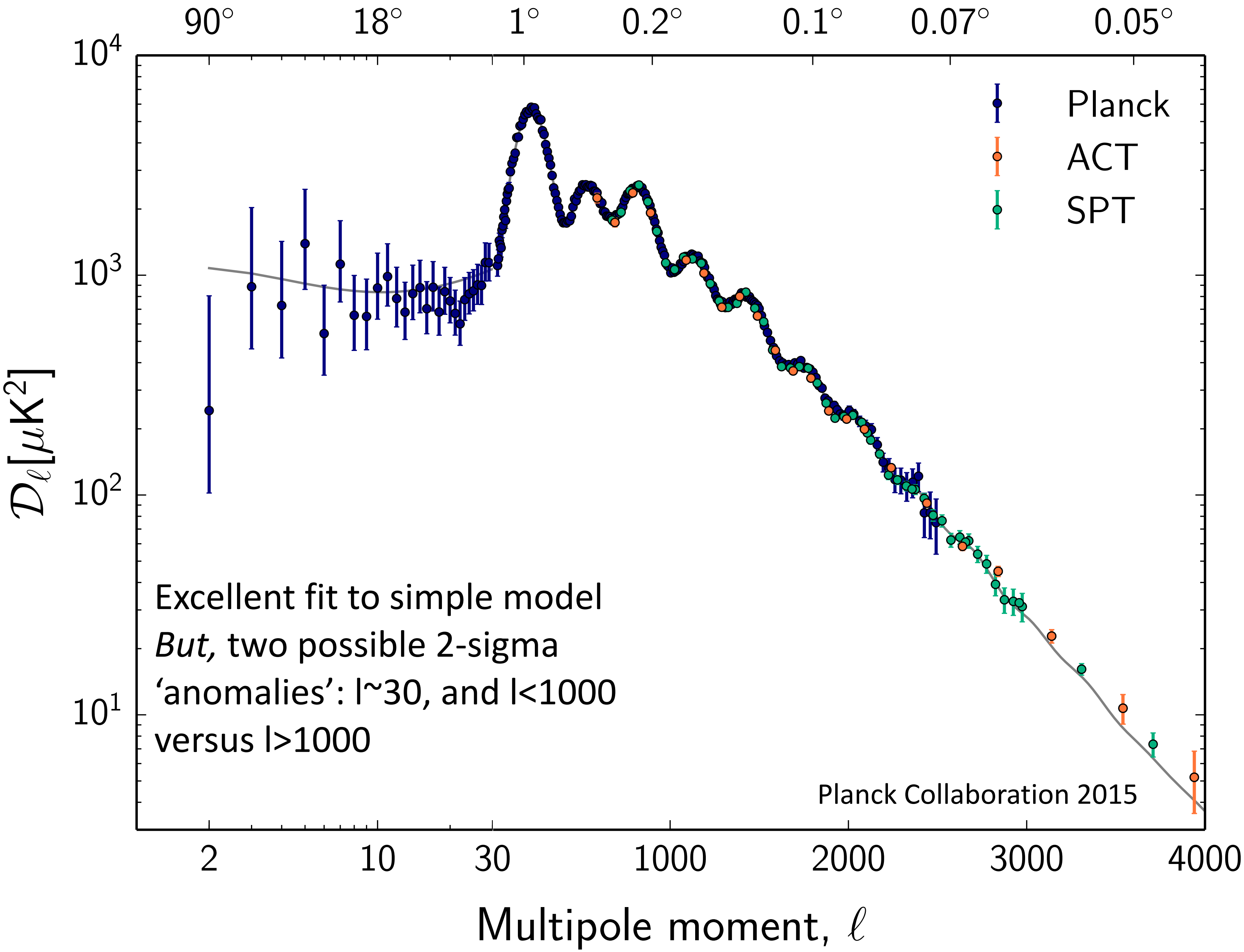
Rough description of CMB analysis process:

'Data' = maps of the blackbody sky (temp, pol, lensing)

Statistic = angular power spectrum of maps

Output = cosmological parameters (reliable codes predict their theory power spectra)

CMB temperature



The ΛCDM model

(1) Contents and expansion

Baryon density $\Omega_b h^2$ = 0.02222 ± 0.00023

CDM density $\Omega_c h^2$ = 0.1197 ± 0.0022

Peak angle 100θ $(\sim r_s/D_A)$ =1.04085 ± 0.00047

(2) Initial fluctuations

Amplitude at k=0.05/Mpc

$\ln(10^{10} A_s)$ = 3.089 ± 0.036

Spectral index n_s = 0.9655 ± 0.0062

(3) Impact of reionization

Reionization optical depth τ =0.078 ± 0.019

→

(1) Contents and expansion rate

Baryon fraction Ω_b

CDM fraction Ω_c = 0.265 ± 0.013

Cosmol constant fraction $\Omega_\Lambda = 1 - \Omega_b - \Omega_c$

Expansion rate H_0 = 67.3 ± 1.0

(2) Late-time size of fluctuations

Amplitude on 8 Mpc/h scales σ_8 = 0.829 ± 0.014

(3) Reionization

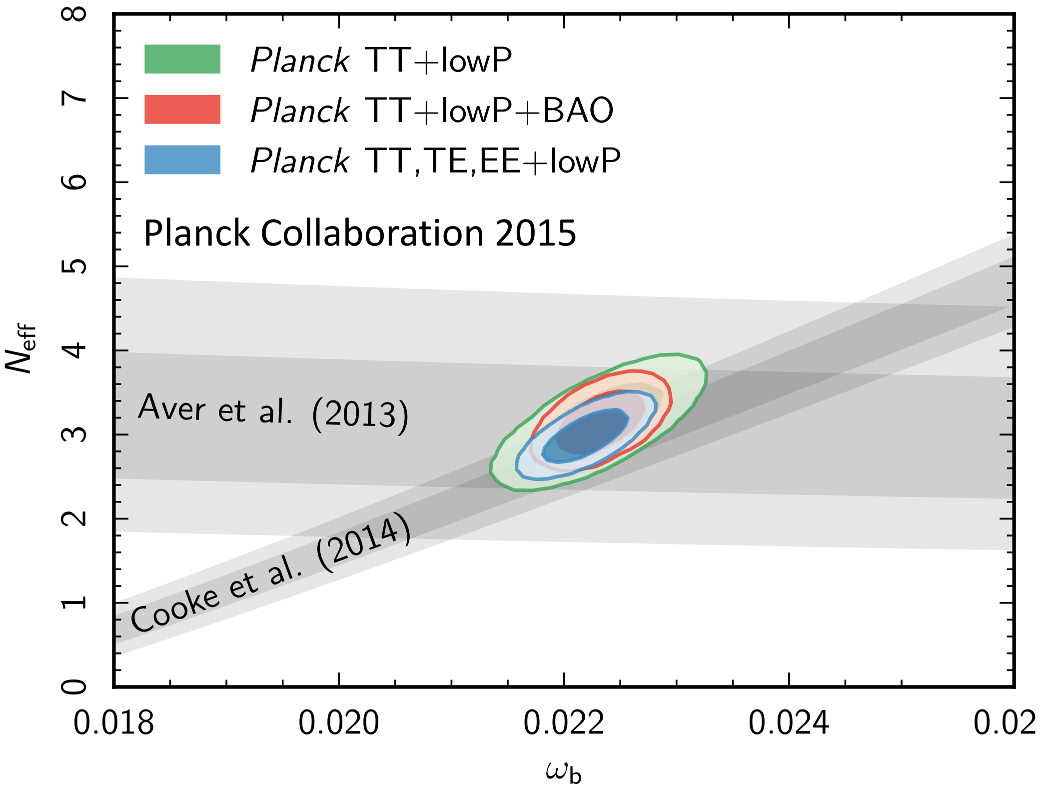
Redshift of reonization z_{re}

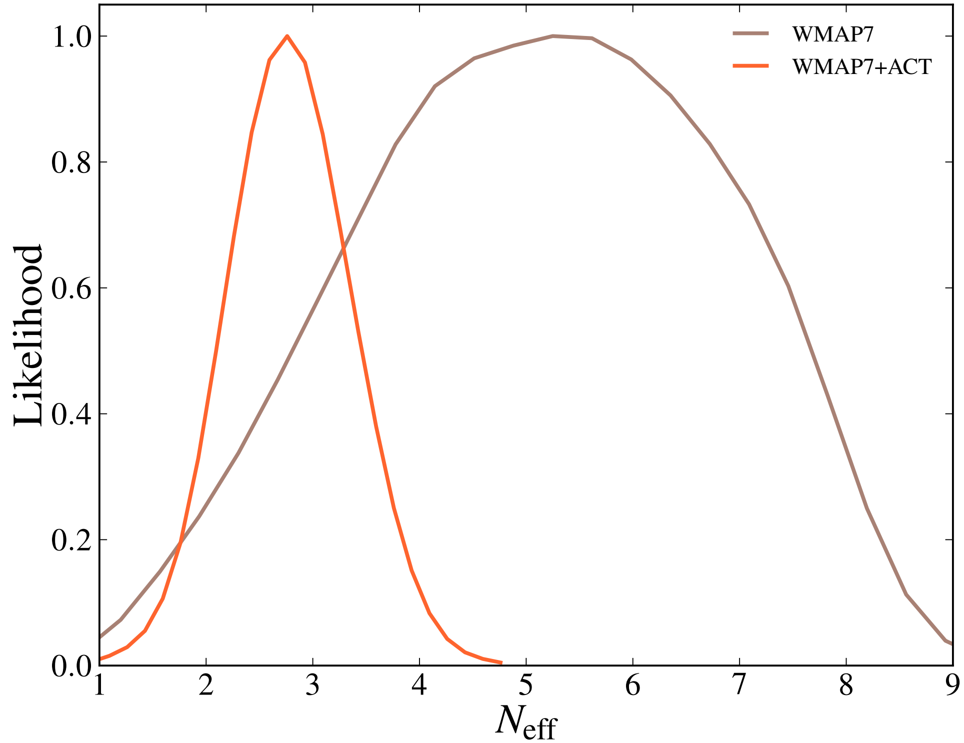
Assumptions:

- Geometry/contents: Flat, w=-1, Σm_ν=0.06eV, no warm dark matter, N_{eff}=3.04, Y_P=0.25
- Primordial fluctuations: adiabatic, power-law $P(k) = A(k/k_0)^{n-1}$, no tensors, no cosmic strings
- Smooth, quick reionization of universe

Neutrino (or relativistic) species

$$\rho_\nu = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$



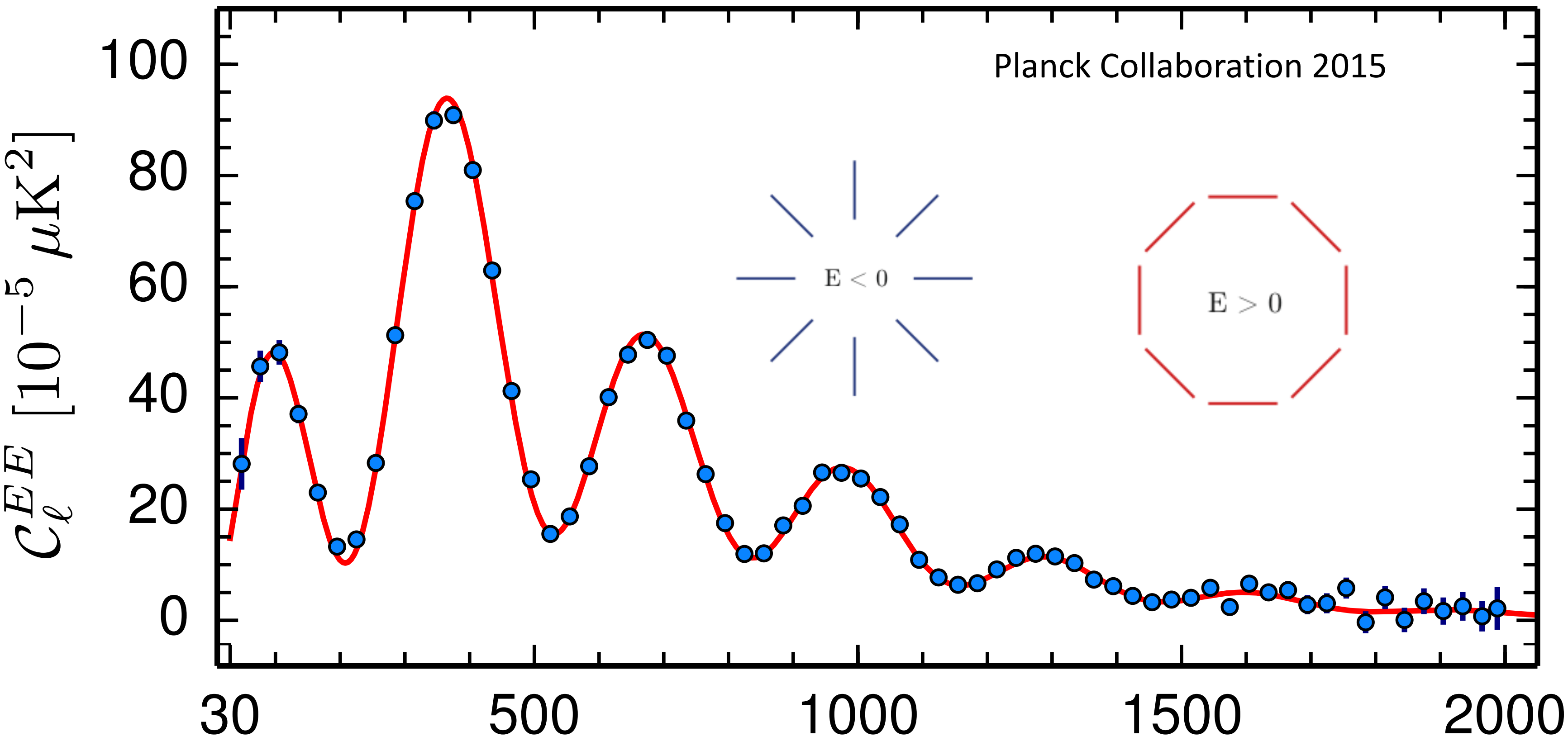


ACT+WMAP9: N_{eff} = 2.9 ± 0.5 (68%, Calabrese et al 2013)

Planck: N_{eff} = 3.1 ± 0.3 (68%, Planck Collab 2015)

Next decade: reduce error to ~0.02

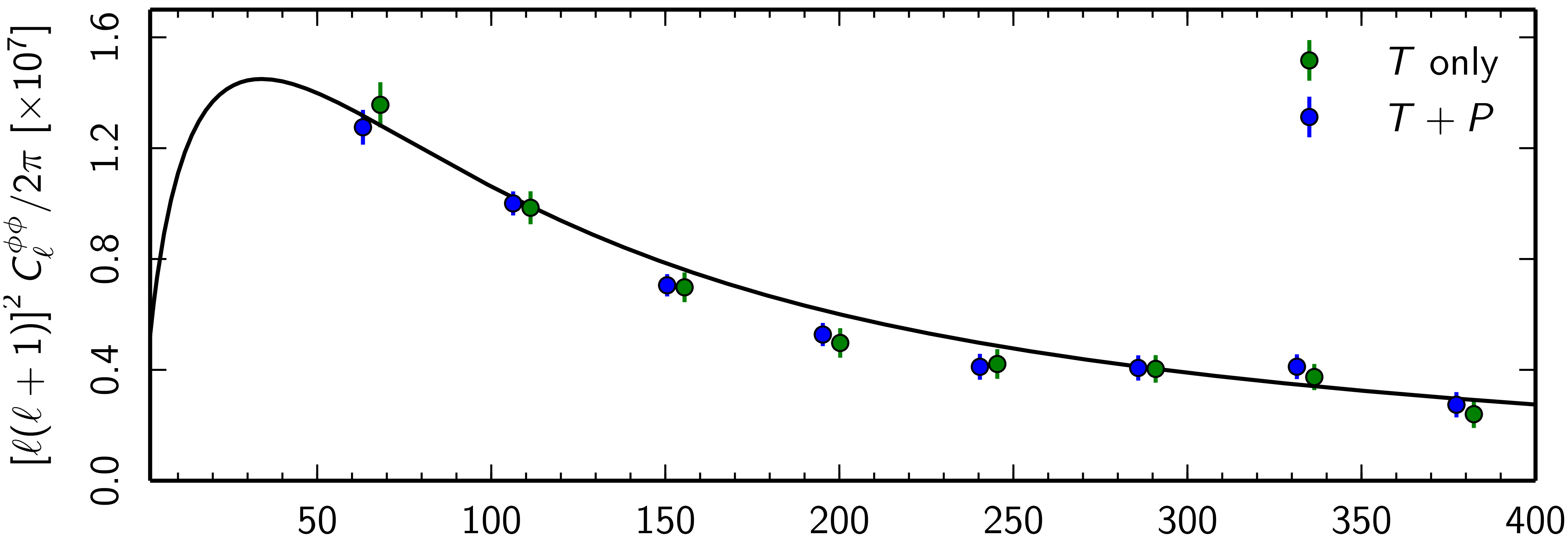
CMB polarization (E-mode)



Greatly limits vast zoo of alternatives to LCDM, e.g.

- different contents: *extra relativistic species, early dark energy*
- different initial fluctuations: *scale-dependent power, tensor or isocurvature fluctuations*
- extra components: *cosmic defects, magnetic fields*
- *non-standard BBN or recombination history, extra energy from dark matter annihilation*

CMB lensing

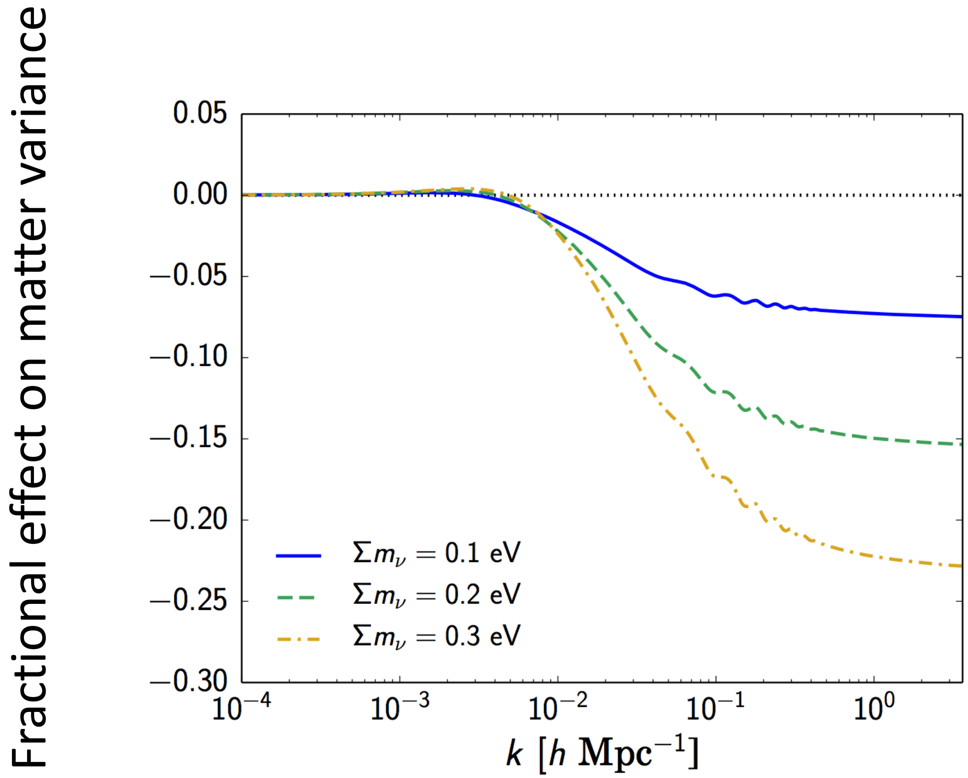


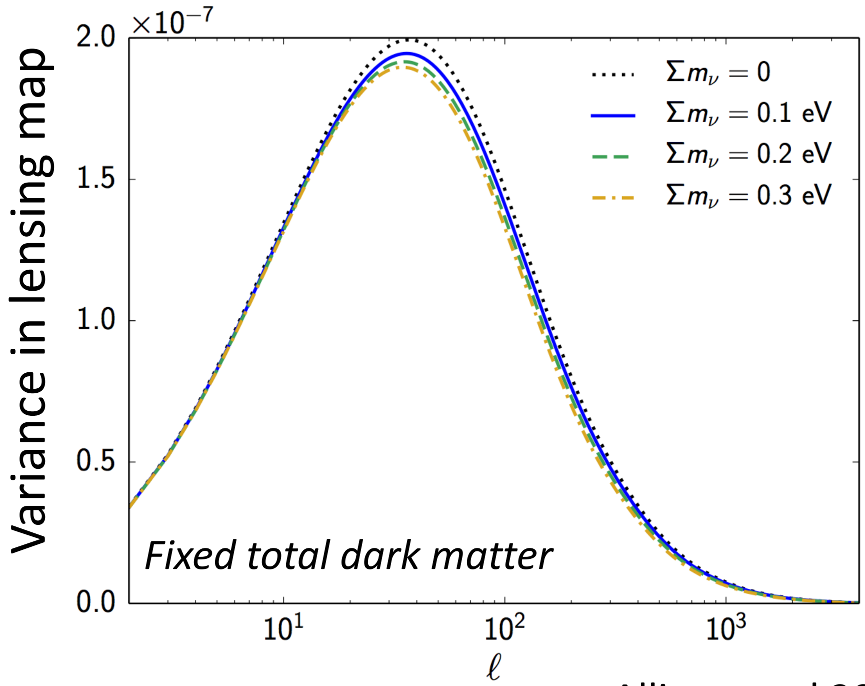
Planck Collaboration 2015

How does mass of neutrinos affect CMB?

Neutrinos start relativistic, suppressing growth compared to cold dark matter

More suppression, less lensing, if more of the dark matter density is in neutrinos



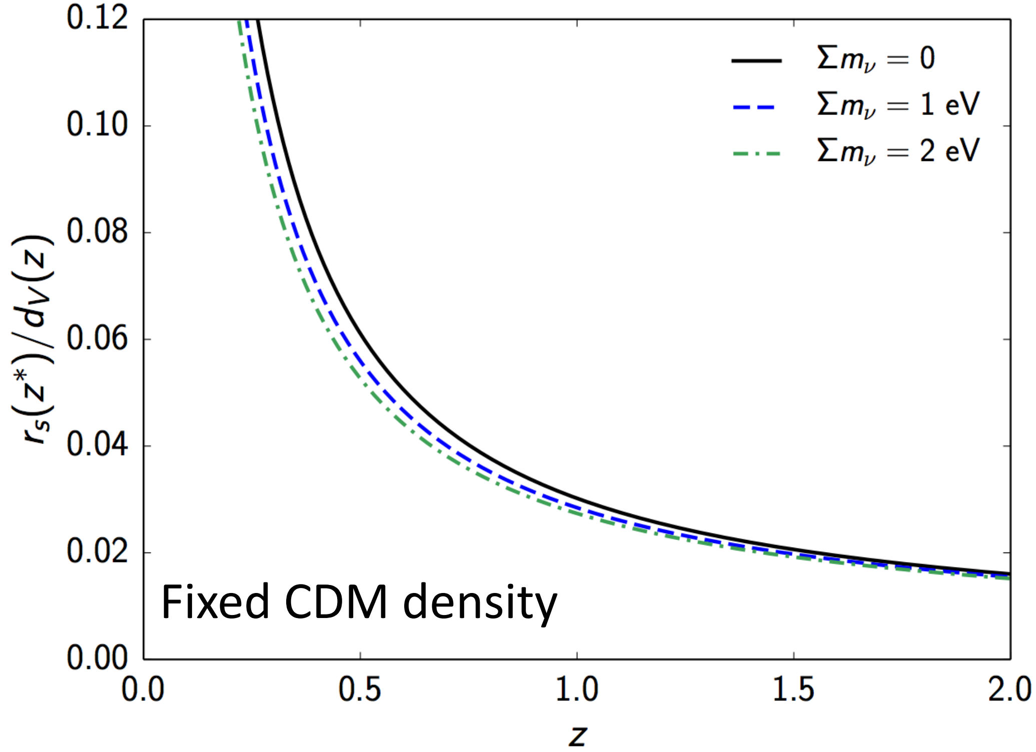


Allison et al 2015

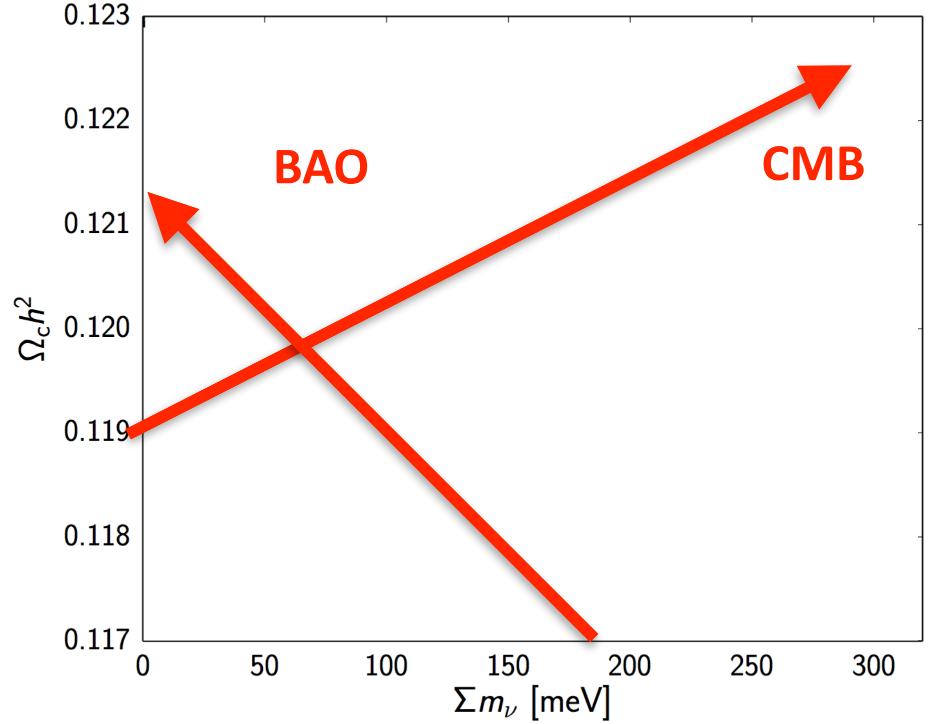
Neutrino mass sum < 0.7 eV (Planck Collab 2015)

How does mass of neutrinos affect cosmic distances?

- Neutrinos behave like cold dark matter at late times (z<~100).
- Distances and expansion rates measure total matter



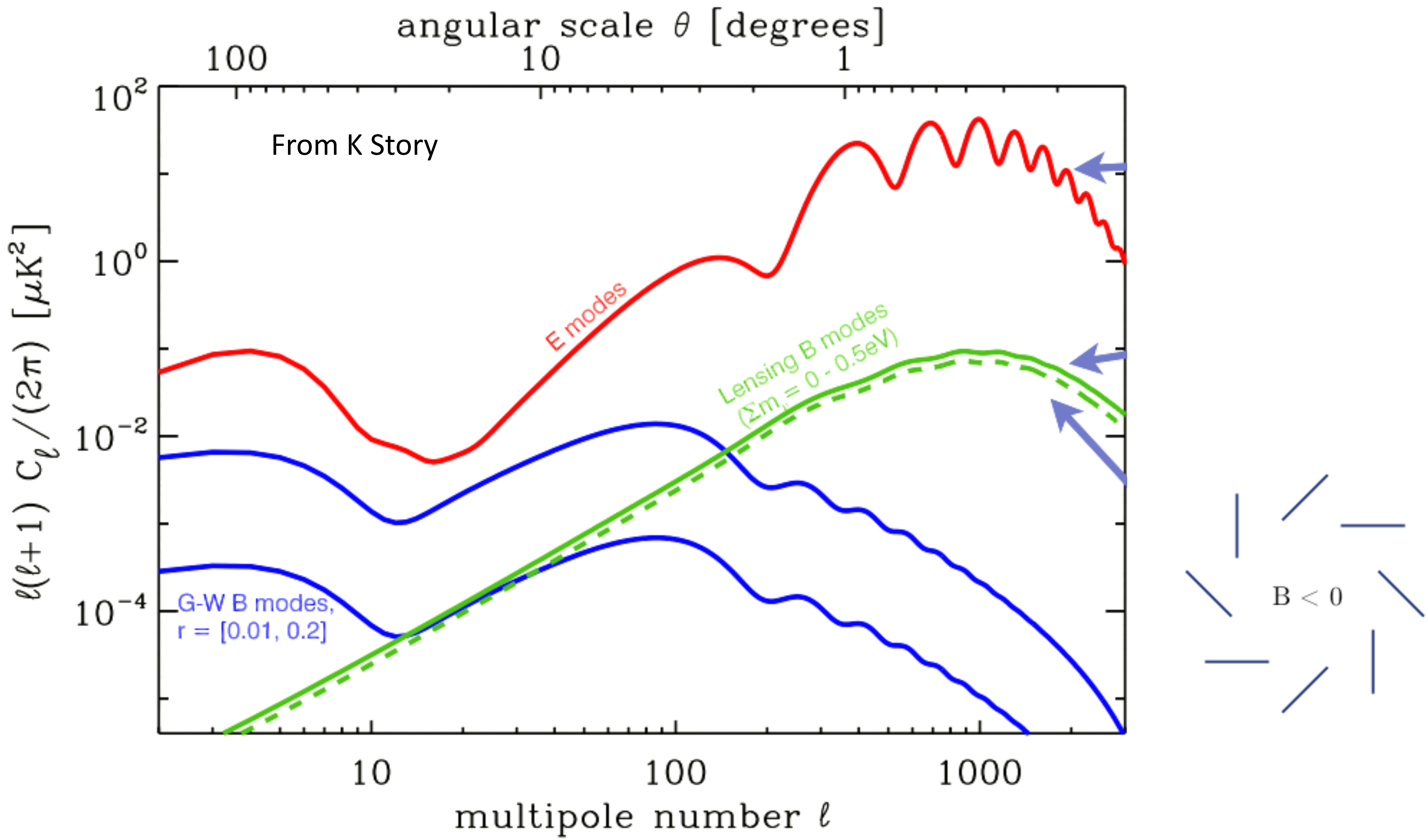
BAO: measures total dark matter
CMB: measures growth of structure

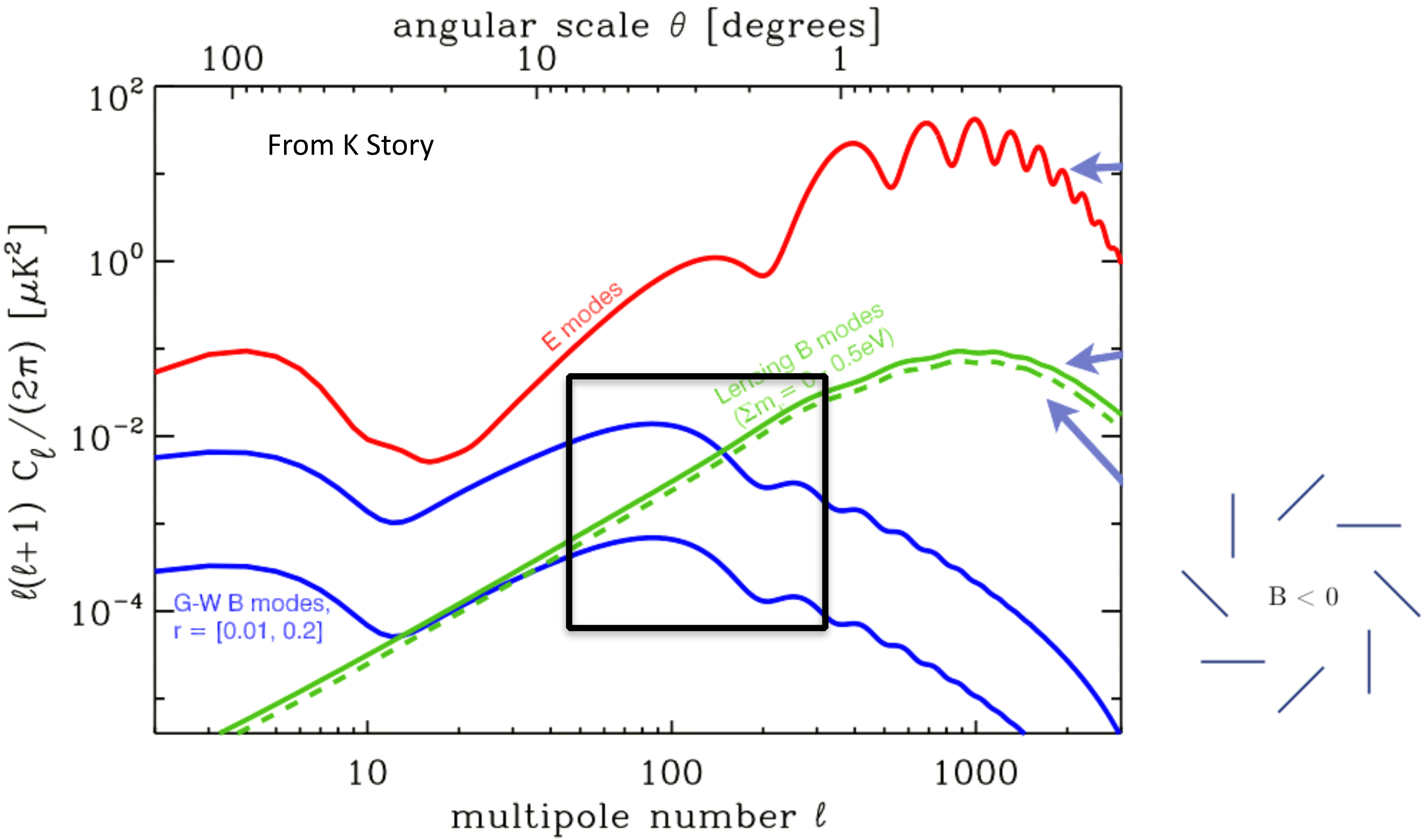


Neutrino mass sum < 0.23 eV (Planck Collab 2015 +BAO distances)

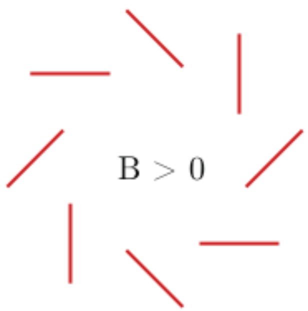
Next decade: should detect 0.06 eV at few sigma

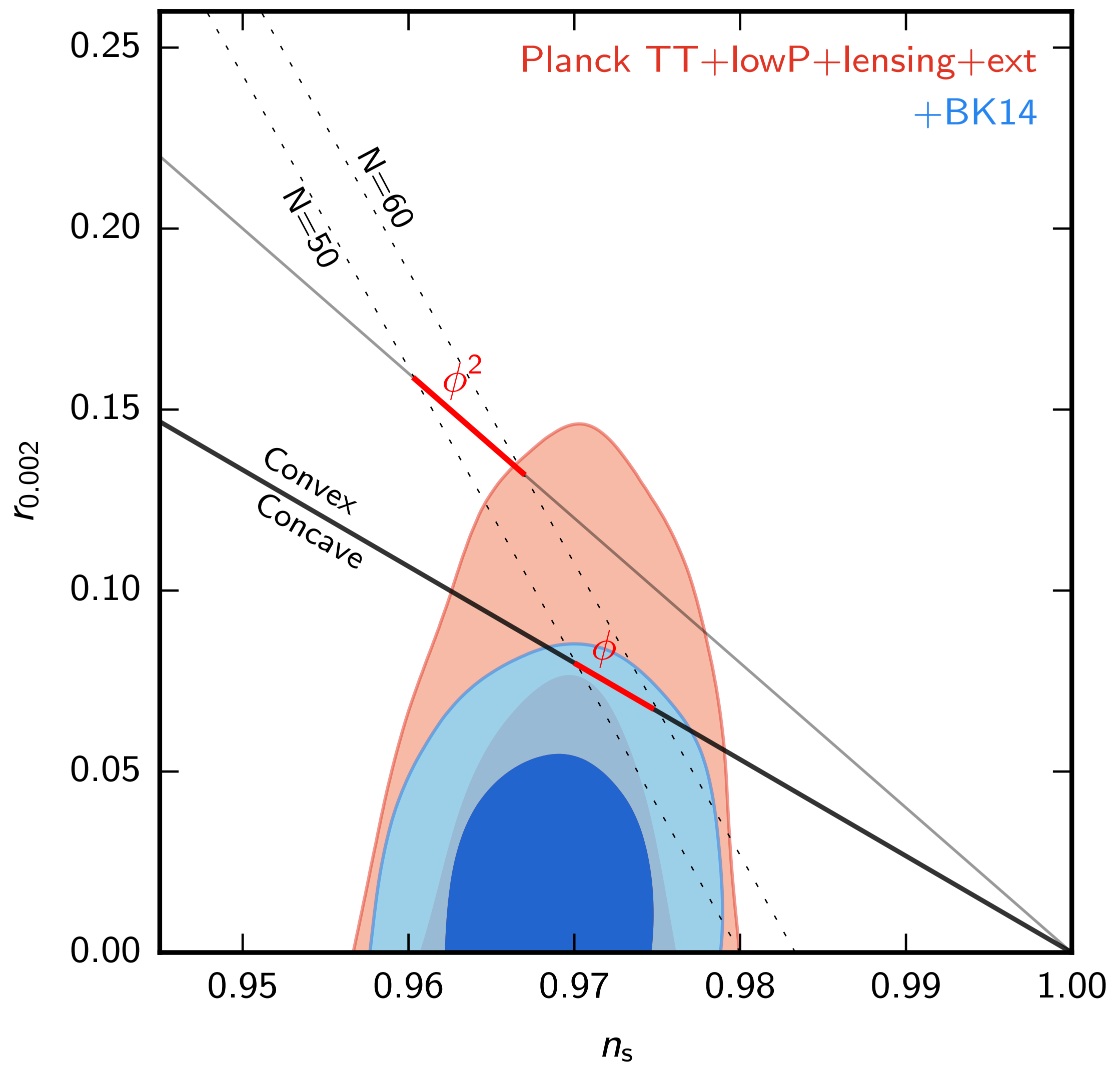
Testing inflation: gravitational waves




angular scale θ [degrees]
100
10
1
10^2
10^0
10^{-2}
10^{-4}
From K Story
E modes
Lensing B modes
(Σm_ν = 0, 0.5eV)
G-W B modes,
r = [0.01, 0.2]
$\ell(\ell+1)\ C_\ell/(2\pi)\ [\mu K^2]$
10
100
1000
multipole number ℓ
B < 0

Primordial fluctuations



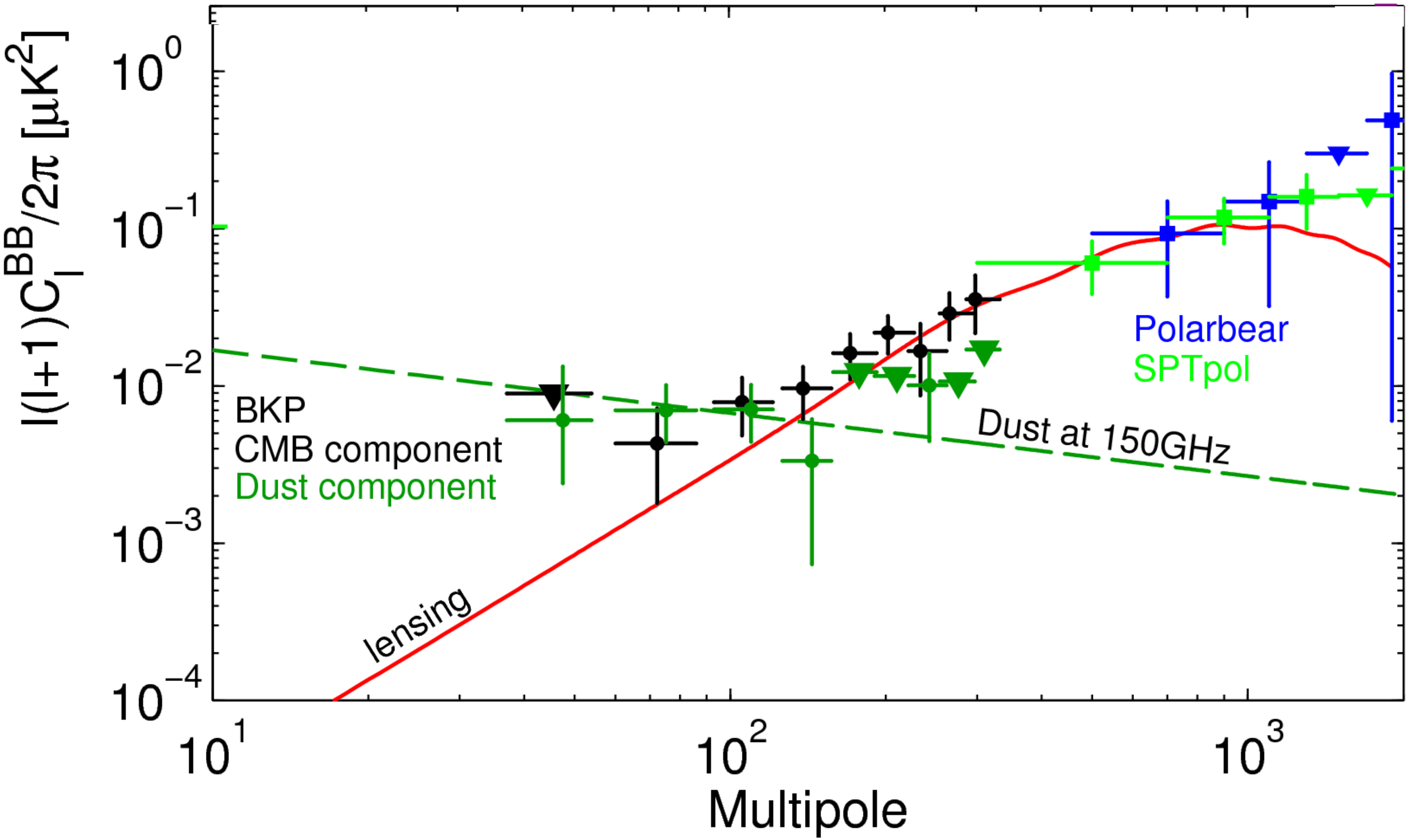


r < 0.07 (95%, Planck+Bicep2/Keck, November 2015)

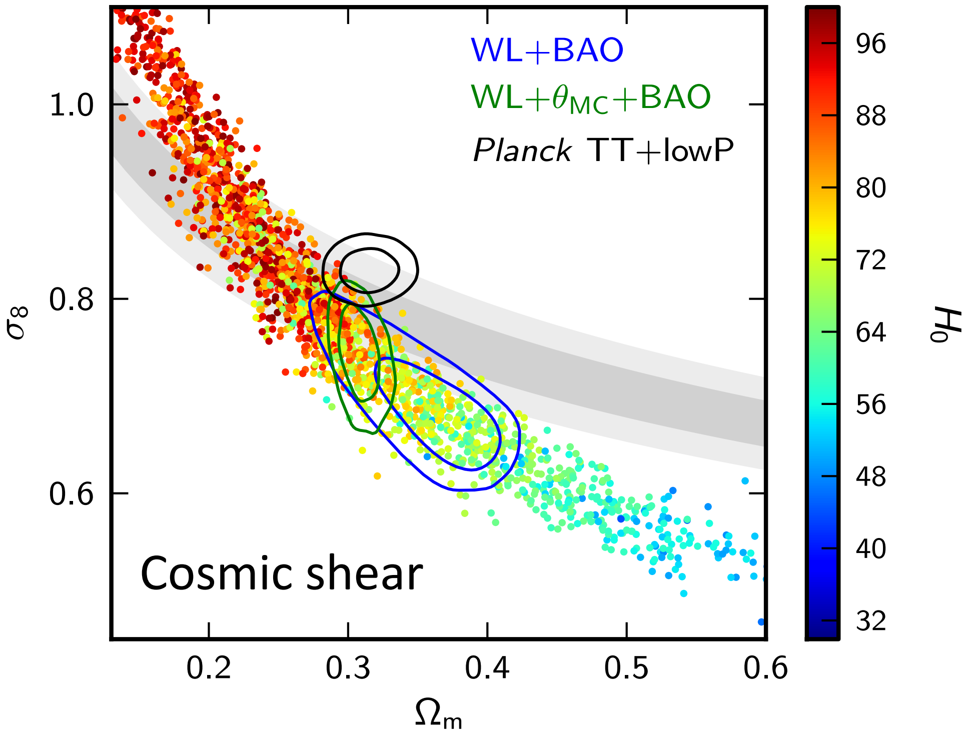
Planck Collaboration 2015
BICEP2/Keck Collaborations Nov 2015

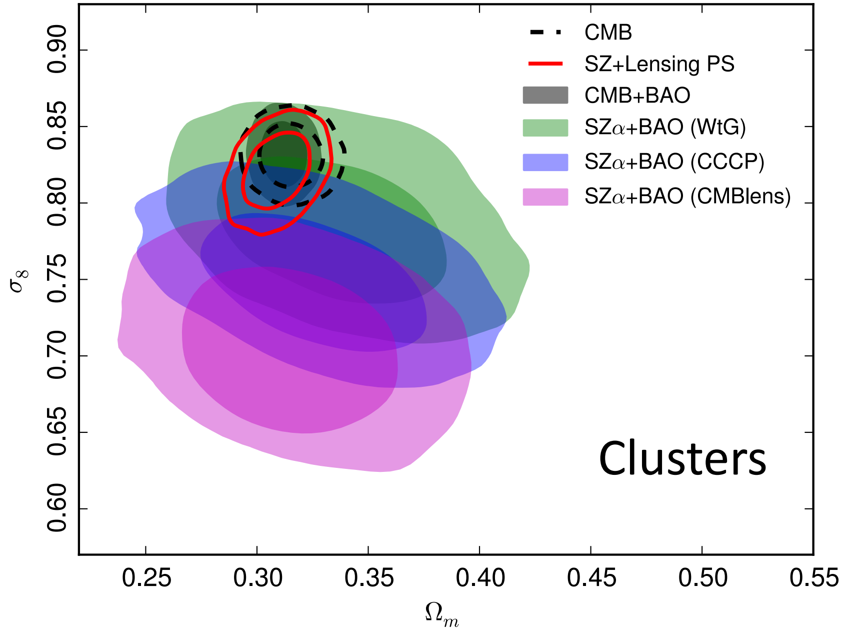
B-modes

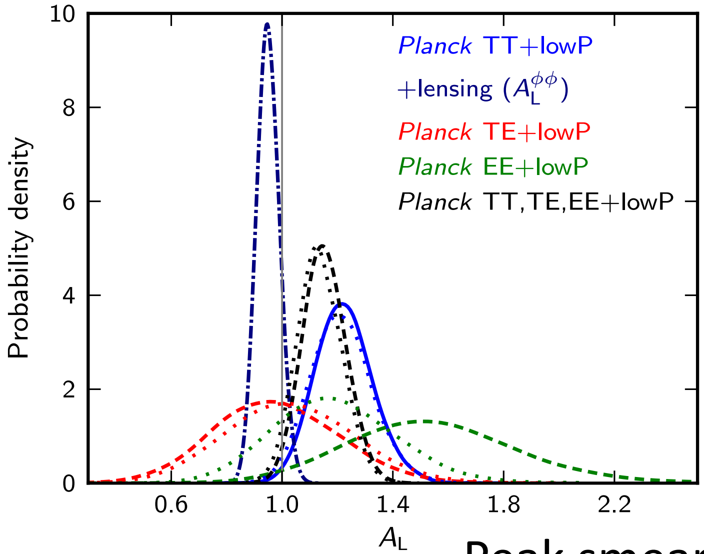
POLARBEAR: 2 sigma (2014)
BICEP2/Keck+Planck: 7-sigma (2015)
SPTPol:4 sigma (Keisler et al 2015)



Anomalies?







Peak smearing