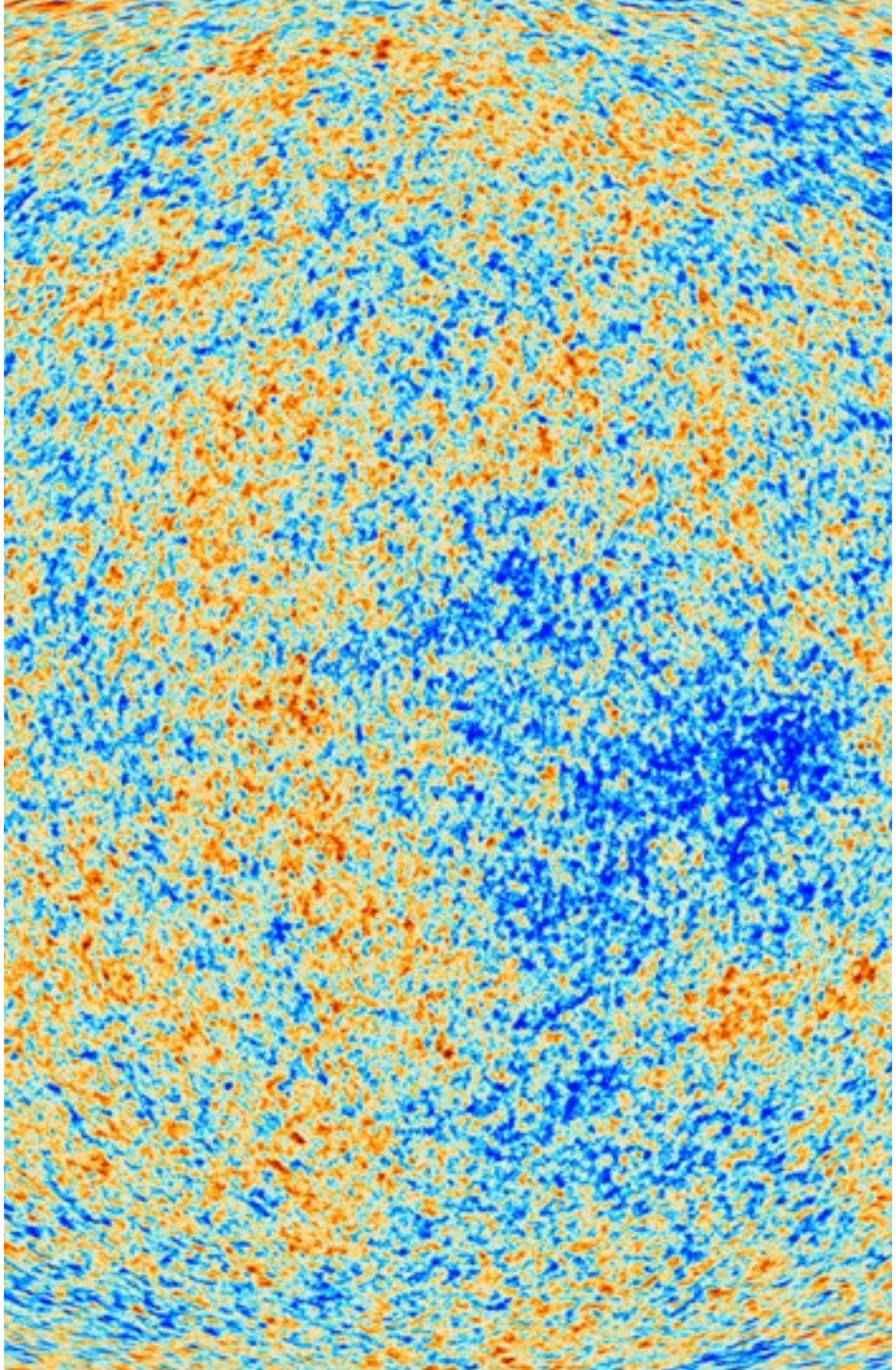


Cosmology from Planck and ACT

Jo Dunkley
University of Oxford

esa

planck

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

CSIC

National Research Council of Italy

HFI PLANCK

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO

CSA ASC

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

UK SPACE AGENCY

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY

irfu cea saclay

cea

CESR

CITA ICAT

IN2P3

ipac Infrared Processing and Analysis Center

ioa

KICC

HELSINKI INSTITUTE OF PHYSICS

IFCA

Imperial College London

Università degli Studi di Milano

NÉEL Institut

IPAG

ISDC

JPL

LAL

l'Observatoire

LERMA

LPSC

MilliLab

NUI MAYNOOTH

INAF

SAPIENZA

Rutherford Appleton Laboratory

UBC

UC

UCSB

SISSA

US

esa

UNIVERSITY OF HELSINKI

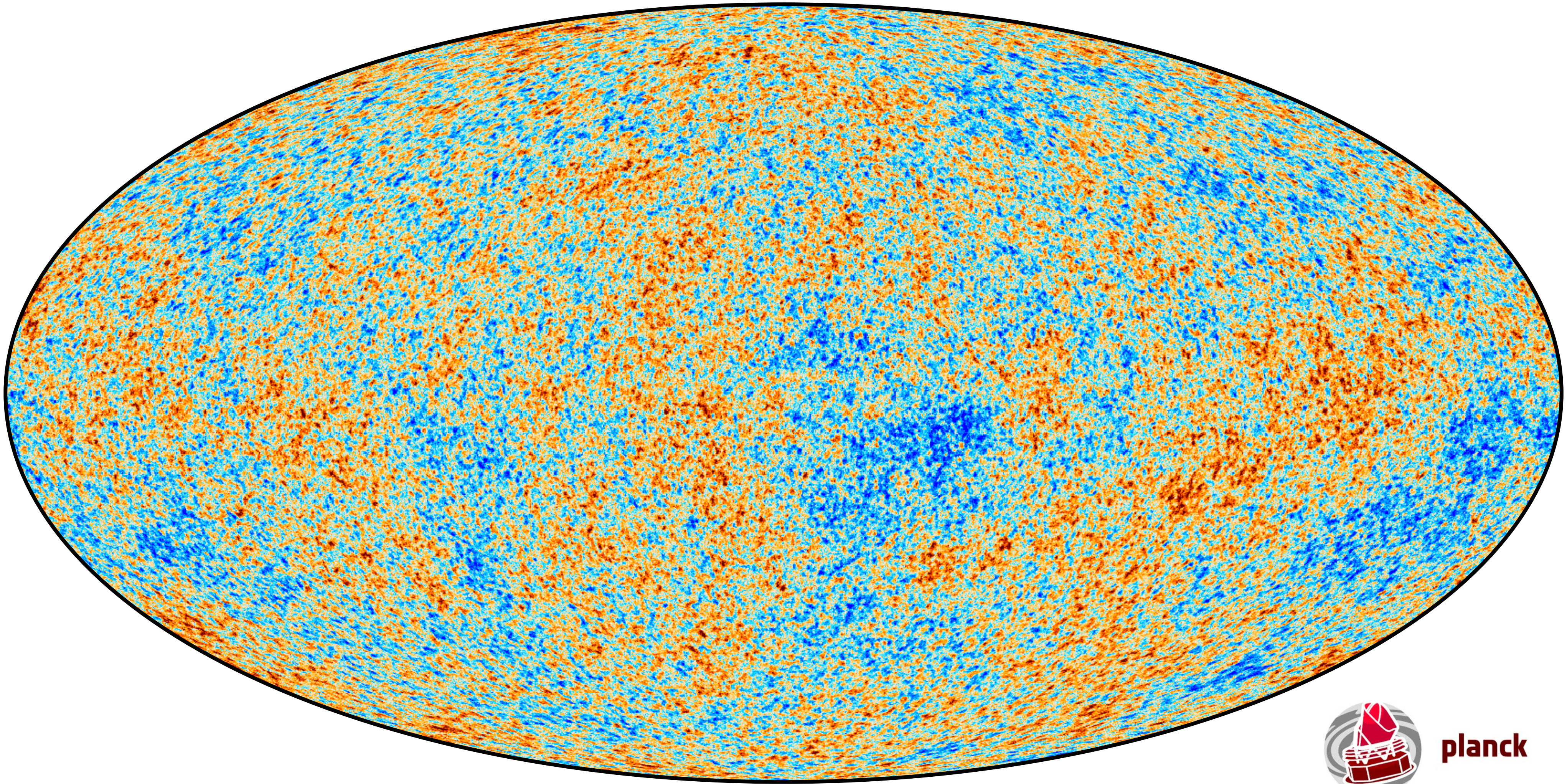
UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

UNIVERSITÉ DE PARIS-SUD XI

asdc

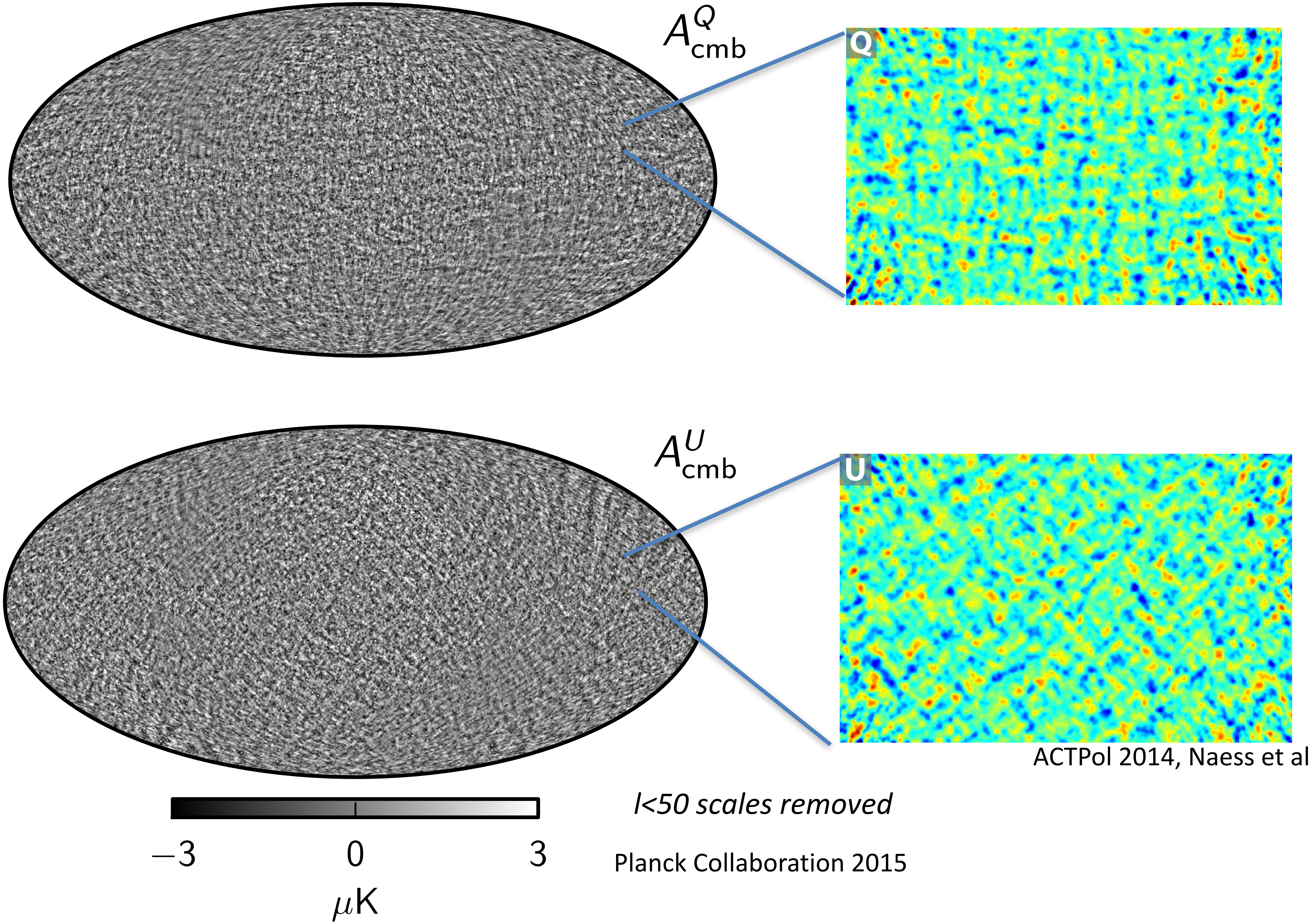
Temperature anisotropy



planck

Planck Collaboration 2015

Polarization anisotropy

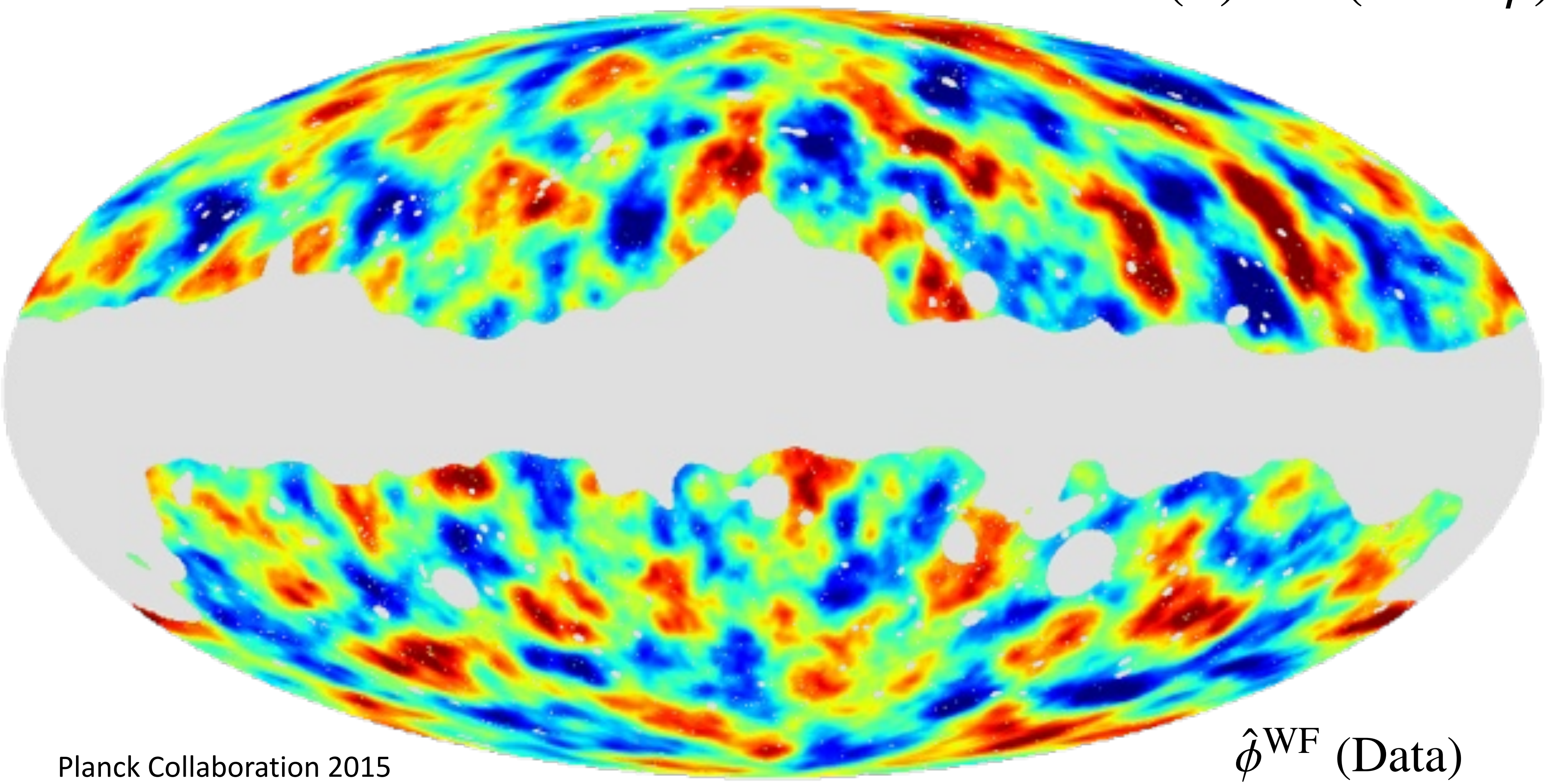


l<50 scales removed

Planck Collaboration 2015

Lensing potential anisotropy

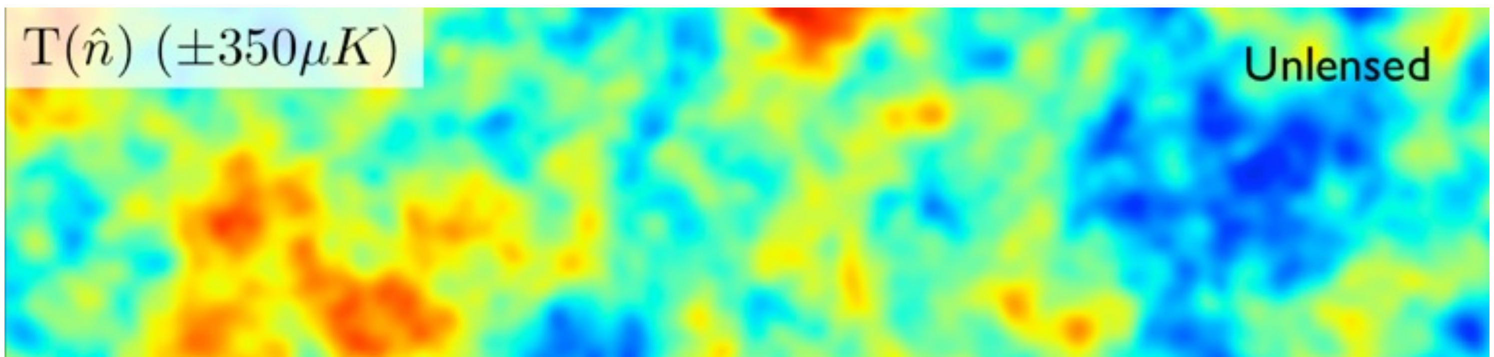
$$T(n) = \tilde{T}(n + \nabla\phi)$$



Planck Collaboration 2015

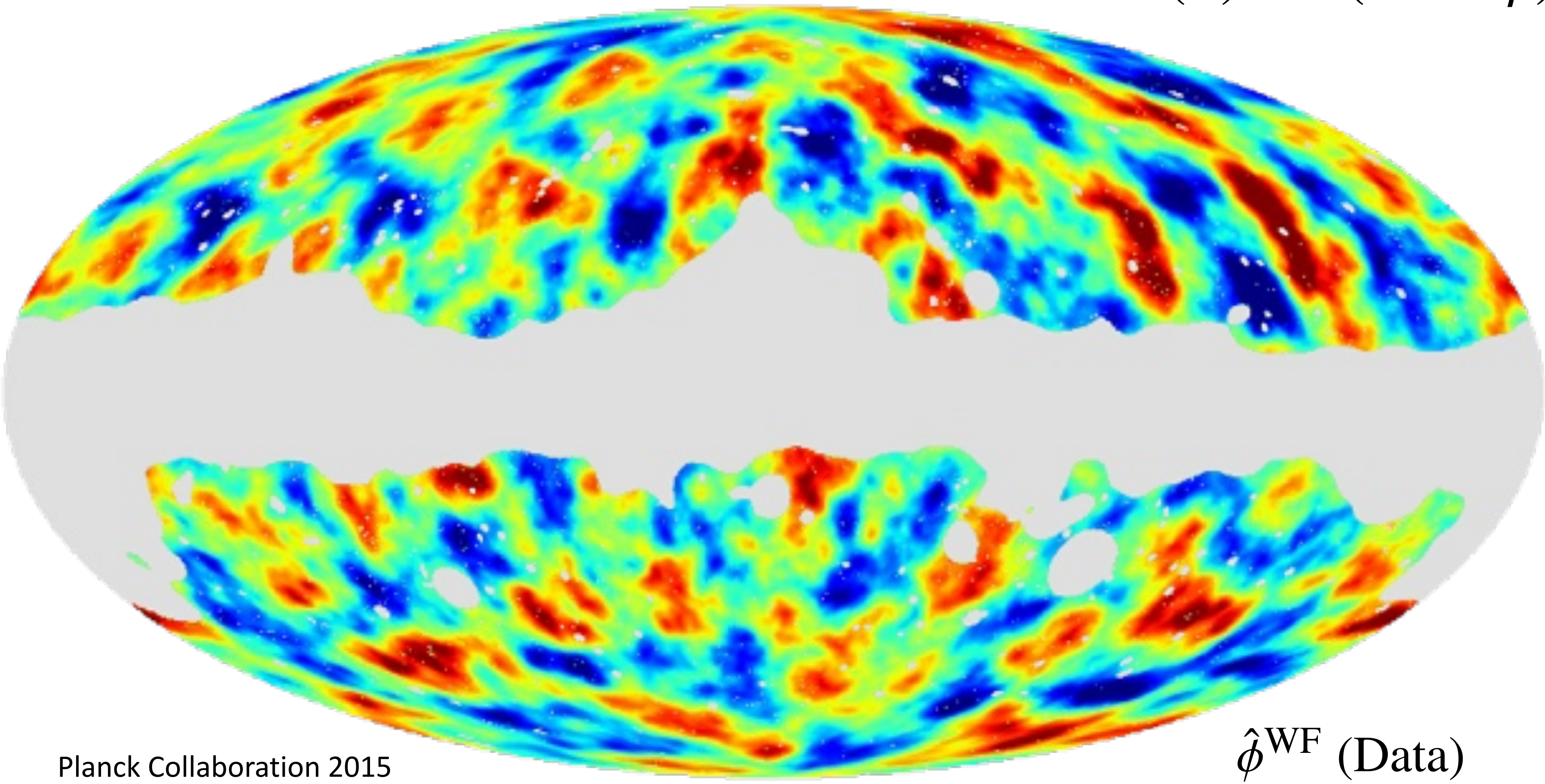
$\hat{\phi}^{\mathrm{WF}}$ (Data)

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



Lensing potential anisotropy

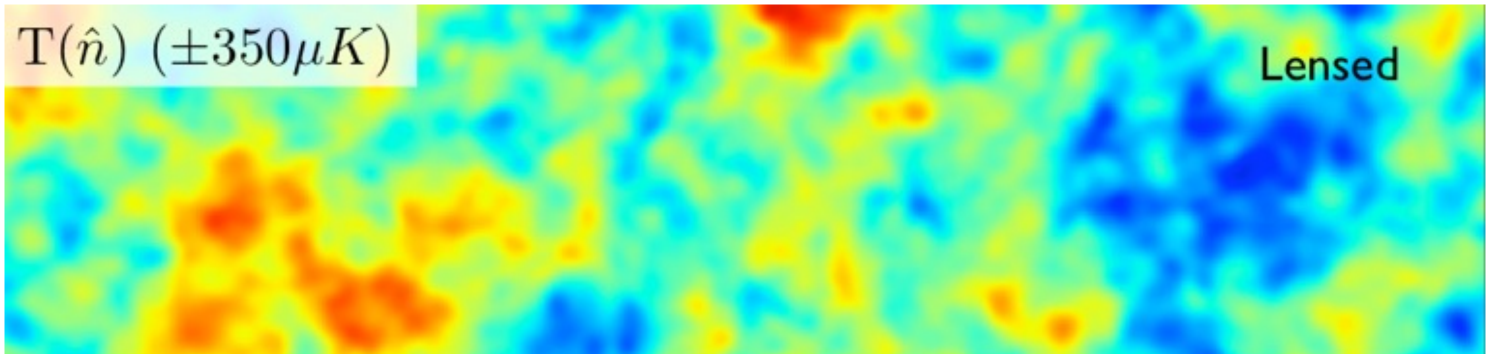
$$T(n) = \tilde{T}(n + \nabla\phi)$$

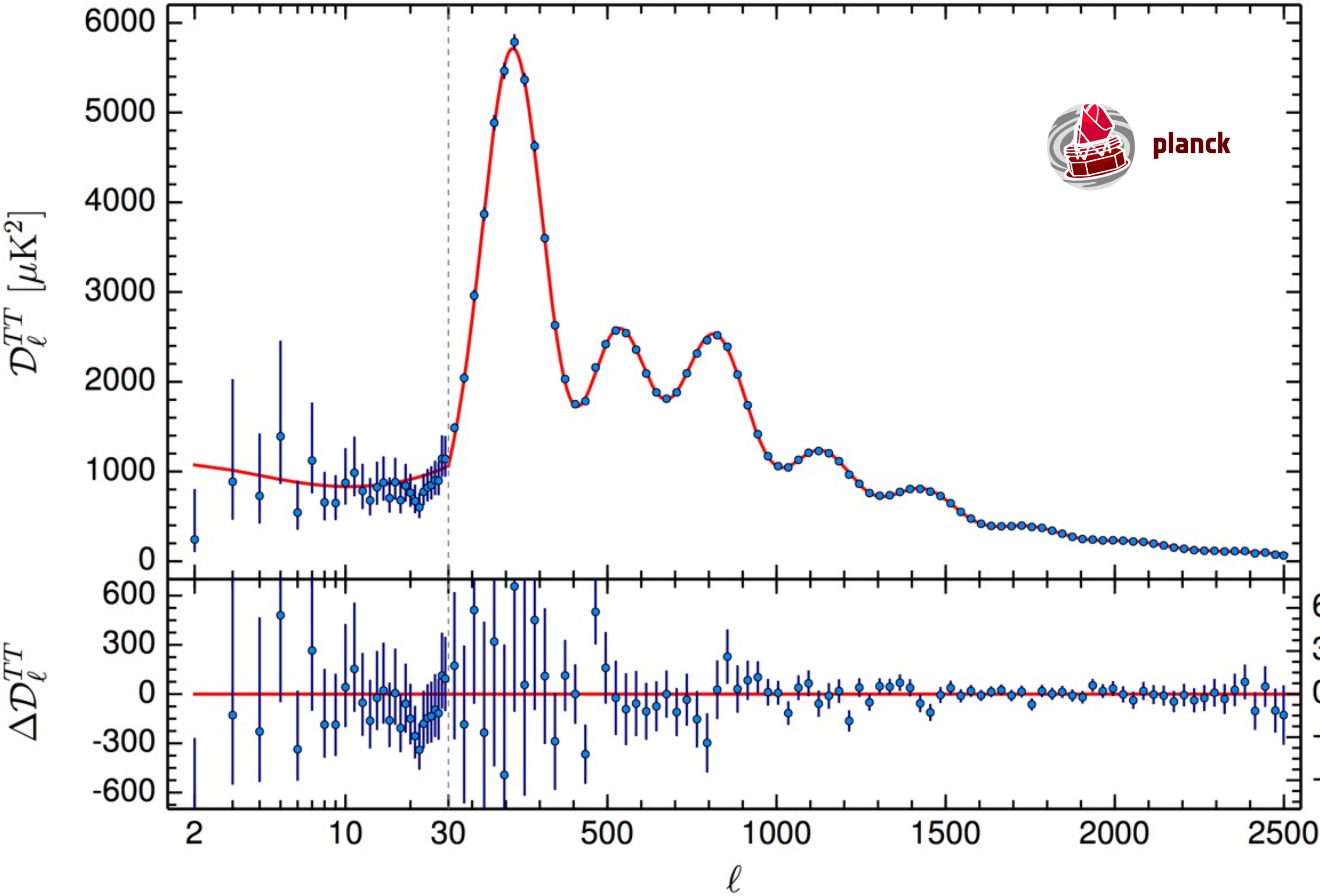


Planck Collaboration 2015

$\hat{\phi}^{\mathrm{WF}}$ (Data)

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





6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}\ [\mu K^2]$
planck
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

The ΛCDM model

(1) Contents and expansion

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

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

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

(2) Initial fluctuations

Amplitude at k=0.05/Mpc

$\ln(10^{10} A_s) = 3.089 \pm 0.036$

Spectral index $n_s = 0.9655 \pm 0.0062$

(3) Impact of reionization

Reionization optical depth $\tau = 0.078 \pm 0.019$

(1) Contents and expansion rate

Baryon fraction Ω_b

CDM fraction $\Omega_c = 0.265 \pm 0.013$

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

Expansion rate $H_0 = 67.3 \pm 1.0$

(2) Late-time size of fluctuations

Amplitude on 8 Mpc/h scales $\sigma_8 = 0.829 \pm 0.014$

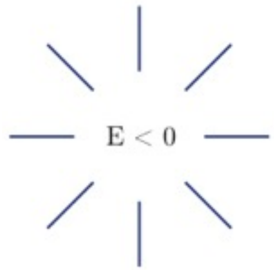
(3) Reionization

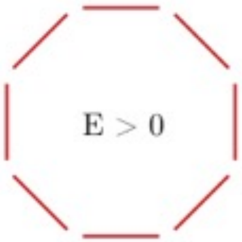
Redshift of reonization z_{re}

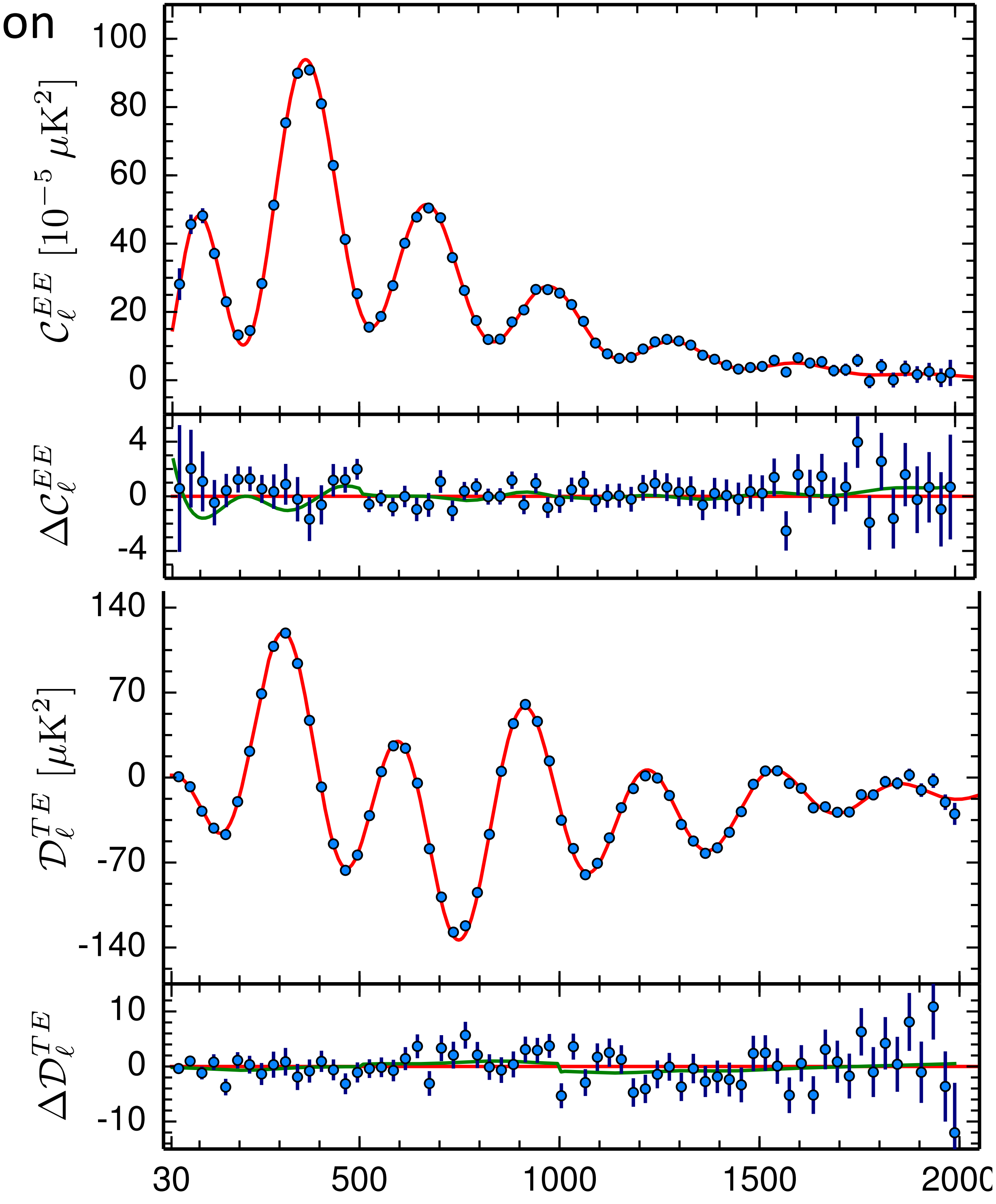
Assumptions:

- 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

CMB polarization (E-mode)





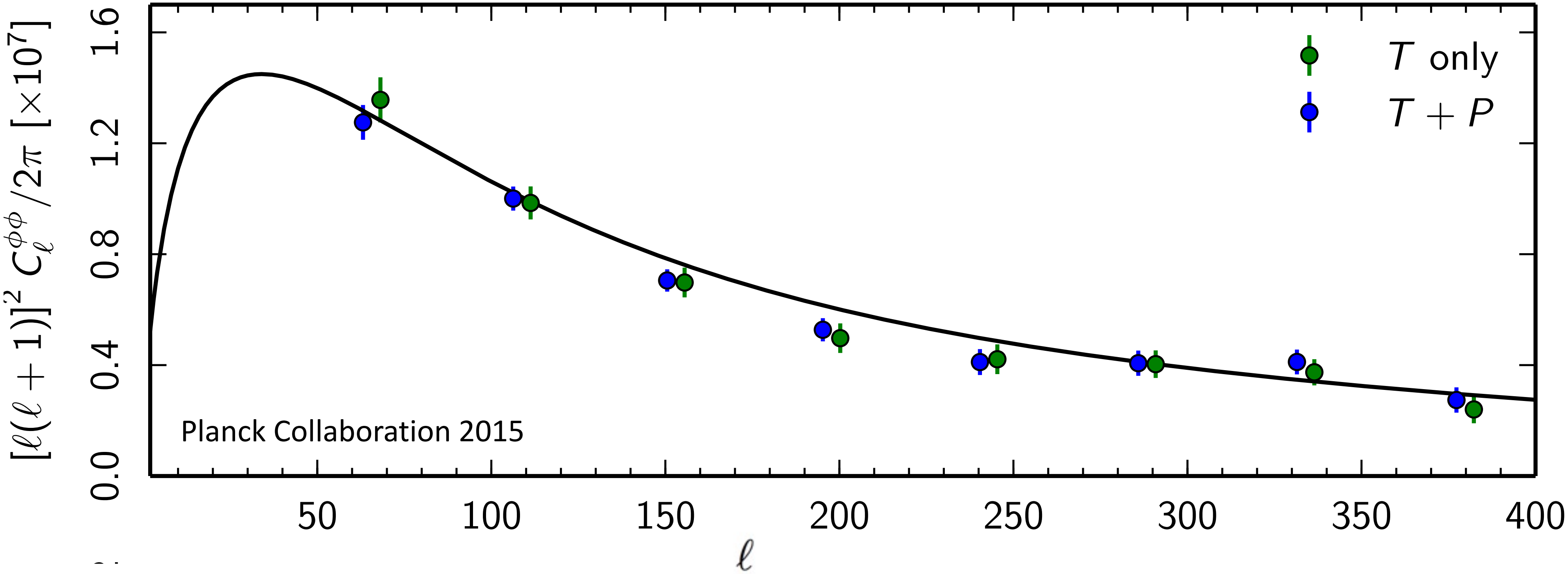


Planck Collaboration 2015

ℓ

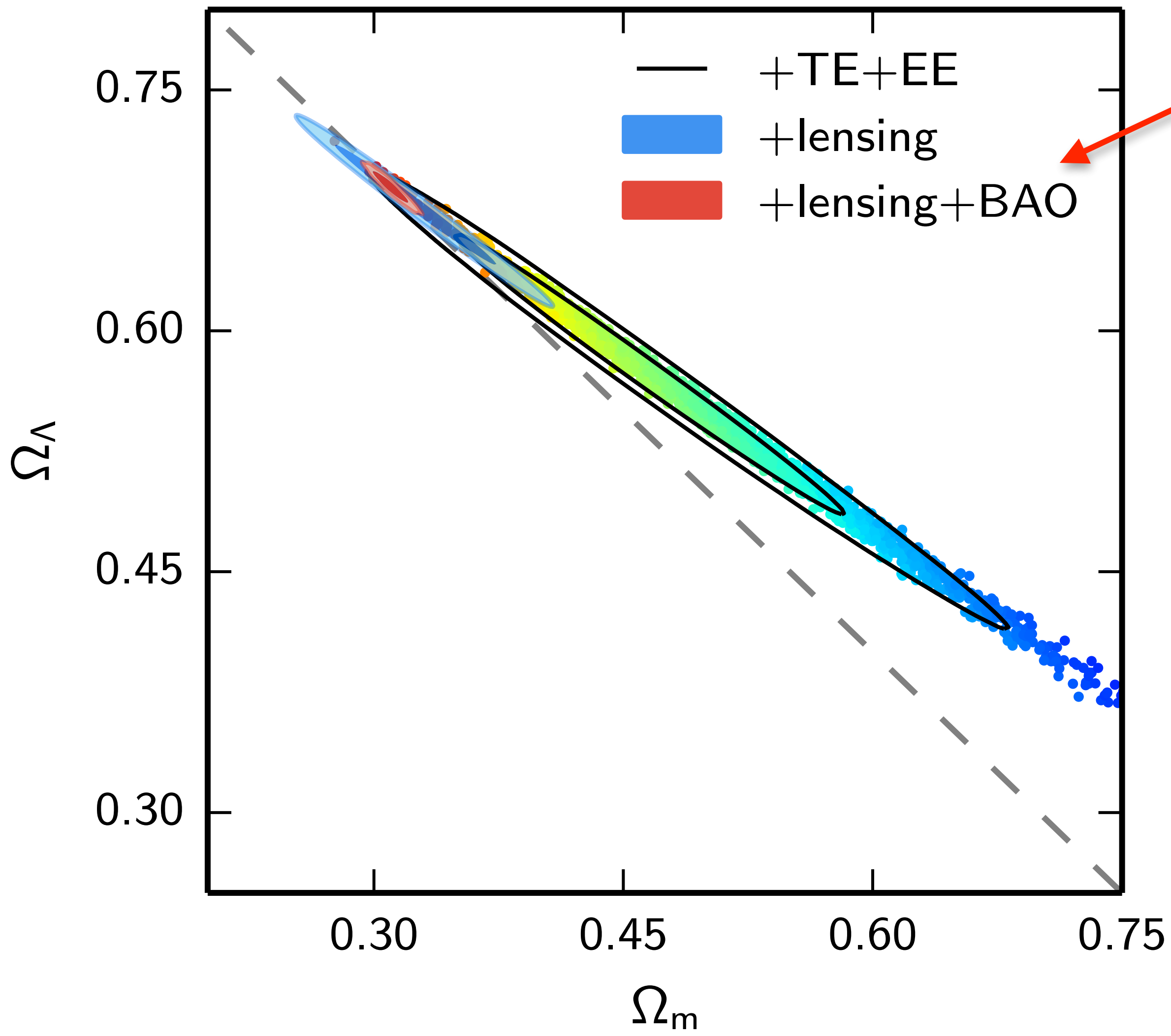
Greatly limits vast zoo of alternatives to LCDM

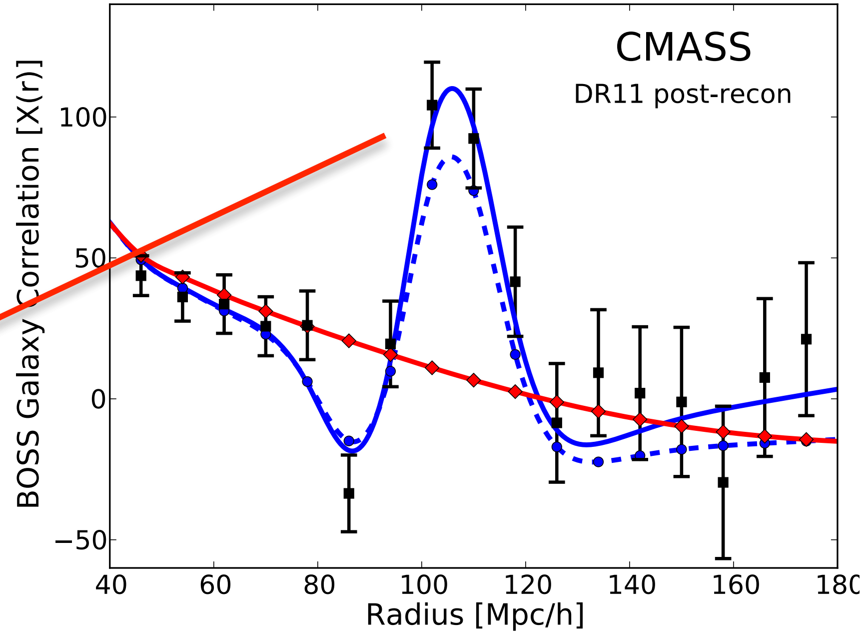
CMB lensing



$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi\ [\times 10^7]$
1.6
1.2
0.8
0.4
0.0
50
100
150
200
250
300
350
400
ℓ
T only
$T + P$
Planck Collaboration 2015

Curvature



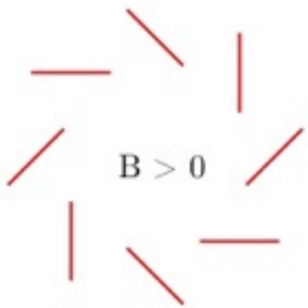


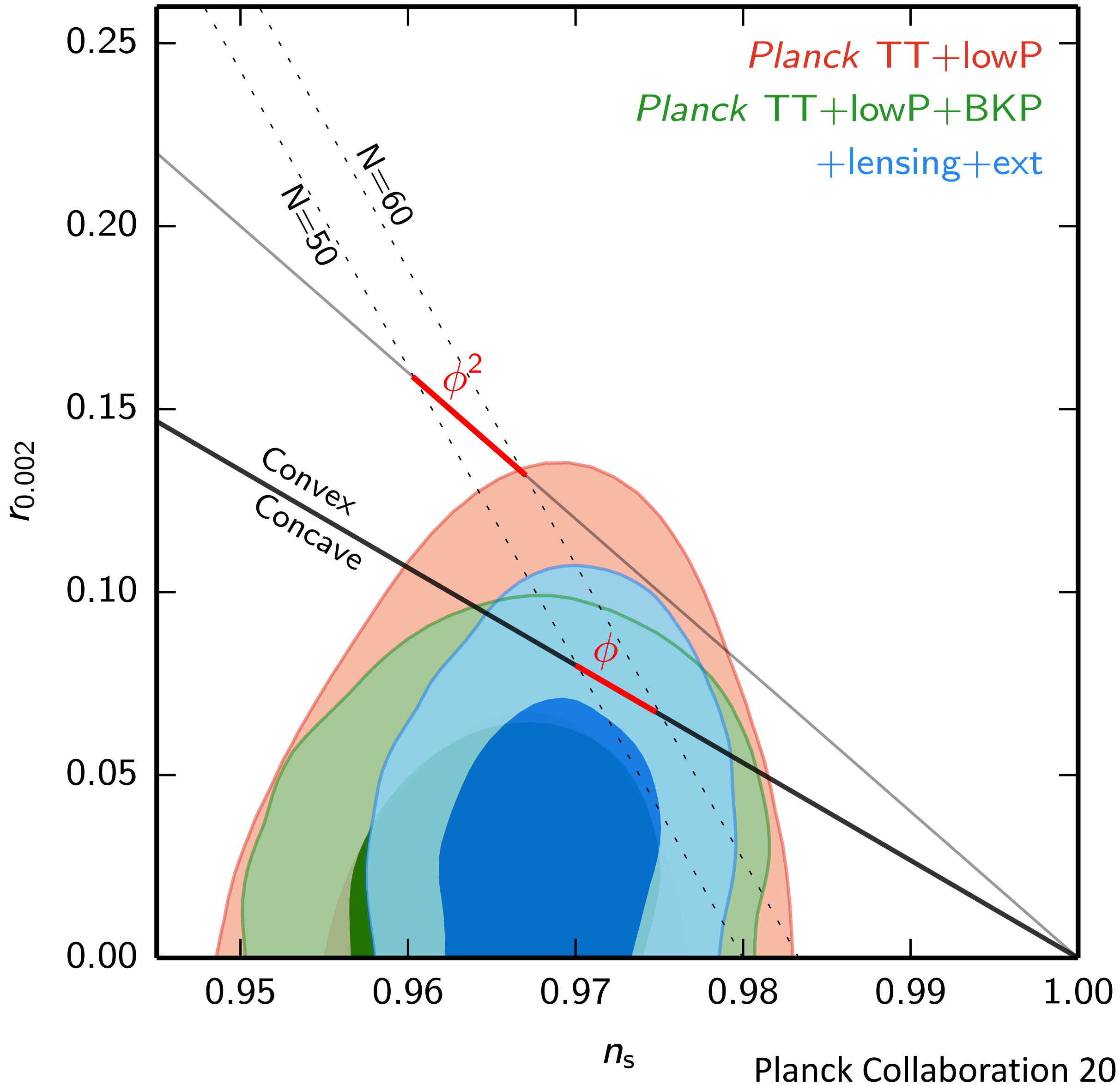
Anderson et al 2014

Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$
	T	T+phi	T+phi+BAO (95%)

Planck Collaboration 2015

Primordial fluctuations



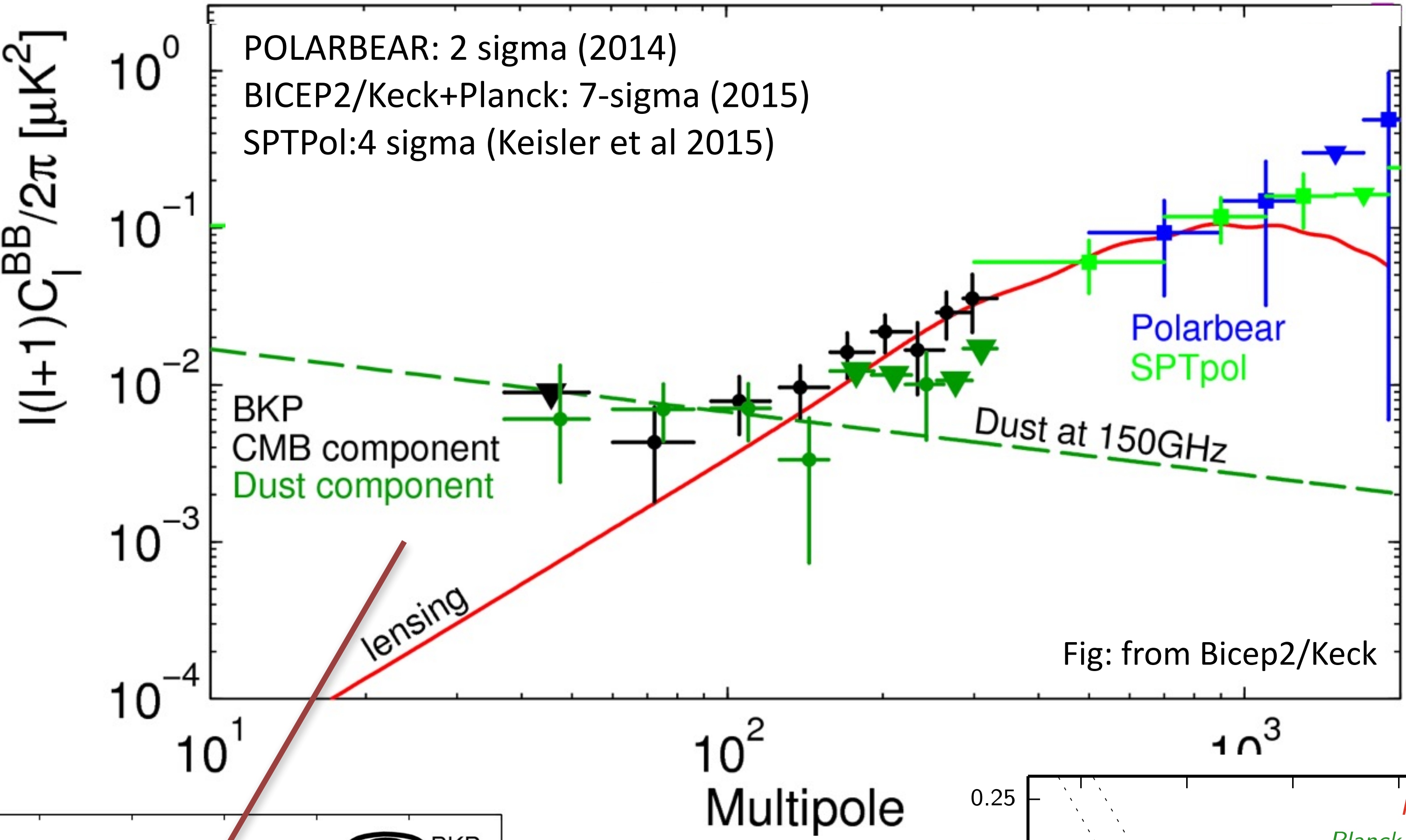


Planck Collaboration 2015

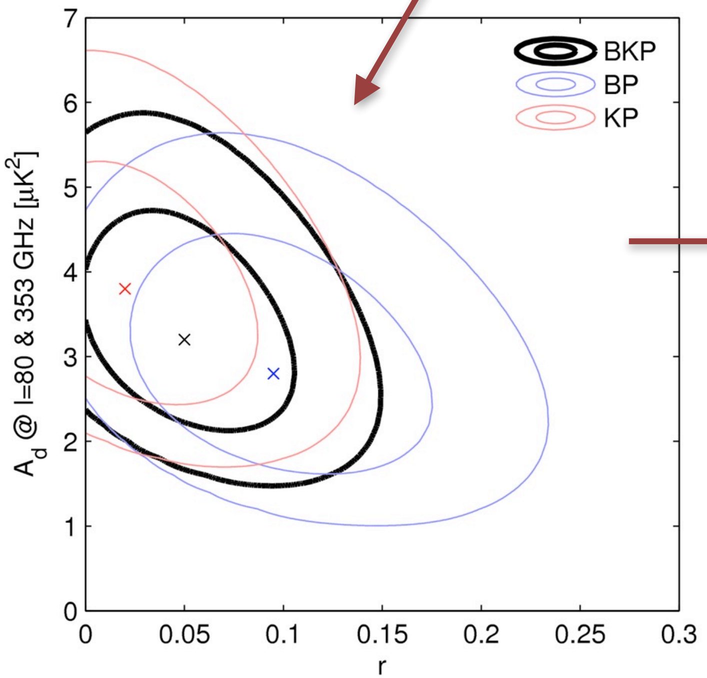
Planck/BICEP2/Keck Collaborations 2015

r < 0.09 (95%, Planck+Bicep2/Keck)

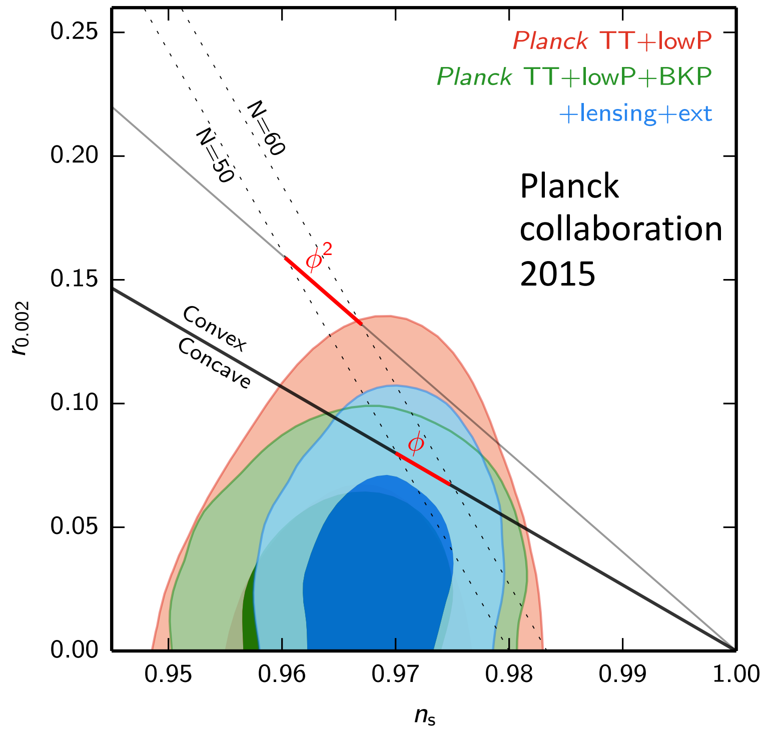
B-modes



POLARBEAR: 2 sigma (2014)
BICEP2/Keck+Planck: 7-sigma (2015)
SPTPol:4 sigma (Keisler et al 2015)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
BKP
CMB component
Dust component
Polarbear
SPTpol
Dust at 150GHz
lensing
Fig: from Bicep2/Keck
Multipole



BKP
BP
KP
A_d @ l=80 & 353 GHz [μK^2]
r

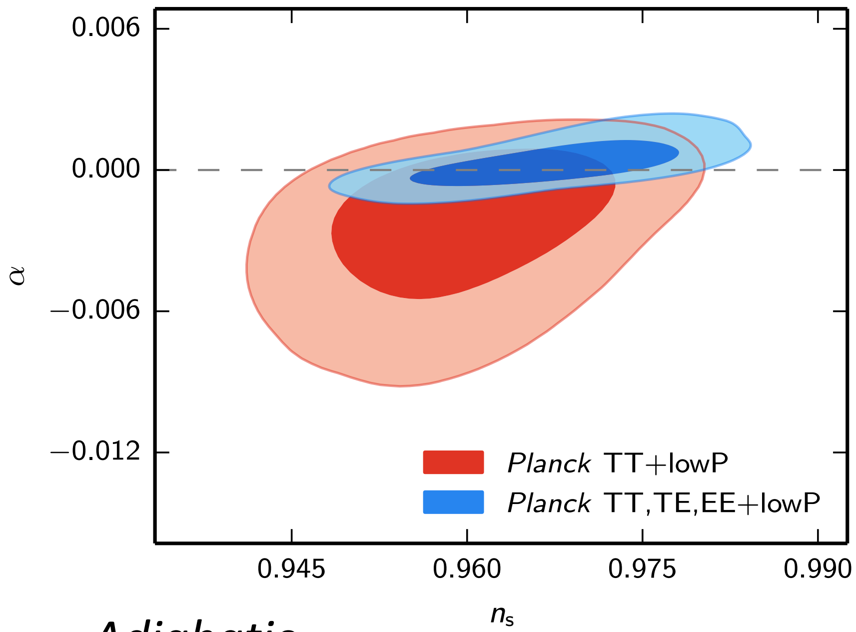


Planck TT+lowP
Planck TT+lowP+BKP
+lensing+ext
N=60
N=50
ϕ^2
ϕ
Convex
Concave
Planck collaboration 2015
$r_{0.002}$
n_s

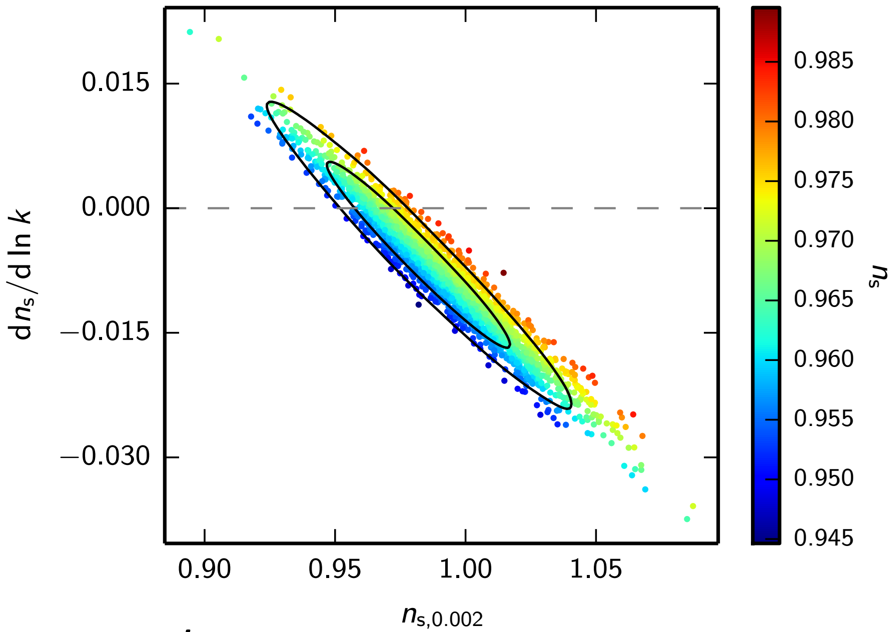
Primordial fluctuations

Shape and method	f_{NL}(KSW) Independent	ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	$\mathbf{2.5} \pm \mathbf{5.7}$
Equilateral	-13 ± 70	$\mathbf{-16} \pm \mathbf{70}$
Orthogonal	-56 ± 33	$\mathbf{-34} \pm \mathbf{33}$

Gaussian



Adiabatic

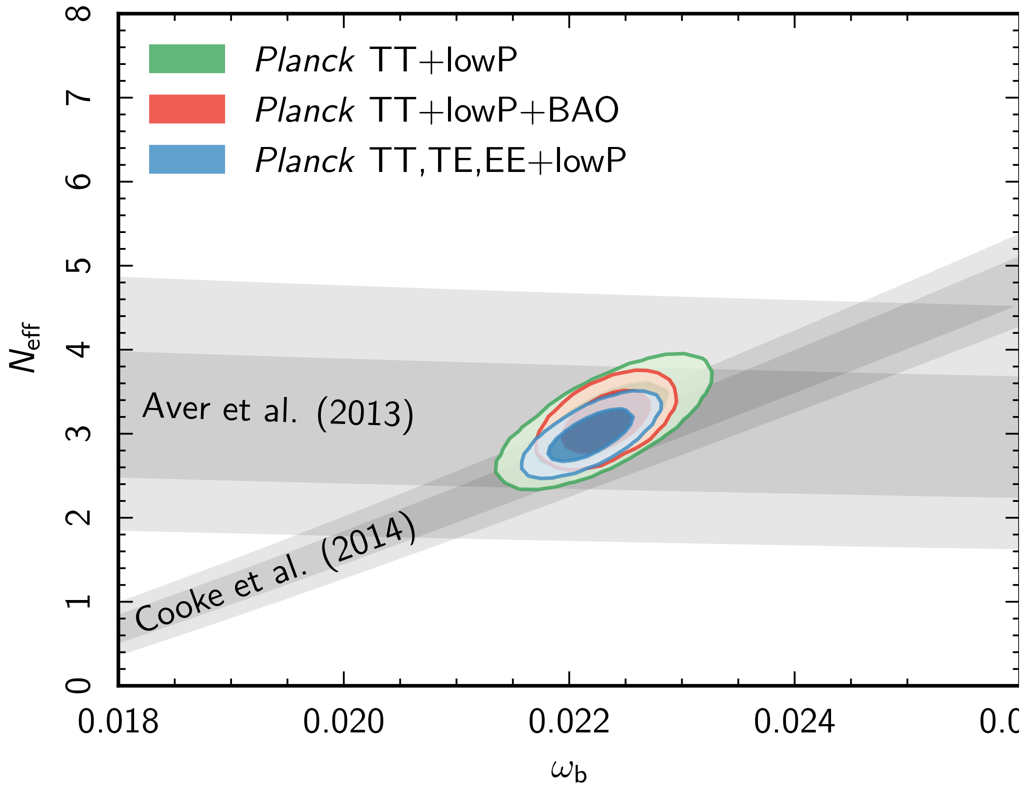


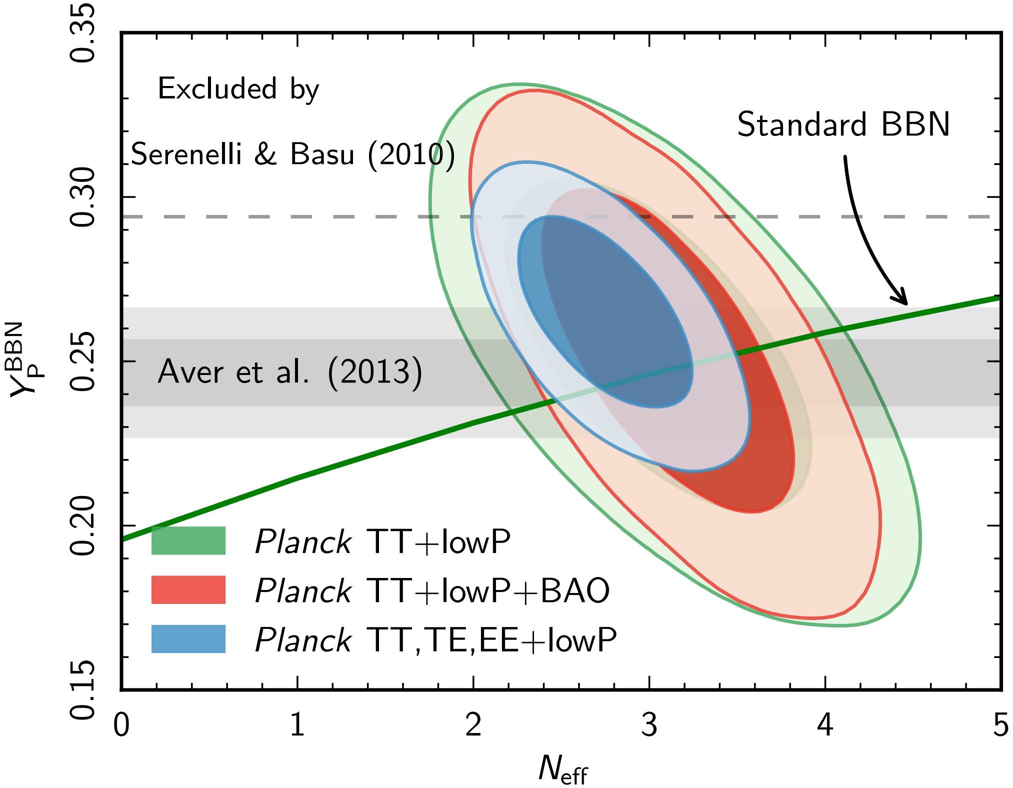
Power-law

Planck Collaboration 2015

Neutrino species

Planck Collaboration 2015

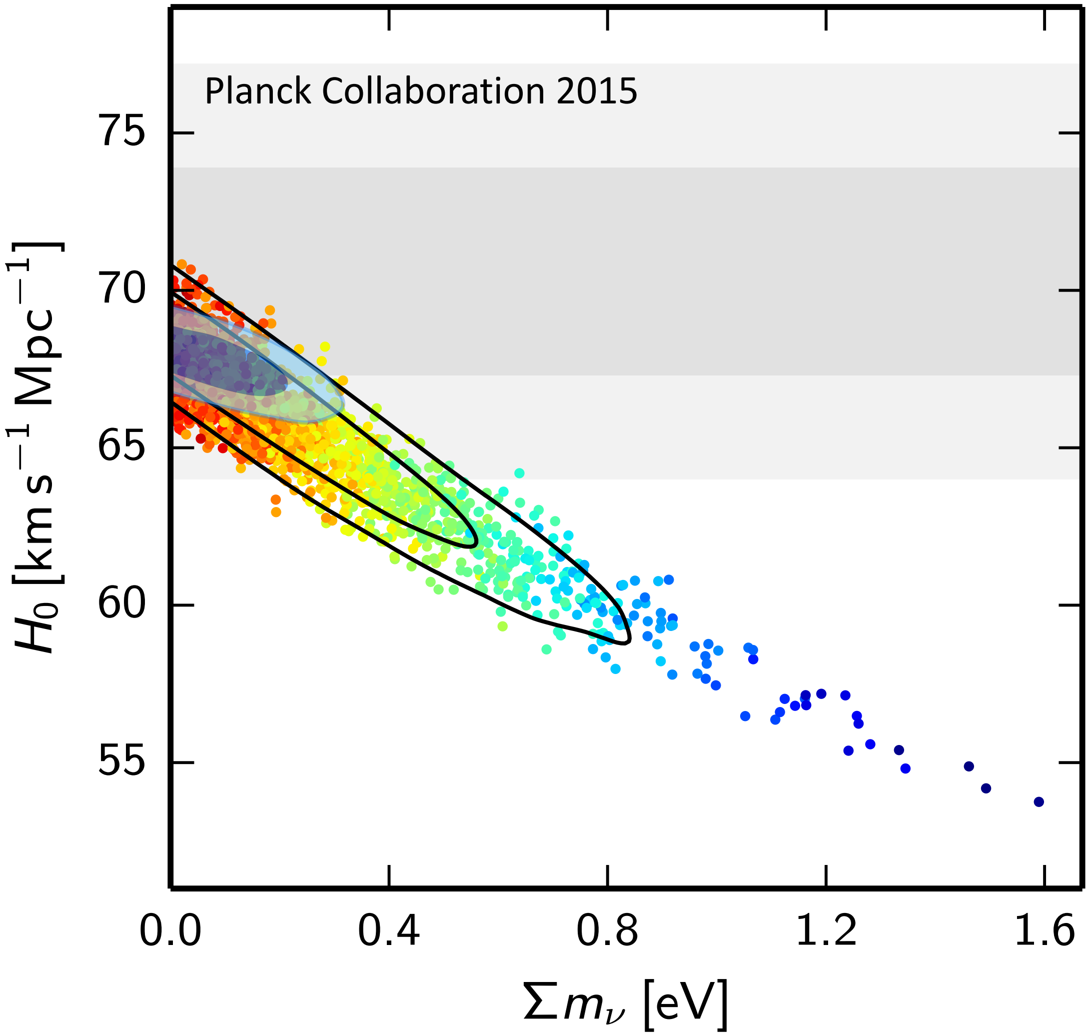




$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,; \ (68\%)$$

$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;$$

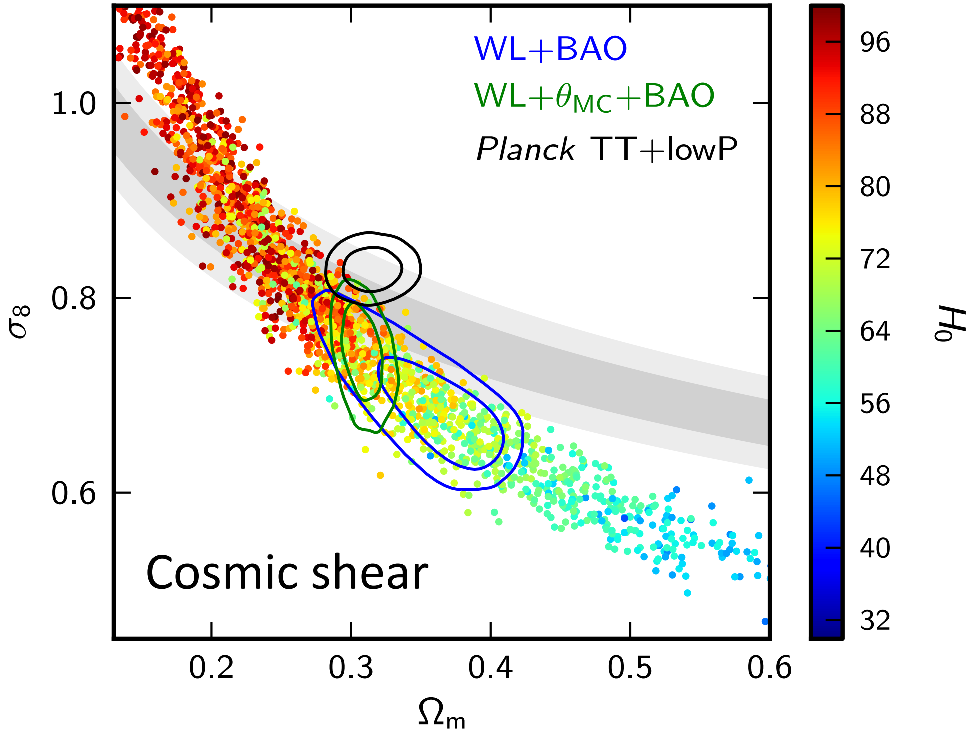
Neutrino mass

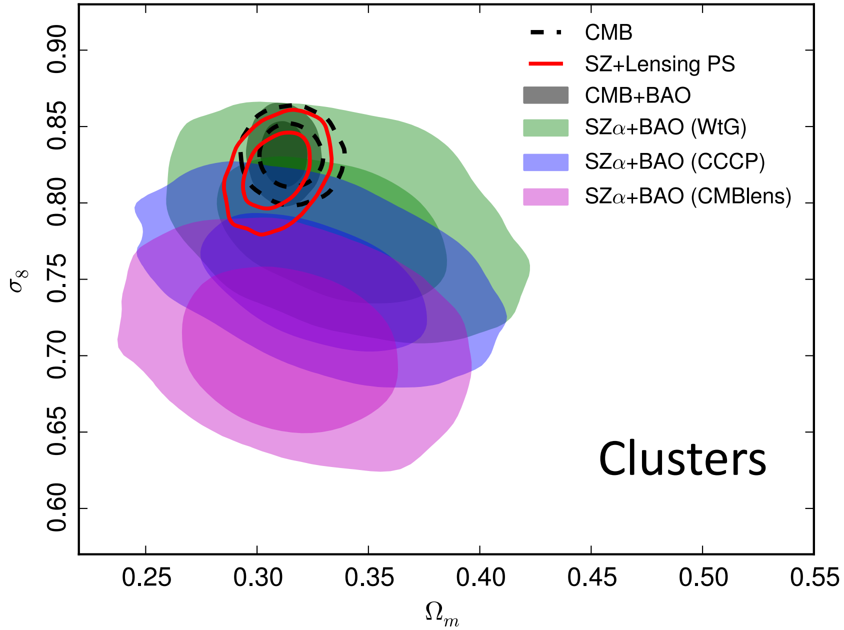


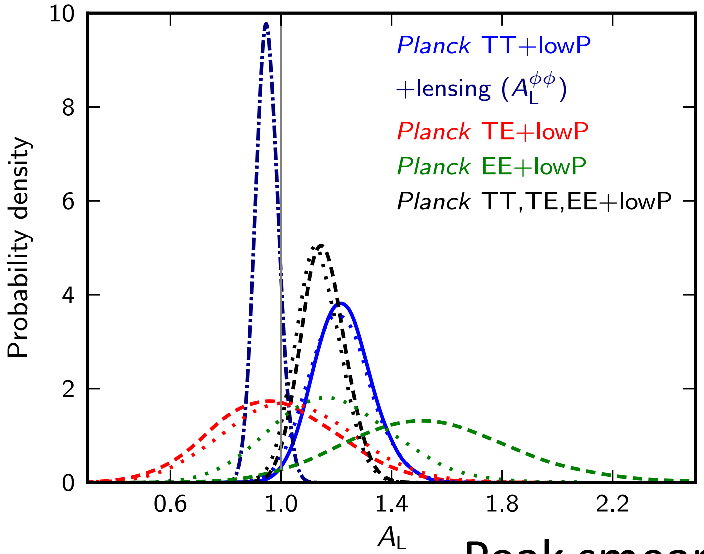
Σm_ν [eV]	< 0.675	< 0.234
	T+phi	T+phi+BAO (95%)

Next decade: should detect 0.06 eV at few sigma

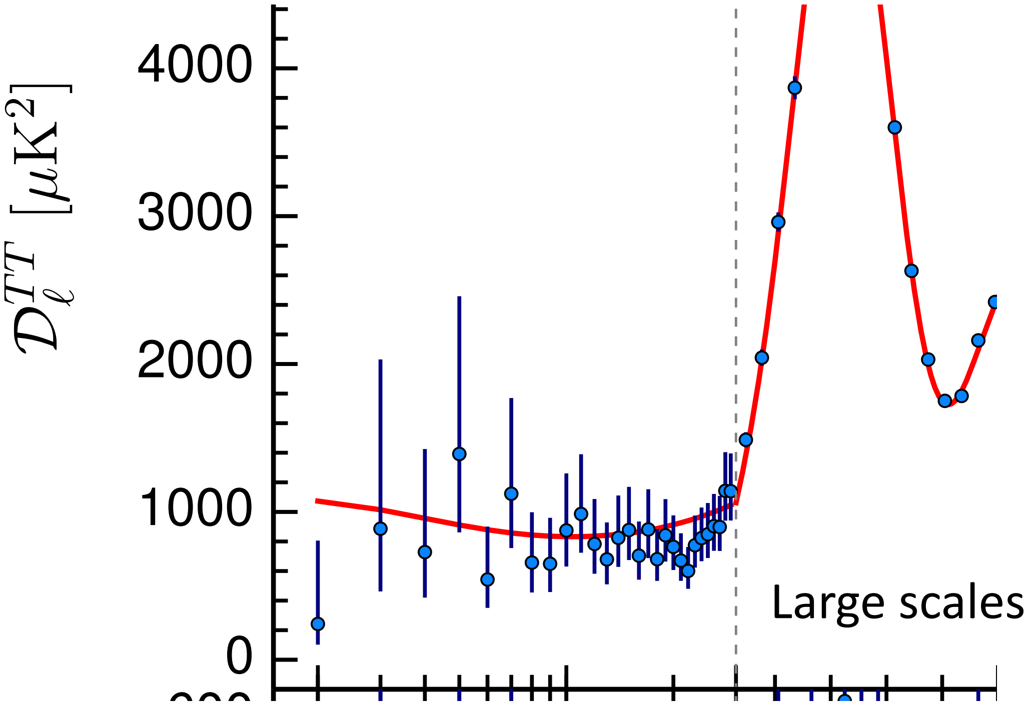
Problems/clues?



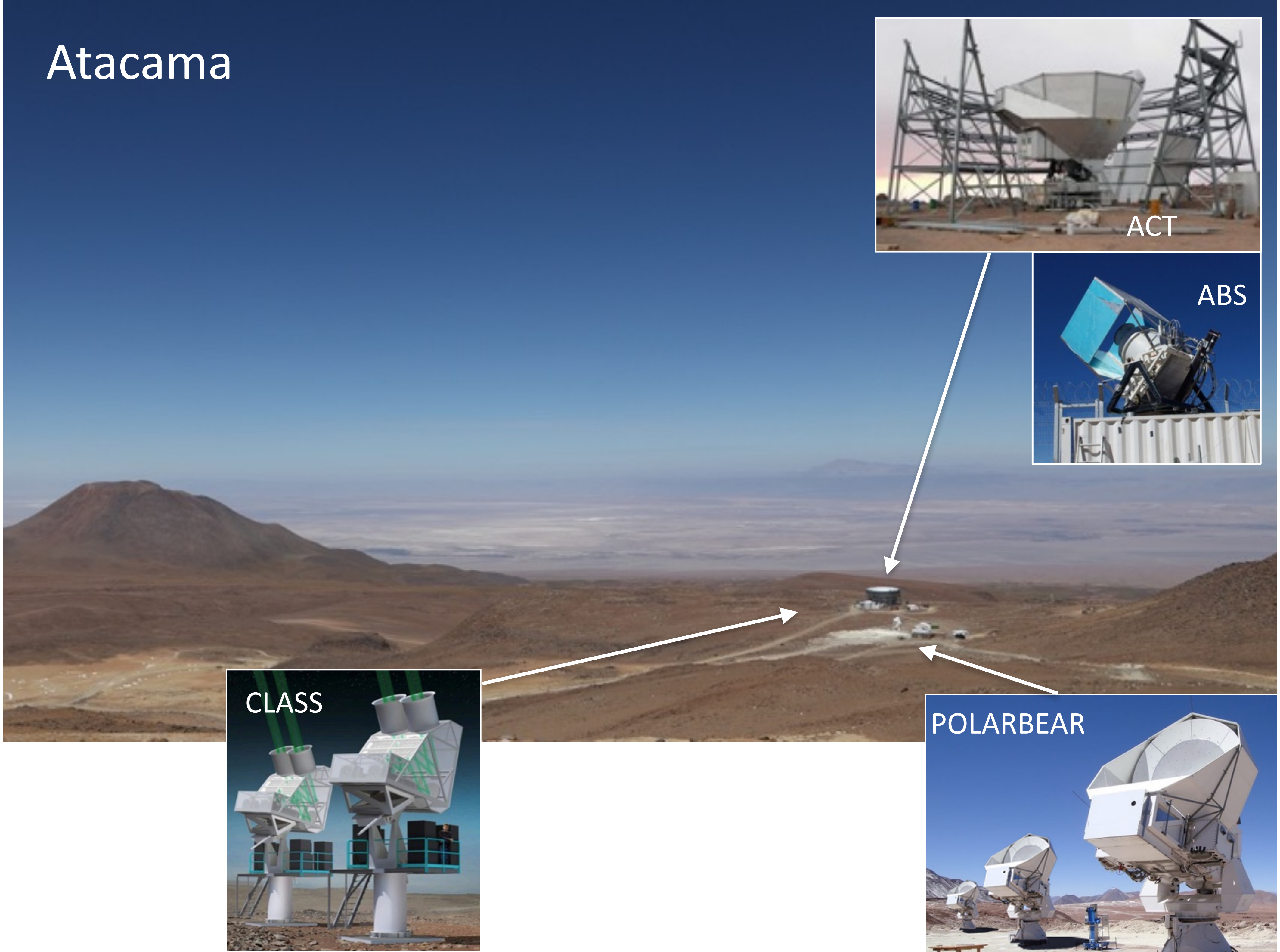




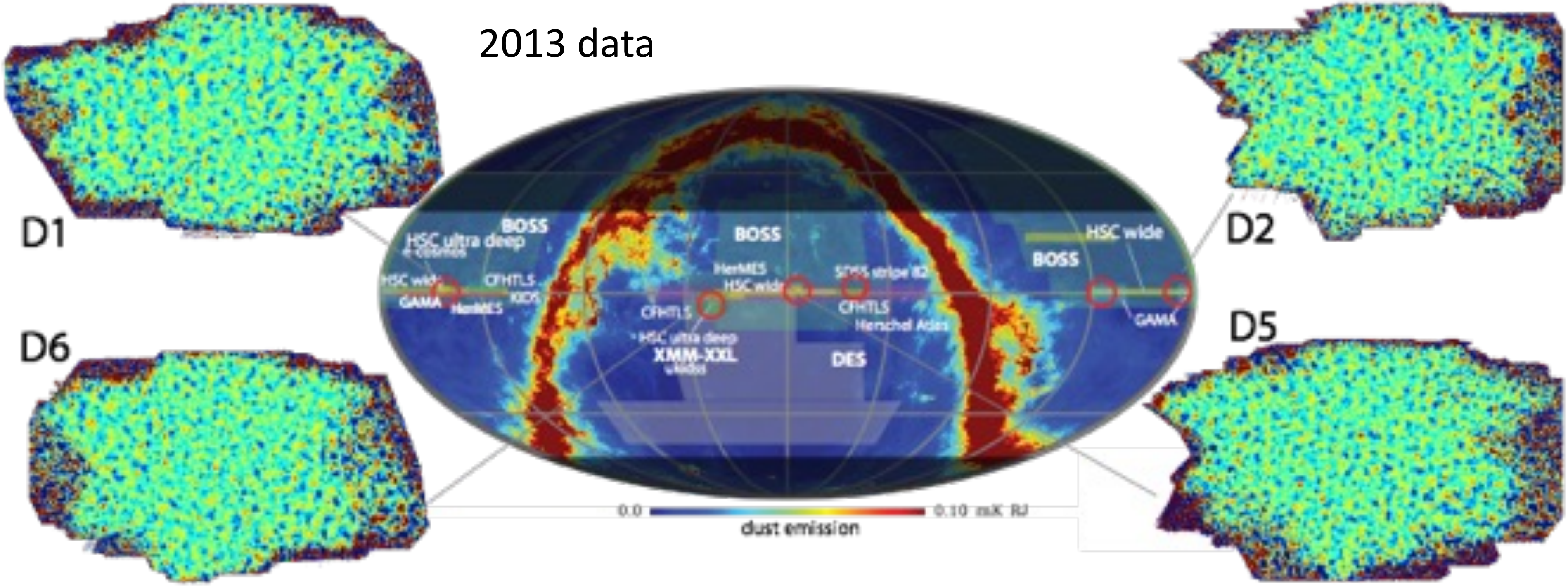
Peak smearing



Atacama Cosmology Telescope


Atacama
ACT
ABS
CLASS
POLARBEAR

2013 data



2014, 2015 coverage

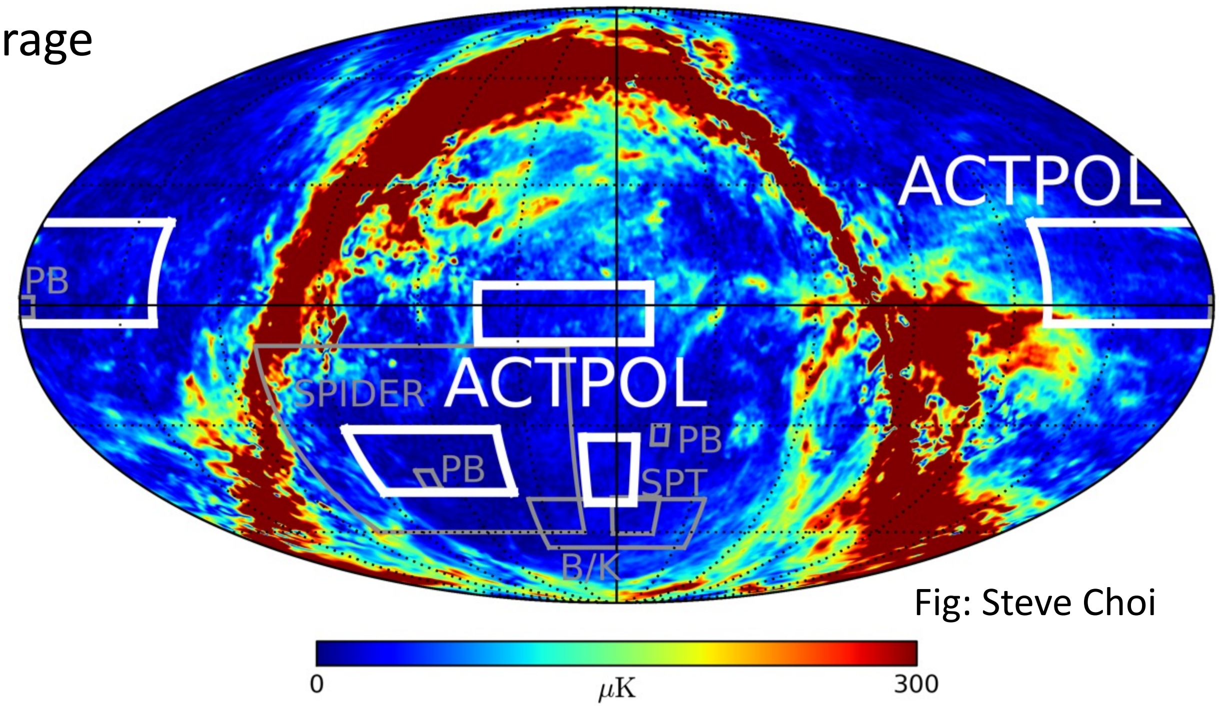
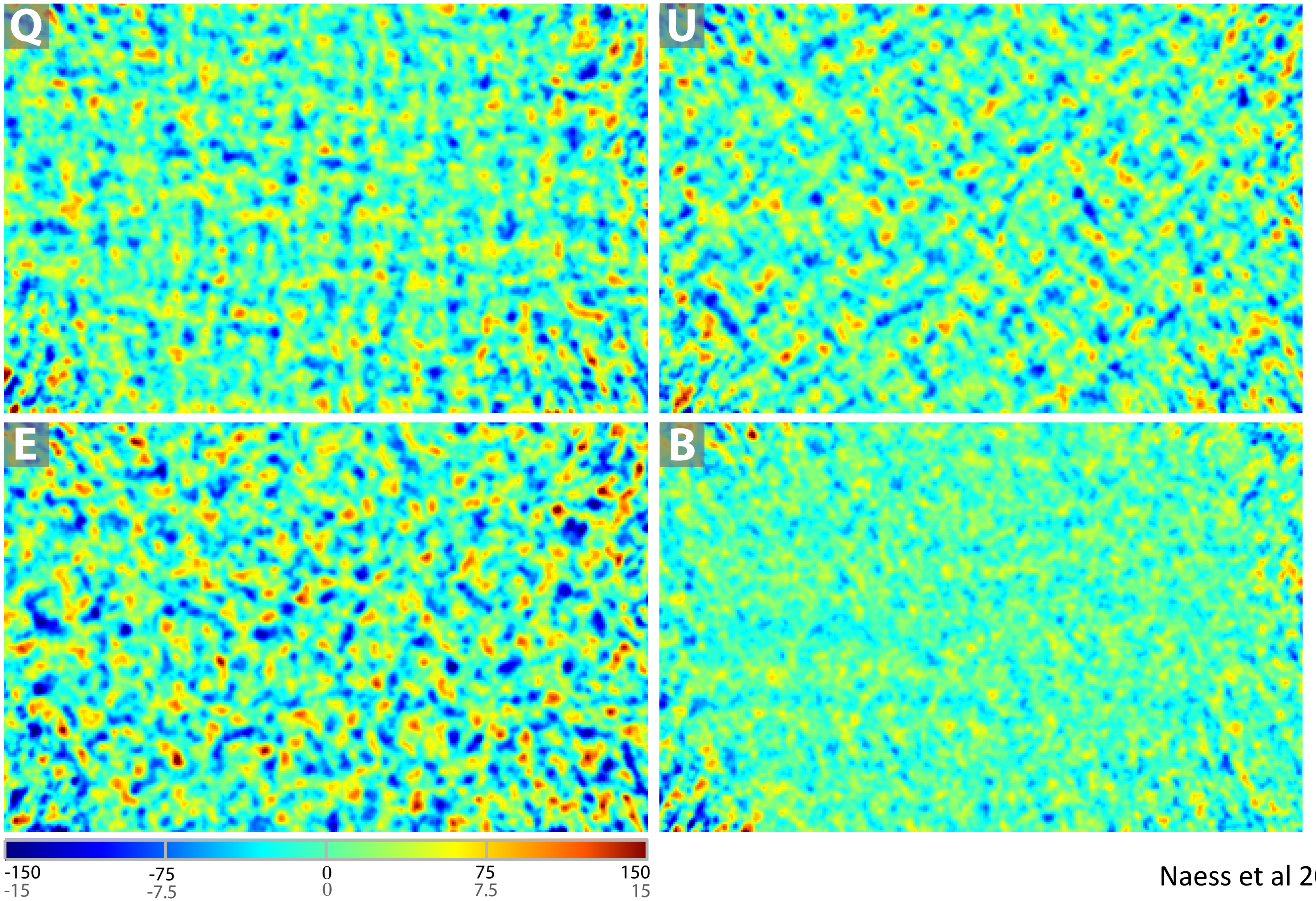
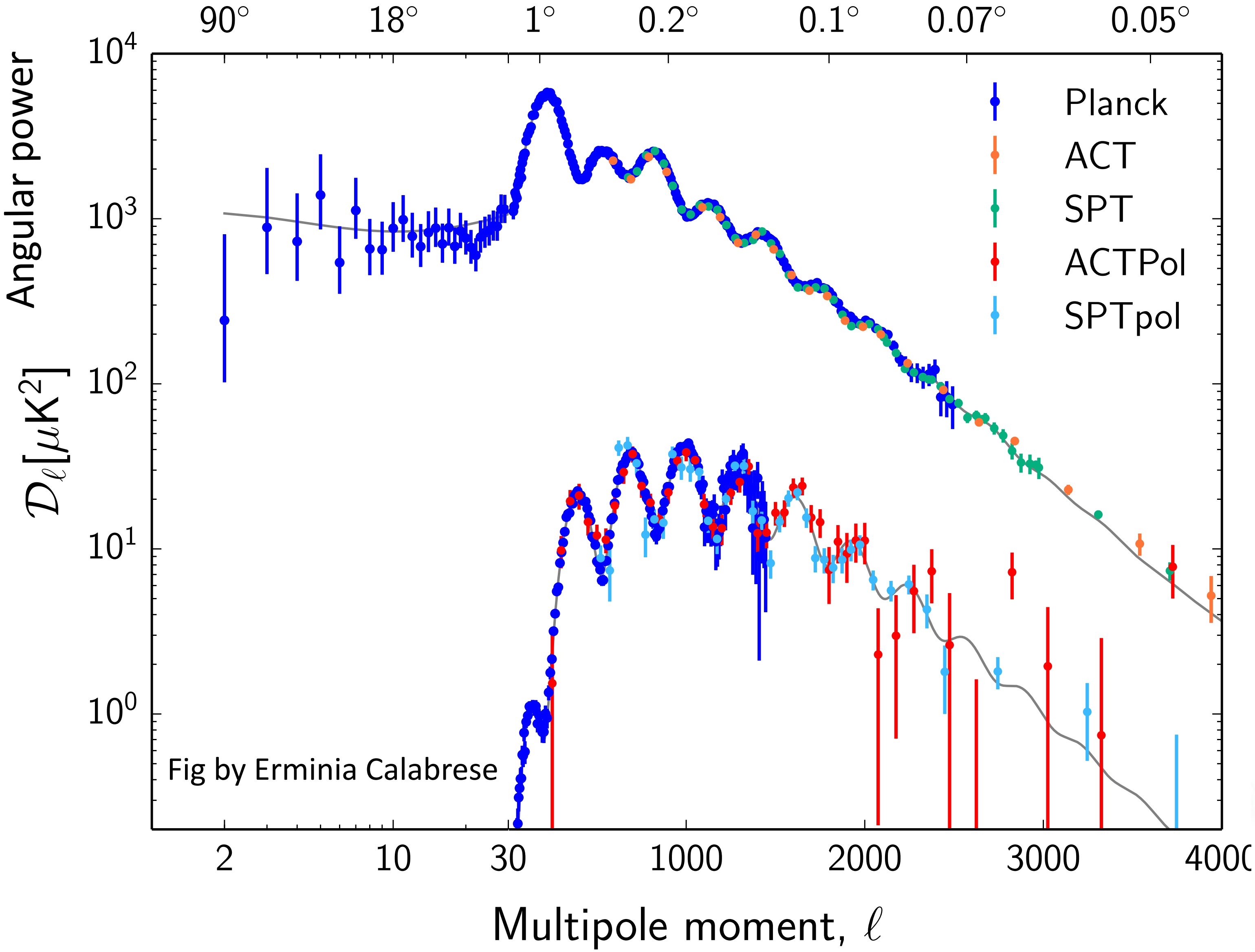
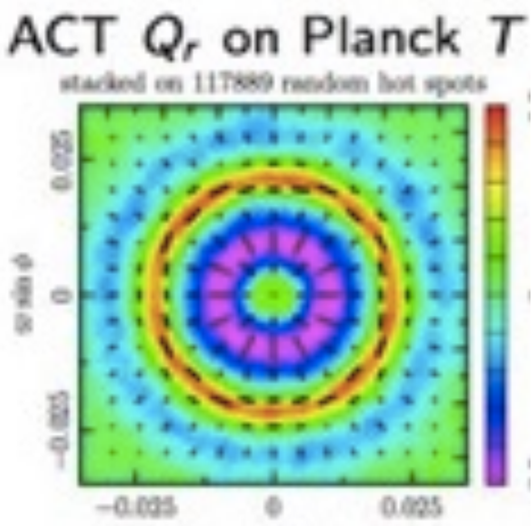


Fig: Steve Choi

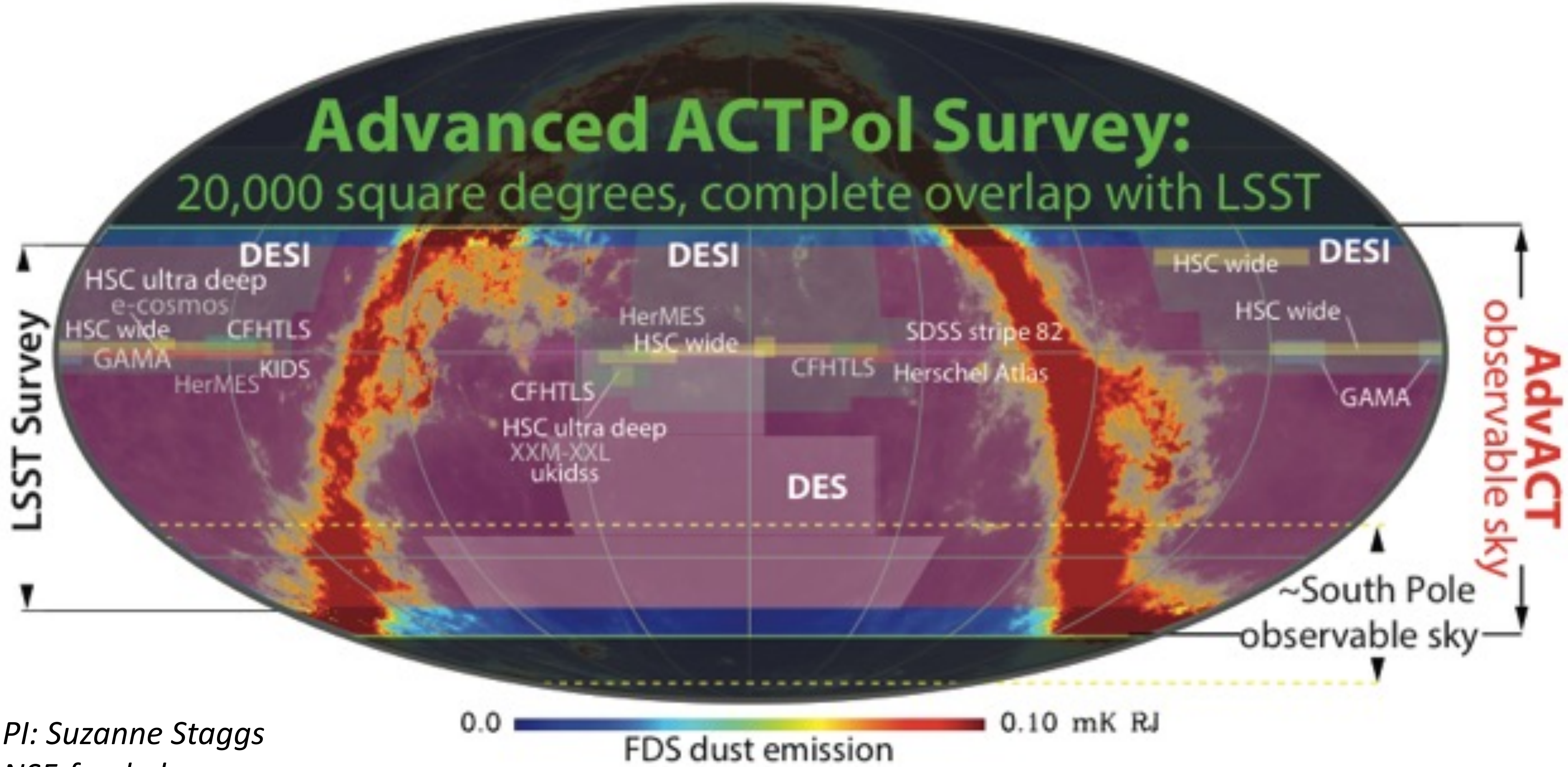


Naess et al 2014



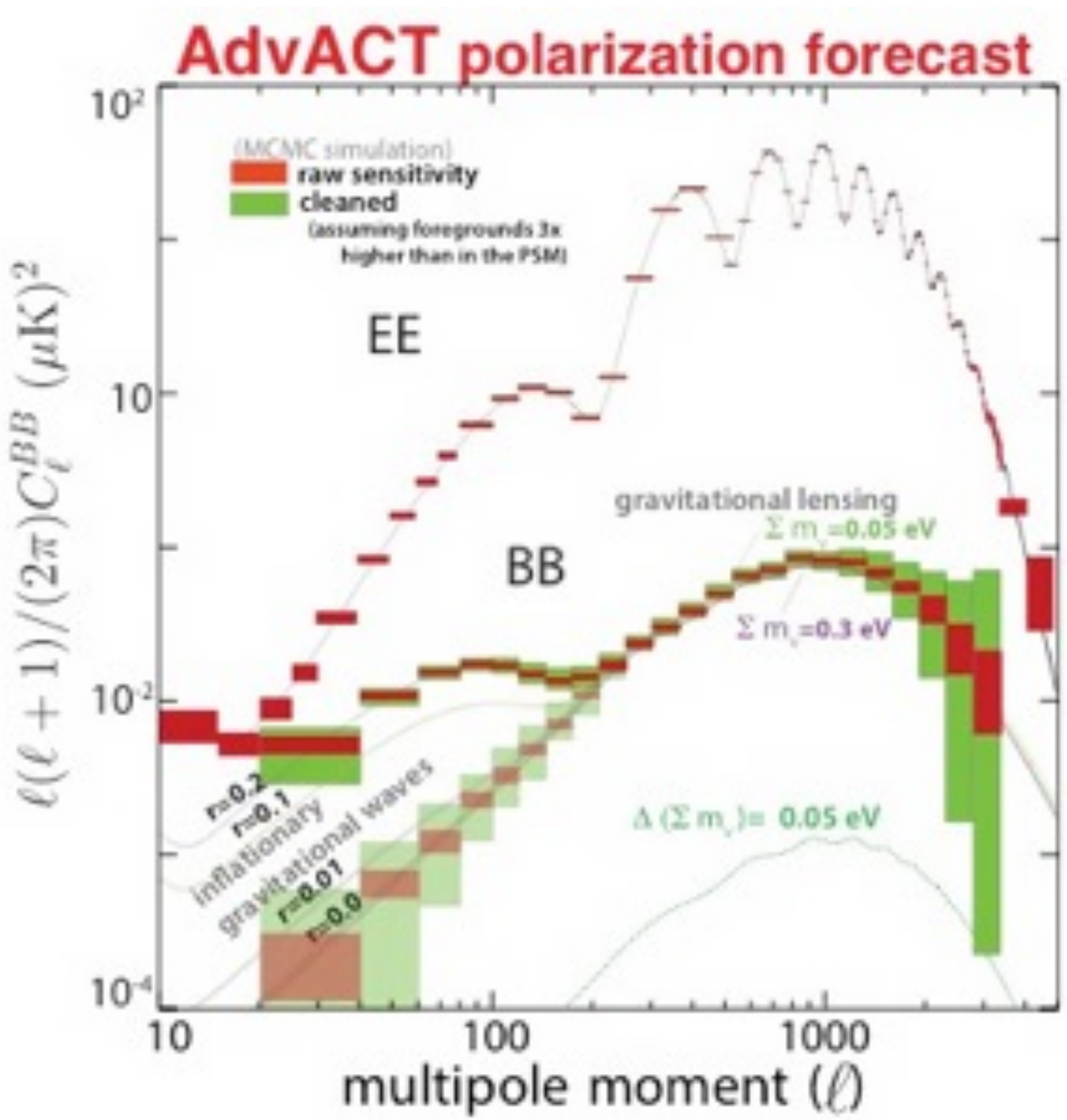


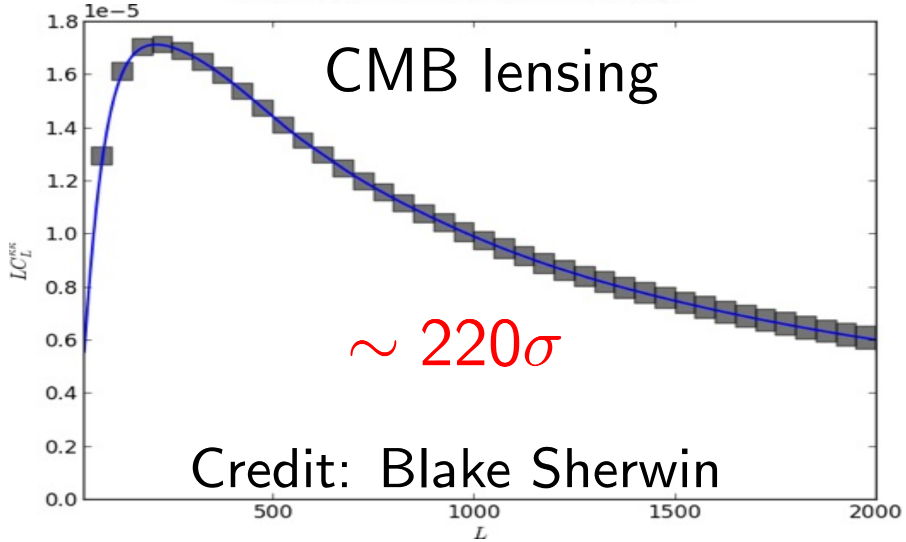
Huang & Bond for ACT

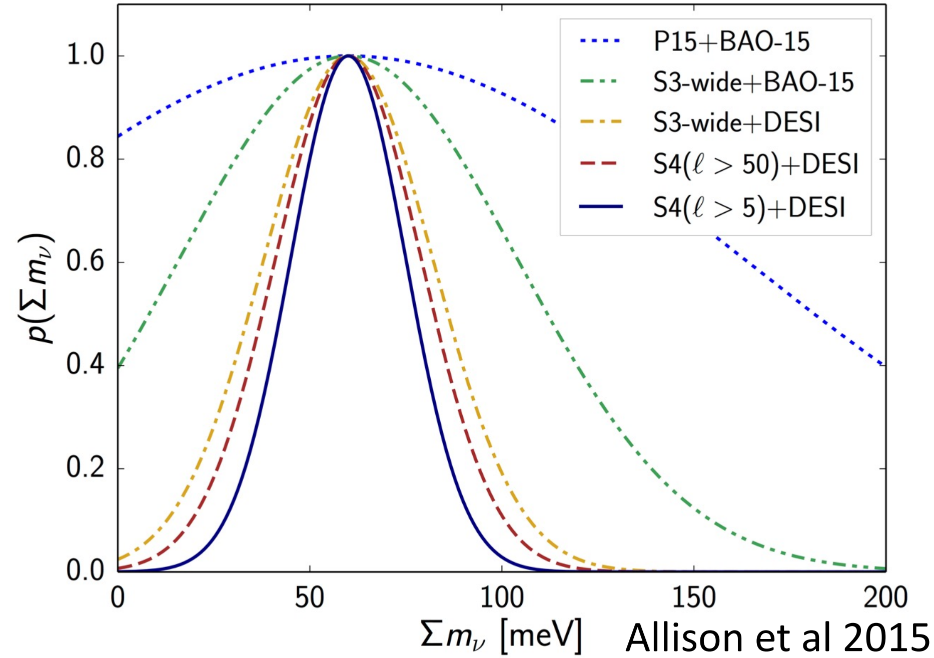


PI: Suzanne Staggs
NSF-funded

Five channels: 28, 41, 90, 150, 230 GHz
Same telescope, new detectors
Estimated noise levels after foreground removal: ~ 8 uK/amin
Three year survey starting 2016







Allison et al 2015

Expect to reach sigma(r) ~ 0.003 (assumes simple dust models!)

Data redundancy: check for common signal in different regions and different channels

Cosmic microwave background data continue to demand LCDM cosmological model. It holds up to new lensing and polarization measurements from the Planck satellite.

- *If inflation is not correct scenario, it has to look a lot like it. Gravitational wave search on; quadratic potential disfavored.*

- *Neutrino sector holds questions that cosmology can help answer in coming decade.*