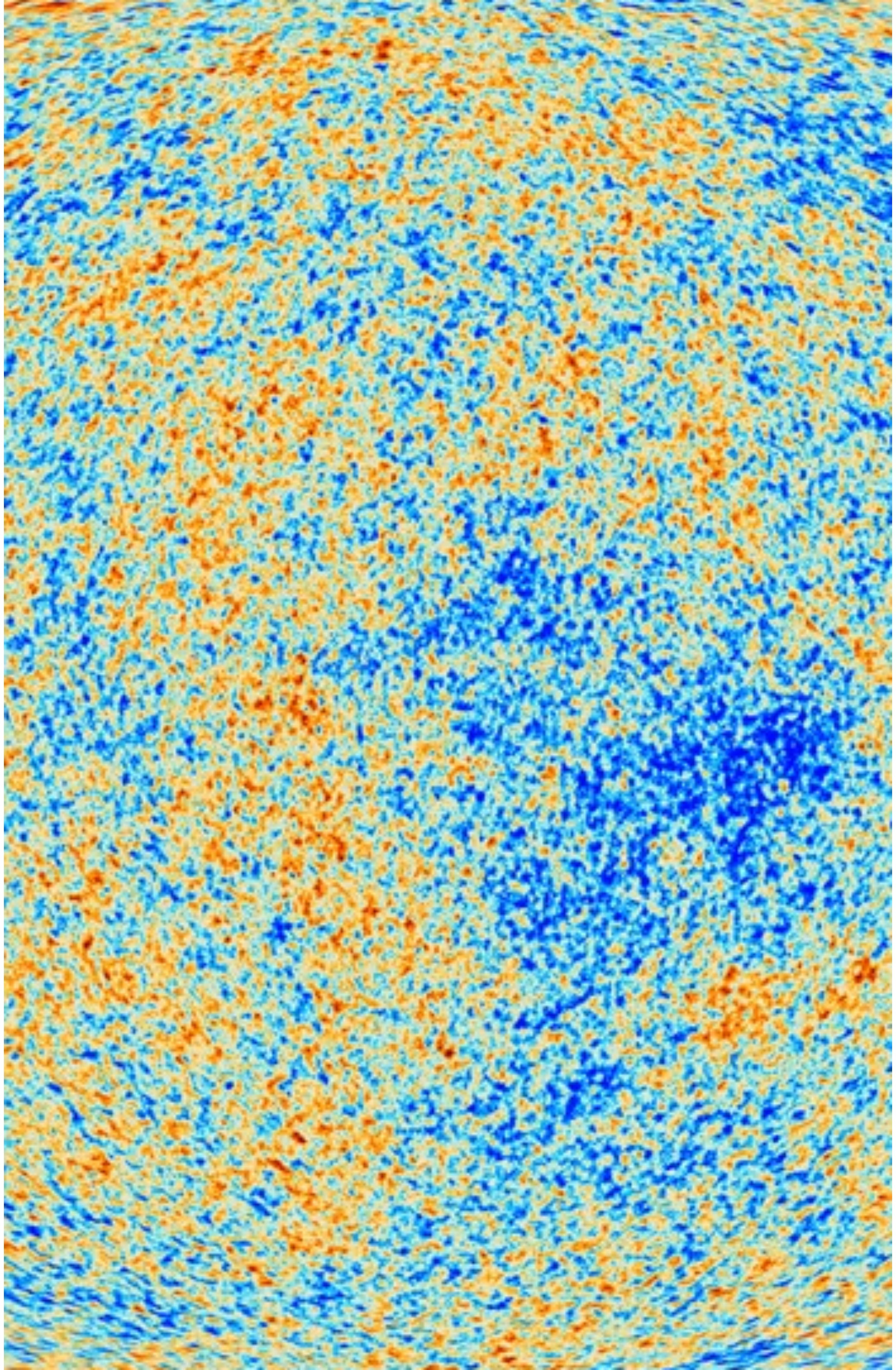


Cosmology from the microwave background

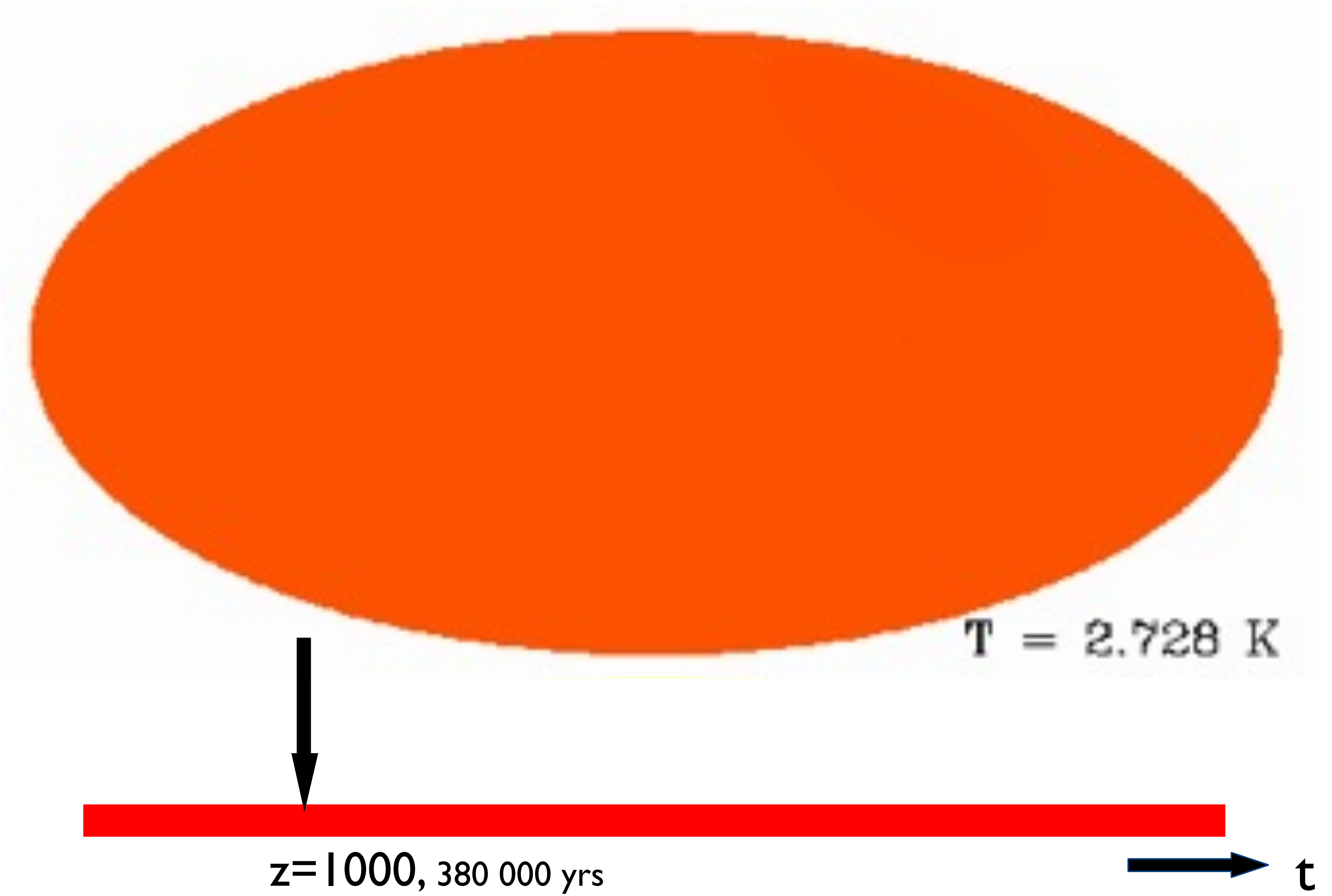
Jo Dunkley
University of Oxford

History of early universe

Inflation?	$T \sim 10^{15}$ GeV	$t \sim 10^{-35}$ s
CDM decoupling?	$T \sim 10$ GeV?	$t \sim 10^{-8}$ s
Neutrino decoupling	$T \sim 1$ MeV	$t \sim 1$s
Big Bang Nucleosynthesis	$T \sim 100$ keV	$t \sim 10$ min
Matter-Radiation Equality	$T \sim 0.8$ eV	$t \sim 60{,}000$ yr
Recombination	$T \sim 0.3$ eV	$t \sim 380{,}000$ yr

Later:

Neutrinos become 'cold'	$< t \sim 100{,}000{,}000$ yr

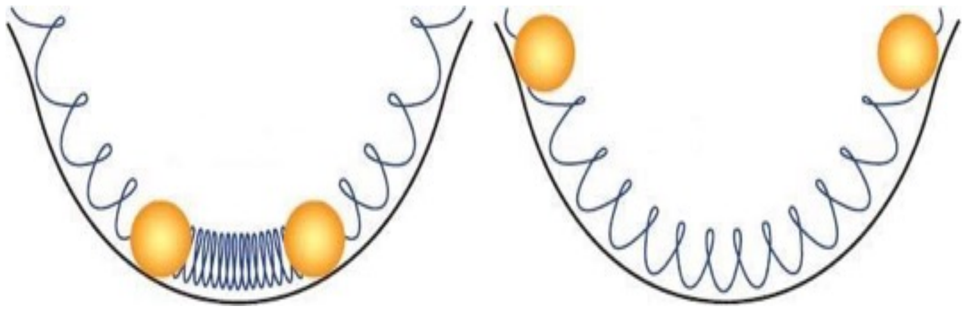

T = 2.728 K
z=1000, 380 000 yrs
t

Seeds of structure

1. Inflation (?) imprints quantum fluctuations.

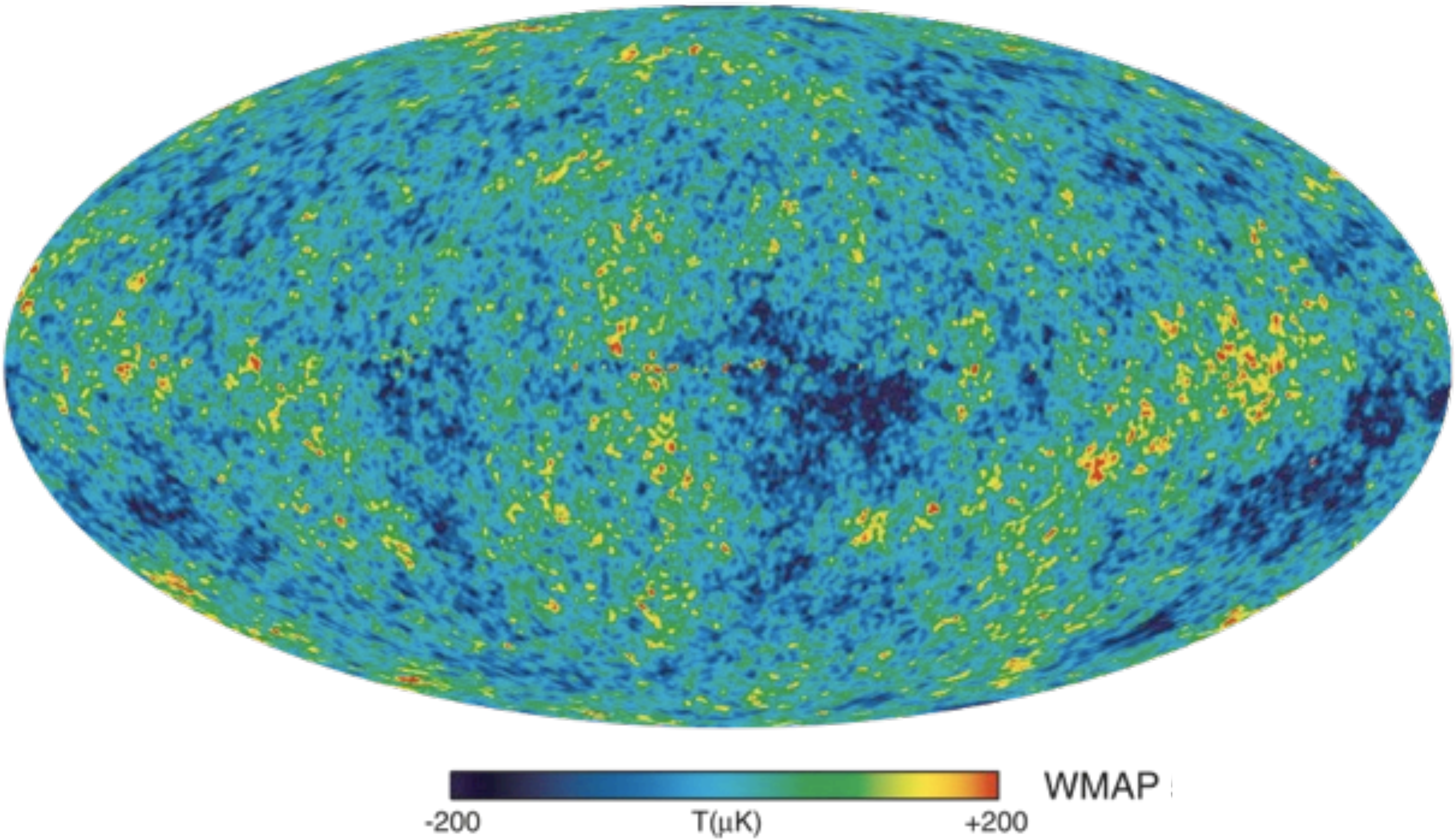
2. Space expands, regions enter into causal contact and start to evolve.

3. Coupled baryons and photons produce oscillations in plasma.



After 380,000 years the fluctuations have evolved, and we see a snapshot of them as anisotropies in CMB.

Linearity means we can use the anisotropies to infer the initial fluctuations and the contents of the Universe.



WMAP
-200
T(μK)
+200

esa

planck

cnes

agenzia spaziale italiana

HFI PLANCK

PLANCK LFI

NASA

CNRS

DTU Space
National Space Institute

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science & Technology Facilities Council

CSIC
Consejo Superior de Investigaciones Científicas

IAS orsay

IAP

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

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

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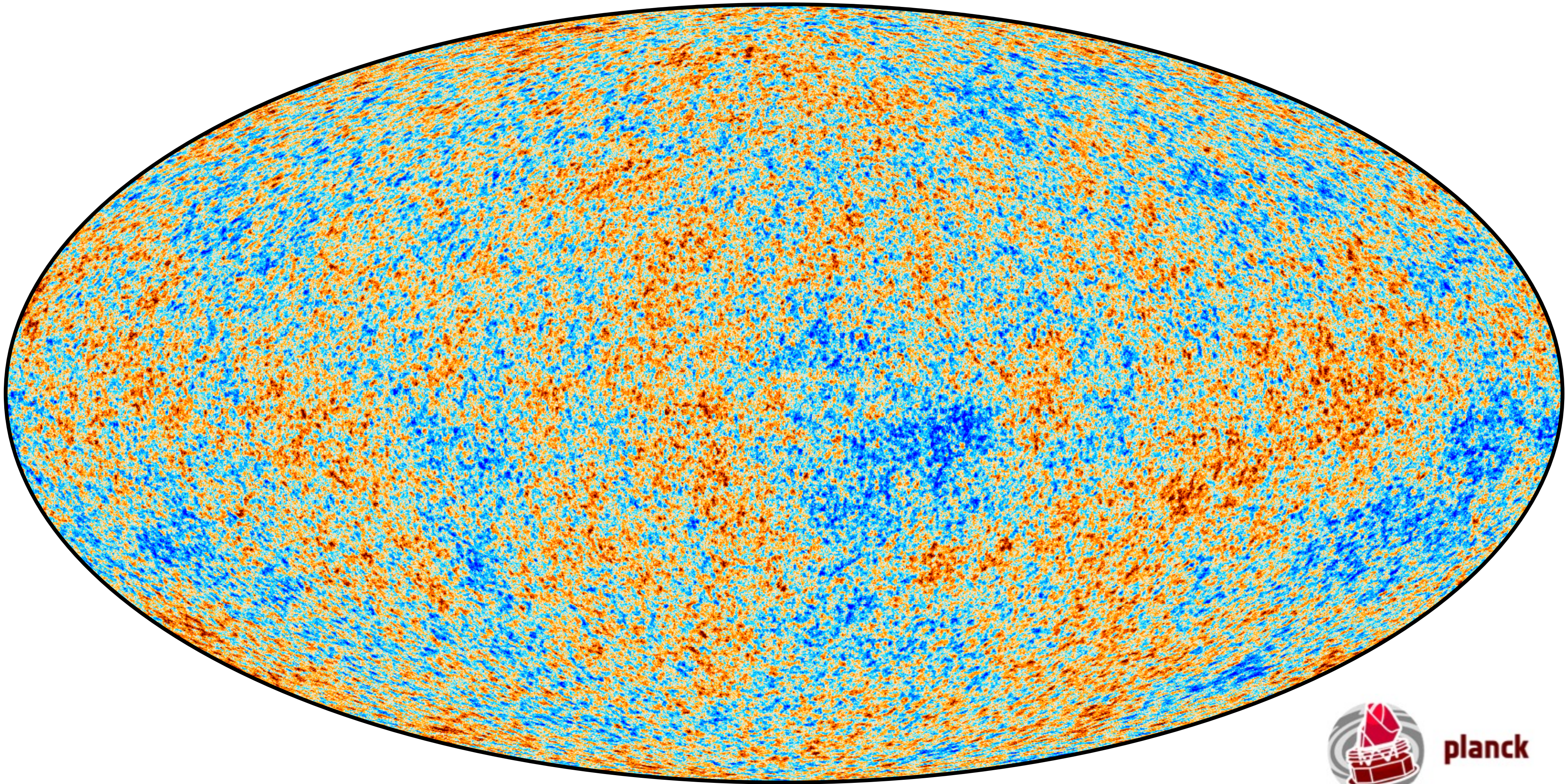
APC
California Institute of Technology
ioa
KICC Kavli Institute for Cosmology Cambridge
Cavendish Astrophysics
UNIVERSITY OF CAMBRIDGE
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
irfu cea saclay
cea énergie atomique • énergies alternatives
CESR
CITA–ICAT
CNRS IN2P3 Les deux infinis
ipac Infrared Processing and Analysis Center

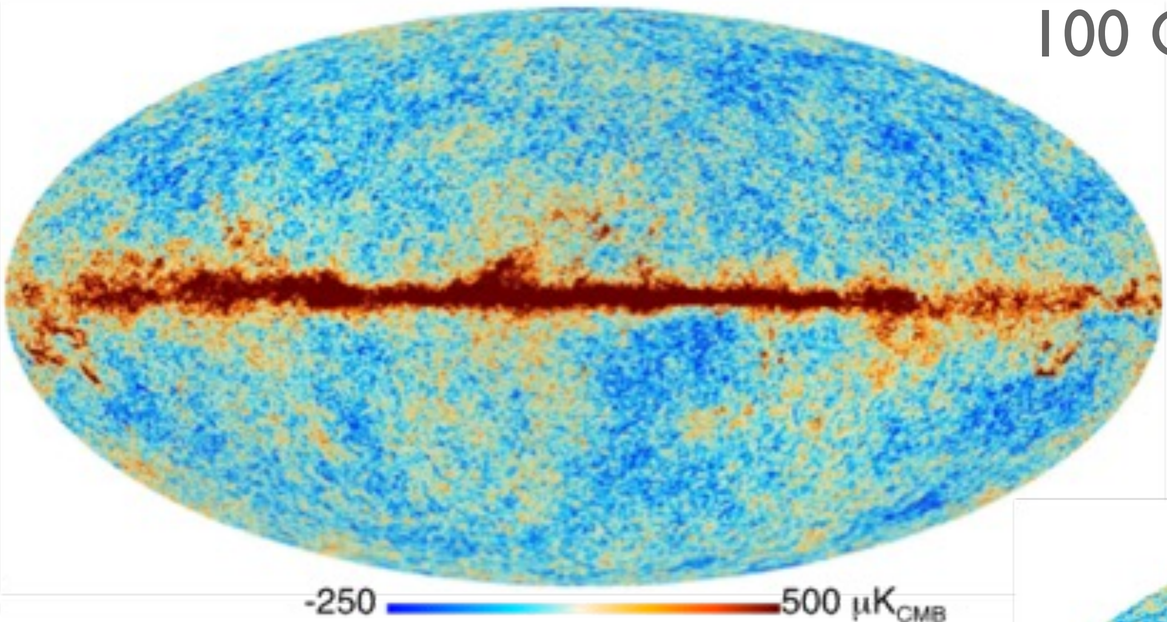
HELSINKI INSTITUTE OF PHYSICS
Instituto de Astrofísica de Canarias
IFCA Instituto de Física de Cantabria
Imperial College London
Università degli Studi di Milano
Néel Institut
IPAG
ISDC Data Centre for Astrophysics
JPL
LAL Laboratoire de l'Accélérateur Linéaire
l'Observatoire de Paris — LERMA
LPSC Grenoble
The University of Manchester

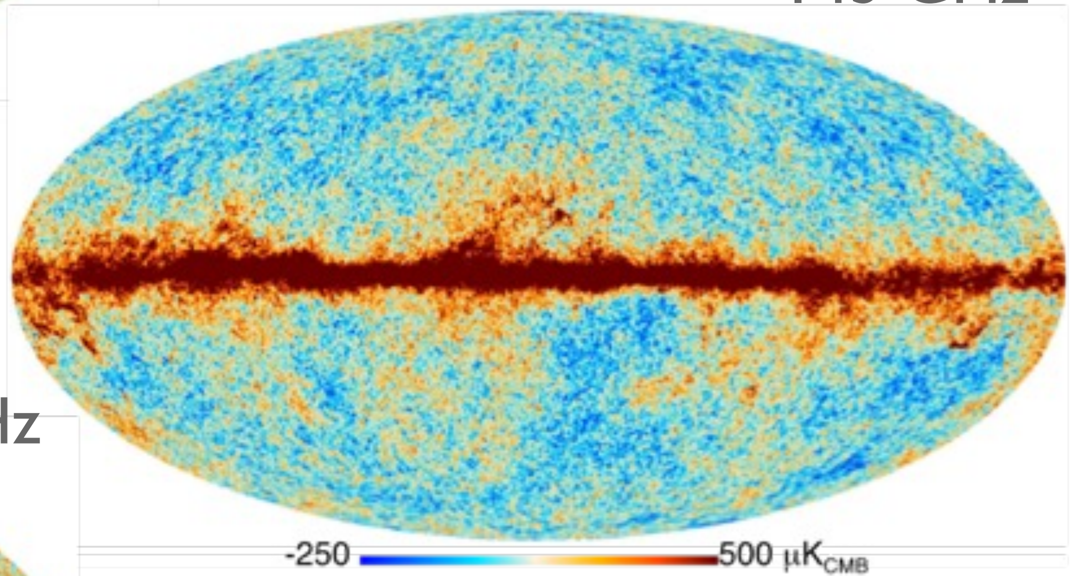
MilliLab
Max-Planck-Institut für Astrophysik
NUI MAYNOOTH
INAF Osservatorio Astronomico di Padova
University of Oxford
Dipartimento di Fisica Sapienza Università di Roma
Science & Technology Facilities Council Rutherford Appleton Laboratory
Università di Roma Tor Vergata
Osservatorio Astronomico Trieste
UBC
UC Universidad de Cantabria
UCSB
SISSA

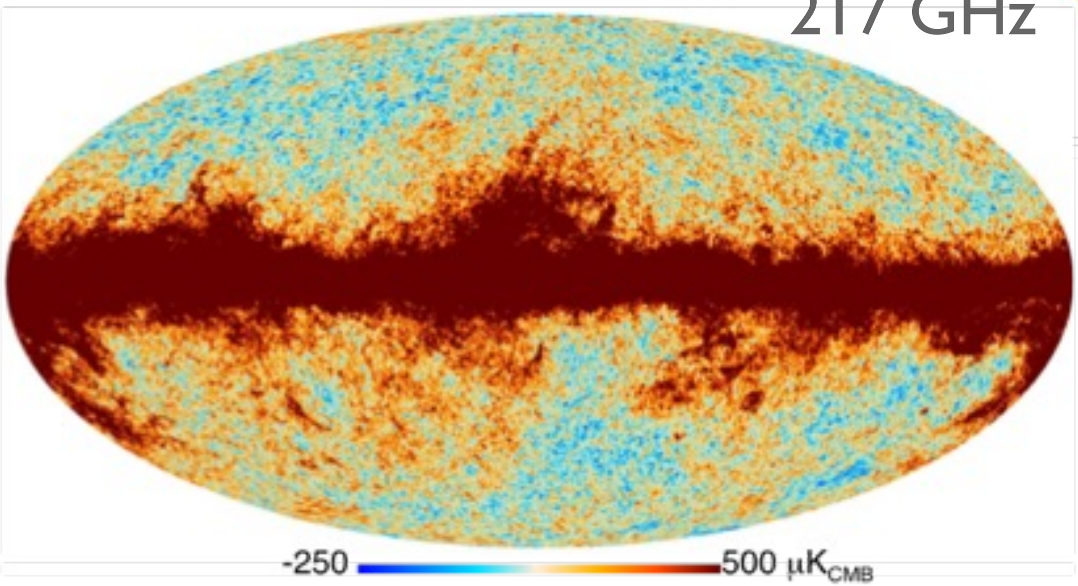
ALMA
ESO
US University of Sussex
esa
UNIVERSITY OF HELSINKI
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF TORONTO
UNIVERSITÉ DE PARIS-SUD XI
ISTI
asdc



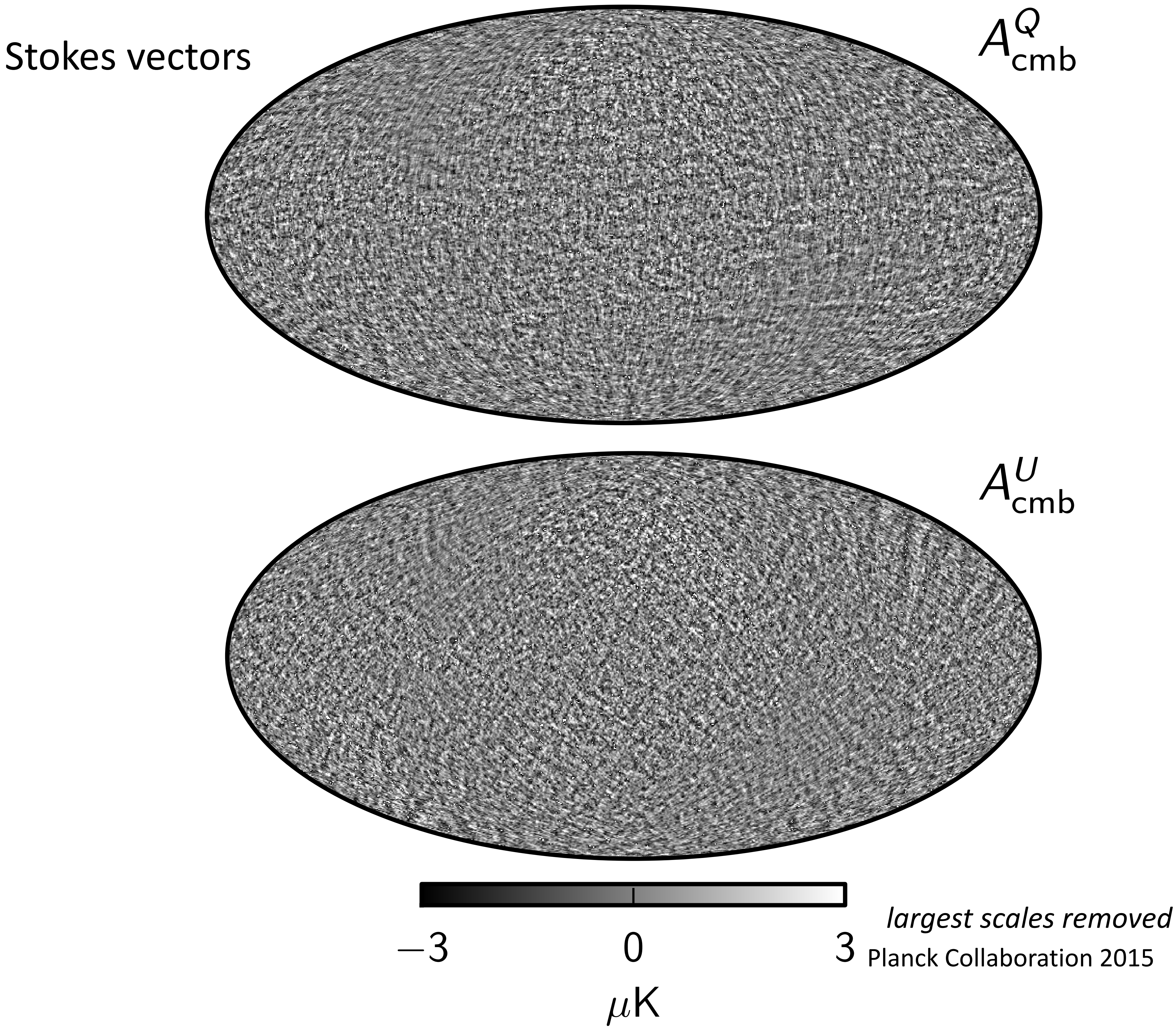
Planck Collaboration 2015

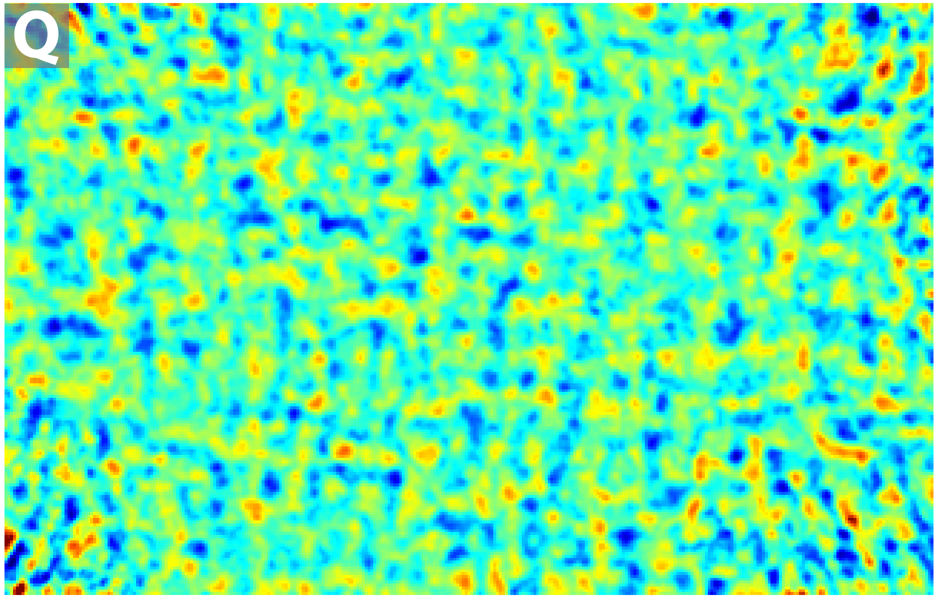


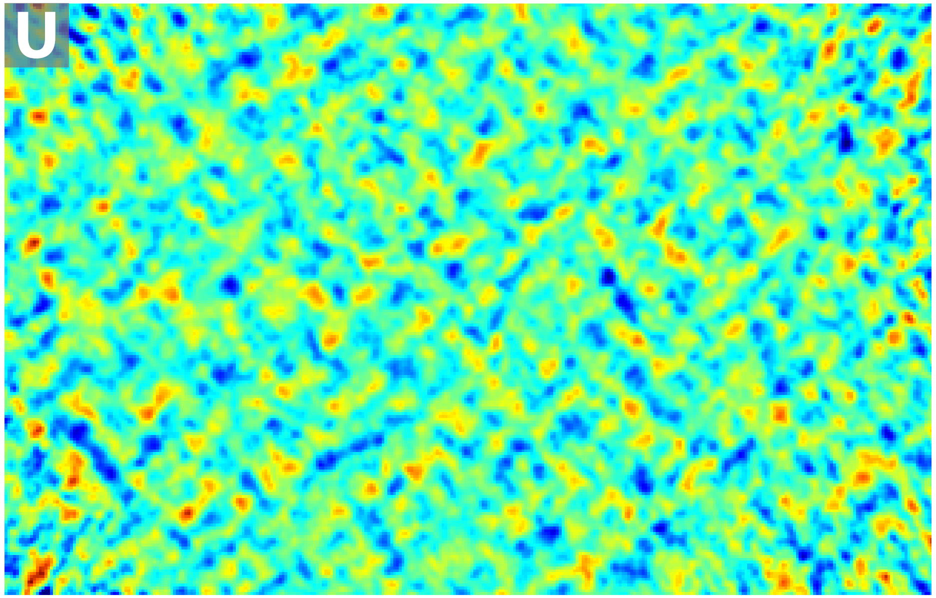


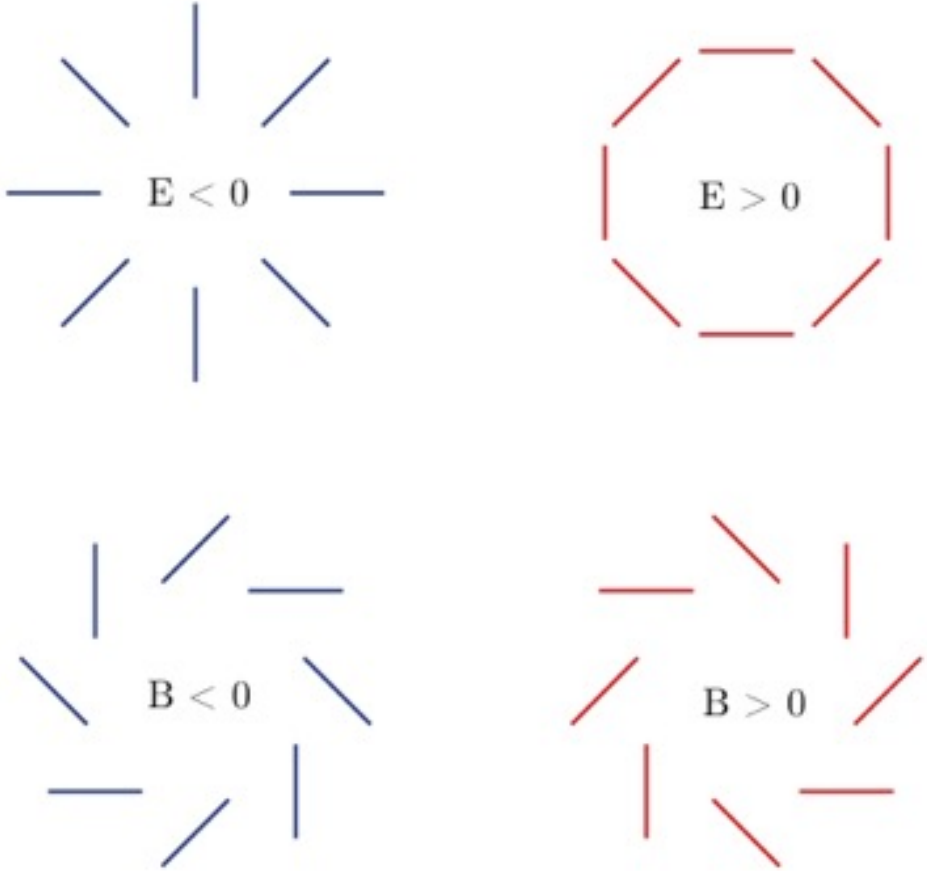


Plus 6 other wavelengths


Stokes vectors
A^{Q}_{cmb}
A^{U}_{cmb}
−3
0
3
μK
largest scales removed
Planck Collaboration 2015

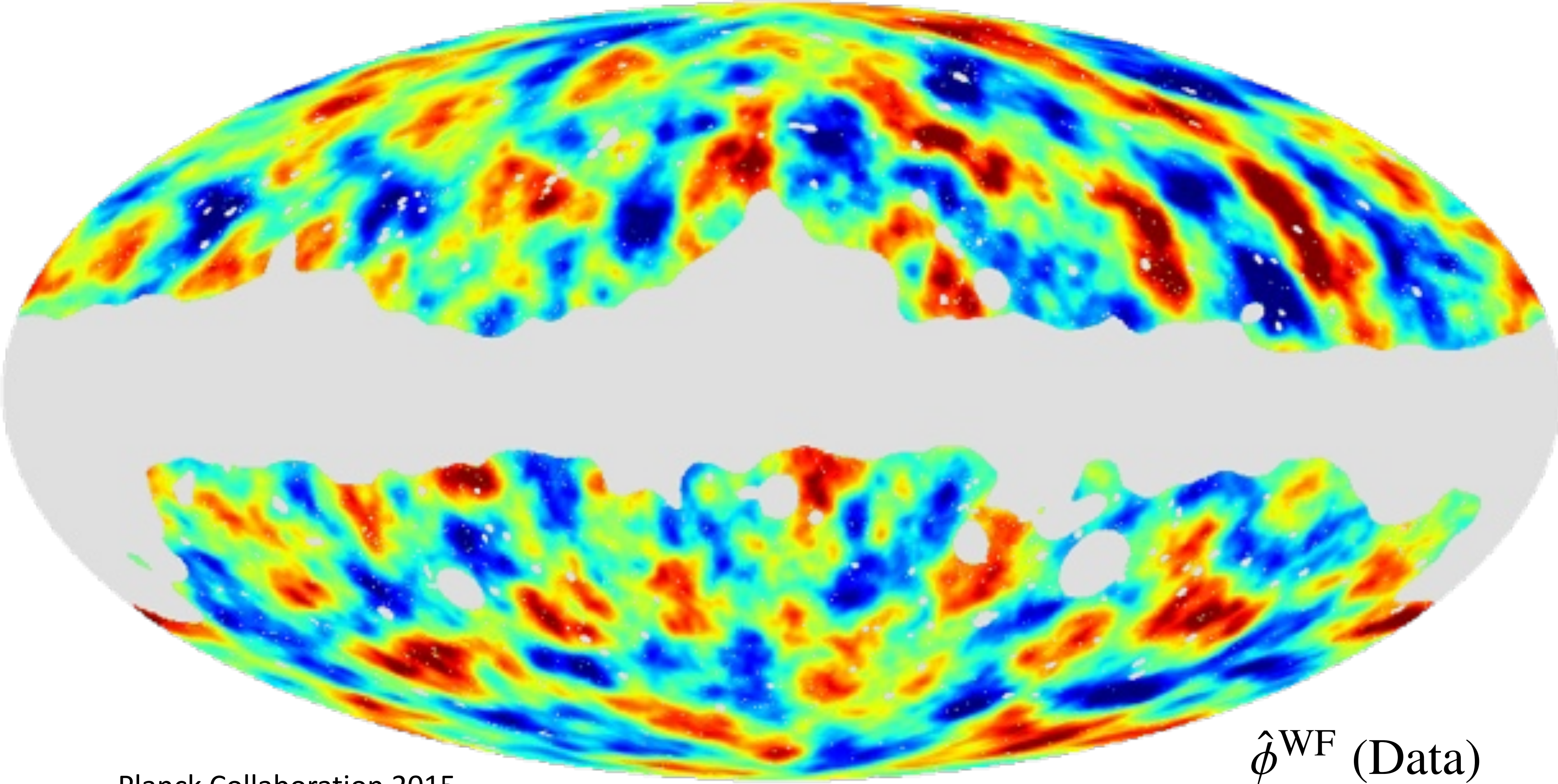






ACTPol maps, scale 15 uK, 10 degrees, Naess et al 2014

Lensing potential, phi



Planck Collaboration 2015

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

What are the geometry, contents, and initial conditions of the Universe?

What happened to start the expansion? Why?

What are the properties of the dark sector?

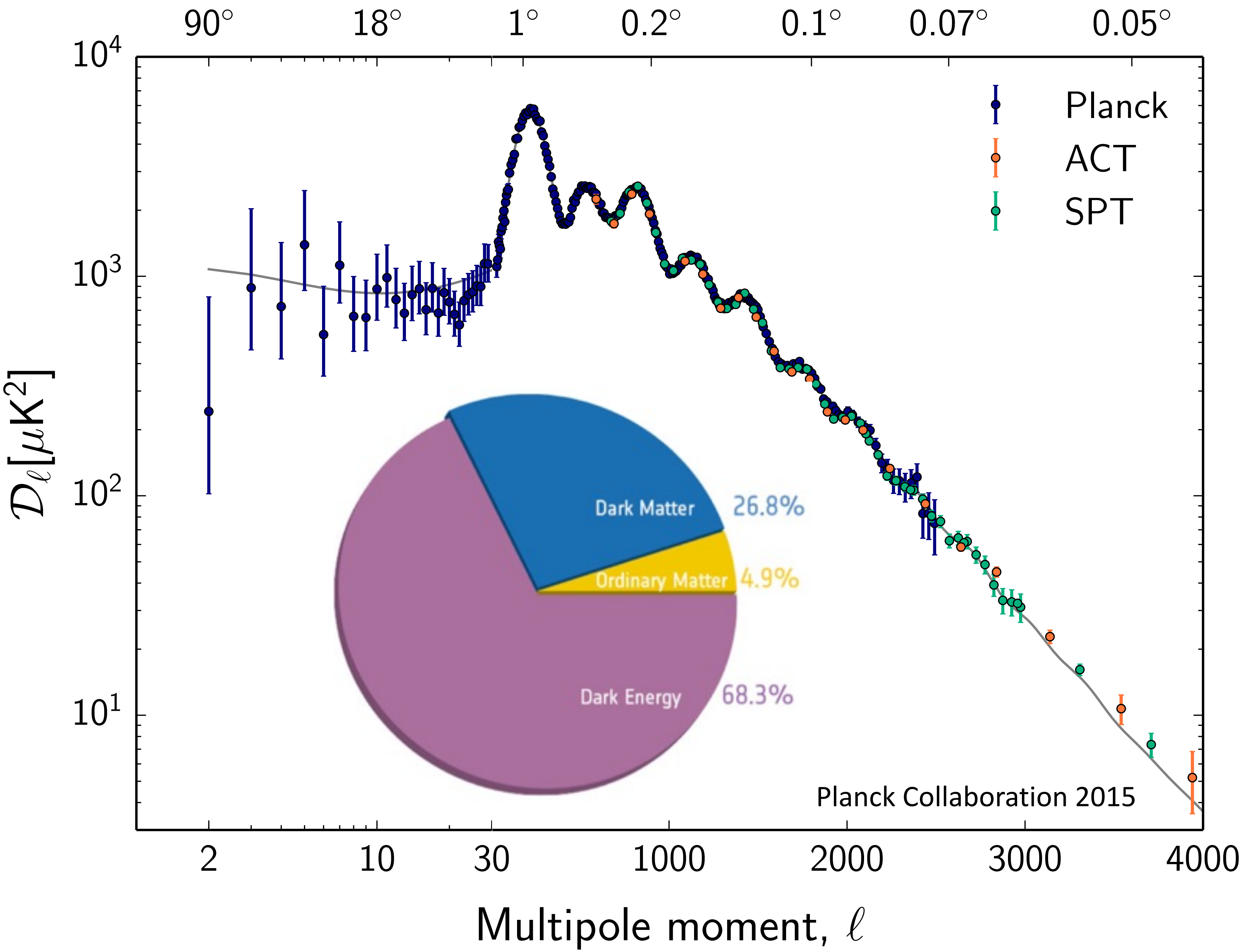
Rough description of CMB analysis process:

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

Statistic = angular power spectrum of maps

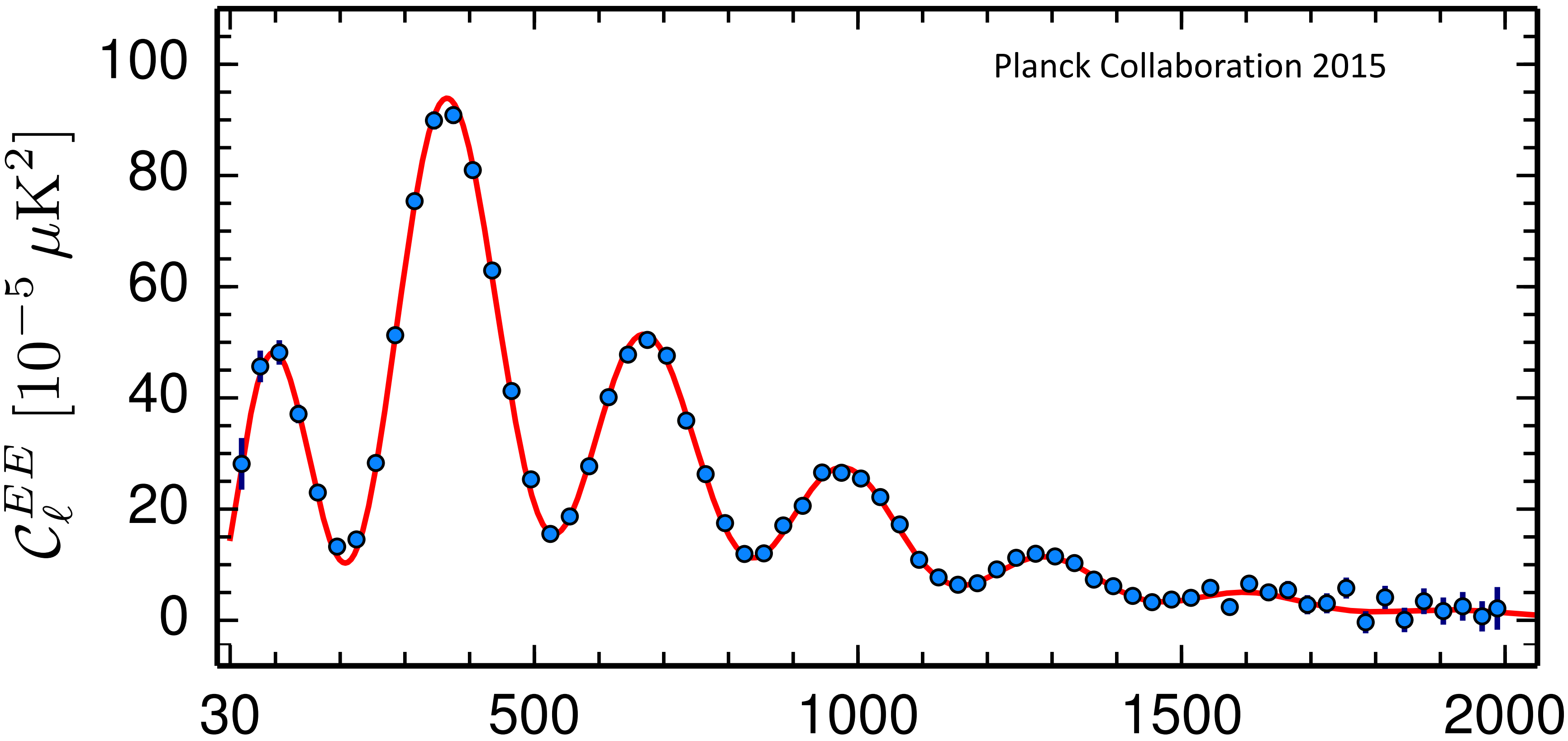
Output = cosmological parameters (reliable codes predict their theory power spectra)

CMB temperature



6-parameter LCDM fits extremely well: constraints on baryon, CDM and Lambda fractions, and size of initial fluctuations. Relic DM density $\Omega_c h^2 = 0.120 \pm 0.003$

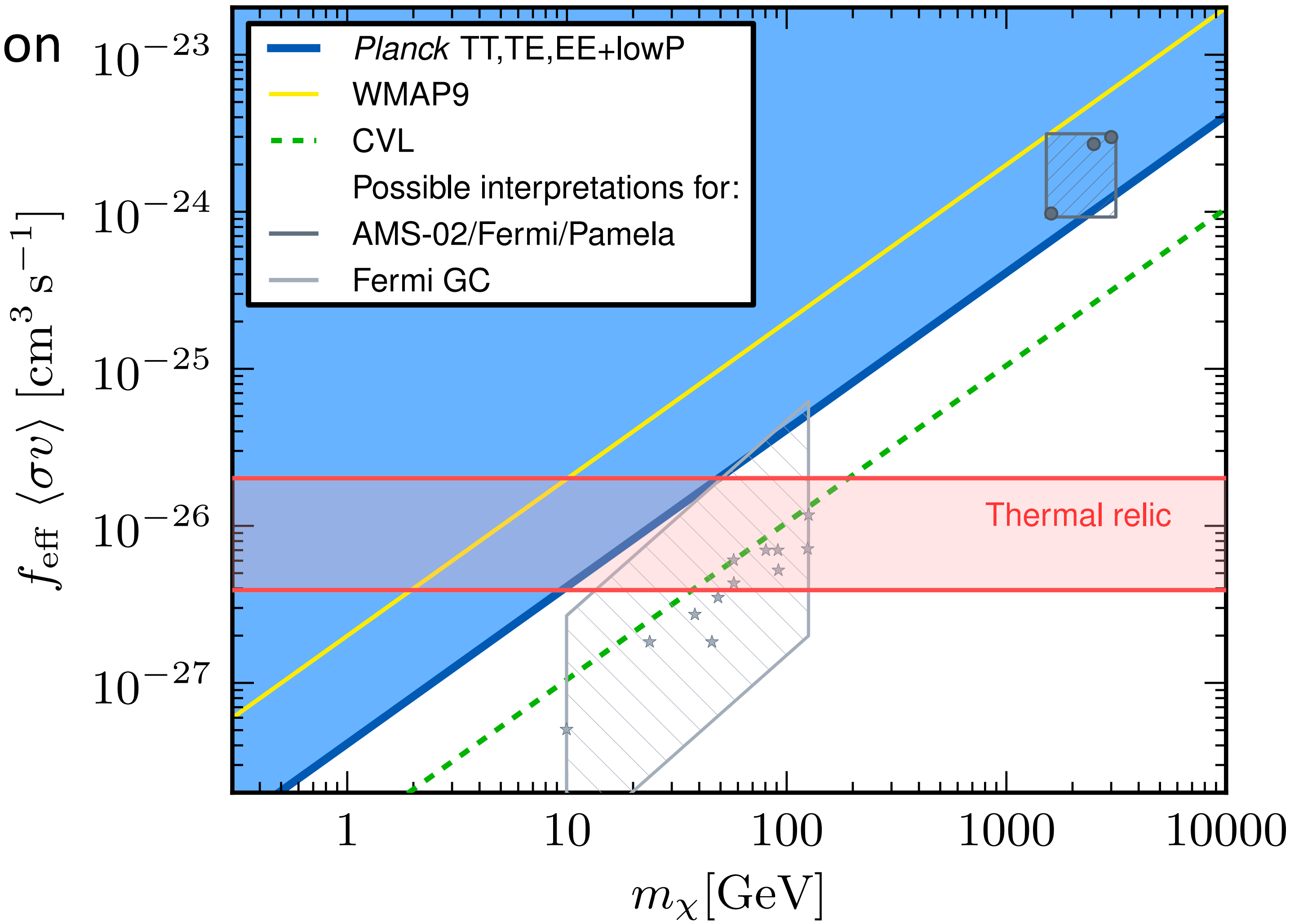
CMB polarization (E-mode)



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, dark matter annihilation*

Dark Matter annihilation

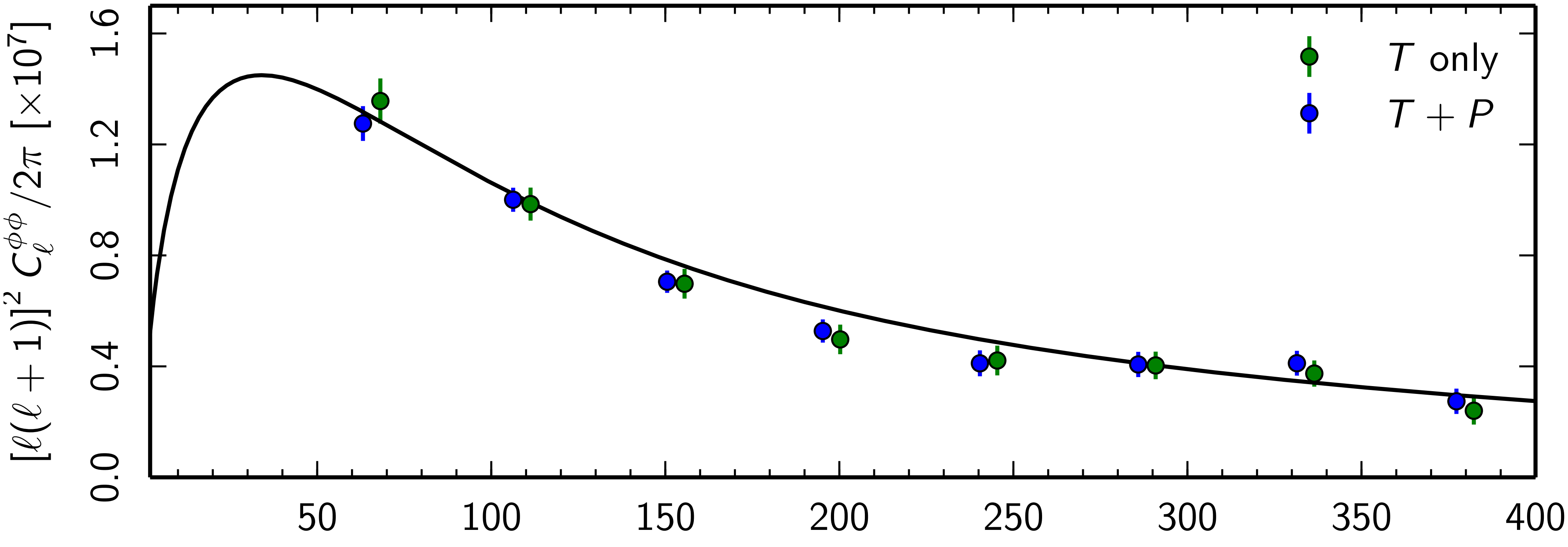


$$\frac{dE}{dtdV}(z) = 2\,g\,\rho^2_{\rm crit}c^2\Omega^2_{\rm c}(1+z)^6 p_{\rm ann}(z), \qquad (81)$$

where $p_{\rm ann}$ is defined as

$$p_{\rm ann}(z) \equiv f(z)\frac{\langle\sigma v\rangle}{m_\chi}, \qquad (82)$$

CMB lensing

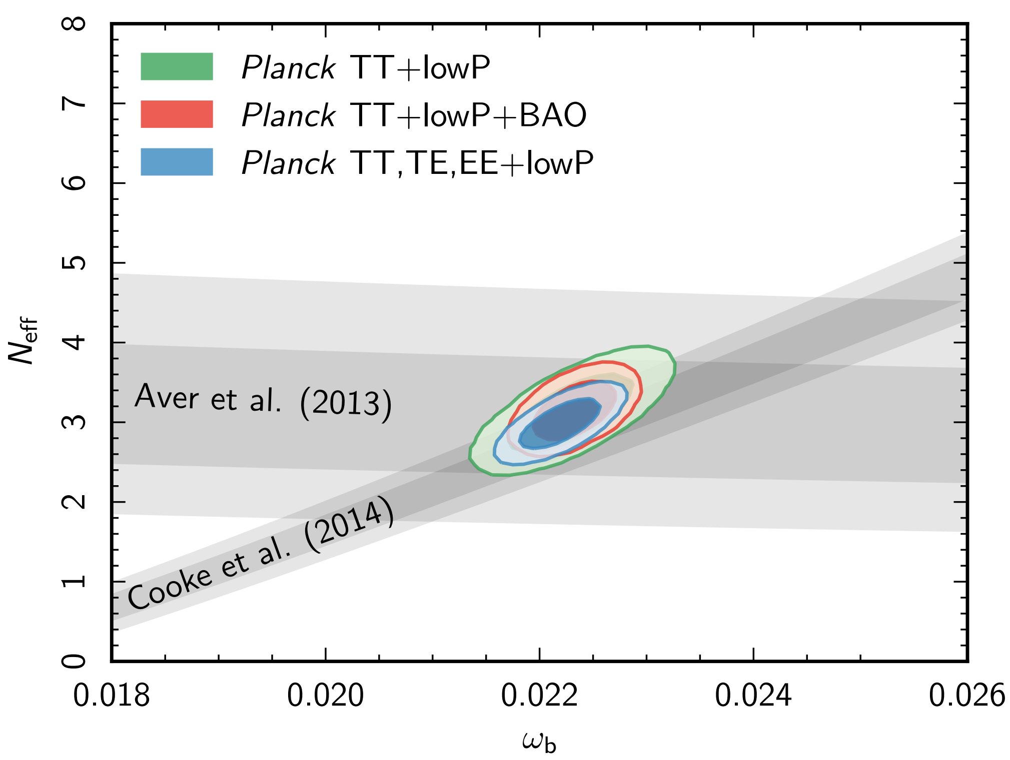


Planck Collaboration 2015

Lensing limits curvature to 2%, and neutrino mass sum to 0.7 eV.

Neutrino properties from cosmology

Planck Collaboration 2015



(1) Number of species:

$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}$$

(2) Neutrino mass

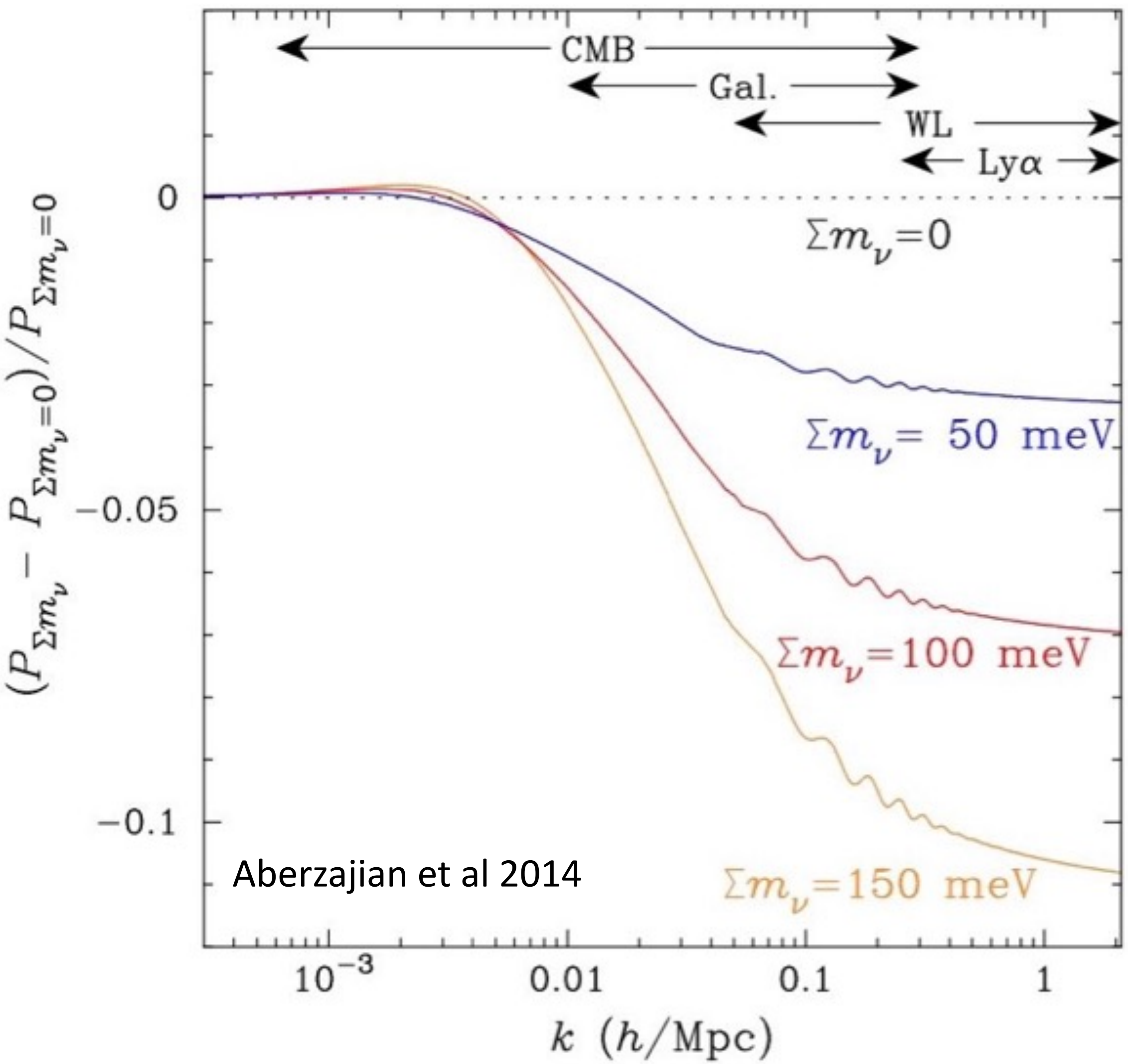
$$\sum m_\nu < 0.68 \text{ eV} \qquad \textit{Planck}$$

$$\sum m_\nu < 0.23 \text{ eV} \qquad \textit{Planck + BAO}$$

More species: longer radiation domination, suppress acoustic oscillations, anisotropic stress shifts peaks

More mass: neutrinos switch from being relativistic (hot) to non-relativistic (cold) earlier. Hot neutrinos free-stream, reducing matter clustering and damping of photon-baryon oscillations compared to CDM.

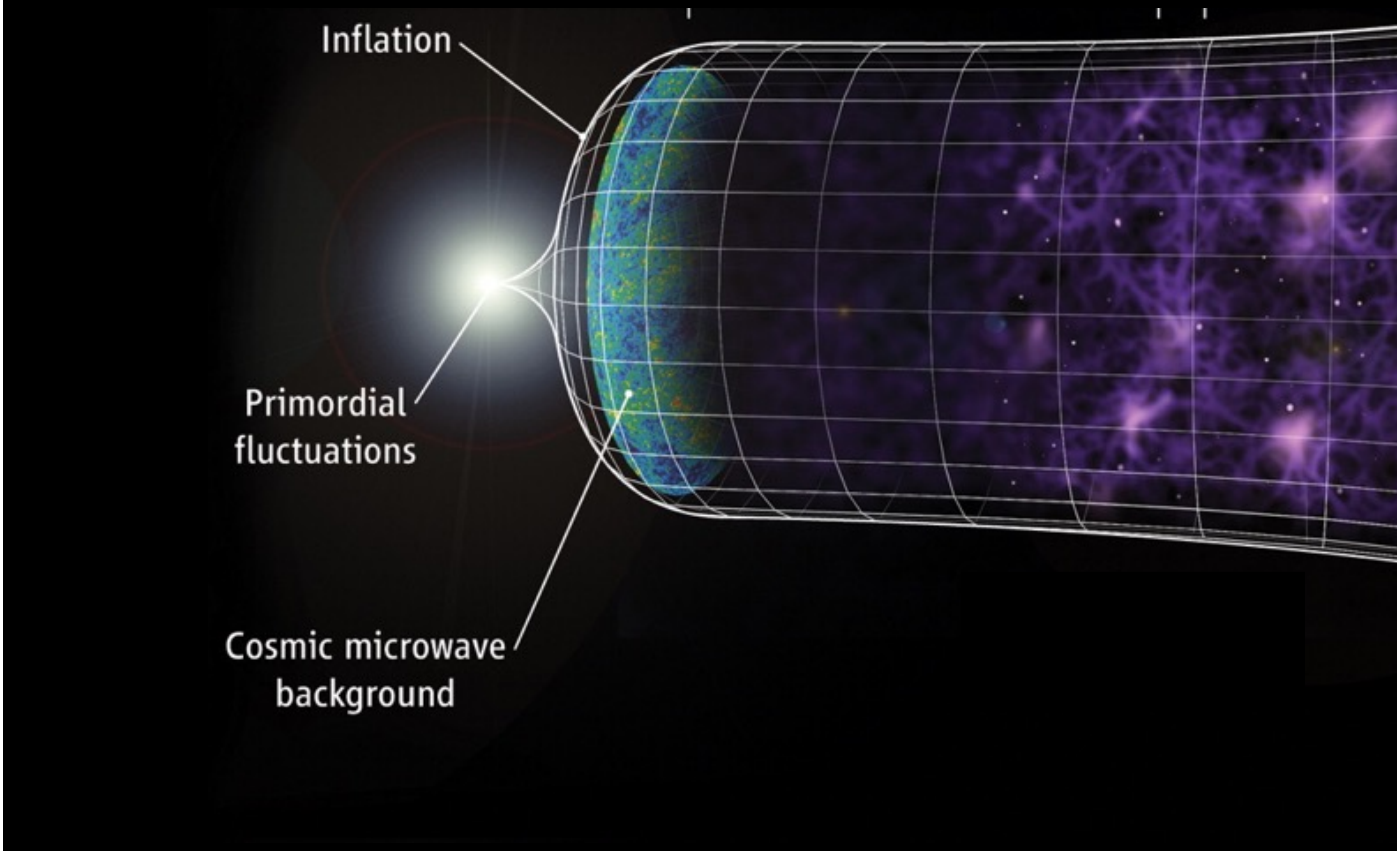
In next decade: measure neutrino mass?



From oscillation expt, minimum mass sum = 60 meV.

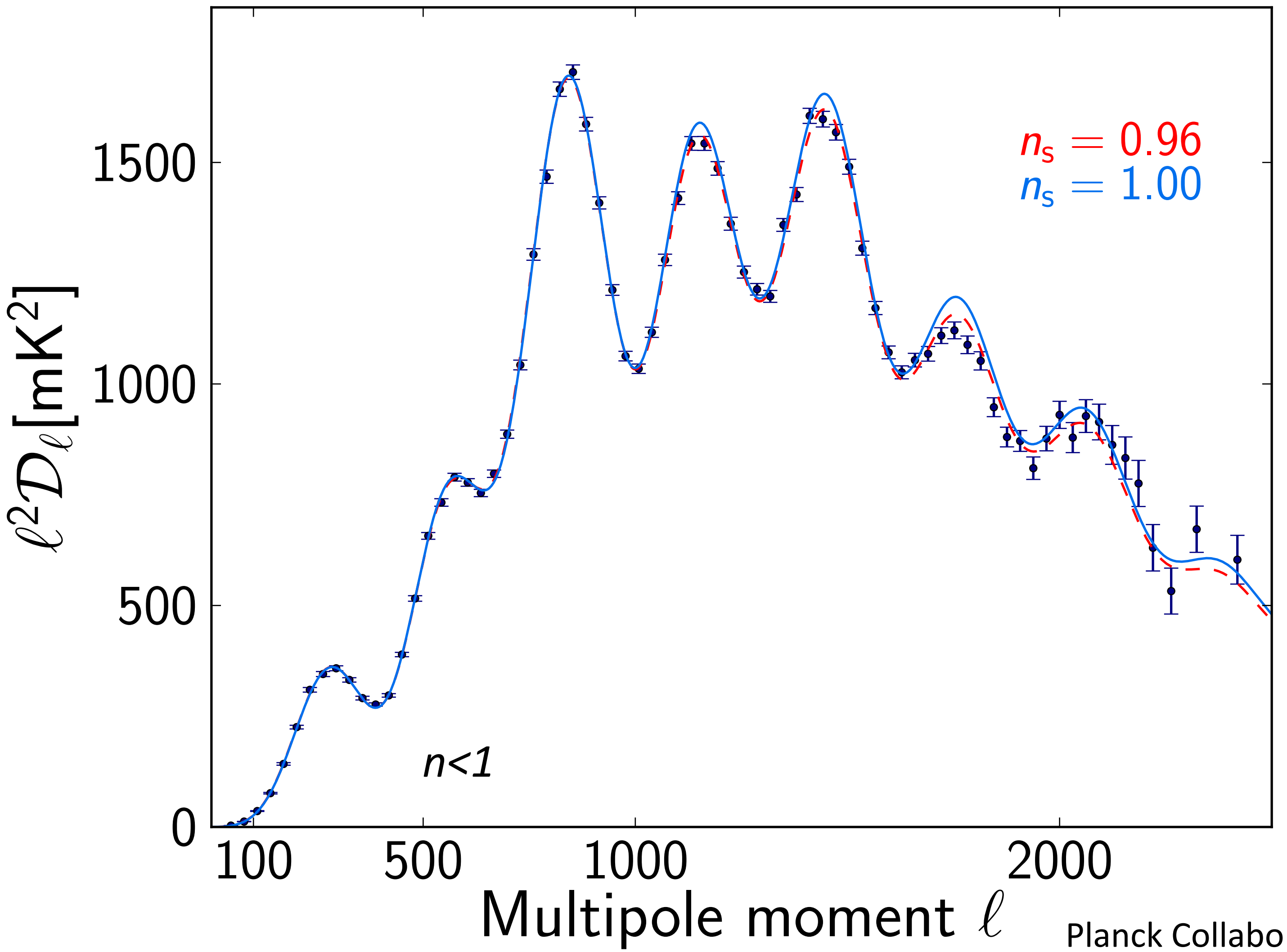
Forecasted errors:

2015	Planck + BOSS	100 meV
2017	ACTPol + BOSS	60
2019	AdvACT + BOSS	40
2021	AdvACT + DESI	20
2020s	CMB-S4 + DESI	16


Inflation
Primordial
fluctuations
Cosmic microwave
background

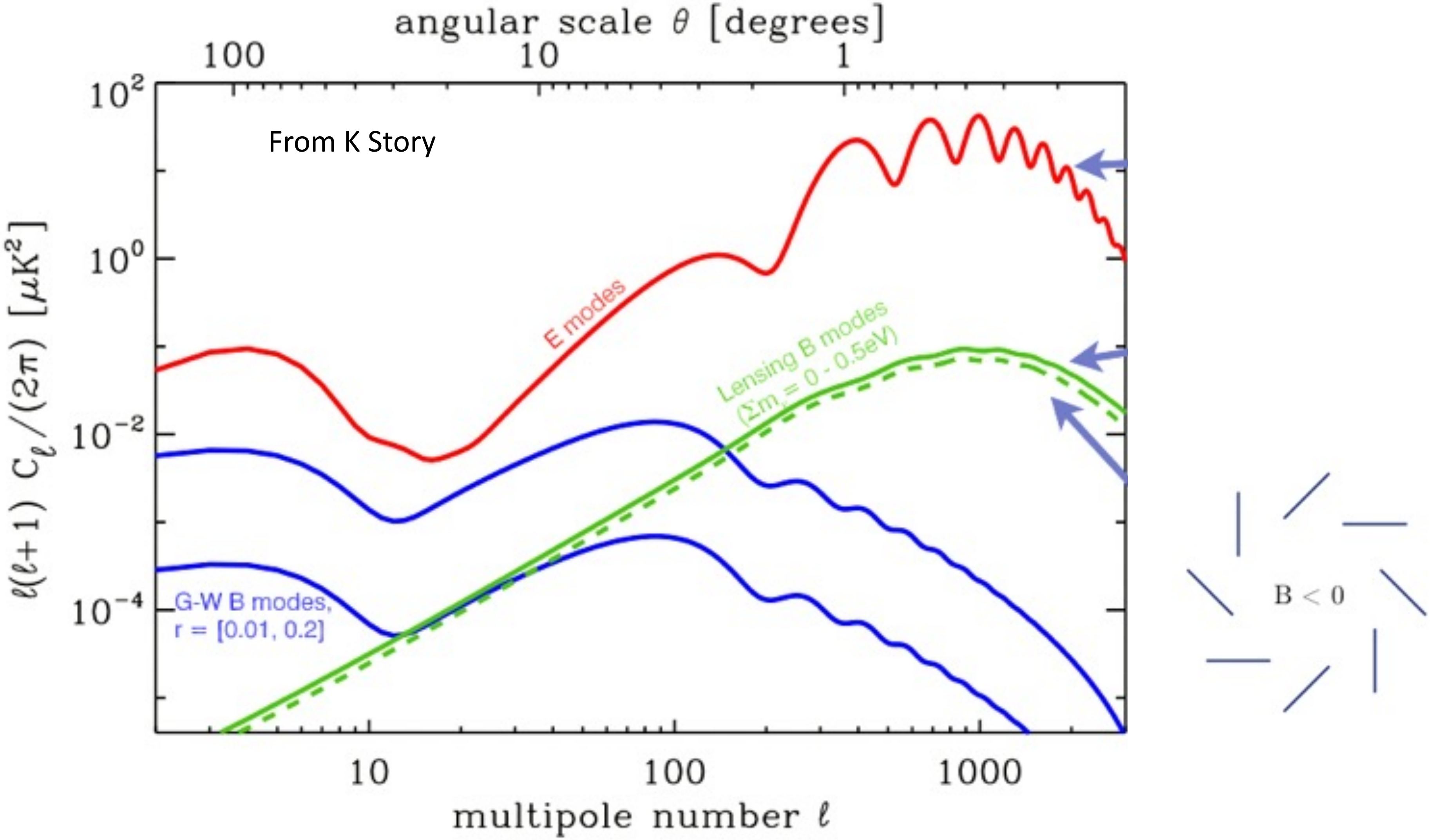
Inflation status from Planck

Universe is flat to 0.5%, fluctuations are super-horizon, Gaussian and adiabatic



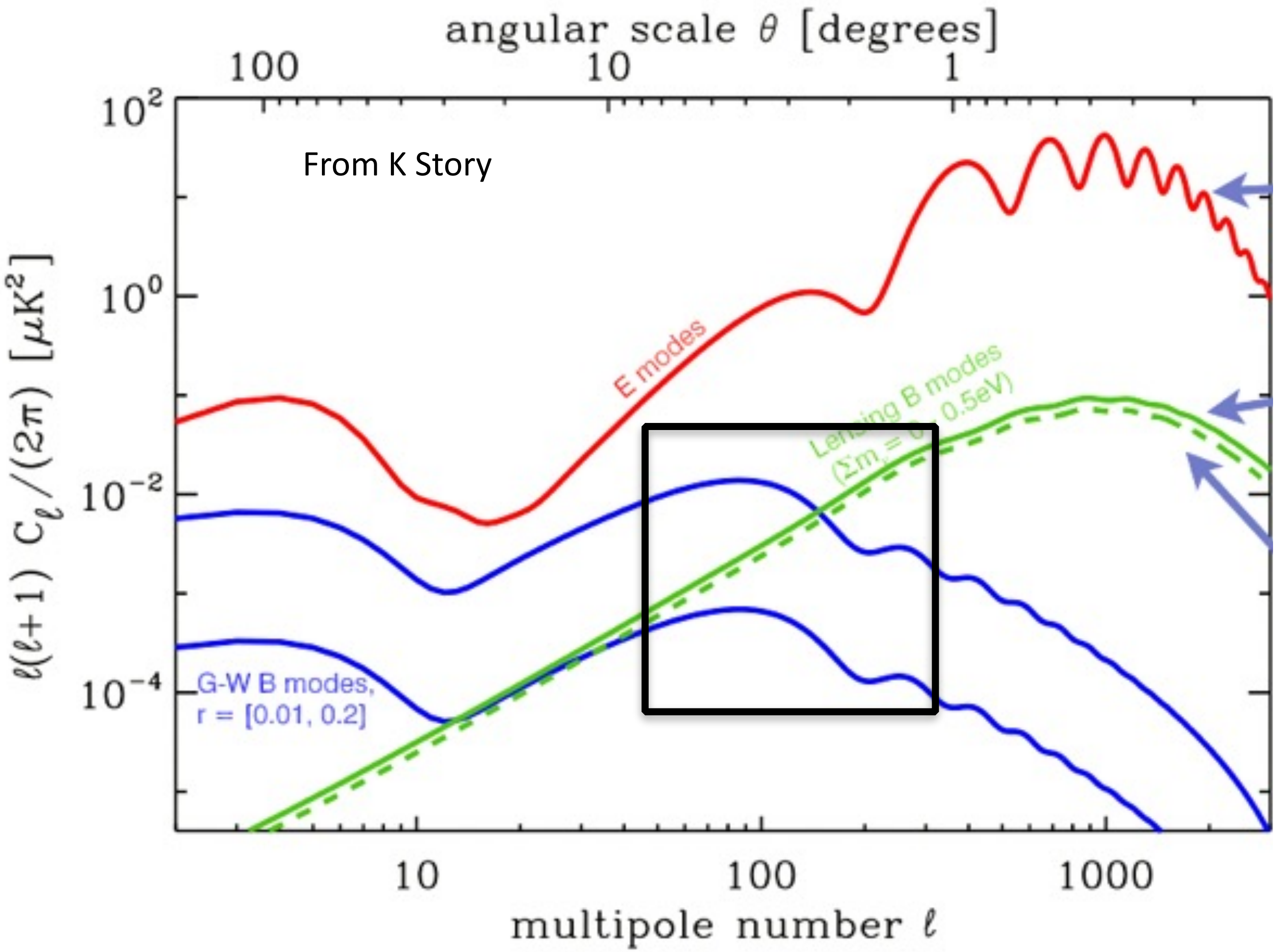
Planck Collaboration 2014, 2015

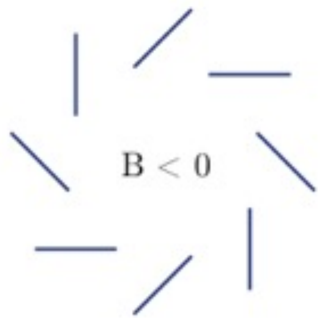
Gravitational waves



$$\ddot{h}_k + 2\frac{\dot{a}}{a}\dot{h}_k - k^2 h_k = 0$$

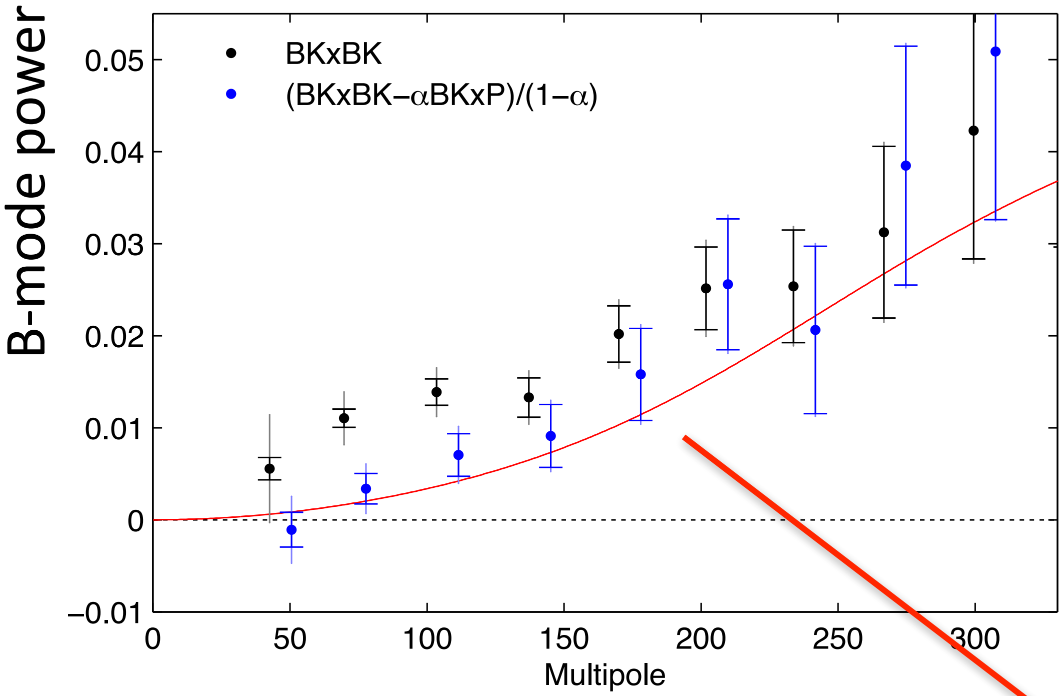
Gravitational waves



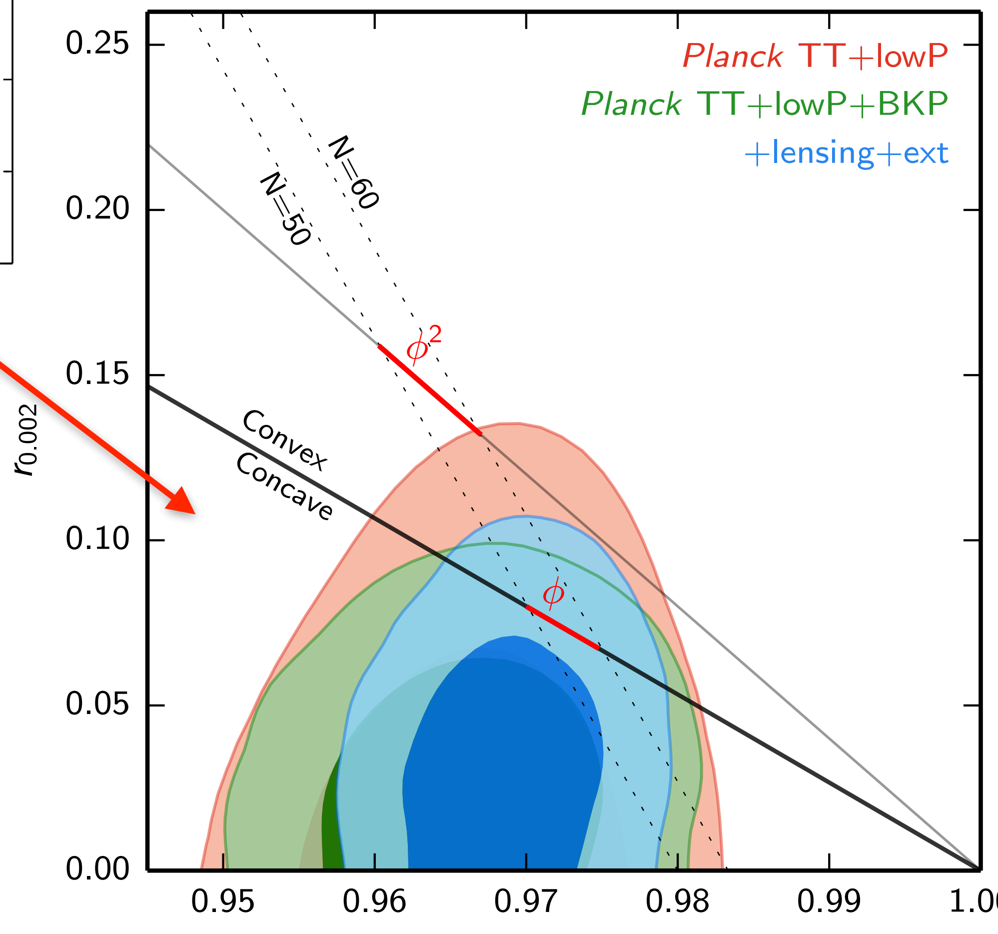


$$\ddot{h}_k + 2\frac{\dot{a}}{a}\dot{h}_k - k^2 h_k = 0$$

New limits on tensor modes

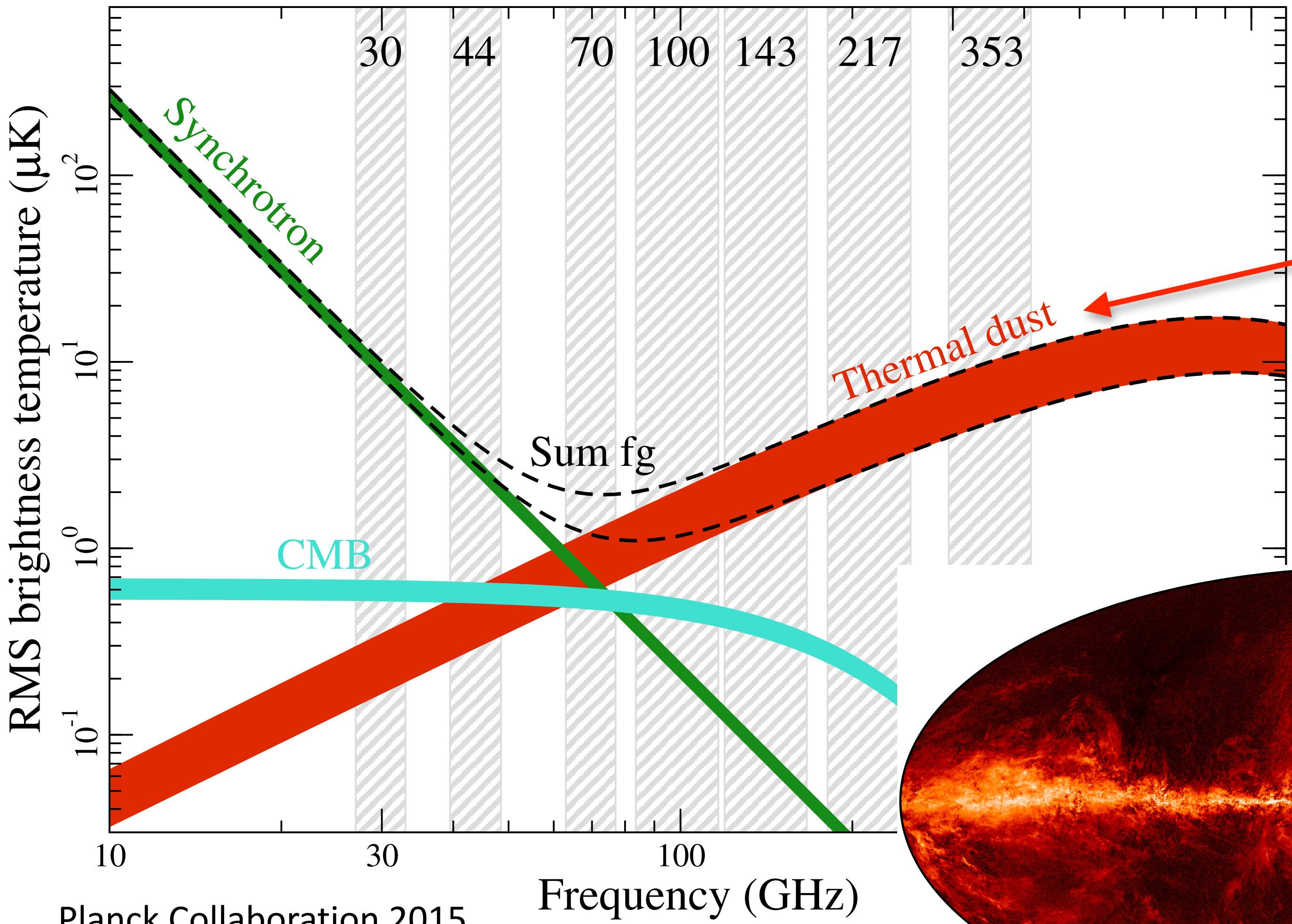


Planck/BICEP2 Collaborations 2015



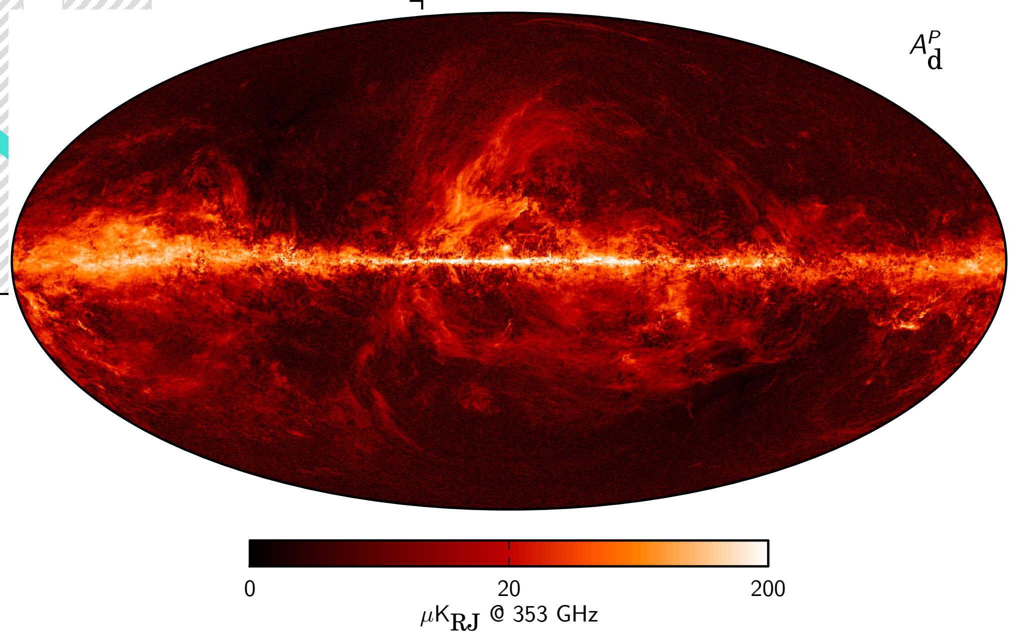
Planck Collaboration 2015

Planck gave us new view of the Galaxy



Until Planck, dust level uncertain to ***order of magnitude***

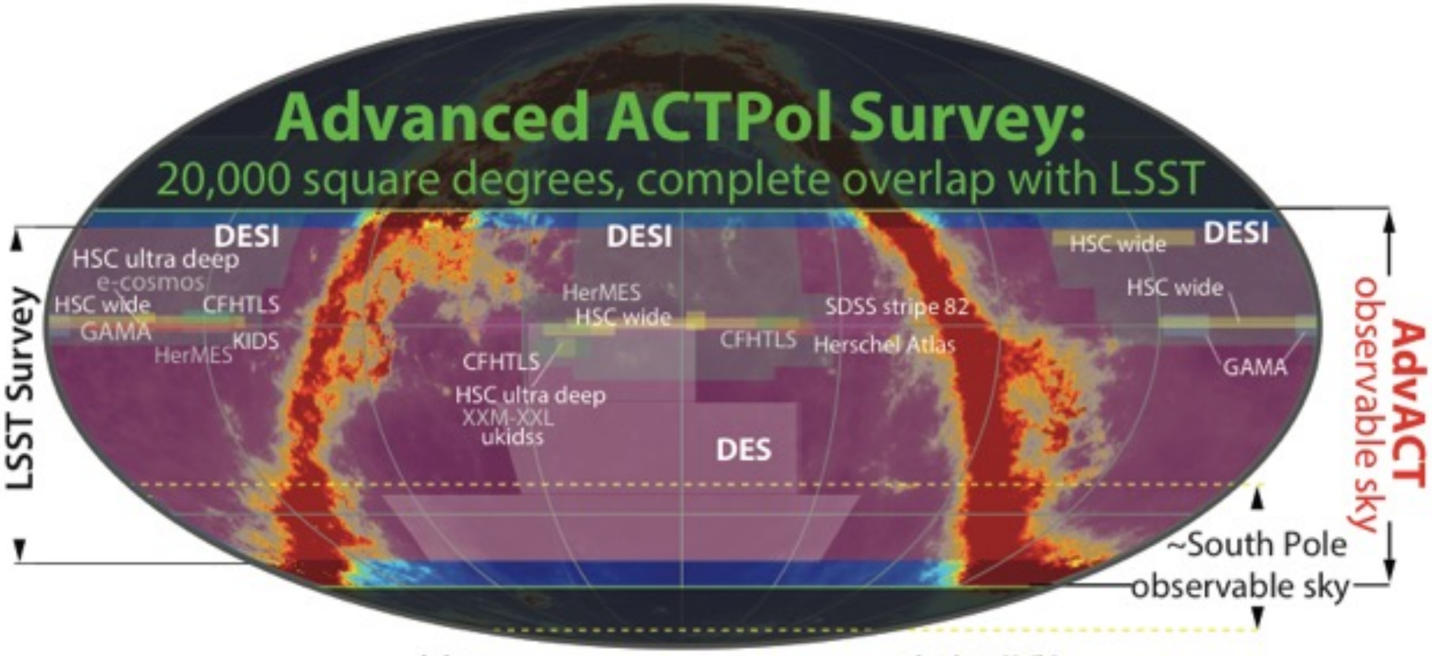
Planck Collaboration 2015
(level over 70-90% of sky)

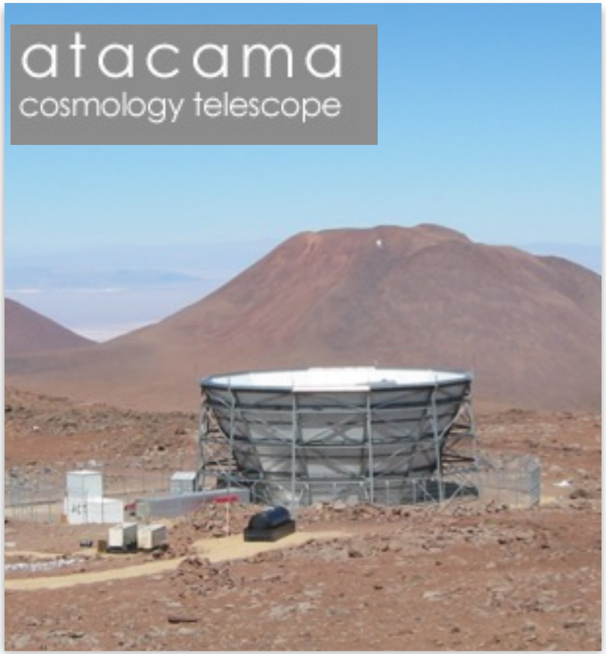


Path ahead

Now: ’Stage-3’ CMB: Spider, PolarBear, BICEP3, Keck, CLASS, SPT-3G, GroundBird

My project (led in Princeton): AdvACT
Targeting r=0.01 with ***five*** wavelengths 2016-18.





Next: CMB-S4 campaign from ~2020-25

Cosmic microwave background data continue to demand LCDM cosmological model. It holds up very well 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 still firmly on.*

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