

Cosmology from the microwave background

Jo Dunkley
University of Oxford

History of early universe

Inflation?

CDM decoupling?

Neutrino decoupling

Big Bang Nucleosynthesis

Matter-Radiation Equality

Recombination

Later:

Neutrinos become 'cold'

$T \sim 10^{15} \text{ GeV}$

$t \sim 10^{-35} \text{ s}$

$T \sim 10 \text{ GeV?}$

$t \sim 10^{-8} \text{ s}$

$T \sim 1 \text{ MeV}$

$t \sim 1 \text{ s}$

$T \sim 100 \text{ keV}$

$t \sim 10 \text{ min}$

$T \sim 0.8 \text{ eV}$

$t \sim 60,000 \text{ yr}$

$T \sim 0.3 \text{ eV}$

$t \sim 380,000 \text{ yr}$

$< t \sim 100,000,000 \text{ yr}$





$T = 2.728 \text{ K}$



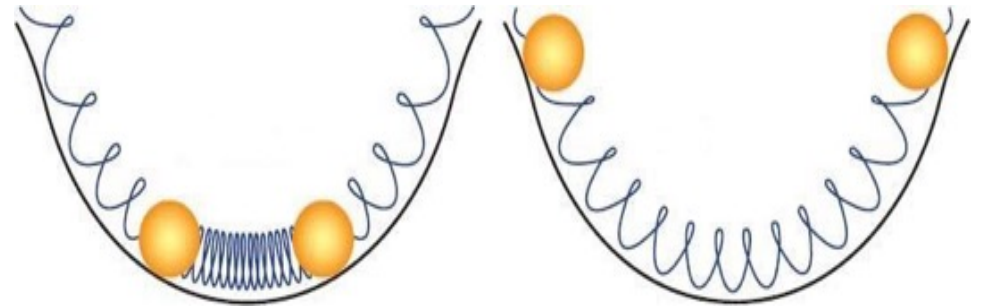
$z = 1000, 380\,000 \text{ yrs}$



t

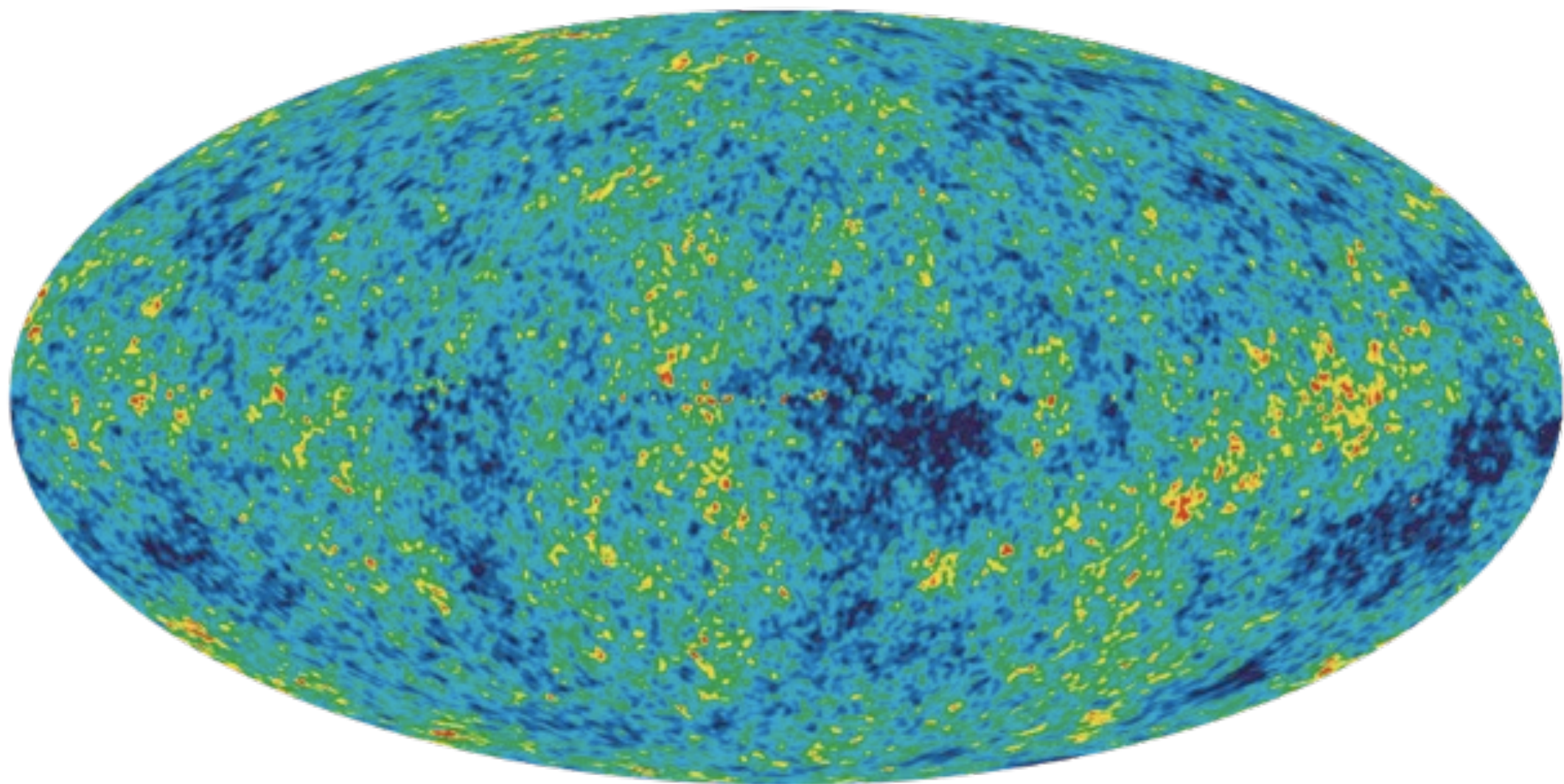
Seeds of structure

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.





planck



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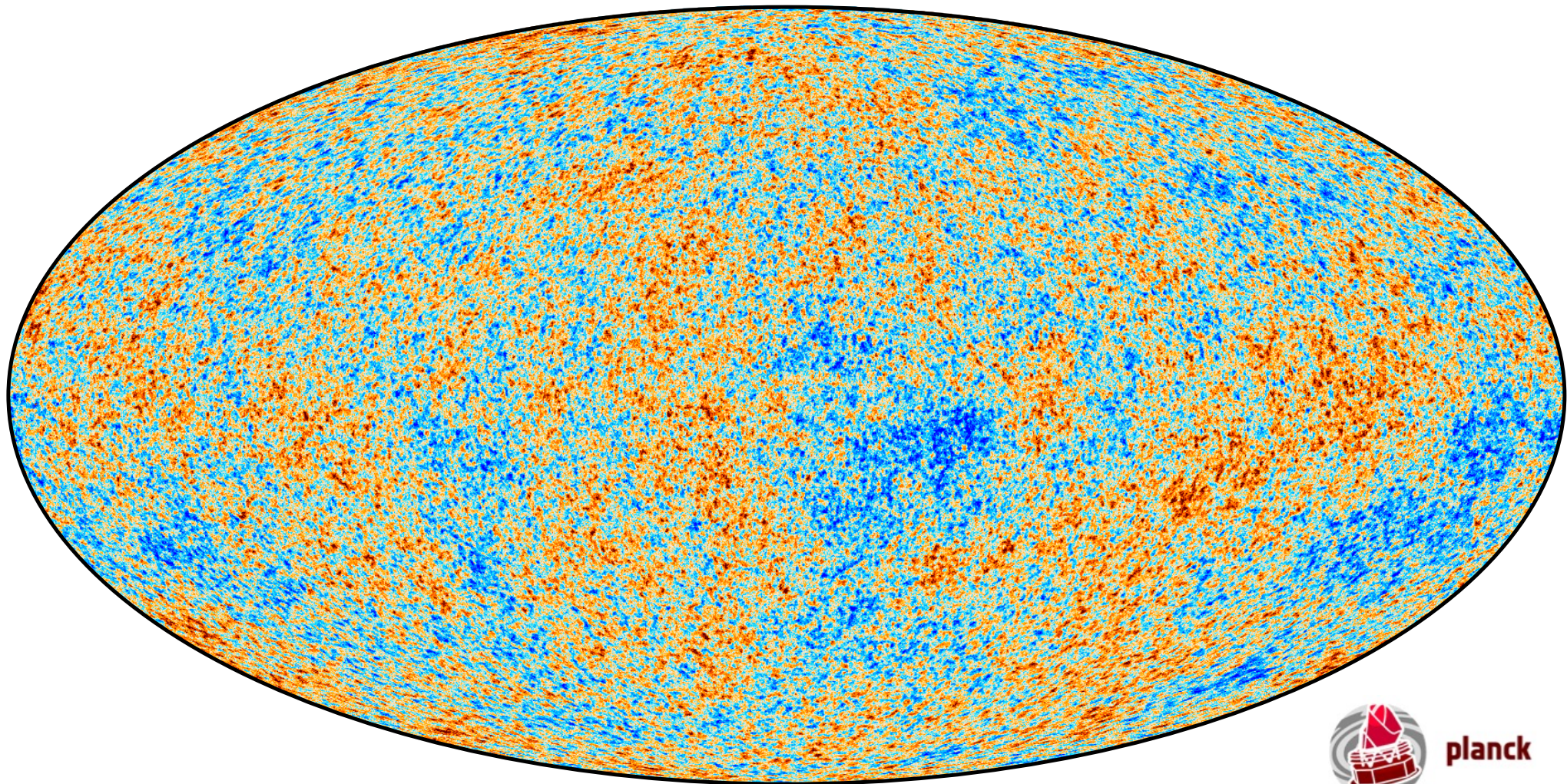


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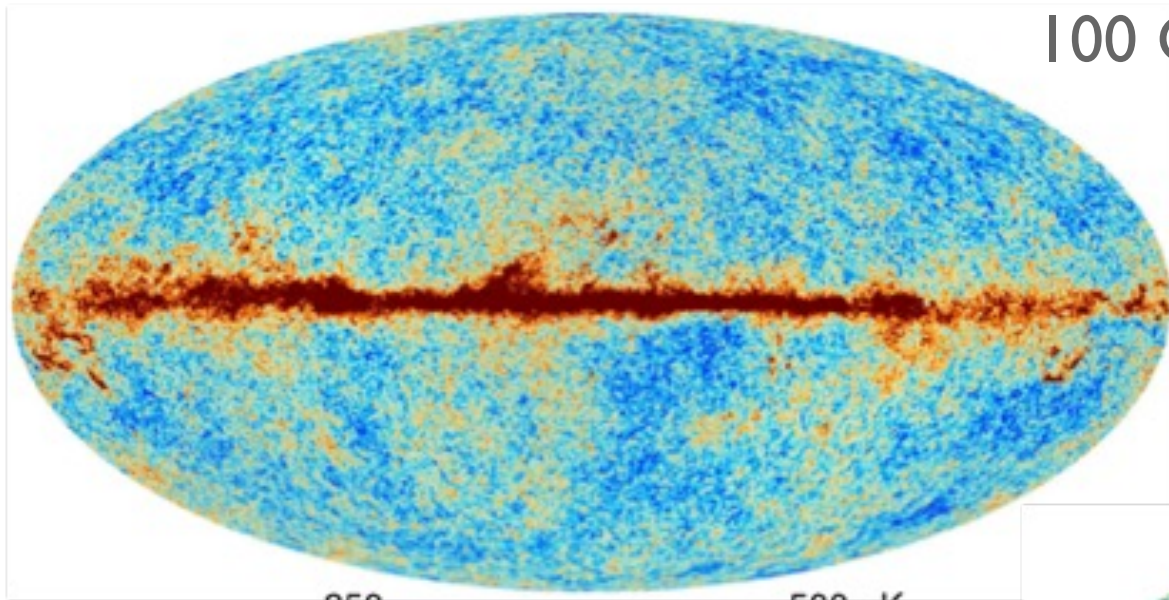
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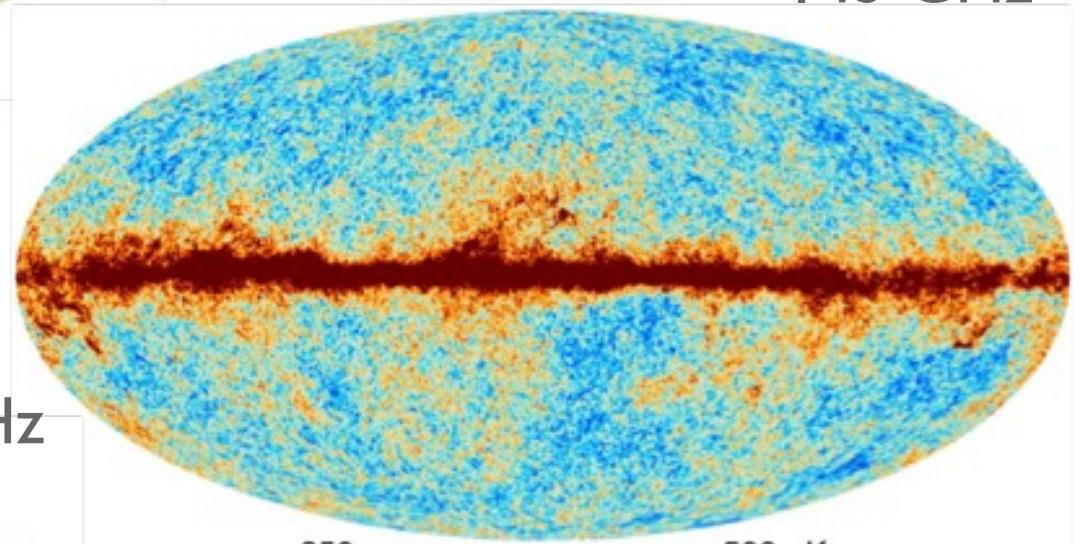


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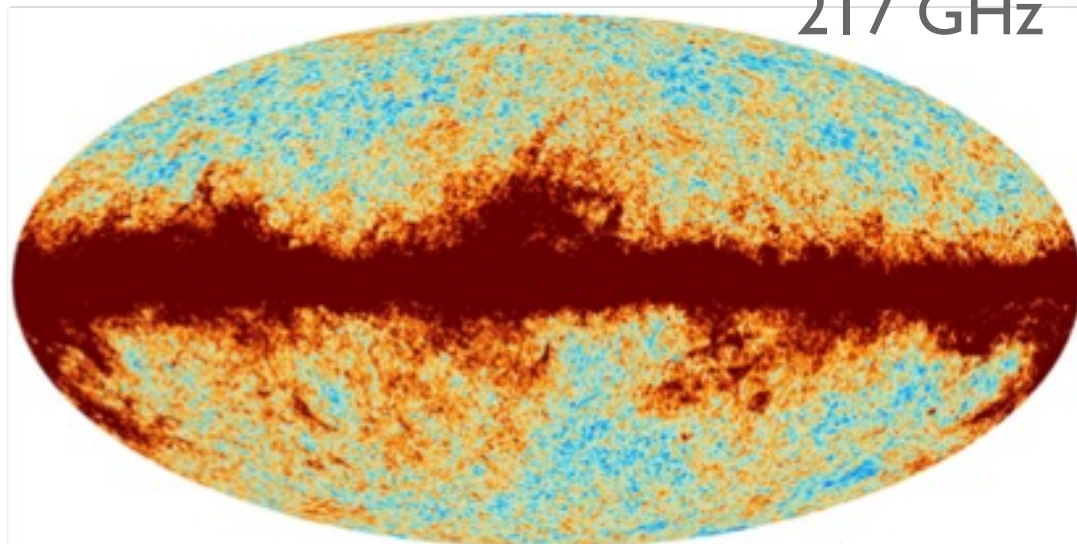
Planck Collaboration 2015



-250 500 μK_{CMB}



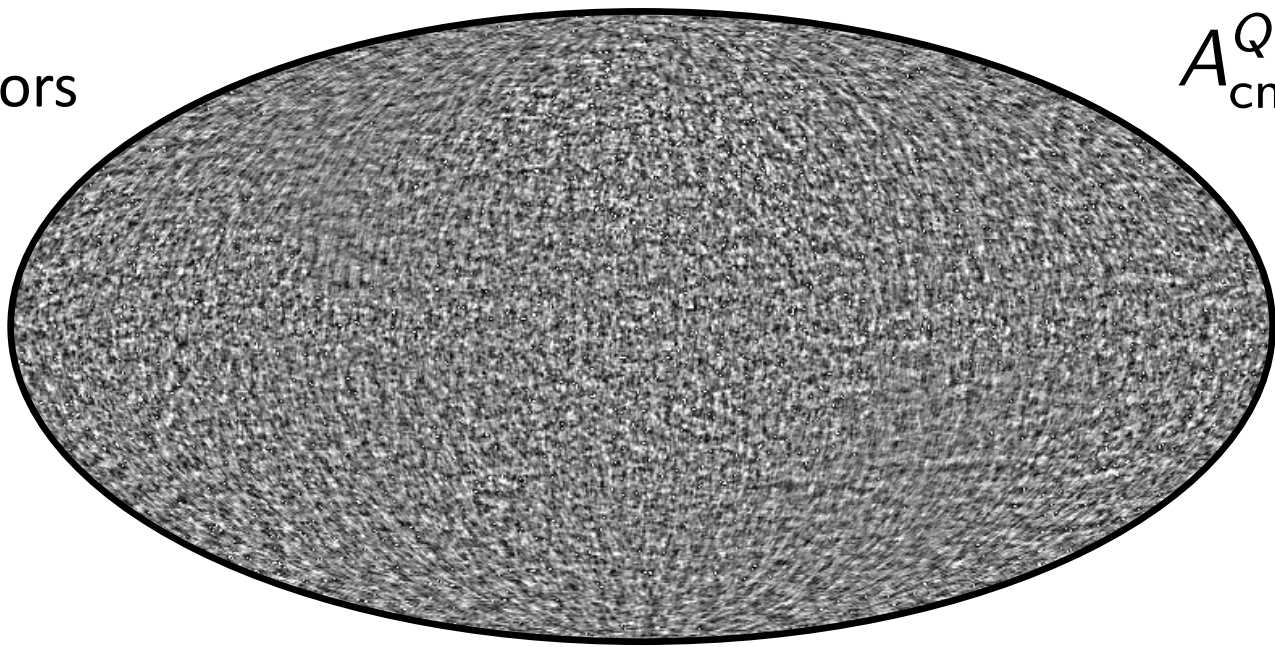
-250 500 μK_{CMB}



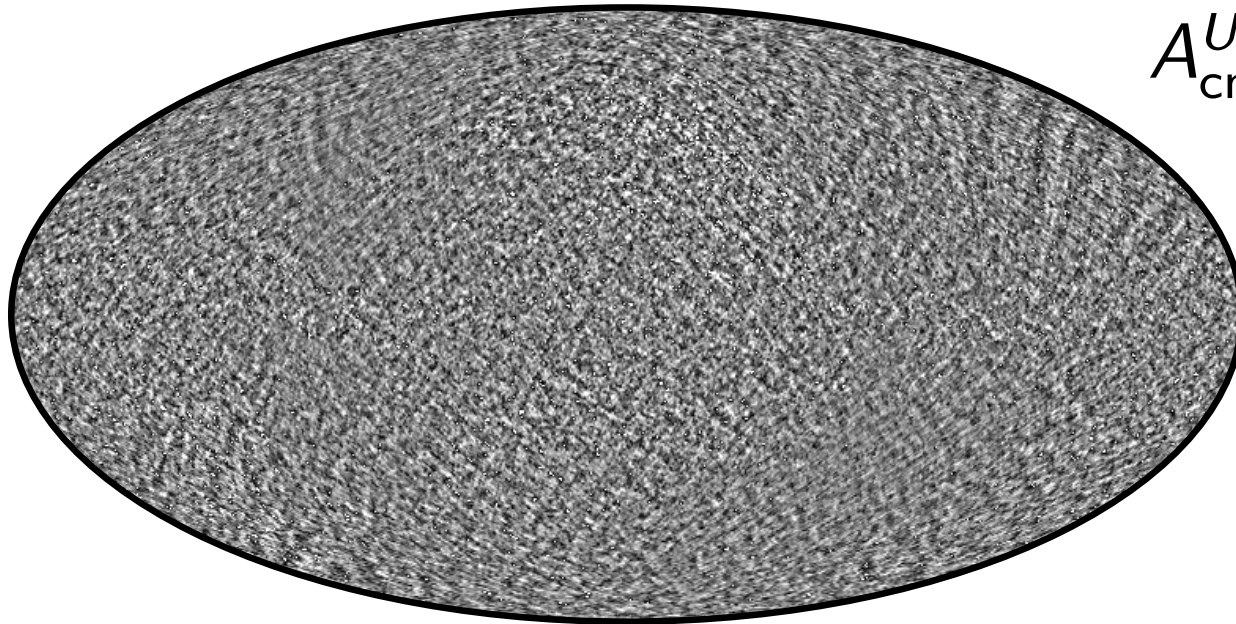
-250 500 μK_{CMB}

Plus 6 other wavelengths

Stokes vectors



A_{cmb}^Q



A_{cmb}^U



-3

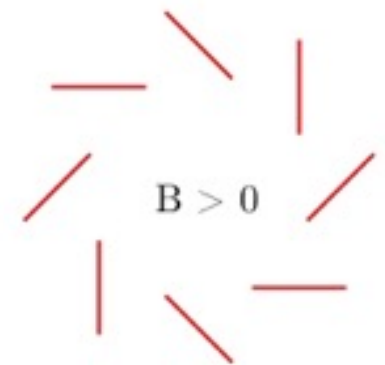
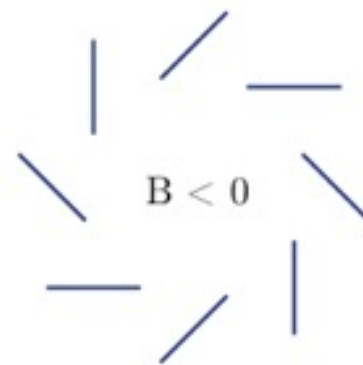
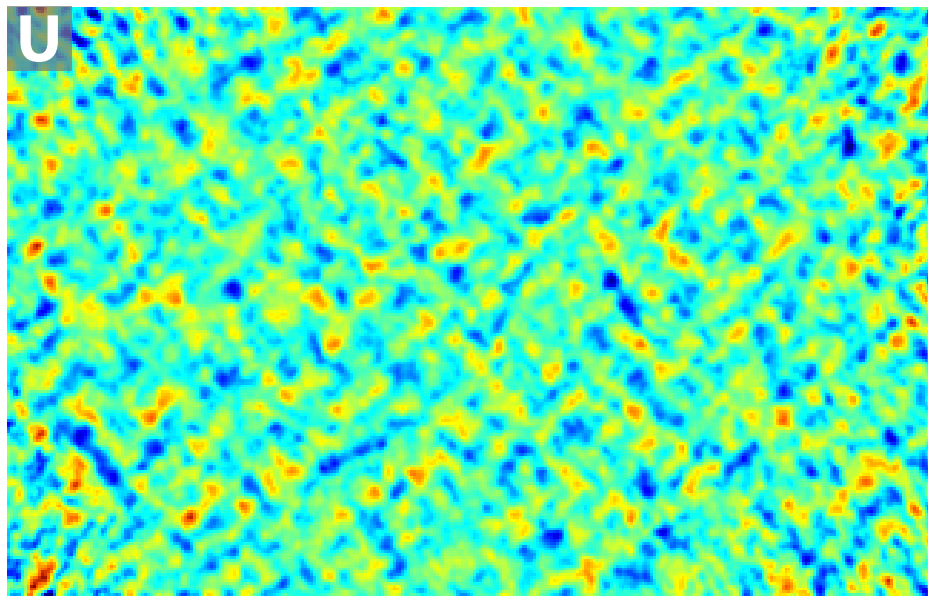
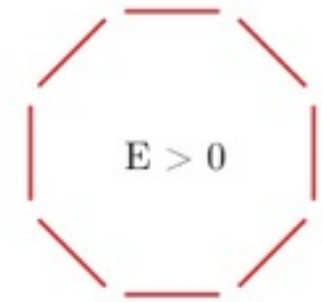
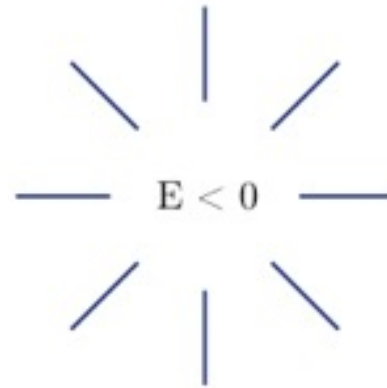
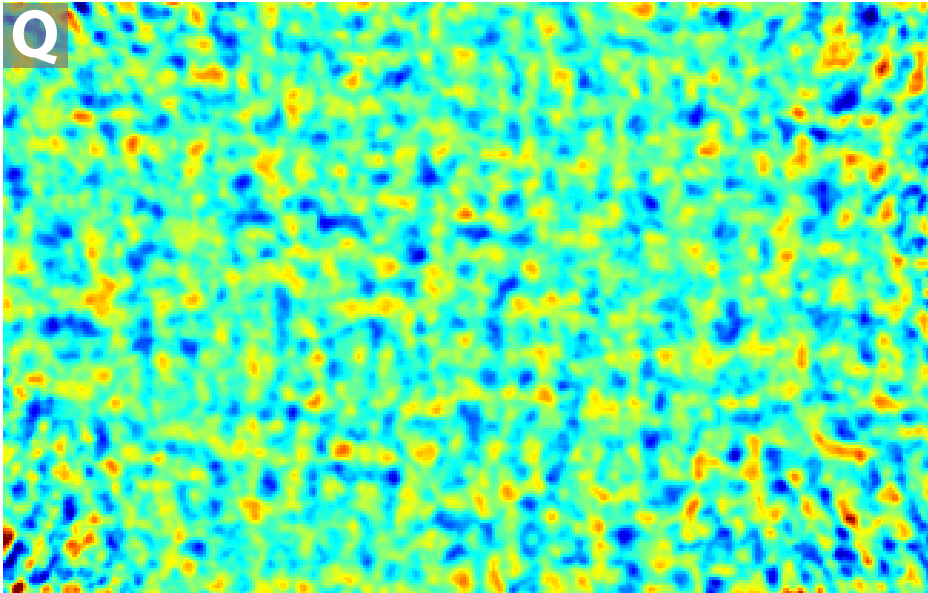
0

3

μK

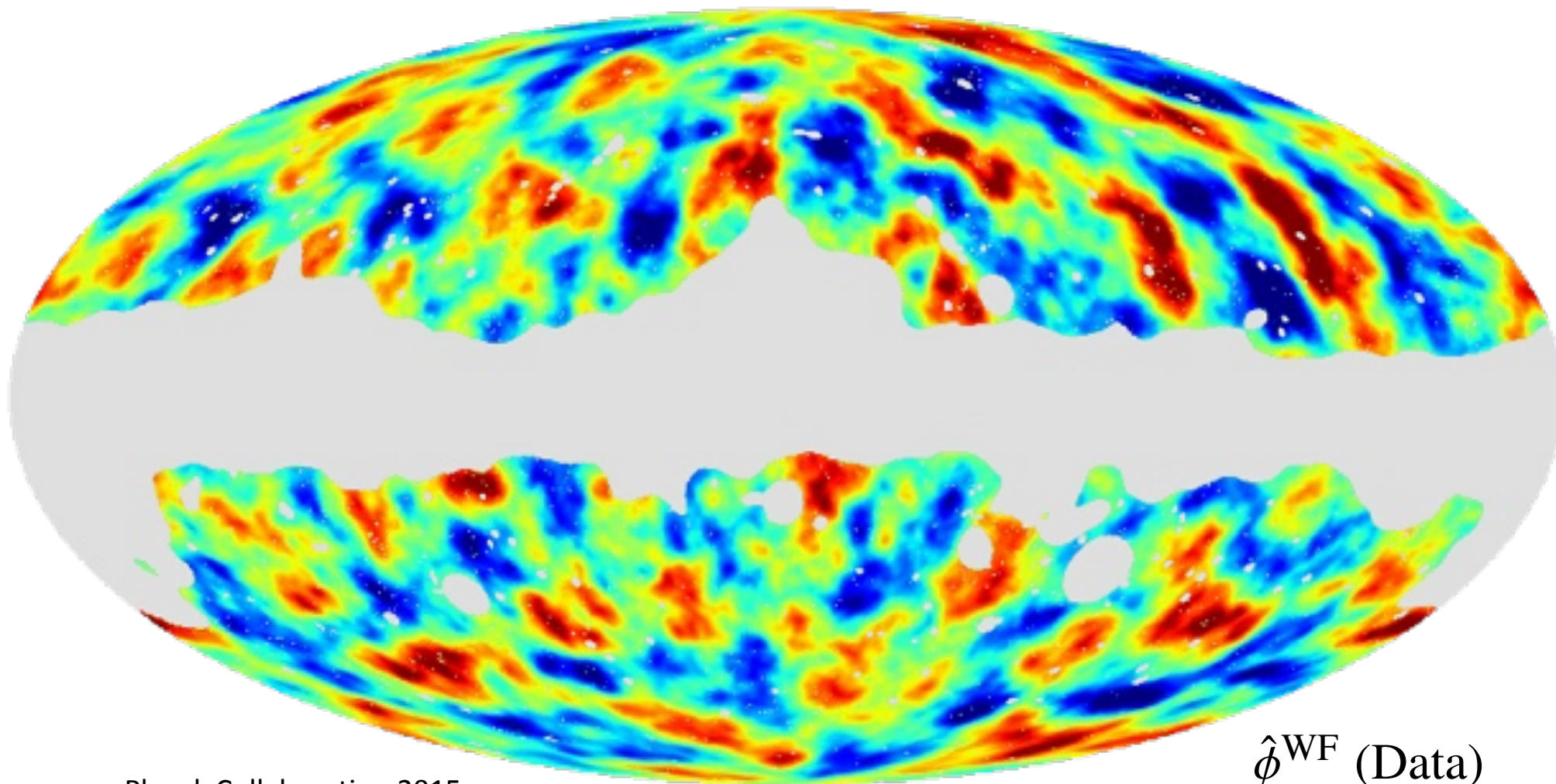
l<50 scales removed

Planck Collaboration 2015



ACTPol maps, scale 15 μ K, 10 degrees, Naess et al 2014

Lensing potential, ϕ



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?

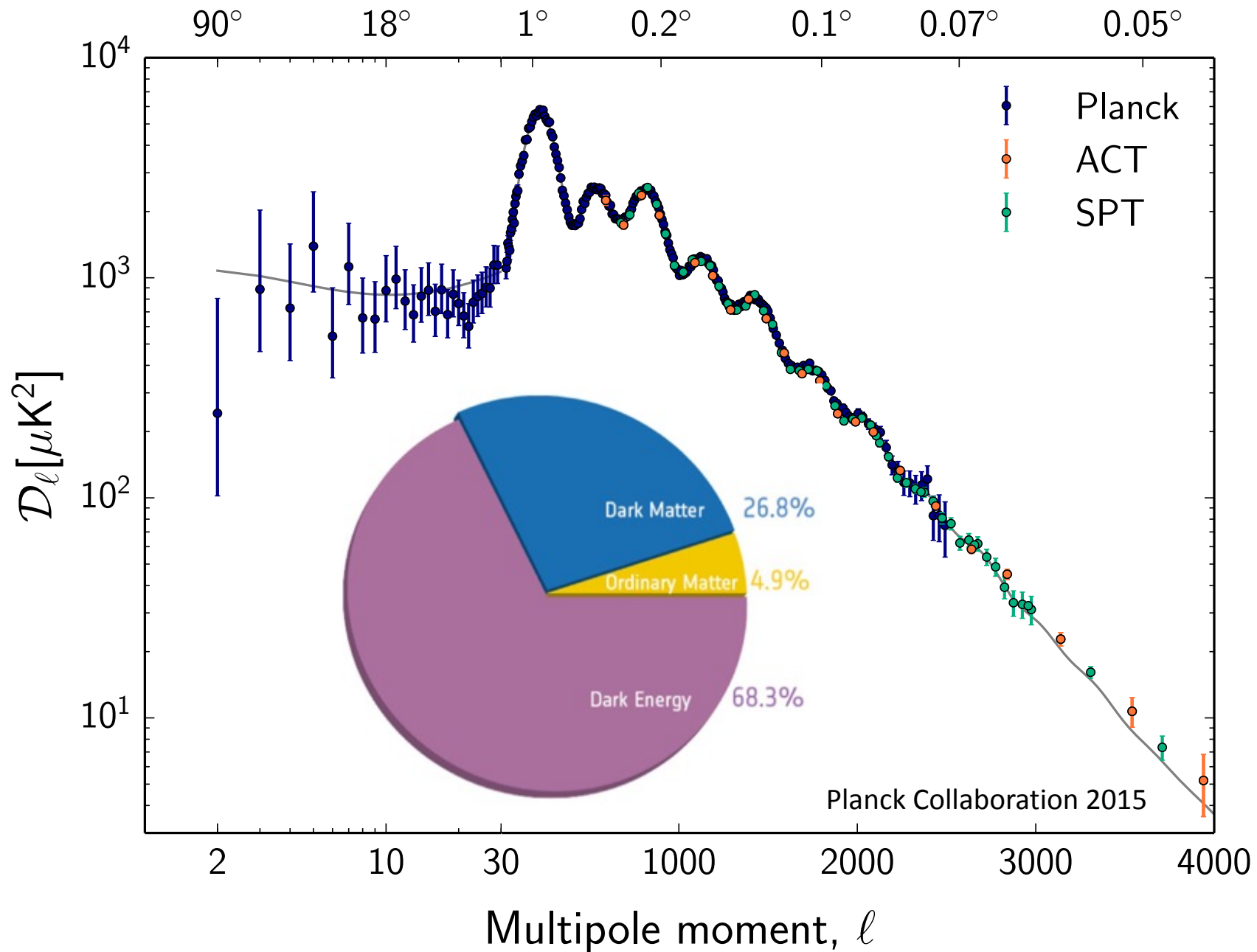
Rough description of CMB analysis process:

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

Statistic = angular power spectrum of maps

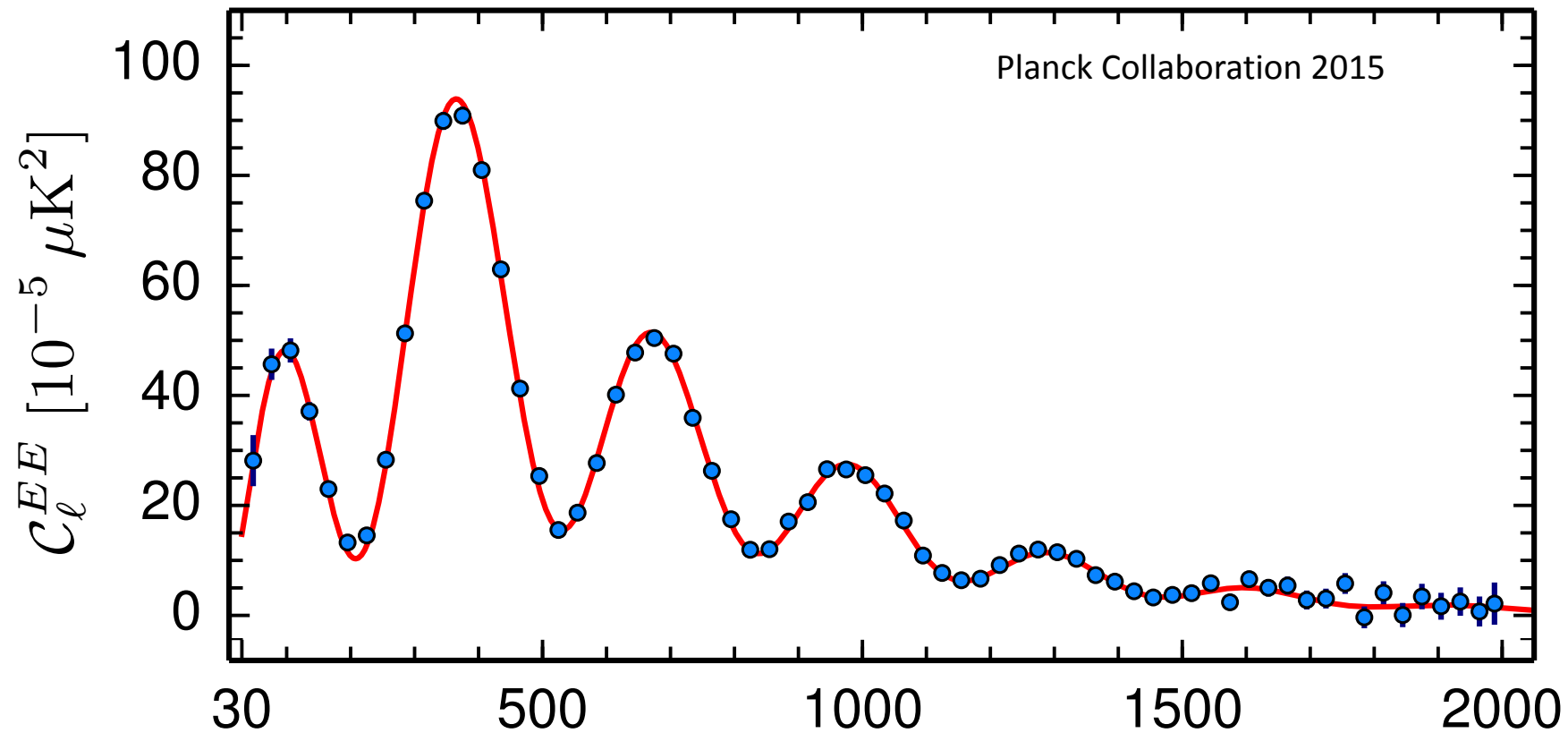
Output = cosmological parameters (reliable codes
predict their theory power spectra)

CMB temperature



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

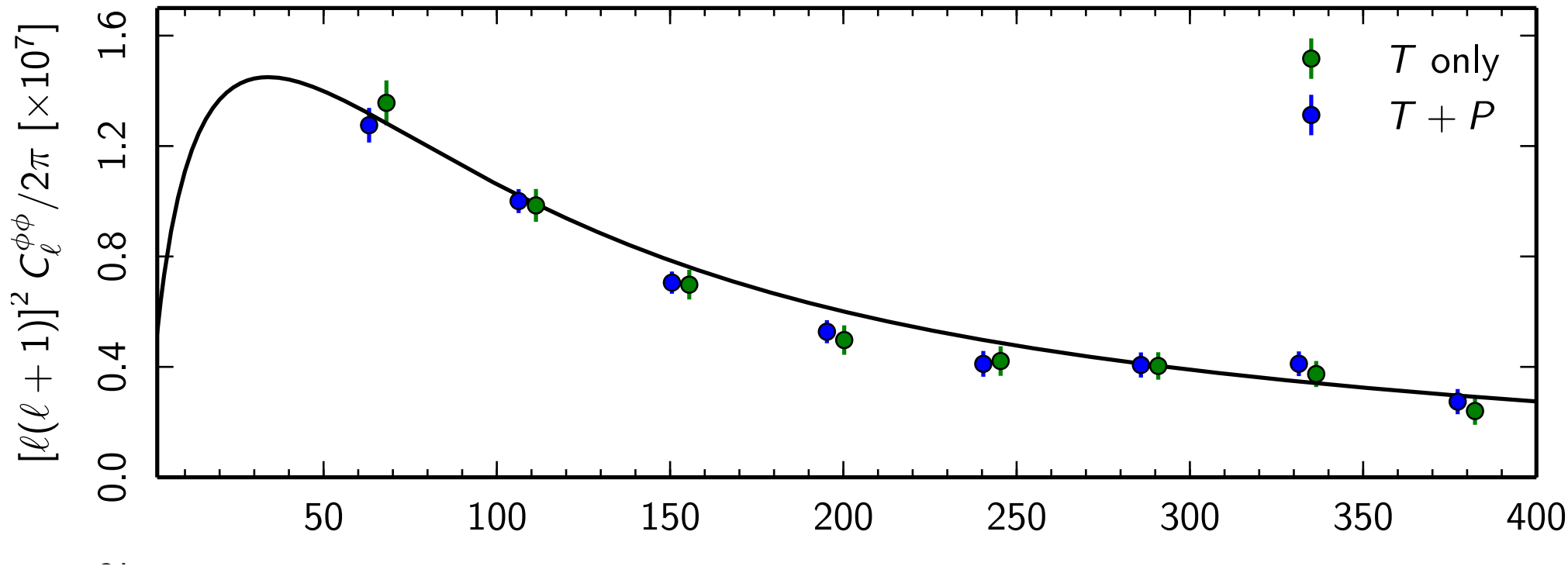
CMB polarization (E-mode)



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*

CMB lensing

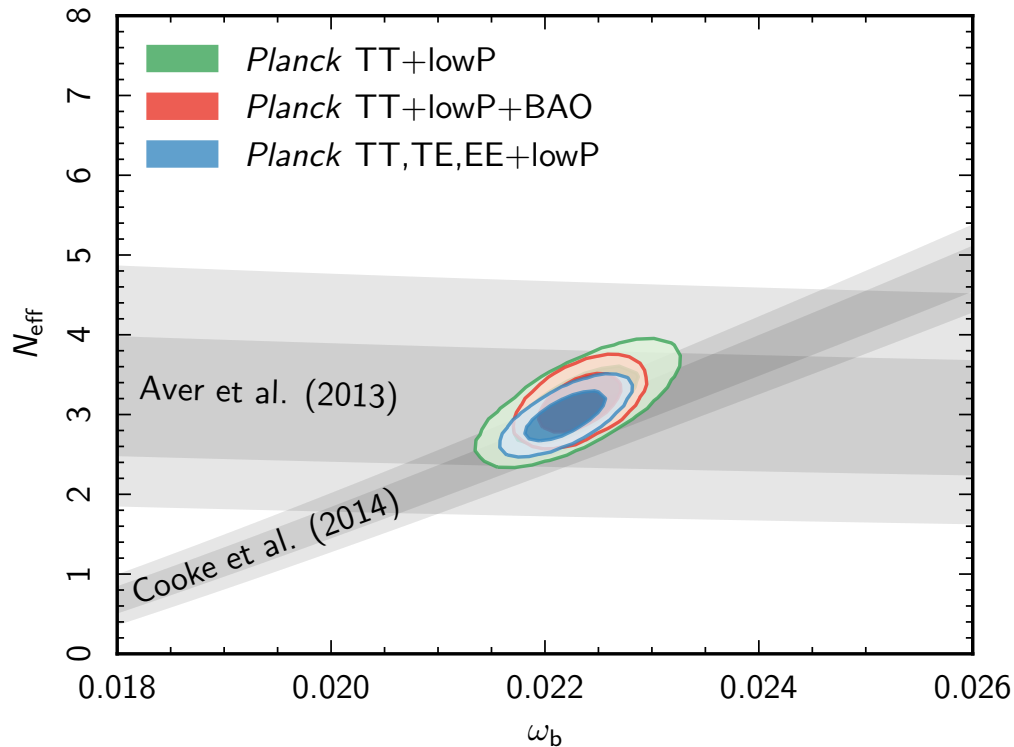


Planck Collaboration 2015

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

Neutrino properties from cosmology

Planck Collaboration 2015



(1) Number of species:

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

(2) Neutrino mass

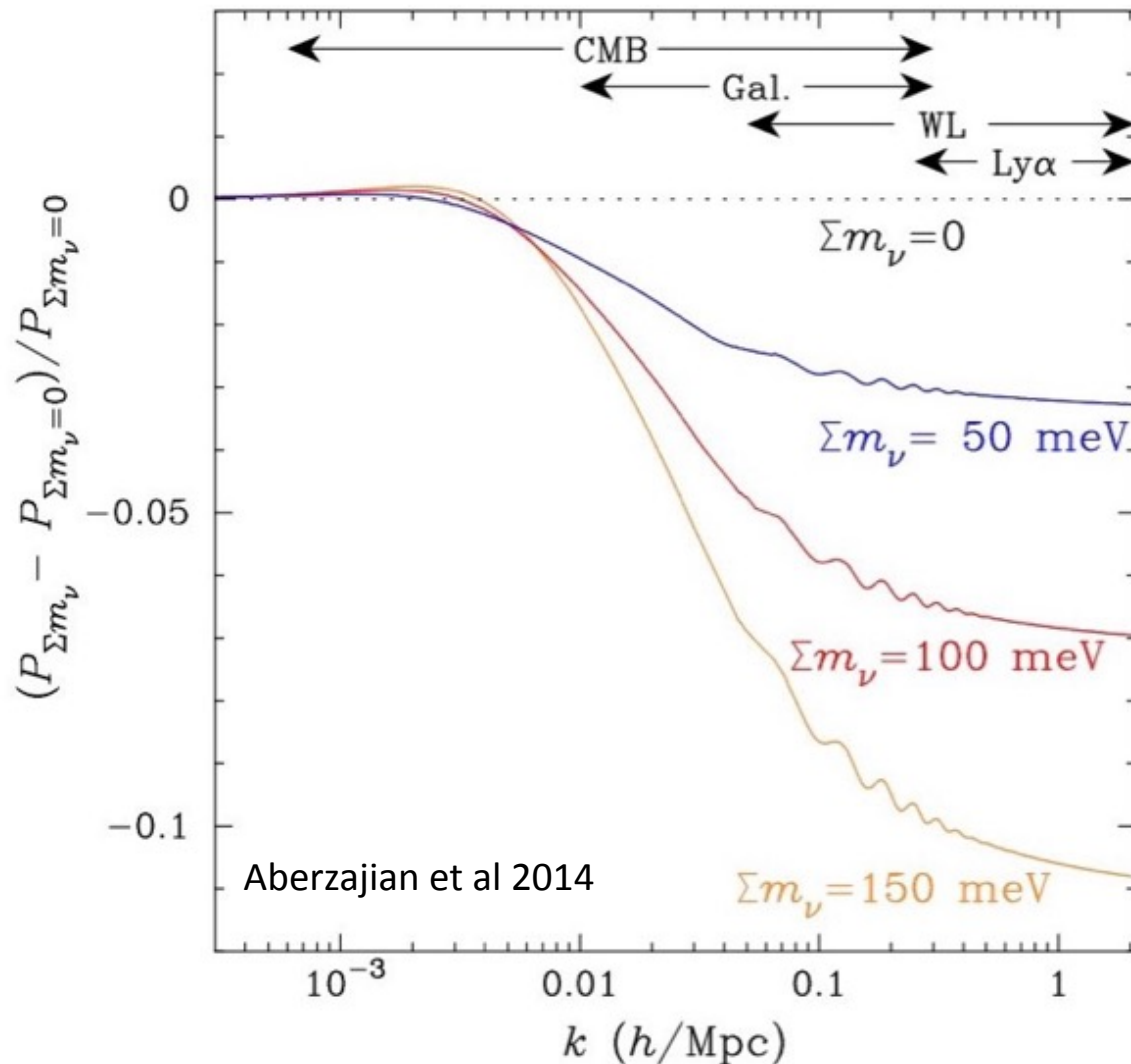
$$\sum m_\nu < 0.68 \text{ eV} \quad \text{Planck}$$

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

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?

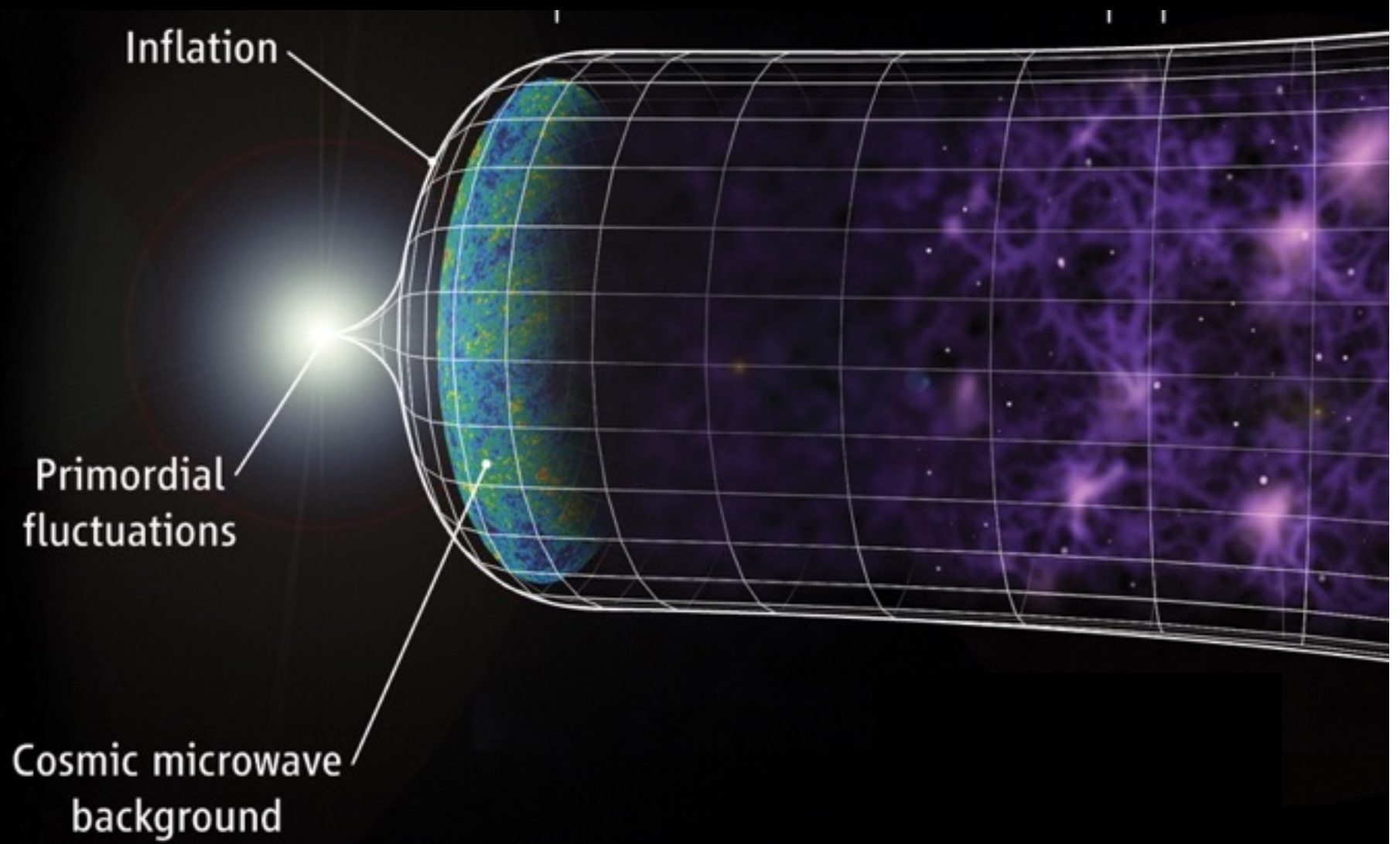


From oscillation expt, minimum mass sum = 60 meV.

Forecasted errors:

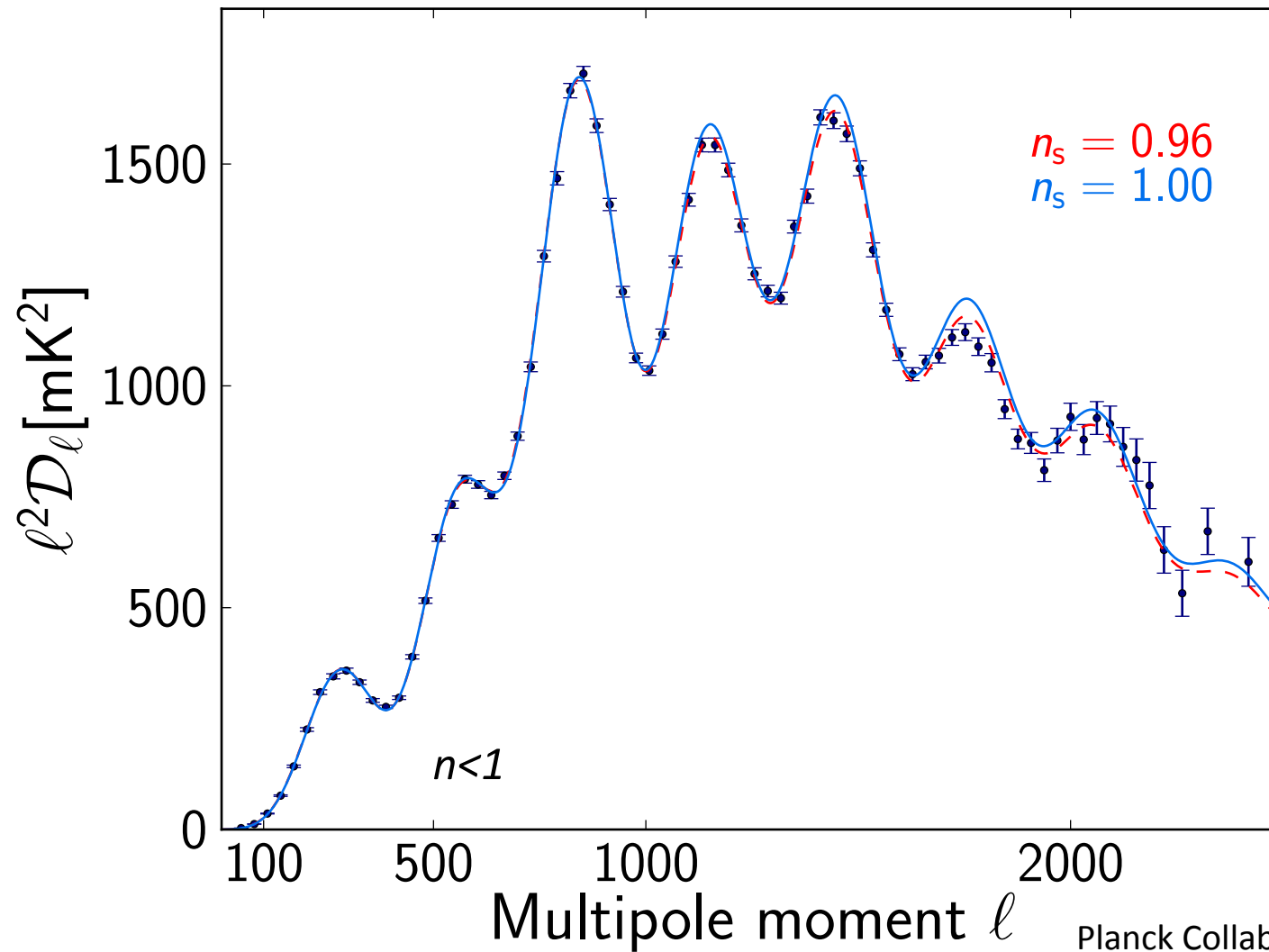
2015	Planck + BOSS	100 meV
2017	ACTPol + BOSS	60
2019	AdvACT + BOSS	40
2021	AdvACT + DESI	20
2020s	CMB-S4 + DESI	16



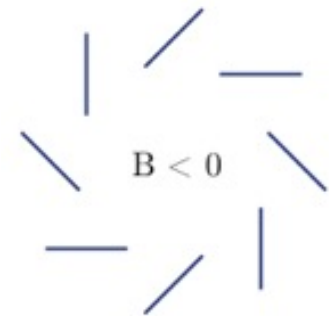
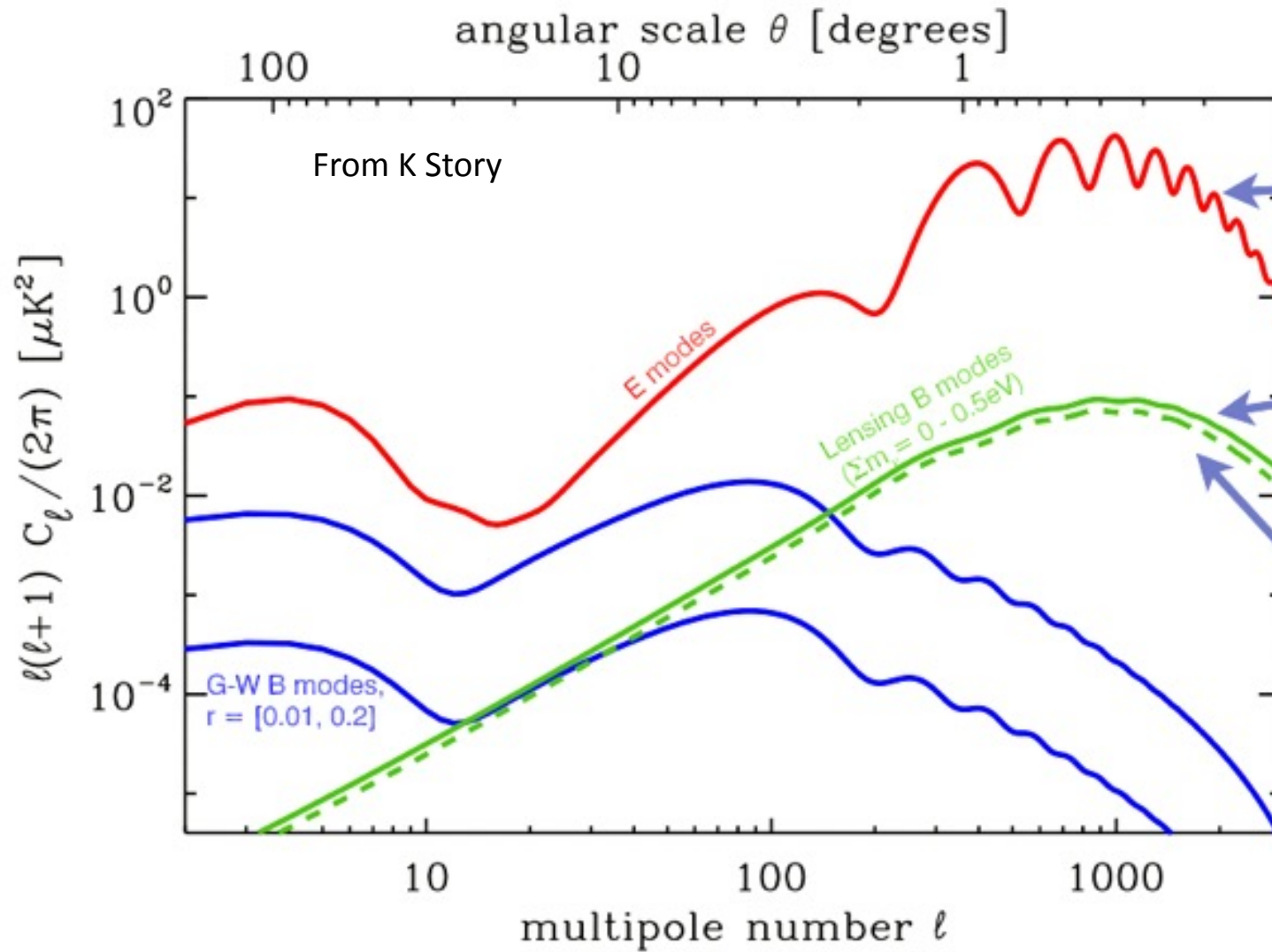


Inflation status from Planck

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

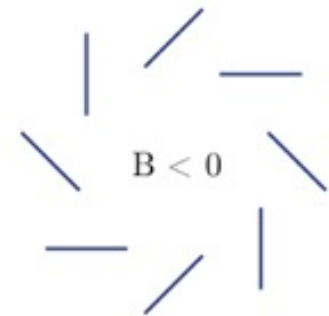
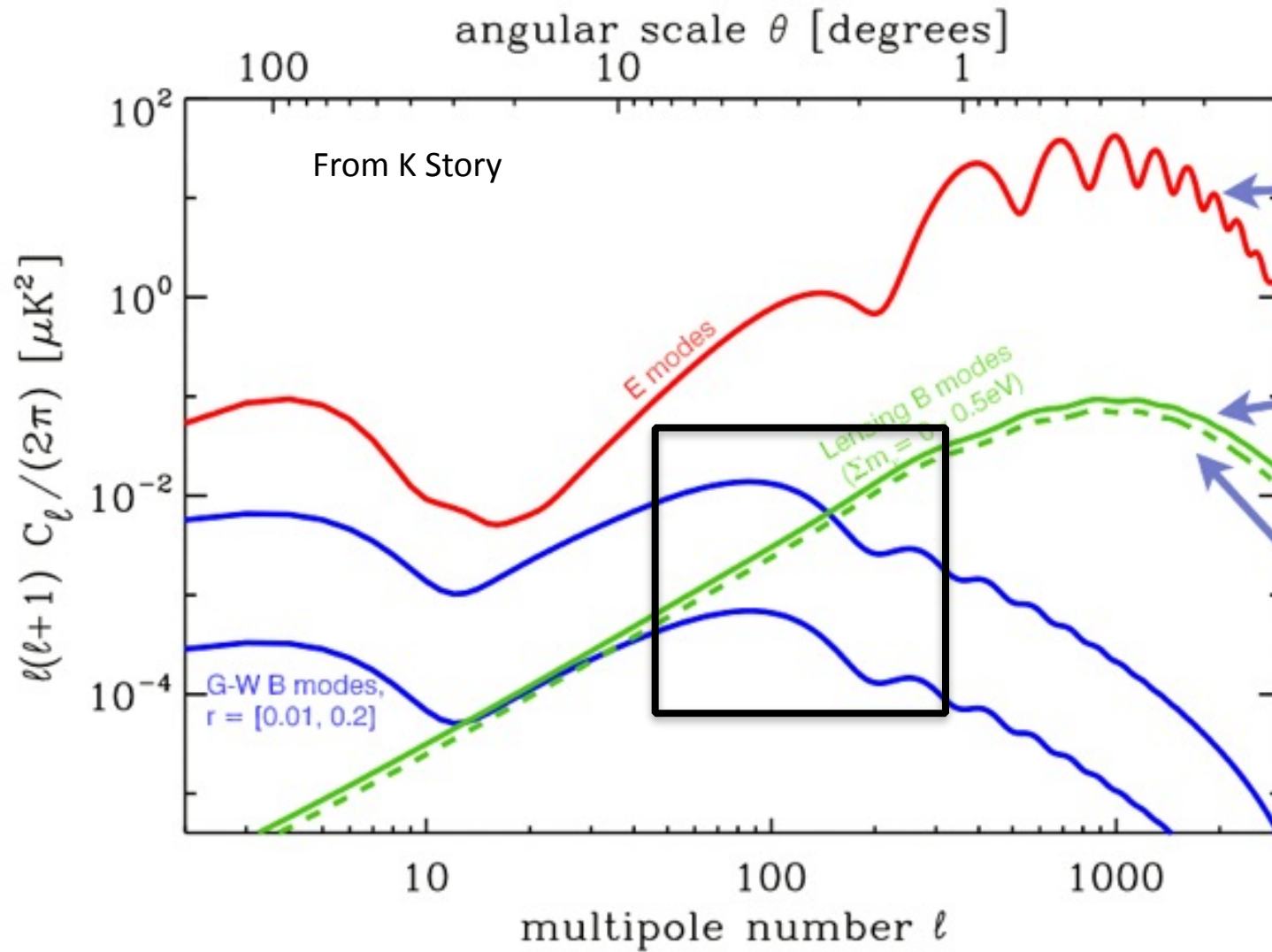


Gravitational waves



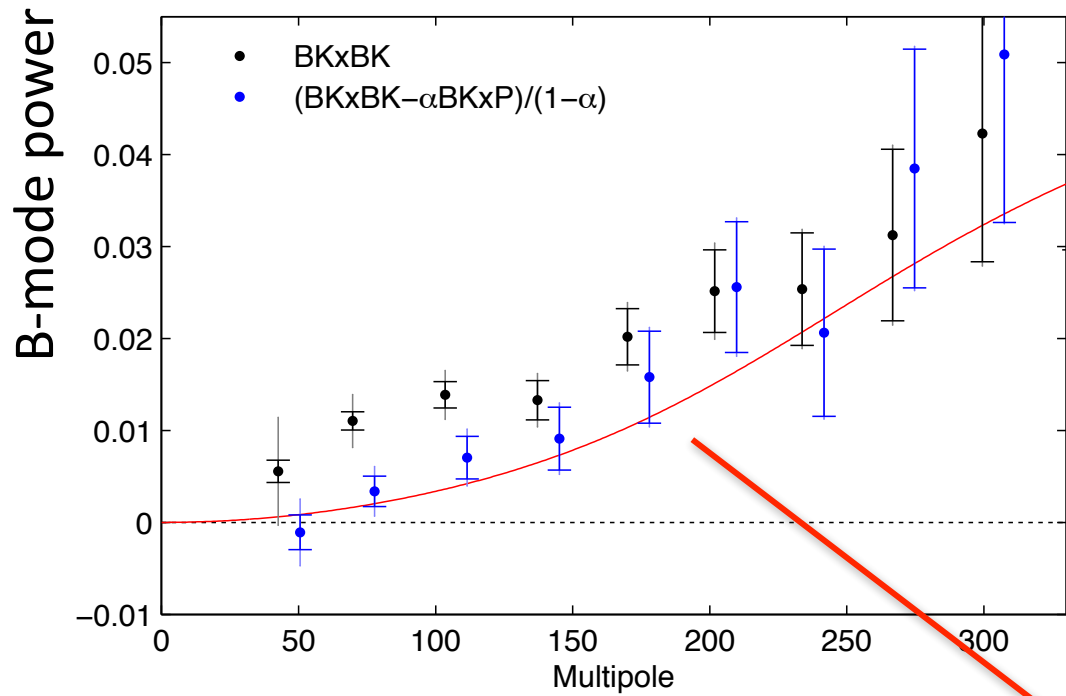
$$\ddot{h}_k + 2\frac{\dot{a}}{a}\dot{h}_k - k^2 h_k = 0$$

Gravitational waves

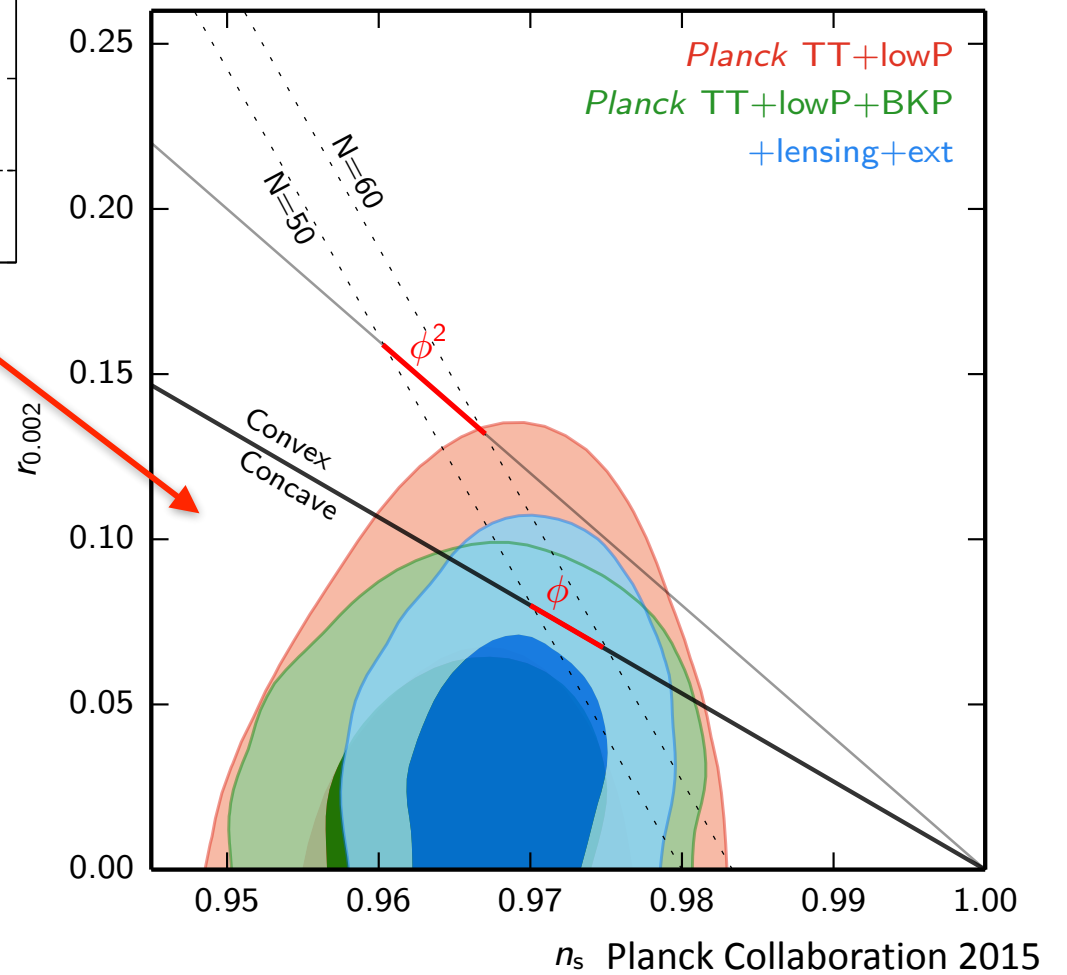


$$\ddot{h}_k + 2\frac{\dot{a}}{a}\dot{h}_k - k^2 h_k = 0$$

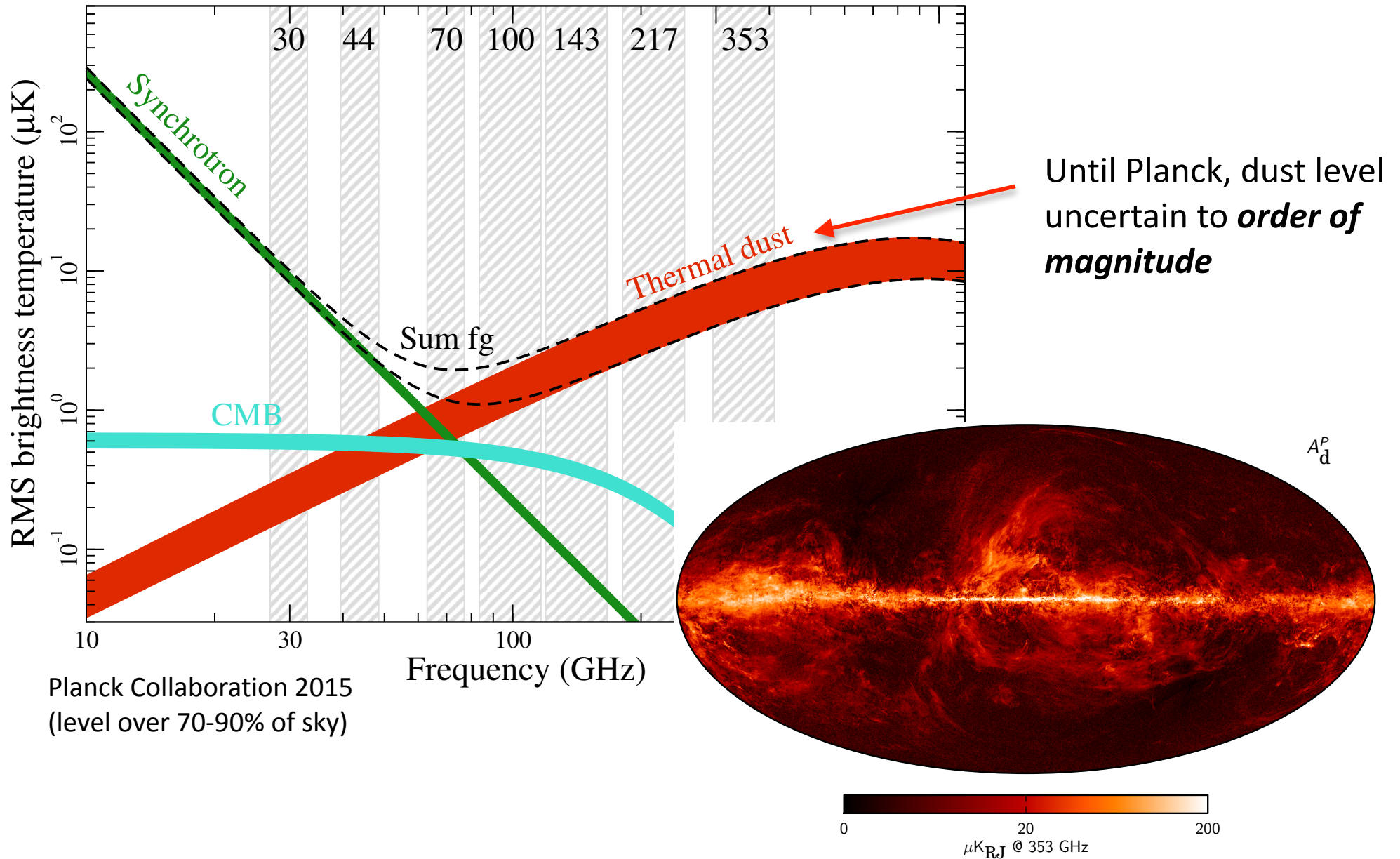
New limits on tensor modes



Planck/BICEP2 Collaborations 2015



Planck gave us new view of the Galaxy

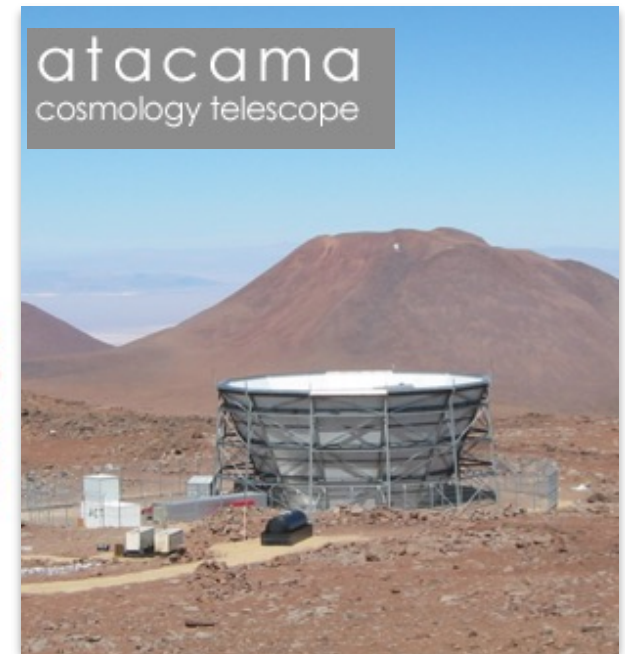
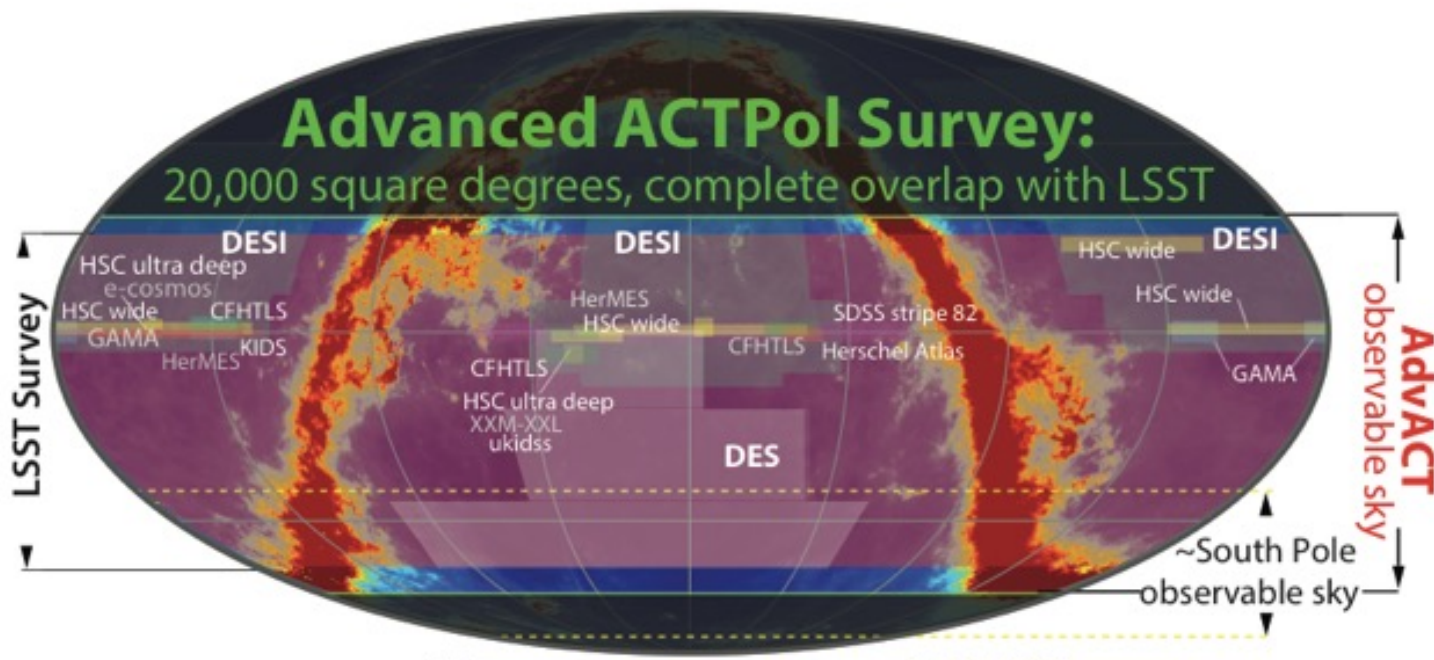


Path ahead

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.*