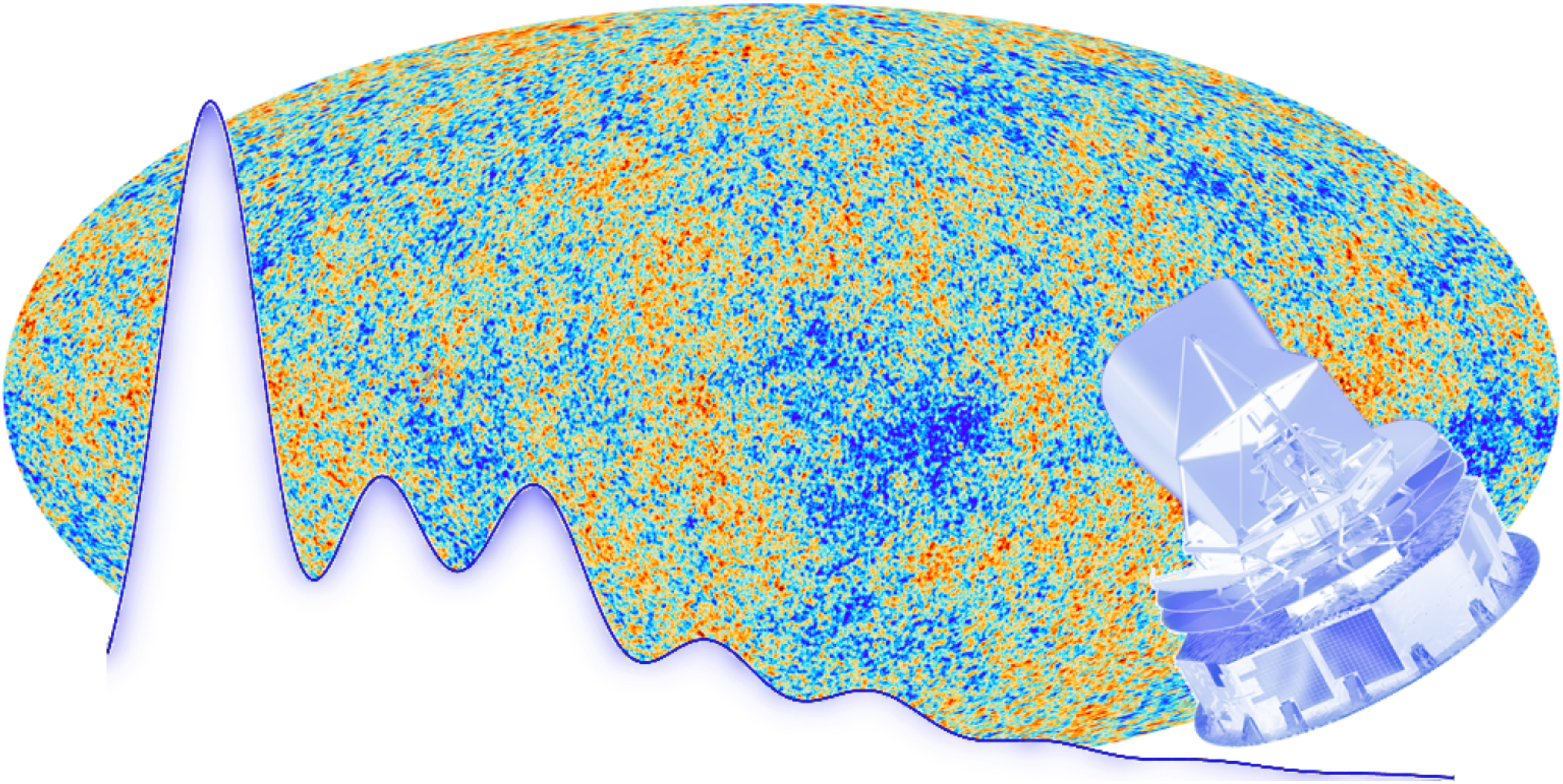
The Cosmological Legacy of Planck



Martin White
Berkeley.

Figs. courtesy V. Pettorino

The cosmic microwave background

- The entire Universe is filled with radiation in the form of a 2.7K black-body.
- This radiation is a relic of the hot, dense, early phase of the Universe (the hot-big bang).
- The light travels to us from a "surface of last scattering" at z~1100 (when the Universe was 10^{-3} times smaller than today and only 380,000yr old).
  - At this *z* the Universe was finally cold enough for protons to capture electrons to form neutral Hydrogen.
  - Optical depth to photon scattering quickly drops from $\tau >> 1$ to $\tau << 1$.
- The radiation is almost the same intensity in all directions, but contains tiny fluctuations in intensity (or temperature) at the level of 10^{-4}: CMB anisotropy.

The cartoon: sound waves in the early Universe

- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering.
  - Short m.f.p. allows fluid approximation.
- Initial fluctuations in density and gravitational potential drive acoustic waves in the bγ fluid: compressions and rarefactions.
- These show up as temperature fluctuations in the CMB, including an almost harmonic series of peaks in the angular power spectrum of ΔT as a function of angular wavenumber l (conjugate to angle θ).

CMB encodes valuable information

- The CMB spectrum depends upon the initial spectrum of perturbations (inflation?) and the conditions in the photon-baryon fluid prior to last scattering.
- The rich structure in the spectrum, and the dependence on many cosmological parameters, provides a gold-mine of information.
- Scattering of an anisotropic temperature field generates (linear) polarization, which allows access to even more information.
- We can also get information about the low z Universe by looking at CMB lensing (and BAO – the sound waves frozen in the matter perturbations).

The magic of CMB …

The CMB contains a gold-mine of information

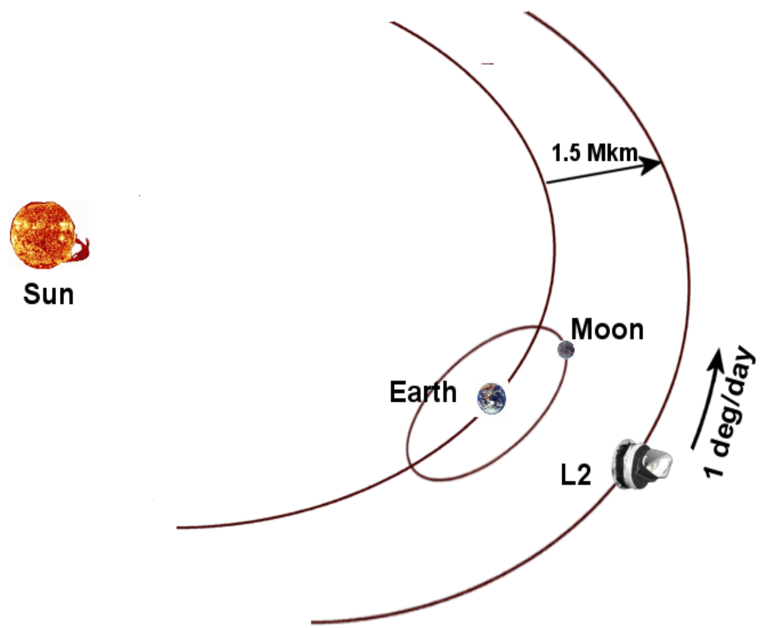
- *if* it can be accurately measured
- *and* compared to precise theoretical predictions with a rich phenomenology
- in a statistically reliable
- and computationally tractable way

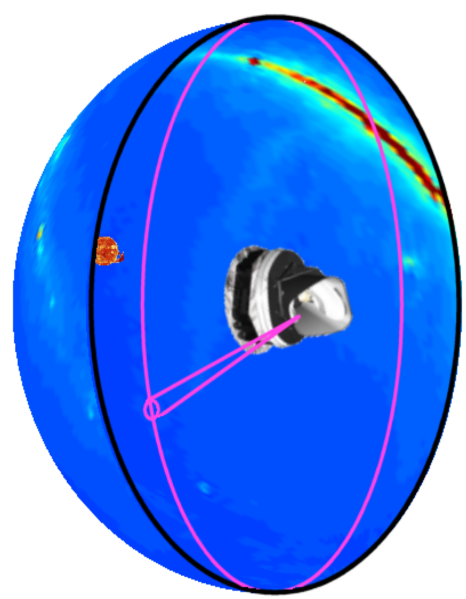
There are very few situations in cosmology, astrophysics (or indeed physics) where all of these conditions are met.

It is the intersection of these qualities that makes CMB such a powerful cosmological probe!

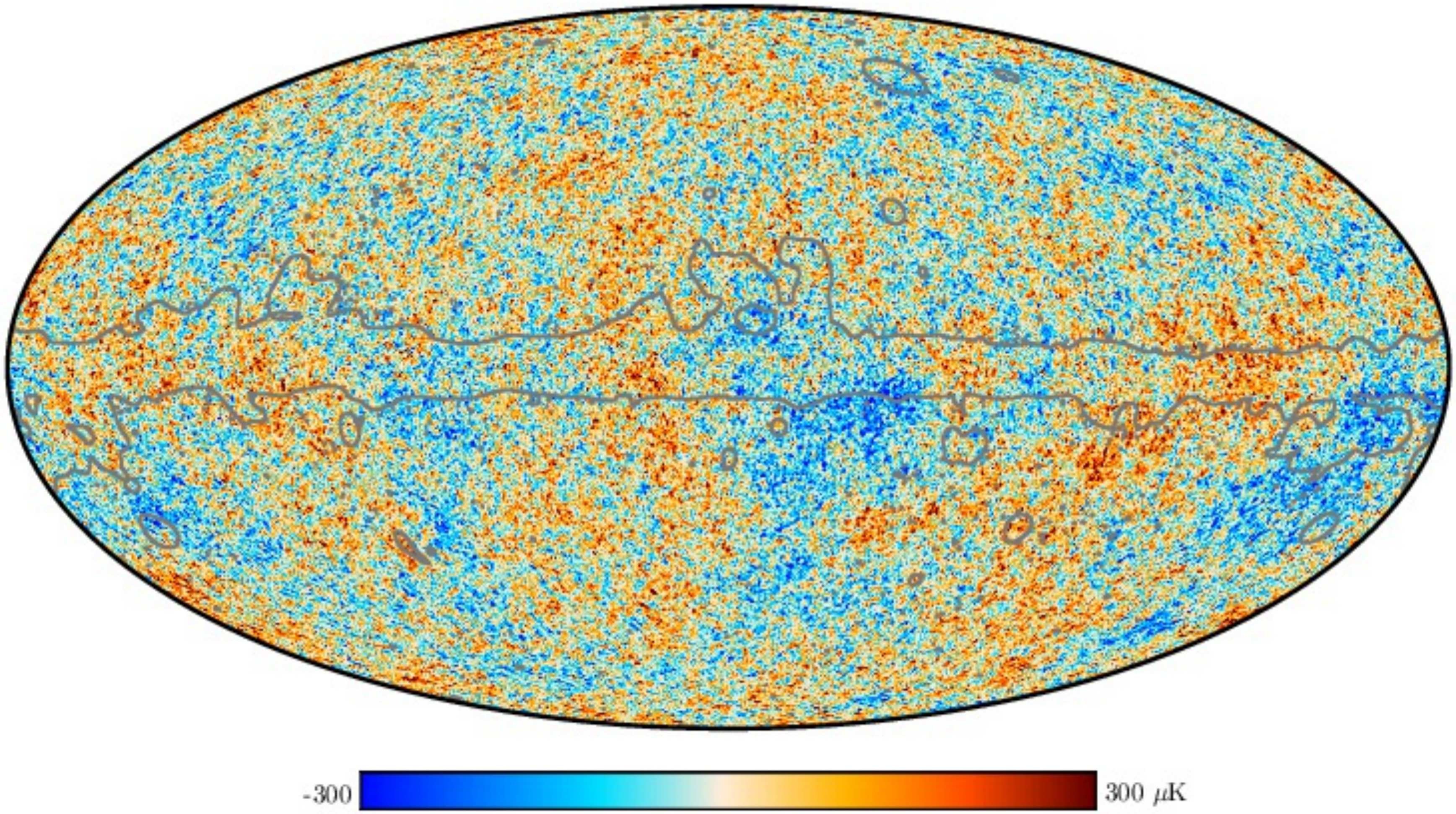
Planck mission

- Planck was a 3rd generation space mission (COBE, WMAP)
  – Like WMAP, Planck observed at "L_2".
- It was part of ESA's "Cosmic Visions" program.
- It was the first sub-mm mission to map the entire sky to sub-Jy sensitivity and resolution better than 10 arcmins.
  – 74 detectors covering 25GHz-1000GHz, resolution 33'-5'.

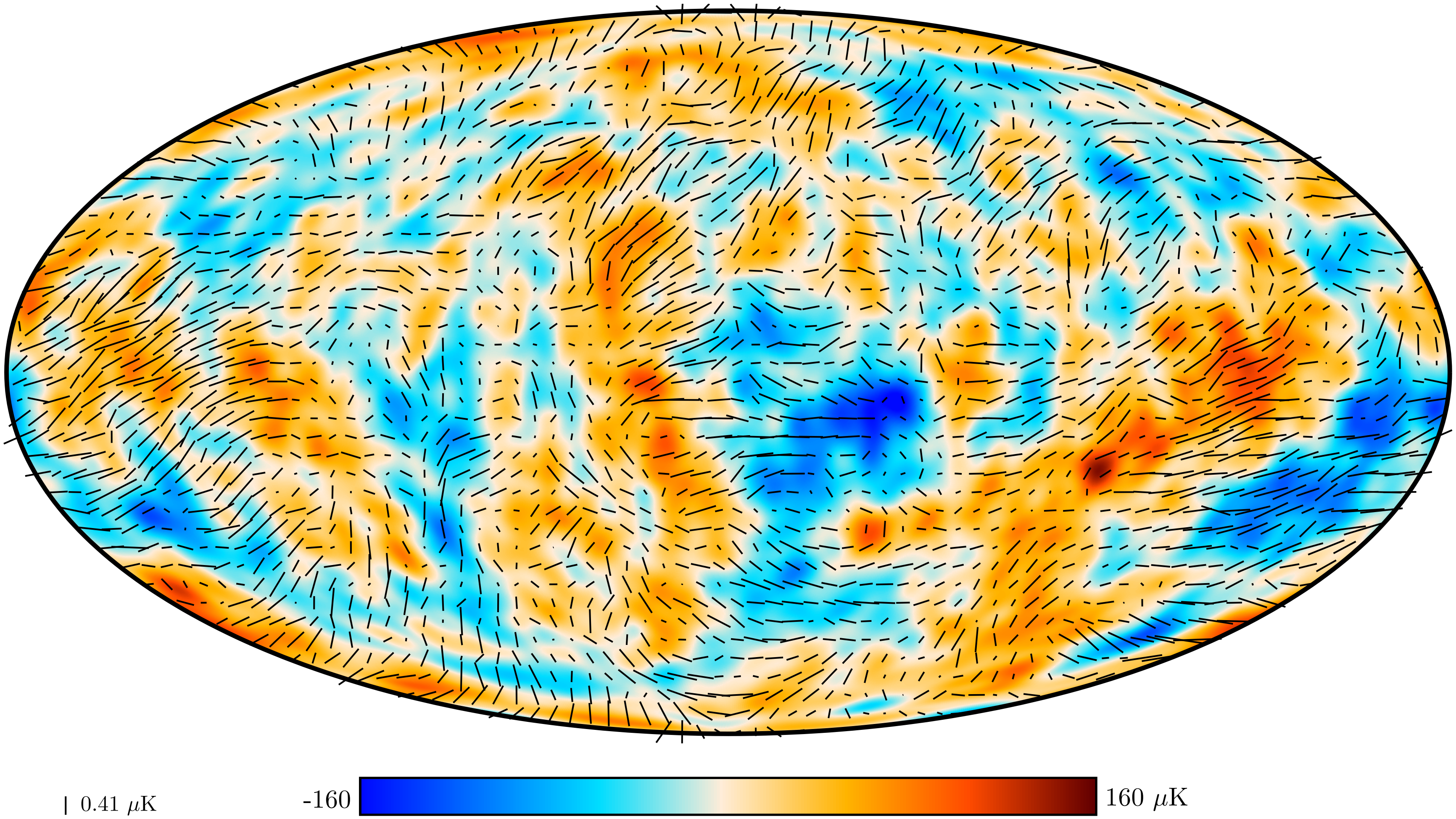




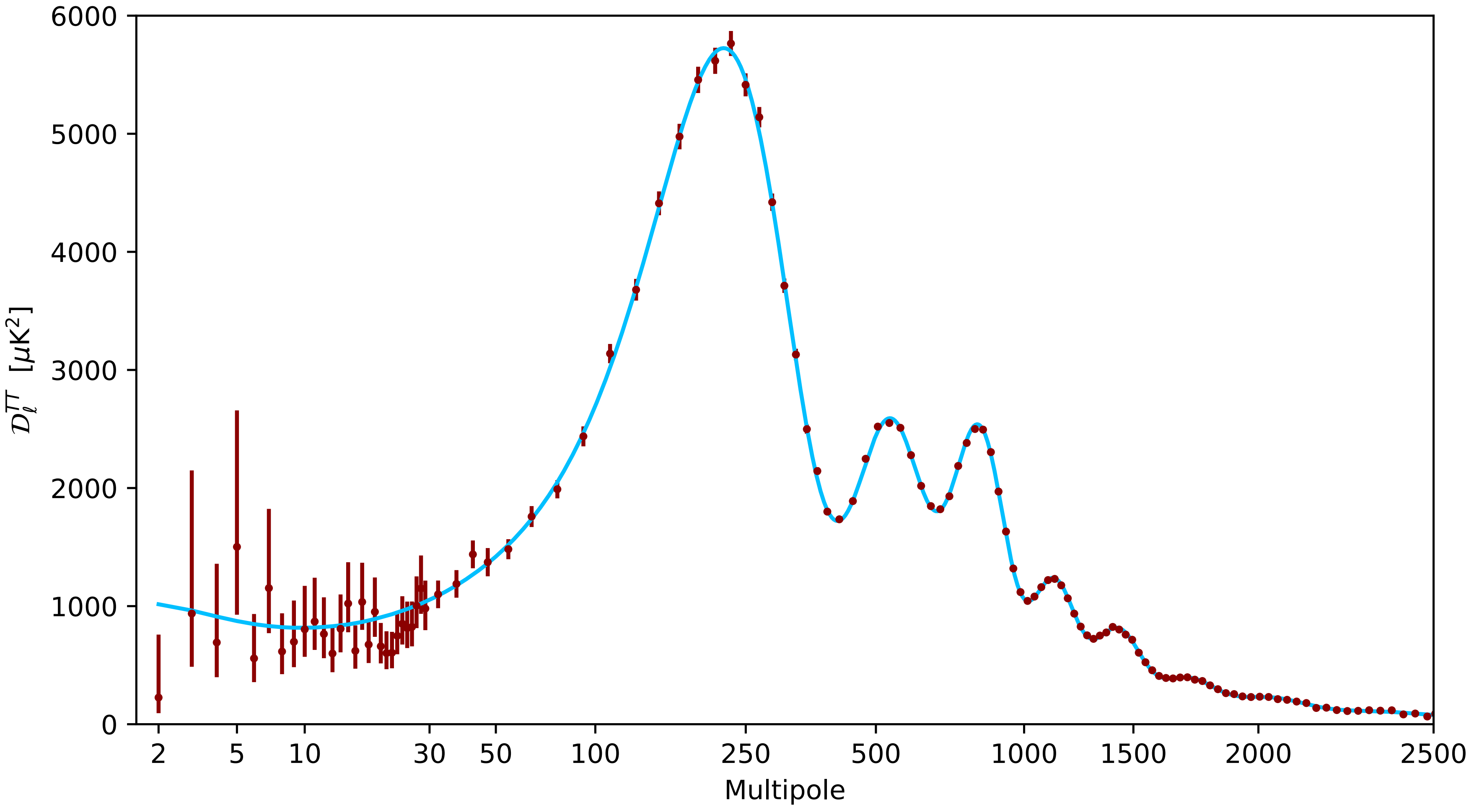
CMB map



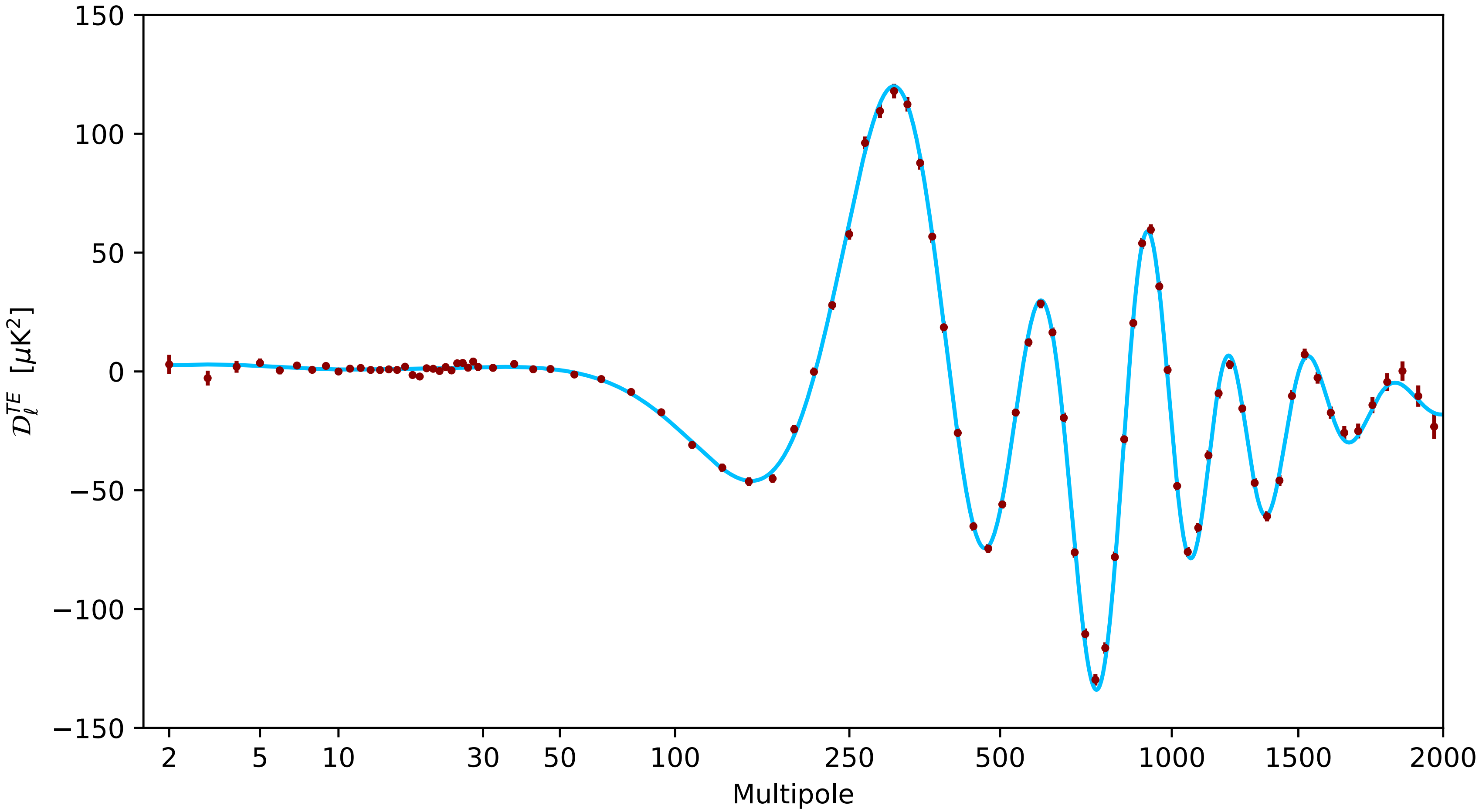
CMB map: smoothed + polarization



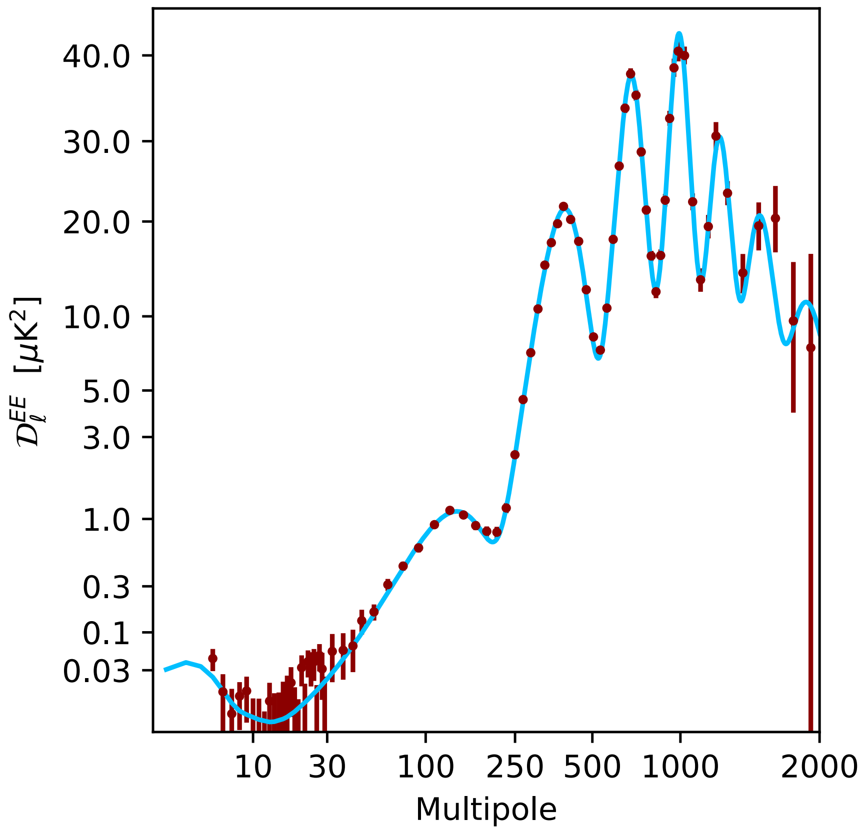
The angular power spectrum

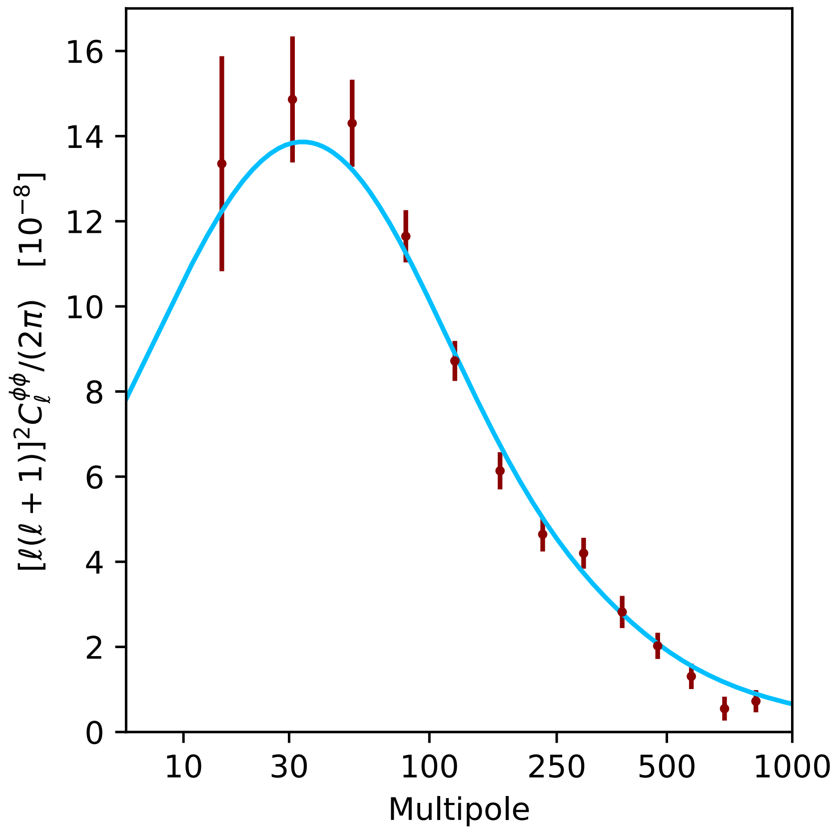


Polarization-Temperature



Polarization and lensing





Data compression!

- We find that a simple, 6 parameter model fits the data extremely well.
  - Data compression: trillions of bits of data are compressed to billions of measurements at 9 frequencies, then tens of millions of modes are compressed to thousands of multipoles which are compressed to 6 cosmological parameters!
  - With no evidence for a 7^{th}.
- For the "base model" the CMB determines all of the parameters, on its own, with exceptional accuracy.
  - If we include polarization, best determined parameter is 0.03%.
  - Only 1 parameter not determined to better than 1%.

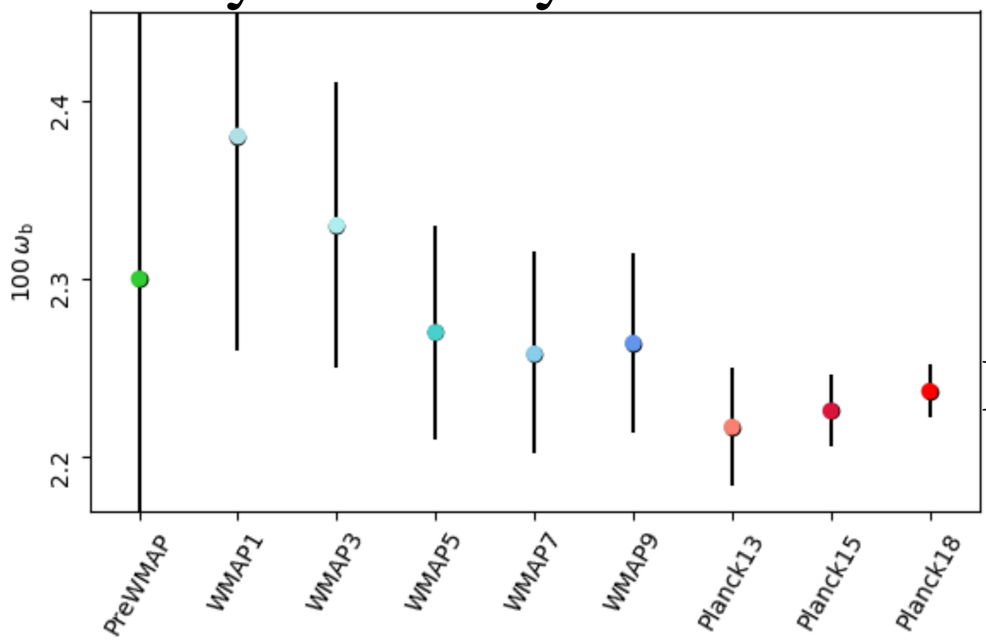
Planck(-only) base ΛCDM model

Parameter	Description	Value
ω_b	Baryon density	0.02237 ± 0.00015
ω_c	Cold dark matter density	0.1200 ± 0.0012
$100\theta_{MC}$	Angular size of acoustic scale	1.04092 ± 0.00031
τ	Optical depth to Thomson scattering	0.0544 ± 0.0073
$\ln(10^{10}A_s)$	Observed fluctuation amplitude	3.044 ± 0.014
n_s	Slope of primordial power spectrum (spectral index)	0.9649 ± 0.0042
H_0 (km/s/Mpc)	Expansion rate of Universe	67.36 ± 0.54
σ_8	Amplitude of fluctuations in matter today	0.8111 ± 0.006

And my favorite derived parameter: $k_{eq} = 0.01038 \pm 0.00008$ Mpc^{-1}

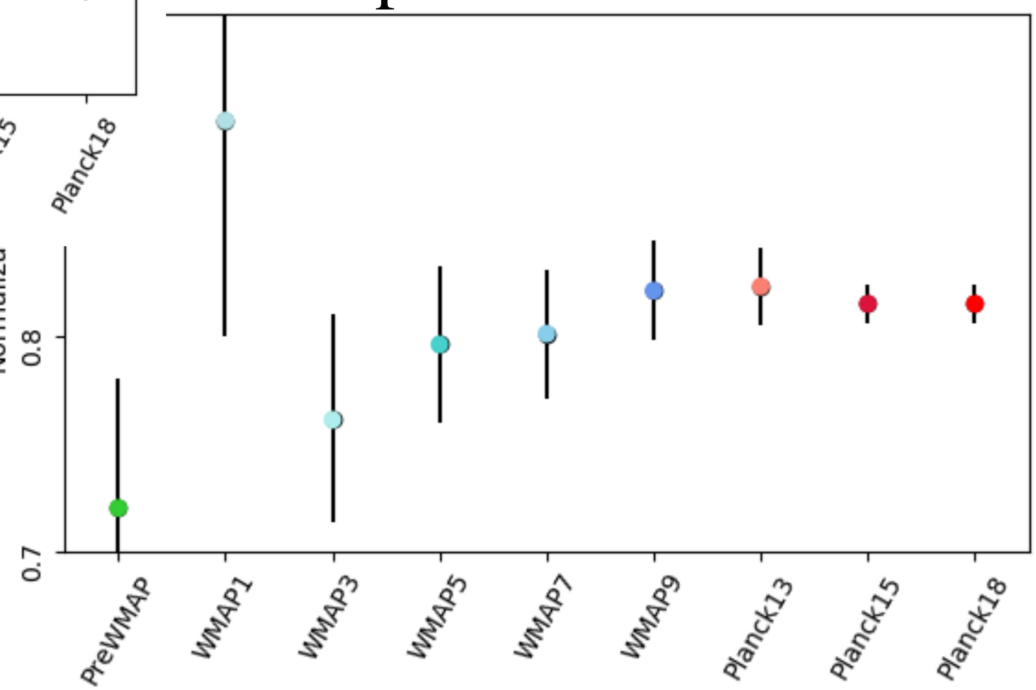
Improvement in parameters in 15yr

Baryon density

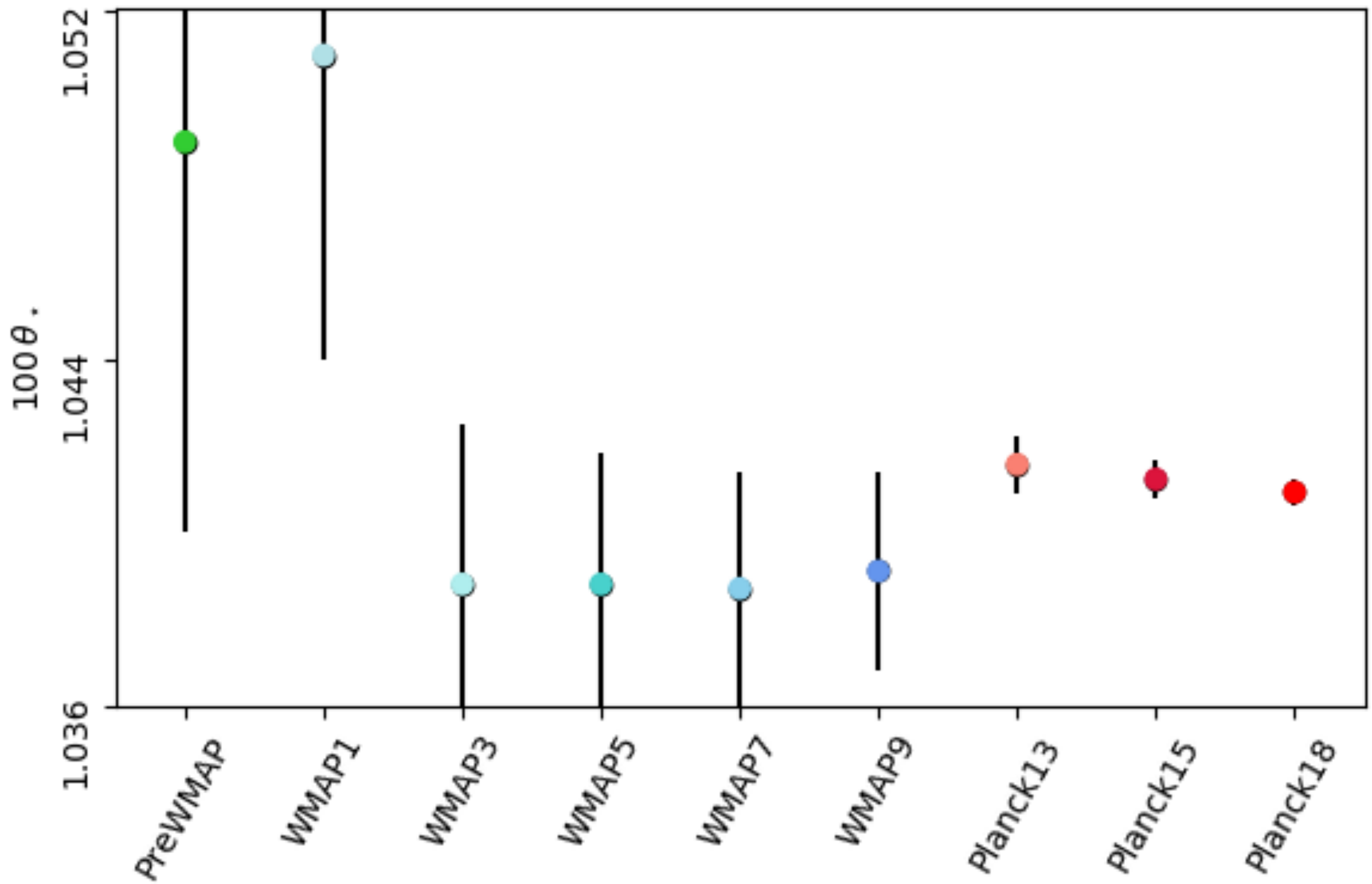


Power spectrum normalization

σ_8

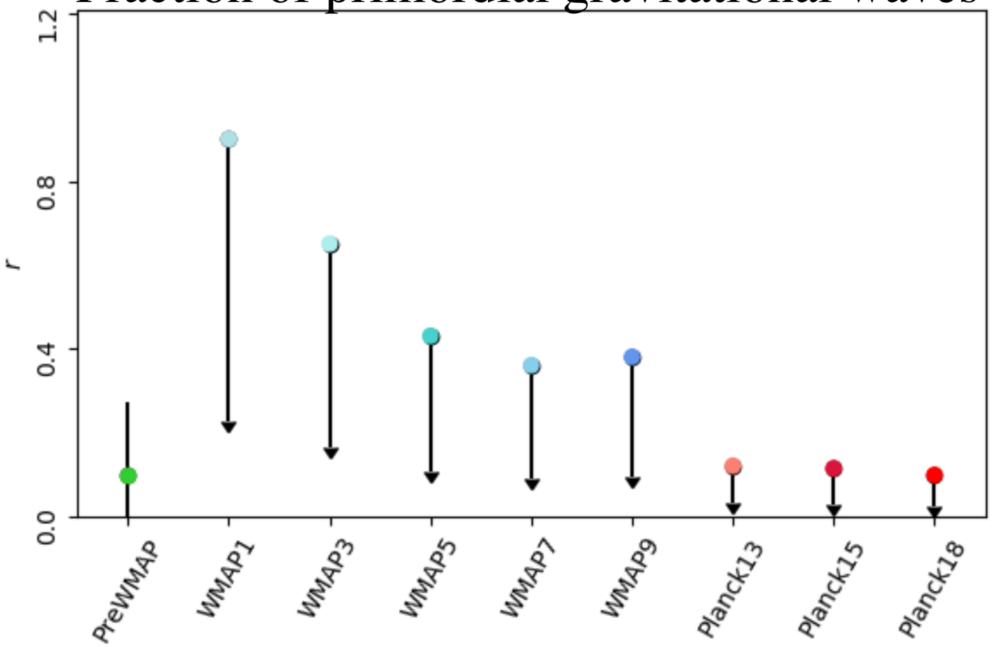


Acoustic scale: known to 0.03%

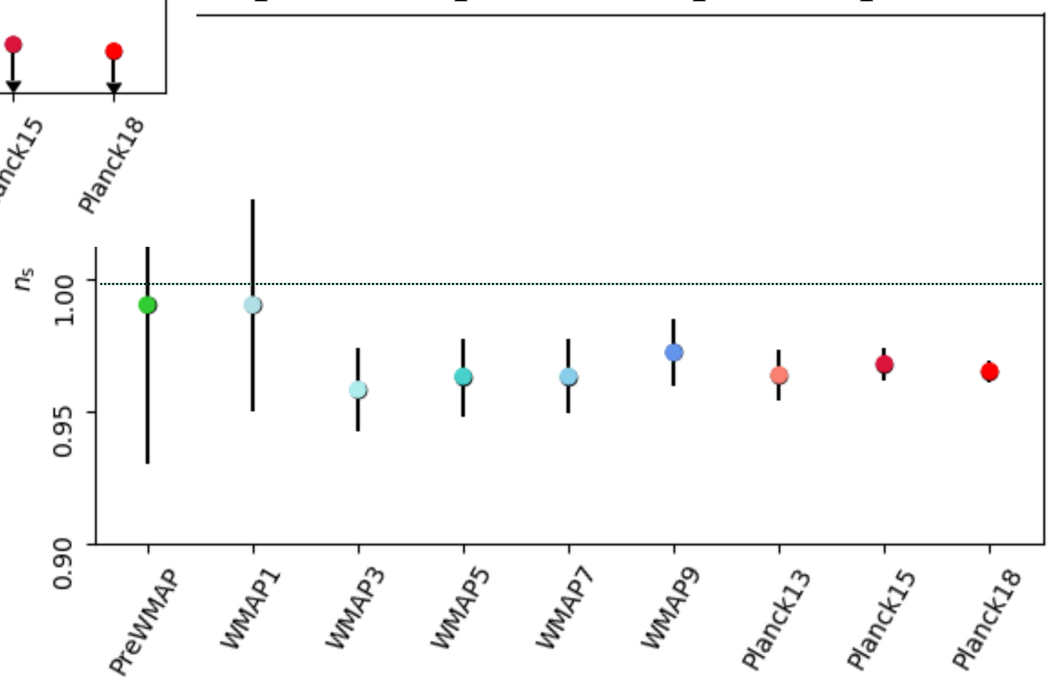


Limits on primordial perturbations ...

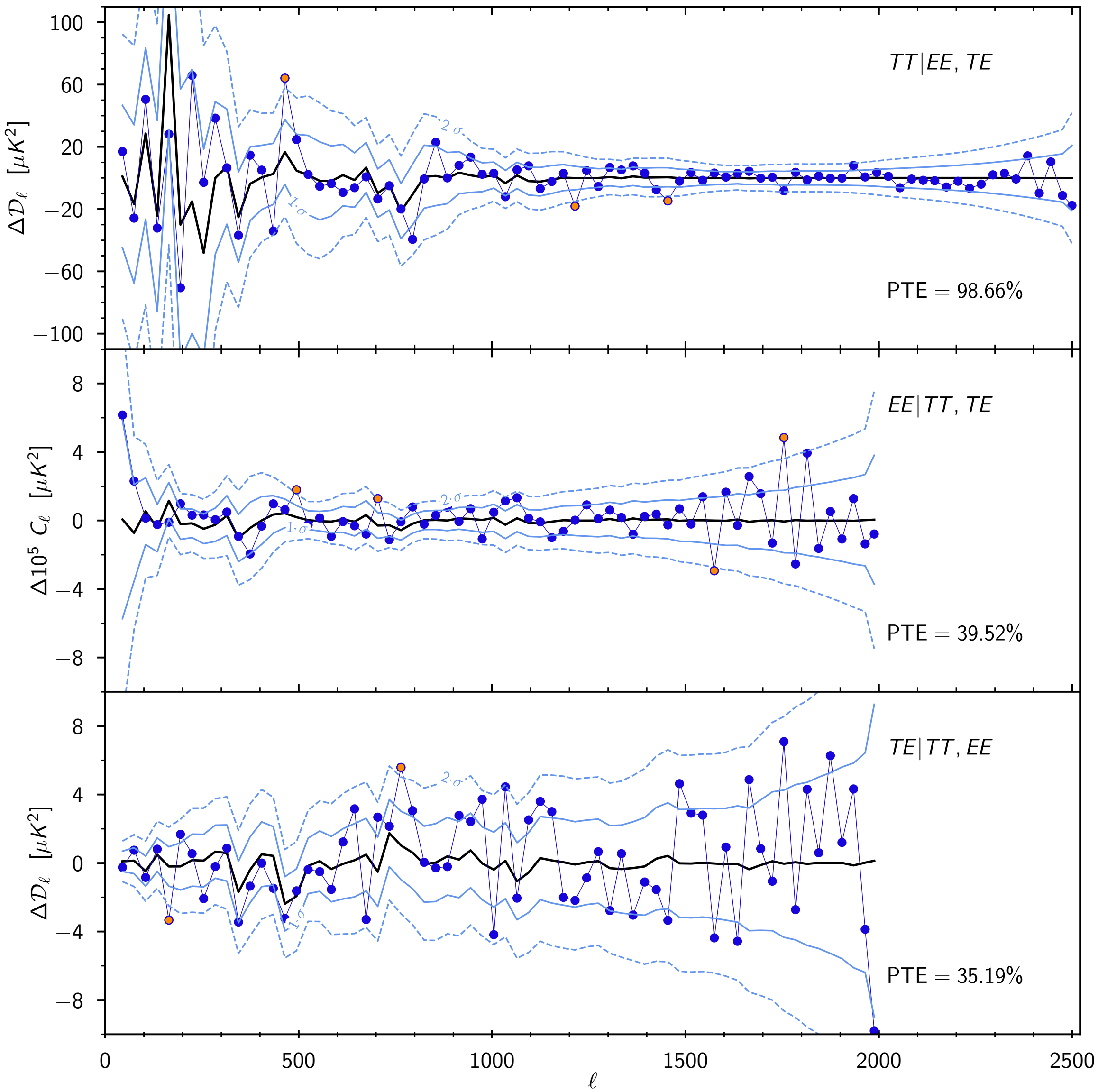
Fraction of primordial gravitational waves



Slope of the primordial power spectrum



T & E consistency



Can use EE,TE to predict TT assuming ΛCDM.

Can use TT,TE to predict EE.

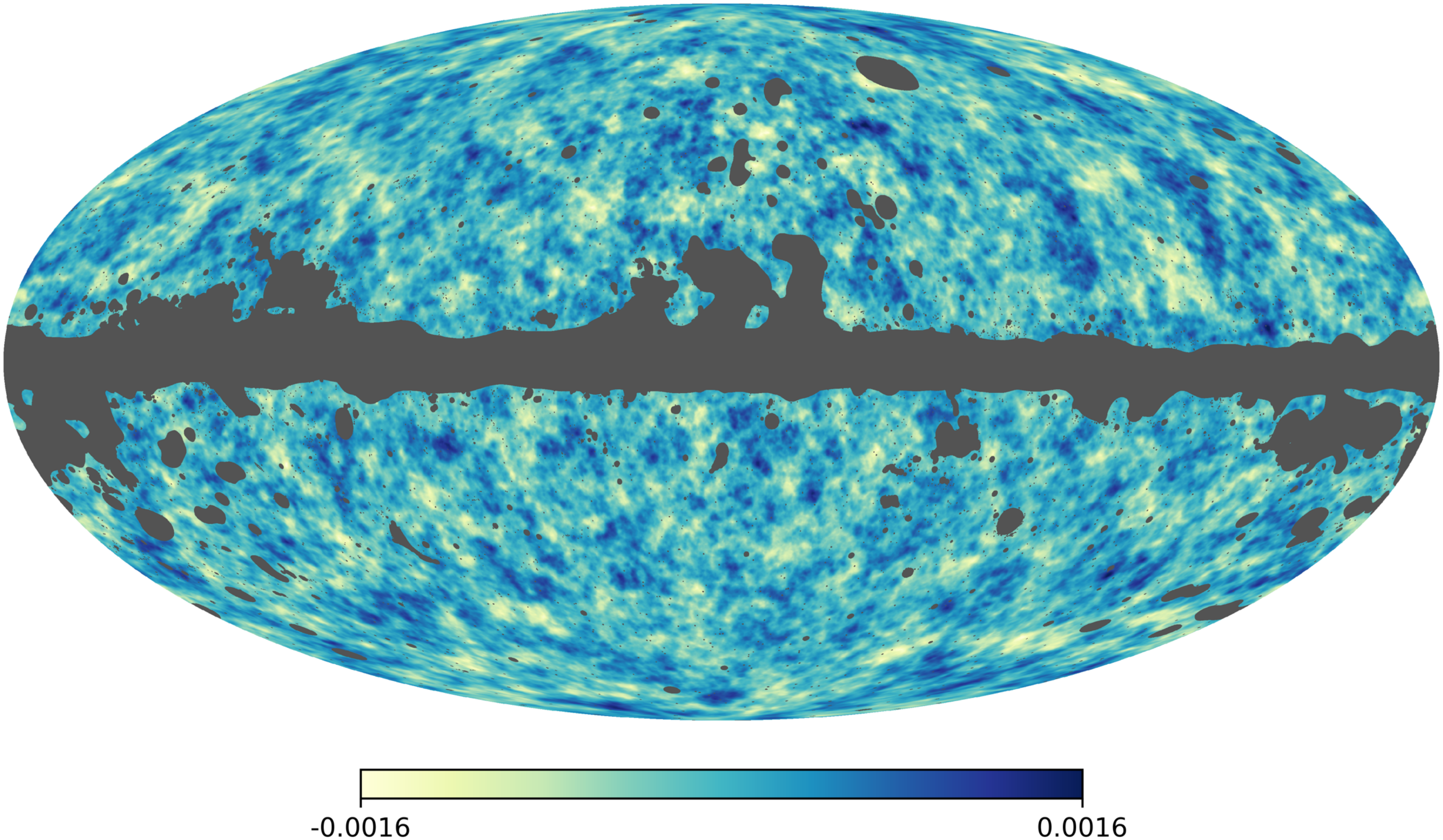
Can use TT,EE to predict TE.

All looks good!

CMB lensing

- Photons from the CMB are deflected on their way to us by the potentials due to large-scale structure.
- The typical deflection is 2-3 arcmin but deflections are coherent over degrees.
  - Signal dominated by structures of tens of Mpc at z~2.
- Gives sensitivity to the “low z” Universe.
  - Allows us to break some degeneracies from purely within the CMB dataset.
  - Provides a cross-check on the paradigm: are the structures we infer at z~2 consistent with the “initial conditions” measured at z~1,000? [After 10^3 growth: $A_L^{\phi\phi}$=0.997±0.03]
- Provides a map, over the whole sky, of the (projected) mass back to the surface of last-scattering (98% of the way to the horizon).

Lensing deflection (E-mode)



Lensing now measured at >40σ.
Better than predicted by anisotropy!

Much future CMB science will be lensing …

Some key "early Universe" results …

- Inflation.
  - Planck has had a huge impact on inflationary model building!
  - A large number of "popular" models now ruled out.
  - The simplest models of inflation predict …

A spatially flat Universe	Ω_K=0.0007 ± 0.0019
with *nearly* scale-invariant (red) spectrum of density perturbations	0.967 ± 0.004
which is almost a power-law	$dn_s/d\ln k$ = -0.0042 ± 0.0067
dominated by scalar perturbations	$r_{0.002}$<0.07 (95%)
which are Gaussian	f_{NL} = 2.5 ± 5.7 ~ 0
and adiabatic	α_{-1} = 0.00013 ± 0.00037
with negligible topological defects	f_{NG} < 0.01 (95%)

Inflationary models

- Coherence of peaks, sign of TE
  - Early Universe origin of perturbations
- $\Omega_K \sim 0$: duration of slow-roll not fine tuned.
- Primordial P(*k*) well approximated by power-law.
  - Inflaton rolls down a featureless, nearly flat potential.
- No isocurvature modes: 1 d.o.f.
- Scalar modes dominate by 1 order of magnitude.
  - Models with $r \sim (1-n_s)$ severely limited.
  - Models with $r \sim (1-n_s)^2$ require next-gen technology to limit.
  - Models with $r \ll (1-n_s)^2$ out of reach of foreseeable technology.
- Surviving models have $V' \sim 0$ and $V'' < 0$
  - special point in potential.

Some key "early Universe" results …

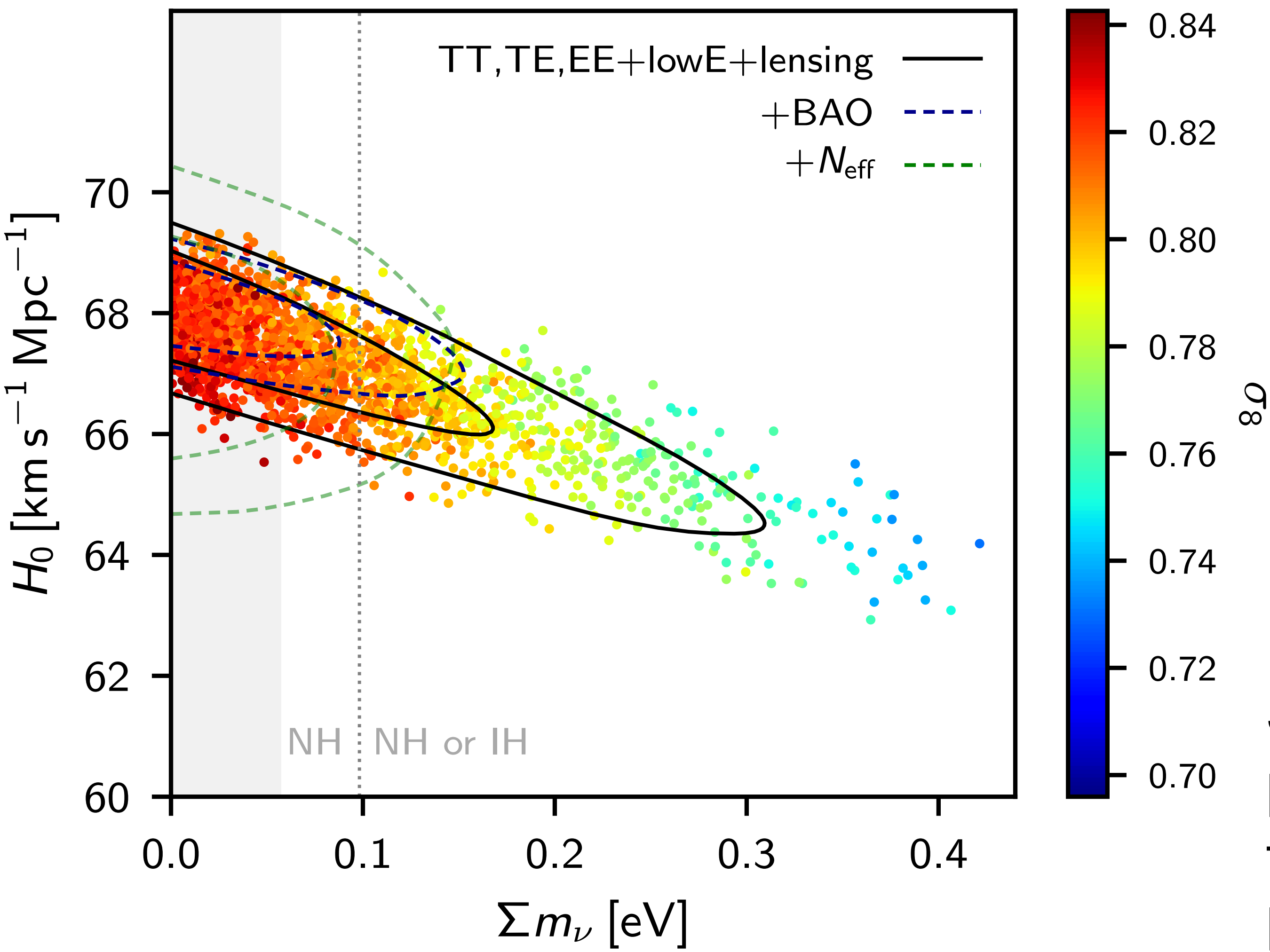
- Light neutrinos.
  - Neutrinos non-relativistic at z~10^3 long ruled out.
  - Current constraints come primarily from lensing and distances.
  - Starting to put pressure on inverted hierarchy.

- Light relic species
  - Dark, relativistic d.o.f. labeled by $N_{\rm eff}$

$$\frac{\rho_{\rm rad}}{\rho_\gamma} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff} \qquad N_{\rm eff} = 3.045 + \Delta N_{\rm eff}$$

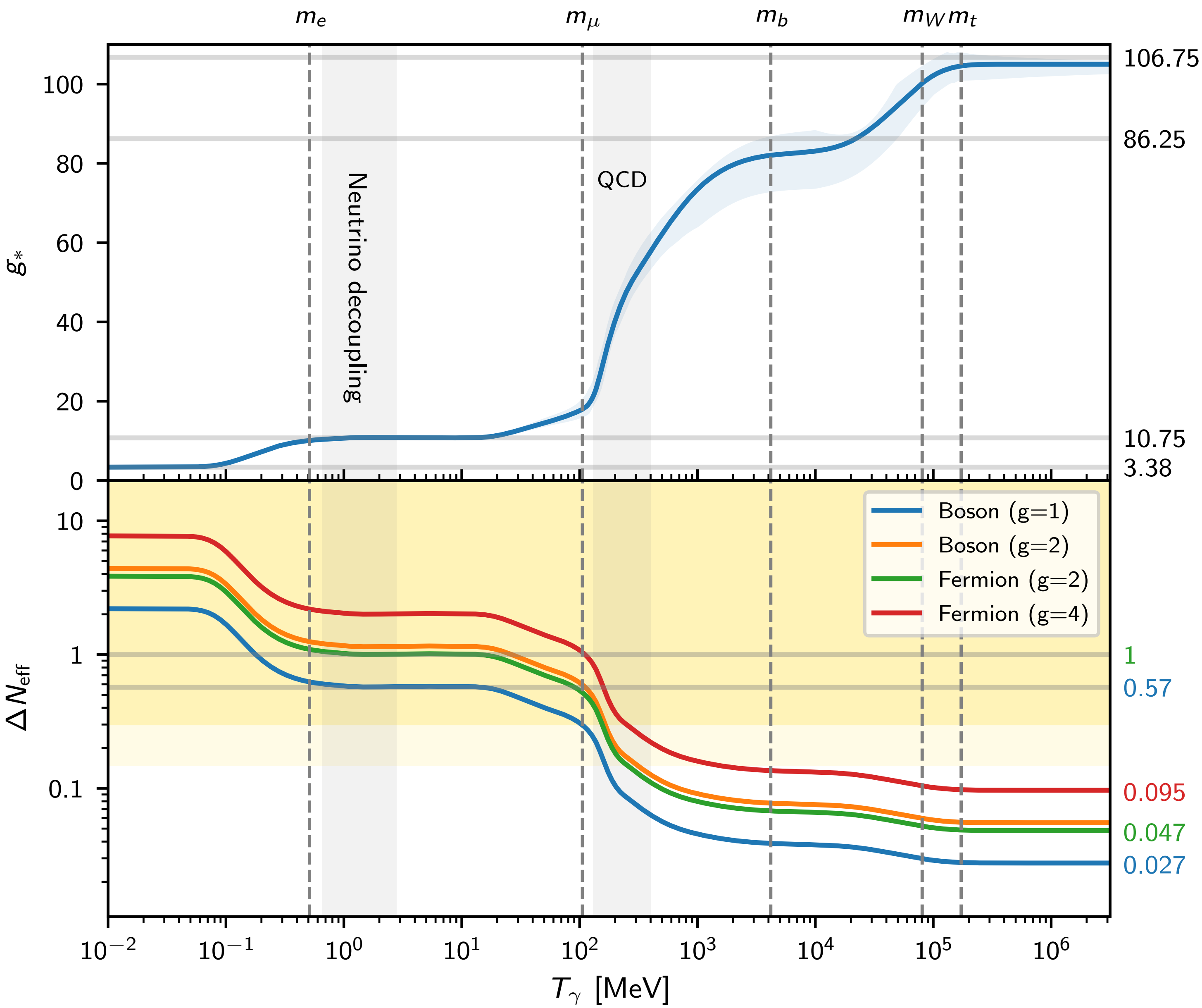
Constraints on neutrinos now tighter

$\Sigma m_\nu < 0.12$ eV (95%)



Starting to put pressure on the inverted hierarchy.

Light degrees of freedom: N_{eff}



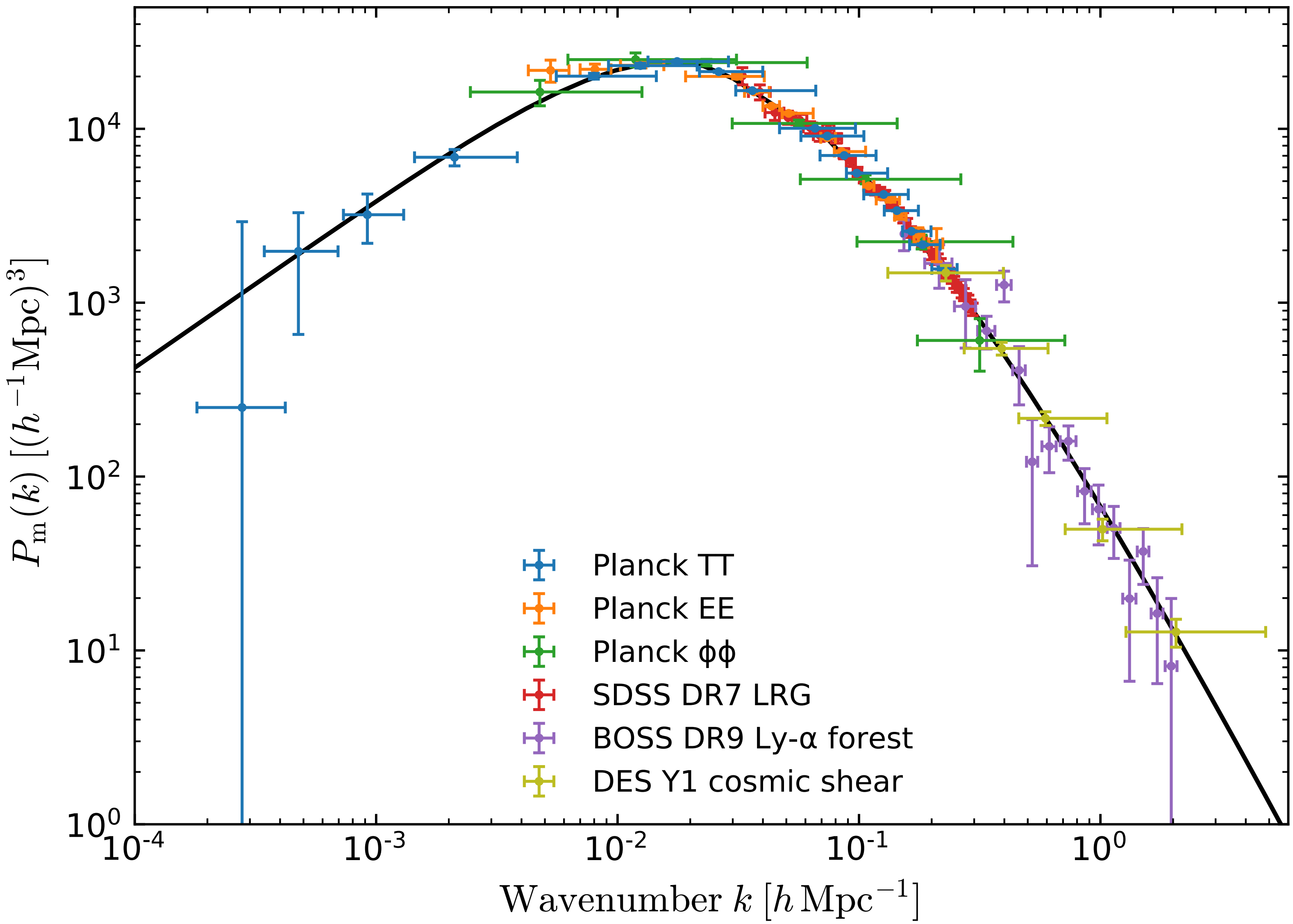
Light degrees of freedom decoupling after the QCD phase transition are disfavored at 95% CL.

CMB + LSS

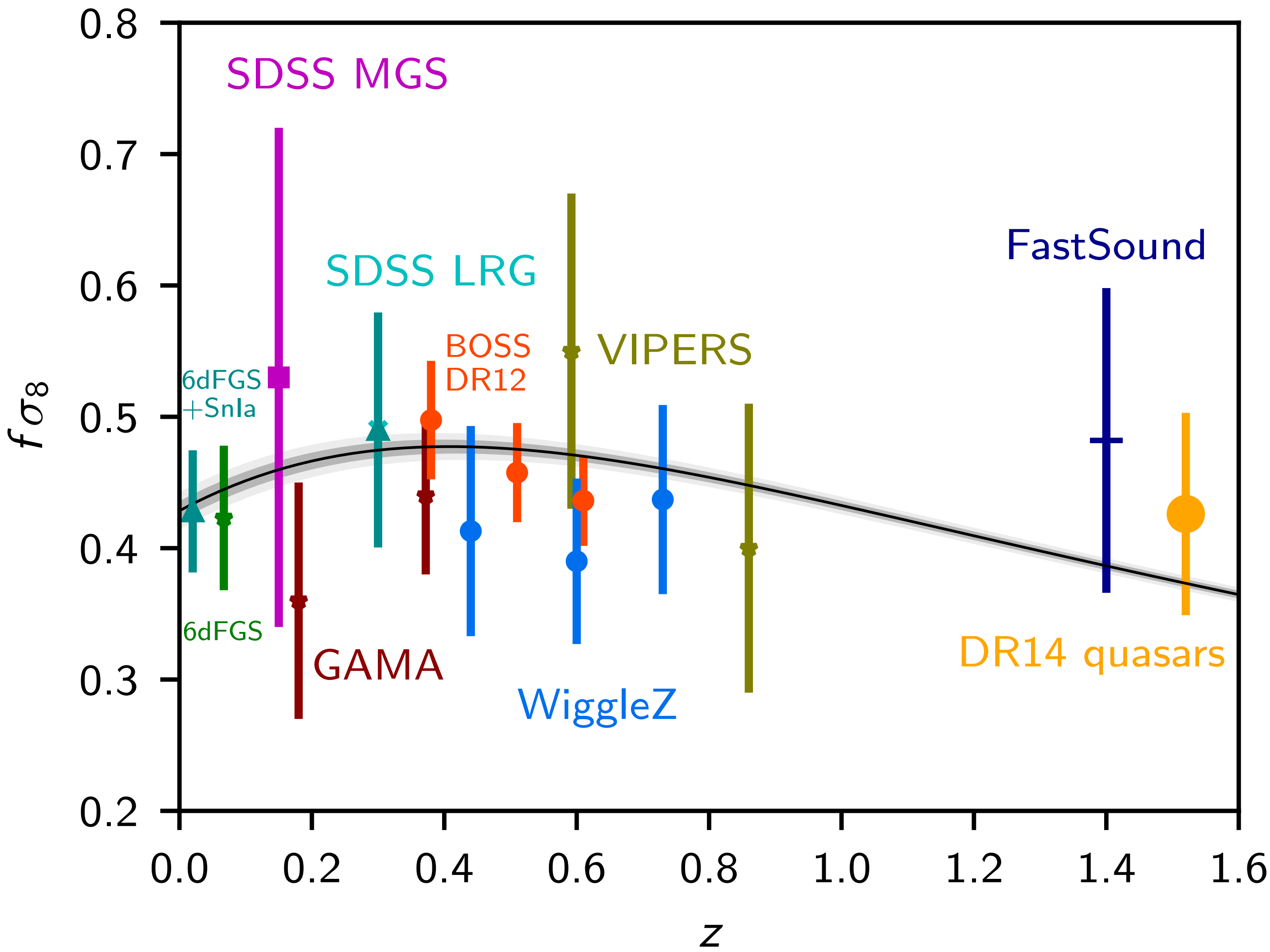
- By cementing the gravitational instability paradigm and measuring the ICs and parameters, Planck sets the framework for LSS.
- Planck precisely determines many of the key parameters for large-scale structure:
  - $k_{eq} = 0.01038 \pm 0.00008$ Mpc^{-1}
  - $\sigma_8(z=2) = 0.3211 \pm 0.0009$
  - $r_{drag} = 147.09 \pm 0.26$ Mpc
- Planck calibrates the "standard fluctuation spectrum".
  - Sets the scale and level of inhomogeneity in the Universe.
  - Governs structure formation, galaxy formation, etc.

Early on, the fields of LSS and CMB were tightly coupled. With time they grew apart and specialized. I think we are witnessing a re-coupling.

Low redshift structure

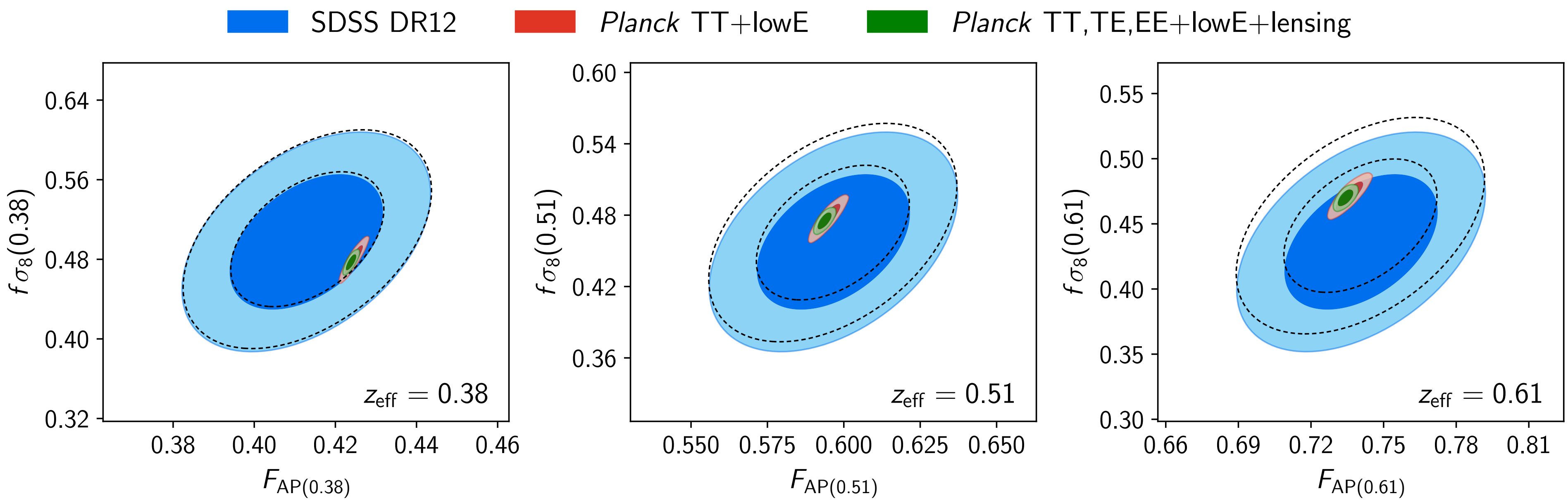


Rate of growth of large-scale structure



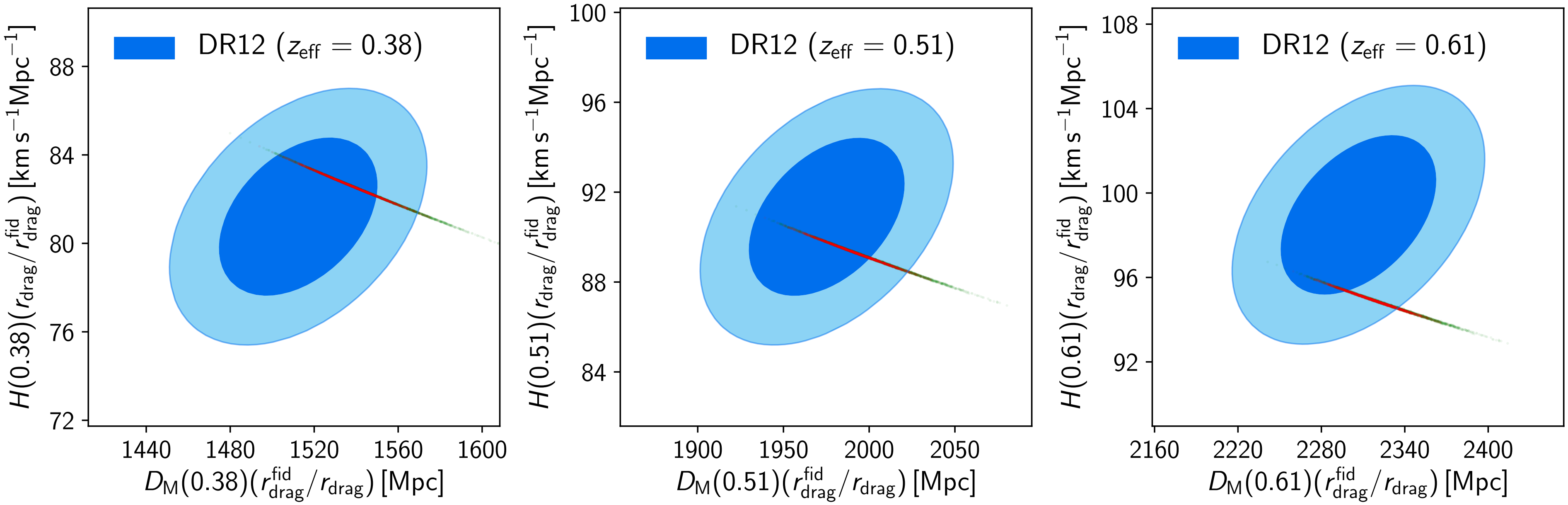
Redshift-space distortions: Planck vs BOSS

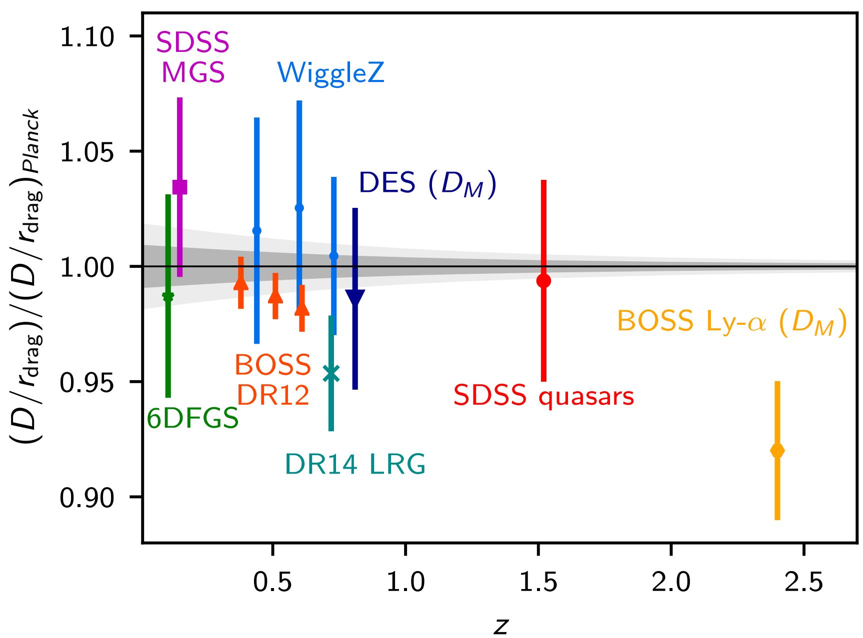
Growth rate ($f\sigma_8$) vs. A-P parameter (F_{AP})

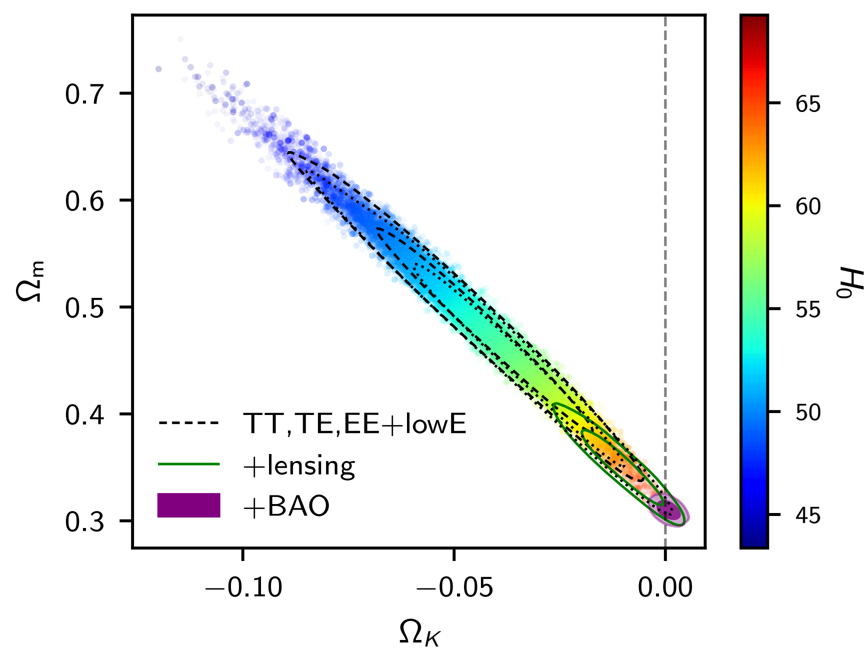


(BOSS results have been marginalized over D_V: dashed lines show results conditioned on Planck)

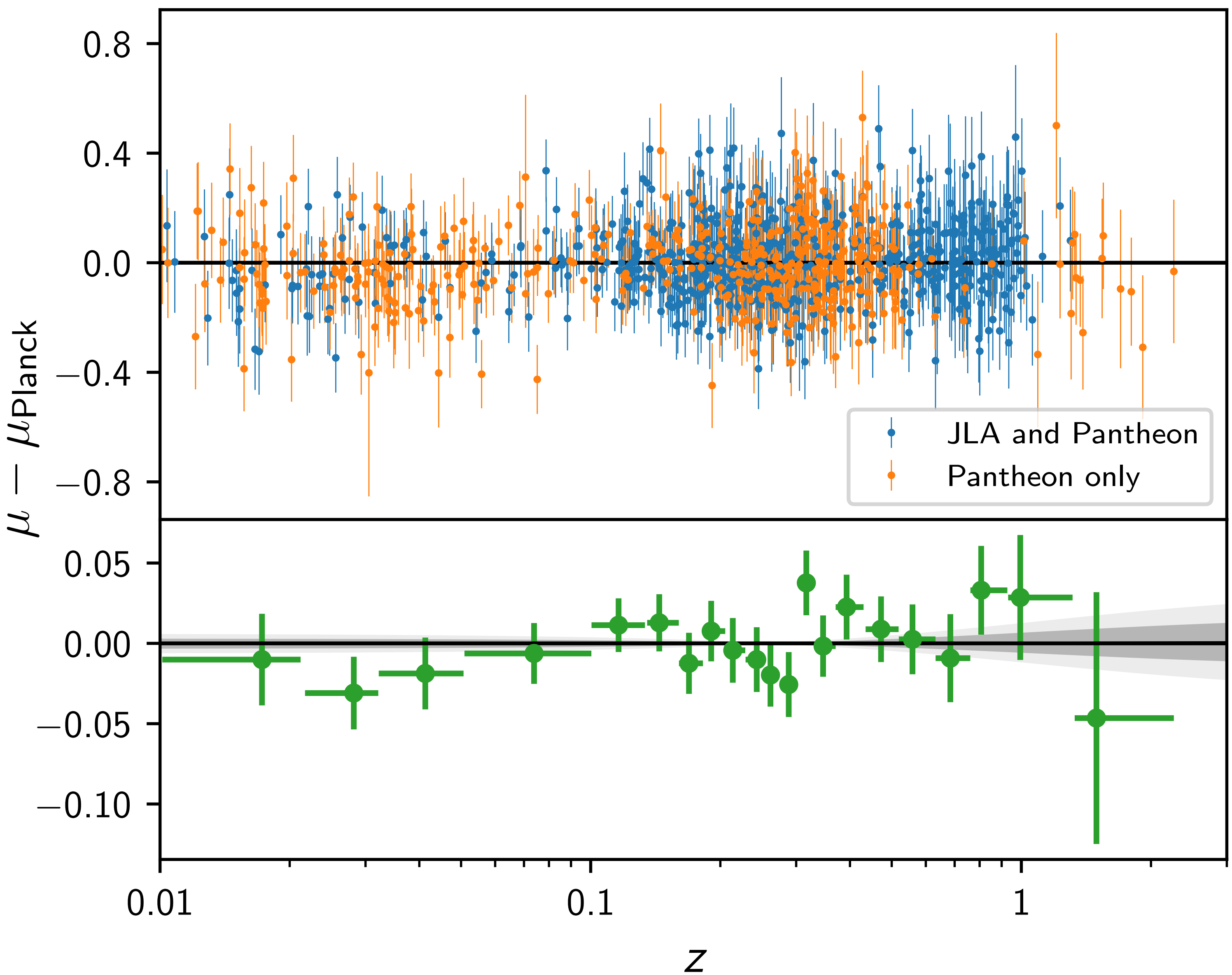
Cosmic distance scale



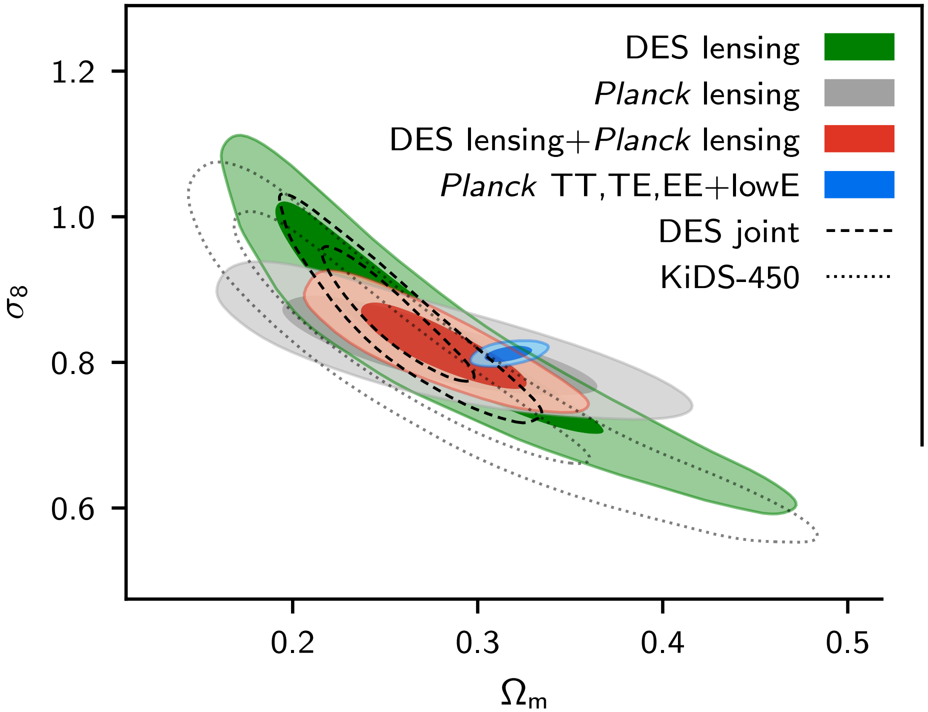




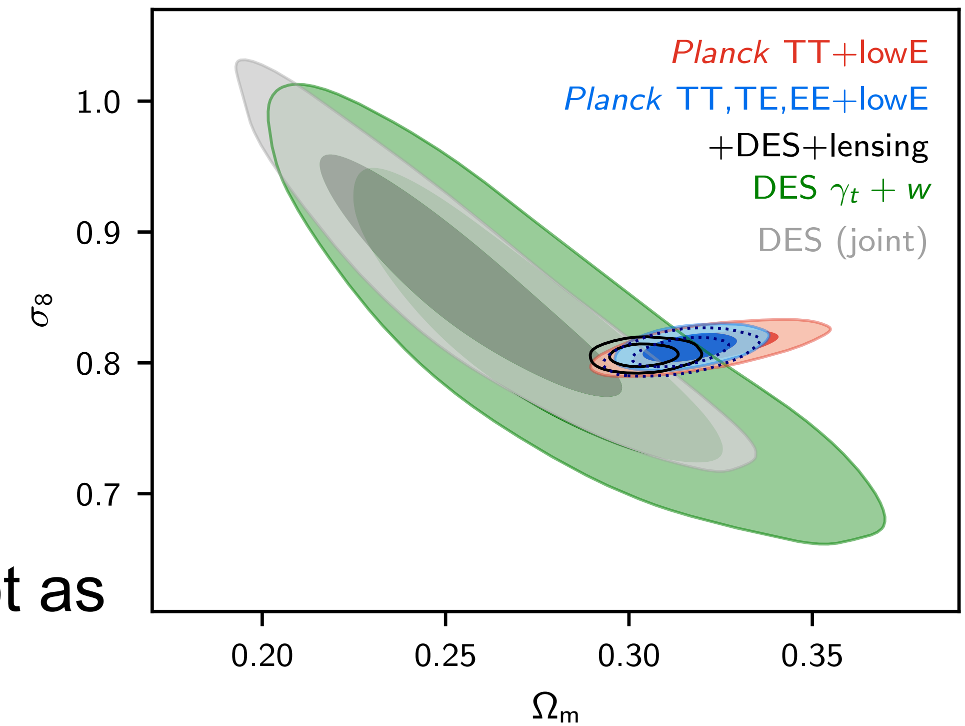
Cosmic distance scale: SNe



Comparison with lensing



Lensing alone is so-so consistent …

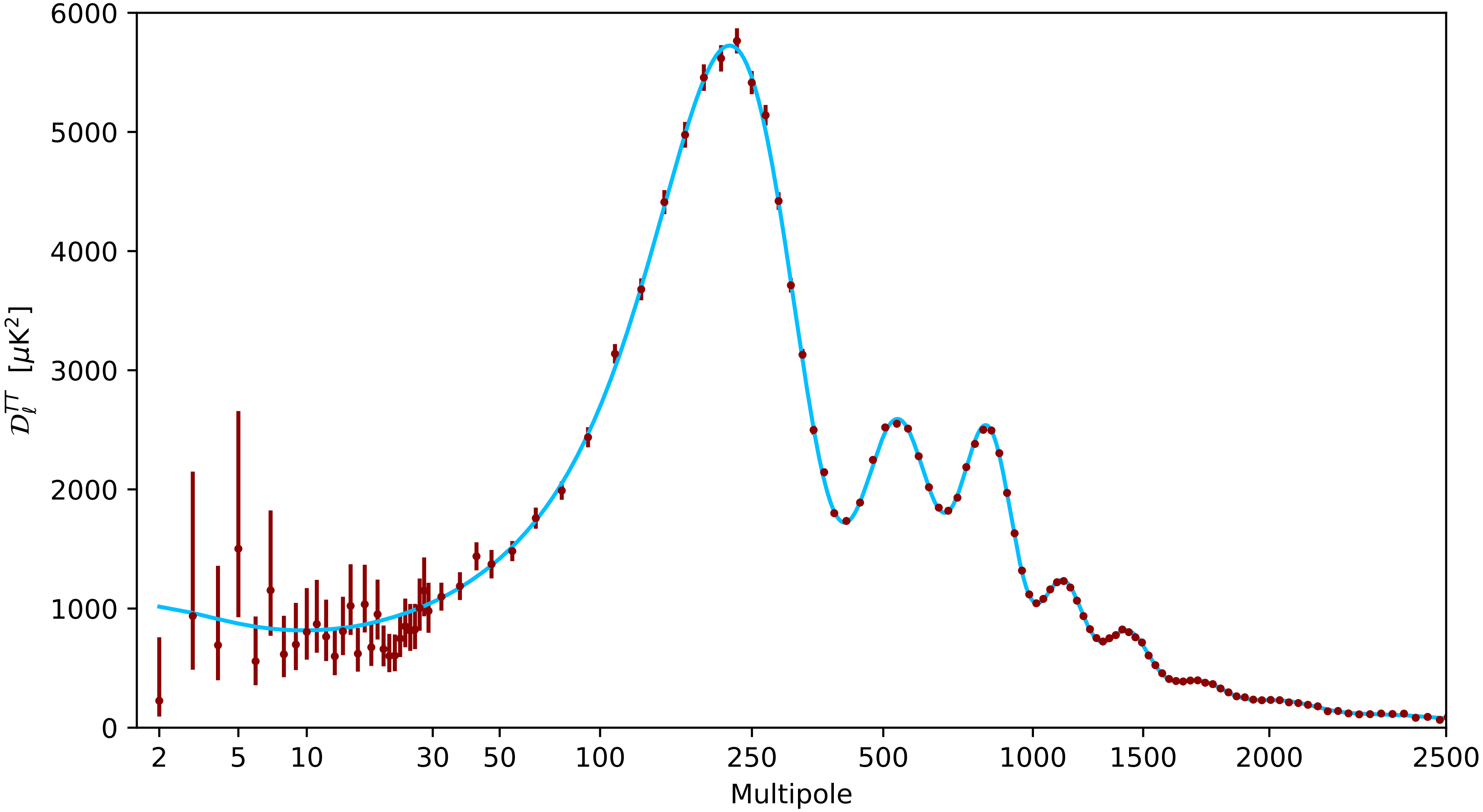


Lensing plus clustering is not as consistent …

Just plain cool …

- In 2013 Planck detected the motion of the Earth in the aberration of the measured CMB anisotropy.
  - Observed at >4σ in 2013 data.
- In 2015 we detected the impact of fluctuations in the 2K neutrino background!
  - Evidence for ν background strong (N_{eff}=0 ruled out @ >10σ)
  - Now have exquisite detection of free-streaming of this component (measures of c_{eff}^2 and c_{vis}^2).
- In 2018 we measured the "gravitational slip" at z=1000 to be 1.004 ± 0.007.
  - GR predicts it is 1.

Temperature story – begun by COBE – is (essentially) done ...



The next generation

- Search for polarization “B-modes”
  - Generated by primordial gravity waves
  - Constrains the energy scale of inflation.
- Primordial non-Gaussianity.
  - Details of inflationary dynamics.
- CMB lensing & cross-correlation.
  - Tests of gravity and large-scale modes.
  - Measurement of neutrino mass.
- tSZ and kSZ.
  - Probes of large-scale velocities, reionization & gastrophysics.

Conclusions

- The CMB is our premier cosmological laboratory.
- Experiments provide a rigorous test of our models using the physics of harmonic oscillators!
  - Established acoustic physics as the “gold standard” probe.
- Impressive confirmation of the standard cosmological model.
  - Precise constraints on model and parameters.
  - Tight limits on deviations from base model.
  - Some indications of internal and external tensions, but with only modest statistical significance.
- Next generation CMB experiments are underway, and planning for CMB-S4 is in progress …
- Synergies between large-scale structure and CMB are only growing in importance!

Planck data

- All Planck papers can be downloaded from
  - http://www.cosmos.esa.int/web/planck/publications
  - Except
    - Power spectra, likelihood (& likelihood code).
    - Isotropy and statistics
    - Primordial non-Gaussianity.
- All Planck data can be downloaded from
  - http://pla.esac.esa.int/pla

The End

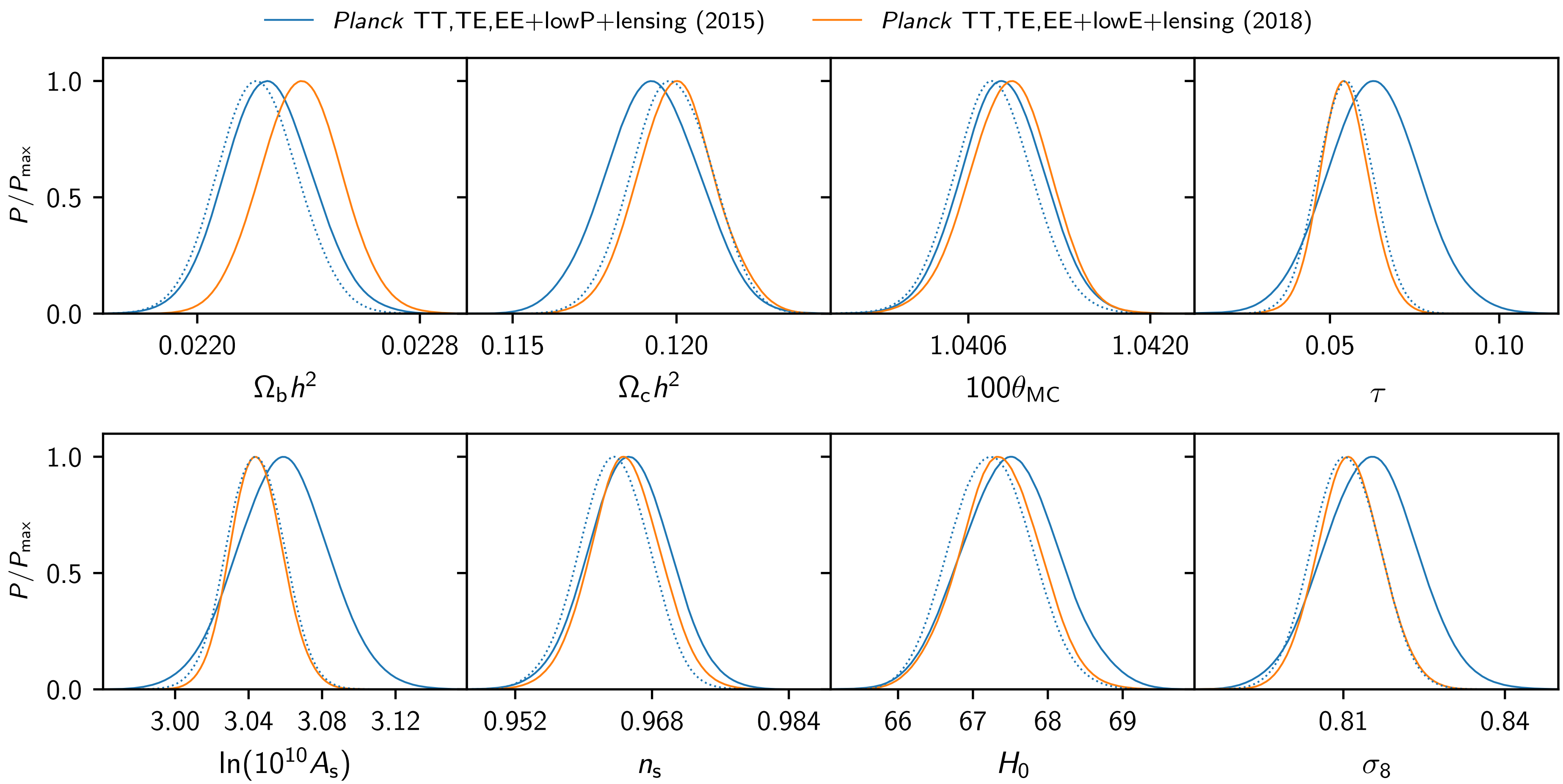
Changes: quick version

- For TT, very little change.
- For EE, tighter τ limit from low *l*
- EE and TE systematics reduced (but not eliminated – roughly $<0.5\sigma$ left).
- $\phi\phi$ pushed to L=8 rather than 40.

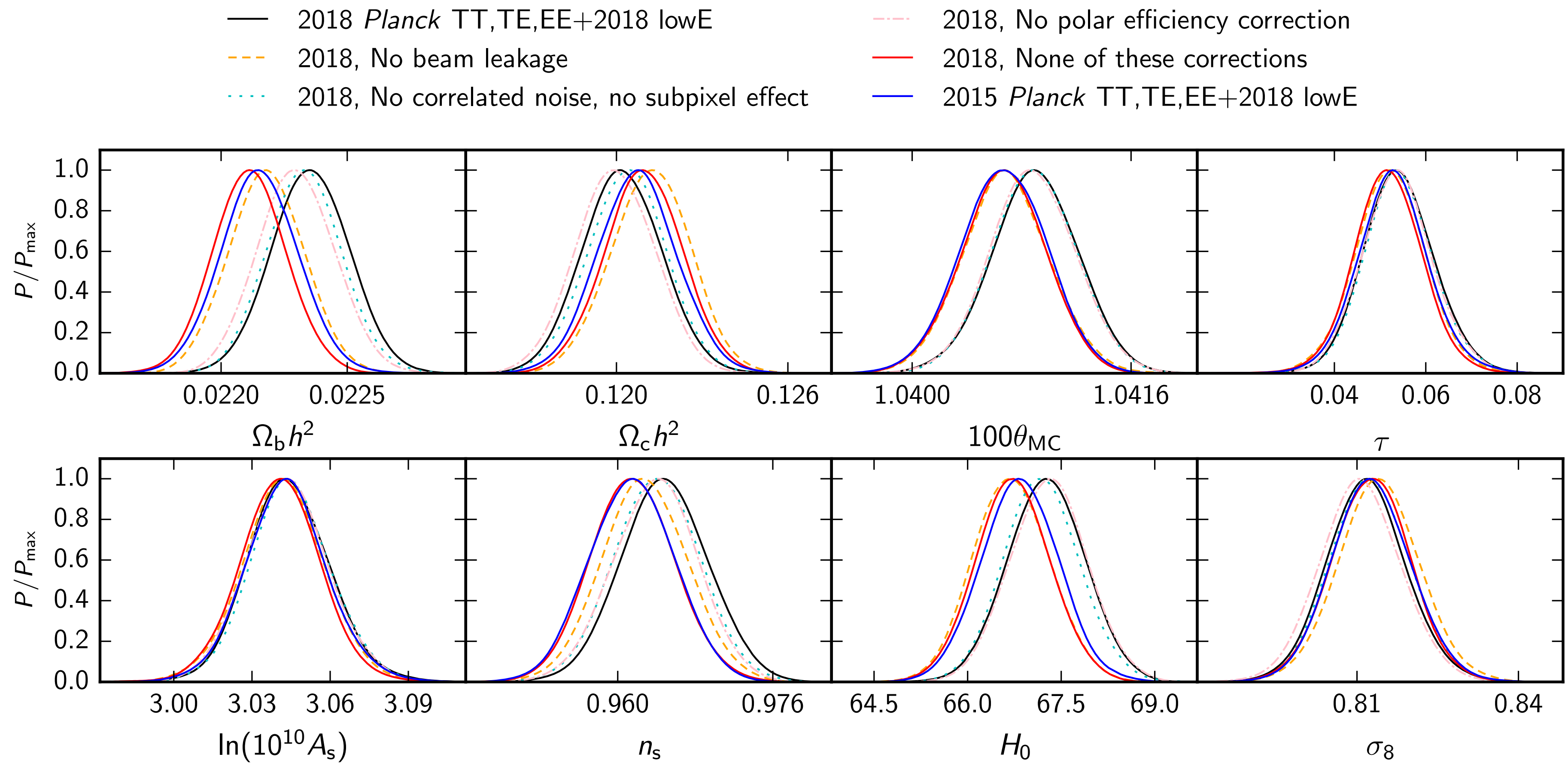
You probably don't care, but the dipole amplitude is now known to 0.025% -- the same uncertainty as for the monopole (i.e. the temperature)!!!

Three CMB numbers known to <0.1%

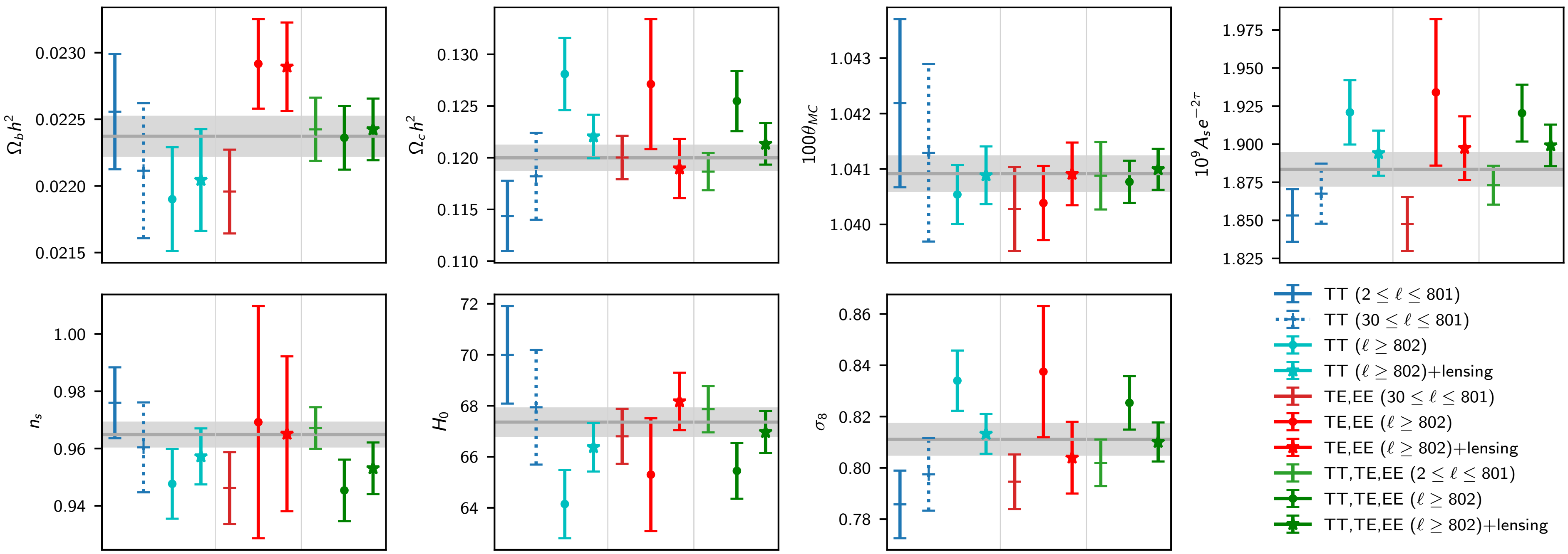
Changes to ΛCDM parameters



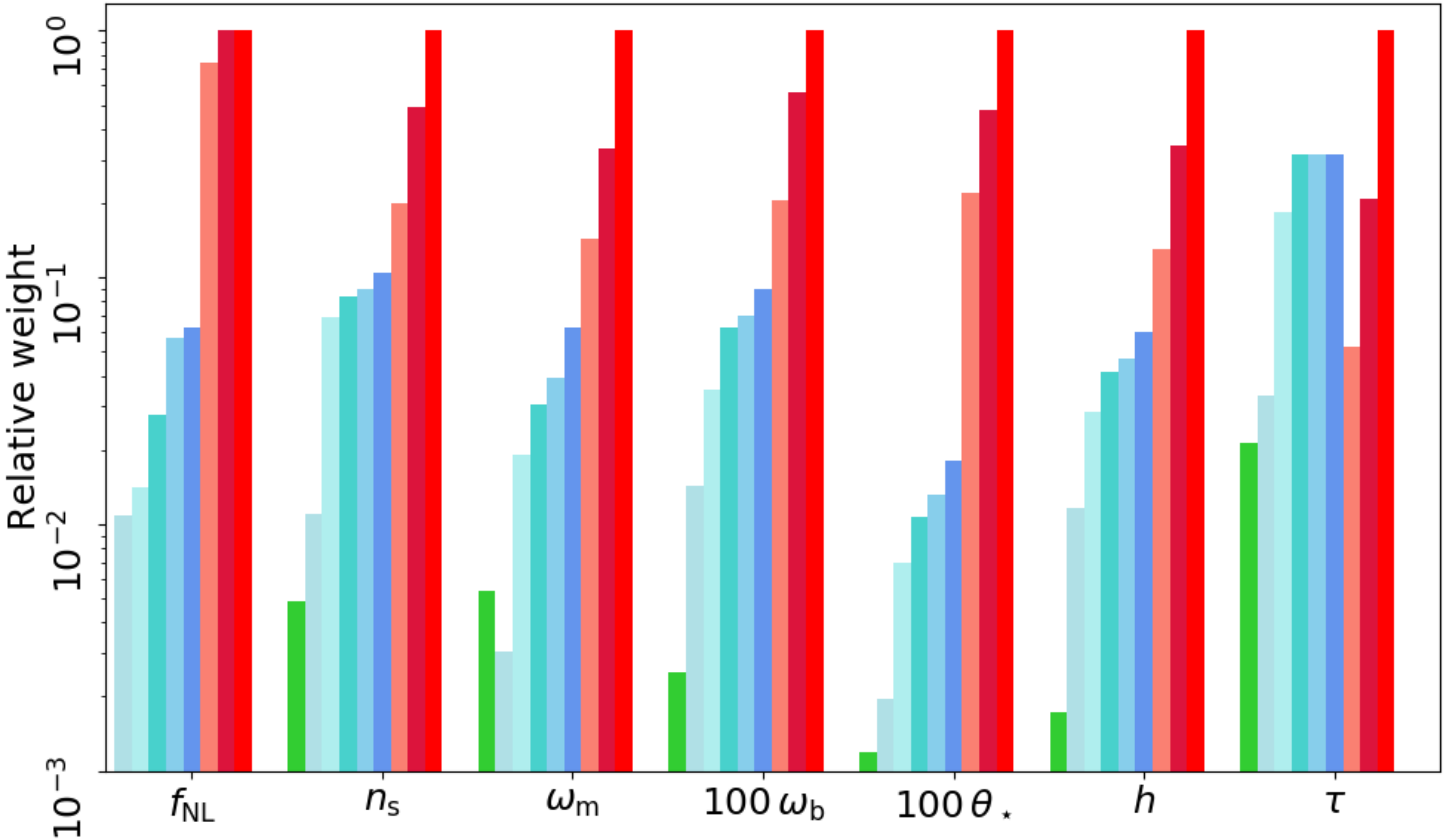
Changes to ΛCDM parameters



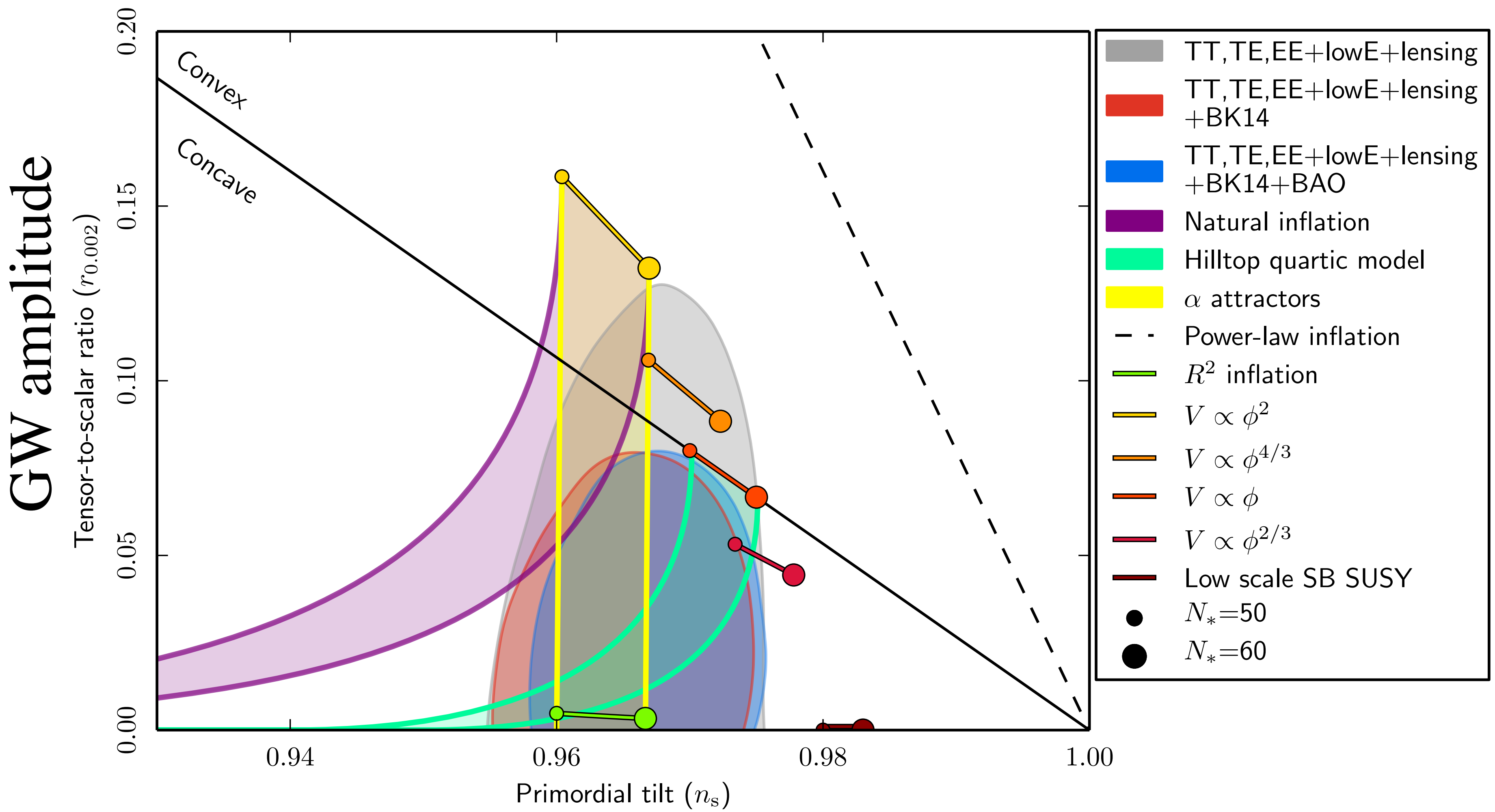
Jackknife tests



Using statistical weight: σ^{-2}



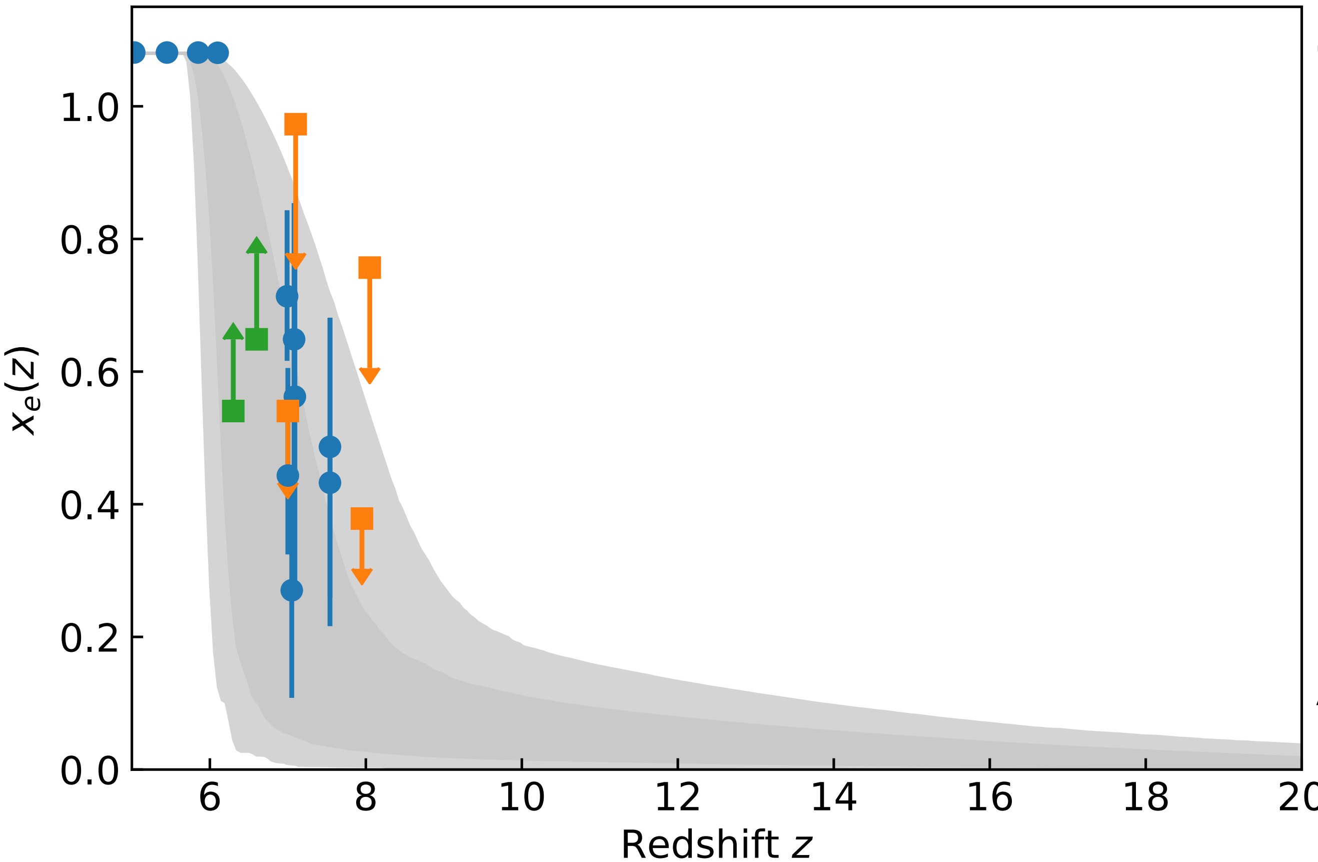
Inflation



Power law index of perturbation spectrum

Optical depth to Thomson scattering

New Planck results point to "*late and fast*" reionization.

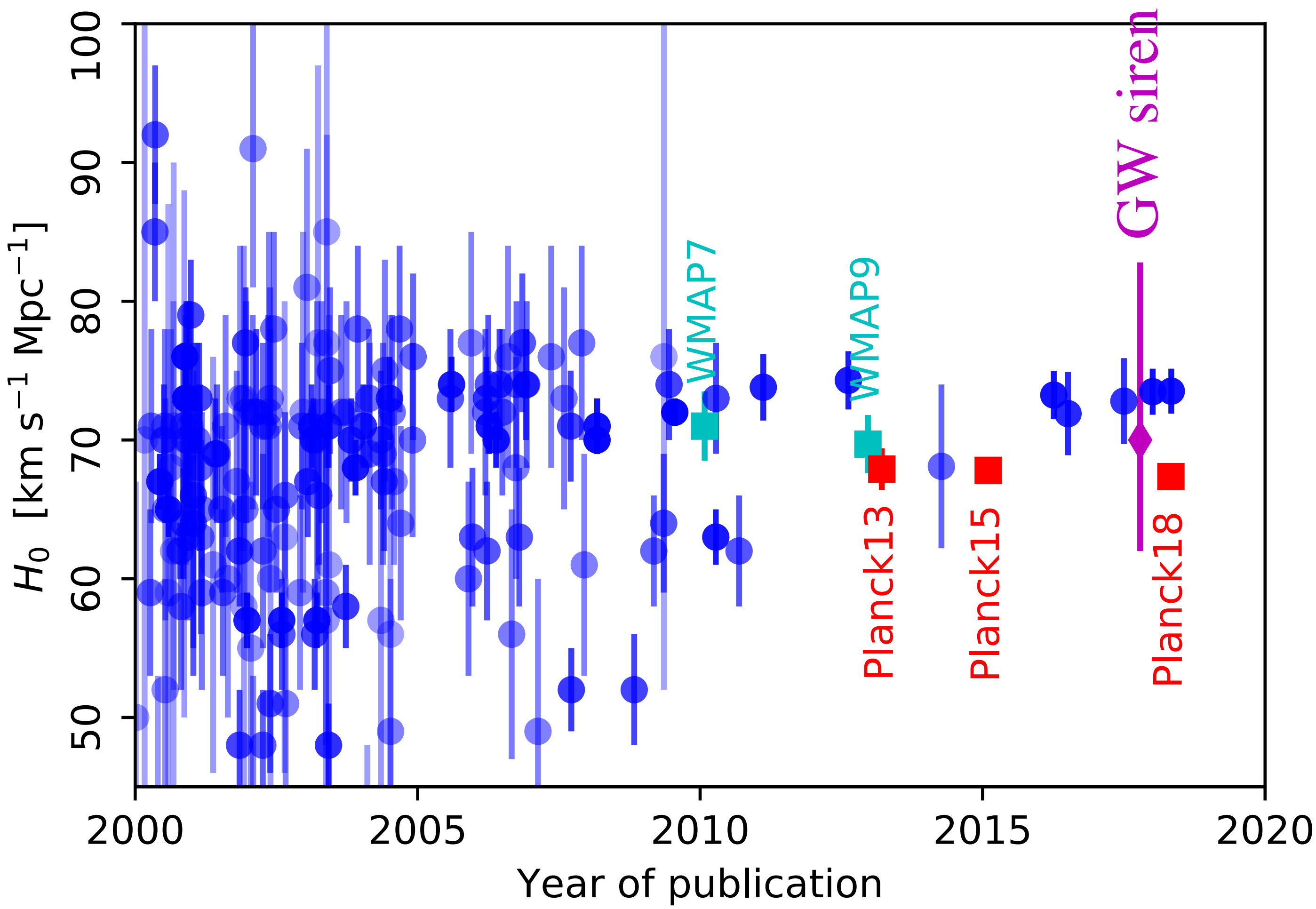


This is easier to accommodate into our view of how reionization occurred based on galaxy counts at early times.

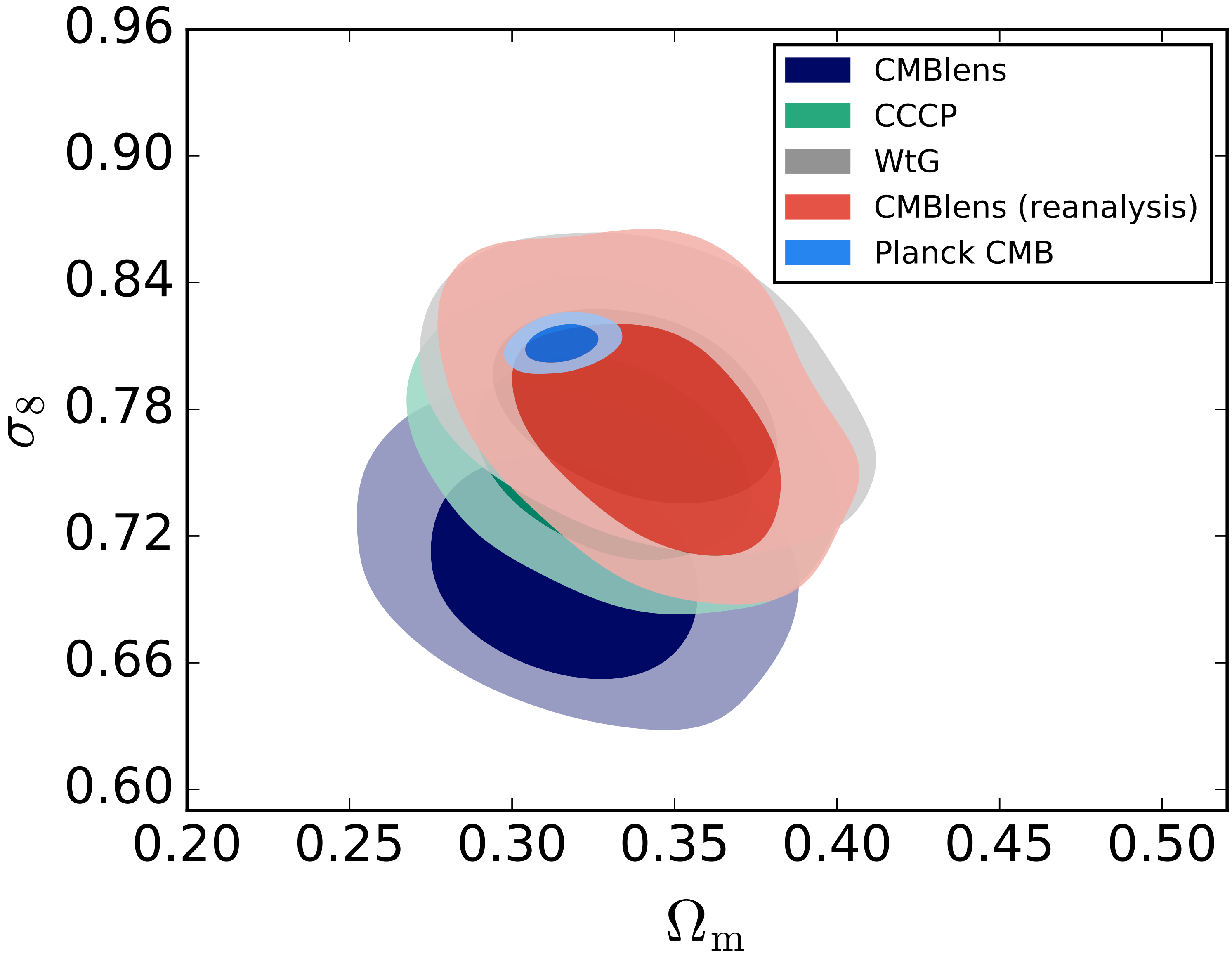
A consistent model is emerging …

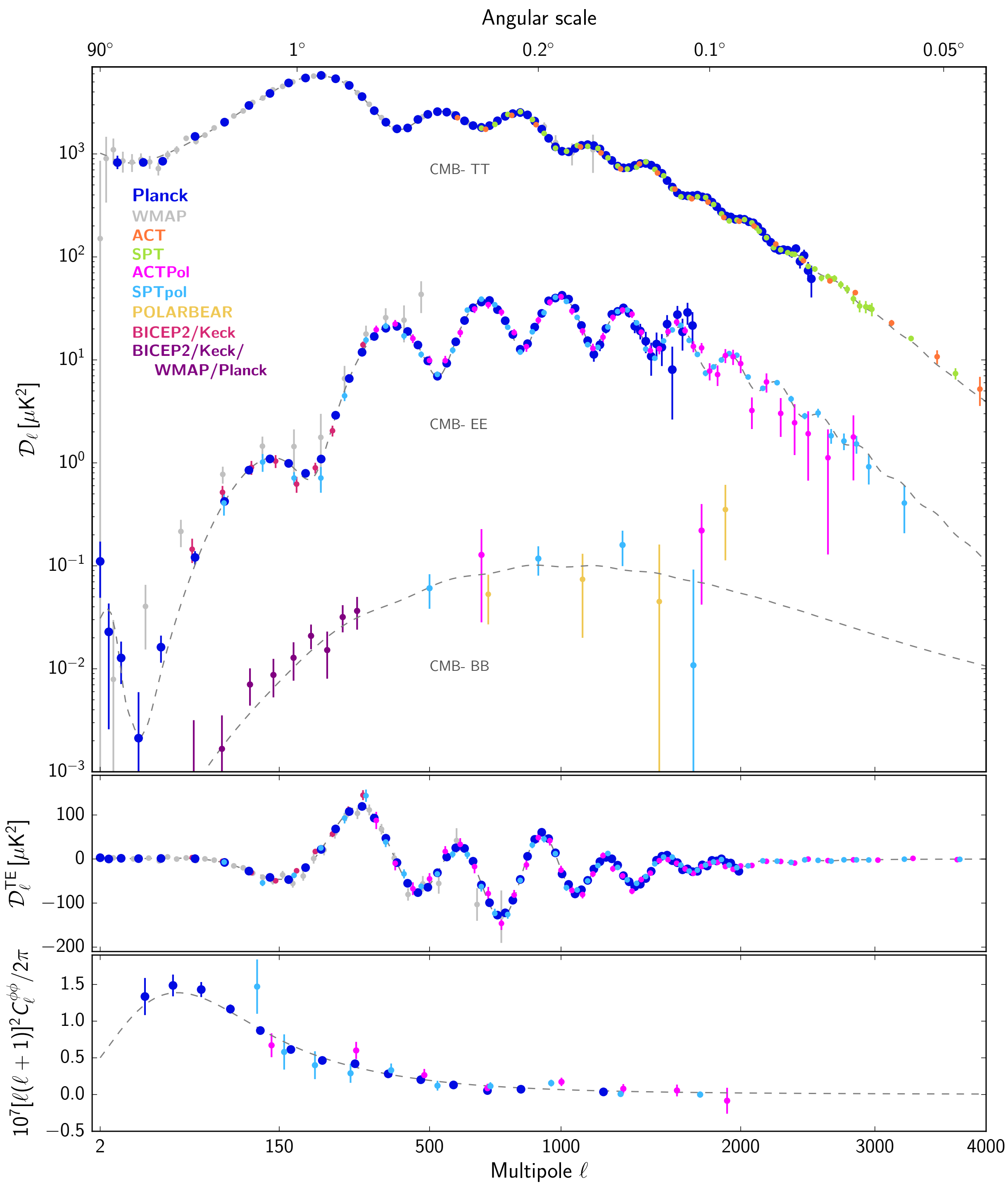
Current Tensions: H_0

Even where tensions remain, dramatic progress has been made!



Current “tensions”: clusters



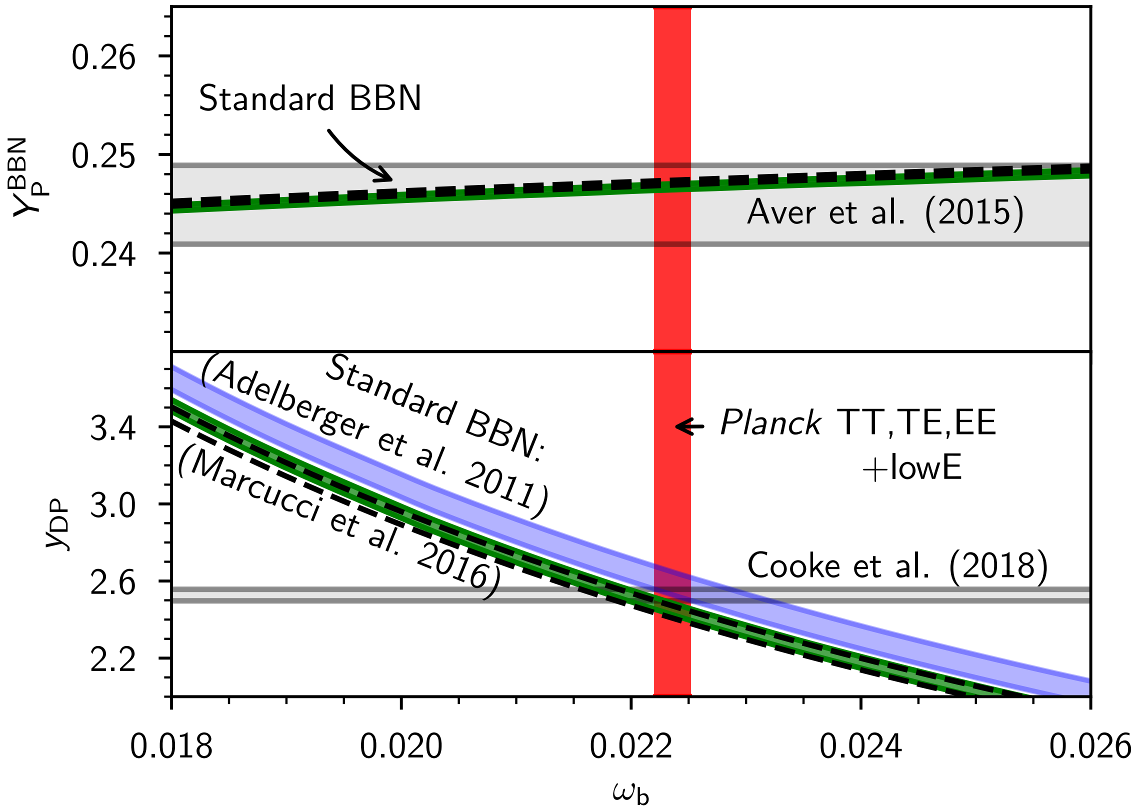


World compilation of CMB anisotropy measurements

Planck dominates TT and (for now) the low ell TE and EE measurements. So far good consistency between experiments.

Physics is Universal!

Baryon density measured by BBN and CMB are in excellent agreement … comparison uses all known laws of physics!



[And we also have a measurement of the Hydrogen 2s➔1s transition which is 5x better than the lab measurement, and in fantastic agreement with the theoretical calculation!]

Consistency with other data

- The Planck data are consistent with the predictions of the simplest ΛCDM models.
- Within the framework of such models we can compare to a wide variety of other astrophysical/cosmological datasets.
  - Primordial nucleosynthesis
  - Baryon Acoustic Oscillations (distance scale).
  - Direct measures of H_0.
  - Redshift-space distortions.
  - Type Ia SNe.
  - Cosmic shear.
  - Counts of rich clusters of galaxies.
  - etc

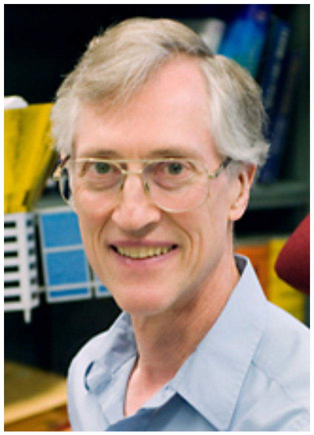
Tensions remain.

Non-Gaussianity: f_{NL}

Type	2013	2014	Generated by…
Local	2.7±5.8	0.7±5.1	Curvaton, reheating, multifield, …
Equilateral	-42±75	-9.5±44	Non-canonical kinetic term or higher derivative (e.g. K-flation, DBI, ghost inflation, with c_s<<1).
Orthogonal	-25±39	-25±22	Non-canonical kinetic term or higher derivative (c_s<<1).

(Other, specific shapes/cases are discussed in papers)

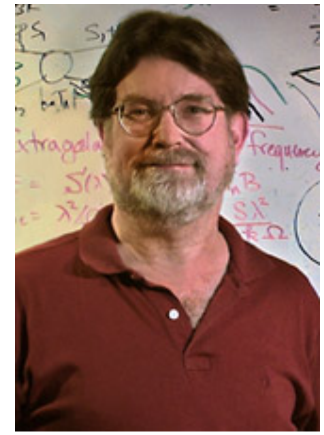
First there was COBE …

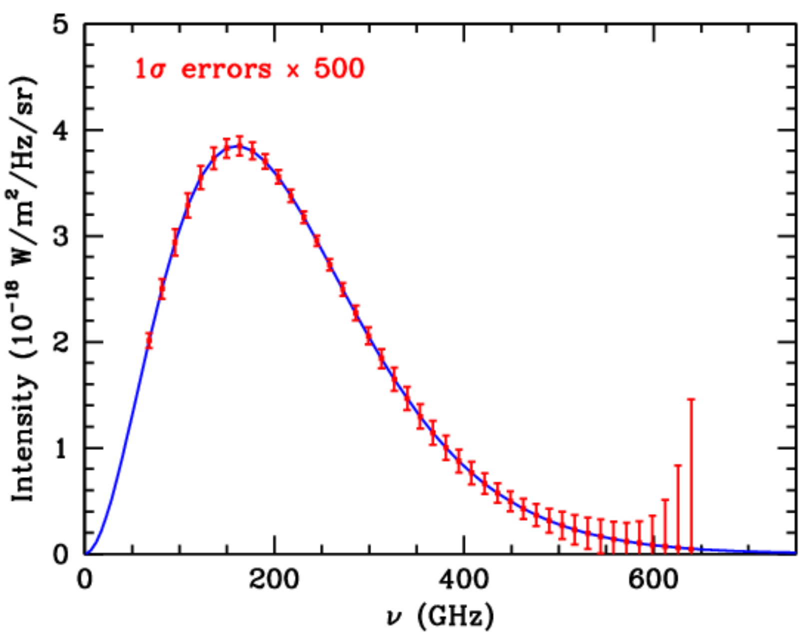


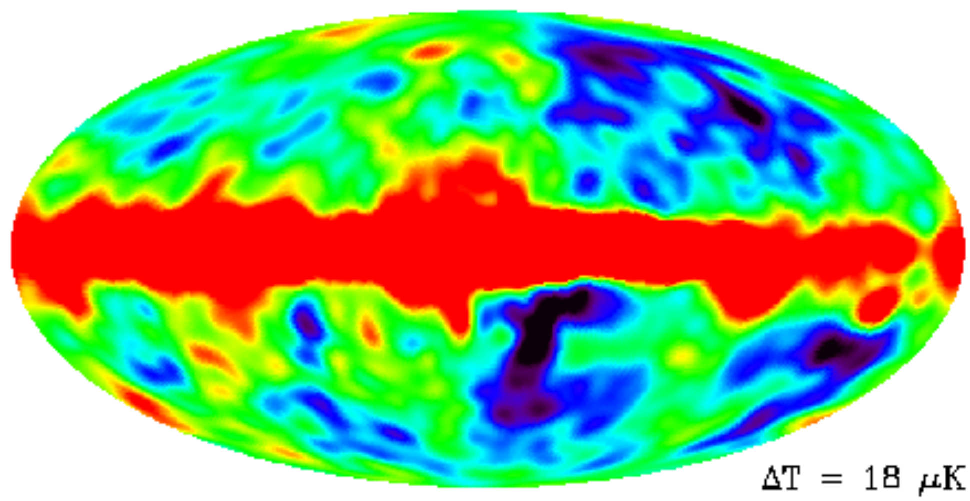
Nobel prize in Physics, 2006, awarded to

Mather and Smoot

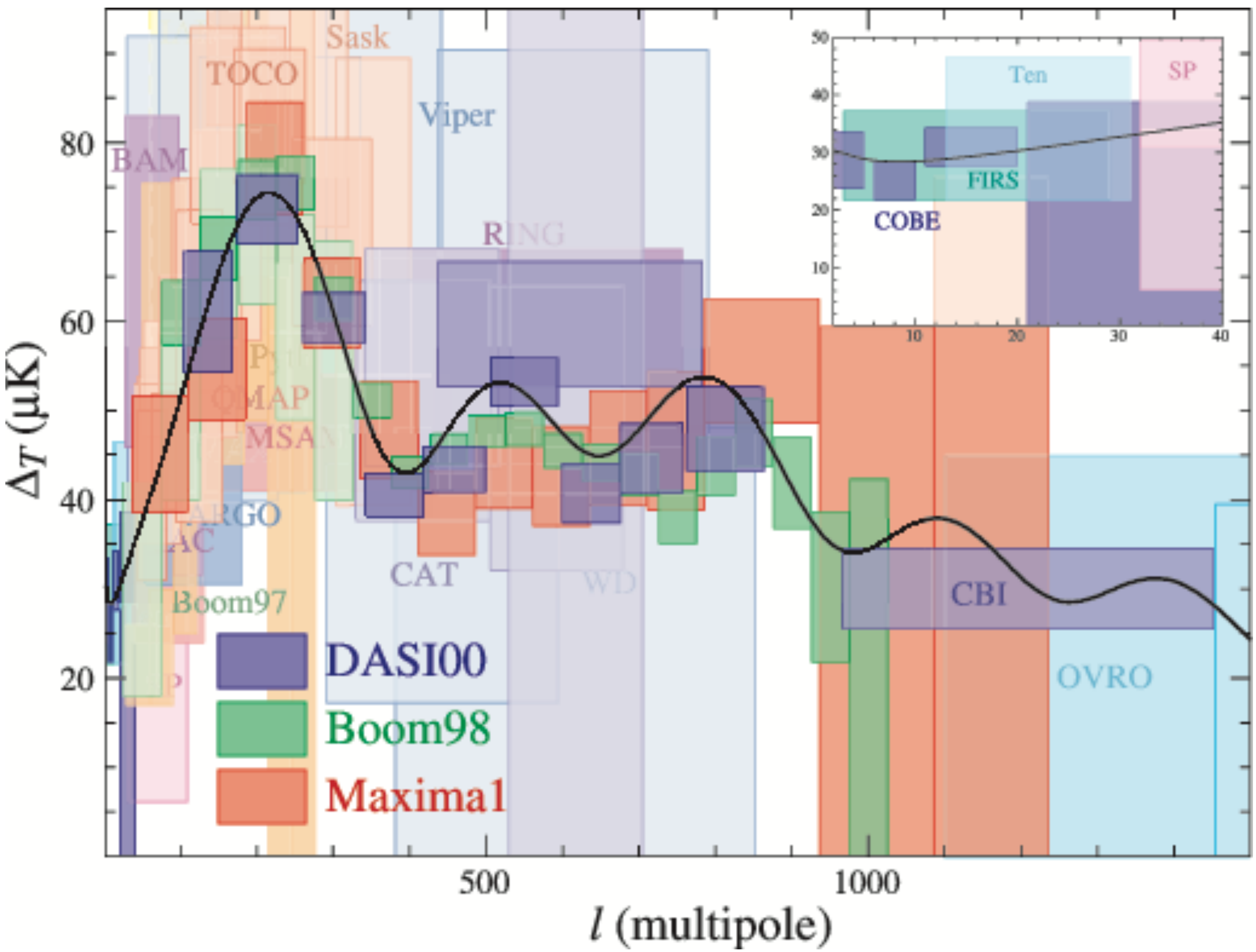
“for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation”



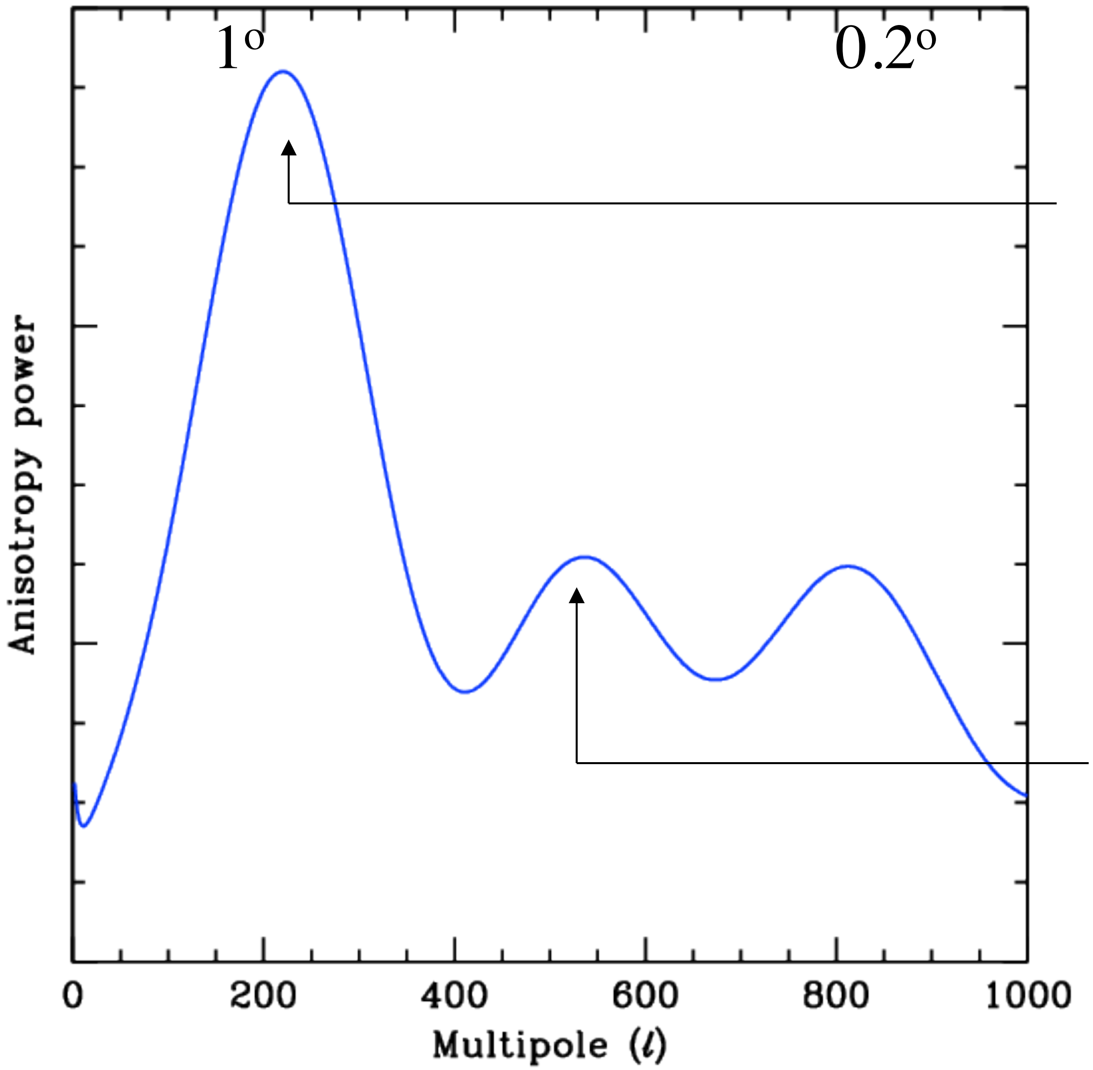




Ground based observations…



Angular power spectrum!

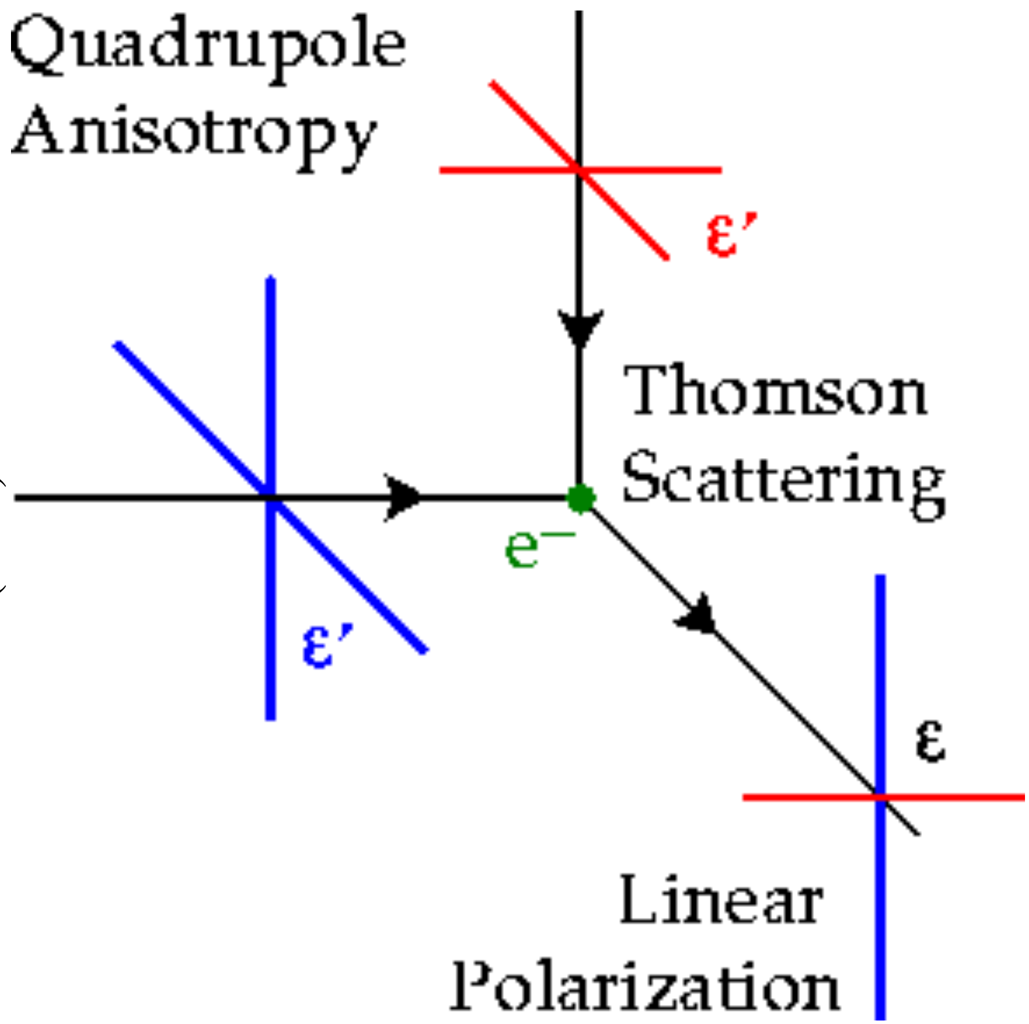


First "compression", at $kc_s t_{ls}=\pi$. Density maximum.

First "rarefaction" peak at $kc_s t_{ls}=2\pi$

→ Smaller scales

Anisotropy generates (linear) polarization



Hu & White (1997)

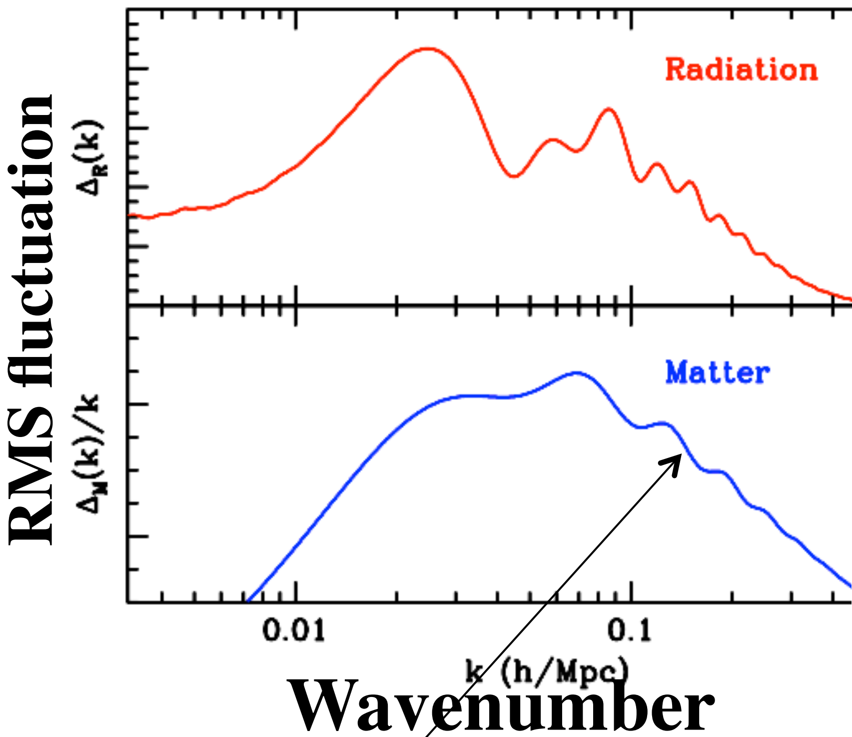
A quadrupole anisotropy generates linear poln.

Normally we define polarization patterns in terms of their parity and (confusingly!) refer to them as E & B modes.

Density perturbations can generate only E-mode polarization, but primordial gravity waves (or vorticity) can generate both E- and B-modes.

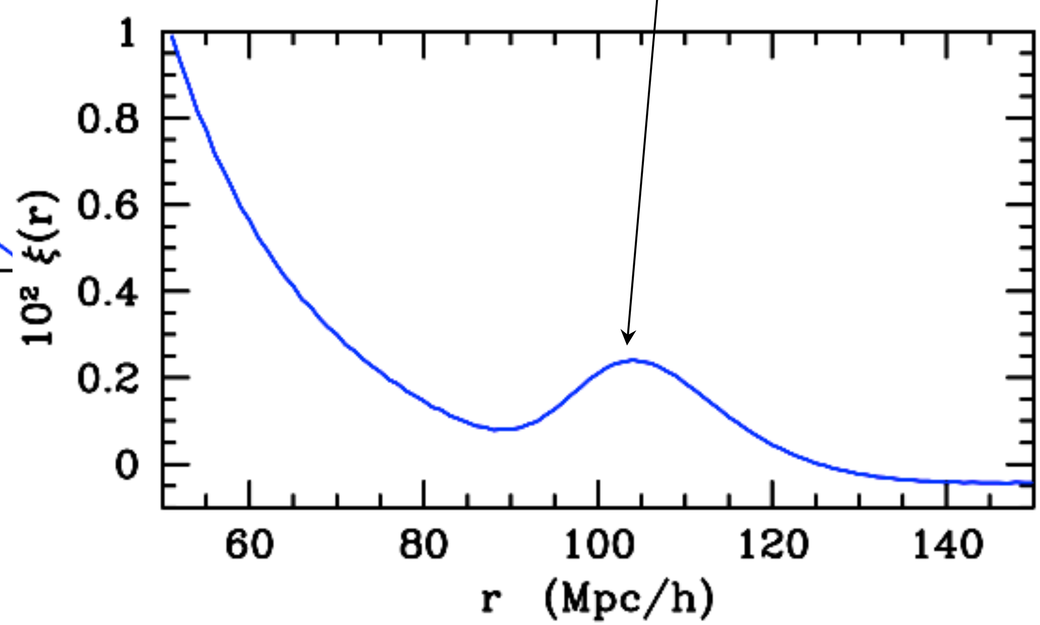
Baryon Acoustic Oscillations?

The oscillations in the photon-baryon fluid also imprint a feature in the late-time clustering of matter … with the same characteristic length scale!
Allows a “standard ruler” test of the expansion history!

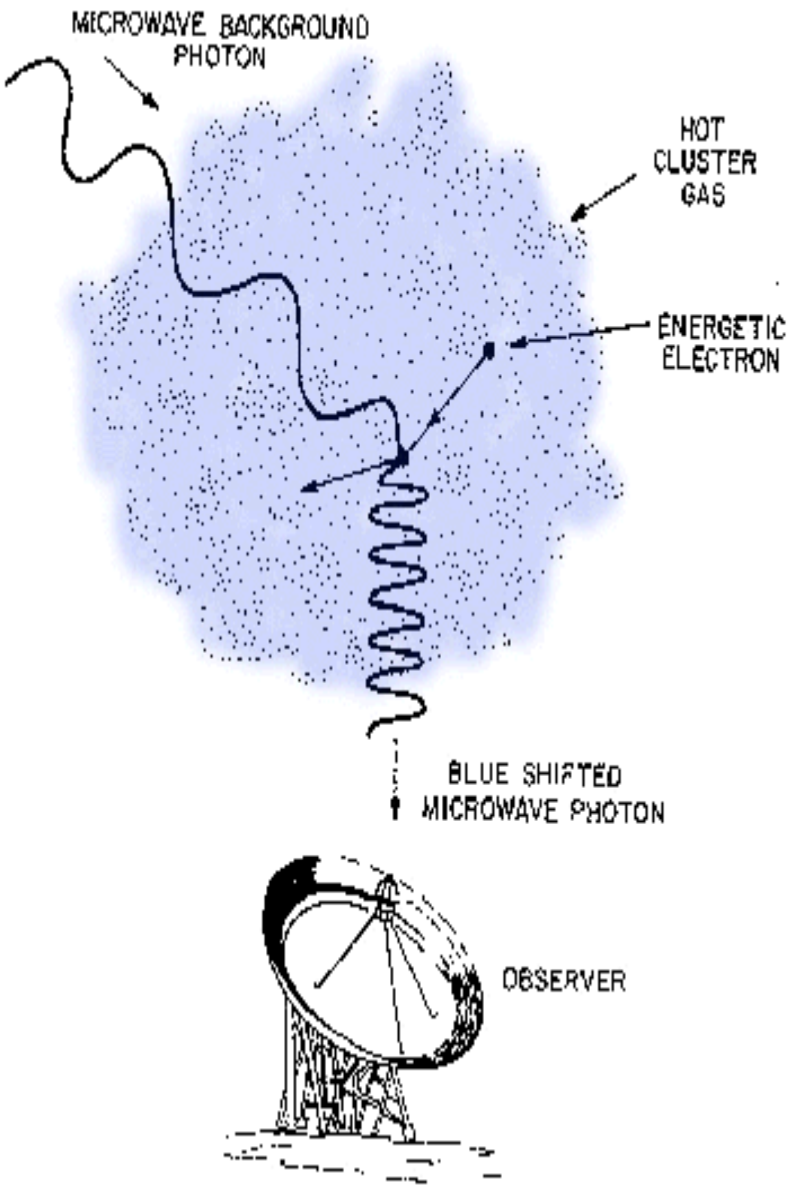


Damped oscillations

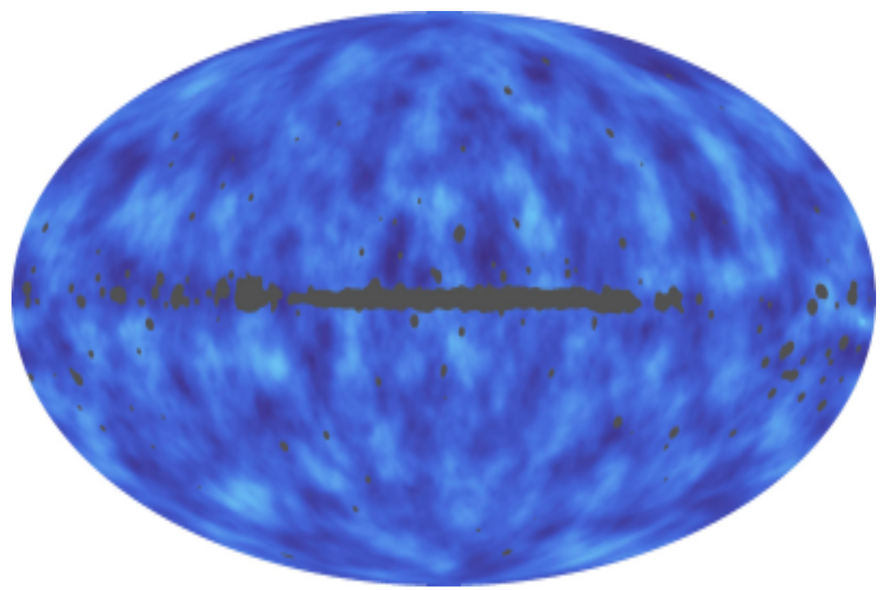
Peak @ ~100 Mpc/*h* with width ~10Mpc/*h*



CMB lensing & SZ effect(s)



"Secondary" anisotropies give us access to information in the "late" Universe – but require higher angular resolution and signal-to-noise ratio.



PLANCK

Looking back to the dawn of time

Planck Telescope
1.5x1.9m off-axis
Gregorian
T = 50 K

LFI Radiometers
30-70 GHz, T = 20 K

HFI Bolometers
100-857 GHz, T = 0.1 K

agenzia spaziale italiana

CENTRE NATIONAL D'ÉTUDES SPATIALES

CMB anisotropy history

- Primordial anisotropy first detected by COBE in 1992.
  - Nobel prize to George F Smoot for "DMR".
- Ground and balloon borne experiments during the 1990s delineated the first peak and the damping tail and first measured polarization anisotropy.
- WMAP – successor to COBE – measured the first 2-3 peaks and begun to fill in the polarization story.
- Planck – latest space mission – currently provides our most precise measurements of temperature and polarization anisotropies.
  - Augmented at small scales by more sensitive, higher resolution, ground-based experiments.