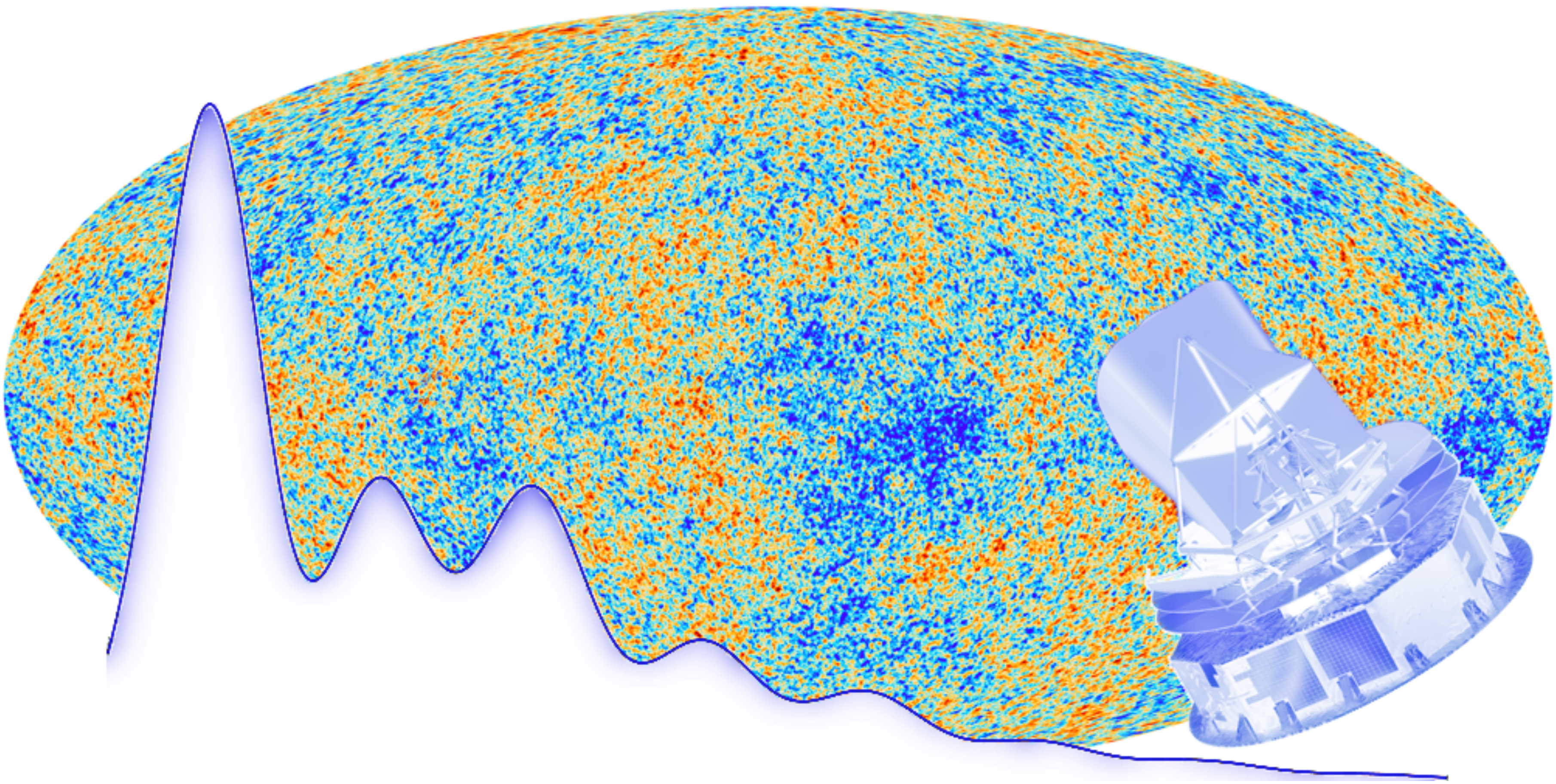
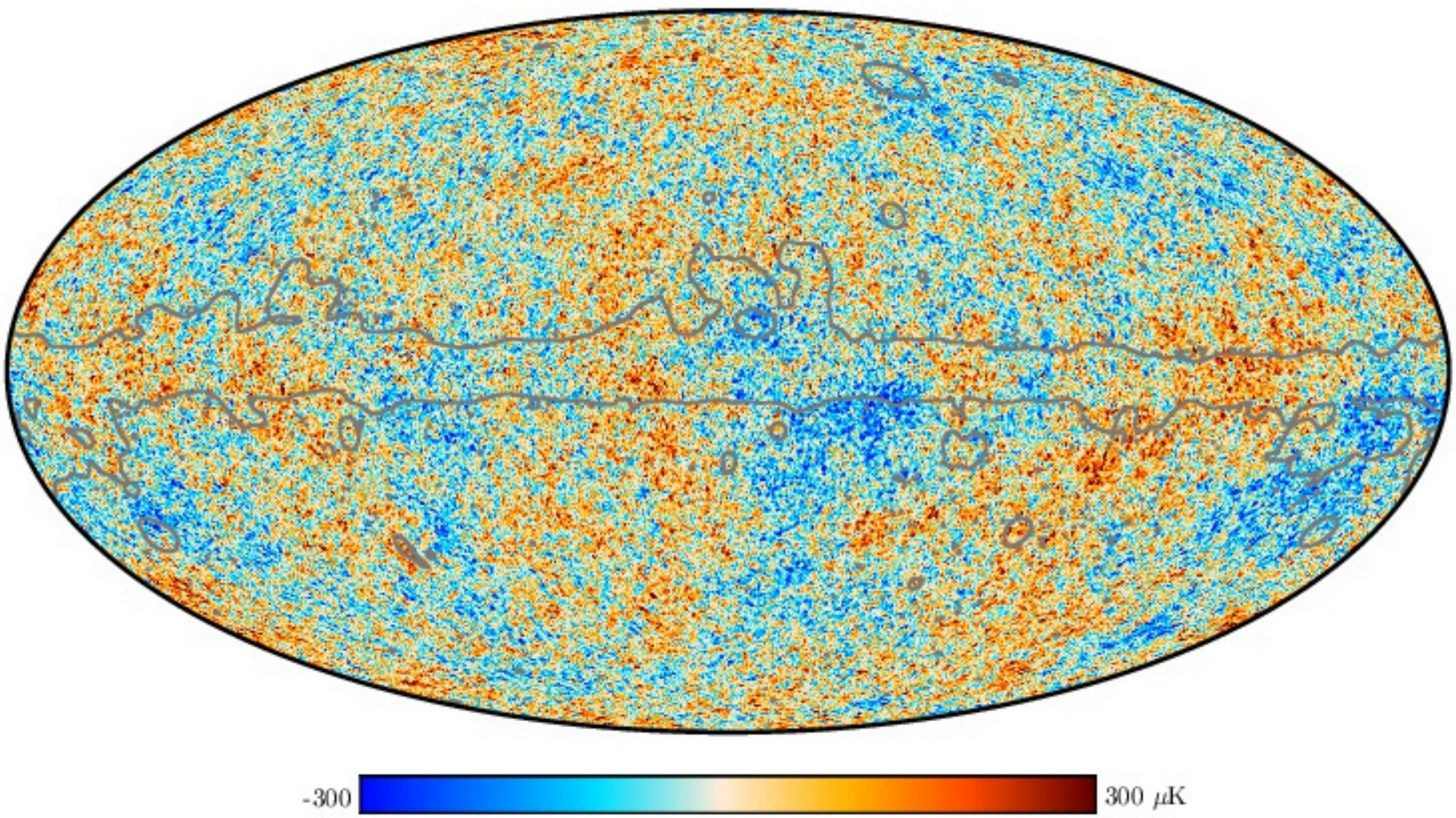
The Cosmological Legacy of Planck



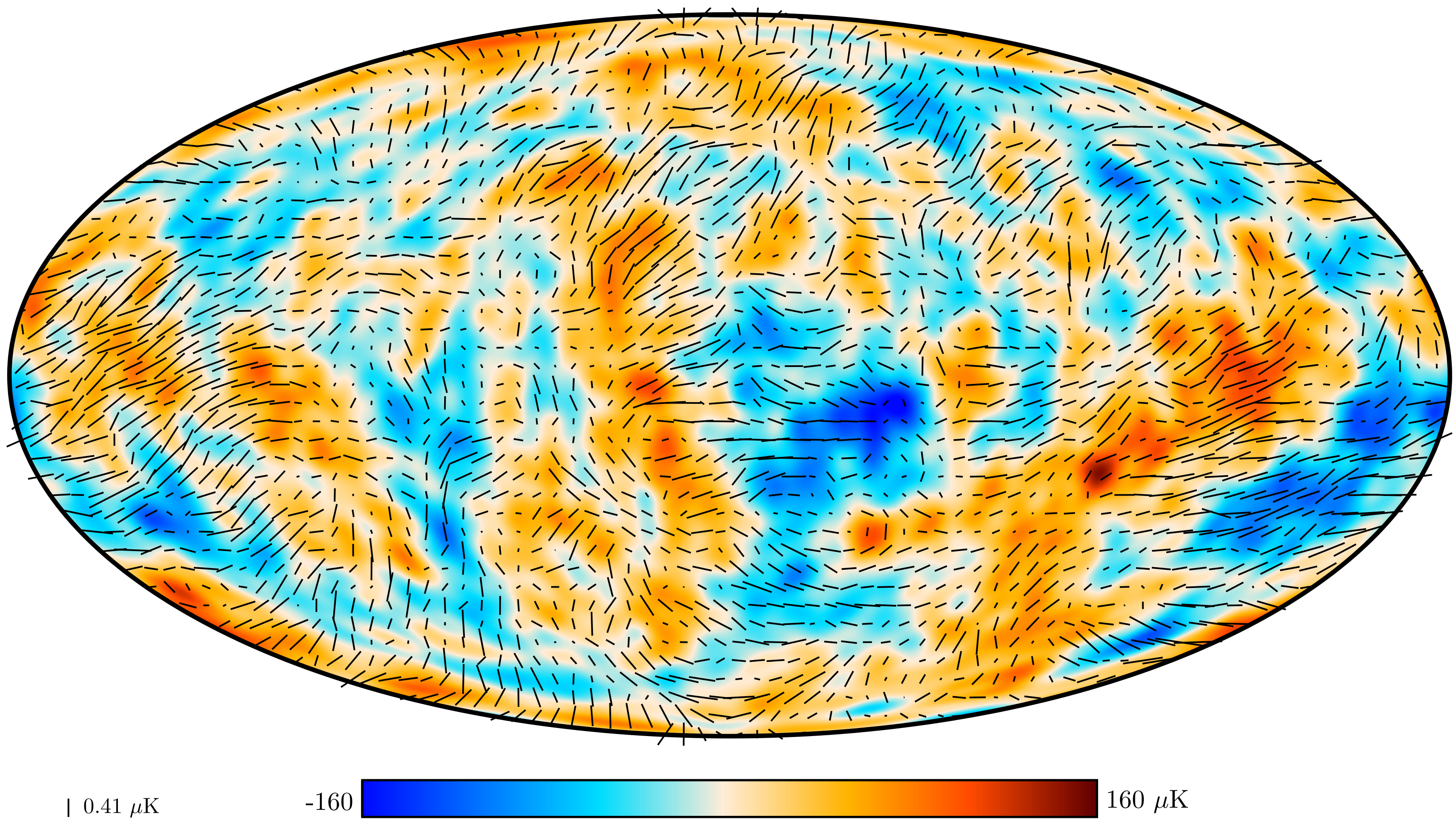
Martin White
Berkeley.

Figs. courtesy V. Pettorino

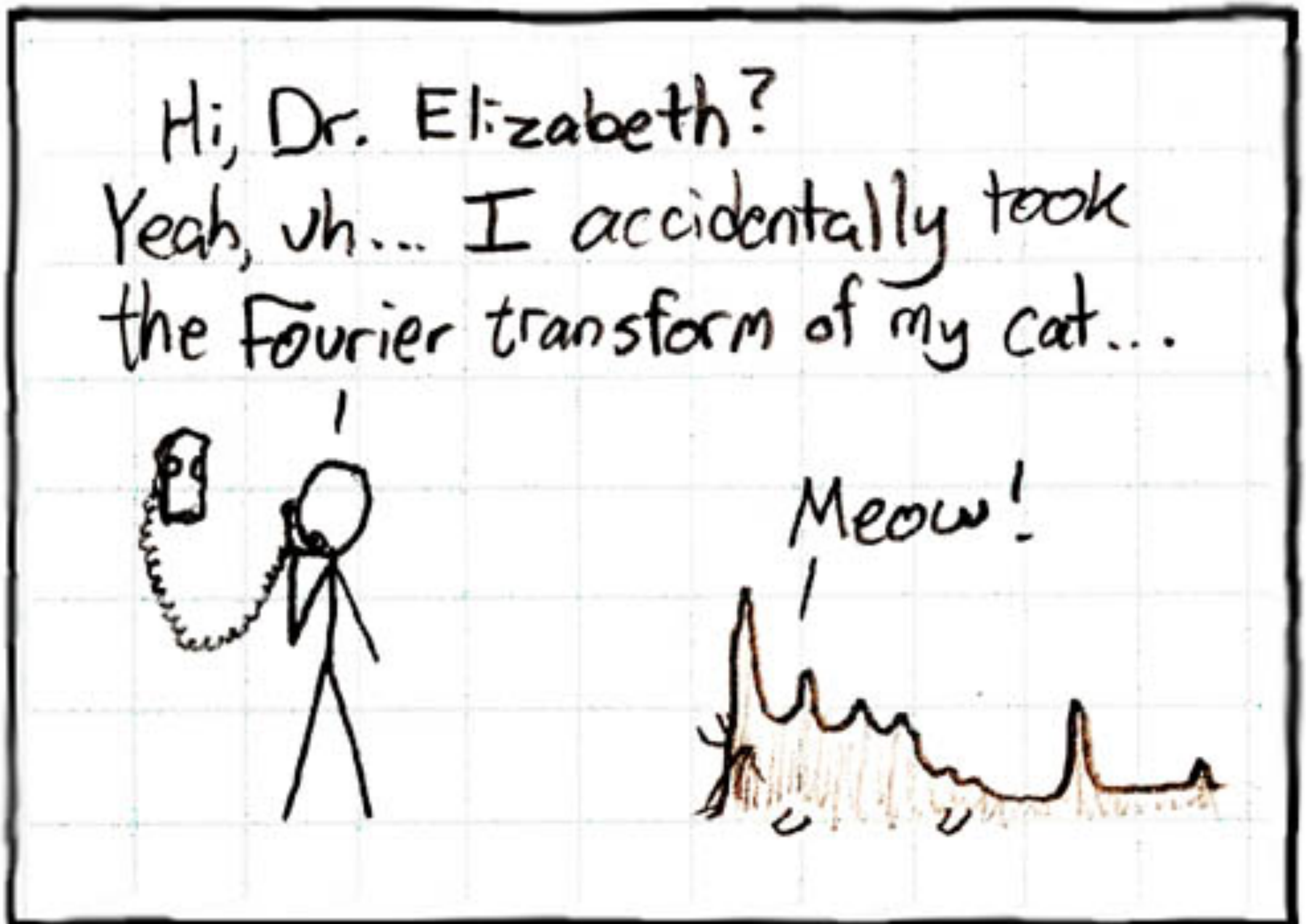
CMB map



CMB map: smoothed + polarization

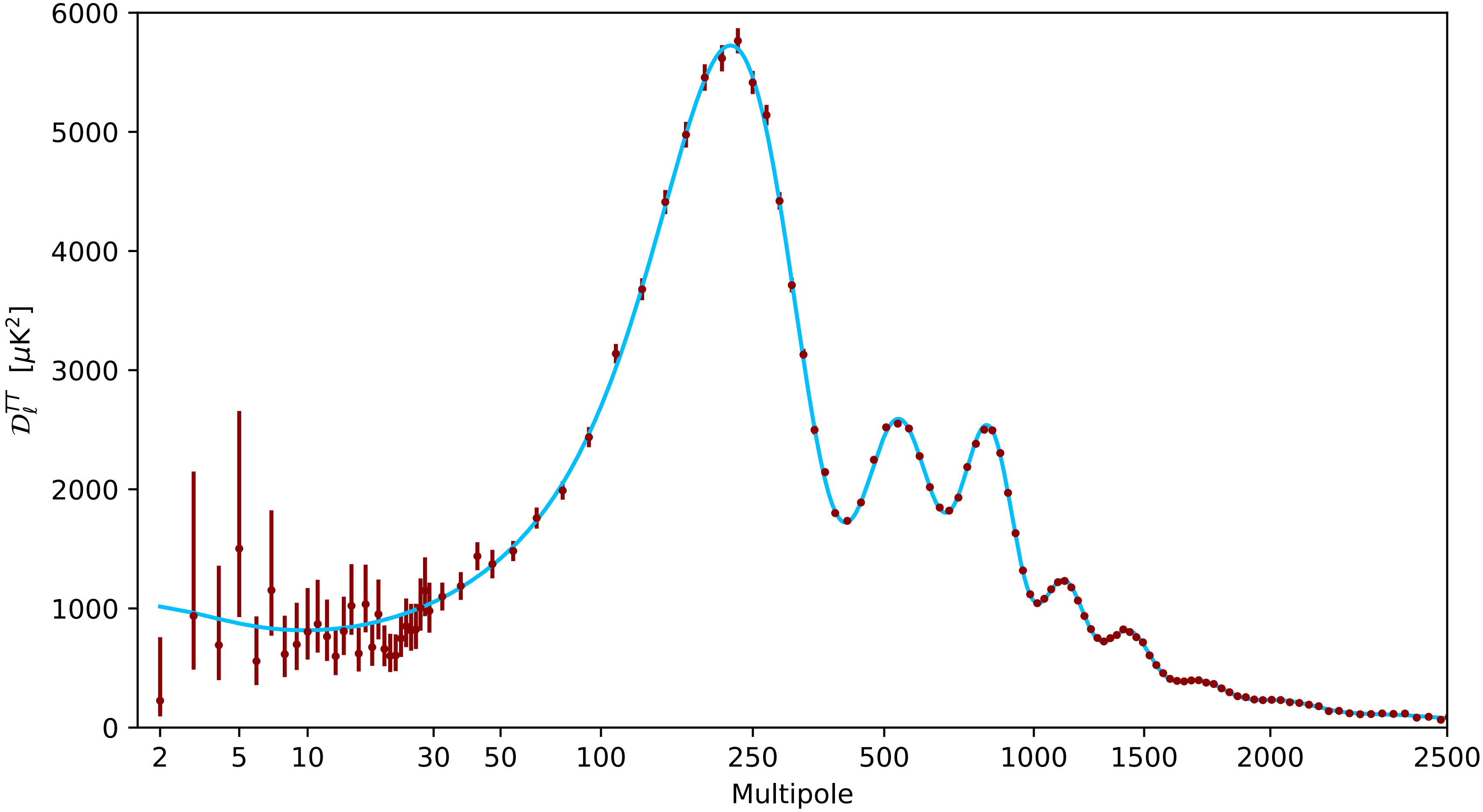


Power spectrum …

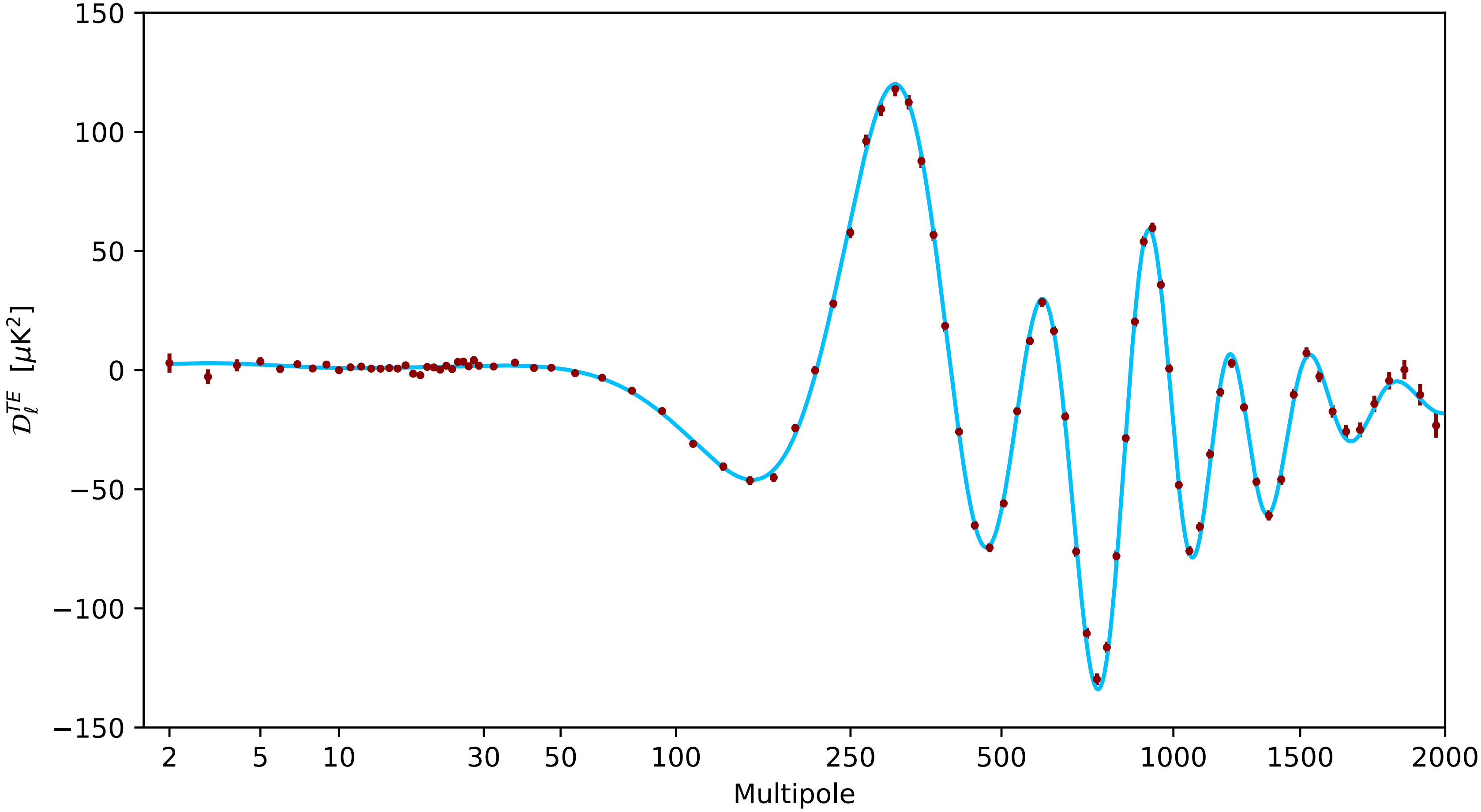


xkcd.com/26

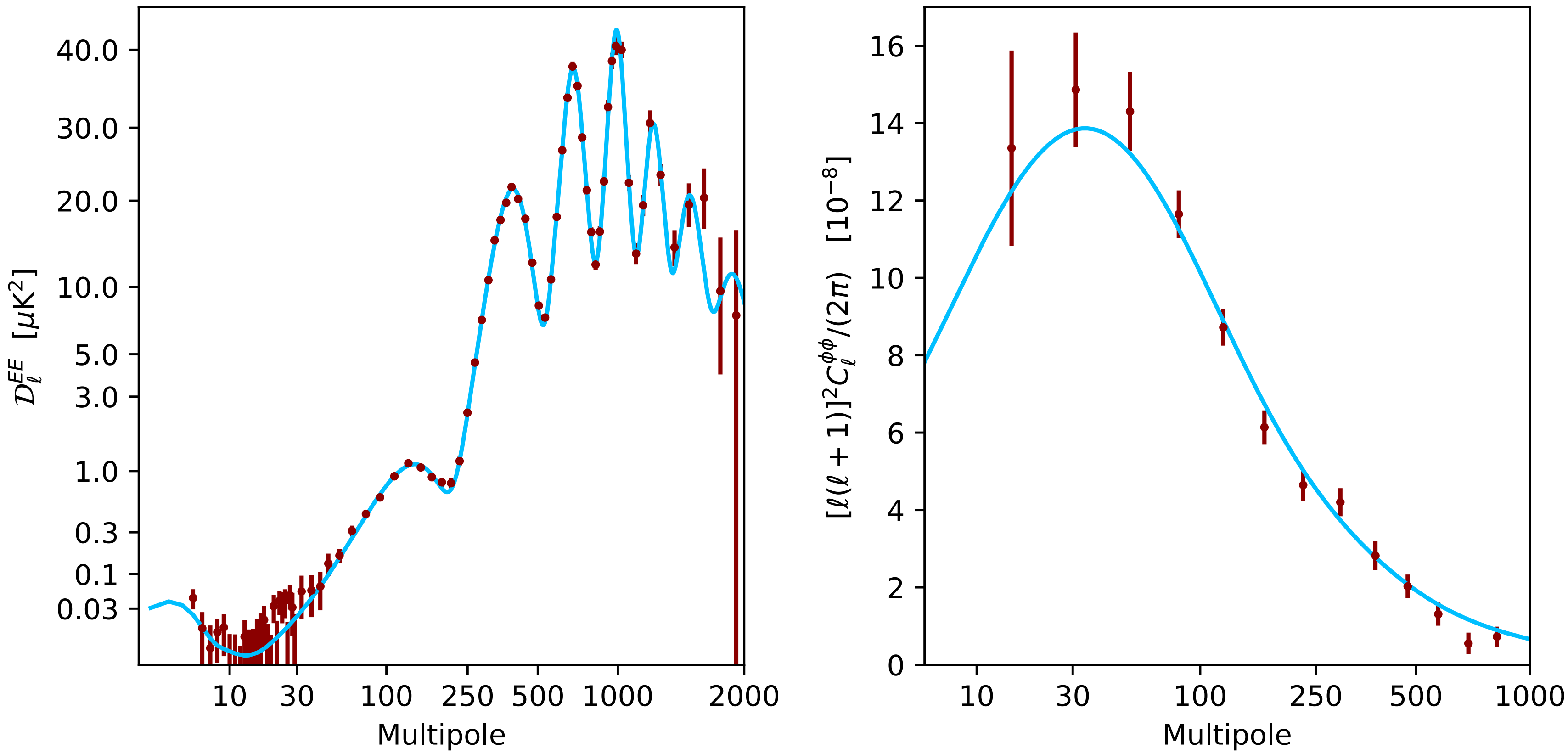
The angular power spectrum



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}

Inflationary ΛCDM: a great phenomenological model

- Model has withstood incredible increases in data quality over the last 3+ decades.
  - Model predictions for anisotropy spectra were quite specific.
  - Many extensions/variants now highly constrained.
- Puzzling contents:
  - Neutrino masses are O(100meV) not O(100GeV).
  - $\omega_B^{BBN} = \omega_B^{CMB} \sim \omega_M$; DE smooth & "turns on" rapidly today.
  - No sign of "extra" relativistic species or spatial curvature ...
- Model connects high-energy physics to cosmology and "explains" 14Gyr of cosmic evolution, but our understanding is "highly incomplete"!

Planck & Inflation

- CMB quickly established early Universe origin of perturbations.
- 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	$r_{0.002}$<0.1 (95%; <0.07+BKP)
which are Gaussian	f_{NL} = -0.9 ± 5.1 ~ 0
and adiabatic	α_{-1} = 0.00013 ± 0.00037
with negligible topological defects	f_{NG} < 0.01 (95%)

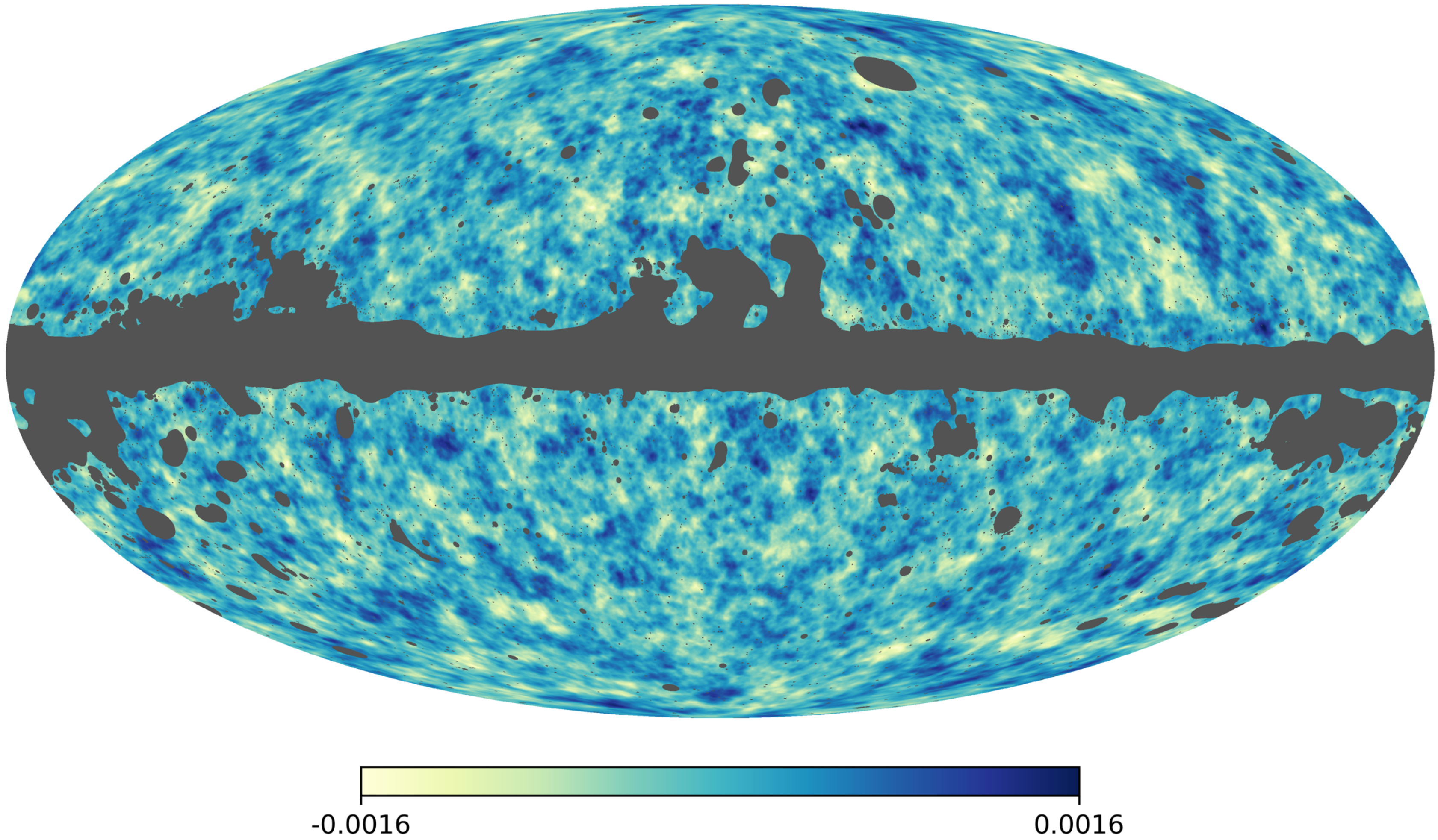
Inflationary models

- Coherence of peaks, sign of TE
  - Early Universe origin of perturbations
- Ω_K~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'~0 and V''<0
  - special point in potential.

CMB lensing

- Photons from the CMB are deflected on their way to us by the potentials due to large-scale structure.
- 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)



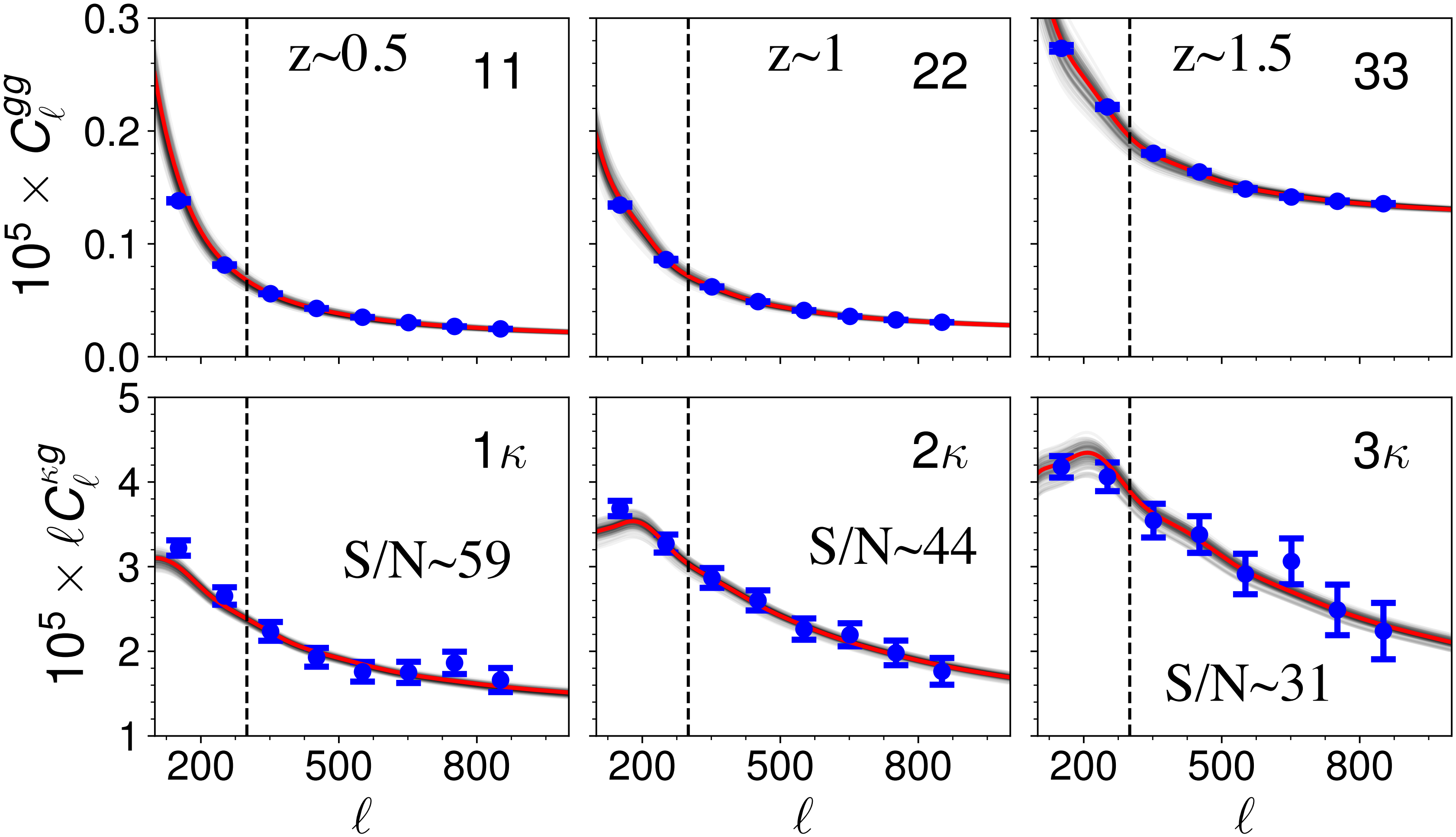
Lensing now measured at >40σ

A lensing first …

- Planck was definitely not the first experiment to
  - Measure gravitational lensing
  - … by large scale structure
  - … of the CMB

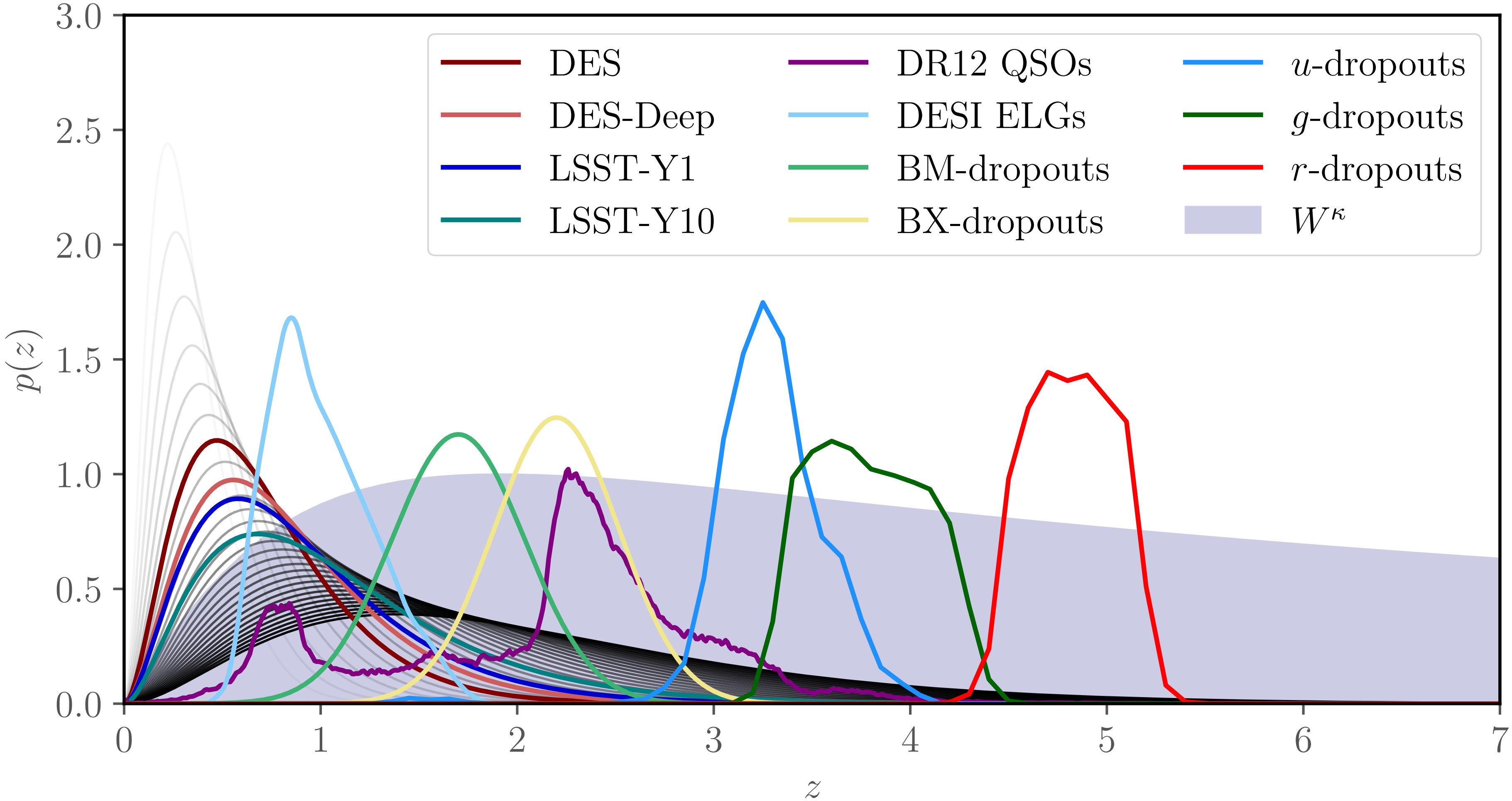
- However it was the first to do it over a significant fraction of the sky with enough S/N to drive fits and provide a sharp test of the theory.
- A "coming of age" story for CMB lensing.
- Planck ushers in a new era of CMB studies of the "intermediate" redshift Universe, synergistically with DES, WISE, HSC, DESI, PFS, LSST, Euclid, WFIRST, …

Cross-correlation with (un)WISE galaxies



Krolewski, Ferraro++

Tomographic decomposition of lensing kernel



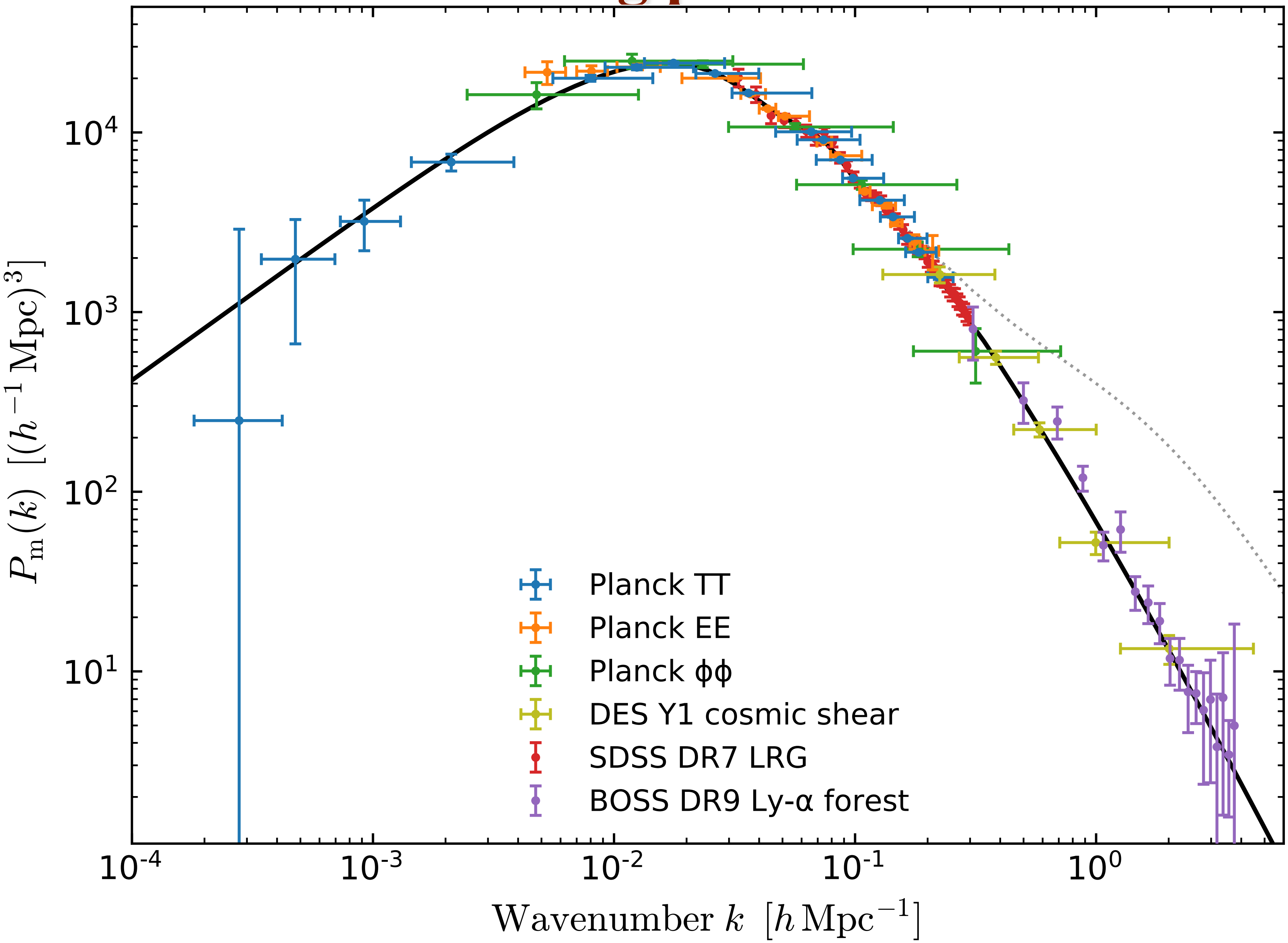
Wilson & White (2019)

CMB + LSS

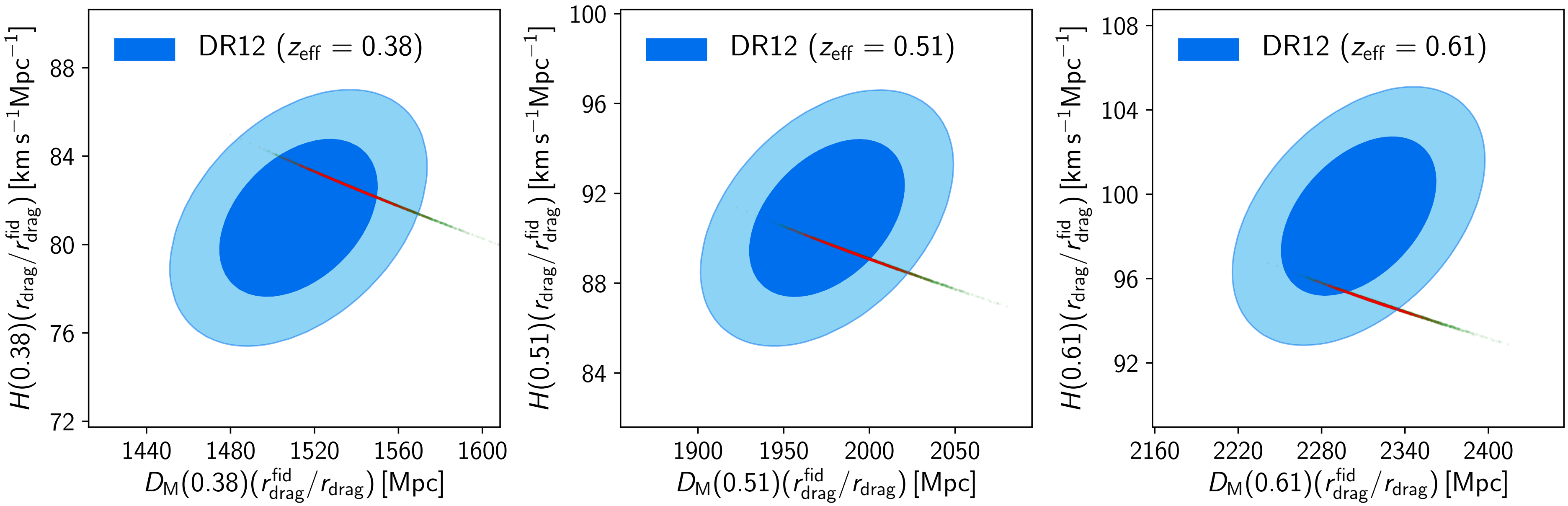
- By cementing the gravitational instability paradigm and measuring the ICs and parameters, Planck sets the framework for LSS.
- Planck precisely determines many of the key parameters for large-scale structure (in ΛCDM):
  - k_{eq} = 0.01038 ± 0.00008 Mpc^{-1} , $\sigma_8(z=2)$ = 0.3211 ± 0.0009
- Planck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

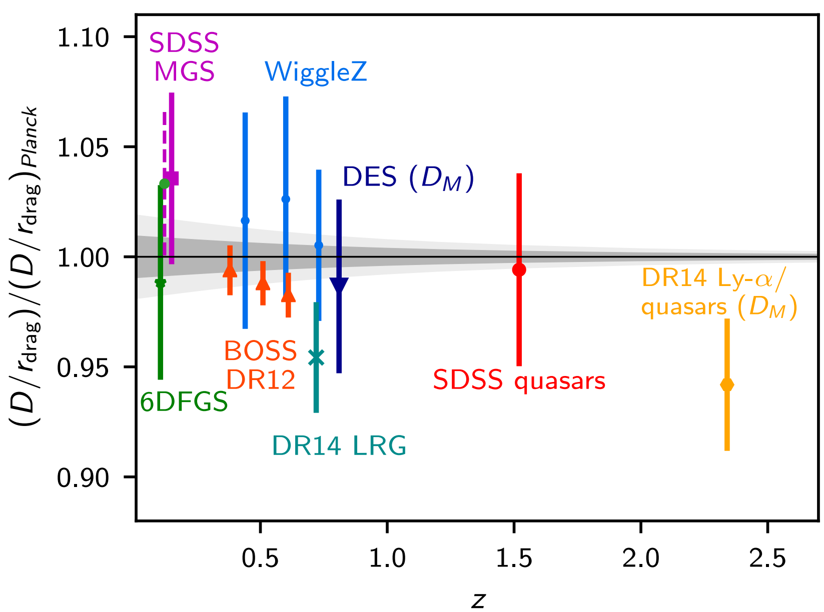
Early on, the fields of LSS and CMB were tightly coupled. With time they grew apart and specialized. I think we are witnessing a re-coupling.

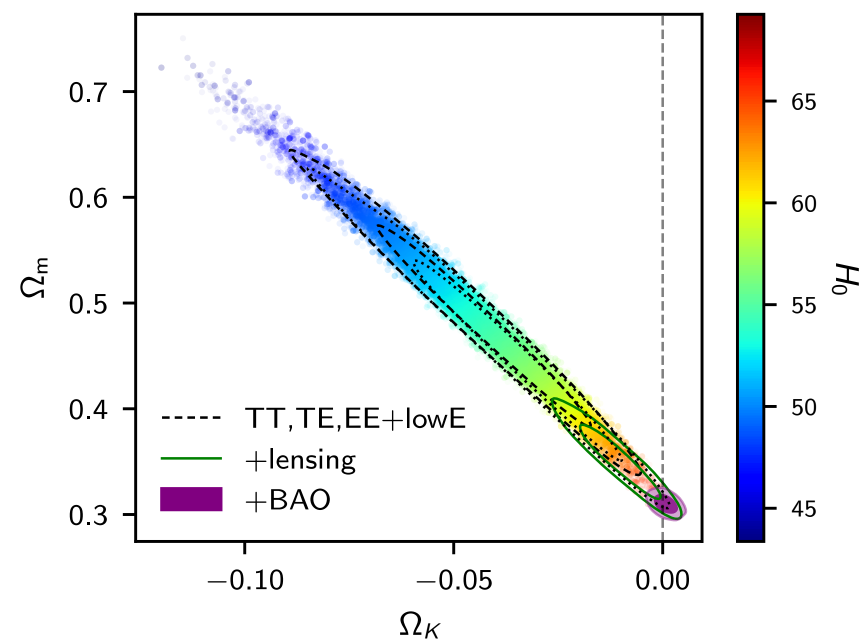
The big picture



Cosmic distance scale

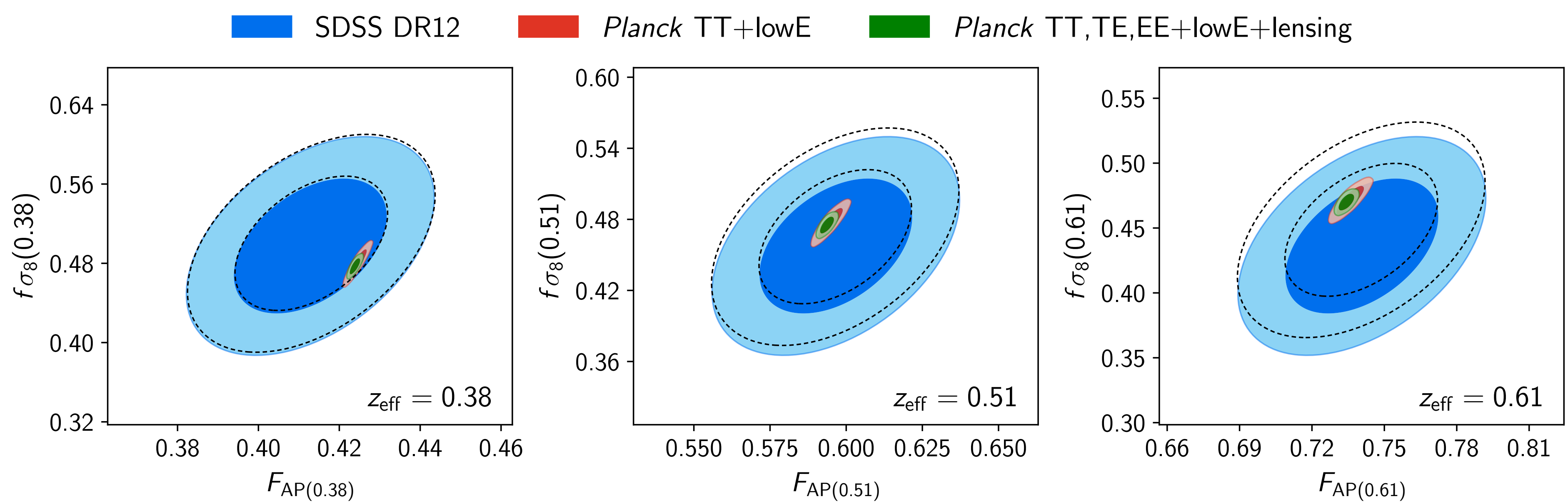






Redshift-space distortions: Planck vs BOSS

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)

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.

Conclusions

- Planck has "completed" the primary temperature anisotropy story begun by COBE.
  - 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.
- Established CMB lensing as a competitive cosmological tool.
  - Synergies between large-scale structure and CMB are only growing in importance!
- The next decade will see a host of new facilities coming on line, enabling increasingly precise tests of our models … building on the cosmological legacy of Planck.

The End