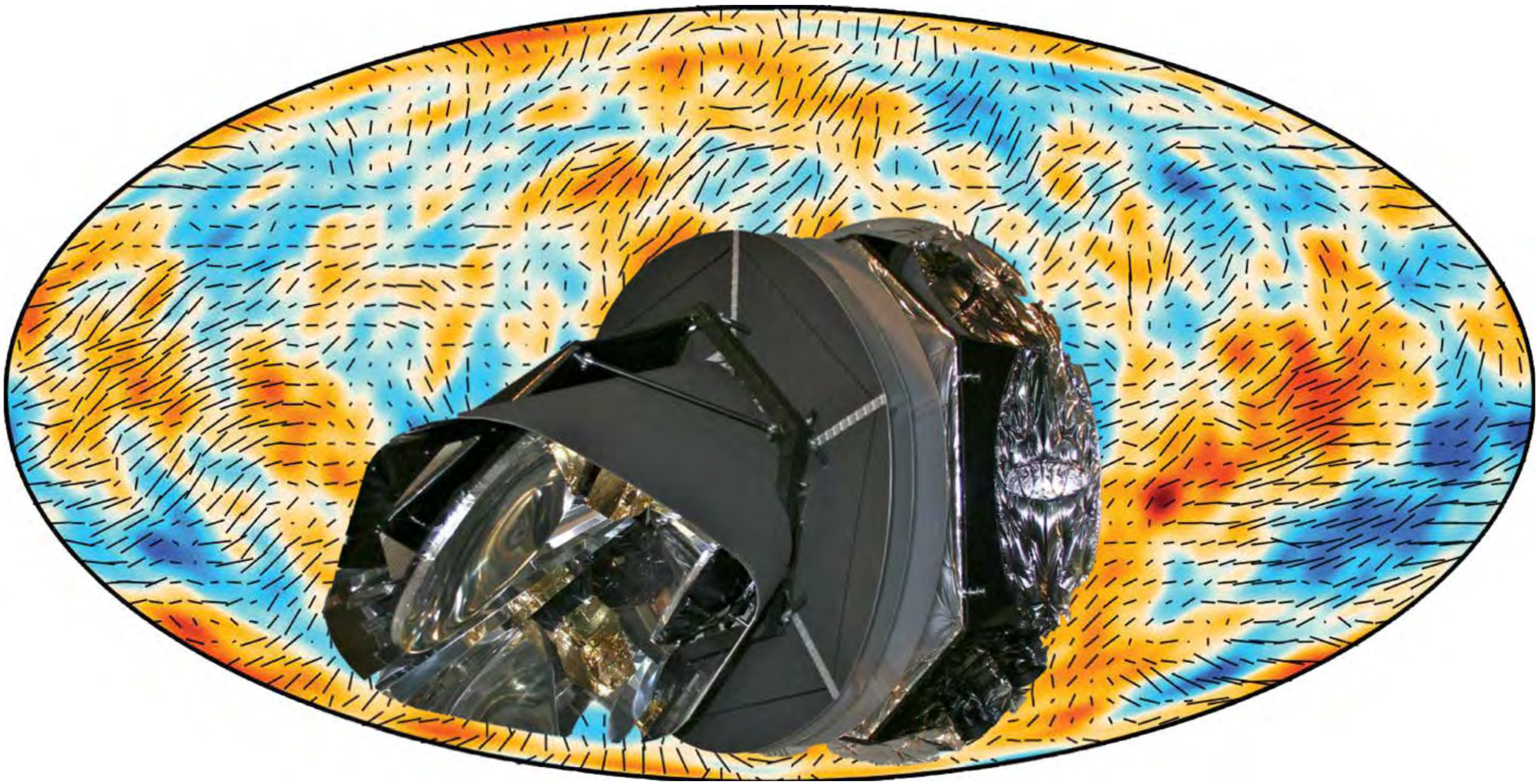
What we have learnt from Planck

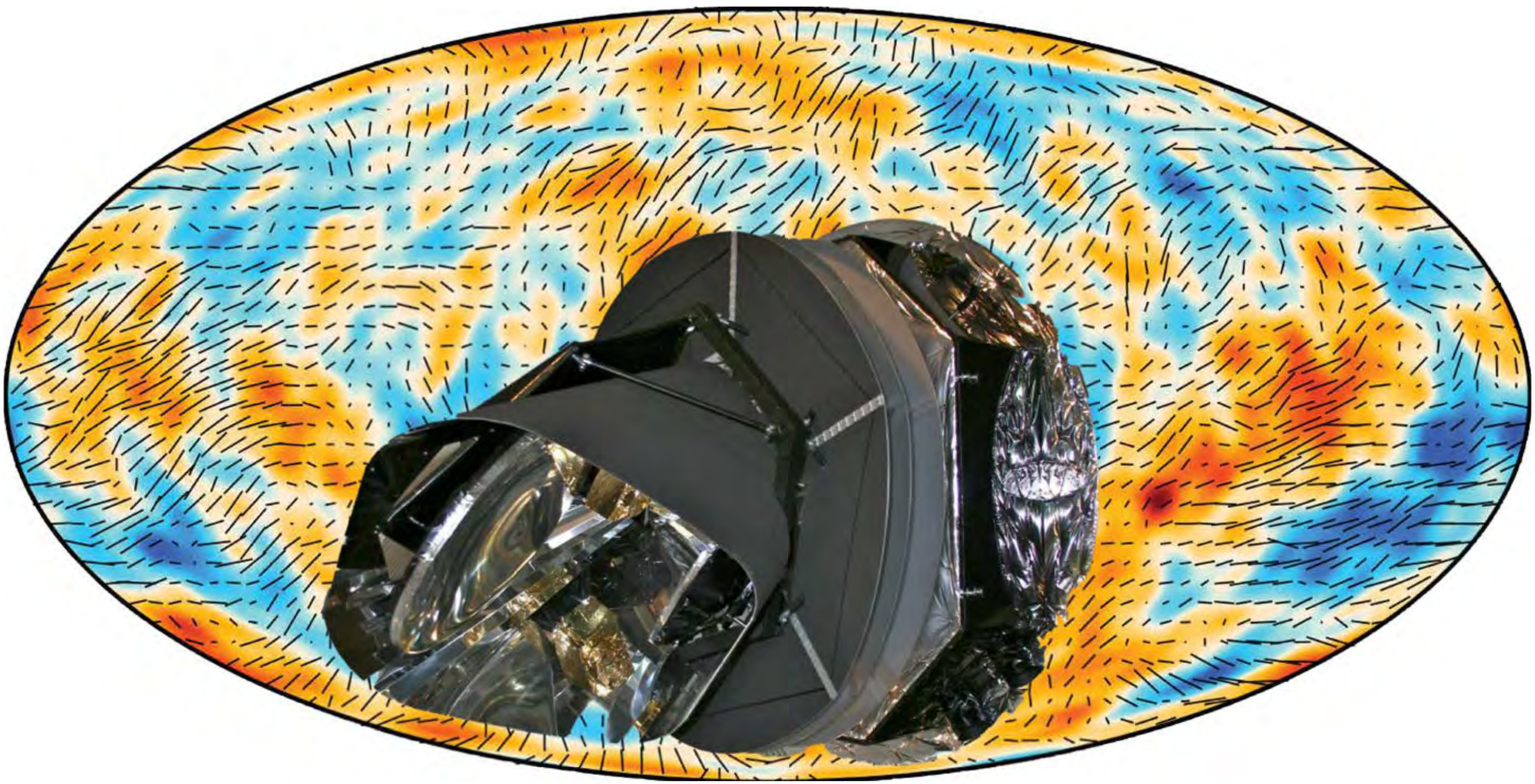
(organizer's title!)



Wayne Hu

IAP, June 2019

What ~~we~~ I have ~~learnt~~ learned from Planck



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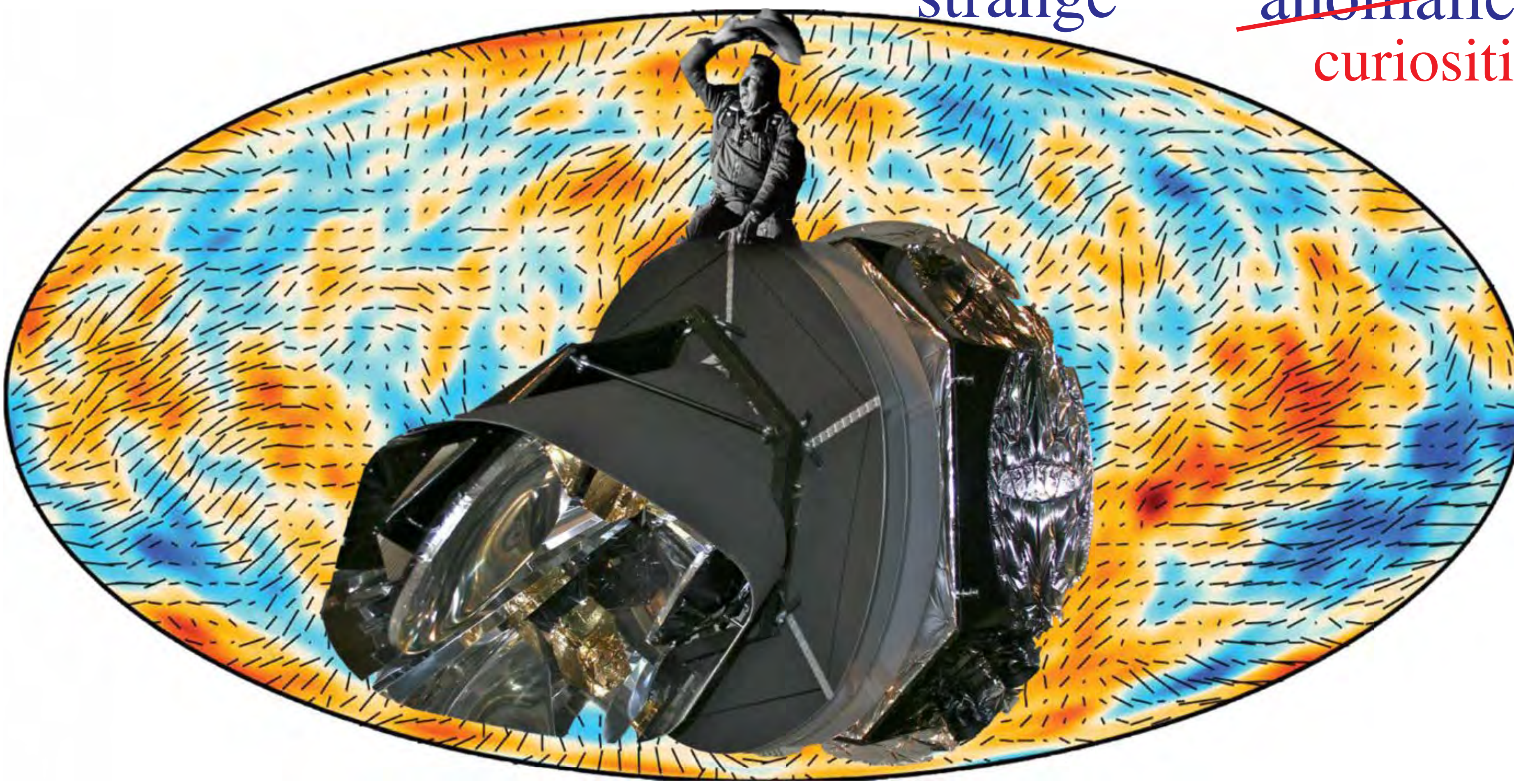
What we have learnt from Planck

(or how I learned to ^love ~~tension~~)

strange ~~anomalies~~

curiosities



Wayne Hu

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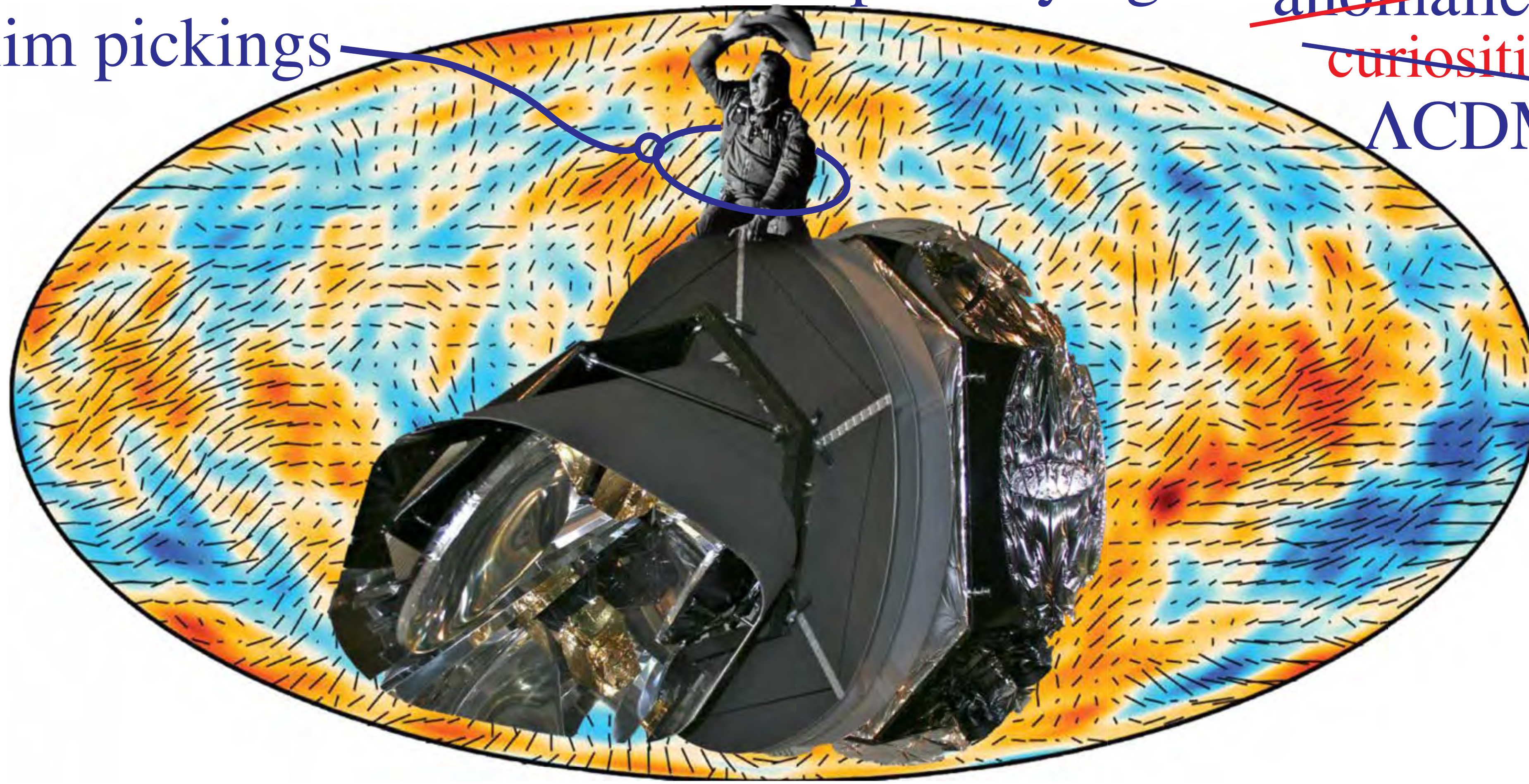
What we have learnt from Planck

(or how I learned to stop worrying and love ~~tension~~ ~~anomalies~~ ~~curiosities~~ ΛCDM?)

slim pickings

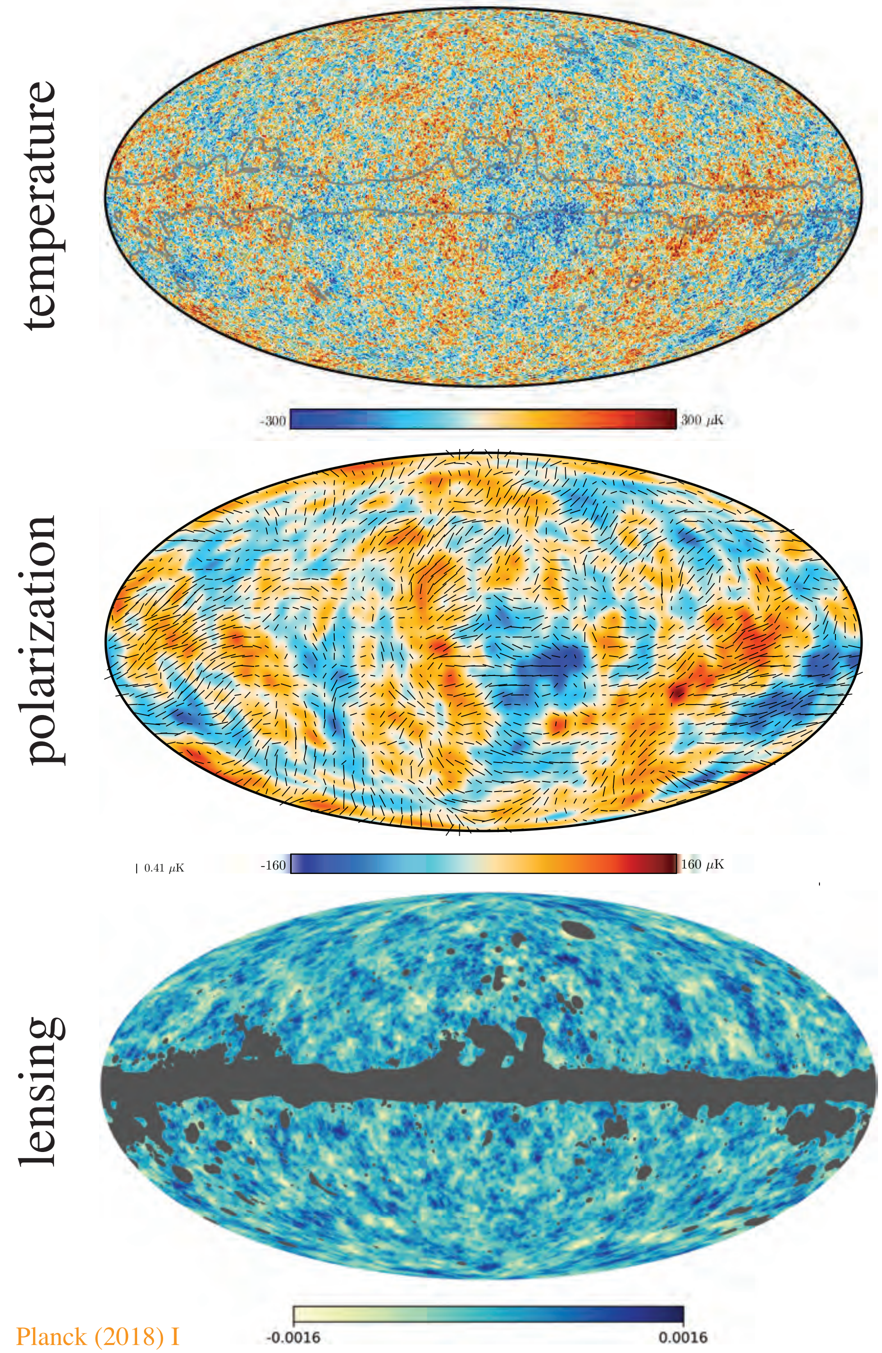


Wayne Hu

IAP, June 2019

Paradigm of Precision Cosmology

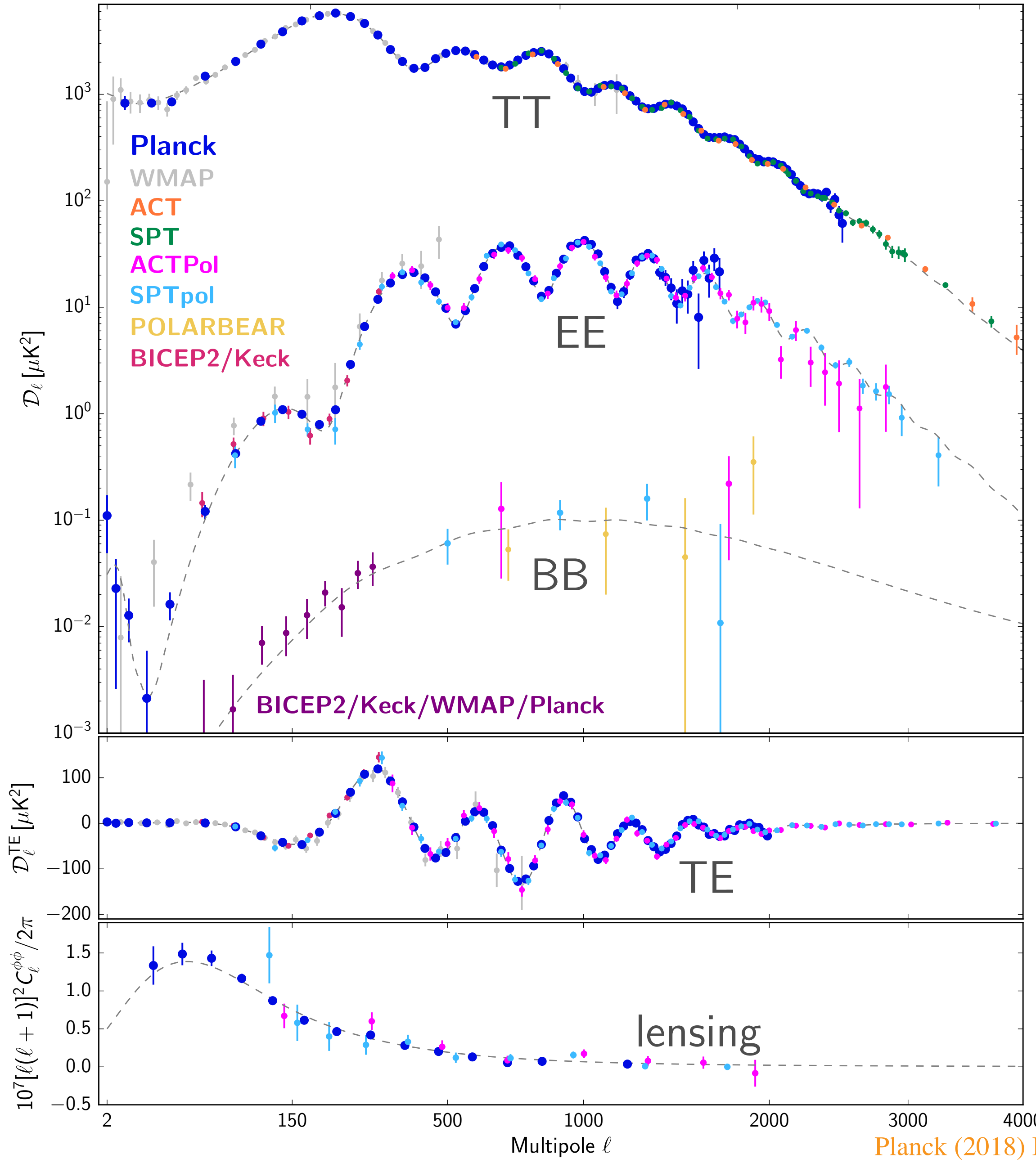
- Precision measurements and maps
  - temperature
  - polarization
  - lensing
  - 9 frequencies
- Control over systematics
  - most recently polarization
- Accurate and precise theoretical predictions
  - Gaussian, adiabatic
  - ΛCDM



Planck (2018) I

Near Perfection in 6 Numbers

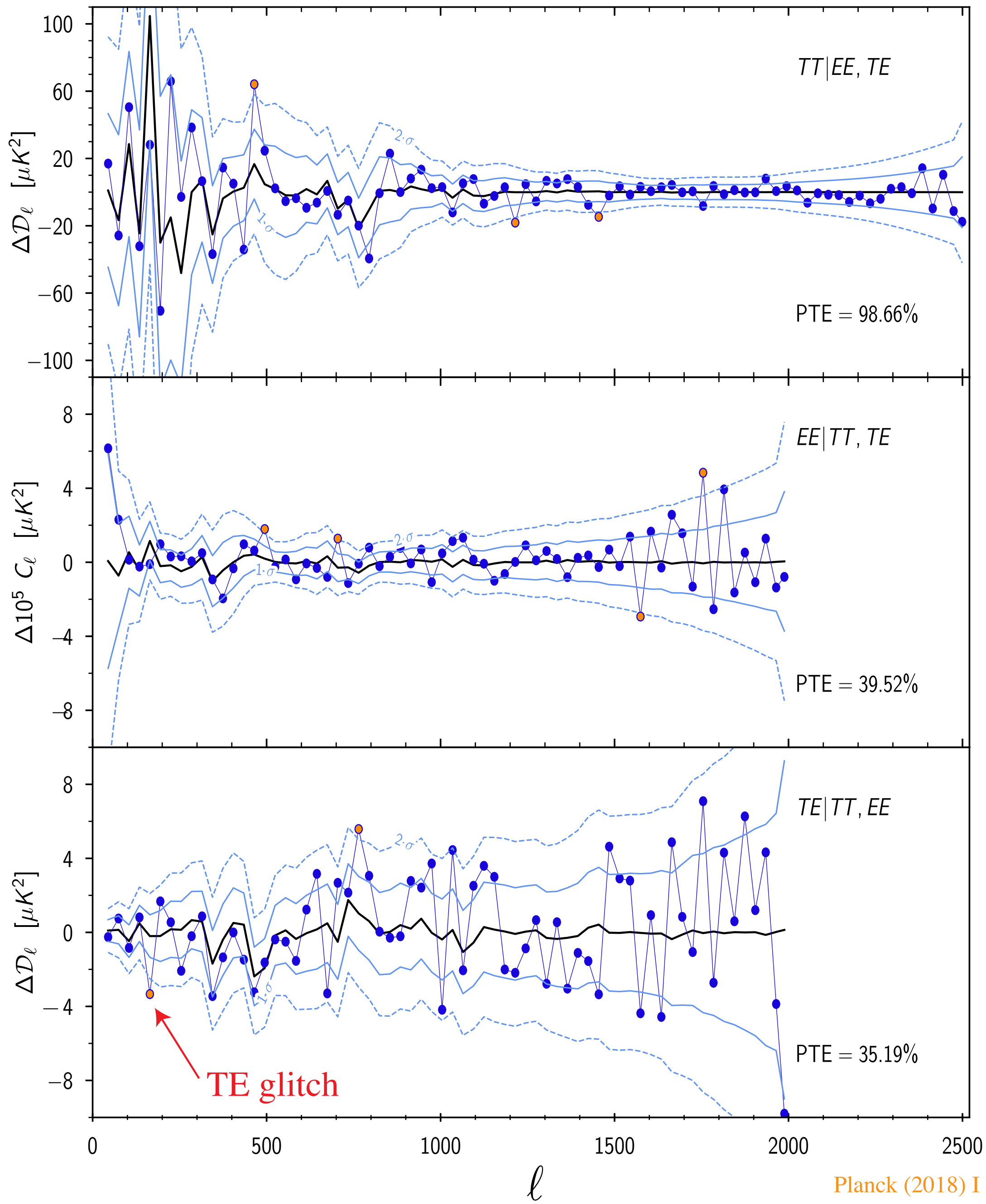
- All this precision data described by 6 ΛCDM parameters
  - – $\Omega_c h^2$: CDM
  - – $\Omega_b h^2$: baryons
  - – θ_s: sound scale
  - – A_s: amplitude
  - – n_s: tilt
  - – τ: reionization
- Measured to sub percent precision (except τ)



Planck (2018) I

Predictive Power

- Small residuals from ΛCDM in various spectra
- Temp ↔ pol residuals in ΛCDM with reduced sample variance
- Largely consistent, but with high precision, moderately significant deviations
- $\sim 2\sigma$ outliers, expected but some also drive parameters

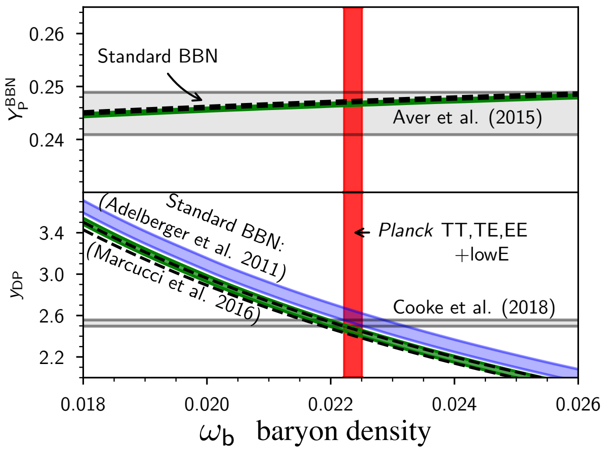


Planck (2018) I

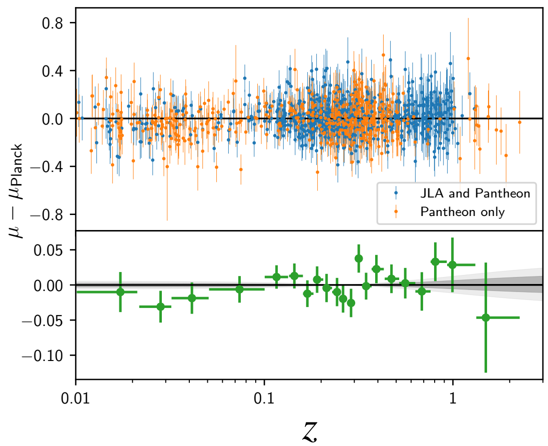
Predictive Power

- Predicts all other observables, which direct measurements test

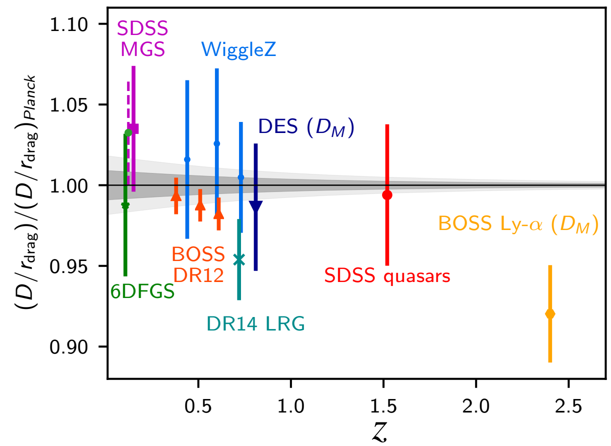
BBN

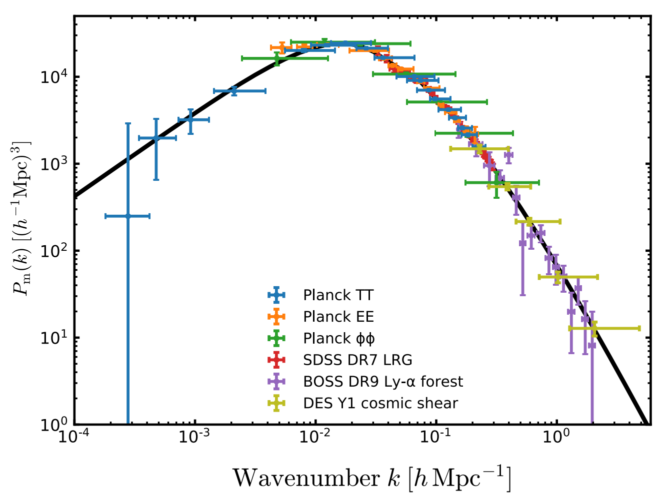


SNIa

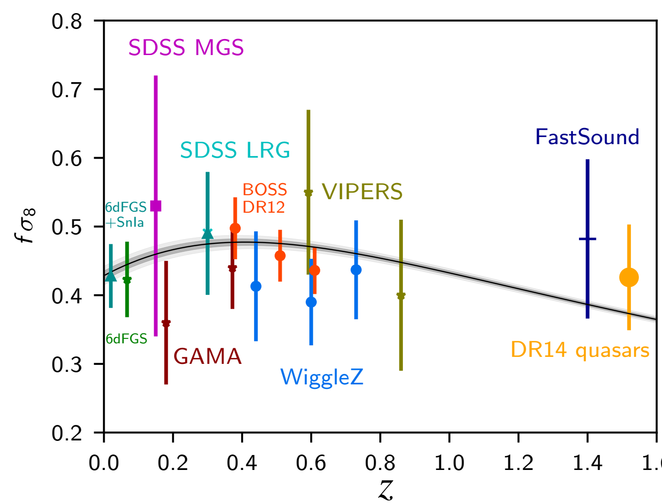


BAO





$P(k)$



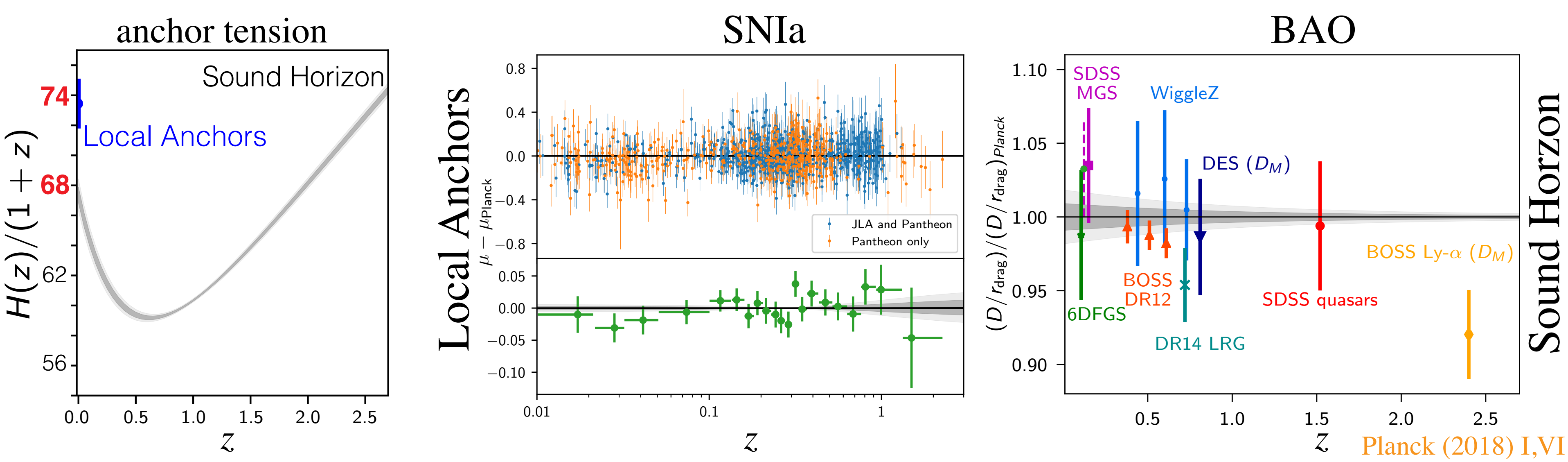
growth rate

Planck (2018) I,VI

- Good agreement, even weak lensing, clusters, and yes H_0 ($< 10\%$)

Anchors Sink ΛCDM?

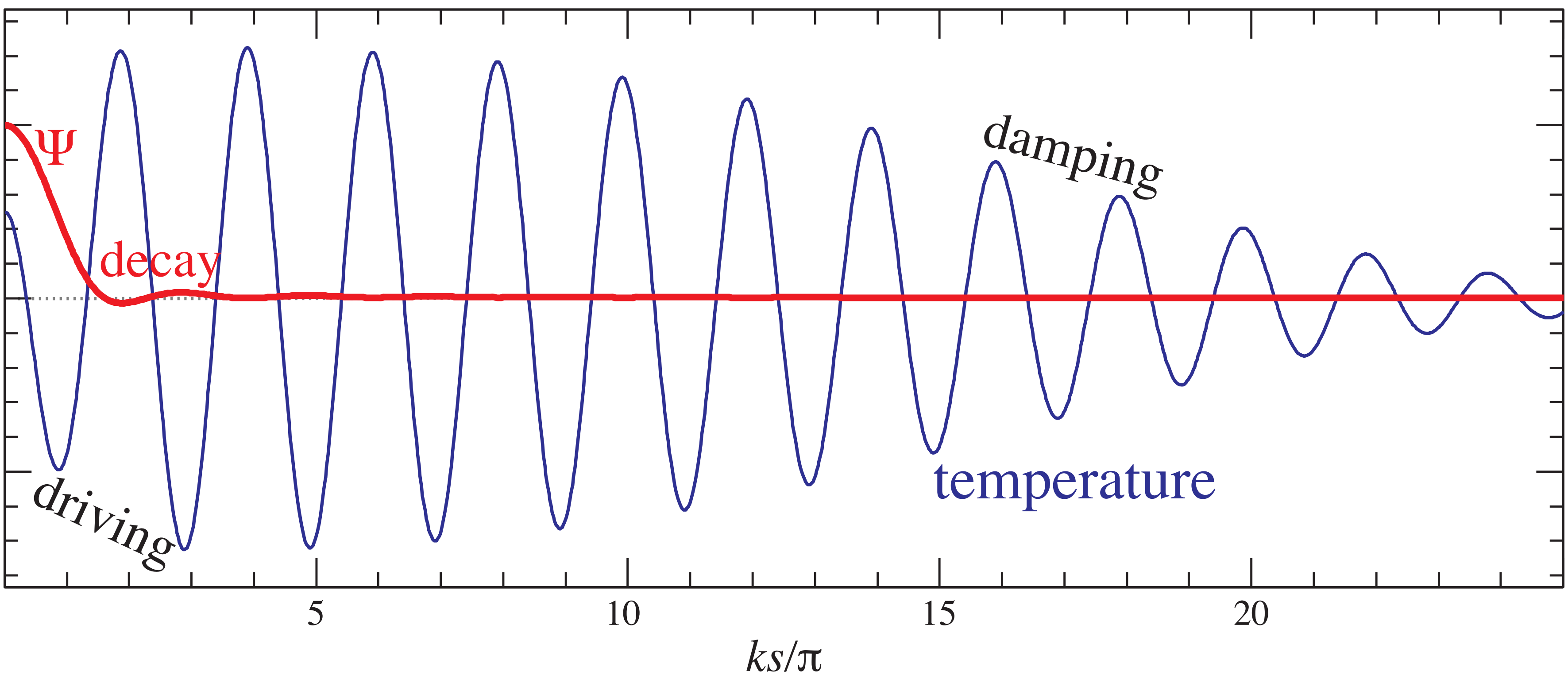
- When distance ladder calibrated by CMB sound horizon, H_0 discrepant with local measurements at 4.4σ (Riess et al 2019)
- Relative distances forward/backwards by ladder: CMB to BAO to SN isolating discrepancy as anchors (e.g. Aylor et al. 2018)
- Relative distances $\sim$ ΛCDM: little room for any new physics at intermediate redshifts to resolve



Driving in the Anchor

- CMB anchor is sound horizon, must calibrate propagation time
- $H(z < 10^3)$: with radiation, baryons fixed only $\Omega_c h^2$ unknown

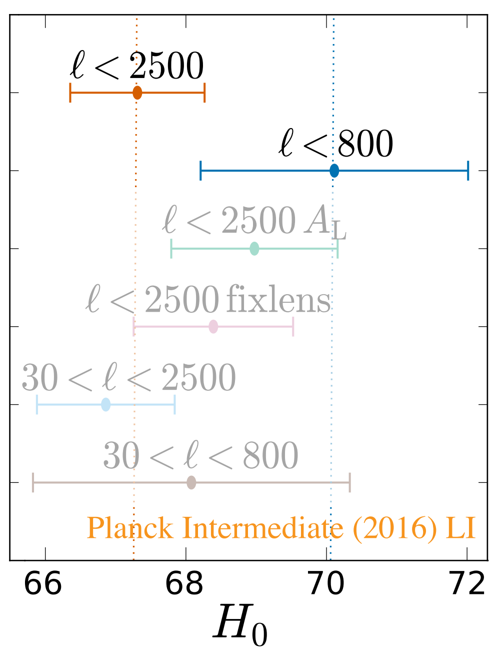
- $\Omega_c h^2$ controls matter-radiation ratio and radiation driving from potential decay due to Jeans stability

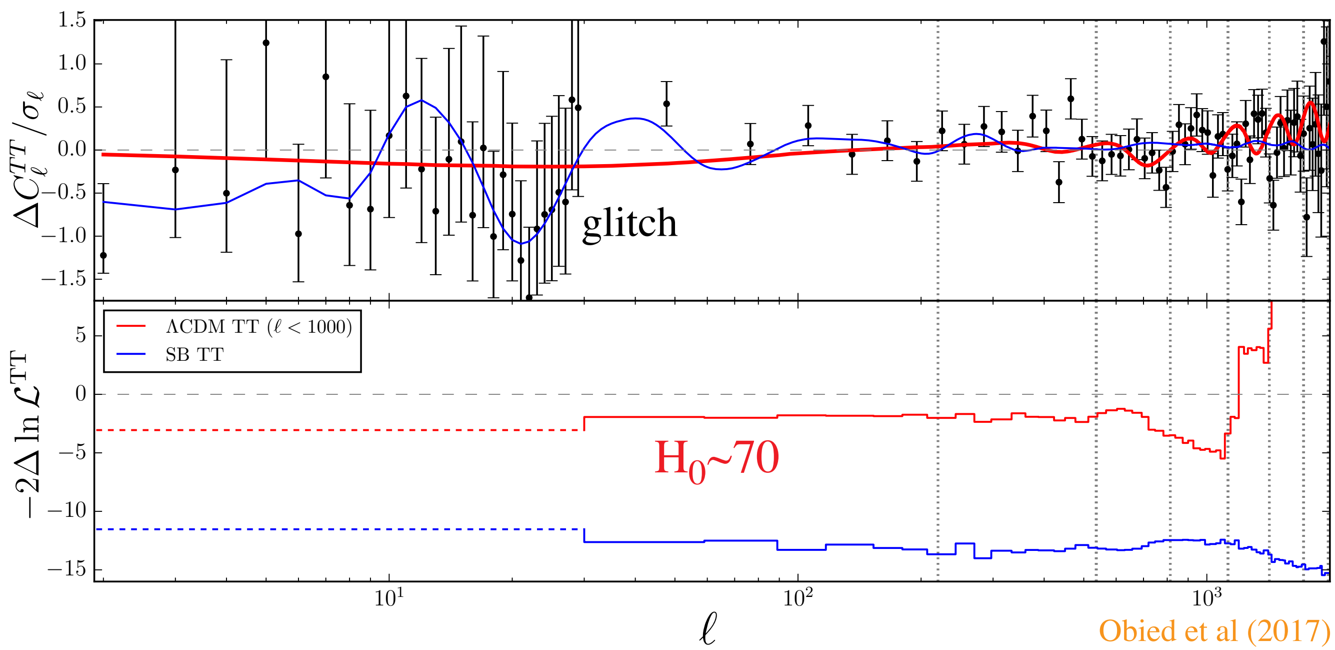


Glitch and Oscillatory Residuals

- Shifts in CMB anchor between low & high ℓ (Addison et al 2015)
- Low multipole glitch – deficit of power – looks like peaks should be higher, more driving, less matter, higher H_0
- High multipole oscillatory residuals: smoother acoustic peaks, less driving, more matter, lower H_0

– also drives "lensing tension": Pavel Motloch's talk

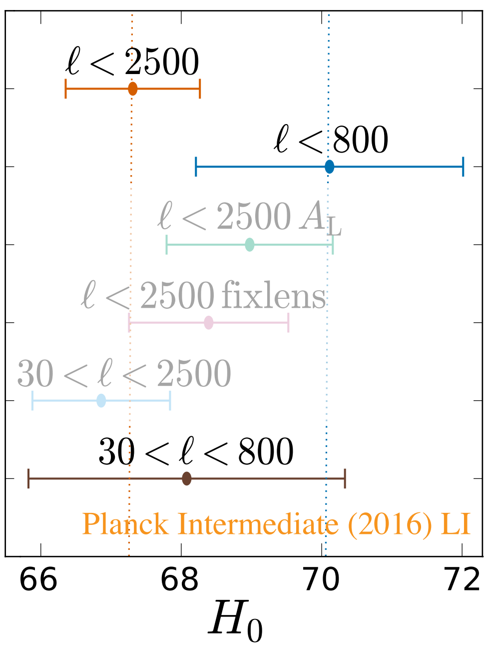


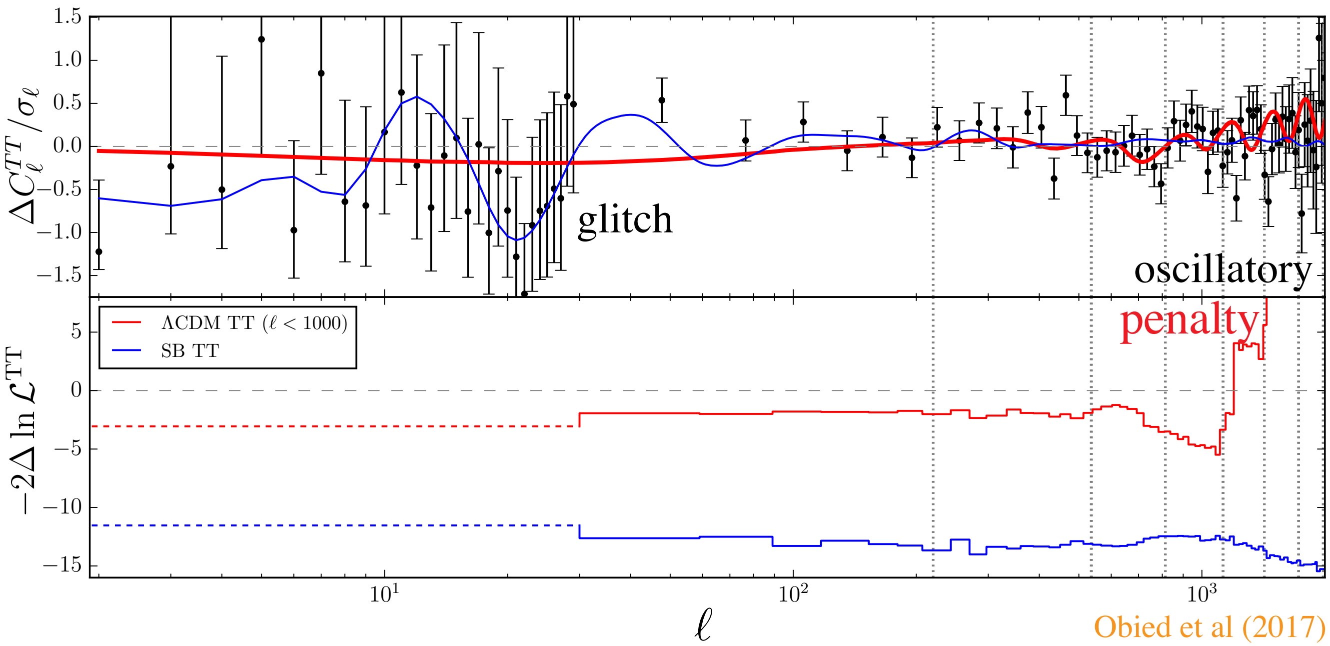


Glitch and Oscillatory Residuals

- Exclude low $\ell < 30$ glitch (Planck Intermediate 2016 LI)
- H_0 falls, consistent with high multipoles within errors

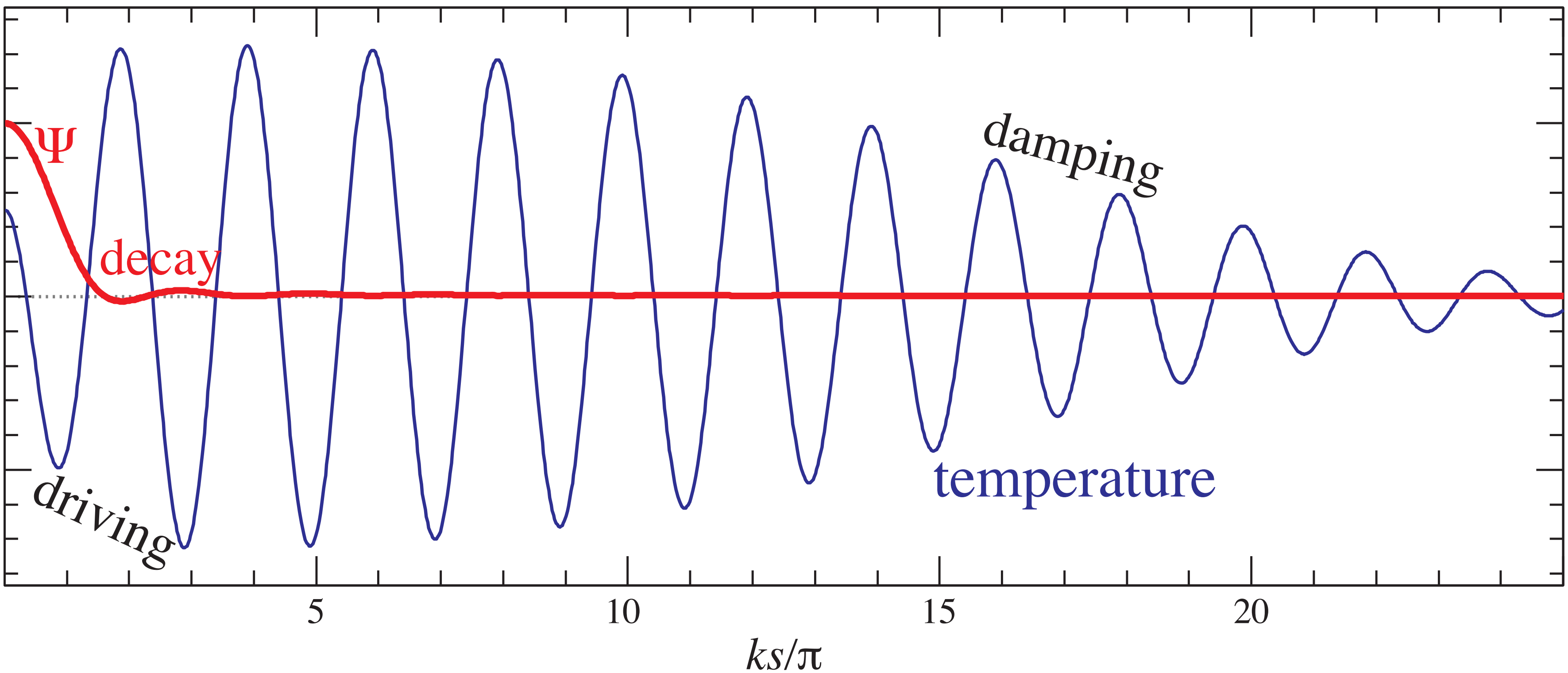
- Alternately marginalize over possible features during inflation, mild $\Delta\chi^2 \sim 12$ improvement, but 5 params
- Likewise H_0 returns to low value (Obied et al 2017)





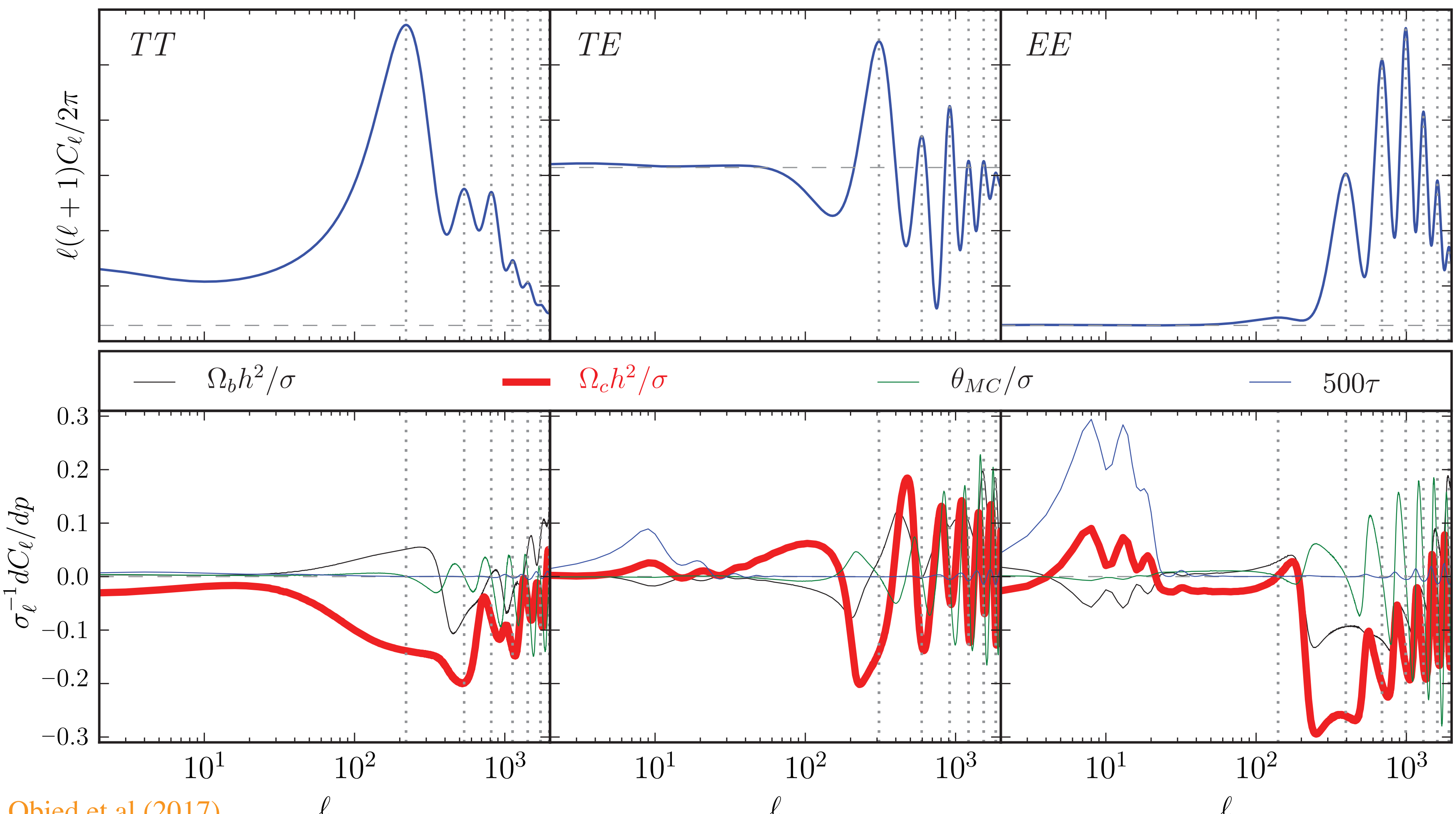
Driving and Oscillatory Residuals

- Oscillatory residuals indicate smoother peaks
- Driving sharpens the peaks
- Residuals indicate less driving, higher matter-radiation ratio
- Higher $\Omega_c h^2$, lower H_0



Driving and CDM

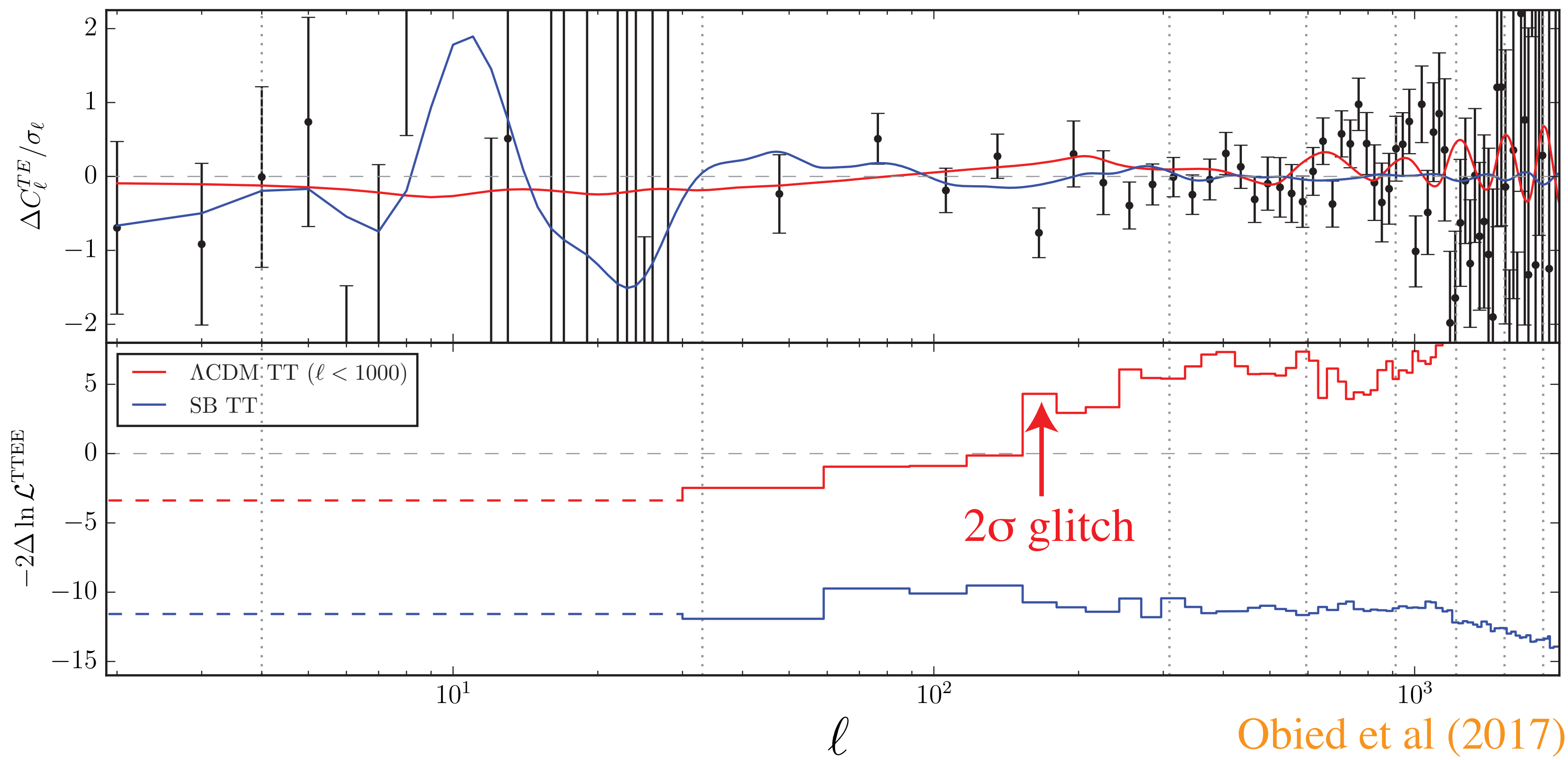
- Signatures of CDM $\Omega_c h^2$: TT amplitude and oscillatory residuals
- Polarization sharper test: projection effects for TT (Galli et al. 2014)



Obied et al (2017)

Polarization Signatures

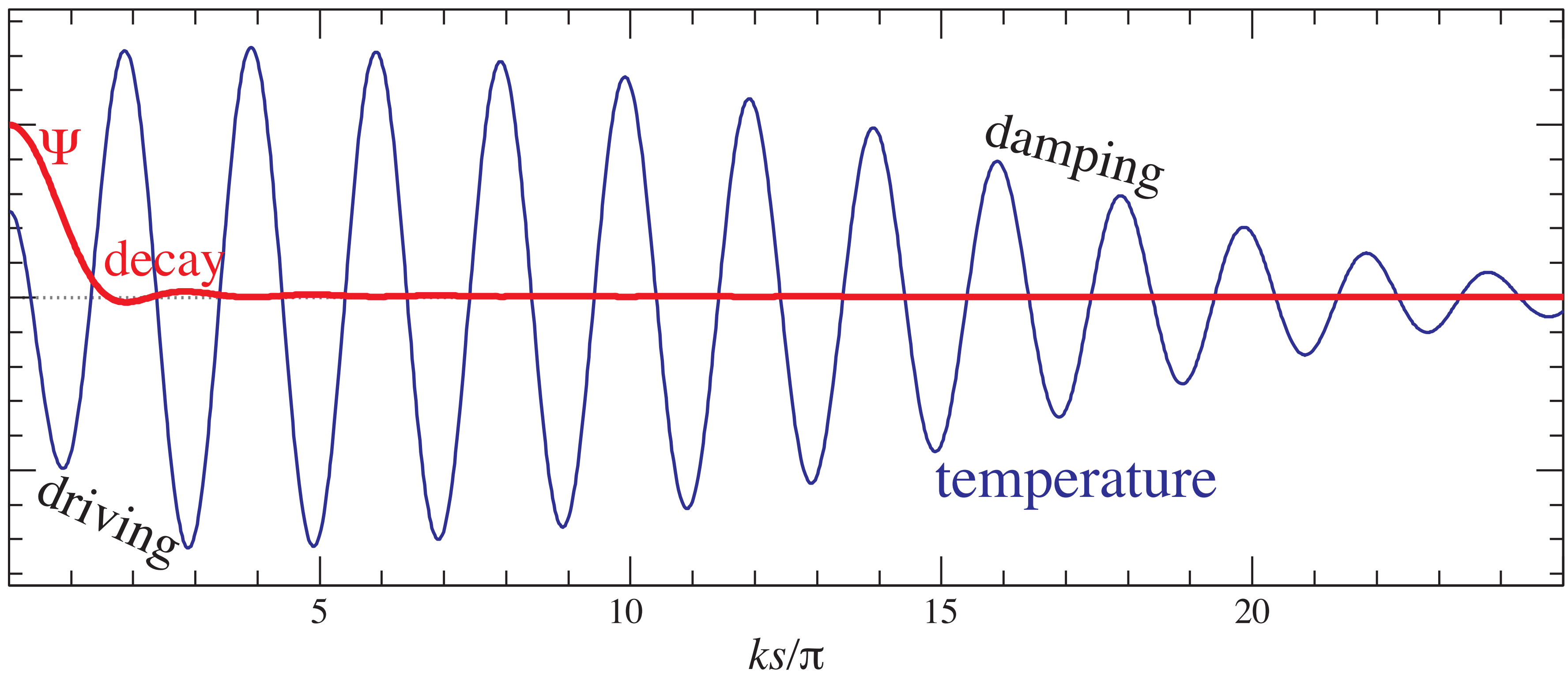
- Polarization sensitivity provides independent calibration using $\ell < 1000$ TE Planck data
- TE glitch at $\ell \sim 165$ enhances sensitivity, since lowering $\Omega_c h^2$ (raising H_0) further raises predictions



Obied et al (2017)

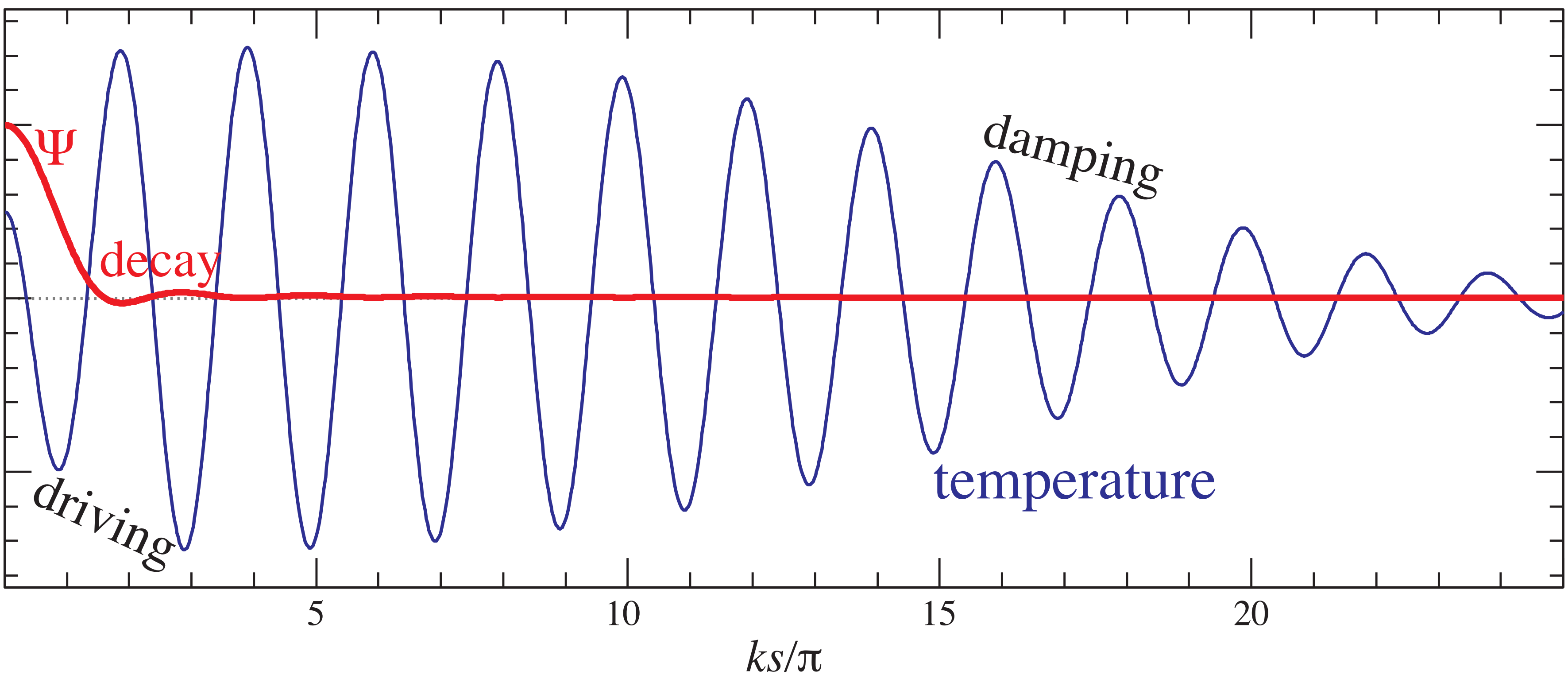
Dark Radiation

- Extra dark species whose energy density redshifts faster than matter change sound horizon calibration
- Raise $H(z < 10^3)$, lower sound horizon, raise H_0 at fixed θ_s
- Additional driving from Jeans stable $\Delta N_{\rm eff}$ radiation compensated by raising matter $\Omega_c h^2$



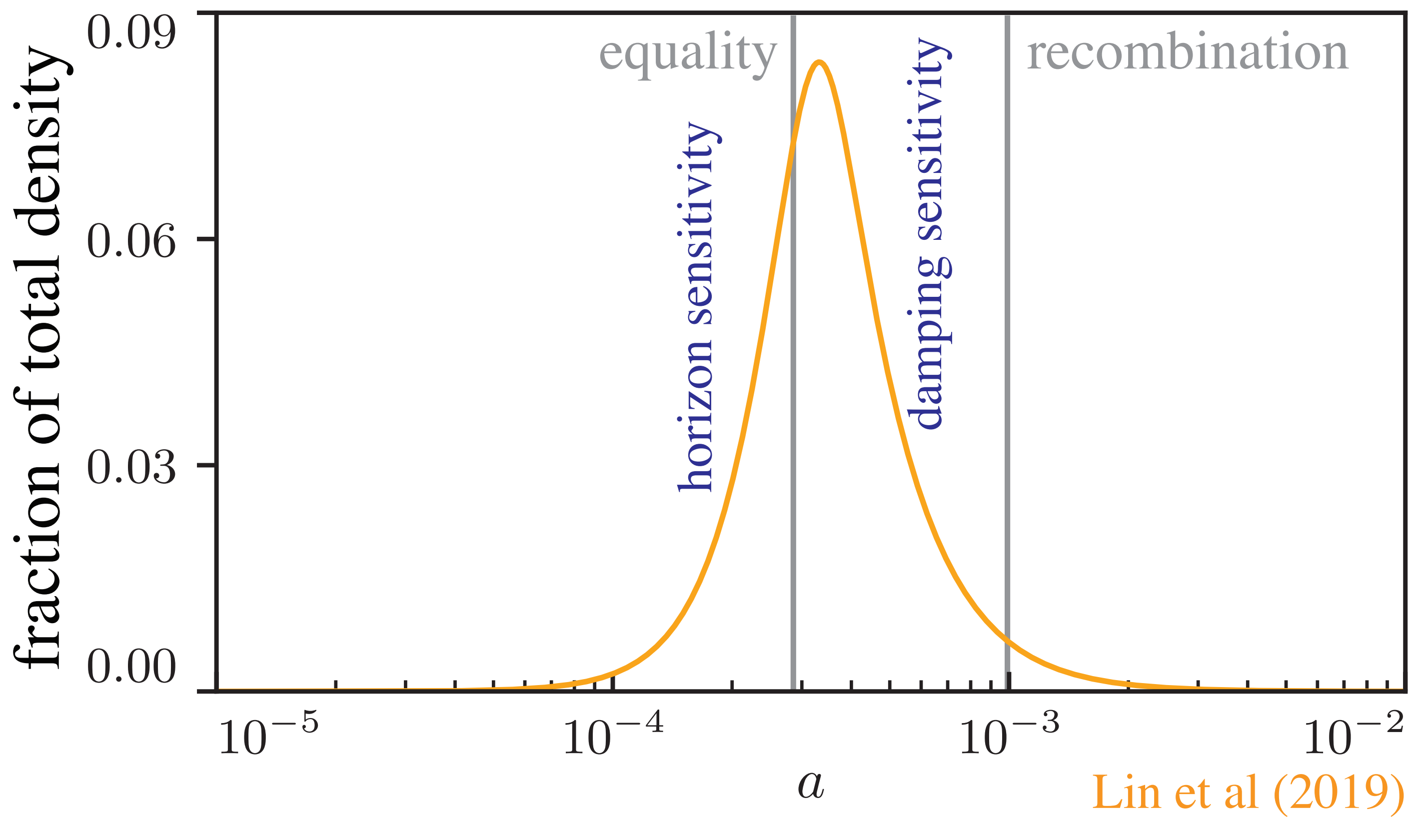
Driving and Damping

- But damping provides second standard ruler in diffusion scale
- Random walk distance of photon scales as harmonic mean between horizon and mean free path
- Consistency check that ΛCDM passes and constrains any additional radiation $\Delta N_{\rm eff}$



Dark Exotica

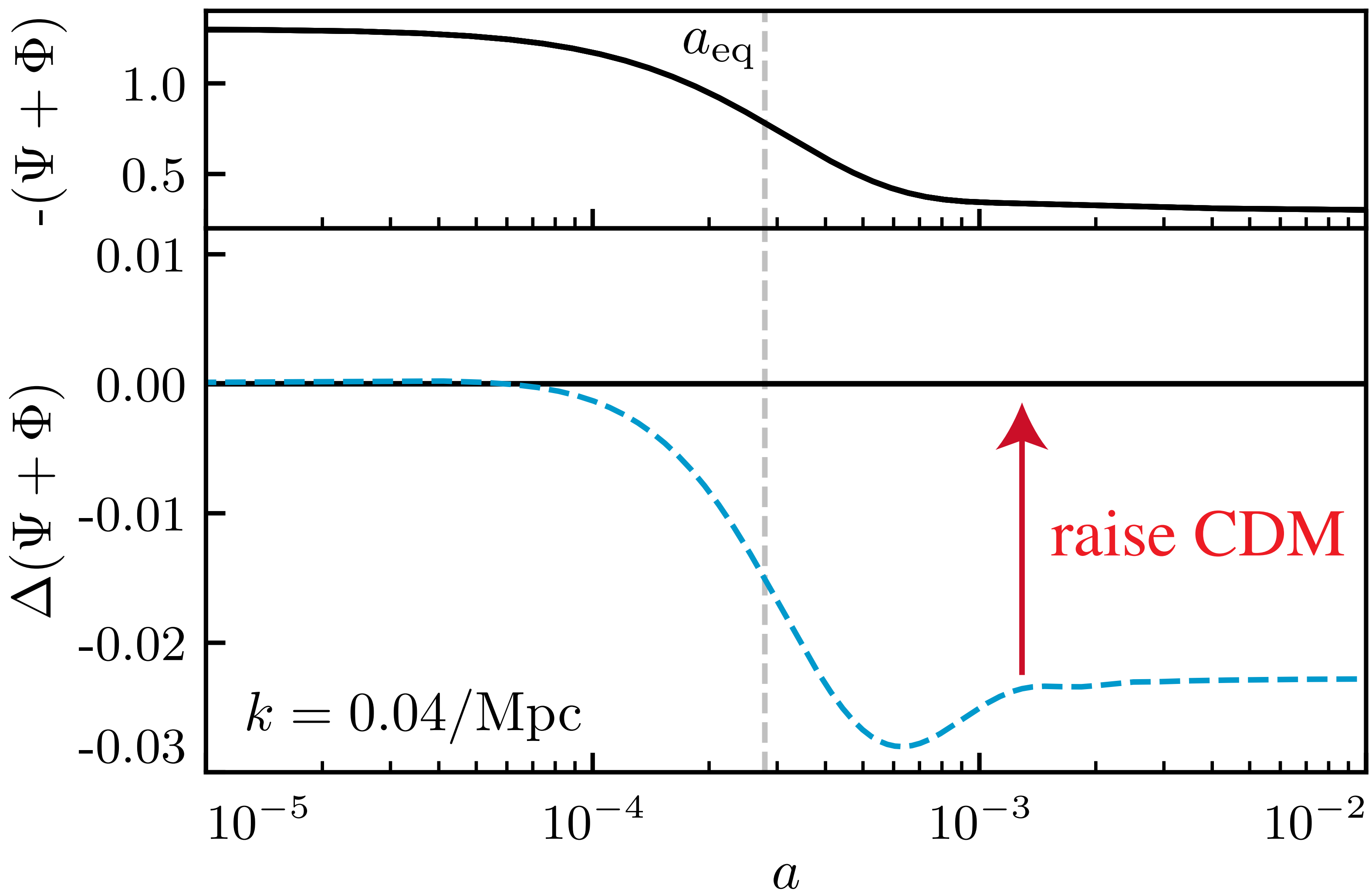
- Decreasing additional dark components during radiation domination changes damping vs sound horizon
- Reconcile ratio if timed exactly right



- Poulin et al (2018): specific anharmonic, periodic scalar potential

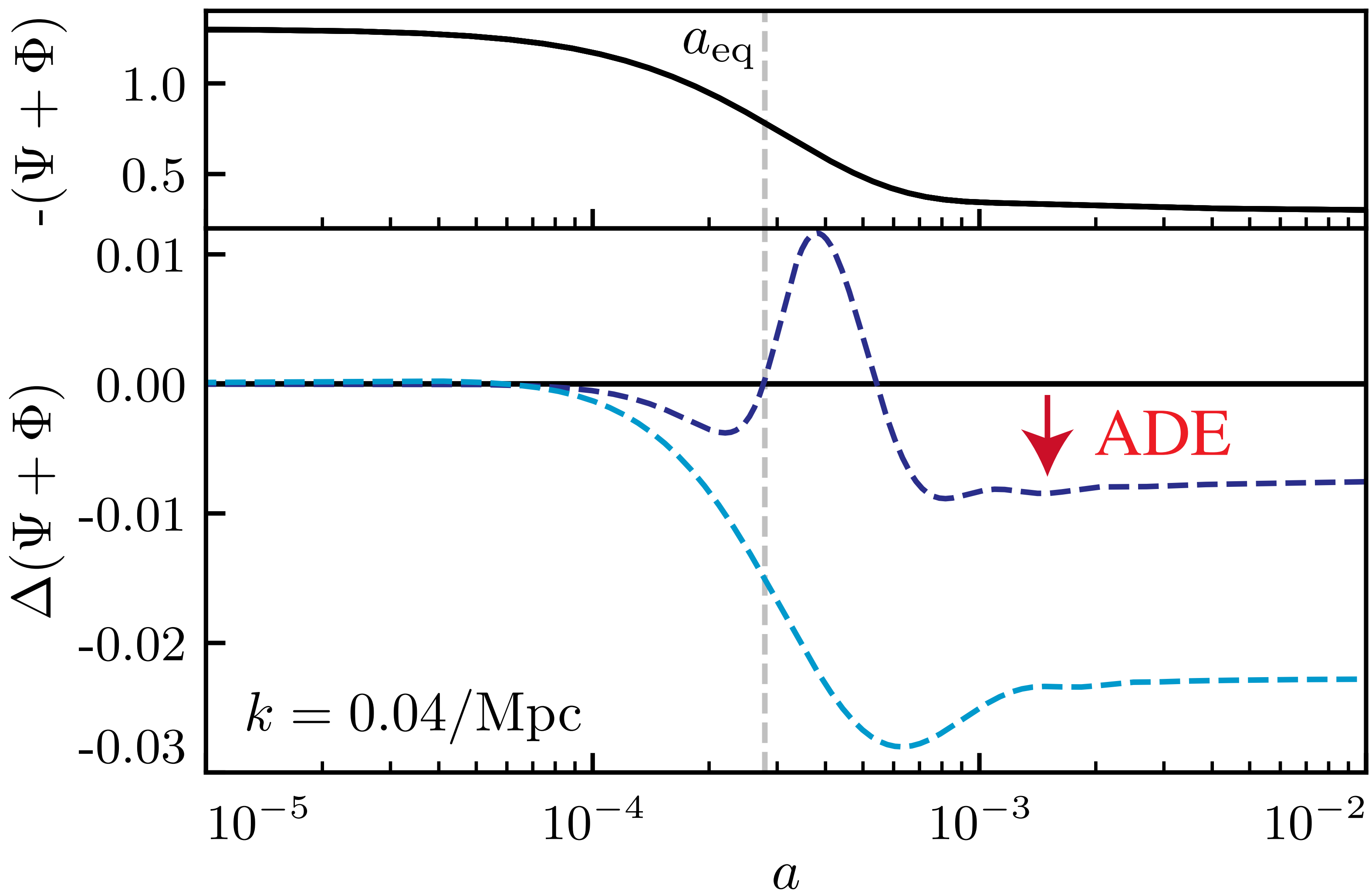
General Mechanism

- Must compensate effect of raising $\Omega_c h^2$ which reduces decay of potential



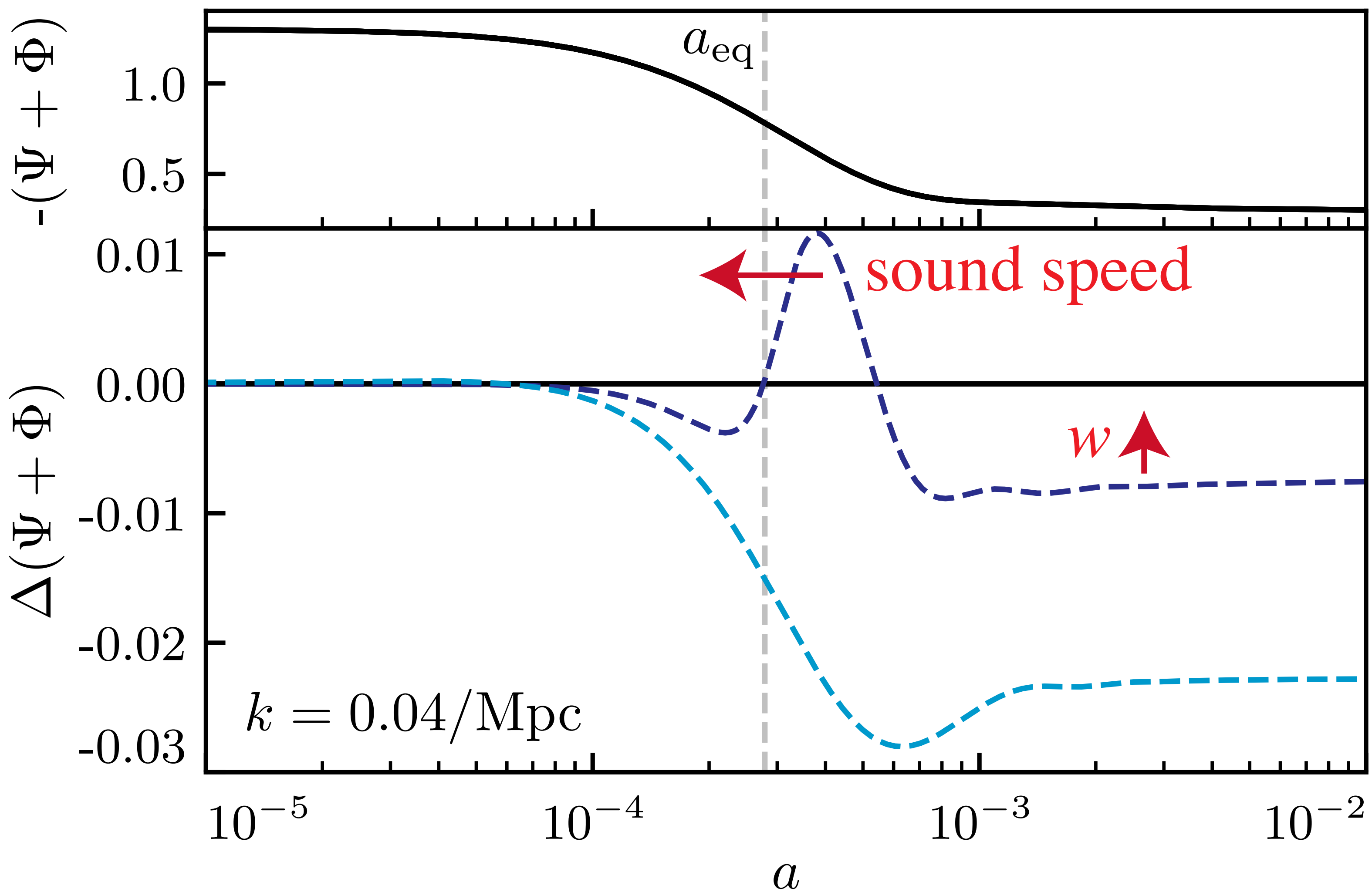
General Mechanism

- Dark exotica with relativistic sound speed, acoustic oscillations, enhances decay



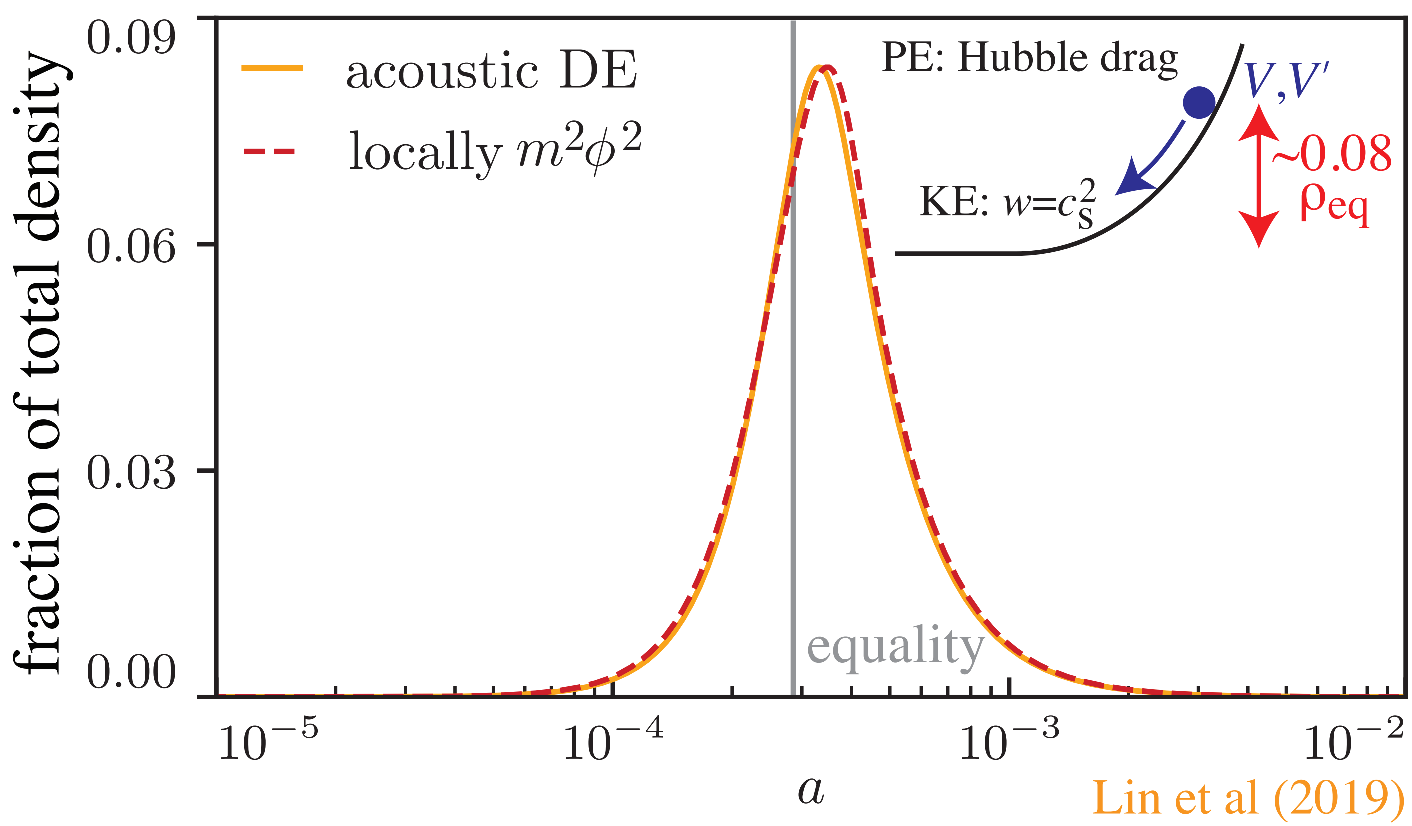
General Mechanism

- Tune the impact with sound speed (first dark acoustic peak) and equation of state (redshifts away faster)



General Mechanism

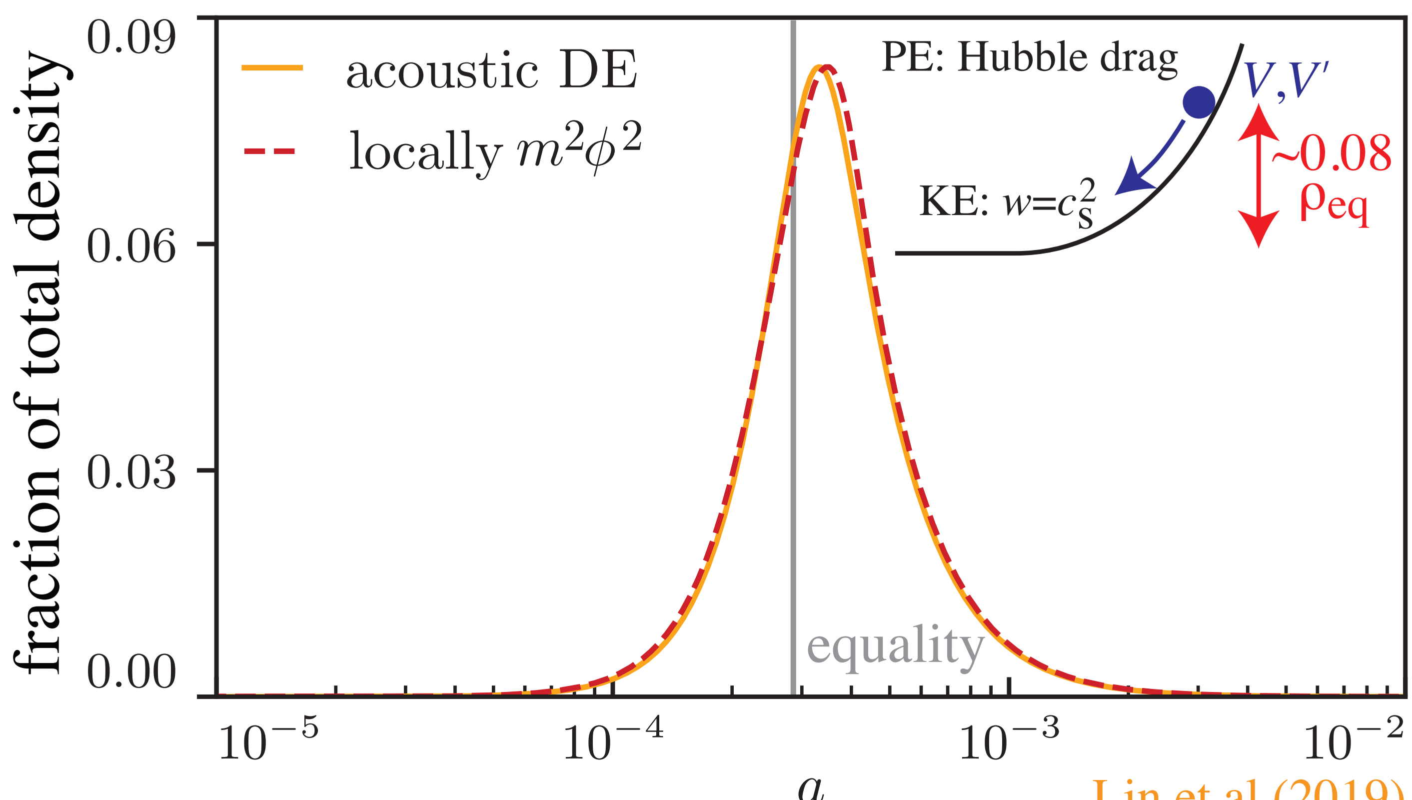
- Poulin et al (2018) 4 parameters, amplitude, time scale, c_s^2 and w must be carefully tuned (top of oscillatory potential $c_s^2 \downarrow$)
- Data favor something both more specific and generic: $c_s^2 = w$, transition to kinetic energy domination (Lin et al 2019)



Lin et al (2019)

Potential to Kinetic

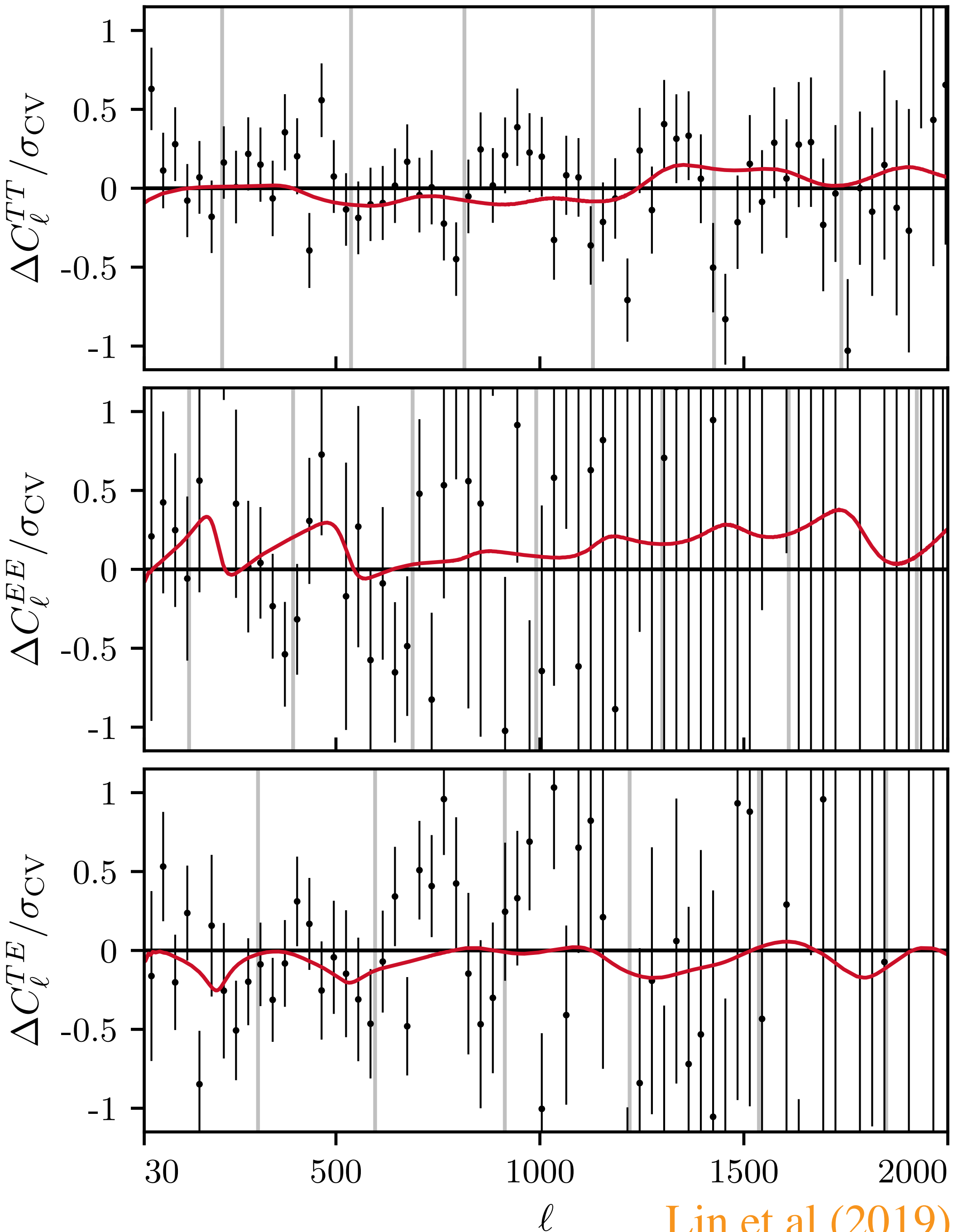
- With $c_s^2 = w = 1$ leaves 2 parameters: amplitude and slope of potential and requires kinetic energy redshift away (not oscillate)
- Amplitude $\sim 0.08\rho_{\rm eq}$ and slope must be large enough to release from Hubble drag



Lin et al (2019)

Fit and Predictive Signatures

- Fits joint data better by $\Delta\chi^2 \sim 12 - 14$ for 2-3 parameters
- Fits CMB itself better, largely TE
- TE glitch $\ell \sim 165$ highly sensitive
- Dark component redshifts away by recombination leaving nearly bare $\Omega_c h^2$ signature

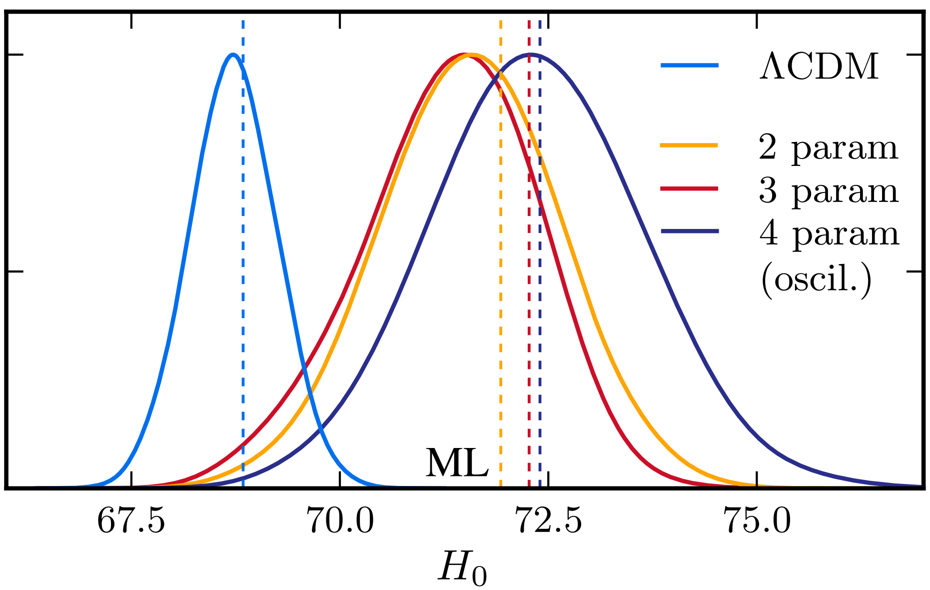


Lin et al (2019)

Potential Conversion of H_0 Tension

- Raises H_0 to bring CMB and local anchors into better agreement
- Minor further improvements with additional parameters
- Posterior depends on parameter volume near ΛCDM, maximum likelihood (ML) more reflective

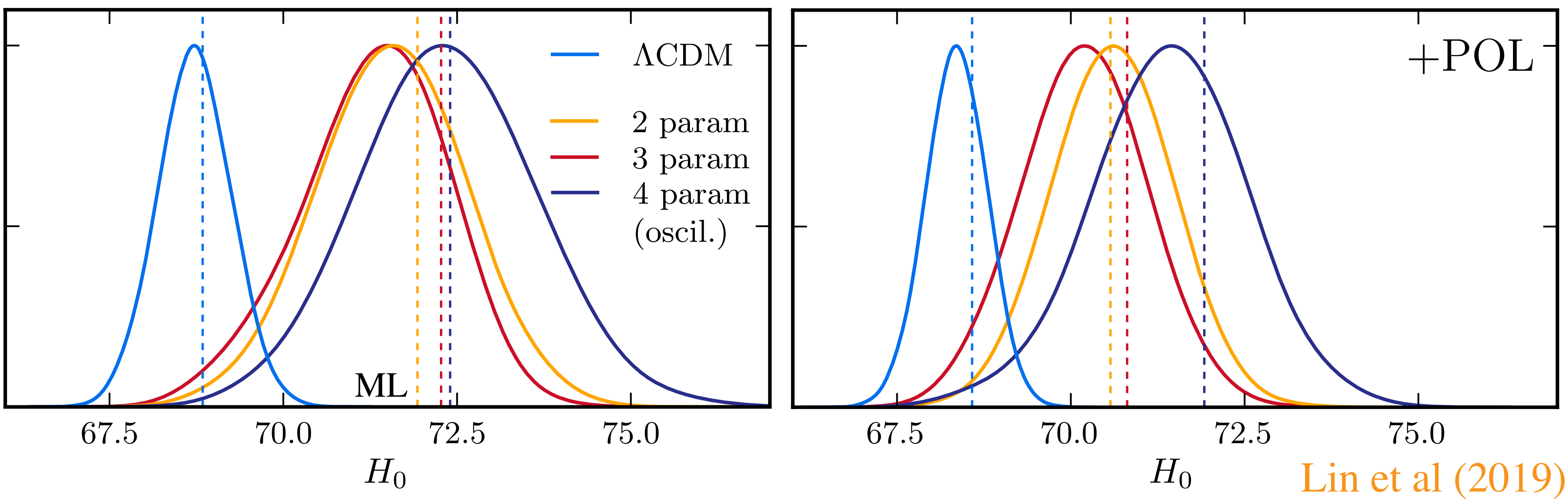
- But mainly converts H_0 question to "why this, why then"!



Potential Conversion of H_0 Tension

- Raises H_0 to bring CMB and local anchors into better agreement
- Minor further improvements with additional parameters
- Posterior depends on parameter volume near ΛCDM, maximum likelihood (ML) more reflective

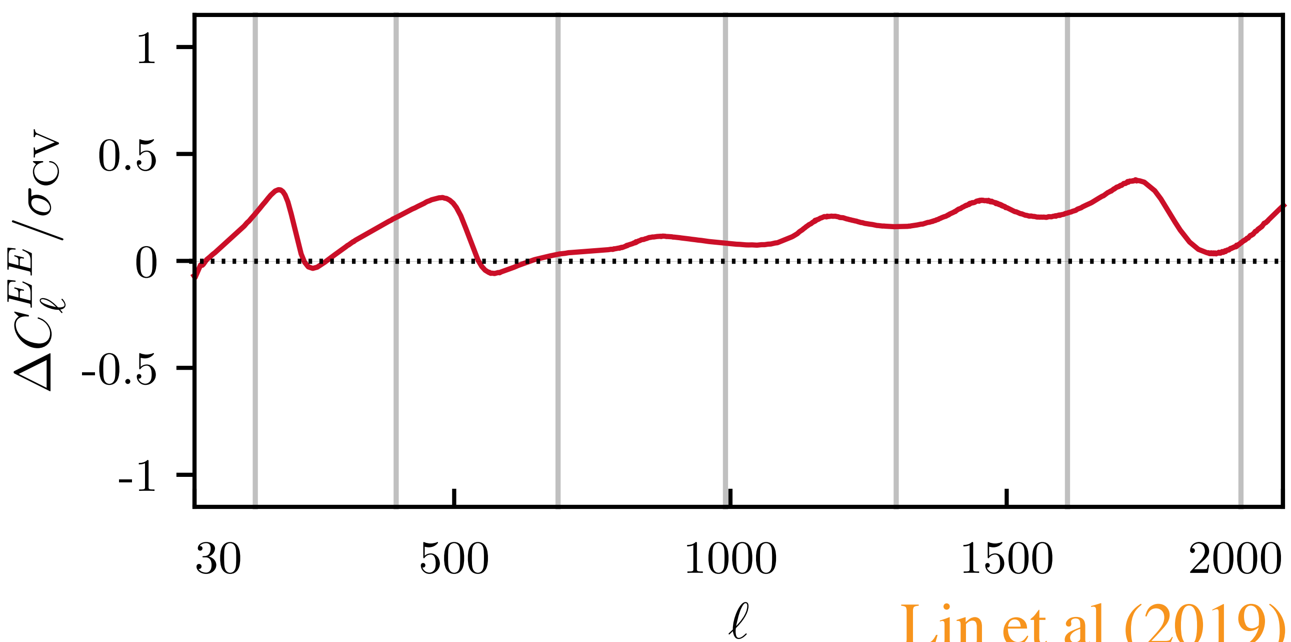
- Already limited by Planck TE polarization, distinguishing details



Lin et al (2019)

Potential Conversion of H_0 Tension

- Raises H_0 to bring CMB and local anchors into better agreement
- Minor further improvements with additional parameters
- Posterior depends on parameter volume near ΛCDM, maximum likelihood (ML) more reflective
- EE residuals are ~ 0.3 vs cosmic variance per multipole



Lin et al (2019)

- Opportunity for testing ideas based on changing CMB anchor!

Summary

- Planck and other precision CMB experiments have firmly established ΛCDM as the standard model
- ΛCDM unreasonably effective and efficient in describing suite of cosmological observables
- 6 numbers, mostly measured to sub percent precision, mostly consistent at this level with everything
- Tensions, anomalies and curiosities: imperfection is more interesting than perfection
- H_0 at 4.4σ, can only be explained by changing one of the anchors
- CMB anchor is sound horizon and cross checked by damping scale
- Potential conversion illustrates designer difficulties, one or more parameters per effect:
  - look for predictive power of any explanation