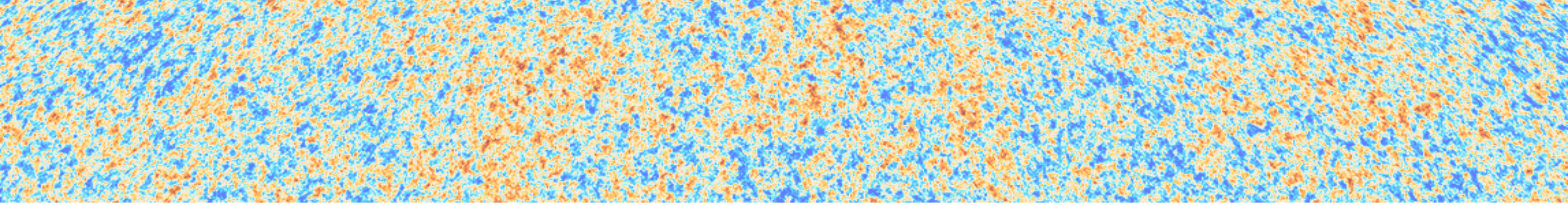

The status of cosmological tensions after Planck

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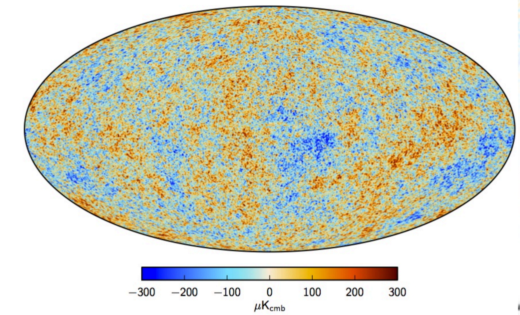
IAP-Institut d'Astrophysique de Paris

Niels Bohr Institute 14/1/2021

Outline

1. Short recap on Planck results
2. Post-Planck Issue 1: Comparison with other probes. The H_0 problem
3. Post-Planck Issue 2: Internal "curiosities" in the Planck data (A_L, curvature etc..)
4. Are Issue 1 and Issue 2 related?

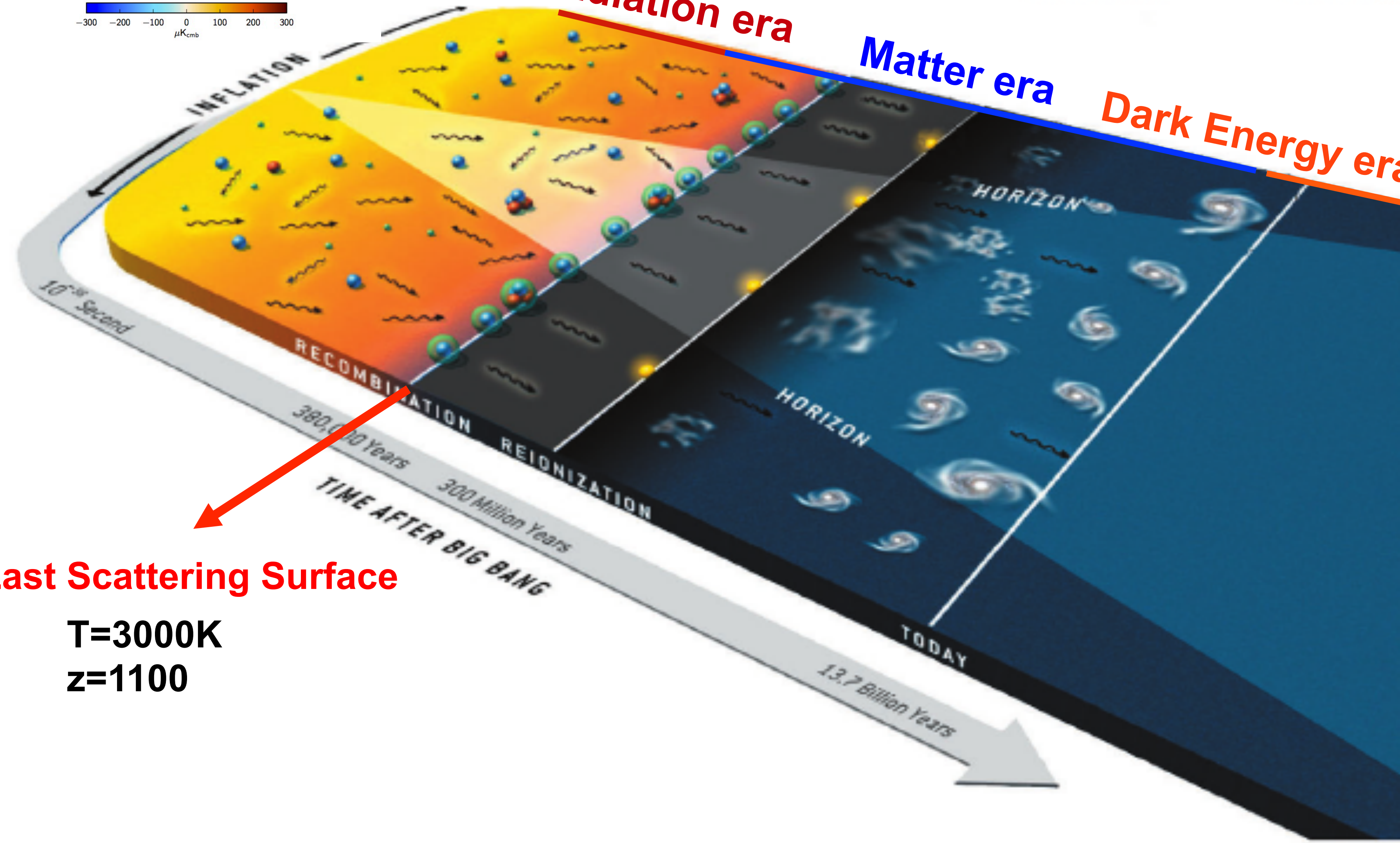
CMB



Radiation era

Matter era

Dark Energy era

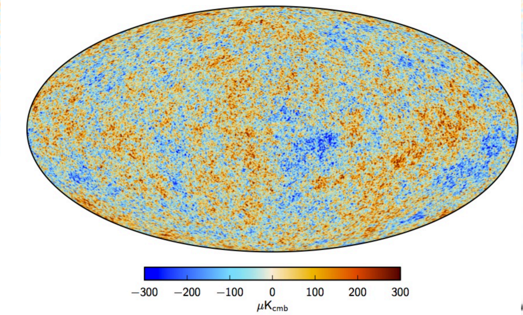


Last Scattering Surface

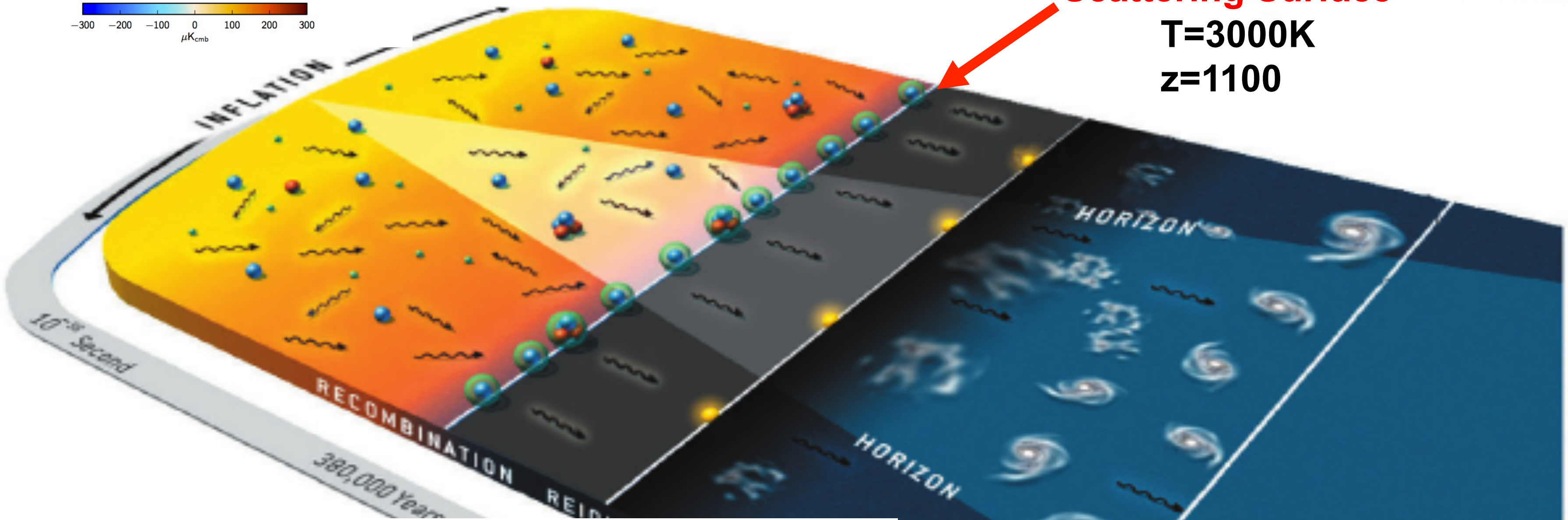
T=3000K
z=1100

Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

CMB

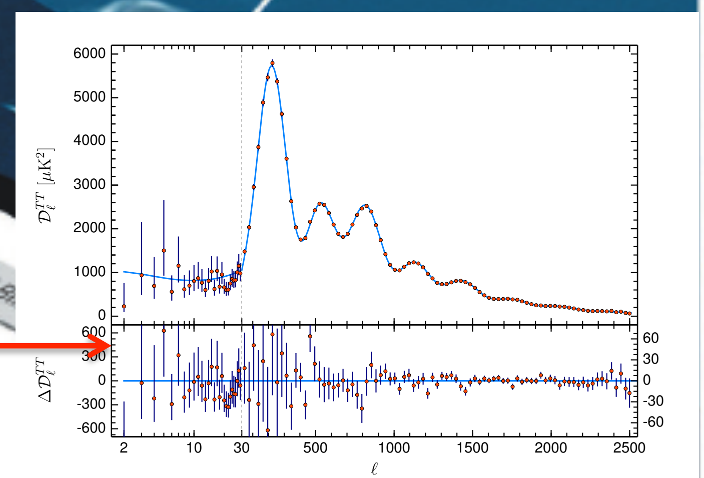


CMB from last Scattering Surface
T=3000K
z=1100



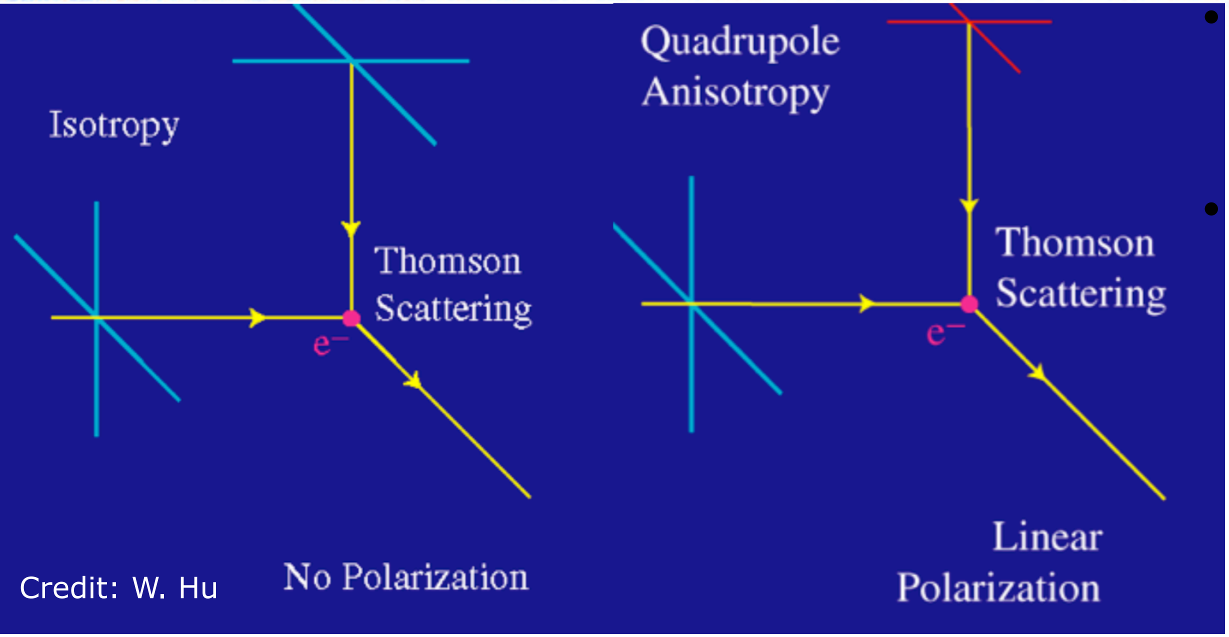
$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

$$\langle a_{lm}a^{*}_{l'm'}\rangle = \delta_{ll'}\delta_{mm'}C_l$$

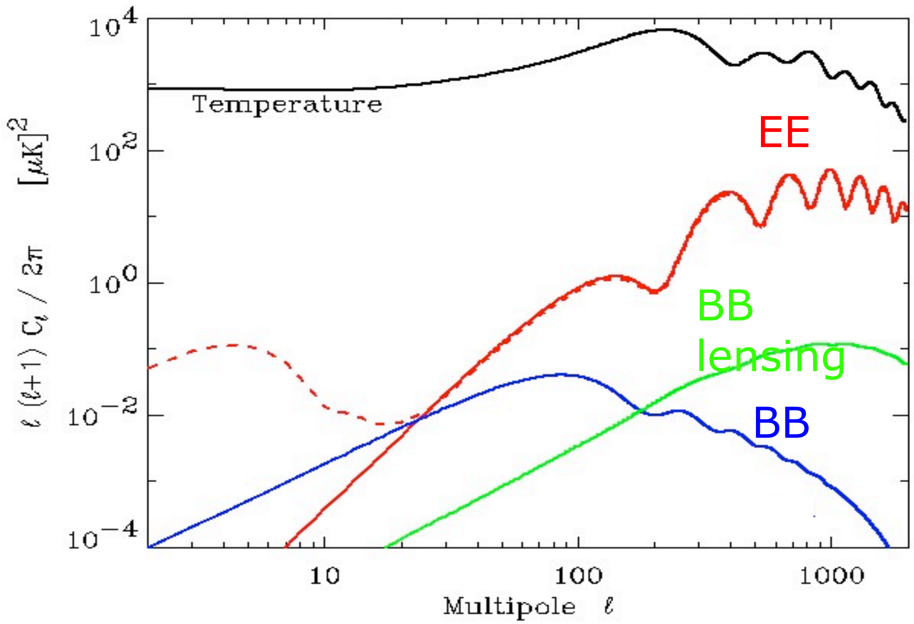


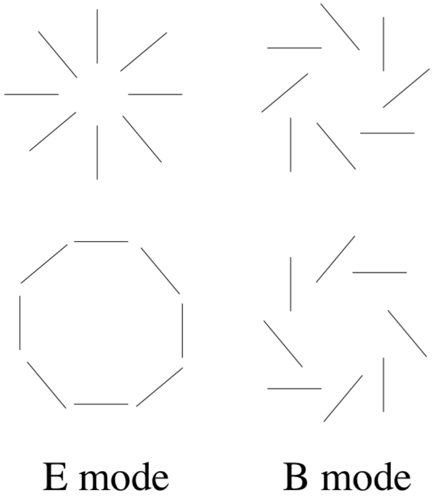
Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

CMB Polarization

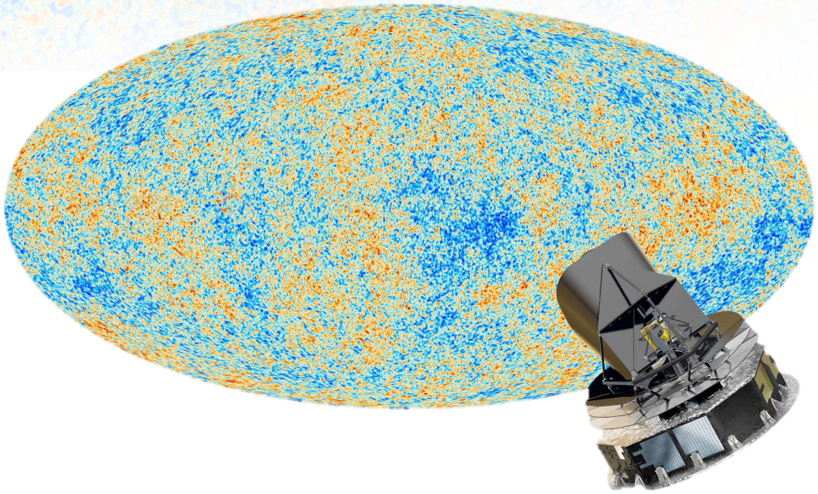


- Polarization generated by local quadrupole in temperature.
- Sources of quadrupole:
  - Scalar: E-mode
  - Tensor: E-mode and B-mode





The Planck satellite



3rd generation full sky satellites (COBE, WMAP)
Launched in 2009, operated till 2013.
2 Instruments, 9 frequencies.

LFI:

- 22 radiometers at
  30, 44, 70 Ghz.

HFI:

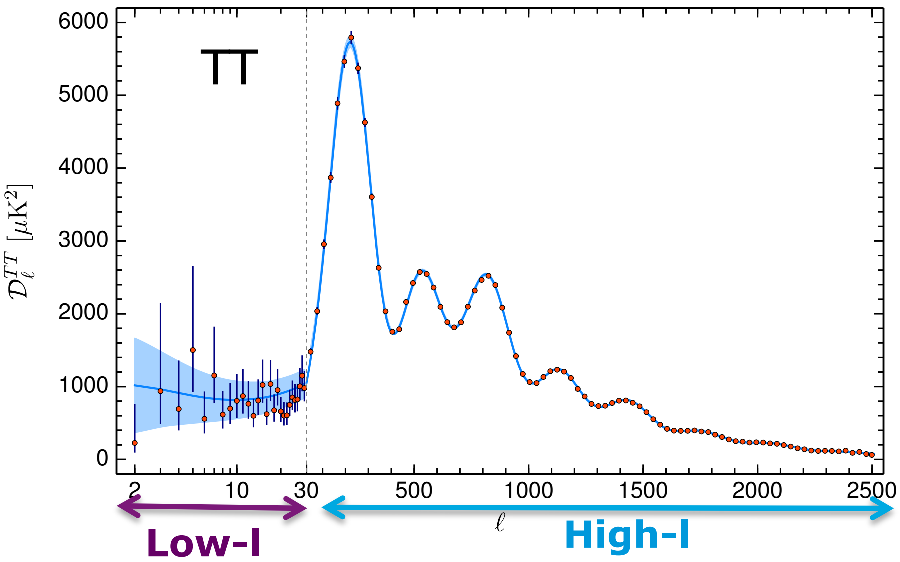
- 50 bolometers (32 polarized) at
  100, 143, 217, 353, 545, 857 Ghz.
- **30-353 Ghz polarized.**

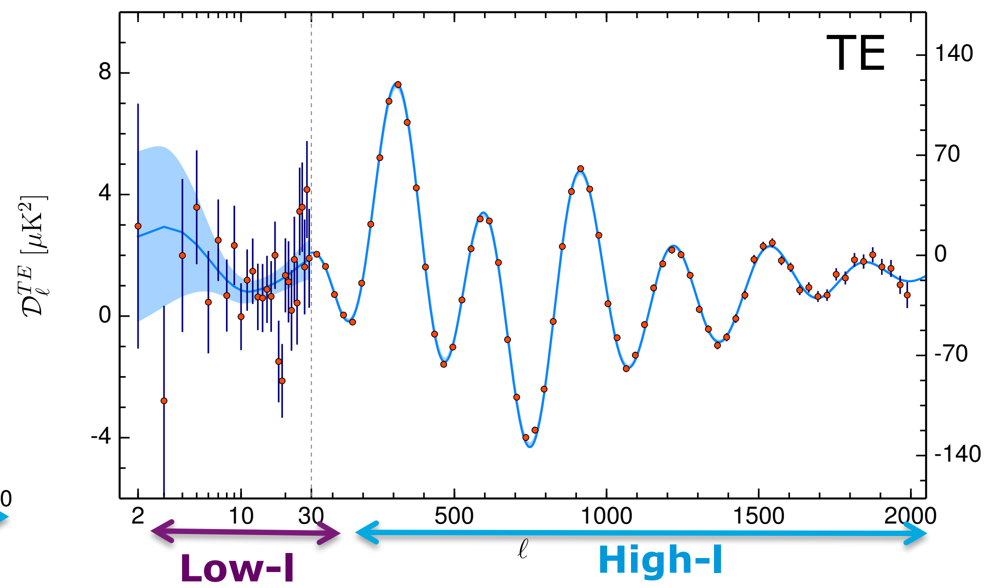
- **1st release 2013: Nominal mission**,15.5 months, Temperature only (large scale polarization from WMAP).
- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization, large scale pol. from LFI.
  Intermediate results 2016: low-l polarization from HFI
- **3rd release 2018: Full mission, improved polarization, low/high-l from HFI.** Better control of systematics specially in pol., still systematics limited.

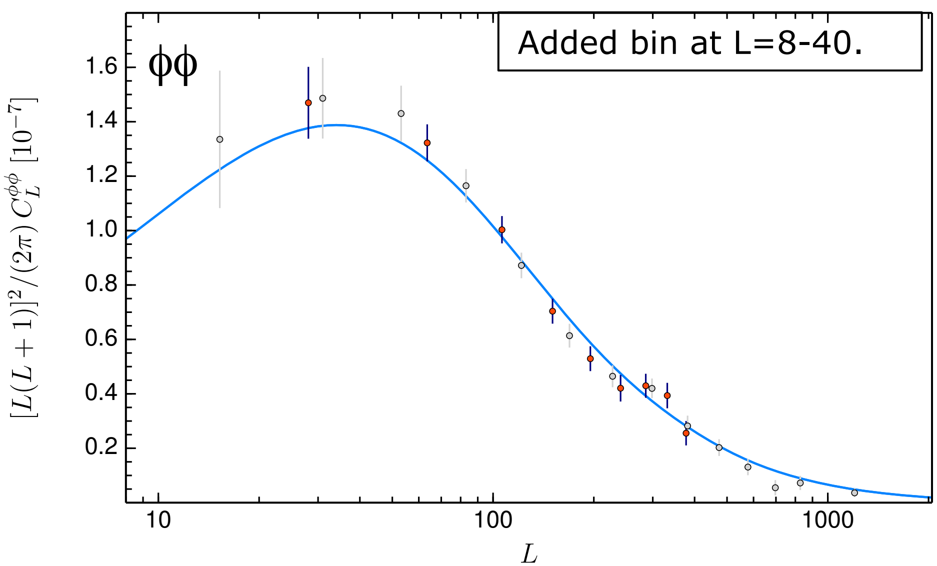
2018 Power spectra

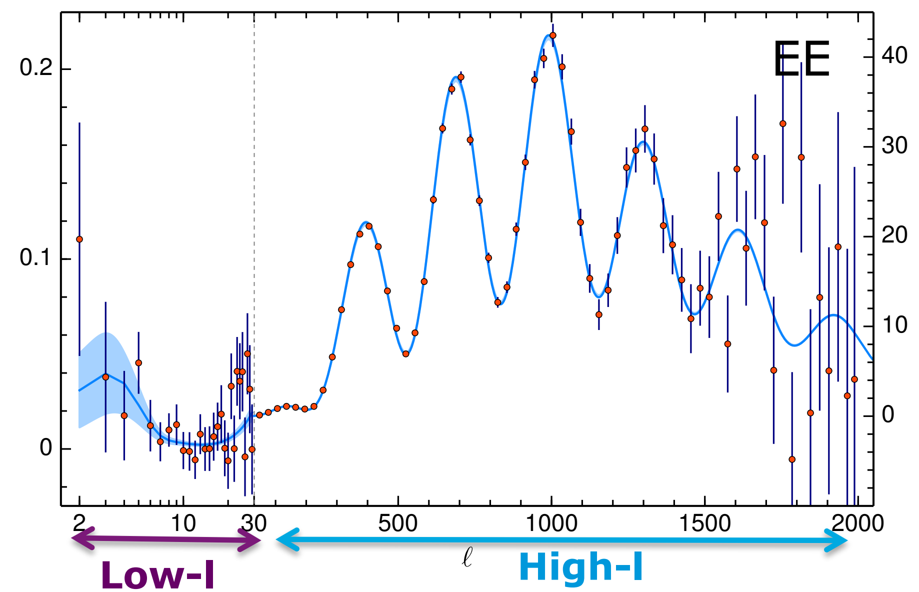
TT, TE, EE: different likelihoods at low-l (<30) and high-l (>30).

Better systematics modeling in polarization

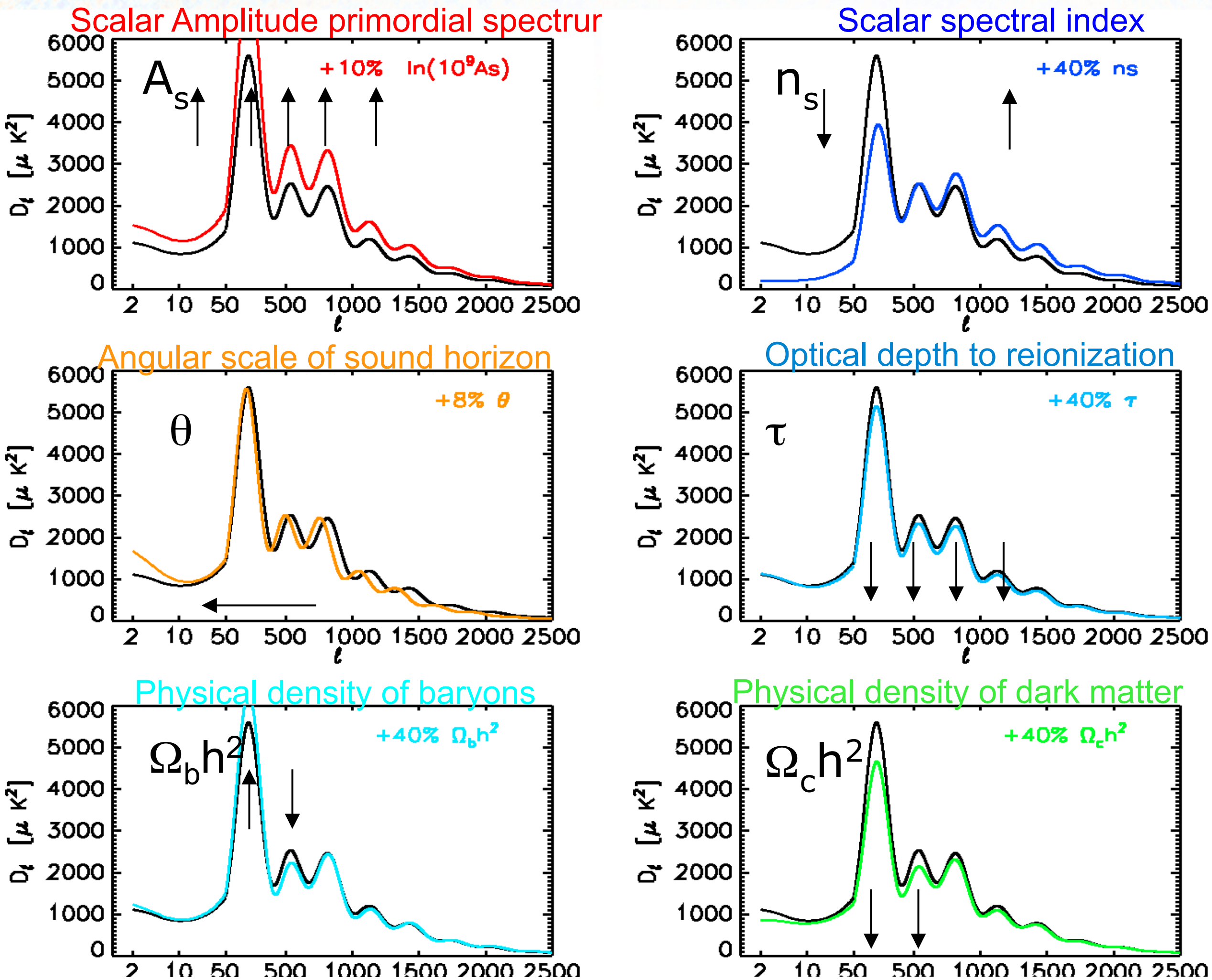








6 ΛCDM parameters



- Initial conditions A_s, n_s:

$$\boxed{\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}}$$

- Acoustic scale of sound horizon θ
- Reionization τ

- Dark Matter density $\Omega_c h^2$
- Baryon density $\Omega_b h^2$

Assumptions:

- Adiabatic initial conditions
- Neff=3.046

- 1 massive neutrino 0.06eV.
- Tanh reionization (Δz=0.5)

planck

Baseline ΛCDM results 2018

(Temperature+polarization+CMB lensing)

	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reion. Optical depth	0.0544	0.0073	13
$\ln(A_s\, 10^{10})$ Power Spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble	67.36	0.54	0.8
Ω_m Matter density	0.3153	0.0073	2.3
σ_8 Matter perturbation amplitude	0.8111	0.0060	0.7

ΛCDM is a good fit to the data
No evidence of preference for classical extensions of ΛCDM

- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- τ lower and tighter due to HFI data at large scales.
- n_s is 8σ away from scale invariance (even in extended models, always $>3\sigma$)
- Best (indirect) **0.8%** determination of the Hubble constant to date.

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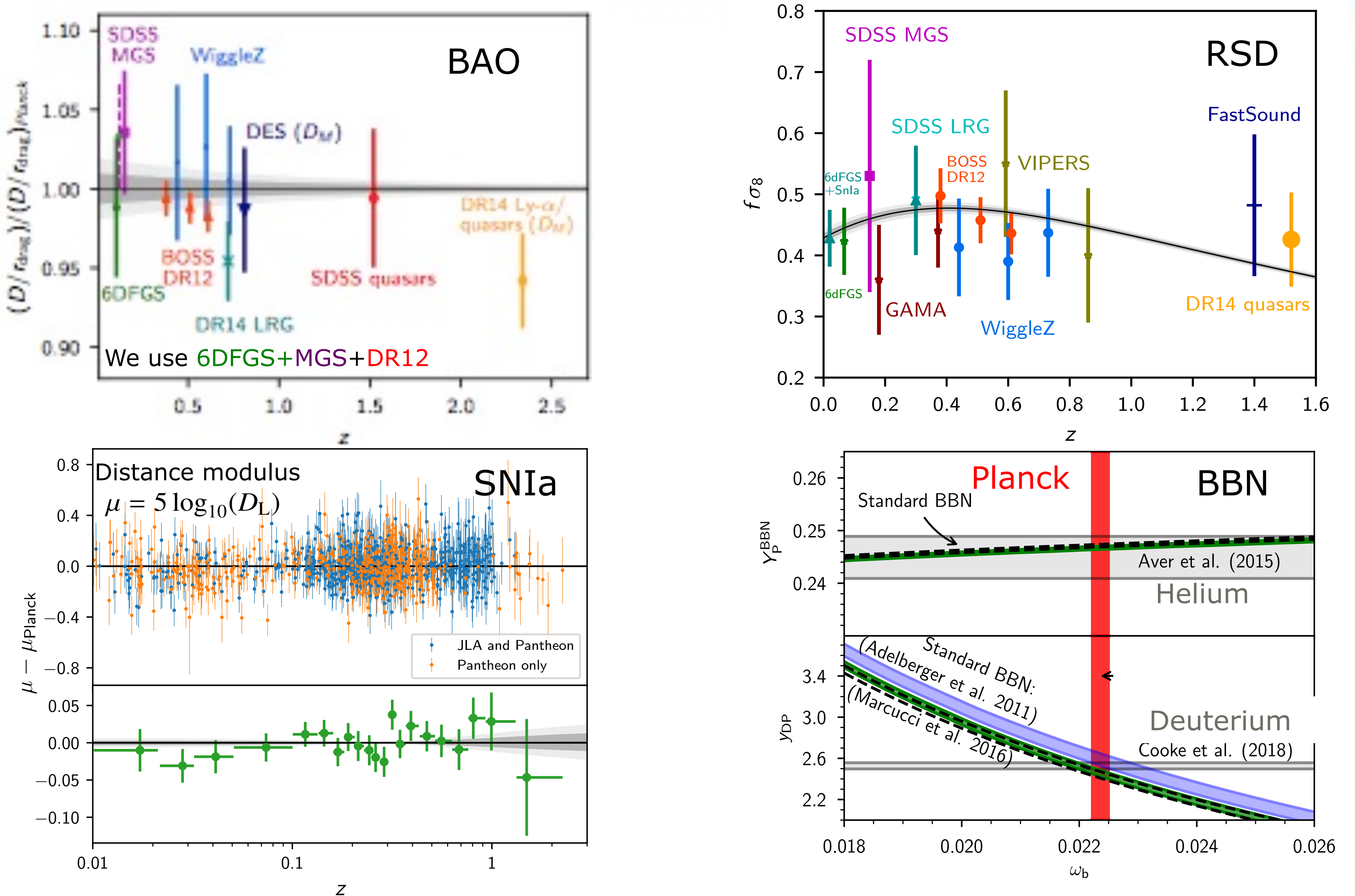
Good consistency with BAO, RSD, SnIa, BBN



Strong tension between early and late universe probes of the Hubble constant H_0

- A type Ia supernova is a star explosion of a white dwarf which reaches the Chandrasekhar limit by accreting mass from a companion.

- It is a standard candle because it's peak luminosity, after some correction, is always the same. It can thus be used to measure distances. However, it's distance-luminosity relation must be calibrated.

https://github.com/shsuyu/H0LiCOW-public/tree/master/H0_tension_plots

Indirect measurement of the Hubble constant from the CMB (and BAO)

See also Knox and Millea 2019 for a review

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

H(z) here is the expansion rate of the universe at **early** times

Measure the **angular scale of sound horizon** from the position of the peaks

$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

H(z) here is the expansion rate of the universe at **late** times

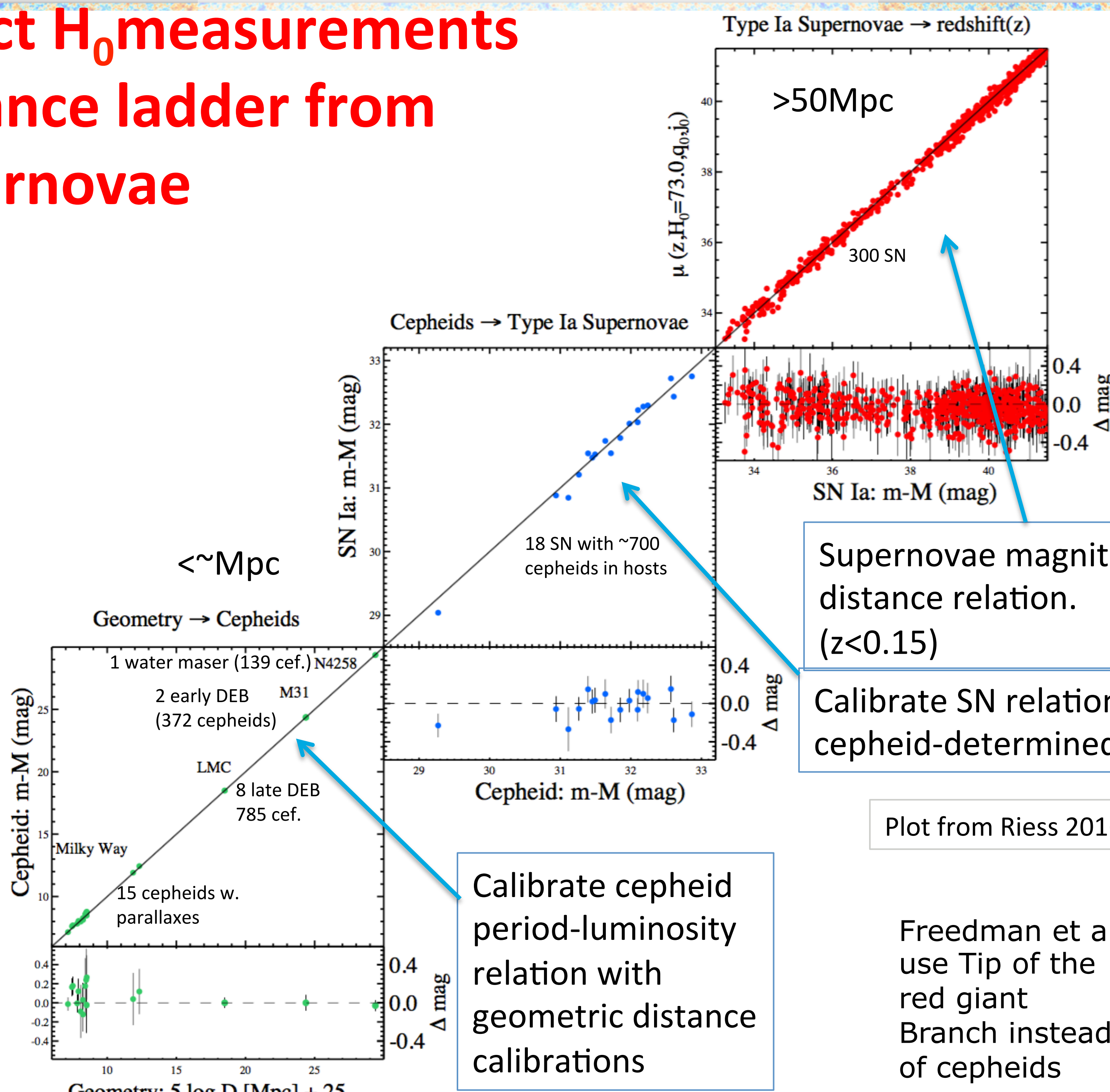
Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

Expansion rate after recombination

$H^2(z)=\mathbf{H_0}^{\mathbf{2}}(\Omega_m (z+1)^3..)$

Model dependent!

Direct H_0 measurements distance ladder from supernovae



Supernovae magnitude-distance relation. (z<0.15)

Calibrate SN relation with cepheid-determined distances

Calibrate cepheid period-luminosity relation with geometric distance calibrations

Plot from Riess 2016

Freedman et al. use Tip of the red giant Branch instead of cepheids

H_0 Tension

Planck | Direct measurements

Planck 1st release :
H_0=67.3±1.2 (TT+WMAP lowlP)

2013 → **2.5σ**

Riess+ 2011
H_0=73.8±2.4
Freedman+ 2012
H_0=74.3 ± 2.5

Planck 2nd release :
H_0=67.26 ± 0.98 (TT+LFI lowlP)
[H_0=67.51 ± 0.64(+TEEE+lensing)]

2015 → **2.5σ**

2.8σ ← 2016

Riess+ 2016
H_0=73.02±1.79

Planck intermediate results :
H_0=66.93±0.62
(TTTEEE+HFI lowlP)

2016 → **3.2σ**

3.8σ ← 2018

Riess+ 2018
H_0=73.52 ± 1.62

Planck 3nd release :
H_0=67.36 ± 0.54
(TTTEEE+HFI lowP+lensing)

2018 → **3.6σ**

4.1σ ← 2019

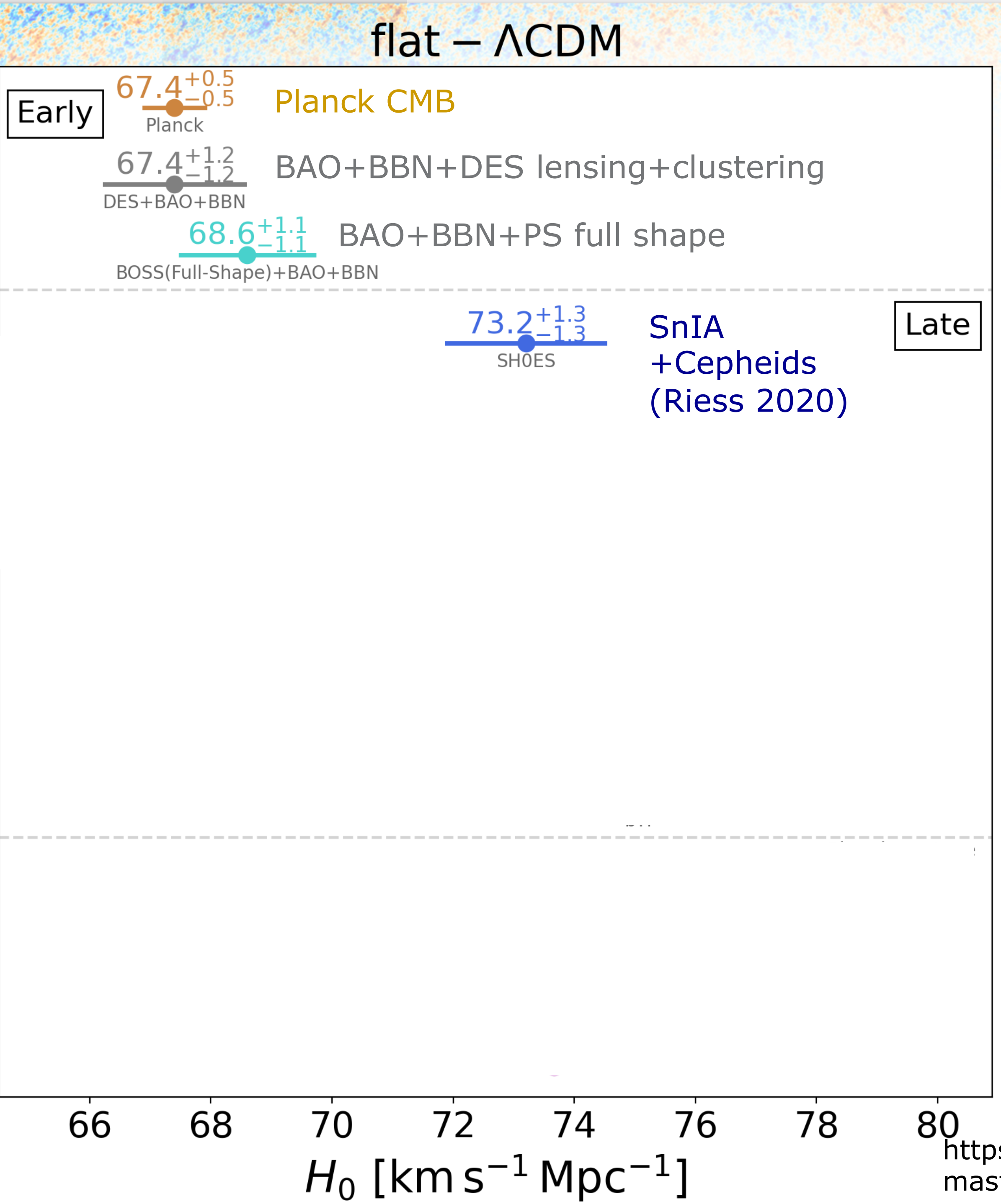
Reid+ 2019
H_0=73.5 ± 1.4
Freedman+ 2019
H_0=69.8 ± 1.9

1.2σ!

[km/s/Mpc]

4.2σ ← 2020

Riess+ 2020
H_0=73.2 ± 1.3



Other early time solutions in agreement with Planck

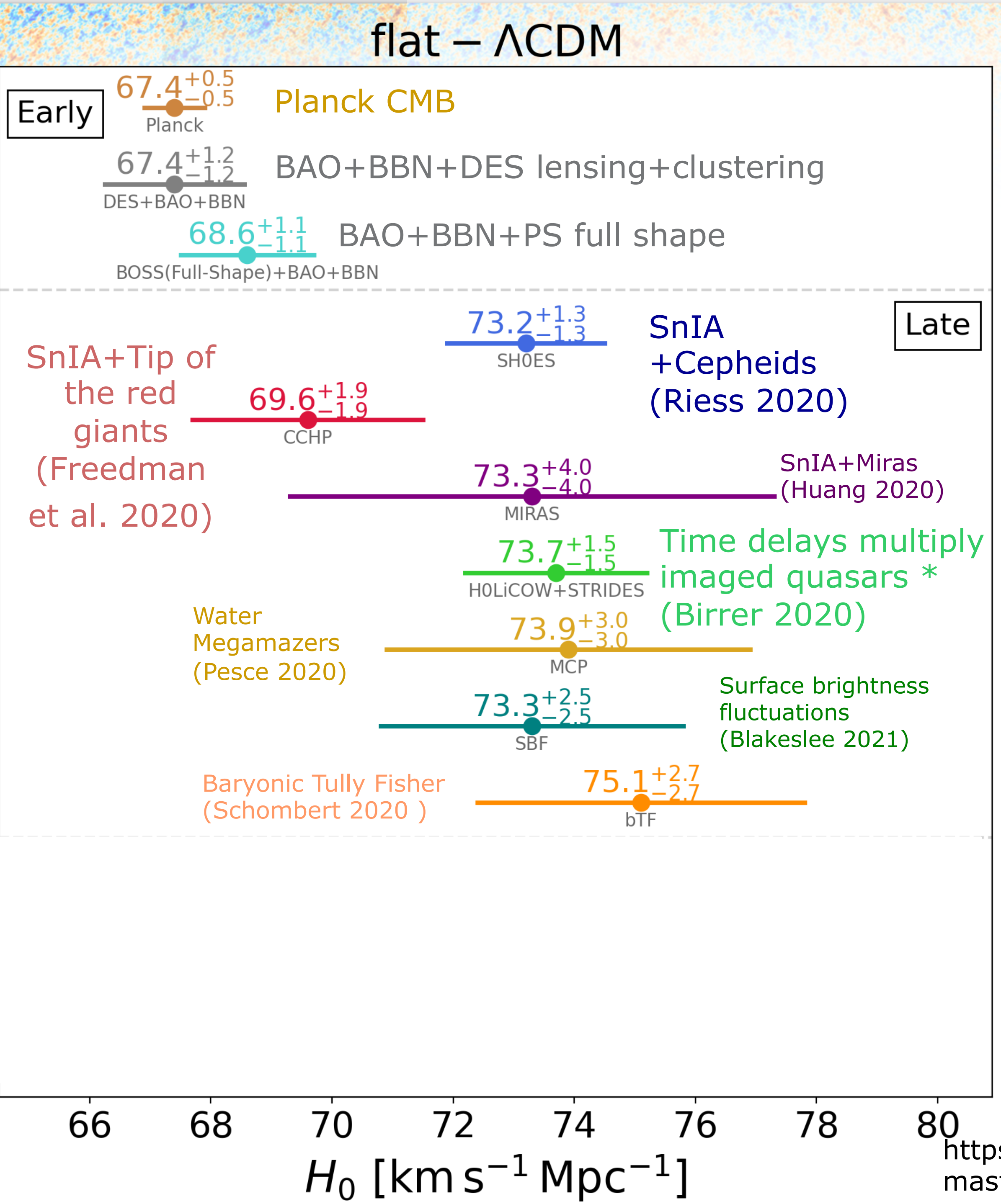
Other CMB experiments in agreement with Planck:

H_0 = 67.9 ± 1.5 Km/s/ Mpc **Atacama Cosmology Telescope DR4 (Aiola+ 2020)**

H_0 = 68.8 ± 1.5 Km/s/ Mpc **South Pole Telescope SPT-3G yr1 (Dutcher+ 2021)**
WMAP+BAO also agrees.

None of these have yet achieved the same statistical power as Planck, all have 2-3 times larger error bars.

https://github.com/shsuyu/H0LiCOW-public/tree/master/H0_tension_plots



More late time measurements in agreement with Shoes

Note:

- Some of these are correlated
- All late have larger error bars then SNIA

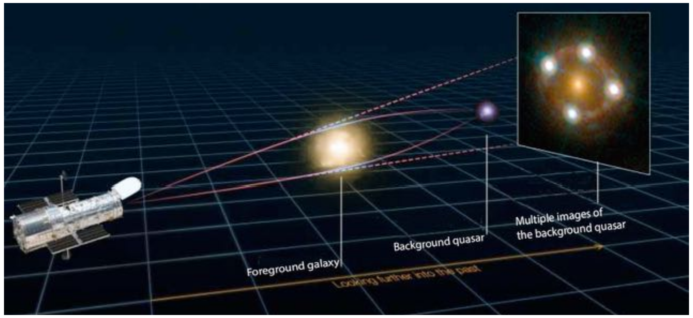
And others:

•Cosmic Chronometers from stellar ages H_0=71±2.8 (H_0=69.3±2.7) km s^{-1} Mpc^{-1} from globular clusters (very-low-metallicity stars) (Jimenez+ 2019).

•Gravitational waves $H_0=68^{+14}{}_{-7}$km $s^{-1}Mpc^{-1}$ (Ligo and Virgo collabs. 2019)

https://github.com/shsuyu/H0LiCOW-public/tree/master/H0_tension_plots

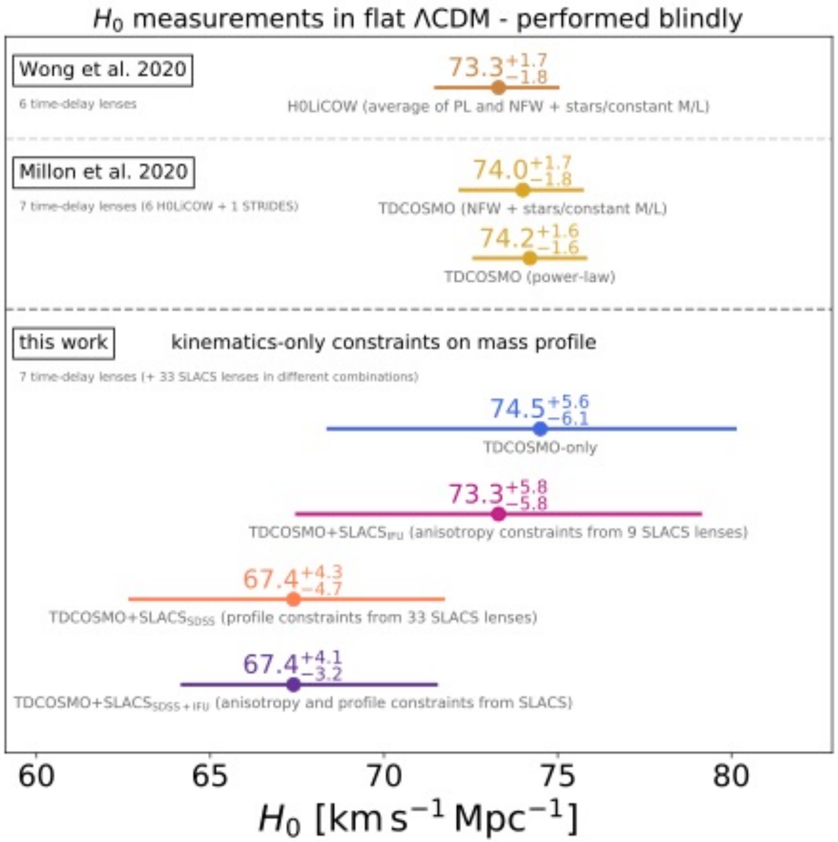
Systematics in the time delay measurements?



Courtesy: Martin Millon

$$\Delta t_{ij} = \frac{D_{\Delta t}}{c}\left[\frac{(\boldsymbol{\theta}_i - \boldsymbol{\beta})^2}{2} - \psi(\boldsymbol{\theta}_i) - \frac{(\boldsymbol{\theta}_j - \boldsymbol{\beta})^2}{2} + \psi(\boldsymbol{\theta}_j)\right]$$

$$D_{\Delta t} \equiv (1 + z_{\rm d})\frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}},$$



- Need lens potential reconstruction to infer H_0
- Mass-sheet degeneracy: degeneracy between source position and lensing convergence profile. It can be broken assuming a deflector mass density profile or using stellar kinematics.
- Not making assumption about the mass profile increases error bars by a factor of ~4.

Birrer+2020. See also Kochanek 2019, Blum+ 2020

So what's wrong?

- ~~Statistical fluctuation unlikely~~
- Systematics in distance ladder?
  - Many reanalysis of the dataset have confirmed high H_0 value
  - However, need strong confirmation from another probe at the same level of accuracy/precision.
  - Still some open debates (cepheid crowding, TRGB reddening, consistency of anchors, environmental effects on SN etc..). Many already addressed by Sh0es team.
- Systematics in CMB and BAO?
  - Planck data have been reanalyzed, finding consistent results. Multiple pipelines, consistency checks all point towards same results.
  - Other CMB experiments and BAO in agreement. However, none yet with the same accuracy.
  - Planck has an internal consistency test deviation (A_L), which however cannot explain as of now the H0 problem.
- New physics?

So what's wrong?

- New physics?

- Caveat: what people mean when they say that a model "works" (or not) to solve the H_0 tensions is very arbitrary. Some would say that a model "works" if you reduce the difference from 4σ to $\sim 2\text{-}3\sigma$ (so that you still need a large statistical fluctuation to explain the rest.)

- Most (all?) of these models do not manage to move the CMB H_0 value all the way to exactly match the Sh0es results, even when combining CMB+H_0.

Indirect measurement of the Hubble constant from the CMB (and BAO)

See also Knox and Millea 2019 for a review

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

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H(z) here is the expansion rate of the universe at **early** times

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H(z) here is the expansion rate of the universe at **late** times

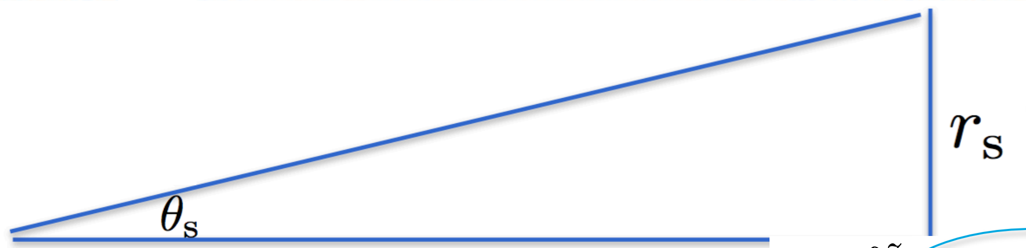
Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

Expansion rate after recombination

$H^2(z)=\mathbf{H_0}^{\mathbf{2}}(\Omega_m (z+1)^3..)$

Model dependent!

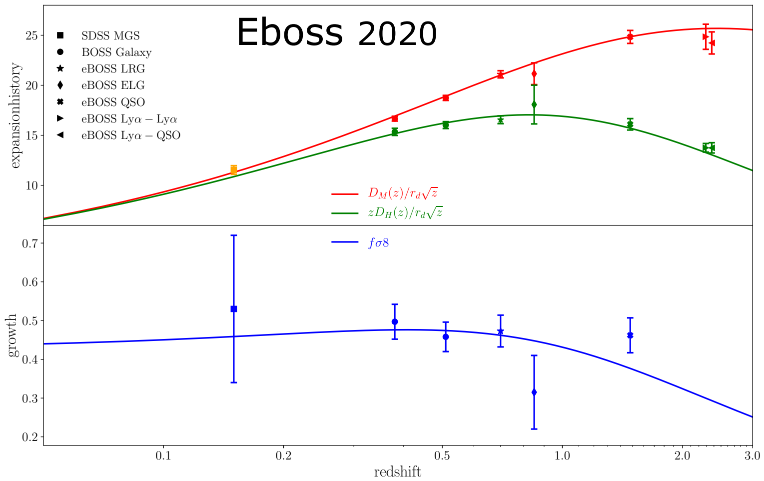
Change in the late universe



$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

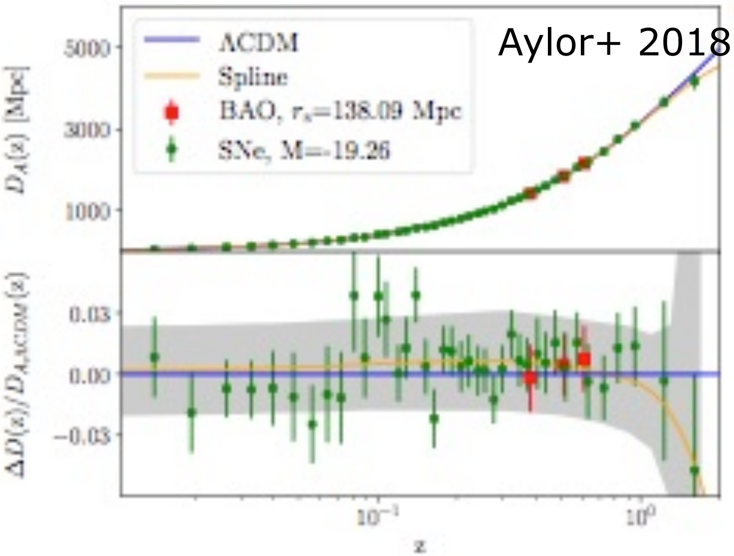
Late-time dynamics of dark matter and/or dark energy, e.g. dynamical dark energy (e.g. Planck collaboration 2015, 2018), decaying DM (Poulin + 2018, Vattis+ 2019,Clark+2020, Haridasu+2020) interacting dark matter-dark energy (Di Valentino+ 2019)), Modified gravity (Raveri 2019), H(z) reconstruction (Bernal+2016, Lemos+ 2018, Raveri 2019 etc…)

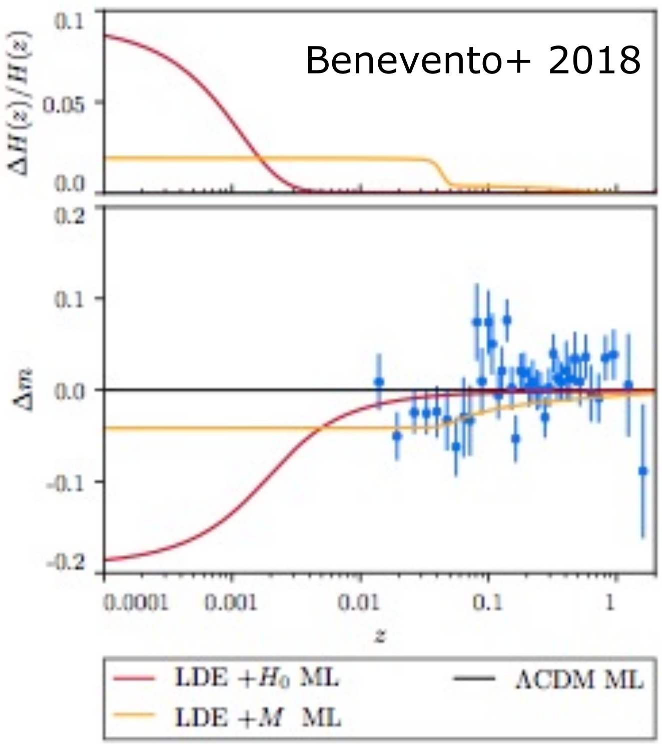
=> highly constrained by BAO, Supernovae and other probes.



Other: e.g. Modified gravity changes to Cepheid period-luminosity relation (Desmond+ 2019)=> but cannot explain time delay H_0 measurement.

Late time solutions: change in H(z)





- The CMB is only sensitive to the integral of the expansion history till decoupling, and so cannot constrain the detailed redshift evolution of H(z).

- However, **BAO and SN cover z~0.01-2, tightly constraining the evolution of H(z).**

- If one tries to solve the tensions with a sharp transition at z<0.01, one cannot just use an H_0 gaussian prior at z=0! The H_0 constraint come from using supernovae at z=0.01-0.15 calibrated with cepheids at z<0.01! A more viable solution is to use the Pantheon SN dataset with the cepheid calibration.

- The tension is on the Supernovae calibration M_b!

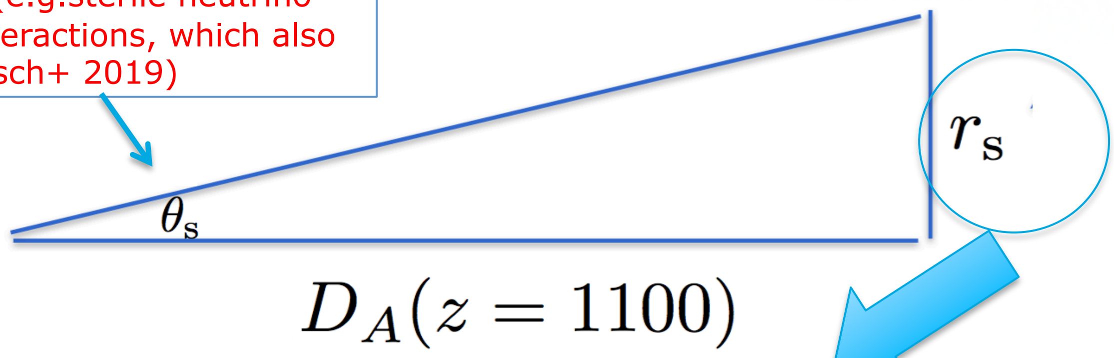
$$\mu(z) = m_B(z) - M_B$$

$$m_B(z) = 5\log_{10}\left[\frac{d_L(z)}{10\mathrm{pc}}\right] + M_B$$

See also Aylor+ 2018, Poulin+ 2018, Benevento+ 2020, Wang 2019, Raveri+ 2019, Dhawan+ 2020, Camarena and Marra 2021.

Changes in the early universe

Change the inference of θ from CMB (e.g.sterile neutrino with strong interactions, which also change r_s Kreisch+ 2019)



In ΛCDM from Planck, r_s^{drag}=147.09 ± 0.26. To solve the Hubble tension one needs r_s^{drag}~138.

Change the time of decoupling (e.g. changing recombination Chiang+ 2018).

Change the sound speed (e.g. DM-baryon interactions, Boddy+ 2018)

$$r_s = \int_0^{\boxed{t_\mathrm{d}}} c_\mathrm{s} dt/a = \int_0^{a_\mathrm{d}} c_\mathrm{s} \frac{da}{a^2 H(a)}$$

Change the expansion history of the universe at early times (e.g. early dark energy Poulin+ 2018)

Some of these work better than others, but a satisfying physical theory that can explain all of the observations has yet to be found…

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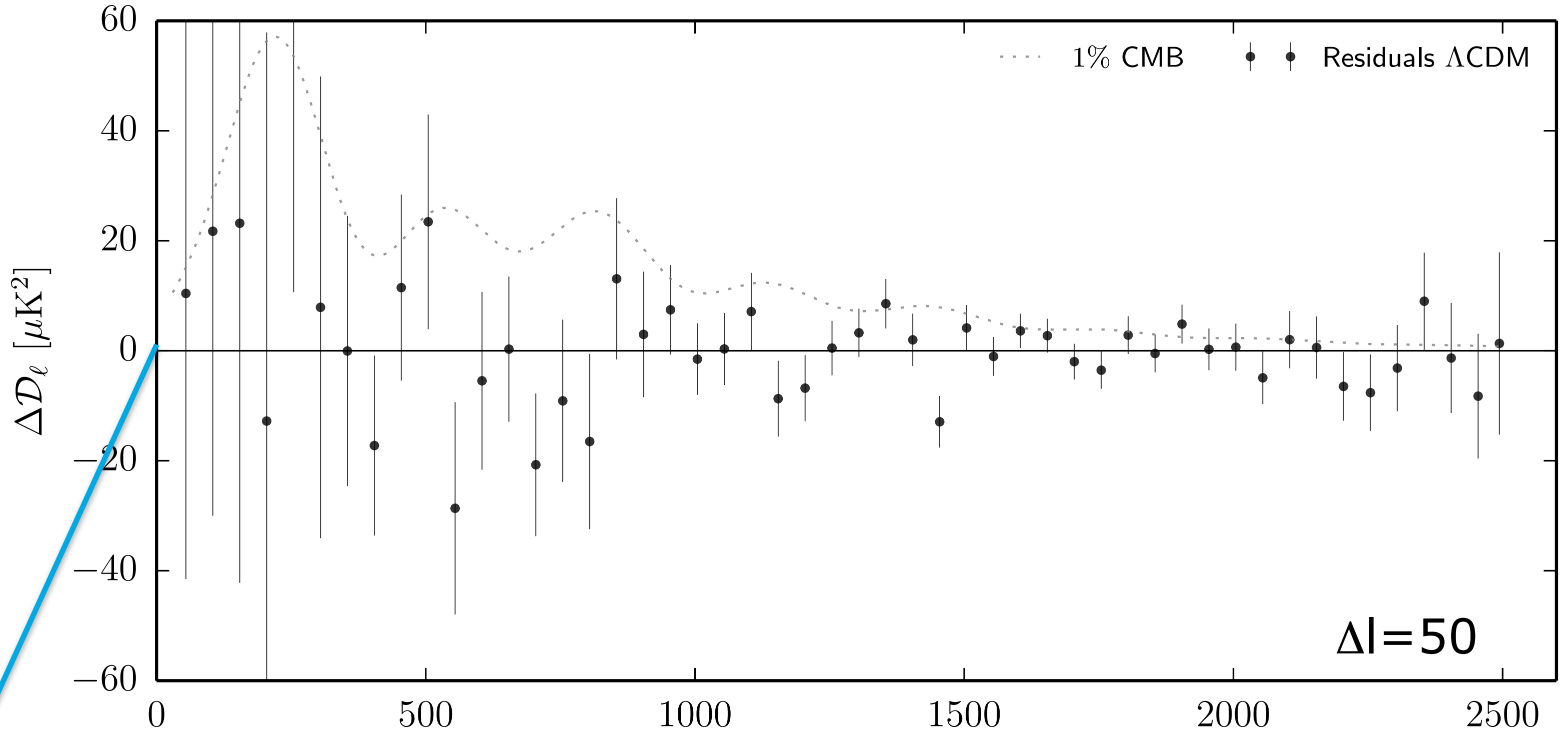
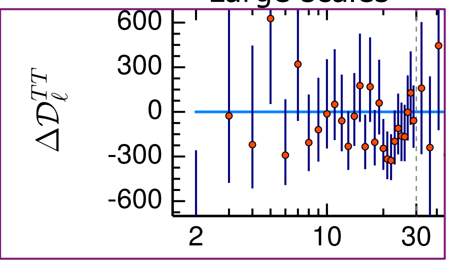
Residuals TT with respect to ΛCDM

Well behaved residuals, very good χ^2 (unbinned coadded* at l=30-2508 PTE=16% dof=2478).

TT+lowlTT+lowE
(lowlTTnot shown in this plot)



Large scales



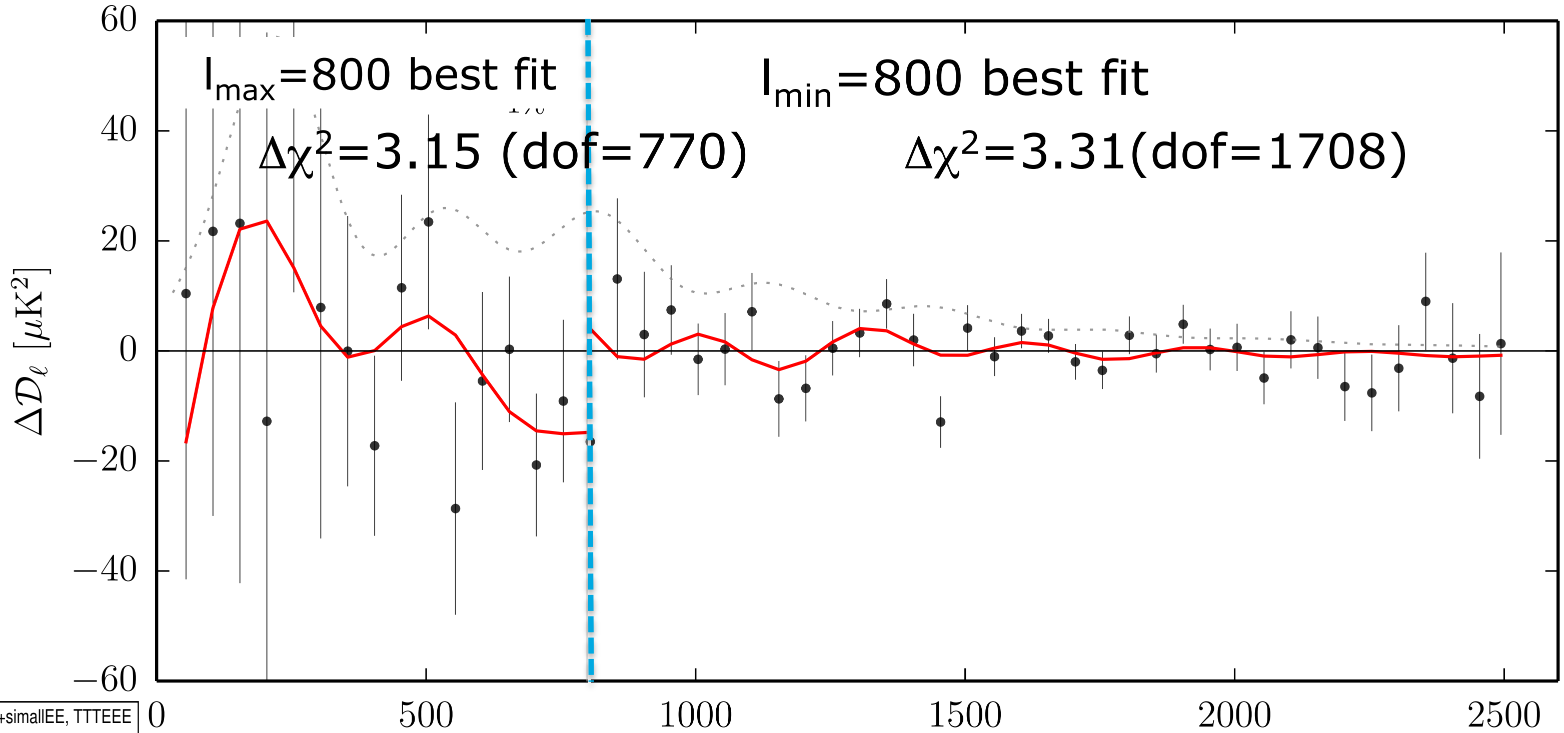
Residuals of the coadded CMB spectrum, assuming the ΛCDM best fit cosmology and foreground model (coadded~weighted average of foreground cleaned 100x100, 143x143, 143x217 and 217x217 spectra)

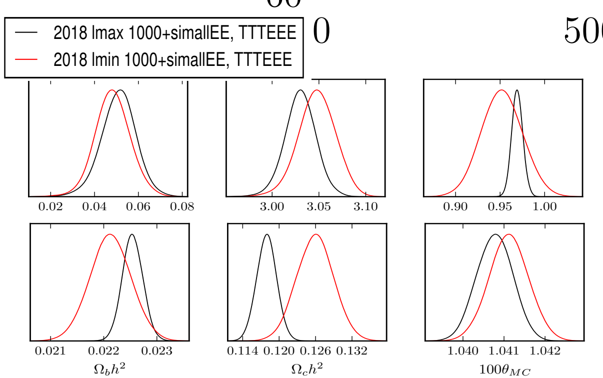
*[χ^2 can vary depending on binning]

Separate ΛCDM fits to low and high-l

TT(lmax=800)+lowlTT*+lowE
(*not shown in this plot)

TT(lmin=800)+lowE
(*not shown in this plot)





The parameters from low and high multipoles are in overall agreement at the ~2σ level.

Planck collaboration (SG) 2015 XI (Likelihood paper)
Addison et al. 2016
Planck collaboration (SG) 2017 LI

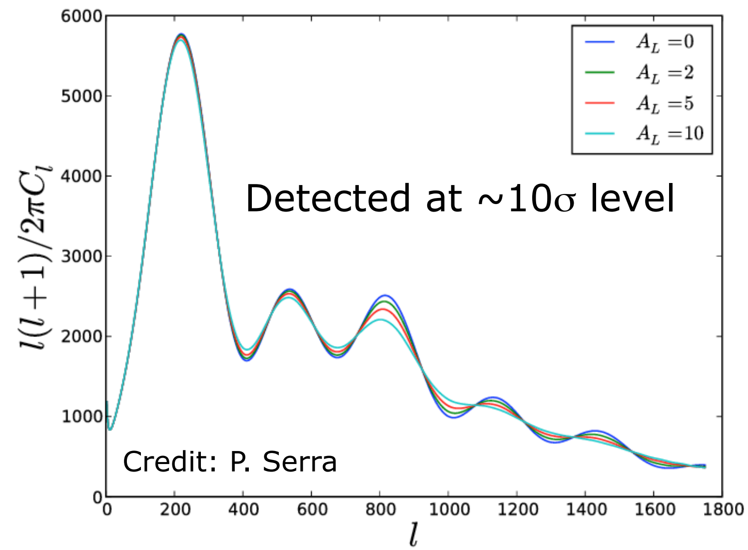
CMB lensing and A_{Lens}

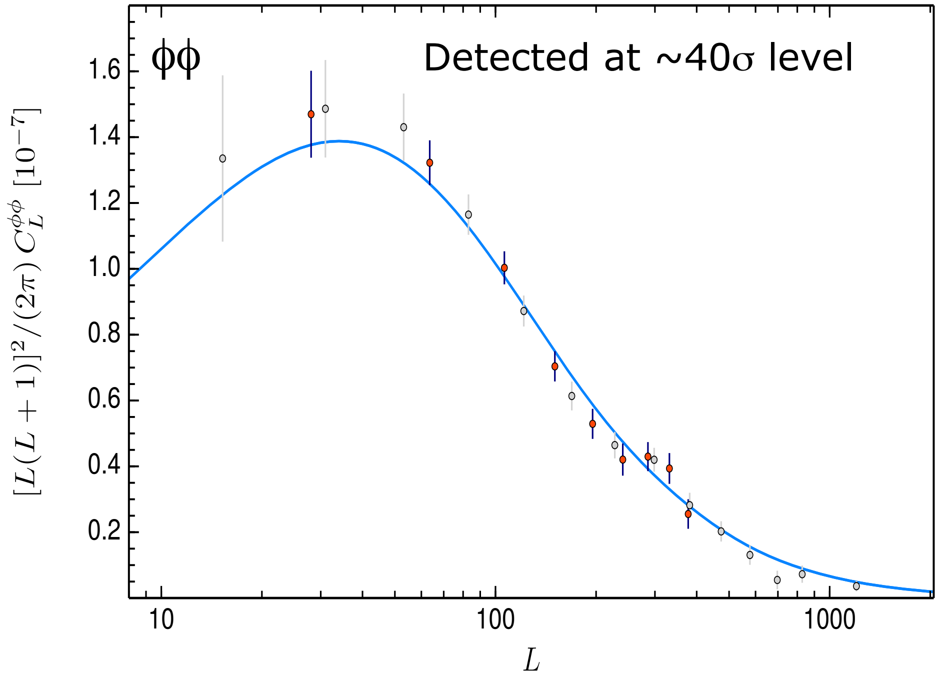
- Lensed CMB power spectrum is a convolution of unlensed CMB with lensing potential power spectrum=>**smoothing of the peaks and throughs**.

- A_L is a consistency parameter, which rescales the amplitude of the lensing potential which smooths the power spectrum.

$$C_\ell^\Psi \rightarrow A_L C_\ell^\Psi$$ Calabrese+ 2008

- Lensing is better measured taking the 4-point correlation function of the CMB maps, since lensing breaks isotropy of the CMB, giving a non-gaussian signal.





See e.g. Lewis & Challinor 2006

Peak smoothing in the power spectra

- A_l is an unphysical parameter used for consistency check.

- Since 2013 preference for high value, TT spectrum prefers 2.4σ deviation from 1.

$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$

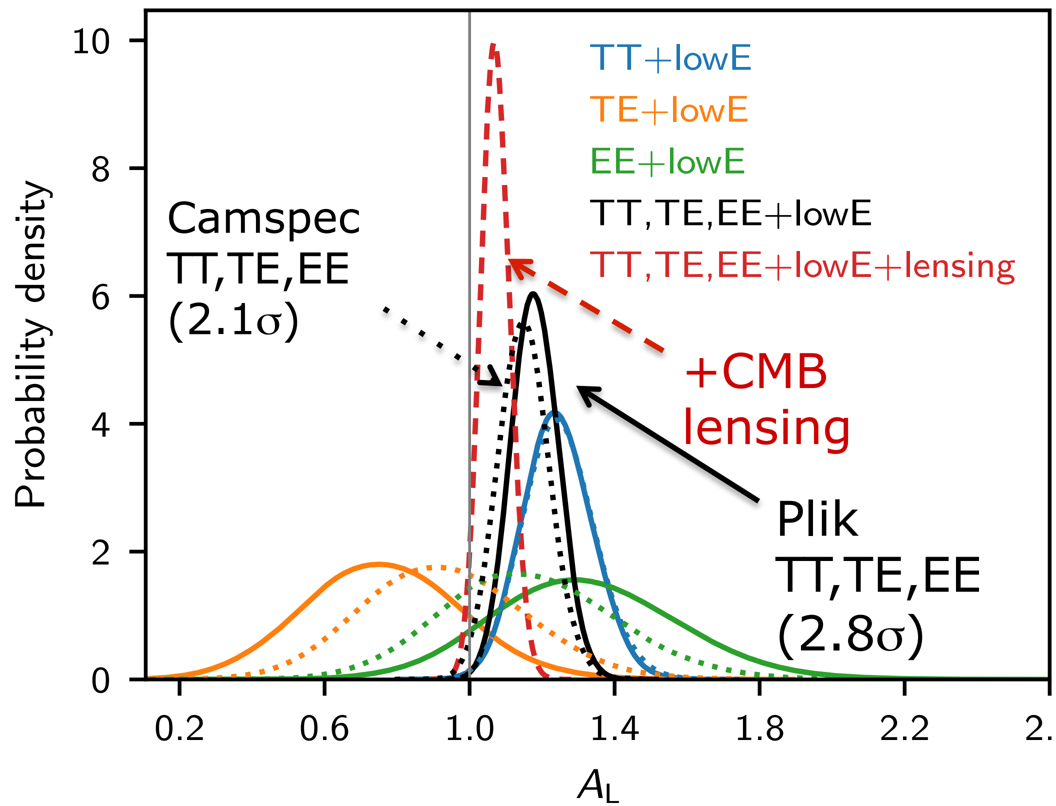
- Not really lensing, not preferred by CMB lensing reconstruction.

- Preference for higher lensing projects into small deviations in extensions which have analogous effect on lensing (Ω_k, w, Σm_ν).

- Adding polarization, A_L degenerate with systematics corrections and thus likelihood used.

$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE})$$
$$A_L = 1.149 \pm 0.072 \ (68\,\%,\ \mathrm{TT,TE,EE{+}lowE\ [CamSpec]})$$

Amplitude of the lensing potential power spectrum.

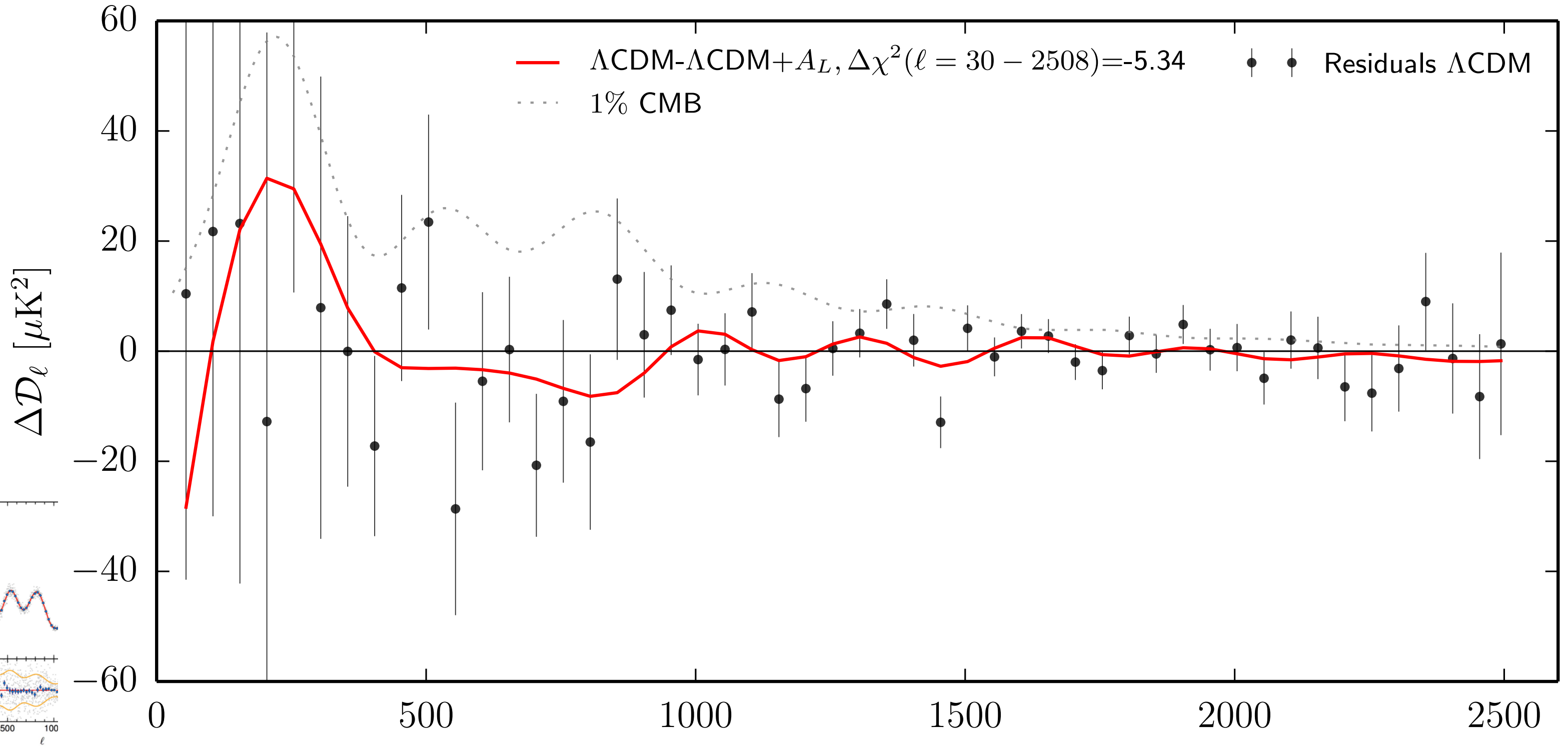


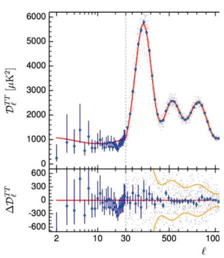
Planck **2018** results. VI. Cosmological parameters

Different treatments of systematics in polarization (as done in our two likelihoods) can impact extensions of ΛCDM at ~0.5σ level.

Residuals TT

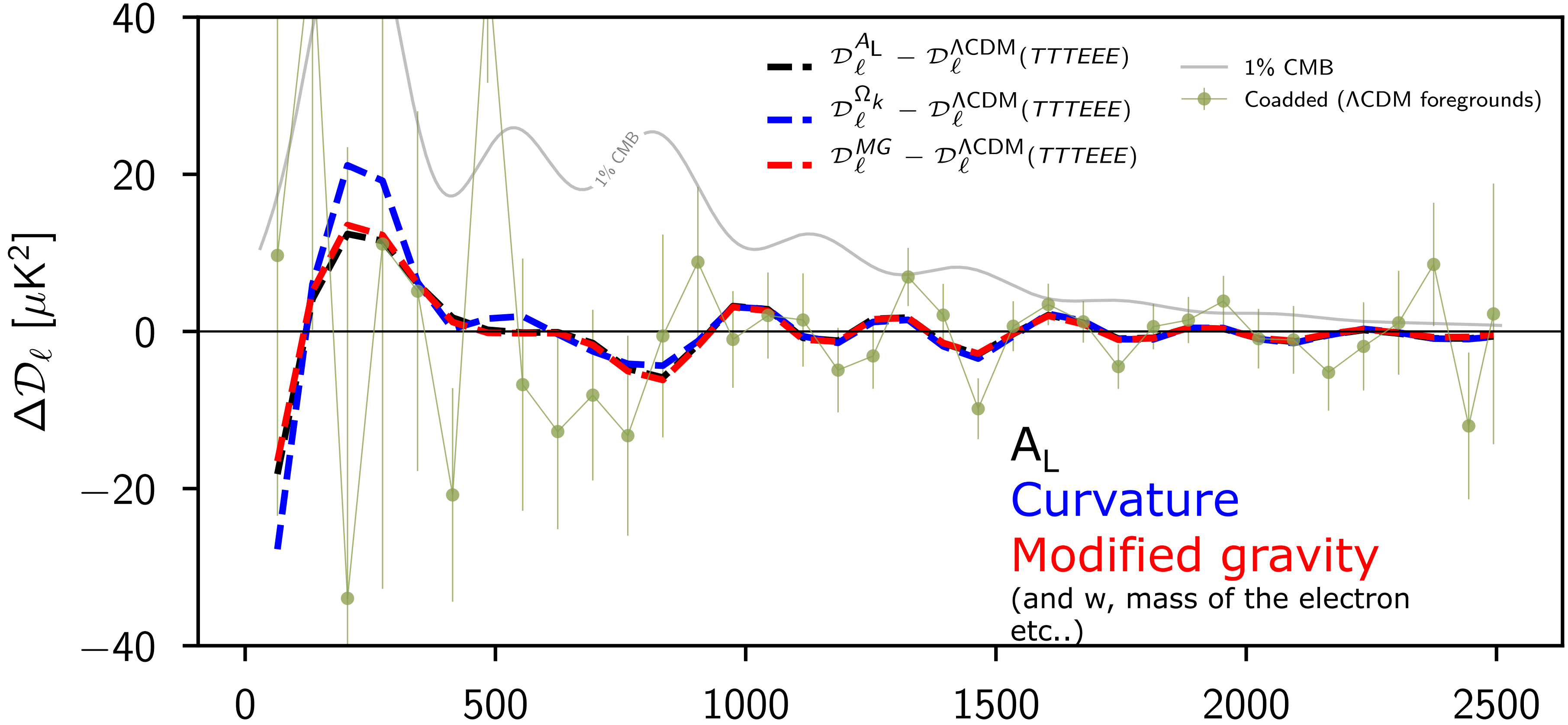
A_L is a phenomenological parameter which allows to better fit both the high and low-ell by $\Delta\chi^2$=5.3 (A_L=1.24 ±0.1) (plus $\Delta\chi^2$=2.3 from lowl TT)





- **The features which lead the the high Alens could just be due to statistical fluctuations!** In other words, Alens might just be fitting noise/cosmic variance.

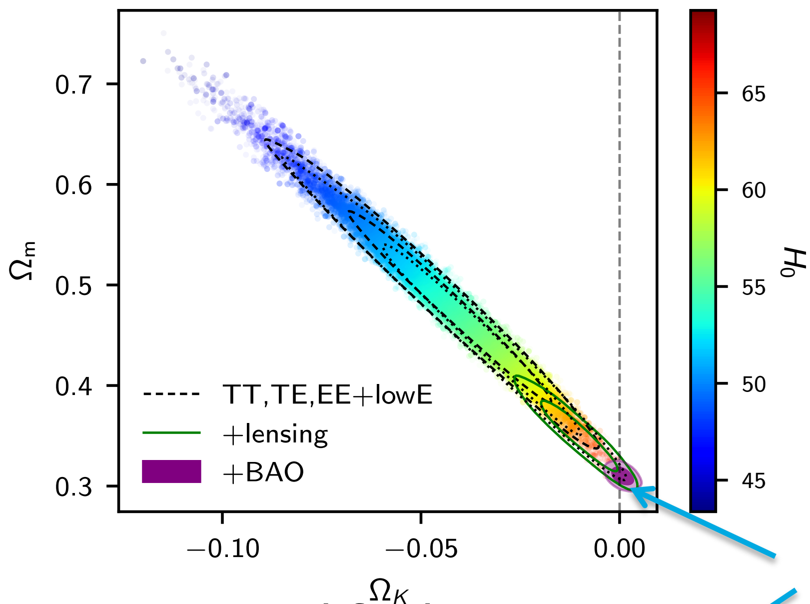
Alens, modified gravity, curvature etc....



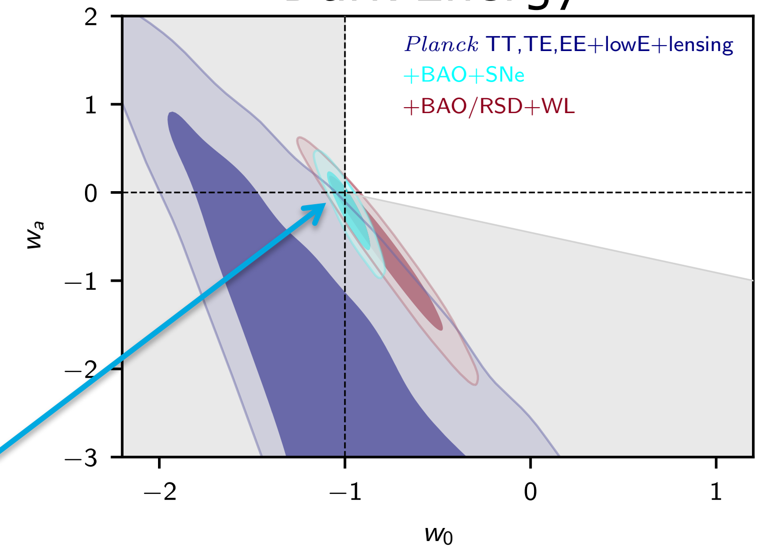
The difference between low and high-l, the deviation in A_L, Ω_k, w, MG, mass of the electron (see e.g. Hart et al. 2019) etc... with Planck power spectra alone all fit similar features in the power spectra at the 2-3σ level.

Planck collaboration 2018 VI

Curvature

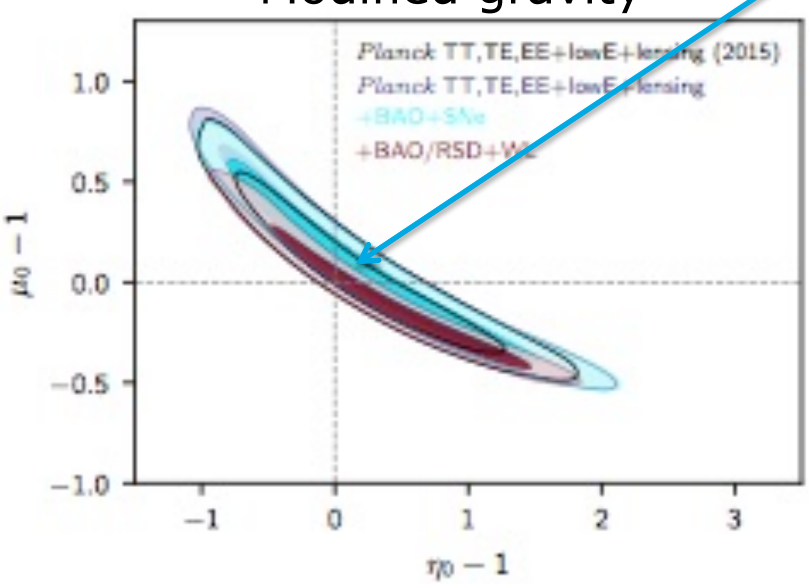


Dark Energy



ΛCDM

Modified gravity



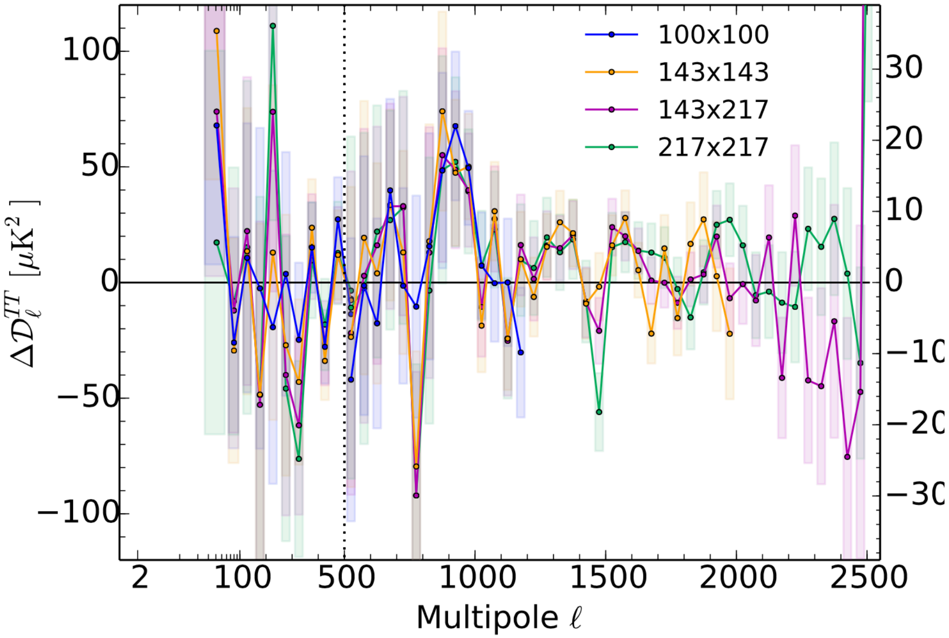
All deviations go back to ΛCDM when combined with other probes.

As of now there is no physical model which can accommodate the Alens anomaly and all other cosmological data.

Planck collaboration 2018 VI. Cosmological parameters

Is this a systematic effect?

1. Planck tested for many different sources of systematics, without finding a good culprit
    a. Galactic foregrounds
    b. Extra-galactic foregrounds
    c. Pointing errors
    d. Aberration
    e. Beam errors



The features which drive the Alens excess in temperature are consistent across frequencies, i.e. across detectors. If this is a systematic, it must affect different detectors in a similar way. Not easy!

Systematics in polarization?

- High A_L driven by TT spectrum **(2.4σ).**

$$A_{\rm L} = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$

- Adding polarization data in the baseline likelihood gives a **2.8σ** deviation from one.

$$A_{\rm L} = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE})$$

- **However, a different treatment of polarization systematics can change the evidence of this!It can bring it down to 2.1σ.**

$$A_{\rm L} = 1.140 \pm 0.066 \ (68\%, \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE}, \text{alternative polarization efficiencies})$$

Planck **2018** results (SG). VI. Cosmological parameters
Planck 2018 results (SG). V. Likelihood

Polarization calibration

Intensity I and Polarization Q and U Stokes parameters

$$P(t) = G\{I + \rho[Q\cos 2(\psi(t)) + U\sin 2(\psi(t))]\} + n(t),$$

Detector gain

Detector polarization efficiency

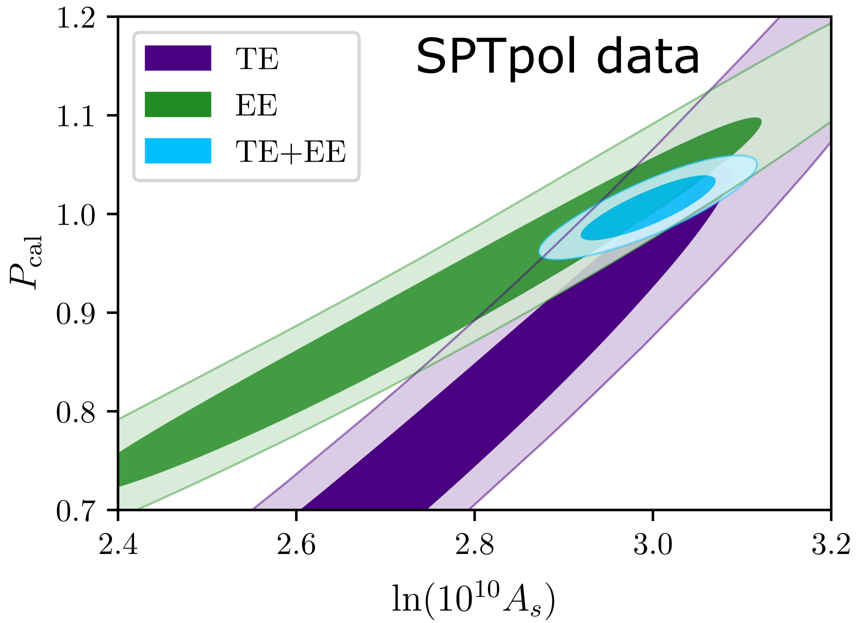
1. In Planck, polarization efficiencies measured on the ground at the 0.1-0.3% level. Found in flight to have much larger uncertainties, at a few % level.
2. A wrong estimate of polarization efficiency can bias cosmology.
3. All current and future ground-based experiments observing small scales rely on Planck to calibrate their polarization efficiencies!
4. We need to find an alternative if we want these new experiments to provide an independent look at tensions and curiosities from Planck!

Effective polarization calibration

- Uncorrected polarization efficiencies can be **modeled at the map level** with an effective parameter (**Pcal)**.
- We define **Pcal** as the polarization calibration parameter adjusting theoretical power spectra at each frequency:

$$TE' = TE / T_{cal}^2 \; P_{cal} \qquad EE' = EE / T_{cal}^2 \; P_{cal}^2$$

- **Just using the combination of EE and TE, without any external information, one can measure polarization efficiencies directly from the data in a model dependent way.**



Current and future can break degeneracies between cosmological parameters and systematic errors from polarization efficiencies with this modeling.

Galli, Wu et al, appearing today

The future is bright and full of new data!

- Current ground-based CMB experiments such as ACT and SPT are exploring the small scale polarization of the CMB.

- They will be able to set constraint on H_0 and other parameters as tight as Planck, and in combination with it potentially to improve by a factor of 2.