How to (try? hope? to) resolve the Hubble tension

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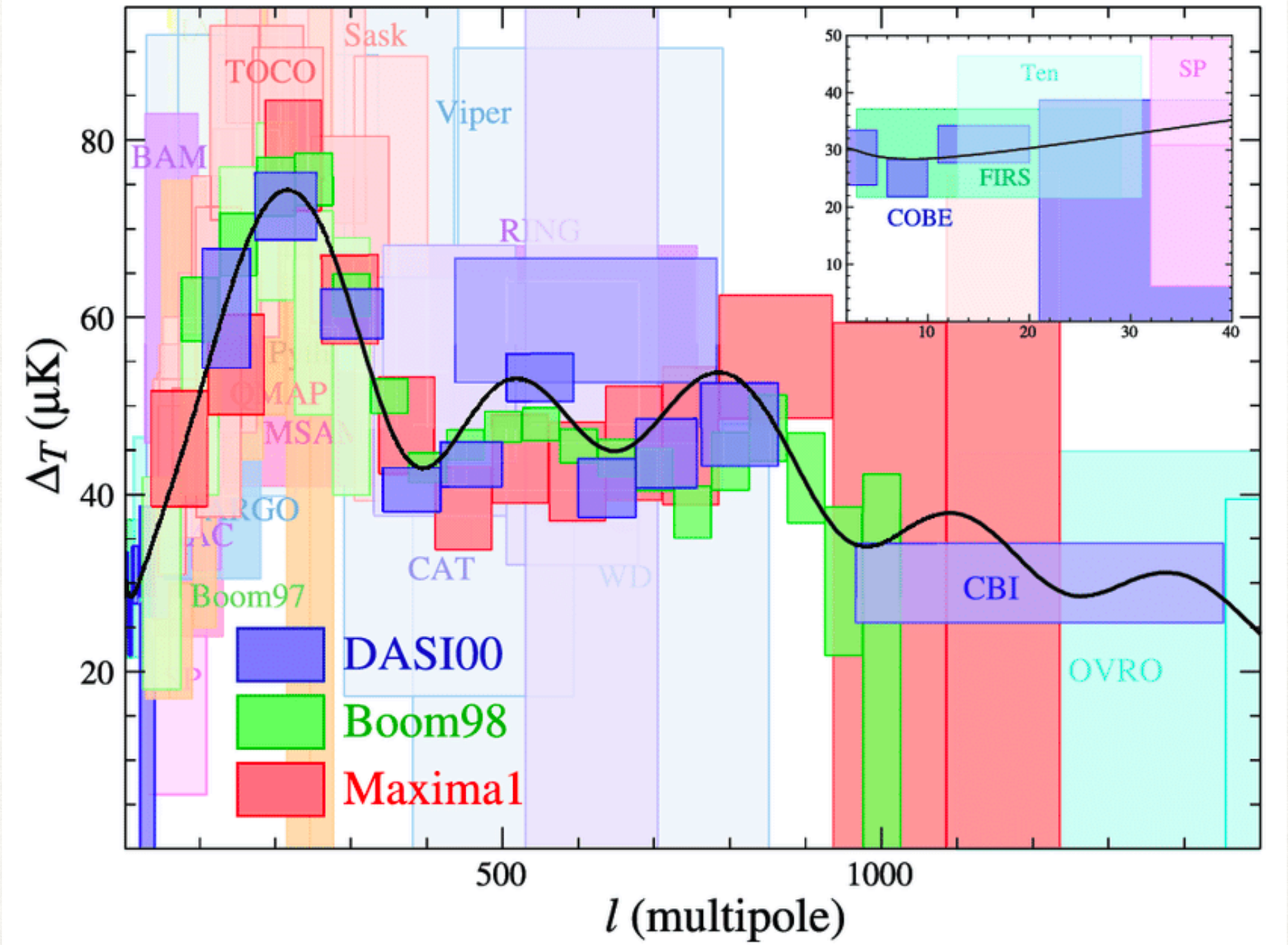
March, 9th 2021

The Era of Precision Cosmology

20 years ago



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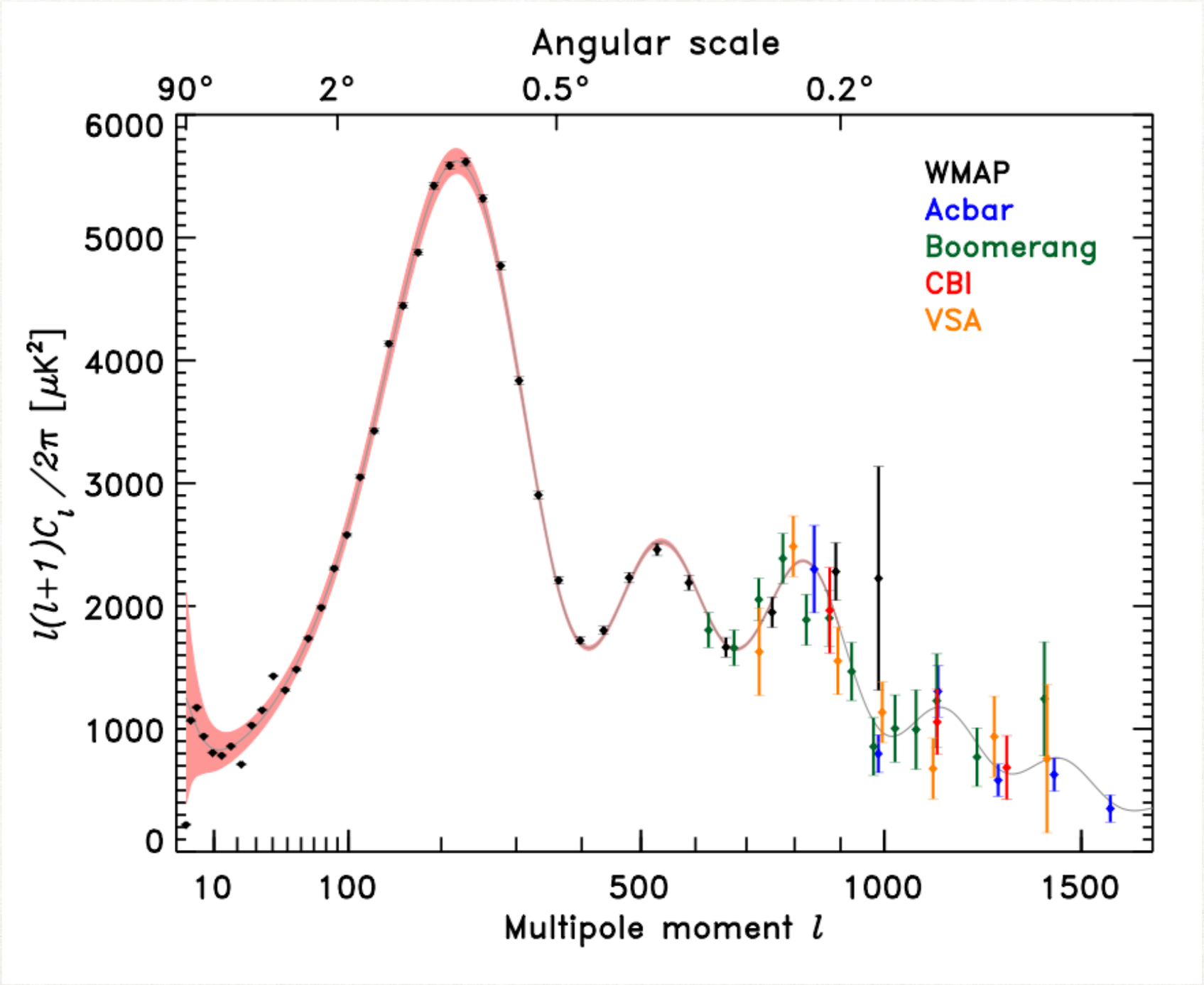
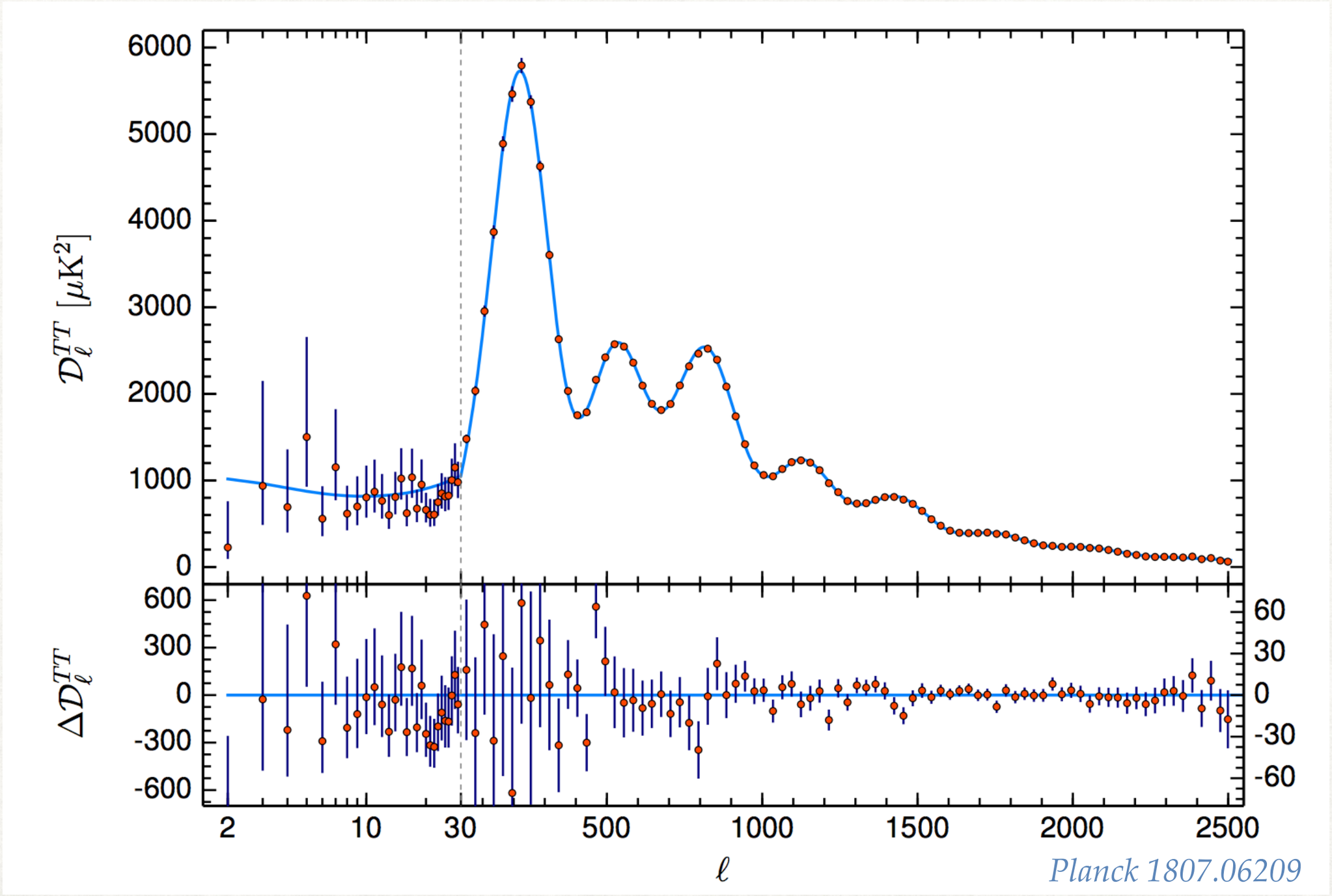
The Era of Precision Cosmology

10 years ago



The Era of Precision Cosmology

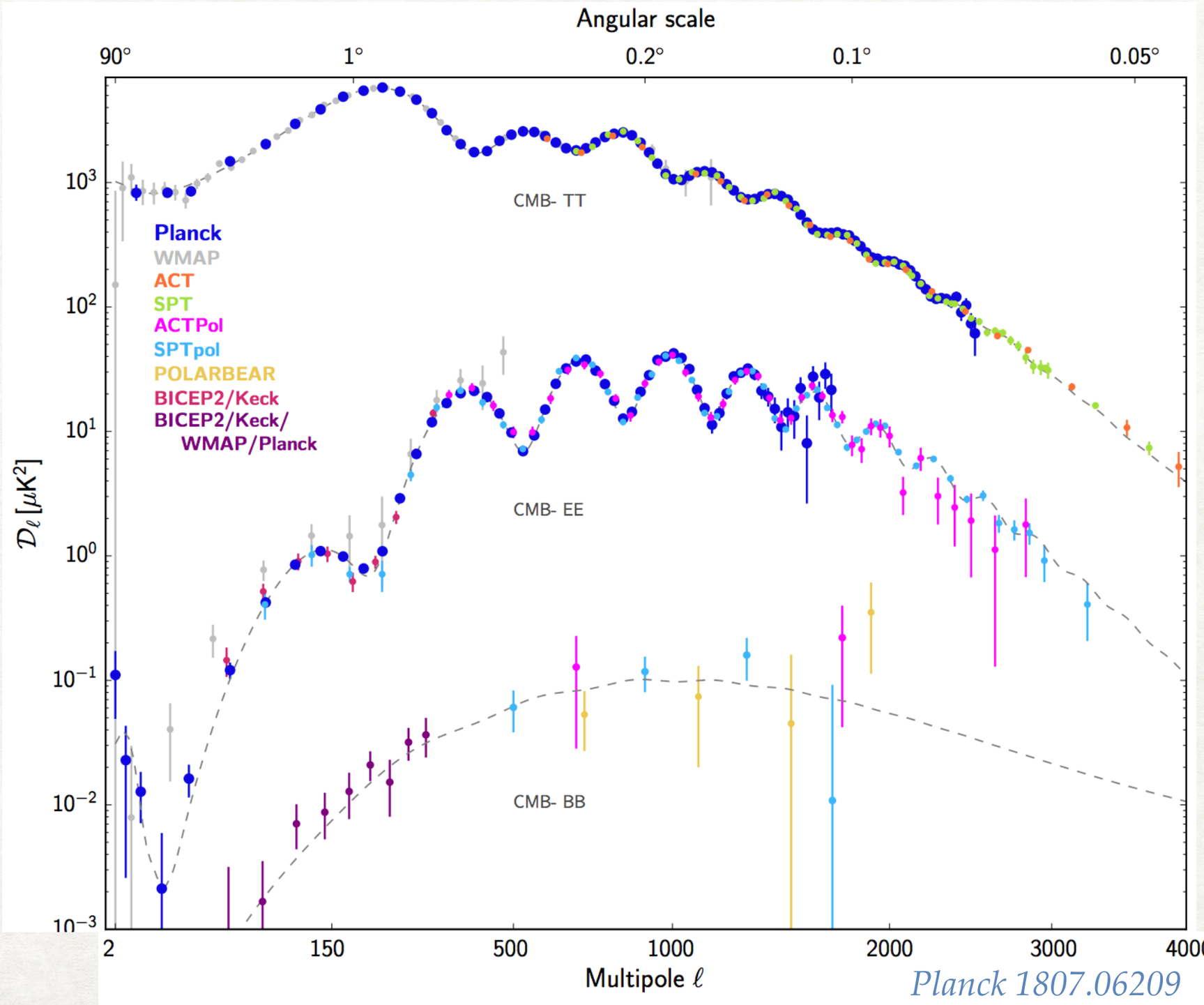
Today



Planck 1807.06209

The Era of Precision Cosmology

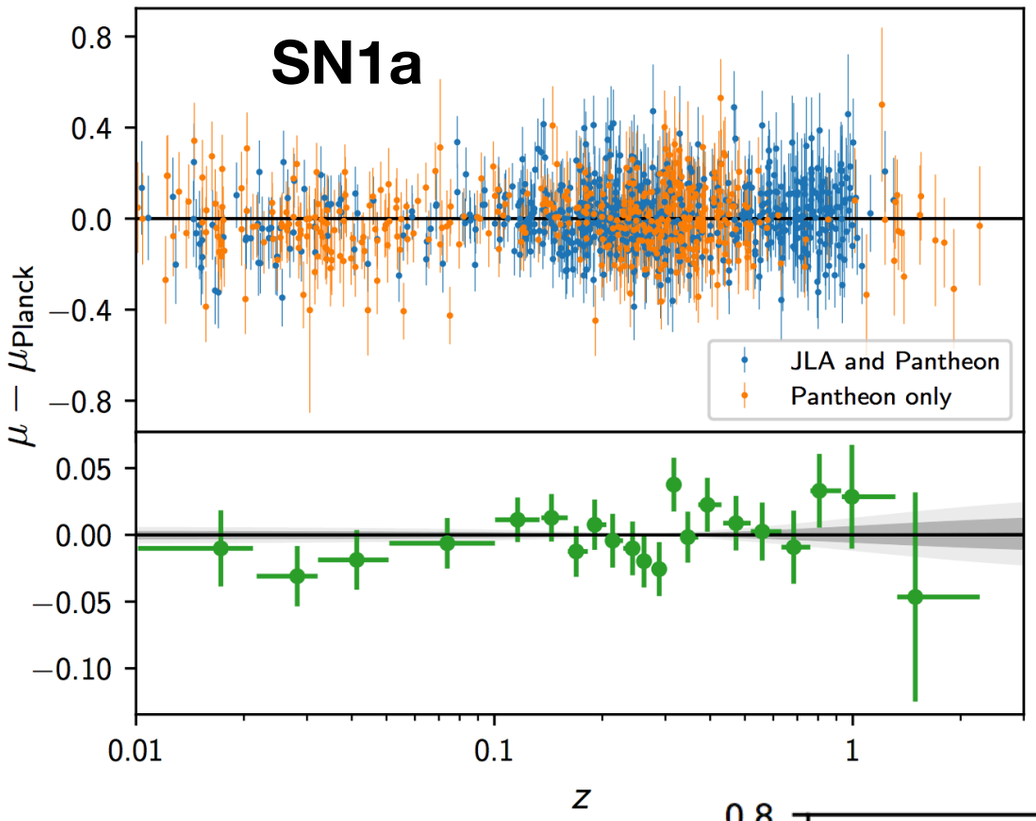
Good agreement between all CMB data!

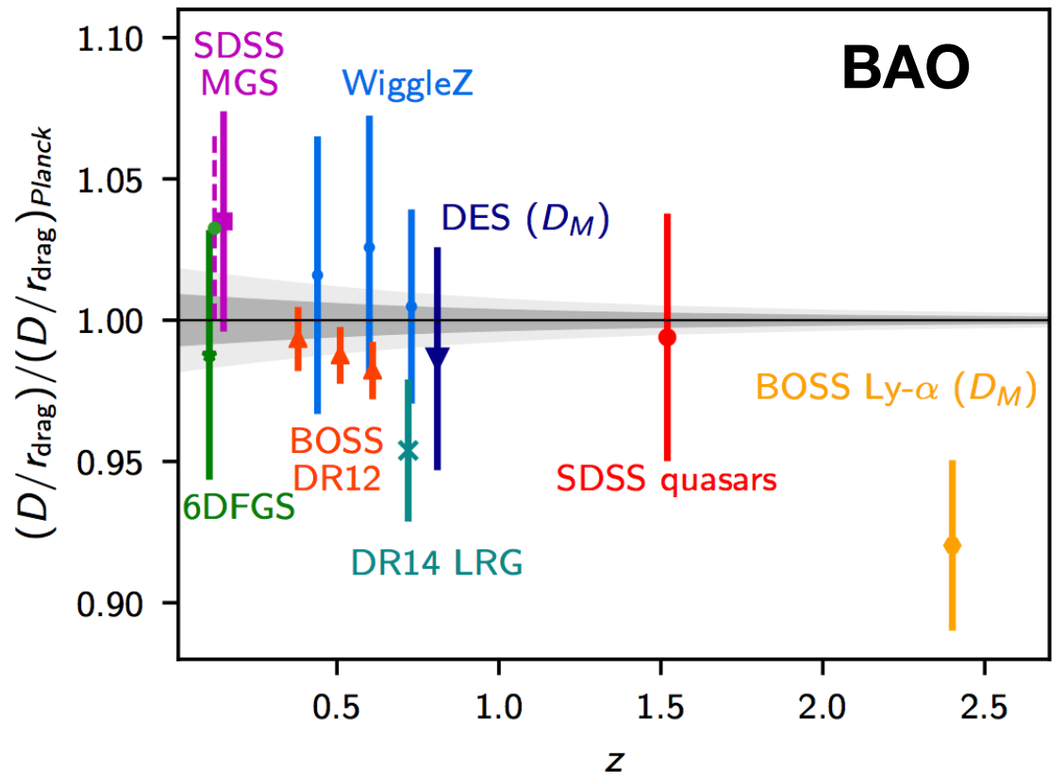


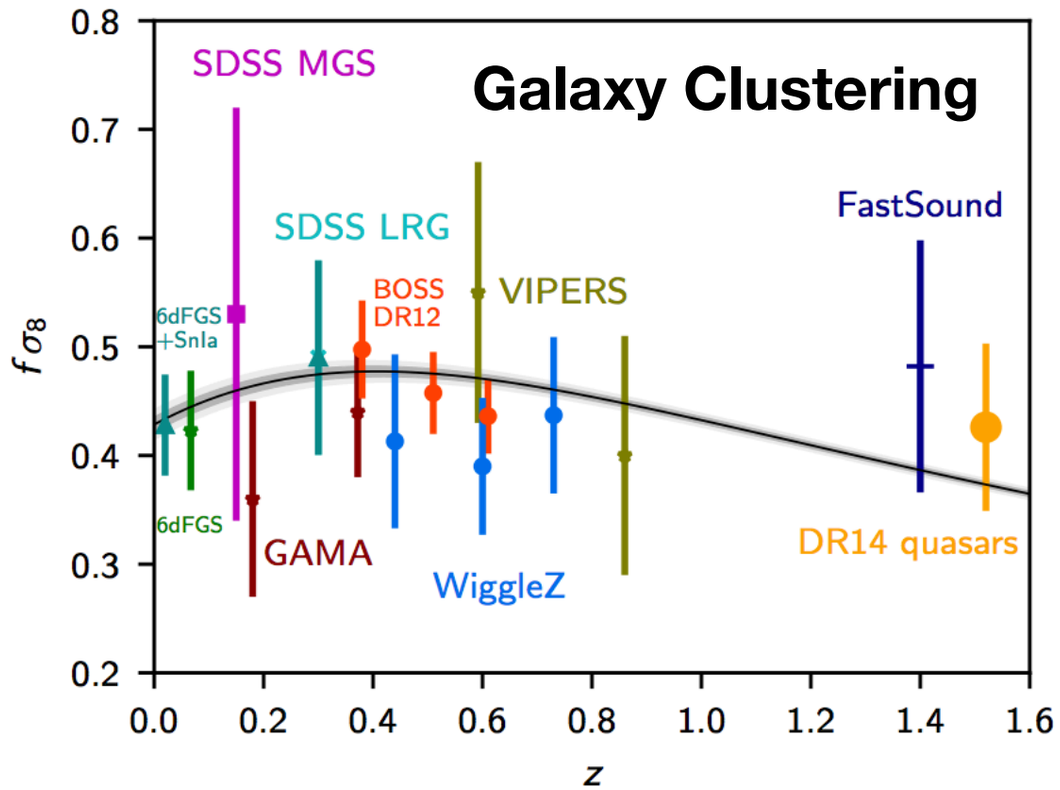
Planck 1807.06209

The Era of Precision Cosmology

And also with non-CMB data!







Planck 1807.06209

The Era of Precision Cosmology

Astonishing success of ΛCDM Cosmology

matter content

expansion rate (H0,Λ)

star formation

Inflation

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42

Planck alone

0.6% precision

1% precision

0.3% precision

13% precision

5% precision

0.5% precision

0.7% precision

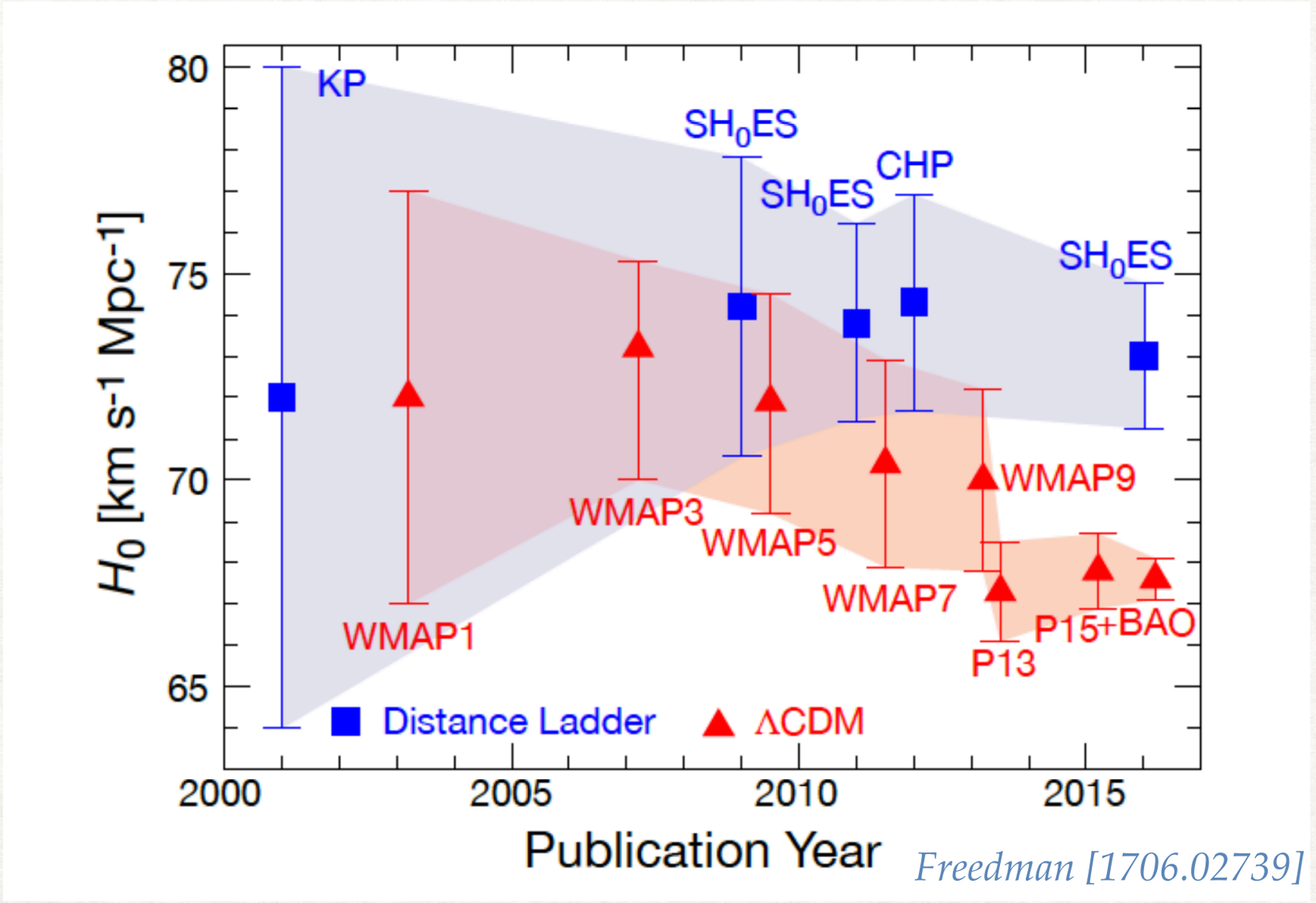
e.g. 2015 data: TT +lowP reduced $\chi^2 = 1.004$

As precision of data has increased, a certain number of "tensions" have emerged

- Hubble tension: Direct H_0 measurements are higher than ΛCDM prediction.
- $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$ prediction is higher at ~2-3σ than that measured by Weak Lensing surveys (CFHTLenS, KiDS, DES, HSC).
- Internal tension(s) within Planck and with other CMB datasets ~ 2-3σ.

See `Cosmology intertwined' Di Valentino, Anchordoqui++ 2008.1128(3-6), Handley&Lemos 2007.08496

The Hubble tension



Freedman [1706.02739]

In 2017: ~3.5σ discrepancy between "direct" measurement from SH0ES and the value inferred from a fit of ΛCDM to *Planck* 2015

The Hubble tension

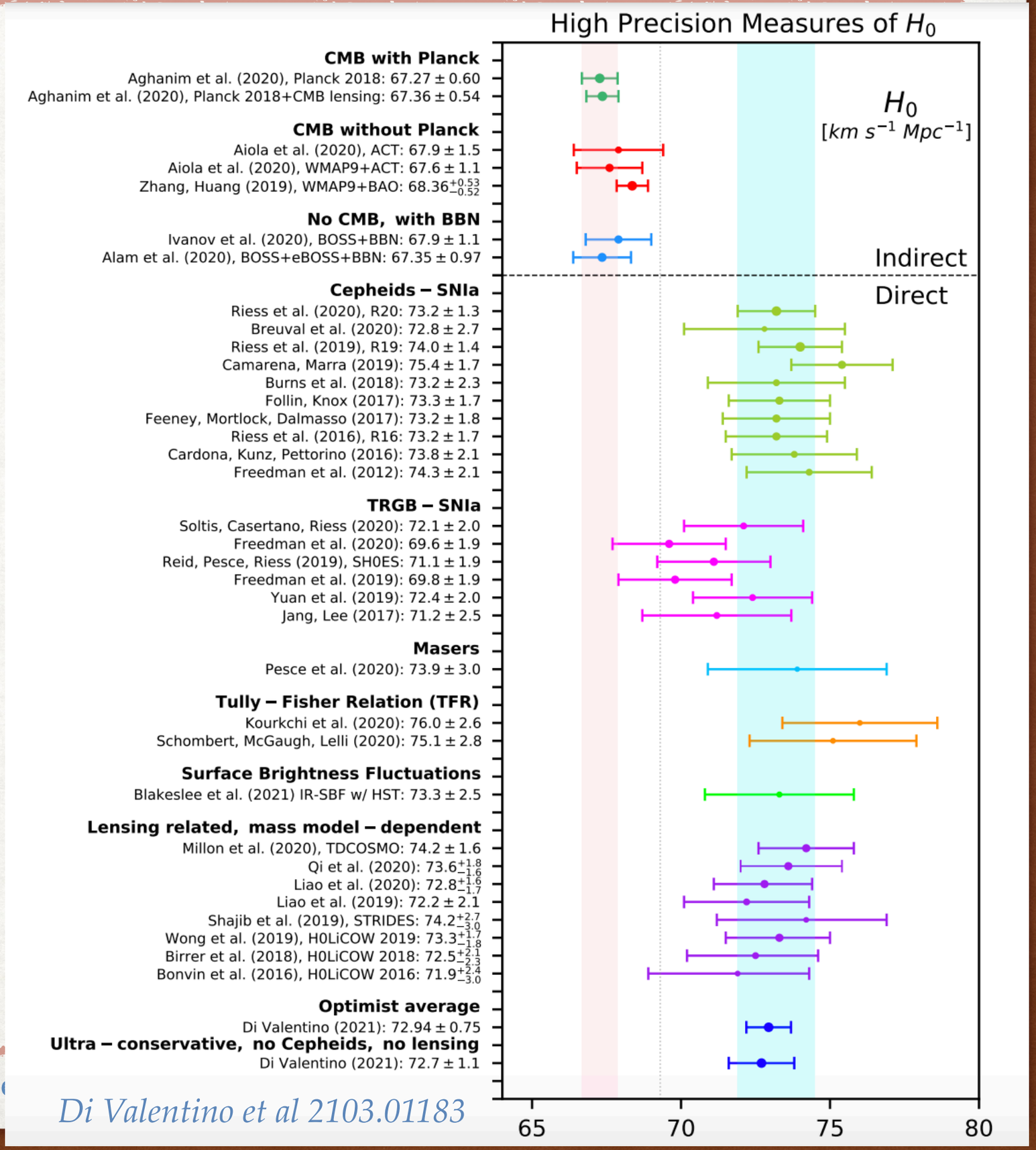
Since then, over 20 measurements and 800 papers!!

- Indirect: H_0 is a prediction from the ΛCDM model constrained with high-z data

- Direct: H_0 is measured at low-z in different ways

- All Direct measurements are higher than Indirect ones, not all are in strong tension

- Average: tension between 4-6σ

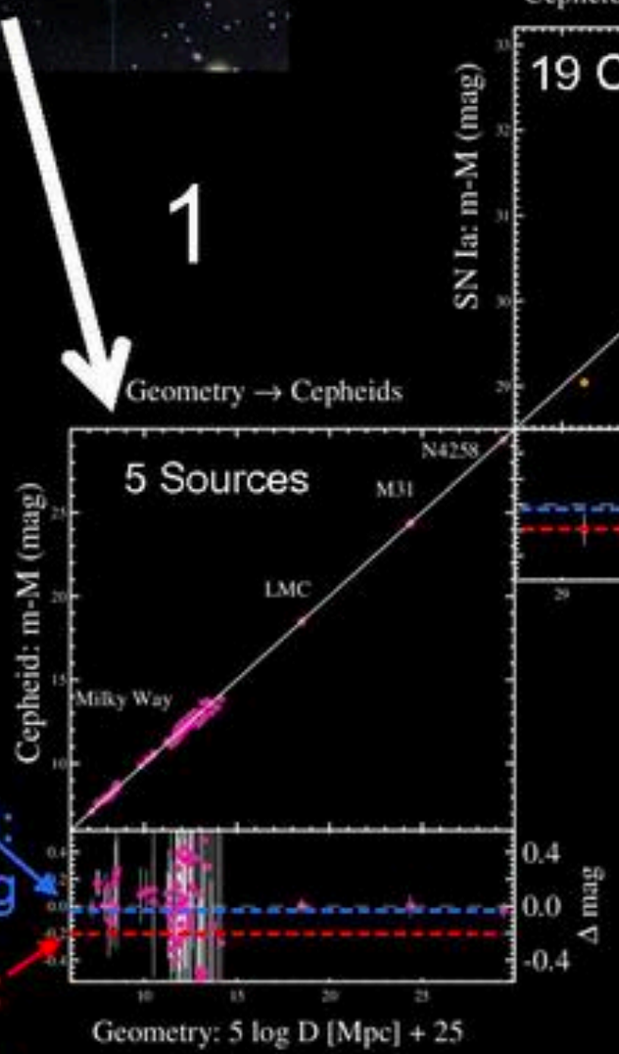


Di Valentino et al 2103.01183

The Hubble Constant in 3 Steps: Present Data

1

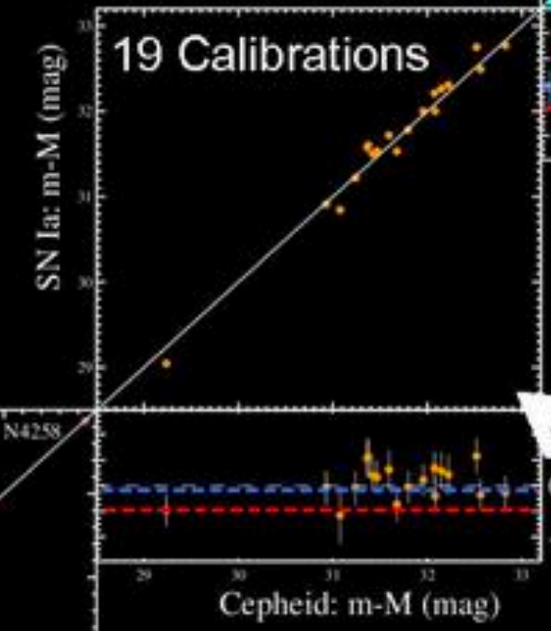
Geometry → Cepheids



1% Goal: 0.02 mag

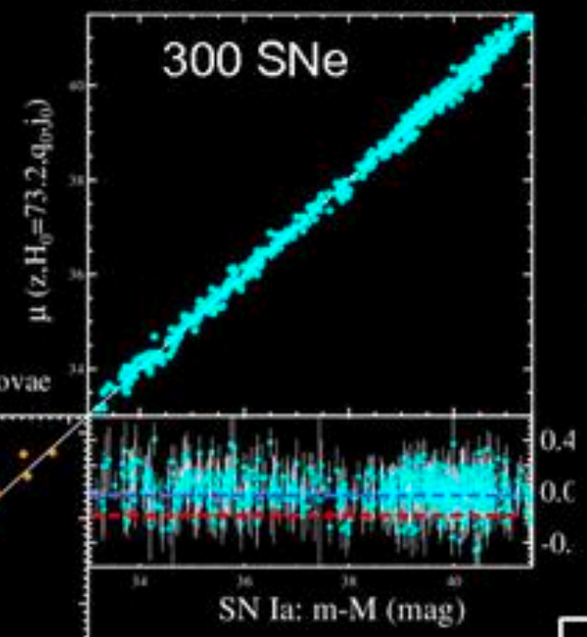
Tension: 0.2 mag

Cepheids → Type Ia Supernovae

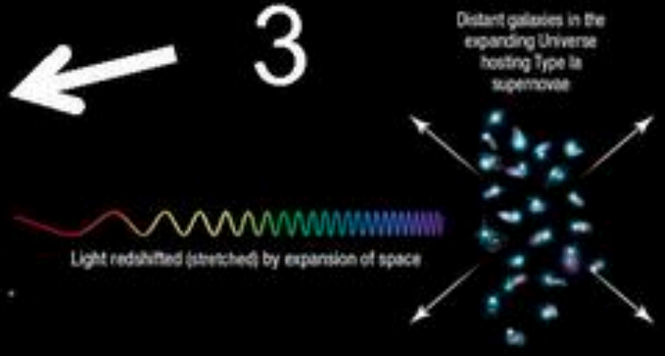


2

Type Ia Supernovae → redshift(z)



3



$5\log H_0 = M_B^0 + 5a_B + 25$

H_0=74.0 +/- 1.4, Km s^{-1} Mpc^{-1} (Riess et al. 2019)

Galaxies hosting Cepheids and Type Ia supernovae

1.9% total uncertainty

4.4σ from CMB + ΛCDM !

Slide by A. Riess, KITP July 2019

See also Efstathiou 2007.10716

Systematics in the 'SN1a' route?

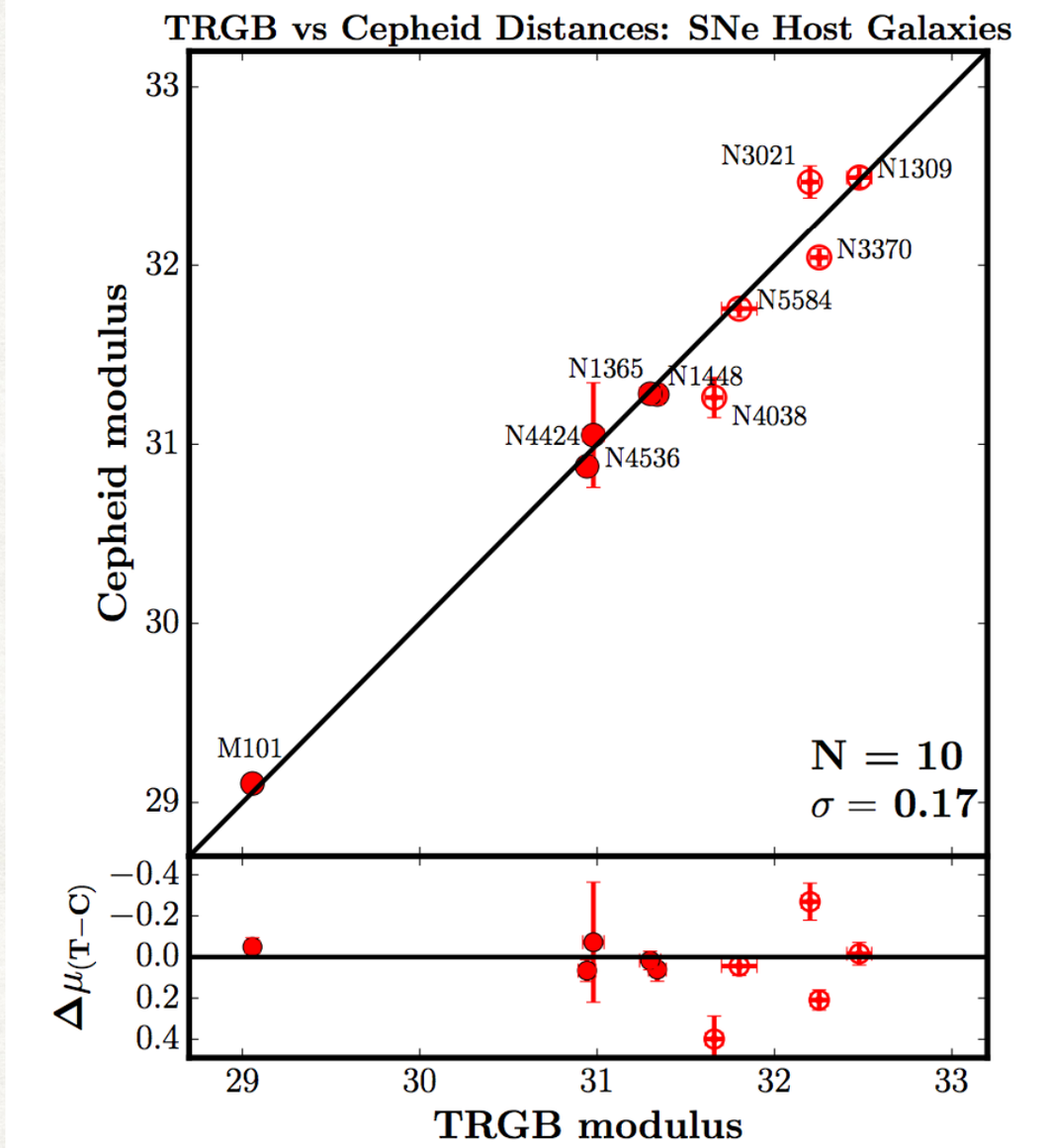
- Tension: -0.2μ shift is on the order of the scatter σ *Freedman et al., Apj 2019*

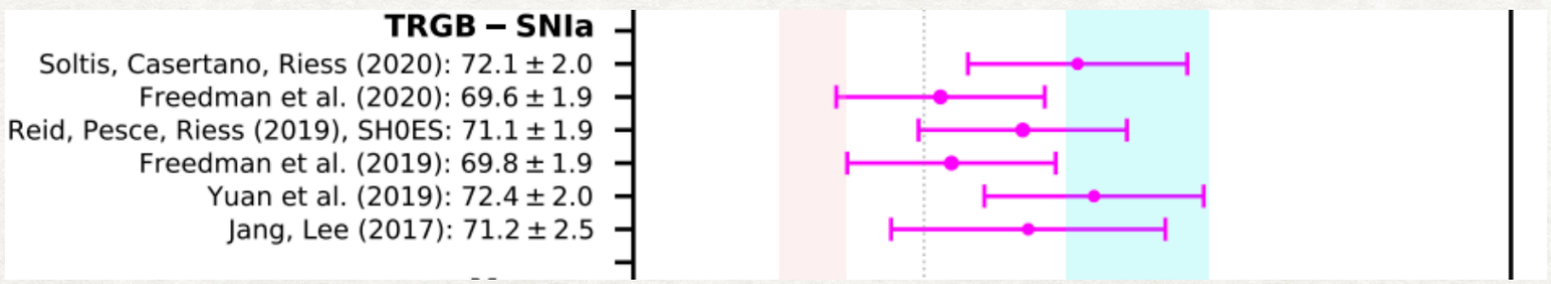
- Discussion about the amount of dust extinction towards the LMC between CCHP and SH0ES team.

Freedman et al., 2019. Yuan et al 2019, Freedman et al. 2020

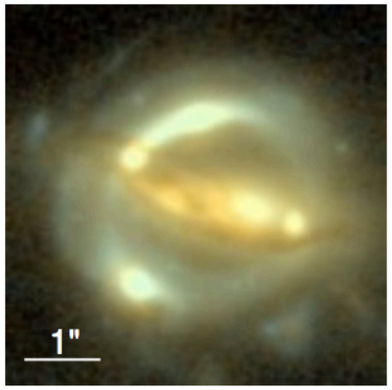
- Latest calibration of TRGB with GAIA DR3:
$H_0 = 72.1 + -2$ km/s/Mpc

Soltis et al 2020

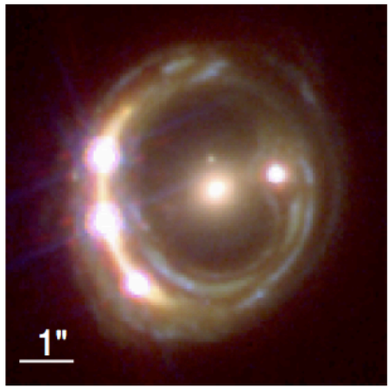




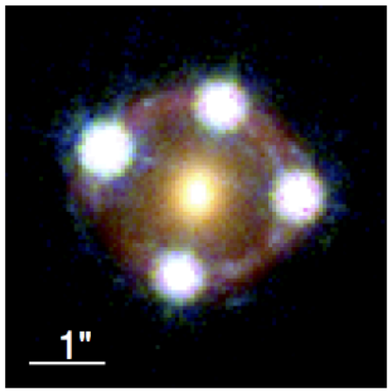
H0LiCOW: QSOs gravitational time delay



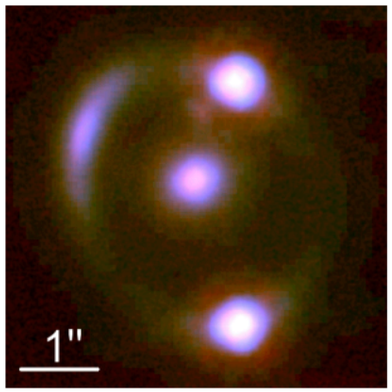
(a) B1608+656



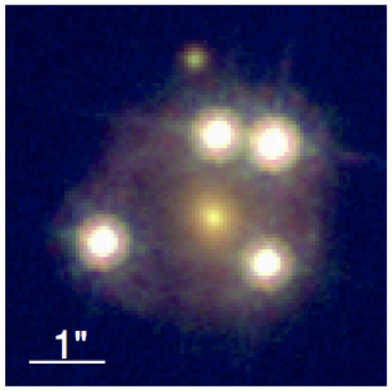
(b) RXJ1131−1231



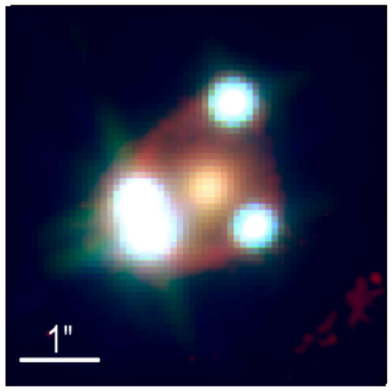
(c) HE 0435−1223



(d) SDSS 1206+4332



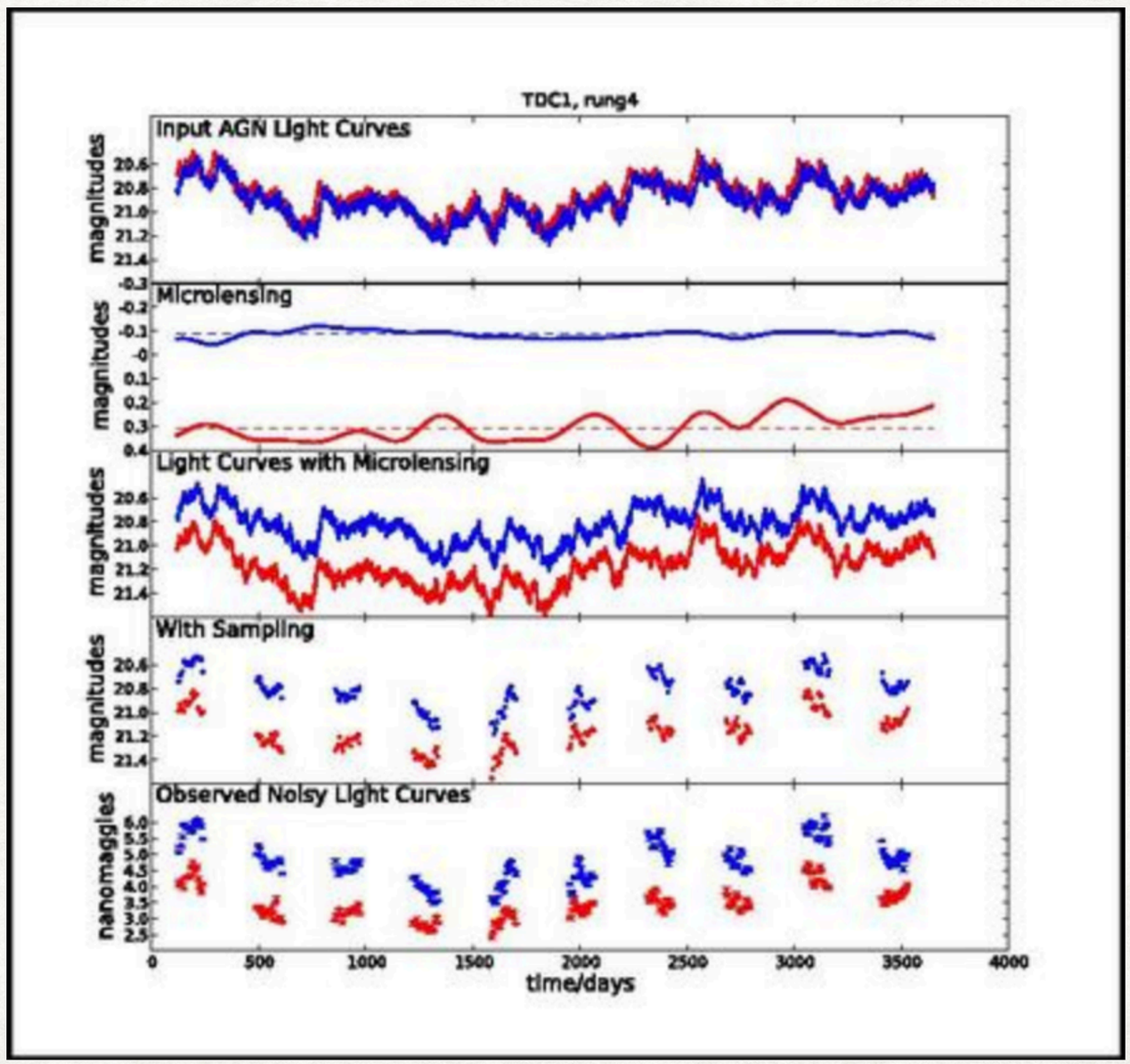
(e) WFI2033−4723



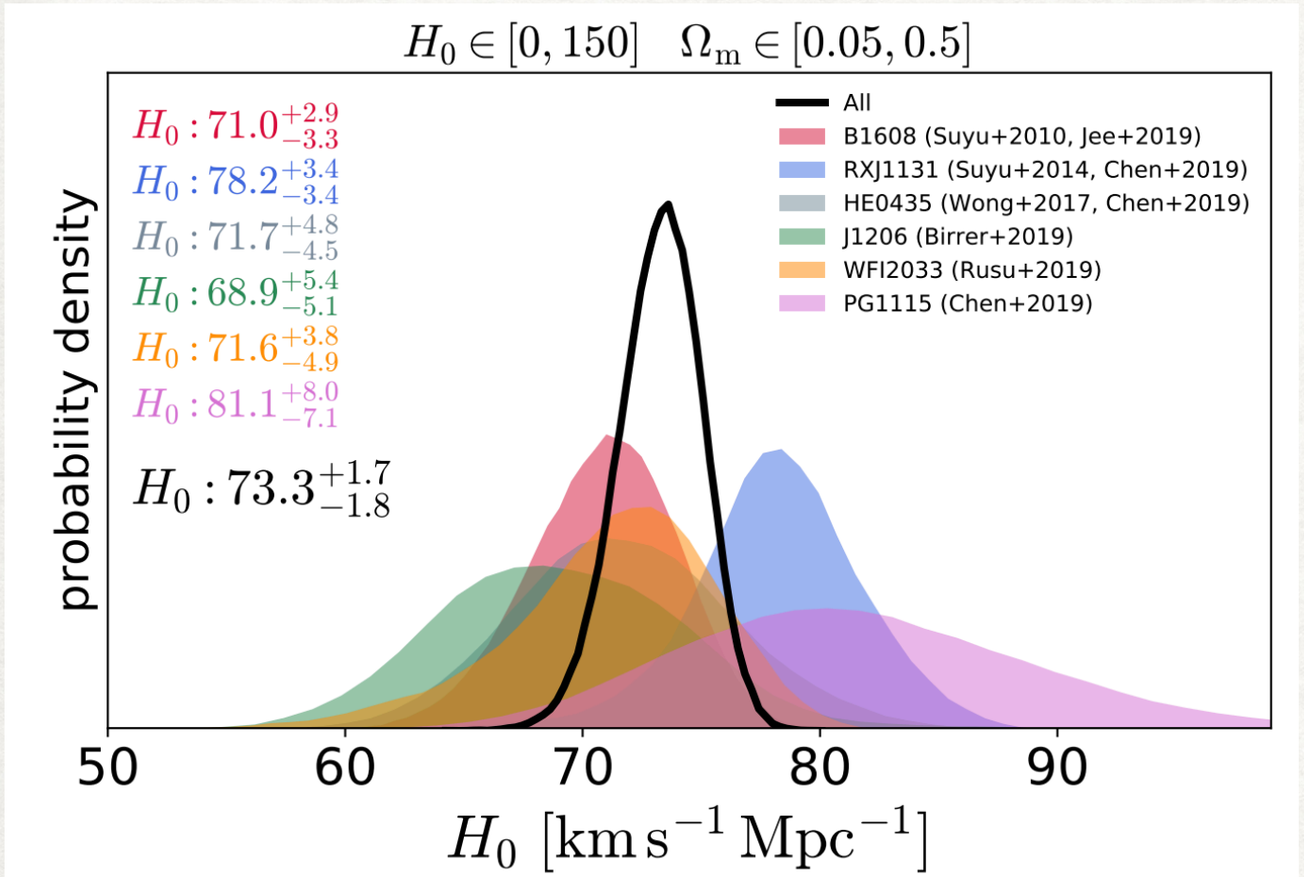
(f) PG 1115+080

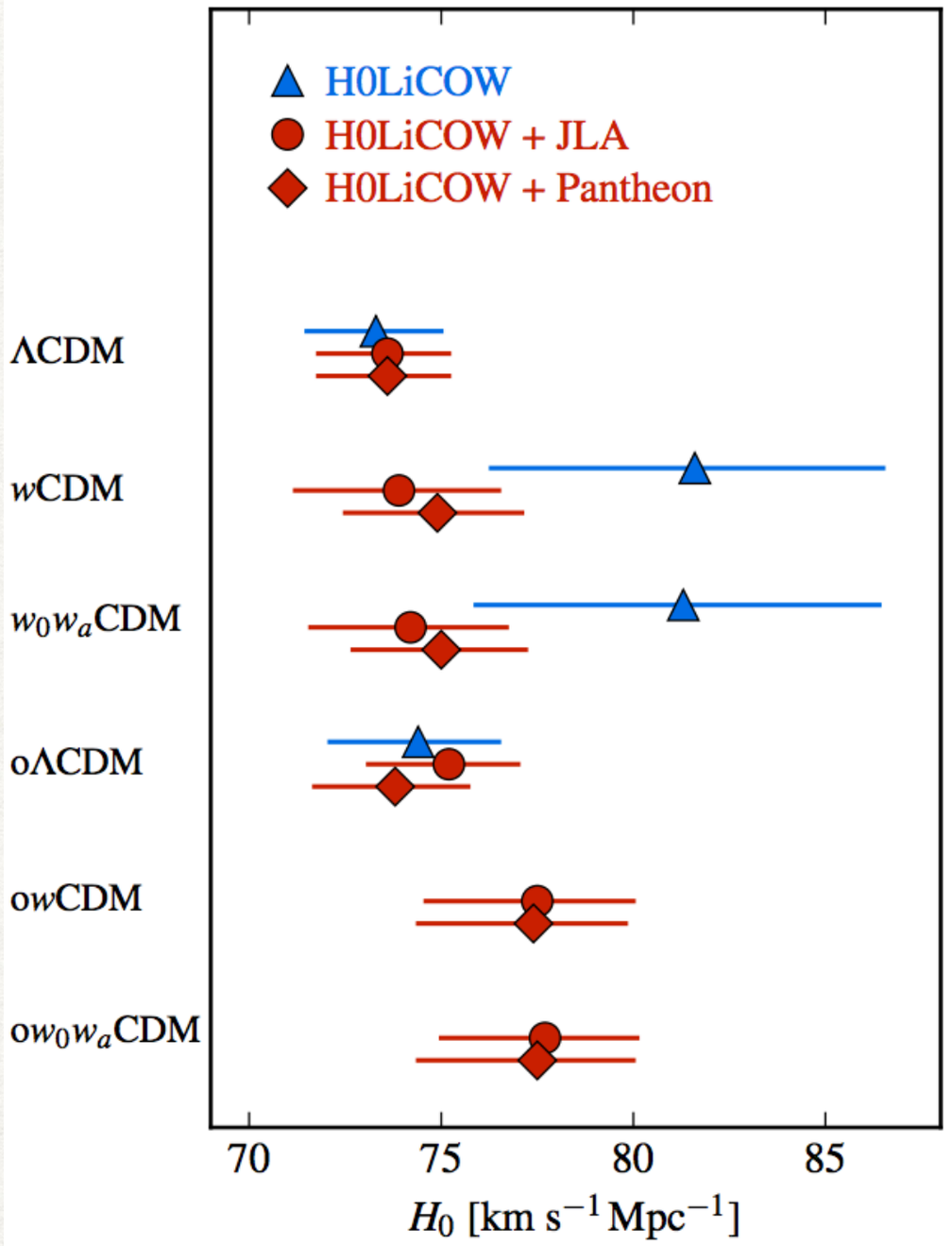
Wong et al. 1907.04869

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



H0LiCOW: H_0 measurement to few %



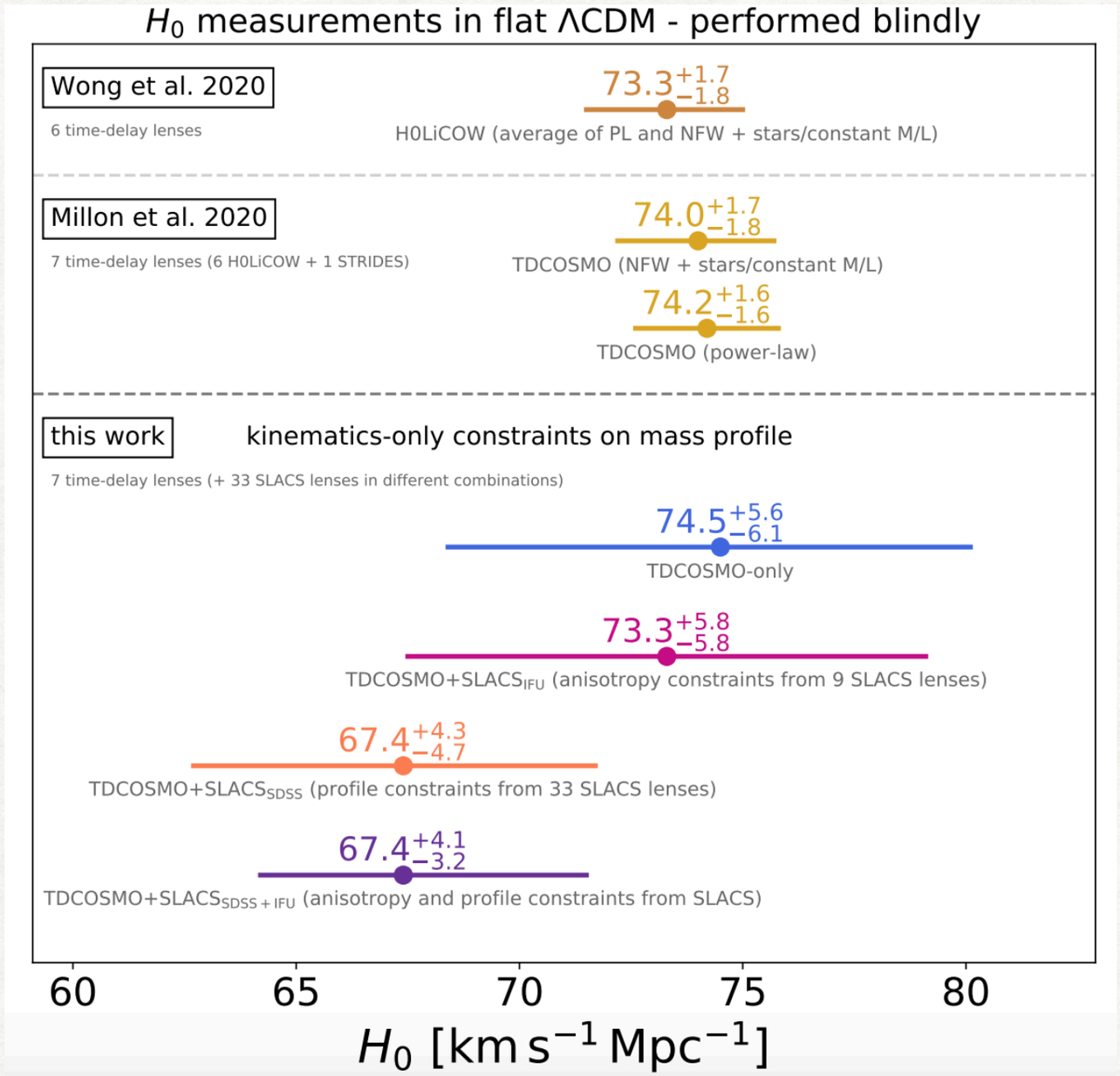


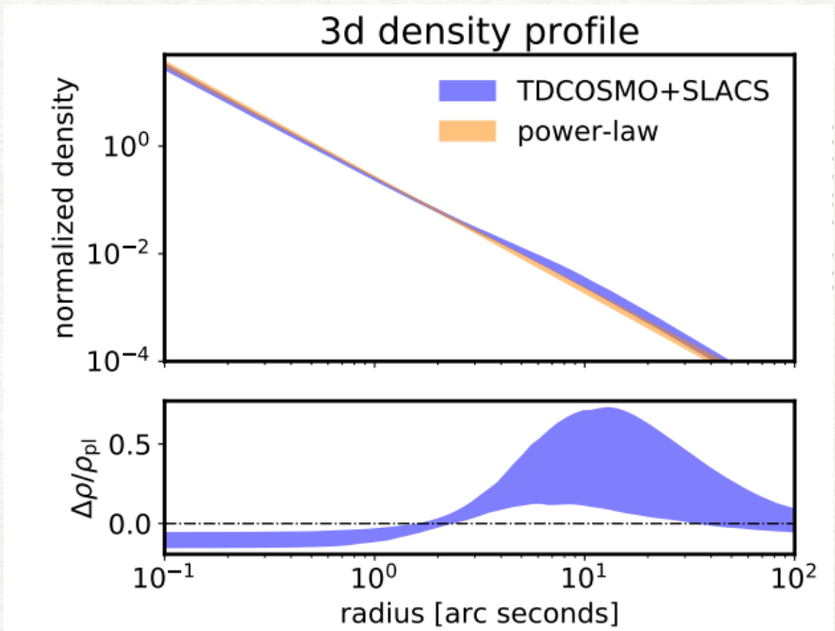
- 6 QSOs: 3.1σ tension with *Planck* within ΛCDM
- Blind analysis
- This assumes a specific shape for the lens mass profile.

Wong et al. 1907.04869

TDCOSMO+SLAC: Agreement with ΛCDM?

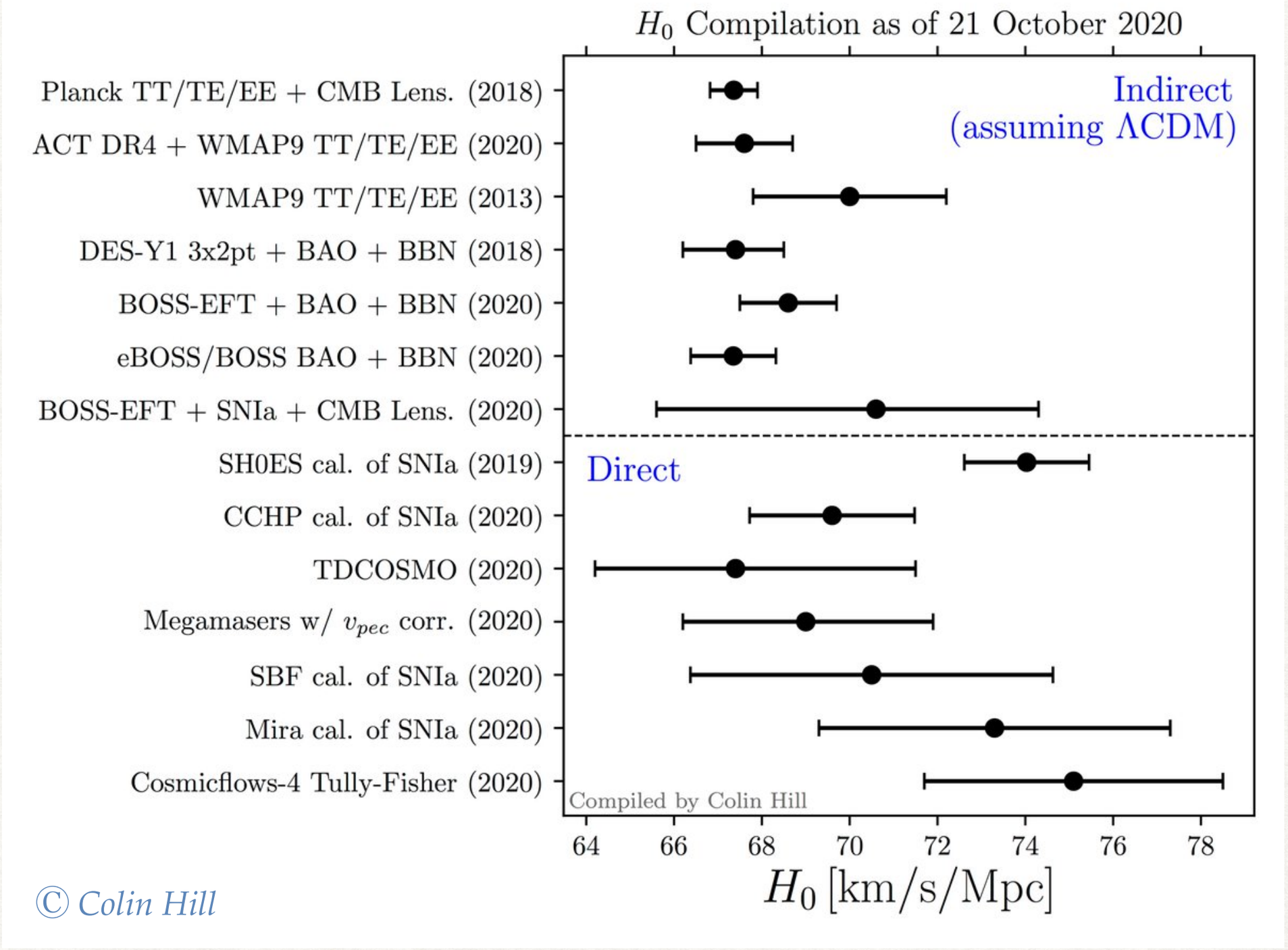
Birrer++ 2007.02941





- New analysis relaxes the power-law profile assumption and rely on stellar kinematics.
- Same sample of galaxies (TDCOSMO): large H_0 but large error bars.
- Add information from the 'SLACS' lenses catalog: 5% error and H_0 decreases.

H_0: the pessimistic (realistic?) view



© *Colin Hill*

- The situation is somewhat complicated… Hopefully resolved in ~year time scale.

How does CMB data measure H_0?

- The 'sound horizon' r_s, a standard ruler in the sky: distance travelled by sound wave until recombination.
- Planck measures θ_s and, given a model, can extract r_s.
- H_0 appears *only* in the angular diameter distance d_A.

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)} = \frac{\int_\infty^{z_*} dz\ c_s(z)/\sqrt{\rho_{\rm tot}(z)}}{\int_0^{z_*} dz/\sqrt{\rho_{\rm tot}(z)}}$$

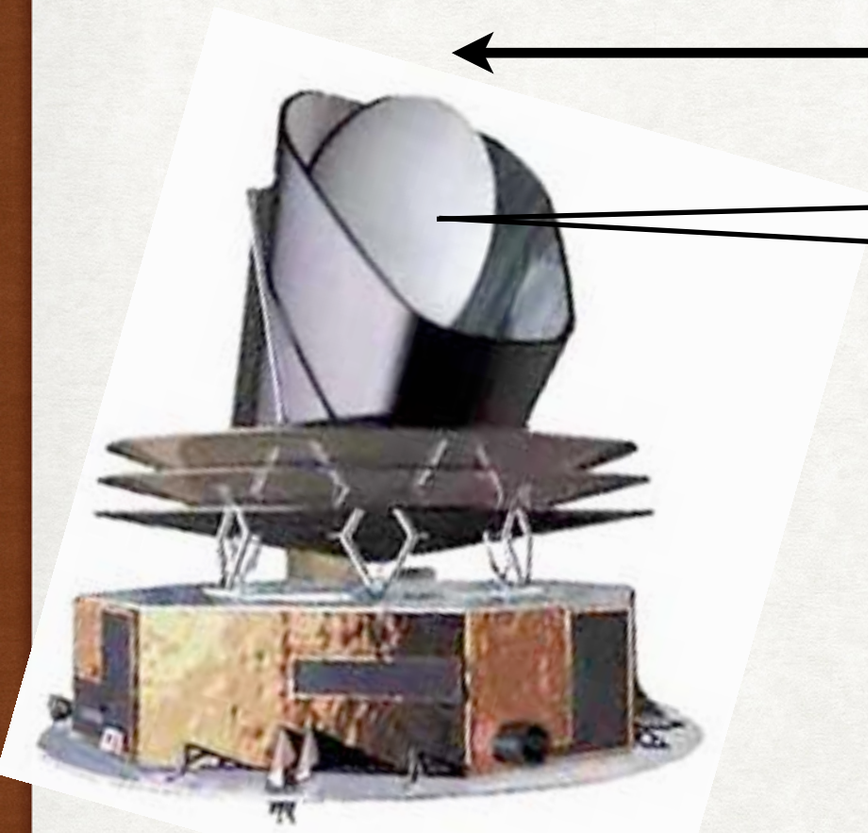


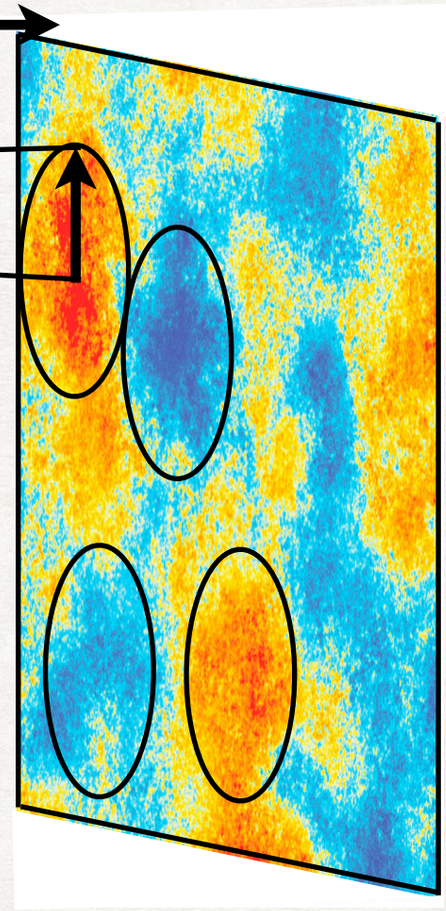
illustration: T. Smith

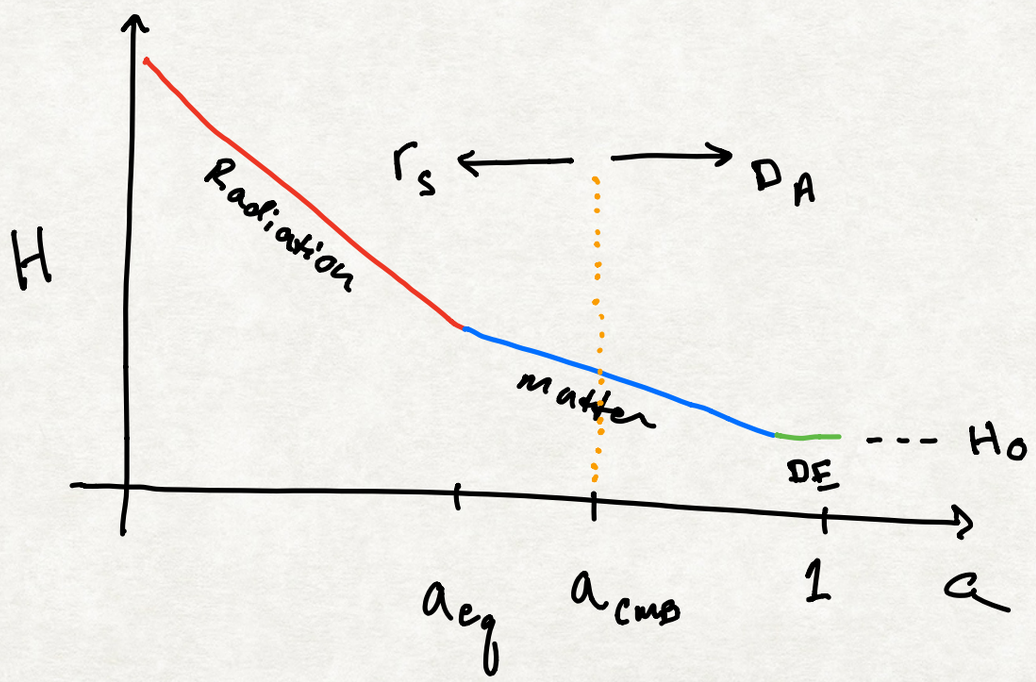
$$d_A \propto H_0^{-1} = \rho_{\rm tot}(0)^{-1/2}$$

$$\theta_s \simeq 1^\circ$$

r_s

0.04% precision!





Geometrical degeneracy in Planck!

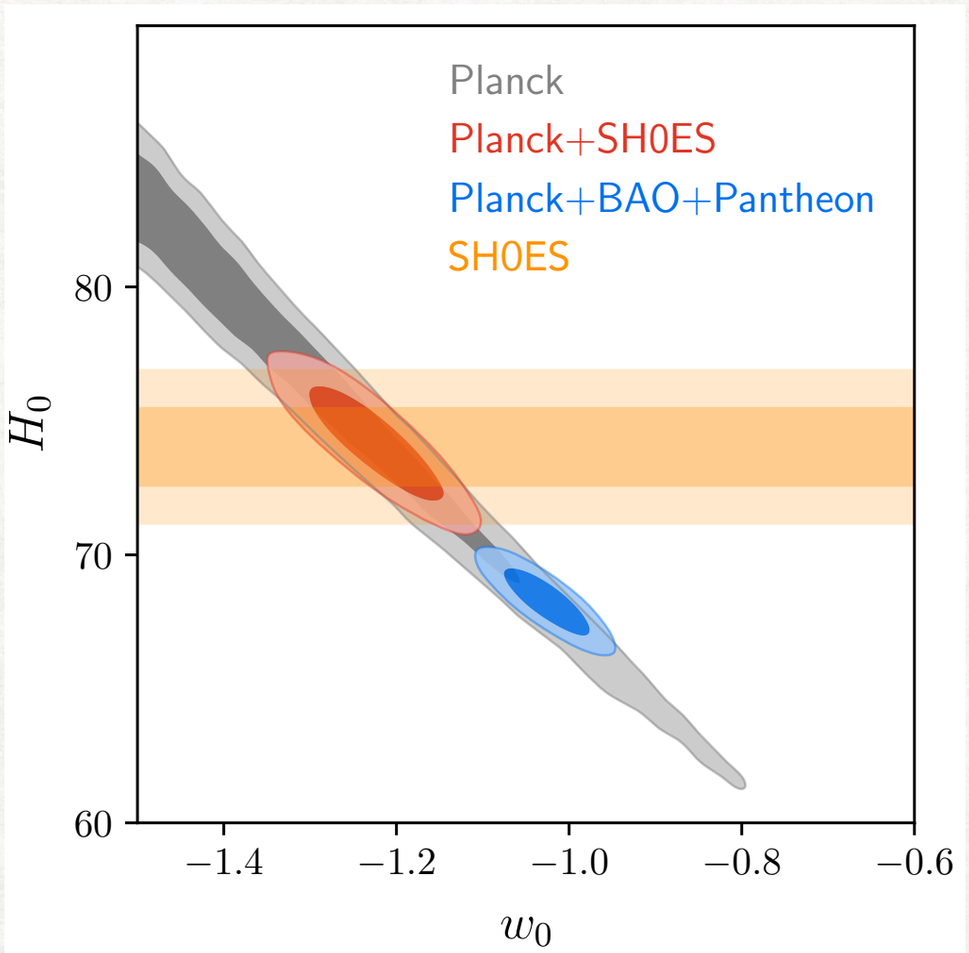
- A higher H_0 can be compensated by a lower $H(z > 0)$ such as to keep $d_A(z_*)$ fixed

$$d_A(z_*) = \frac{1}{1+z_*} \int_0^{z_*} \frac{dz}{100\sqrt{\omega_{\rm M}(1+z)^3 + \Omega_{\rm DE}(z)h^2}}$$

- 'phantom dark energy' w < -1, DE phase transition, DE-DM interaction, decaying/annihilating DM, and many more…

[http://arxiv/insert_your_favorite_ model_here.com]

- Planck can easily accommodate a higher H_0: problem with BAO and Pantheon

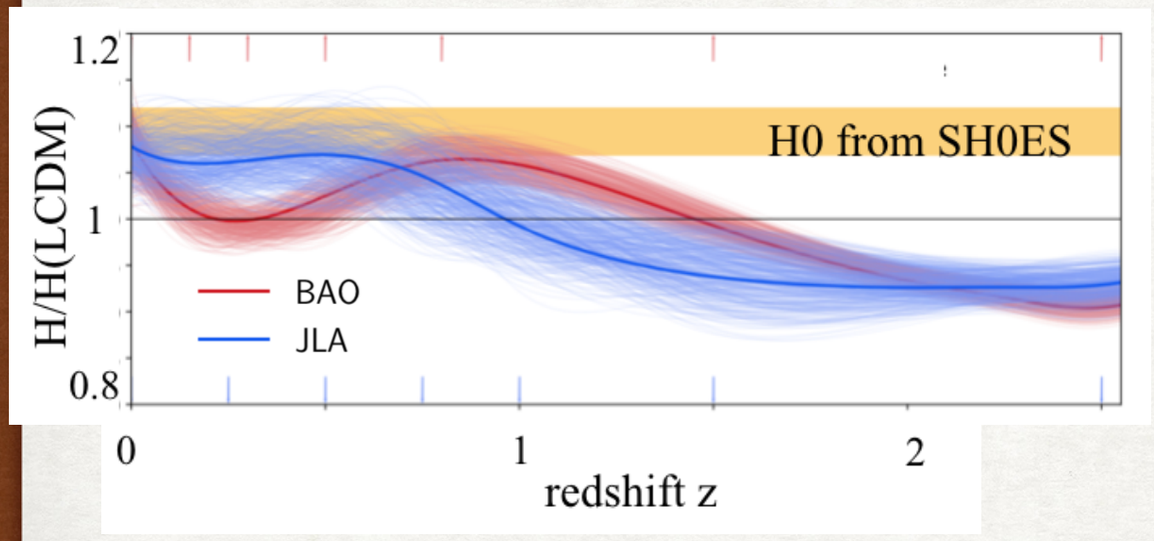


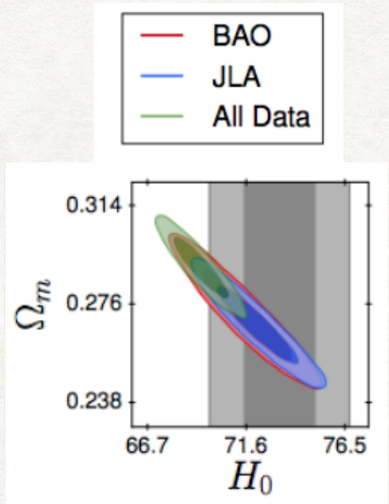
BAO and SN1a constrain late-time resolution

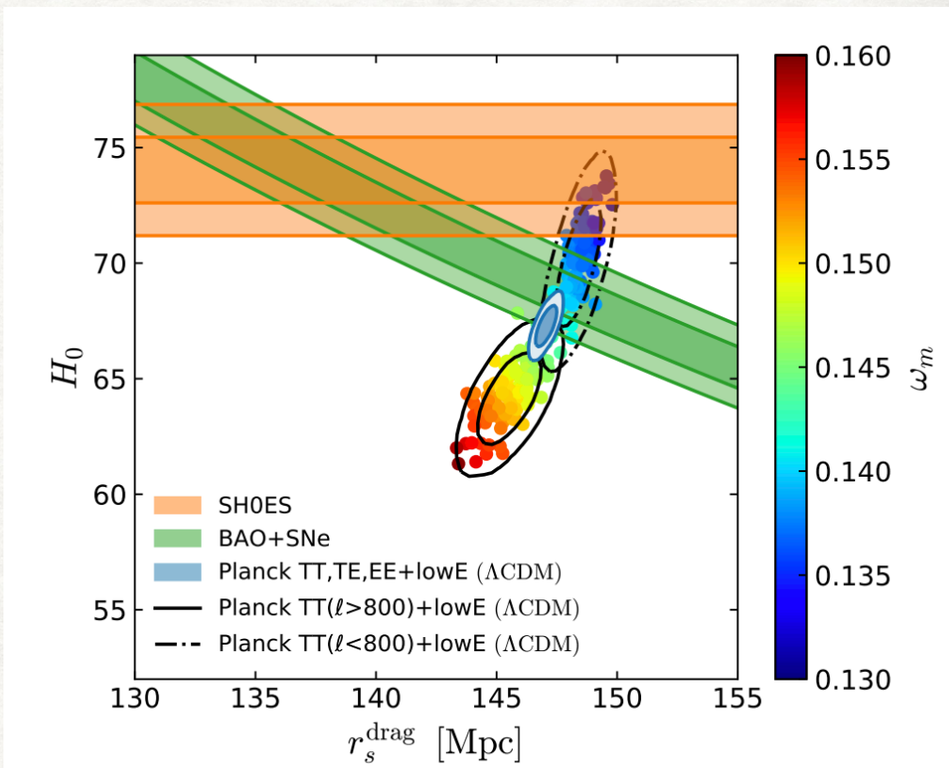
$$d_A(z_*) = \frac{1}{1+z_*}\int_0^{z_*} \frac{dz}{100\sqrt{\omega_{\rm M}(1+z)^3 + \Omega_{\rm DE}(z)h^2}}$$

see also Wang++ 1807.03772, Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Benevento++ 2002.11707.

VP, Boddy, Bird, Kamionkowski 1803.02474







Knox&Milllea 1908.03663

$$\theta_d(z)^{\perp} = \frac{r_s(z_{\rm drag})}{D_A(z)}\,, \theta_d(z)^{\parallel} = r_s(z_{\rm drag})H(z)$$

$$\mu(z) = 5{\rm Log}_{10}D_L(z) + {\rm const}\,.$$

- $r_s(z_{\rm drag})$ from Planck
- Calibration constant from e.g. SH0ES.

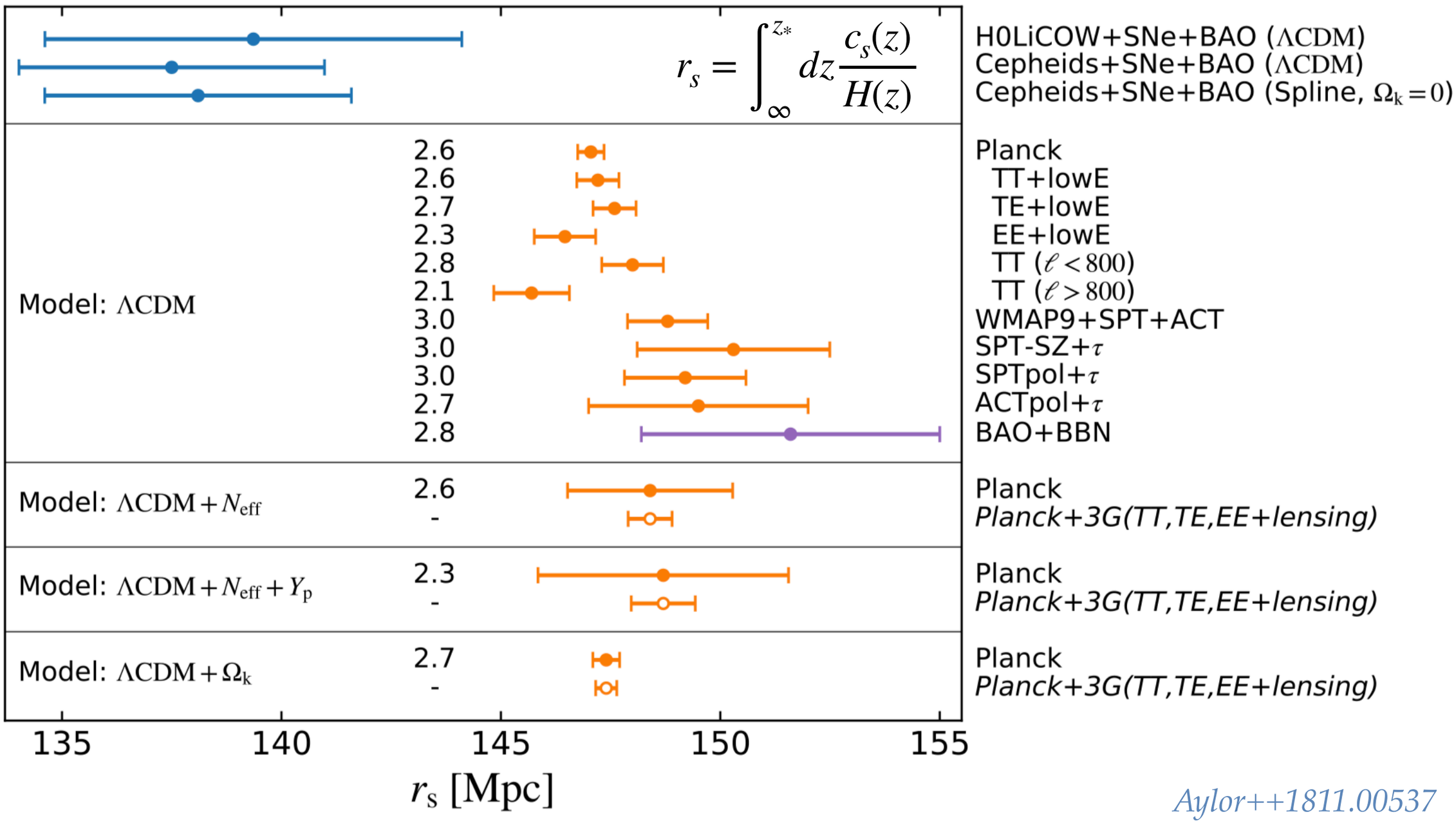
In GR: $D_A = D_L/(1+z)^2$; it is impossible to resolve the tension without changing calibration!

- Nb: unless of a 'cosmological crisis' *Di Valentino++ 1911.02087*

H_0 tension or r_s tension?

One can deduce the co-moving sound horizon r_s from H_0 and BAO

r_s from CMB needs to decrease by ~ 10 Mpc



Aylor++1811.00537

A sketch of the physics at play

- Could the CMB be closer to us than ΛCDM tells us? This is what a higher H_0 suggests.
- Therefore, could spot in the CMB be smaller? This is what new physics must achieve.

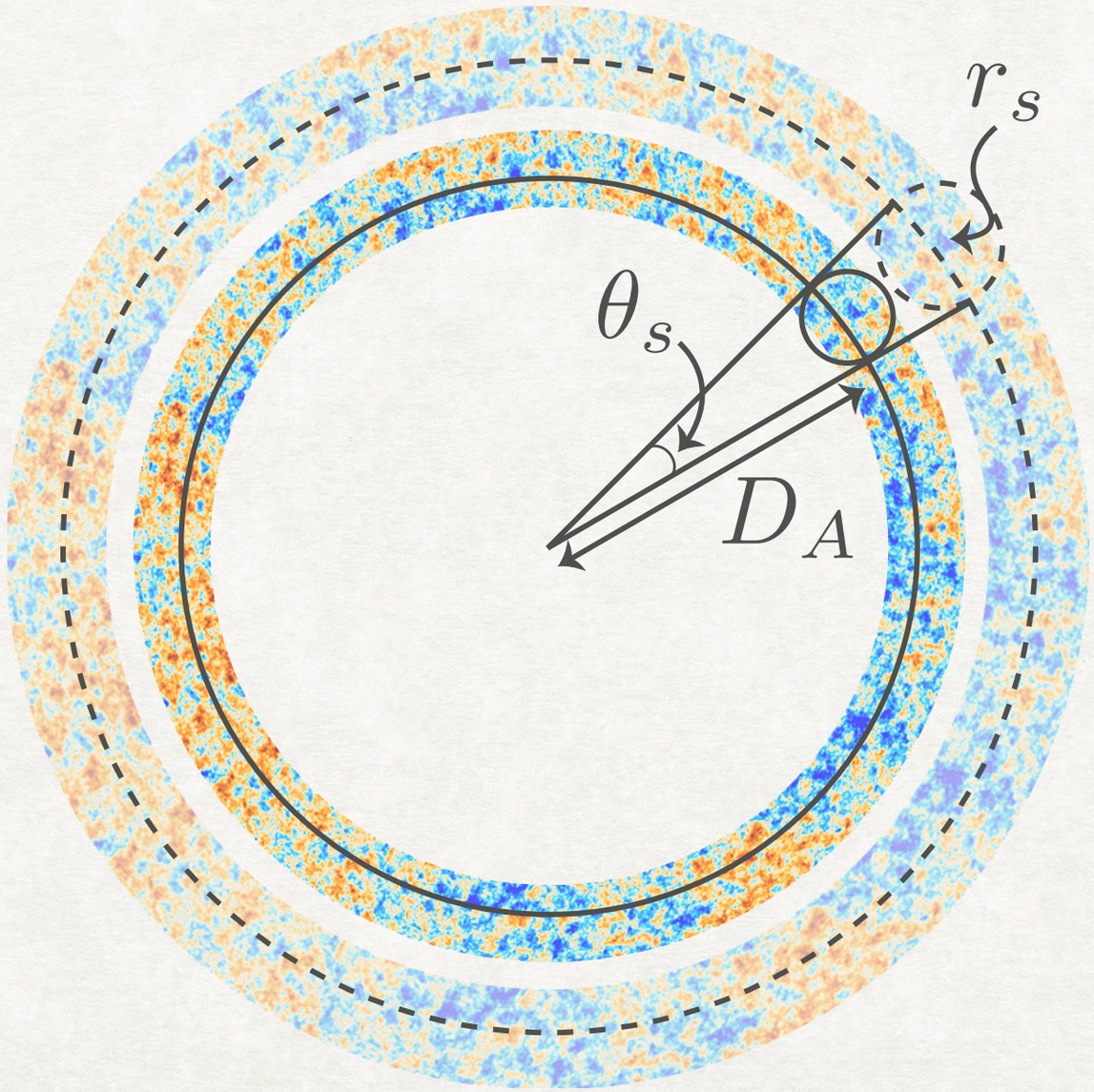


illustration: T. Smith

Early-time resolution to the H_0 tension

affect z*: modified recombination physics?

Chiang&Slosar 1811.03624

see also Hart&Chluba 1912.03986

Jedamzik&Pogosian 2004.09487

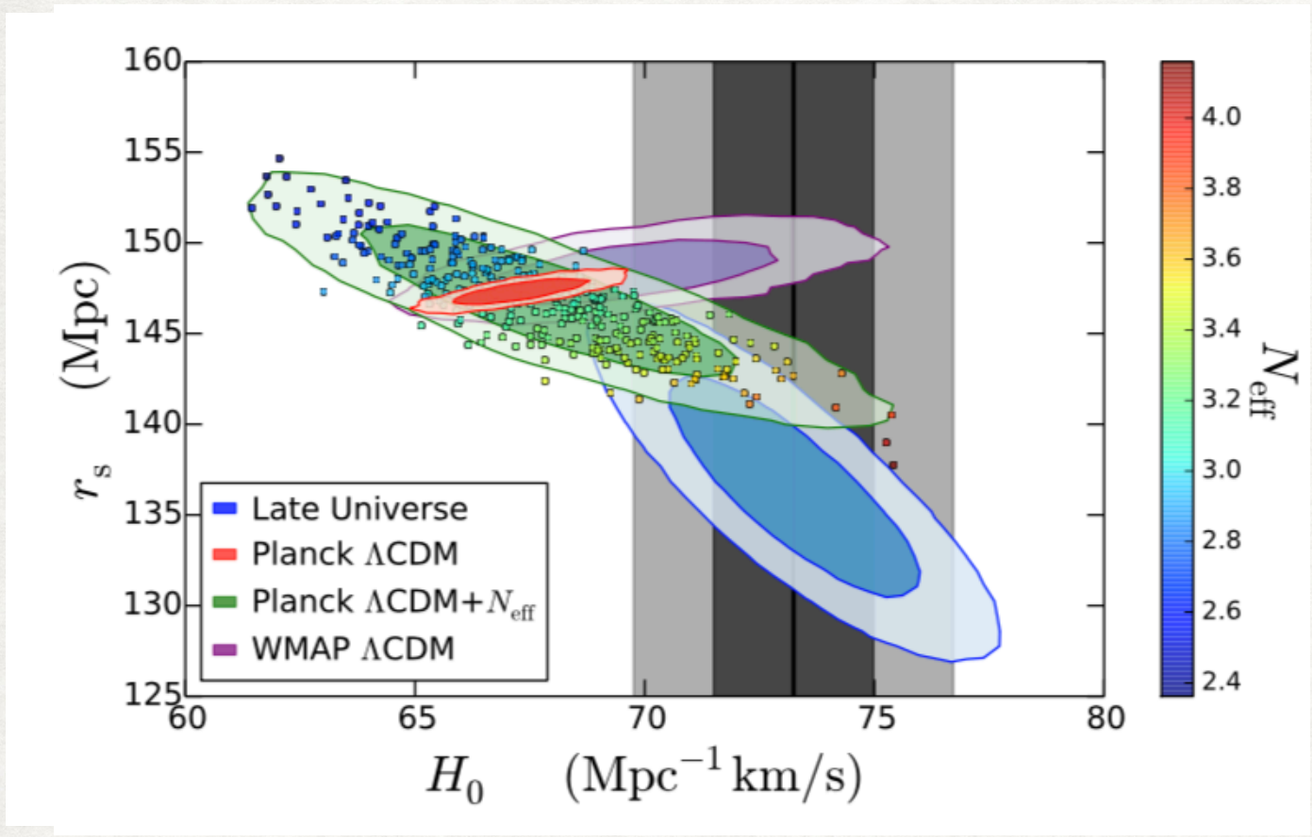
affect c_s: DM-photon scattering? DM-b scattering?

*Boddy, Gluscevic, **VP**++1808.00001*

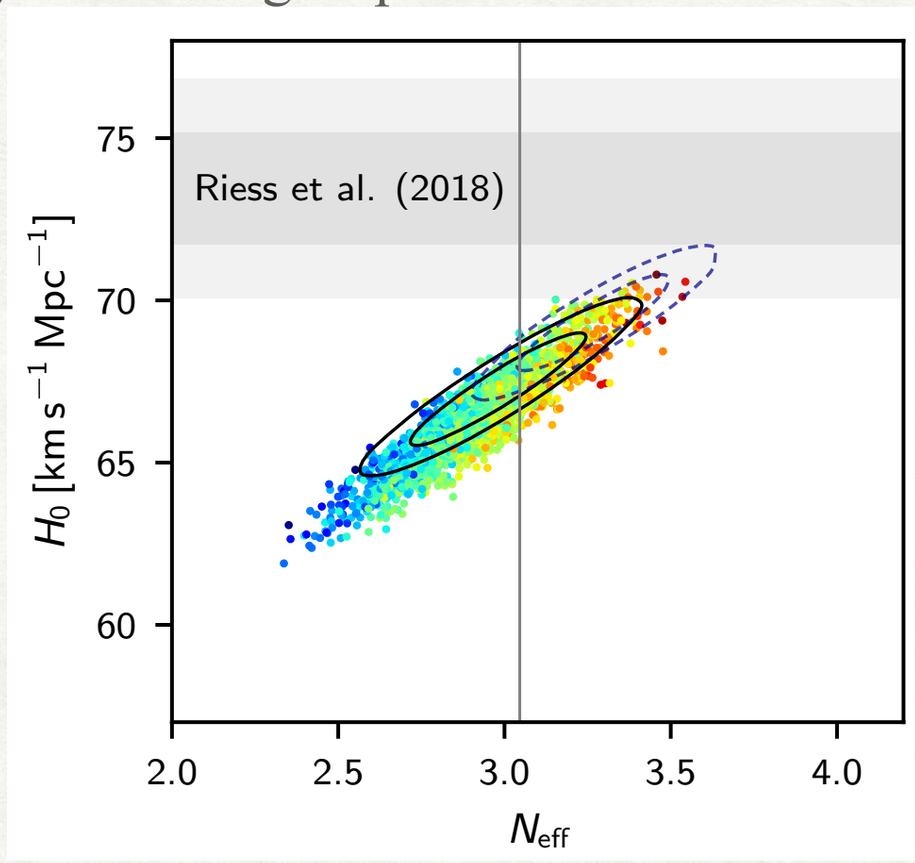
$$r_s = \int_\infty^{z_*} dz \frac{c_s(z)}{H(z)}$$

affect H(z): Neff? Early Dark Energy?

- Neff (free streaming) ~ 3.5-4 is needed : disfavored by *Planck* high-l polarization and BAO



Bernal++ 1607.05617

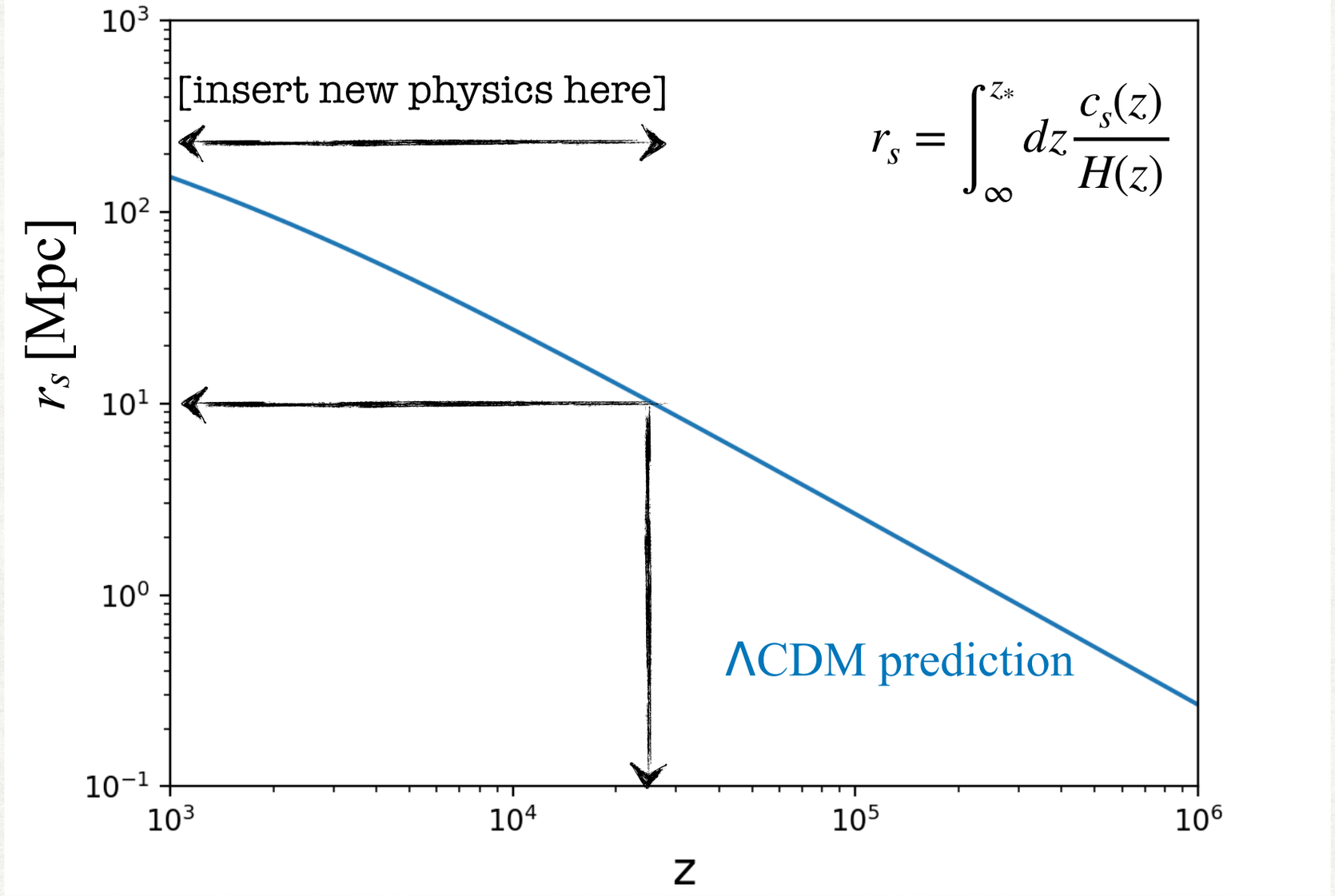


Aghanim++ 1807.06209

- Interacting neutrinos might work, although TBC with Planck 18 *Kreisch++ 1902.00534*

Early-Universe solution to H_0

- r_s does not reach 10Mpc before ~ 25000 in ΛCDM



GOAL: decreasing r_s by 10Mpc while keeping r_s/r_d and r_s/r_{eq} fixed

Early Dark Energy(s) is a promising solution

Not all have the same success…

Early dark energy, the Hubble-parameter tension, and the string axiverse

Tanvi Karwal and Marc Kamionkowski
Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218
(Dated: November 8, 2016)

Early Dark Energy Can Resolve The Hubble Tension

Vivian Poulin[1], Tristan L. Smith[2], Tanvi Karwal[1], and Marc Kamionkowski[1]
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Rock 'n' Roll Solutions to the Hubble Tension

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Acoustic Dark Energy: Potential Conversion of the Hubble Tension

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Is the Hubble tension a hint of AdS around recombination?

Gen Ye[1]* and Yun-Song Piao[1,2†]
[1] *School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China and*
[2] *Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China*

Early dark energy from massive neutrinos — a natural resolution of the Hubble tension

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Dark Energy, H_0 and Weak Gravity Conjecture

Nemanja Kaloper[a,1]
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Thermal Friction as a Solution to the Hubble Tension

Kim V. Berghaus[1] and Tanvi Karwal[1,2]
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(Dated: November 15, 2019)

Scalar-tensor theories of gravity, neutrino physics, and the H_0 tension

Mario Ballardini,[a,b,c,d,1] Matteo Braglia,[a,b,c] Fabio Finelli,[b,c] Daniela Paoletti,[b,c] Alexei A. Starobinsky,[e,f] Caterina Umiltà[g]

Gravity in the Era of Equality: Towards solutions to the Hubble problem without fine-tuned initial conditions

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(Dated: June 11, 2020)

New Early Dark Energy

Florian Niedermann[1,*] and Martin S. Sloth[1,†]
CP³-Origins, Center for Cosmology and Particle Physics Phenomenology

Scalar field and Early Dark Energy

- Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

- Oscillating (toy) potential:

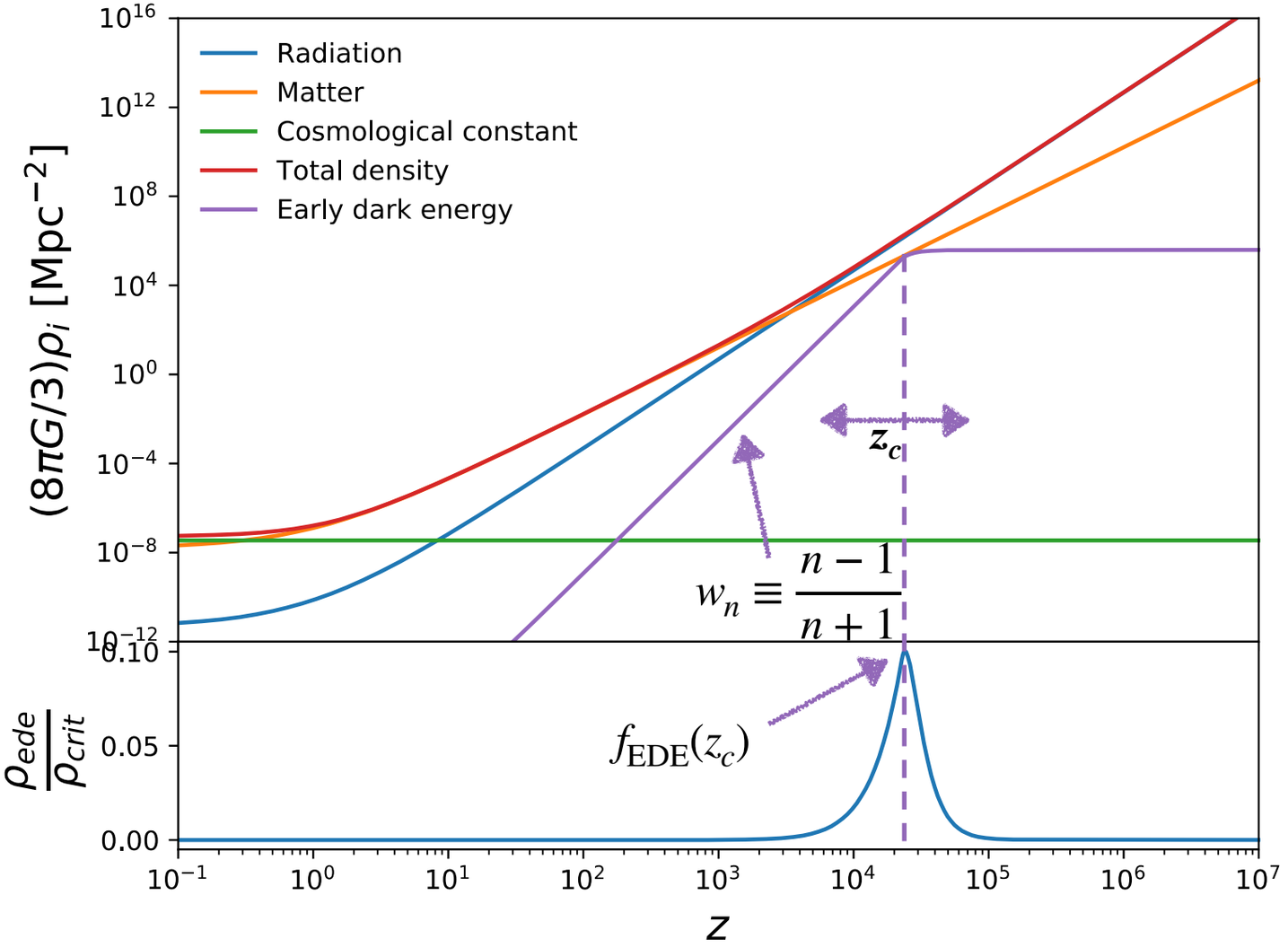
$$V(\phi) \propto (1 - \cos\phi)^n$$

VP++ 1806.10608 & 1811.04083
Smith, VP ++ 1908.06995

- Specified by $f_{\rm EDE}(z_c)$, z_c, $w(n)$, $c_s^2(k,\tau)$

$$\begin{cases} z > z_c \Rightarrow w_n = 1 \\ z < z_c \Rightarrow w_n = (n-1)/(n+1) \end{cases}$$

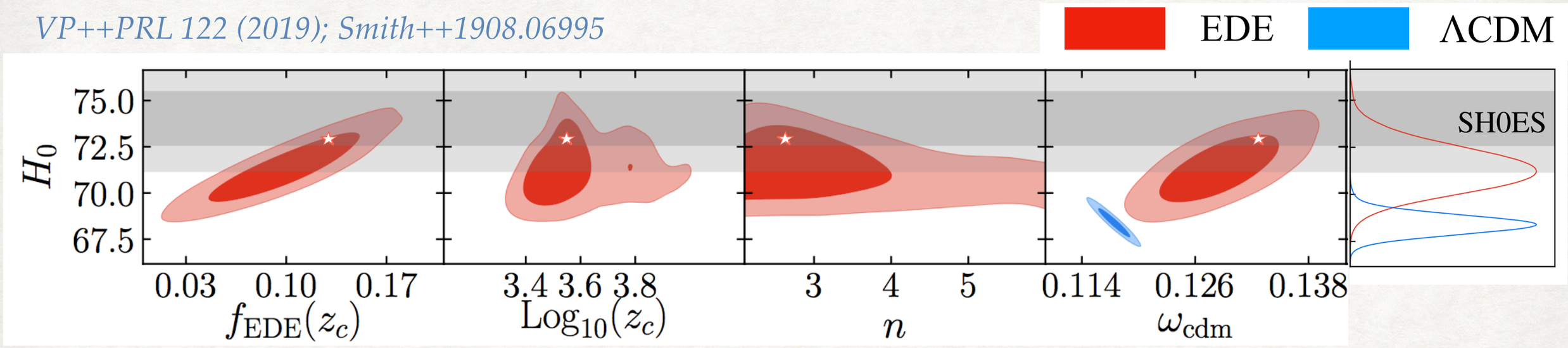
$n = 1$: matter, $n = 2$: radiation, etc.



See also Niedermann&Sloth for different EDE model 1910.10739, 2006.06686, 2009.00006

EDE Can Resolve The Hubble Tension

VP++PRL 122 (2019); Smith++1908.06995



- Planck high-ℓ TT,TE, EE+lowTEB+lensing+BAO+Pantheon+SH0ES 19

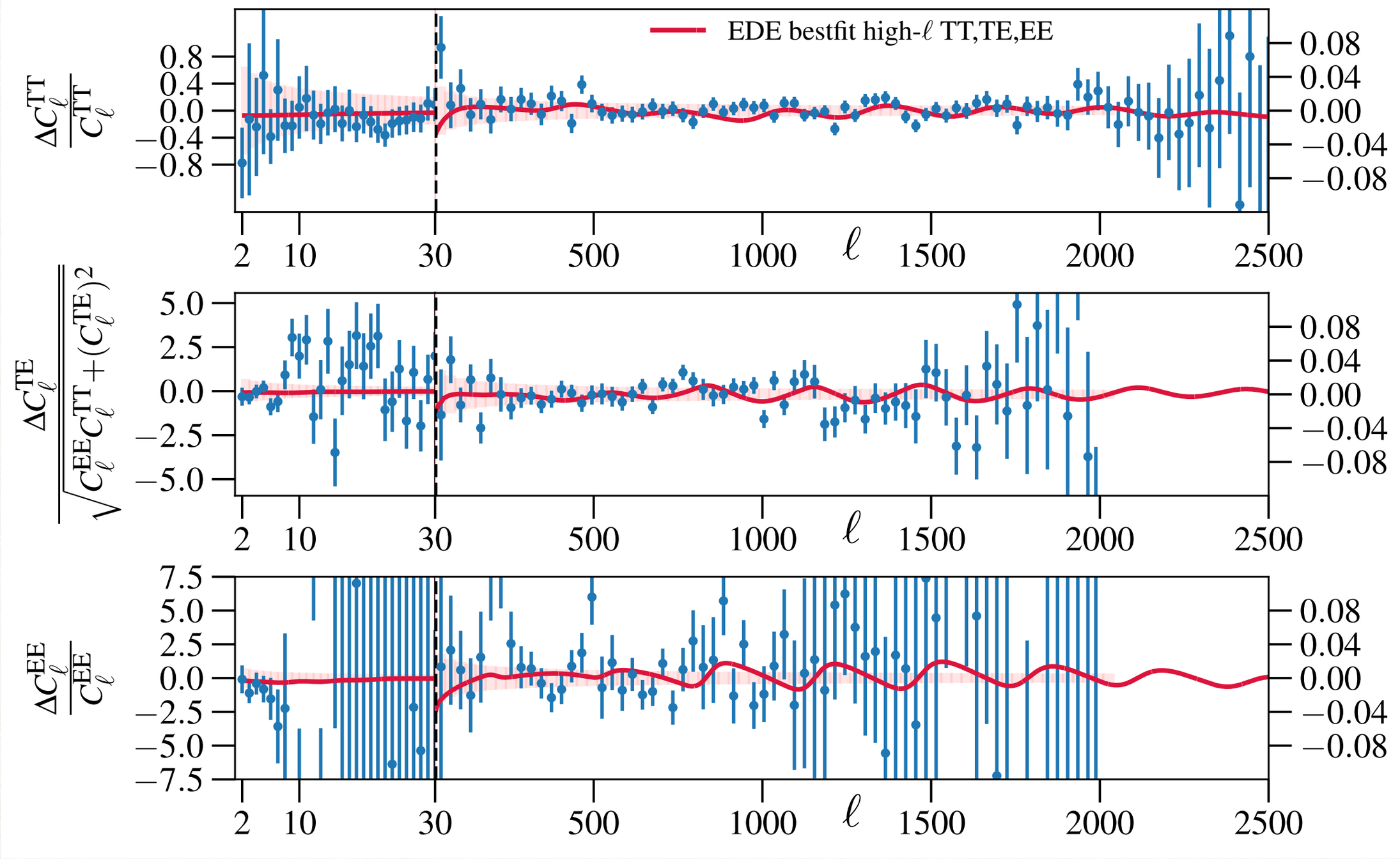
$f(z_c) = 0.10\ (0.13) \pm 0.03$ $\quad$ $\mathrm{Log}_{10}(z_c) = 3.56\ (3.53)^{+0.05}_{-0.1}$ $\quad$ $H_0 = 71.5\ (72.8) \pm 1.2$ km/s/Mpc

- n < 3.5 at 1σ: scalar field oscillations are favored over non-oscillating solutions

Datasets	ΛCDM	n free
Planck high-ℓ TT, TE, EE	2446.66	2445.53
Planck low-ℓ TT, TE, EE	10496.65	10493.65
Planck lensing	10.37	9.14
SH0ES	16.80	0.73
Total $\chi^2_{\rm min}$	14001.23	13980.90
$\Delta\chi^2_{\rm min}$	0	-20.33

See also recent update in Murgia, Abellan, VP 2009.10733

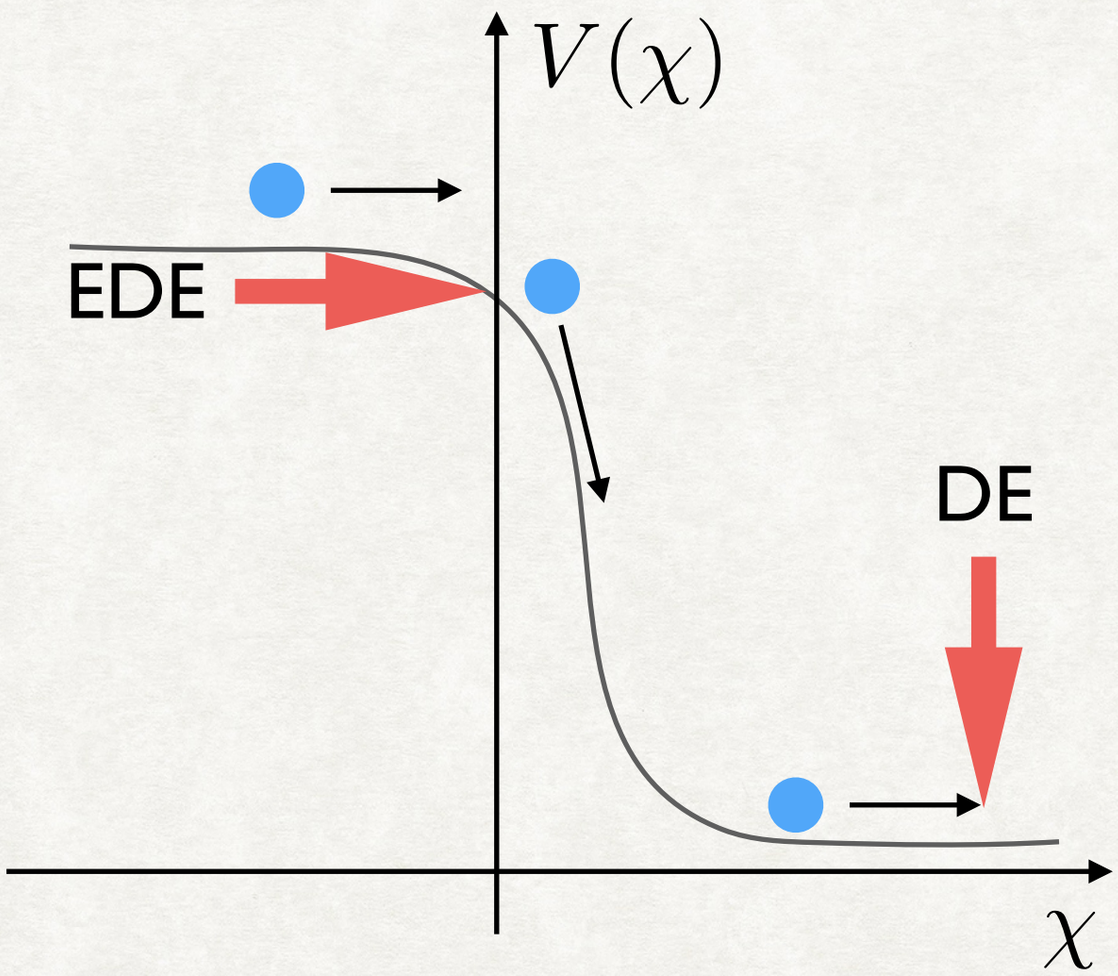
EDE leaves an imprint in CMB power spectra

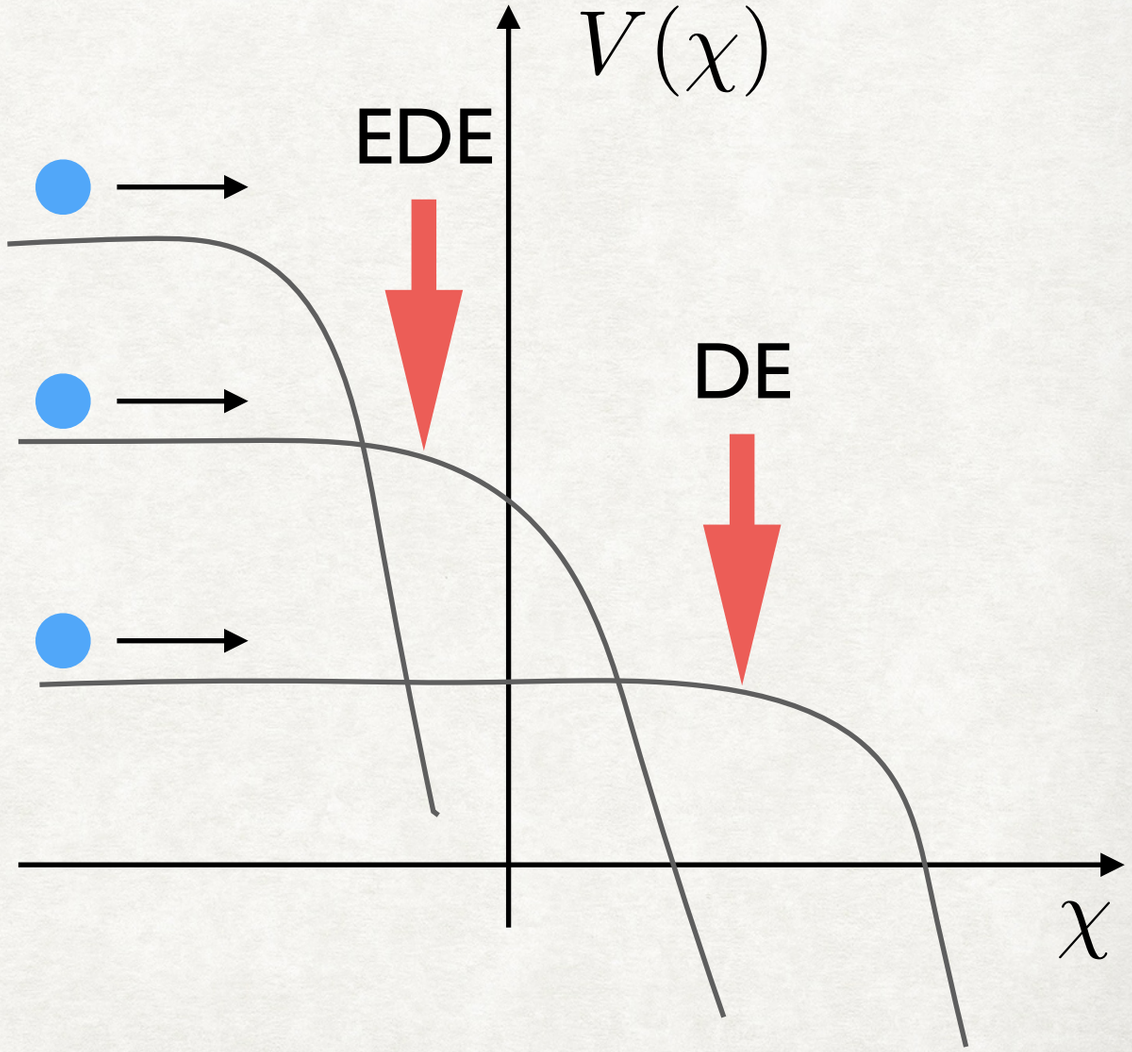


A New Understanding Of Λ?

- The field becomes dynamical around z_{eq}: Fine tuning ? Coincidence problem 2.0?
- What if there were more of such era to be discovered? We already have seen two (three?) of them.
- Is their one field with a complicated potential or many fields with simple potentials?

e.g. Dodelson++astro-ph/0002360, Griest astro-ph/0202052, Kamionkowski++1409.0549



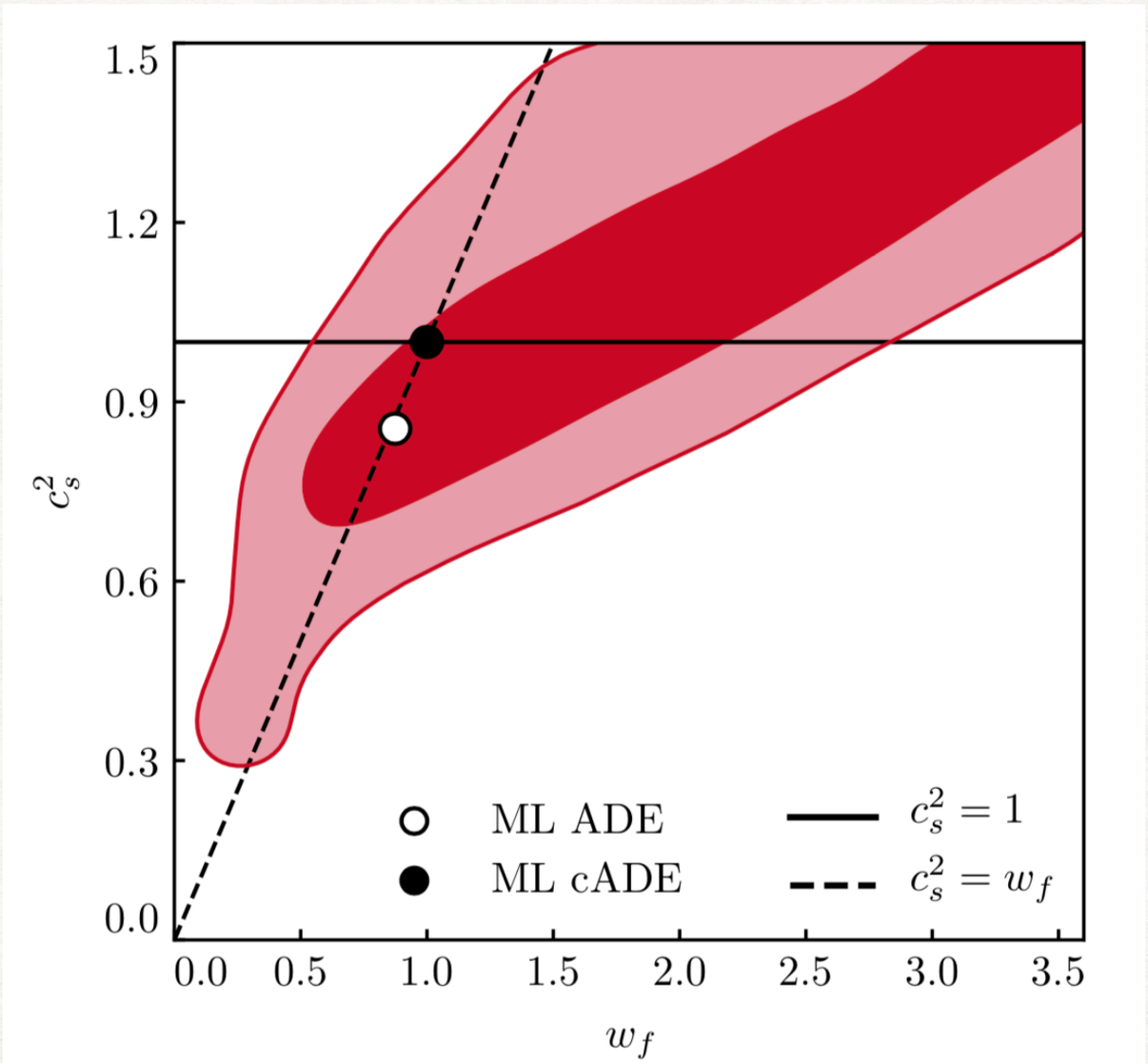


CMB data can constrain c_s^2

- In Lin, Beneveto, Hu, Raveri 1905.12618: "Acoustic" Dark Energy with constant c_s^2.

$$P(X,\phi) = \left(\frac{X}{A}\right)^{\frac{1-c_s^2}{2c_s^2}} X - V(\phi),$$

$$V(\phi) = \begin{cases} A\,\phi^m, & \phi > 0\,, \\ 0, & \phi \leq 0\,. \end{cases}$$

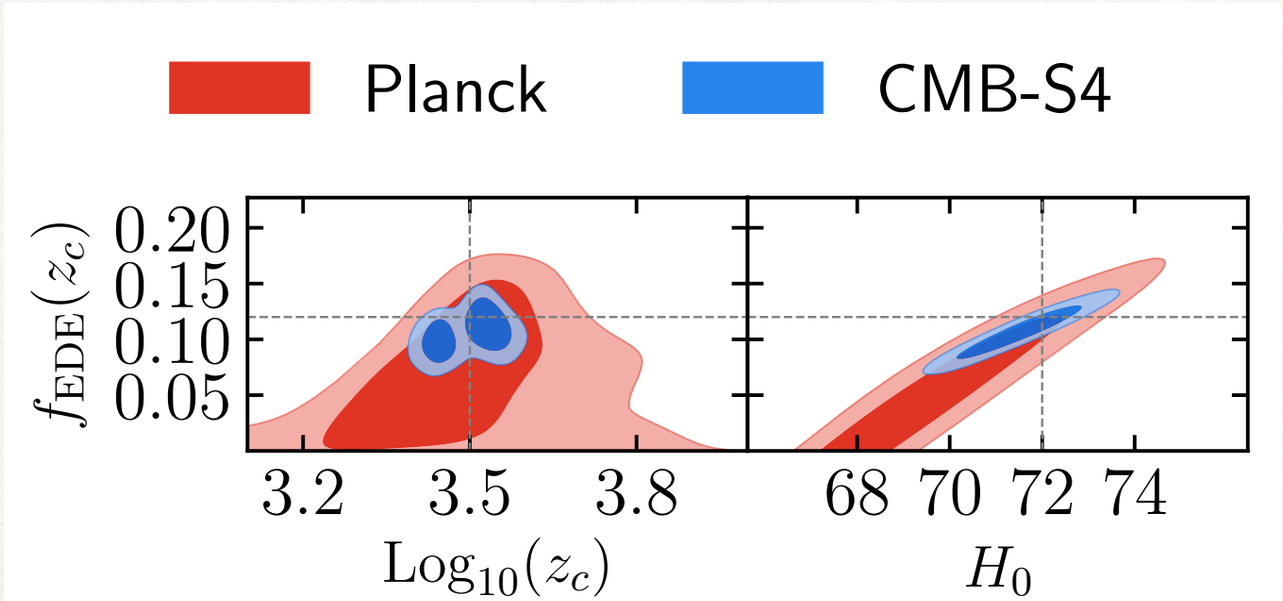


For w = 0.5 (n=3) data favors $c_s^2 < 0.9$ at 95% C.L.

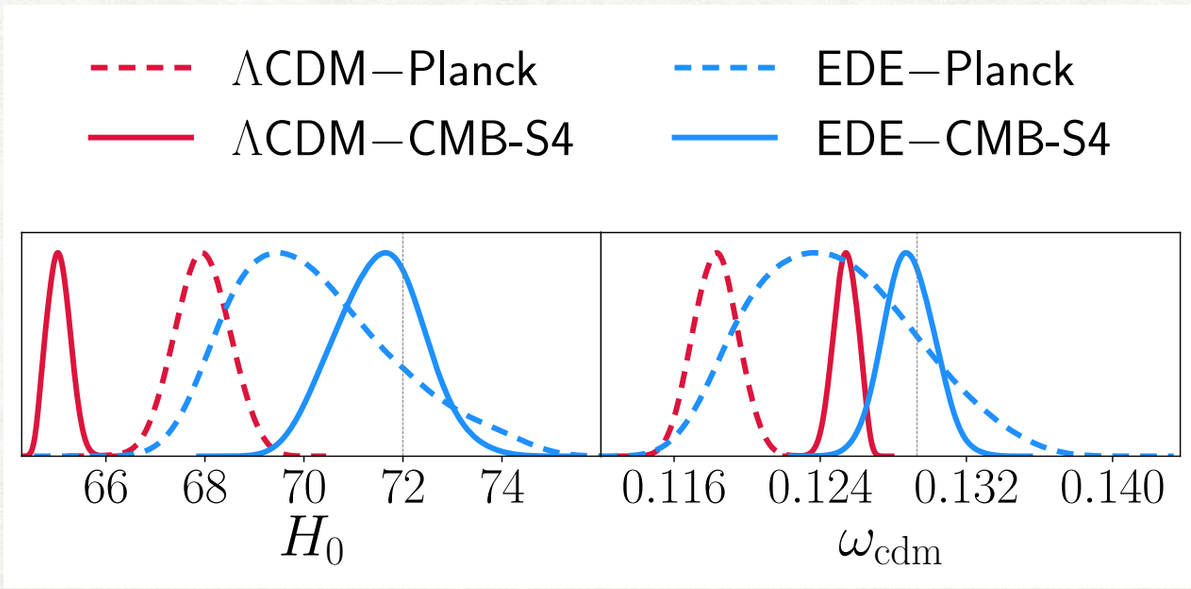
Detecting the EDE with CMB data only

- Future CMB experiment like CMB-S4 will be able to detect the EDE without SH0ES data.

Fiducial model:
$f(z_c) = 0.12$
$z_c = 10^{3.5}$
$h = 0.72$

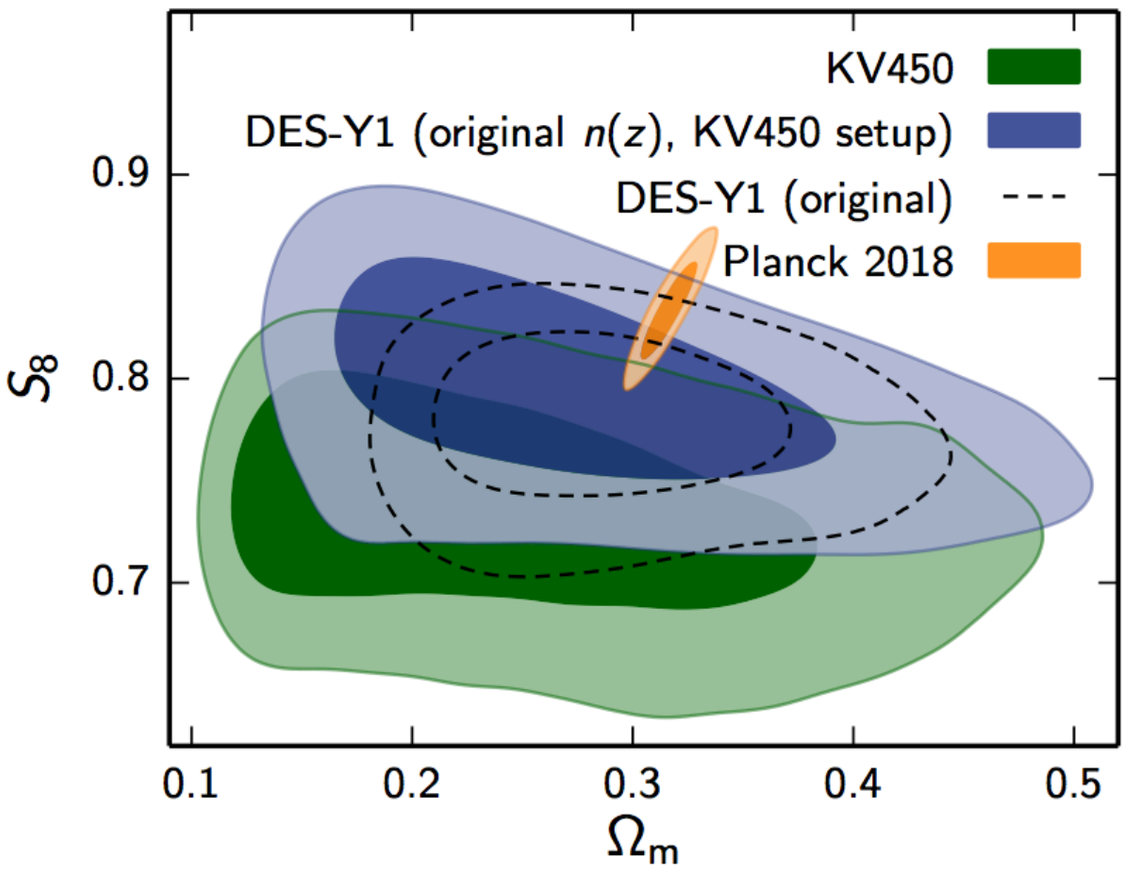


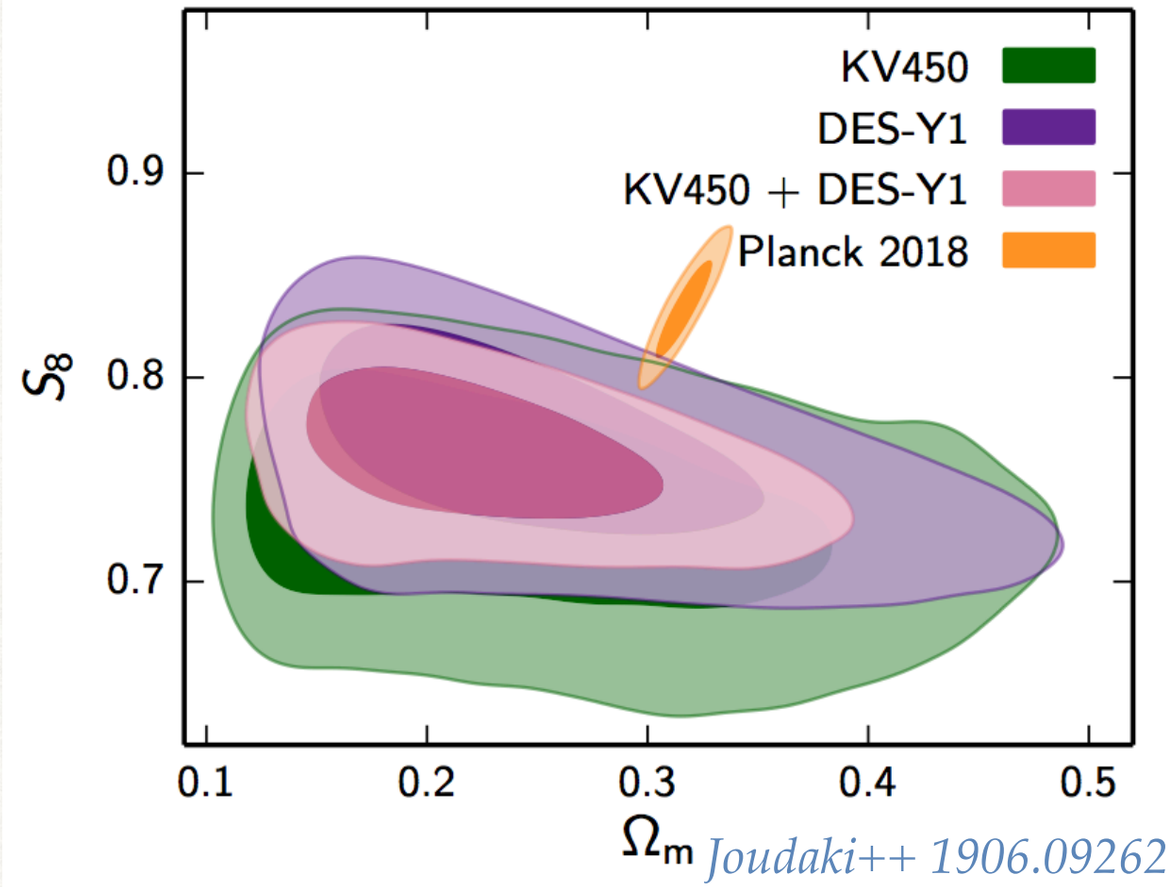
- Without including the EDE: one might strongly bias H_0 and $\omega_{\rm cdm}$ values.



$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$

The S_8 tension



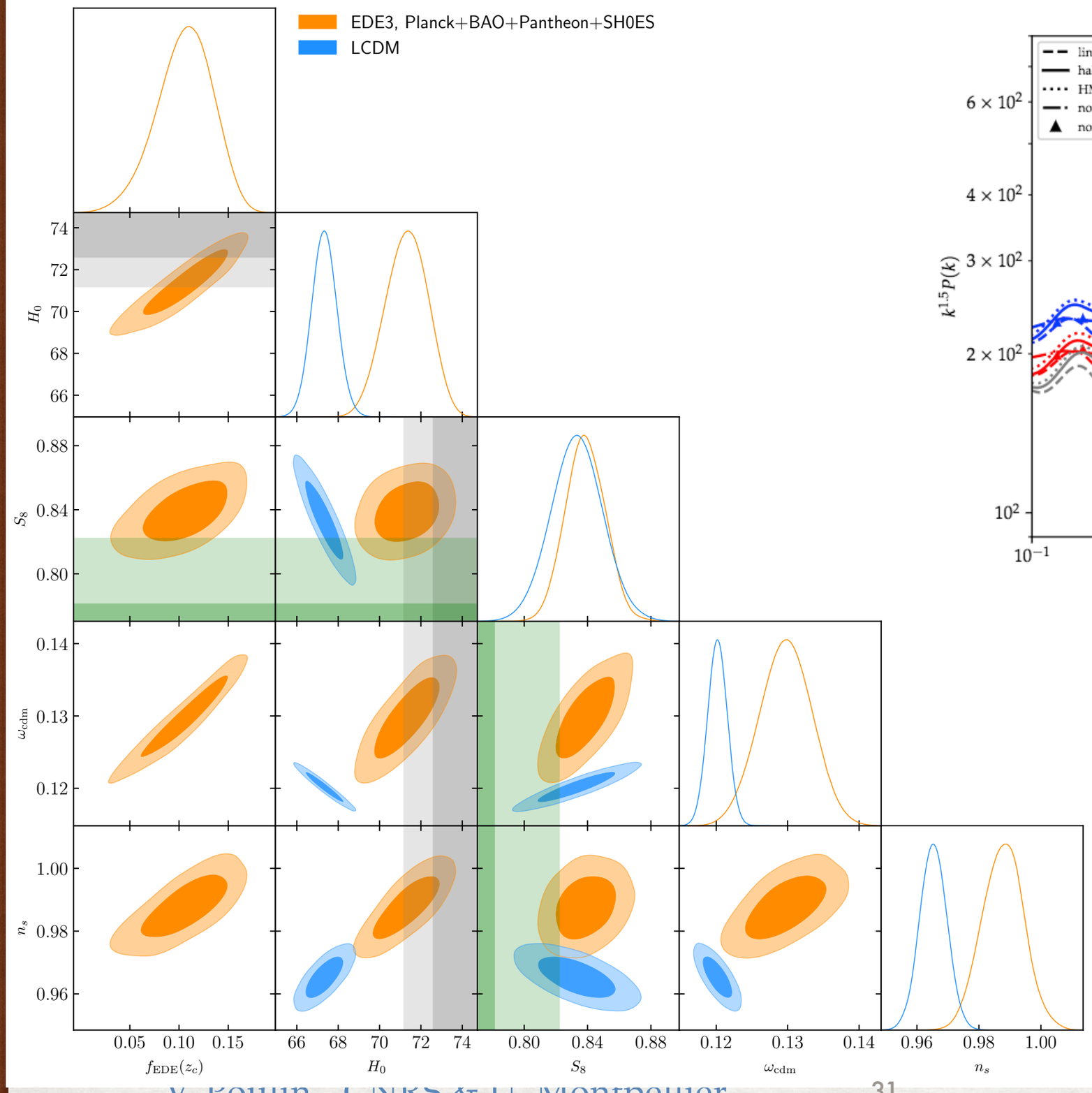


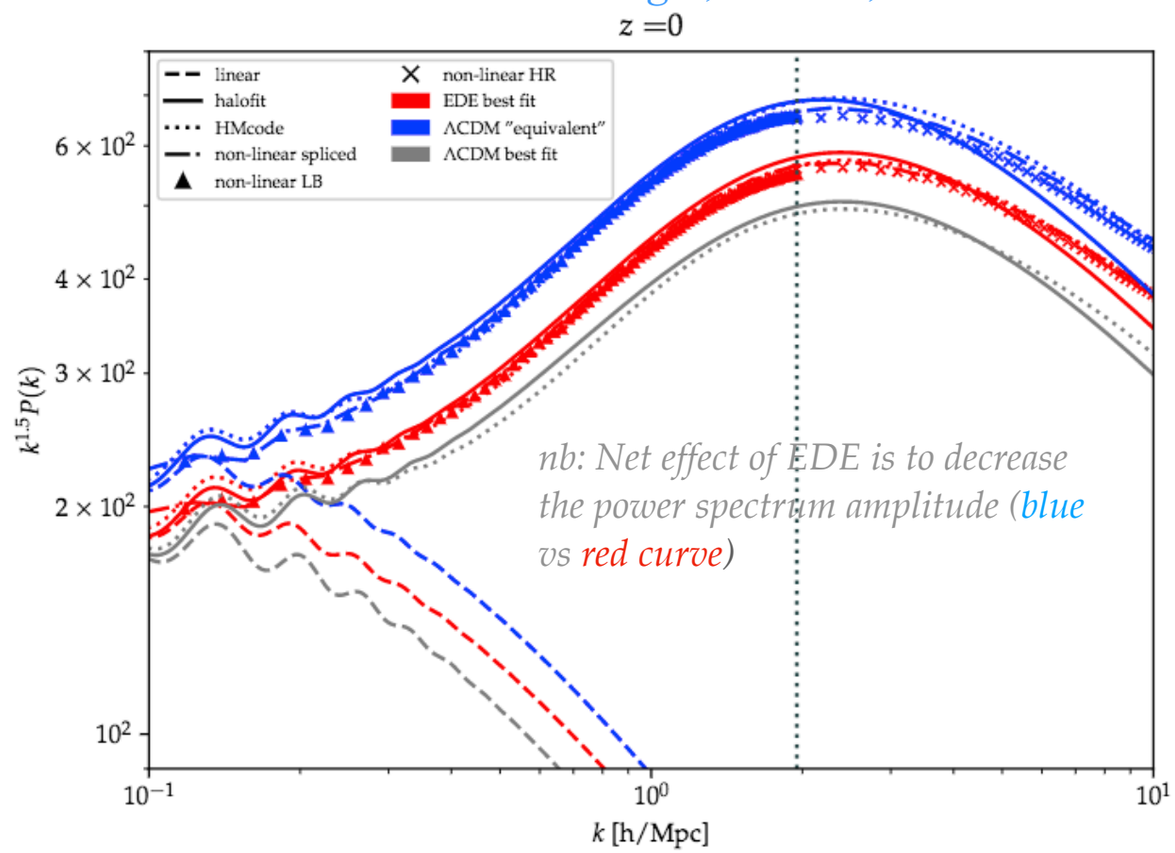
Joudaki++ 1906.09262

- $\sim 2.5\sigma$ tension between CFHTLenS/HSC/KiDS and *Planck*. (Also Planck SZ?)
  Heymans++ MNRAS 2013, KiDS MNRAS 2017 , HSC PASJ 2019, DES PRD 2018, Salvati++ PoS 1901.05289
- DES galaxies or shear alone in agreement with *Planck,* while galaxies+shear shows 2σ tension. Hot discussion about calibration of photometric redshift.
  DES collab. PRD 2018, Joudaki++ 1906.09262
- To resolve the tension: reduce power at scales $k \gtrsim 0.1$ h/Mpc. DM interactions, decay, massive neutrinos, (warm or fuzzy dark matter?)
  [insert your favorite paper here]

EDE can be constrained by LSS

Murgia, Abellan, VP 2009.10733

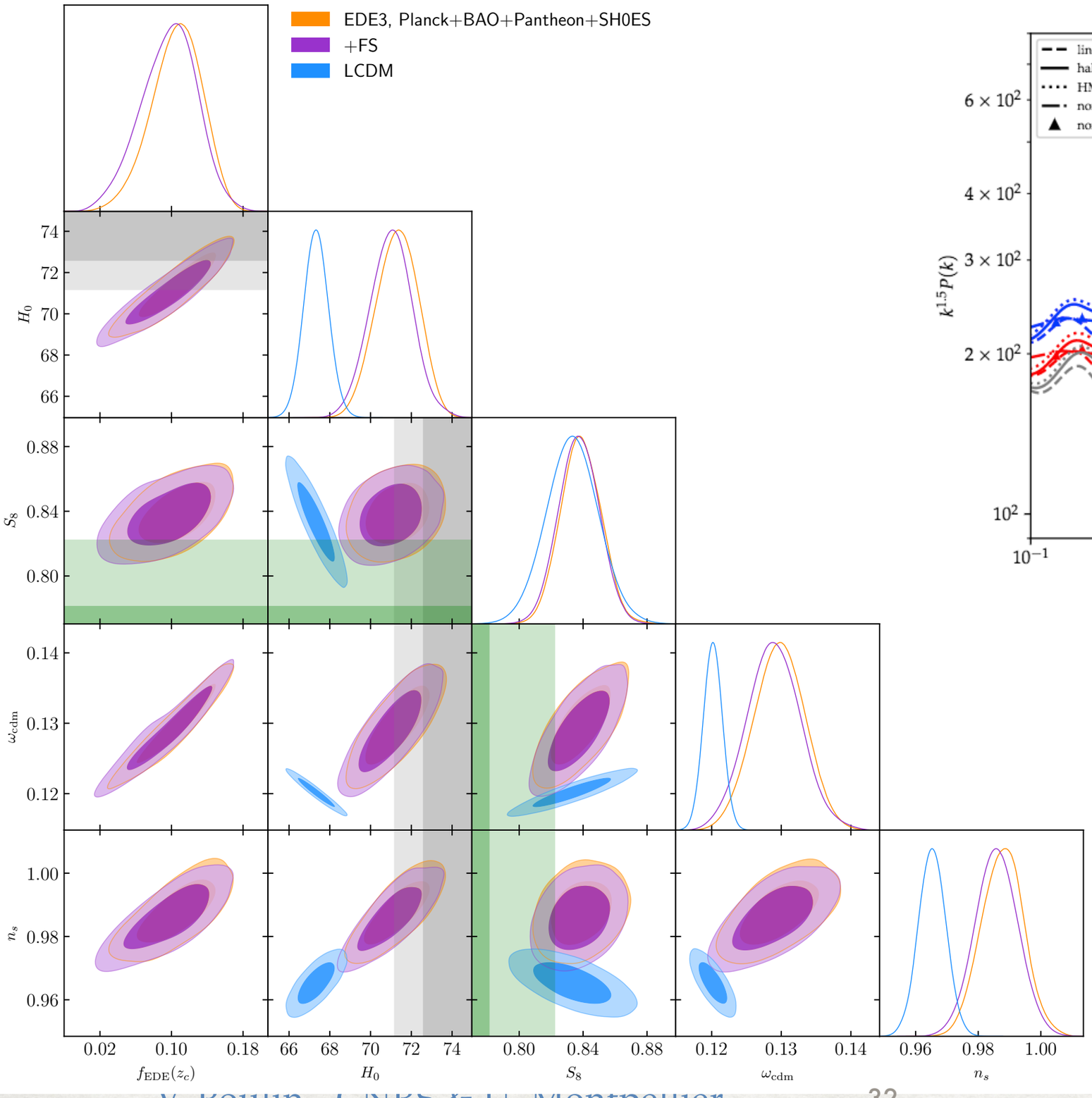


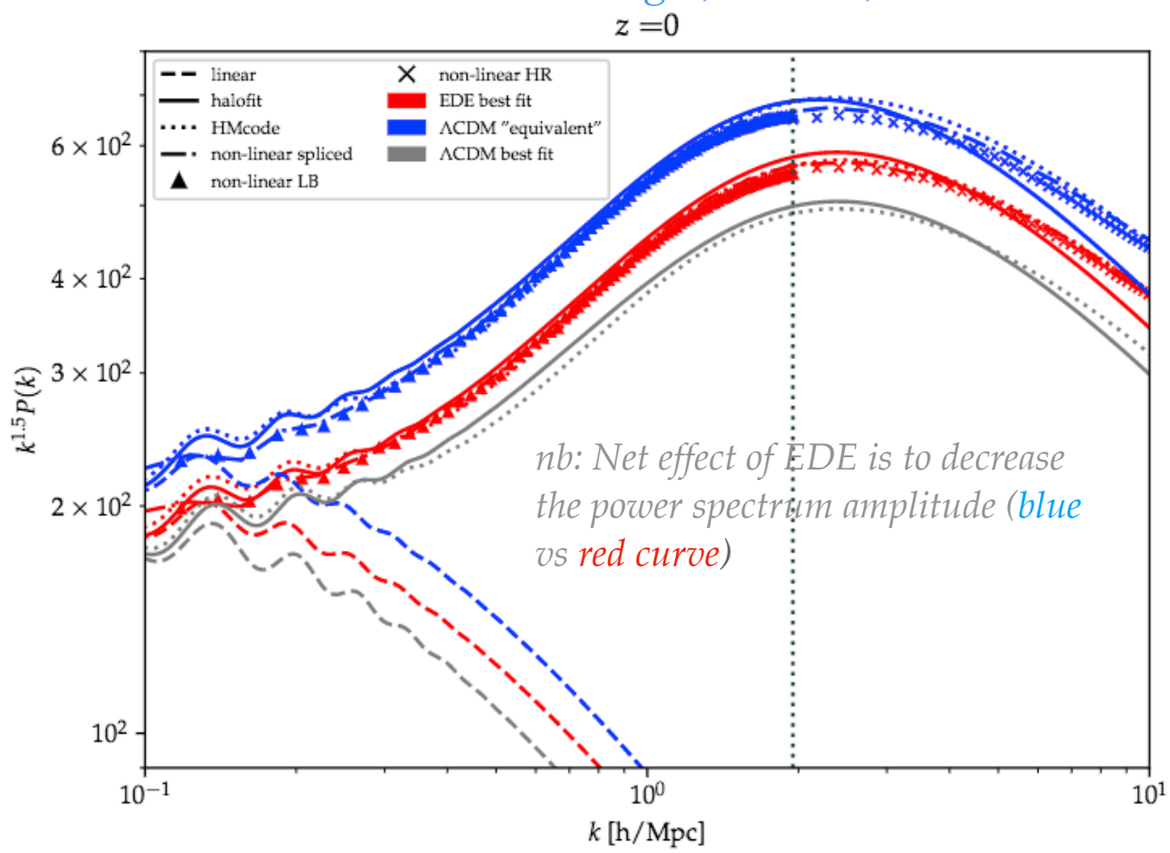


- The increase in $\omega_{\rm cdm}$ & n_s leads to an increase in S_8.
- The S_8 tension increases by $\sim 0.5\sigma$.
- Constraints from KIDS? DES? BOSS?

EDE can be constrained by LSS

Murgia, Abellan, VP 2009.10733

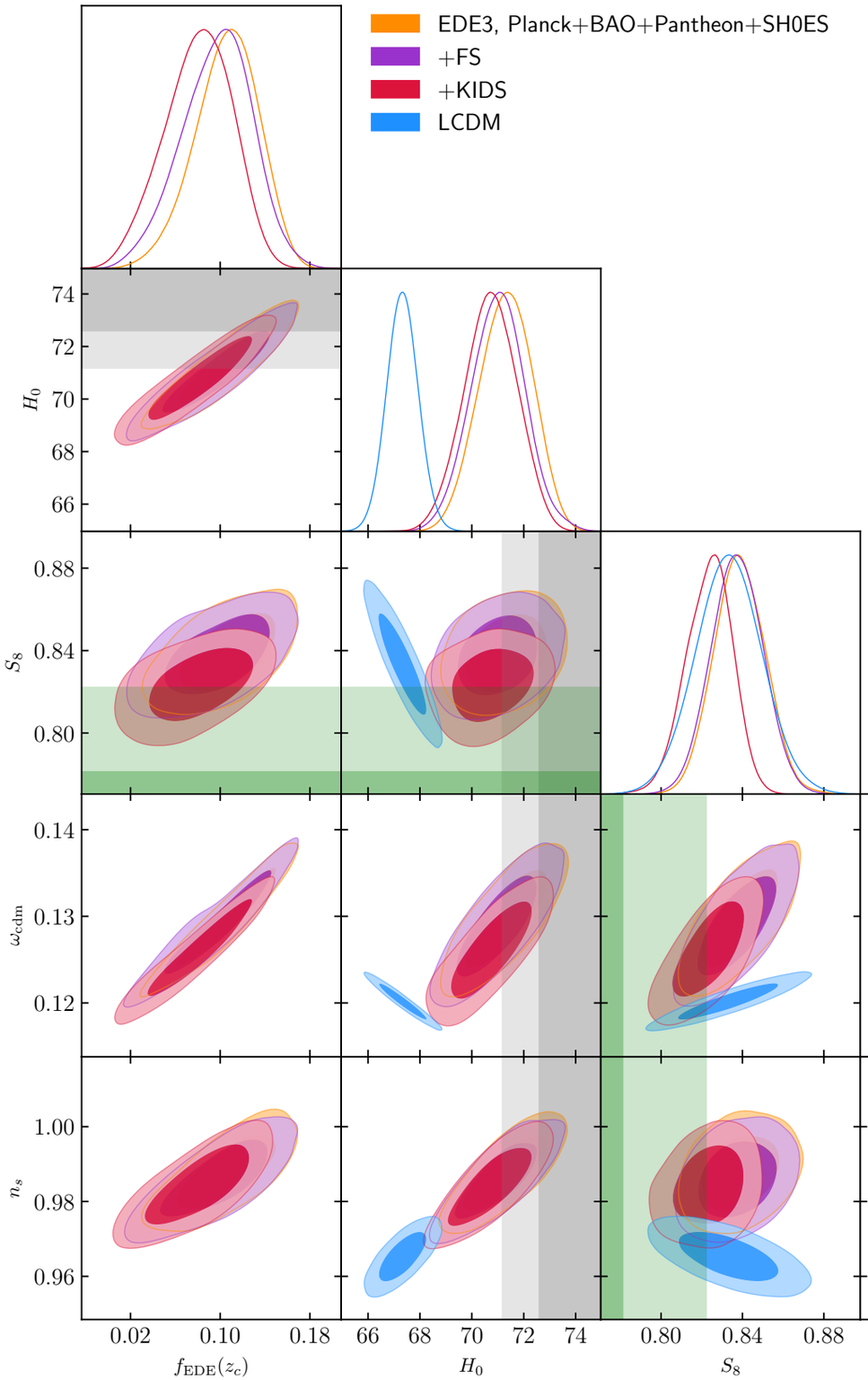


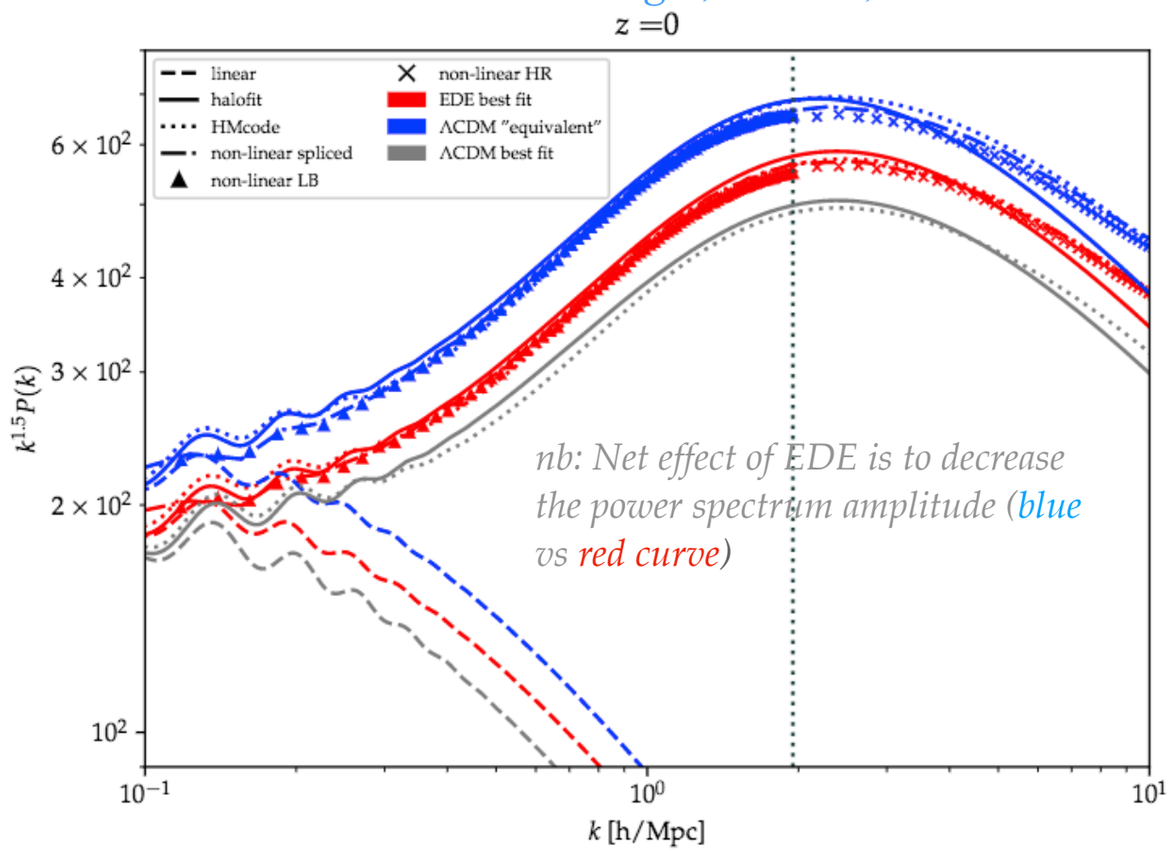


- Including BOSS RSD measurements of $f\sigma_8$:
  $f_{\rm EDE}(a_c) = 0.097^{+0.035}_{-0.029}$
  $H_0 = 71^{+1.1}_{-1}$
- $\Delta\chi^2 \simeq -20$ (stable)

EDE can be constrained by LSS

Murgia, Abellan, VP 2009.10733

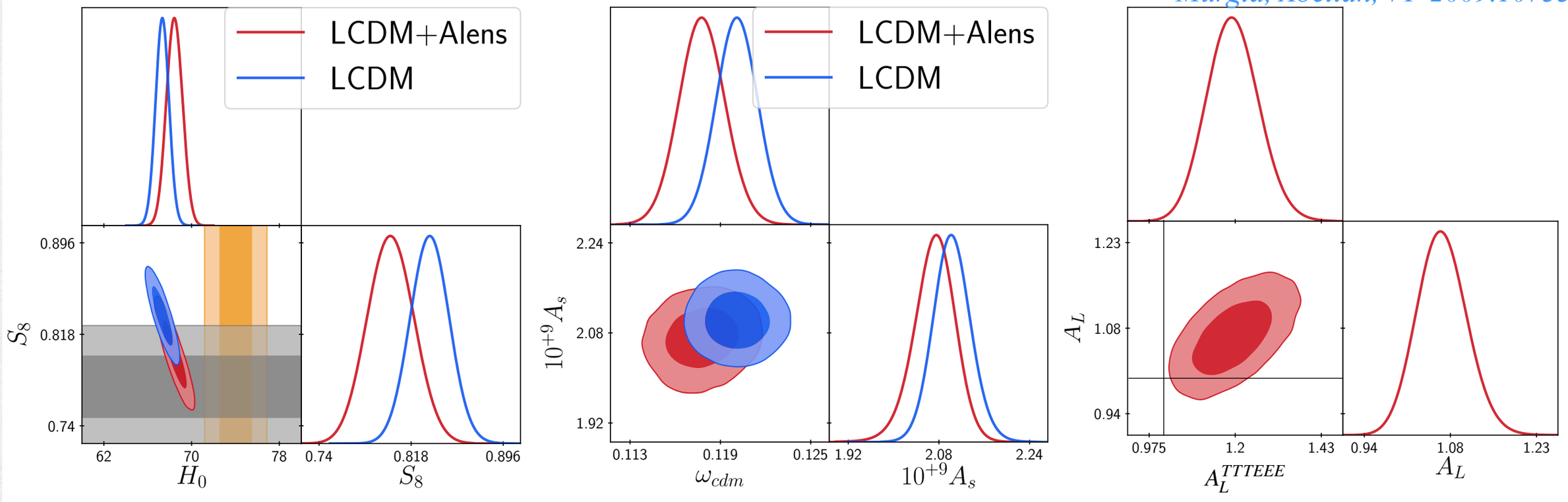




- Combining with KiDS/KV(+H0): $f_{\rm EDE} = 0.085^{+0.034}_{-0.022}$ $H_0 = 70.87^{+1}_{-0.91}$
- KIDS/VIKING/DES(-H0): $f_{\rm EDE}(z_c) < 0.06$ $H_0 = 68.92^{+0.57}_{-0.59}$ *Hill et al. 2003.07355*
- Statistical inconsistency! 'compromise' cosmology is a bad fit to S_8 data *Raveri&Hu 1806.04649*

Could the A_L anomaly be related to S_8?

Murgia, Abellan, VP 2009.10733

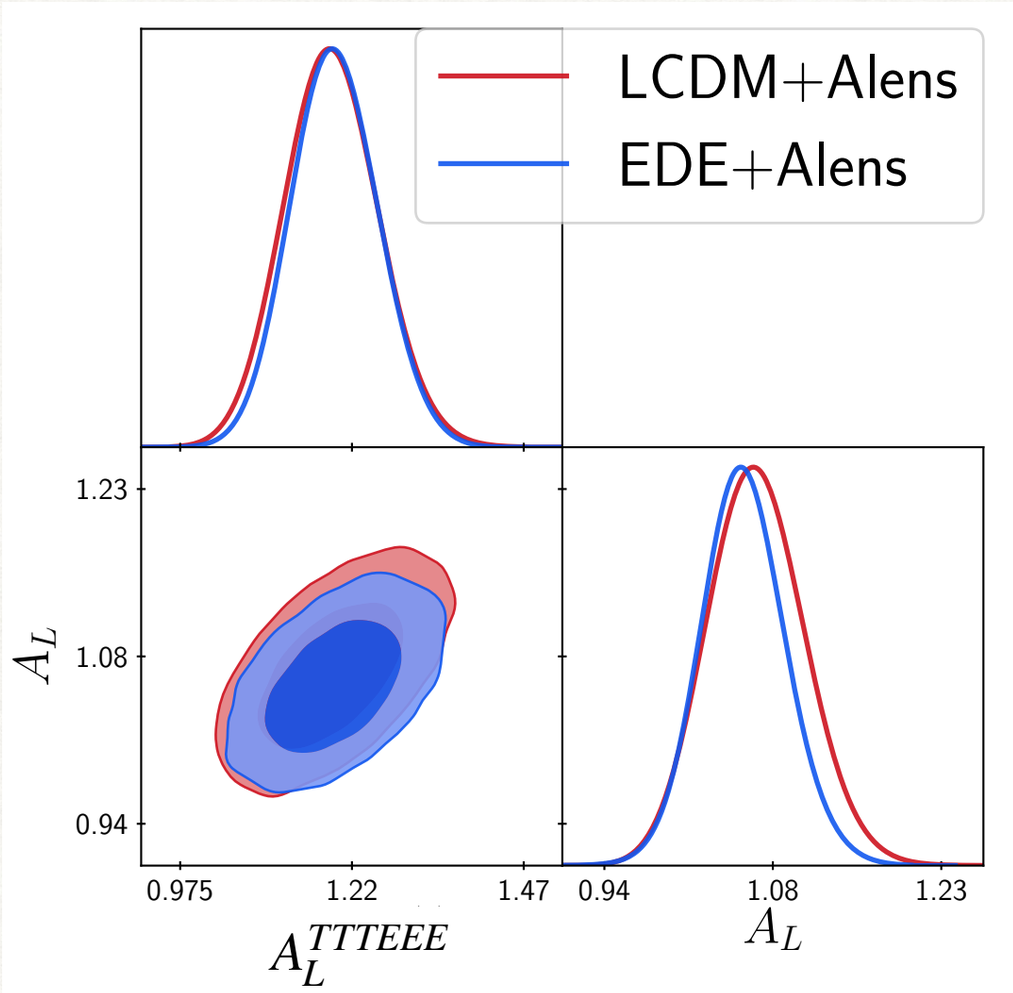


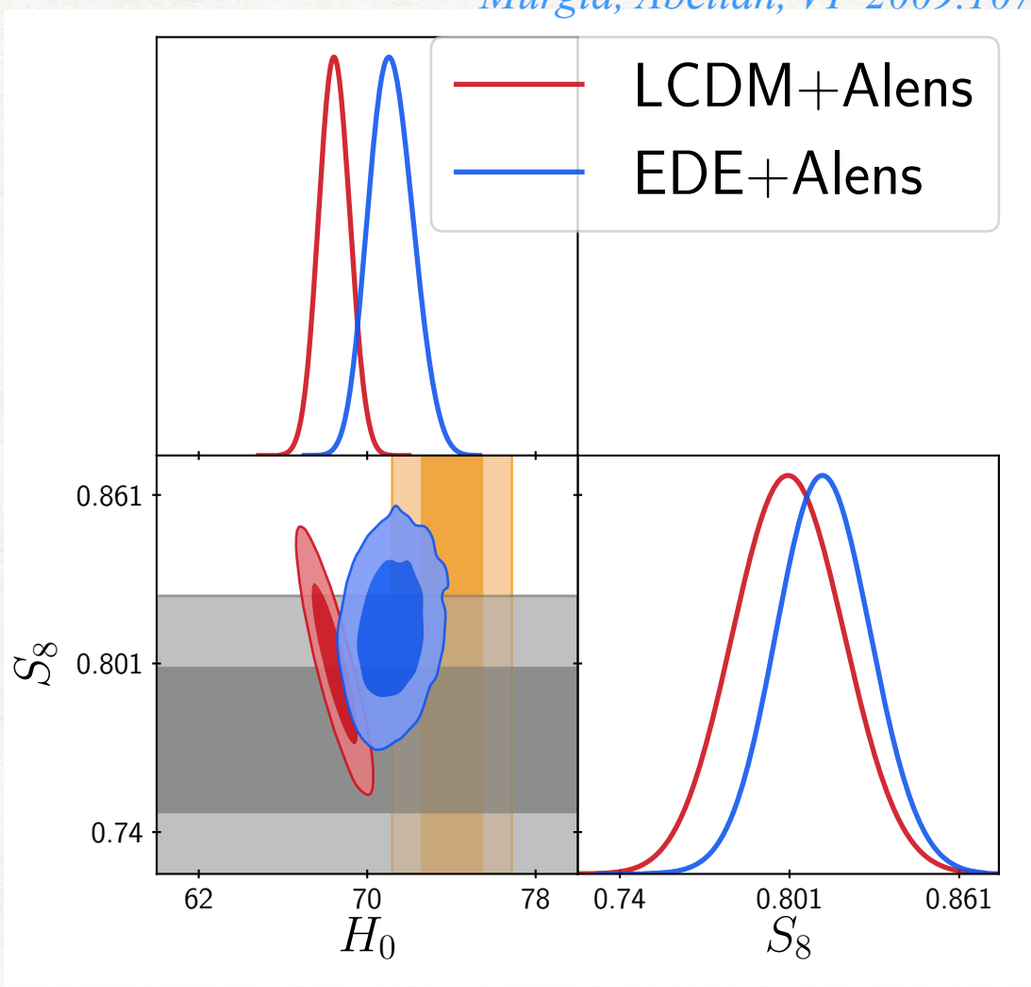
- Marginalize over lensing information in *Planck*: Lensing power spectrum amplitude A_L+ peak smoothing amplitude A_L^{TTTEEE}
- 'A_L anomaly': The lensing amplitude deduced from peak smoothing A_L^{TTTEEE} in *Planck* data is higher than that from lensing reconstruction A_L.
- In ΛCDM: extra smoothing requires higher A_s and $\omega_{\rm cdm} \Rightarrow$ higher S_8.
- Once marginalizing over the 'A_L anomaly'; no S_8 tension! no anomaly in ACT&SPT.

see also Di Valentino&Bridle 2018, Planck 1807.06209, SPTPol 1910.07157

Lensing-marginalized EDE cosmology vs S_8

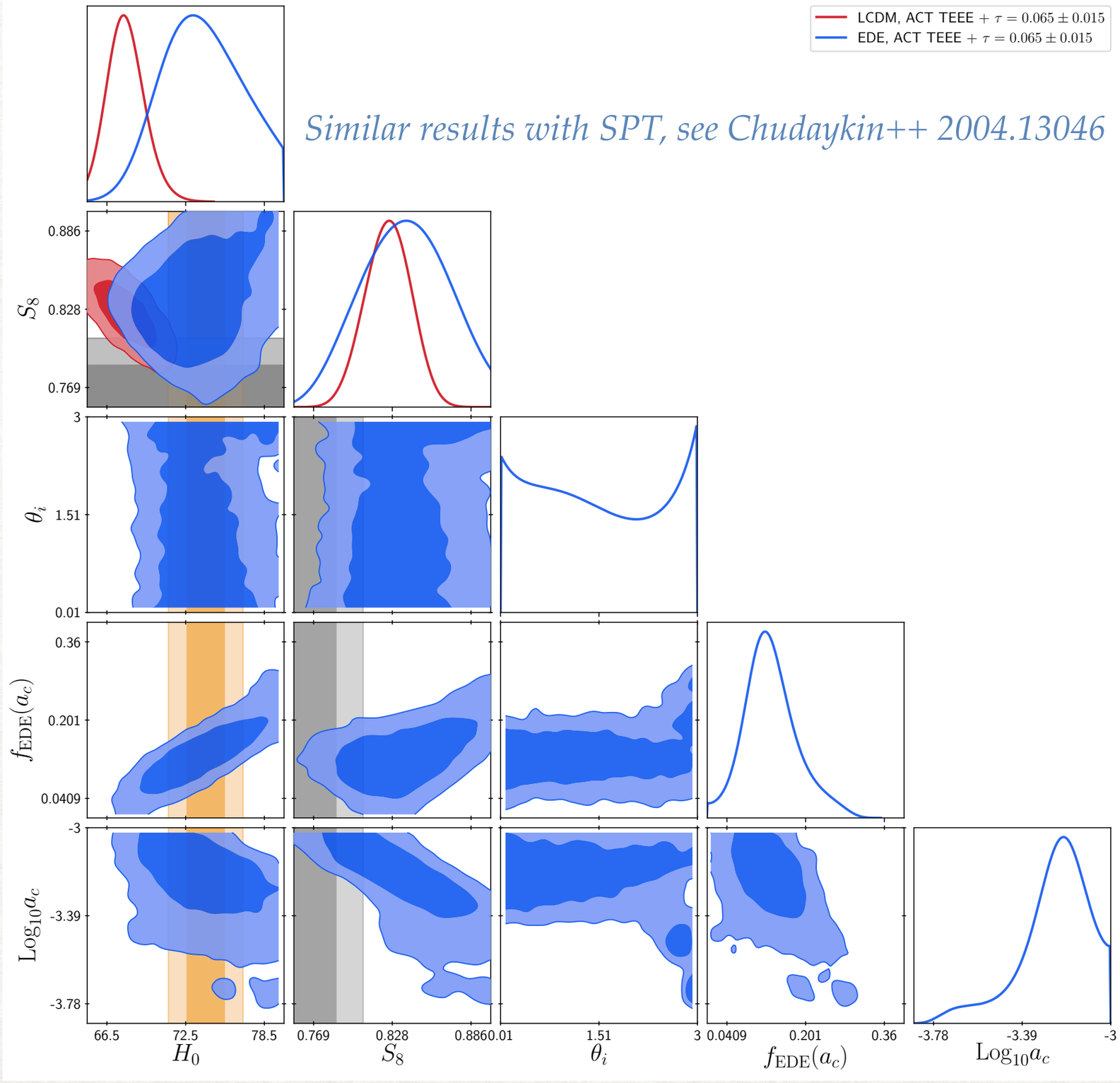
Murgia, Abellan, VP 2009.10733





- Once marginalizing over the A_L anomaly; EDE in agreement with S_8 data!
- The determination of A_L and A_L^{TTTEEE} is unaffected by the EDE parameters!
- This is also supported by SPTPol analysis.

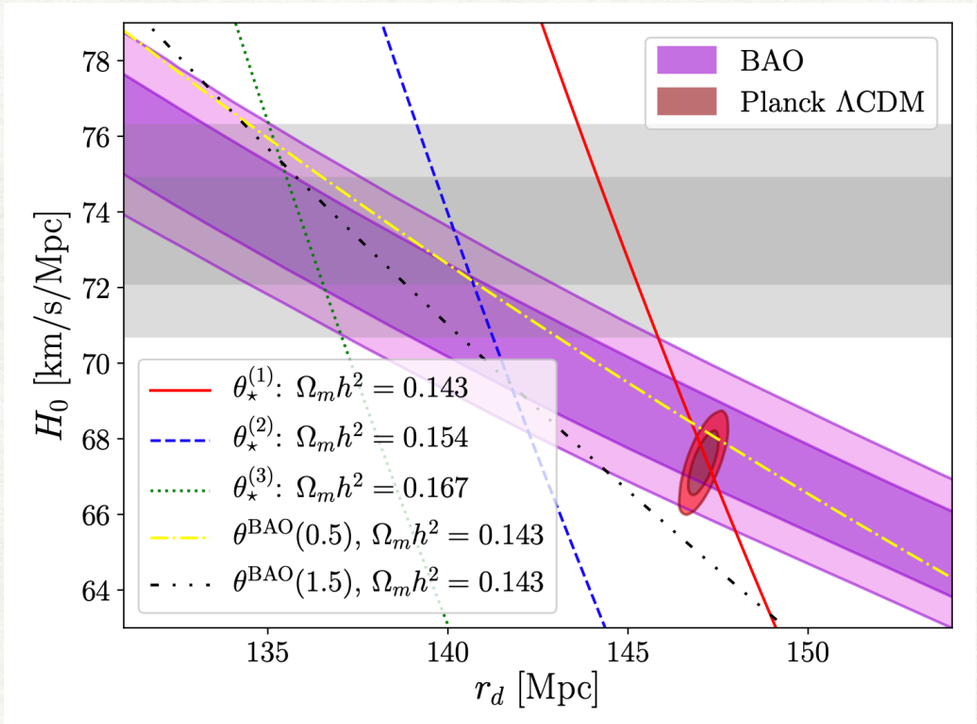
No S8-tension with ACT and SPT

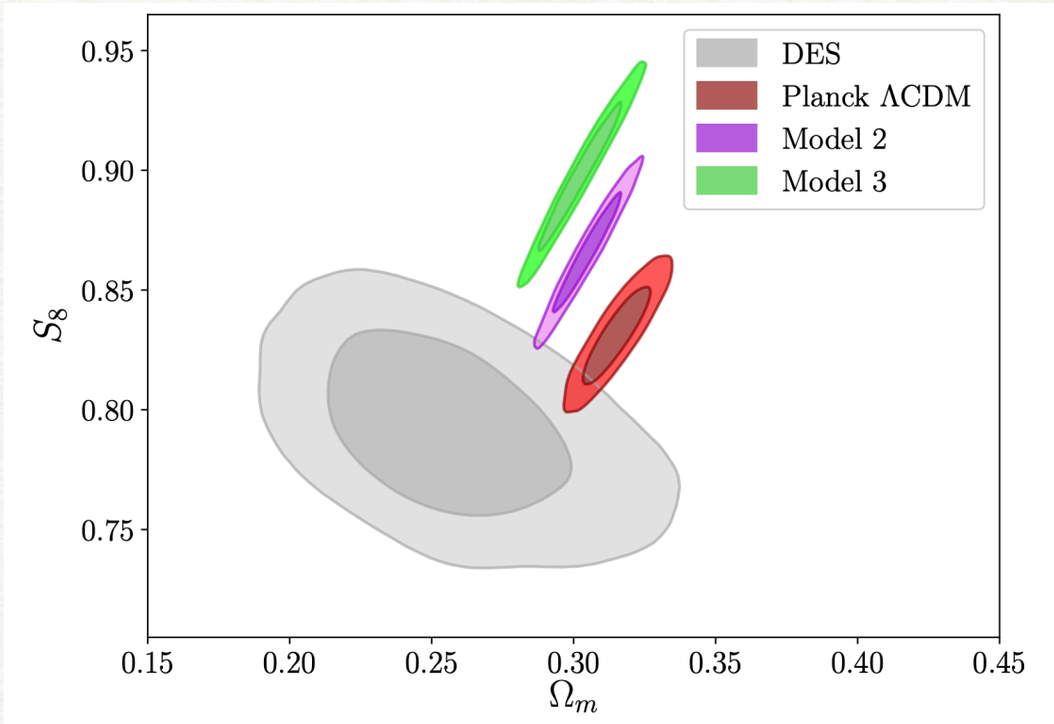


Similar results with SPT, see Chudaykin++ 2004.13046

What will it take to find a concordance model?

Jedamzik & Pogosian 2010.04158





- Fitting Planck, H_0 and BAO with lower $r_s(z_{\rm rec})$ requires higher $\omega_{\rm cdm}$: the S_8 tension increases.
- Resolving both tensions (unless systematics!) will likely require multiple extensions
- H_0: measure the background expansion rate. S_8: measure the amplitude of perturbations.
- It is likely that a solution will need some specific background & perturbation dynamics.
- This is already the case in a variety of model! Interacting DM-DR, interacting neutrinos, EDE-m_ν model… But very limited success so-far.

Conclusions

- H_0 from local measurements is in tension with LCDM-inferred value from Planck. Systematics are still possible!
- This is better understood when recast as a sound-horizon tension: CMB r_s too high by 10Mpc.
- A frozen scalar field acting like Early Dark Energy until zc~3500 with f(zc)~10% and diluting faster than radiation later can solve the Hubble tension.
- Slightly better fit to Planck data, once SH0ES is included "definite" evidence for n>=3, $\Delta\chi^2_{\rm min} \sim -20$.
- Future CMB data will unambiguously detect (or exclude) EDE. If this is the "correct" resolution: there might be new ways of interpreting Λ and inflation.
- This naive model is disfavored (not ruled out!) by recent KiDS and BOSS data. Combining Planck and LSS data might not be statistically sound! S_8 tension, A_L anomalous, A_s discrepancy.
- Connections between S_8 and H_0 exist but are not automatic (perturbations vs background).

Thanks for your attention!