Early Dark Energy, the Hubble tension and ACT data

The Atacama Cosmology Telescope (act.princeton.edu)

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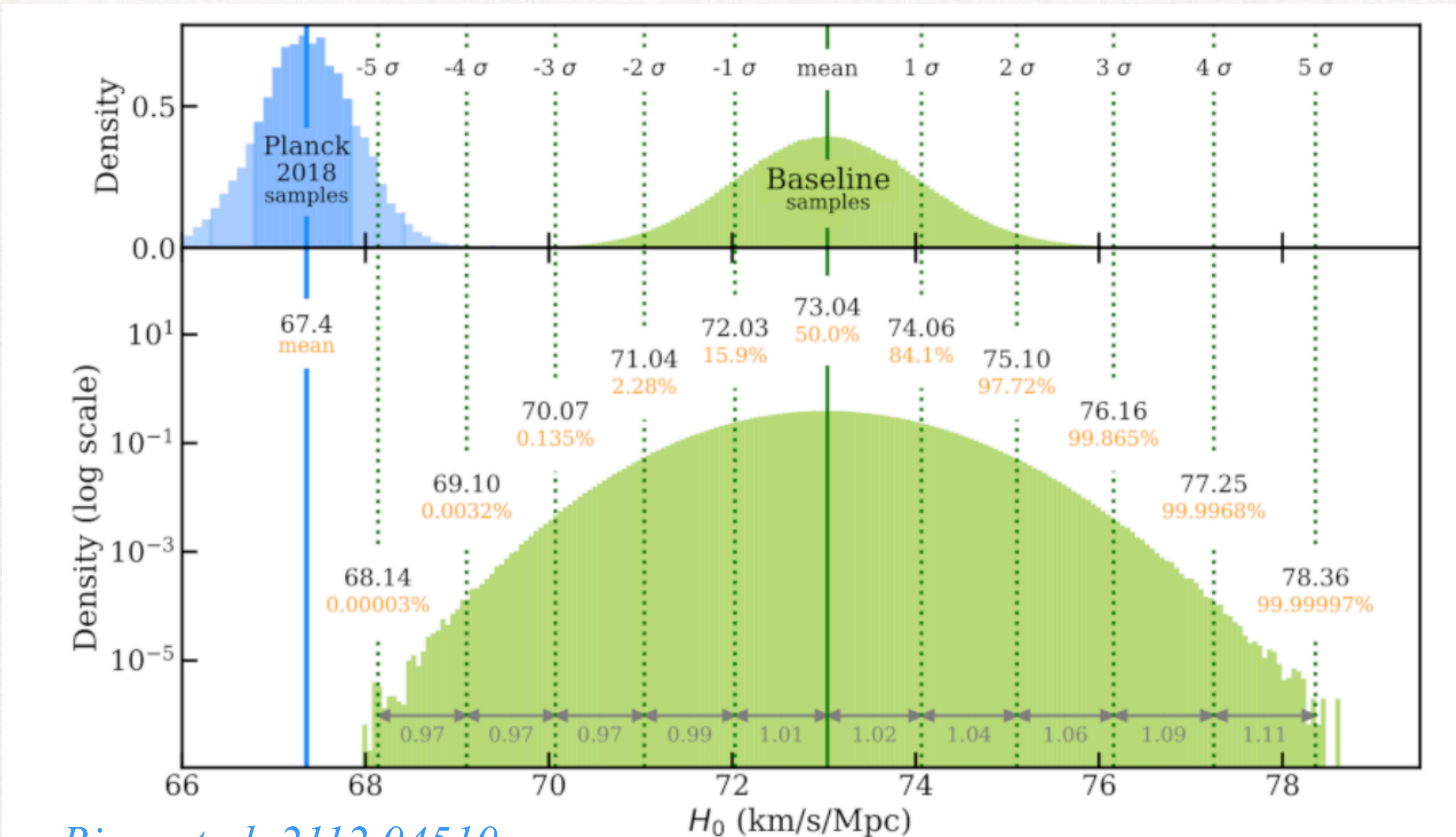
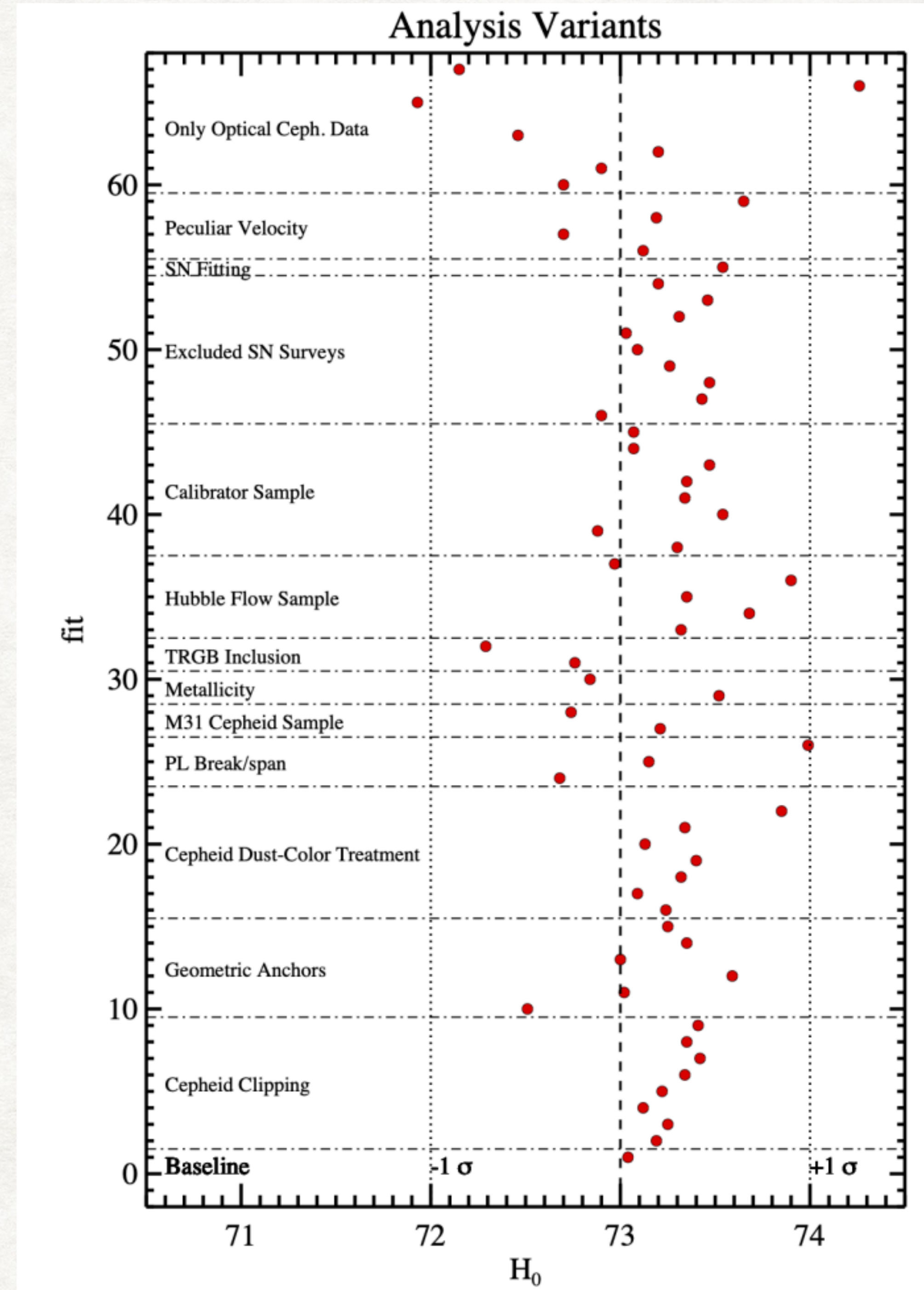
2109.06229 with Tristan Smith & Alexa Bartlett (Swarthmore Coll.)

TUG workshop, Paris
December, 14th 2021

The Hubble tension



Riess et al. 2112.04510



$H_0(\text{SH0ES}) = 73.04 \pm 1.04$ **km/s/Mpc**

$H_0(\Lambda\text{CDM/Planck}) = 67.4 \pm 0.06$ **km/s/Mpc**

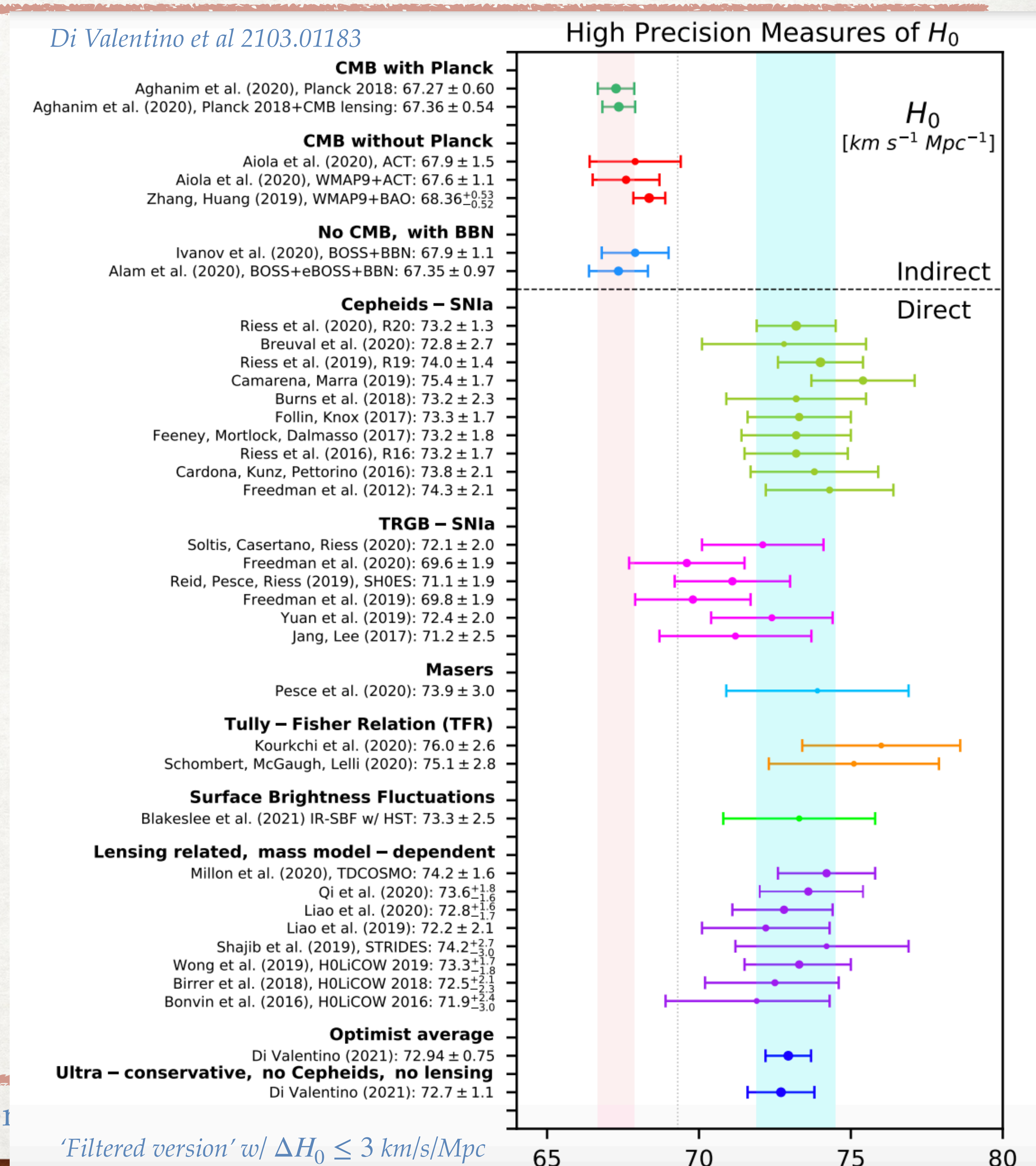
There is a 5σ discrepancy between the SH0ES and Planck determination of the Hubble parameter

No (known) systematic error can explain the discrepancy

The Hubble tension beyond SH0ES

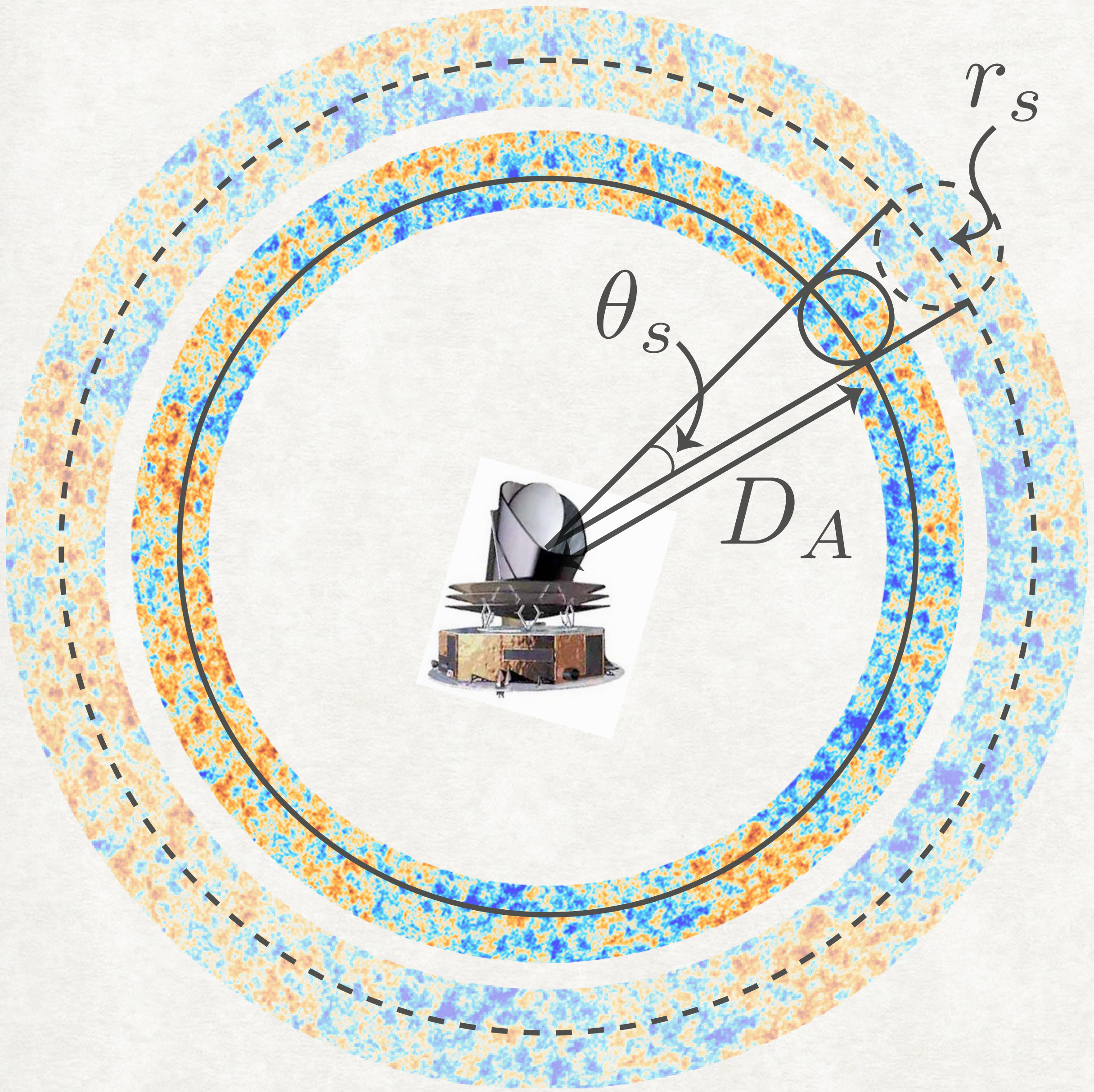
As of 2021, over 20 measurements and 800 papers!!

- 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
- Direct measurements are higher than predictions, not all are in strong tension.
- Average: tension between 4-6σ
- Systematics? New Physics?



How can we change the H_0 prediction?

- Could the CMB be closer to us than ΛCDM tells us? $d_A(z_*) \propto 1/H_0$
- Therefore, could spot in the CMB be smaller? This is what new physics must achieve.



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

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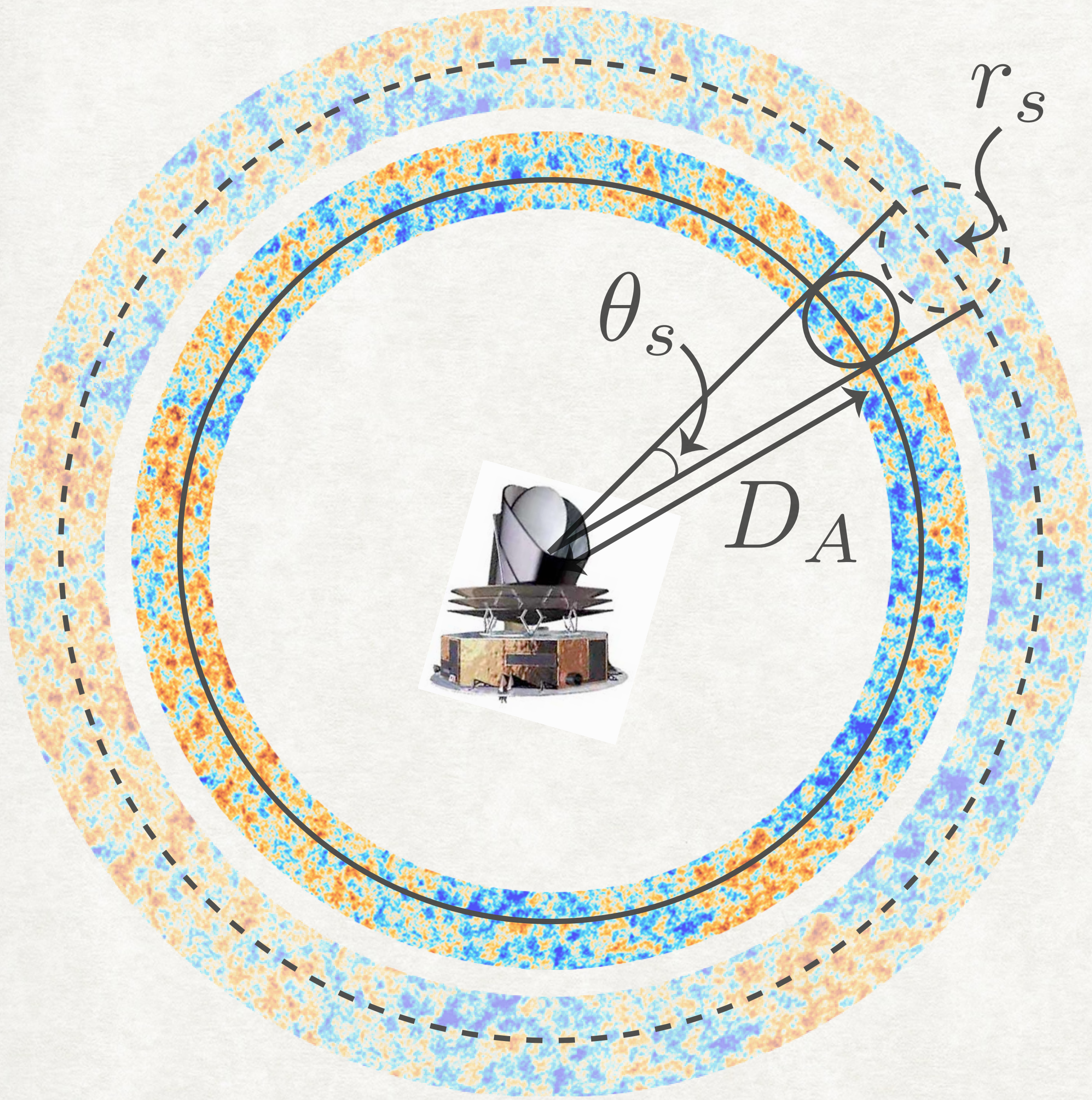

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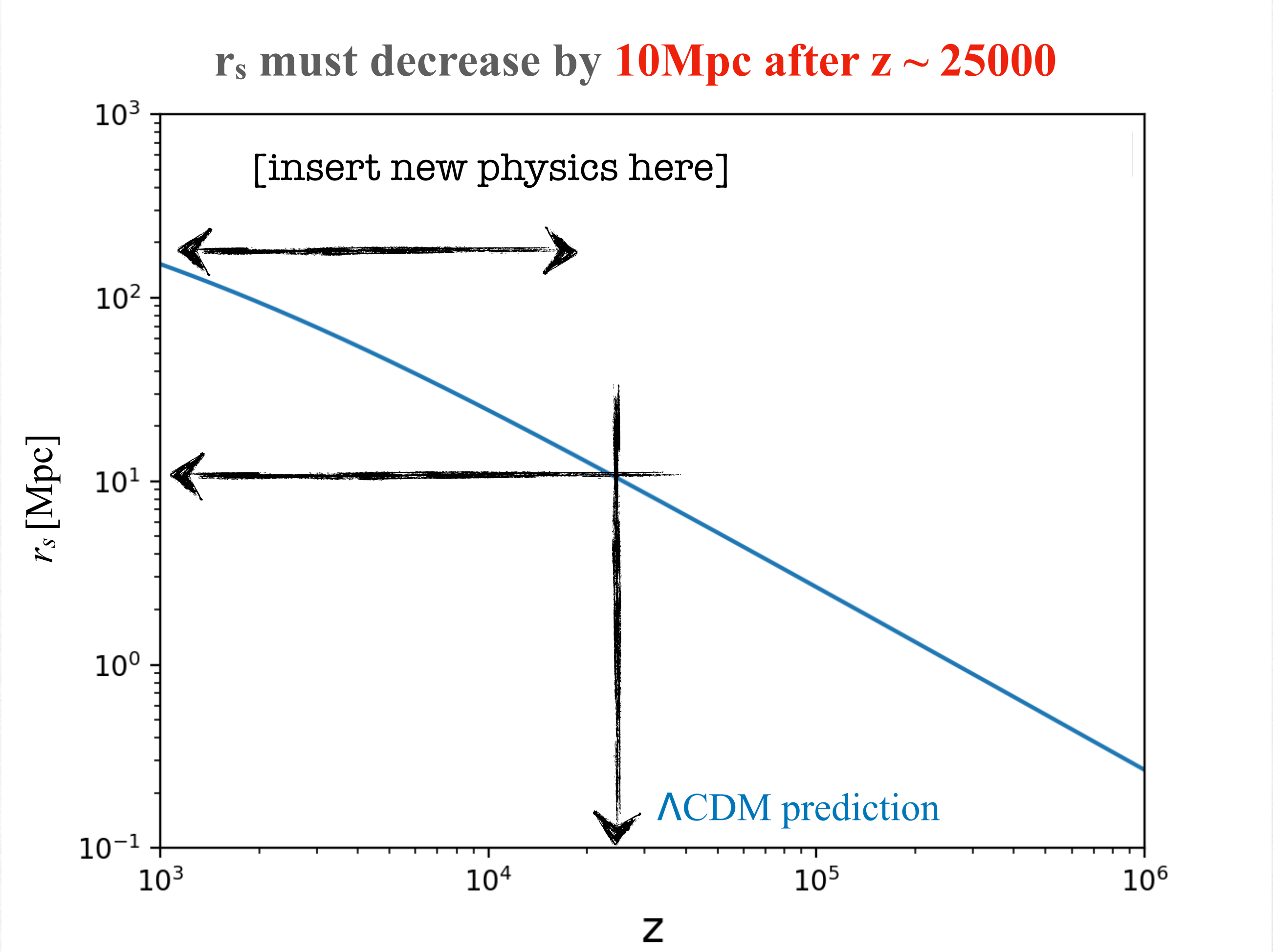

What is Early Dark Energy?

For earlier work Wetterich astro-ph/0403289

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

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

- We consider an oscillating (toy) potential:

$$V(\phi) = m^2 f^2 (1 - \cos(\phi/f))^n$$

VP++ 1806.10608 & 1811.04083; Smith++ 1908.06995
Murgia++ 2009.10733; Smith++ 2009.10740

- Perform 'cycle-averaging' over oscillations.
- 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.

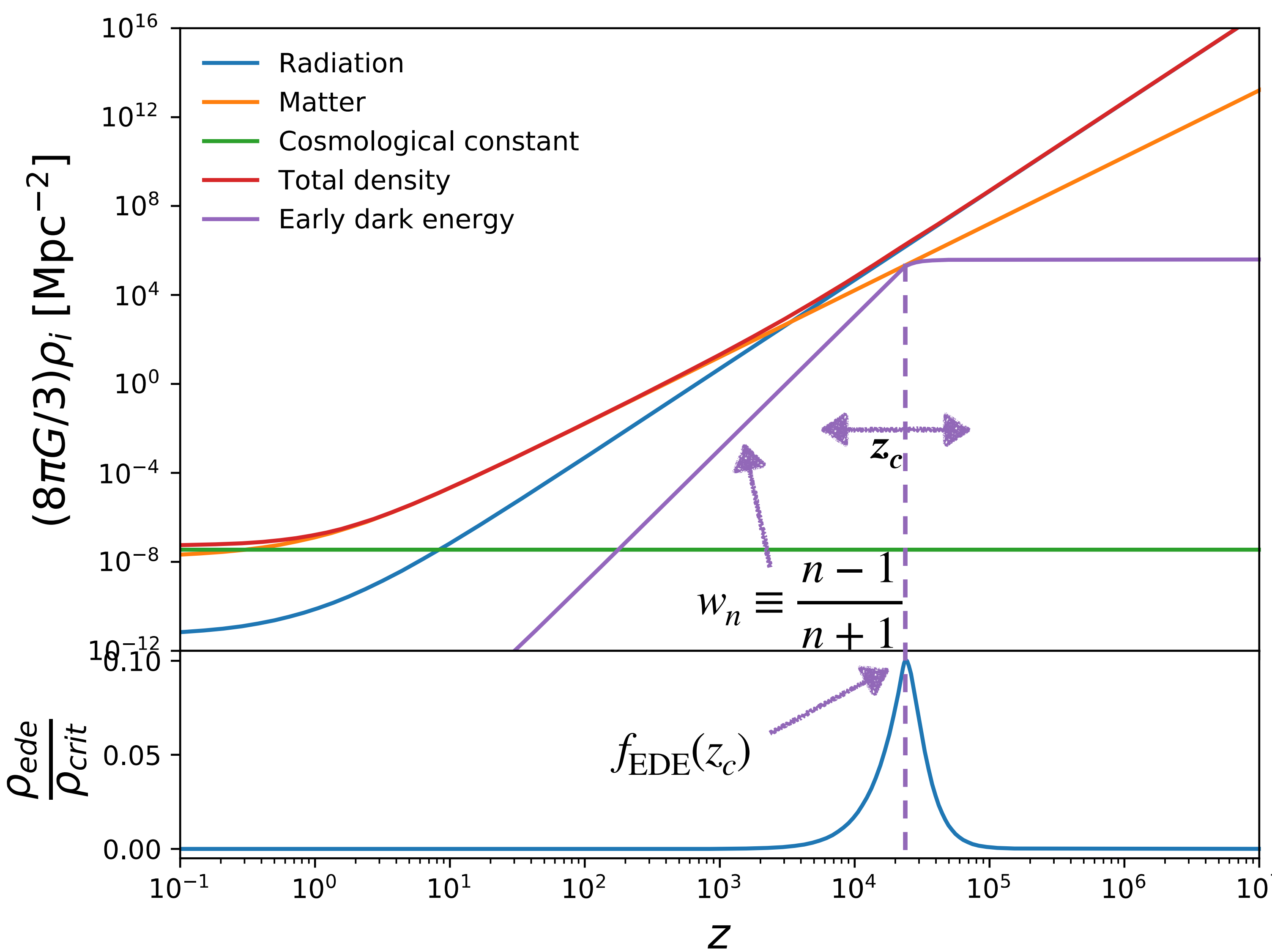

Fig by T. Karwal

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- First-order phase transition (NEDE model)

Niedermann&Sloth 1910.10739, 2006.06686, 2009.00006, 2112.00770; Freese&Winkler 2102.13655

- α-attractors: $V(\phi) = f^2\left[\tanh(\phi/\sqrt{6\alpha}M_{\rm pl})\right]$

Linder 1505.00815, Braglia++ 2005.14053

- Early MG: $(M_{\rm pl}^2 + \xi\phi^2)R + \lambda\phi^4$ leads to a similar phenomenology if $\xi > 0$

Braglia++ 2011.12934

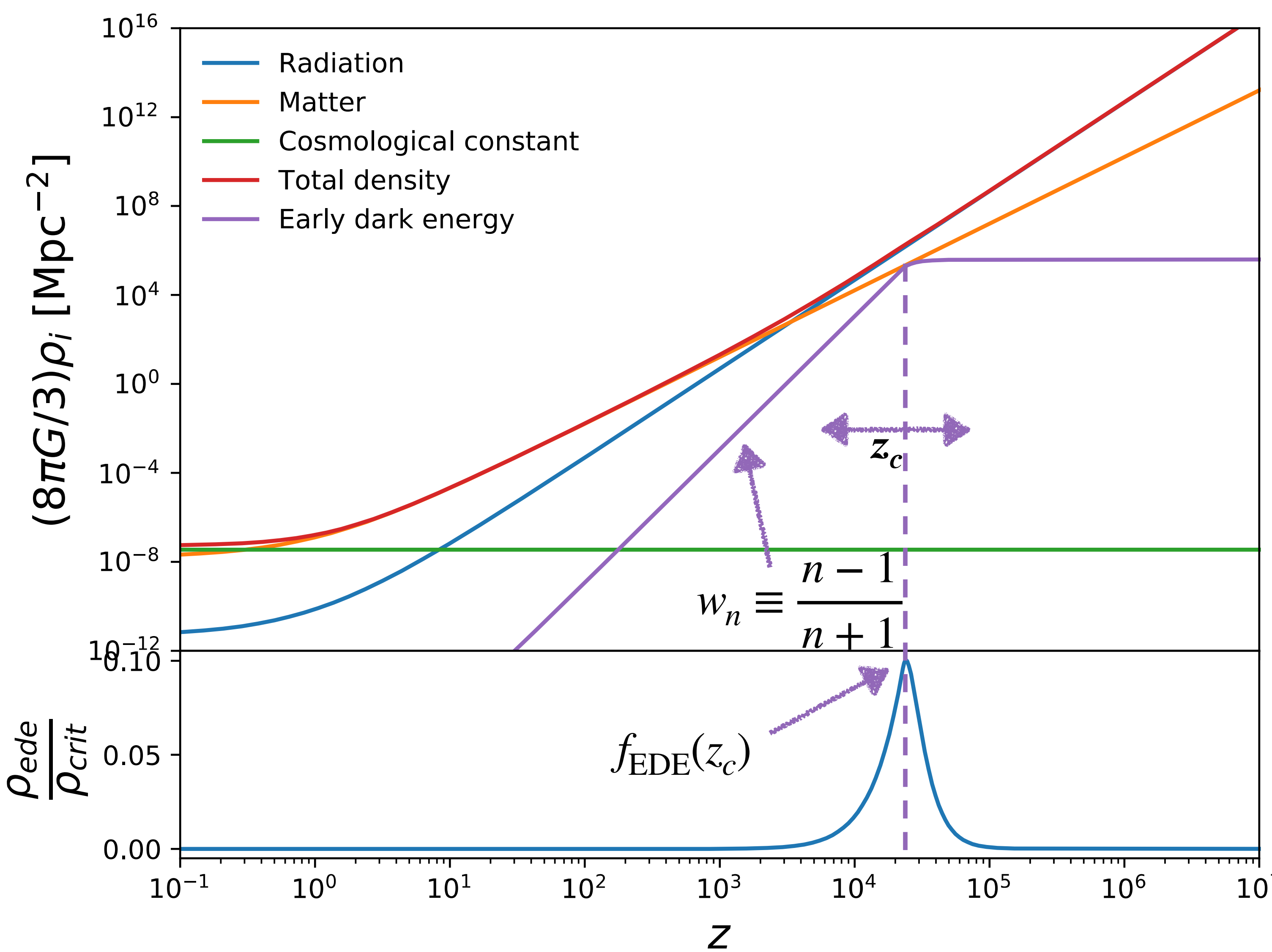
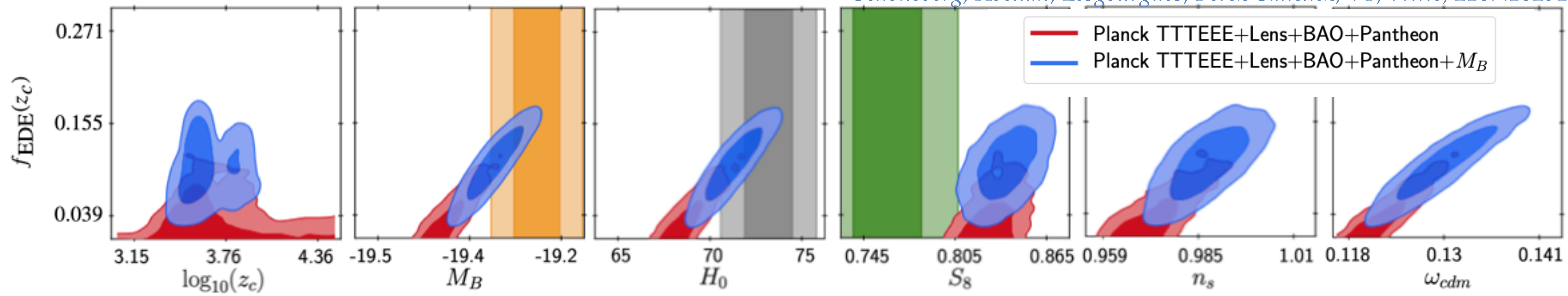


Fig by T. Karwal

Previously: EDE vs *Planck* data

Schöneberg, Abellán, Lesgourgues, Pérez-Sánchez, VP, Witte, 2107.10291



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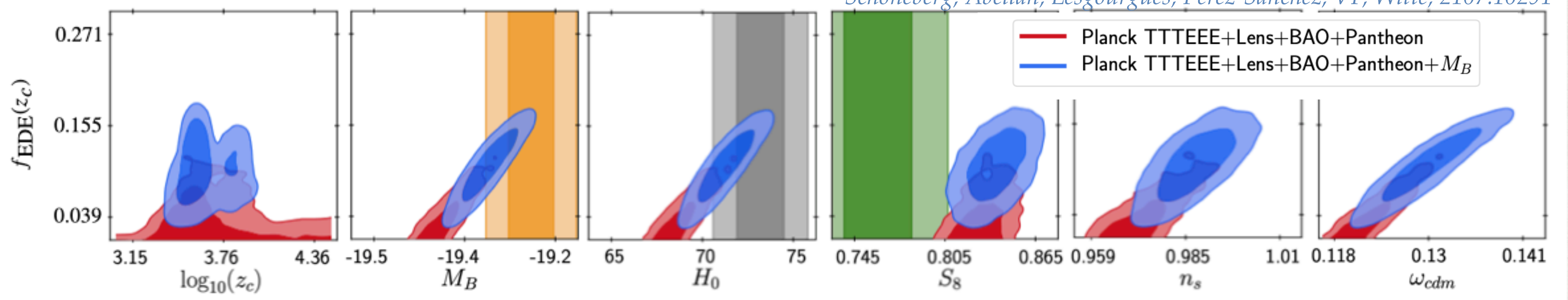

- Planck high-ℓ TT,TE, EE+lowTEB+lensing+BAO+Pantheon: 95% C.L (best-fit).

$$f(z_c) < 0.08\ (0.07), \qquad H_0 < 70.6\ (69.8)\ \mathrm{km/s/Mpc}$$

$$\Delta\chi^2 = \chi^2_{\Lambda\mathrm{CDM}} - \chi^2_{\mathrm{EDE}} \simeq -5.7$$

- Adding the M_b prior from SH0ES

$$f(z_c) = 0.10\ (0.12) \pm 0.03 \qquad z_c = 4073\ (3715)^{+393}_{-838} \qquad H_0 = 71.2\ (72) \pm 1.1\ \mathrm{km/s/Mpc}$$

$$\Delta\chi^2 = \chi^2_{\Lambda\mathrm{CDM}} - \chi^2_{\mathrm{EDE}} \simeq -22$$

$$Q_{\mathrm{DMAP}} \equiv \sqrt{\chi^2(\mathrm{w/\ SH0ES}) - \chi^2(\mathrm{w/o\ SH0ES})} = 1.6\sigma$$

- This corresponds to $m \sim 10^{-27} - 10^{-28}$ eV and $f \sim \mathrm{M_{pl}}$. Note: $n_s \sim 1$ at 2σ!

Takahashi1 & Yin 2112.06710

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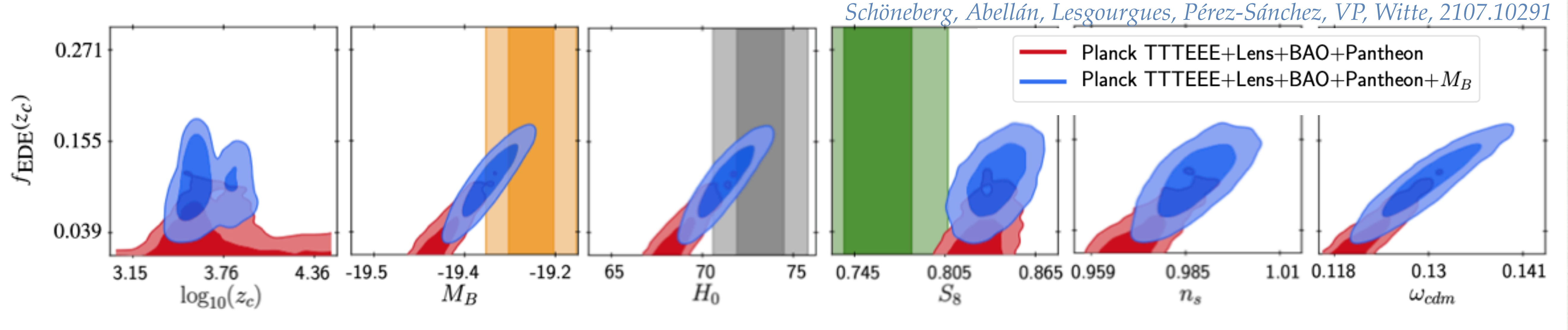

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- Fix $z_c \simeq z_{\text{eq}}$, $\theta_i \simeq \pi$: Planck favors 1param EDE at $\sim 2\sigma$: $f_{\text{EDE}} \simeq 0.08 \pm 0.04$ with $H_0 = 70.1 \pm 1.5$ km/s/Mpc! *Murgia, Abellán, VP 2009.10733*

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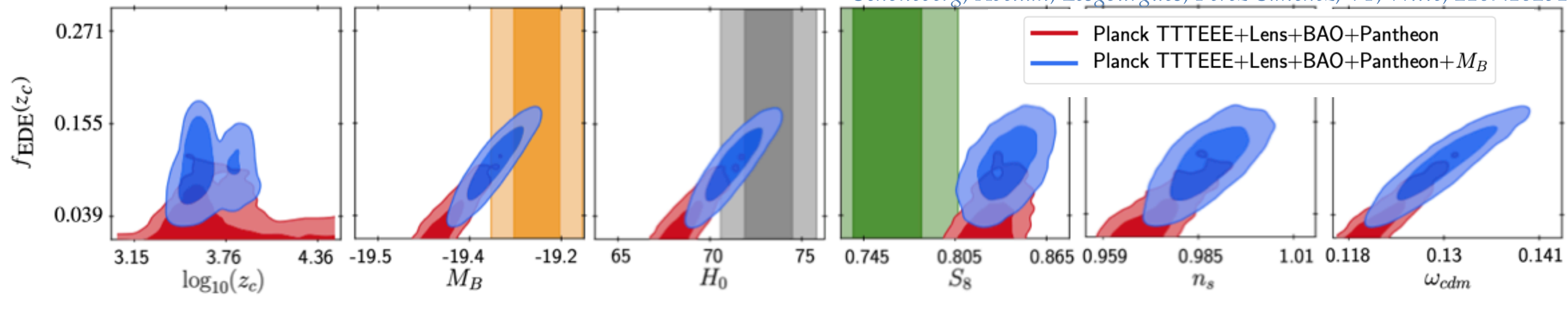

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Murgia, Abellán, VP 2009.10733

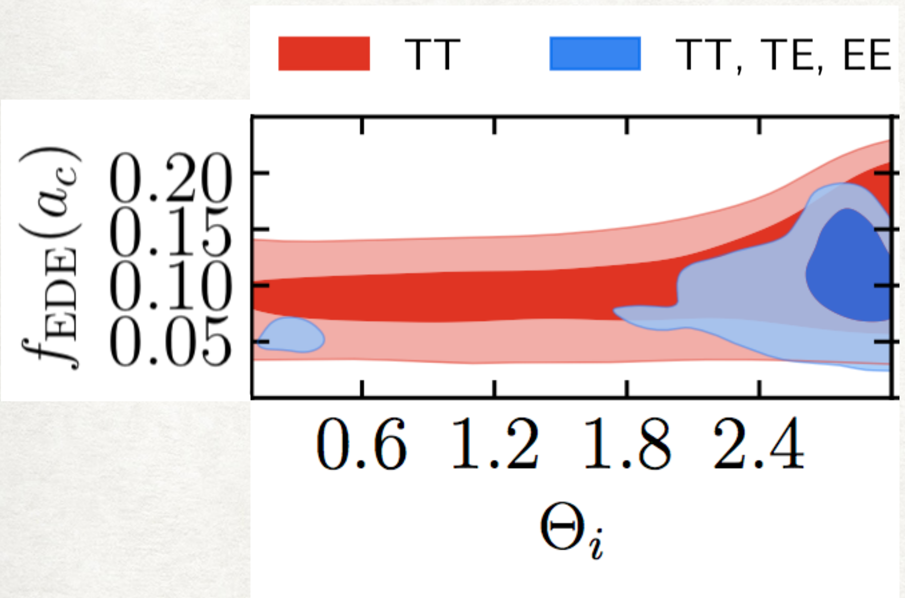
- Theoretical problem: the field becomes dynamical around z_{eq}: Fine-tuning ? Coincidence problem 2.0?

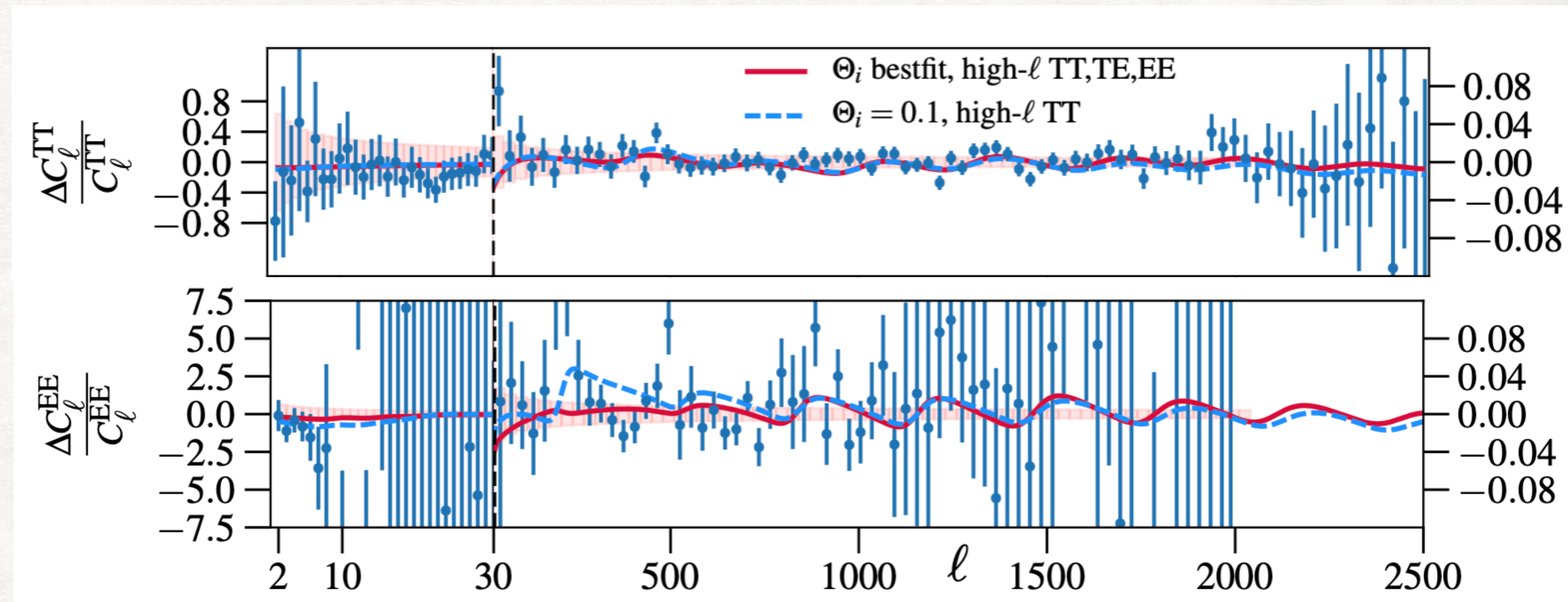
e.g. Griest astro-ph/0202052, Kamionkowski++1409.0549, Sakstein&Trodden 1911.11760, Carrillo González++ 2011.09895, Niedermann&Sloth 2112.00759

Preference for large Θ_i / flat potential

- Polarisation data favors large value of Θ_i (controls perturbations c_s^2)

$$c_s^2 = \frac{2a^2(n-1)\varpi^2(a) + k^2}{2a^2(n+1)\varpi^2(a) + k^2}$$





- $\varpi(\Theta_i)$ controls the frequency of oscillations.

see also Agrawal++ 1904.01016; Lin, Raveri, Hu 1905.12618

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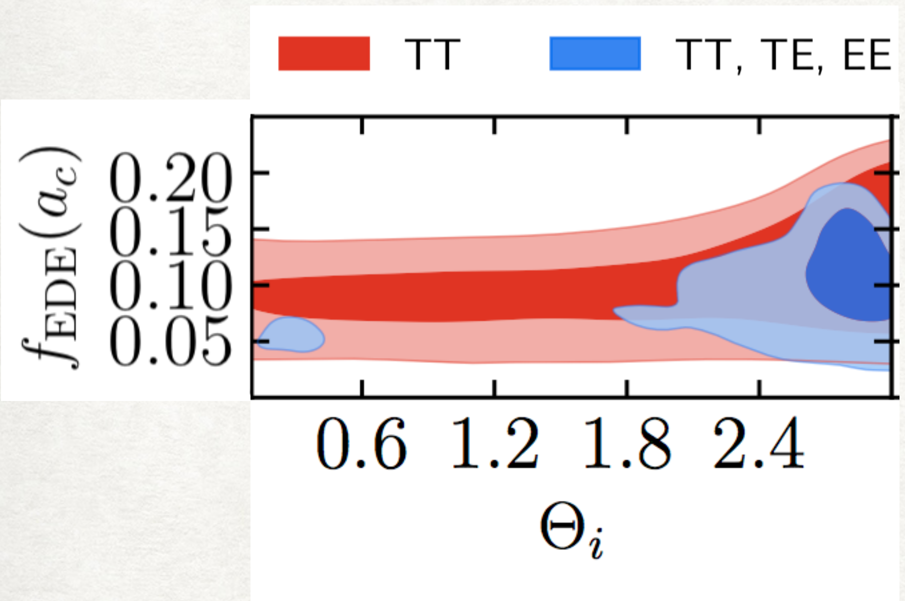

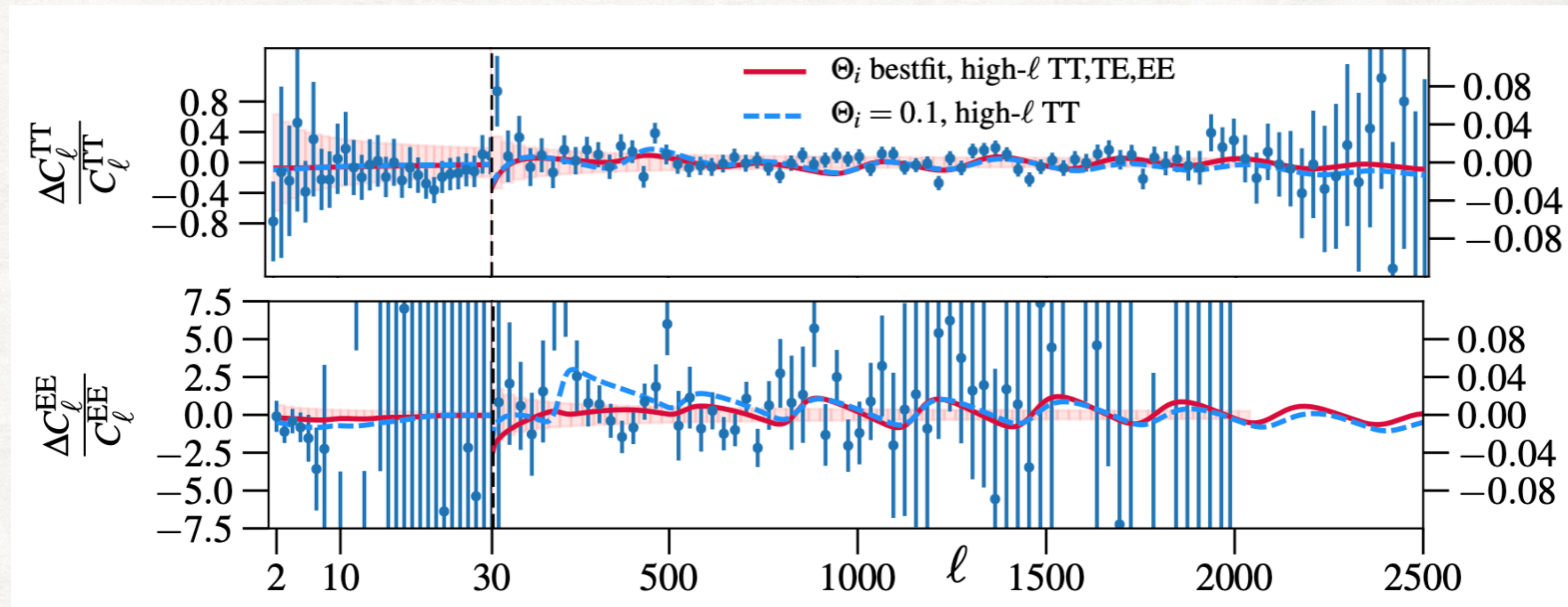

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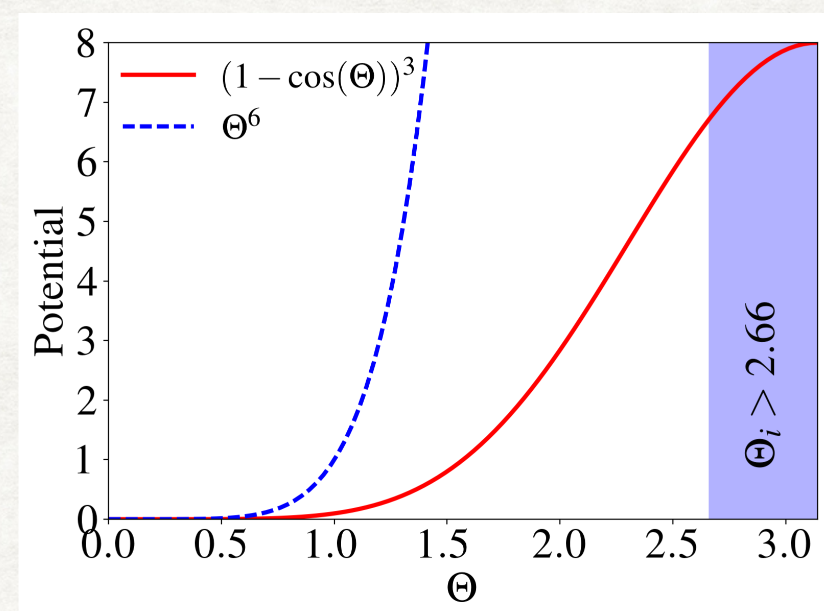
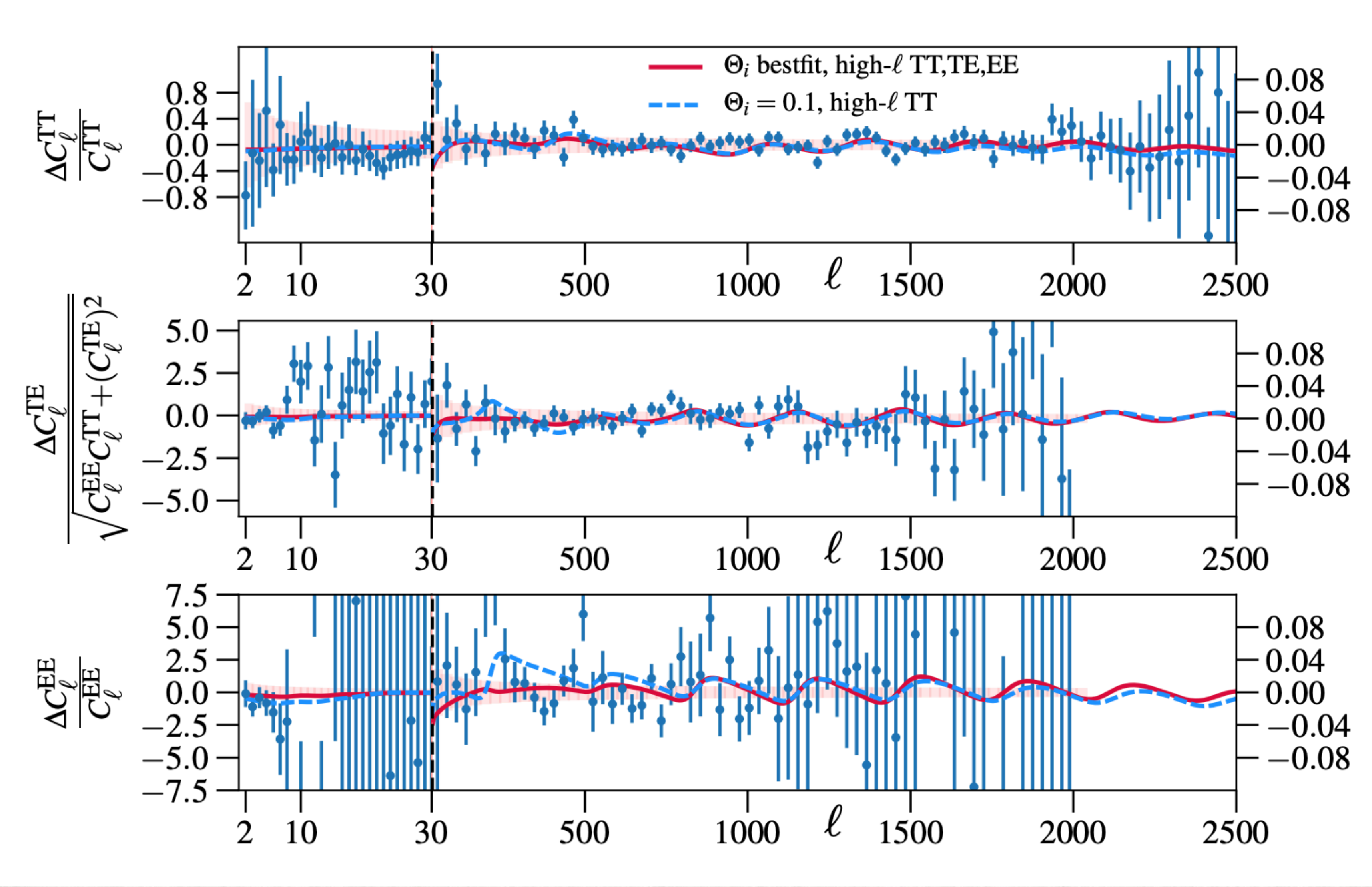


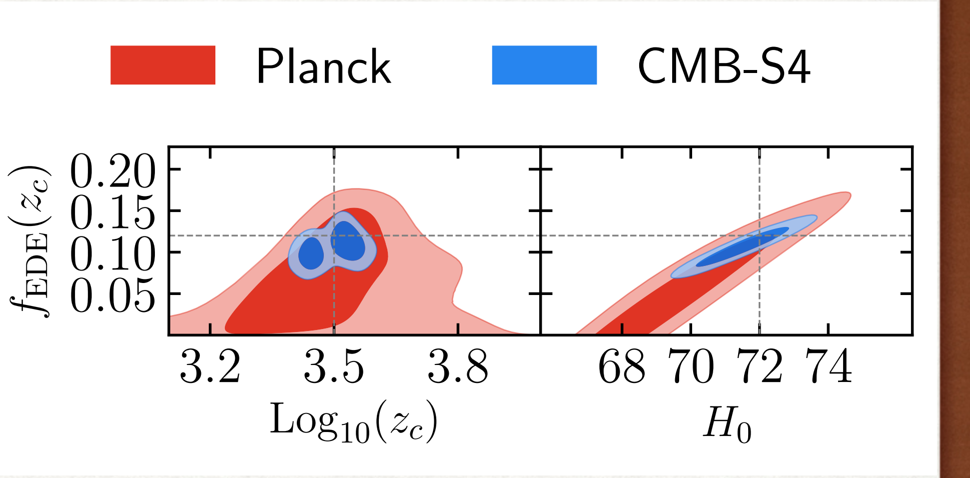
- $c_s^2 < 0.9 \Rightarrow \Theta_i/\pi > 0.85$ (68% CL) from polarization.

- Simple 'Power-law potential' do not work.

see also Agrawal++ 1904.01016; Lin, Raveri, Hu 1905.12618

EDE leaves an imprint in CMB power spectra



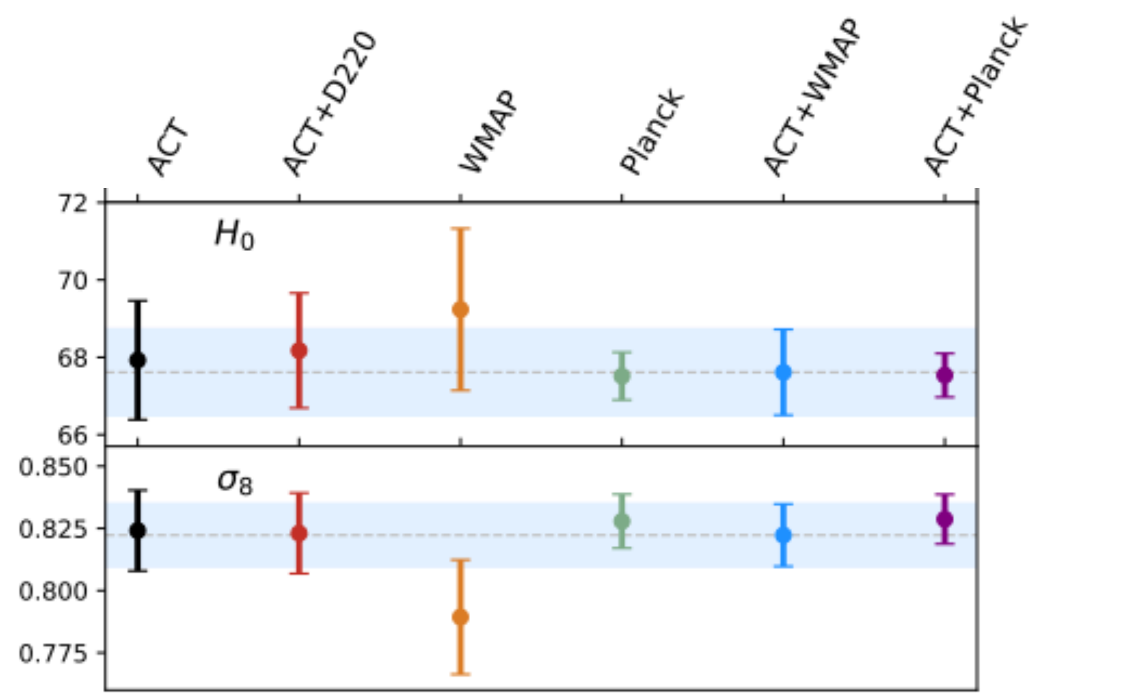


Smith, VP, Amin 1908.06995

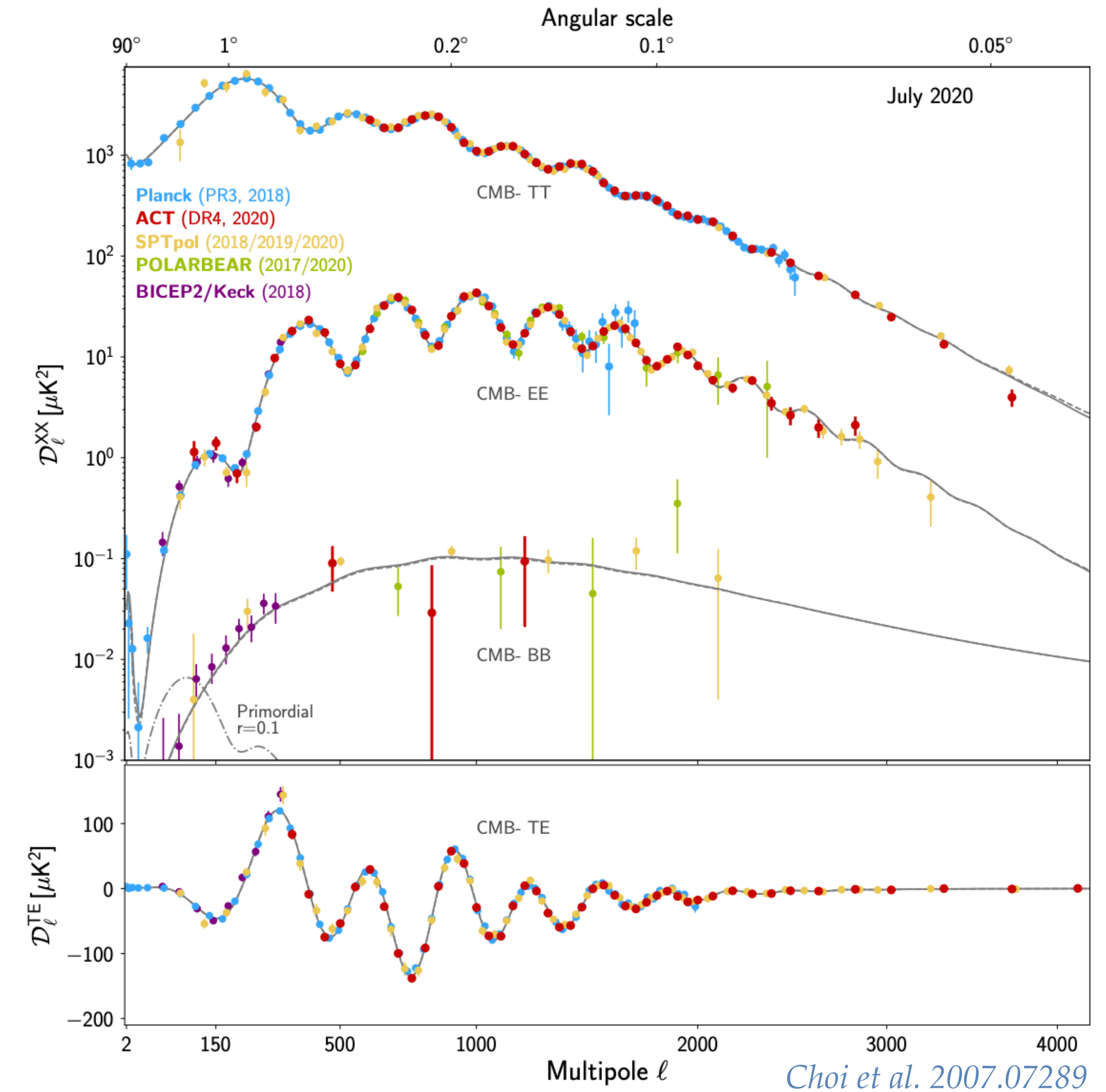
- Planck alone *cannot* detect $f_{\rm EDE}(z_{\rm eq}) \sim 10\,\%$ and $H_0 = 72$ km/s/Mpc.
- An experiment like CMB-S4 would certainly detect $f_{\rm EDE}(z_{\rm eq}) \sim 10\,\%$.
- What about ACT? SPT?

The Atacama Cosmology Telescope

The Atacama Cosmology Telescope (act.princeton.edu)



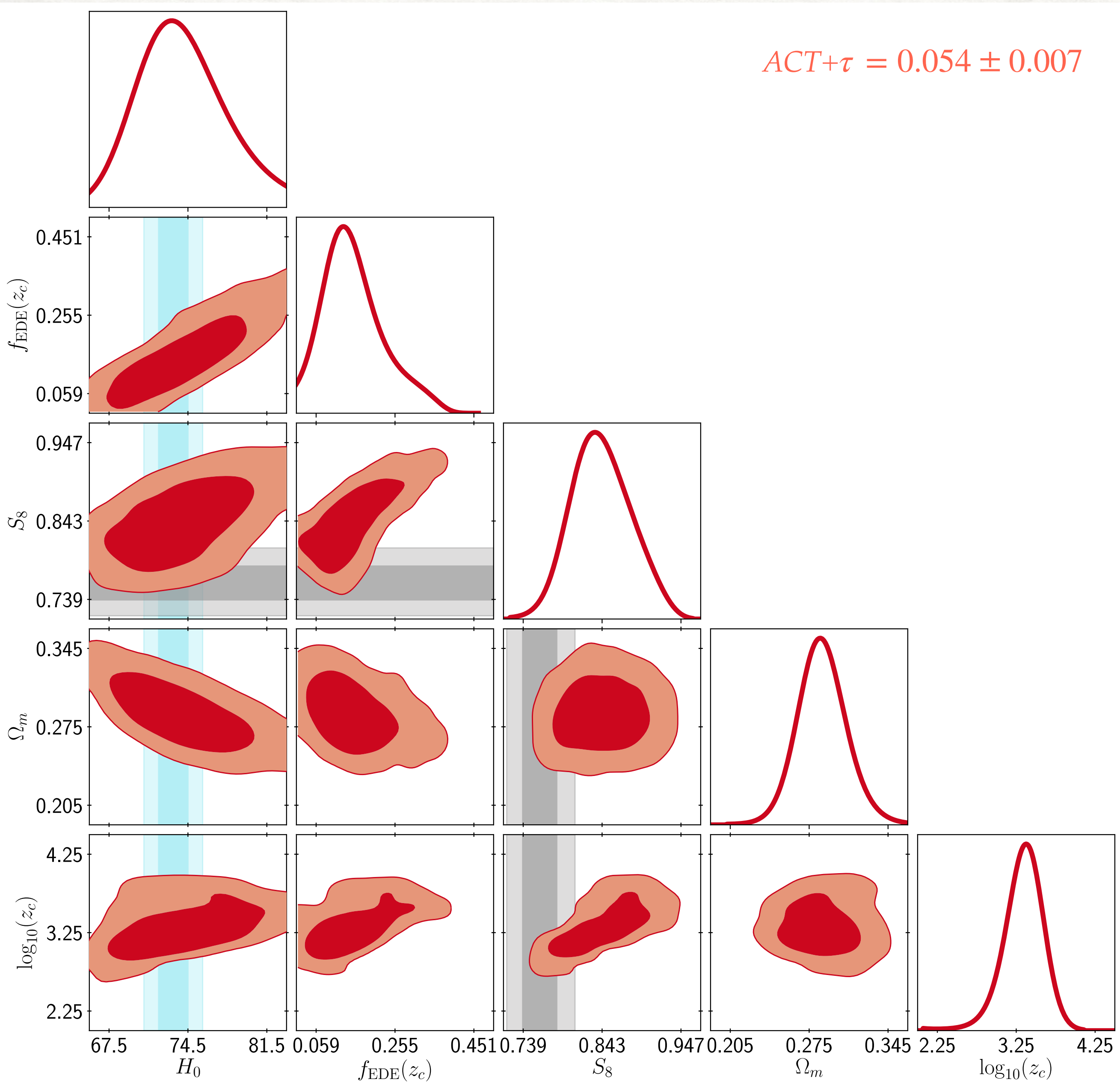
Aiola et al. 2007.07288



Choi et al. 2007.07289

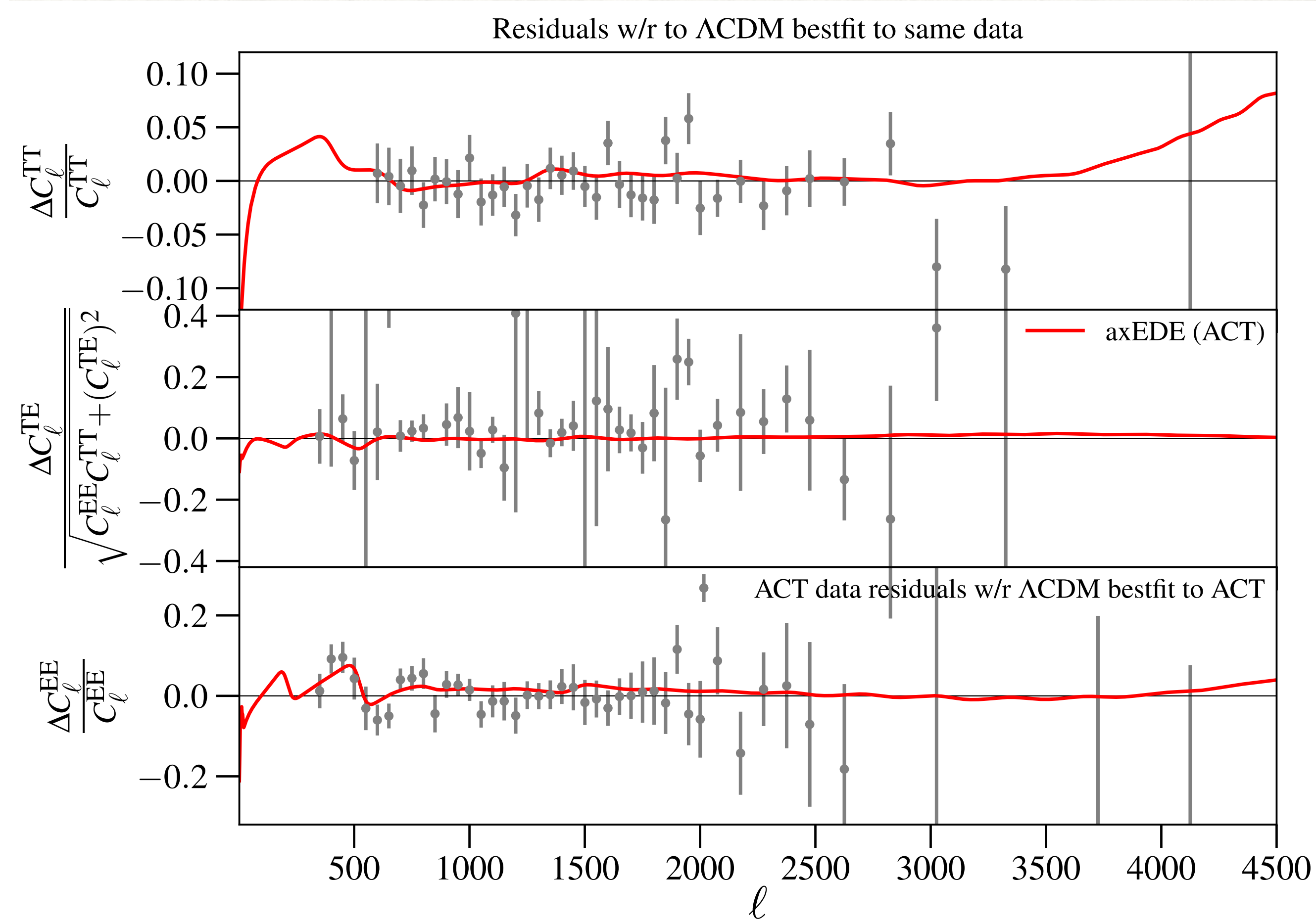
EDE vs ACT

- ACT measures TT from $\ell \sim 500-4000$ and TE/EE in $\ell \sim 350-4000$* *VP, Smith & Bartlett 2109.06229 (PRD in press)*



	ΛCDM	axEDE
ACTPol	280.19	270.774
τ prior	0.01	0.13
total χ^2	280.20	270.90

+3params



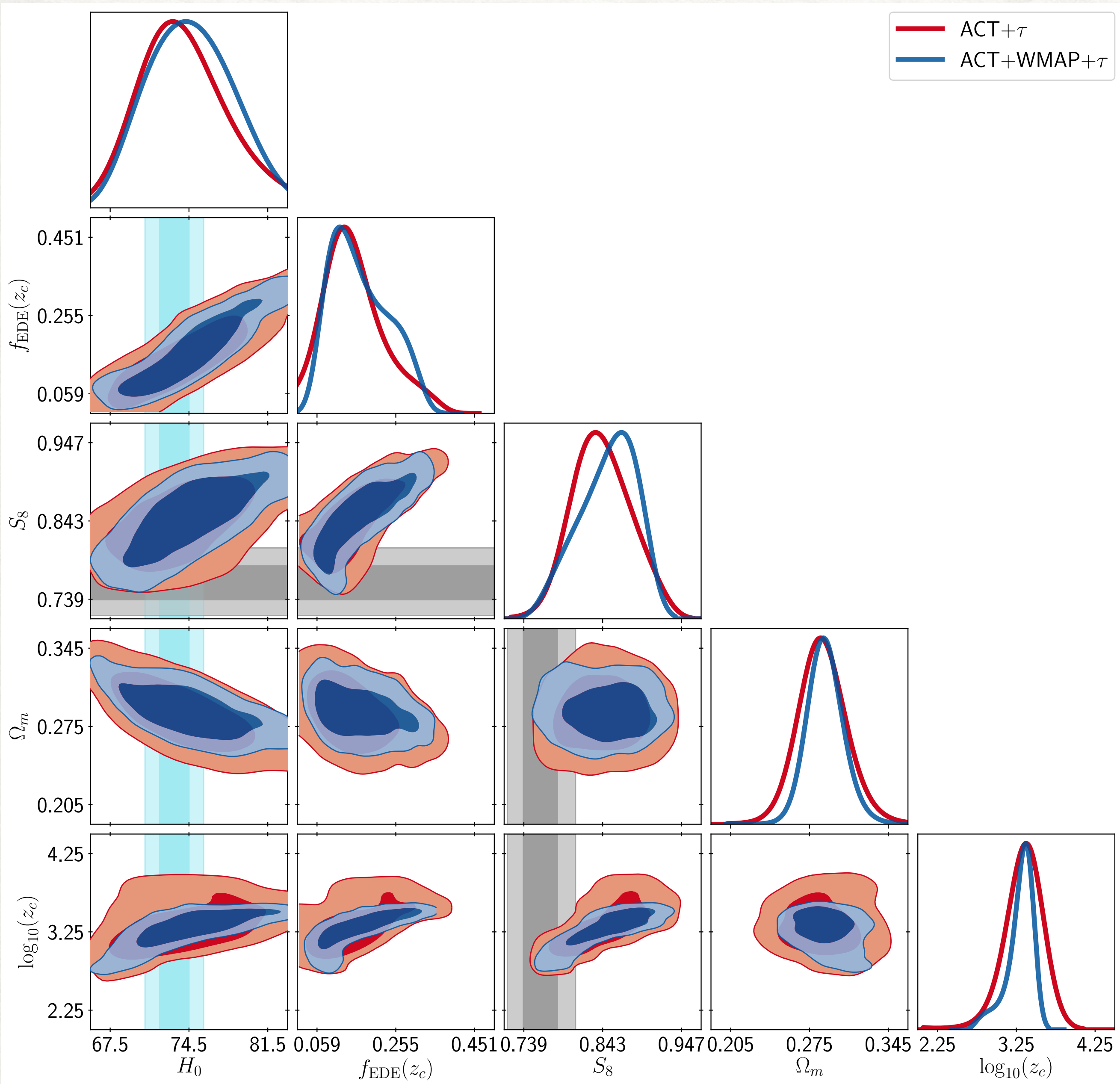
- $f_{\rm EDE}(z_c) = 0.152^{+0.054}_{-0.091}$ $z_c = 2032^{+1263}_{-990}$ $H_0 = 74.2^{+3.6}_{-4.8}$ km/s/Mpc

*ΛCDM fit to ACT data yields $H_0 = 67.8 \pm 1.6$ km/s/Mpc *See also Hill et al. 2109.04451, Moss et al. 2109.14848*

EDE vs ACT+WMAP

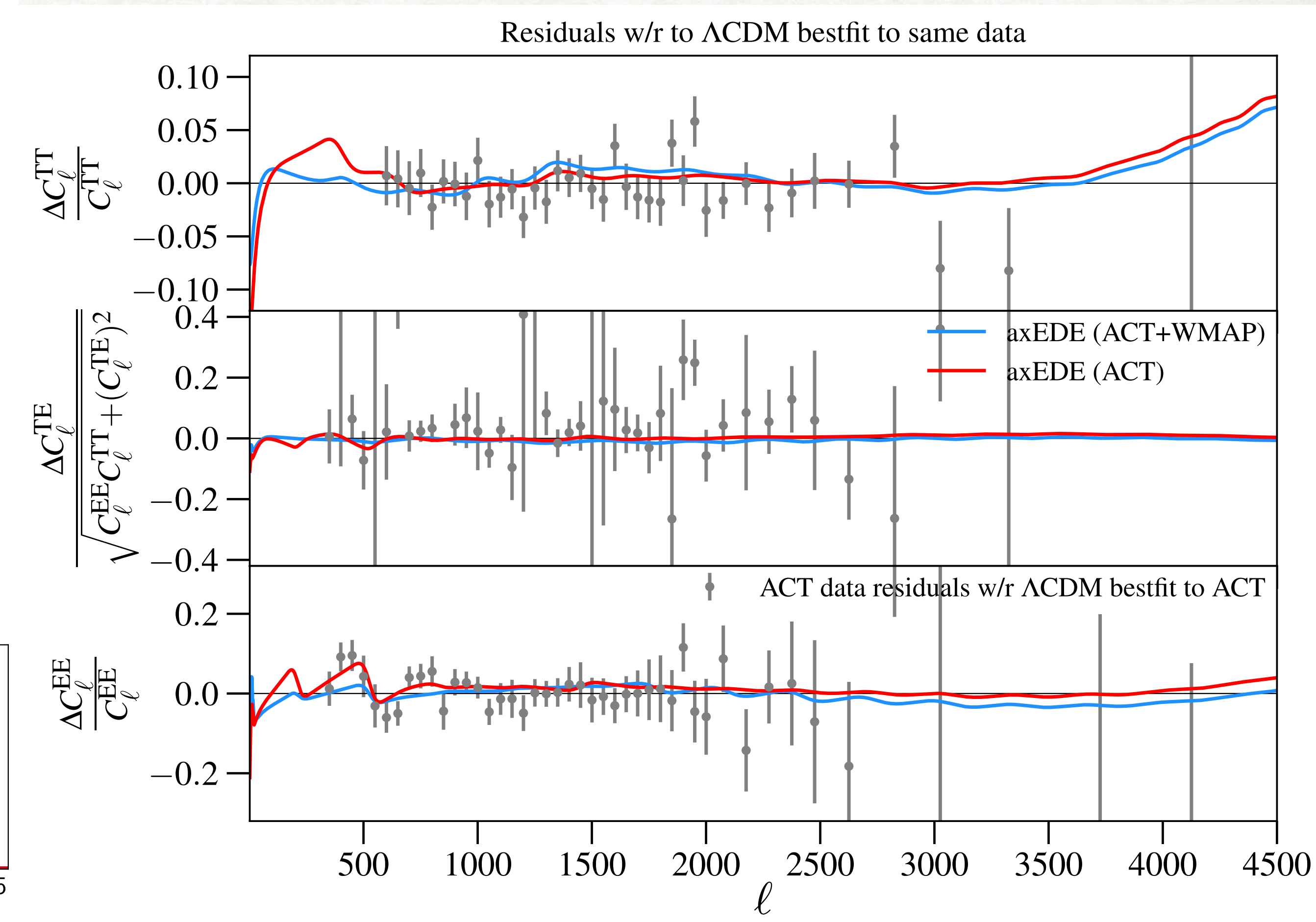
- Add information from WMAP at $\ell \lesssim 650$

VP, Smith & Bartlett 2109.06229 (PRD in press)



	ΛCDM	axEDE
ACTPol	286.59	275.07
WMAP	5627.56	5623.87
τ prior	0.06	0.05
total χ^2	5914.22	5898.99

+3params



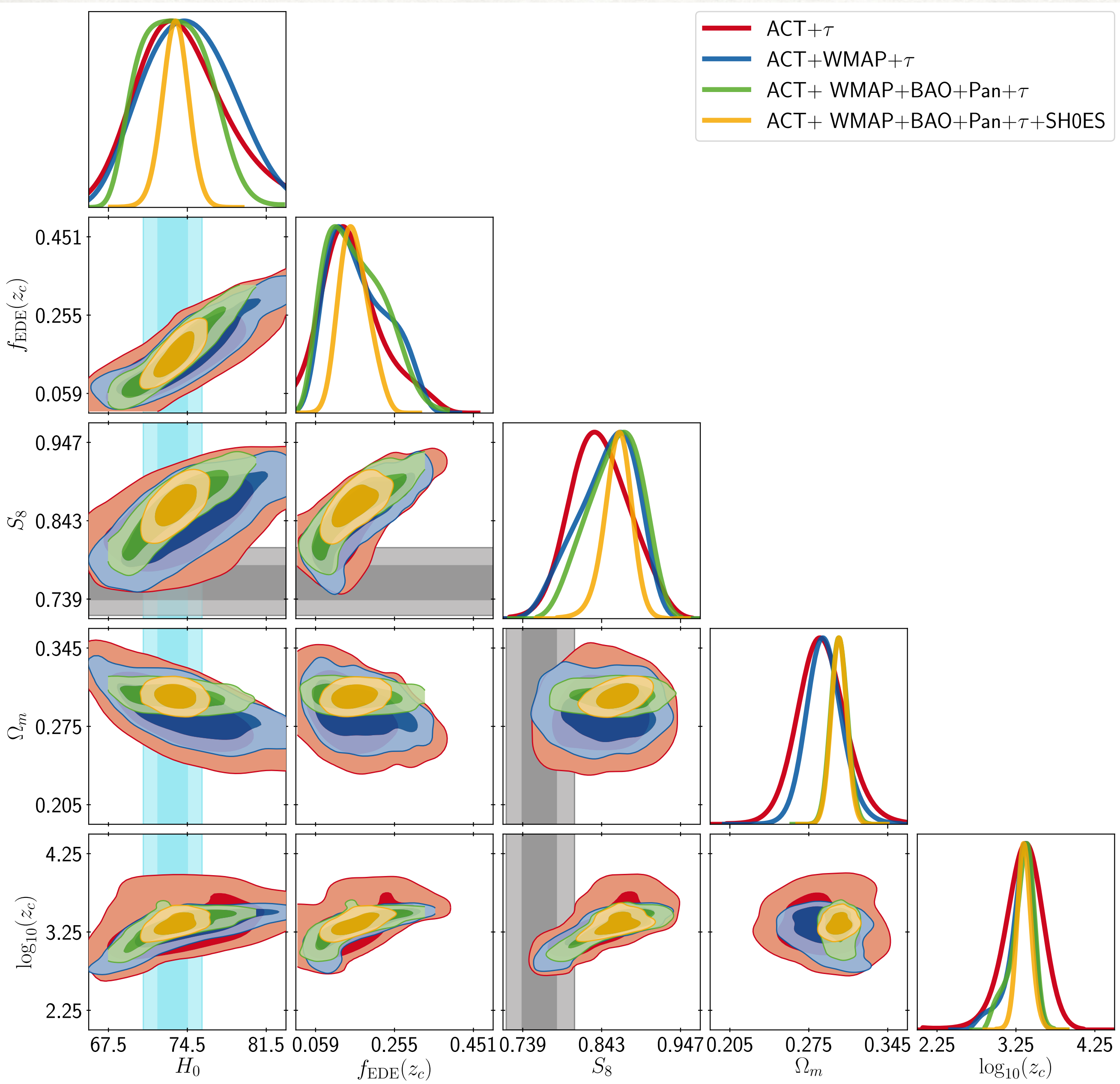
- $f_{\rm EDE}(z_c) = 0.166^{+0.055}_{-0.097}$ $z_c = 1990^{+1390}_{-358}$ $H_0 = 74.65^{+3.6}_{-4.1}$ km/s/Mpc

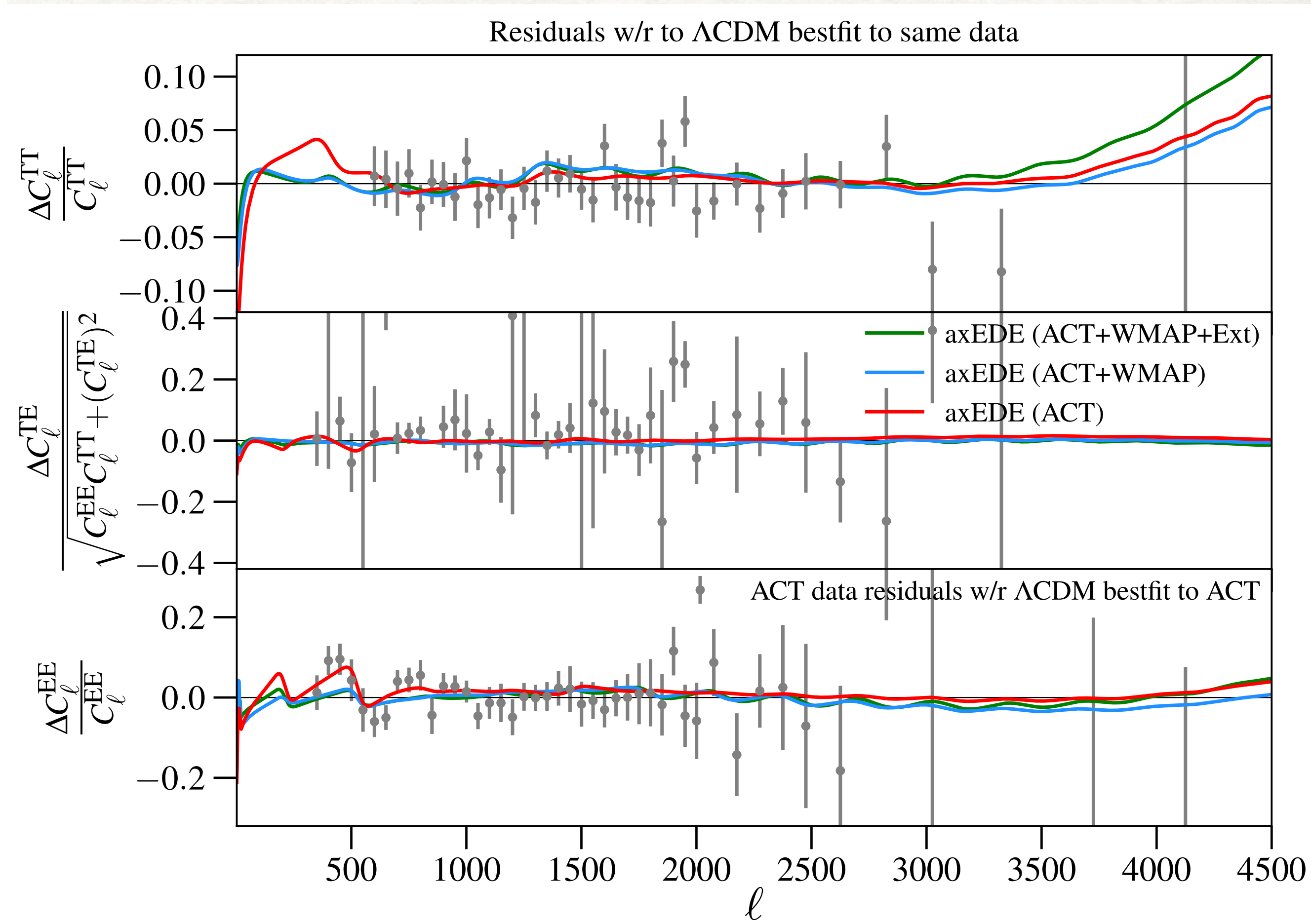
See also Hill et al. 2109.04451, Moss et al. 2109.14848

EDE vs ACT+WMAP+Ext

- Add ‘external’ BAO and Pantheon data: restricts Ω_m

	ΛCDM		axEDE	
ACTPol	287.06	287.93	276.04	276.174
WMAP	5627.16	5626.71	5623.74	5624.20
Pantheon SNIa	1026.86	1026.92	1026.71	1026.68
BAO BOSS low−z	1.38	1.81	1.71	1.94
BAO BOSS DR12	3.85	3.35	3.45	3.36
τ prior	0.001	0.02	0.05	0.001
SH0ES	–	17.29	–	0.14
total χ^2	6946.31	6964.04	6931.70	6932.50
$\Delta\chi^2$	0	0	-14.61	-31.54
$Q_{\rm DMAP}$	4.5σ		0.9σ	



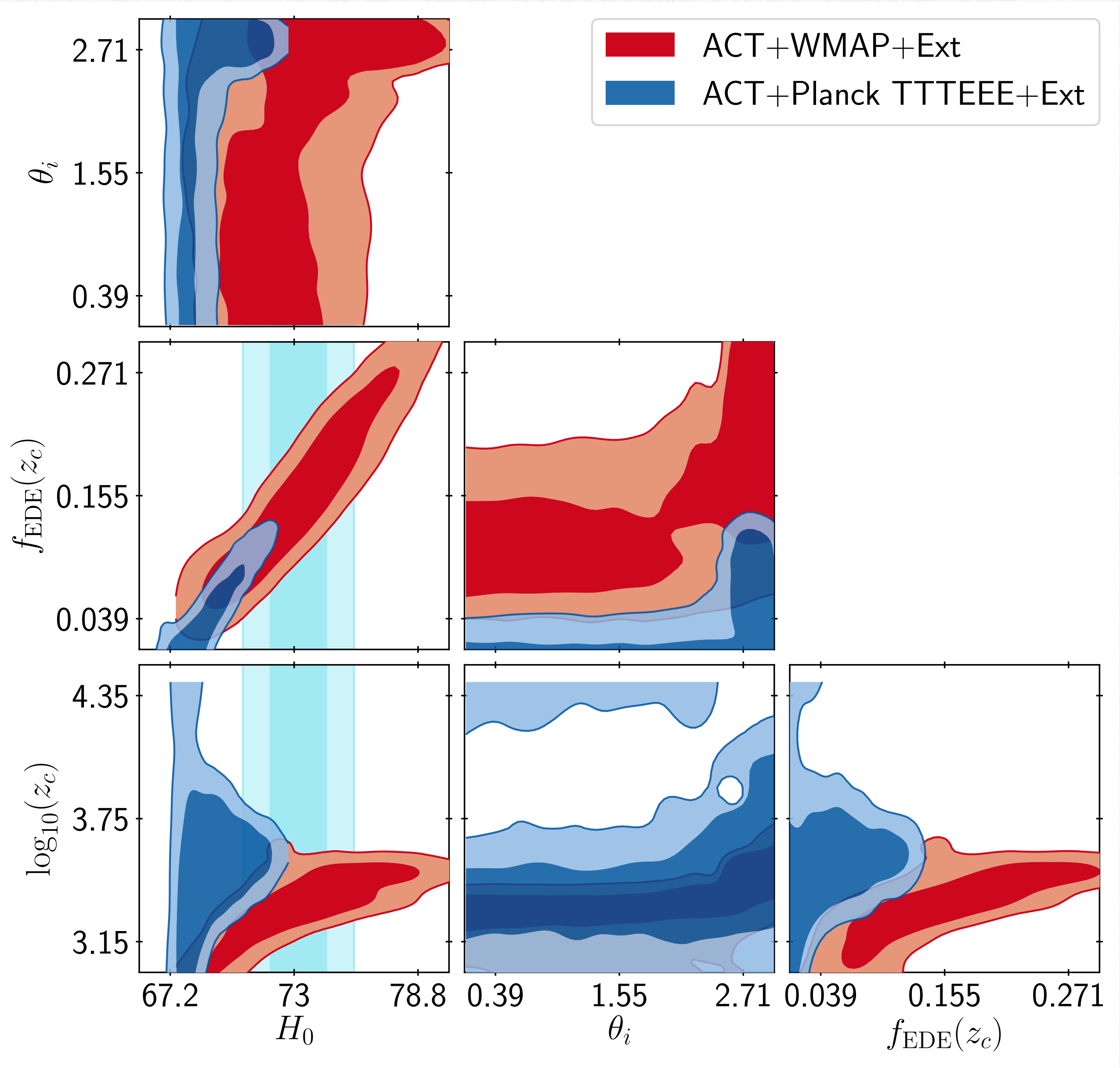


- $f_{\rm EDE}(z_c) = 0.158^{+0.054}_{-0.091}$ $\quad z_c = 2118^{+1239}_{-408}$ $\quad H_0 = 73.4^{+2.6}_{-3.4}$ km/s/Mpc

See also Hill et al. 2109.04451, Moss et al. 2109.14848

ACT+*Planck* vs ACT+WMAP

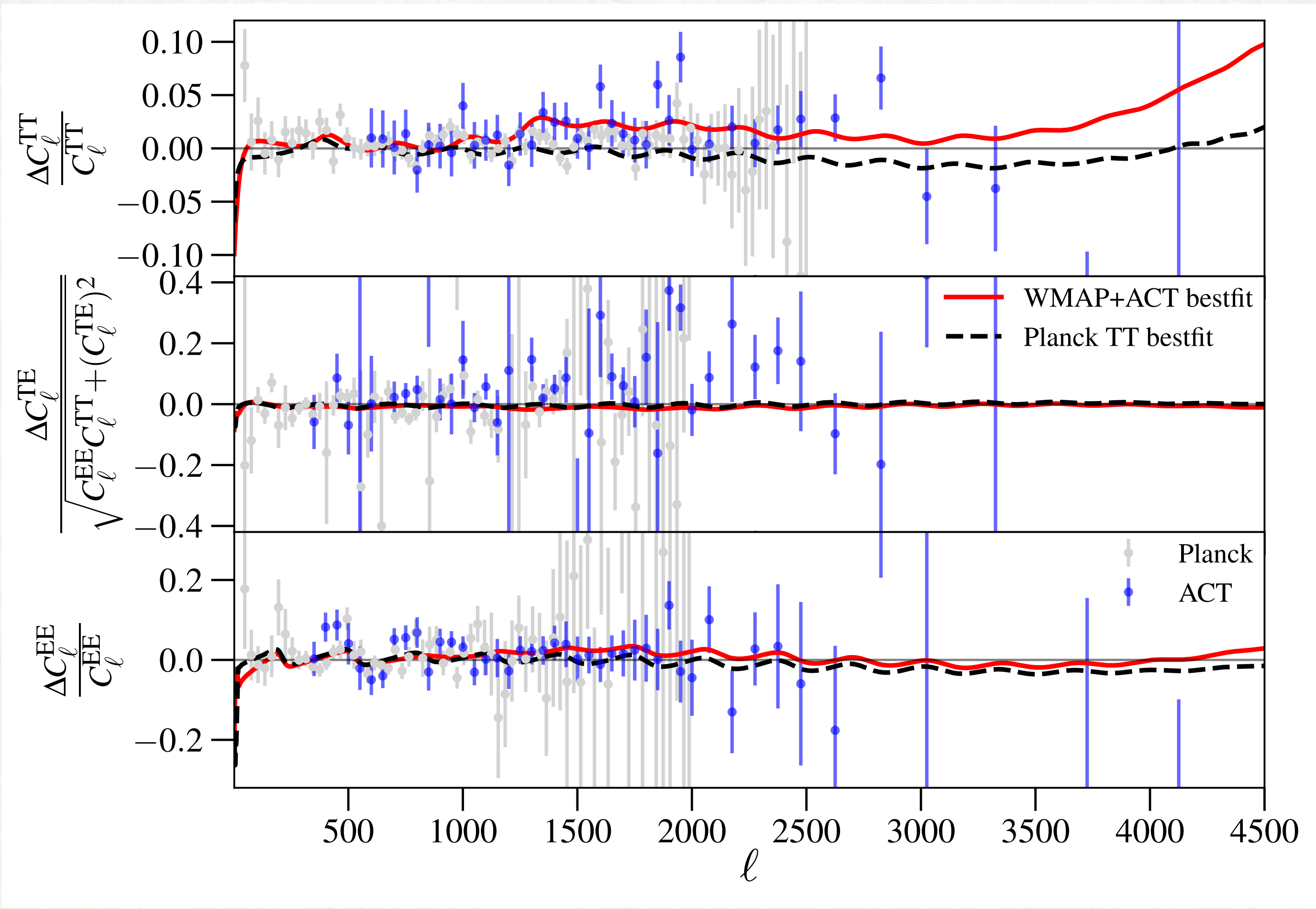
VP, Smith & Bartlett 2109.06229 (PRD in press)

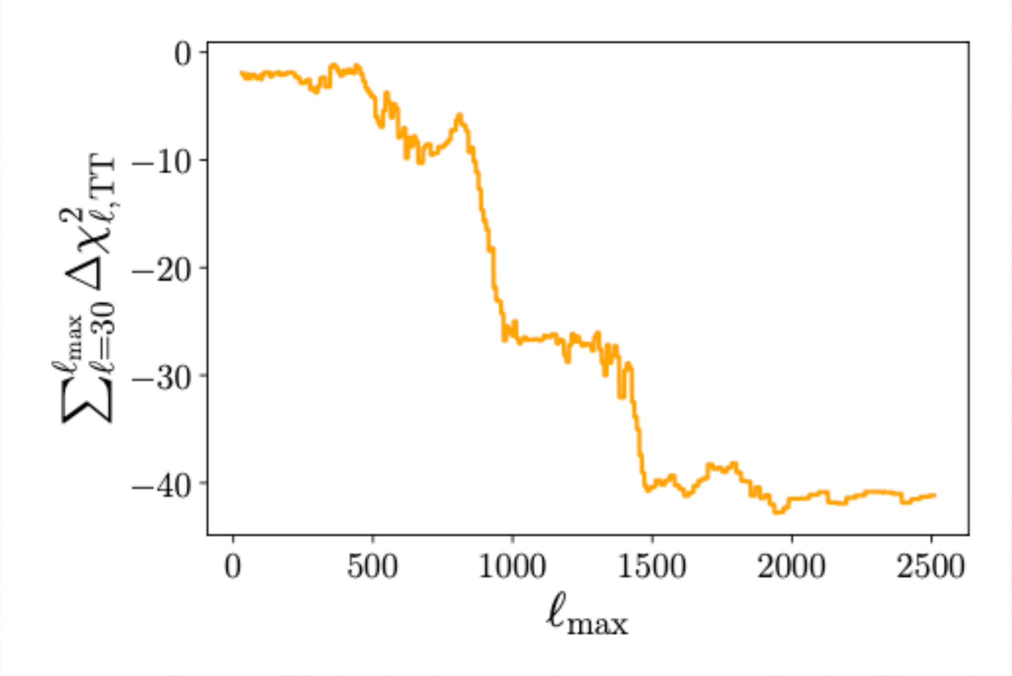


- *Planck*: $f_{\rm EDE}(z_c) < 0.08$ and $H_0 < 70.6$ (95%) $\qquad Q_{\rm DMAP} \equiv \sqrt{\chi^2(\text{w/ SH0ES}) - \chi^2(\text{w/o SH0ES})} = 1.6\sigma$
- *Planck*+ACT: $f_{\rm EDE}(z_c) < 0.11$ and $H_0 < 71.6$ (95%) $\qquad Q_{\rm DMAP} \equiv \sqrt{\chi^2(\text{w/ SH0ES}) - \chi^2(\text{w/o SH0ES})} = 0.3\sigma$

A mismatch between *Planck* and ACT TT data?

VP, Smith & Bartlett 2109.06229 (PRD in press)





Cumulative $\Delta\chi^2$ of Planck TT data between EDE best-fit to ACT and EDE best-fit to Planck TT

- Differences around $\ell \sim 1000$ and $\ell \sim 1500$ between *Planck* and ACT disfavor the EDE best-fit to ACT data.

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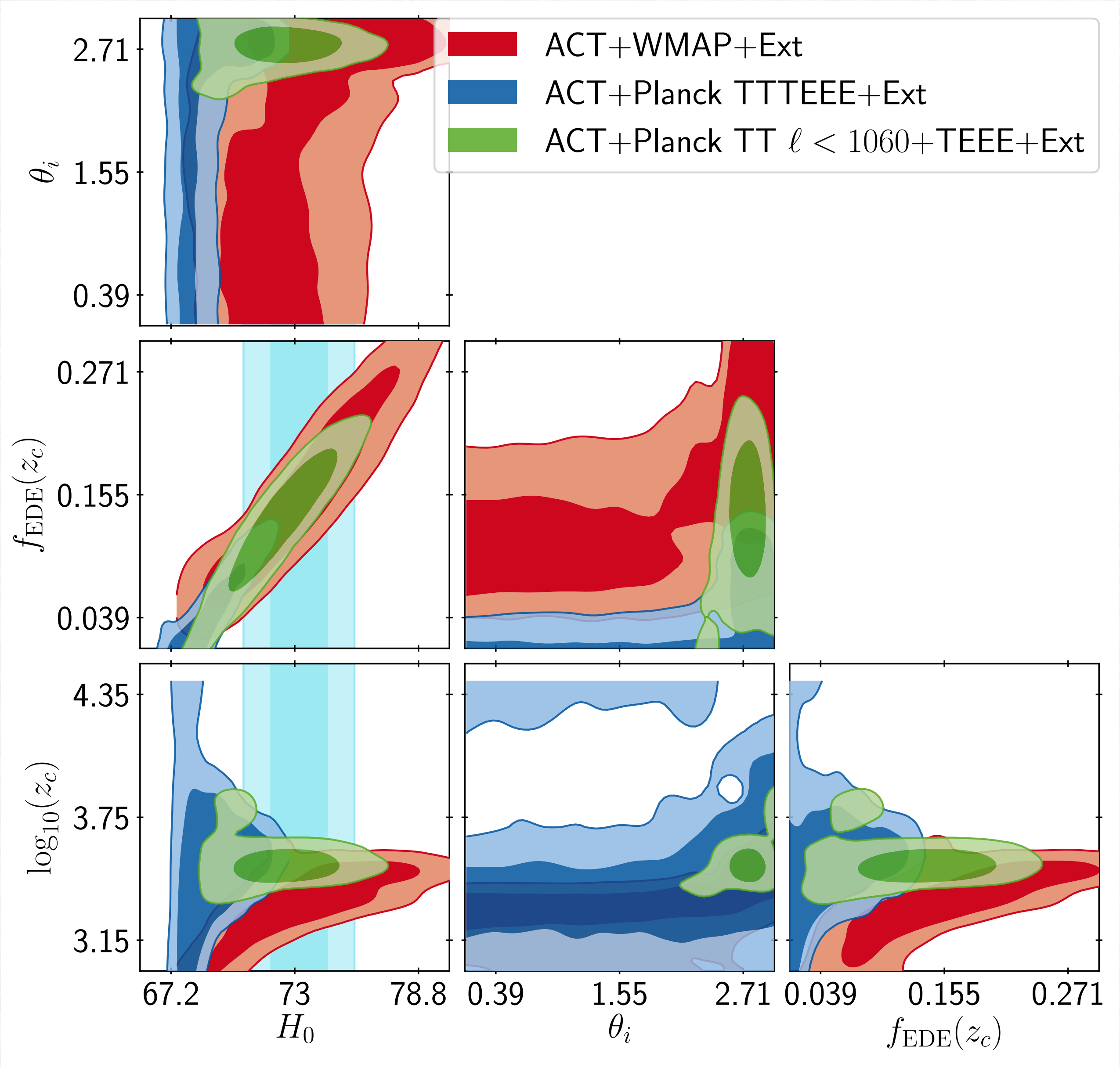
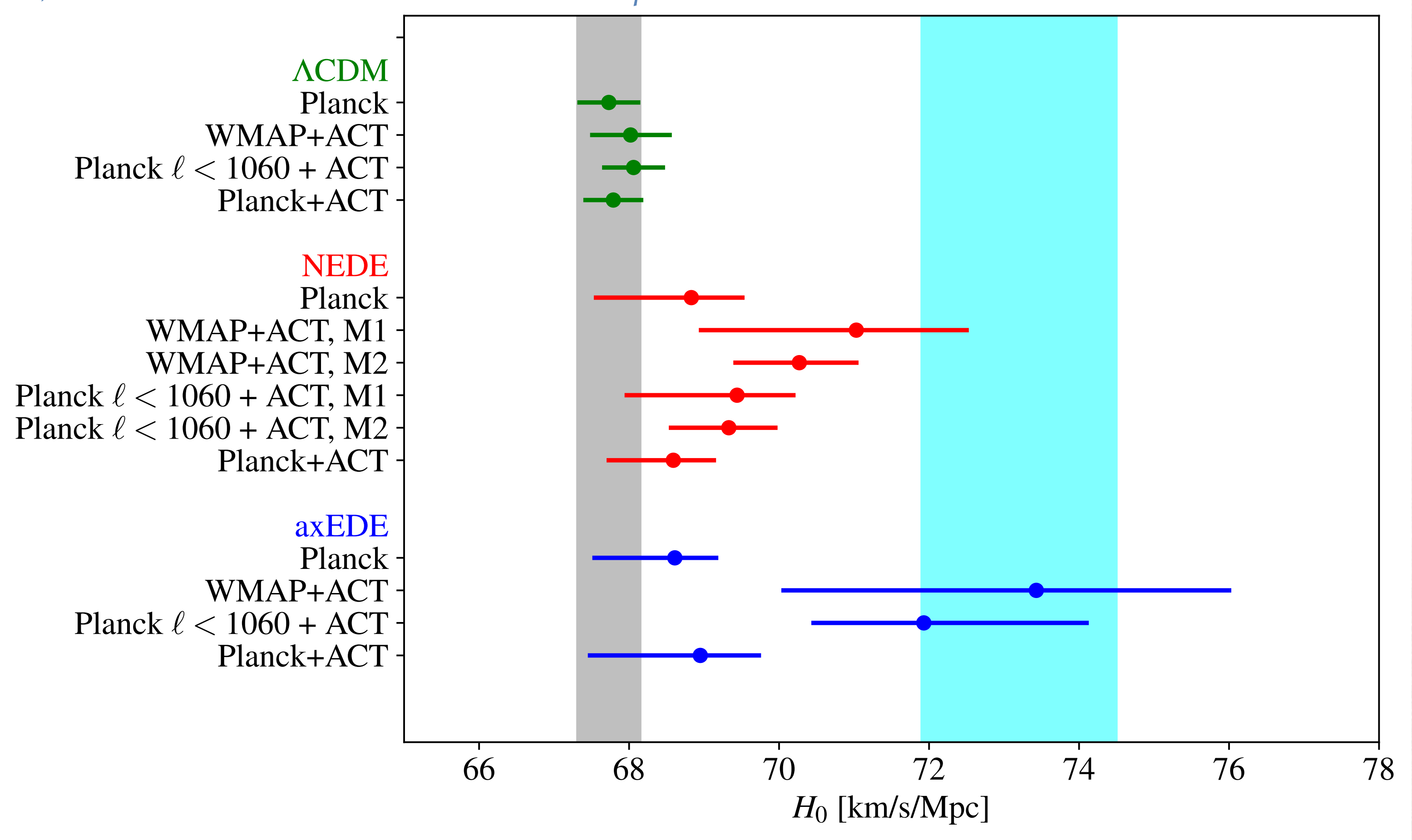


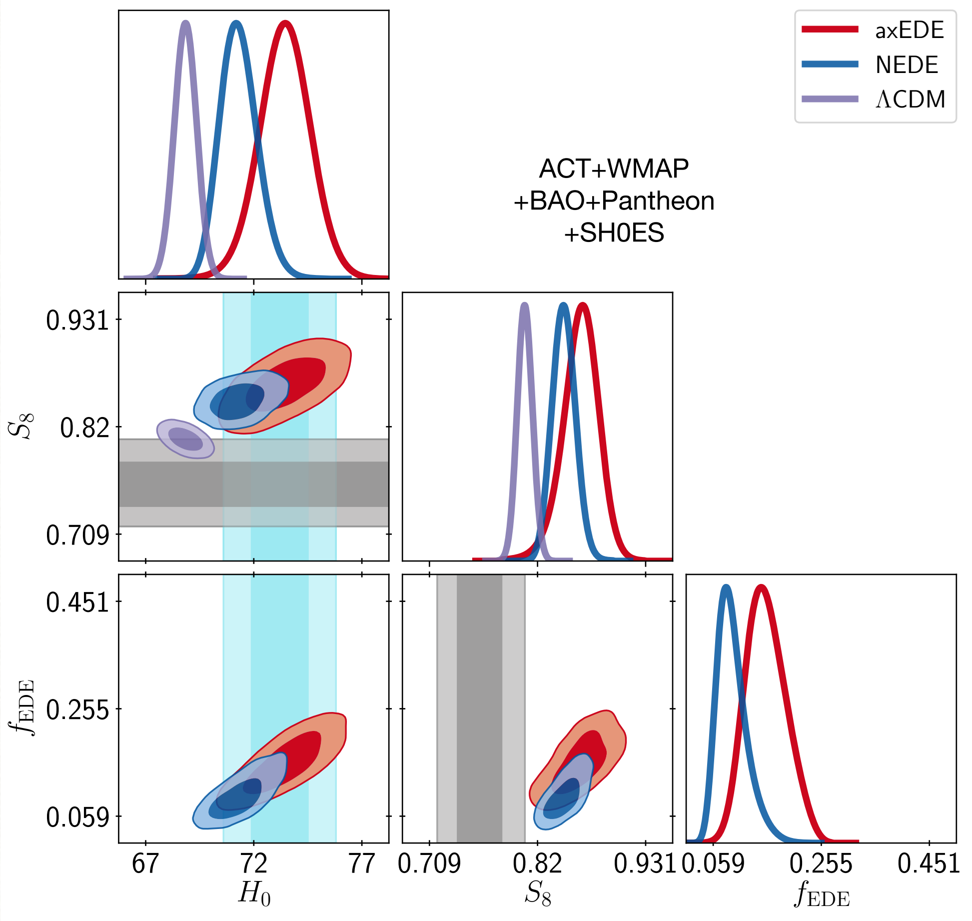
- Removing *Planck* TT $\ell > 1060$: $f_{\rm EDE}(z_c) = 0.131^{+0.051}_{-0.039}$ $z_c = 3350^{+298}_{-472}$ $H_0 = 72.35^{+1.8}_{-1.6}$ km/s/Mpc

Conclusions

VP, Smith & Bartlett 2109.06229 (PRD in press)

See also Hill et al. 2109.04451, Moss et al. 2109.14848





- ACT (with and without WMAP) favors EDE at $2-3\sigma$: there is no residual H_0-tension, but a 3.2σ S_8-tension.

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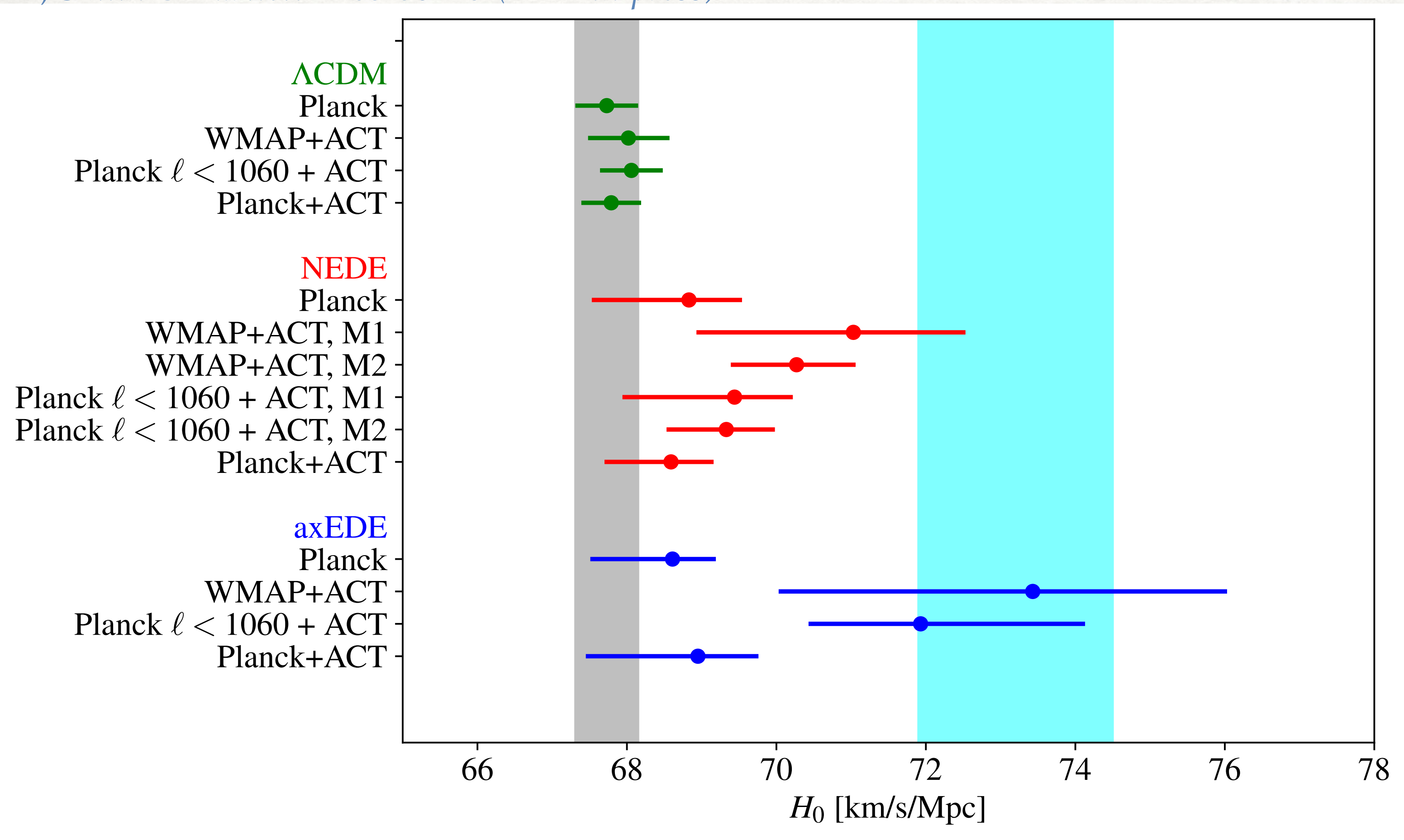

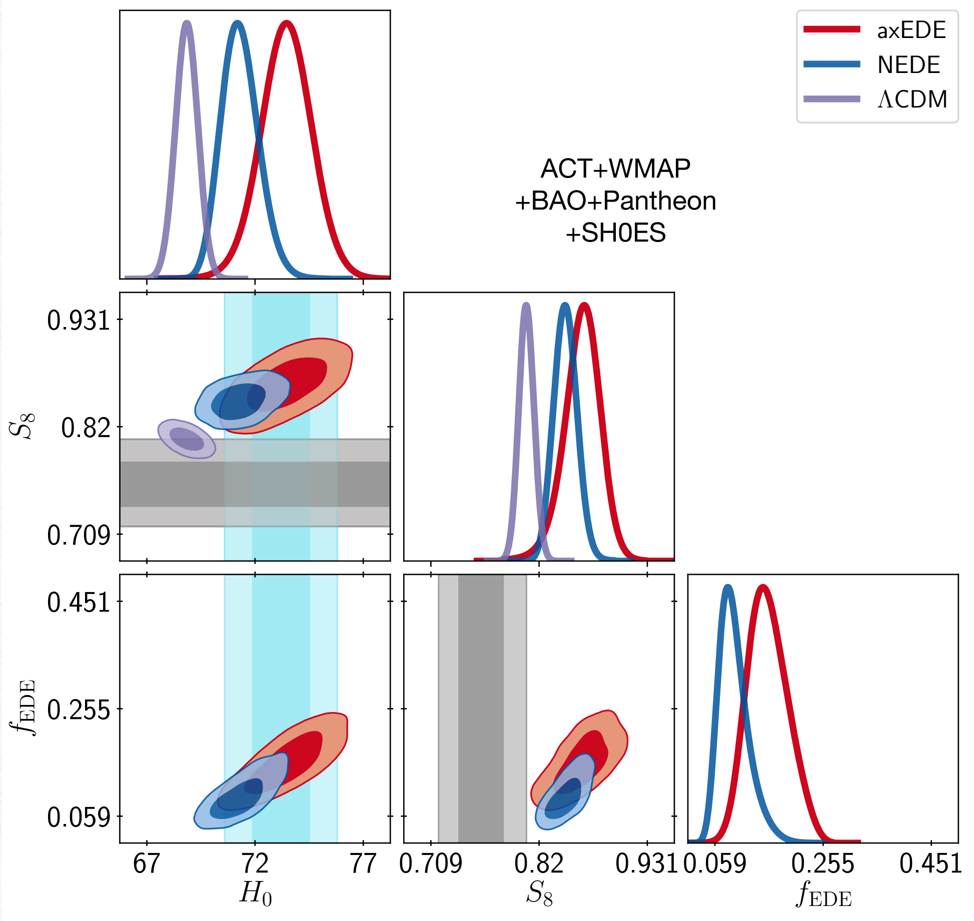

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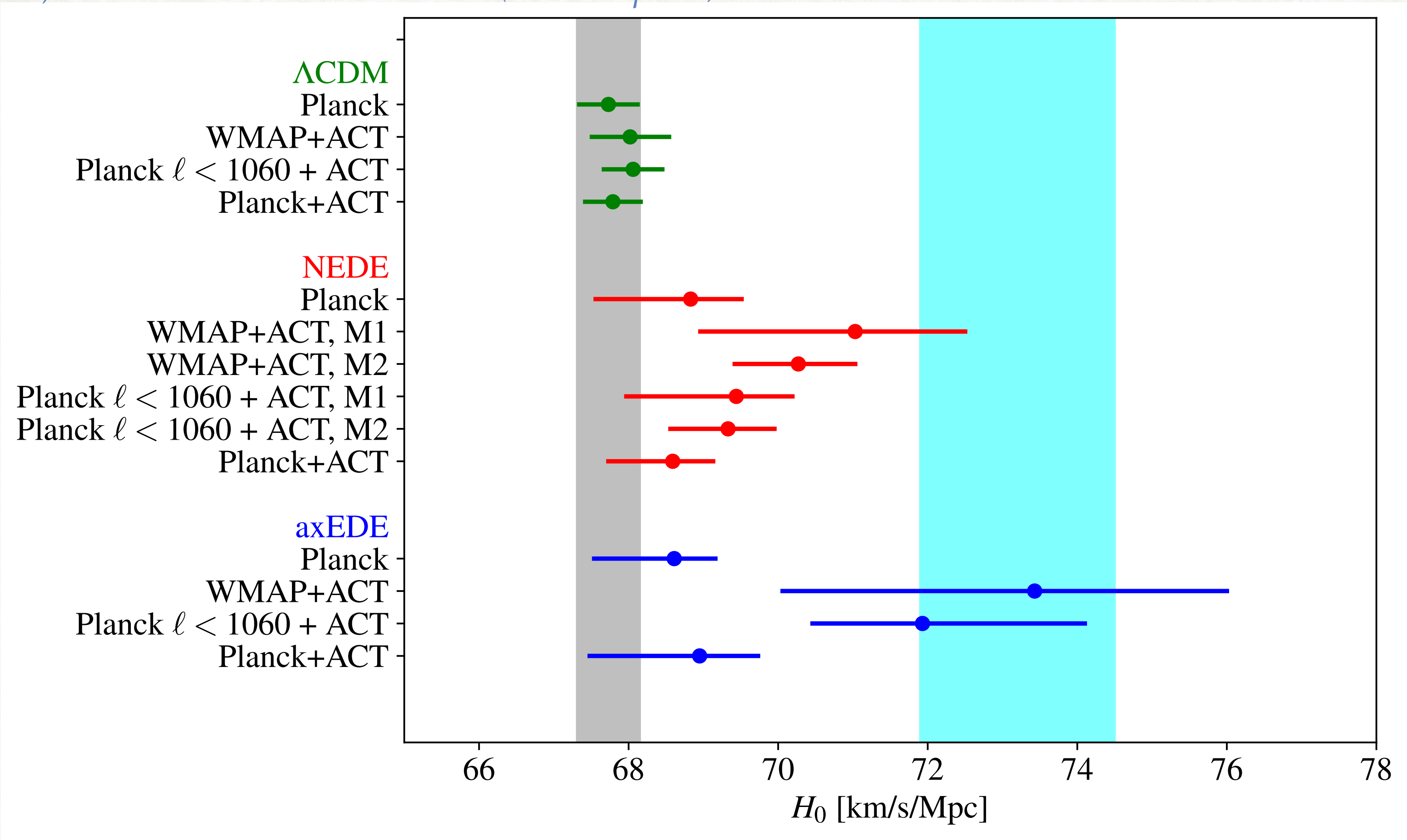

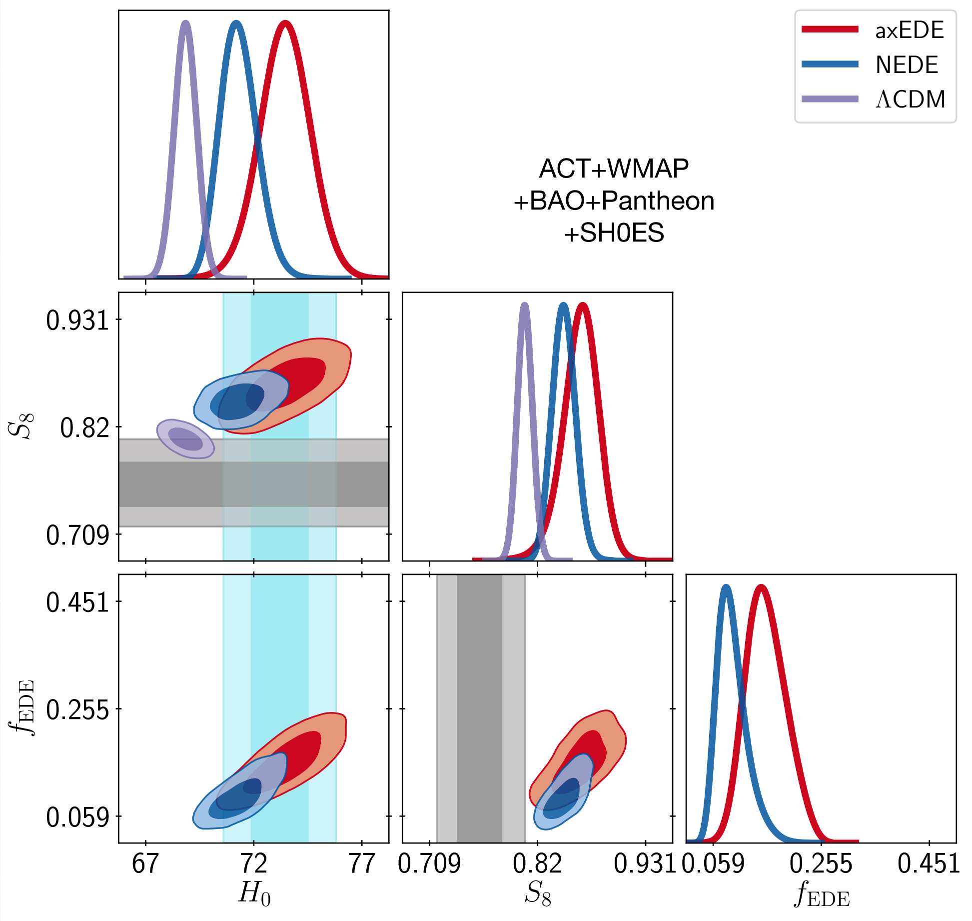

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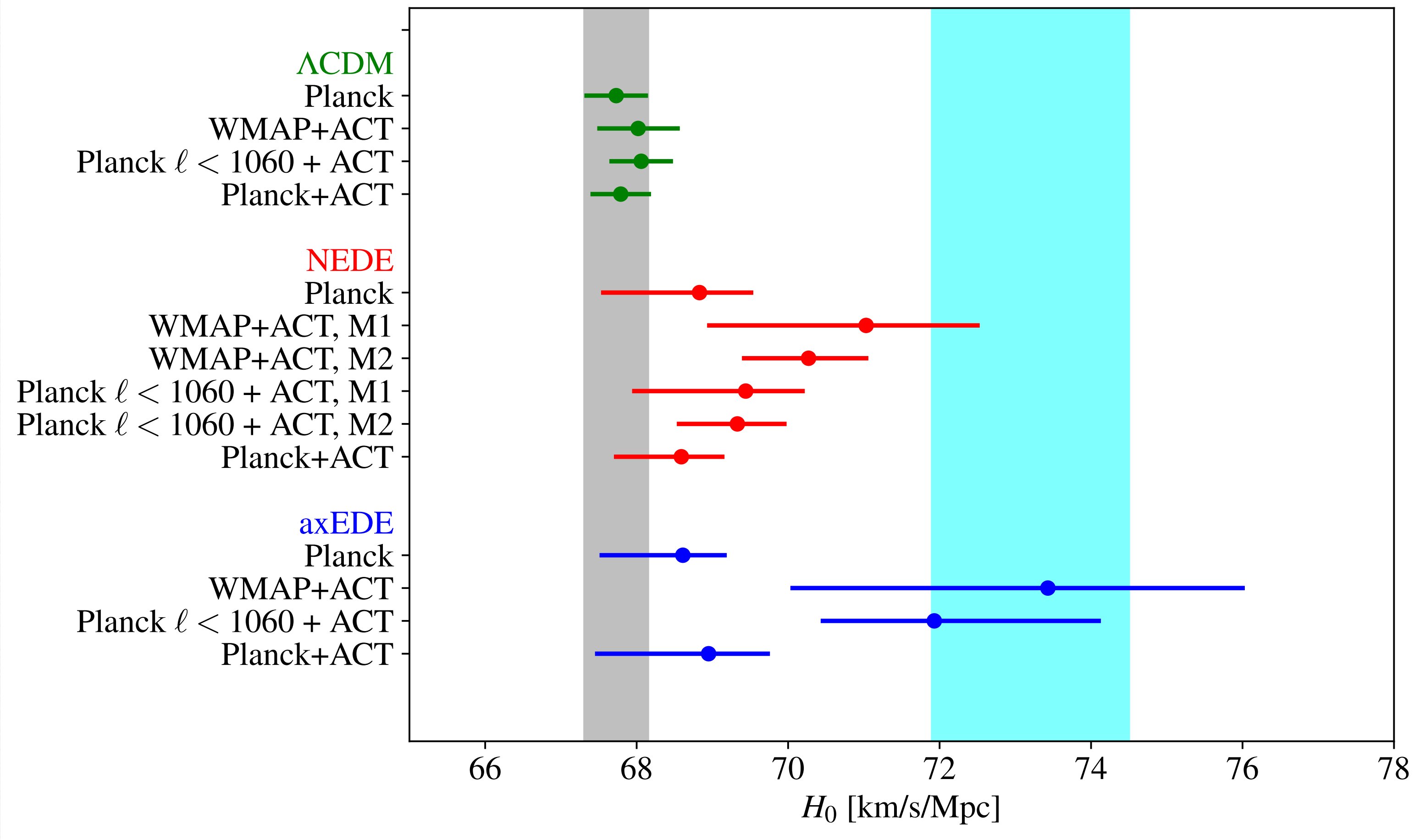

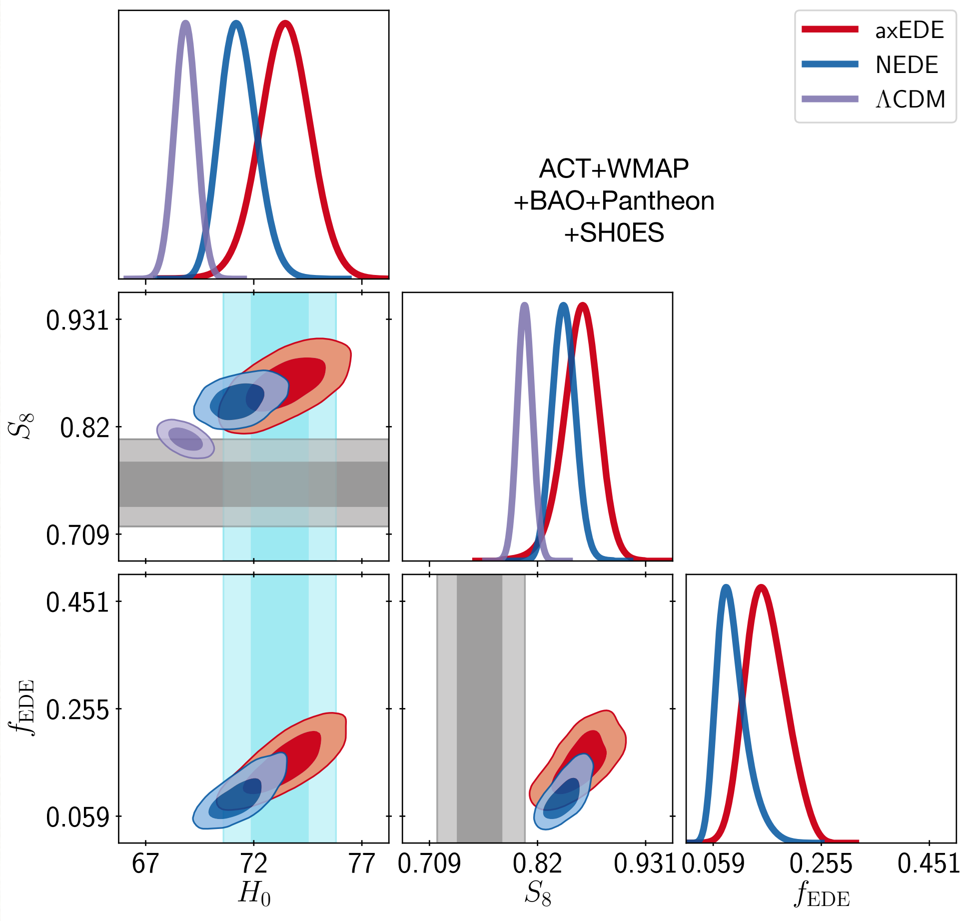

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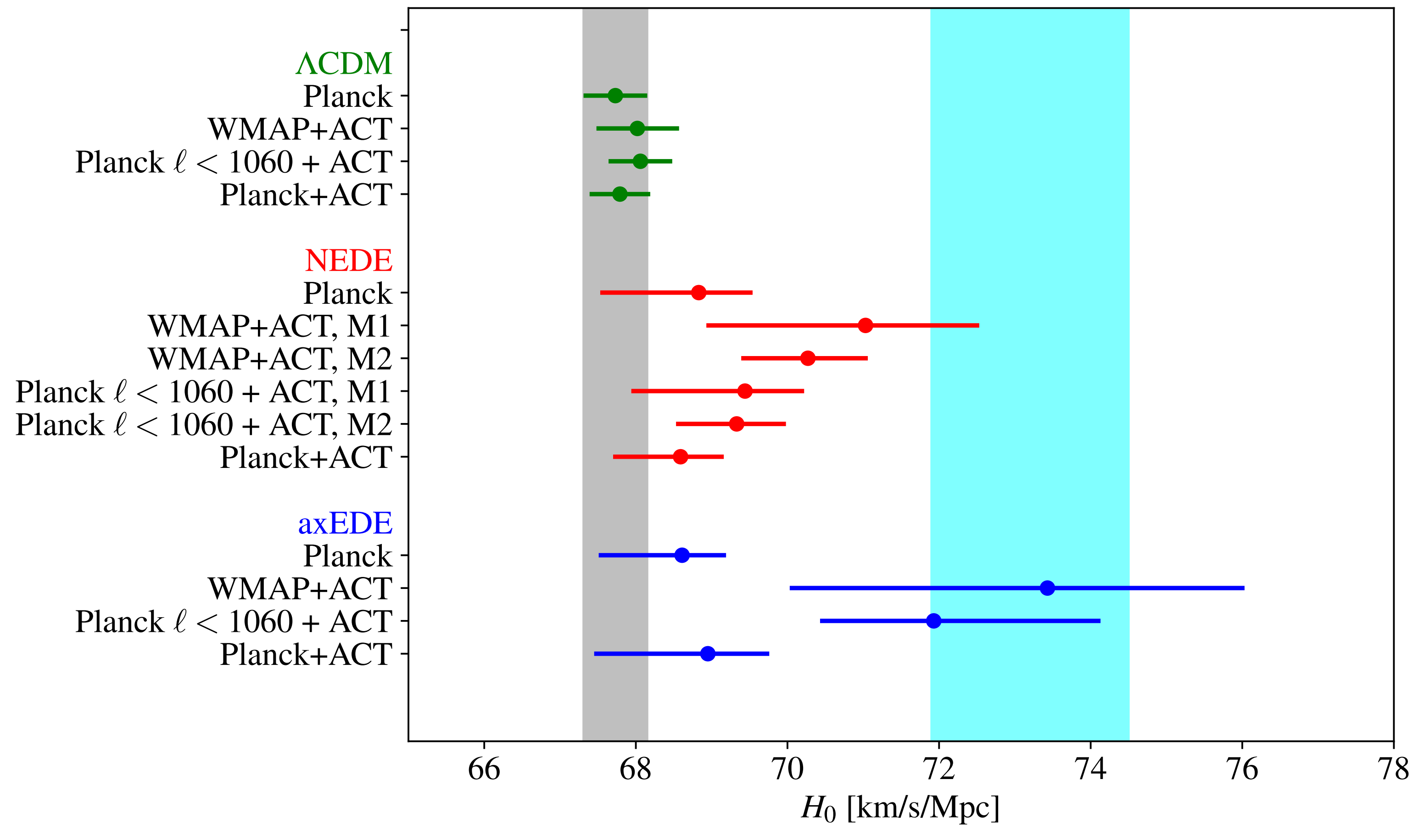

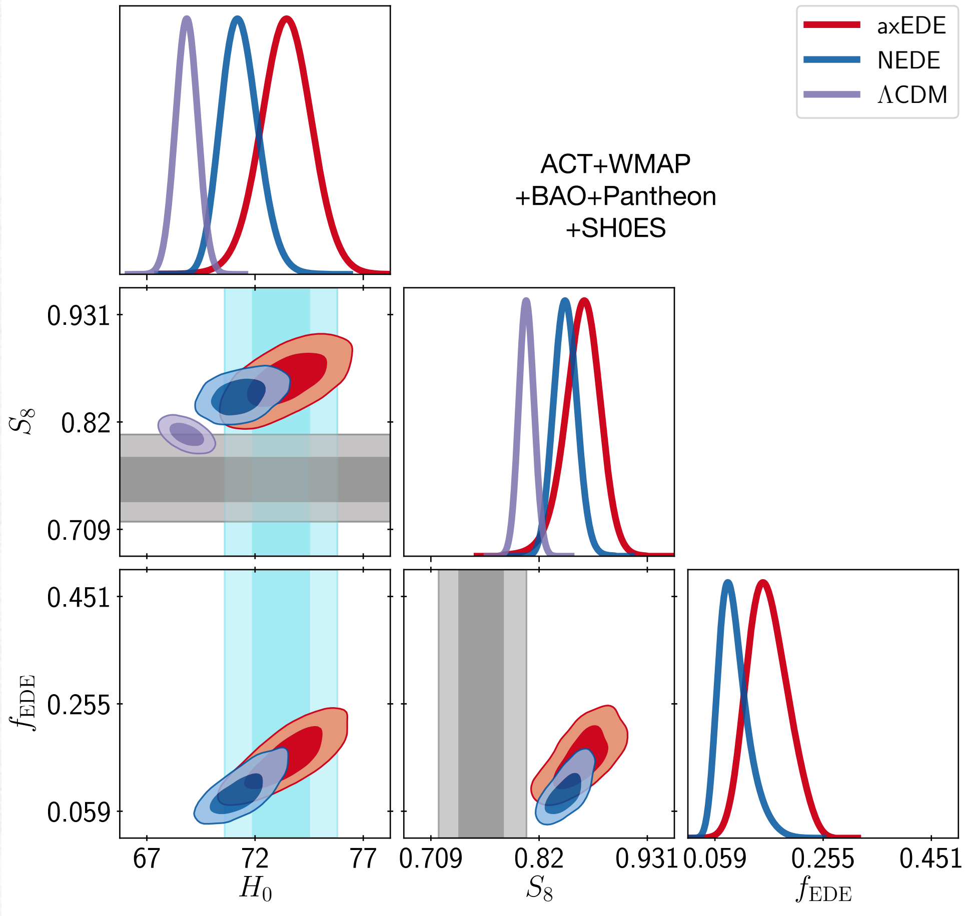

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- Future data (AdvACT? Simons Observatory? CMB-s4?) will confirm or exclude this model. SPT? Ongoing.

Thanks for your attention!

The Atacama Cosmology Telescope (act.princeton.edu)

Vivian Poulin

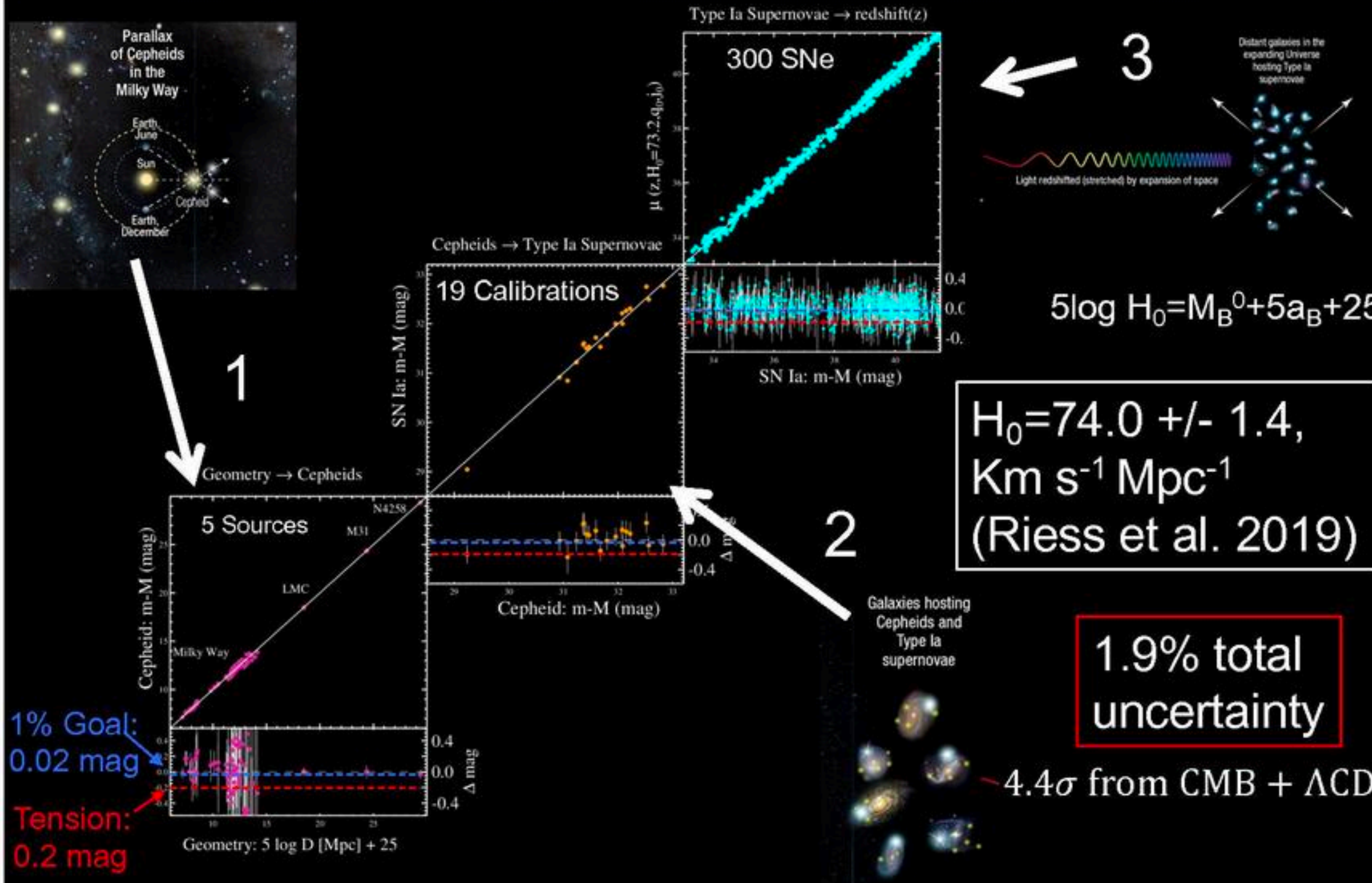
Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

vivian.poulin@umontpellier.fr

2109.06229 with Tristan Smith & Alexa Bartlett (Swarthmore Coll.)

TUG workshop, Paris
December, 14th 2021

The Hubble Constant in 3 Steps: Present Data



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

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

1.9% total uncertainty

4.4σ from CMB + ΛCDM !

Slide by A. Riess, KITP July 2019

Systematics? A non-exhaustive list

See review Di Valentino++ 2103.01183 for all relevant references

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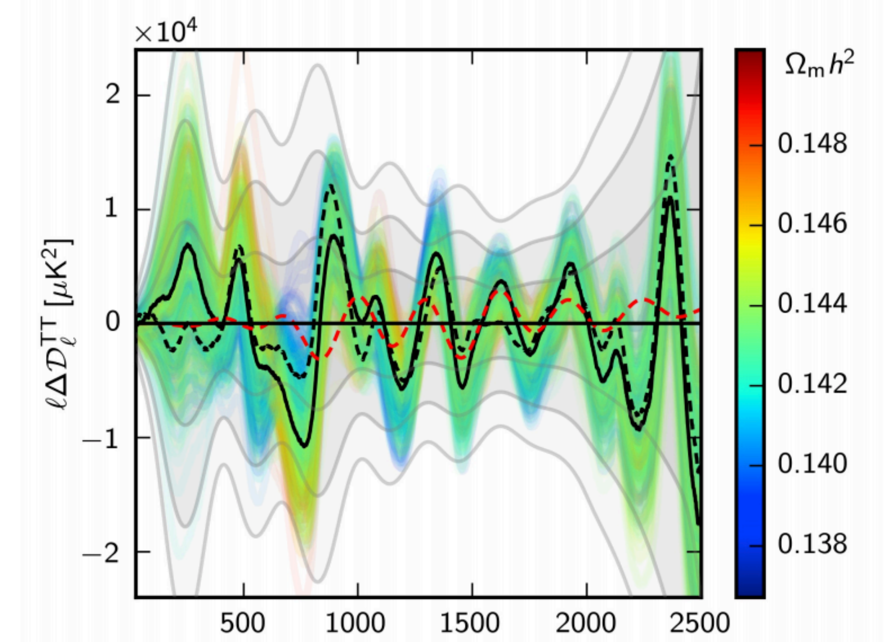
Experimental efforts are of utmost importance! But if it is new physics, it is essential to: i) understand what causes this tension; ii) make predictions for other observables.

Anomalies in *Planck*: is the Universe closed?

$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$

Unless specified, Figs. from Di Valentino++ 1911.02087



Planck 1807.06209

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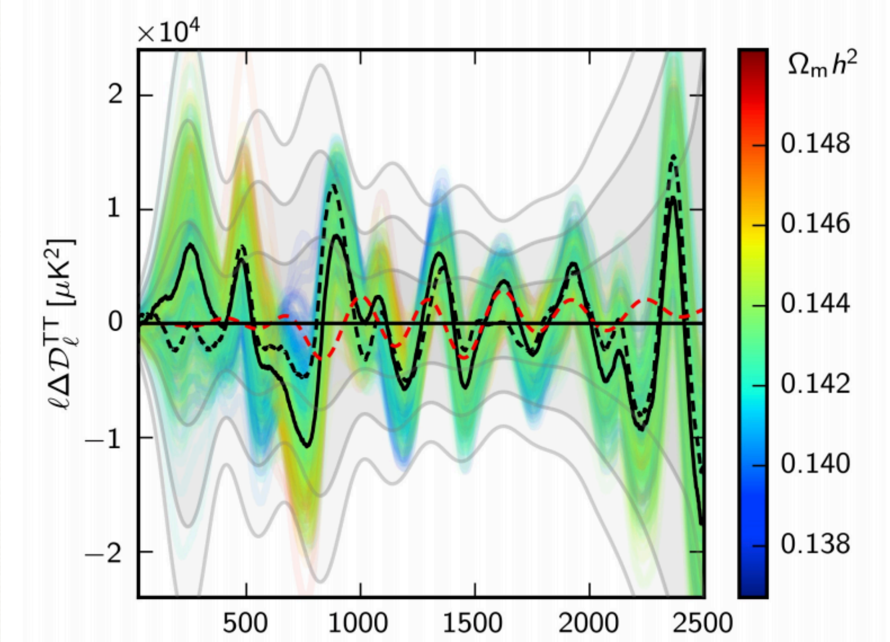

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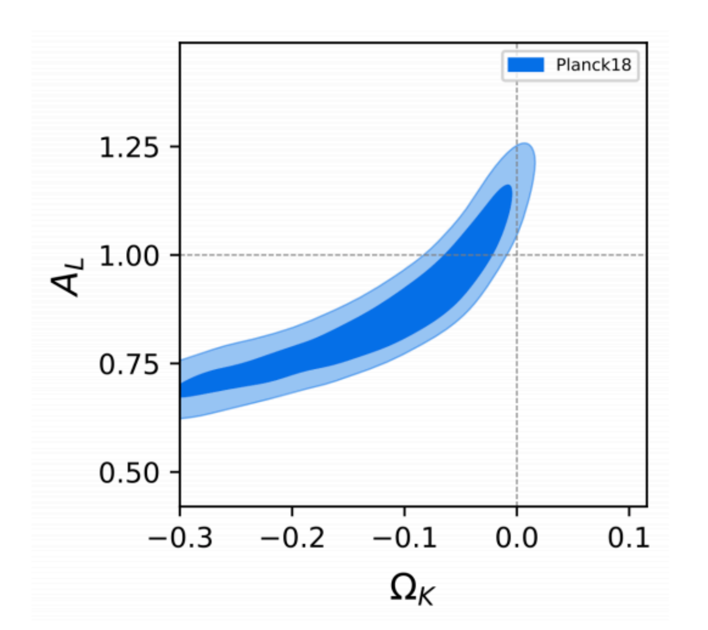

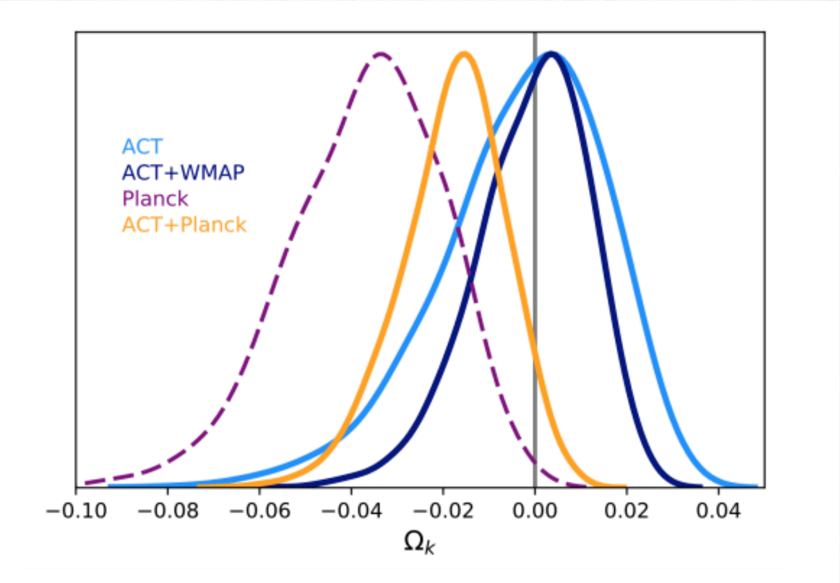

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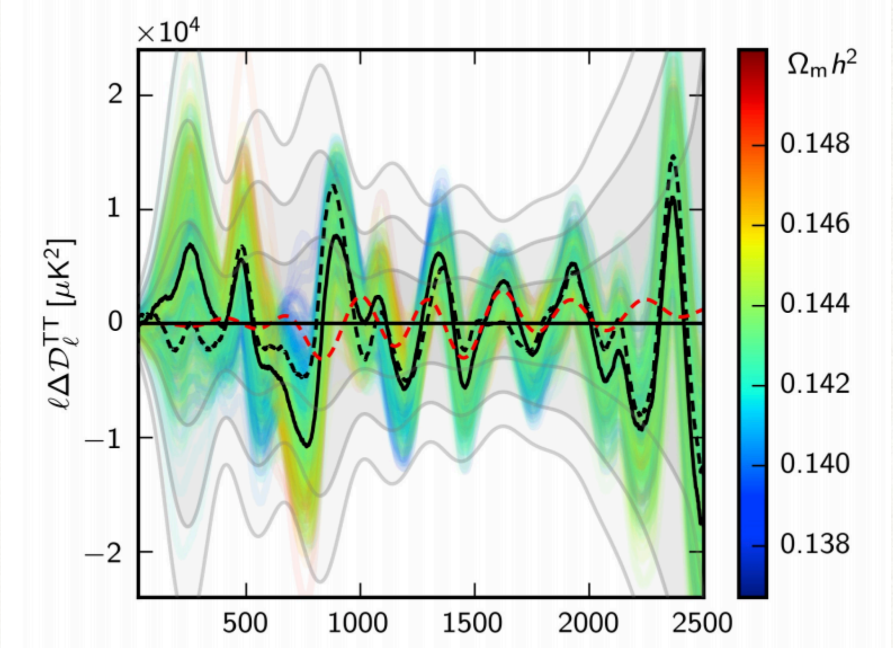

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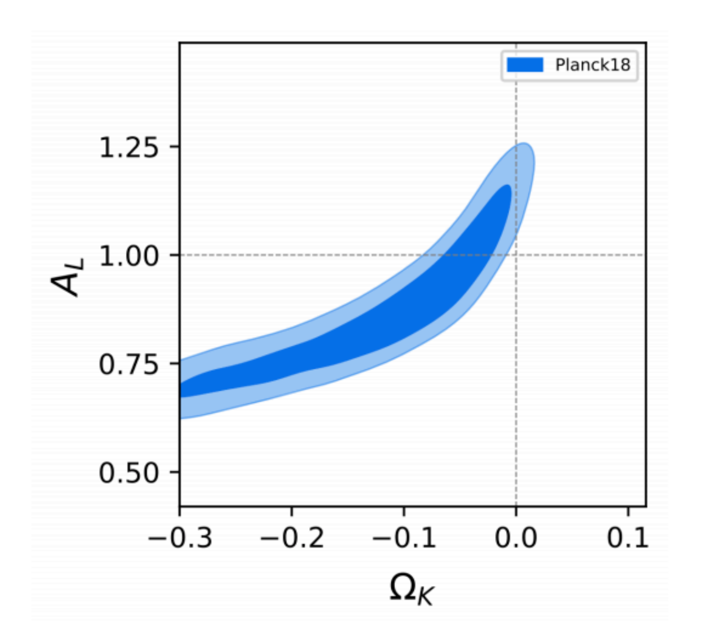

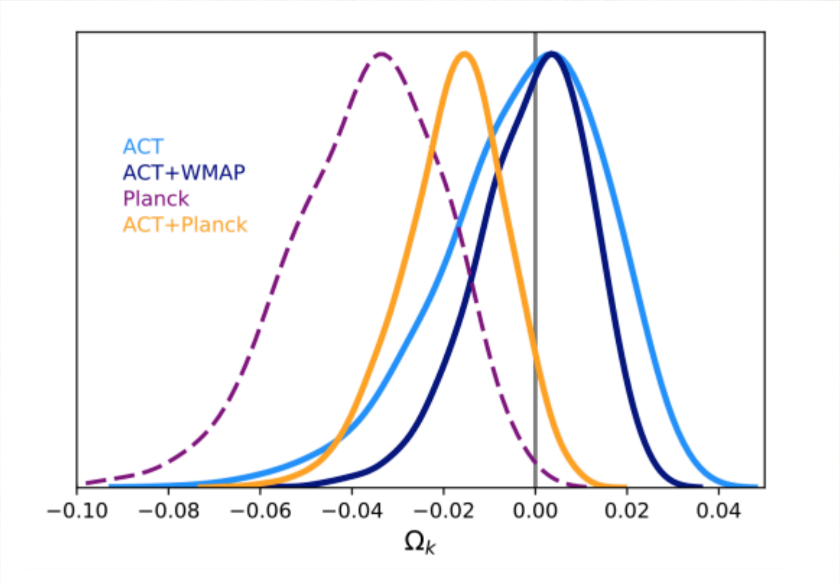

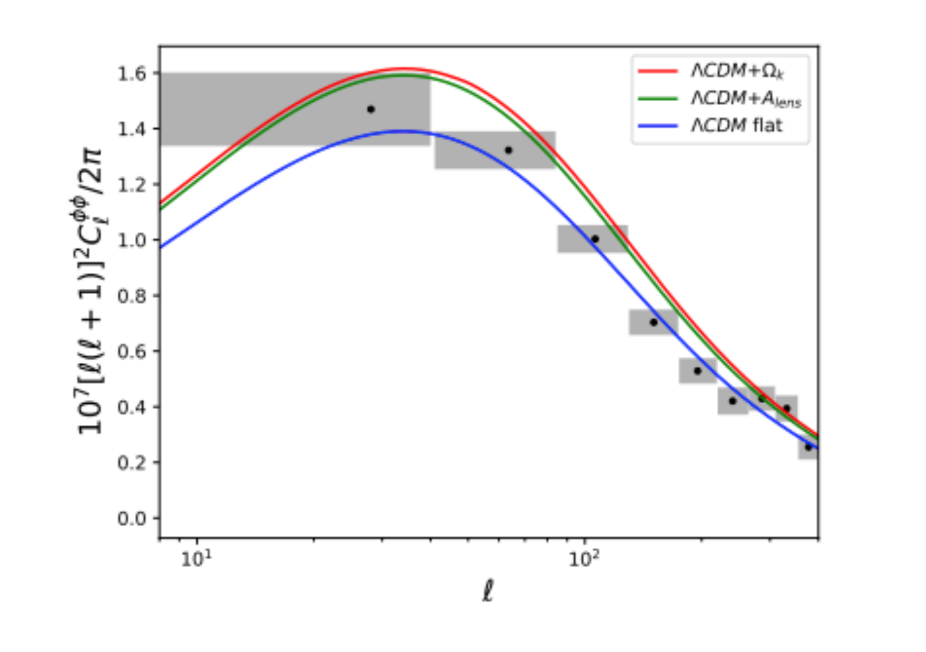

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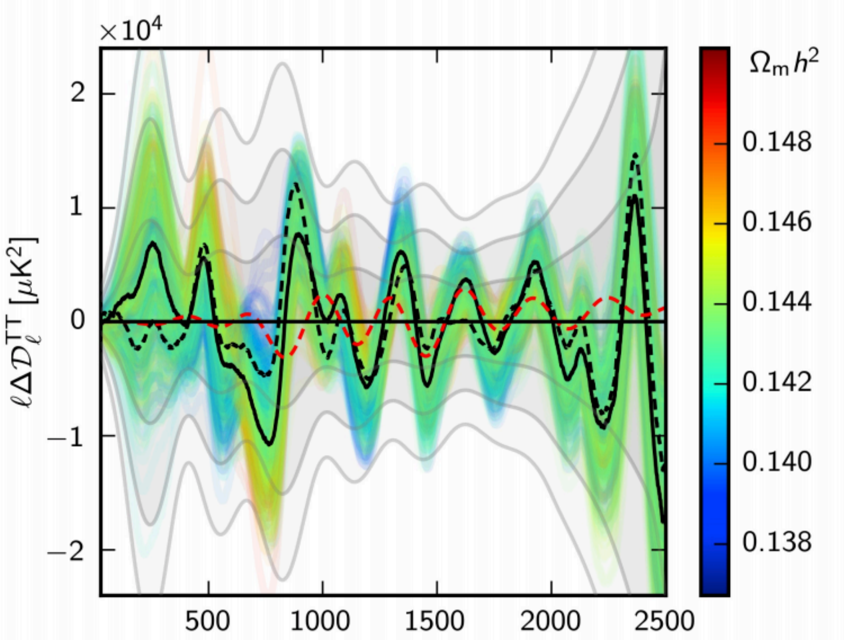

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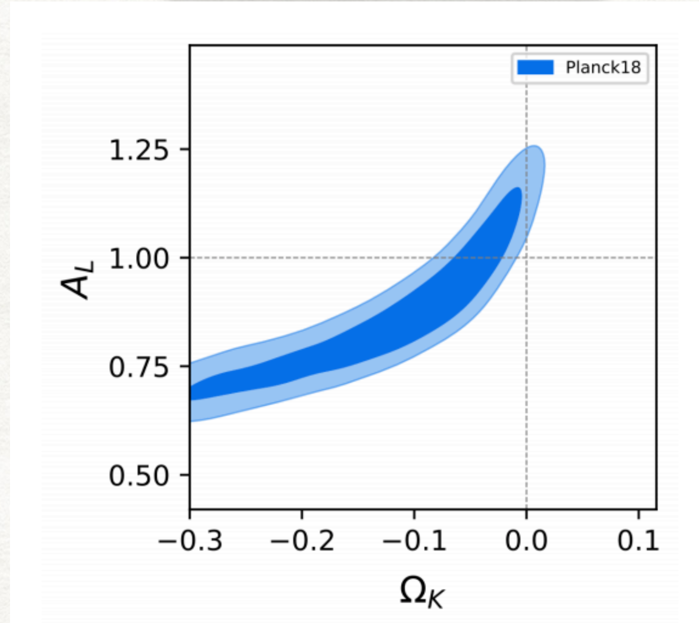

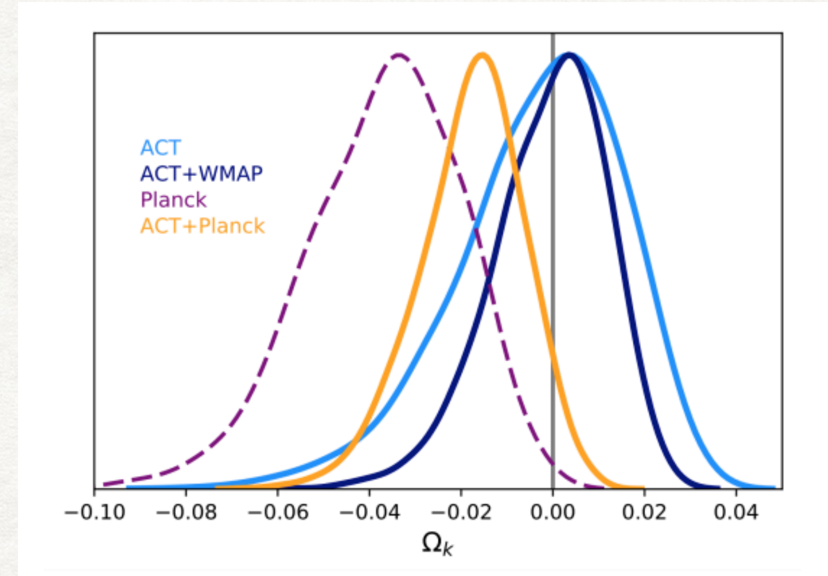

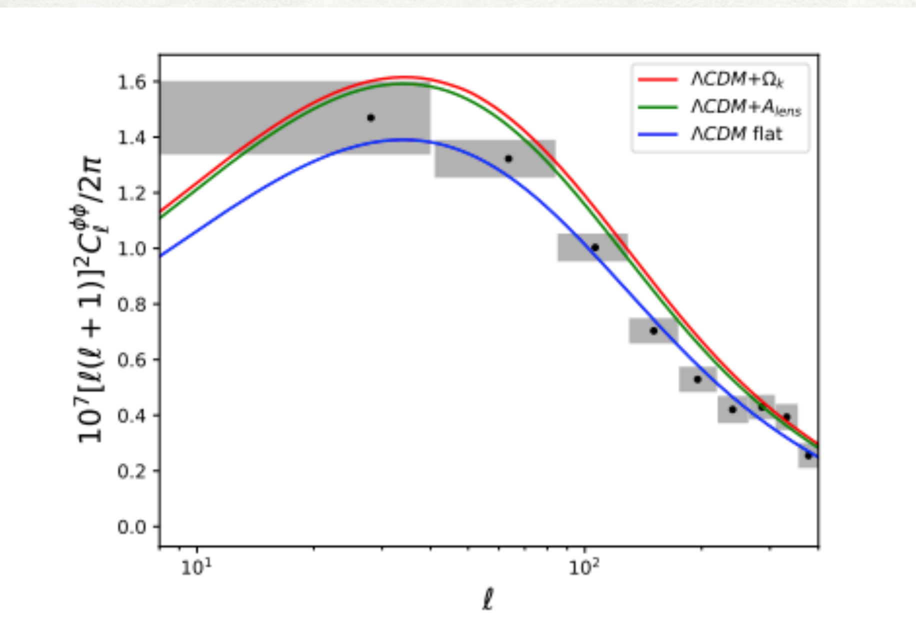

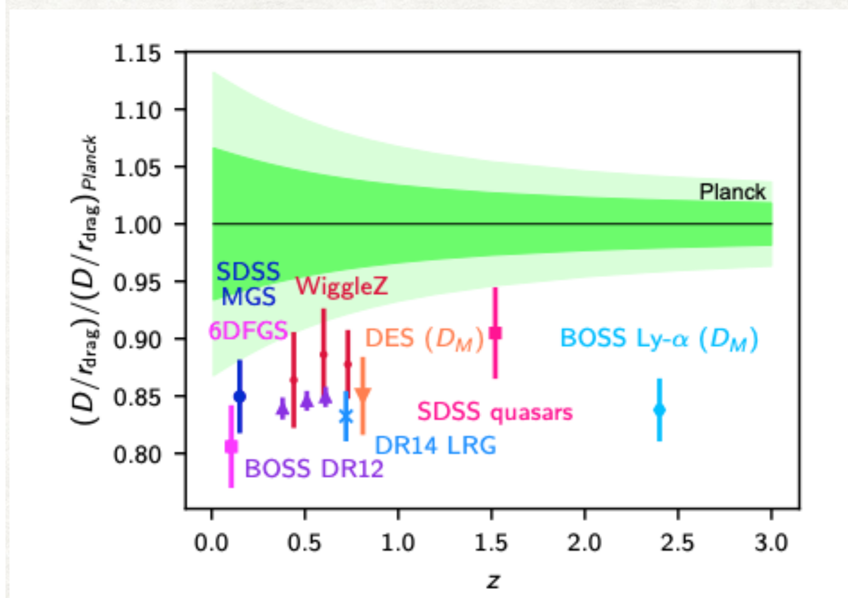

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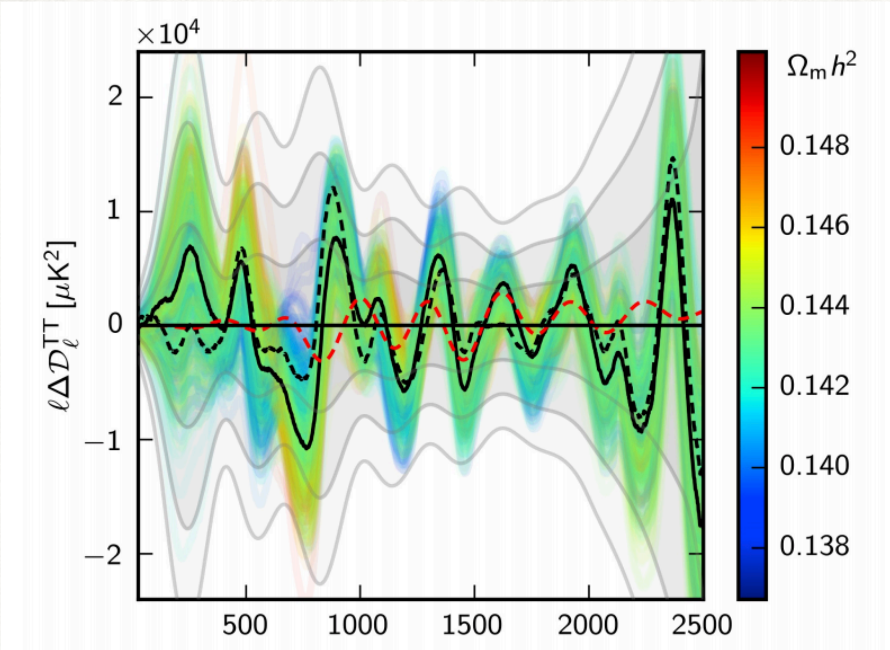

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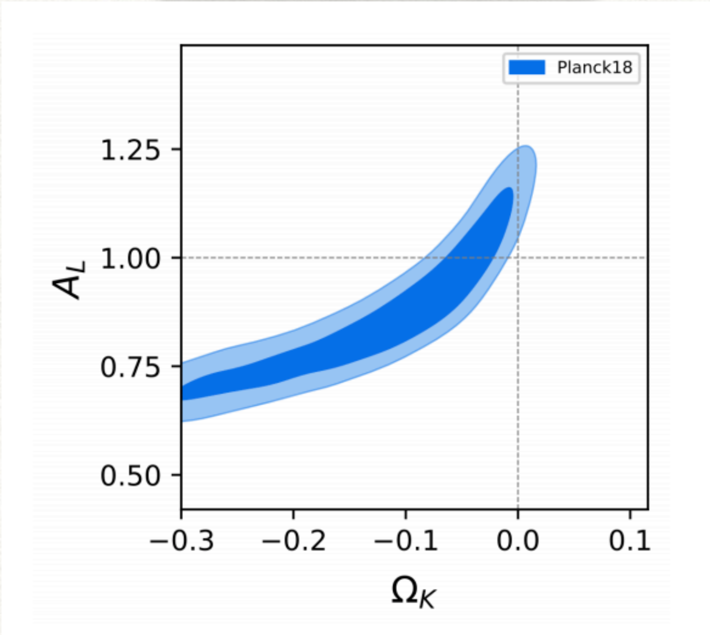

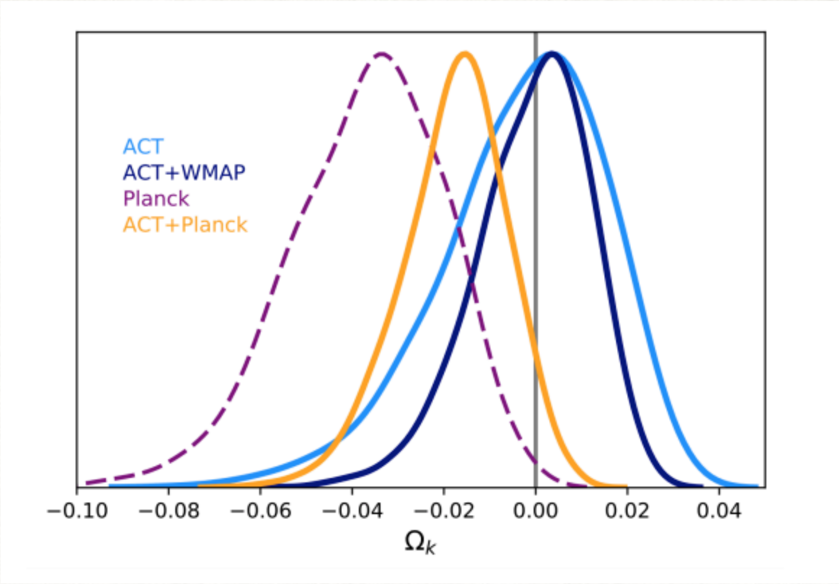

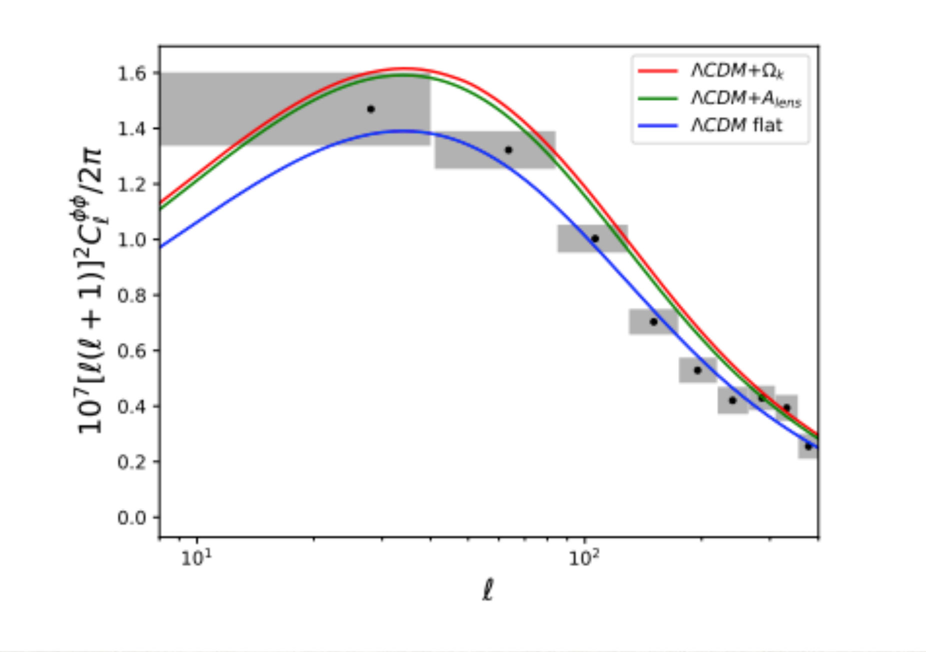

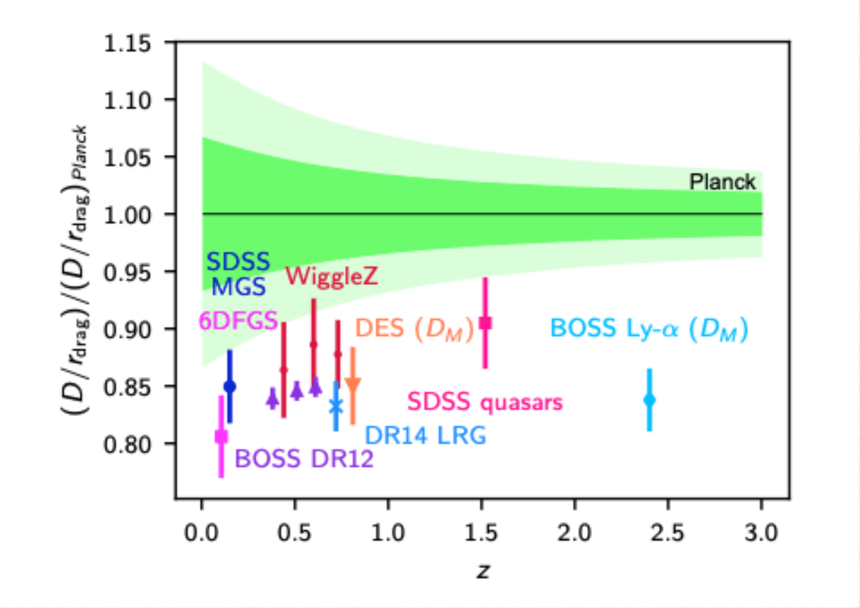

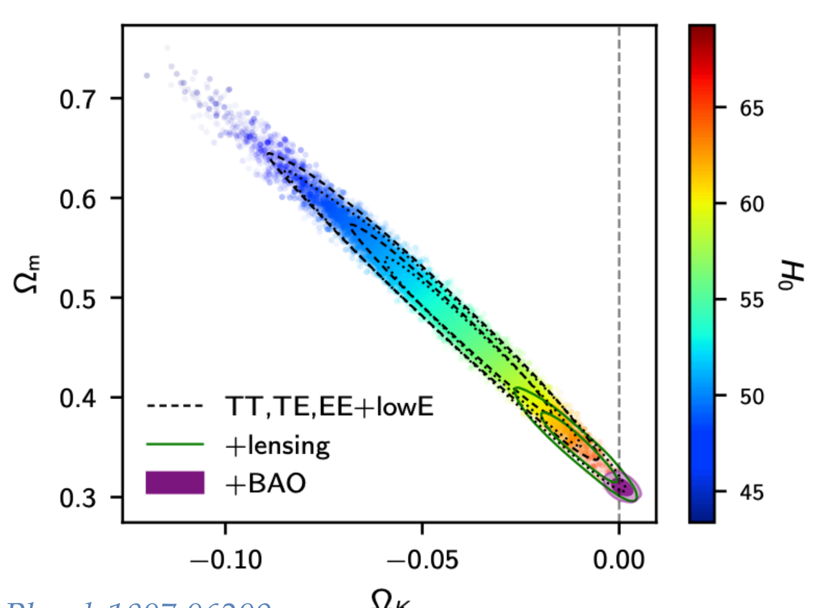

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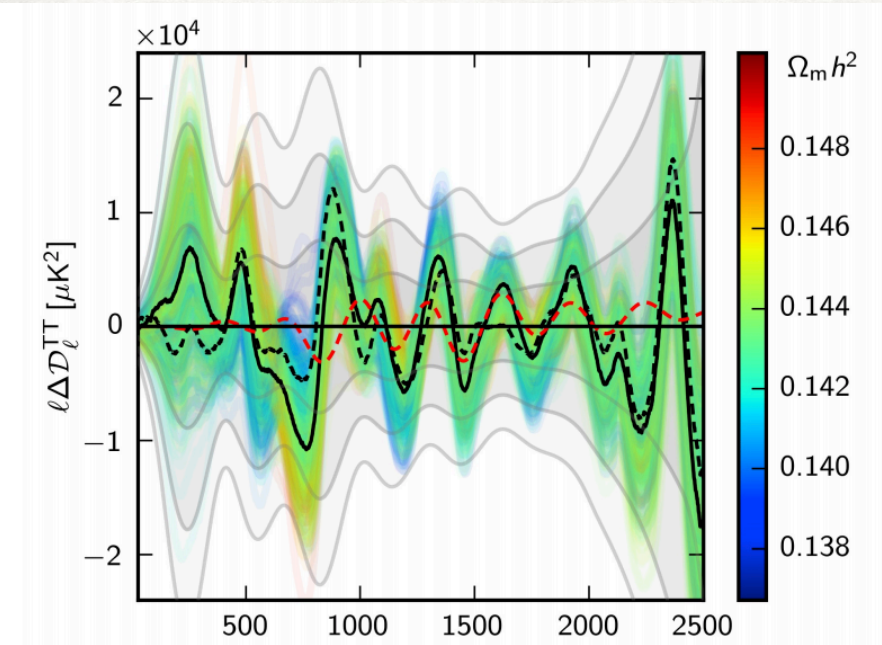

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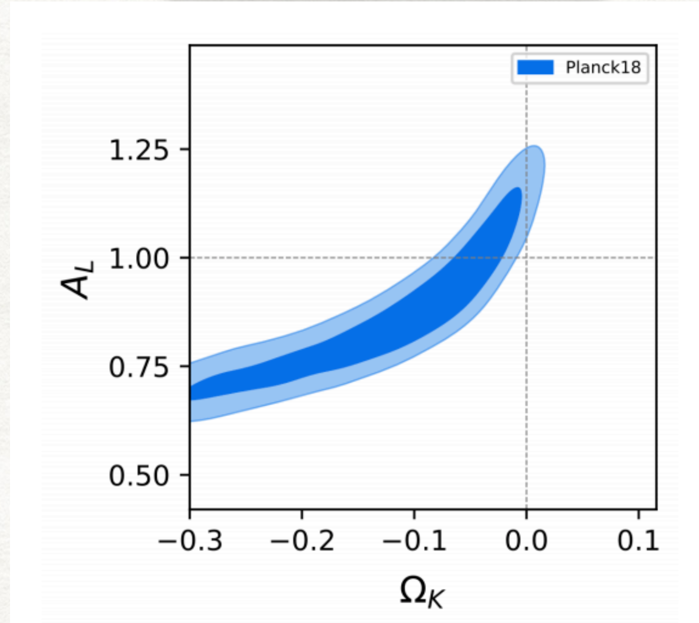

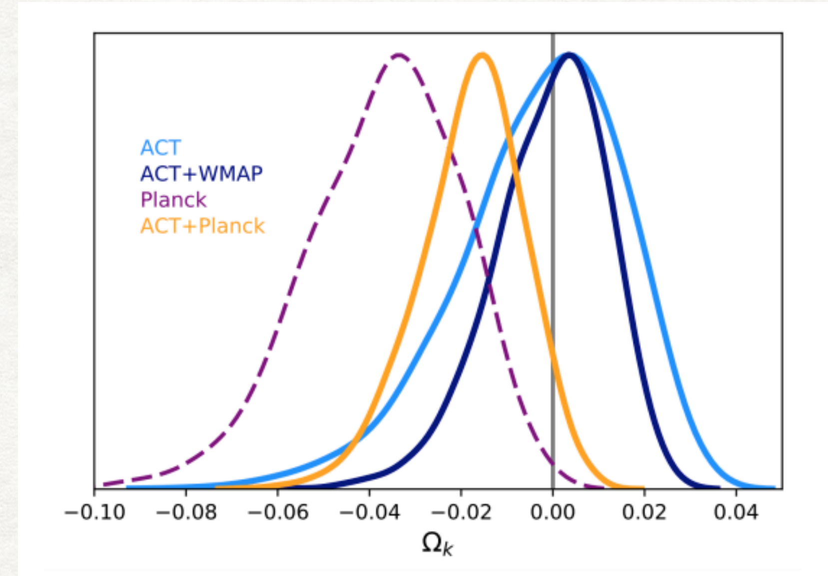

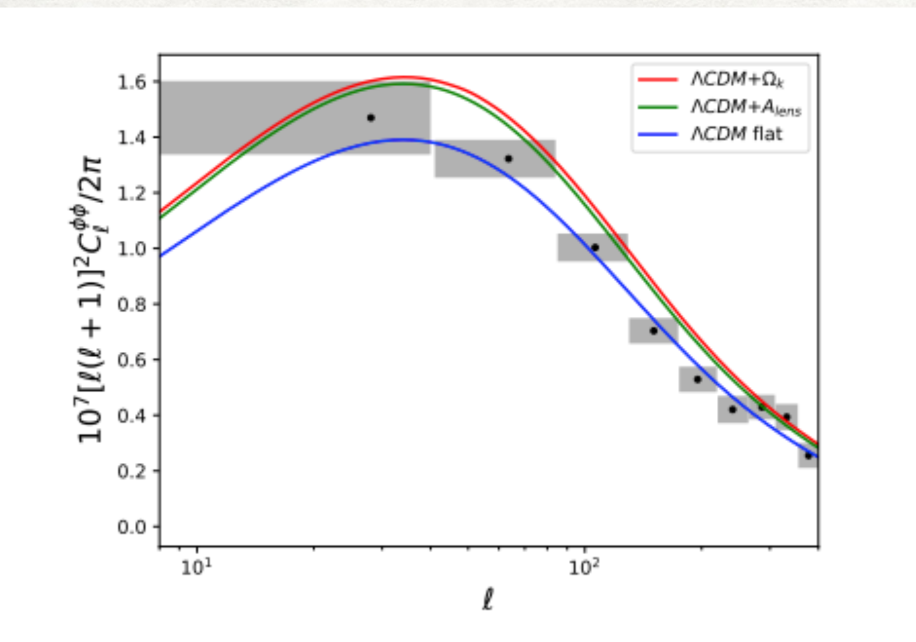

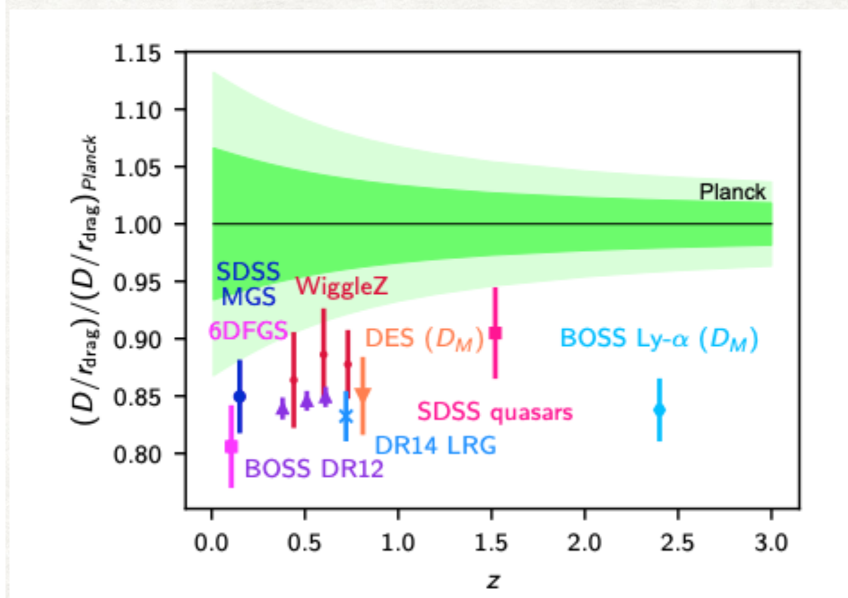

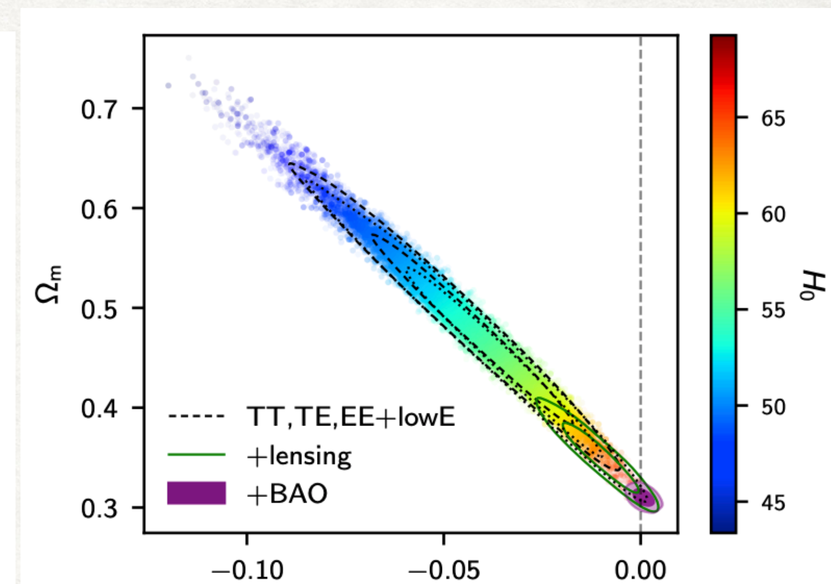

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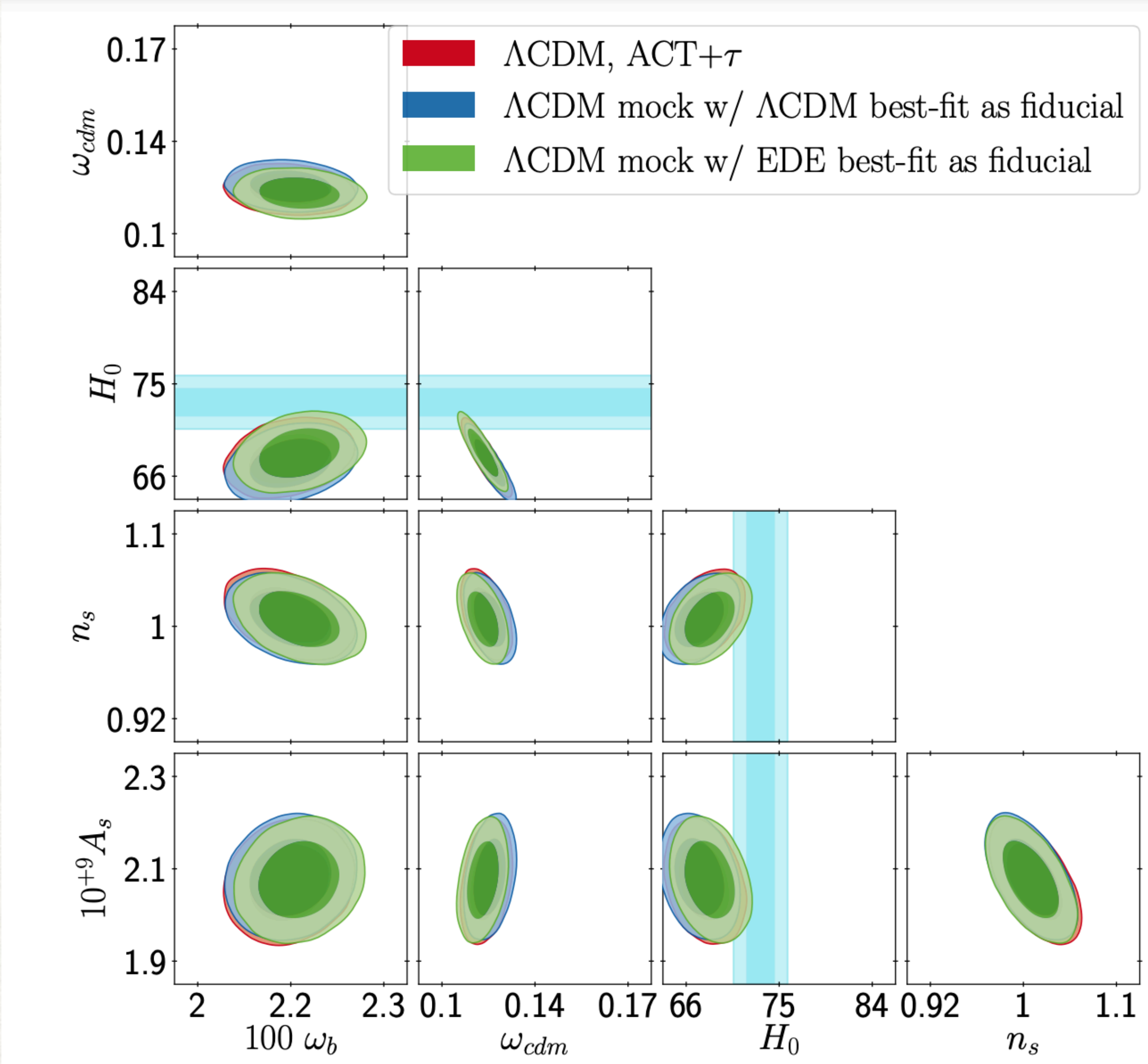
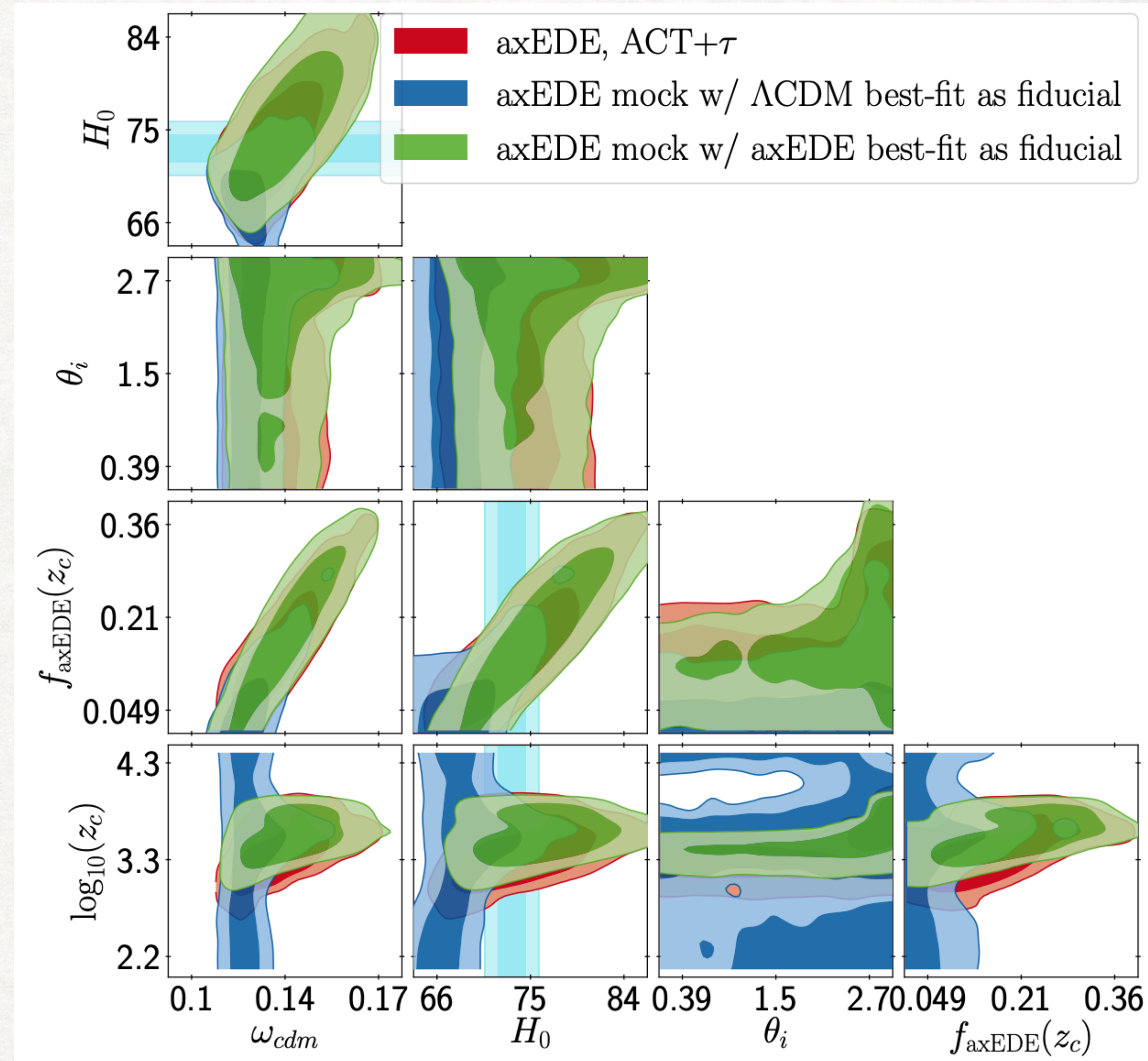
- The Universe is flat unless of a true ‘cosmological crisis’.
- Flat universe is also supported by BOSS and Cosmic Chronometers. *Vagnozzi++2010.02230, 2011.11645*
- Nb: A_L could also be explained in modified gravity framework, it suffers from the same issues.

Preference for EDE in ACT is not artificial





- The apparent preference for EDE does not come from a lack of information at small/intermediate multipoles.
- ΛCDM reconstruction could be largely biased (if EDE were the true model). $\Delta\chi^2(\text{mock EDE}) \simeq \Delta\chi^2(\text{real data})$.

BAO and SN1a constrain late-time resolution

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

see also Wang++ 1807.03772, Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Benevento++ 2002.11707.

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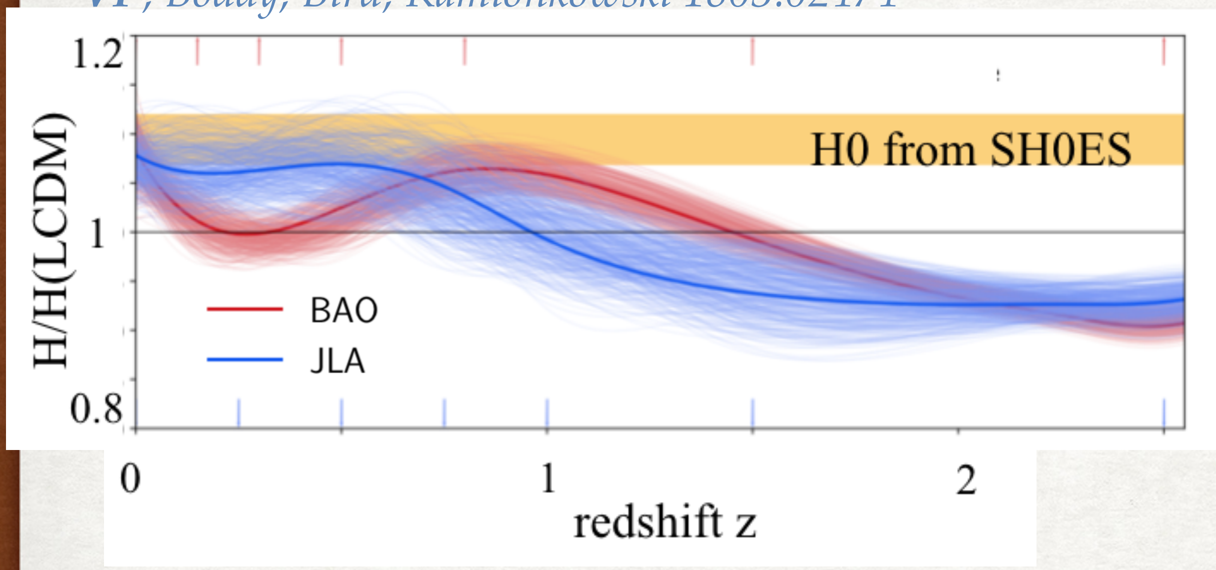

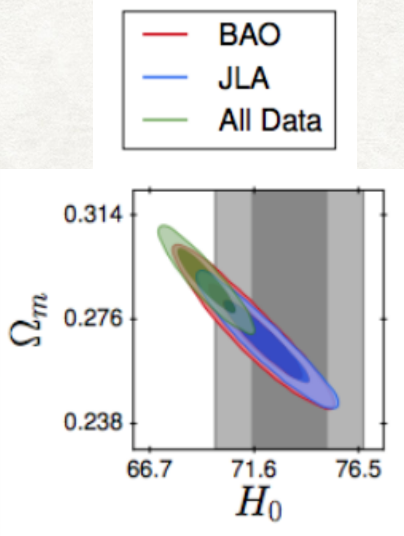

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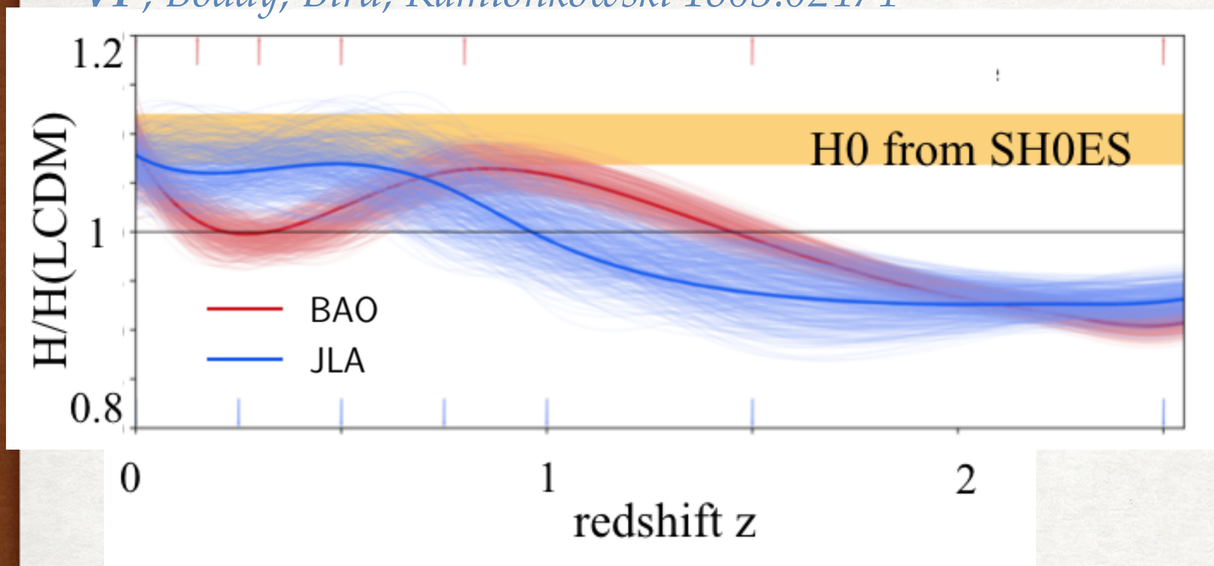

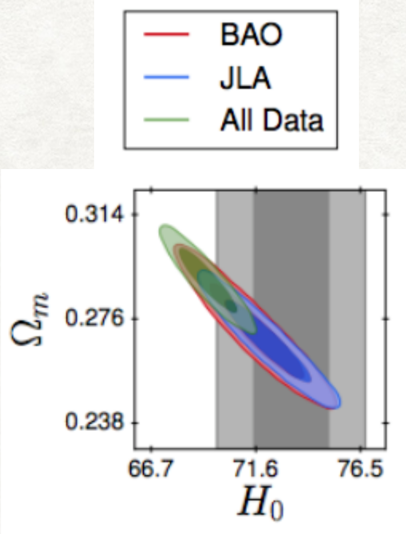

$$\theta_d(z)^\perp = \frac{r_s(z_{\rm drag})}{D_A(z)}\,,\theta_d(z)^\parallel = r_s(z_{\rm drag})H(z)$$

- $r_s(z_{\rm drag})$ from Planck

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

- 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!

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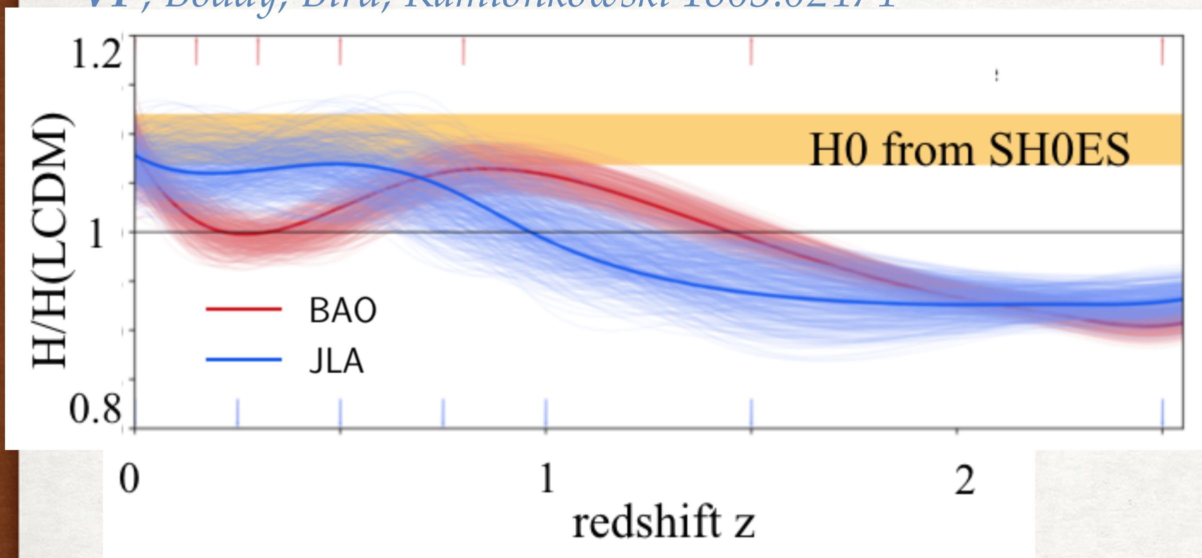
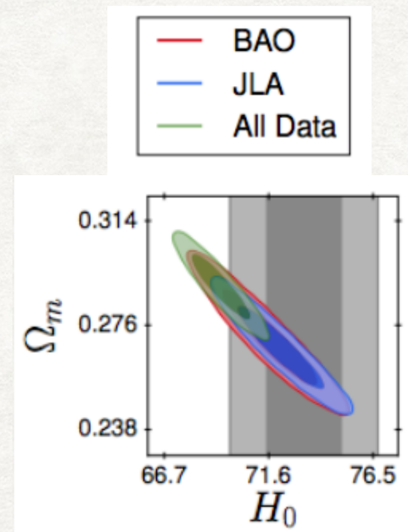
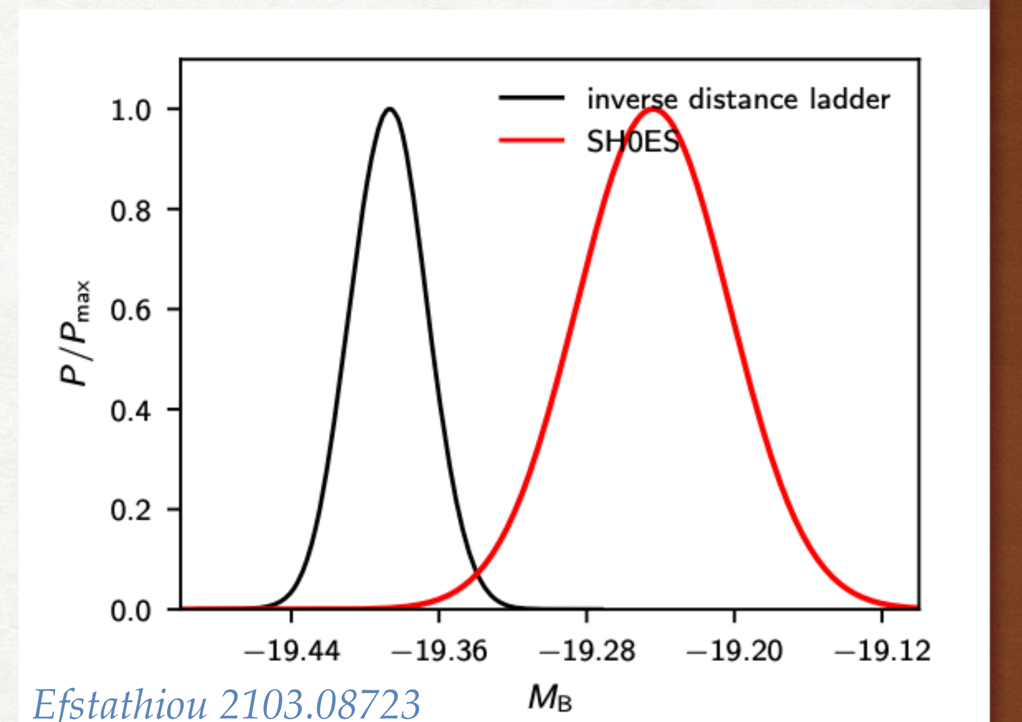
see also Wang++ 1807.03772, Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Benevento++ 2002.11707.

VP, Boddy, Bird, Kamionkowski 1803.02474







Efstathiou 2103.08723

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

- $r_s(z_{drag})$ from Planck

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

- 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!

- The true tension is with the intrinsic SN1a magnitude!

Beenakker++2101.01372, Efstathiou 2103.08723

Barring systematic errors: no ‘concordance cosmology’ just yet

- ΛCDM explains CMB, BAO, ‘uncalibrated’ SN1a, BBN (<2σ), but there exists a 4−6σ H_0−tension and 3σ σ_8−tension.
- What extension(s) could resolve these tensions?

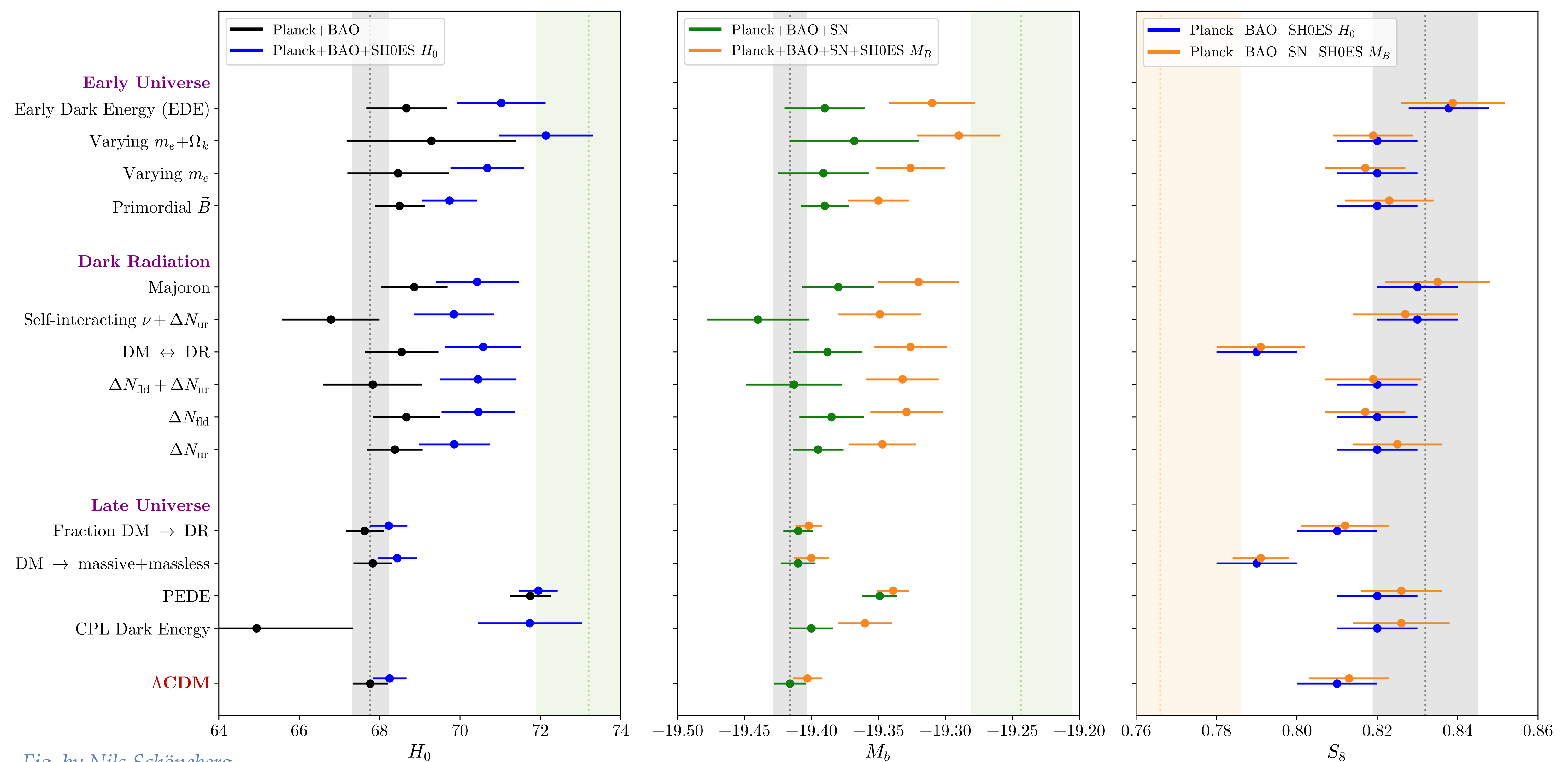


Fig. by Nils Schöneberg

Schöneberg, Abellán, Pérez-Sánchez, Witte, VP, Lesgourgues 2107.10291

- H_0: measure the background expansion rate. S_8: measure the amplitude of perturbations.
- Background: reduce the sound horizon at early times. Perturbations: reduce power at scales $k \sim 0.1 - 1$ h/Mpc.