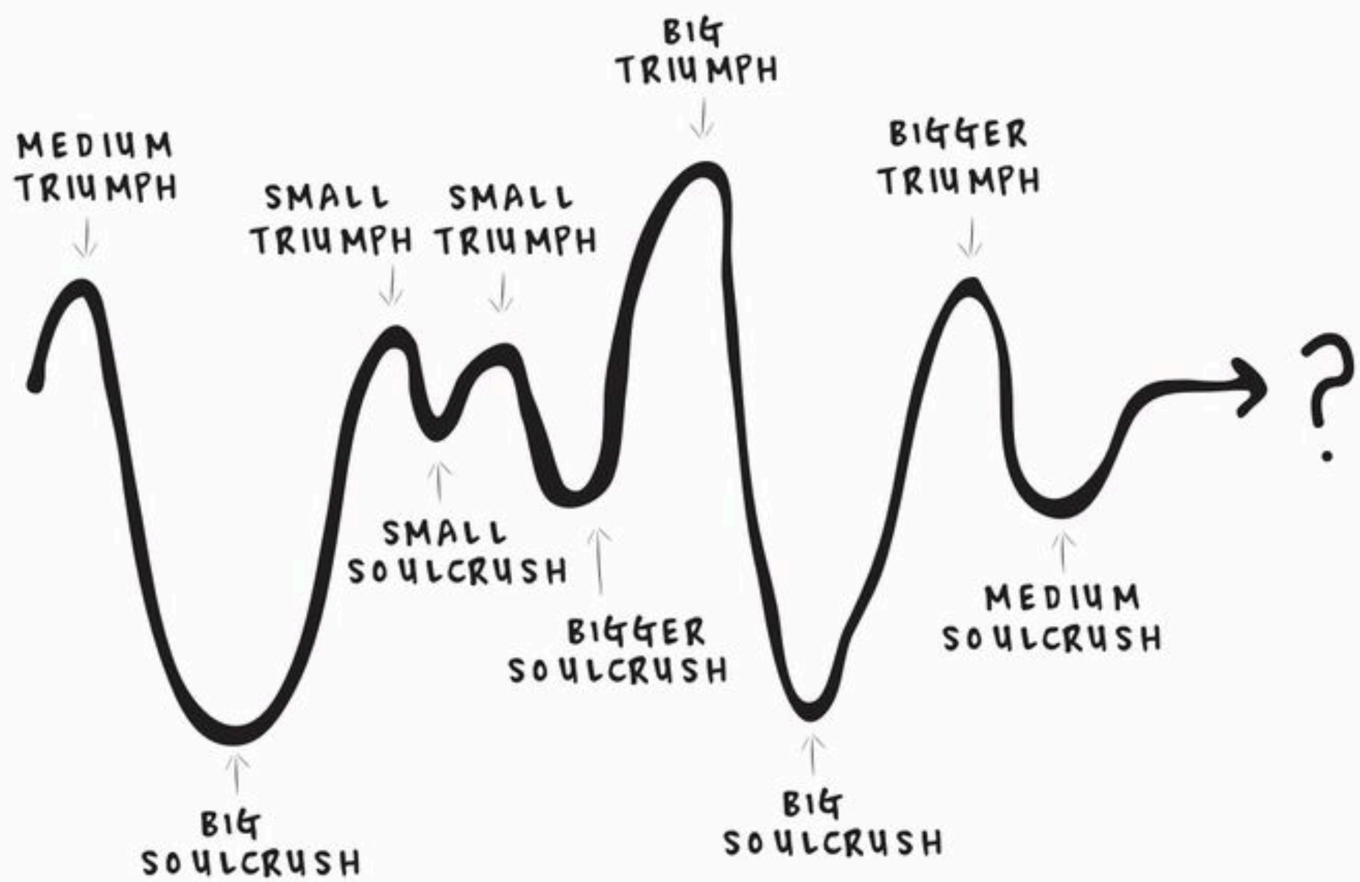
The Ups and Downs of ~~LIFE~~ Early Dark Energy



Vivian Poulin

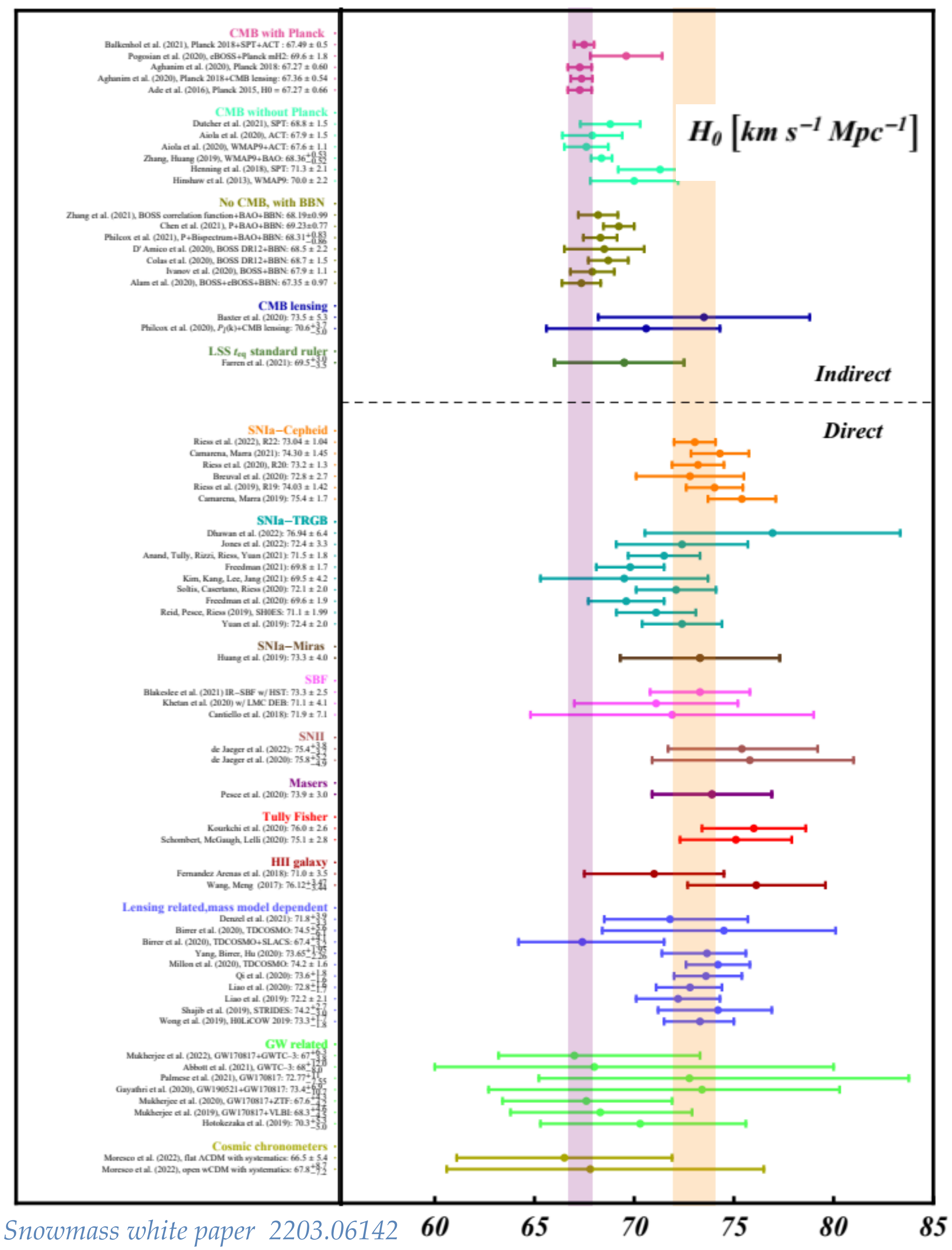
Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

In collaboration with Tristan L. Smith (Swarthmore), Tanvi Karwal (UPenn), Marc Kamionkowski (JHU), and many others

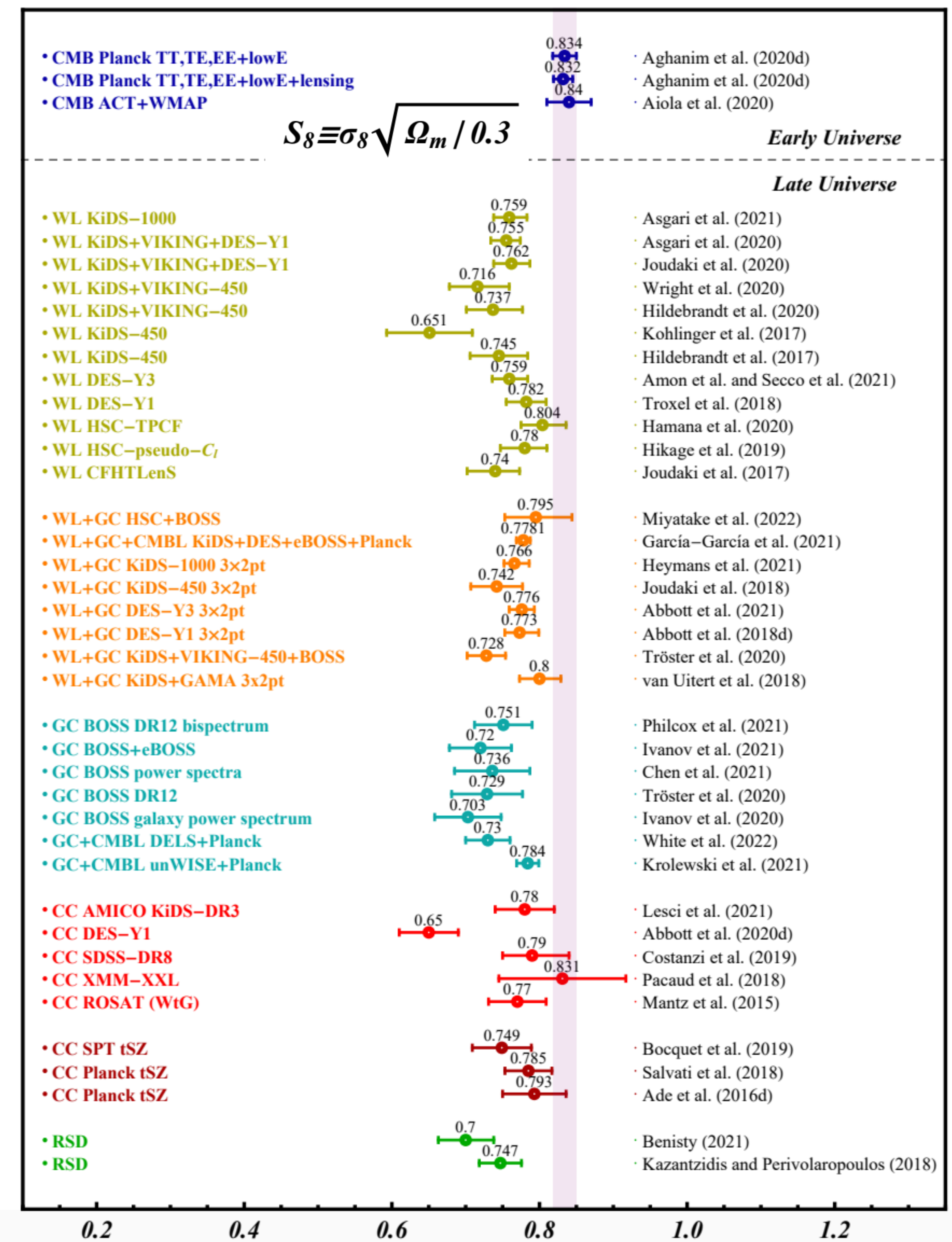
CosmoVerse@Lisbon
Lisbon, Portugal
May, 31st 2023

LUPM LABORATOIRE UNIVERS & PARTICULES MONTPELLIER · cnrs dépasser les frontières · Université de Montpellier · erc European Research Council Established by the European Commission

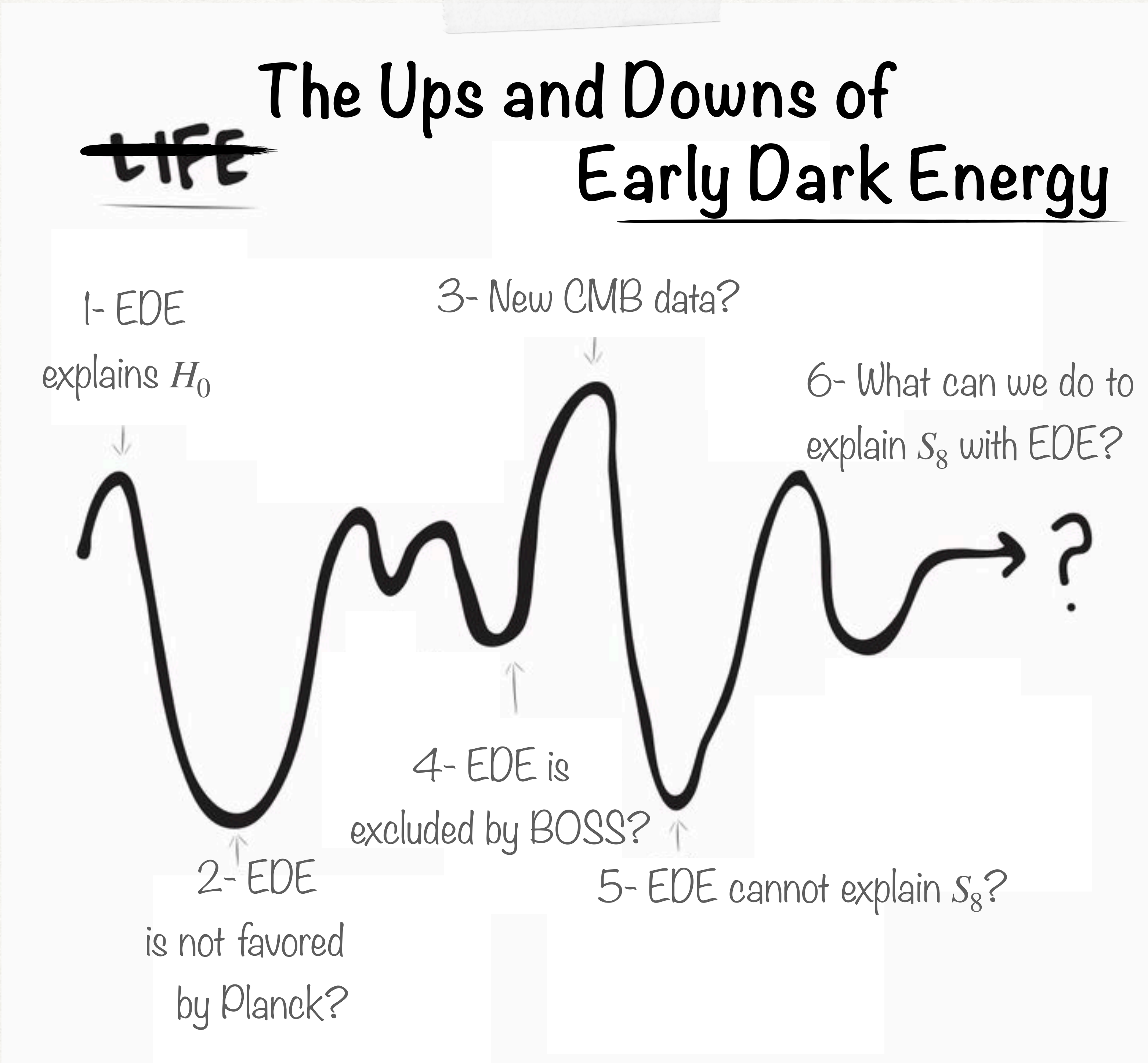
How can we explain the H_0 and S_8 tension?



Snowmass white paper 2203.06142

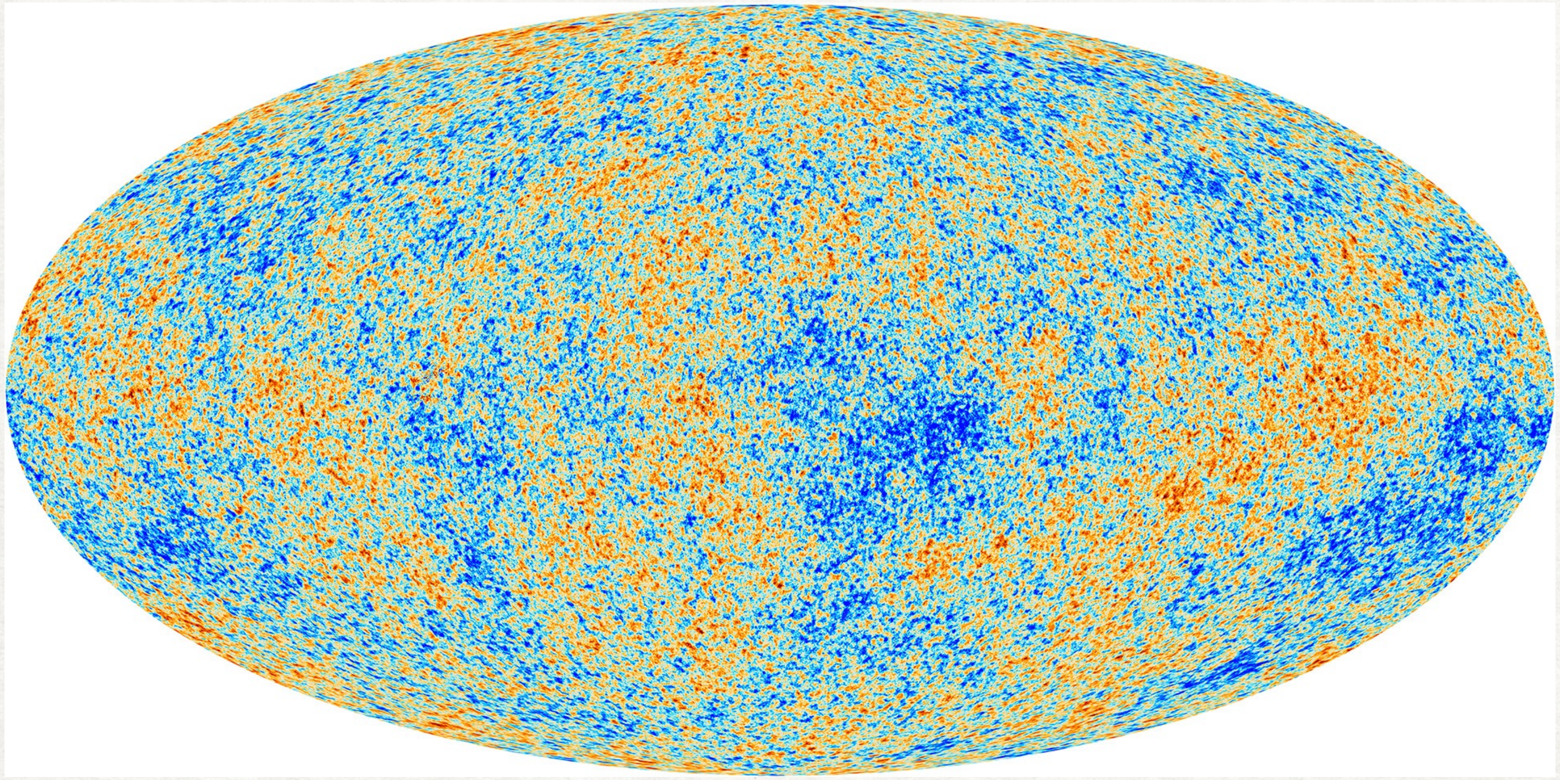


Can Early Dark Energy explain the H_0 and S_8 tension?



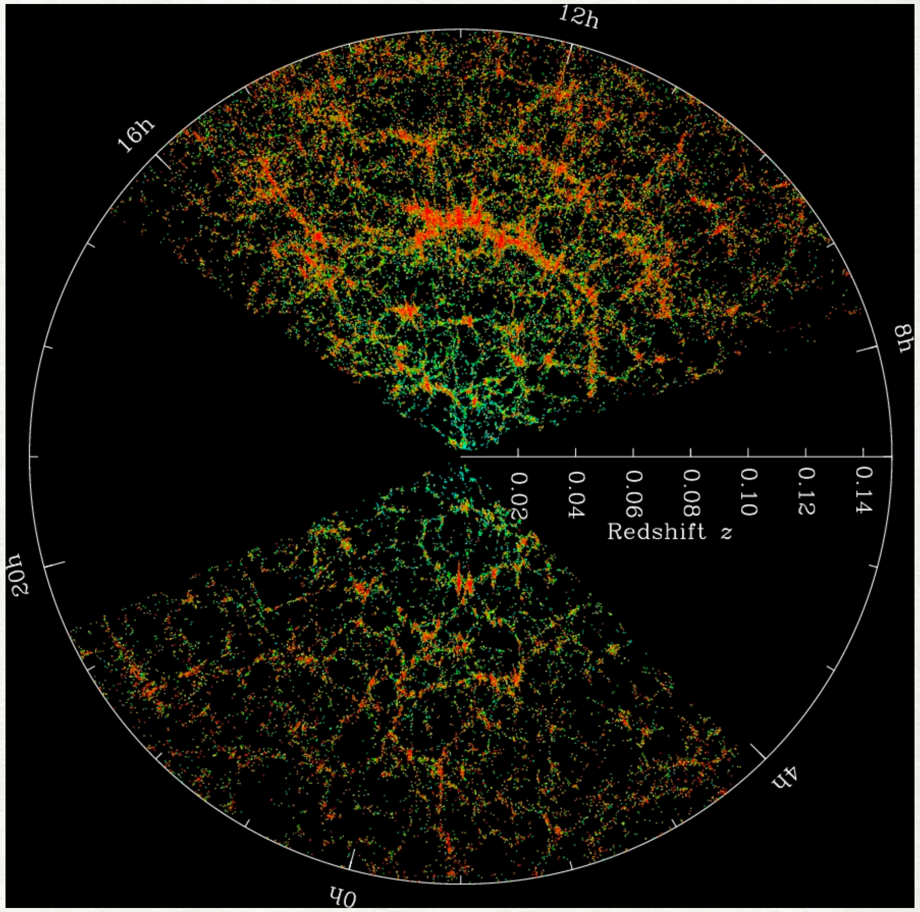
The BAO: a standard ruler in the sky

- The same pattern is seen within CMB anisotropies and galaxy surveys at different epoch.
- It can be used to measure distances and infer H_0 given a model.



Planck 1807.06209

$z \sim 1100$



BOSS/SDSS collaboration

$z \sim 0 - 1$

How does CMB data measure H_0?

- *Planck* measures θ_s at 0.04% precision! r_s & d_A are model dependent.
- H_0 appears only in the angular diameter distance d_A.

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)}$$

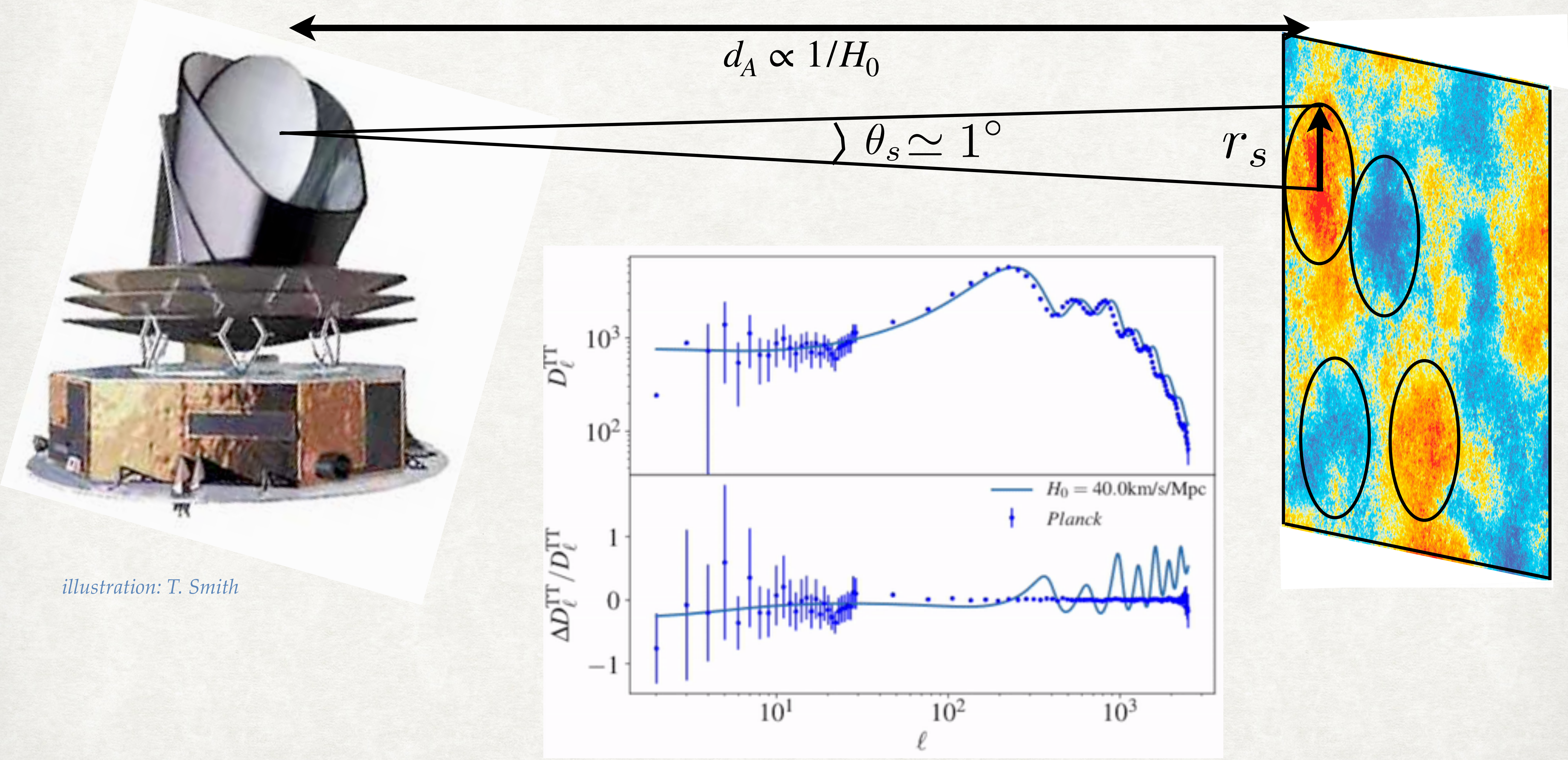


illustration: T. Smith

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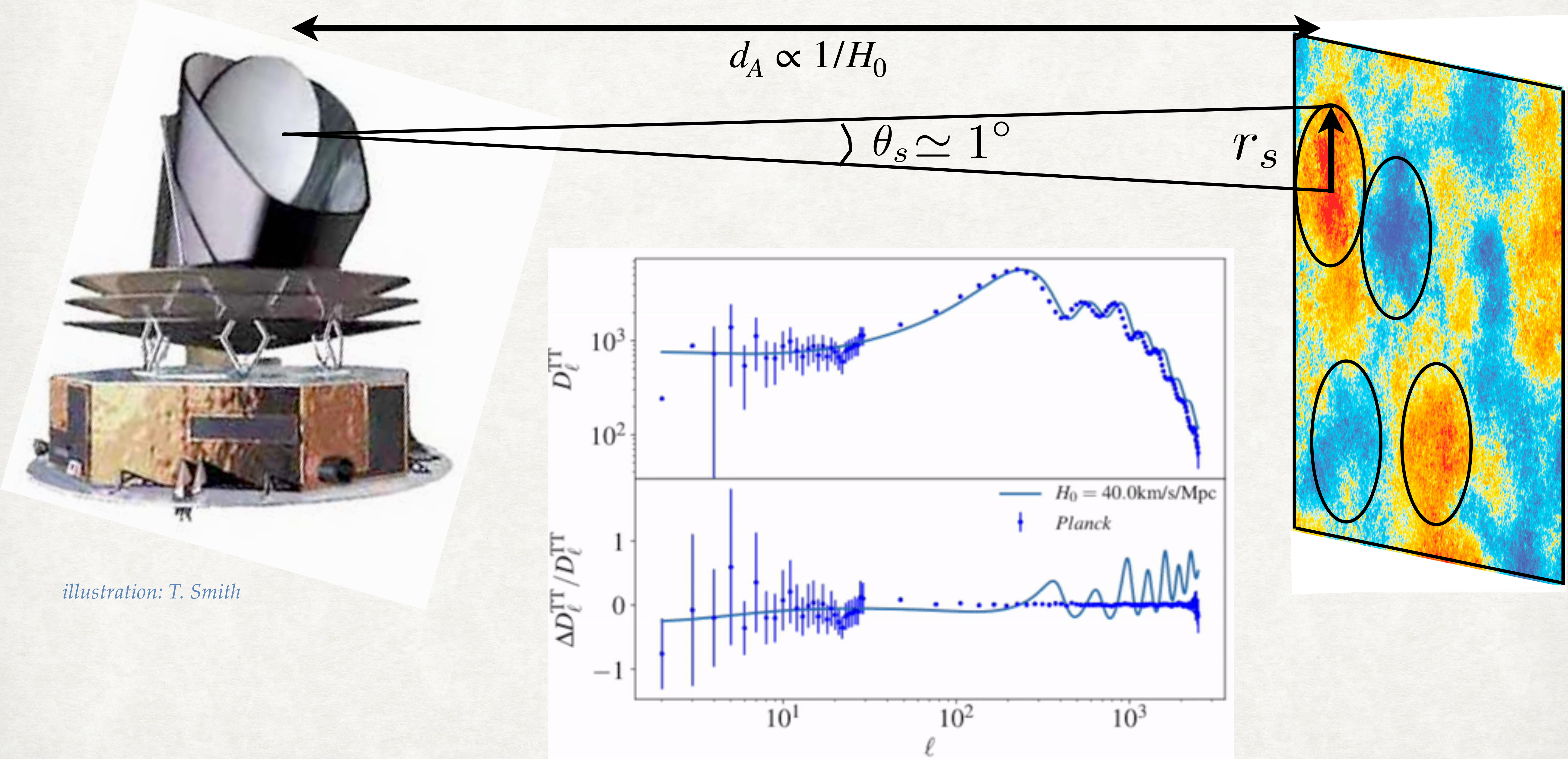
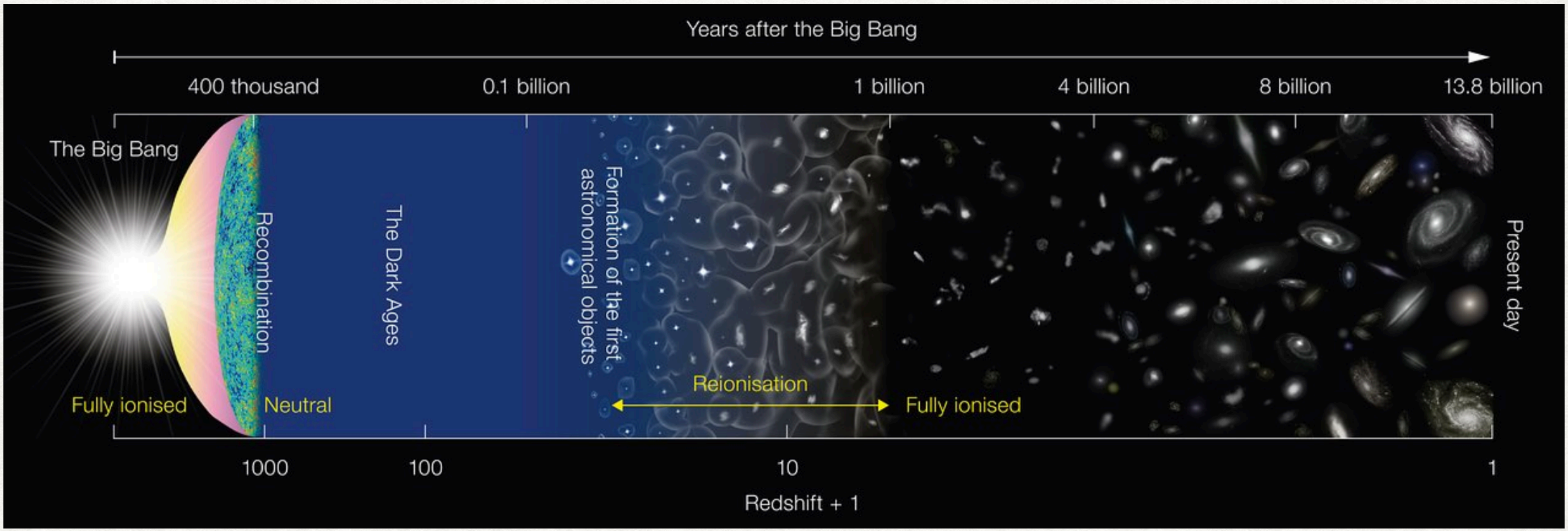


New physics in the Universe?

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)} = \frac{H_0 r_s(z_*)}{\int_0^{z_*} 1/E(z')dz'}$$

$$E(z) \equiv \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \cdots}$$



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Late-universe models

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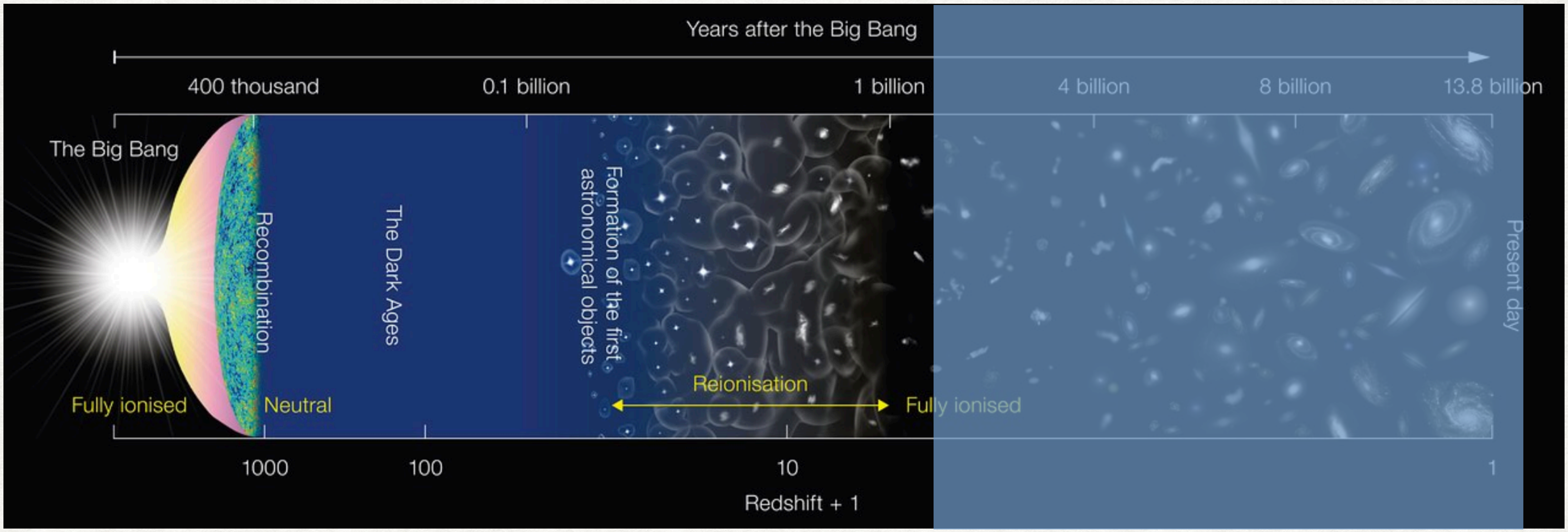

$$\frac{H_0 \nearrow r_s}{\int_0^{z_*} 1/E(x) \searrow \mathrm{d}x}$$

Change expansion history

New physics in the Universe?

Early universe models

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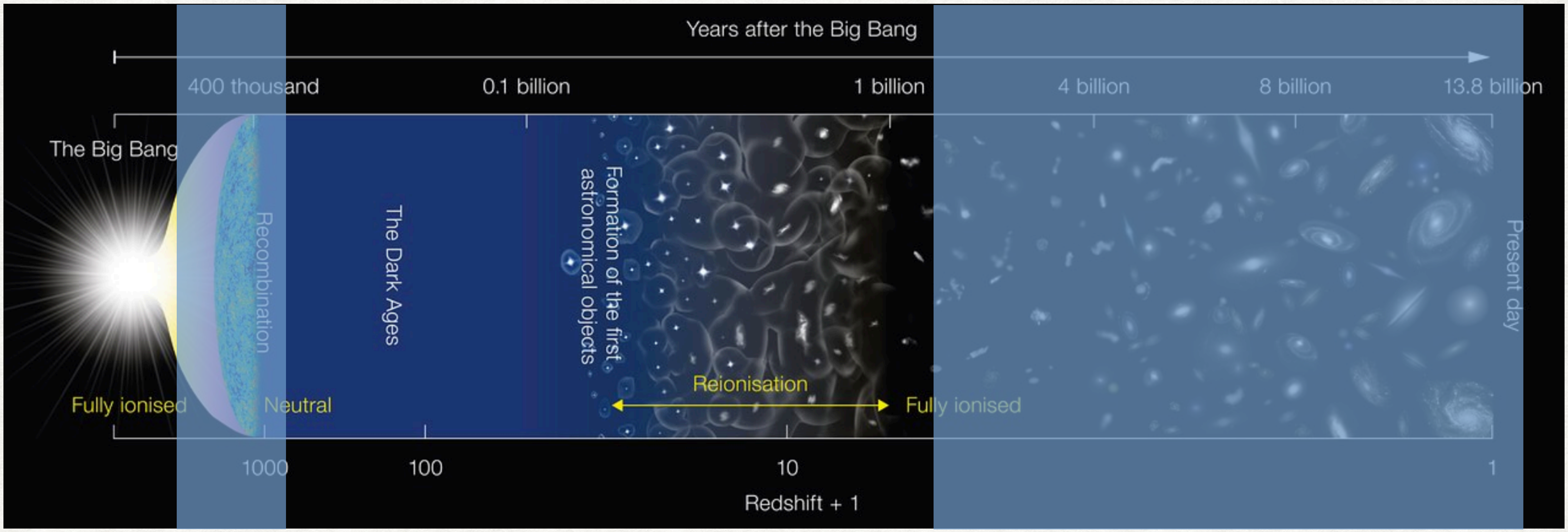

$$\frac{H_0 \nearrow r_s \searrow}{\int_0^z 1/E(x)\mathrm{d}x}$$

Change calibrator

$$\frac{H_0 \nearrow r_s}{\int_0^{z_*} 1/E(x) \searrow \mathrm{d}x}$$

Change expansion history

Geometrical degeneracy in the late-universe!

—> talk by Olga Mena

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

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

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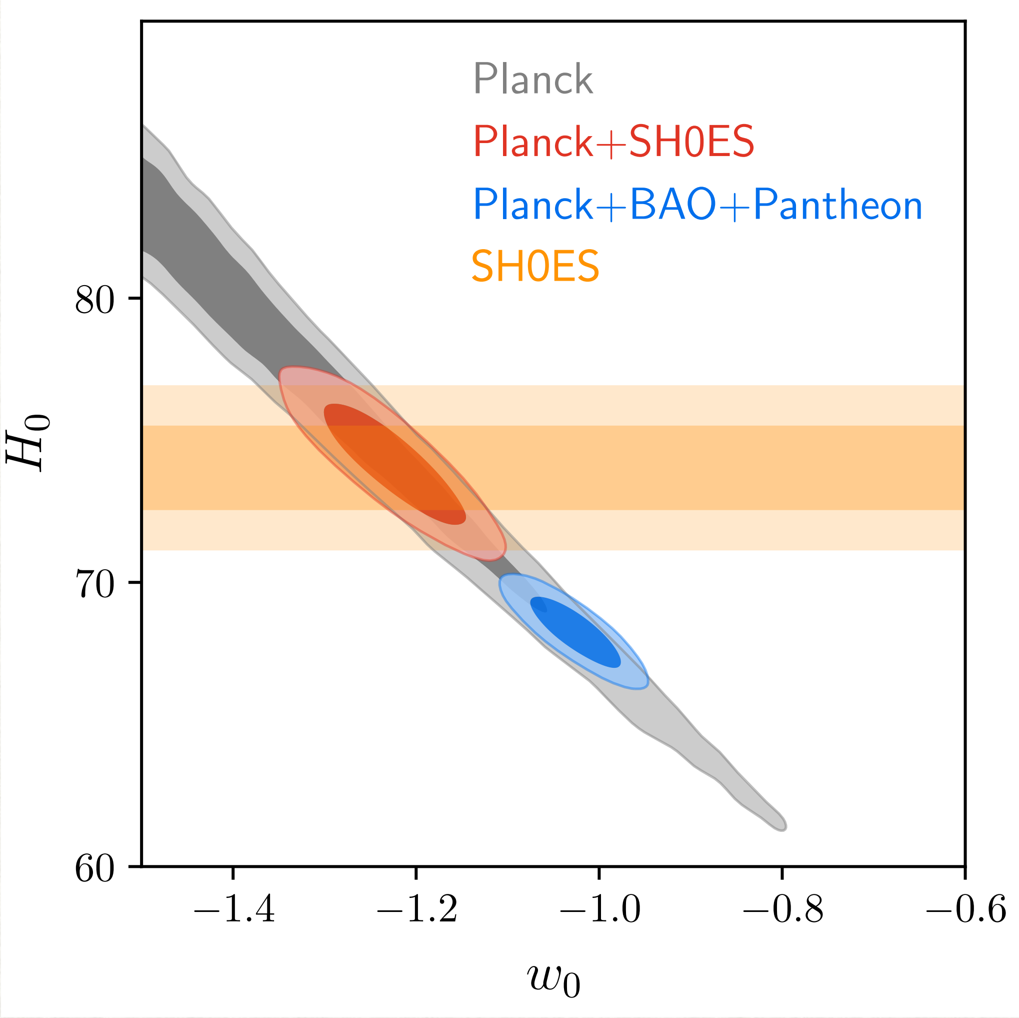
- Planck can easily accommodate a higher H_0: problem with BAO and Pantheon



The tension is truly between calibrators!

Beenakker++2101.01372, Efstathiou 2103.08723

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

BAO: $\theta_d(z) = \dfrac{r_s(z_{\rm drag})}{D_A(z)}$

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

SN1a: $\mu(z) = 5{\rm Log}_{10}D_L(z) + M_b$

- Calibration M_b from cepheids, TRGB…

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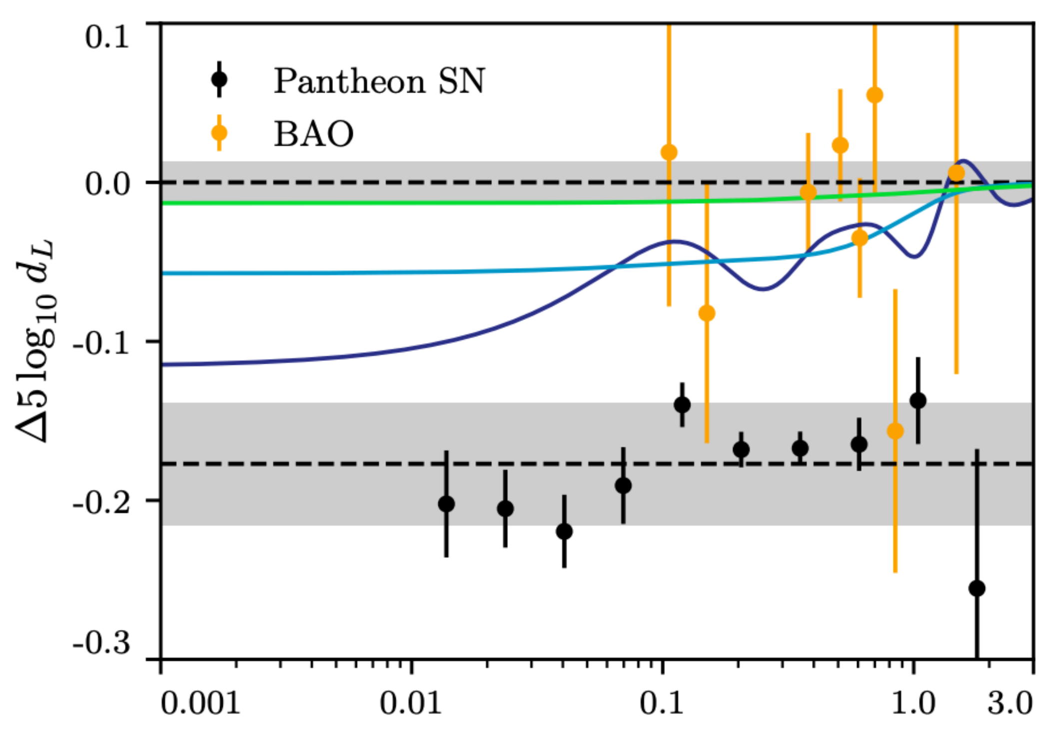

Raveri++ 2107.12992

- Without changing calibration, $D_A(z)$ and $D_L(z)$ are incompatible!

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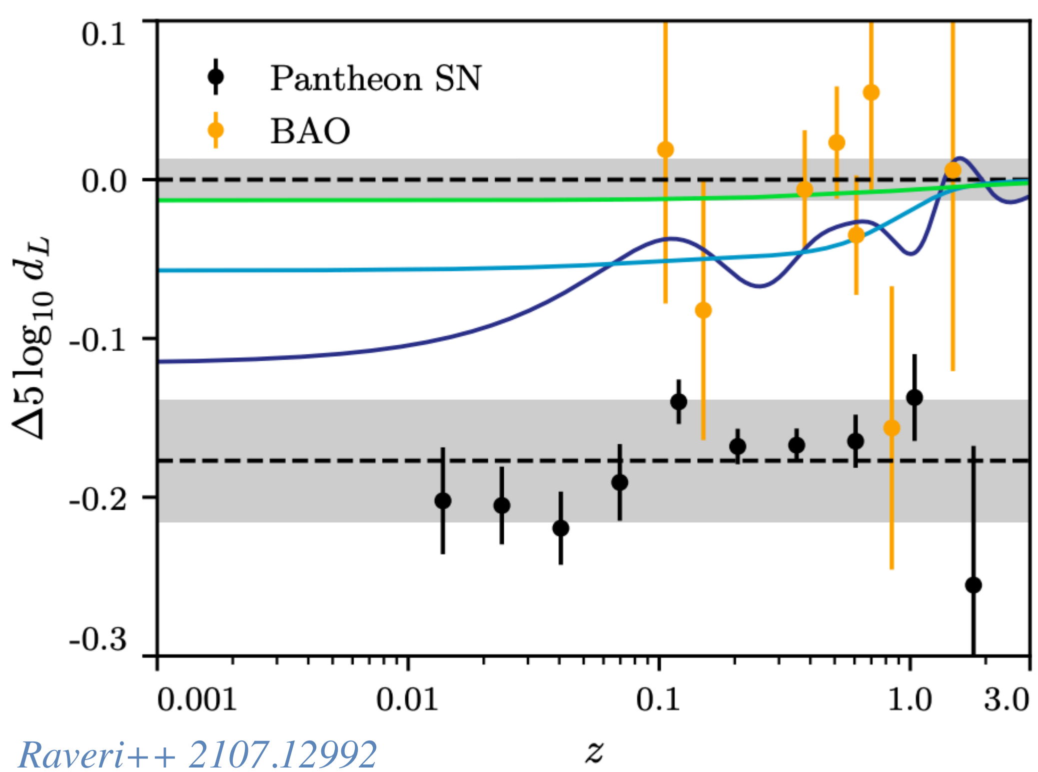

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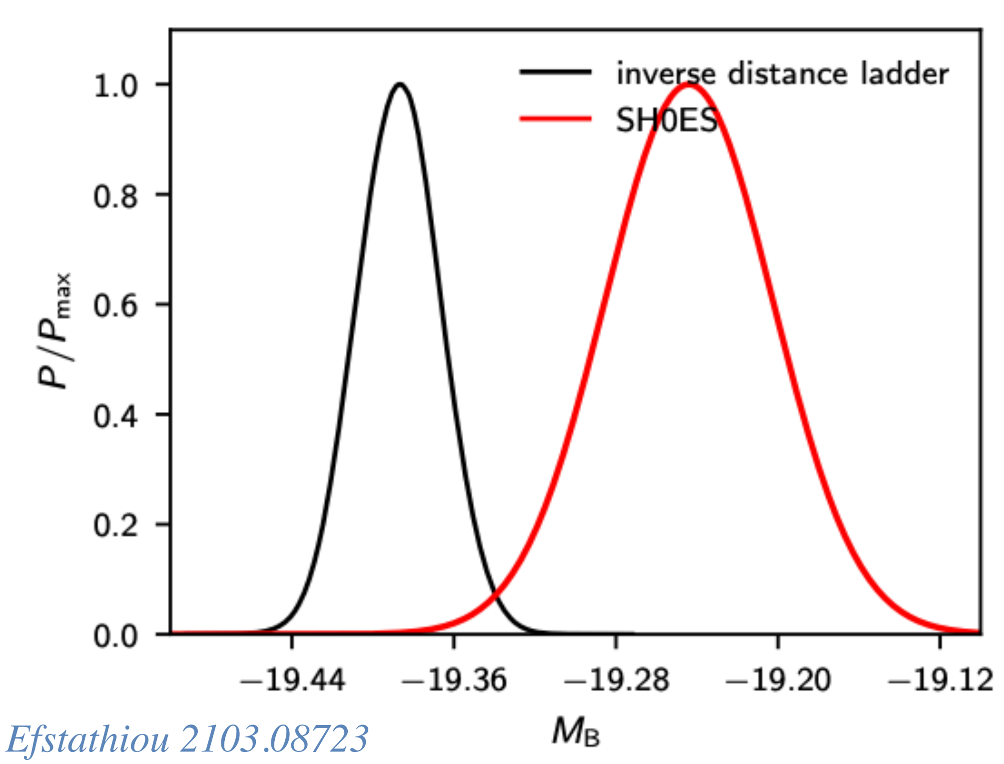
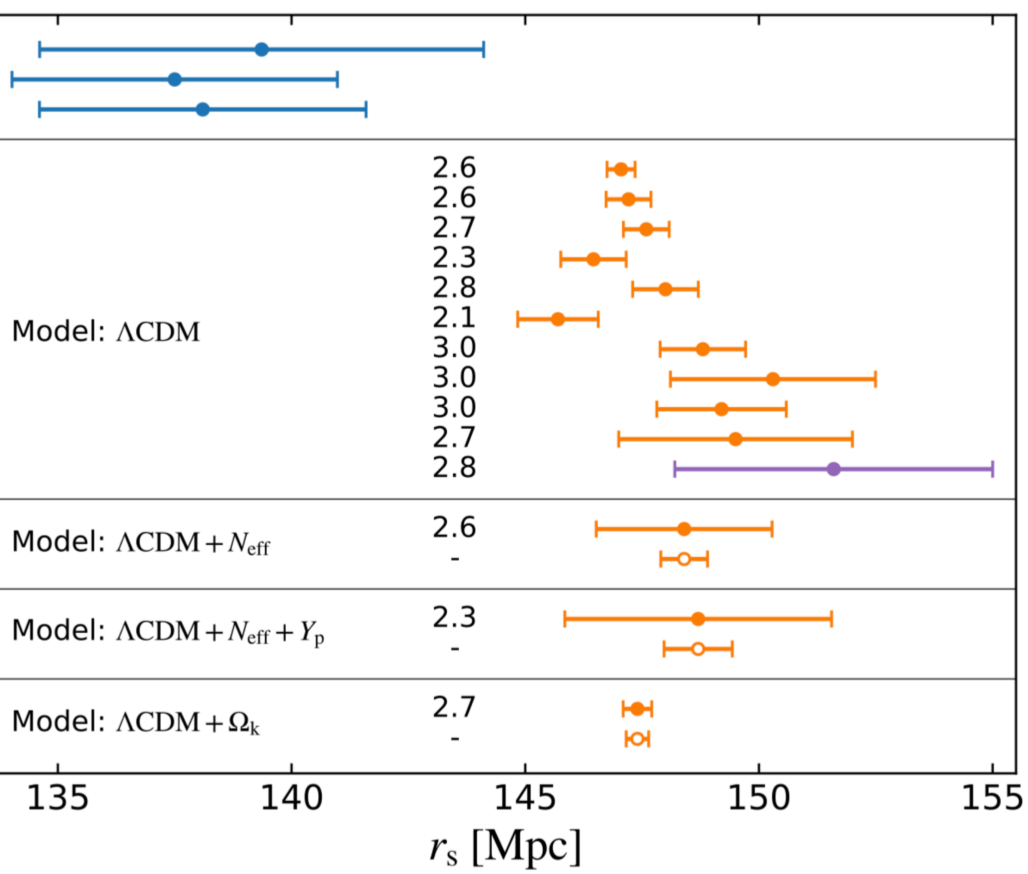


Efstathiou 2103.08723

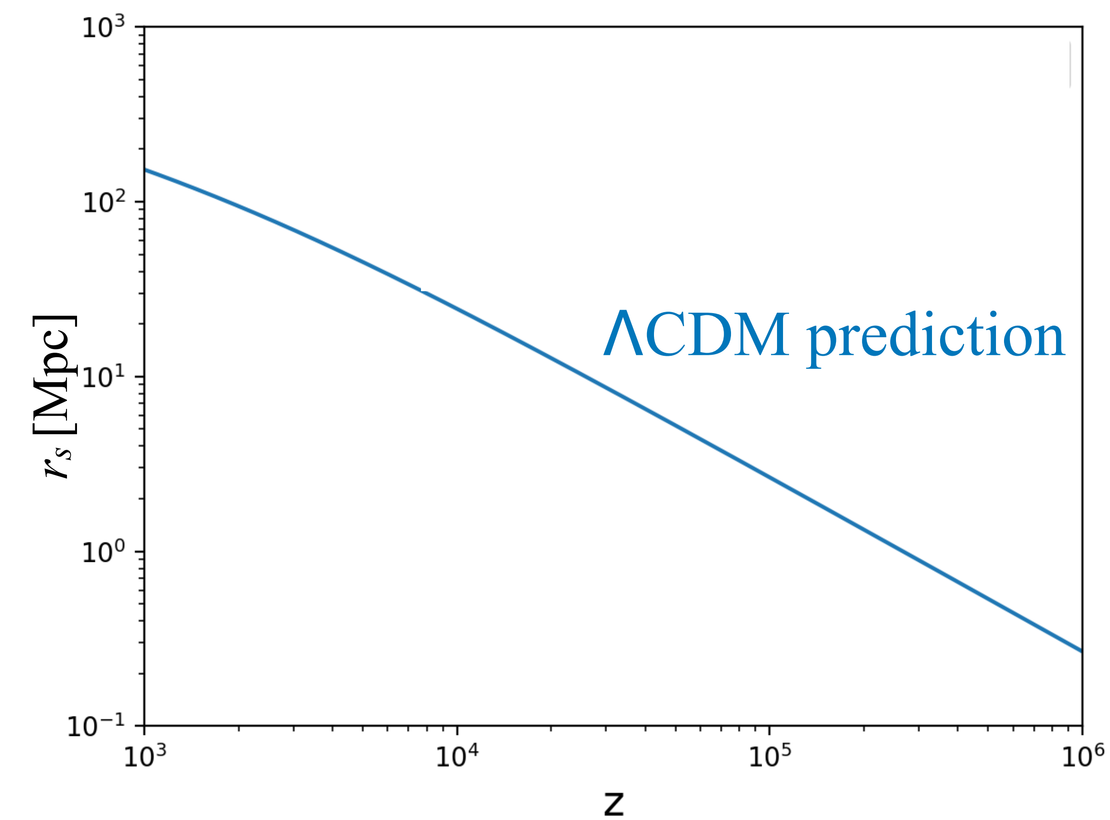
- Without changing calibration, $D_A(z)$ and $D_L(z)$ are incompatible!
- inverse distance ladder calibration: BAO+r_s(ΛCDM) predict M_B incompatible with SH0ES

H_0 tension or r_s tension?

- One can deduce the co-moving sound horizon r_s from H_0 and BAO: CMB estimate must decrease by ~ 10 Mpc



Aylor++1811.00537



$$r_s = \int_\infty^{z_*} dz \frac{c_s(z)}{8\pi G/3\sqrt{\rho_{\rm tot}(z)}}$$

Knox & Millea 1908.03663

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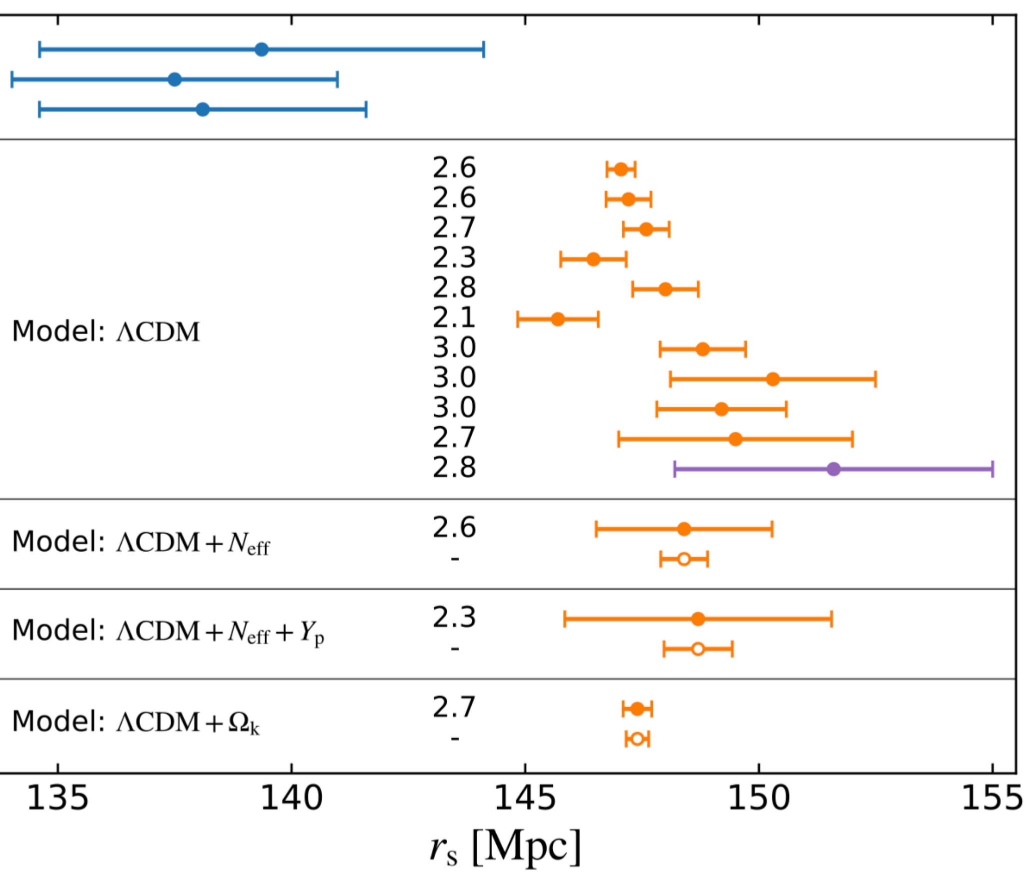

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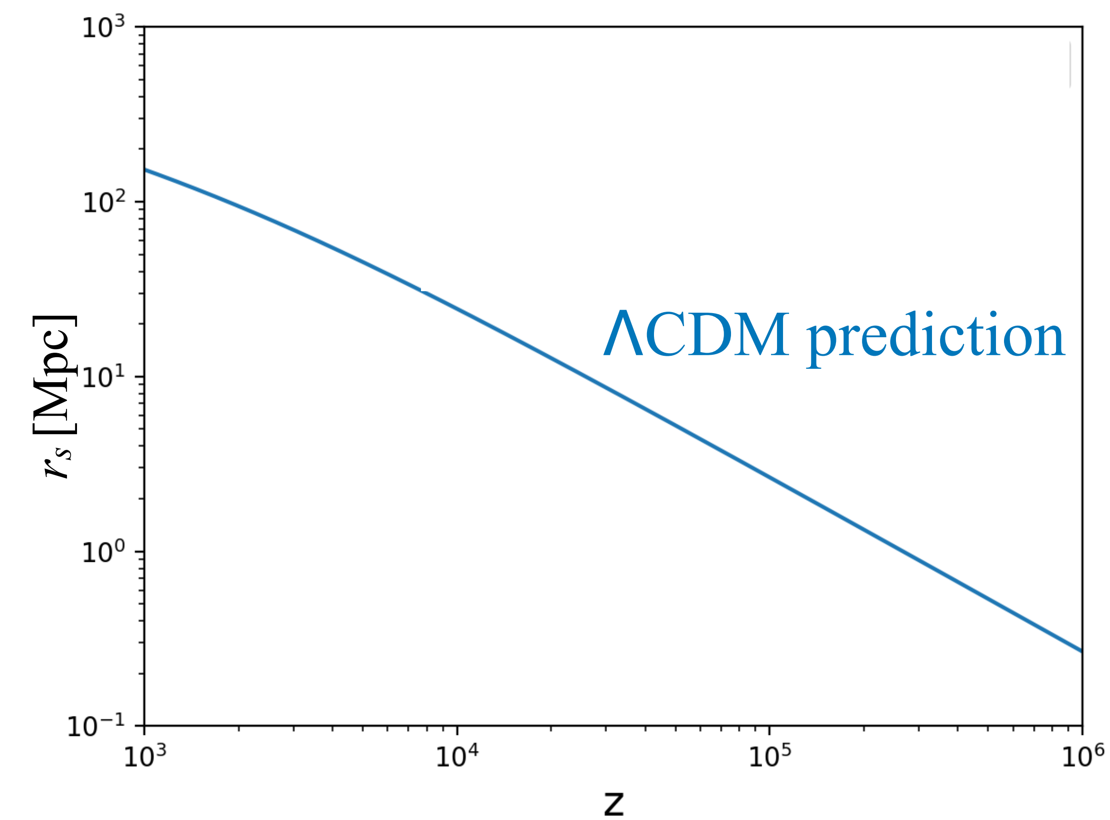

affect c_s: DM-photon scattering? DM-b scattering?

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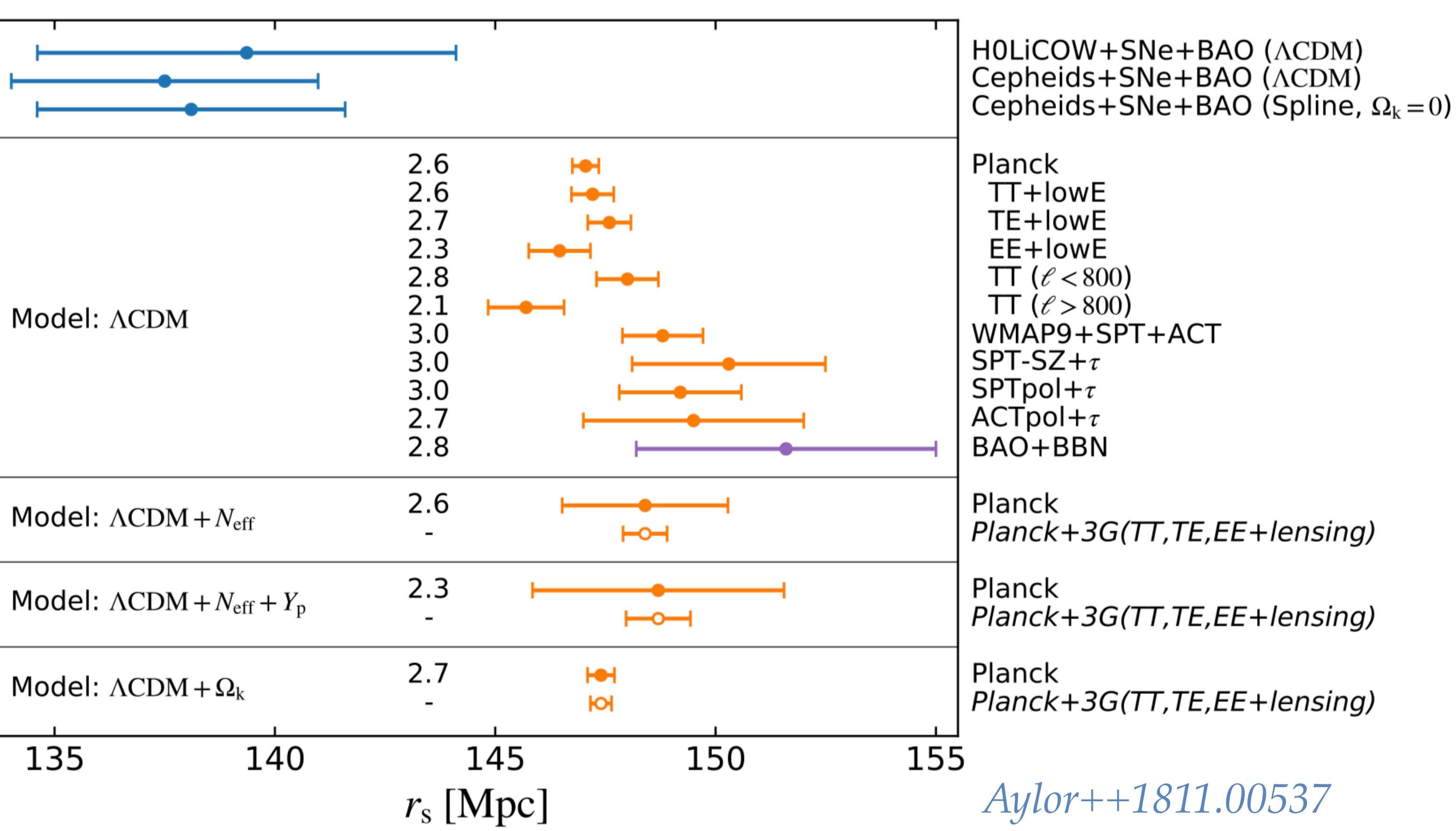

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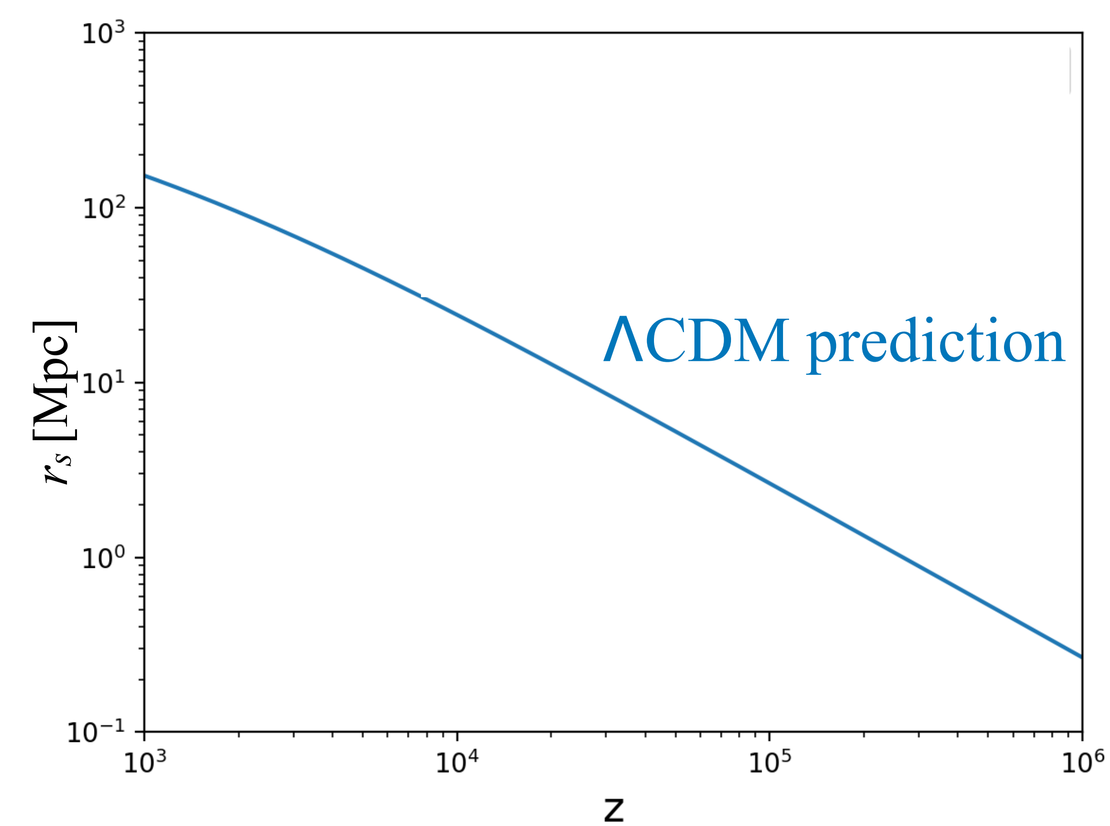

affect z*: modified recombination physics?

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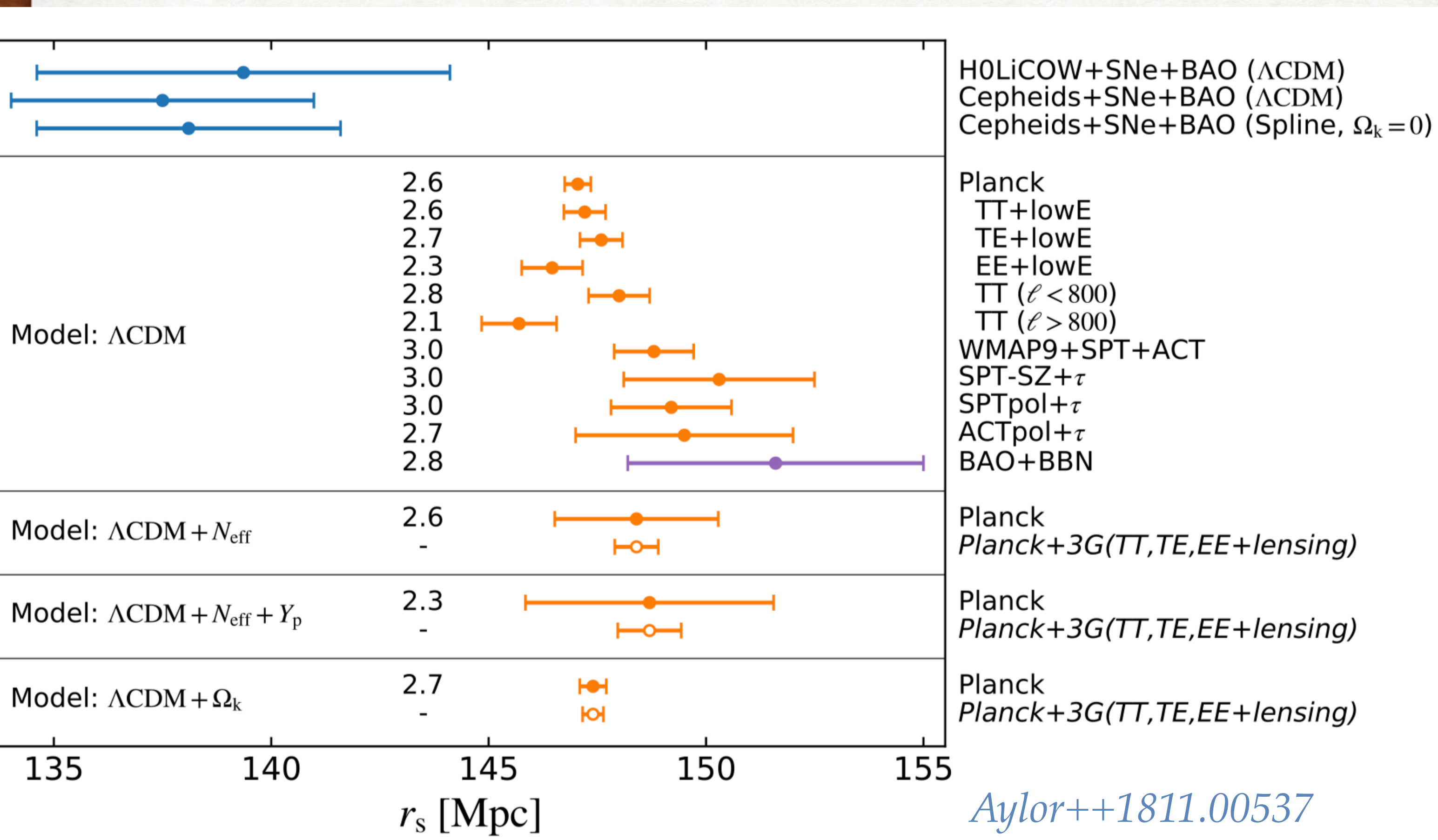

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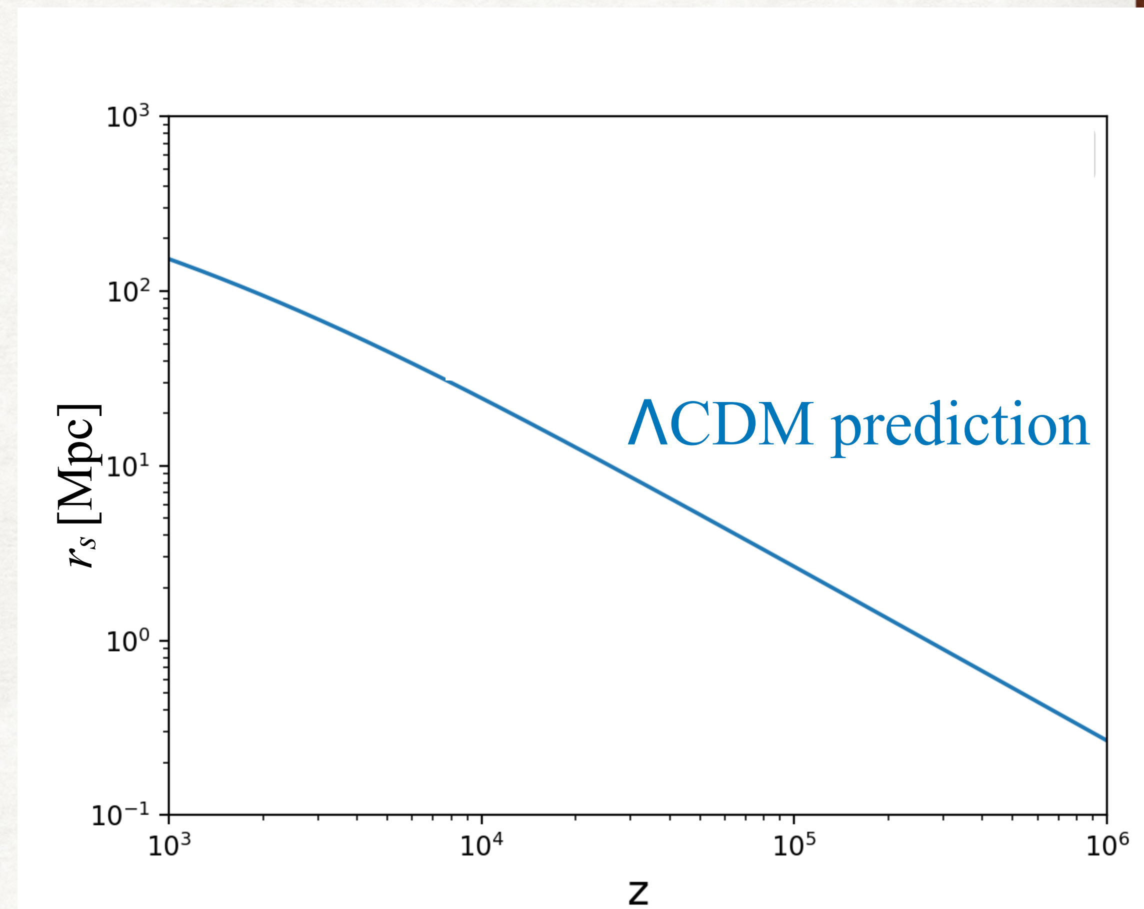

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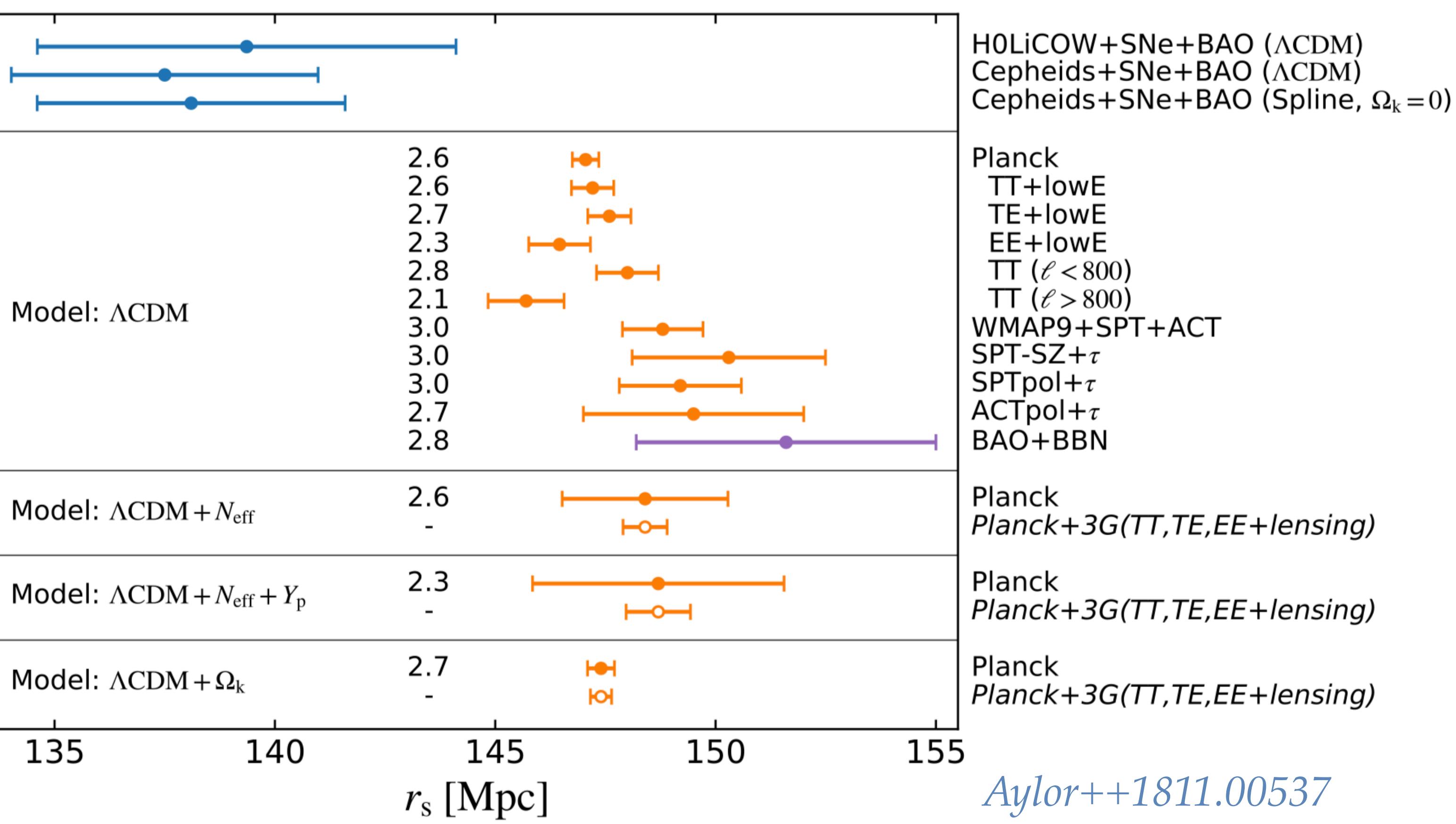

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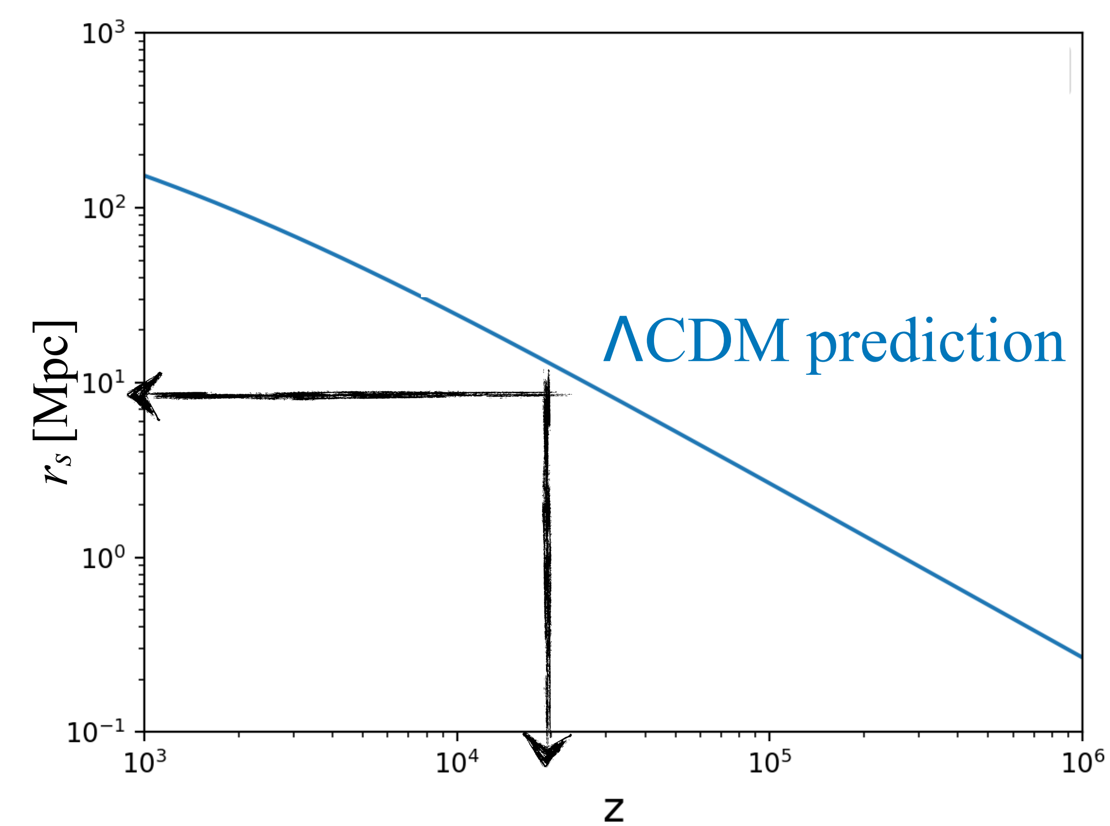

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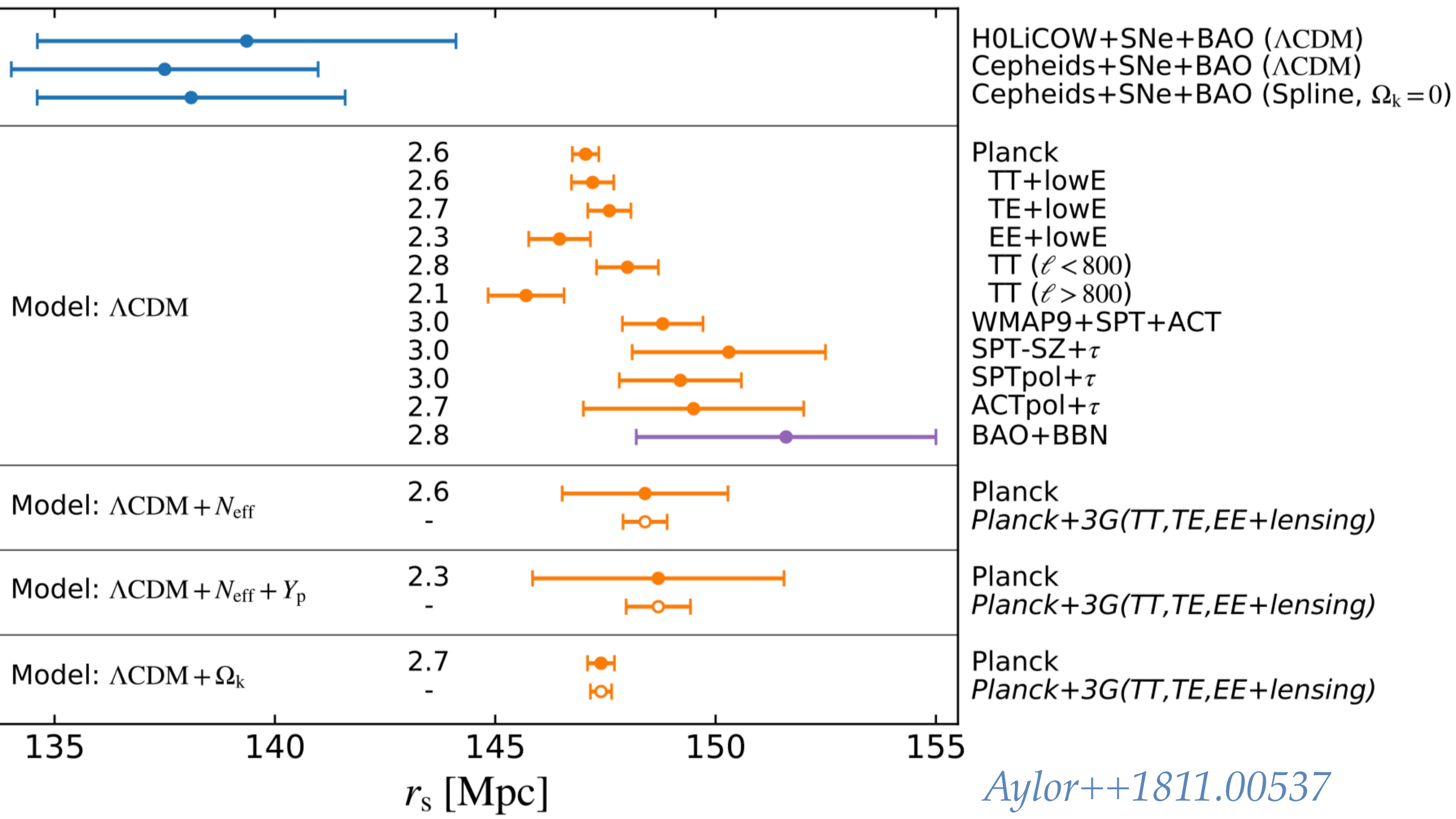

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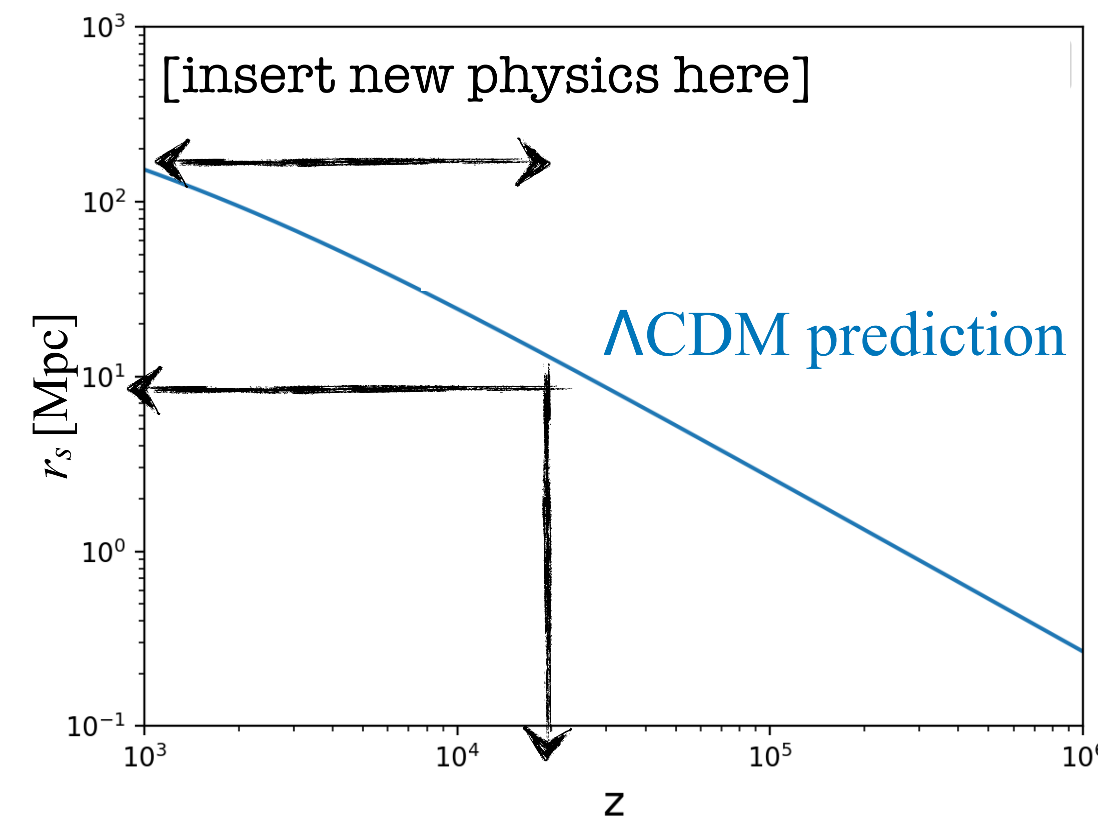

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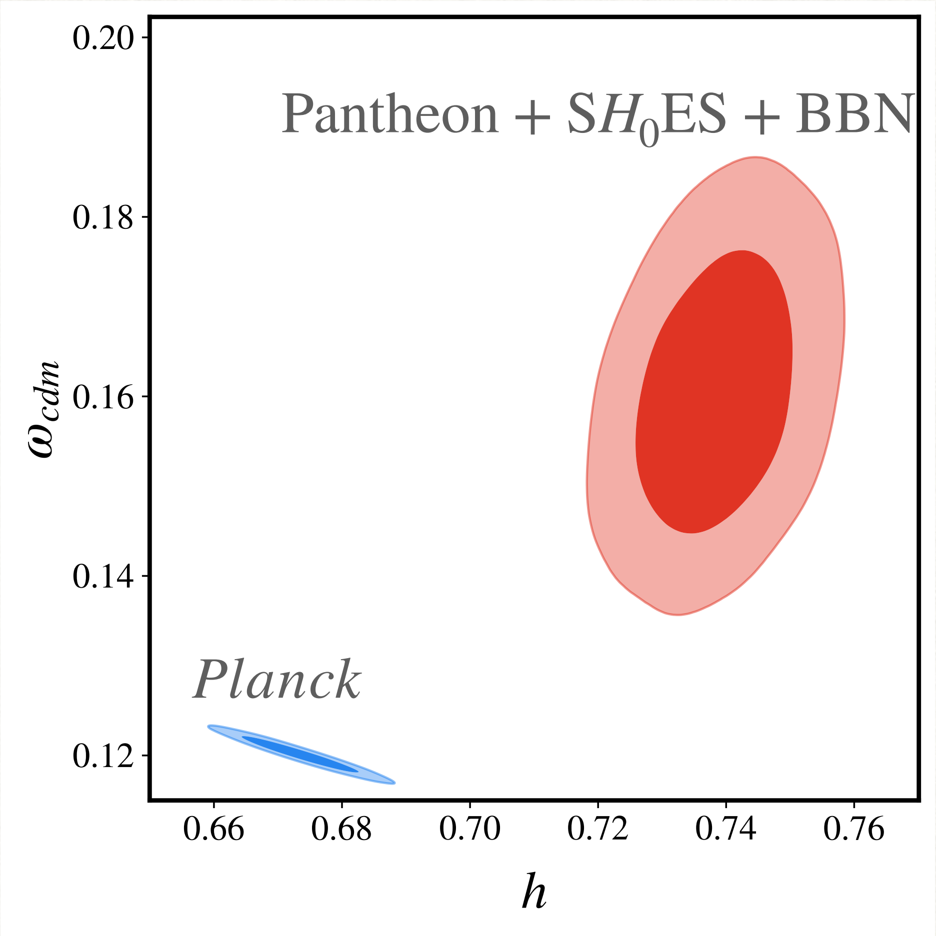
Adding BBN: a higher dimensional tension?

- Pantheon+ $\Omega_m = (\omega_{\rm cdm} + \omega_b)/h^2 \simeq 0.34$
  —> *talk by Dillon Brout*
- BBN fixes ω_b: $\omega_{\rm cdm}$ must increase



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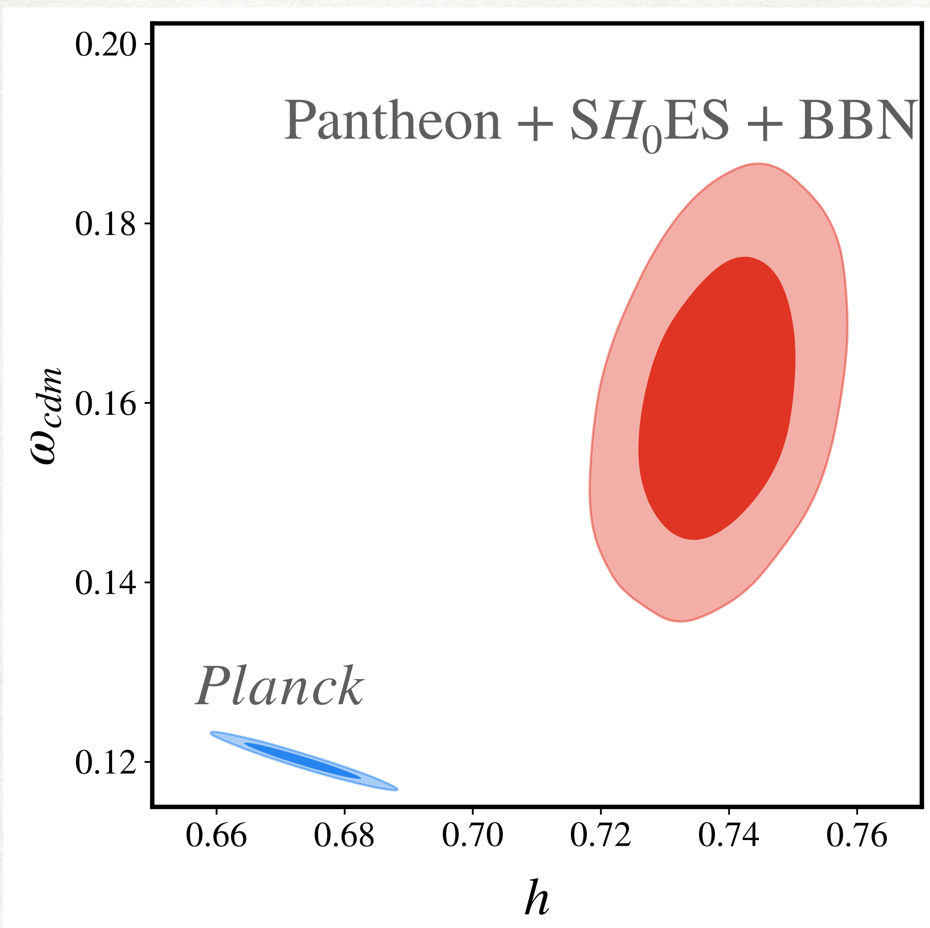

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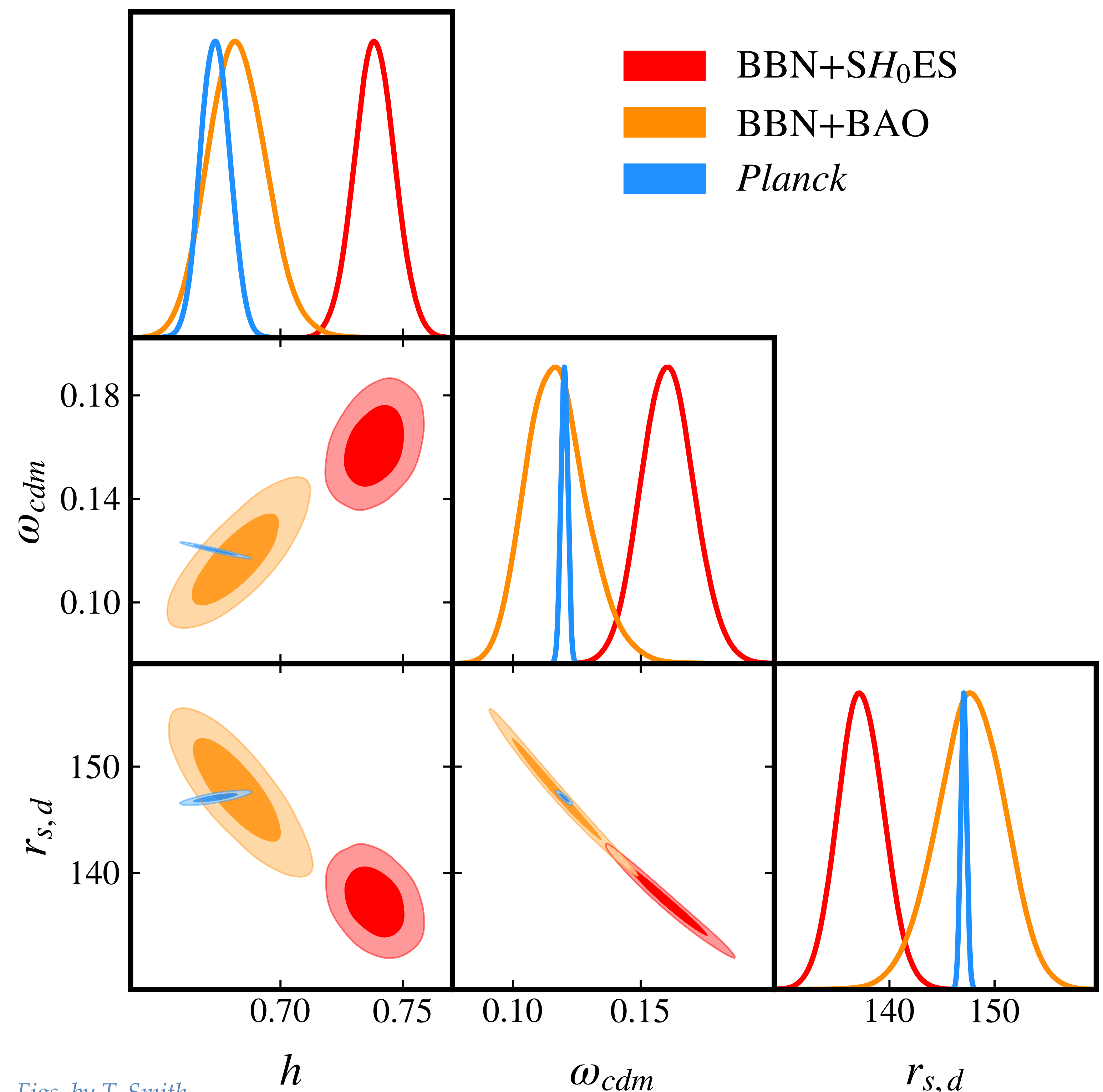

Figs. by T. Smith

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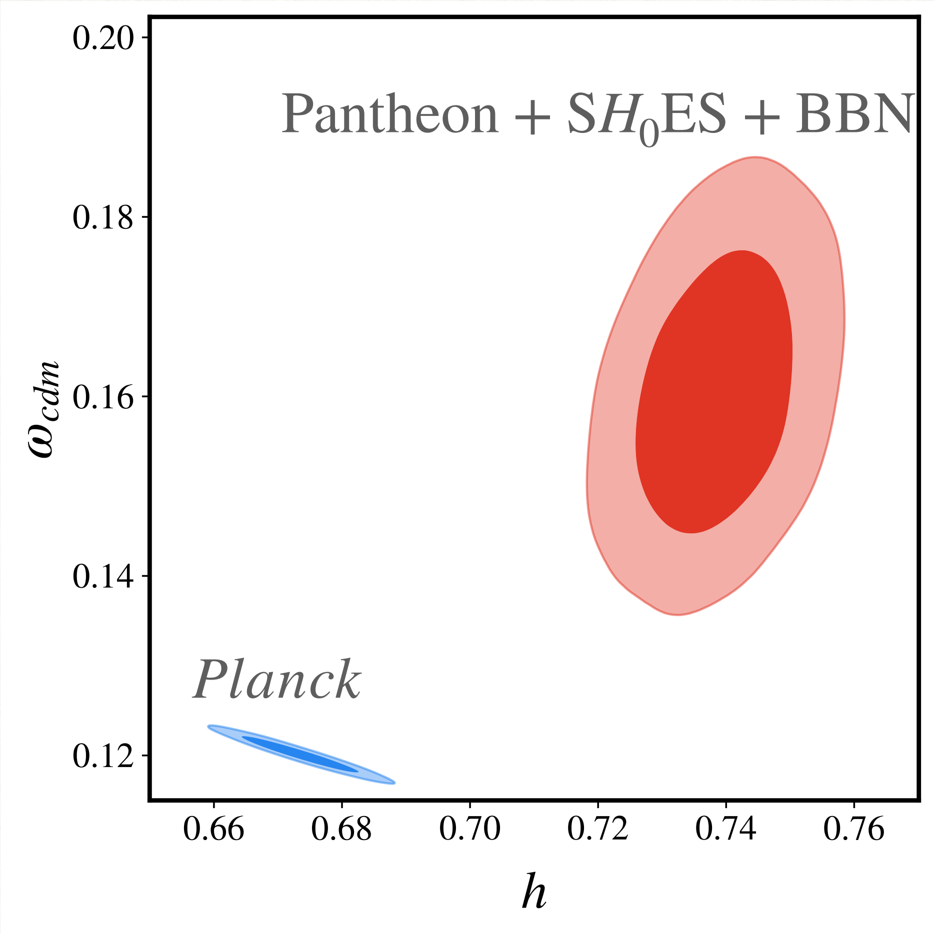
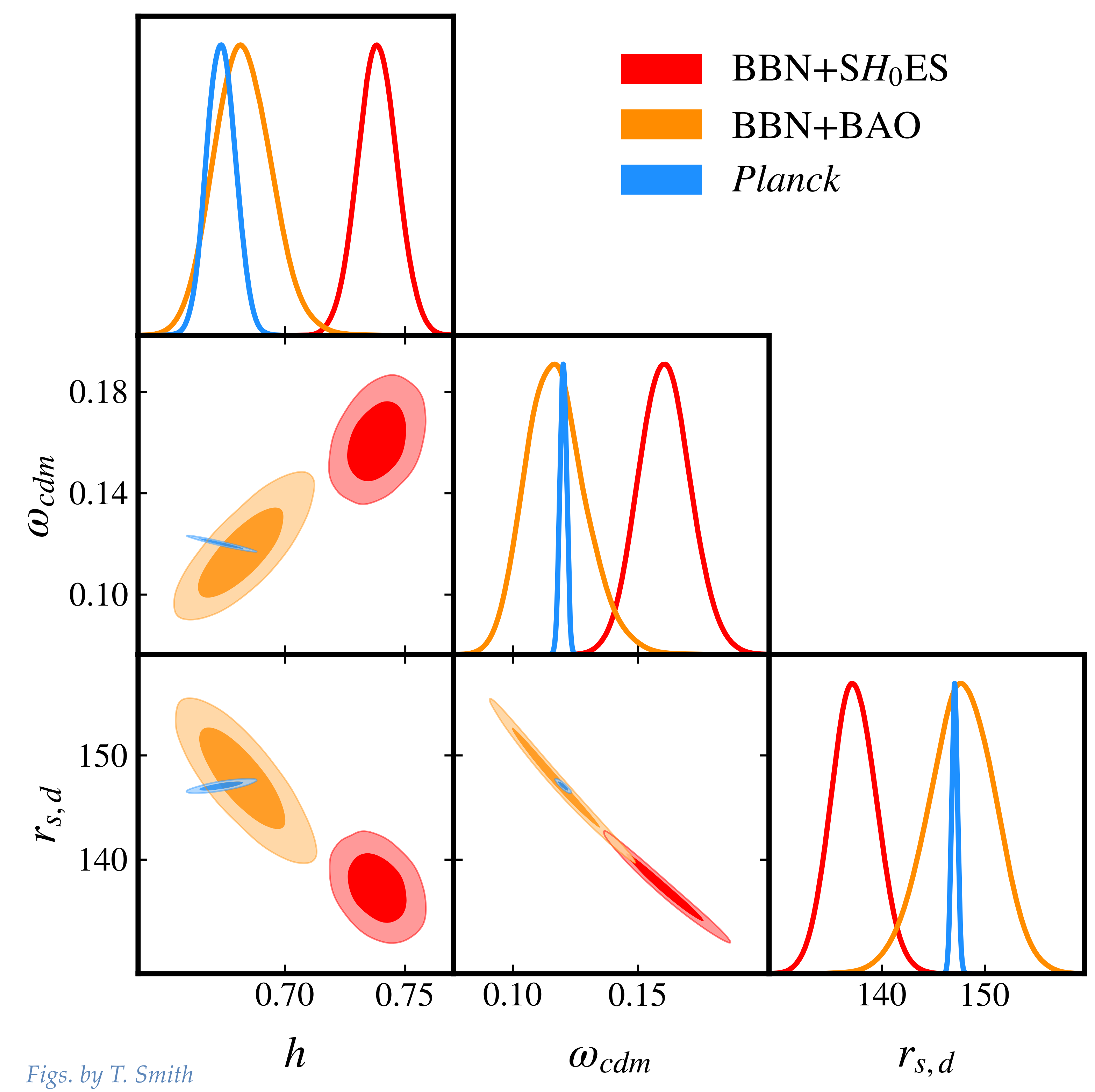


- Resolving H_0 requires decrease in r_s and increase in $\omega_{\rm cdm}$
- This necessarily increases the S_8 tension
  See also Jedamzik, Pogosian, and Zhao 2010.04158



Figs. by T. Smith

Early Dark Energy(s)

Review: VP, Smith, Karwal, 2302.09032 Kamionkowski&Riess 2211.04492

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)

Rock 'n' Roll Solutions to the Hubble Tension

Prateek Agrawal[1], Francis-Yan Cyr-Racine[1,2], David Pinner[1,3], and Lisa Randall[1]
[1]*Department of Physics, Harvard University, 17 Oxford St., Cambridge, MA 02138, USA*
[2]*Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Blvd NE, Albuquerque, NM 87131, USA*
[3]*Department of Physics, Brown University, 182 Hope St., Providence, RI 02912, USA*

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

Jeremy Sakstein* and Mark Trodden†
Center for Particle Cosmology, Department of Physics and Astronomy,
University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA

Chain Early Dark Energy:
Solving the Hubble Tension and Explaining Today's Dark Energy

Katherine Freese*[1,2,3] and Martin Wolfgang Winkler†[1,2]

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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]

Early Dark Energy Can Resolve The Hubble Tension

Vivian Poulin[1], Tristan L. Smith[2], Tanvi Karwal[1], and Marc Kamionkowski[1]
[1]*Department of Physics and Astronomy, Johns Hopkins University,*
3400 N. Charles St., Baltimore, MD 21218, United States and
[2]*Department of Physics and Astronomy, Swarthmore College,*
500 College Ave., Swarthmore, PA 19081, United States

Acoustic Dark Energy: Potential Conversion of the Hubble Tension

Meng-Xiang Lin,[1] Giampaolo Benevento,[2,3,1] Wayne Hu,[1] and Marco Raveri[1]
[1]*Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics,*
Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA
[2]*Dipartimento di Fisica e Astronomia "G. Galilei",*
Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy
[3]*INFN, Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy*

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*
nstitute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China

Thermal Friction as a Solution to the Hubble Tension

Kim V. Berghaus[1] and Tanvi Karwal[1,2]
[1]*Department of Physics and Astronomy, Johns Hopkins University,*
3400 N. Charles St., Baltimore, MD 21218, United States and
[2]*Center for Particle Cosmology, Department of Physics and Astronomy,*
University of Pennsylvania, 209 S. 33rd St., Philadelphia, PA 19104, United States
(Dated: November 15, 2019)

New Early Dark Energy

Florian Niedermann[1,*] and Martin S. Sloth[1,†]
CP[3]-Origins, Center for Cosmology and Particle Physics Phenomenology

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

Miguel Zumalacárregui[1,2,3,*]
[1]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute)*
Am Mühlenberg 1, D-14476 Potsdam-Golm, Germany
[2]*Berkeley Center for Cosmological Physics, LBNL and University of California at Berkeley,*
Berkeley, California 94720, USA
[3]*Institut de Physique Théorique, Université Paris Saclay CEA, CNRS, 91191 Gif-sur-Yvette, France*
(Dated: June 11, 2020)

What is Early Dark Energy?

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

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

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- Oscillating potential: $V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$

Karwal& Kamionkowski 1608.01309, VP, Smith,Karwal++ 1806.10608 & 1811.04083; Smith, VP++ 1908.06995

- 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

- First-order phase transition (NEDE model)

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

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- Oscillating potential: $V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$

  Karwal& Kamionkowski 1608.01309, VP, Smith,Karwal++ 1806.10608 & 1811.04083; Smith, VP++ 1908.06995

- 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

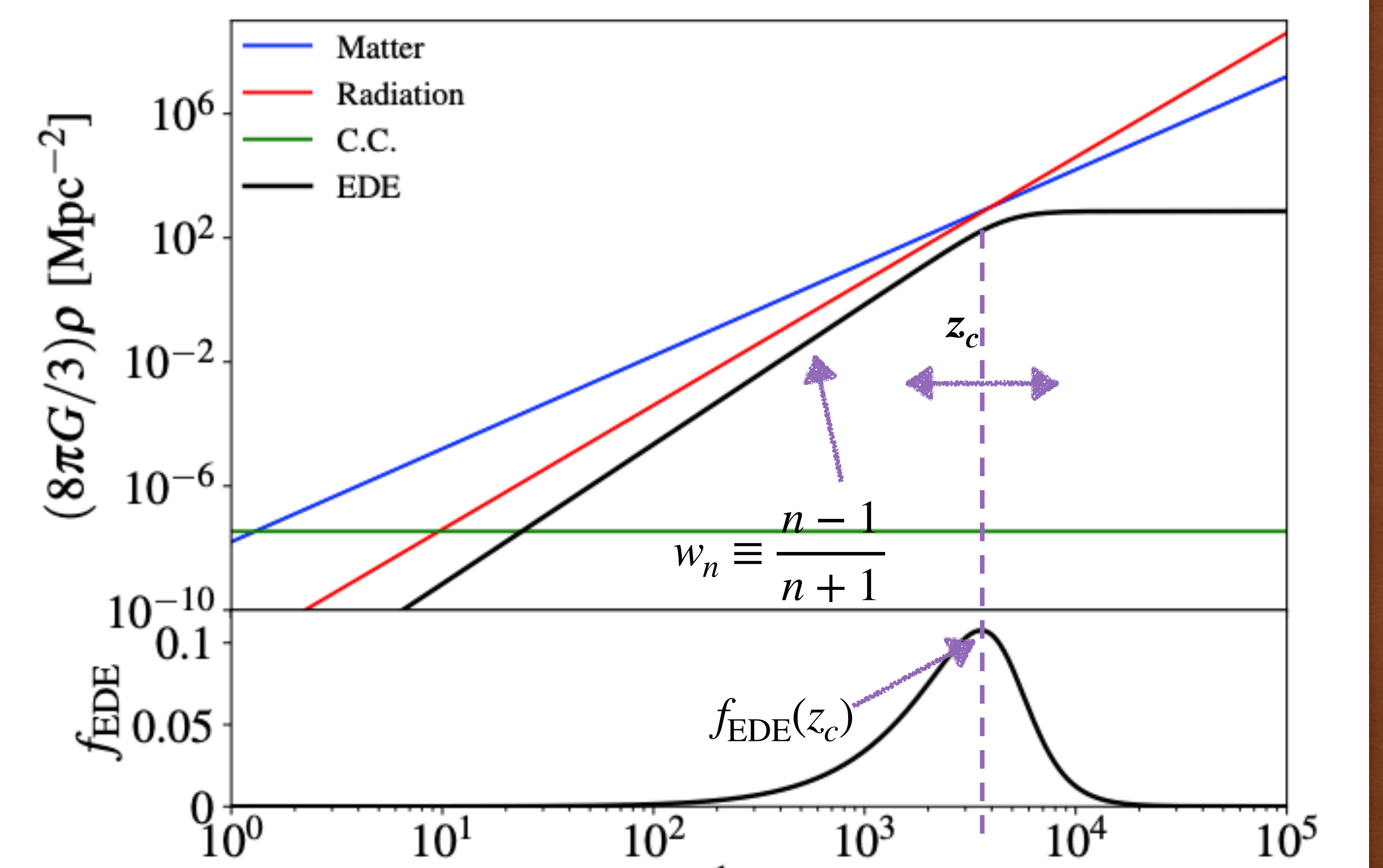
- First-order phase transition (NEDE model)

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

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

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

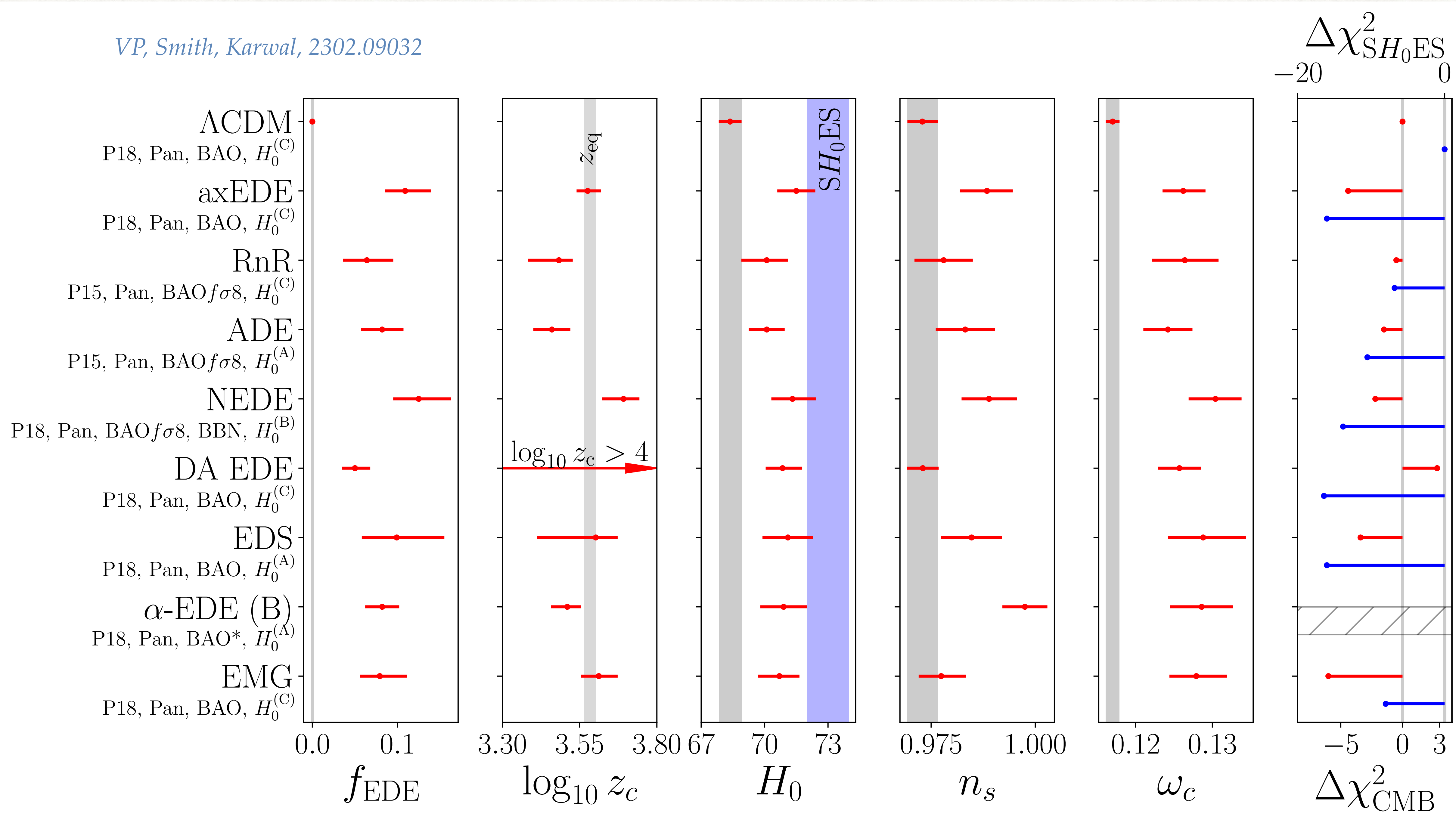
$n = 1$: matter, $n = 2$: radiation, etc.



VP, Smith, Karwal, 2302.09032

Status of EDE solutions

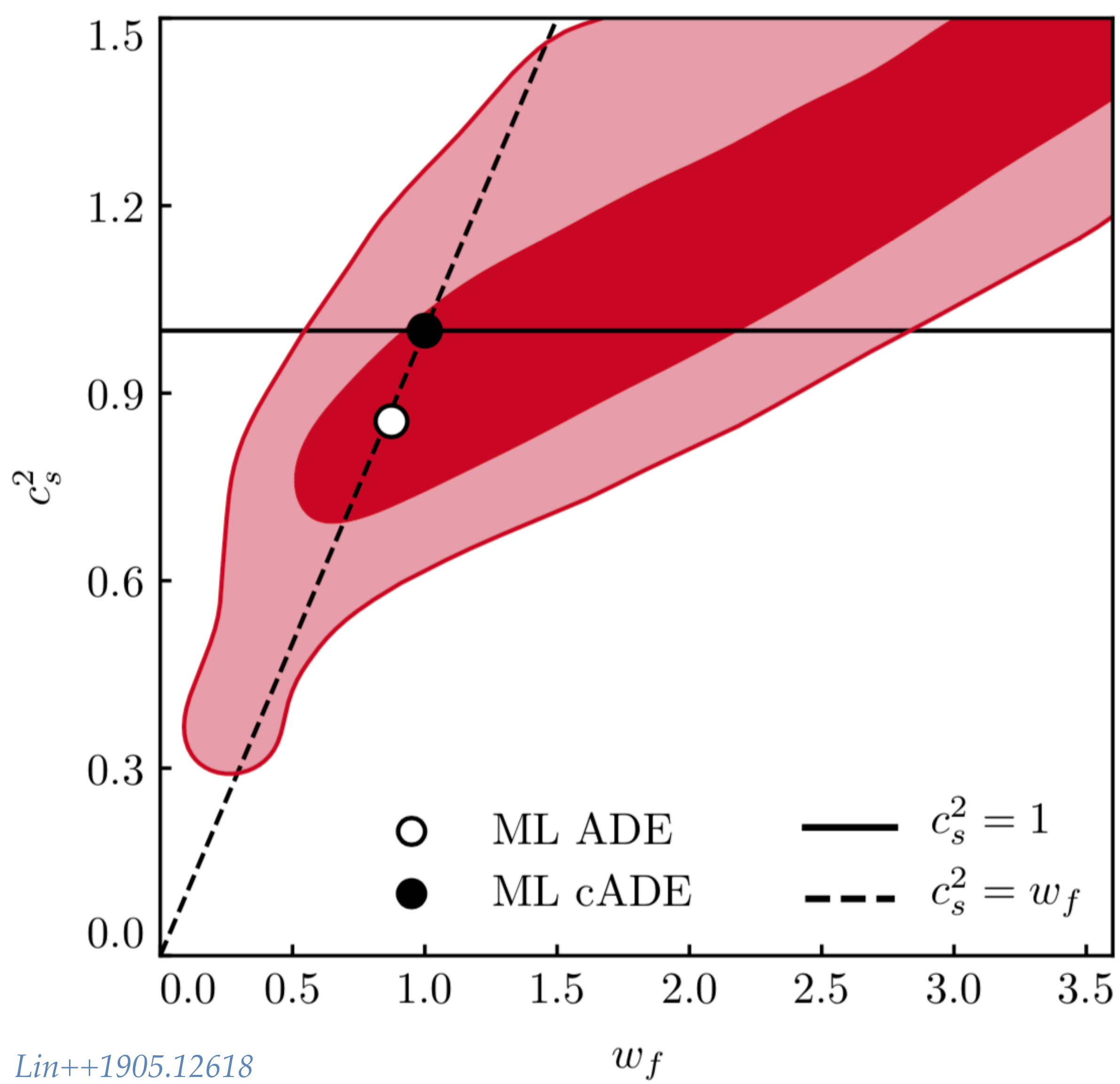
- *Planck* + BAO + Pantheon + SH0ES : a good fit with strong preference over ΛCDM



- Similar background properties although not all models yield the same overall improvement

EDE "microphysics" is constrained

- CMB data can constrain more than $f_{\rm EDE}$ and z_c: tight relation between w and c_s^2



Lin++1905.12618

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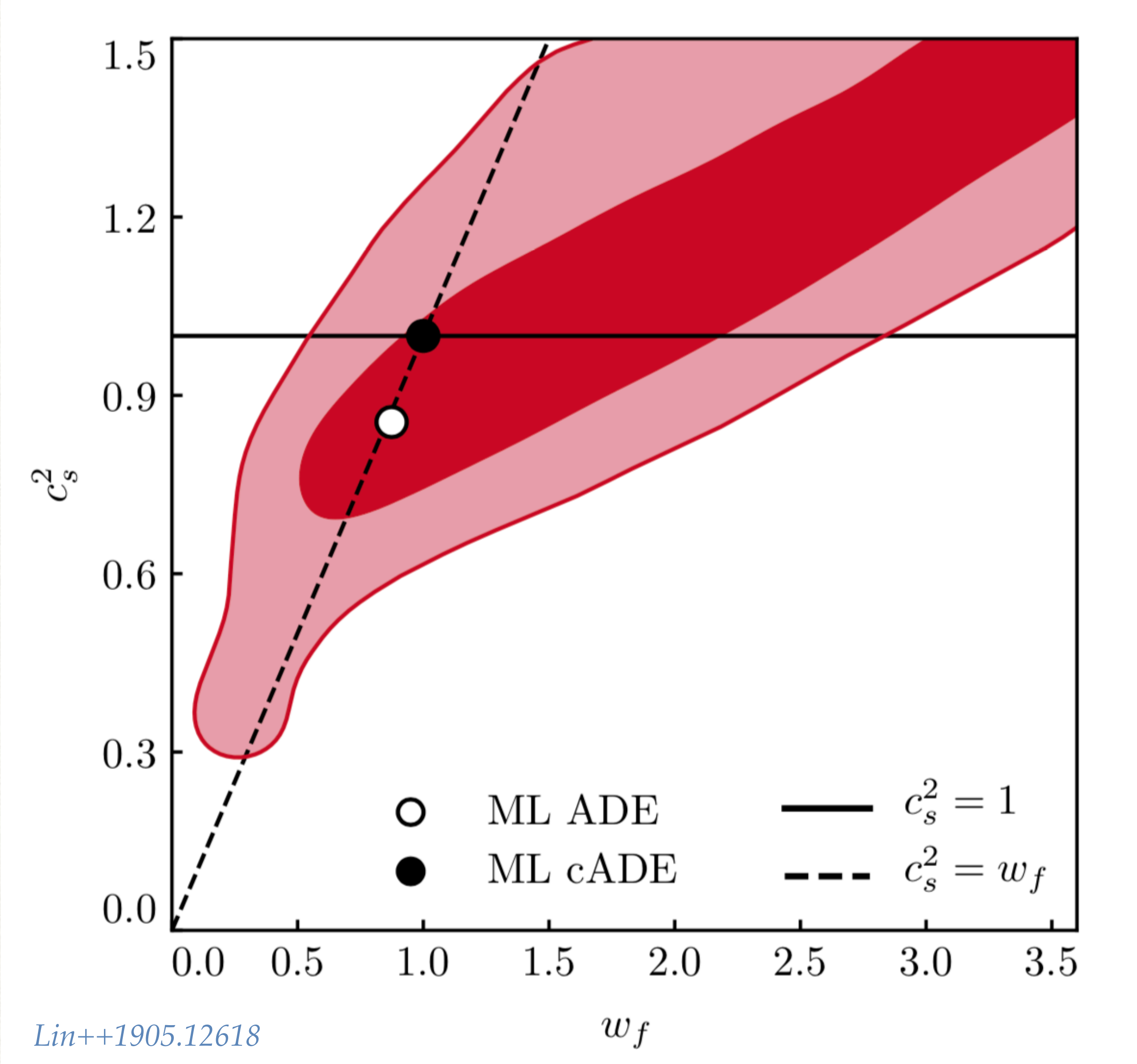
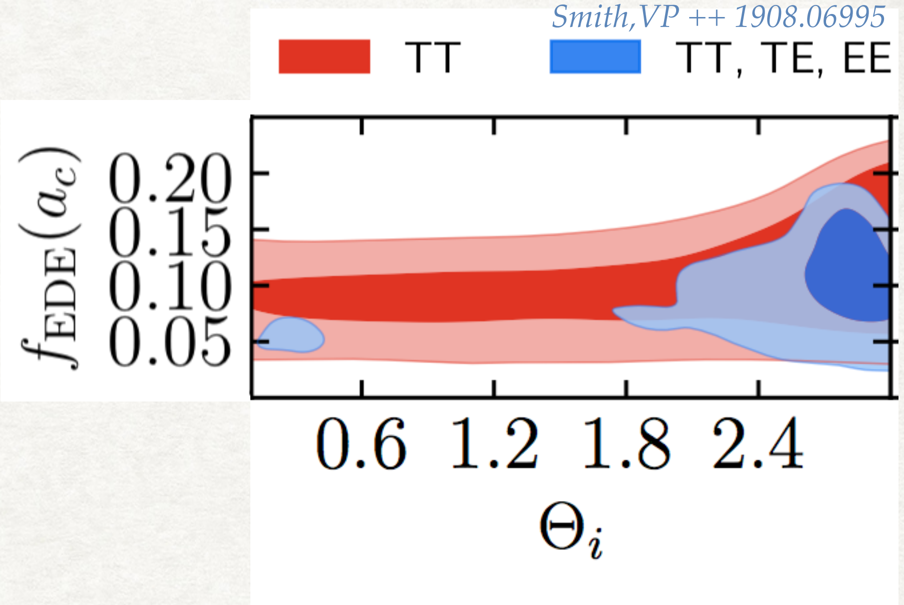
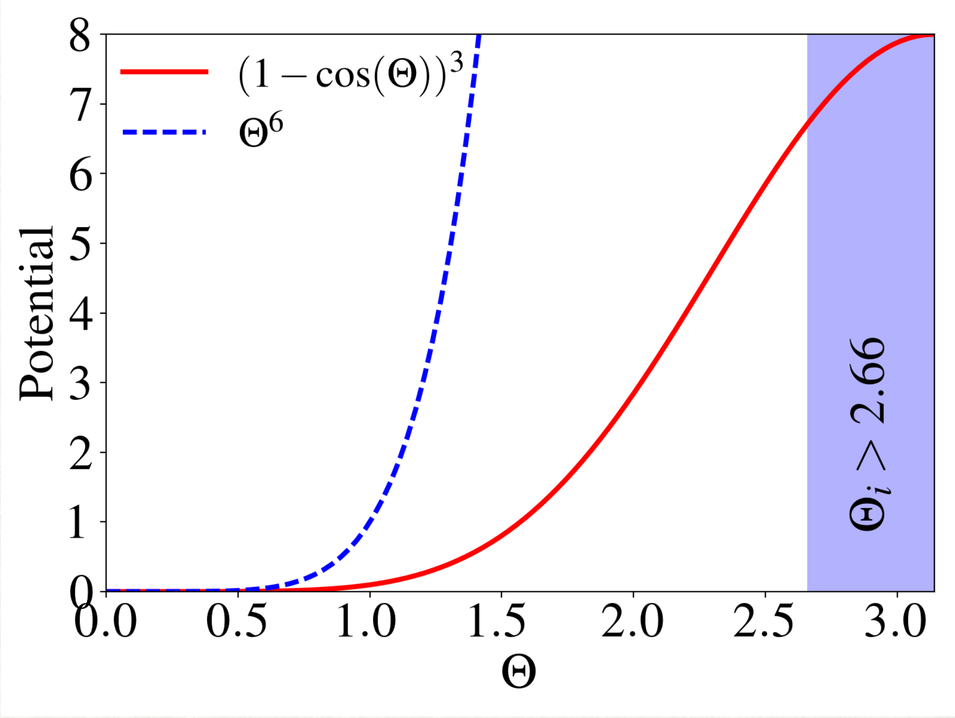






- In the "axion-like" model, this translates into tight constrain on the initial field value

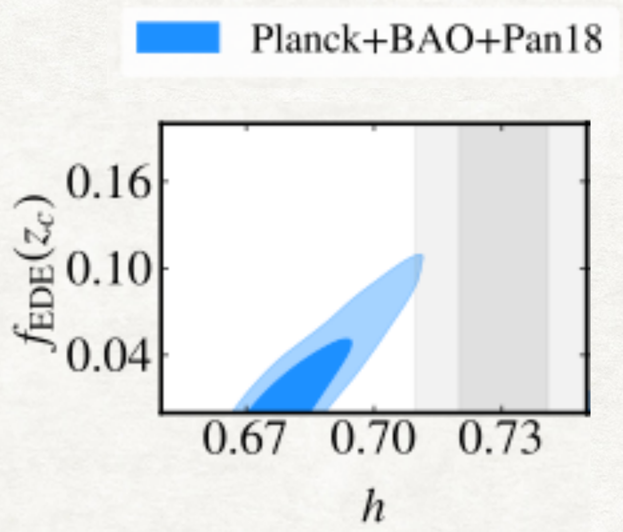
Barefoot analyses: evidence for prior-volume effects

—> Adrià Gómez-Valent's talk, 2203.16285

- Without information from SH0ES: only upper limits.

$$f(z_c) < 0.082\ (0.087), \qquad H_0 < 70.5\ (70.6)\ \mathrm{km/s/Mpc}$$

$$\Delta\chi^2 = \chi^2_{\Lambda\mathrm{CDM}} - \chi^2_{\mathrm{EDE}} \simeq -5$$



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- Adding the prior from SH0ES: EDE is detected at 4σ.

$$f(z_c) = 0.10\ (0.12) \pm 0.03 \qquad H_0 = 71.4\ (72) \pm 1.1\ \text{km/s/Mpc}$$

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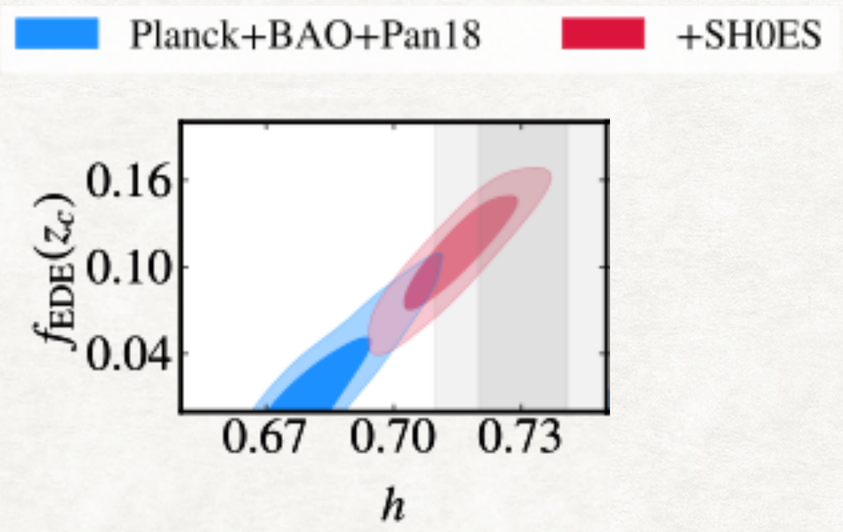

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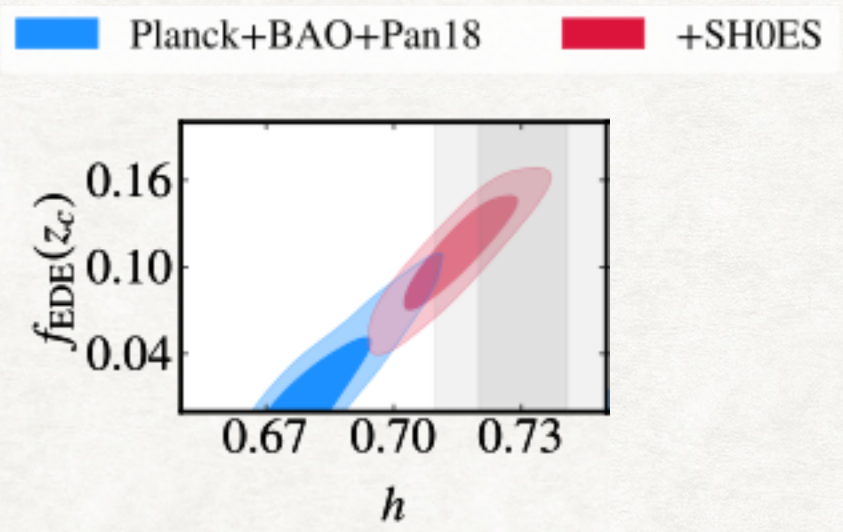

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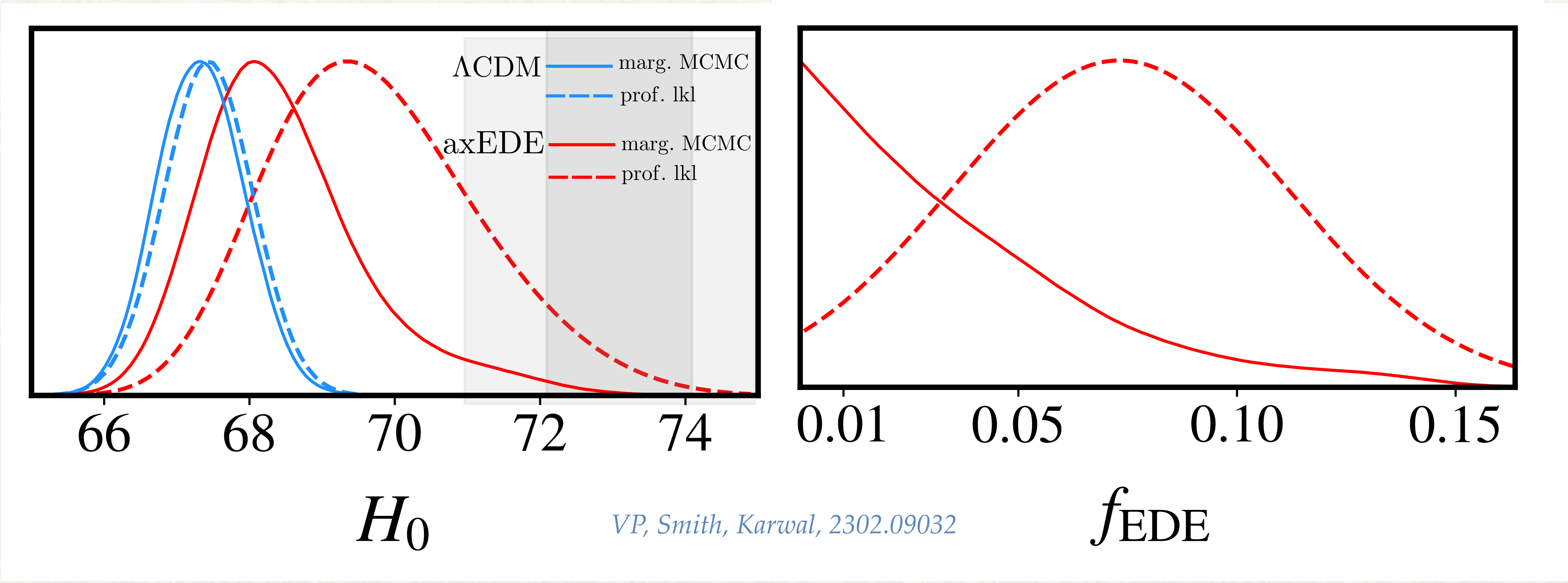
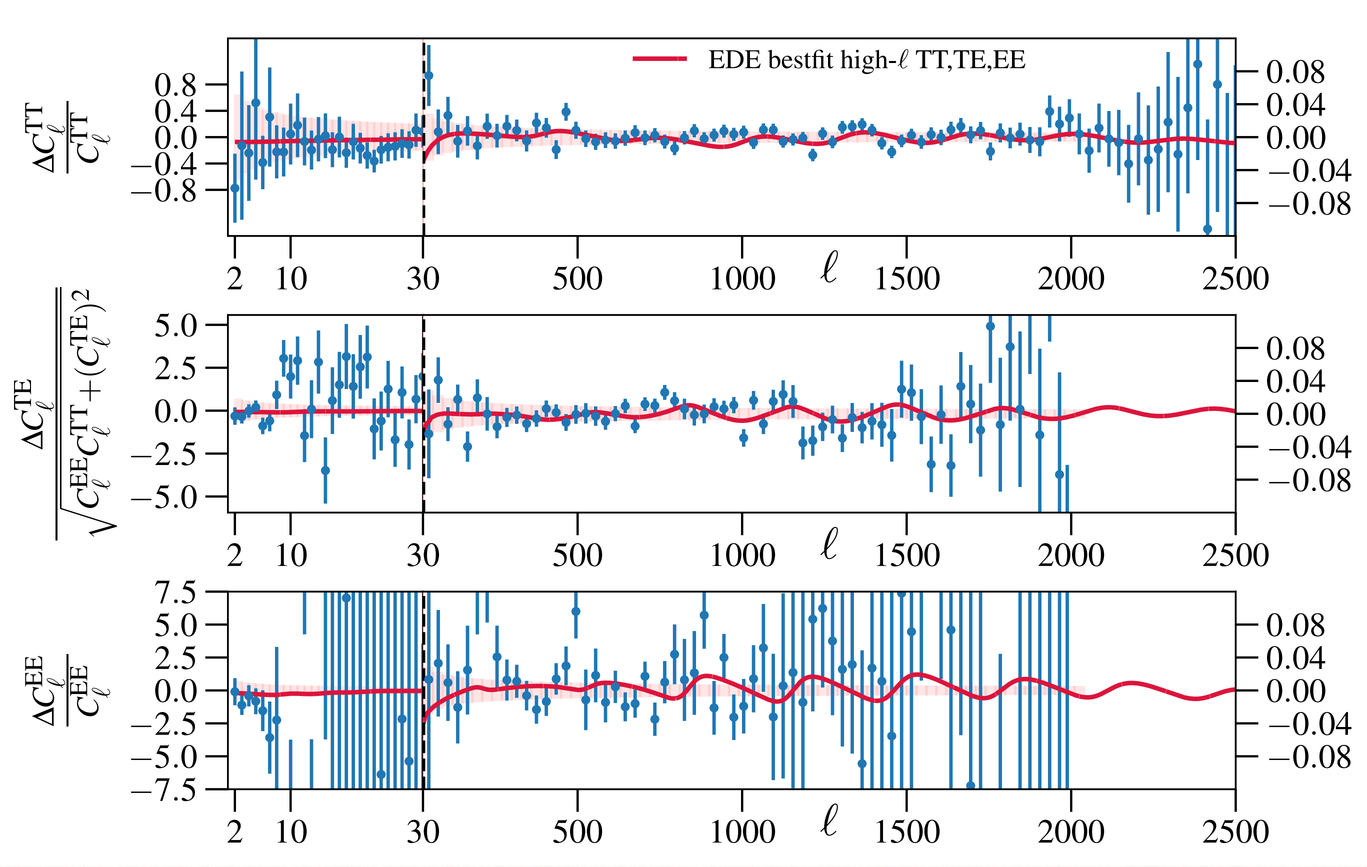
- The confidence intervals from a profile likelihood do not match the bayesian credible intervals *Herold ++ 2112.12140, 2210.16296*

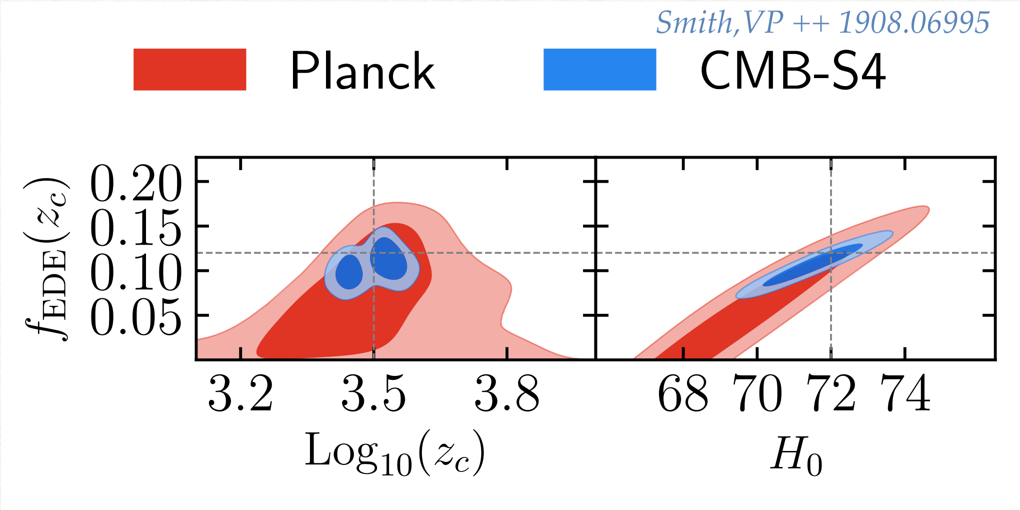


VP, Smith, Karwal, 2302.09032

$\sim 2.5\sigma$ preference from *Planck* alone

Future CMB data will confirm/exclude EDE



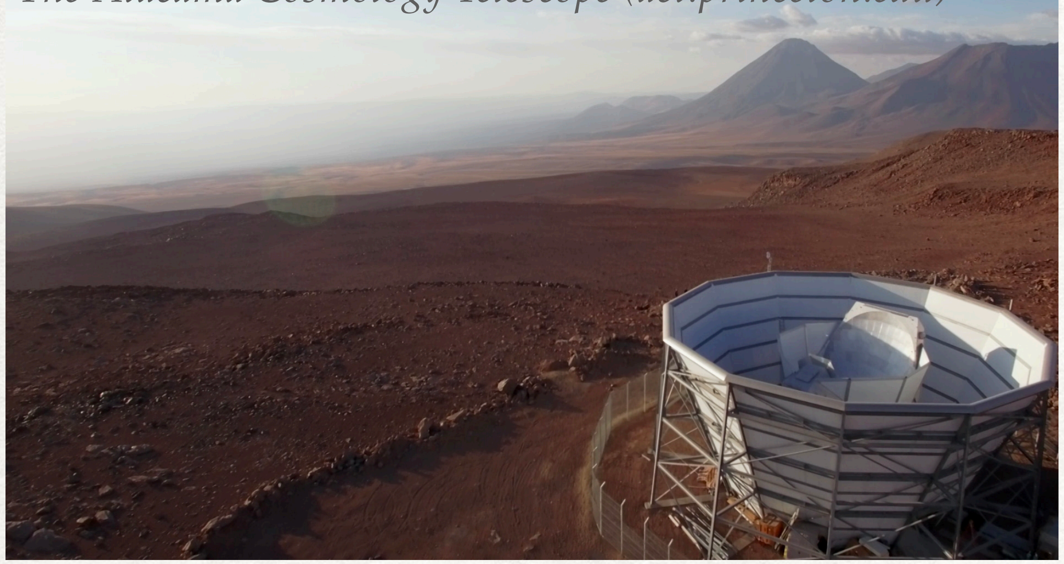


- Mock *Planck* data with $f_{\rm EDE}(z_{\rm eq}) \sim 10\,\%$ & $H_0 = 72$ km/s/Mpc: *Planck* ***cannot*** detect EDE
- Future experiments (Simons Observatory, CMB-S4) could unambiguously detect EDE.

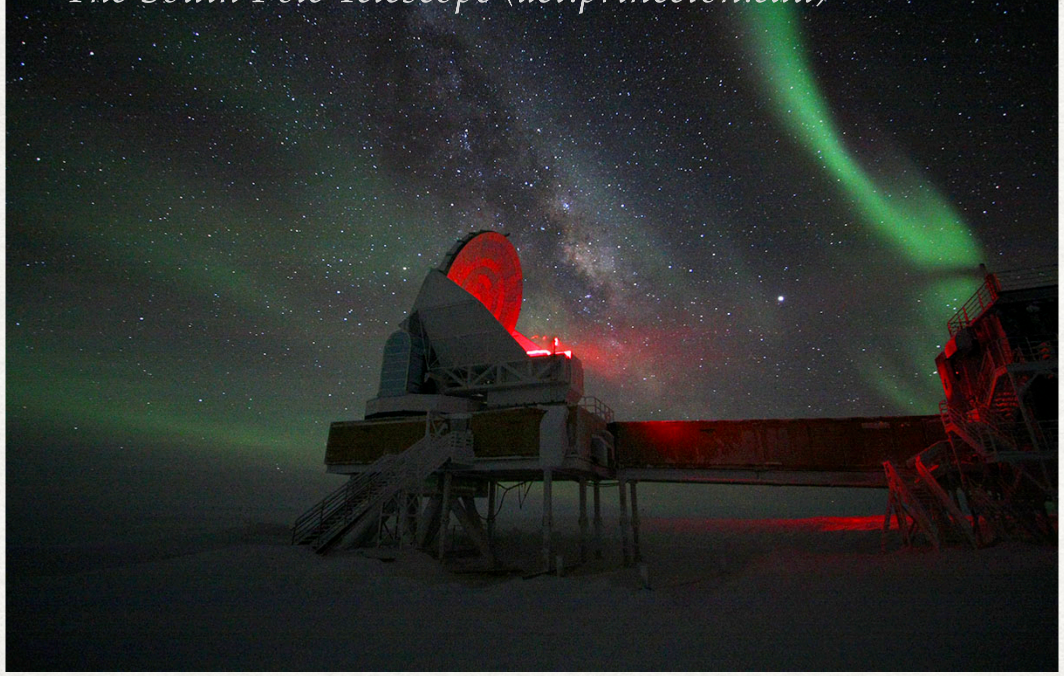
New CMB data at small scales

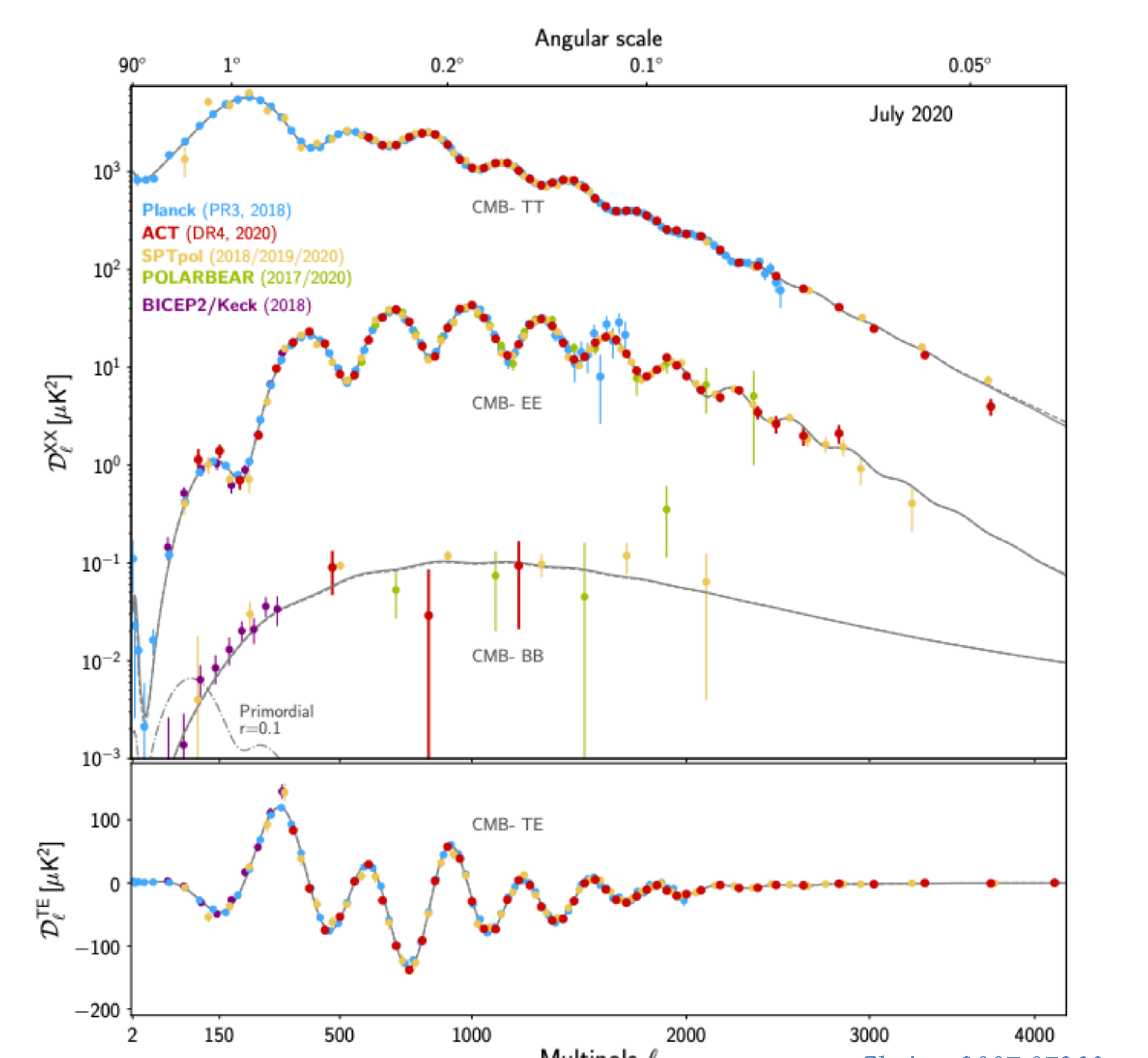
- ACT and SPT adds information at $\ell \sim 500 - 4000$ in TT,TE,EE. (SPT3G only TE,EE).

The Atacama Cosmology Telescope (act.princeton.edu)



The South Pole Telescope (act.princeton.edu)





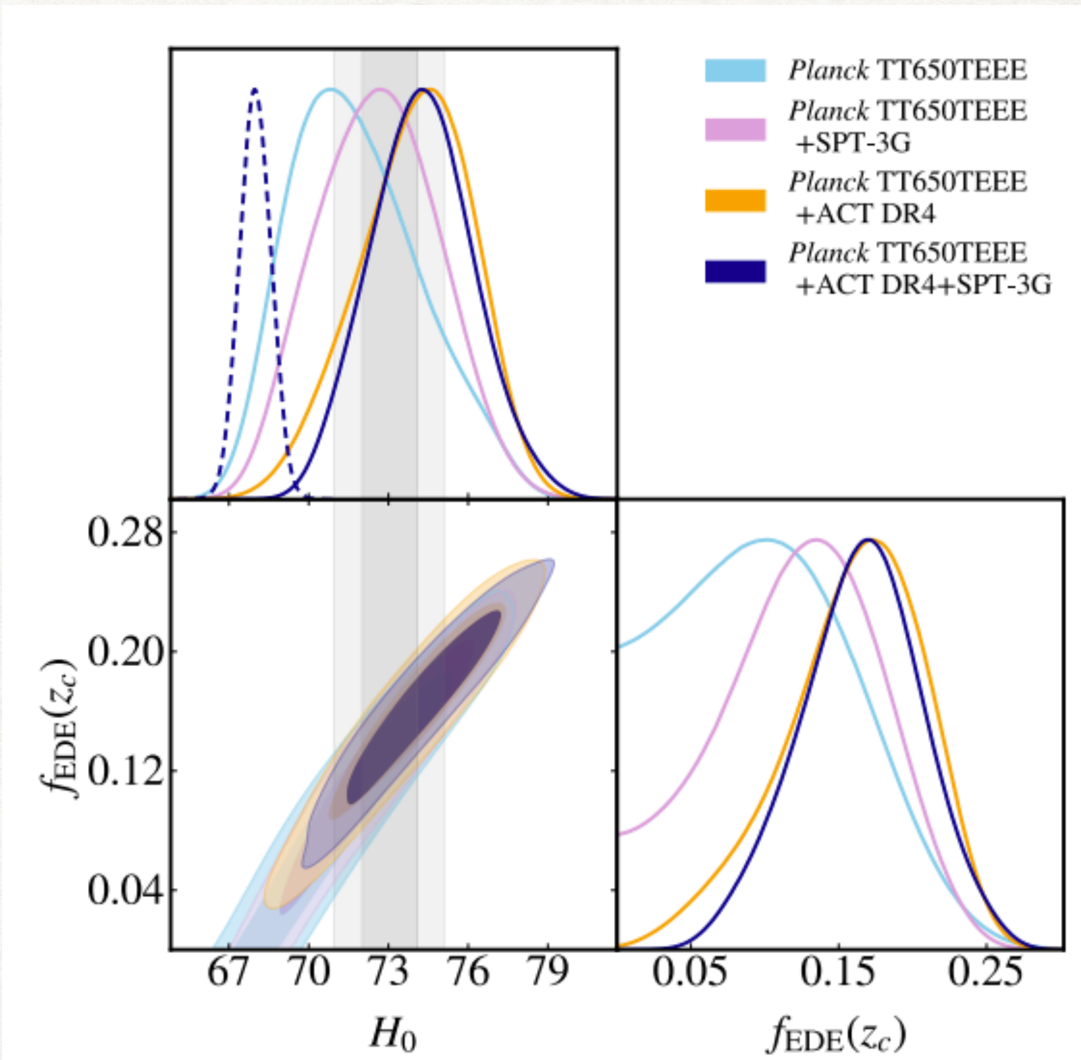
Choi++ 2007.07289

Consistency test: Planck vs WMAP+ACT+SPT

- *Planck*650TT$\simeq$ WMAP

See also Hill et al. 2109.04451; VP, Smith & Bartlett 2109.06229; Moss et al. 2109.14848

Smith, Lucca, VP++ 2202.09379

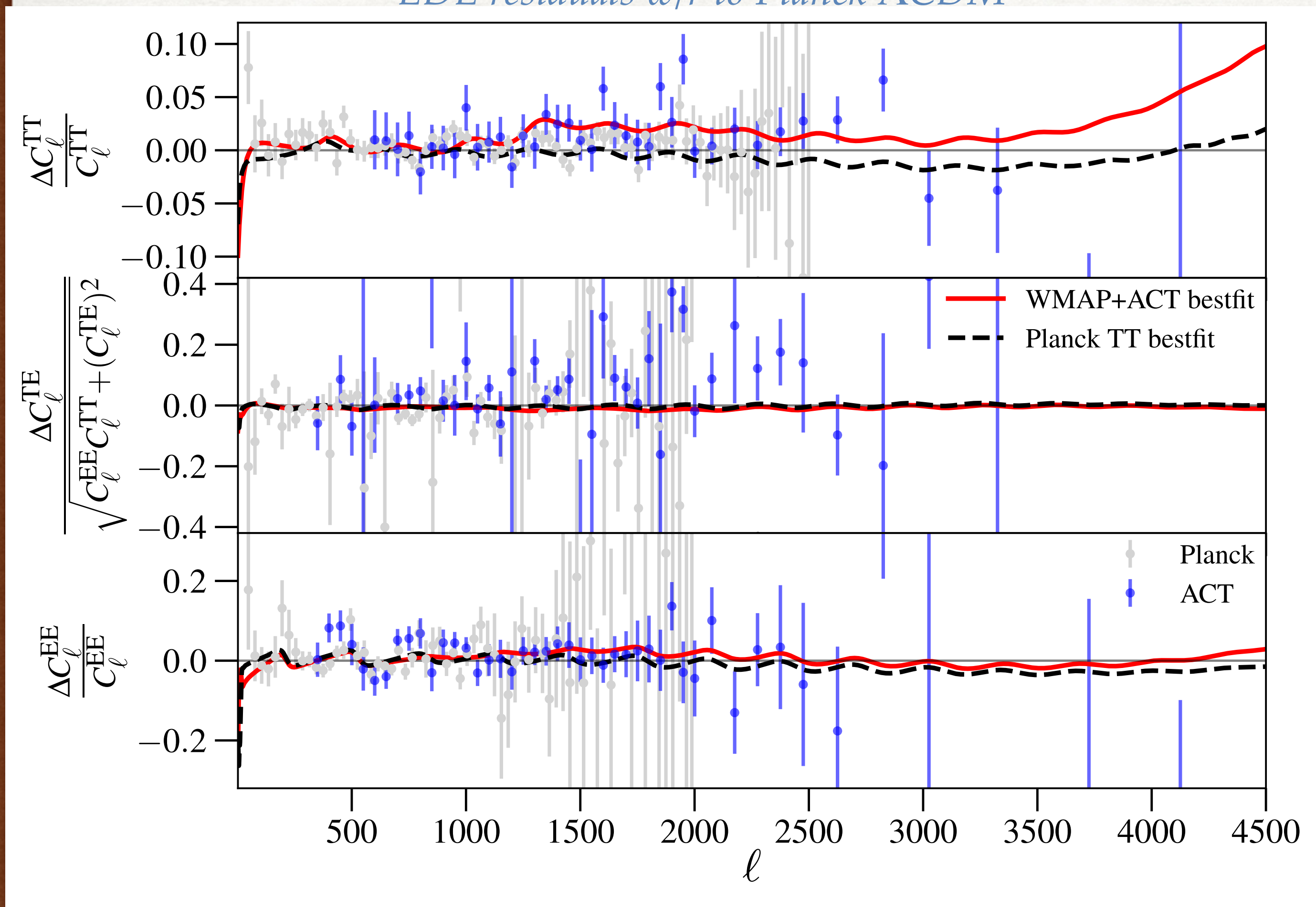


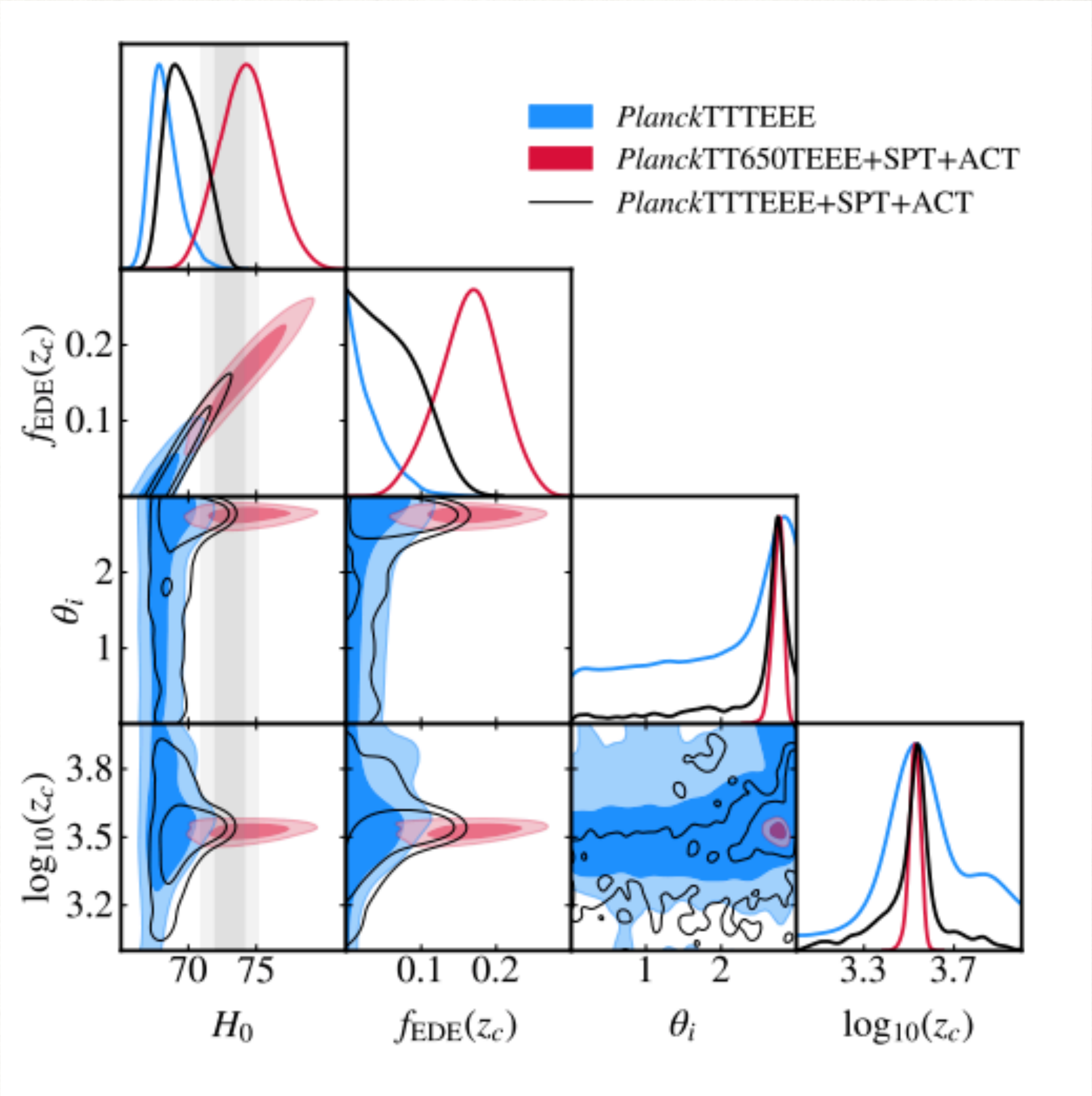
Model	ΛCDM	EDE
$f_{\rm EDE}(z_c)$	–	$0.163(0.179)^{+0.047}_{-0.04}$
$\log_{10}(z_c)$	–	$3.526(3.528)^{+0.028}_{-0.024}$
θ_i	–	$2.784(2.806)^{+0.098}_{-0.093}$
m (eV)	–	$(4.38 \pm 0.49) \times 10^{-28}$
f (Mpl)	–	0.213 ± 0.035
H_0 [km/s/Mpc]	$68.02(67.81)^{+0.64}_{-0.6}$	$74.2(74.83)^{+1.9}_{-2.1}$
100 ω_b	$2.253(2.249)^{+0.014}_{-0.013}$	$2.279(2.278)^{+0.018}_{-0.02}$
$\omega_{\rm cdm}$	$0.1186(0.1191)^{+0.0014}_{-0.0015}$	$0.1356(0.1372)^{+0.0053}_{-0.0059}$
$10^9 A_s$	$2.088(2.092)^{+0.035}_{-0.033}$	$2.145(2.146)^{+0.041}_{-0.04}$
n_s	$0.9764(0.9747)^{+0.0046}_{-0.0047}$	$1.001(1.003)^{+0.0091}_{-0.0096}$
$\tau_{\rm reio}$	$0.0510(0.0510)^{+0.0087}_{-0.0078}$	$0.0527(0.052)^{+0.0086}_{-0.0084}$
S_8	$0.817(0.821) \pm 0.017$	$0.829(0.829)^{+0.017}_{-0.019}$
Ω_m	$0.307(0.309)^{+0.008}_{-0.009}$	$0.289(0.287) \pm 0.009$
Age [Gyrs]	$13.77(13.78) \pm 0.023$	$12.84(12.75) \pm 0.27$
$\Delta\chi^2_{\rm min}$ (EDE−ΛCDM)	–	-16.2
Preference over ΛCDM	–	99.9% (3.3σ)

- There is a 3.3σ preference for EDE with no residual tension with SH0ES ($H_0 = 74 \pm 2$ km/s/Mpc)
- The preference is driven by *Planck* polarization and ACT data

A new tension between CMB data?

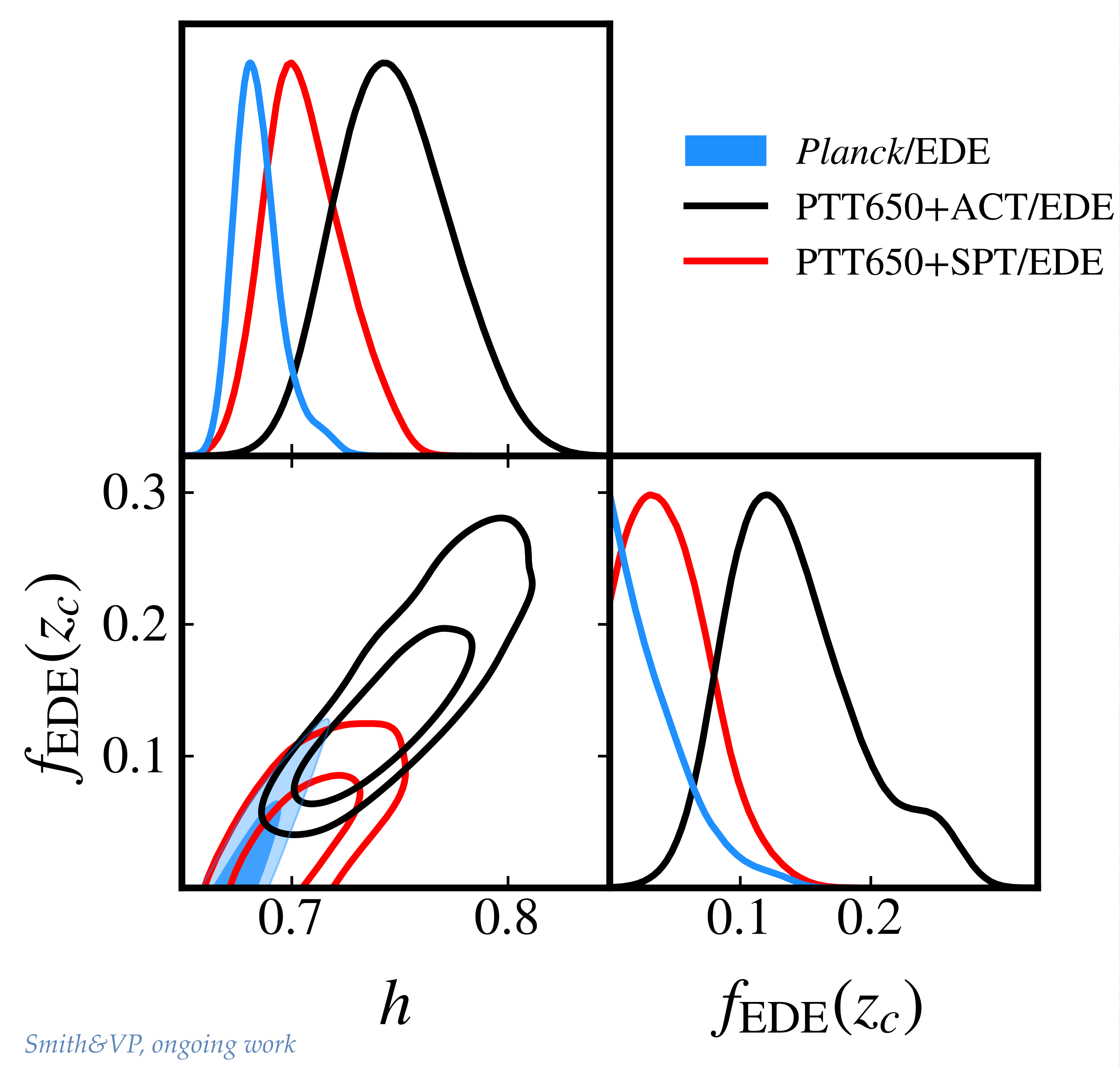
EDE residuals w/r to Planck ΛCDM





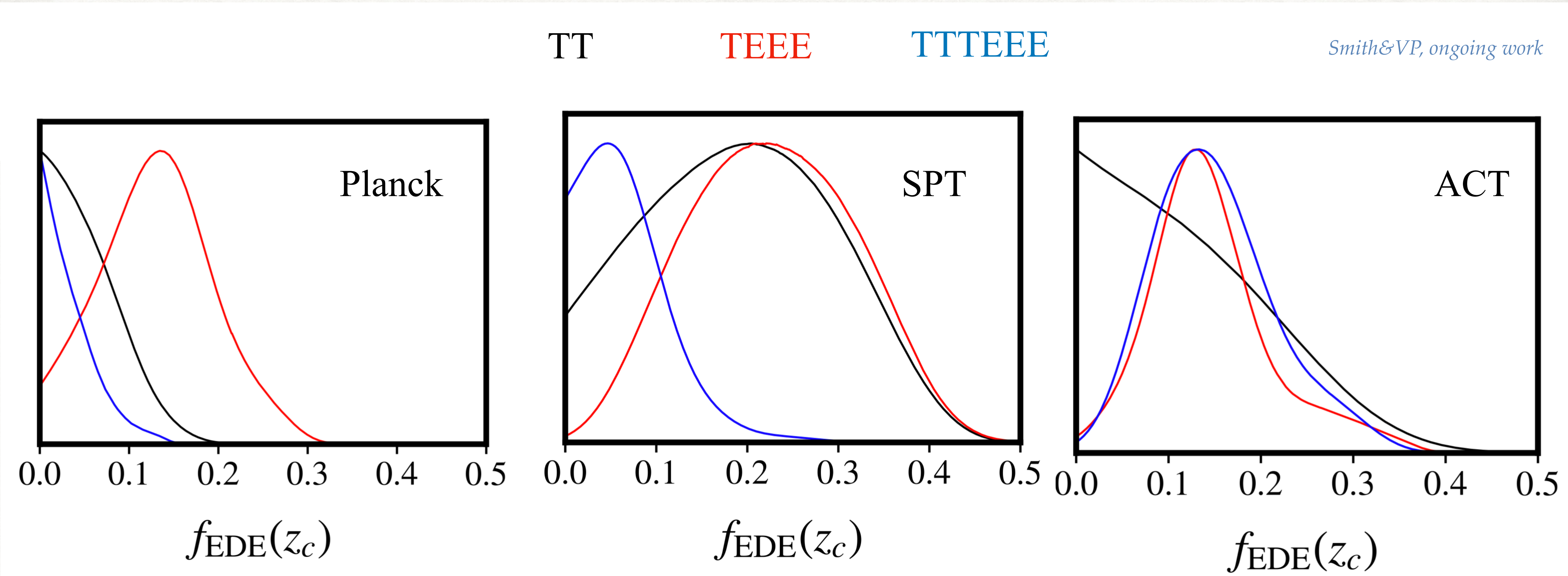
- Planck TT > 1300 disfavor such large $f_{\rm EDE}(z_c)$: tension between *Planck*/ACT?

New SPT TT data seem to agree with Planck



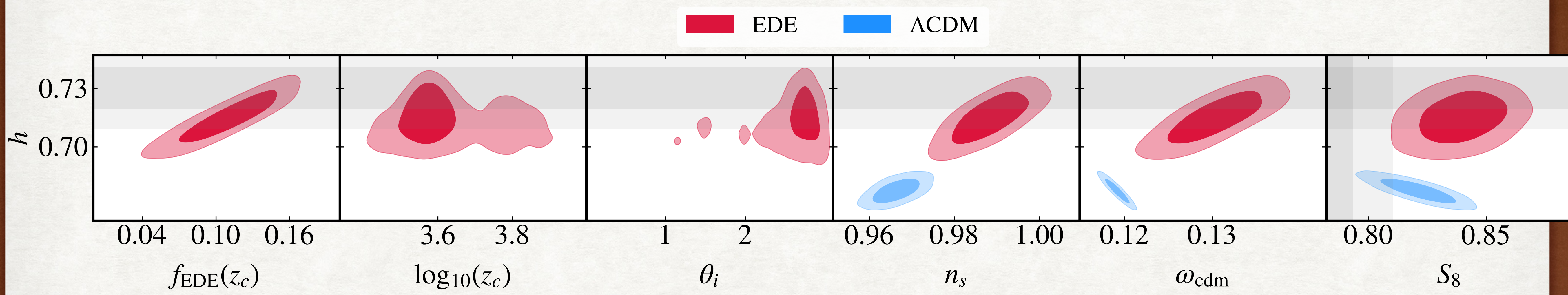
- No preference for axion-like EDE in PTT650+SPT3G: disfavor ACT hint of EDE?

TT vs TEEE: "Curiosities" in Planck & SPT ?



- TEEE data all favor EDE
- TT data only weak constraints
- TTTEEE stronger constraints than expected

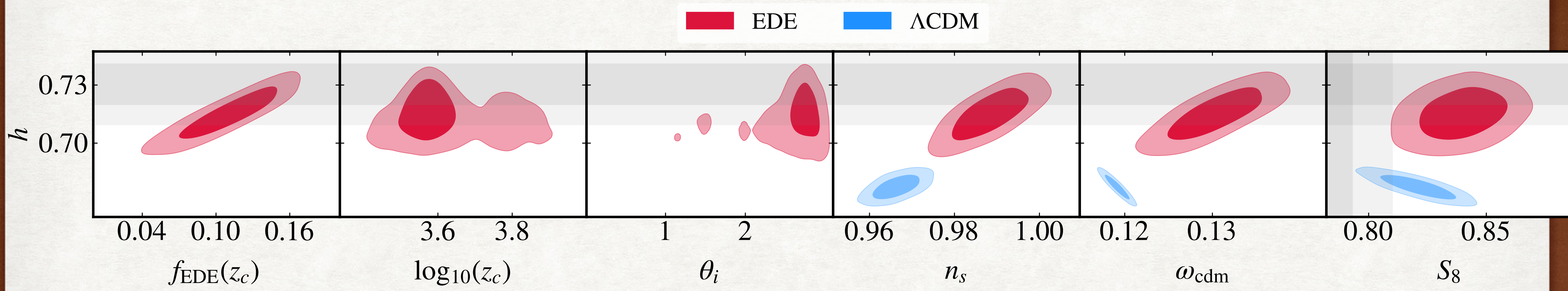
Challenges to EDE



- The field becomes dynamical around $z_{\rm eq}$: A new 'why-then' problem?

Sakstein++1911.11760, Lin++2212.08098

Challenges to EDE



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- EDE cosmology has a higher $\omega_{\rm cdm}$ and n_s: in tension with GC and WL surveys? Implications for inflation?

Hill et al. 2003.07355, Ivanov++ 2006.11235 , d'Amico++ 2006.12420 Niedermann++ 2009.00006, Smith++ 2009.10740, Murgia++ 2009.10733

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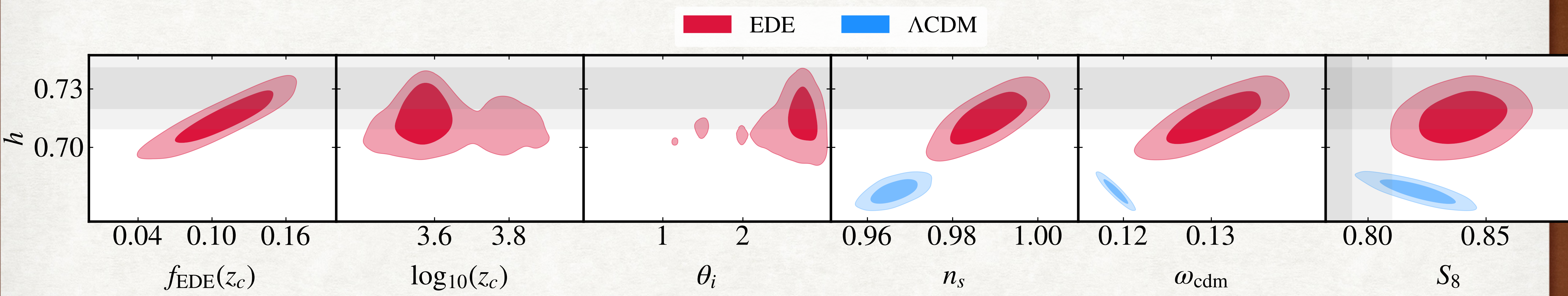

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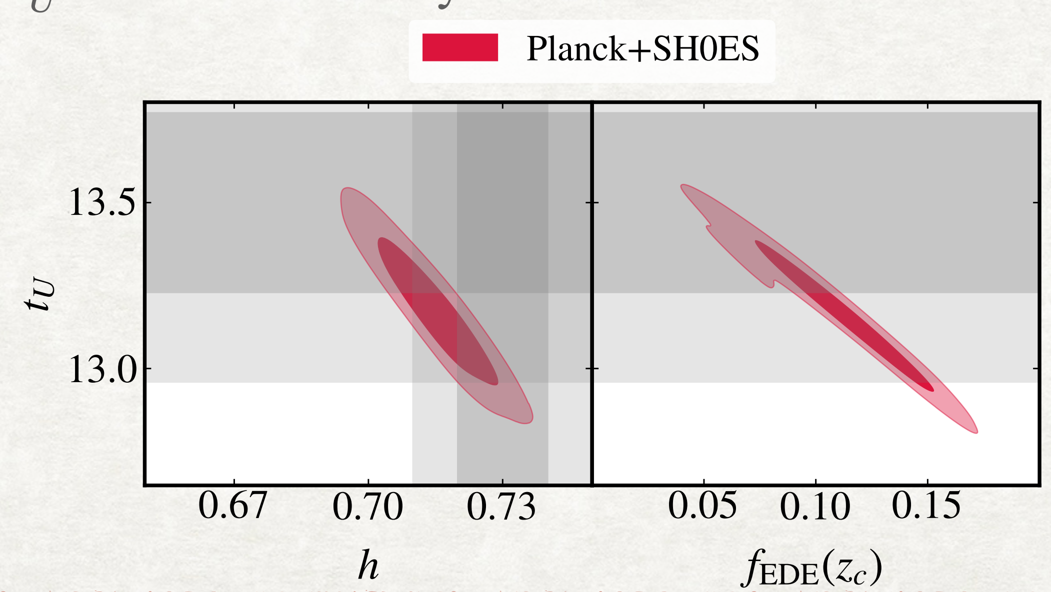
- Age of the universe tension? $t_U \simeq 13.2 \pm 0.15$ Gyr while GC measures 13.5 ± 0.27 Gyr

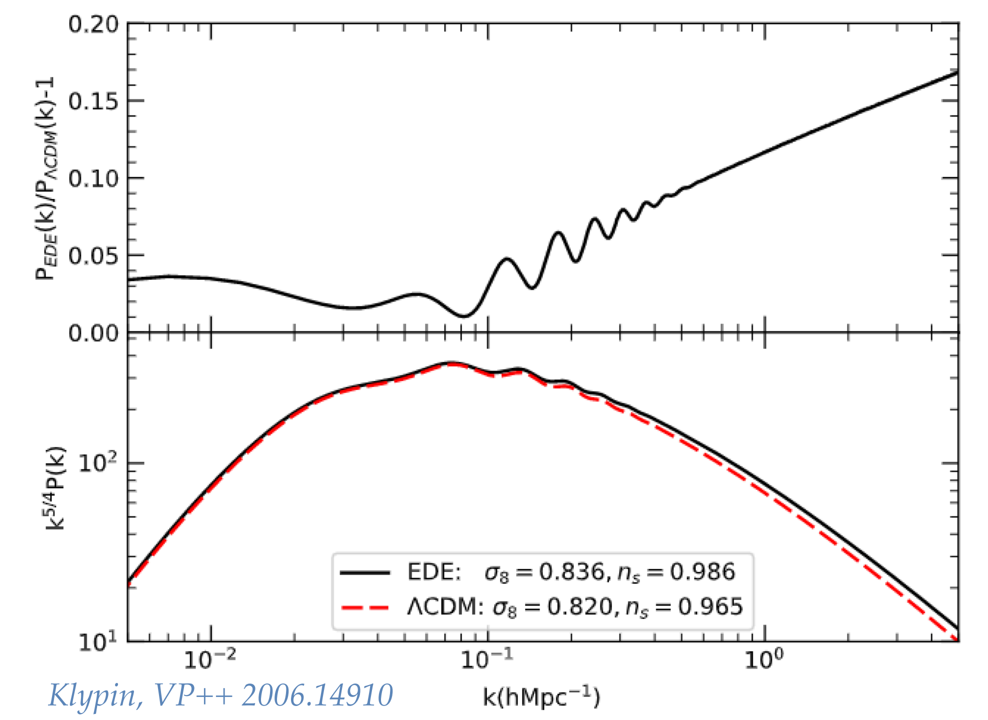
Bernal++ 2102.05066, Boylan-Kolchin 2103.15824



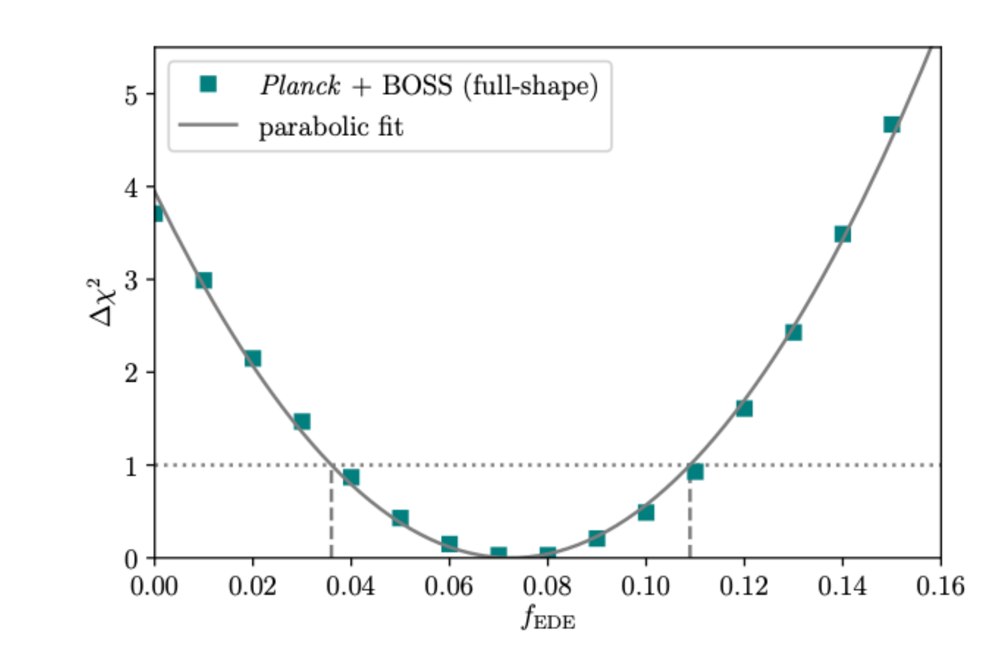
EFTofLSS analyses of EDE

- EDE cosmology predicts 5-15% increase in power at small scales in the linear matter power spectrum

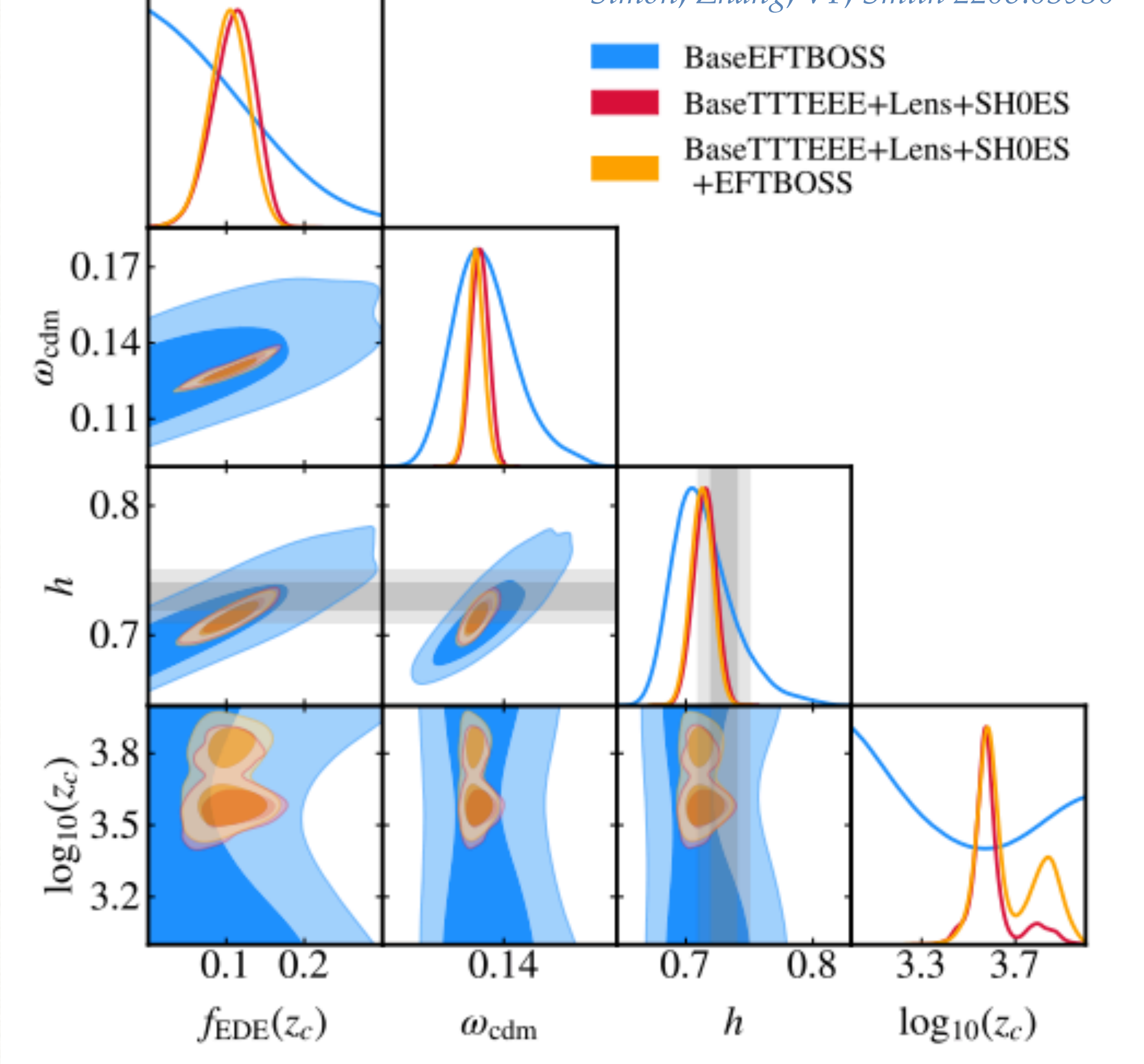
Hill et al. 2003.07355, Ivanov++ 2006.11235 ,D'Amico++ 2006.12420, Niedermann++ 2009.00006, Smith++ 2009.10740, Murgia++ 2009.10733



Klypin, VP++ 2006.14910



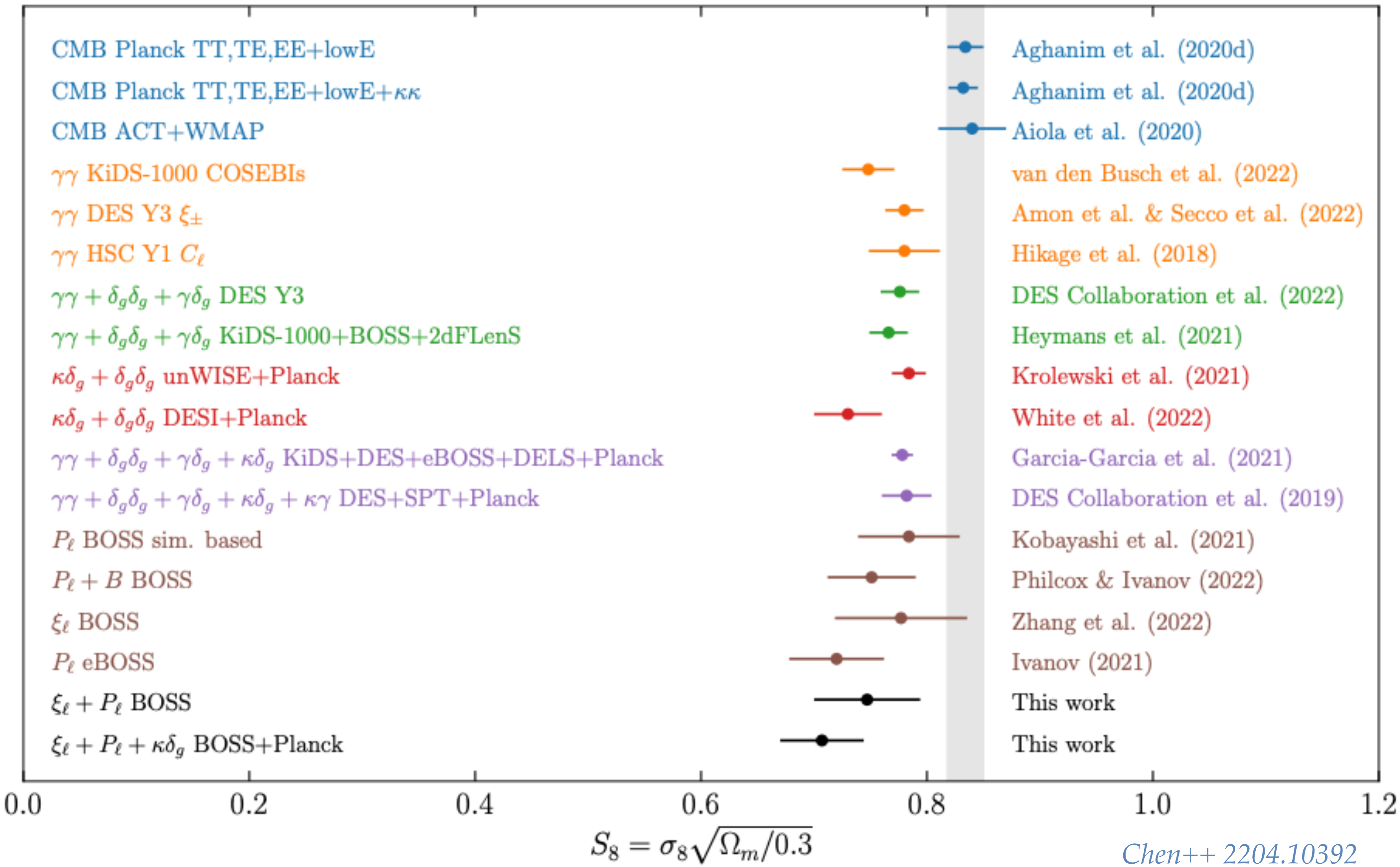
Simon, Zhang, VP, Smith 2208.05930



- EFT analyses of BOSS do not exclude Early Dark Energy

The S_8 tension

—> Marika Asgari's talk

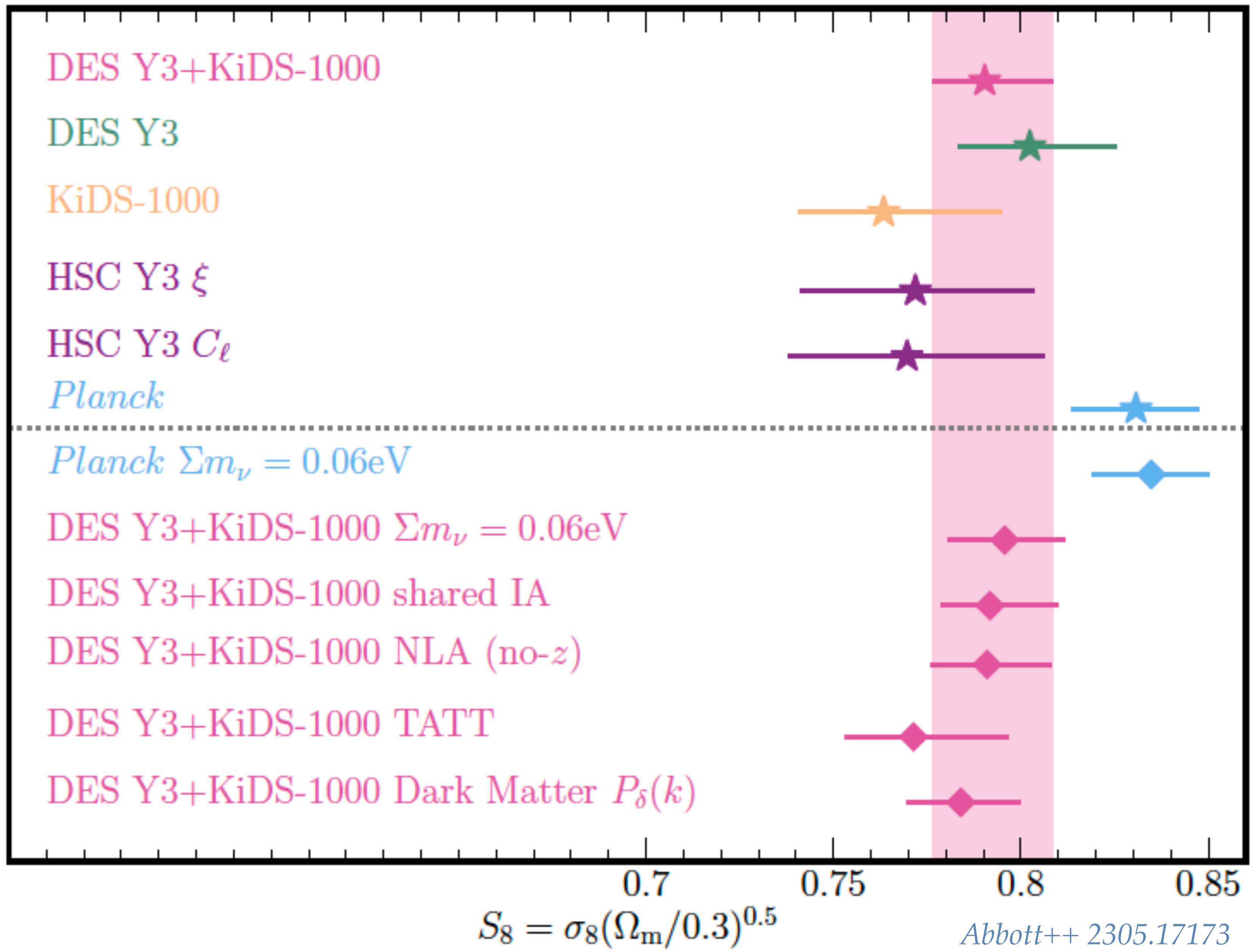


Chen++ 2204.10392

Early Dark Energy cannot resolve the S_8 tension

The S_8 tension updated

—> *Marika Asgari's talk*

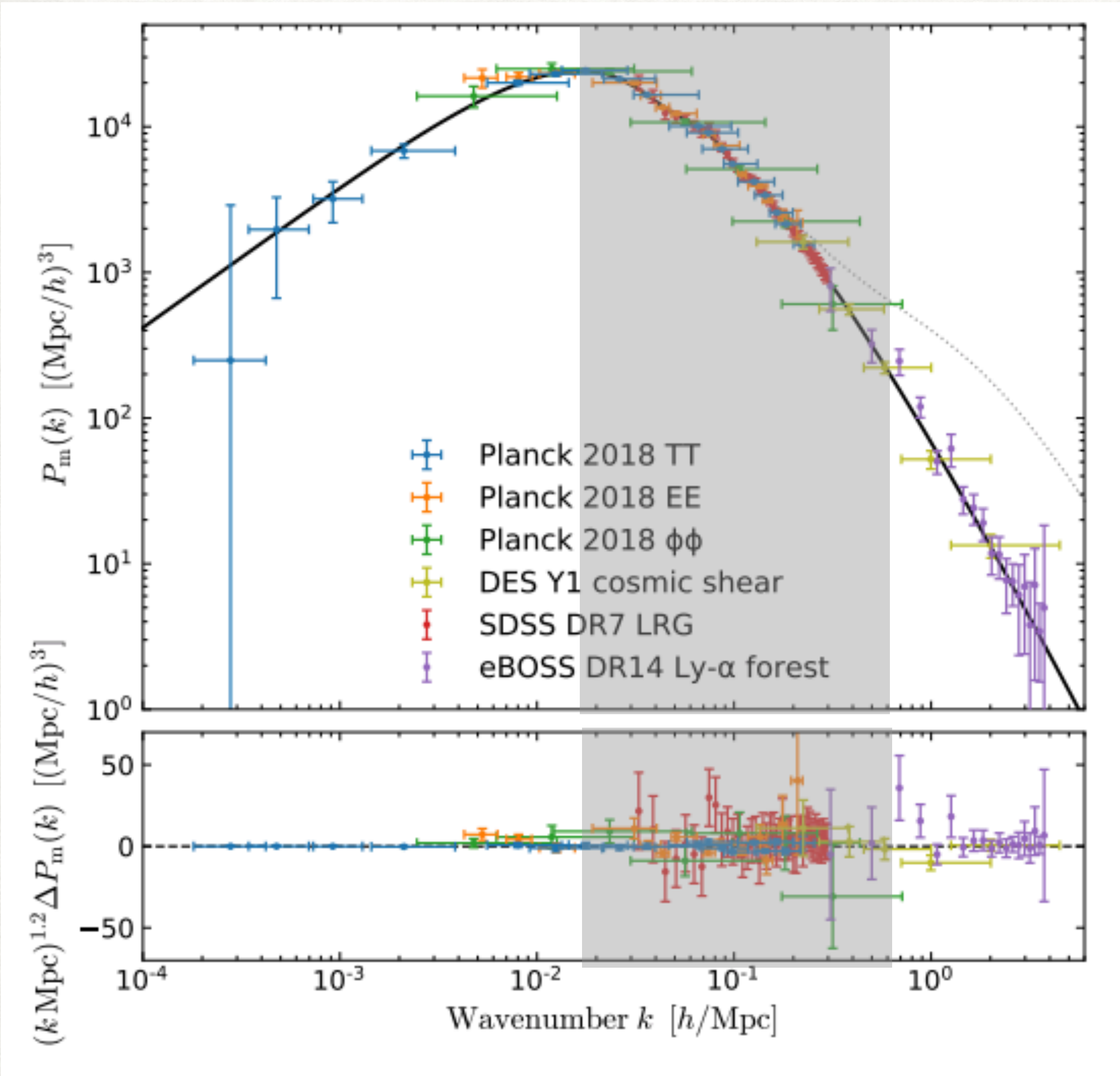


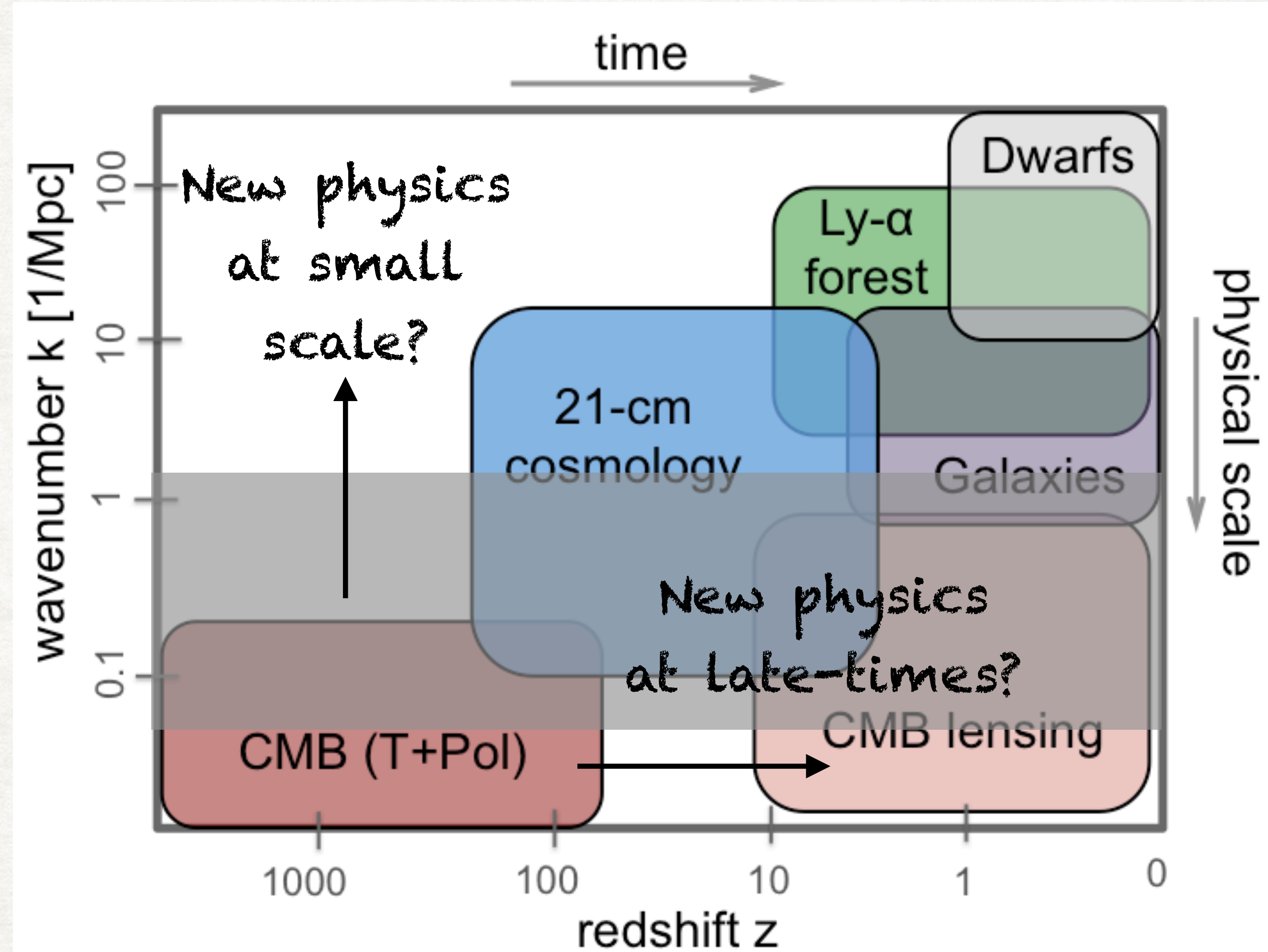
Abbott++ 2305.17173

- New Hybrid "KiDS+DES" analysis results in 1.7σ tension with *Planck*
- Role of baryon feedback / non-linearities / intrinsic alignements may be important

Amon& Efstathiou 2206.11794, Aricò++ 2303.05537

How to resolve the S_8 tension

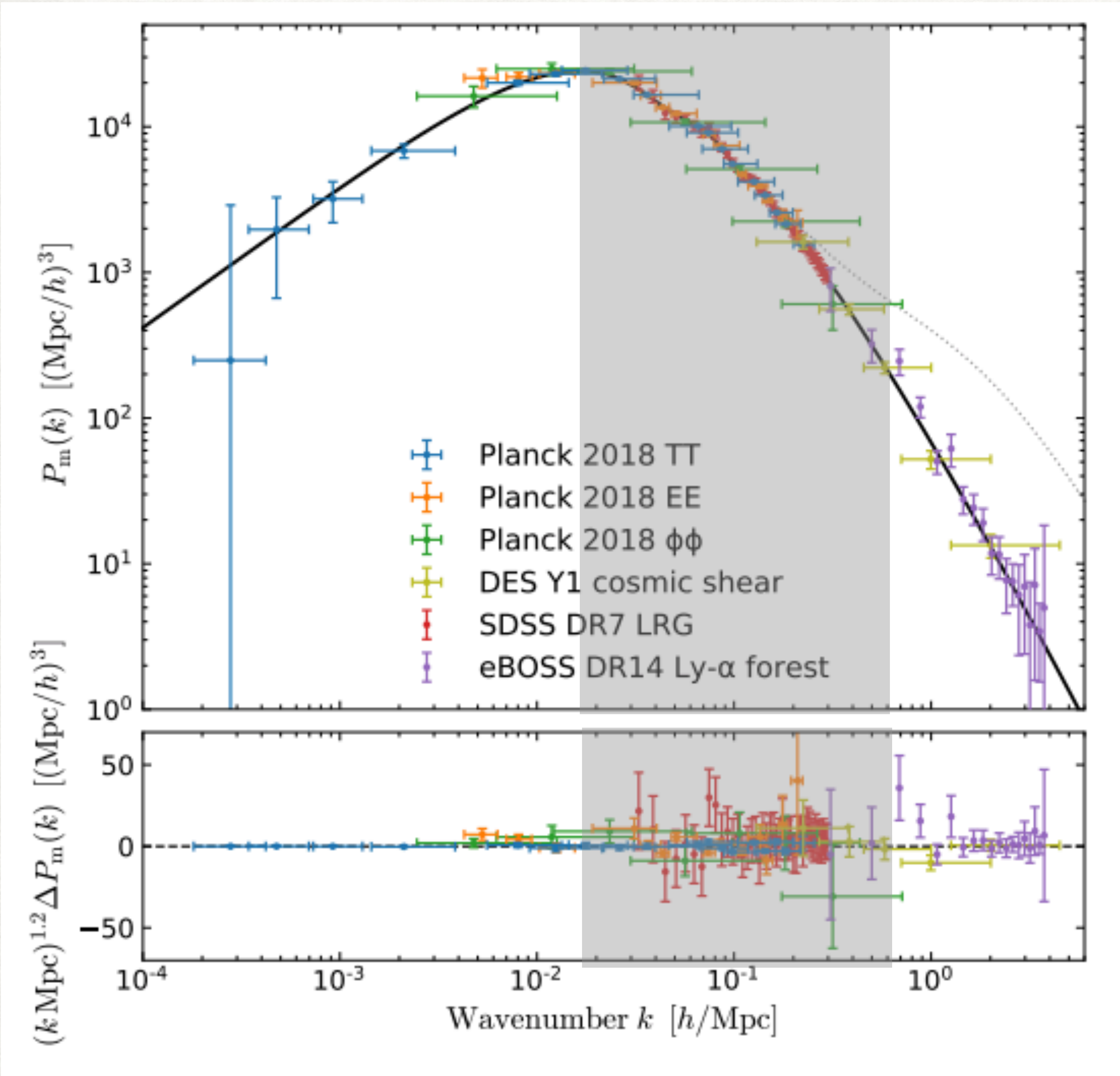


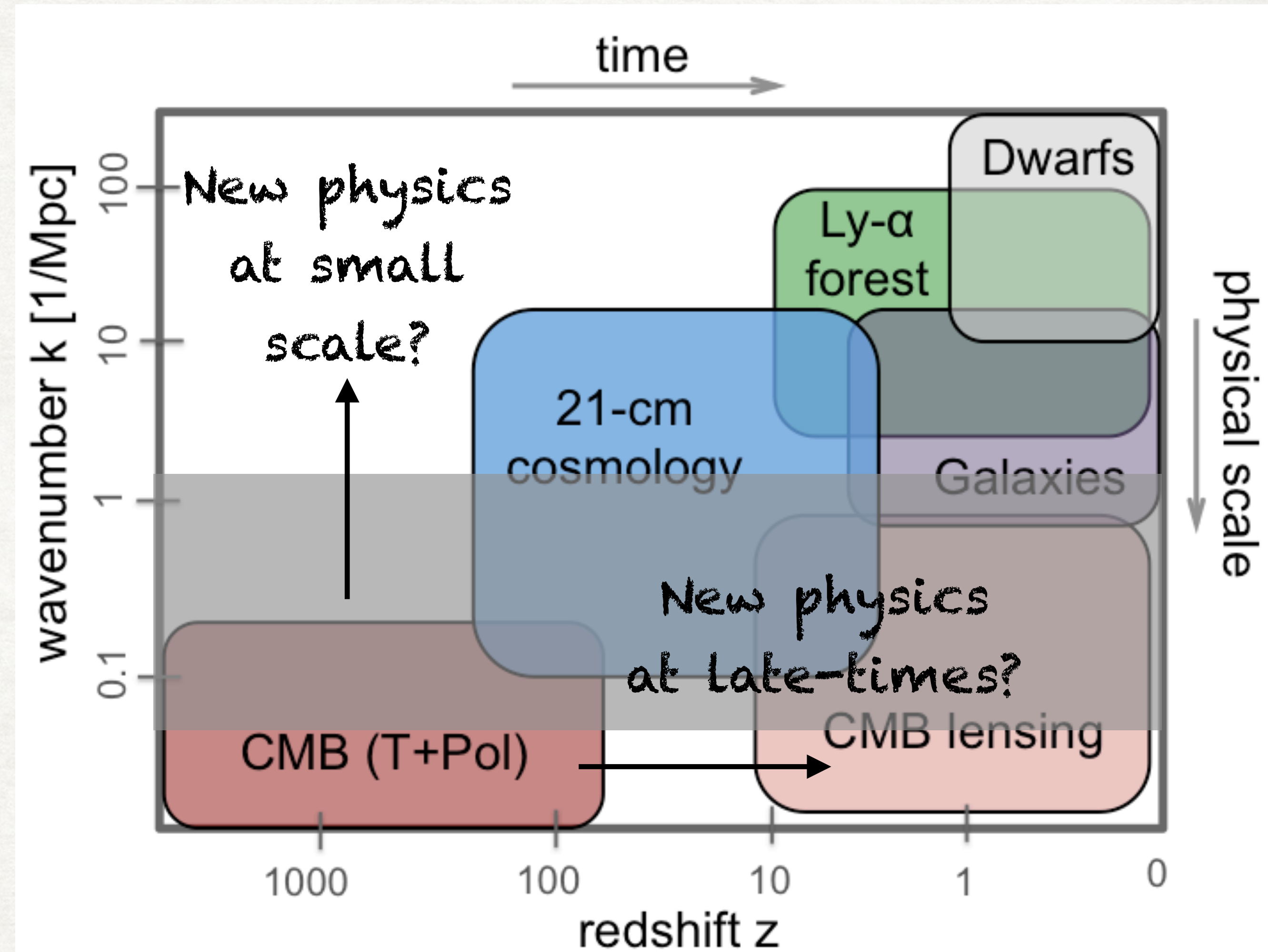


- σ_8 is a derived parameter measuring scales $k \sim 0.1$ h/Mpc. Fit the CMB at $z \sim 1100$ and predict $\sigma_8(z=0)$.

Abdalla++ 2203.06142

How to resolve the S_8 tension

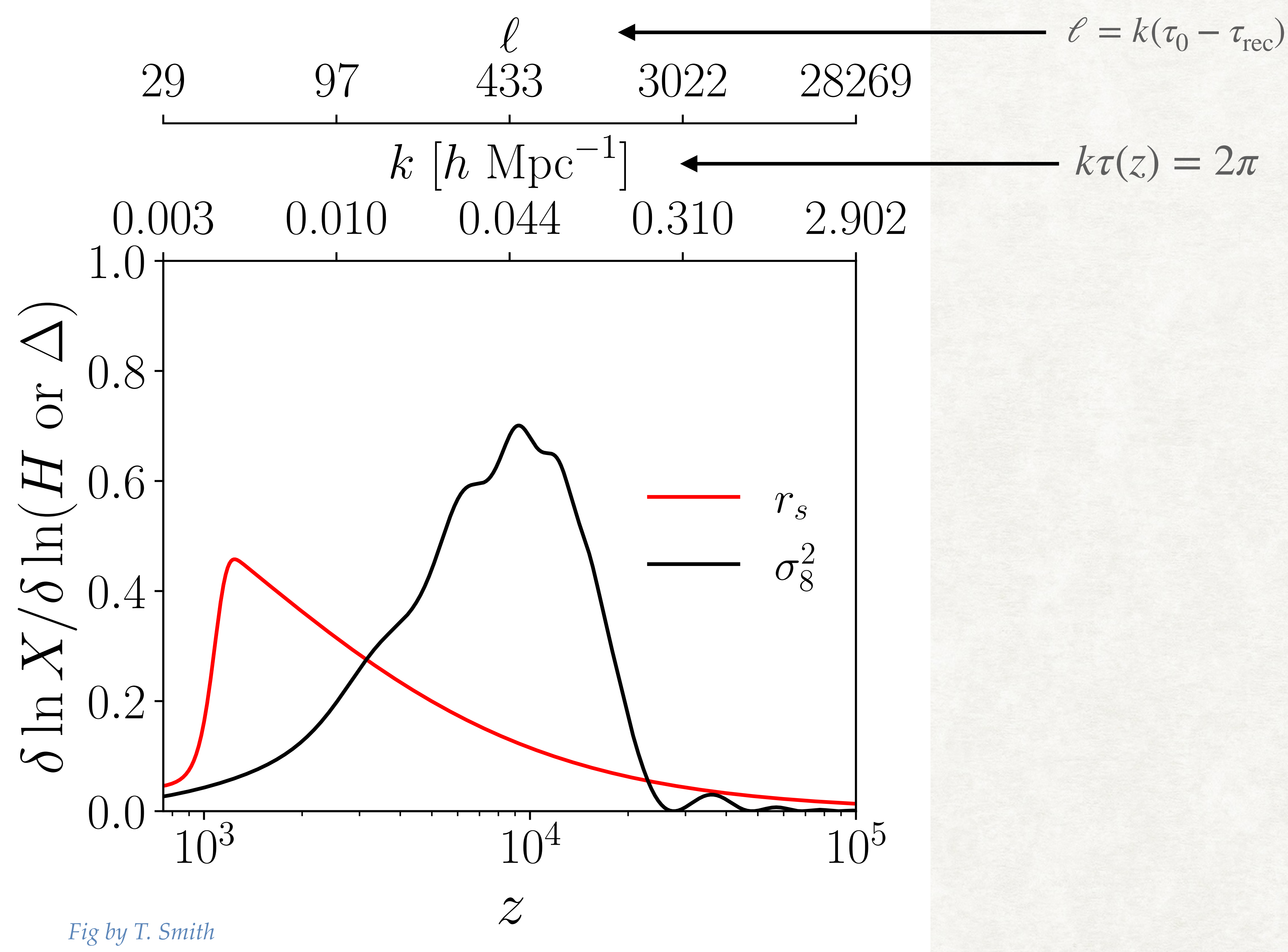




- σ_8 is a derived parameter measuring scales $k \sim 0.1$ h/Mpc. Fit the CMB at $z \sim 1100$ and predict $\sigma_8(z=0)$.
- To resolve the tension: Either suppress scales $k \gtrsim 0.2$ h/Mpc or change late-time evolution at $z < 0.5$
- Dark Sector physics: Ultra-light axions, Decaying DM, Interacting DM-DR, Interacting DM-DE…

Abdalla++ 2203.06142

Resolving H_0 and S_8 with the same mechanism



- All modes controlling σ_8 are within the horizon around / before the sound horizon starts growing.

Could EDE "drag" DM and reduce S_8?

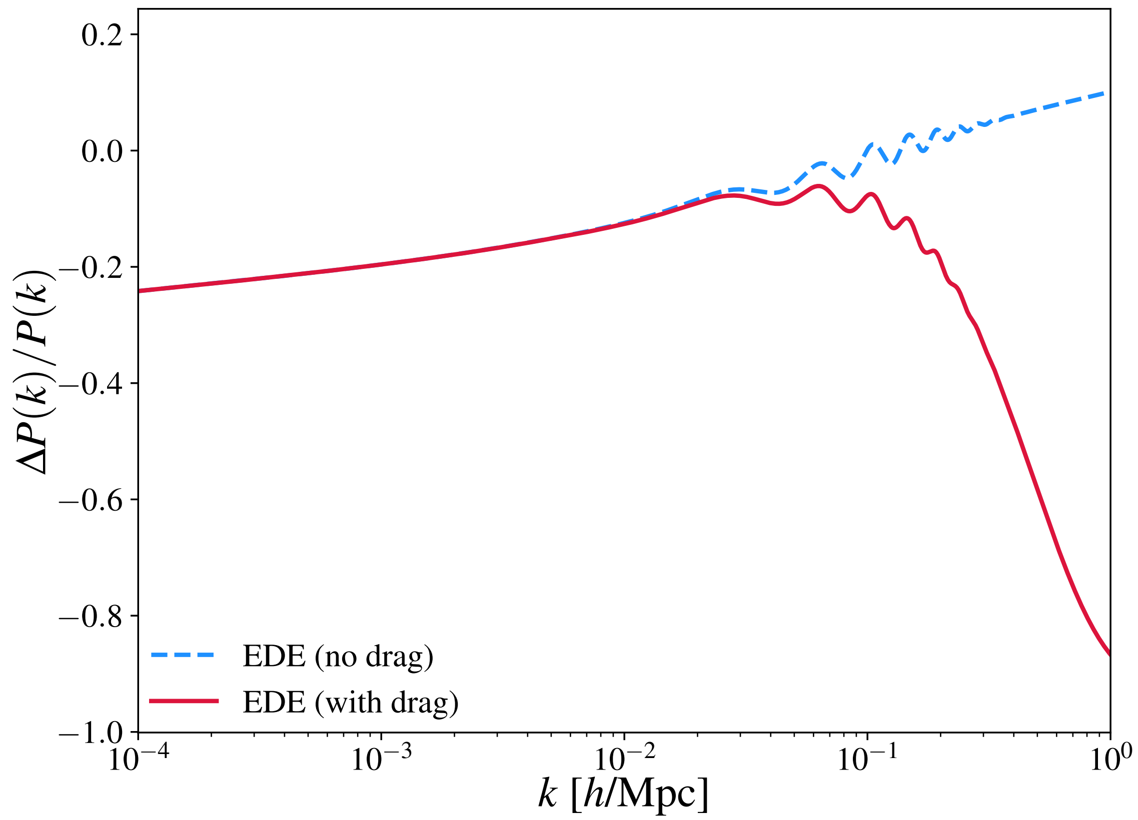
- With a phenomenological "EDE+DM" drag: one can resolve both tensions!

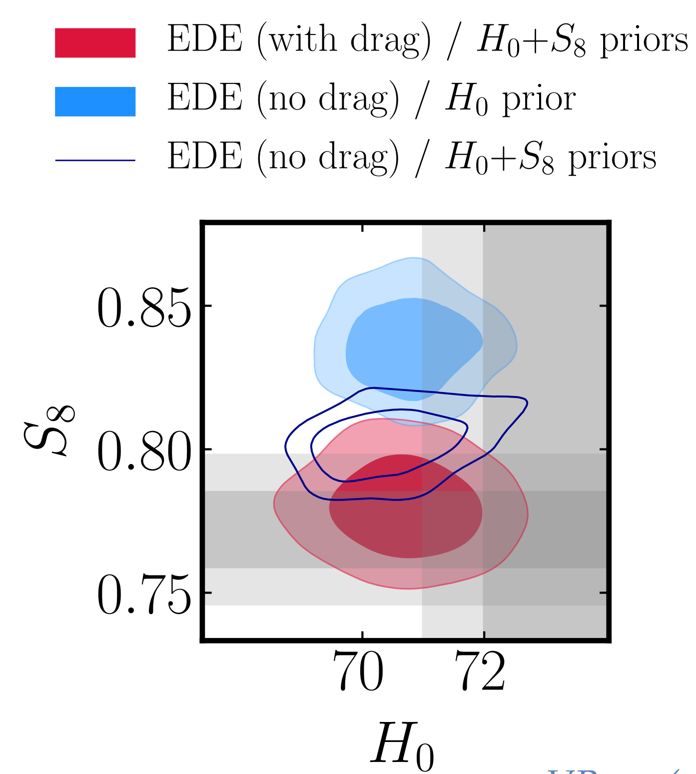
Similar to ``step" dark radiation Joseph++ 2207.03500

$$\theta'_{\rm DM} = -\frac{a'}{a}\theta_{\rm DM} + k^2\psi + \Gamma_{\rm DM/EDE}(a)(\theta_{\rm EDE} - \theta_{\rm DM})$$

$$\theta'_{\rm EDE} = -(1 - 3c^2_{s,\rm EDE})\frac{a'}{a}\theta_{\rm EDE} + \frac{k^2 c^2_{s,\rm EDE}}{(1 + w_{\rm EDE})}\delta_{\rm EDE} + k^2\psi - \Gamma_{\rm DM/EDE}(a)R(\theta_{\rm EDE} - \theta_{\rm DM})$$

$$\Gamma_{\rm DM/EDE}(a) \propto f_{\rm EDE}(a)$$





VP ++ (ongoing work)

- Work in progress to model via scalar field coupled to DM through $L(u_\mu \nabla^\mu \phi)$

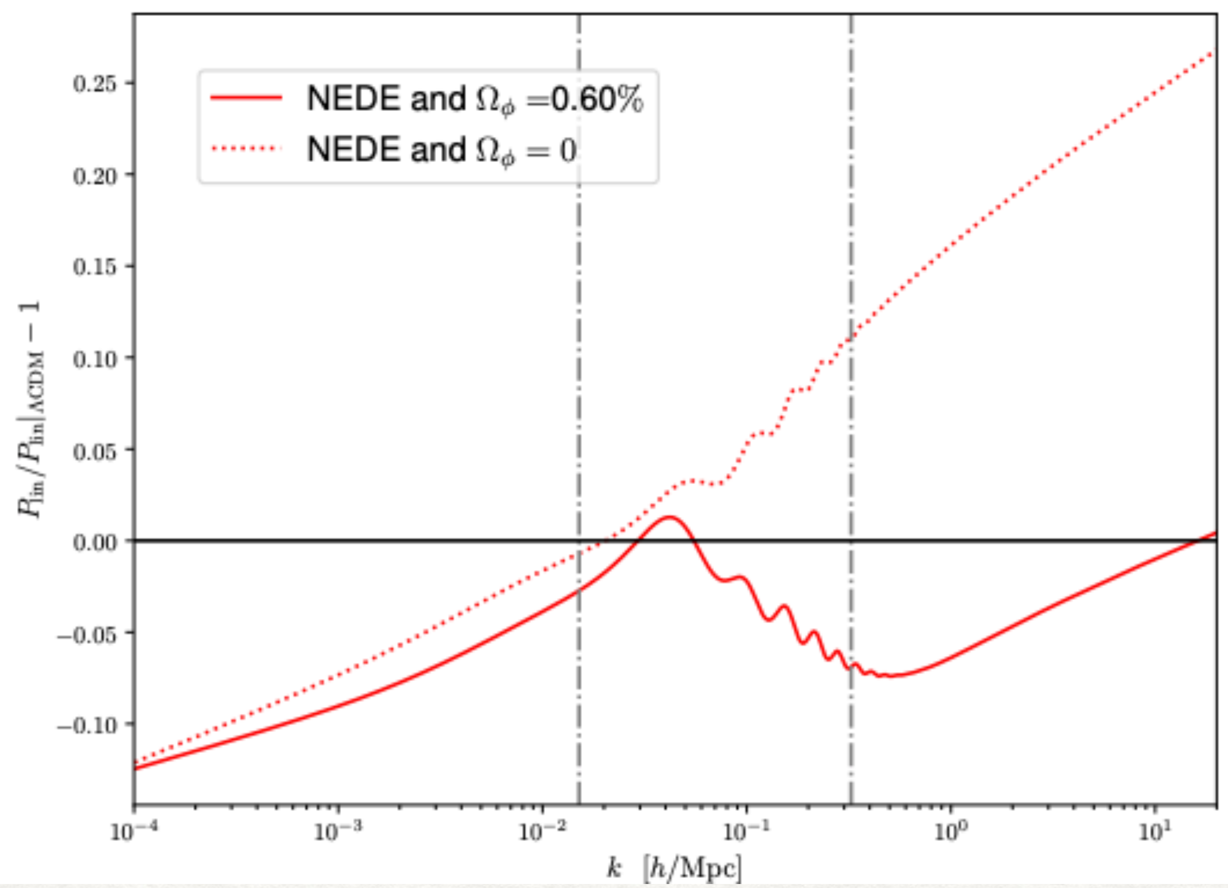
Skordis++ 1502.07297, Pourtsidou++ 1604.04222

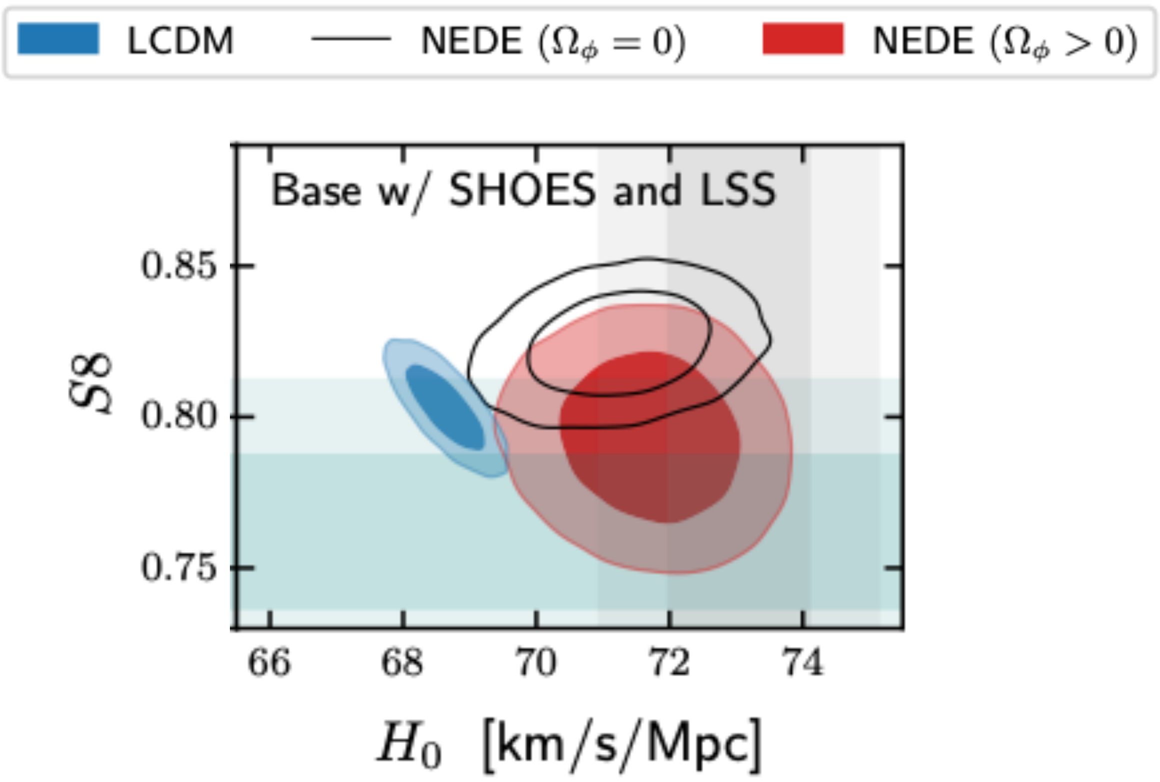
- Connection with the coincidence problem? DM dominance can trigger the rolling of EDE field *Lin++2212.08098*

"New" EDE + fraction of axion dark matter

Cruz++ 2305.08895

- New EDE: the EDE field experiences a 1st order PT due to another "trigger field" rolling down its potential.
- The trigger field can be an ultra-light axion representing a small fraction of CDM.





- Non-trivial coincidence: The trigger field has the right mass to trigger the PT around $z_{\rm eq}$ and reduce σ_8
- This requires $m_{\rm ula} \simeq 10^{-27}$ with $f_{\rm ula} \equiv \rho_{\rm ula}/\rho_{\rm cdm} \simeq 2.5\,\%$

See also Allali++ 2104.12798

Early Dark Energy: more Ups than Downs?

- The Hubble tension is multidimensional: it requires (at least) a *decrease* in r_s and an *increase* in $\omega_{\rm cdm}$
- Resolving the Hubble Tension with EDE requires $f_{\rm EDE}(z_c) \sim 10\,\%$ at $z_c \simeq 3500 - 4500$
- Perturbations / microphysics also constrained: tight relation between $c_s^2 - w$, constrain on the initial field value.

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- Combination of TTTEEE leads to stronger constraints than naively expected. Curiosities? Statistical fluke?

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- EDE cannot resolve the S_8 tension (but no strong constraints from EFTBOSS)
- One can extend this model to reduce the growth of DM perturbations and resolve both tensions simultaneously
- Alternatively, (if not fluke) S_8 could be resolved by some independent mechanism… including baryons!

Early Dark Energy: more Ups than Downs?

- The Hubble tension is multidimensional: it requires (at least) a *decrease* in r_s and an *increase* in $\omega_{\rm cdm}$
- Resolving the Hubble Tension with EDE requires $f_{\rm EDE}(z_c) \sim 10\,\%$ at $z_c \simeq 3500 - 4500$
- Perturbations / microphysics also constrained: tight relation between $c_s^2 - w$, constrain on the initial field value.

- *Planck* alone results show prior-volume effect: frequentist confidence intervals do not follow posteriors.
- ACT / SPT TEEE / *Planck* TEEE favors EDE at $2-3\sigma$: there is no residual H_0-tension.
- Combination of TTTEEE leads to stronger constraints than naively expected. Curiosities? Statistical fluke?

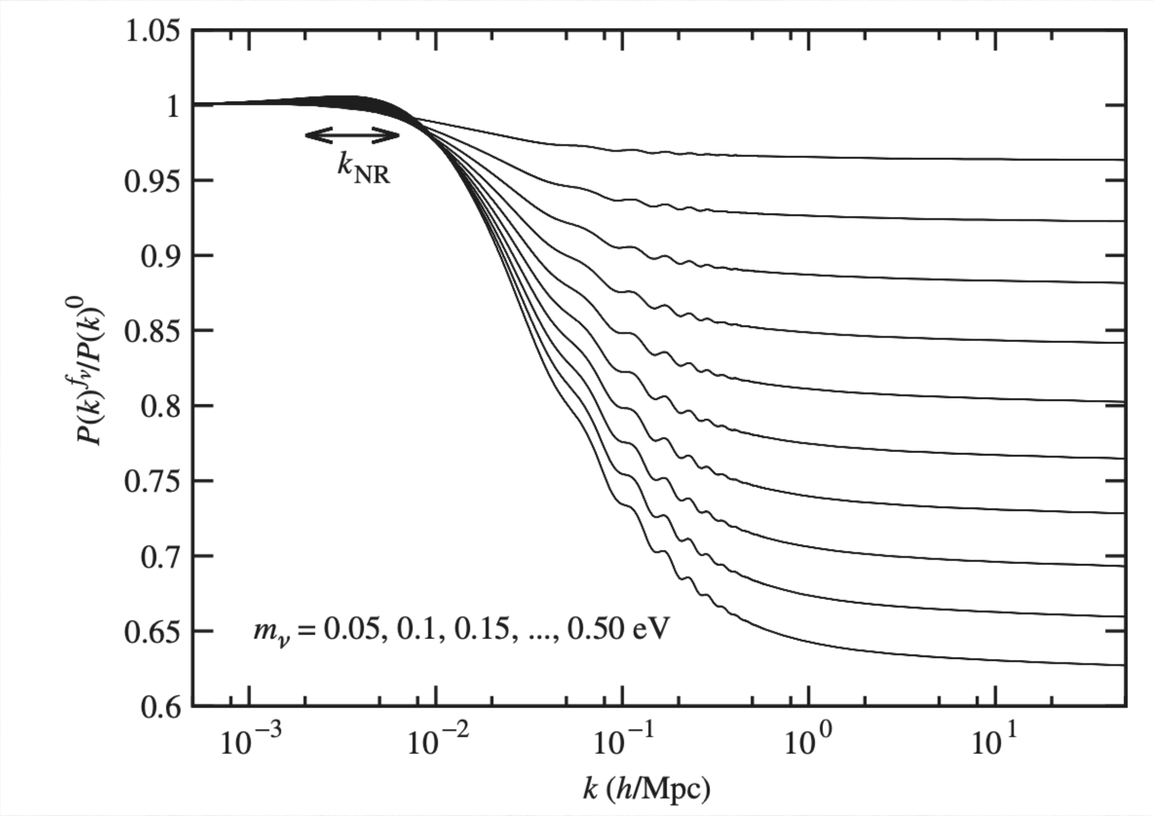
- EDE cannot resolve the S_8 tension (but no strong constraints from EFTBOSS)
- One can extend this model to reduce the growth of DM perturbations and resolve both tensions simultaneously
- Alternatively, (if not fluke) S_8 could be resolved by some independent mechanism… including baryons!

Future CMB data will detect/exclude EDE!

Could ν's explain the S_8 tension?

Power suppression: $k \geq k_{nr} \equiv 0.01 \left(\frac{m_\nu}{1\text{eV}}\right)^{1/2} \left(\frac{\Omega_m}{0.3}\right)^{1/2} h\text{Mpc}^{-1}$ with amplitude $\frac{\Delta P}{P} \simeq -8\frac{\omega_\nu}{\omega_\text{m}}$

Need $\sum m_\nu \sim 0.2$ eV to explain S_8



- Including EDE does not change massive neutrinos constraints / cannot resolve S_8 *Reeves++ 2207.01501*

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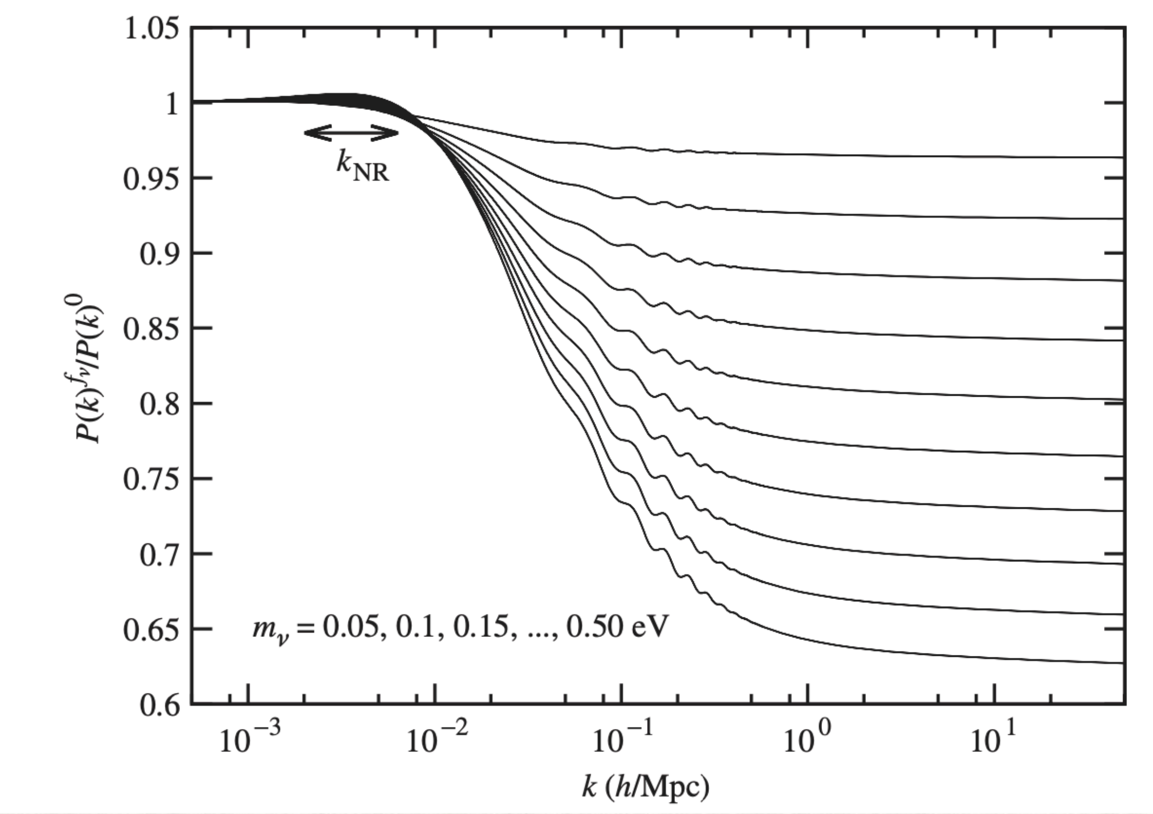

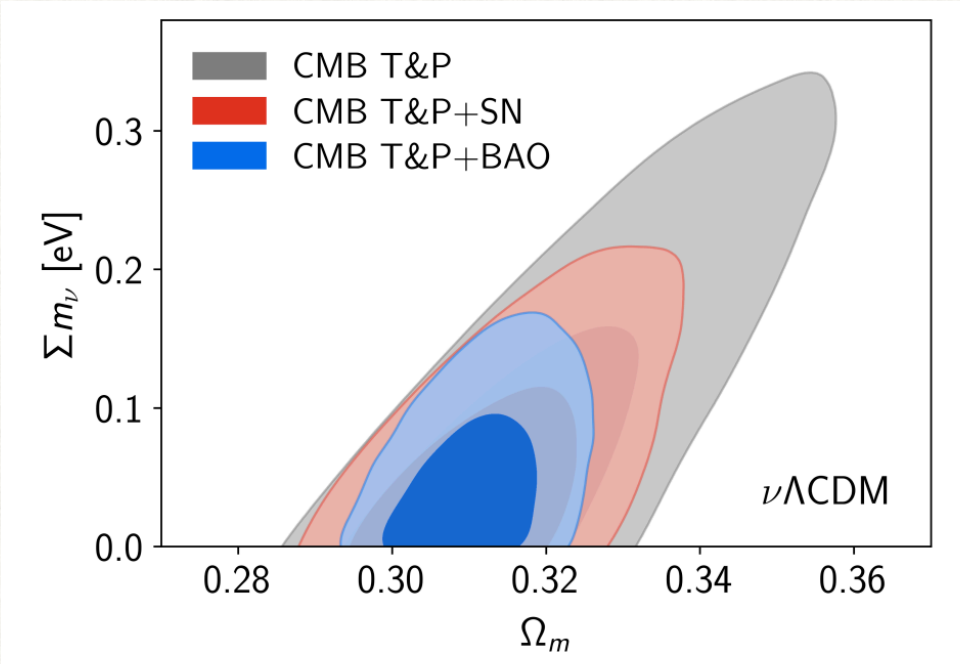

Planck 2018 + BAO < 0.12eV *Planck 1807.06205*

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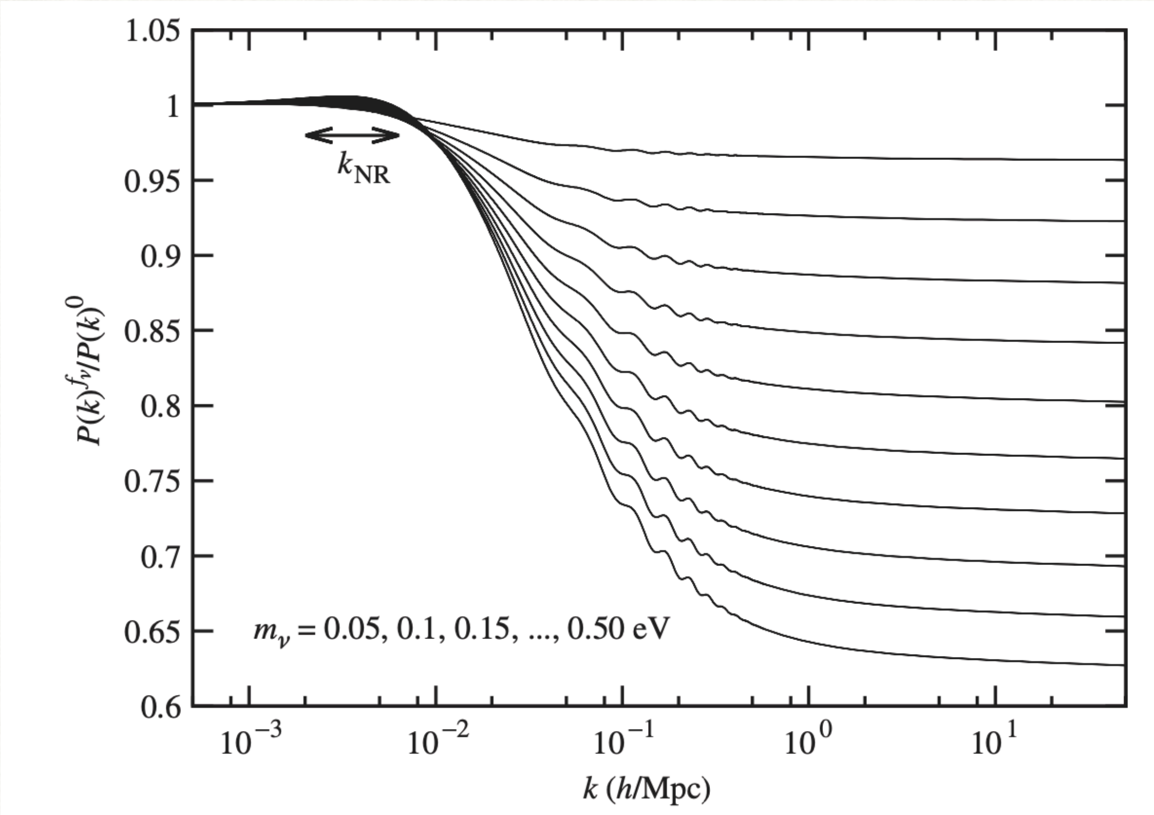
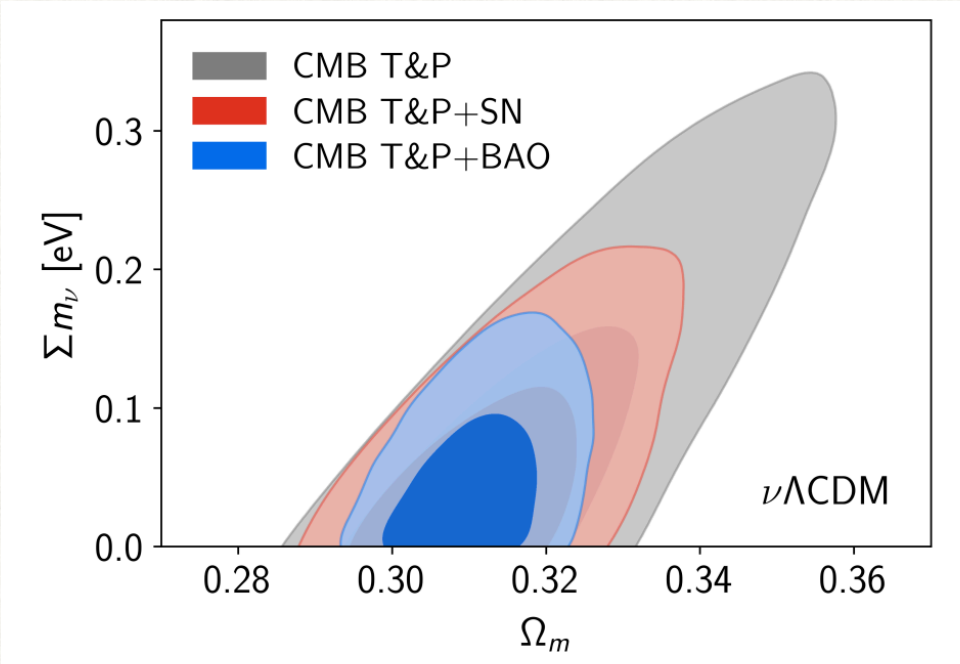




Planck 2018 + BAO < 0.12eV *Planck 1807.06205*

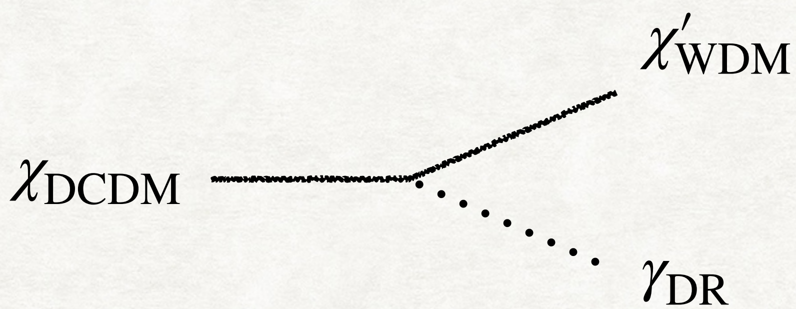
Planck 2018 + BAO + Ly$-\alpha$ < 0.089eV *Palanque-Delabrouille++ 1911.09073*

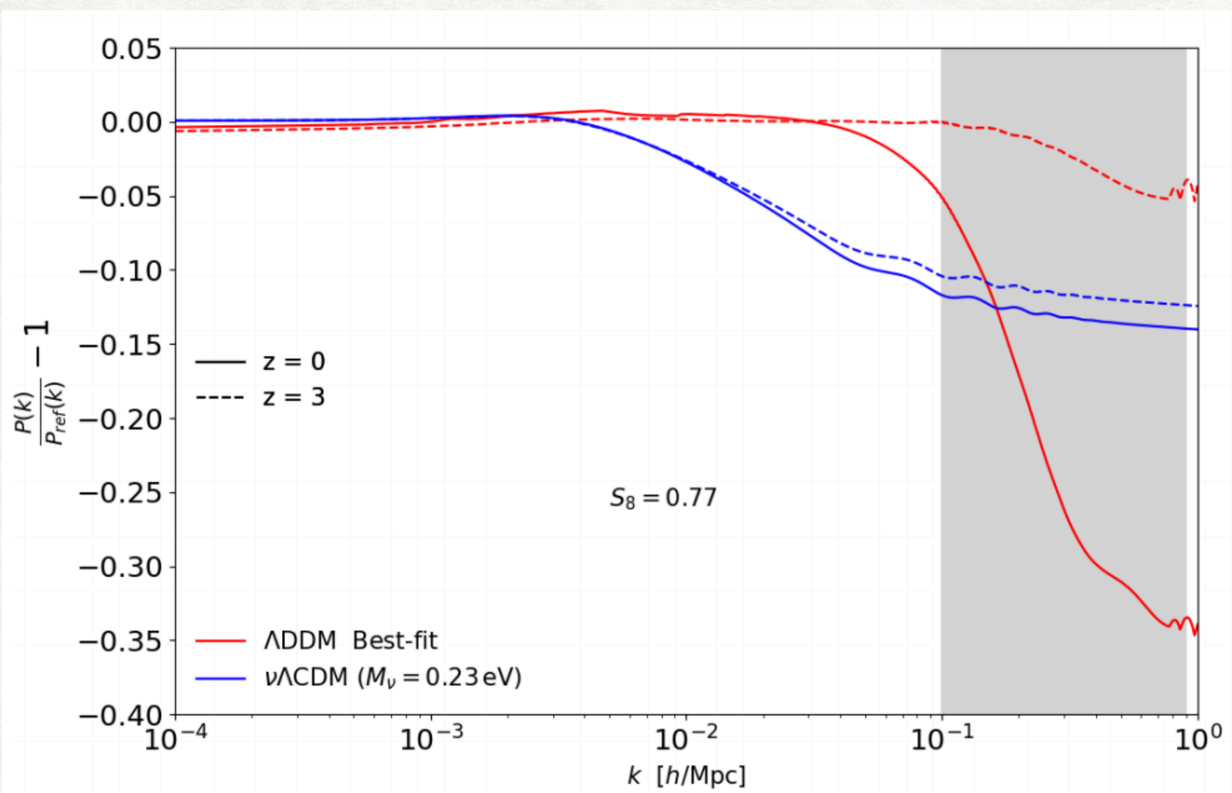
Planck 2018 + BOSS + eBOSS < 0.082eV *Brieden++ 2204.11868, Simon++ 2210.14931*

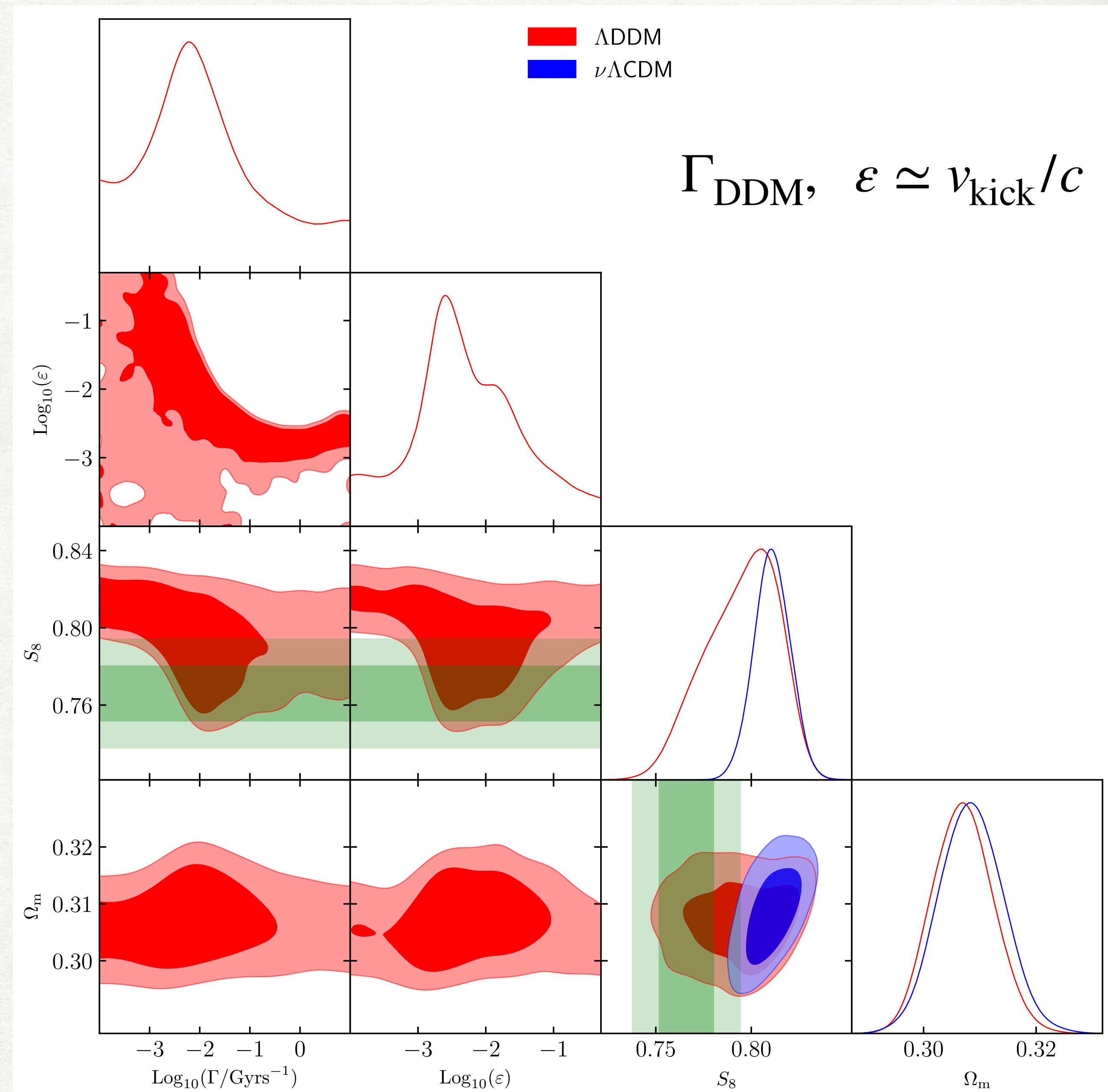
- Including EDE does not change massive neutrinos constraints / cannot resolve S_8 *Reeves++ 2207.01501*

How to generate a late-time suppression

- Generate $\sim 20\,\%$ of WDM at late-time via decay of CDM into a dark sector







- DM with $\Gamma^{-1} \simeq 55(\varepsilon/0.007)^{1.4}$ Gyrs can explain low S_8 (1.3σ agreement) *Abellan++ 2008.09615 & 2104.03329*
- Similar results if there exists a fraction of ultra-light axion in the universe *Rogers++ 2023*

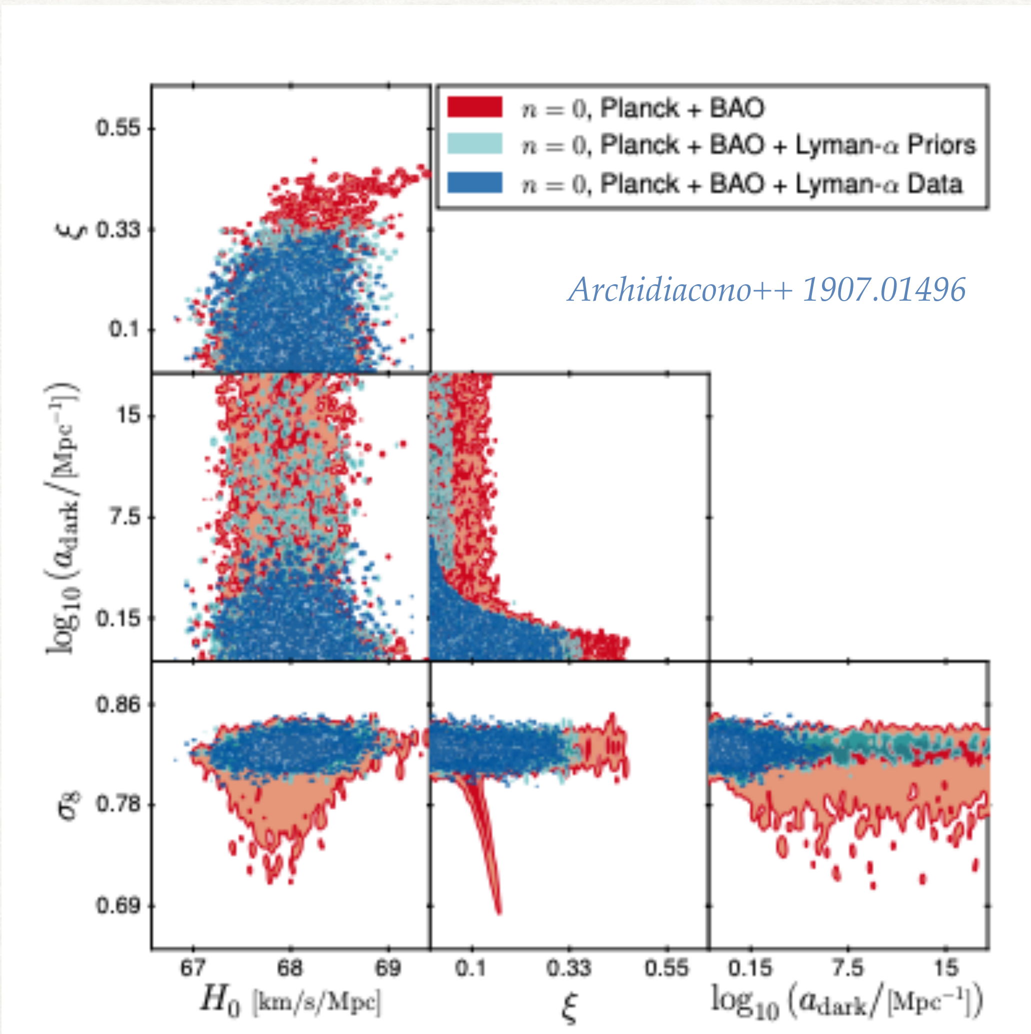
DM "drag" suppresses power at small-scales

DM<=>DR

$$\dot{\delta}_{\rm DM} + \theta_{\rm DM} - 3\dot{\phi} = 0,$$
$$\dot{\theta}_{\rm DM} - k^2 c^2_{\rm DM}\delta_{\rm DM} + \mathcal{H}\theta_{\rm DM} - k^2\psi = \Gamma_{\rm DM-DR}\left(\theta_{\rm DM} - \theta_{\rm DR}\right),$$

$$\Gamma_{\rm DR-DM} = -\Omega_{\rm DM}h^2 a_{\rm dark}\left(\frac{1+z}{1+z_d}\right)^n,$$

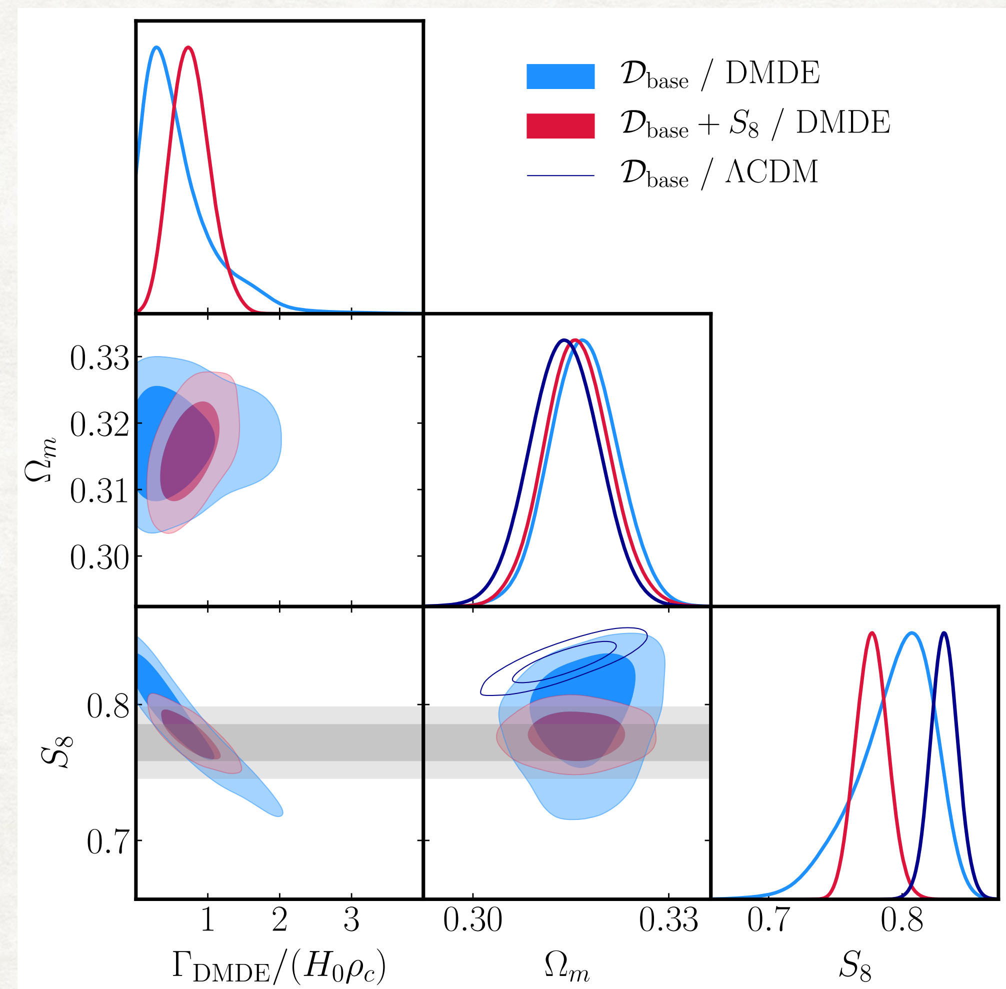
$$\xi = T_{\rm DR}/T_\gamma$$



DM<=>DE

VP, Bernal, Kovetz, Kamionkowski 2209.06217

$$\theta'_{\rm DM} = -\frac{a'}{a}\theta_{\rm DM} + k^2\psi + \Gamma_{\rm DMDE}(a)(\theta_{\rm DE} - \theta_{\rm DM}),$$
$$\theta'_{\rm DE} = -(1-3c^2_{s,\rm DE})\frac{a'}{a}\theta_{\rm DE} + \frac{k^2 c^2_{s,\rm DE}}{(1+w_{\rm DE})}\delta_{\rm DE} + k^2\psi - \Gamma_{\rm DMDE}(a)R(\theta_{\rm DE} - \theta_{\rm DM}),$$



See also Di Valentino++ 1908.04281

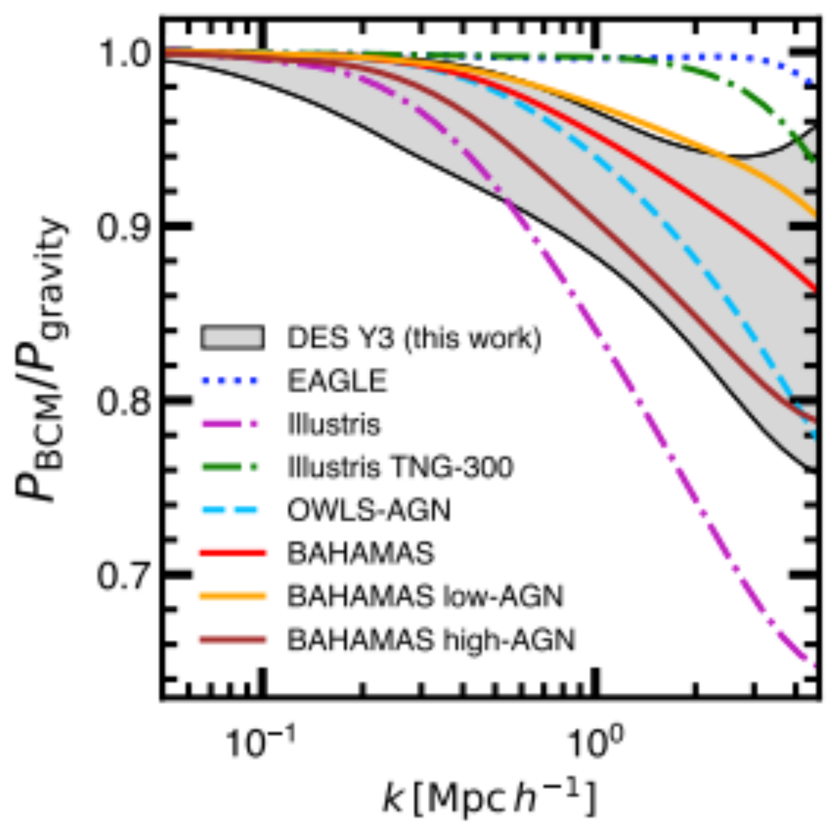
- Non-Abelian dark matter model, Cannibal dark matter, also with sub-component of strongly interacting DM

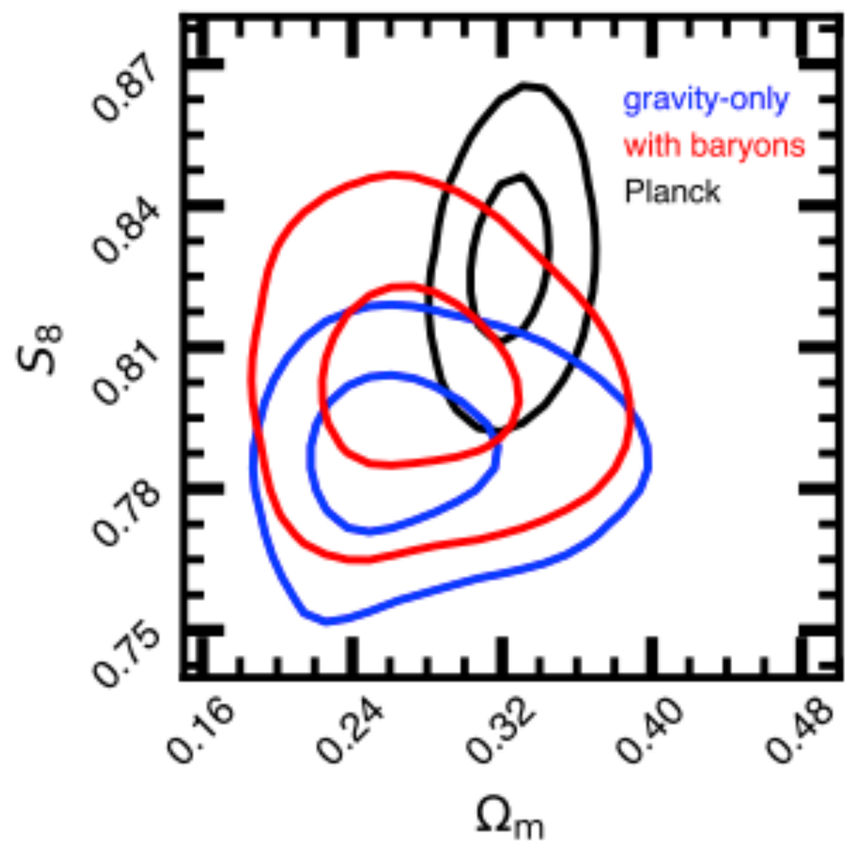
Buen-Abad++1505.03542, Lesgourgues++1507.04351, Heimersheim++ 2008.08486, Chacko++1609.03569, Buen-Abad++ 1708.09406, Raveri++ 1709.04877

Could the σ_8-tension be non-linear astrophysics?

- Reanalysis of DES data with improved non-linear / baryons / intrinsic alignements modeling at small scales

Aricò++ 2303.05537



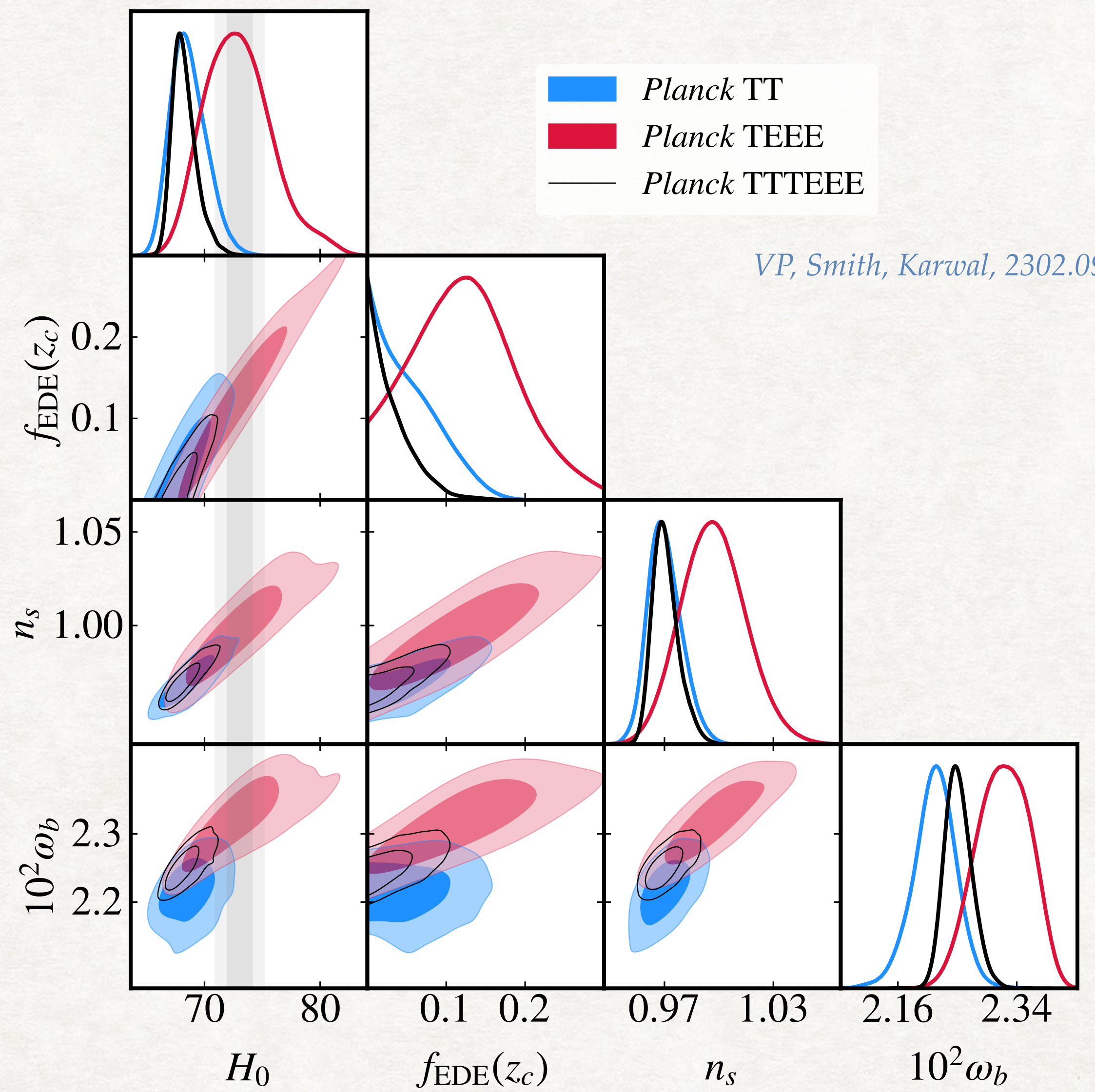


- The σ_8 tension may be astrophysics! Strong feedback + improved non-linear physics could explain the tension.

See also Amon& Efstathiou 2206.11794

- New analysis is in 0.9σ agreement with Planck/LCDM. Implications for EDE have yet to be investigated.

Curiosities in *Planck*?



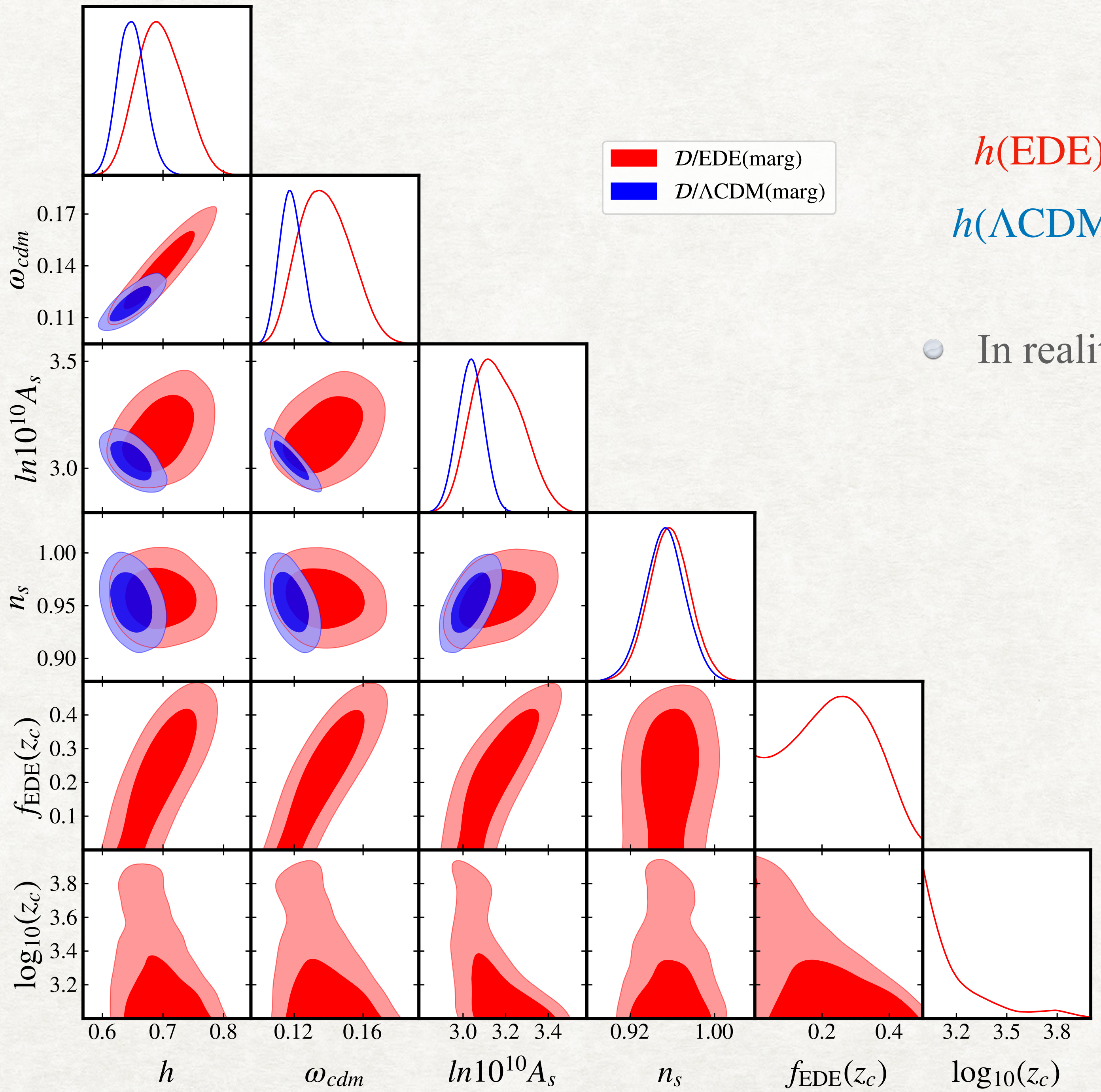
VP, Smith, Karwal, 2302.09032

- Preference for EDE is coming from the TEEE data
- Disagreements in ω_b & n_s drive the constraints in the combined analysis
- Uncertainty in modeling the Planck TE polarization efficiency calibration: preference can be altered.

Smith, Lucca, VP++ 2202.09379

k_{eq}-based estimate of H_0

- The (too short) story: matter power spectrum turnover measures $k_{eq} d_A \sim \Omega_m h$ *Philcox++ 2204.02984*
- Combining with a measurement of Ω_m get a 'sound-horizon independent' measurement! *Smith, Simon, VP 2208.12992*



$h(\text{EDE}) = 0.696^{+0.036}_{-0.041}$

$h(\Lambda\text{CDM}) = 0.648^{+0.021}_{-0.024}$

- In reality A_s and n_s priors matter!