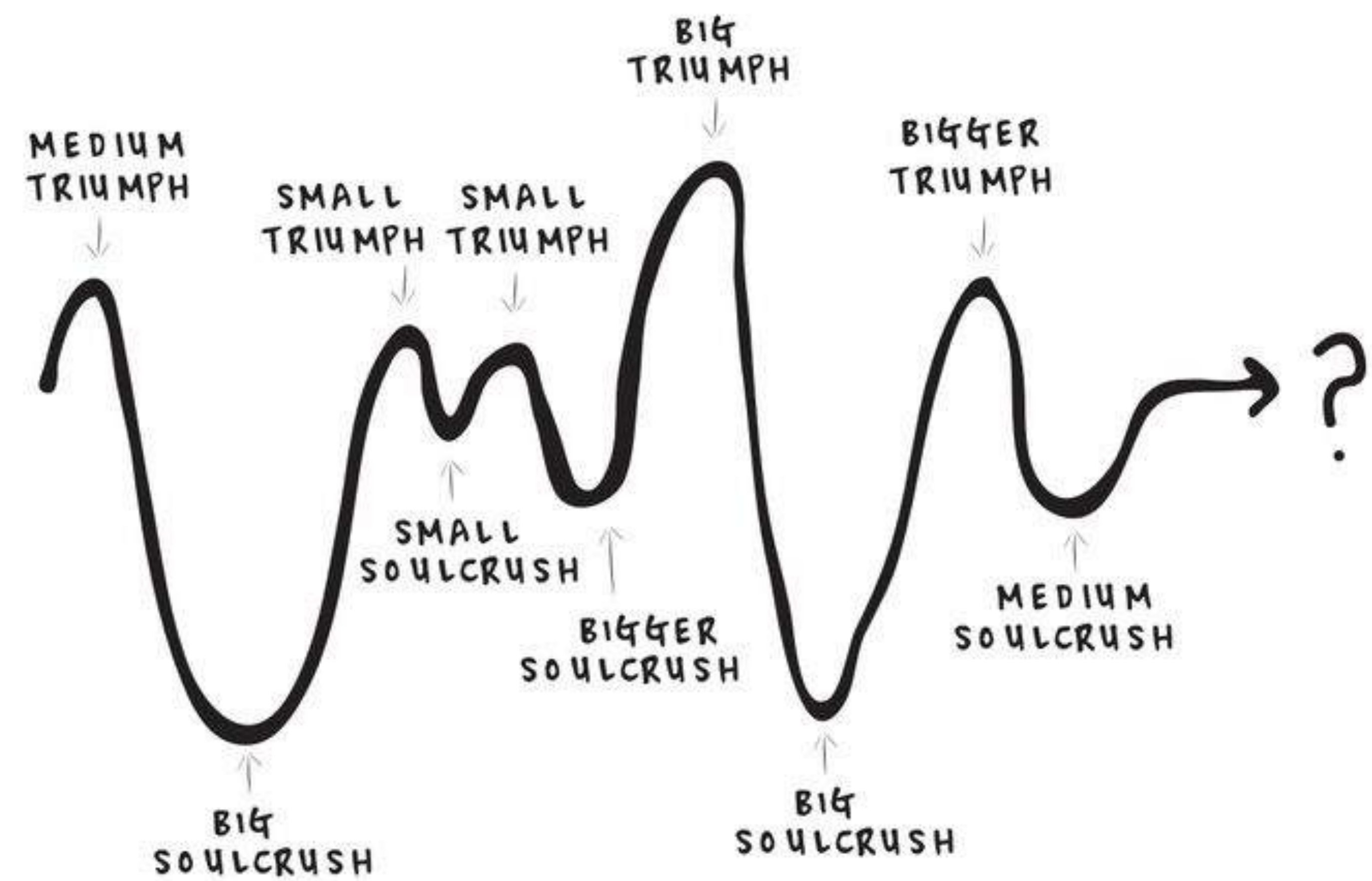
# The Ups and Downs of ~~LIFE~~ Early Dark Energy




Vivian Poulin

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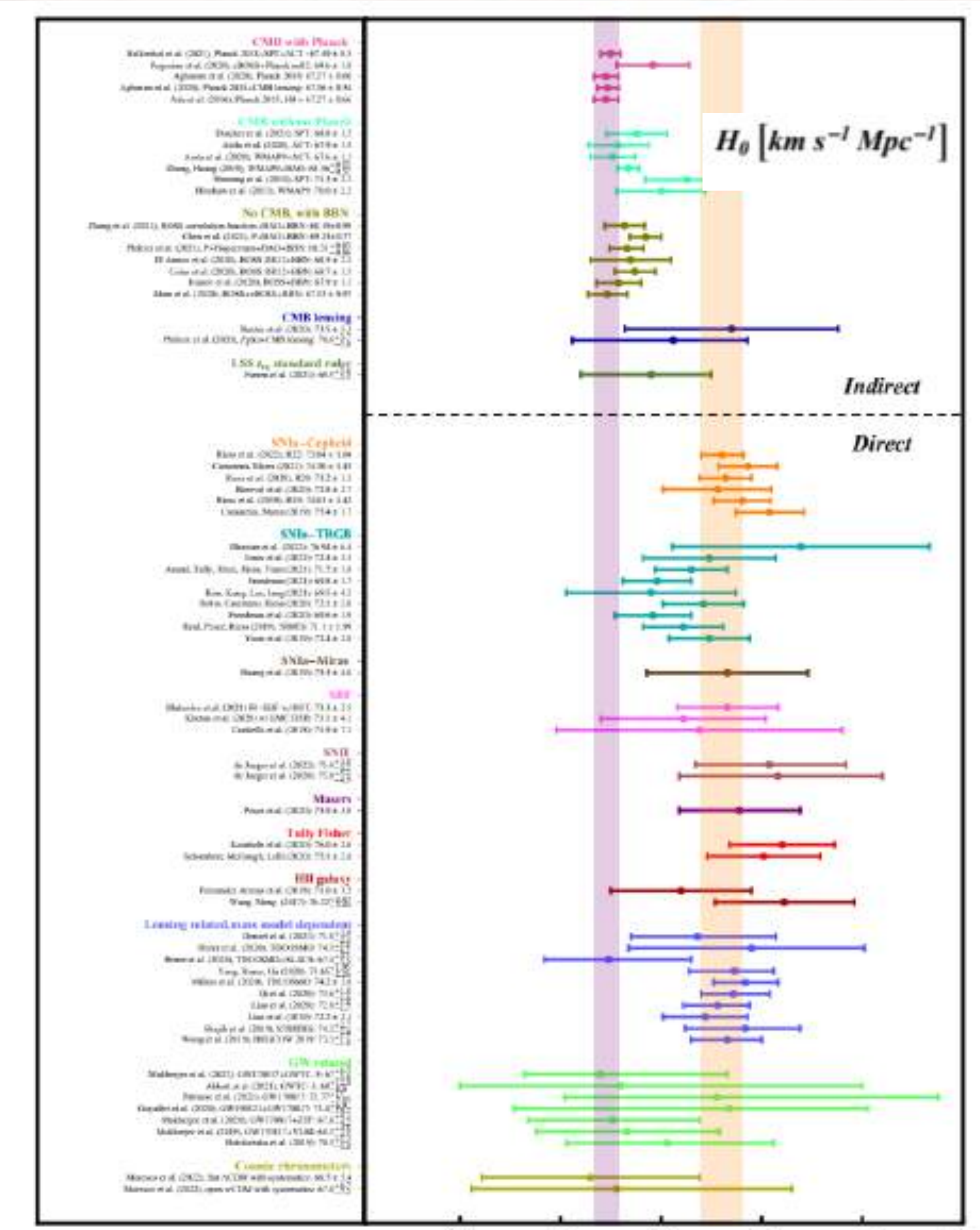
CNRS & Université de Montpellier

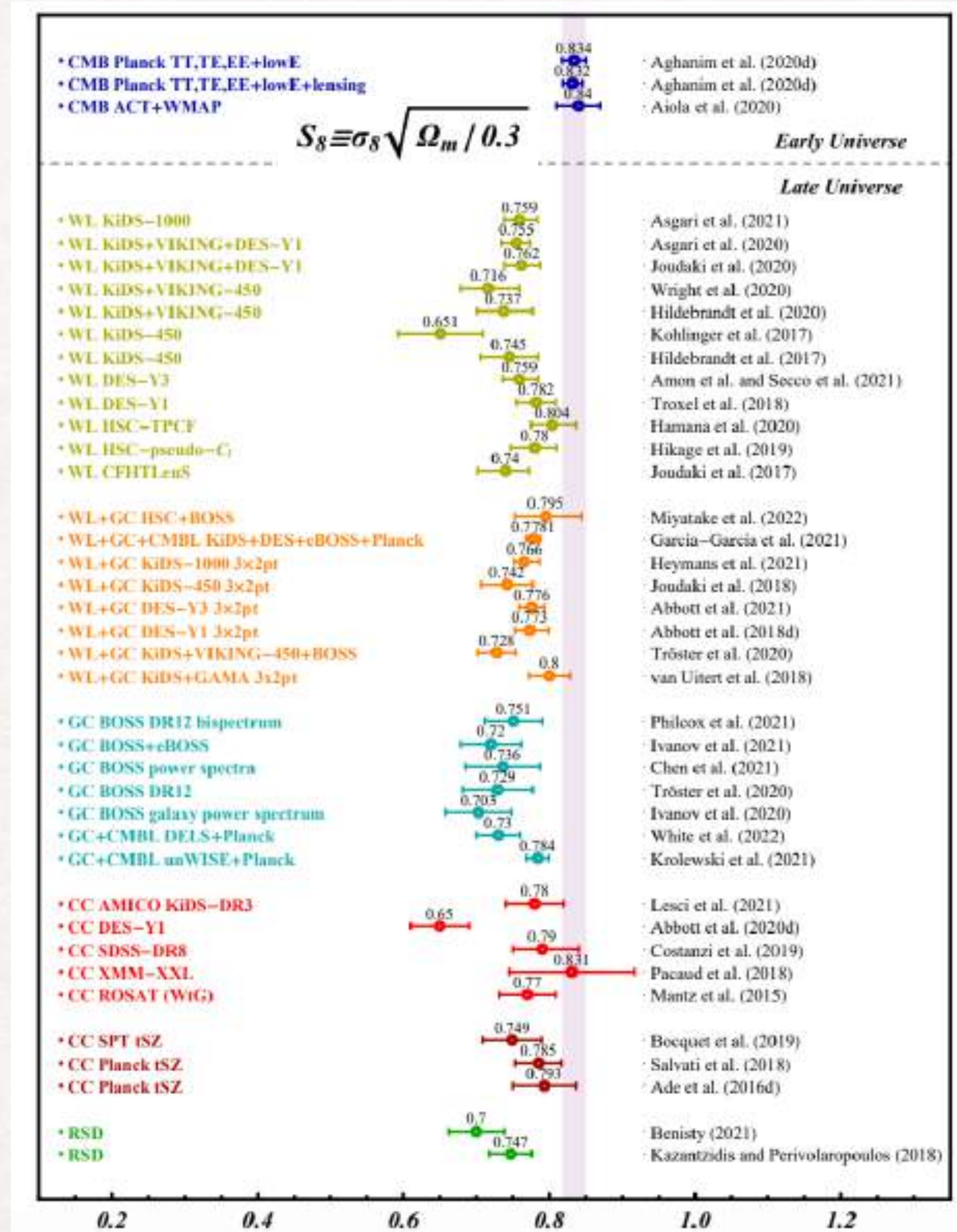
*In collaboration with Tristan L. Smith (Swarthmore), Tanvi Karwal (UPenn), Marc Kamionkowski (JHU), and many others*

CosmoVerse@Lisbon
Lisbon, Portugal
May, 31st 2023

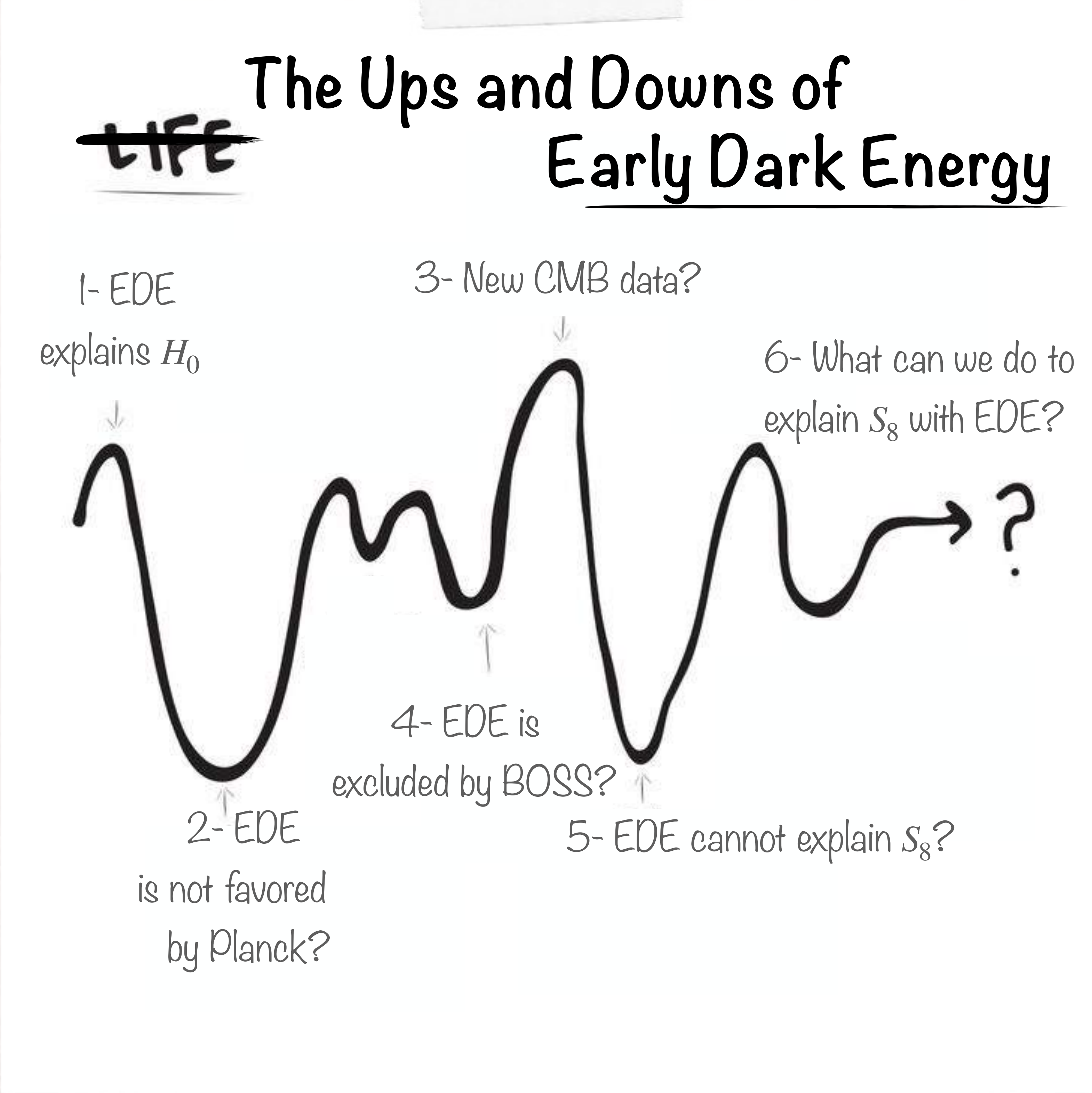
# How can we explain the $H_0$ and $S_8$ tension?




Snowmass white paper 2203.06142



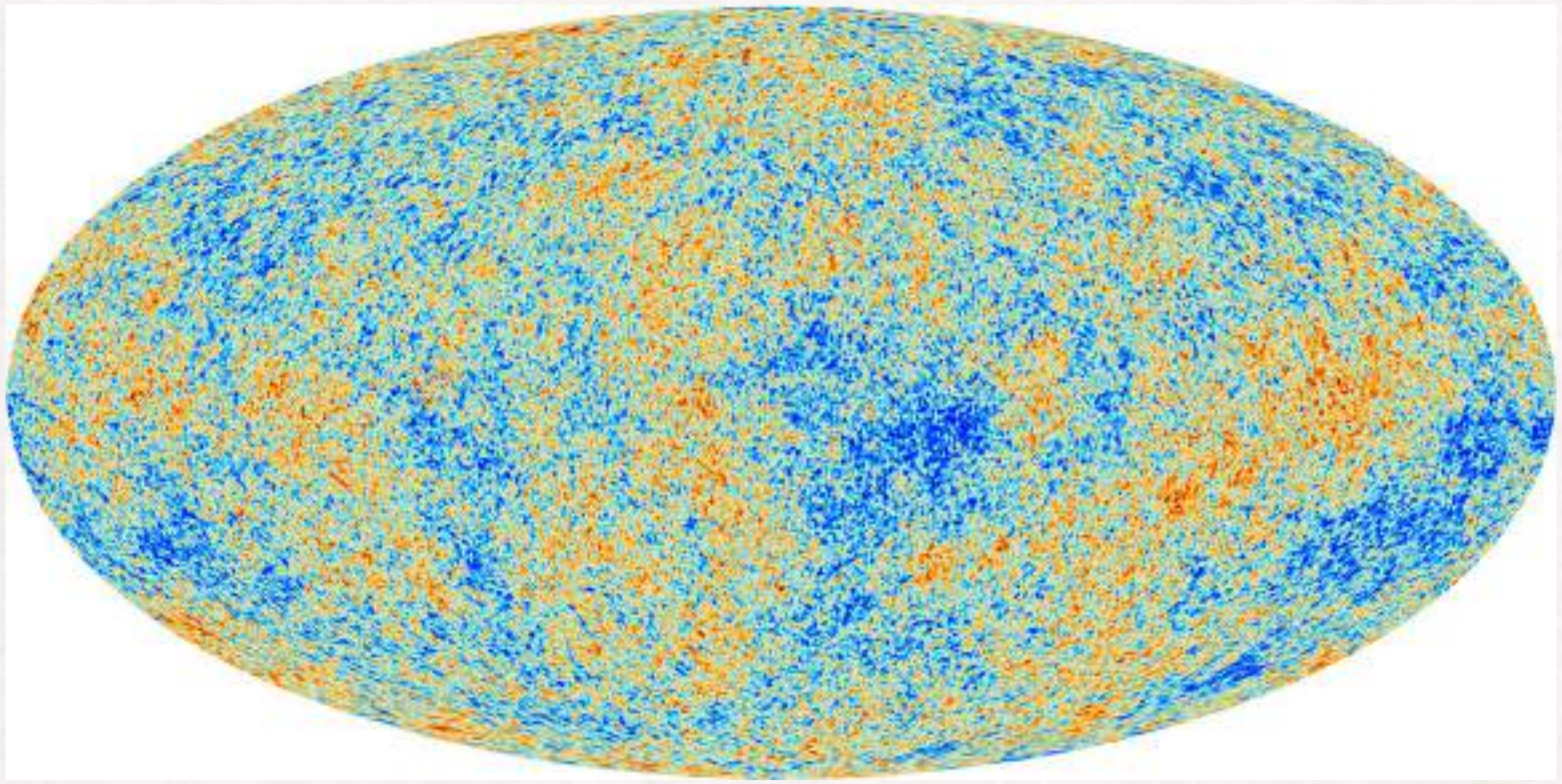
# Can Early Dark Energy explain the $H_0$ and $S_8$ tension?



# The BAO: a standard ruler in the sky

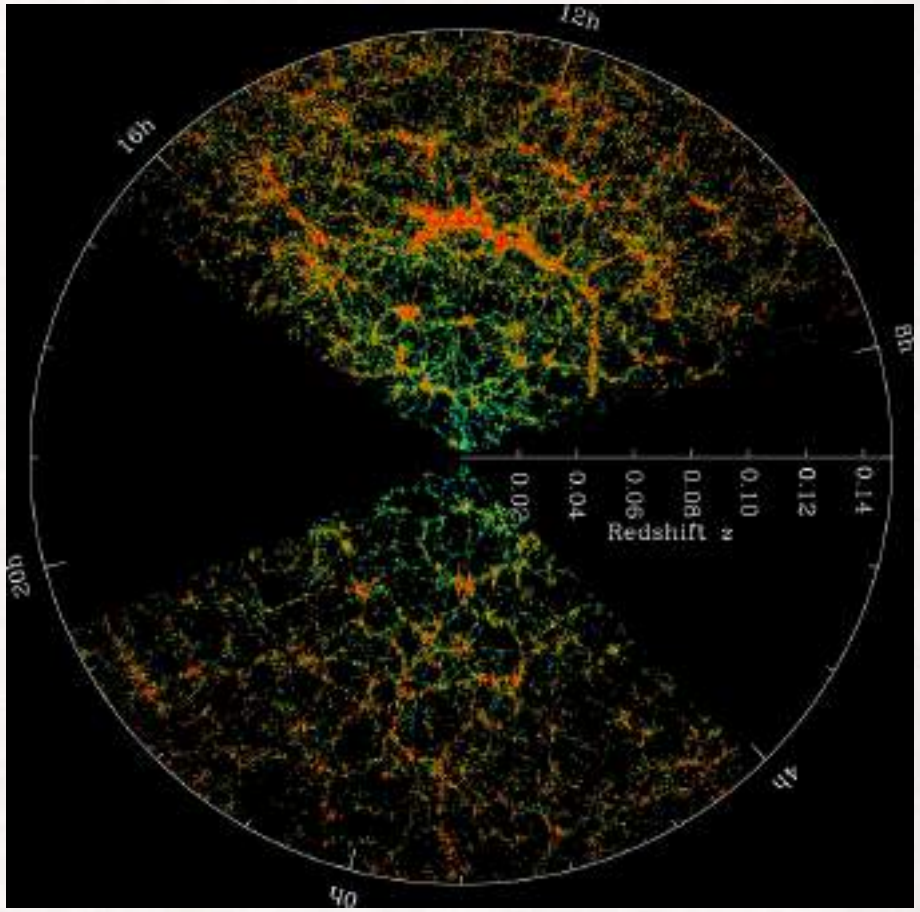
- The same pattern is seen within CMB anisotropies and galaxy surveys at different epoch.

- It can be used to measure distances and infer $H_0$ given a model.



*Planck 1807.06209*

$z \sim 1100$



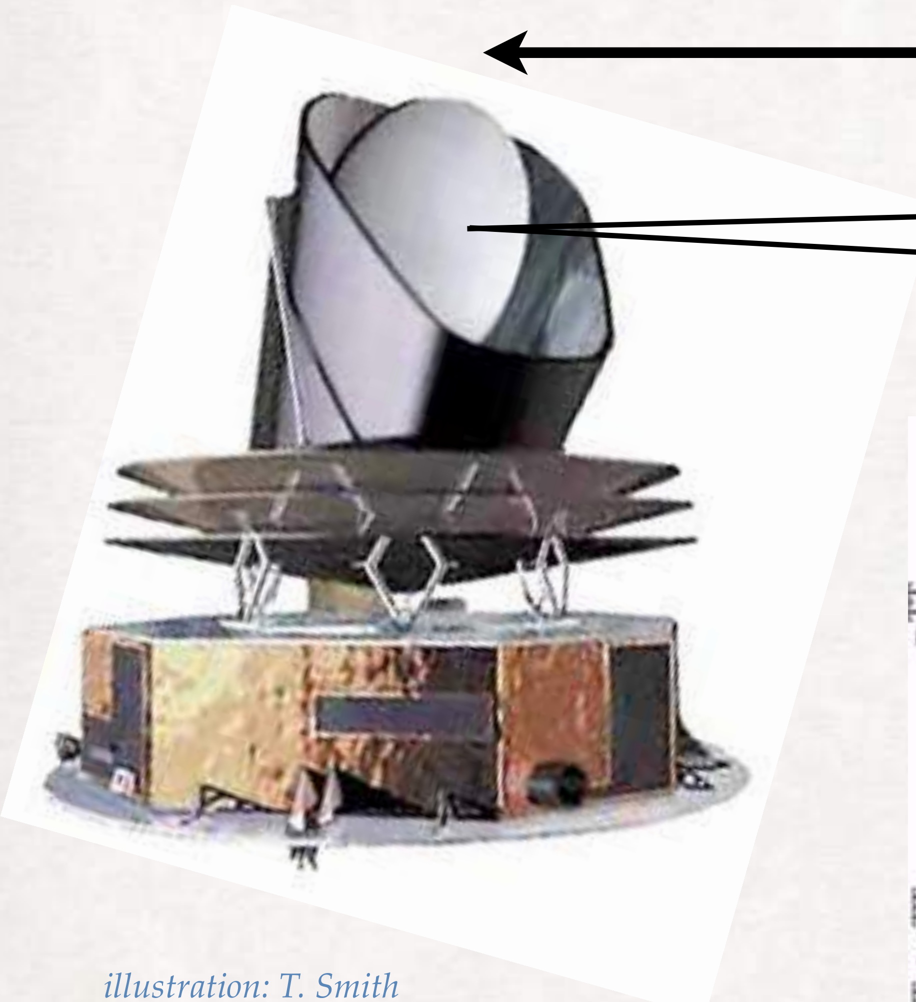

*BOSS/SDSS collaboration*

$z \sim 0 - 1$

# How does CMB data measure $H_0$?

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

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



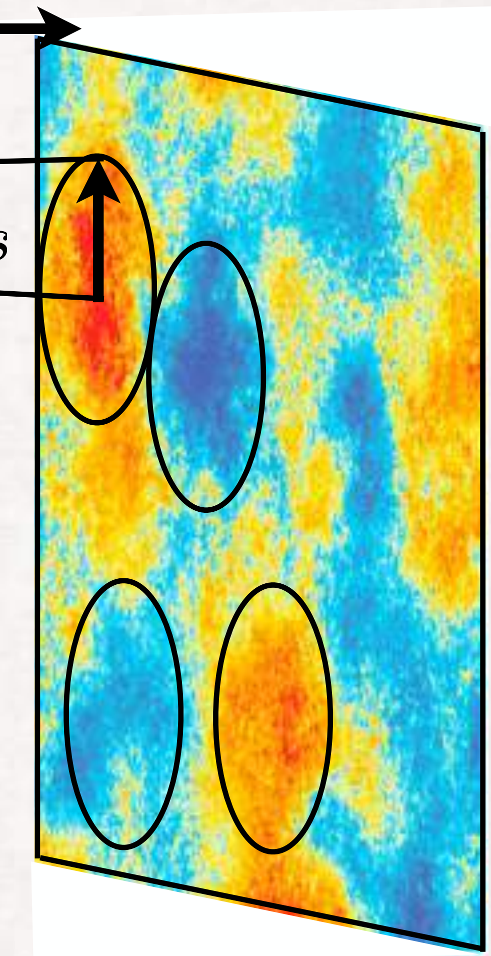
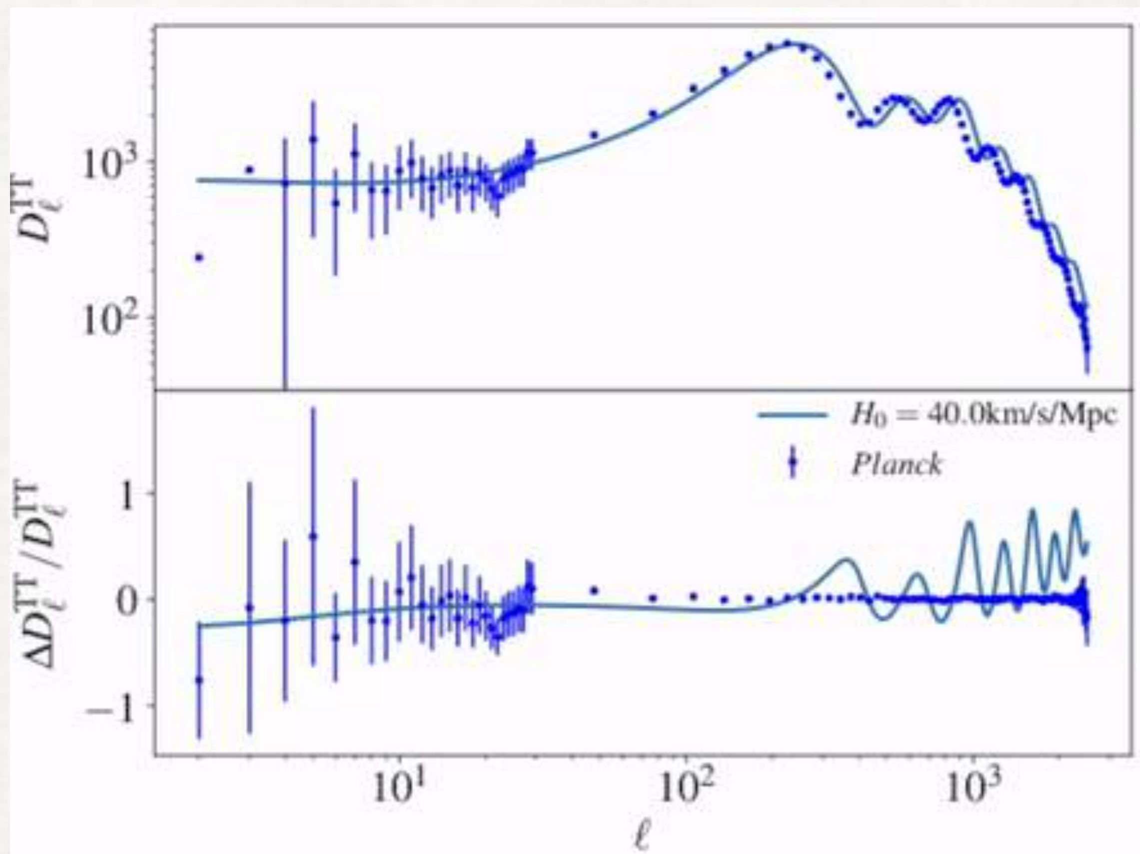



*illustration: T. Smith*



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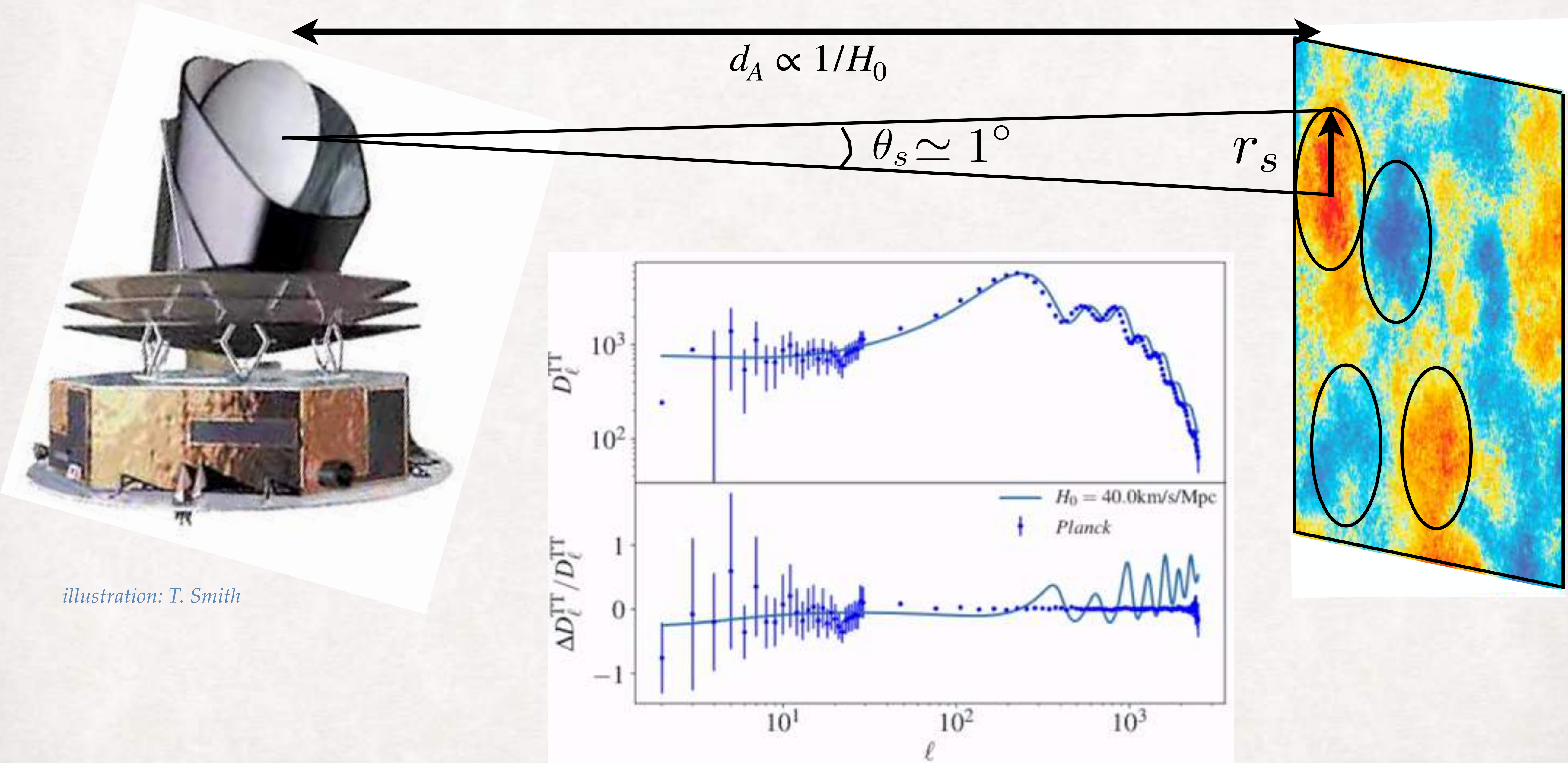


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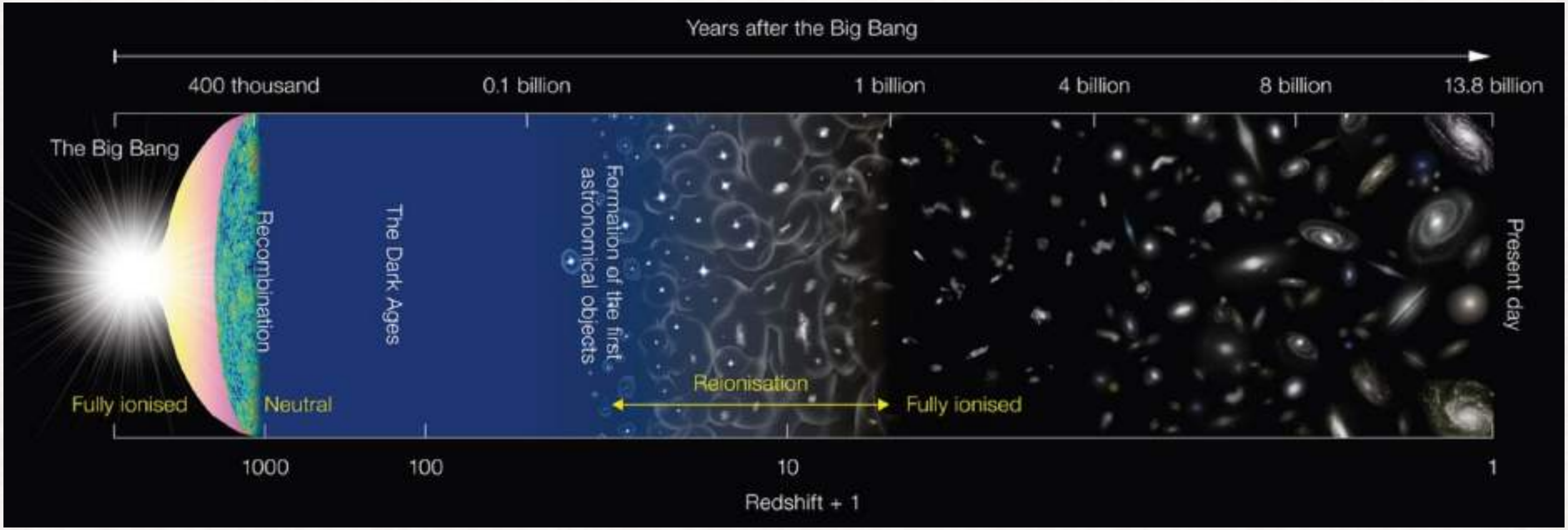
# New physics in the Universe?

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

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



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**Late-universe models**

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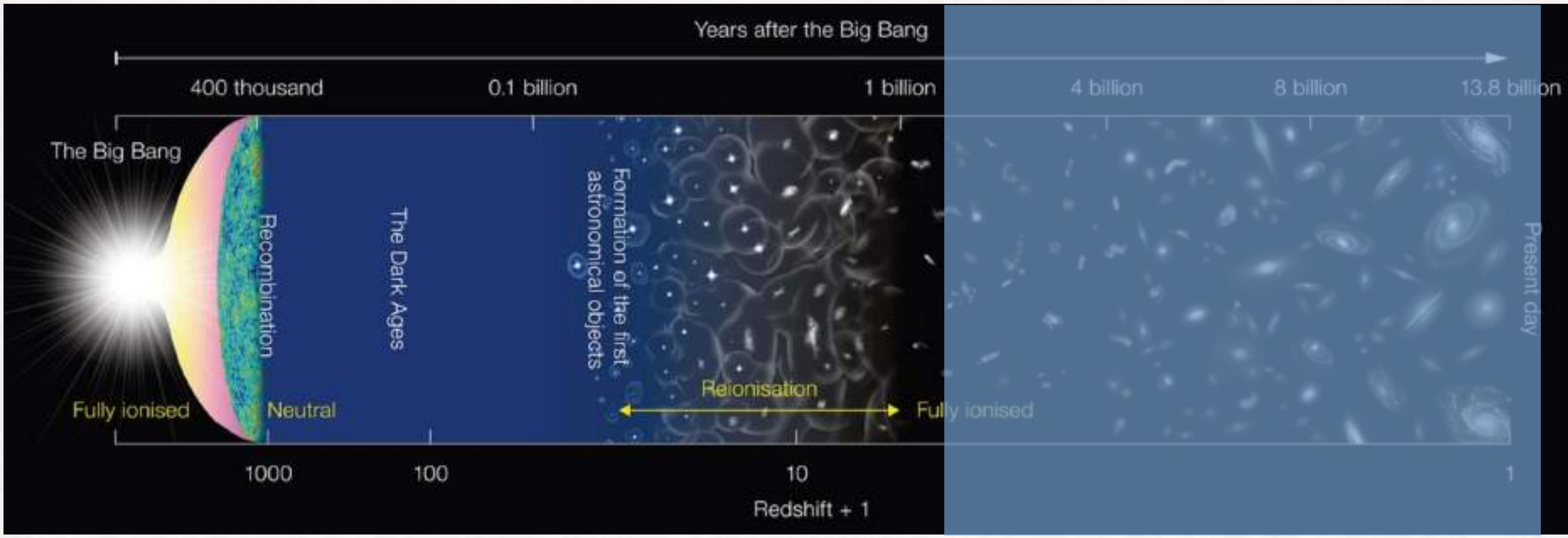


$$\frac{H_0 \nearrow r_s}{\int_0^{z_*} 1/E(x) \searrow \mathrm{d}x}$$

Change expansion history

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**Early universe models**

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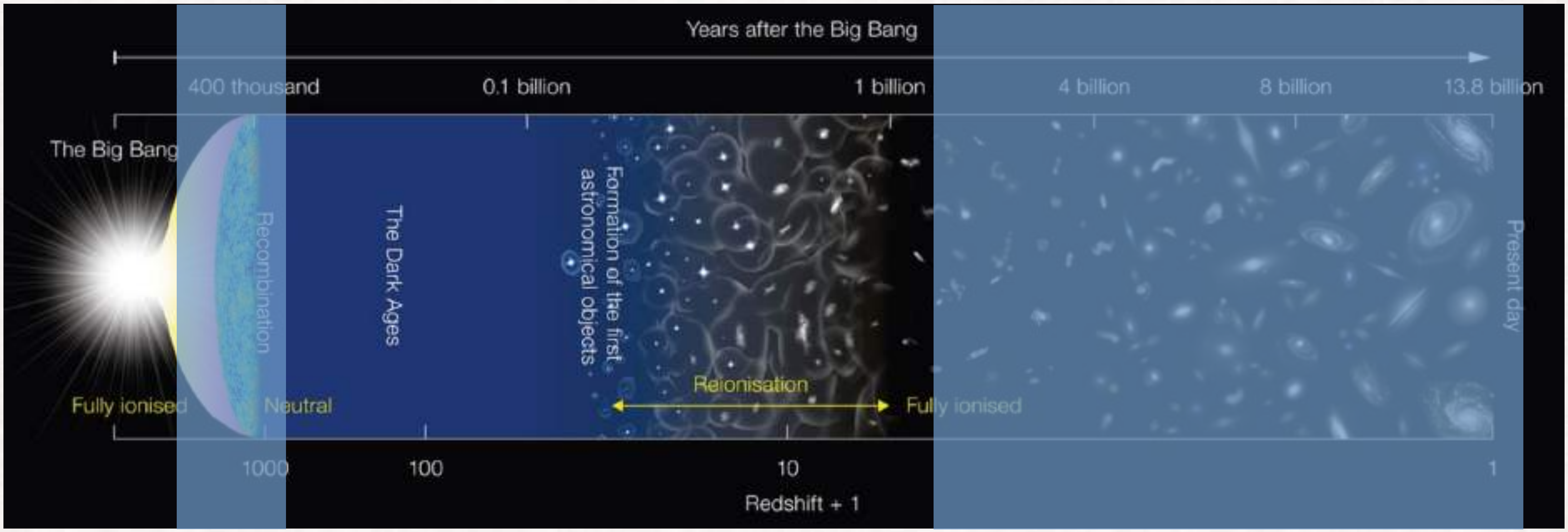


$$\frac{H_0 \nearrow r_s \searrow}{\int_0^z 1/E(x)\mathrm{d}x}$$

Change calibrator

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

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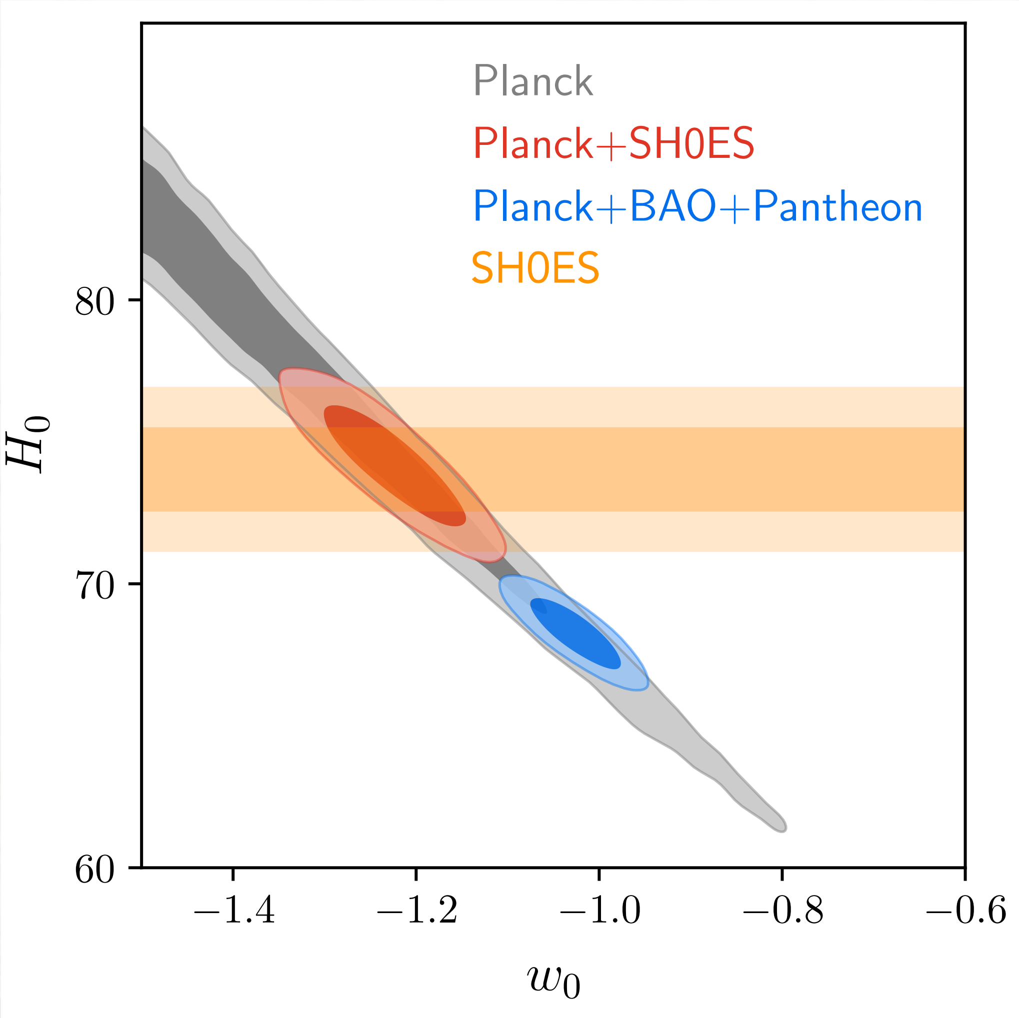
- Planck can easily accommodate a higher $H_0$: problem with BAO and Pantheon



# 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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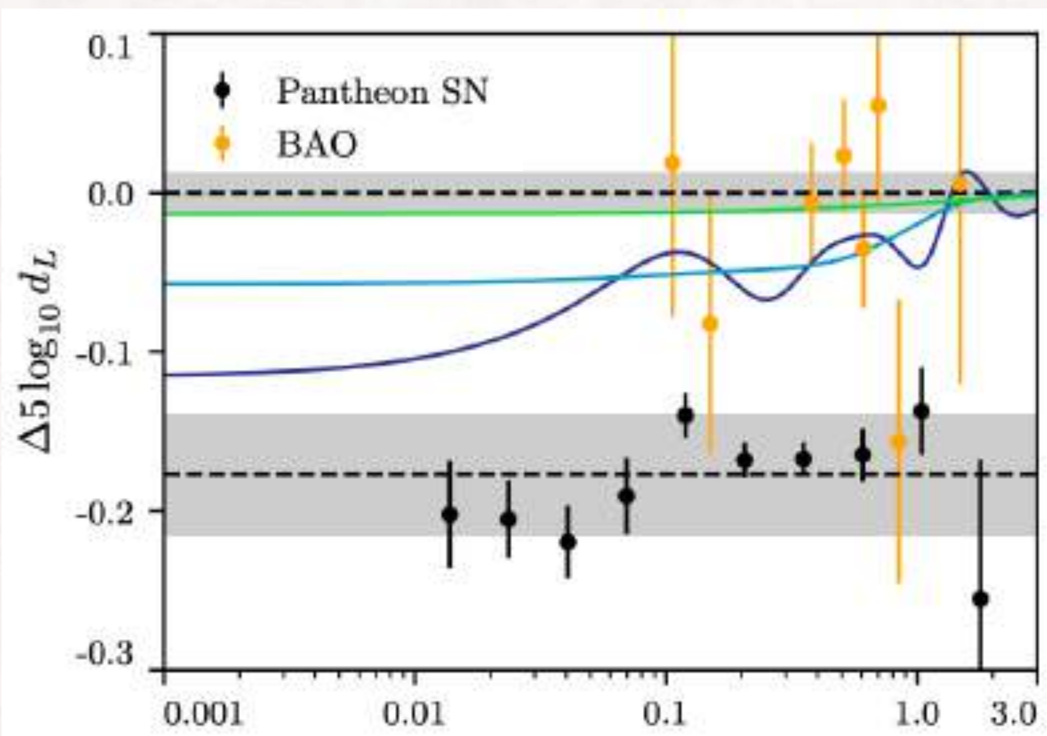


Raveri++ 2107.12992

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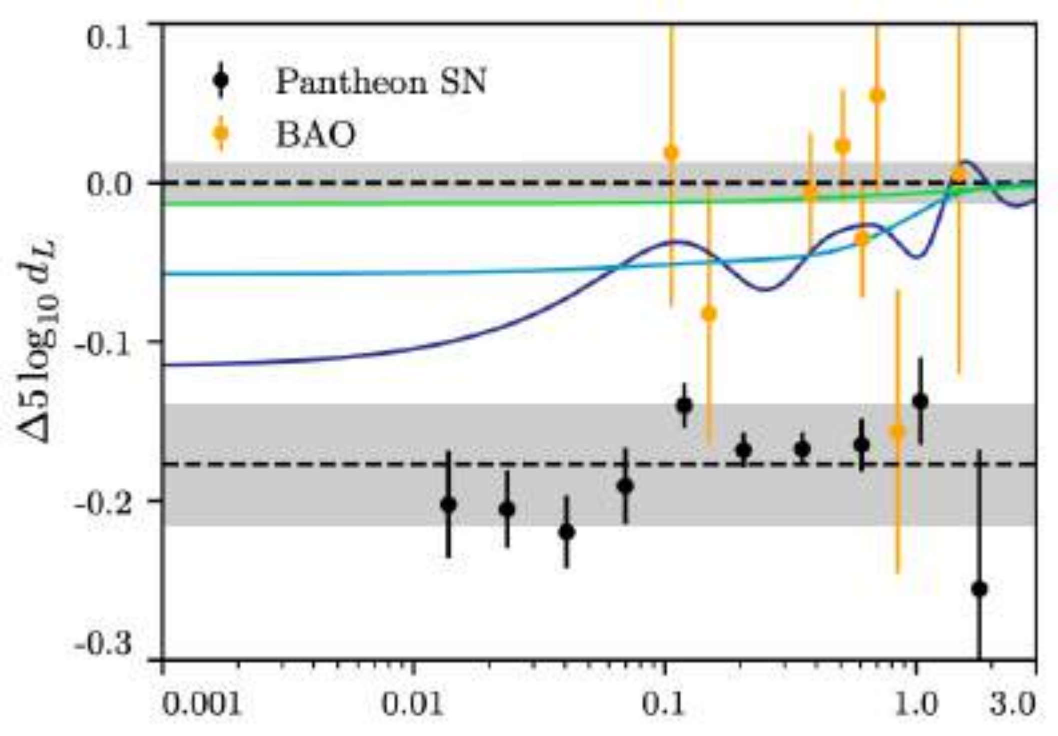


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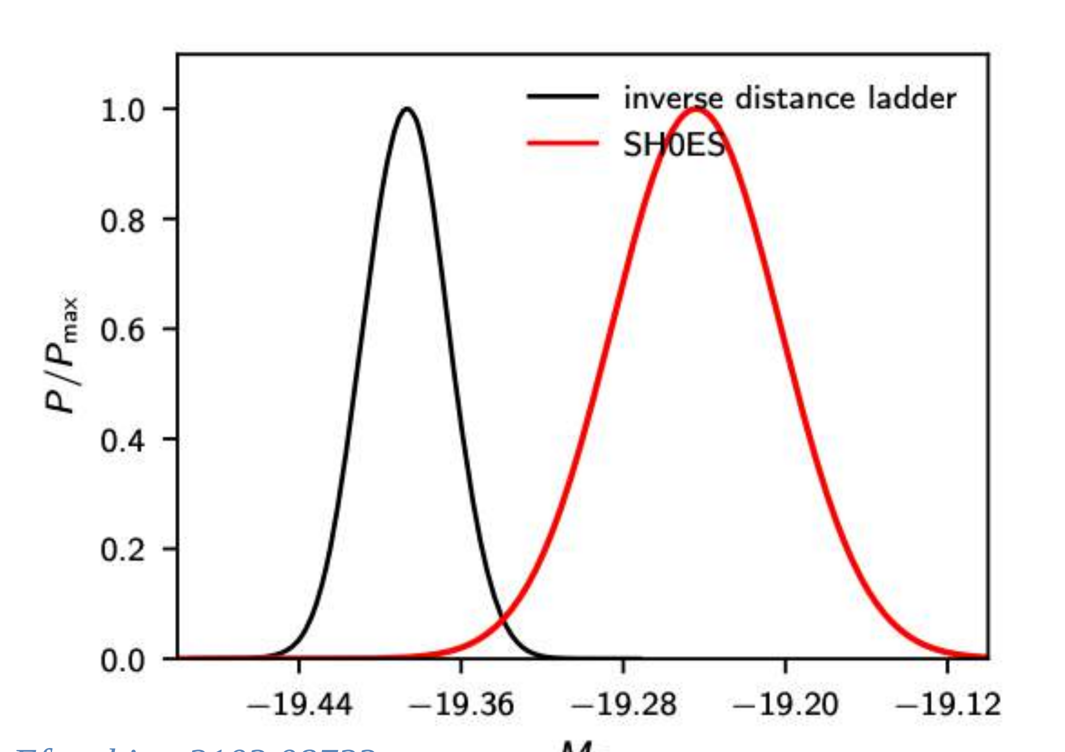
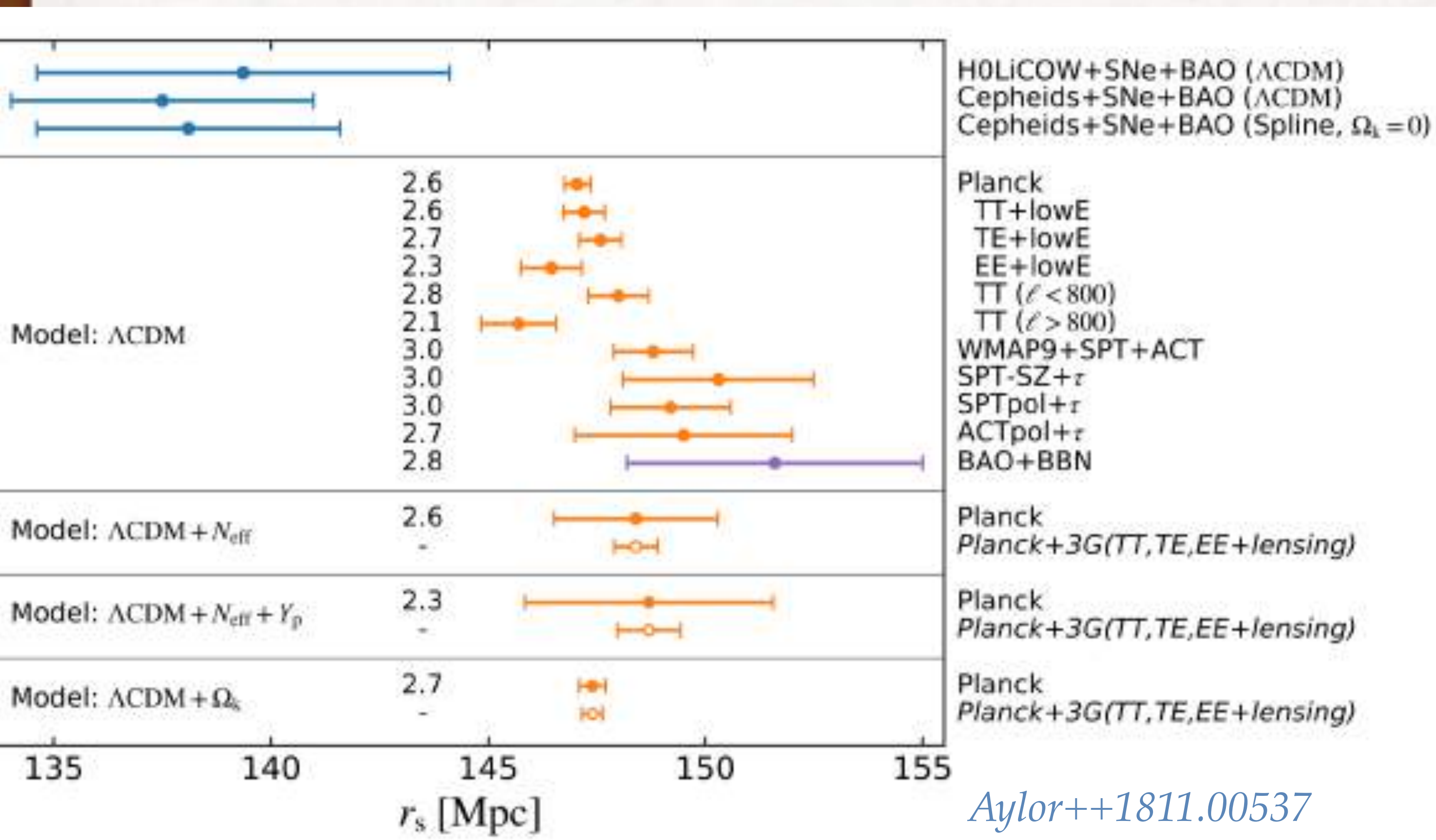


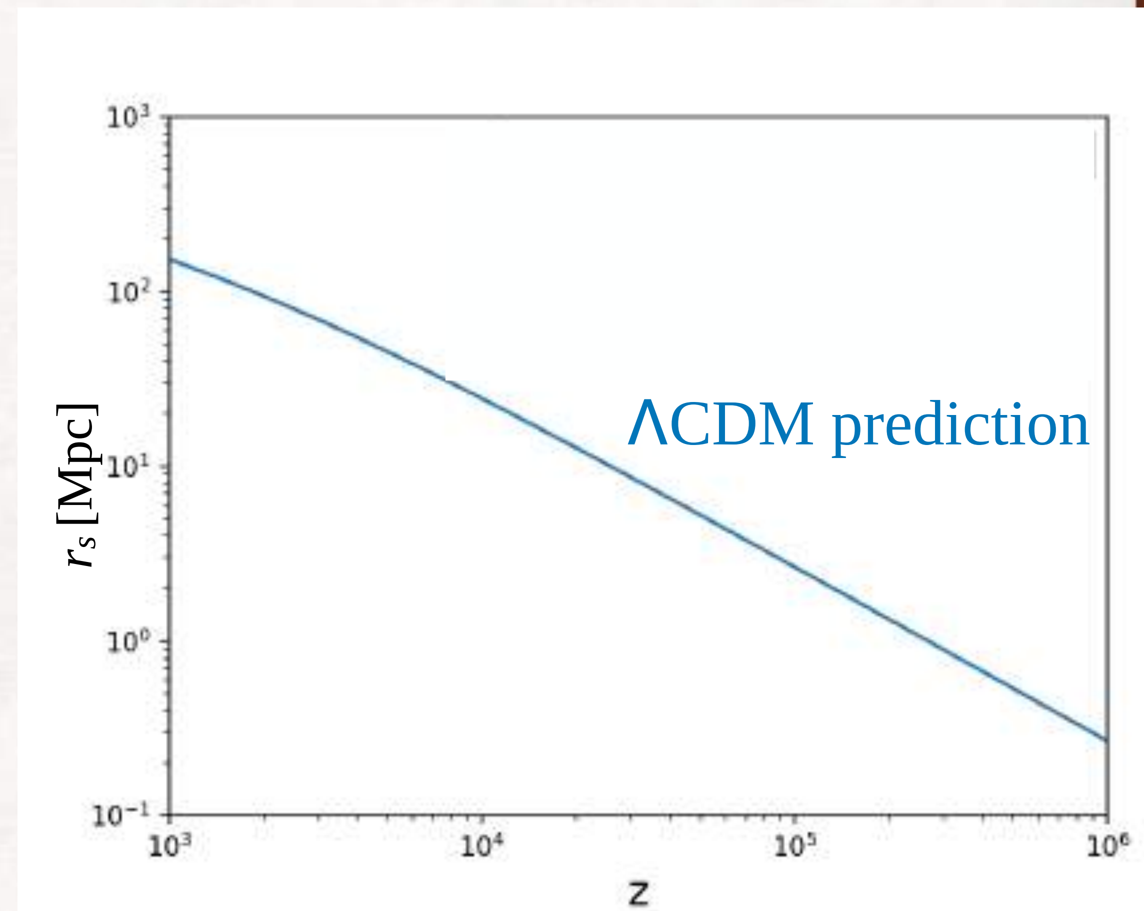

*Efstathiou 2103.08723*

- 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




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

*Knox & Millea 1908.03663*

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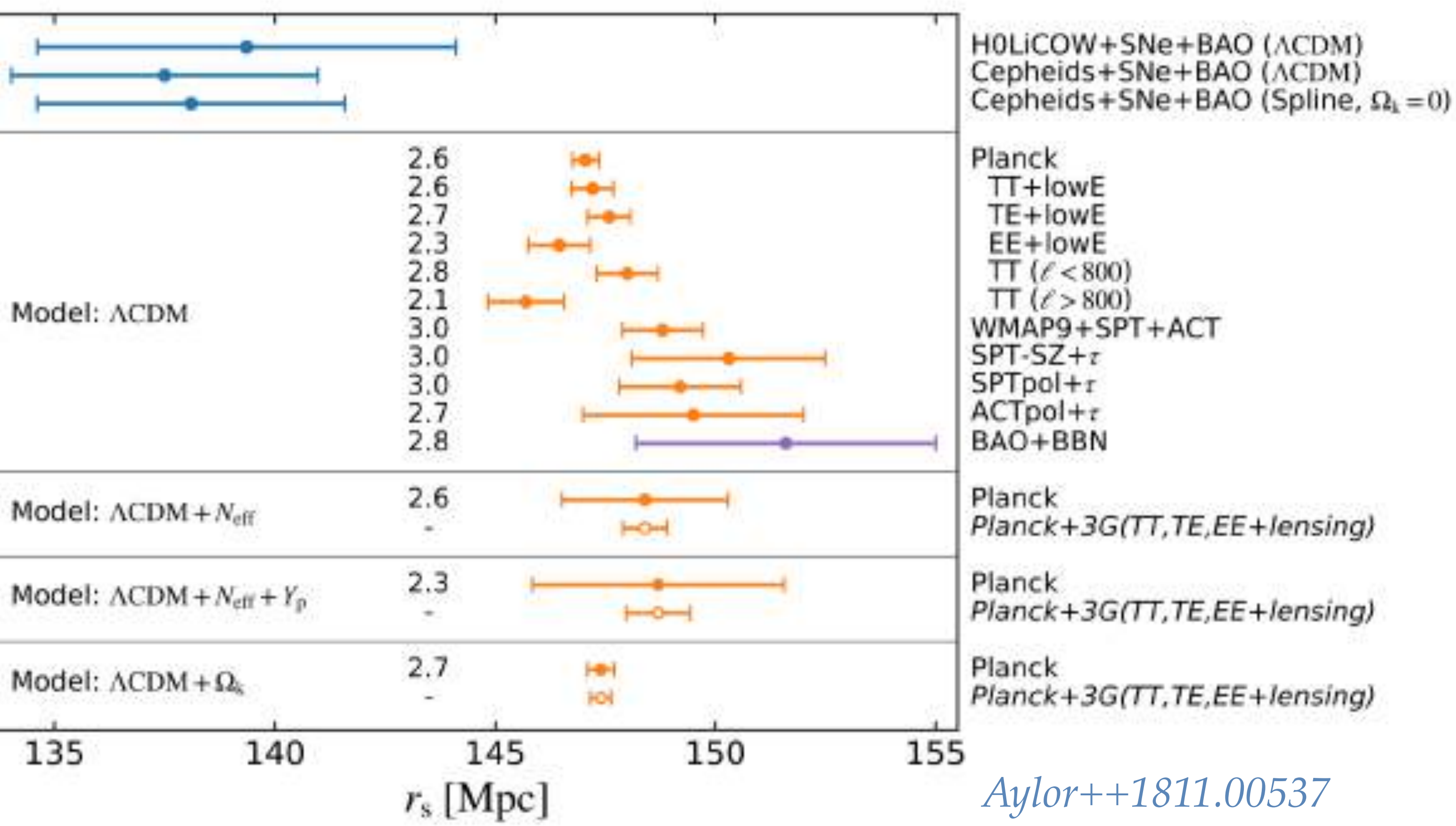
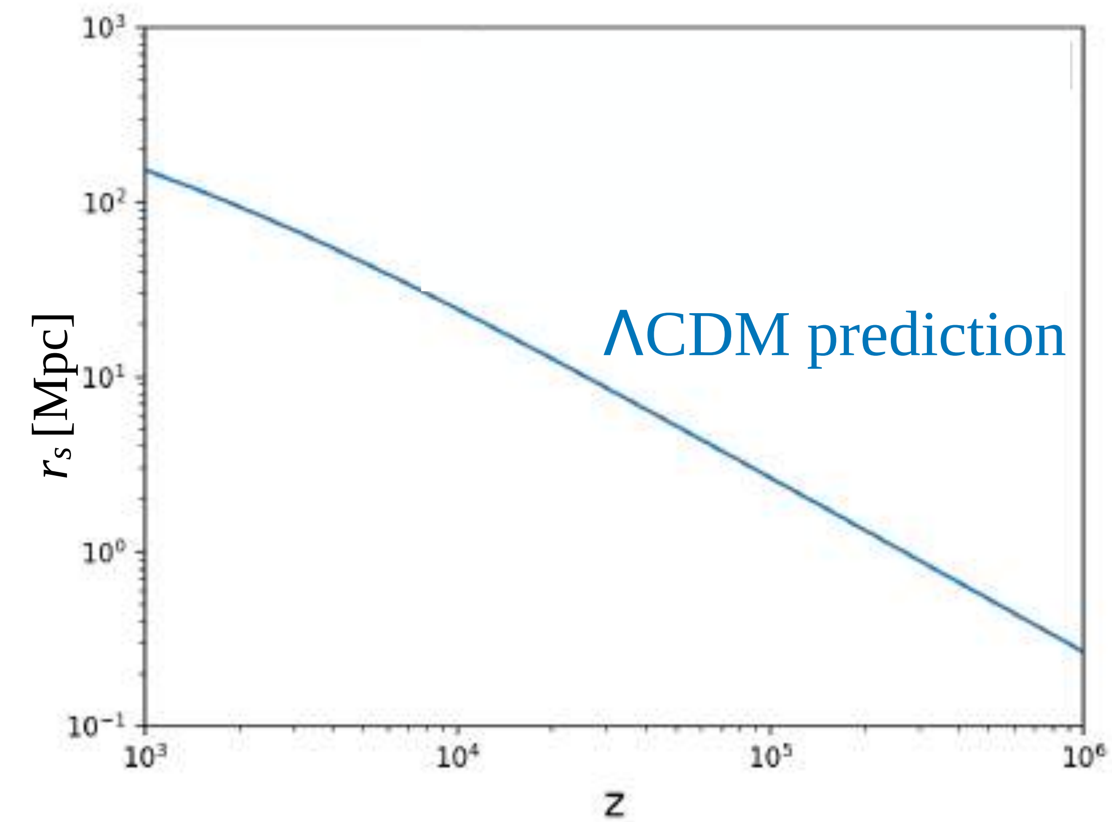



*Aylor++1811.00537*




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

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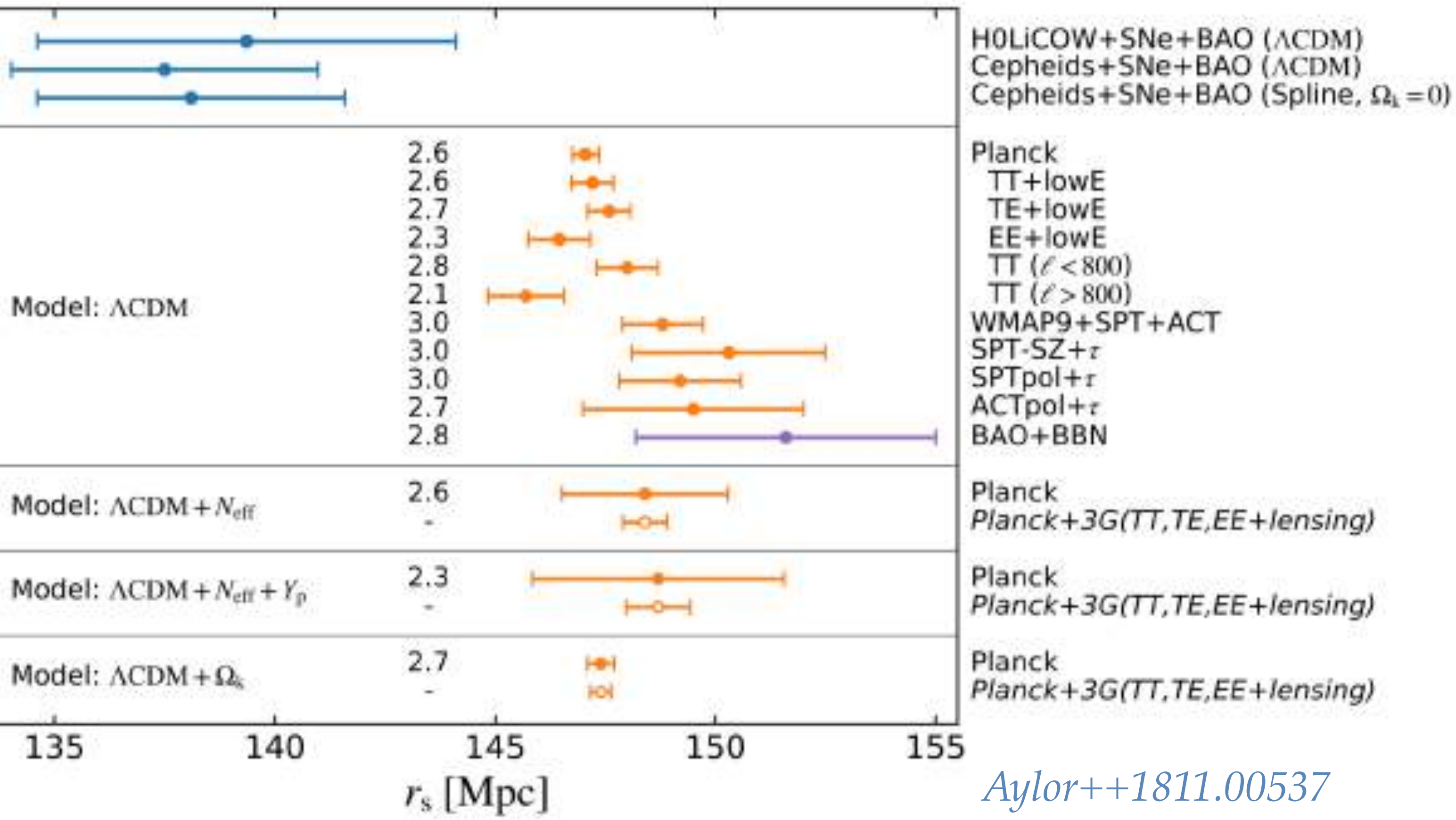


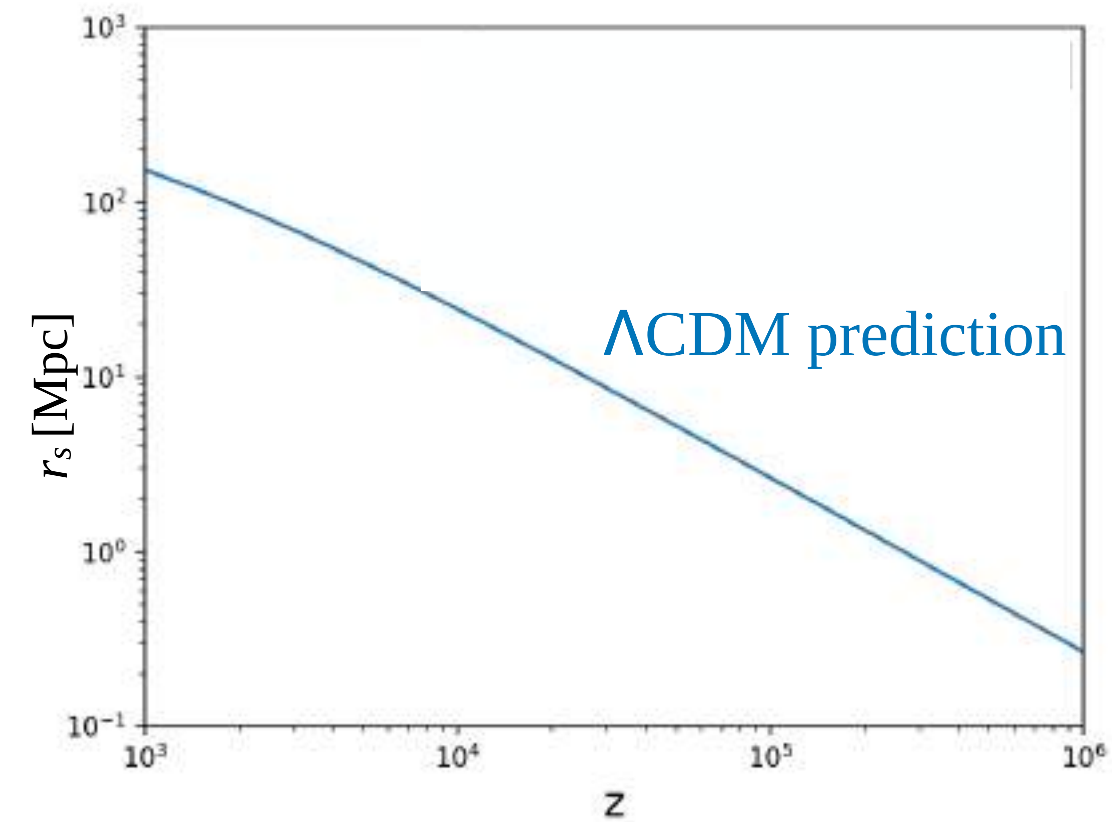


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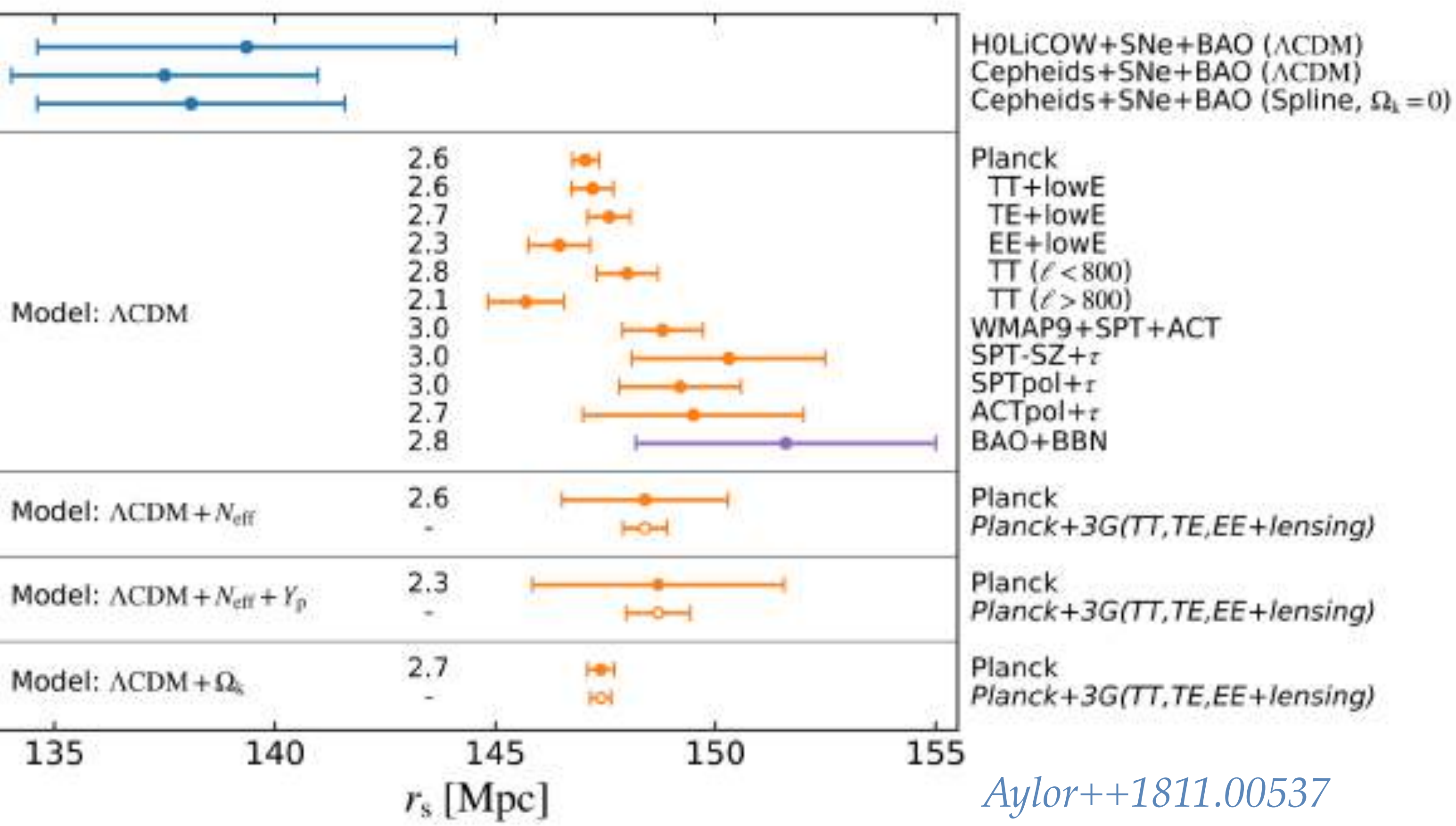


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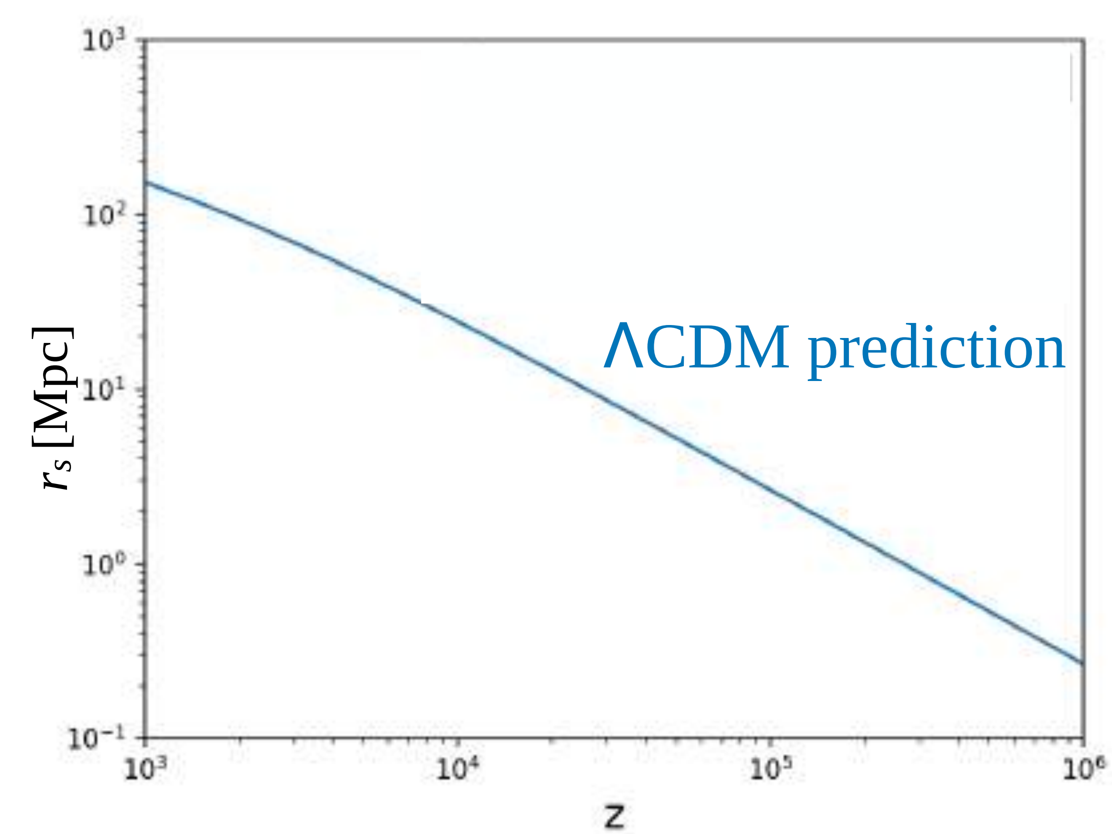


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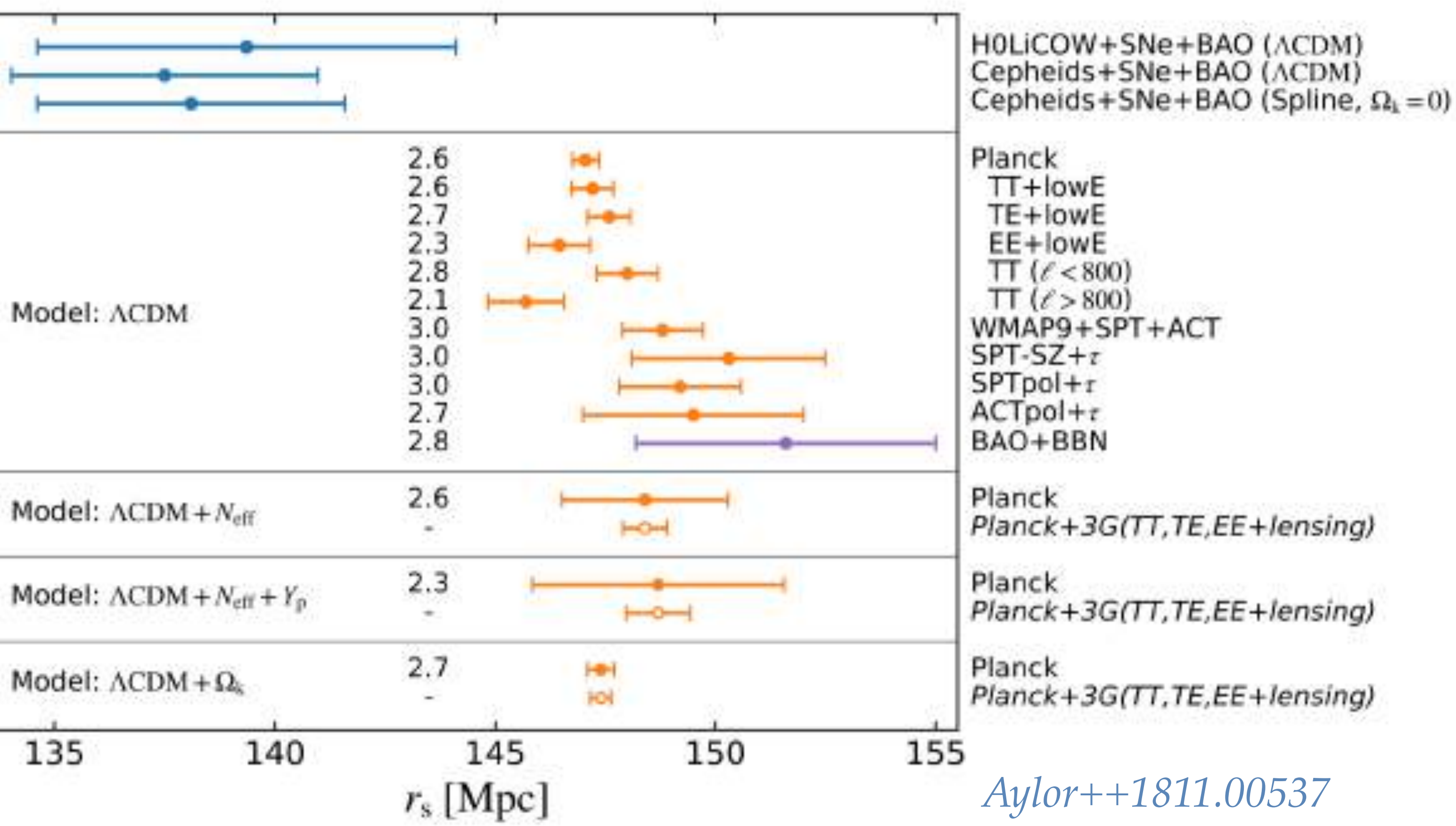


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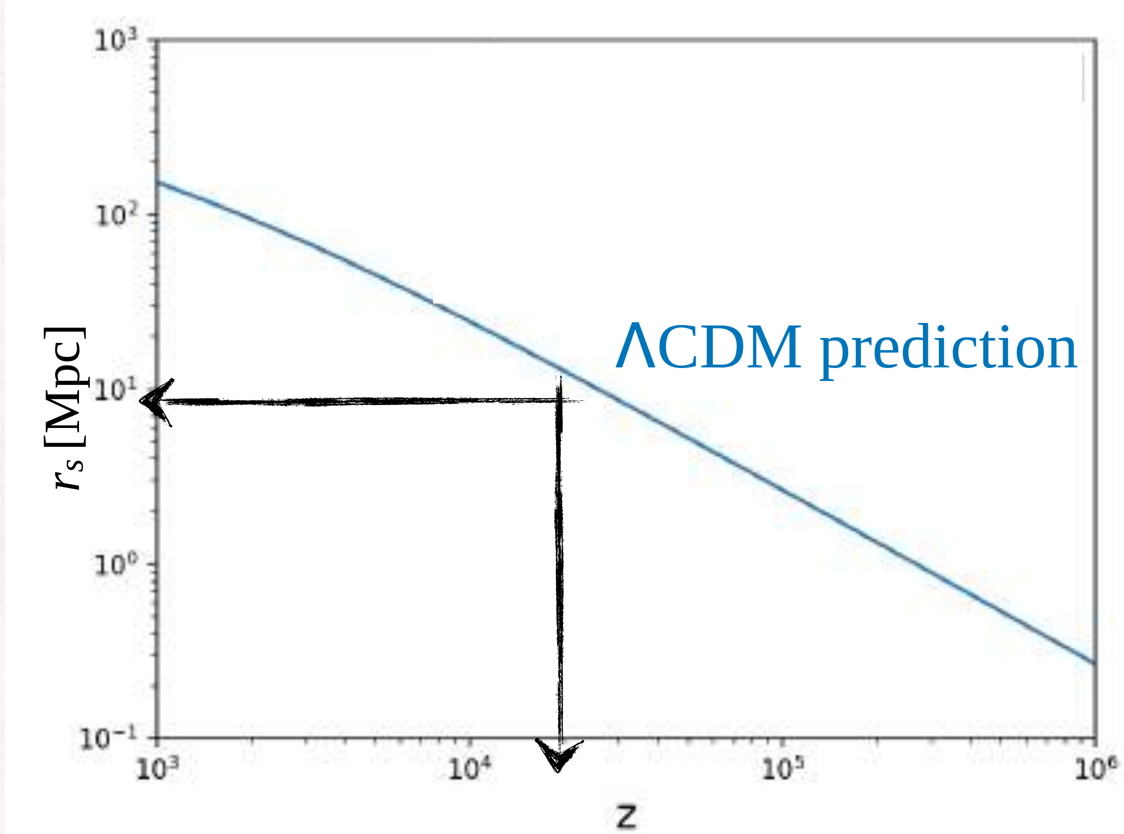


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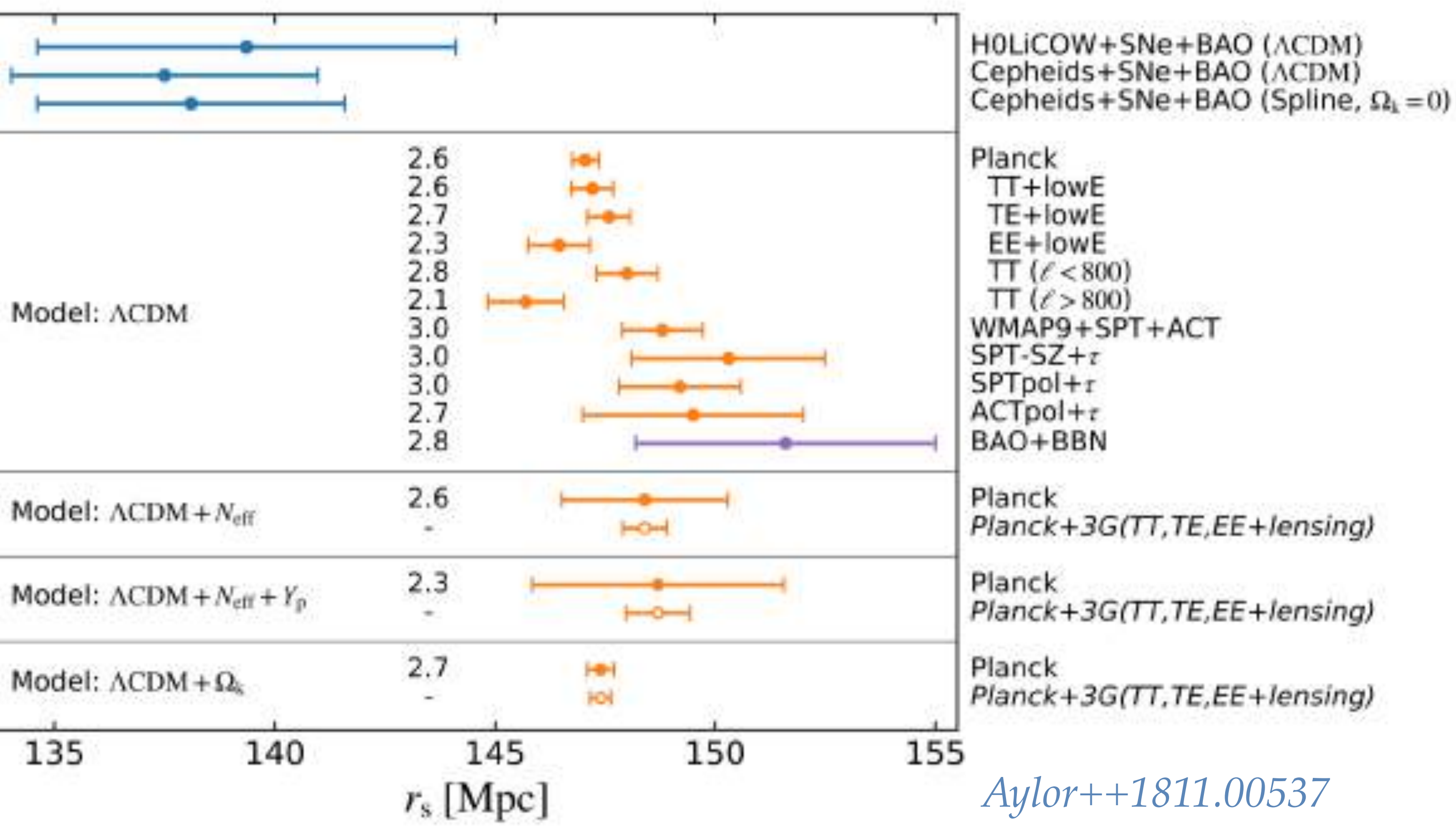


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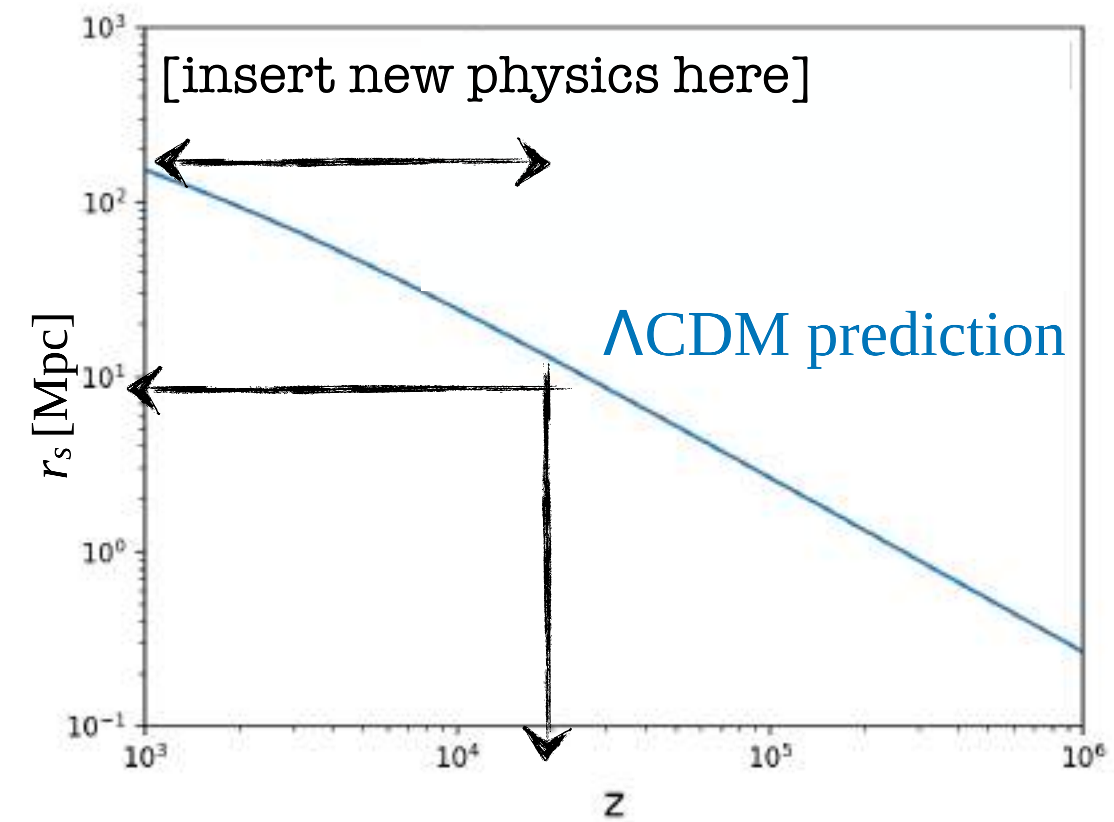


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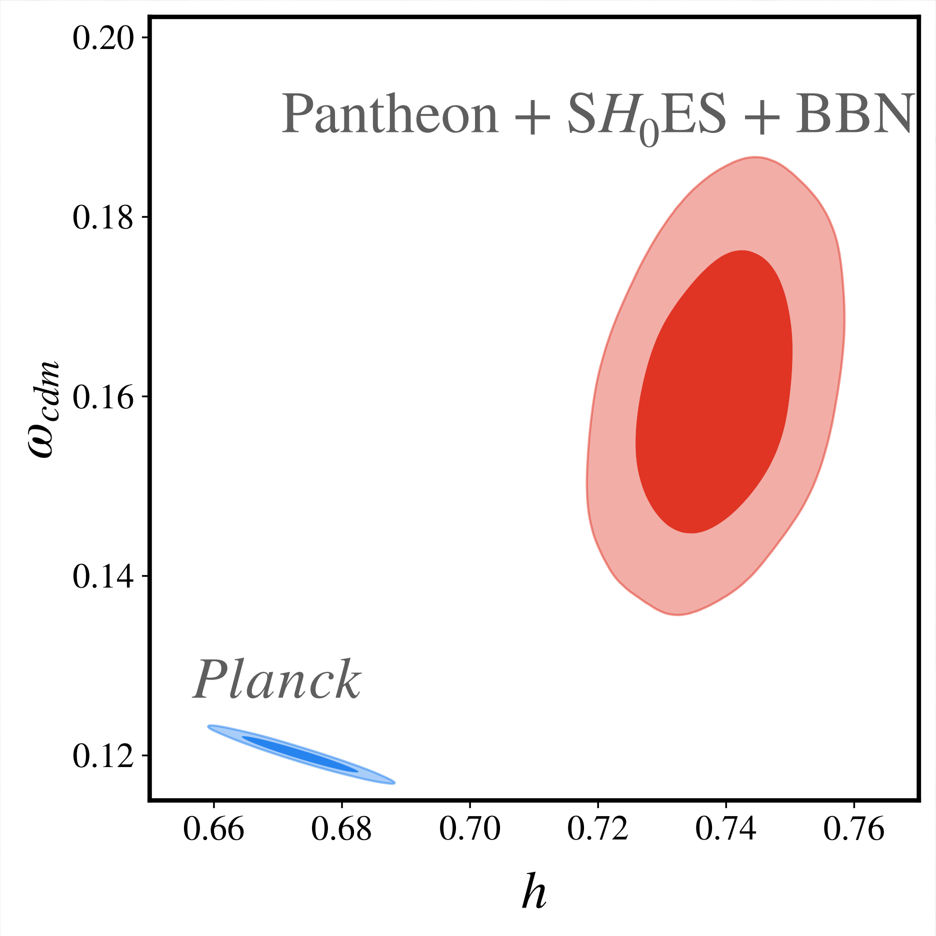
# Adding BBN: a higher dimensional tension?

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



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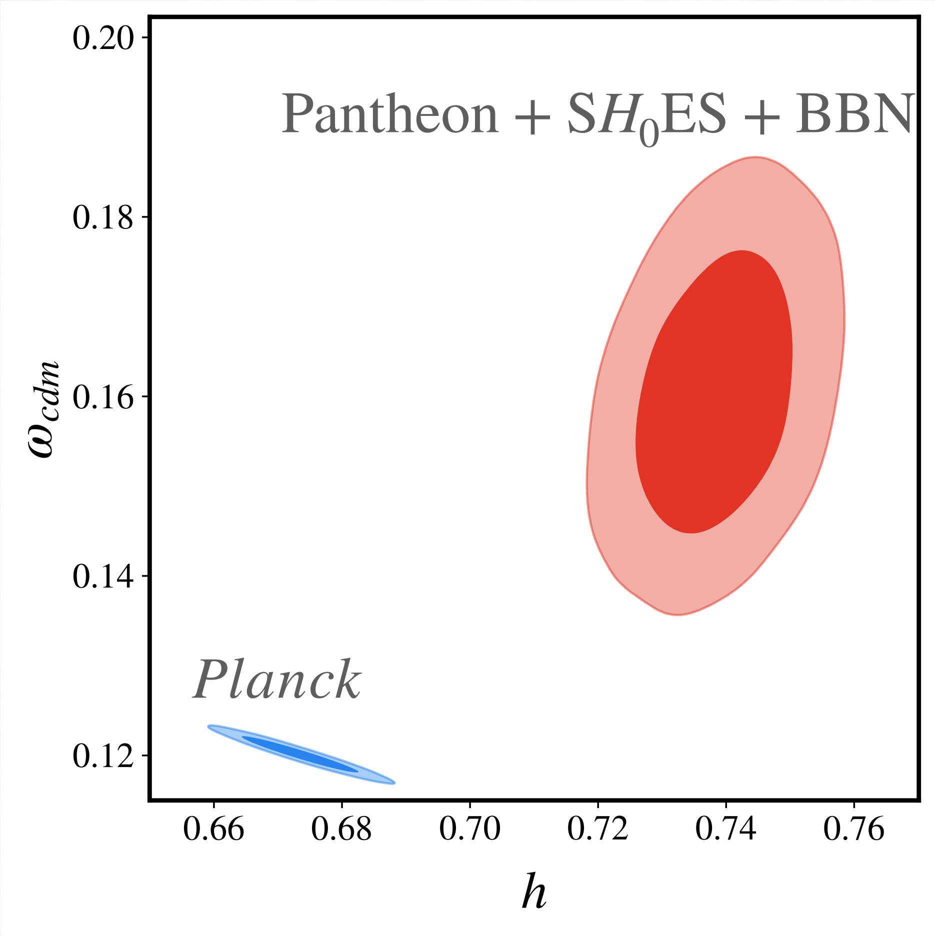


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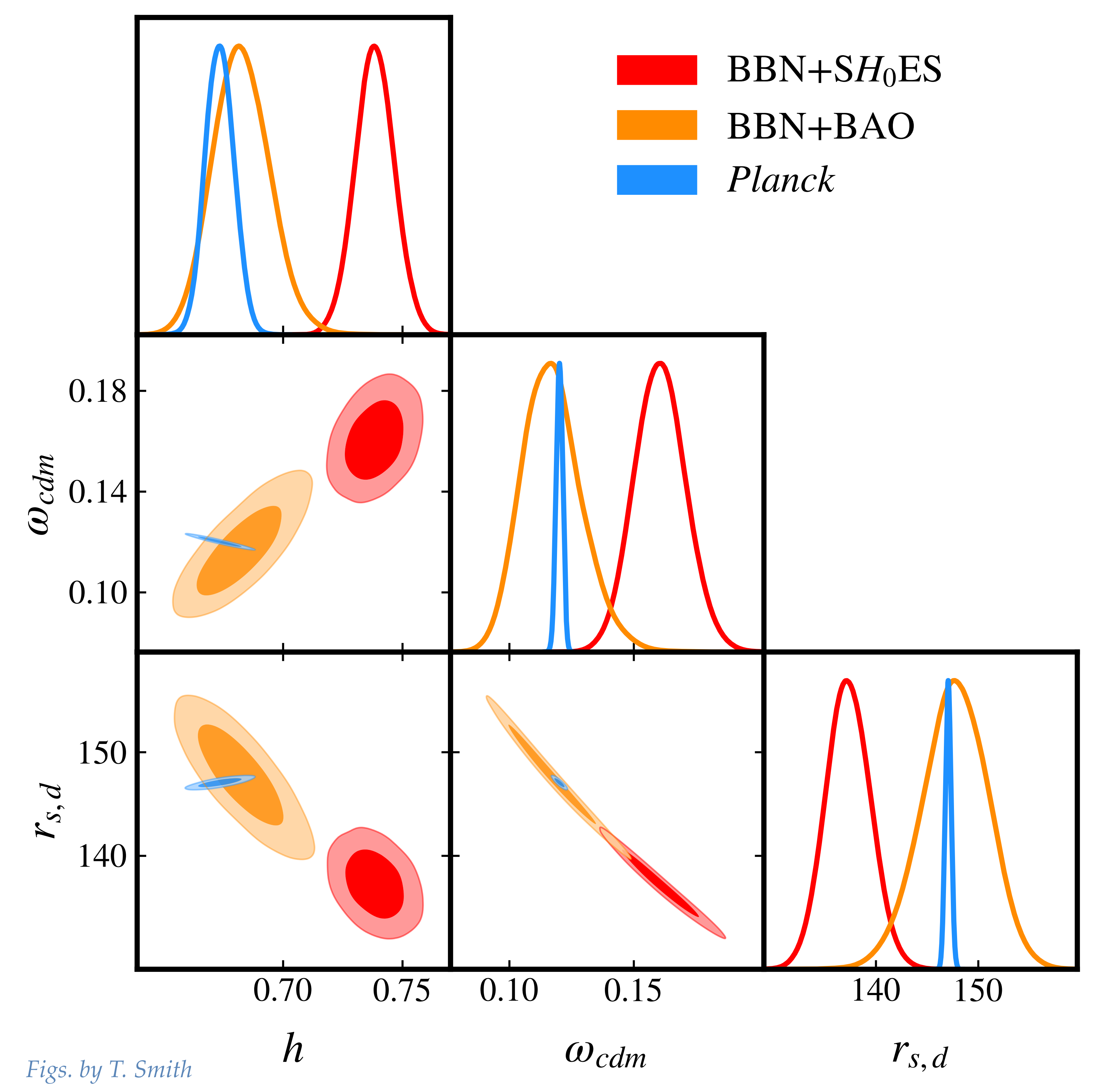


*Figs. by T. Smith*

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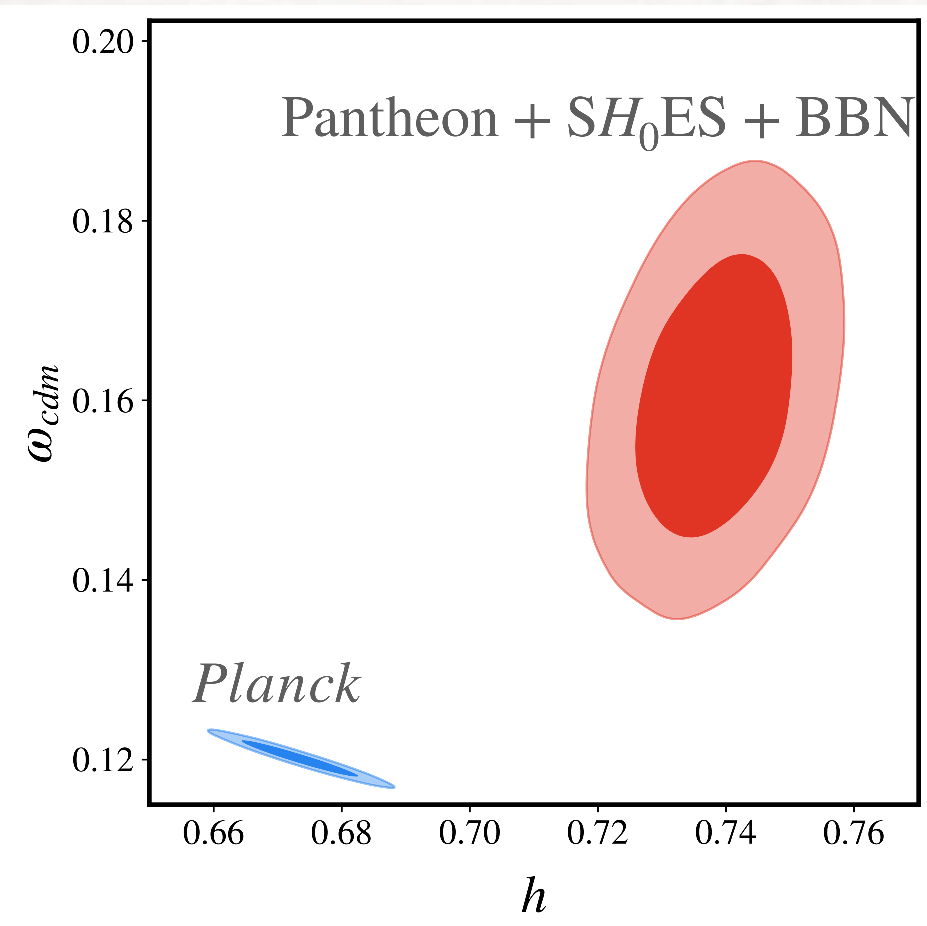
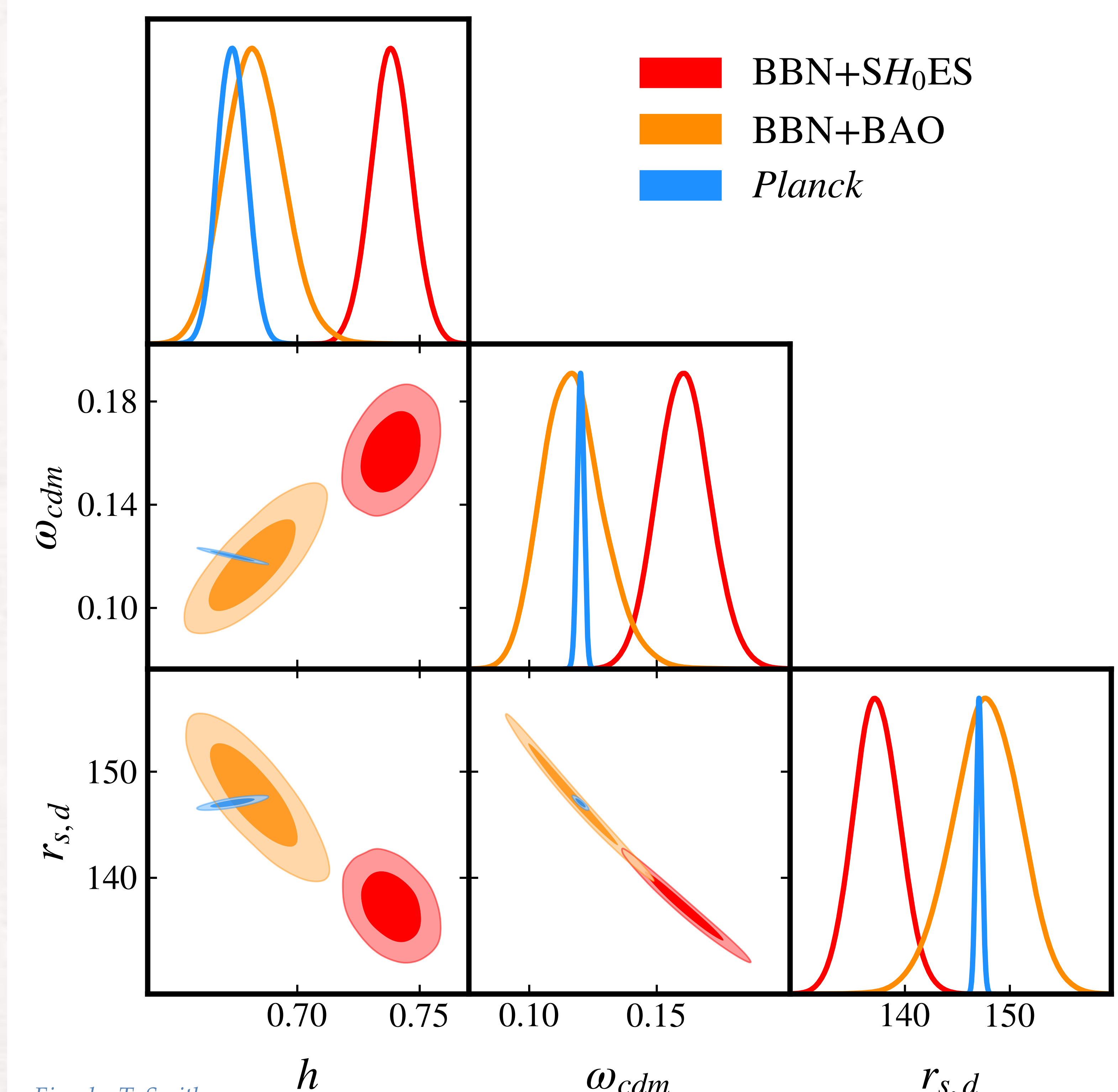



- Resolving $H_0$ requires decrease in $r_s$ and increase in $\omega_{\rm cdm}$
- This necessarily increases the $S_8$ tension
  *See also Jedamzik, Pogosian, and Zhao 2010.04158*




*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)

**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*

**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*

**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*

**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*

**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*

**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]

**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)

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**New Early Dark Energy**

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

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

Mario Ballardini,[a,A,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**

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*

- $\alpha$-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*

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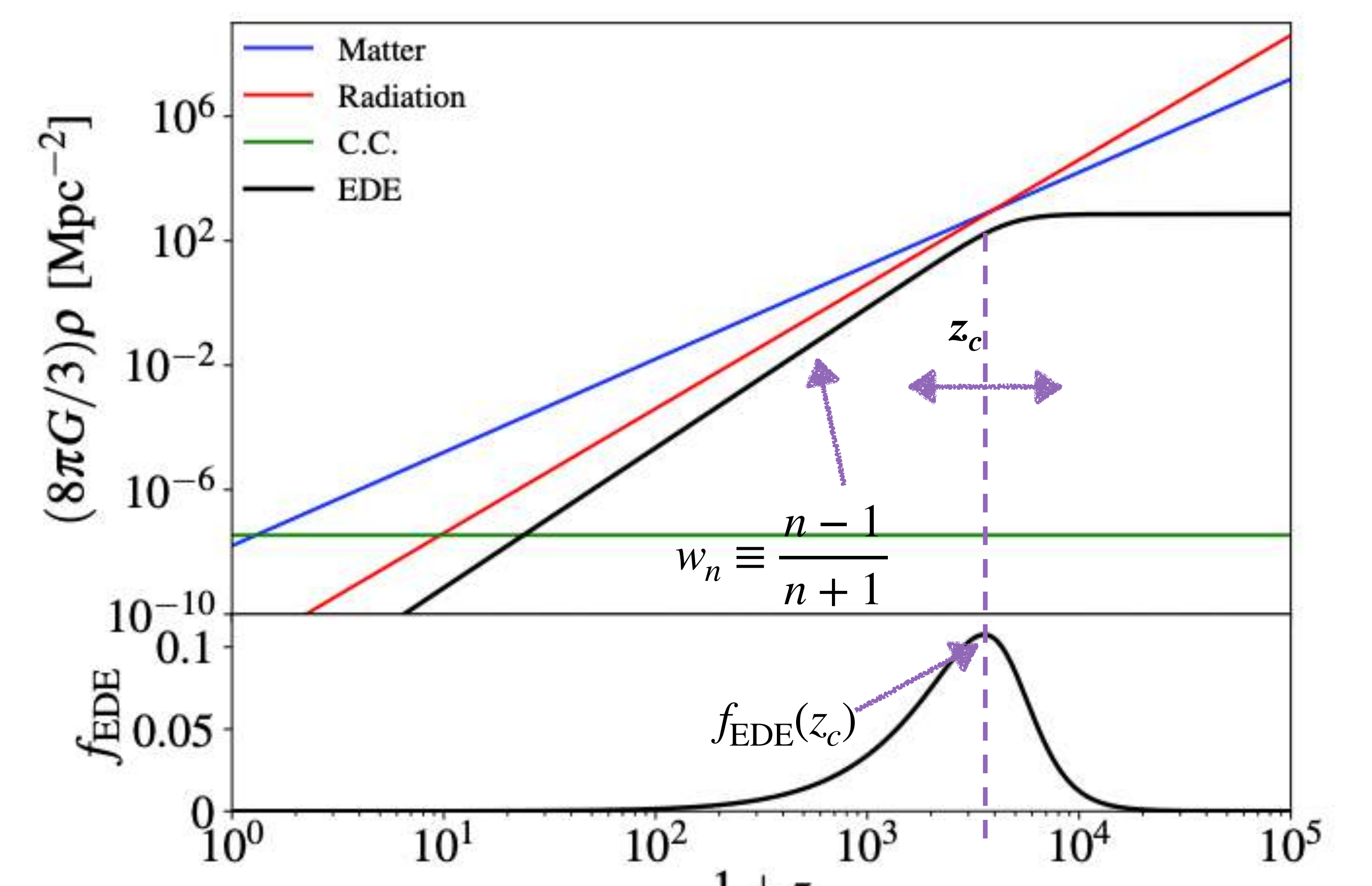
- Specified by $f_{\rm EDE}(z_c),\ z_c,\ w(n),\ c_s^2(k,\tau)$

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

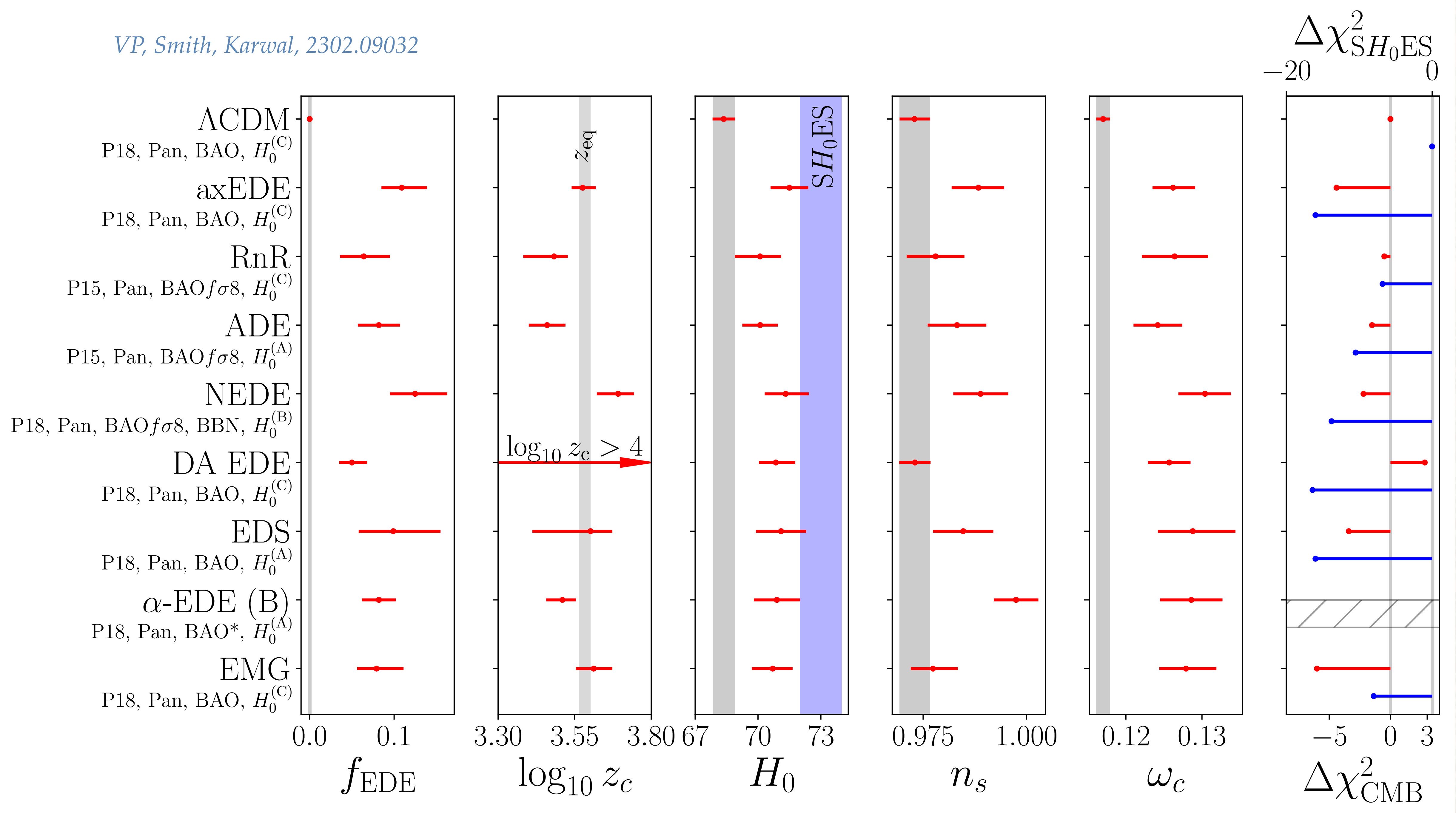
$n = 1$: matter, $n = 2$: radiation, etc.




*VP, Smith, Karwal, 2302.09032*

# Status of EDE solutions

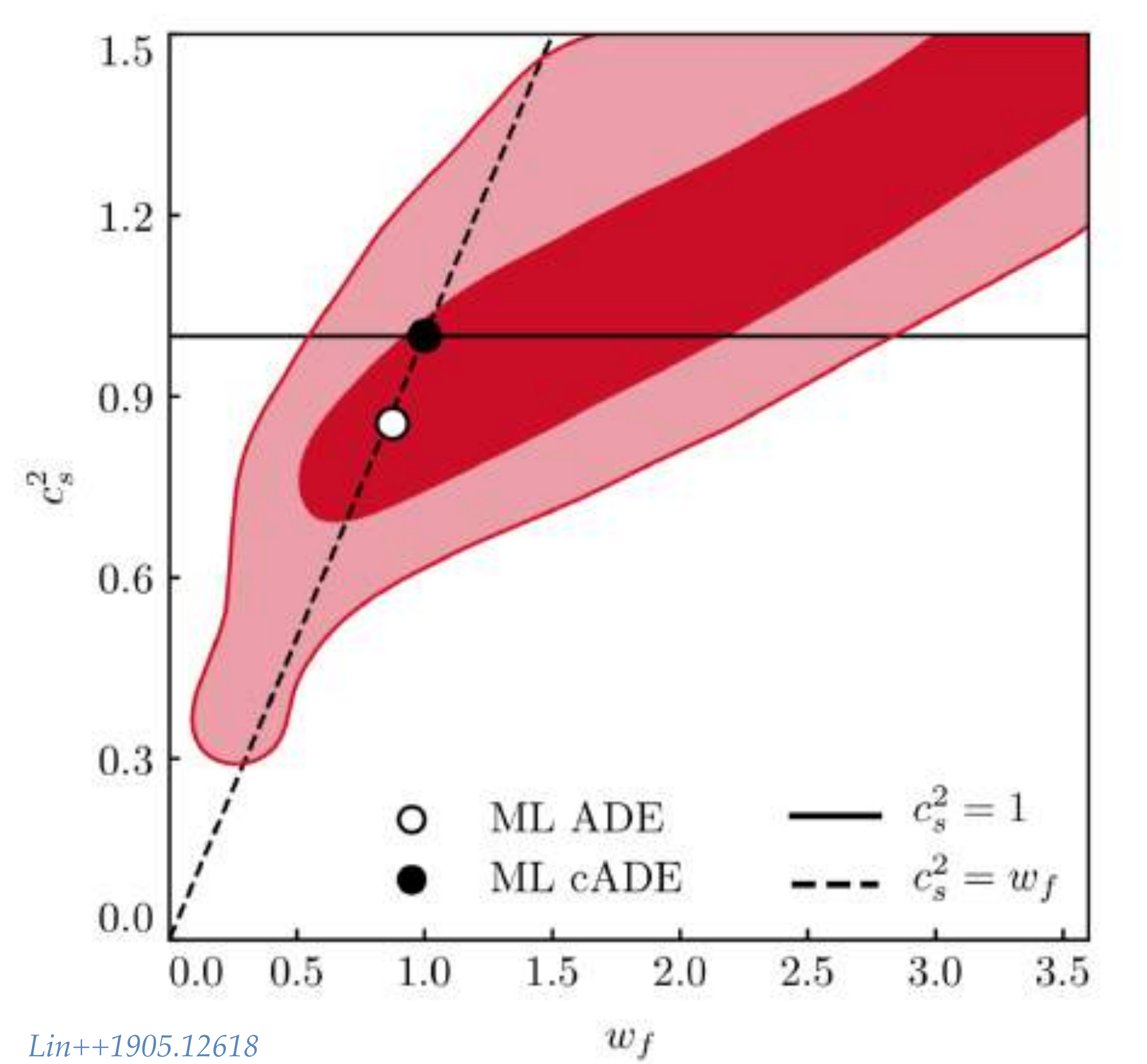
- *Planck* + BAO + Pantheon + SH0ES : a good fit with strong preference over ΛCDM




- 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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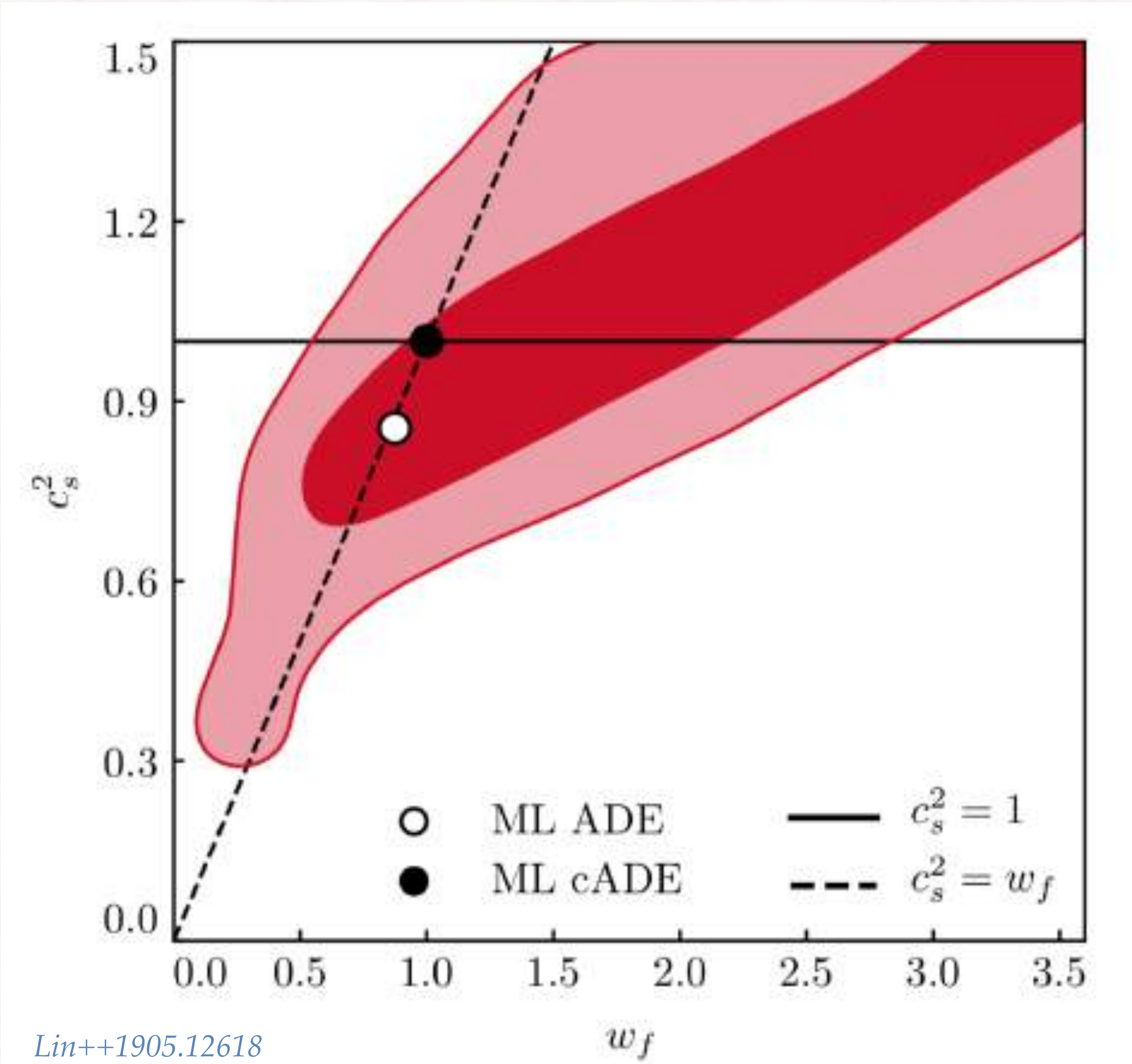
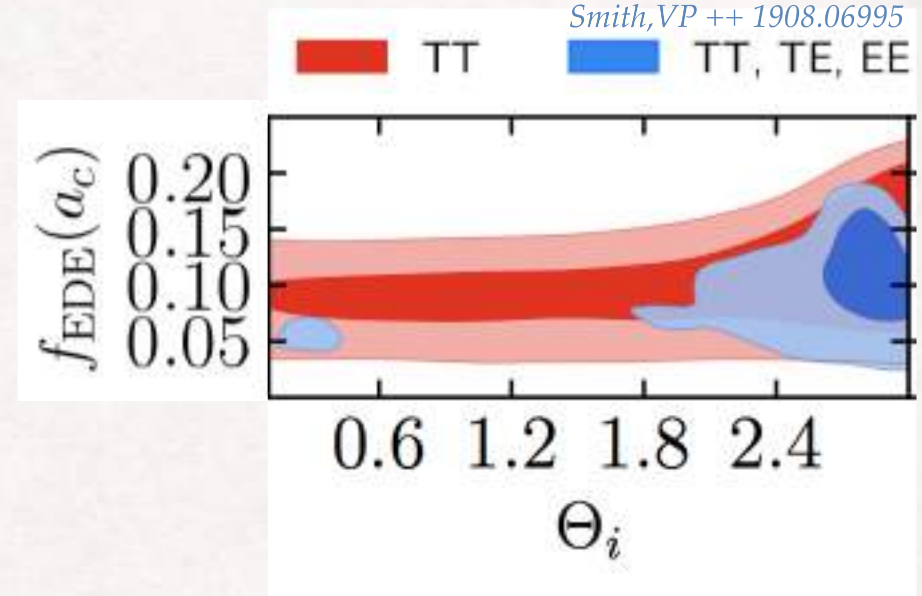
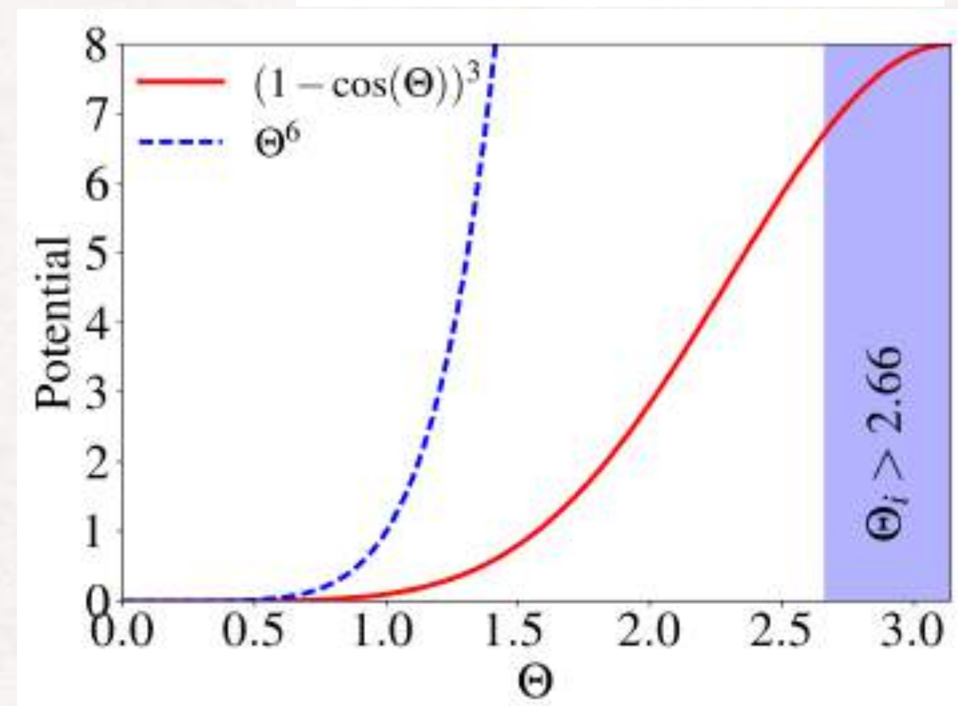



- In the "axion-like" model, this translates into tight constrain on the initial field value

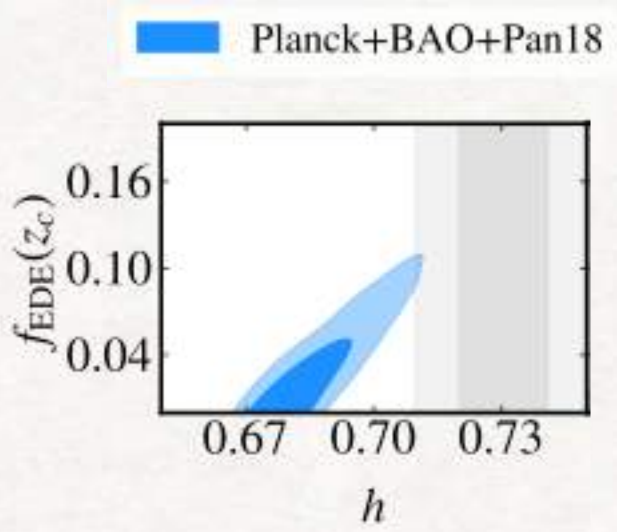
# Barefoot analyses: evidence for prior-volume effects

*—> 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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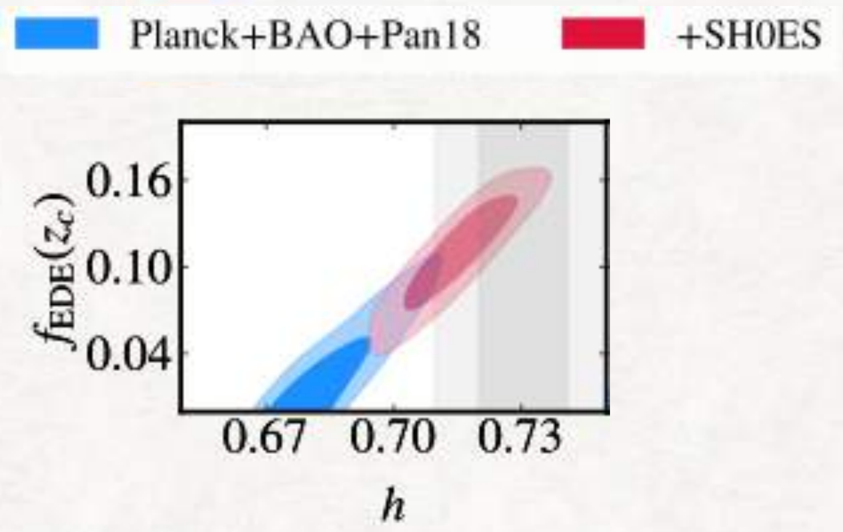
- Adding the prior from SH0ES: EDE is detected at $4\sigma$.

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

$$\Delta\chi^2 = \chi^2_{\Lambda\mathrm{CDM}} - \chi^2_{\mathrm{EDE}} \simeq -24.8$$



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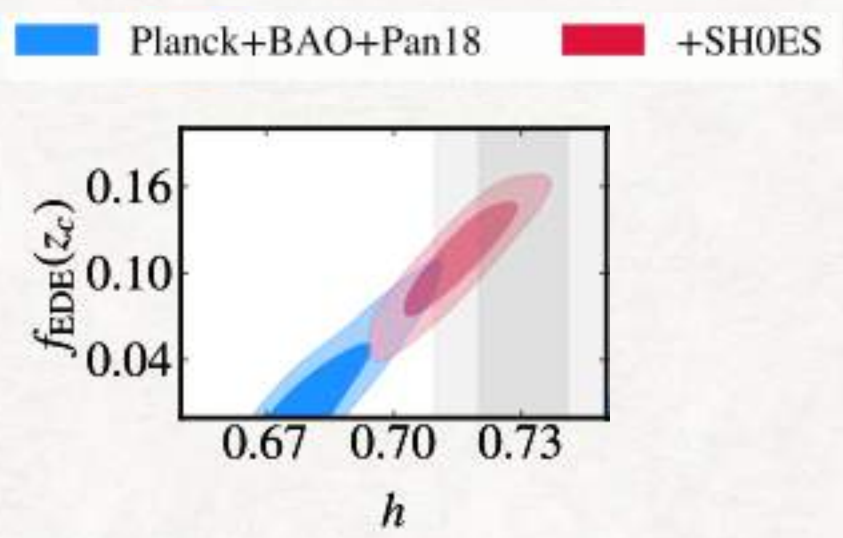


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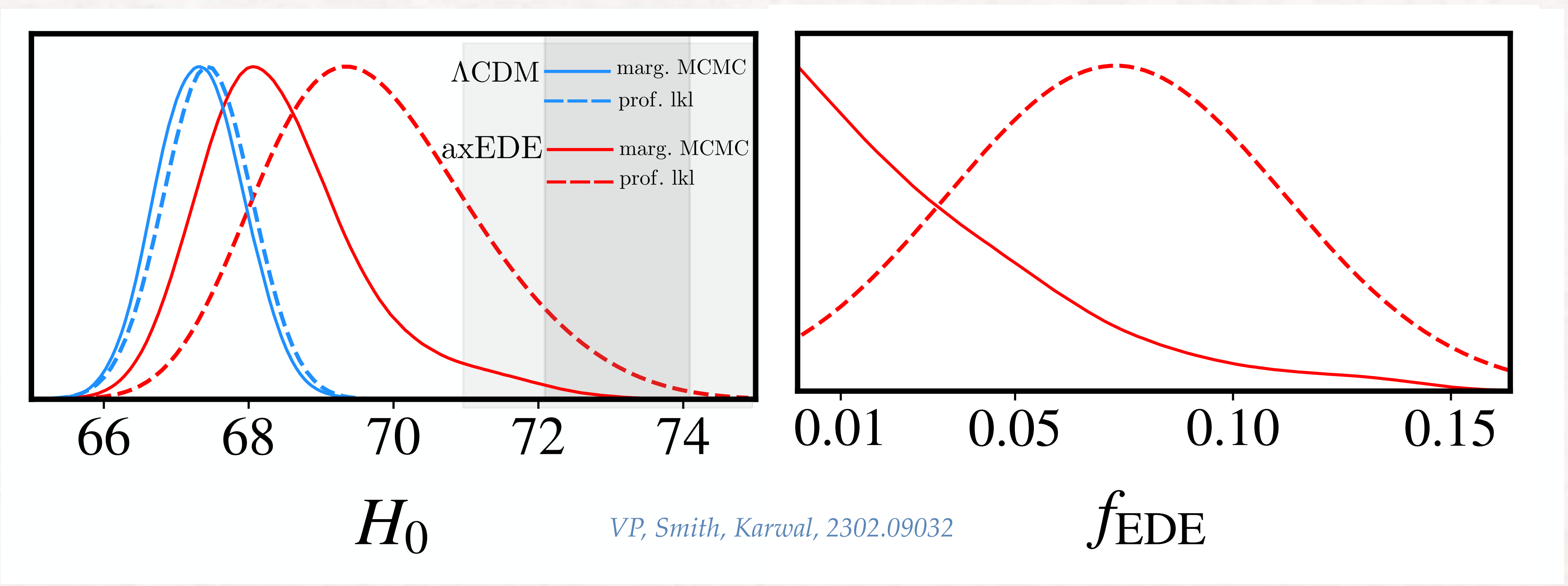
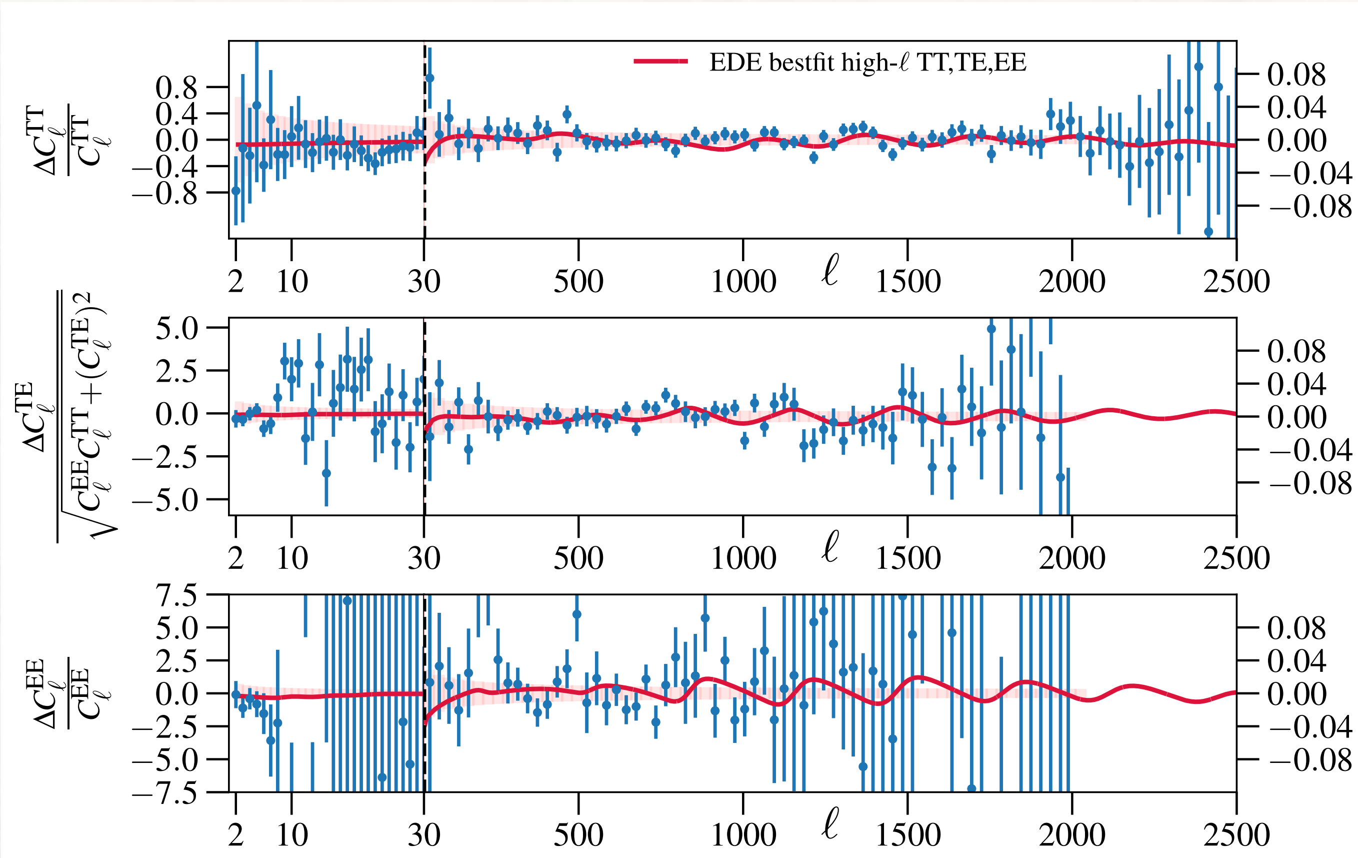
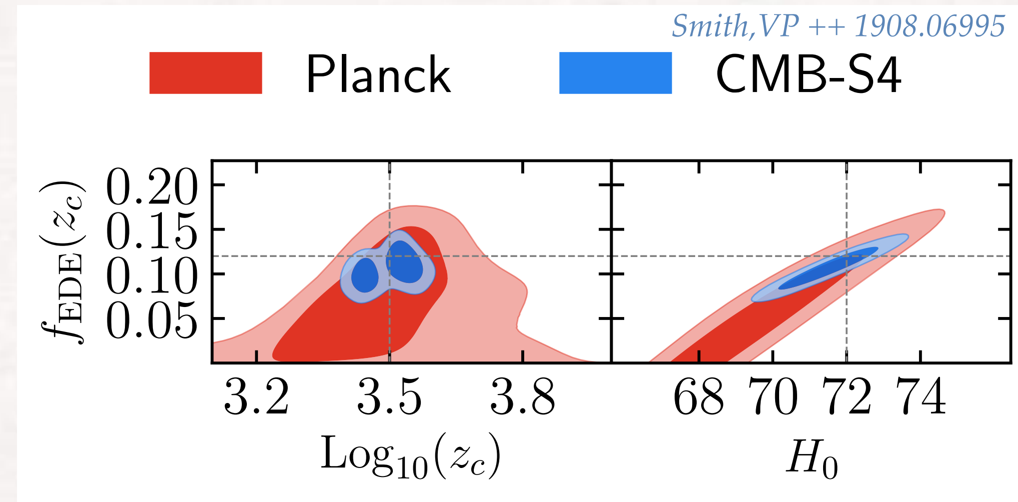
- The confidence intervals from a profile likelihood do not match the bayesian credible intervals *Herold ++ 2112.12140, 2210.16296*




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

# Future CMB data will confirm/exclude EDE



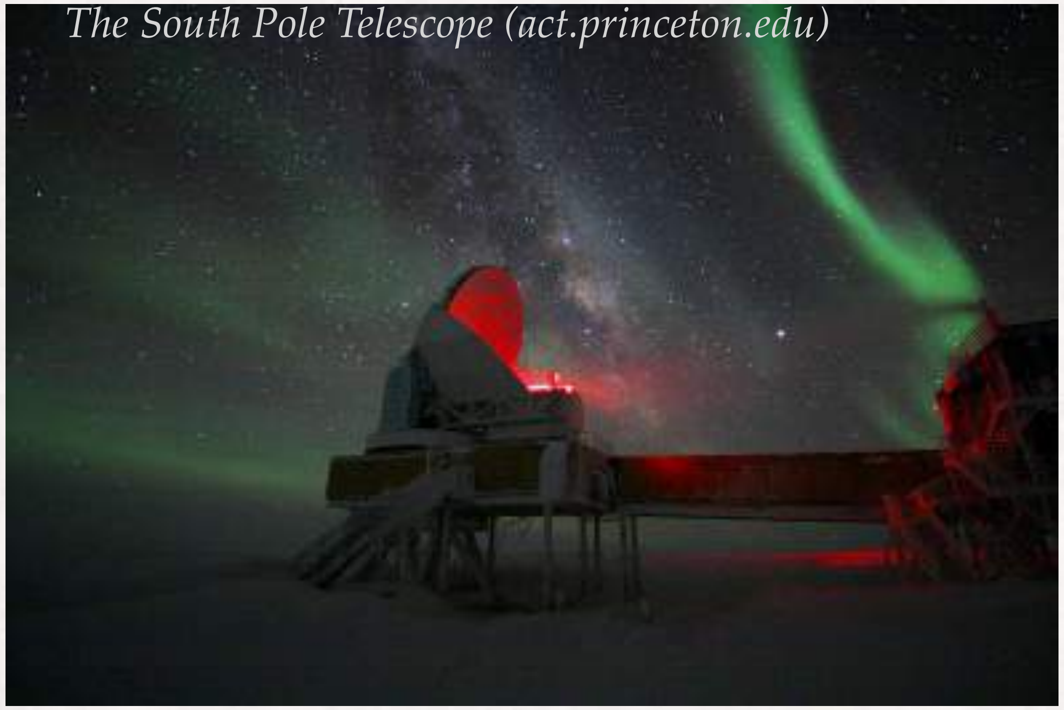




- Mock *Planck* data with $f_{\rm EDE}(z_{\rm eq}) \sim 10\,\%$ & $H_0 = 72$ km/s/Mpc: *Planck* ***cannot*** detect EDE
- Future experiments (Simons Observatory, CMB-S4) could unambiguously detect EDE.

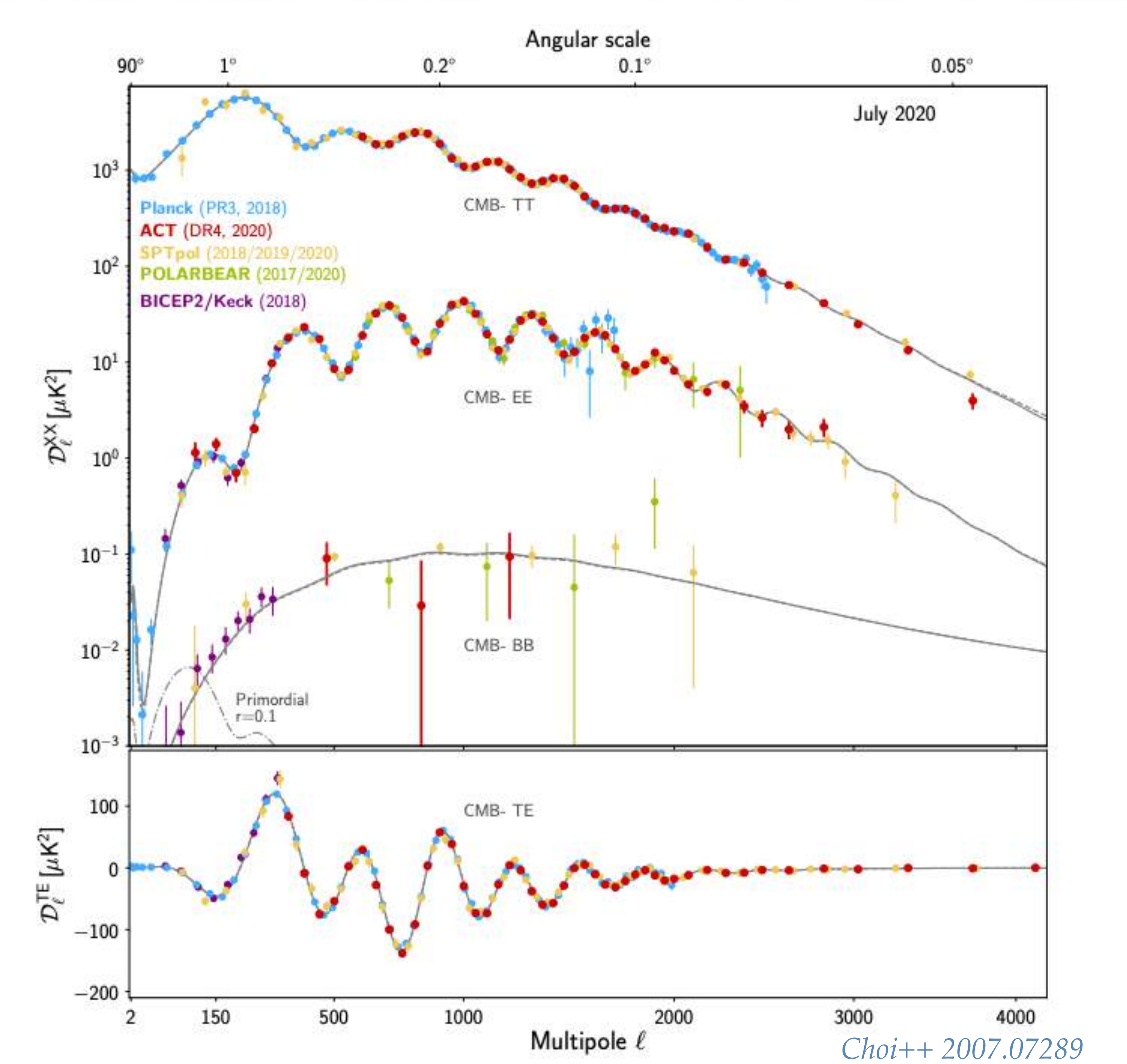
# New CMB data at small scales

- 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)*



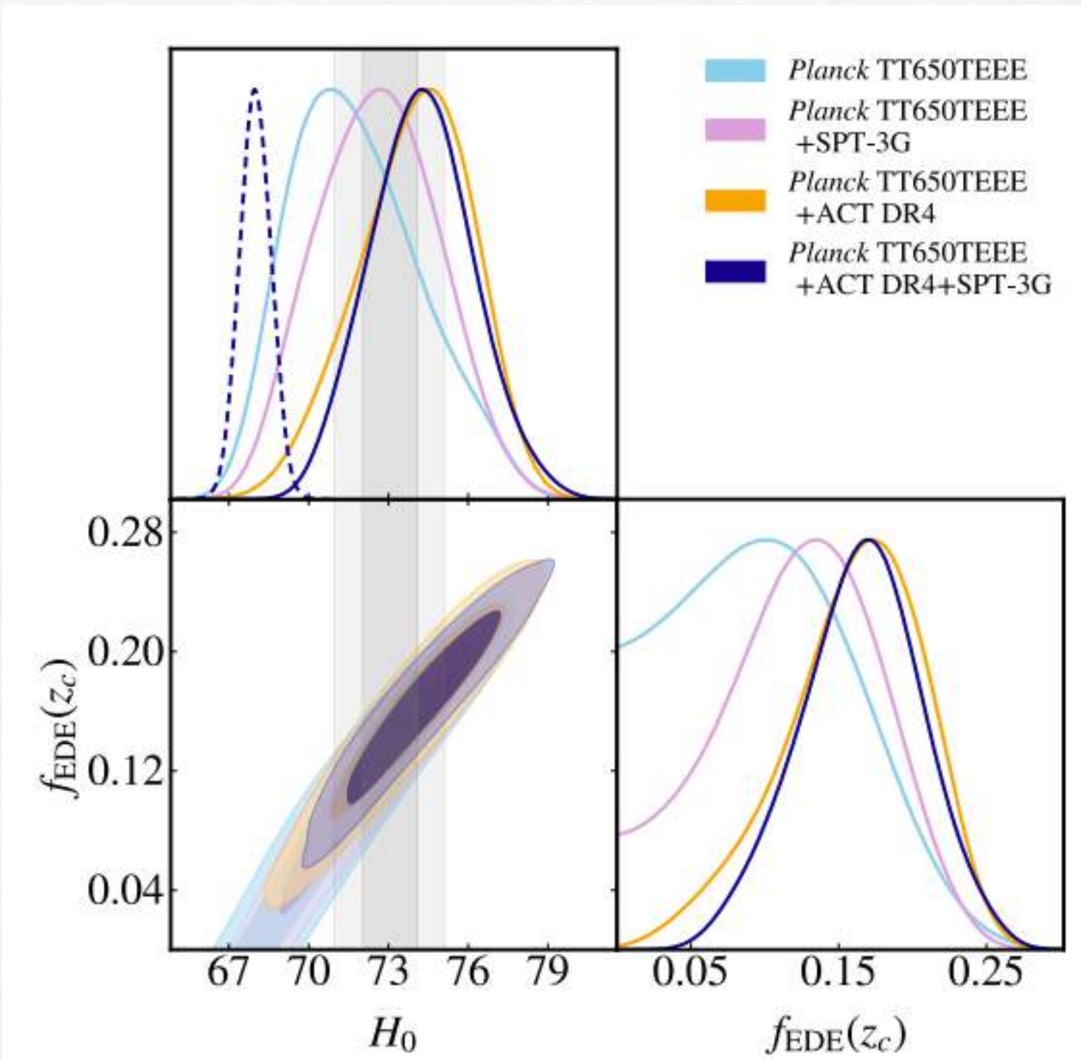

Choi++ 2007.07289

# Consistency test: Planck vs WMAP+ACT+SPT

- *Planck*650TT≃ WMAP

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

*Smith, Lucca, VP++ 2202.09379*

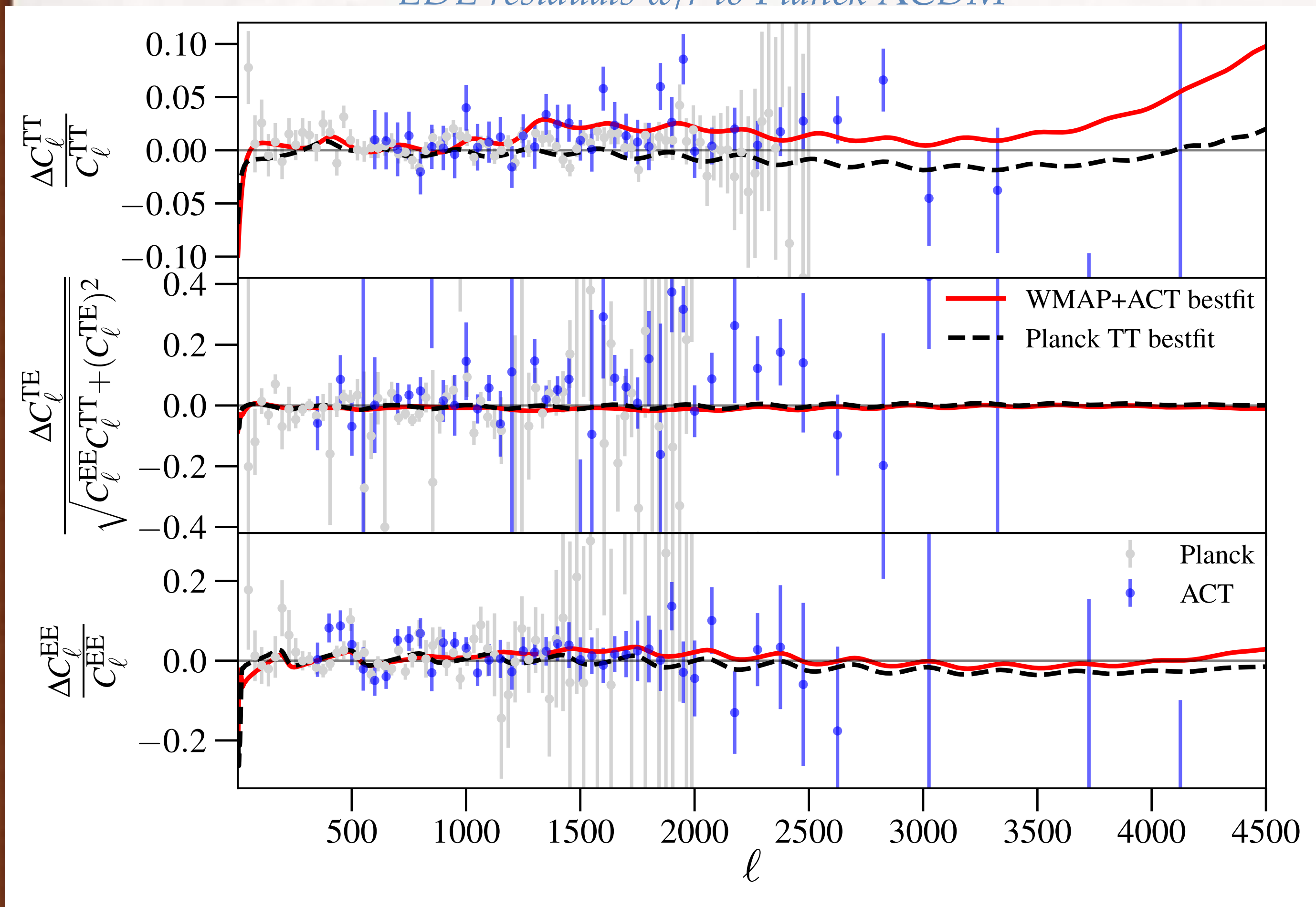


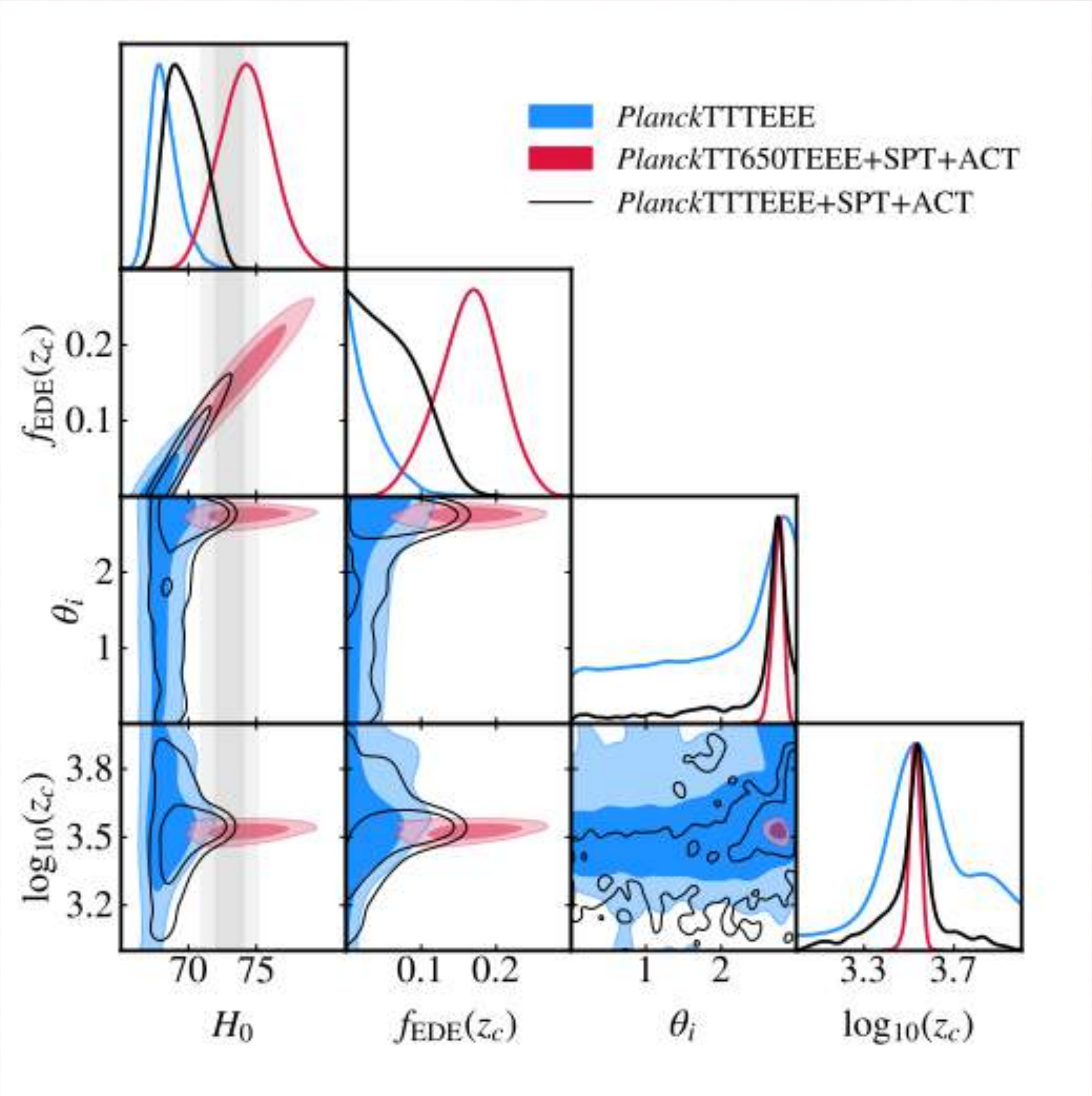

| Model | ΛCDM | EDE |
|---|---|---|
| $f_{\rm EDE}(z_c)$ | – | $0.163(0.179)^{+0.047}_{-0.04}$ |
| $\log_{10}(z_c)$ | – | $3.526(3.528)^{+0.028}_{-0.024}$ |
| $\theta_i$ | – | $2.784(2.806)^{+0.098}_{-0.093}$ |
| $m$ (eV) | – | $(4.38 \pm 0.49) \times 10^{-28}$ |
| $f$ (Mpl) | – | $0.213 \pm 0.035$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

- There is a $3.3\sigma$ 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?

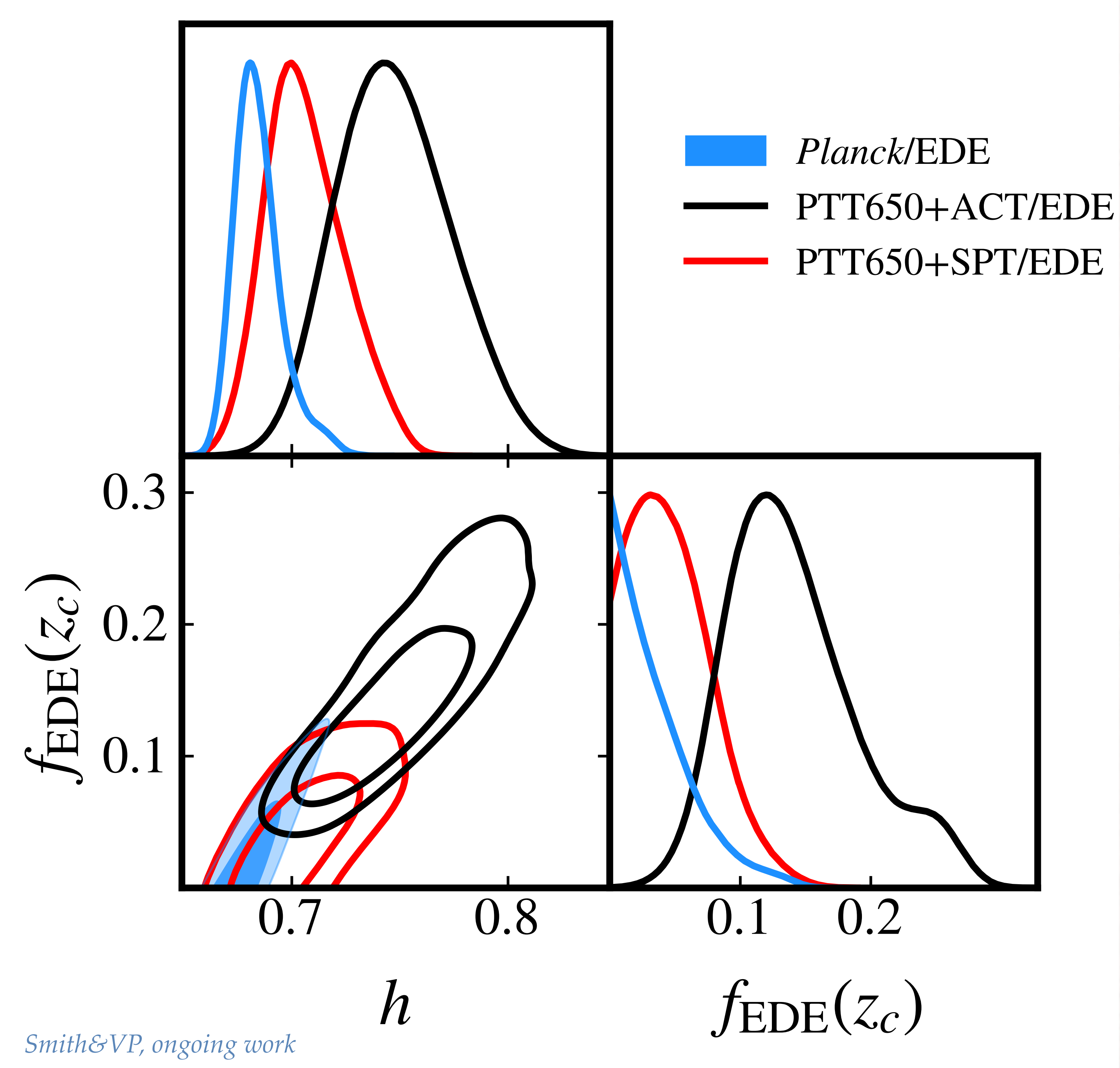
*EDE residuals w/r to Planck ΛCDM*



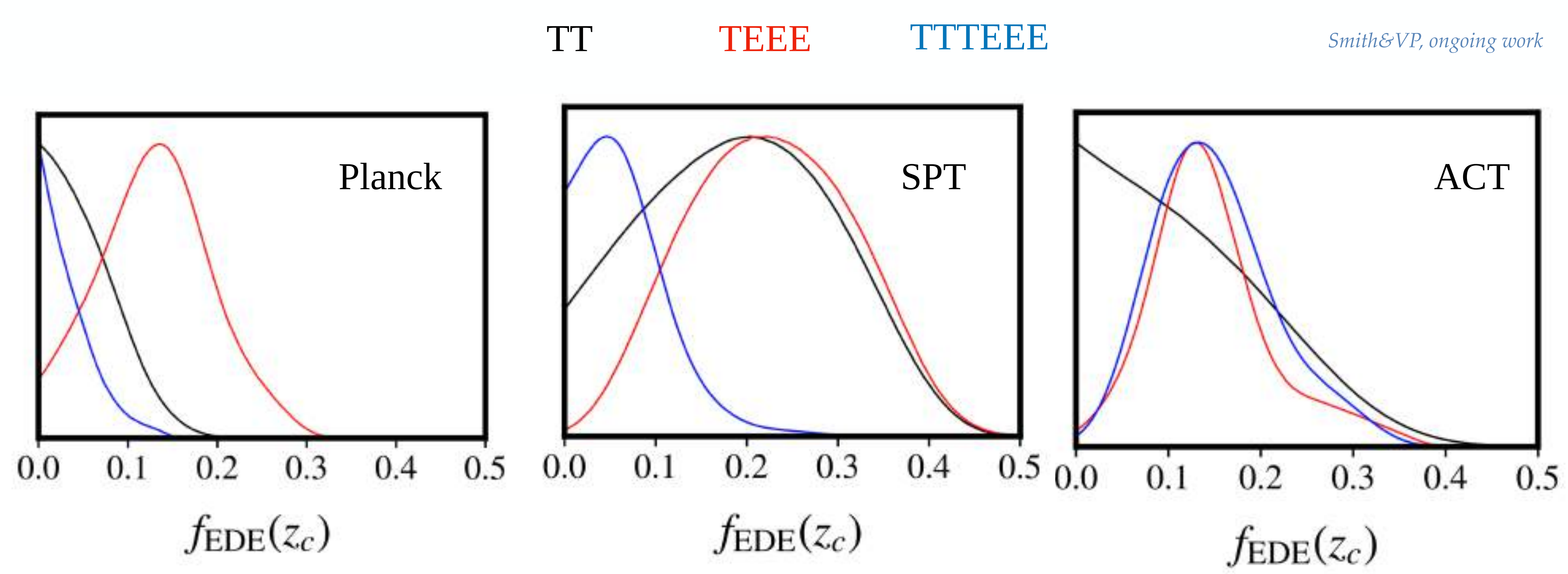

- Planck TT > 1300 disfavor such large $f_{\rm EDE}(z_c)$: tension between *Planck*/ACT?

# New SPT TT data seem to agree with Planck



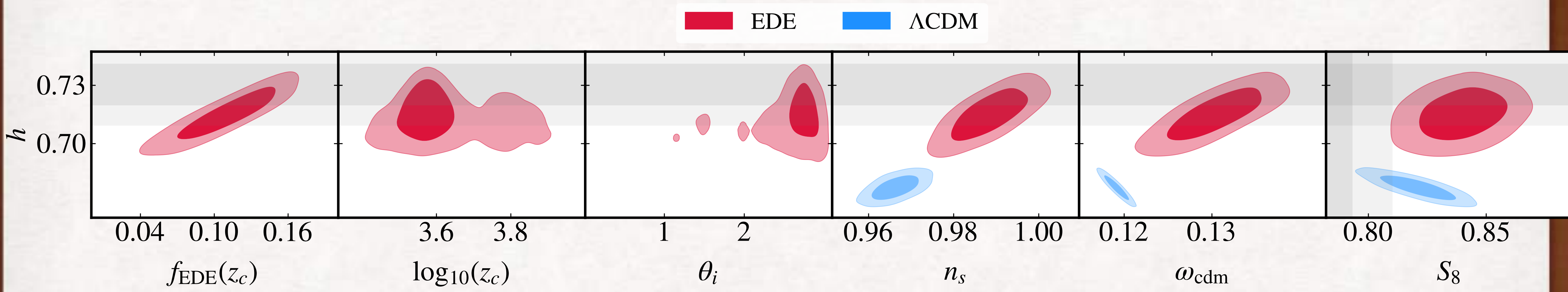

- No preference for axion-like EDE in PTT650+SPT3G: disfavor ACT hint of EDE?

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




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

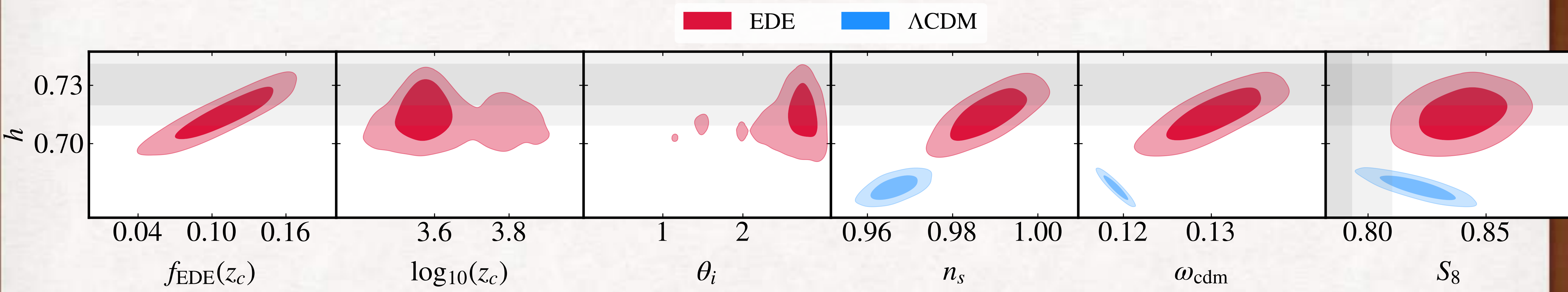
# Challenges to EDE




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

*Sakstein++1911.11760, Lin++2212.08098*

# Challenges to EDE




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

  *Sakstein++1911.11760, Lin++2212.08098*

- EDE cosmology has a higher $\omega_{cdm}$ 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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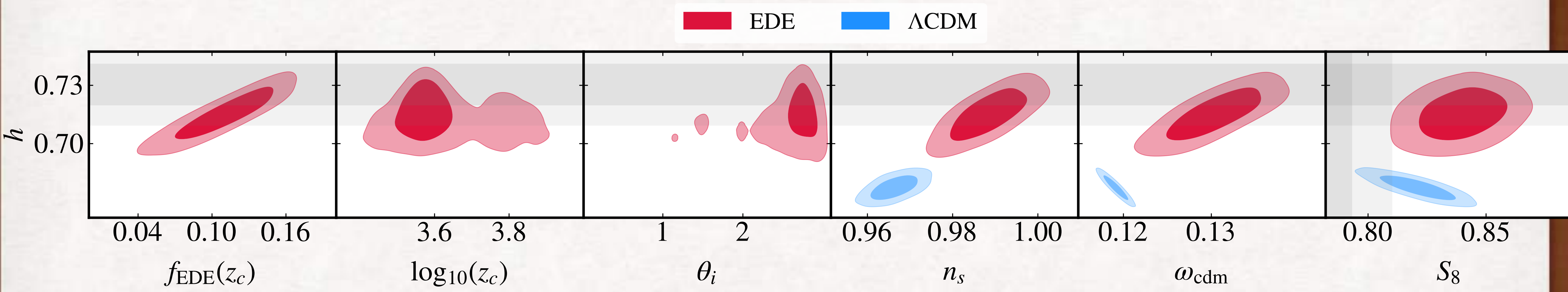


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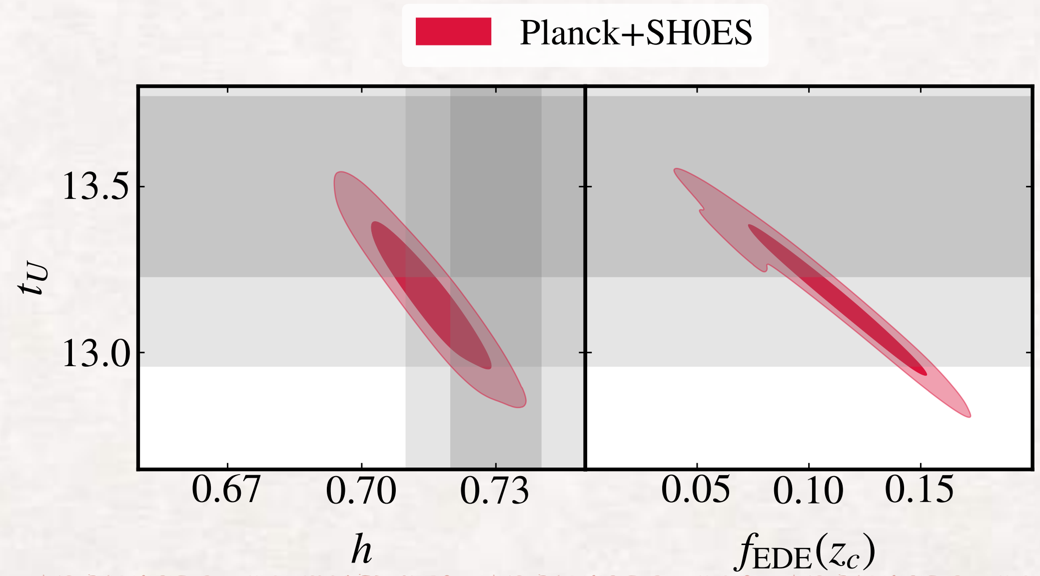
- Age of the universe tension? $t_U \simeq 13.2 \pm 0.15$ Gyr while GC measures $13.5 \pm 0.27$ Gyr

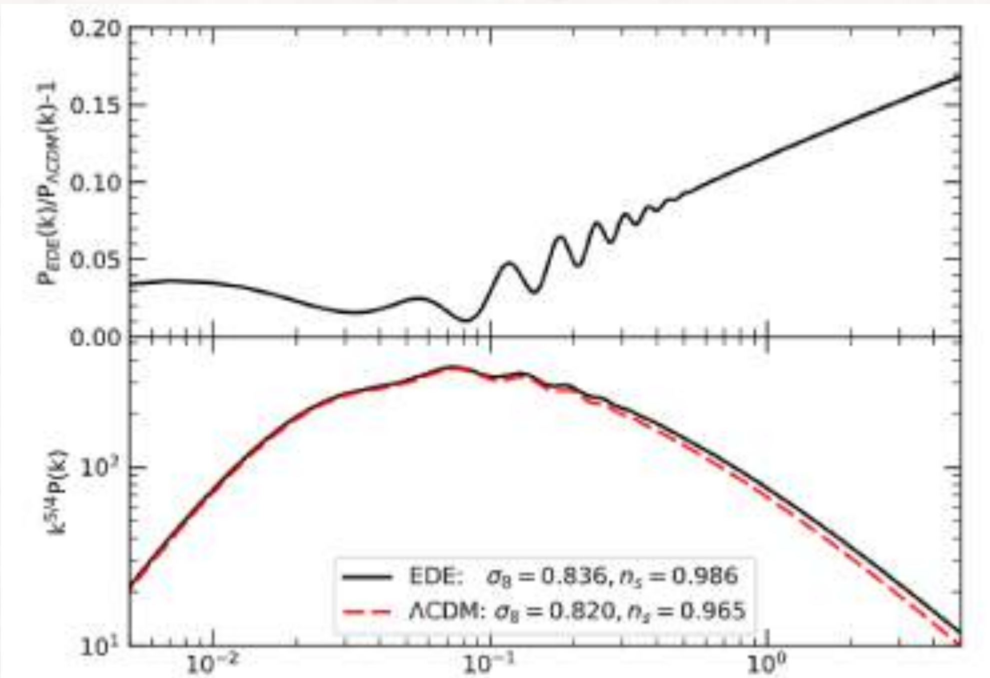
  *Bernal++ 2102.05066, Boylan-Kolchin 2103.15824*



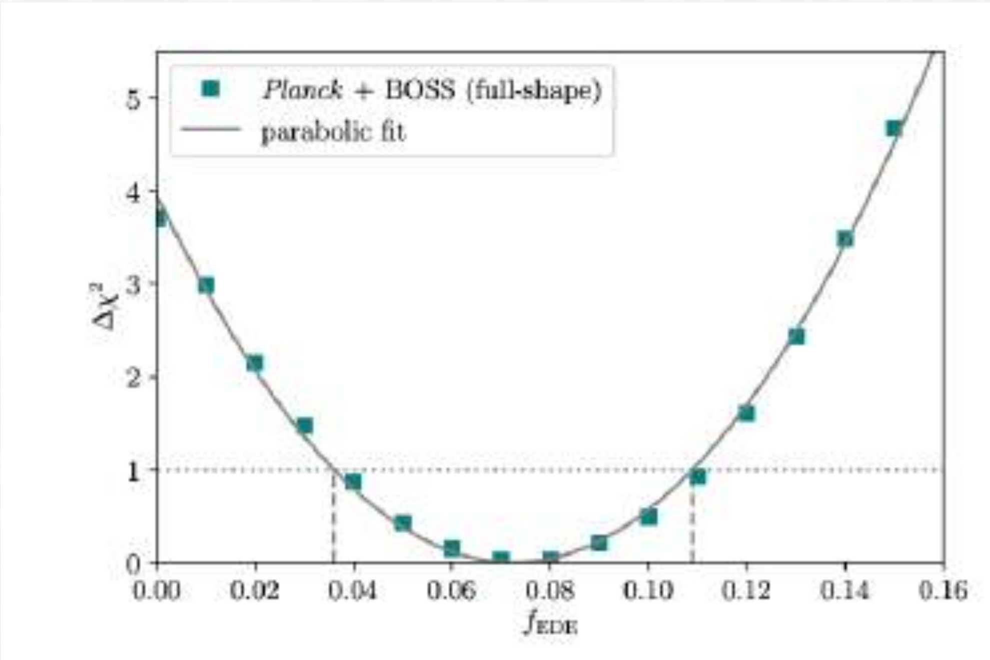
# EFTofLSS analyses of EDE

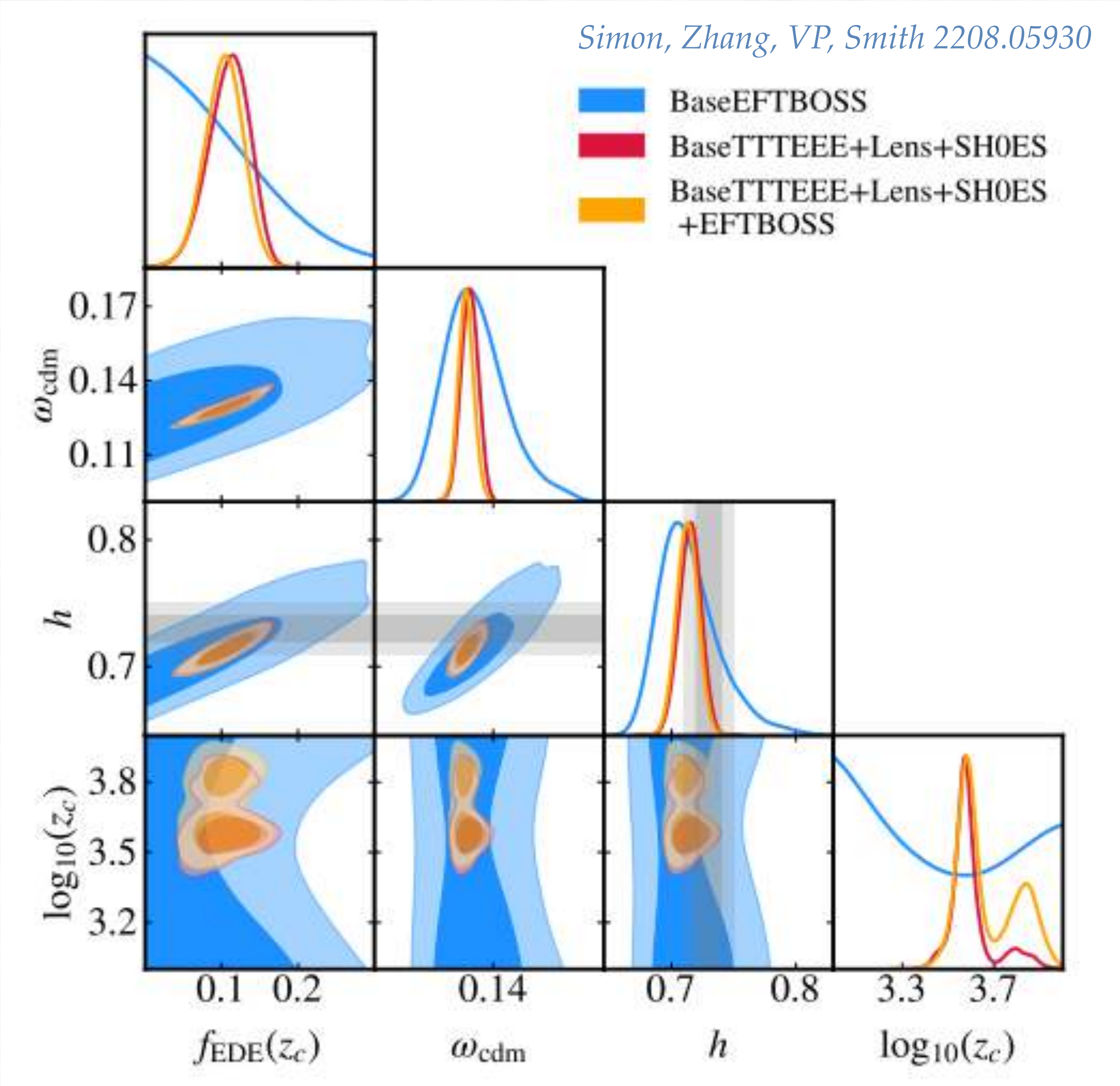
- EDE cosmology predicts 5-15% increase in power at small scales in the linear matter power spectrum

*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*

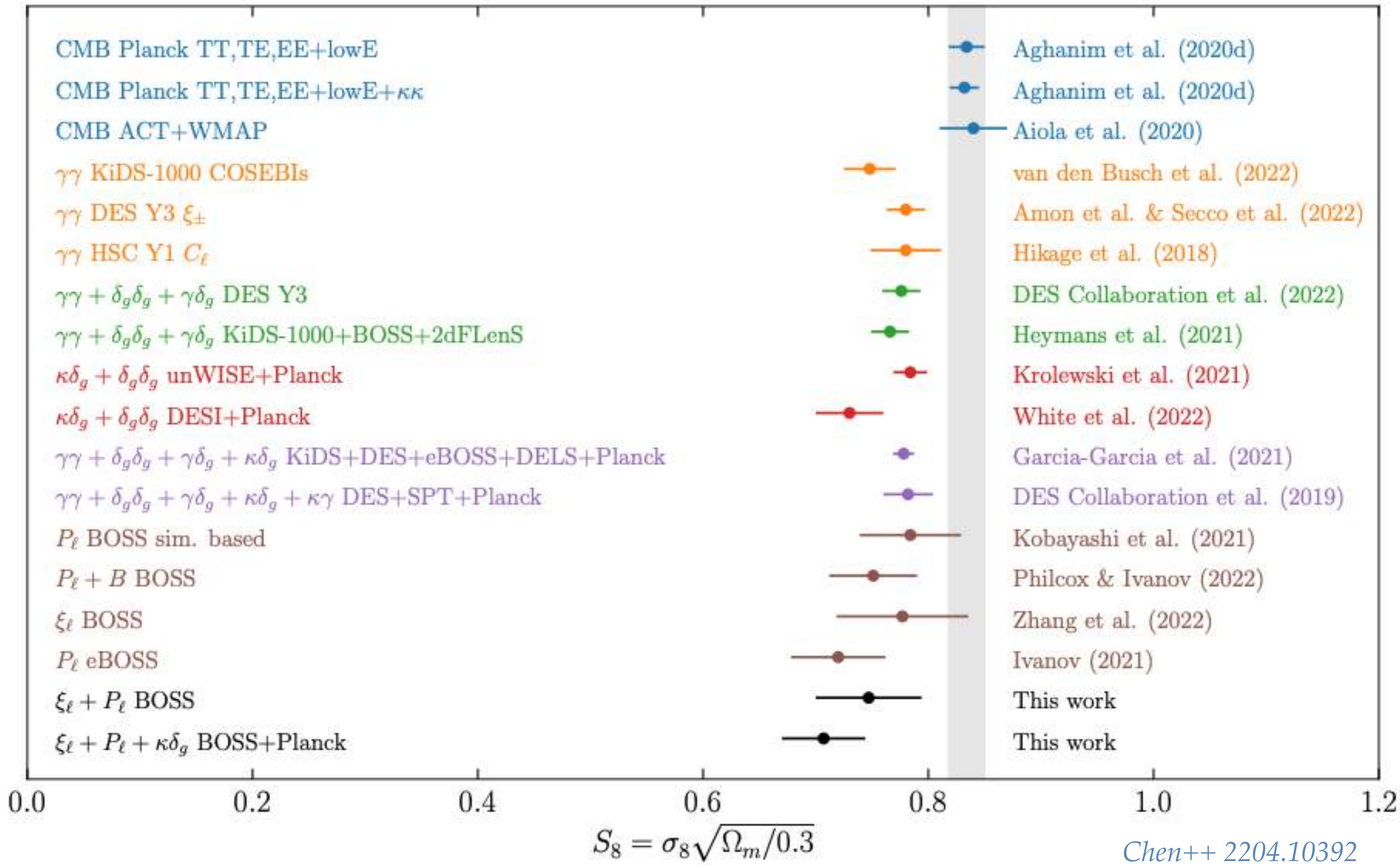



- EFT analyses of BOSS do not exclude Early Dark Energy

# The $S_8$ tension

—> *Marika Asgari's talk*

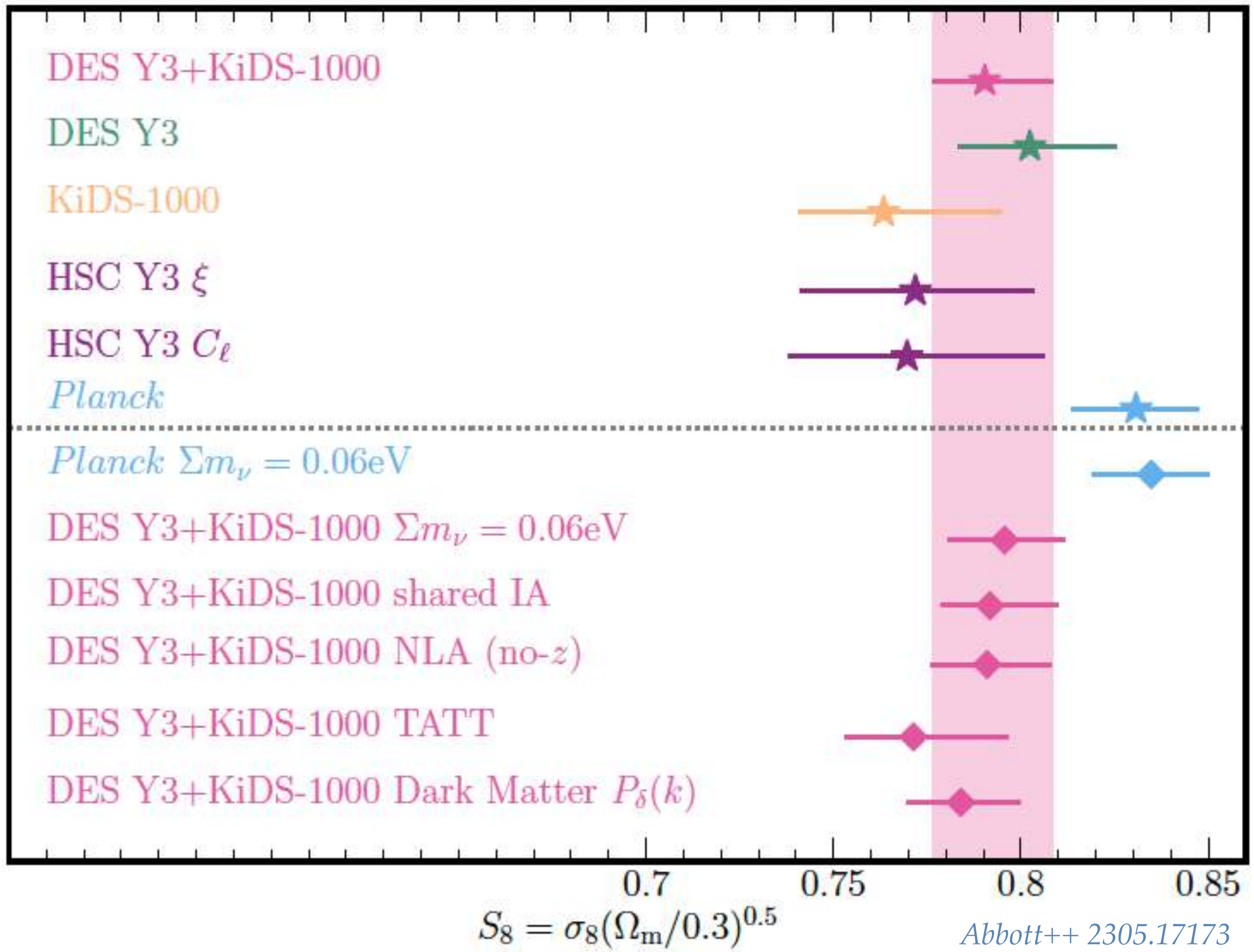



*Chen++ 2204.10392*

**Early Dark Energy cannot resolve the $S_8$ tension**

# The $S_8$ tension updated

—> *Marika Asgari's talk*

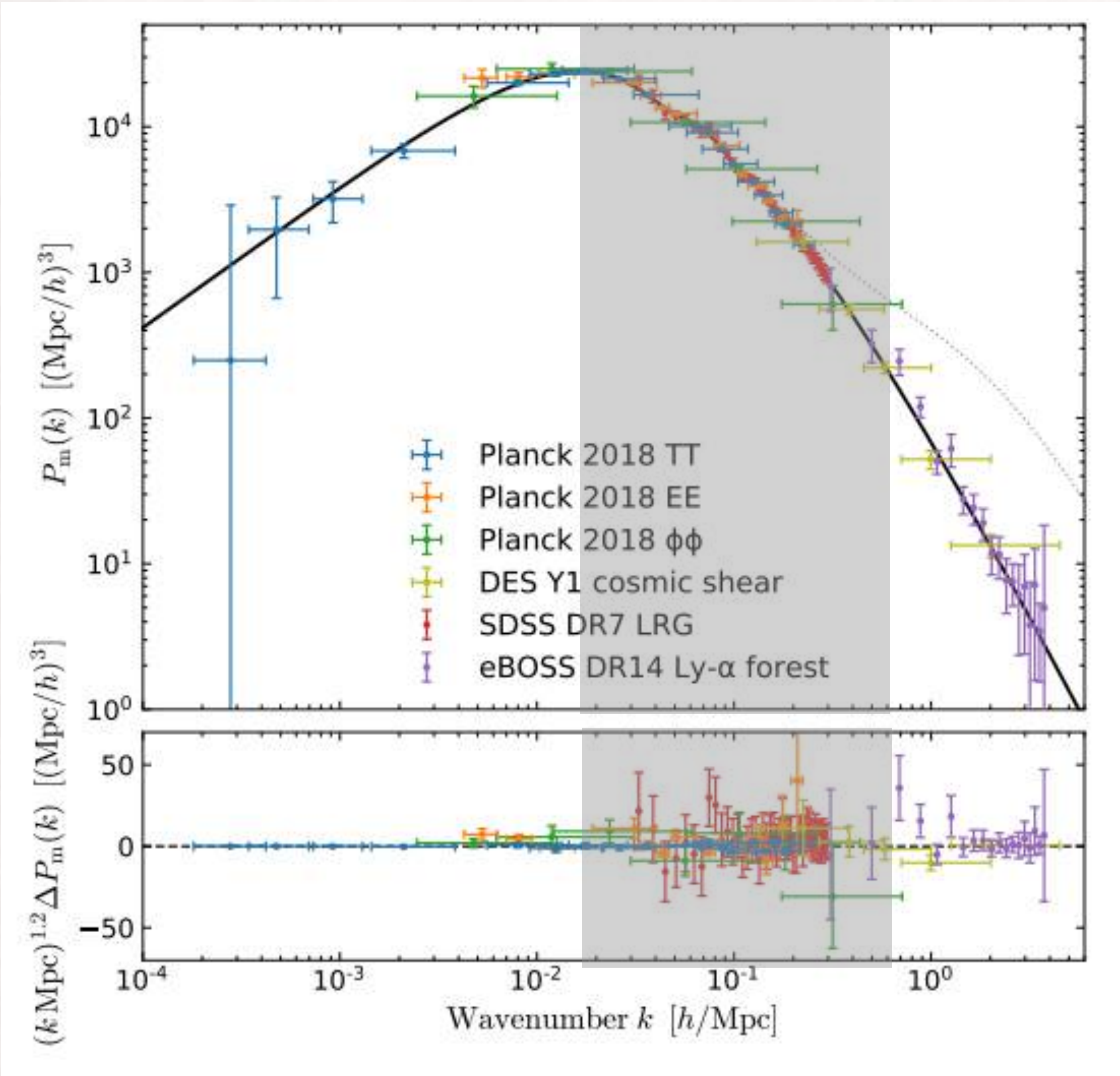


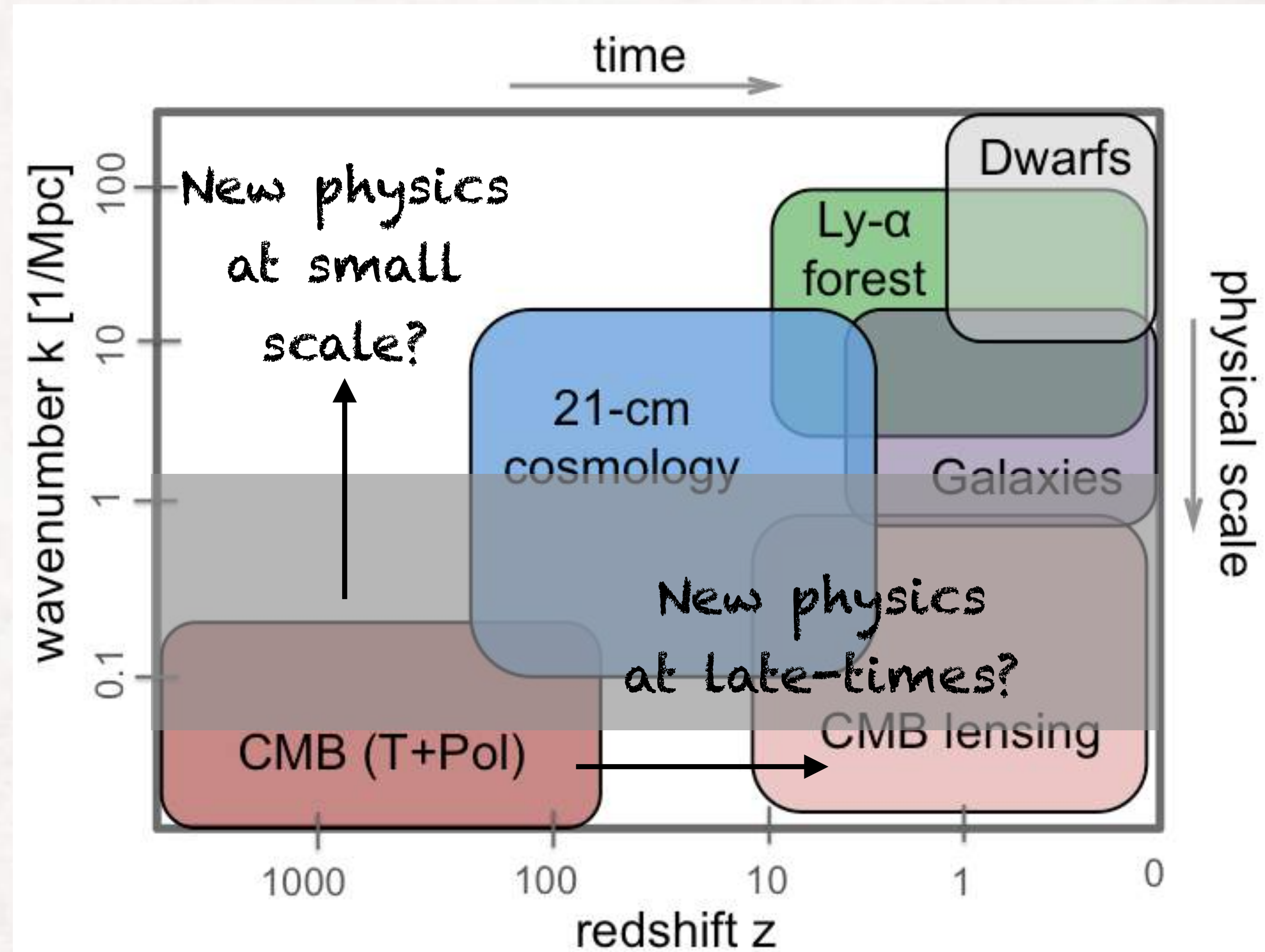

*Abbott++ 2305.17173*

- New Hybrid "KiDS+DES" analysis results in 1.7$\sigma$ 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




- $\sigma_8$ 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*

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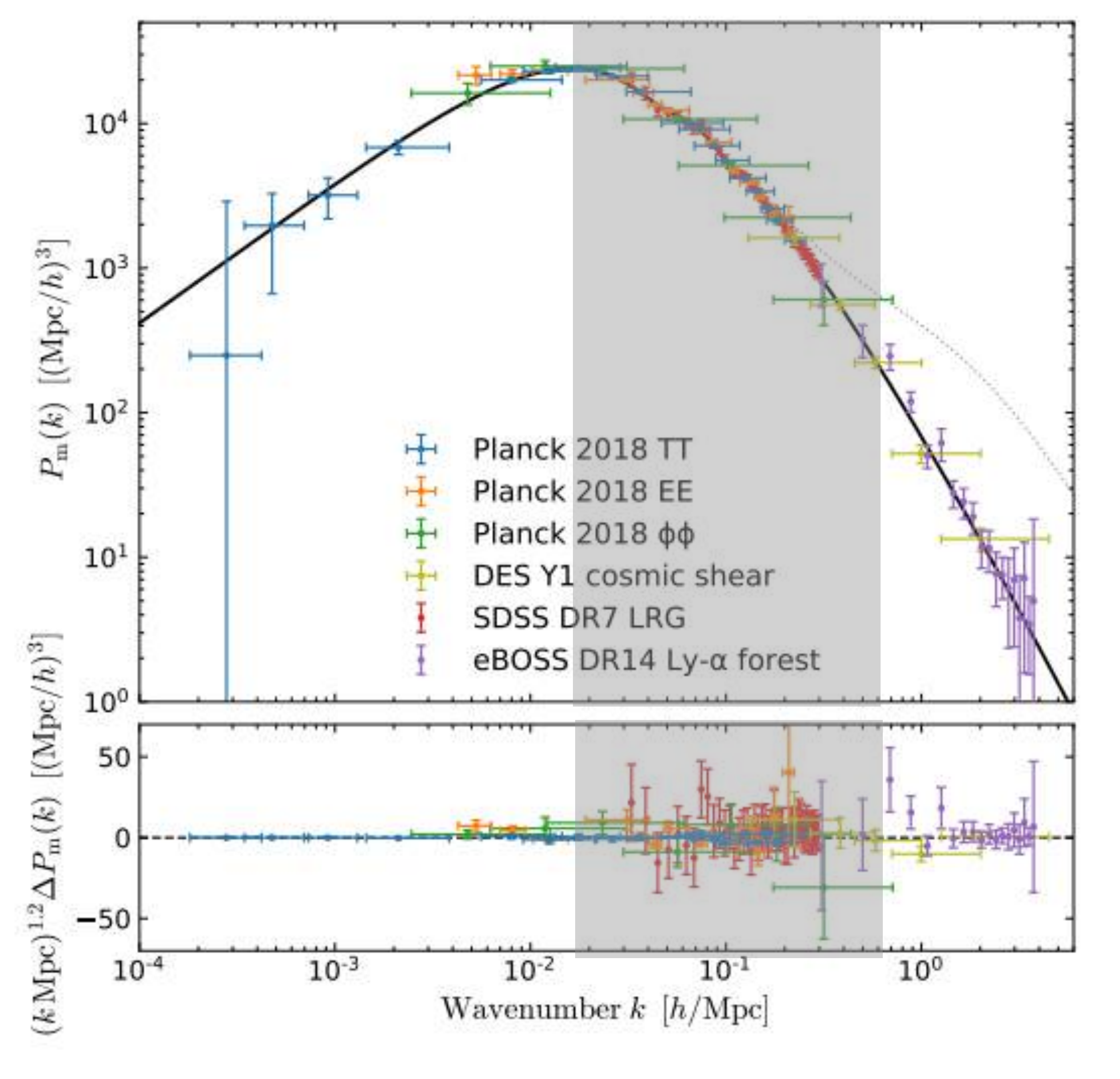
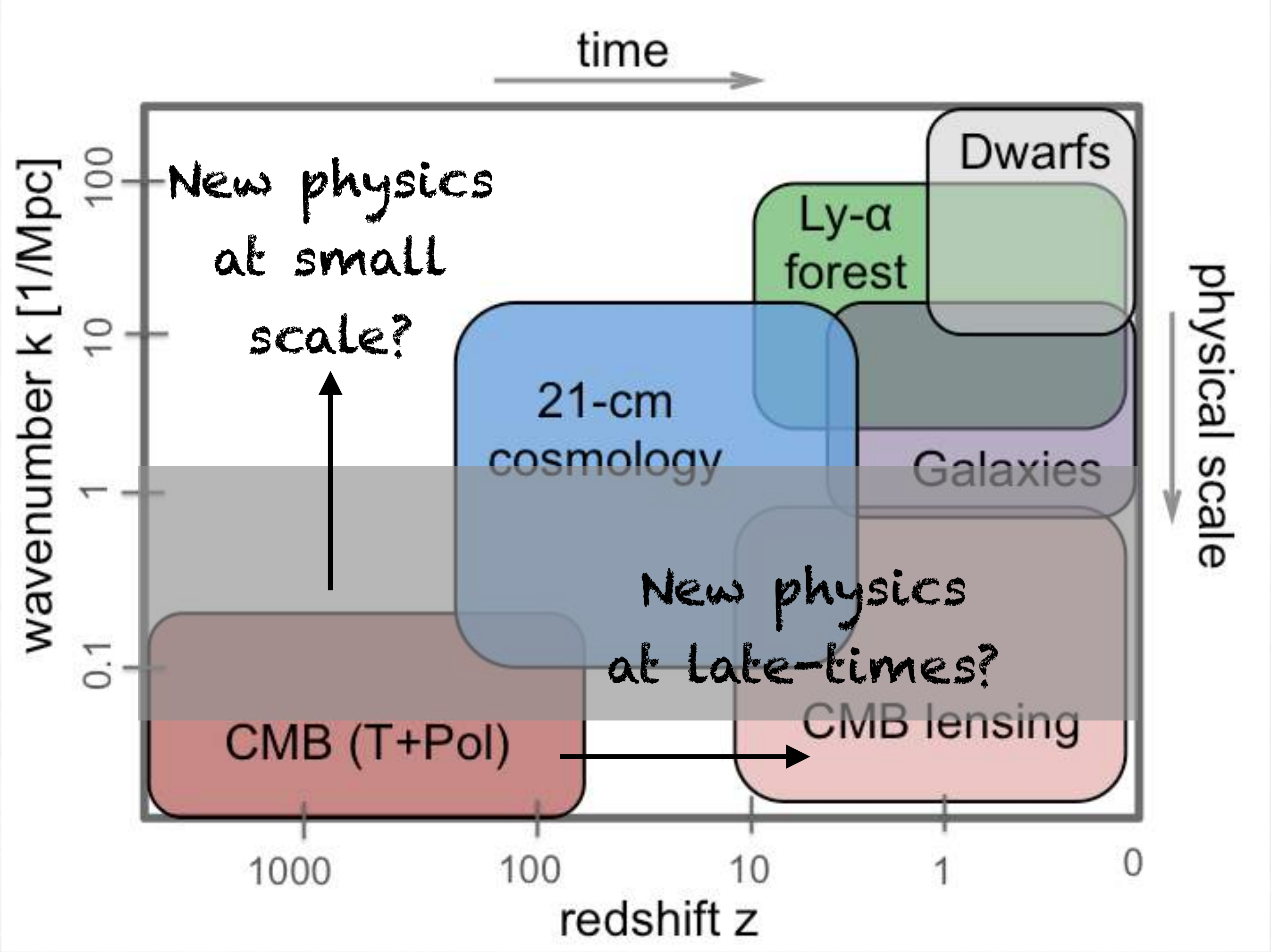
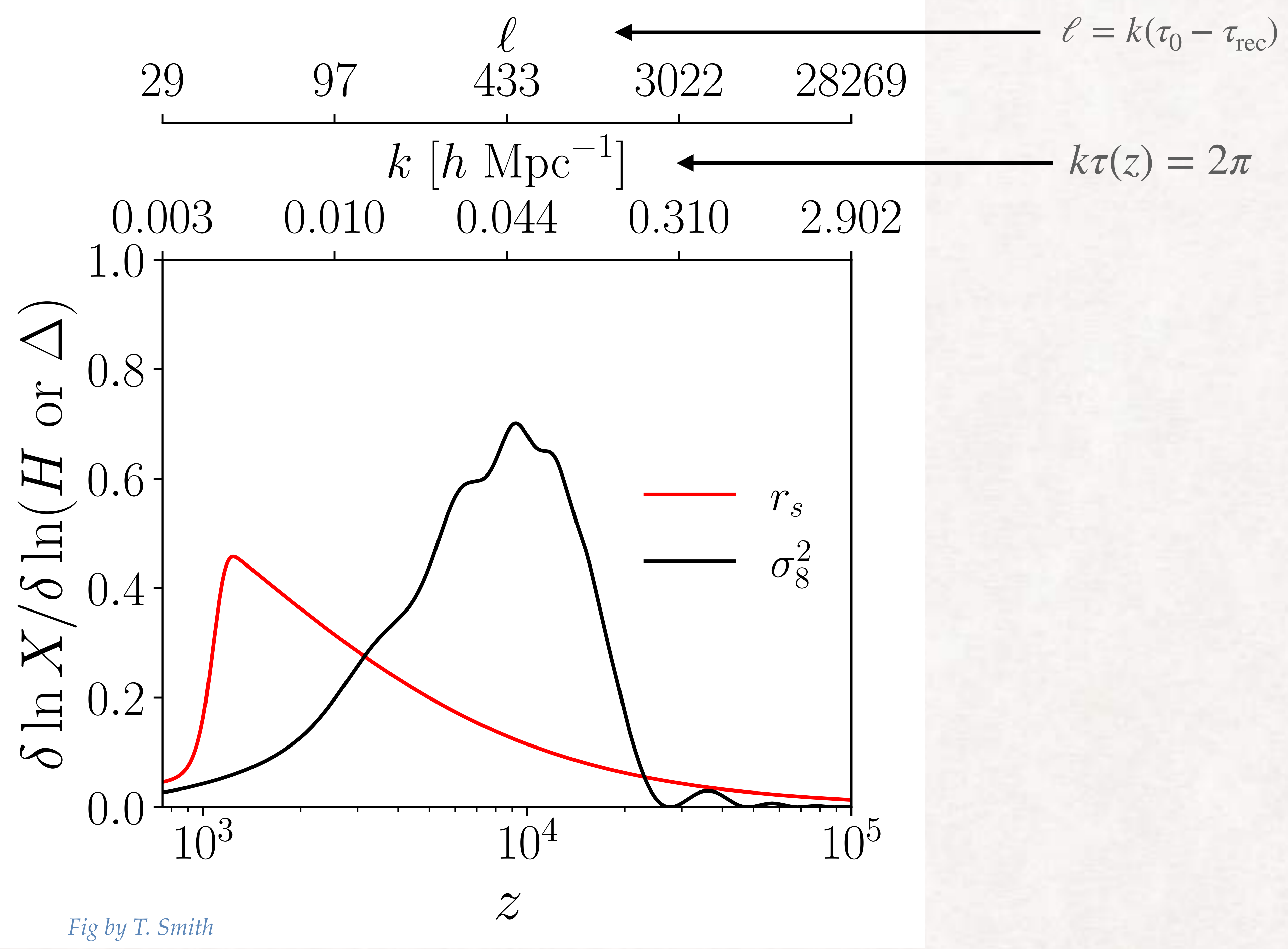



- $\sigma_8$ is a derived parameter measuring scales $k \sim 0.1$ h/Mpc. Fit the CMB at $z \sim 1100$ and predict $\sigma_8(z=0)$.
- To resolve the tension: Either suppress scales $k \gtrsim 0.2$ h/Mpc or change late-time evolution at $z < 0.5$
- Dark Sector physics: Ultra-light axions, Decaying DM,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

*Abdalla++ 2203.06142*

# Resolving $H_0$ and $S_8$ with the same mechanism




- All modes controlling $\sigma_8$ are within the horizon around / before the sound horizon starts growing.

# Could EDE "drag" DM and reduce $S_8$?

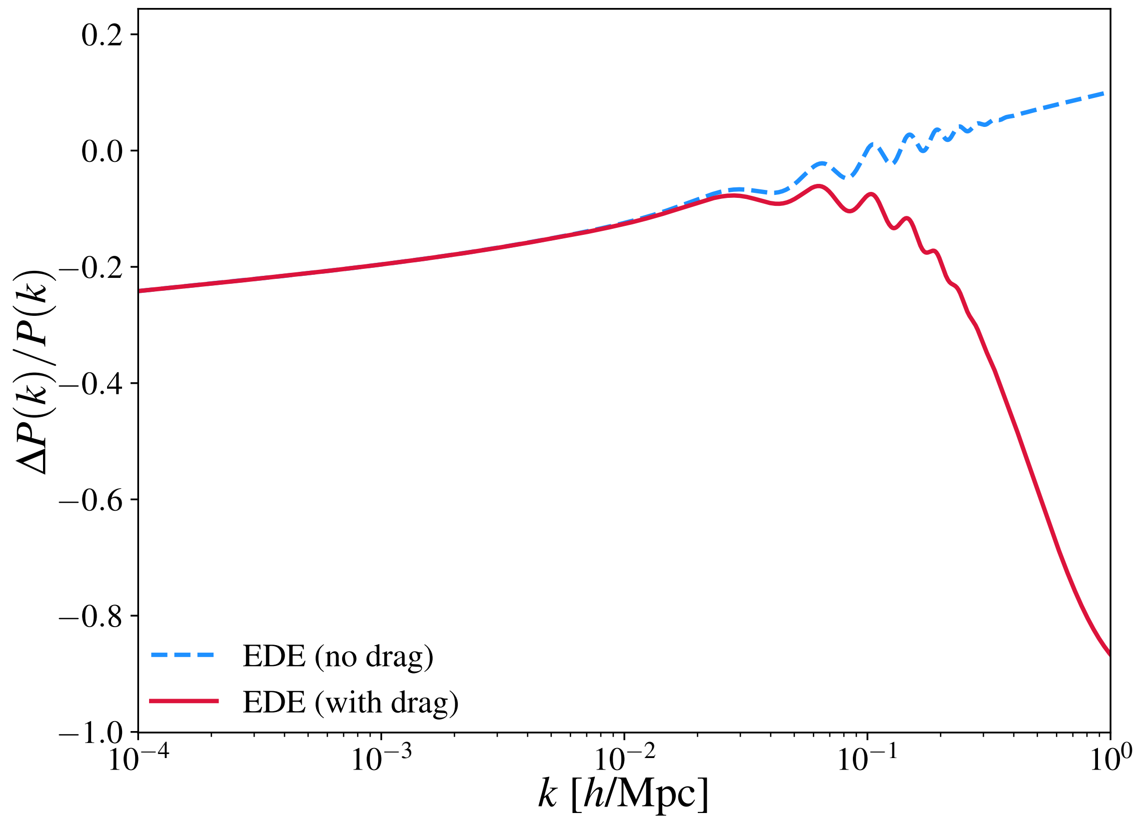
- With a phenomenological "EDE+DM" drag: one can resolve both tensions!

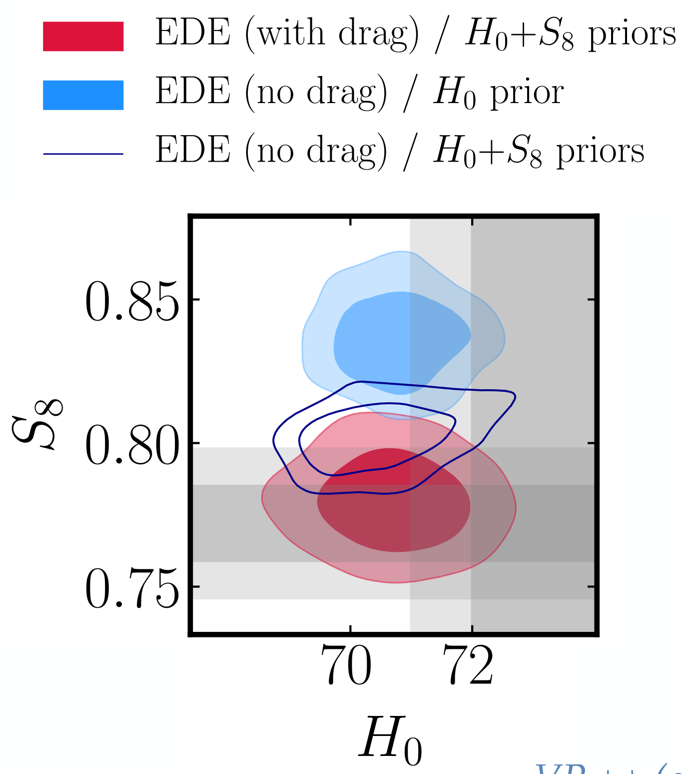
*Similar to ``step" dark radiation Joseph++ 2207.03500*

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

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

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




*VP ++ (ongoing work)*

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

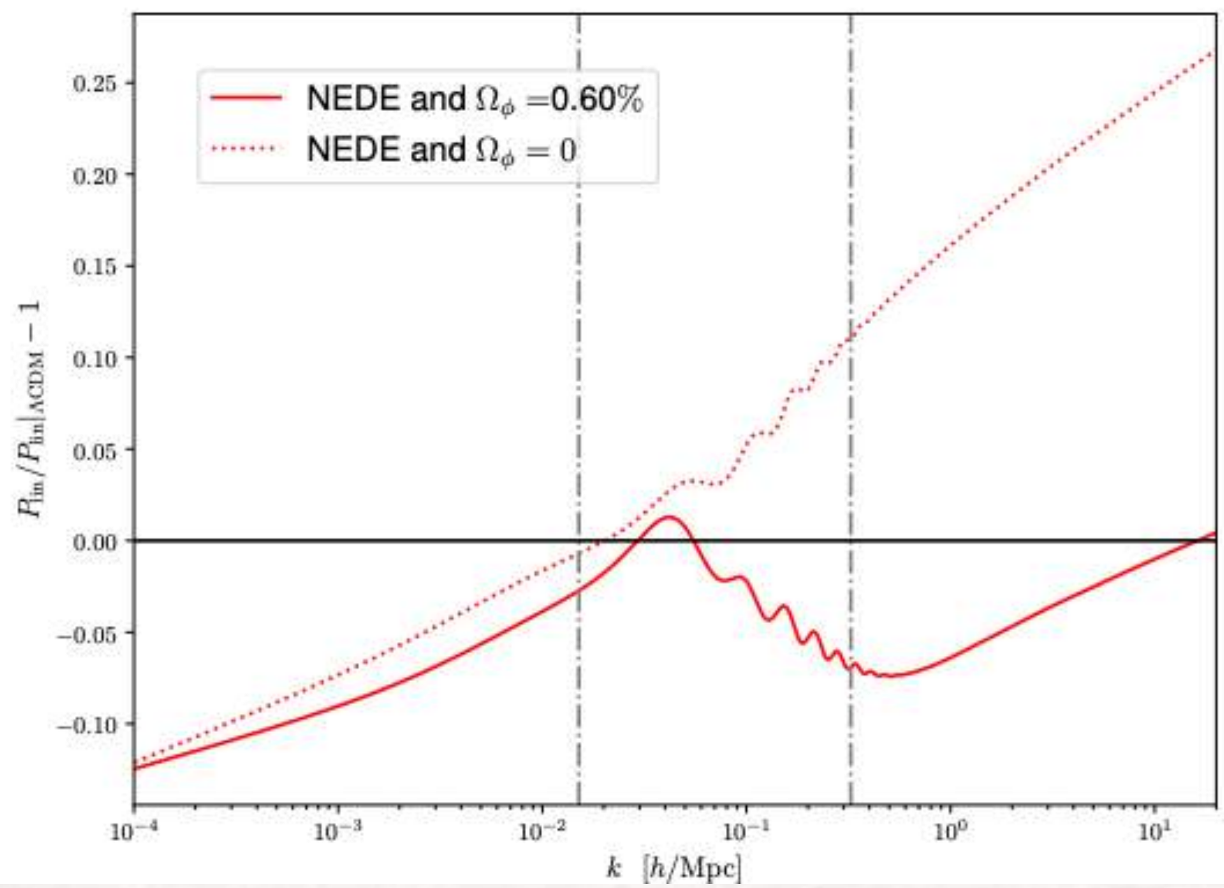
*Skordis++ 1502.07297, Pourtsidou++ 1604.04222*

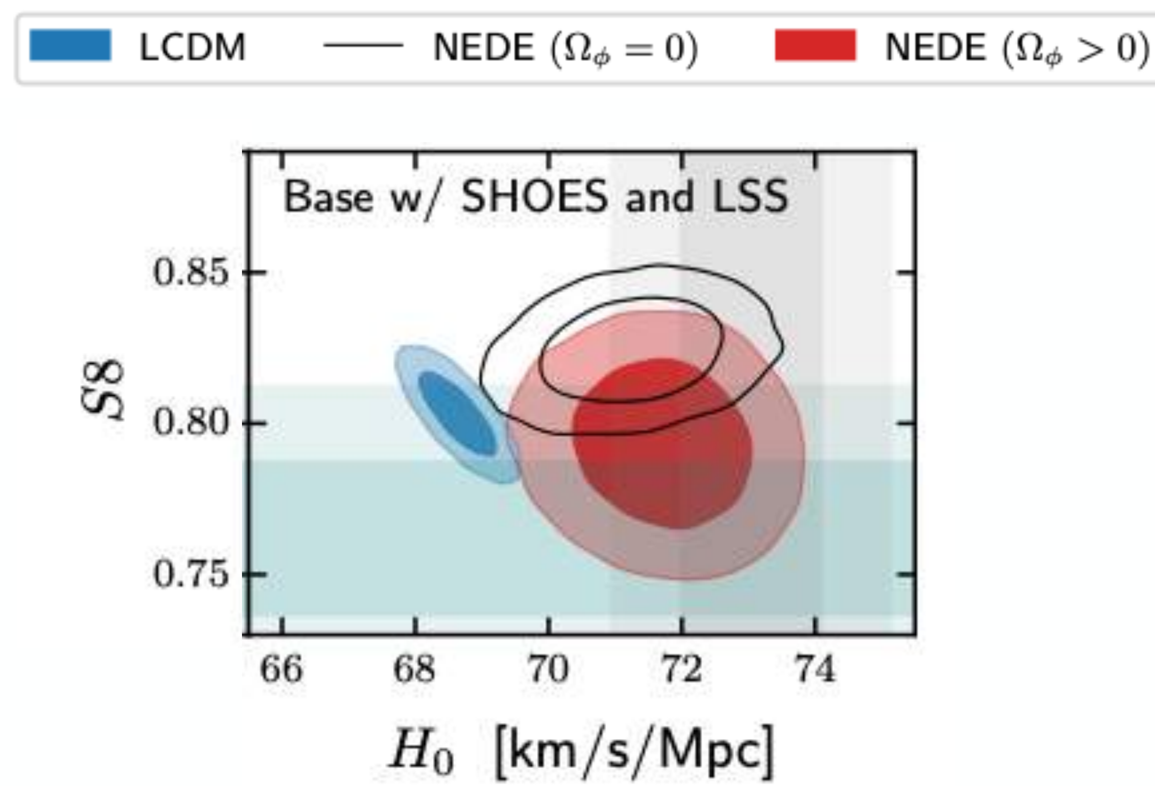
- Connection with the coincidence problem? DM dominance can trigger the rolling of EDE field *Lin++2212.08098*

# “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 $\sigma_8$
- 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.

# Early Dark Energy: more Ups than Downs?

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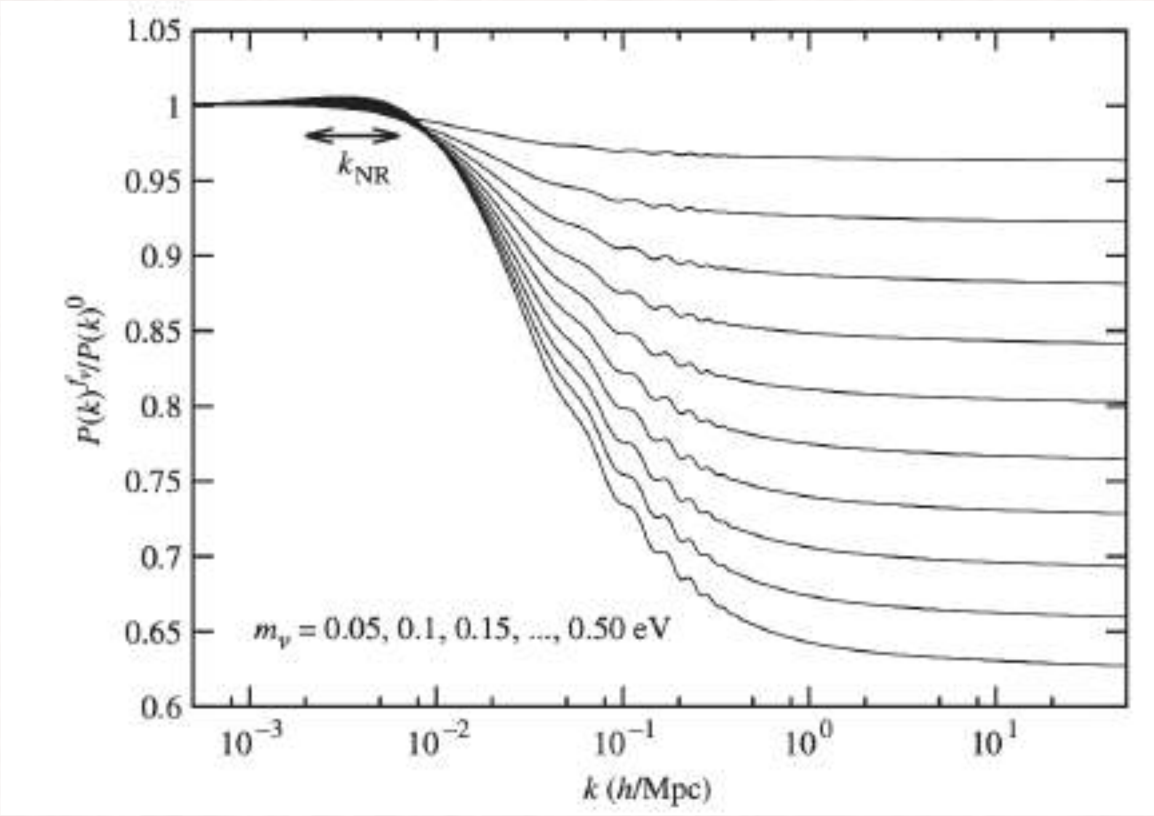
**Future CMB data will detect/exclude EDE!**

# Could $\nu$'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 $S_8$

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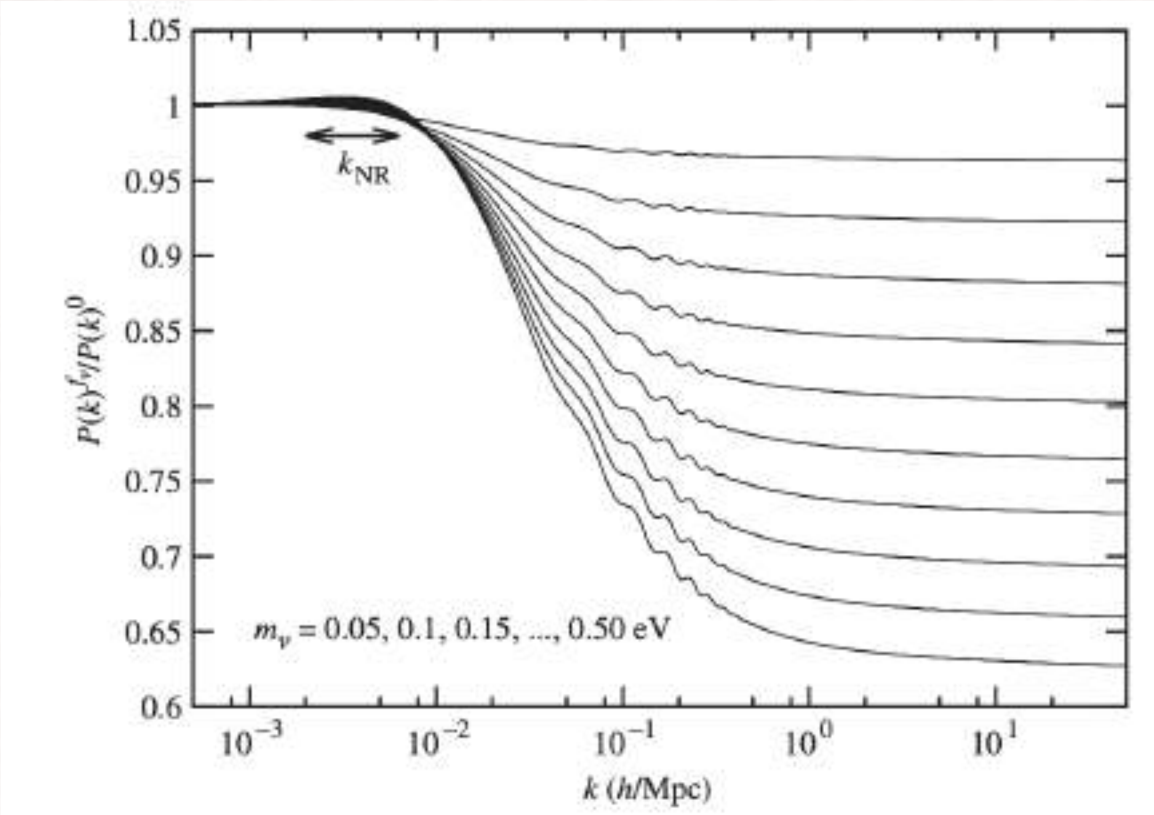


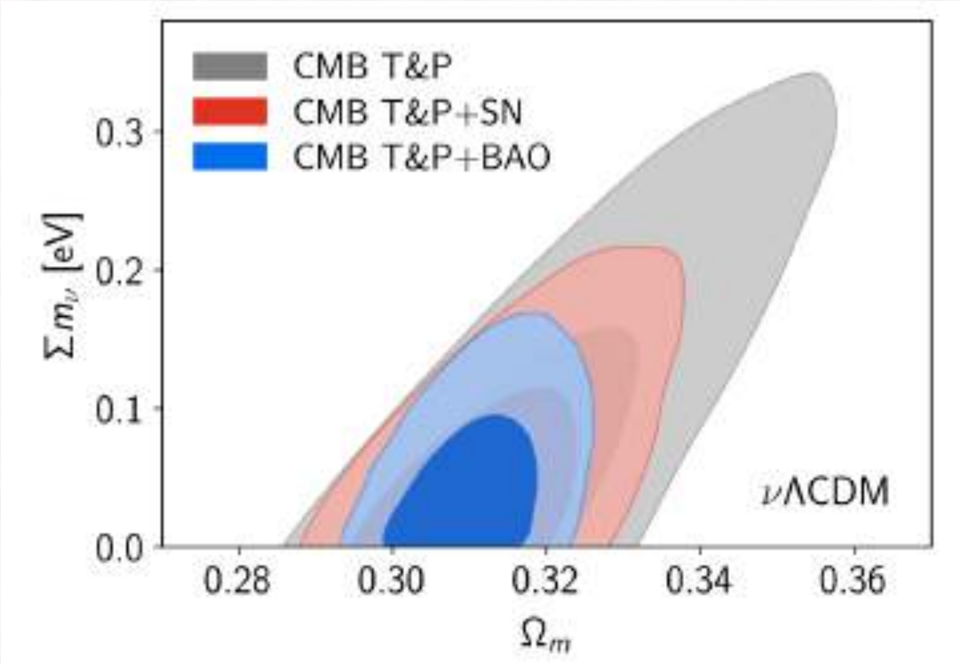


*Planck* 2018 + BAO $< 0.12$eV Planck 1807.06205

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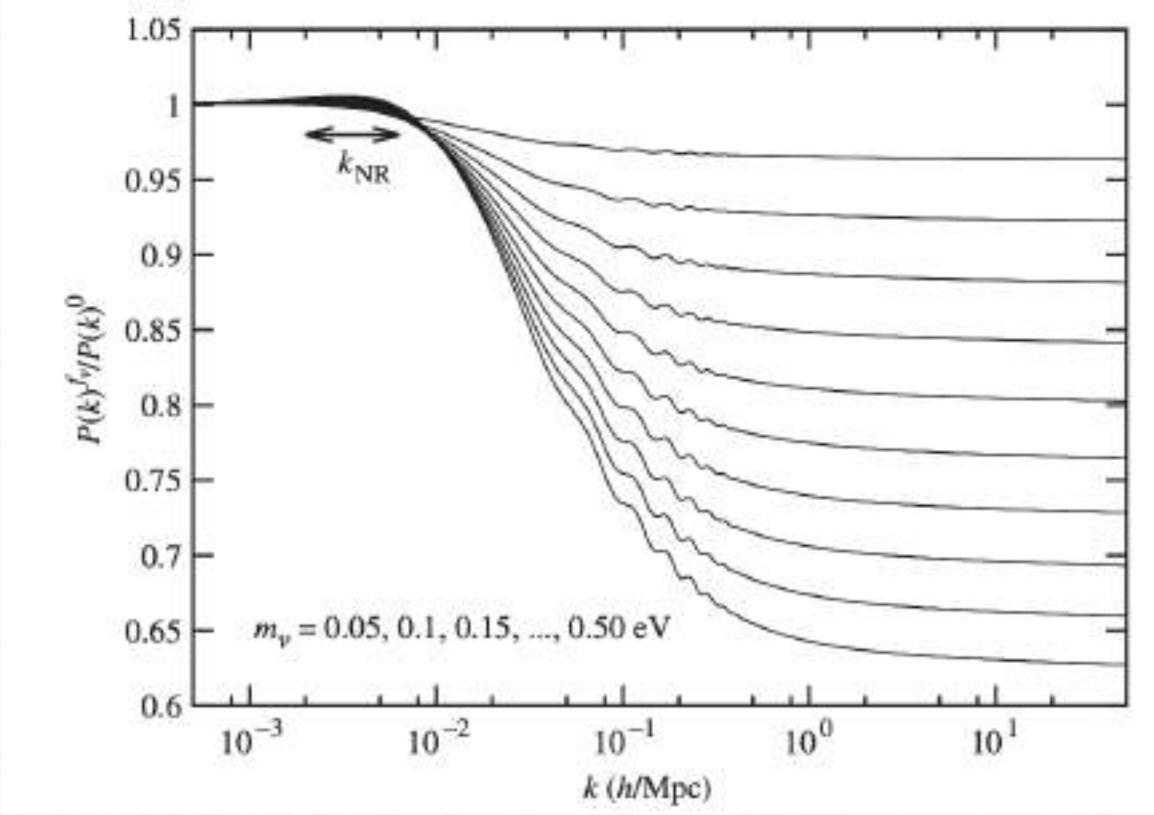
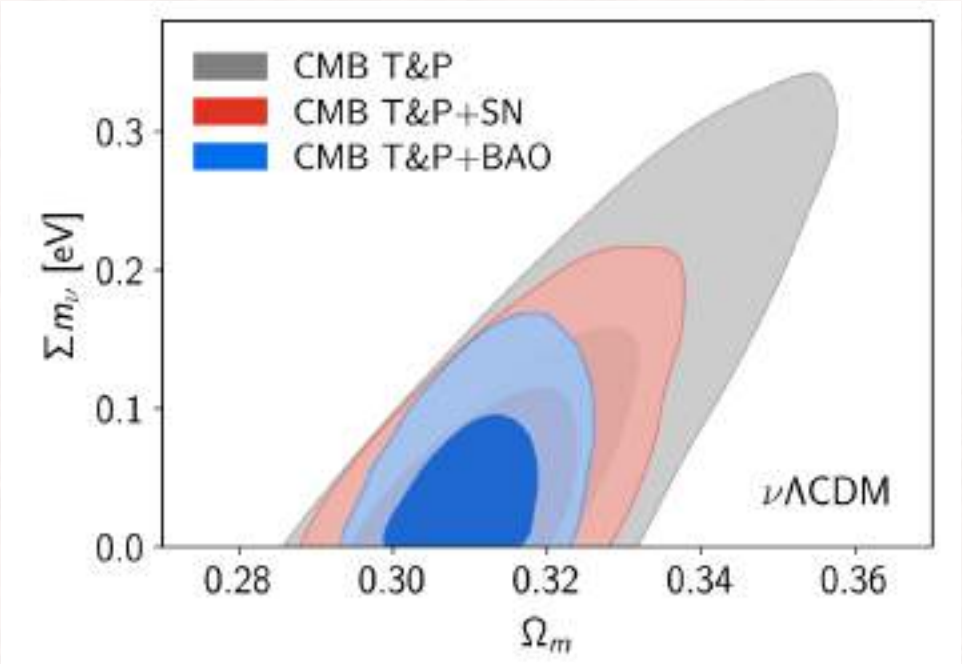



*Planck* 2018 + BAO $< 0.12$eV *Planck 1807.06205*

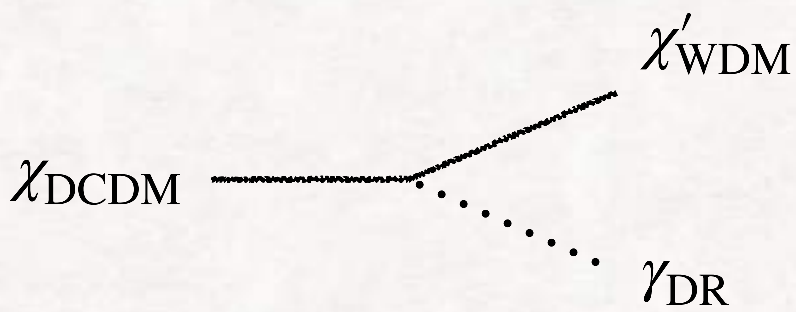
*Planck* 2018 + BAO + Ly$-\alpha$ $< 0.089$eV *Palanque-Delabrouille++ 1911.09073*

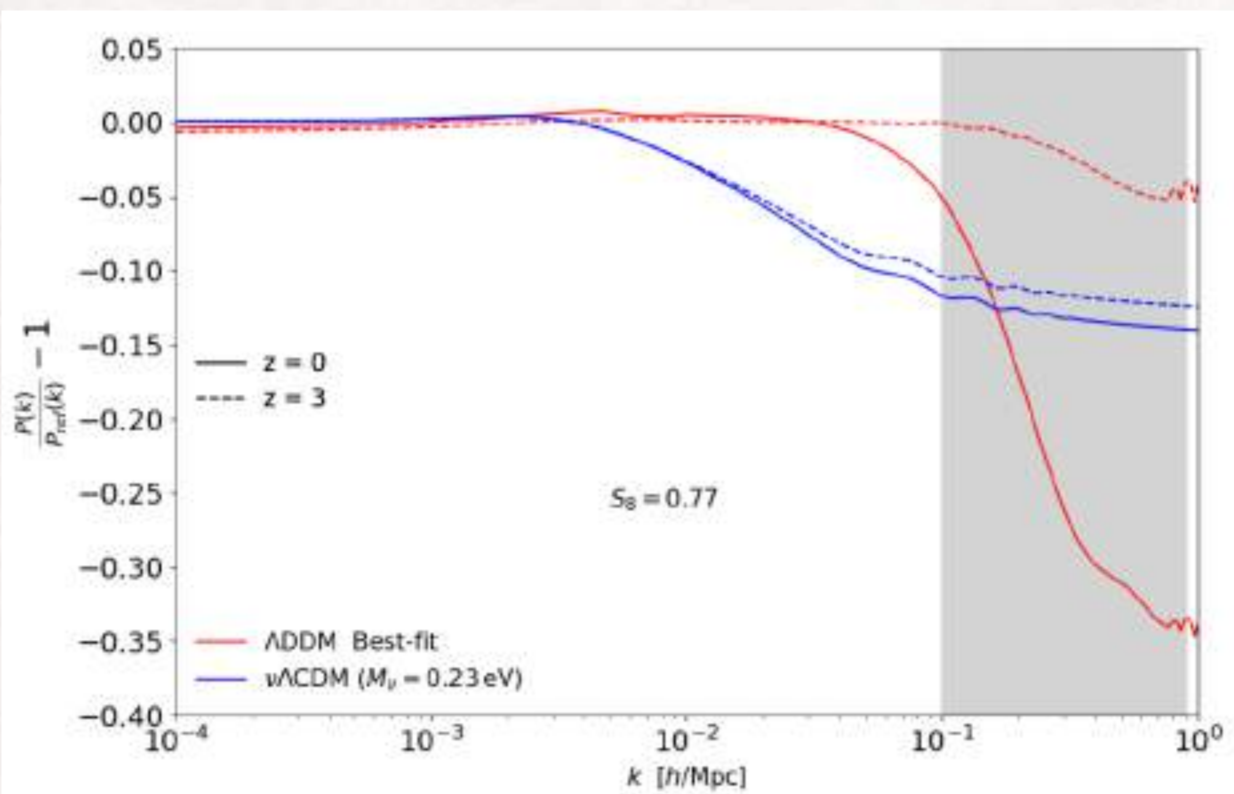
*Planck* 2018 + BOSS + eBOSS $< 0.082$eV *Brieden++ 2204.11868, Simon++ 2210.14931*

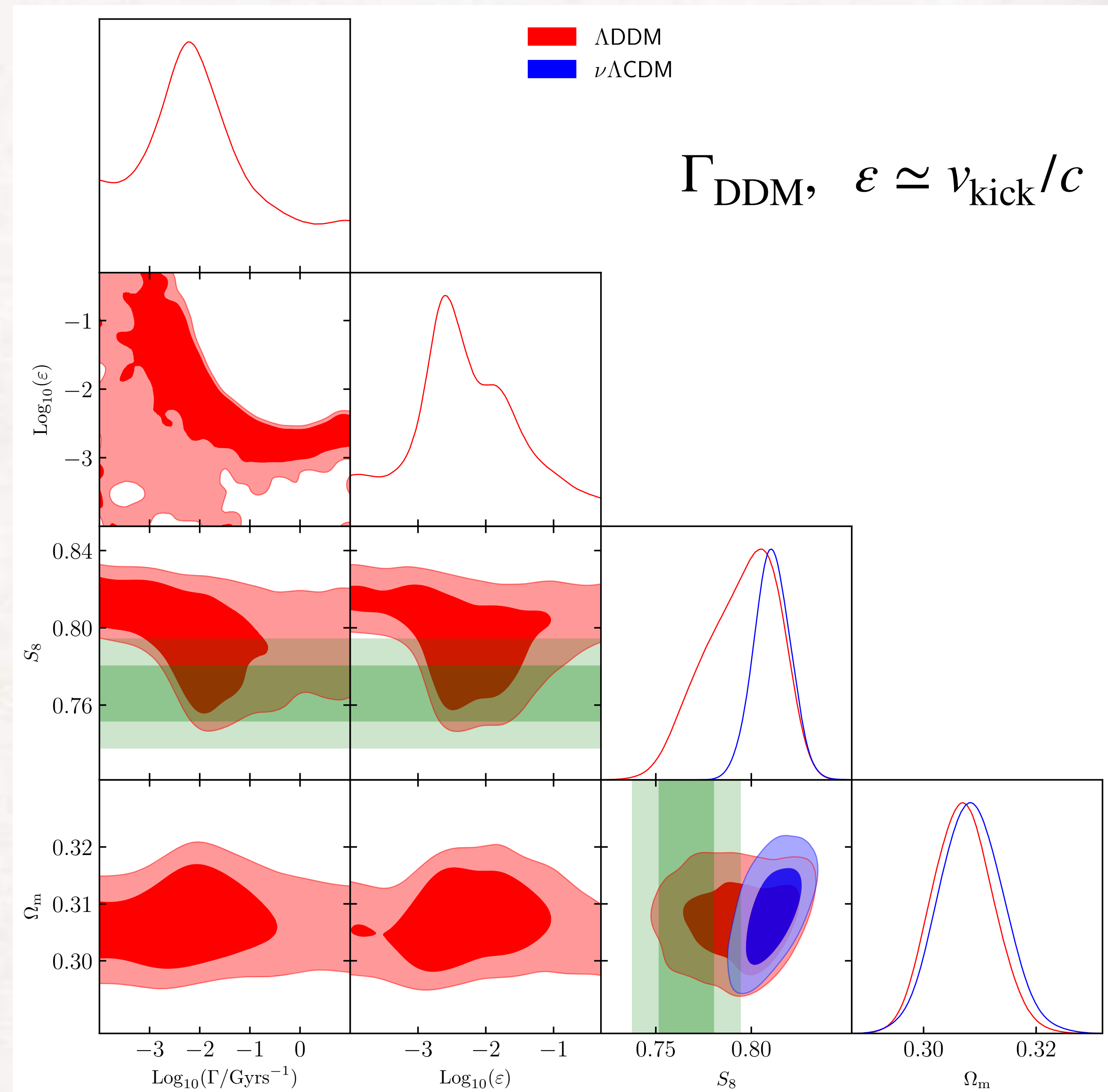
- Including EDE does not change massive neutrinos constraints / cannot resolve $S_8$ *Reeves++ 2207.01501*

# How to generate a late-time suppression

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



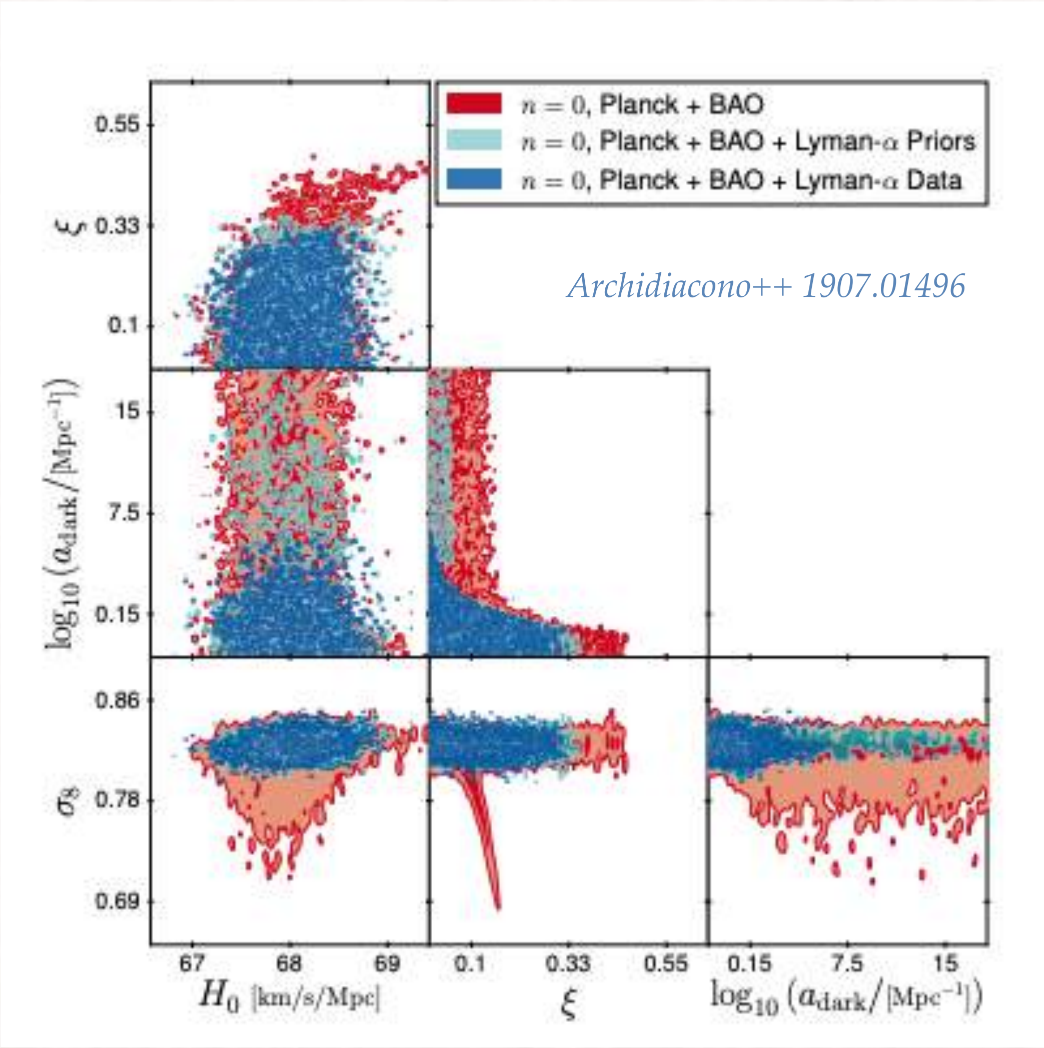

- DM with $\Gamma^{-1} \simeq 55(\varepsilon/0.007)^{1.4}$ Gyrs can explain low $S_8$ ($1.3\sigma$ agreement) *Abellan++ 2008.09615 & 2104.03329*
- Similar results if there exists a fraction of ultra-light axion in the universe *Rogers++ 2023*

# DM "drag" suppresses power at small-scales

**DM<=>DR**

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

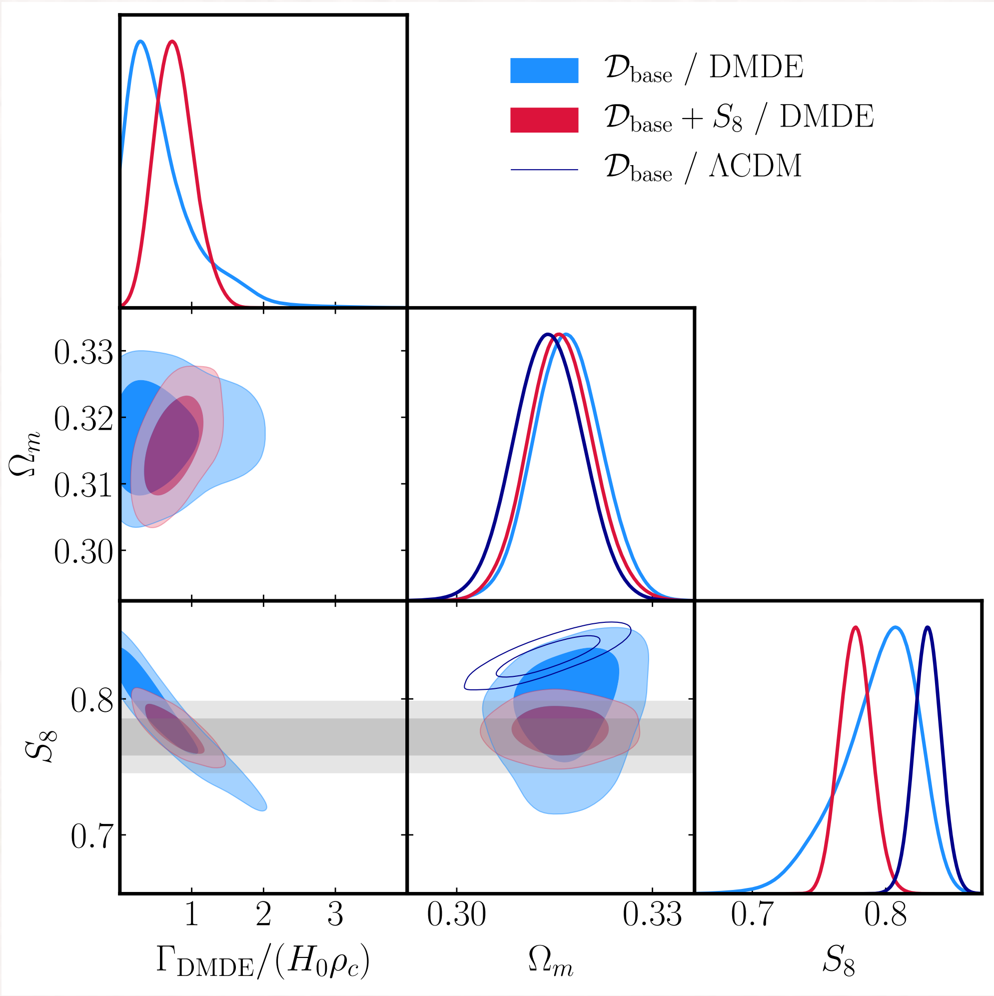
$$\Gamma_{\rm DR-DM} = -\Omega_{\rm DM} h^2 a_{\rm dark}\left(\frac{1+z}{1+z_d}\right)^n, \qquad \xi = T_{\rm DR}/T_\gamma$$




**DM<=>DE**

*VP, Bernal, Kovetz, Kamionkowski 2209.06217*

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




*See also Di Valentino++ 1908.04281*

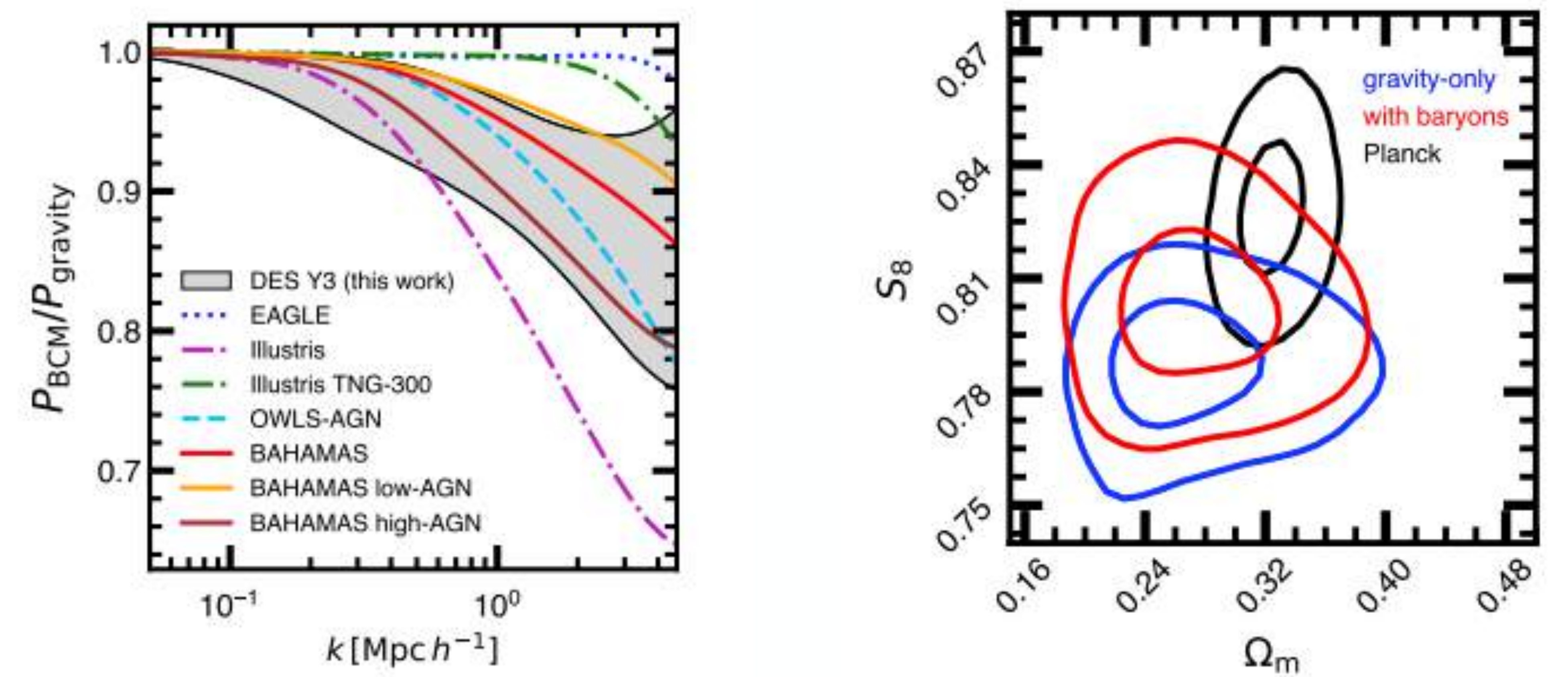
- Non-Abelian dark matter model, Cannibal dark matter, also with sub-component of strongly interacting DM

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

# Could the $\sigma_8$-tension be non-linear astrophysics?

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

*Aricò++ 2303.05537*

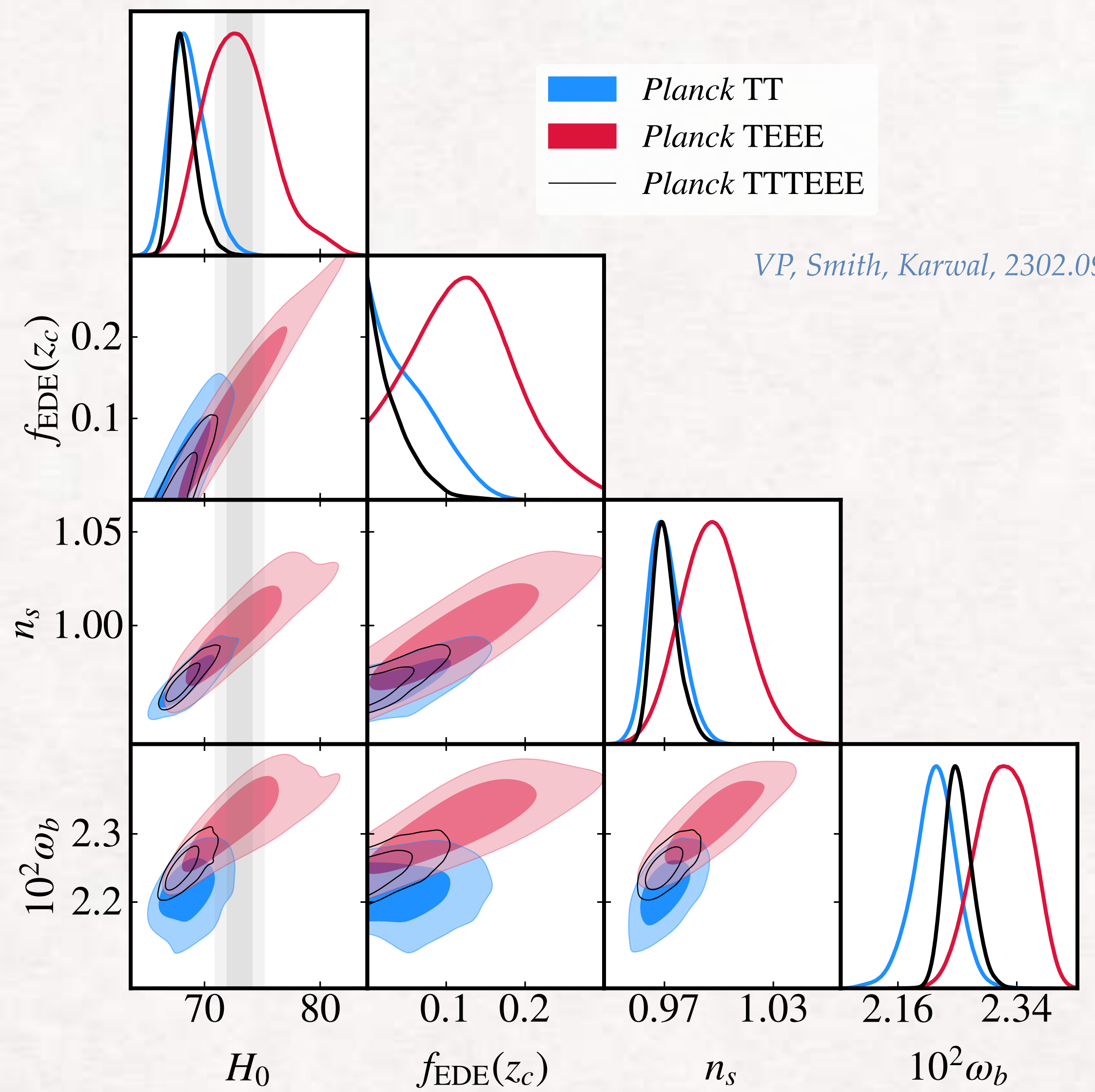



- The $\sigma_8$ tension may be astrophysics! Strong feedback + improved non-linear physics could explain the tension.

*See also Amon& Efstathiou 2206.11794*

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

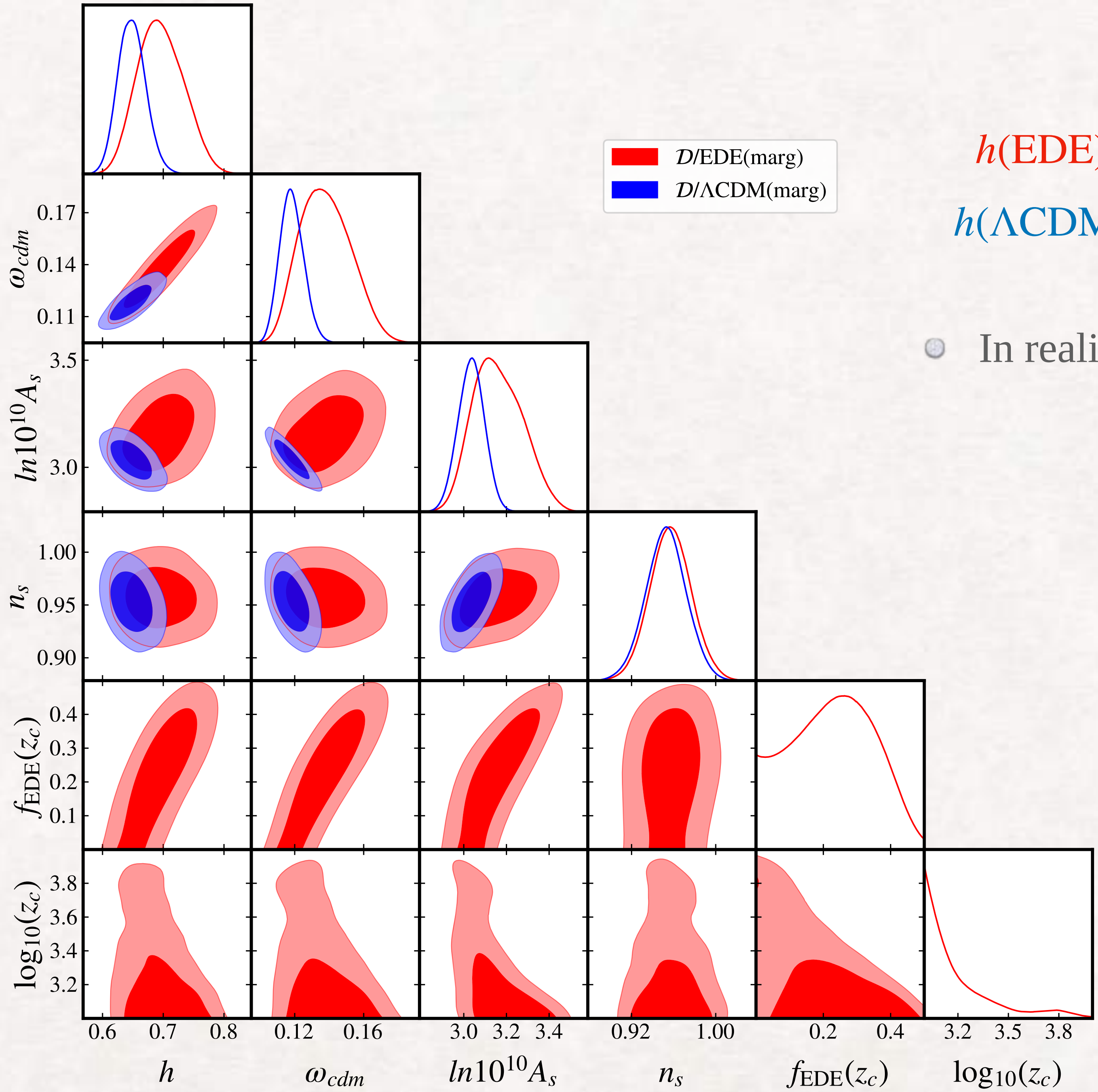
# Curiosities in *Planck*?




- Preference for EDE is coming from the TEEE data
- Disagreements in $\omega_b$ & $n_s$ 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*

# $k_{\rm eq}$-based estimate of $H_0$

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




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

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

- In reality $A_s$ and $n_s$ priors matter!