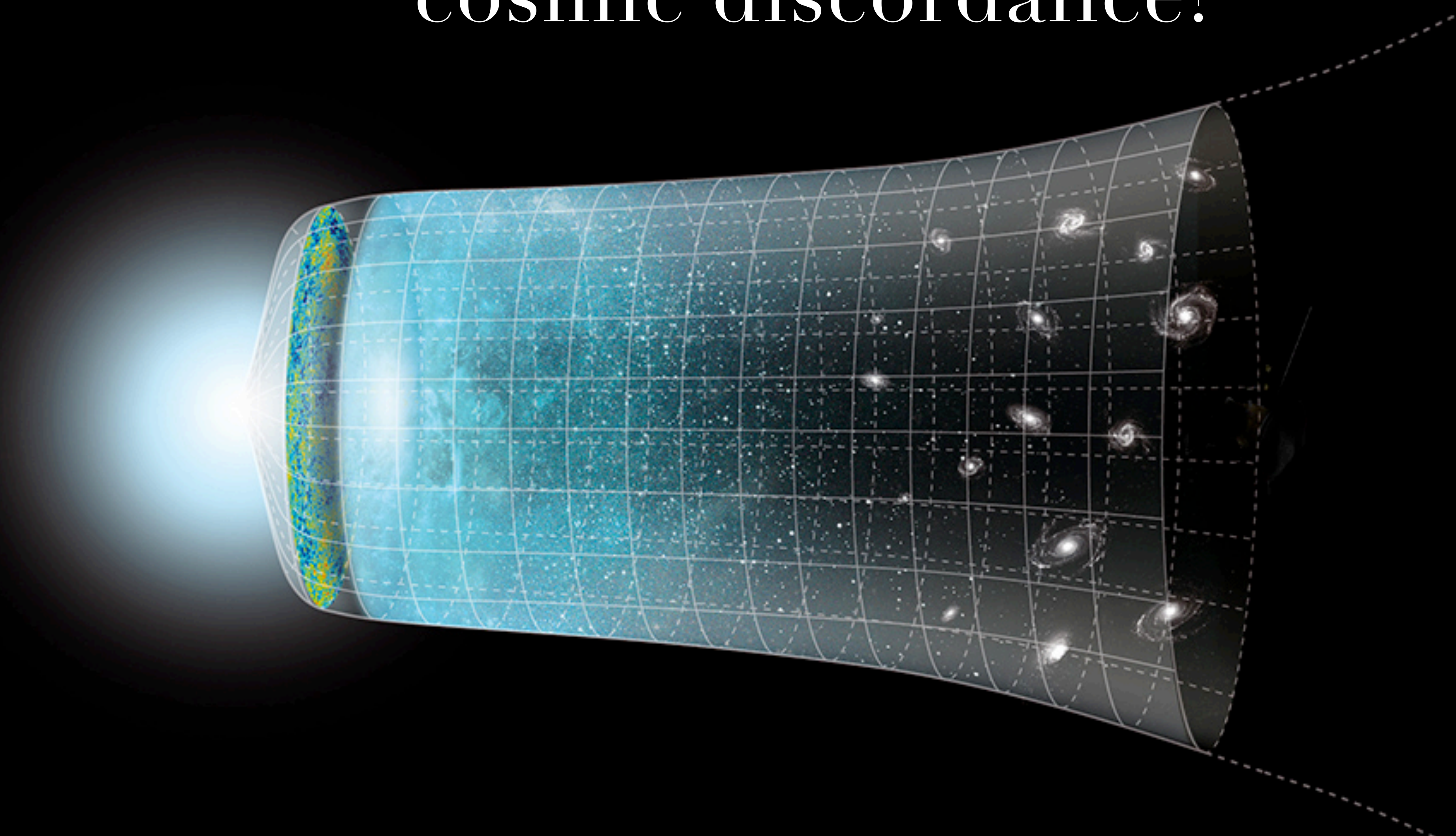
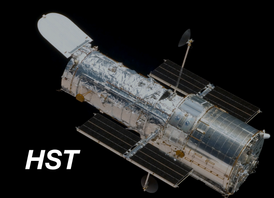
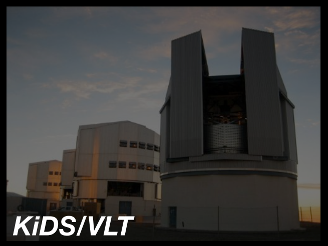
CMB, LSS and the distance ladder: cosmic discordance?







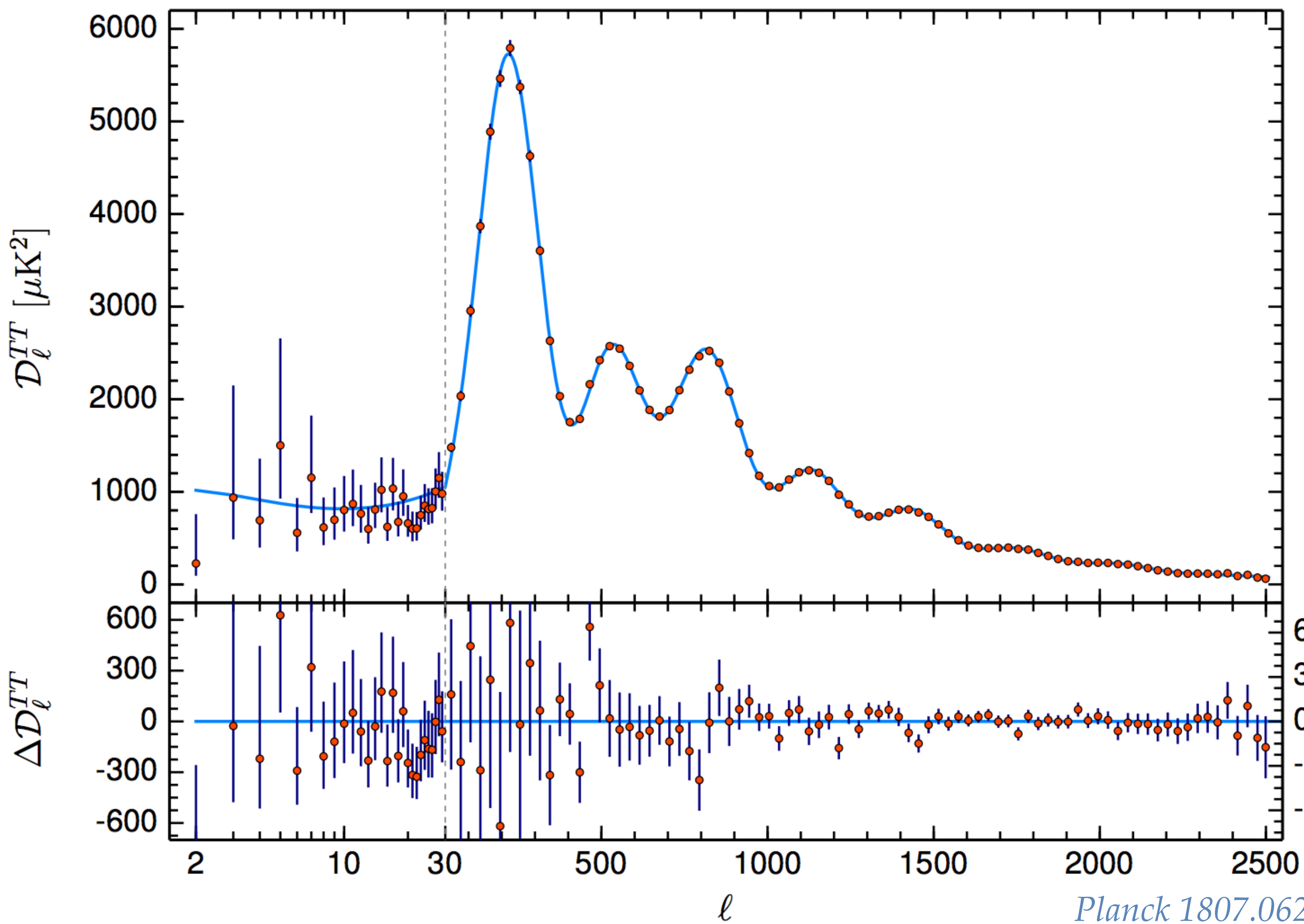
Vivian Poulin

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

EuCAPT Symposium
May, 6th 2021

The Era of Precision Cosmology

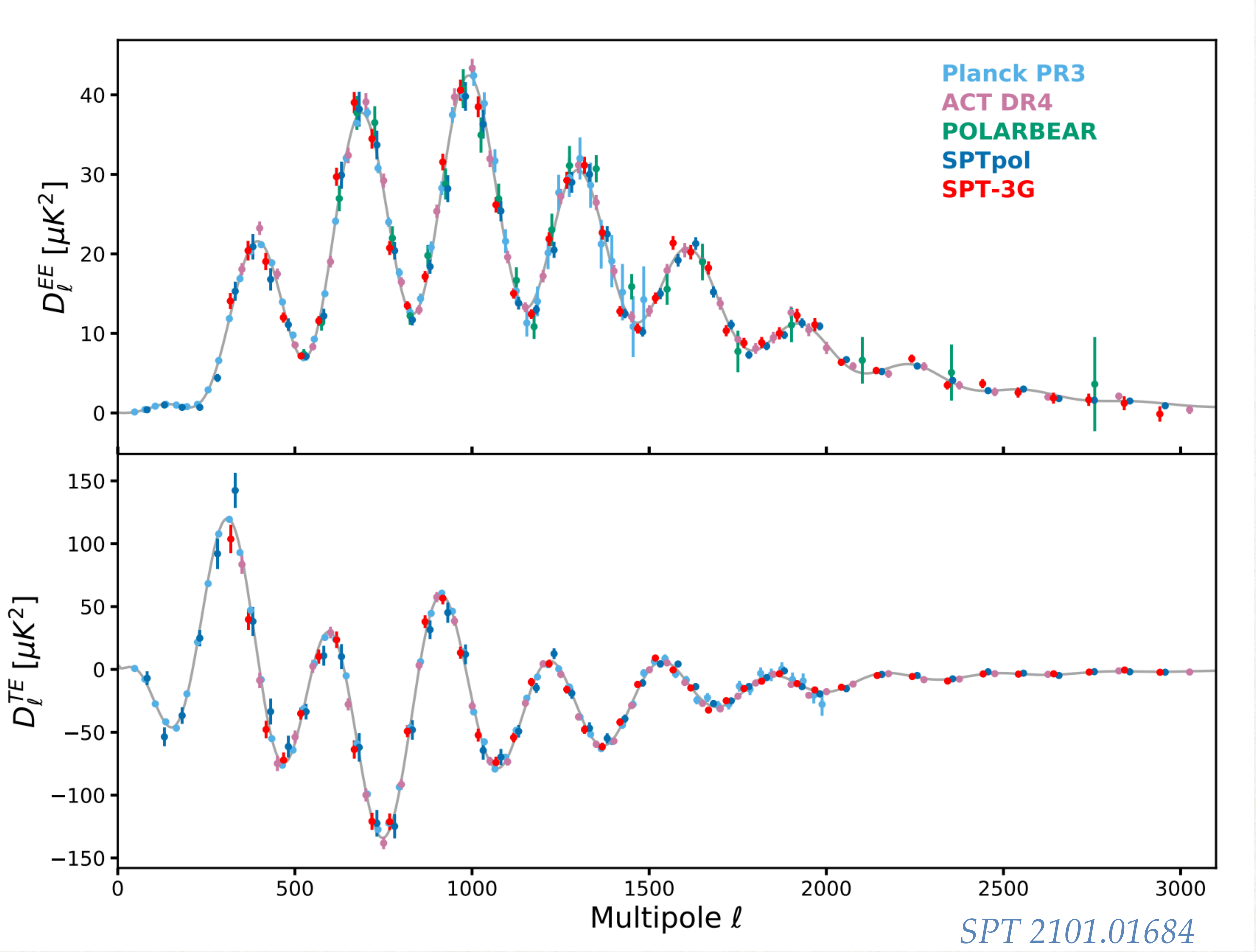
The CMB temperature power spectrum measured by *Planck*



Planck 1807.06209

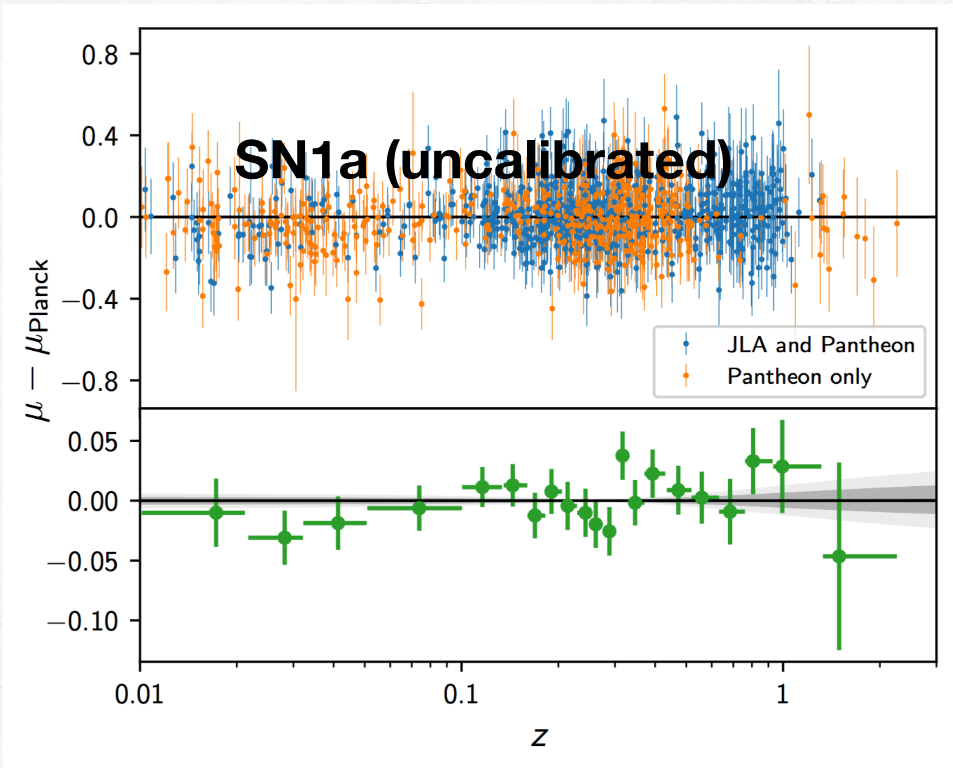
The Era of Precision Cosmology

Good agreement between all CMB data!

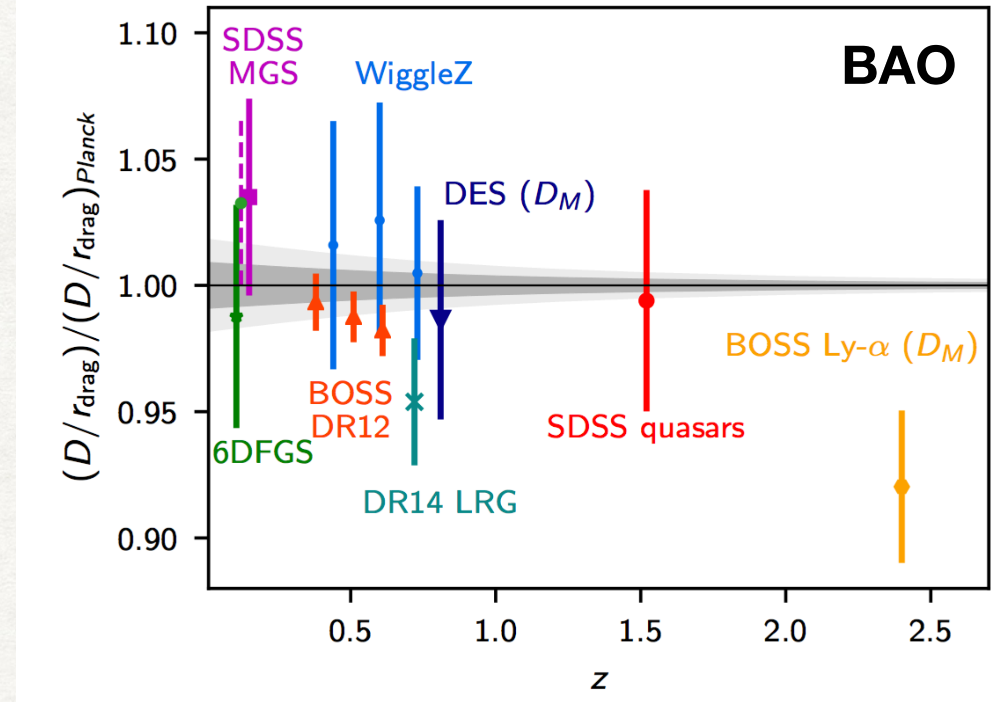


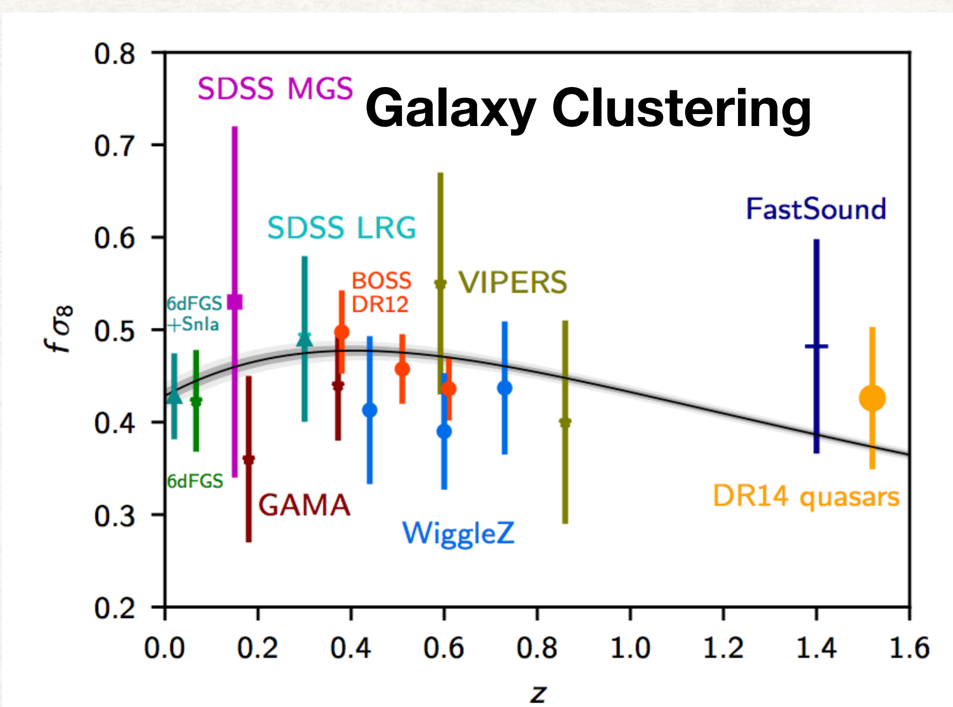
See ACT 2007.07288, SPT 2101.01684, Handley&Lemos 2007.08496 for discussion about statistical agreement ($\sim 2\sigma$)

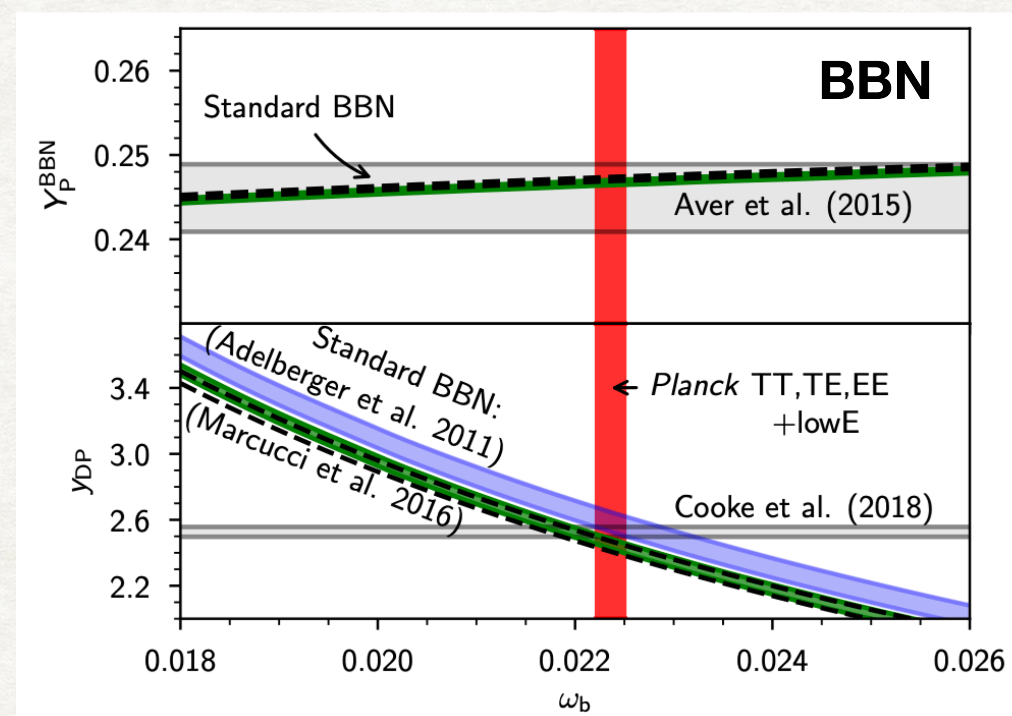
The Era of Precision Cosmology



Planck 1807.06209







- ΛCDM explains a wide variety of data (well-)within 2σ

A concordance model: ΛCDM

Astonishing success of ΛCDM Cosmology: GR+ Cosmological Principle

	Parameter	*Planck* alone	*Planck* + BAO	***Planck alone***
matter content	$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014	**0.6% precision**
	$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091	**1% precision**
expansion rate ($H0$,Λ)	$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029	**0.03% precision**
star formation	τ	0.0544 ± 0.0073	0.0561 ± 0.0071	**13% precision**
Inflation	$\ln(10^{10}A_s)$	3.044 ± 0.014	3.047 ± 0.014	**0.5% precision**
	n_s	0.9649 ± 0.0042	0.9665 ± 0.0038	**0.4% precision**

Planck 1807.06209

- There are additional predictions of ΛCDM to compare with observations (e.g.)

H_0	67.36 ± 0.54	67.66 ± 0.42
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ ...	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020

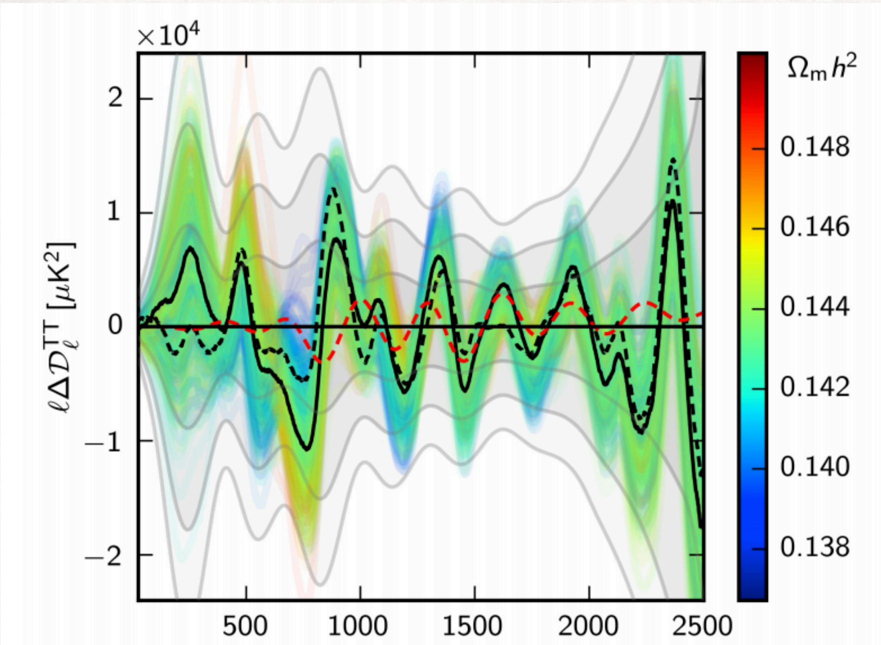
- As the precision of data has increased, a certain number of "tensions" have emerged.

Are these the first signs of the true nature of DM and DE?

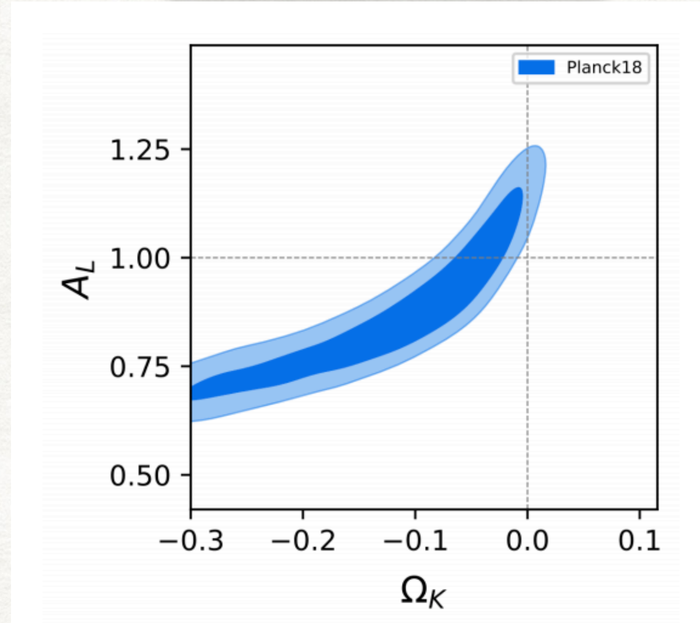
Anomalies in *Planck*: is the Universe closed?

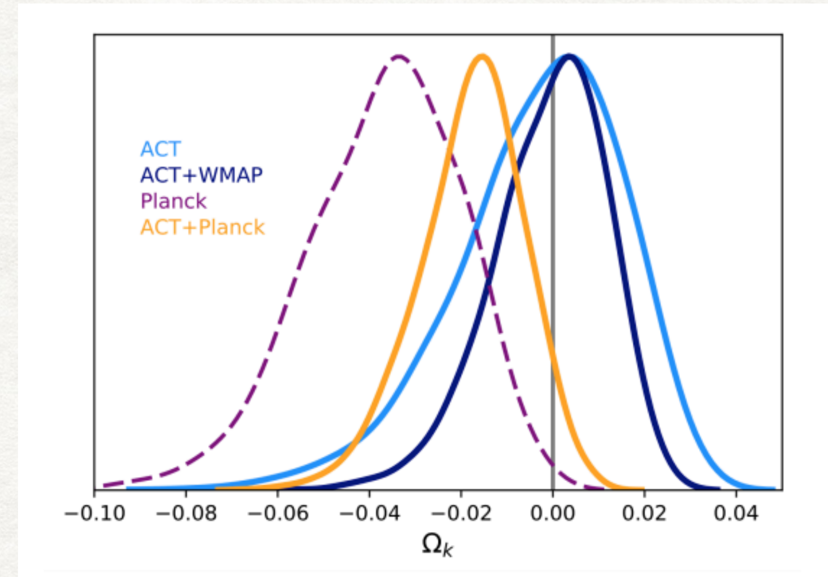
$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$

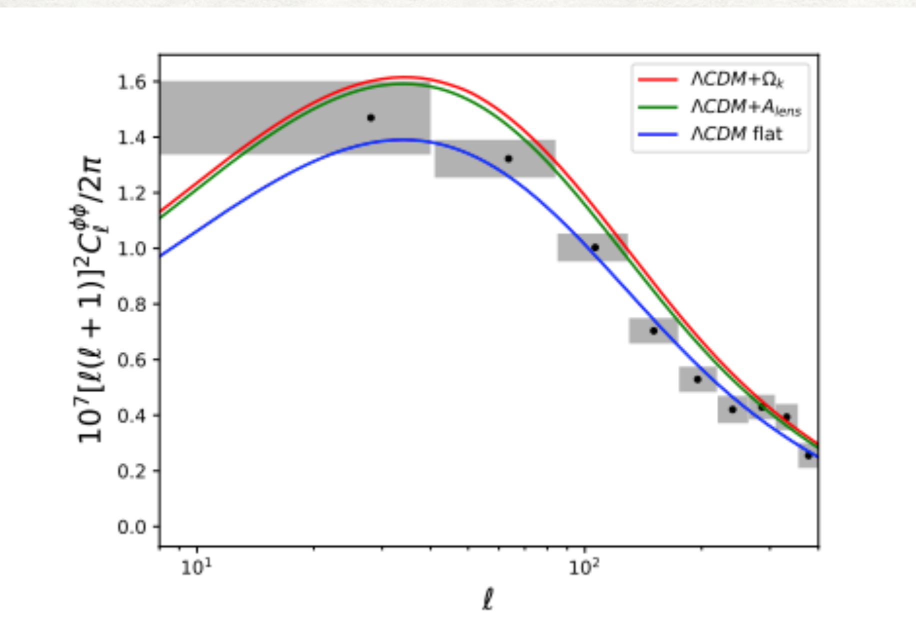
Unless specified, Figs. from Di Valentino++ 1911.02087

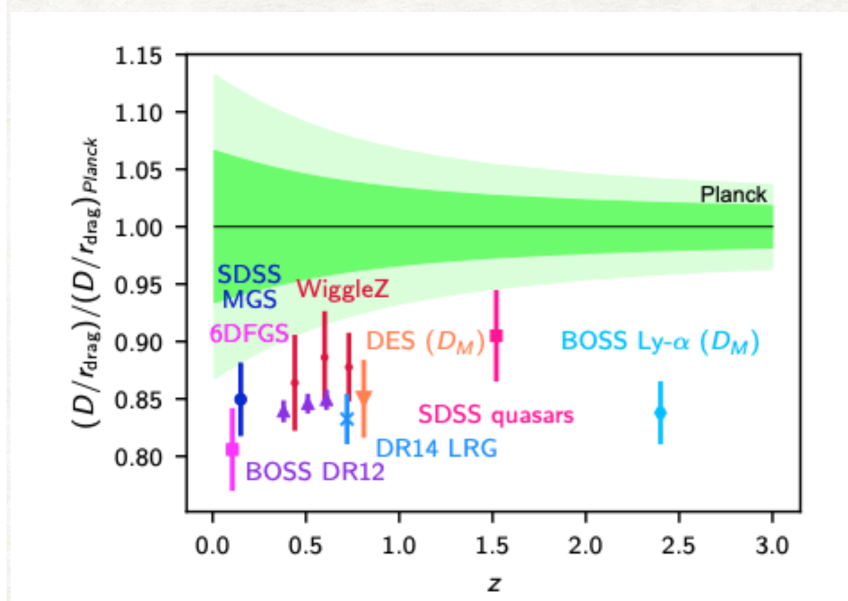


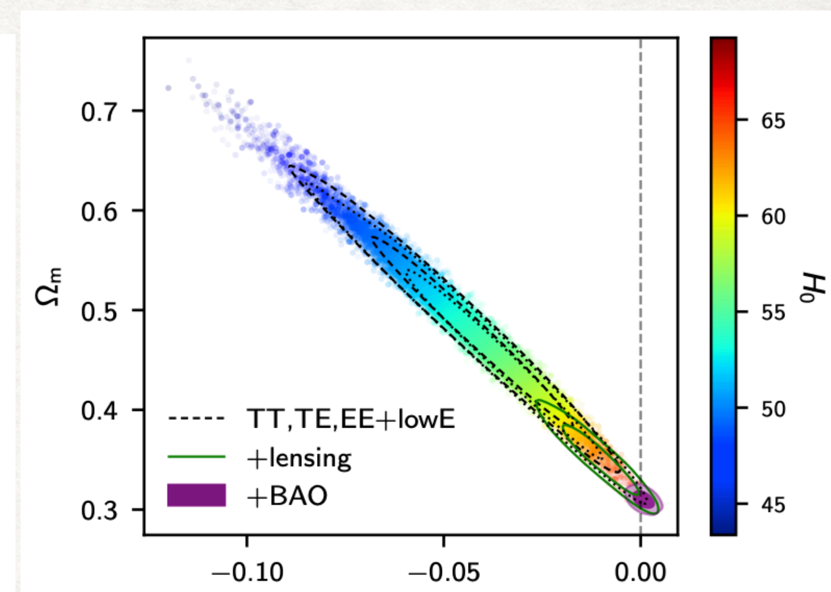
Planck 1807.06209











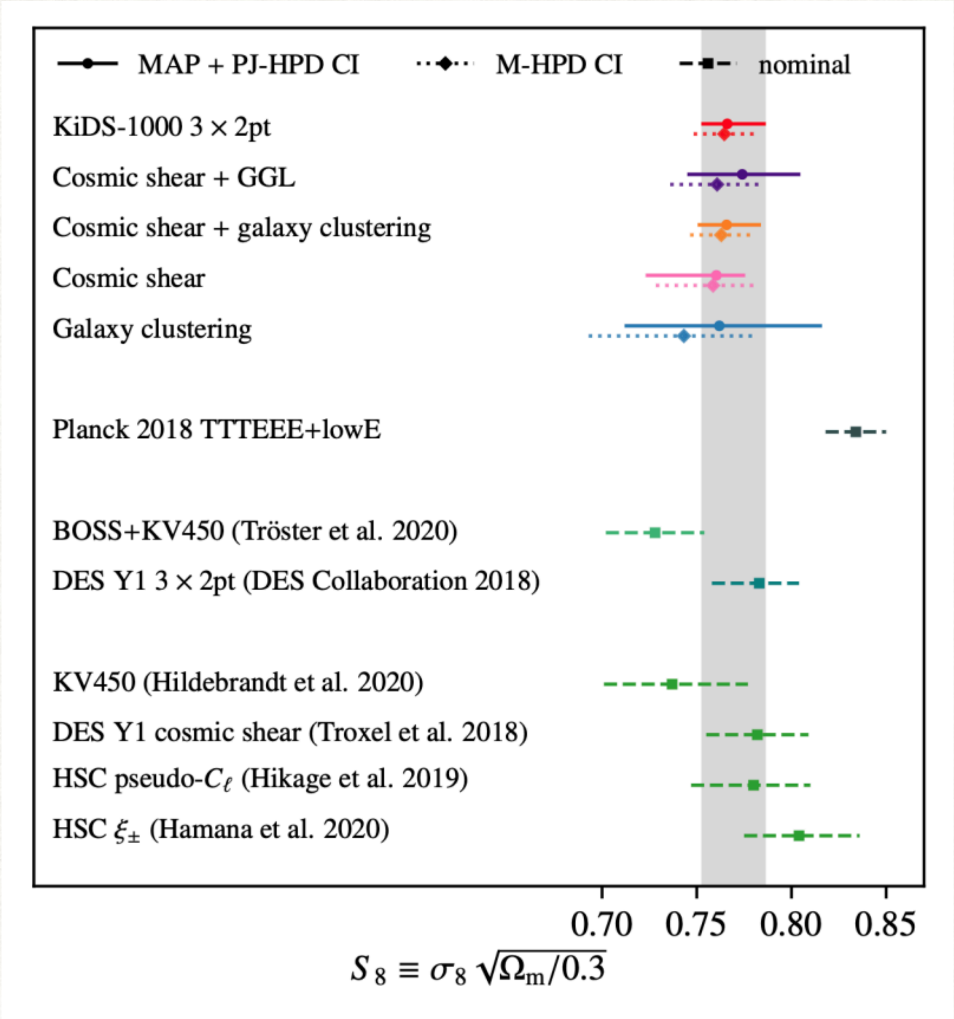
Planck 1807.06209

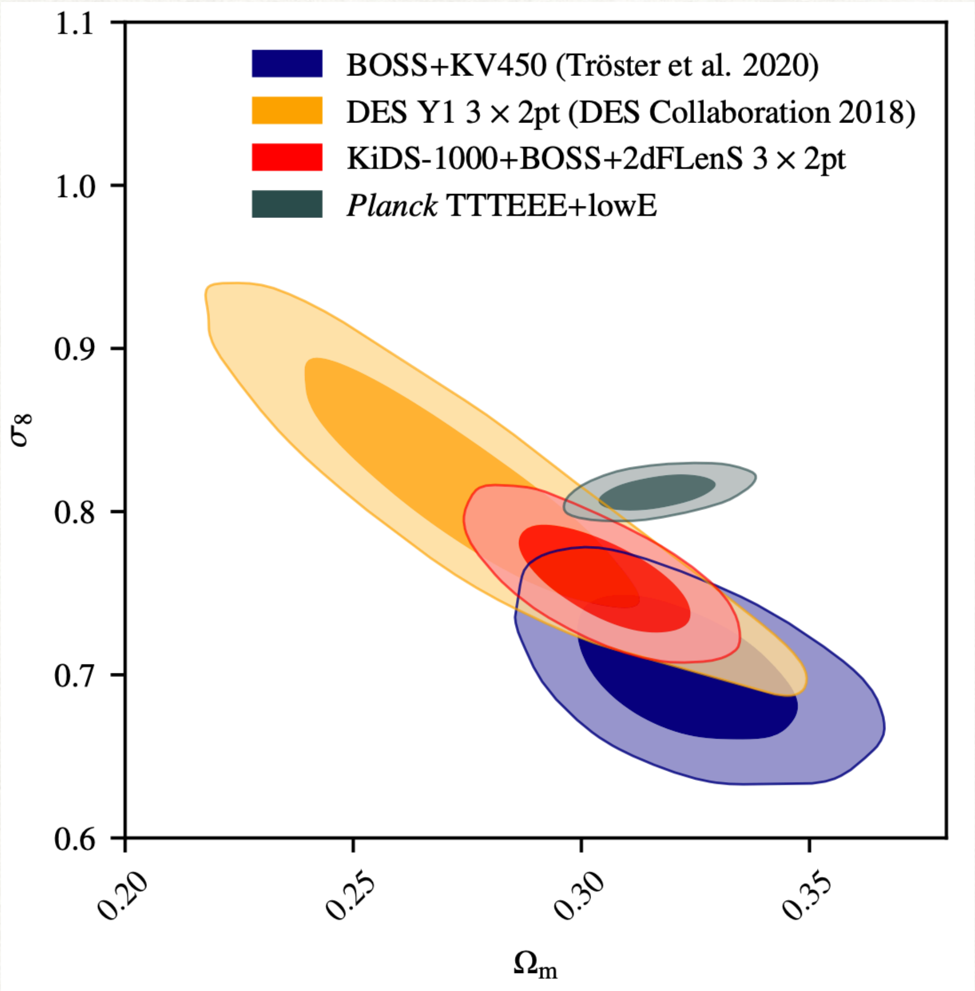
- The Universe is flat unless of a true ‘cosmological crisis’.
- Flat universe is also supported by BOSS and Cosmic Chronometers. *Vagnozzi++2010.02230, 2011.11645*
- Nb: A_L could also be explained in modified gravity framework, it suffers from the same issues.

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

The S_8 tension

Figs. from Heymans++ 2007.15632





- $\sim 2-3\sigma$ tension between CFHTLenS/HSC/KiDS/DES and *Planck*. (Potentially also Planck SZ).

  CFHTLenS MNRAS 2013, HSC PASJ 2019, DES PRD 2018, Salvati++ PoS 1901.05289

- BOSS alone also in $\sim 2\sigma$ tension. When combined with KiDS-1000, points to a $\sigma_8 \sim 3\sigma$ tension.

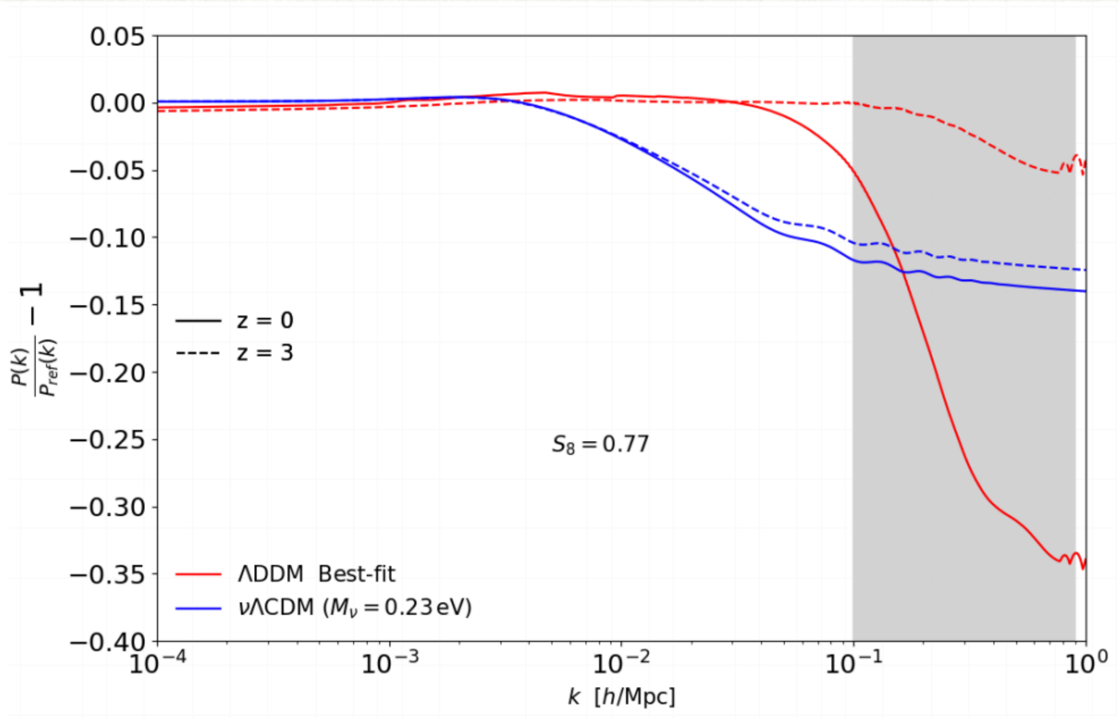
  Ivanov++ 1909.05277, d'Amico++ 1909.05271, Heymans++ 2007.15632

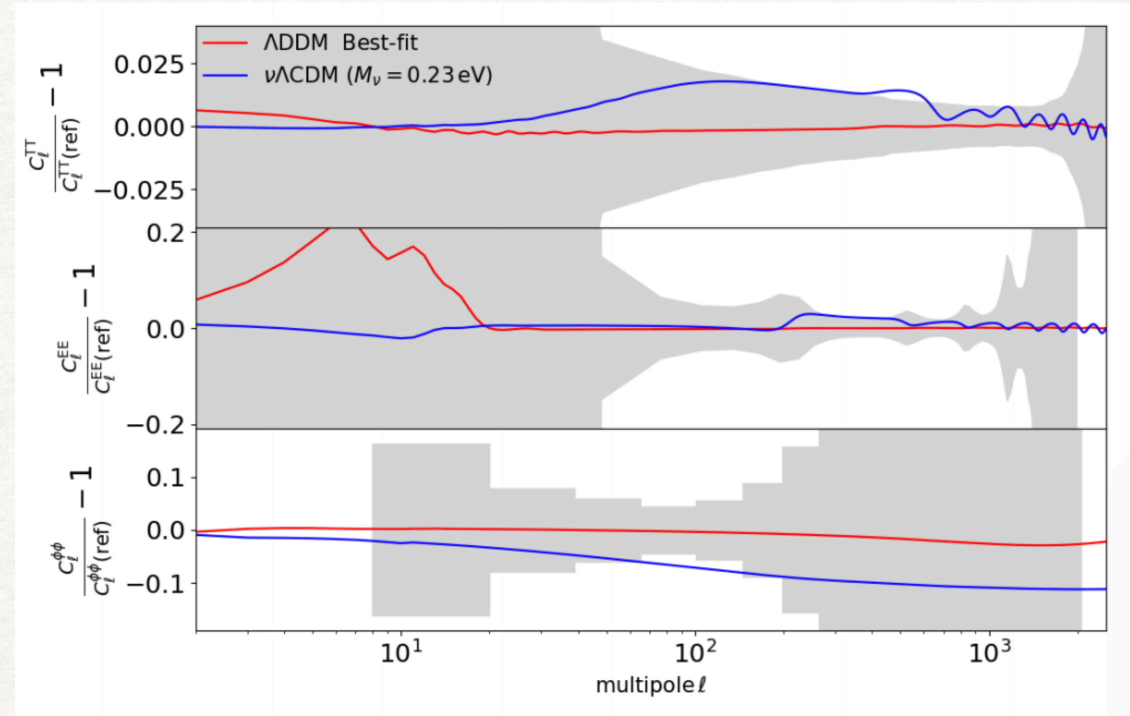
- To resolve the tension: reduce power at scales $k \sim 0.1-1$ h/Mpc. DM interactions or decays, fuzzy dark matter, hot dark matter.

  See `cosmology intertwined' white paper Di Valentino++ 2008.11285

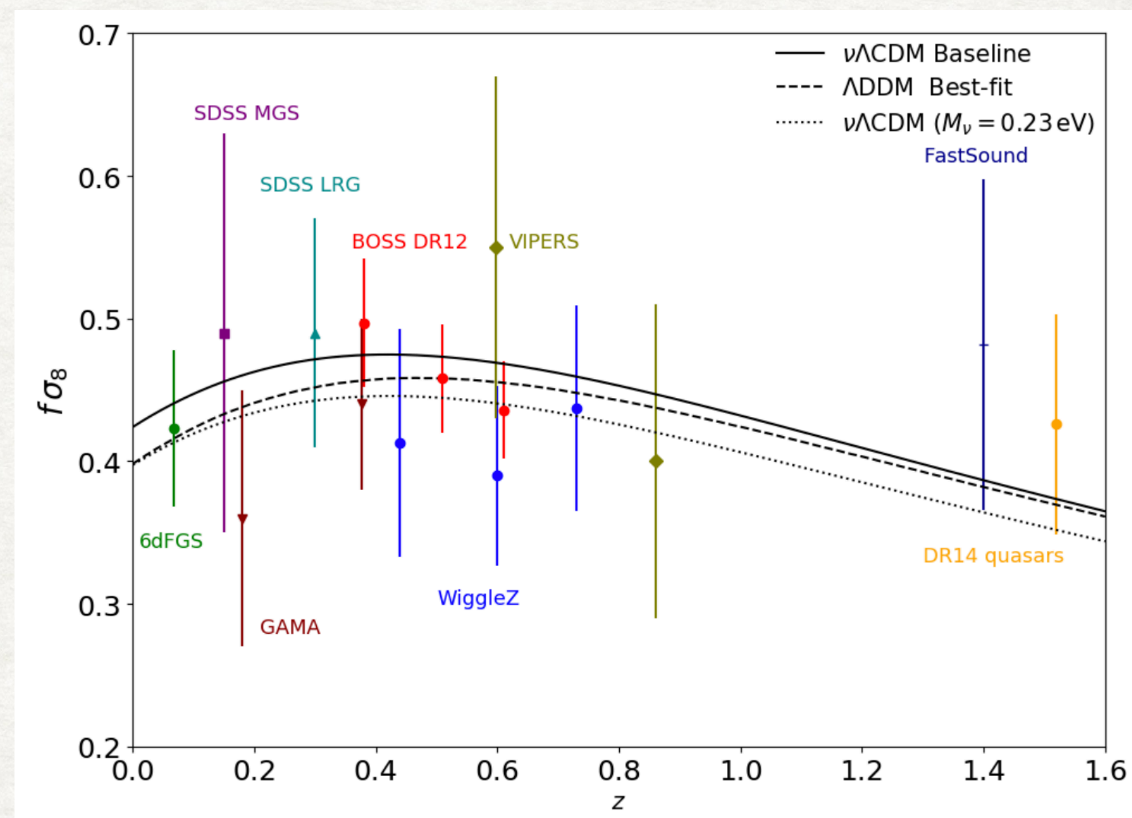
Decaying Dark Matter and the S_8 tension

Abellan, Murgia++ 2008.09615, 2104.03329 *See also Vattis++ 1903.06220*





- DM with $\Gamma^{-1} \simeq 55(\epsilon/0.007)^{1.4}$ Gyrs with $\epsilon \simeq v_{\rm wdm}/c$ can explain low S_8.
- The warm daughter induces a power suppression similar to hot DM or non-zero m_ν but different time evolution.
- Future LSS measurements (EUCLID, VRO/LSST, DESI) will test the scenario.
- (Fraction of) HDM disfavored *Das++ 2104.03329*
- (Fraction of) Fuzzy DM seems to work *Laguë++ 2104.07802*

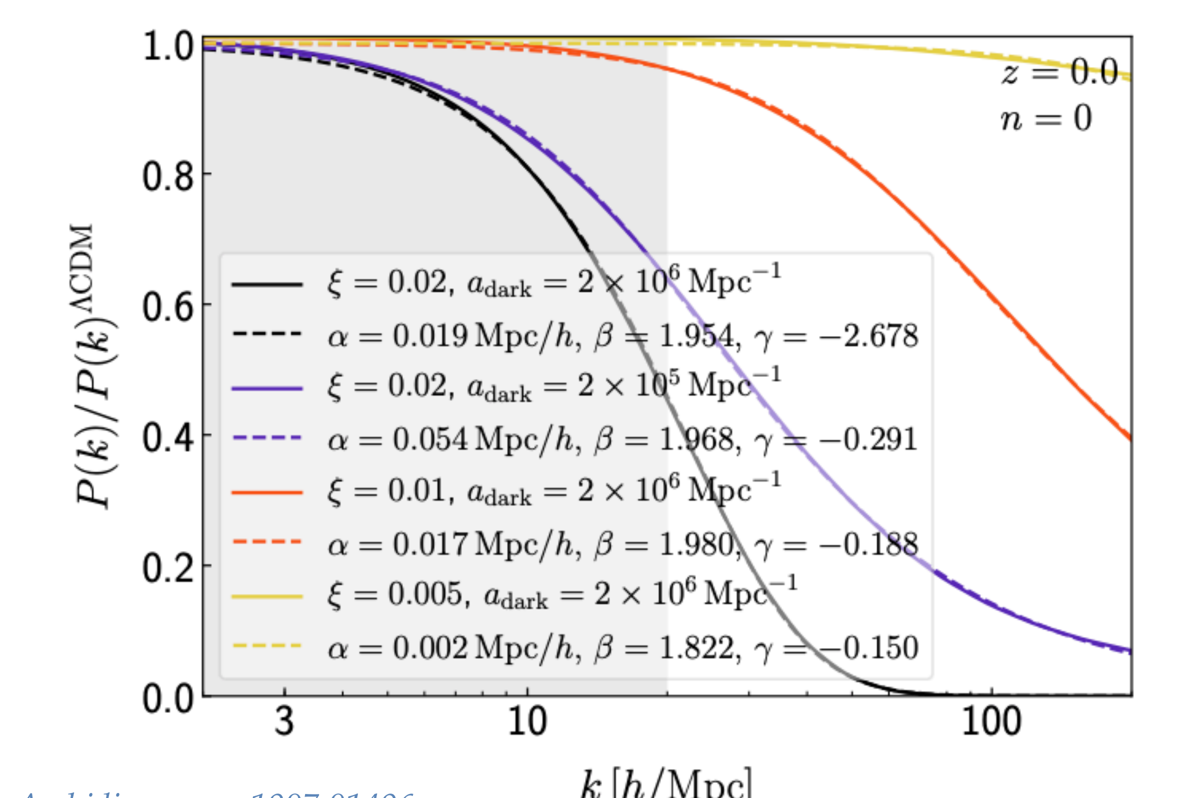


Interacting Dark Matter and the S8 tension

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

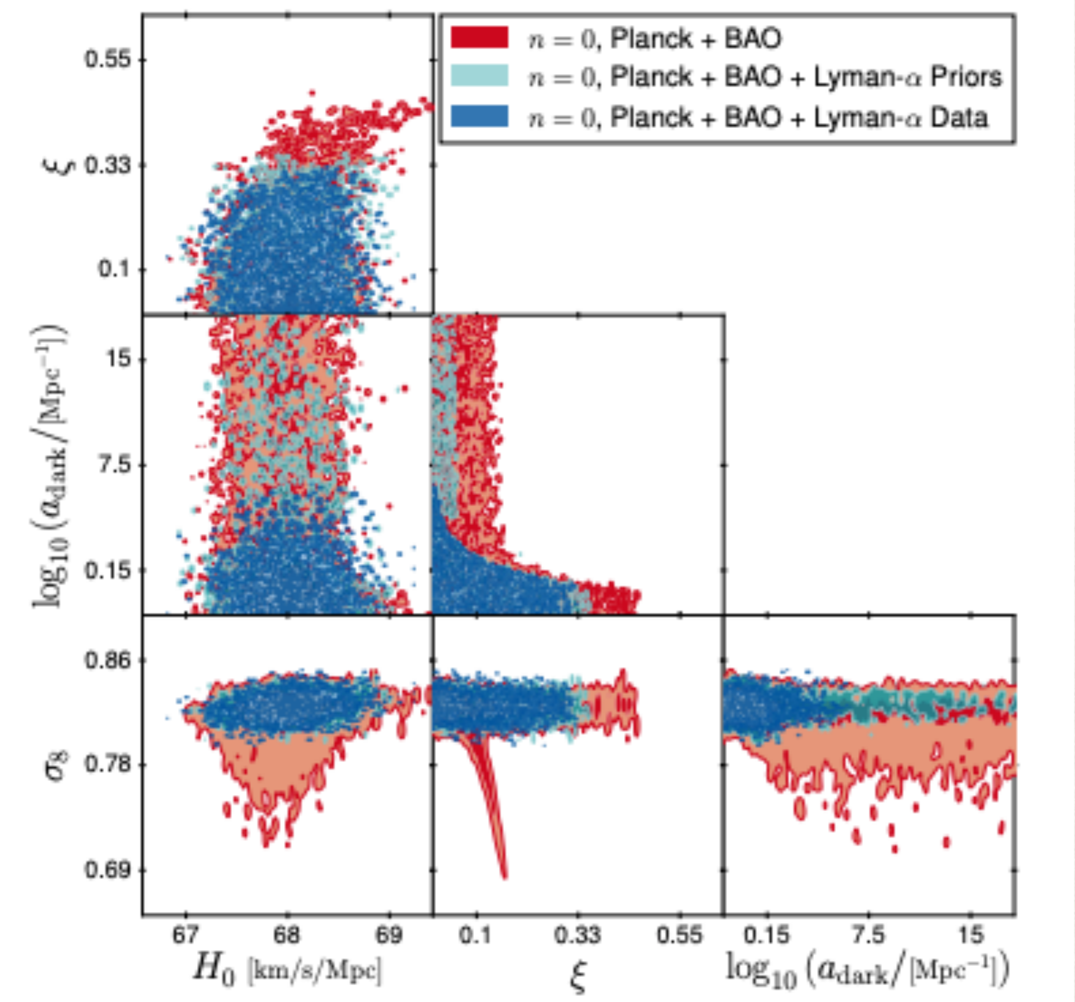
$$\Gamma_{\rm DR-DM} = -\Omega_{\rm DM} h^2 a_{\rm dark}\left(\frac{1+z}{1+z_d}\right)^n,$$

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



Archidiacono++ 1907.01496

Archidiacono++ 1907.01496

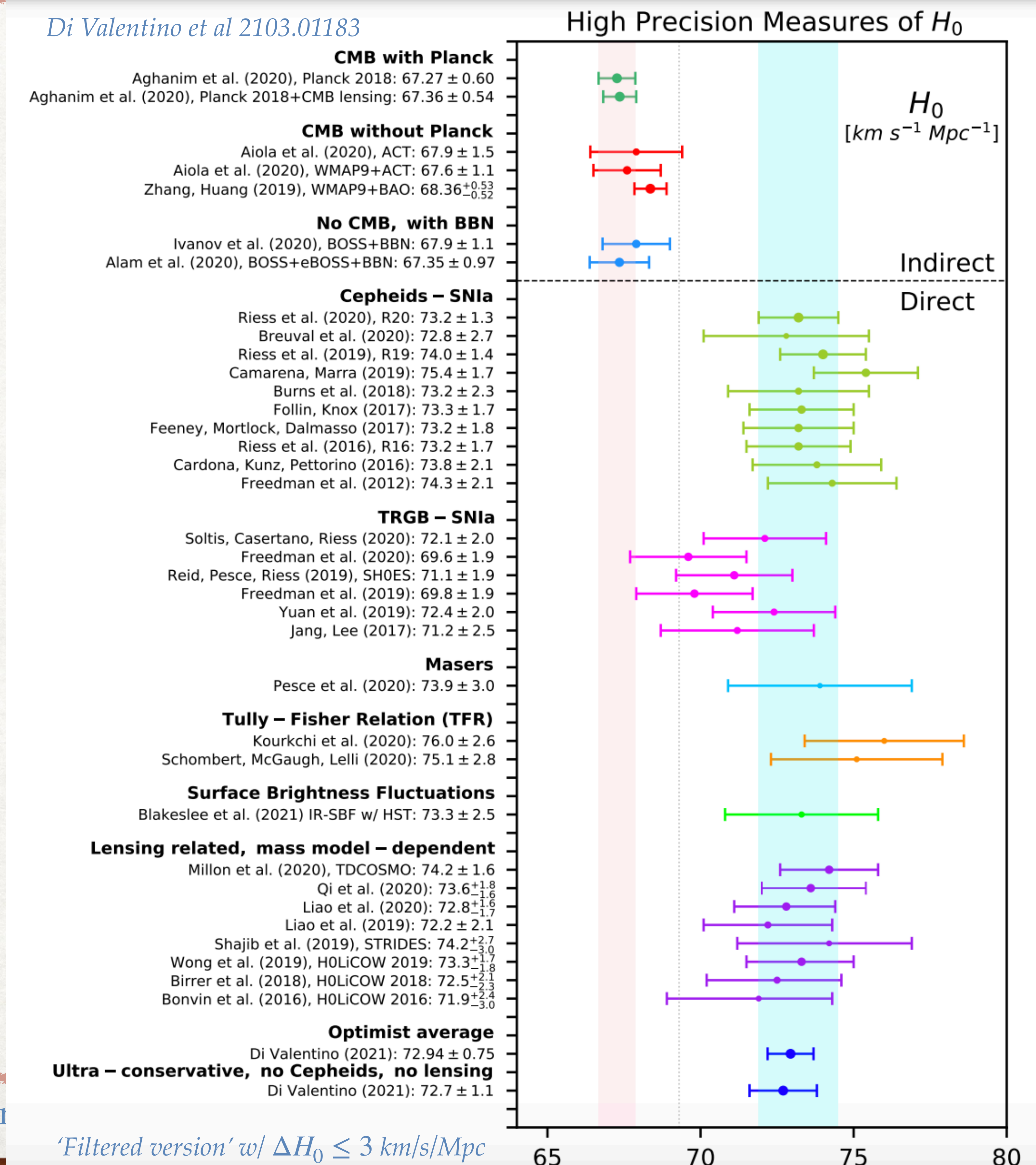


- Beware the Lyman-α!
- Non-Abelian dark matter model
  Buen-Abad++1505.03542, Lesgourgues++1507.04351
- Cannibal dark matter
  Heimersheim++ 2008.08486
- Works also with sub-component of strongly interacting DM
  Chacko++1609.03569, Buen-Abad++ 1708.09406, Raveri++ 1709.04877

The Hubble tension

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?



Systematics? A non-exhaustive list

See review Di Valentino++ 2103.01183 for all relevant references

- A single systematic is not enough: several independent measurements point to a high(-ish) H_0

- Systematic in SN1a?:
  - Are SN1a correctly calibrated? multi-step process!
    - Test several calibration methods (e.g. Cepheids vs TRGB vs Miras).
    - Is their dust in the TRGB / Cepheid calibration?
    - Is there a bias in the peculiar velocity correction?
    - Is there a metallicity correction?
    - Is GAIA parallax correct?

  Follin&Knox 1707.01175, Feeney++ 1707.00007, Freedman++ 1907.05922, Freedmann++2002.01550, Yuan++1908.00993, Efstathiou++ 2007.10716, Soltis++2012.09196

  - Are there different populations of SN1a between "local" and "Hubble flow" SN1a?

  Rigault++ 1412.6501, Jones++1805.05911, Brout&Scolnic 2004.10206

  - Do we live in a void? We would need a "5σ" void with $\delta \simeq -0.8$ within 150Mpc. No evidence from SN1a at z <~2.

  Wu&Huterer 1706.09723, D'Arcy Kenworthy++ 1901.08681, Cai++ 2012.08292

- Systematic in strongly-lensed quasars?
  - Are Lens profiles correctly modeled? The "H0LiCOW" result could be explained by a cored density profile. TDCosmo: favored by kinematic data.

  Blum et al. 2001.07182, Birrer++ 2007.02941

- Is the cosmological principle wrong? What is the importance of back-reaction?

  Colin++1808.04597, Heinesen&Buchert 2002.10831, Secrest++ 2009.14826

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.

How does CMB data measure H_0?

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

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

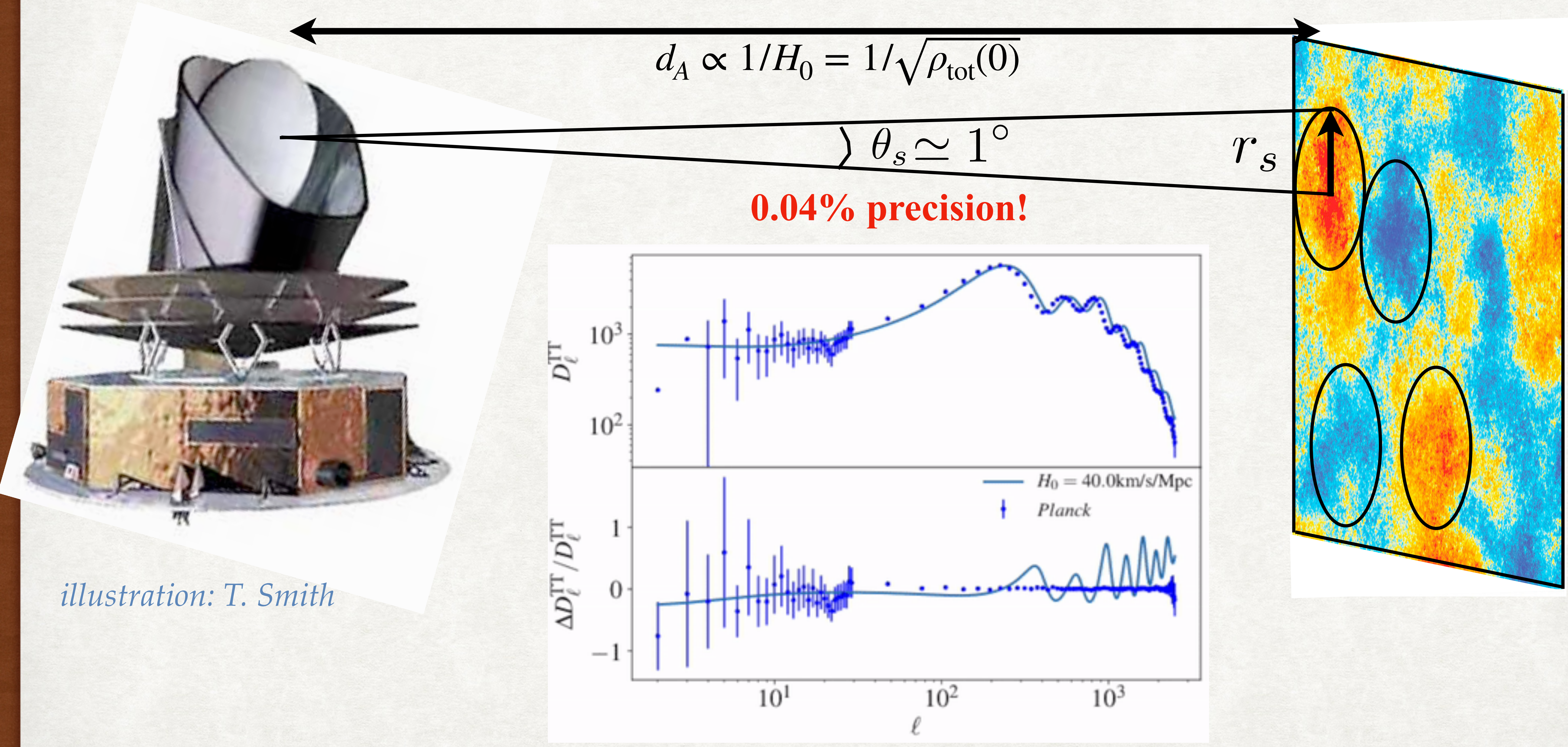


illustration: T. Smith

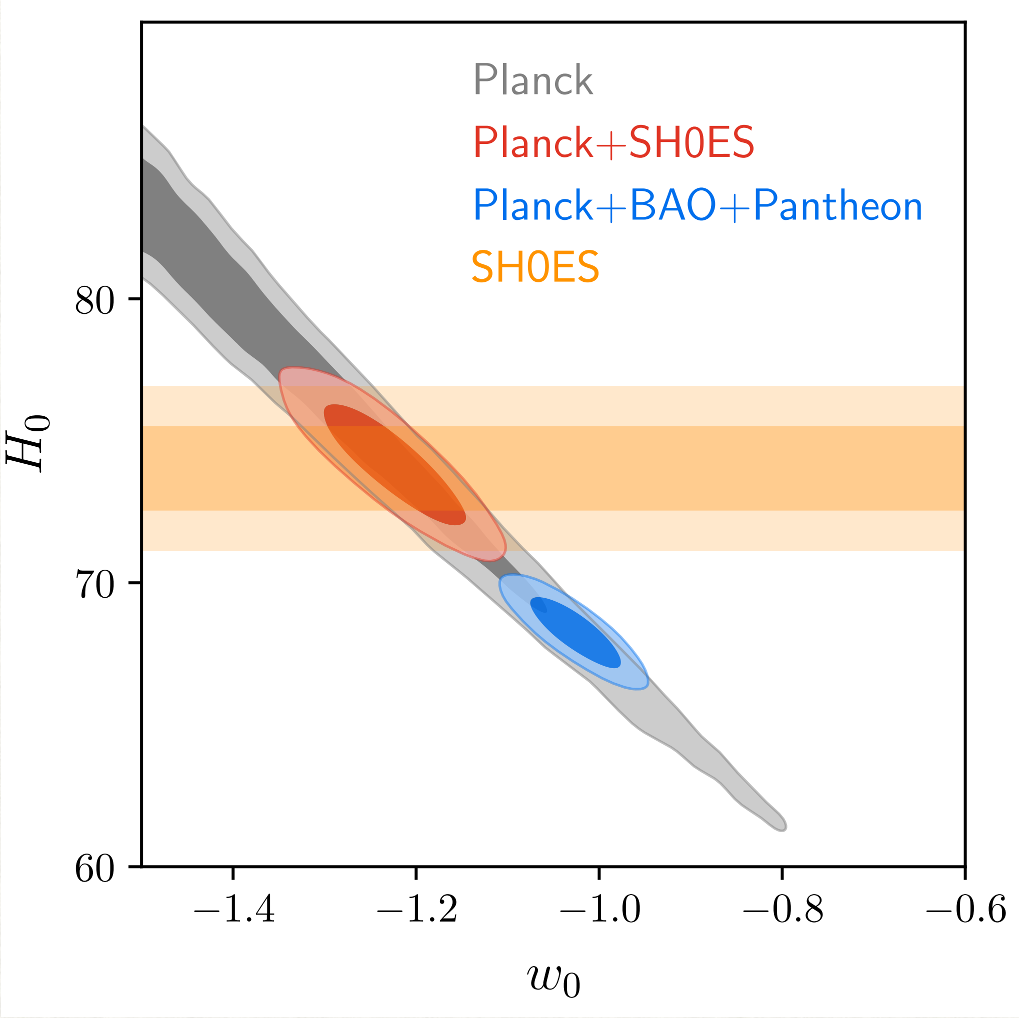
Geometrical degeneracy in Planck!

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

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

- 'phantom dark energy' w < -1, DE phase transition, DE-DM interaction, decaying/annihilating DM, and many more…
  [http://arxiv/insert_your_favorite_ model_here.com]

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

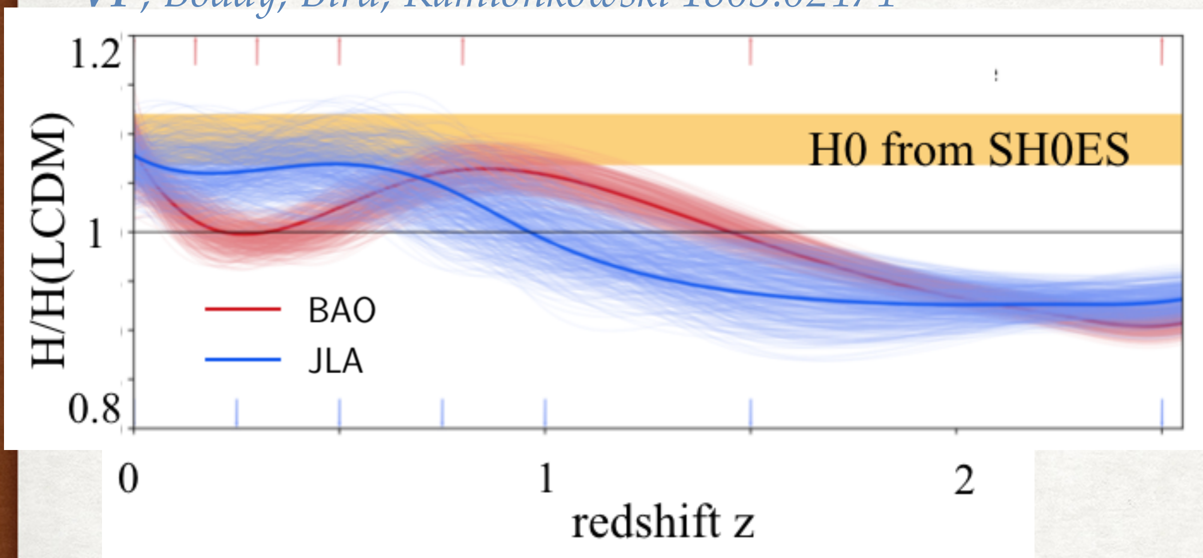


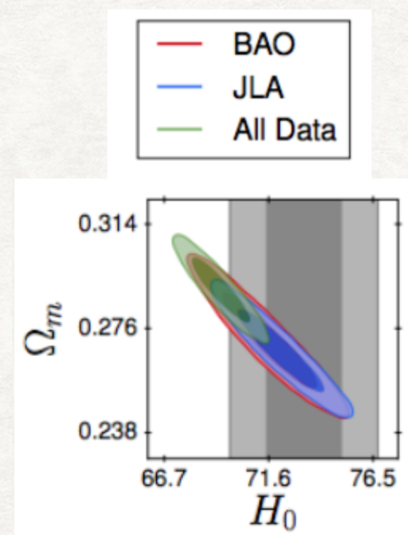
BAO and SN1a constrain late-time resolution

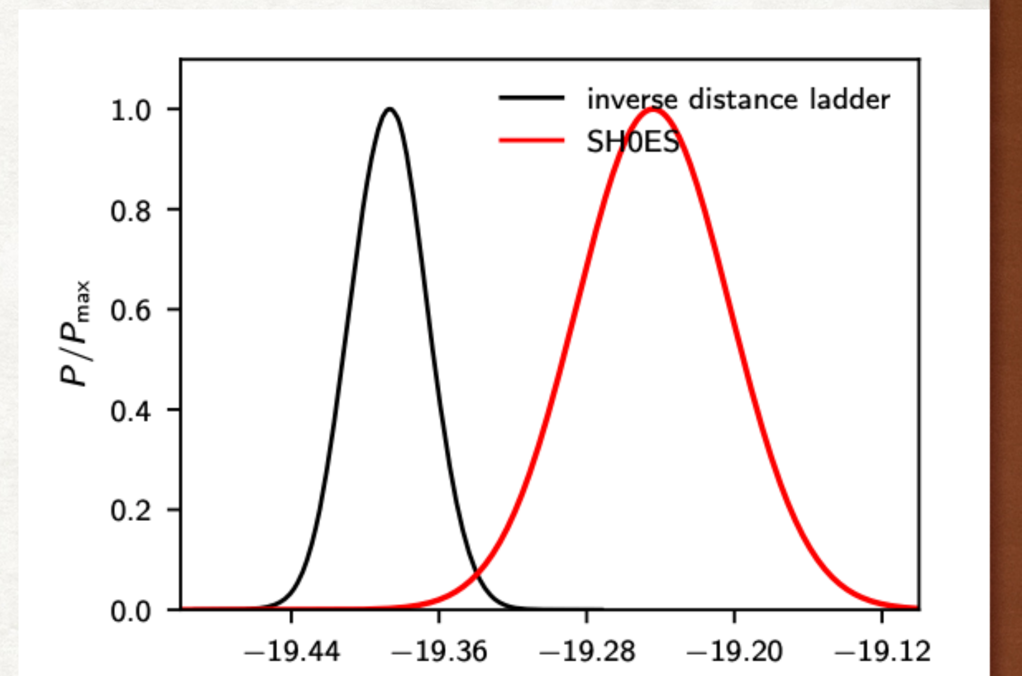
$$d_A(z_*) = \frac{1}{1+z_*}\int_0^{z_*}\frac{dz}{100\sqrt{\omega_{\rm M}(1+z)^3+\Omega_{\rm DE}(z)h^2}}$$

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

VP, Boddy, Bird, Kamionkowski 1803.02474







Efstathiou 2103.08723

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

- $r_s(z_{\rm drag})$ 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!

- The true tension is with the intrinsic SN1a magnitude!

Beenakker++2101.01372, Efstathiou 2103.08723

Late-universe solutions to H_0 are ruled out

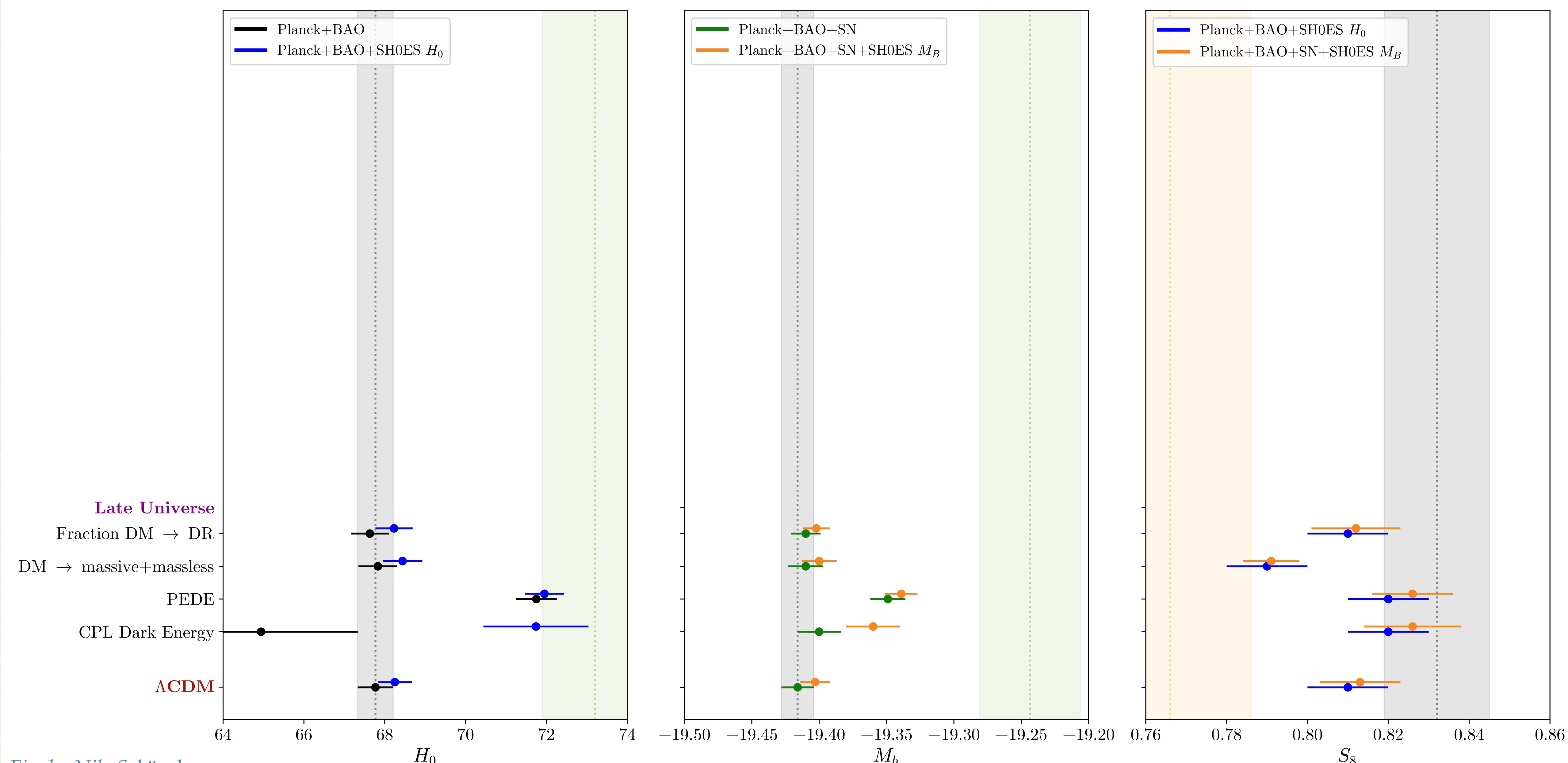


Fig. by Nils Schöneberg *Schöneberg, Abellán, Lesgourgues, Pérez-Sánchez, VP, Witte (to appear)*

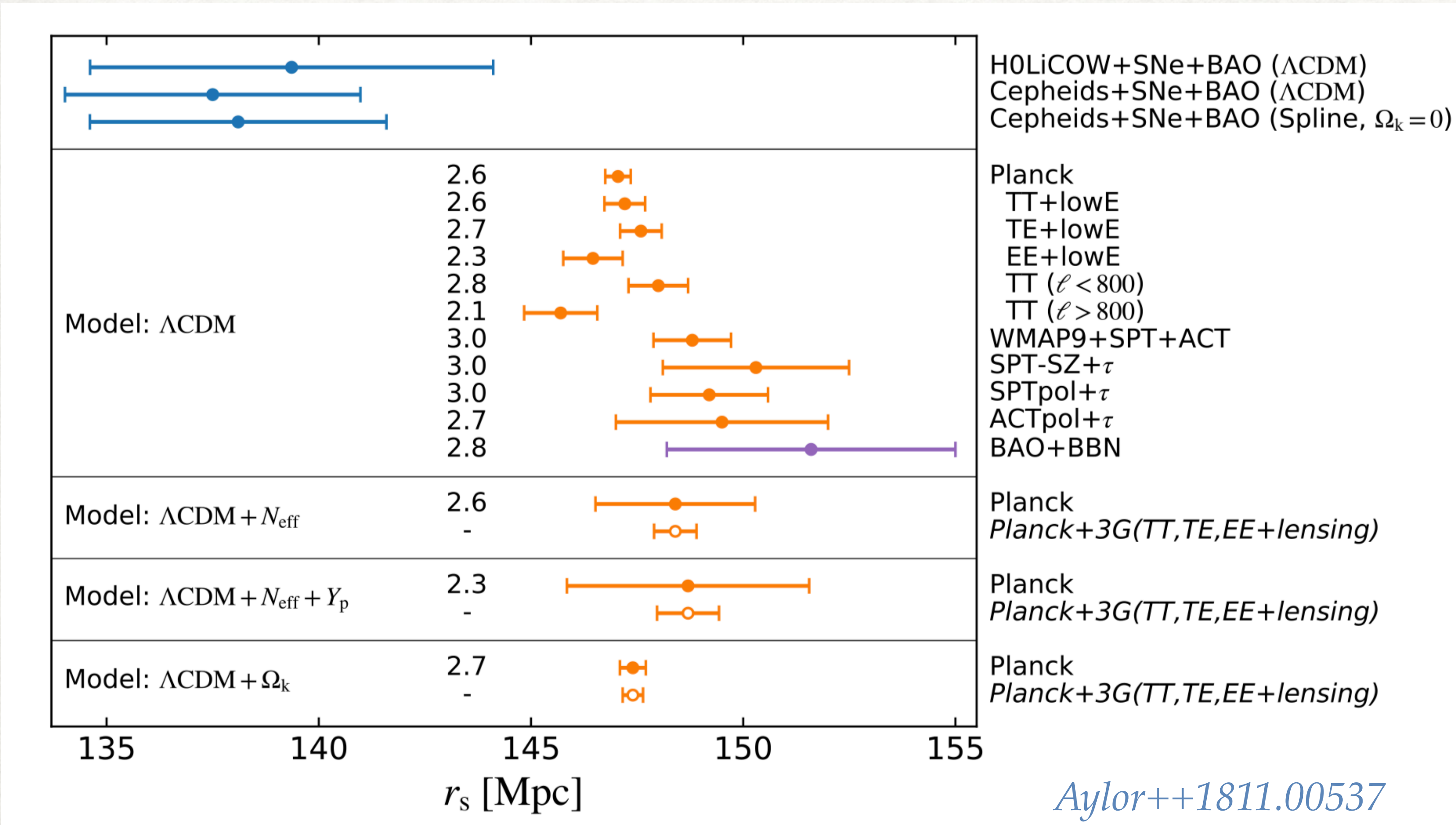
- While some solutions seem to resolve the 'H_0-tension', they introduce a 'M_b-tension'.
- The question is: can one make the inverse ladder calibration of Pantheon SN1a compatible with SH0ES measurement?

Beenakker++2101.01372, Efstathiou 2103.08723

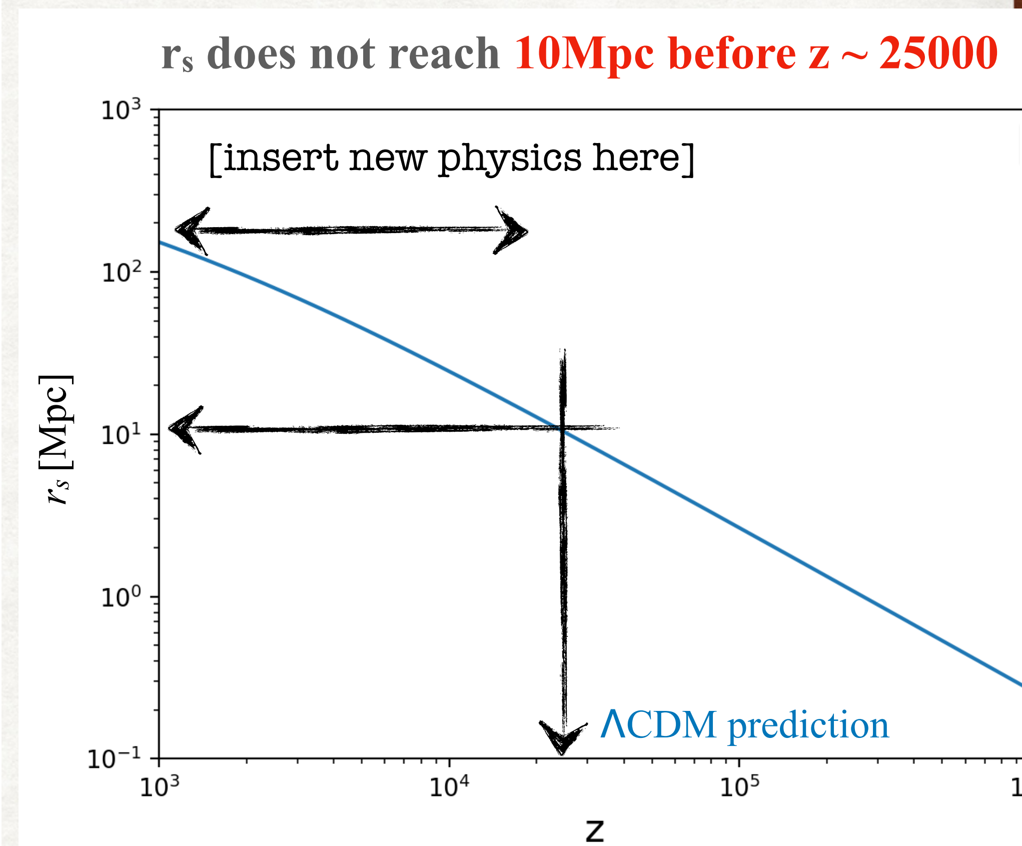
H_0 tension or r_s tension?

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

r_s from CMB needs to decrease by ~ 10 Mpc



Aylor++1811.00537



affect z*: modified recombination physics?

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

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

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

increase $\rho(z)$: Neff? Early Dark Energy? Modified Gravity?

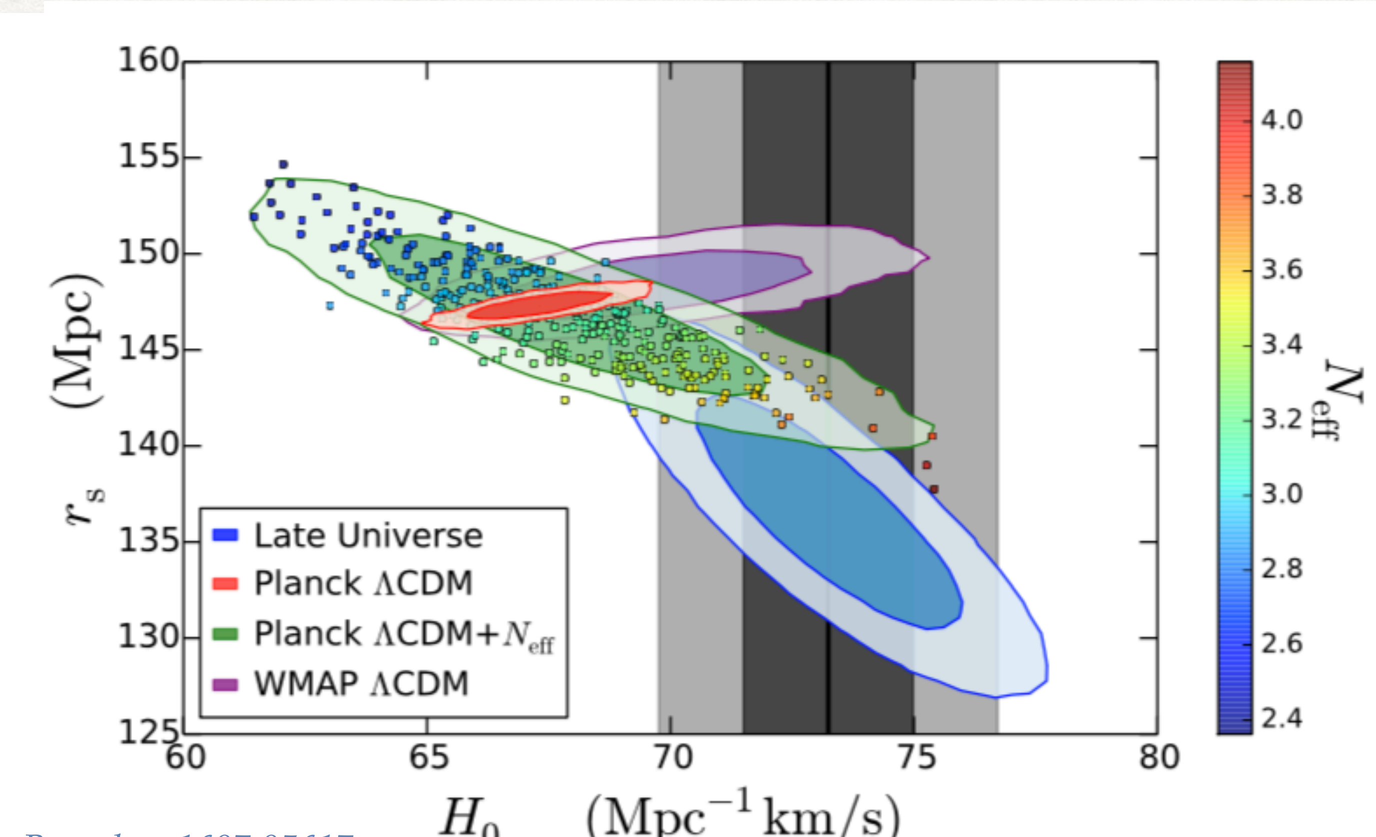
Early-time resolution to the H_0 tension

- Additional relativistic degrees of freedom can be parametrized by $N_{\rm eff}$ at the background level

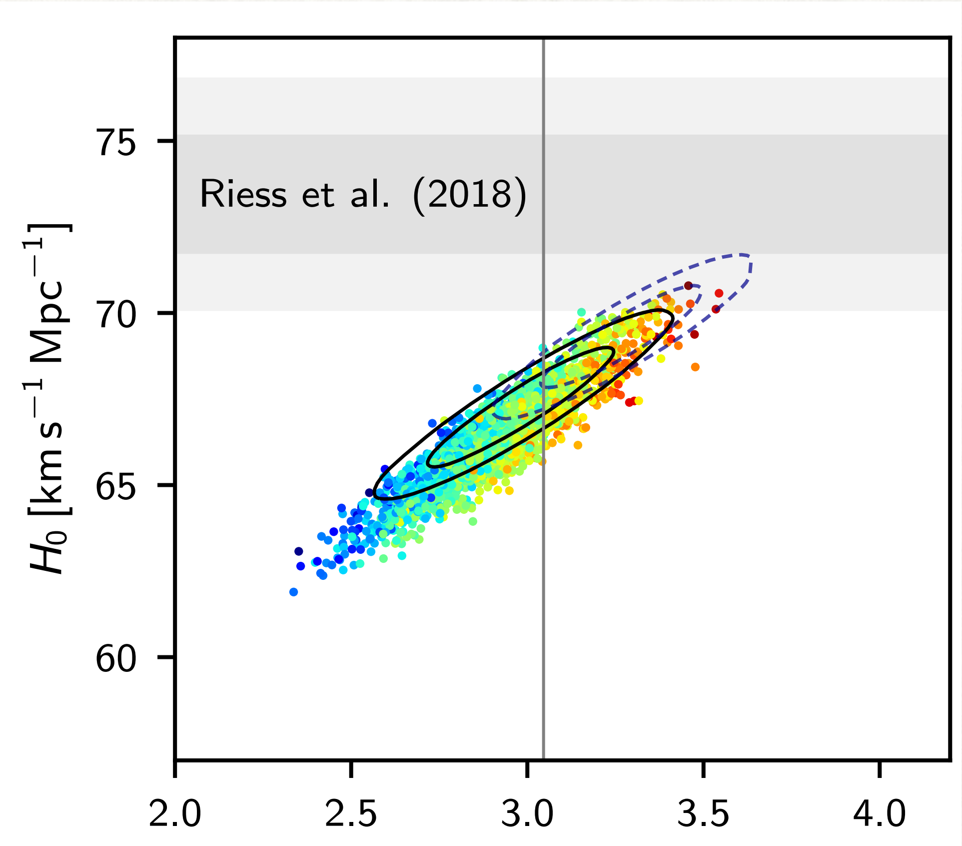
$$\rho_R = \rho_\gamma\left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

- Standard Model neutrinos behave as *free-streaming radiation* since T~1MeV with $N_{\rm eff} = 3.046$

- $\Delta N_{\rm eff}$ (free streaming) ~0.5-1 is needed : disfavored by *Planck* high-l polarization and BAO

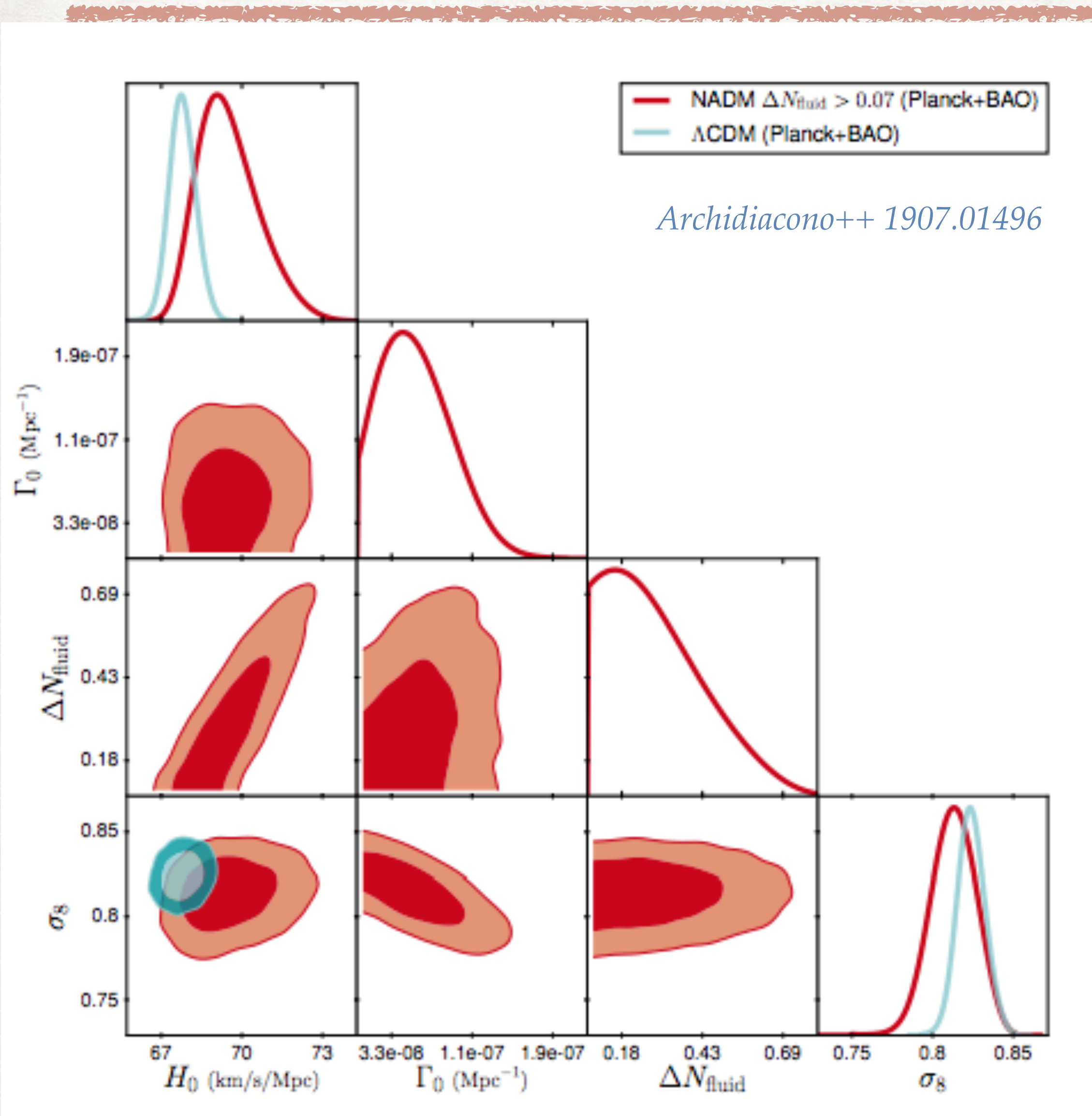


Bernal++ 1607.05617



Aghanim++ 1807.06209

DM-DR interactions could resolve both tensions



parameter	ΛCDM	$\Gamma_0 > 0,\ \Delta N_{\rm fluid} > 0.07$
Γ_0 / [Mpc^{-1}]	–	$< 1.2 \cdot 10^{-7}$
$\Delta N_{\rm fluid}$	–	< 0.59
H_0 / [km/(s Mpc)]	$67.94^{+0.46}_{-0.49}$	$69.55^{+0.84}_{-1.3}$
σ_8	$0.8234^{+0.0085}_{-0.0090}$	$0.813^{+0.015}_{-0.012}$
$\Delta\chi^2$	–	1.90

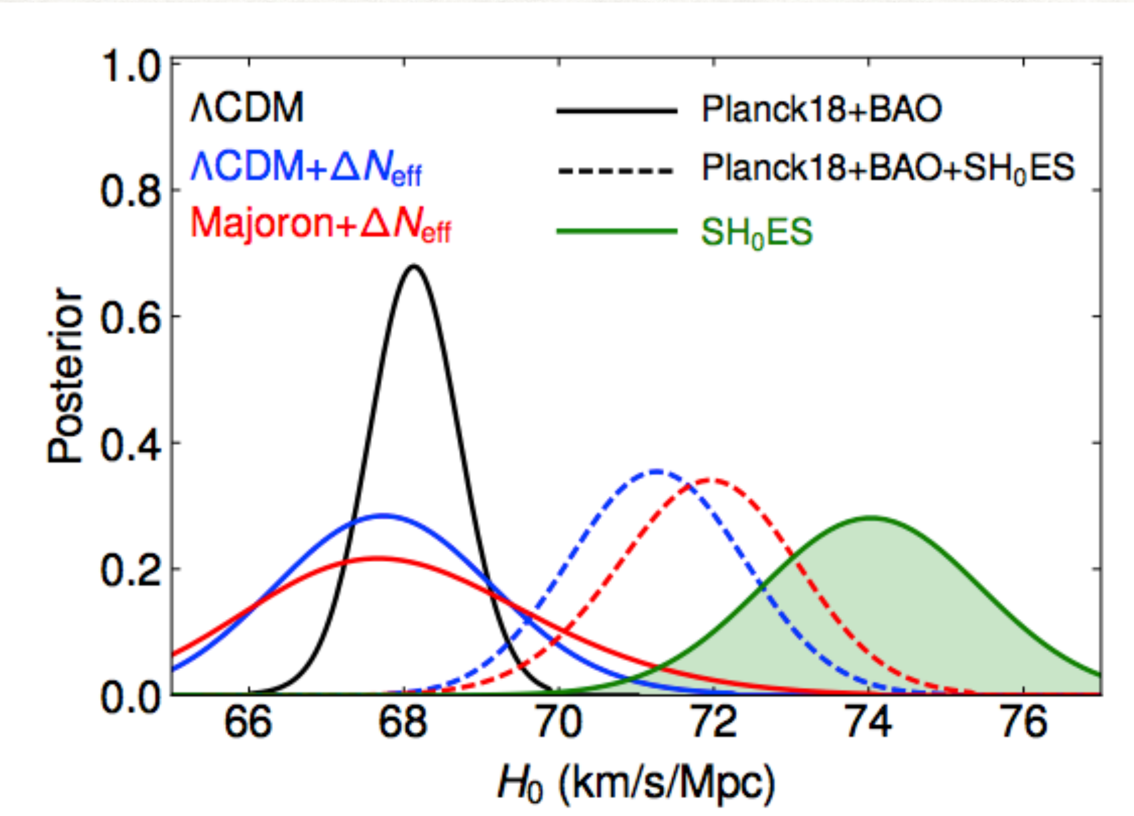
- Replace free-streaming $\Delta N_{\rm eff}$ by an interacting $\Delta N_{\rm fluid}$.
- Example: 'Non-abelian dark matter' with theoretical prior $\Delta N_{\rm fluid} > 0.07$.

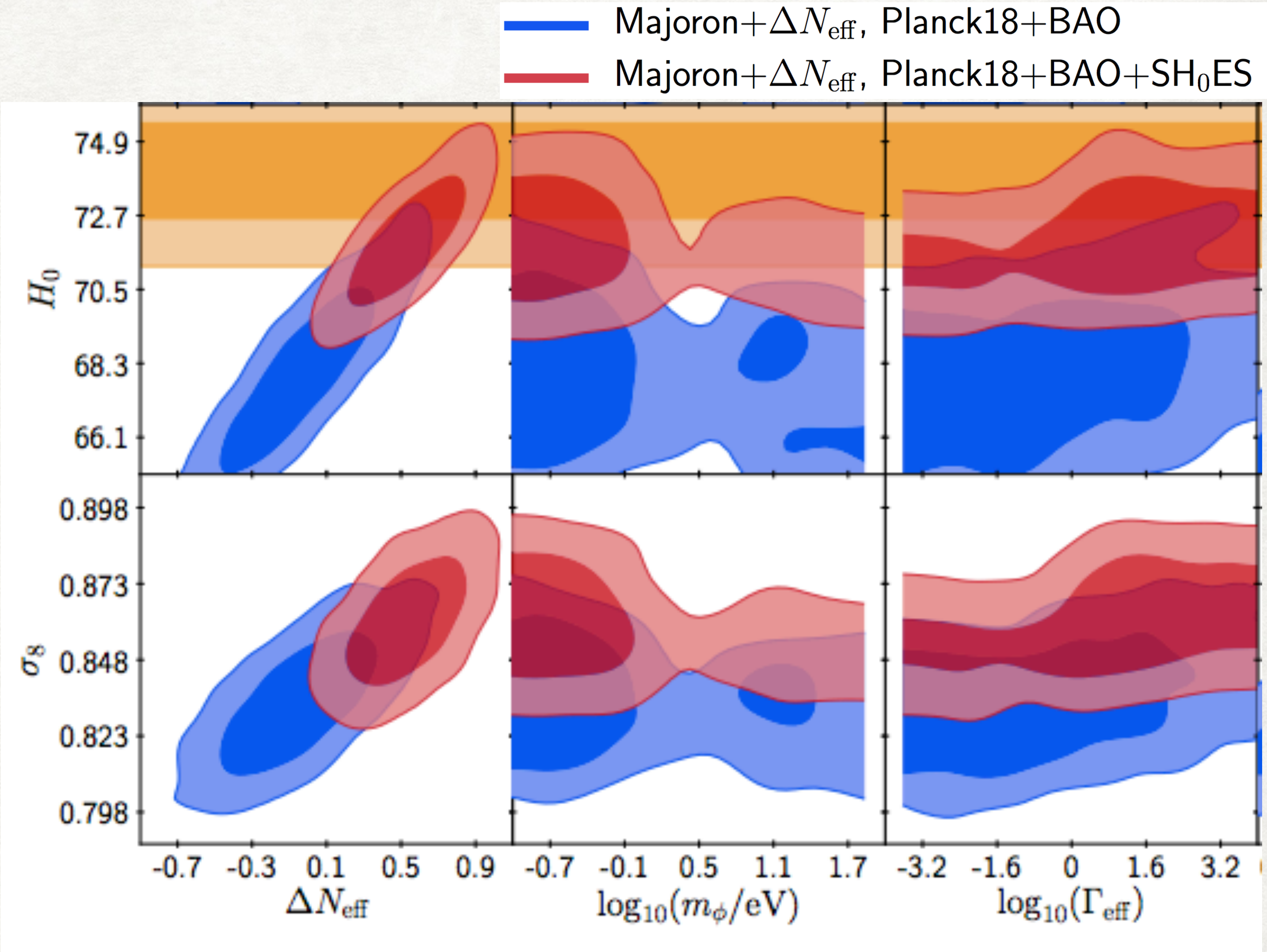
  Buen-Abad++1505.03542, *Lesgourgues++1507.04351*
- Resolves the S_8 tension but *Planck* polarization excludes the range of $\Delta N_{\rm fluid}$ necessary to resolve H_0 tension.

  see also Buen-Abad++ 1708.09406, Raveri++ 1709.04877, Blinov++ 2004.06114

Interacting neutrinos could resolve H_0 tension

Escudero&Witte 1909.04044, 2103.03249





- Interaction with a majoron decreases the neutrino-induced phase-shift.
- Non-zero $N_{\rm eff}$ from majoron production in the early universe.
- Well-motivated model explaining neutrino masses through type-1 seesaw, potentially connected to leptogenesis as well.
- neglect neutrino masses: could the inclusion of M_ν help for the S_8 tension?

$$\theta_{\rm peak} = \theta_s + \delta\theta \sim 0.6\left(\frac{\rho_\nu}{\rho_g}\right)$$

Bashinsky&Seljak, astro-ph/0310198

See also Archidiacono++ 2006.12885, Kreisch++ 1902.00534

Extra relativistic species: 2021 update

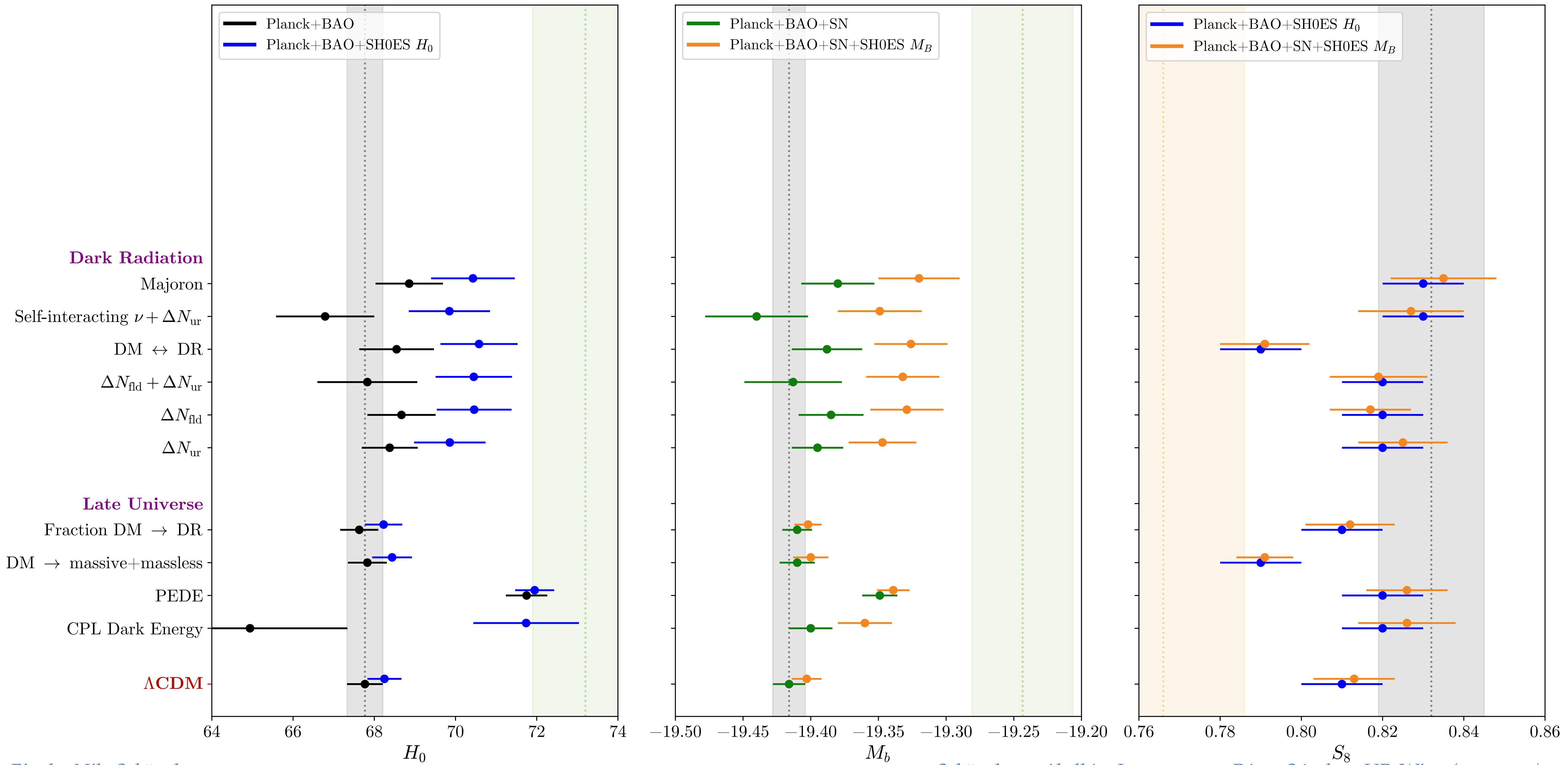
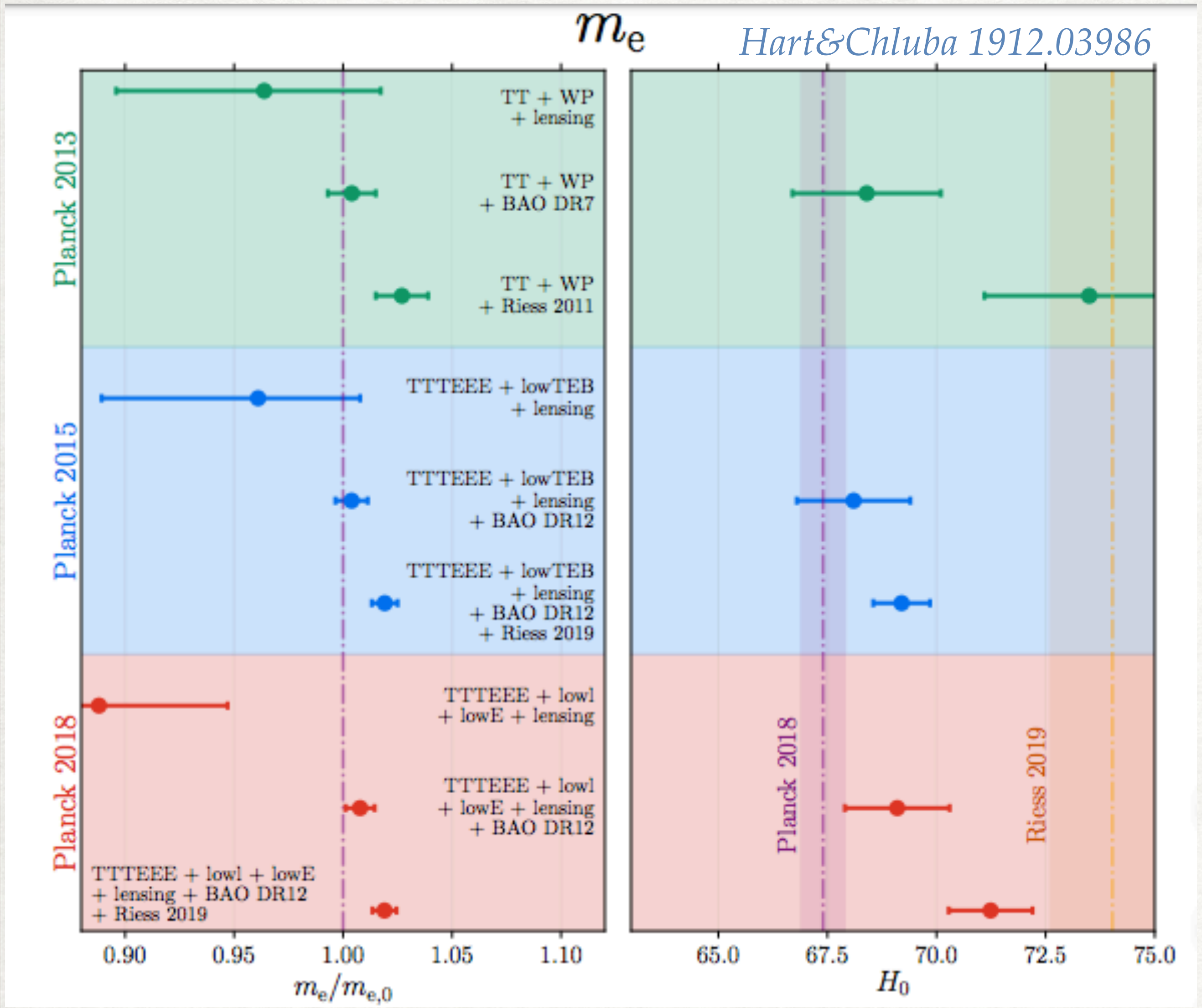


Fig. by Nils Schöneberg

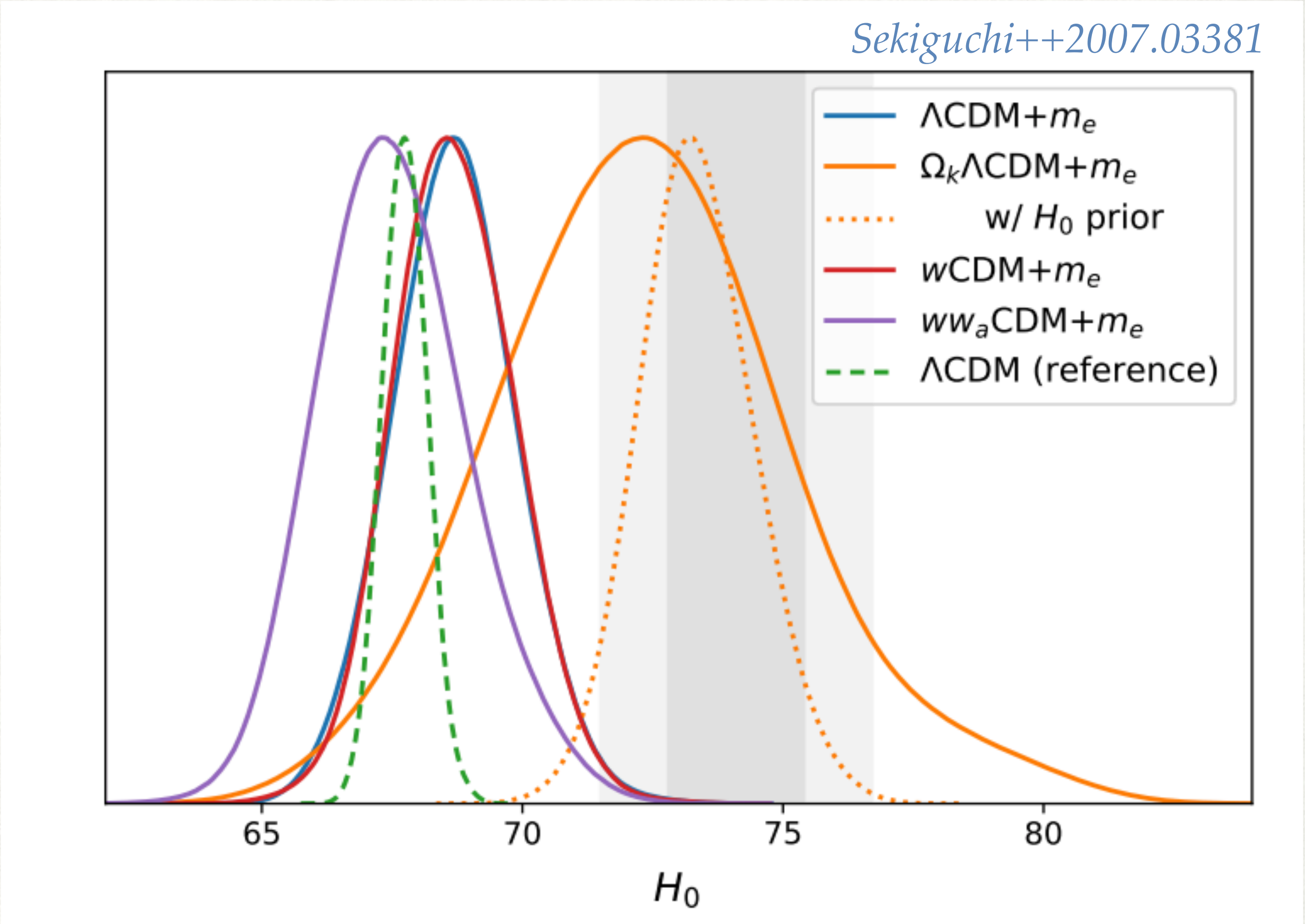
Schöneberg, Abellán, Lesgourgues, Pérez-Sánchez, VP, Witte (to appear)

- DM-DR interactions and ‘strongly interacting’ ν-cosmology are disfavored by Planck polarization data.
- The ‘majoron’ model performs better (especially in terms of $\Delta\chi^2$)
- These models are promising to provide us with a common resolution to both H_0 and S_8 tensions

A higher m_e could resolve the H_0 tension



- Goal: accelerate recombination



- A single-parameter extension that reduces the tension to the 2.6σ level.
- The model m_e+ Ω_k particularly interesting: What is the impact of *Planck* “curiosities” on the proposed resolutions?
- To be confirmed against M_b value.
- Primordial magnetic fields: could resolve H0 & S8 — *Jedamzik&Pogosian 2004.09487*
- Accelerate recombination through a different $A_{2s->1s}$ transition rate. — *Liu++ 1912.00190*

Exotic recombination: 2021 update

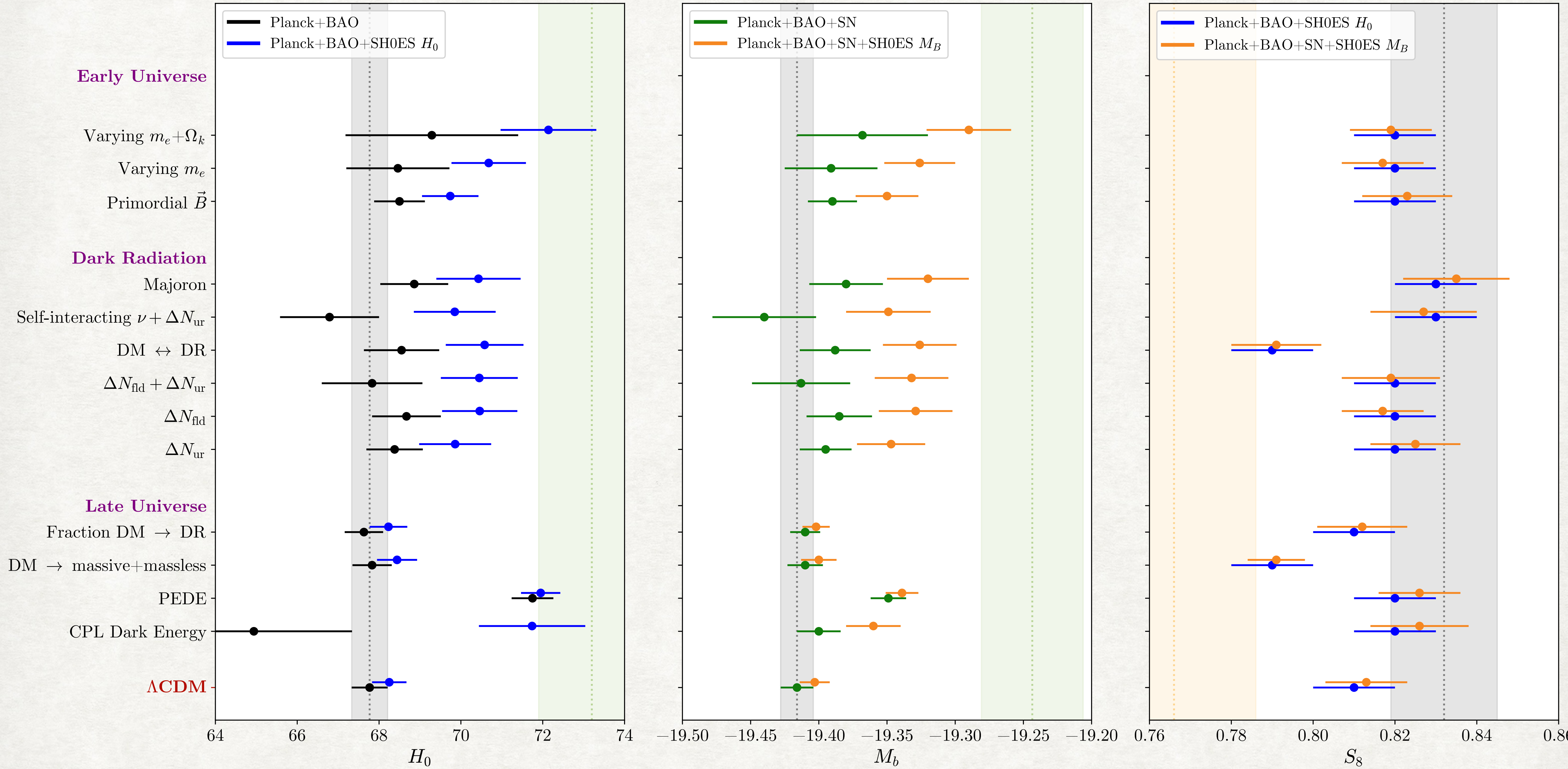


Fig. by Nils Schöneberg

Schöneberg, Abellán, Lesgourgues, Pérez-Sánchez, VP, Witte (to appear)

- Interplay between exotic recombination and other ΛCDM extension is promising (e.g. Ω_k, $N_{\rm eff}$)
- Connection to S_8 tension?

Early Dark Energy(s) & Modified Gravity

Not all have the same level of success…

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

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

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]

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

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)

Scalar field and Early Dark Energy

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

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

- Oscillating (toy) potential:

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

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

- 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.

- Phase transition in the EDE sector

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

- EDE-m_ν coupling in MG framework

Sakstein&Trodden 1911.11760 Carrillo González++ 2011.09895

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

Braglia++ 2011.12934

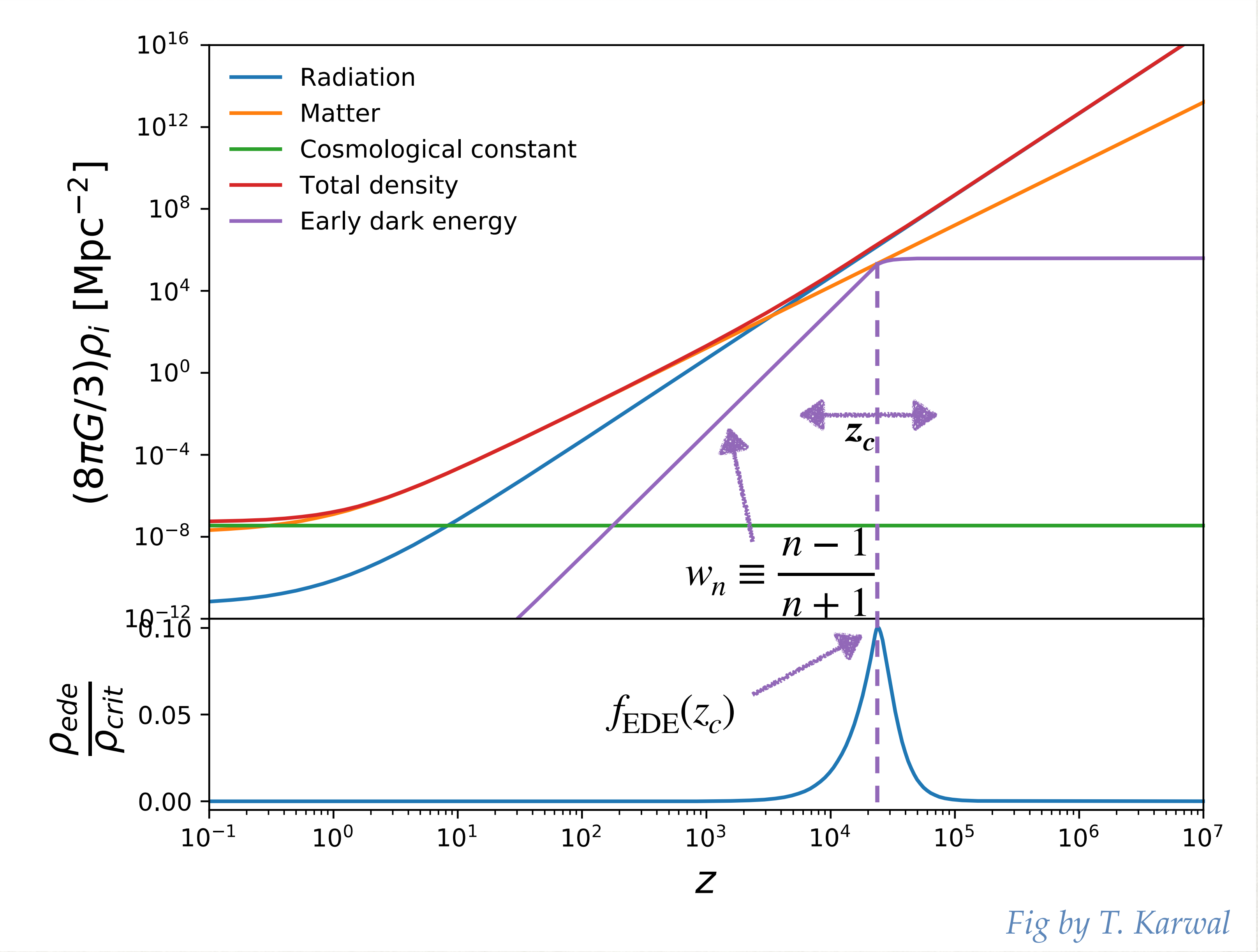
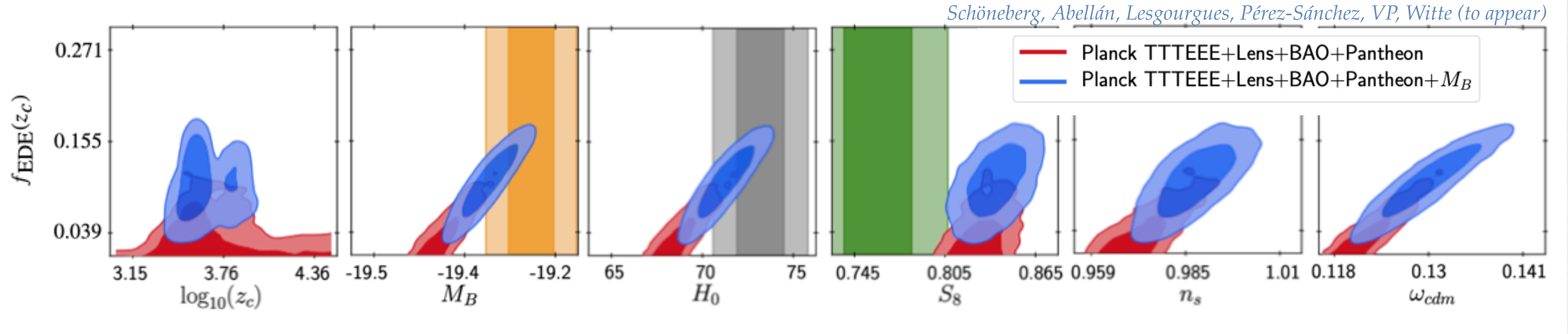


Fig by T. Karwal

Early Dark Energy can resolve the H_0 tension



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

$$f(z_c) < 0.08\ (0.05), \qquad H_0 < 70.6\ (69.8)\ \text{km/s/Mpc}$$

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

- Adding the M_b prior from SH0ES

$$f(z_c) = 0.10\ (0.12) \pm 0.03 \qquad z_c = 4073\ (3715)^{+393}_{-838} \qquad H_0 = 71.25\ (71.6) \pm 1.1\ \text{km/s/Mpc}$$

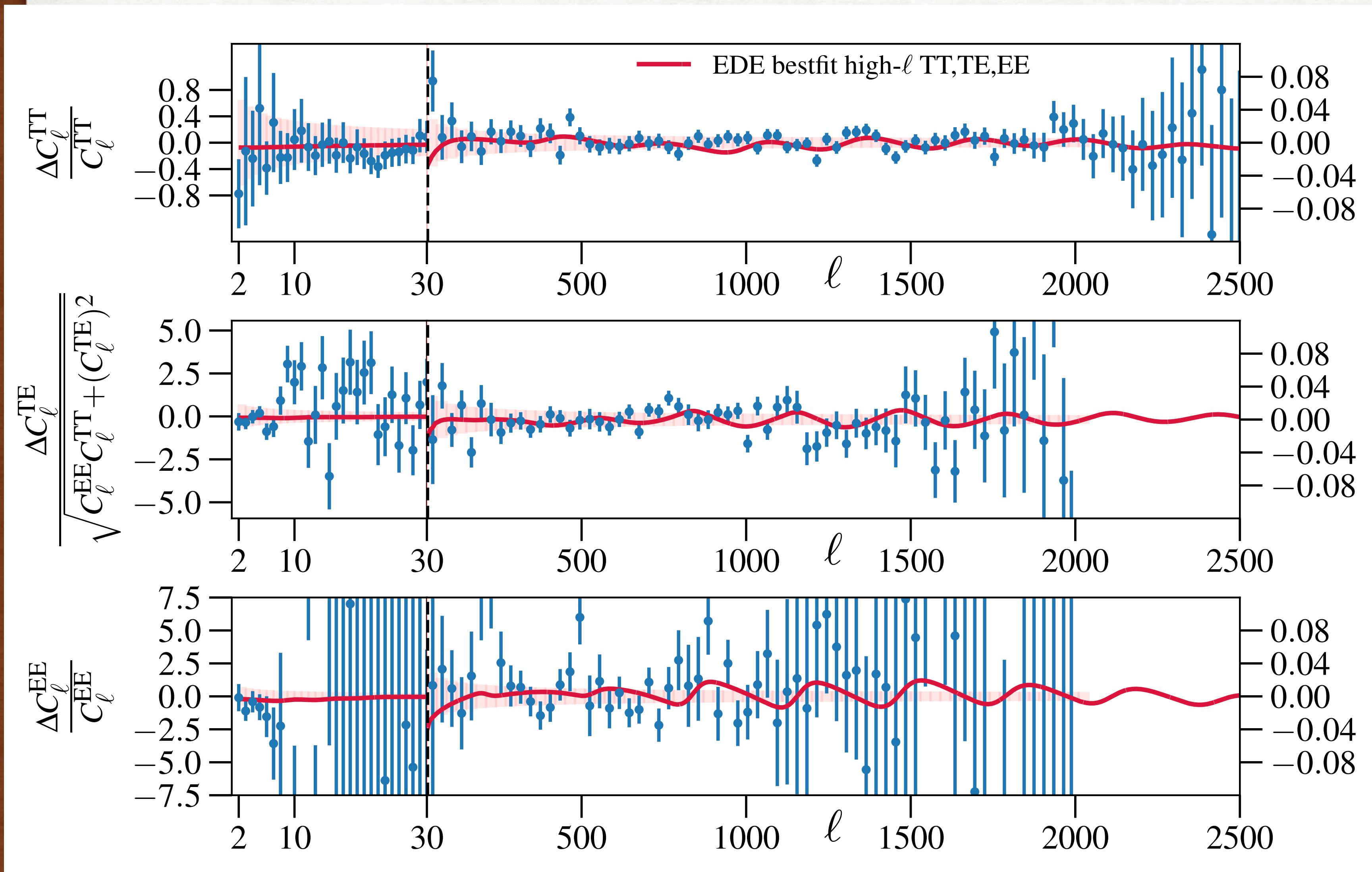
$$\Delta\chi^2 = \chi^2_{\Lambda\text{CDM}} - \chi^2_{\text{EDE}} \simeq -24.8$$

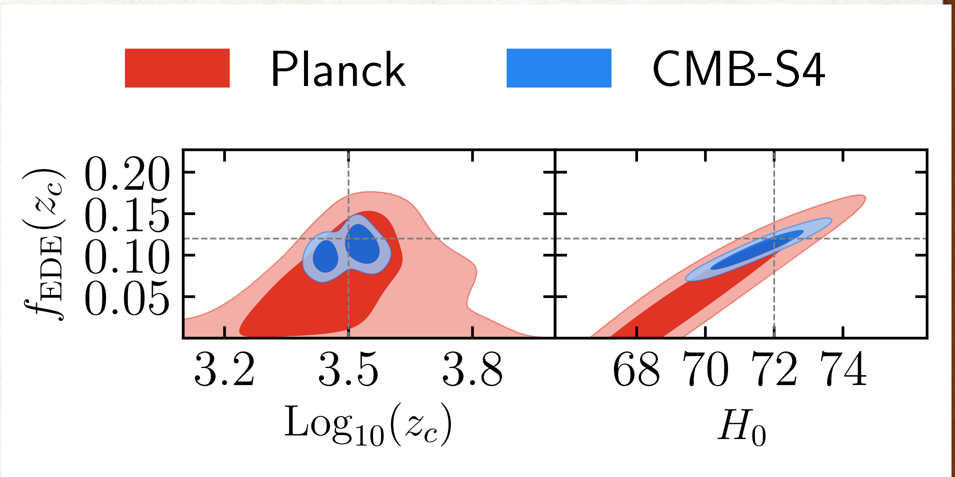
- Theoretical problem: the field becomes dynamical around $z_{\rm eq}$: Fine-tuning ? Coincidence problem 2.0?
  e.g. Dodelson++astro-ph/0002360, Griest astro-ph/0202052, Kamionkowski++1409.0549, Sakstein&Trodden 1911.11760, Carrillo González++ 2011.09895

- Observational problem: EDE cosmology has a higher $\omega_{\rm cdm}$ and n_s: S_8-tension increases from 2.8σ to 3.1σ.

- Potentially interesting constraints from KiDS/DES/BOSS. Beware of inconsistent data-set! But clearly EDE alone does not resolve S_8-tension. *Hill et al. 2003.07355, Ivanov++ 2006.11235 , d'Amico++ 2006.12420 Niedermann++ 2009.00006, Smith++ 2009.10740, Murgia++ 2009.10733*

EDE leaves an imprint in CMB power spectra



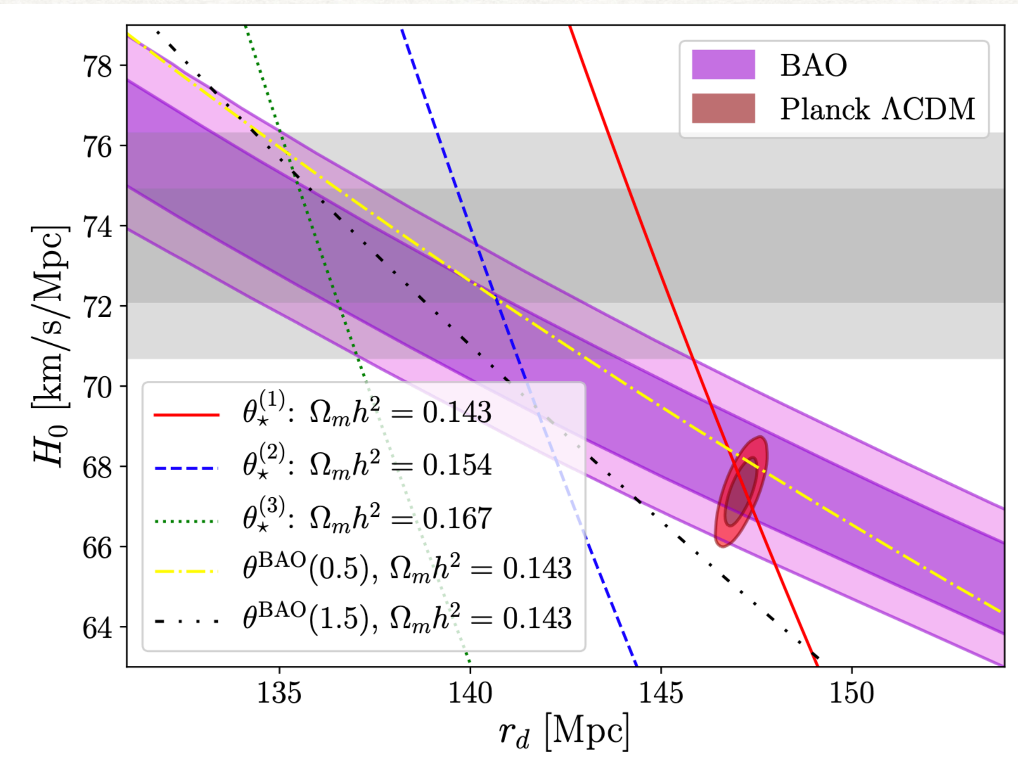


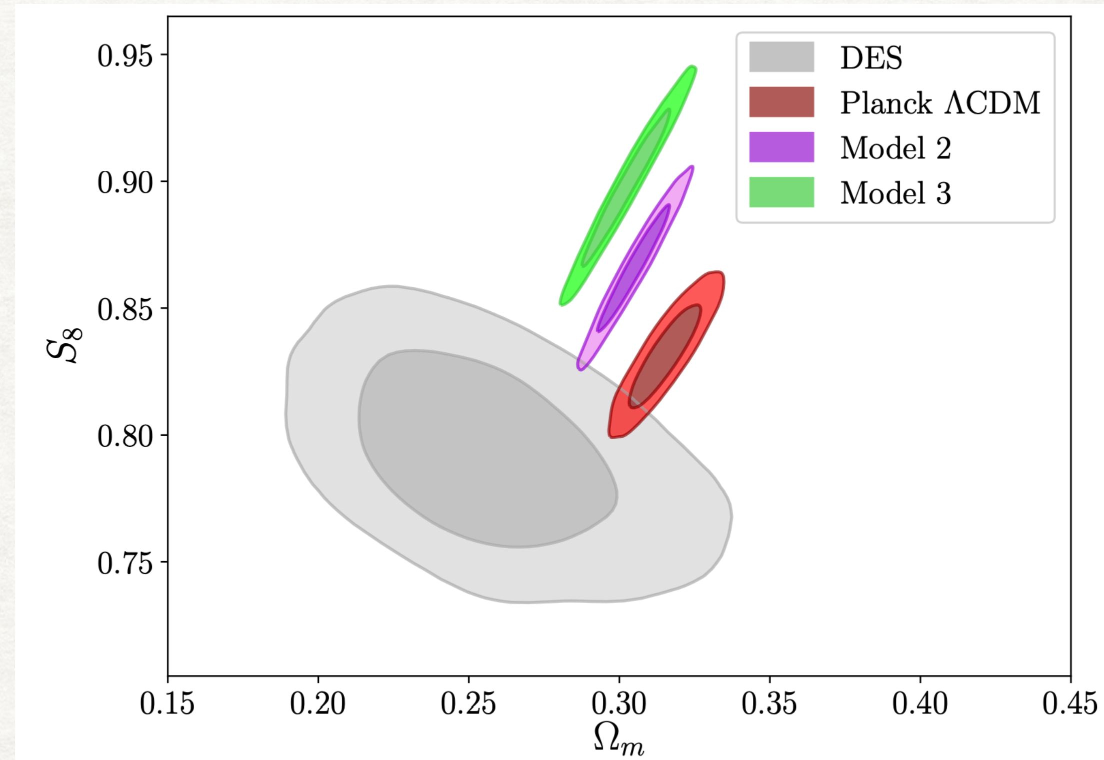
Smith ++ 1908.06995

- An experiment like CMB-S4 would certainly detect $f_{\rm EDE}(z_{\rm eq}) \sim 10\,\%$.

What will it take to find a concordance model?

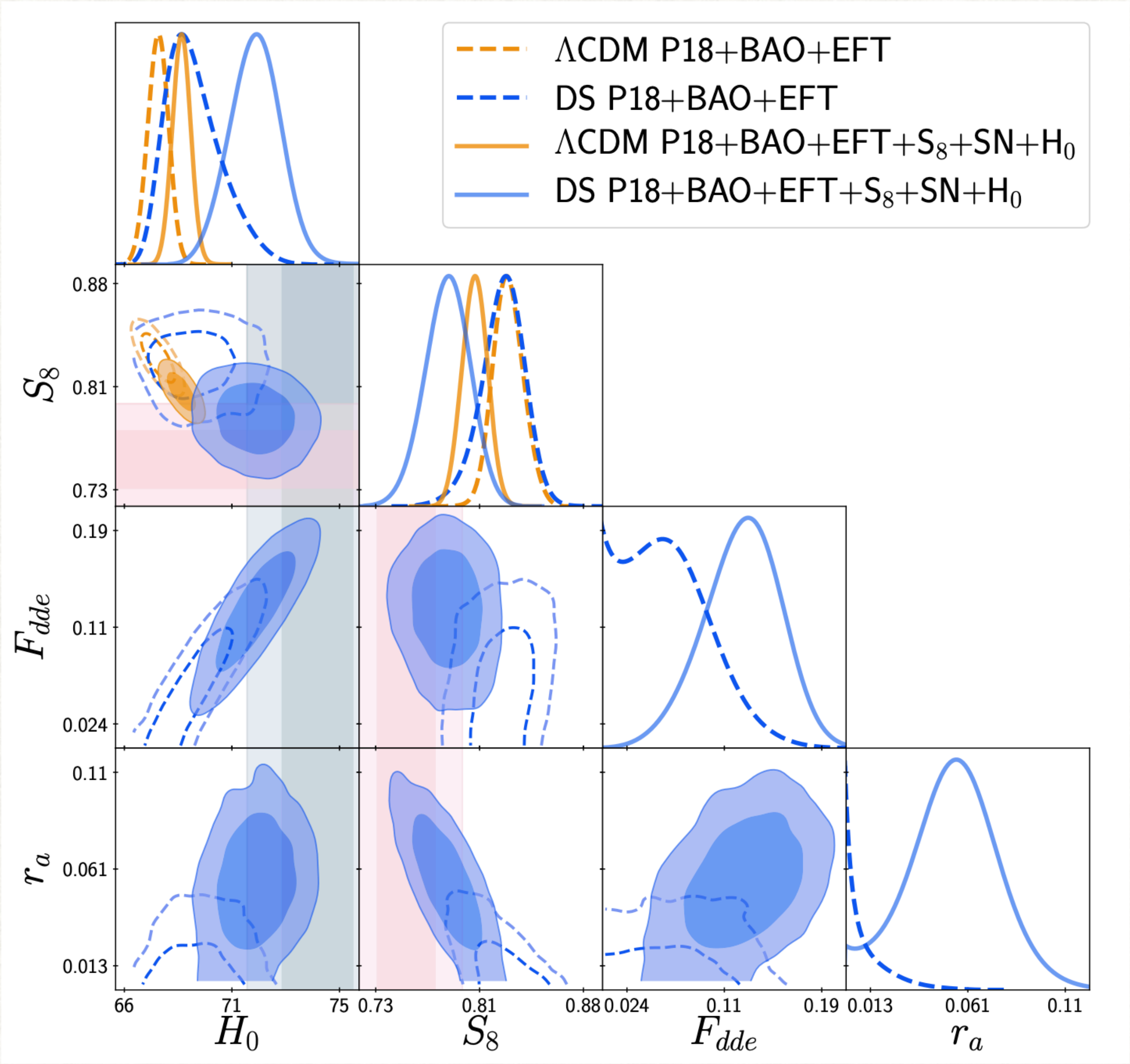
Jedamzik & Pogosian 2010.04158





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

Towards a concordance cosmology?



- Early Dark Energy (here DDE) together with an ultra-light axion with $m_a \sim 10^{-26}$ eV and $r_a \equiv \omega_a/\omega_{\rm cdm} \simeq 5\,\%$ could resolve both tensions.

Allali++ 2104.12798, for more on ULA see also Laguë++ 2104.07802

- Could the EDE become the ULA?

Barring systematic errors: no 'concordance cosmology' just yet

- ΛCDM explains CMB and BBN (<2σ), but there exists a $4-6\sigma$ H_0-tension and 3σ σ_8-tension.
- What extension(s) could resolve these tensions?

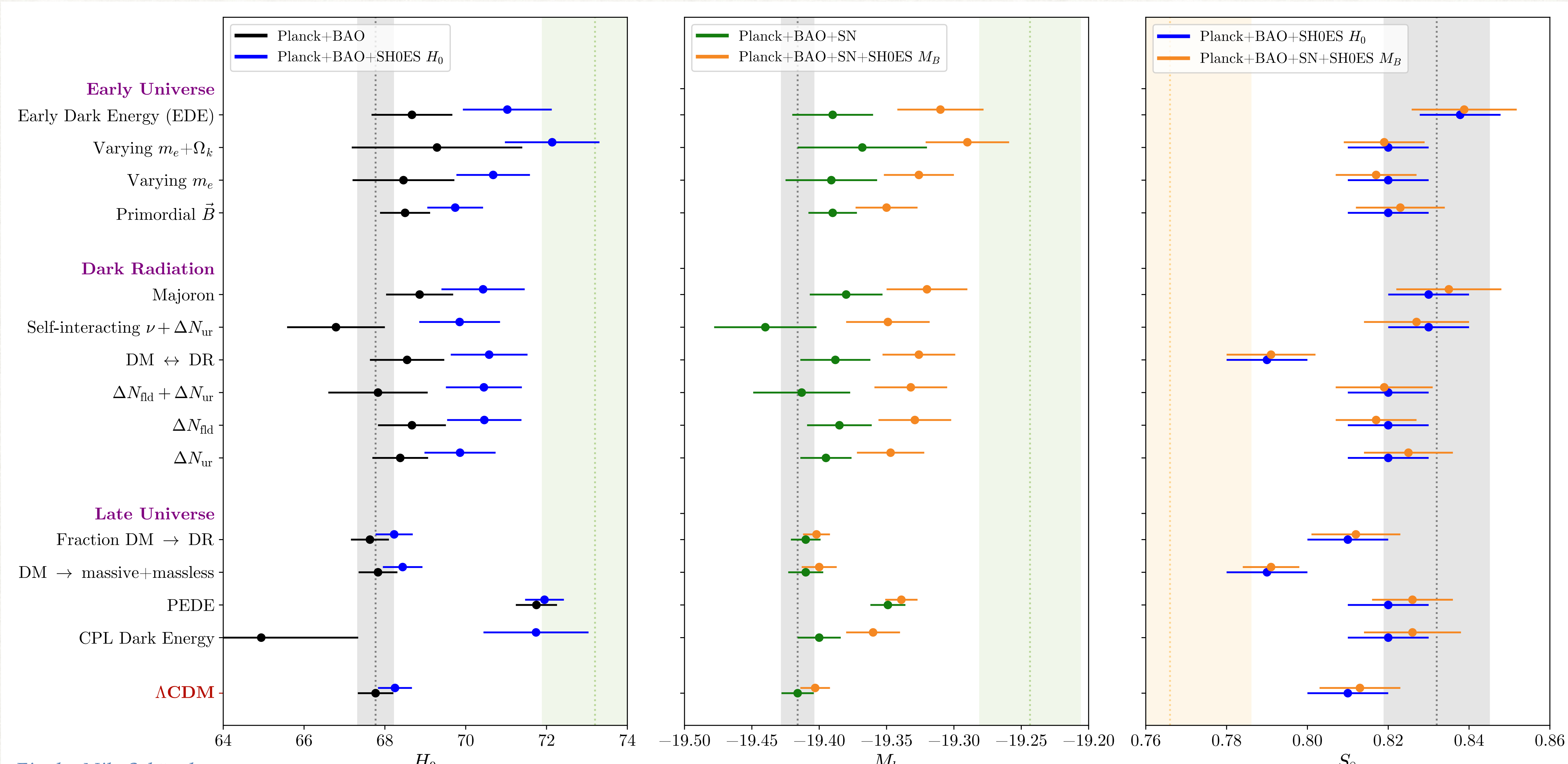


Fig. by Nils Schöneberg

Schöneberg, Abellán, Lesgourgues, Pérez-Sánchez, VP, Witte (to appear)

- 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.