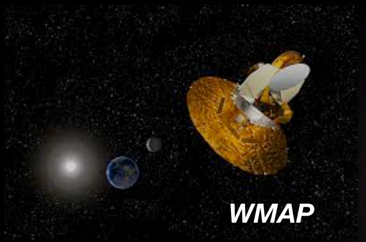
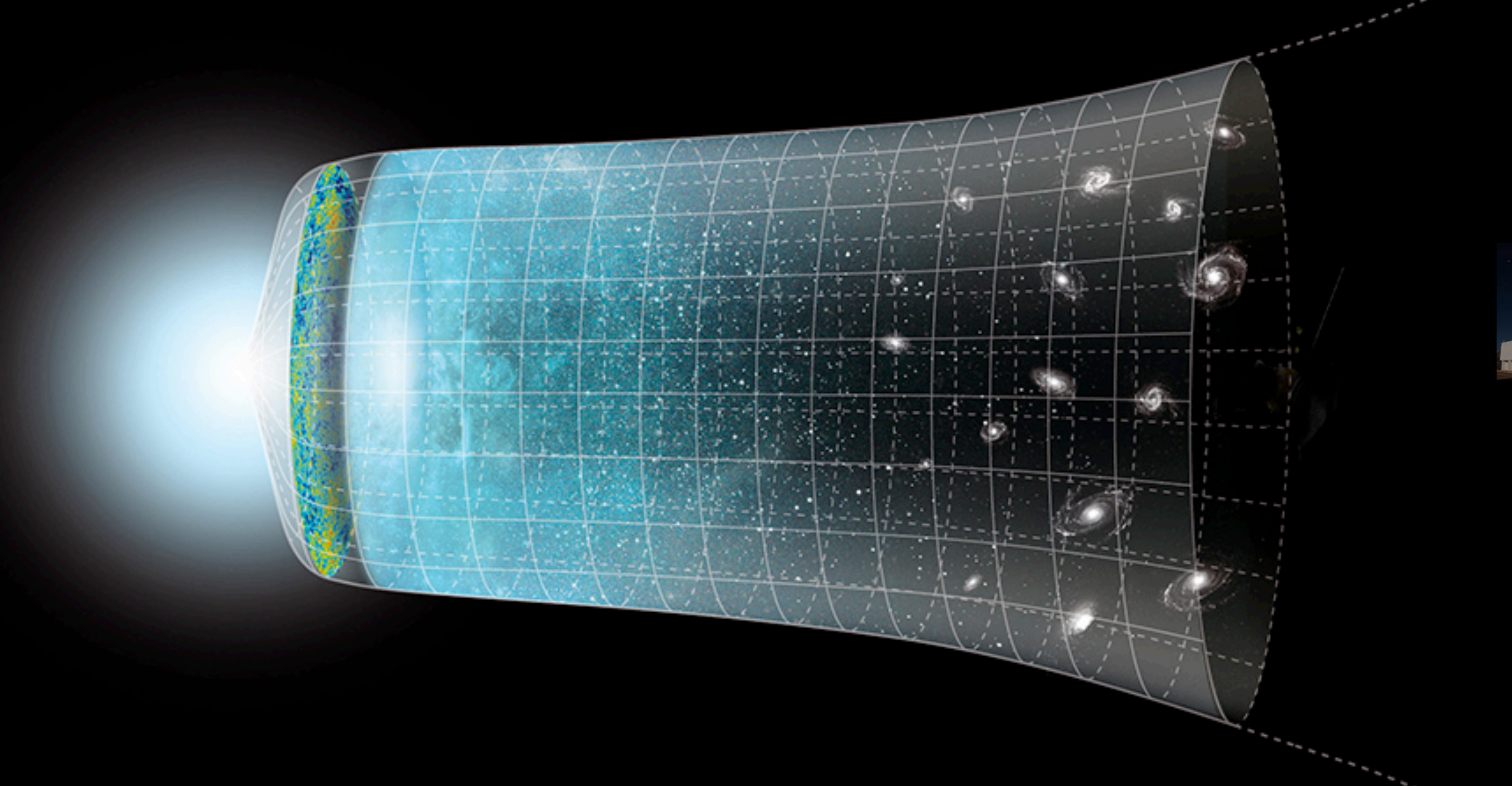
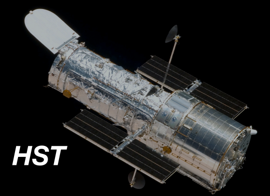
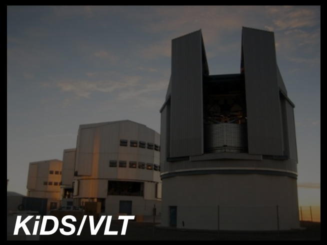
Status of the Hubble Tension and Suggested Solutions









Vivian Poulin

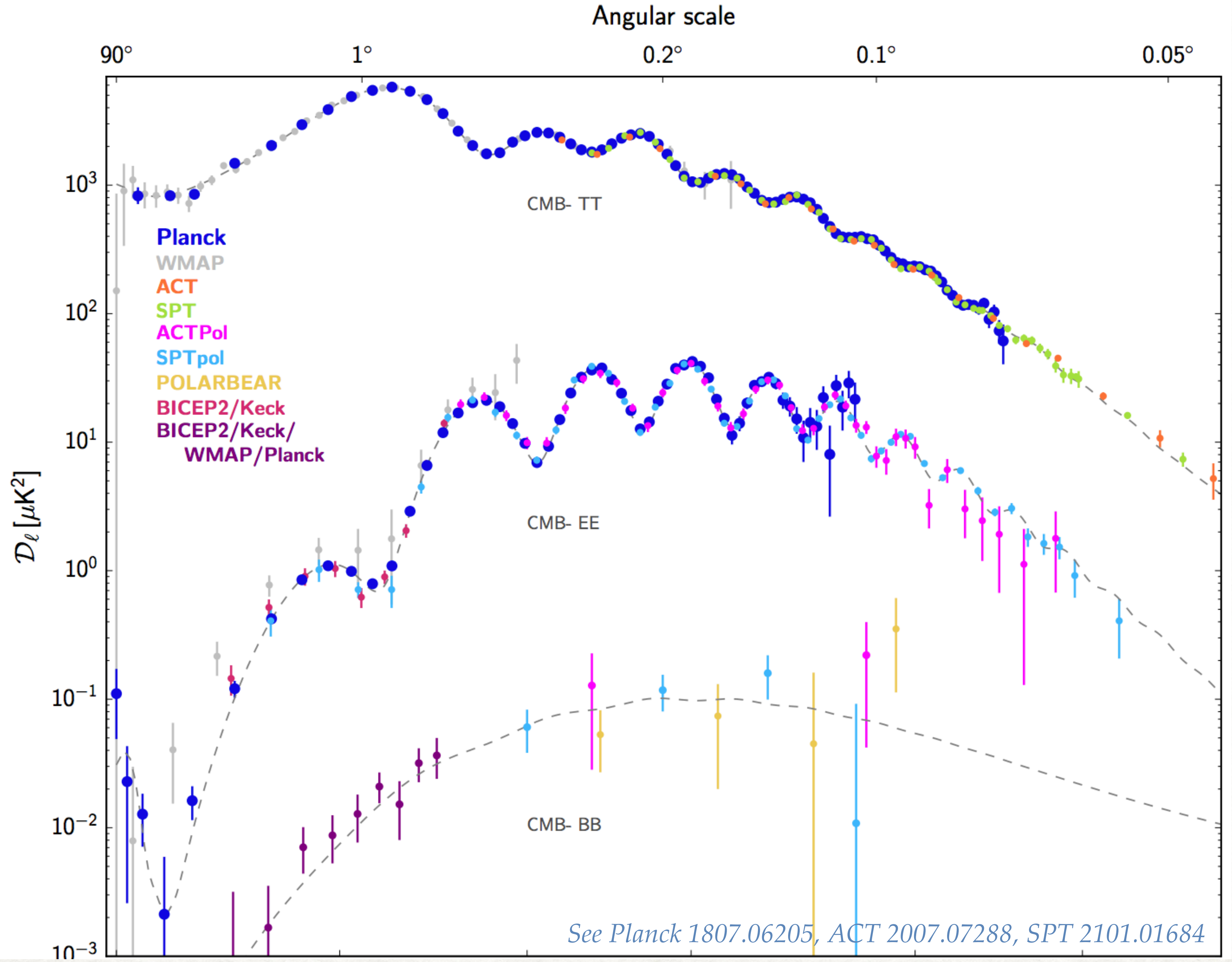
Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

vivian.poulin@umontpellier.fr

Rencontres de Blois
May, 27th 2022

The Era of Precision Cosmology

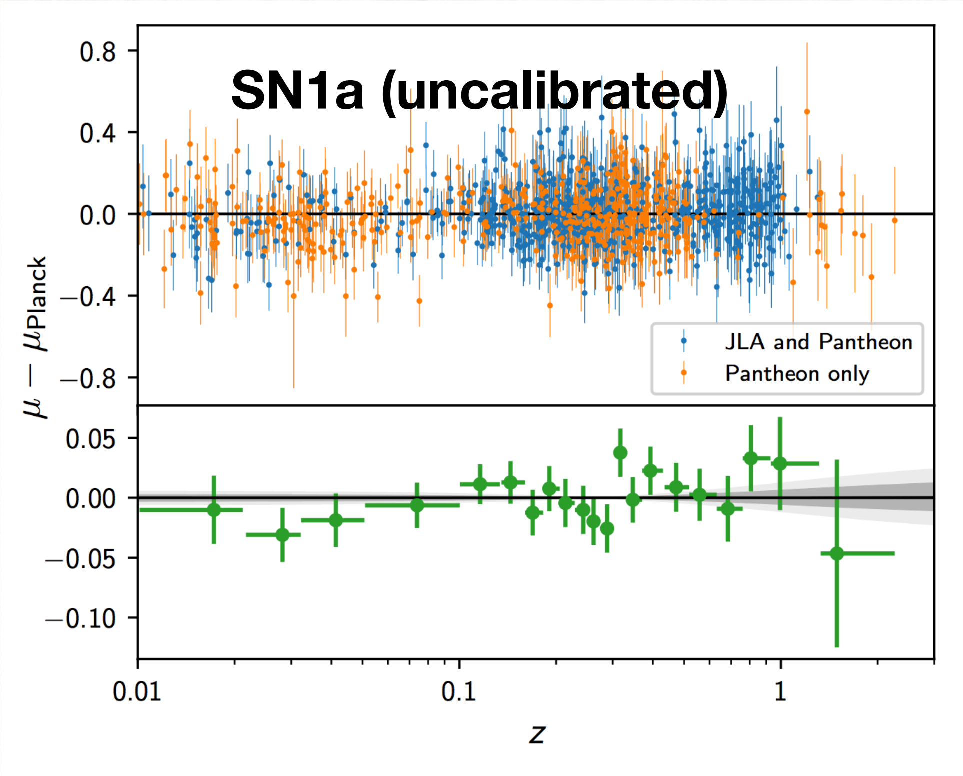
Within ΛCDM, 2σ agreement between all CMB data!



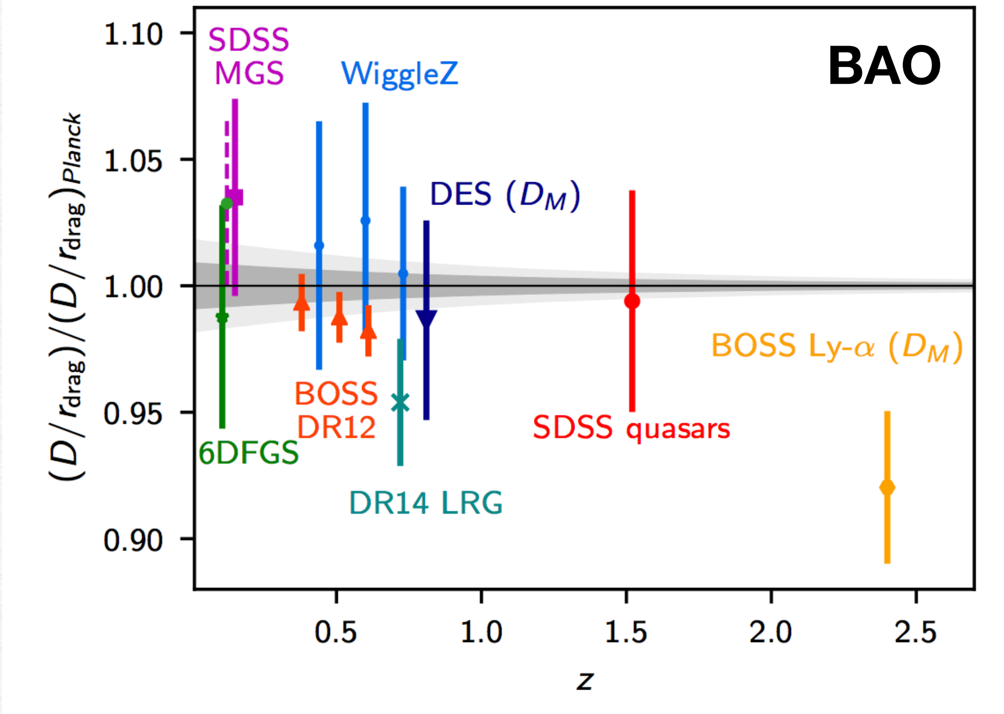
See Planck 1807.06205, ACT 2007.07288, SPT 2101.01684

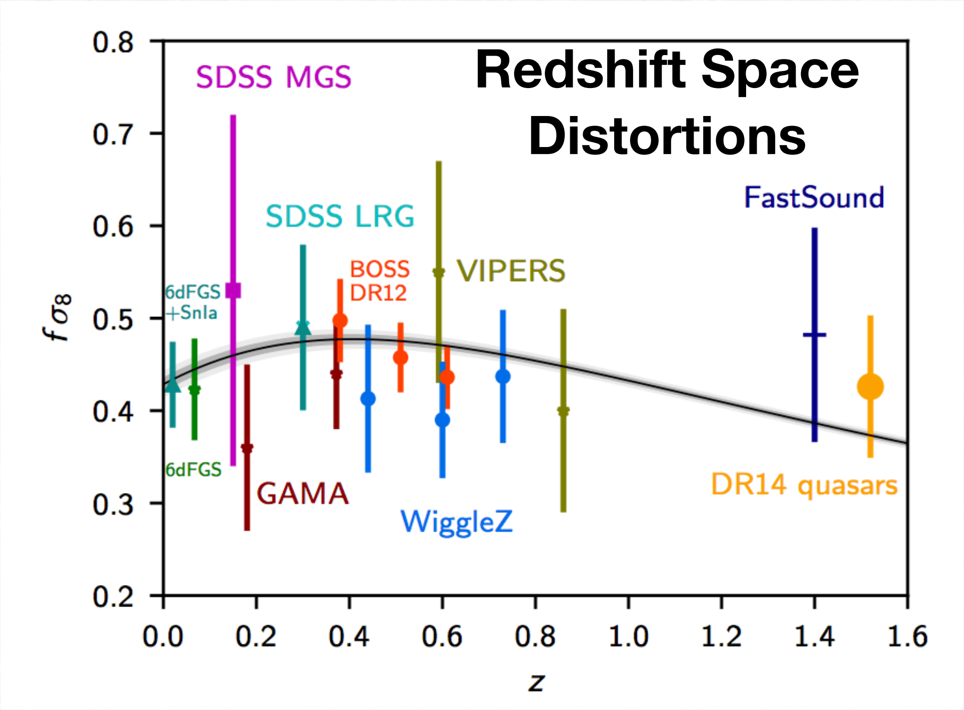
- Snapshot of inhomogeneities in our universe 380 000 years after the Big Bang
- Very sensitive probe of the early universe, in particular the era of recombination

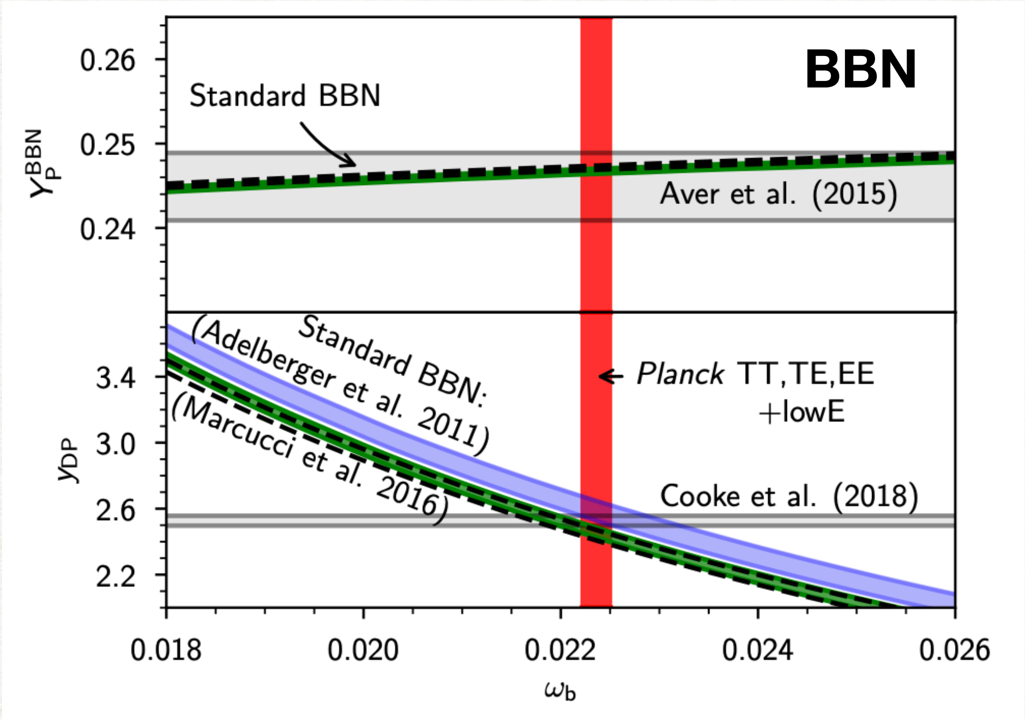
The Era of Precision Cosmology



Planck 1807.06209







Talks by Andreu Font-Ribeira

- ΛCDM explains a wide variety of data (well-)within 1σ

A concordance model: ΛCDM

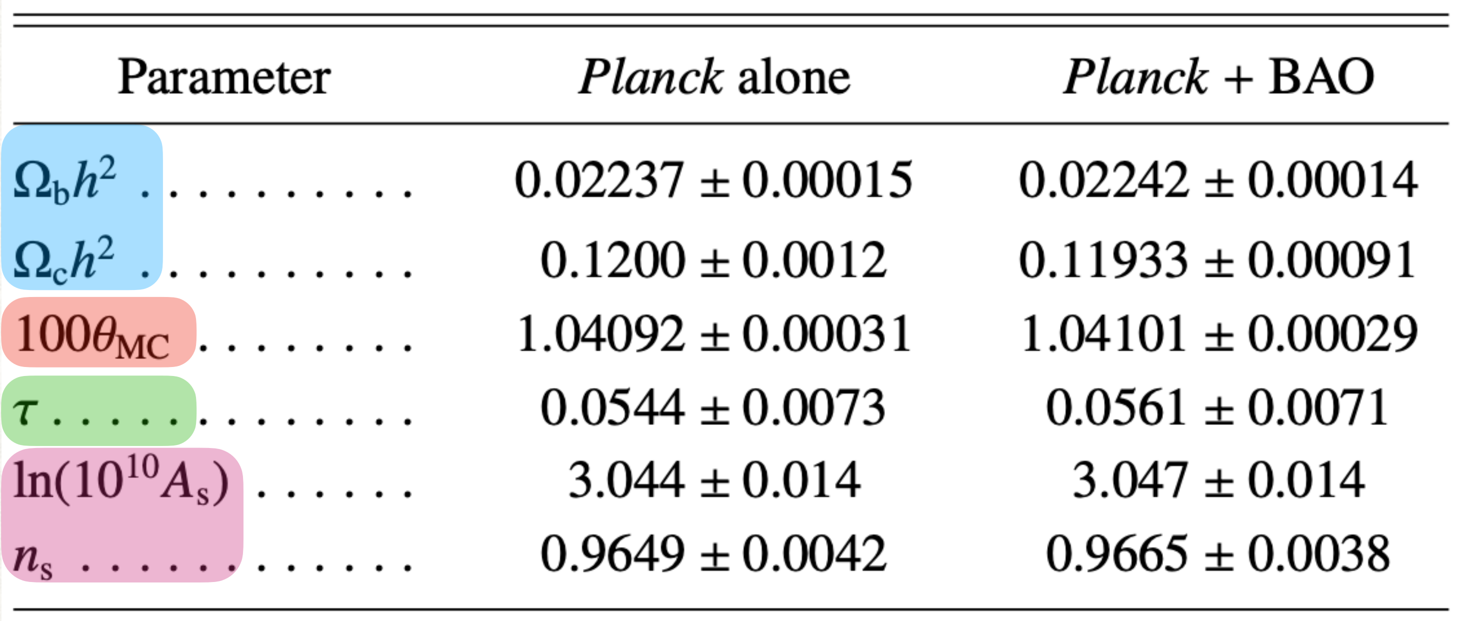
Astonishing success of ΛCDM Cosmology: GR+ Cosmological Principle

matter content

expansion rate H_0, Λ

star formation

Inflation



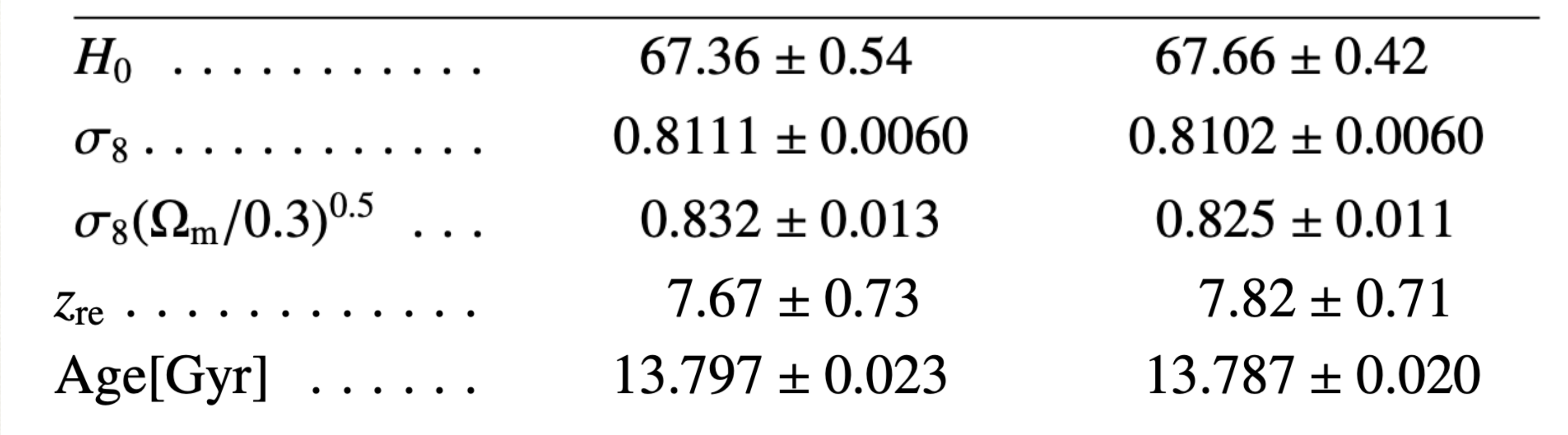
Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665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

Planck alone

0.6% precision
1% precision
0.03% precision
13% precision
0.5% precision
0.4% precision

Planck 1807.06209

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

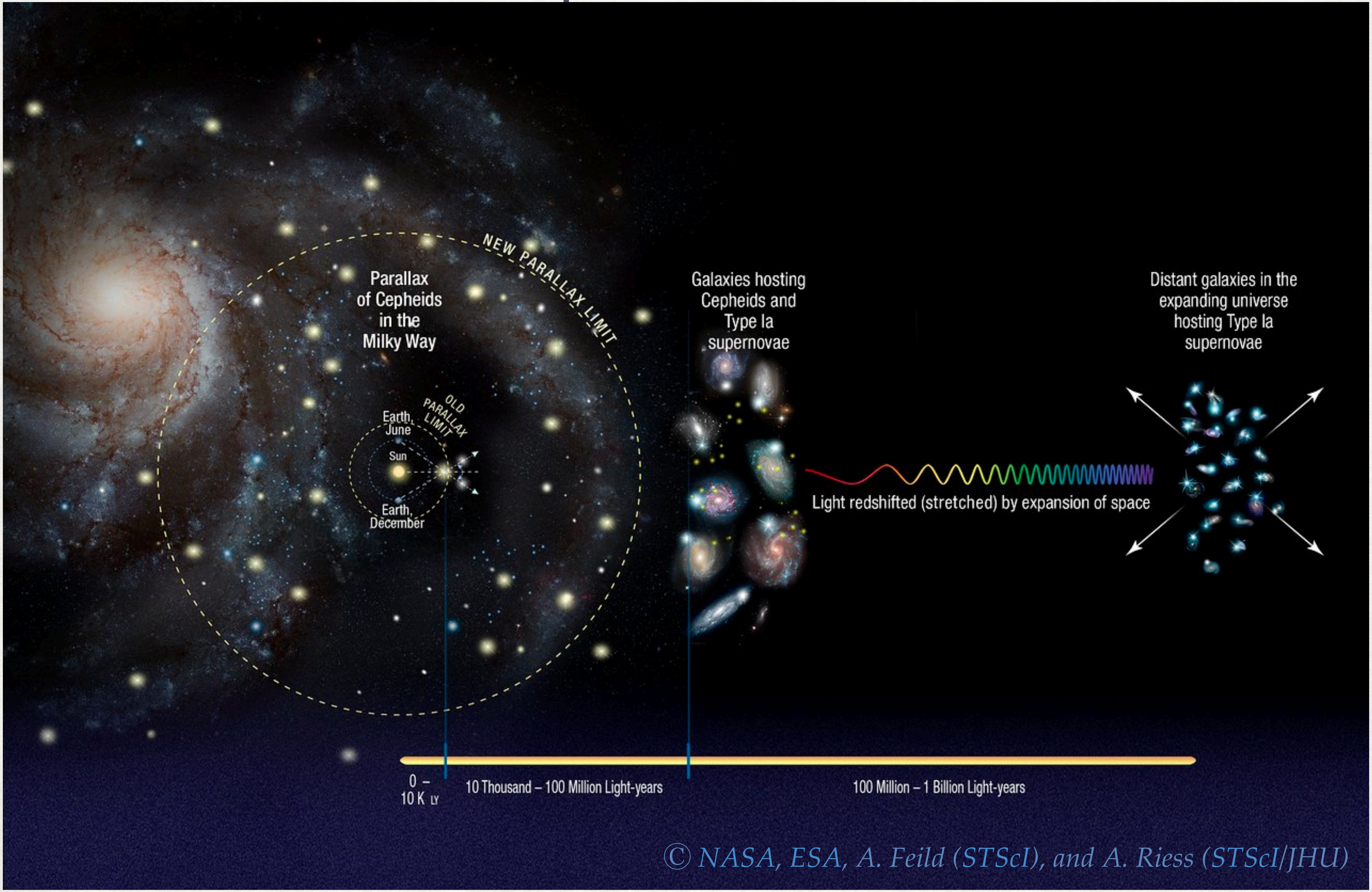


H_0	67.36 ± 0.54	67.66 ± 0.42
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020

- 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?

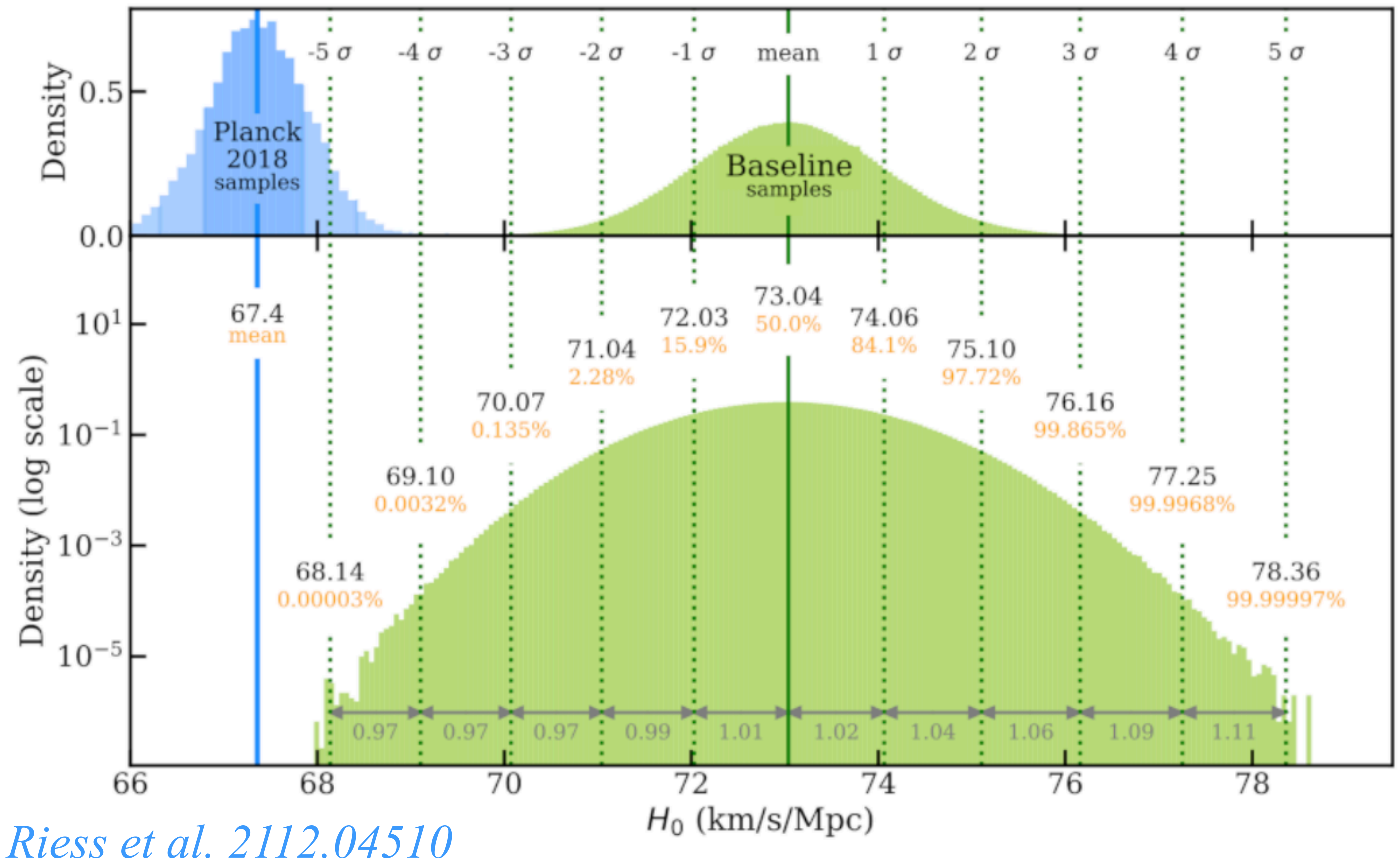
SH0ES: three steps to the Hubble constant



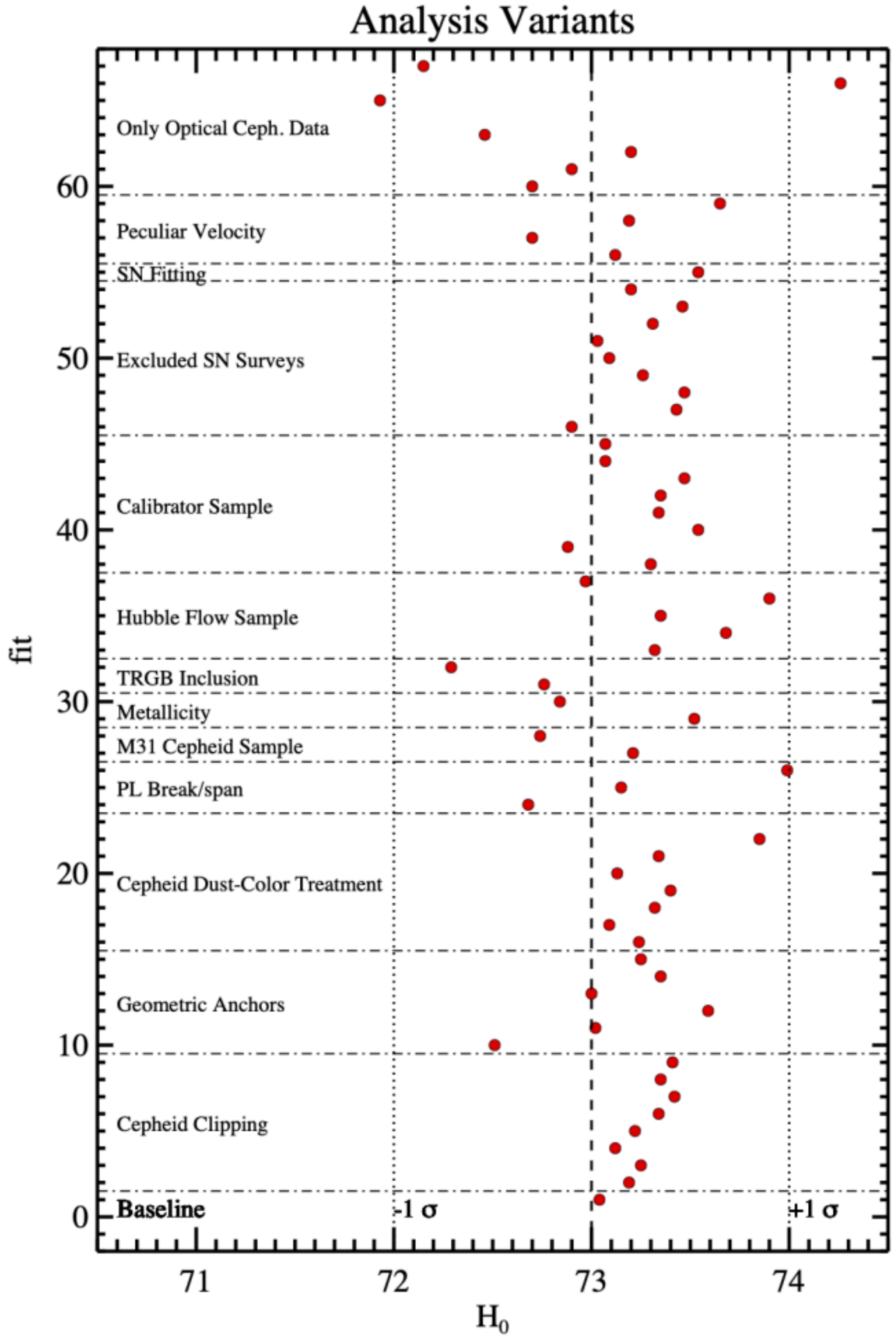
© NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

The Hubble tension between SH0ES & *Planck*

Talk by Louise Breuval on Wednesday



Riess et al. 2112.04510



- Now 42 cepheid-SN1a calibrators!

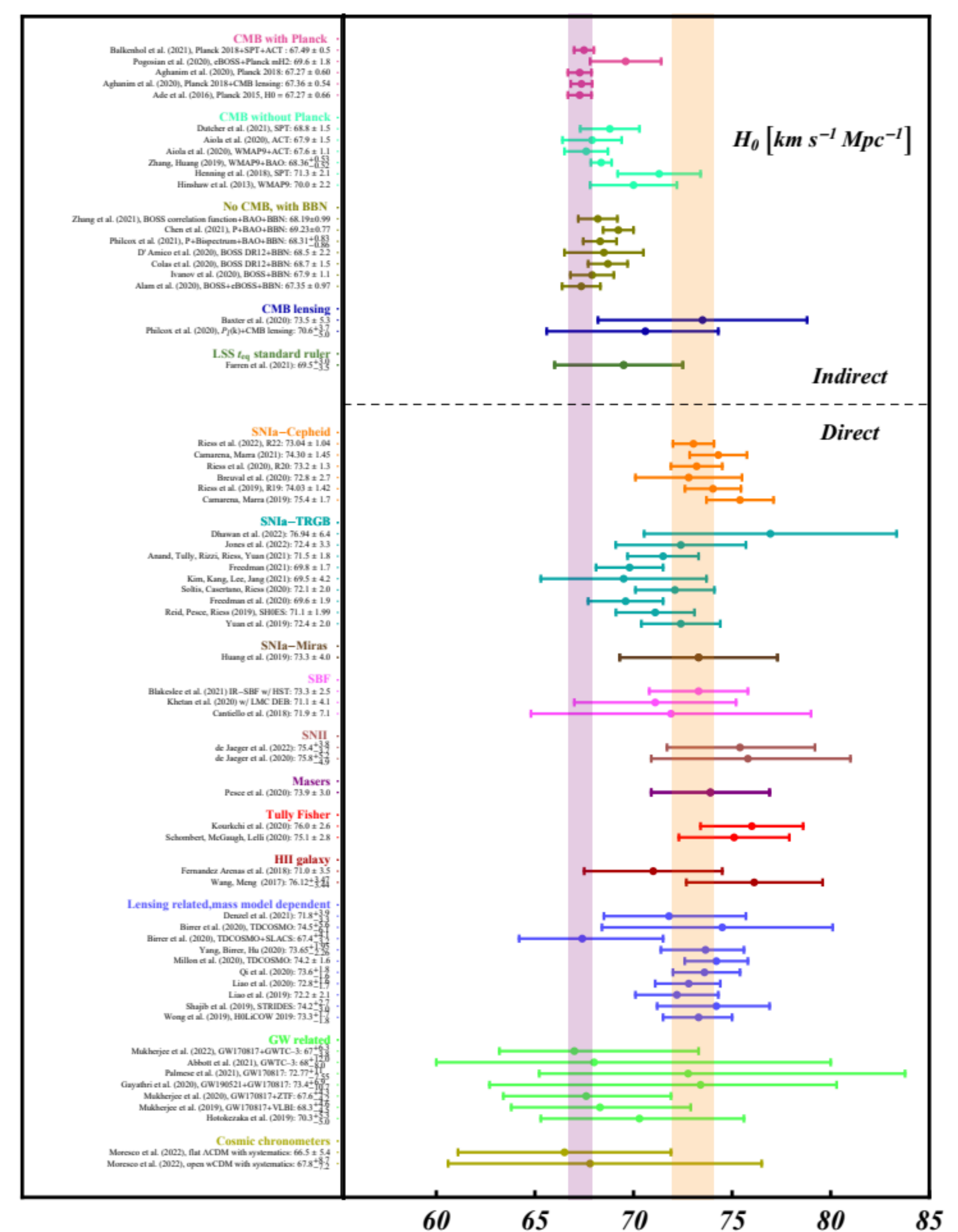
$$H_0(\Lambda\mathrm{CDM/Planck}) = 67.4 \pm 0.06 \textbf{ km/s/Mpc}$$

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

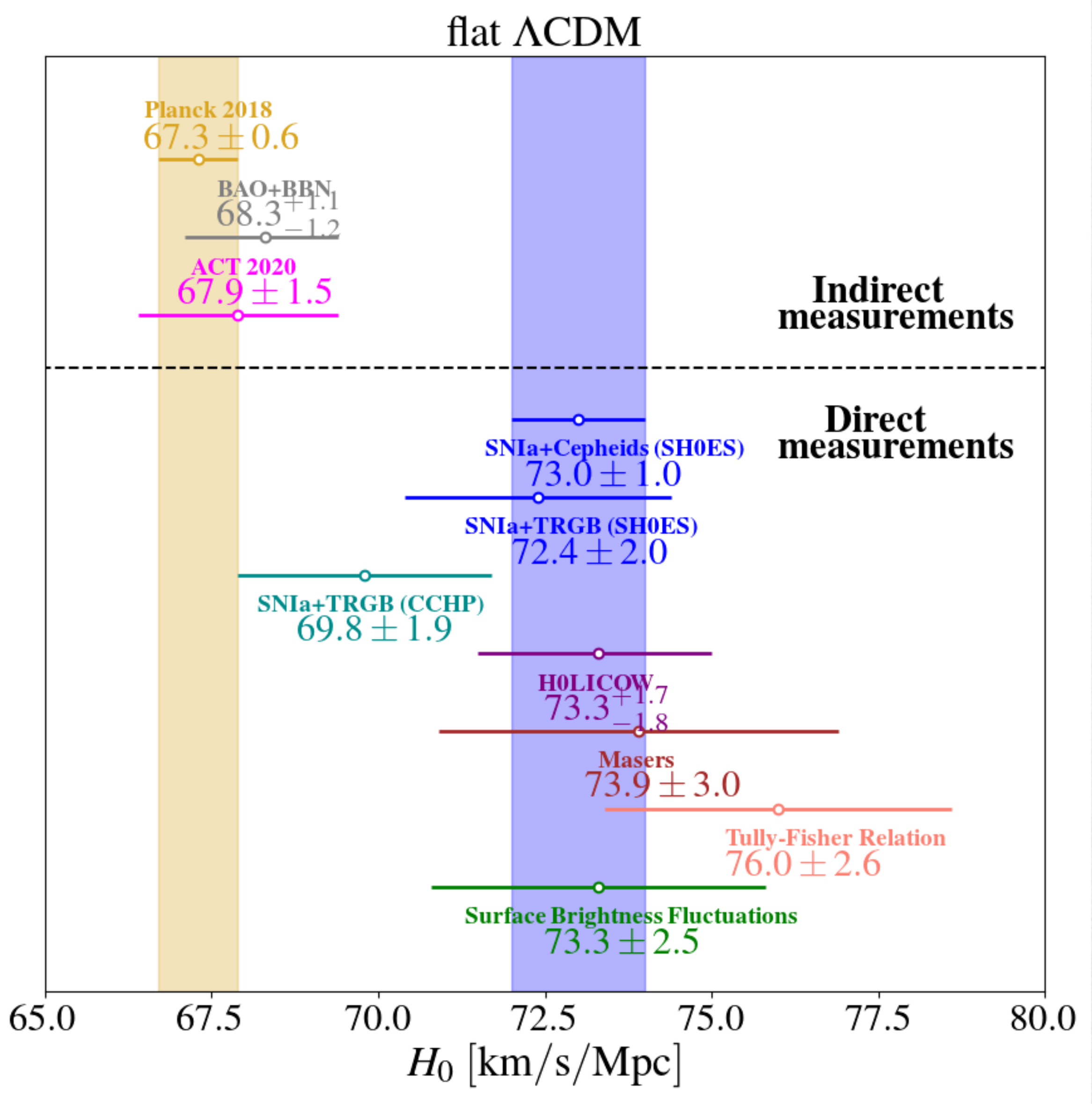
There is a 5σ discrepancy between the SH0ES and *Planck* determination of the Hubble parameter

No (known) systematic error can explain the discrepancy

The Hubble tension beyond SH0ES & *Planck*



Snowmass white paper 2203.06142



A summary of current measurements with $\Delta H_0 < 3\text{km/s/Mpc}$

Talk by Kenneth Wong on Tuesday

Talk by Soares-Santos on Tuesday

Systematics? A non-exhaustive list

See review Di Valentino++ 2103.01183 for all relevant references

Talk by Louise Breuval on Wednesday

- 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?
    - Cepheid crowding?
    - Is there a bias in the peculiar velocity correction?
    - Is there a metallicity correction?
    - Is GAIA parallax incorrect?

Kenworthy++ 2204.10866

Cepheids alone: $H_0 = 73.1 \pm 2.5$ km/s/Mpc

Freedman++ 1907.05922, Freedmann++2002.01550, Yuan++1908.00993, Efstathiou++ 2007.10716, Soltis++2012.09196, Freedman++ 2106.15656, Anand++ 2108.00007

- Are there different populations of SN1a between "cepheid-SN1a calibrator" 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.
  At odds with measurements from SN1a at z <~2.

Wu&Huterer 1706.09723, Kenworthy++ 1901.08681, Cai++ 2012.08292

- Recently assuming ΛLTB model: $\delta \approx -0.04$ up to 300 Mpc but still 3.8σ tension with SH0ES.

Camarena++ 2205.05422

Talk by Kenneth Wong on Tuesday

- Systematic in strongly-lensed quasars?
  - Are Lens profiles correctly modeled? Mass-sheet degeneracy! The "H0LiCOW" result could be explained by a cored density profile. TDCosmo + SLACS: favored by kinematic data but large errors.

Blum et al. 2001.07182, Birrer++ 2007.02941

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

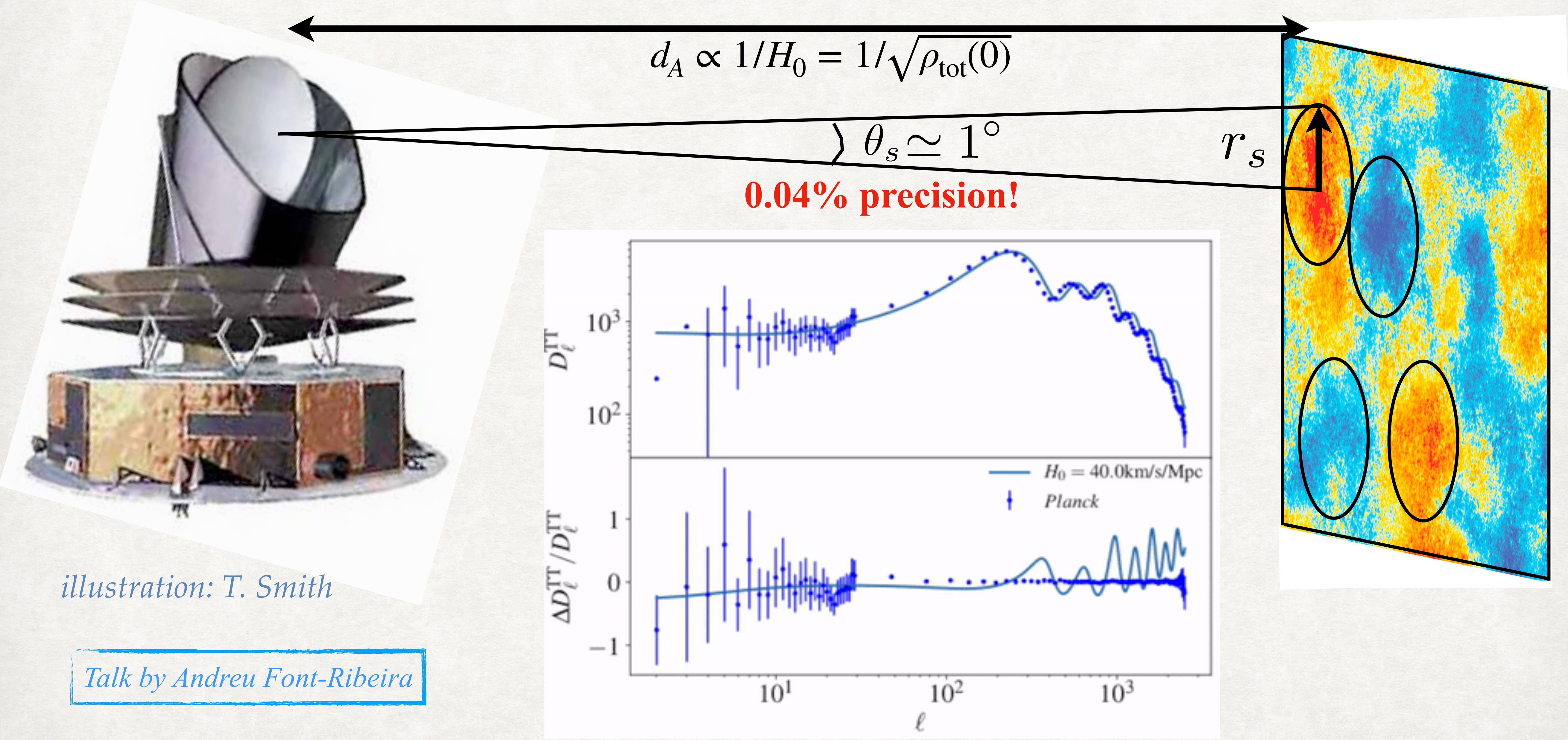
Colin++1808.04597, Heinesen&Buchert 2002.10831, Secrest++ 2009.14826

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.

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



0.04% precision!

illustration: T. Smith

Talk by Andreu Font-Ribeira

How can we change the H_0 prediction?

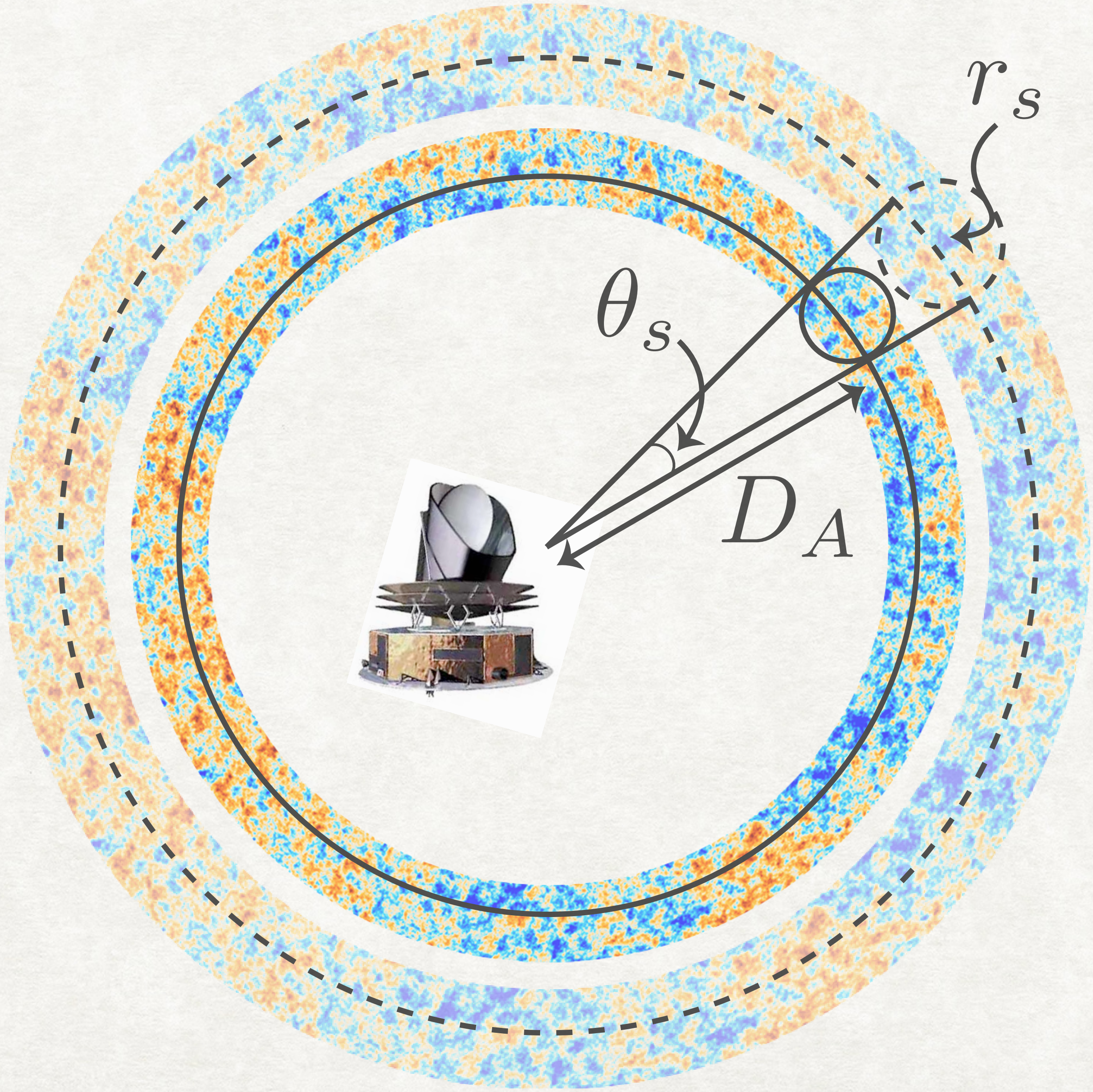
$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)} = \frac{\int_\infty^{z_*} dz\ c_s(z)/H(z)}{\int_0^{z_*} dz/H(z)}$$

- Either one breaks the relation $d_A(z_*) \propto 1/H_0$:

  => new physics at late times $z \sim 0 - 1$

- Or the CMB is closer to us, and one must decrease $r_S(z_*)$:

  => new physics at early times $z \sim 10^3 - 10^4$



The H_0 olympics: fairly ranking models

- We compare 17 different models suggested to resolve the Hubble tension.

Schöneberg (VP) ++ 2107.10291

Late-Universe models

- CPL Dark Energy
- Emergent Dark Energy
- Generalized Emergent Dark Energy
- Decaying Dark matter to massless particles
- Decaying Dark matter to massive particles

Dark Radiation models

- Free-streaming $N_{\rm eff}$
- Self-Interacting $N_{\rm DR}$
- Mixture of $N_{\rm eff} + N_{\rm DR}$
- DM-DR interaction + $N_{\rm DR}$
- Self interacting $\nu + N_{\rm eff}$

Exotic Early Universe models

- Early Dark Energy
- New Early Dark Energy
- Early modified Gravity
- Primordial magnetic fields
- Varying electron mass m_e
- Varying electron mass $m_e + \Omega_k$

- We differentiate:
  - i) a model resolves the tension: a model gives a good fit to all data combined with a prior on H_0;
  - ii) a model is favored over ΛCDM with a prior on H_0;
  - iii) a model is favored over ΛCDM without a prior on H_0 and leads to a high H_0.

- We use 3 simple metrics: Gaussian tension metric vs Non-Gaussian $Q_{\rm DMAP}$ vs Bayesian-like approach with ΔAIC

See Raveri&Hu 2018

$$\frac{\bar{M}_b^{\rm CMB+BAO+SN1a} - \bar{M}_b^{\rm SH0ES}}{\sqrt{\sigma^2_{M_b^{\rm CMB+BAO}} + \sigma^2_{M_b^{\rm SH0ES}}}}$$

$$Q_{\rm DMAP} = \sqrt{\chi^2(\text{w/ SH0ES}) - \chi^2(\text{no SH0ES})}$$

$$\Delta\text{AIC} = \Delta\chi^2 - 2\Delta N_{\rm params}$$

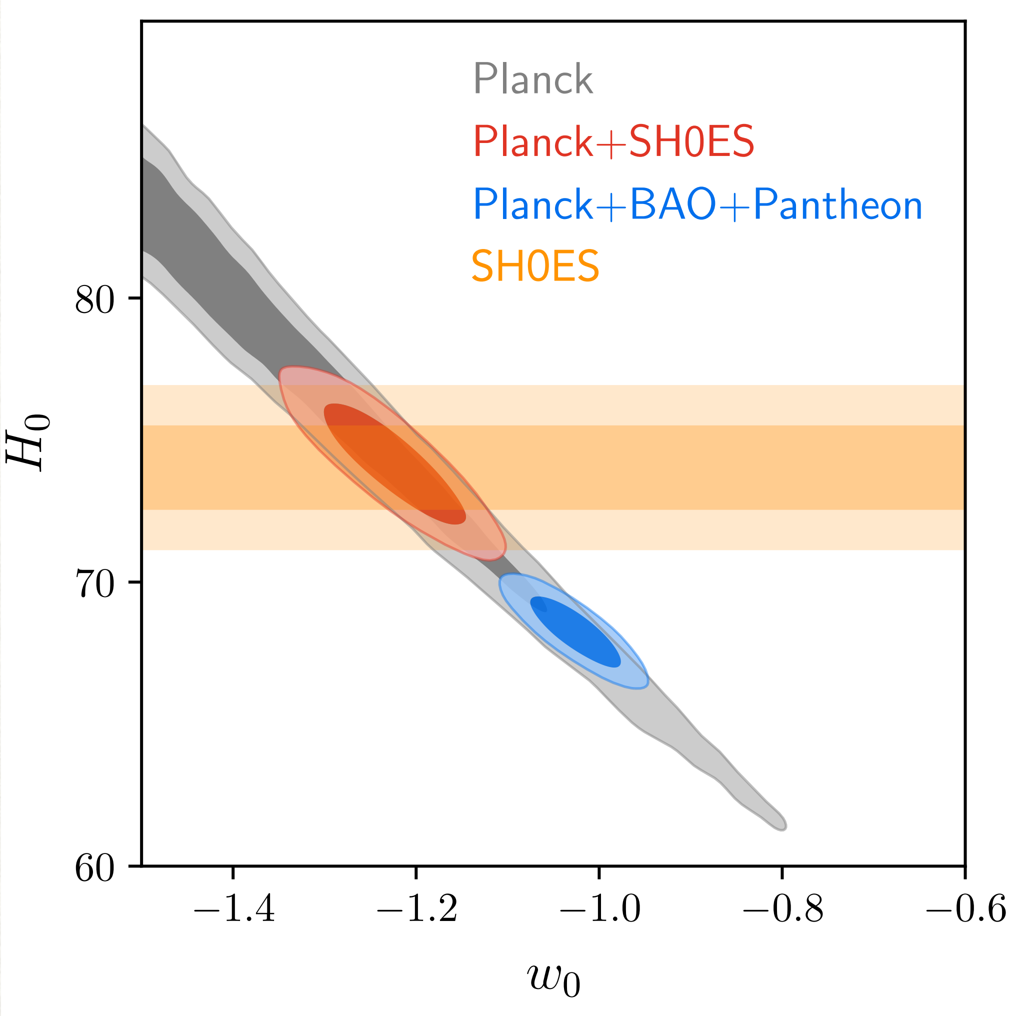
i) simple to understand; ii) simple to implement; iii) representative

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

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

- ‘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



The true tension is with the SN1a magnitude!

Beenakker++2101.01372, Efstathiou 2103.08723

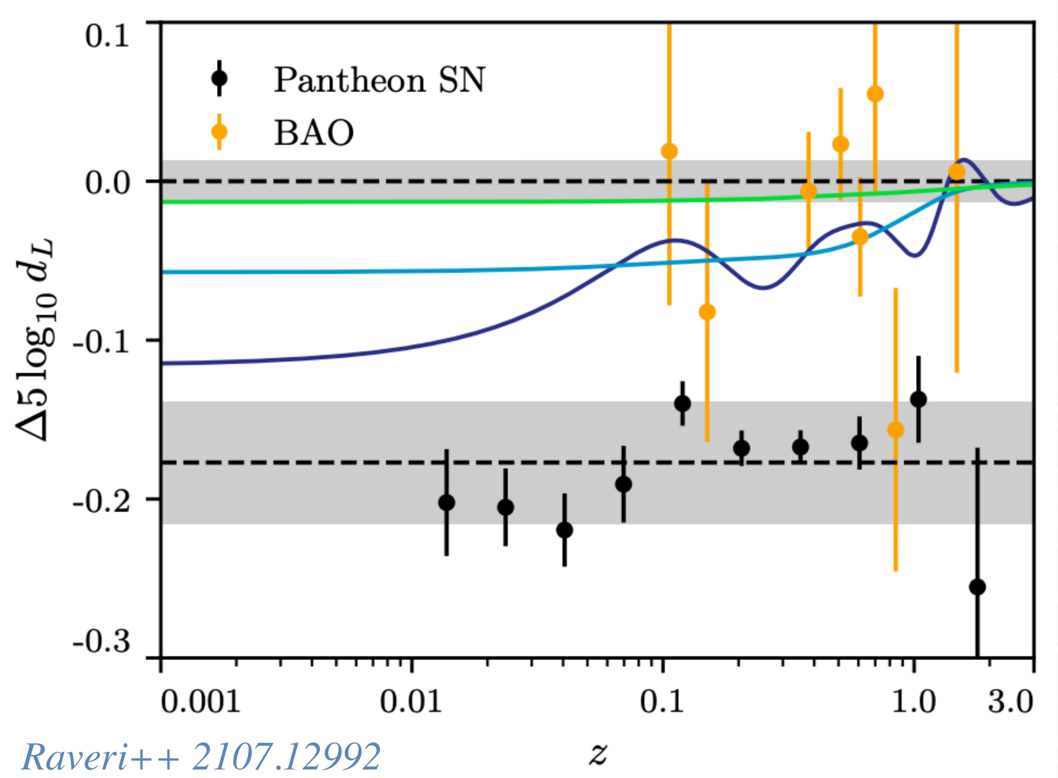
In GR: $D_A = D_L/(1+z)^2$; it is impossible to resolve the tension without changing calibration!

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

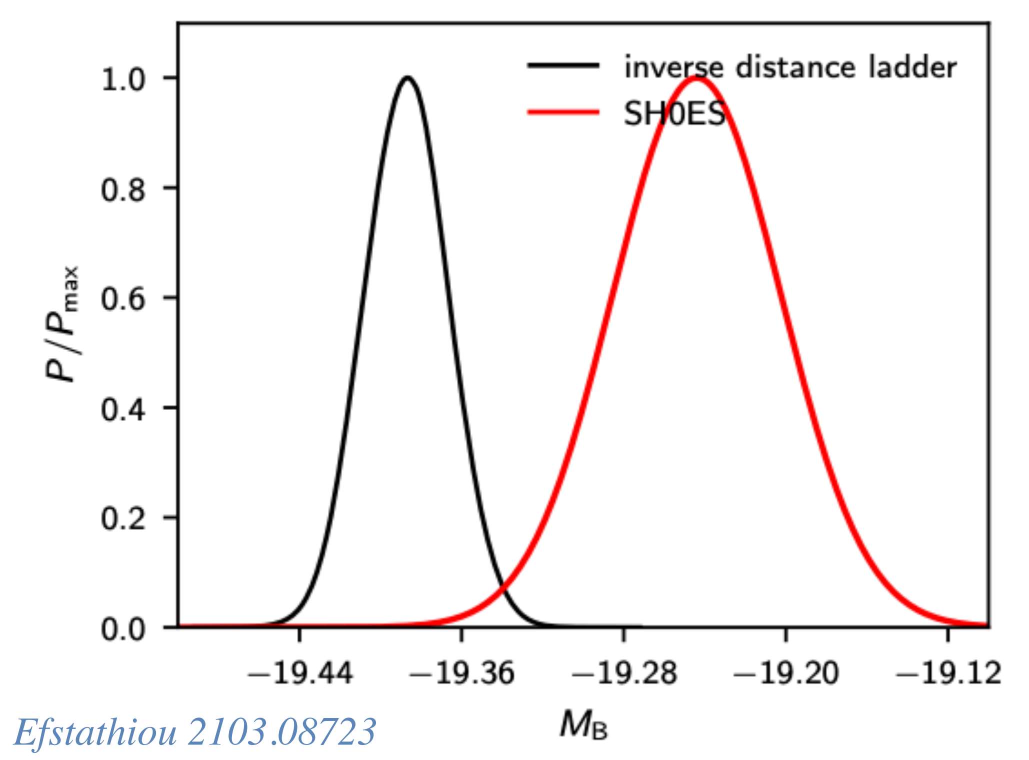
$$\mu(z) = 5{\rm Log}_{10}D_L(z) + M_b$$

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

- Calibration constant from e.g. SH0ES.



Raveri++ 2107.12992



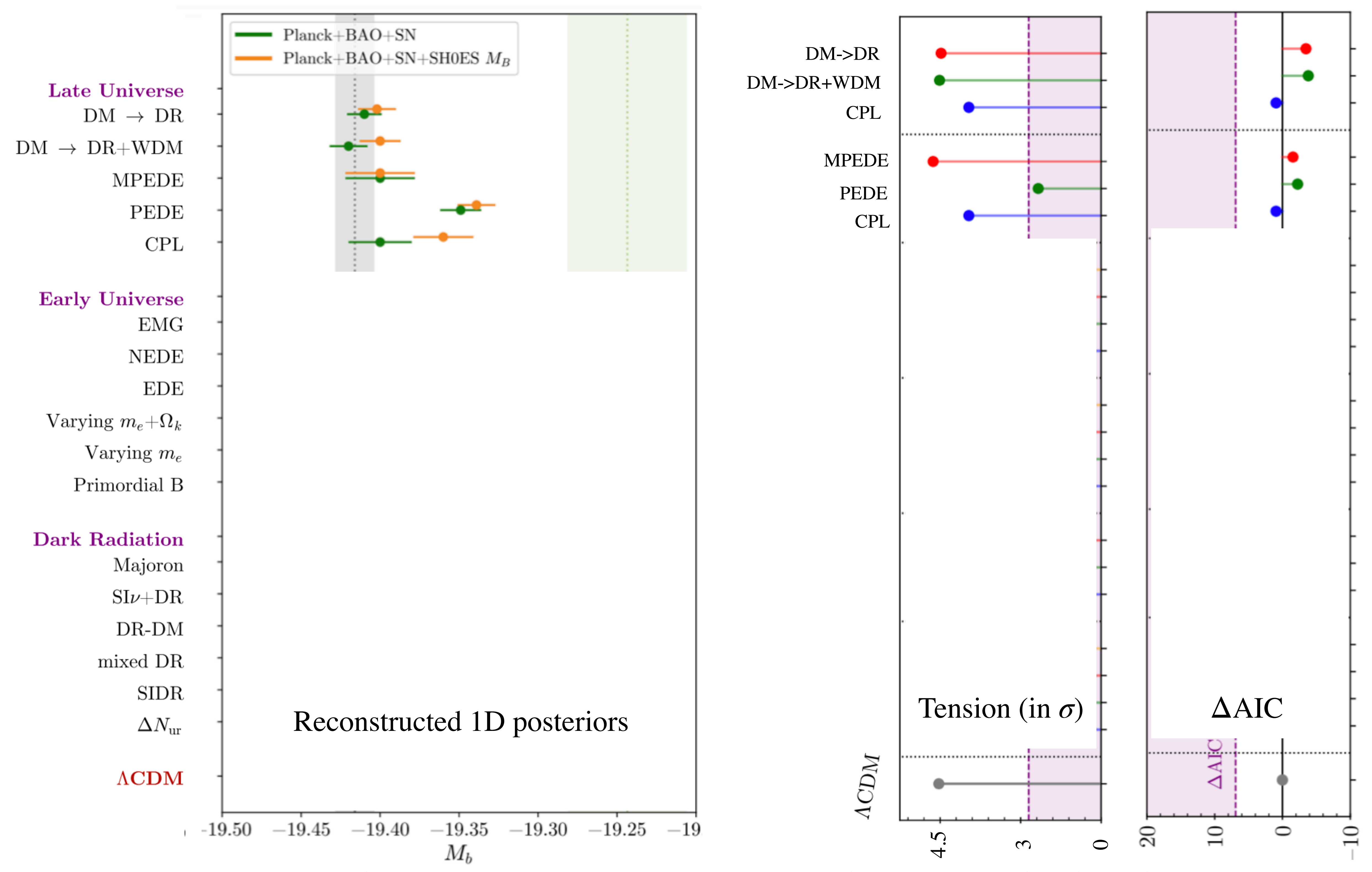
Efstathiou 2103.08723

- While some late-time solutions seem to resolve the ‘H_0-tension’, they introduce a ‘M_b-tension’.

- The question is: how to make the inverse ladder calibration of Pantheon SN1a compatible with SH0ES?

Status of "late-universe" modifications

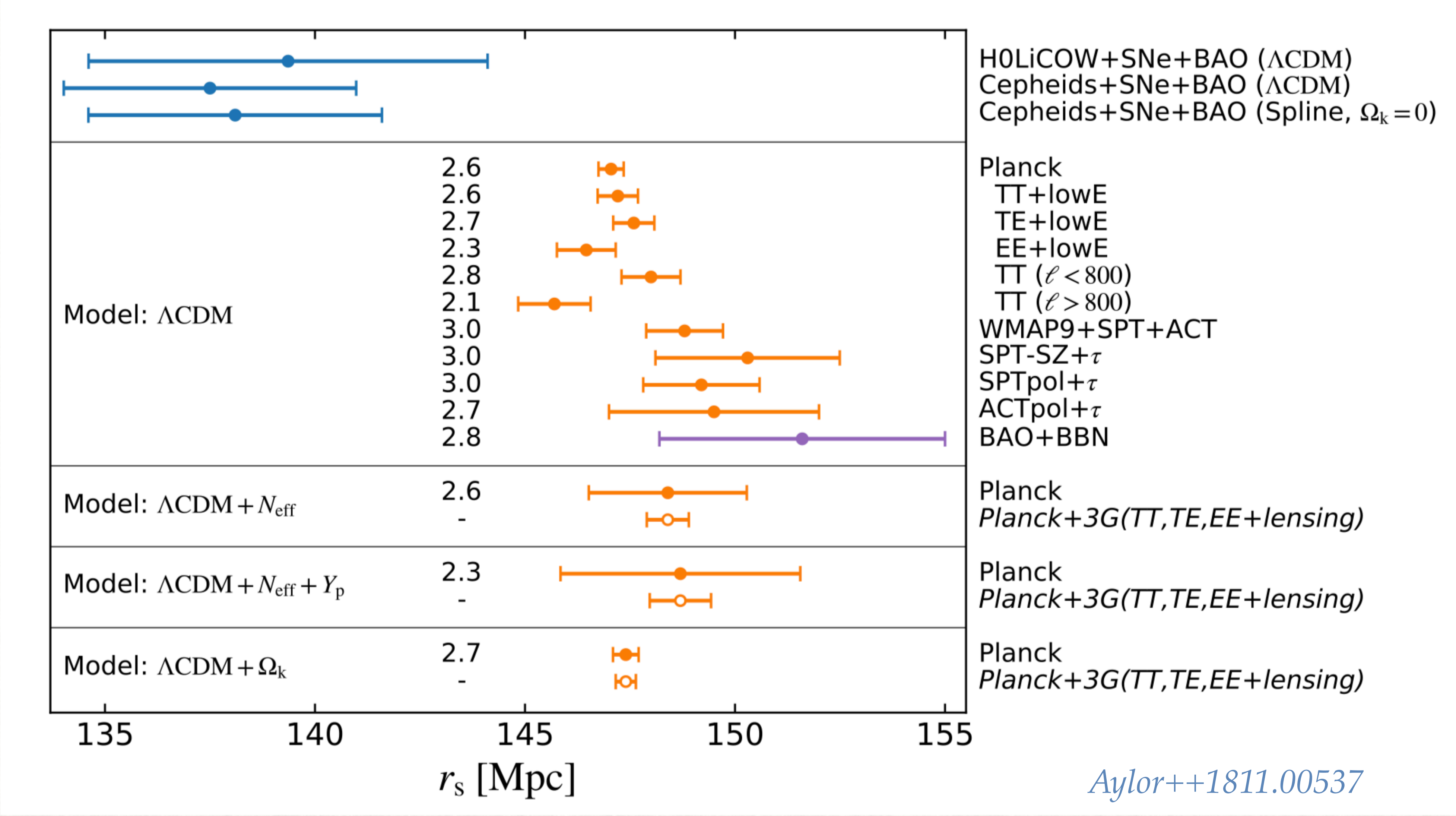
Schöneberg (VP) ++ 2107.10291



Late-universe models are excluded as a resolution to the tension (alone)

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

affect z*: modified recombination physics?

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

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

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

Knox & Millea 1908.03663

Extra-relativistic degrees of freedom $N_{\rm eff}$

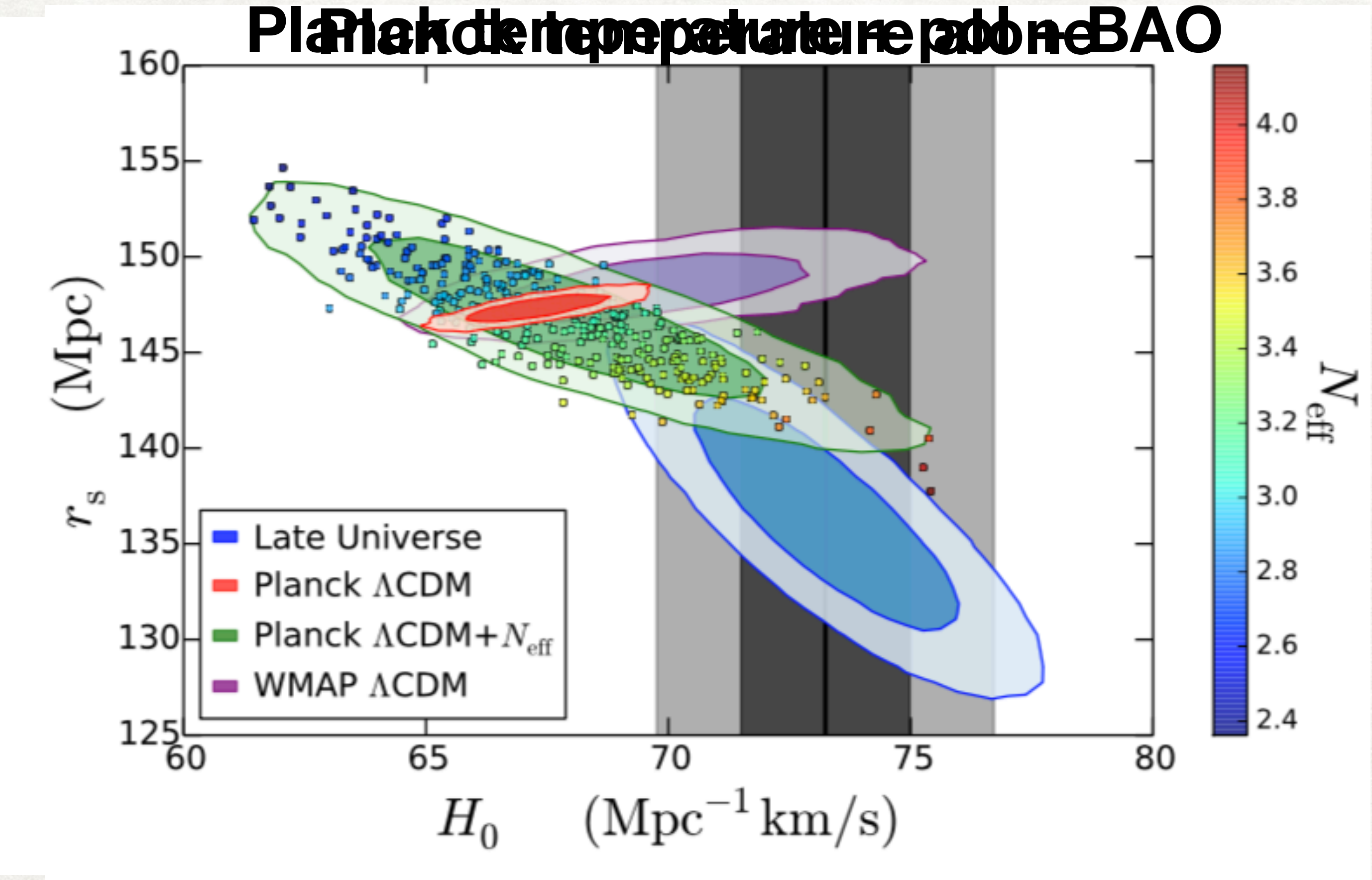
- Additional relativistic degrees of freedom can be parametrized by $N_{\rm eff}$ at the background level

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

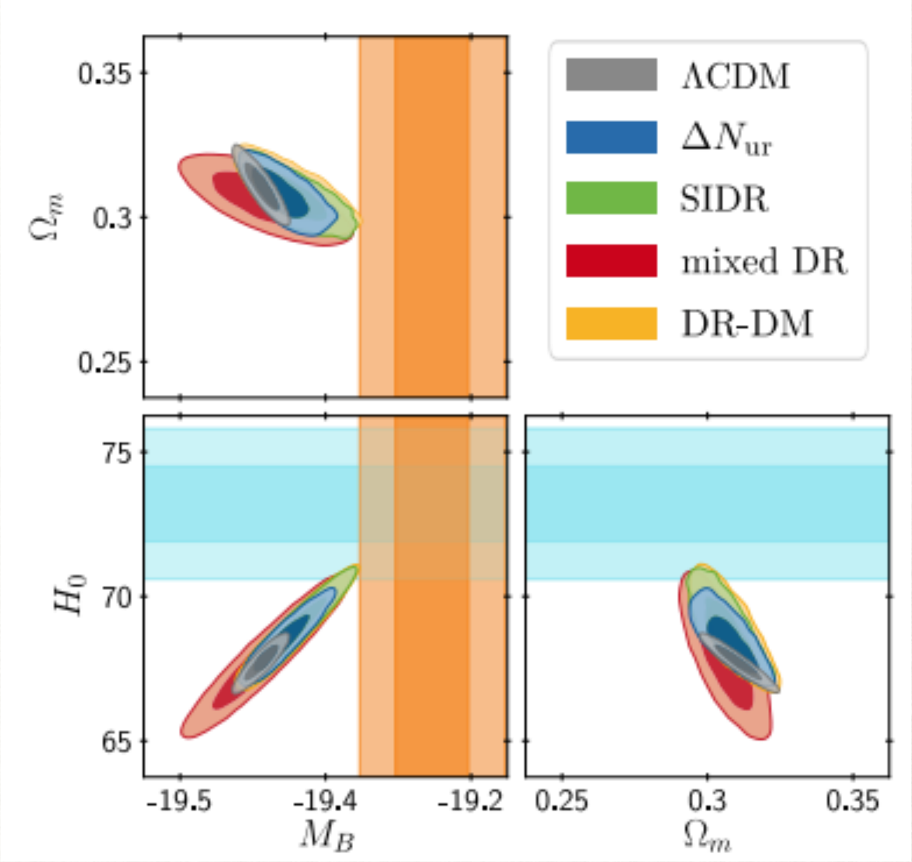
Talks by Yvonne Wong

- 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



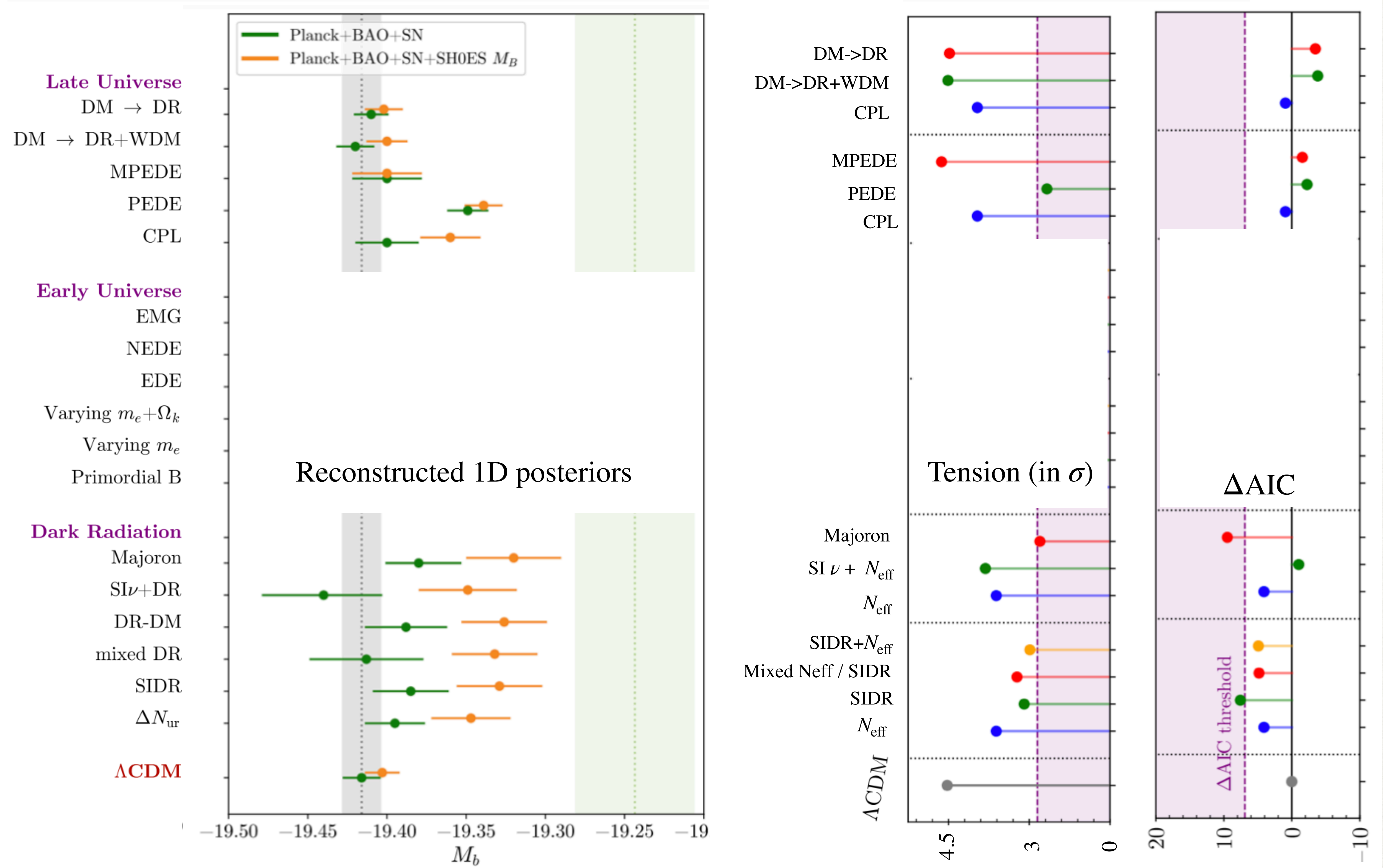
Bernal++ 1607.05617



Schöneberg++2107.10291

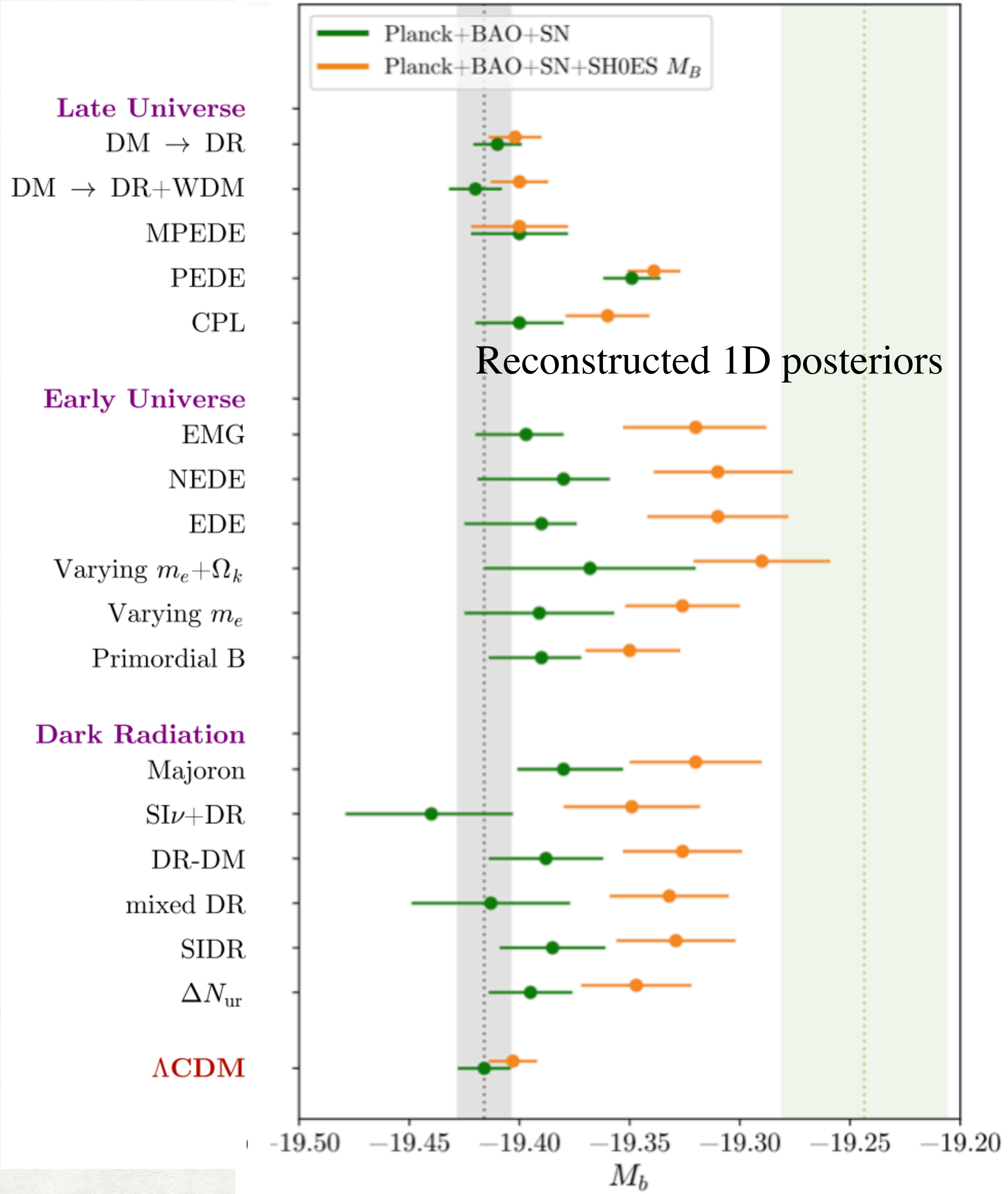
- Reducing neutrino anisotropic stress (generated by free-streaming) only mildly affect the contraints.

Status of “N_{eff}–like” solutions

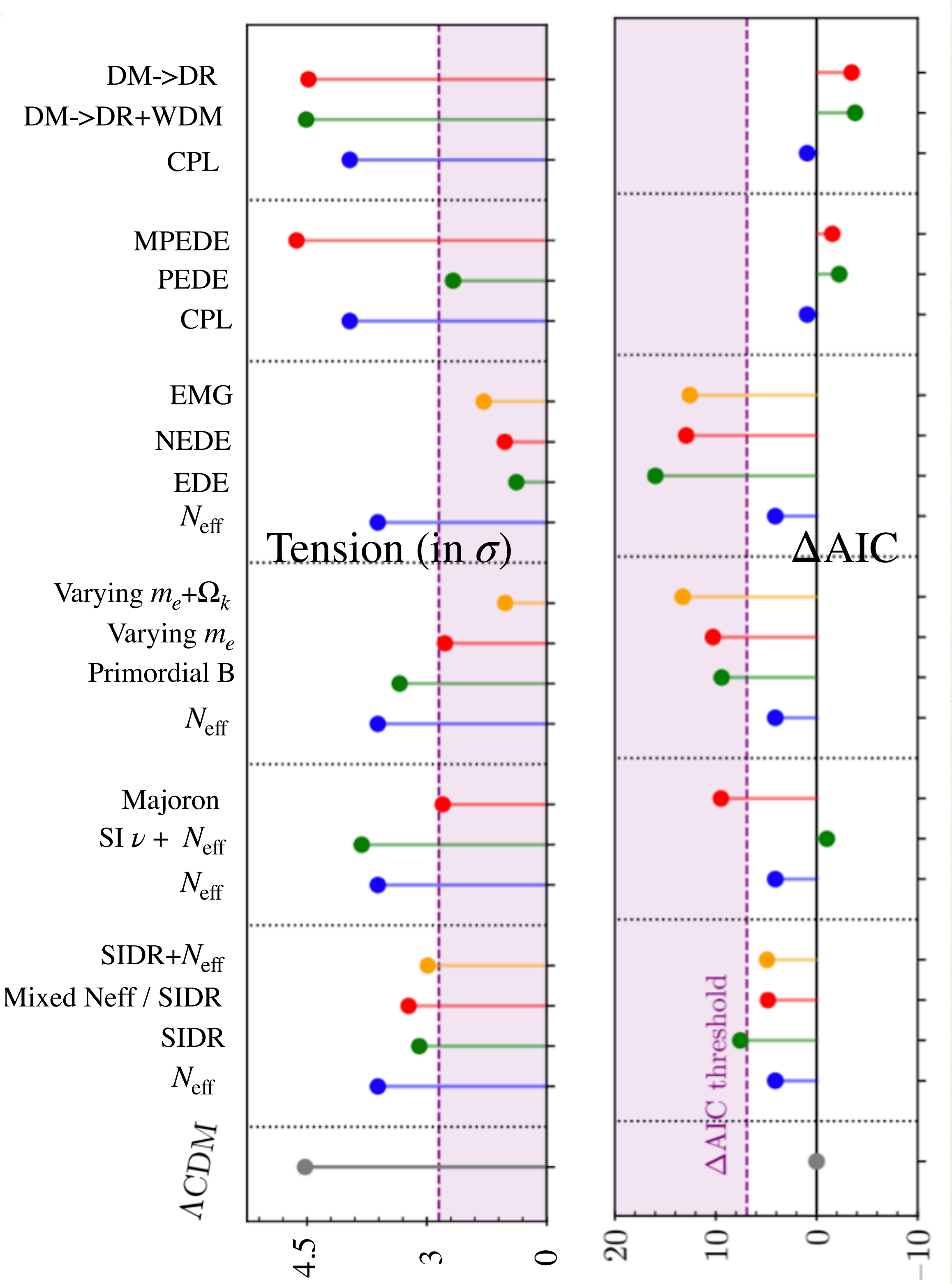


Extra-radiation can bring the tension down to the 3σ level but are not favored without H_0 prior

Status of “Early-Universe” solutions



Reconstructed 1D posteriors



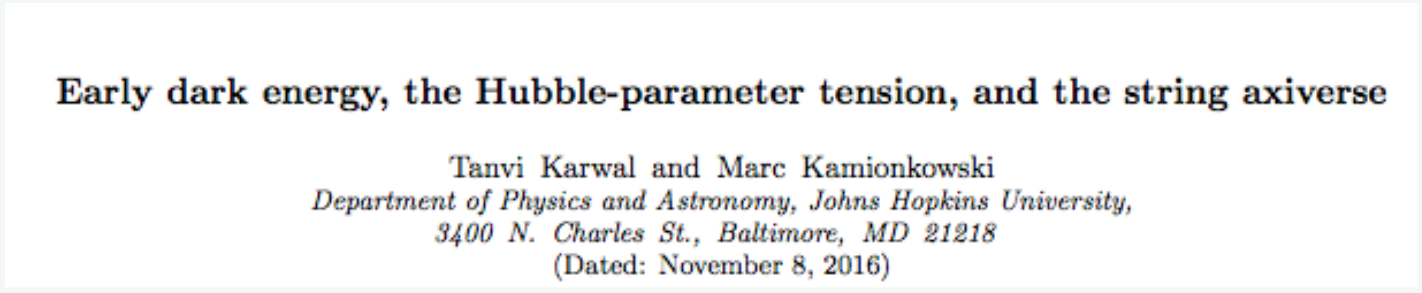
Tension (in σ)

ΔAIC

EDE / EMG / $m_e + \Omega_k$ can bring the tension down to the 1.5-2σ level but are not favored without H_0 prior

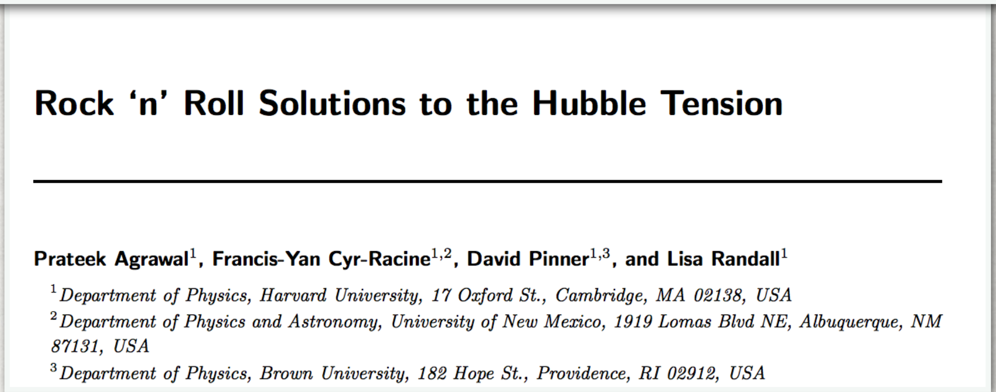
Early Dark Energy(s) & Modified Gravity

Not all have the same
level of success…



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

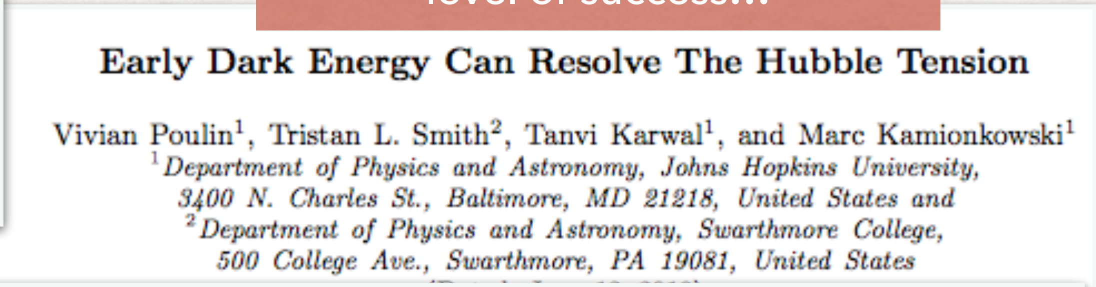
Tanvi Karwal and Marc Kamionkowski
Department of Physics and Astronomy, Johns Hopkins University,
3400 N. Charles St., Baltimore, MD 21218
(Dated: November 8, 2016)



Rock 'n' Roll Solutions to the Hubble Tension

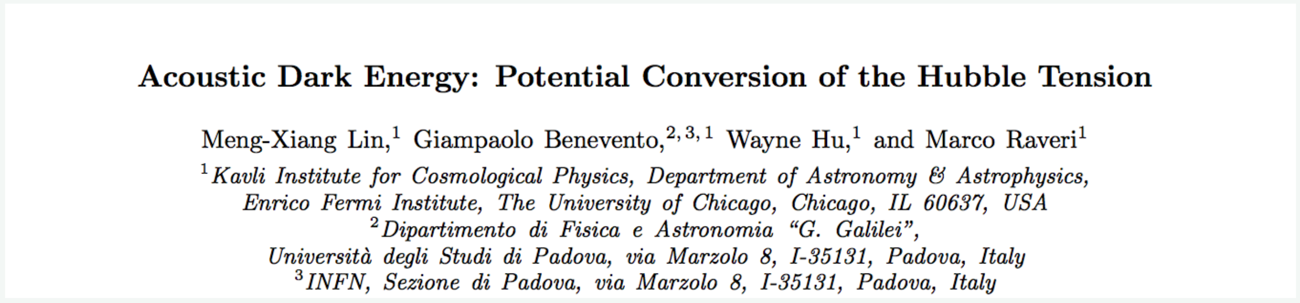
Prateek Agrawal[1], **Francis-Yan Cyr-Racine**[1,2], **David Pinner**[1,3], **and Lisa Randall**[1]

[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*



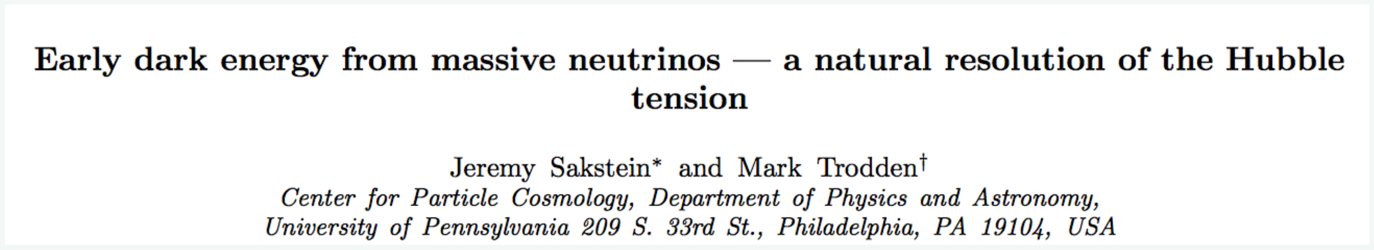
Early Dark Energy Can Resolve The Hubble Tension

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



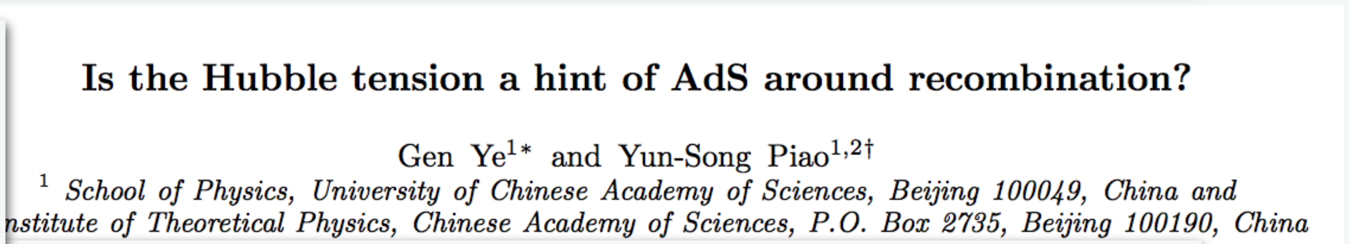
Acoustic Dark Energy: Potential Conversion of the Hubble Tension

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*



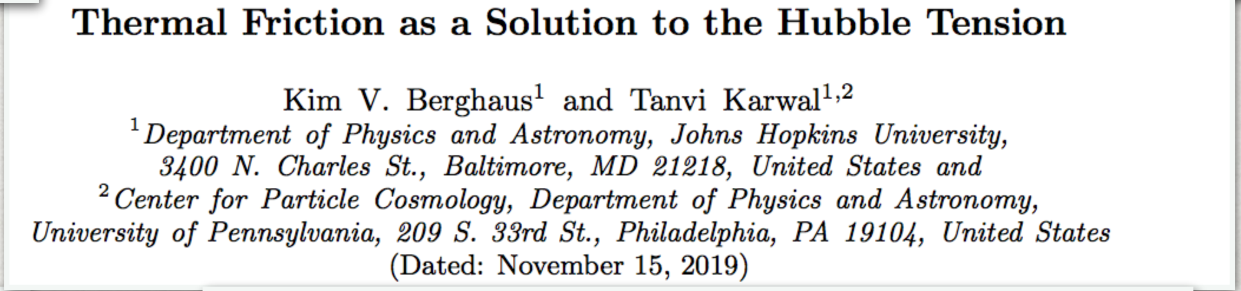
Early dark energy from massive neutrinos — a natural resolution of the Hubble tension

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



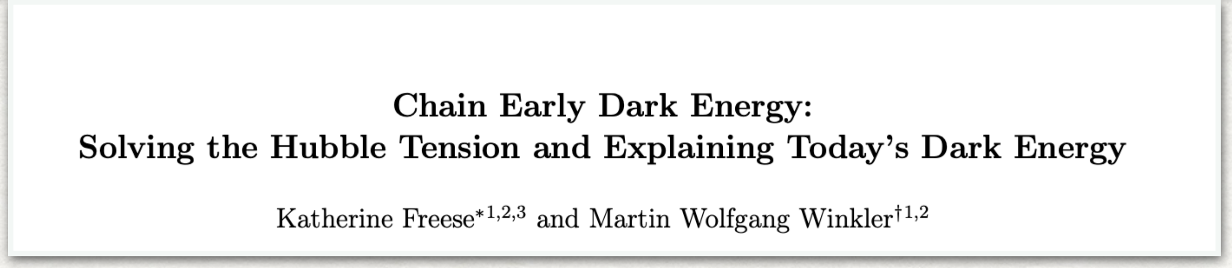
Is the Hubble tension a hint of AdS around recombination?

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



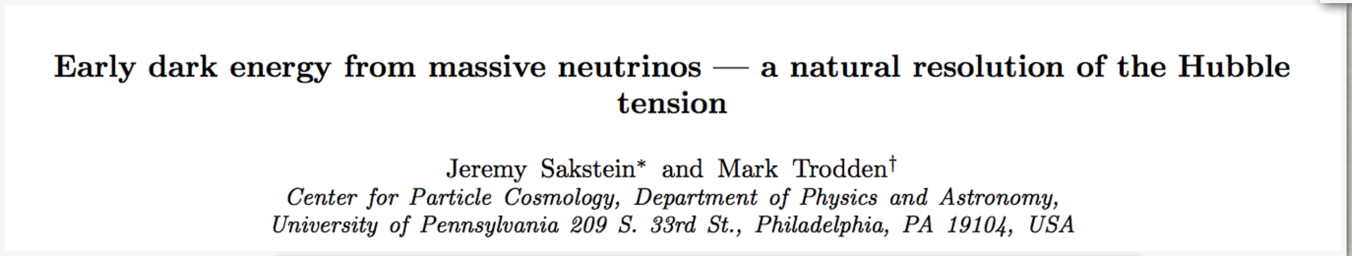
Thermal Friction as a Solution to the Hubble Tension

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)



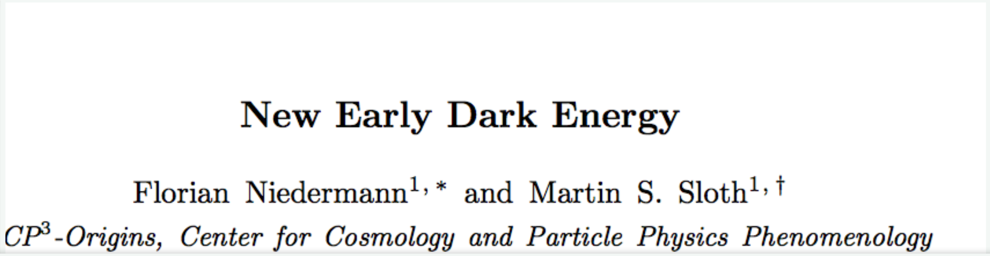
Chain Early Dark Energy:
Solving the Hubble Tension and Explaining Today's Dark Energy

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

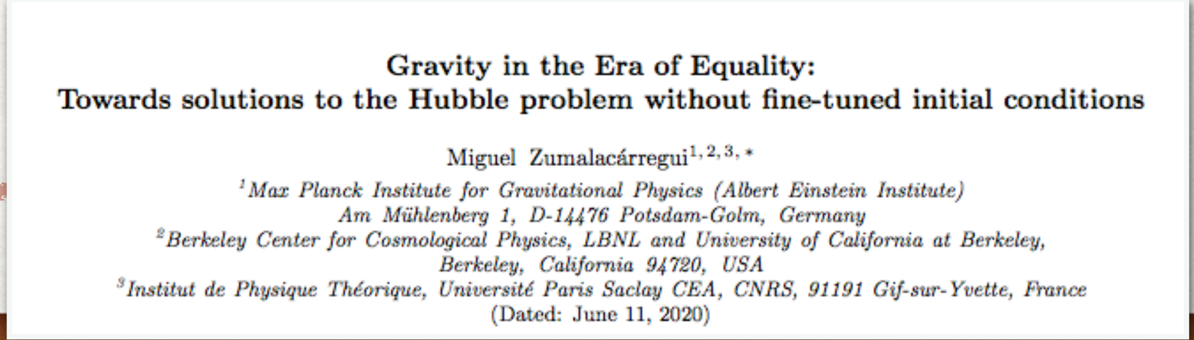


New Early Dark Energy

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



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

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

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

- Oscillating (toy) potential:

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

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

- Perform 'cycle-averaging' over oscillations.
- Specified by $f_{\rm EDE}(z_c)$, z_c, $w(n)$, $c_s^2(k,\tau)$

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

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

- First-order phase transition (NEDE model)

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

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

Linder 1505.00815, Braglia++ 2005.14053

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

Braglia++ 2011.12934

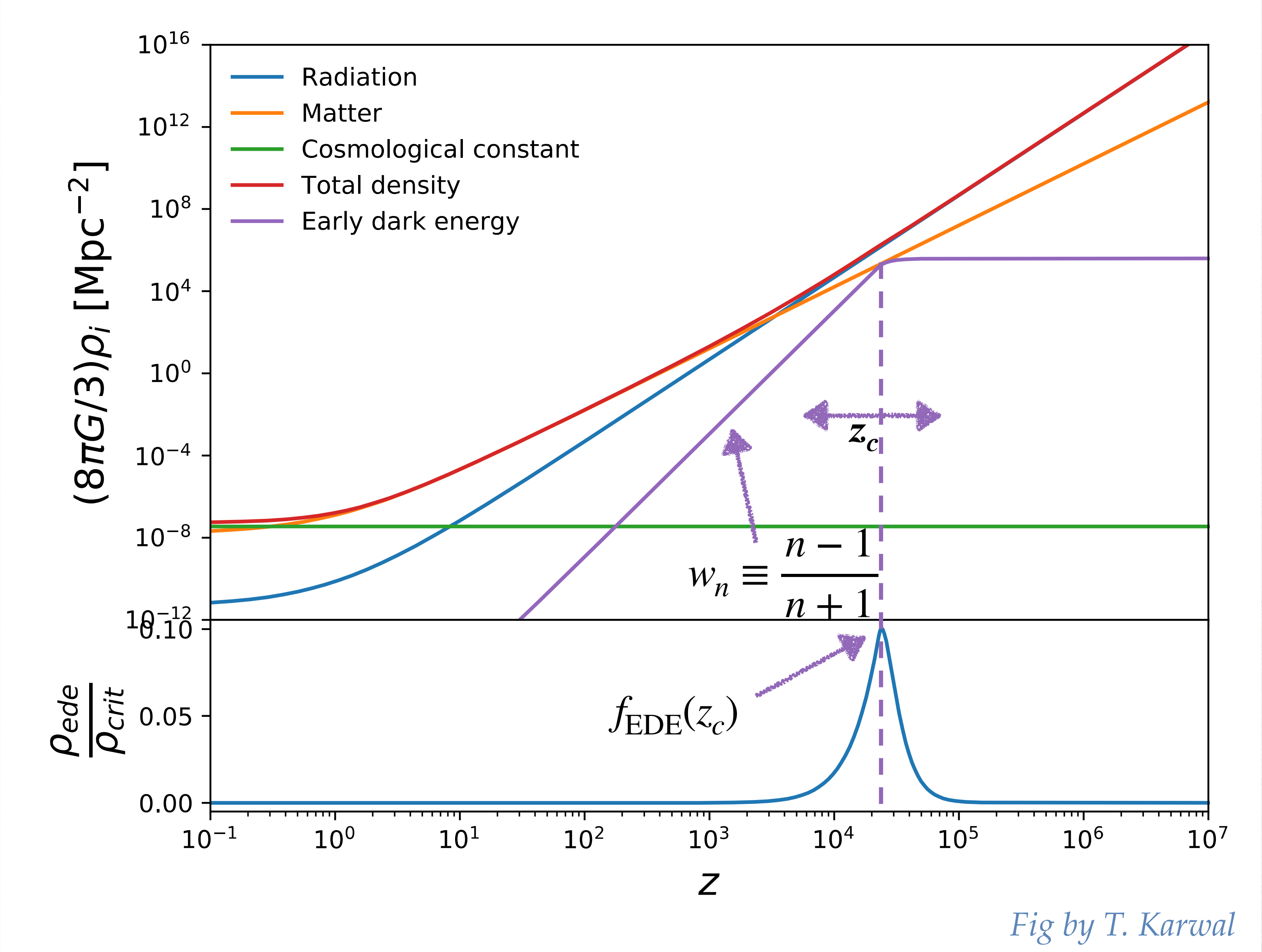
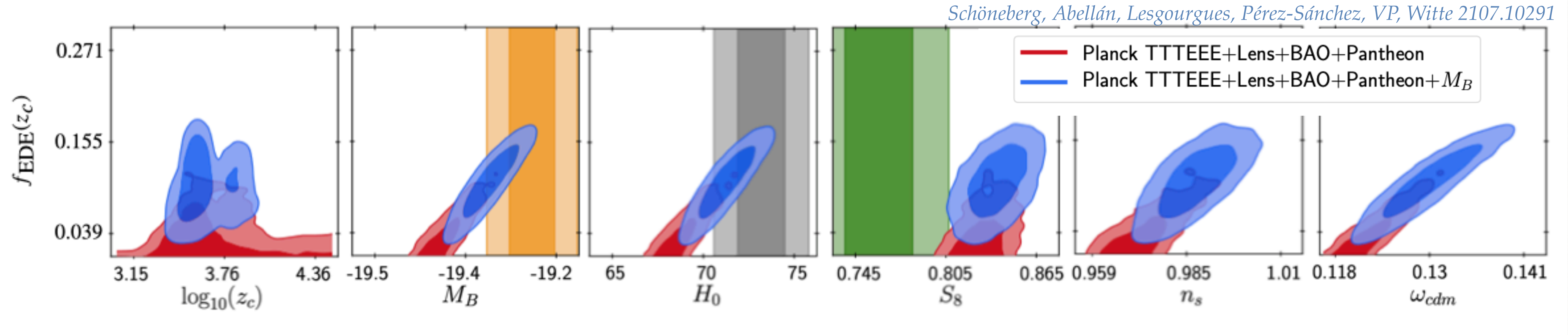


Fig by T. Karwal

EDE vs *Planck* data



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

- Without information from SH0ES: 95% C.L (best-fit). Beware of long tails! Statistics is NOT Gaussian.

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

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

- Adding the M_b prior from SH0ES: tension is reduced to 1.5σ and EDE is detected at 3.5σ.

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

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

$$Q_{\text{DMAP}} \equiv \sqrt{\chi^2(\text{w/ SH0ES}) - \chi^2(\text{w/o SH0ES})} = 1.5\sigma$$

- Our results favor $f_{\text{axion}} \sim 0.1M_{\text{pl}}$ & $m \sim 10^{-28}$ eV, with $n \sim 3^{+0.18}_{-1}$ and disfavor pure power-law (large θ_i).

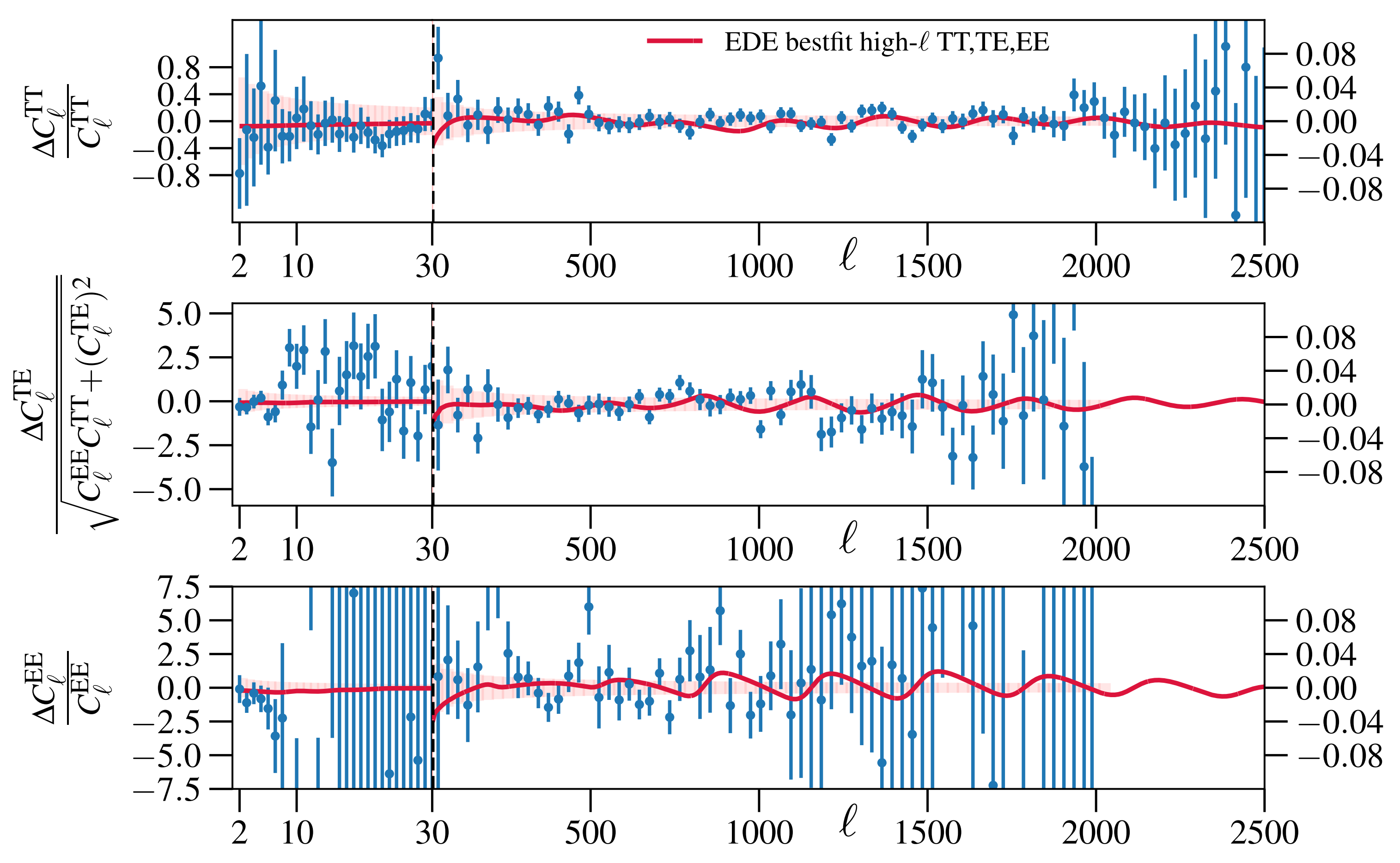
- Theoretical problem: the field becomes dynamical around z_{eq}: Fine-tuning ? Coincidence problem 2.0?

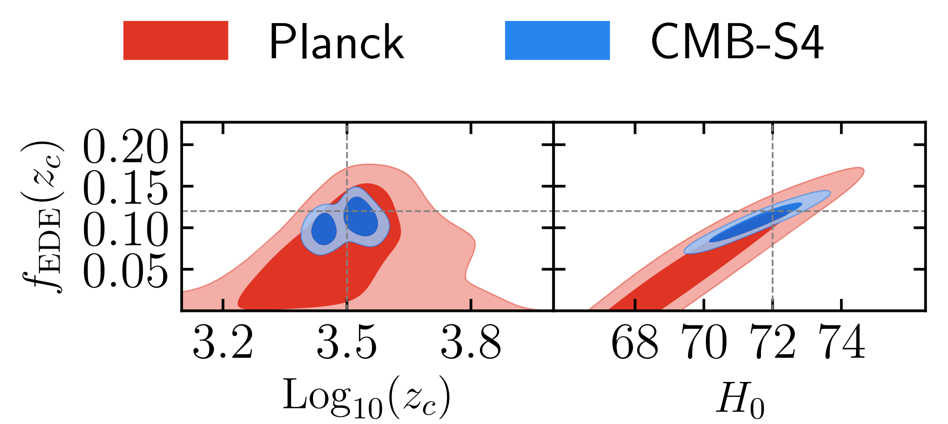
e.g. Dodelson++astro-ph/0002360, Griest astro-ph/0202052, Kamionkowski++1409.0549, Sakstein&Trodden 1911.11760, Carrillo González++ 2011.09895

- Observational problem: EDE cosmology has a higher ω_{cdm} and n_s: in tension with GC and WL surveys?

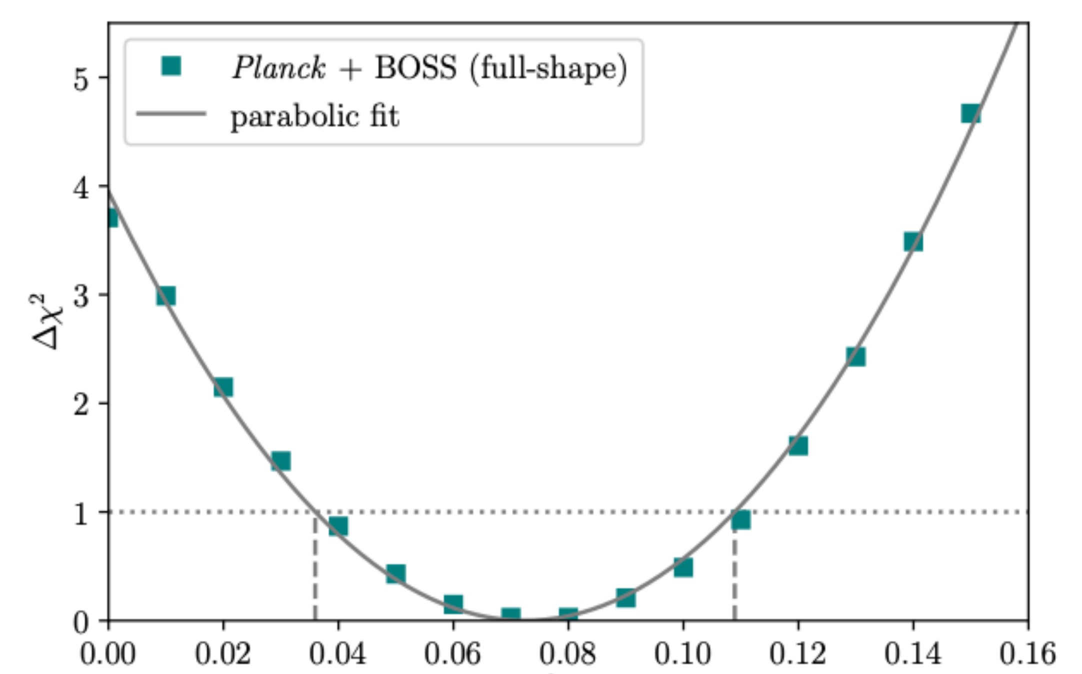
Hill et al. 2003.07355, Ivanov++ 2006.11235 , d'Amico++ 2006.12420 Niedermann++ 2009.00006, Smith++ 2009.10740, Murgia++ 2009.10733

EDE leaves a signature but too small for *Planck*





Smith ++ 1908.06995



Herold ++ 2112.12140

- *Planck* 'alone' cannot detect $f_{EDE}(z_{eq}) \sim 10\,\%$ & $H_0 = 72$ km/s/Mpc: limits are biased!
- Analysis with profile likelihood indicates 2.5σ preference for EDE from *Planck* + BOSS!
- Future experiments (Simons Observatory, CMB-S4) could unambiguously detect EDE.

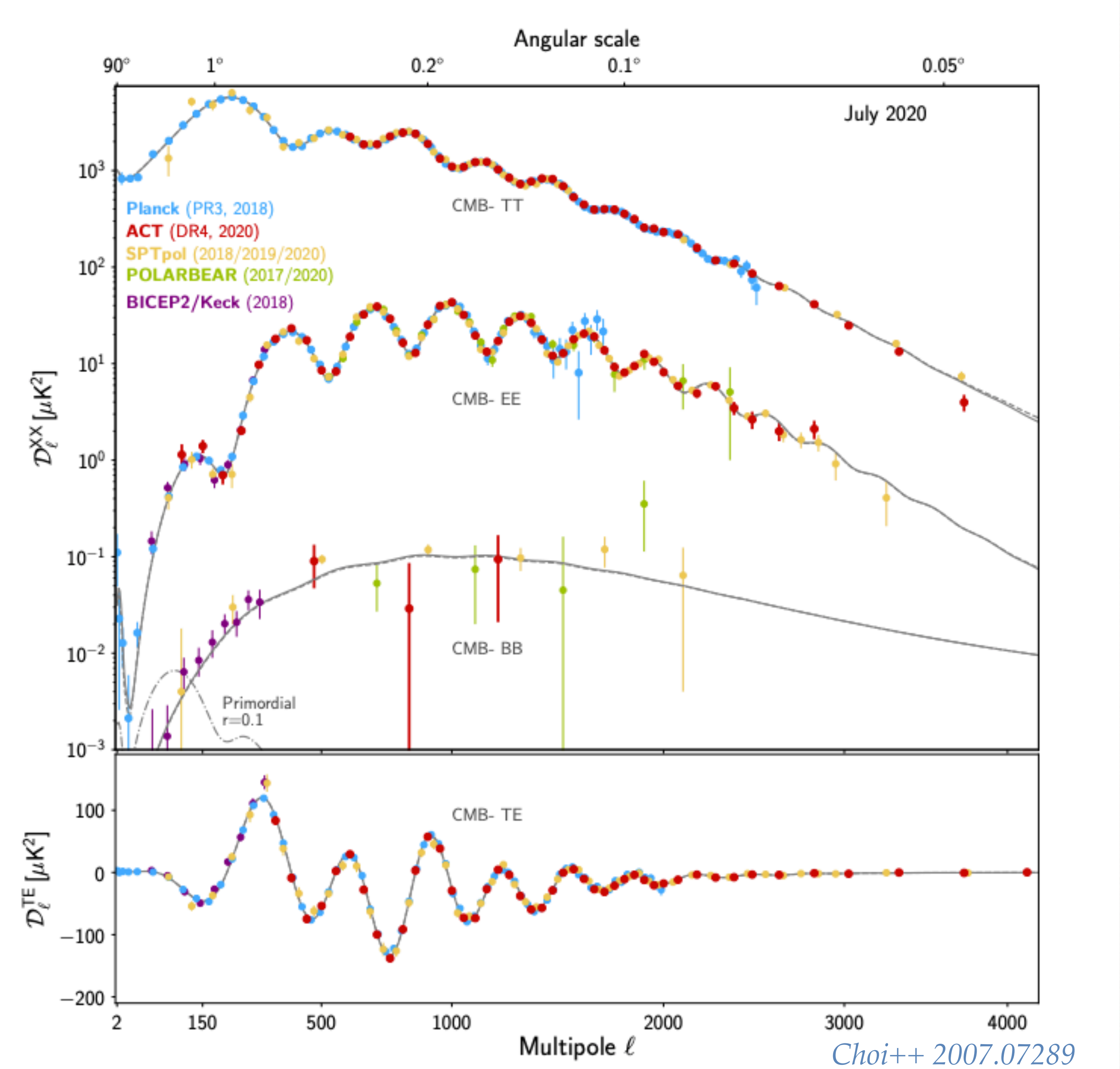
New CMB data at small scales

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

Talk by Steve Choi *Talk by Alexandra Rahlin*


The Atacama Cosmology Telescope (act.princeton.edu)

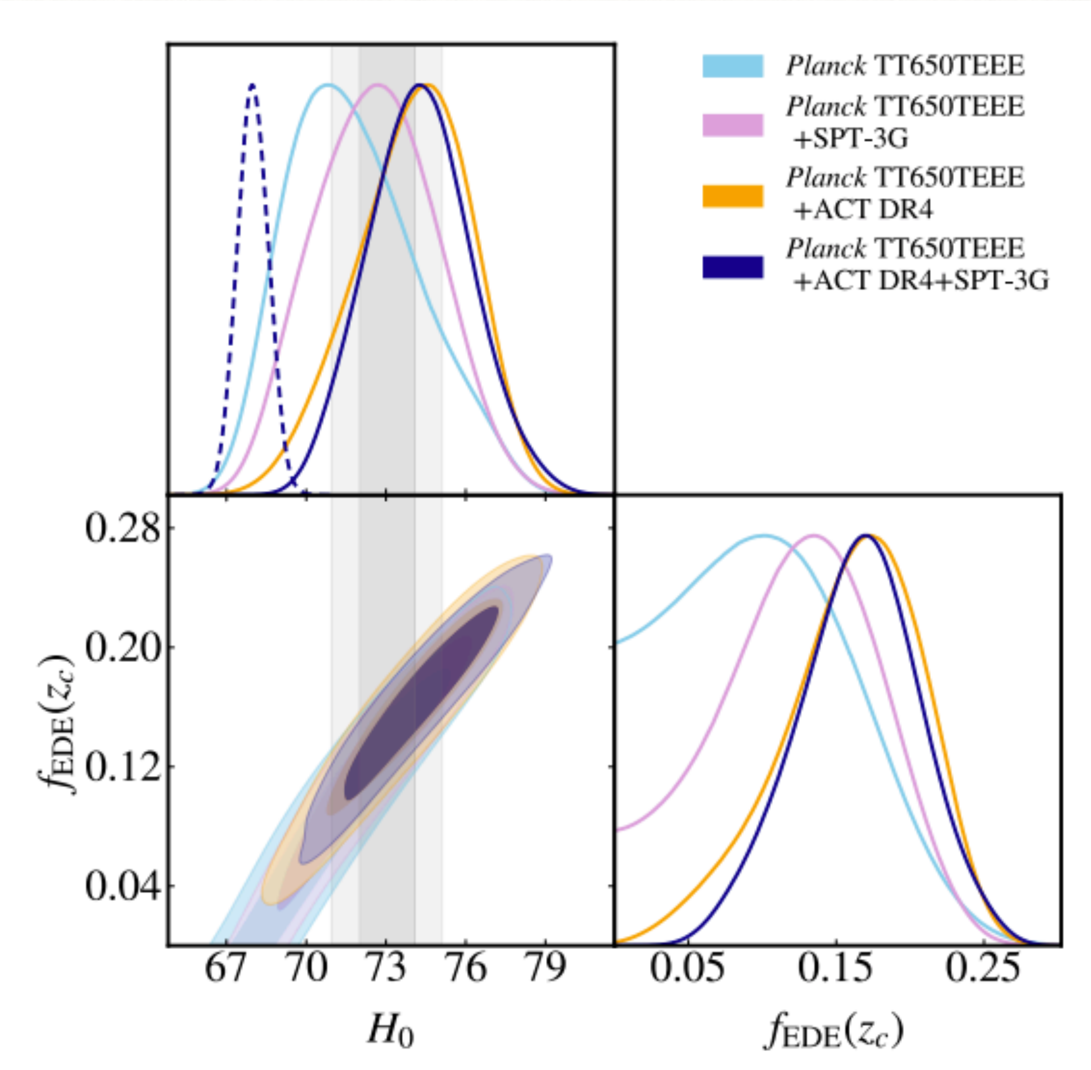

The South Pole Telescope (act.princeton.edu)



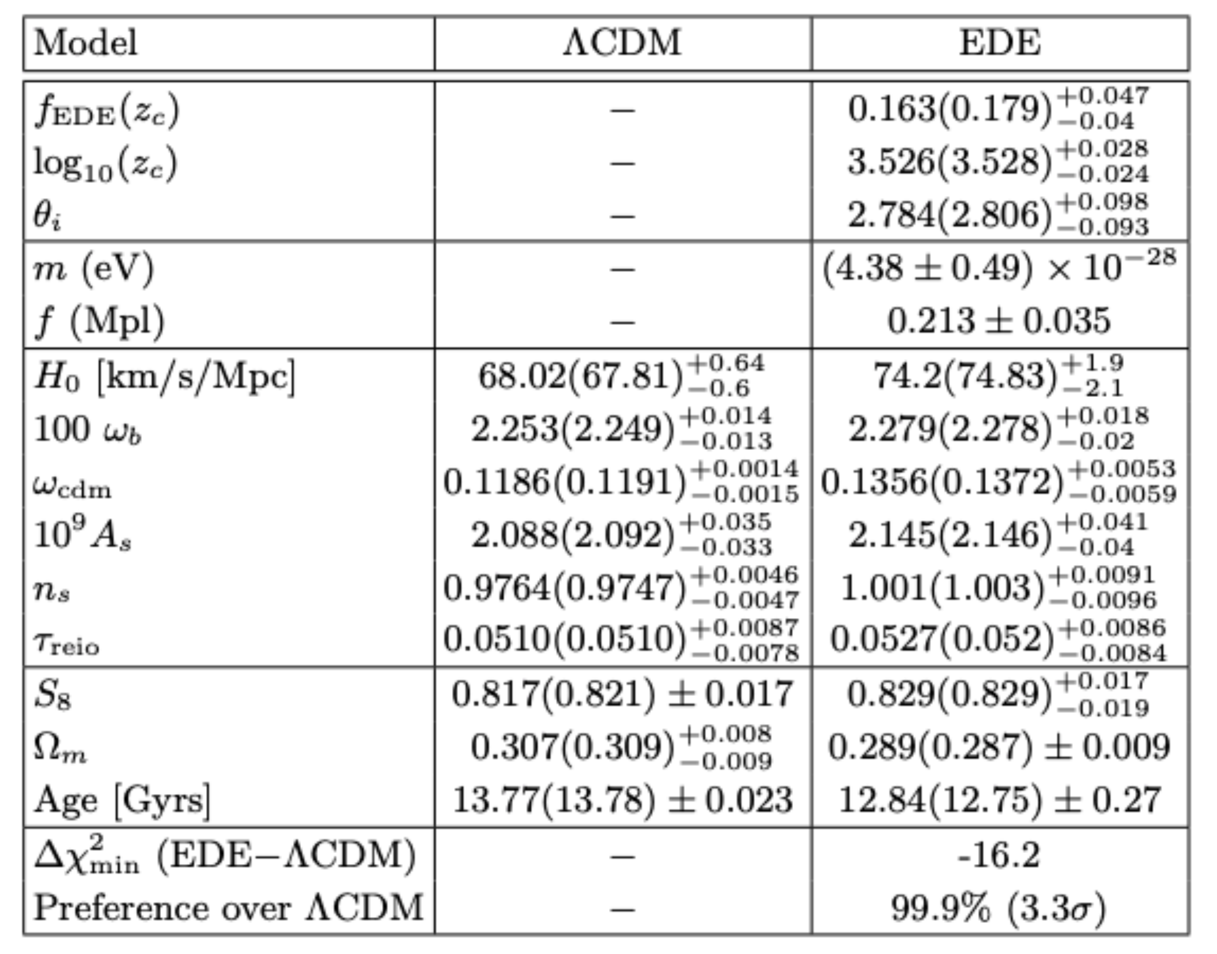
Choi++ 2007.07289

Consistency test: *Planck* vs WMAP+ACT+SPT

- *Planck*650TT$\simeq$ WMAP



Smith, Lucca, VP++ 2202.09379

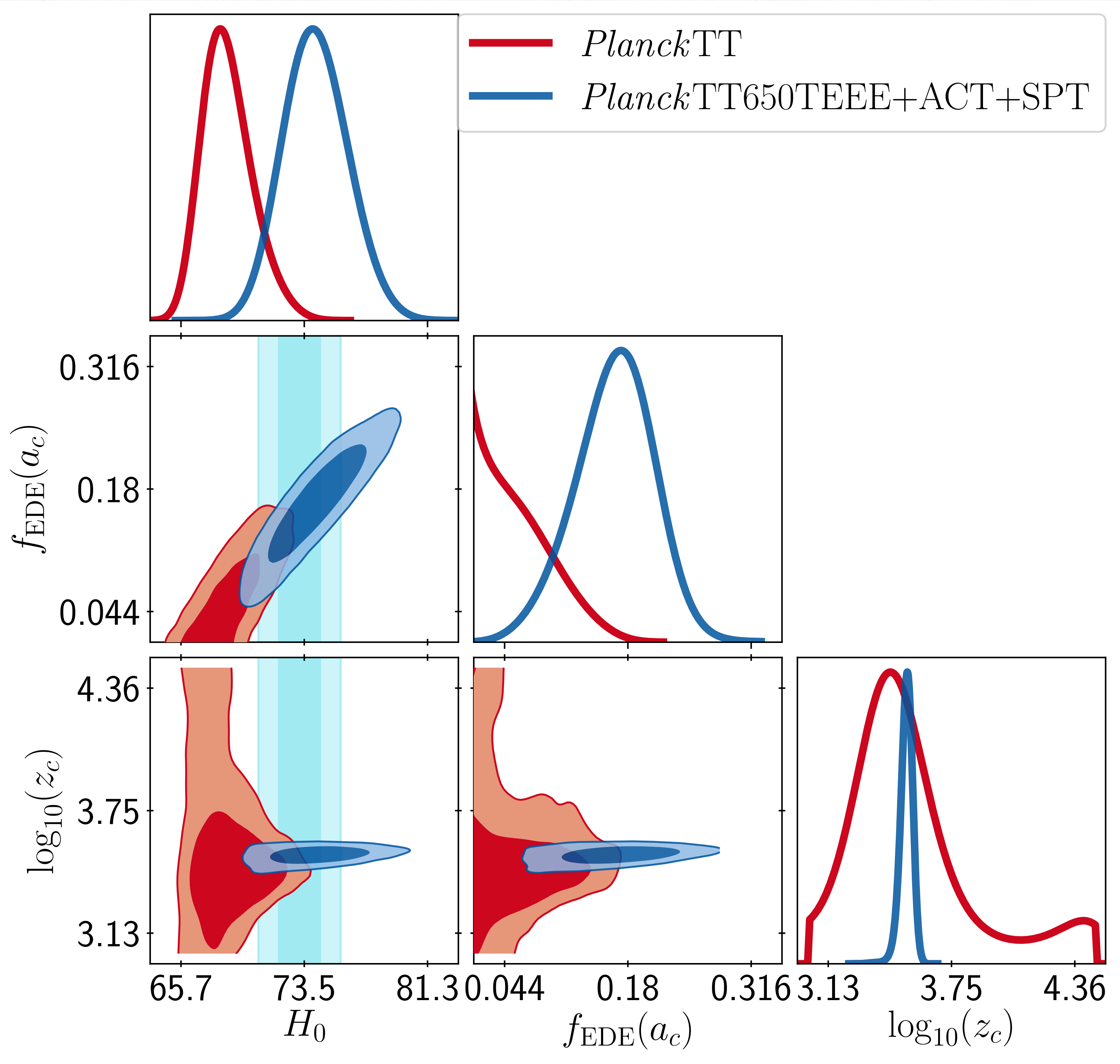


Model	ΛCDM	EDE
$f_{\rm EDE}(z_c)$	–	$0.163(0.179)^{+0.047}_{-0.04}$
$\log_{10}(z_c)$	–	$3.526(3.528)^{+0.028}_{-0.024}$
θ_i	–	$2.784(2.806)^{+0.098}_{-0.093}$
m (eV)	–	$(4.38 \pm 0.49) \times 10^{-28}$
f (Mpl)	–	0.213 ± 0.035
H_0 [km/s/Mpc]	$68.02(67.81)^{+0.64}_{-0.6}$	$74.2(74.83)^{+1.9}_{-2.1}$
100 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$-\Lambda$CDM)	–	-16.2
Preference over ΛCDM	–	99.9% (3.3σ)

- There is a 3.3σ preference for EDE with no residual tension with SH0ES.
- The preference is driven by *Planck* polarization and ACT data.
- 2.1-2.3σ S_8-tension with KiDS-1000 and DESY3.

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

PlanckTT vs PlanckTEEE+ACT+SPT



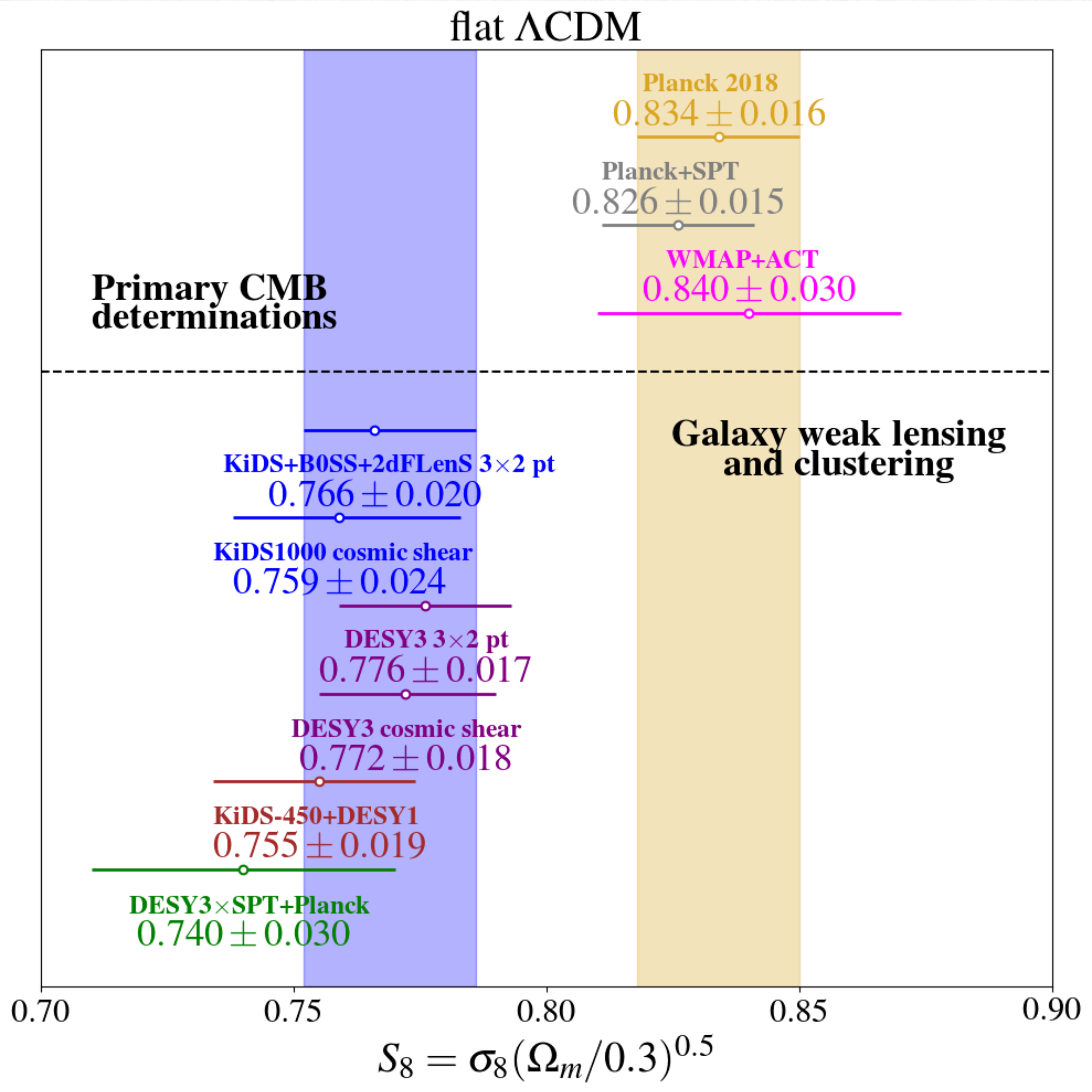
- (Small) tension between *Planck*TT and *Planck*TEEE+ACT+SPT?

The S_8 tension

Talk by Theo Simon

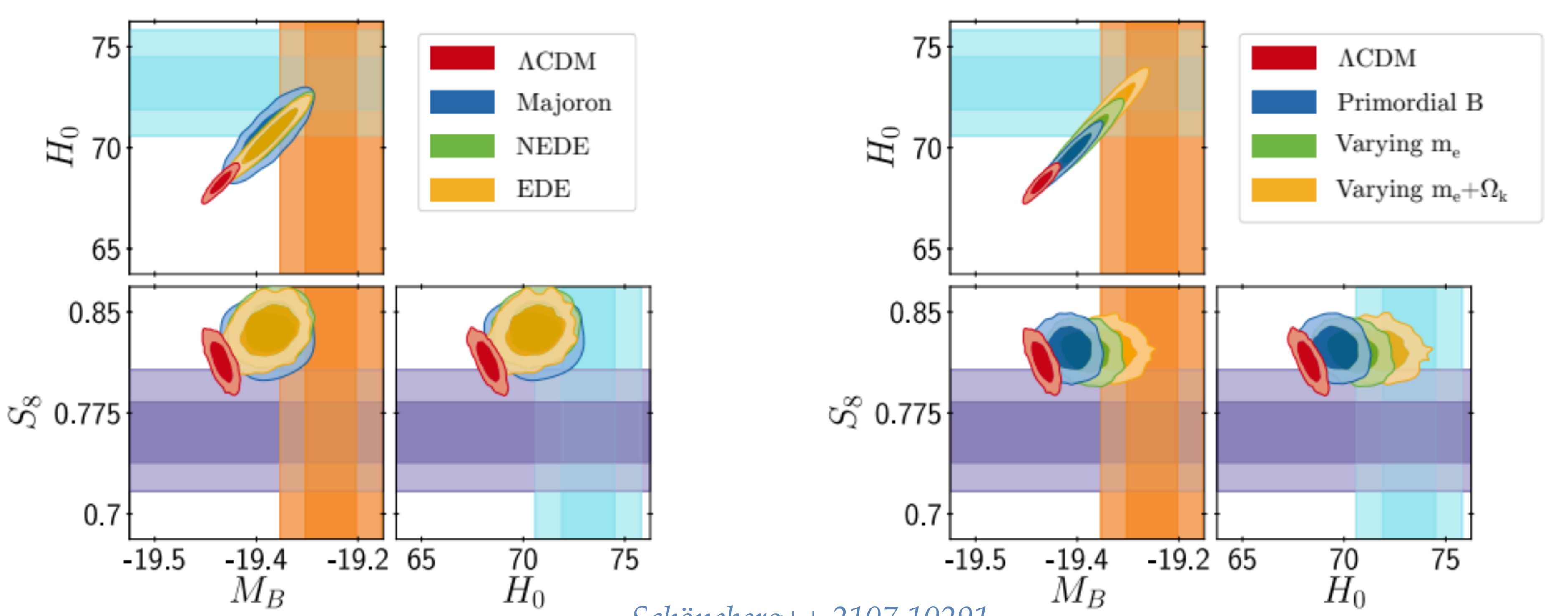
Talk by Jozef Bucko

Talk by Keir Rogers



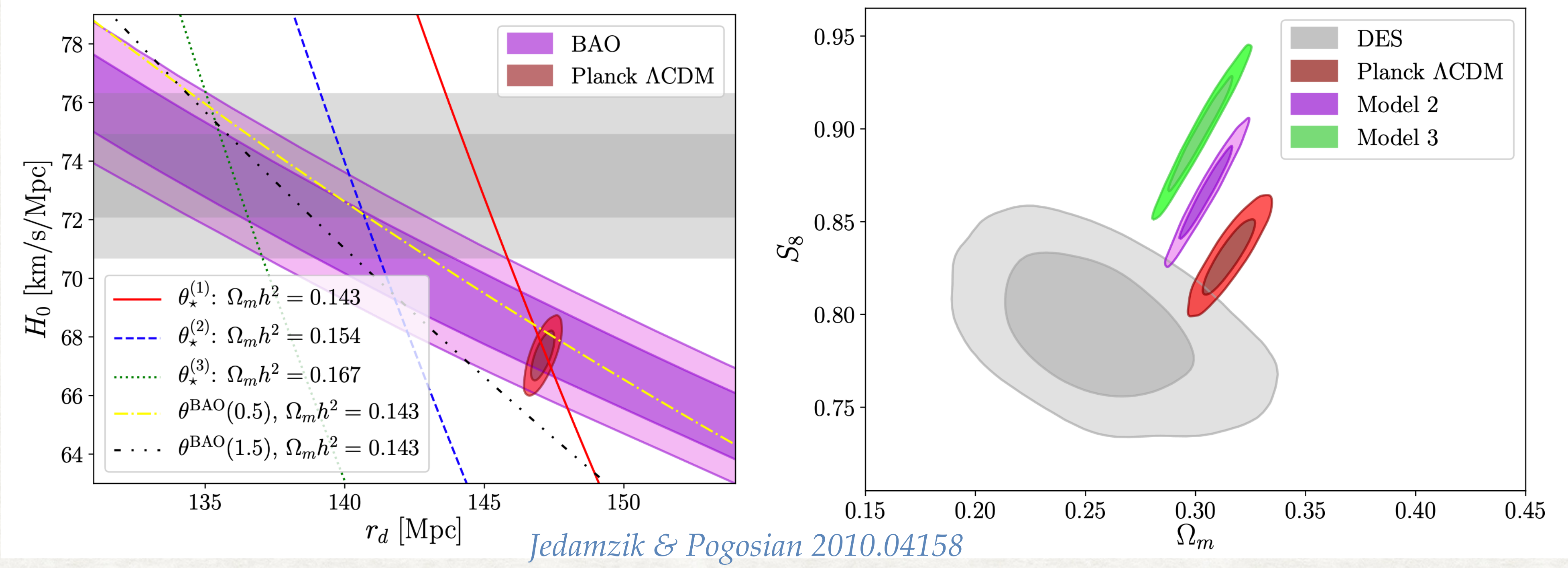
There is a 2-3σ tension between S_8 from WL x GC measurements and *Planck*

Early universe models cannot explain low S_8



Schöneberg++ 2107.10291

- EDE (and other models) cannot explain both tensions! It requires some additional dynamics (DDM? ULA? DM/DR?).



Jedamzik & Pogosian 2010.04158

- Fitting CMB, H_0 and BAO with lower $r_s(z_{\rm rec})$ requires higher $\omega_{\rm cdm}$: the S_8 tension increases! Very generic.

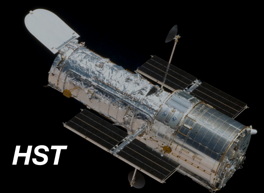
Barring systematic errors: no 'concordance cosmology' just yet

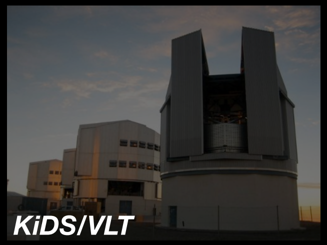
- ΛCDM explains CMB and BBN (<2σ), but there exists a $4{-}6\sigma$ H_0-tension and a $2-3\sigma$ σ_8-tension.
- Late-time models are excluded: one needs to adjust the CMB/BAO sound horizon r_s to match SH0ES calibration.
- $N_{\rm eff}$ and other Dark-radiation like models lead to $\sim 3\sigma$ tension, but are perhaps the best motivated models.
- "Exotic Early-Universe" (EDE / EMG / $m_e + \Omega_k$) models bring down to $\sim 1.5\sigma$ but do not explain S_8.
  ==> A common solution must come from different sectors (DDM/ULA/DM-DR) or a more complexe dynamics.
- Future CMB experiments will tell! Hints of EDE from ACT to be confirmed with better data. Early-universe models lead to signatures that will be tested with SO / CMB-S4.

- Some recent twist: "step-like" dark radiation can do slightly better than what was discussed here. *Alloni ++ 2111.00014*
- The "mirror world": a scaling symmetry involving a copy of the SM in the dark (at odds with BBN) *Cyr-Racine++2107.13000*
- The age of the Universe: Early-Universe models predict $t_u \sim 13$ Gyrs! Globular clusters $t_U = 13.5 \pm 0.027$ Gyr. *Boylan-Kolchin++ 2103.15825, Bernal++ 2102.05066*
- Effective field theory analysis of BOSS rules out EDE and other early-universe models? *Hill et al. 2003.07355, Ivanov++ 2006.11235 , d'Amico++ 2006.12420 Niedermann++ 2009.00006, Smith++ 2009.10740, Philcox++ 2204.02984*

The challenge is immense but ΛCDM is purely parametric: H_0 and σ_8-tensions could be the first signs of a rich dark sector!

Thanks for your attention!





Vivian Poulin

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

vivian.poulin@umontpellier.fr

Rencontres de Blois
May, 27th 2022