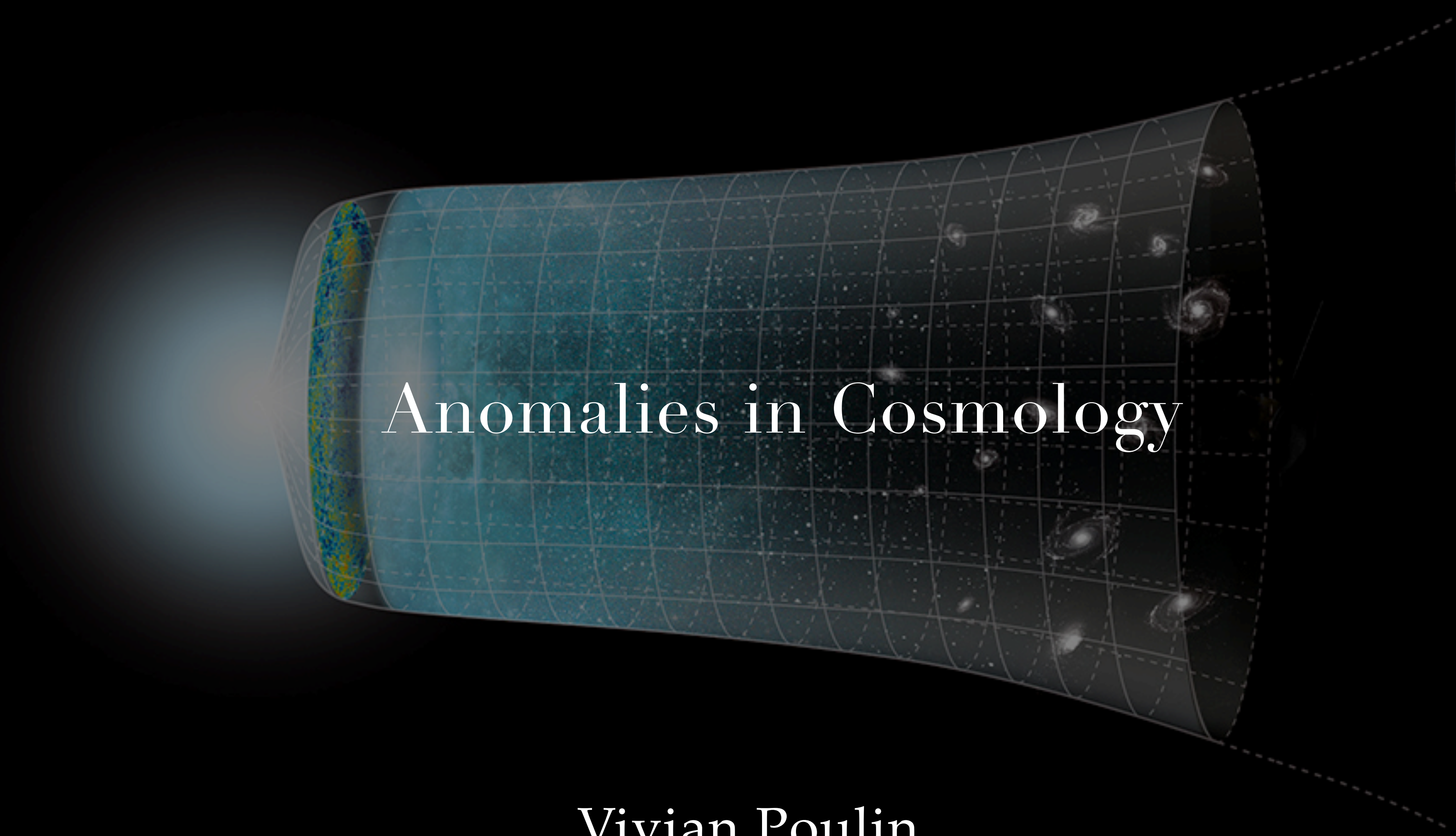
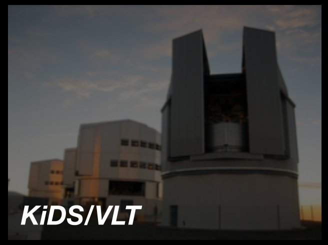
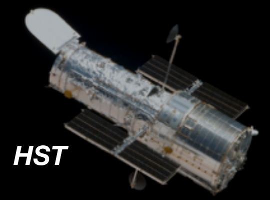


Anomalies in Cosmology





Vivian Poulin

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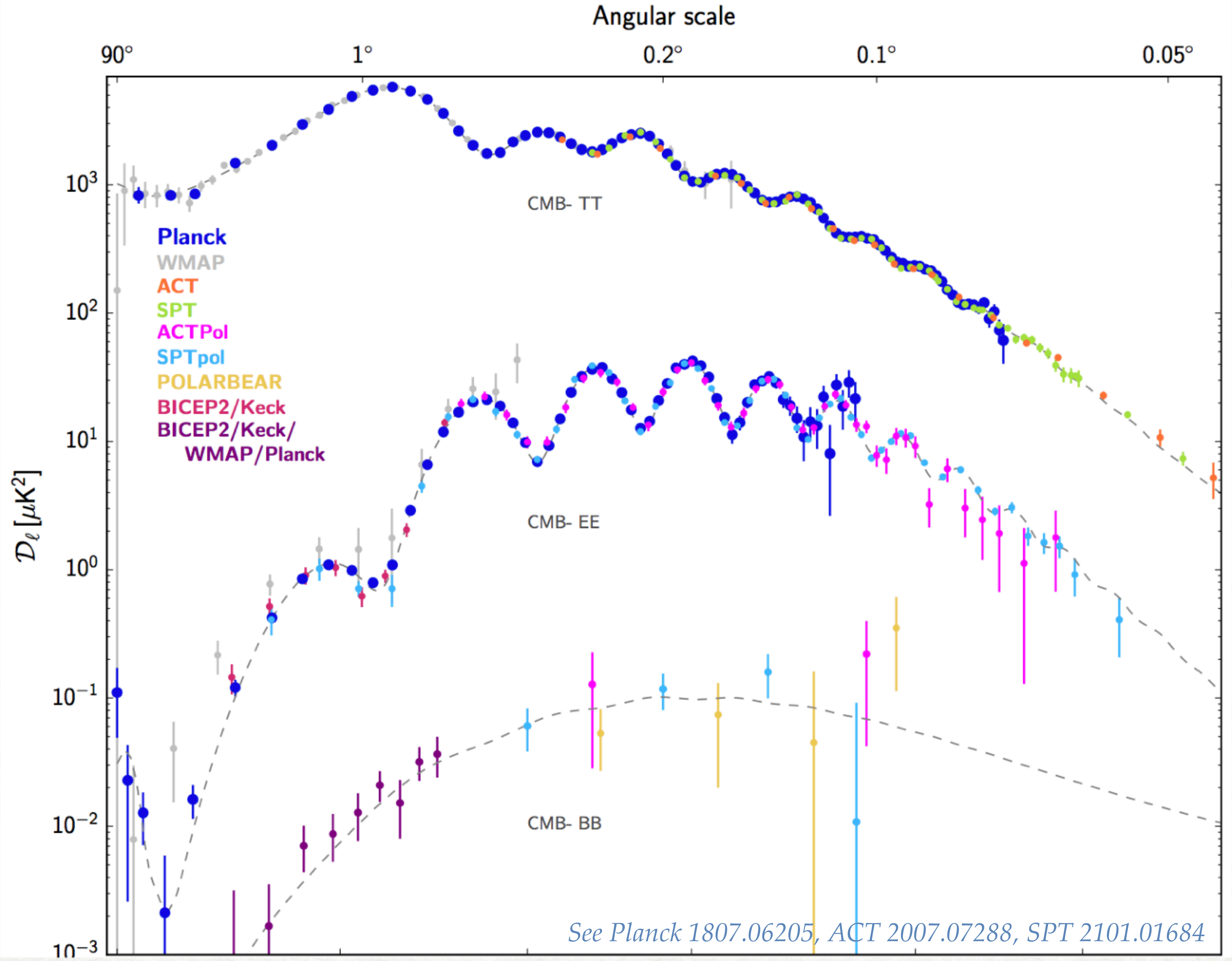
ALPS conference
Obergurgl, Austria
March, 26th 2023

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

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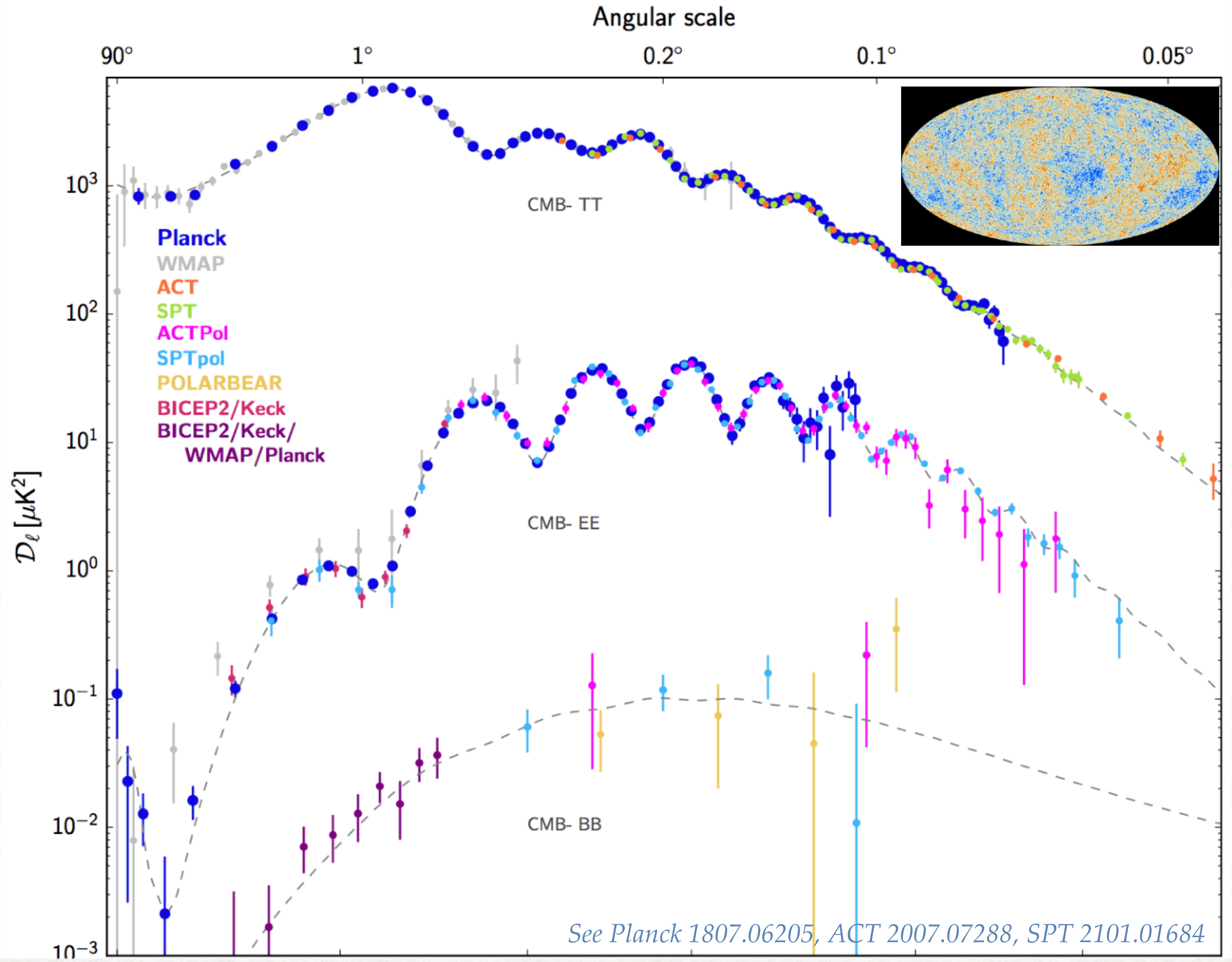

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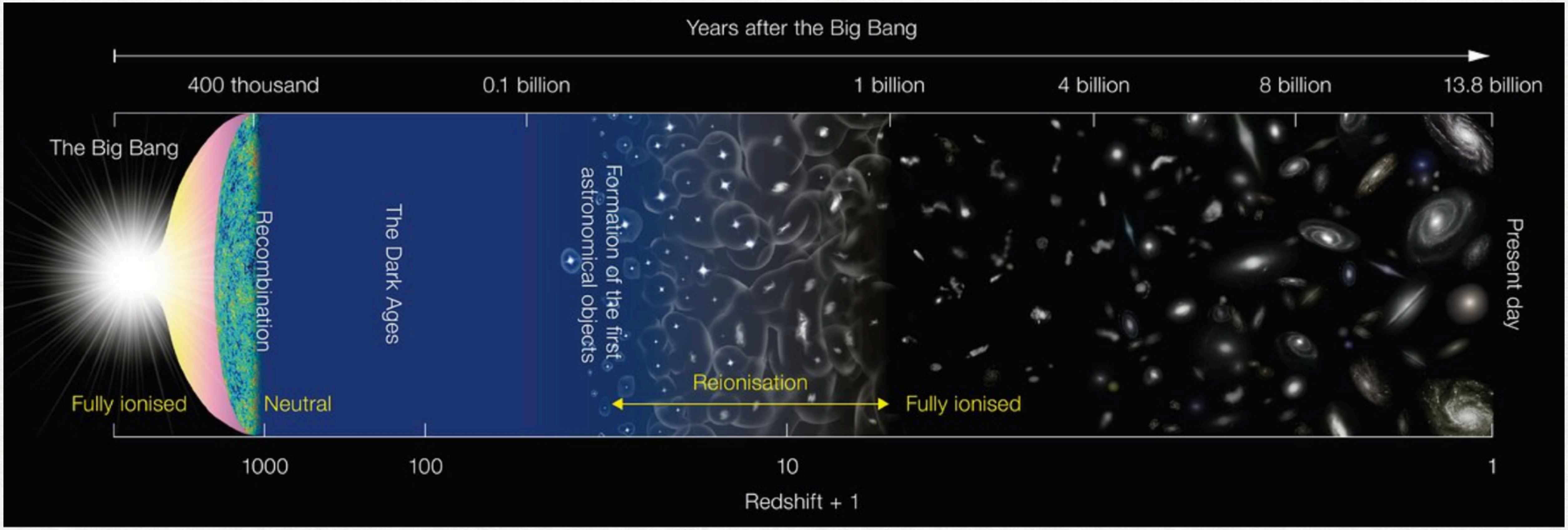
Astonishing success of ΛCDM Cosmology: GR+ Cosmological Principle

$\omega \equiv \Omega h^2, \;\; H_0 = 100h \;\; \mathrm{km/s/Mpc}$ $\quad\{H_0, \;\; \omega_b, \;\; \omega_{\rm cdm}, \;\; A_s, \;\; n_s, \;\; \tau_{\rm reio}\}$



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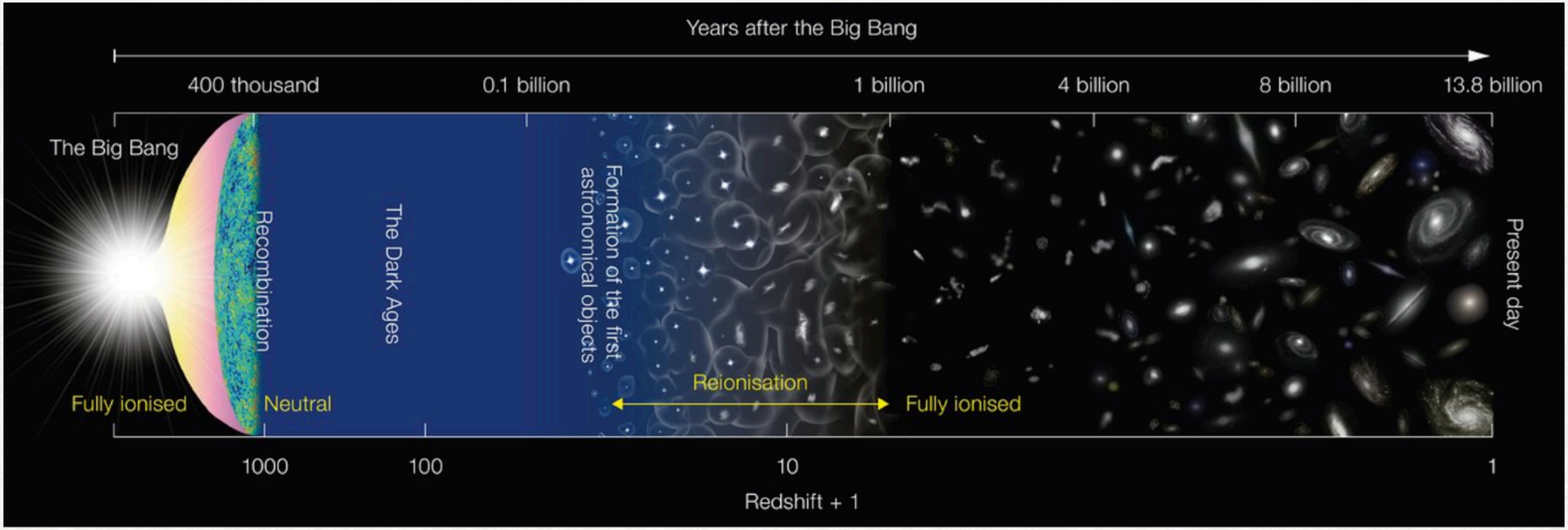

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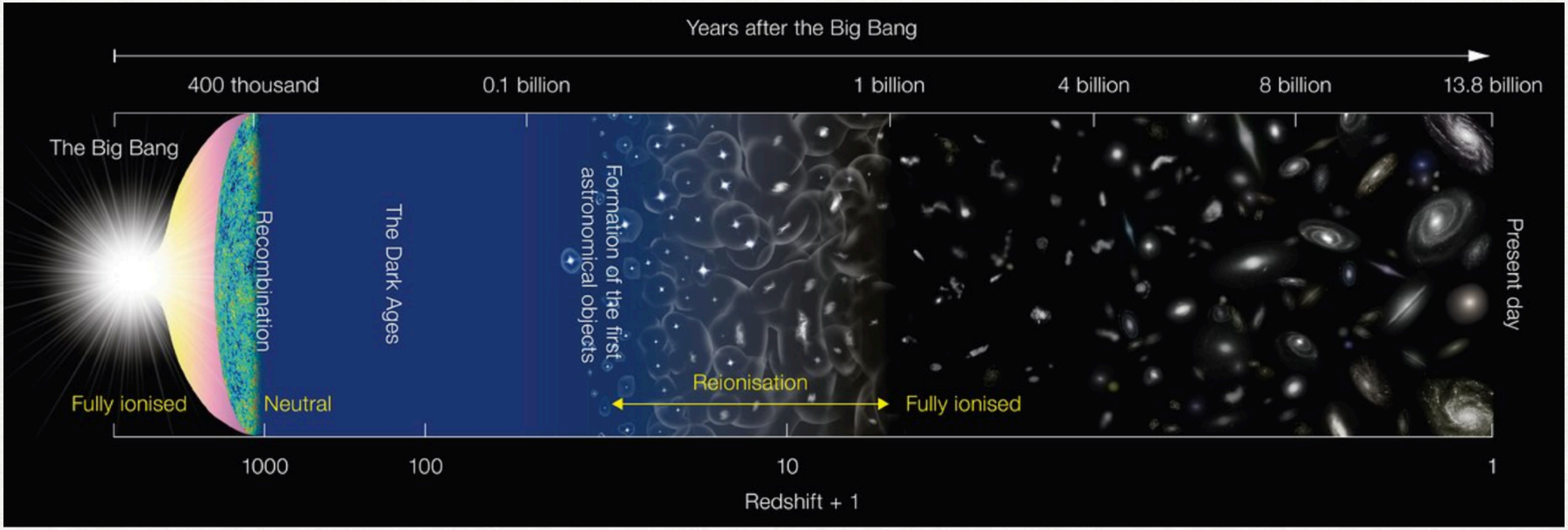
matter content

Inflation



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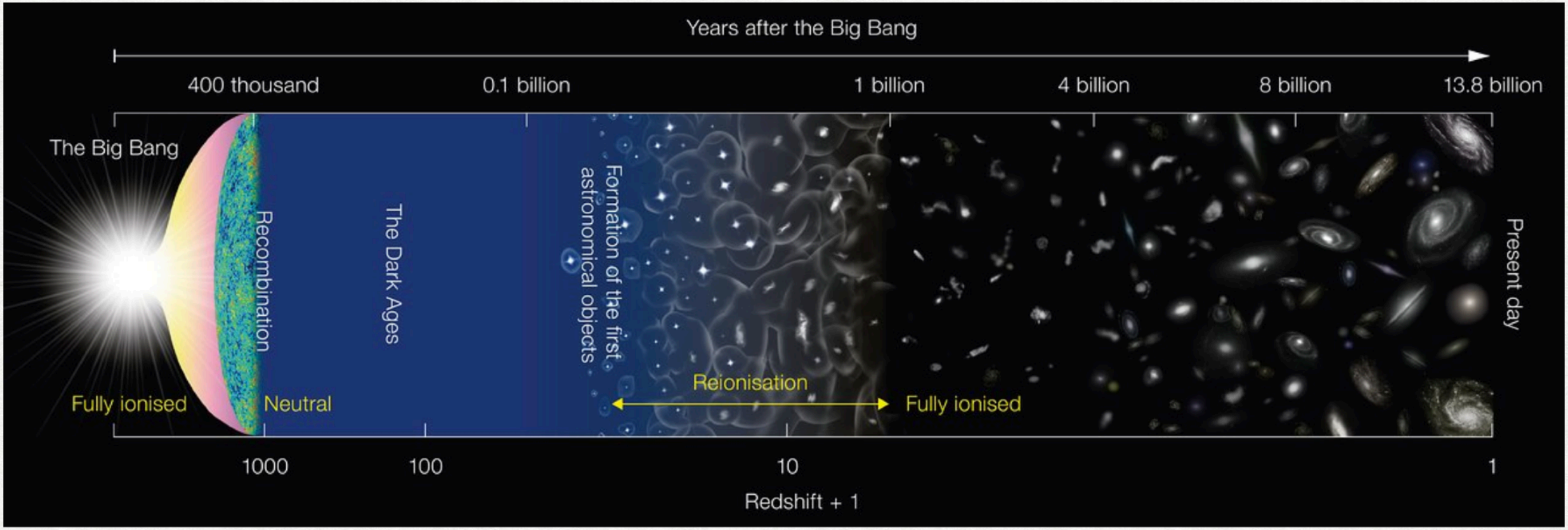
star formation



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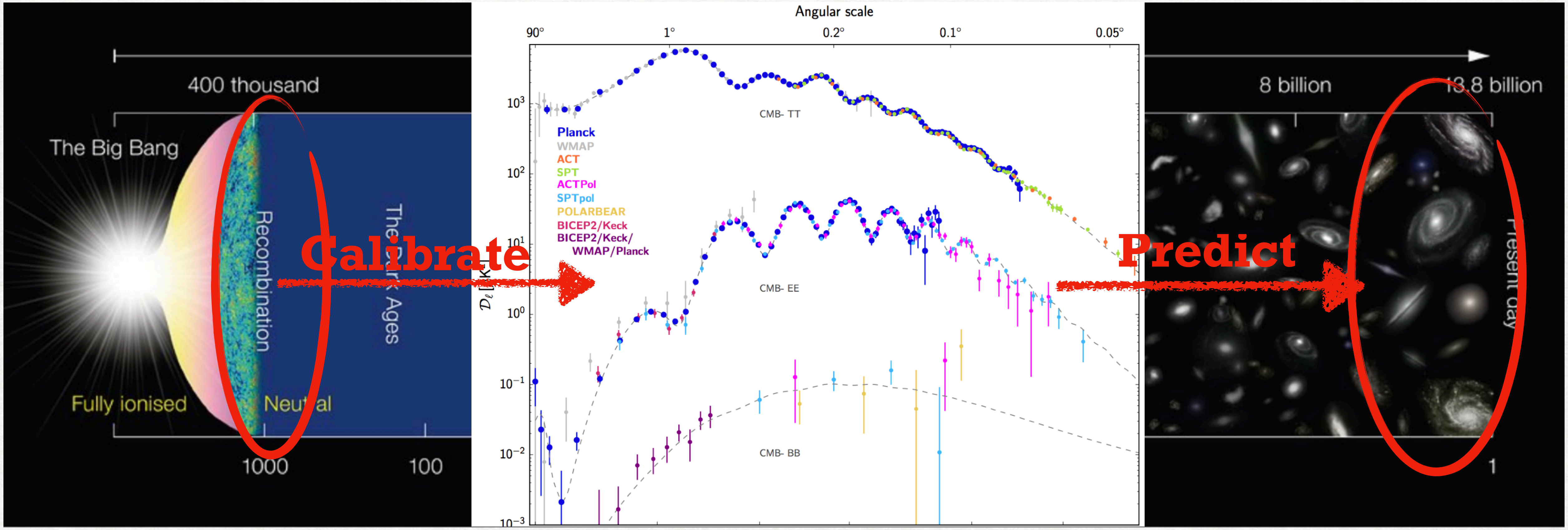

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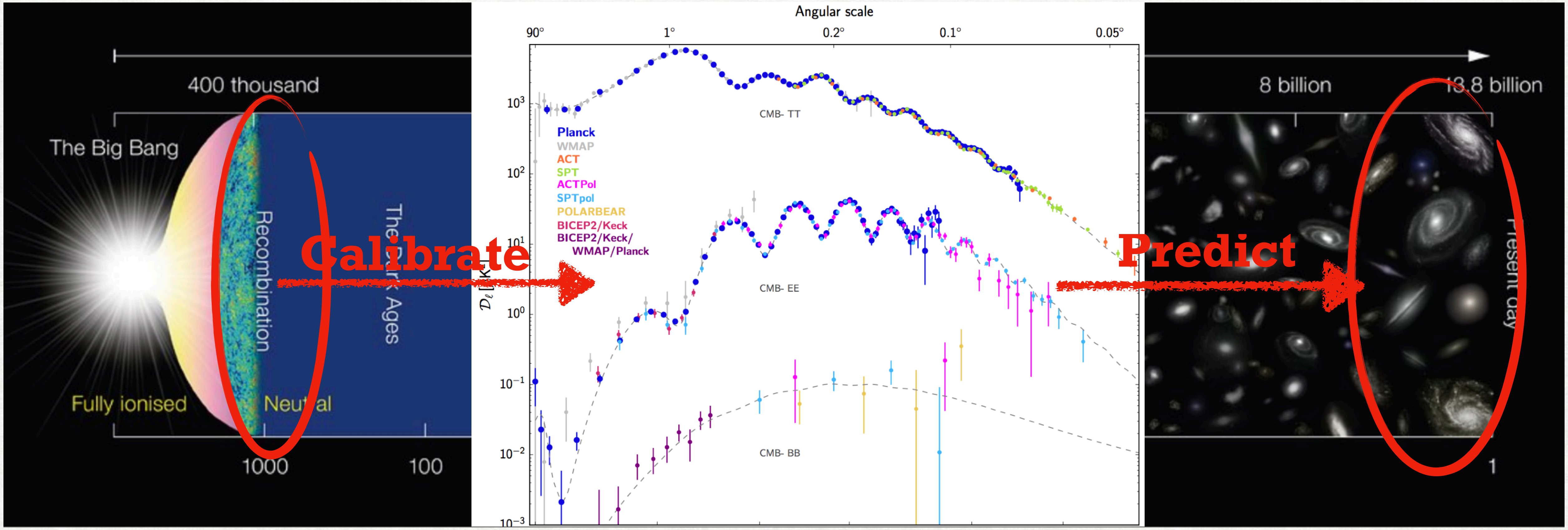

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~95% of the matter/energy content (today) is unknown!

Precision Cosmology or Cosmic discordance?

The ΛCDM Cosmology is under extreme scrutiny

- Cosmic dipole anomaly? The universe is not isotropic?

Colin++ 1703.09376, 1808.04597, Secrest++ 2009.14826, Alari++ 2207.05765 , Guandalin++ 2212.04925

- Cosmic void? The universe is not locally homogeneous?

Wu&Huterer 1706.09723, Kenworthy++ 1901.08681, Cai++ 2012.08292, Camarena++ 2205.05422

- Tensions in cosmological parameters?

Abdalla++ 2203.06142

- Anomalies in *Planck*? Evidence for a curved universe?

Di Valentino++ 1911.02087

- Anomalous cosmological 21cm signal? Is the IGM too cold or too bright (in radio)?

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- (Too) High redshift galaxies with JWST?

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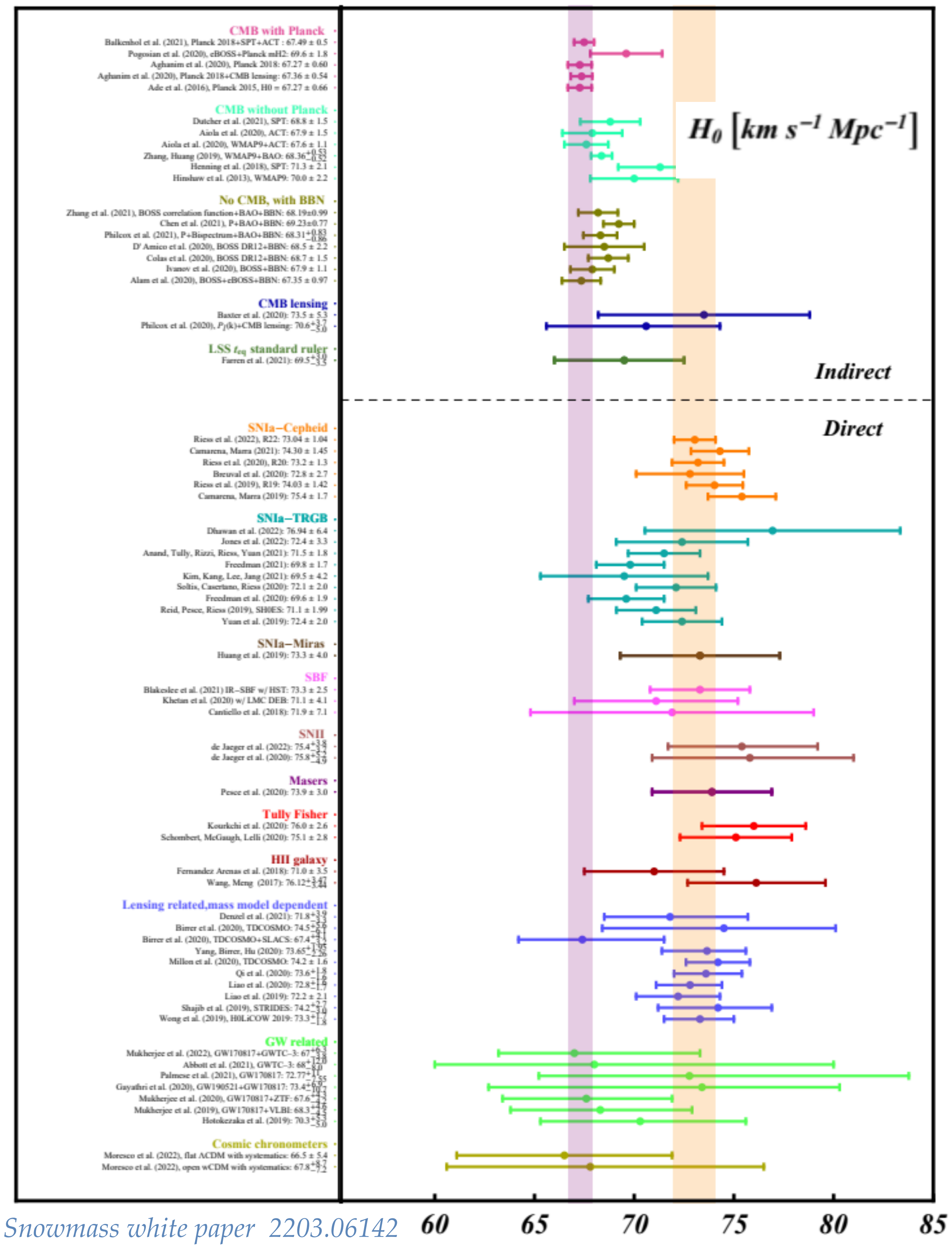
Is this a sign of a break down in the cosmological principle?

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

The H_0 and S_8 tension: two sides of the same coin?



Snowmass white paper 2203.06142

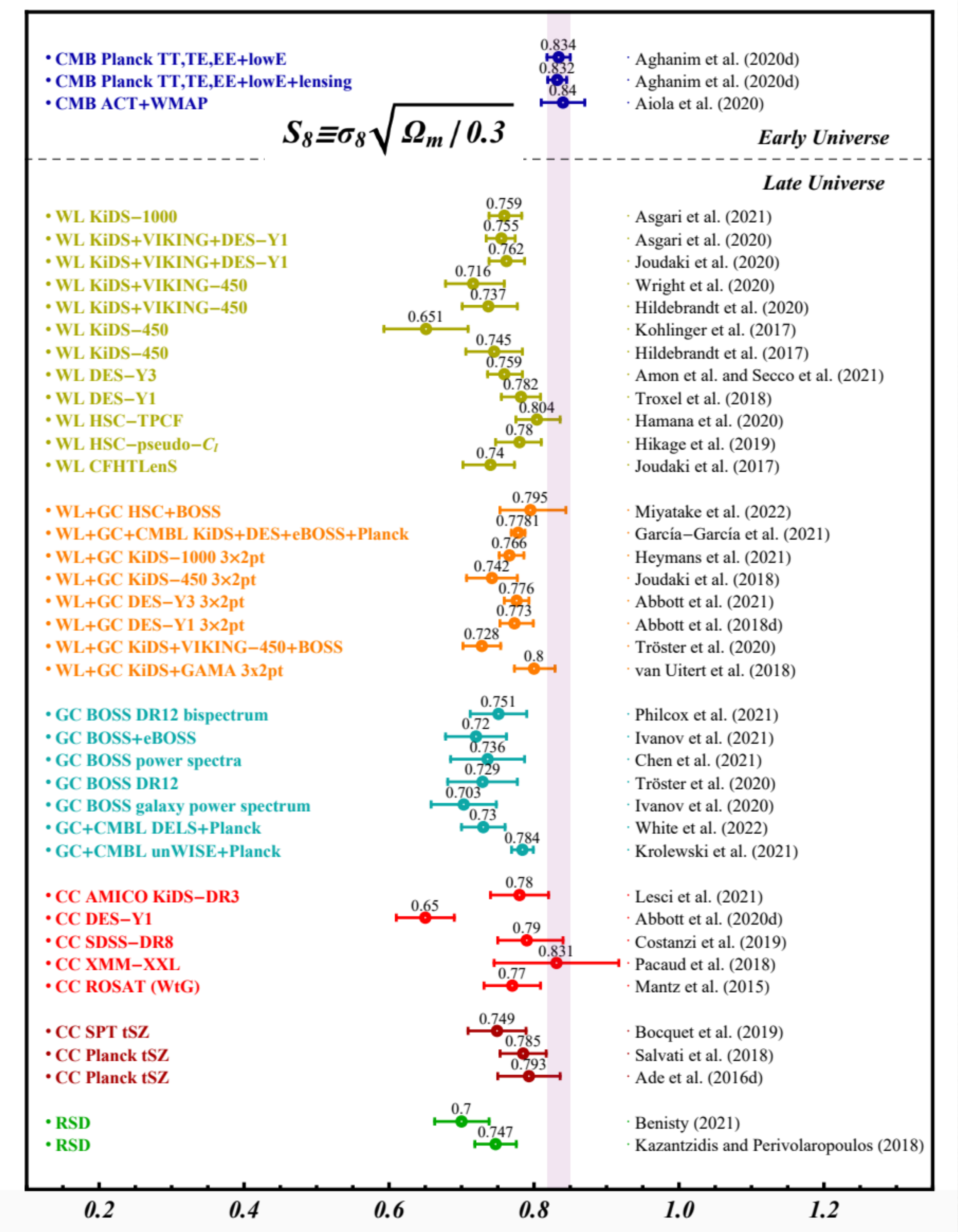


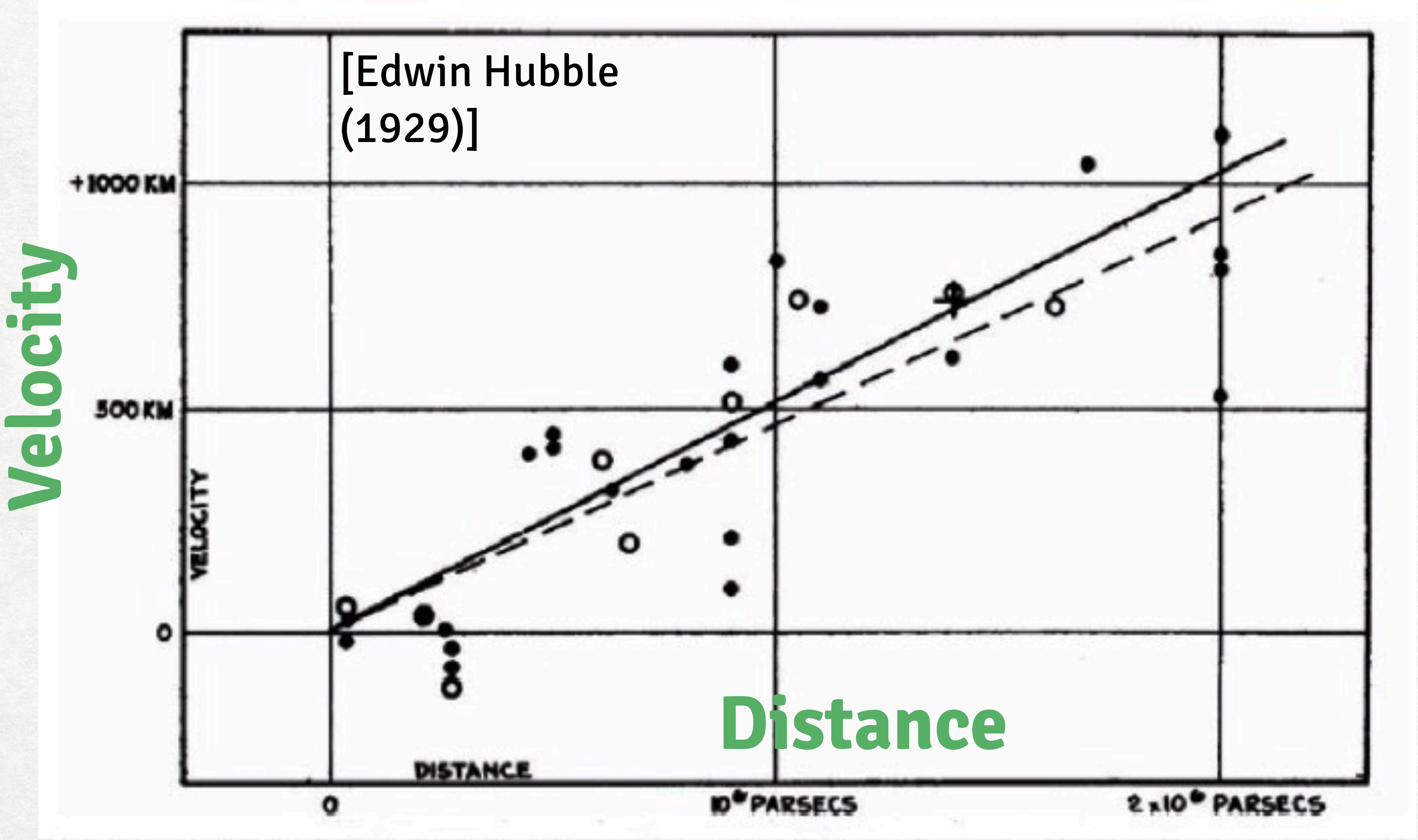
Table of Contents

The Hubble parameter

- The Hubble constant H_0 measures the **expansion rate** of the universe at $z = 0$

$$F = \frac{L}{4\pi D_L^2}$$

$$H_0^2 \equiv H^2(z \simeq 0) = \frac{8\pi G}{3}\left(\rho_{\mathrm{DE},0} + \rho_{m,0}\right)$$



$$v \simeq cz \simeq H_0 D$$

- Only valid at large distance! Otherwise "peculiar" velocities are important

The cosmic distance ladder

- **Standard candle:** Object of known luminosity, such that its distance to us can be determined

$$\boxed{F = \frac{L}{4\pi D_L^2}}$$

$$m \equiv -2.5\log F + \text{const}\,.$$
$$M \equiv -2.5\log F(10\ \text{pc}) + \text{const}\,.$$

$$\boxed{m - M = 5\log D_L[\text{Mpc}] + 25}$$

$*1\ \text{Mpc} = 3.2 \times 10^6\ \text{l.y.}$

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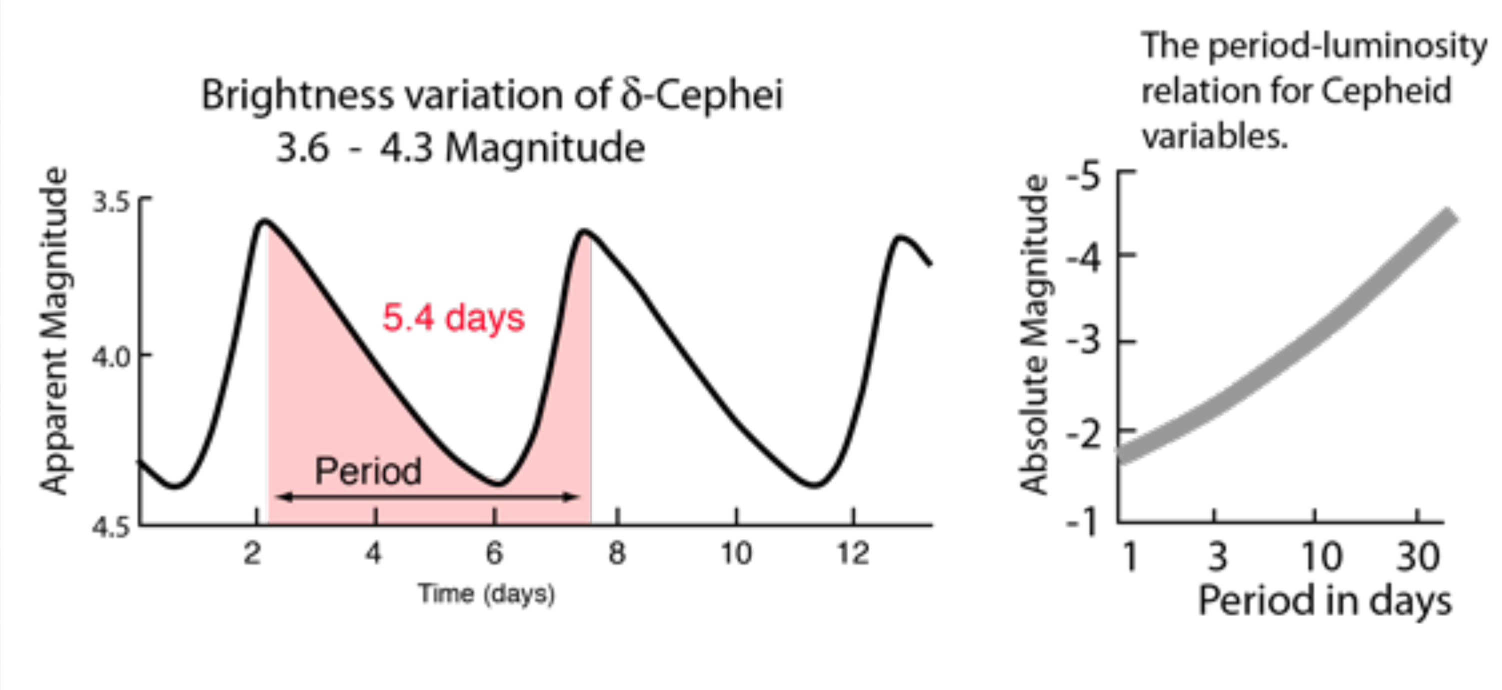
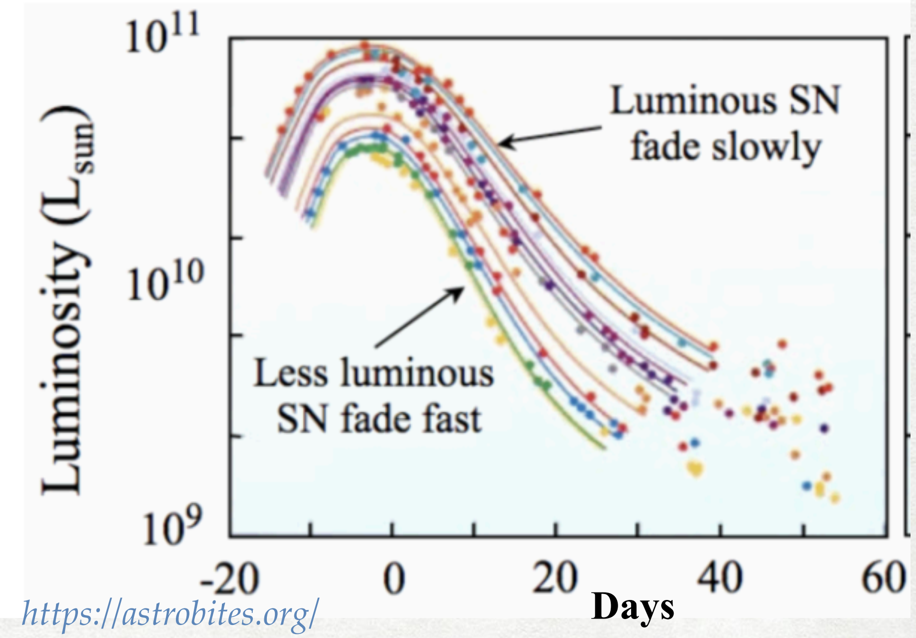
Cepheid stars



(D ~ 10^3 -10^6 l.y.)

Supernovae Ia



https://astrobites.org/

(D ~ 10^9 l.y.)

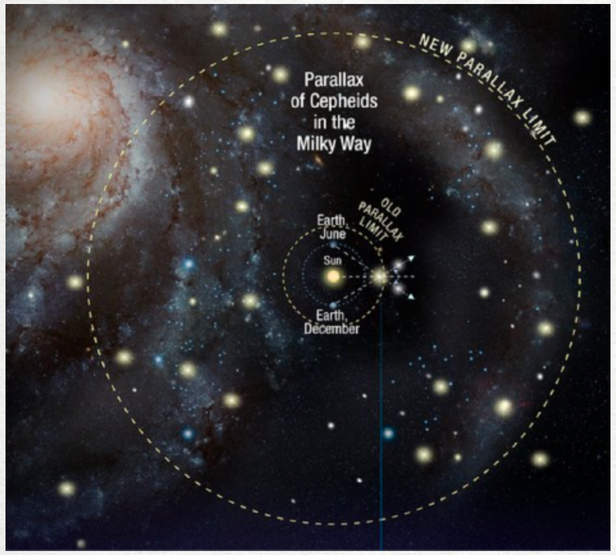
- Pulsating stars
Period-luminosity relation

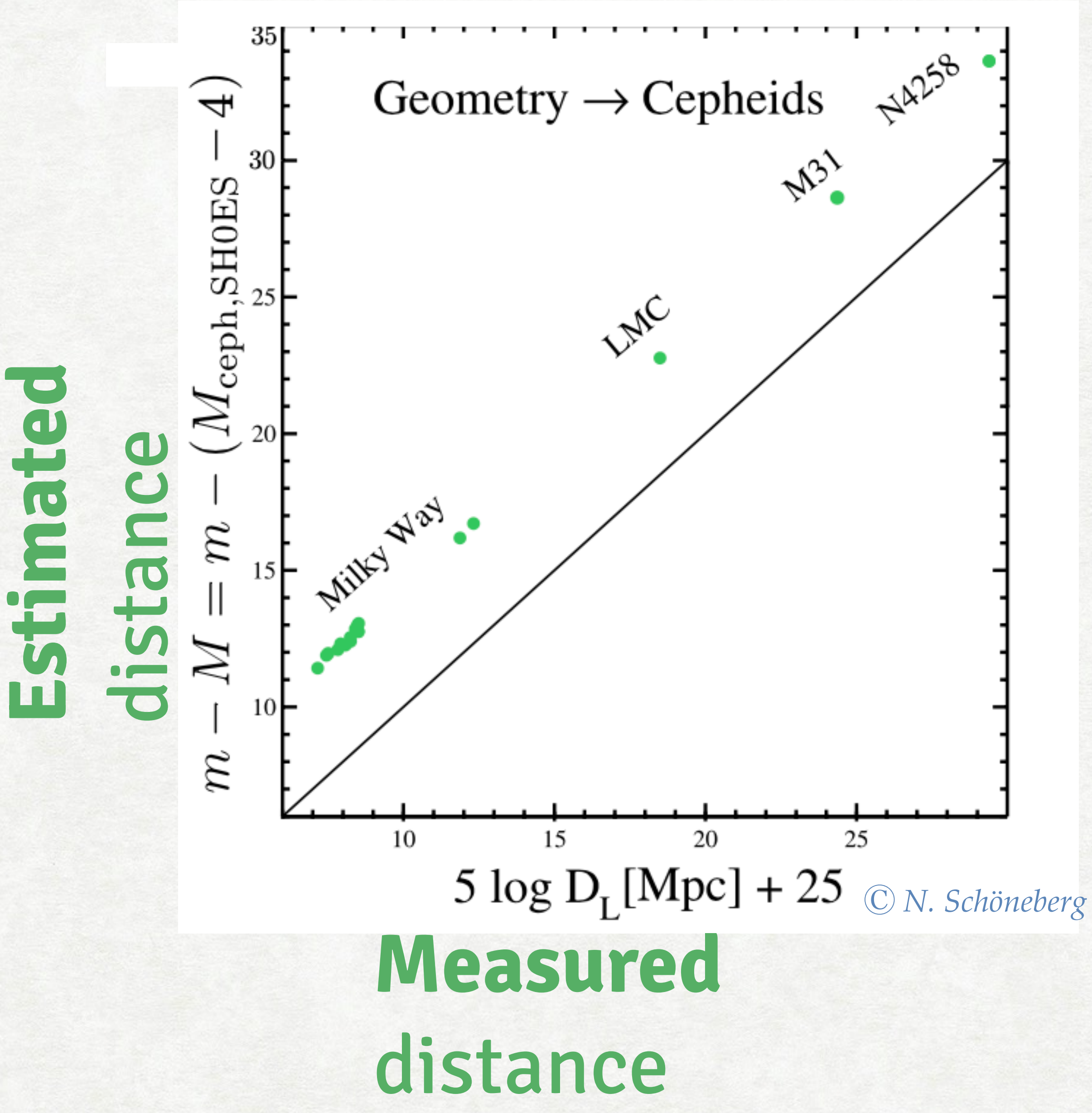
- Bright "standardizable" objects
relation between peak & slope of the light curve

The cosmic distance ladder

Different geometric calibrators: GAIA parallaxes, masers NGC 4258, DEB in the LMC

$m - M = 5\log\ D_L[\mathrm{Mpc}] + 25$





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[Riess+1604.01424 (edited)]

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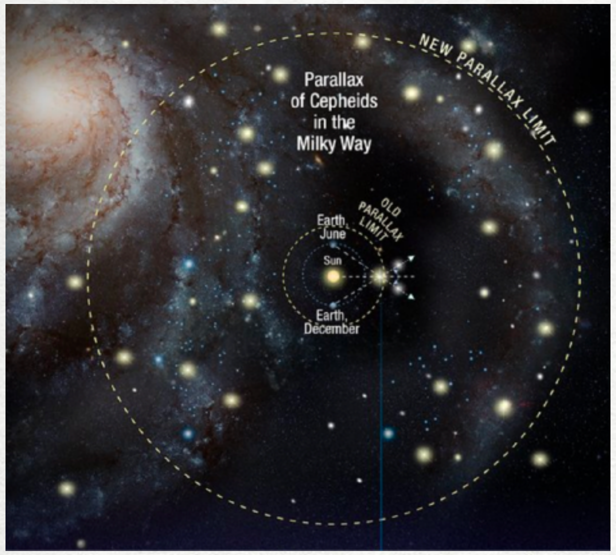
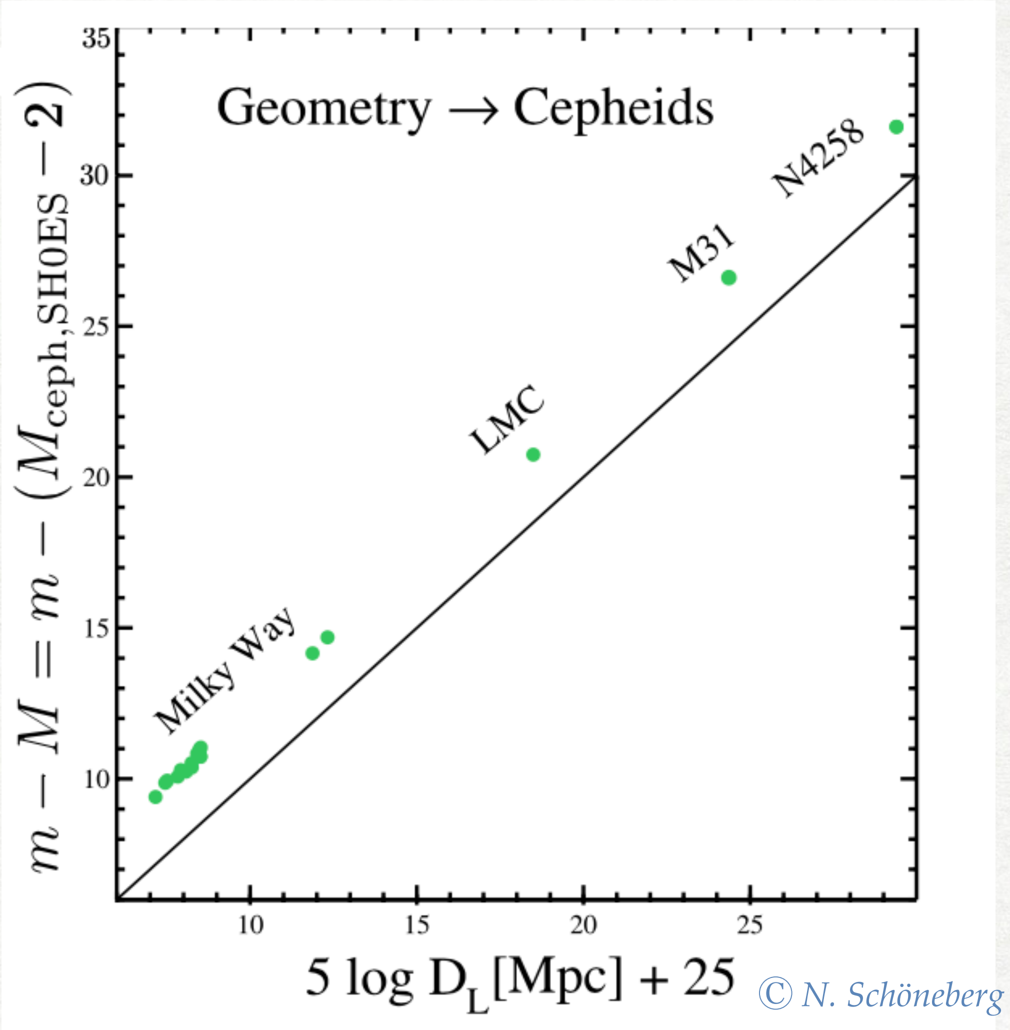


Estimated distance



Measured distance

[Riess+1604.01424 (edited)]

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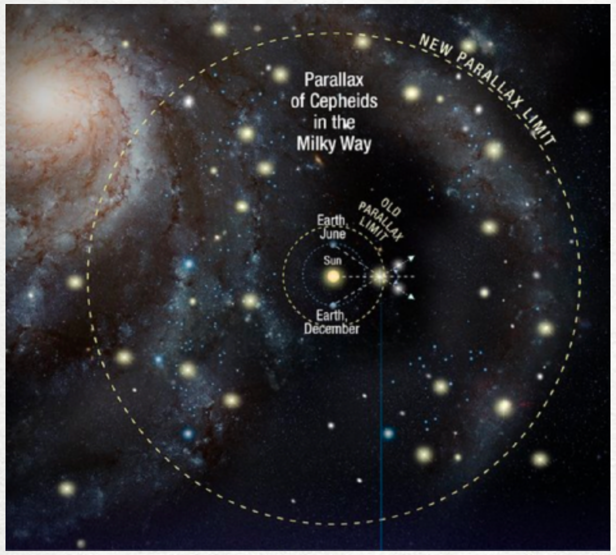

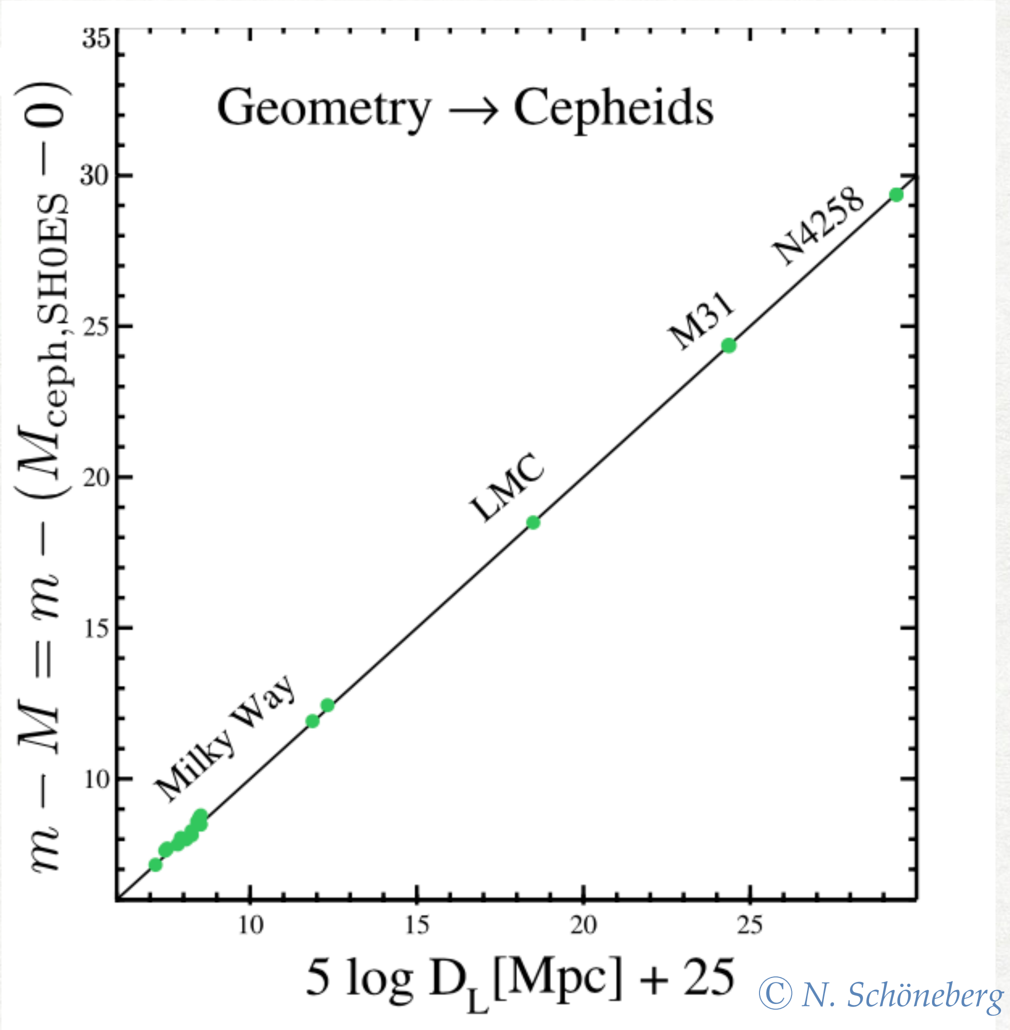

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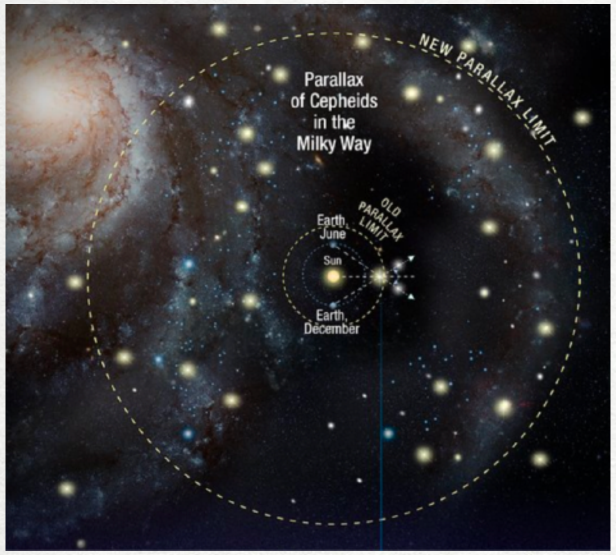

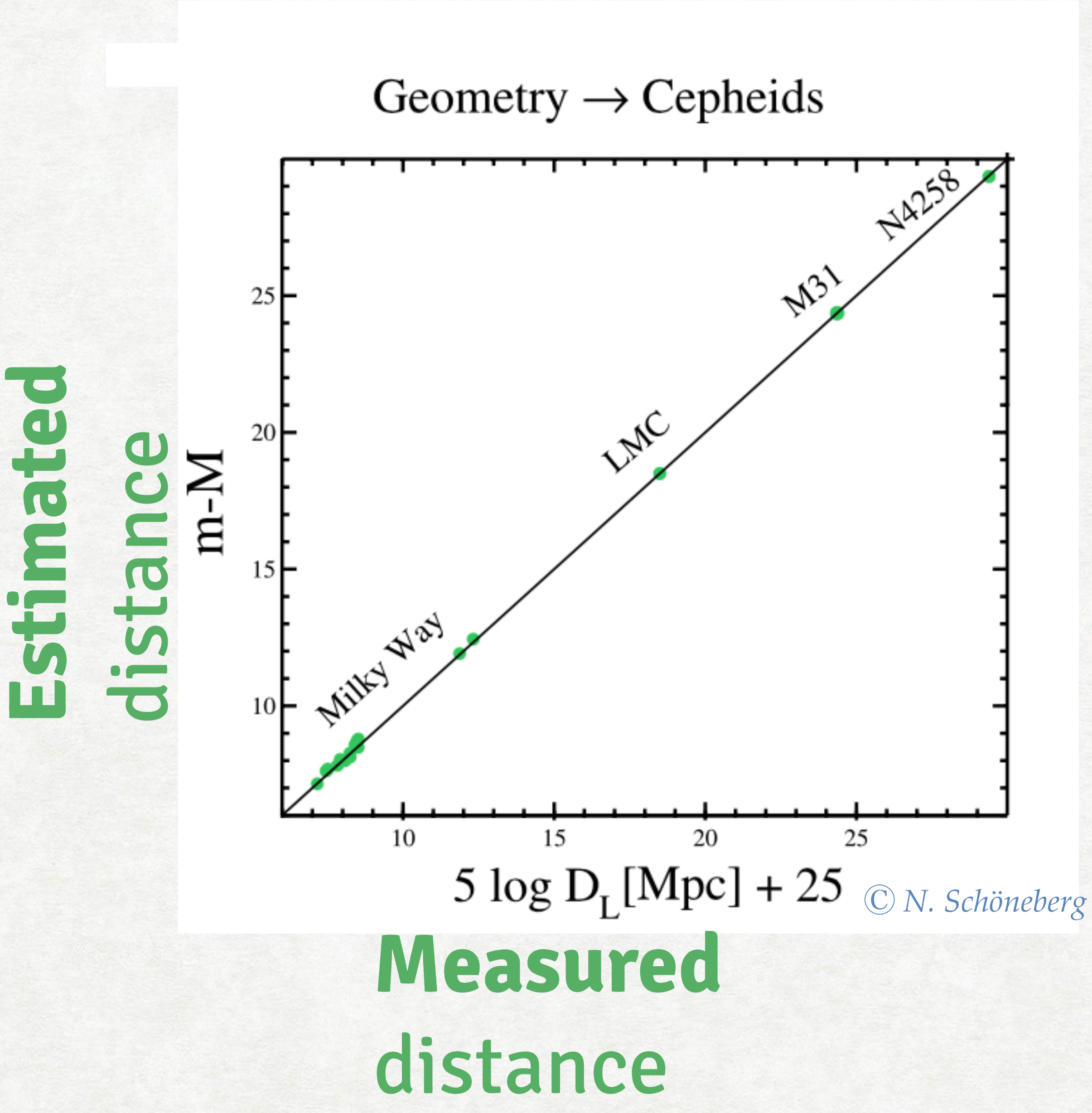

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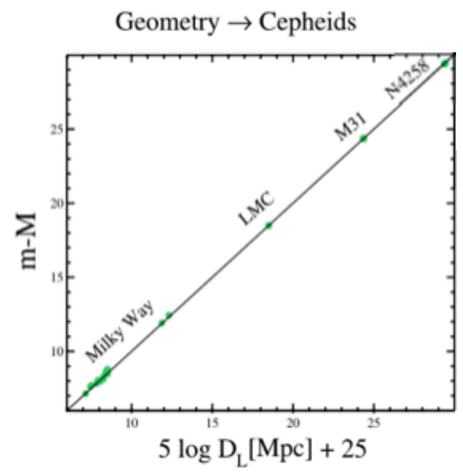
Three steps to the Hubble constant



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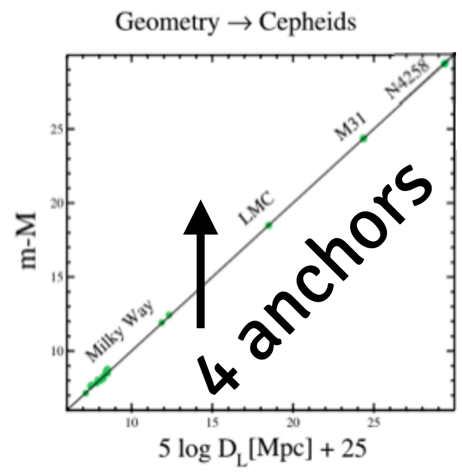

→ M_{ceph} (P-L relation)

[Riess+1604.01424 (edited)]

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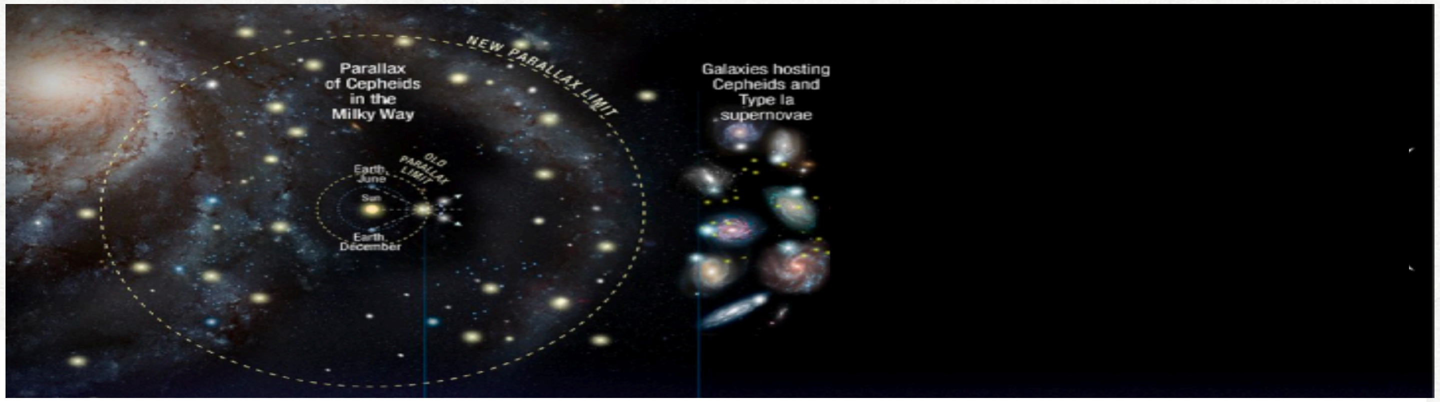

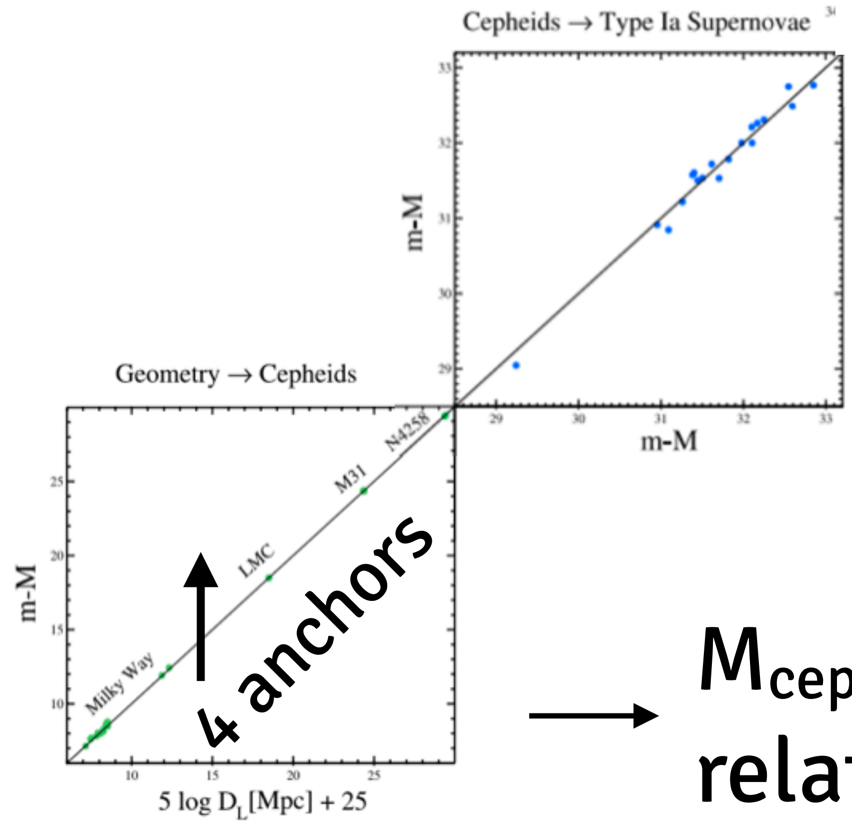

4 anchors

→ M_{ceph} (P-L relation)

[Riess+1604.01424 (edited)]

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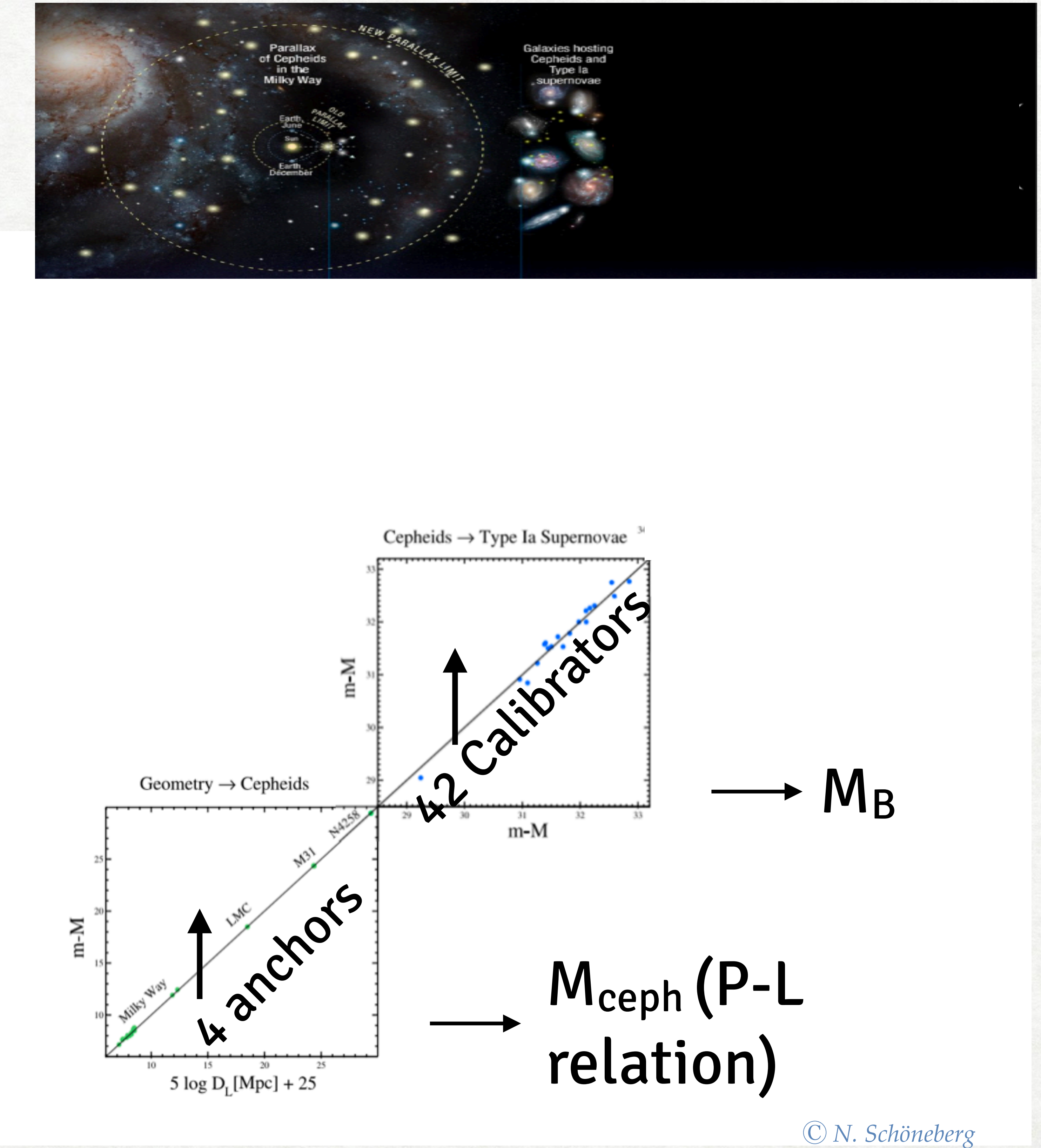
Three steps to the Hubble constant



42 Calibrators

4 anchors

→ M_B

→ M_{ceph} (P-L relation)

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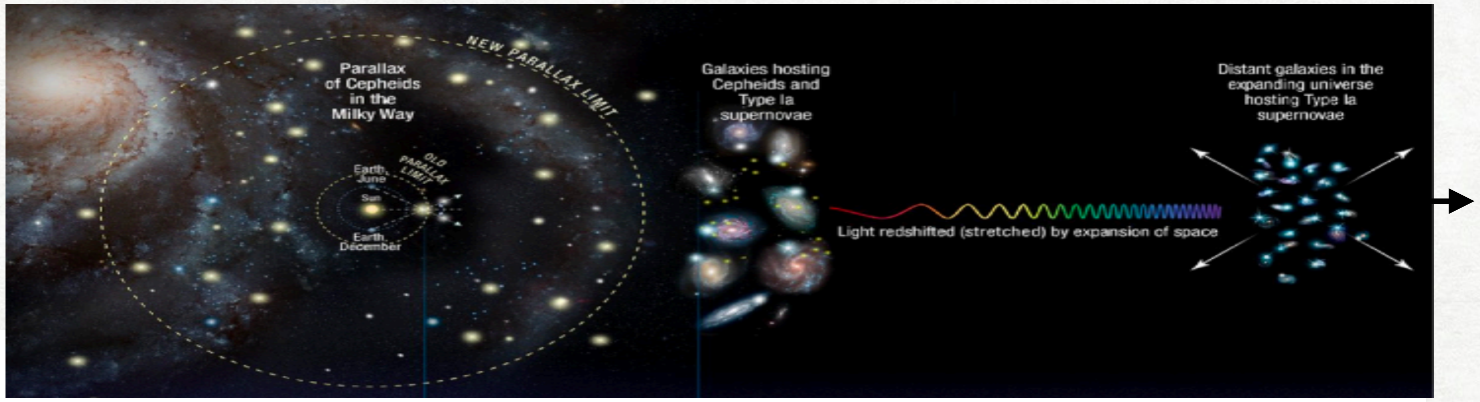
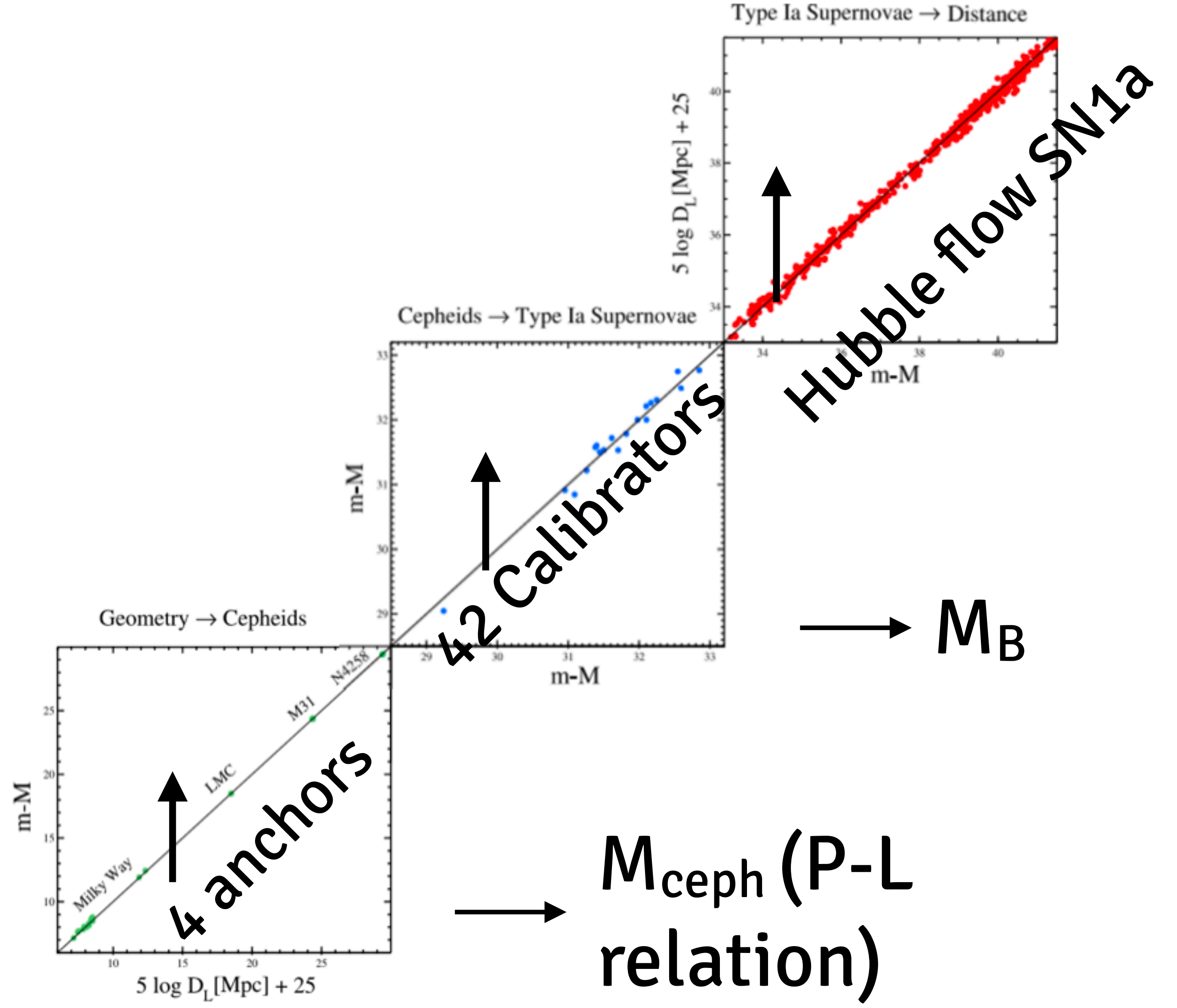
[Riess+1604.01424 (edited)]

Three steps to the Hubble constant



→ D_L + (measured) z

$$v \simeq cz \simeq H_0 D_L$$



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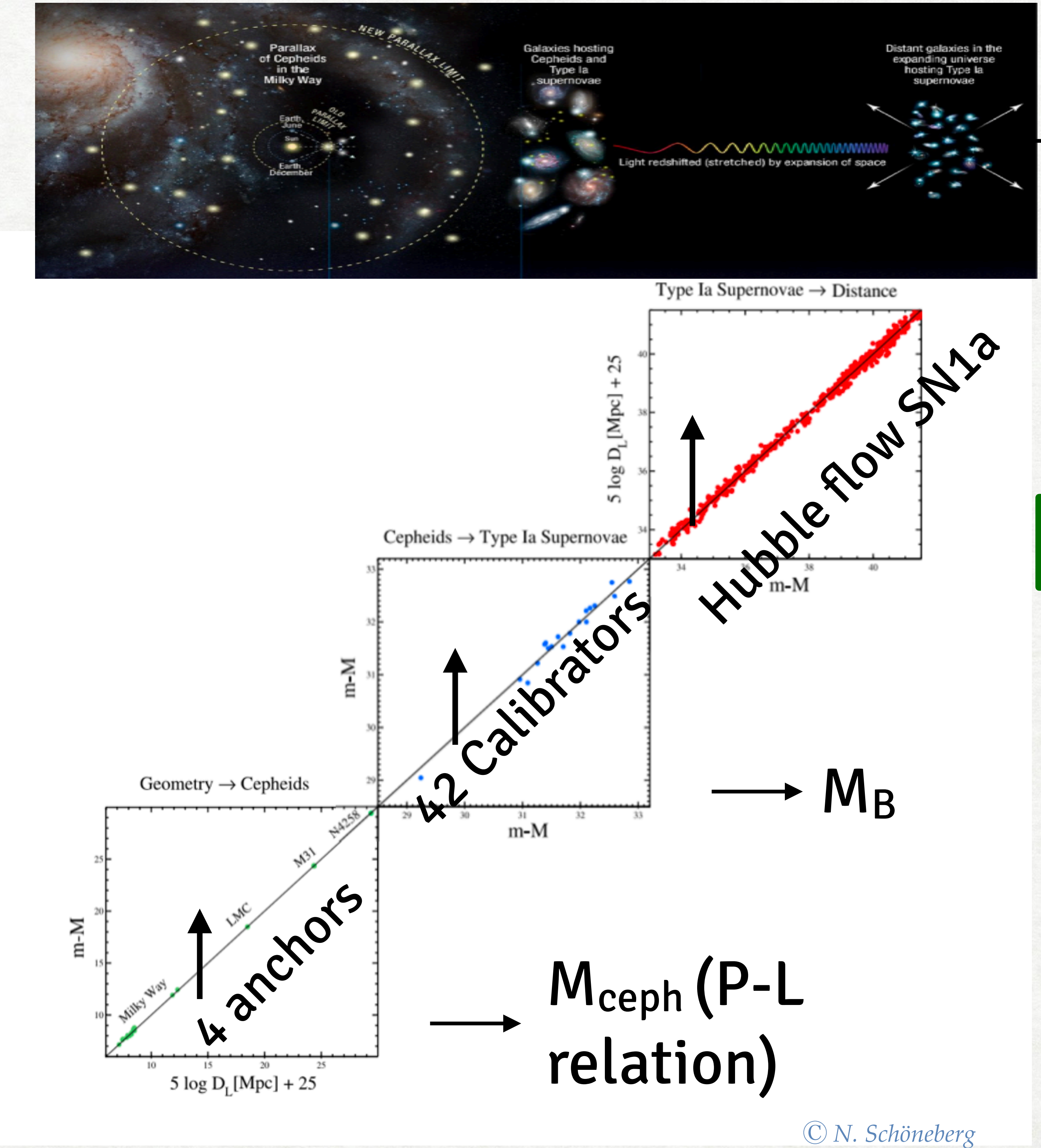


→ D_L + (measured) z

$$v \simeq cz \simeq H_0 D_L$$

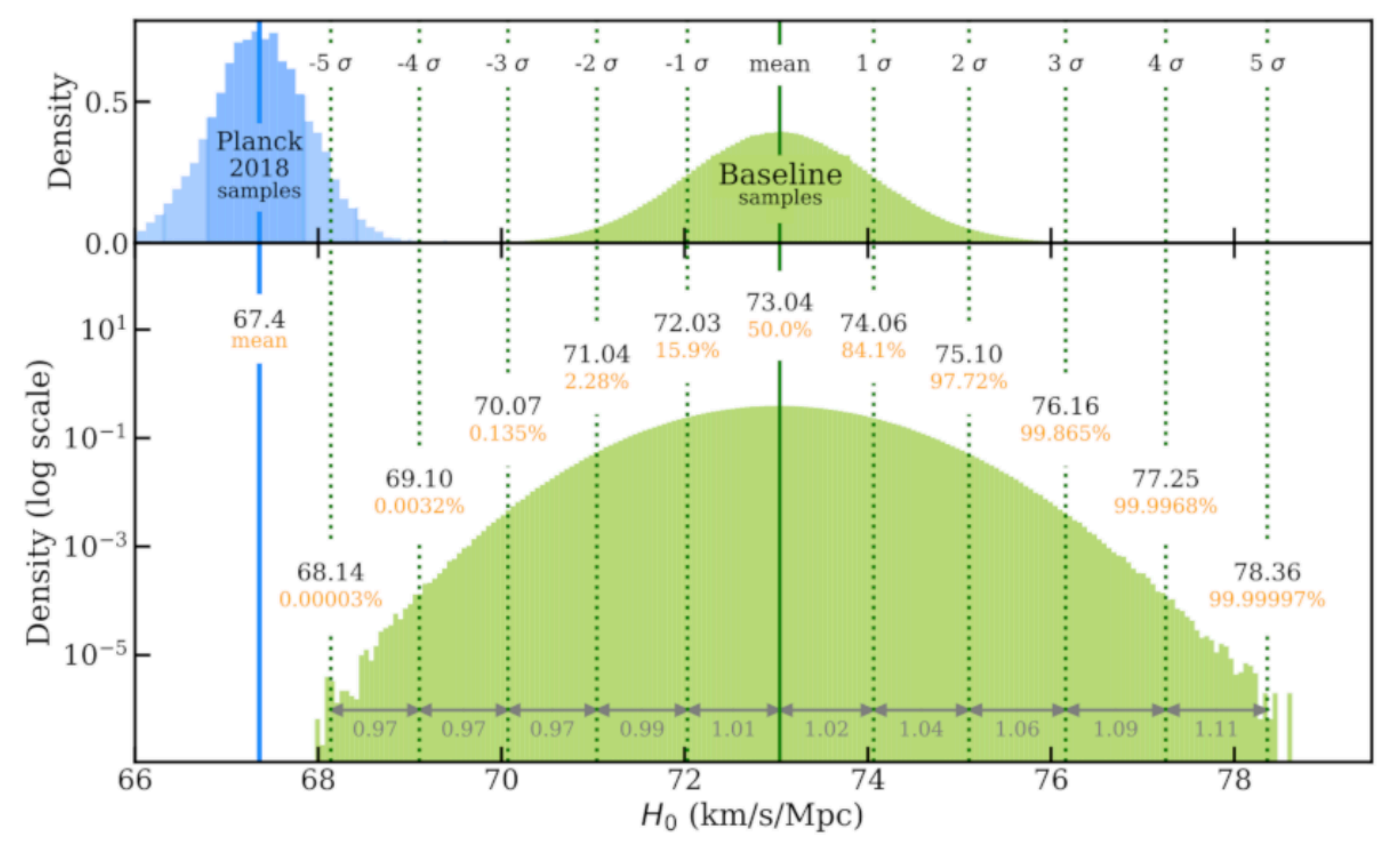
$H_0 = 73 \pm 1$ km/s/Mpc

→ M_B

→ M_{ceph} (P-L relation)

[Riess+1604.01424
(edited)]

The Hubble tension between SH0ES & *Planck*



Riess et al. 2112.04510

$$H_0(\Lambda\mathrm{CDM/Planck}) = 67.4 \pm 0.5 \text{ km/s/Mpc}$$

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

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

No (known) systematic error can explain the discrepancy

Systematics? A non-exhaustive list

See review Di Valentino++ 2103.01183 for all relevant references

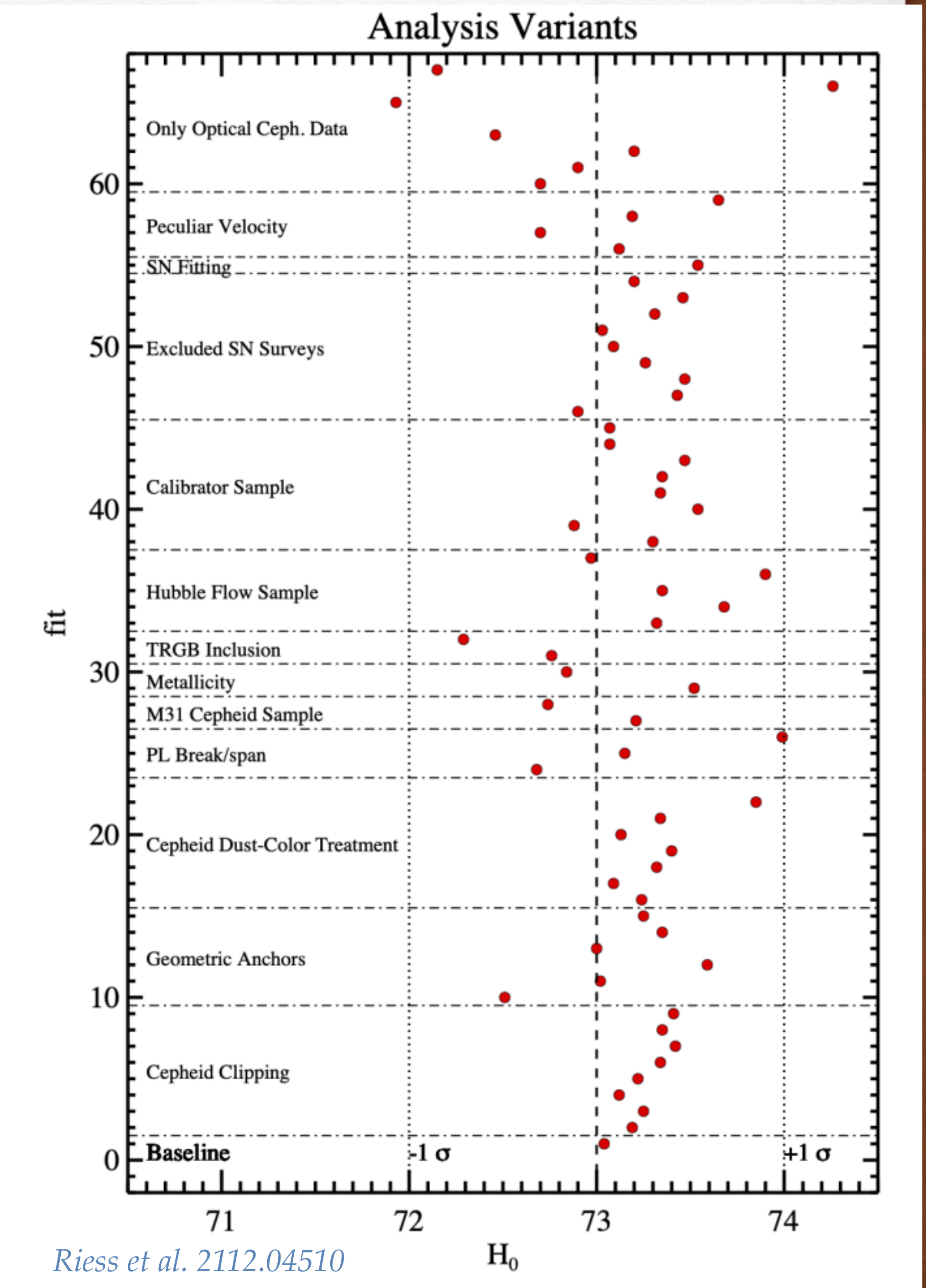
- Cosmological measurements are hard… "because" of astrophysics!

- Are SN1a correctly calibrated? multi-step process!
    - Test several calibration methods (e.g. Cepheids vs TRGB vs Miras).
    - Effect of Dust?
    - Cepheid crowding?
    - Is there a bias in the peculiar velocity correction?
    - Is there a metallicity correction?
    - Is GAIA parallax incorrect?

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



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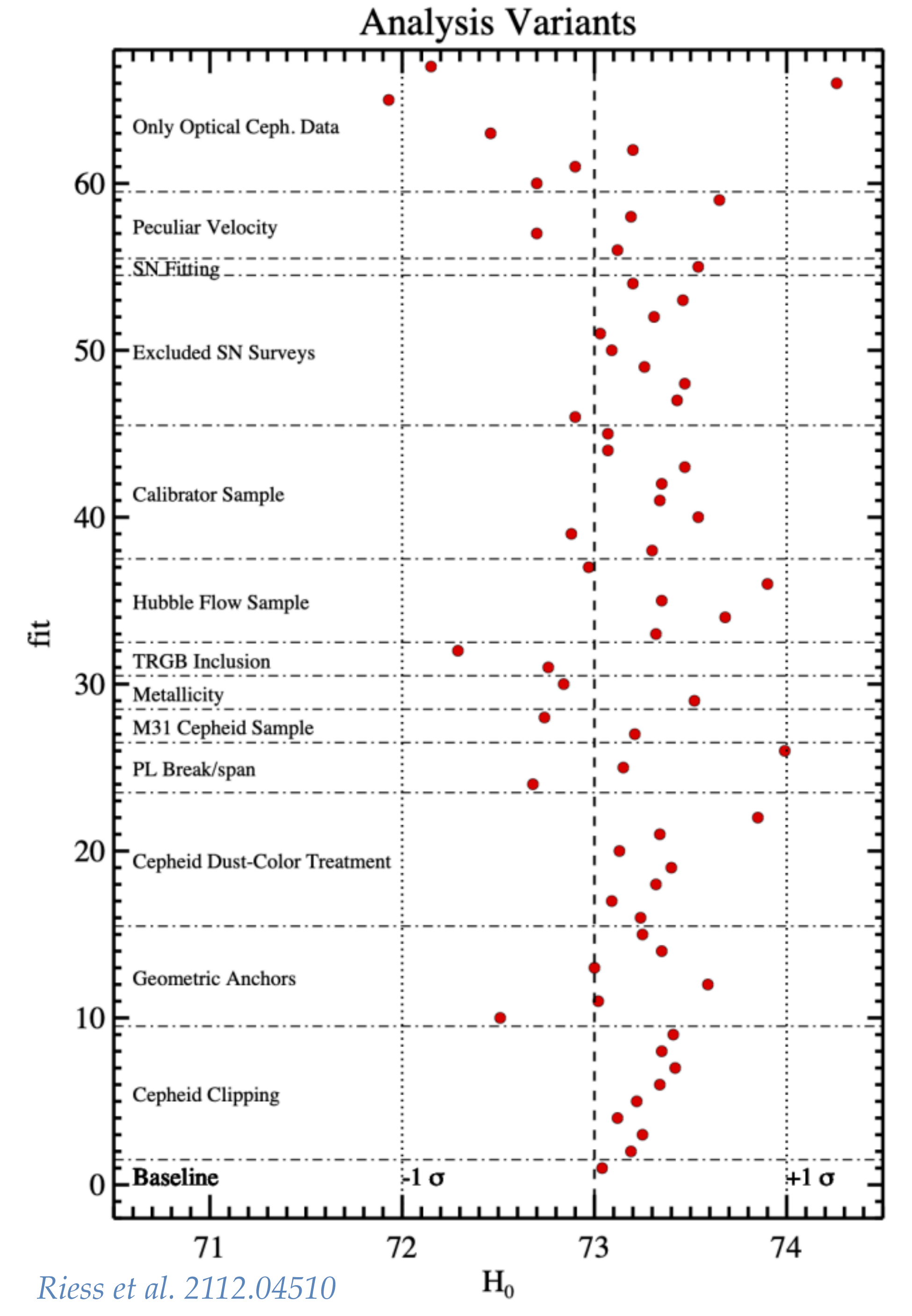
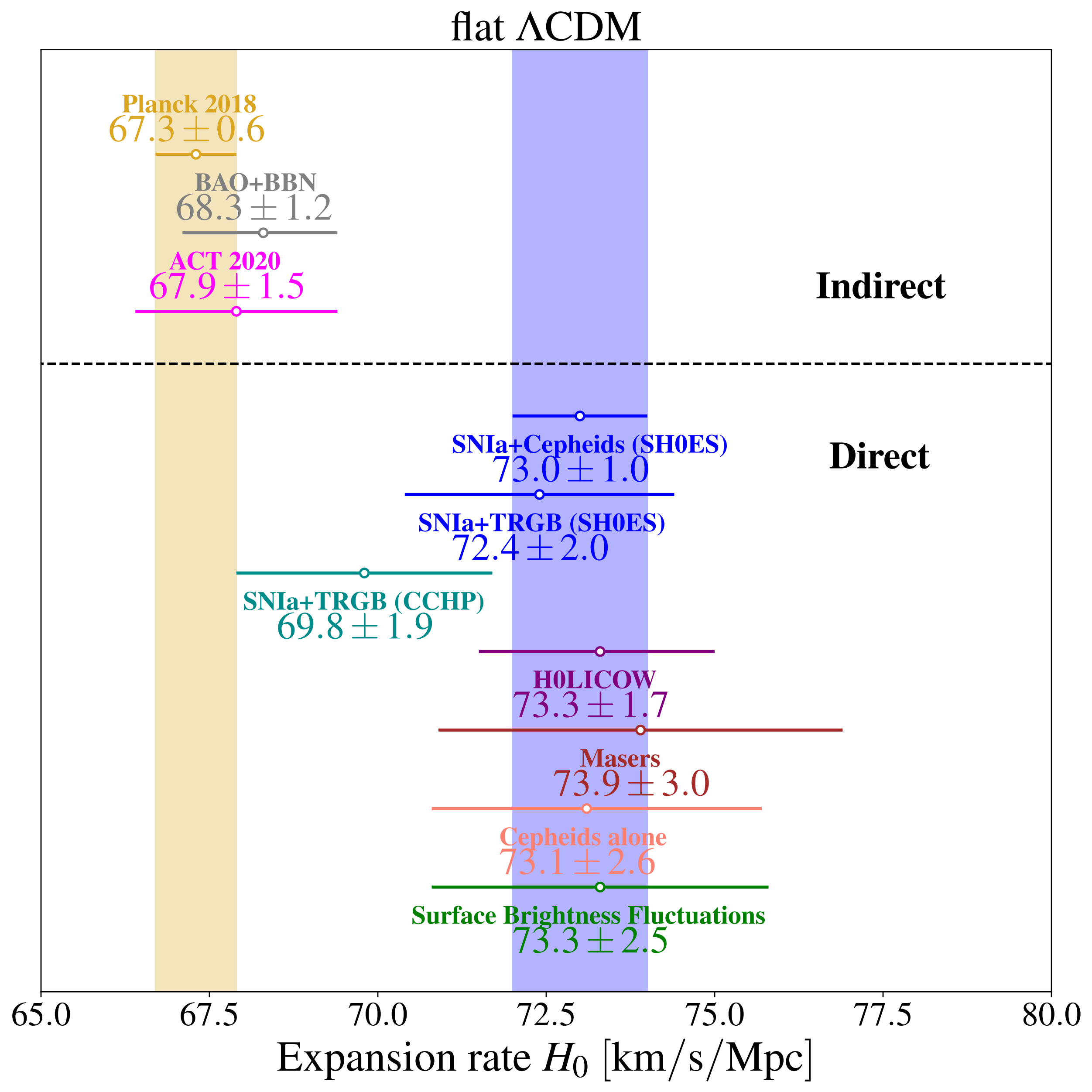
Rigault++ 1412.6501, Jones++1805.05911, Brout&Scolnic 2004.10206

The question of systematics is not settled, but it is not easy to "hide" a 5σ bias!



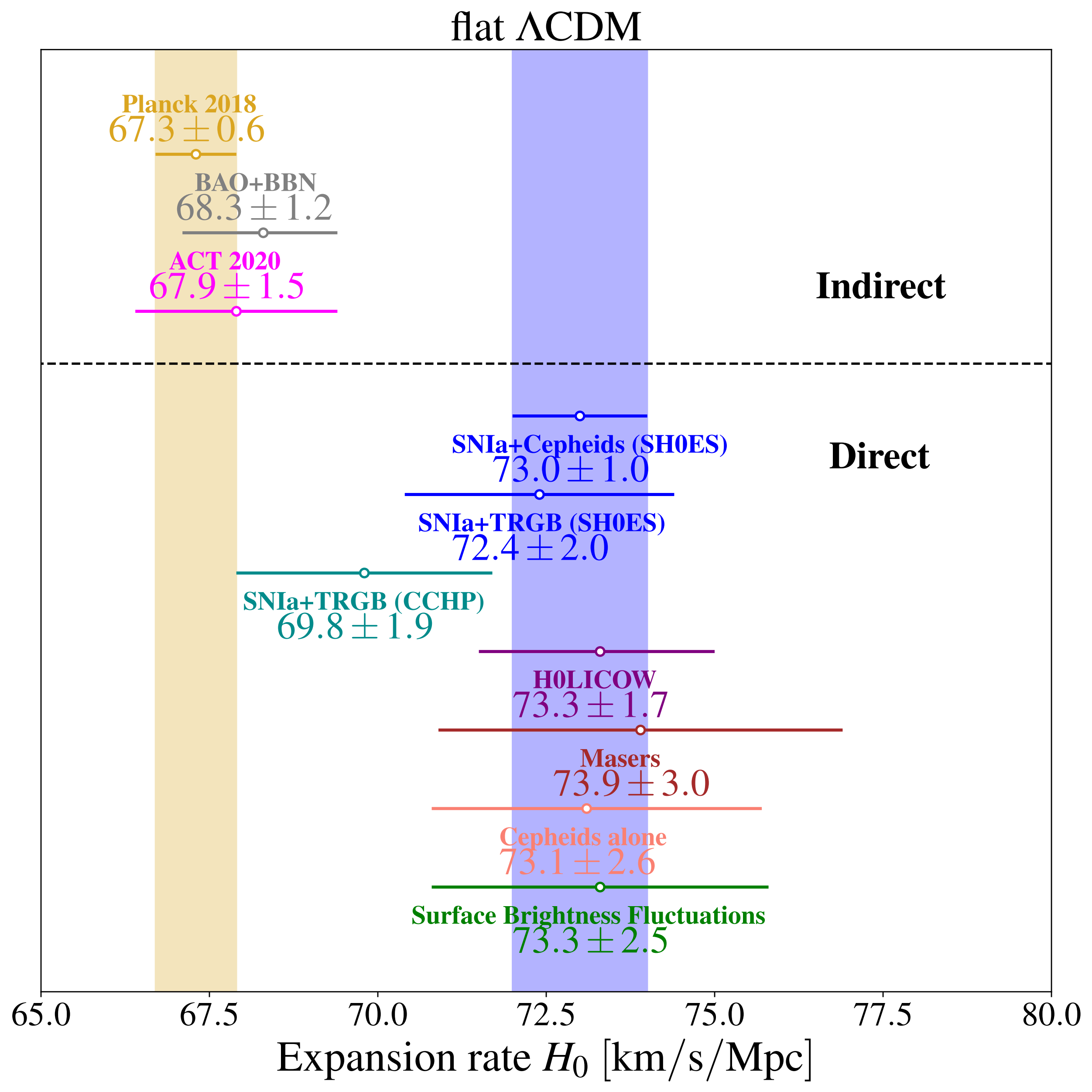
Riess et al. 2112.04510

The Hubble tension beyond SH0ES & *Planck*



The Hubble tension beyond SH0ES & *Planck*

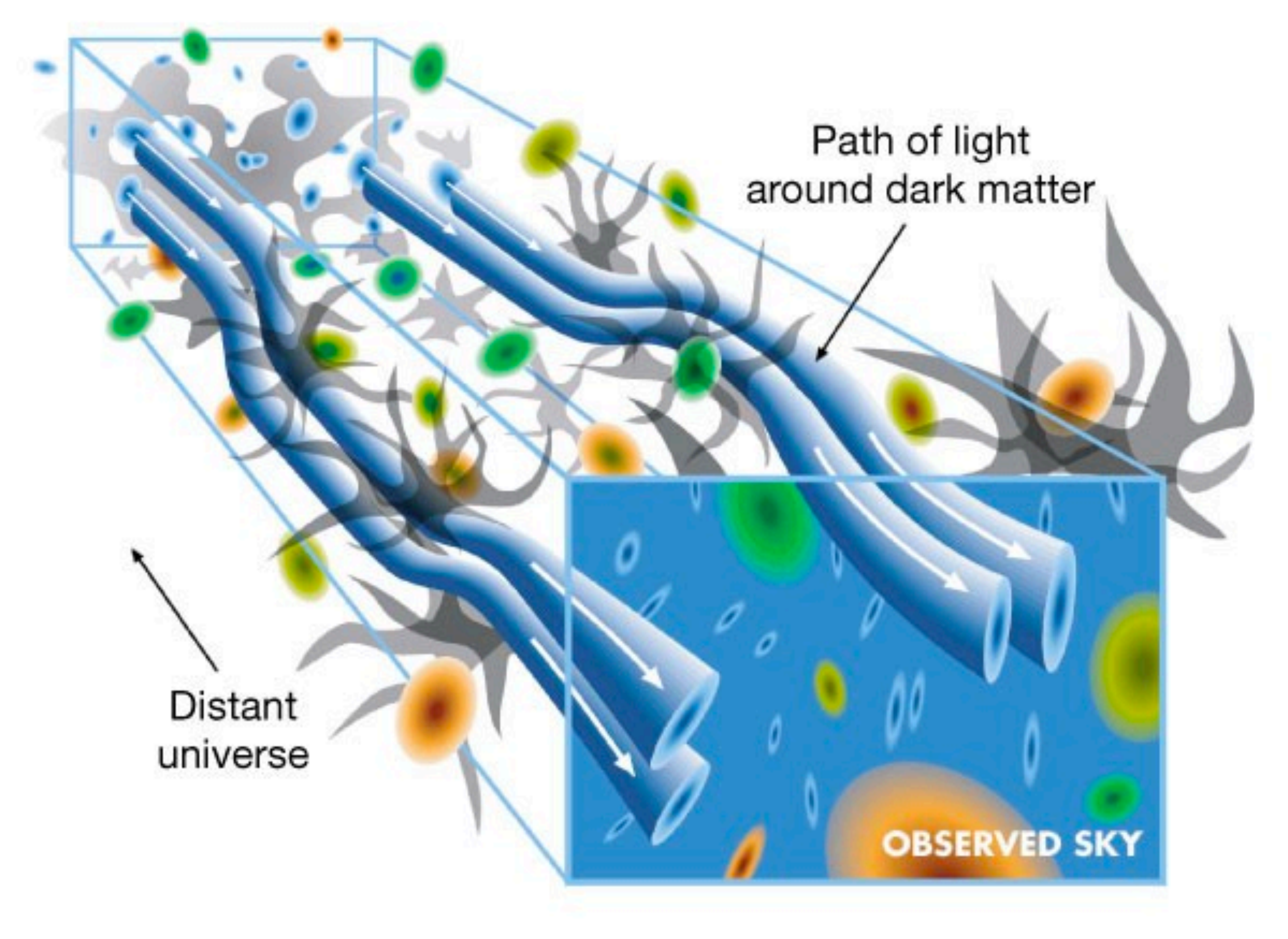
A summary of current measurements with $\Delta H_0 < 3$km/s/Mpc

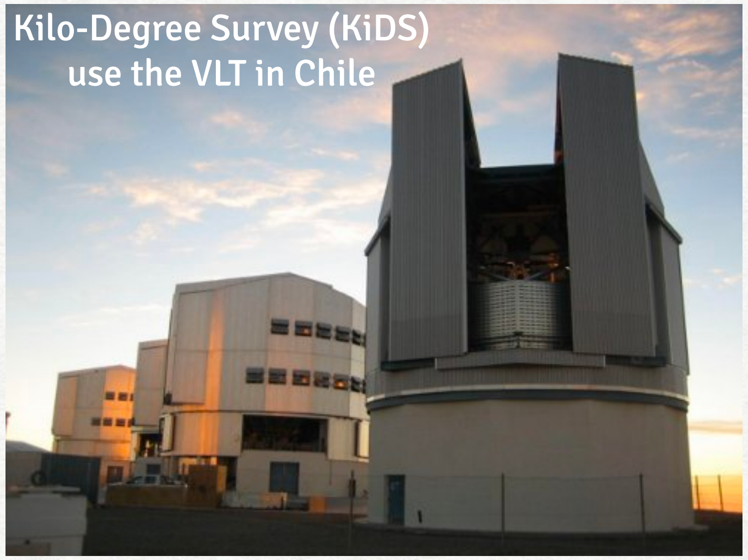


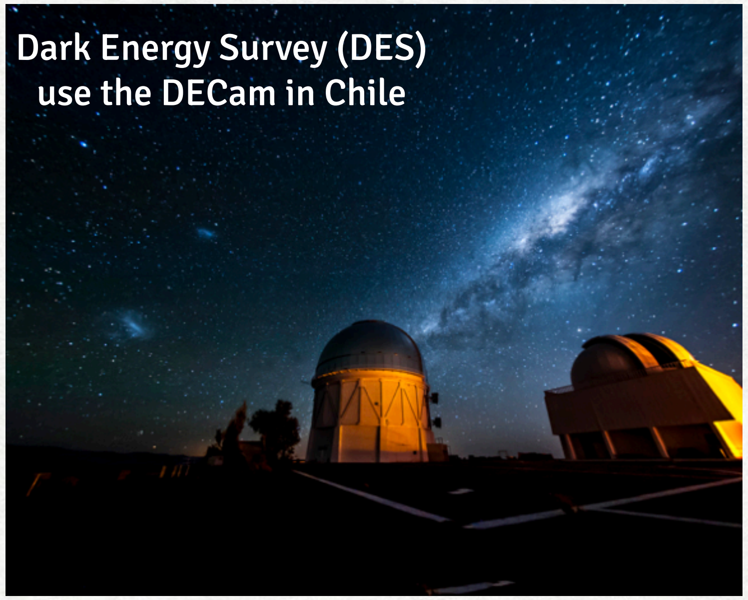
High-accuracy measurements (very different systematics) all indicate large H_0

Galaxy weak lensing

- "Weak gravitational lensing" observations measure the distortions in the shape of galaxies







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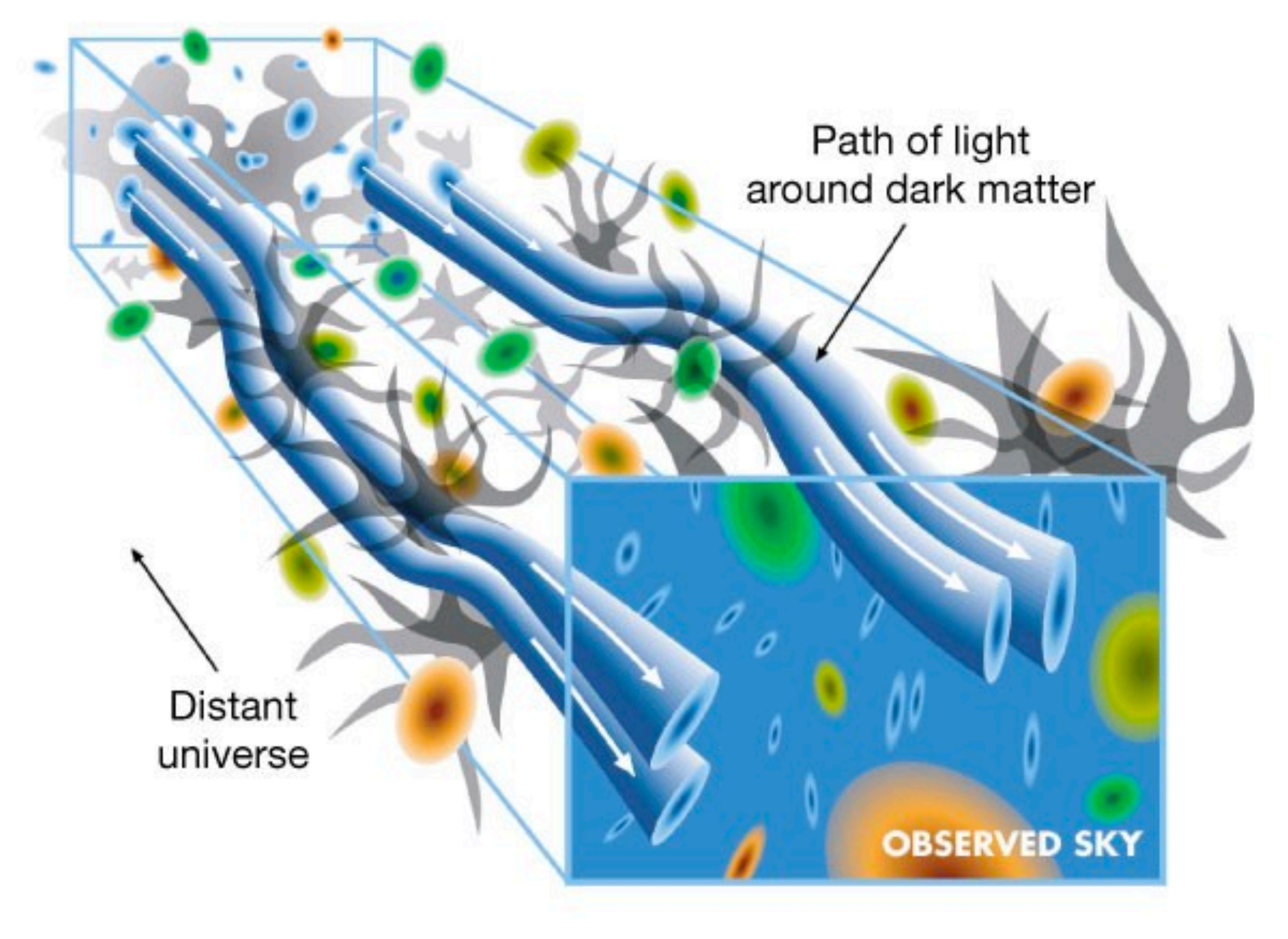
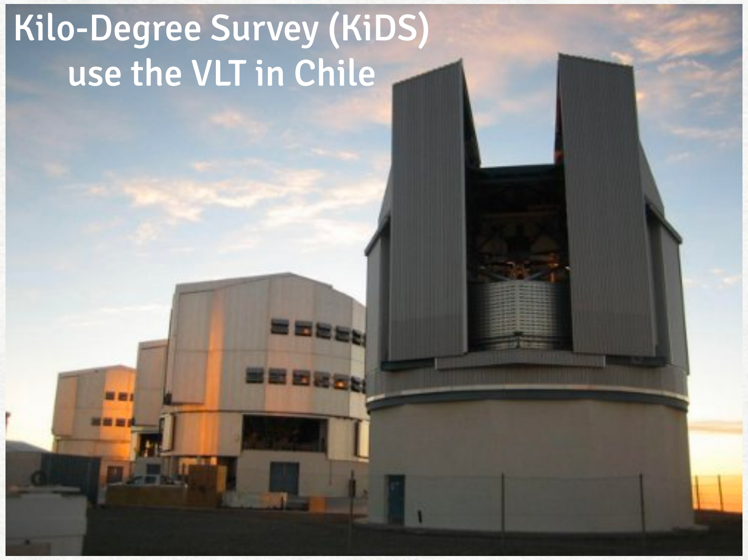
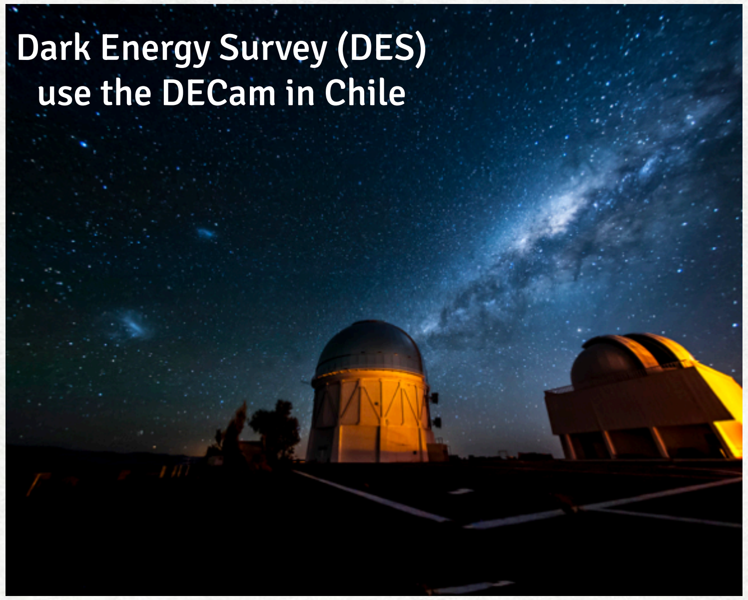
- "Weak gravitational lensing" observations measure the distortions in the shape of galaxies



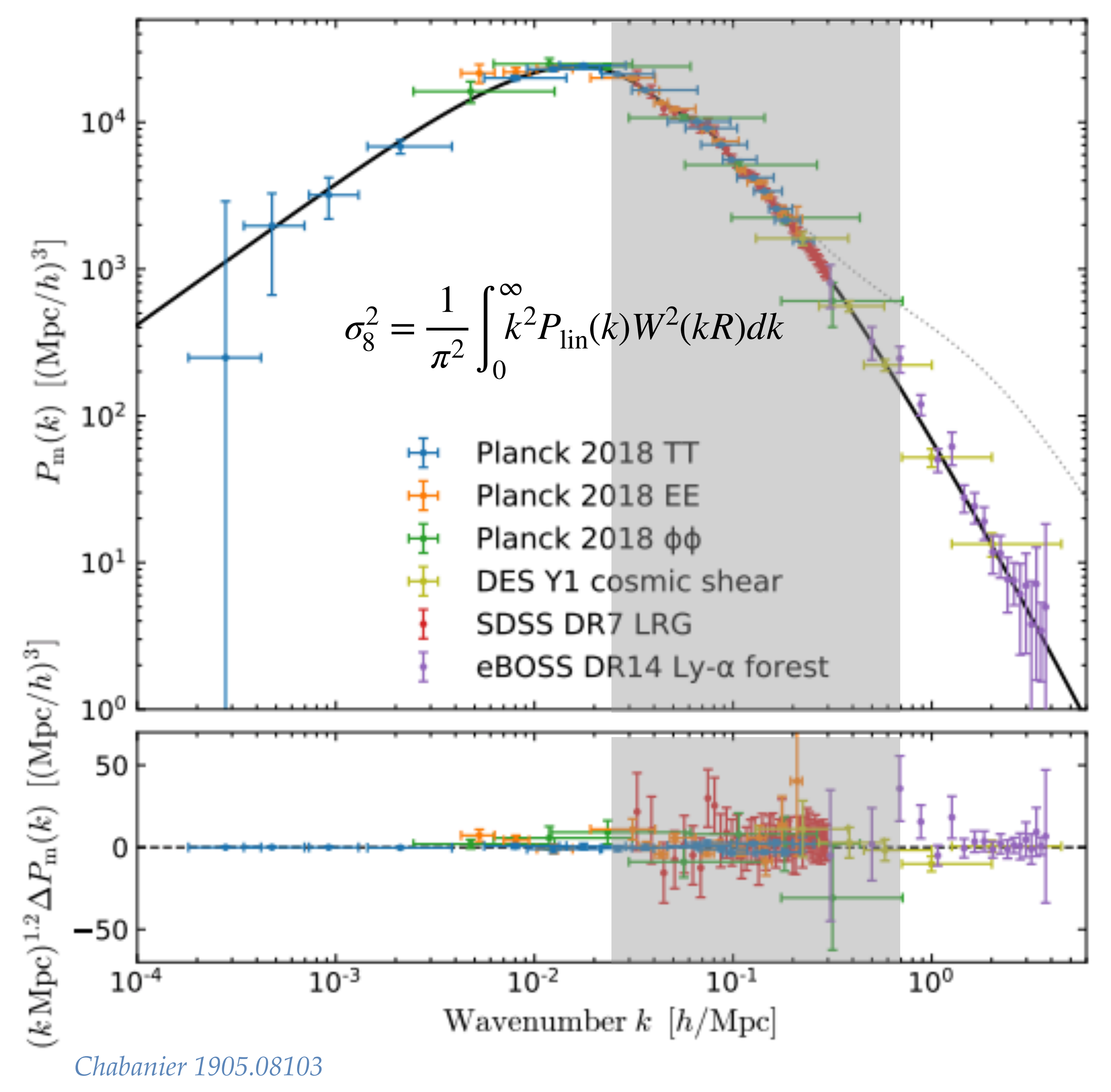

Kilo-Degree Survey (KiDS)
use the VLT in Chile


Dark Energy Survey (DES)
use the DECam in Chile

- There are three main WL observatory: DES, KiDS and HSC (Hawaii)

The S_8 parameter

- WL observations are mostly sensitive to the 'S_8 parameter'.



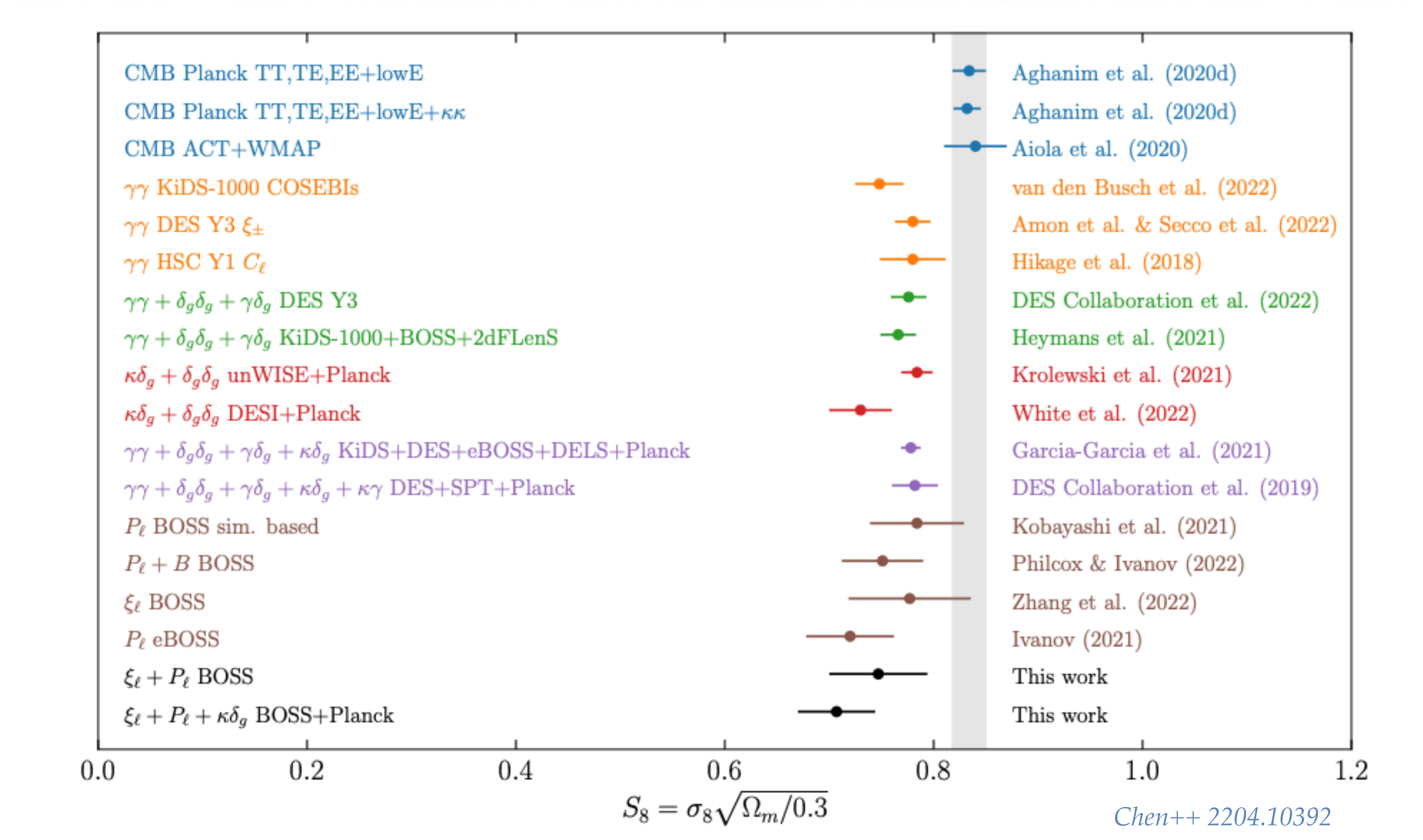
Chabanier 1905.08103

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

$$\sigma_8^2 = \int_0^\infty \frac{k^3}{2\pi^2} P_{\rm lin}(k) W^2(kR) d\ln k$$

- The S_8 parameter quantifies how "clumpy" the universe is on scales of $\sim$ 30 million-ly

The S_8 tension

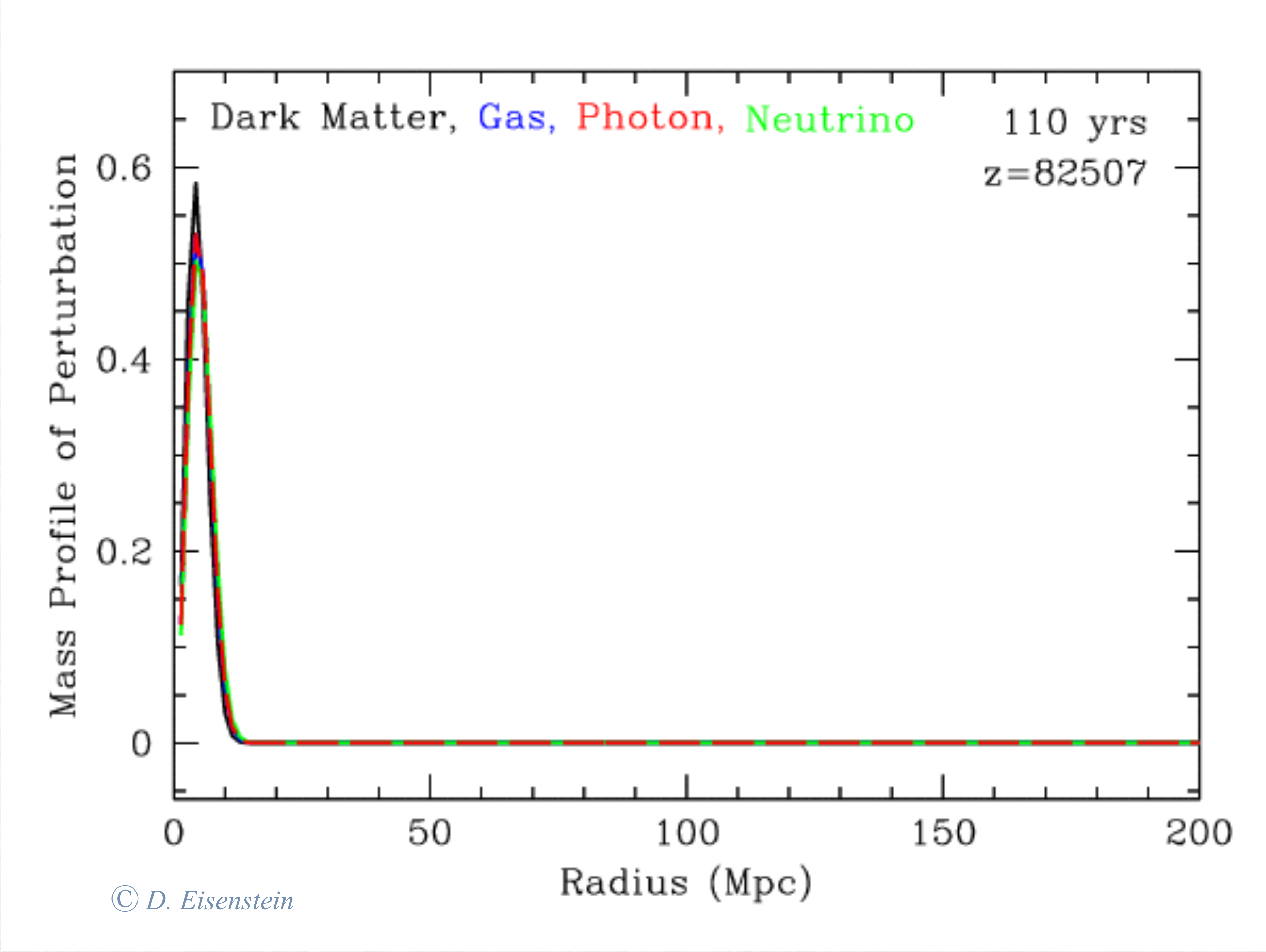


Chen++ 2204.10392

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

The BAO: a standard ruler in the sky

- H_0 measurement with CMB and LSS data thanks to a standard ruler: the sound horizon r_s
- The 'sound horizon' is the distance travelled by sound wave until recombination.



© D. Eisenstein

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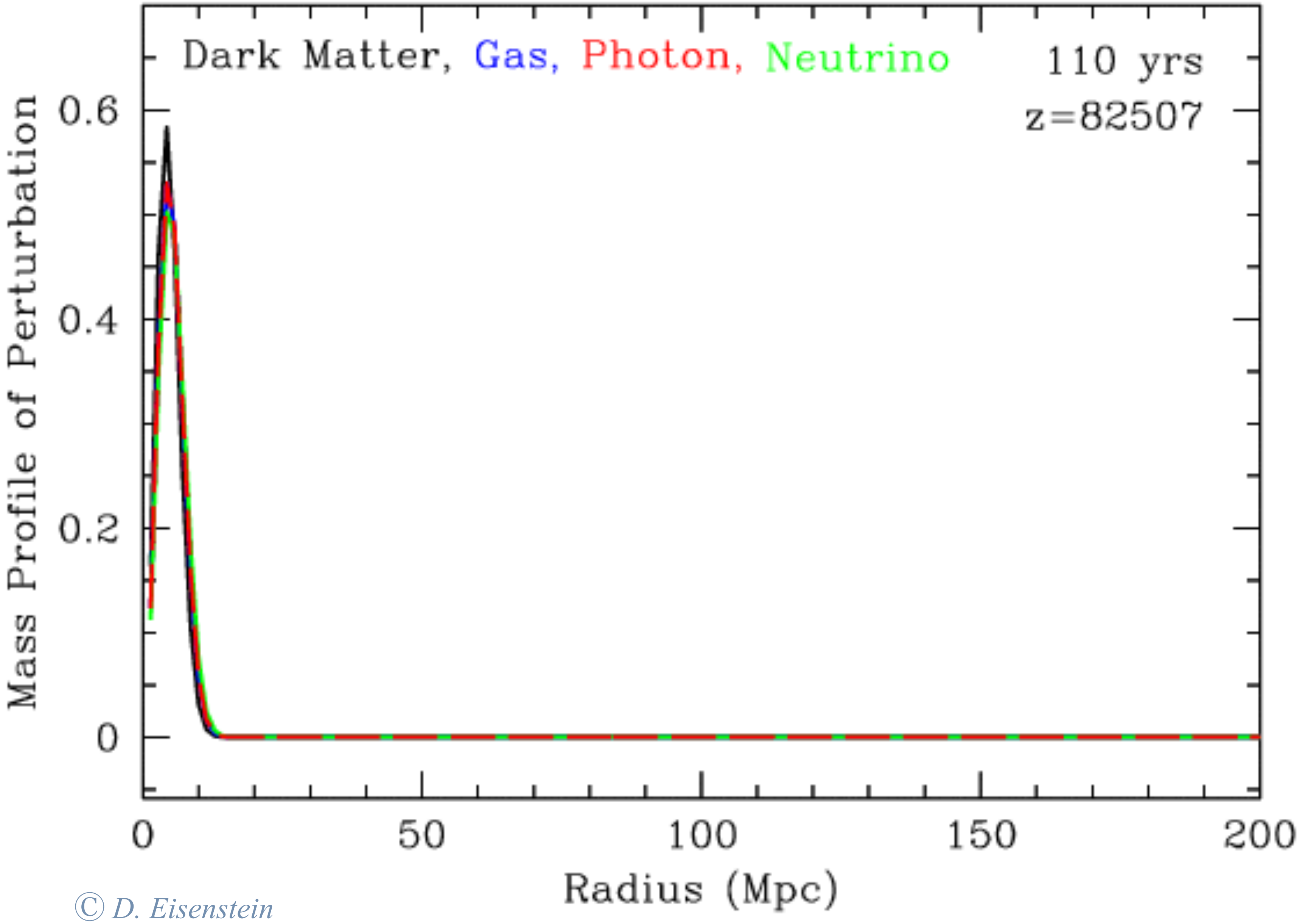
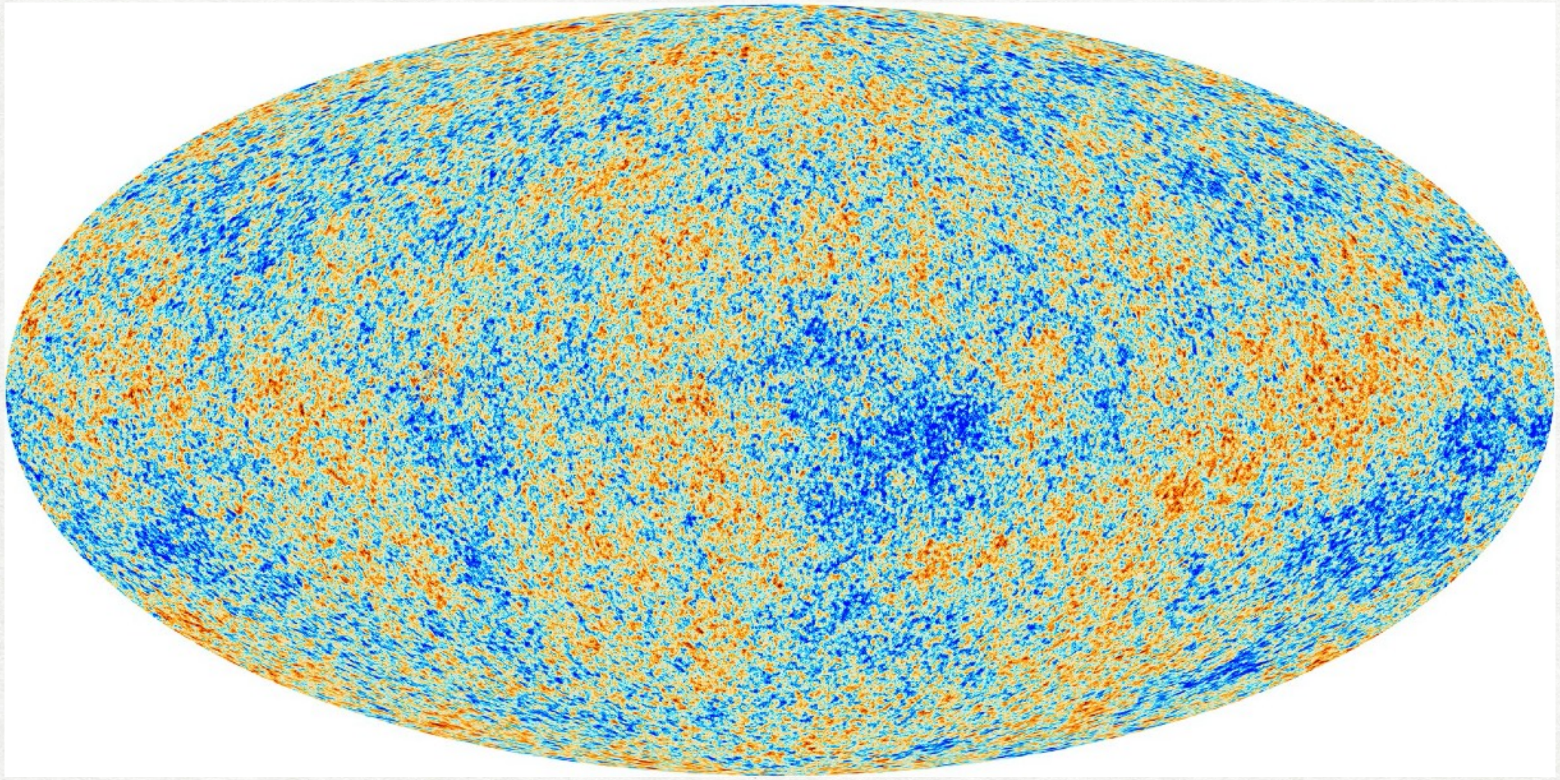


Ⓒ D. Eisenstein

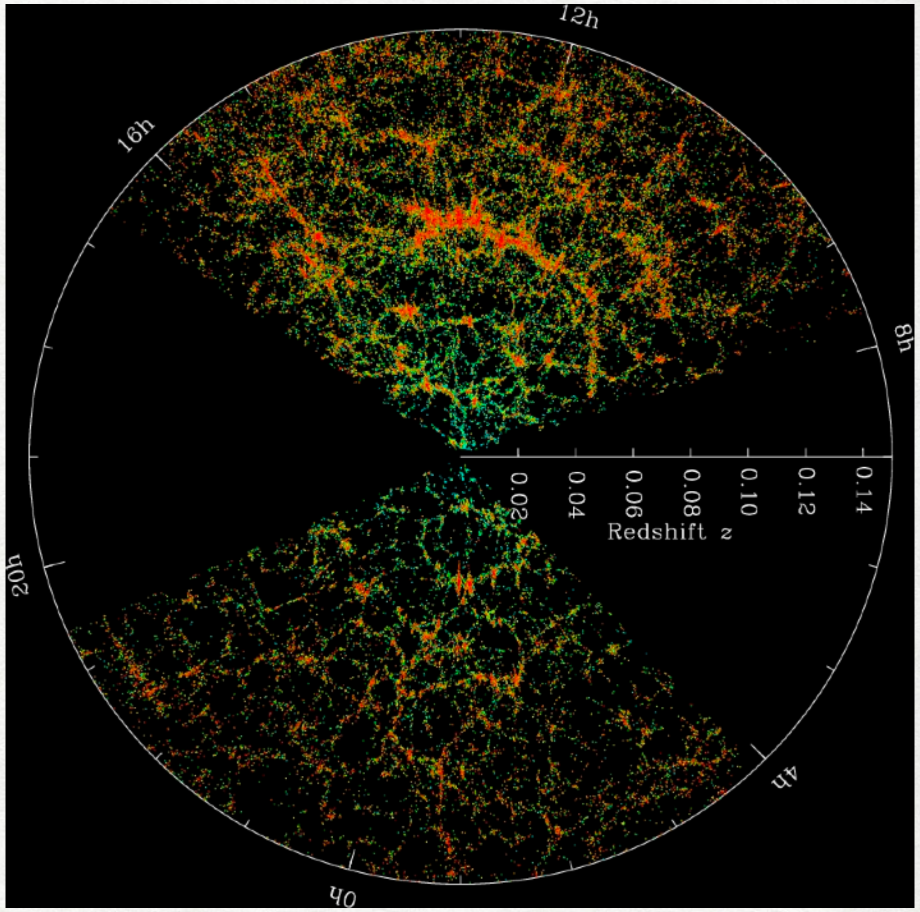
The BAO: a standard ruler in the sky

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



Planck 1807.06209

$z \sim 1100$



BOSS/SDSS collaboration

$z \sim 0 - 1$

How does CMB data measure H_0?

- *Planck* measures θ_s and, *given a model,* can extract r_s.
- H_0 appears only in the angular diameter distance d_A.

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

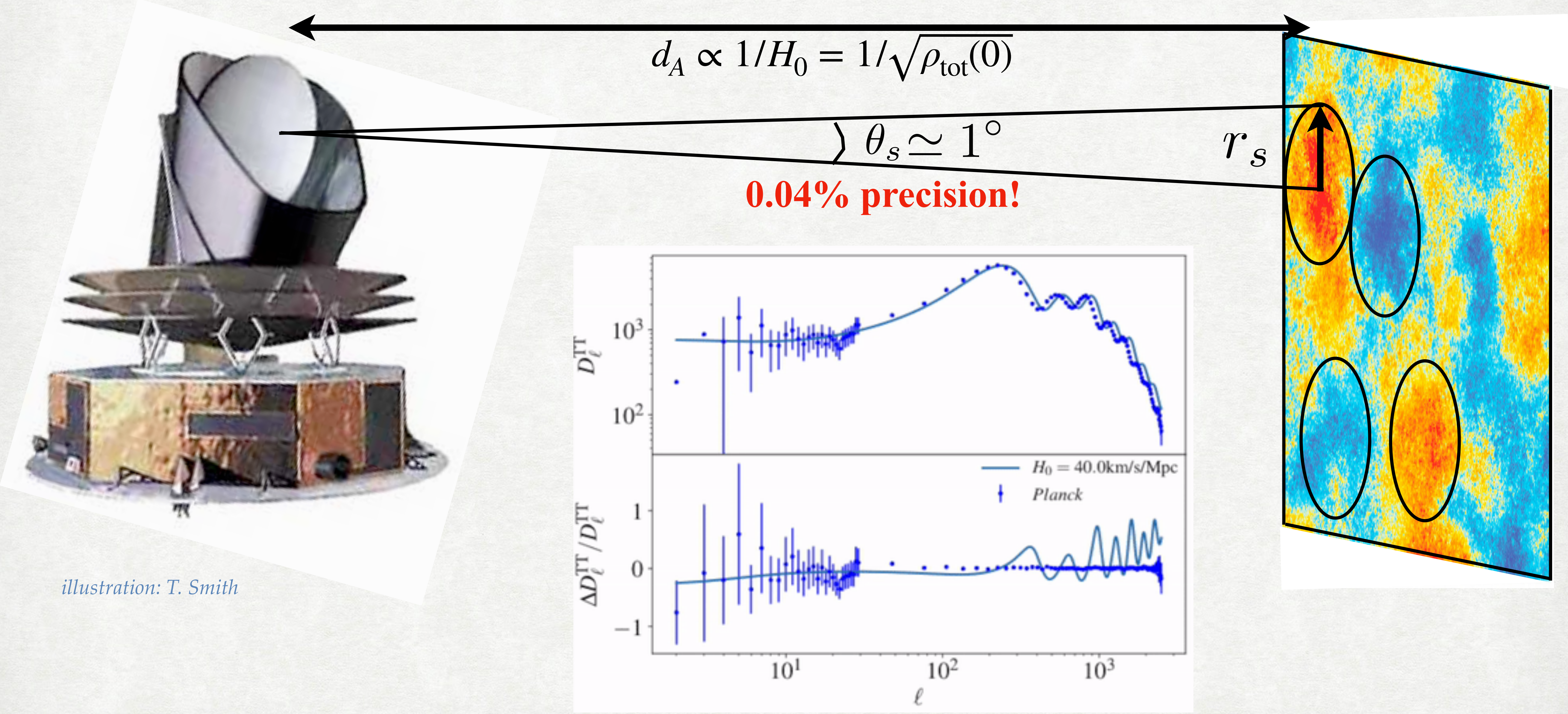


illustration: T. Smith

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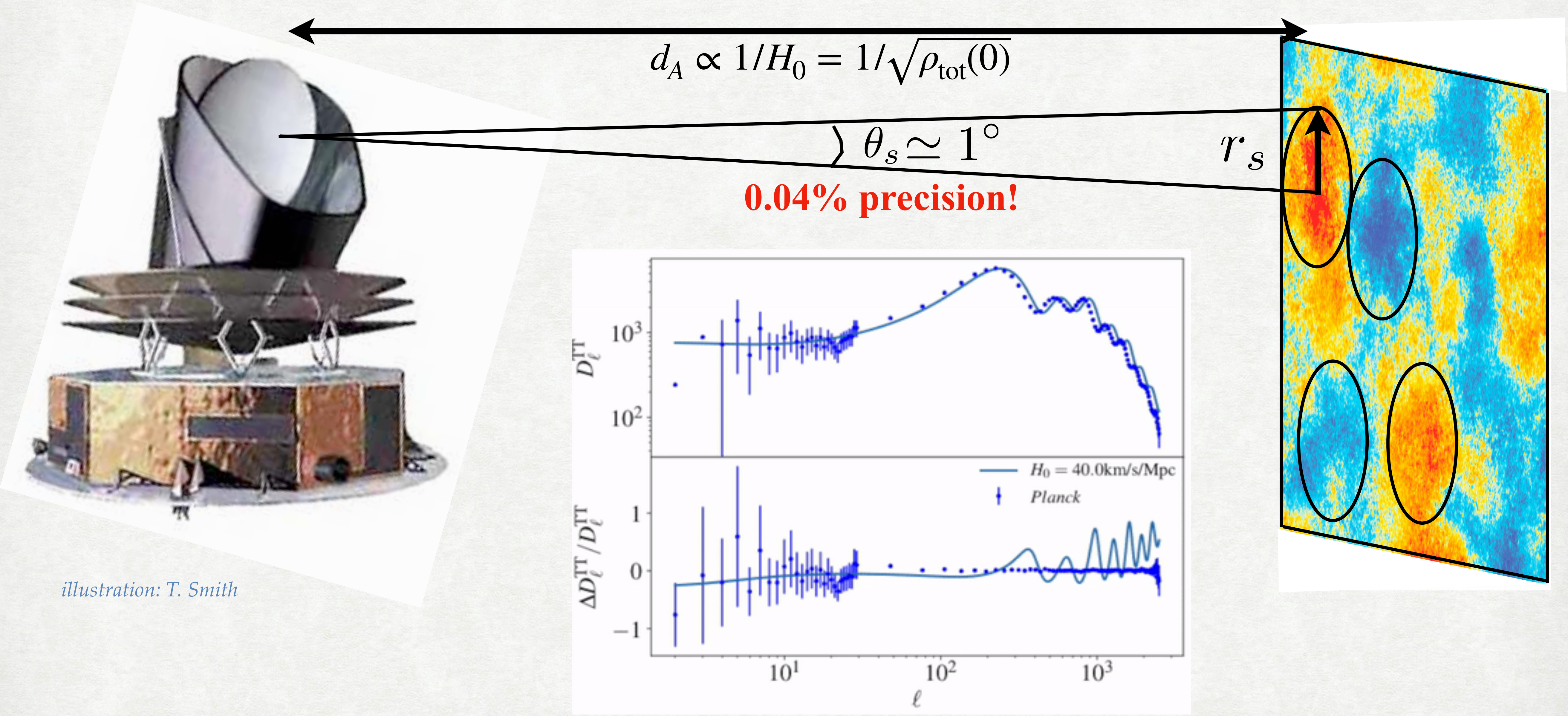
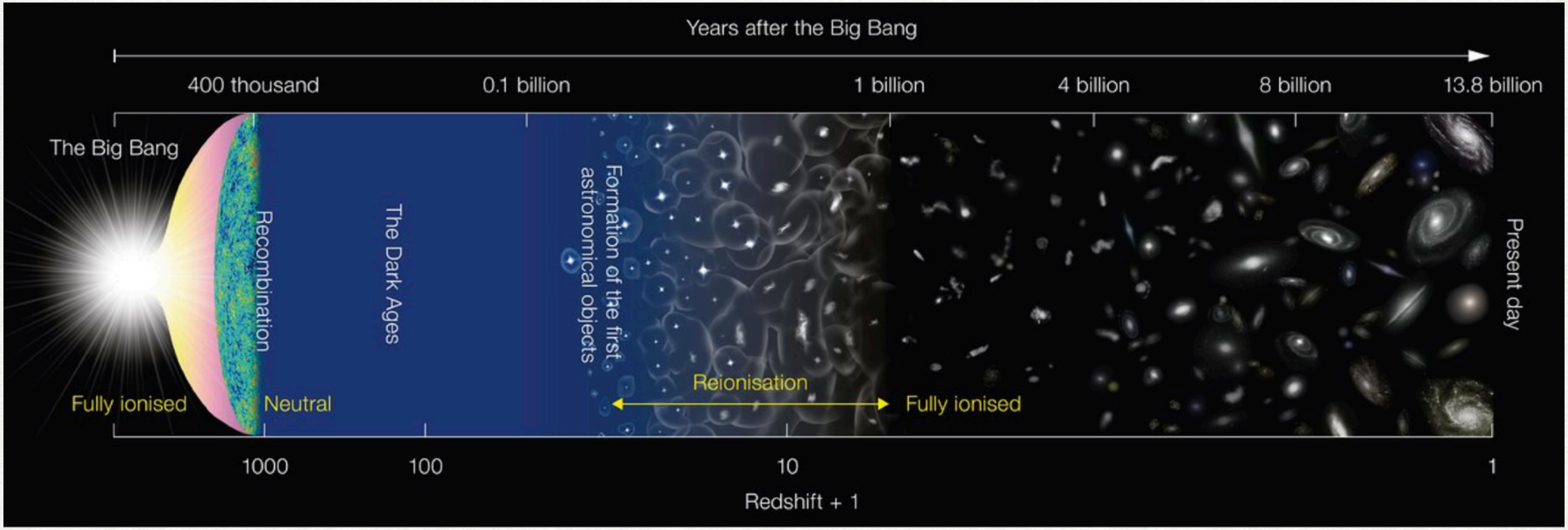


0.04% precision!

illustration: T. Smith

New physics in the Universe?

$$\theta_s = \frac{r_s}{r_A} = \frac{H_0 r_s}{\int_0^{z_*} 1/E(x)\mathrm{d}x}$$



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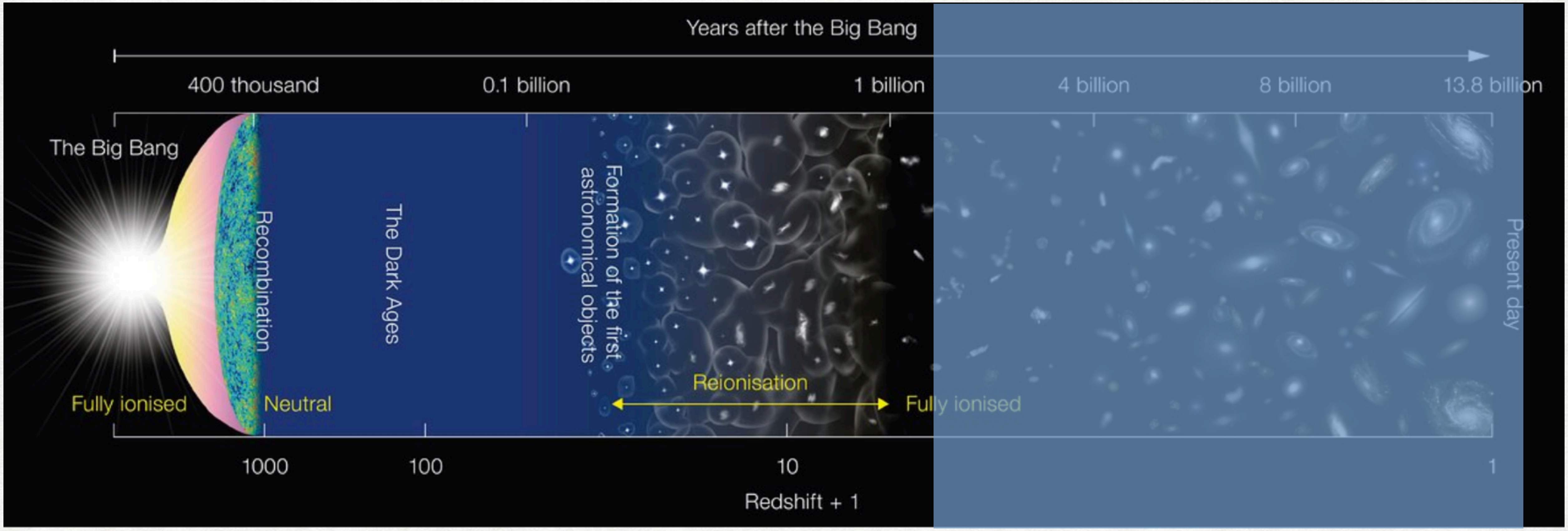
Late-universe models



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

Change expansion history

New physics in the Universe?

Early universe models

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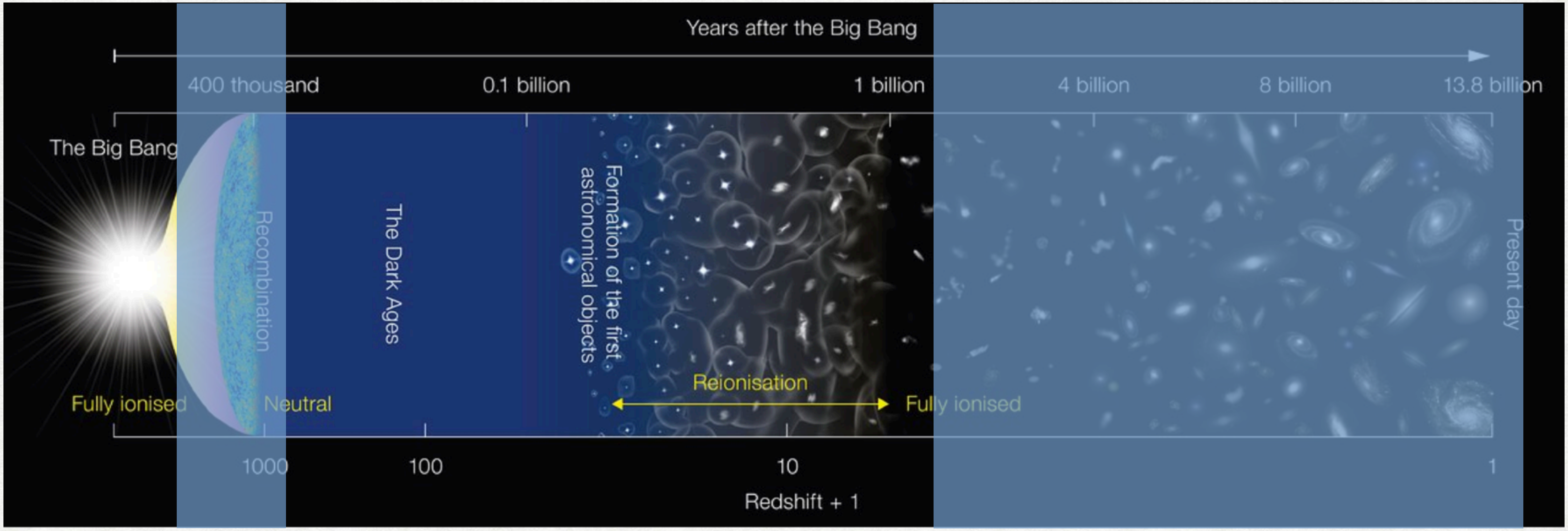
Late-universe models



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

Change calibrator

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

Change expansion history

Geometrical degeneracy in the late-universe!

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

$$d_A(z_*) = \frac{1}{1+z_*}\int_0^{z_*} \frac{dz}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{\rm DE}(1+z)^{3(1+w)}}}$$

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- '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]

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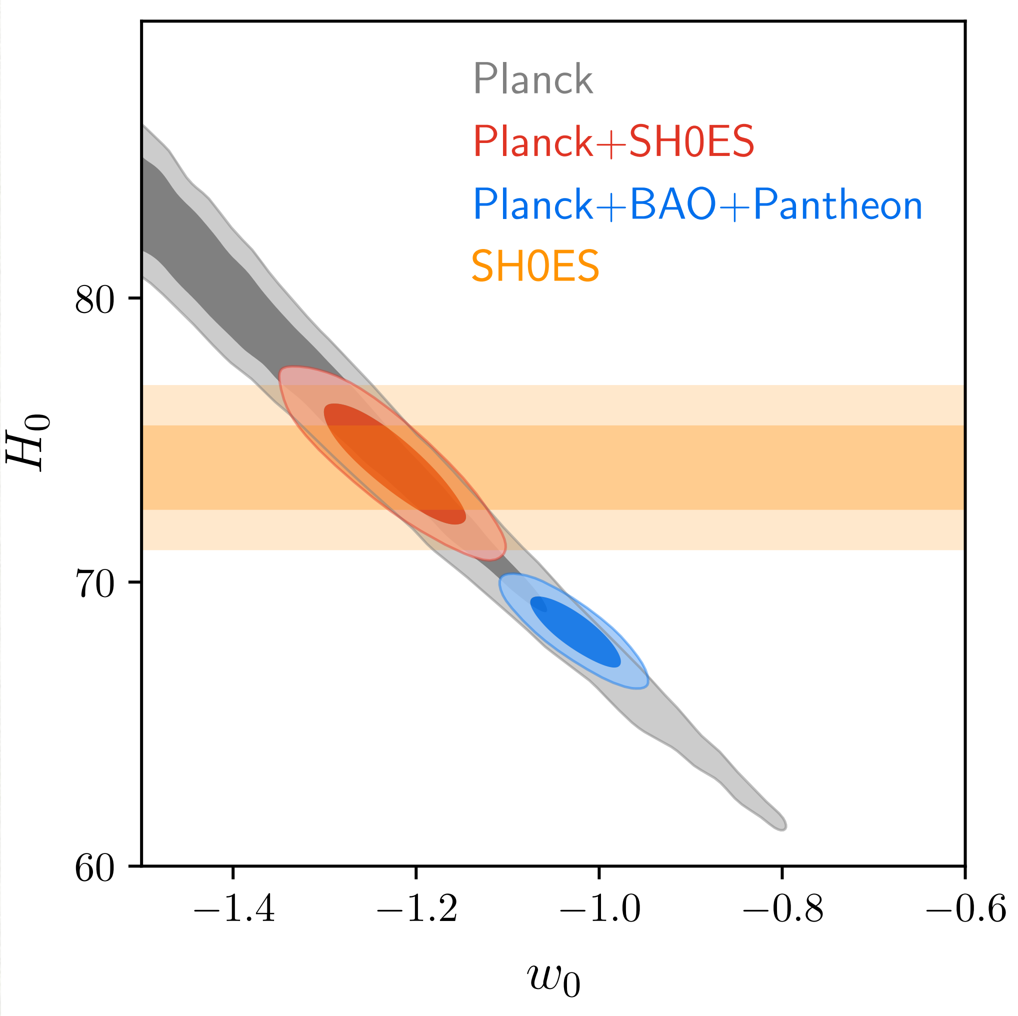
- Planck can easily accommodate a higher H_0: problem with BAO and Pantheon



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!

$$\theta_d(z) = \frac{r_s(z_{\rm drag})}{D_A(z)}$$

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

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

- Calibration M_b from e.g. SH0ES.

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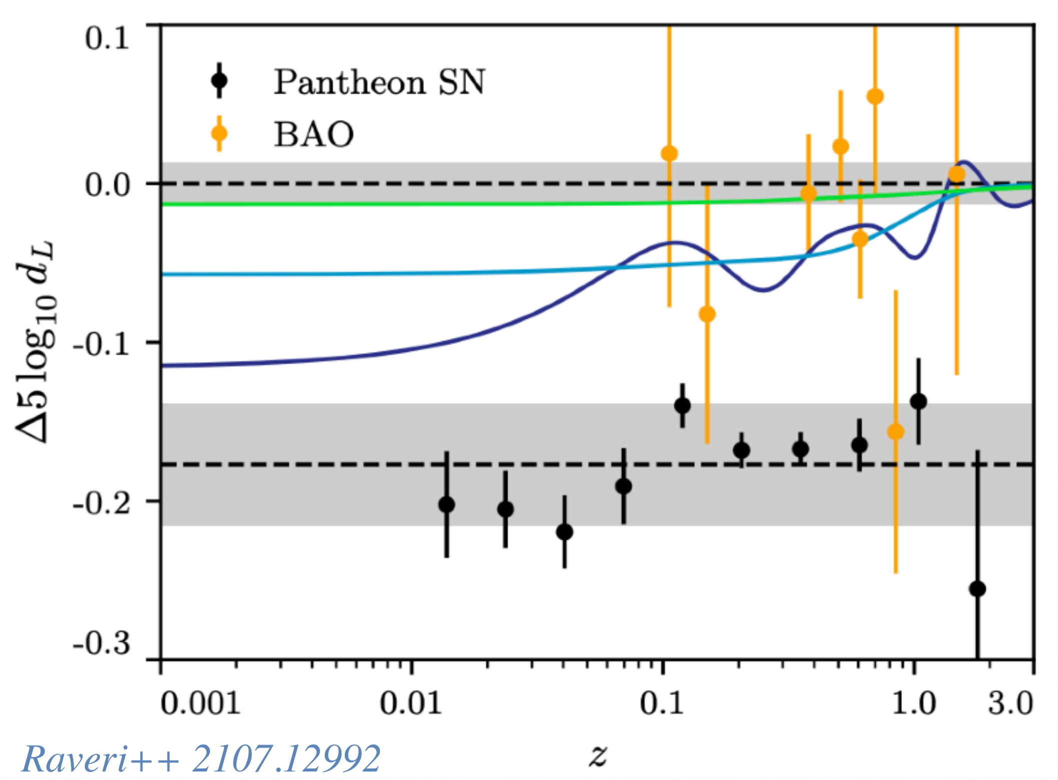

Raveri++ 2107.12992

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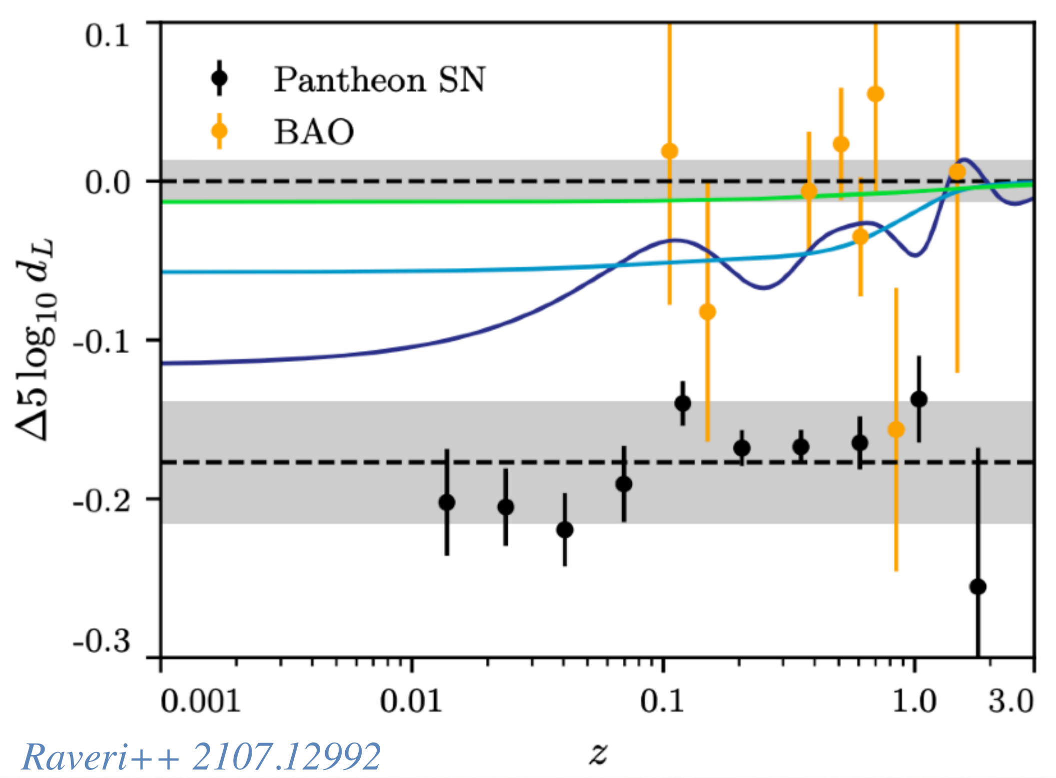

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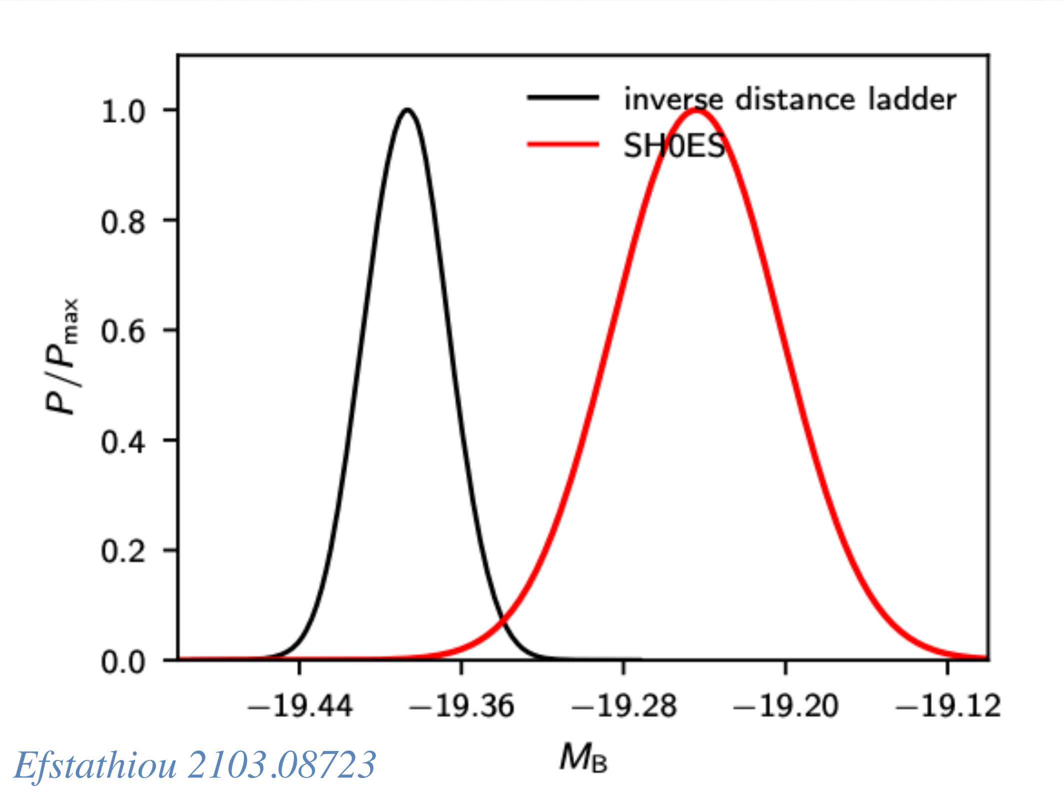

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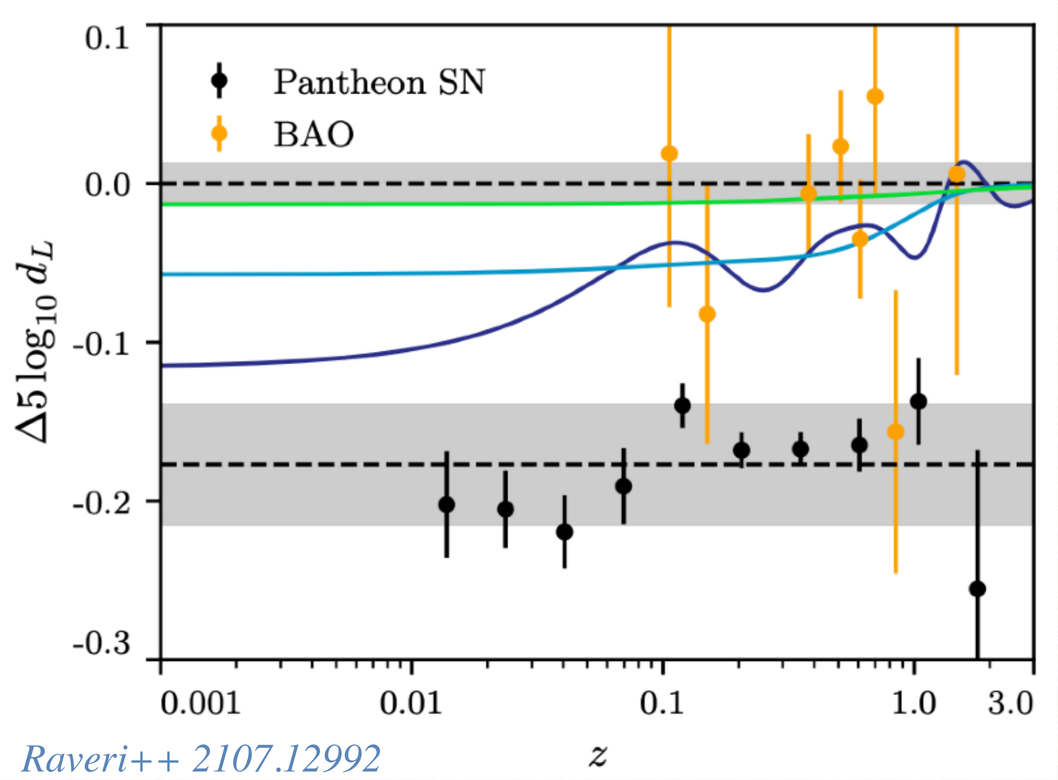

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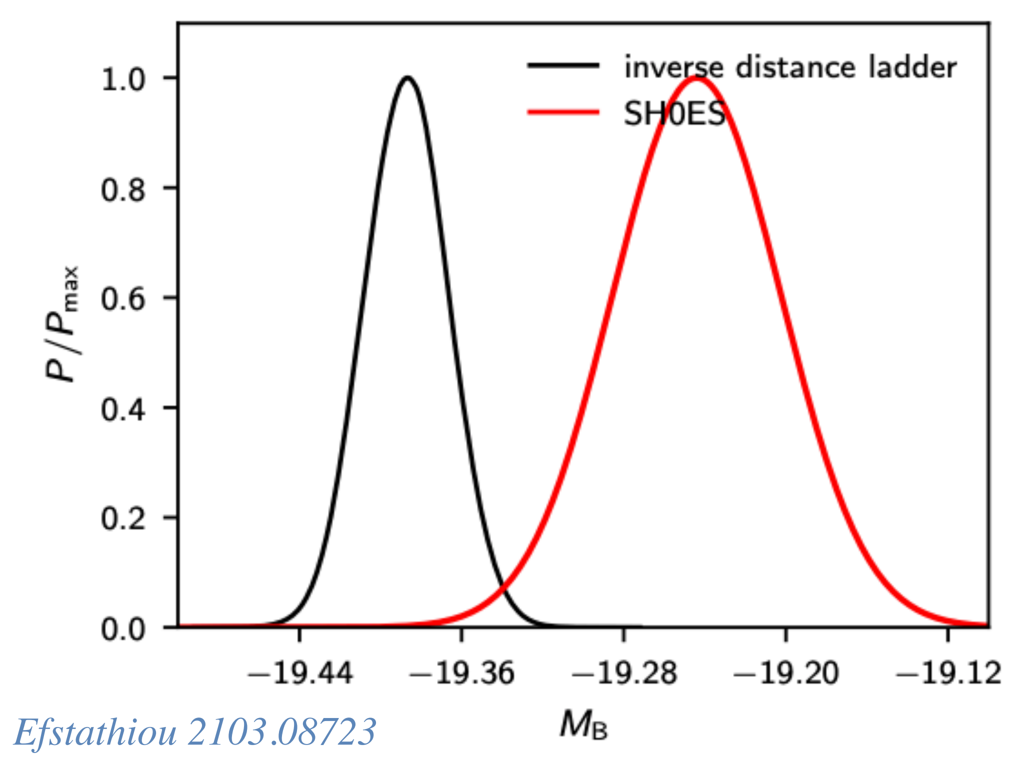

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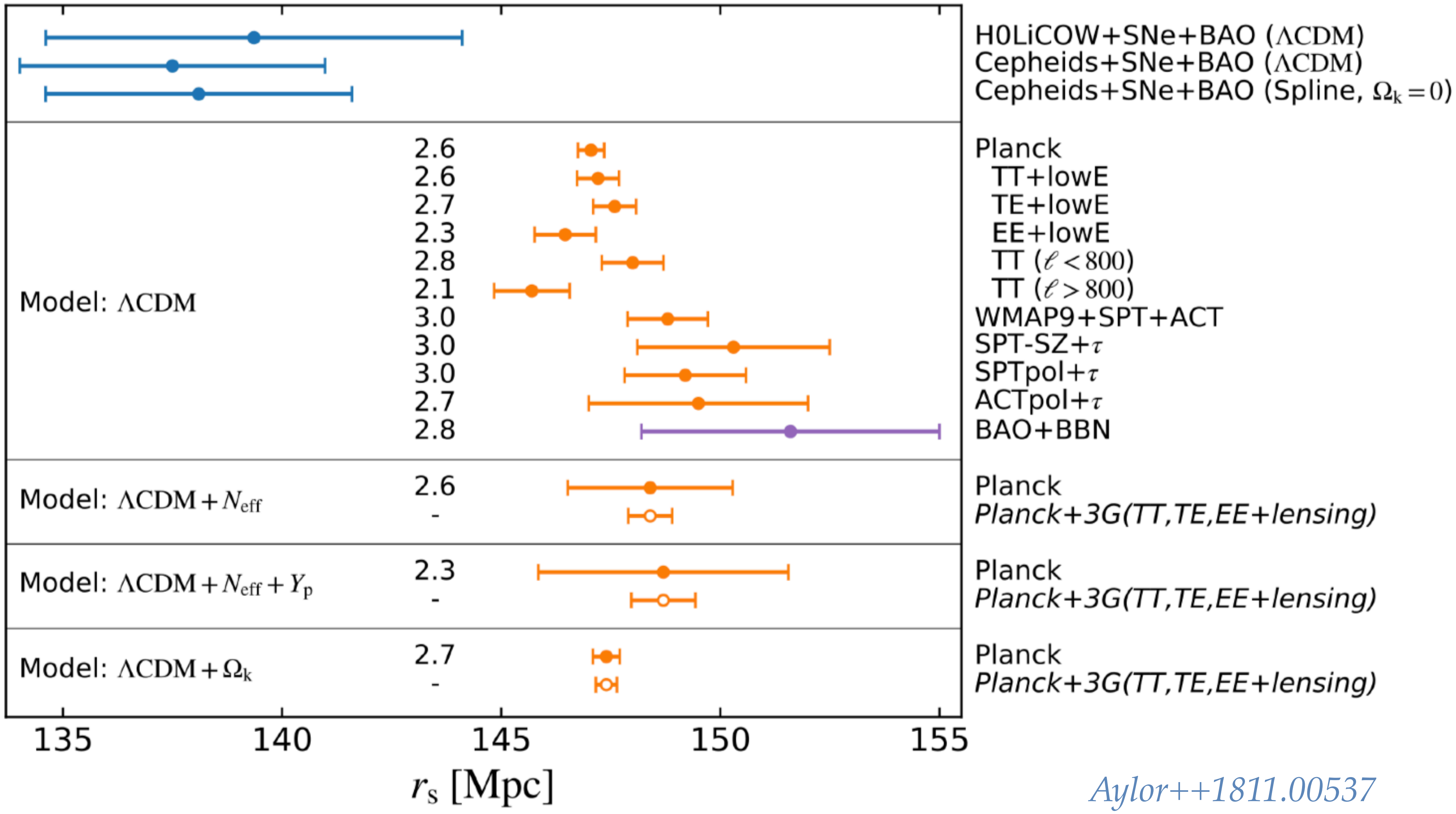
- One can calibrate the SN1a using the sound horizon and predict M_B: inverse distance ladder calibration
- How can one make the inverse ladder calibration of M_B compatible with SH0ES?

H_0 tension or r_s tension?

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



Aylor++1811.00537

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Knox & Millea 1908.03663

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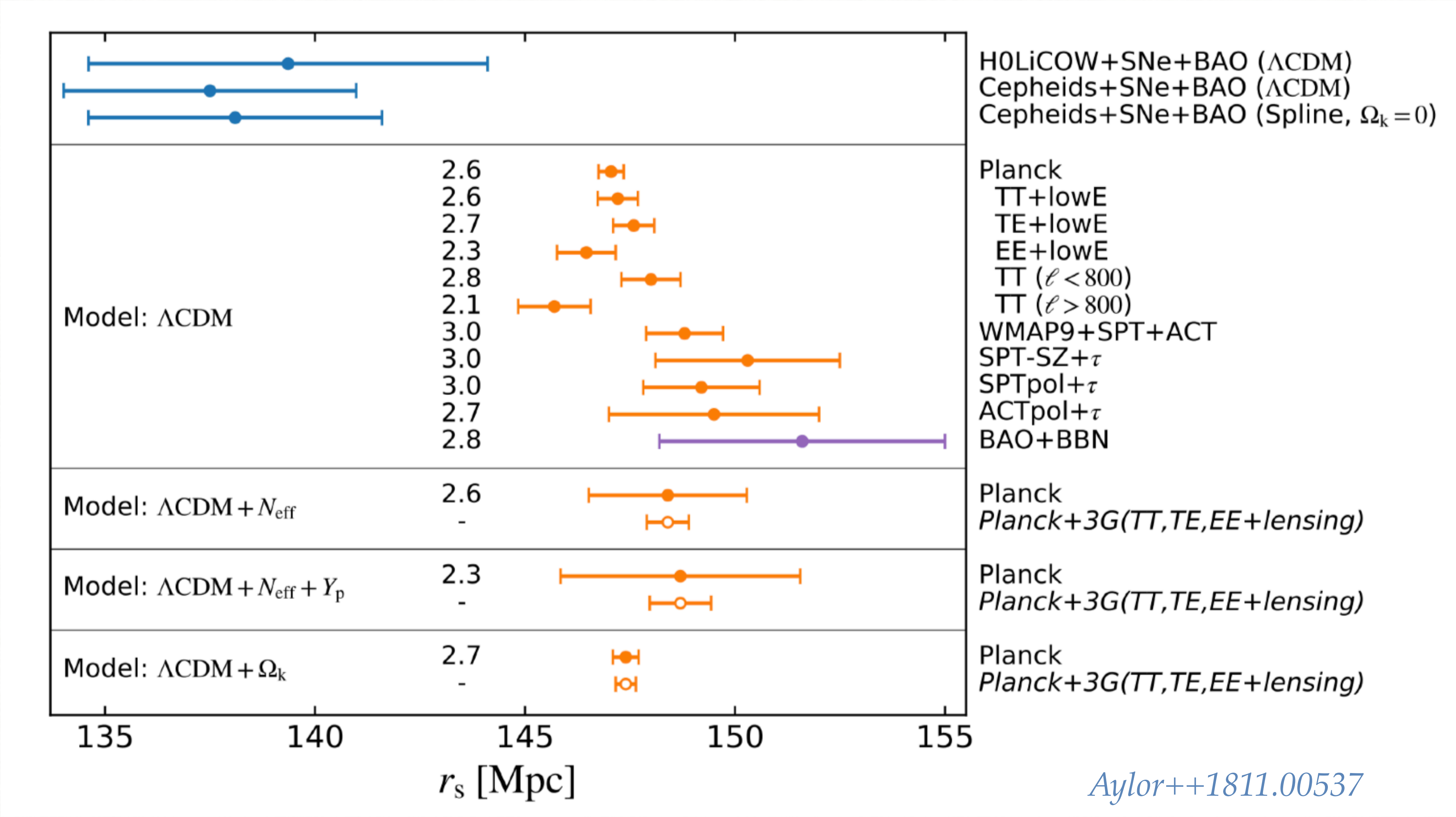

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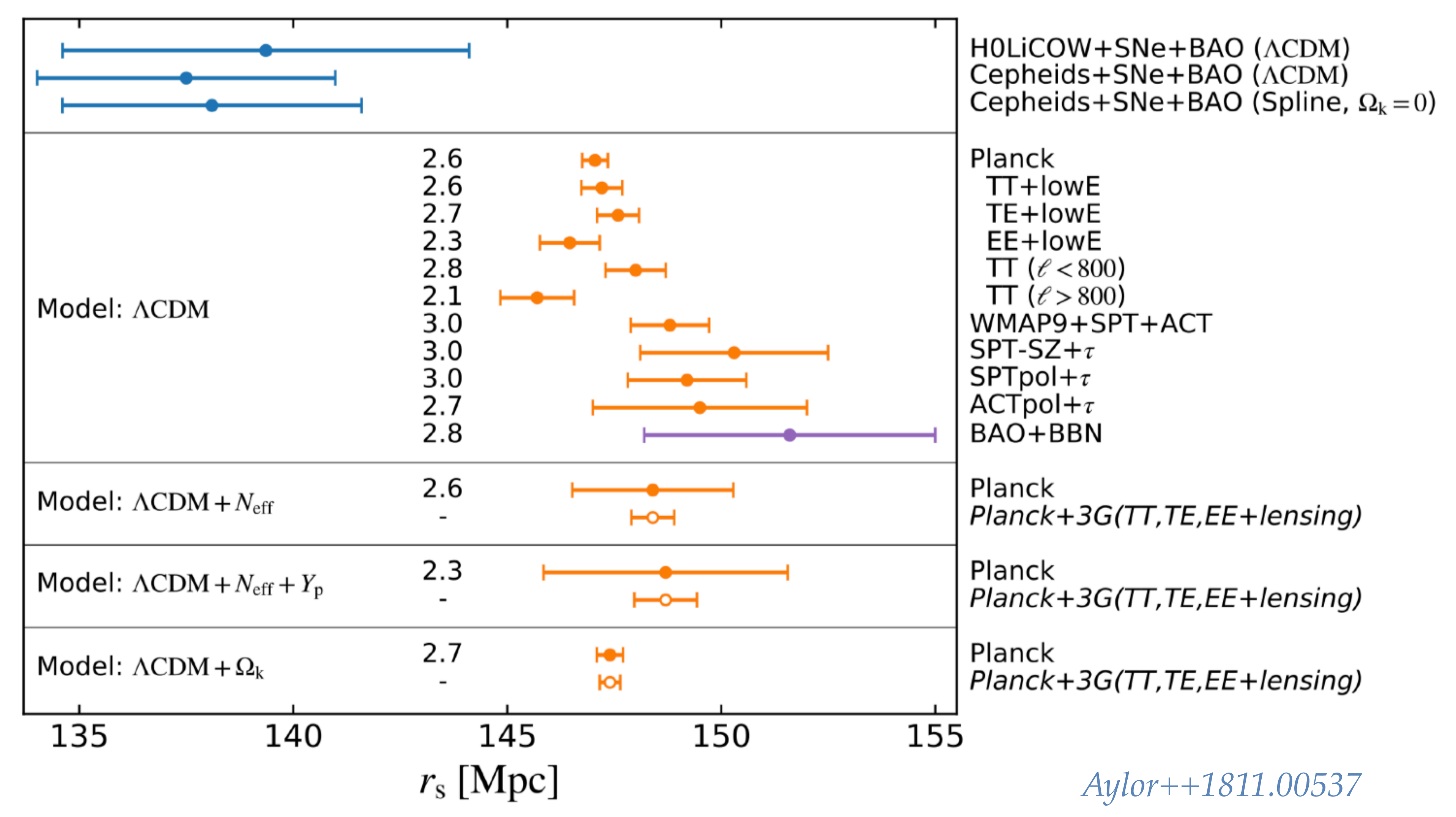

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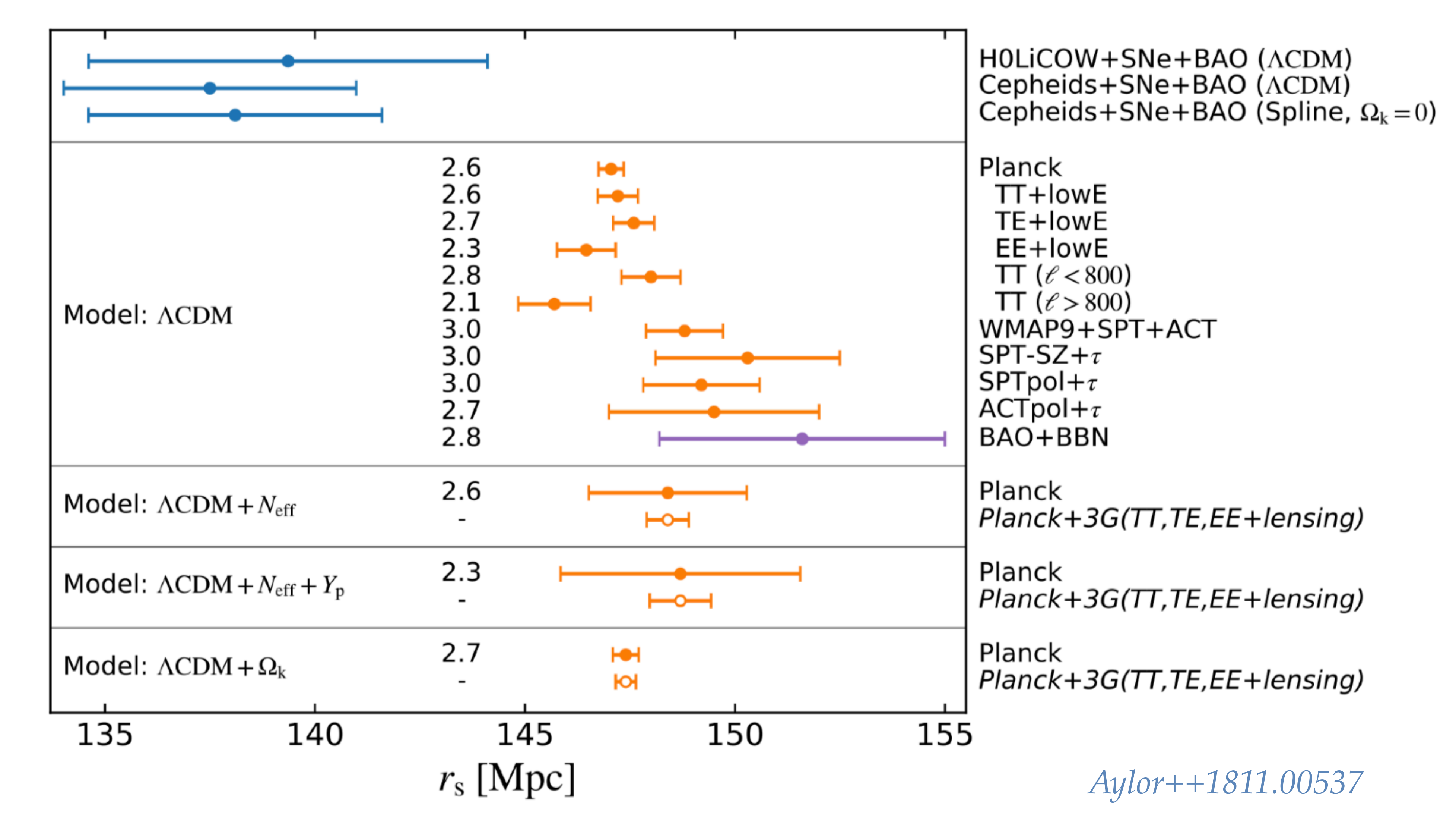

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increase ρ(z): Neff? Early Dark Energy?
Modified Gravity?

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

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

- Standard Model neutrinos behave as *free-streaming radiation* since T~1MeV with $N_{\rm eff} = 3.044$

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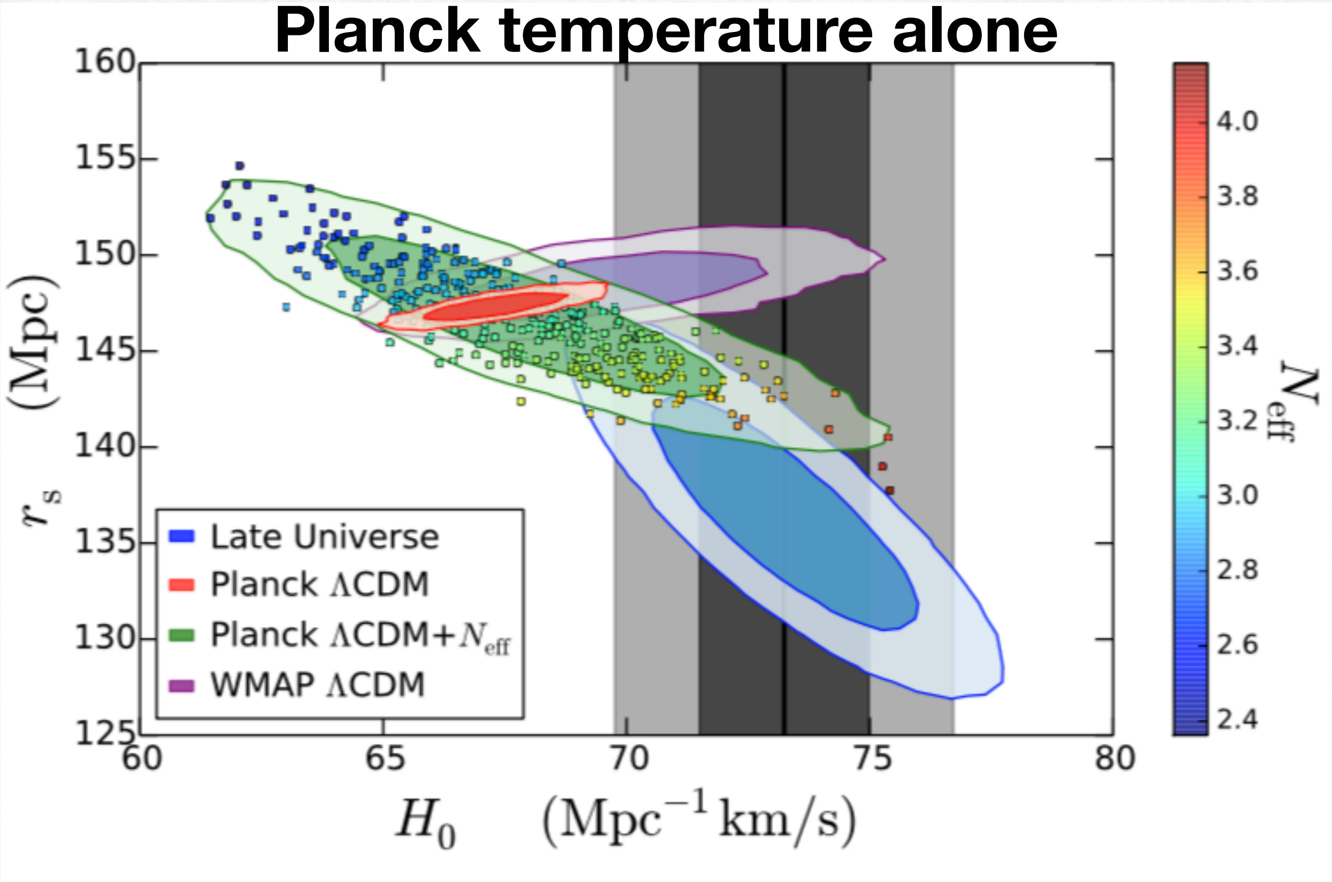

Bernal++ 1607.05617

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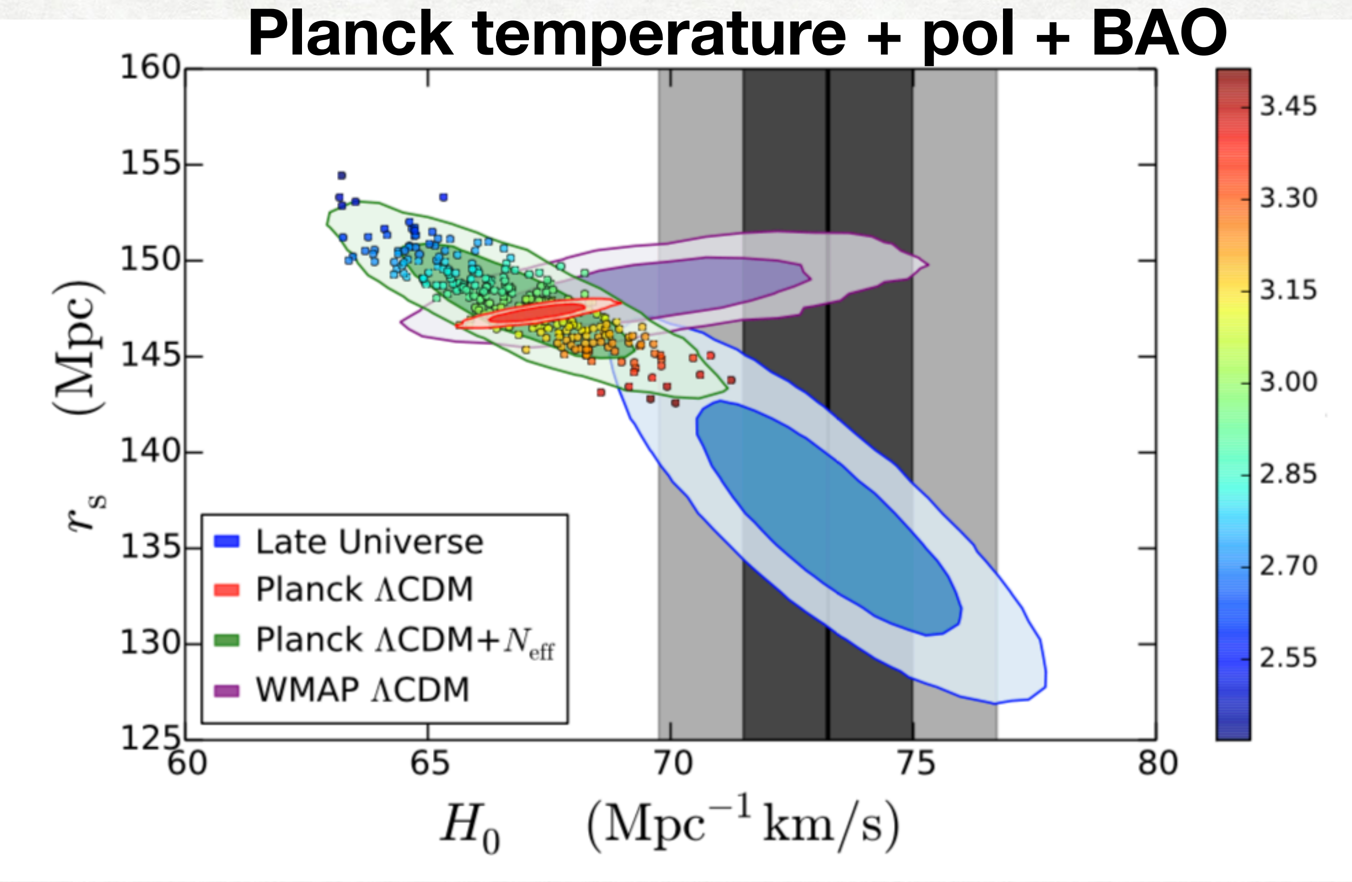

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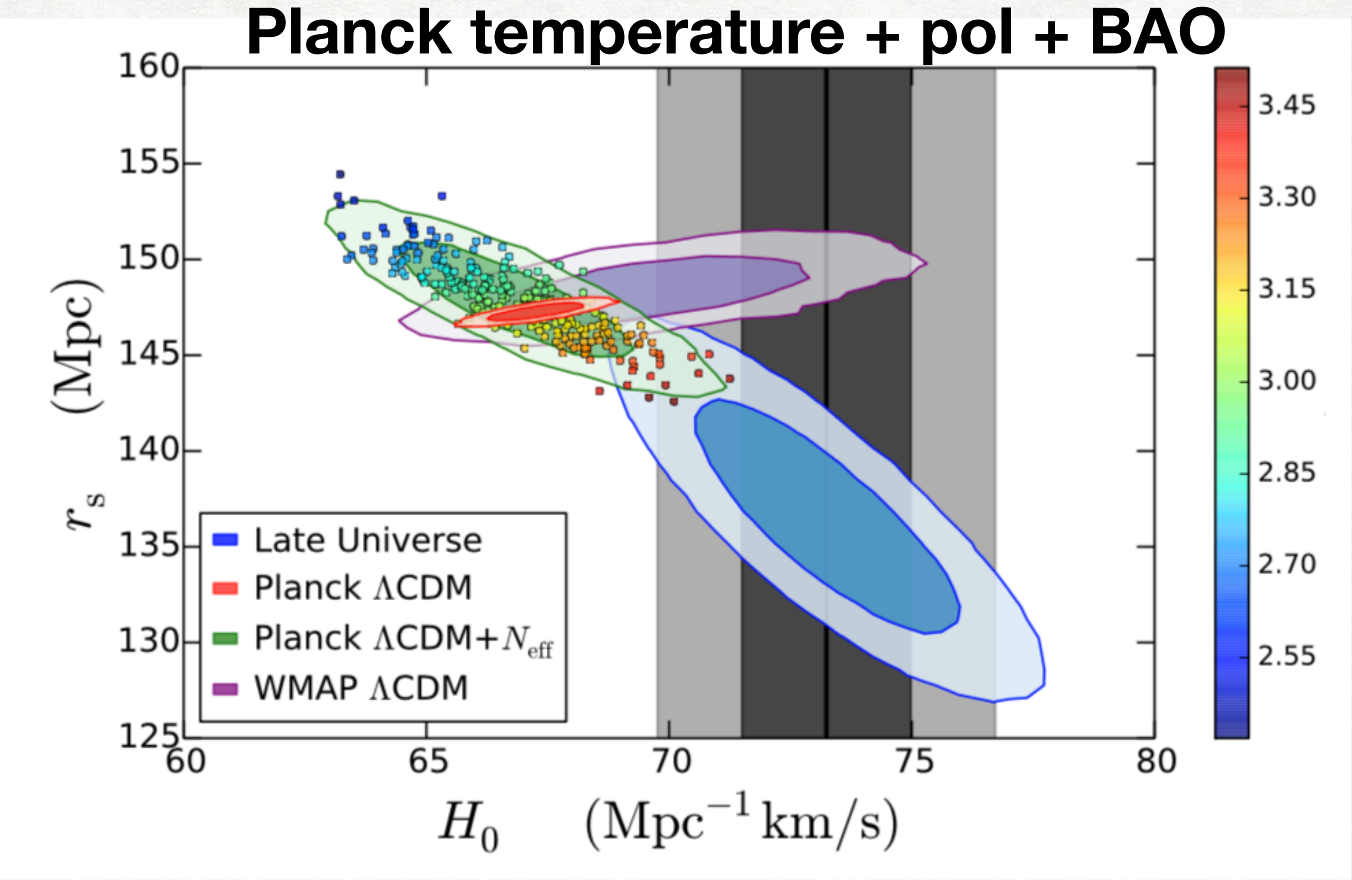

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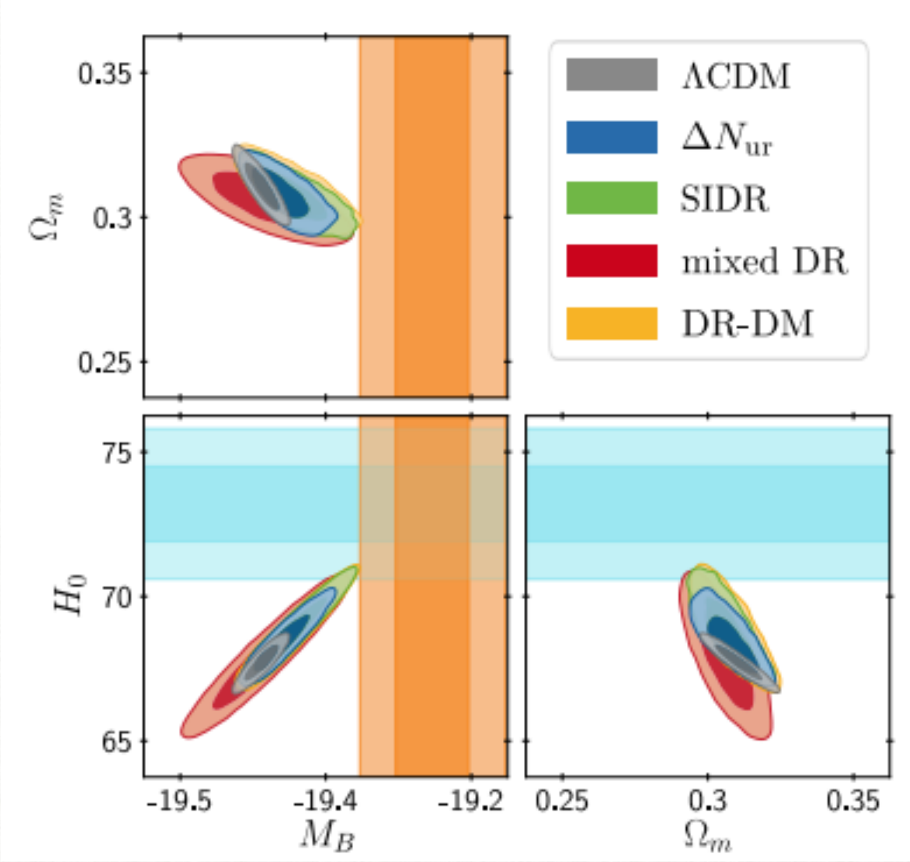
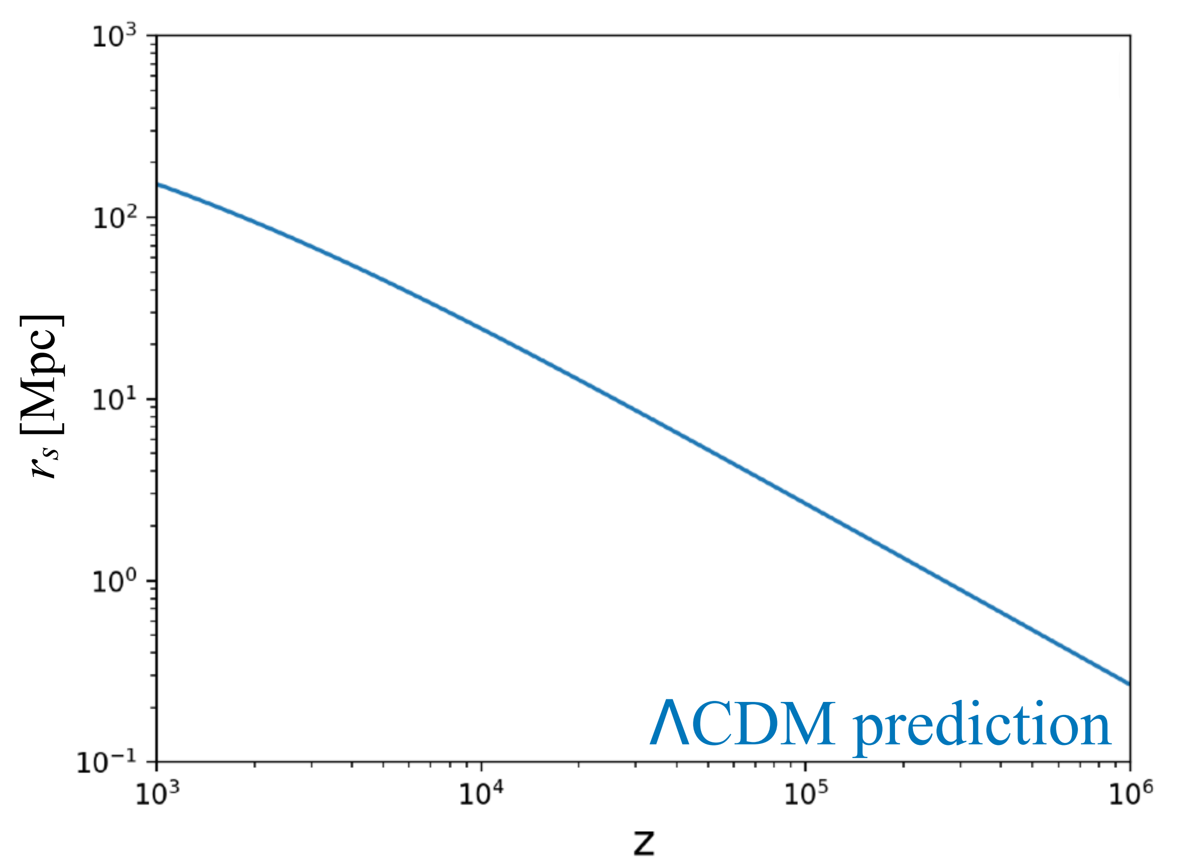


Schöneberg++2107.10291

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

Exotic energy injection to resolve the H_0 tension

- r_s must decrease by ~10Mpc.



See the `Hubble Hunter's guide' Knox&Millea 1908.03663

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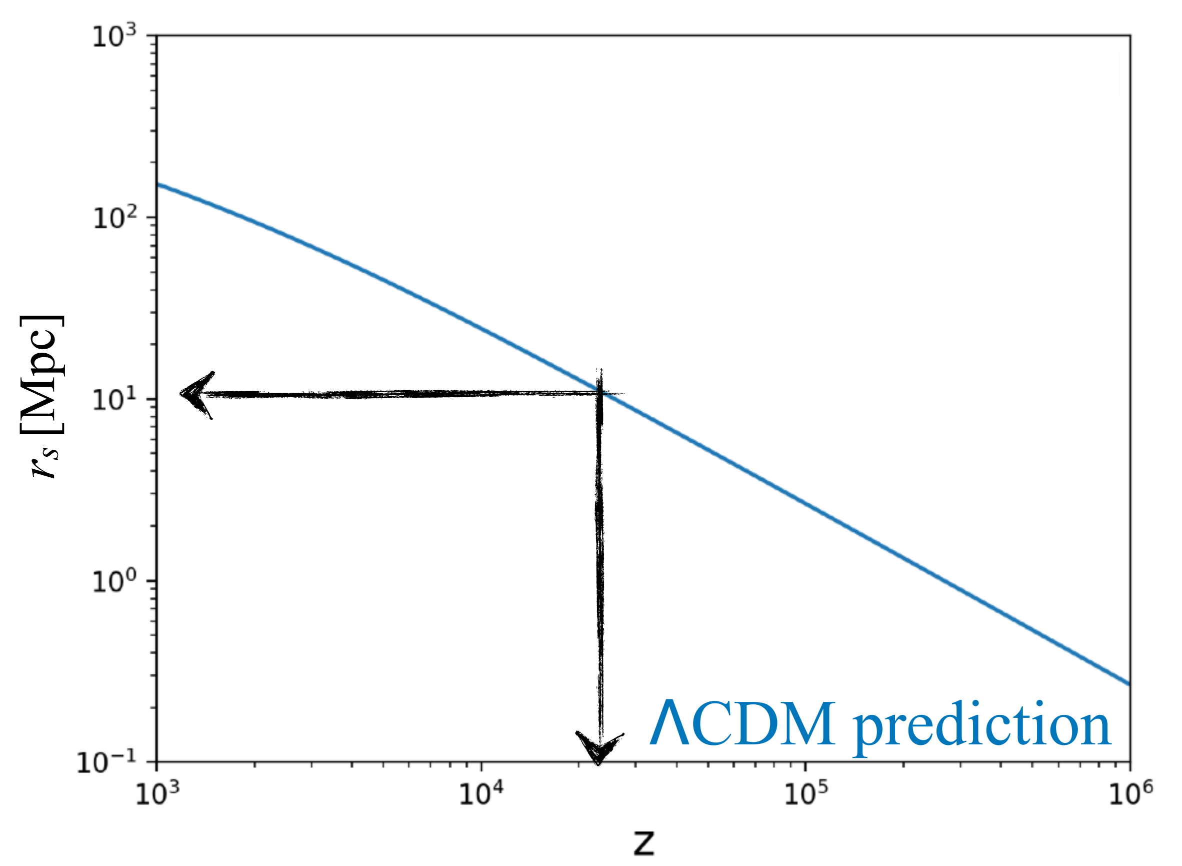

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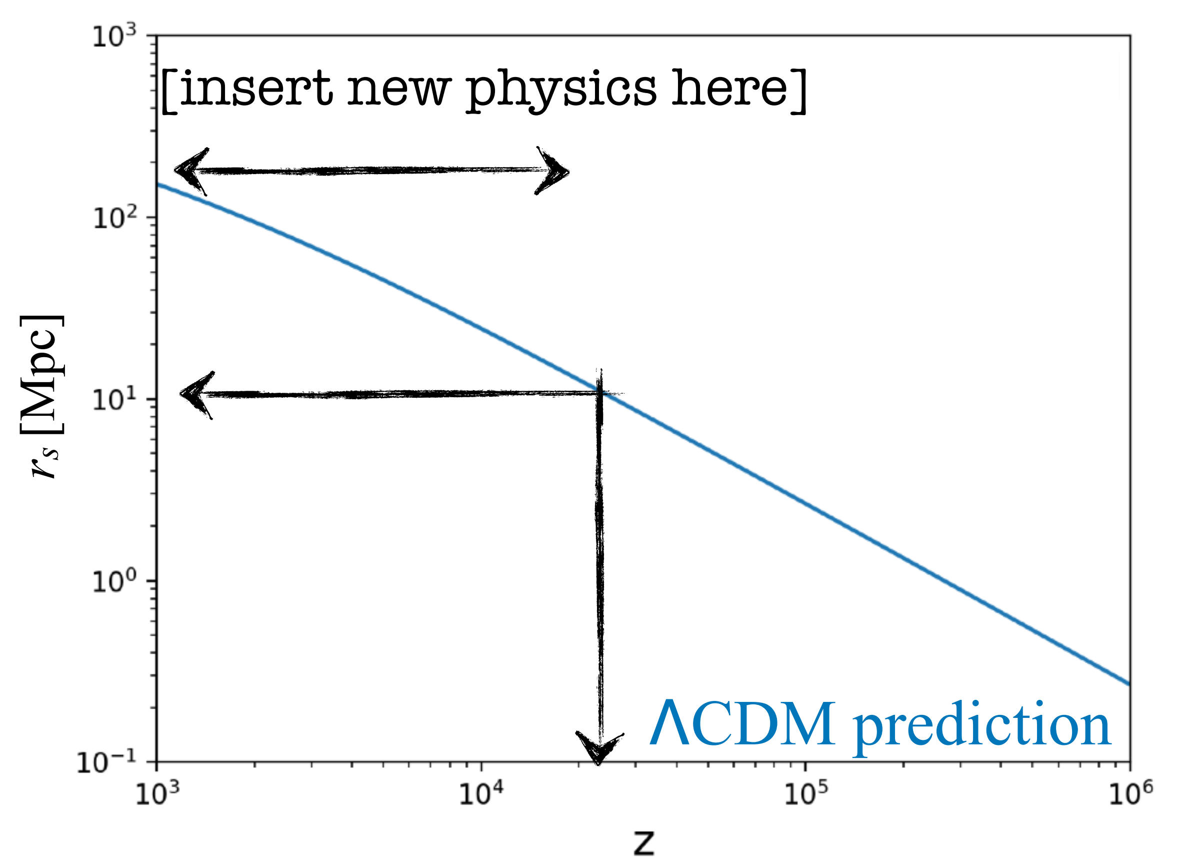

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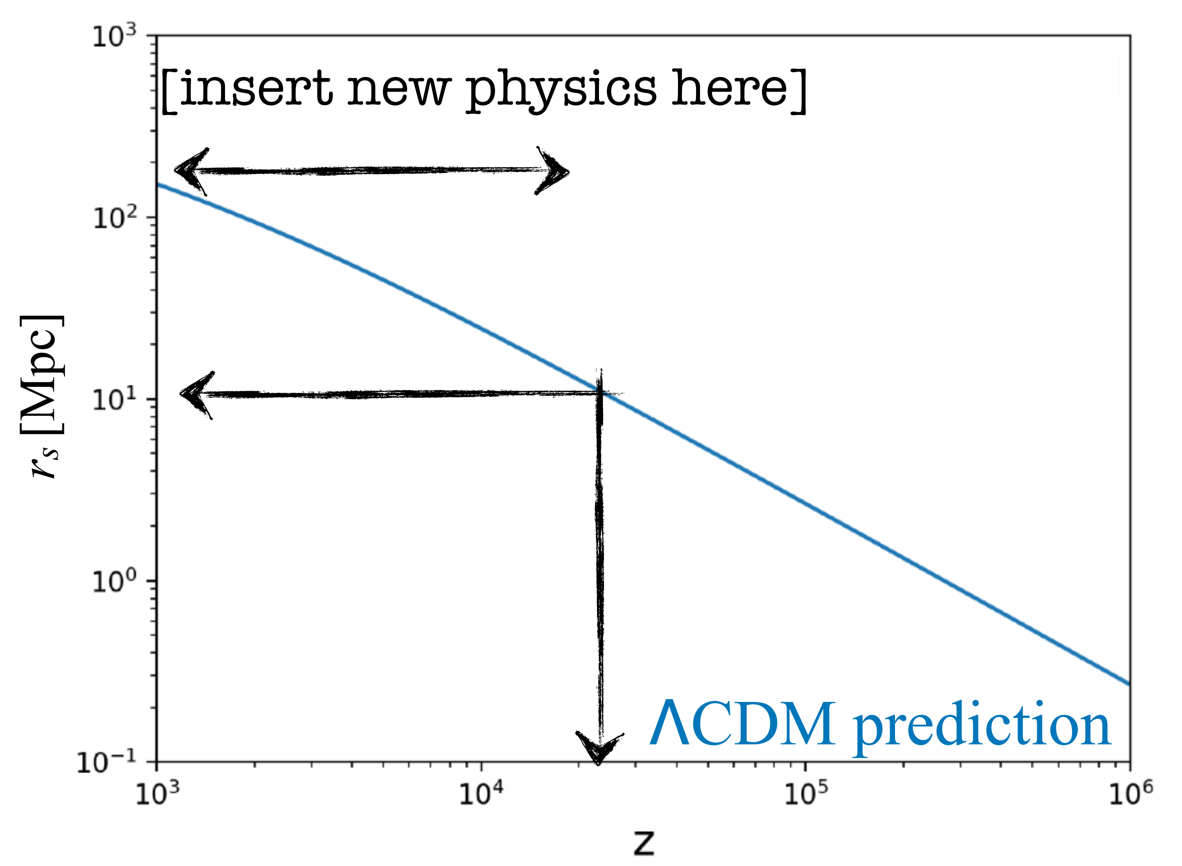

- Inject energy between recombination and $z \sim 2 \times 10^4$ to reduce r_s ==> Early Dark Energy?

See the `Hubble Hunter's guide' Knox&Millea 1908.03663

Early Dark Energy(s) & Modified Gravity

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)

In the H_0 olympics we focus on:
Axion EDE / NEDE / EMG

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]
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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,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)*
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(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 (toy) potential:

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

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

- 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.

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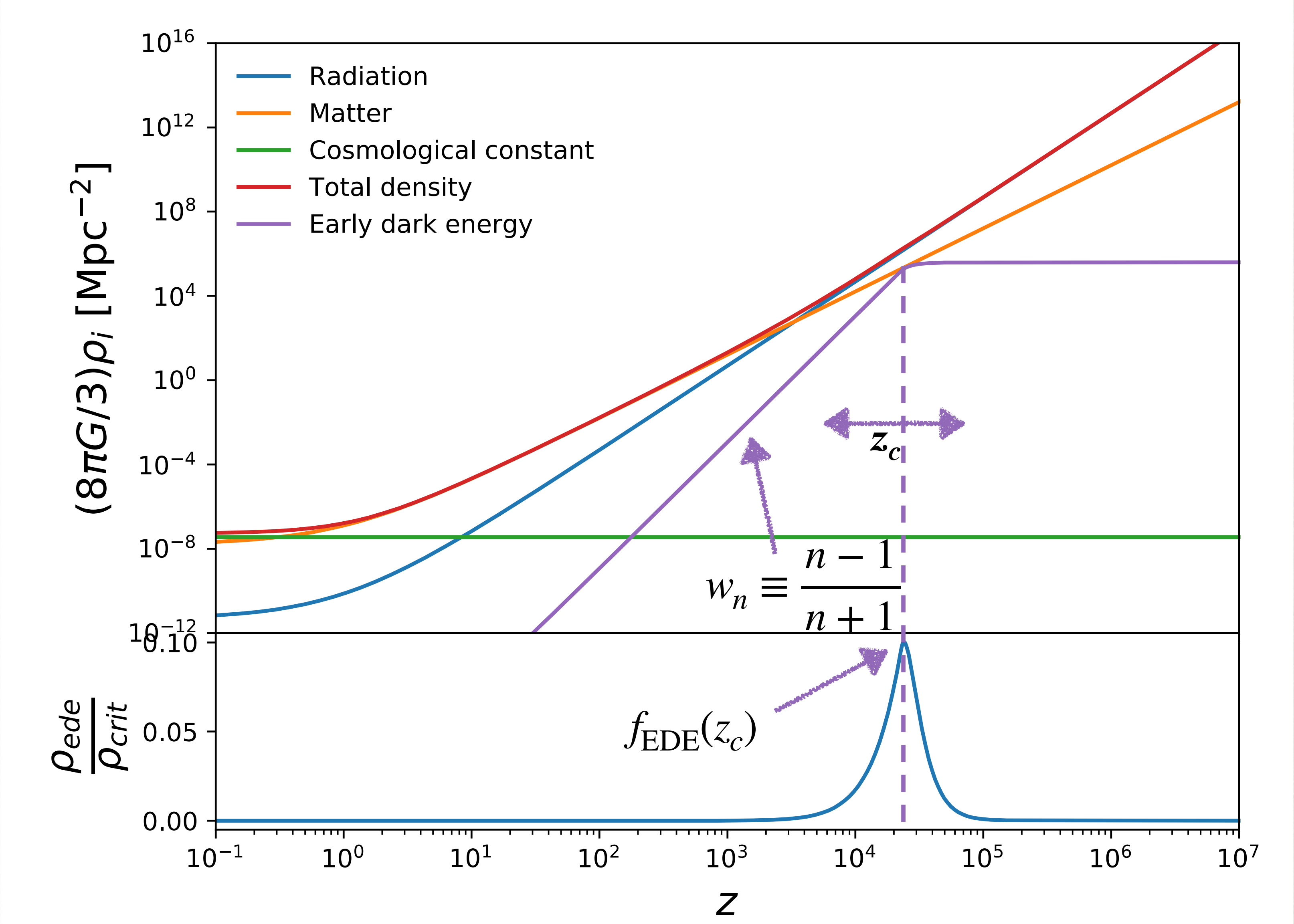

Fig by T. Karwal

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- First-order phase transition (NEDE model)

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

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

Linder 1505.00815, Braglia++ 2005.14053

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

Braglia++ 2011.12934

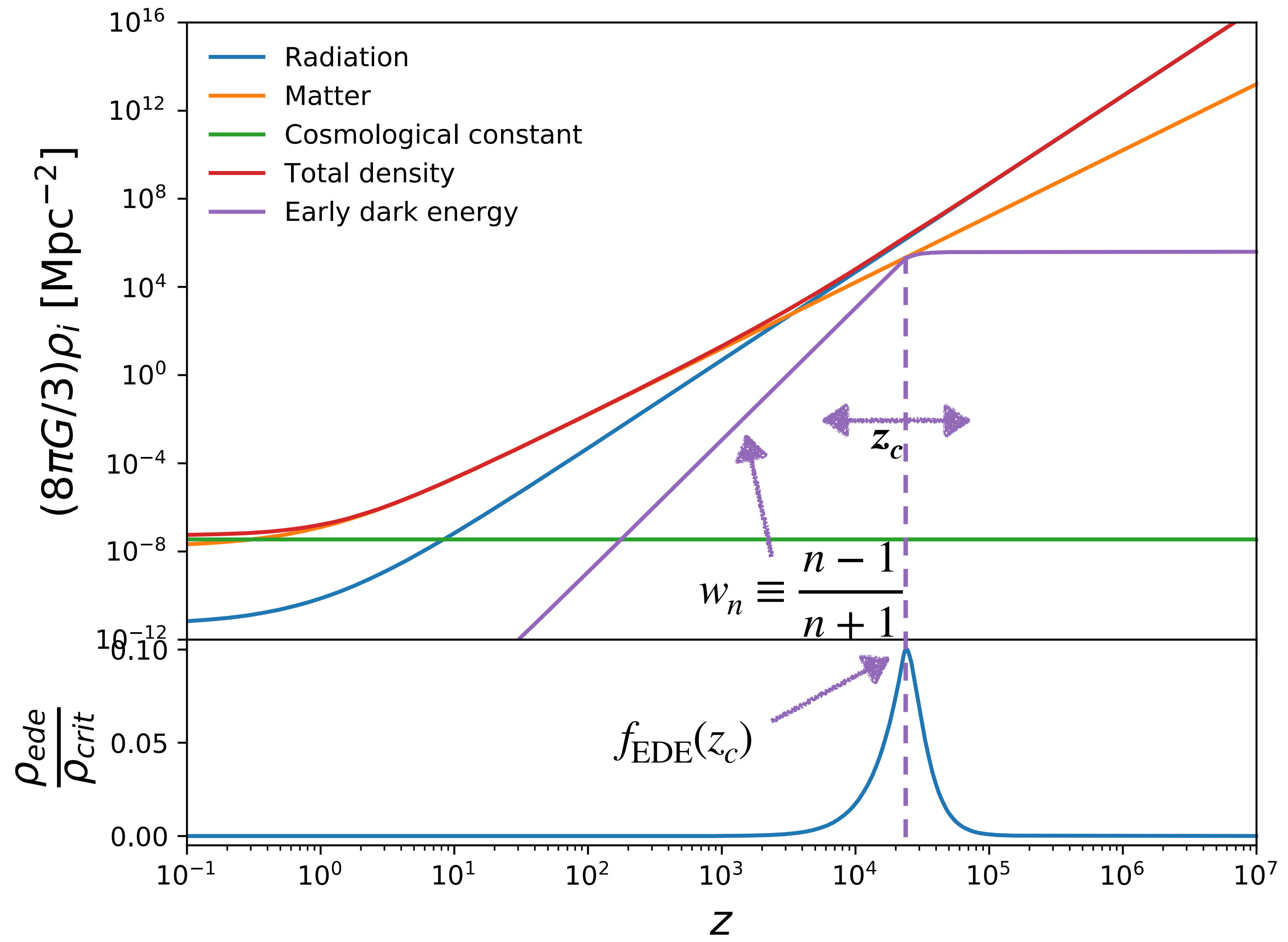
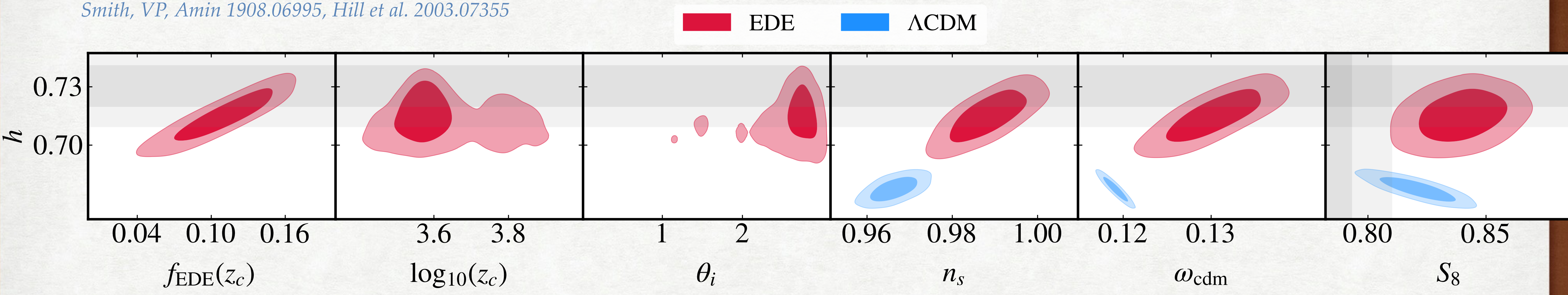


Fig by T. Karwal

Axion-like EDE vs *Planck* data

VP, Smith, Karwal++ 1806.10608 & 1811.04083;
Smith, VP, Amin 1908.06995, Hill et al. 2003.07355



- Analysis of Planck and SH0ES with $n = 3$ data yields: tension is reduced to 1.5σ and EDE is detected at 3.5σ.

$$f(z_c) = 0.10\ (0.12) \pm 0.03 \qquad z_c = 4073\ (3715)^{+393}_{-838} \qquad H_0 = 71.4\ (72) \pm 1.1\ \text{km/s/Mpc}$$

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

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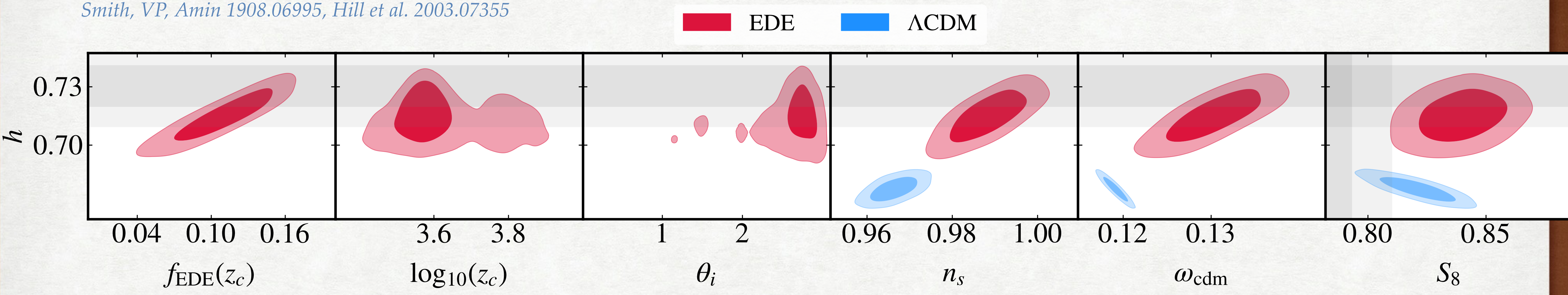

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- The field becomes dynamical around $z_{\rm eq}$: A new 'why-then' problem? *Sakstein++1911.11760, Lin++2212.08098*
- $(1 - \cos\theta)^3$ poorly motivated: requires fine-tuning of lower-order instantons?

Gonzales++ 2006.13959, McDonough++ 2209.00011, Rudelius 2203.05575, Cicoli++ 2303.03414

- $m \sim 10^{-28}$eV, $f_{\rm axion} \sim 0.1 M_{\rm pl}$ and $\theta_i \sim \pi \times f_{\rm axion}$: fine-tuning of initial conditions and near-planckian excursion.

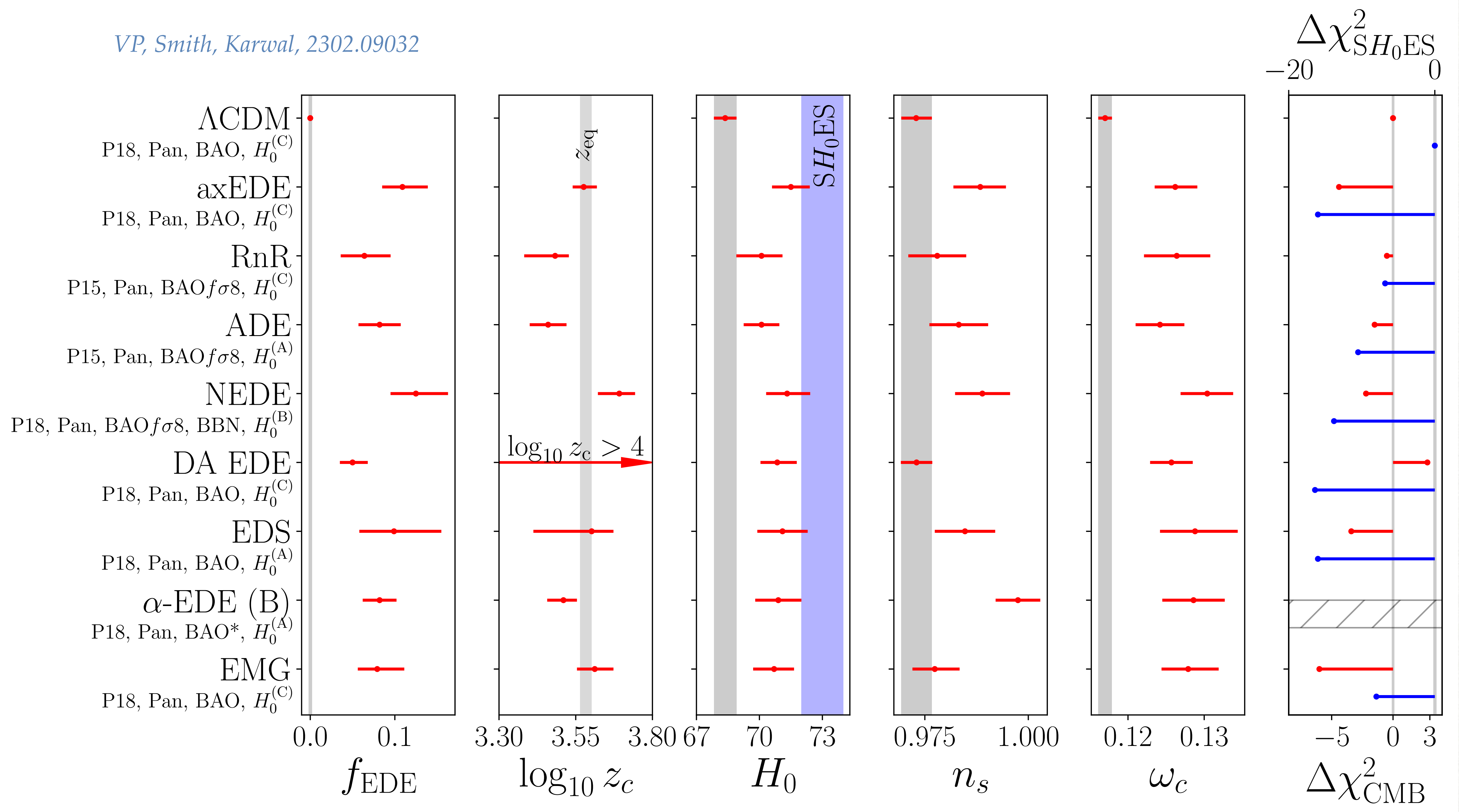
Kaloper 1903.11676, Rudelius 2203.05575

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

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

Status of EDE solutions circa 2023

- Lots of efforts toward better-motivated EDE potentials/models.



- Many models yields similar results as axEDE: future CMB data will disentangle between models

The H_0 olympics: fairly ranking models

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

Schöneberg (VP) ++ 2107.10291

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

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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_{eff}
- Self-Interacting N_{DR}
- Mixture of $N_{\mathrm{eff}} + N_{\mathrm{DR}}$
- DM-DR interaction + N_{DR}
- Self interacting $\nu + N_{\mathrm{eff}}$

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 $m_e + \Omega_k$

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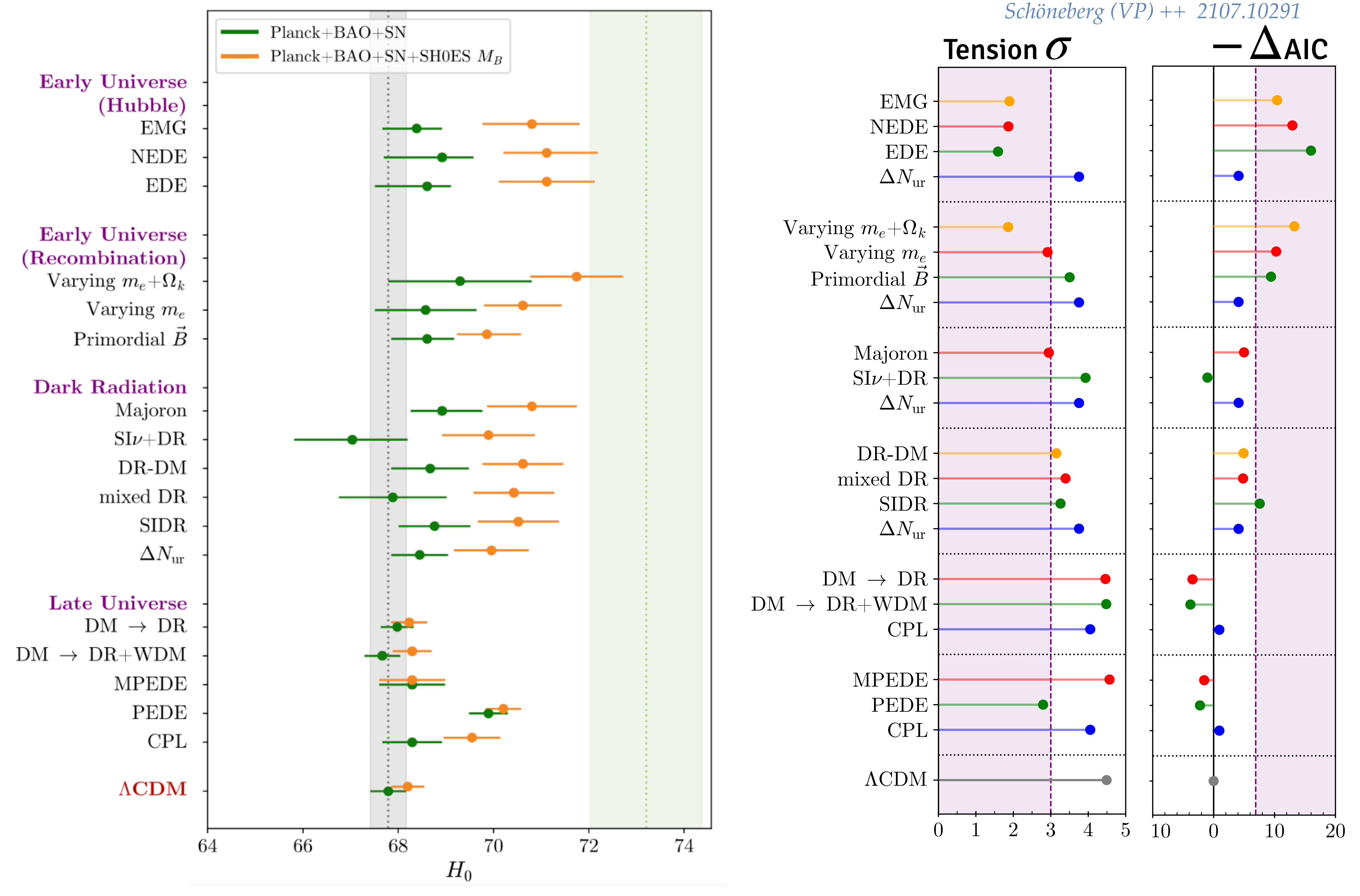
- I/ Frequentist: Can a model give a good fit to all data including SH0ES and be favored over ΛCDM.
- II/ Bayesian: Can a model be favored over ΛCDM independently of SH0ES and “predict” a high H_0.

Results of the contest



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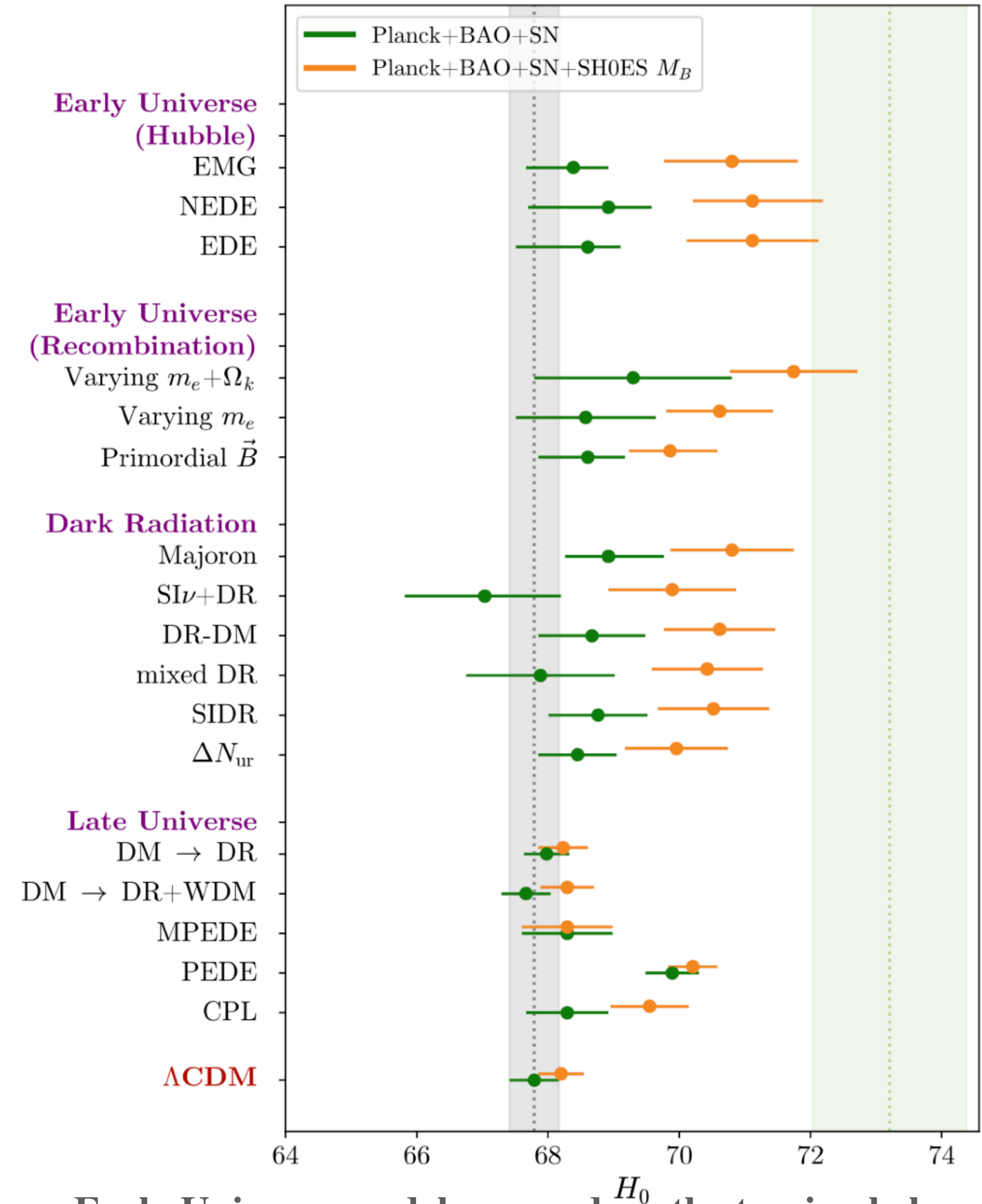

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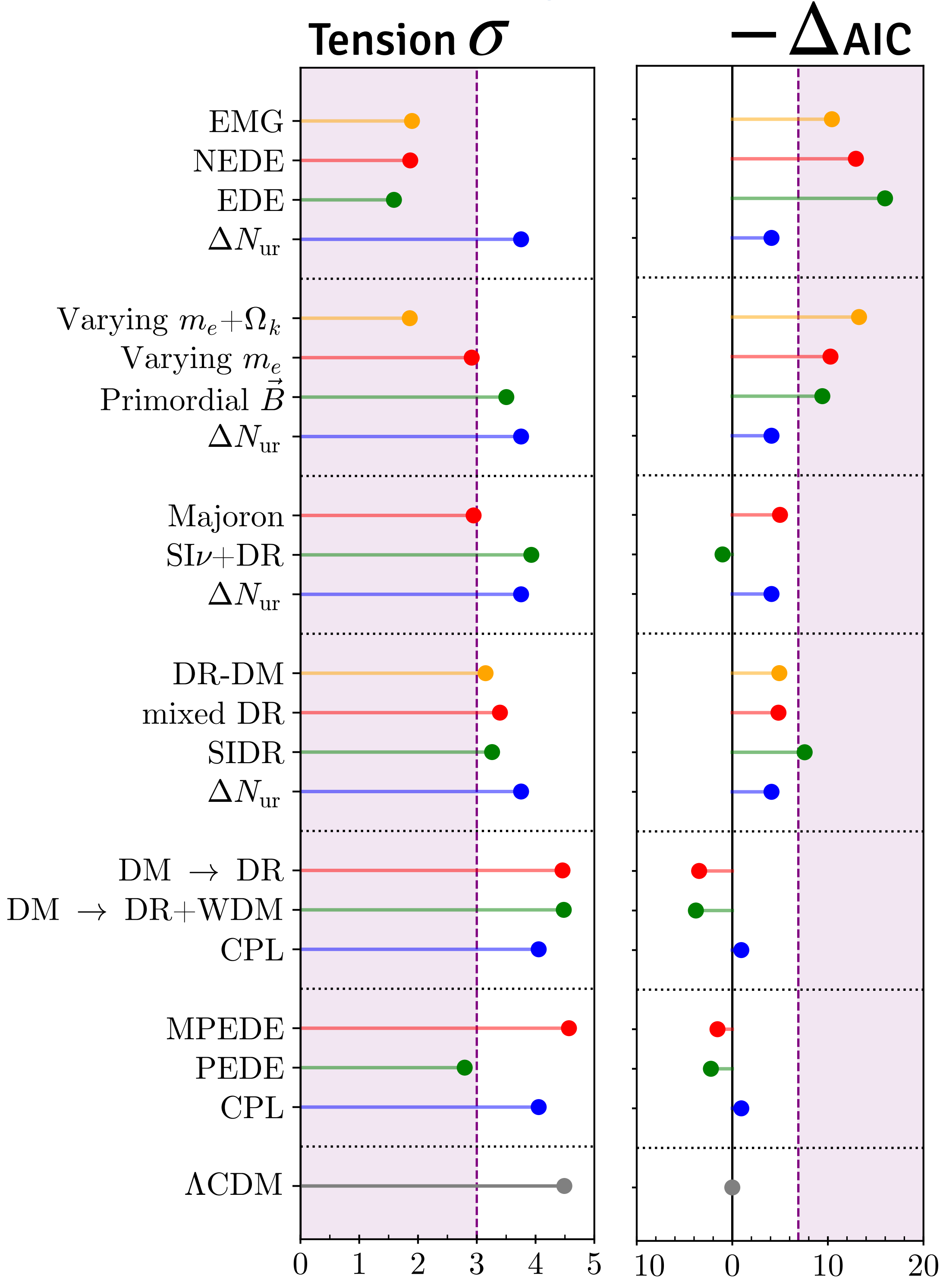
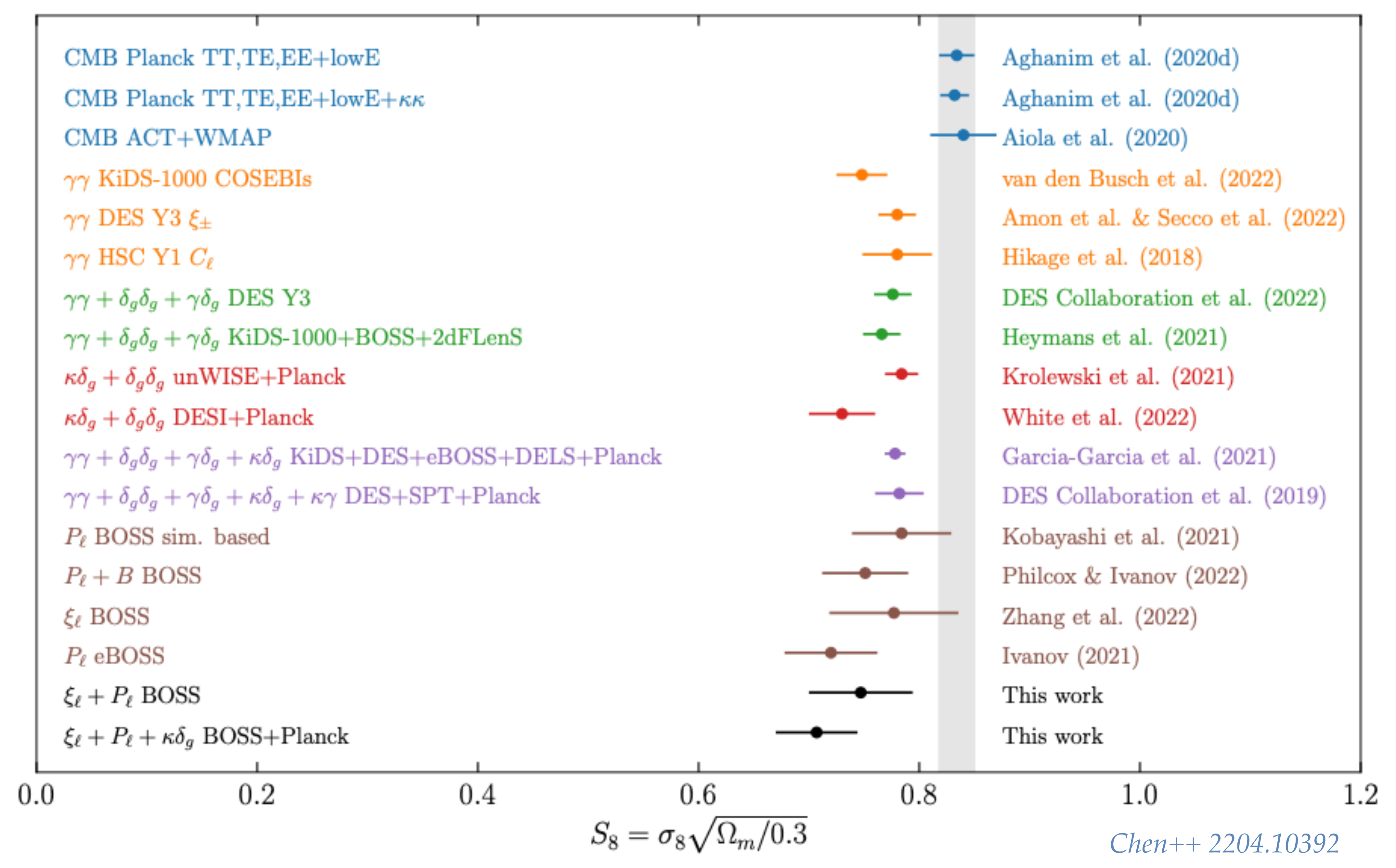


Early Universe models can reduce the tension below 1.5-2σ level but are not favored without SH0ES prior

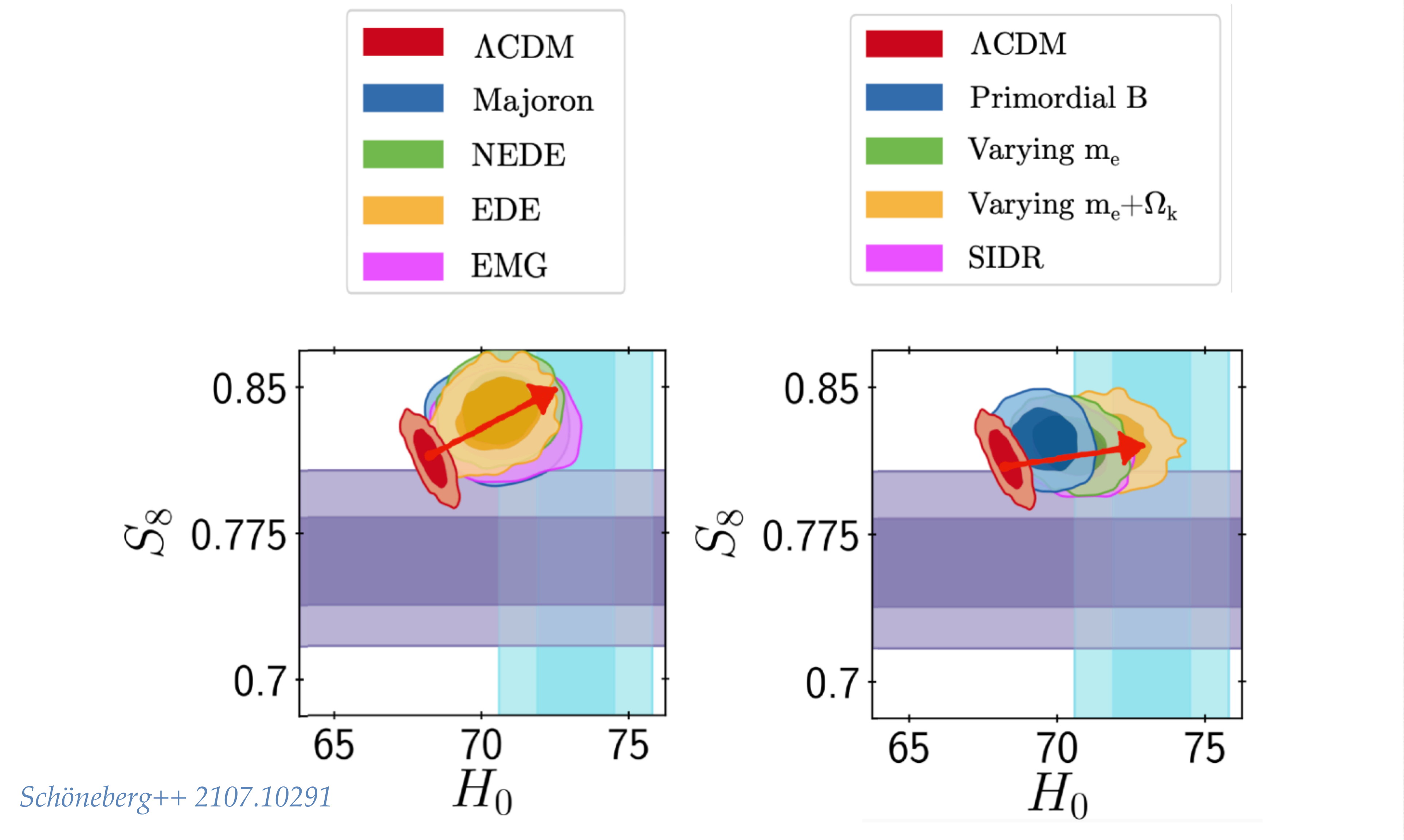
The S_8 tension, again



Chen++ 2204.10392

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

Early universe models cannot explain low S_8



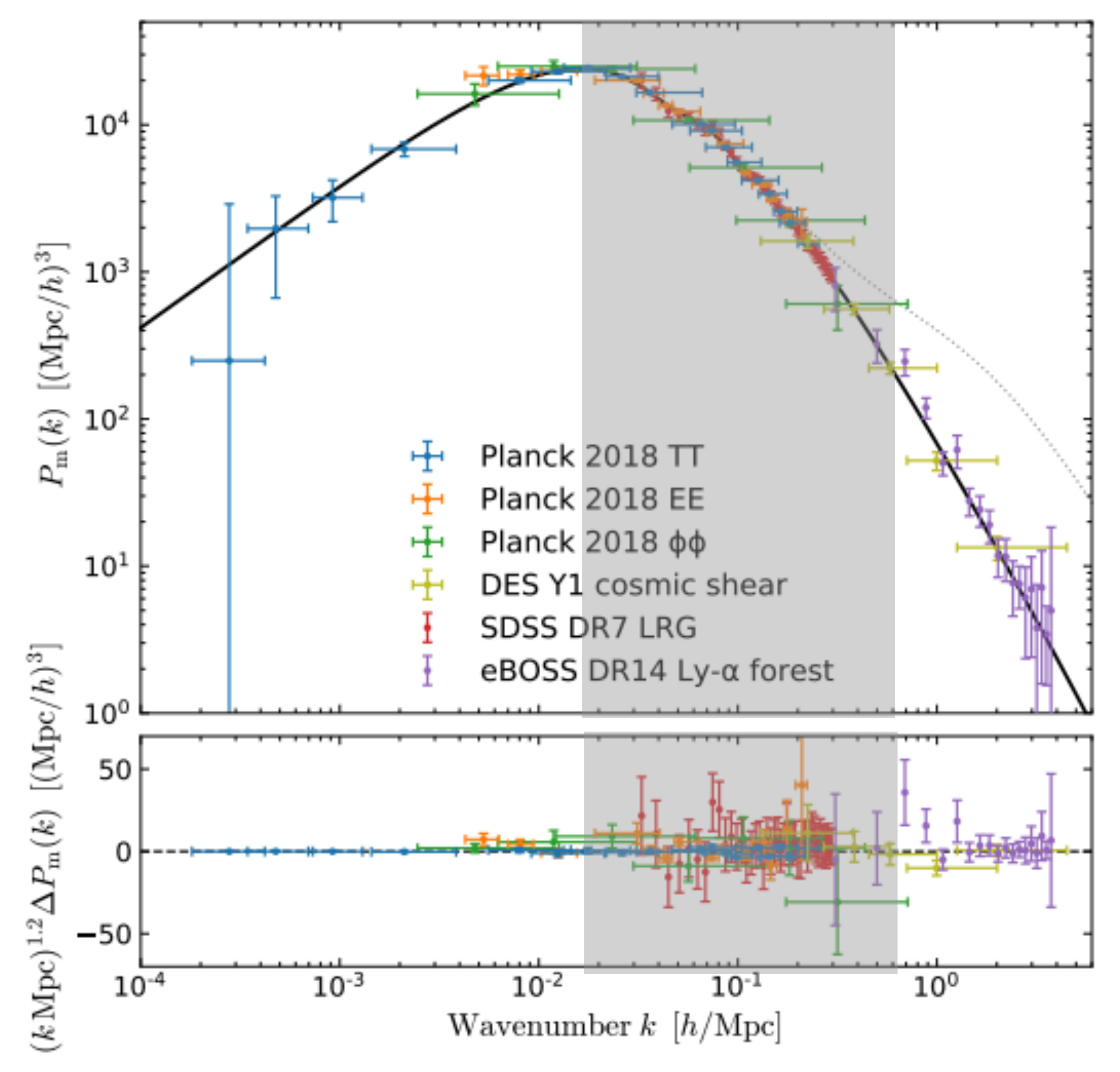
Schöneberg++ 2107.10291

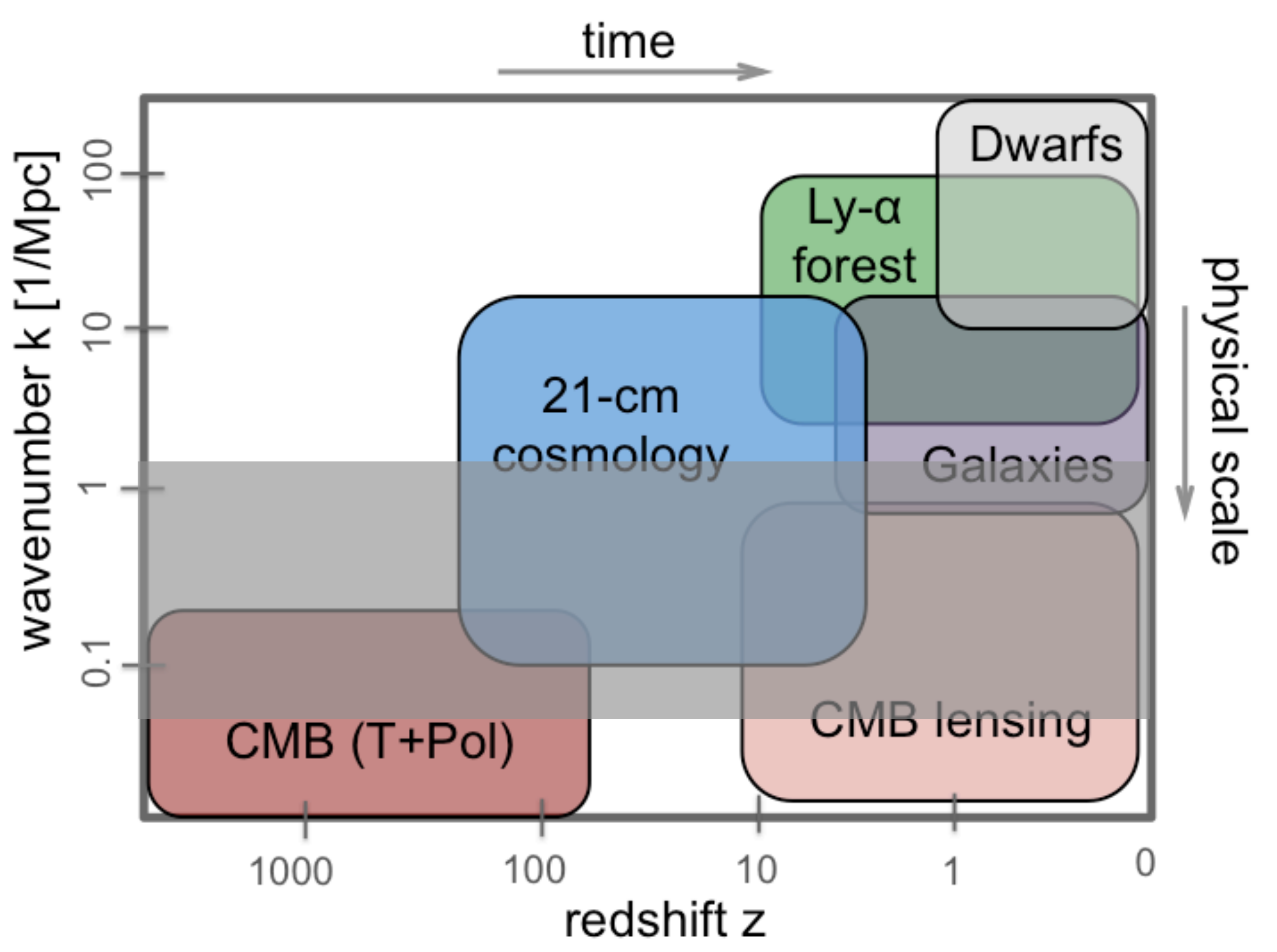
- Fitting CMB, H_0 and BAO with lower r_s requires higher $\omega_{\rm cdm}$: the S_8 tension increases! Very generic.

Jedamzik & Pogosian 2010.04158, Vagnozzi 2105.10425

- EDE (and other models) cannot explain both tensions! It requires some additional dynamics.

How to resolve the S_8 tension





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

Abdalla++ 2203.06142

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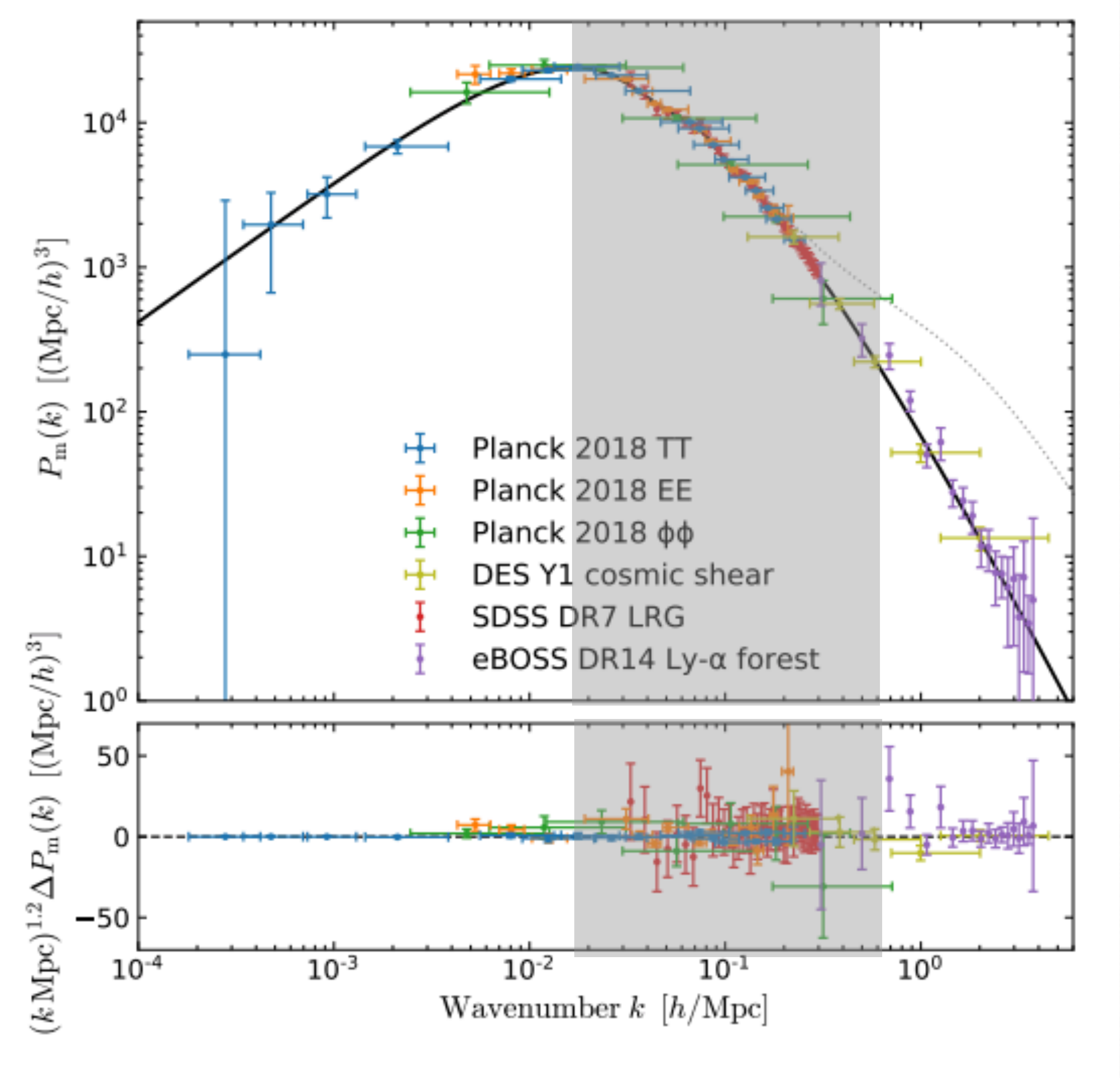

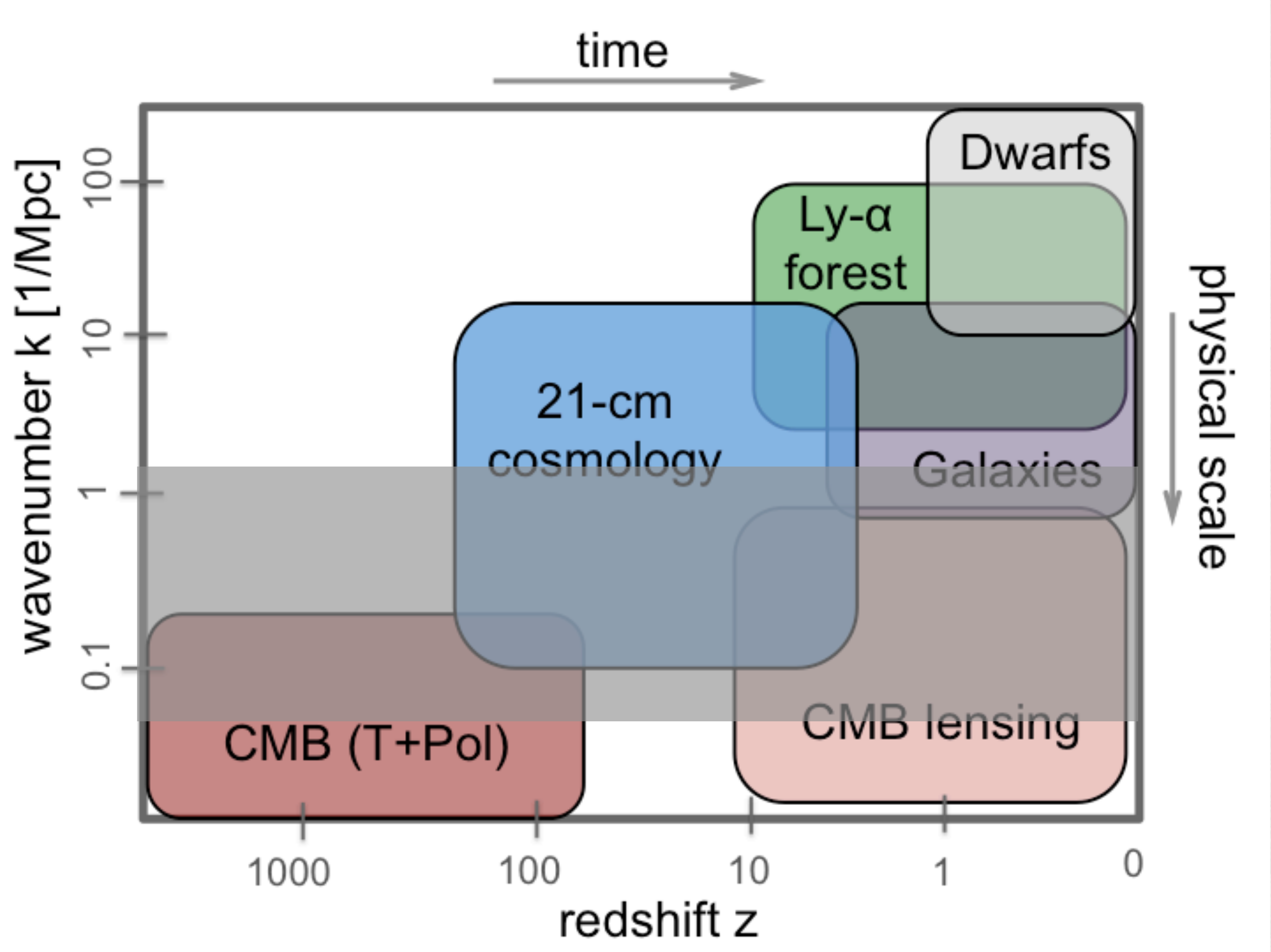

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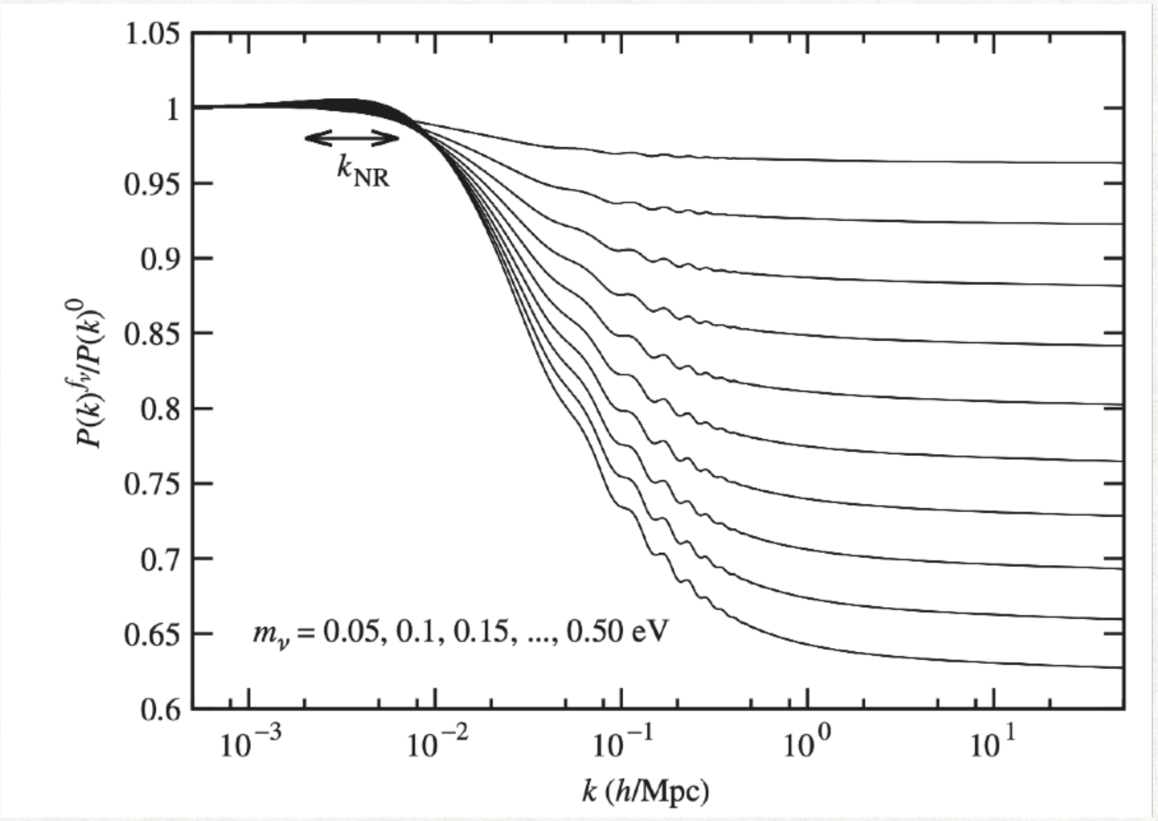
- To resolve the tension: Either suppress scales $k \gtrsim 0.2$ h/Mpc or change late-time evolution.
- Dark Sector physics: Ultra-light axions, Decaying DM, Interacting DM-DR, Interacting DM-DE…

Abdalla++ 2203.06142

Could ν's explain the S_8 tension?

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

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



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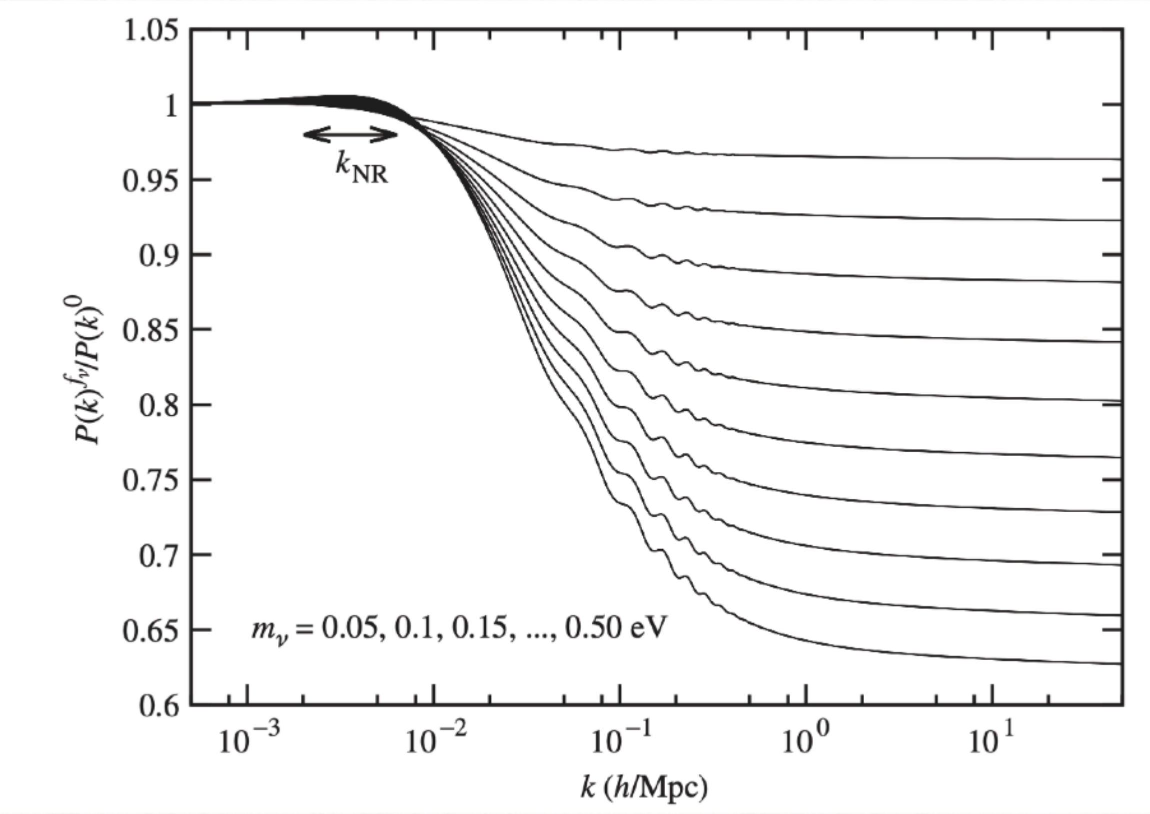
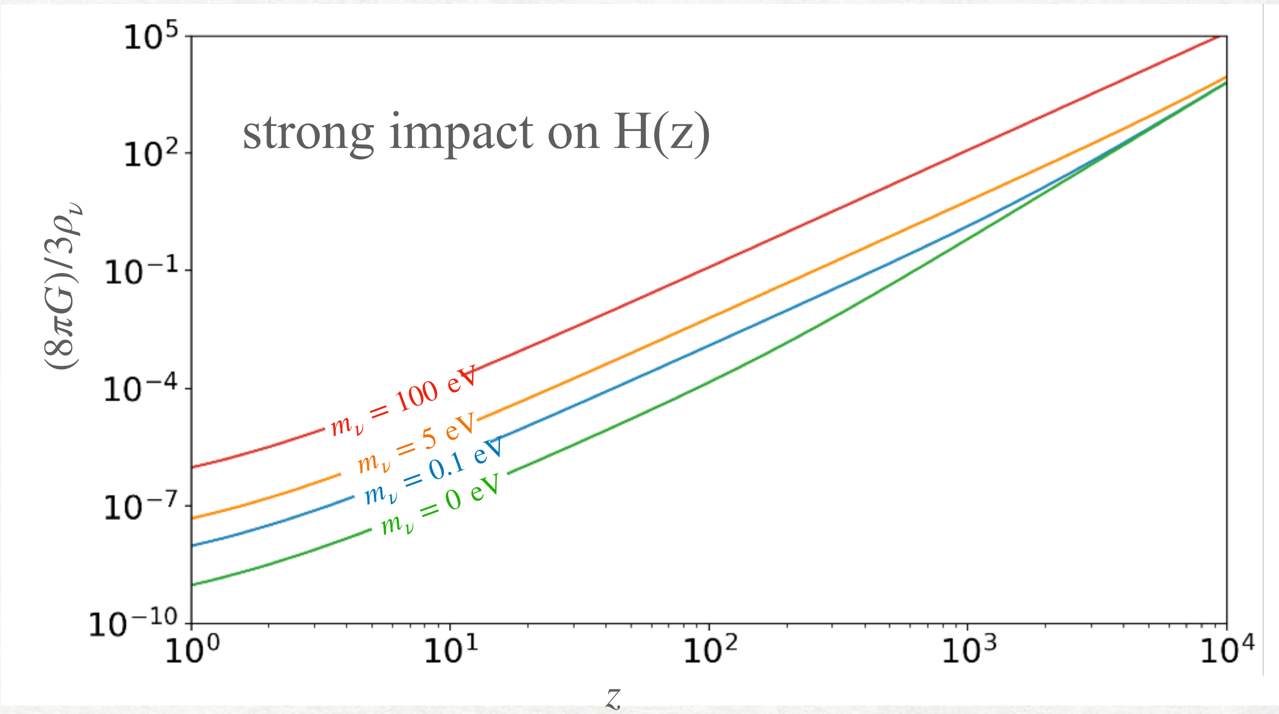
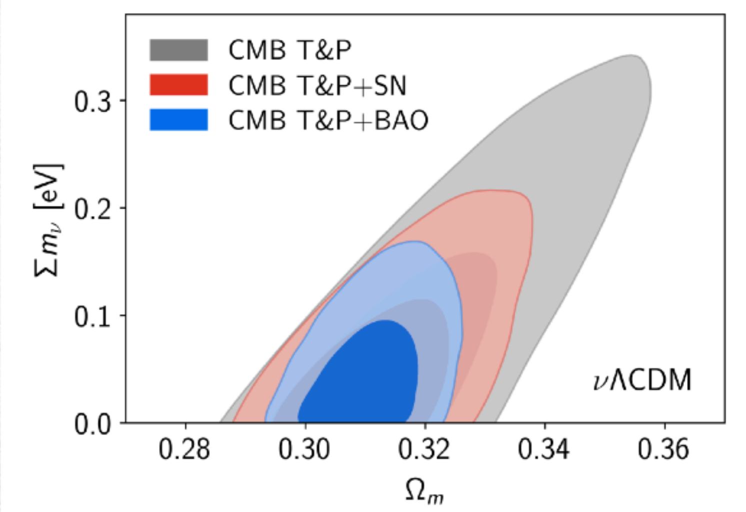




Planck 2018 + BAO < 0.12eV

Planck 1807.06205



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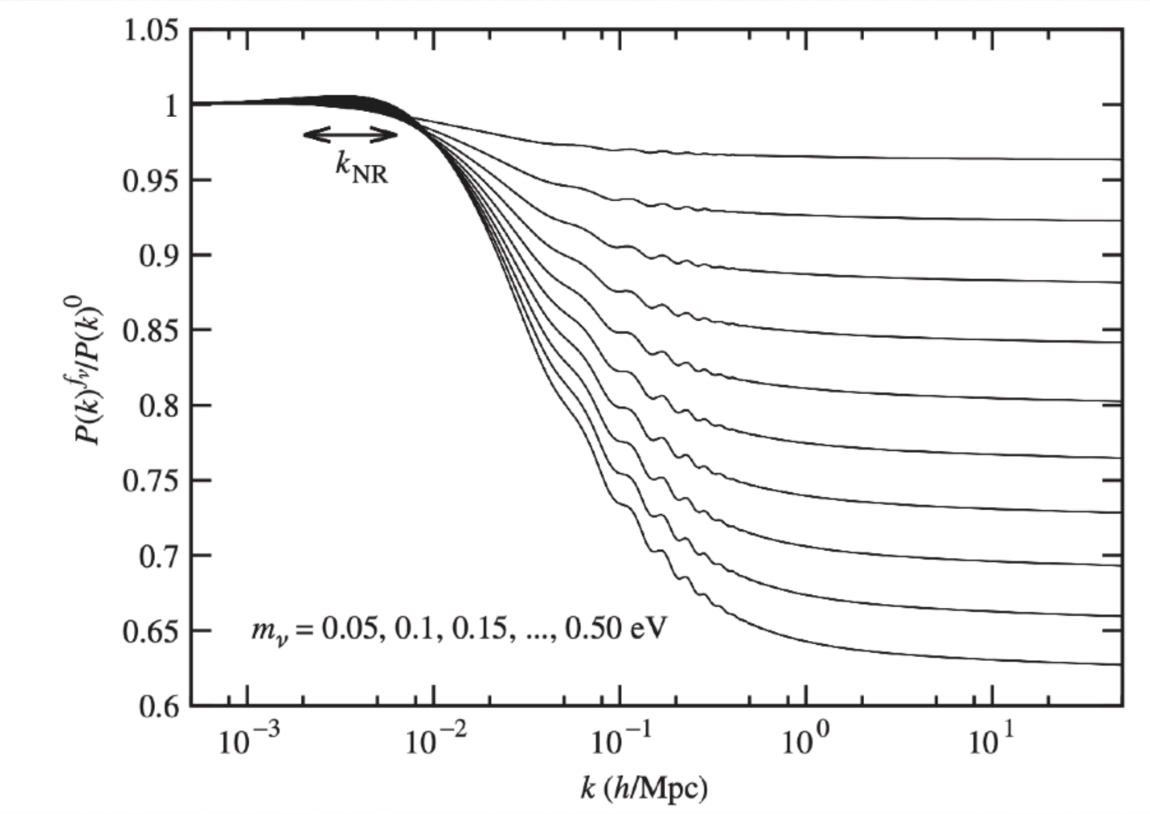
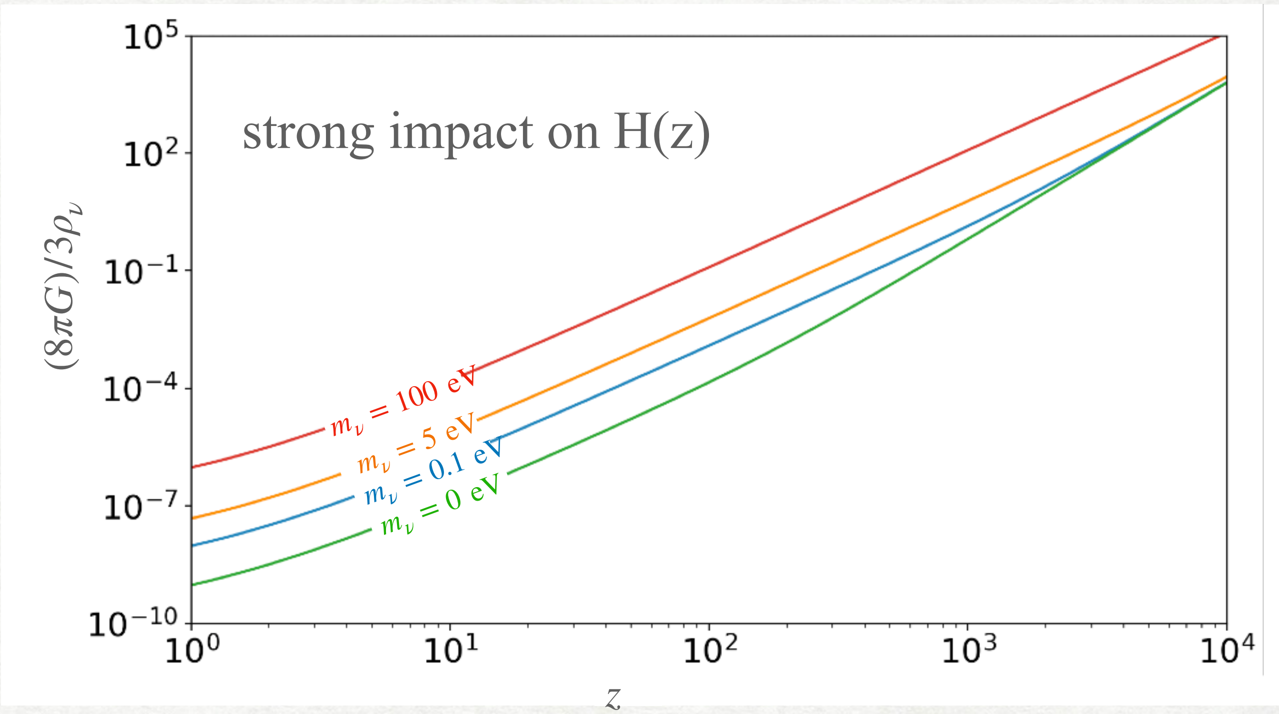




Planck 2018 + BAO < 0.12eV

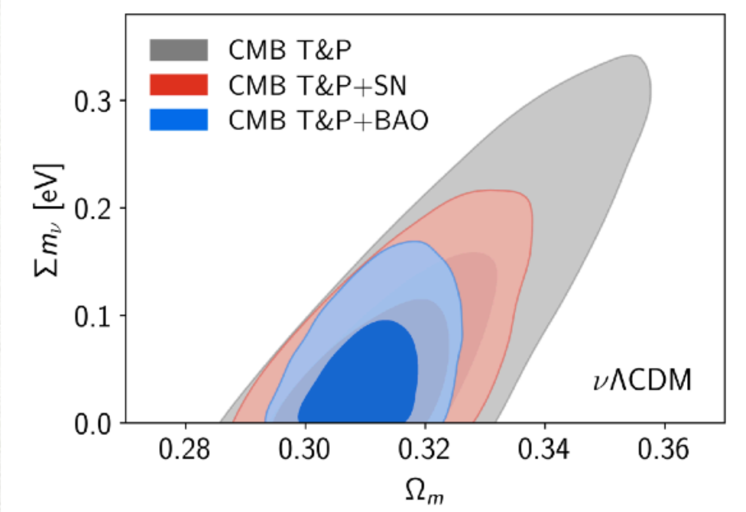
Planck 1807.06205

Planck 2018 + BAO + Ly$-\alpha$ < 0.089eV

Palanque-Delabrouille++ 1911.09073

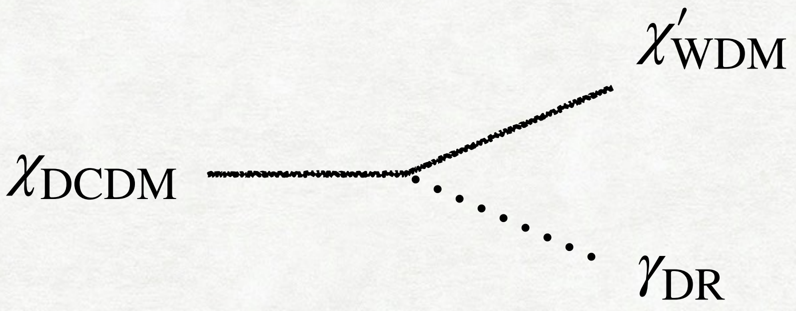
Planck 2018 + BOSS + eBOSS < 0.082eV

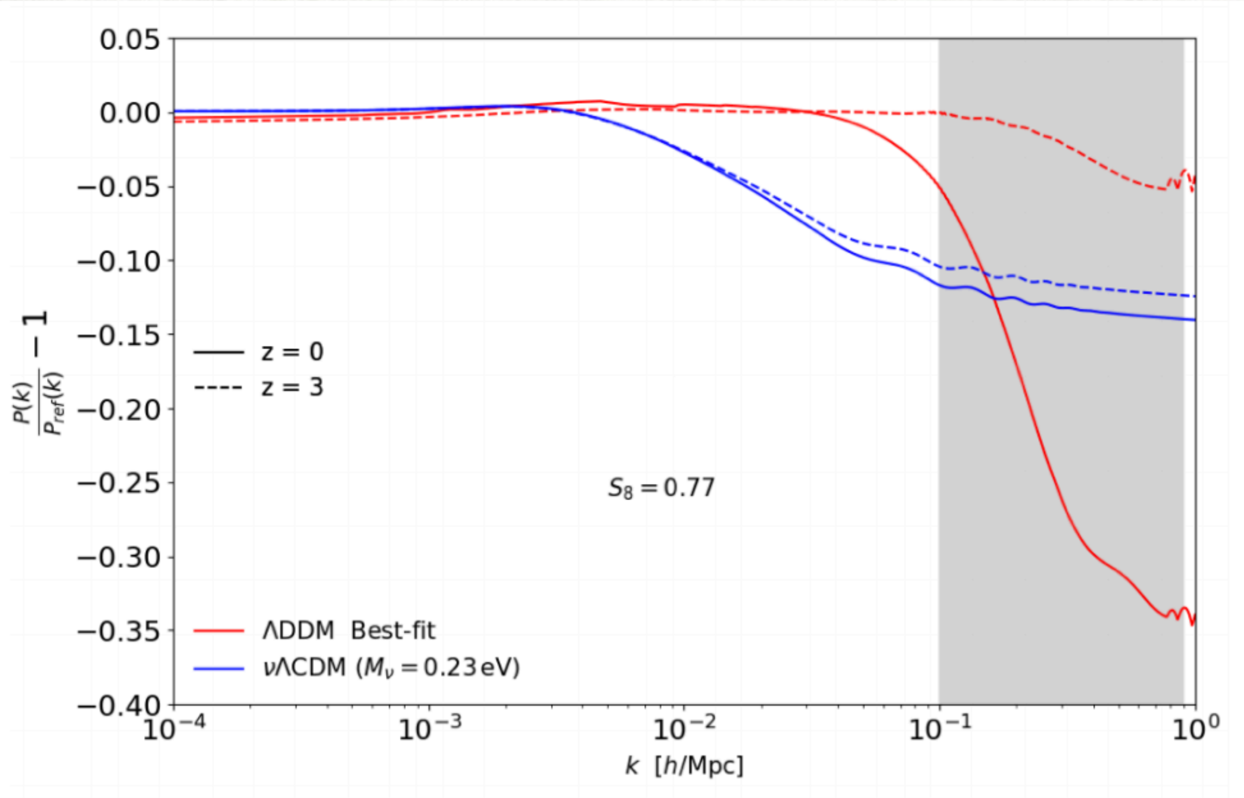
Brieden++ 2204.11868, Simon++ 2210.14931

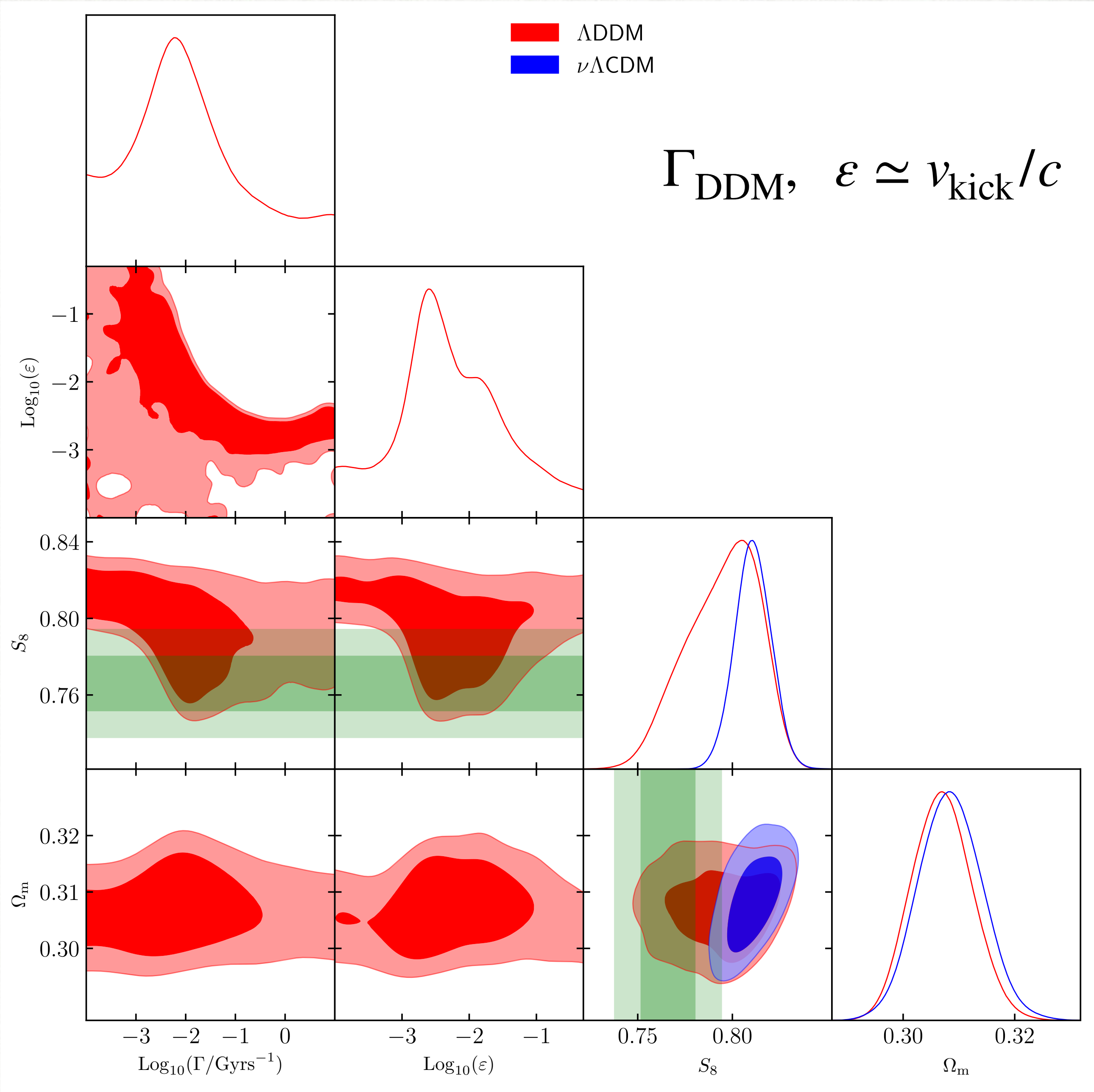


How to generate a late-time suppression

- Generate “neutrinos” (here, WDM) at late-time via decay of CDM into a dark sector







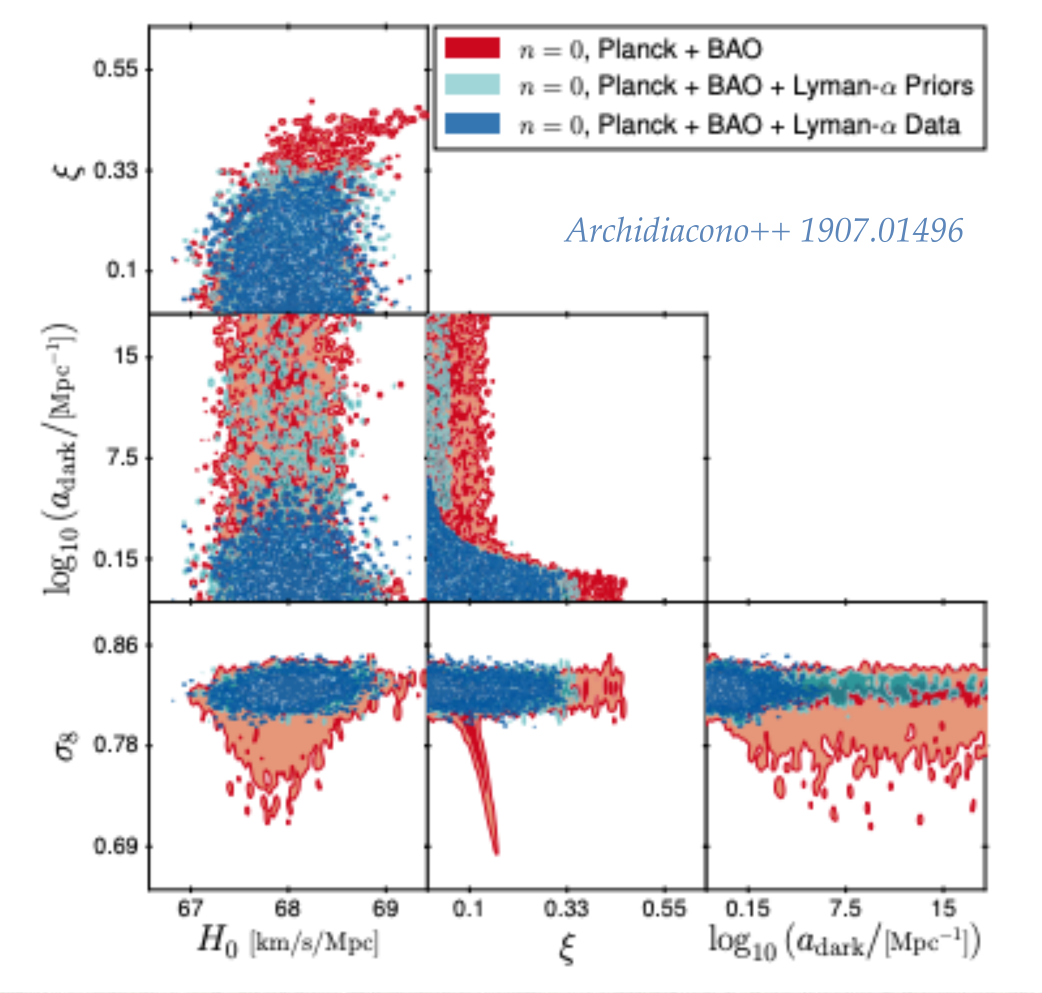
- DM with $\Gamma^{-1} \simeq 55(\varepsilon/0.007)^{1.4}$ Gyrs can explain low S_8 (1.3σ agreement) *Abellan++ 2008.09615 & 2104.03329*
- Similar results if there exists a fraction of ultra-light axion in the universe *Rogers++ 2023*

The S_8 tension is a drag…

DM<=>DR

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

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

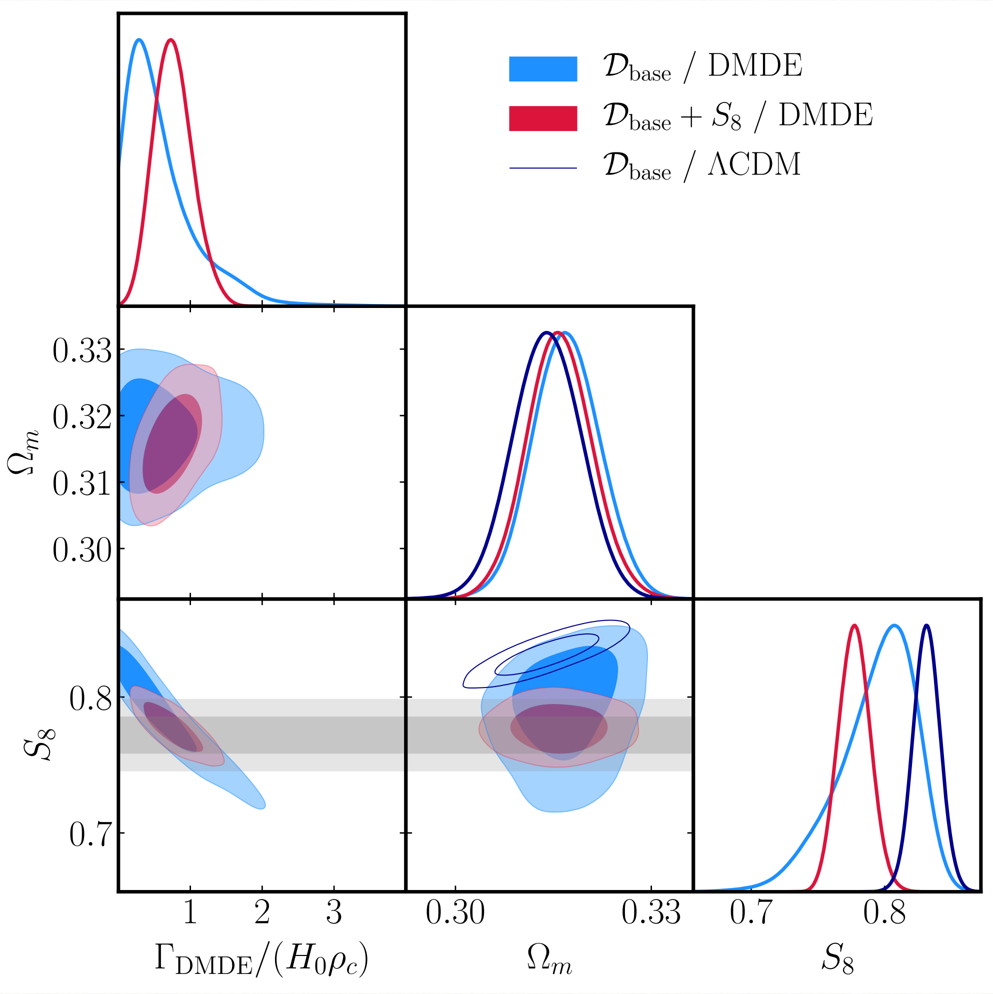


Archidiacono++ 1907.01496

DM<=>DE

VP, Bernal, Kovetz, Kamionkowski 2209.06217

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



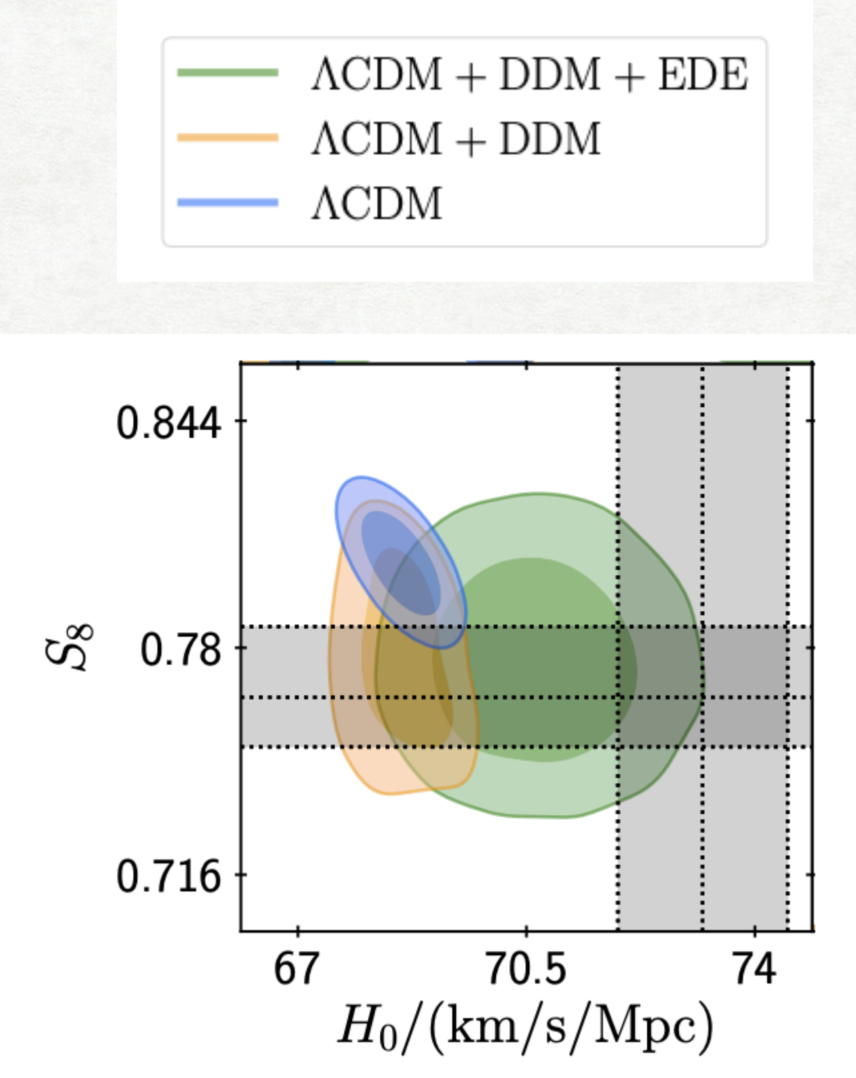
See also Di Valentino++ 1908.04281

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

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

Tensions may hint to a complicated dark sectors…

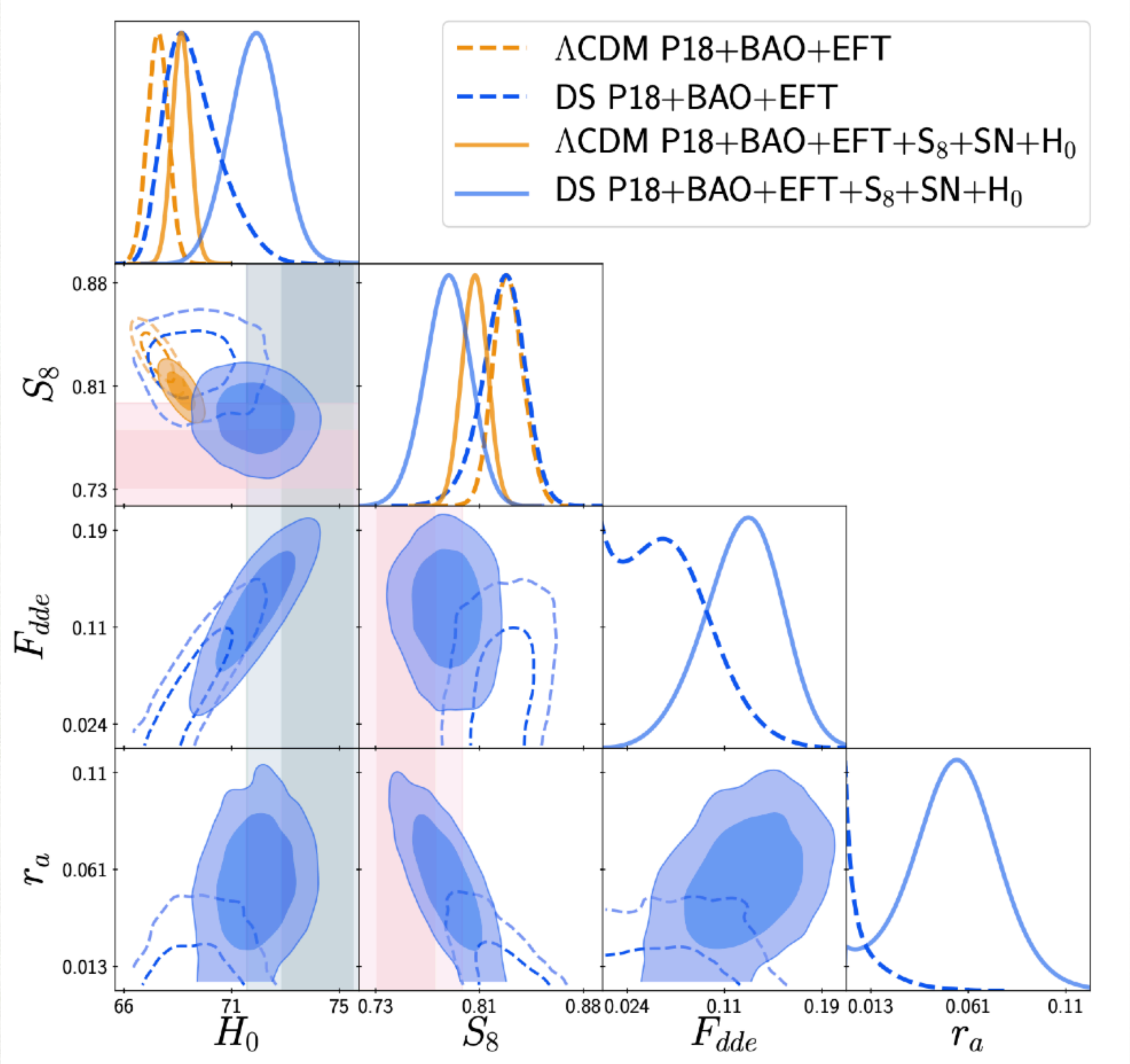
- H_0-tension: early-time new physics / mostly background. σ_8-tension: late-time new physics / mostly perturbations.



- The combination of EDE and decaying dark matter could resolve both tensions. Occam's razor?

Clark++ 2110.09562

See also Diamond++ 2207.03500, Abellan, Murgia, VP, Lavalle 2008.0961



- 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, Laguë++ 2104.07802

Could the σ_8-tension be due to baryons?

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

Aricò++ 2303.05537.

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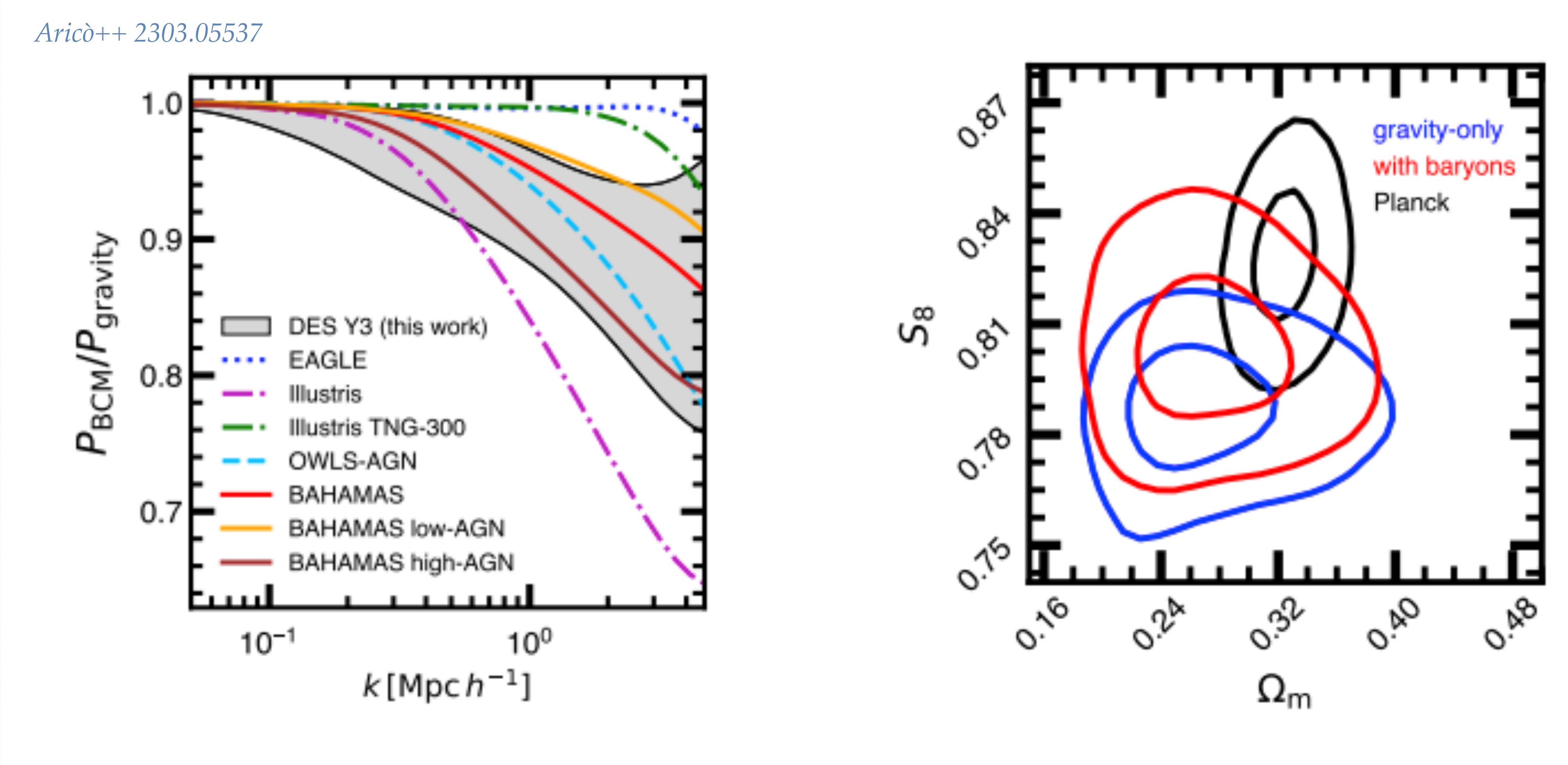
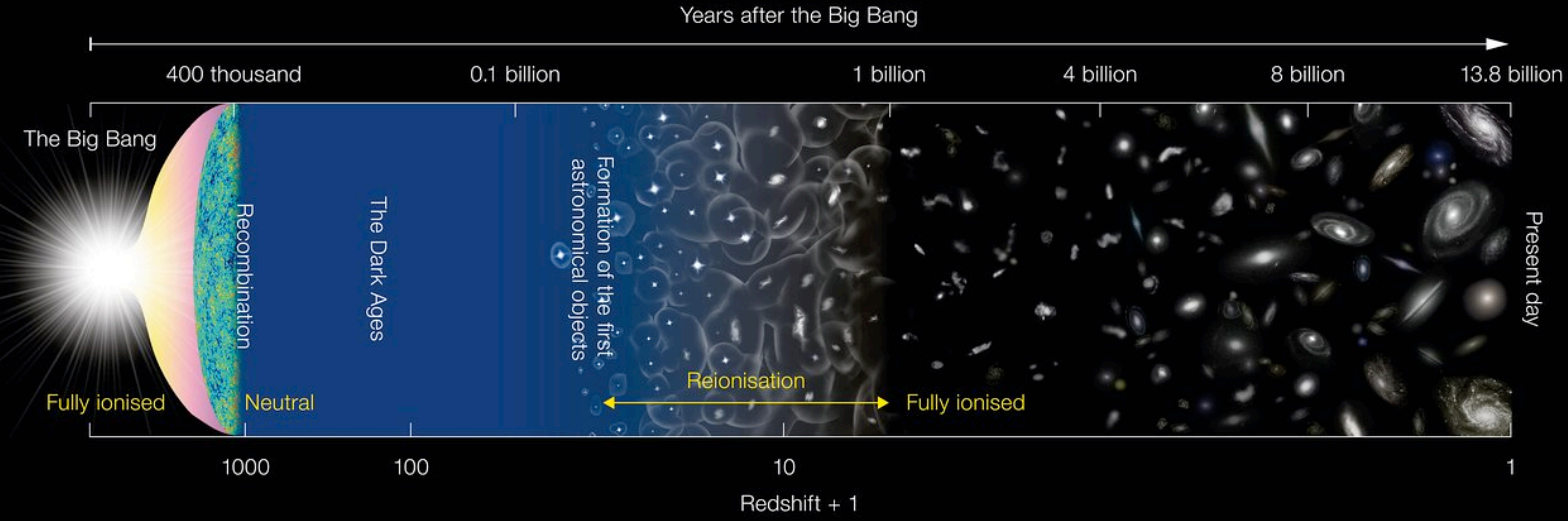


- The σ_8 tension may be baryonic physics! Strong feedback + improved non-linear physics could explain the tension.
- New analysis is in 0.9σ agreement with Planck/LCDM. Implications for EDE have yet to be investigated.

Anomalies in Cosmology: what do we know so far?

- Anomalies have emerged with the advent of “precision cosmology”: cosmic discordance?
- Most significant / studied ones: H_0 tension at 5 σ and S_8 tension at 3σ



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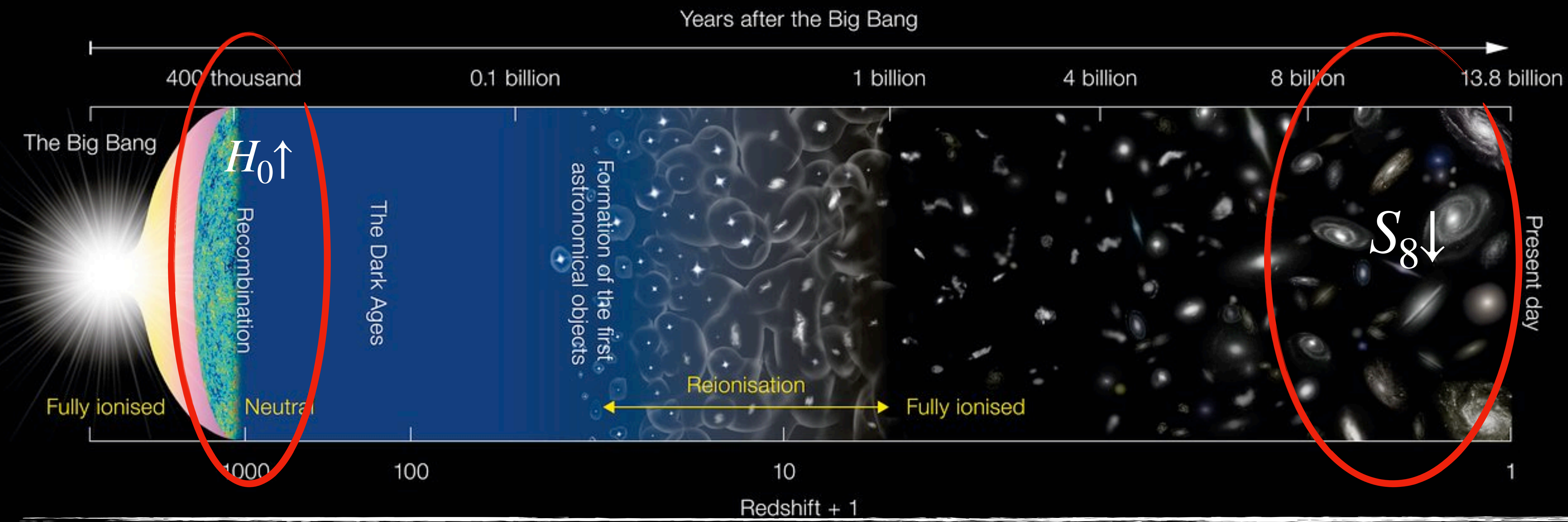
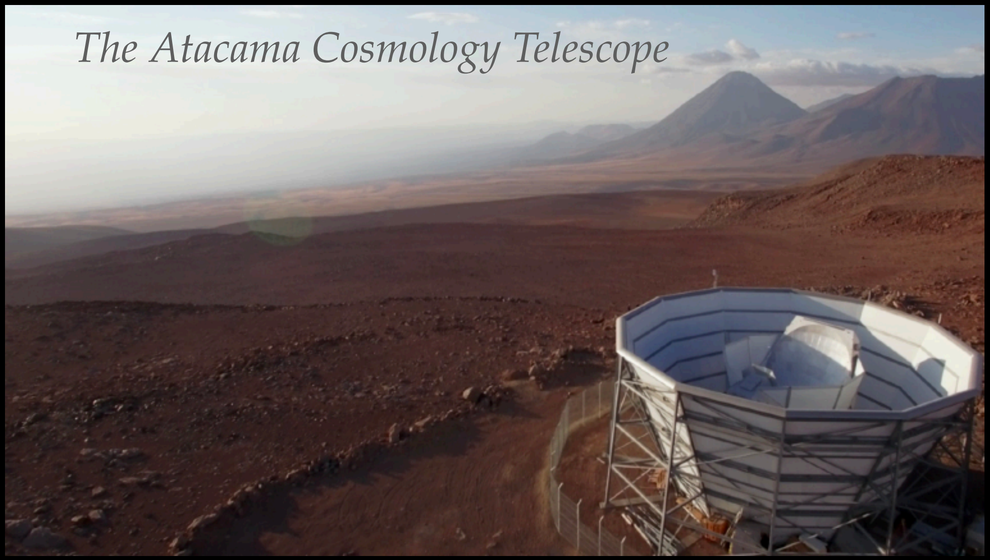


- H_0 tension solutions require new physics **before or around the time of recombination.**
- Increase Hubble rate or accelerate recombination.

- No models can simultaneously explain a low S_8
- Additional dynamics to reduce the growth of matter perturbations, DDM/ULA … or baryons?

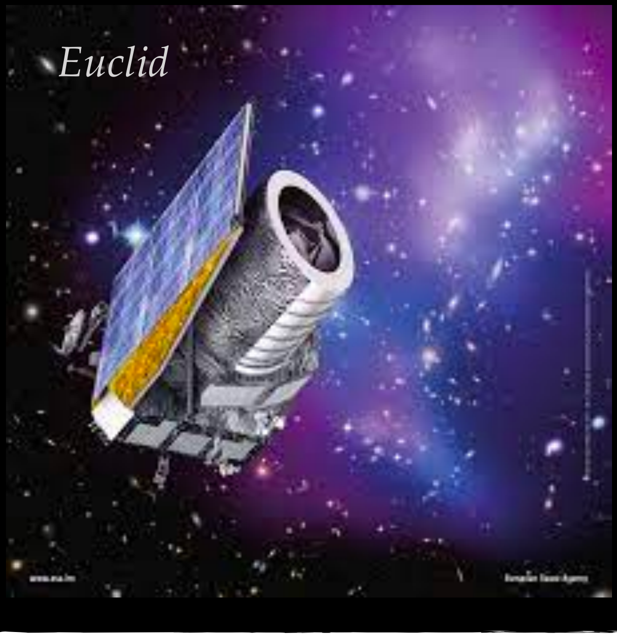
Anomalies in Cosmology: where are we going next?


The Atacama Cosmology Telescope


The South Pole Telescope

PARQUE ASTRONÓMICO ATACAMA, CHILE
SIMONS
OBSERVATORY
22°57' S, 67°47' W
ELEVATION: 5190m
www.simonsobservatory.org


DESI


Euclid


LSST/Vera Rubin Observatory

- New CMB data are coming: very sensitive to new physics around recombination!
- New LSS data are coming: measure $P(k, z)$, improve "baryons", neutrino masses?
- JWST and gravitational wave measurements of H_0.

Anomalies in cosmology will be settled within the decade!
They may hint at a rich dark sector!

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Obergurgl, Austria
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