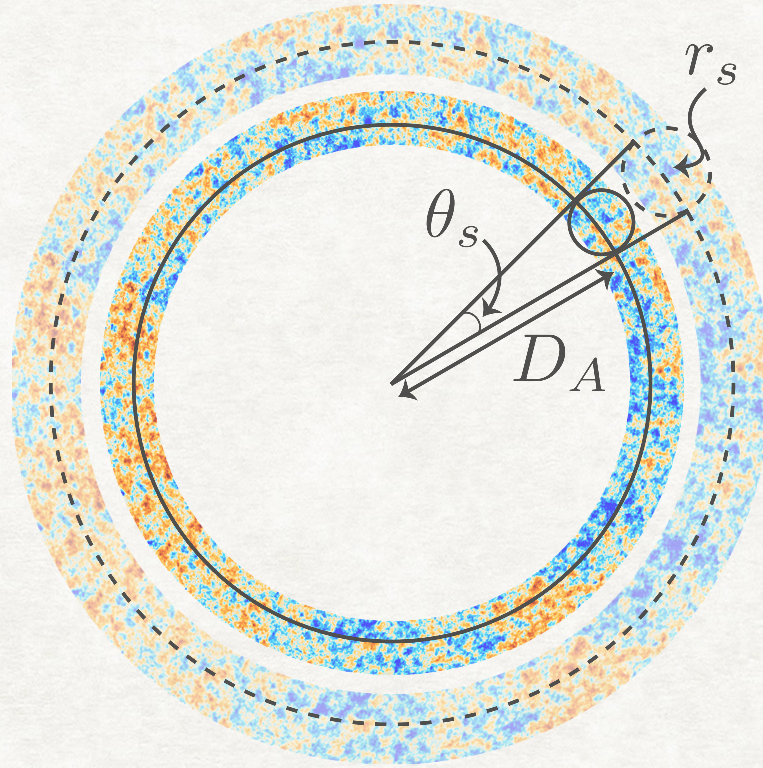
The Trouble with Hubble: Signs of New Physics?



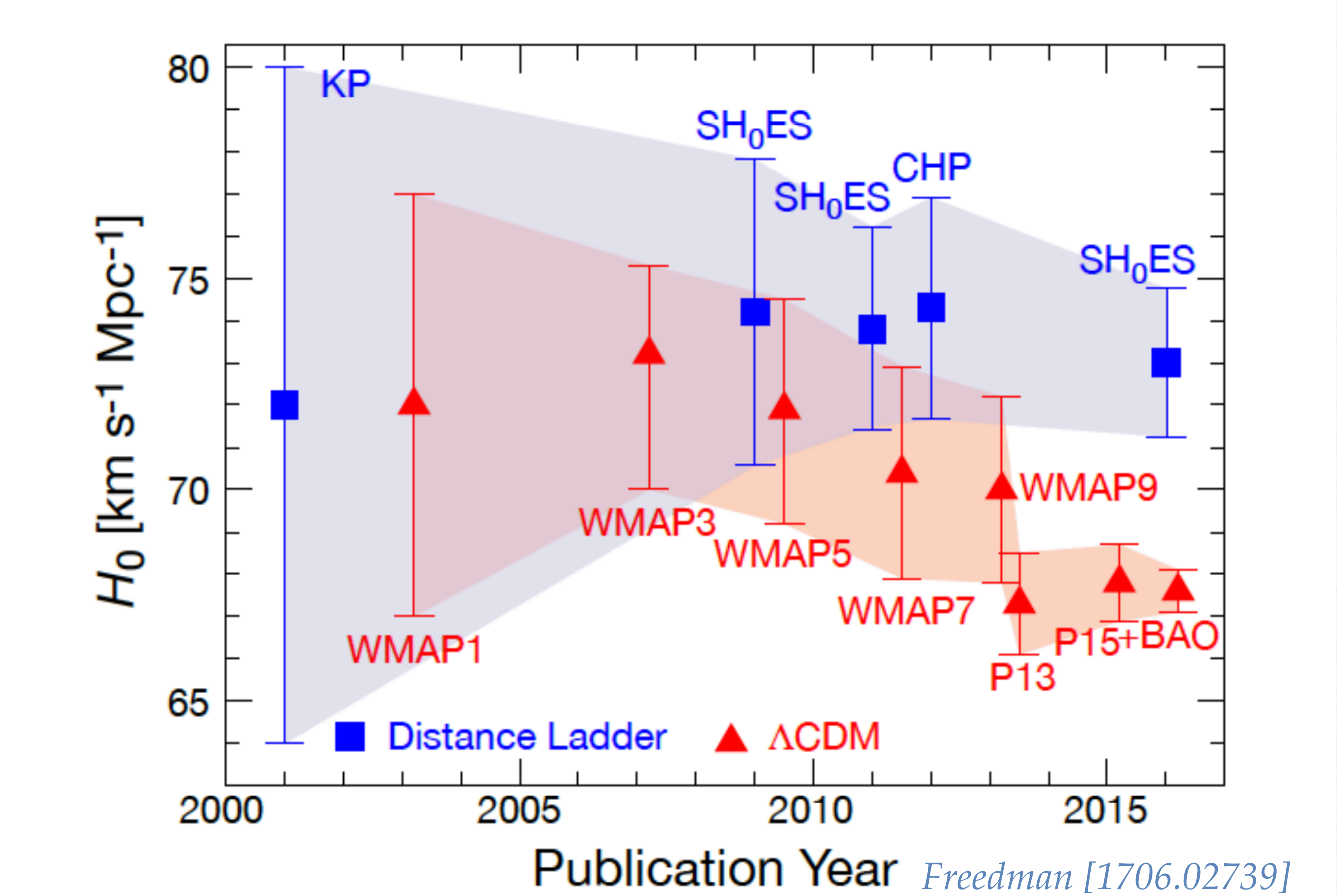
Vivian Poulin

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

w/ T. Smith, T. Karwal, M. Kamionkowski, PRL 122 (2019)
w/ T. Smith, M. Amin, 1908.06995 (PRD in press)

Rencontres de Physique des Particules 2020, École Polytechnique
29 Janvier 2020

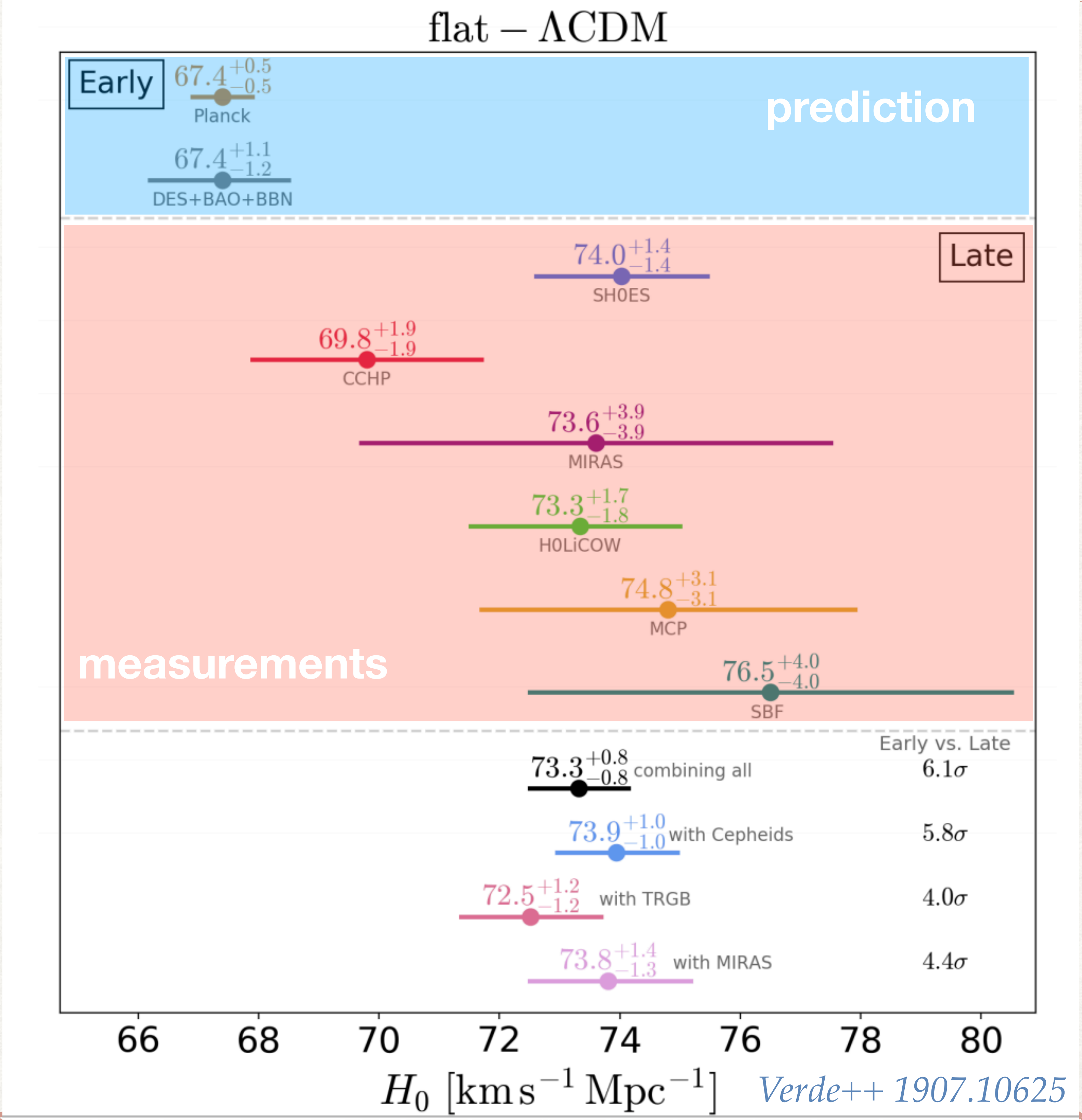
H_0 measurements over 20 years



Freedman [1706.02739]

$$H^2(z=0) = \frac{\sum_i \rho_i(z=0)}{3m_{\rm pl}^2}$$

The H_0 tension now reaches $4-6\sigma$



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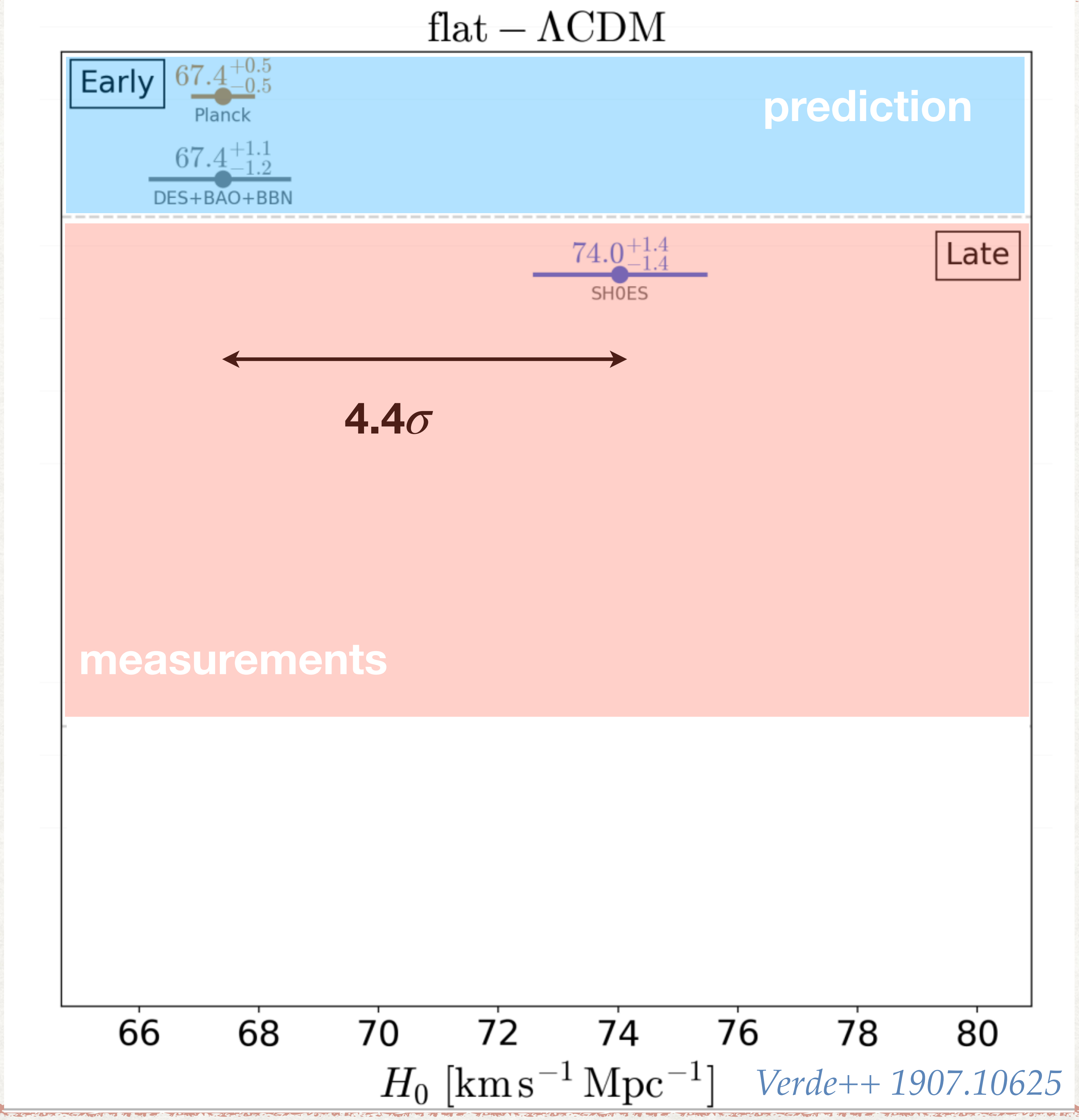
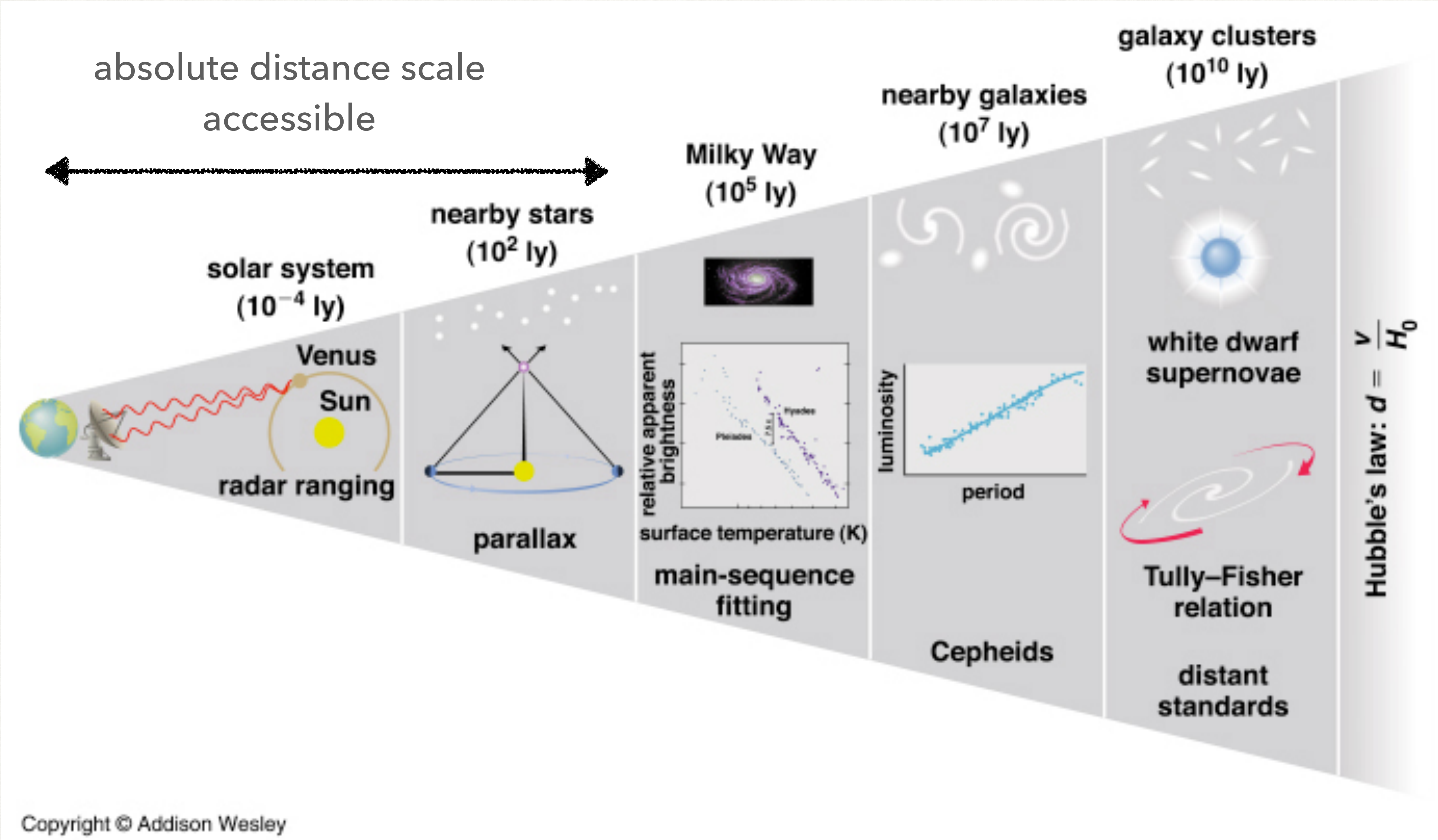


Verde++ 1907.10625

The Distance Ladder in 3 steps



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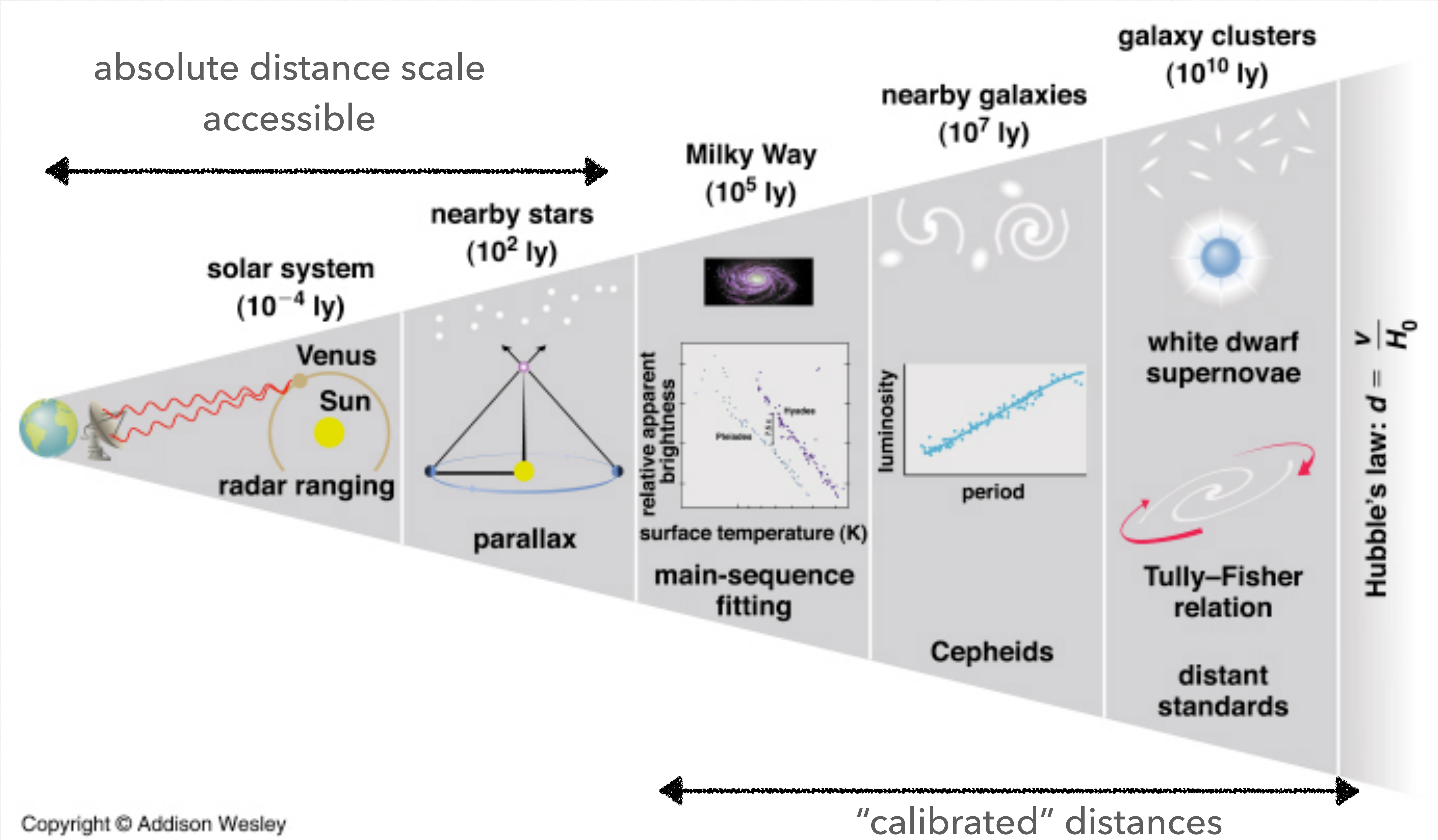
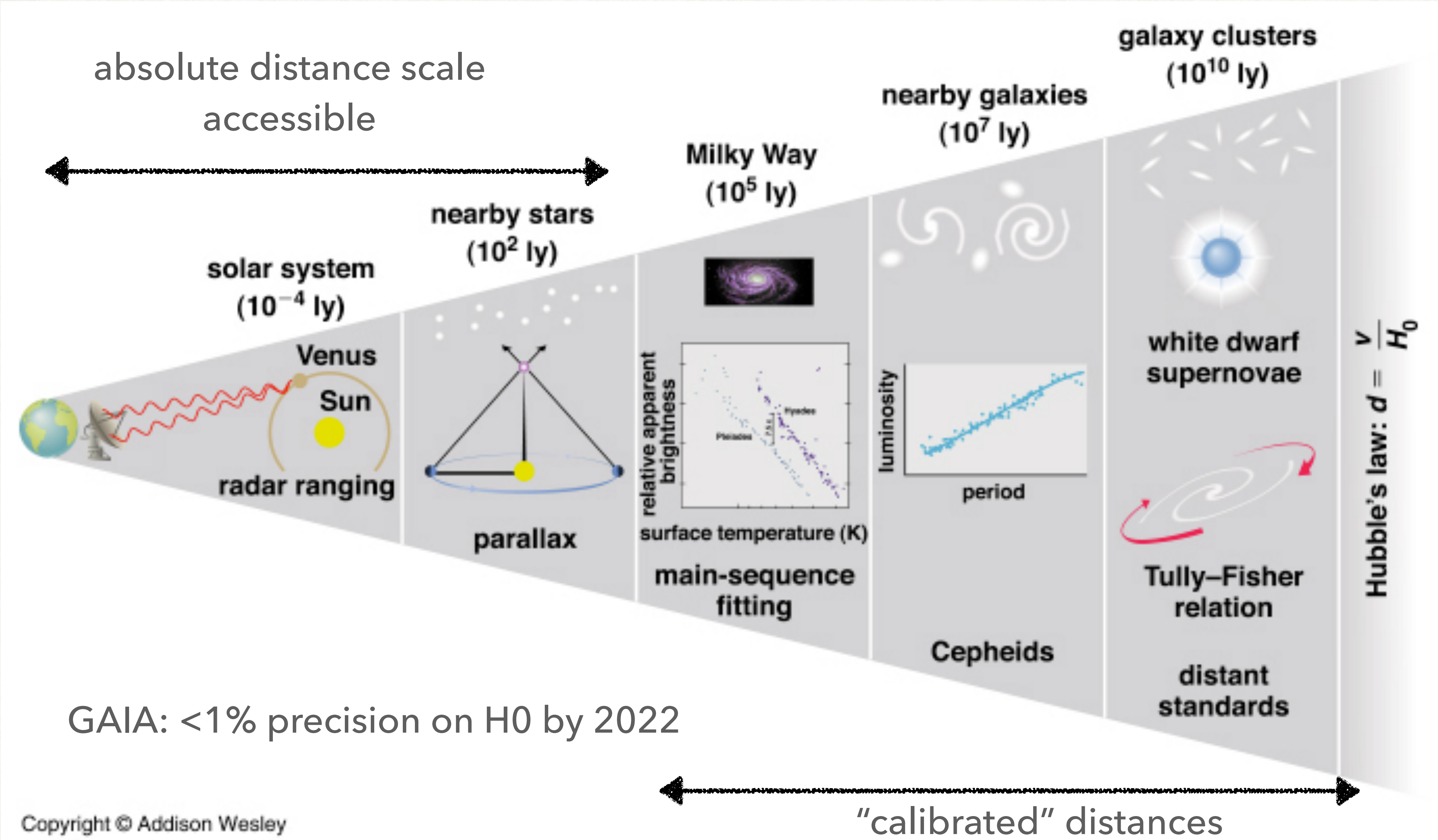


The Distance Ladder in 3 steps

absolute distance scale accessible



GAIA: <1% precision on H0 by 2022

"calibrated" distances

Could it be due to systematics in SN data?

- Sources of error are numerous (non-exhaustive list):
  i) measurement of parallaxes.
  ii) cepheids->SN1a calibration issues.
  iii) are SN1a really standard candles? Are there different SN1a population?
  iv) effect of local environment: is there a Local void? corrections to peculiar velocities?

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  Cardina++ 1611.06088, Zhang++1706.07573, Feeney++ 1707.00007, Follin&Knox 1707.01175
- Environmental effects exist but cannot explain more than ~1% of the difference.

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  see discussion in Riess++1810.03526

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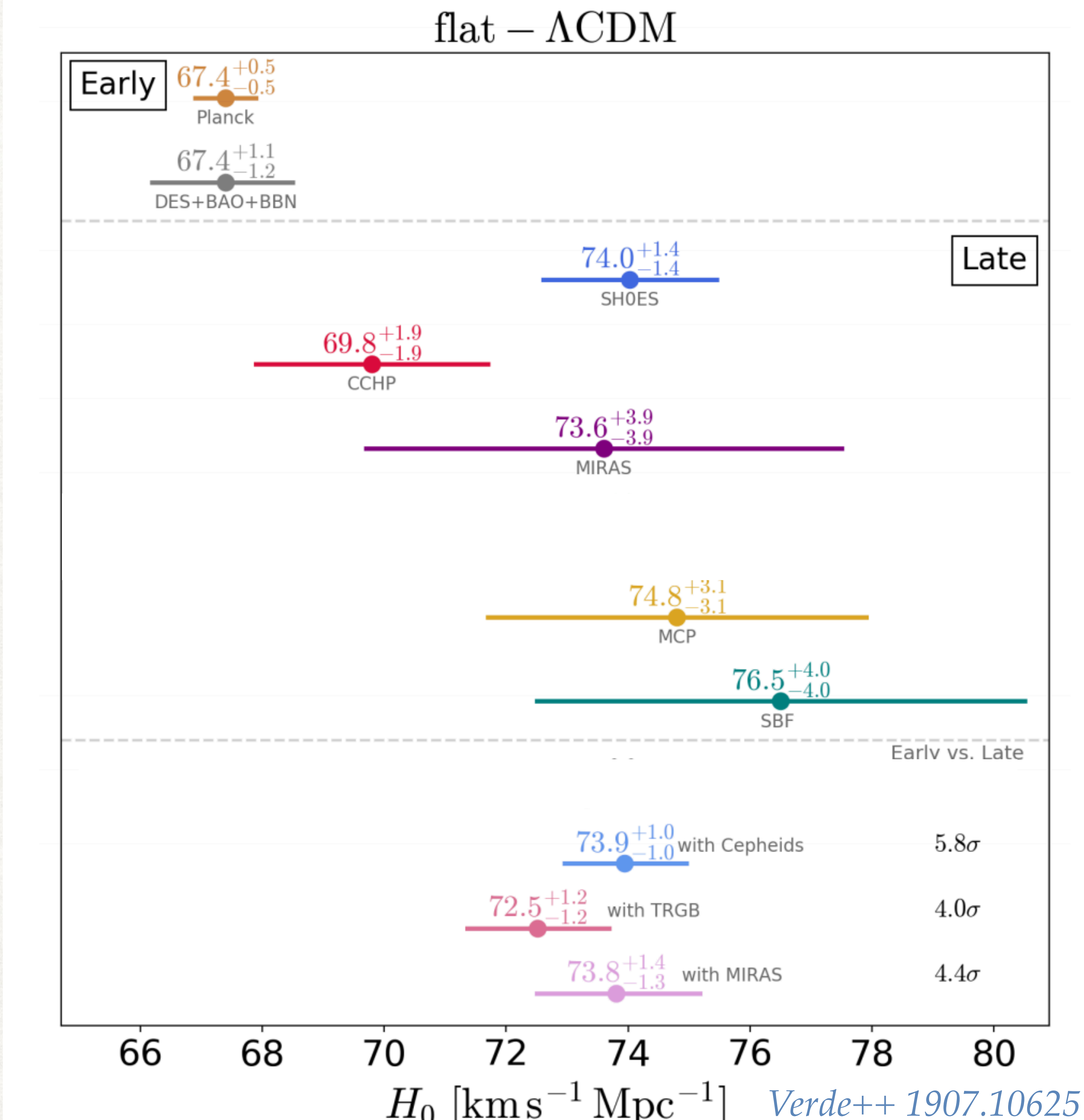
- There might exist different SN1a population. *Rigault et al. 2015, 2018*

- Tension even with non-SN data: Gravitational time delay of strongly lensed quasars is in tension with Planck.

  $H0 = 73.3 \pm 1.8$ km s^{-1} Mpc^{-1} *Wong et al 1907.04869*

What about other SN1a calibrations?



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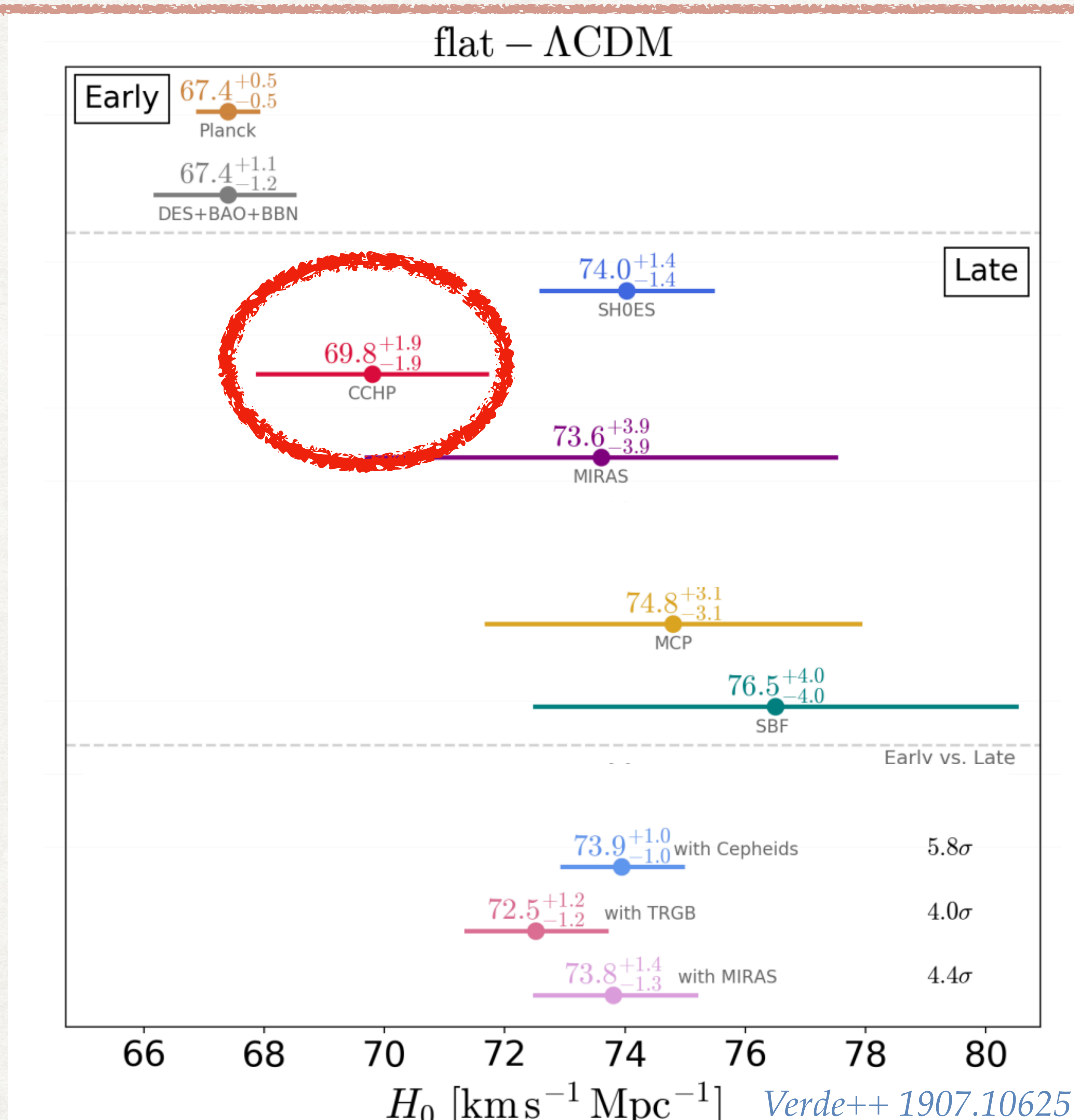
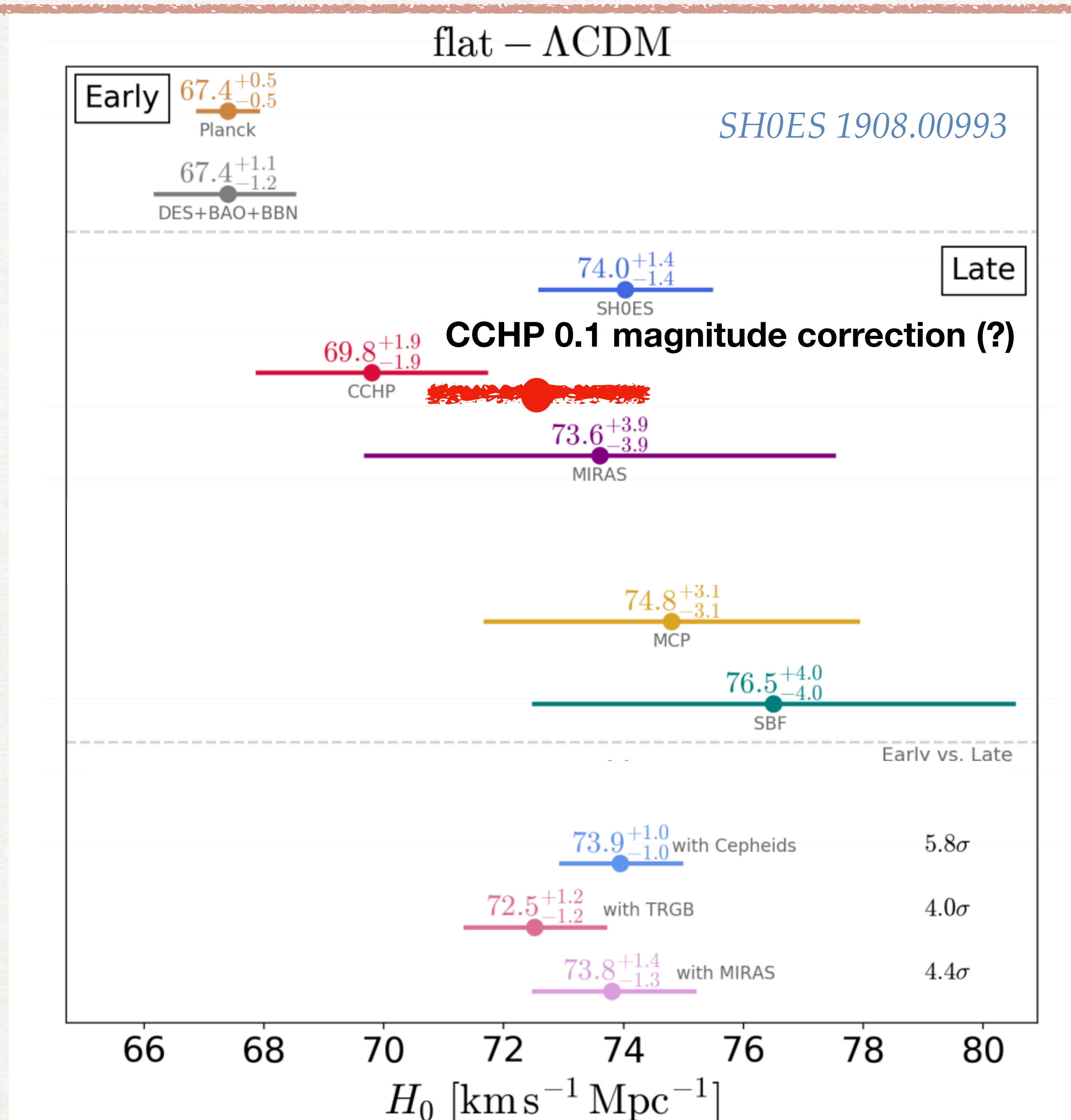
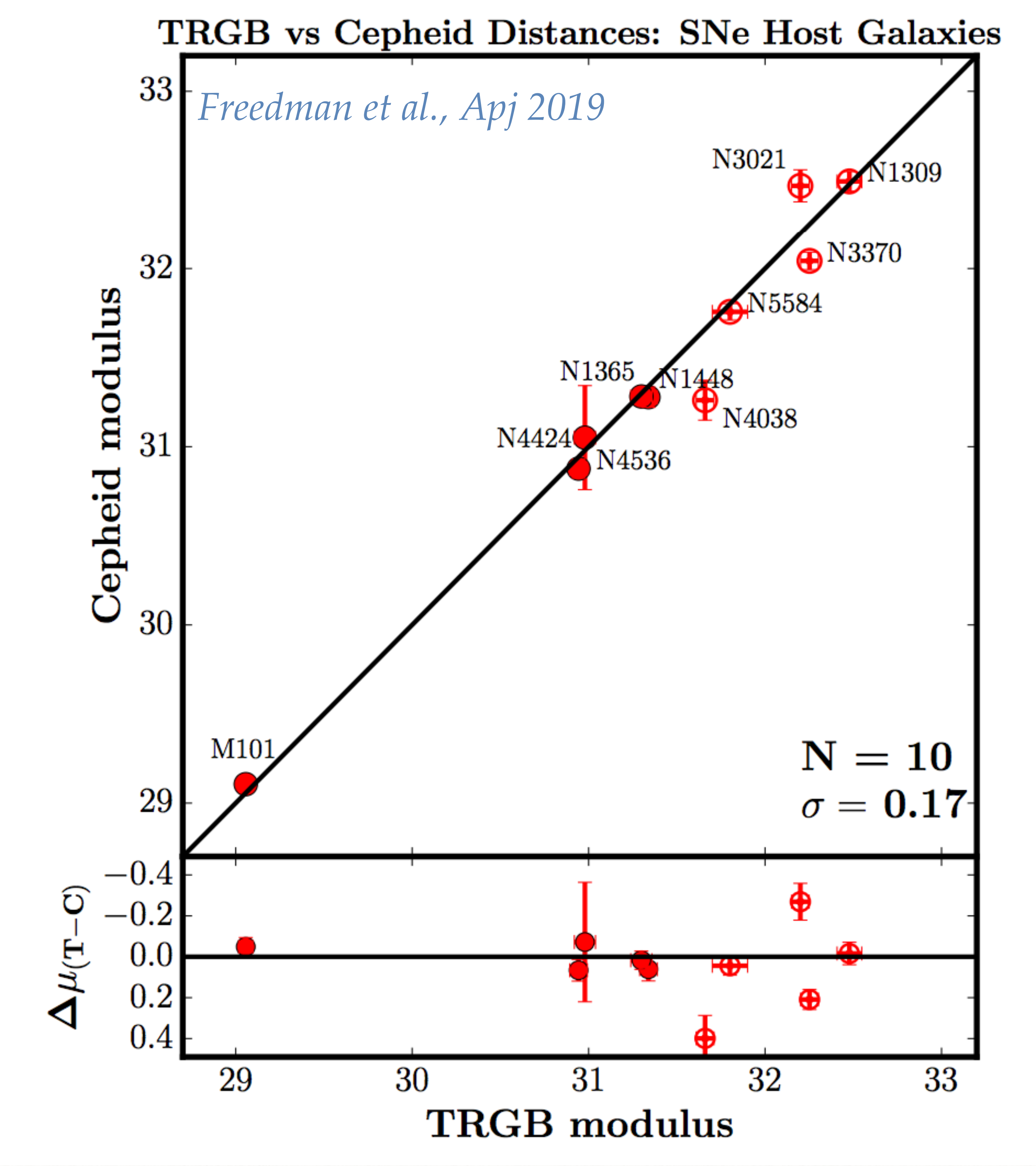


Verde++ 1907.10625

Bias in TRGB calibration?



Systematic uncertainties might be large



CMB determination of H_0

- standard ruler in the sky: distance travelled by sound wave until recombination.
- problem: only angular scale of sound horizon is accessible

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

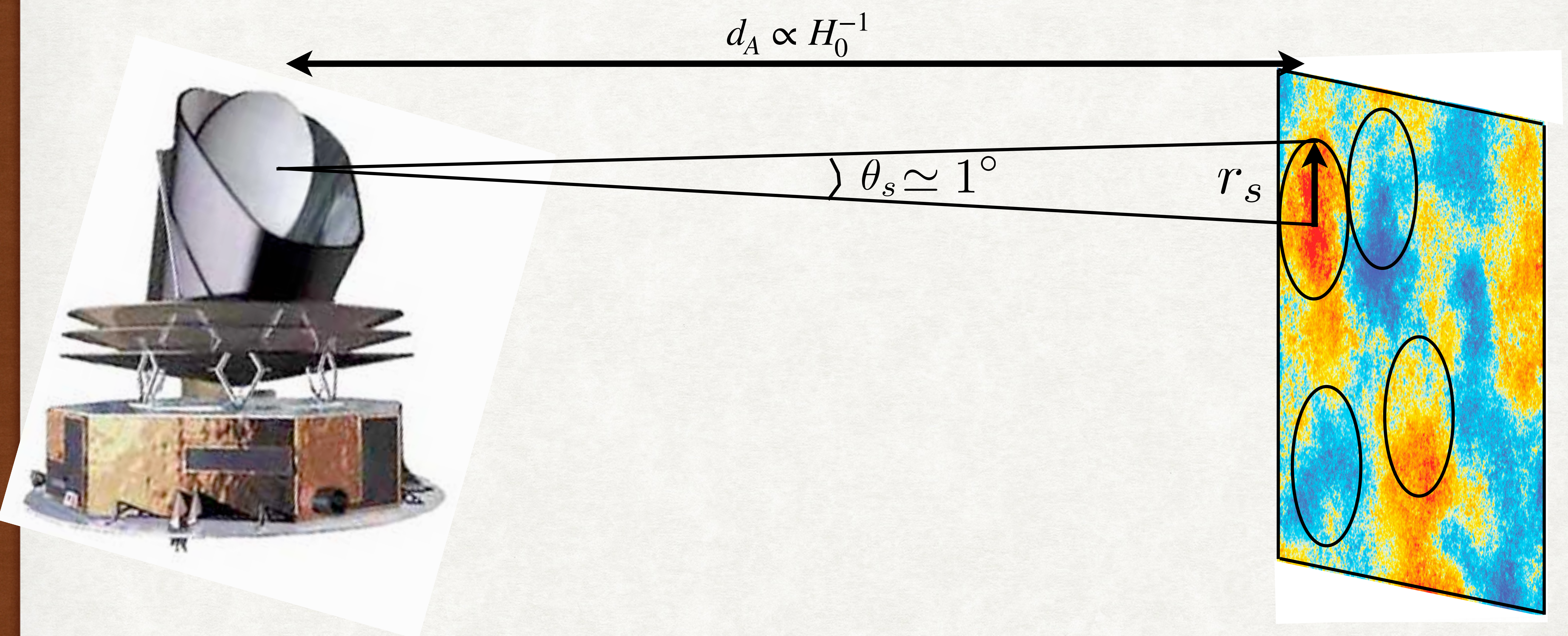


illustration: T. Smith

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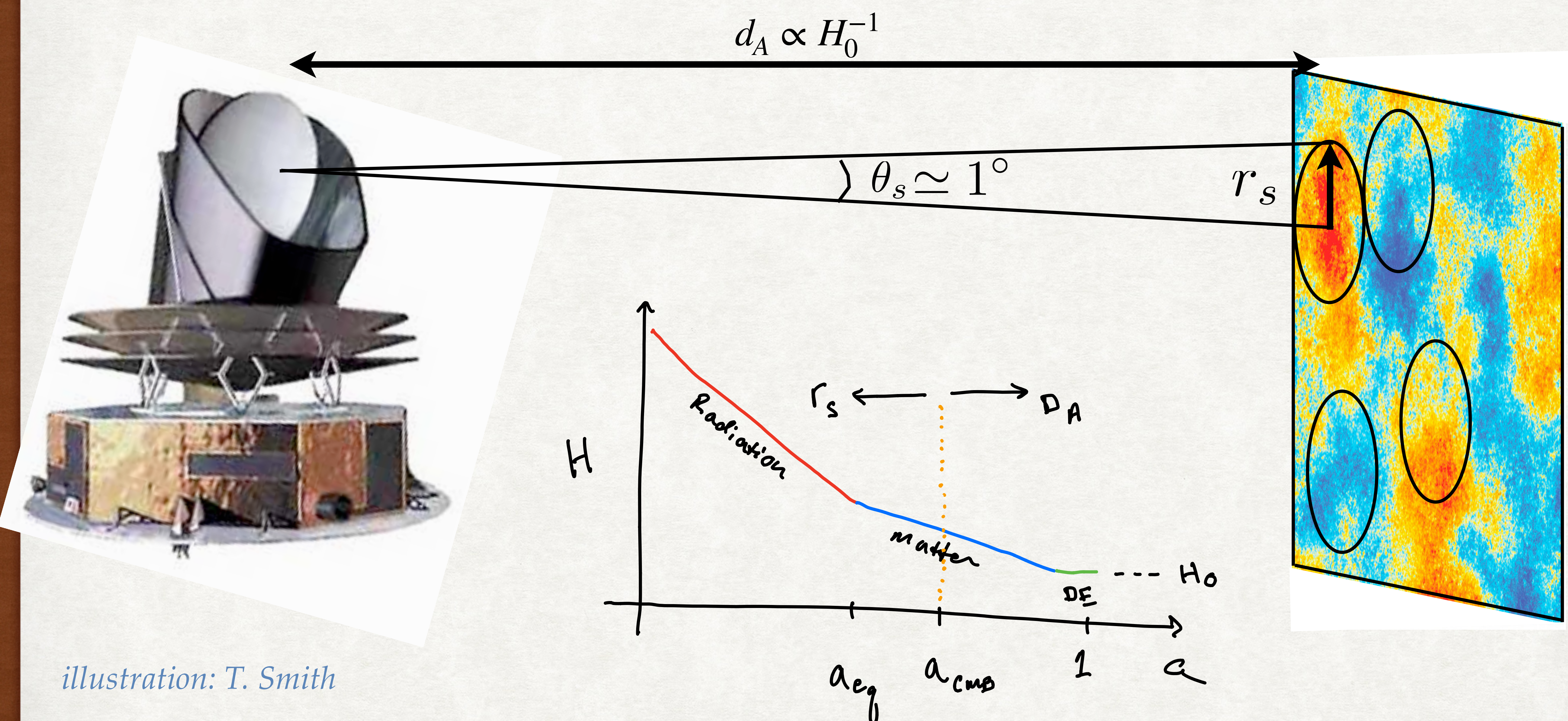

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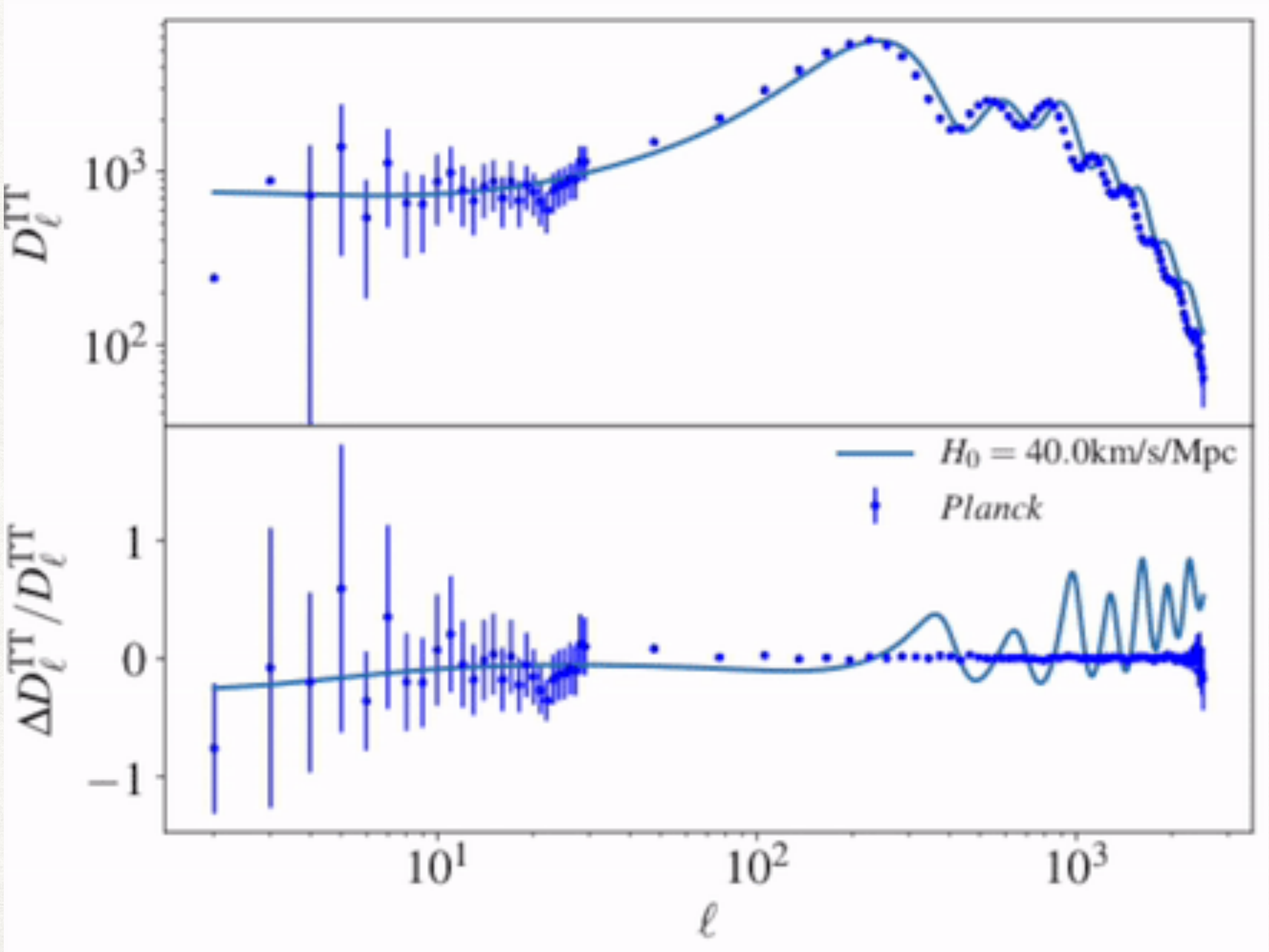
- Change in H_0 affects the peak positions, the angular damping scale and angular horizon scale at z_{eq}.



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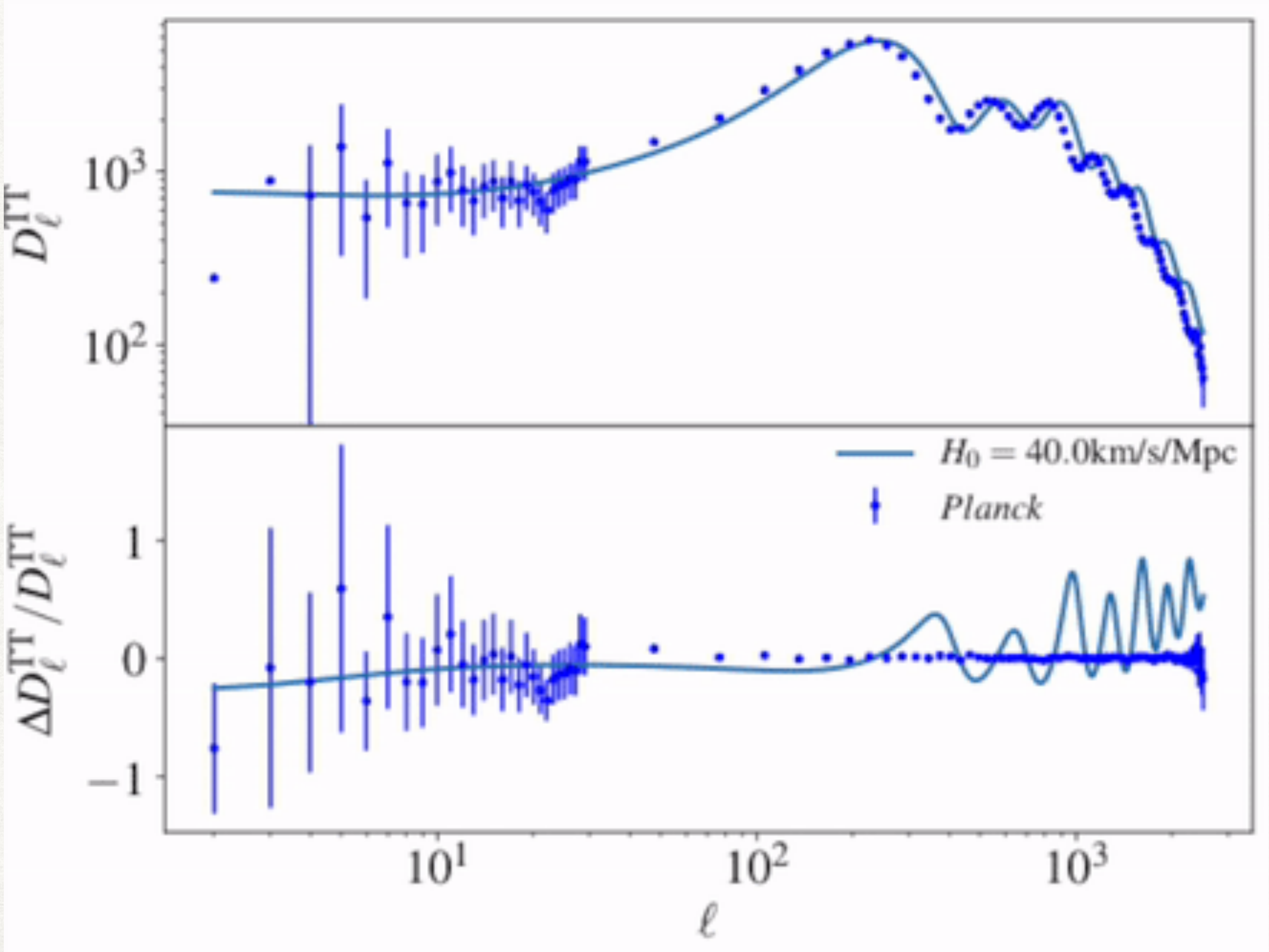

Resolving H_0 tension: a cookbook

see Knox&Millea 1808.03663

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- early-universe solution: decrease $r_s(z_*)$ at fixed θ_s to decrease $d_A(z_*)$ and increase H_0.

Hints for Dynamical Dark-Energy?

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

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- ‘phantom dark energy’ w < -1

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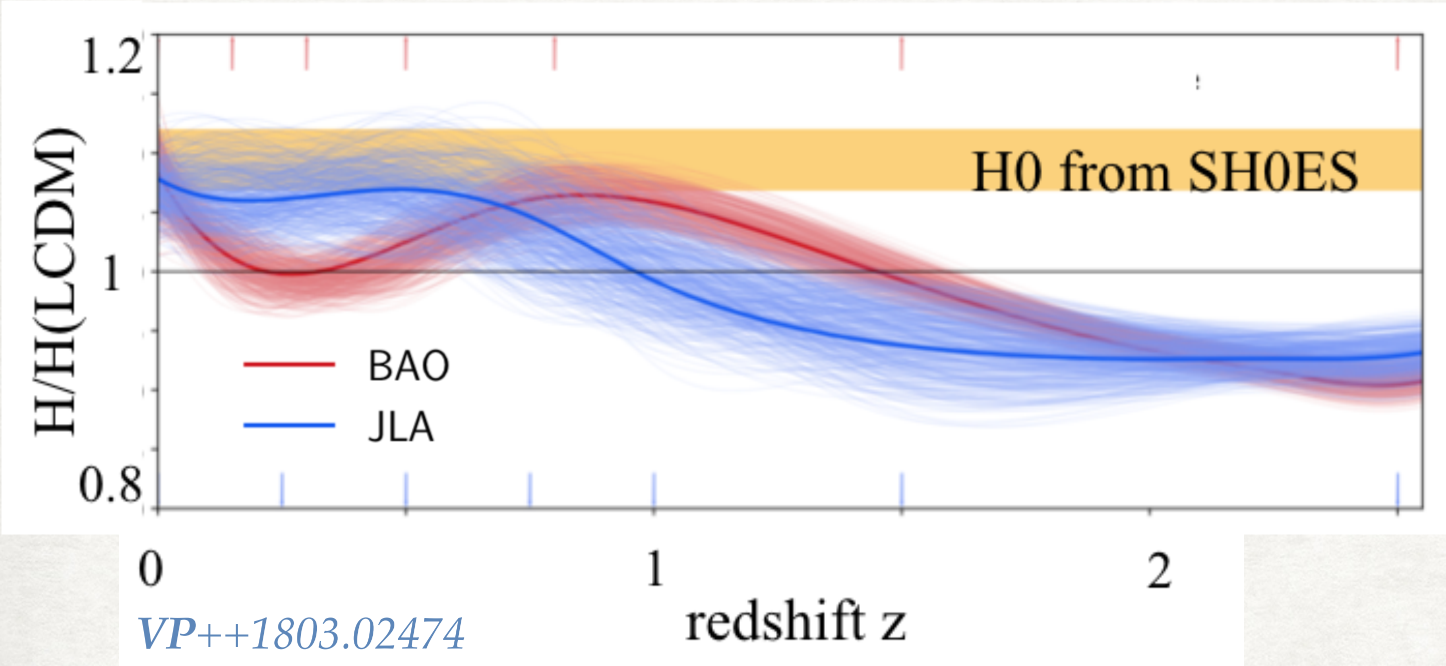
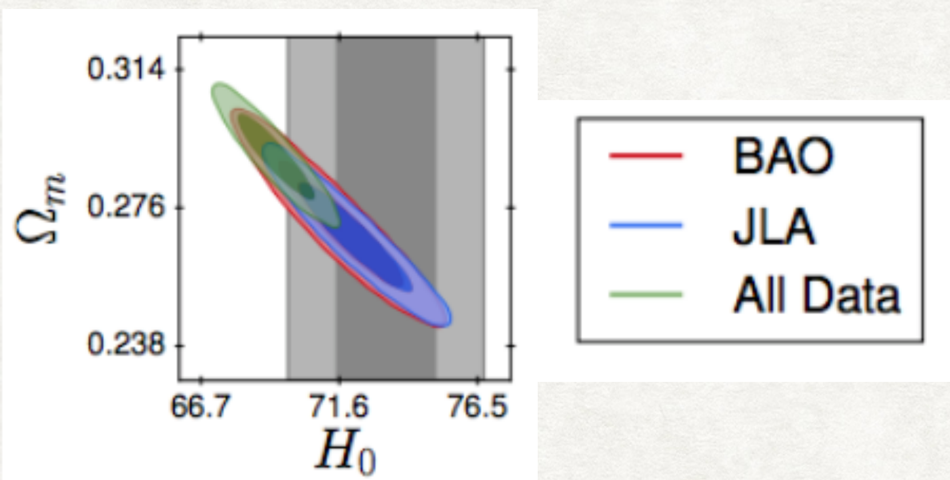


VP++1803.02474



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- BAO measures d_A/r_s while SN1a measures $H_0 d_A/(1+z)$.
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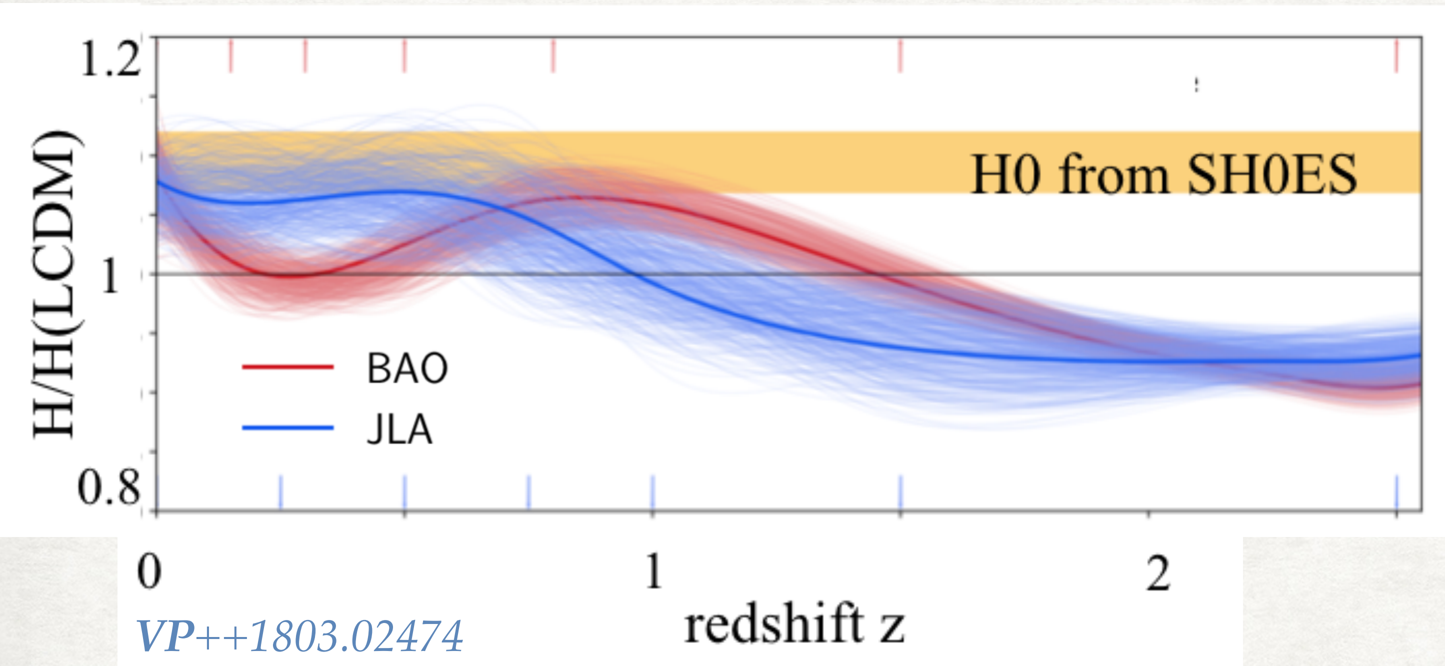

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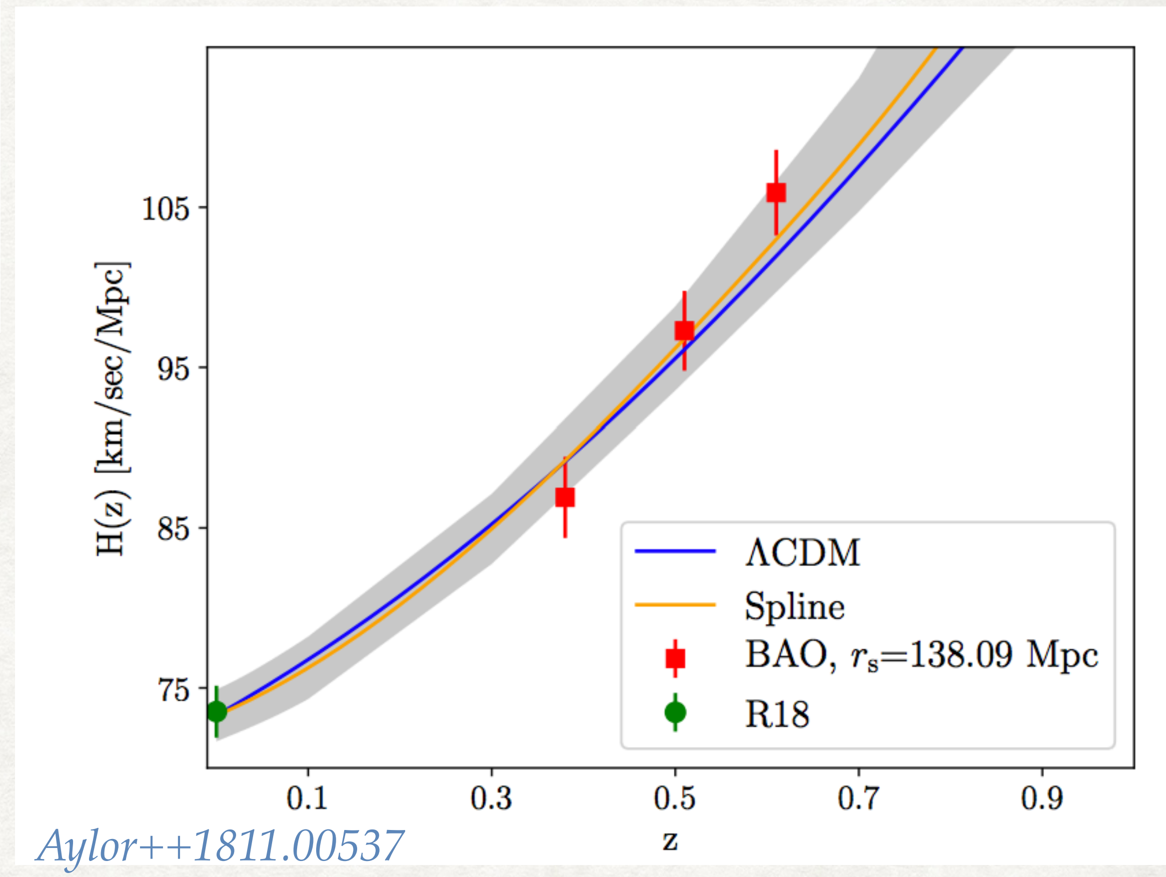
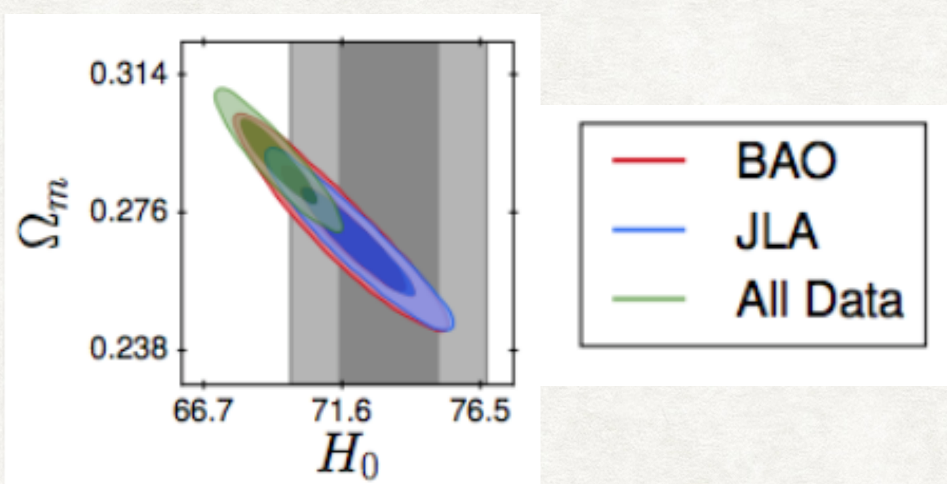


Aylor++1811.00537



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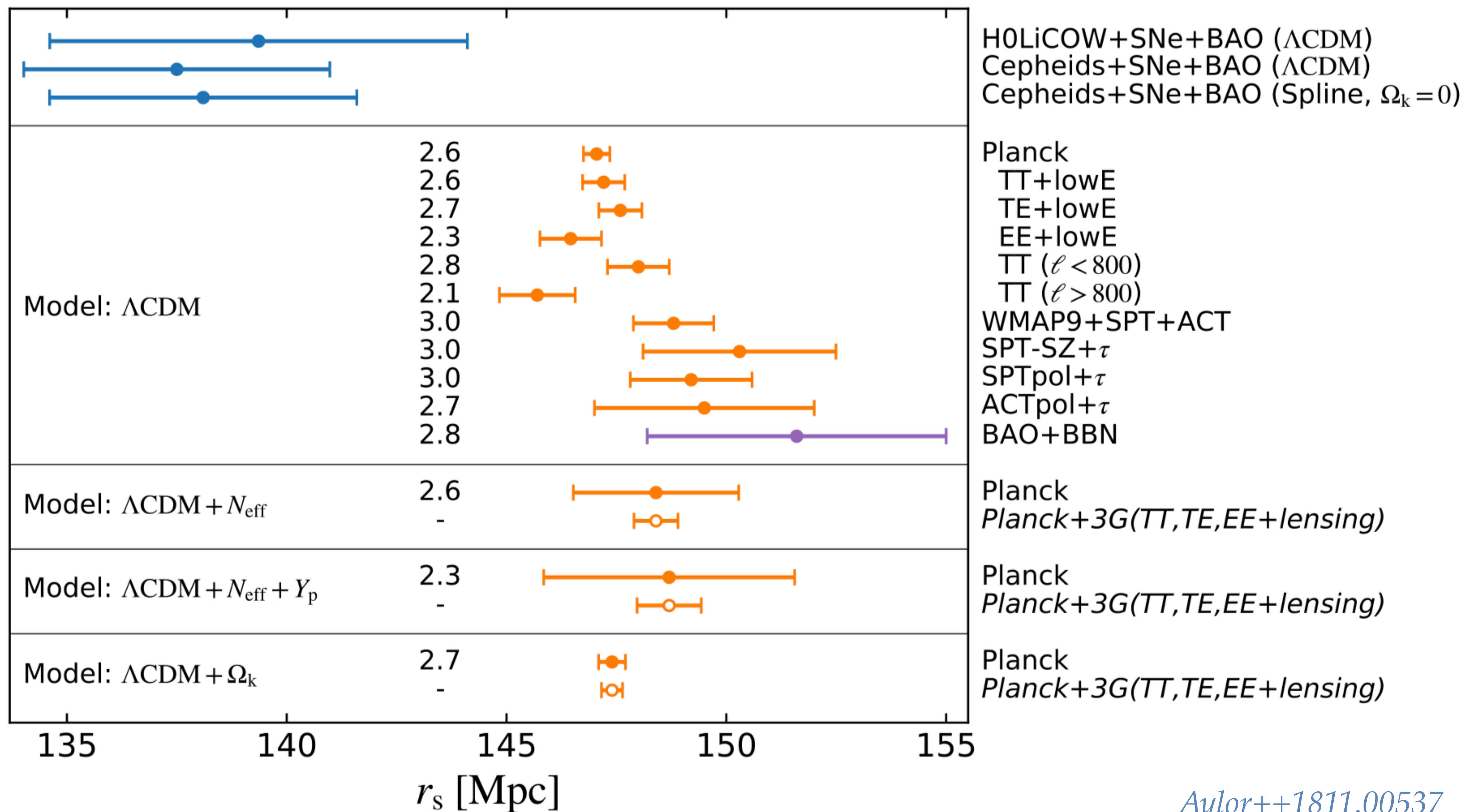
H_0 tension or r_s tension?

One can deduce the co-moving sound horizon r_s from H0 and BAO

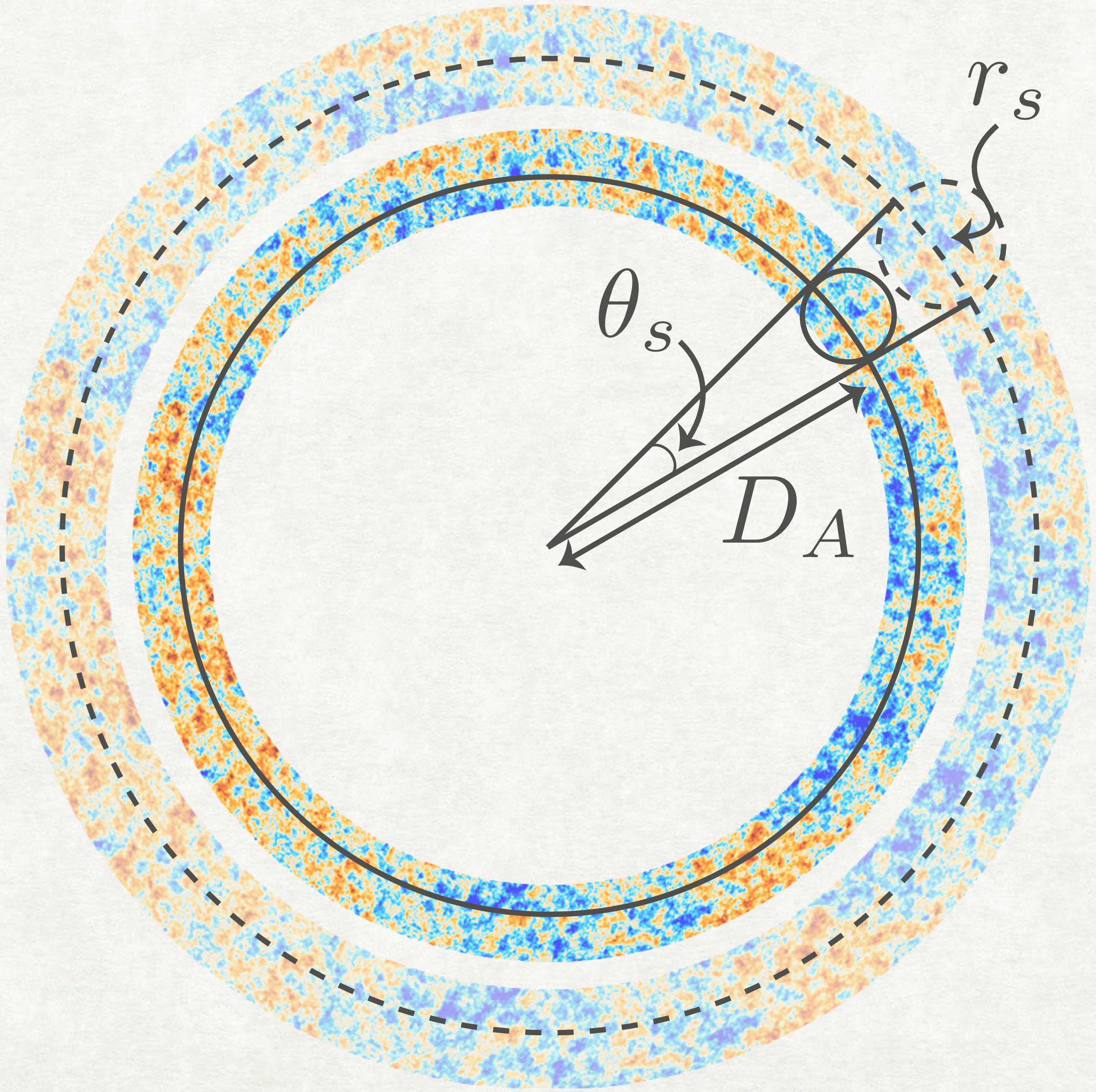
r_s from CMB needs to decrease by ~ 10 Mpc



Aylor++1811.00537

A sketch of the physics at play

- Could the CMB be closer to us than ΛCDM tells us? This is what a higher H_0 suggests.
- Therefore, could spot in the CMB be smaller? This is what new physics must achieve.



Early-time resolution to the H_0 tension

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

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

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Chiang&Slosar 1811.03624

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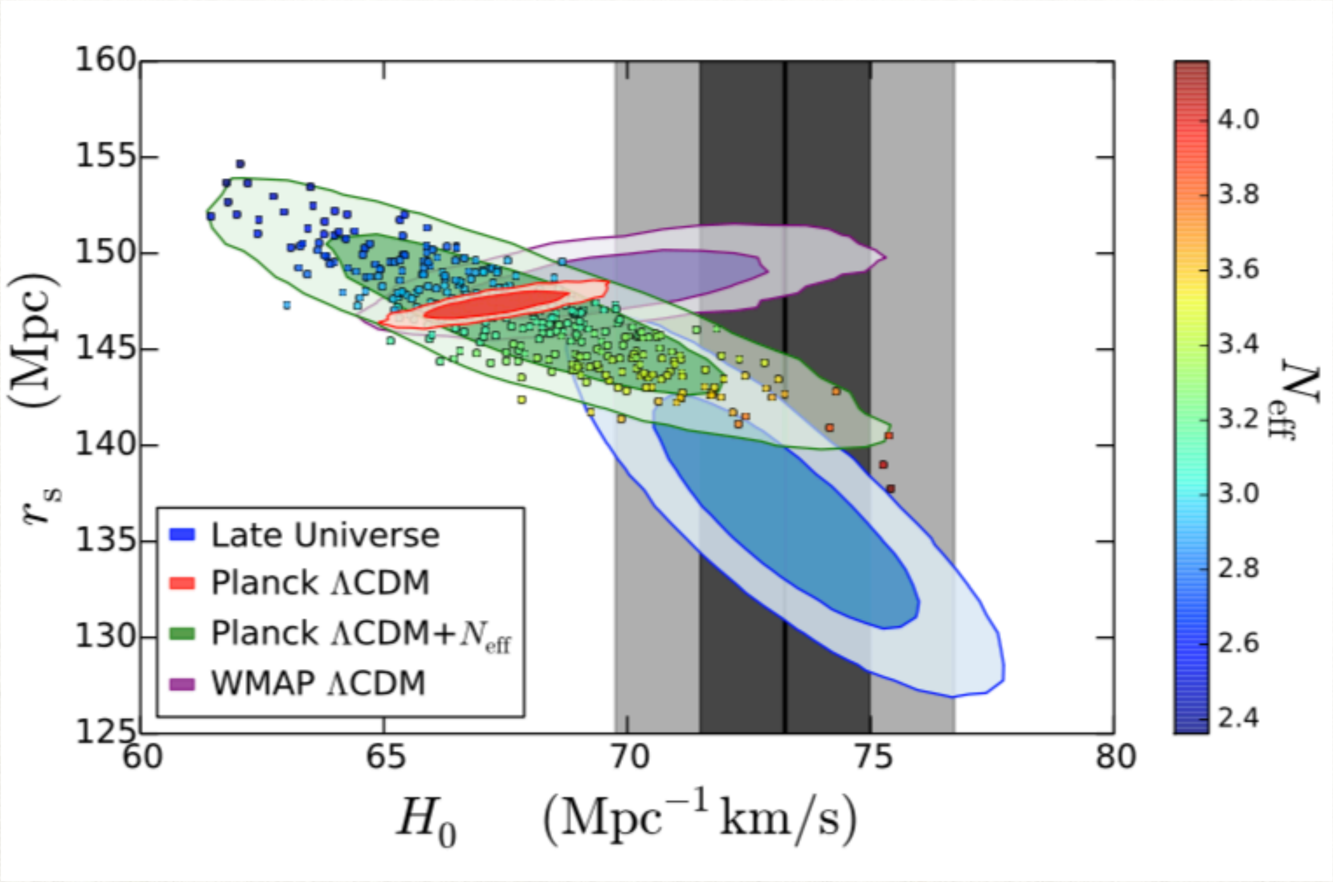

Bernal++ 1607.05617

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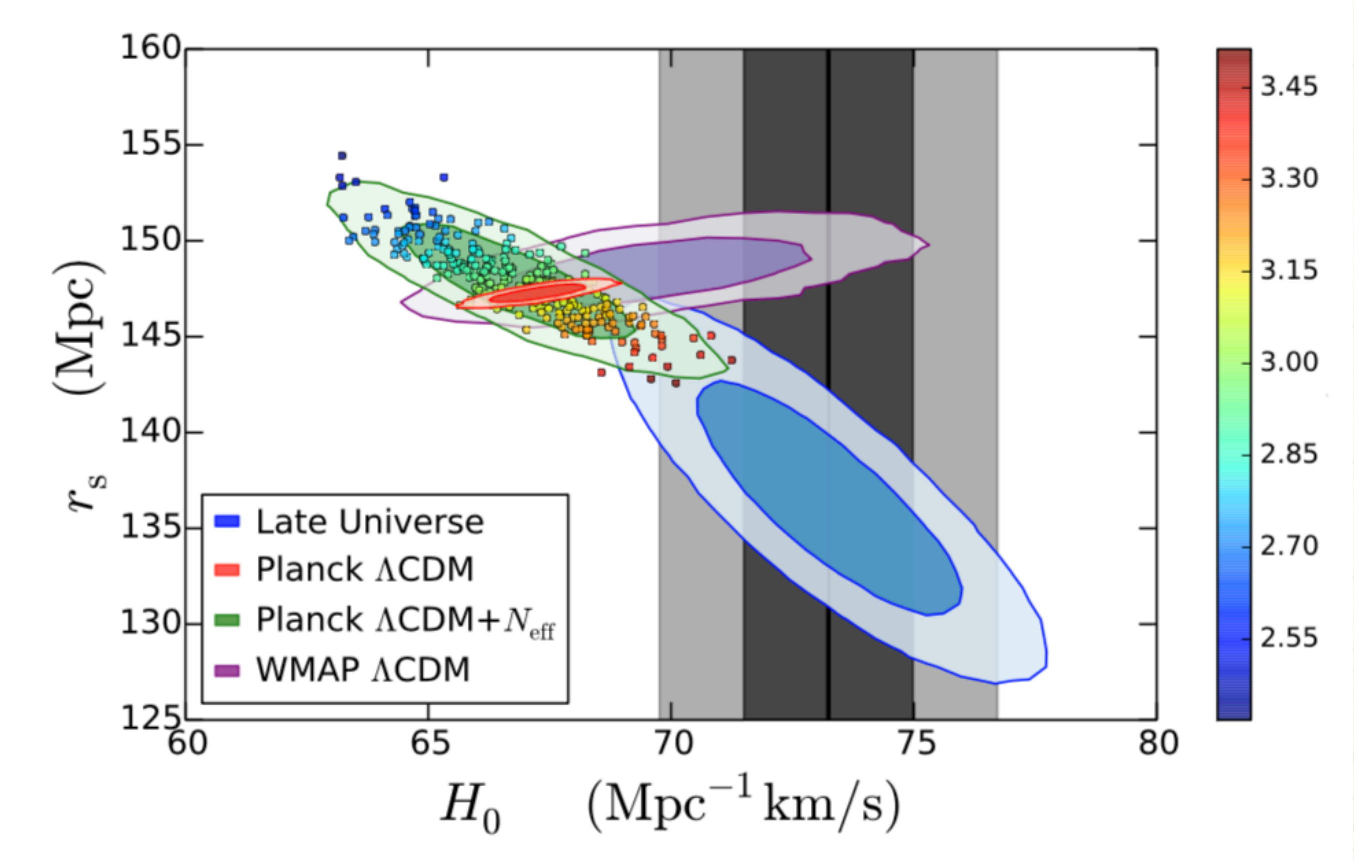

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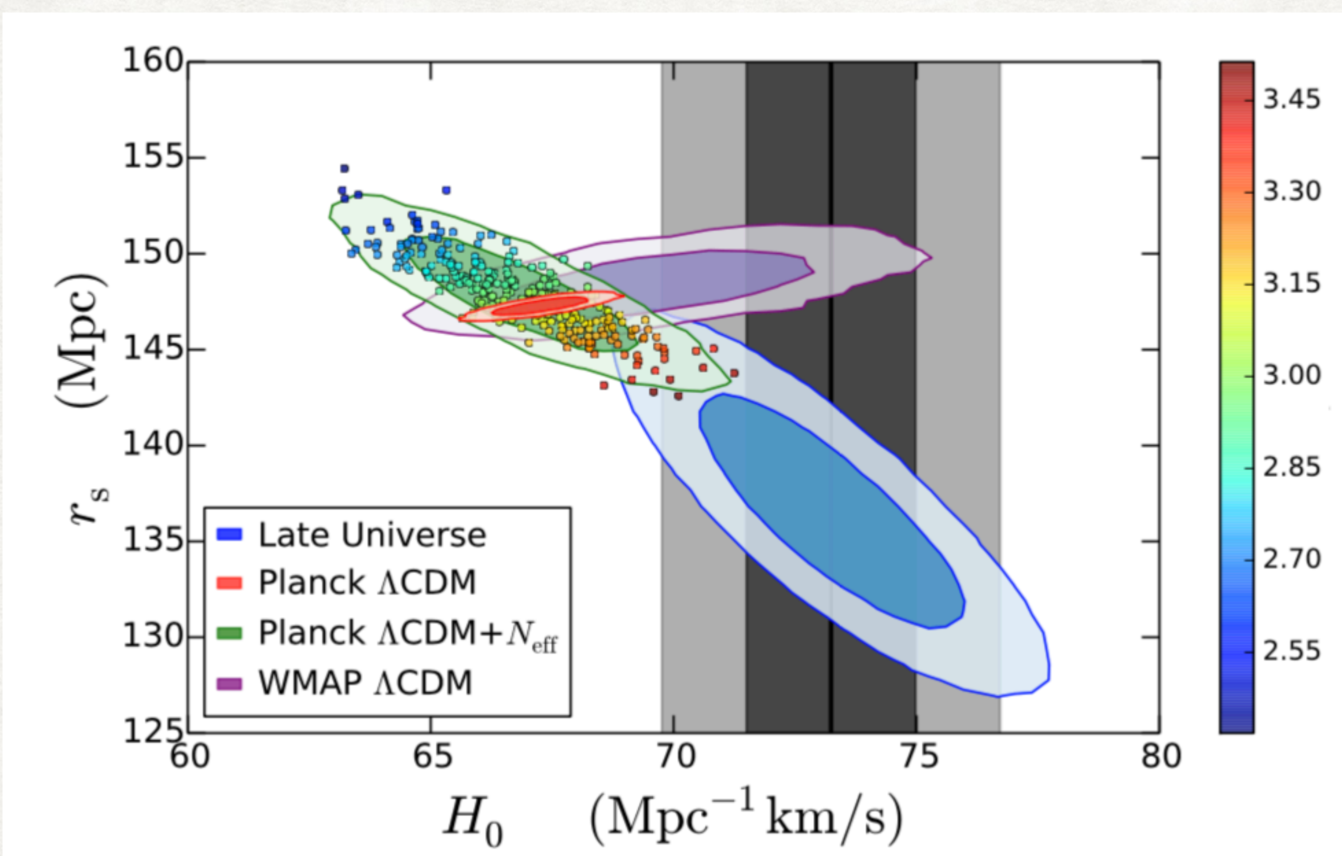

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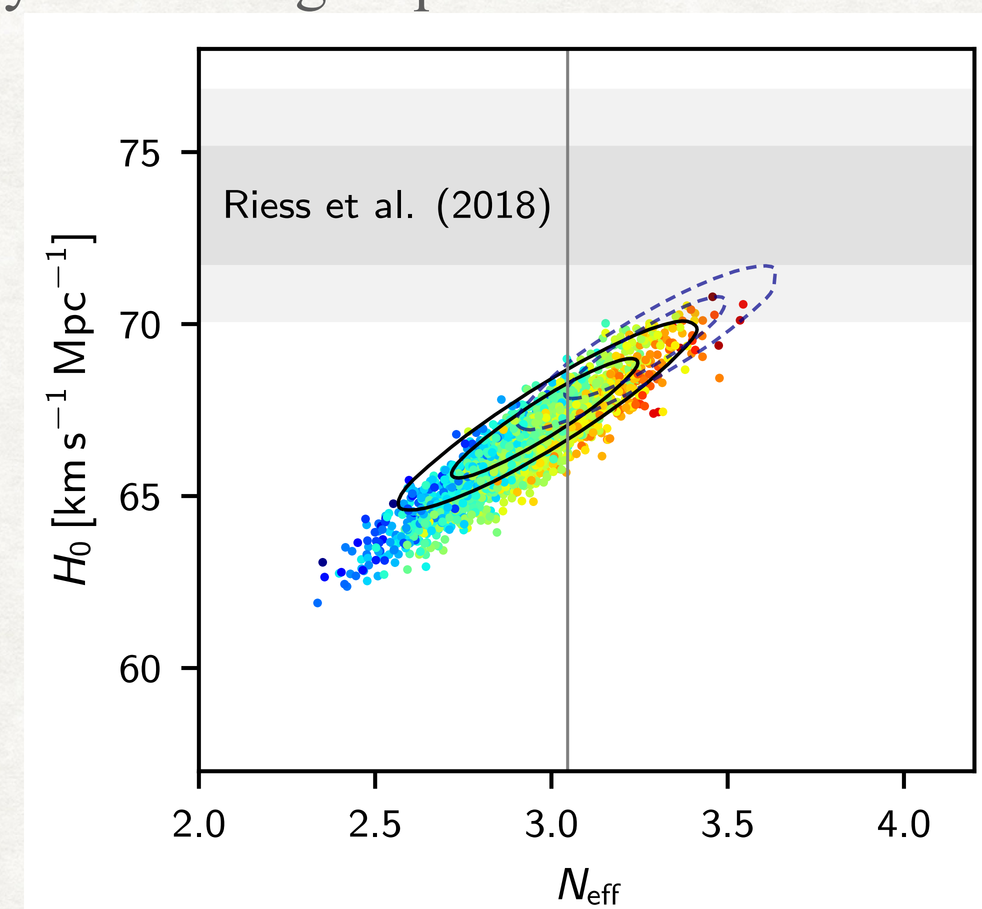

Aghanim++ 1807.06209

Interacting neutrinos can resolve H_0 tension

- Perturbation effect: free-streaming neutrinos lead to a phase shift: $\delta\theta \sim 0.6\left(\frac{\rho_\nu}{\rho_g}\right)$
- Peak position is really $\theta^* = \theta_s + \delta\theta$ *Bashinsky&Seljak, astro-ph/0310198, Baumann++ 1508.06342*
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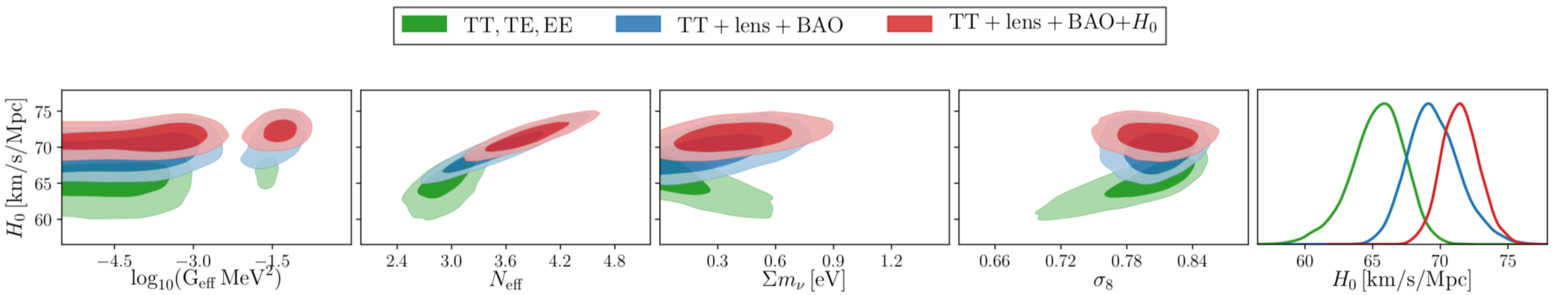


- Solution requires 4 strongly interacting neutrinos with M ~ 0.4eV
- "For free": solve S_8 tension and reactor anomalies!
- BBN & Lab. requires majorana neutrinos and a heavy mediator coupled to ν_τ

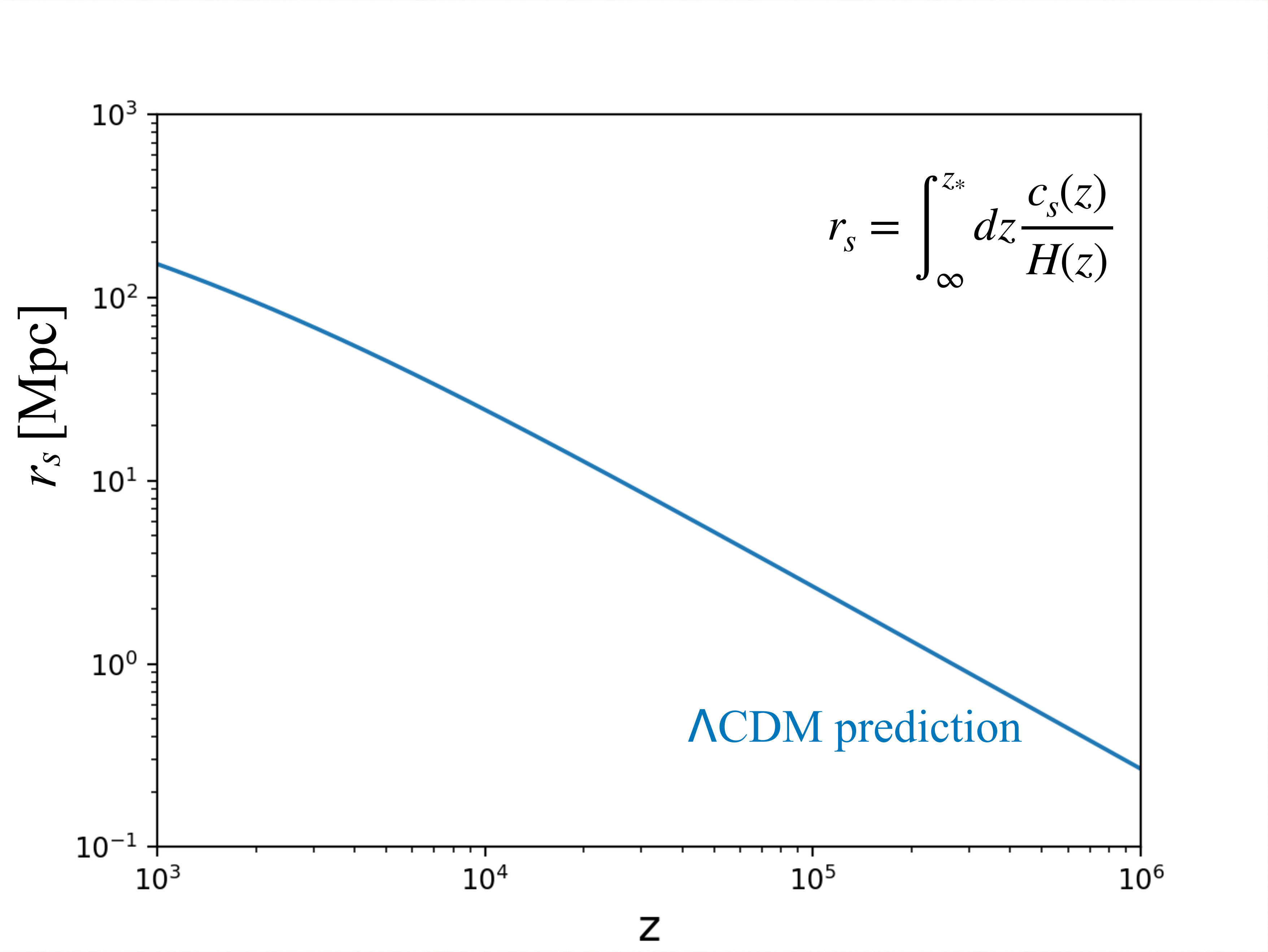
Blinov++ 1905.02727

- Might also work with a light mediator (different scaling of Γ/H)

Escudero&Witte 1909.04044

Early-Universe solution to H_0

- r_s does not reach 10Mpc before ~ 25000 in ΛCDM



GOAL: decreasing r_s by 10Mpc while keeping r_s/r_d and r_s/r_{eq} fixed

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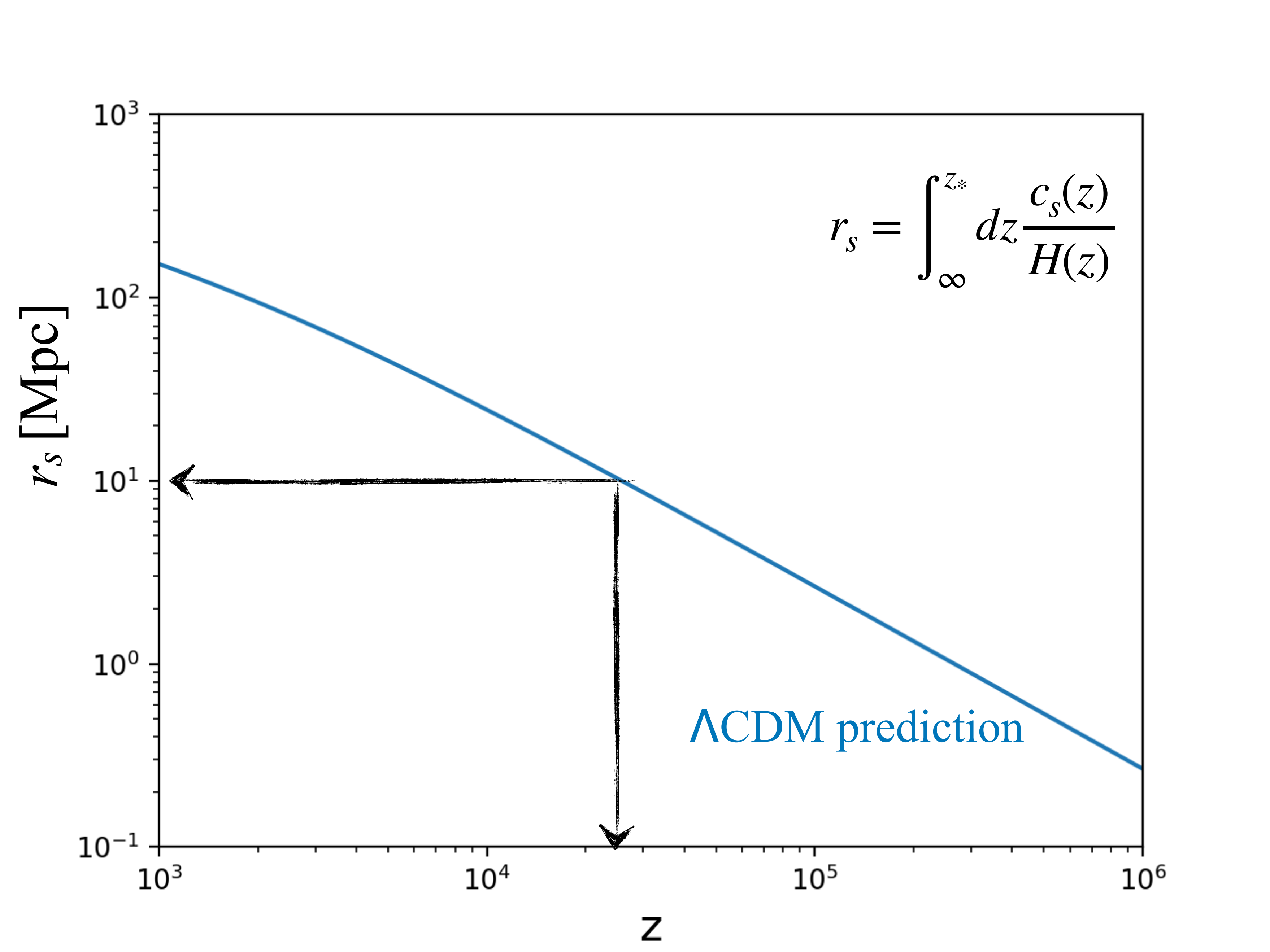

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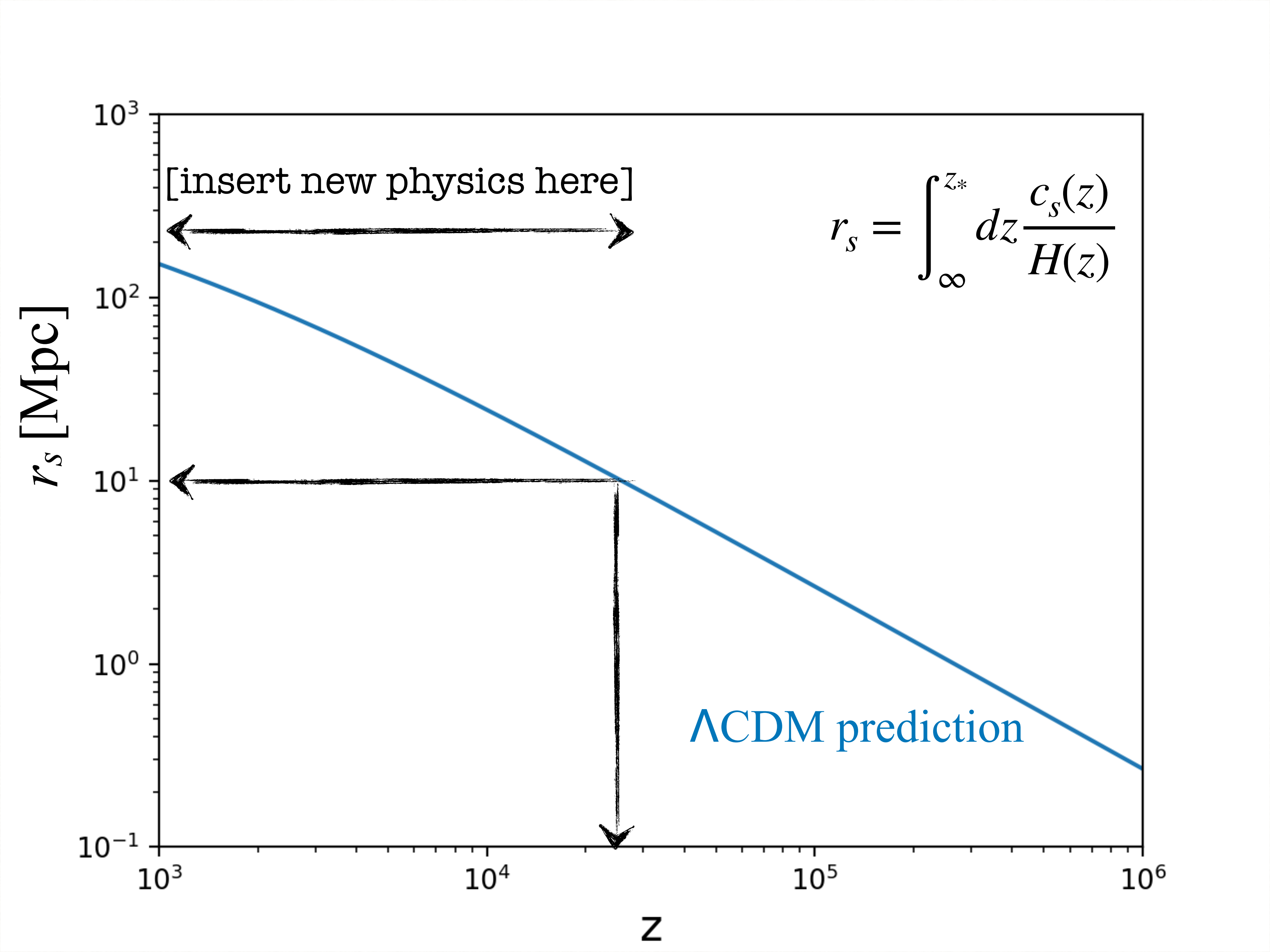

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Scalar field and Early Dark Energy

- 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:

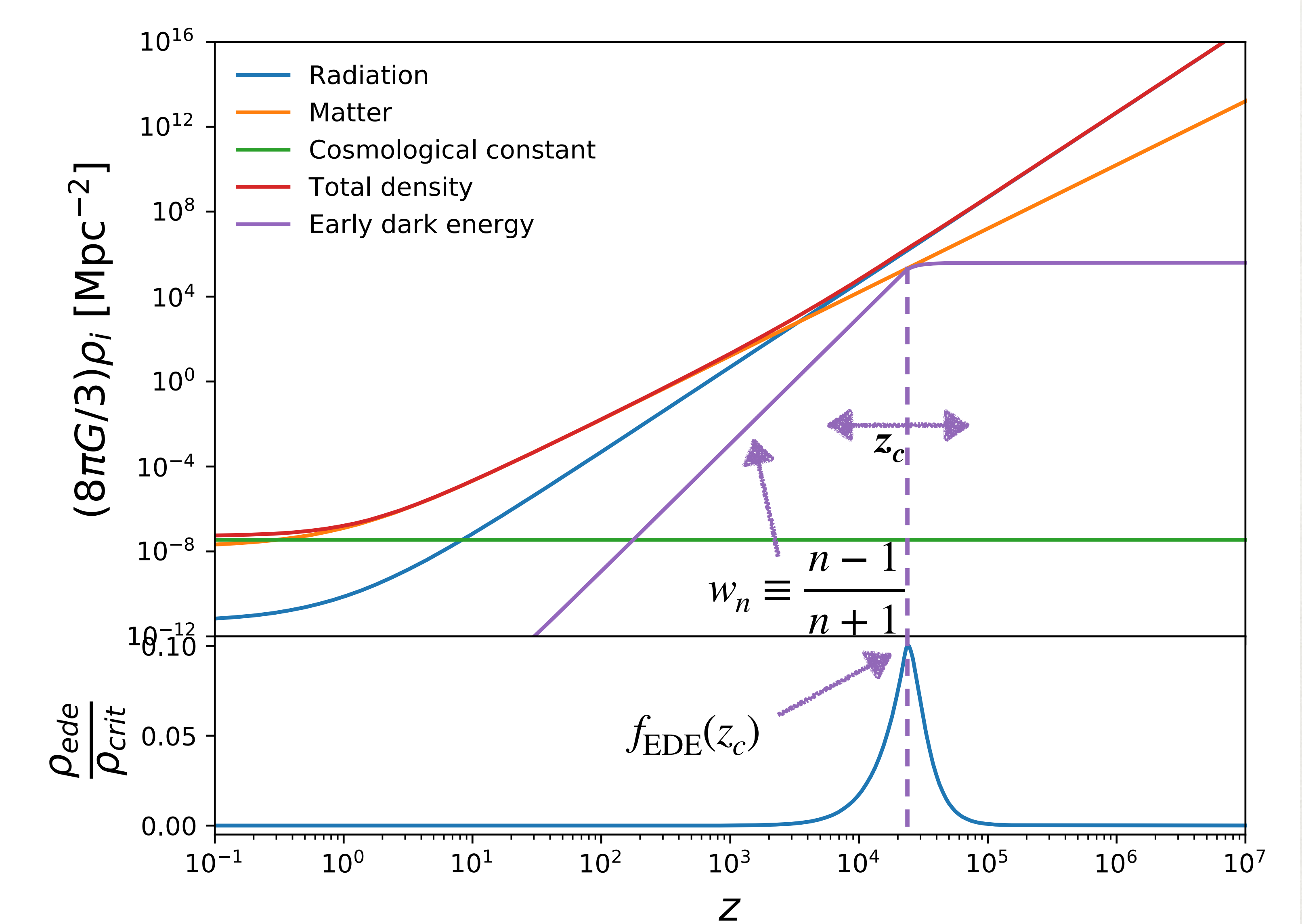
$$V(\phi) \propto (1 - \cos\phi)^n$$

VP++ 1806.10608 & 1811.04083
Smith, VP ++ 1908.06995

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

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

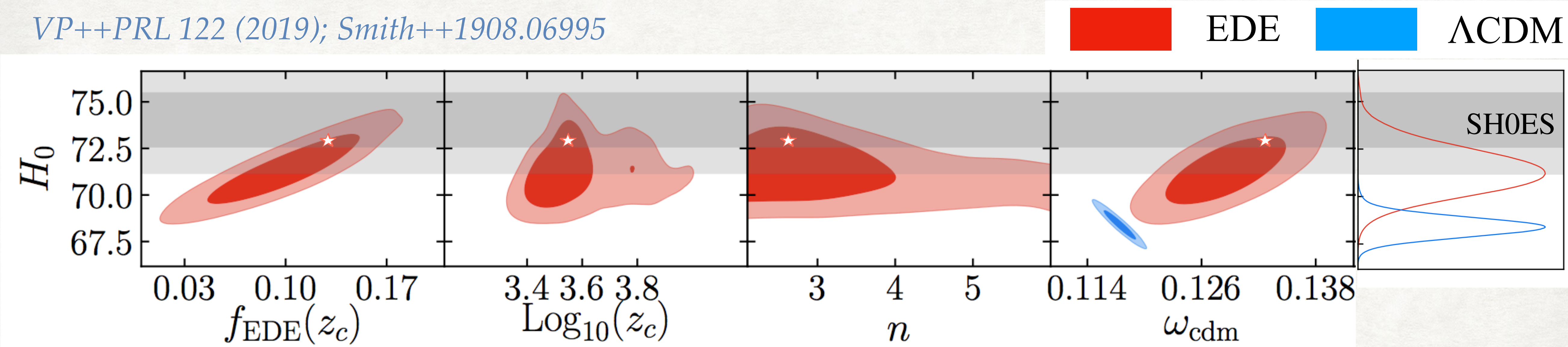
$n = 1$: matter, $n = 2$: radiation, etc.



plot by T. Karwal

EDE Can Resolve The Hubble Tension

VP++PRL 122 (2019); Smith++1908.06995



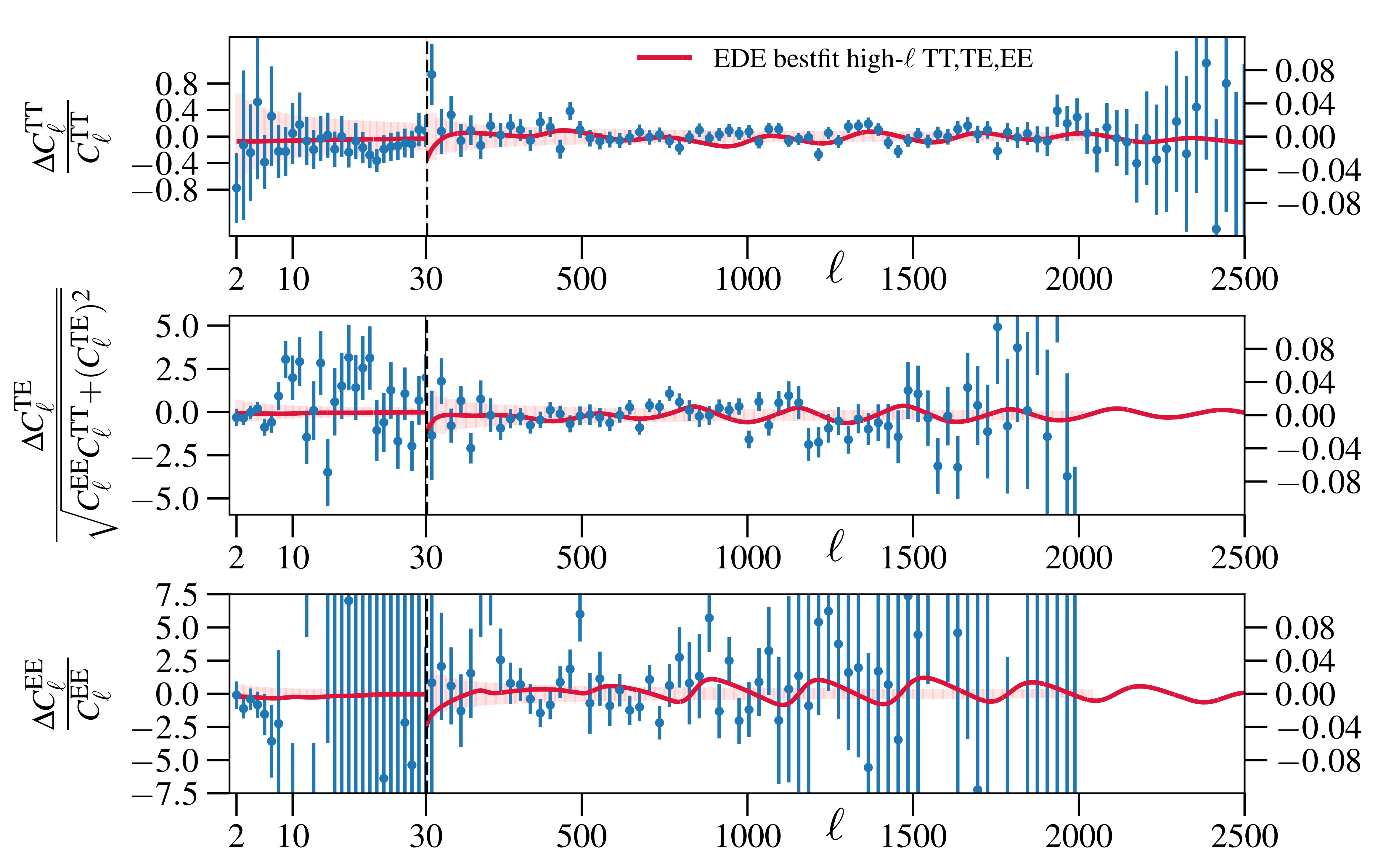
- Planck high-ℓ TT,TE, EE+lowTEB+lensing+BAO+Pantheon+SH0ES 19

$f(z_c) = 0.10\ (0.13) \pm 0.03$ $\quad \mathrm{Log}_{10}(z_c) = 3.56\ (3.53)^{+0.05}_{-0.1}$ $\quad H_0 = 71.5\ (72.8) \pm 1.2$ km/s/Mpc

- n < 3.5 at 1σ: scalar field oscillations are favored over non-oscillating solutions

Datasets	ΛCDM	n free
Planck high-ℓ TT, TE, EE	2446.66	2445.53
Planck low-ℓ TT, TE, EE	10496.65	10493.65
Planck lensing	10.37	9.14
SH0ES	16.80	0.73
Total $\chi^2_{\rm min}$	14001.23	13980.90
$\Delta\chi^2_{\rm min}$	0	-20.33

EDE leaves an imprint in CMB power spectra

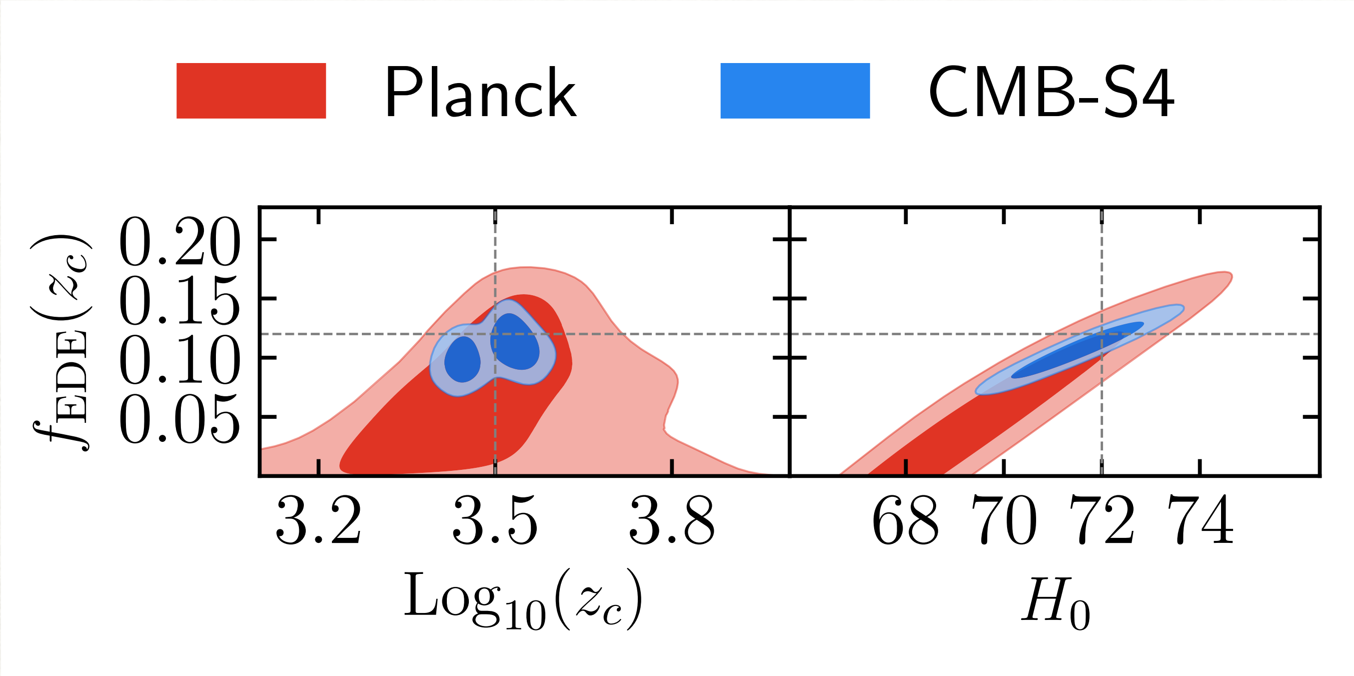


Detecting the EDE with CMB data only

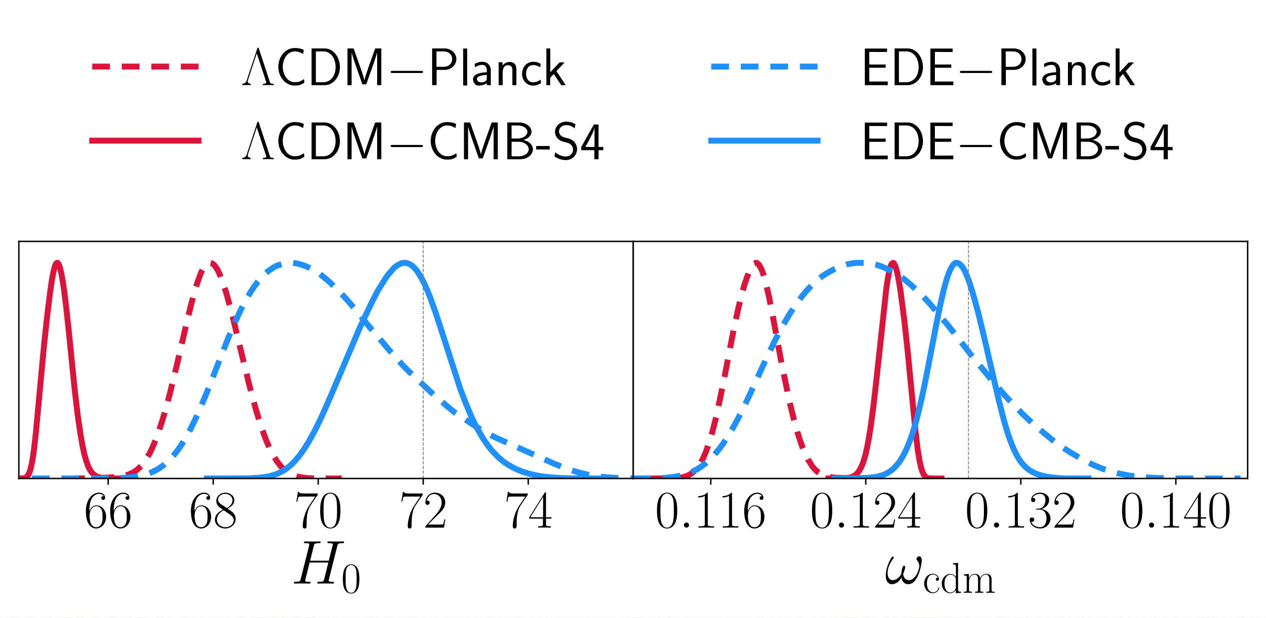
Smith, VP, Amin, 1908.06995

- Future CMB experiment like CMB-S4 will be able to detect the EDE without SH0ES data.

Fiducial model:
$f(z_c) = 0.12$
$z_c = 10^{3.5}$
$h = 0.72$



- Without including the EDE: one might strongly bias H_0 and $\omega_{\rm cdm}$ values.



A New Understanding Of Λ?

- The field becomes dynamical around z_{eq}: Fine tuning ? Coincidence problem 2.0?
- What if there were more of such era to be discovered? We already have seen two (three?) of them.
- Is their one field with a complicated potential or many fields with simple potentials?

e.g. Dodelson++astro-ph/0002360, Griest astro-ph/0202052, Kamionkowski++1409.0549

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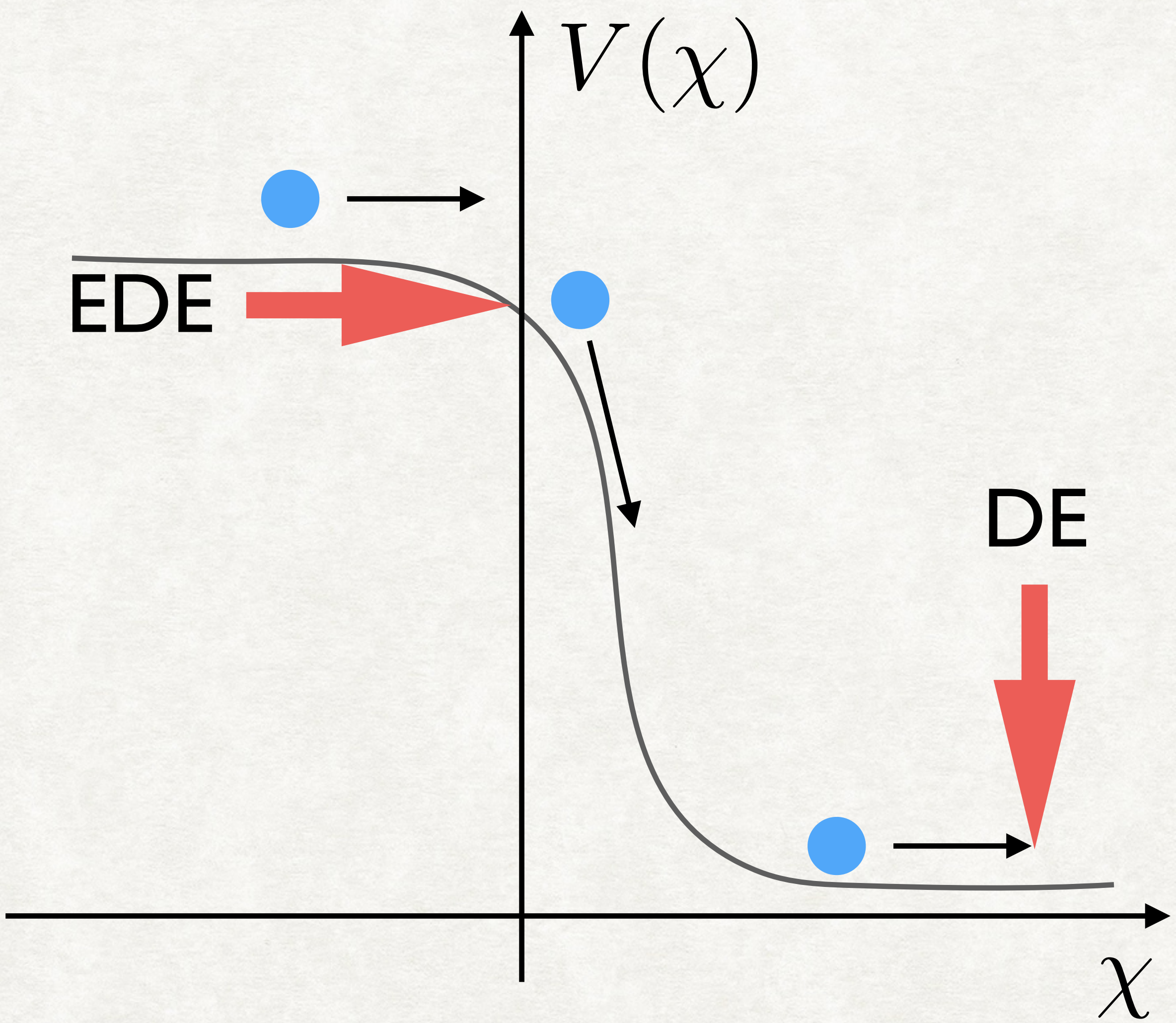

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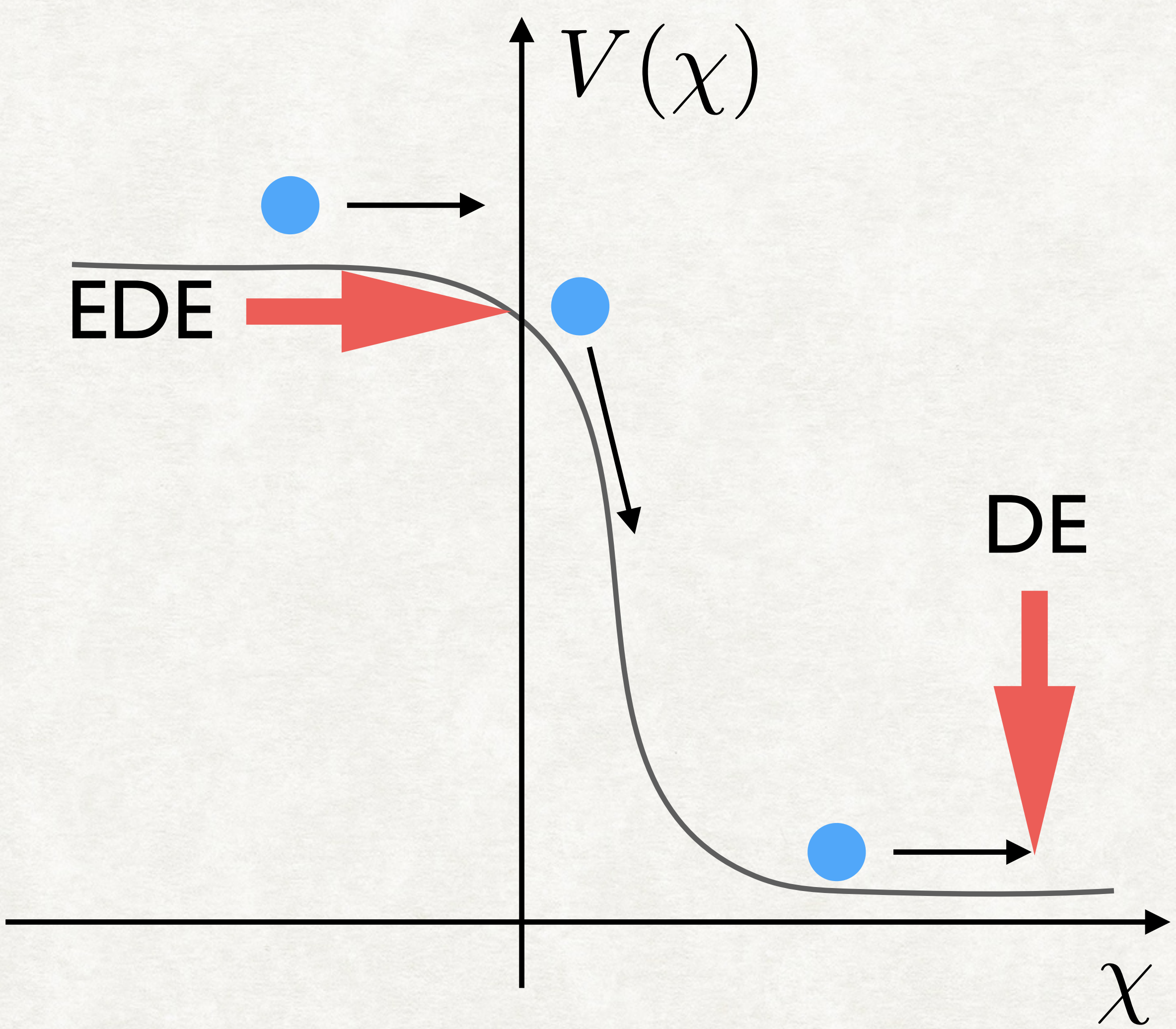

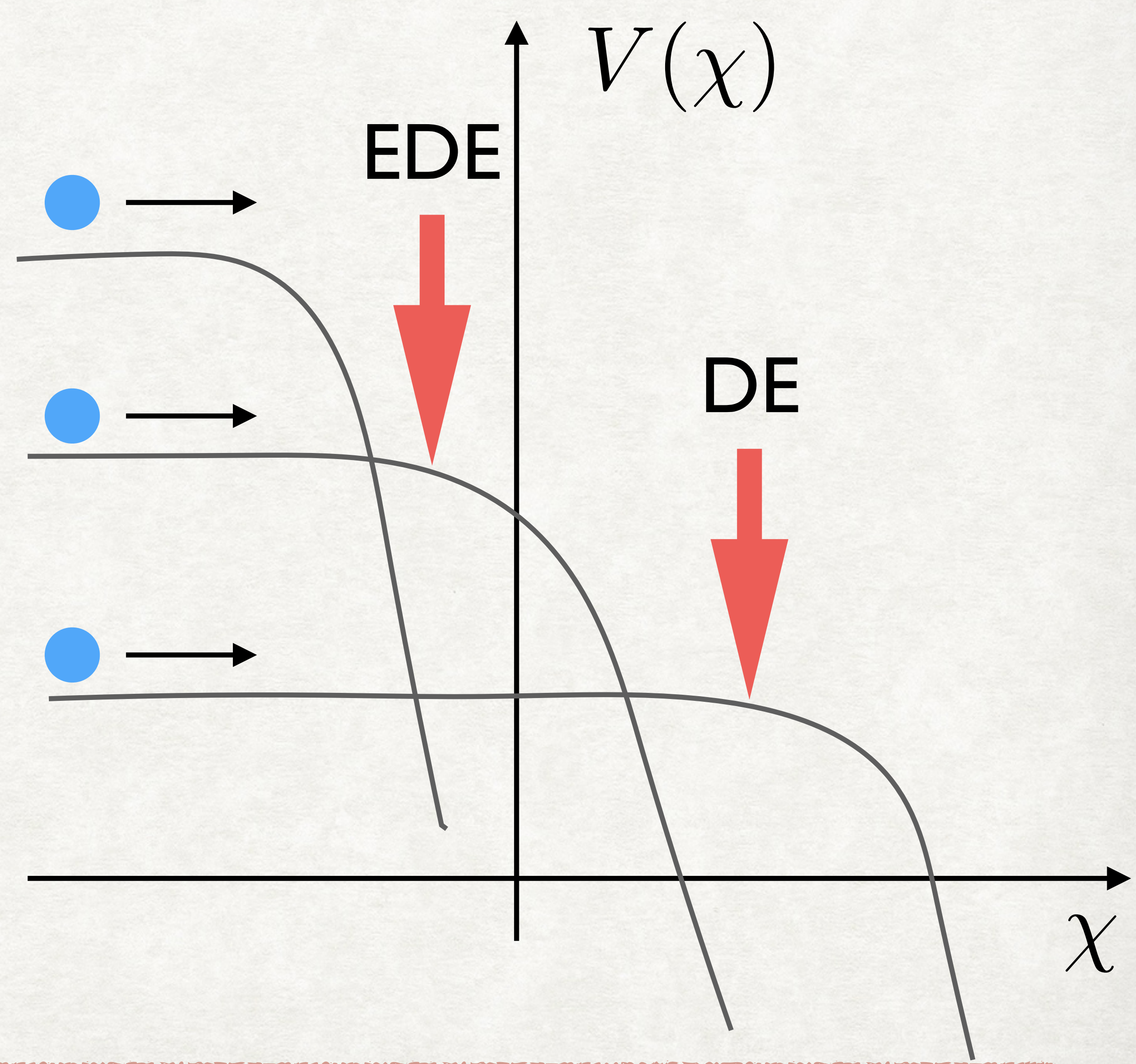

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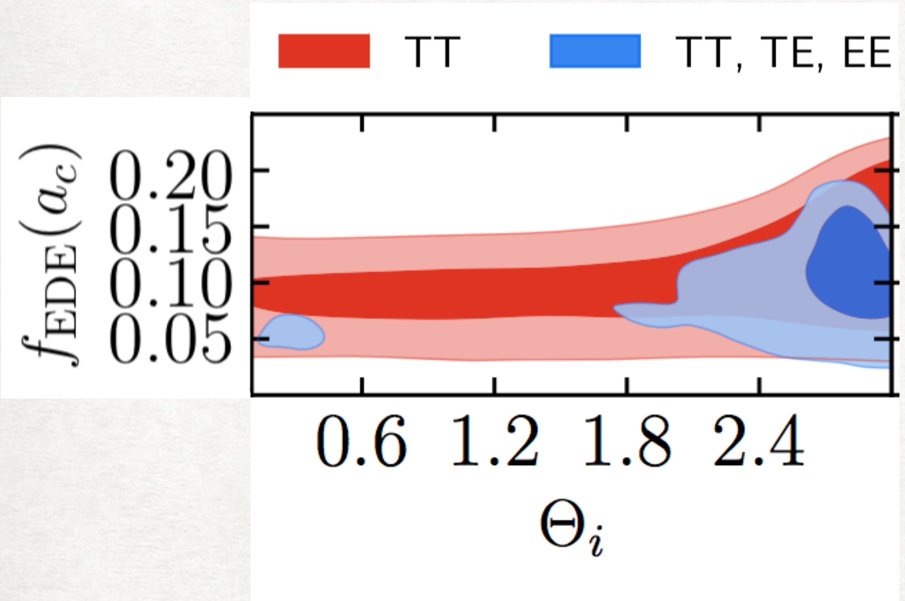
- If this is the "correct" resolution: there might be new ways of interpreting Λ and inflation.

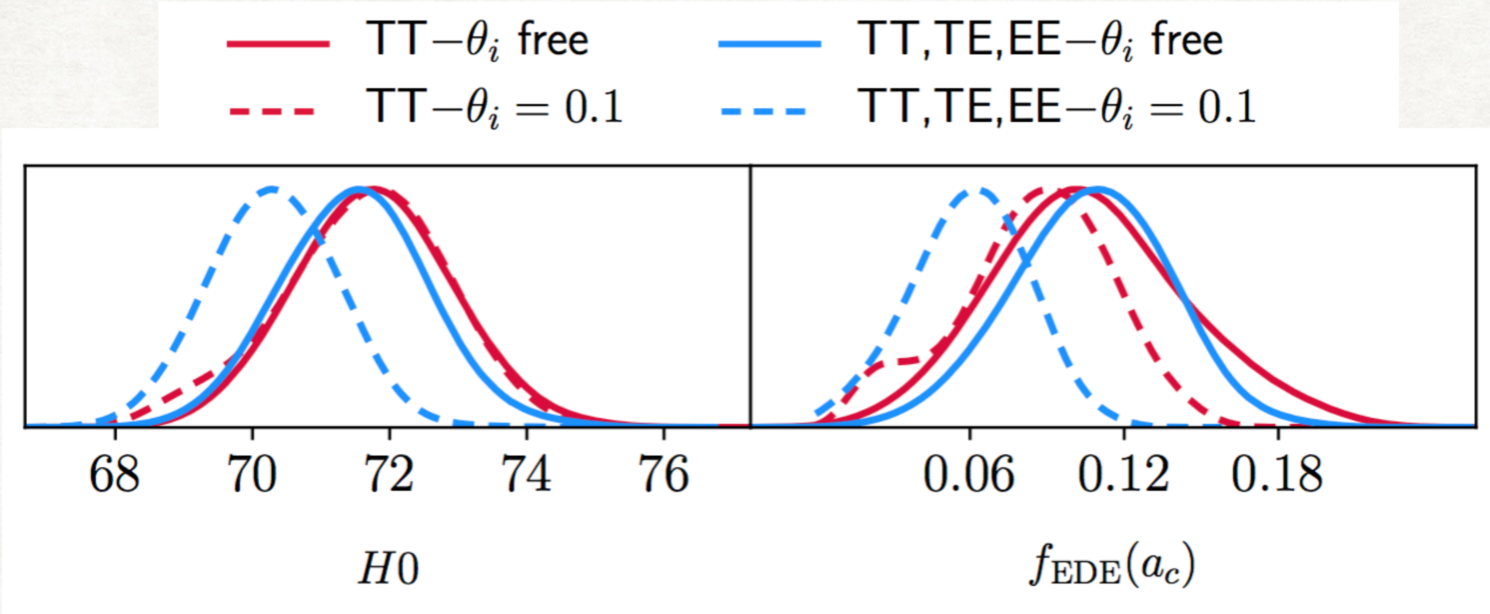
Back up

Preference for large Θ_i: first detection?

- Polarisation data favors large value of Θ_i (controls perturbations c_s^2)

see also Lin++1905.12618





Smith, VP, Amin, 1908.06995

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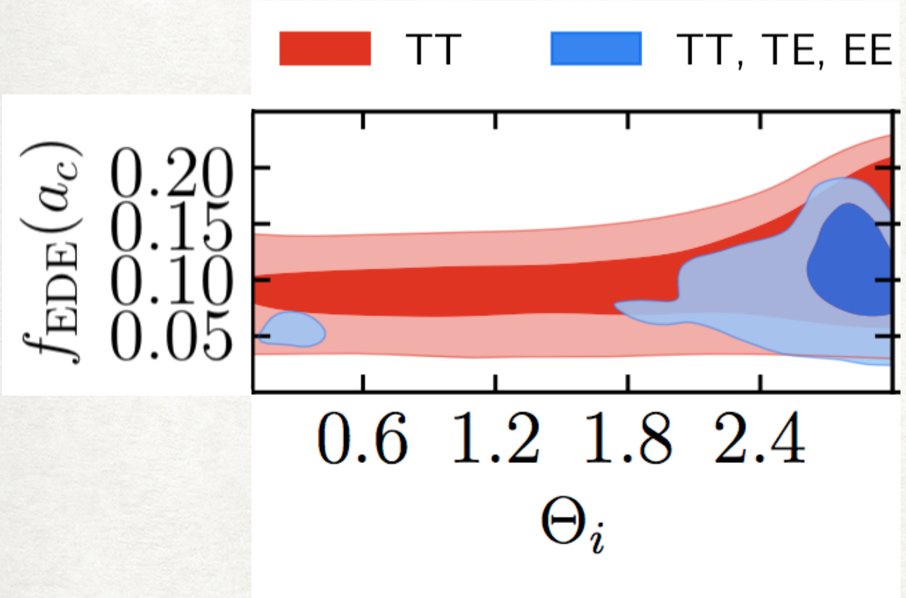
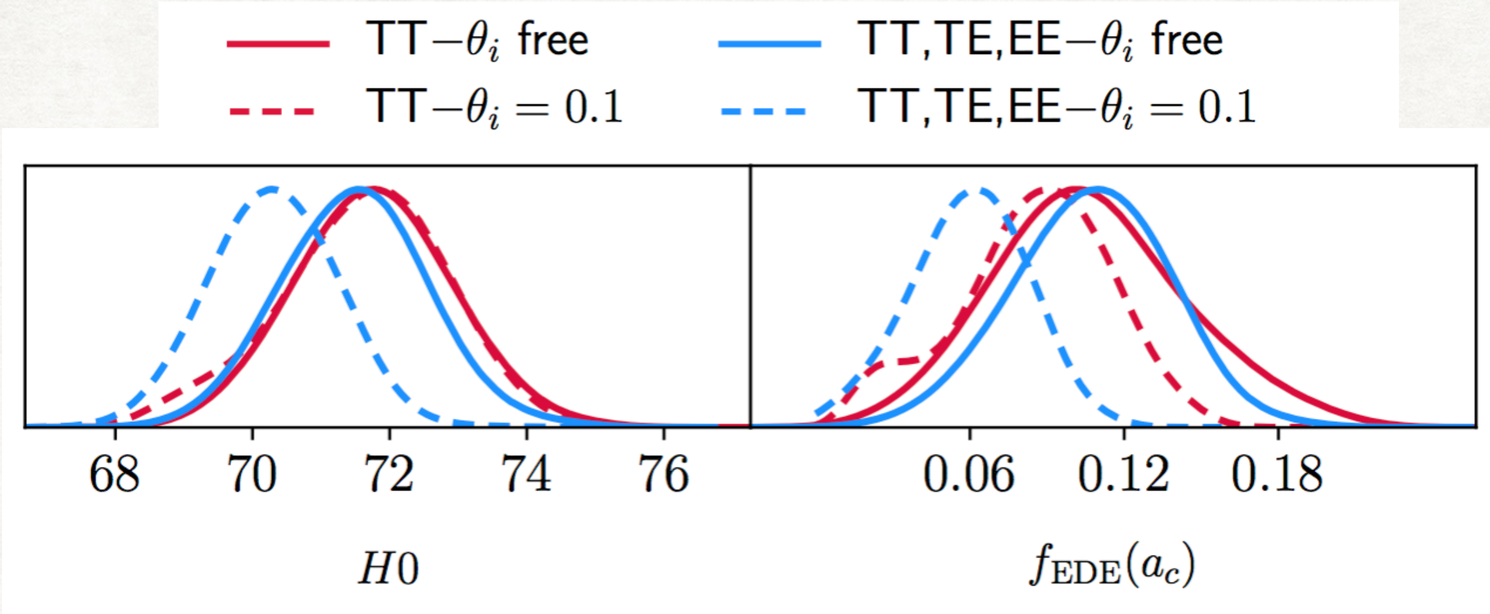
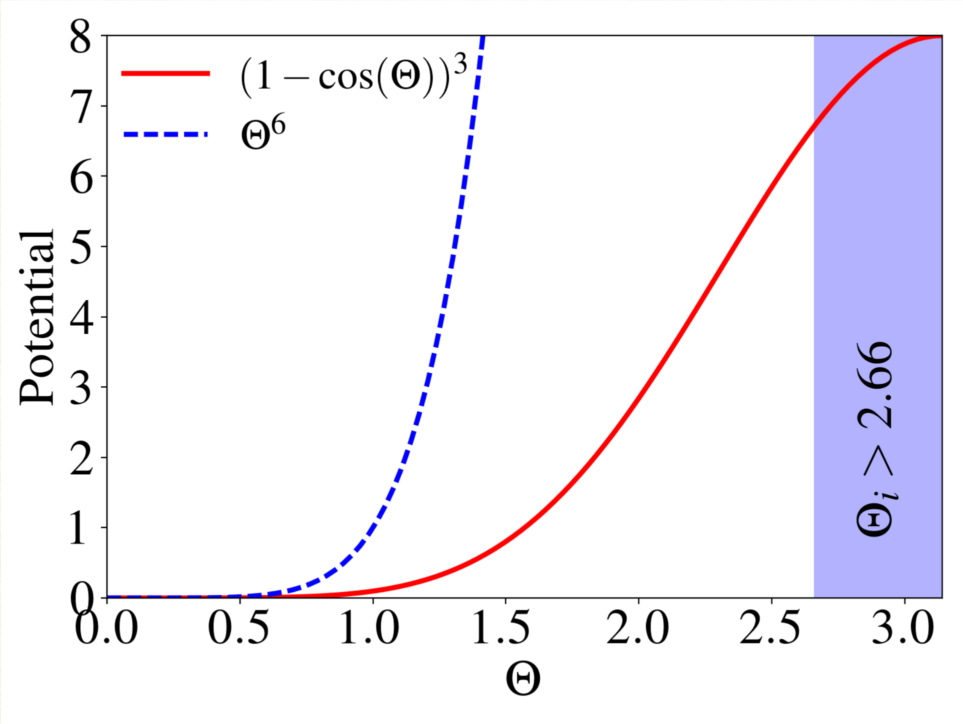




Smith, VP, Amin, 1908.06995



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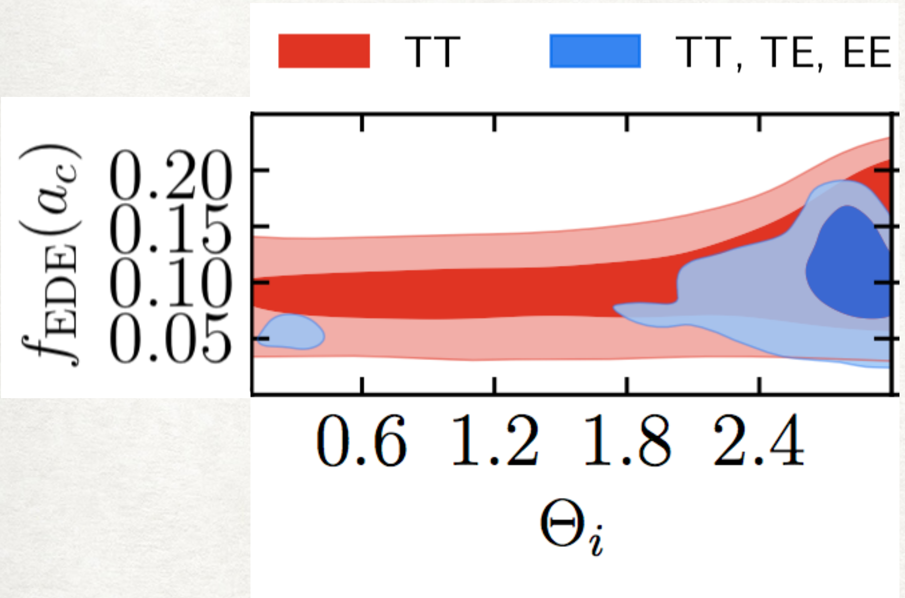

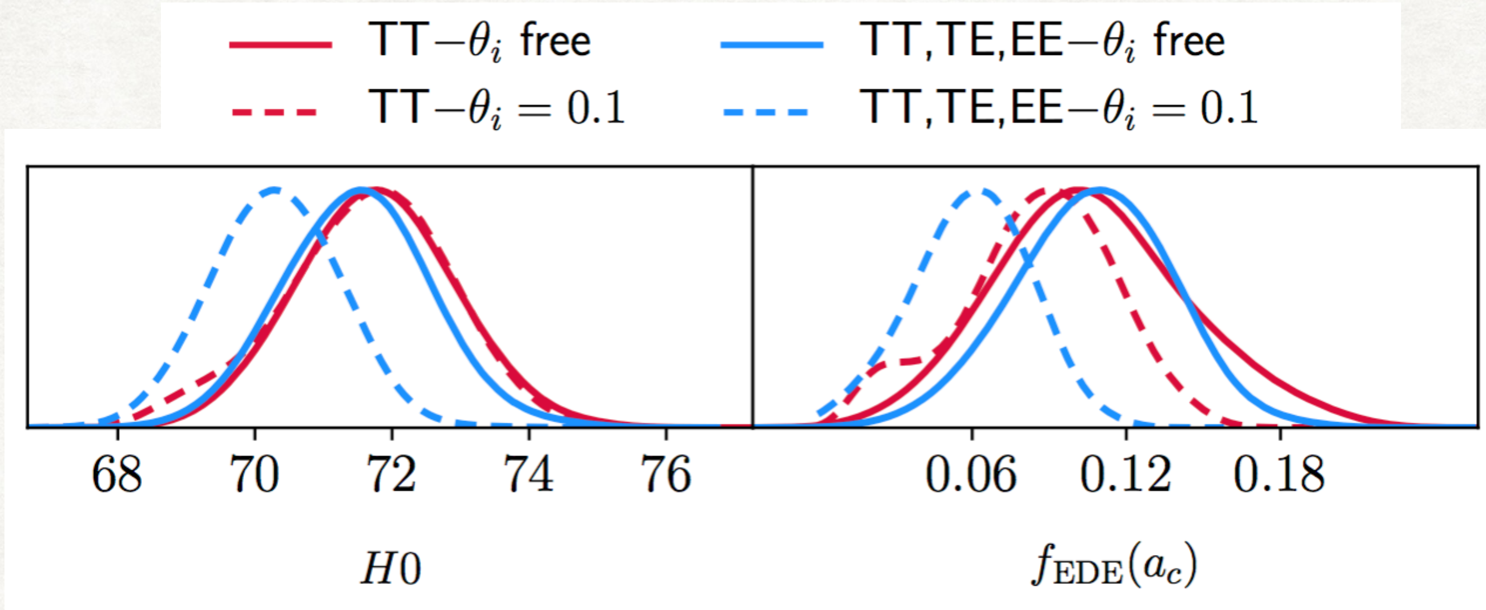

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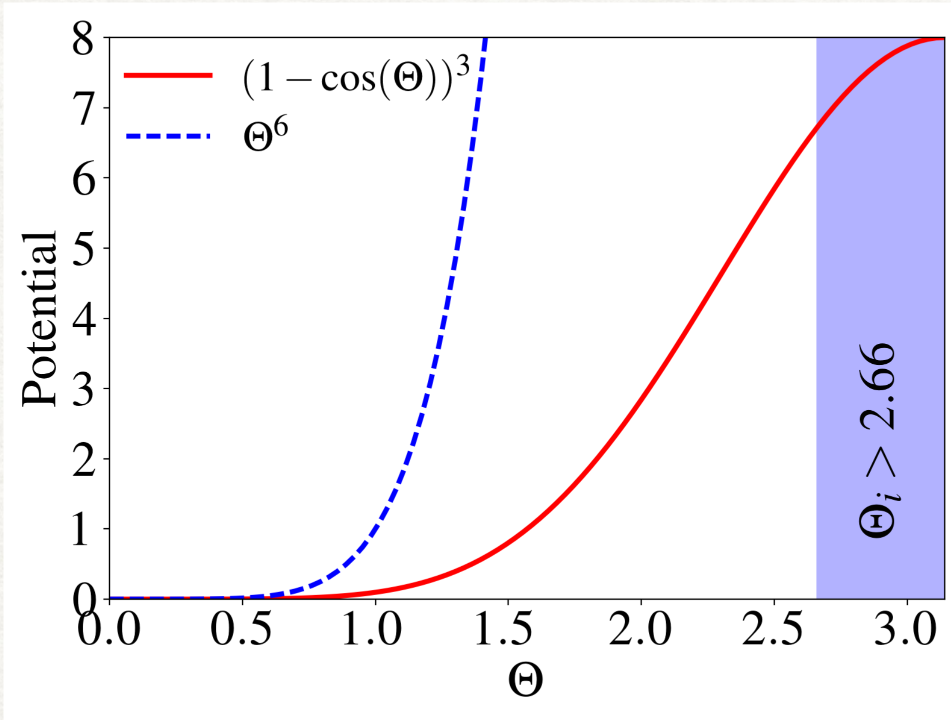

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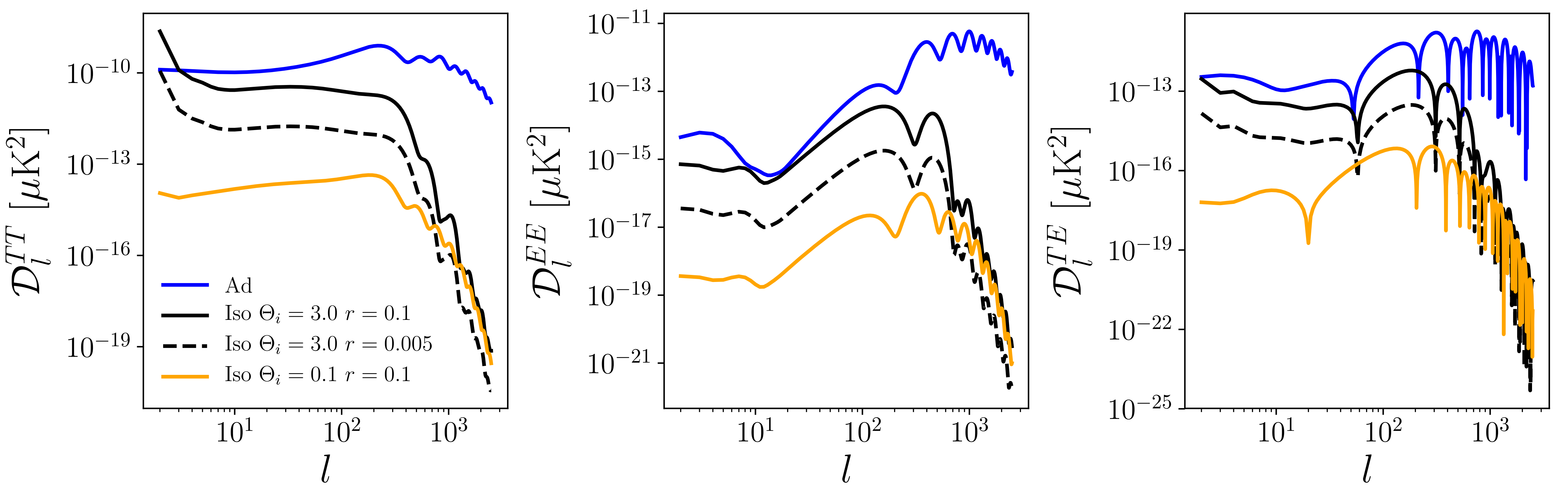
- Also confirms Agrawal++ 1904.01016: n=3 power-law potential do not solve the Hubble Tension.

Iso-curvature modes from the EDE

- If EDE field is present during inflation: iso-curvature perturbations are expected.
- The tensor-to-scalar ratio r also controls the amplitude of the iso-curvature power spectrum.

e.g. Hlozek, Marsch, Grin, MNRAS 476 (2018)



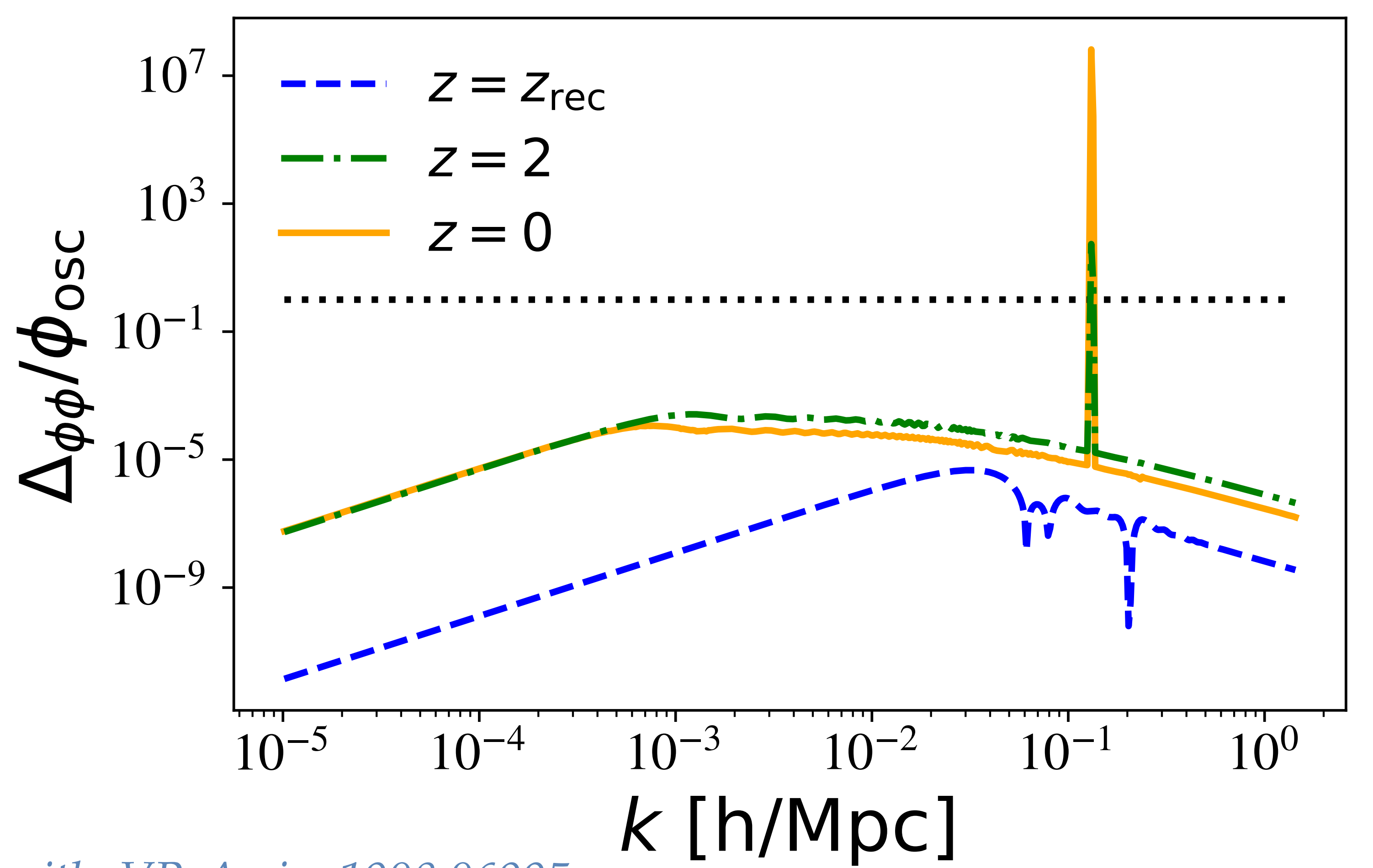
Smith, VP, Amin, 1908.06995

- Measurements of r will allow to constrain / confirm the EDE solution.

Non-linear structures from the EDE

- The linear Klein-Gordon equation exhibits parametric resonance: modes passing through the resonance band experiences growth, potentially becoming non-linear.
e.g. Amin++ 1410.3808

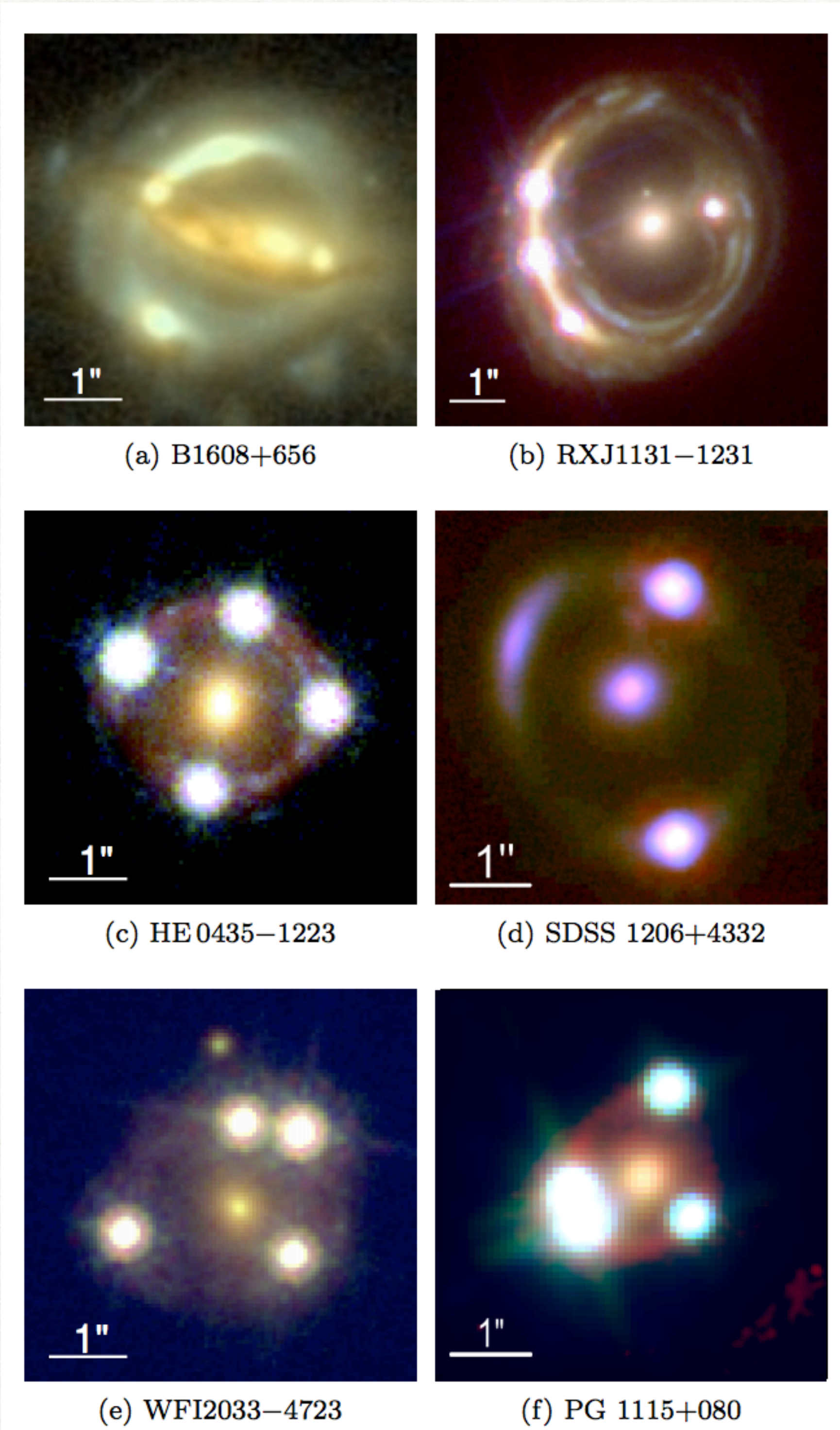
- Foquet analysis: EDE models with $n < 2.5$ become non linear, but only $n \simeq 2$ has $f(z_c) \gtrsim 1\ \%$ when non-linear.



Smith, VP, Amin, 1908.06995

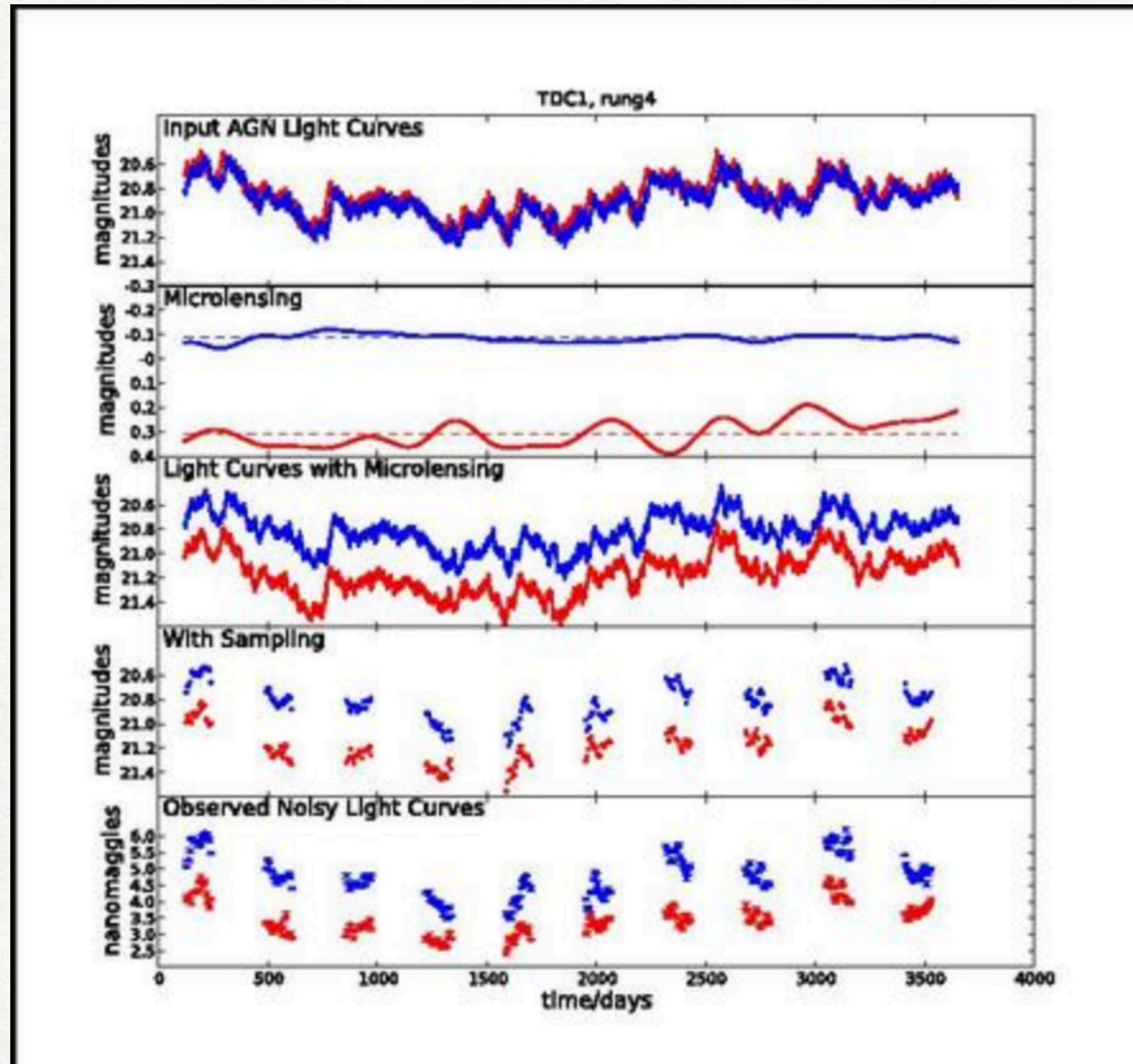
- This could lead to the formation of bound structures to look for!

H0LiCOW: QSOs gravitational time delay

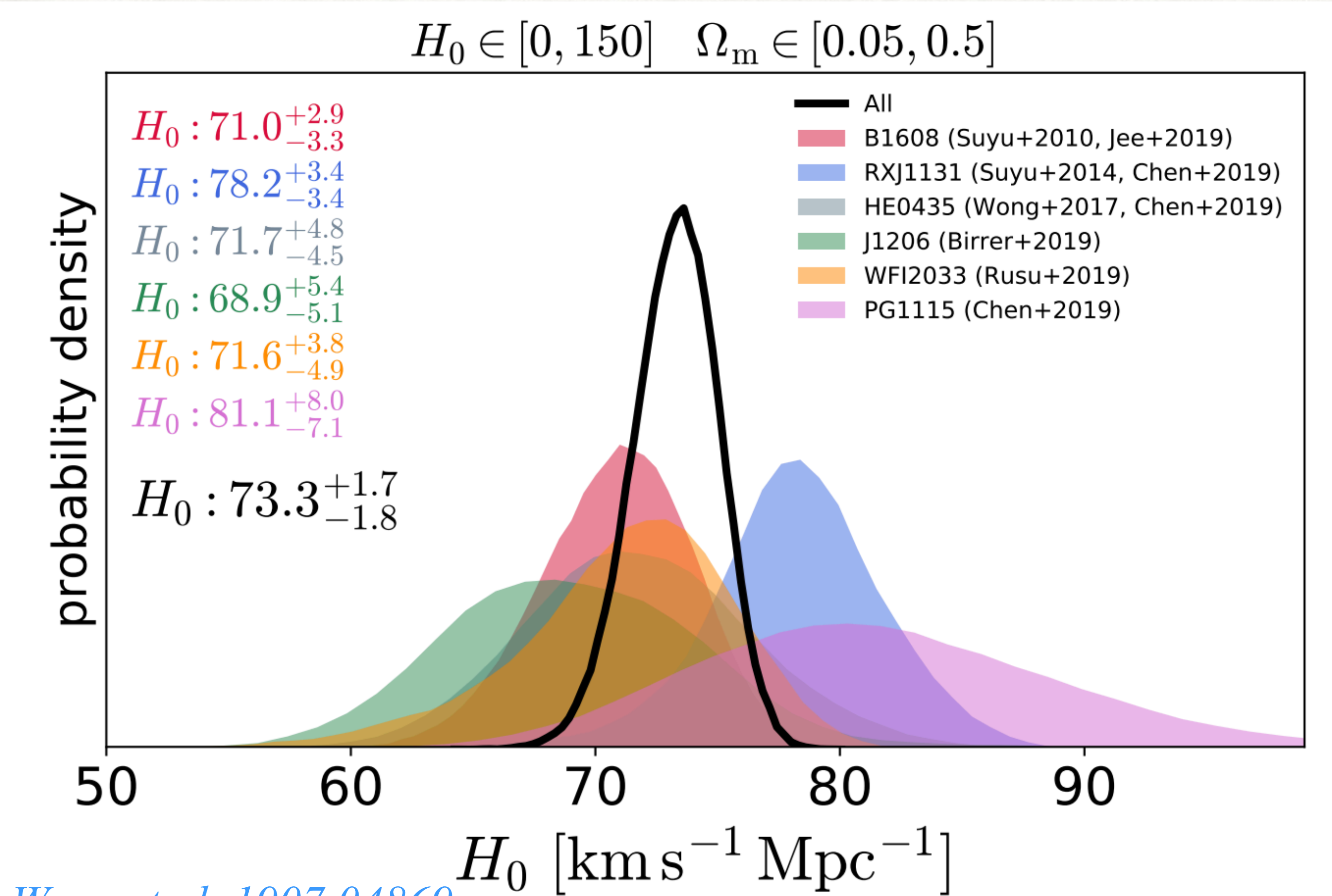


Wong et al. 1907.04869

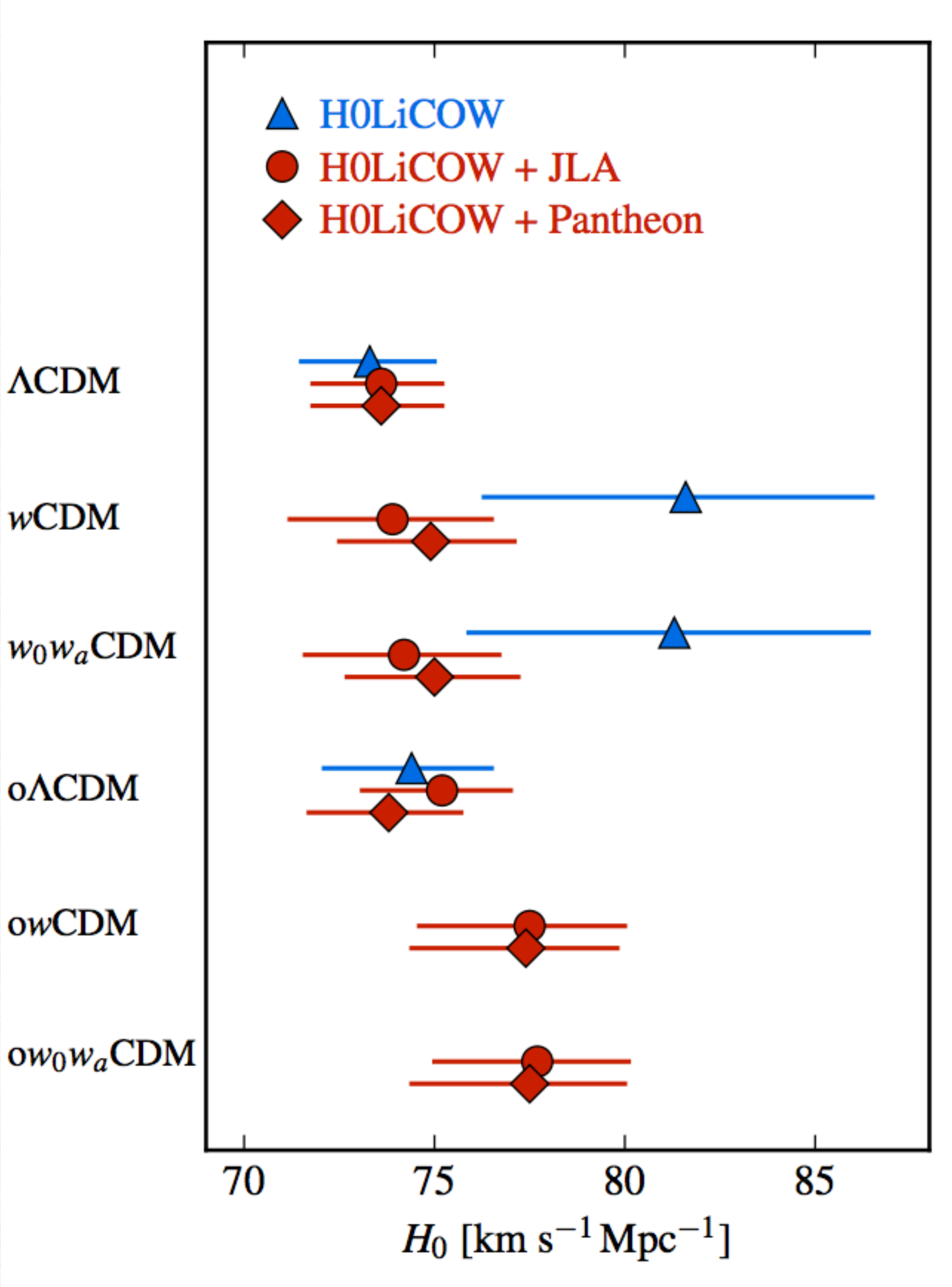
$$D_{\Delta t} \equiv (1 + z_{\rm d}) \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}}$$



HOLiCOW: H_0 measurement to few %



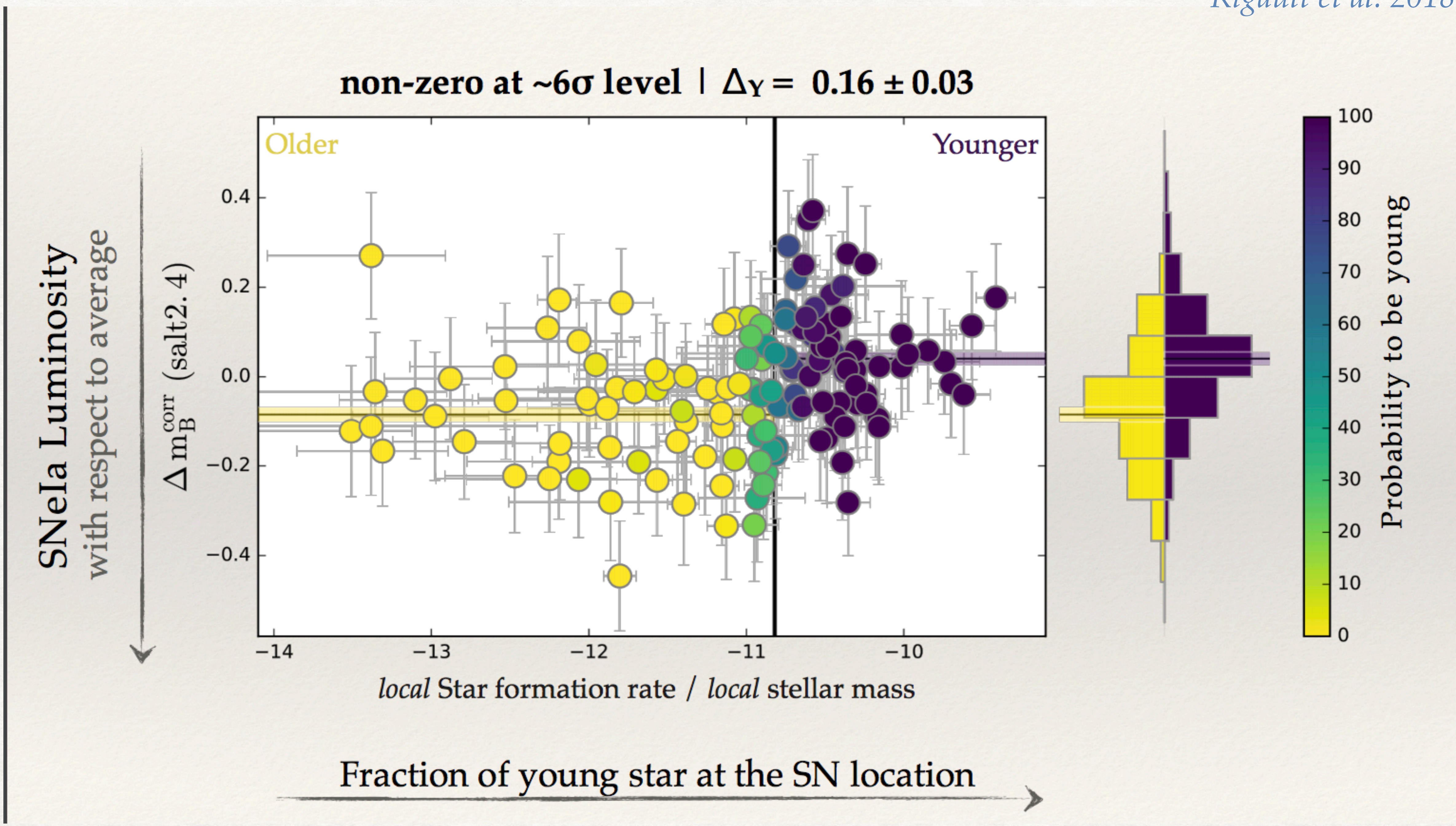
Wong et al. 1907.04869



- 6 QSOs: 3.1σ tension with *Planck* within ΛCDM
- Blind analysis.
- Confirmed by DES. *1910.06306*
- Will (must) now receive much more attention to check systematic errors.
- e.g. are error bars under-estimated? *Kochanek 1911.05083*

The progenitor bias

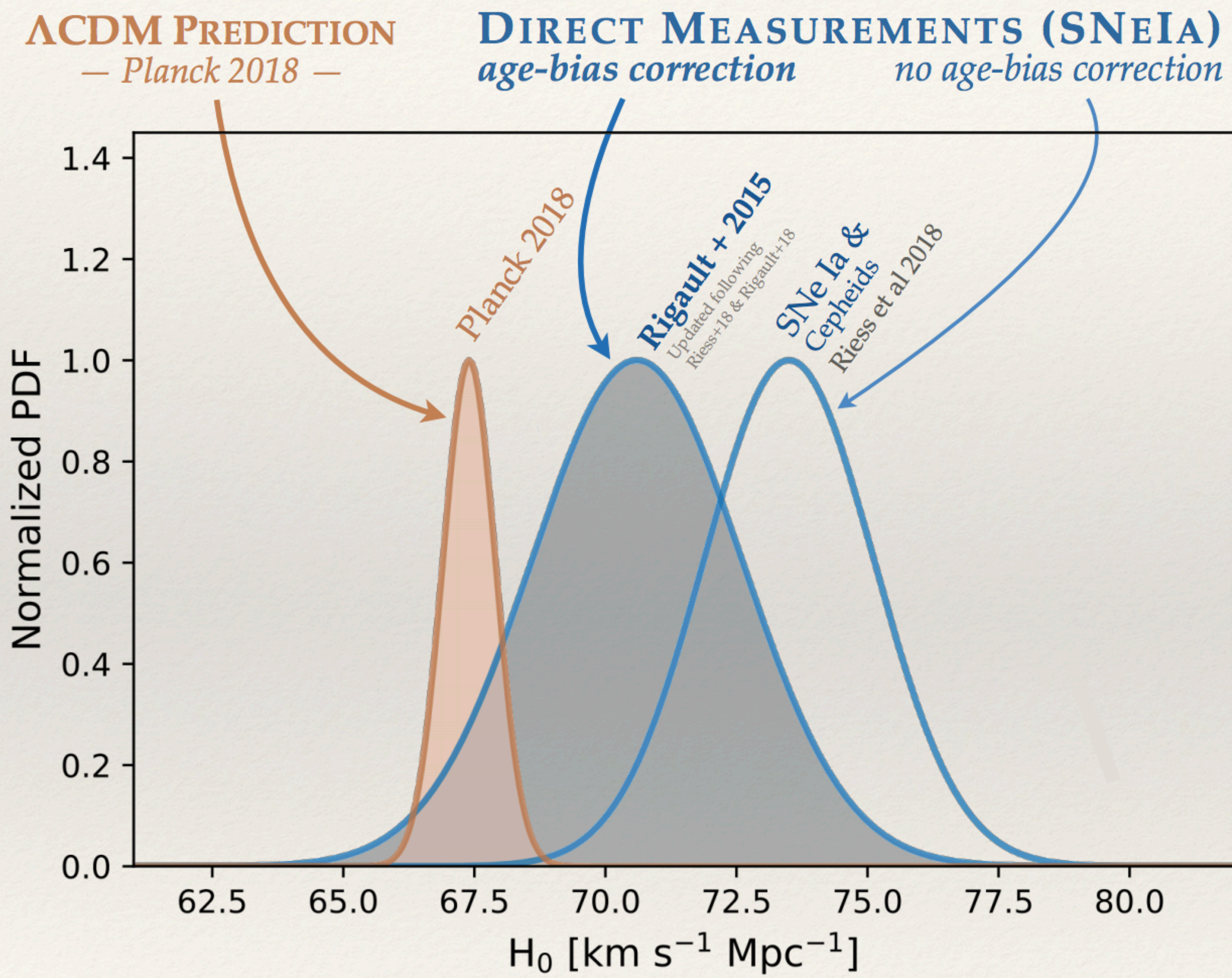
Rigault et al. 2018



Slide by M. Rigault, IAP 2018

Could it be a pure systematic?

Rigault et al. 2015, 2018



Astrophysical bias on H_0
Up to 3% if :

1. Different fraction of prompt
~90% in Cepheid-SN
vs. ~50% in Hubble flow-SN

2. Magnitude difference between prompts and delayed SNeIa
age step ~0.15 mag

To be confirmed using Riess's SNeIa

Slide by M. Rigault, IAP 2018

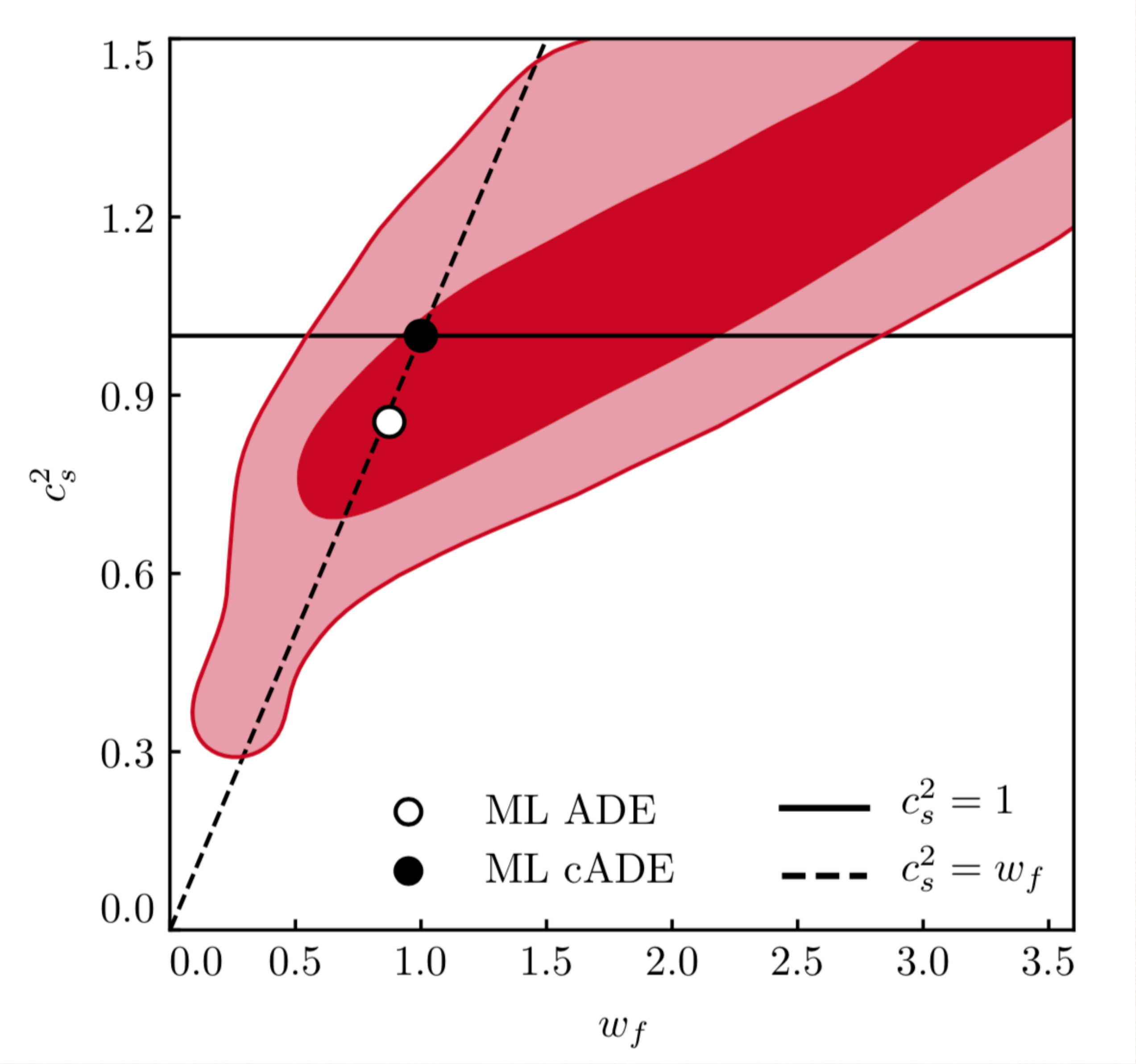
CMB data can constrain c_s^2

- In Lin, Beneveto, Hu, Raveri 1905.12618

$$P(X,\phi) = \left(\frac{X}{A}\right)^{\frac{1-c_s^2}{2c_s^2}} X - V(\phi),$$

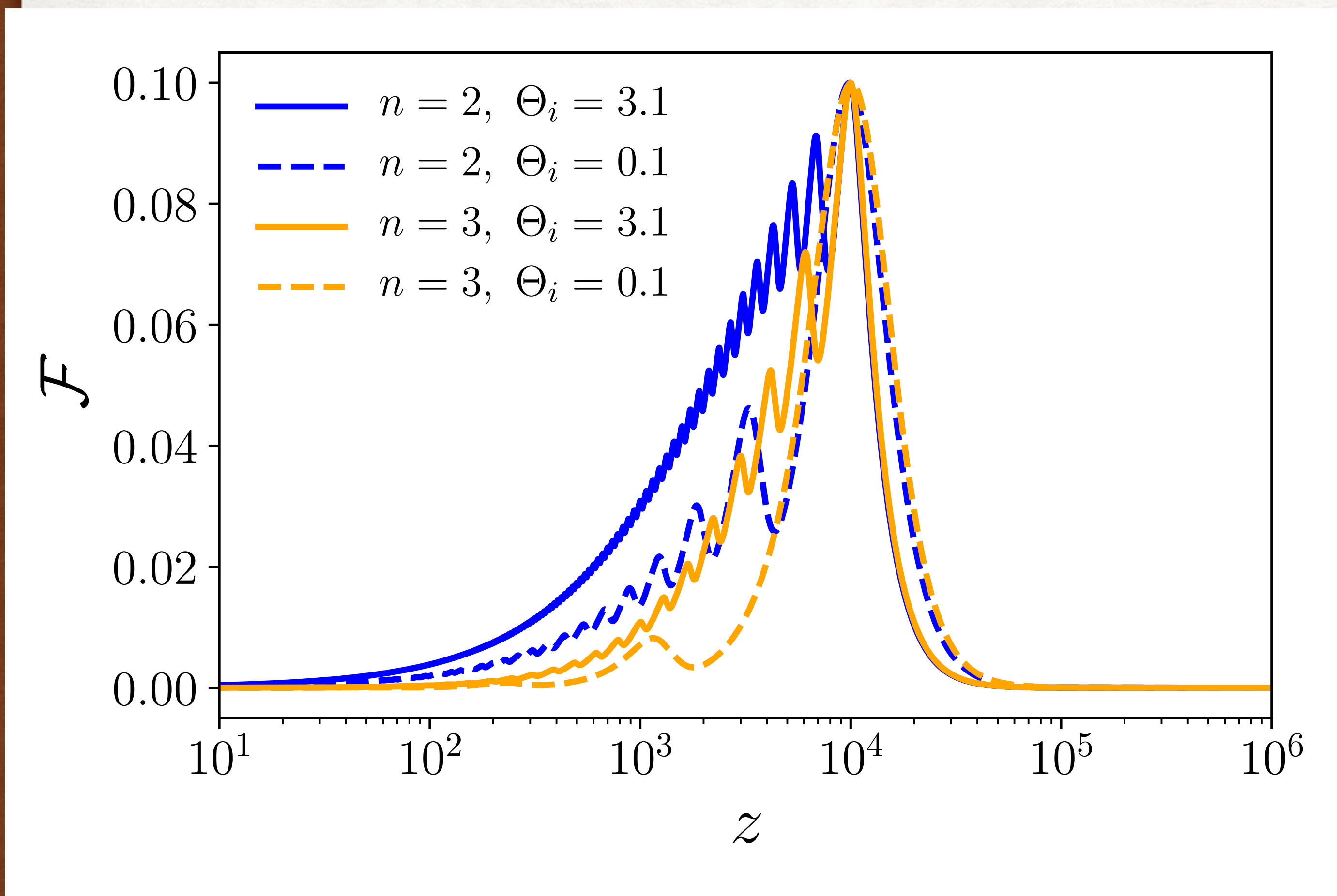
$$V(\phi) = \begin{cases} A\,\phi^m, & \phi > 0\,, \\ 0, & \phi \le 0\,. \end{cases}$$

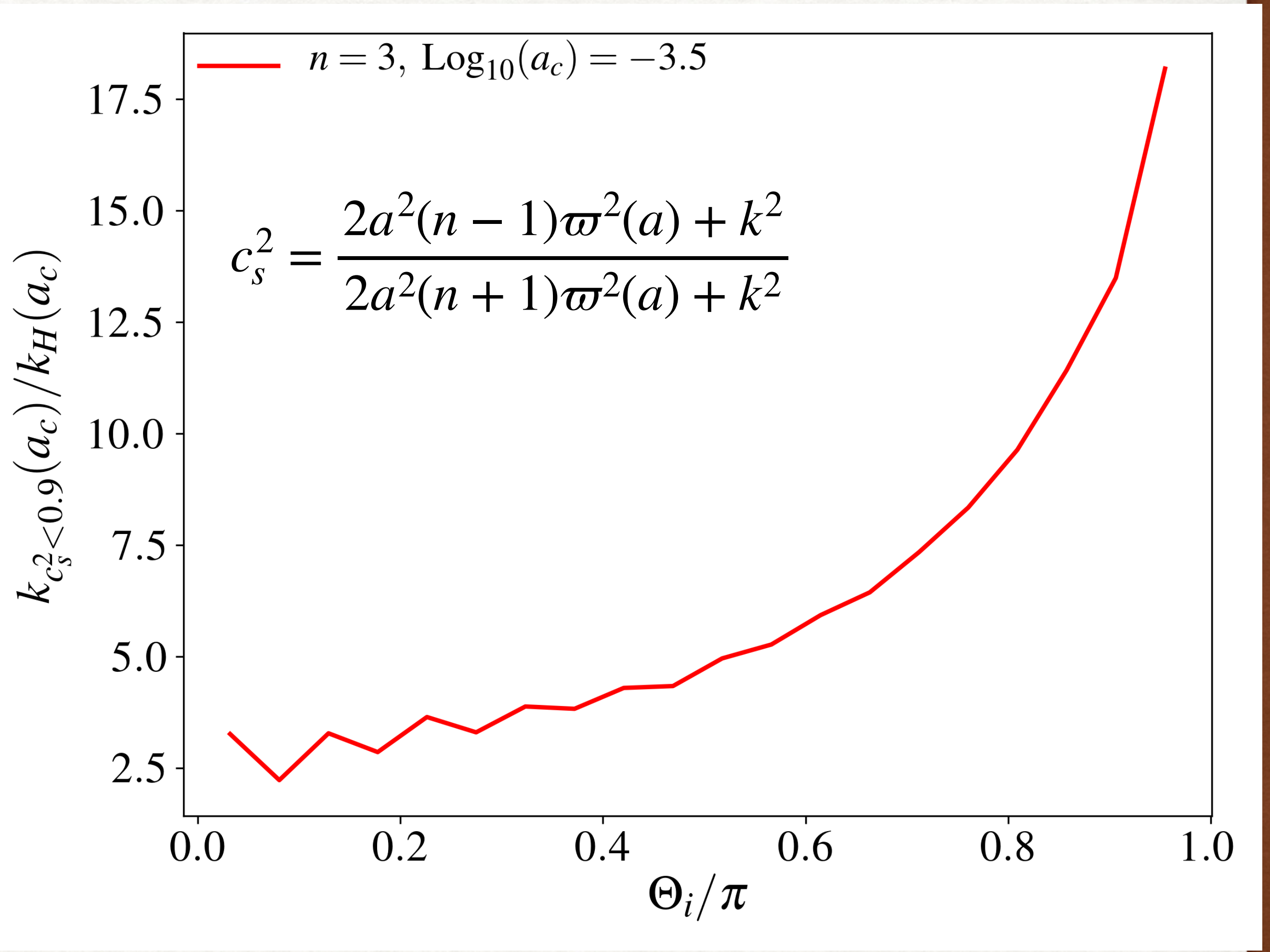
- for $w < 1$, CMB data constrains $c_s^2 < 1$ at 2σ



Impact of Θ_i on EDE dynamics

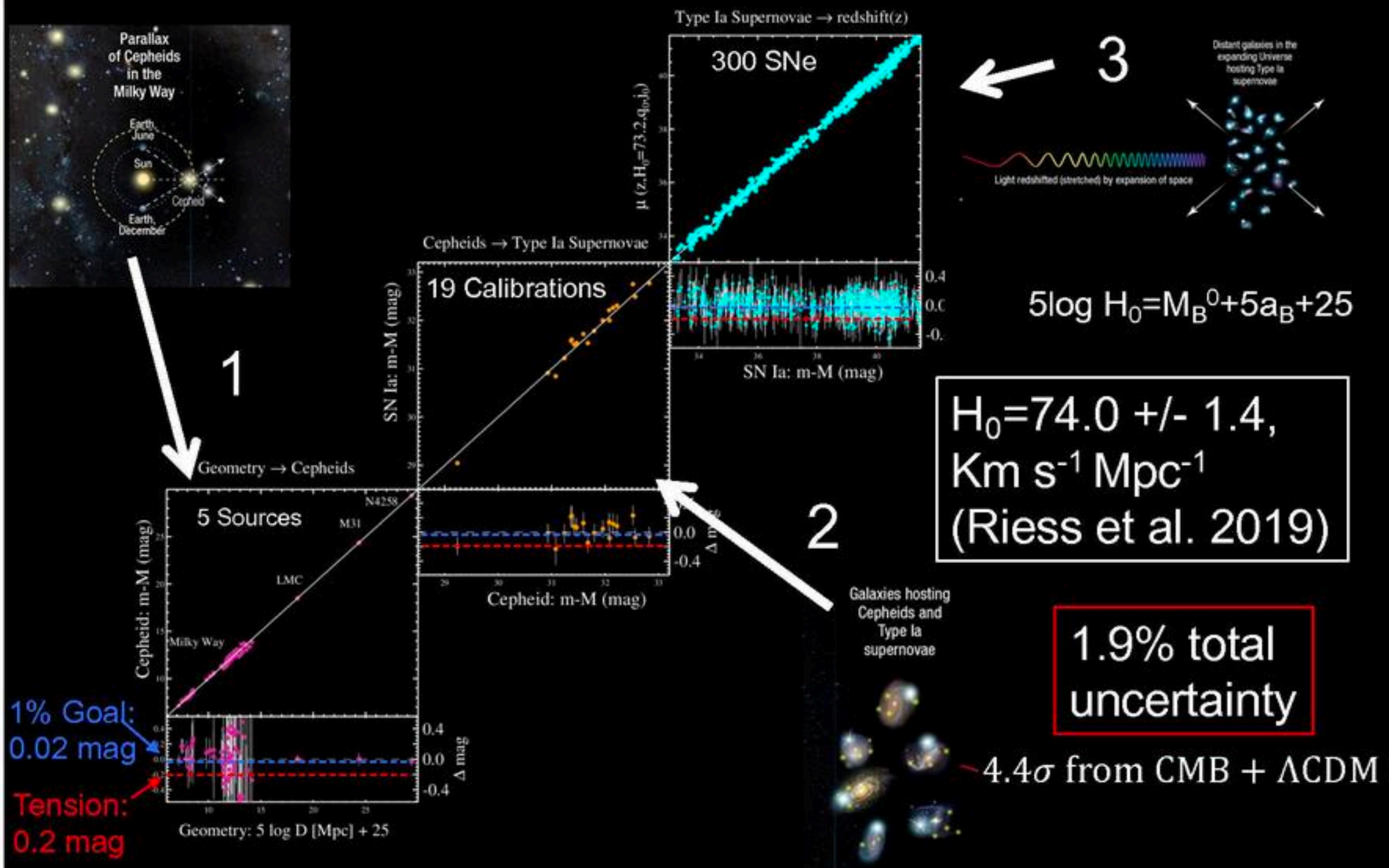
- Θ_i affects the oscillation frequency $\varpi(a)$ and asymmetry of the energy injection as well as the range of modes having $c_s^2 < 1$





- For the oscillating Dark Energy, a larger range of mode satisfies this constraint as Θ_i increases.

The Hubble Constant in 3 Steps: Present Data



Slide by A. Riess, KITP July 2019

Systematics? 23 Analysis Variants—we propagate variation to error

Analysis Variants	H_0
Best Fit (R16, w/ HST,Gaia , R18=73.53)	74.03
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.89
Reddening Law: Bulge-like (N15)	74.40
No Cepheid Outlier Rejection (normally 2%)	74.32
No Correction for Cepheid Extinction	75.72
No Truncation for Incomplete Period Range	75.08
Metallicity Gradient: None (normally fit)	74.51
Period-Luminosity: Single Slope	74.34
Period-Luminosity: Restrict to P>10 days	74.24
Period-Luminosity: Restrict to P<60 days	74.60
Supernovae z>0.01 (normally z>0.023)	74.16
Supernova Fitter: MLCS (normally SALT)	75.91
Supernova Hosts: Spiral (usually all types)	74.14
Supernova Hosts: Locally Star Forming	74.32

See Rigault et al. 2015, 2018 for evidence of a progenitor bias

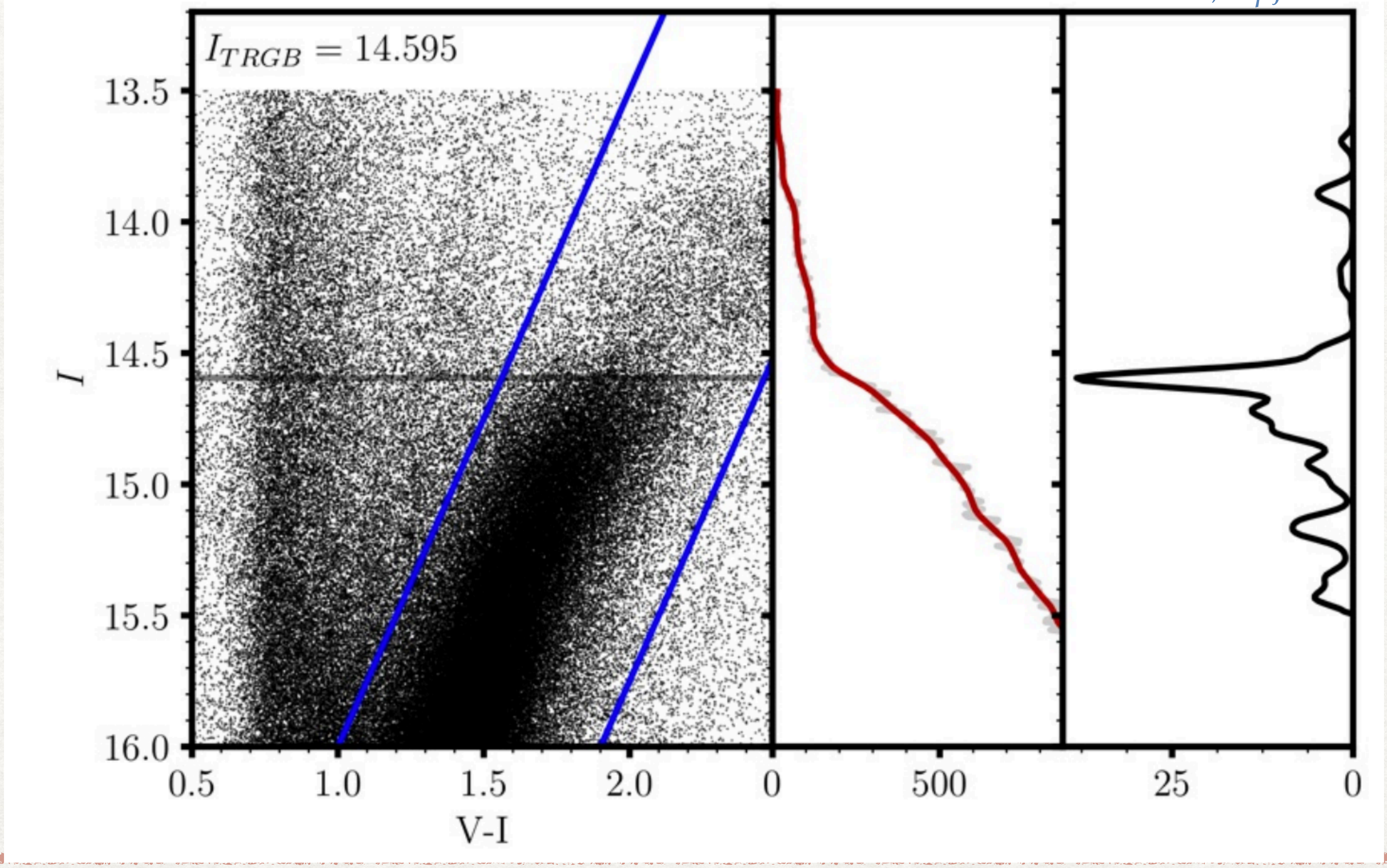
Could a difference in SN calibrator & Hubble flow sample selection change H_0? No, (Jones et al. 2018) and talks by Scolnic, Jones

Slide by A. Riess, KITP July 2019

Chicago-Carnegie Hubble Program

- 1) Measure the absolute distance to LMC (parallax, detached eclipsed binaries)
- 2) Measure the ‘tip’ luminosity of the red giant branch in the LMC
- 3) Use this to measure distance to SN1a host galaxies.

Freedman et al., ApJ 2019



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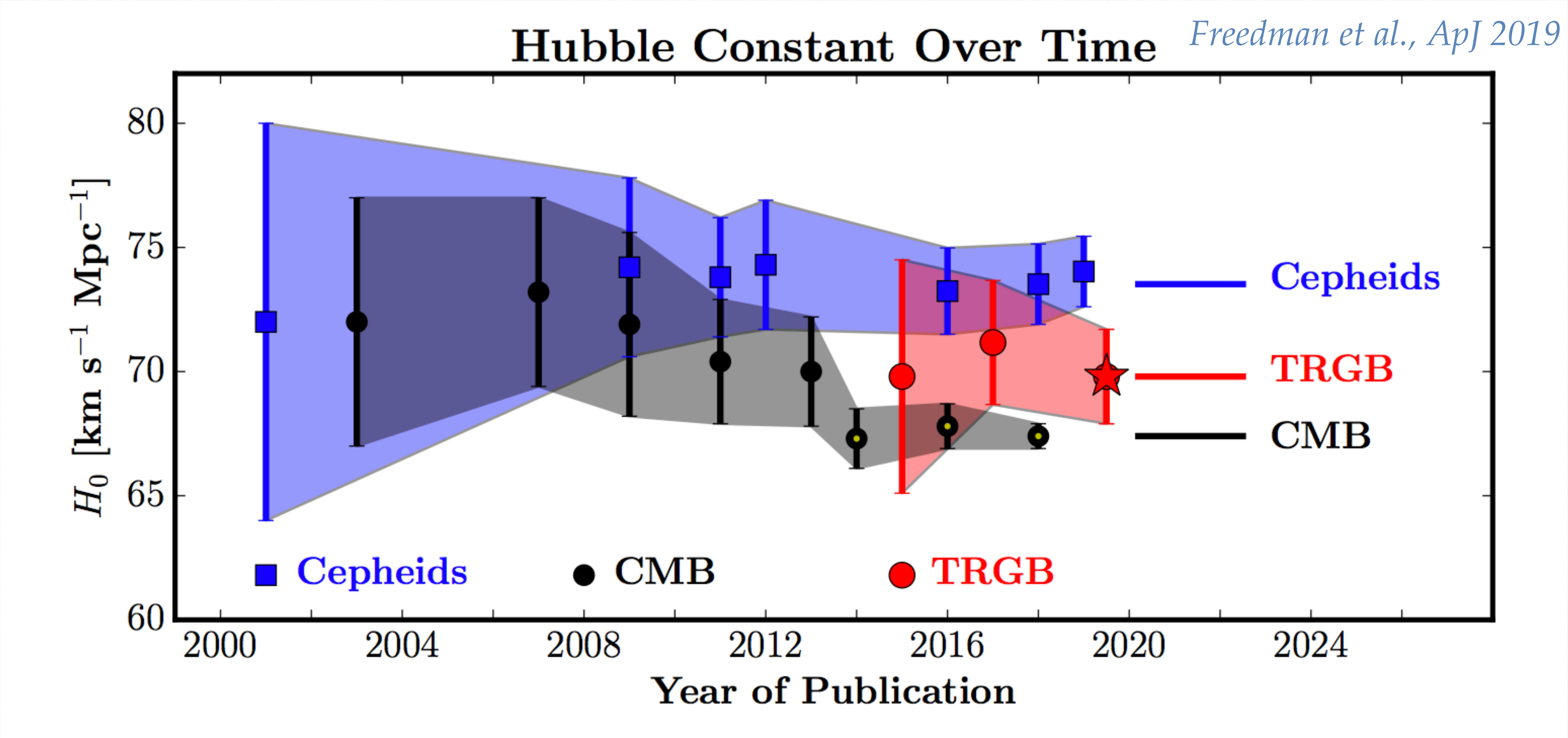
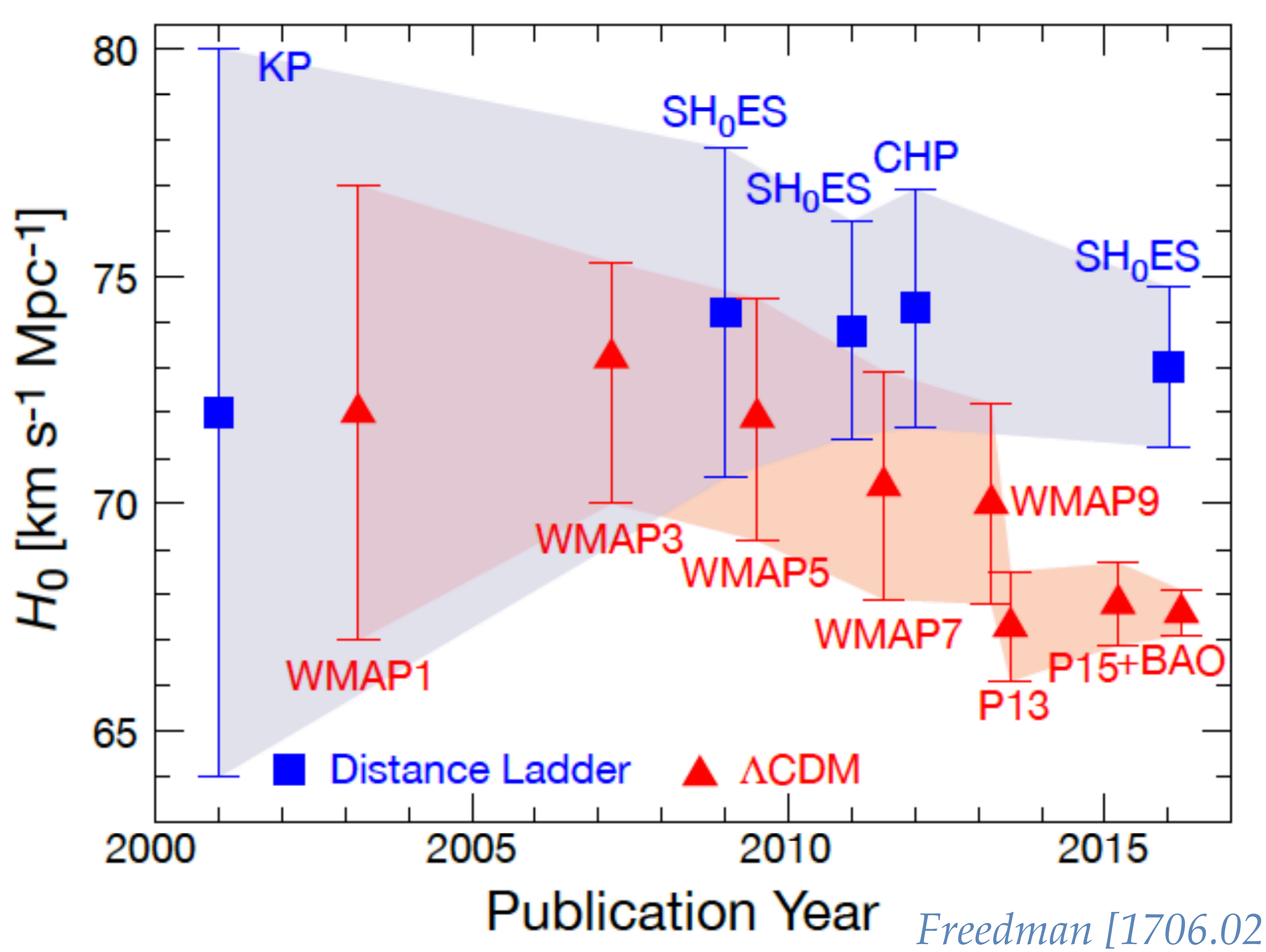


- Independent sets of SN1a and different calibration method: in agreement with *Planck*?

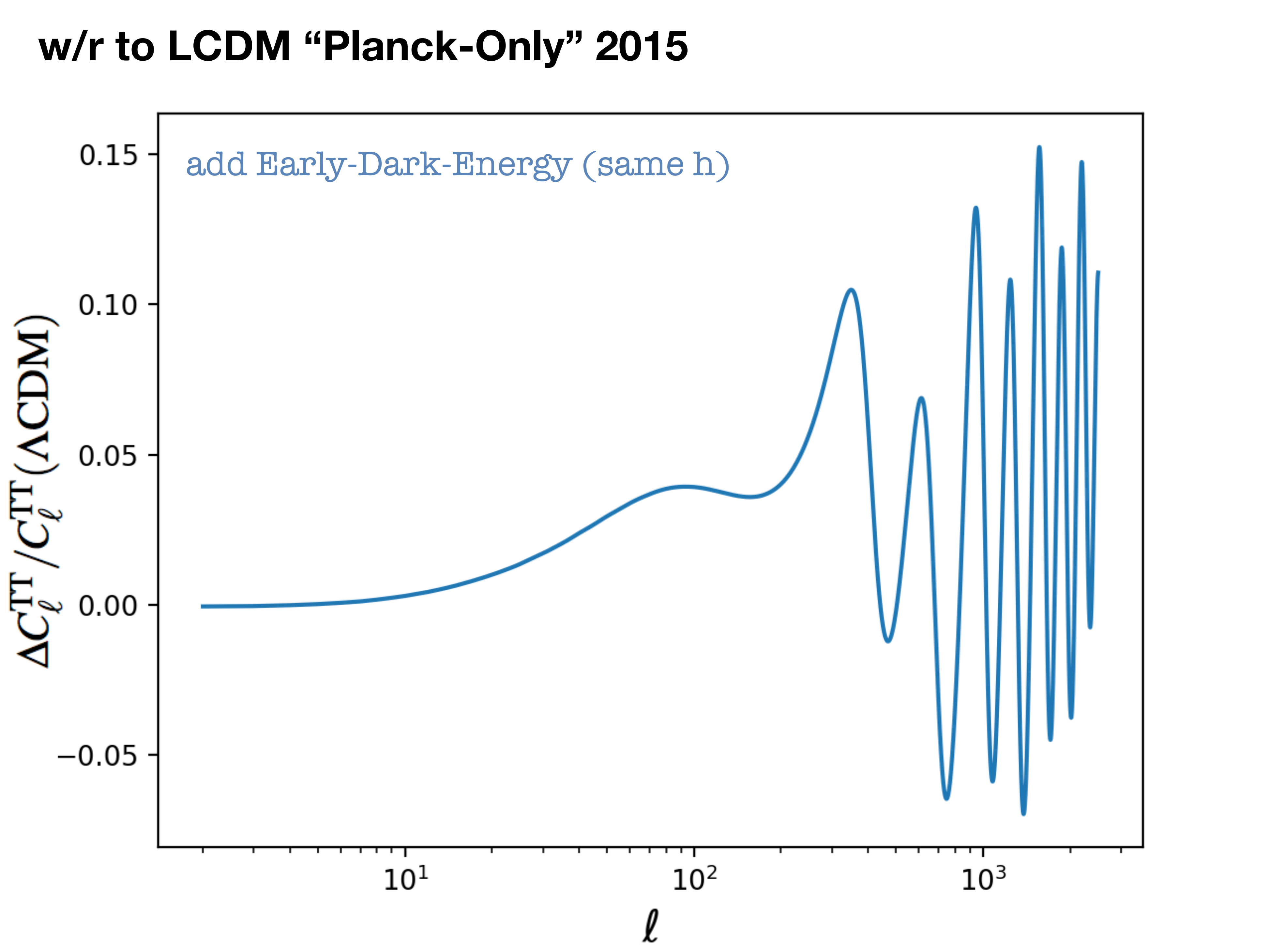
“Devil’s advocate”

- If true H0 is 74 km/s/Mpc: one expects strong bias towards low H0 from CMB data, as precision at high multipole increases.



Freedman [1706.02739]

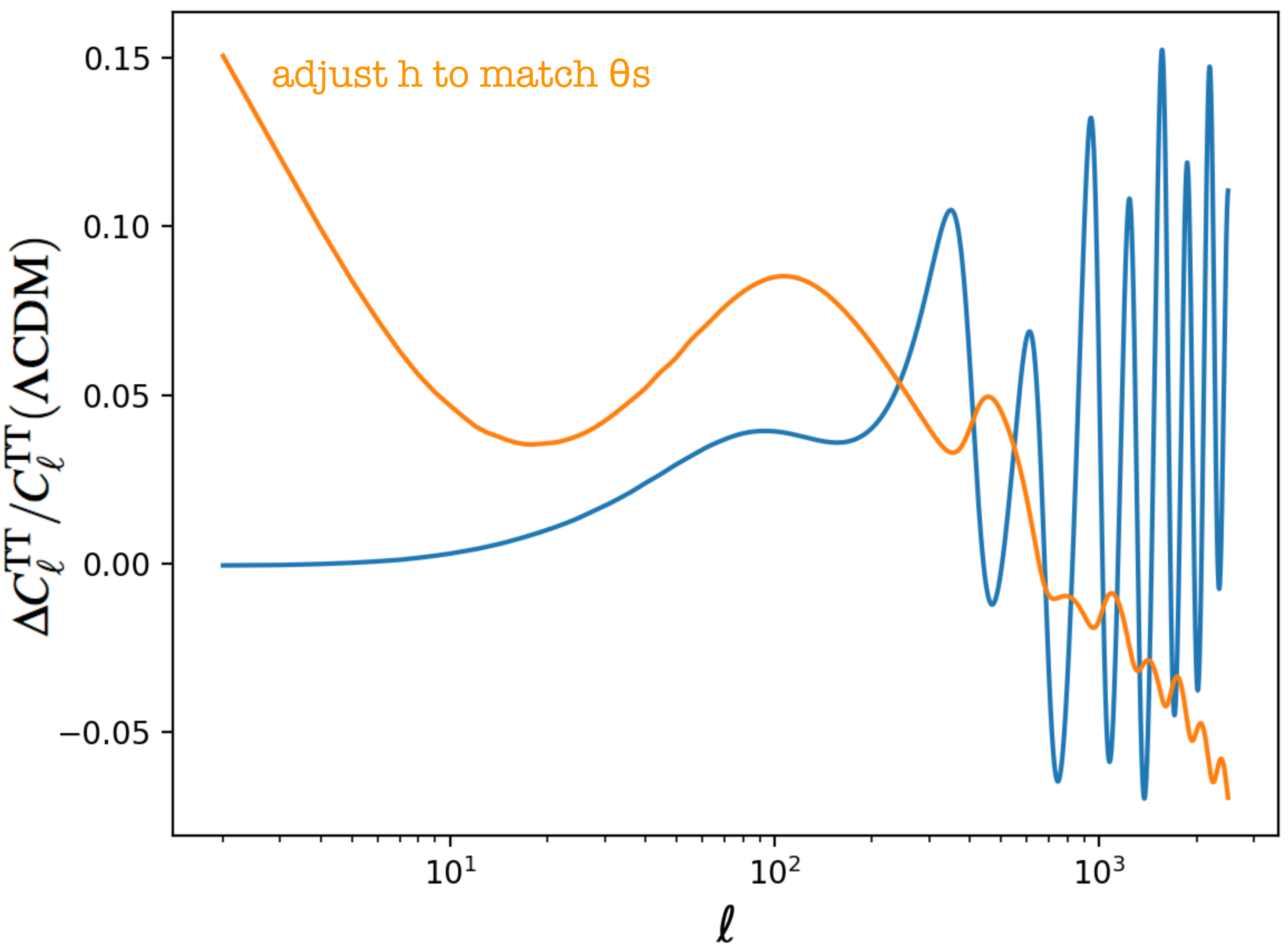
- Did that already happened when going from WMAP to Planck?



w/r to LCDM "Planck-Only" 2015
add Early-Dark-Energy (same h)
$\Delta C_\ell^{TT}/C_\ell^{TT}(\Lambda CDM)$
0.15
0.10
0.05
0.00
−0.05
10^1
10^2
10^3
ℓ

Towards the best-fit cosmology step-by-step

w/r to LCDM "Planck-Only" 2015



Towards the best-fit cosmology step-by-step

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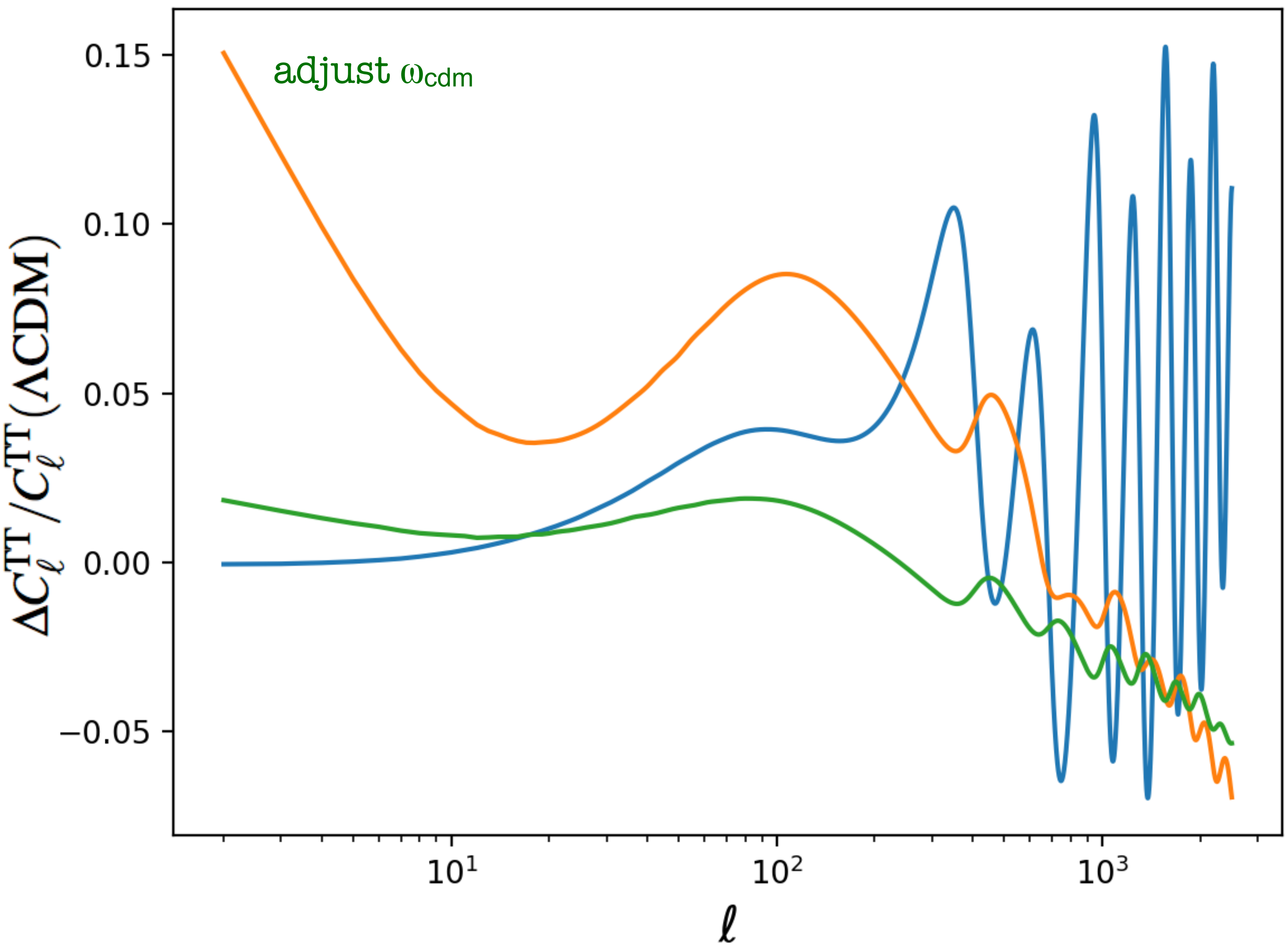

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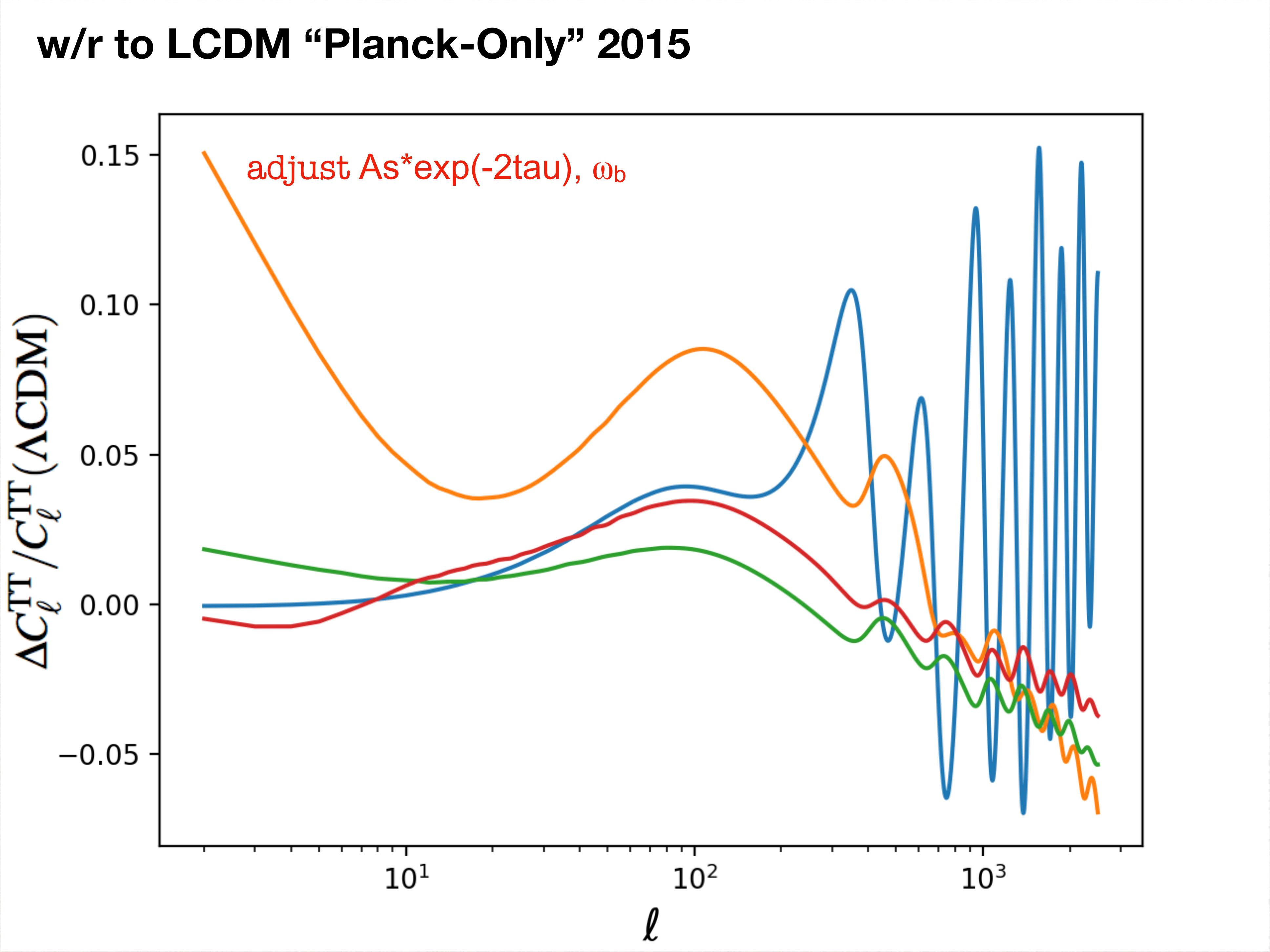

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