On The "Hubble Tension" And How To Resolve It

Vivian Poulin

LUPM (France) and Johns Hopkins University

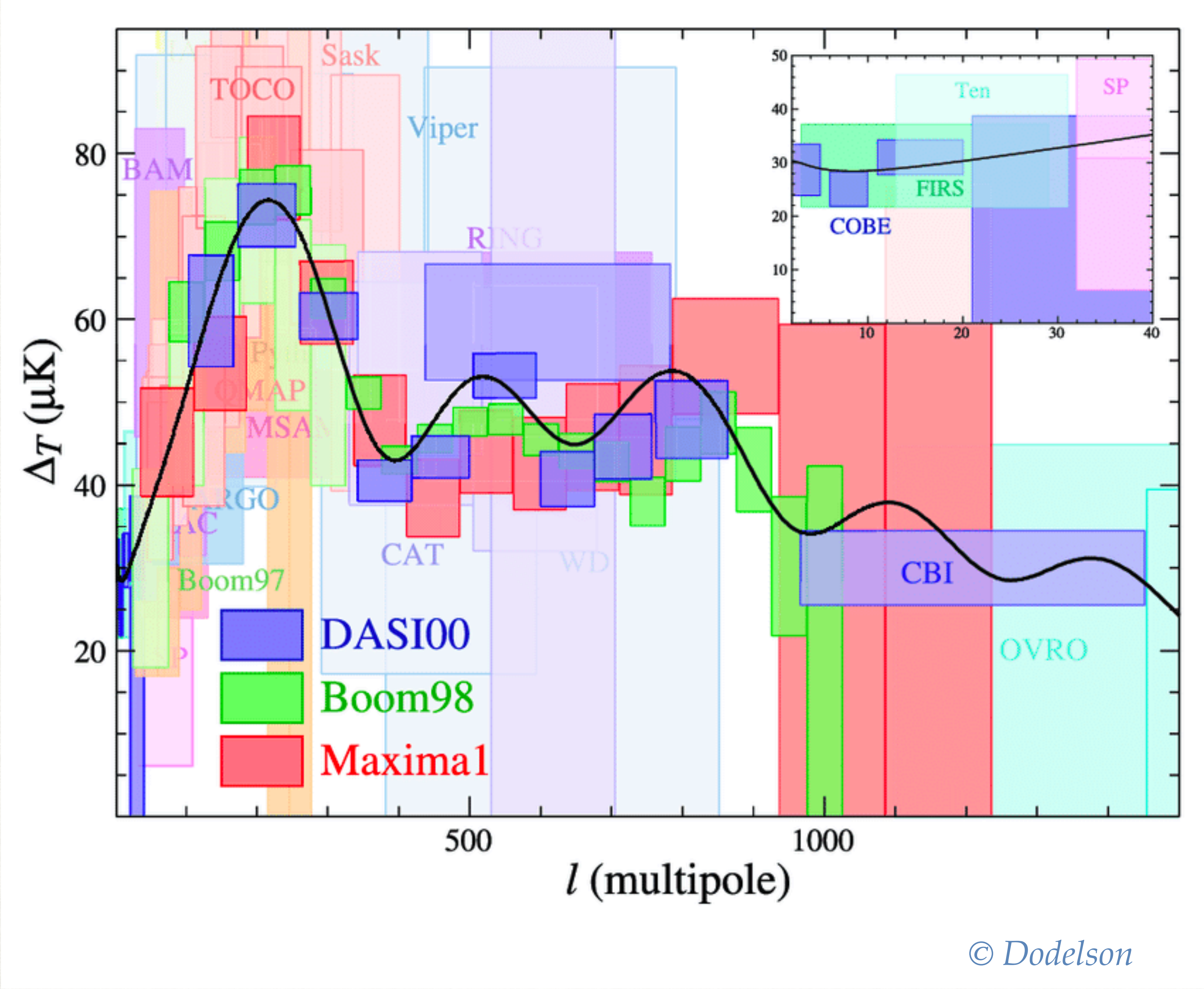
w/ T. Smith, T. Karwal and M. Kamionkowski 1811.04083

+ D. Grin 1806.10608

Stony Brook
24 January 2019

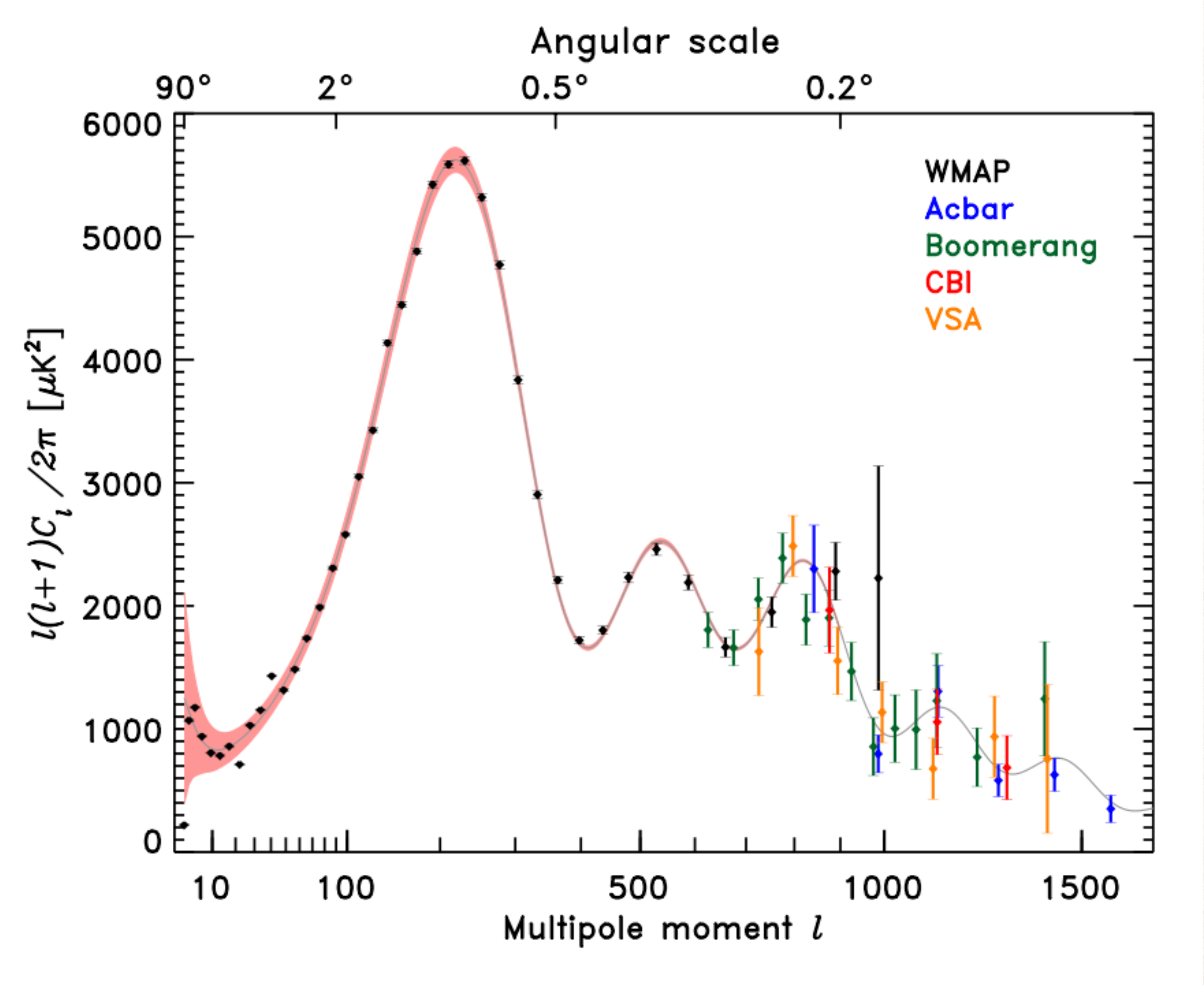
The Era of Precision Cosmology

20 years ago



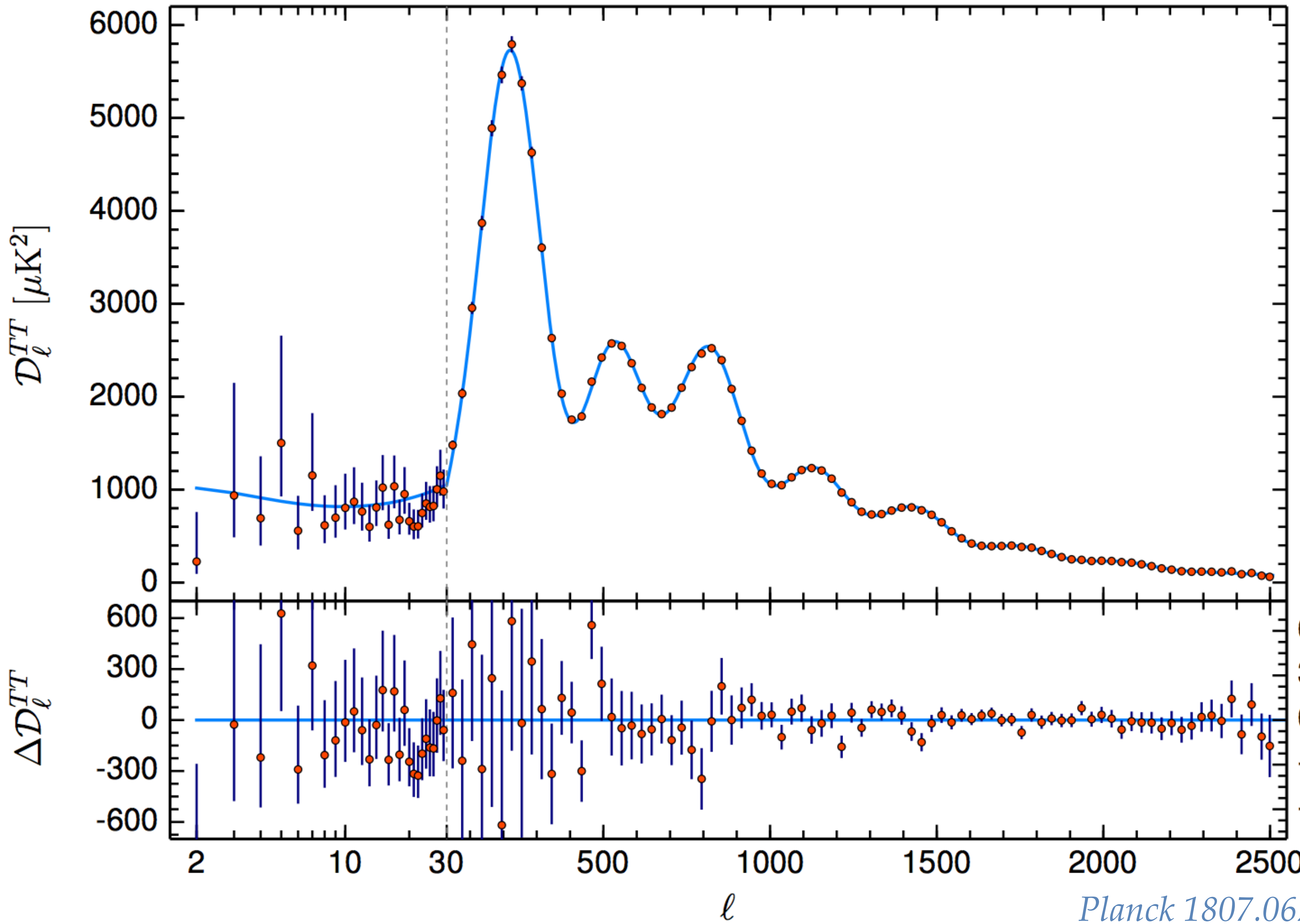
The Era of Precision Cosmology

10 years ago



The Era of Precision Cosmology

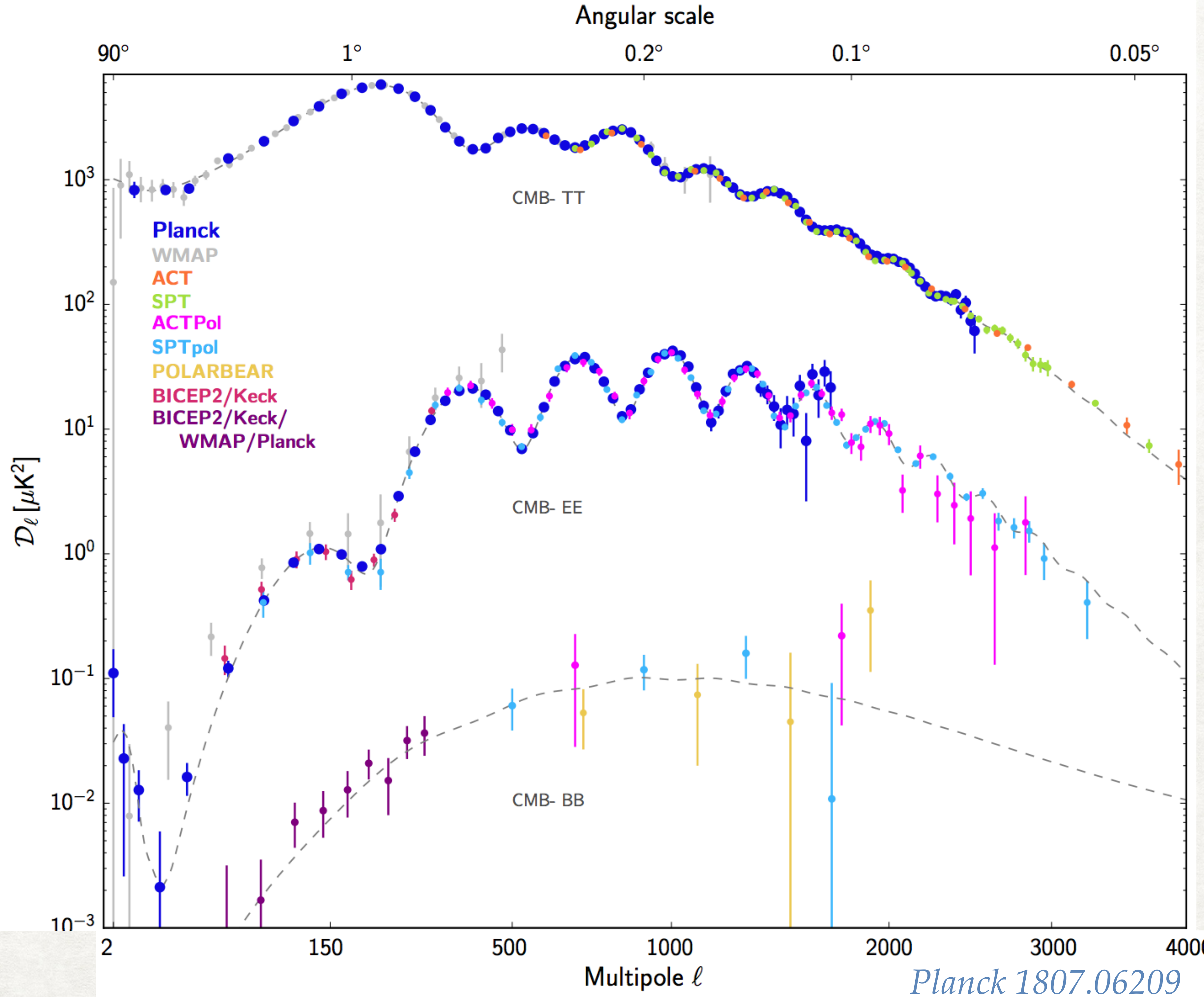
Today



Planck 1807.06209

The Era of Precision Cosmology

Very good agreement between all CMB data!



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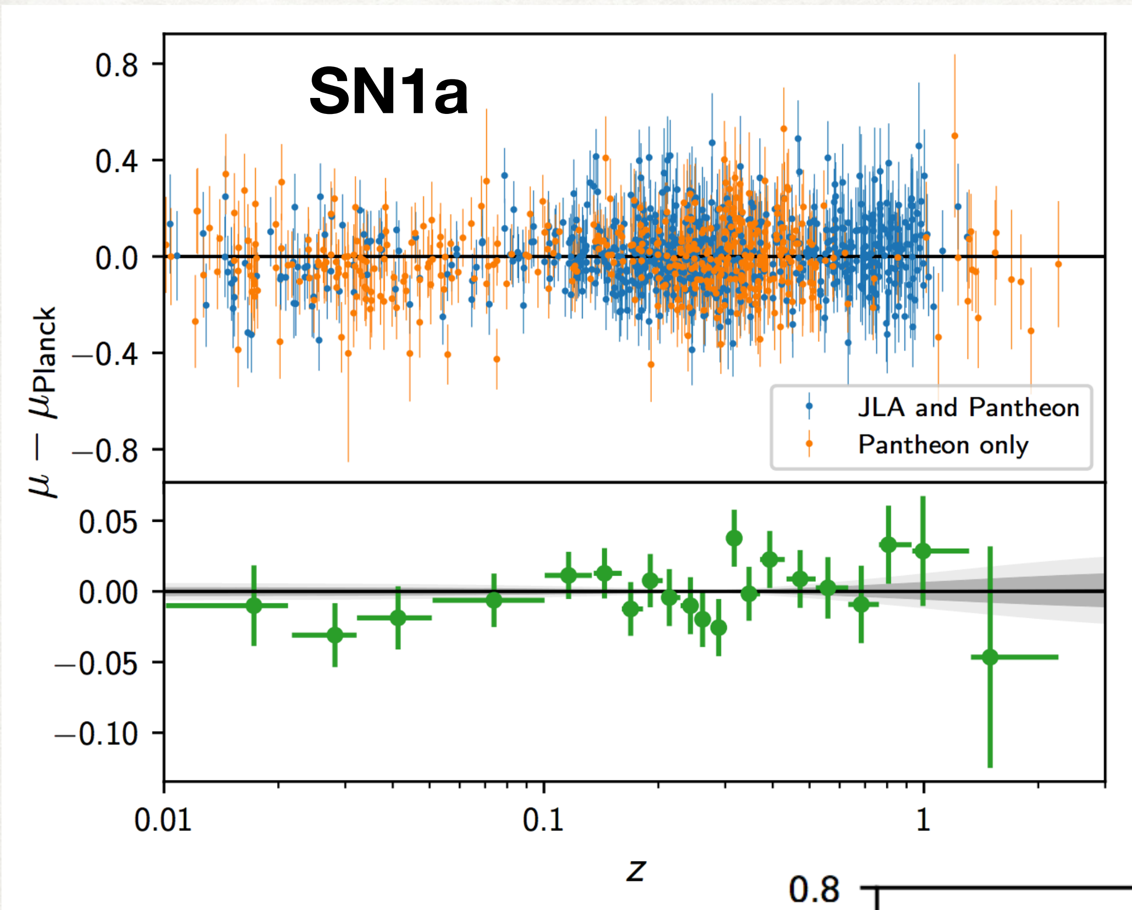
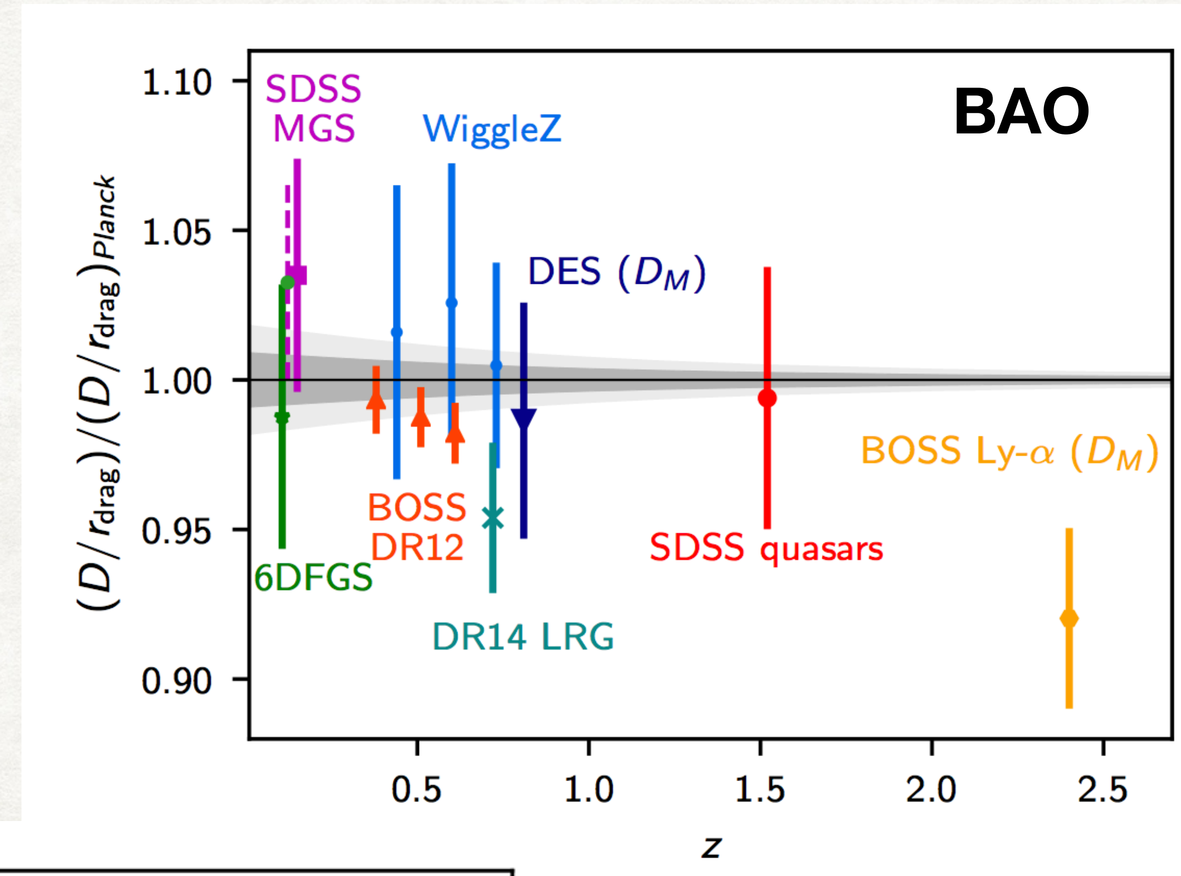
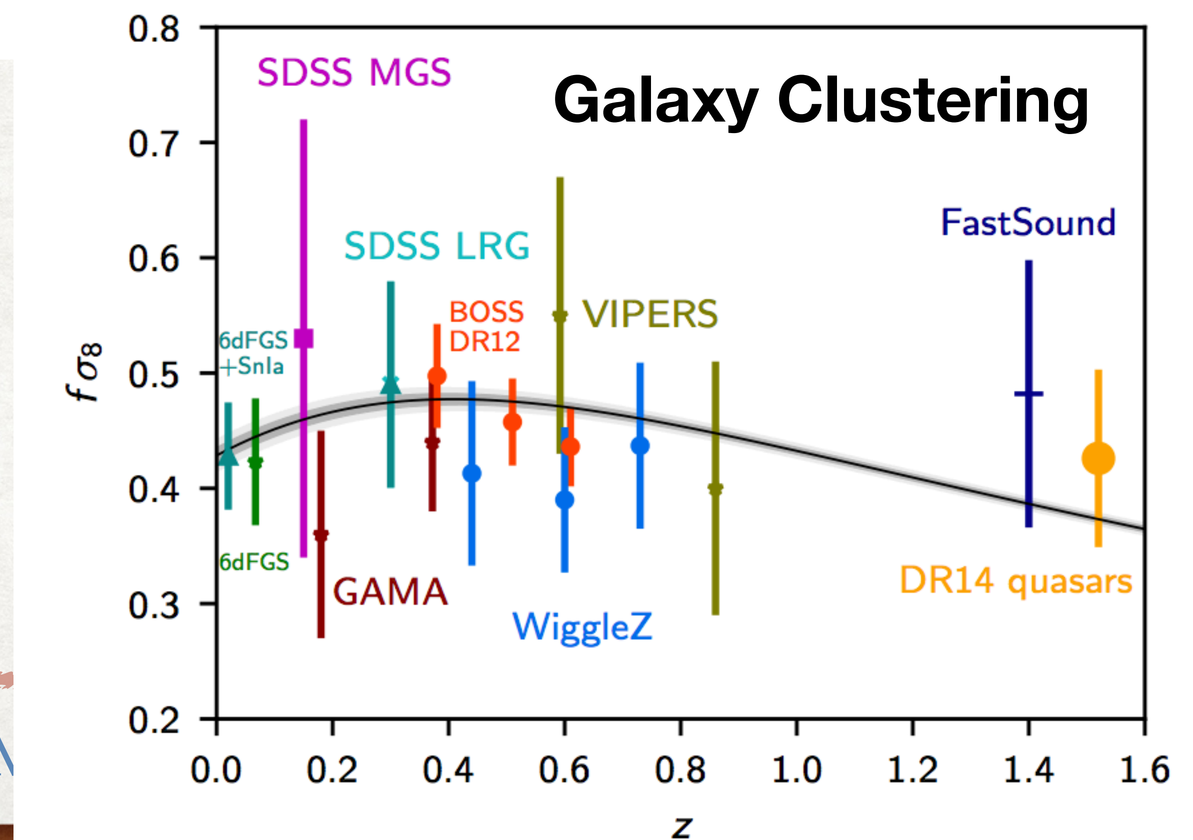
The Era of Precision Cosmology

And also with non-CMB data!







Planck 1807.06209

The Era of Precision Cosmology

Astonishing success of ΛCDM Cosmology

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
H_0	67.36 ± 0.54	67.66 ± 0.42

Planck alone

0.6% precision
1% precision
0.3% precision
13% precision
5% precision
0.5% precision
0.7% precision

e.g. 2015 data: TT +lowP reduced $\chi^2 = 1.004$

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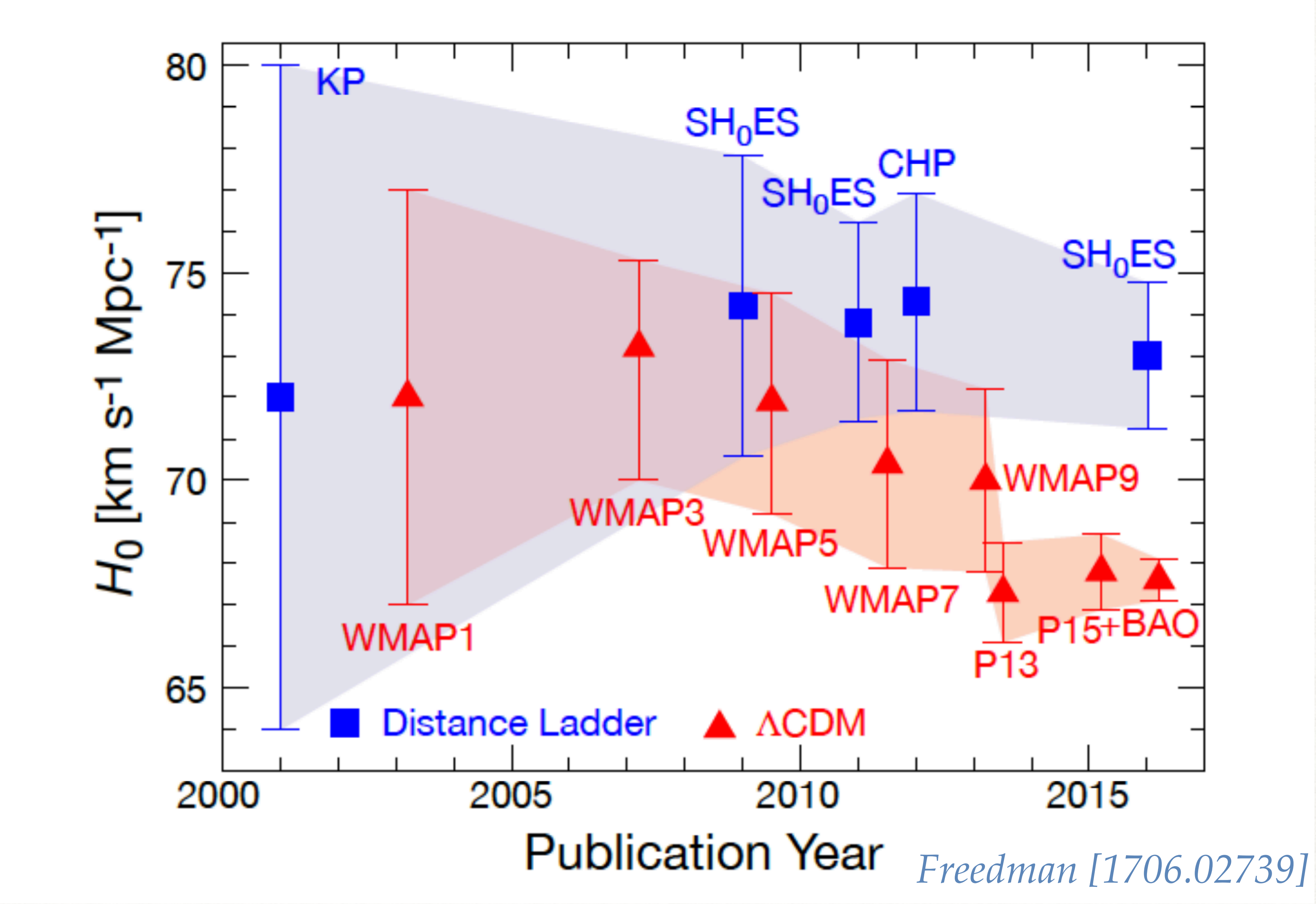
e.g. 2015 data: TT +lowP reduced $\chi^2 = 1.004$

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

- $S8 = \sigma_8(\Omega_m/0.3)^{0.5}$ is higher at ~2-3σ than that measured by low-z probes (SZ cluster count, Weak Lensing surveys CFHTLenS, KiDS, DES…)
- Amplitude of lensing potential $Cl^{\phi\phi}$ is higher than deduced from peak smoothing in TT/TE/EE at ~2σ.

Potentially very interesting but still very premature…

The Hubble Tension



Freedman [1706.02739]

3.8σ discrepancy between latest "direct" measurement from SH0ES and the value inferred from a fit of ΛCDM to *Planck* 2018

H0(SH0ES) = 73.52 ± 1.62 km/s/Mpc
Riess++ 1804.10655

H0(ΛCDM) = 67.27 ± 0.60 km/s/Mpc
Aghanim++ 1807.06209

Outline

- Is the Hubble Tension Real?
- Is it a “Hubble Tension” or “Sound Horizon” tension?
- Early Dark Energy Can Resolve The Hubble Tension
- Towards a new concordance model beyond ΛCDM?

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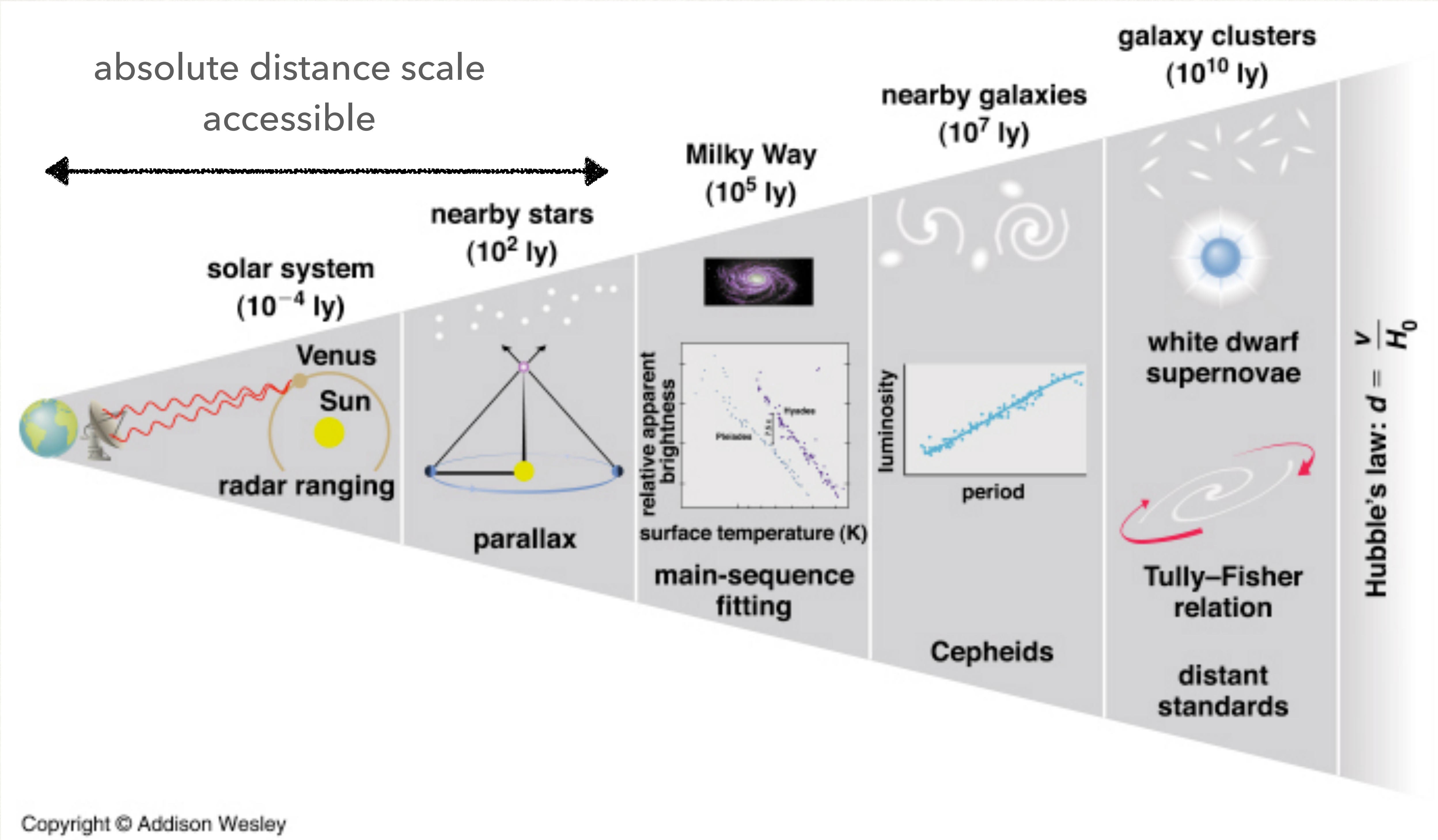
SYSTEMATICS??

NEW PHYSICS??

The Distance Ladder



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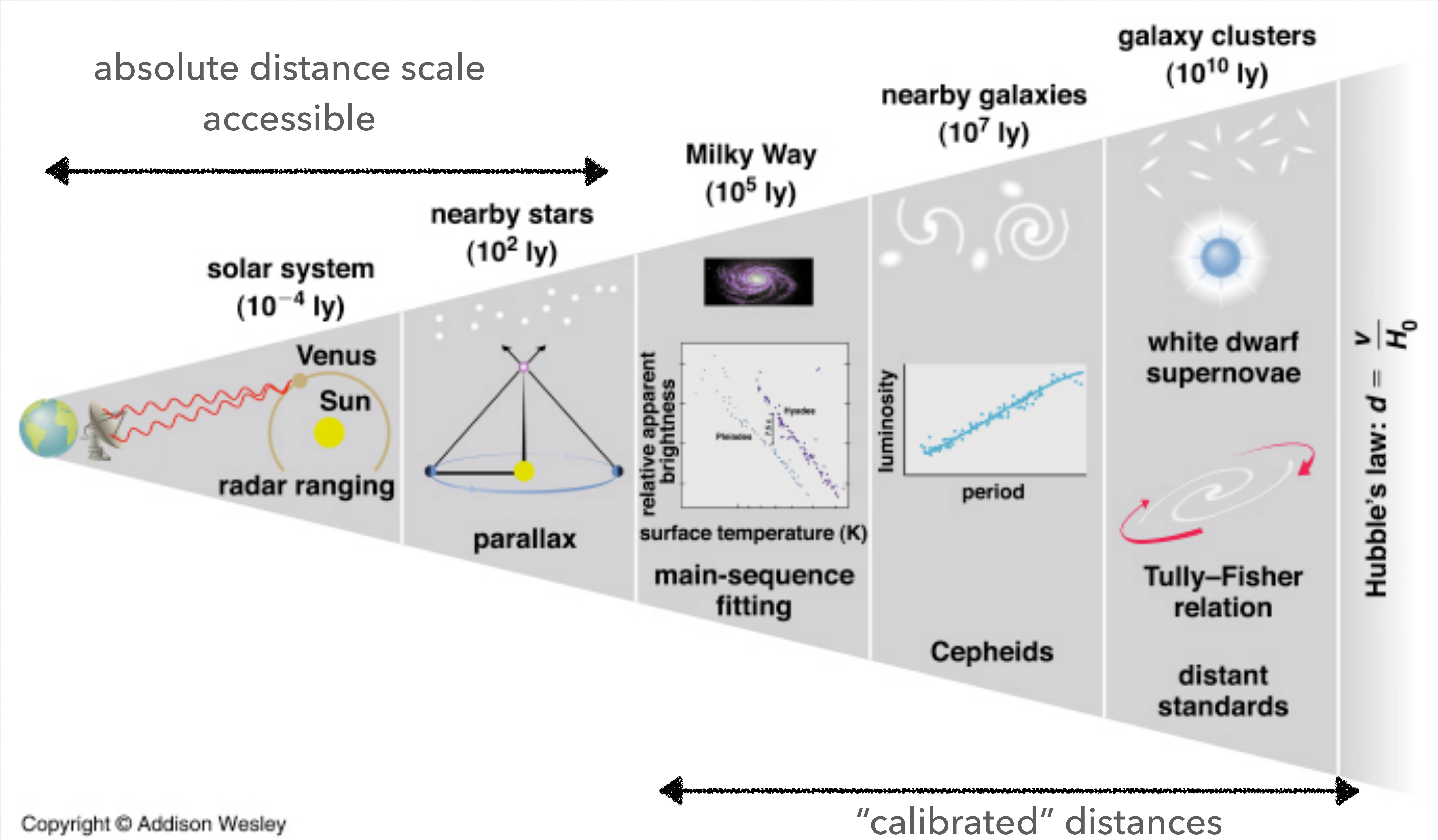

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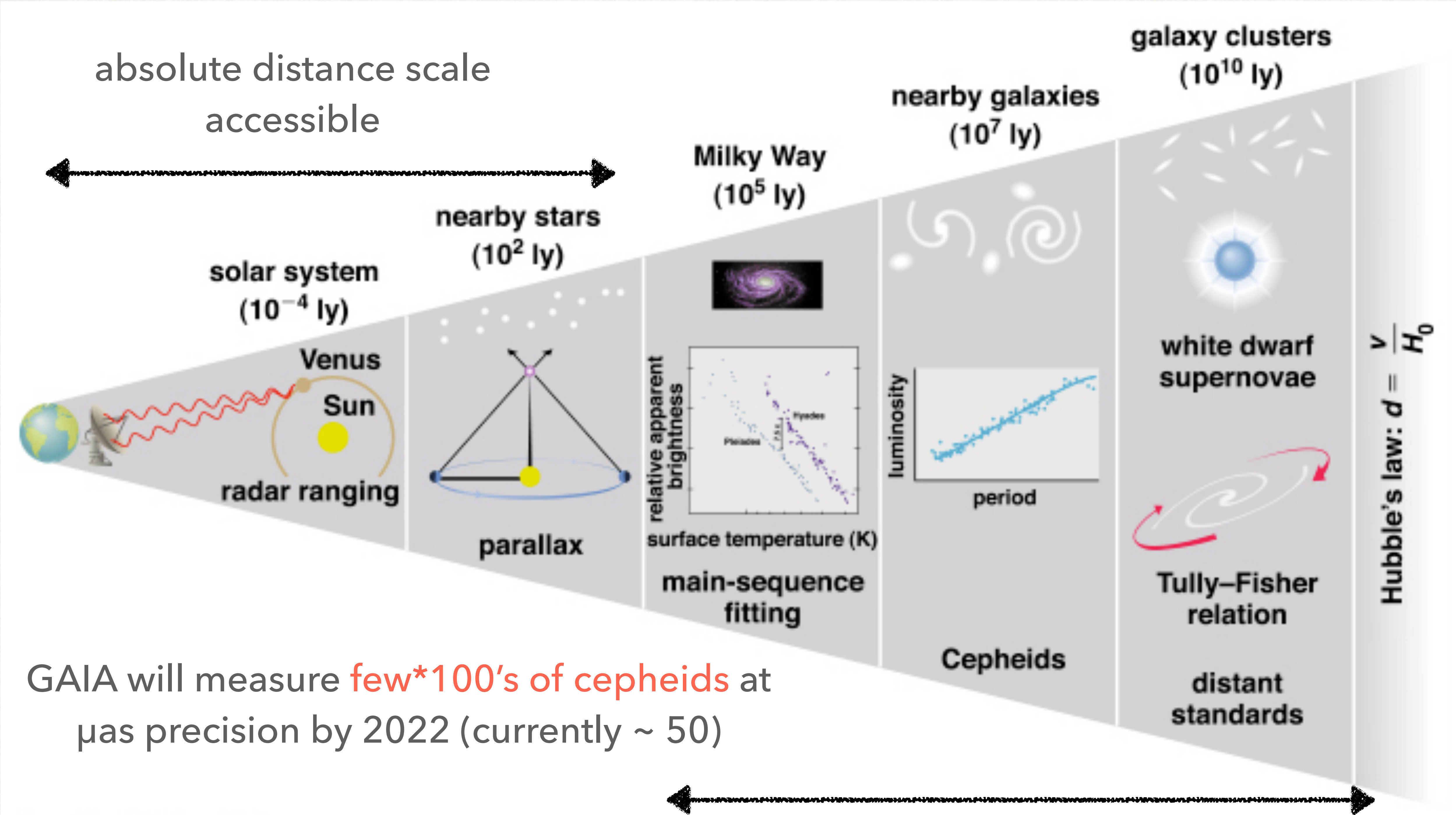

GAIA will measure few*100's of cepheids at µas precision by 2022 (currently ~ 50)

Could it be systematics in SN data?

- Sources of error are numerous (non-exhaustive list):
  i) measurement of parallaxes.
  ii) measurement of (apparent) magnitudes.
  iii) calibration issues: are SN1 really standard candles?
  iv) effect of local environment: could “local, young” cepheids be different from the “old, Hubble flow” cepheids?

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- High value of H0 is supported by numerous studies, including non-SH0ES ones.
  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.
  Macpherson++ 1807.01714, Jones++ 1805.05911

- 5 different calibration methods all giving consistently high values of H0.
  see discussion in Riess++1810.03526

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- Exists even with non-SN data: Gravitational time delay of strongly lensed quasars is in (mild) tension with Planck.

  $H0 = 72.5 \pm 2.1$ km s^{-1} Mpc^{-1}

  Bonvin++ 1607.01790, S. Birrer++, 1809.01274

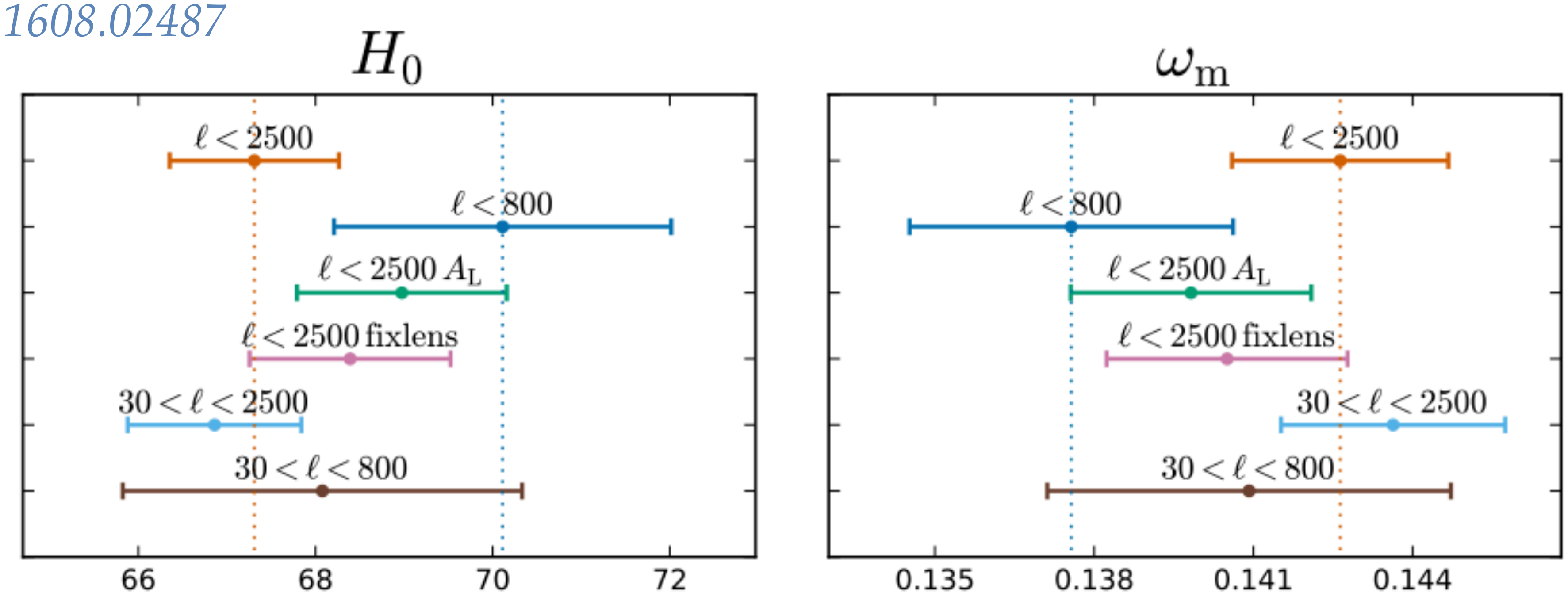
- In the (near) future: Gravitational wave standard sirens (~5 yrs) expect to get to 1km/s/Mpc.
  Mortlock++ 1811.11723

Could it be systematics in Planck data?

- It is driven by residuals oscillations at l > 800 and the low-l ~30 deficit.

Addison++ 1511.00055, Planck Col. 1608.02487

1608.02487



TT + τ prior, 1σ error

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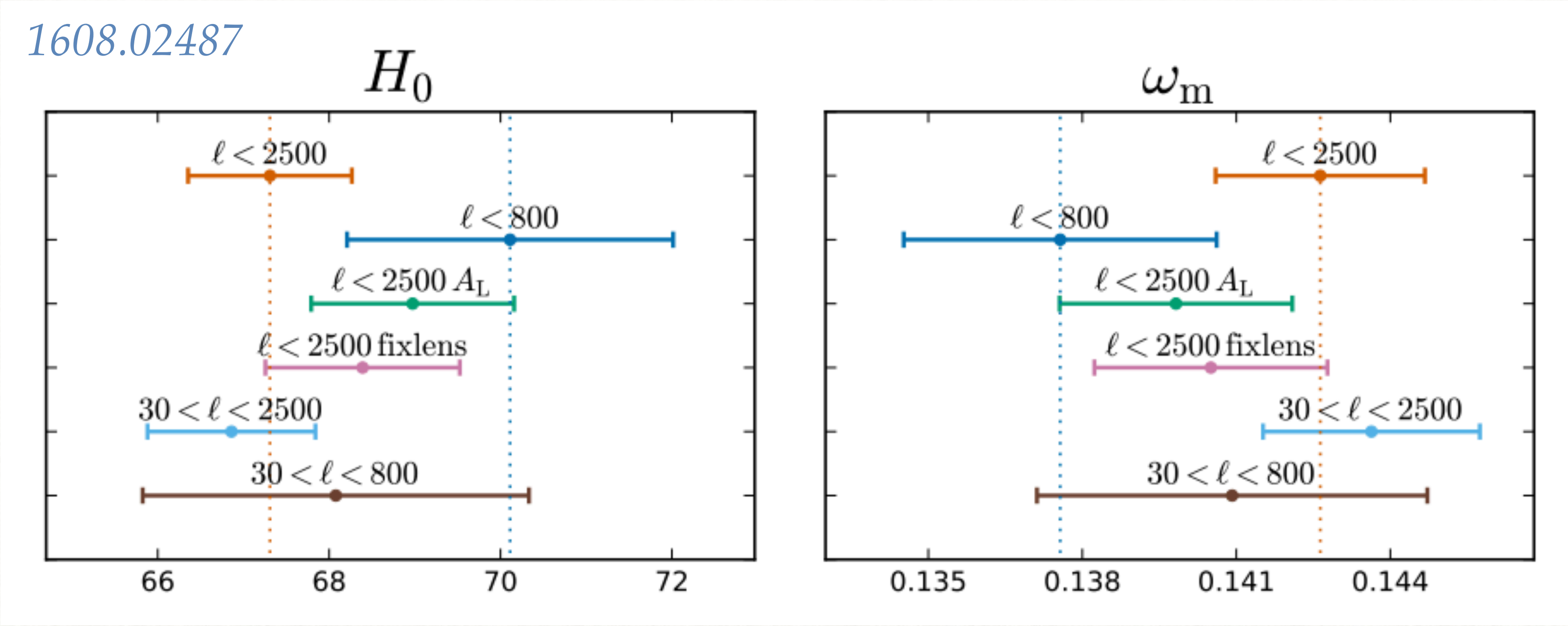


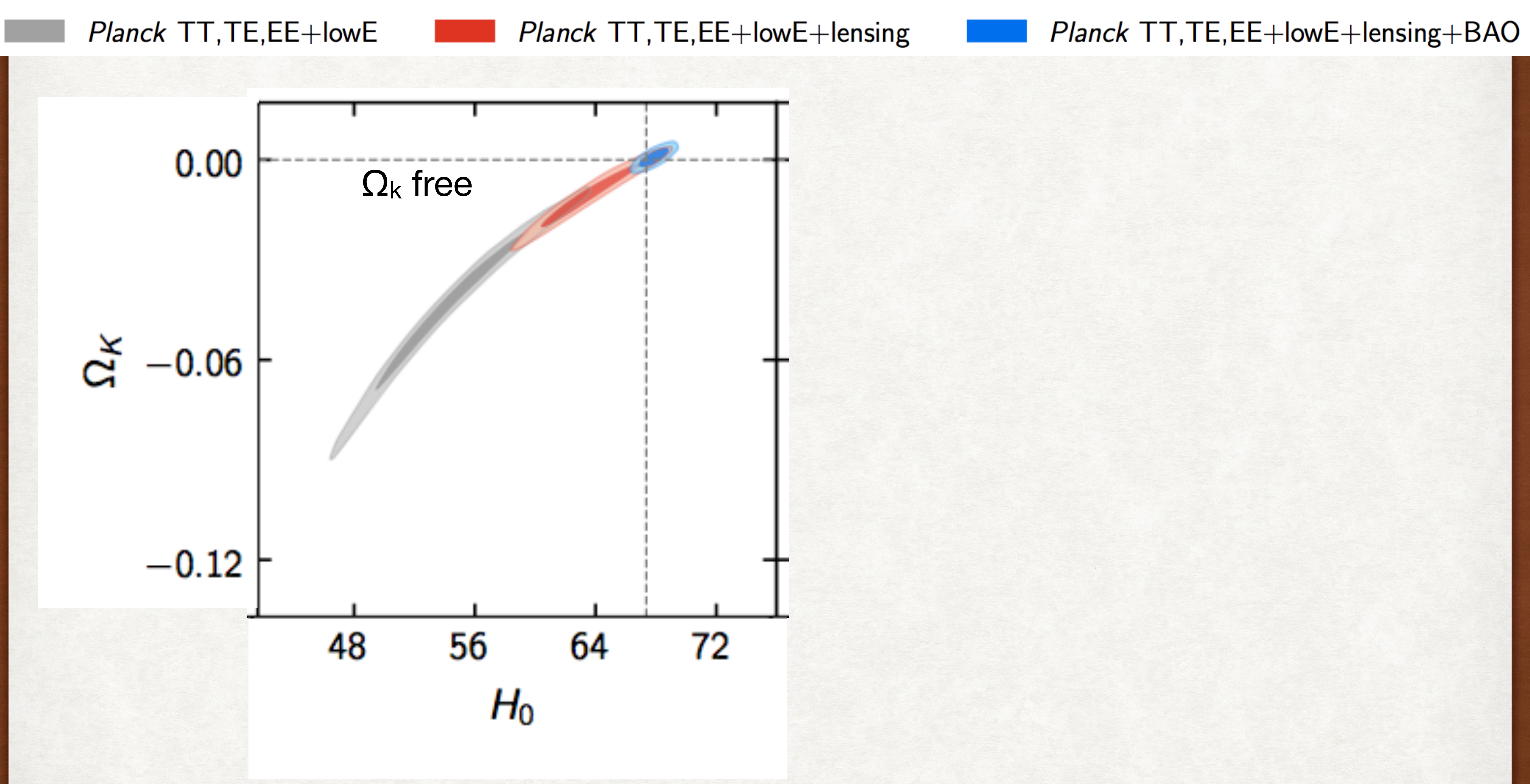
TT + τ prior, 1σ error

- It exists with other CMB data: WMAP+SPT/ACT+BAO ~ 2.4-3.1σ with SH0ES.

- It exists even with non-CMB data! BAO+BBN ~ 3σ with SH0ES.

Addison++ 1707.06547

H0 from the CMB is model dependent



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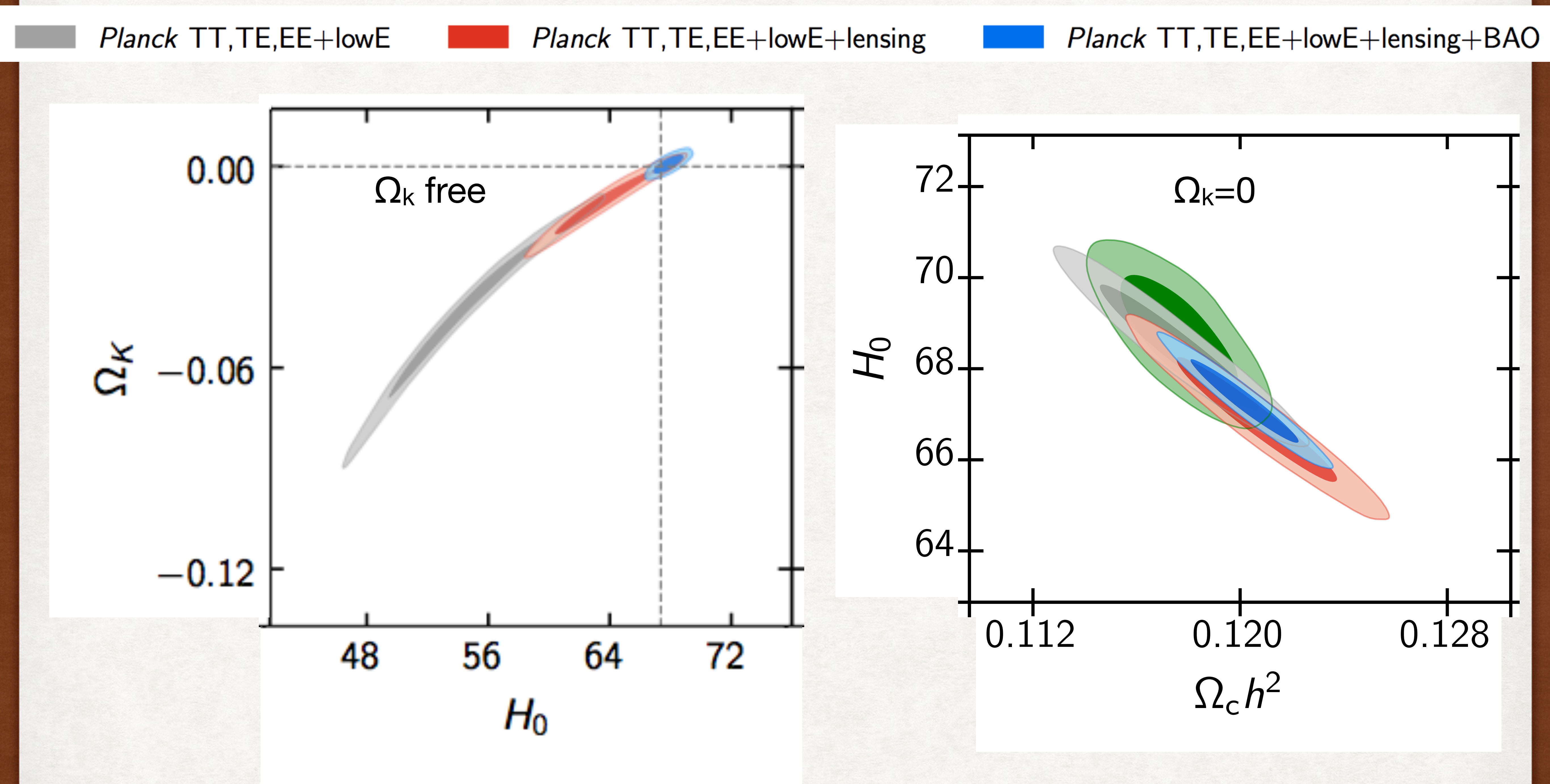

Planck measurement is strongly model dependent! baseline assumes “flat” universe

Early/late universe physics are degenerate

- standard ruler in the sky: distance travelled by sound wave until recombination.
- problem: only angular scale of sound horizon is accessible $\theta_s = r_s/D_A$

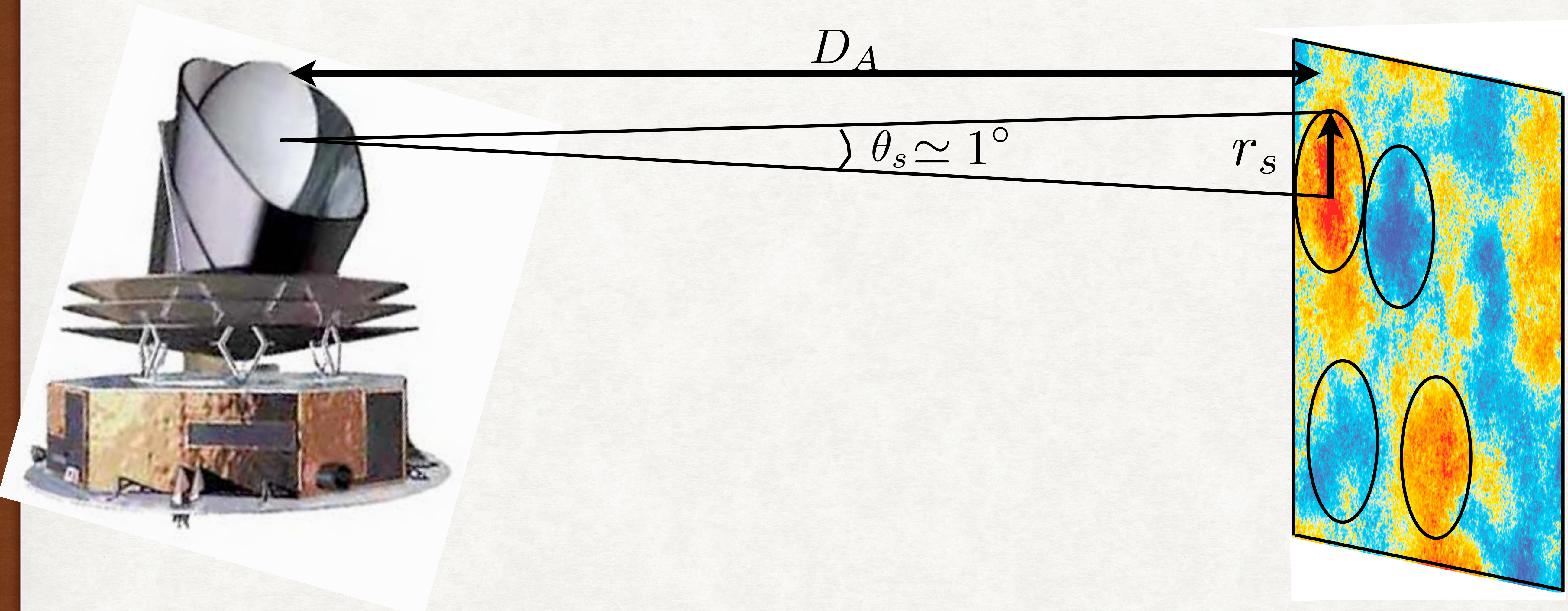

illustration: T. Smith

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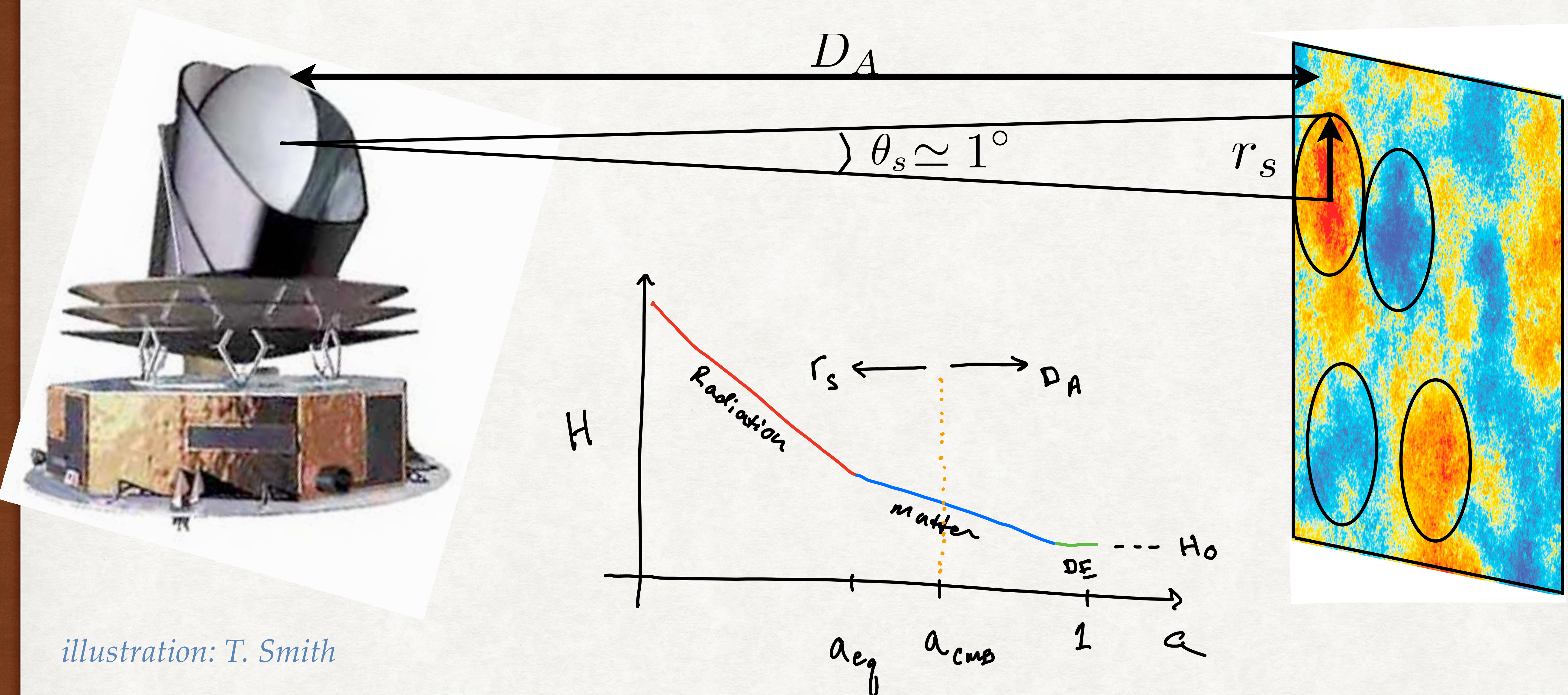


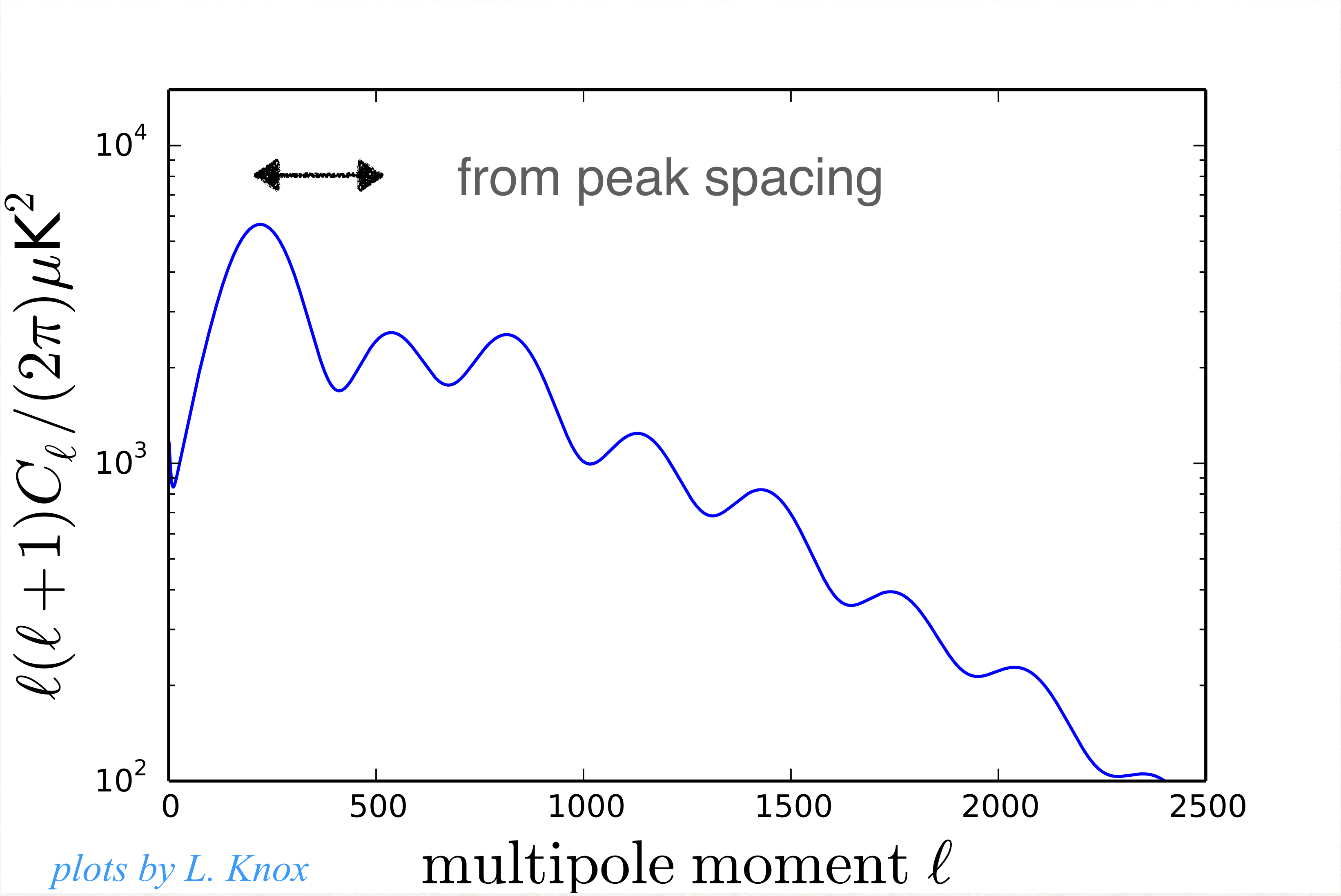
illustration: T. Smith

- rs pre-recombination physics: DOES NOT depend on H_0, but on physical densities ω_X
- d_A angular diameter distance: post-recombination physics. $d_A \propto \omega_M^{-0.35} H_0^{-0.2}$

How does CMB data measure H0?

- It comes from the measurement of three angular scales: ℓ_s, ℓ_d, ℓ_{eq} <=> θ_s, θ_d, θ_{eq}

θ_s sound horizon at last scattering ~1.0404



(nb: any $\theta_x = r_x/D_A$)

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436

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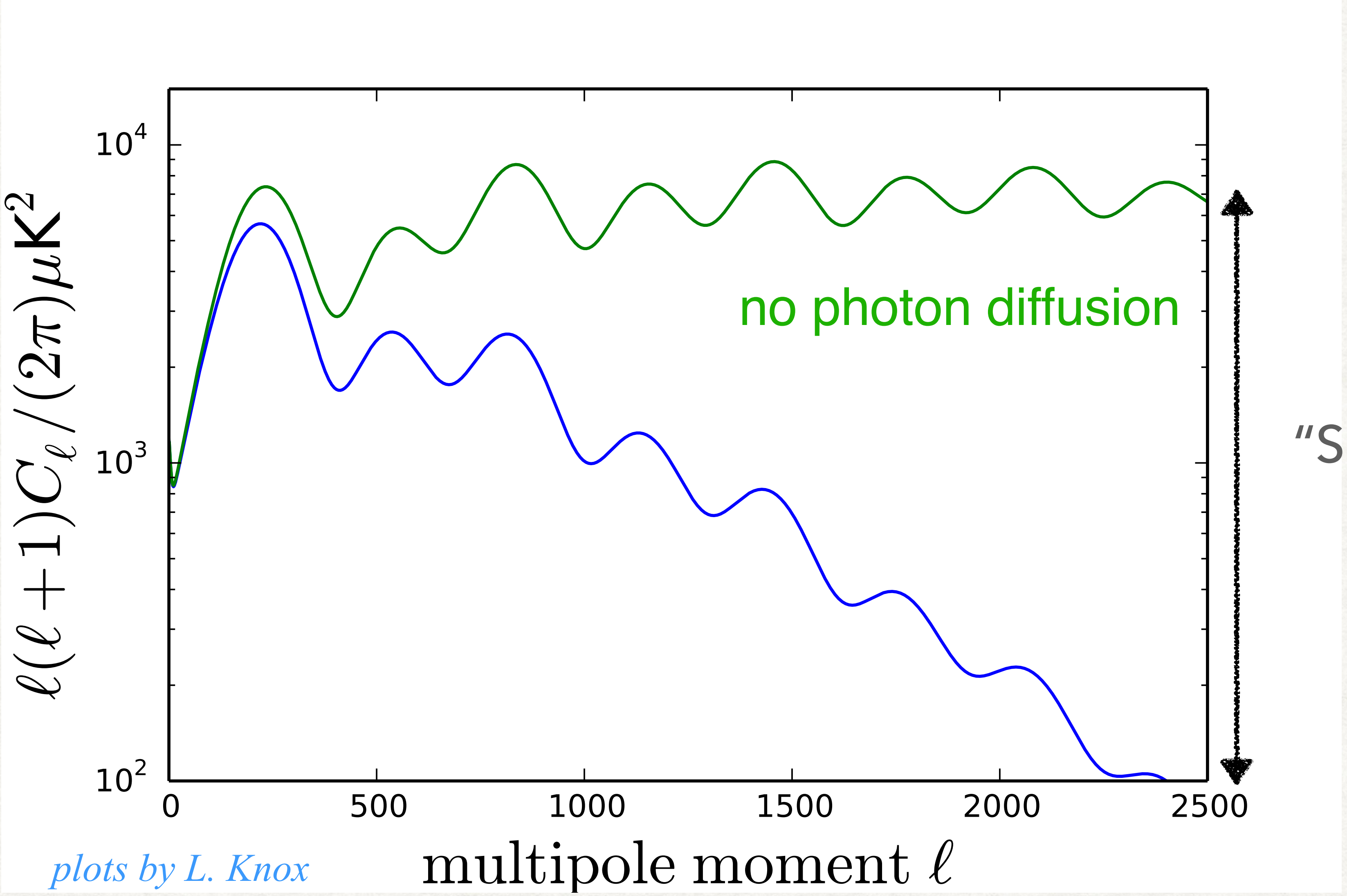
θ_d photon diffusion length at last scattering ~ 0.1609



"Silk Damping"

(nb: any $\theta_x = r_x/D_A$)

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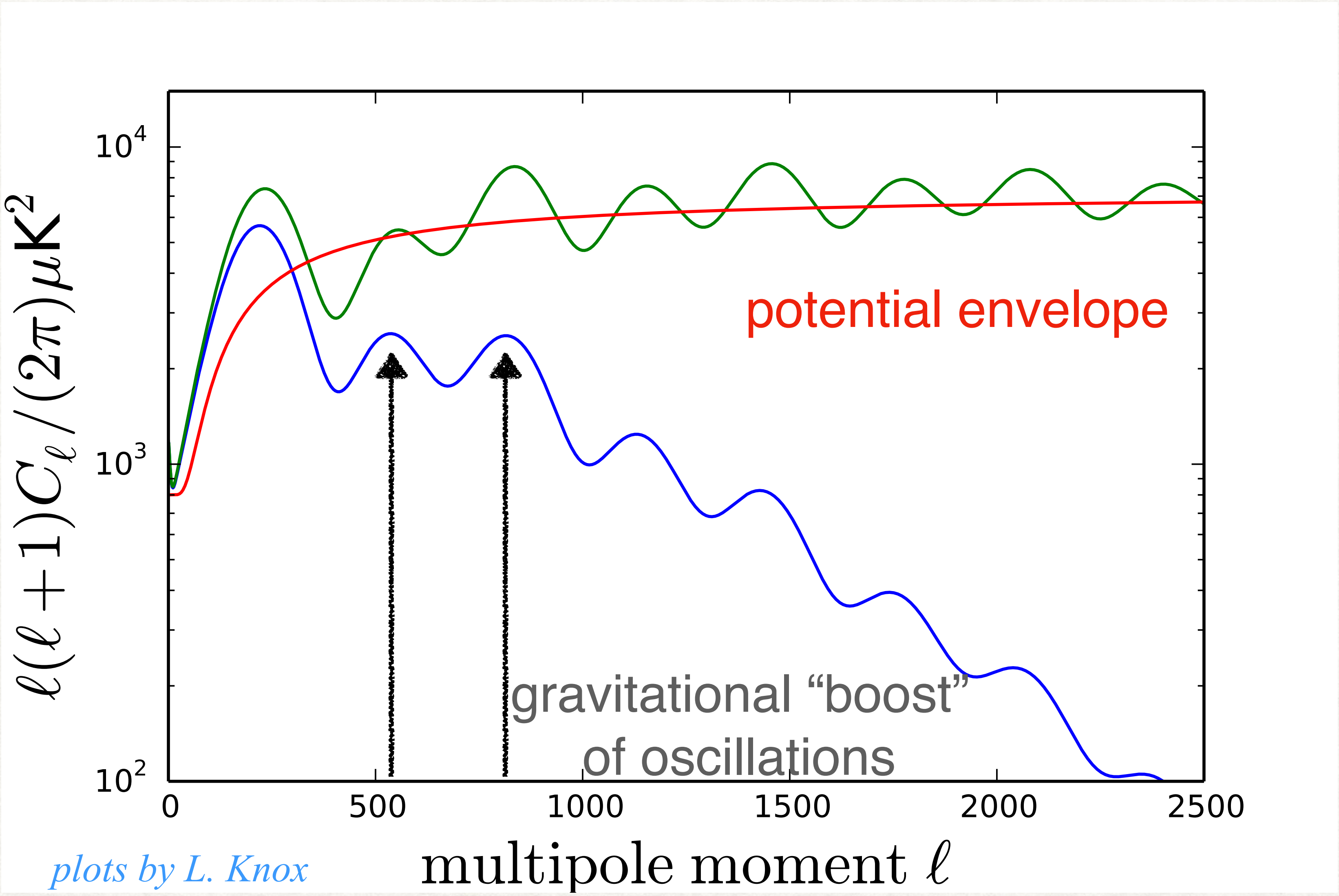
θ_{eq} horizon size at matter-radiation equality ~ 0.81



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A modified Dark-Energy sector?

- *h* increases but $d_A(z_*)$must be kept constant: decrease Ω_{DE} at $z < z_*$

$$\theta_X \equiv \frac{r_X}{d_A} \qquad d_A(z_*) = \int_0^{z_*} \frac{dz}{100\sqrt{\omega_M(1+z)^3 + \Omega_{DE}(z)h^2}}$$

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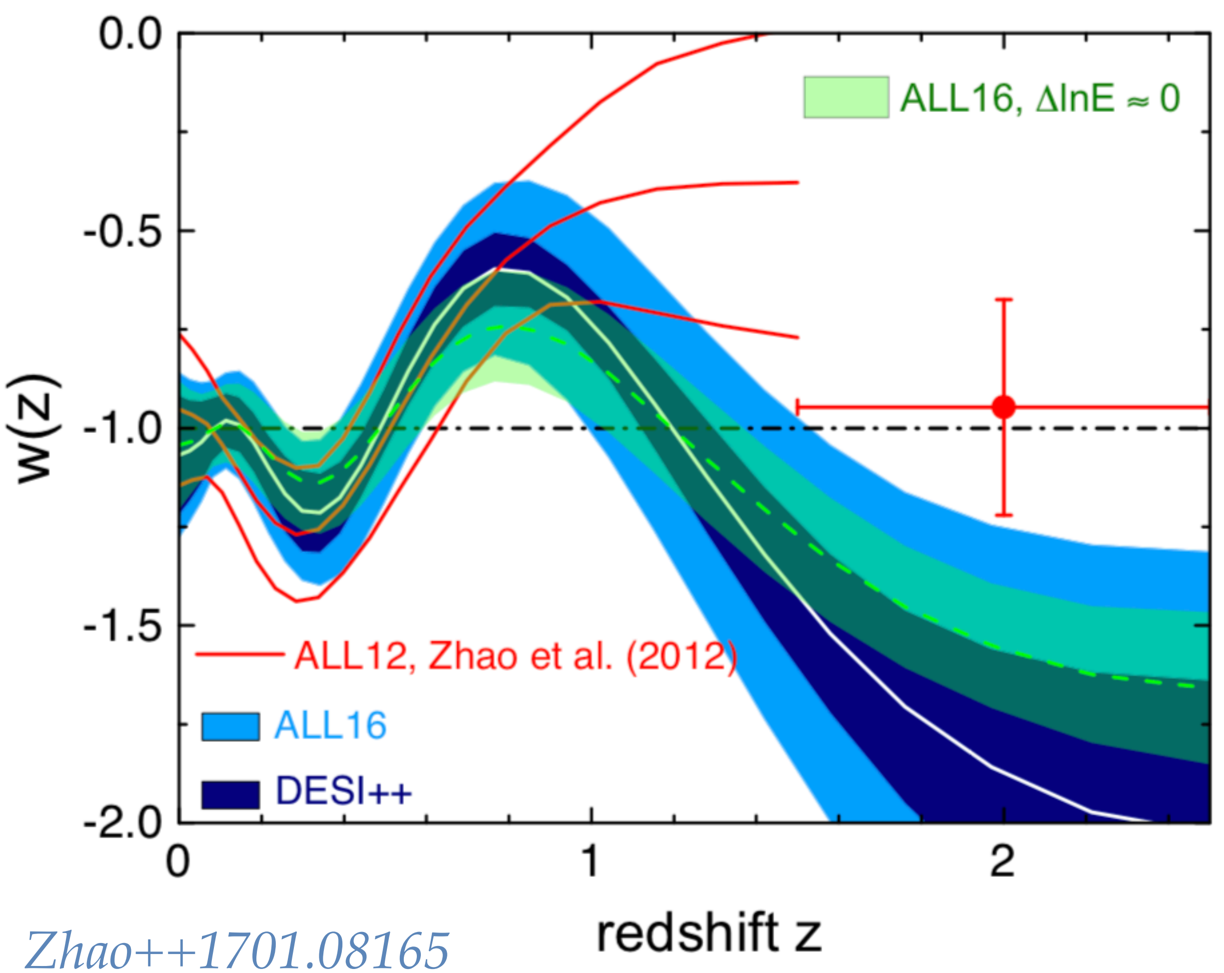

Zhao++1701.08165

- Requires phantom crossing (stability of perturbations?)

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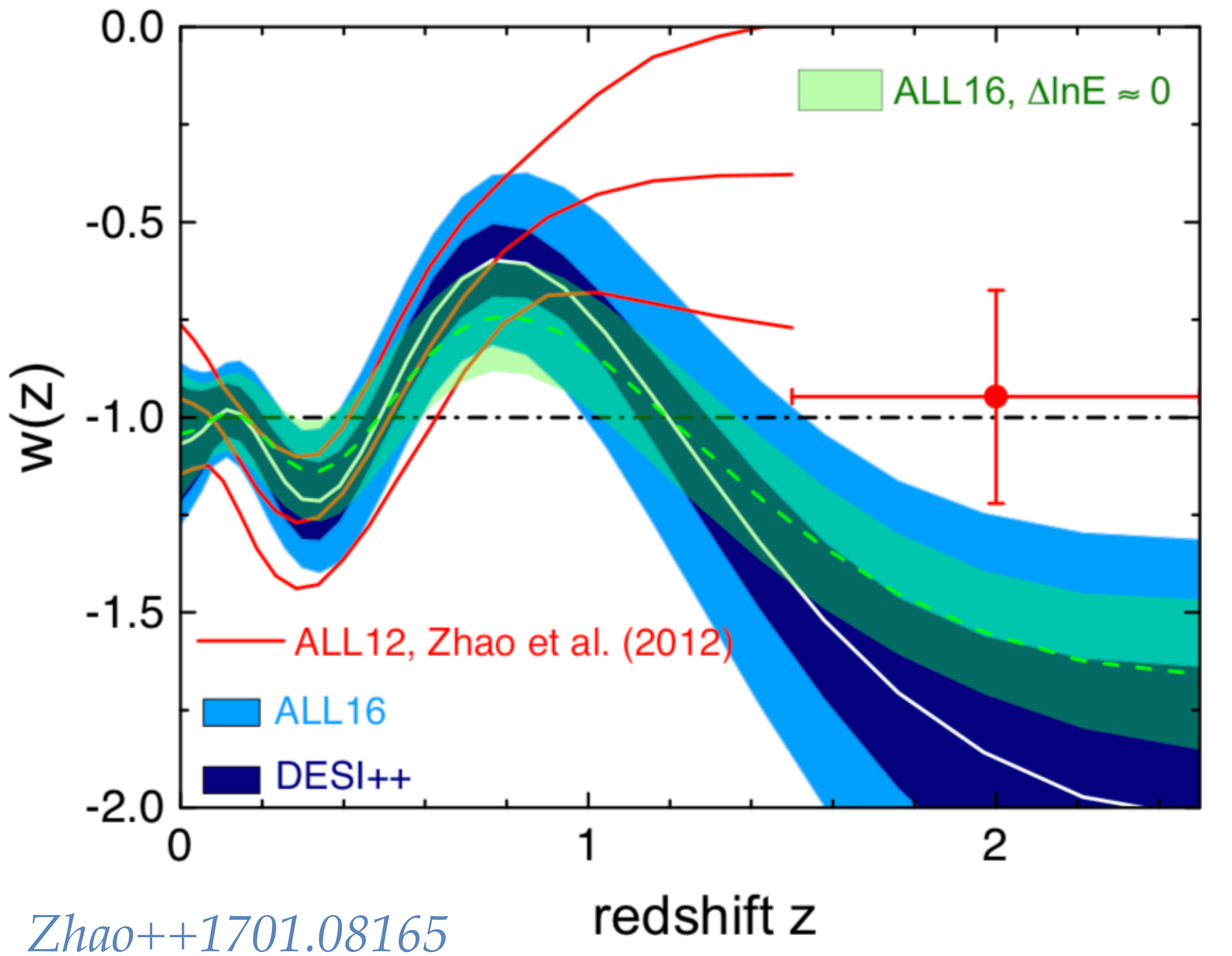

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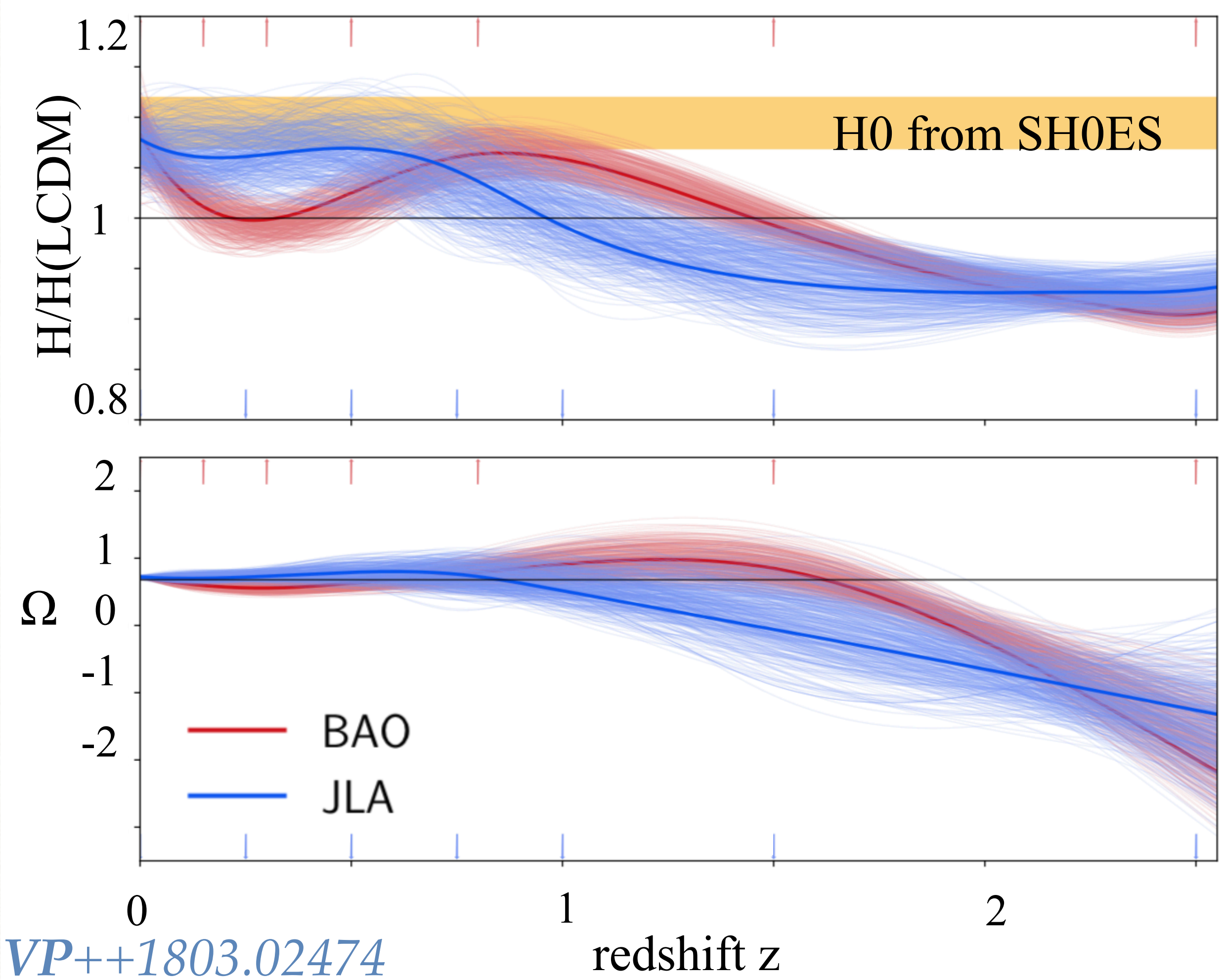
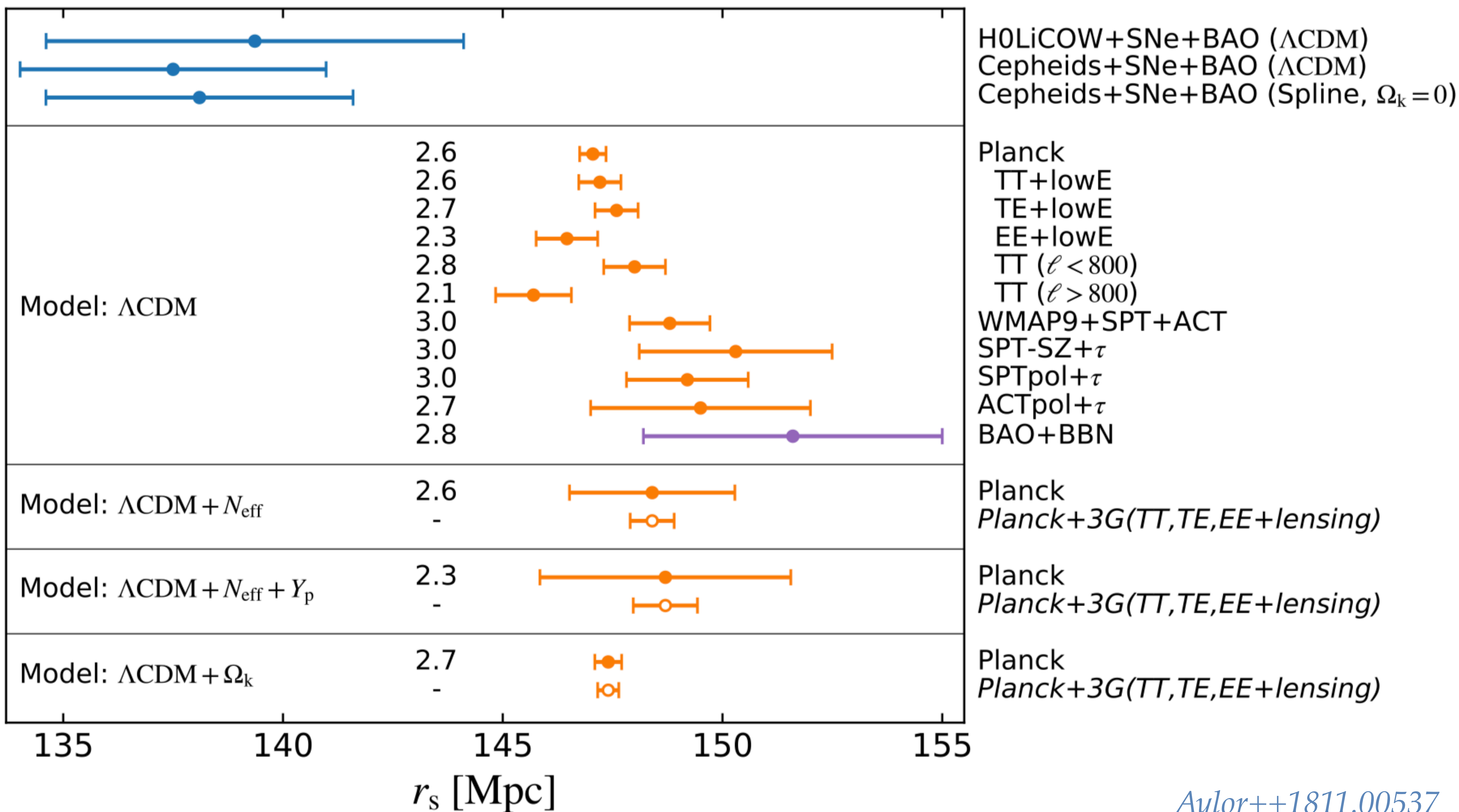


VP++1803.02474

- Requires phantom crossing (stability of perturbations?)
- JLA favors "flat" expansion history / BAO favors oscillation: 2σ residual tension

The H0 tension is a r_s tension

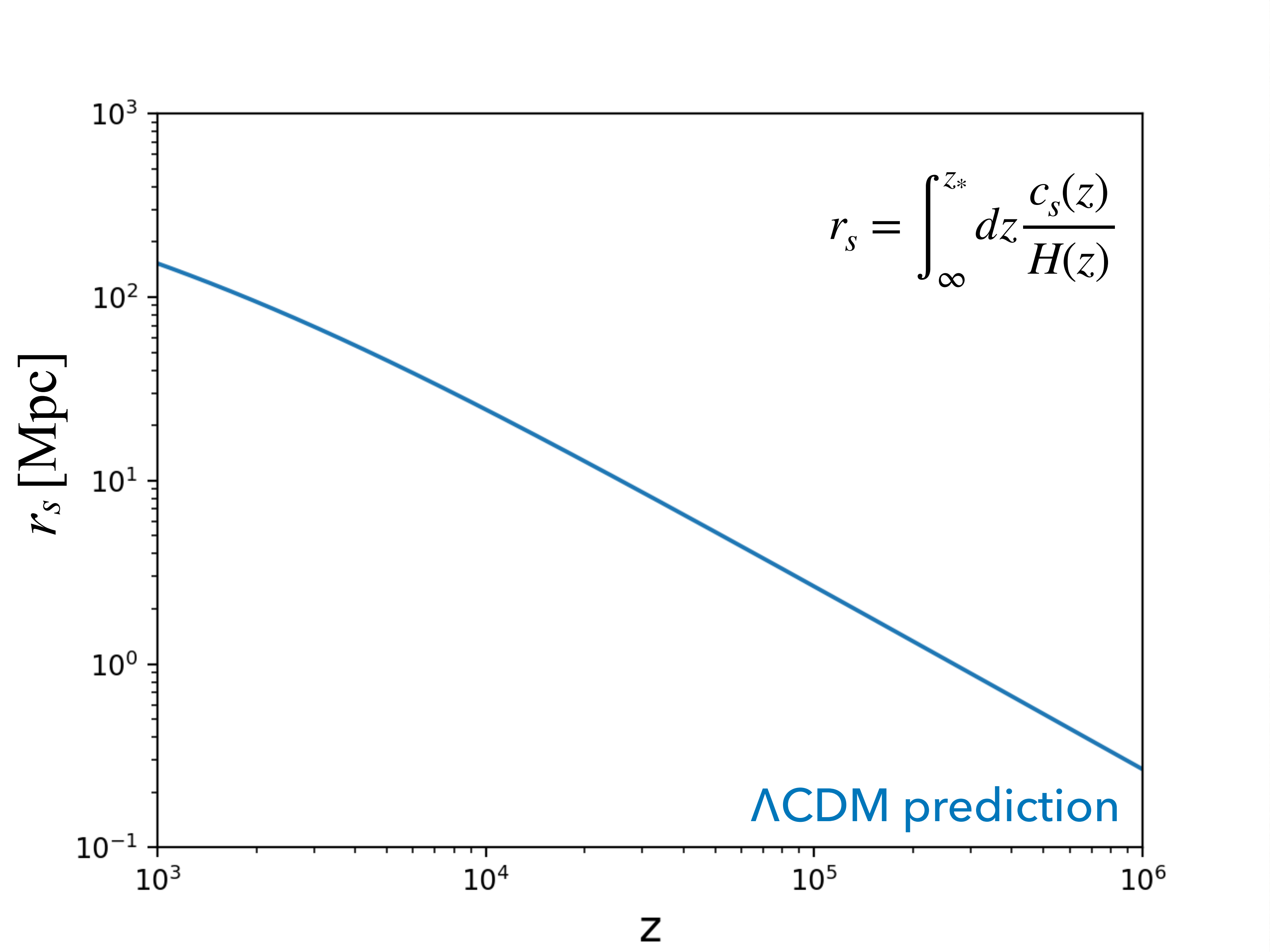
One can deduce the co-moving sound horizon r_s from H0 and BAO
r_s from CMB needs to decrease by ~ 10 Mpc



Aylor++1811.00537

How to solve the Hubble tension

- r_s does not reach 10Mpc before ~ 25000 in ΛCDM
- r_s receives most of its contribution close to recombination



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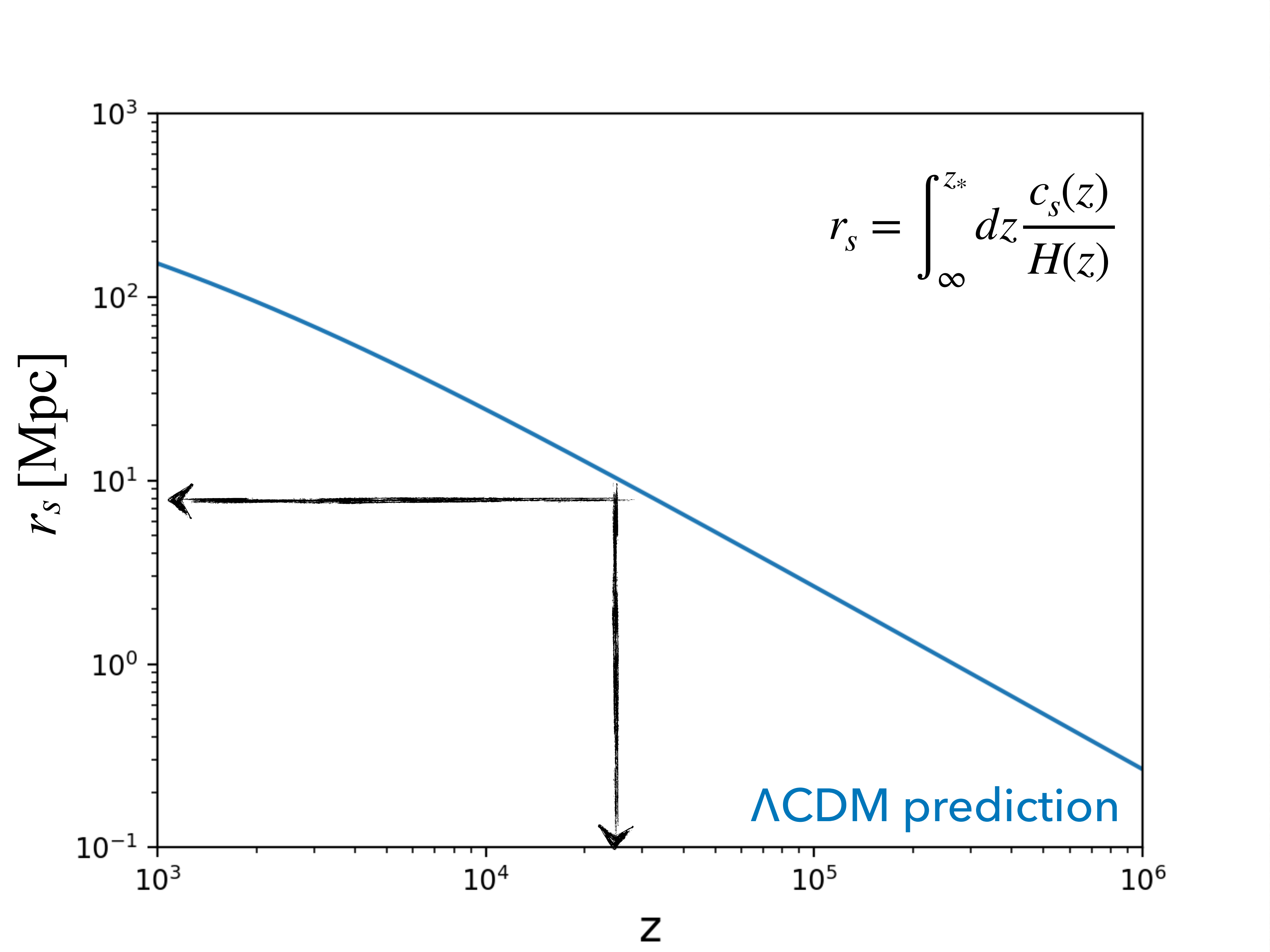

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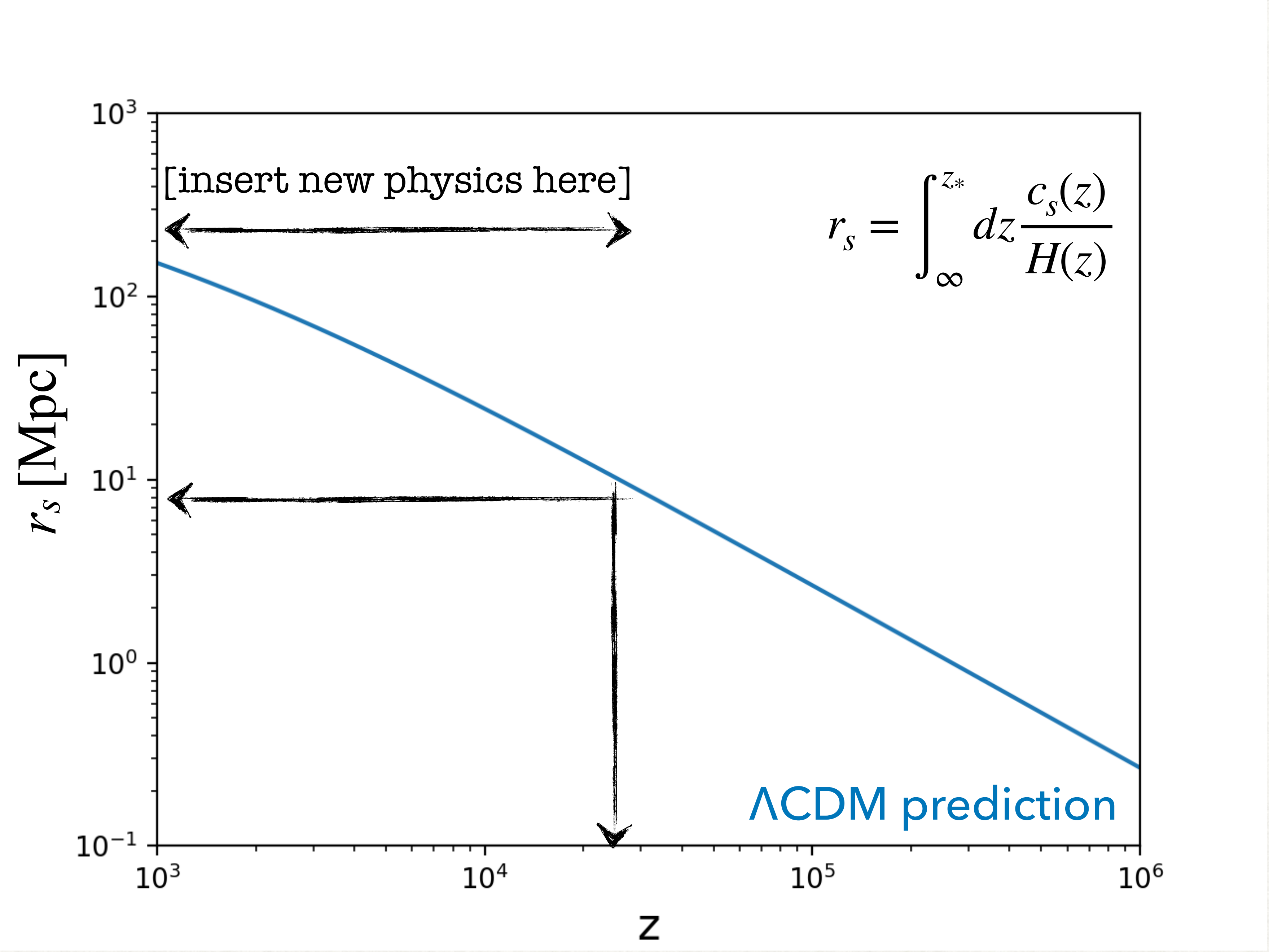

How to Resolve the Hubble tension

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

How to Resolve the Hubble tension

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

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

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Chiang&Slozar 1811.03624

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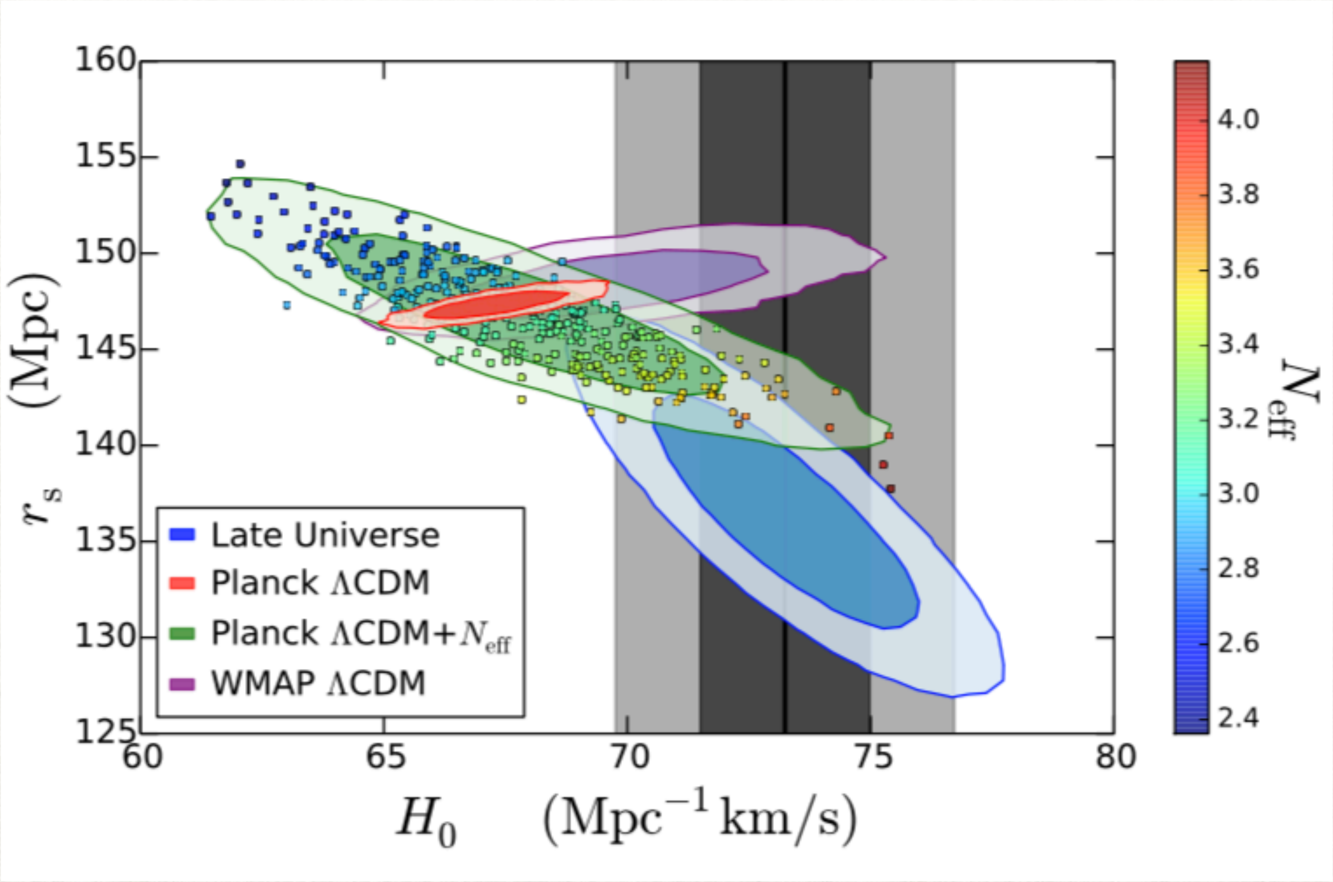

Bernal++ 1607.05617

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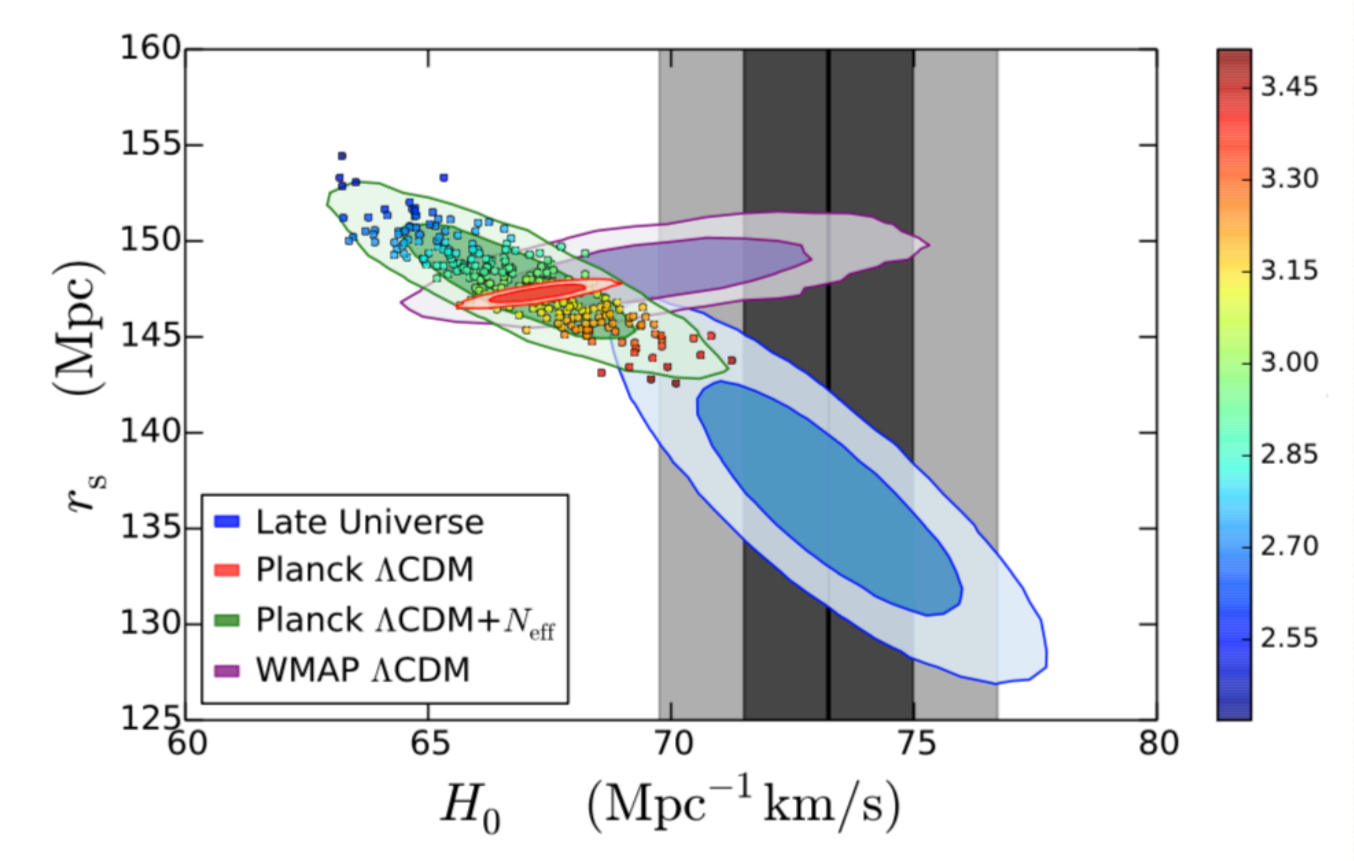

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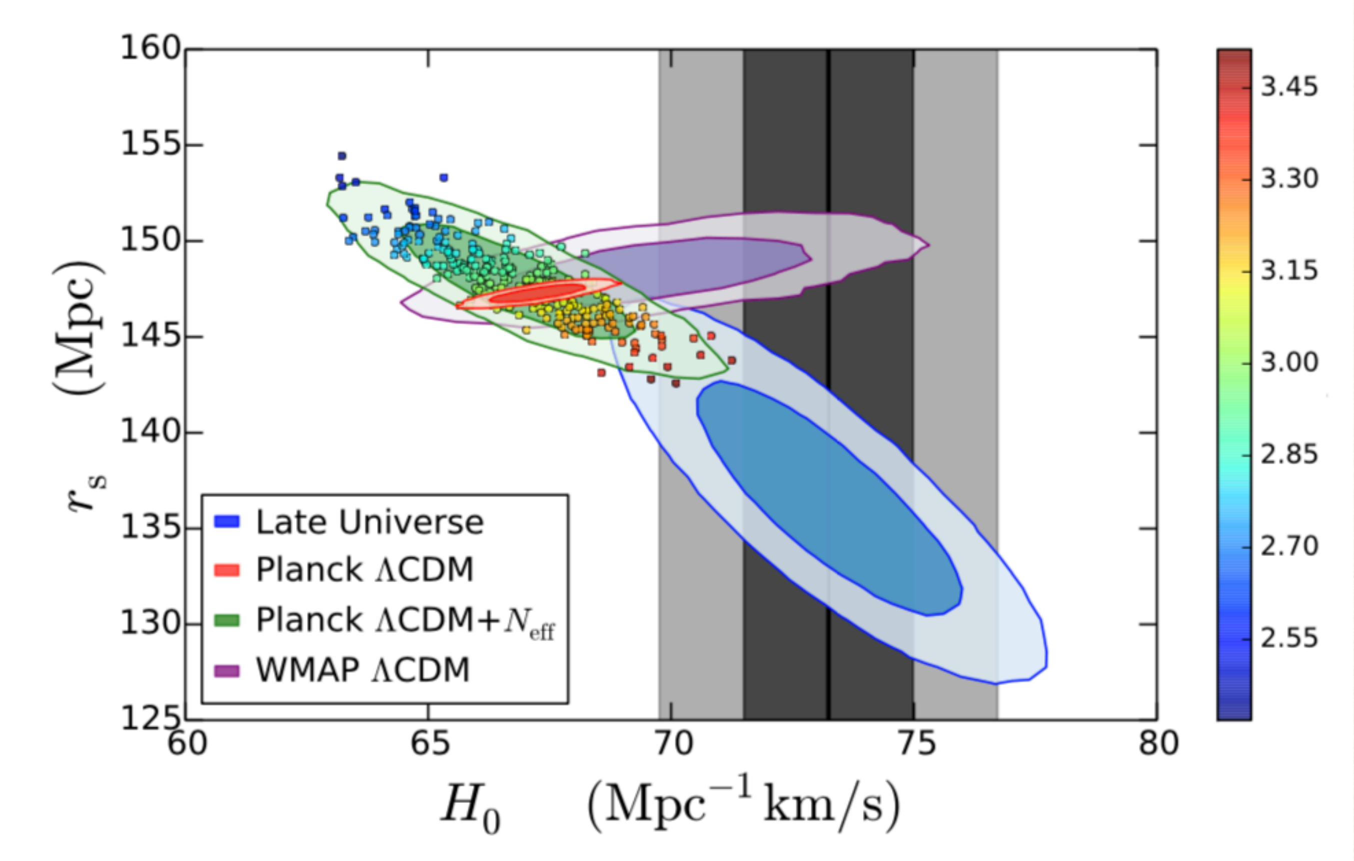

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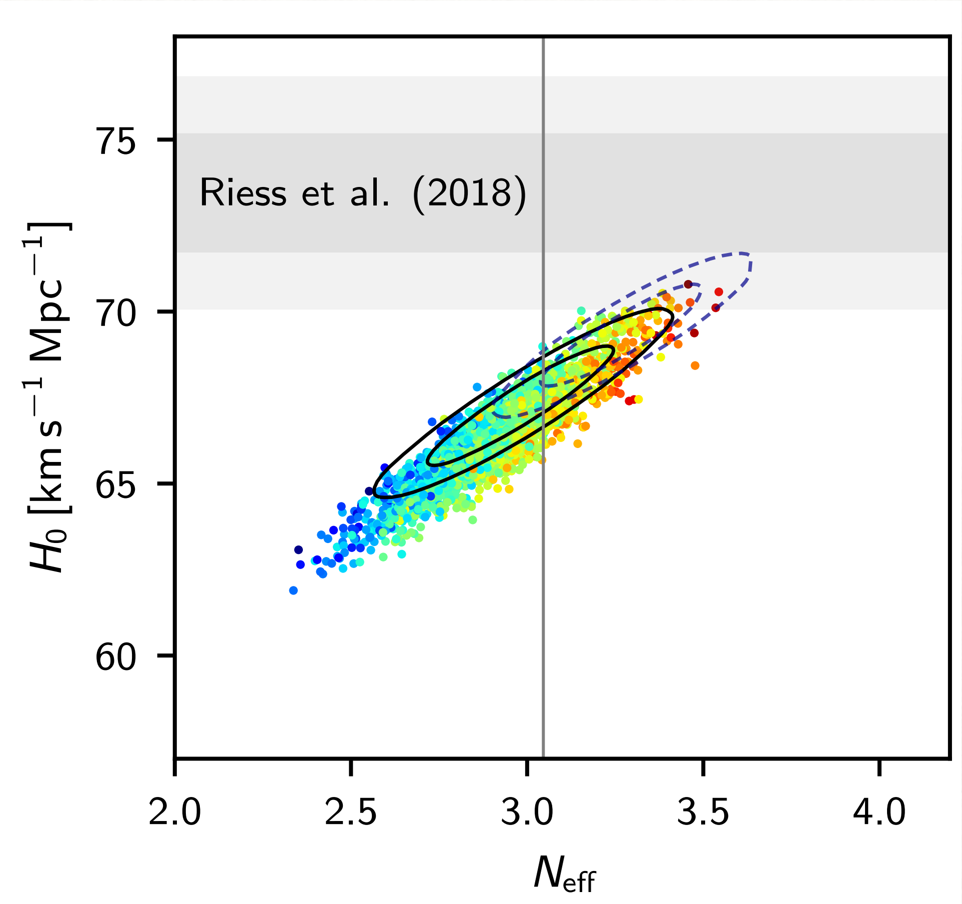

Aghanim++ 1807.06209

Scalar field and Early Dark Energy

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

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

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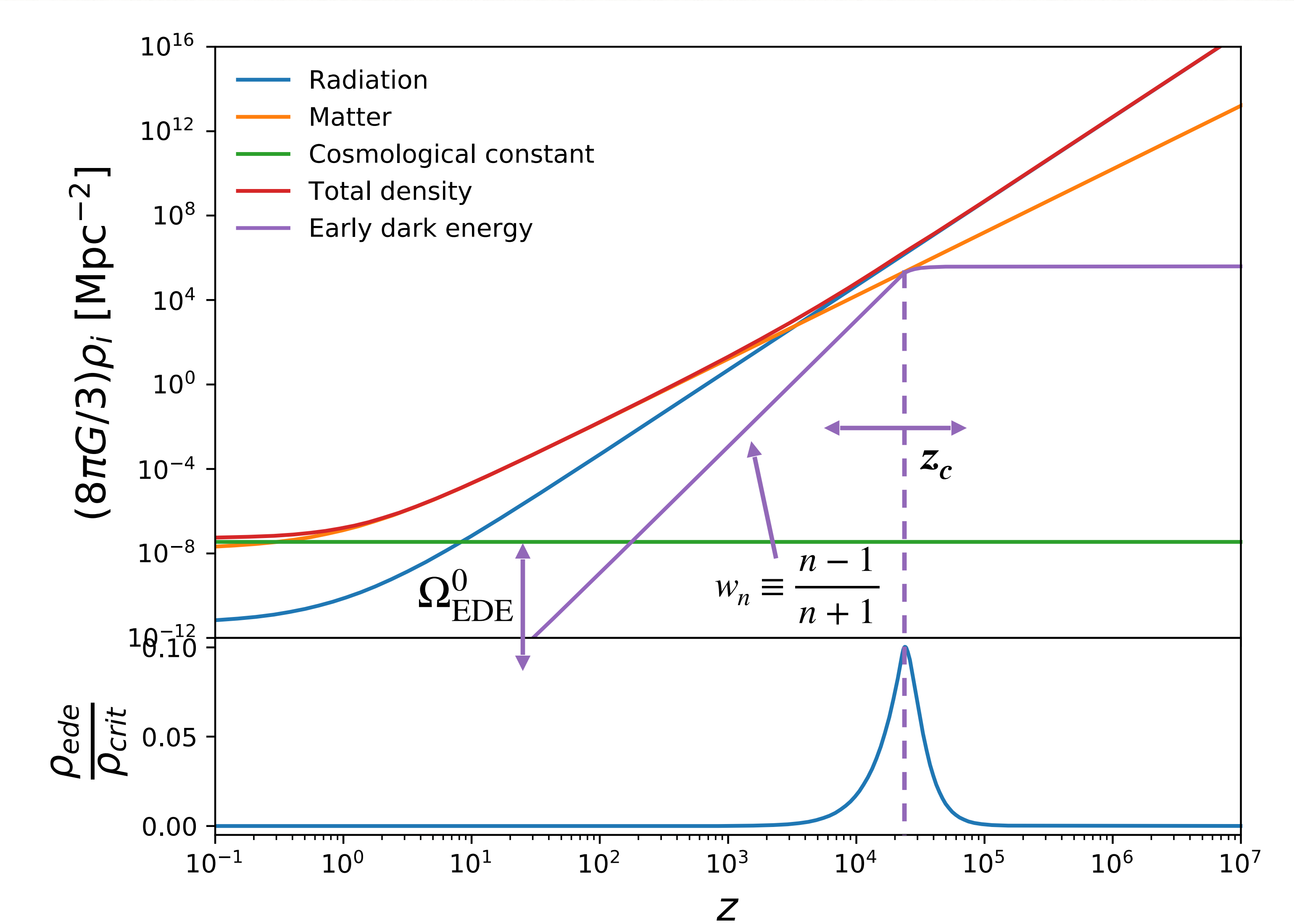
- We use the GDM formalism with:

$$\begin{cases} \Omega_{\rm EDE}(z \gg z_c) = \Omega_{\rm EDE}(z_c) \\ \Omega_{\rm EDE}(z \ll z_c) = \Omega^0_{\rm EDE}(1+z)^{3(w_n+1)} \end{cases}$$

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

GDM: Hu astro-ph/9801234



plot by T. Karwal

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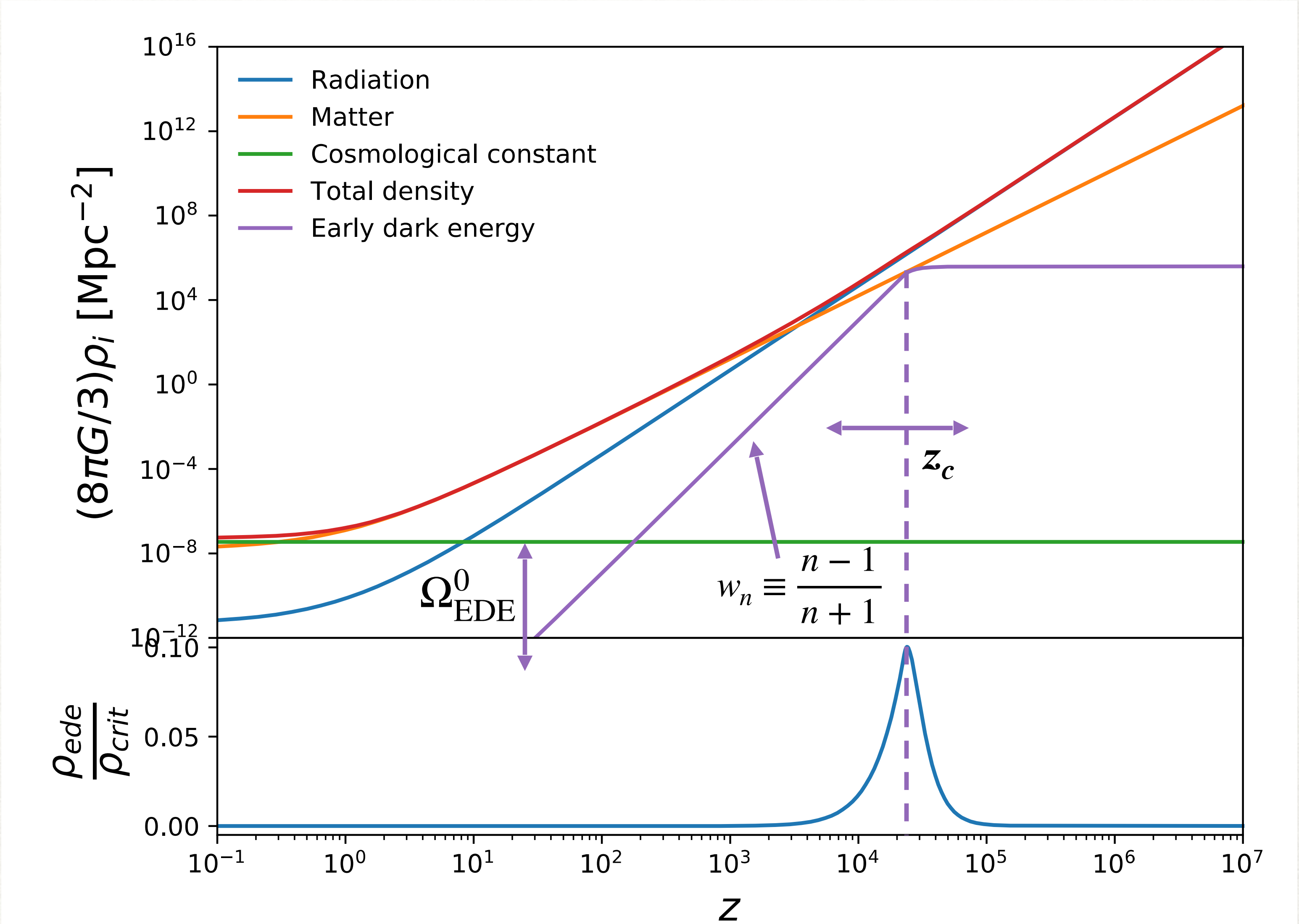
GDM: Hu astro-ph/9801234

- Realized in (at least) two models:

One with oscillating potential ("axion-like") and a simple linear potential

$$V(\phi) \propto \phi^{2n}$$

VP++*1806.10608; Karwal,* ***VP++****(in prep)*



plot by T. Karwal

Scalar field and Early Dark Energy

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

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

- We use the GDM formalism with:

$$\begin{cases} \Omega_{\rm EDE}(z \gg z_c) = \Omega_{\rm EDE}(z_c) \\ \Omega_{\rm EDE}(z \ll z_c) = \Omega^0_{\rm EDE}(1+z)^{3(w_n+1)} \end{cases}$$

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

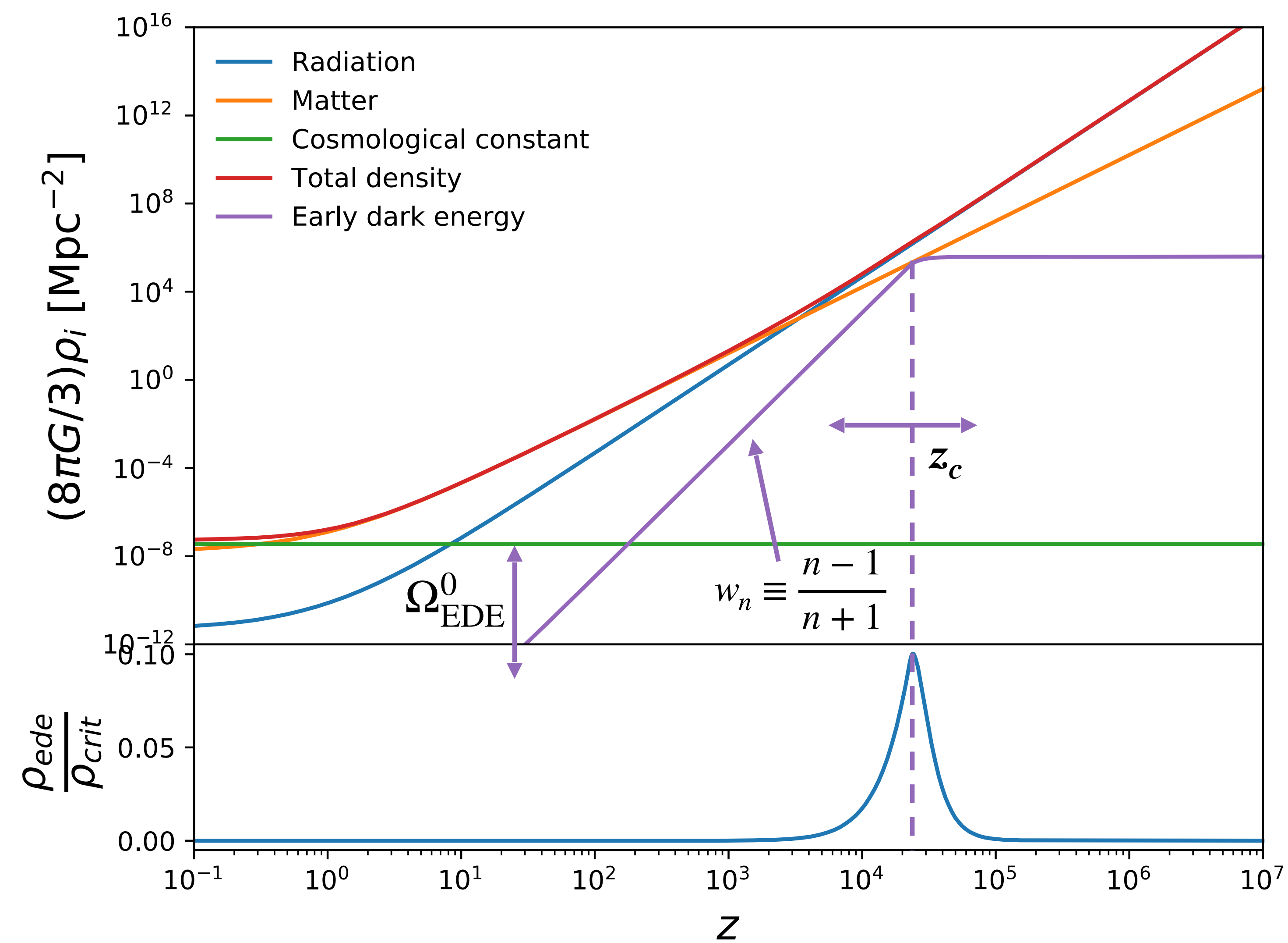
GDM: Hu astro-ph/9801234

- Realized in (at least) two models:

One with oscillating potential ("axion-like") and a simple linear potential

$$V(\phi) \propto \phi^{2n}$$

VP++1806.10608; Karwal, VP++(in prep)



plot by T. Karwal

- This allows us to treat perturbations in the fluid consistently: this is essential to the success of the solution.

background only: Karwal&Kamionkowski 1608.01309

We also include linear perturbations!

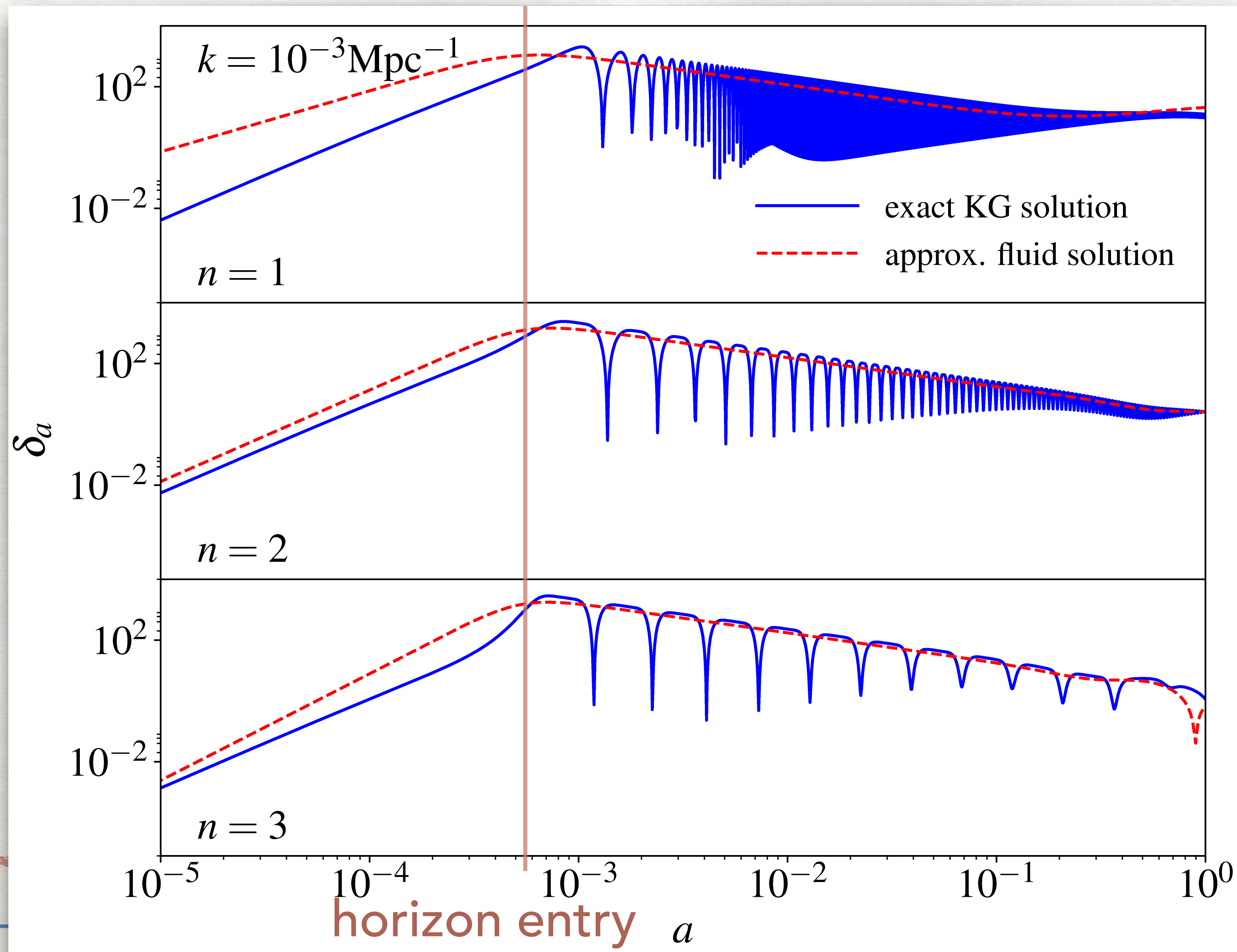
$$\ddot{\phi}_1 + 3H\dot{\phi}_1 + \left(\frac{k^2}{a^2} + V''\right)\phi_1 = (\dot{A} + 3\dot{H}_L - k/aB)\dot{\phi}_0 - 2AV'$$

- 1 hour

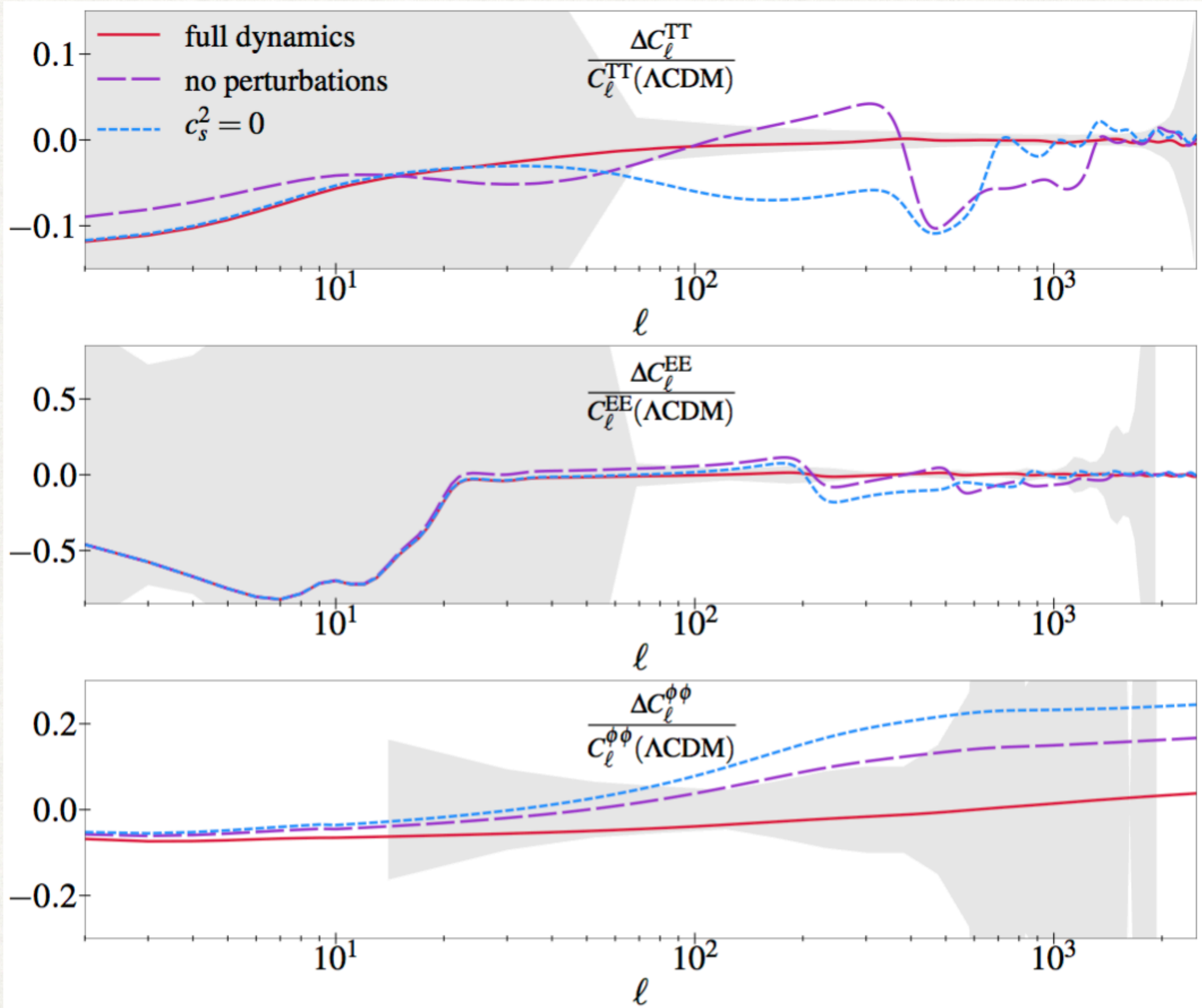
WKB approx.
fluid with c_s^2, c_a^2 & w

$$\begin{aligned}\dot{\delta}_a &= -\left[u_a + (1+w_a)\frac{\dot{h}}{2}\right] - 3(c_s^2 - w_a)\mathcal{H}\delta_a \\ &\quad -9(c_s^2 - c_a^2)\mathcal{H}\frac{u_a}{k^2}\,, \\ \dot{u}_a &= -(1-3c_s^2)\mathcal{H}u_a + 3\mathcal{H}(w_a - c_a^2)u_a \\ &\quad + c_s^2 k^2 \delta_a\,.\end{aligned}$$

- 1 sec!



Perturbations are important



no perturbations: Karwal&Kamionkowski 1608.01309

Early Dark Energy In Cosmological Data?

- CMB+BAO+Pantheon+SH0ES

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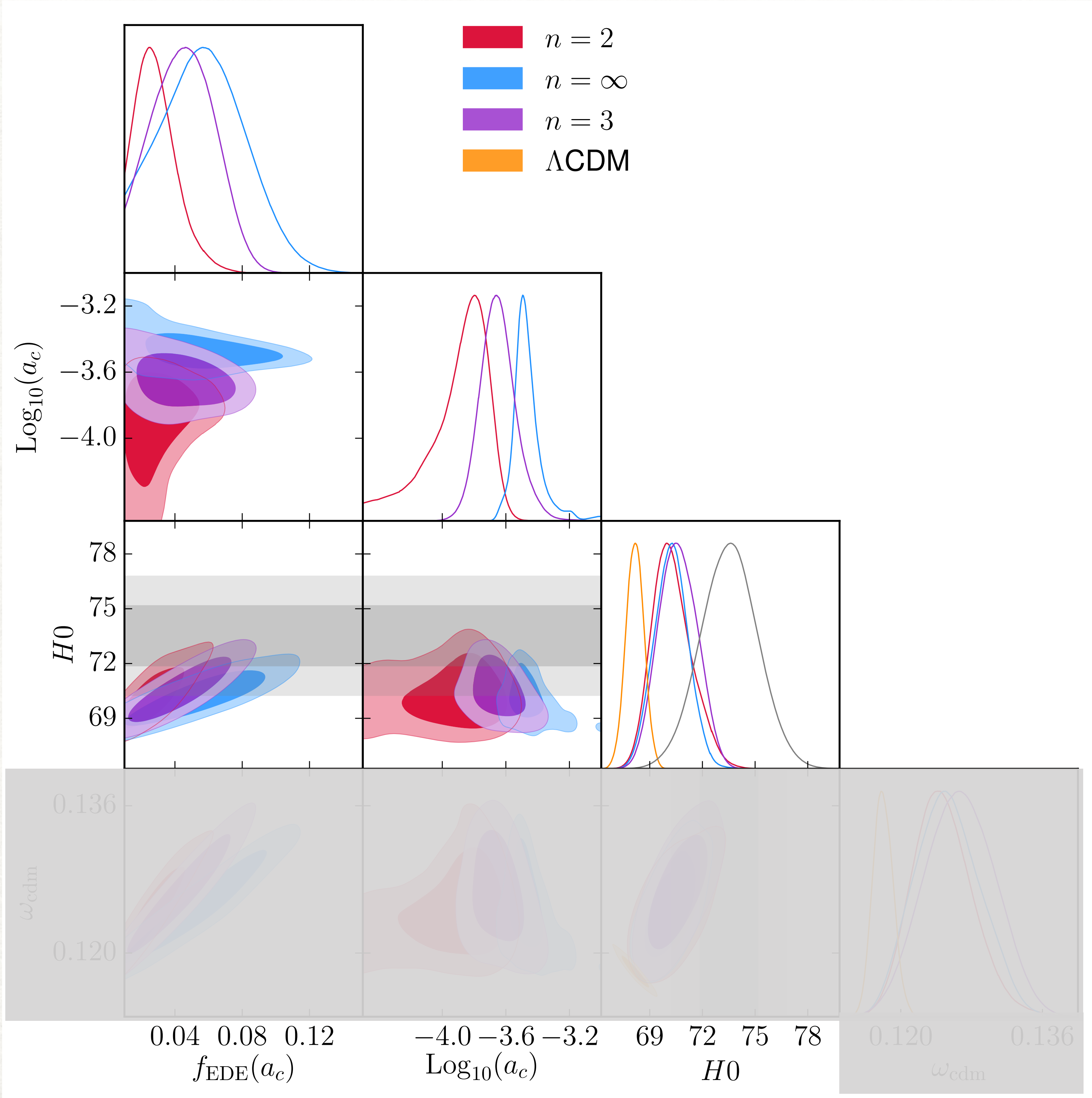


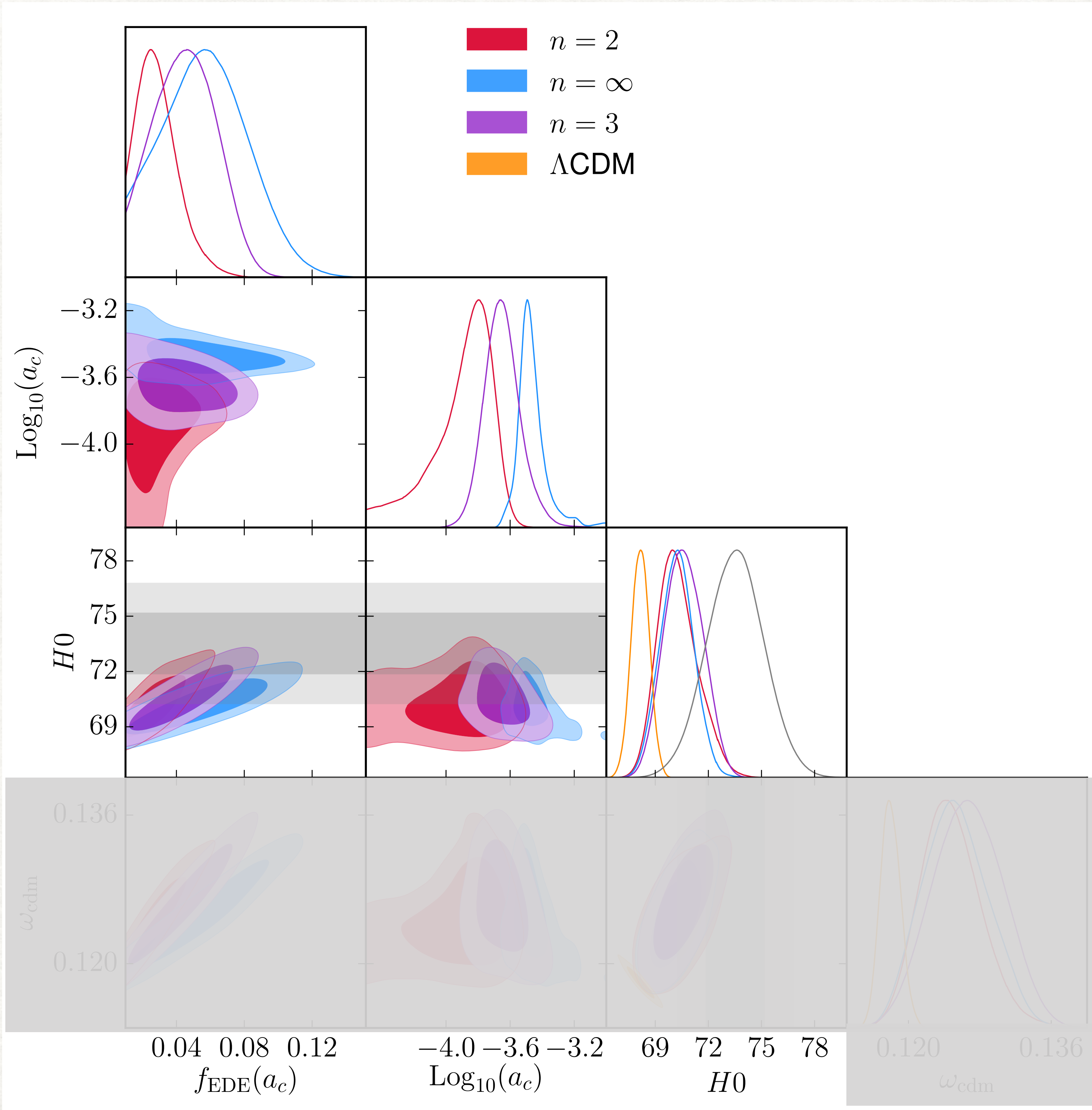
Early Dark Energy In Cosmological Data?

- CMB+BAO+Pantheon+SH0ES

- For n >= 2: ~2σ detection

$$f_{\rm EDE}(z_c) \equiv \frac{\rho_{\rm EDE}(z_c)}{\rho_{\rm tot}(z_c)} \sim 5 \pm 2\,\%$$

$$z_c \sim 4000 - 7000$$



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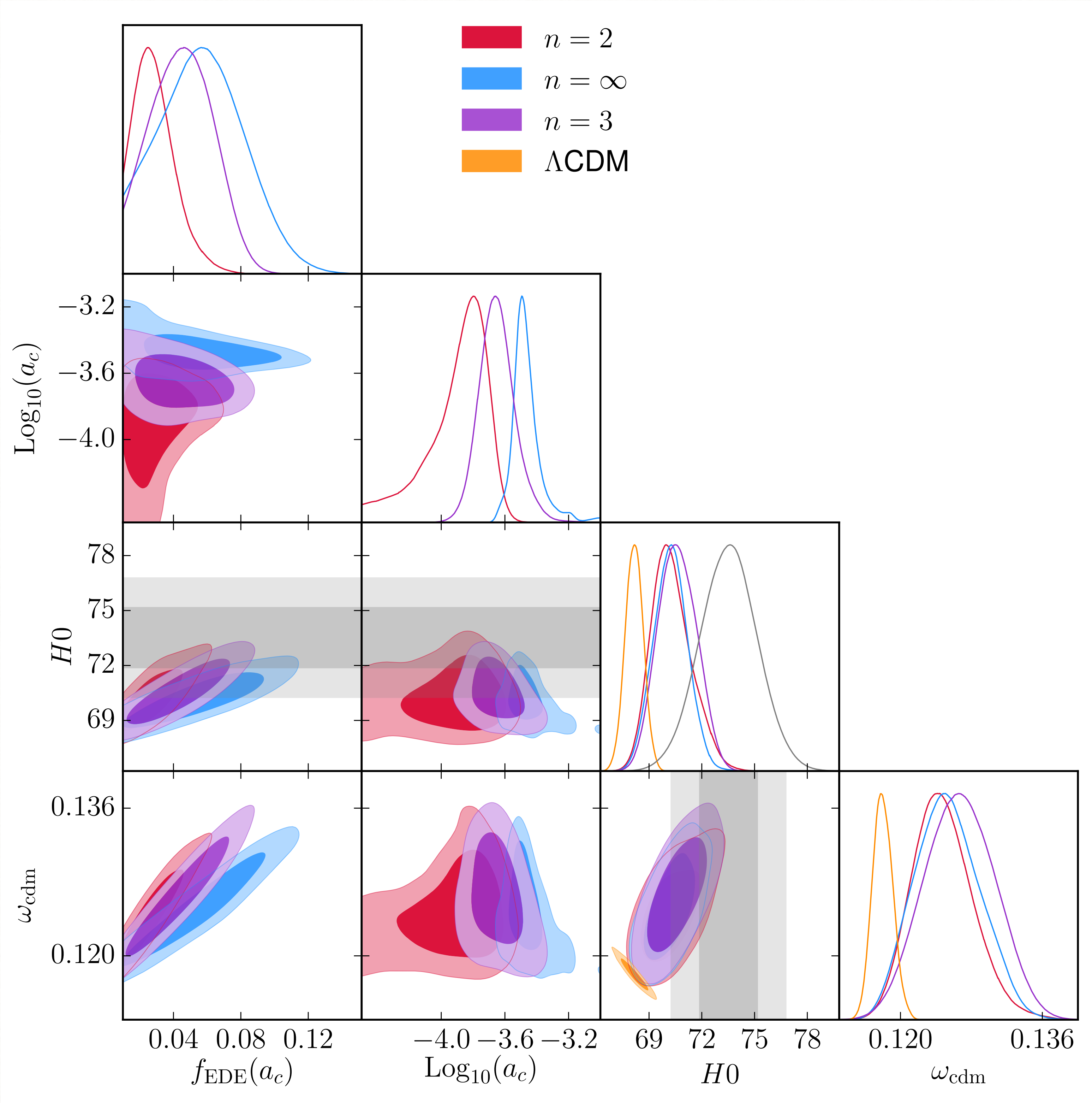
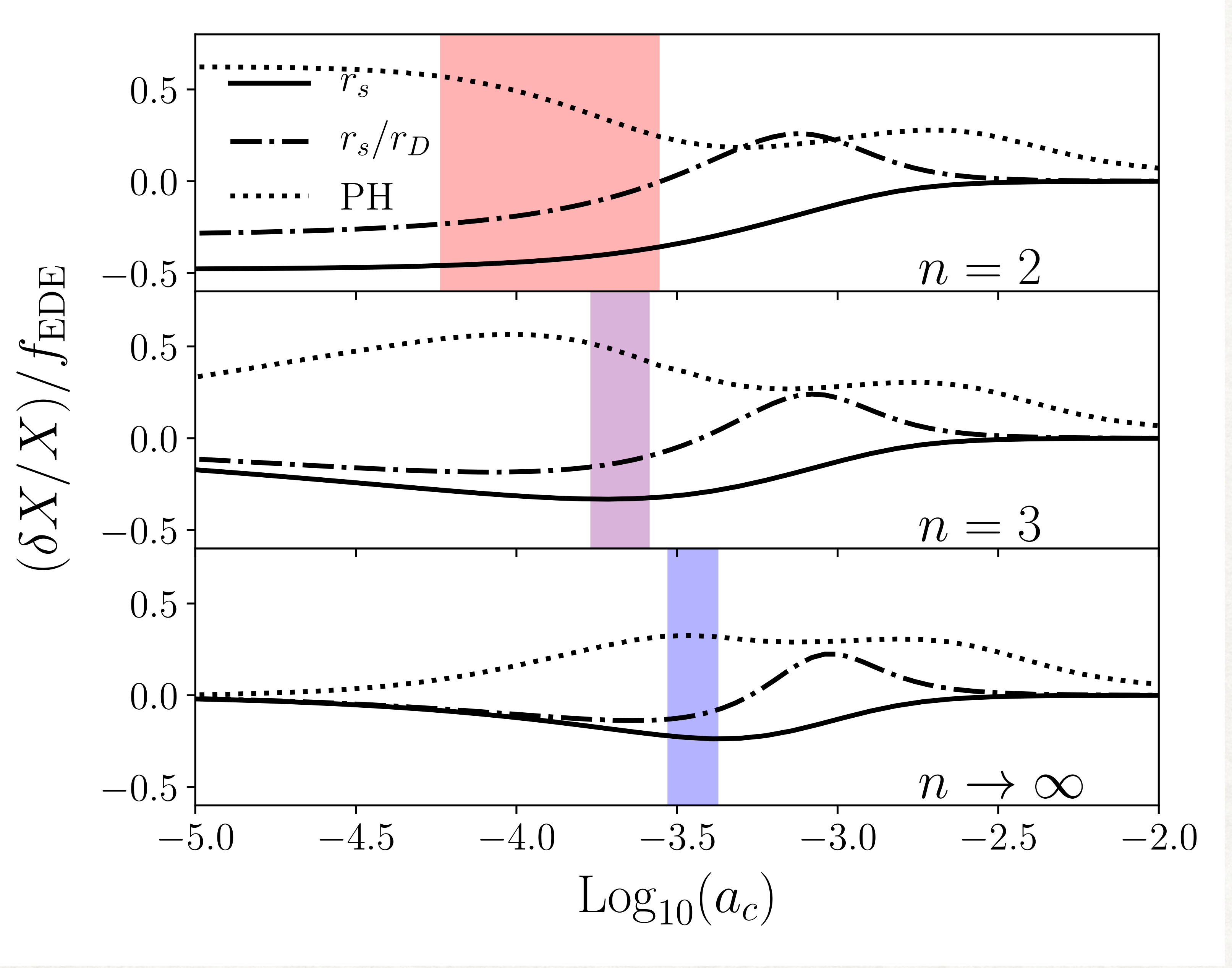
- strong increase in $\omega_{\rm cdm}$



Why $z_c \sim 5000$?

Change in r_s, rs/r_D, Peak Height -vs- a_c



r_s = sound horizon
r_D = damping scale
PH = Peak Height

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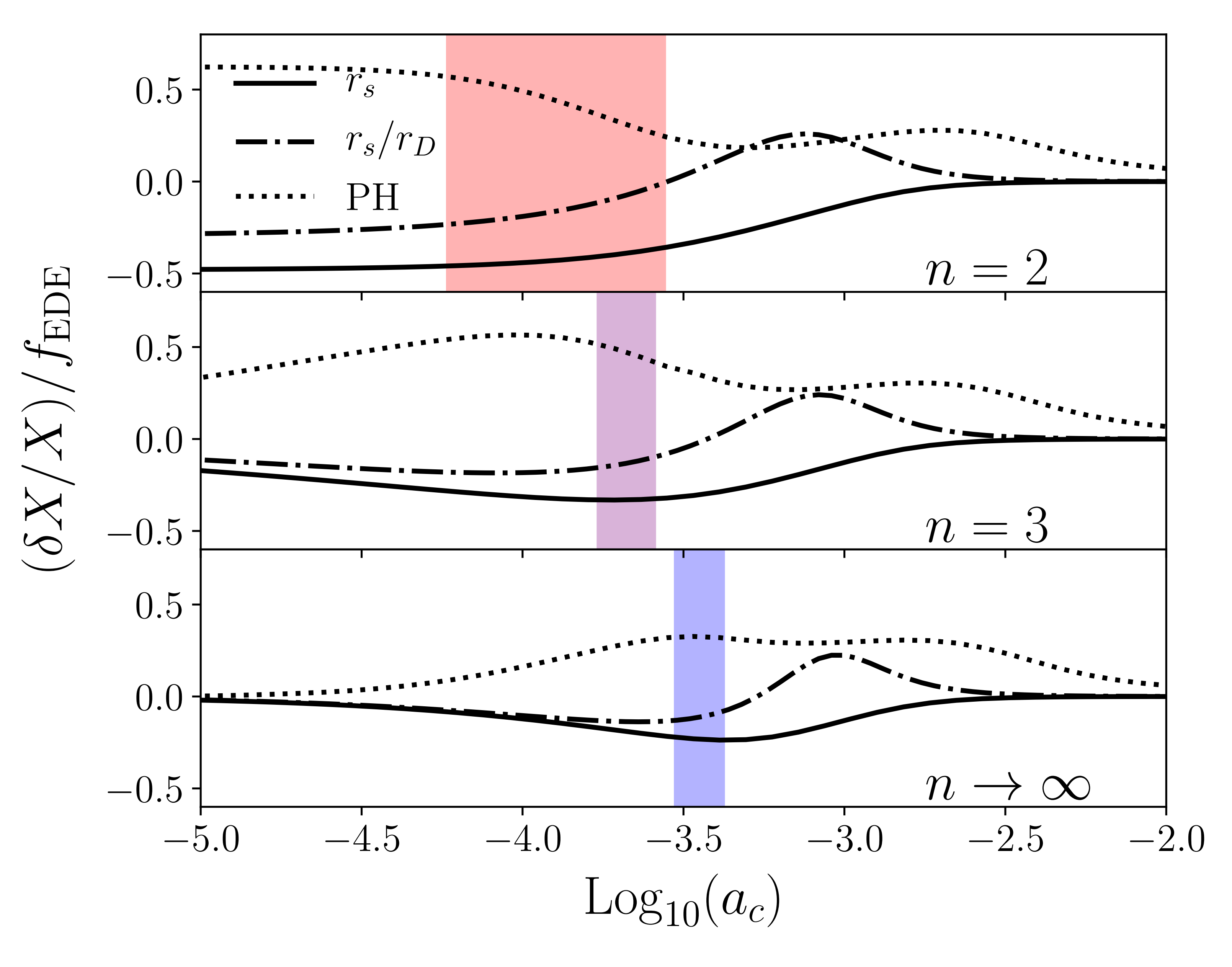

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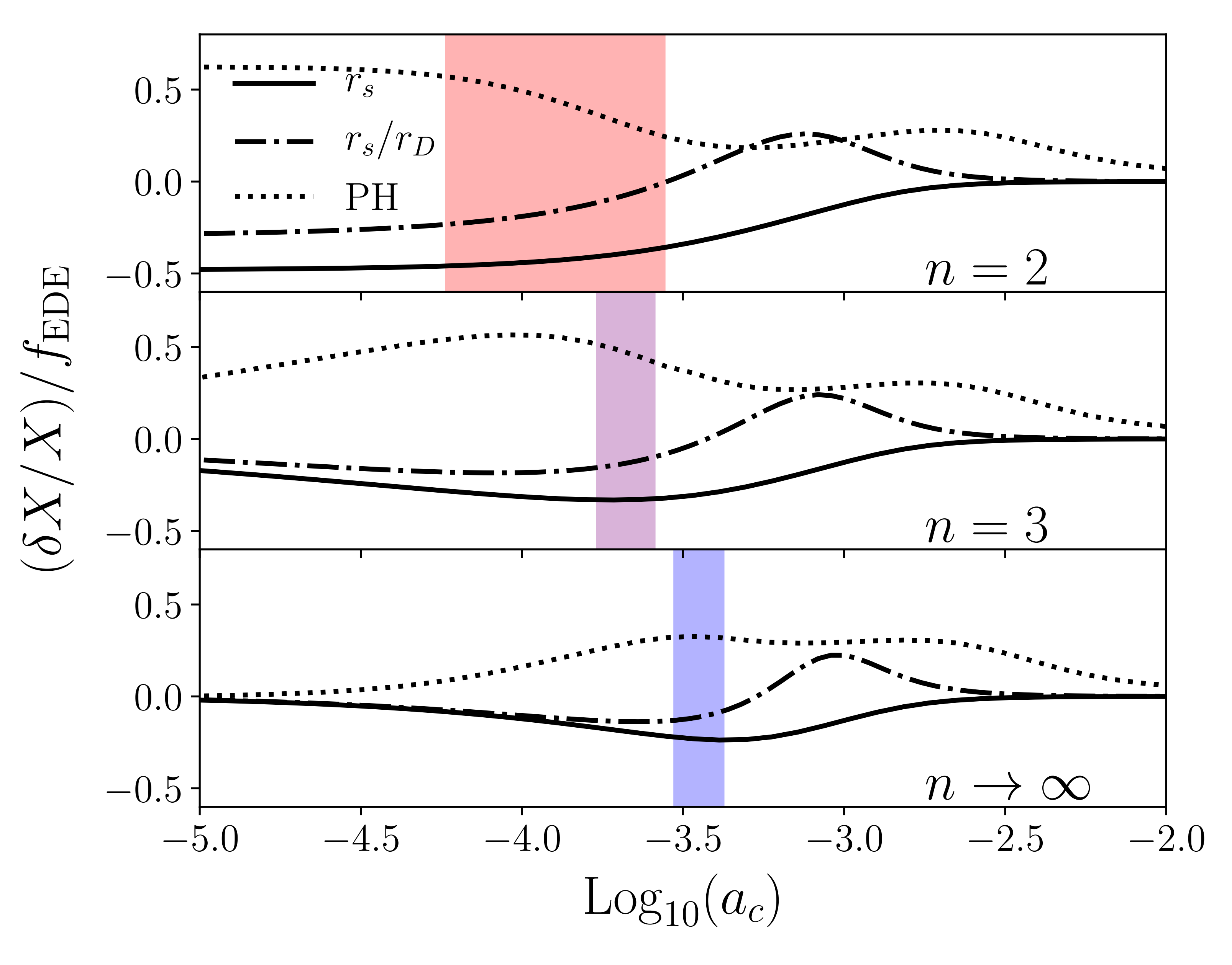

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- From requiring δr_s~10 Mpc; $\delta(r_s/r_d)$~0: Neff is disfavored; n=3 fairs slightly better.

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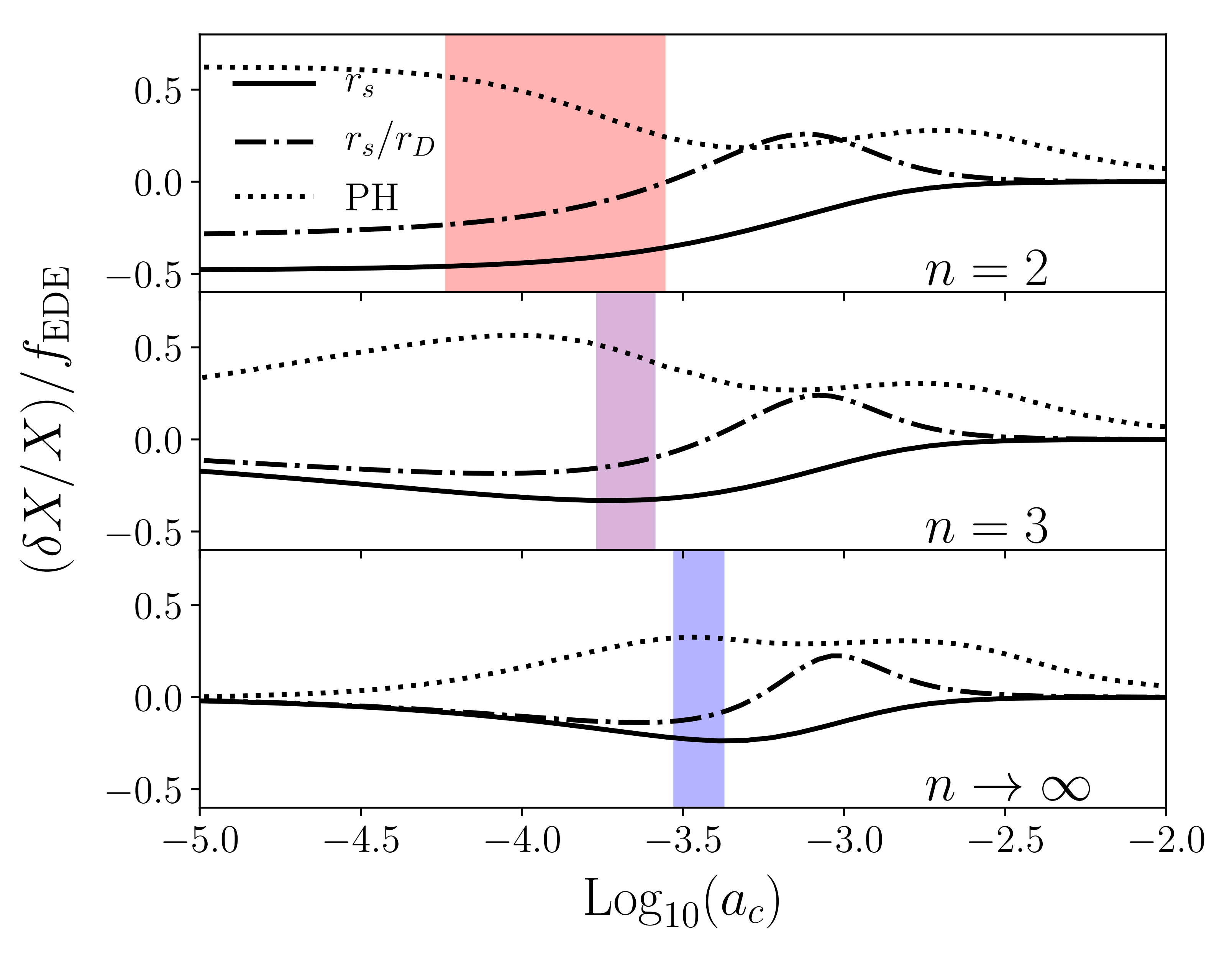

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- Increase in Peak Height (and θ_{eq}) is compensated via increase in ω_{cdm}.

Some Statistics

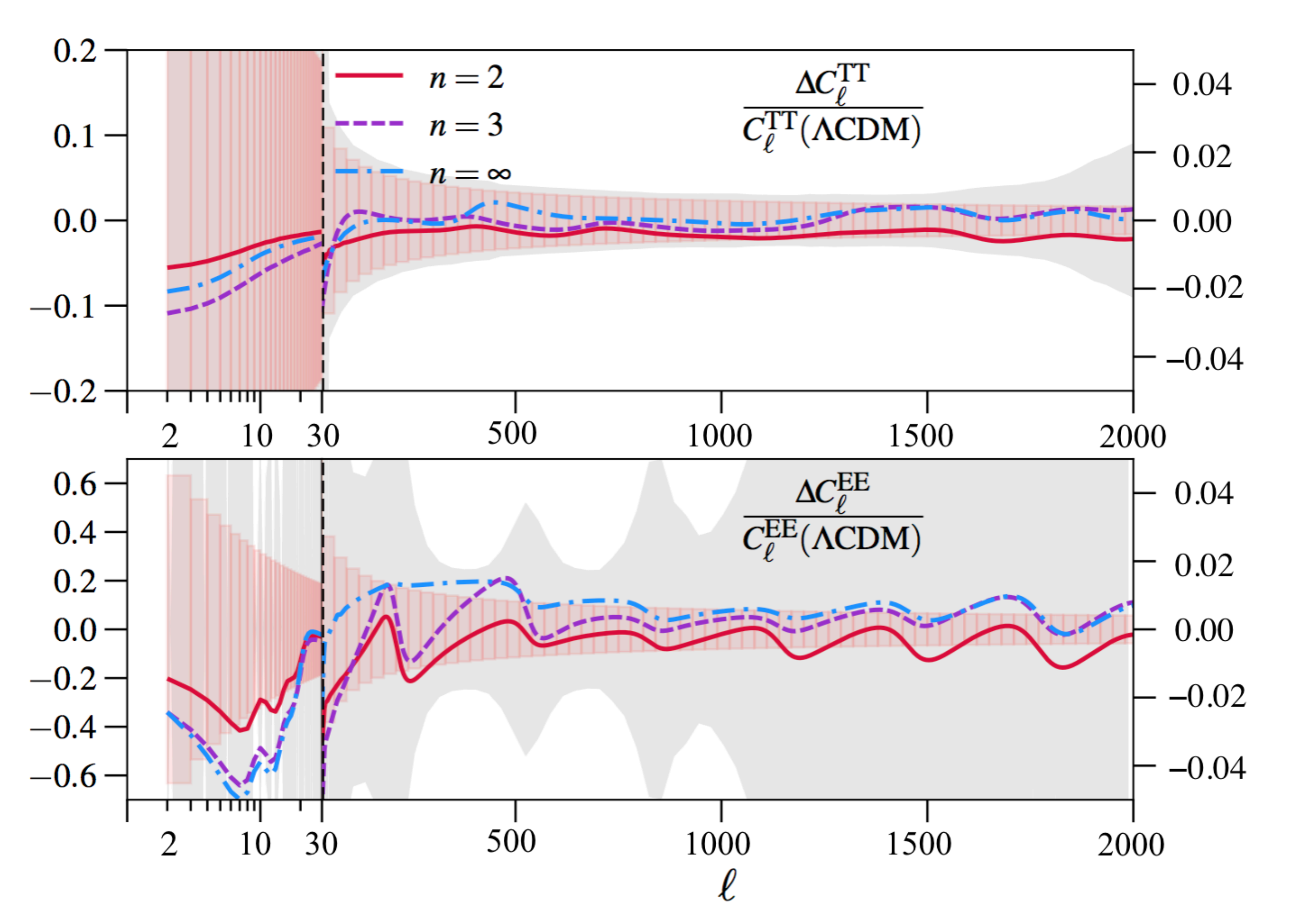
- Slight preference for n=3. “Definite” evidence according to Jeffrey’s scale.

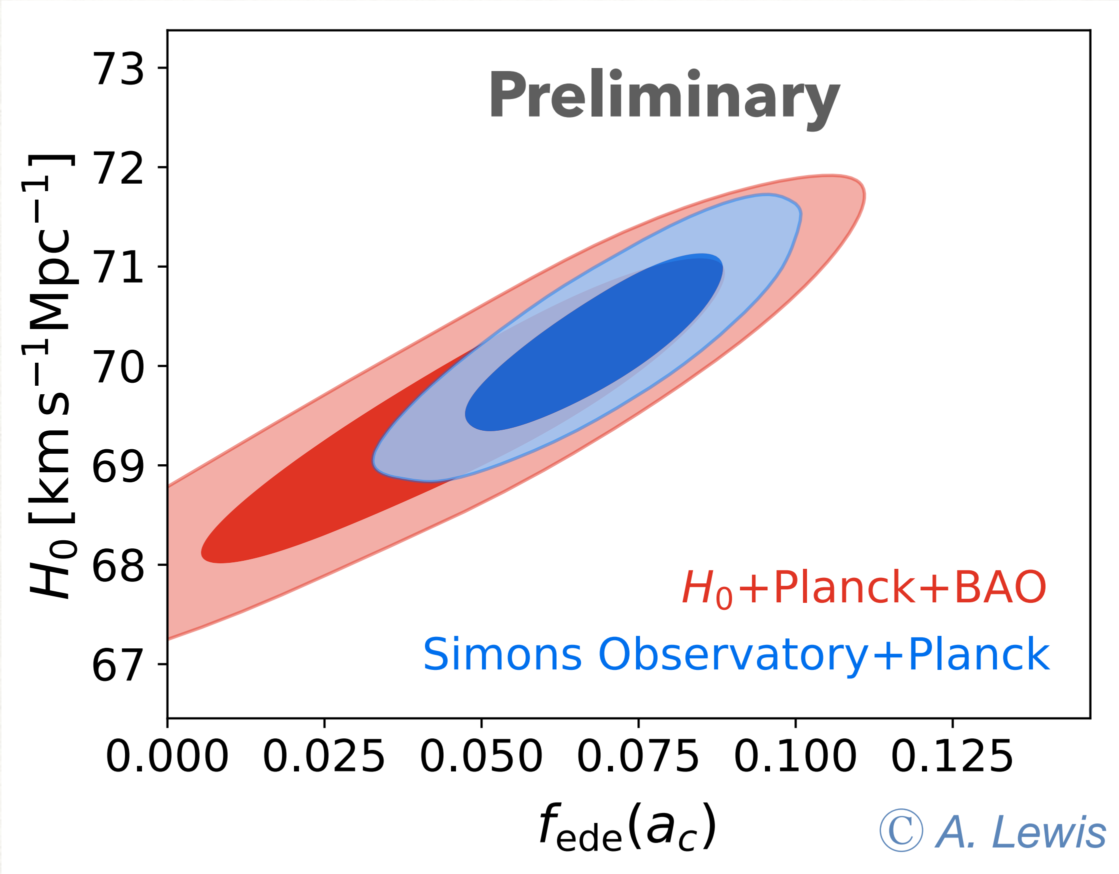
Datasets	ΛCDM	$n=2$	$n=3$	$n=\infty$	$N_{\rm eff}$
Planck high-ℓ	2449.5	2445.5	2445.3	2445.9	2451.9
Planck low-ℓ	10494.7	10494.6	10493.1	10494.4	10493.8
Planck lensing	9.2	9.6	10.0	10.1	9.8
BAO-low z	1.7	1.8	2.3	1.7	2.7
BAO-high z	1.8	1.9	2.1	1.9	2.0
Pantheon	1027.1	1026.9	1027.2	1027.3	1027.1
SH0ES	11.1	4.7	0.92	4.2	3.9
Total $\chi^2_{\rm min}$	13995.1	13985.1	13980.8	13985.4	13991.2
$\Delta\chi^2_{\rm min}$	0	-10	-14.3	-9.7	-3.9
$\Delta \log B$	0	-0.51	+2.51	+2.41	-0.44

- Planck Only: Very slight improvement.

$$\chi^2_{\rm high-\ell} \simeq 2446.2,\ \chi^2_{\rm low-\ell} \simeq 10495.9,\ \chi^2_{\rm lensing} \simeq 9.4$$

Future CMB experiments can probe the model

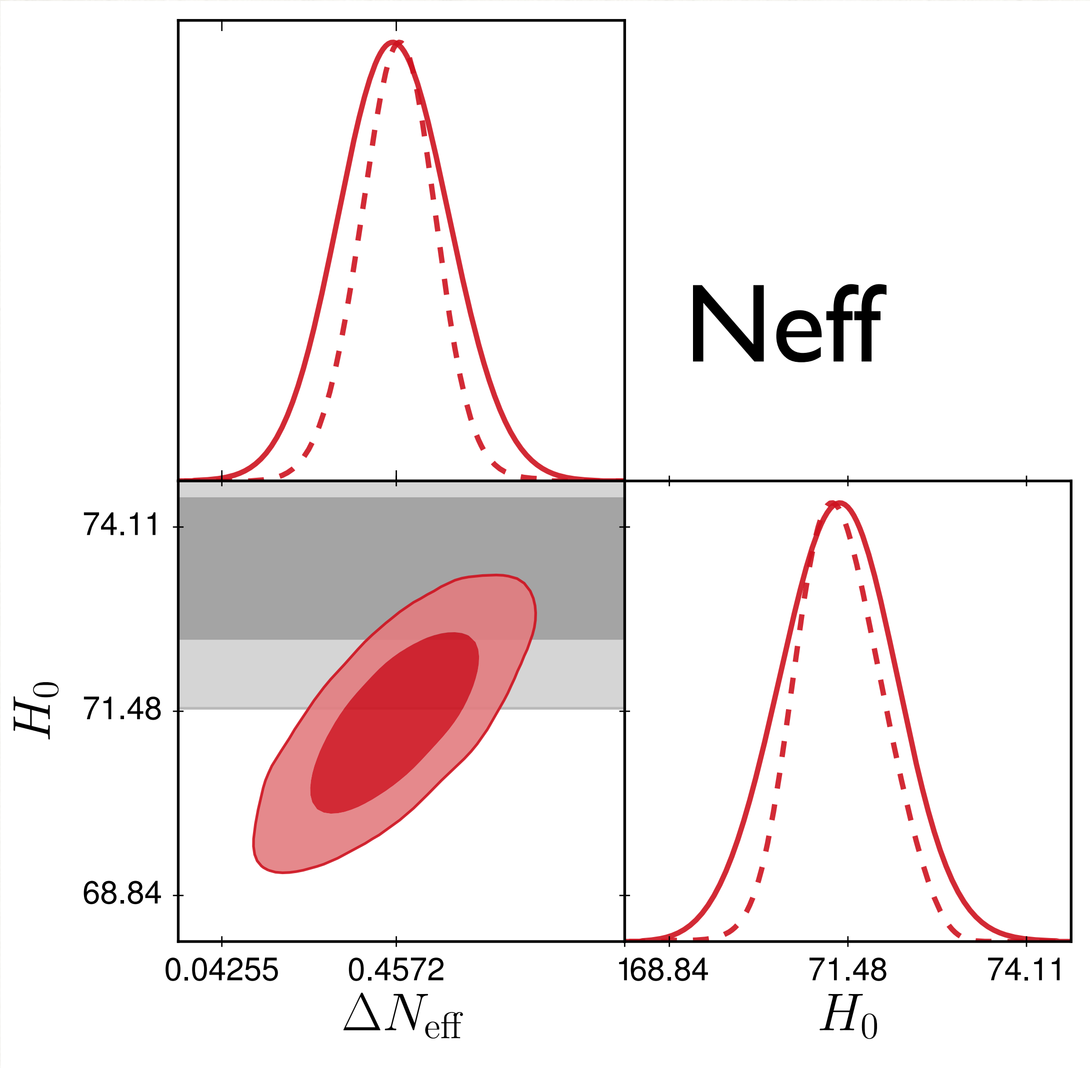


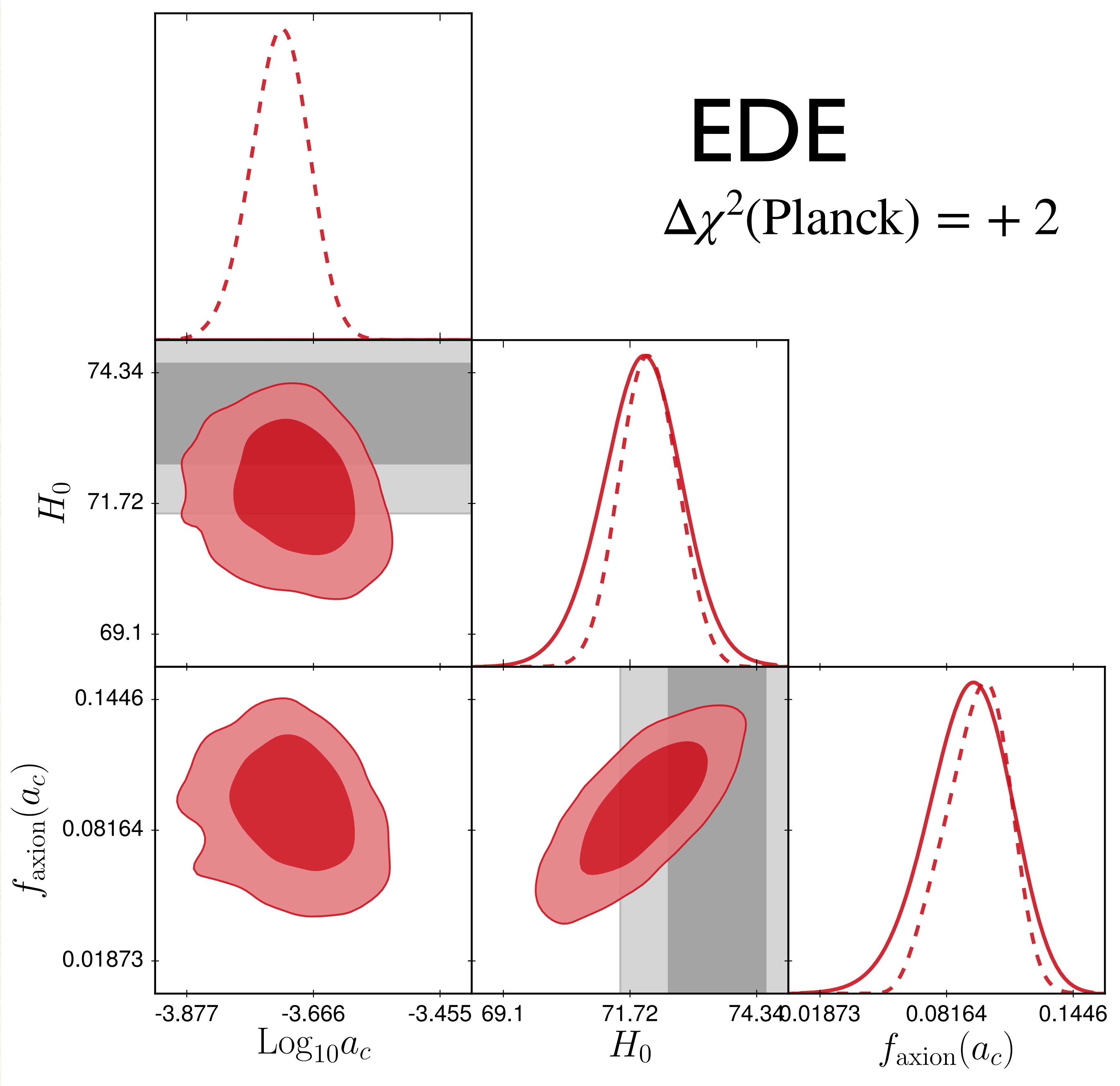


Oscillations in EE would definitely be detected by CoRE/ SO / CMB-S4

Future H0 measurements can help too

what if we had Planck+BAO+Pantheon+ $H_0 = 73.4 \pm 1 \ \frac{\text{km}}{\text{s}}\text{Mpc}^{-1}$

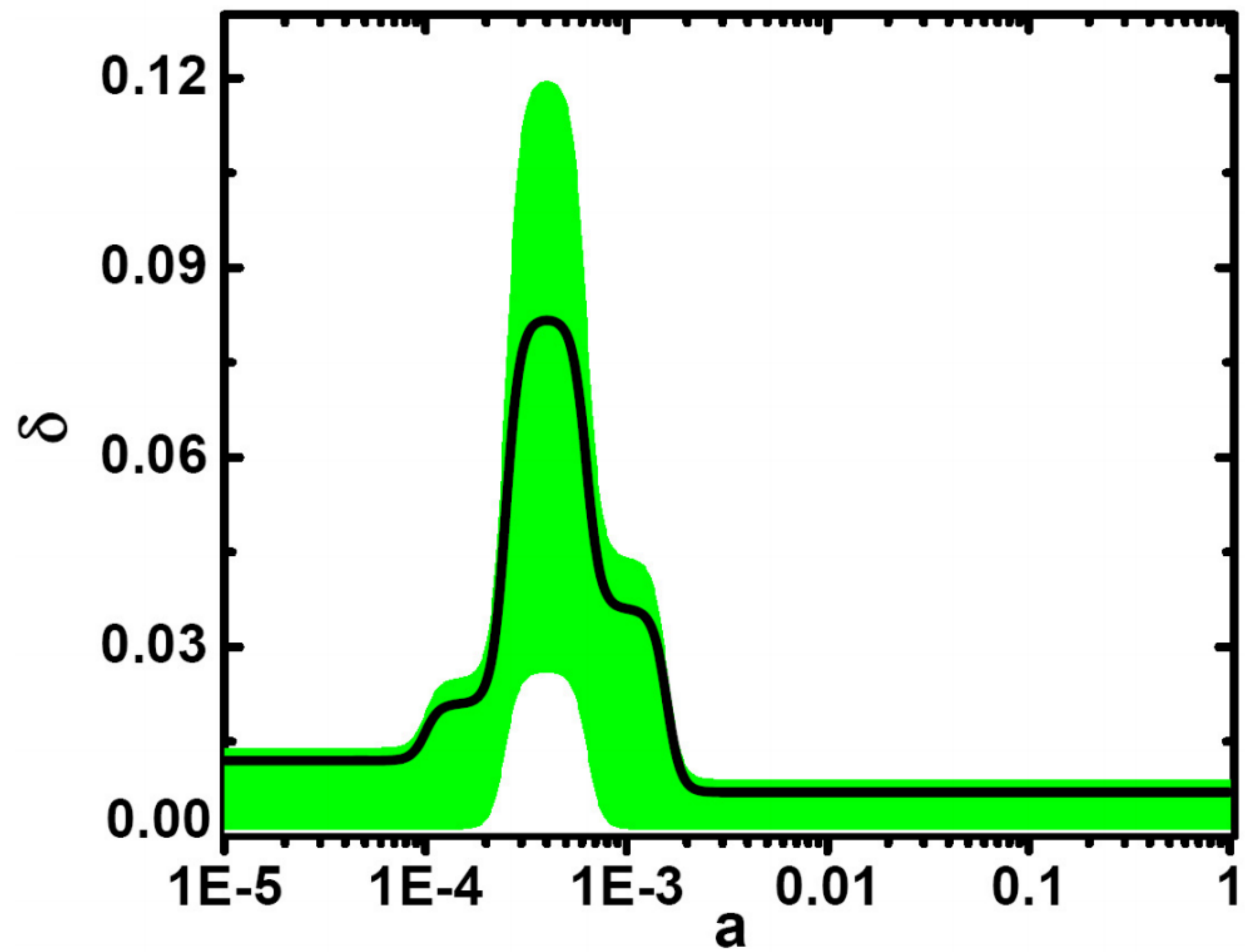




$$\Delta\chi^2 = 14$$

Towards a new concordance model?

Planck 2013 data already hinted at accelerated expansion history around a~5*10^{-4}!



$$H^2(a) = \frac{8\pi G}{3}[\rho_m(a) + \rho_r(a) + \rho_\Lambda][1 + \delta(a)]$$

Hojjati, Linder, Samsing 1304.3724

Here Planck TT 2013 + WMAP EE and TE, to be confirmed with 2018 data…

Some lessons to be learned

- If the "Hubble Tension" is confirmed by other local H0 measurements, the EDE solution represents the best possible "early-universe" solution.
- There are many open questions with the potential presence of such an EDE phase.
- Obvious "fine tuning" issues: why would it need to kick right around matter-radiation equality? why in such amount?

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- Obvious "fine tuning" issues: why would it need to kick right around matter-radiation equality? why in such amount?

ΛCDM already has similar issues!

- The 'coincidence problem': why now? Structure cannot grow in CC dominated universe.

- Hierarchy problem: why is this scale $(0.002\ \mathrm{eV})^4$ so different from Weak / Planck scales?

A New Understanding Of Λ?

with Tenkanen, Smith, and Kamionkowski

- Accelerated expansion era might be related to each other. What if there were more of such era to be discovered?
- 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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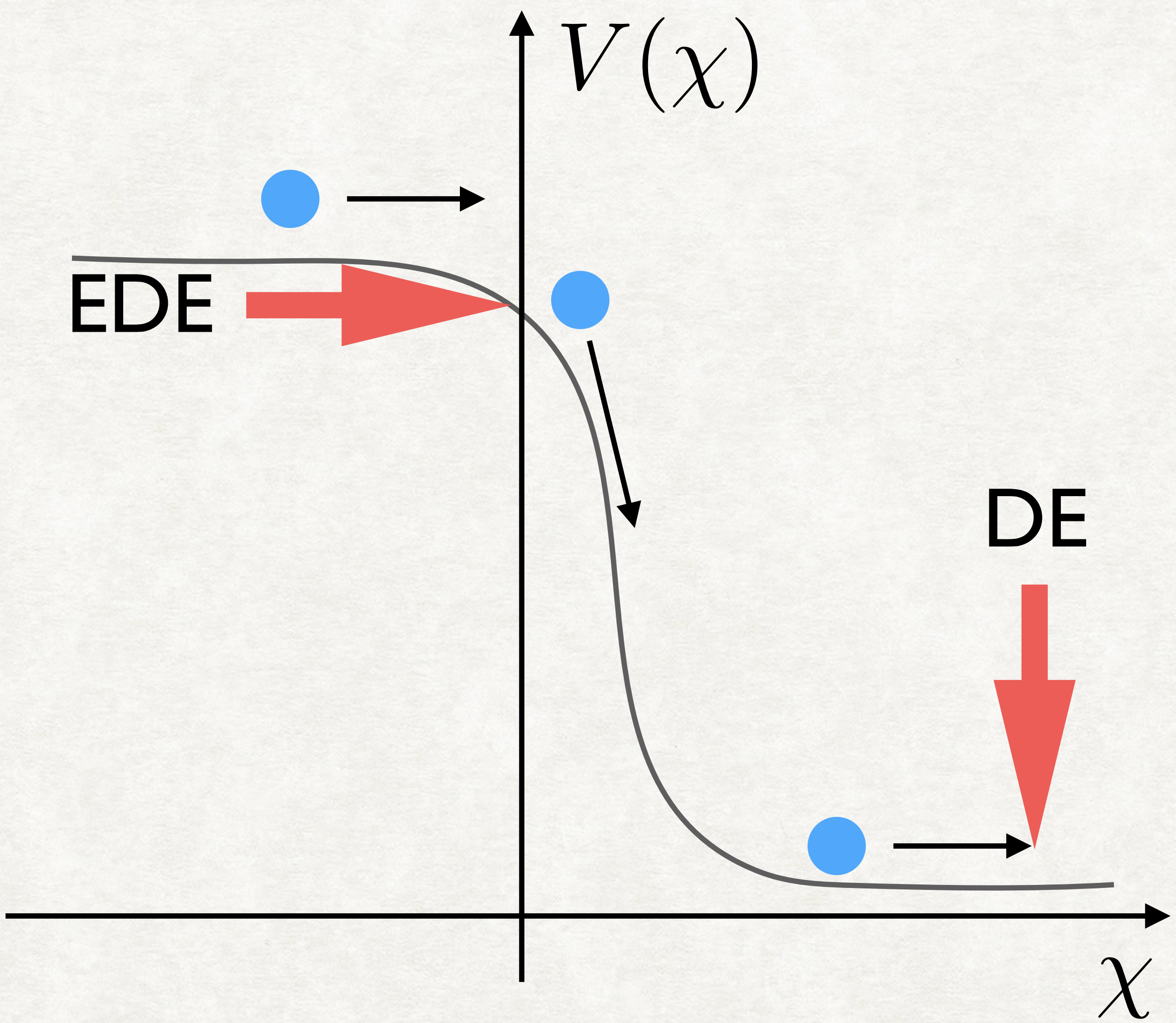

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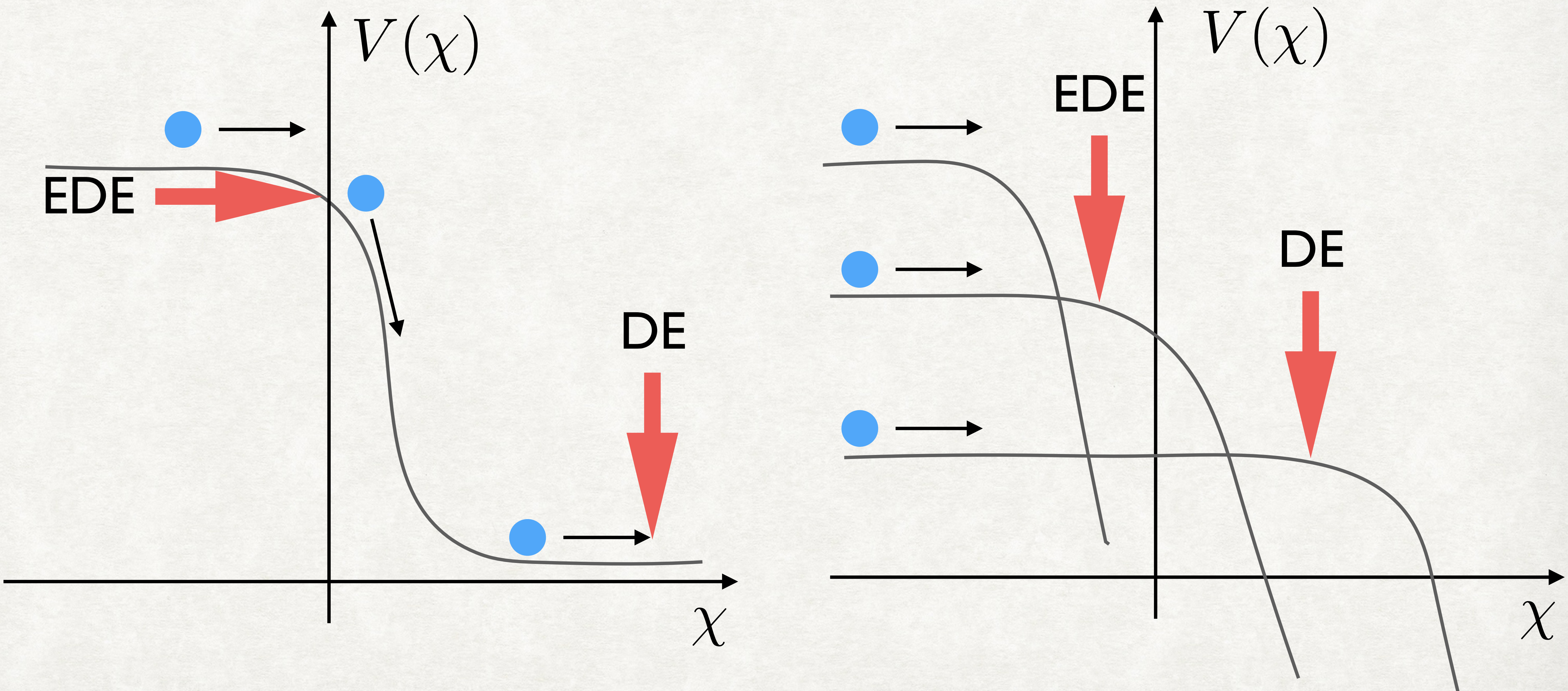

Conclusions

- H_0 from local measurement is in 3.8σ tension with LCDM-inferred value from Planck: this tension also exists with non-SN and non-CMB data! It is a tension between our understanding of the early and late universe.

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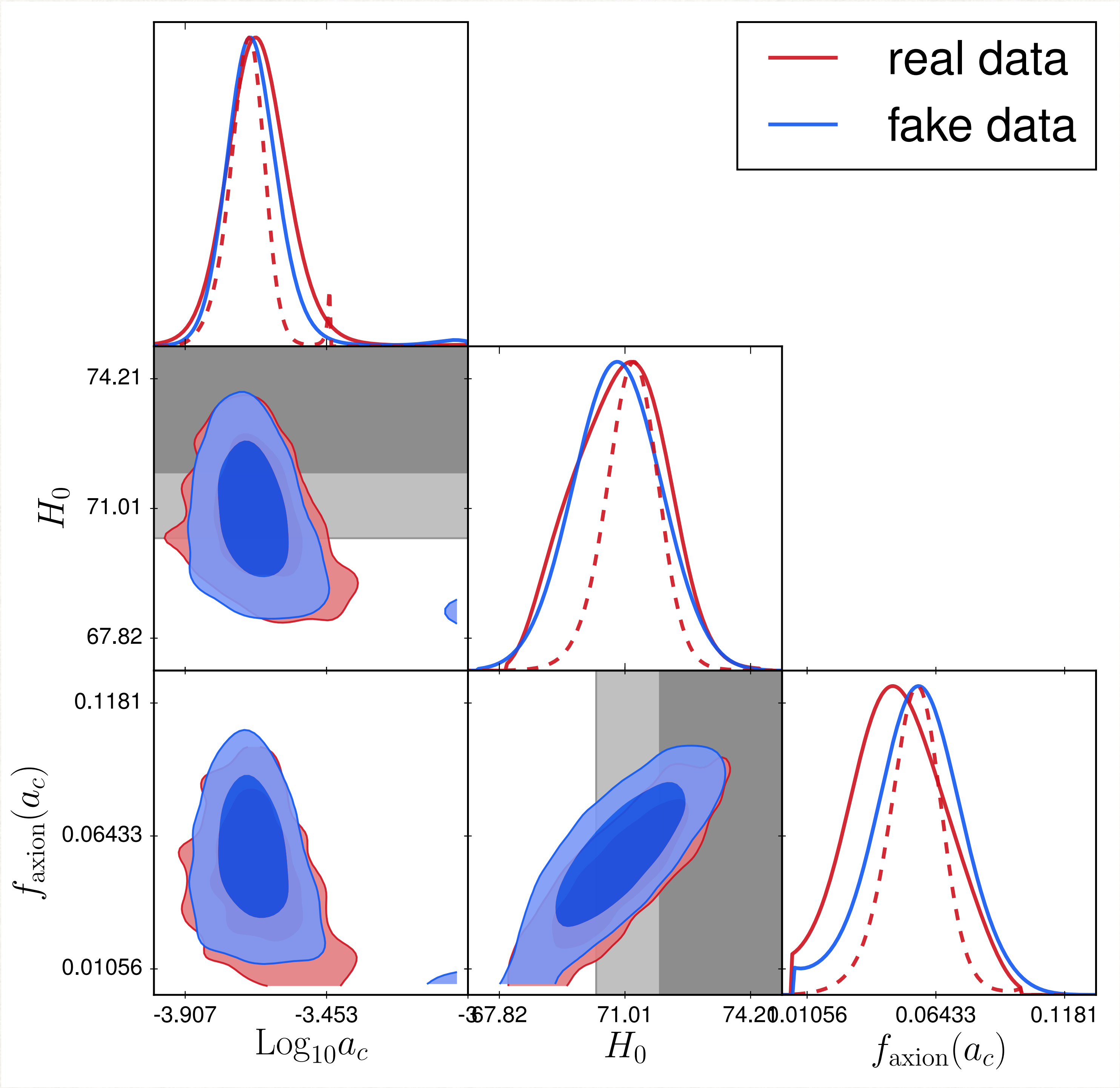
- If this is the "correct" solution: there might be new ways of interpreting Λ and inflation.

And the winner is?

Thank you!

Back Up

Should we detect 5% EDE with Planck?



Fiducial = best fit model with EDE. Optimistic Planck + SH0ES cannot see it at >2sig.

How does CMB data measure H0?

$$\theta_X \equiv \frac{r_X}{d_A}$$

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436

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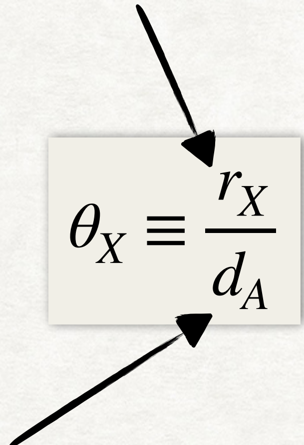

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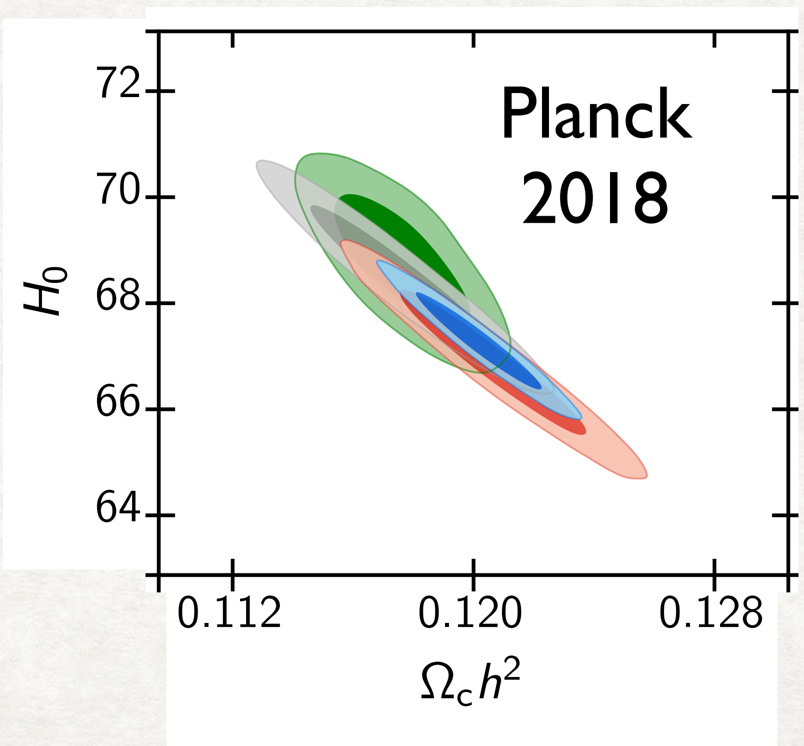

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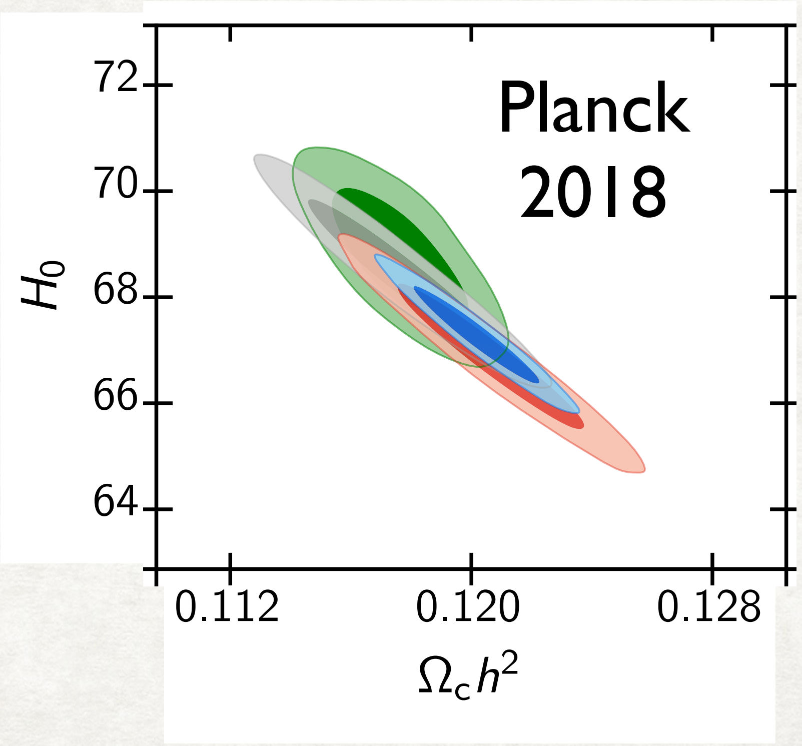

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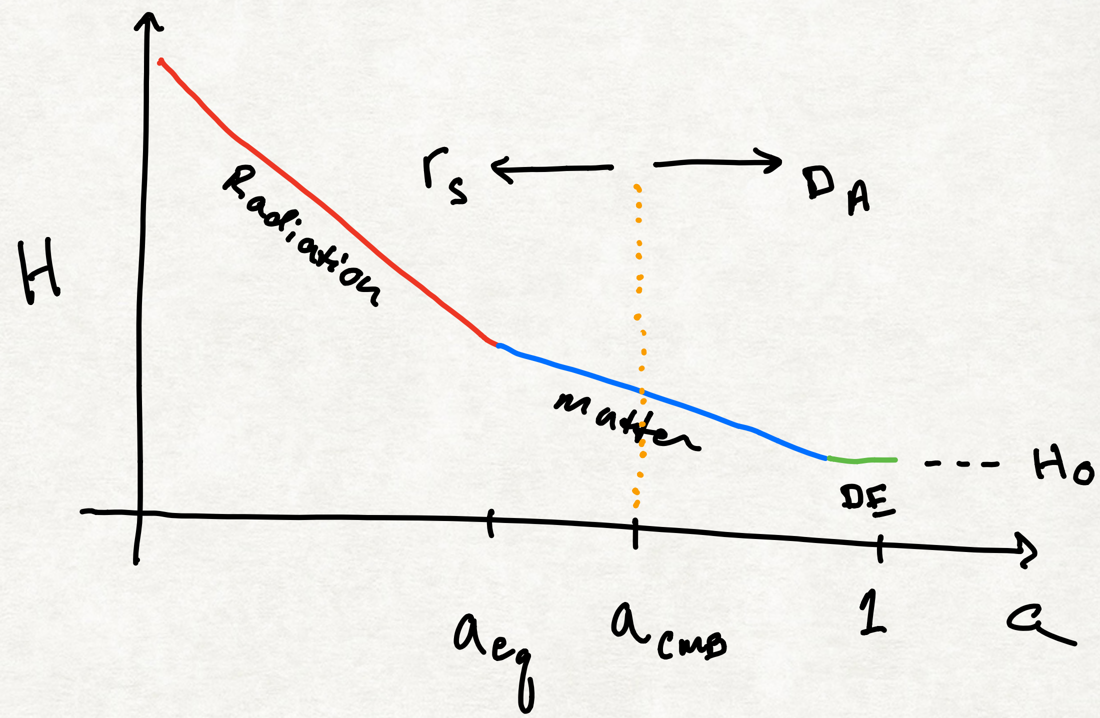

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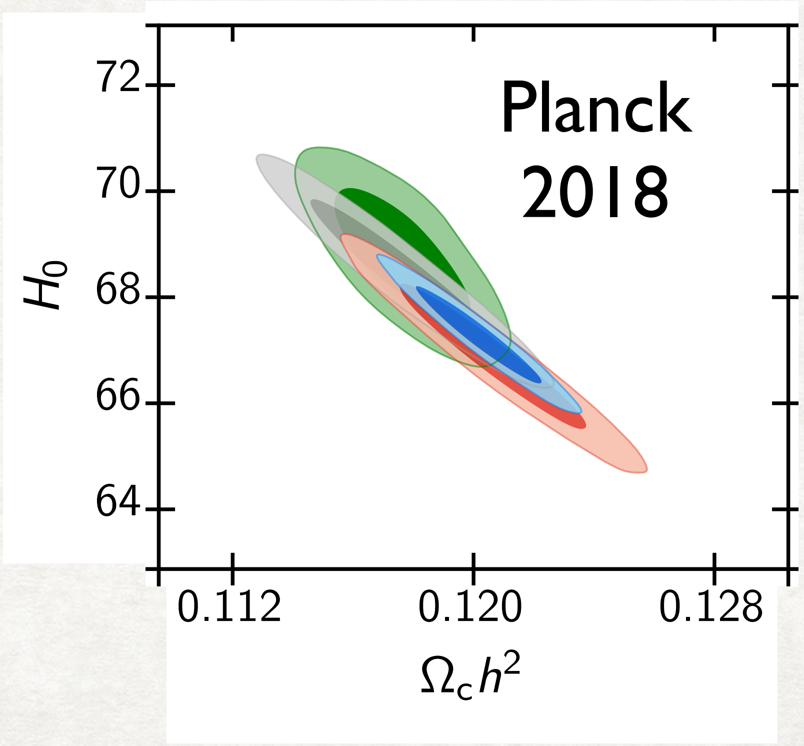

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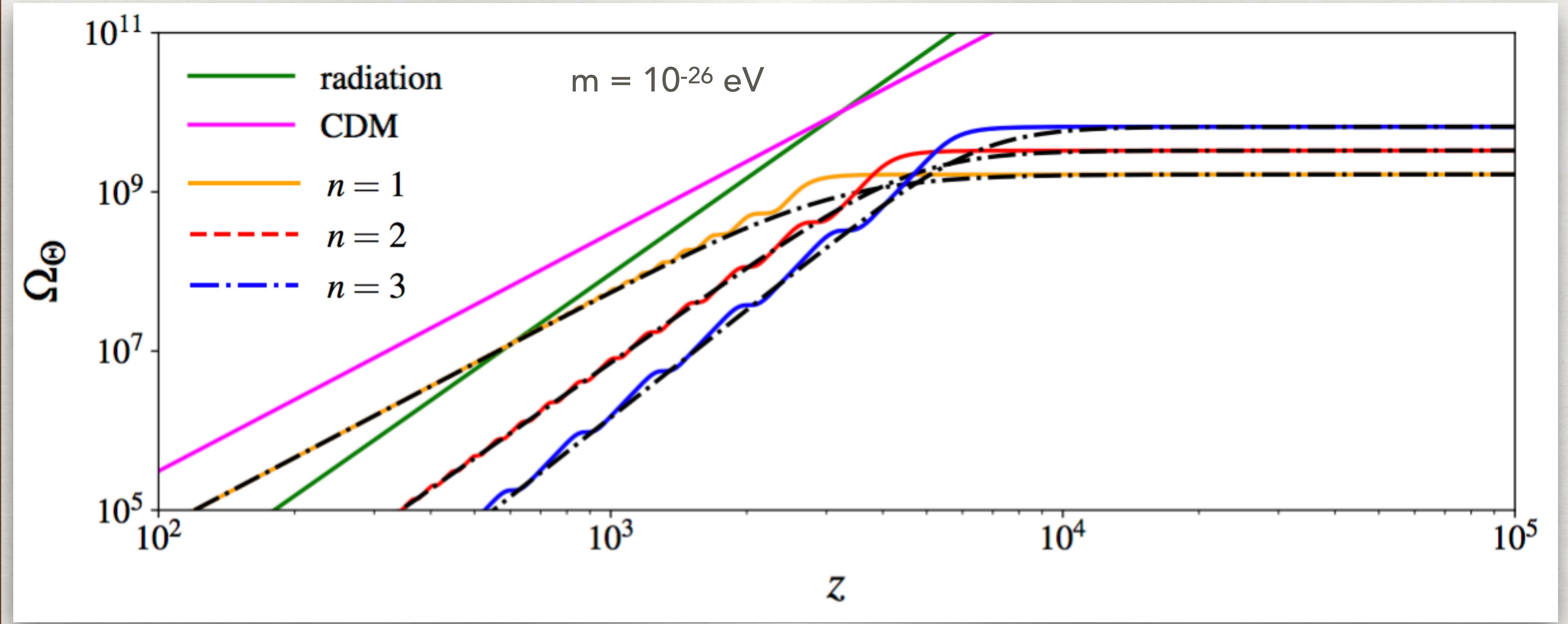
Typical (background) dynamics of ULA

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608



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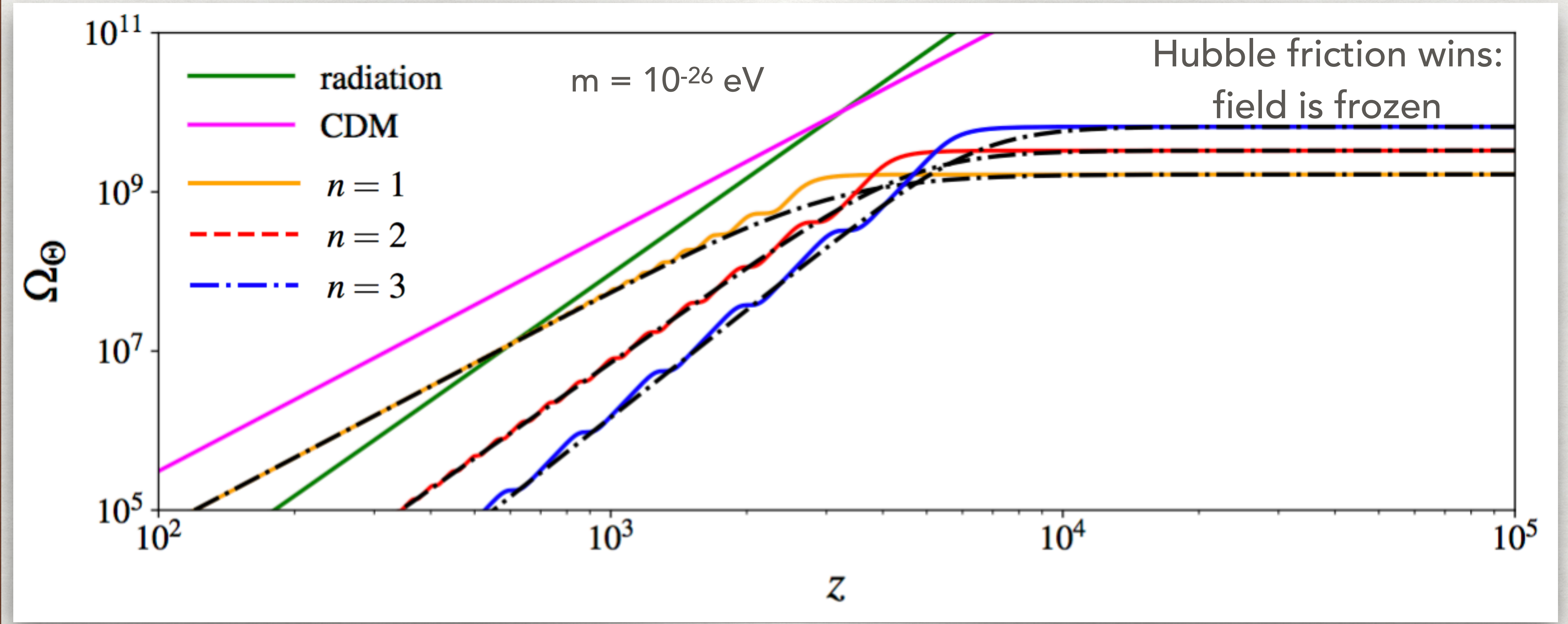

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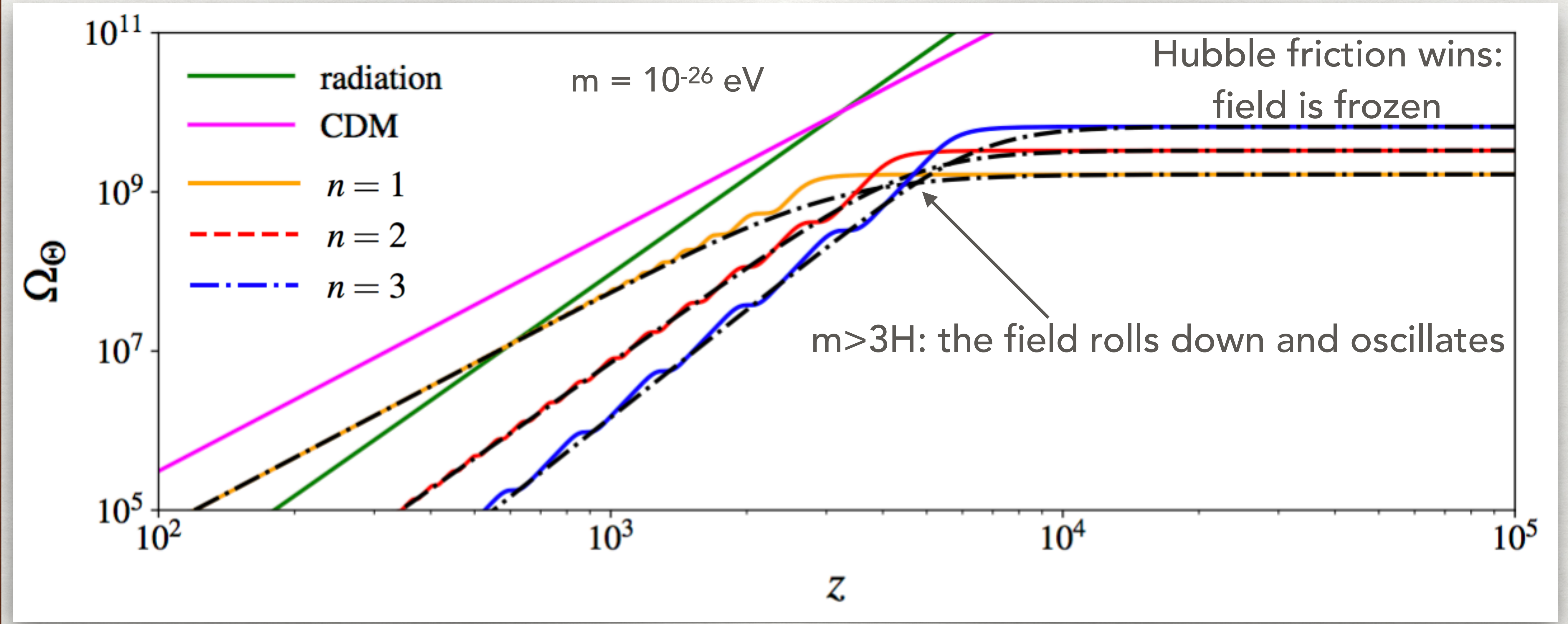

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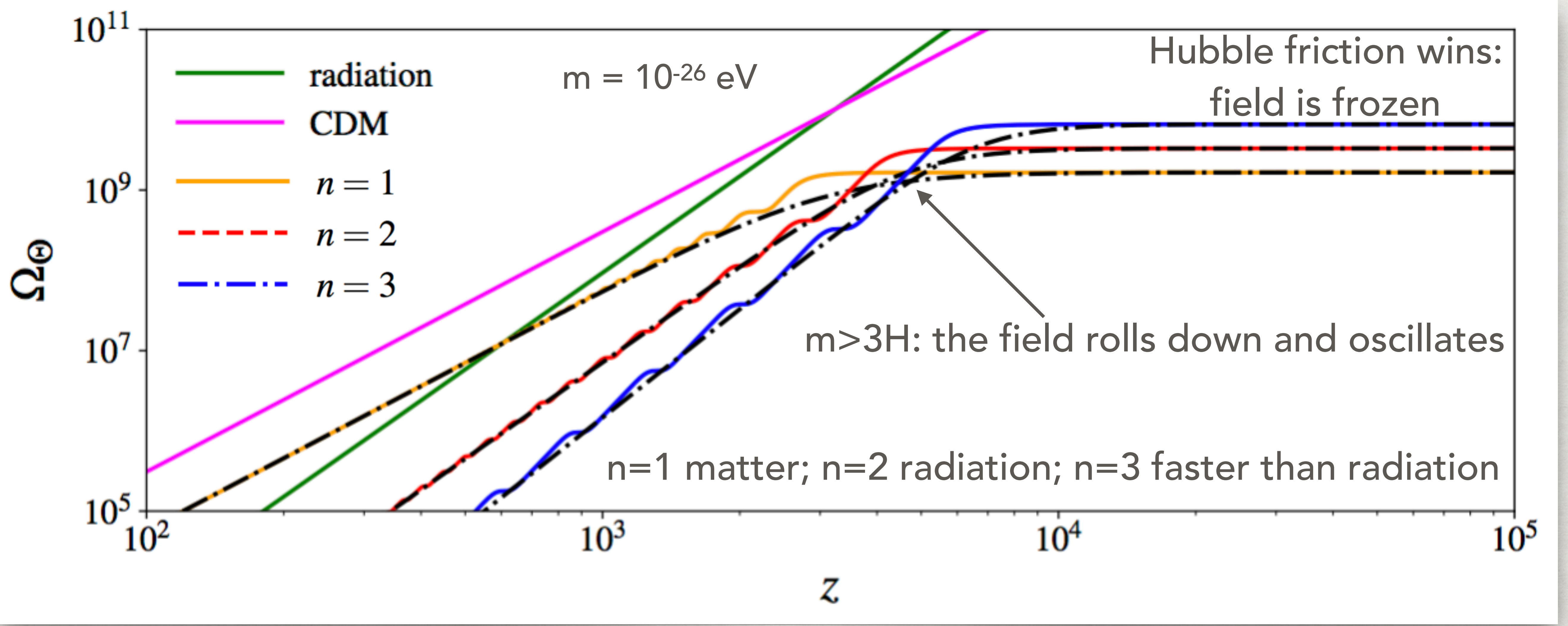

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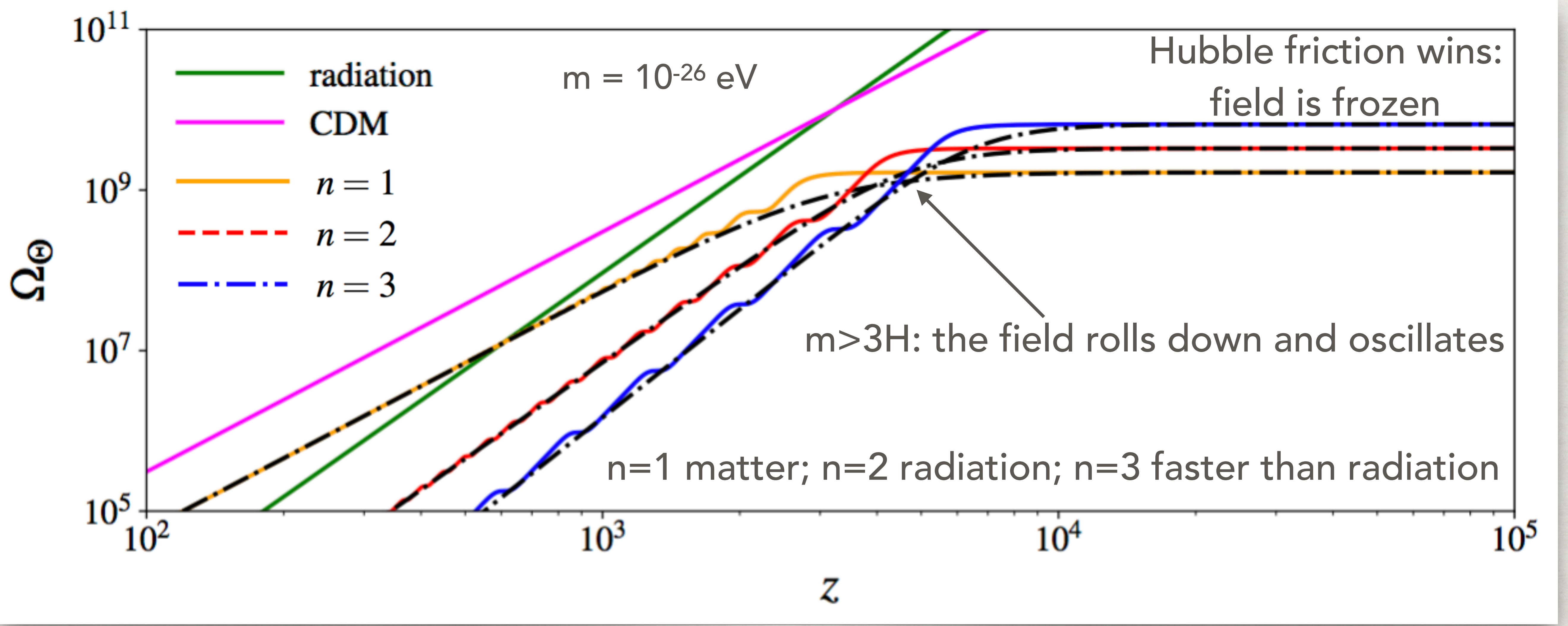


Key Idea: Early Dark Energy can increase expansion rate and solve various tensions.
Once the field becomes dynamical, it dilutes away (the faster the better)!

When is the WKB approximation valid?

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608

- Our WKB approximation requires oscillation time-scale << Hubble time-scale

- The oscillation time-scale can be obtained from requiring that energy is conserved over several oscillations (no friction).

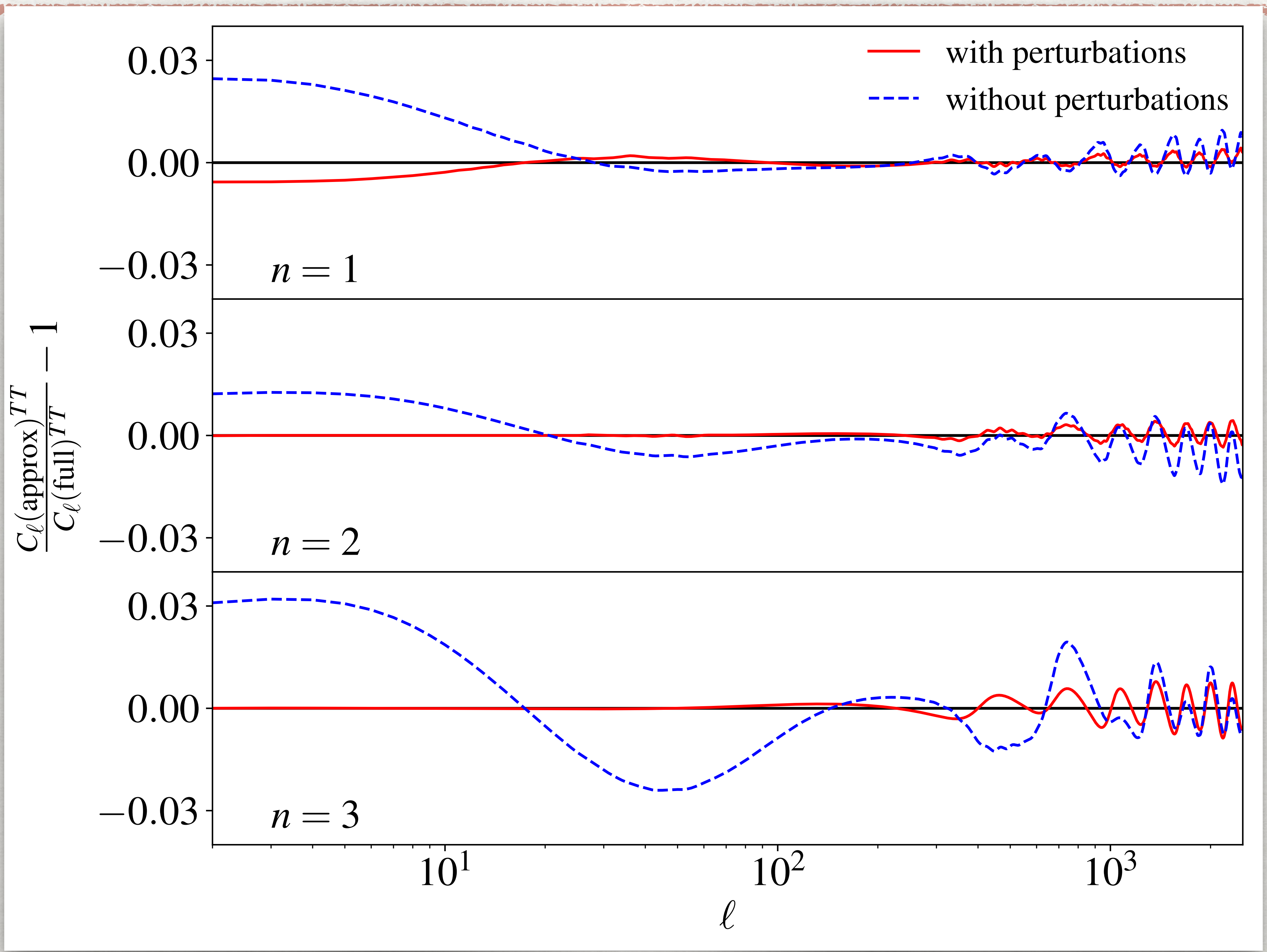
$$\frac{\varpi}{H} \propto \begin{cases} a^{(5-n)/(1+n)} & a < a_{\rm eq}, \\ a^{6/(1+n)-3/2} & a > a_{\rm eq}, \end{cases}$$

see also Johnson and Kamionkowski, 0805.1748

- This ratio increases with time for $n < 5$ during radiation domination and for $n < 3$ for matter domination.

- The condition $\omega > H$ holding at all time requires $n < 3$.

Comparison with full KG calculation



- Without perturbations, precision is >3% given Planck constraints. Planck is ~1% precise!
- With perturbations, sub-percent agreement: 1h vs 1sec computation time!