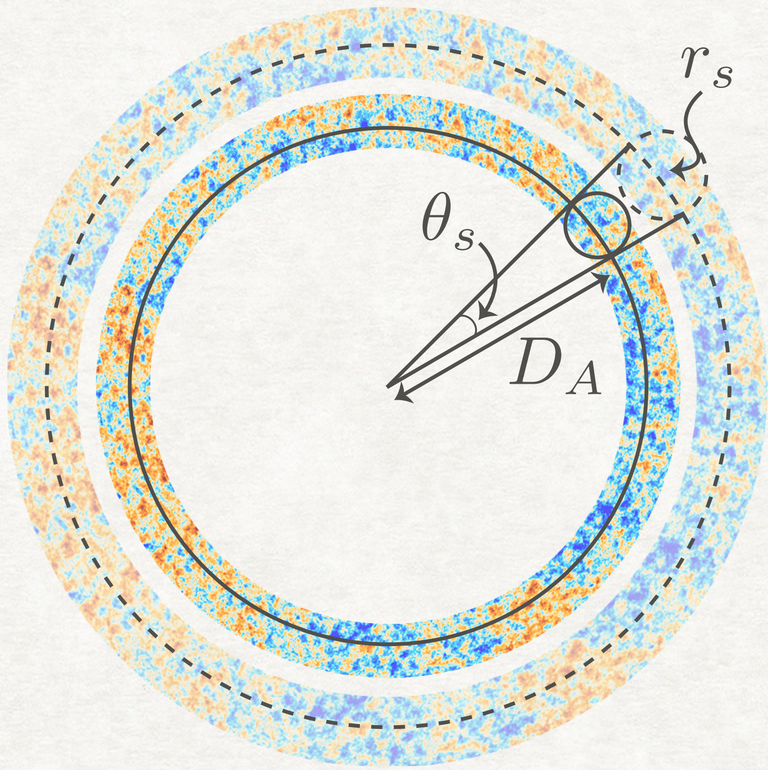
# Early Dark Energy resolution of the Hubble Crisis





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, to appear*

*KITP Workshop - Tensions between the Early and the Late Universe*
*Santa Barbara, CA*
*15 July 2019*

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- Inference of $H_0$ from the CMB is model dependent.
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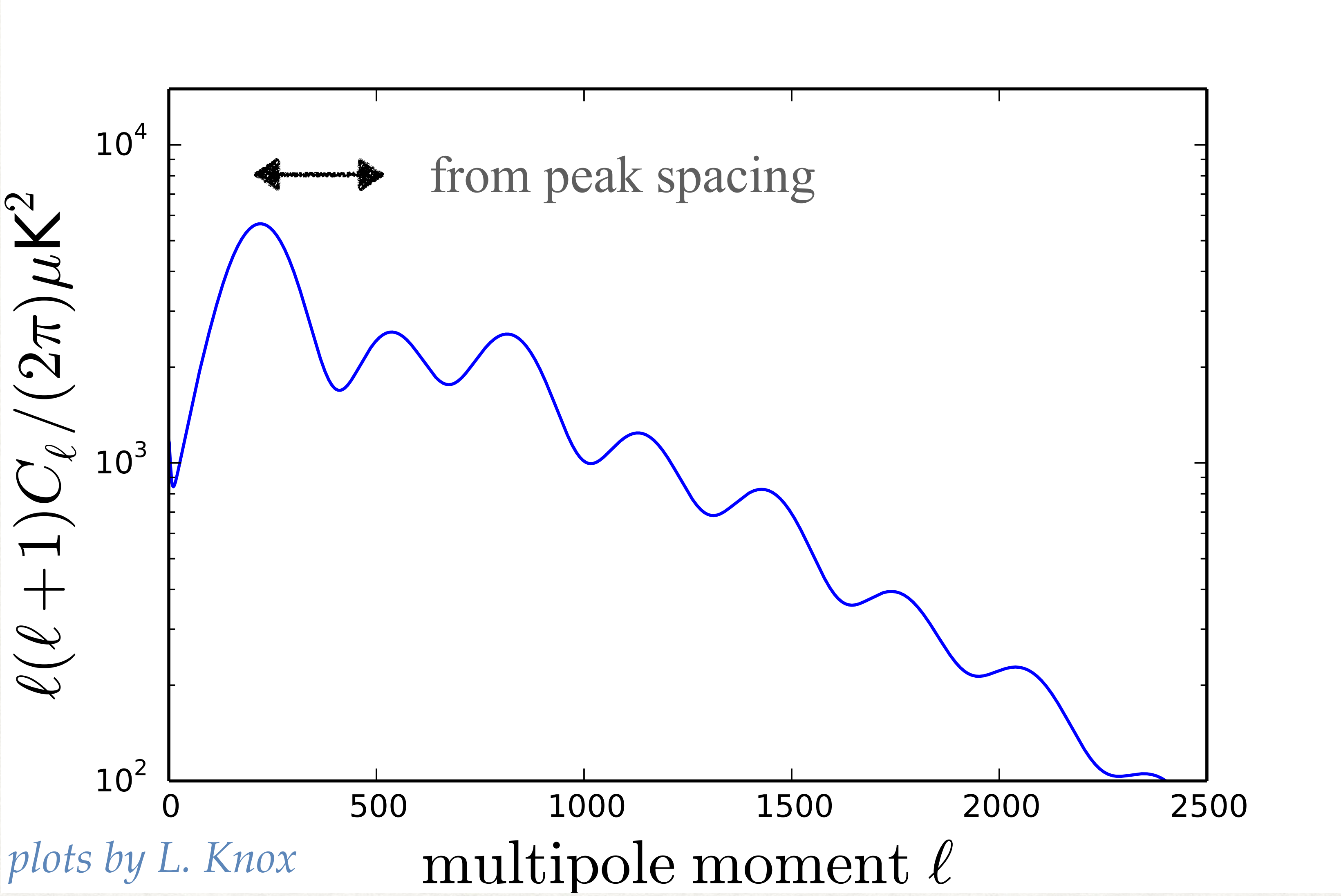
**$\theta_s$ sound horizon at last scattering ~1.0404**



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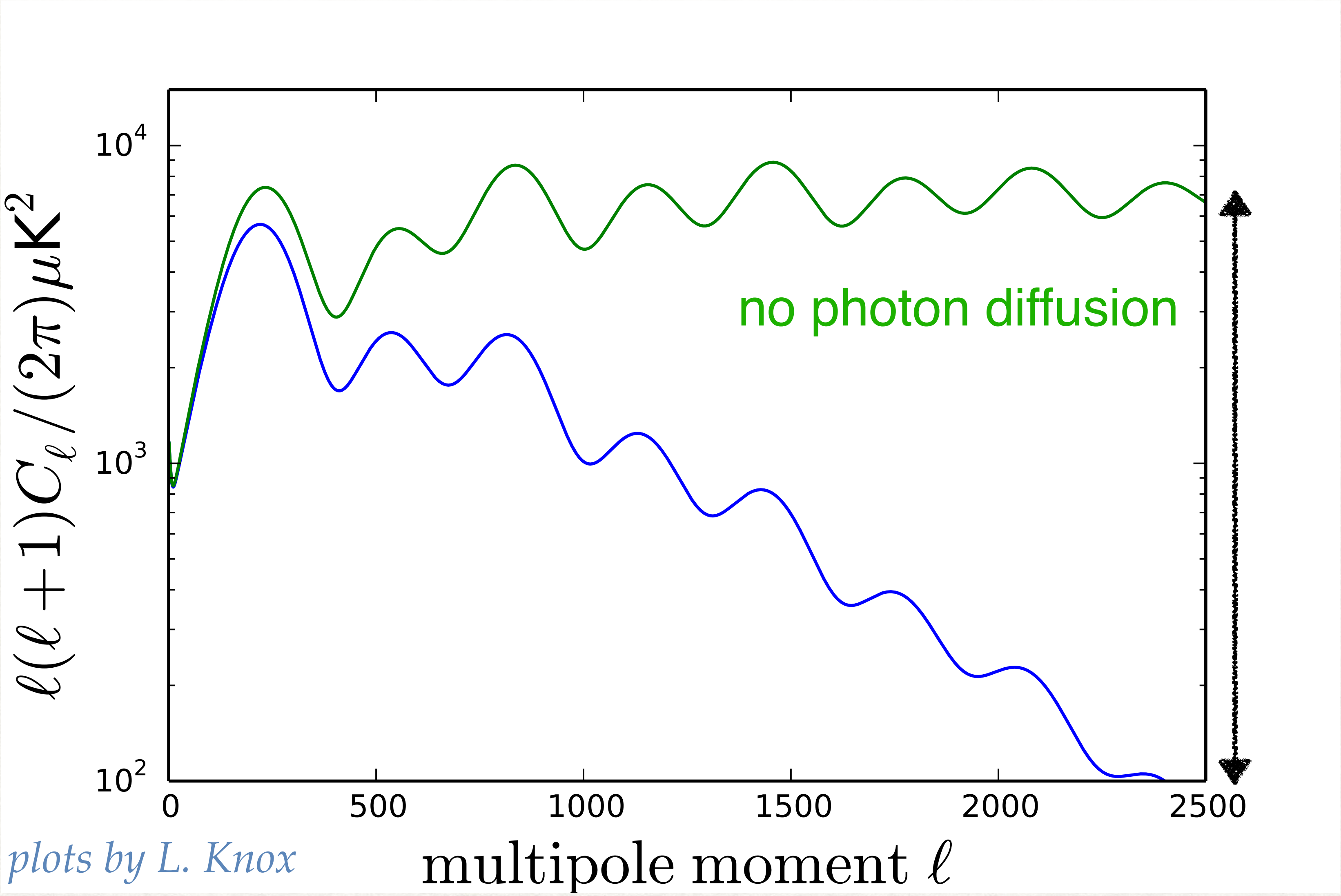
**$\theta_d$ photon diffusion length at last scattering ~ 0.1609**




"Silk Damping"

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

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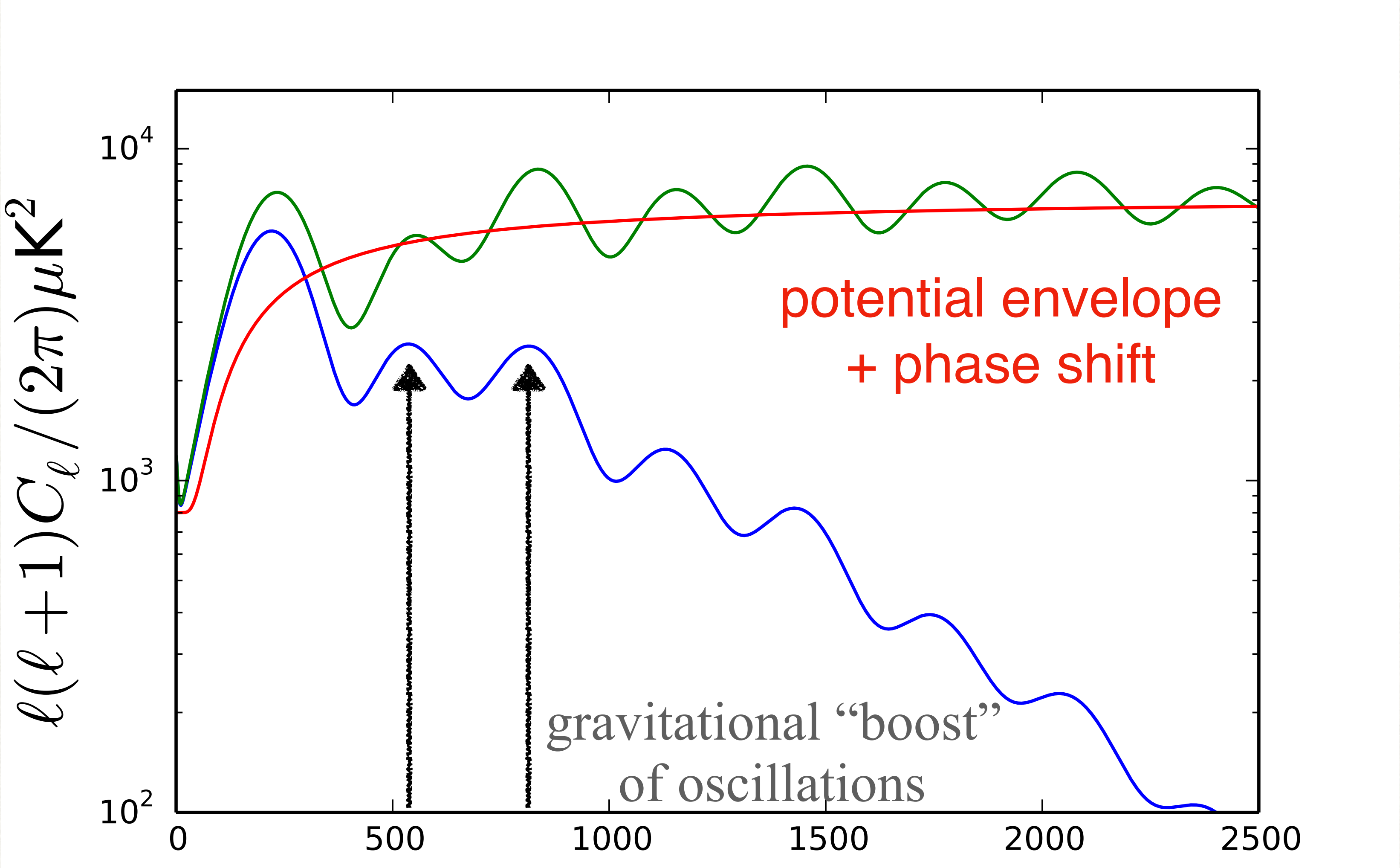
**$\theta_{eq}$ horizon size at matter-radiation equality ~ 0.81**




*plots by L. Knox*

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

# Solving H0: a “background-level” cookbook

$$\theta_X \equiv \frac{r_X(z_*)}{d_A(z_*)}$$

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- Early universe physics is left unaffected => three angular scales fixed at once.
- Weak CMB constraints from LISW/lensing but strong constraints from BAO/SN.

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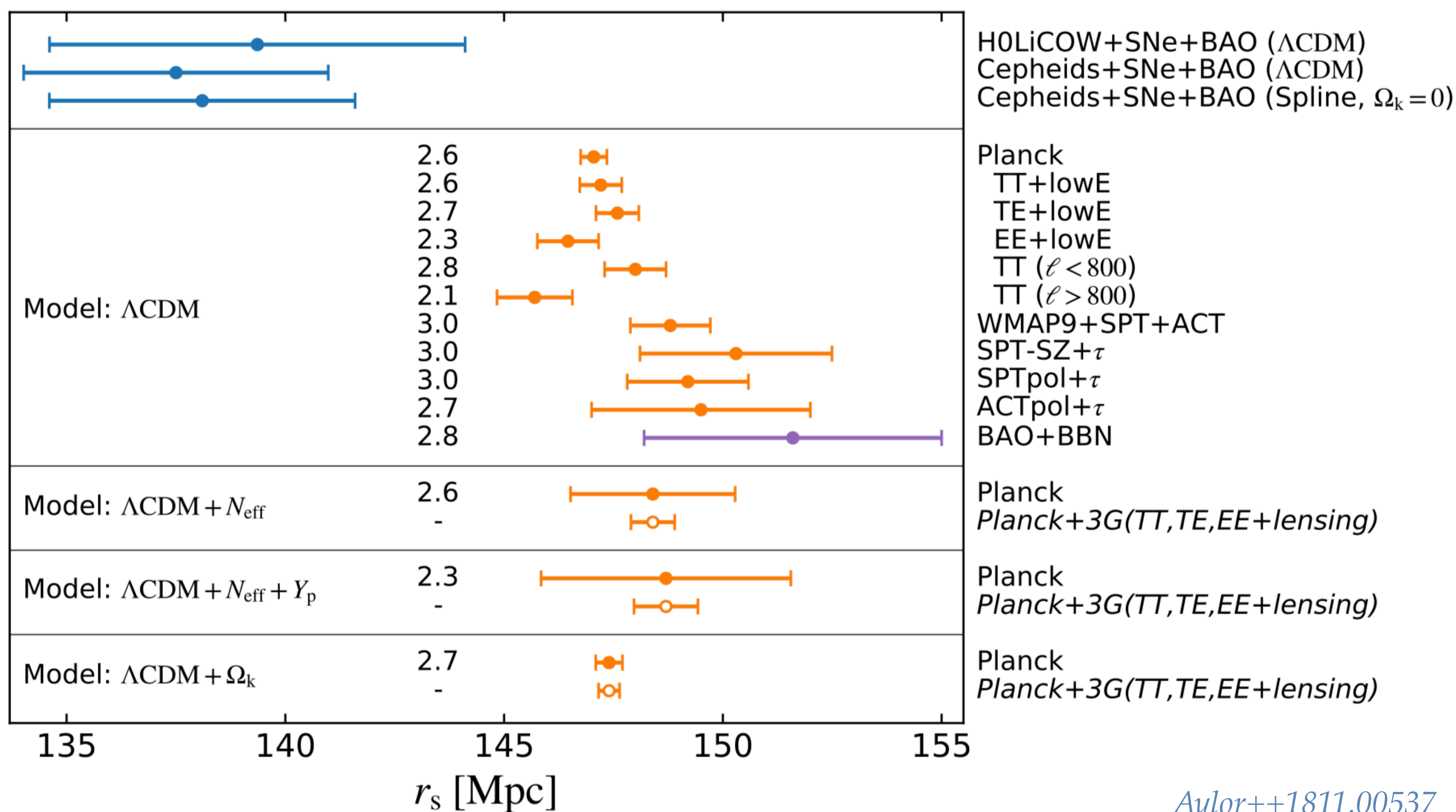
- early-universe solution: decrease $r_s$ at fixed $\theta_s$ to decrease $d_A(z^*)$ and increase H0.
- Late universe observables are basically unaffected.
- The solution must lead to the same shift in $r_d$ and $r_{eq}$: tuning required?

# H0 tension or $r_s$ tension?

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

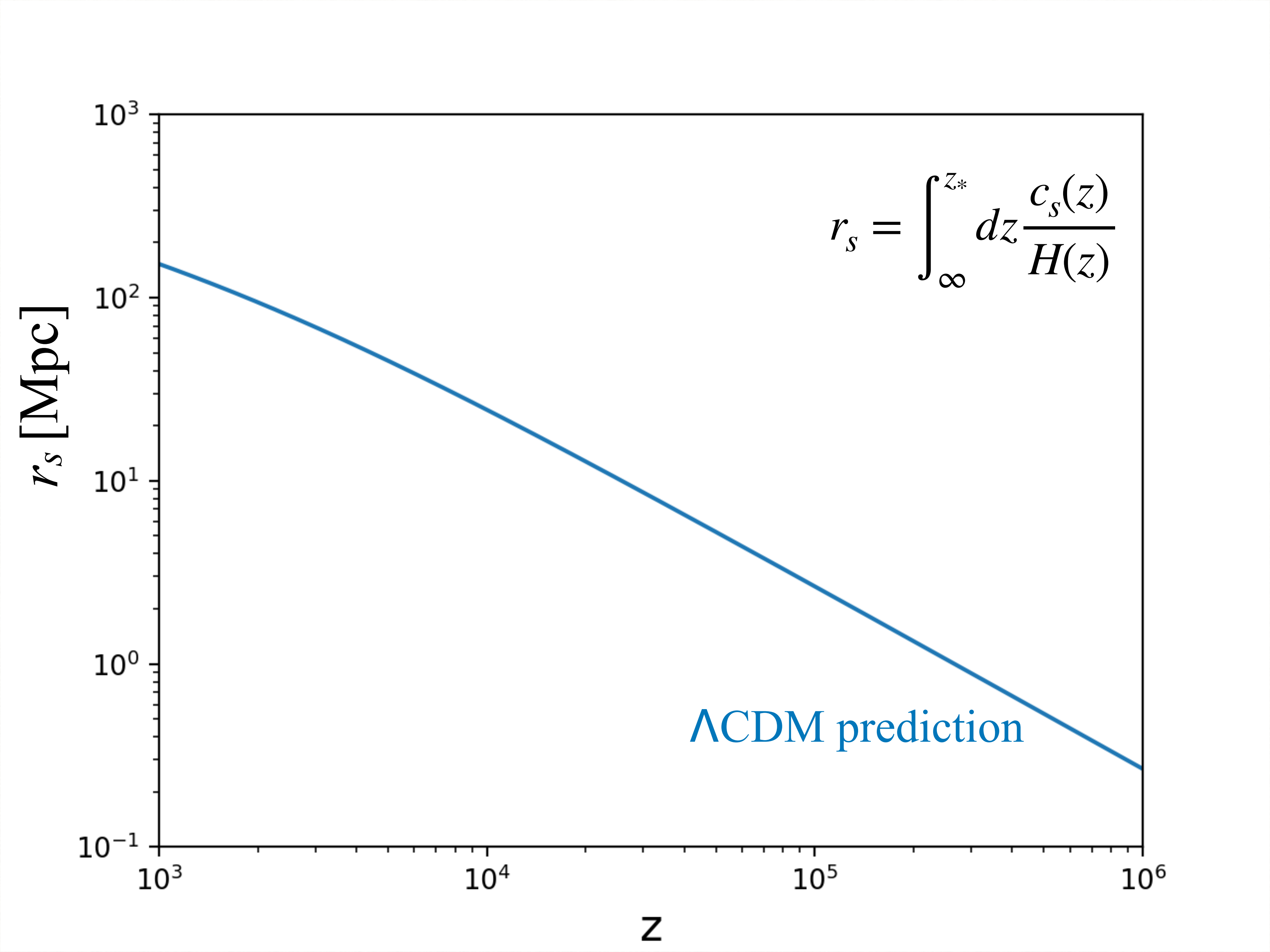
$r_s$ from CMB needs to decrease by ~ 10 Mpc




*Aylor++1811.00537*

# Early-Universe solution to H0

- $r_s$ 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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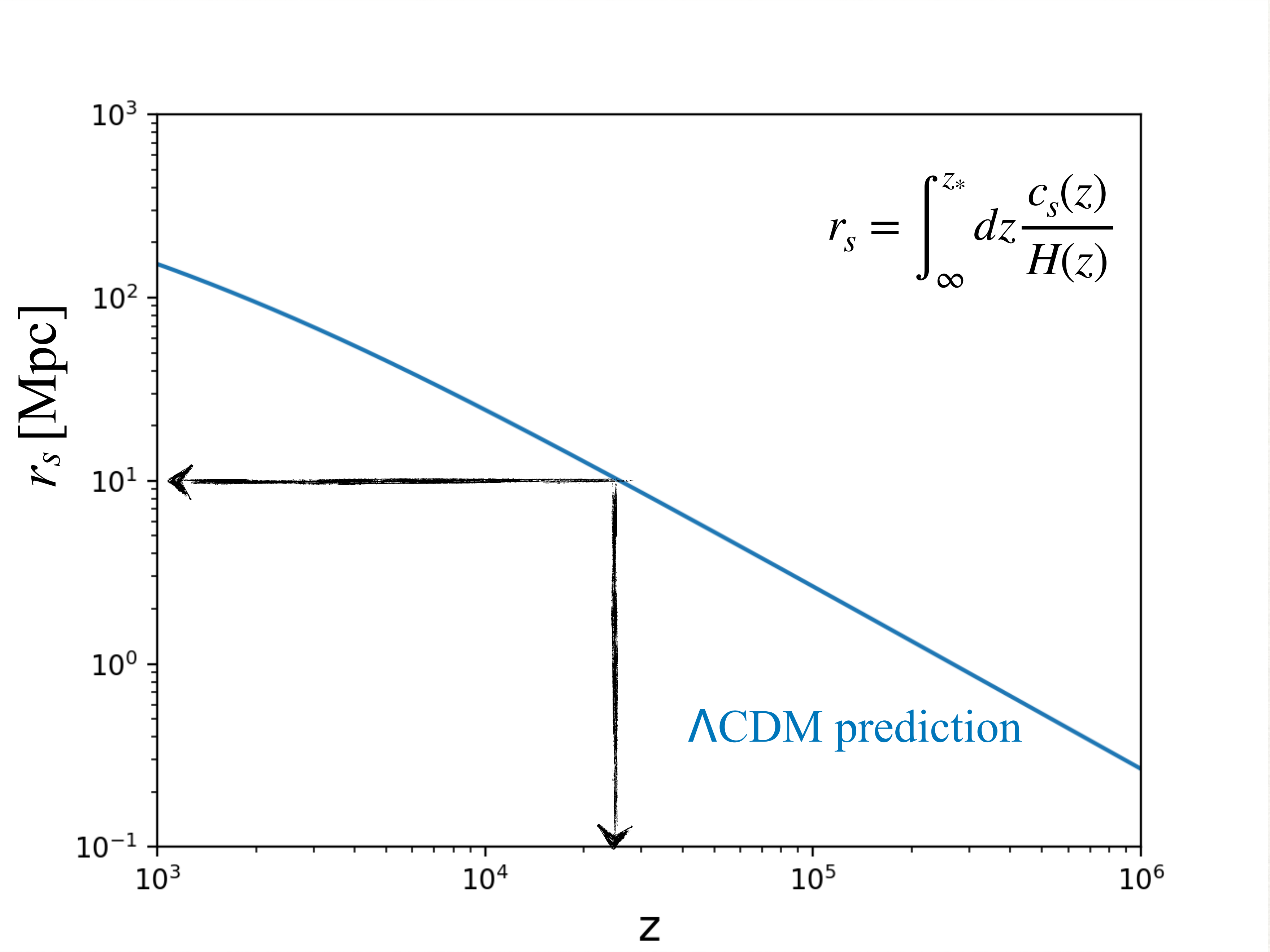


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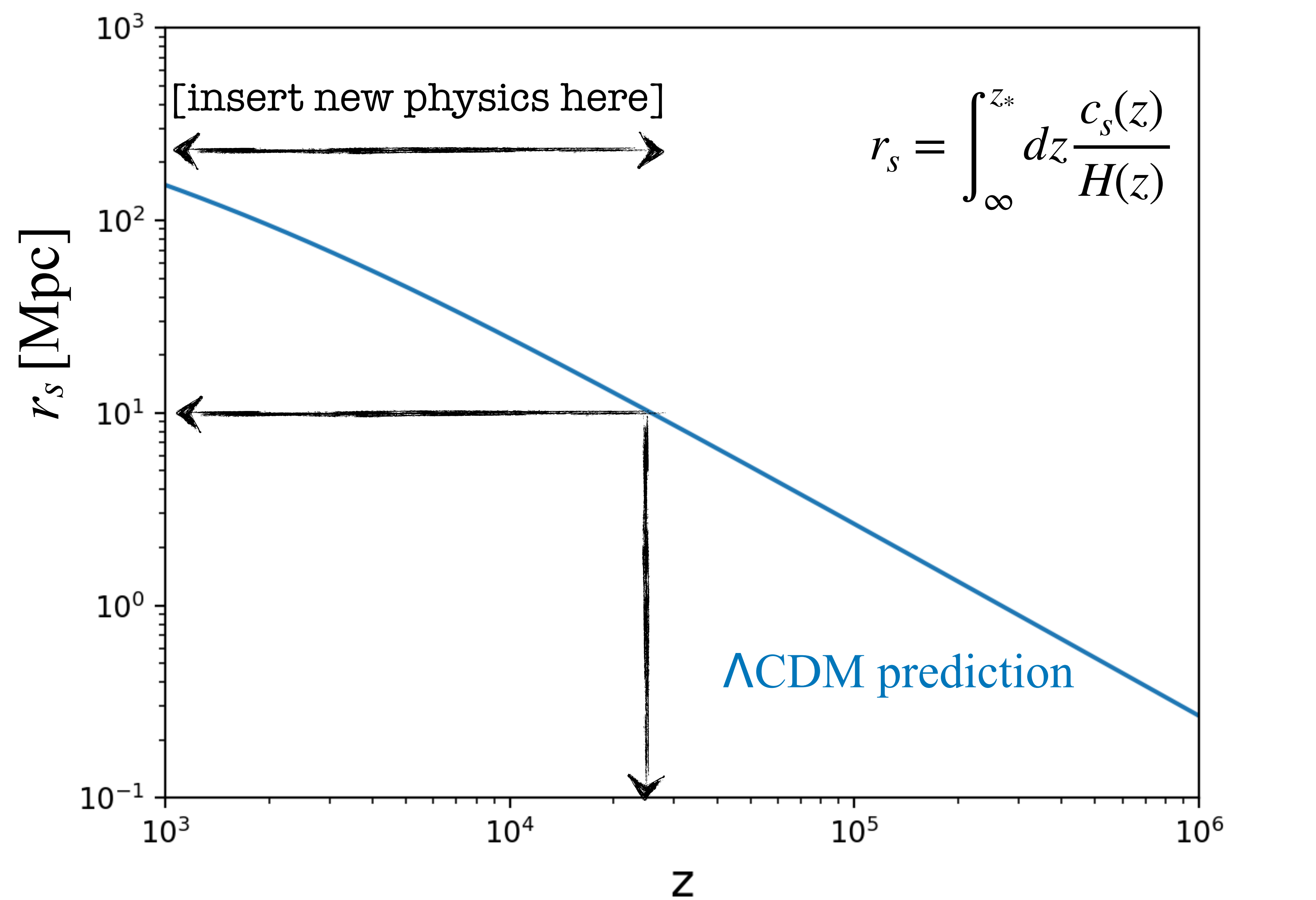


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# Scalar field and Early Dark Energy

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

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

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

*Poulin++ 1806.10608 & 1811.04083*

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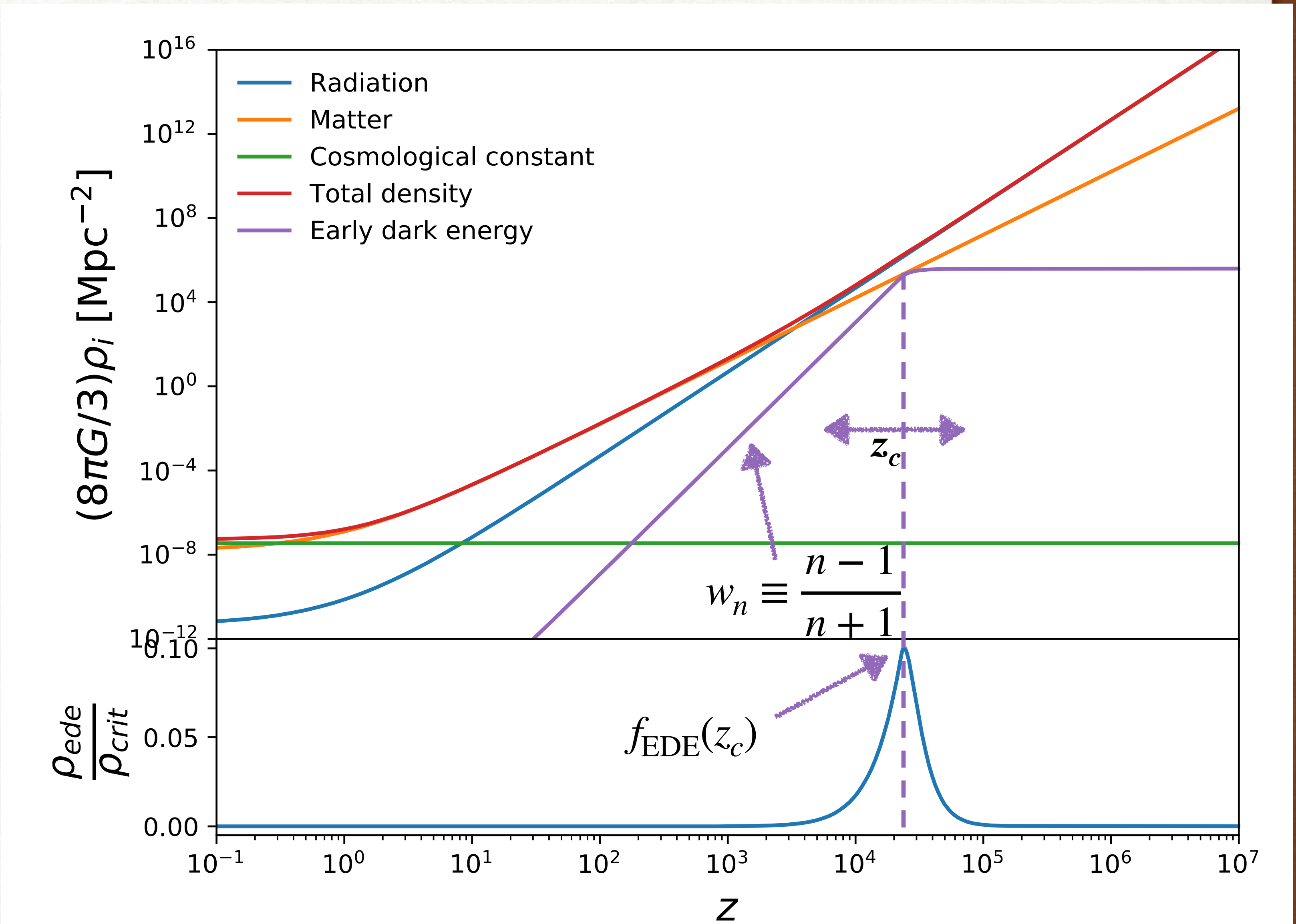
- We use the: GDM formalism

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

*GDM: Hu astro-ph/9801234*

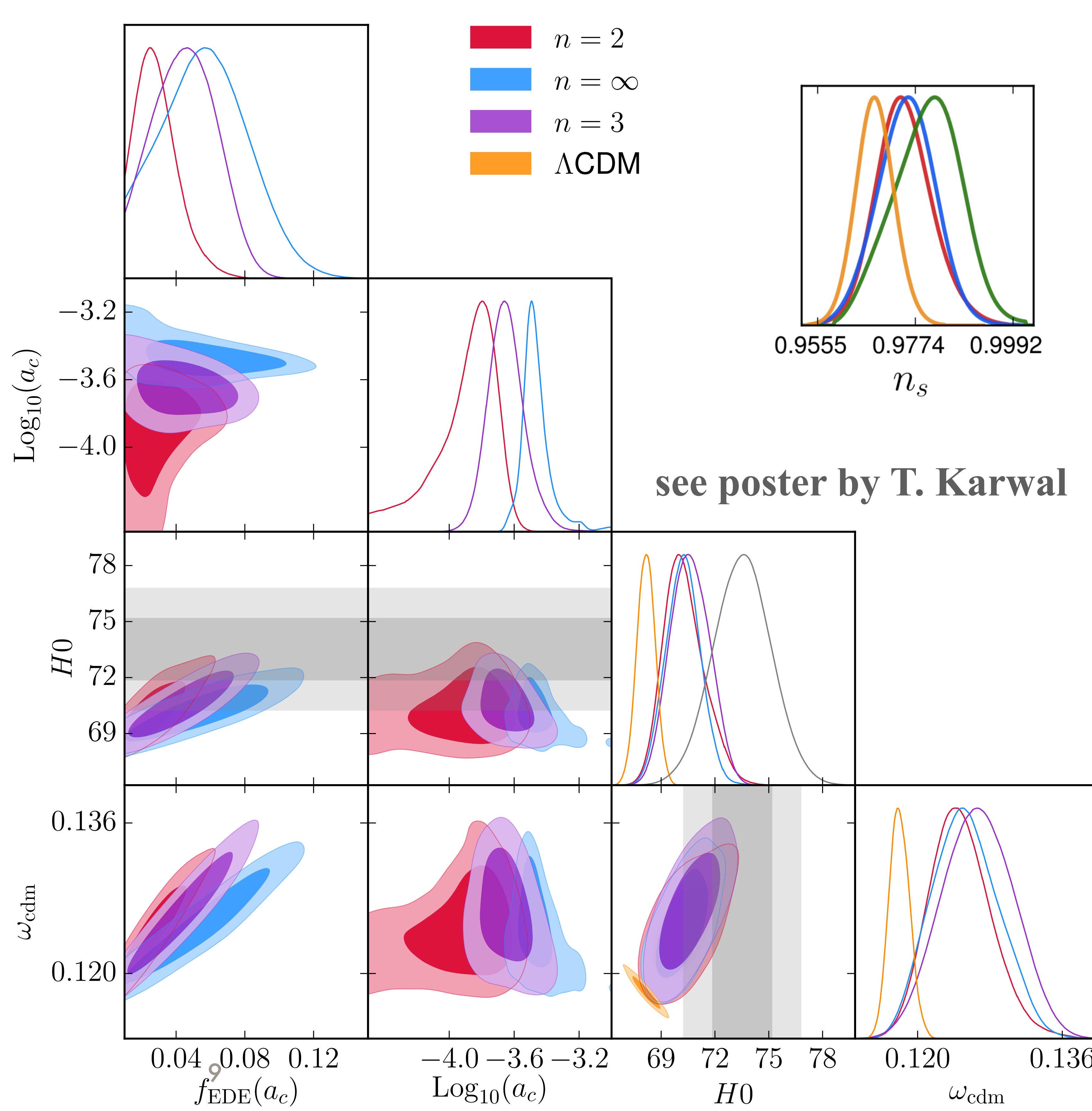



*plot by T. Karwal*

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

# Early Dark Energy In Cosmological Data?

- high-l TTTEEE+lowTEB+lensing +BAO (no Lya)+Pantheon +SH0ES 2016




*VP, Smith, Karwal, Kamionkowski, PRL 122 (2019)*

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

$$z_c \sim 4000 - 7000$$

$$H_0 = 70.6\ (71.6) \pm 1.3\ \mathrm{km/s/Mpc}$$

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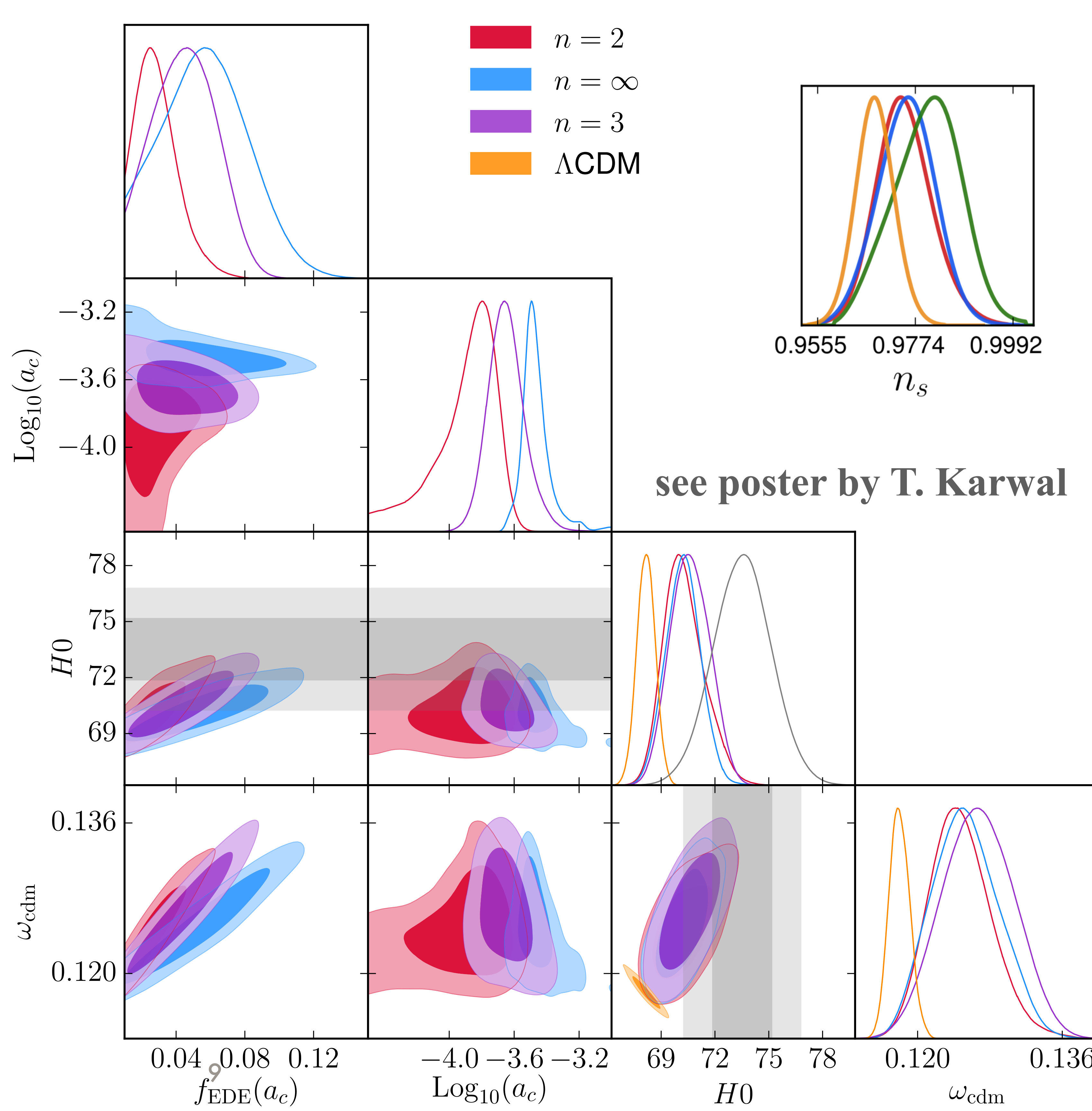


**see poster by T. Karwal**

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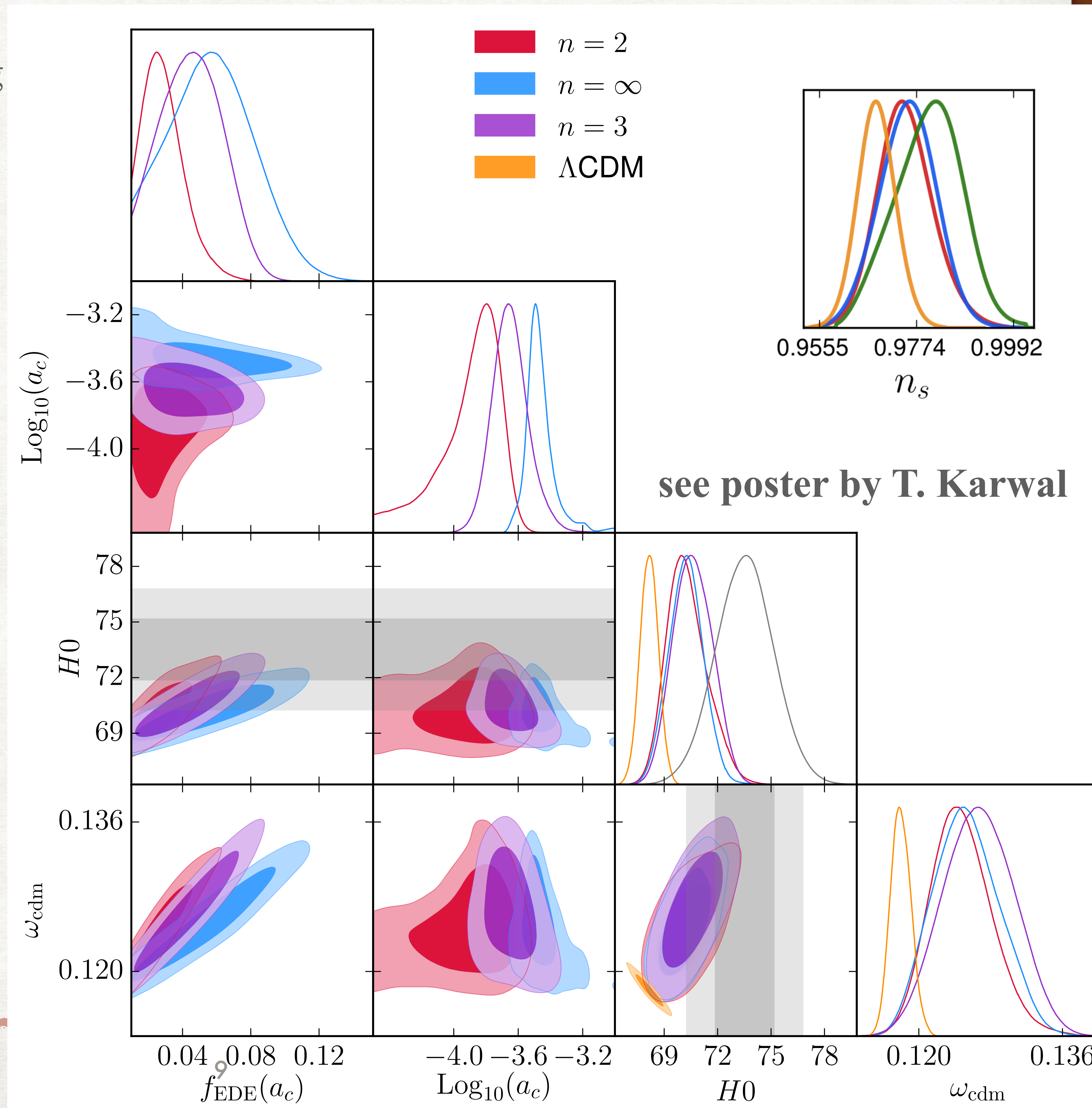
- strong increase in $\omega_{cdm}$
- upward shift in $n_s$

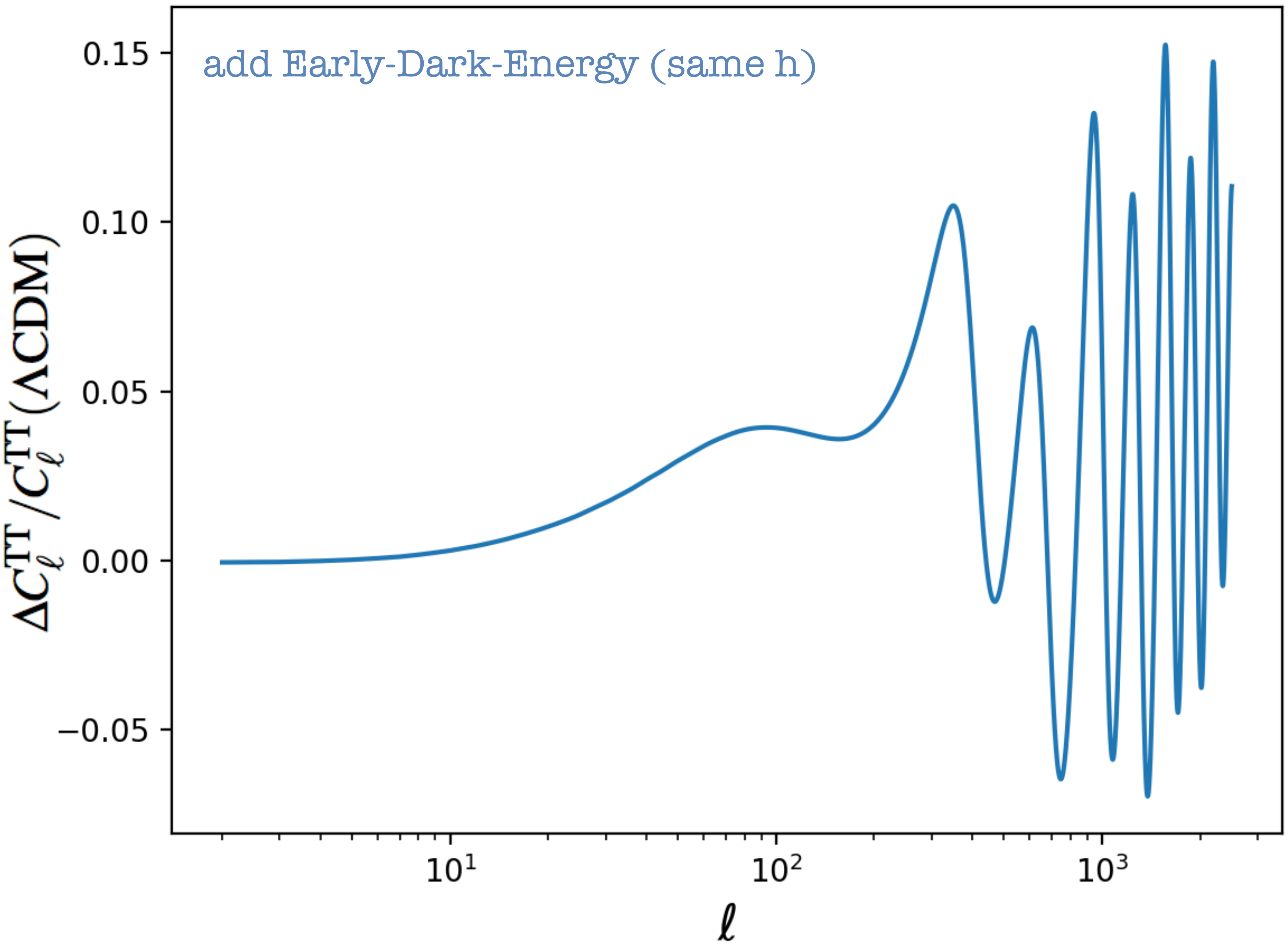
*VP, Smith, Karwal, Kamionkowski, PRL 122 (2019)*




**see poster by T. Karwal**

# Towards the best-fit cosmology step-by-step

w/r to LCDM "Planck-Only" 2015



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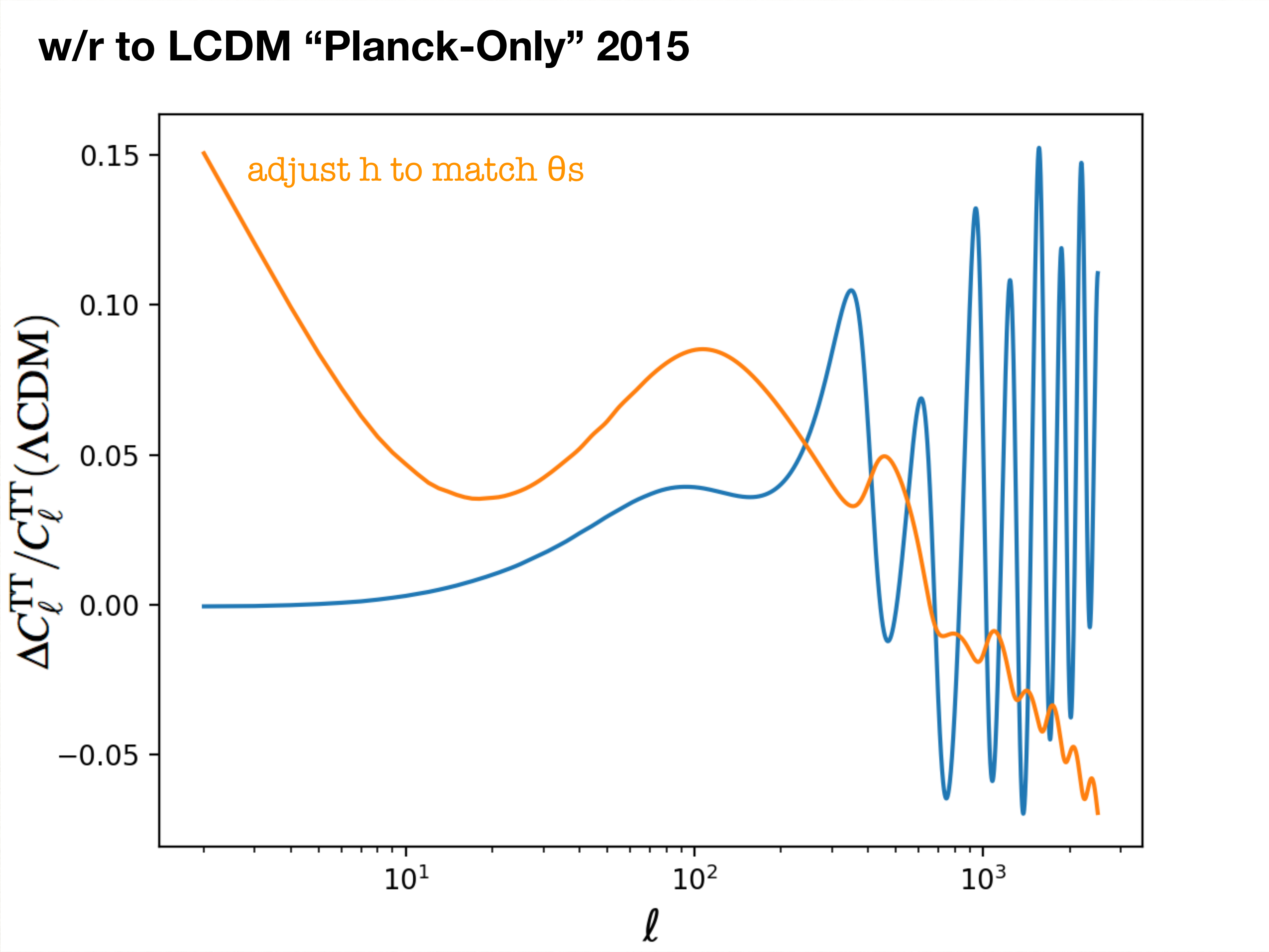

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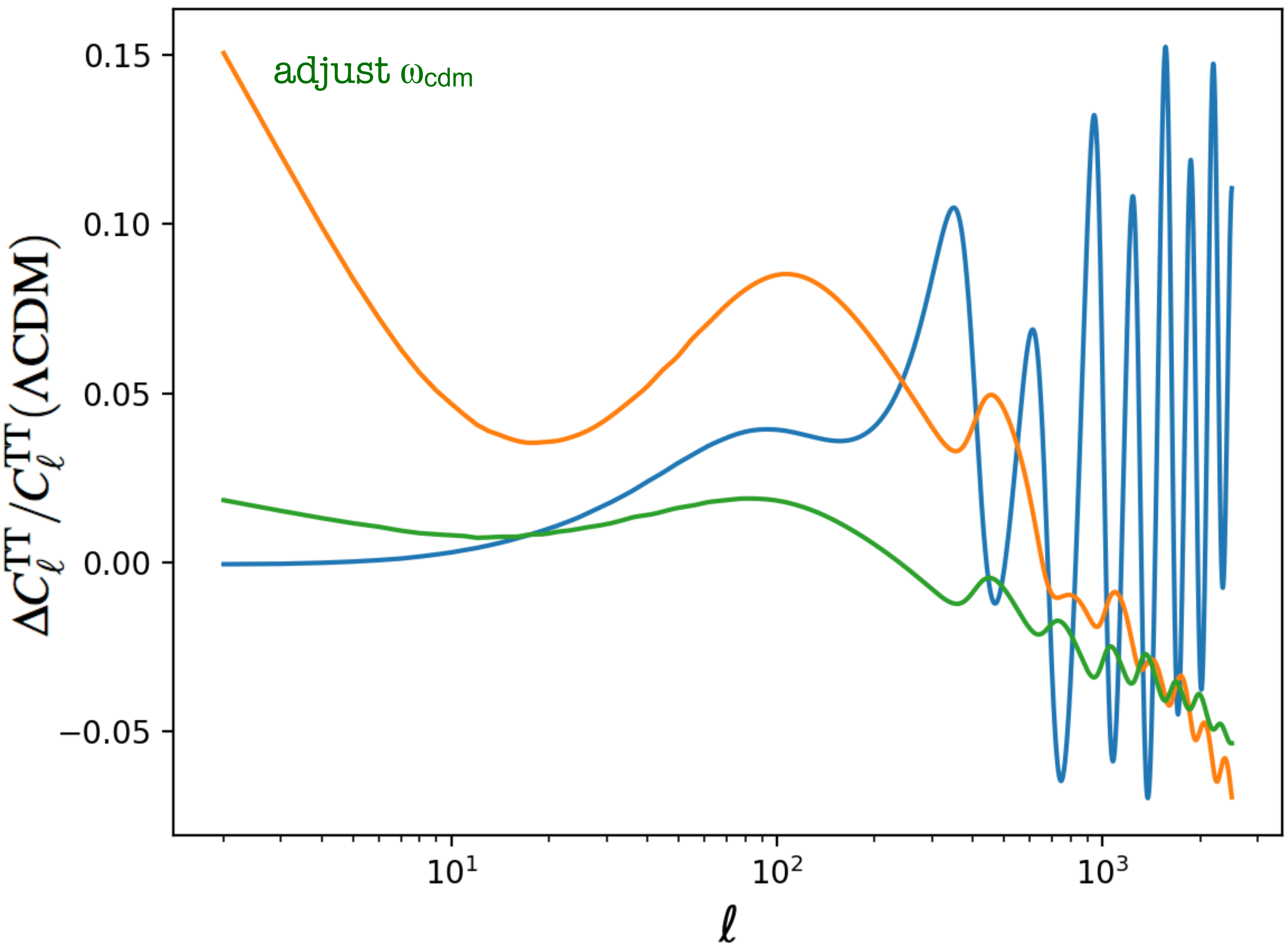

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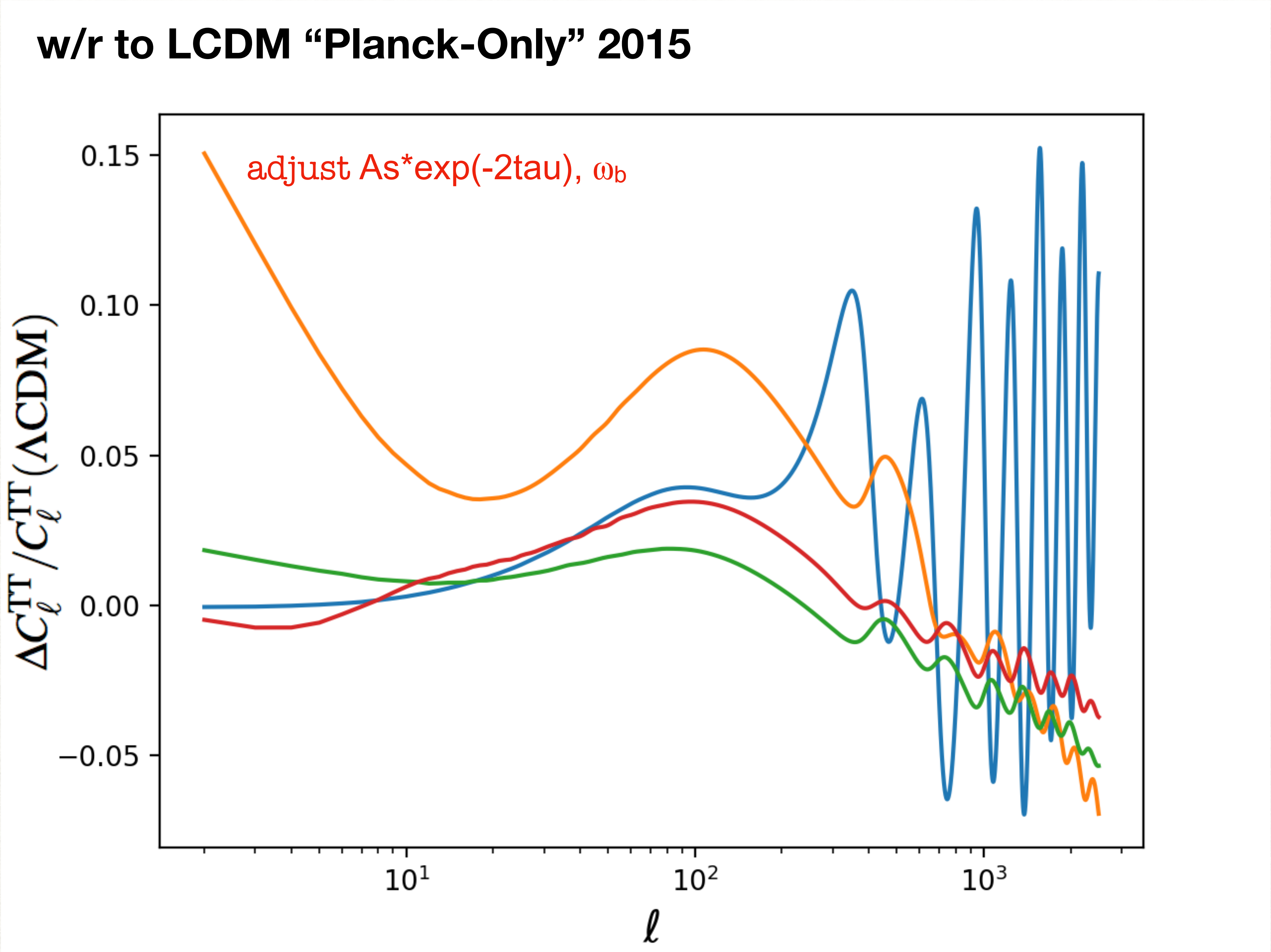

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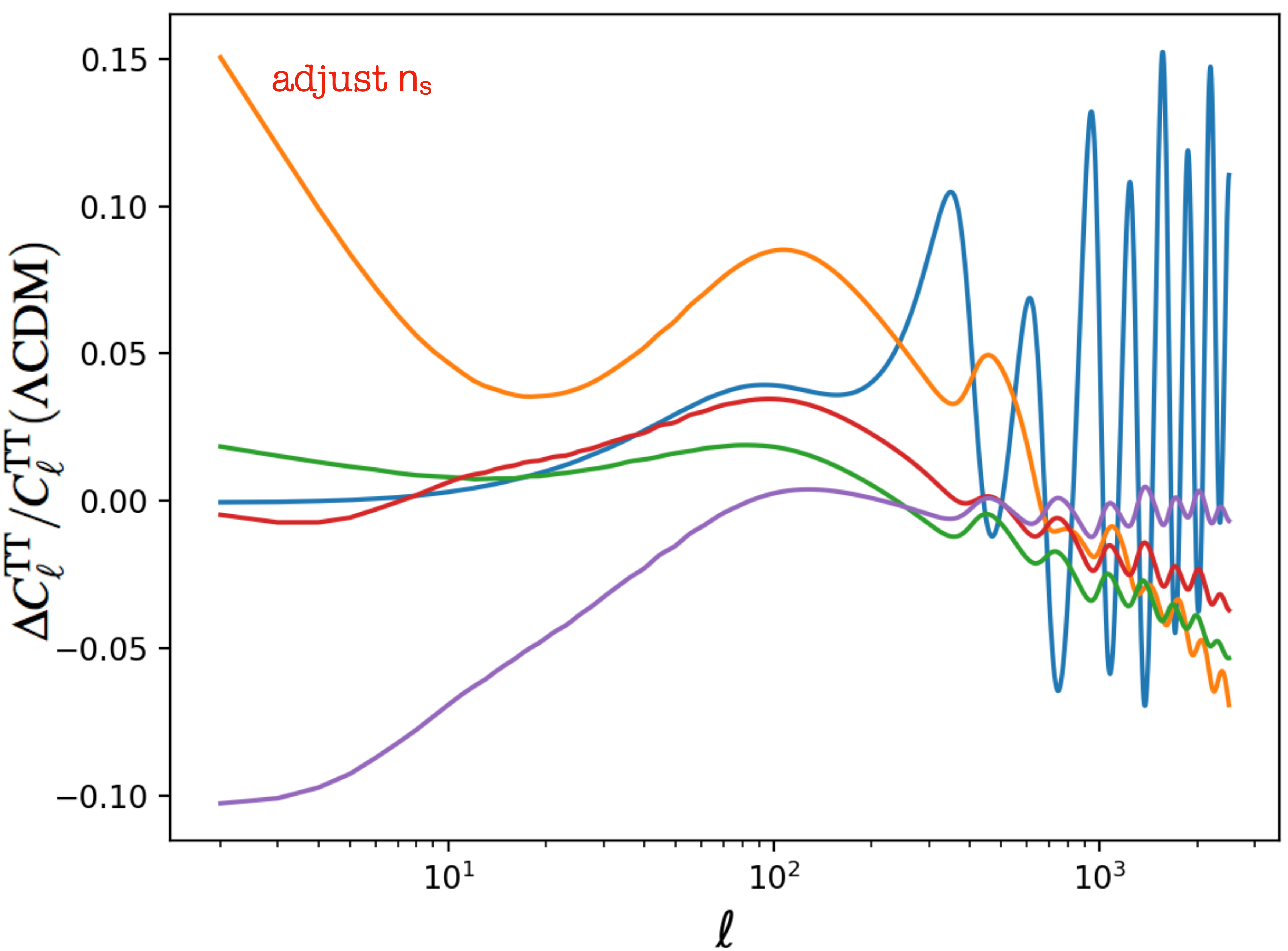
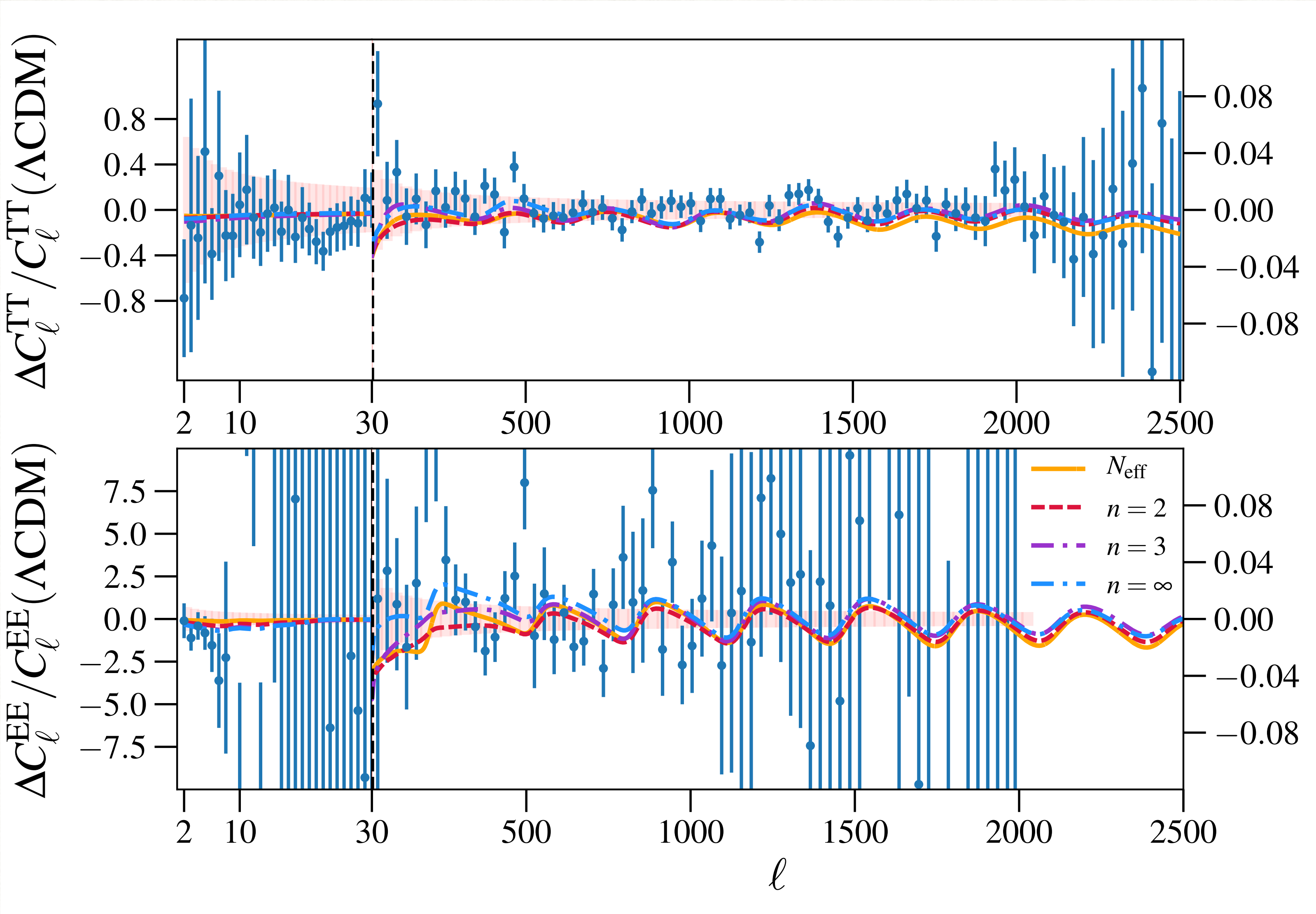


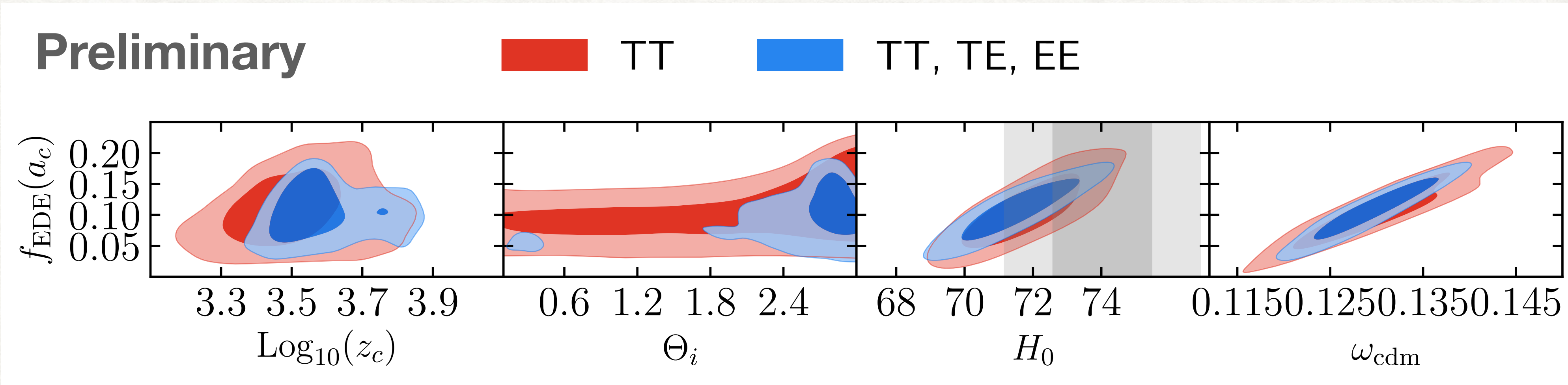
# Best-fit w/r to “Planck-only” ΛCDM




| | ΛCDM | $n=2$ | $n=3$ | $n=\infty$ | $N_{\rm eff}$ |
|---|---|---|---|---|---|
| Total $\chi^2_{\rm min}$ | 13995.1 | 13985.6 | 13980.6 | 13986.0 | 13991.2 |
| $\Delta\chi^2_{\rm min}$ | 0 | -9.5 | -14.5 | -9.1 | -3.9 |
| $\Delta$ log $B$[a] | 0 | -0.51 | +2.51 | +2.41 | -0.44 |

# Beyond the fluid approximation

- We study the n=3 case without fluid approximation and compare the use of high-$\ell$ TT vs TT,TE,EE data:



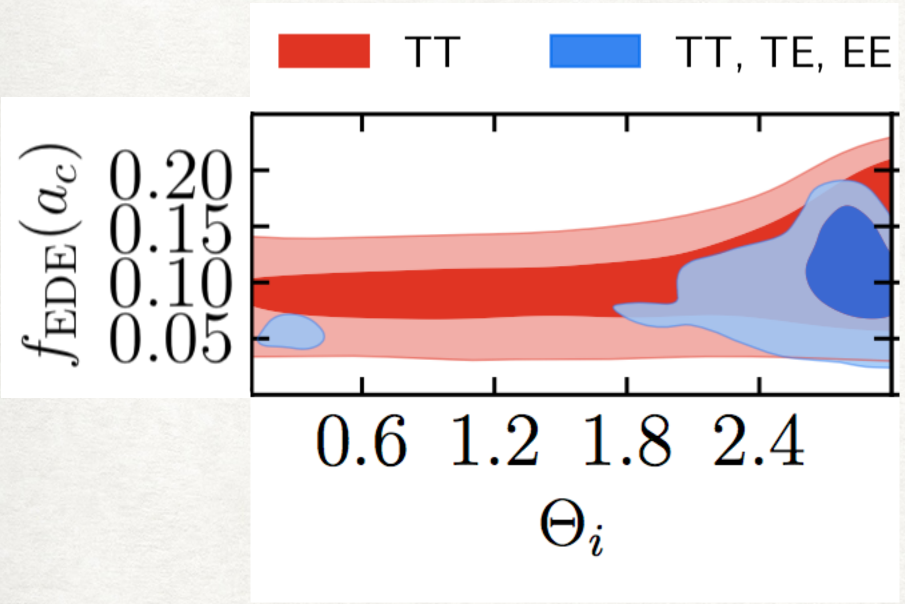

- Our results are in very good agreement with fluid approximation (if not even "better"):

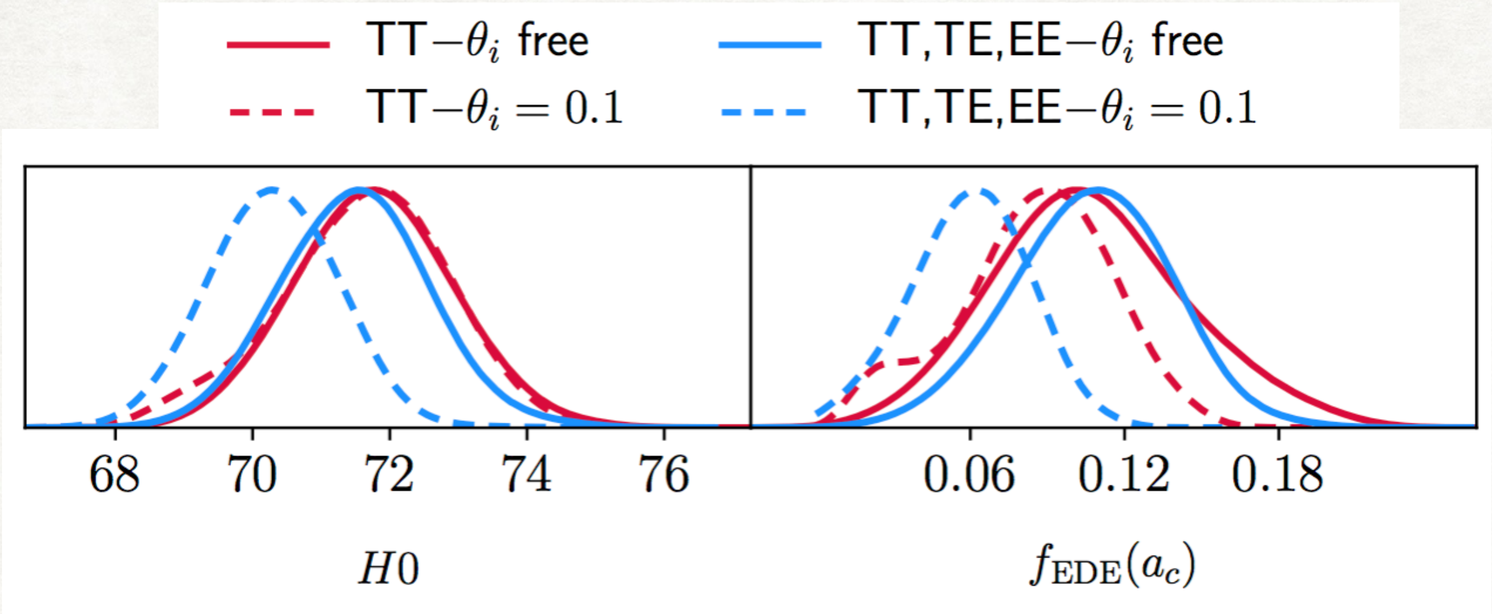
$$f(z_c) = 0.11\ (0.13) \pm 0.03,\ z_c = 3.57\ (3.5)^{+0.04}_{-0.1},\ h = 0.716\ (0.722) \pm 0.011$$

| Datasets | $\Lambda$CDM | $n = 3$ |
|---|---|---|
| *Planck* high-$\ell$ TT, TE, EE | 2446.66 | 2444 |
| *Planck* low-$\ell$ TT, TE, EE | 10496.65 | 10493.25 |
| *Planck* lensing | 10.37 | 10.24 |
| BAO-low $z$ | 1.86 | 2.53 |
| BAO-high $z$ | 1.84 | 2.1 |
| Pantheon | 1027.04 | 1027.11 |
| SH0ES | 16.80 | 1.68 |
| Total $\chi^2_{\rm min}$ | 14001.23 | 13980.94 |
| $\Delta\chi^2_{\rm min}$ | 0 | -20.29 |

# Preference for large $\Theta_i$

- Polarisation data favors large value of $\Theta_i$ in the n=3 case: in agreement with Lin++1905.12618



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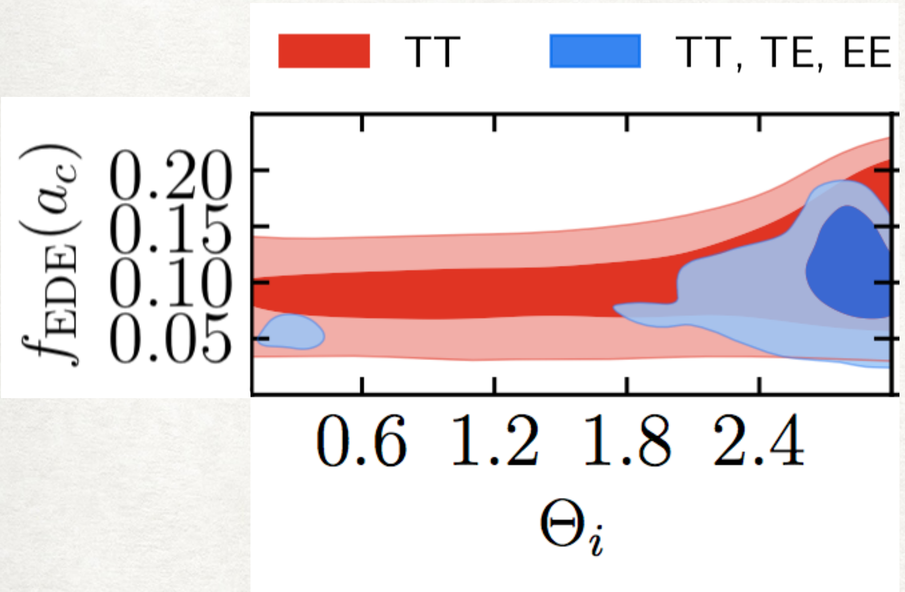


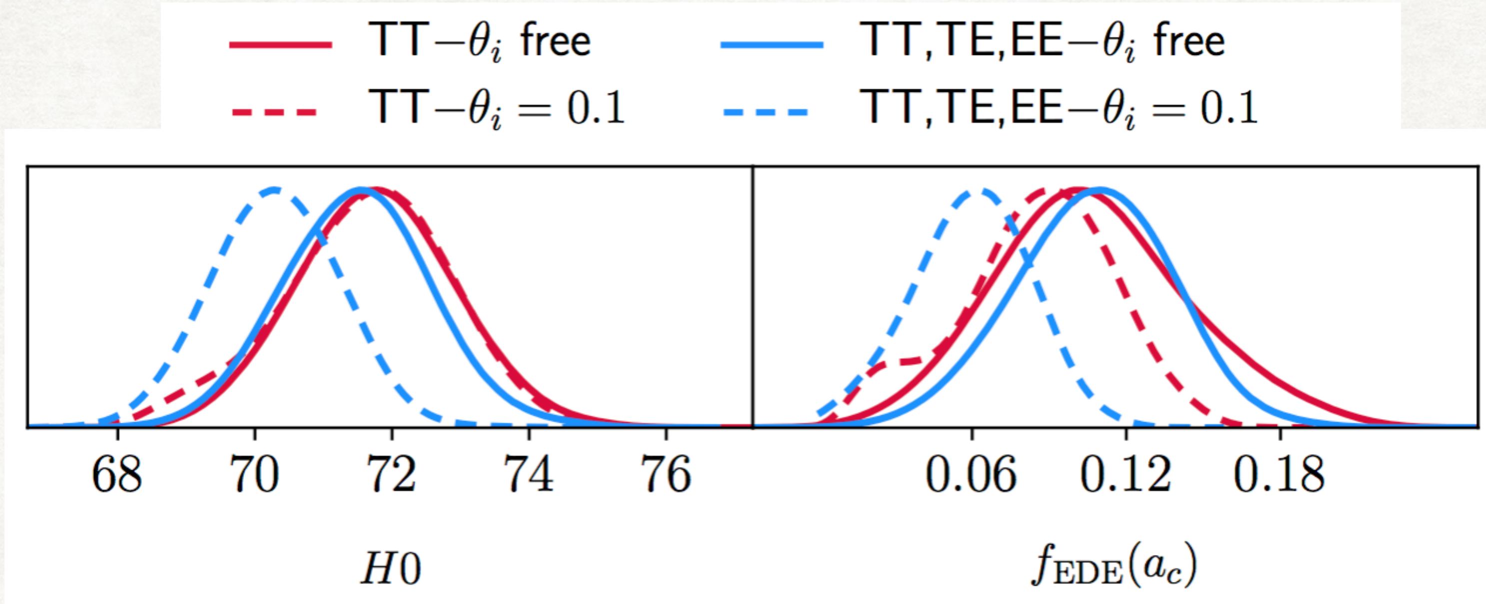


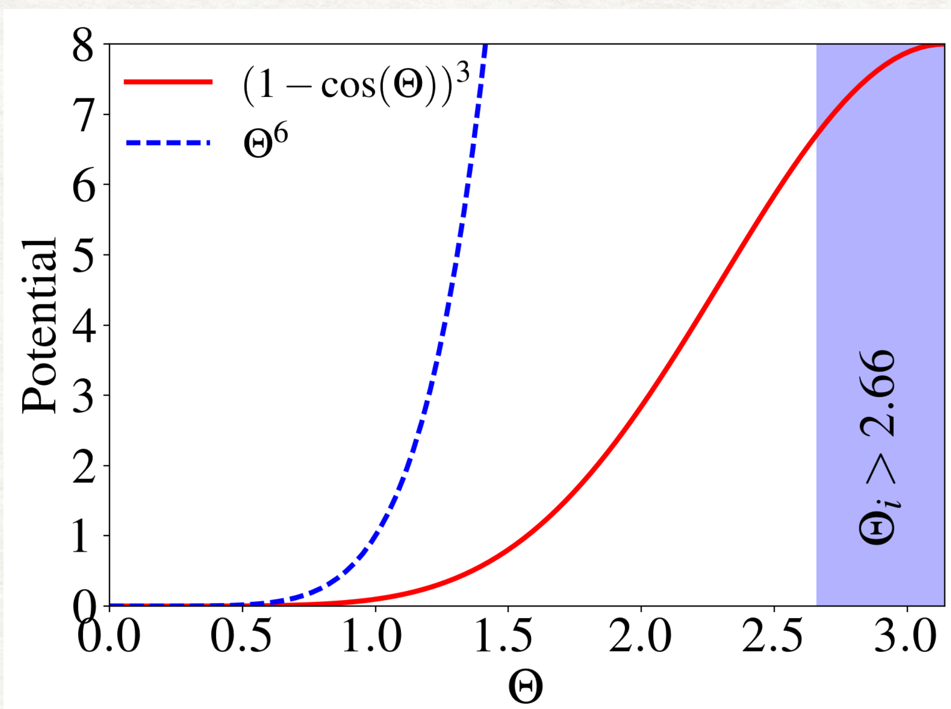


- $\Theta_i/\pi > 0.85$ (68% CL) from polarization. Systematics? Real dynamical preference?

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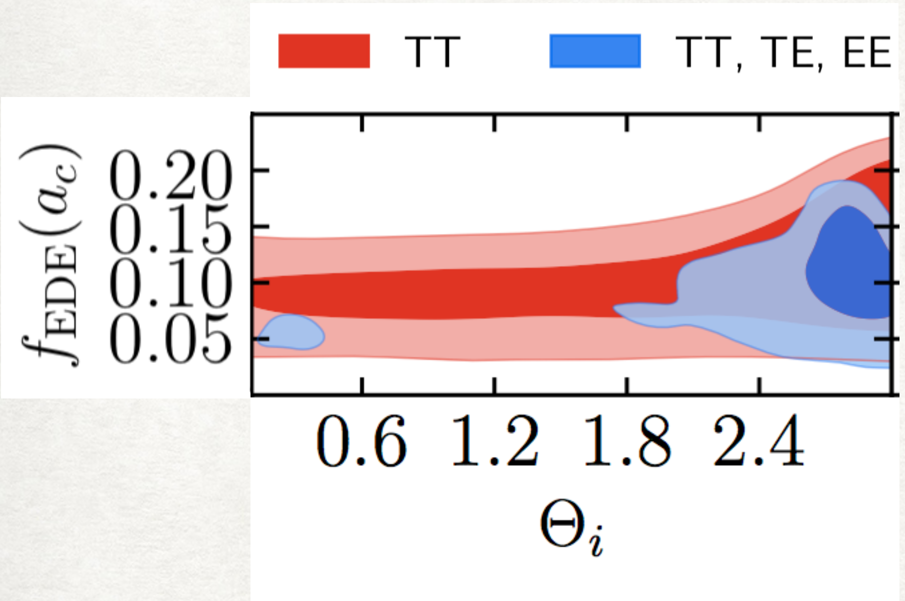


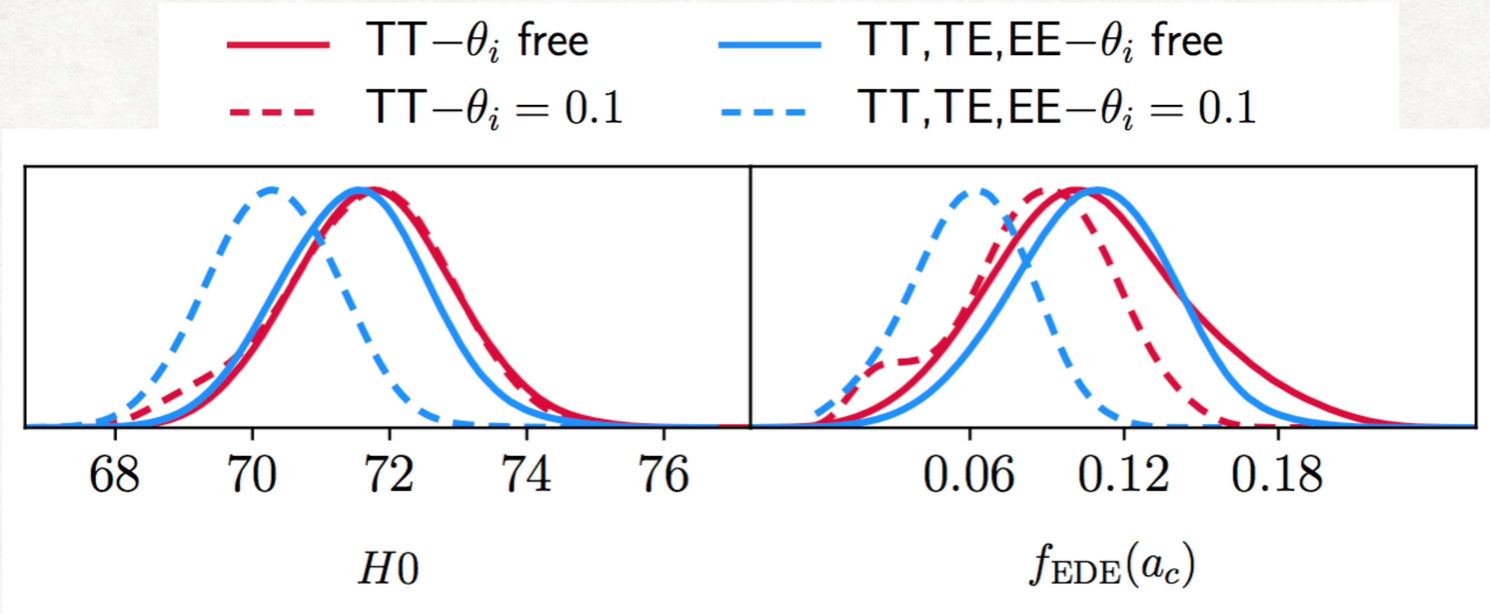


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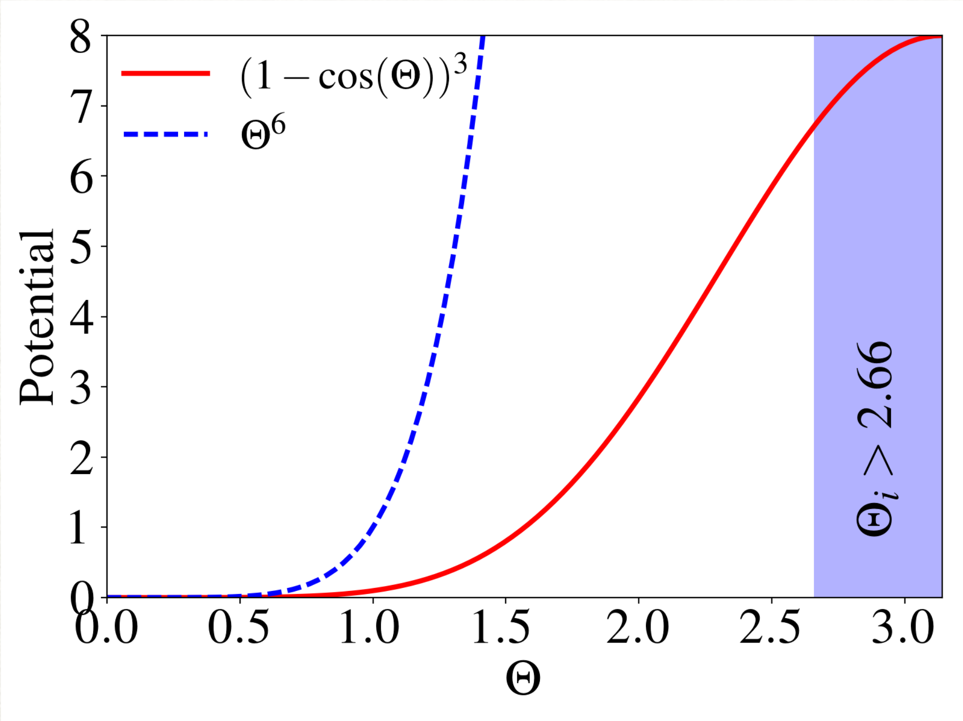
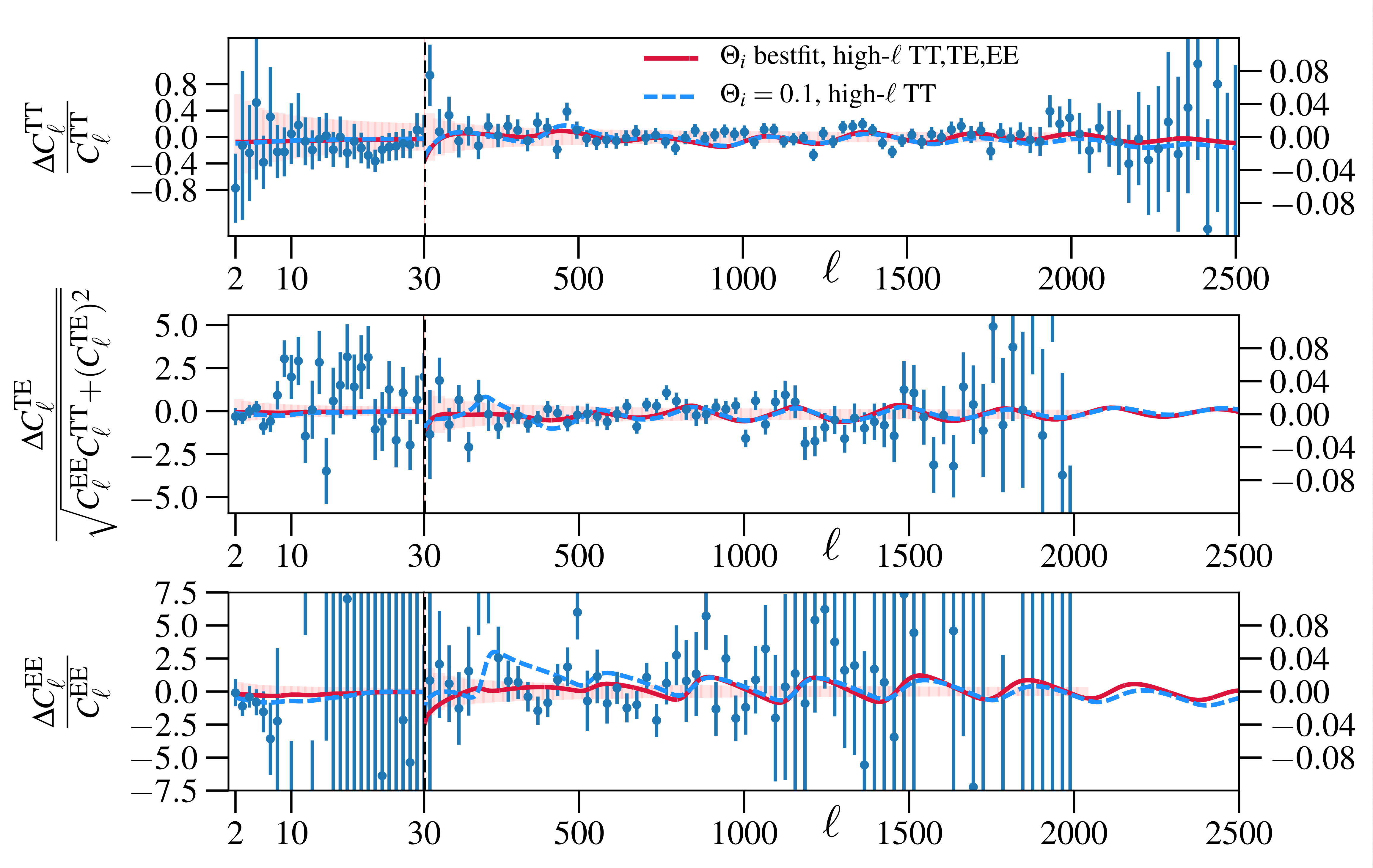



- Also confirms Agrawal++ 1904.01016: n=3 power-law potential do not solve the Hubble Tension.

# Why does polarization favor large $\Theta_i$?

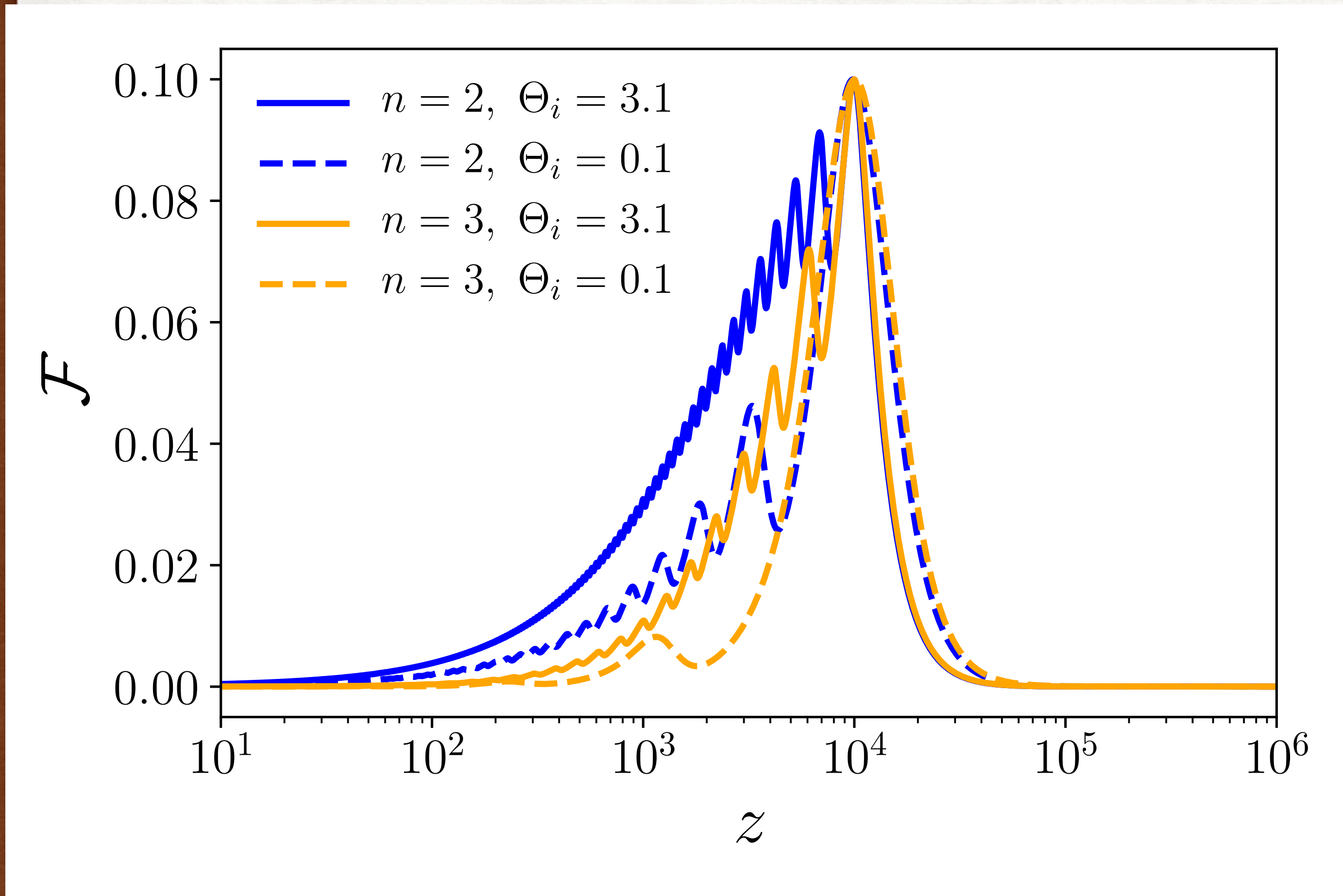
- Residuals features in polarization for modes entering the horizon around $z_c$: $\ell \sim 30 - 500$

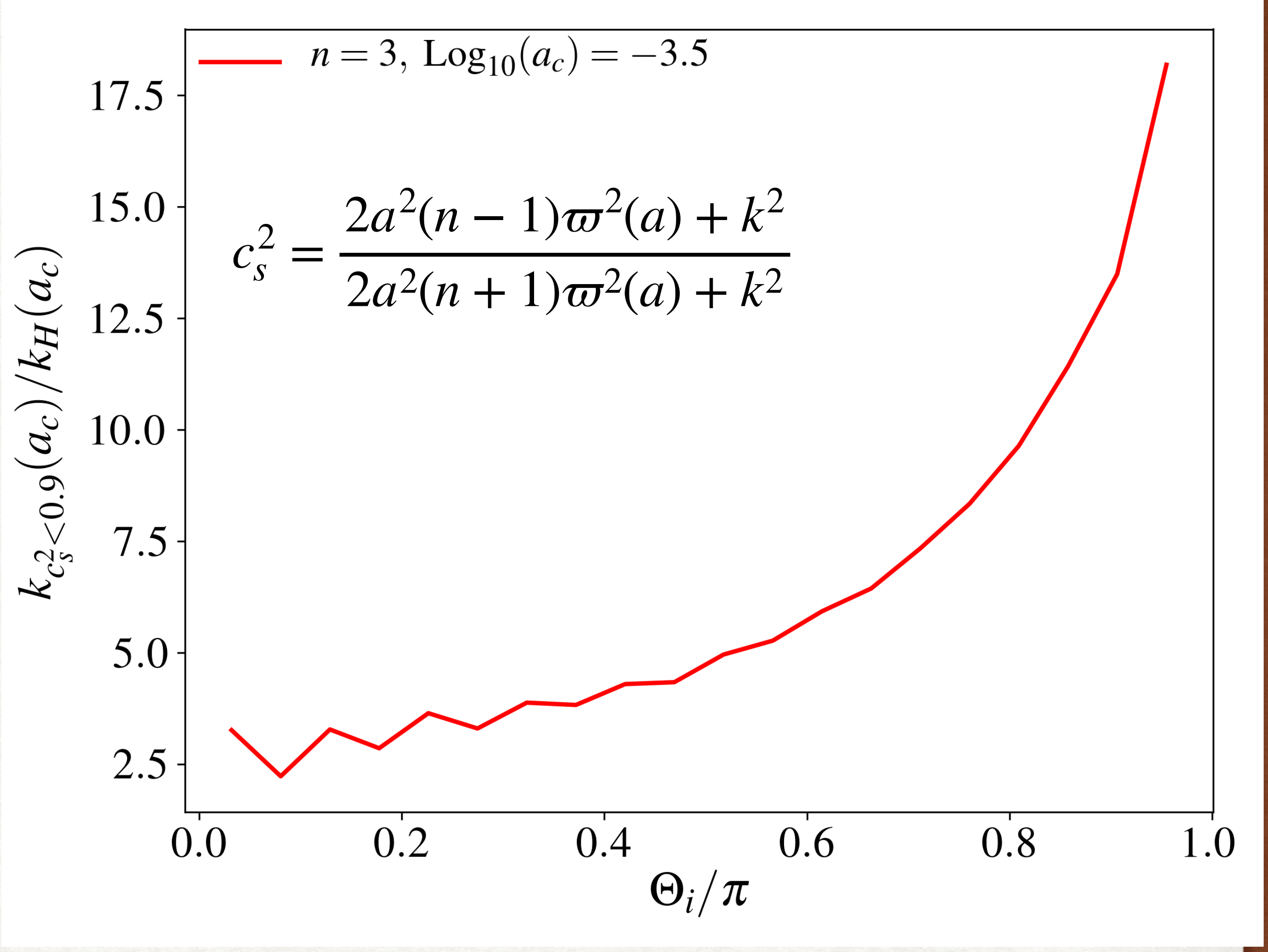



*see also Lin++1905.12618*

# Impact of $\Theta_i$ on EDE dynamics

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



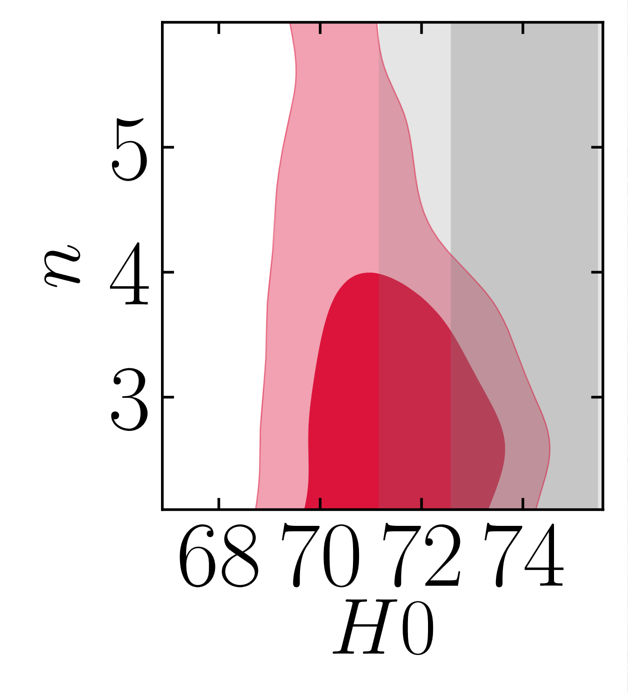

- Lin++1905.12618: "Acoustic" Dark Energy (ADE) with time and scale *in*-dependent $c_s^2$.

For n=3, data favors $c_s^2 < 0.9$ at 95% C.L.

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

# The exponent $n$ as a free parameter

- We perform runs with all data, varying $n \in [2,6]$.




- We find $n = 3^{+0.3}_{-0.9}$ (68% C.L.): scalar field oscillations are favored over non-oscillating solutions.

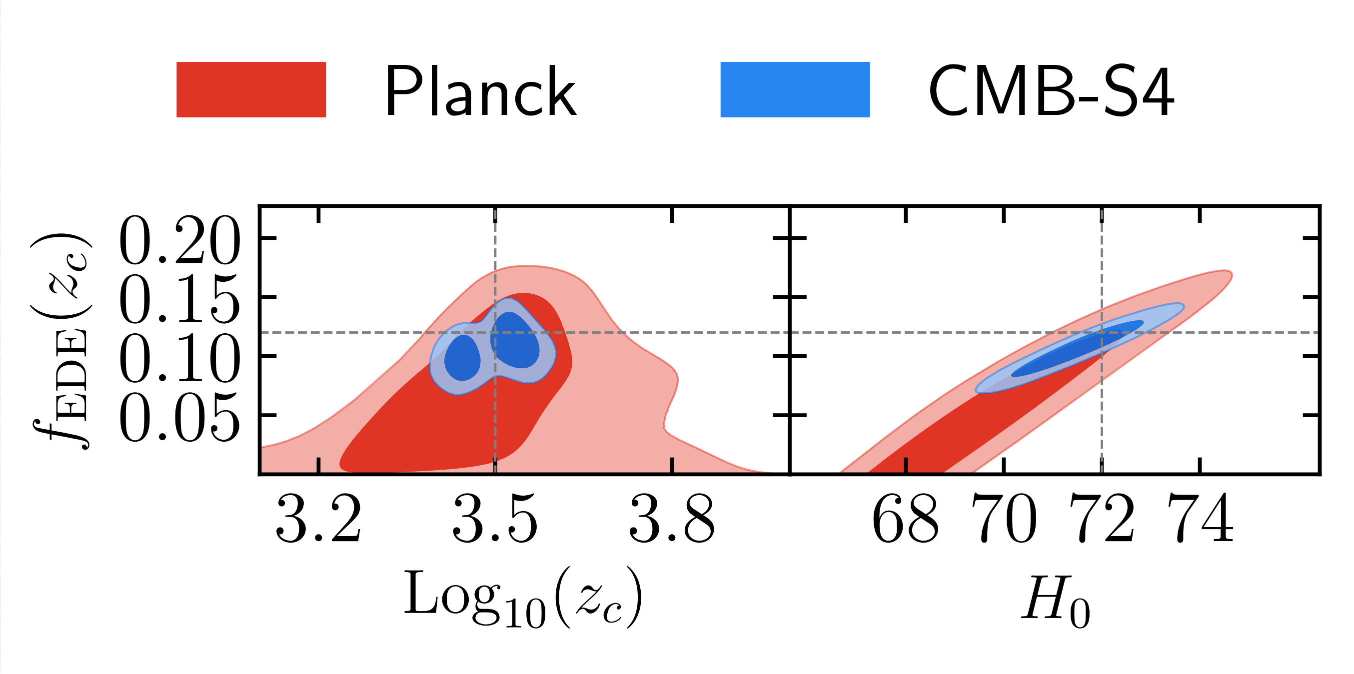
- This is also found by Lin++1905.12618: ADE has no oscillations, slightly worst $\chi^2_{\rm min}$

| model (data) | $\Delta N$ | $H_0$ | $\Delta\chi^2_{\rm tot}$ | $\Delta\chi^2_{\rm CMB}$ | $\Delta\chi^2_{\rm H0}$ |
|---|---|---|---|---|---|
| cADE | 2 | 70.57(70.60±0.85) | -12.7 | -3.6 | -8.8 |
| ADE | 4 | 70.81(70.20±0.88) | -14.1 | -3.7 | -9.6 |
| EDE | 4 | 71.92(71.40±1.09) | -16.6 | -3.7 | -12.5 |

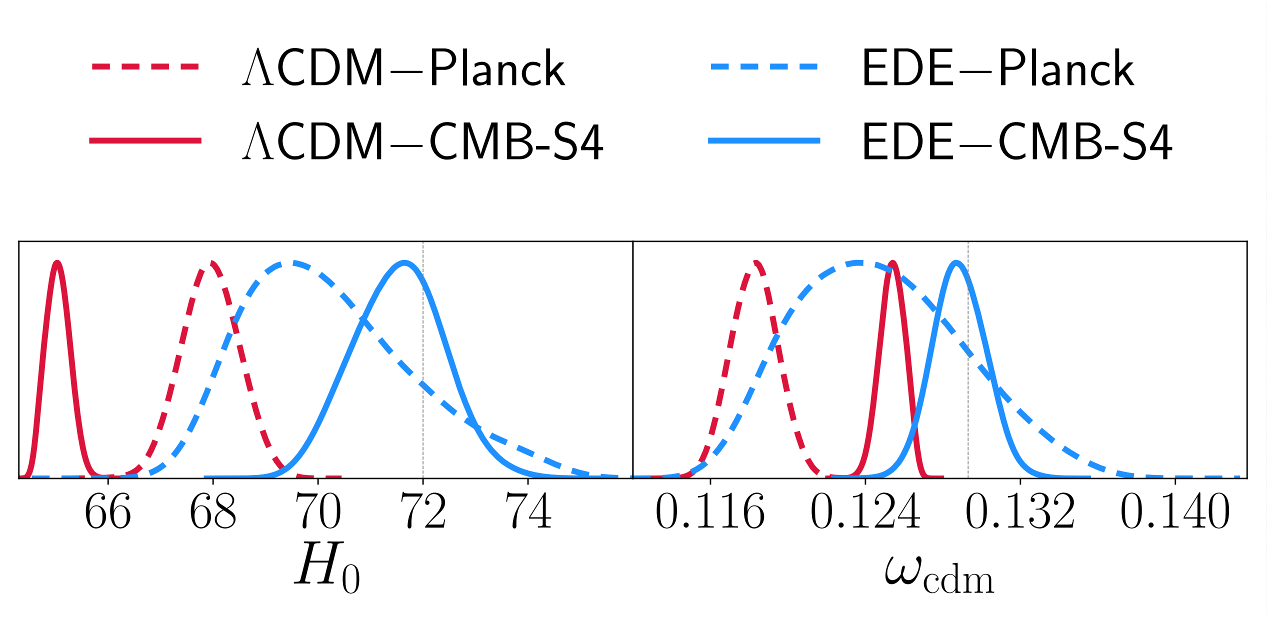
# Detecting the EDE with CMB data only

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

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

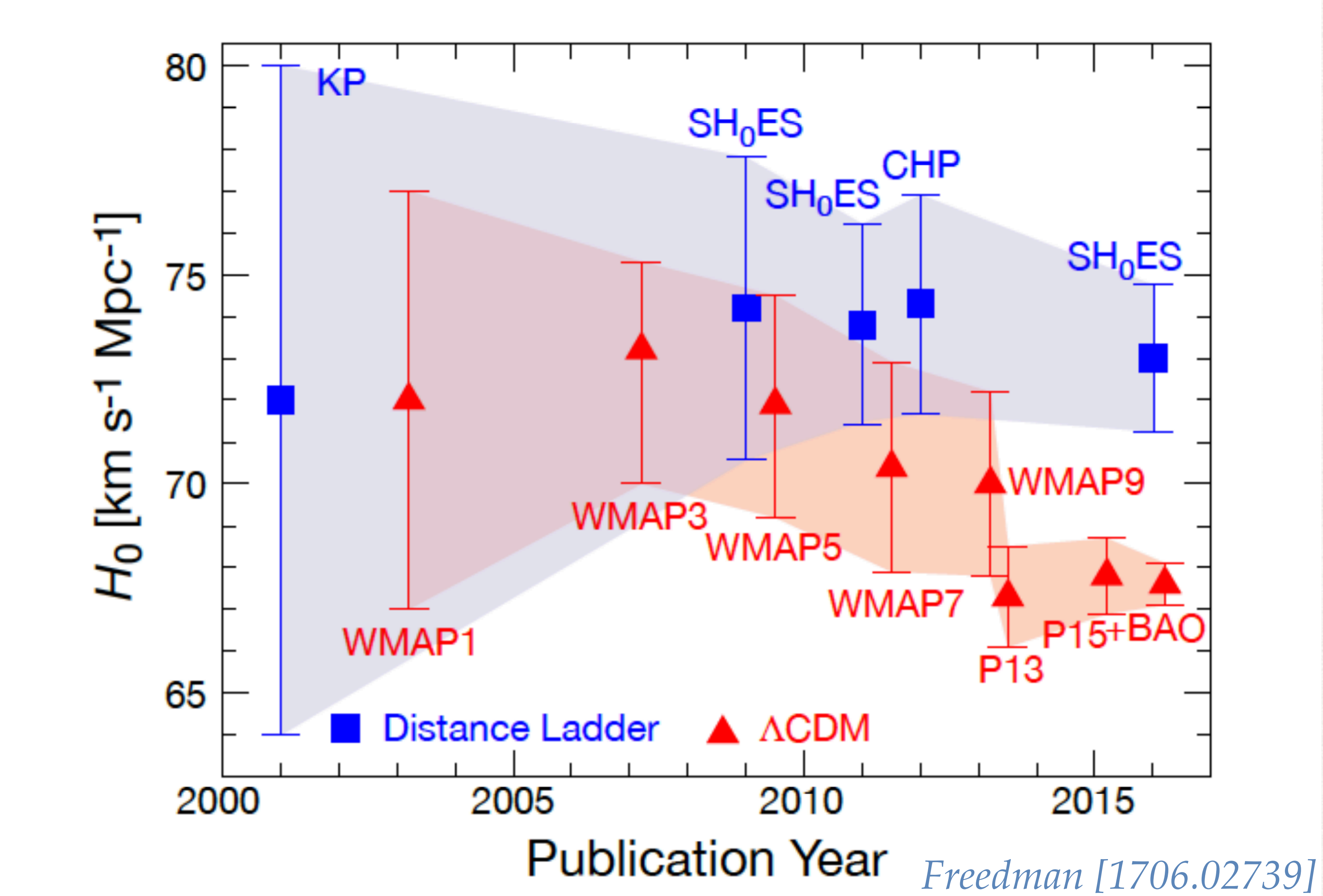



- Without including the EDE: one might strongly bias $H_0$ and $\omega_{\rm cdm}$ values.



# "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]

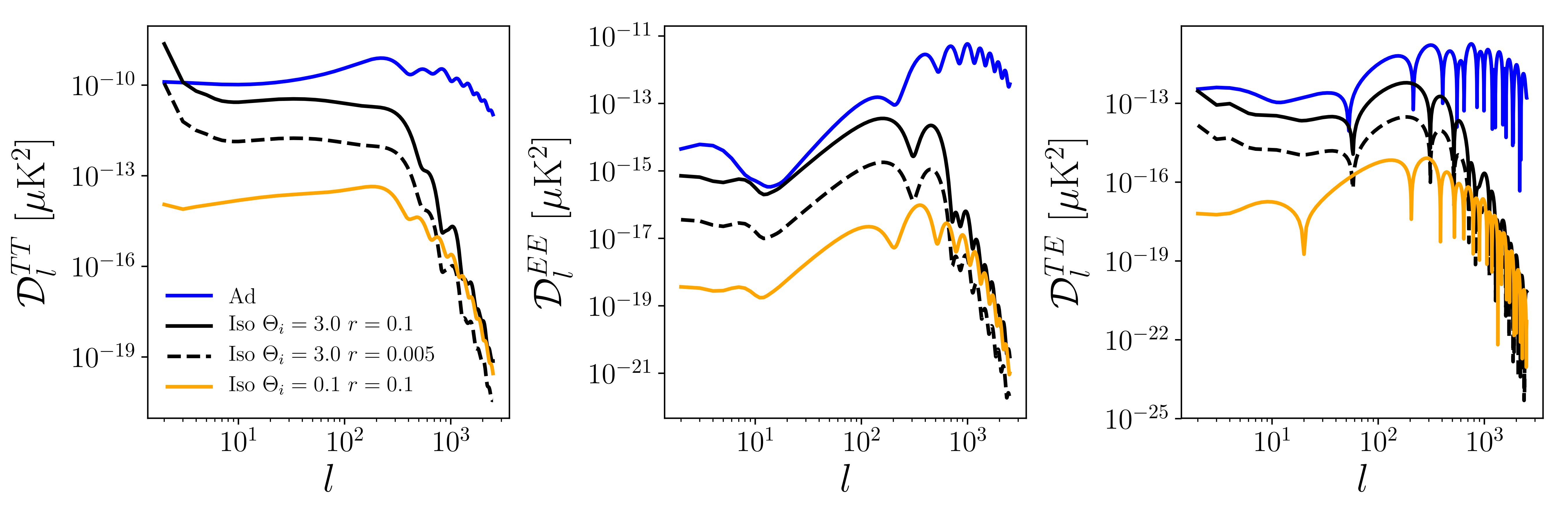
- Did that already happened when going from WMAP to Planck?

# 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)*



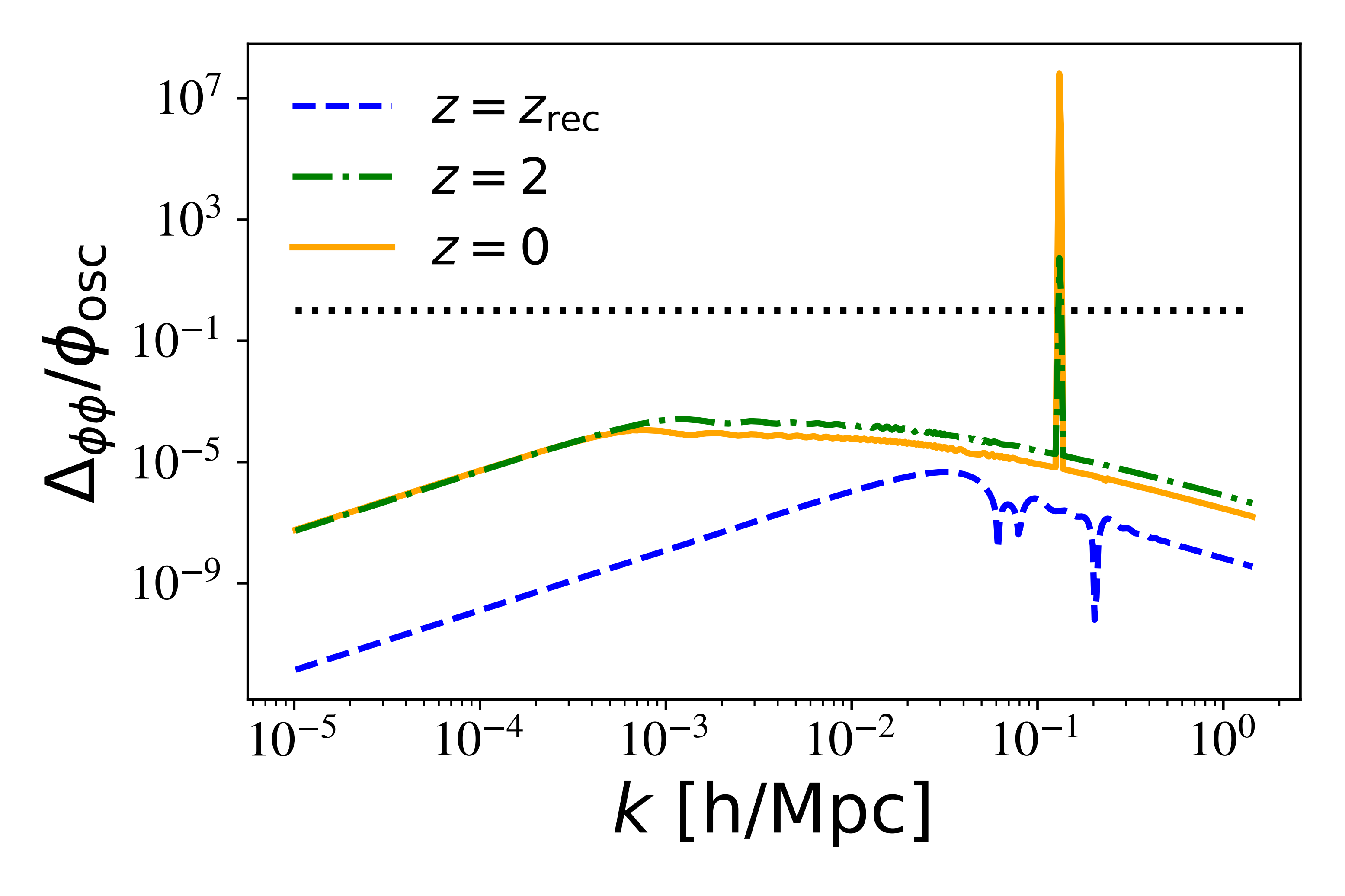

- Measurements of $r$ will allow to constrain / confirm the EDE solution.

# 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.




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

# A New Understanding Of Λ?

- The field becomes dynamical around $z_{\rm eq}$: 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?

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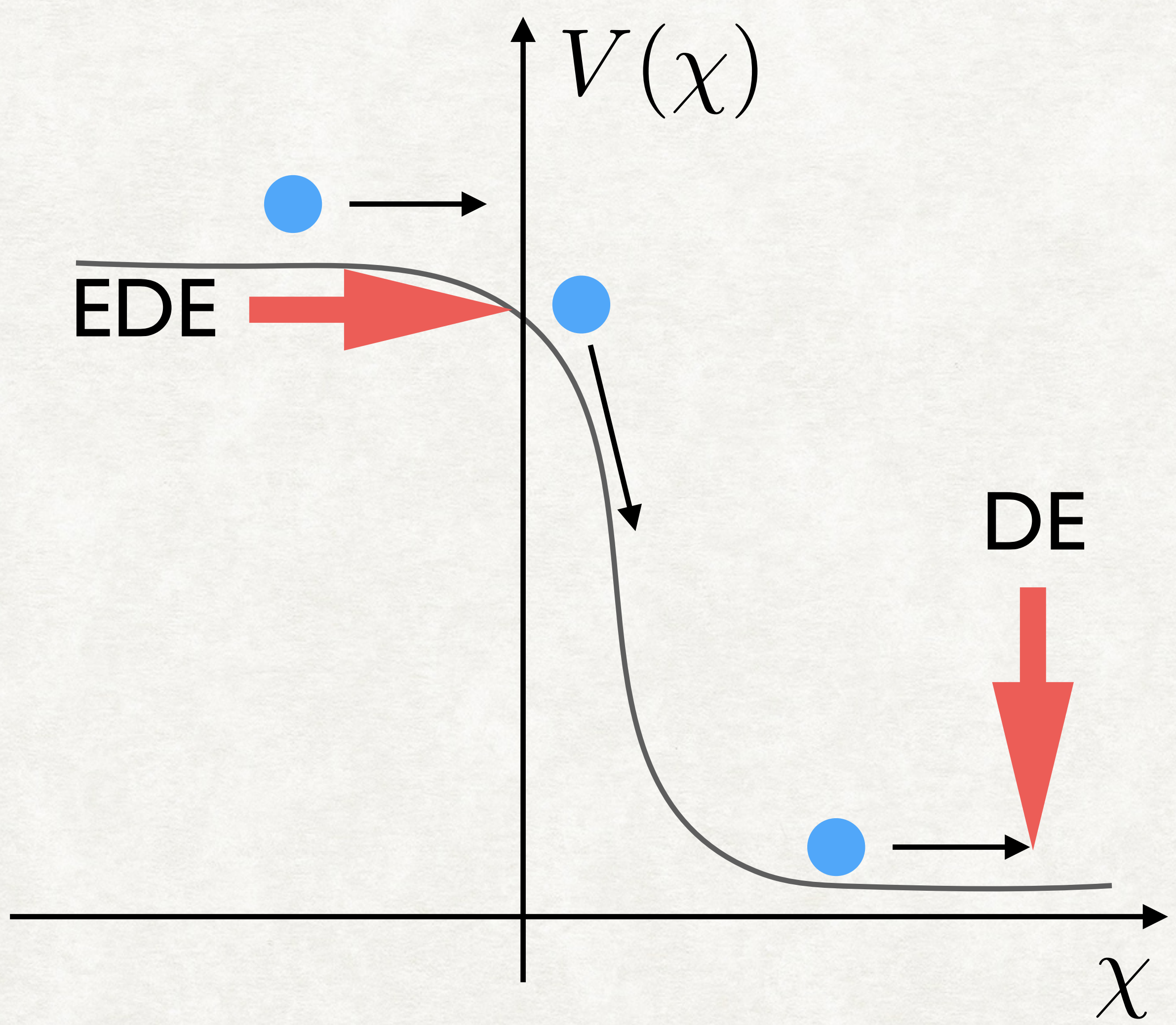

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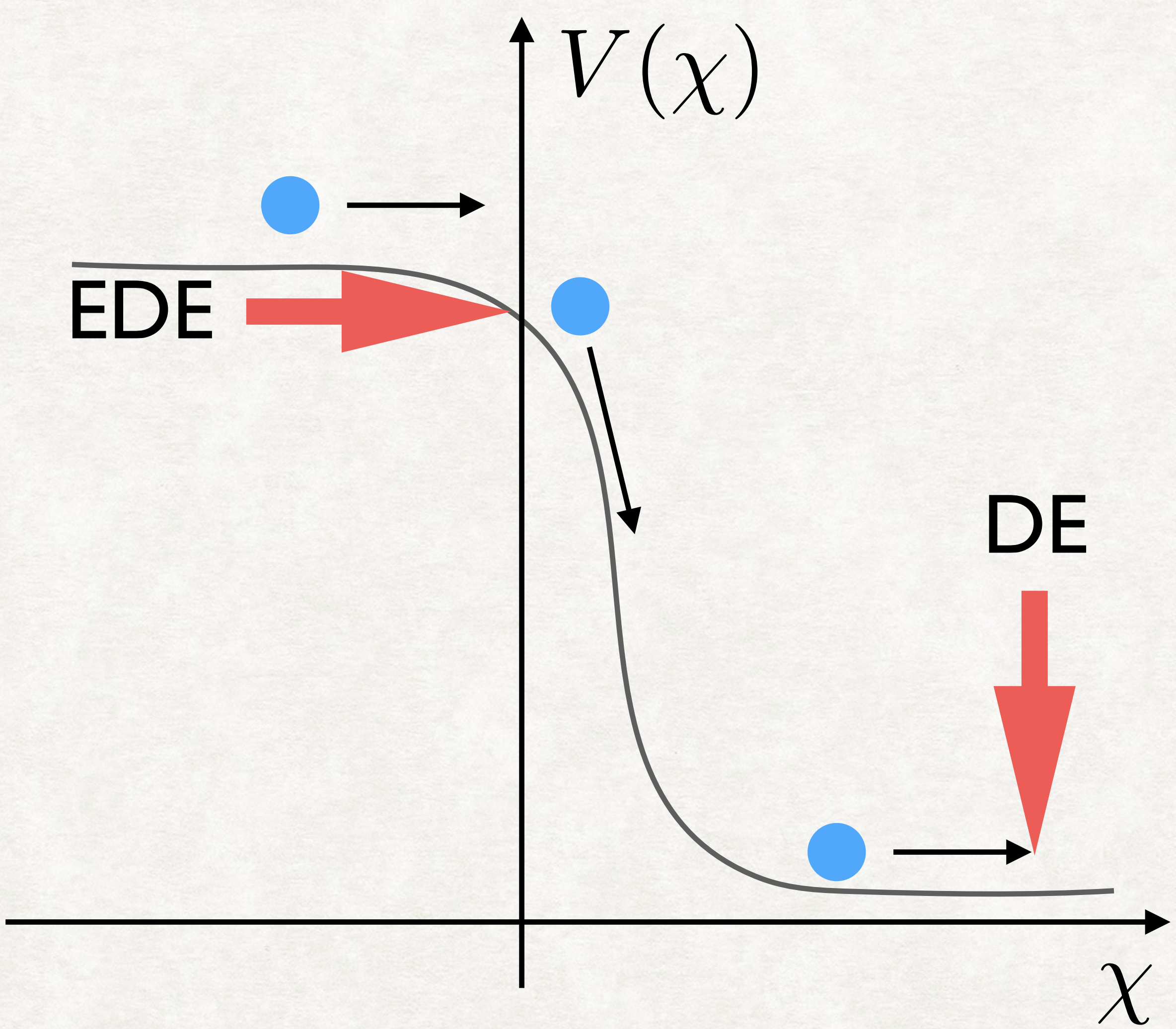


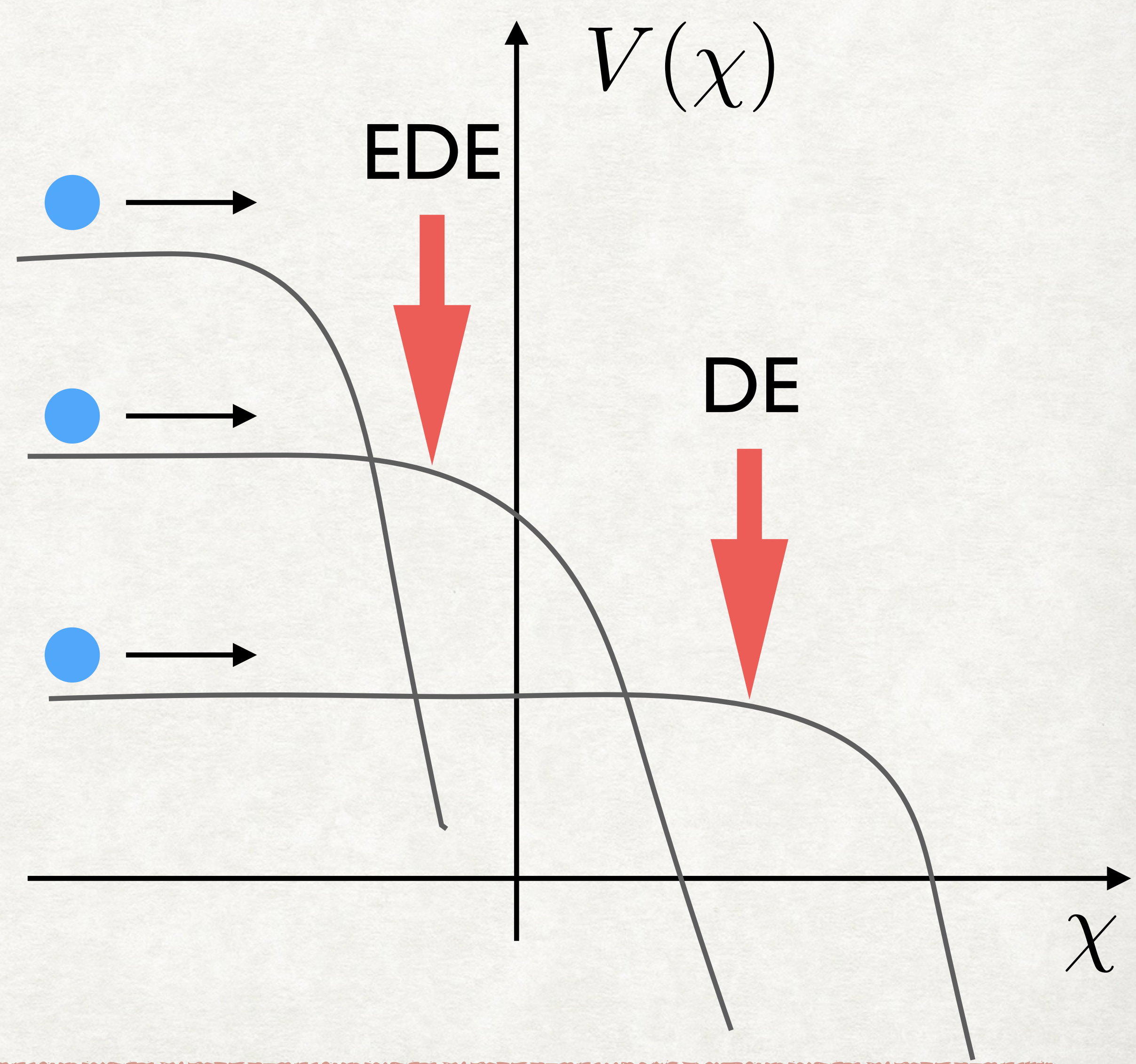

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- If this is the "correct" resolution: there might be new ways of interpreting Λ and inflation.