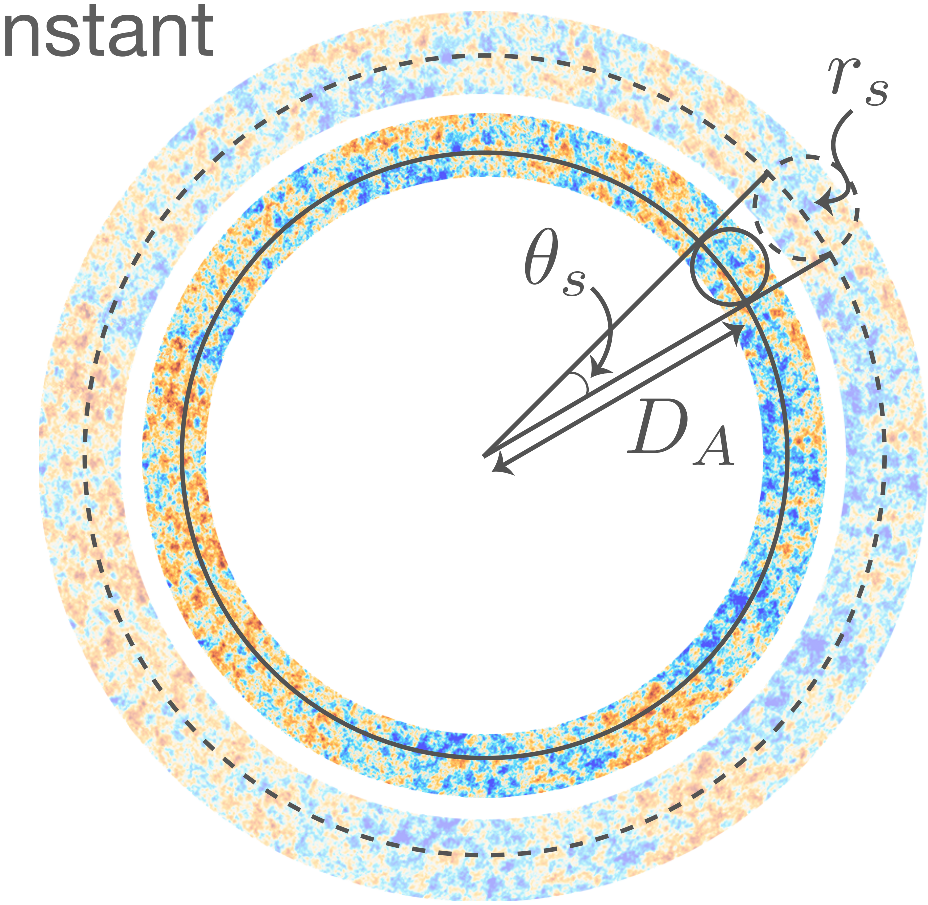
Pre-recombination resolutions to the Hubble tension

- Angular structure of the CMB must remain $\simeq$ constant



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

$$\theta_s = \frac{r_s(z_{\rm rec})}{D_A(z_{\rm rec})} \sim \frac{c_s(z_{\rm rec})/H(z_{\rm rec})}{F(\Omega_m)/H_0} = \frac{H_0}{H(z_{\rm rec})} \frac{c_s(z_{\rm rec})}{F(\Omega_m)}$$

- If $H(z_{\rm rec})$ increases then Silk damping angular scale <u>must</u> increase

$$\theta_D \sim \frac{H_0}{\sqrt{\dot{\tau}(z_{\rm rec}) H(z_{\rm rec})}} \quad \Rightarrow \quad \delta\theta_D/\theta_D \sim \sqrt{H_0/H_0^{\Lambda\rm CDM}}$$

"Damping starts at larger scales"

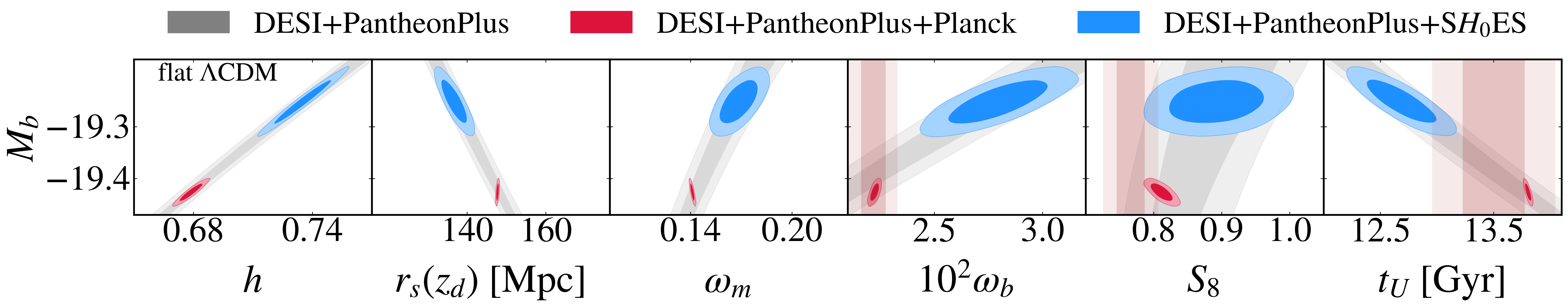
$\Rightarrow$ n_s also generically increases

See Poulin, TLS, and Karwal 2302.09032

Stop calling it the Hubble tension!

Aylor++ 1811.00537
Knox and Millea 1908.03663
Bernal, Verde++ 2102.05066
Poulin, TLS++ 2407.18292
Pedrotti++ 2408.04530

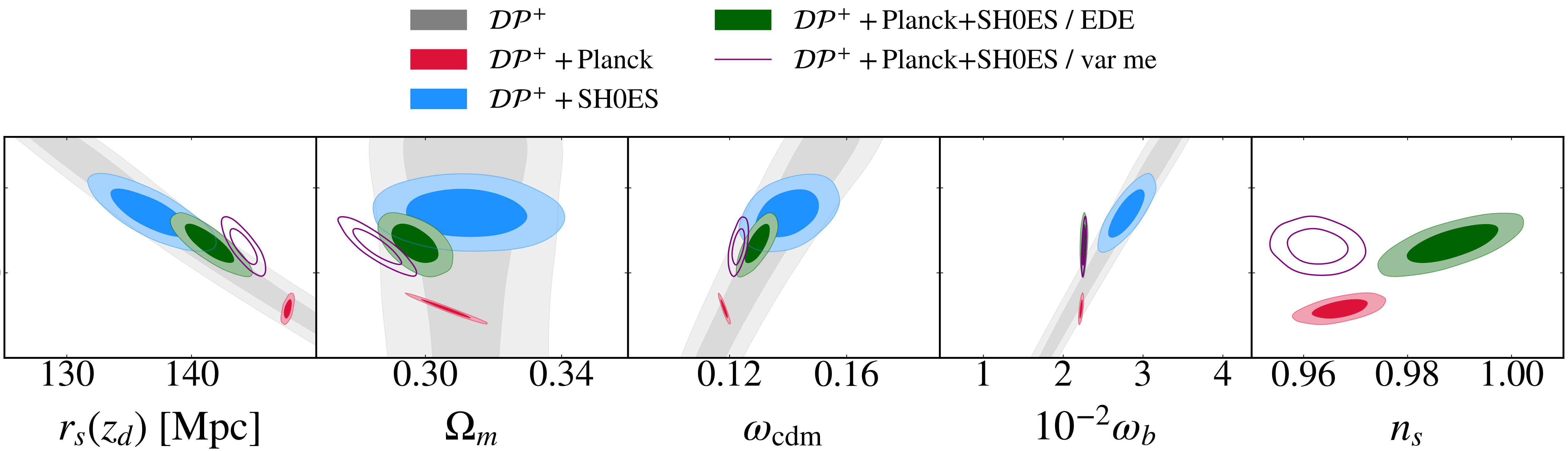
In this paper we called it the "cosmic calibration tension"

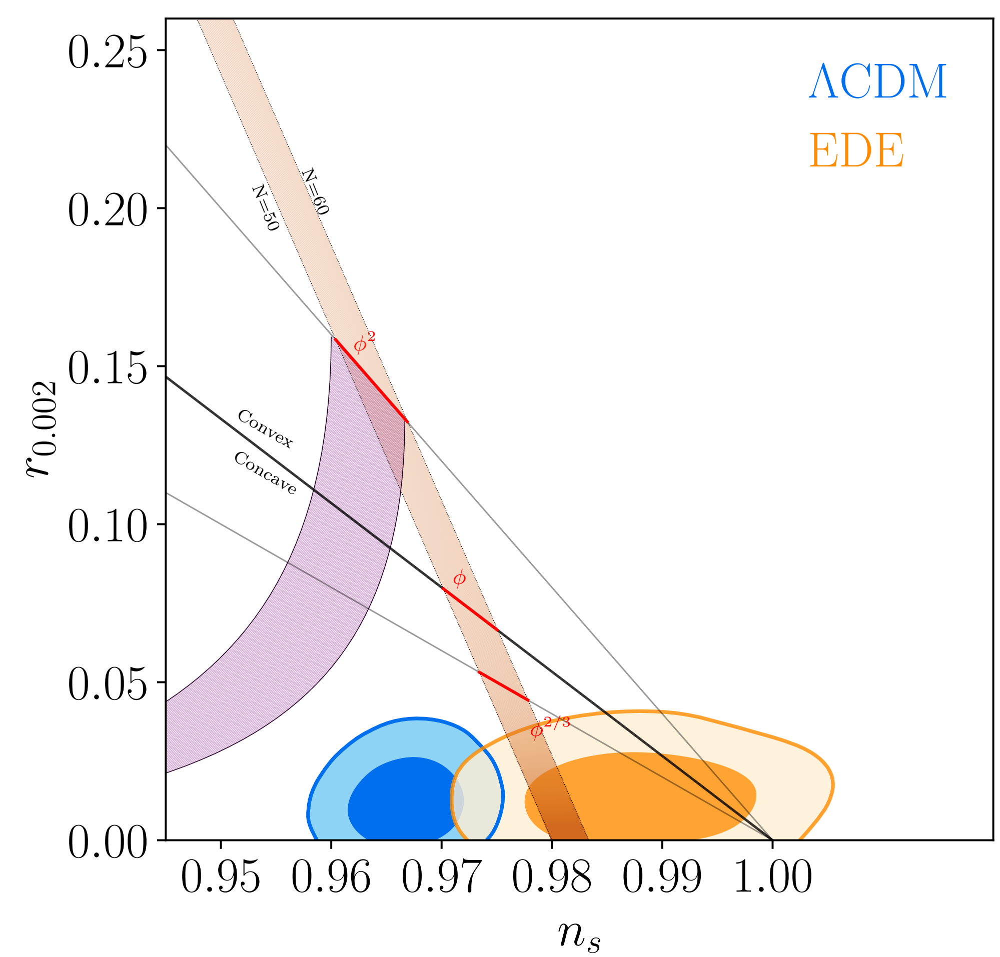


$$\omega_m = \Omega_m h^2$$

Stop calling it the Hubble tension!

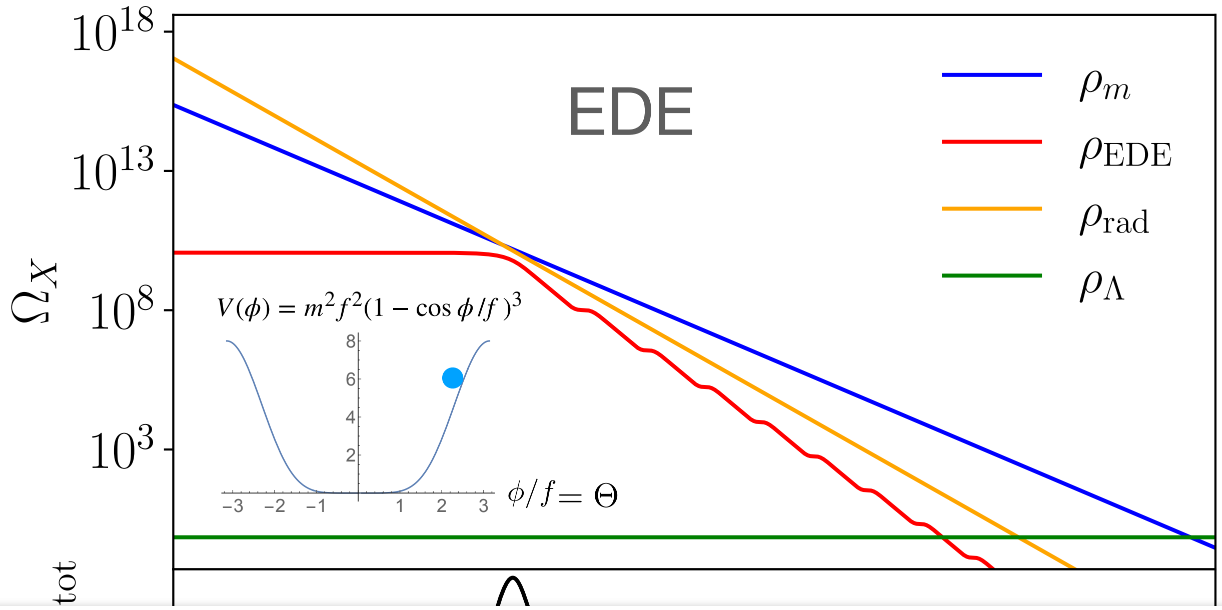
See Poulin, TLS++ 2407.18292

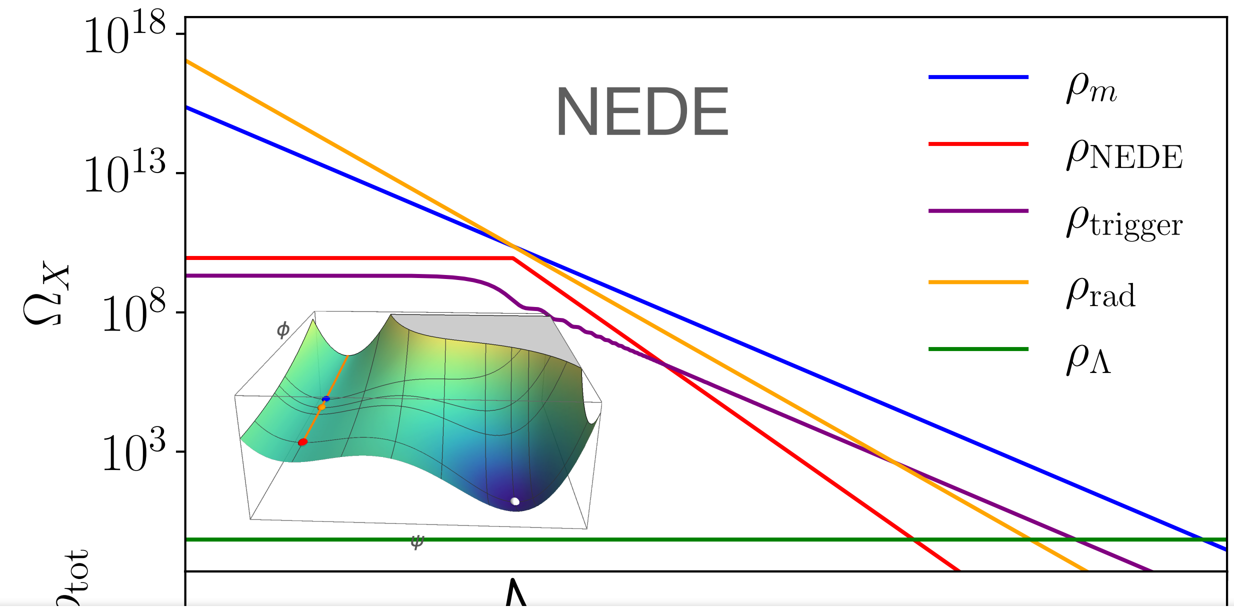


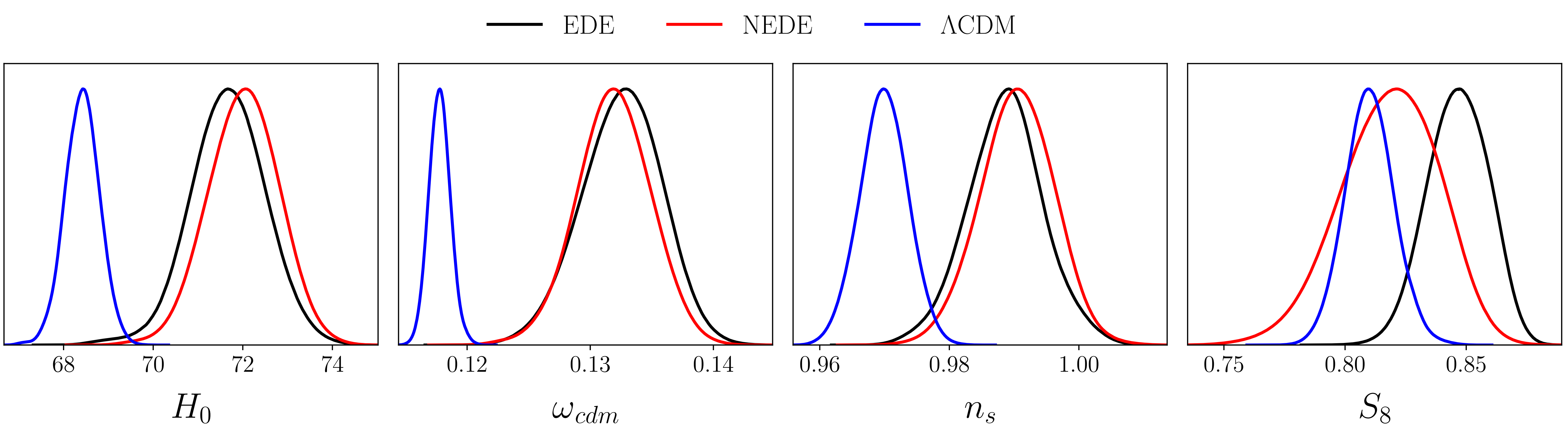


Two case studies: axion-like EDE and ‘new’ EDE

- Axion-like EDE is a cosmological scalar field initially fixed by Hubble friction which then oscillates
- ‘New’ EDE is a field in a false vacuum which undergoes a phase transition







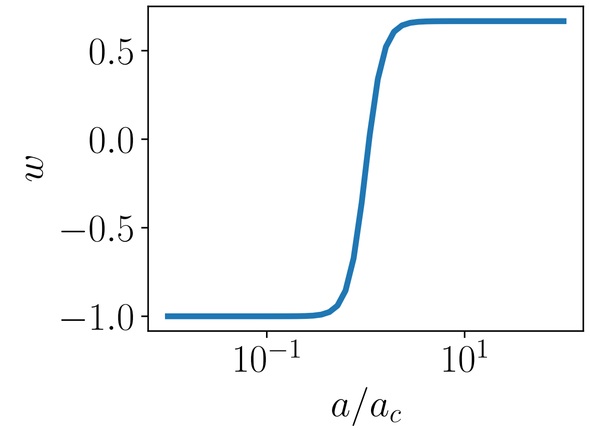
What we learn from a fluid model

Lin++ 1905.12618

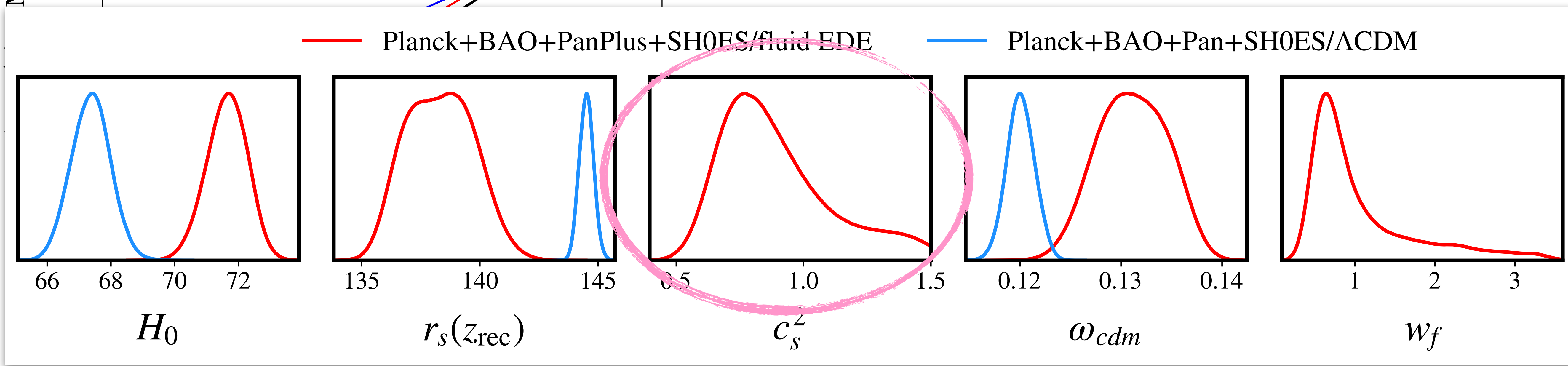
Poulin, TLS, Karwal 2302.09032

$$\rho_{\rm EDE}(a) = \rho_{\rm EDE,0}\, e^{3\int_a^1 [1+w_{\rm EDE}(a)]da/a}$$

$$w_{\rm EDE}(a) = \frac{1+w_f}{1+(a_c/a)^{3(1+w_f)}} - 1$$



Perturbations are important!

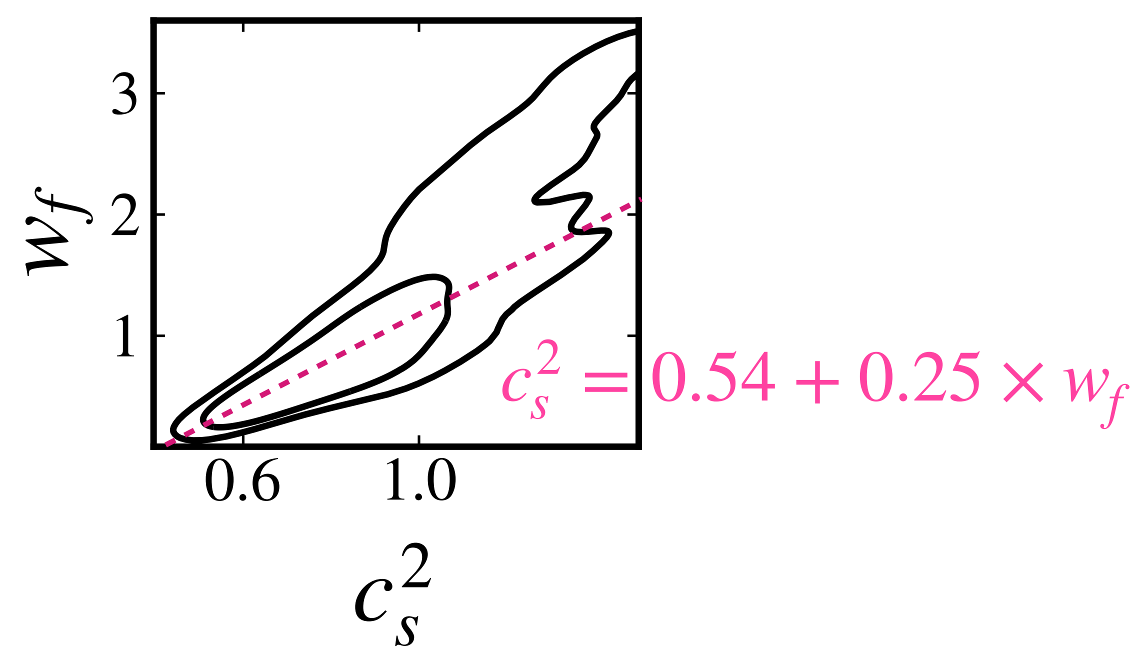


Perturbation equations:

$$\frac{d}{d\eta}\left(\frac{\delta_{\rm EDE}}{1+w_{\rm EDE}}\right) = -\left(\theta_{\rm EDE}+h'_\delta\right) - 3\frac{a'}{a}\left(c_s^2 - c_a^2\right)\left(\frac{\delta_{\rm EDE}}{1+w_{\rm EDE}} + 3\frac{a'}{a}\frac{\theta_{\rm EDE}}{k^2}\right)$$

$$\theta'_{\rm EDE} = -\frac{a'}{a}\left(1-3c_s^2\right)\theta_{\rm EDE} + c_s^2 k^2 \frac{\delta_{\rm EDE}}{1+w_{\rm EDE}} + k^2 h_v,$$

$$c_a^2 = \frac{\rho'_{\rm EDE}}{P'_{\rm EDE}} = w_{\rm EDE} - \frac{1}{3}\frac{dw_{\rm EDE}/d\ln a}{1+w_{\rm EDE}}$$



Extensions:

- Coupling DM & EDE to address S_8

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + i\bar{\psi}\not{D}\psi - V(\phi) - m_{\rm DM}(\phi)\bar{\psi}\psi$$

$$m_{\rm DM}(\phi) = m_0 e^{c\phi/M_{\rm pl}}$$

Karwal ++ 2106.13290
McDonough ++ 1811.04083

Leads to <u>enhanced</u> DM growth:

$$G_{\rm eff} = G_N\left(1 + \frac{2c^2k^2}{k^2 + a^2 d^2V/d\phi^2}\right)$$

Bean ++ 0808.1105

- Modified gravity

$$S = \int {\rm d}^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R - \frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma - \Lambda - V(\sigma) + \mathcal{L}_m\right]$$

$$V(\sigma) = \lambda\sigma^4/4$$

Adi and Kovetz 2011.13853
Abellan, Braglia++ 2308.12345

- Non-minimal coupling to address fine tuning

$$S = \int {\rm d}^4x\sqrt{-g}\left[\frac{M_{\rm pl}{}^2R(g)}{2} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right] + S_\nu[\tilde{g}_{\mu\nu}],$$

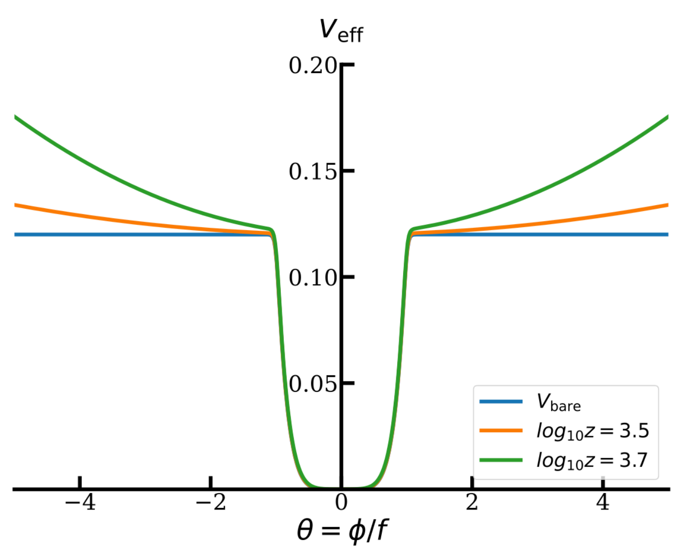
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\beta}{M_{\rm pl}}\Theta(\nu),$$

Sakstein and Trodden 1911.11760
Gonzalez, Liang, Sakstein and Trodden 2011.09895

Lin, McDonough, Hill, and Hu 2212.08098

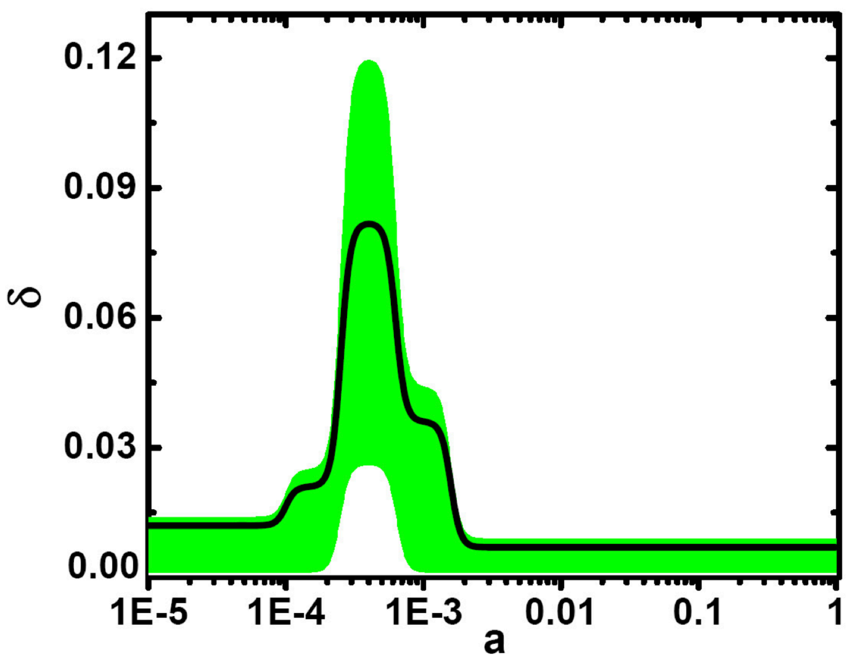
$$m_{\rm DM}(\phi) = m_0\left(1 + g\frac{\phi^2}{M_{\rm pl}^2}\right)$$

$$V_{\rm eff} \approx V(\phi) + g\frac{\phi^2}{M_{\rm pl}^2}\rho_{\rm DM}$$



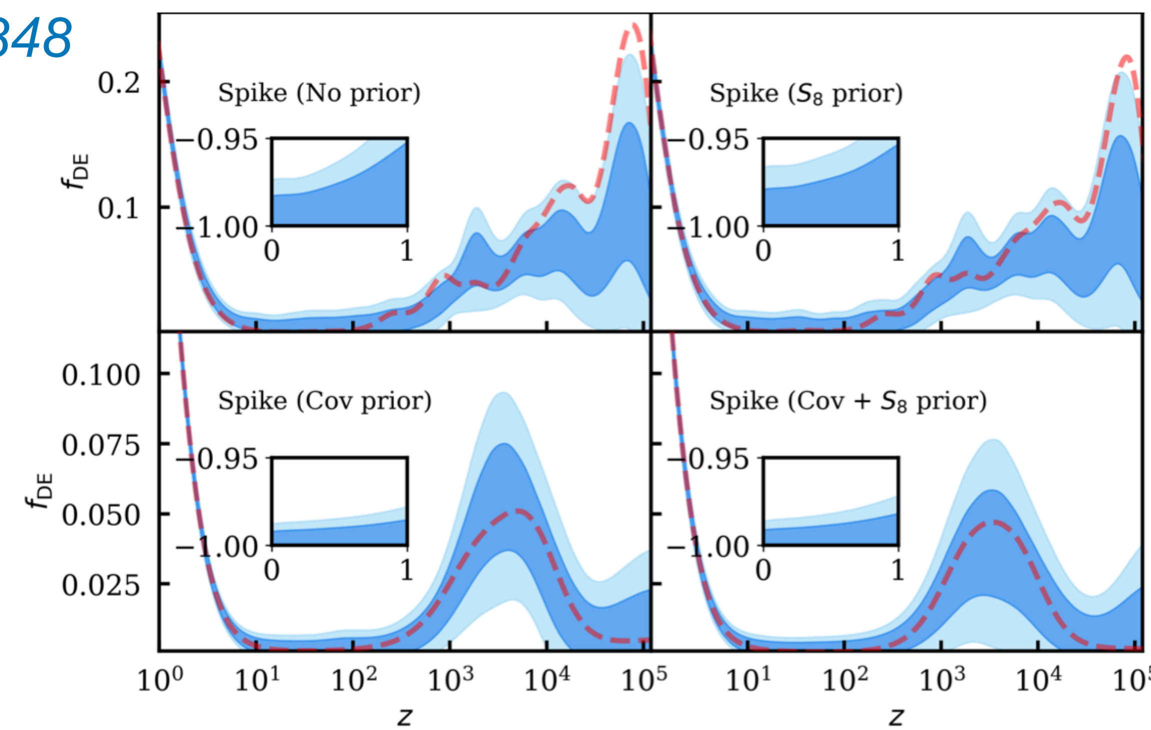
‘Model independent’ approaches?

Hojjati et al. 1304.3724 $H^2(a) = \frac{8\pi G}{3}\left[\rho_m(a) + \rho_r(a) + \rho_\Lambda\right]\left[1 + \delta(a)\right]$ $\delta = \sum_i \delta_i \left[\frac{1}{1 + e^{(\ln a - \ln a_{i+1})/\tau}} - \frac{1}{1 + e^{(\ln a - \ln a_i)/\tau}}\right]$



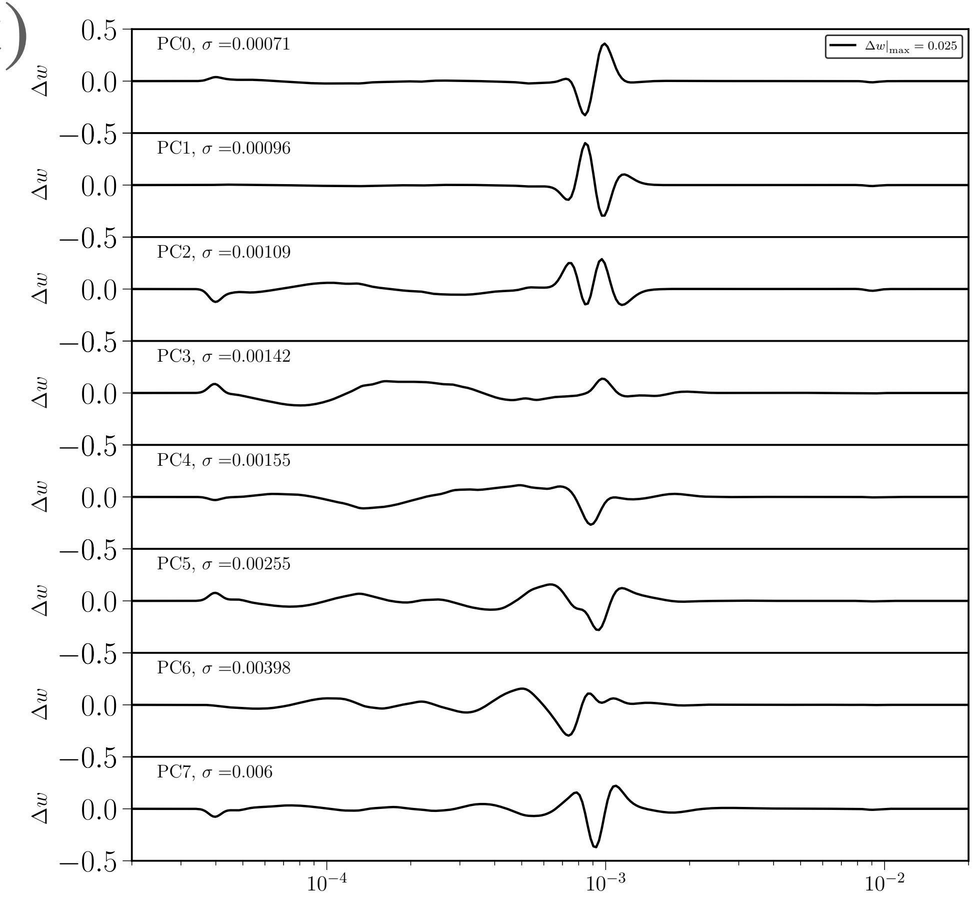
Moss et al. 2109.14848

- Binned $\Delta\rho(a_i)$



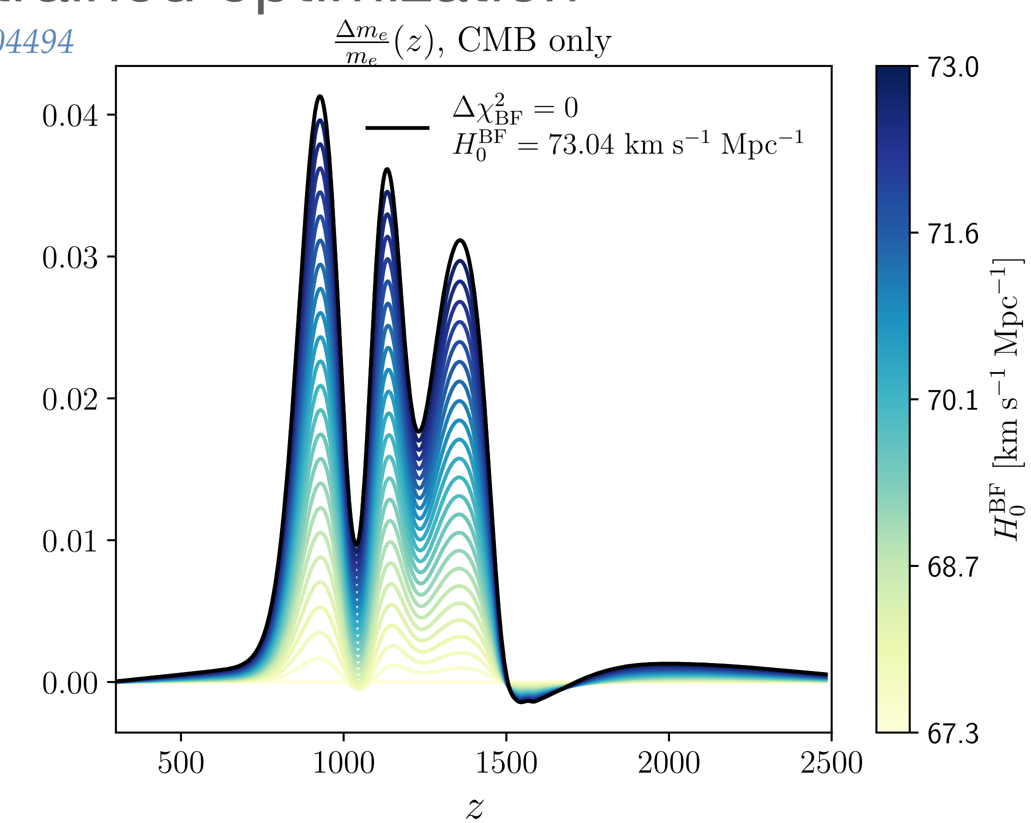
- PCA of $w(a)$

TLS and Grin, in prep.



- ‘constrained optimization’

Lee++ 2212.04494

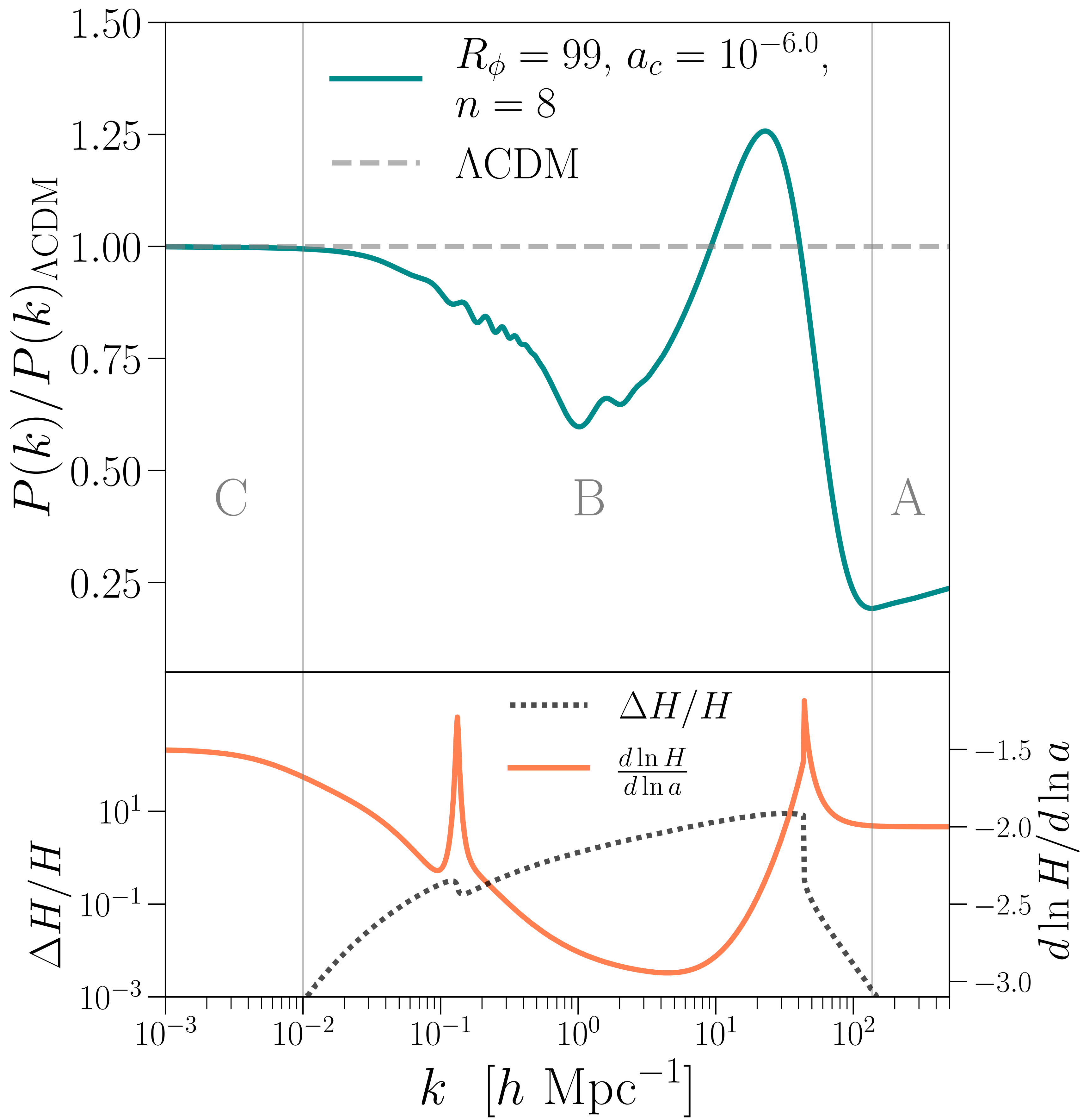


Very Early Dark Energy

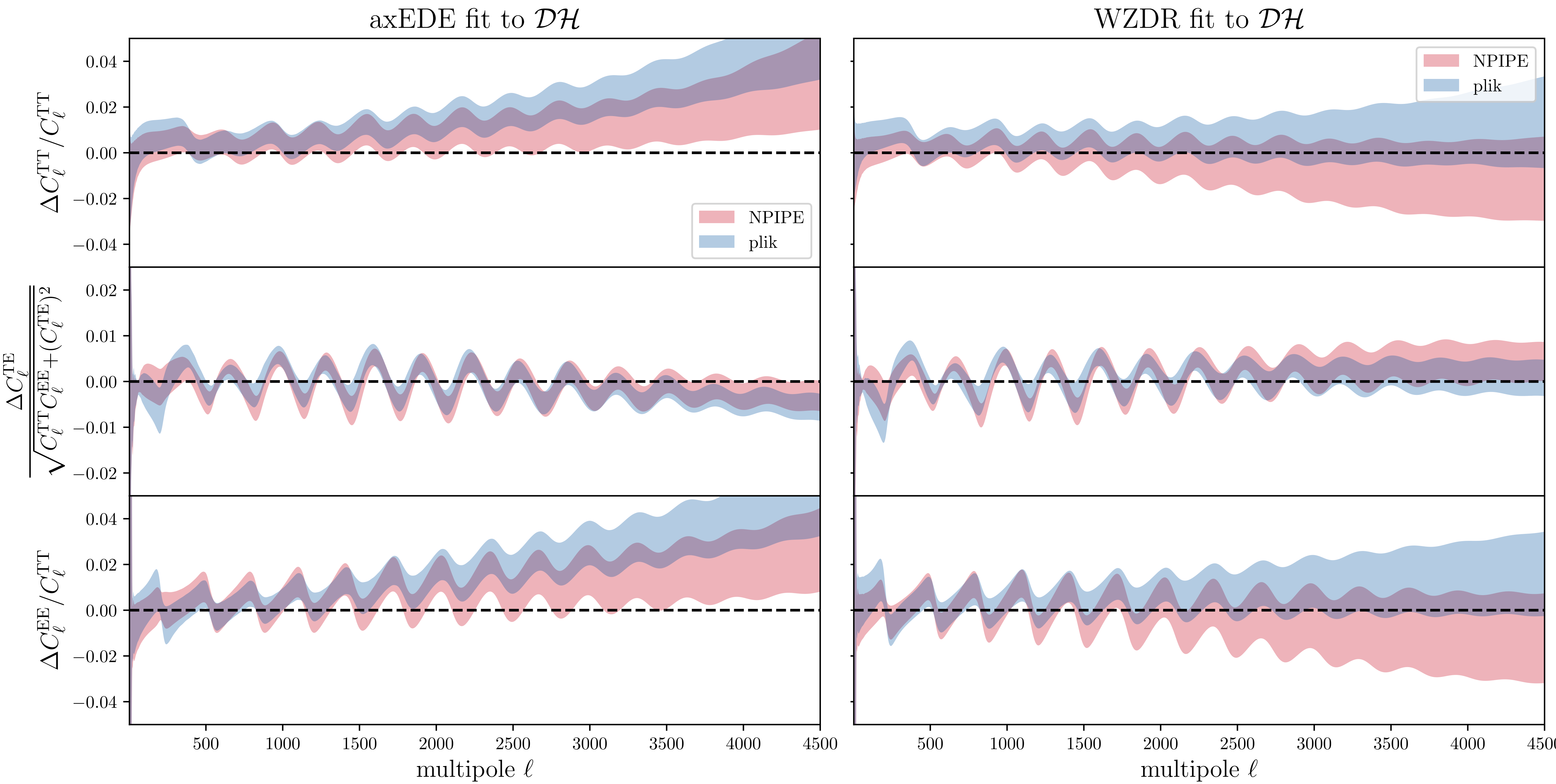
Sobotka, Erickcek, and TLS, in prep.

$$V(\phi) = f^2 m^2 (1 - \cos\theta)^8$$

$$R_\phi \equiv \frac{\rho_\phi(a_c)}{\rho_{\rm tot}(a_c) - \rho_\phi(a_c)}$$

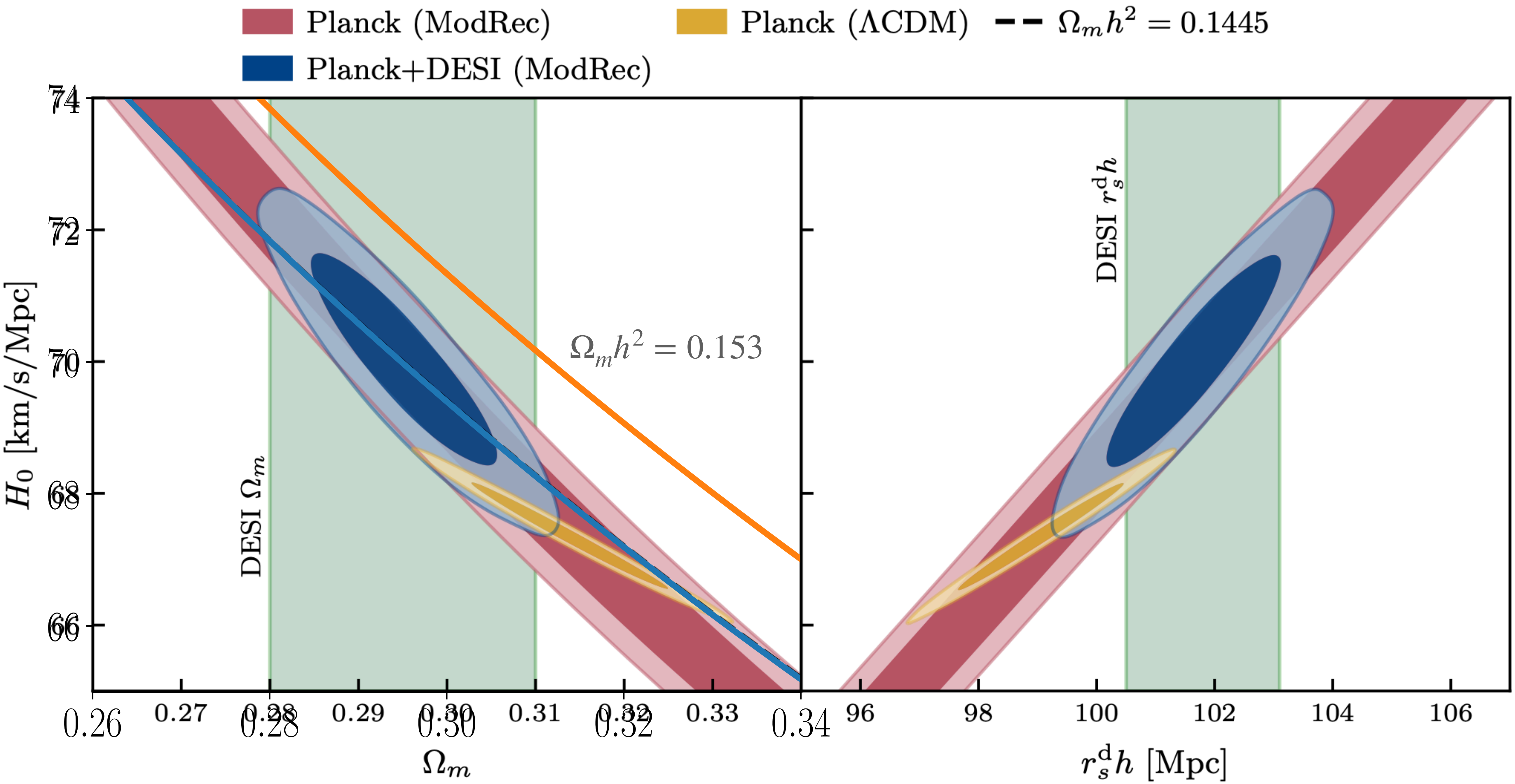


Projecting into the future



Stop calling it the Hubble tension!

Lynch, Knox, and Chluba, 2406.10202



The preferred shape of the potential

$$V(\phi) = m^2 f^2 E(\theta \equiv \phi/f)$$

Axion-like: $E = (1 - \cos\theta)^3$

Double power law: $E = \left(1 + \theta^{2n}\right)^{q/(2n)} - 1$