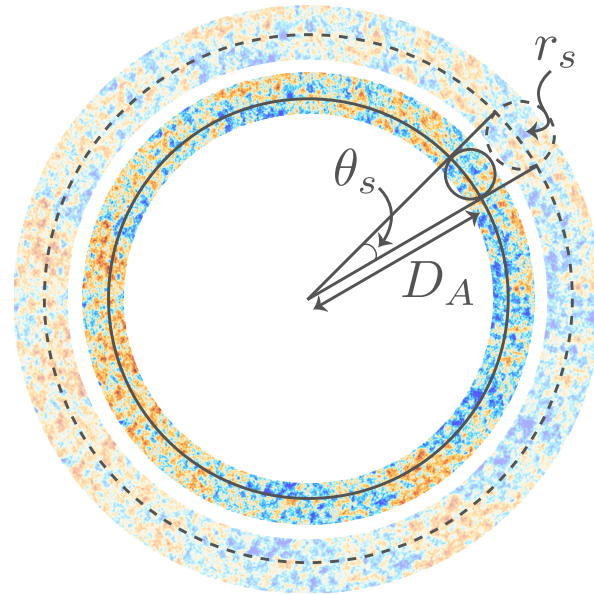
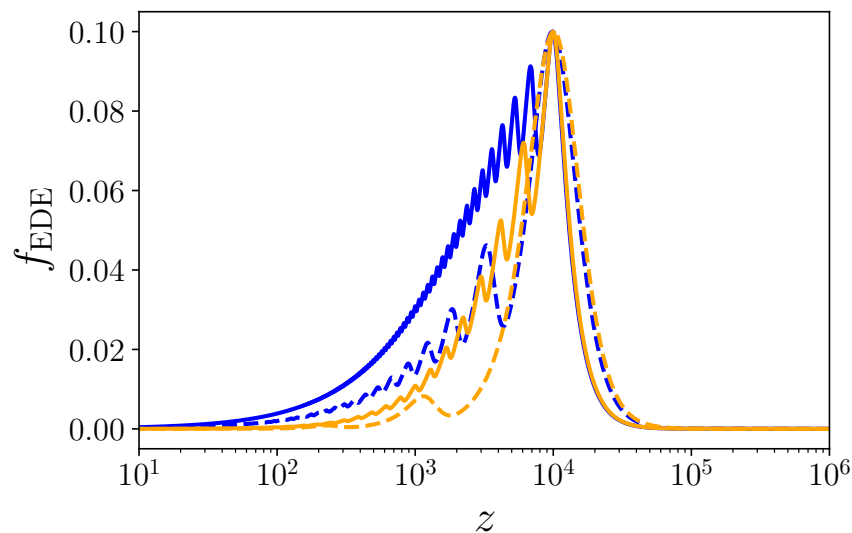
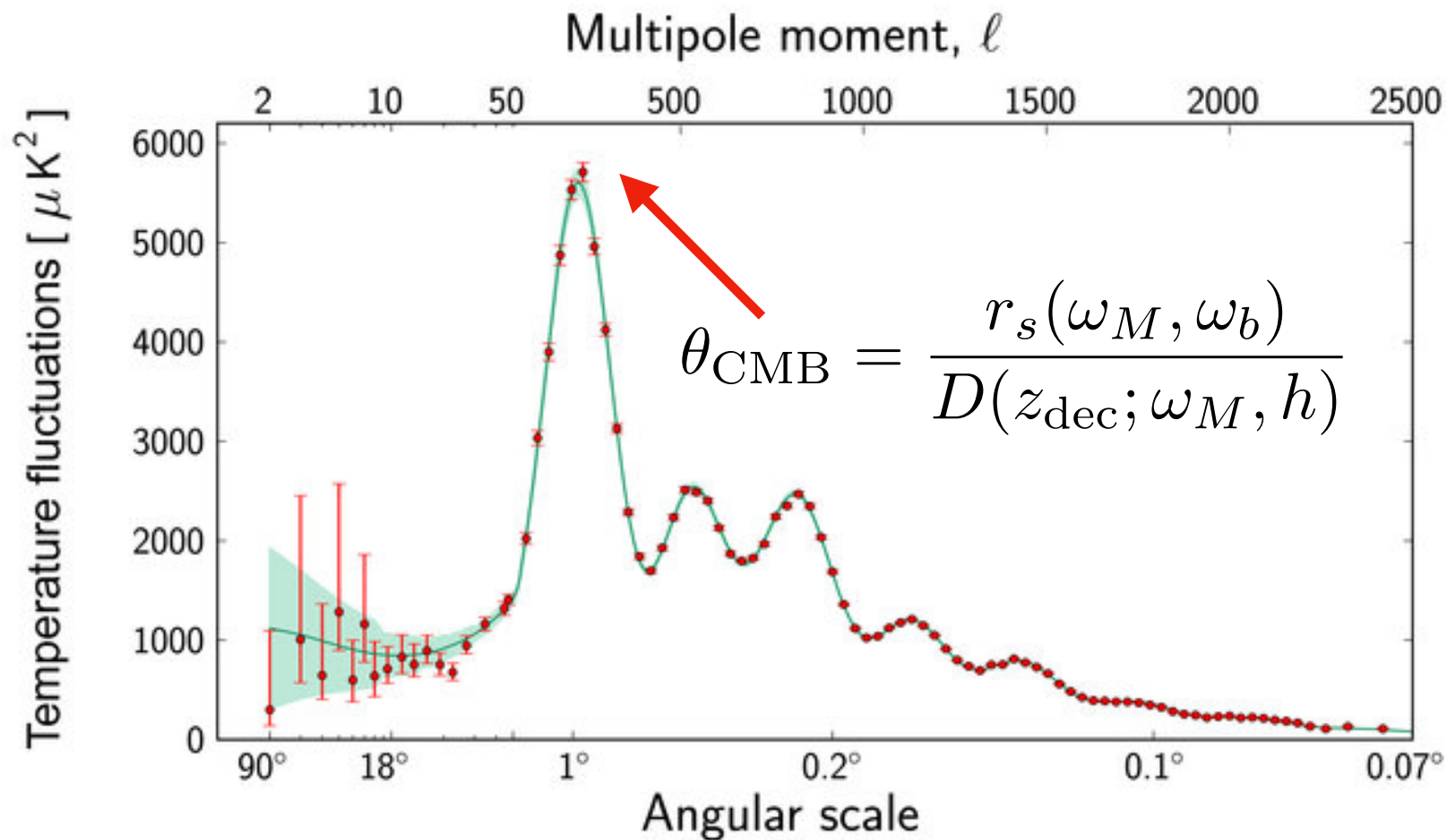


Oscillating scalar fields and the Hubble tension: a solution with novel features



Tristan L. Smith
Swarthmore College

CMB as a standard ruler



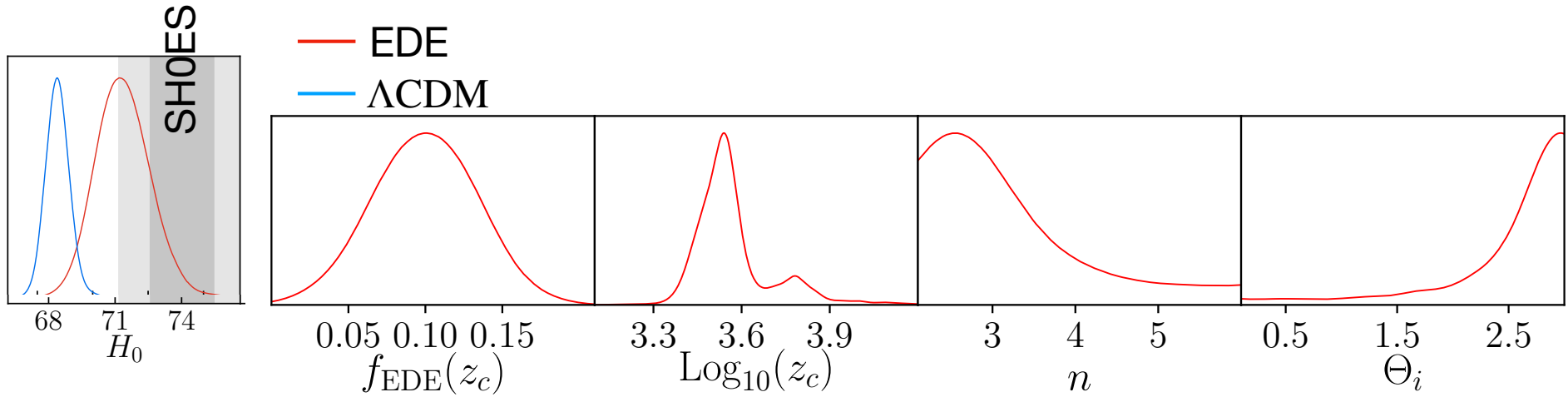
$$\theta_{\text{CMB}} \sim H_0 r_s \quad \longrightarrow \quad \frac{\delta h}{h} = -\frac{\delta r_s}{r_s} = \frac{0.74 - 0.67}{0.67} = 0.1$$

Aylor++ 1811.00537

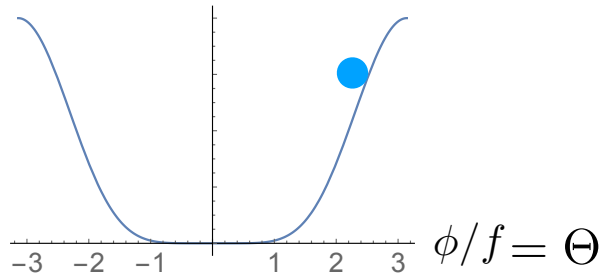
$$r_s = \int_{\infty}^{z_*} dz \frac{c_s(z)}{H(z)}$$

Early dark energy and the Hubble tension

- Studied ‘cycle-averaged’ ($c_{\text{eff}}^2 = \langle \delta P \rangle / \langle \delta \rho \rangle$) in **PRL 122 (2019)** *Poulin, Smith, Karwal, Kamionkowski*
- Solved exact (linear) equations in 1908.06995 *Smith, Poulin, and Amin*



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



- Fit *Planck* CMB, JLA, BAO, SHOES

$$f = 0.18 \pm 0.06 M_{\text{pl}} \quad m = 3.4_{-3.0}^{+2.3} \times 10^{-27} \text{ eV}$$

- Θ_i controls effective sound-speed; in order to fit CMB, $c_{\text{eff}}^2 \simeq 0.8$

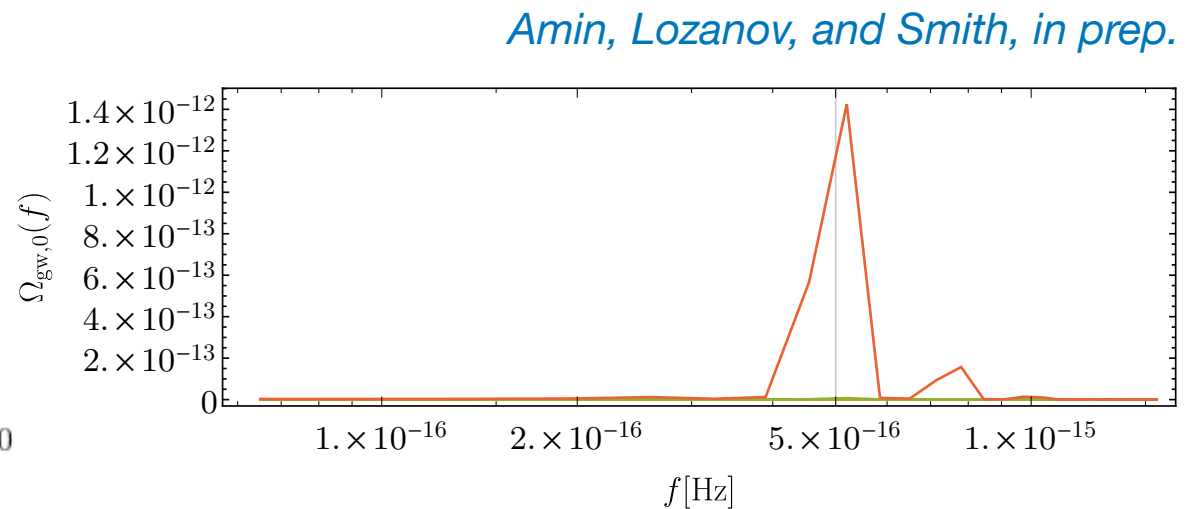
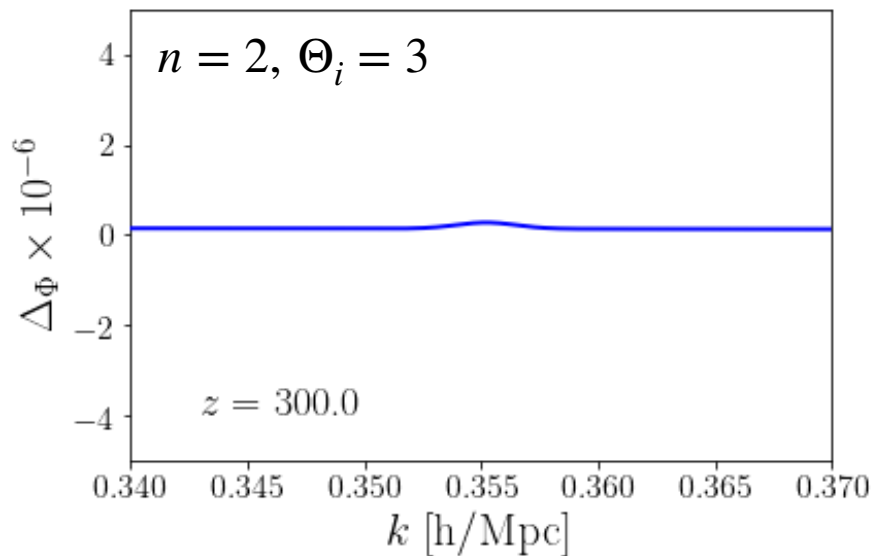
See also ‘Acoustic Dark Energy’, Lin++ 1905.12618

- The EDE cosmology fits cosmological observations just as well as Λ CDM

Novel prediction: 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



Amin, Lozanov, and Smith, in prep.

- GWs and non-linear structures may have observable consequences in the small-scale CMB
- May produce features in TT power spectrum at small scales ($\ell \sim 3000$ & 6000)

CMB-HD, Sehgal++ 1906.10134

Early dark energy and the LSS

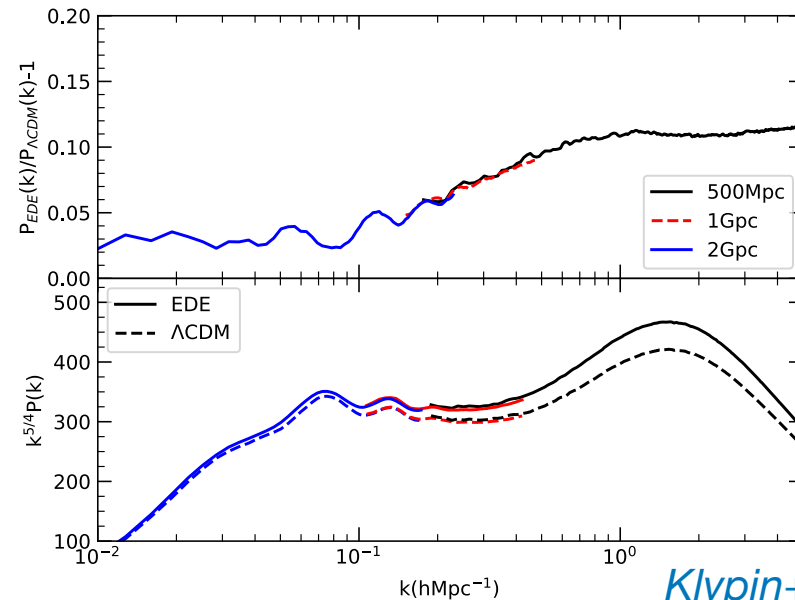
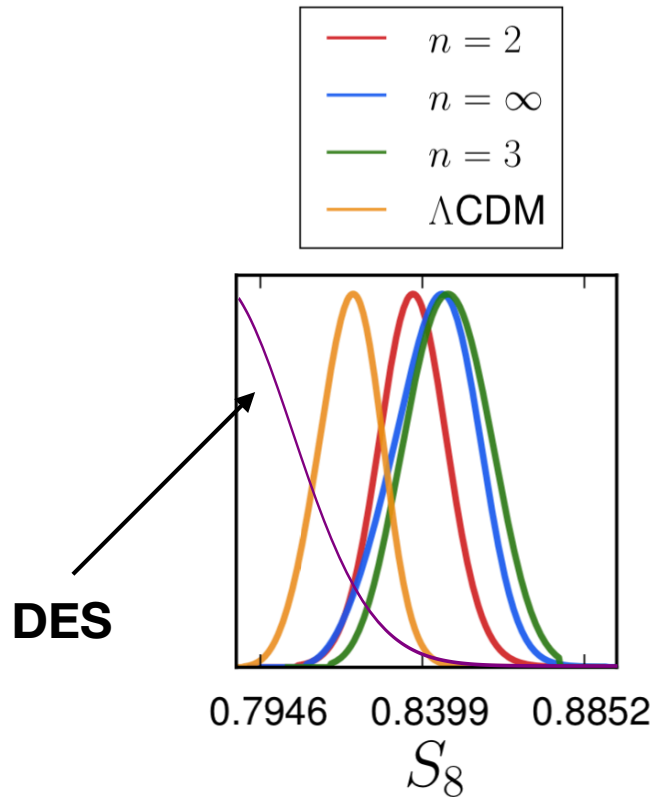
- LSS will provide useful information

Hill++ [arXiv:2003.07355](#)

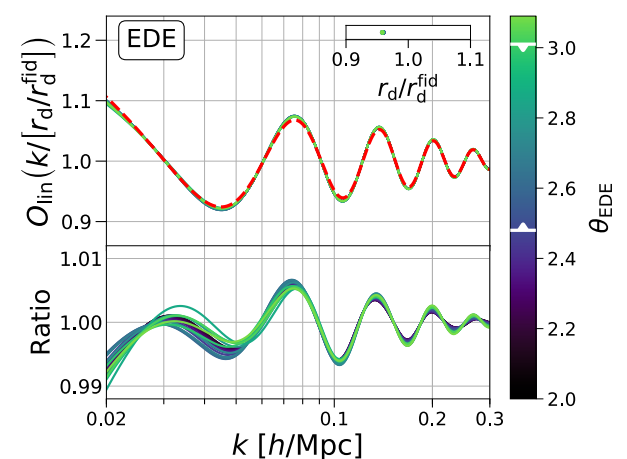
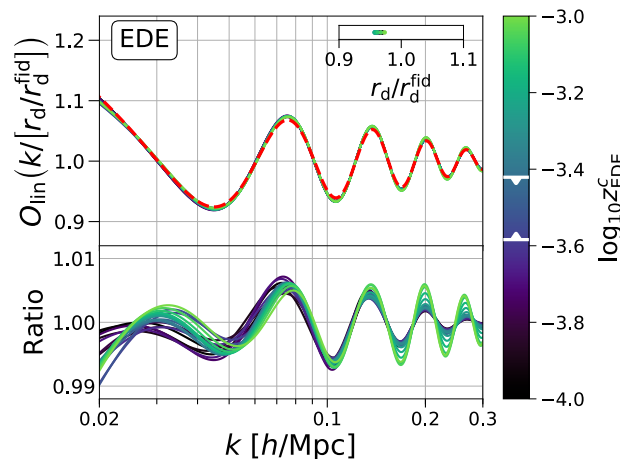
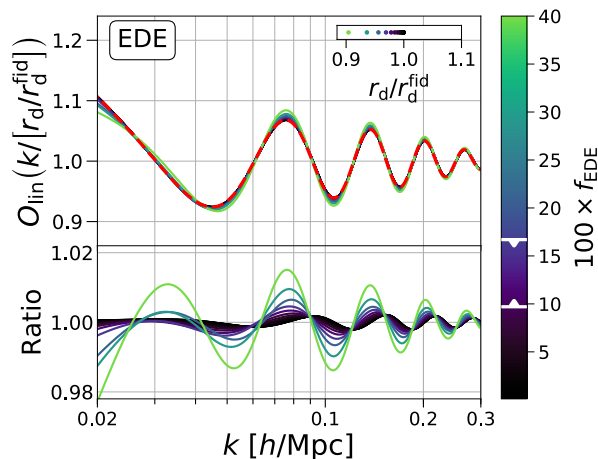
Murgia++ [arXiv:2009.10733](#)

Ivanov++ [arXiv:2006.11235](#)

D'Amico++ [arXiv:2006.12420](#)



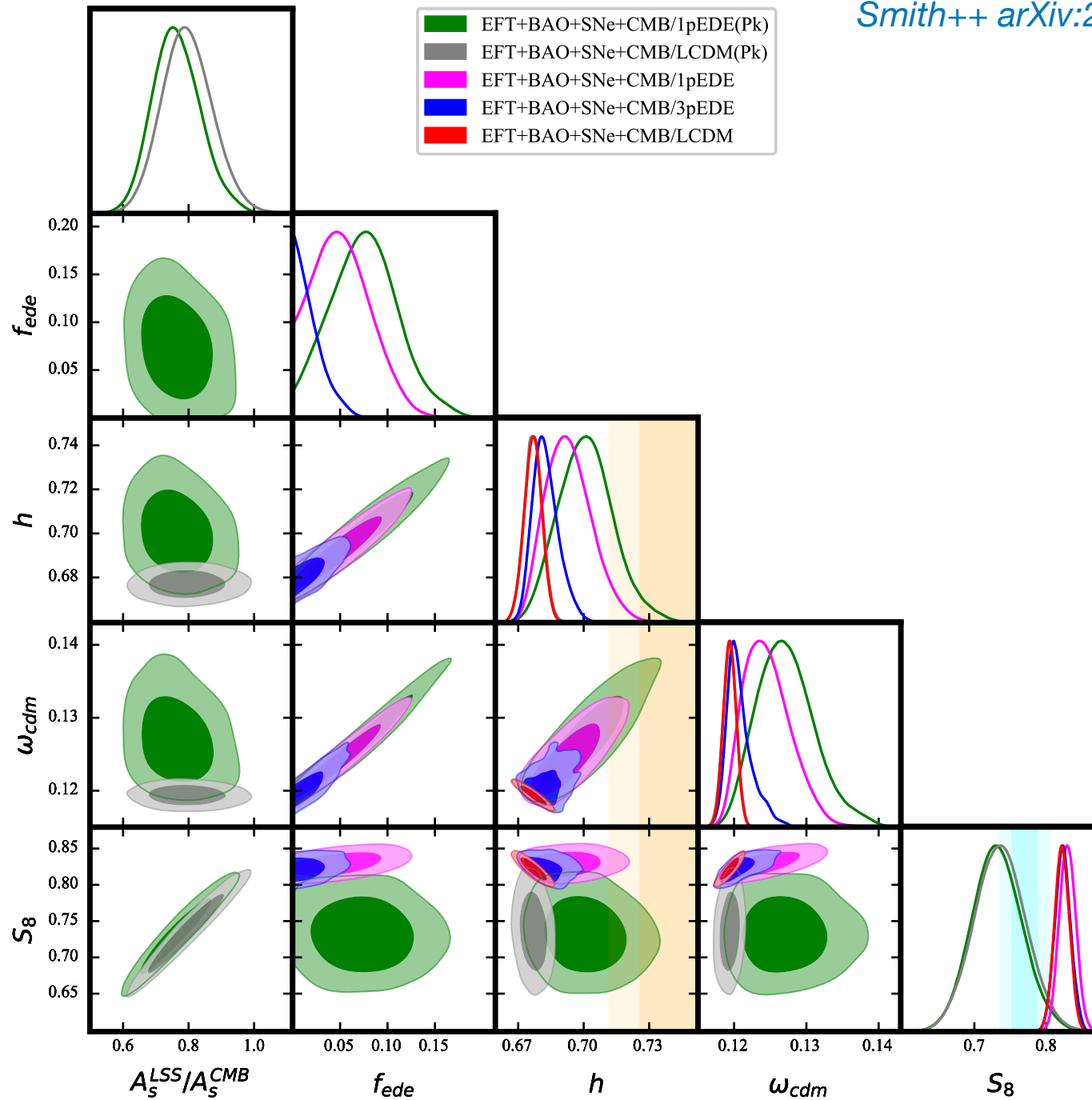
Klypin++ [arXiv:2006.14910](#)



Bernal++ [arXiv:2004.07263](#)

Early dark energy and EFT of LSS

Smith++ arXiv:2009.10740



Detecting the EDE with CMB data only

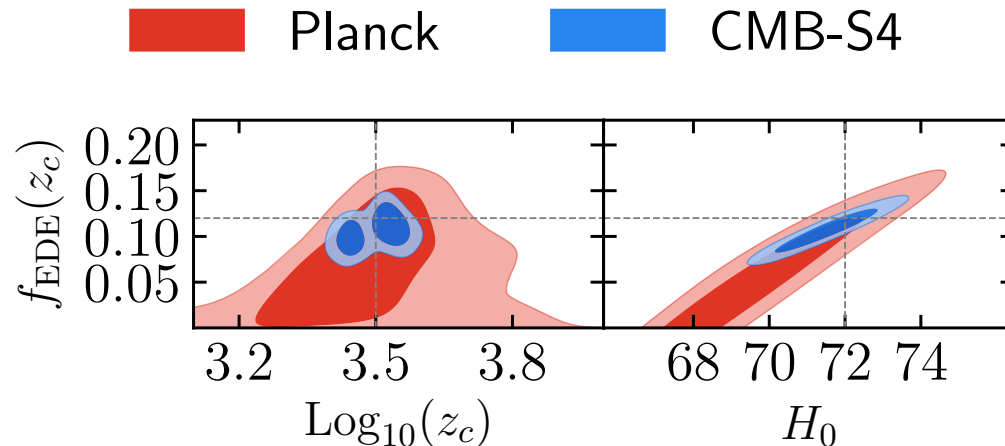
- Future CMB experiment like CMB-S4 **will be able to detect the EDE** without SH0ES data.

Fiducial model:

$$f(z_c) = 0.12$$

$$z_c = 10^{3.5}$$

$$h = 0.72$$

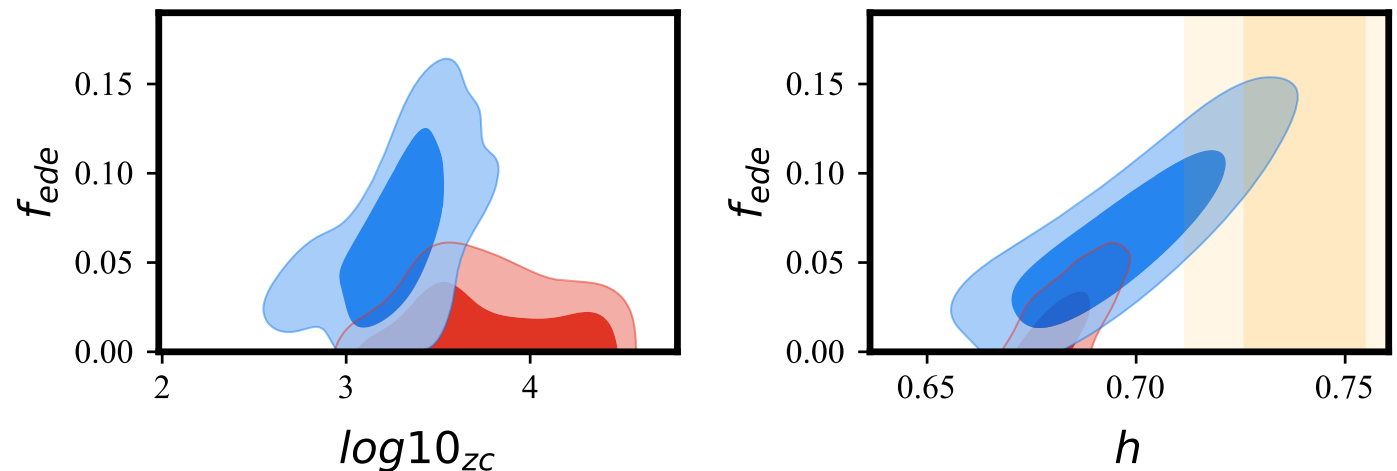


- Preliminary result:* EDE is preferred over LCDM with PlanckTT+ACTPol (no SH0ES)

Planck PlanckTT+ACTPol

- Possibly related to TE feature at $\ell \sim 500$

Lin, Hu, and Raveri
arXiv:2009.08974



Conclusions

- An EDE can resolve the Hubble tension and fit other cosmological datasets
- Planned CMB missions (i.e., CMB-S4) will see the EDE if it is there!
- Unique predictions: if $V(\phi) = \lambda\phi^4$ around minimum, parametric resonance leads to late-time ($z \simeq 10 - 100$) non-linear scalar field dynamics (including GWs)
- Makes LSS predictions
- May fit into a larger class of scalar fields/mechanisms

