Can Neutrinos save Early Dark Energy? Based on arXiv:2207.01501 [1]

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NBIA Neutrino Summer School
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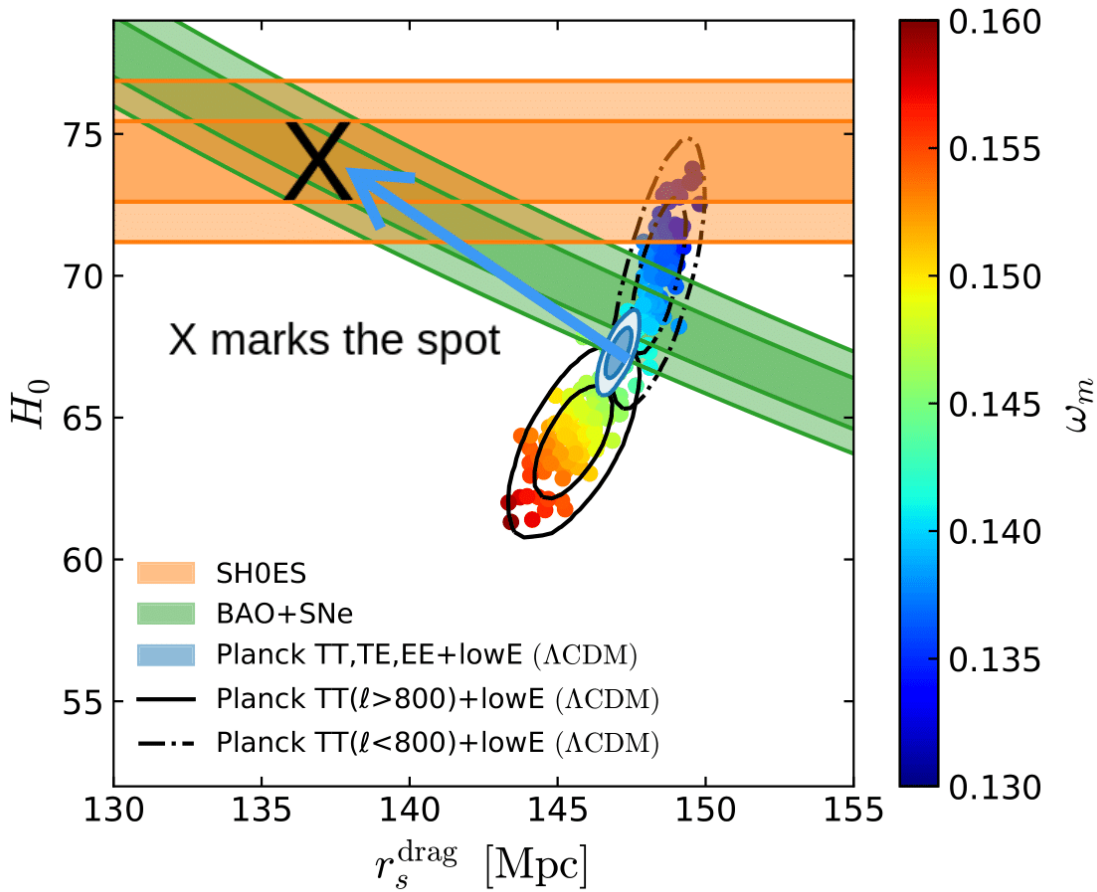
[1] A.R, Laura Herold (MPA Garching), Sunny Vagnozzi (Cambridge), Blake Sherwin (Cambridge), Elisa Ferreira (Tokyo)

The Hubble tension

Hubble tension *appears* to call for early-time new physics to lower r_s

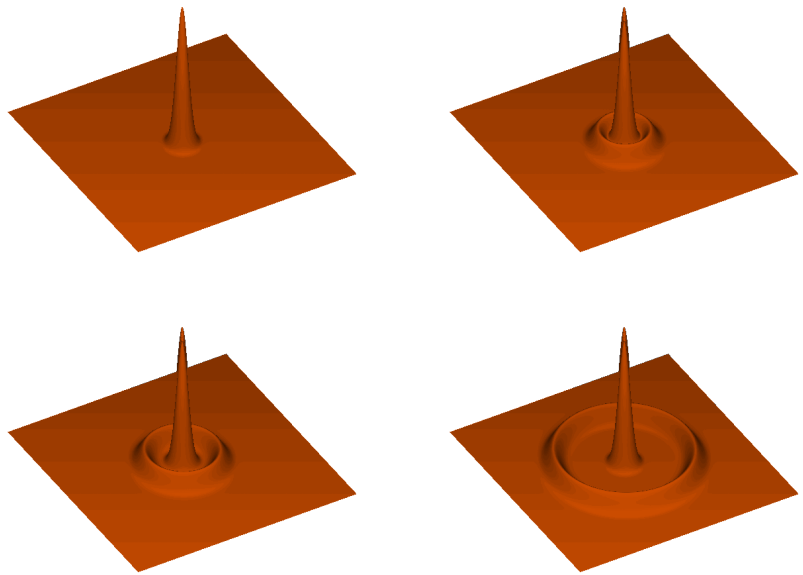


Credits: Knox & Millea, PRD 101 (2020) 043533

The EDE model

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

- Solving the Hubble tension via EDE: lower r_s
- EDE: add extra scalar field to ΛCDM acting like DE component and accelerating expansion just prior to z_*



The evolution of a sound wave prior to recombination

EDE ruled out by large scale structure data?

Featured in Physics Editors' Suggestion

Early Dark Energy can Resolve the Hubble Tension

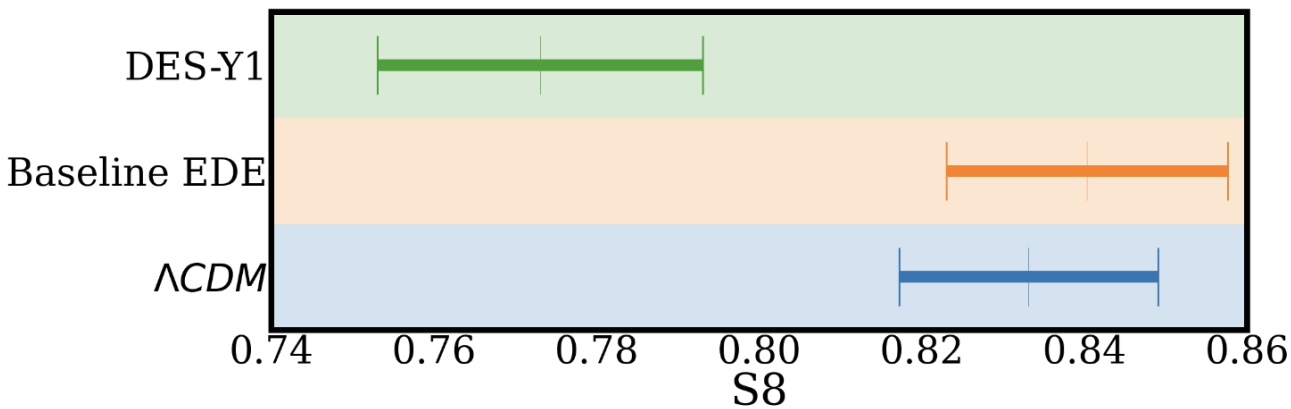
Vivian Poulin, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski
Phys. Rev. Lett. **122**, 221301 – Published 4 June 2019

Editors' Suggestion

Early dark energy does not restore cosmological concordance

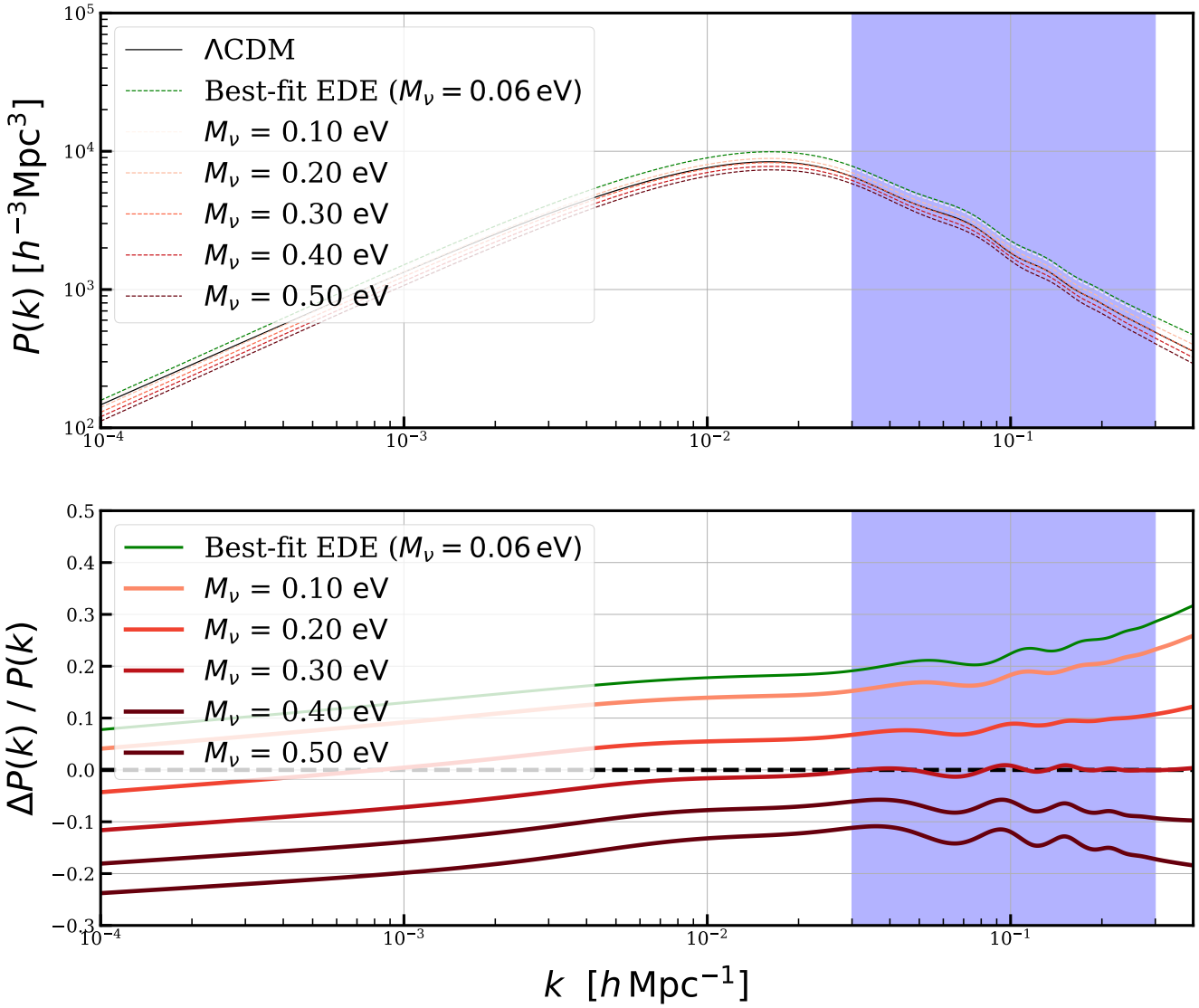
J. Colin Hill, Evan McDonough, Michael W. Toomey, and Stephon Alexander
Phys. Rev. D **102**, 043507 – Published 5 August 2020

- Maintaining a good fit to CMB data for EDE requires $\omega_{cdm} \uparrow$
- When solving the Hubble tension in the EDE scenario worsen the 'S8 tension'



Models fit to Primary CMB data alone (TTTEEE), values taken from Hill *et al.* (2020) PRD 102.043507

Rescuing EDE with massive neutrinos?



Methodology: datasets

- Idea: allow for a free neutrino mass in the EDE model to help resolve excess clustering problem.

Planck CMB likelihood

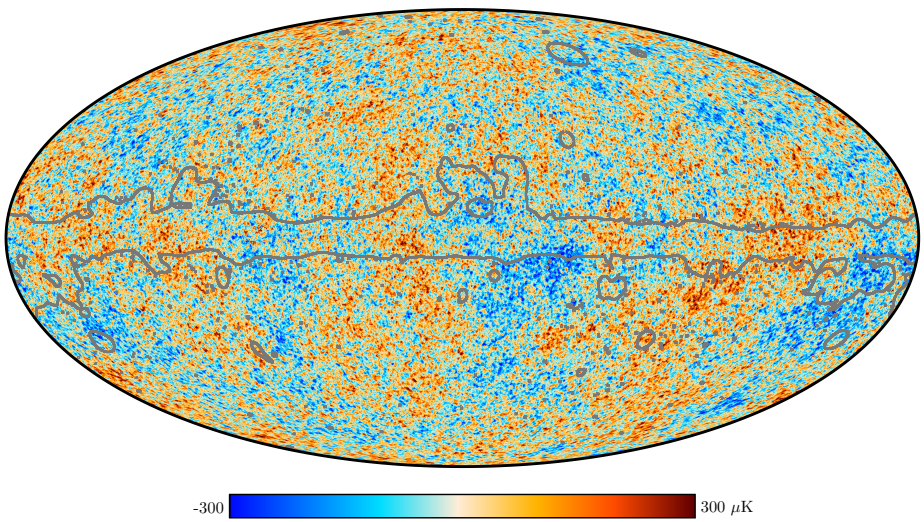


Image from

https://www.cosmos.esa.int/web/planck/picture-gallery

BOSS full-shape likelihood

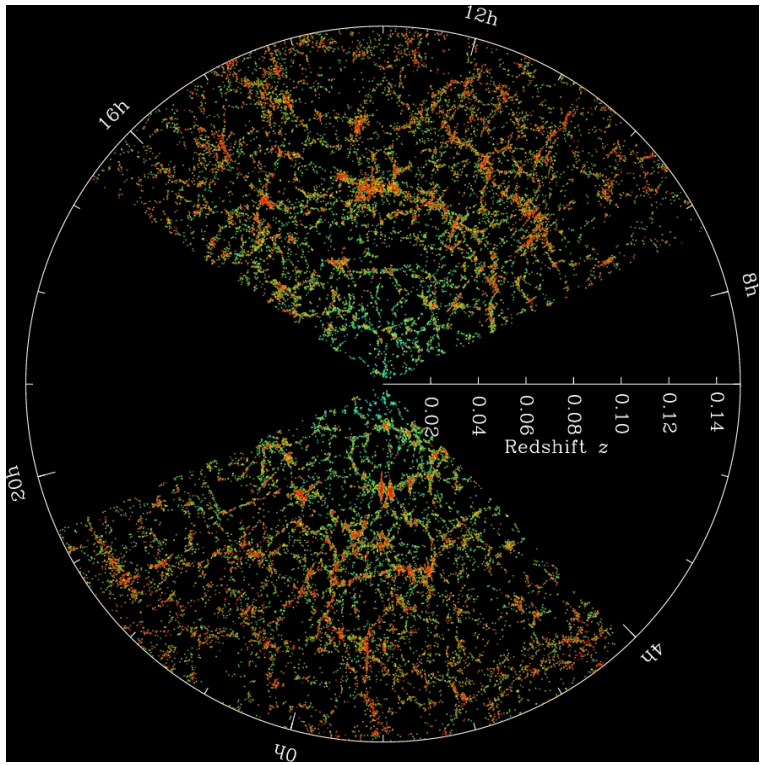
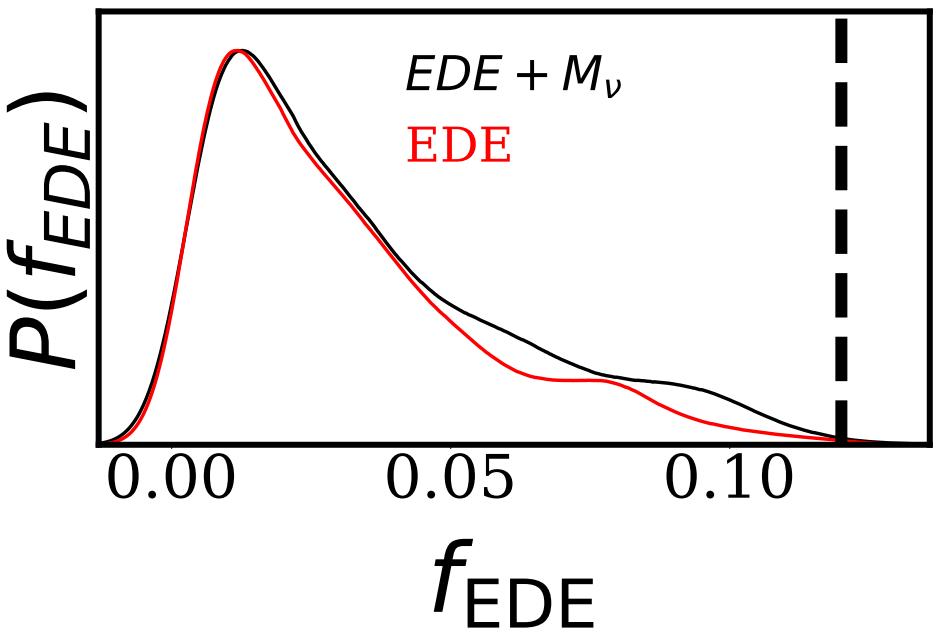
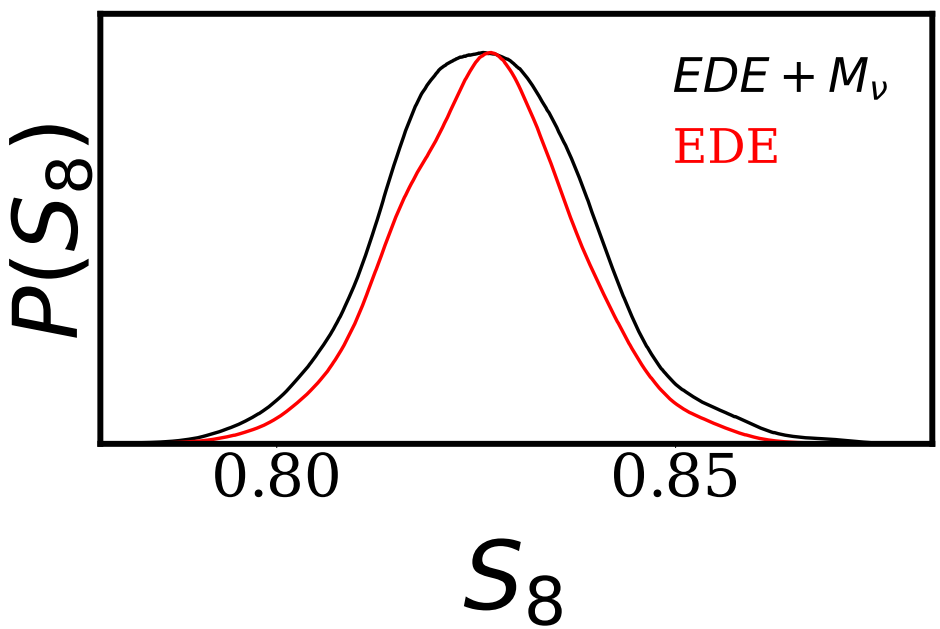


Image from https://www.sdss3.org/science/gallery.php

Massive neutrinos and EDE I: Bayesian results

- MCMC analysis of $EDE + M_\nu$ (with free M_ν) and baseline EDE model (fixed $M_\nu = 0.06eV$)
- Likelihoods: Planck 2018 (+lensing) + BOSS full-shape + BAO

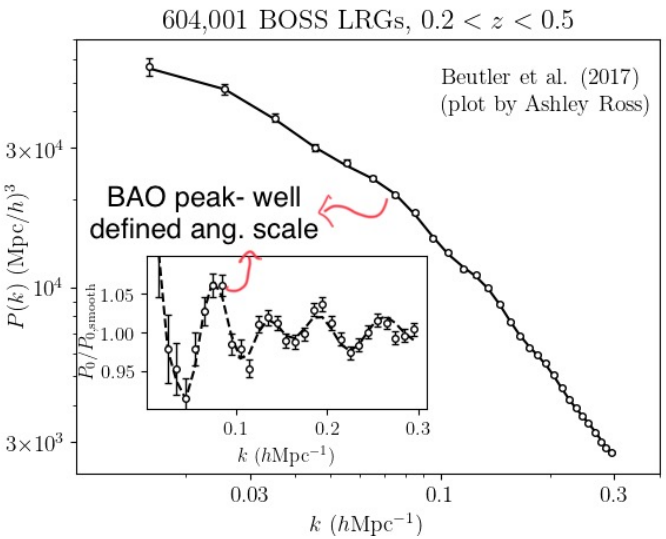


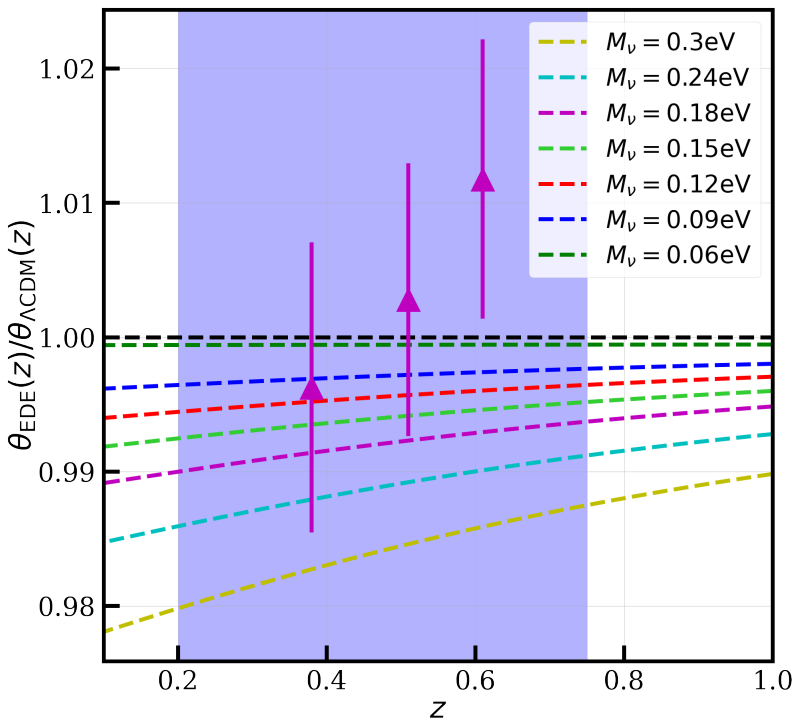


A.R, L.Herold, S.Vagnozzi, B.Sherwin, E.Ferreira, arXiv:2207.01501 (submitted to MNRAS)

Massive neutrinos and EDE II: Frequentist results

- Fix M_ν to 7 different values ($0.06 < M_\nu(eV) < 0.3$) and find bestfit cosmology using minimization routine
- Worse fit to BOSS likelihood as we increase M_ν due to impact on background expansion leading to worse fit to BAO angular scale
- For BOSS likelihood geometry more important than amplitude





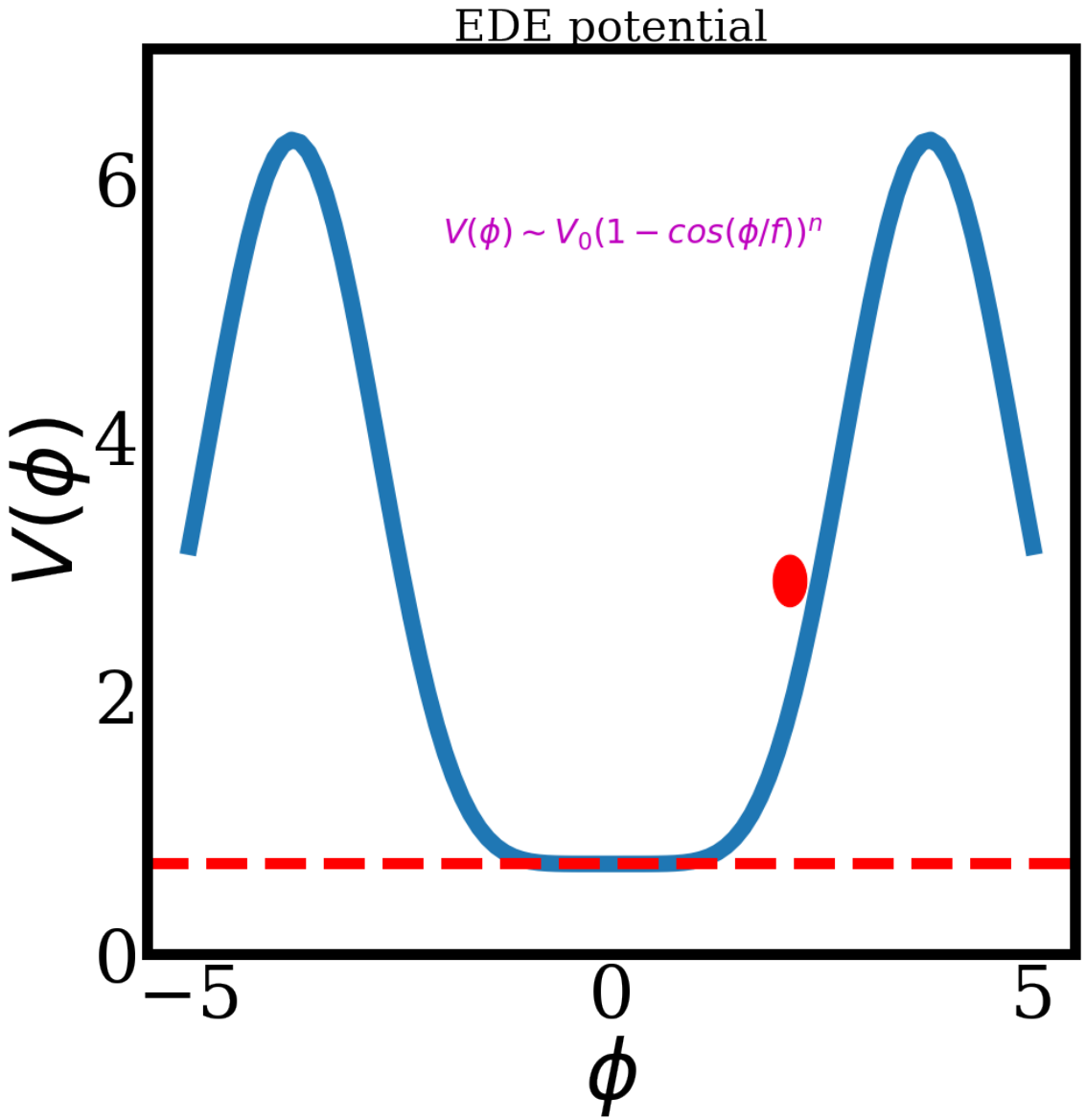
A.R, L.Herold, S.Vagnozzi, B.Sherwin, E.Ferreira, arXiv:2207.01501 (submitted to MNRAS)

Conclusions

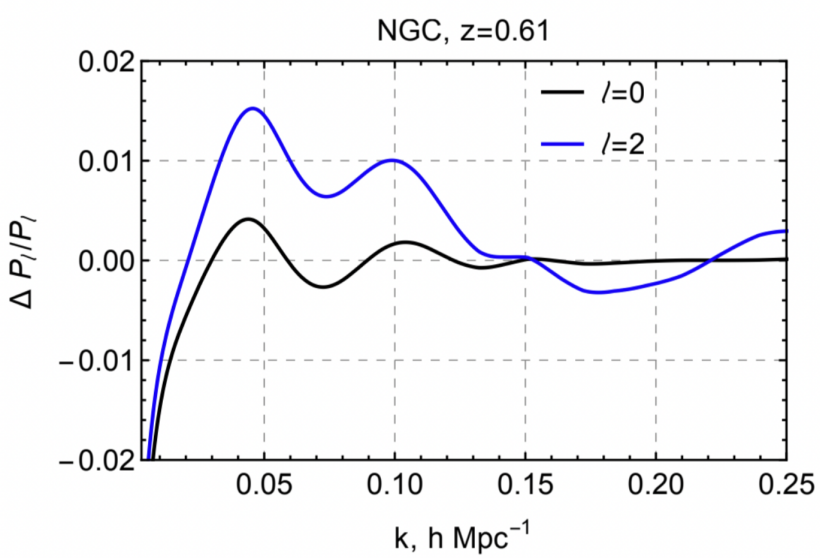
- Both Bayesian and frequentist results show no benefit of freeing M_ν in the *EDE* model painting a bleak picture for the future of EDE at face value- time to consider other models?
- BAO angular position in galaxy clustering data constrains the late-time expansion rate giving tight M_ν constraints that are not much weakened in EDE scenario
- Analysis is conservative: further work include datasets more sensitive to M_ν "benefits" (e.g. WL)

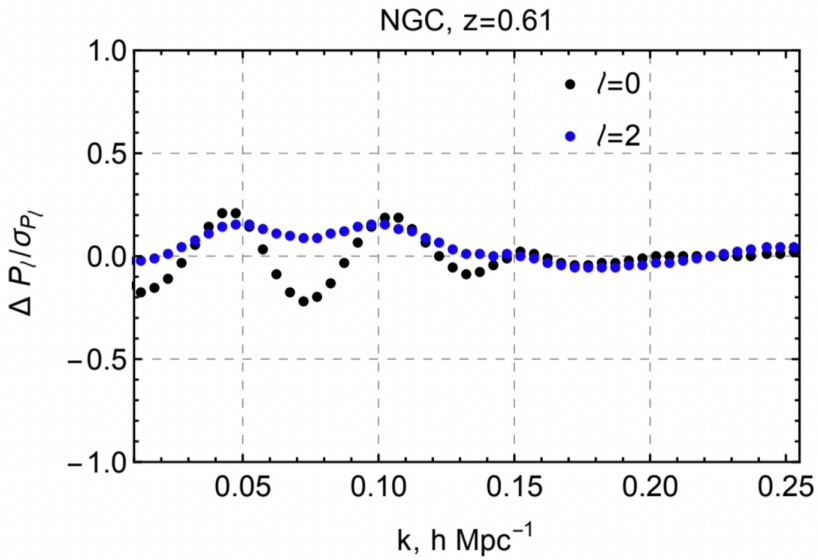
EXTRA SLIDE1: EDE potential and physics

- Axion EDE field ϕ, $V_0 = m^2 f^2$
- Modified axion potential broken by 'non-perturbative instanton effects' to give this specific form
- $\phi'' + 2aH\phi' + m^2 a^2 \frac{dV}{d\phi} = 0$: held up by Hubble friction in early Universe $\rightarrow$ acts as DE



EXTRA SLIDE2: sensitivity to clustering amplitude

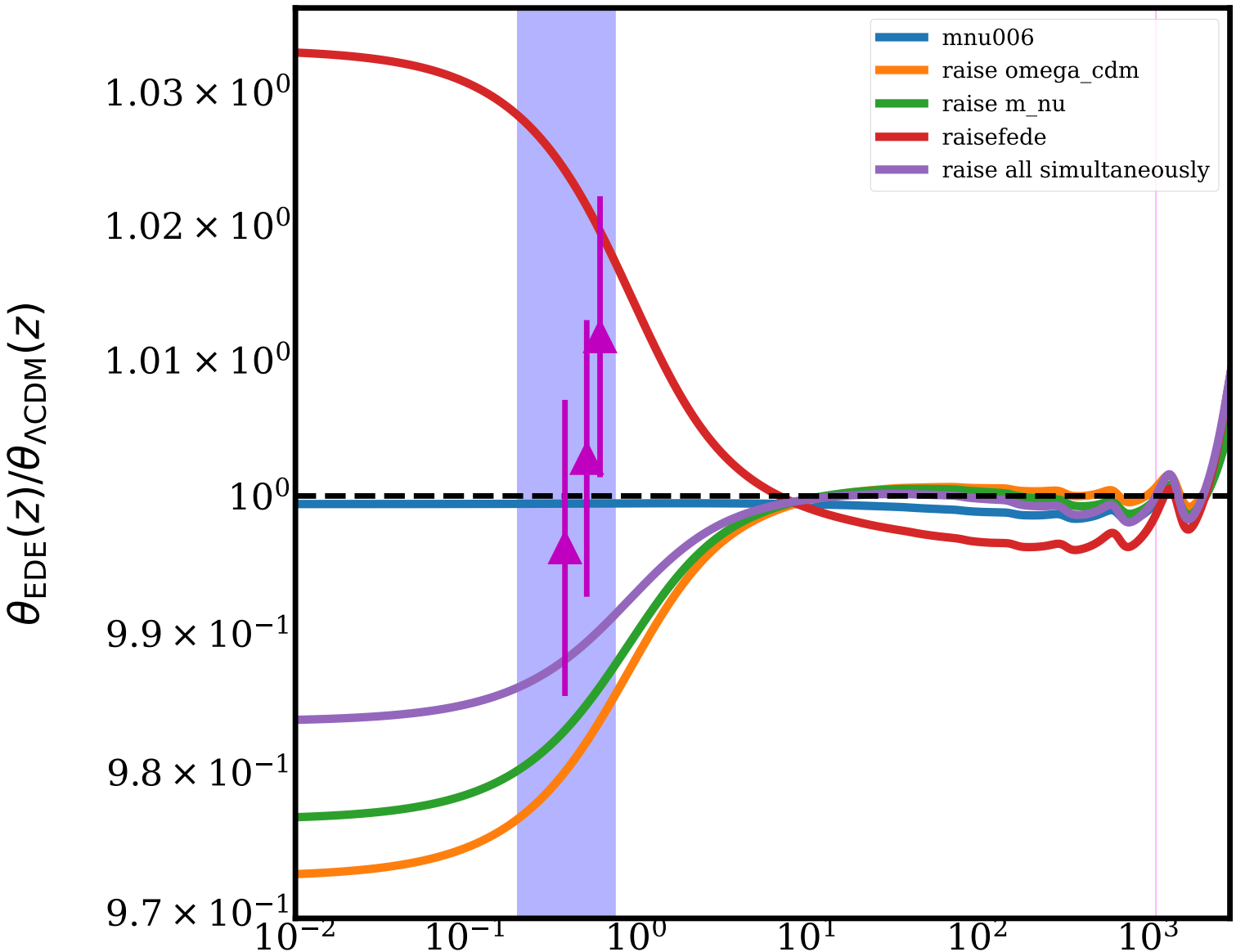




Credits: Ivanov *et al.*, PRD 102 (2020) 10, 103502

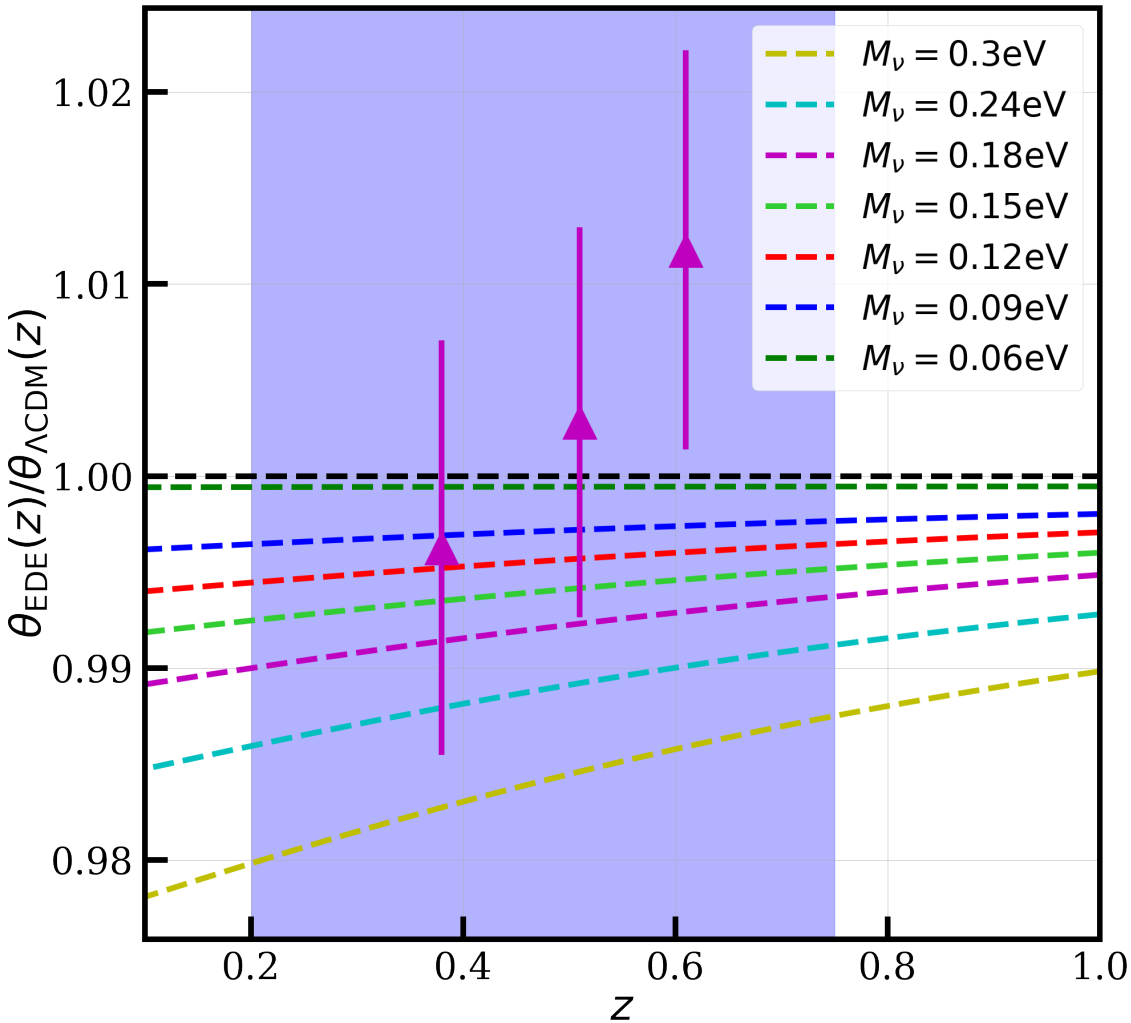
EXTRA SLIDE3: EDE + M_ν reason for hope?

$M_\nu - f_{EDE}$ symbiotic?



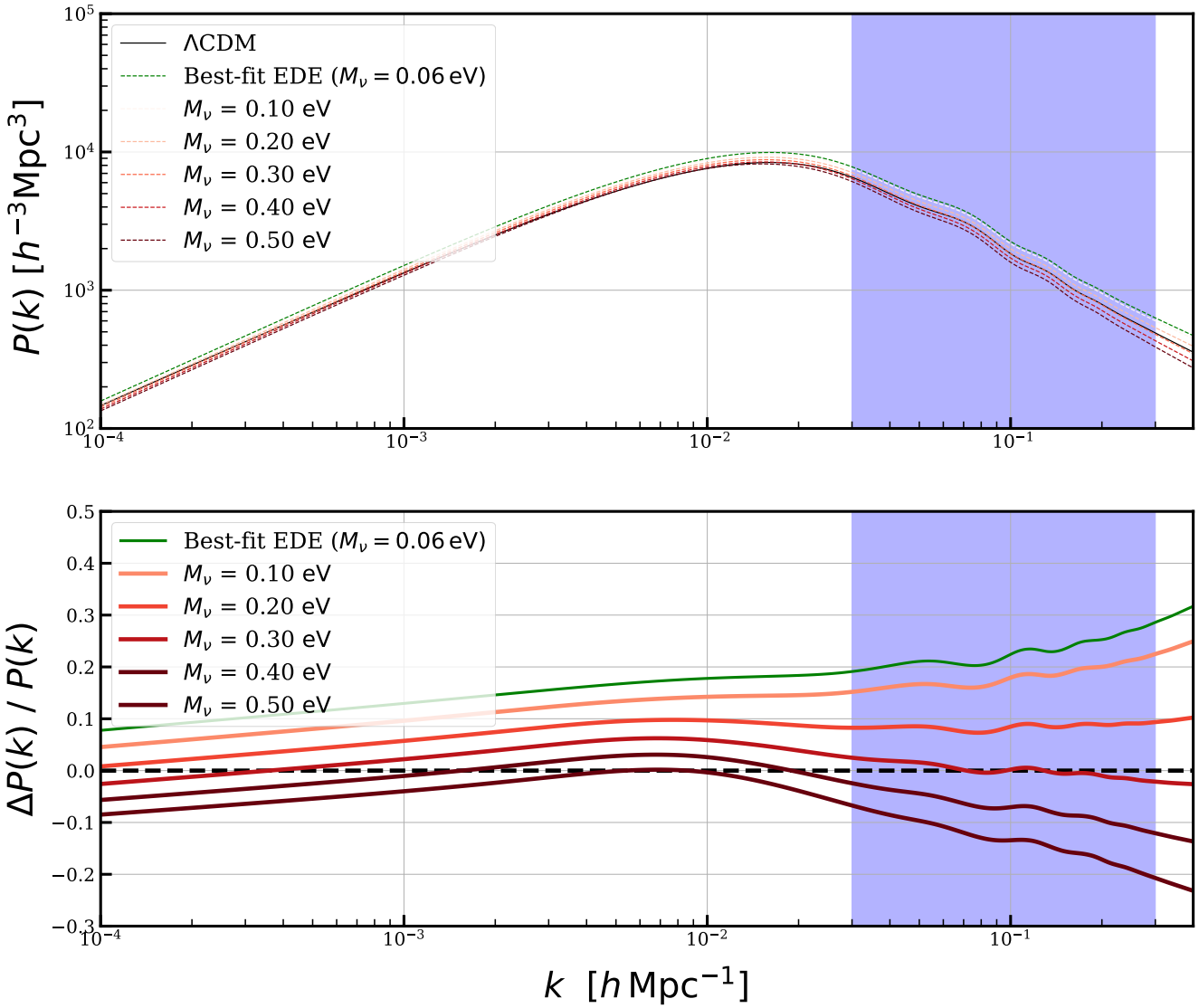
EXTRA SLIDE 4: BACKGROUND IMPACT OF M_ν

- $\theta = r_s(drag)/D(z)$: characterises position of BAO feature in galaxy clustering data
- Background effects of M_ν lead to a worsening fit to BAO position than in baseline EDE model
- BOSS(fs) + BAO likelihood more sensitive to geometry information than overall clustering amplitude



AR, arXiv:2207.01501 (submitted to MNRAS)

EXTRA SLIDE 5: *cdm* compensate



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