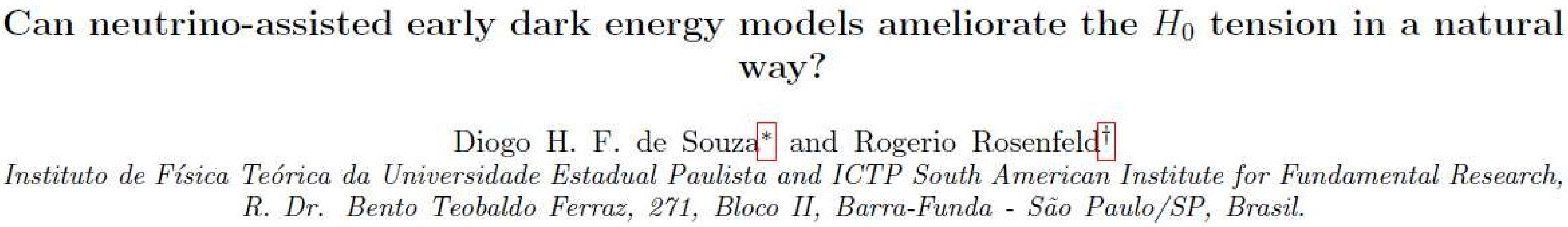

Can neutrino-assisted early dark energy models ameliorate the H_0 tension in a natural way?

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arXiv:2302.04644 – to appear in PRD

Cosmology 2023 in Miramare – August 31st

2023

Mar. 05 - Dec. 01	Física de Fronteira Online em Portugûes
Mar. 12 - Dec. 01	Física de Frontera Online em Español
Jul. 17 - Jul. 23	Perimeter-SAIFR-IFT Journeys in Theoretical Physics
Jul. 24 - Aug. 04	School on Modern Amplitude Methods for Gauge and Gravity Theories
Aug. 02	Colloquium by Nima Arkani-Hamed on the Future of Particle Physics
Aug. 08	Cine Sci-SAIFR Cine-debate 2 do Oppenheimer
Aug. 12	Public Lecture by David Gross on 50 years of QCD
Aug. 12 - Sep. 02	Minicurso para Estudantes de Ensino Médio A matemática no mundo
Aug. 14 - Sep. 01	Gravitational Waves meet Amplitudes in the Southern Hemisphere
Aug. 21 - Sep. 01	School on Quantum Chaos

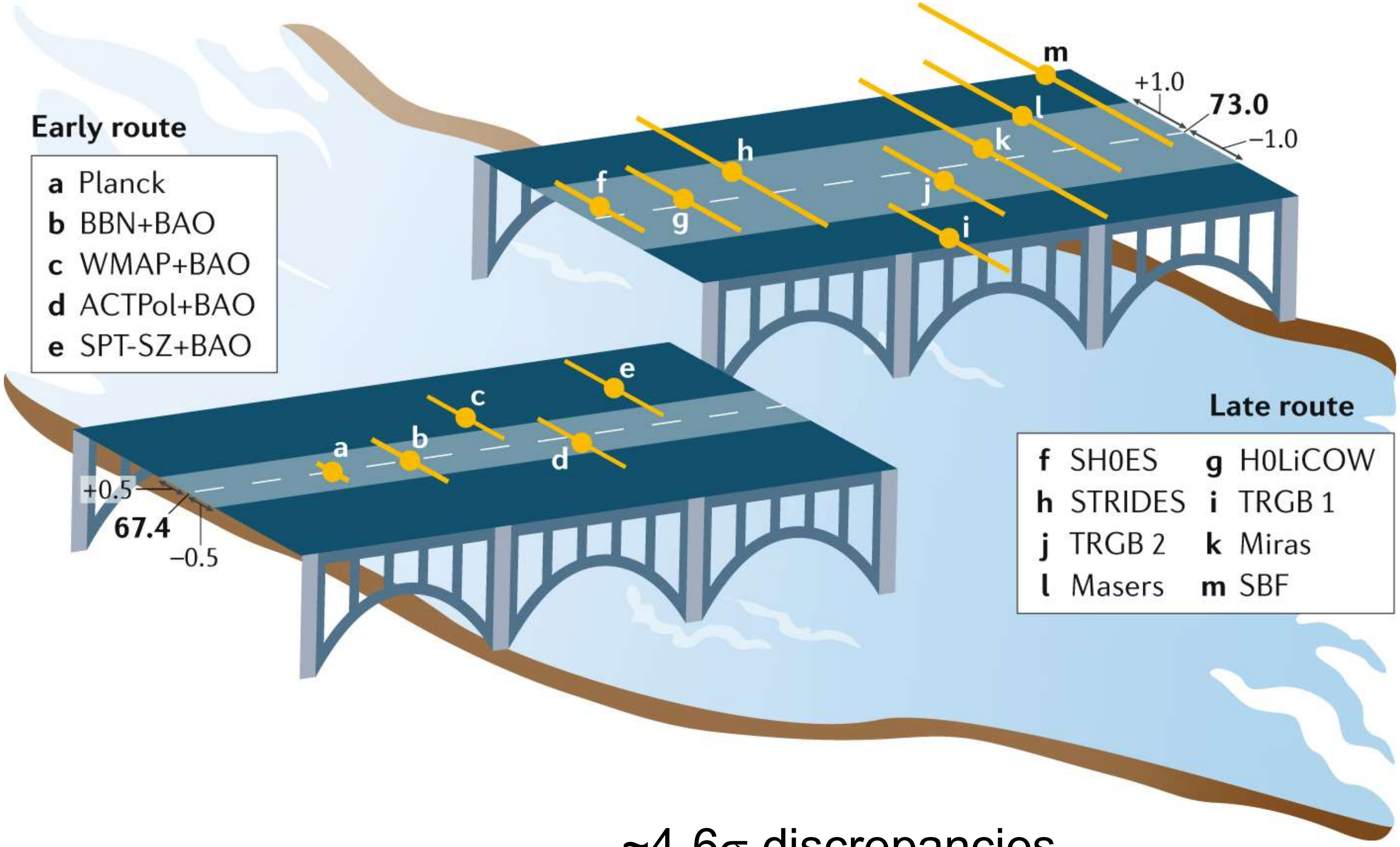
Application deadline: December 10, 2023

- 2023 ICTP-SAIFR Prize in Classical Gravity and Applications
  Application deadline: April 30, 2023
- Proposals to Organize 2024 Activities
  Submission deadline: January 15, 2023
- 2 Simons-FAPESP Research Professor Positions
  Application deadline: January 15, 2023
- Fapesp Public High-School Teacher Fellowships
  Applications are open
- Scientific Visits

DOSES DE FÍSICA

Aug. 21, 2023 Inflação Cósmica: o Universo é todo igual? (#31)

Hubble tension



Adam G. Riess
Nature Reviews Physics - 2001.03624

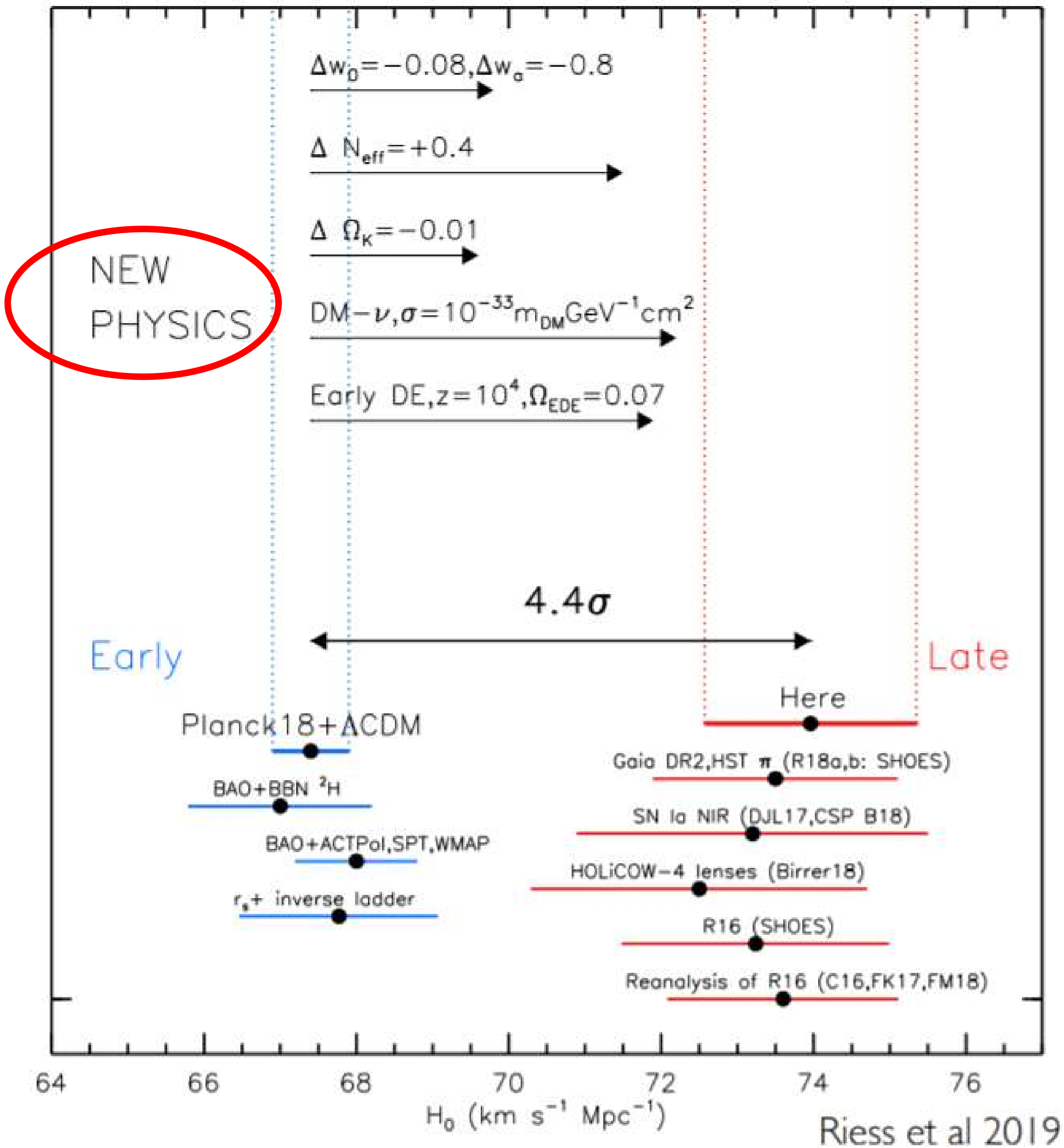
~4-6σ discrepancies

Systematic errors? New physics?

Attempts to reconcile CMB with local measurements: New Physics!

If there is an extra contribution to the energy density (=faster expansion rate) with respect to ΛCDM around the recombination era then in order to keep θ_* fixed requires **a larger value of H_0**

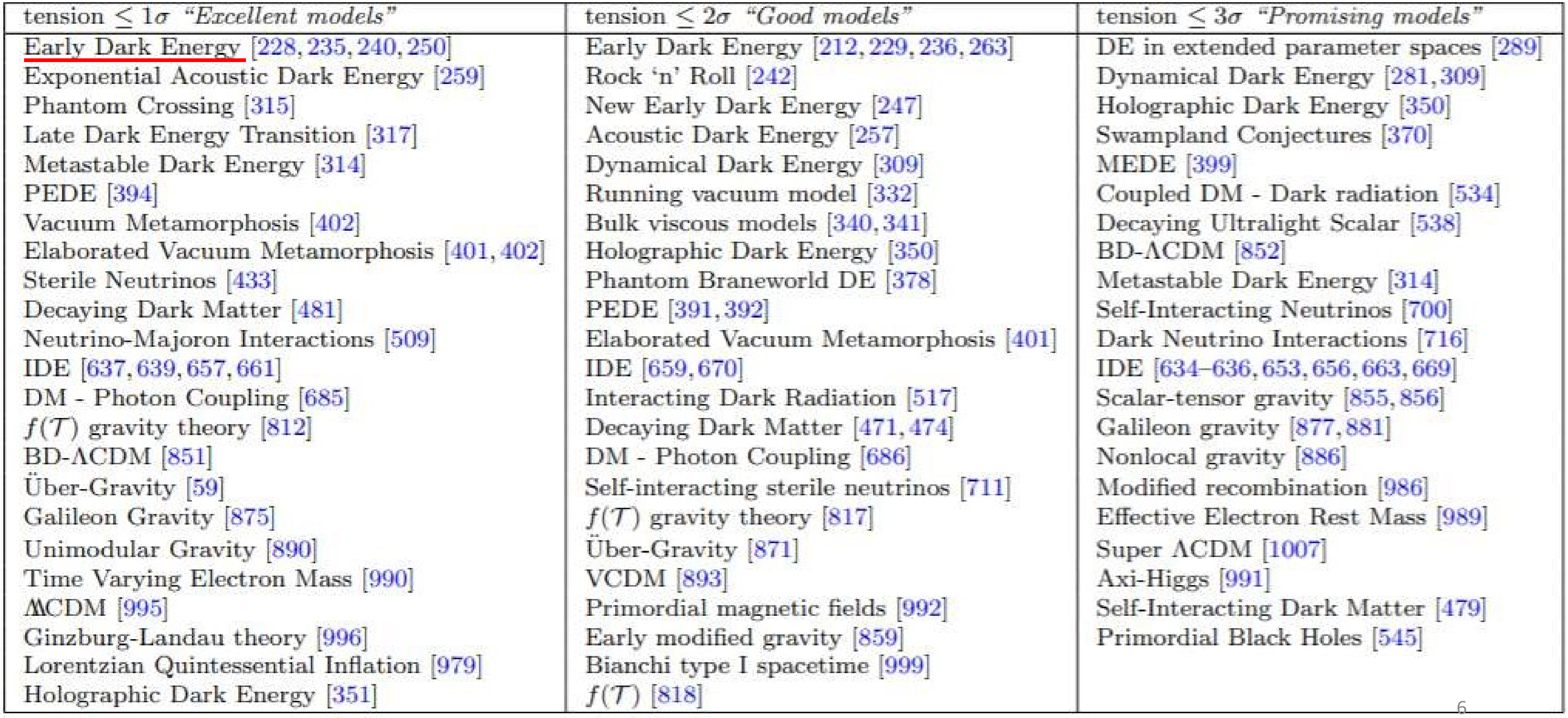
New relativistic degrees of freedom, early dark energy, decaying dark matter,...



Riess et al 2019

Models abound:

In the Realm of the Hubble tension − a Review of Solutions 2103.01183
E. Di Valentino, O. Mena, S. Pan, L. Visinelli, W. Yang, A. Melchiorri, D. F. Mota, A. G. Riess, J. Silk



tension $\lesssim 1\sigma$ *"Excellent models"*	tension $\lesssim 2\sigma$ *"Good models"*	tension $\lesssim 3\sigma$ *"Promising models"*
Early Dark Energy [228, 235, 240, 250]	Early Dark Energy [212, 229, 236, 263]	DE in extended parameter spaces [289]
Exponential Acoustic Dark Energy [259]	Rock 'n' Roll [242]	Dynamical Dark Energy [281, 309]
Phantom Crossing [315]	New Early Dark Energy [247]	Holographic Dark Energy [350]
Late Dark Energy Transition [317]	Acoustic Dark Energy [257]	Swampland Conjectures [370]
Metastable Dark Energy [314]	Dynamical Dark Energy [309]	MEDE [399]
PEDE [394]	Running vacuum model [332]	Coupled DM - Dark radiation [534]
Vacuum Metamorphosis [402]	Bulk viscous models [340, 341]	Decaying Ultralight Scalar [538]
Elaborated Vacuum Metamorphosis [401, 402]	Holographic Dark Energy [350]	BD-ΛCDM [852]
Sterile Neutrinos [433]	Phantom Braneworld DE [378]	Metastable Dark Energy [314]
Decaying Dark Matter [481]	PEDE [391, 392]	Self-Interacting Neutrinos [700]
Neutrino-Majoron Interactions [509]	Elaborated Vacuum Metamorphosis [401]	Dark Neutrino Interactions [716]
IDE [637, 639, 657, 661]	IDE [659, 670]	IDE [634–636, 653, 656, 663, 669]
DM - Photon Coupling [685]	Interacting Dark Radiation [517]	Scalar-tensor gravity [855, 856]
$f(\mathcal{T})$ gravity theory [812]	Decaying Dark Matter [471, 474]	Galileon gravity [877, 881]
BD-ΛCDM [851]	DM - Photon Coupling [686]	Nonlocal gravity [886]
Über-Gravity [59]	Self-interacting sterile neutrinos [711]	Modified recombination [986]
Galileon Gravity [875]	$f(\mathcal{T})$ gravity theory [817]	Effective Electron Rest Mass [989]
Unimodular Gravity [890]	Über-Gravity [871]	Super ΛCDM [1007]
Time Varying Electron Mass [990]	VCDM [893]	Axi-Higgs [991]
ΛCDM [995]	Primordial magnetic fields [992]	Self-Interacting Dark Matter [479]
Ginzburg-Landau theory [996]	Early modified gravity [859]	Primordial Black Holes [545]
Lorentzian Quintessential Inflation [979]	Bianchi type I spacetime [999]	
Holographic Dark Energy [351]	$f(\mathcal{T})$ [818]	

Early dark energy (EDE)

Main idea: some amount of dynamical dark energy (= scalar field) that contributes a non-negligible amount of energy density at around recombination (changing the expansion rate) and decaying away afterwards. [Karwal and Kamionkowski (2016) + ...]

Very generally the two relevant parameters are:
. The redshift where EDE contribution peaks (z_c)
. The fraction of EDE at the peak ($f_{EDE} = \rho_{EDE} / \rho_{Total}$ at z_c)

Rebouças et al (arXiv:2302.07333)

f_{EDE} ~10% in order to ease Hubble tension

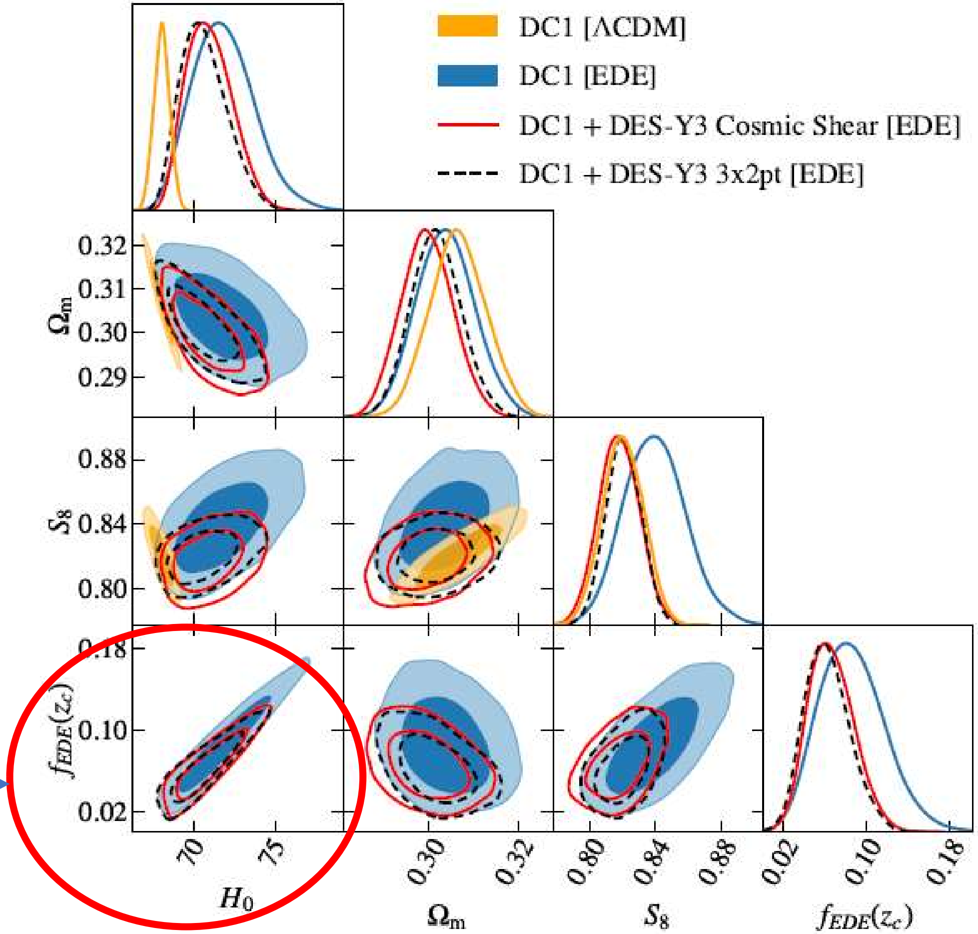


Figure 1. Constraints for the ΛCDM and effective fluid early dark energy models using the dataset combination DC1: ACT TT, TE, EE spectra with $\ell_{\max} = 650$, Planck 2018 TT spectrum with $\ell_{\max} = 650$ + Planck 2018 low-ℓ EE spectrum, BAO from 6dFGS, SDSS DR7 main galaxy sample and SDSS BOSS DR12 consensus sample, Pantheon supernovae and Planck 2018 CMB Lensing spectrum. We also include DES-Y3 3x2-point correlation function as well as cosmic shear alone.

Early dark energy

Prototypical scalar field model: “axion-like” potentials:

$$V(\phi) = \mu^4 (1\text{-}\cos(\phi/f))^n$$

Model fixed by:
n: n=1 for usual axion models
μ: small energy scale related to explicit breaking of shift symmetry
f: large energy scale related to spontaneous breaking of a global symmetry [in axion case, m= μ^2/f]
Initial conditions for the field

Early dark energy “decay”

The power “n” in the potential is related to the equation of state when the field is coherently oscillating about the minimum of the potential:

$$w = (n - 1)/(n + 1)$$

$$\rho_{EDE} \sim (1+z)^{3(1+w)}$$

For n>2 EDE decays faster than radiation and quickly becomes negligible: one usually assumes n=3.

Early dark energy “coincidence problem”

Why EDE becomes relevant at around the recombination epoch?

Usual answer: fine-tuning of model parameters.

Not really satisfactory.

Recently a generalization of this model was proposed to address the “why now?” problem: neutrino-assisted EDE

[Sakstein and Trodden, PRL (2019); González, Liang, Sakstein and M. Trodden, JCAP (2020)]

Neutrino-assisted early dark energy - νEDE

νEDE postulates a coupling between neutrinos and the EDE scalar field (coupling constant denoted by β)

Two main effects:
. EDE field acquires an effective (time-dependent) potential
. The coupling to neutrinos induces a kick in the field

Neutrino-assisted early dark energy - νEDE

The neutrino kick happens because the coupling turns out to be related to ($\rho_\nu - 3 P_\nu$): it is zero for relativistic particles (zero coupling) and turns on when neutrinos transition to non-relativistic.

This kick happens at the neutrino mass scale – around O(eV)

We assume in the following three degenerate neutrinos with

$$\Sigma\, m_{\nu o} = 0.3 \text{ eV}$$

Neutrino-assisted early dark energy - νEDE

We investigate this model in more details, assessing to what extent the coupling to neutrinos can help in the fine-tuning problem.

We developed an implementation of the νEDE model in CAMB at the background level to analyse the evolution of the EDE scalar field in the time-dependent effective potential given some initial conditions and model parameters.

Neutrino-assisted early dark energy - νEDE

We study two cases for the initial conditions:

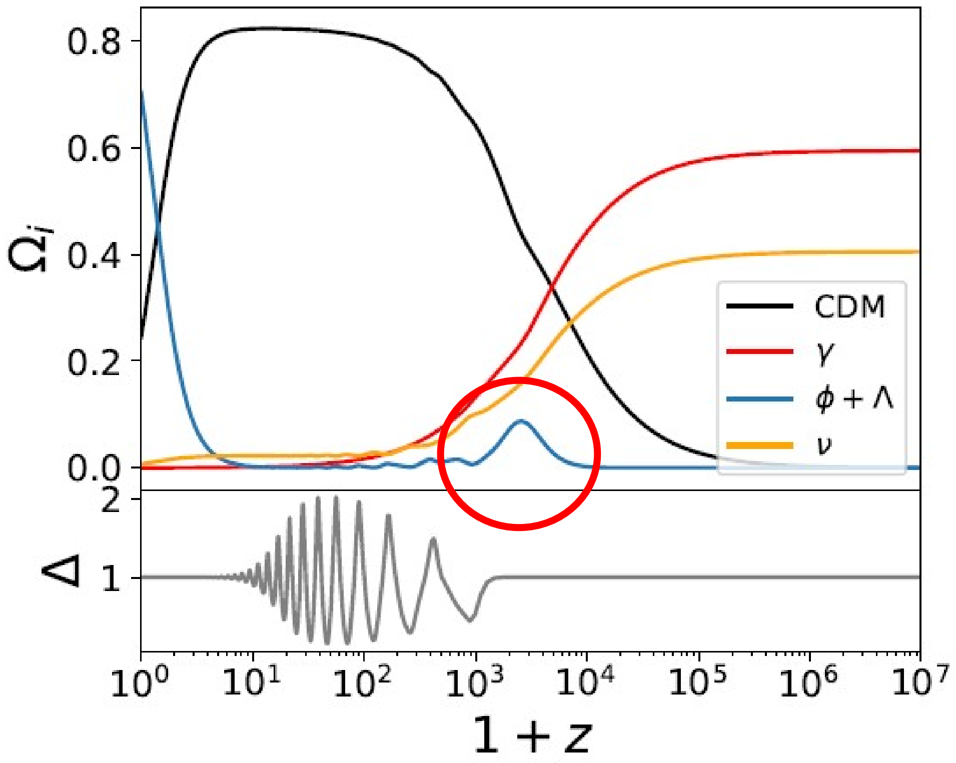
. the field starting at some arbitrary value (field initialy frozen by Hubble friction).

. the field starting at the minimum of the effective potential (field is dynamical and relaxed to the minimum).

In the second case the neutrino transition would move the field from the minimum and solve the fine-tuning issue.

νEDE: results

Example of the EDE energy density contribution:

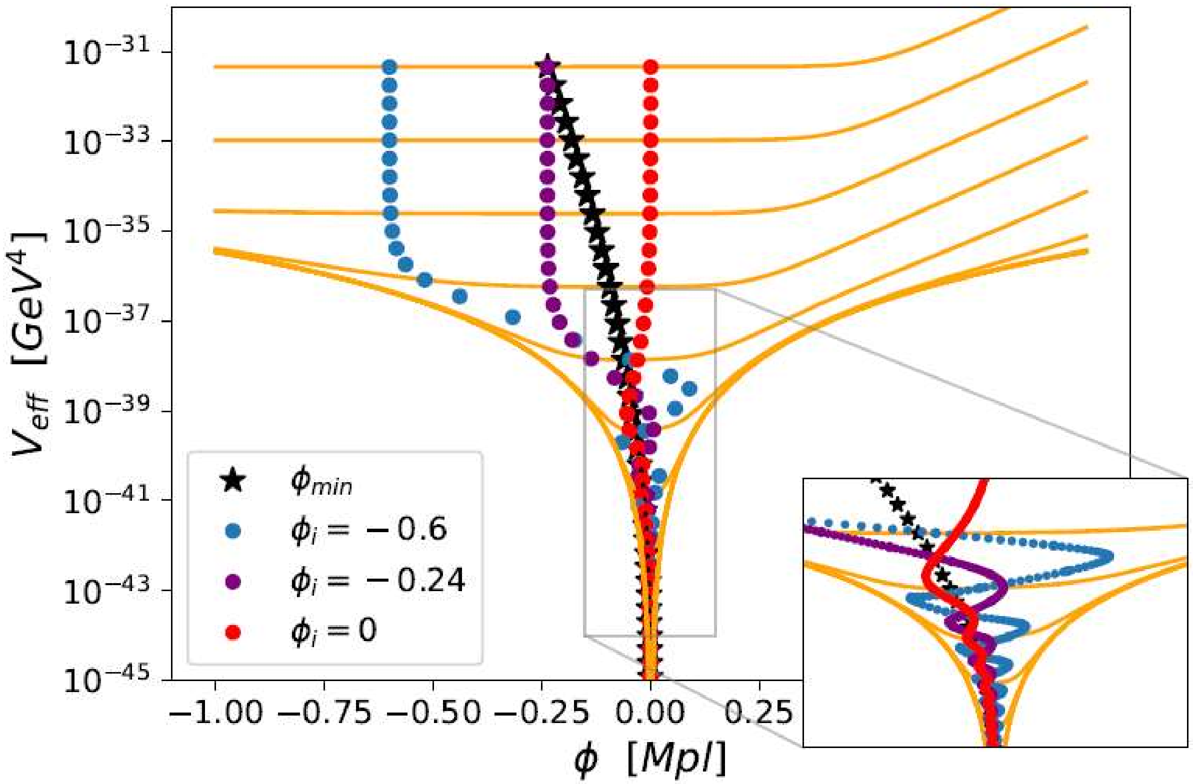


$$\Delta \equiv \frac{f_{\rm EDE}}{f_{\rm EDE}^{\beta=0}}$$

νEDE: results

Example of the EDE field evolution in the effective potential for different initial conditions (field initially frozen):

z = 10^5



νEDE: results

Example of the EDE field evolution and contribution to the energy density:

f_{EDE} ~10% around recombination but it is NOT due to coupling to neutrinos! Coupling does not play a significant role in this case.

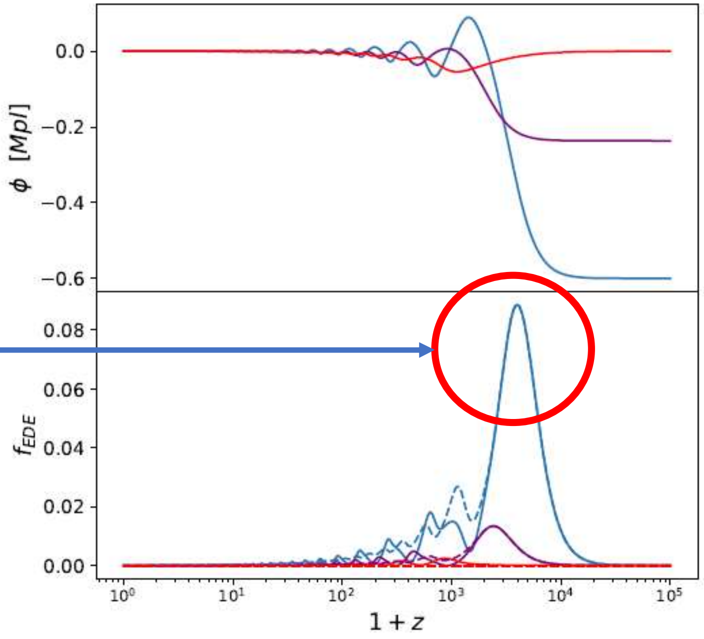
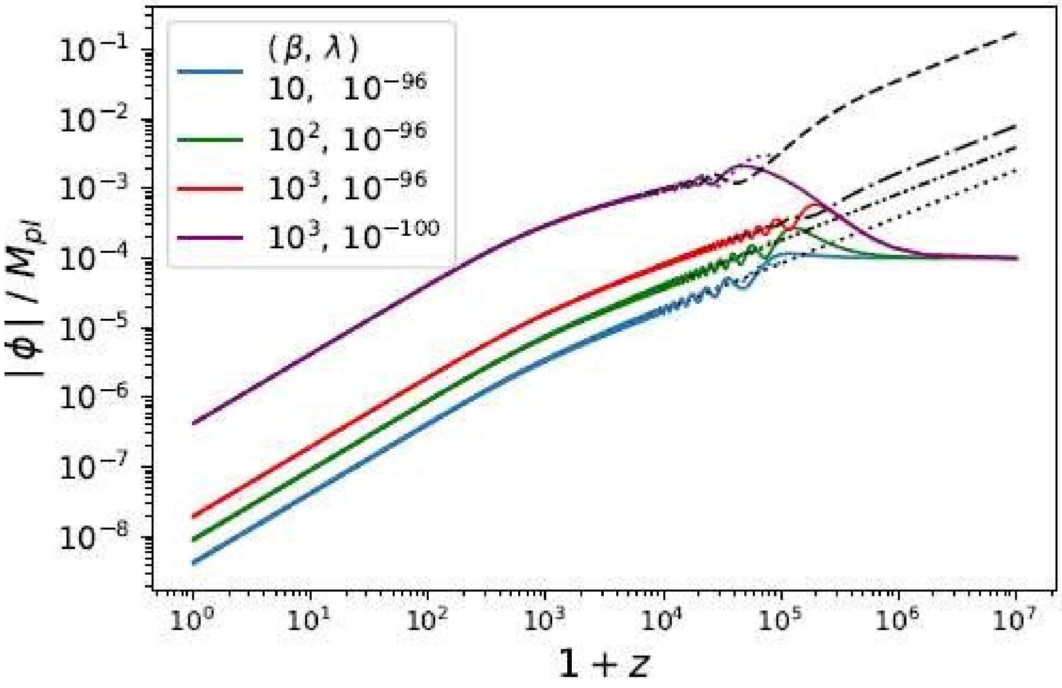


FIG. 4. The scalar field evolution and the fraction of energy density for the same three initial conditions as in Fig. 3: $\phi_i/M_{Pl} = -0.6, -0.24, 0$ for the blue, purple and red lines, respectively. The dashed lines in the bottom panel shows the uncoupled case with all other parameters kept fixed at the same values.

νEDE: results

Example of the EDE field evolution when the field has already relaxed and is tracking the minimum of the effective potential at high redshift – avoid initial condition issue (natural initial value).



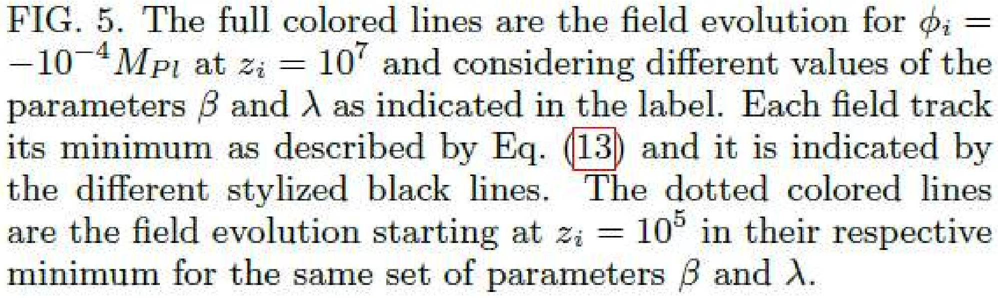
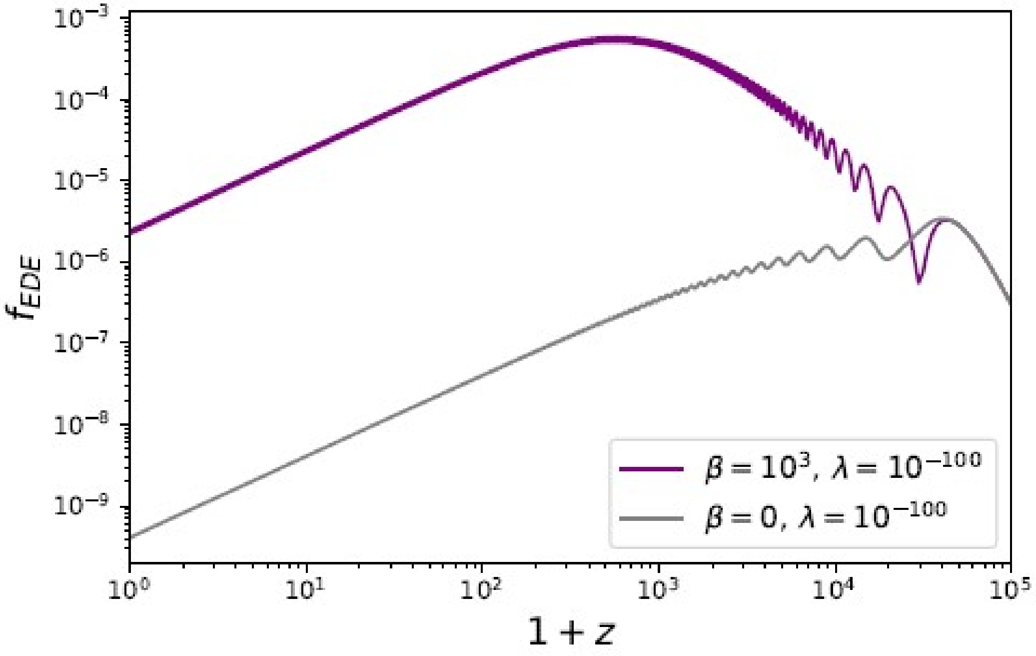


FIG. 5. The full colored lines are the field evolution for $\phi_i = -10^{-4} M_{Pl}$ at $z_i = 10^7$ and considering different values of the parameters β and λ as indicated in the label. Each field track its minimum as described by Eq. (13) and it is indicated by the different stylized black lines. The dotted colored lines are the field evolution starting at $z_i = 10^5$ in their respective minimum for the same set of parameters β and λ.

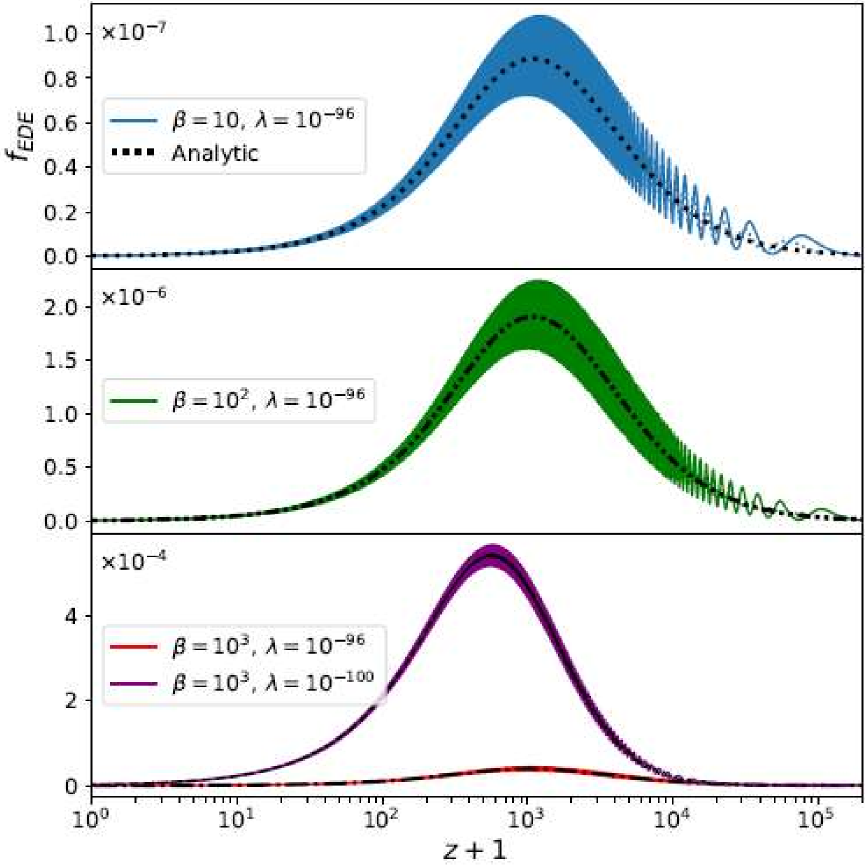
νEDE: results

In this case the neutrino coupling is relevant and produces a large enhancement in the EDE density:



νEDE: results

However, the amount is insufficient to ameliorate the Hubble tension:



νEDE: conclusions

We conclude that νEDE models do not seem to naturally provide a significant amount of early dark energy which is one of the criteria usually required for the model to ease the Hubble tension.

However, one should perform a more detailed study using a full Bayesian analysis to take into account not only the peak contribution of EDE in this case. Also, other type of potentials and couplings should be studied.