A flexible parameterization to test early physics solutions to the Hubble tension with future CMB data

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CMB - France

Di Valentino (2021)

Hubble tension

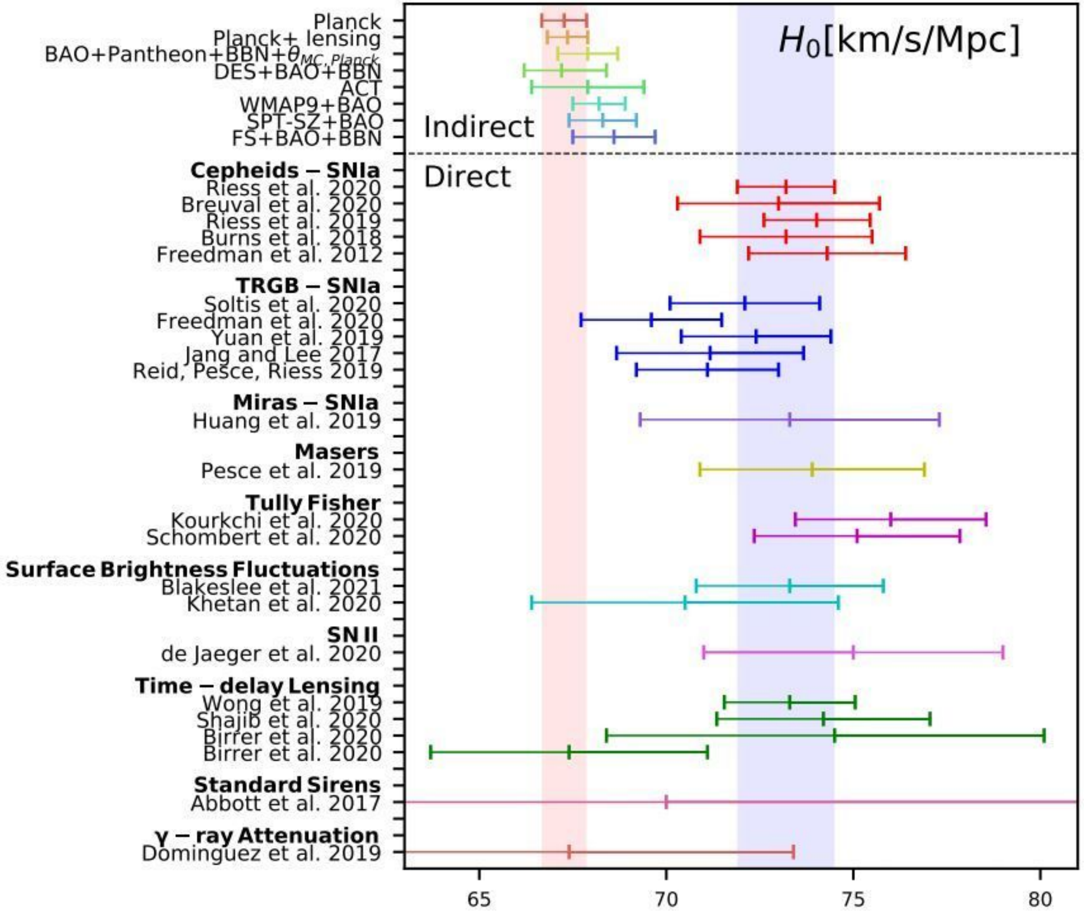
- Discrepancy between direct/indirect measurements of H0:
  - Latest SH0ES analysis:

$$H_0 = 73.17 \pm 0.86\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

  - Planck (PR3) analysis:

$$H_0 = 67.27 \pm 0.60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- If new physics, future CMB experiments may be able to detect it without any H0 prior.



Early Dark Fluid (EDF) approach (this analysis)

Using the Generalized Dark Matter approach (Hu 2001), any fluid can be described at background and perturbation levels by choosing:

- Equation of state (or equivalently, the evolution of density with scale factor)
- Sound speed
- Anisotropic stress

Early Dark Fluid (EDF) - Density

$$H^2(a) = H_0^2 \left[\Omega_{\Lambda\mathrm{CDM}}(a) + \Omega_{\mathrm{EDF}}(a)\right]$$

$$\Omega_{\mathrm{EDF}}(a) = \sum_{i=1}^{N} \Omega_i(a)$$

Parameterization based on Moss et al. 2021

$$\Omega_i(a) = \Omega_i \Omega_{\Lambda\mathrm{CDM}}(a_i) \left(\frac{2a_i^\beta}{a^\beta + a_i^\beta} \right)^{6/\beta}$$

We use a set of N=50 spikes whose amplitudes are parameterized through Ω_i parameters.

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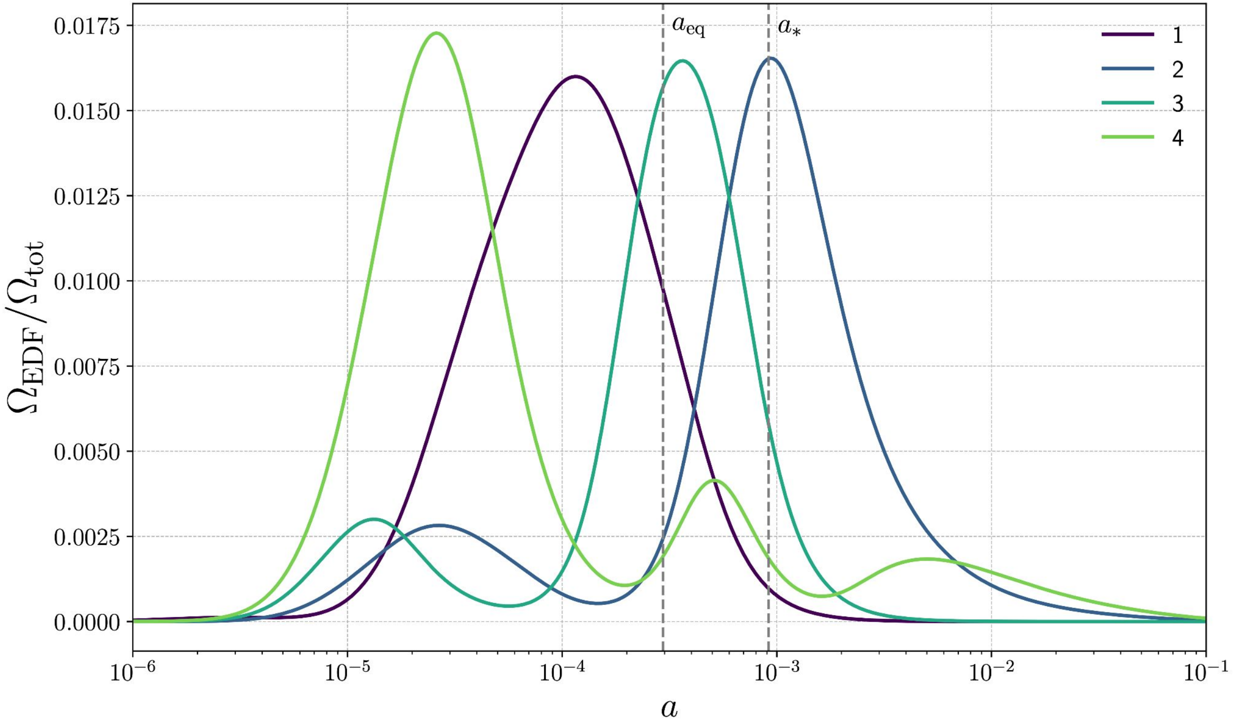
PCA-like analysis to estimate the best constrained combination of Ω_i parameters.

=> Based on Fisher forecasts using Simons Observatory's noise curves and sky coverage.

Early Dark Fluid (EDF) - Density

We estimated 10 modes and kept the first 4:

- reduce degeneracies
- make MCMC analysis computationally possible
- contain most of the information



Early Dark Fluid (EDF) - Sound speed

The sound speed of the fluid relates the rest-frame pressure and density perturbations:

$$\delta\overline{p}(a,k) = \overline{c}_s^2(a,k)\delta\overline{\rho}(a,k)$$

Some known cases:

- 1 for scalar fields
- ⅓ for radiation
- 0 for cold dark matter

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We let it vary and probe its scale factor dependence:

$$\overline{c}_s^2(a) = \begin{cases} c_1^2 & \text{if } a \leq a_1 = 10^{-5} \\ c_1^2 + (c_2^2 - c_1^2)\frac{\log a - \log a_1}{\log a_2 - \log a_1} & \text{if } a_1 \leq a \leq a_2 \\ c_2^2 & \text{if } a \geq a_2 = 10^{-3} \end{cases}$$

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Our model therefore has 6 additional parameters:

- 4 amplitudes of the density modes: (d_1, d_2, d_3, d_4)
- 2 sound speed parameters: c_1^2 and c_2^2

Test cases

Is our model able to reproduce the effect of some specific theoretical models on the CMB power spectra?

4 Test cases:

- Axion-like early dark energy
- New early dark energy

} EDE

- Additional neutrinos (N_{eff})
- Self-interacting dark radiation

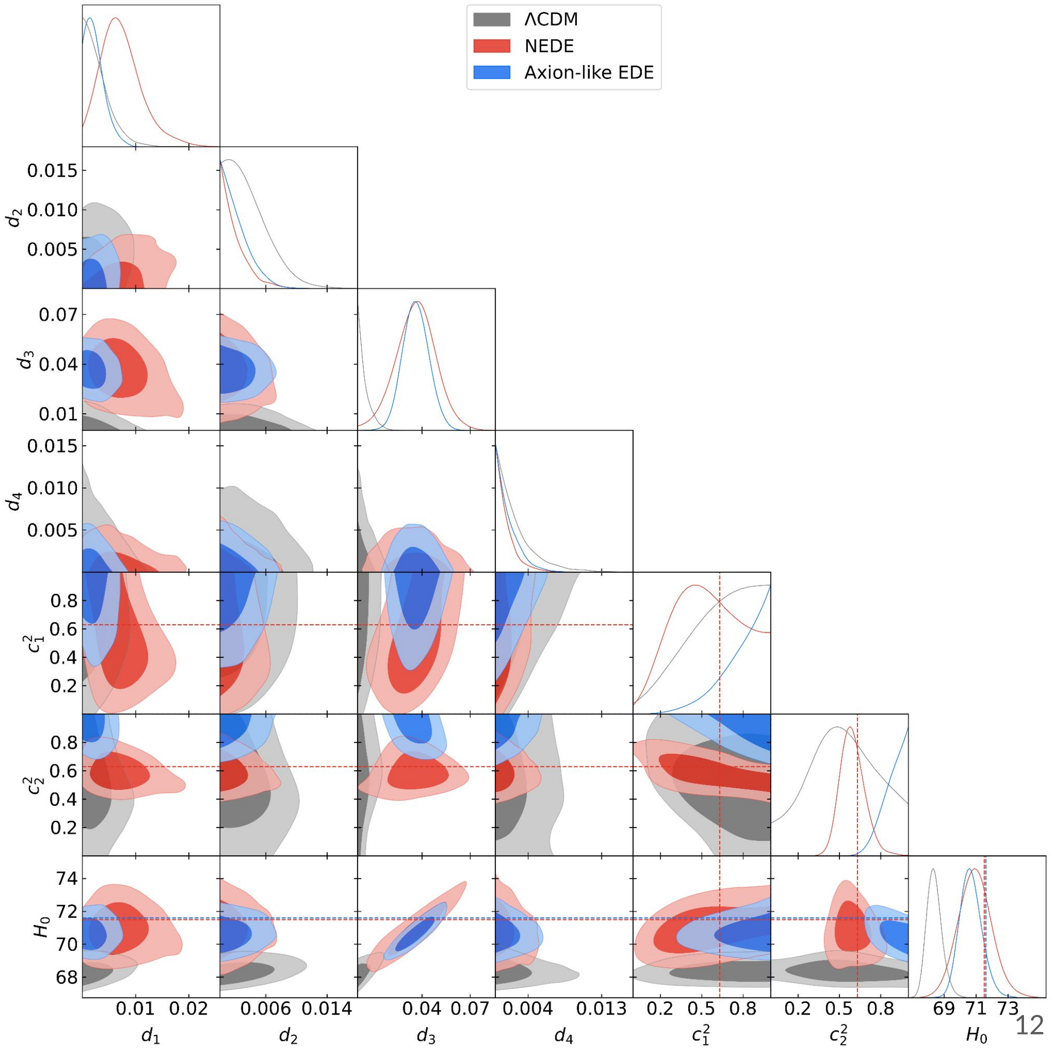
} Dark radiation

Test cases - Methodology

- We generate fiducial TT, EE and TE power spectra using (modified) CAMB/CLASS for the 4 test cases (+LCDM)
  - Best-fit EDE models from Poulin et al. 2018 and Cruz et al. 2023.
  - 95% upper-limit from Planck for the density of dark radiation models.
- We use our EDF model implemented in CAMB to fit those spectra
  - assuming Simons Observatory’s noise
  - running MCMC chains with COBAYA.

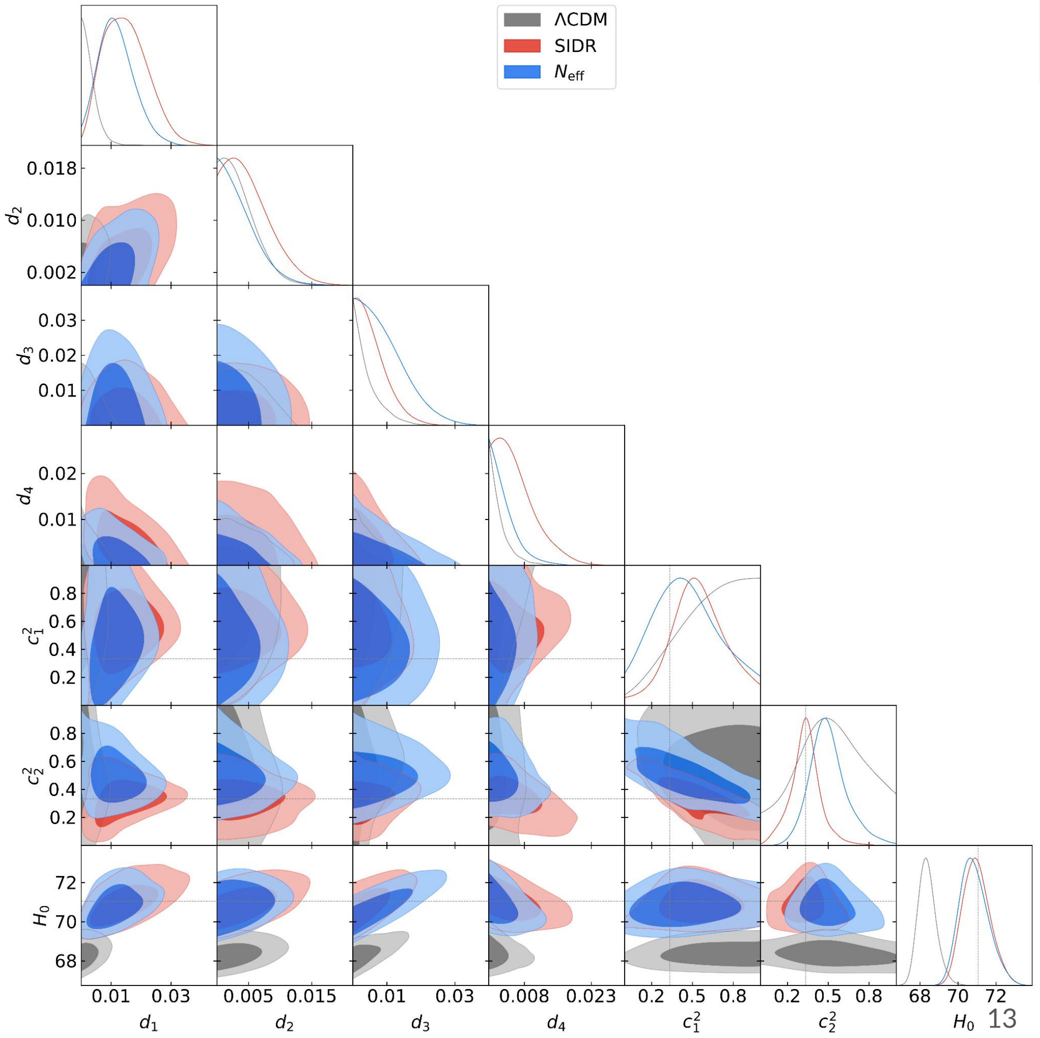
Results - EDE

- Both EDE models mainly reproduced through the third mode
- Sound speed and H_0 quite well reproduced



Results - Dark radiation

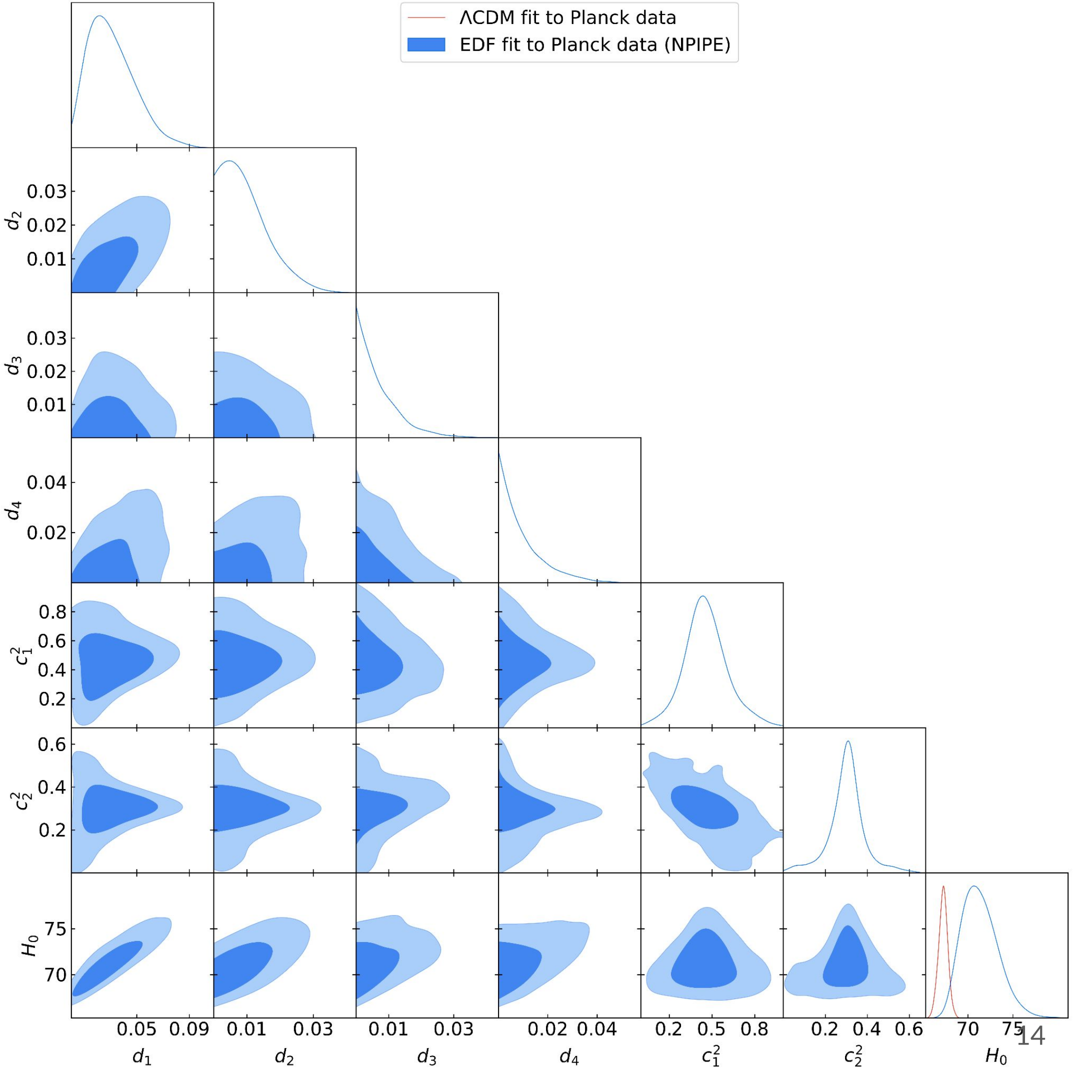
- Both dark radiation models mainly reproduced through the first mode
- Sound speed and H_0 quite well reproduced



Constraints with Planck

- First mode can take high values if sound speed of the order of ⅓ => looks closely to a dark radiation component.
- Highly degenerate with H_0 and large H_0 values can be reached.
- Not statistically significant and even slightly disfavoured if we look at AIC:

	ΛCDM	EDF
χ^2	10963.7	10960.0
ΔAIC	-	-8.3



Conclusion

- EDF model can reproduce a variety of specific theoretical models.
- EDF could also capture deviations from LCDM not corresponding to existing theoretical models.
- Analysis with Planck data shows good consistency with LCDM and no preference for EDF.
- EDF is not ruled out either and significant deviations from LCDM are possible.
- High H0 values can be obtained, especially something that looks like a dark radiation.
- Volume effects will be less severe for Simons Observatory than they are for Planck.

Back-up slides

Early universe solutions

$$\theta_* = r_*/D(z_*)$$

- Angular acoustic scale θ_* measured in the CMB at 0.05% accuracy (Planck)
- Increasing H_0 leads to a decrease of $D(z_*)$
- Idea of early physics solutions: Add a new component before recombination
  - Decreases r_*
  - Keeps θ_* fixed

Results - Goodness of fits

Theoretical model	$\chi^2_{\rm EDF}$	$\chi^2_{\Lambda\rm CDM}$	$\Delta\chi^2$	ΔAIC	$f_{\rm max}$
Axion-like EDE	4.58	30.13	-25.55	13.55	0.068
NEDE	10.33	36.72	-26.39	14.39	0.120
$N_{\rm eff}$	2.09	16.29	-14.20	2.2	0.037
SIDR	0.81	20.08	-19.27	7.27	0.037

$$\text{AIC} = 2k - 2\log\mathcal{L}$$

Test cases - EDE

EDE consists in the addition of a new scalar field:

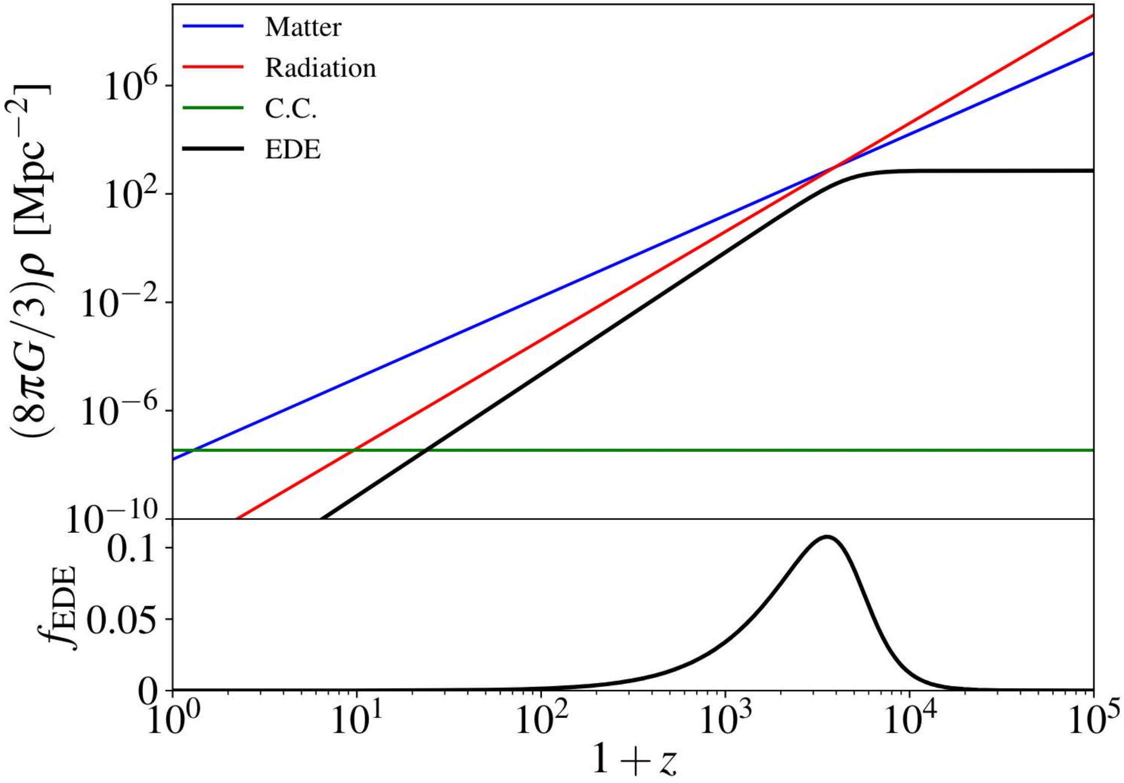
- Frozen at very high redshift ($z > 10^3$-10^4)

  => constant density

- Dynamic at lower redshifts

  => dilutes faster than matter

Poulin et al. (2023)

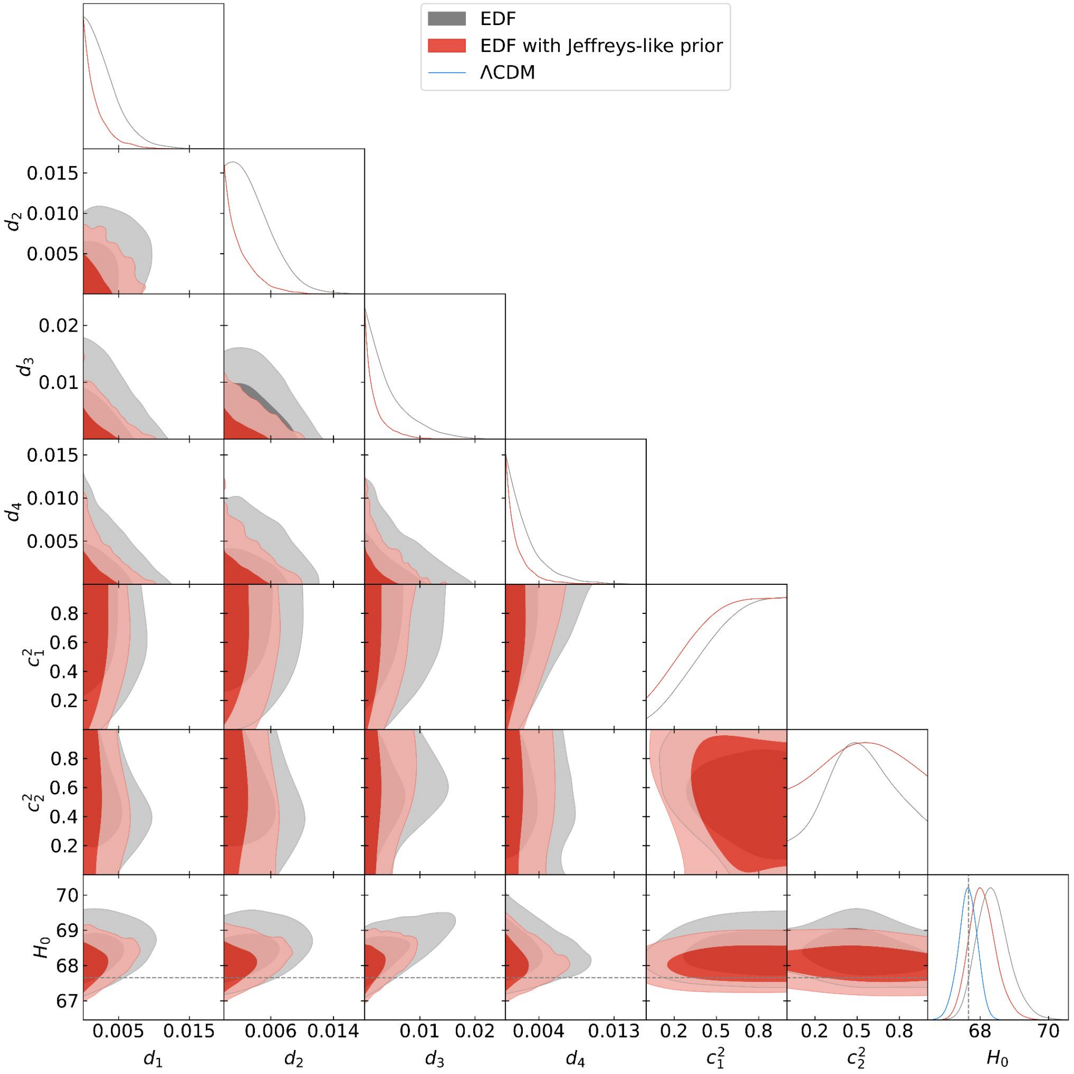


Test cases - Dark radiation

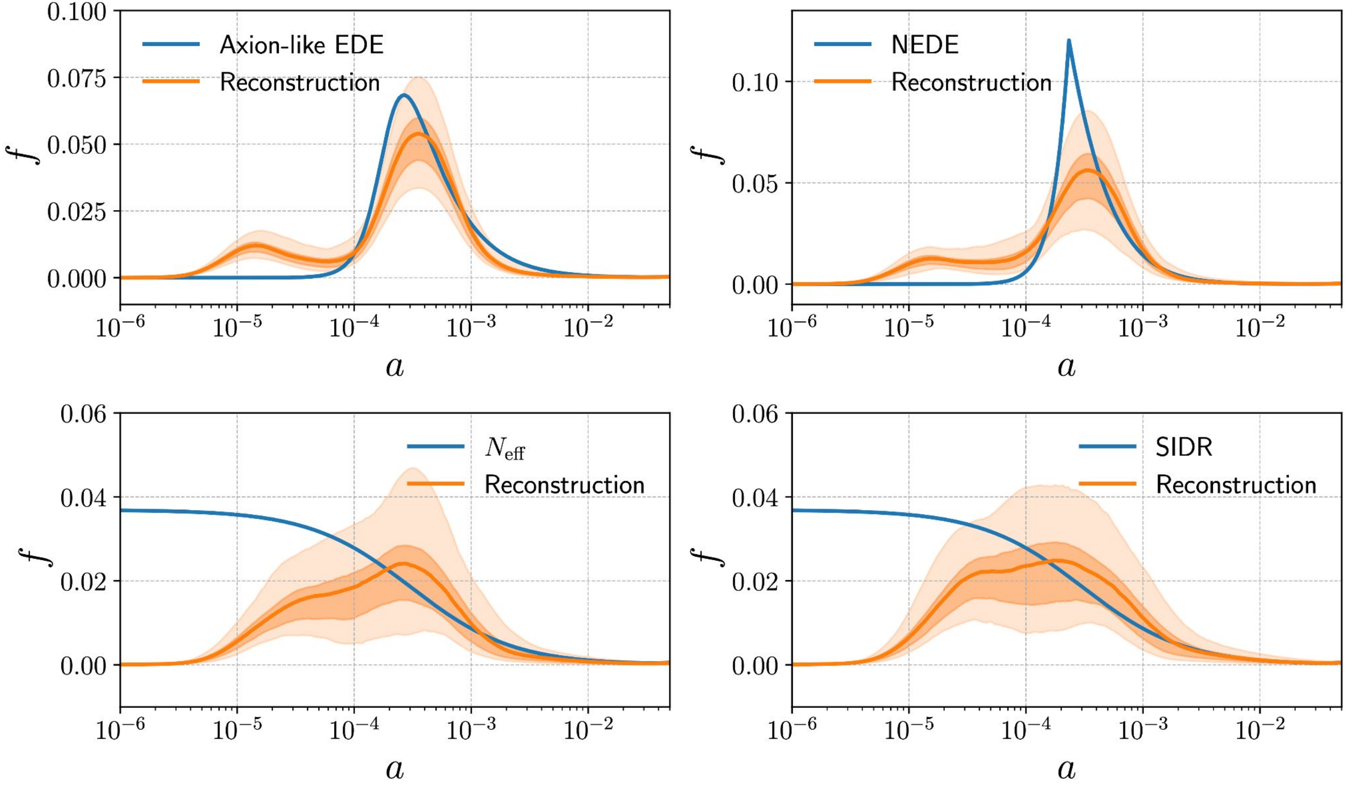
$$\rho_R = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right)$$

Similar idea: adding some density in the early Universe

- Additional neutrinos: free-streaming => have anisotropic stress, need to describe the full Boltzmann hierarchy
- Self-interacting dark radiation => non free-streaming, no anisotropic stress


EDF
EDF with Jeffreys-like prior
ΛCDM
d_1
d_2
d_3
d_4
c_1^2
c_2^2
H_0
0.005
0.015
0.006
0.014
0.01
0.02
0.004
0.013
0.2
0.5
0.8
68
70
0.010
0.6
0.4
69
67

Results - Density reconstructions



Constraints with Planck

Very significant volume effects

- Median H0 much larger than the value used to generate the LCDM mock data.
- Preference for sound speed of ⅓.
- Overall, the analysis shows very good consistency with LCDM.