Early and not so early dark energy. What do cosmological observations tell us about them?

Adrià Gómez-Valent

MG16, CM3 session July 5, 2021



ZUKUNFT SEIT 1386



• Constraints on the fraction of early dark energy in the pre- and post-recombination epochs. [arXiv:2107.XXXX]

in collaboration with:

L. Amendola, V. Pettorino, C. Wetterich and Z. Zheng

2 Early dark energy in Quintessence models with scaling solutions

3 Scaling EDE: a parametrized approach

4 Reconstruction of EDE: binned $\rho_{de}(z)$

5 Conclusions

- Poulin, Smith, Grin, Karwal and Kamionkowski [arXiv:1806.10608]
- Poulin, Smith, Karwal and Kamionkowski [arXiv:1811.04083]

- Poulin, Smith, Grin, Karwal and Kamionkowski [arXiv:1806.10608]
- Poulin, Smith, Karwal and Kamionkowski [arXiv:1811.04083]

Scalar field potential:
$$V(\phi) \propto \left[1-\cos\left(rac{\phi}{f}
ight)
ight]^n$$



- Poulin, Smith, Grin, Karwal and Kamionkowski [arXiv:1806.10608]
- Poulin, Smith, Karwal and Kamionkowski [arXiv:1811.04083]

Scalar field potential:
$$V(\phi) \propto \left[1-\cos\left(rac{\phi}{ar{f}}
ight)
ight]^n$$



Klein-Gordon equation: $\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$





3



3



2

Effective fluid description:

$$ho_{\phi}(a) = rac{2
ho_{\phi}(a_c)}{\left(rac{a}{a_c}
ight)^{rac{6n}{n+1}}+1} \qquad ; \qquad w_{\phi}(a) = rac{2n}{n+1}rac{1}{\left(rac{a_c}{a}
ight)^{rac{6n}{n+1}}+1}-1$$

with $\hat{c}_s^2 = 1$ when $a \ll a_c$ and $\hat{c}_s^2(a, k) = \frac{2a^2(n+1)\beta_0 a^{-3}\left(\frac{n-1}{n+1}\right) + k^2}{2a^2(n-1)\beta_0 a^{-3}\left(\frac{n-1}{n+1}\right) + k^2}$ for $a \gg a_c$.



э



э

-



э

э.

< 行



э

< E.

< 行



э

< E

< 行

Increase of the σ_8/S_8 tension

Results from Poulin et al. [arXiv:1811.04083] Data set: Planck 2018+SNIa+BAO+ H_0

Parameter	ΛCDM	n = 2	n = 3
100 θ_s	$1.04198~(1.04213)\pm 0.0003$	$1.04175 (1.0414)^{+0.00046}_{-0.00064}$	$1.04138~(1.0414)\pm 0.0004$
$100 \omega_b$	$2.238(2.239) \pm 0.014$	$2.244 (2.228)^{+0.019}_{-0.022}$	$2.255~(0.258)\pm0.022$
$\omega_{ m cdm}$	$0.1179~(0.1177)\pm 0.0012$	$0.1248 \ (0.1281)^{+0.003}_{-0.0041}$	$0.1272 \ (0.1299)_{\pm} 0.0045$
$10^{9}A_{s}$	$2.176(2.14) \pm 0.051$	$2.185~(2.230) \pm 0.056$	$2.176~(2.177) \pm 0.054$
n_s	$0.9686~(0.9687)\pm0.0044$	$0.9768 \ (0.9828)^{+0.0065}_{-0.0072}$	$0.9812 \ (0.9880) \pm 0.0080$
$\tau_{\rm reio}$	$0.075~(0.068)\pm 0.013$	$0.075~(0.083)\pm0.013$	$0.068~(0.068)\pm 0.013$
$\log_{10}(a_c)$	-	$-4.136 (-3.728)^{+0.57}_{-0.013}$	$-3.737 (-3.696)^{+0.110}_{-0.094}$
$f_{\rm EDE}(a_c)$	-	$0.028 (0.044)^{+0.011}_{-0.016}$	$0.050 \ (0.058)^{+0.024}_{-0.019}$
$r_s(z_{ m rec})$	$145.05~(145.1) \pm 0.26$	$141.4 (139.8)^{+2}_{-1.5}$	$140.3 (138.9)^{+1.9}_{-2.3}$
S_8	$0.824~(0.814)\pm 0.012$	$0.826~(0.836) \pm 0.014$	$0.838~(0.842)\pm 0.015$
H_0	$68.18~(68.33) \pm 0.54$	$70.3~(71.1) \pm 1.2$	$70.6~(71.6) \pm 1.3$

▶ ∢ ∃ ▶

Increase of the σ_8/S_8 tension

Results from Poulin et al. [arXiv:1811.04083] Data set: Planck 2018+SNIa+BAO+ H_0

Parameter	ΛCDM	n = 2	n = 3
100 θ_s	$1.04198~(1.04213)\pm0.0003$	$1.04175 \ (1.0414)^{+0.00046}_{-0.00064}$	$1.04138~(1.0414)\pm 0.0004$
100 ω_b	$2.238~(2.239)\pm 0.014$	$2.244 (2.228)^{+0.019}_{-0.022}$	$2.255~(0.258)\pm0.022$
$\omega_{\rm cdm}$	$0.1179~(0.1177)\pm 0.0012$	$0.1248 \ (0.1281)^{+0.003}_{-0.0041}$	$0.1272 \ (0.1299)_{\pm} 0.0045$
$10^{9}A_{s}$	$2.176(2.14) \pm 0.051$	$2.185~(2.230) \pm 0.056$	$2.176~(2.177) \pm 0.054$
n_s	$0.9686~(0.9687)\pm0.0044$	$0.9768 \ (0.9828)^{+0.0065}_{-0.0072}$	$0.9812~(0.9880)\pm 0.0080$
$\tau_{\rm reio}$	$0.075~(0.068) \pm 0.013$	$0.075~(0.083)\pm0.013$	$0.068~(0.068)\pm 0.013$
$\log_{10}(a_c)$	-	$-4.136 (-3.728)^{+0.57}_{-0.013}$	$-3.737 (-3.696)^{+0.110}_{-0.094}$
$f_{\rm EDE}(a_c)$	-	$0.028 \ (0.044)^{+0.011}_{-0.016}$	$0.050 \ (0.058)^{+0.024}_{-0.019}$
$r_s(z_{\rm rec})$	$145.05(145.1) \pm 0.26$	$141.4 (139.8)^{+2}_{-1.5}$	$140.3 (138.9)^{+1.9}_{-2.3}$
S_8	$0.824 0.814 \pm 0.012$	$0.826 (0.836) \pm 0.014$	$0.838(0.842) \pm 0.015$
H_0	$68.18(68.33) \pm 0.54$	$70.3(71.1) \pm 1.2$	$70.6\ (71.6) \pm 1.3$

Enhancement of the amount of LSS in the universe!

- J.C. Hill et al. [arXiv:2003.07355]
- M.M. Ivanov et al. [arXiv:2006.11235]

• Can other shapes of $\Omega_{de}(z)$ help to solve the tensions?

- (日)

3 1 4 3 1

- Can other shapes of $\Omega_{de}(z)$ help to solve the tensions?
- Can EDE in the post-recombination epoch mitigate the S_8/σ_8 tension?

- ∢ ∃ →

- Can other shapes of $\Omega_{de}(z)$ help to solve the tensions?
- Can EDE in the post-recombination epoch mitigate the S_8/σ_8 tension?
- What if we consider both, EDE and a late-time dynamical DE?

- Can other shapes of $\Omega_{de}(z)$ help to solve the tensions?
- Can EDE in the post-recombination epoch mitigate the S_8/σ_8 tension?
- What if we consider both, EDE and a late-time dynamical DE?
- Is EDE able to loosen the "SH0ES-Planck" tension if we formulate it in terms of the absolute magnitude of SNIa measured in the first steps of the cosmic distance ladder instead of H_0 ?

- Can other shapes of $\Omega_{de}(z)$ help to solve the tensions?
- Can EDE in the post-recombination epoch mitigate the S_8/σ_8 tension?
- What if we consider both, EDE and a late-time dynamical DE?
- Is EDE able to loosen the "SH0ES-Planck" tension if we formulate it in terms of the absolute magnitude of SNIa measured in the first steps of the cosmic distance ladder instead of H_0 ?
- Does EDE also lead to large values of σ_{12} and S_{12} with respect to the ΛCDM ?

EDE in Quintessence models with scaling solutions

• EDE models are not new.

- EDE models are not new.
- For instance, EDE in quintessence with an exponential potential, $V(\phi) = V_0 e^{-\lambda \kappa \phi}$ exhibits scaling solutions with

$$\Omega_{\phi}=rac{3}{\lambda^2}(1+w)$$
 ; $w_{\phi}=w$

with w the EoS parameter of the dominant fluid, and $\hat{c}_s^2 = 1$.

- EDE models are not new.
- For instance, EDE in quintessence with an exponential potential, $V(\phi) = V_0 e^{-\lambda \kappa \phi}$ exhibits scaling solutions with

$$\Omega_{\phi}=rac{3}{\lambda^2}(1+w)$$
 ; $w_{\phi}=w$

with w the EoS parameter of the dominant fluid, and $\hat{c}_s^2 = 1$. References:

- Wetterich, Nucl. Phys. B, 302, 668 (1988).
- Copeland, Liddle and Wands (1997) [arXiv:gr-qc/9711068]

The EDEp parametrization

EDE density:

$$\rho_{de}(z) = \rho_1(1+z)^4 + \rho_2(1+z)^3 + \rho_3(1+z)^{3(1+w)}$$

æ

The EDEp parametrization

EDE density:

$$\rho_{de}(z) = \rho_1(1+z)^4 + \rho_2(1+z)^3 + \rho_3(1+z)^{3(1+w)}$$

EDE pressure:

$$p_{de}(z) = \frac{\rho_1}{3}(1+z)^4 + w\rho_3(1+z)^{3(1+w)}$$

æ

The EDEp parametrization

EDE density:

$$\rho_{de}(z) = \rho_1(1+z)^4 + \rho_2(1+z)^3 + \rho_3(1+z)^{3(1+w)}$$

EDE pressure:

$$p_{de}(z) = \frac{\rho_1}{3}(1+z)^4 + w\rho_3(1+z)^{3(1+w)}$$

Useful to define:

$$\rho_1 = \chi_1 \Omega_{r,*}^{(0)} \rho_c^{(0)} ; \qquad \rho_2 = \chi_2 \Omega_{m,*}^{(0)} \rho_c^{(0)} ,$$

and

$$\Omega_{\textit{ede}}^{\rm RD} = \frac{\chi_1}{1 + \chi_1}; \qquad \Omega_{\textit{ede}}^{\rm MD} = \frac{\chi_2}{1 + \chi_2}$$

æ

∃ ► < ∃ ►</p>

< A[™]

$\mathsf{EDEp}^{\mathrm{MD}}$ and $\mathsf{EDEp}^{\mathrm{MD,z_{\mathrm{thr}}}}$ parametrizations

 $\mathsf{EDEp}^{\mathrm{MD}}$:

$$\rho_{de}(z) = \rho_2(1+z)^3 + \rho_3(1+z)^{3(1+w)}$$

 $\mathsf{EDEp}^{\mathrm{MD},\mathrm{z_{thr}}}$:

$$\rho_{de}(z) = \rho_2(1+z)^3 \theta(z_{thr}-z) + \rho_3(1+z)^{3(1+w)}$$



æ

< □ > < 同 > < 回 > < 回 > < 回 >

Quintessence energy density and pressure:

$$ho_\phi=rac{\dot{\phi}^2}{2}+V$$
 ; $p_\phi=rac{\dot{\phi}^2}{2}-V$.

Image: Image:

∃ ► < ∃ ►

Quintessence energy density and pressure:

$$egin{aligned} &
ho_{\phi}=rac{\dot{\phi}^2}{2}+V & ; & p_{\phi}=rac{\dot{\phi}^2}{2}-V\,. \ &\dot{\phi}=\sqrt{
ho_{\phi}+p_{\phi}} & ; & V(a)=rac{1}{2}\left[
ho_{\phi}(a)-p_{\phi}(a)
ight] \end{aligned}$$

æ

Quintessence energy density and pressure:

$$egin{aligned} &
ho_{\phi}=rac{\dot{\phi}^2}{2}+V & ; & p_{\phi}=rac{\dot{\phi}^2}{2}-V \,. \ &\dot{\phi}=\sqrt{
ho_{\phi}+
ho_{\phi}} & ; & V(a)=rac{1}{2}\left[
ho_{\phi}(a)-
ho_{\phi}(a)
ight] \end{aligned}$$

In the RDE:

$$V_{RD}(\phi) = \frac{\chi_1}{3} \rho_r(a_{ini}) \exp\left[-\sqrt{32\pi G\left(1+\frac{1}{\chi_1}\right)} \left(\phi-\phi_{ini}\right)\right]$$

æ

- *Planck* 2018 TT,TE,EE data [CMBpol]; also considering the CMB lensing [CMBpolens].
- Pantheon SNIa compilation.
- The SH0ES prior on the absolute magnitude of SNIa, $M = -19.2191 \pm 0.0405$.
- BAO data from various galaxy surveys.
- Data from redshift-space distortions.
- Weak lensing data from KiDS+VIKING-450 and DES-Y1, $S_8 = 0.762^{+0.025}_{-0.024}$.

Parameter	ΛCDM	wCDM	EDEp	$EDEp^{MD}$
ω_b	$0.02239^{+0.00014}_{-0.00015}$	$0.02237\substack{+0.00016\\-0.00015}$	$0.02238^{+0.00017}_{-0.00016}$	$0.02234^{+0.00015}_{-0.00016}$
ω_{cdm}	$0.1199^{+0.0014}_{-0.0013}$	0.1204 ± 0.0014	$0.1218^{+0.0016}_{-0.0015}$	$0.1208^{+0.0014}_{-0.0015}$
au	$0.055^{+0.007}_{-0.008}$	0.054 ± 0.008	0.054 ± 0.008	$0.053\substack{+0.007\\-0.008}$
n_s	0.9659 ± 0.0044	$0.9646\substack{+0.0044\\-0.0045}$	$0.9642\substack{+0.0044\\-0.0045}$	$0.9642\substack{+0.0043\\-0.0046}$
$H_0 \; [\rm km/s/Mpc]$	$67.60^{+0.59}_{-0.61}$	$68.55^{+1.12}_{-1.10}$	68.71 ± 1.16	$68.61^{+1.09}_{-1.16}$
σ_8	$0.811\substack{+0.007\\-0.008}$	0.823 ± 0.014	$0.817\substack{+0.014\\-0.015}$	$0.818\substack{+0.015\\-0.014}$
$r_d \; [{ m Mpc}]$	$147.02^{+0.28}_{-0.32}$	146.92 ± 0.30	$146.18^{+0.66}_{-0.43}$	$146.75_{-0.30}^{+0.36}$
w	-1	$-1.039^{+0.035}_{-0.039}$	$-1.050^{+0.041}_{-0.040}$	$-1.053^{+0.038}_{-0.042}$
$\Omega_{ede}^{ m RD}\left(\% ight)$	0	0	< 0.91 (< 2.08)	0
$\Omega_{ede}^{\mathrm{MD}}\left(\% ight)$	0	0	< 0.27 (< 0.69)	< 0.29 (< 0.69)

æ

Parameter	ΛCDM	w CDM	EDEp
ω_b	$0.02257\substack{+0.00015\\-0.00014}$	$0.02241\substack{+0.00014\\-0.00016}$	$0.02245\substack{+0.00015\\-0.00019}$
ω_{cdm}	0.1179 ± 0.0012	0.1200 ± 0.0015	0.1212 ± 0.0016
au	$0.057\substack{+0.007 \\ -0.008}$	0.054 ± 0.008	0.055 ± 0.008
n_s	0.9709 ± 0.0044	$0.9658\substack{+0.0044\\-0.0047}$	$0.9659\substack{+0.0045\\-0.0044}$
$H_0 \; [{\rm km/s/Mpc}]$	$68.56\substack{+0.56\\-0.54}$	$70.55_{-0.88}^{+0.86}$	$70.63\substack{+0.86 \\ -0.82}$
σ_8	$0.811\substack{+0.007\\-0.008}$	0.838 ± 0.014	$0.830\substack{+0.014\\-0.013}$
$r_d \; [{ m Mpc}]$	$147.36\substack{+0.28\\-0.29}$	$146.98\substack{+0.33\\-0.30}$	$146.21\substack{+0.73\\-0.44}$
w	-1	$-1.098\substack{+0.035\\-0.032}$	$-1.099\substack{+0.034\\-0.032}$
$\Omega_{ede}^{ m RD}\left(\% ight)$	0	0	< 1.14(2.44)
$\Omega_{ede}^{\mathrm{MD}}\left(\% ight)$	0	0	< 0.22 (0.52)

æ

(日) (四) (日) (日) (日)

Results for $\mathsf{EDE}\mathsf{p}^{\mathrm{MD}_{\mathrm{Z_{thr}}}}(I)$



æ

Results for $\mathsf{EDEp}^{\mathrm{MD},\mathrm{z_{thr}}}(II)$



æ

< □ > < 同 > < 回 > < 回 > < 回 >

The impact of \hat{c}_s^2



æ

In order to pass the strong constraints on $\Omega_{de}(z_{dec})$ we need to consider a more flexible shape for the latter

In order to pass the strong constraints on $\Omega_{de}(z_{dec})$ we need to consider a more flexible shape for the latter \longrightarrow Binned $\rho_{de}(z)$, with

Redshift bin	$\rho_{de}(z)$
$z \leq 5$	$\rho_{de}^{(0)}(1+z)^{3(1+w)}$
$5 < z \le 10$	$\rho_A(1+z)^3$
$10 < z \le 50$	$\rho_B (1+z)^3$
$50 < z \le 200$	$\rho_C (1+z)^3$
$200 < z \le 500$	$\rho_D (1+z)^3$
$500 < z \le 1000$	$\rho_E (1+z)^3$
$1000 < z \le 2000$	$\rho_F (1+z)^4$
$2000 < z \le 3000$	$\rho_G (1+z)^4$
$3000 < z \le 5000$	$\rho_H (1+z)^4$
$5000 < z \le 10^4$	$\rho_I (1+z)^4$
$z > 10^4$	$\rho_J (1+z)^4$



21/24

3



21 / 24

æ

Parameter	CMBpol+SNIa	CMBpol+SNIa+M	CMBpol+SNIa+M+BAO	CMBpol+SNIa+M+BAO+S ₈
ω	$0.02257^{+0.00022}_{-0.00023}$	$0.02277^{+0.00023}_{-0.00025}$	$0.02282^{+0.00024}_{-0.00025}$	0.02259 ± 0.00021
ω_{cdm}	$0.1222^{+0.0020}_{-0.0021}$	0.1221 ± 0.0022	$0.1223^{+0.0020}_{-0.0021}$	$0.1200^{+0.0013}_{-0.0014}$
τ	0.055 ± 0.009	0.056 ± 0.009	$0.057^{+0.008}_{-0.009}$	0.053 ± 0.008
ns	$0.9727^{+0.0072}_{-0.0073}$	$0.9752^{+0.0067}_{-0.0069}$	$0.9760^{+0.0070}_{-0.0071}$	$0.9740^{+0.0061}_{-0.0067}$
$H_0 [\rm km/s/Mpc]$	$68.29^{+1.26}_{-1.36}$	$70.86^{+1.00}_{-1.10}$	$70.38^{+0.84}_{-0.89}$	$69.85^{+0.76}_{-0.77}$
М	-19.405 ± 0.032	$-19.342^{+0.023}_{-0.024}$	$-19.350^{+0.019}_{-0.020}$	$-19.365^{+0.018}_{-0.017}$
σ_8	$0.854^{+0.023}_{-0.025}$	$0.880^{+0.025}_{-0.029}$	$0.877^{+0.026}_{-0.029}$	$0.833^{+0.016}_{-0.017}$
S_8	$0.869^{+0.025}_{-0.029}$	0.863 ± 0.029	$0.866^{+0.026}_{-0.028}$	$0.819^{+0.014}_{-0.016}$
σ_{12}	$0.840^{+0.019}_{-0.022}$	0.843 ± 0.022	$0.843^{+0.020}_{-0.022}$	$0.806^{+0.012}_{-0.013}$
S_{12}	$0.851^{+0.022}_{-0.025}$	$0.854^{+0.024}_{-0.027}$	$0.855^{+0.023}_{-0.026}$	$0.810^{+0.014}_{-0.016}$
r_d [Mpc]	$145.66^{+0.90}_{-0.70}$	$145.22^{+0.95}_{-0.90}$	$145.06^{+0.97}_{-0.89}$	$146.51^{+0.64}_{-0.51}$
w	$-1.037^{+0.043}_{-0.041}$	-1.070 ± 0.038	$-1.048^{+0.037}_{-0.034}$	$-1.037^{+0.032}_{-0.031}$
Parameter	CMBpolens+SNIa	CMBpolens+SNIa+M	CMBpolens+SNIa+M+BAO	${\rm CMBpolens+SNIa+M+BAO}{+}S_8$
ω	$0.02255^{+0.00020}_{-0.00022}$	$0.02274^{+0.00023}_{-0.00025}$	$0.02277^{+0.00022}_{-0.00024}$	$0.02266^{+0.00021}_{-0.00020}$
ω_{odm}	0.1915+0.0015			10.0010
	0.1210-0.0016	0.1211 ± 0.0017	0.1214 ± 0.0016	$0.1193^{+0.0013}_{-0.0014}$
τ	$0.1213_{-0.0016}$ 0.054 ± 0.008	0.1211 ± 0.0017 $0.056^{+0.008}_{-0.009}$	0.1214 ± 0.0016 0.056 ± 0.008	$0.1193^{+0.0013}_{-0.0014}$ $0.055^{+0.008}_{-0.007}$
τ n _s	$0.1213_{-0.0016}$ 0.054 ± 0.008 $0.9723_{-0.0069}^{+0.0068}$	$\frac{0.1211 \pm 0.0017}{0.056^{+0.008}_{-0.009}}$ $\frac{0.9748^{+0.0067}_{-0.0071}}{0.0071}$	0.1214 ± 0.0016 0.056 ± 0.008 $0.9746^{+0.0068}_{-0.0069}$	$\frac{0.1193^{+0.0013}_{-0.0014}}{0.055^{+0.008}_{-0.007}}$ $0.9727^{+0.0061}_{-0.0068}$
au n_s $H_0 [km/s/Mpc]$	$\begin{array}{r} 0.1213_{-0.0016} \\ \hline 0.054 \pm 0.008 \\ \hline 0.9723^{+0.0068}_{-0.0069} \\ \hline 68.26^{+1.17}_{-1.27} \end{array}$	$\begin{array}{c} 0.1211 \pm 0.0017 \\ 0.056^{+0.008}_{-0.009} \\ \hline 0.9748^{+0.0067}_{-0.0071} \\ 70.84^{+1.04}_{-1.07} \end{array}$	$\begin{array}{c} 0.1214 \pm 0.0016 \\ \hline 0.056 \pm 0.008 \\ \hline 0.9746^{+0.0068}_{-0.0069} \\ \hline 70.21^{+0.80}_{-0.84} \end{array}$	$\frac{0.1193^{+0.0013}_{-0.0014}}{0.055^{+0.008}_{-0.007}}$ $\frac{0.9727^{+0.0061}_{-0.0068}}{70.09^{+0.76}_{-0.73}}$
au n_s $H_0 [km/s/Mpc]$ M	$\begin{array}{r} 0.1213_{-0.0016} \\ \hline 0.054 \pm 0.008 \\ \hline 0.9723^{+0.0069}_{-0.0069} \\ \hline 68.26^{+1.17}_{-1.27} \\ \hline -19.406^{+0.027}_{-0.029} \end{array}$	$\begin{array}{c} 0.1211 \pm 0.0017 \\ \hline 0.056^{+0.008}_{-0.009} \\ \hline 0.9748^{+0.0067}_{-0.0071} \\ \hline 70.84^{+1.04}_{-1.07} \\ \hline -19.343^{+0.024}_{-0.025} \end{array}$	$\begin{array}{c} 0.1214 \pm 0.0016 \\ 0.056 \pm 0.008 \\ 0.9746^{+0.0068}_{-0.0069} \\ \overline{0.0746^{+0.0069}_{-0.0069}} \\ \overline{0.21^{+0.84}_{-0.84}} \\ -19.355 \pm 0.018 \end{array}$	$\begin{array}{c} 0.1193\substack{+0.0013\\-0.0014}\\ 0.055\substack{+0.008\\-0.007}\\ 0.9727\substack{+0.0061\\-0.73}\\ \hline 70.00\substack{+0.76\\-0.73}\\ -19.362\pm 0.016 \end{array}$
au $H_0 [km/s/Mpc]$ M σ_8	$\begin{array}{r} 0.1213_{-0.0016} \\ \hline 0.054 \pm 0.008 \\ 0.9723_{+0.0068}^{+0.008} \\ \hline 68.26_{-1.27}^{+1.17} \\ \hline -19.406_{-0.029}^{+0.017} \\ \hline 0.845_{-0.020}^{+0.017} \end{array}$	$\begin{array}{c} 0.1211 \pm 0.0017 \\ 0.056 \substack{+0.008\\-0.009} \\ 0.9748 \substack{+0.0067\\-0.0071 \\ \hline 70.84 \substack{+1.04\\-1.07} \\ -19.343 \substack{+0.024\\-0.025 \\ \hline 0.868 \substack{+0.019\\-0.021} \end{array}$	$\begin{array}{c} 0.1214\pm 0.0016\\ \hline 0.056\pm 0.008\\ 0.9746^{+0.0089}_{-0.0099}\\ \hline 70.21^{+0.80}_{-0.84}\\ \hline -19.355\pm 0.018\\ \hline 0.864^{+0.019}_{-0.021}\\ \end{array}$	$\begin{array}{c} 0.1193\substack{+0.0013\\-0.0014}\\ 0.055\substack{+0.008\\-0.007}\\ 0.9727\substack{+0.0061\\-0.73}\\ \hline 70.00\substack{+0.76\\-0.73}\\ -19.362\pm0.016\\ 0.839\substack{+0.013\\-0.0215}\\ \end{array}$
au $H_0 [km/s/Mpc]$ M σ_8 S_8	$\begin{array}{c} 0.1213_{-0.016} \\ 0.054 \pm 0.008 \\ 0.9723_{-0.0069}^{+0.17} \\ 68.26_{-1.27}^{+1.17} \\ -19.406_{-0.029}^{+0.017} \\ 0.845_{-0.020}^{+0.019} \\ 0.857_{-0.021}^{+0.019} \end{array}$	$\begin{array}{c} 0.1211 \pm 0.0017 \\ 0.056 \substack{+0.008 \\ -0.009} \\ 0.9748 \substack{+0.0067 \\ -0.0071} \\ 70.84 \substack{+1.04 \\ -1.07} \\ -19.343 \substack{+0.024 \\ -0.025} \\ 0.868 \substack{+0.019 \\ -0.021} \\ 0.848 \substack{+0.020 \\ -0.022} \end{array}$	$\begin{array}{c} 0.1214\pm 0.0016\\ 0.056\pm 0.008\\ 0.9746^{+0.008}_{-0.009}\\ \overline{}70.21^{+0.80}_{-0.84}\\ -19.355\pm 0.018\\ 0.864^{+0.019}_{-0.021}\\ 0.853^{+0.019}_{-0.020}\\ \end{array}$	$\begin{array}{c} 0.1193^{+0.0014}_{-0.0014}\\ \hline 0.055^{+0.008}_{-0.007}\\ 0.0727^{+0.0061}_{-0.008}\\ \hline 70.00^{+0.76}_{-0.7}\\ -19.362\pm0.016\\ 0.839^{+0.013}_{-0.023}\\ 0.824^{+0.012}_{-0.013}\\ \hline 0.824^{+0.012}_{-0.013}\\ \end{array}$
$ \frac{ au}{H_0 \ [km/s/Mpc]} \\ \frac{ extsf{M}}{ extsf{M}} \\ extsf{M} \\ extsf{\sigma}_8 \\ extsf{S}_8 \\ extsf{\sigma}_{12} \\ extsf{\sigma}_{12} \\ extsf{M} \\ extsf{$	$\begin{array}{c} 0.1213_{-0.0016}\\ 0.054\pm0.008\\ 0.9723_{-0.0069}^{+0.008}\\ 68.26_{-1.27}^{+1.17}\\ -19.406_{-0.029}^{-0.029}\\ 0.845_{-0.020}^{-0.020}\\ 0.857_{-0.021}^{+0.017}\\ \end{array}$	$\begin{array}{c} 0.1211 \pm 0.0017 \\ 0.056^{+0.008} \\ 0.0748^{+0.0067} \\ -0.097 \\ 1.0748^{+0.0067} \\ -19.343^{+0.024} \\ -19.343^{+0.024} \\ 0.868^{+0.019} \\ 0.868^{+0.019} \\ 0.848^{+0.022} \\ 0.841^{+0.015} \\ 0.831^{+0.015} \\ \end{array}$	$\begin{array}{c} 0.1214\pm0.0016\\ 0.056\pm0.008\\ 0.9746^{+0.0088}_{-0.0099}\\ 70.21^{+0.84}_{-0.84}\\ -19.355\pm0.018\\ 0.864^{+0.019}_{-0.019}\\ 0.833^{+0.019}_{-0.029}\\ 0.833^{+0.015}_{-0.016}\\ \end{array}$	$\begin{array}{c} 0.1193^{+0.0014}_{-0.0014}\\ 0.055^{+0.008}_{-0.007}\\ 0.9727^{+0.008}_{-0.008}\\ \overline{}\\ 70.00^{+0.76}_{-0.73}\\ -1.9.362\pm0.016\\ 0.839^{+0.015}_{-0.0215}\\ 0.824^{+0.012}_{-0.012}\\ 0.824^{+0.012}_{-0.011}\\ 0.810^{-0.011}_{-0.011}\\ \end{array}$
$ au = rac{ au + r_{s}}{ extsf{Mpc}} = rac{ extsf{M}}{ extsf{M}} + tridtrid{ extsf{M}} + trid{ extsf{M}} + tridt + trid{ extsf{M}} + trid{$	$\begin{array}{c} 0.1243 \pm 0.0016\\ 0.054 \pm 0.008\\ 0.9723 \pm 0.0068\\ 68.26 \pm 1.17\\ -19.406 \pm 0.029\\ 0.845 \pm 0.019\\ 0.845 \pm 0.019\\ 0.857 \pm 0.019\\ \end{array}$	$\begin{array}{c} 0.1211\pm0.0017\\ 0.056^{+0.008}\\ 0.9748^{+0.0071}\\ -0.984^{+1.04}\\ -19.343^{+0.027}\\ -19.343^{+0.029}\\ 0.868^{+0.029}\\ 0.848^{+0.029}\\ 0.848^{+0.029}\\ 0.841^{+0.016}\\ 0.840^{+0.016}\\ 0.840^{+0.016}\\ \end{array}$	$\begin{array}{c} 0.1214\pm0.0016\\ 0.056\pm0.008\\ 0.9764^{+0.0008}\\ 70.21^{+0.008}\\ -19.355\pm0.018\\ 0.864^{+0.001}\\ 0.853^{+0.019}\\ 0.853^{+0.019}\\ 0.833^{+0.018}\\ 0.843\pm0.018\\ \end{array}$	$\begin{array}{c} 0.1133 \substack{+0.001\\-0.005} \atop +0.008\\0.055 \substack{+0.008\\-0.007} \\ 0.0727 \substack{+0.001\\-0.006} \\ 7.0.00 \begin{array}{+}0.0727 \atop +0.016 \\ 0.839 \substack{+0.015\\-0.018} \\ 0.834 \substack{+0.015\\-0.013} \\ 0.834 \substack{+0.012\\-0.013} \\ 0.834 \substack{+0.012\\-0.012} \\ 0$
$\begin{array}{c} \tau \\ \hline n_s \\ H_0 \; [{\rm km/s/Mpc}] \\ M \\ \hline \sigma_8 \\ \hline S_8 \\ \sigma_{12} \\ \hline S_{12} \\ \hline r_s(z_d) \; [{\rm Mpc}] \end{array}$	$\begin{array}{c} 0.1243 \pm 0.0016\\ 0.054 \pm 0.008\\ 0.9723 \pm 0.0068\\ 0.9723 \pm 0.0068\\ 0.8.26 \pm 1.17\\ -19.406 \pm 0.029\\ 0.845 \pm 0.019\\ 0.845 \pm 0.019\\ 0.857 \pm 0.019\\ 0.857 \pm 0.019\\ 0.857 \pm 0.019\\ 145.98 \pm 0.71\\ 145.98 \pm 0.71\\ \end{array}$	$\begin{array}{c} 0.211\pm0.0017\\ 0.056^{+0.008}_{-0.007}\\ 0.9748^{+0.007}_{-0.007}\\ -19.343^{+0.007}_{-0.05}\\ 0.868^{+0.019}_{-0.05}\\ 0.848^{+0.019}_{-0.05}\\ 0.848^{+0.019}_{-0.01}\\ 0.844^{+0.015}_{-0.01}\\ 0.840^{+0.017}_{-0.01}\\ \end{array}$	$\begin{array}{c} 0.1214\pm0.0016\\ 0.056\pm0.008\\ 0.9746^{+0.0089}\\ \overline{10,214^{+0.008}_{-0.009}}\\ 1.09.355\pm0.018\\ 0.854^{+0.019}_{-0.009}\\ 0.853^{+0.019}_{-0.009}\\ 0.833^{+0.019}_{-0.018}\\ 0.843\pm0.018\\ 145.51^{+0.05}_{-0.71}\end{array}$	$\begin{array}{c} 0.1193\substack{-0.001\\-0.005} \\ 0.0972\substack{-0.001\\-0.0000} \\ \hline 70.00^{+0.75}\\ -1.9.602\pm 0.016 \\ 0.839\substack{+0.015\\-0.011} \\ 0.834\substack{+0.012\\-0.011} \\ 0.834\substack{+0.012\\-0.011} \\ 0.834\substack{+0.012\\-0.011} \\ 0.834\substack{+0.012\\-0.011} \\ 0.834\substack{+0.012\\-0.011} \\ 146.64\substack{+0.012\\-0.010} \\ \hline \end{array}$

Parameter	CMBpolens+SNIa	CMBpolens+SNIa+M+BAO	${\rm CMBpolens+SNIa+M+BAO+}S_8$
ω_b	$0.02255^{+0.00020}_{-0.00022}$	$0.02277^{+0.00022}_{-0.00024}$	$0.02266^{+0.00021}_{-0.00020}$
ω_{cdm}	$0.1215^{+0.0015}_{-0.0016}$	0.1214 ± 0.0016	$0.1193^{+0.0013}_{-0.0014}$
τ	0.054 ± 0.008	0.056 ± 0.008	$0.055^{+0.008}_{-0.007}$
n_s	$0.9723^{+0.0068}_{-0.0069}$	$0.9746^{+0.0068}_{-0.0069}$	$0.9727^{+0.0061}_{-0.0068}$
$H_0 \; [{\rm km/s/Mpc}]$	$68.26^{+1.17}_{-1.27}$	$70.21_{-0.84}^{+0.80}$	$70.00^{+0.76}_{-0.73}$
М	$-19.406^{+0.027}_{-0.029}$	-19.355 ± 0.018	-19.362 ± 0.016
σ_8	$0.845^{+0.017}_{-0.020}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
S_8	$0.857^{+0.019}_{-0.021}$	$0.853^{+0.019}_{-0.020}$	$0.824^{+0.012}_{-0.013}$
σ_{12}	$0.830^{+0.015}_{-0.016}$	$0.833^{+0.015}_{-0.016}$	$0.810^{+0.010}_{-0.011}$
S_{12}	0.844 ± 0.021	0.843 ± 0.018	$0.815^{+0.011}_{-0.013}$
$r_s(z_d)$ [Mpc]	$145.98^{+0.71}_{-0.53}$	$145.51^{+0.83}_{-0.71}$	$146.46_{-0.44}^{+0.56}$
w	$-1.035^{+0.039}_{-0.040}$	$-1.050^{+0.034}_{-0.035}$	-1.045 ± 0.032

Parameter	CMBpolens+SNIa	CMBpolens+SNIa+M+BAO	${\rm CMBpolens+SNIa+M+BAO+}S_8$
ω_b	$0.02255^{+0.00020}_{-0.00022}$	$0.02277^{+0.00022}_{-0.00024}$	$0.02266^{+0.00021}_{-0.00020}$
ω_{cdm}	$0.1215^{+0.0015}_{-0.0016}$	0.1214 ± 0.0016	$0.1193^{+0.0013}_{-0.0014}$
τ	0.054 ± 0.008	0.056 ± 0.008	$0.055^{+0.008}_{-0.007}$
n_s	$0.9723^{+0.0068}_{-0.0069}$	$0.9746^{+0.0068}_{-0.0069}$	$0.9727^{+0.0061}_{-0.0068}$
$H_0 \; [\rm km/s/Mpc]$	$68.26^{+1.17}_{-1.27}$	$70.21_{-0.84}^{+0.80}$	$70.00^{+0.76}_{-0.73}$
	2.77 sigma	1.95 sigma	2.13 sigma
σ_8	$0.845^{+0.017}_{-0.020}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
S_8	$0.857^{+0.019}_{-0.021}$	$0.853^{+0.019}_{-0.020}$	$0.824^{+0.012}_{-0.013}$
σ_{12}	$0.830^{+0.015}_{-0.016}$	$0.833^{+0.015}_{-0.016}$	$0.810^{+0.010}_{-0.011}$
S_{12}	0.844 ± 0.021	0.843 ± 0.018	$0.815^{+0.011}_{-0.013}$
$r_s(z_d)$ [Mpc]	$145.98^{+0.71}_{-0.53}$	$145.51^{+0.83}_{-0.71}$	$146.46_{-0.44}^{+0.56}$
w	$-1.035^{+0.039}_{-0.040}$	$-1.050^{+0.034}_{-0.035}$	-1.045 ± 0.032

Parameter	CMBpolens+SNIa	CMBpolens+SNIa+M+BAO	${\rm CMBpolens+SNIa+M+BAO+}S_8$
ω_b	$0.02255^{+0.00020}_{-0.00022}$	$0.02277^{+0.00022}_{-0.00024}$	$0.02266^{+0.00021}_{-0.00020}$
ω_{cdm}	$0.1215^{+0.0015}_{-0.0016}$	0.1214 ± 0.0016	$0.1193^{+0.0013}_{-0.0014}$
τ	0.054 ± 0.008	0.056 ± 0.008	$0.055^{+0.008}_{-0.007}$
n_s	$0.9723^{+0.0068}_{-0.0069}$	$0.9746^{+0.0068}_{-0.0069}$	$0.9727^{+0.0061}_{-0.0068}$
	3.80 sigma	3.07 sigma	3.28 sigma
М	$-19.406^{+0.027}_{-0.029}$	-19.355 ± 0.018	-19.362 ± 0.016
σ_8	$0.845^{+0.017}_{-0.020}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
S_8	$0.857^{+0.019}_{-0.021}$	$0.853^{+0.019}_{-0.020}$	$0.824^{+0.012}_{-0.013}$
σ_{12}	$0.830^{+0.015}_{-0.016}$	$0.833^{+0.015}_{-0.016}$	$0.810^{+0.010}_{-0.011}$
S_{12}	0.844 ± 0.021	0.843 ± 0.018	$0.815^{+0.011}_{-0.013}$
$r_s(z_d)$ [Mpc]	$145.98^{+0.71}_{-0.53}$	$145.51^{+0.83}_{-0.71}$	$146.46_{-0.44}^{+0.56}$
w	$-1.035^{+0.039}_{-0.040}$	$-1.050^{+0.034}_{-0.035}$	-1.045 ± 0.032

Parameter	CMBpolens+SNIa	CMBpolens+SNIa+M+BAO	${\rm CMBpolens+SNIa+M+BAO+}S_8$
ω_b	$0.02255^{+0.00020}_{-0.00022}$	$0.02277^{+0.00022}_{-0.00024}$	$0.02266^{+0.00021}_{-0.00020}$
ω_{cdm}	$0.1215^{+0.0015}_{-0.0016}$	0.1214 ± 0.0016	$0.1193^{+0.0013}_{-0.0014}$
τ	0.054 ± 0.008	0.056 ± 0.008	$0.055^{+0.008}_{-0.007}$
n_s	$0.9723^{+0.0068}_{-0.0069}$	$0.9746^{+0.0068}_{-0.0069}$	$0.9727^{+0.0061}_{-0.0068}$
$H_0 \; [{\rm km/s/Mpc}]$	$68.26^{+1.17}_{-1.27}$	$70.21_{-0.84}^{+0.80}$	$70.00^{+0.76}_{-0.73}$
М	$-19.406^{+0.027}_{-0.029}$	-19.355 ± 0.018	-19.362 ± 0.016
σ_8	$0.845^{+0.017}_{-0.020}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
S_8	$0.857^{+0.019}_{-0.021}$	$0.853^{+0.019}_{-0.020}$	$0.824^{+0.012}_{-0.013}$
σ_{12}	$0.830^{+0.015}_{-0.016}$	$0.833^{+0.015}_{-0.016}$	$0.810^{+0.010}_{-0.011}$
S_{12}	0.844 ± 0.021	0.843 ± 0.018	$0.815^{+0.011}_{-0.013}$
$r_s(z_d)$ [Mpc]	$145.98^{+0.71}_{-0.53}$	$145.51^{+0.83}_{-0.71}$	$146.46_{-0.44}^{+0.56}$
w	$-1.035^{+0.039}_{-0.040}$	$-1.050^{+0.034}_{-0.035}$	-1.045 ± 0.032

Parameter	CMBpolens+SNIa	CMBpolens+SNIa+M+BAO	${\rm CMBpolens+SNIa+M+BAO+}S_8$
ω_b	$0.02255^{+0.00020}_{-0.00022}$	$0.02277^{+0.00022}_{-0.00024}$	$0.02266^{+0.00021}_{-0.00020}$
ω_{cdm}	$0.1215^{+0.0015}_{-0.0016}$	0.1214 ± 0.0016	$0.1193^{+0.0013}_{-0.0014}$
τ	0.054 ± 0.008	0.056 ± 0.008	$0.055^{+0.008}_{-0.007}$
n_s	$0.9723^{+0.0068}_{-0.0069}$	$0.9746^{+0.0068}_{-0.0069}$	$0.9727^{+0.0061}_{-0.0068}$
$H_0 \; [\rm km/s/Mpc]$	$68.26^{+1.17}_{-1.27}$	$70.21_{-0.84}^{+0.80}$	$70.00^{+0.76}_{-0.73}$
М	$-19.406^{+0.027}_{-0.029}$	-19.355 ± 0.018	-19.362 ± 0.016
σ_8	$0.845^{+0.017}_{-0.020}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
S_8	$0.857^{+0.019}_{-0.021}$	$0.853^{+0.019}_{-0.020}$	$0.824^{+0.012}_{-0.013}$
σ_{12}	$0.830^{+0.015}_{-0.016}$	$0.833^{+0.015}_{-0.016}$	$0.810^{+0.010}_{-0.011}$
S ₁₂	0.844 ± 0.021	0.843 ± 0.018	$0.815^{+0.011}_{-0.013}$
$r_s(z_d)$ [Mpc]	$145.98^{+0.71}_{-0.53}$	$145.51^{+0.83}_{-0.71}$	$146.46_{-0.44}^{+0.56}$
w	$-1.035^{+0.039}_{-0.040}$	$-1.050^{+0.034}_{-0.035}$	-1.045 ± 0.032

• We have obtained very tight upper bounds on the EDE fraction in the RDE and MDE epochs, in the context of DE models with scaling solutions.

- We have obtained very tight upper bounds on the EDE fraction in the RDE and MDE epochs, in the context of DE models with scaling solutions.
- They do not alleviate significantly the cosmological tensions.

- We have obtained very tight upper bounds on the EDE fraction in the RDE and MDE epochs, in the context of DE models with scaling solutions.
- They do not alleviate significantly the cosmological tensions.
- We have performed a more model independent reconstruction of $\Omega_{de}(z)$, still assuming $\hat{c}_s^2 = 1$.

- We have obtained very tight upper bounds on the EDE fraction in the RDE and MDE epochs, in the context of DE models with scaling solutions.
- They do not alleviate significantly the cosmological tensions.
- We have performed a more model independent reconstruction of $\Omega_{de}(z)$, still assuming $\hat{c}_s^2 = 1$.
- We find very strong constraints around the CMB decoupling time.

- We have obtained very tight upper bounds on the EDE fraction in the RDE and MDE epochs, in the context of DE models with scaling solutions.
- They do not alleviate significantly the cosmological tensions.
- We have performed a more model independent reconstruction of $\Omega_{de}(z)$, still assuming $\hat{c}_s^2 = 1$.
- We find very strong constraints around the CMB decoupling time.
- Large values of $\Omega_{ede}^{\rm RD}$ allow larger values of H_0 , but typically lead to a worsening of the LSS tension.

- We have obtained very tight upper bounds on the EDE fraction in the RDE and MDE epochs, in the context of DE models with scaling solutions.
- They do not alleviate significantly the cosmological tensions.
- We have performed a more model independent reconstruction of $\Omega_{de}(z)$, still assuming $\hat{c}_s^2 = 1$.
- We find very strong constraints around the CMB decoupling time.
- Large values of Ω_{ede}^{RD} allow larger values of H_0 , but typically lead to a worsening of the LSS tension.
- The latter can also be loosened with a greater EDE fraction in the MDE.

- We have obtained very tight upper bounds on the EDE fraction in the RDE and MDE epochs, in the context of DE models with scaling solutions.
- They do not alleviate significantly the cosmological tensions.
- We have performed a more model independent reconstruction of $\Omega_{de}(z)$, still assuming $\hat{c}_s^2 = 1$.
- We find very strong constraints around the CMB decoupling time.
- Large values of Ω_{ede}^{RD} allow larger values of H_0 , but typically lead to a worsening of the LSS tension.
- The latter can also be loosened with a greater EDE fraction in the MDE.
- We have studied these tensions in terms of M and s_{12}/S_{12} .

Thanks for your attention!

(日) (四) (日) (日) (日)