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

Adrià Gómez-Valent

MG16, CM3 session
July 5, 2021

This talk is based on...

- **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

Outline

1. Early dark energy (in the modern literature)
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

Early dark energy (in the modern literature)

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

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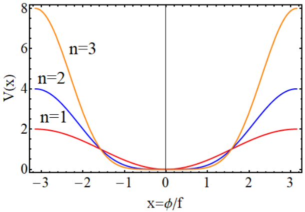
Scalar field potential: $V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$



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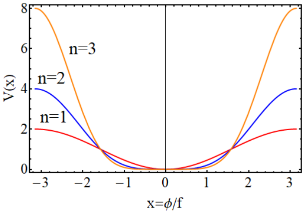
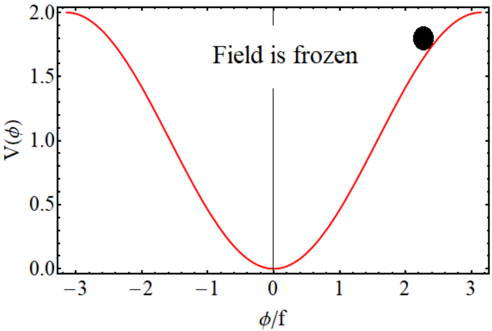


Klein-Gordon equation: $\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$



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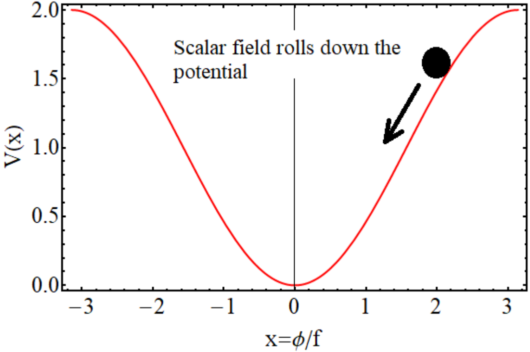

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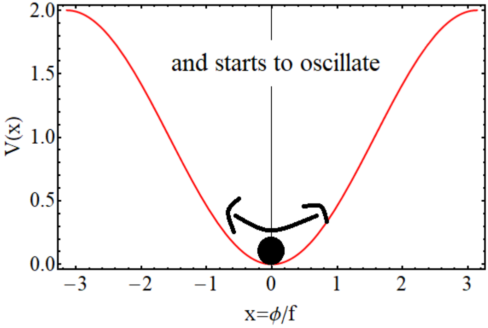
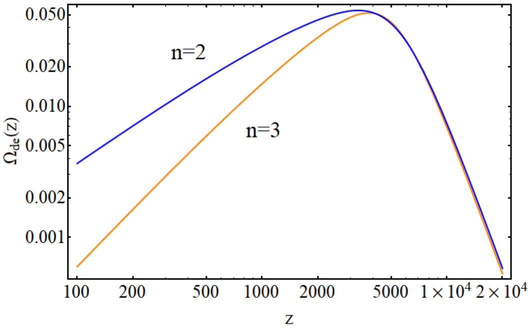


$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

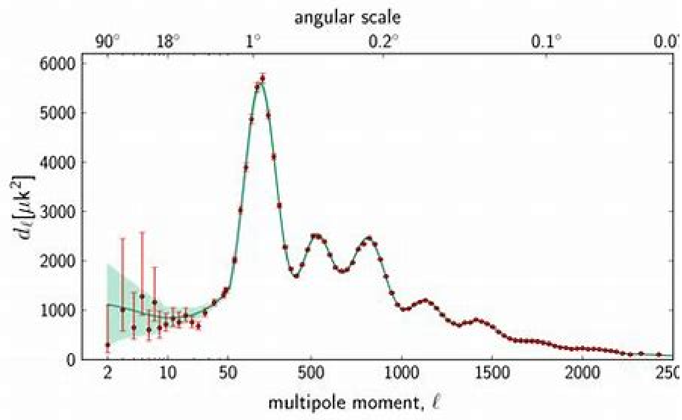
Effective fluid description:

$$\rho_\phi(a) = \frac{2\rho_\phi(a_c)}{\left(\frac{a}{a_c}\right)^{\frac{6n}{n+1}} + 1} \qquad ; \qquad w_\phi(a) = \frac{2n}{n+1}\frac{1}{\left(\frac{a_c}{a}\right)^{\frac{6n}{n+1}} + 1} - 1$$

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 $a \gg a_c$.



Alleviation of the H_0 tension



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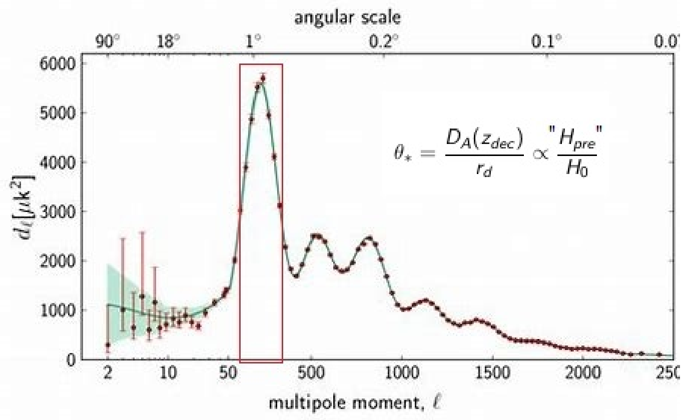

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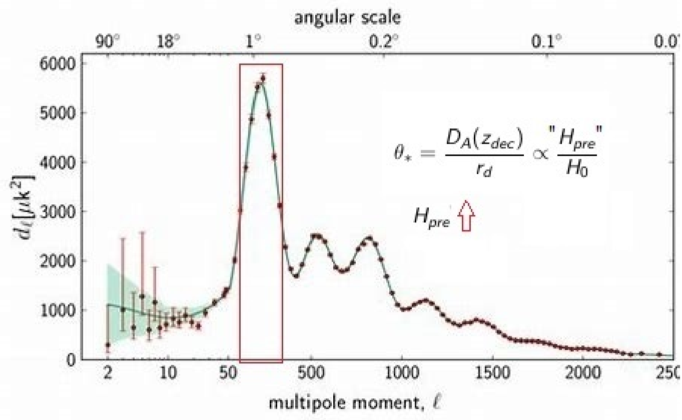

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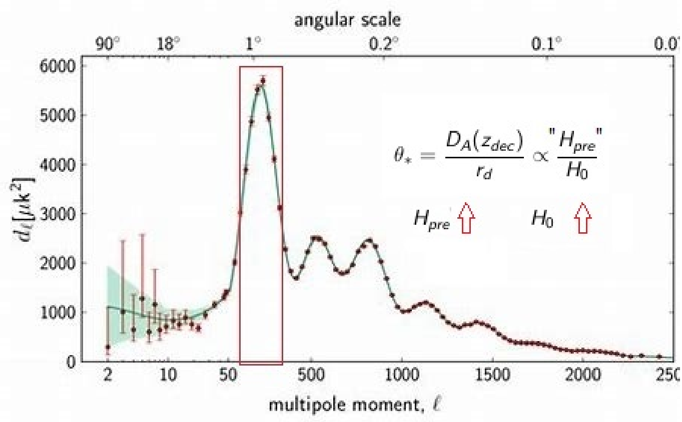

Increase of the σ_8/S_8 tension

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

Parameter	ΛCDM	$n=2$	$n=3$
$100\ \theta_s$	$1.04198\ (1.04213) \pm 0.0003$	$1.04175\ (1.0414)^{+0.00046}_{-0.00064}$	$1.04138\ (1.0414) \pm 0.0004$
$100\ \omega_b$	$2.238\ (2.239) \pm 0.014$	$2.244\ (2.228)^{+0.019}_{-0.022}$	$2.255\ (0.258) \pm 0.022$
$\omega_{\rm cdm}$	$0.1179\ (0.1177) \pm 0.0012$	$0.1248\ (0.1281)^{+0.003}_{-0.0041}$	$0.1272\ (0.1299)_{\pm}0.0045$
$10^9 A_s$	$2.176\ (2.14) \pm 0.051$	$2.185\ (2.230) \pm 0.056$	$2.176\ (2.177) \pm 0.054$
n_s	$0.9686\ (0.9687) \pm 0.0044$	$0.9768\ (0.9828)^{+0.0065}_{-0.0072}$	$0.9812\ (0.9880) \pm 0.0080$
$\tau_{\rm reio}$	$0.075\ (0.068) \pm 0.013$	$0.075\ (0.083) \pm 0.013$	$0.068\ (0.068) \pm 0.013$
$\mathrm{Log}_{10}(a_c)$	–	$-4.136\ (-3.728)^{+0.57}_{-0.013}$	$-3.737\ (-3.696)^{+0.110}_{-0.094}$
$f_{\rm EDE}(a_c)$	–	$0.028\ (0.044)^{+0.011}_{-0.016}$	$0.050\ (0.058)^{+0.024}_{-0.019}$
$r_s(z_{\rm rec})$	$145.05\ (145.1) \pm 0.26$	$141.4\ (139.8)^{+2}_{-1.5}$	$140.3\ (138.9)^{+1.9}_{-2.3}$
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	$68.18\ (68.33) \pm 0.54$	$70.3\ (71.1) \pm 1.2$	$70.6\ (71.6) \pm 1.3$

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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]

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- 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?

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References:

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

The EDEp parametrization

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Useful to define:

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

and

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

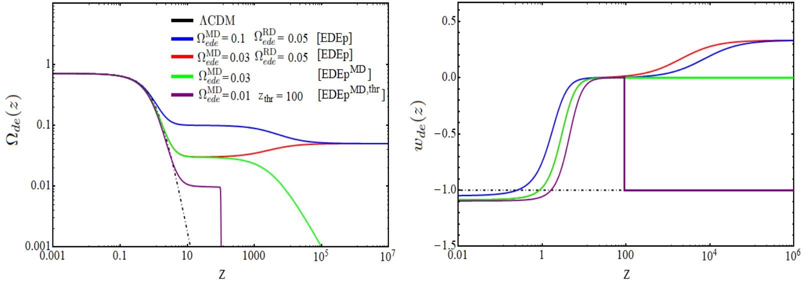
EDEp$^{\mathrm{MD}}$ and EDEp$^{\mathrm{MD},z_{\mathrm{thr}}}$ *parametrizations*

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

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

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

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



The scalar field equivalent

Quintessence energy density and pressure:

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + V \qquad ; \qquad p_\phi = \frac{\dot{\phi}^2}{2} - V \,.$$

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In the RDE:

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

The data sets

- *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, $S_8 = 0.762^{+0.025}_{-0.024}$.

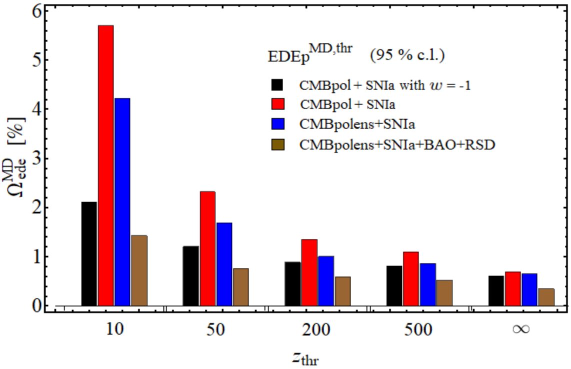
Results with CMBpol+SNIa

Parameter	ΛCDM	wCDM	EDEp	EDEp$^{\rm MD}$
ω_b	$0.02239^{+0.00014}_{-0.00015}$	$0.02237^{+0.00016}_{-0.00015}$	$0.02238^{+0.00017}_{-0.00016}$	$0.02234^{+0.00015}_{-0.00016}$
ω_{cdm}	$0.1199^{+0.0014}_{-0.0013}$	0.1204 ± 0.0014	$0.1218^{+0.0016}_{-0.0015}$	$0.1208^{+0.0014}_{-0.0015}$
τ	$0.055^{+0.007}_{-0.008}$	0.054 ± 0.008	0.054 ± 0.008	$0.053^{+0.007}_{-0.008}$
n_s	0.9659 ± 0.0044	$0.9646^{+0.0044}_{-0.0045}$	$0.9642^{+0.0044}_{-0.0045}$	$0.9642^{+0.0043}_{-0.0046}$
H_0 [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	$0.811^{+0.007}_{-0.008}$	0.823 ± 0.014	$0.817^{+0.014}_{-0.015}$	$0.818^{+0.015}_{-0.014}$
r_d [Mpc]	$147.02^{+0.28}_{-0.32}$	146.92 ± 0.30	$146.18^{+0.66}_{-0.43}$	$146.75^{+0.36}_{-0.30}$
w	-1	$-1.039^{+0.035}_{-0.039}$	$-1.050^{+0.041}_{-0.040}$	$-1.053^{+0.038}_{-0.042}$
$\Omega^{\rm RD}_{ede}$ (%)	0	0	$< 0.91\,(< 2.08)$	0
$\Omega^{\rm MD}_{ede}$ (%)	0	0	$< 0.27\,(< 0.69)$	$< 0.29\,(< 0.69)$

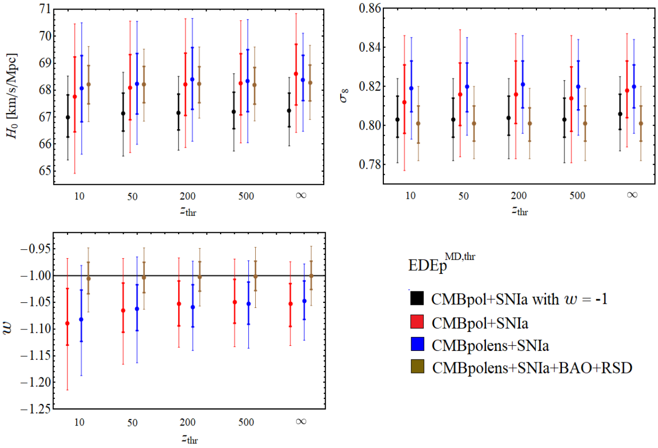
Results with CMBpolens+SNIa+M

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

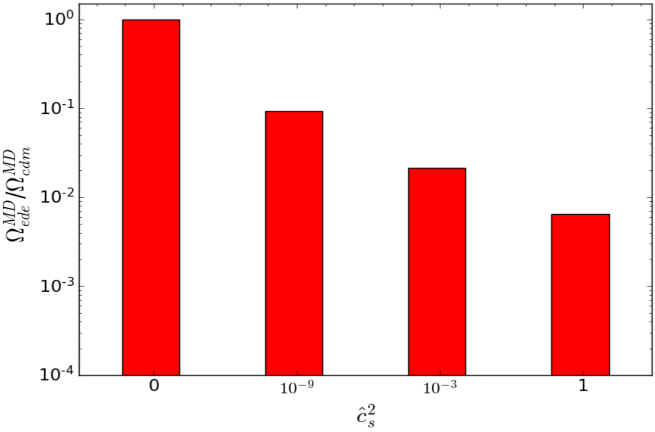
Results for EDEp$^{\mathrm{MD}z_{\mathrm{thr}}}$ (I)



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



The impact of $\hat{c}_s^2$



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

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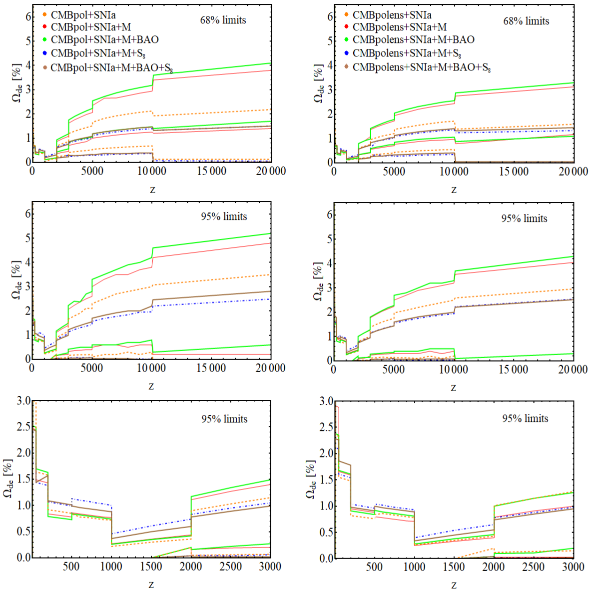
In order to pass the strong constraints on $\Omega_{de}(z_{dec})$ we need to consider a more flexible shape for the latter $\longrightarrow$ Binned $\rho_{de}(z)$, with

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



CMBpol+SNIa
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68% limits
CMBpolens+SNIa
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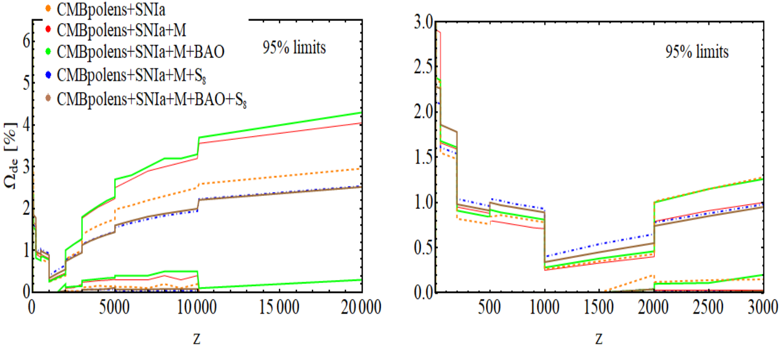
CMBpolens+SNIa+M+BAO+S_8
68% limits
95% limits
95% limits
95% limits
95% limits
Ω_{de} [%]
z


CMBpolens+SNIa
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Ωde [%]
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Parameter	CMBpol+SNIa	CMBpol+SNIa+M	CMBpol+SNIa+M+BAO	CMBpol+SNIa+M+BAO+S_8
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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
n_s	$0.9727^{+0.0072}_{-0.0073}$	$0.9752^{+0.0067}_{-0.0069}$	$0.9760^{+0.0070}_{-0.0071}$	$0.9740^{+0.0061}_{-0.0067}$
H_0 [km/s/Mpc]	$68.29^{+1.26}_{-1.36}$	$70.86^{+1.00}_{-1.10}$	$70.38^{+0.84}_{-0.89}$	$69.85^{+0.76}_{-0.77}$
M	-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	CMBpolens+SNIa+M+BAO+S_8
ω_b	$0.02255^{+0.00020}_{-0.00022}$	$0.02274^{+0.00023}_{-0.00025}$	$0.02277^{+0.00022}_{-0.00024}$	$0.02266^{+0.00021}_{-0.00020}$
ω_{cdm}	$0.1215^{+0.0015}_{-0.0016}$	0.1211 ± 0.0017	0.1214 ± 0.0016	$0.1193^{+0.0013}_{-0.0014}$
τ	0.054 ± 0.008	$0.056^{+0.008}_{-0.009}$	0.056 ± 0.008	$0.055^{+0.008}_{-0.007}$
n_s	$0.9723^{+0.0068}_{-0.0069}$	$0.9748^{+0.0067}_{-0.0071}$	$0.9746^{+0.0068}_{-0.0069}$	$0.9727^{+0.0061}_{-0.0068}$
H_0 [km/s/Mpc]	$68.26^{+1.17}_{-1.27}$	$70.84^{+1.04}_{-1.07}$	$70.21^{+0.80}_{-0.84}$	$70.00^{+0.76}_{-0.73}$
M	$-19.406^{+0.027}_{-0.029}$	$-19.343^{+0.024}_{-0.025}$	-19.355 ± 0.018	-19.362 ± 0.016
σ_8	$0.845^{+0.017}_{-0.020}$	$0.868^{+0.019}_{-0.021}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
S_8	$0.857^{+0.019}_{-0.021}$	$0.848^{+0.020}_{-0.022}$	$0.853^{+0.019}_{-0.020}$	$0.824^{+0.012}_{-0.013}$
σ_{12}	-	$0.831^{+0.015}_{-0.016}$	$0.833^{+0.015}_{-0.016}$	$0.810^{+0.010}_{-0.011}$
S_{12}	-	$0.840^{+0.017}_{-0.020}$	0.843 ± 0.018	$0.815^{+0.011}_{-0.013}$
$r_s(z_d)$ [Mpc]	$145.98^{+0.71}_{-0.53}$	$145.65^{+0.82}_{-0.71}$	$145.51^{+0.83}_{-0.71}$	$146.46^{+0.56}_{-0.44}$
w	$-1.035^{+0.039}_{-0.040}$	$-1.067^{+0.037}_{-0.036}$	$-1.050^{+0.034}_{-0.035}$	-1.045 ± 0.032

Parameter	CMBpolens+SNIa	CMBpolens+SNIa+M+BAO	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 [km/s/Mpc]	$68.26^{+1.17}_{-1.27}$	$70.21^{+0.80}_{-0.84}$	$70.00^{+0.76}_{-0.73}$
M	$-19.406^{+0.027}_{-0.029}$	-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]	$145.98^{+0.71}_{-0.53}$	$145.51^{+0.83}_{-0.71}$	$146.46^{+0.56}_{-0.44}$
w	$-1.035^{+0.039}_{-0.040}$	$-1.050^{+0.034}_{-0.035}$	-1.045 ± 0.032

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n_s	$0.9723^{+0.0068}_{-0.0069}$	$0.9746^{+0.0068}_{-0.0069}$	$0.9727^{+0.0061}_{-0.0068}$
H_0 [km/s/Mpc]	$\boxed{68.26^{+1.17}_{-1.27}}$	$\boxed{70.21^{+0.80}_{-0.84}}$	$\boxed{70.00^{+0.76}_{-0.73}}$
	2.77 sigma	1.95 sigma	2.13 sigma
σ_8	$0.845^{+0.017}_{-0.020}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
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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
M	$-19.406^{+0.027}_{-0.029}$	-19.355 ± 0.018	-19.362 ± 0.016
σ_8	$0.845^{+0.017}_{-0.020}$	$0.864^{+0.019}_{-0.021}$	$0.839^{+0.013}_{-0.0215}$
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- We have studied these tensions in terms of M and s_{12}/S_{12}.

Thanks for your attention!