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arXiv: 2606.11368

GGI workshop:
Exploring New Frontiers in Cosmology
10 July, Florence

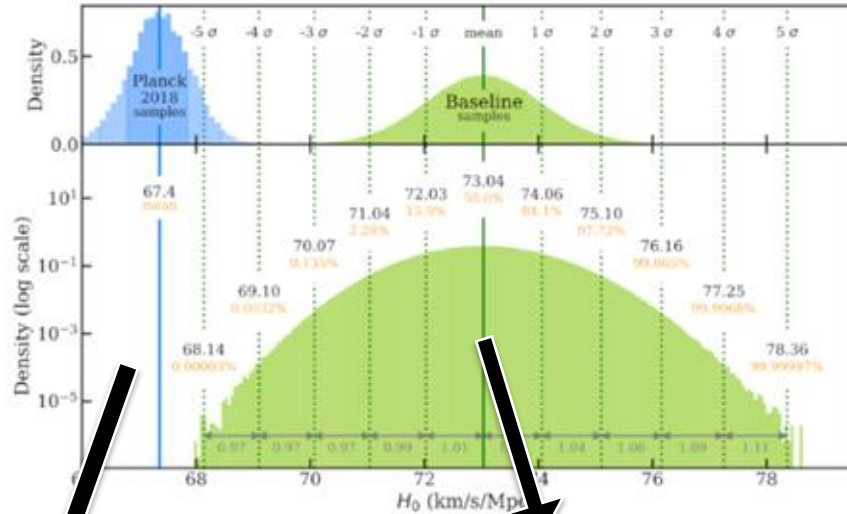
Non-linear Structure of Interacting Dark Energy Model

Based on work with Eleonora Di Valentino, Carsten van de Bruck,
Baojiu Li, and Rafael Nunes.

OUTLINE

- Motivation: cosmological tensions
- The Interacting Dark Energy model
- Constraints from Bayesian analysis with CMB
- N-body simulations: method and results
- Conclusions

Hubble tension



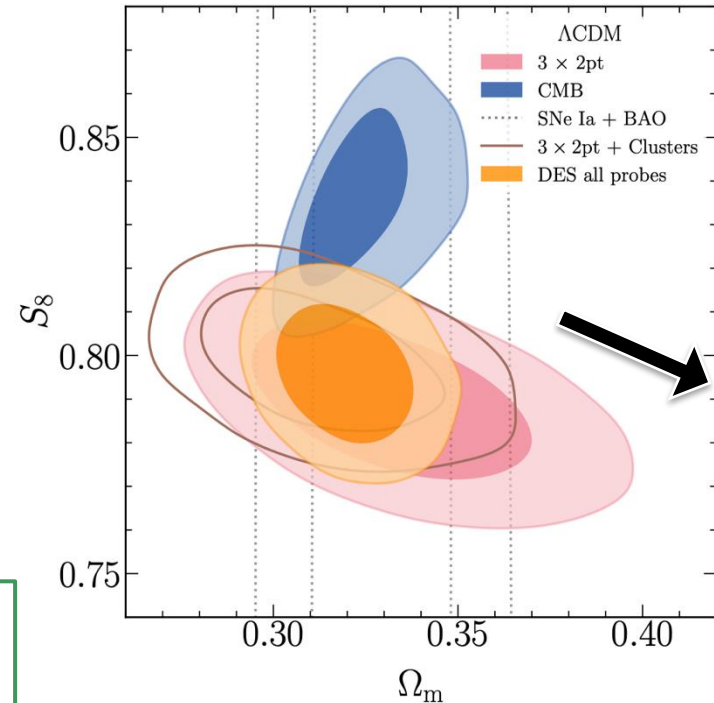
Riess et al. ApJL 934 (2021)

Assuming a Λ CDM cosmological model:
 $H_0 = 67.27 \pm 0.60$
 km/s/Mpc

SH0ES collaboration, directly
 measuring the distance ladder:
 $H_0 = 73.04 \pm 1.04$ km/s/Mpc

S8 tension

$$S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$$



DES Collaboration: T.M.C. Abbott et al. (2026)

2.8 σ
 tension

INTERACTING DARK ENERGY MODEL

- Energy-momentum conservation:

$$\nabla_{\mu} T_{DM}^{\mu}{}_{\nu} = + \frac{Q(v_{DM})_{\nu}}{a}$$

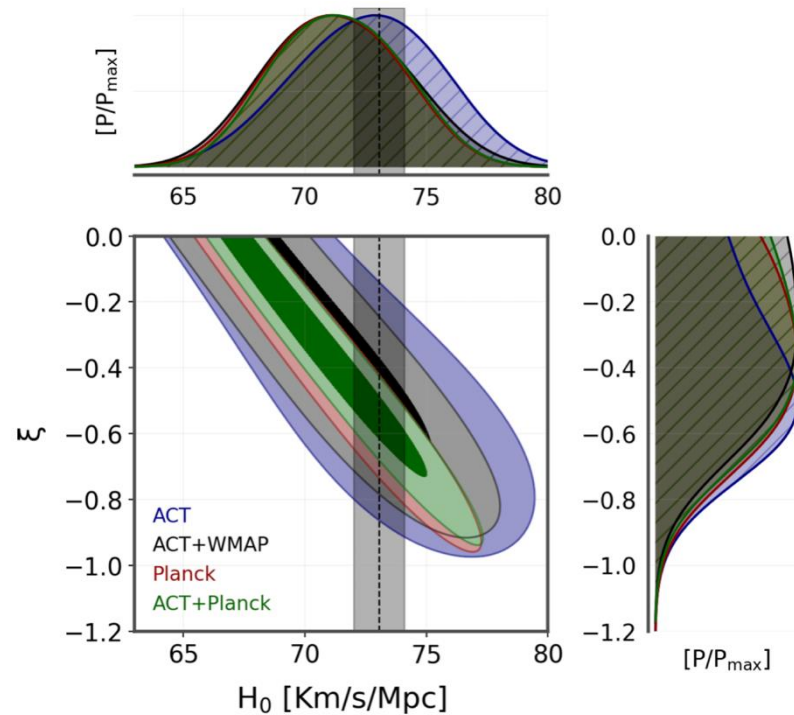
$$\nabla_{\mu} T_{DE}^{\mu}{}_{\nu} = - \frac{Q(v_{DM})_{\nu}}{a}$$

with energy density transfer rate:

$$Q = \xi H \rho_{DE}$$

Gavela et al. JCAP 07 (2009) 034

- $\xi < 0$ corresponds to energy transfer:
dark matter $\longrightarrow$ dark energy



Y Zhai et al. JCAP 07 (2023) 032

DATA & METHOD

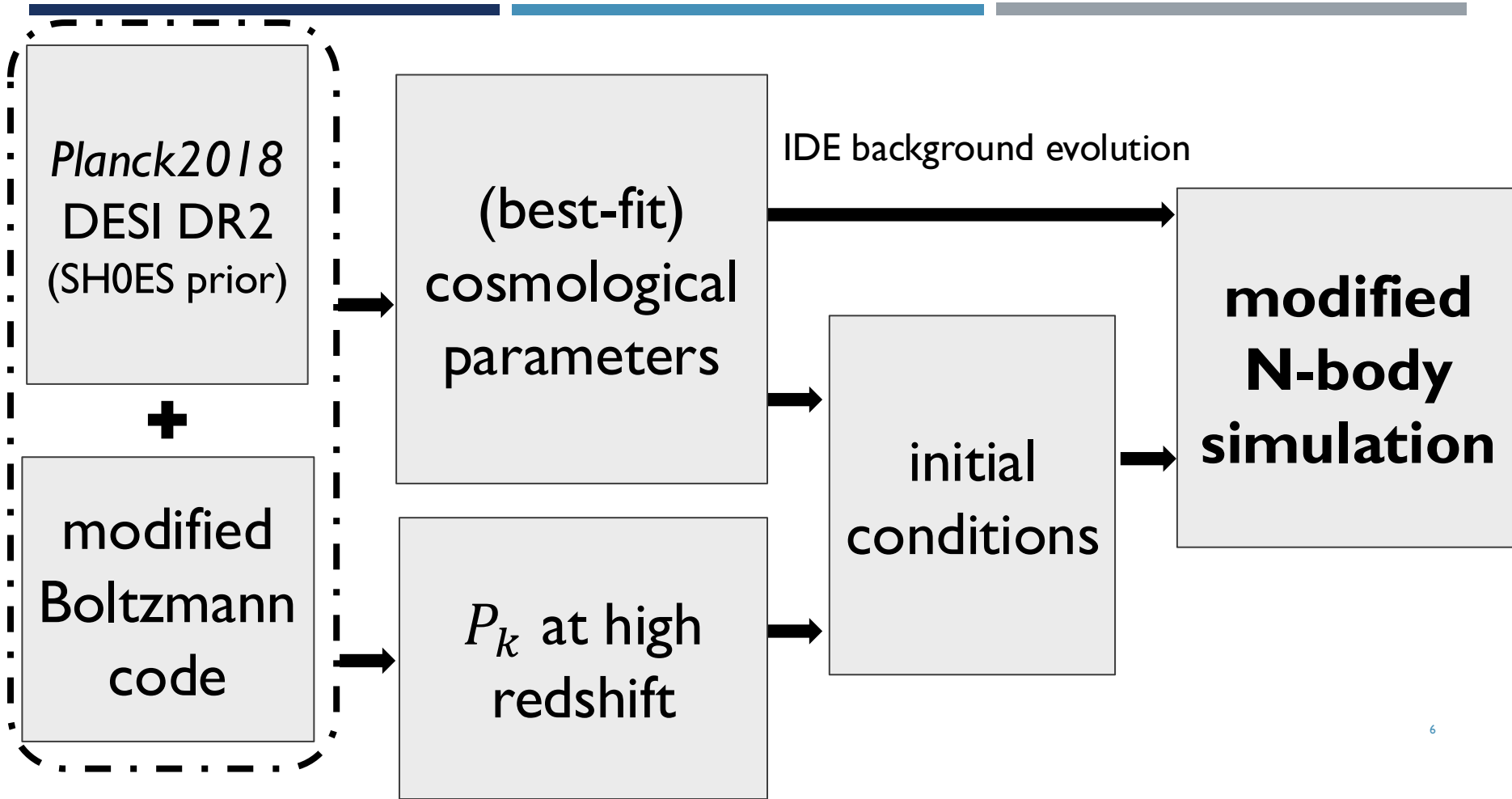
RAMSES: N-body simulation code

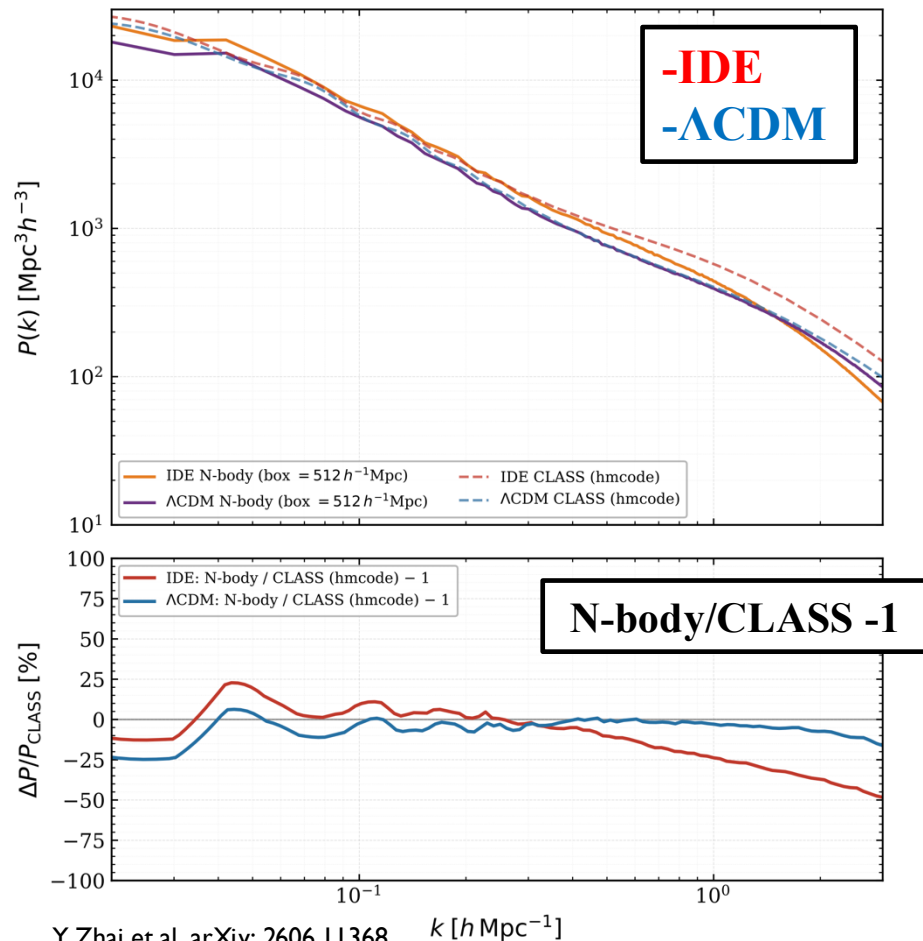
github.com/ramses-organisation/ramses.git

- Developed based on its predecessor ART
- Tree-based Adaptive Mesh Refinement technique

RAMSES N-body runs with two settings:

	Preliminary runs (A)	Production runs (B)
Periodic box	$256^3 (Mpc/h)^3$	$512^3 (Mpc/h)^3$
Particles	256^3	512^3





MATTER POWER SPECTRUM

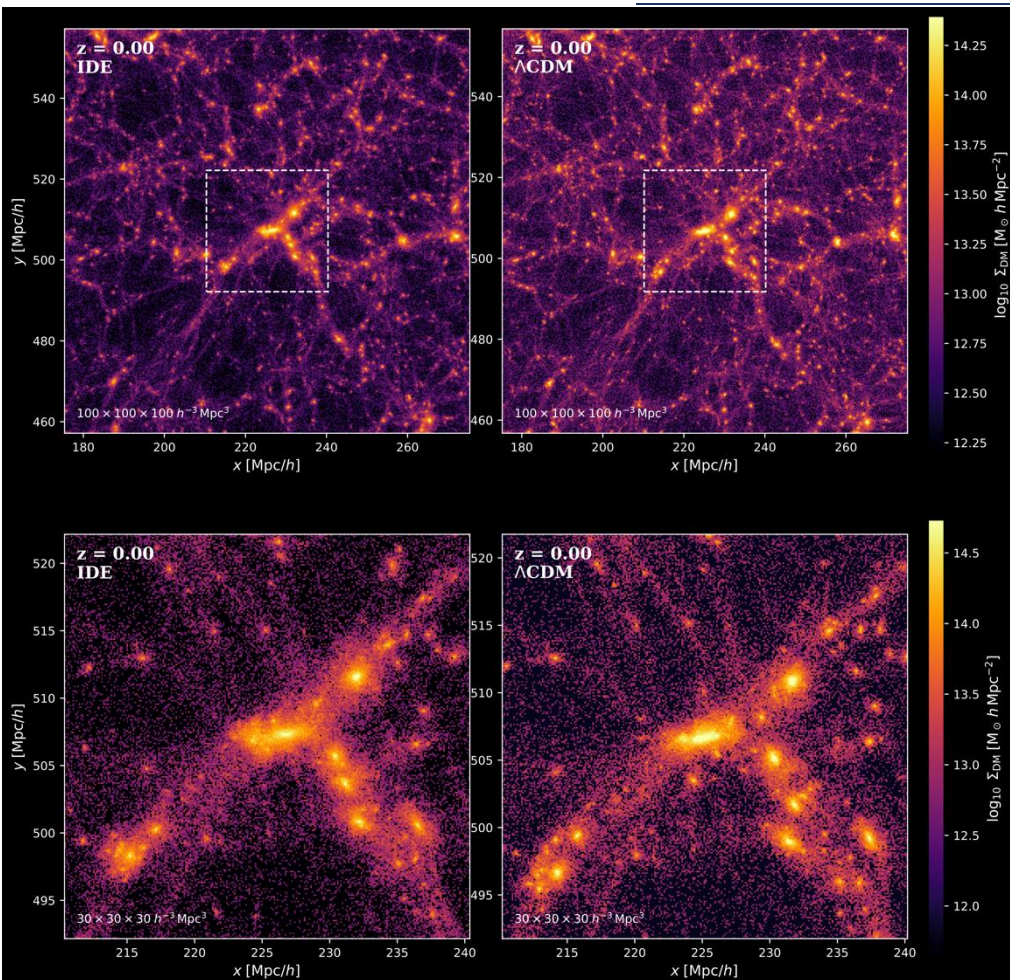
- The IDE matter power spectrum is enhanced on large scales ($\lesssim 20\%$) but suppressed on quasi-linear and non-linear scales (up to $\sim 50\%$);
- HMCode predictions deviate from N-body results, with the deviation growing toward small scales.

DARK MATTER DENSITY MAP

- With significantly lower Ω_m , IDE model forms the same filamentary structure but is less concentrated around dense regions;
- IDE predicts fewer halos at all resolved masses;
- Λ CDM peak density ~ 3.5 times larger than IDE peak density.

100 Mpc/h

30 Mpc/h



CONCLUSIONS

- We performed N-body simulations for the IDE model with interaction rate $Q = \xi H \rho_{DE}$, with best-fit parameters from *Planck 2018*, DESI DR2 and SH0ES prior.
- We adapted full IDE modifications to the pipeline from initial conditions to the RAMSES code.
- The large-scale matter clustering is enhanced in the IDE scenario but suppressed on quasi-linear and non-linear scales.
- The S8 constraints on IDE depend sensitively on the non-linear modelling. Model-consistent treatments are needed.

CONSTRAINTS FROM DIFFERENT DATASETS

CMB

Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031} (< 0.115)$	$< 0.0754 (< 0.111)$	$0.070^{+0.046}_{-0.021} (< 0.117)$	$0.067^{+0.042}_{-0.030} (< 0.115)$
H_0	71.6 ± 2.1	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
τ_{reio}	0.0534 ± 0.0079	0.063 ± 0.015	0.061 ± 0.014	0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.042 ± 0.016	3.046 ± 0.030	3.064 ± 0.028	3.047 ± 0.014
n_s	0.9655 ± 0.0045	1.010 ± 0.016	$0.9741^{+0.0066}_{-0.0064}$	0.9699 ± 0.0038
ξ	$-0.40^{+0.23}_{-0.20}$	$-0.46^{+0.20}_{-0.28}$	$-0.38^{+0.35}_{-0.14}$	$-0.40^{+0.27}_{-0.23}$
S_8	$1.10^{+0.19}_{-0.35}$	$1.18^{+0.26}_{-0.38}$	$1.08^{+0.19}_{-0.31}$	$1.09^{+0.19}_{-0.34}$
$\ln \mathcal{B}_{ij}$	-0.17	-0.07	0.06	-0.25

Y Zhai et al. JCAP 07 (2023) 032

Negative Bayes factor: IDE is preferred over Λ CDM

CMB+DESI

Parameter	Planck-2018+DESI
$\Omega_b h^2$	$0.02243 \pm 0.00014 (0.02243^{+0.00028}_{-0.00026})$
$\Omega_c h^2$	$0.079^{+0.025}_{-0.016} (0.079^{+0.037}_{-0.042})$
$100\theta_s$	$1.04198 \pm 0.00029 (1.04198^{+0.00056}_{-0.00056})$
τ_{reio}	$0.0555 \pm 0.0074 (0.055^{+0.015}_{-0.014})$
n_s	$0.9672 \pm 0.0037 (0.9672^{+0.0073}_{-0.0072})$
$\log(10^{10} A_s)$	$3.045 \pm 0.014 (3.045^{+0.029}_{-0.028})$
ξ	$-0.32^{+0.18}_{-0.14} (-0.32^{+0.30}_{-0.29})$
H_0 [km/s/Mpc]	$70.8^{+1.4}_{-1.7} (70.8^{+2.8}_{-2.7})$
Ω_m	$0.206^{+0.056}_{-0.044} (0.206^{+0.090}_{-0.096})$
σ_8	$1.23^{+0.14}_{-0.36} (1.23^{+0.74}_{-0.52})$
r_{drag} [Mpc]	$147.28 \pm 0.23 (147.28^{+0.45}_{-0.45})$
$\Delta\chi^2$	-1.02
$\ln \mathcal{B}_{ij}$	-0.10

10

W Giarè et al. Phys. Rev. Lett. 133, 251003

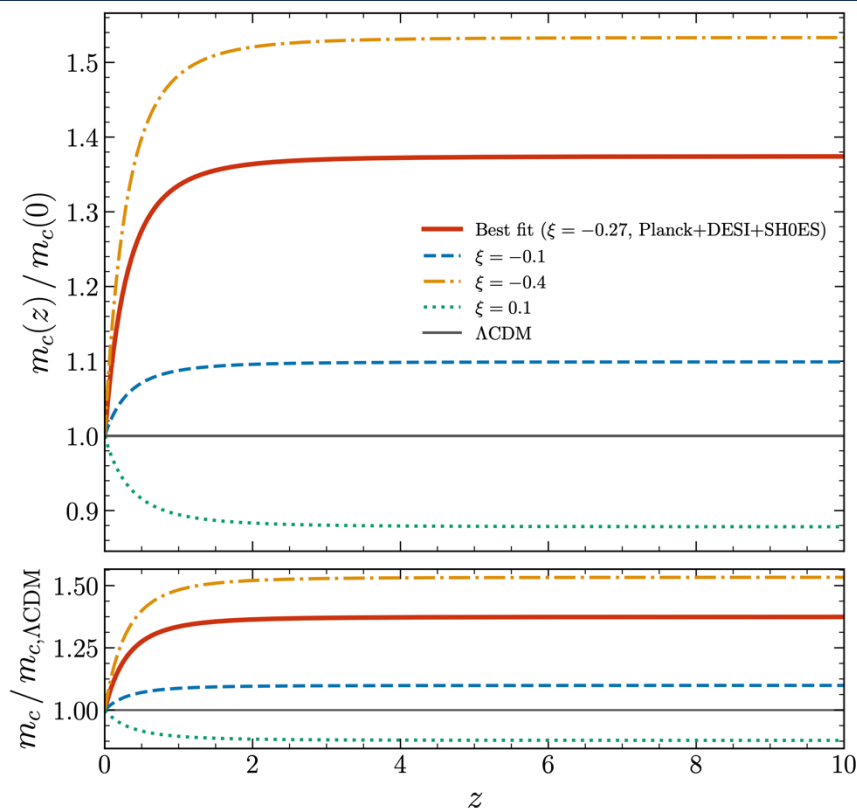
What can be simplified in the N-body simulation pipeline?

- Dark energy clustering can be safely neglected since:

$$\beta(k, z) \equiv \frac{\rho_{DE}}{\rho_{DM}} \frac{\delta_{DE}}{\delta_{DM}} \ll 1$$

- This allows us to treat DE as a smooth component and only simulate DM particles.
- We simulate the DM particles by rescaling mass of each particle at redshift z by:

$$\frac{m_c(z)}{m_c(z=0)}$$



COSMOLOGICAL SETTINGS FOR IDE AND Λ CDM RUNS

Model	IDE	Λ CDM
[setup]		
starting redshift	49	49
ℓ_{min} (coarse level)	8	8
ℓ_{max} (fine level)	16	14 to 16
[cosmology]		
Ω_m	0.2191	0.3158
Ω_Λ	0.7809	0.6842
$\ln 10^{10} A_s$	3.0395	3.0448
n_s	0.9701	0.9661
ξ	-0.27	-
$H_0(\text{km s}^{-1} \text{Mpc}^{-1})$	70.63	67.32
σ_8	1.0674	0.8120

While reported for completeness, σ_8 is not directly used as an input parameter in the N-body simulations.