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arXiv: 2606.11368

GGI workshop
20 July, Florence, Italy

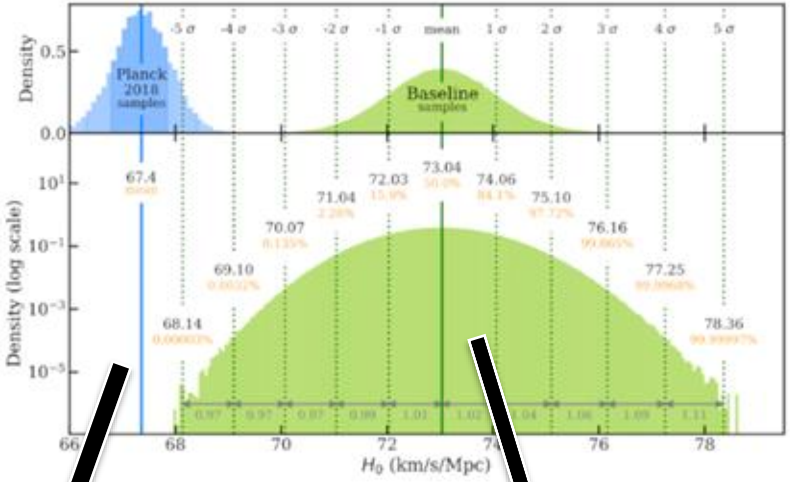
Non-linear Structure of Interacting Dark Energy Model

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

OUTLINE

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

Hubble tension

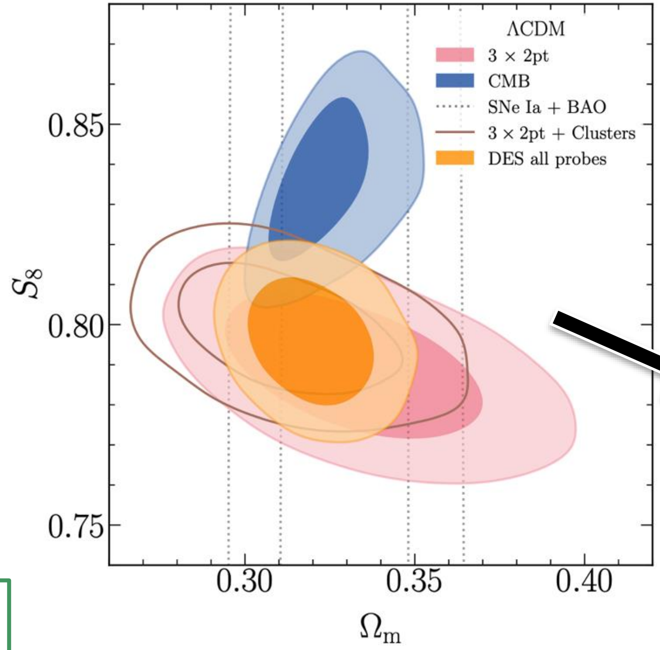


Riess et al. ApJL 934 (2021)

Assuming a ΛCDM cosmological model: H0 = 67.27 ± 0.60 km/s/Mpc

SH0ES collaboration, directly measuring the distance ladder: H0 = 73.04 ± 1.04 km/s/Mpc

S8 tension $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$



2.8σ tension

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

INTERACTING DARK ENERGY MODEL

- Energy-momentum conservation:

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

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

with energy density transfer rate:

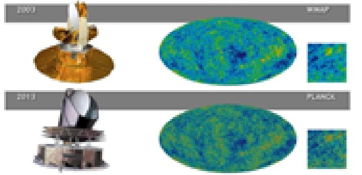
$$Q = \xi H \rho_{DE}$$

- $\xi < 0$ corresponds to energy transfer:

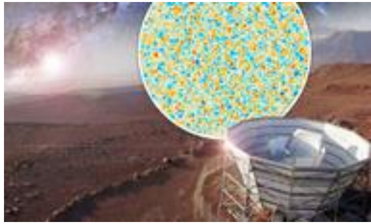
Dark matter ➡ dark energy

Gavela et al. JCAP 07 (2009) 034

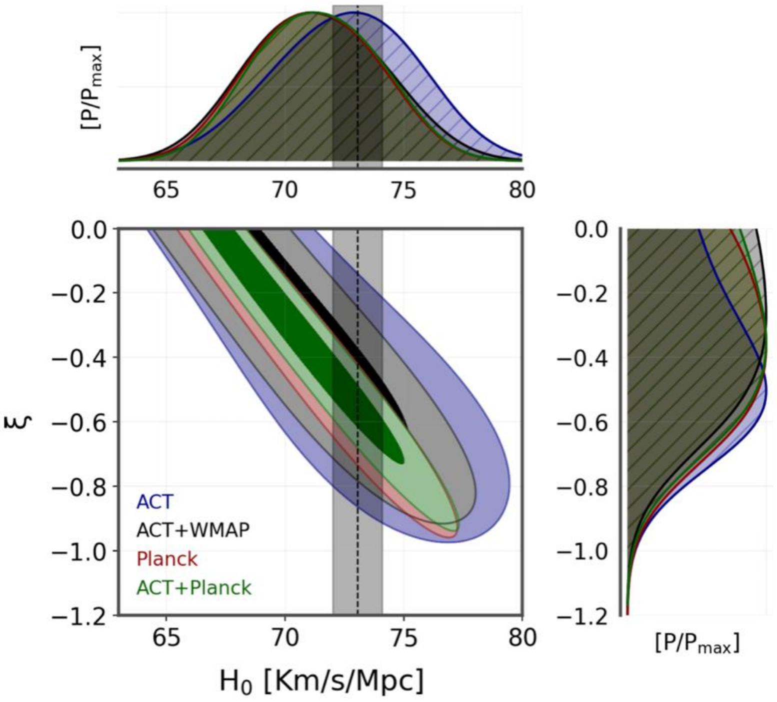
A consistent view across all CMB probes

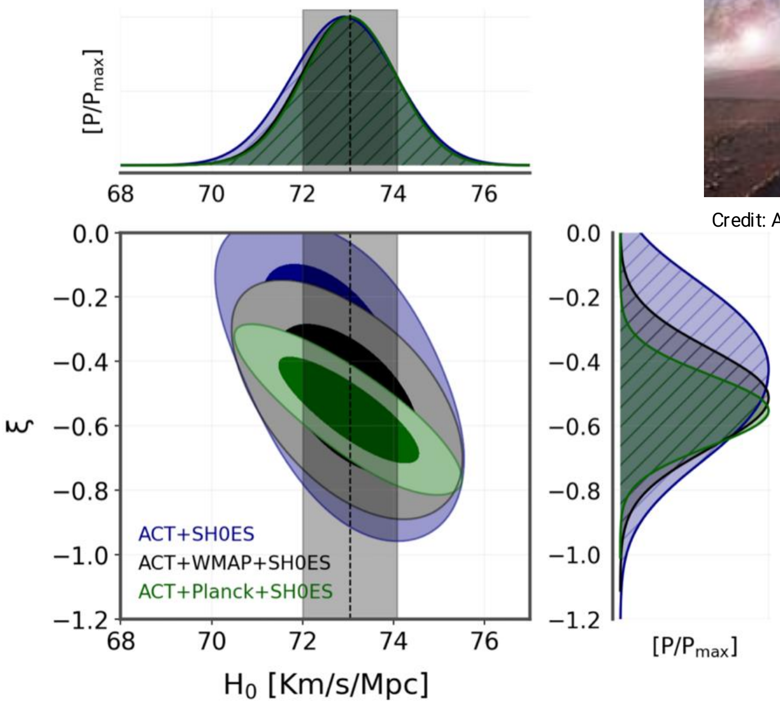


Credit: NASA / LAMBDA Archive Team



Credit: ACT Collaboration/Debra Kellner





Y Zhai et al. JCAP 07 (2023) 032

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	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
$\tau_{\rm reio}$	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

CMB+DESI

Parameter	Planck-2018+DESI
$\Omega_b h^2$	$0.02243 \pm 0.00014\,(0.02243^{+0.00028}_{-0.00026})$
$\Omega_c h^2$	$0.079^{+0.025}_{-0.016}\,(0.079^{+0.037}_{-0.042})$
$100\theta_s$	$1.04198 \pm 0.00029\,(1.04198^{+0.00056}_{-0.00056})$
$\tau_{\rm reio}$	$0.0555 \pm 0.0074\,(0.055^{+0.015}_{-0.014})$
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	$1.23^{+0.14}_{-0.36}\,(1.23^{+0.74}_{-0.52})$
$r_{\rm drag}$ [Mpc]	$147.28 \pm 0.23\,(147.28^{+0.45}_{-0.45})$
$\Delta\chi^2$	-1.02
$\ln \mathcal{B}_{ij}$	-0.10

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

Negative Bayes factor: IDE is preferred over ΛCDM

Move forward to non-linear scales

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

initial conditions, cosmological parameters → dark-matter N-body simulation

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

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

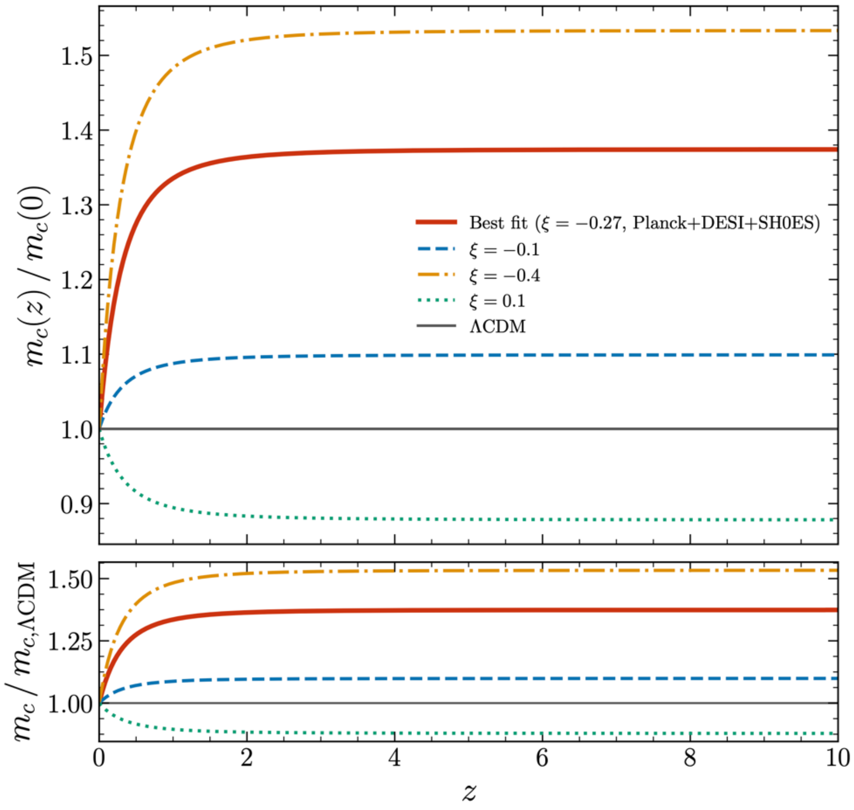
- Dark energy clustering can be safely neglected since:

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

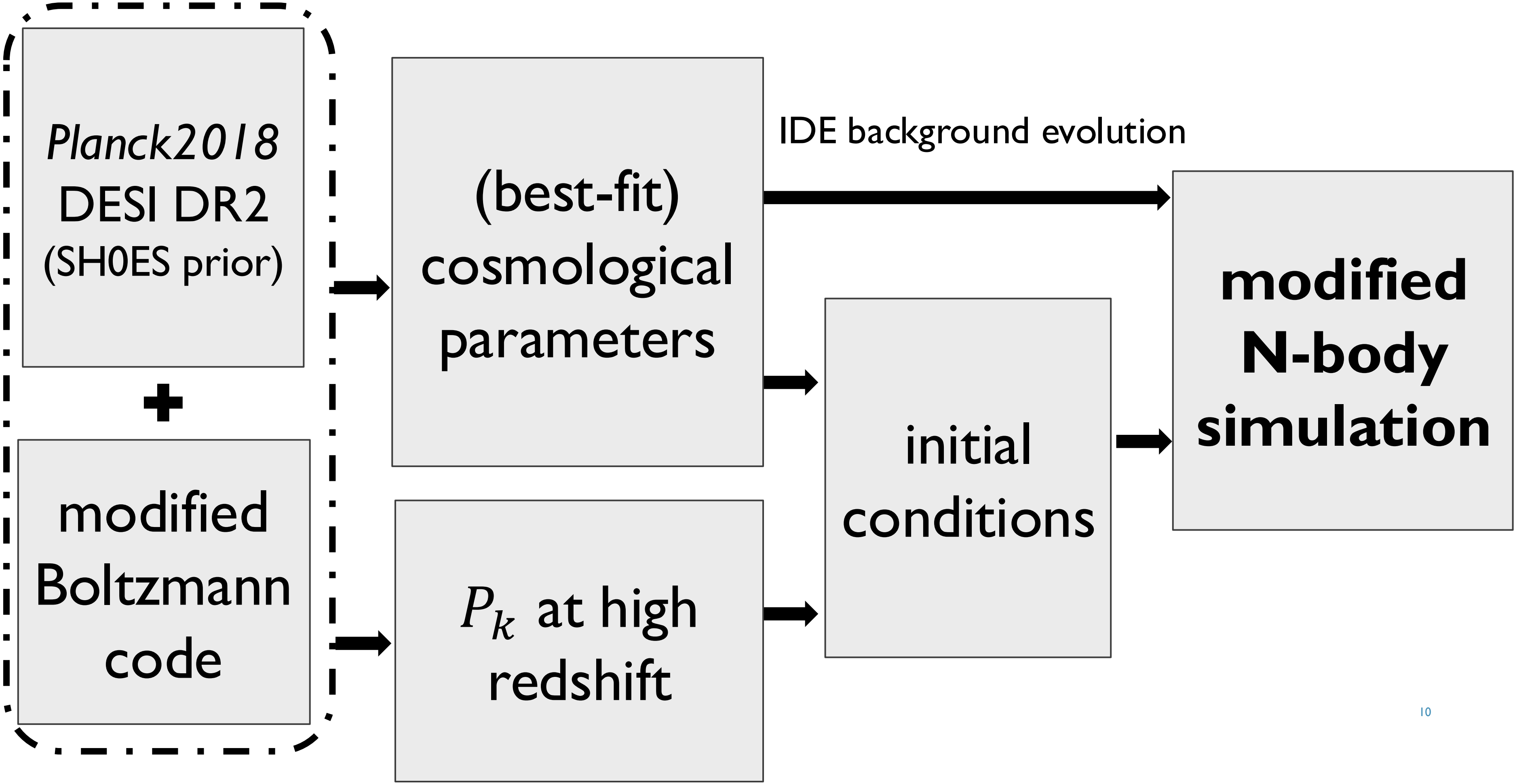
- This allows us to treat DE as a smooth component and only simulate DM particles.

- We simulate the DM particles by rescaling mass of each particle at redshift z by:

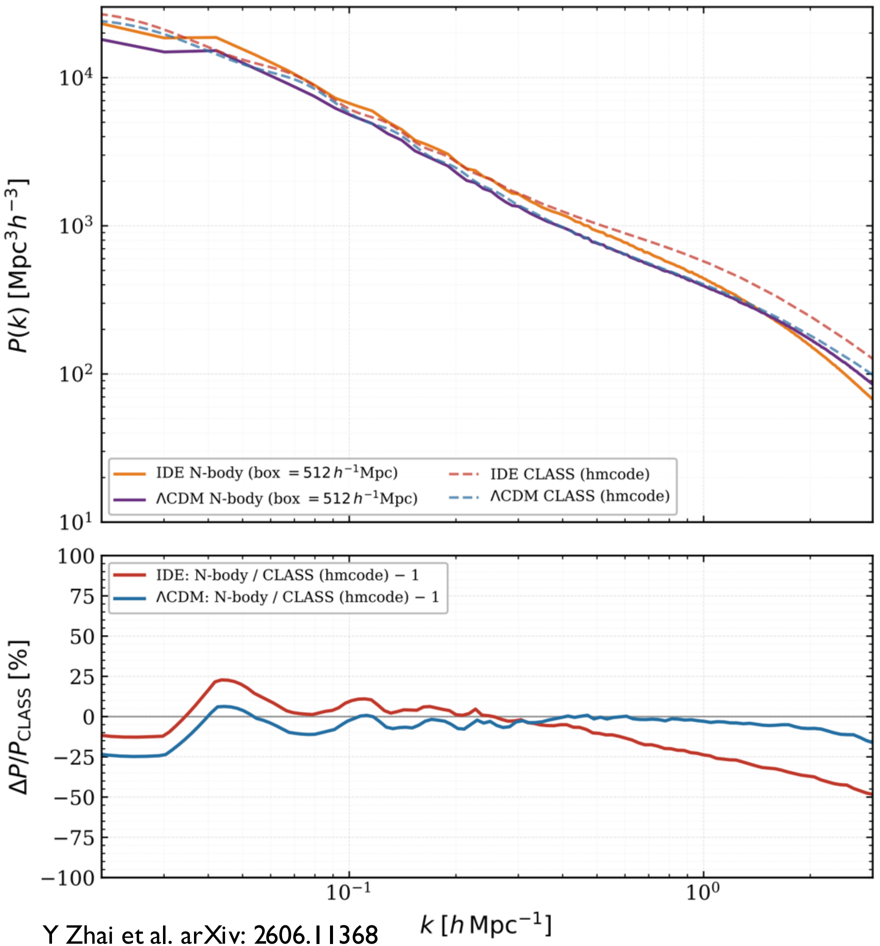
$$\frac{m_c(z)}{m_c(z=0)}$$



Y Zhai et al. arXiv: 2606.11368



Planck2018
DESI DR2
(SH0ES prior)
+
modified
Boltzmann
code
(best-fit)
cosmological
parameters
P_k at high
redshift
IDE background evolution
initial
conditions
modified
N-body
simulation



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MATTER POWER SPECTRUM

- The IDE matter power spectrum is enhanced on large scales but suppressed on quasi-linear and non-linear scales;
- HMCode predictions deviate from N-body results, with the deviation growing toward small scales.

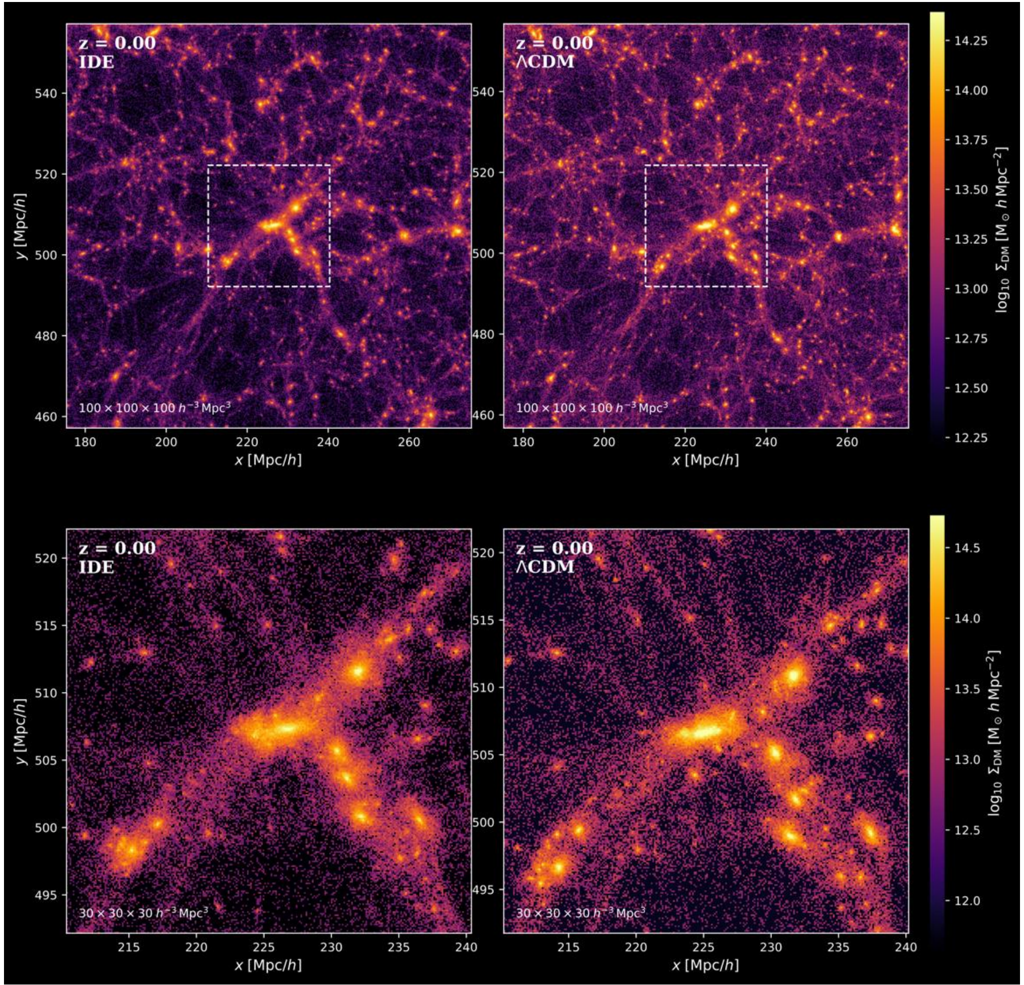
DARK MATTER DENSITY MAP

- 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;
- ΛCDM peak density ~3.5 times larger than IDE peak density.

z=0 snapshots

100Mpc/h

30Mpc/h



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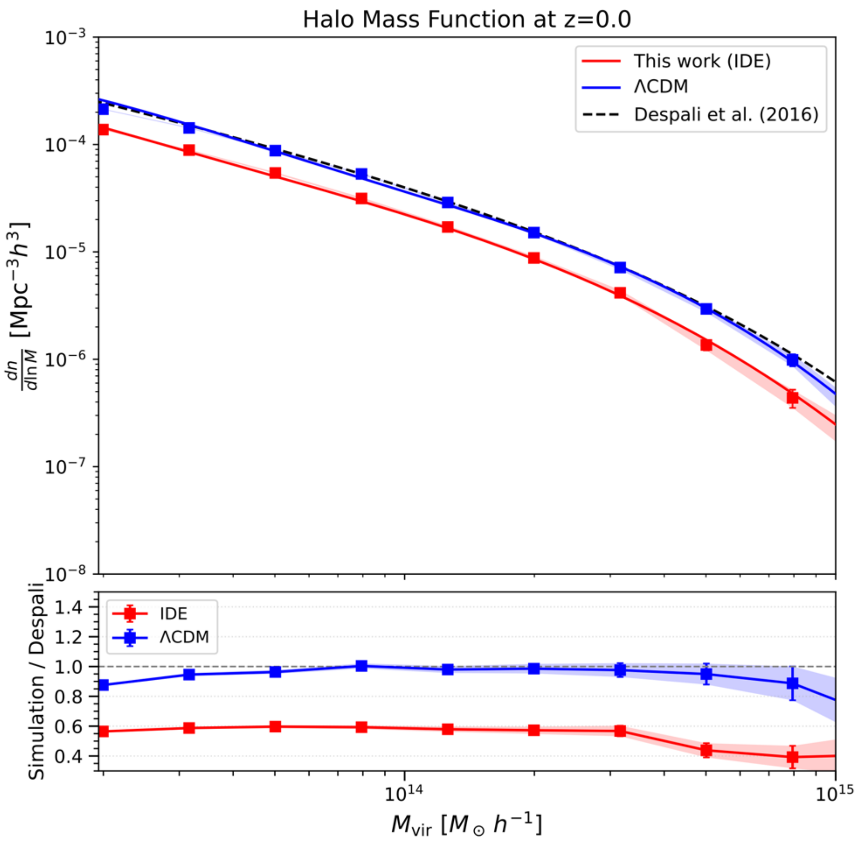

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HALO MASS FUNCTION

- The suppression is much stronger at the high-mass end;
- The suppression is consistent across the high-mass range of halos (~40%);
- This is the result of the ~27% cumulative mass transfer from DM to DE.

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.

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Thank you for your attention

COSMOLOGICAL SETTINGS FOR IDE AND ΛCDM RUNS

Model	IDE	ΛCDM
[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	-
$H_0(\mathrm{km}\ s^{-1} Mpc^{-1})$	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.