Evolution of clustering in cosmological models with time-varying dark energy

Tomoaki Ishiyama (Chiba University)
Francisco Prada (The Instituto Astrofísica Andalucía, CSIC)
Anatoly Klypin (University of Virginia)

Ishiyama, Prada, Klypin, 2025, PRD

Cosmological constraints from the DESI Y1

DESI collaboration, 2025

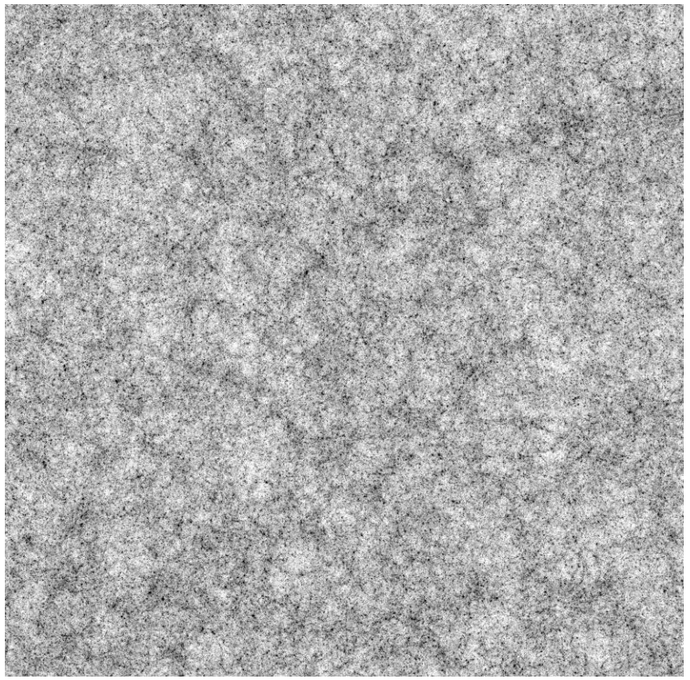
- Spectroscopy galaxy / QSO survey at 0.1< z< 4.2
  - 7,500 deg^2
  - 6 million objects
- Cosmology constraint by baryon acoustic oscillation signal
  → Preference of time-varying dark energy (dynamical dark energy: DDE)
- DESI DR2 (DESI Y3) gives consistent results (arXiv:2503.14738)

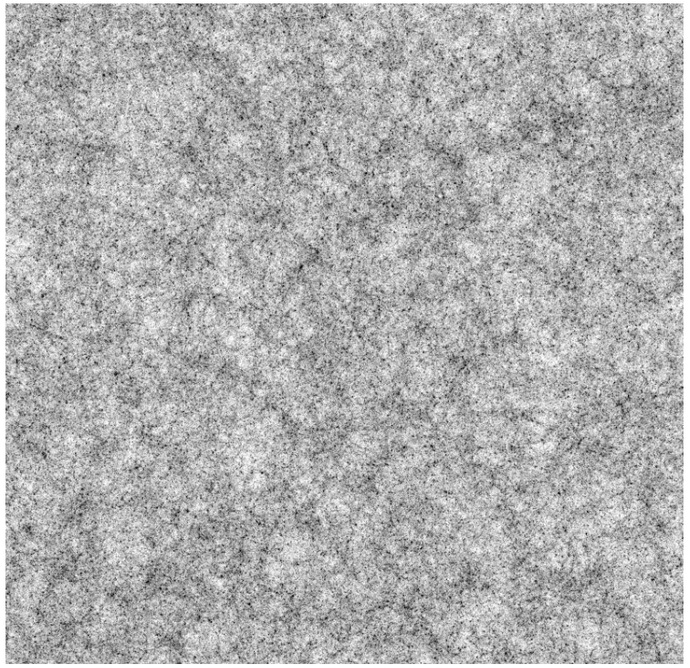
model/dataset	Ω_m	H_0 $[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	$10^3\Omega_K$	w or w_0	w_a
Flat ΛCDM					
DESI	0.295 ± 0.015	—	—	—	—
DESI+BBN	0.295 ± 0.015	68.53 ± 0.80	—	—	—
DESI+BBN+θ_*	0.2948 ± 0.0074	68.52 ± 0.62	—	—	—
DESI+CMB	0.3069 ± 0.0050	67.97 ± 0.38	—	—	–
w_0w_aCDM					
DESI	$0.344^{+0.047}_{-0.026}$	—	—	$-0.55^{+0.39}_{-0.21}$	< -1.32
DESI+BBN+θ_*	$0.338^{+0.039}_{-0.029}$	$65.0^{+2.3}_{-3.6}$	—	$-0.53^{+0.42}_{-0.22}$	< -1.08
DESI+CMB	$0.344^{+0.032}_{-0.027}$	$64.7^{+2.2}_{-3.3}$	—	$-0.45^{+0.34}_{-0.21}$	$-1.79^{+0.48}_{-1.0}$
DESI+CMB+Panth.	0.3085 ± 0.0068	68.03 ± 0.72	—	-0.827 ± 0.063	$-0.75^{+0.29}_{-0.25}$
DESI+CMB+Union3	0.3230 ± 0.0095	66.53 ± 0.94	—	-0.65 ± 0.10	$-1.27^{+0.40}_{-0.34}$
DESI+CMB+DESY5	0.3160 ± 0.0065	67.24 ± 0.66	—	-0.727 ± 0.067	$-1.05^{+0.31}_{-0.27}$

$$w(a) = w_0 + w_a(1-a) \qquad \left[\frac{H(a)}{H_0}\right]^2 = \frac{\Omega_0}{a^3} + \frac{\lambda_0}{a^{3(1+w_a+w_0)}} \exp(-3w_a(1-a))$$

This work

- Investigate the effect of dynamical dark energy on various statistics of large scale structures using large cosmological N-body simulations
  - power spectrum
  - mass function
  - correlation function
  - BAO analysis
- The first BAO analysis based on cosmological simulations with DESY DDE cosmology





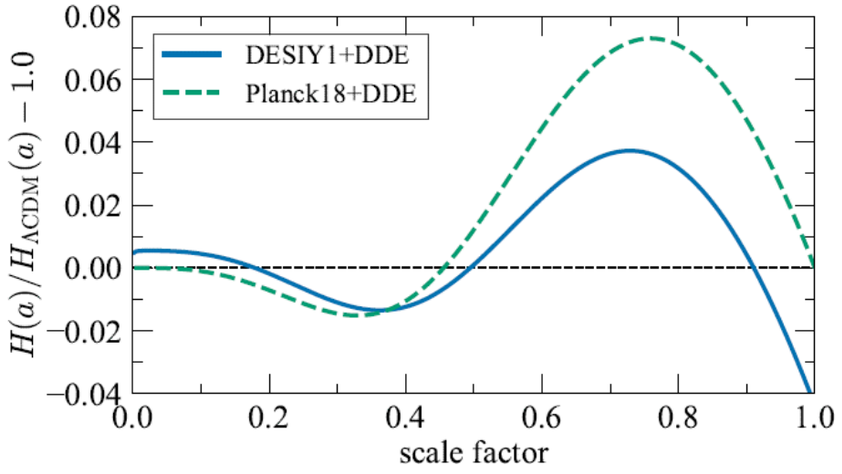
Simulation

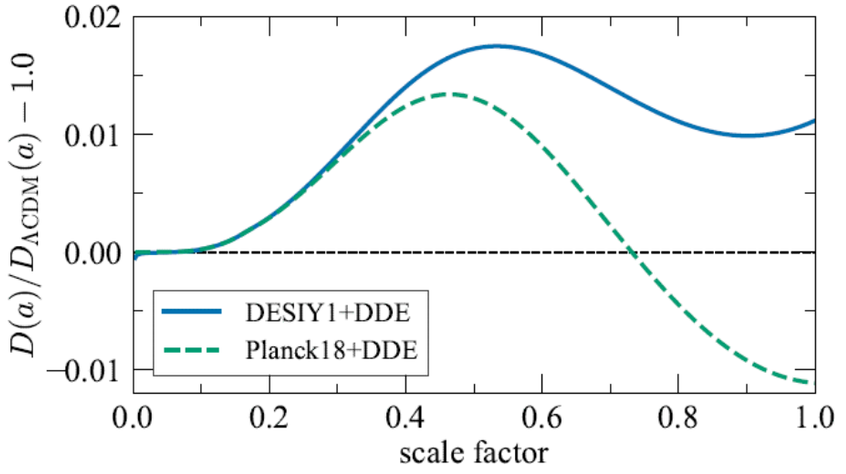
Ishiyama, Prada, Klypin, 2025, PRD)

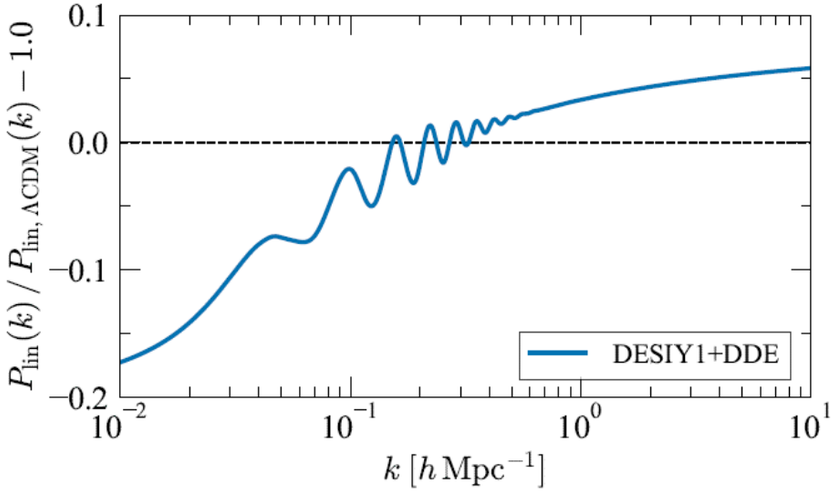
- N=4096^3, L= 2.0 Gpc/h, n_s = 0.9665, σ_8 = 0.8102
- particle mass = 1.0 or 1.1 x 10^{10} Msun/h
- monofonIC (Michaux+2021) 3LPT IC (z=24)
- GreeM (Ishiyama+ 2009, 2012, 2022) TreePM poisson solver
- MPI-Rockstar (Behroozi+2013, Tokuue+2024) halo/subhalo finder
- Supercomputer Fugaku
- Halo catalogs are available (https://skun.iaa.csic.es/SUsimulations/DDE/)

Parameter	Planck18	Planck18+DDE	DESIY1+DDE
Ω_0	0.3111	0.3111	0.3440
h	0.6766	0.6766	0.6470
w_0	-1.0	-0.45	-0.45
w_a	0.0	-1.79	-1.79
z_d	1060.02	1060.02	1055.70
r_d $[h^{-1}\mathrm{Mpc}]$	99.61	99.61	96.05

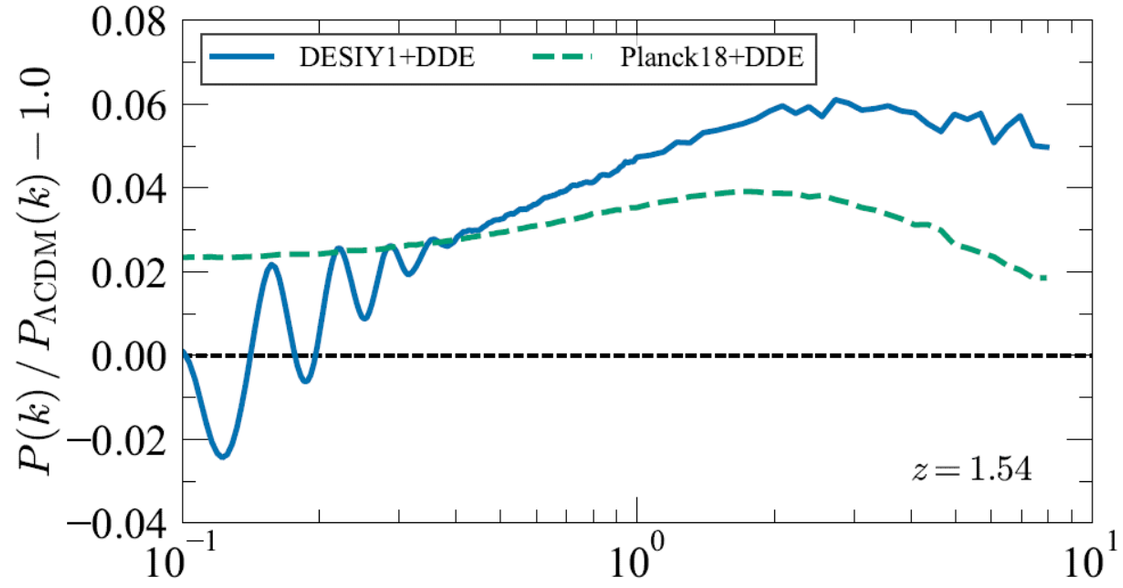
Same initial seed, cosmic variance free in the comparison

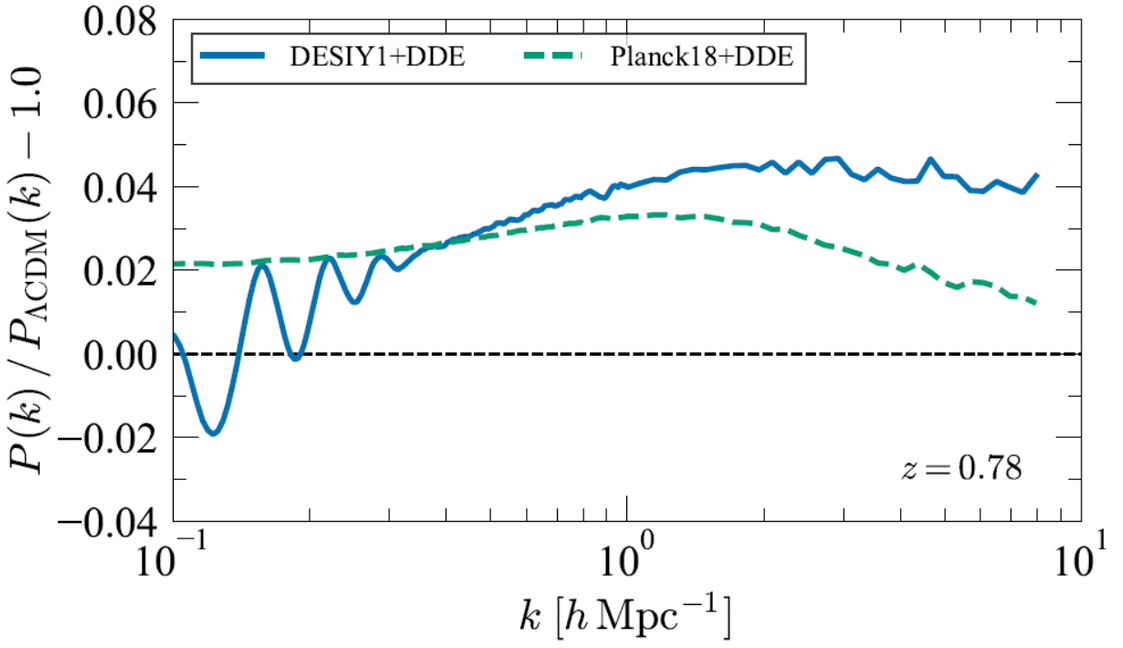


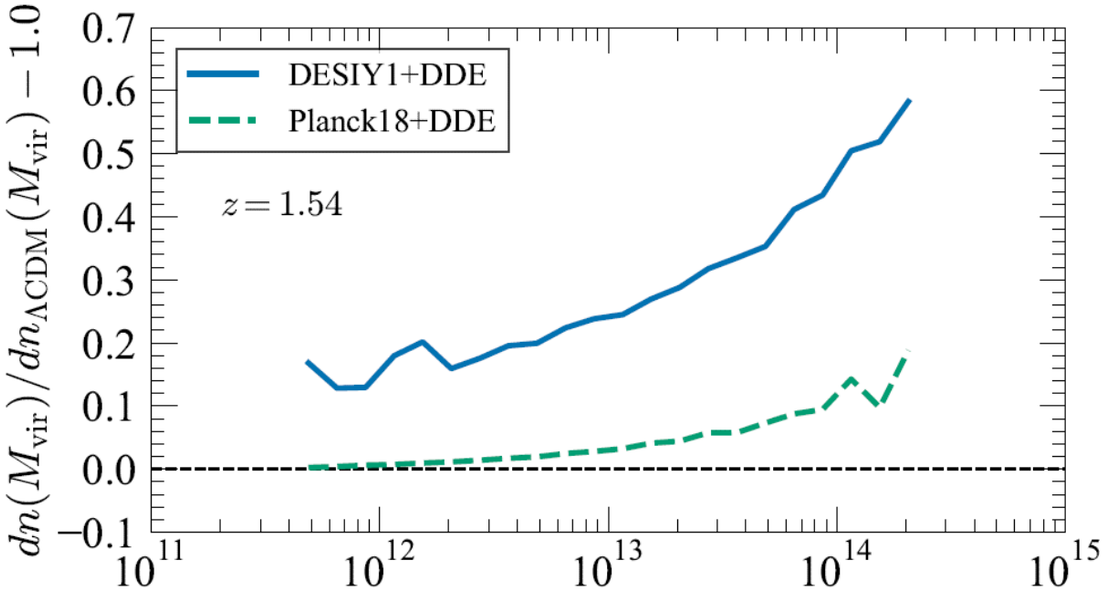


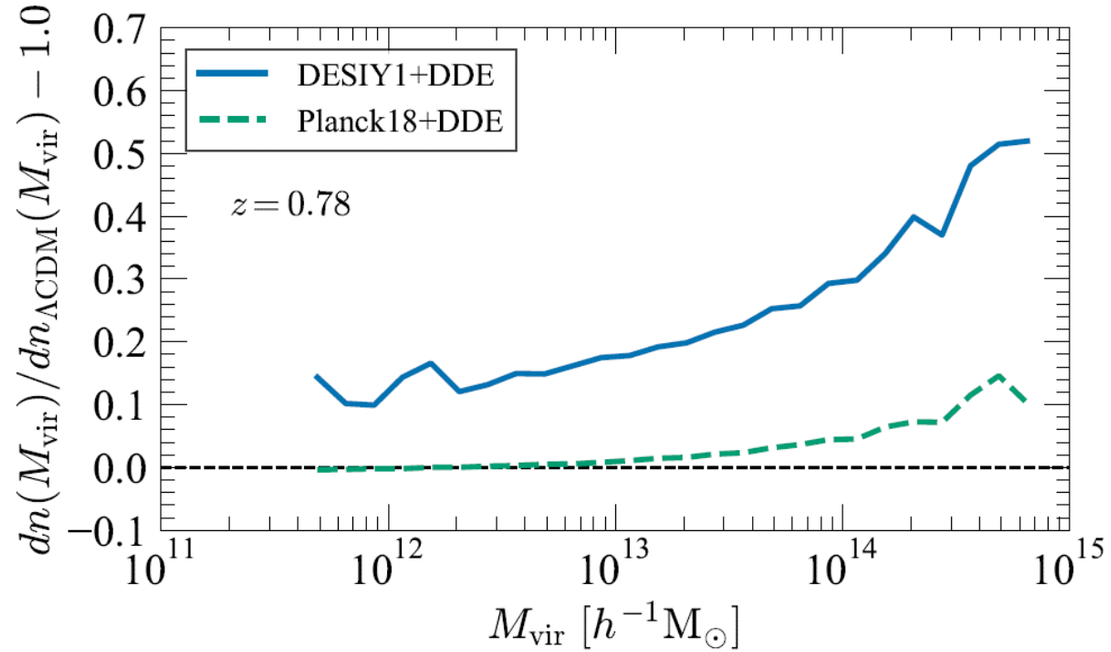


Matter power spectrum, halo mass funtion

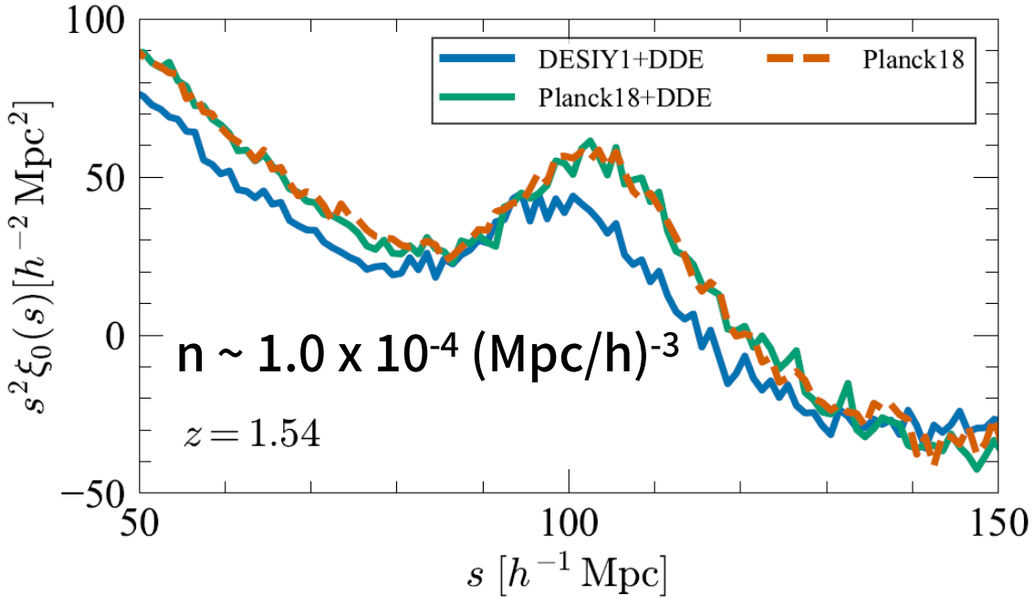


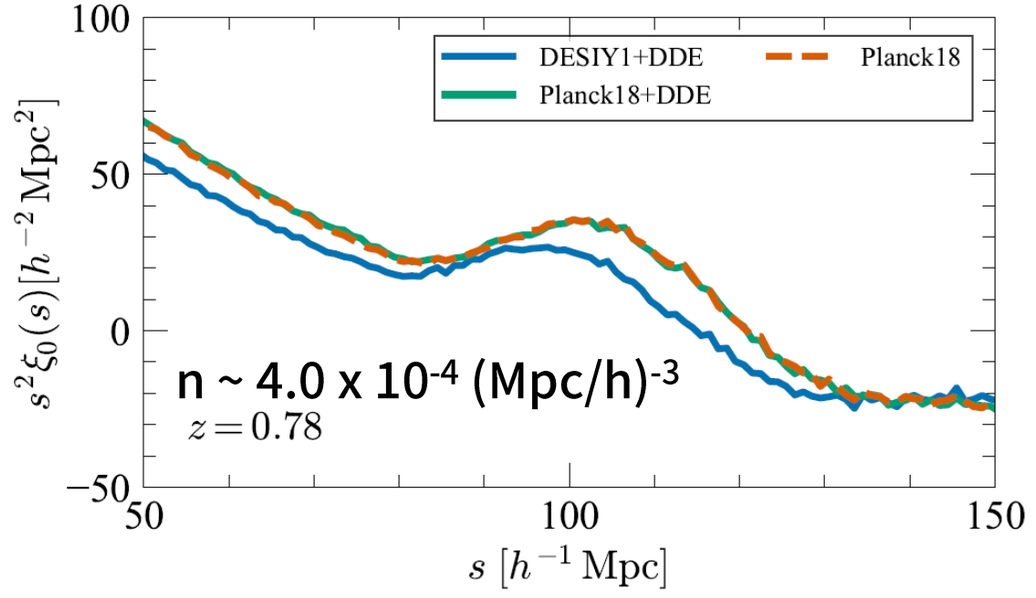


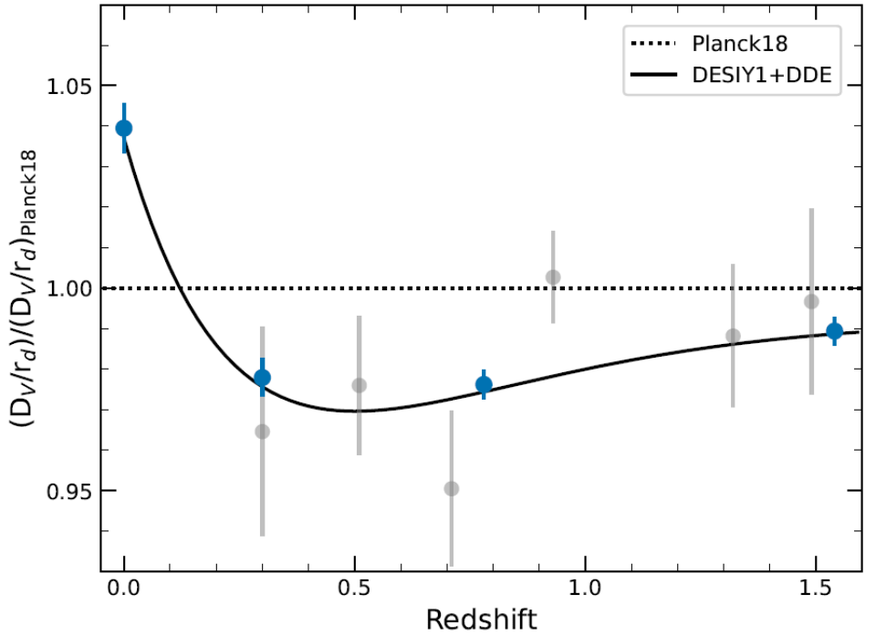




Baryon acoustic oscillation



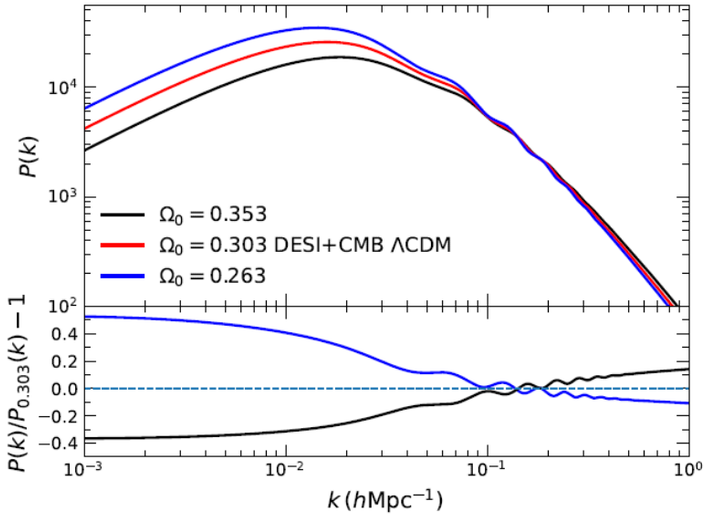




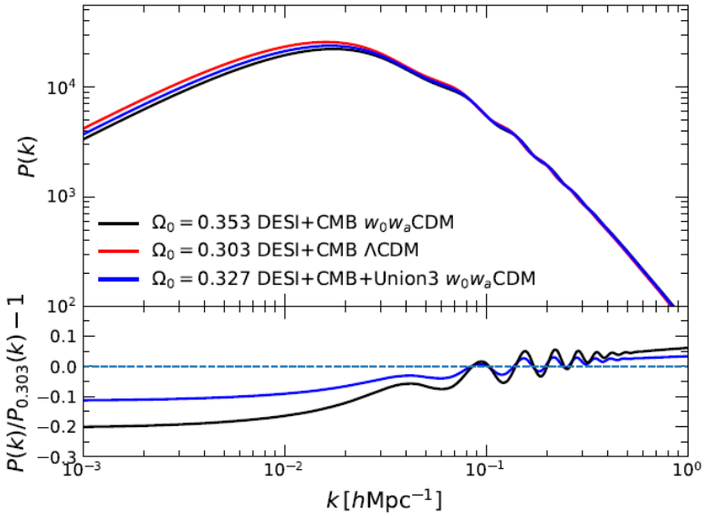
- The effect of DDE is not observed in the correlation function
- 3.71% shift of the BAO (Baryon Acoustic Oscillation) peak toward smaller scales in DESIY1+DDE, consistent with its reduced sound horizon compared to Planck18
- The simulation-based observational dilation parameter closely matches DESI Y1 data

Discussion

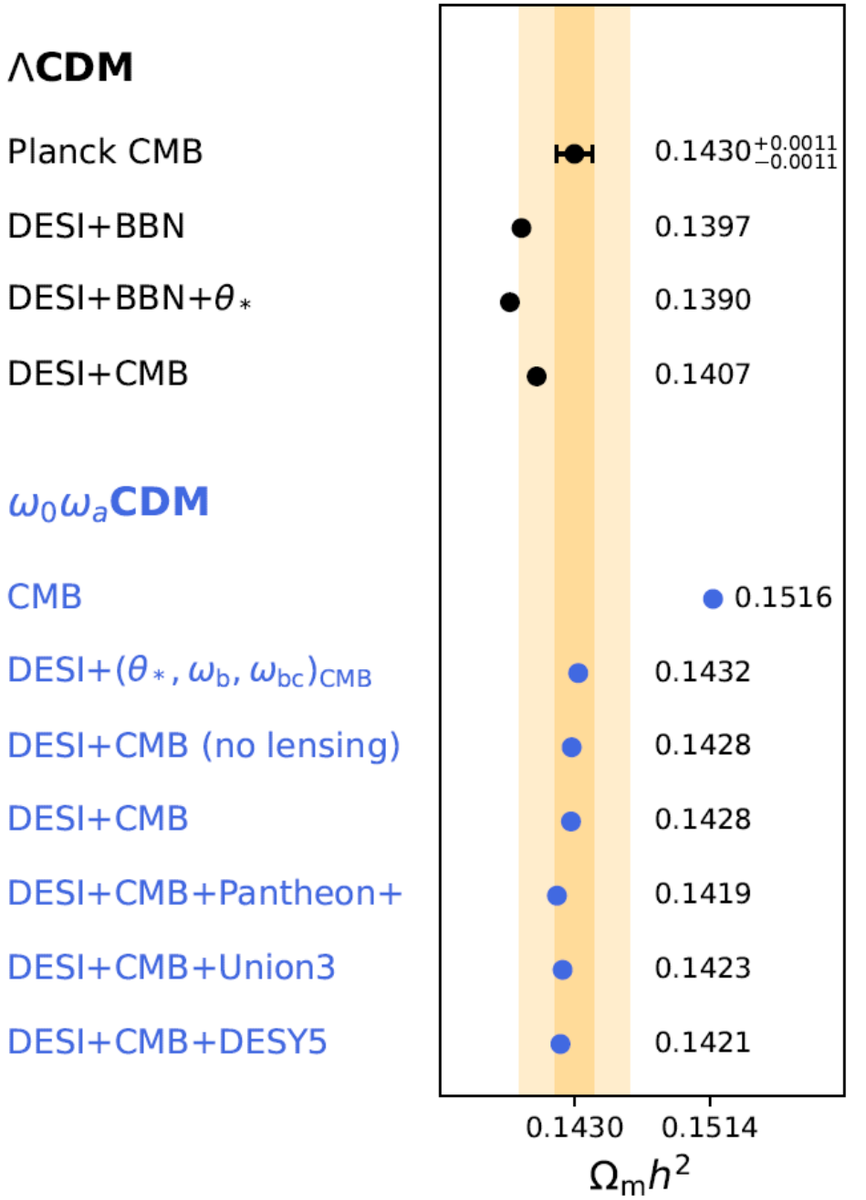
Fixed hubble parameter



Fixed $\Omega_0 h^2 \approx 0.143$



- The impact of DDE is severely limited by current observational constraints, which strongly favor cosmological models—whether including DDE or not—with a tightly constrained parameter $\Omega_0 h^2 \approx 0.143$, within 1%–2% uncertainty



Toward further understanding

Big simulation campaign

- MPI-Rockstar (Behroozi+2013, Tokuue+2024) halo/subhalo finder (incl. inertia tensor)
- Halo catalogs, merger trees will be publicly available

Name	#N	Box (Gpc/h)	particle mass ($M_\odot/h$)	Softening (kpc/h)	cosmology	reference
Uchuu	12800^3	2.0	3.27×10^8	4.27	Planck15	Ishiyama+ 2021
Shin-Uchuu	6400^3	0.14	8.96×10^5	0.4	Planck15	Ishiyama+ 2021
Big-Uchuu	**12800^3**	**4.0**	2.63×10^9	4.0	Planck18	coming soon
Big-Uchuu-DDE	**12800^3**	**4.0**	2.7×10^9	4.0	**DESIY3+DDE**	ready to run

Mucho-Uchuu project

"Mucho" means many in Spanish

Name	#N	Box (Gpc/h)	particle mass ($M_\odot/h$)	softening (kpc/h)	Cosmolgoy	#realizations	Target
Mucho-Uchuu-6G	6144^3	**6.0**	8.0×10^{10}	16	Planck18	**100**	>= LRG
Mucho-Uchuu-1G	4096^3	**1.0**	1.3×10^9	8	Planck18	**~400 (+~300 in 2025)**	>= ELG

- For covariance matrix. Running on Fugaku

Summary

Ishiyama, Prada, Klypin, 2025, PRD)

Parameter	Planck18	Planck18+DDE	DESIY1+DDE
Ω_0	0.3111	0.3111	0.3440
h	0.6766	0.6766	0.6470
w_0	-1.0	-0.45	-0.45
w_a	0.0	-1.79	-1.79
$z_{\rm d}$	1060.02	1060.02	1055.70
$r_{\rm d}$ $[h^{-1}{\rm Mpc}]$	99.61	99.61	96.05

- We investigate the effect of dynamical dark energy on various statistics of large scale structures using large cosmological N-body simulations
- Variations in cosmological parameters, particularly Ω_0, have a greater influence on structure formation than the dynamical dark energy component alone
- Halo catalogs are available (https://skun.iaa.csic.es/SUsimulations/DDE/)
- New large simulation suite is coming soon