Euclid preparation: simulations and non-linearities beyond ΛCDM

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Simulations & non-linearities beyond LCDM

- Joint effort between **Theory** and **Simulation** groups
- 4 papers in this project

Title	Content	Status
Numerical methods and validation	N-body methods code comparison challenge for modified gravity	Accepted (after revision)
Results from non-standard simulations	Pipeline and data release from non-standard simulations	Accepted (after revision)
Cosmological constraints on non-standard cosmologies from simulated Euclid probes	Parameter inference from RSD analysis	In prep
Constraints on $f(R)$ models from the photometric primary probes	Forecasts on MG effects on 3×2-point statistics	Accepted

N-body comparison challenge

Setup (from Winther et al. 2015)

- ΛCDM cosmology
- Box length : 256 h^{-1}Mpc
- 512^3 particles
- 2LPT with $z_{ini} = 49$

Assess the impact of MG

- Power spectrum
- Halo mass function

Codes in N-body comparison challenge

Code (Reference)	Models	Solver type – gravity	Solver type – scalar field	Approximations	Treatment of massive neutrinos
C-Gadget (Baldi et al. 2010)	interacting DE, dark scattering	TreePM (FFT)	linear Poisson	quasi-static approximation	N-body particles
ECOSMOG (Li et al. 2012, 2013b)	$f(R)$, nDGP, cubic galileon	AMR + multigrid	NGS + multigrid	quasi-static approximation	–
ISIS (Llinares et al. 2014)	$f(R)$, nDGP, symmetron	AMR + multigrid	NGS + multigrid	quasi-static approximation	–
MG-Gadget (Puchwein et al. 2013)	$f(R)$	TreePM (FFT)	NGS + multigrid	quasi-static approximation	N-body particles
MG-Arepo (Arnold et al. 2019; Hernández-Aguayo et al. 2021)	$f(R)$, nDGP + hydro	TreePM	NGS + multigrid	quasi-static approximation	N-body particles
PANDA (Casalino & Baldi in prep.)	$f(R)$, nDGP	TreePM (FFT)	linear Poisson + screening	quasi-static approximation, type 2 parameterised modified gravity	N-body particles
PySCo (Breton in prep.)	$f(R)$	PM + multigrid	cubic multigrid	quasi-static approximation	–
MG-COLA (Winther et al. 2017; Wright et al. 2017)	$f(R)$, nDGP; cubic galileon, symmetron	2LPT + PM (FFT)	linear Poisson + screening	quasi-static approximation, type 1 or type 2 parameterised modified gravity	mesh

$f(R)$ gravity

Cosmological action (GR + ΛCDM)

$$S = \int \left[\frac{1}{2\kappa} (R - 2\Lambda) + \mathcal{L}_m \right] \sqrt{-g}\, d^4x \qquad (1)$$

$f(R)$ action

$$S = \int \left[\frac{1}{2\kappa} (R + f(R)) + \mathcal{L}_m \right] \sqrt{-g}\, d^4x \qquad (2)$$

Hu & Sawicki (2007) model

$$f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1} \qquad (3)$$

Only two free parameters (one is constrained by observations)

$$\frac{c_1}{c_2} = 6 \frac{\Omega_{\Lambda,0}}{\Omega_{m,0}} \qquad \frac{c_1}{c_2^2} = -\frac{1}{n} \left[3 + 12 \frac{\Omega_{\Lambda,0}}{\Omega_{m,0}} \right] f_{R0} \qquad (4)$$

Modified set of equations

- Exact solution

$$\nabla^2\phi = \underbrace{4\pi G a^2 \delta\rho}_{Newton} - \frac{c^2}{2}\nabla^2 f_R \quad (5)$$

linear Poisson equation with modified source term

$$\nabla^2 f_R = A\delta\rho + B + f_R^{-\frac{1}{n+1}} C \quad (6)$$

Non-linear equation : need appropriate tools (such as non-linear multigrid)

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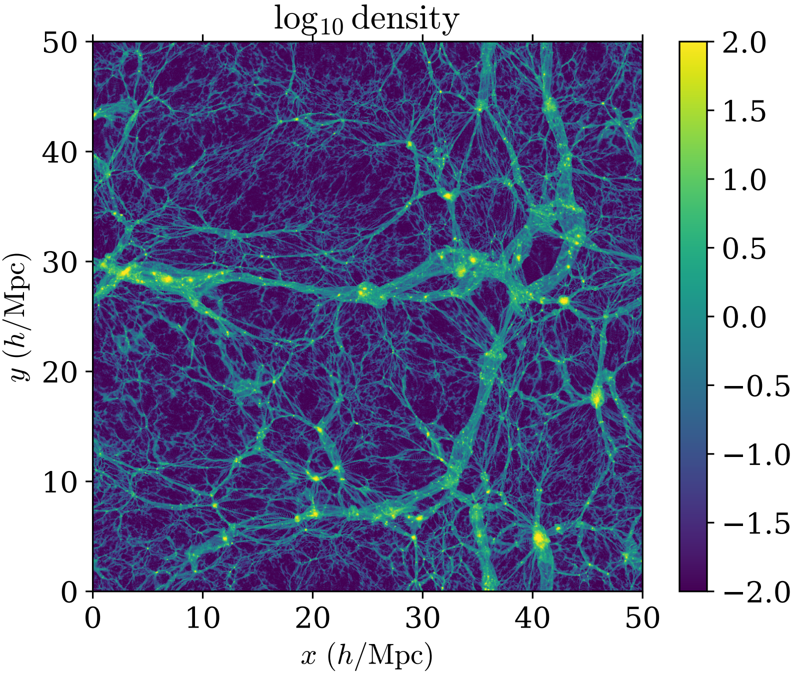
$$\nabla^2 f_R = A\delta\rho + B + f_R^{-\frac{1}{n+1}} C \quad (6)$$

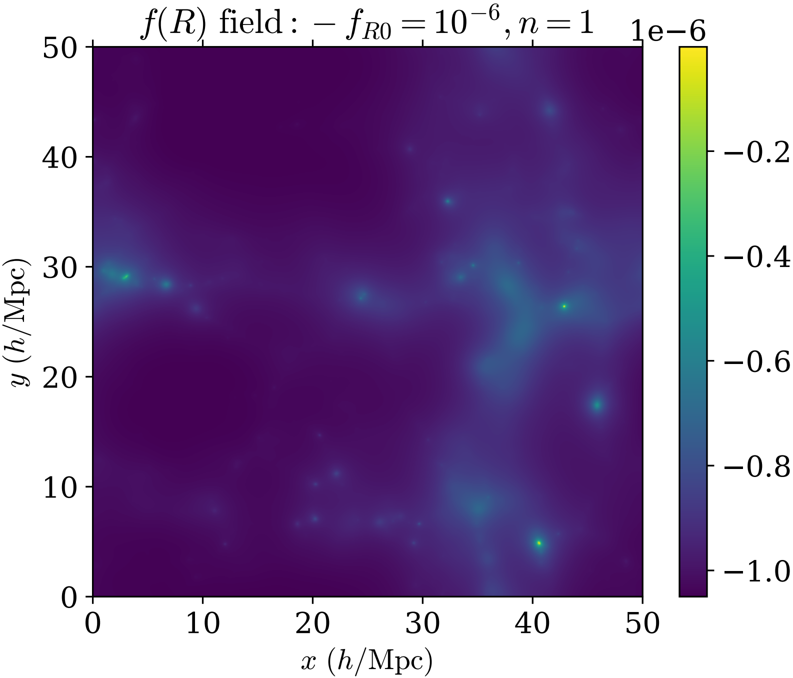
Non-linear equation : need appropriate tools (such as non-linear multigrid)

- Approximated solution

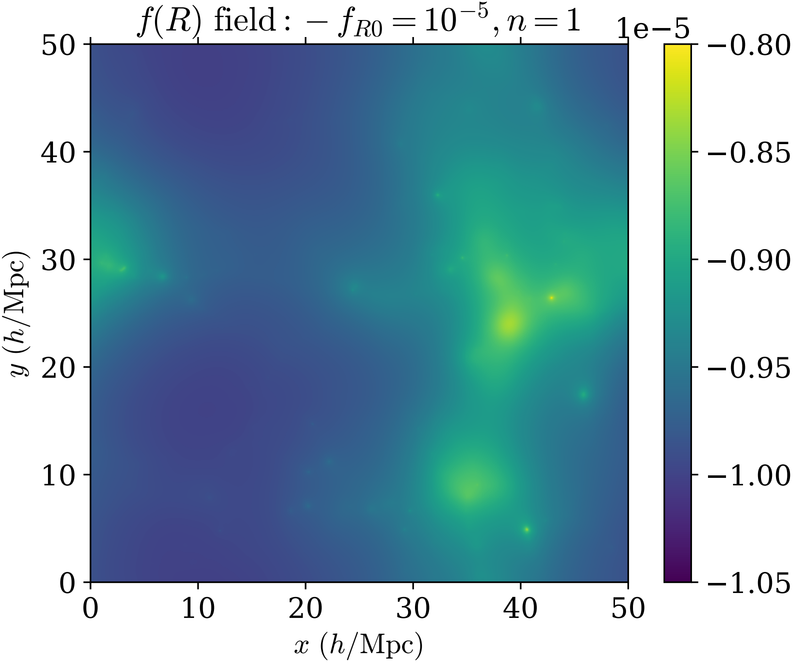
$$-k^2\phi = 4\pi G_{eff}(a,k) a^2\delta\rho \quad (7)$$

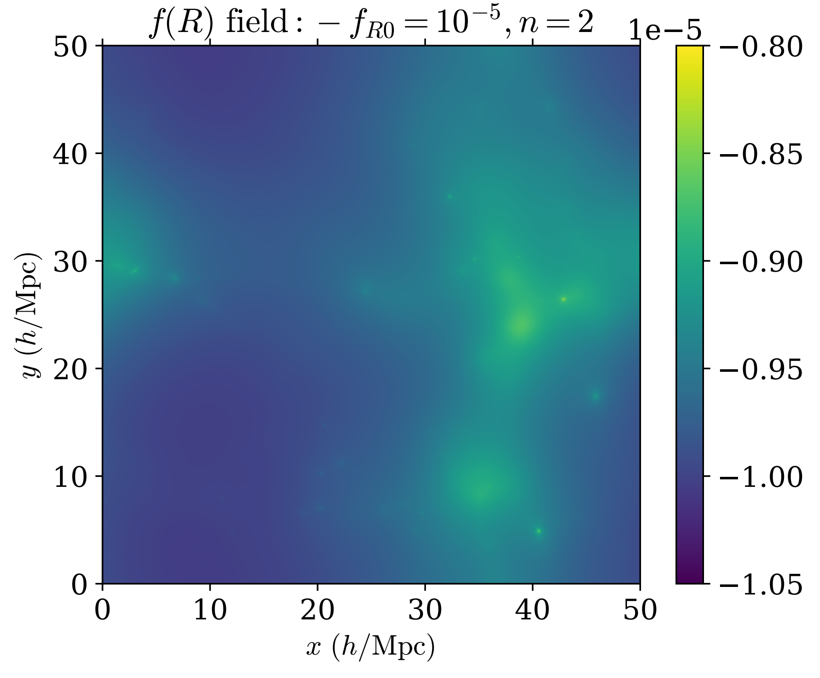
linear Poisson equation with scale and time-dependent gravitational constant


$\log_{10}$ density
x (h/Mpc)
y (h/Mpc)
0
10
20
30
40
50
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0

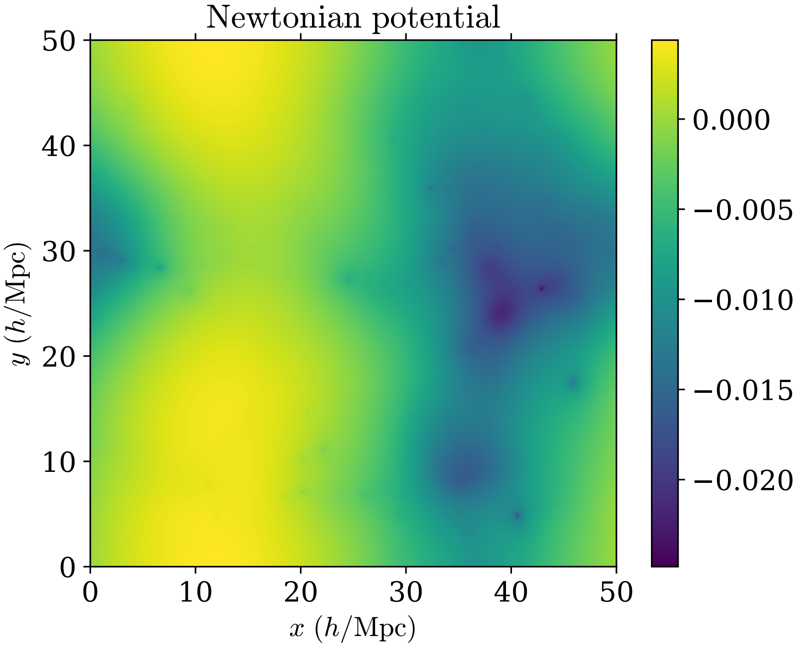


$f(R)$ field: $-f_{R0}=10^{-6}, n=1$
1e−6
−0.2
−0.4
−0.6
−0.8
−1.0
0
10
20
30
40
50
y (h/Mpc)
x (h/Mpc)

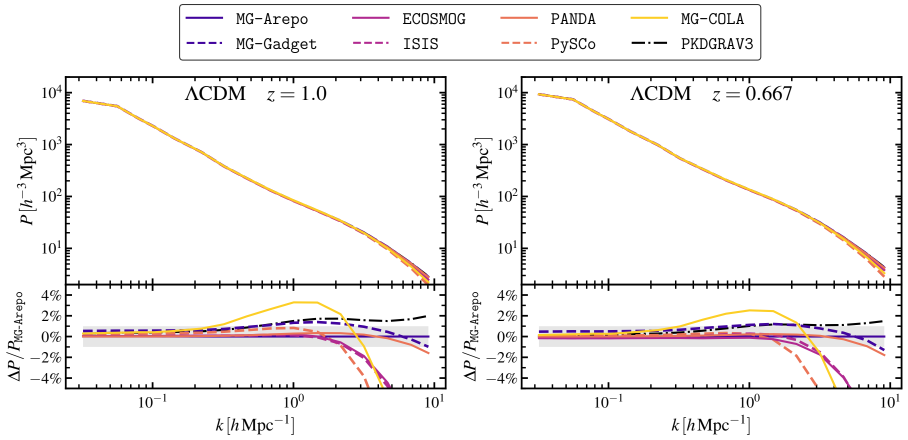

$f(R)$ field : $-f_{R0} = 10^{-5}, n = 1$
1e−5
−0.80
−0.85
−0.90
−0.95
−1.00
−1.05
y (h/Mpc)
x (h/Mpc)
0
10
20
30
40
50



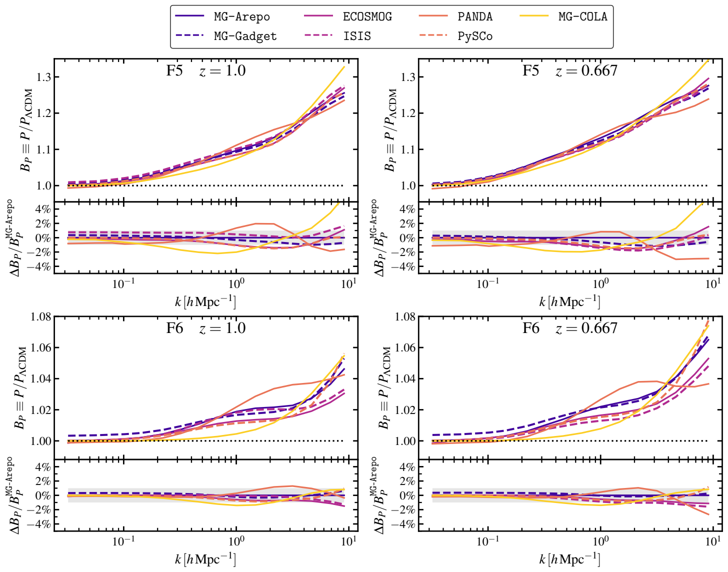
$f(R)$ field : $-f_{R0} = 10^{-5}, n = 2$
1e−5
−0.80
−0.85
−0.90
−0.95
−1.00
−1.05
y (h/Mpc)
0
10
20
30
40
50
x (h/Mpc)


Newtonian potential
y (h/Mpc)
x (h/Mpc)
0
10
20
30
40
50
0.000
−0.005
−0.010
−0.015
−0.020

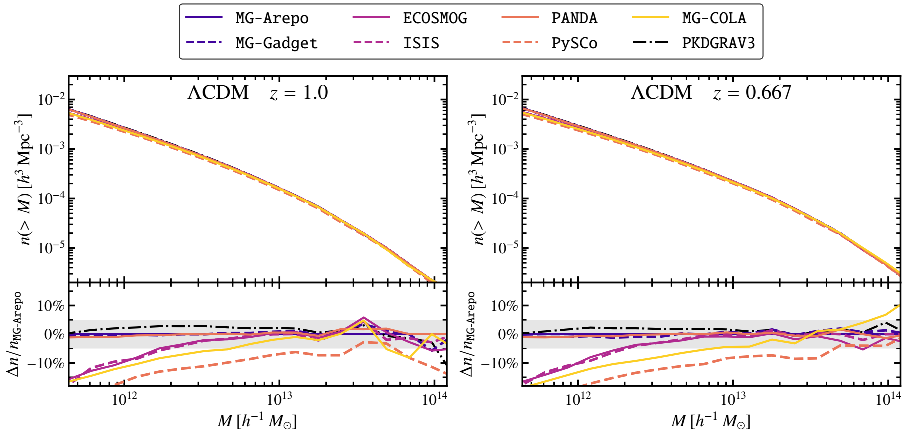
ΛCDM Power spectrum



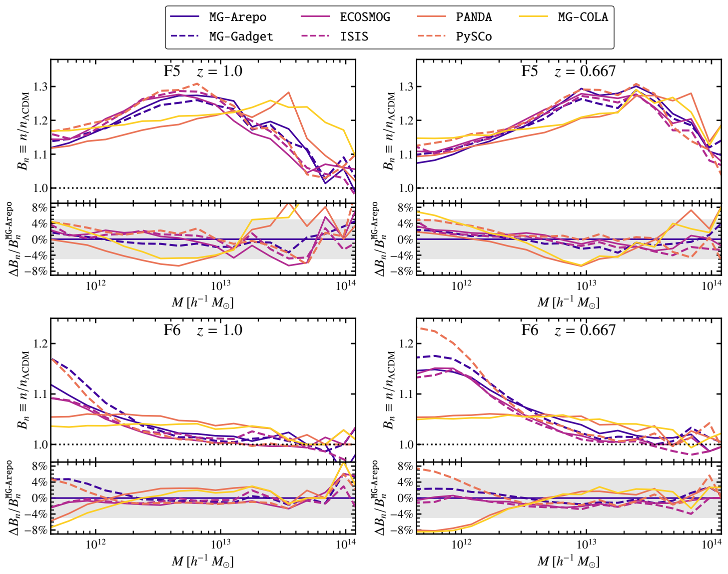
$f(R)$ Power spectrum



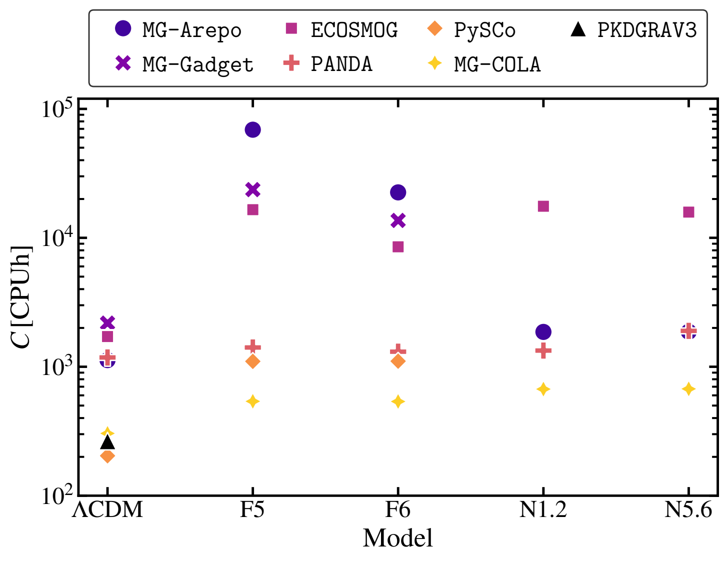
ΛCDM Halo mass function



$f(R)$ Halo mass function



Runtime comparison



Paper II : Scientific results from non-standard simulations

Common pipeline to analyse simulation snapshots

Models

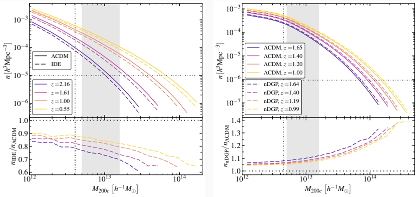
- ΛCDM
- w_0CDM
- $w_0 w_a$CDM
- K-essence
- Interacting dark energy
- Modified gravity : $f(R)$, nDGP
- Massive neutrinos
- Primordial non-Gaussianities

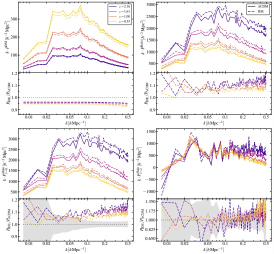
Name/Reference	Code	$N_{\rm sim}$	L [h^{-1} Gpc]	$N_{\rm DM}$	$m_{\rm DM}$ [h^{-1} $M_\odot$]	$z_{\rm init}$	LPT order	Model
COMPLEMENTARY	GIZMO	2	1.5	2160^3	2.89×10^{10}	127	1LPT	ΛCDM
Rácz et al. (2023)		2	1.5	2160^3	2.88×10^{10}			wCDM
DEMNUNI	p-GADGET3	100	1.0	1024^3	8×10^{10}	99	1LPT	ΛCDM $+m_\nu$
Carbone et al. (2016)	p-GADGET3	15	2.0	2048^3	8×10^{10}			CPL $+ m_\nu$
	p-GADGET3	2	0.5	2048^3	1.25×10^9			ΛCDM $+m_\nu$
RAYGAL	RAMSES	1	2.625	4096^3	1.88×10^{10}	49	2LPT	ΛCDM
Rasera et al. (2022)		1	2.625	4096^3	2.0×10^{10}			wCDM
ELEPHANT	ECOSMOG	11	1.024	1024^3	8.85×10^{10}	49	2LPT	ΛCDM
Cautun et al. (2018)		11	1.024	1024^3	8.85×10^{10}			nDGP
COLA HIRES	MG-COLA	5	1.024	2048^3	1.07×10^{10}	127	2LPT	nDGP
Fiorini et al. (2023)		2	1.024	2048^3	1.07×10^{10}			ΛCDM
DUSTGRAIN	MG-GADGET	3	2.0	2048^3	8.27×10^{10}	99	1LPT	nDGP
Giocoli et al. (2018)		11	0.75	768^3	8.1×10^{10}			$f(R) + m_\nu$
CIDER Baldi (2023)	c-GADGET	4	1.0	1024^3	8.1×10^{10}	99	2LPT	cDE
DAKAR (1&2) Baldi & Simpson (2017)	c-GADGET	5	1.0	1024^3	8.1×10^{10}	99	1LPT	DS
CLUSTERING DE	k-evolution	1	2.0	2400^3	4.2×10^{10}	100	1LPT	$w_0 c_s^2$CDM
Hassani et al. (2019, 2020)		1	2.0	1200^3	3.3×10^{11}			$w_0 c_s^2$CDM
FORGE	MG-Arepo	100	0.5	1024^3	$\sim 10^{10}$	127	2LPT	ΛCDM
Arnold et al. (2021)		98	0.5	1024^3	$\sim 10^{10}$			$f(R)$
BRIDGE Harnois-Déraps et al. (2023)	MG-Arepo	98	0.5	1024^3	$\sim 10^{10}$	127	2LPT	nDGP
PNG-UNIT Adame et al. (2023)	GADGET-2	1	1.0	4096^3	1.2×10^9	99	2LPT	PNG

Paper II : Scientific results from non-standard simulations

For each simulation snapshot

- Halo catalogues : modified ROCKSTAR (new inputs, added cosmological models, extra output info, etc.)
- DM and halo density fields
- Power spectra : DM/halo and real/redshift space
- Covariance for redshift-space multipoles
- Halo bias
- Halo mass function
- Halo density profiles
- Void catalogues





Soon available on Cosmohub !

Summary

- Fair consensus among different numerical implementation for the outputs of different simulation codes beyond ΛCDM regarding the $P(k)$ and HMF boost.
- Small differences due to convergence thresholds
- Approximated methods to solve the additional field have a clear different trend from compared to exact methods. **Not sure if important**
- Exact solvers are much more expensive than approximated ones
- Production of halo catalogues and statistical outputs from hundreds of non-standard simulations (DE, MG, PNG etc. . .)
- Soon available publicly
- To do : extend to lightcones