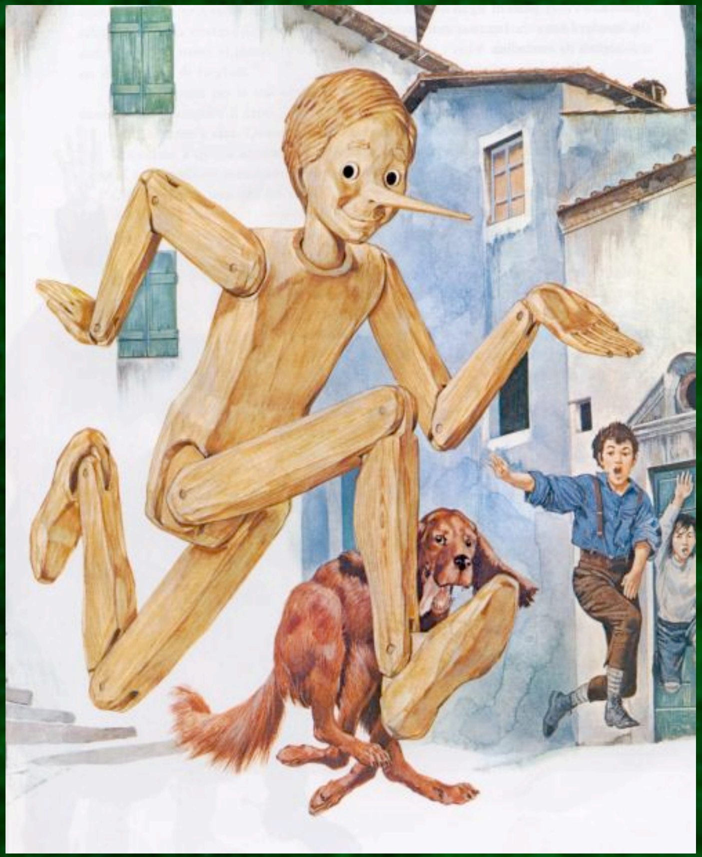
Approximate methods in the era of precision cosmology: the PINOCCHIO code



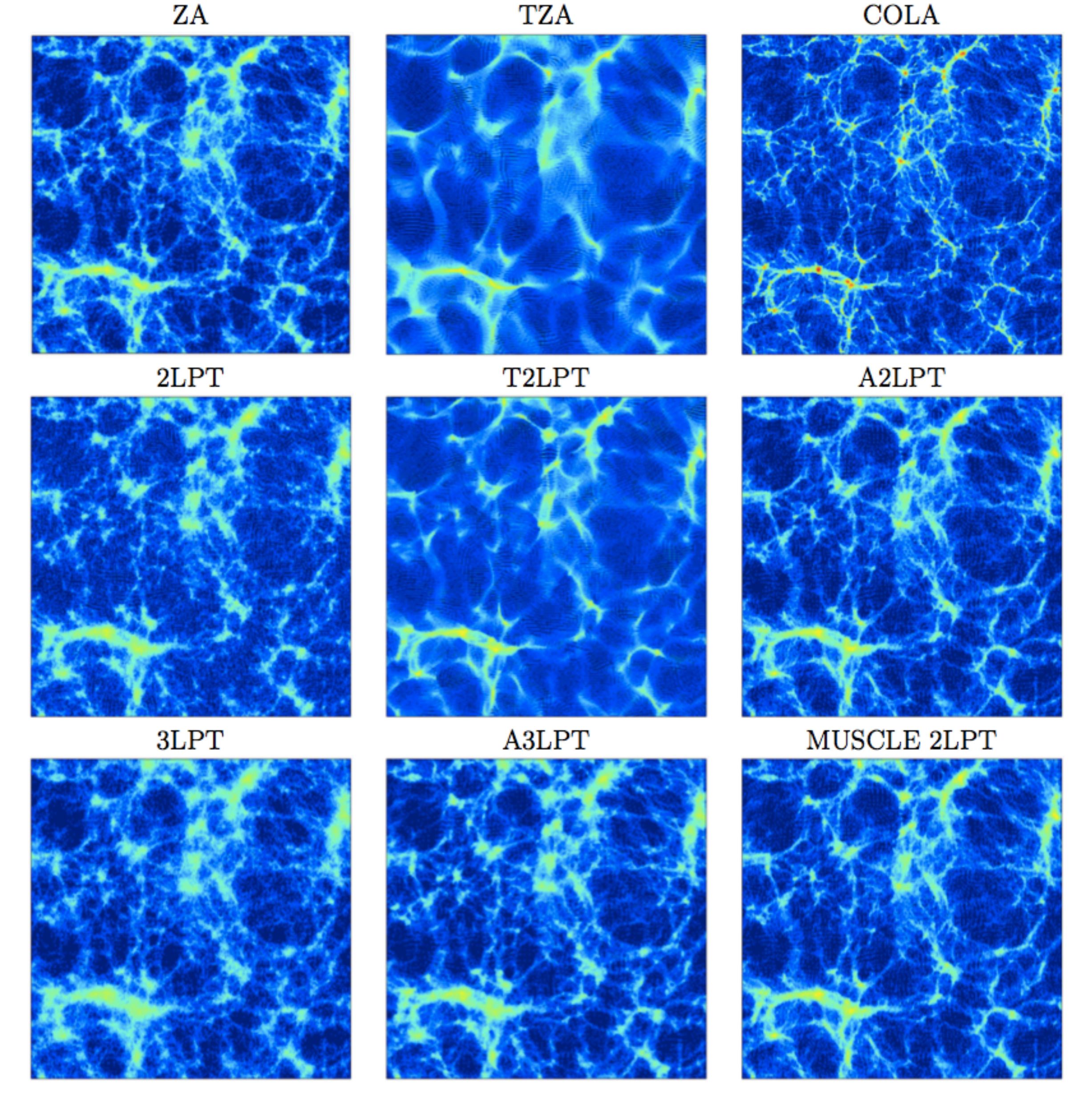
P. Monaco,
University of Trieste & INAF-OATs & INFN-TS

Background image credit: E. Munari

Precision cosmology requires production of thousands of independent realizations of the observable universe. This has prompted a new burst in the development of approximate methods to predict the clustering of dark matter and dark matter halos

P. M., 2016, *Galaxies* 4, 53

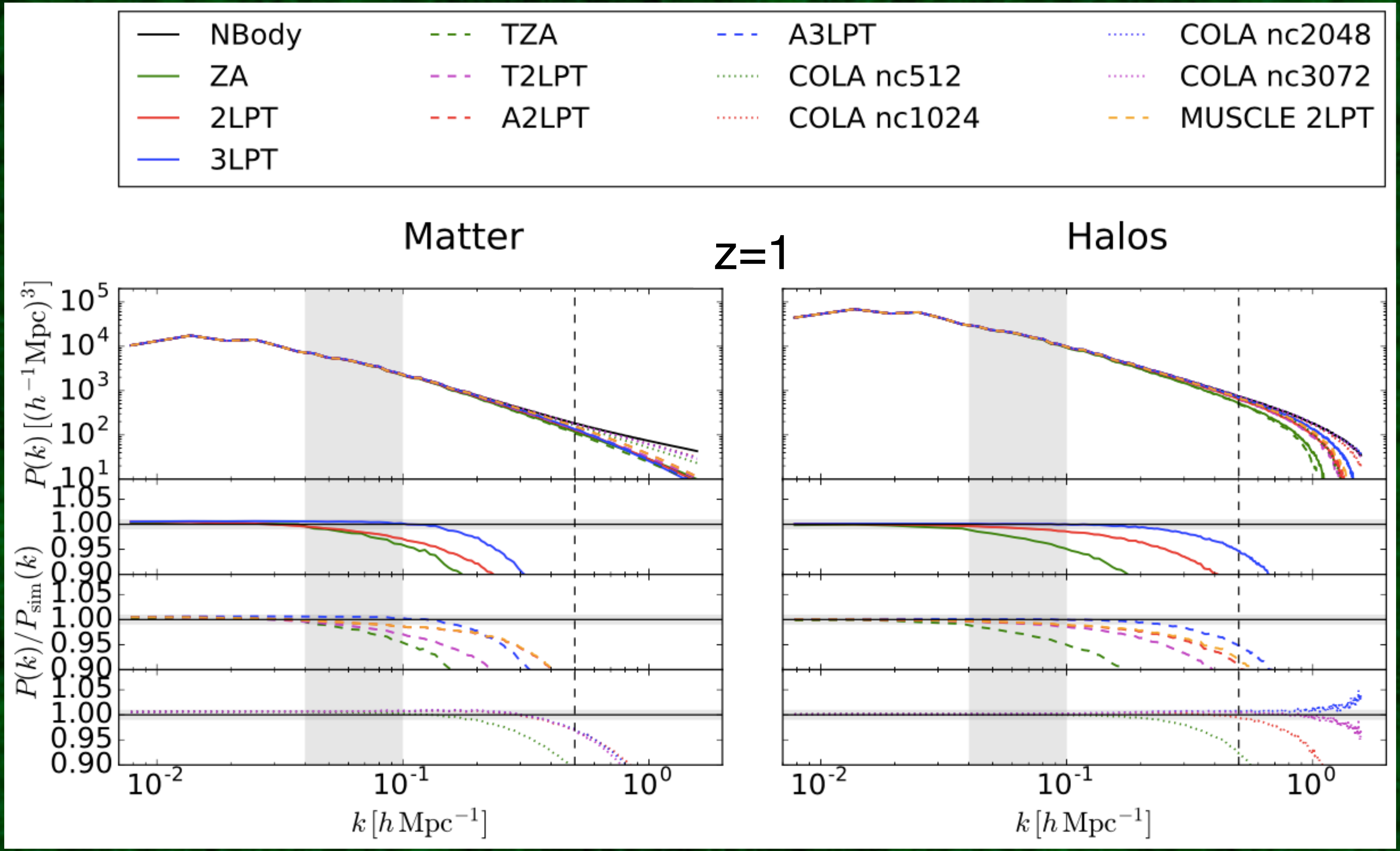
"The search for analytic and semi-analytic approximations to gravitational clustering, more than being pushed out of fashion, has been boosted by precision cosmology."



Two problems to solve:

- displace particles from Lagrangian to final position
- collect particles into halos

Power spectrum of dark matter halos



E. Munari, P.M., J. Koda, F. Kitaura, E. Sefusatti, S. Borgani, JCAP 7-2017, 50

“Lagrangian” methods:

generate the ICs of a simulation and apply the method to find halos

- Peak-Patch (Bond & Myers 1996)
- Pinocchio (Monaco+ 2002, 2013, Munari 2016)
- PTHalos (Scoccimarro & Sheth 2002) as in Manera+ (2013)
- Quick PM integrators:
  - → White+ 2010
  - → FastPM: Fen
  - → PPM-GLAM
  - → COLA: Tass

Pros: predictive, c

Cons: memory re

Table 1. Estimated cost of one realization of 4 h^{-1} Gpc box where halos of 10^{12} $M_{\odot}$ are resolved. The last column gives the estimated cost of running 1000 realizations.

Method	Memory	N. Cores	Elapsed Time	CPU Time	1000 Realizations
EZmocks	40 GB	16	7.5 m	2 h + calibration N-body	822,000 h
PATCHY	40 GB	16	7.5 m	2 h + calibration N-body	822,000 h
PINOCCHIO	14 TB	2048	30 m	1024 h	1,024,000 h
COLA	33 TB	4096	2.5 h	10,240 h	10,240,000 h
N-body (HugeMDPL)	6.5 TB	2000	410 h	820,000 h	820,000,000 h

“Bias-based” methods:

generate a density field and populate it with halos using a bias scheme

- Patchy (Kitaura+ 2014, 2016)
- EZMocks (Chuang+ 2015)
- Halogen (Avila+ 2015)

Pros: very quick, resolution limits are much lighter

Cons: less predictive, they need to be calibrated each time against a big simulation

P. M., 2016, *Galaxies* 4, 53

PINpointing Orbit Crossing-Collapsed HIerarchical Objects

P.M., T. Theuns, G. Taffoni et al., 2002, ApJ, 564, 8

P.M., T. Theuns & G. Taffoni, 2002, MNRAS, 331, 587

G. Taffoni, P.M. & T. Theuns, 2002, MNRAS, 333, 623

P.M., E Sefusatti, S. Borgani, M. Crocce, P. Fosalba, R.K. Sheth, T. Theuns, 2013, MNRAS, 433, 2389

E. Munari, P.M., E. Sefusatti, E. Castorina, F. Mohammad, S. Anselmi, S. Borgani, 2017, MNRAS 465, 4658

L. A. Rizzo, F. Villaescusa-Navarro, P.M., E. Munari, S. Borgani, E. Sefusatti, JCAP 1-2017, 8

He's cheating: he's not N-body, he's way too fast!

http://adlibitum.oats.inaf.it/monaco/pinocchio/

https://github.com/pigimonaco/Pinocchio

Three foundations:

+ Ellipsoidal collapse for mass elements

+ LPT to compute collapse times

+ Excursion sets theory to deal with smoothing scales

Computing the "collapse" (OC) time of a fluid element

- Taylor expansion of the gravitational potential:

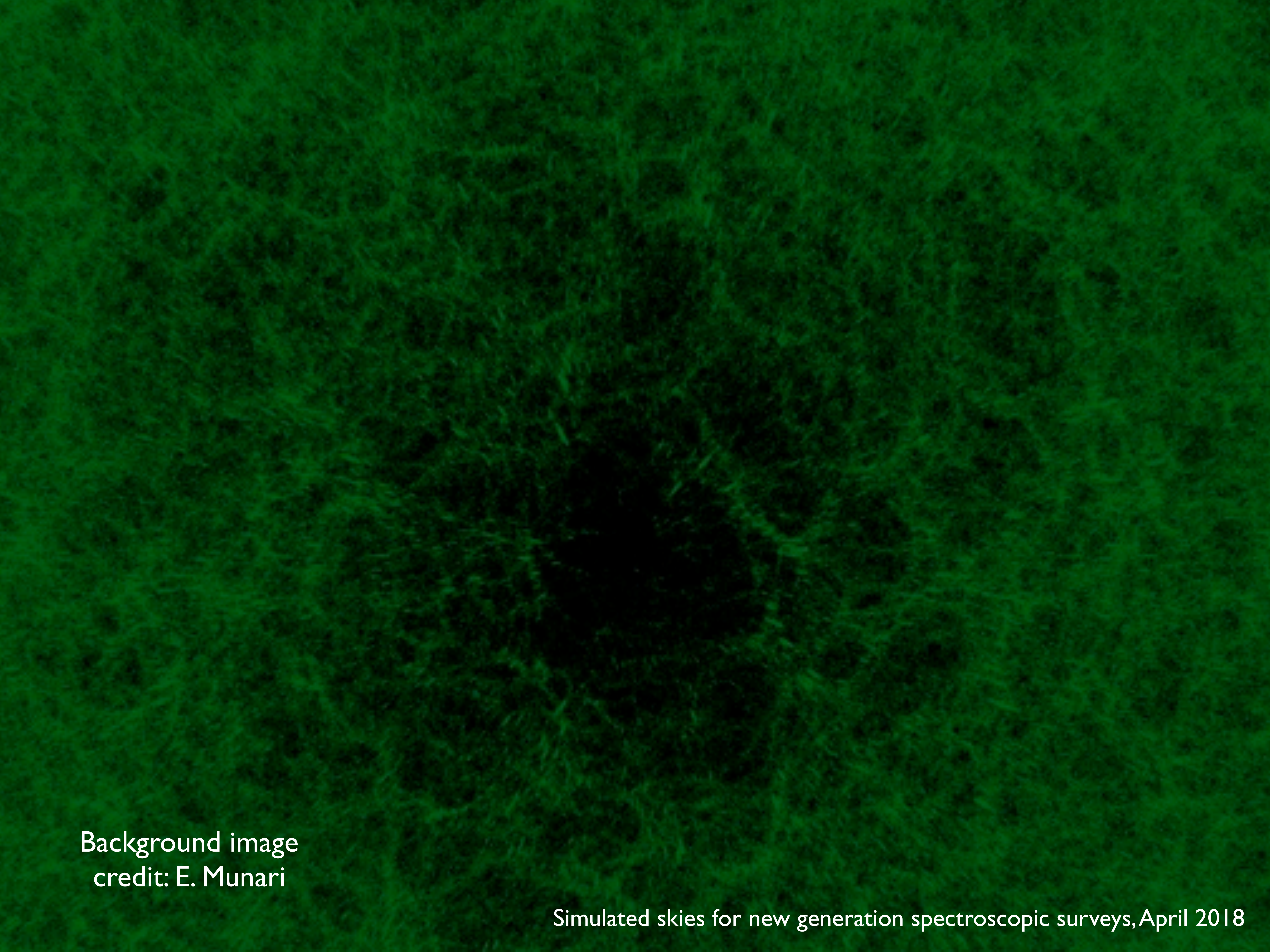
$$\phi(\vec{q}_0) \simeq \cancel{\phi_0} + \underbrace{\phi_{,i}(\vec{q}_0)(\vec{q}-\vec{q}_0)_i}_{\text{bulk flow}} + \underbrace{\phi_{,ij}(\vec{q}_0)(\vec{q}-\vec{q}_0)_{ij}}_{\text{second-order term}}$$

- => evolution of a homogeneous ellipsoid
  - numerical solution, or
  - solution with 3LPT up to **ORBIT CROSSING**

  + correction for quasi-spherical cases

(P.M. 1995, 1997a)

and an algorithm to mimic hierarchical assembly of particles into halos



Background image
credit: E. Munari

Project	Number	Cosmology	Box size (Gpc/h)	Parts.	Part. mass (Msun/h)	PLC semi-aperture	PLC redshift range
Covariances	10,000	Minerva	1.5	1000^3	2.7e11	30 deg (1000 only)	0.9 - 1.8 (1000 only)
Systematics	20	Minerva	3.2	4096^3	3.8e10	60 deg	0.0 - 2.5
Systematics	10	Flagship	3.2	4096^3	4.2e10	60 deg	0.0 - 2.5
Bispectrum	300	Flagship	1.2	2160^3	1.5e10	20 deg	0.0 - 2.0
Clusters	100	Flagship	3.87	2160^3	4.9e11	60 deg	0.0 - 2.5

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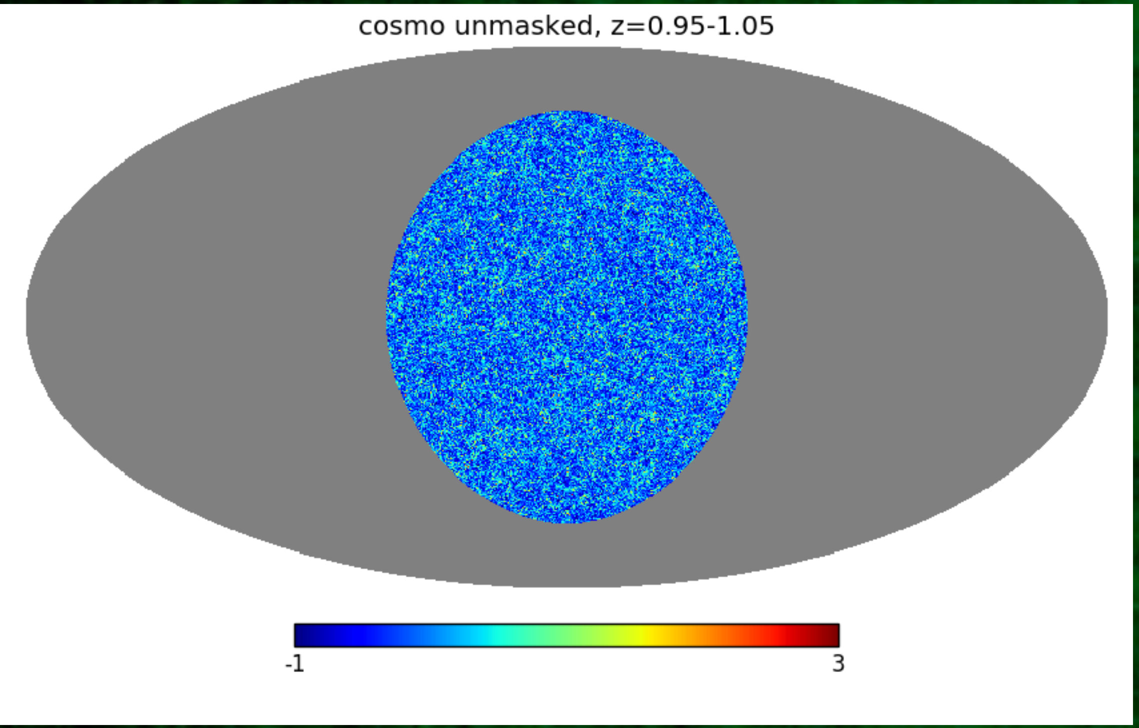
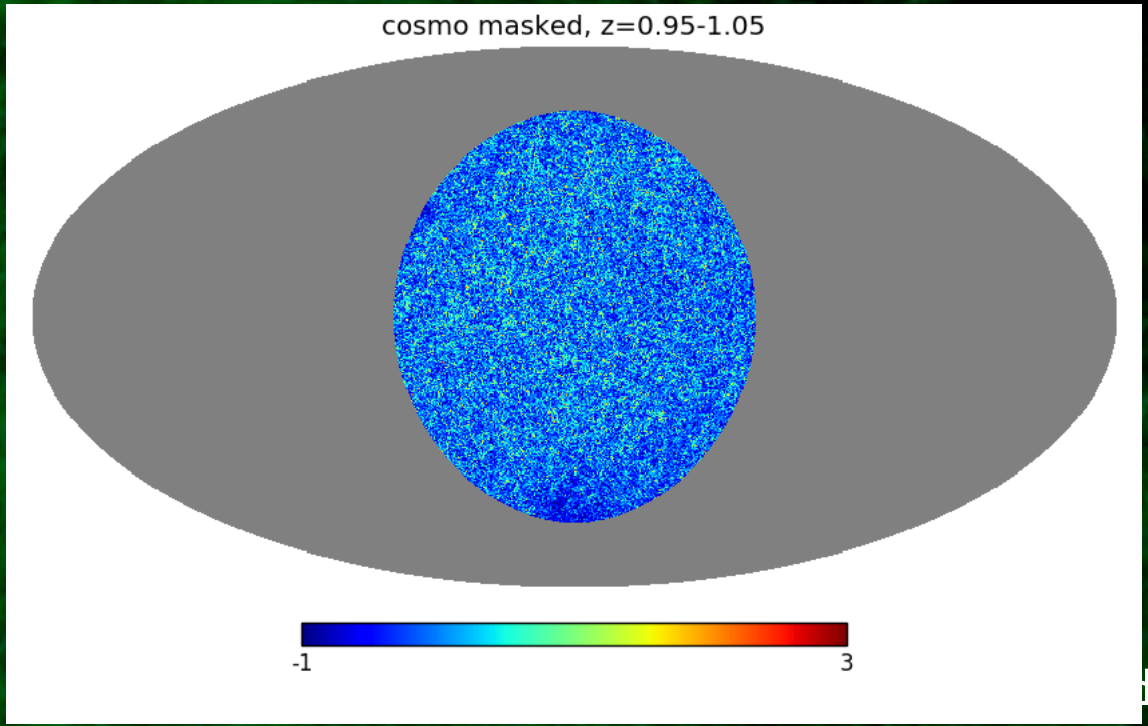
- 3.2 Gpc/h box sampled with 4096^3 particles
- 10^{12} M_{sun} well resolved
- light cone from z=2.5 to z=0
- 120 deg aperture, 1/4 of the sky





with C. Giocoli

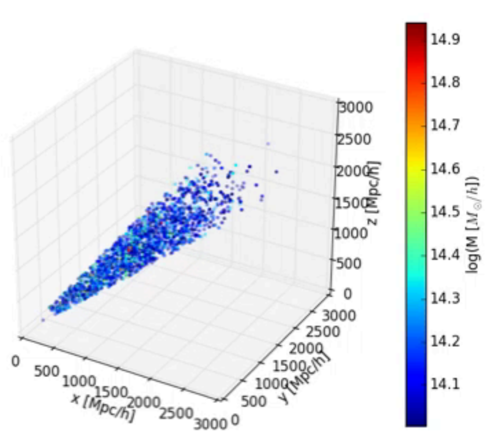
Halo Convergence Power Spectra

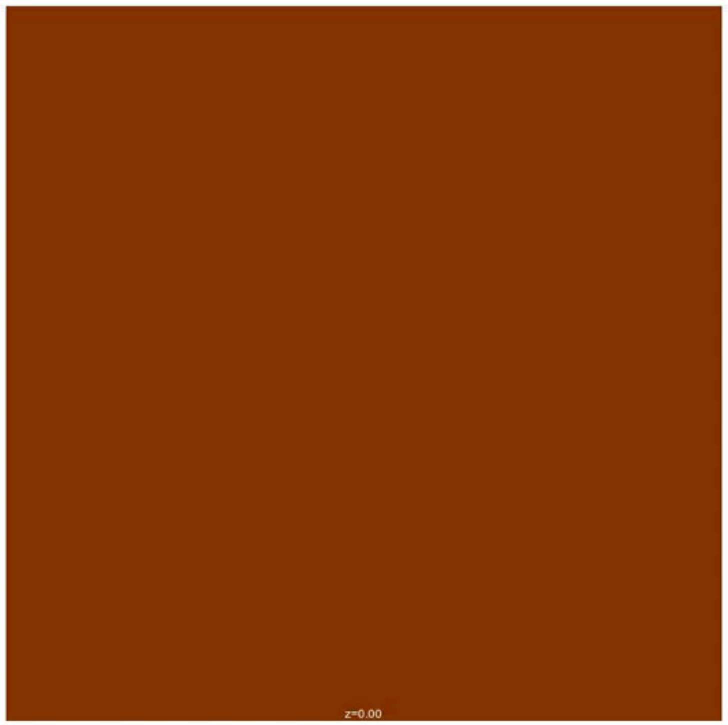
64 light-cone realisations

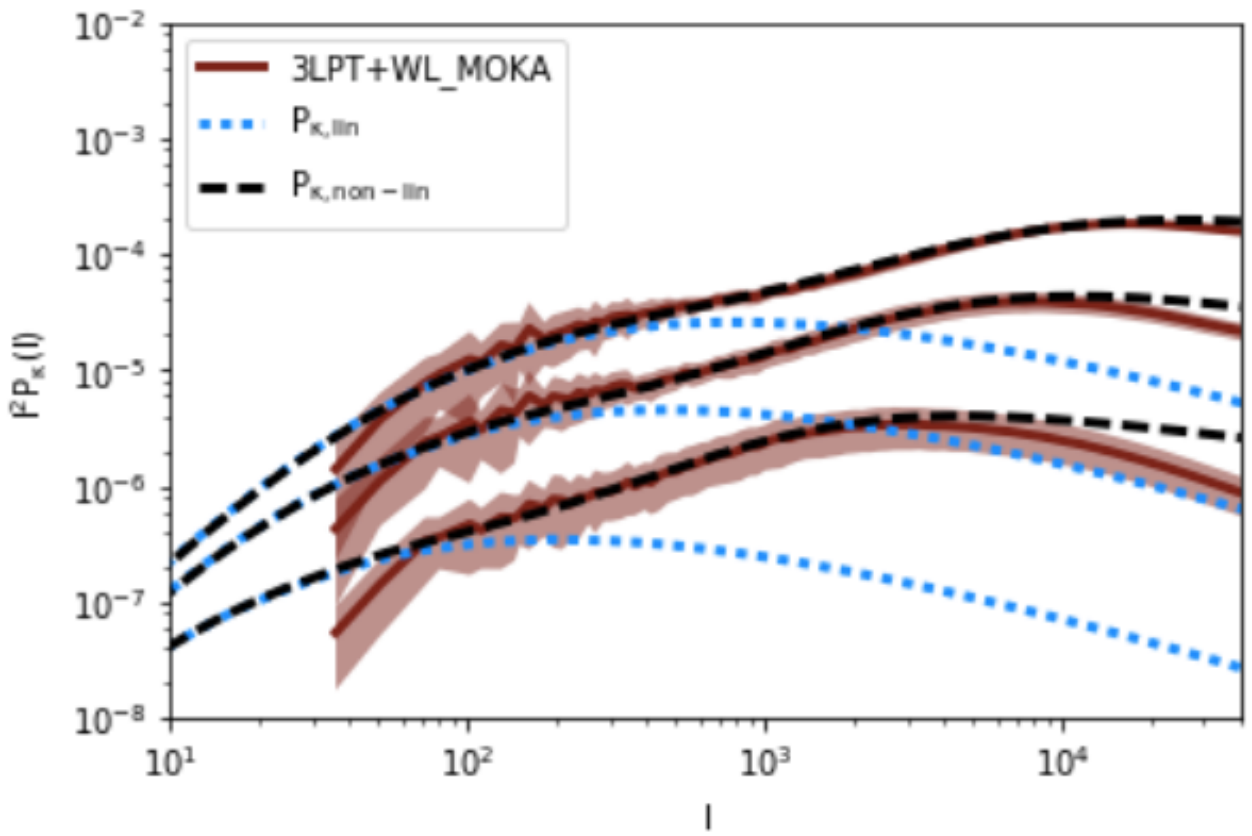
modelling of the matter not resolved in haloes as in Giocoli+17

Light-Cone reconstruction using Pinocchio catalogues

sample the haloes within the past-light-cone

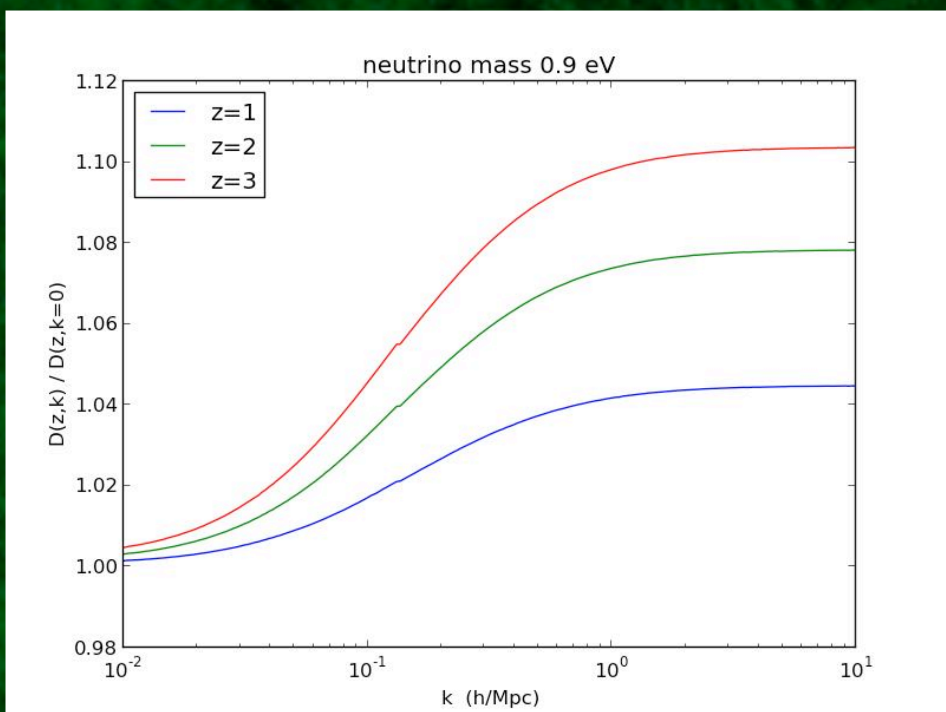




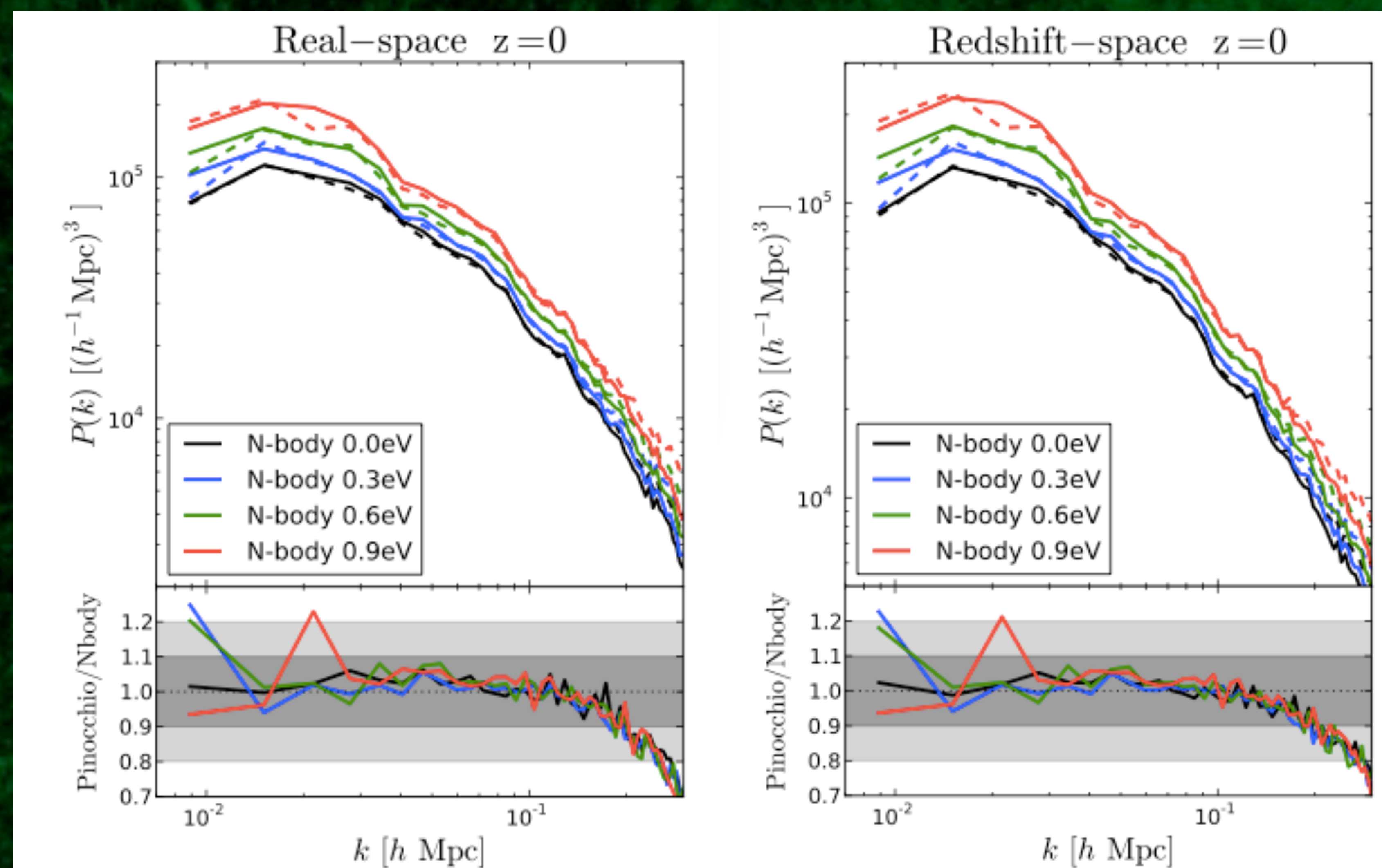


Beyond ΛCDM: massive neutrinos

L.A. Rizzo, F. Villaescusa-Navarro, P.M., E. Munari, S. Borgani, E. Sefusatti, JCAP 1-2017, 8

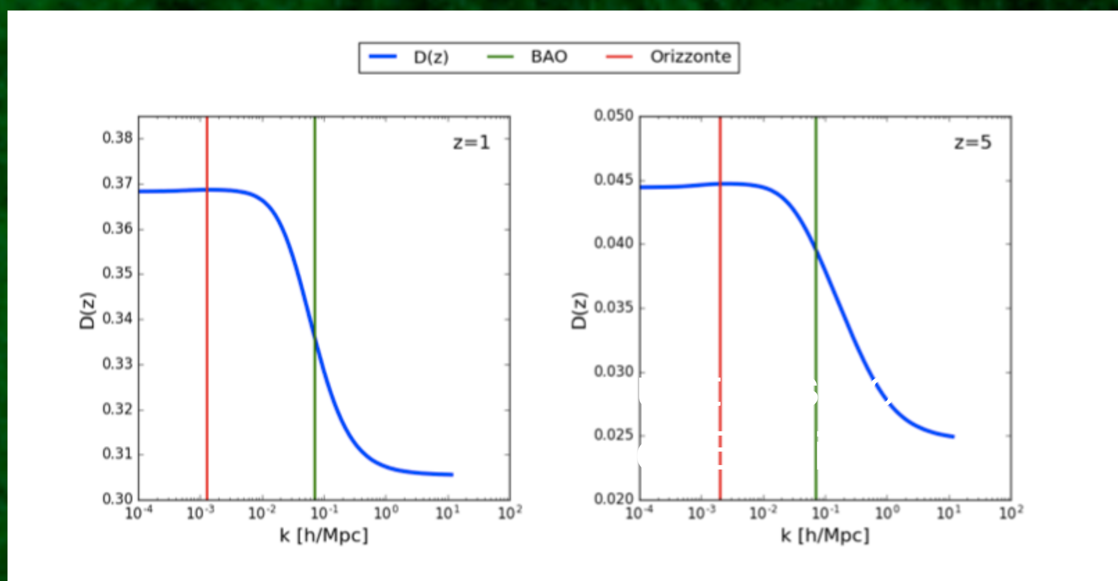


In this case the linear growth rate is scale-dependent

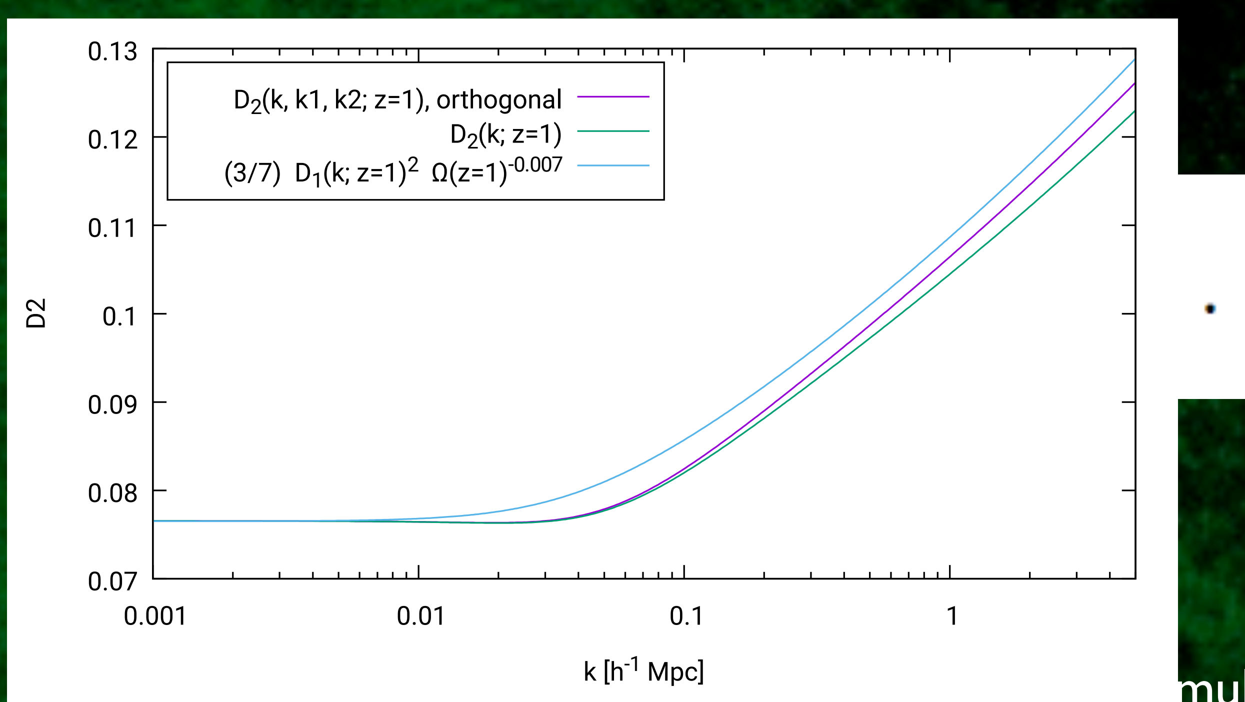


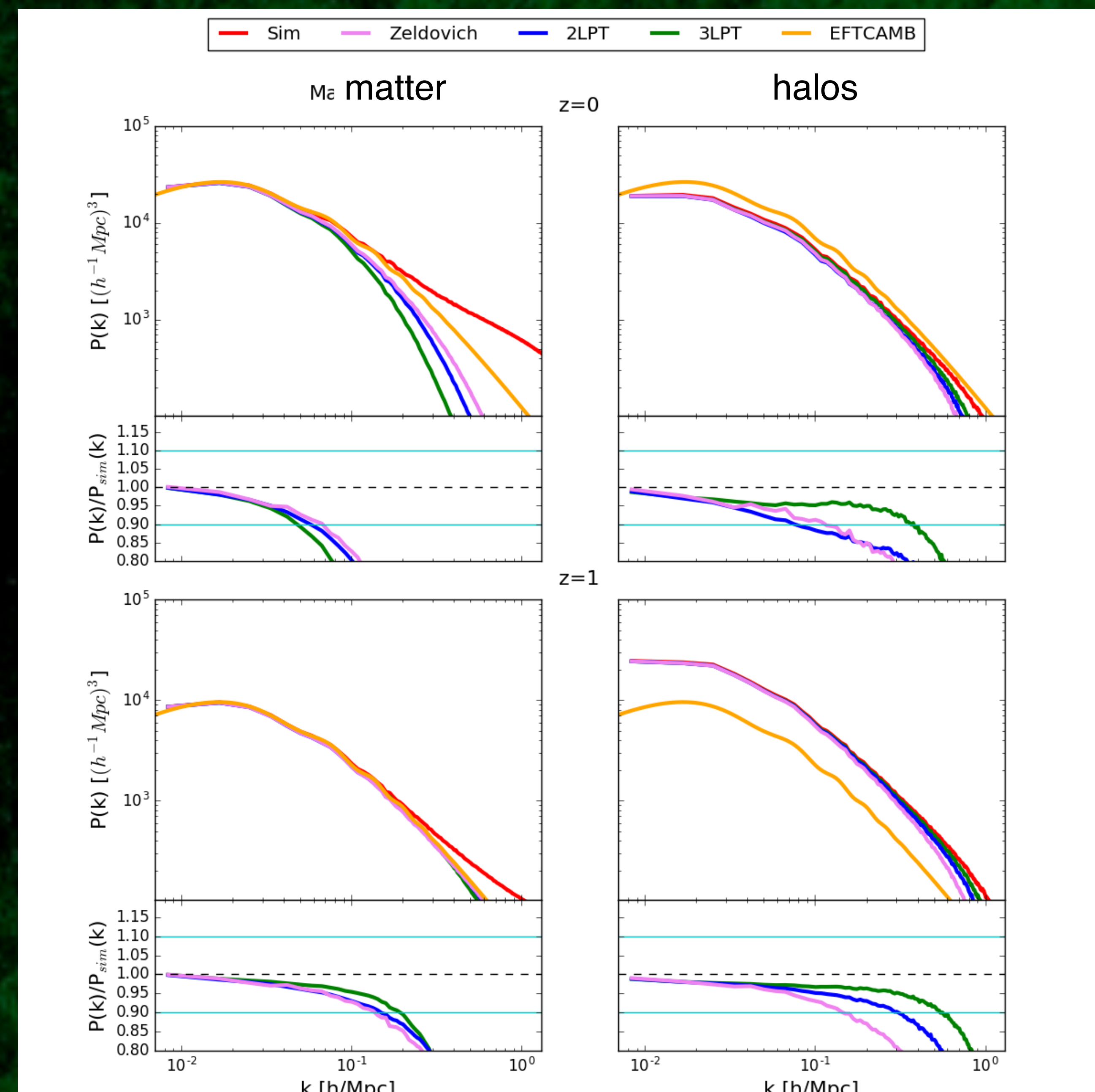
Beyond ΛCDM: f(R) theories

with Simone Mozzon, Chiara Moretti, Lorenzo Pizzuti, Marco Baldi, Alessandra Silvestri, Jorgos Papadomanolakis, Bin Hu, Marco Raveri



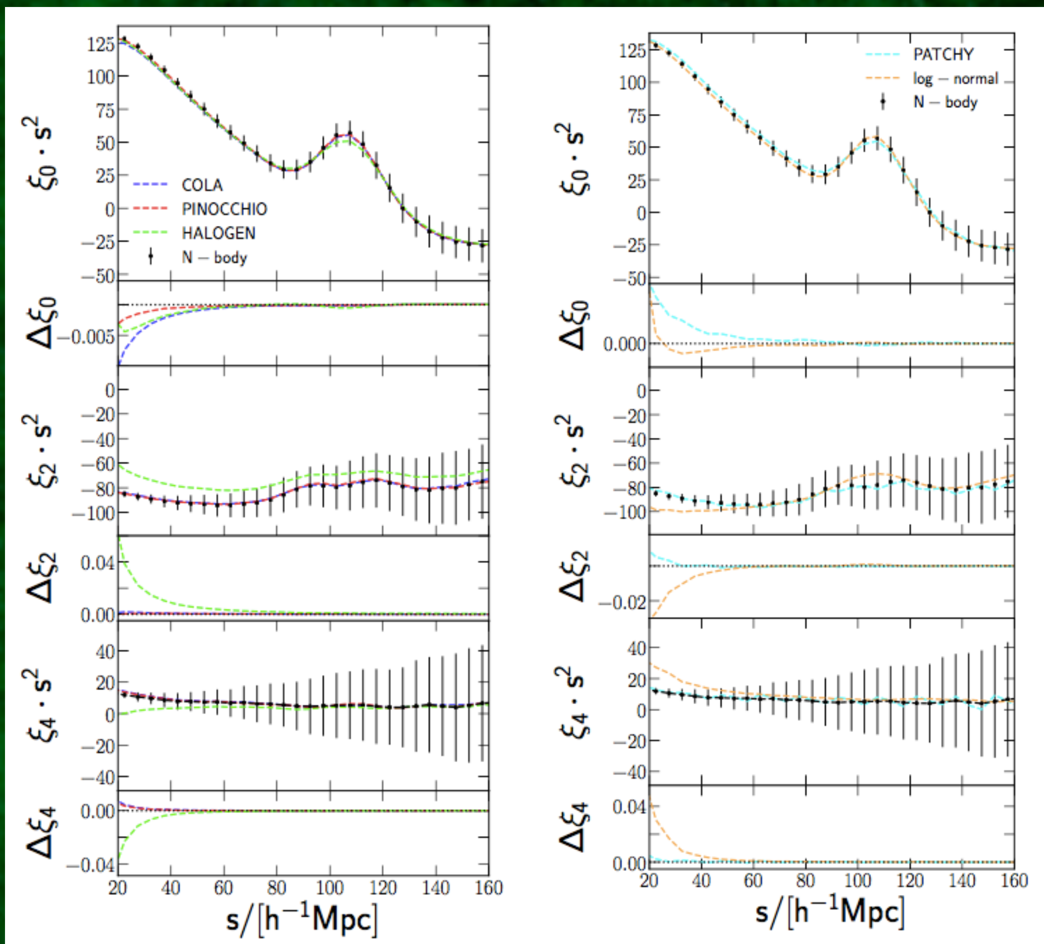
from EFTCAMB P(k)

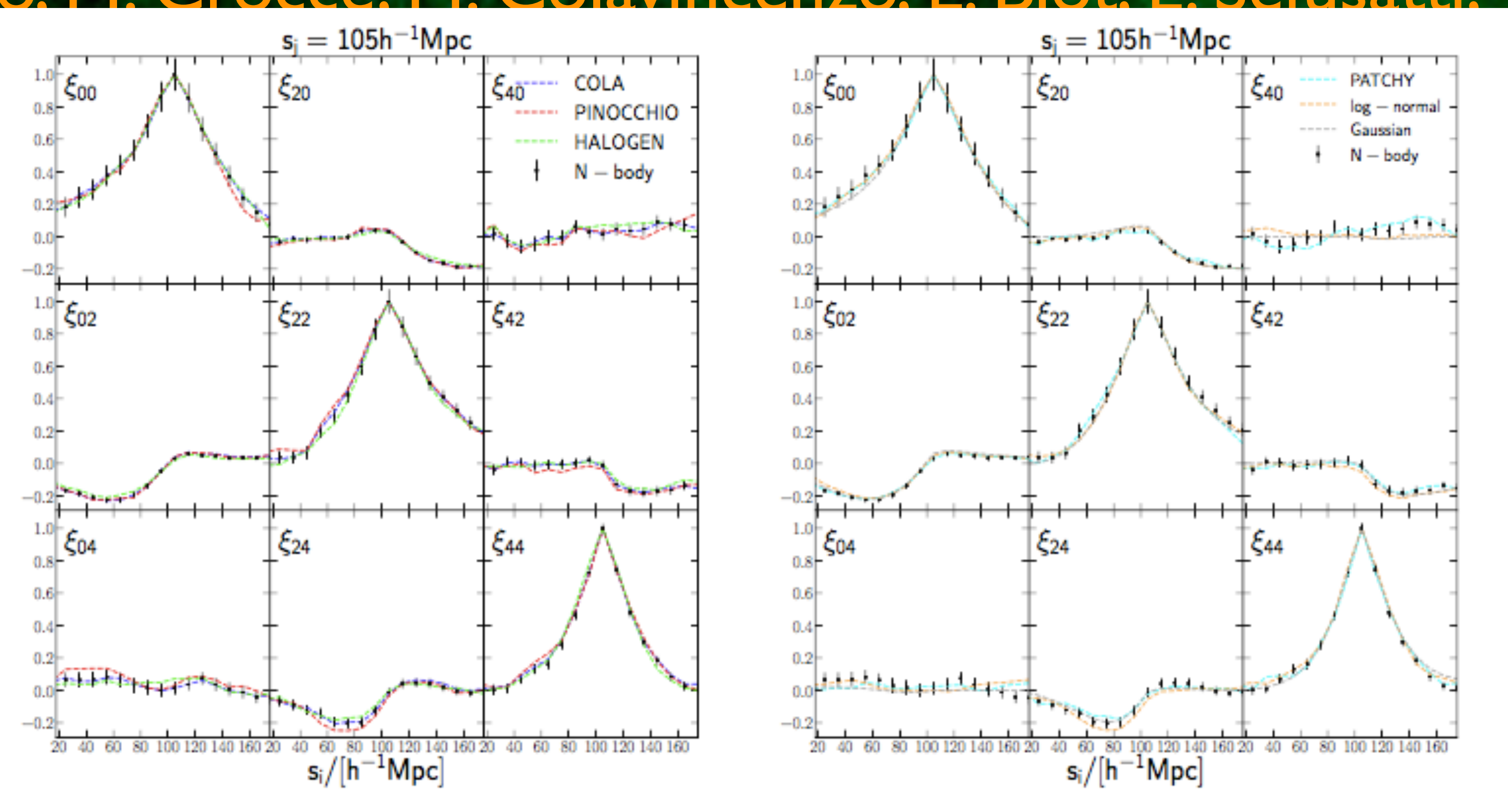


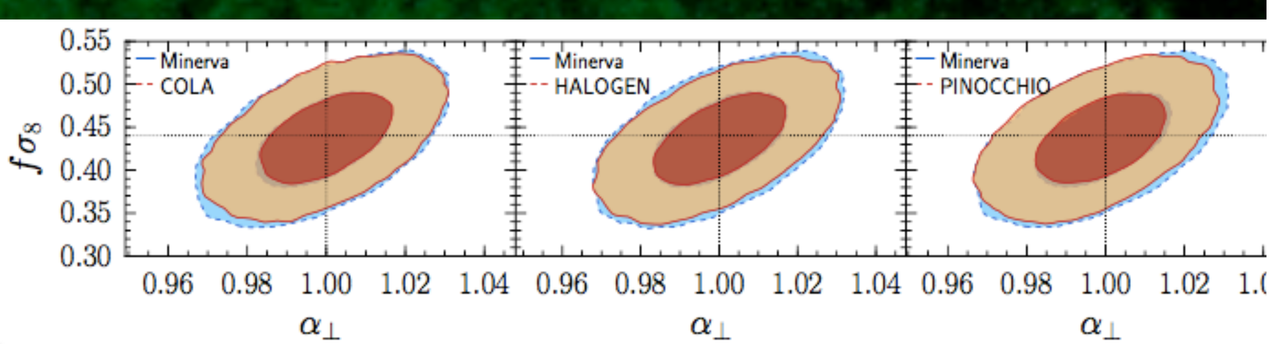


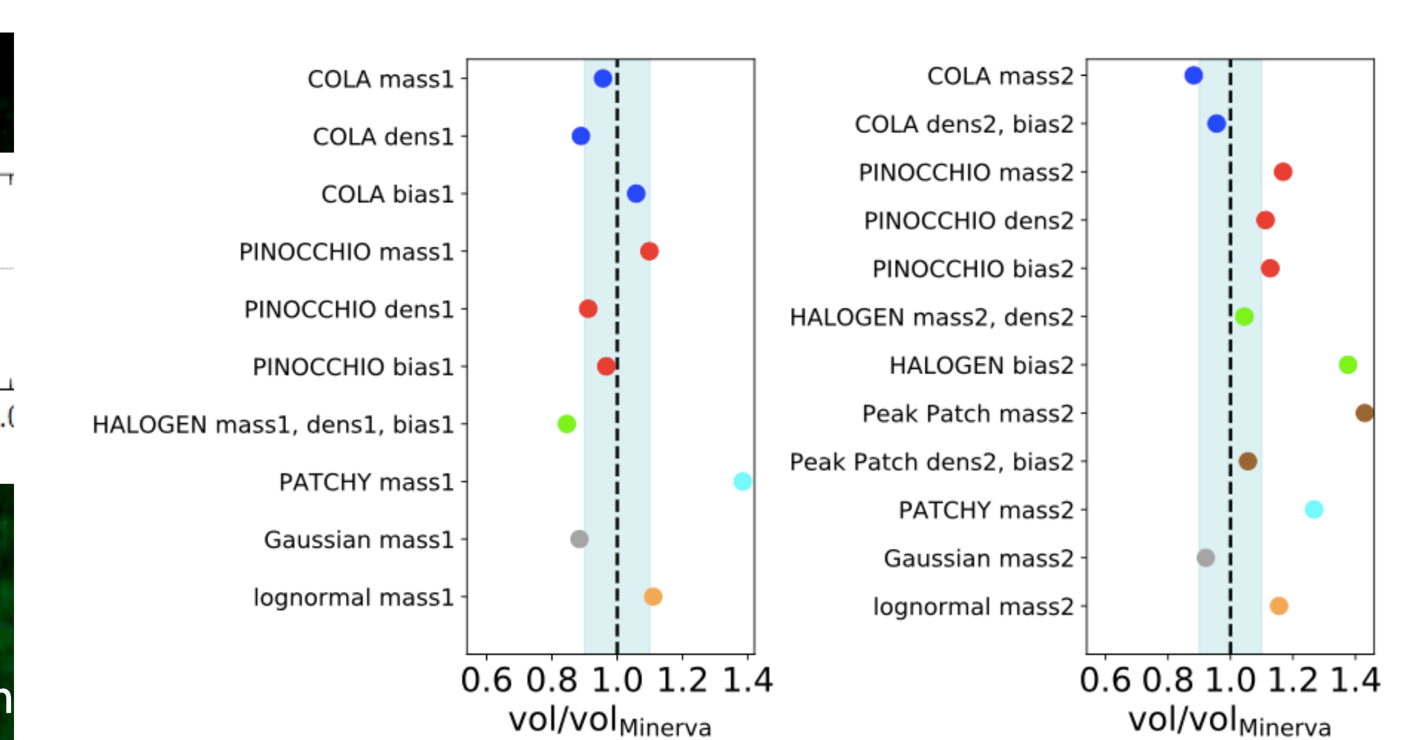
A comparison of covariances from approximate methods: 2-point CF

co, M. Crocce, M. Colavincenzo, L. Blot, E. Sefusatti,









Sim

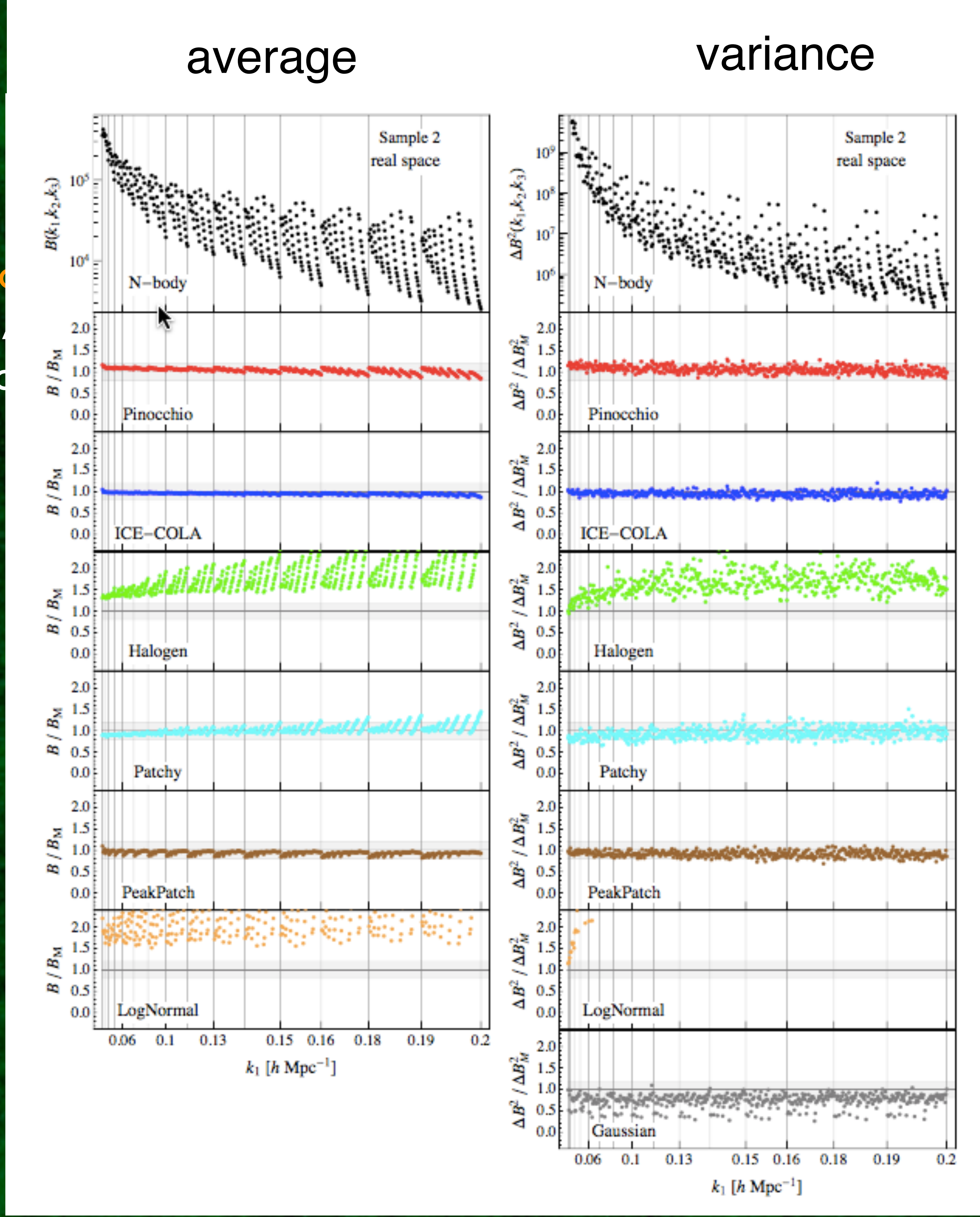
A comparison of covariances from approximate methods: bispectrum

M. Colavincenzo, E. Sefusatti, P. Monaco, M. Crocce, A. G. Sanchez, L. Blot, M. Lippich,
M. Alvarez, A. Agrawal, S. Avila, A. Balaguera-Antolınez, R. Bond, S. Codis, C. Dalla Vecchia, A. Dorta, P. Fosalba, A. Izard, F. S. Kitaura, M. Pellejero-Ibanez, G. Stein, M. Vakili, G. Yepes

M. Colavincenzo

M. Alvarez, A.

Vecchia, A. Do

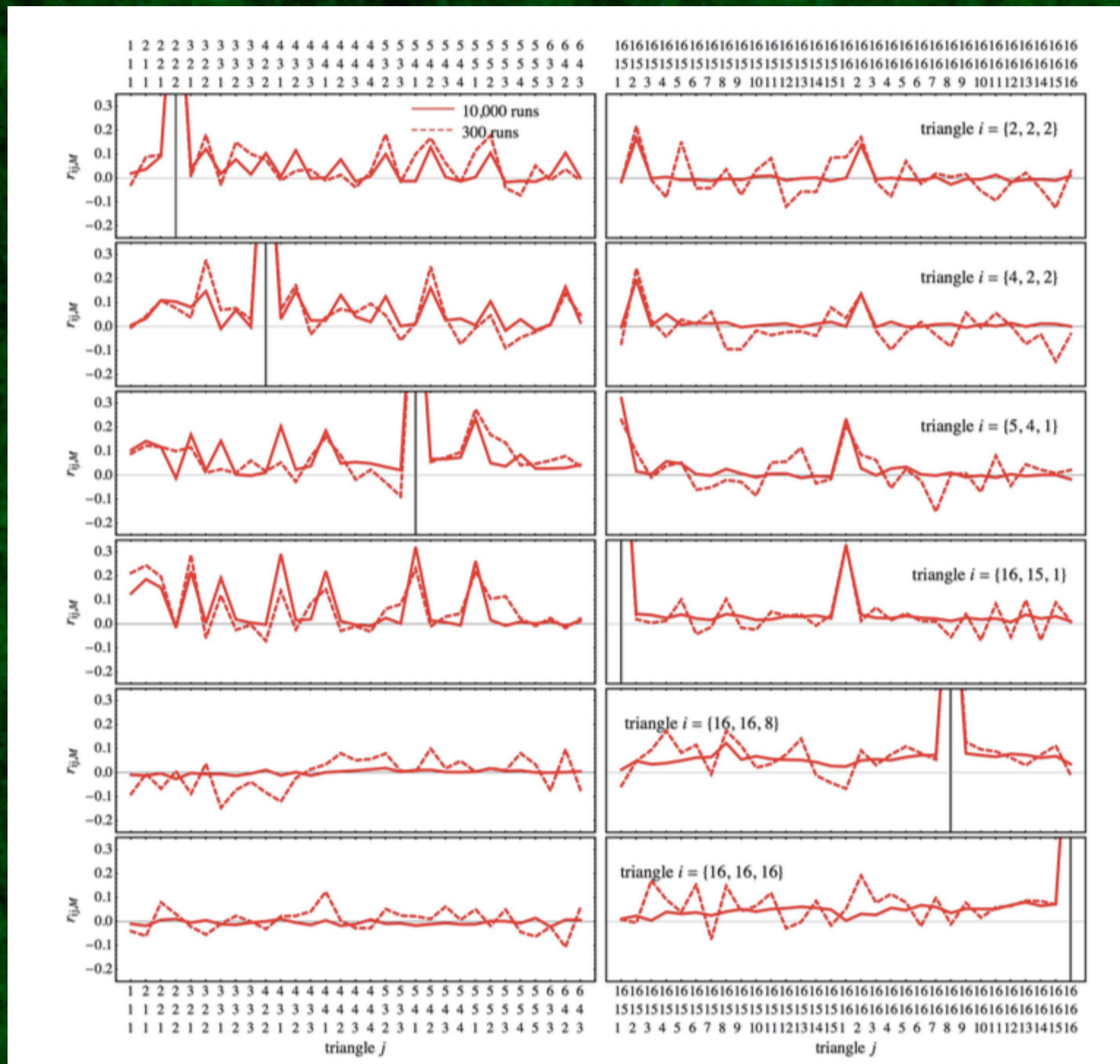


t, M. Lippich,

dis, C. Dalla

G. Stein, M.

Covariance matrix of the bispectrum



Present developments

+ Extend PINOCCHIO to modified gravity theory:

- extend LPT to f(R) theories (Winther et al. 2017, Aviles & Cervantes-Cota 2017)

- extend ellipsoidal collapse using LPT

+ Scale to millions of cores (ExaNeSt, L. Tornatore, G. Taffoni)

+ Power PINOCCHIO displacements with a PM code

+ ...thousands of boxes and light cones for Euclid... (with M. Colavincenzo, E. Sefusatti and Euclid collaboration)