Ateliers action Dark Energy (Jun 2021)

The cosmological imprint of massive neutrinos in dark matter simulations

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Outline

1. Massive neutrinos
2. Non-linear structure formation
3. DEMNUni (phase I)
4. DEMNUni (phase II)
5. DEMNUni (phase III)
6. Conclusions

Massive neutrinos

Experiments on oscillations of neutrinos of different flavours: Masse difference

WHAT IS THEIR ABSOLUTE MASSE ?

Fermi-Dirac momentum distribution $\rho_\nu \propto T^4 \int_0^\infty \frac{q^2 \sqrt{q^2 + (m/T)^2}}{1 + e^q}$

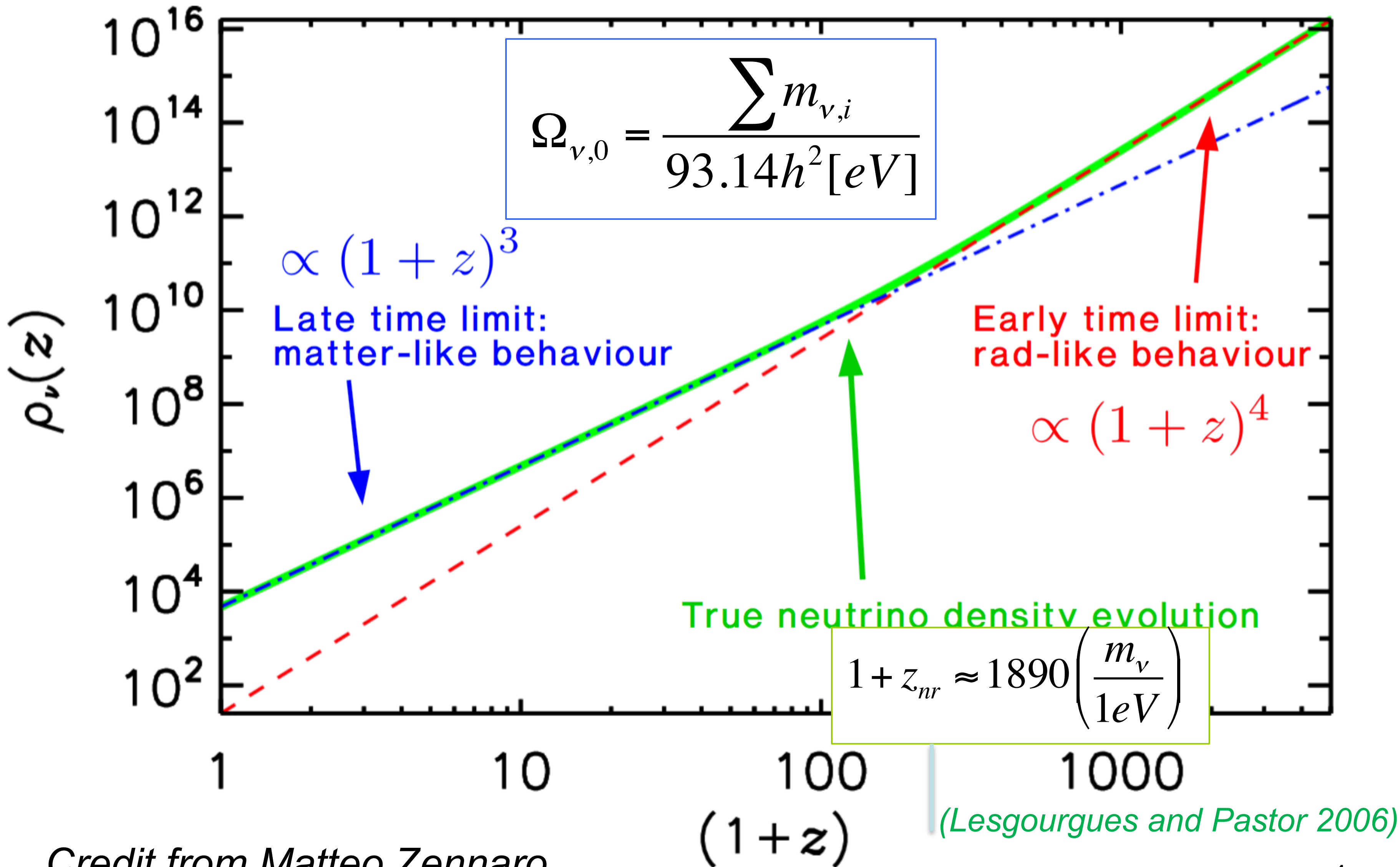
High redshift: $\rho_\nu \propto (1+z)^4$

Low redshift: $\rho_\nu \propto (1+z)^3$

-At high redshift they behave as radiation

-At low redshift they are indistinguishable from matter

Massive neutrinos



$$\Omega_{\nu,0} = \frac{\sum m_{\nu,i}}{93.14h^2[eV]}$$

$$1+z_{nr} \approx 1890\left(\frac{m_\nu}{1eV}\right)$$

(Lesgourgues and Pastor 2006)

Credit from Matteo Zennaro

Massive neutrinos

Non-negligible velocity dispersion:

Newtonian approximation and linearized

$$\frac{\partial \delta_\nu}{\partial \tau} + \vec{\nabla} \cdot \vec{v}_\nu = 0$$ (Continuity equation for neutrinos)

$$\frac{\partial \delta_c}{\partial \tau} + \vec{\nabla} \cdot \vec{v}_c = 0$$ (Continuity equation for CDM)

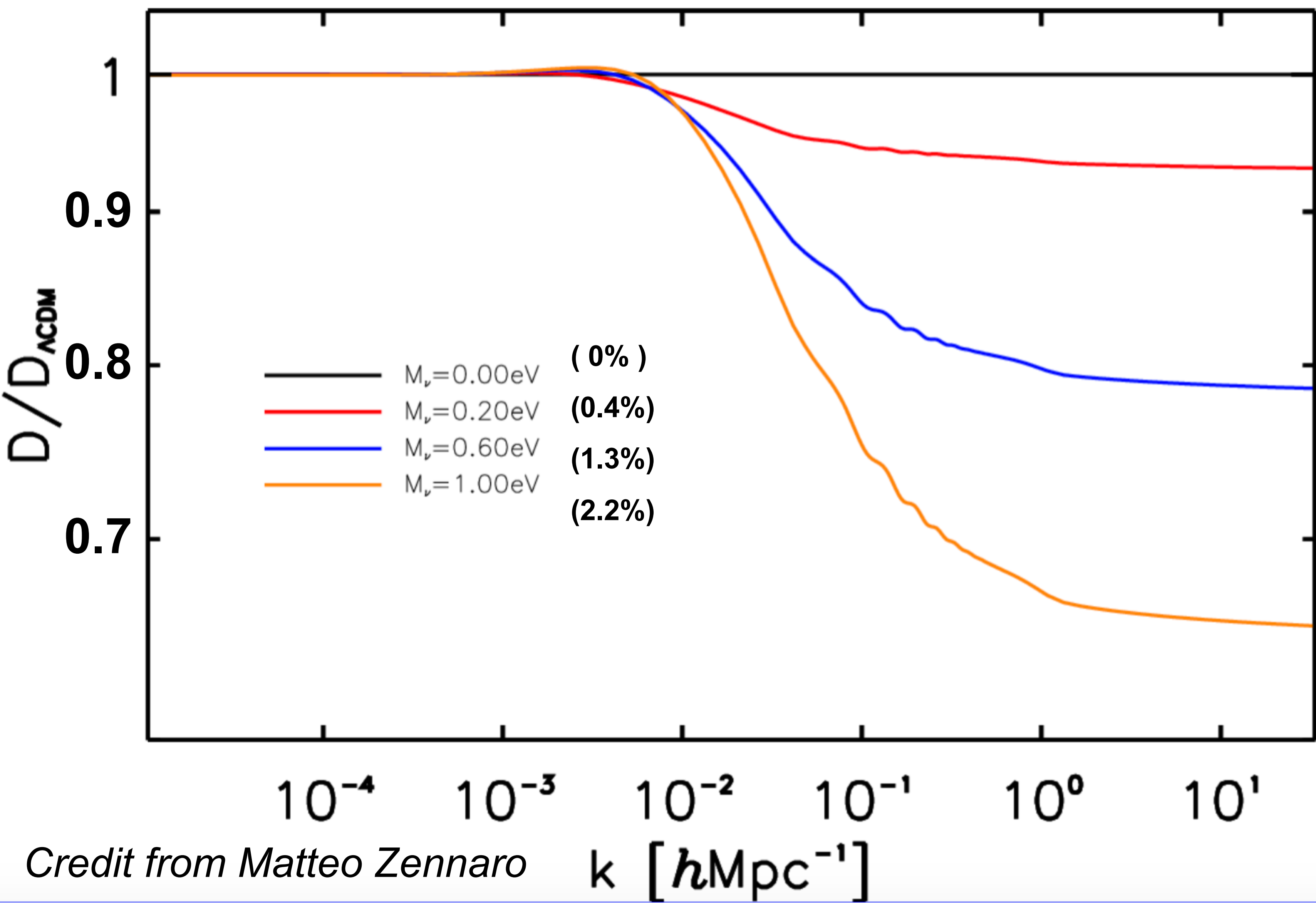
$$\frac{\partial \vec{\nabla} \cdot \vec{v}_\nu}{\partial \tau} + aH\vec{\nabla} \cdot \vec{v}_\nu + \frac{2}{3}\Omega_m (aH)^2 [(1-\nu)\delta_c + \nu\delta_\nu] - c_{eff}^2 \Delta\delta_\nu = 0$$

(Eq. of motions)

$$\frac{\partial \vec{\nabla} \cdot \vec{v}_c}{\partial \tau} + aH\vec{\nabla} \cdot \vec{v}_c + \underbrace{\frac{2}{3}\Omega_m (aH)^2 [(1-\nu)\delta_c + \nu\delta_\nu]}_{\Delta\phi} = 0$$

(Blas et al. 2014)

Massive neutrinos



Credit from Matteo Zennaro

Non linear structure formation

Add a neutrino component to usual particle based dark matter simulations (Viel et al. 2010):

-Like cold dark matter, neutrinos only interact gravitationally

-Starting late enough they behave as non relativistic matter

-They are characterised by a non negligible velocity dispersion

As a result they can be treated as cold dark matter particles with an additional initial velocity distribution following a Fermi-Dirac.

A specific care must be taken in the initial conditions to avoid a large scale loss of power (Zennaro et al. 2017) due to neglecting relativistic effects.

Non linear structure formation

There are other alternatives less expensive than the particle based approach.

Grid based approach : Brandbyge and Hannestad (2008)

Comparisons between grid based and particle based algorithms are presented in Viel et al. 2010

- Euler equation for neutrinos with the non linear gravitational potential (Hali-Haimoud and Bird 2013)

- Solve non-linear neutrino hierarchy on a grid (Dakin et al. 2017)

- Add relativistic corrections on the total Newtonian potential (Adamek et al. 2017; Tram et al. 2018)

- Hybrid methods (Banerjee and Dalal 2016; Bird et al. 2018)

- Rescaling LCDM cosmology to take into account massive neutrinos (Zennaro et al. 2019)

Massive neutrinos effects on LSS

Overall: Lower non-linear evolution of the CDM (reduction of the variance σ_8)

-Halo mass function (Castorina et al. 2015) $\frac{dN}{dM}$

-Void abundance (Massara et al. 2015; Kreisch et al. 2019) $\frac{dN}{dR}$

-Void correlations (Massara et al. 2015; Kreisch et al. 2019; Schuster et al. 2020) $\langle\delta_g\delta_v\rangle$ $\langle\delta_v\delta_v\rangle$

-two-point correlation function linear point (Parimbelli et al. 2021)

-Higher order statistics; Bi-spectrum; Tri-spectrum etc… (Ruggeri et al. 2017)

-CDM velocity field -> Redshift space distortions (Villaescusa-Navarro et al. 2017)

-Integrated Sachs-Wolfe and Rees-Sciama effects (Carbone et al. 2016)

$$\Delta T(\hat{n}) = \frac{2}{c^3}\bar{T}_0 \int_0^{r_{\rm L}} \dot{\Phi}(r,\hat{n})\, a\, dr$$

DEMNUni simulations

The Dark Energy and Massive Neutrinos Universe project

Research Group:

Carmelita Carbone (**PI**),

Emiliano Sefusatti,

Adam Hawken,

Matteo Zennaro,

Matteo Calabrese,

Mauro Roncarelli,

Francisco Villaescusa-Navarro,

Klaus Dolag, …

DEMNUni simulations

- 8×10^6 cpu-hours on BGQ/FERMI at CINECA (PI: C. Carbone)
- 10 mixed dark matter cosmological simulations for CMB and LSS analysis in the presence of evolving dark-energy (w_0, w_a) and massive neutrinos
- Baseline Planck cosmology
- Gadget-3 with ν-particle component (Viel et al. 2010)
- box-side size: 2 Gpc/h
- particle number: 2×2048^3 (CDM+ν)
- CDM mass: 8×10^{10} $M_\odot$/h (neutrino particle mass depends on M_ν)
- softening length: 20 kpc/h
- starting redshift: z_{in}=99

$$k_{\rm nr} = 0.018 (m_\nu / 1 {\rm eV})^{1/2} \Omega_m^{1/2} h/{\rm Mpc}$$

DEMNUni simulations

Simulations outputs:

- 62 temporary snapshots per simulation: ~0.54 TB/snap (CDM+ ν)
- 10 halo-catalogs per simulation
- 10 sub-halo catalogs per simulation
- Matter power-spectra for all the 62 snapshots
- 62 temporary gravitational potential grids of size 4096^3 (for CMB weak-lensing)
- 62 temporary grids of size 4096^3 for the derivative of the gravitational potential (for ISW/Rees-Sciama)
- 90 TB of data in total per simulation

DEMNUni (Phase I)

The DEMNUni cosmology:

$$h = 0.67$$
$$\Omega_\Lambda = 0.68$$
$$\Omega_m = 0.32$$
$$\Omega_b = 0.05$$
$$n_s = 0.96$$

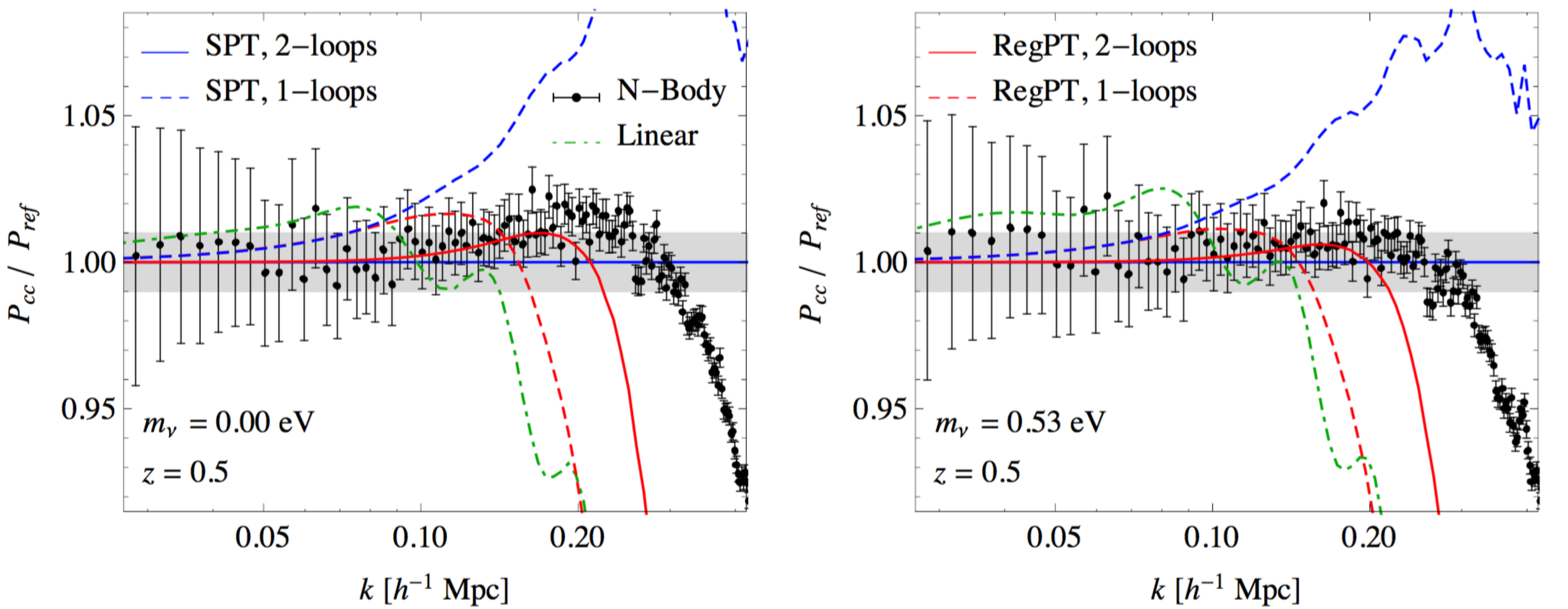
$$M_\nu = 0, \quad 0.17, \quad 0.3, \quad 0.53 eV$$

$$\sigma_{8,m} = 0.85, \quad 0.80, \quad 0.77, \quad 0.72$$ (total matter)

$$\sigma_{8,c} = 0.85, \quad 0.81, \quad 0.79, \quad 0.74$$ (cold dark matter)

DEMNUni (Phase I)

Comparison with perturbation theory:

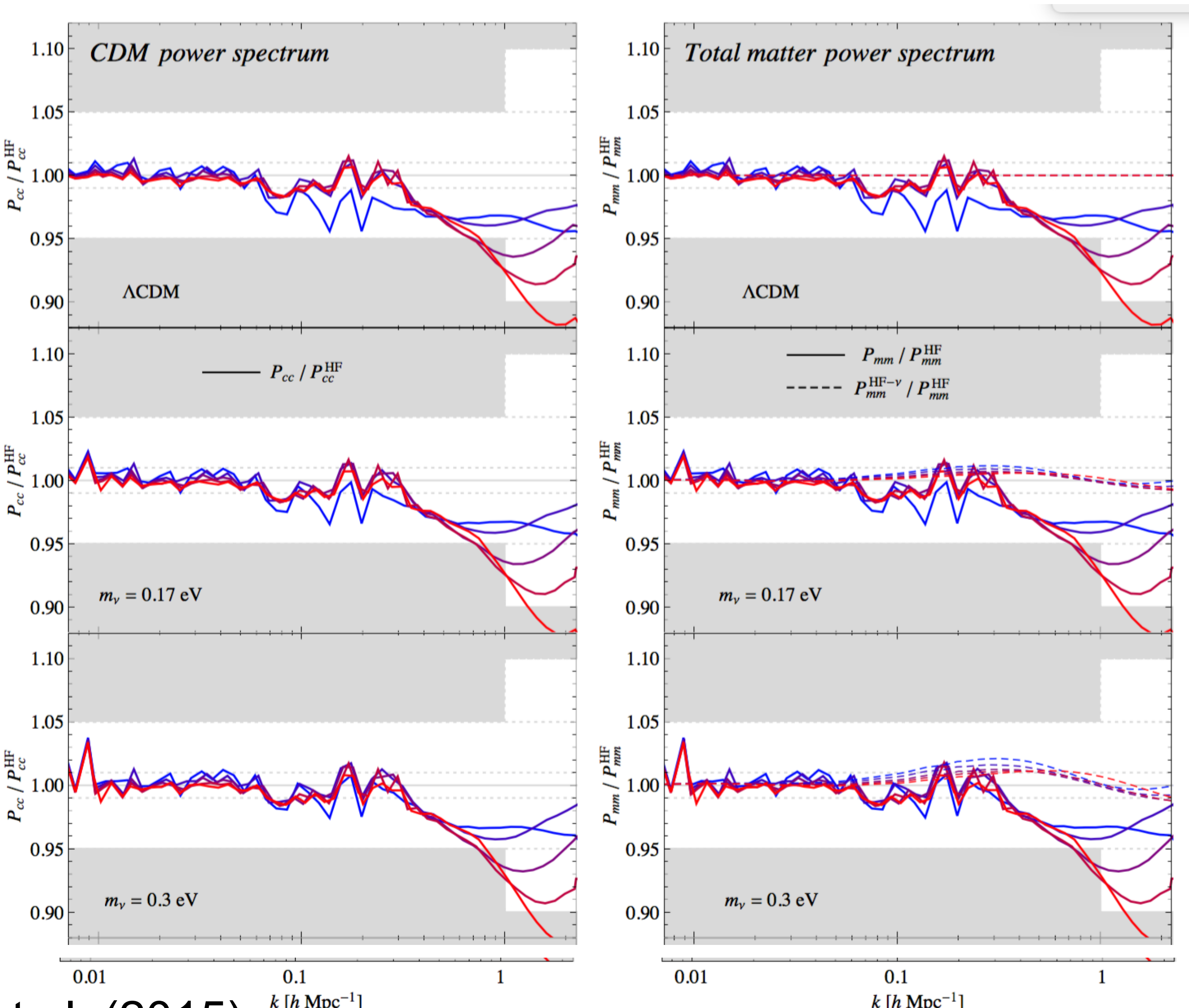


LCDM perturbation techniques can be applied to the CDM only

Castorina et al. (2015)

DEMNUni (Phase I)

Comparison with Halofit:



Castorina et al. (2015)

DEMNUni (Phase I)

CDM velocity spectra (useful for RSD analysis)

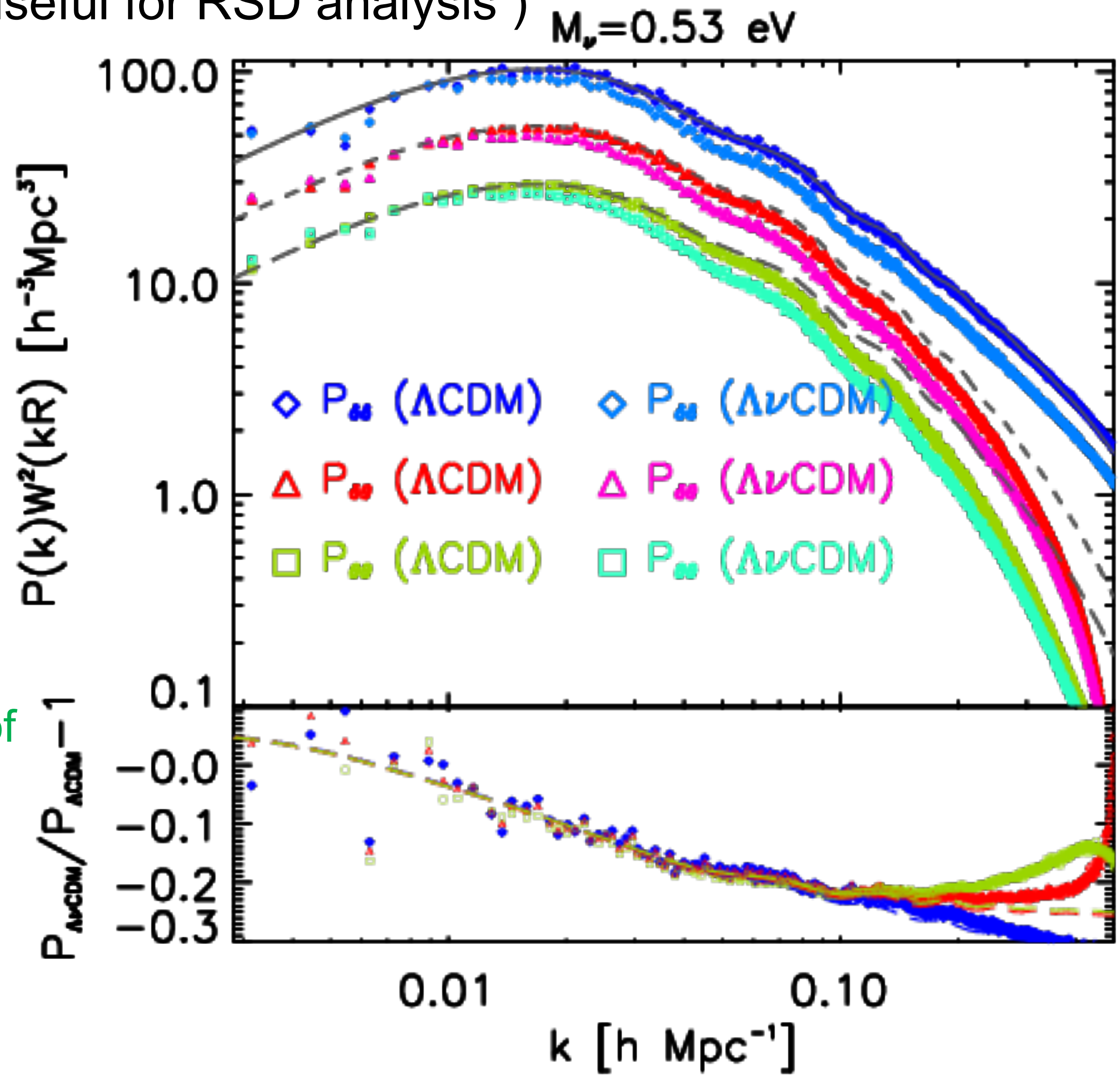
$$\theta \equiv \vec{\nabla} \cdot \vec{v}$$

$$P_{\delta\theta}(k) = k_F^3 \langle \delta_{\vec{k}} \theta_{\vec{k}}^* \rangle$$

$$P_{\theta\theta}(k) = k_F^3 \langle \theta_{\vec{k}} \theta_{\vec{k}}^* \rangle$$

$$k_F = \frac{2\pi}{L}$$

Fundamental frequency of the simulation comoving output (*box*)



2048^3 particles in a L^3=**2000**^{3} $h^{-3}Mpc^3$ box

Pezzota et al. (2019)

DEMNUni (Phase II)

Change the expansion rate with dynamical dark energy:

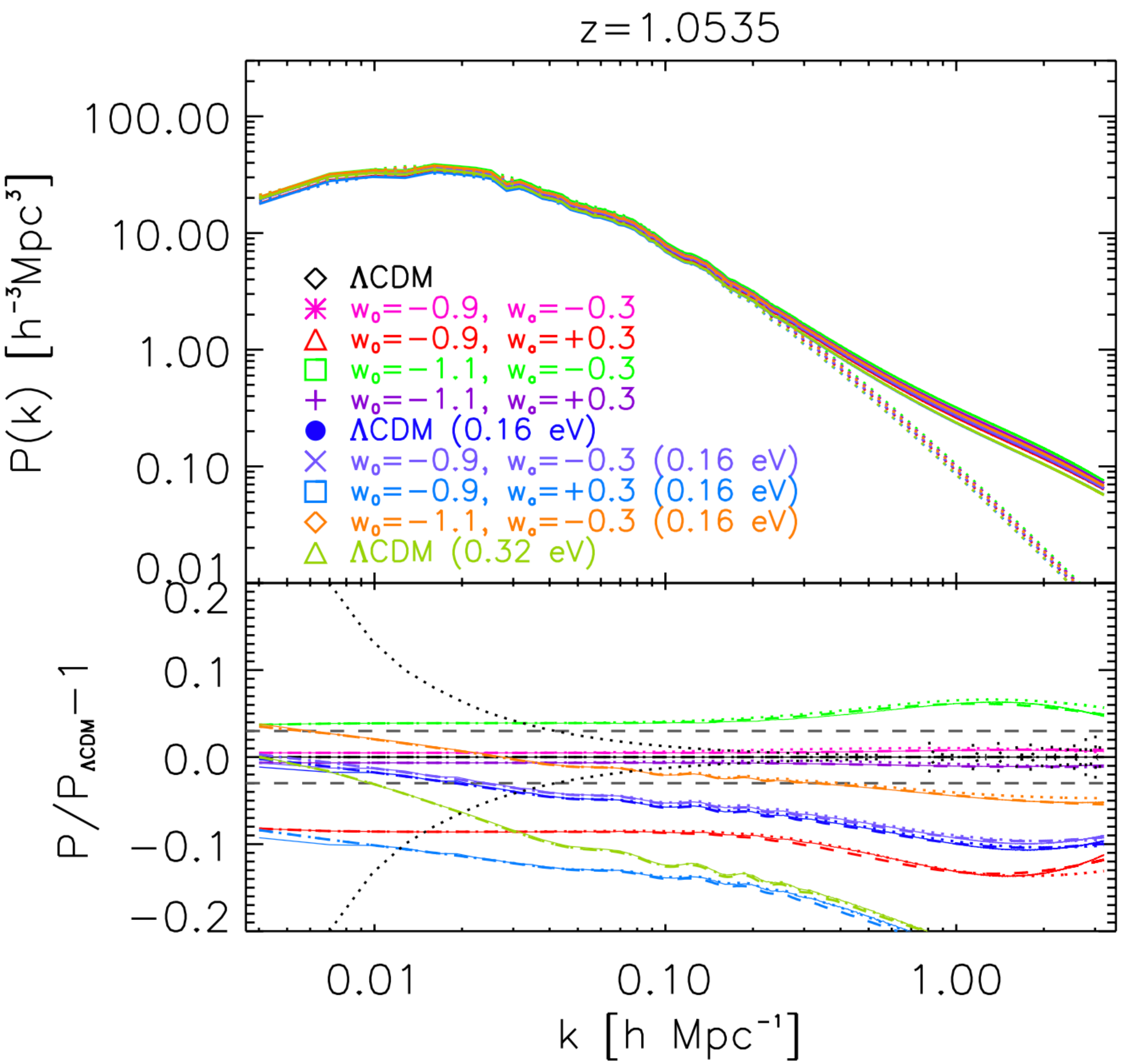
$$w(z) = w_0 + w_a z/(1+z)$$

- ◇ ΛCDM
- ✳ $w_0=-0.9,\ w_a=-0.3$
- △ $w_0=-0.9,\ w_a=+0.3$
- □ $w_0=-1.1,\ w_a=-0.3$
- \+ $w_0=-1.1,\ w_a=+0.3$
- ● ΛCDM (0.16 eV)
- × $w_0=-0.9,\ w_a=-0.3$ (0.16 eV)
- □ $w_0=-0.9,\ w_a=+0.3$ (0.16 eV)
- ◇ $w_0=-1.1,\ w_a=-0.3$ (0.16 eV)
- △ ΛCDM (0.32 eV)

} new neutrino masses

DEMNUni (Phase II)

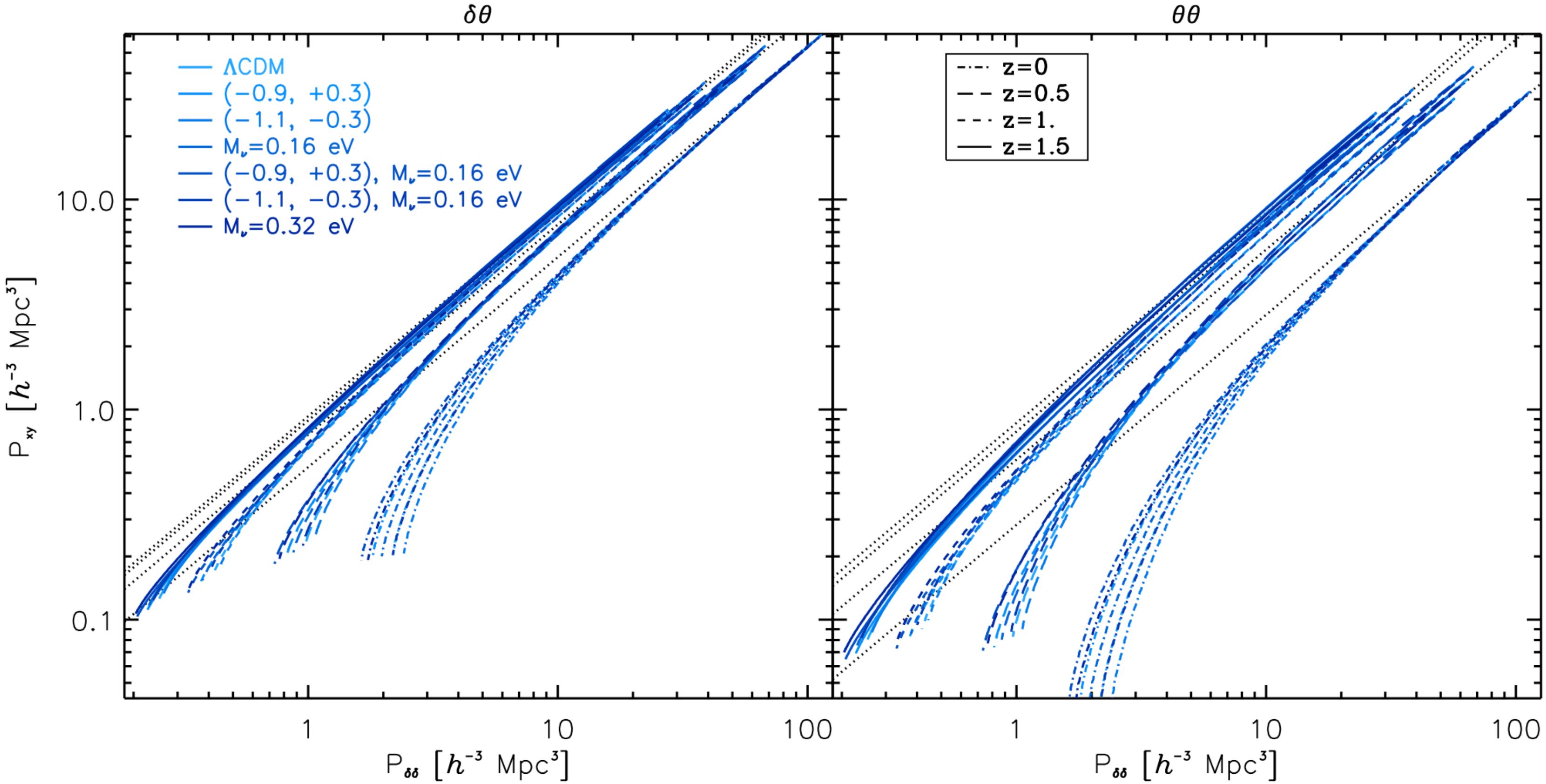
Power spectra with good spatial resolution ($k_{Nyquist}$=3.14 hMpc^{-1}):



Ongoing project…

DEMNUni (Phase II)

Velocity field on 512^3 grid at 4 redshifts (z = 0., 0.5, 1., 1.5)



Linear theory: $\vec{\nabla}\cdot\vec{v} = -aHf\,\delta(t,\vec{x})$

Ongoing project…

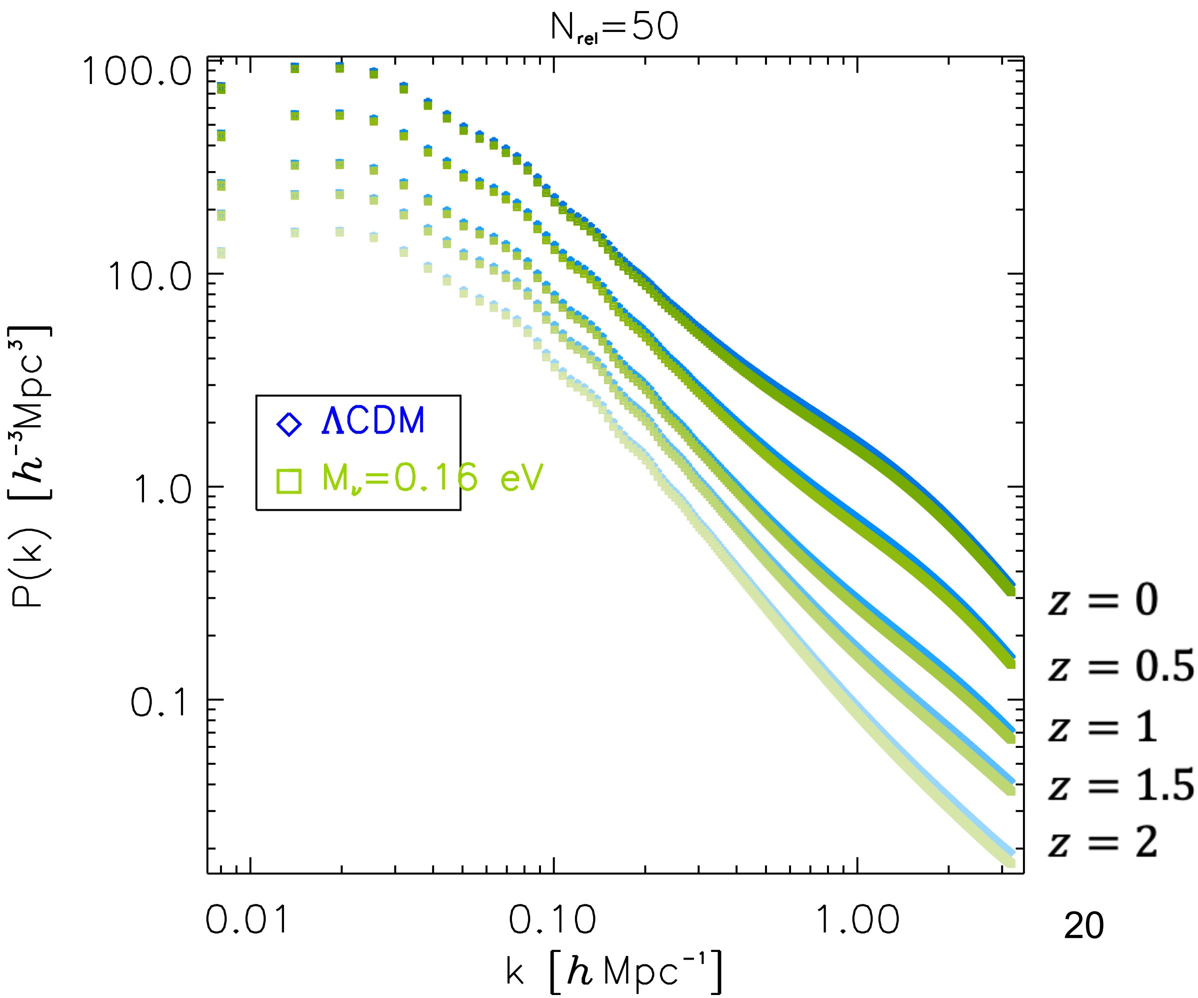
DEMNUni (Phase III)

Select two cosmologies: LCDM and LCDM + Mnu = 0.16eV

Smaller volume (same resolution): 1 h^{-3}Gpc^3

-> 50 realisations for both cosmologies

Real space CDM mean spectra:

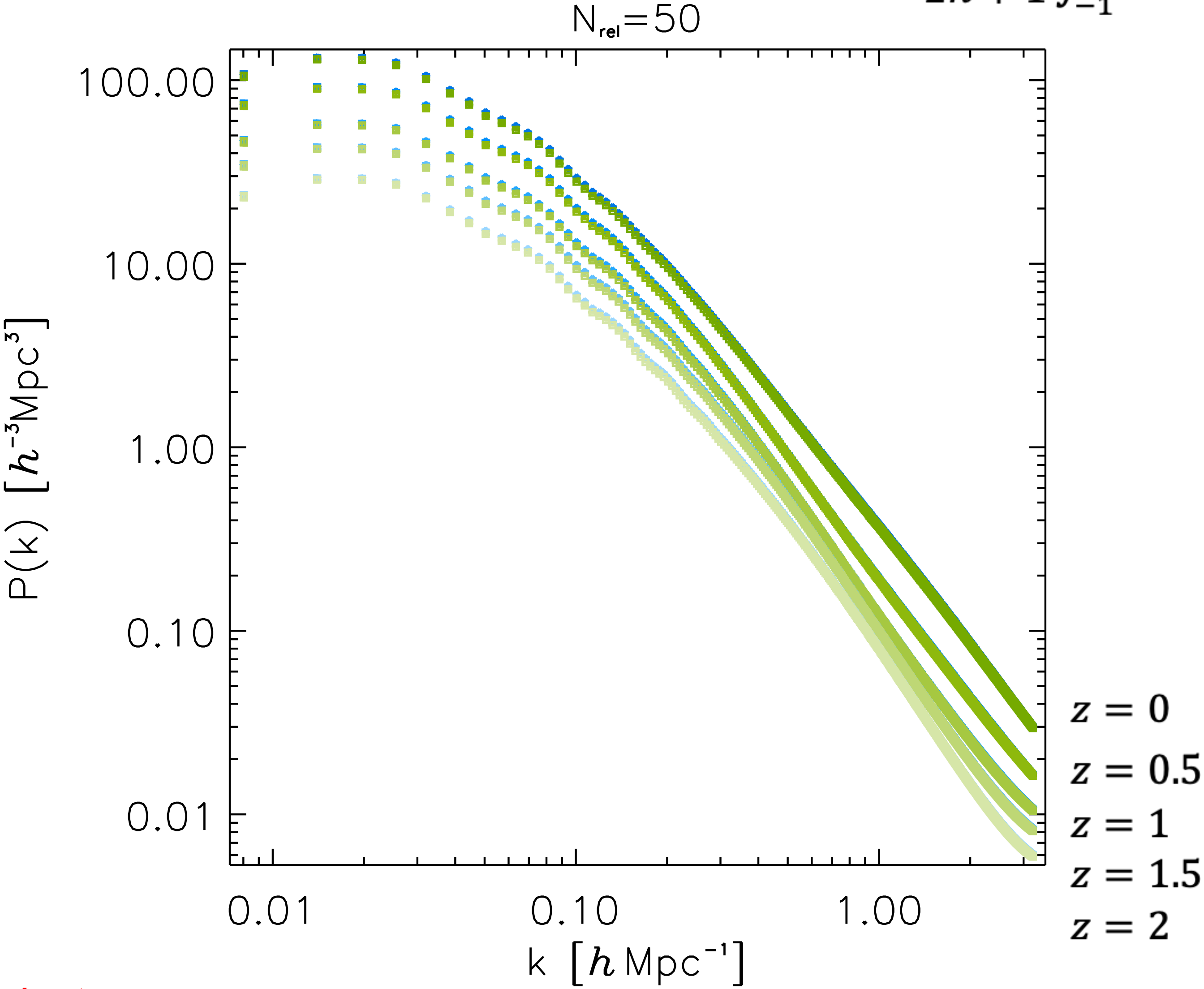


Ongoing project…

DEMNUni (Phase III)

Monopole (n=0):

$$P^{(n)}(k) = \frac{2}{2n+1}\int_{-1}^{1} P(k,\mu)L_n(\mu)d\mu$$

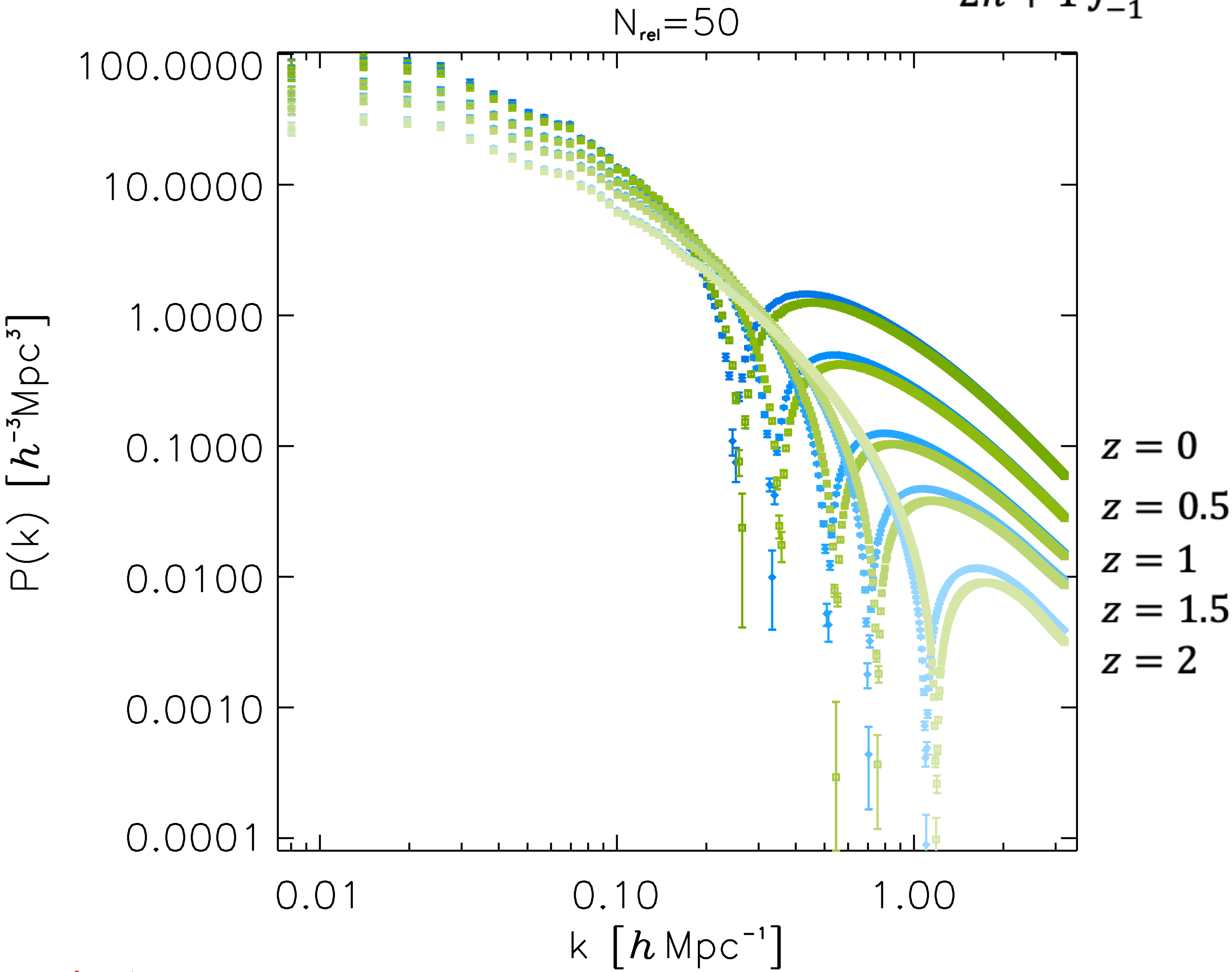


Ongoing project…

DEMNUni (Phase III)

Quadrupole (n=2):

$$P^{(n)}(k) = \frac{2}{2n+1}\int_{-1}^{1} P(k,\mu)L_n(\mu)d\mu$$

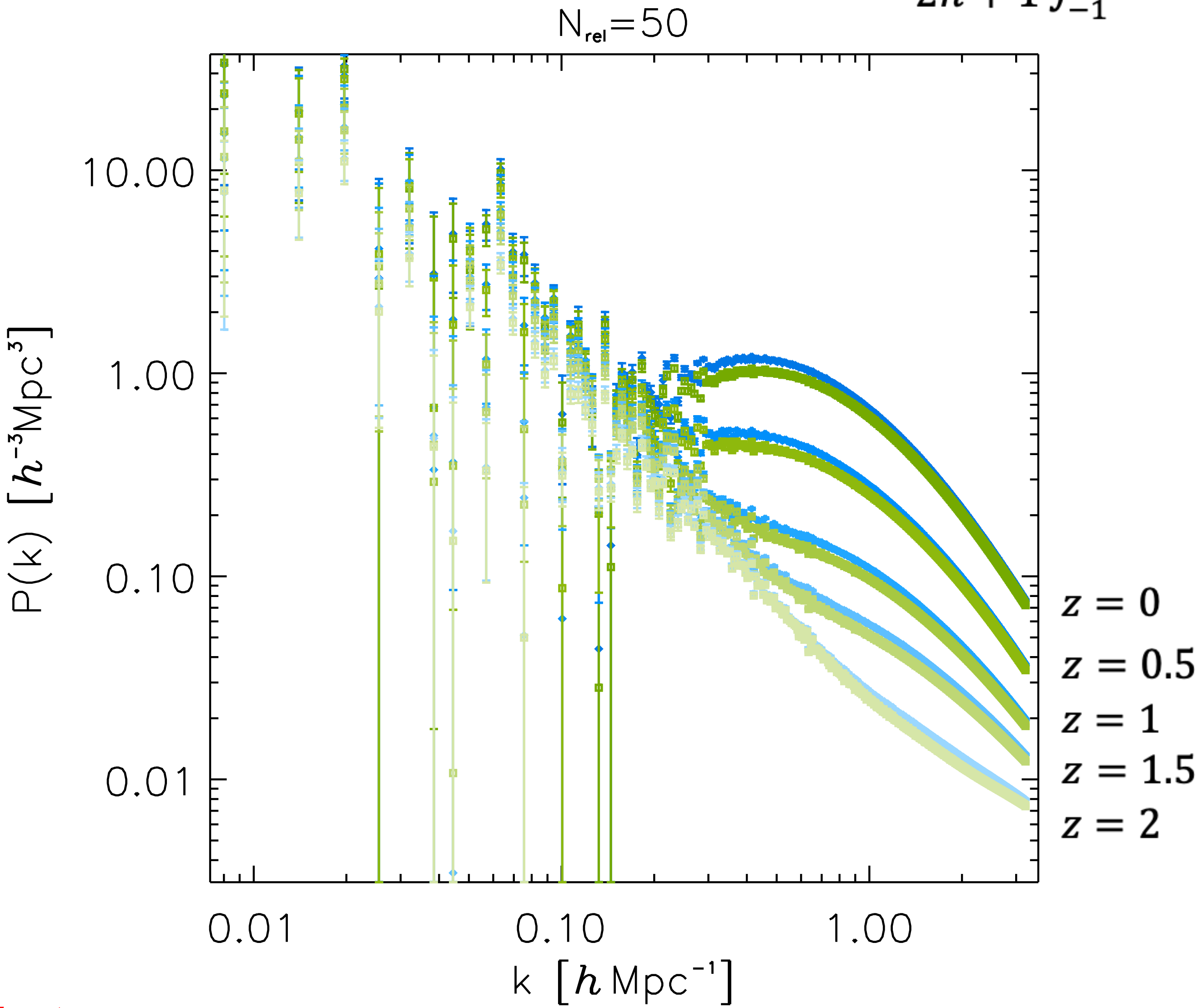


Ongoing project…

DEMNUni (Phase III)

Hexadecapole (n=4):

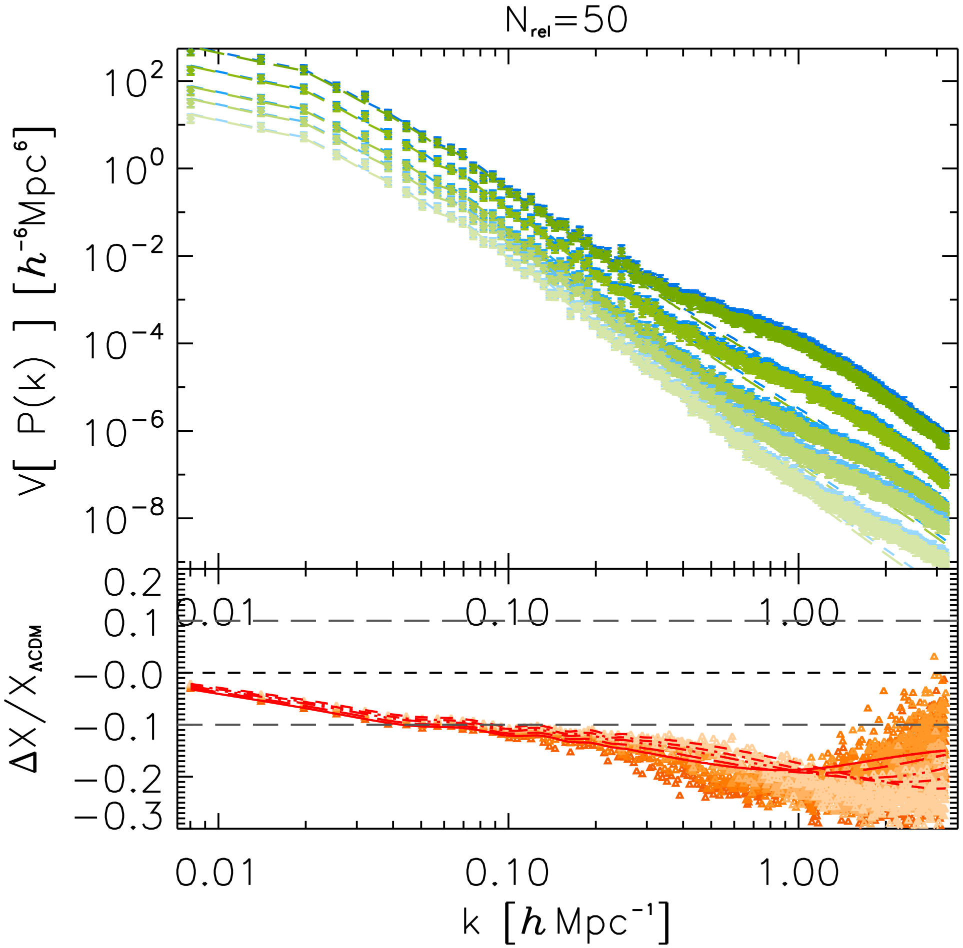
$$P^{(n)}(k) = \frac{2}{2n+1}\int_{-1}^{1} P(k,\mu)L_n(\mu)d\mu$$



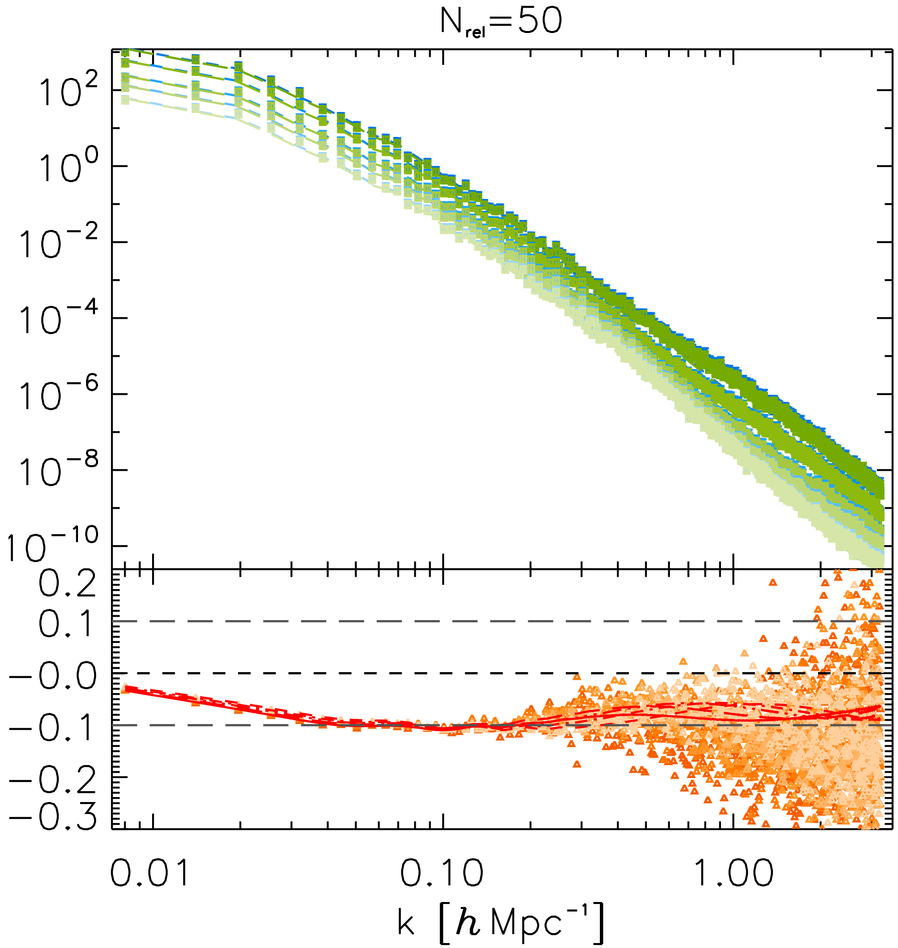
Ongoing project…

DEMNUni (Phase III)

Real space Variance:



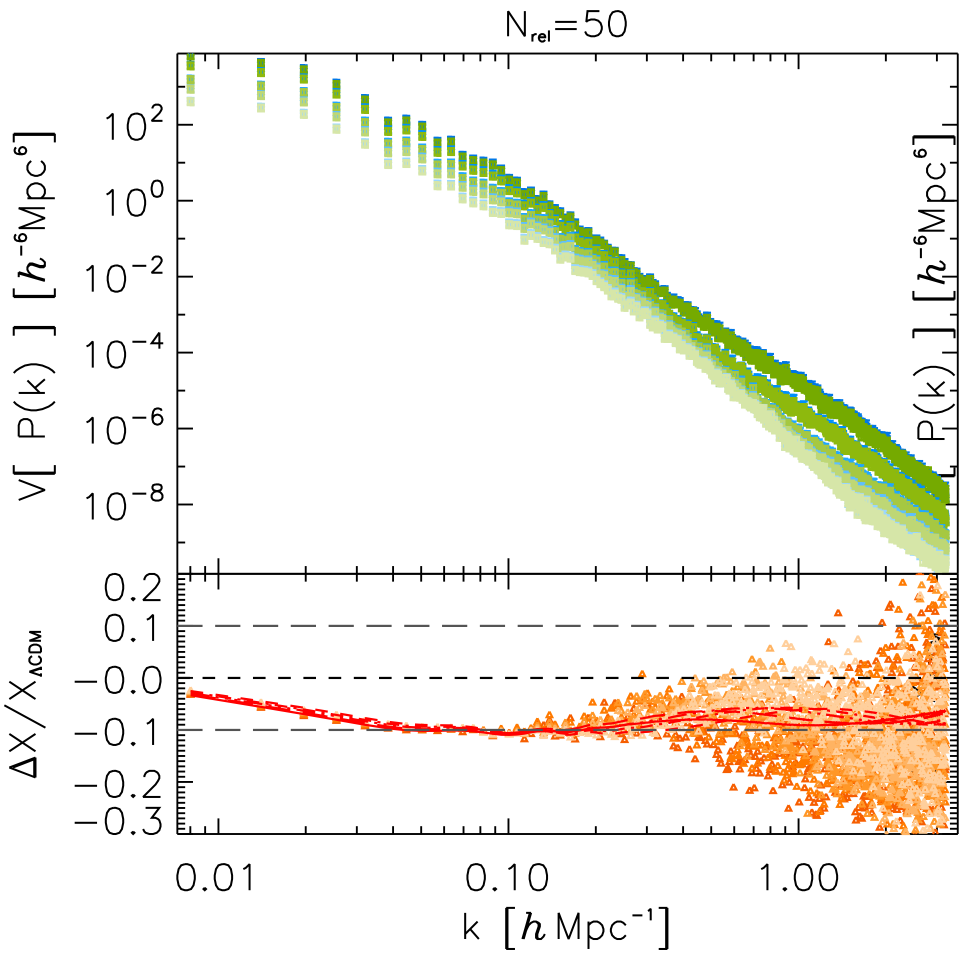
Redshift space Variance:



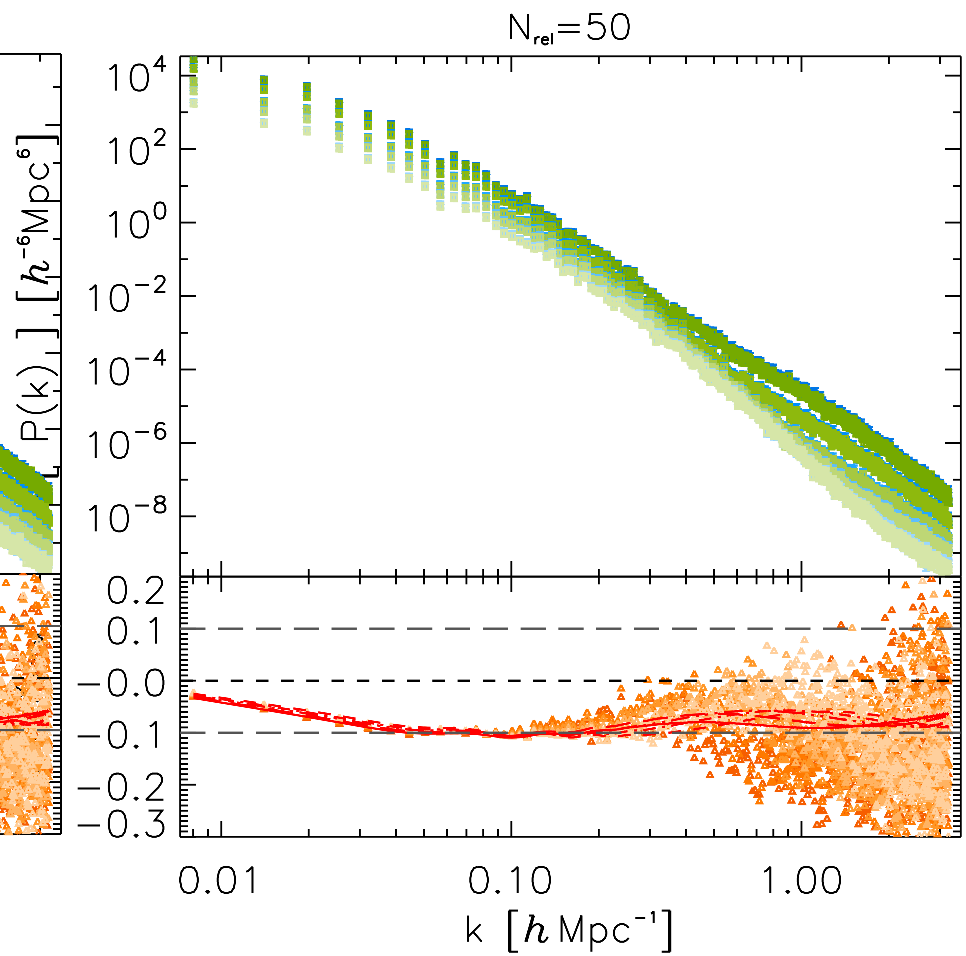
Ongoing project…

DEMNUni (Phase III)

Redshift space quadrupol
Variance:



Redshift space hexadecapol
Variance:



Ongoing project…

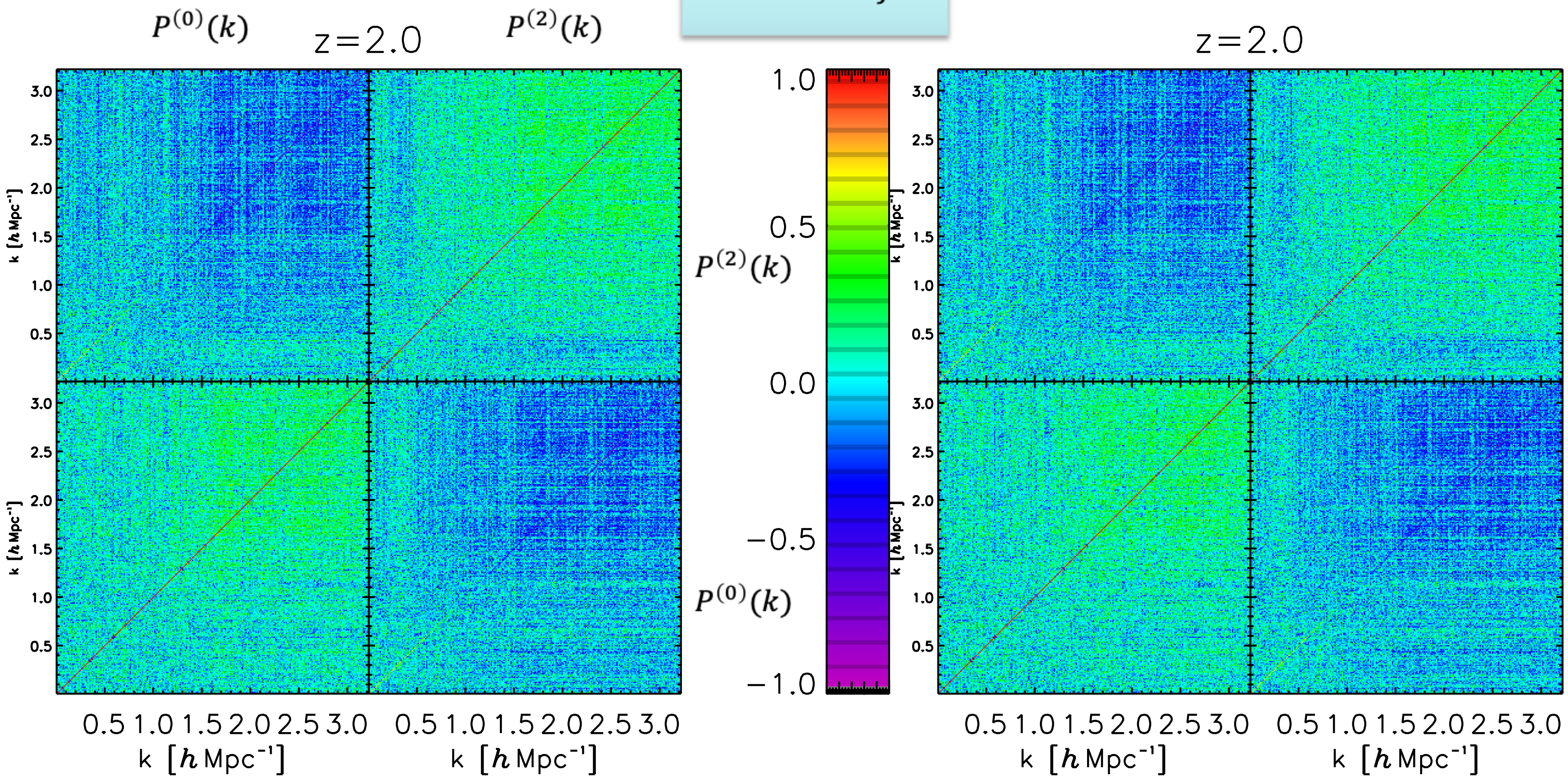
$$C_{ij} = \langle (P(k_i) - \langle P(k_i) \rangle)(P(k_j) - \langle P(k_j) \rangle) \rangle$$

DEMNUni (Phase III)

LCDM:

Mnu = 0.16 eV:

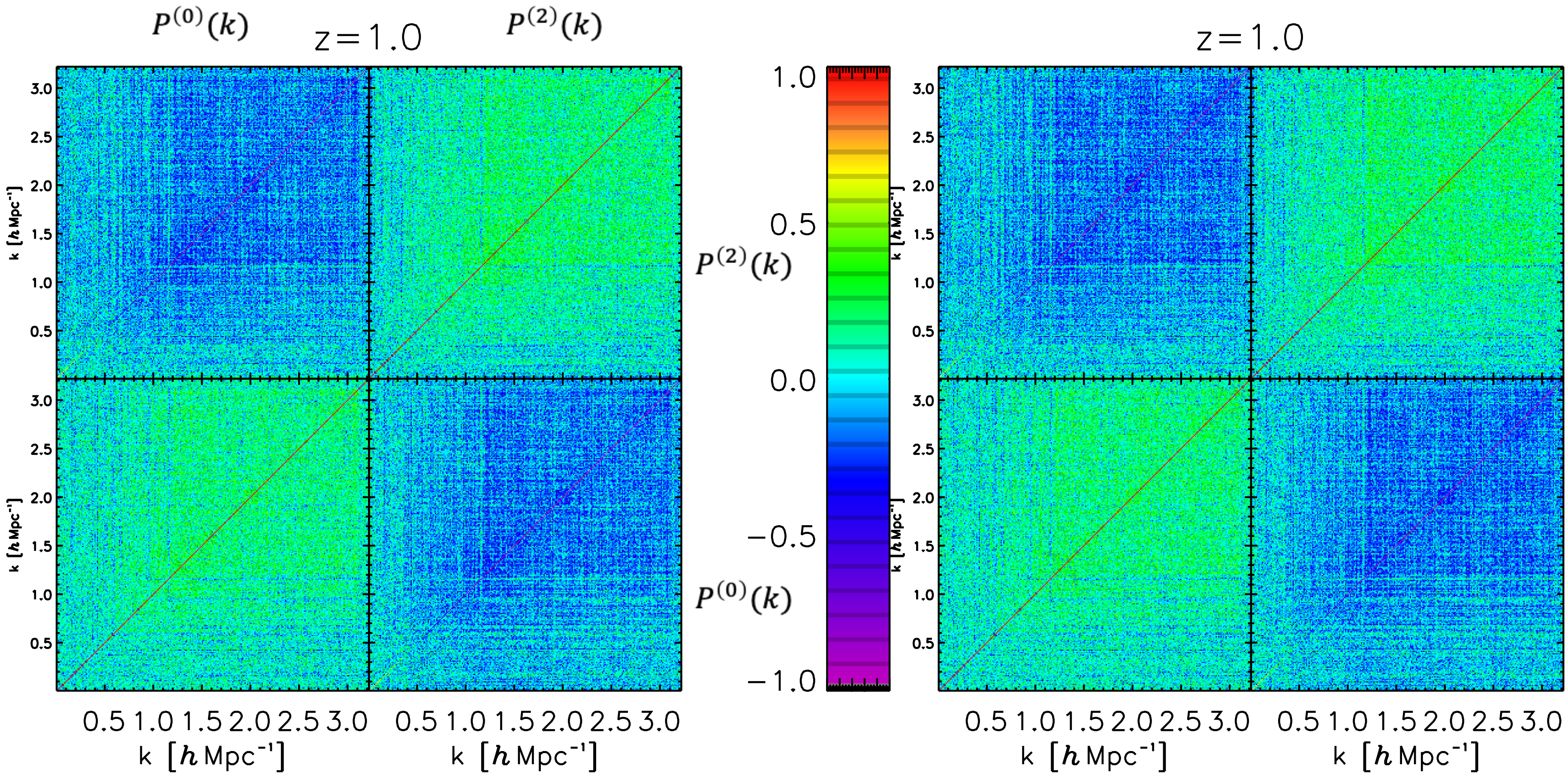
$$r_{ij} \equiv \frac{C_{ij}}{\sigma_i \sigma_j}$$



Ongoing project…

DEMNUni (Phase III)

LCDM: Mnu = 0.16 eV:

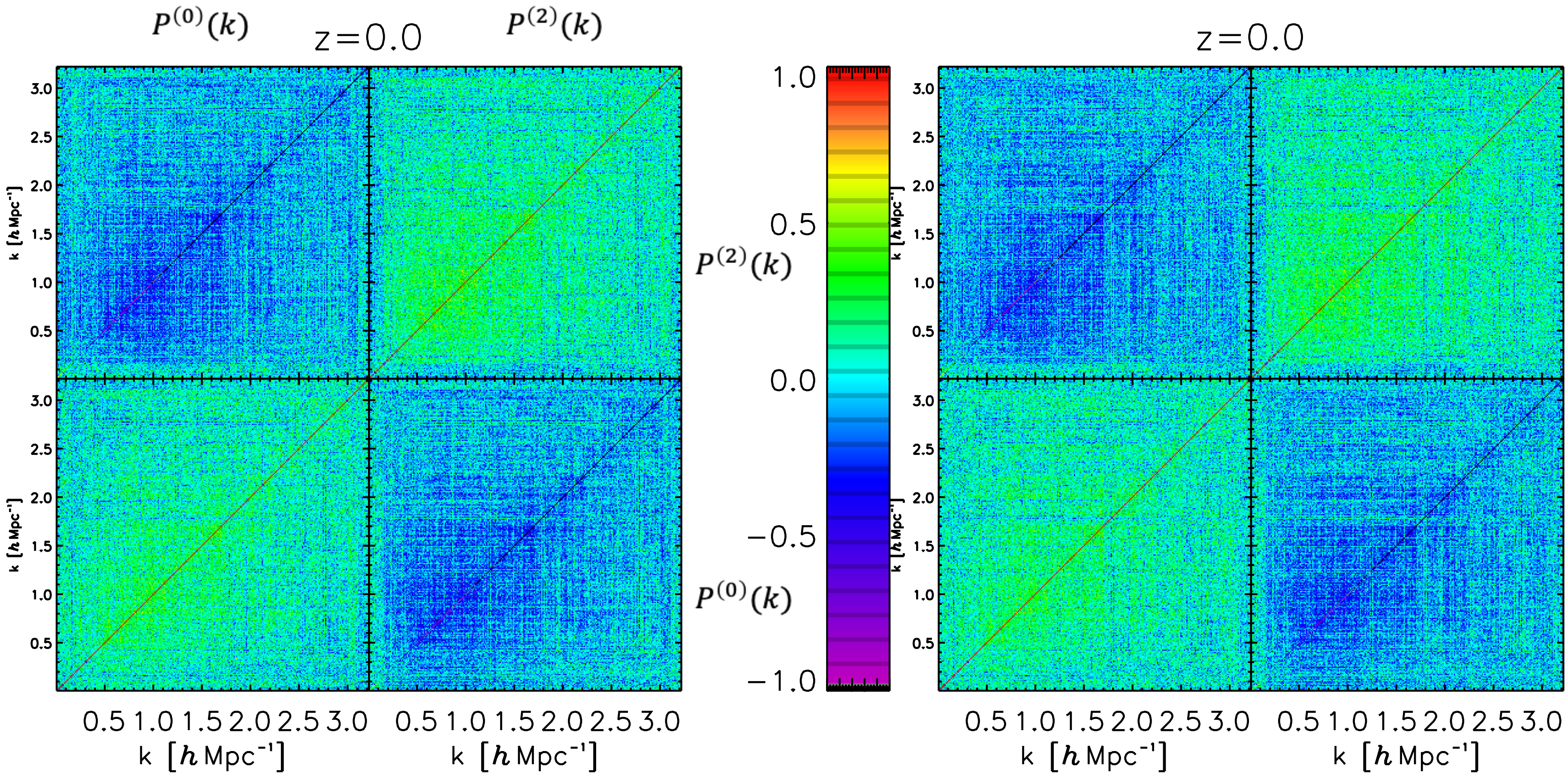


Ongoing project…

DEMNUni (Phase III)

LCDM:

Mnu = 0.16 eV:



Ongoing project…

DEMNUni (Phase III)

Phase III simulations are being used in other ongoing projects:

-Validation of Monte Carlo methods (Barrata et al. 2020) to estimate the covariances of LSS 2-point observables (Barrata et al. in preparation)

-Constraints on neutrino mass from the matter power spectrum (Gouyou-Beauchamps et al. in preparation)

-2-point correlation function in redshift space (Ambrogio Collombo)

-Put galaxies inside haloes (Elisabeta Carella)

Ongoing projects…

Possible projects

-Study halo bias (Non-linear; Non-local) $M_{halo,min} = 2{\times}10^{12}h^{-1}M_{sol}$

-Higher order correlations (cosmological dependence and covariance)

-1-point statistics (pdf of matter/neutrino)

-Correlation between haloes/galaxies and cdm velocity field

-Gravitational potential

-Modelling of the pairewise velocity distribution (relevant for RSD)

…

Conclusions

• A lot of work has been done in the past decade to take into account massive neutrinos effects in the large scale structure.

• The DEMNUni project is part of this scientific effort

• There are already many aspects of the study of LSS in the presence of massive neutrinos which have been published

• However it remains a lot to investigate

• Anyone interested in already ongoing projects or who would like to collaborate on a project on his own is welcome to contact Carmelita Carbone (and myself)