The Dark Energy and Massive Neutrino Universe simulations

Matteo Zennaro

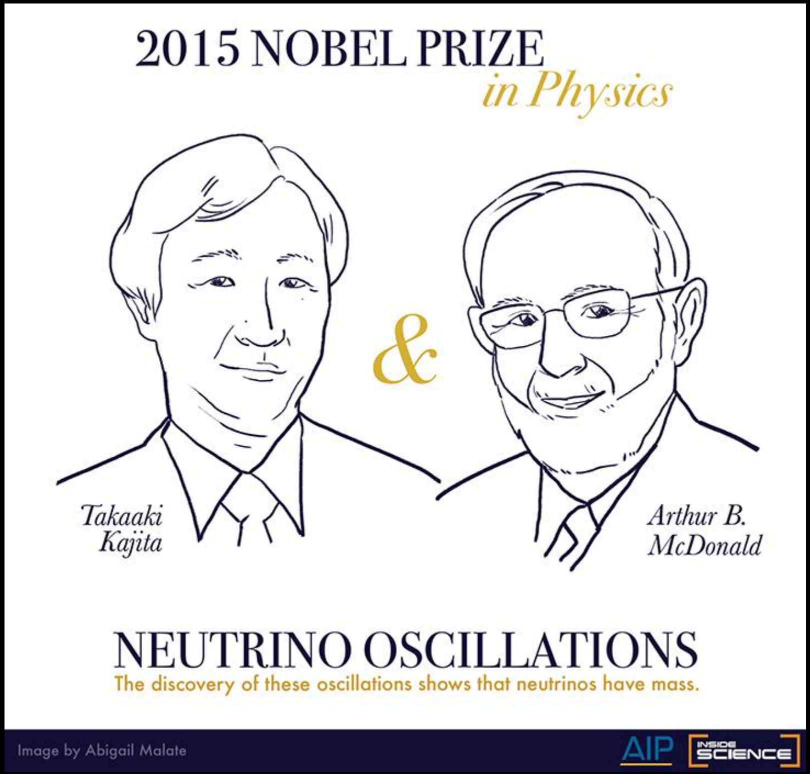
Università degli studi di Milano (Milan- Italy)

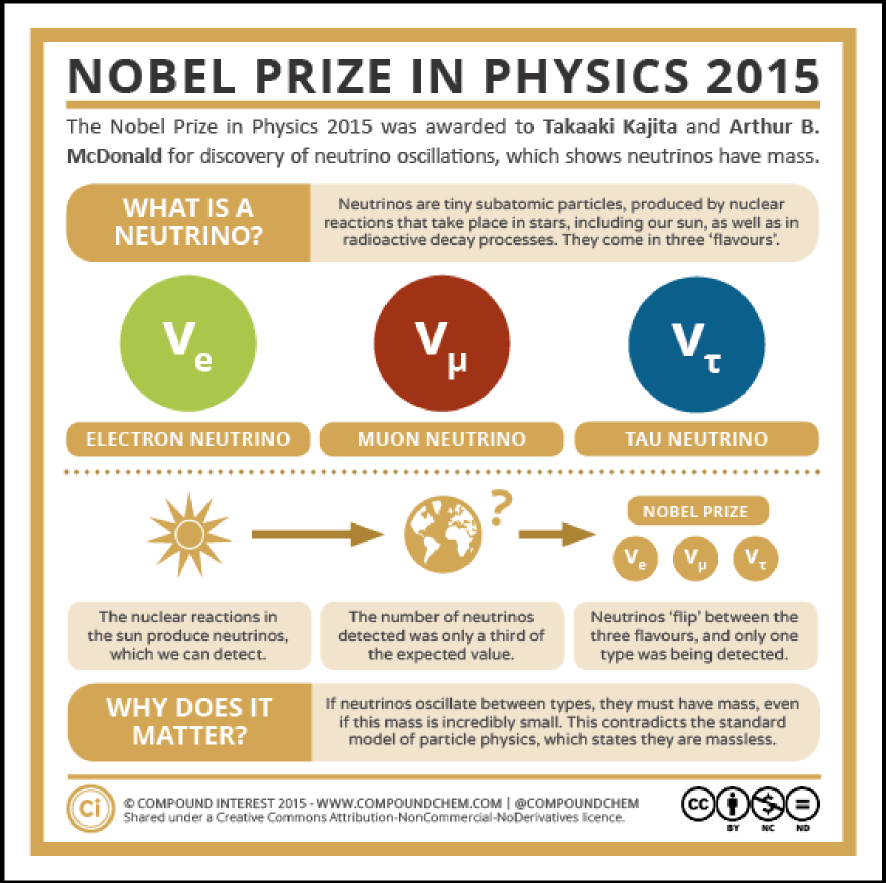
This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 291521

July 10th 2017, Rencontres du Vietnam, Quy Nhon

Neutrinos: Physics beyond the standard model

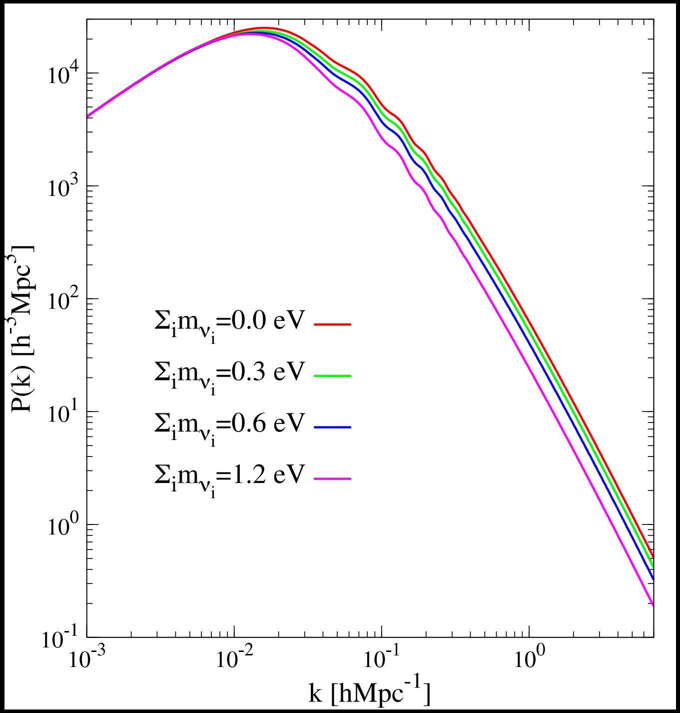
Neutrino astronomy: account for neutrino oscillations to estimate expected fluxes

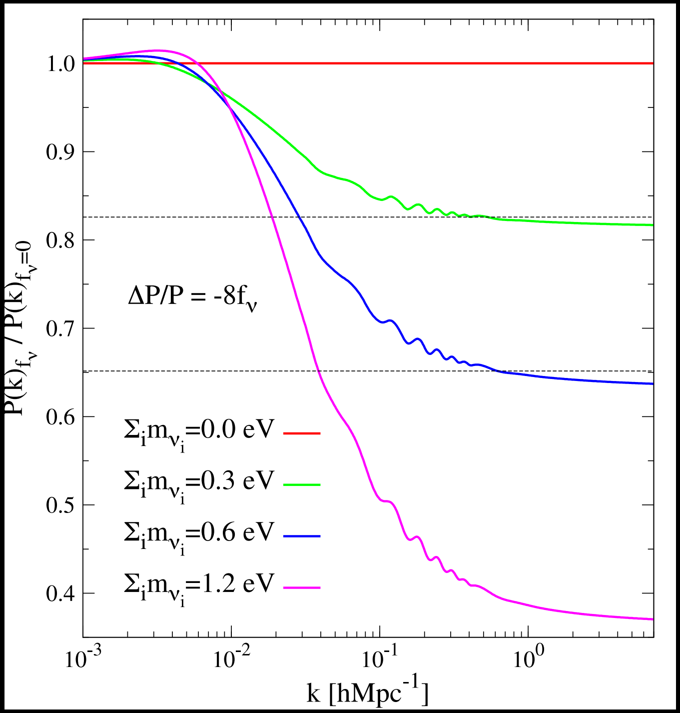




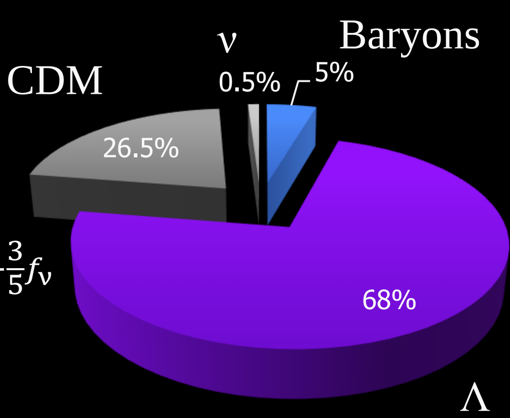
Cosmology: LSS gives constraints on neutrino absolute mass. Degeneracy with other cosmological parameters.

Massive neutrino effects in the linear regime





$$\Omega_{DM} = \Omega_{CDM} + \Omega_{\nu} = \text{fixed}$$



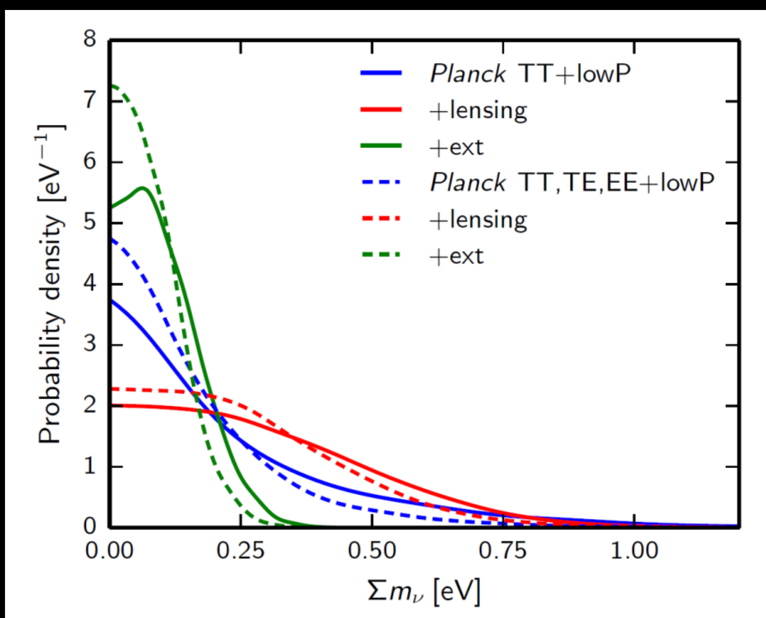
$$\delta_{CDM} \propto a^{1-\frac{3}{5}f_\nu}$$

1. **Modification of the Matter-Radiation equality time**
2. **Slow down the growth of matter perturbations**

Lesgourgues & Pastor, Physics Reports, 429, 6, 2006

Planck constraints on neutrinos (95% CL)

Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114	< 0.0987	< 0.112	< 0.113
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$



Planck-XIII (2015): the lensing reconstruction data, which directly probes the lensing power, prefers lensing amplitudes slightly below (but consistent with) the base LCDM prediction. The Planck+lensing constraint therefore pulls the constraints slightly away from zero towards higher neutrino masses. Extending the analysis up to L<900 , Planck lensing gives non-zero best-fit value for the neutrino mass:

$$\sum m_\nu = 0.16^{+0.08}_{-0.11}\ \text{eV} \quad (\textit{Planck}\ \text{TT+lowP+aggressive lensing + BAO; 68\%})$$

Pellejero-Ibanez et al 2016 (BOSS collaboration)

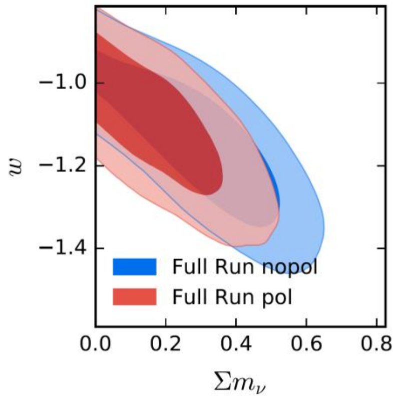


Figure 10. 2D marginalized contours for 68% and 95% confidence level for w and Σm_ν (wCDM model assumed) from Planck+BOSS. The blue contours are from full-likelihood-analysis without using a polynomial function to remove the overall shape information of monopole; the red contours are from the analysis removing overall shape information with a polynomial function. One can see that the overall shape information shift the Σm_ν to a larger value.

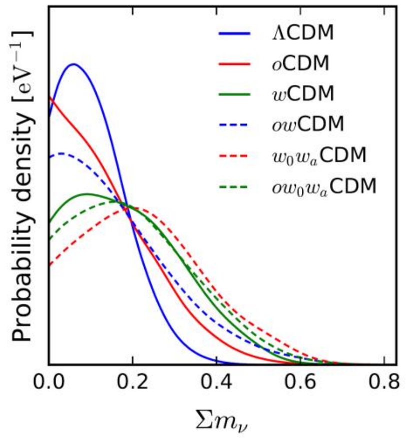


Figure 11. Probability density for Σm_ν from the full-likelihood-analysis of the joint data set. Σm_ν is one of the parameters to be constrained. Planck data includes lensing with $A_L = 1$. The overall shape information of the monopole of the correlation function from the BOSS galaxy clustering is removed with a polynomial function (see Sec. 7.2 and Table 10).

M_ν<0.16 eV from BOSS

Full shape measurement of the monopole of the galaxy 2-point correlation function introduces some detection of neutrino mass but non-linear modelling is needed.

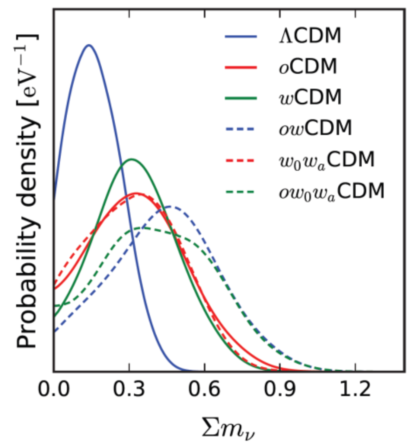


Figure 12. Probability density for Σm_ν from full-likelihood-analysis from the joint data set. Both Σm_ν and A_L are the parameters to be constrained. The overall shape information of the monopole of the correlation function from the BOSS galaxy clustering is removed with a polynomial function (see Sec. 7.2 and Table 11). One can see that the maximum of Σm_ν increases comparing to the cases with fixing $A_L = 1$ (see Fig. 11).

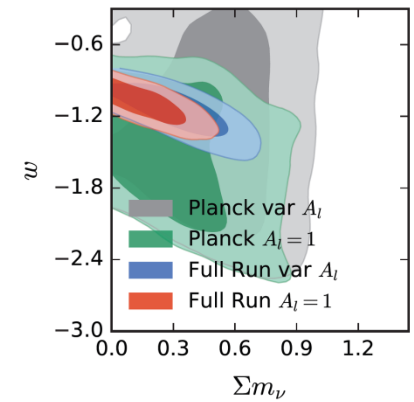
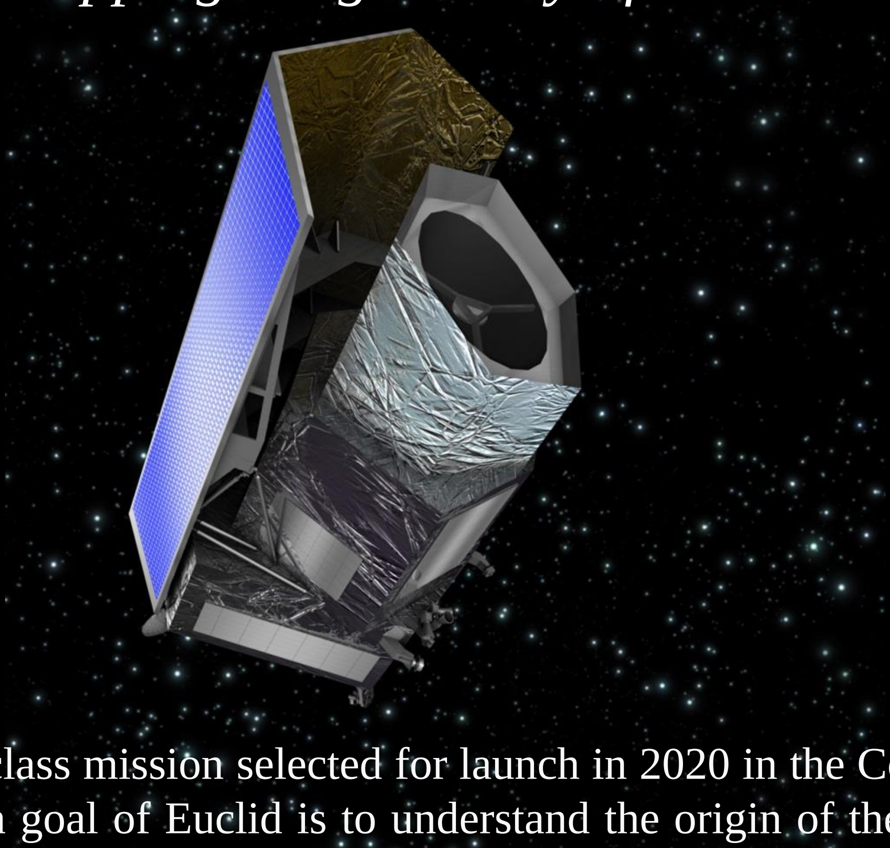


Figure 13. 2D marginalized contours for 68% and 95% confidence level for w and Σm_ν (wCDM model assumed) from full run methodology and Planck only for different lensing information used. Gray contours and green contours are from Planck only with varying A_L and fixing $A_L = 1$ respectively; the blue contours and the red contours are from Planck+BOSS with varying A_L and fixing $A_L = 1$ respectively using full-likelihood-analysis. One can see that Σm_ν shift to a large value when varying A_L for both data combinations.

Euclid: Mapping the geometry of the dark Universe



Euclid is an ESA M-class mission selected for launch in 2020 in the Cosmic Vision 2015-2025 programme. The main goal of Euclid is to understand the origin of the accelerating expansion of the Universe. To achieve this goal, it is proposed to build a satellite equipped with a 1.2 m telescope and three imaging and spectroscopic instruments working in the visible and near-infrared wavelength domains. These instruments will explore the expansion history of the Universe and the evolution of cosmic structures by measuring shapes and redshifts of galaxies as well as the distribution of galaxy-clusters as function of redshift $0.5<z<2$, over 15000 deg^2 of the sky. The satellite will be launched by a Soyuz ST-2.1B rocket and transferred to the L2 Lagrange point for a 6 years mission.

Spectro-Euclid forecasts

Table 5: $\sigma(M_\nu)$ and $\sigma(N_{\rm eff})$ marginalised errors from LSS+CMB

			General cosmology			
fiducial→	M_ν=0.3 eV[a]	M_ν=0.2 eV[a]	M_ν=0.125 eV[b]	M_ν=0.125 eV[c]	M_ν=0.05 eV[b]	$N_{\rm eff}$=3.04[d]
slitless+BOSS+Planck	0.035	0.043	0.031	0.044	0.053	0.086
			ΛCDM cosmology			
slitless+BOSS+Planck	0.017	0.019	0.017	0.021	0.021	0.023

[a]for degenerate spectrum: $m_1 \approx m_2 \approx m_3$; [b]for normal hierarchy: $m_3 \neq 0$, $m_1 \approx m_2 \approx 0$
[c]for inverted hierarchy: $m_1 \approx m_2$, $m_3 \approx 0$; [d]fiducial cosmology with massless neutrinos

Only 3 active neutrinos for M_ν errors

Carbone et al. 2011

If M_ν is > 0.1 eV, spectroscopic Euclid will be able to determine the neutrino mass scale independently of the model cosmology assumed. If M_ν is < 0.1 eV, the sum of neutrino masses, and in particular the minimum neutrino mass required by neutrino oscillations, can be measured in the context of a LCDM model. DE FoM decreases by a factor 2-3 wrt the massless case. Important to include NL info.

Effects in the non-linear regime

Why?

- Important on small scales
- Important at low redshift
- Lots of modes in the middle—non-linear regime

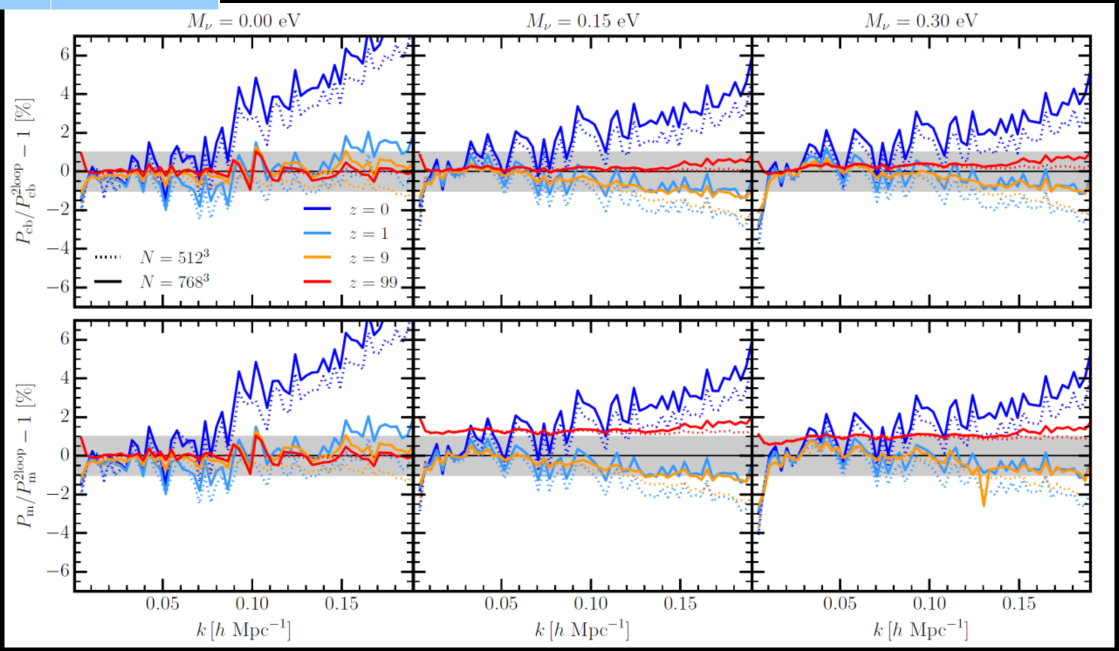
How?

- Semi-analytic methods
  N-1-body, Ringwald & Wong, 2004
  (see also Singh & Ma, 2003)
- Perturbation theory
  Blas, Garny, Konstandin, Lesgourgues, 2014
- N-body simulations
  Particle/Grid based/Boltzmann

Initial Conditions improvements

S1: No radiation & constant initial growth rates $\Omega_{\gamma,0} = 0$ $\quad f_{cb} = f_\nu = \Omega_m^{0.55}(z) = const$	4%
S2: No radiation $\Omega_{\gamma,0} = 0$	2%
S3: Constant initial growth rates $f_{cb} = f_\nu = \Omega_m^{0.55}(z) = const$	6% 1%
S4: No relativistic neutrino perturbations $\delta\rho_\nu^{\rm rel} = 0 \ (M_{p,\nu} = const)$	0.6%
S5: No relativistic neutrinos $\delta\rho_\nu^{\rm rel} = 0 \ (M_{p,\nu} = const)$ $\quad \rho_\nu(z) = \rho_{\nu,0}(1+z)^3$	0.9%

MZ et al. 2016



MZ et al. 2016

"Dark Energy and Massive Neutrino Universe" (DEMNUni) simulations

(PI Carmelita Carbone)

1. DEMNUni-I: 5M cpu-hr on Fermi Tier-0 @CINECA (**COMPLETED**)

2. DEMNUni-II: 8M cpu-hr on Fermi Tier-0 @CINECA (**COMPLETED**)

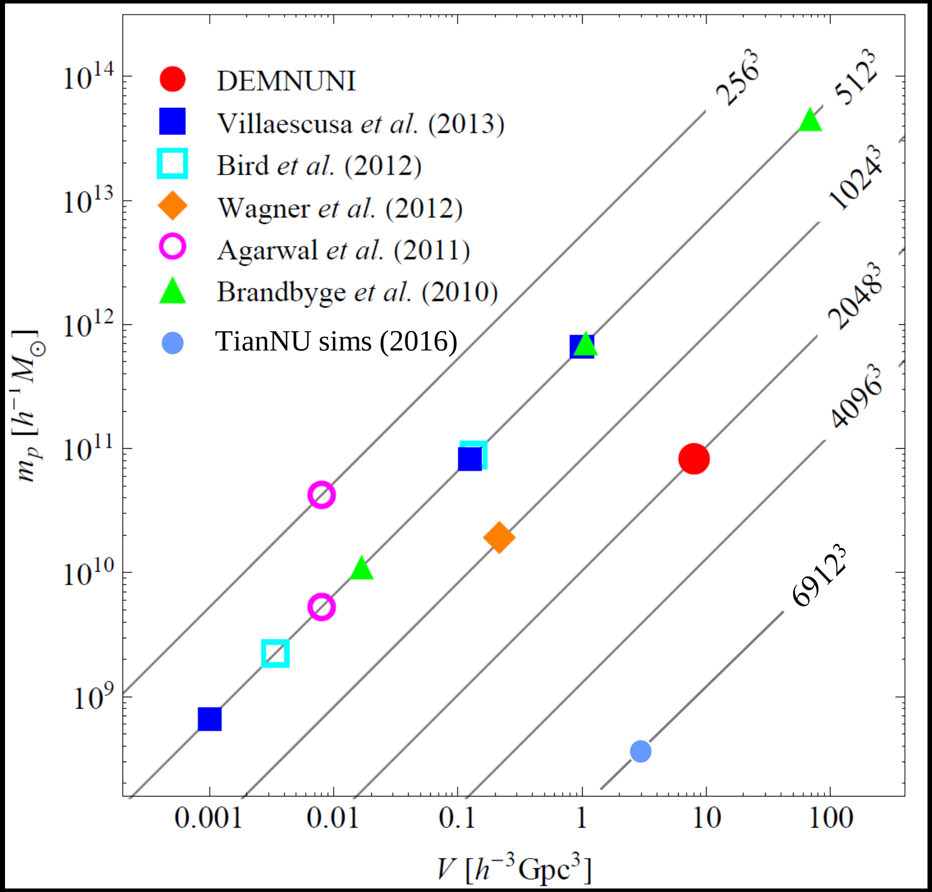
14 cosmological simulations with volume: $(2\ \mathrm{Gpc/h})^3$ and N_{part}: 2×2048^3 (CDM+ν)
baseline Planck cosmology +
M_ν=0, 0.17, 0.3, 0.53 eV & $(M_\nu, w_0, w_a)=(0\div0.16,-0.9,\pm0.3),(0\div0.16,-1.1,\pm0.3)$

3. DEMNUni-Covariances: 3M cpu-hr on Marconi Tier-0 @CINECA (**STARTED**)

→ 300 cosmological simulations with $V=1\ (\mathrm{Gpc/h})^3$ and $N_{part}=2 \times 1024^3$ (CDM+ν)

Simulation outputs

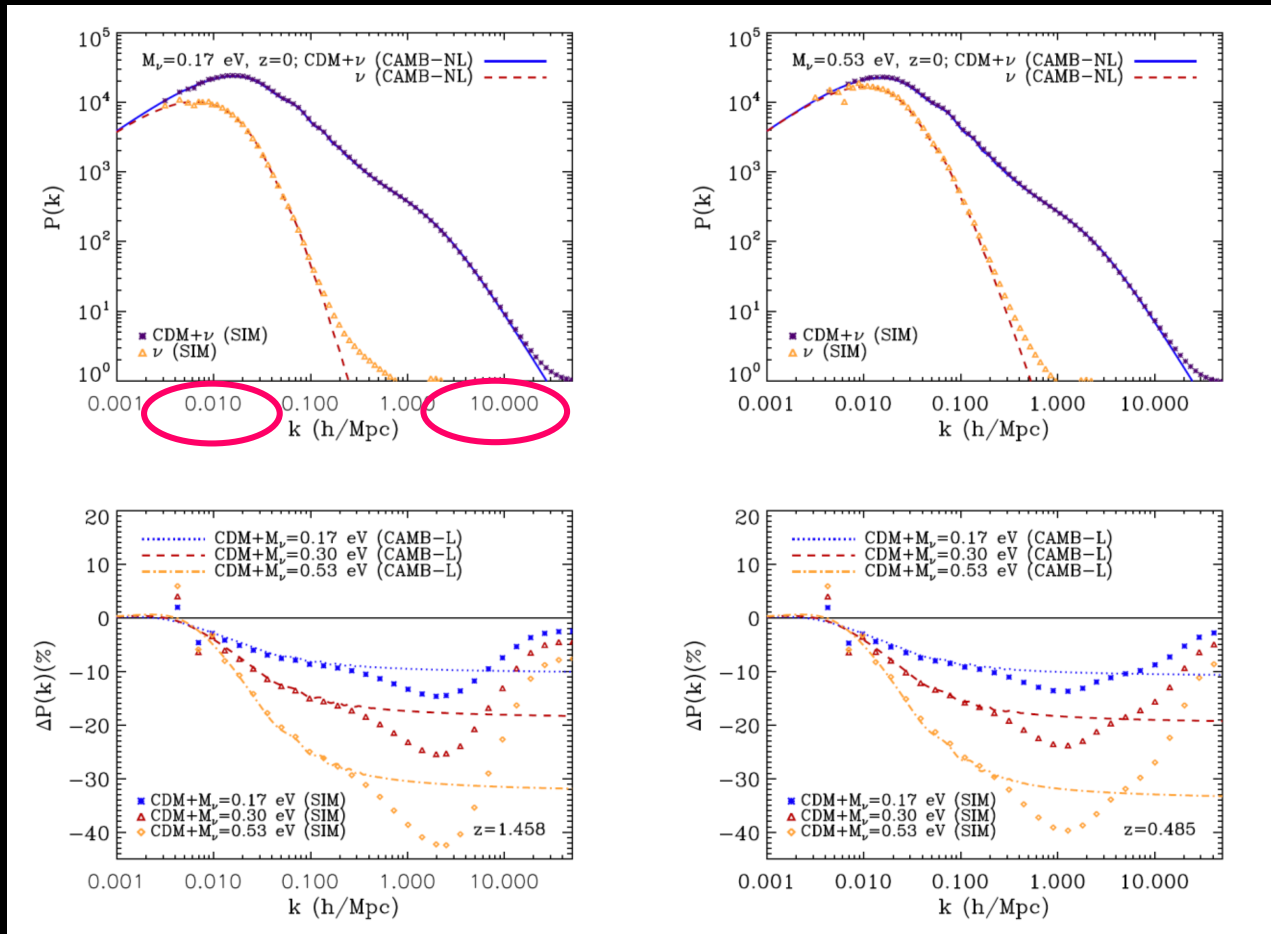
- 90 TB/sim of data
- 62 temporary snapshots per simulation: ~0.54 TB/snap (CDM+ ν)
- 62 halo-catalogs
- 62 sub-halo catalogs
- Matter power-spectra and correlation functions for all the 62 snapshots
- 62 temporary gravitational potential grids of size 4096^3 (for CMB weak-lensing)
- 62 temporary grids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



Comparison between the DEMNUni runs and recent simulations of massive neutrino cosmologies in terms of cold dark matter mass resolution and volume

DEMNUni matter power spectra for M_ν=0.3 eV

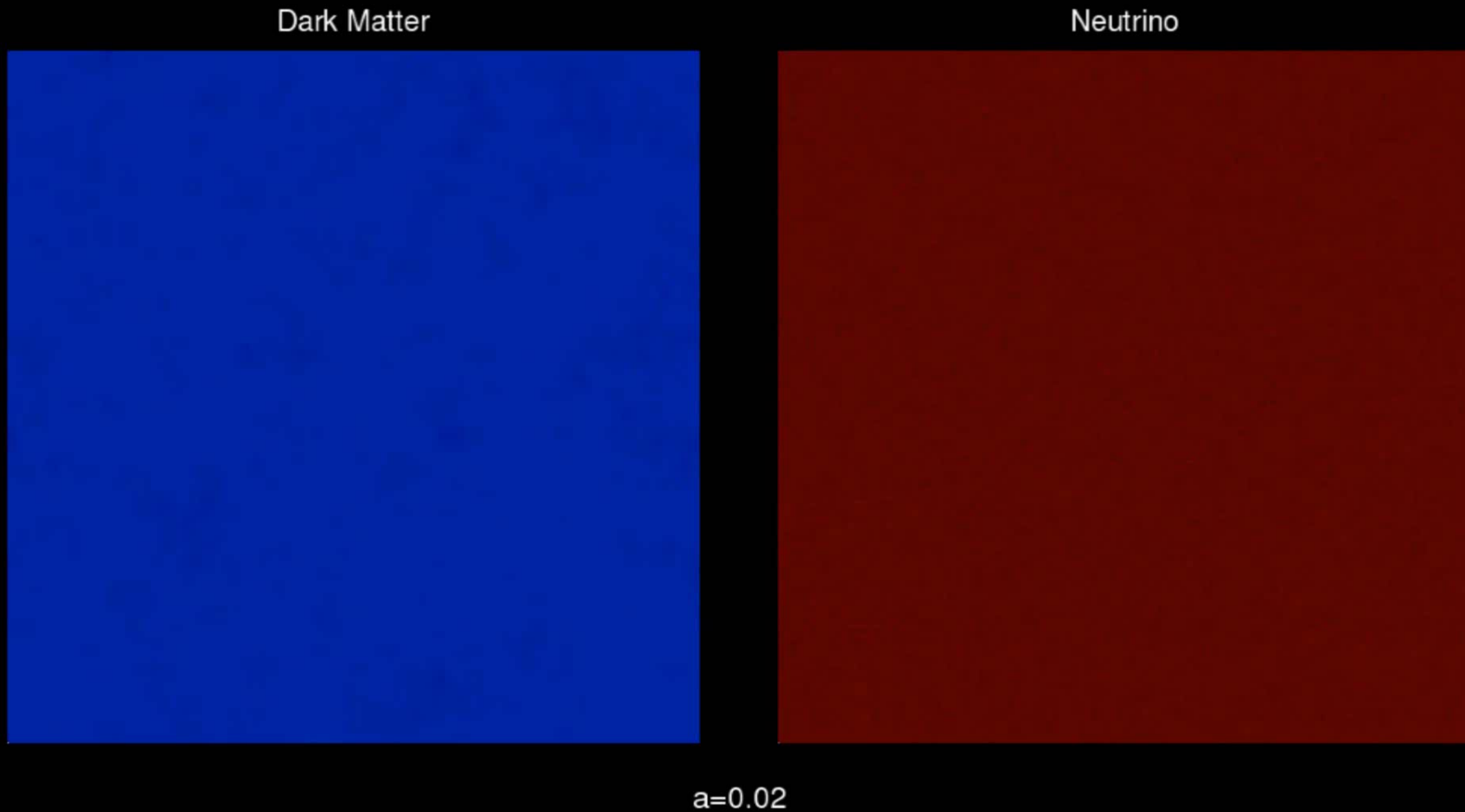
Carbone et al. 2016



The large volume and mass resolution of the DEMNUni simulations allow to test different probes, and their combinations, in massive neutrino cosmologies, at the level of accuracy required by current and future galaxy surveys up to k=1 *h*/Mpc.

$$k_{\rm fs}(z) = 0.82 H(z)/H_0/(1+z)^2 (m_\nu/1{\rm eV})\ h\,{\rm Mpc}^{-1}$$

CDM/ν clustering in high resolution simulations
(2400 times smaller than DEMNUni)

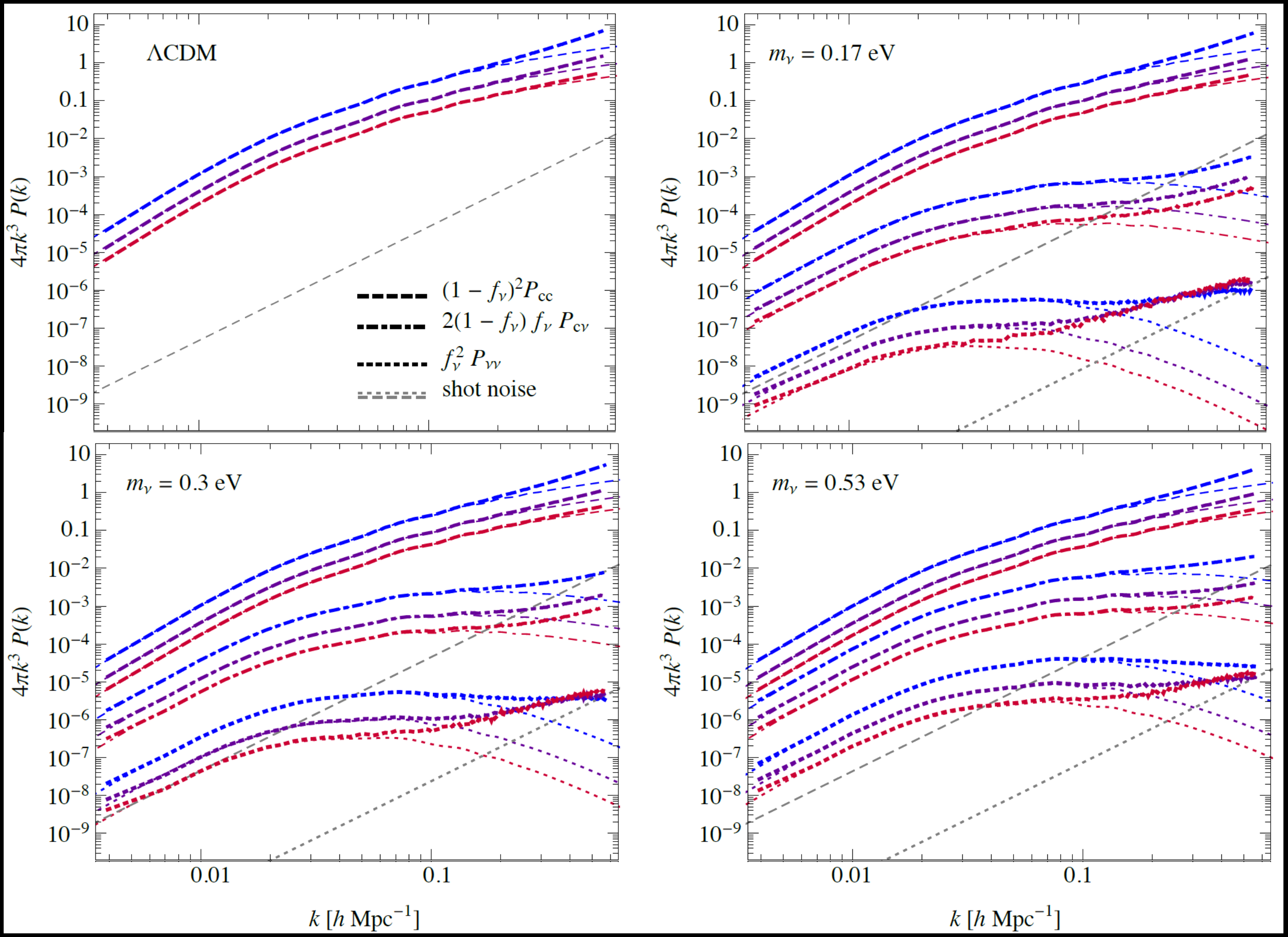


Courtesy of Villaescusa-Navarro

L=150 Mpc/h **$N_{cdm}=512^3$** **$N_{\nu}=1024^3$** **$z_{in}=49$**

Different contributions to the total matter P(k)

Castorina, Carbone et al. 2015

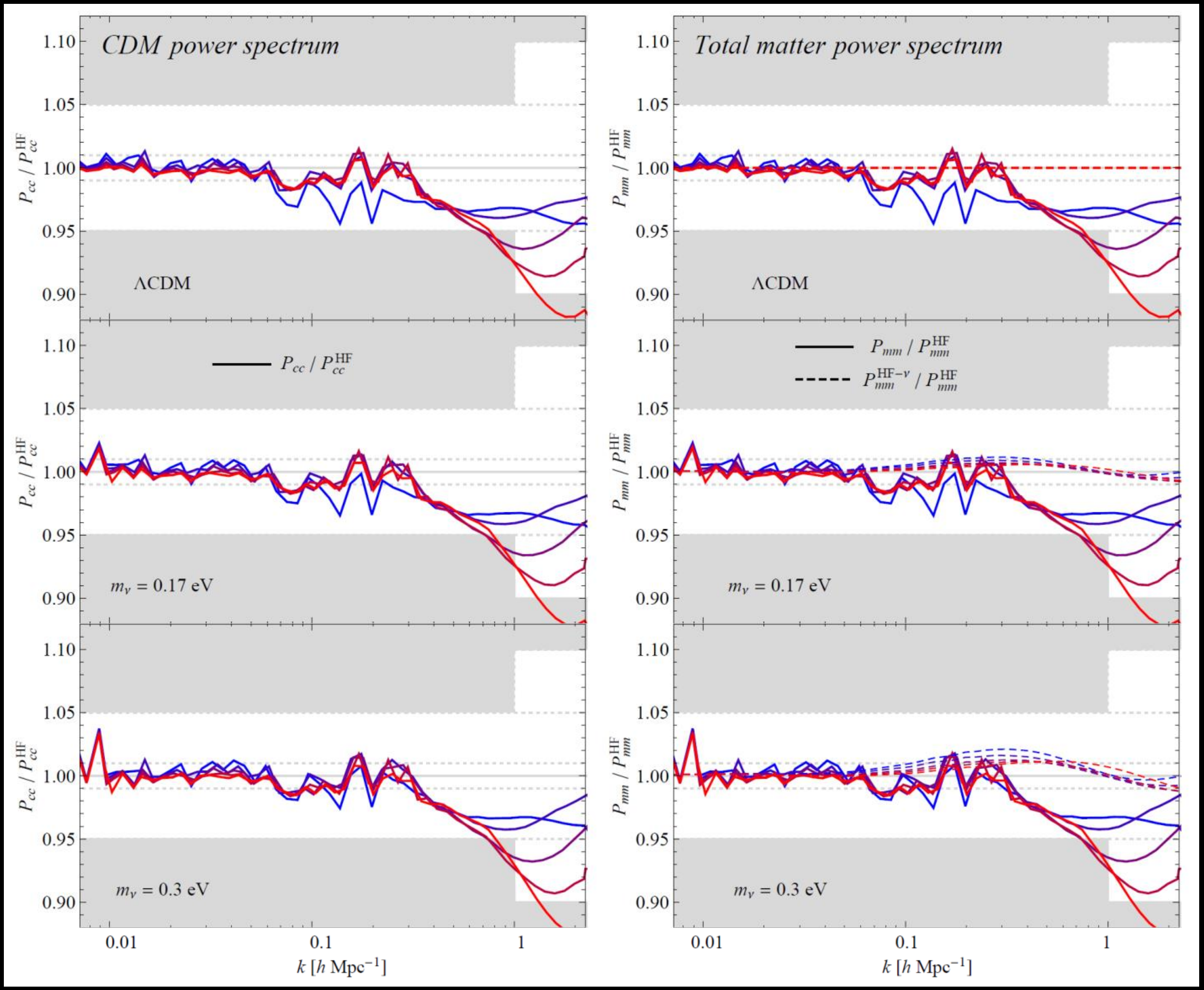


$$P_m(k;z) = (1-f_\nu)^2\, P_{cb}(k;z) + 2\,(1-f_\nu) f_\nu\, P_{cb,\nu}(k;z) + f_\nu^2\, P_\nu(k;z)$$

$P_m(k)$ **is described at the 1% level accuracy up to k=1*h*/Mpc, assuming the nonlinear evolution of CDM alone, and the linear prediction for the other components**

Modifications to Halofit

Castorina, Carbone et al. 2015



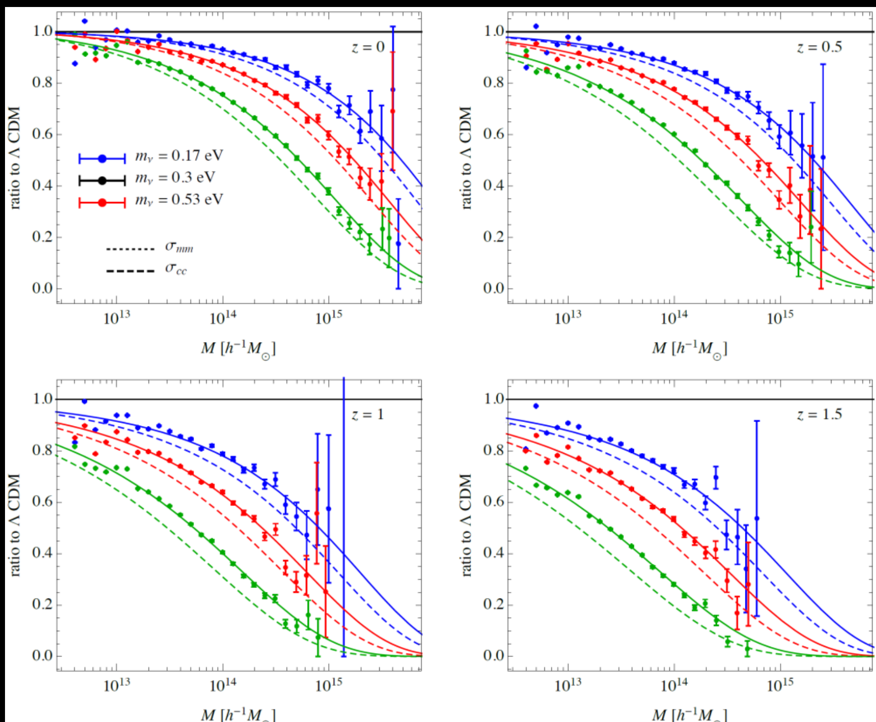
$$P_{mm}^{HF}(k) \equiv (1-f_\nu)^2\, P_{cc}^{HF}(k) + 2\, f_\nu\, (1-f_\nu)\, P_{c\nu}^{L}(k) + f_\nu^2\; P_{\nu\nu}^{L}(k)$$

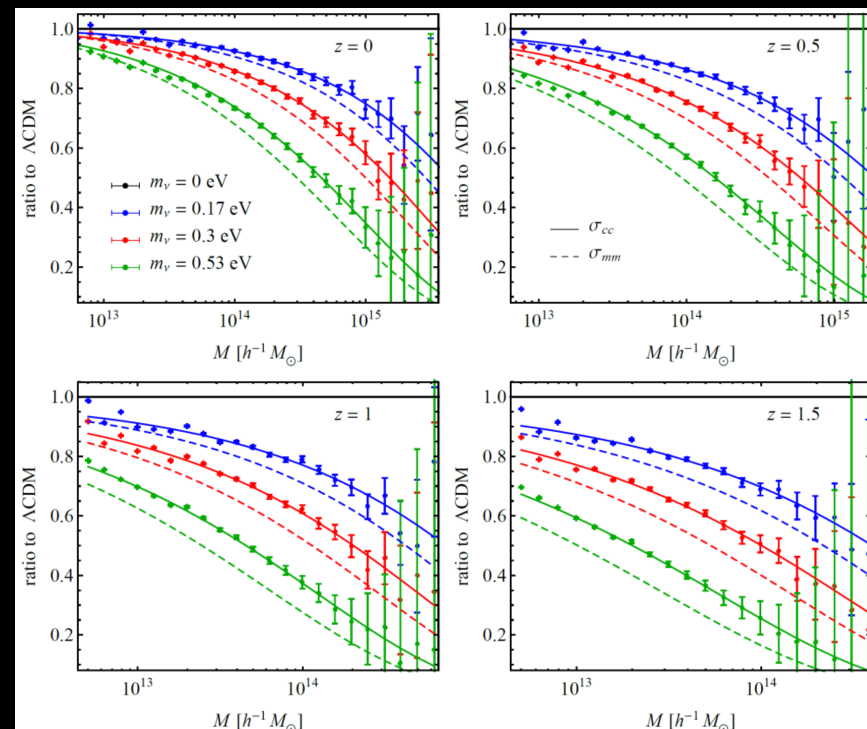
$$P_{cc}^{HF}(k) \;=\; \mathcal{F}_{HF}[P_{cc}^{L}(k)]$$

HALOFIT mapping only for CDM, other contributions are assumed to be linear.
Shaded areas denote regions beyond the accurracy expected from Halofit.

Halo Mass Function: FoF (MICE) vs SO (Tinker)

Castorina, Carbone et al. 2015

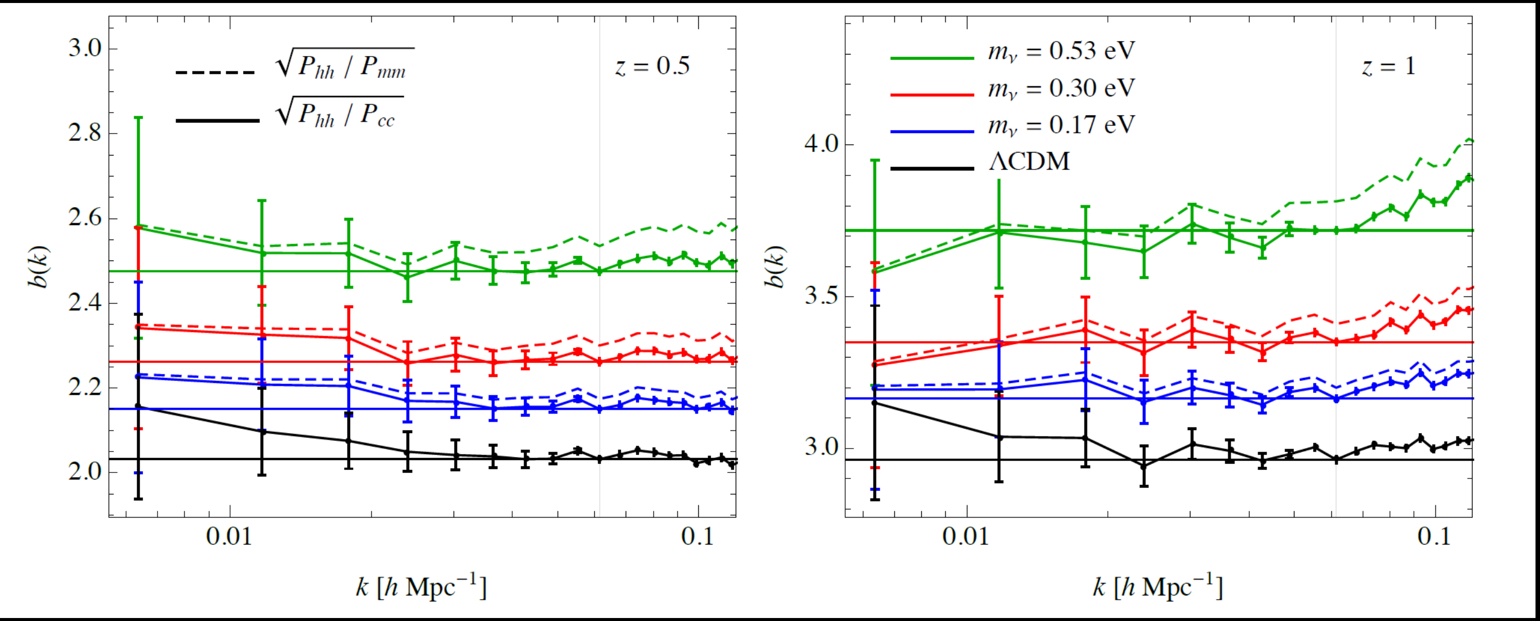




The ρ_{cc} and σ_{cc} prescriptions (Ichiki&Takada, 2012 & Castorina et al, 2014) allow to recover the theoretical MF for both FoF and SO halos

Same conclusions for the bias

Castorina, Carbone et al. 2015

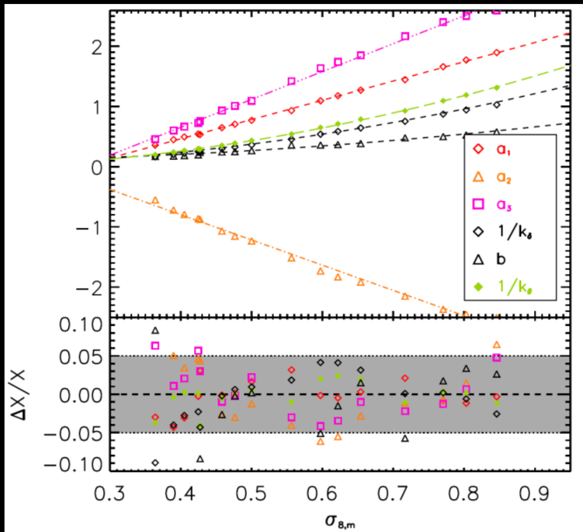


$$b_c = \sqrt{\frac{P_{hh}}{P_{cc}}}$$

$$b_m = \sqrt{\frac{P_{hh}}{P_{mm}}}$$

The σ_{cc} prescription mitigates the ν-induced scale dipendence of the bias at intermediate scales. The halo bias defined with respect to DM presents a spurious scale-dependence due to the difference between the cold and total matter power spectra.

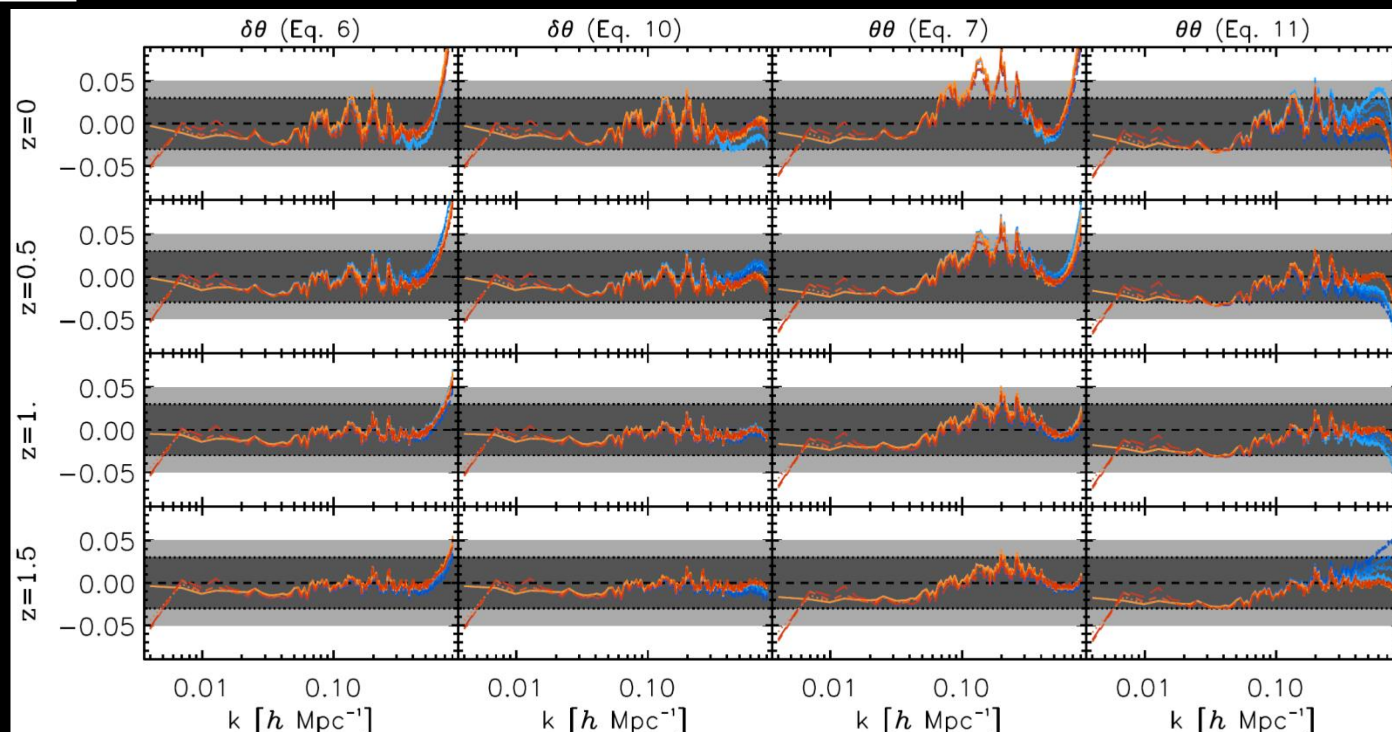
Velocity spectra from DEMNUni: no σ_{cc} prescription



$$
\begin{aligned}
a_1 &= -0.817 + 3.198\sigma_{8,m} \\
a_2 &= 0.877 - 4.191\sigma_{8,m} \\
a_3 &= -1.199 + 4.629\sigma_{8,m} \\
1/k_\delta &= 0.111 + 3.811\sigma_{8,m}^2 \\
b &= 0.091 + 0.702\sigma_{8,m} \\
1/k_\theta &= -0.048 + 1.917\sigma_{8,m}^2
\end{aligned}
$$

$$P_{\delta\theta}(k) = \left\{(P^{\rm HF}_{\delta\delta}(k)P^{\rm Lin}_{\theta\theta}(k)\right\}^{\frac{1}{2}} e^{-\frac{k}{k_\delta}}$$

$$P_{\theta\theta}(k) = P^{\rm Lin}_{\theta\theta}(k)e^{-\frac{k}{k_\theta}}$$



Bel et al. in prep

$$P_{\delta\theta}(k) = \left\{(P^{\rm HF}_{\delta\delta}(k)P^{\rm Lin}_{\theta\theta}(k)\right\}^{\frac{1}{2}} e^{-\frac{k}{k_\delta}-bk^6}$$

$$P_{\theta\theta}(k) = P^{\rm Lin}_{\theta\theta}(k)e^{-k(a_1+a_2k+a_3k^2)}$$

Lensing and ISW-RS: no σ_{cc} prescription

$$\Psi(\hat{\mathbf{n}}) \equiv -2 \int_0^{r_*} \frac{r_* - r}{r_* r} \frac{\Phi(r\hat{\mathbf{n}}; \eta_0 - r)}{c^2} \, \mathrm{d}r$$

Lensing potential in the small-angle scattering limit (Born approximation)

r= comoving distance from the observer

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

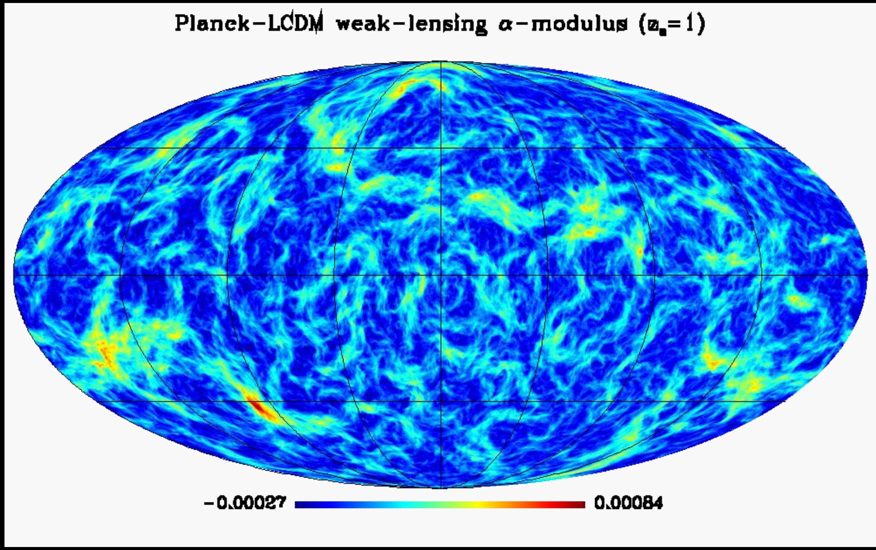
Total ISW-RS effect

$$\widetilde{X}(\hat{\mathbf{n}}) = X(\hat{\mathbf{n}} + \nabla\psi(\hat{\mathbf{n}}))$$

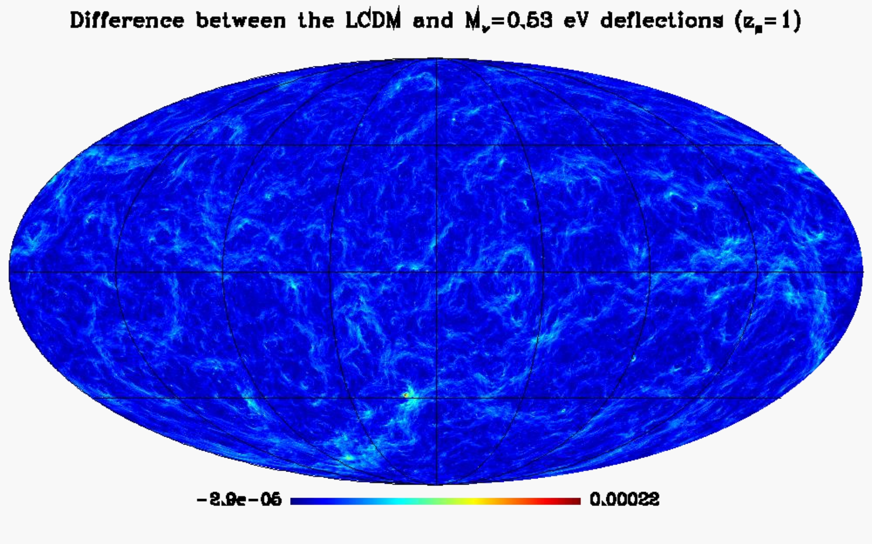
$$X = T, Q, U$$

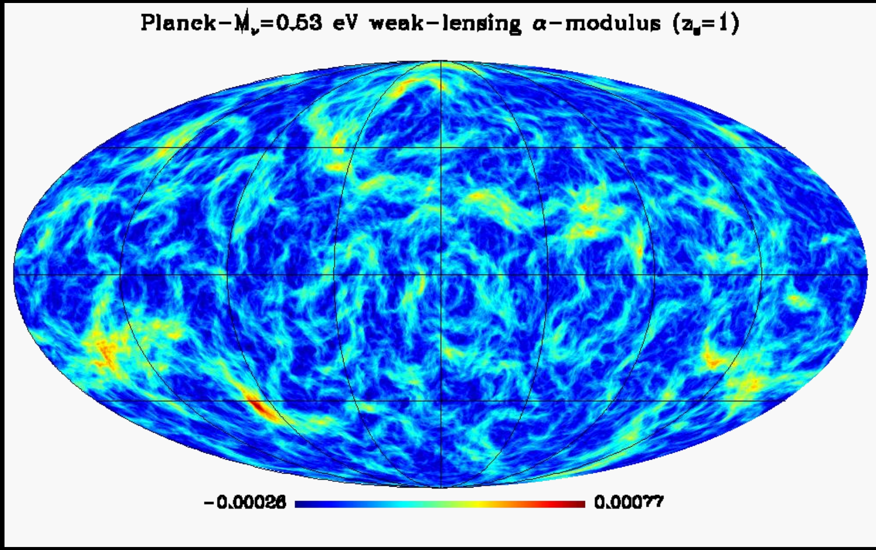
Gradients in the grav. potential generated by LSS cause deviations in the CMB photon propagation from LS to us:

points in a direction **n`** actually come from points on the last scattering surface in a displaced direction **n`**= **n** $+\nabla\psi$



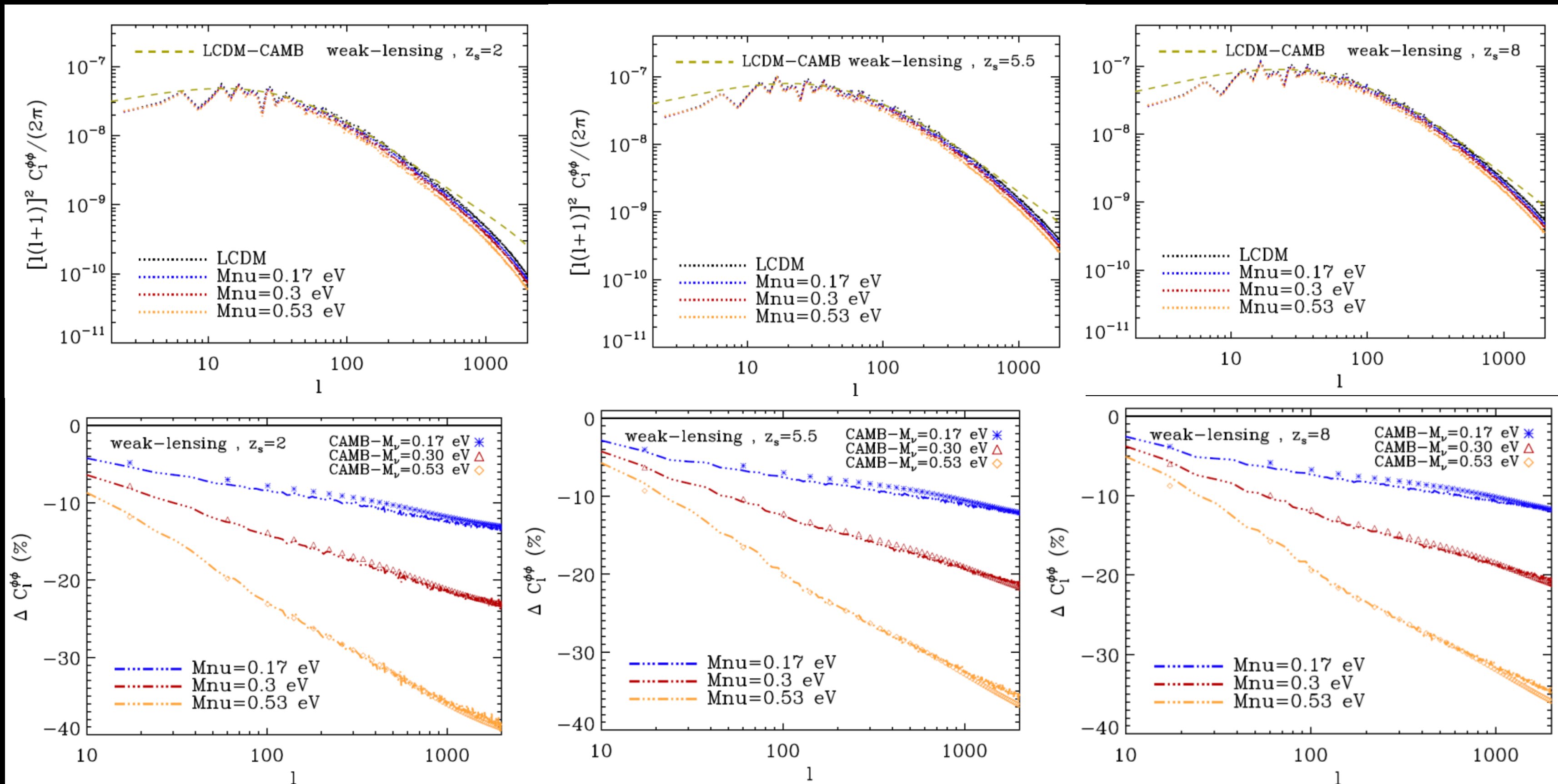
Deflection angle maps for z_s=1





Carbone et al. 2016

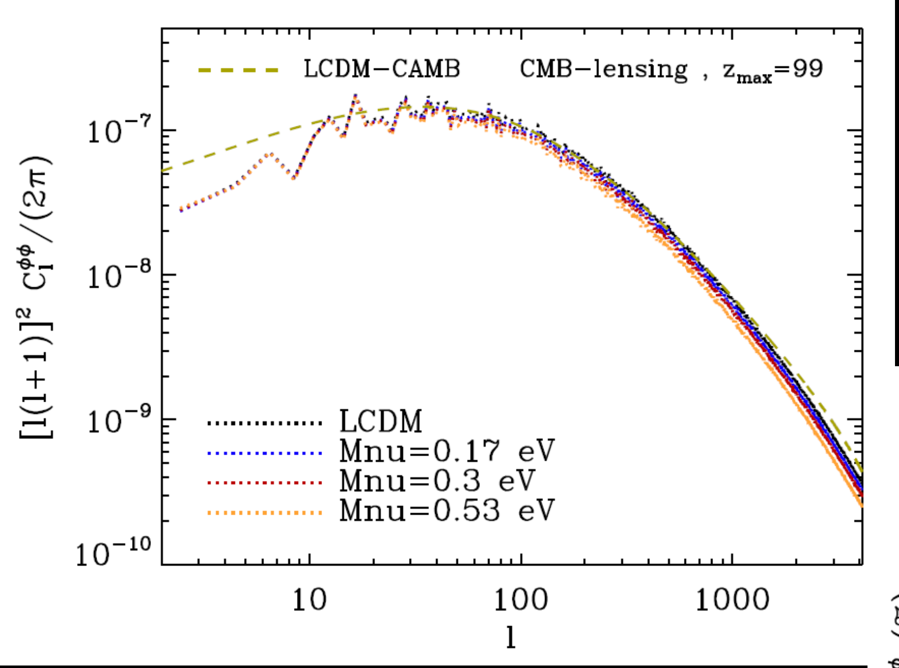
Weak-lensing angular power spectra at different redshifts



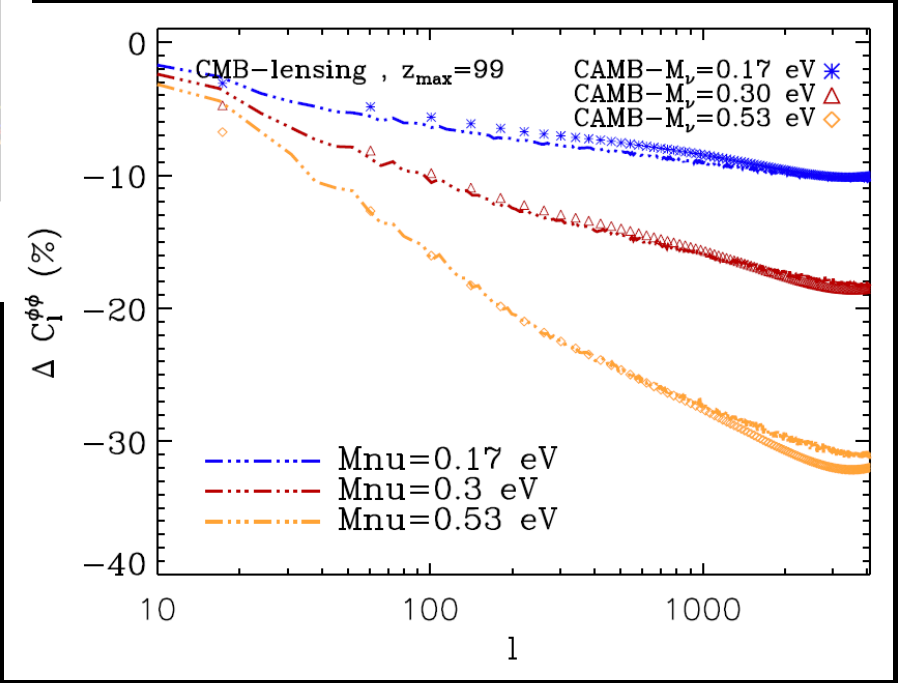
Carbone et al. 2016

Lack of power on small scales due to grid resolution.
The neutrino damping effect is correctely recovered up to *l*=2000

CMB-lensing angular power spectra

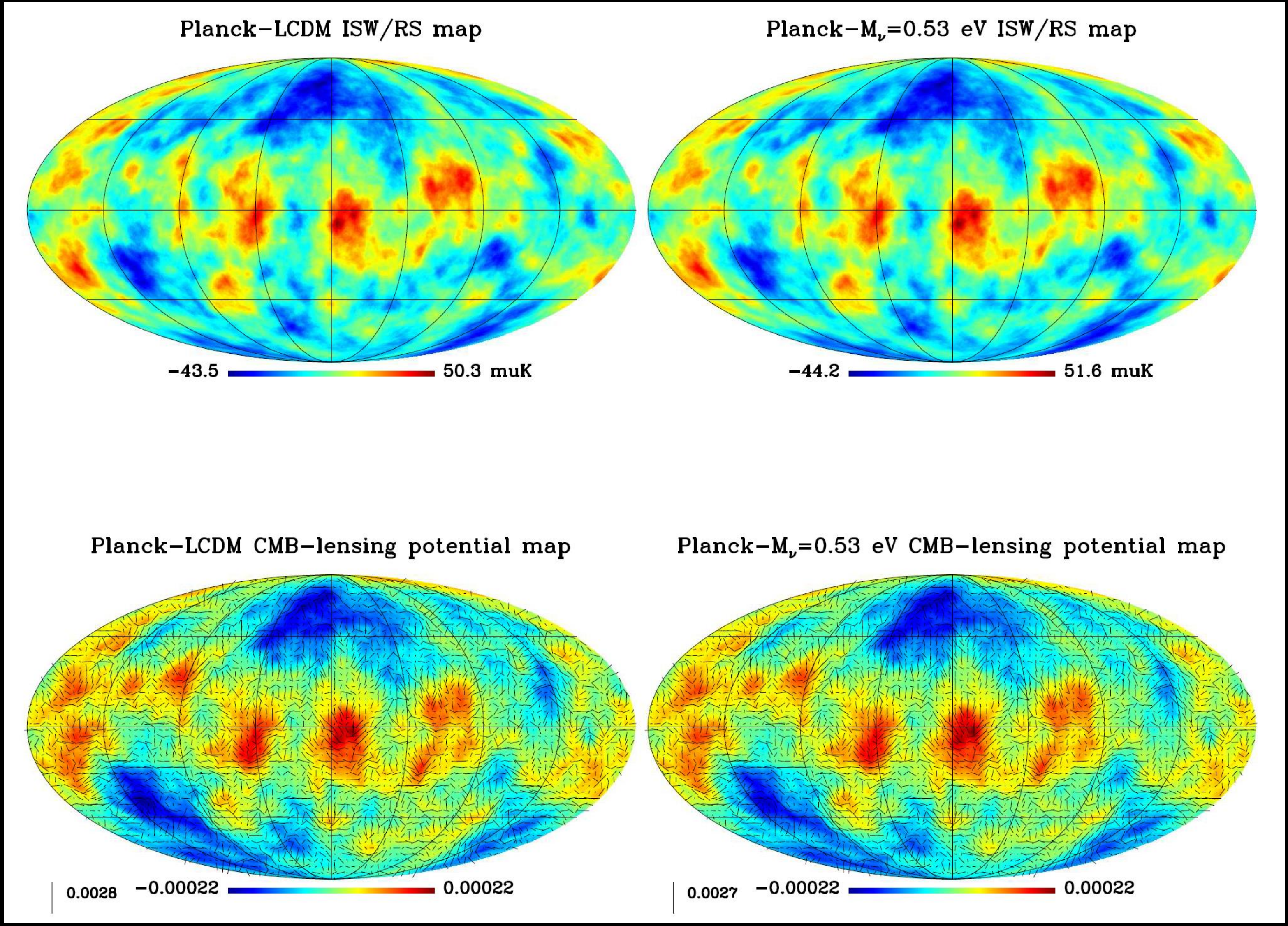


Power suppression is less than in the weak-lensing case since there is the contribution from higher z



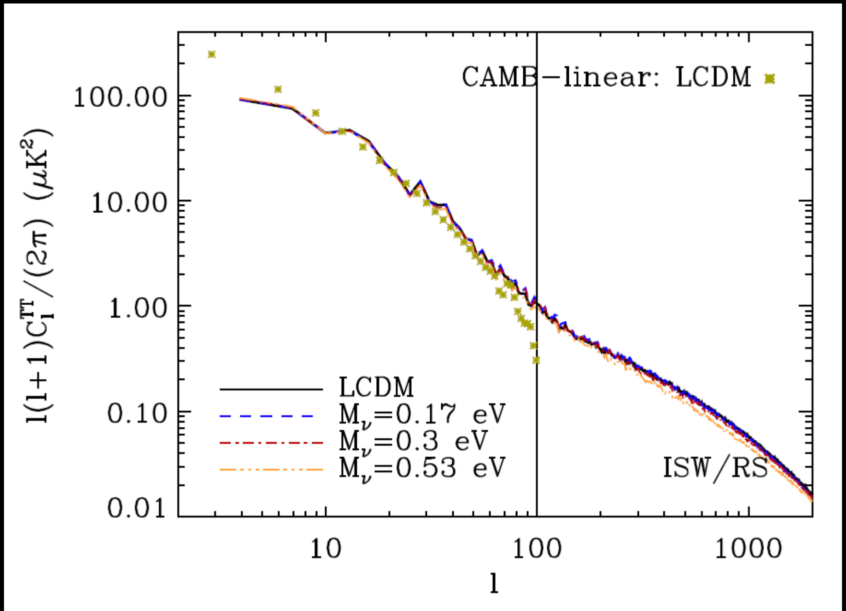
Carbone et al. 2016

CMB-lensing vs ISW/Rees-Sciama



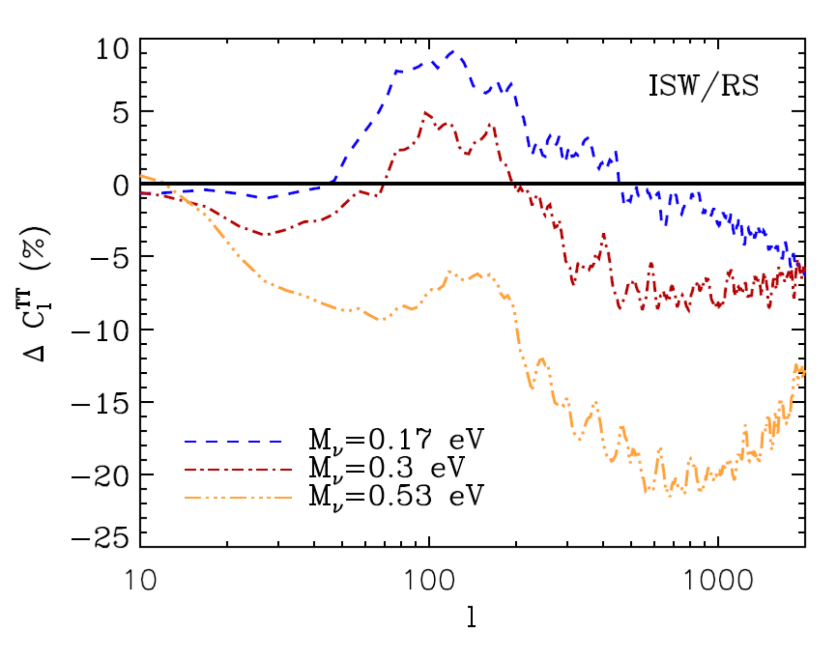
Carbone et al. 2016

ISW/Rees-Sciama angular power spectra



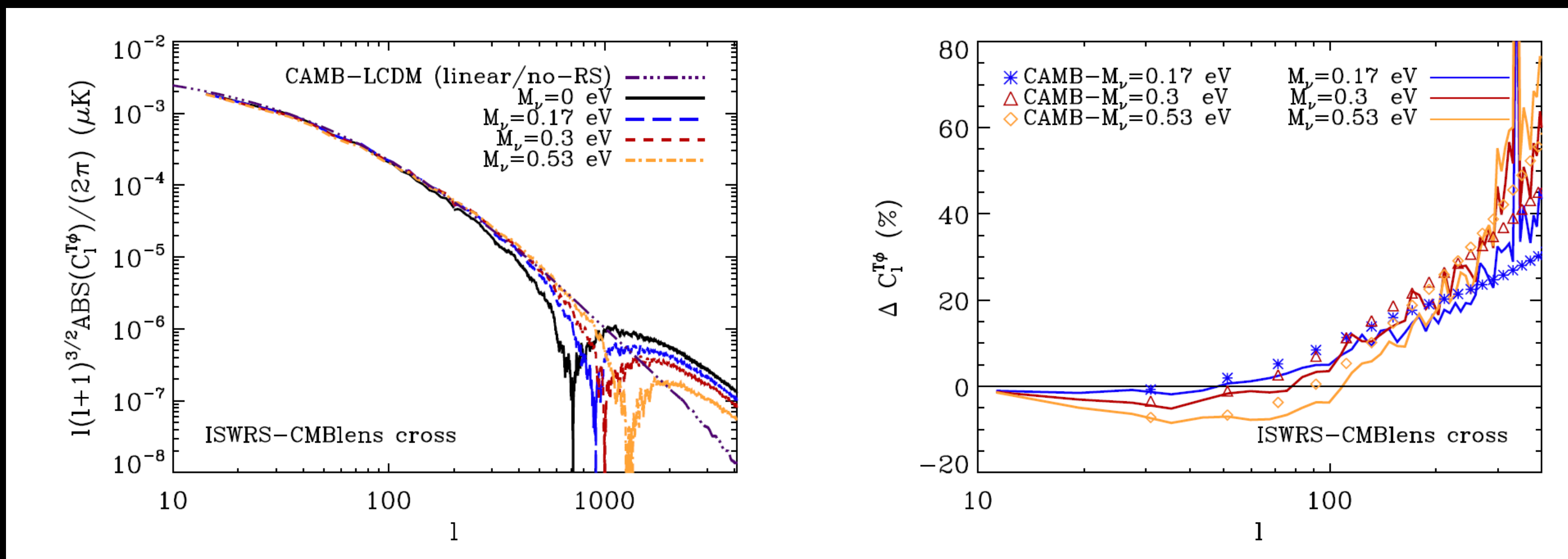
At high redshift, the ISW effect would be null on all scales for M_ν=0, while for M_ν>0 it is still active on small scales because of free-streaming.

Carbone et al. 2016



$$k_{fs}(z) = 0.82 H(z)/H_0/(1+z)^2 (m_\nu/1\mathrm{eV}) \ \ h\,\mathrm{Mpc}^{-1}$$

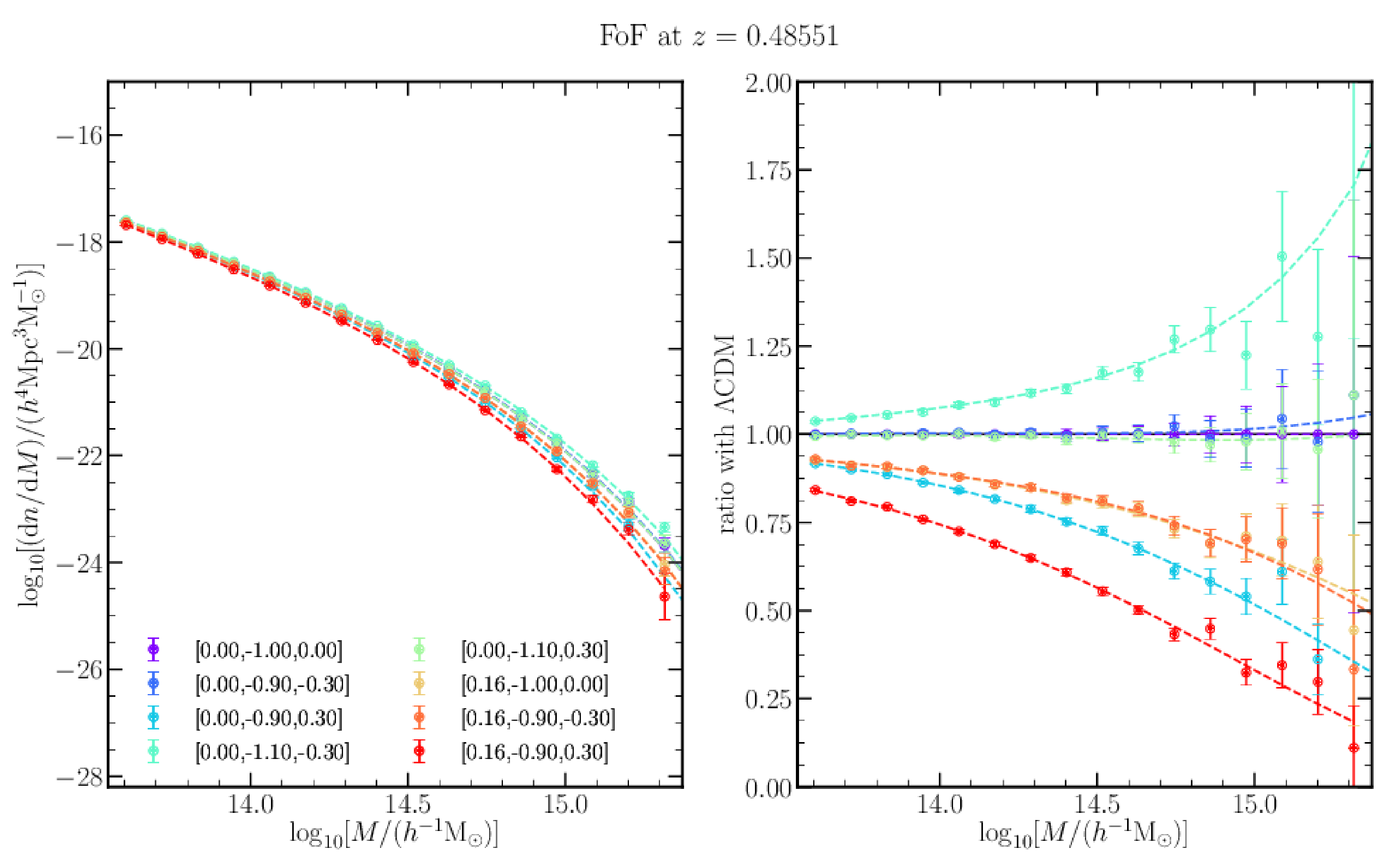
ISWRS-CMBlens cross correlation



Carbone et al. 2016

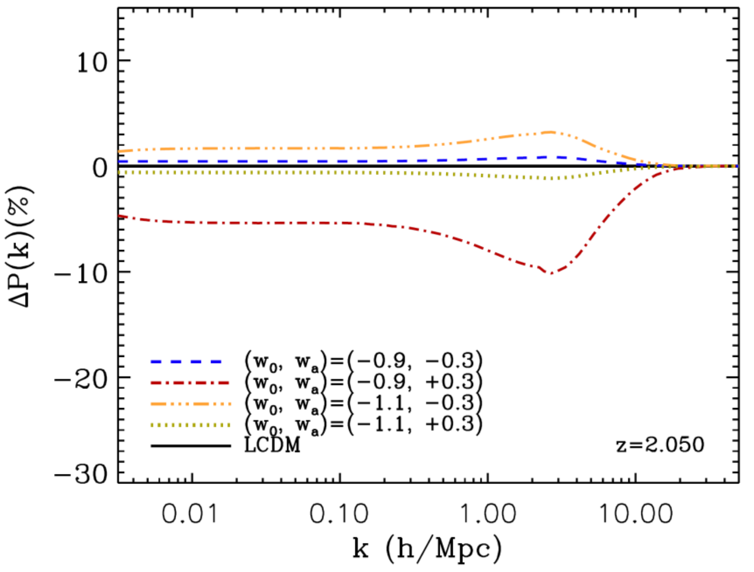
Sign inversion: the non-linear transition moves toward smaller scales with increasing neutrino mass

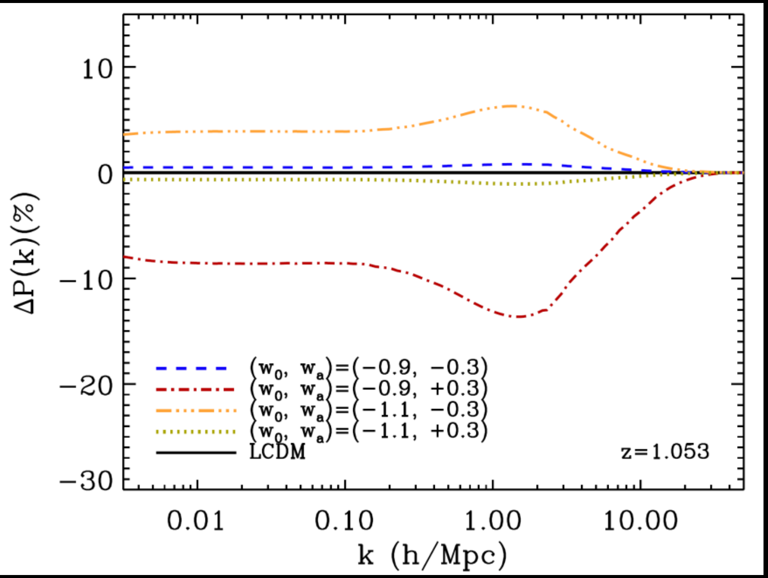
DEMNUni-II: first results

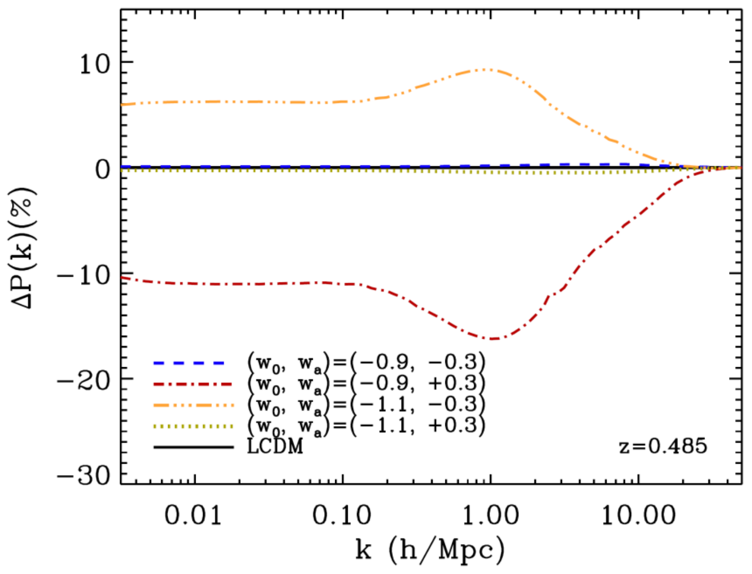


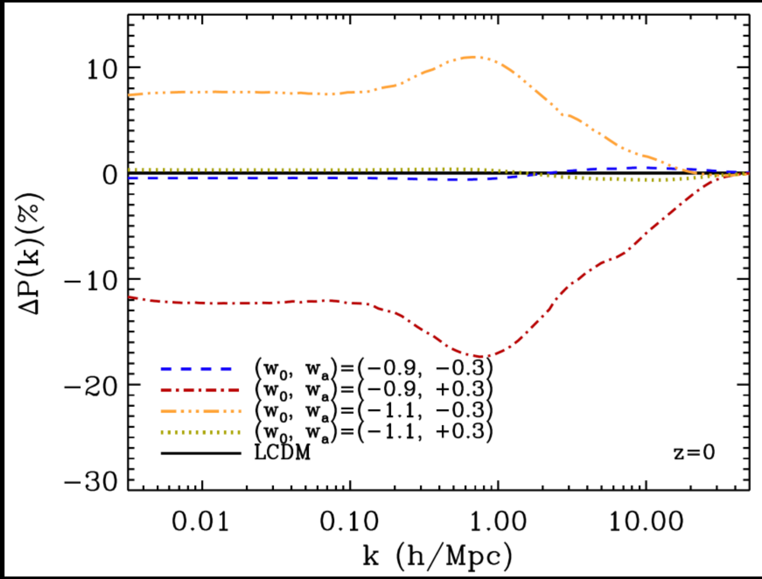
Carbone et al (in prep)

DEMNUni-II: first results

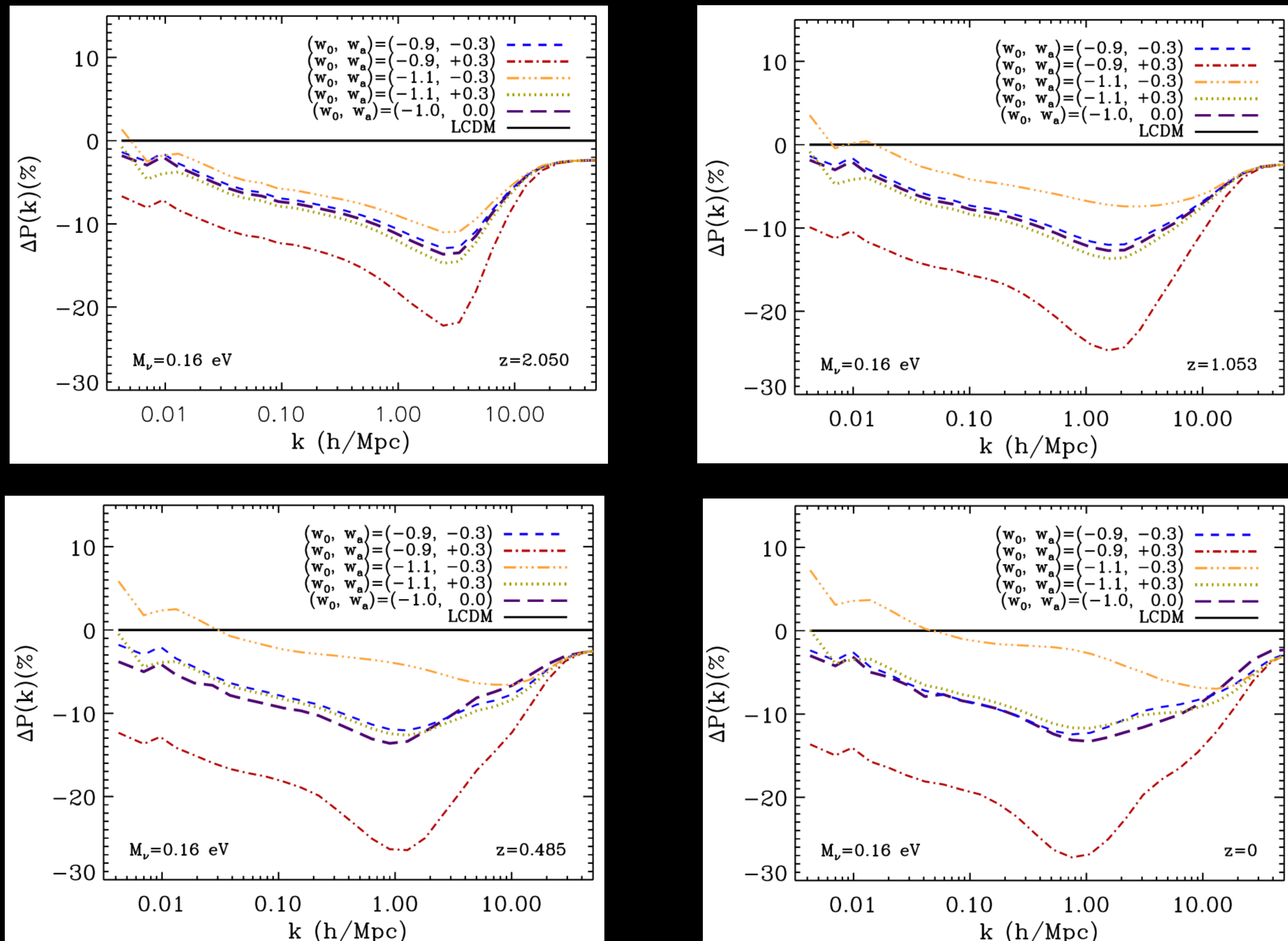




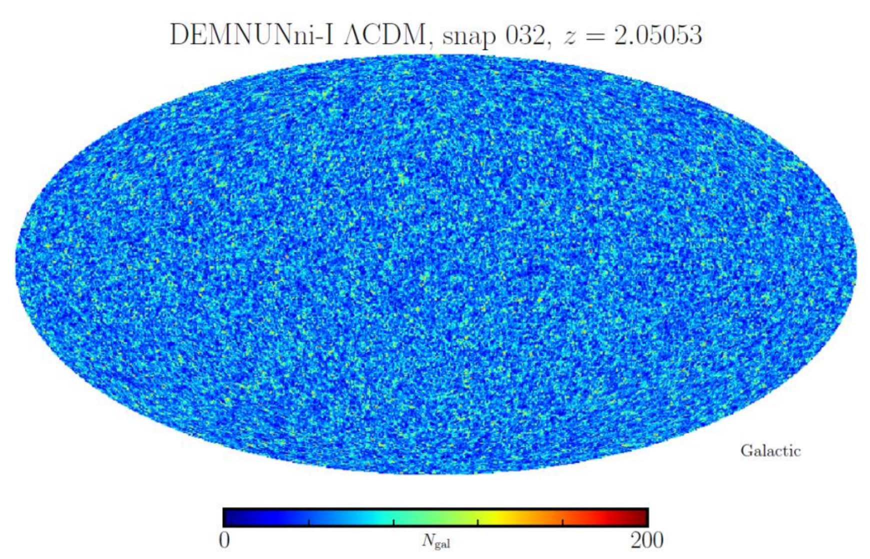


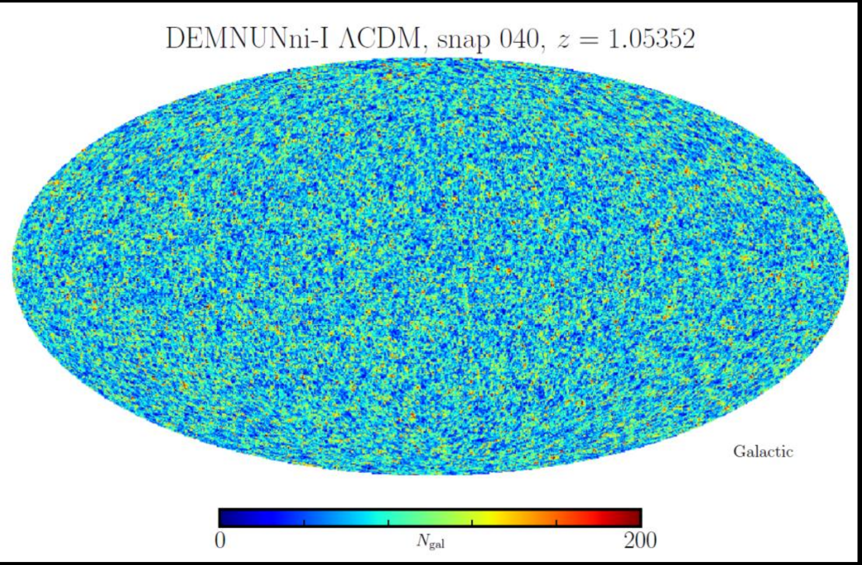


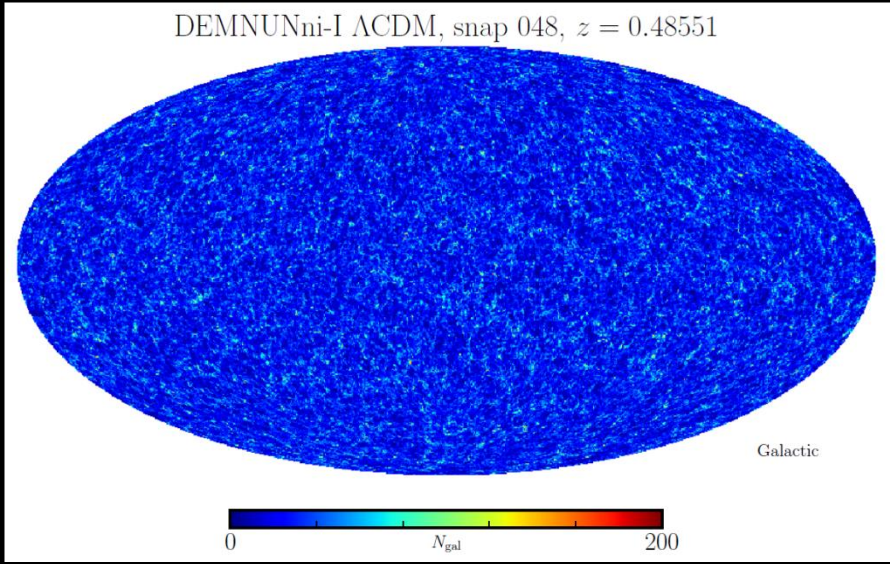
DEMNUni-II: first results



DEMNUni: populating with galaxies







HOD a la Zheng et al. (2007), fitting HOD parameters against SDSS galaxies with magnitude M_r <-20

MZ et al. in prep

Conclusion

- DEMNUni simulations – massive neutrinos and dynamical dark energy
- Confirmed nonlinear prescription for power spectrum applies to cold component alone
- Confirmed σ_{cc} prescription for mass functions
- Velocities and lensing require the total matter contribution (cold + neutrinos)
- Allows for the study of nonlinear ISW/RS
- Cross correlations of CMB/weak lensing with ISW/RS
- Soon → cross correlations with LSS
- Soon → calibration of emulators & study of covariances