# Clustering, lensing and ISW/RS from the DEMNUni simulations


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*Illuminating Dark energy with the next generation of cosmological redshift surveys*

ICTP, May 15th, 2015, Trieste, Italy

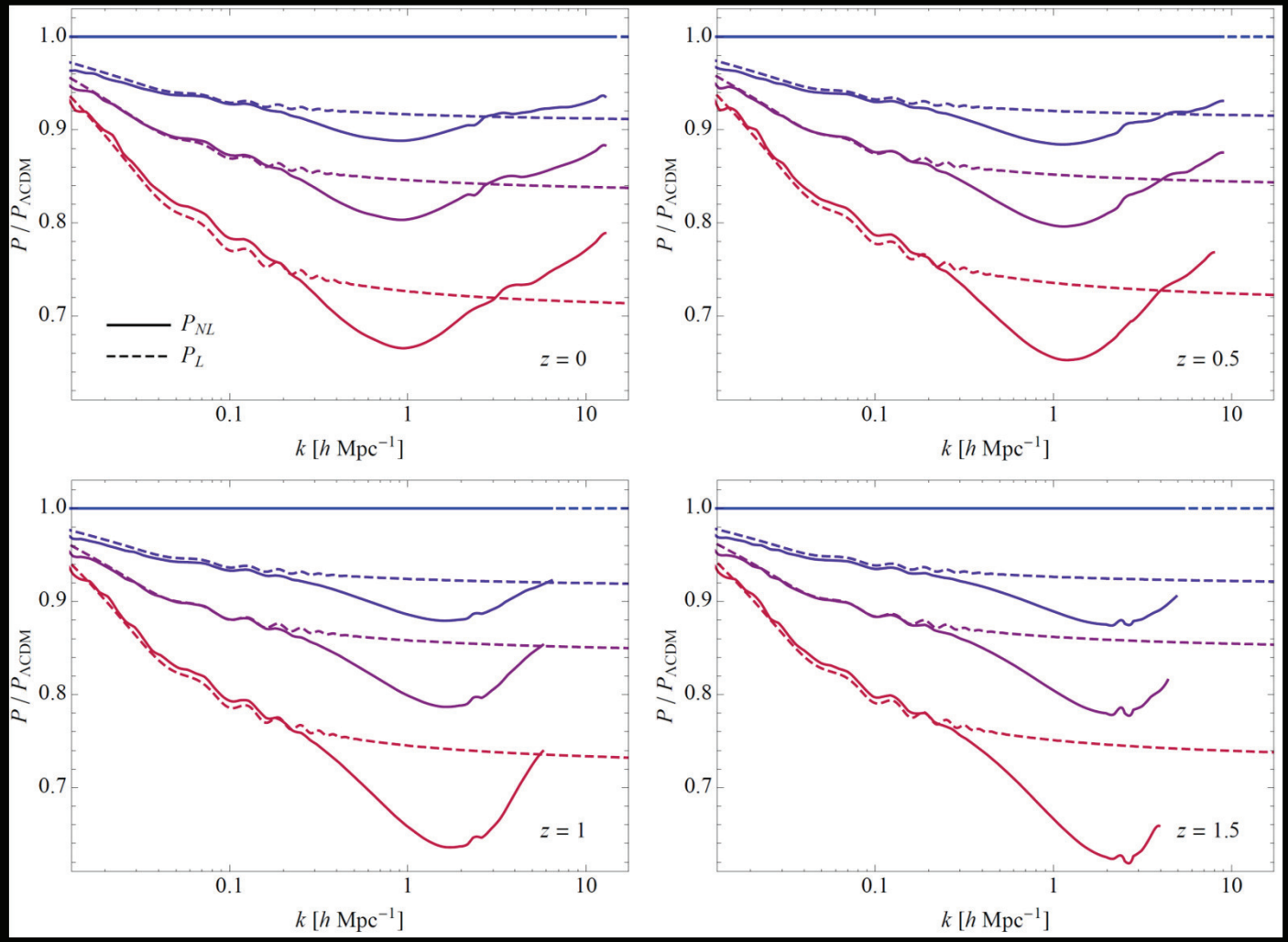
# Outline

- DEMNUni: Dark Energy and Massive Neutrino Universe simulations

- "DEMNUni: The clustering of large-scale structures in the presence of massive neutrinos", Castorina et al 2015, in prep

- "DEMNUni: ISW, Rees-Sciama, and weak-lensing in the presence of massive neutrinos", Carbone et al 2015, in prep

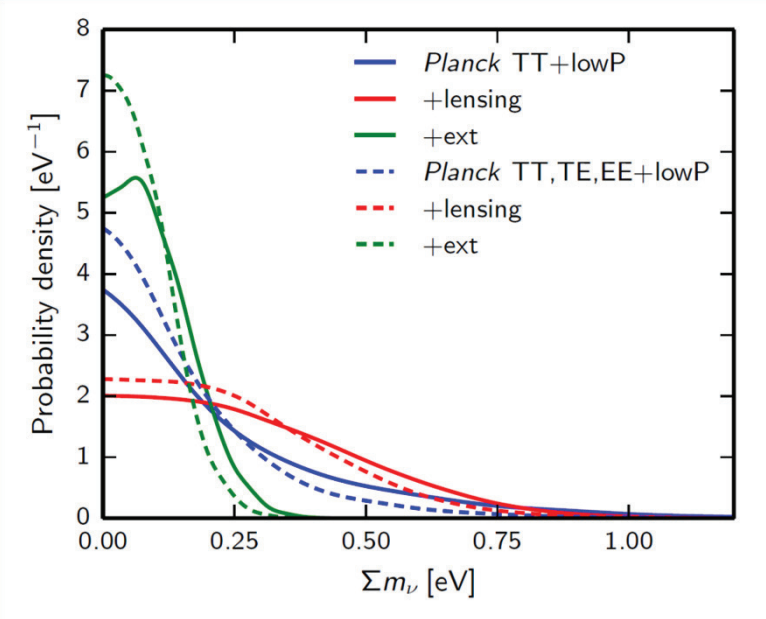
# Total matter P(k) ratios with respect to LCDM




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

# Planck constraints on neutrinos (95% CL)

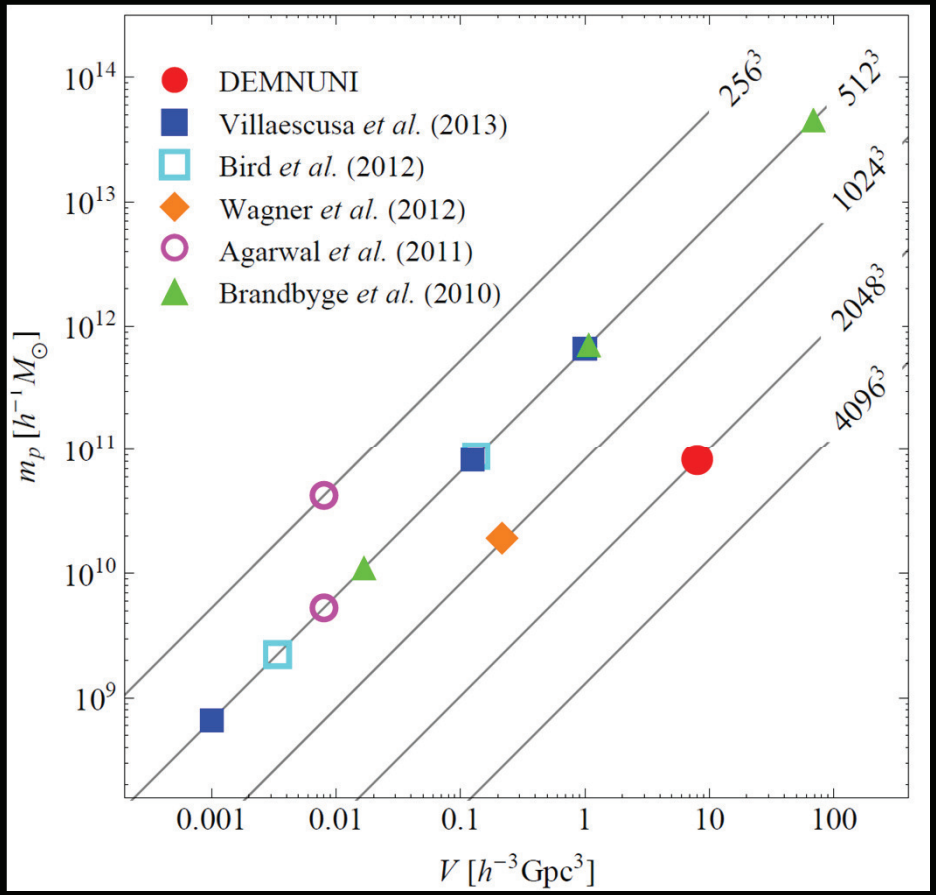
| Parameter | TT | TT+lensing | TT+lensing+ext | TT, TE, EE | TT, TE, EE+lensing | TT, TE, EE+lensing+ext |
|---|---|---|---|---|---|---|
| $\Omega_K$ | $-0.052^{+0.049}_{-0.055}$ | $-0.005^{+0.016}_{-0.017}$ | $-0.0001^{+0.0054}_{-0.0052}$ | $-0.040^{+0.038}_{-0.041}$ | $-0.004^{+0.015}_{-0.015}$ | $0.0008^{+0.0040}_{-0.0039}$ |
| $\Sigma m_\nu$ [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 a detection for the neutrino mass:

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

Castorina, CC et al in prep




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

# DEMNUni simulations

- **$5 \times 10^6$ cpu-hours on BGQ/FERMI at CINECA**
- **4 mixed dark matter cosmological simulations for CMB and LSS analysis in the presence of massive neutrinos**
- **Planck cosmology, $M_\nu$=0, 0.17, 0.3, 0.53 eV**
- **Gadget-3 with ν-particle component (Viel et al. 2010)**
- **box-side size: 2 Gpc/h**
- **particle number: $2 \times 2048^3$ (CDM+ν)**
- **CDM mass: $8 \times 10^{10}$ $M_\odot$/h (neutrino particle mass depends on $M_\nu$)**
- **softening length: 20 kpc/h**
- **starting redshift: $z_{in}$=99**

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

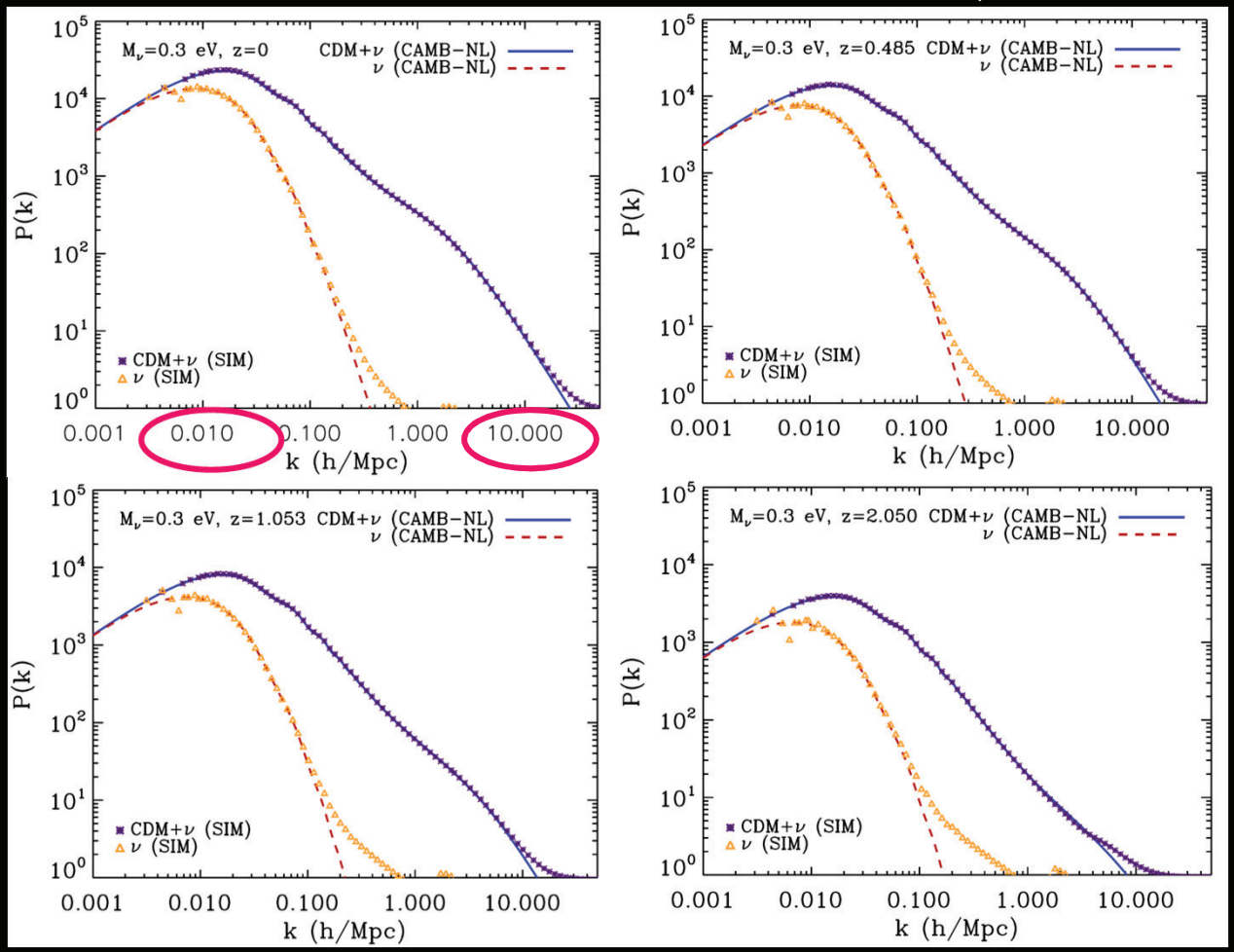
# Simulation outputs

- 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
- 50 temporary gravitational potential grids of size 4096^3 (for CMB weak-lensing)
- 50 temporary grids of size 4096^3 for the derivative of the gravitational potential (for ISW/Rees-Sciama)

# DEMNUni collaboration

- P-Gadget3 code with massive neutrinos: M. Viel
- Simulation runs: C. Carbone (PI), K. Dolag
- CMB-lensing and ISW/Rees-Sciama maps: C. Carbone, M. Petkova
- Galaxy clustering: E. Castorina, M. Zennaro, J. Bel, D. Bianchi, E. Sefusatti
- HOD with massive neutrinos: A. J. Hawken
- SZ-maps and cross-correlation with lensing: M. Roncarelli, C. Giocoli, C. Carbone
- Convergenge maps and cross-correlation with ISW/RS: C. Carbone , C. Giocoli
- High-order statistics: M. Moresco, J. Bel, E.Sefusatti
- Voids with massive neutrinos: A. J. Hawken, C. Carbone, B. Granett, A. Iovino

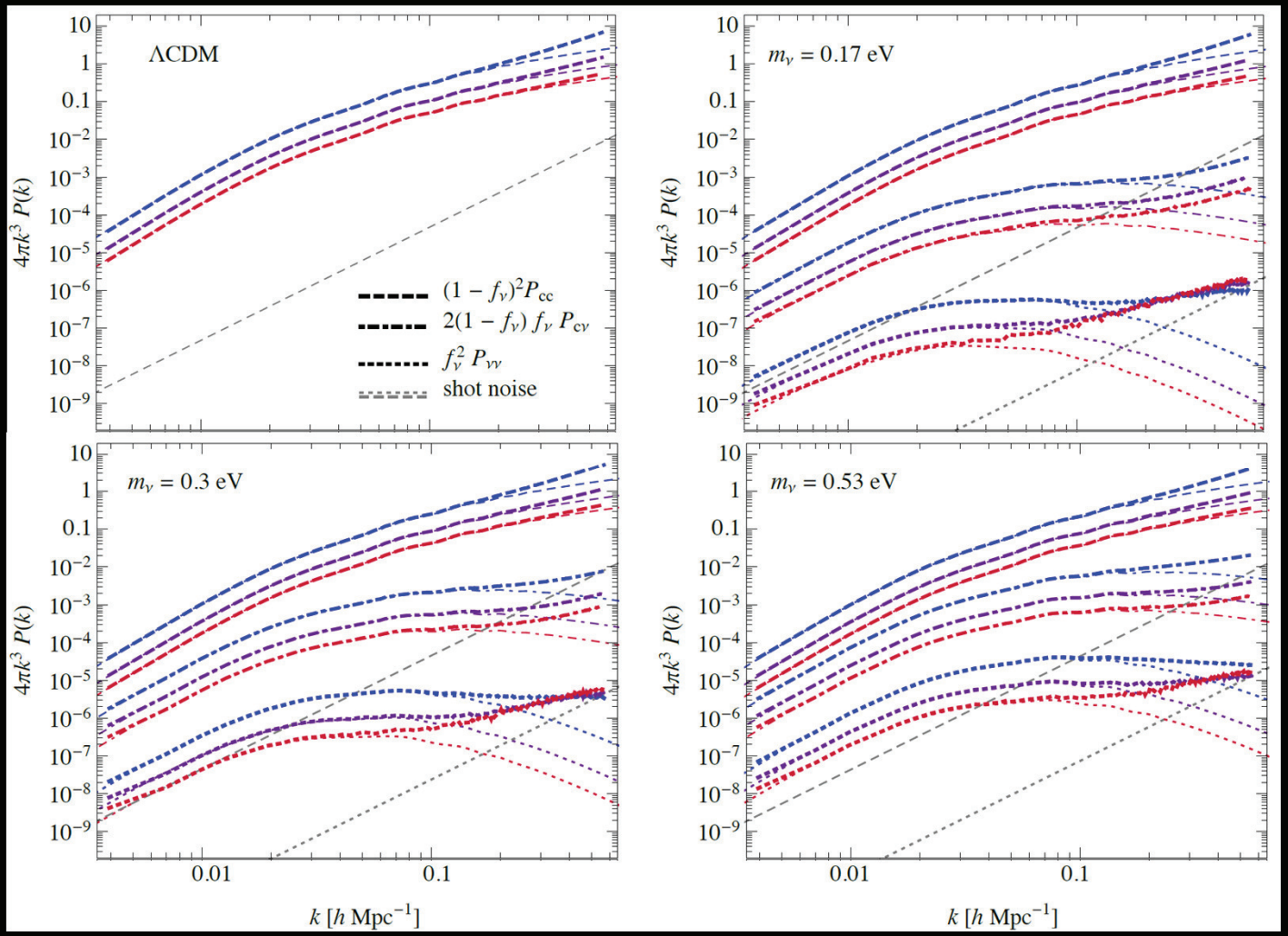
# DEMNUni matter power spectra for $M_\nu$=0.3 eV




**The large volume of the DEMNUni simulation suite allows to measure the power spectrum in neutrino cosmologies at the 1% level on the scales characterised by BAO, allowing a test of perturbation theory predictions at the level of accuracy required by current and futures galaxy surveys.**

# Different contributions to the total matter P(k)

Castorina, CC et al in prep

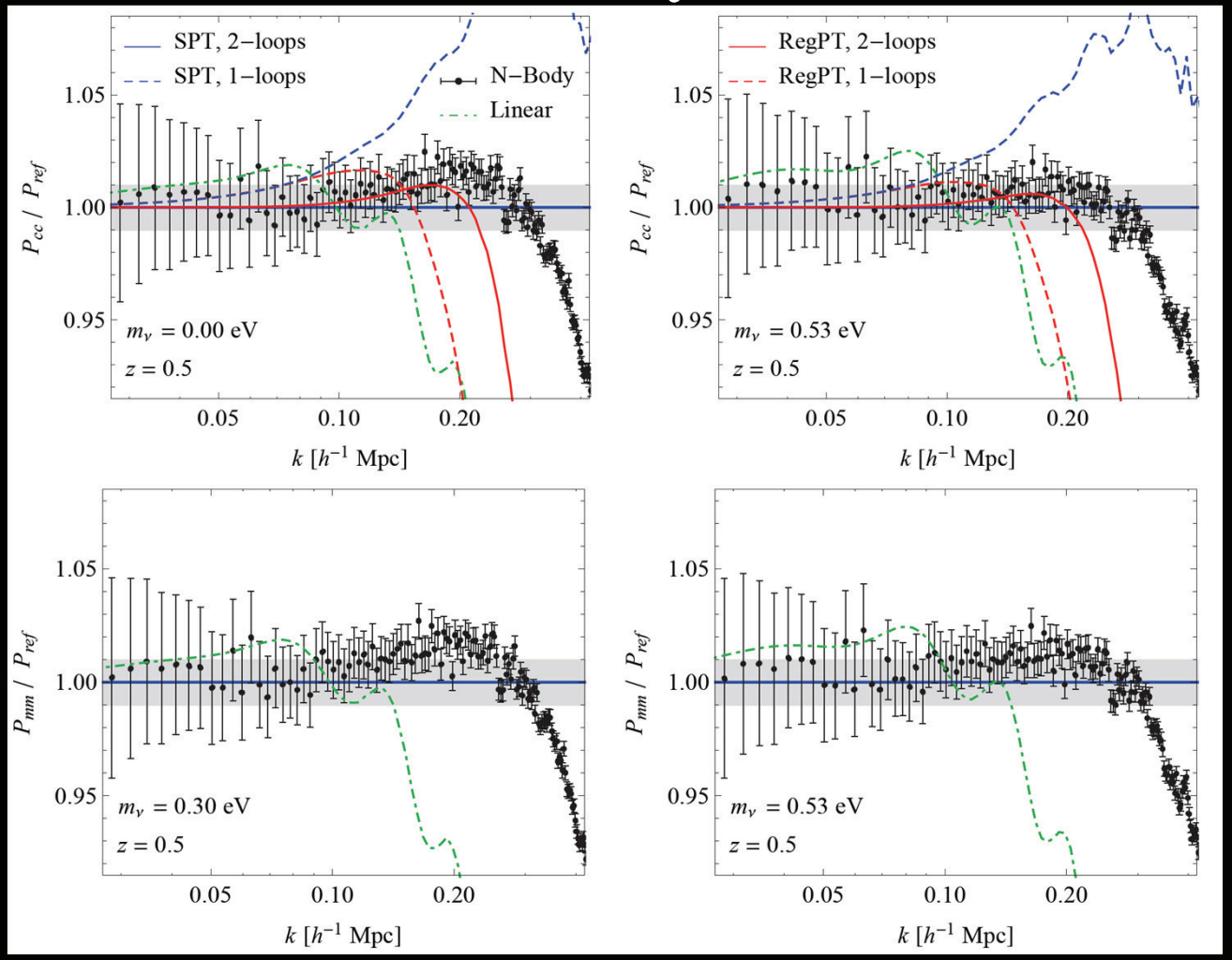



$$P_m(k;z) = (1-f_\nu)^2\, P_{cb}(k;z) + 2\,(1-f_\nu) f_\nu\, P_{cb,\nu}(k;z) + f_\nu^2\, P_\nu(k;z)$$

***$P_m(k)$* is described at the 1% level assuming the nonlinear evolution of CDM alone, and the linear prediction for the other components**

# Perturbation theory vs Simulations

Castorina, CC et al in prep



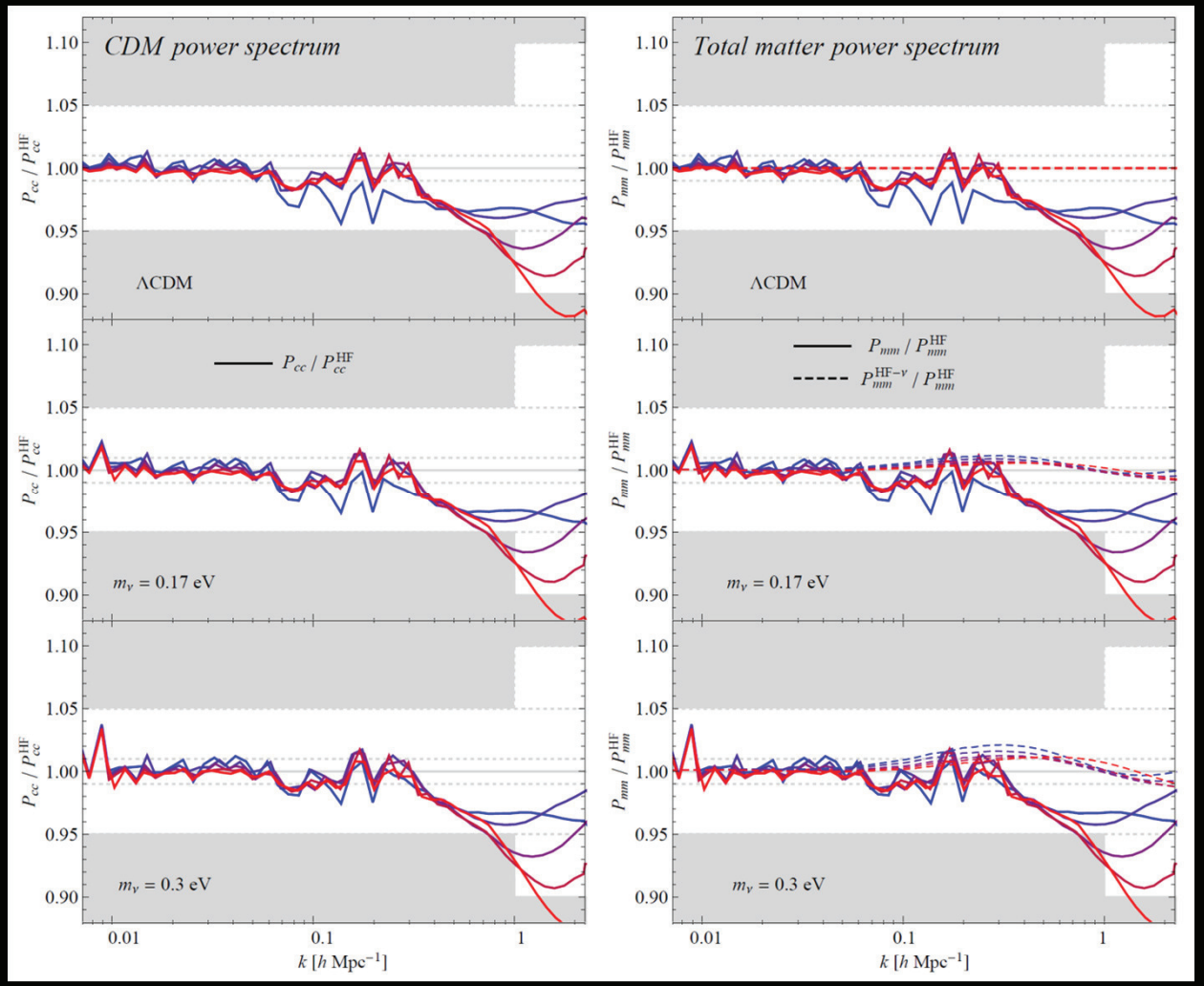

$$P^{PT}_{mm}(k) = (1-f_\nu)^2\, P^{PT}_{cc}(k) + 2\,(1-f_\nu)\, f_\nu\, P^{L}_{c\nu}(k) + f_\nu^2\, P^{L}_{\nu\nu}(k)$$

(RegularizedPT: Bernardau et al 2008, Taruya et al 2012)

**Here the neutrino induced scale-dependence is limited to the linear growth factor, *D(k,z)*, while the perturbation kernels are standard ones. PT works better with $M_\nu$**

# Modifications to Halofit

Castorina, CC et al in prep



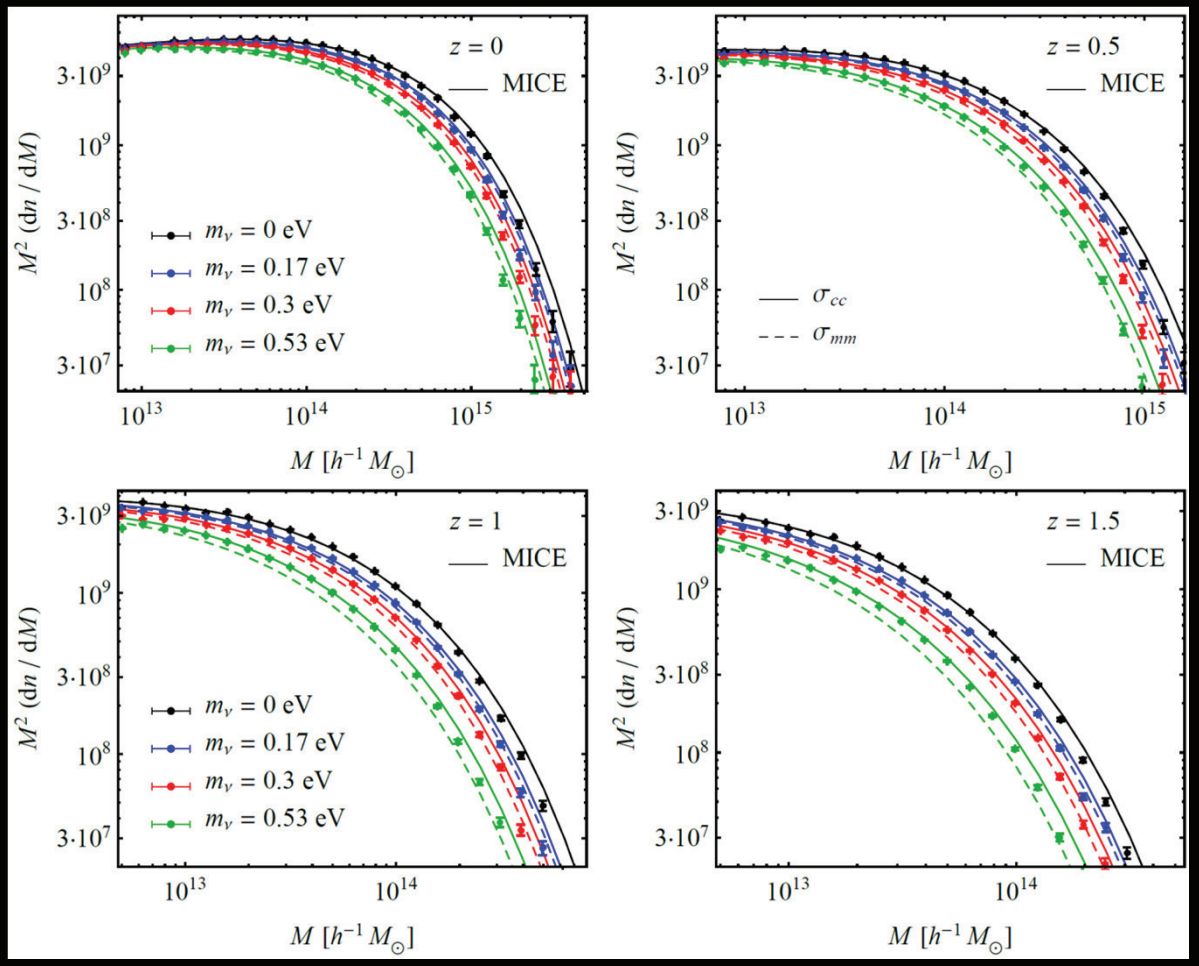

$$P_{mm}^{HF}(k) \equiv (1-f_\nu)^2\, P_{cc}^{HF}(k) + 2\, f_\nu\, (1-f_\nu)\, P_{c\nu}^{L}(k) + f_\nu^2\ P_{\nu\nu}^{L}(k)$$

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

**HALOFIT mapping only for CDM, other contributions are assumed to be linear**

# Halo Mass Function: FoF

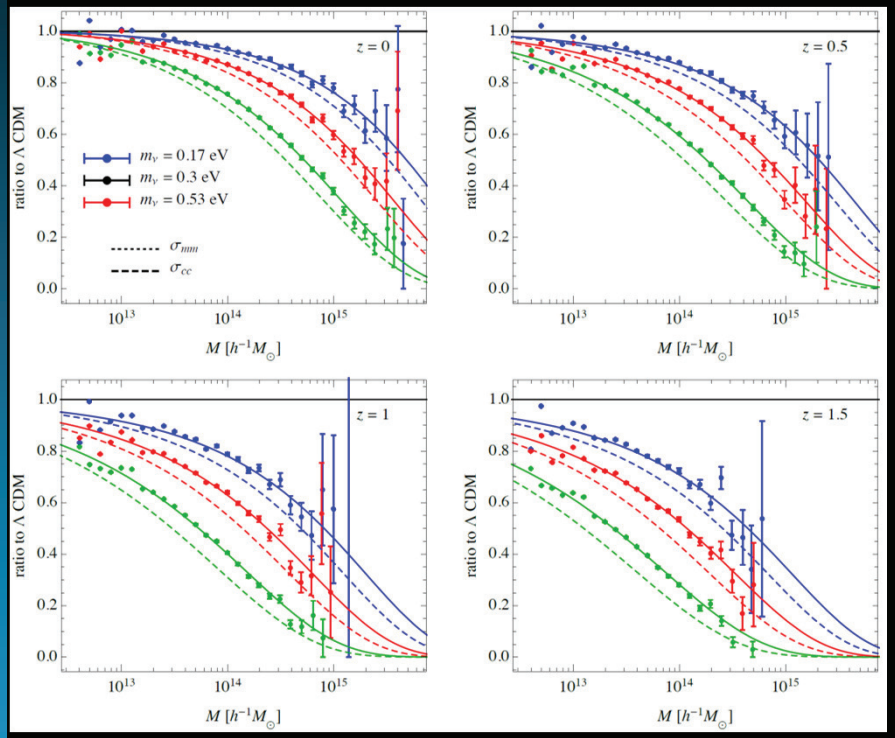
Castorina, CC et al in prep

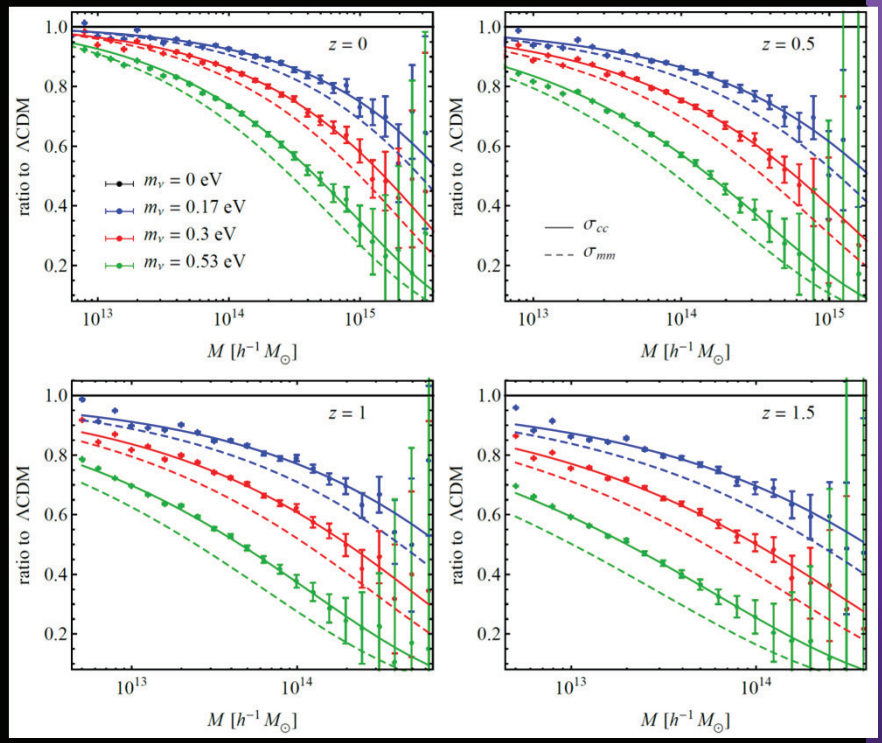



**We recover the $\rho_{cc}$ and $\sigma_{cc}$ prescription from Ichiki&Takada (2012) and Castorina et al (2014)**

# Halo Mass Function: FoF vs SO

## Castorina, CC et al in prep

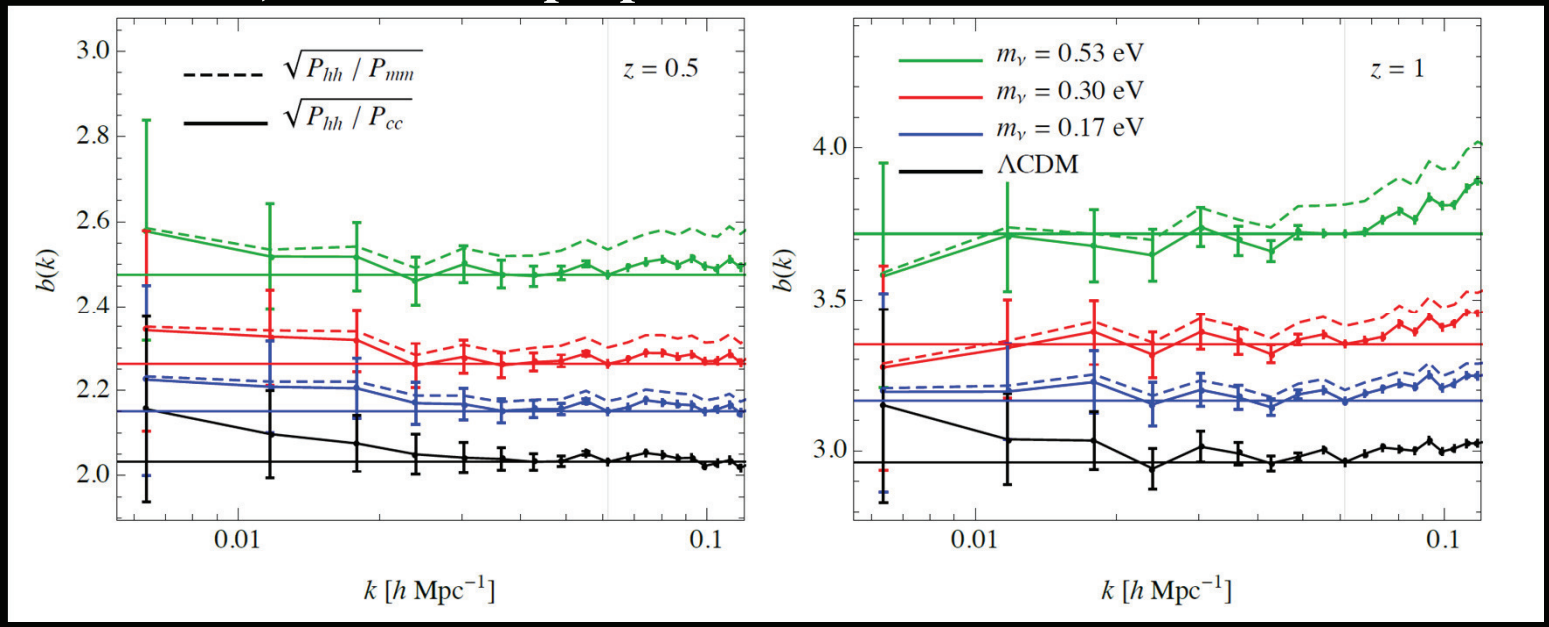



**The $\rho_{cc}$ and $\sigma_{cc}$ prescriptions allow to recover the theoretical MF for both FoF and SO halos**

# Analogous conclusions for the bias

## Castorina, CC et al in prep



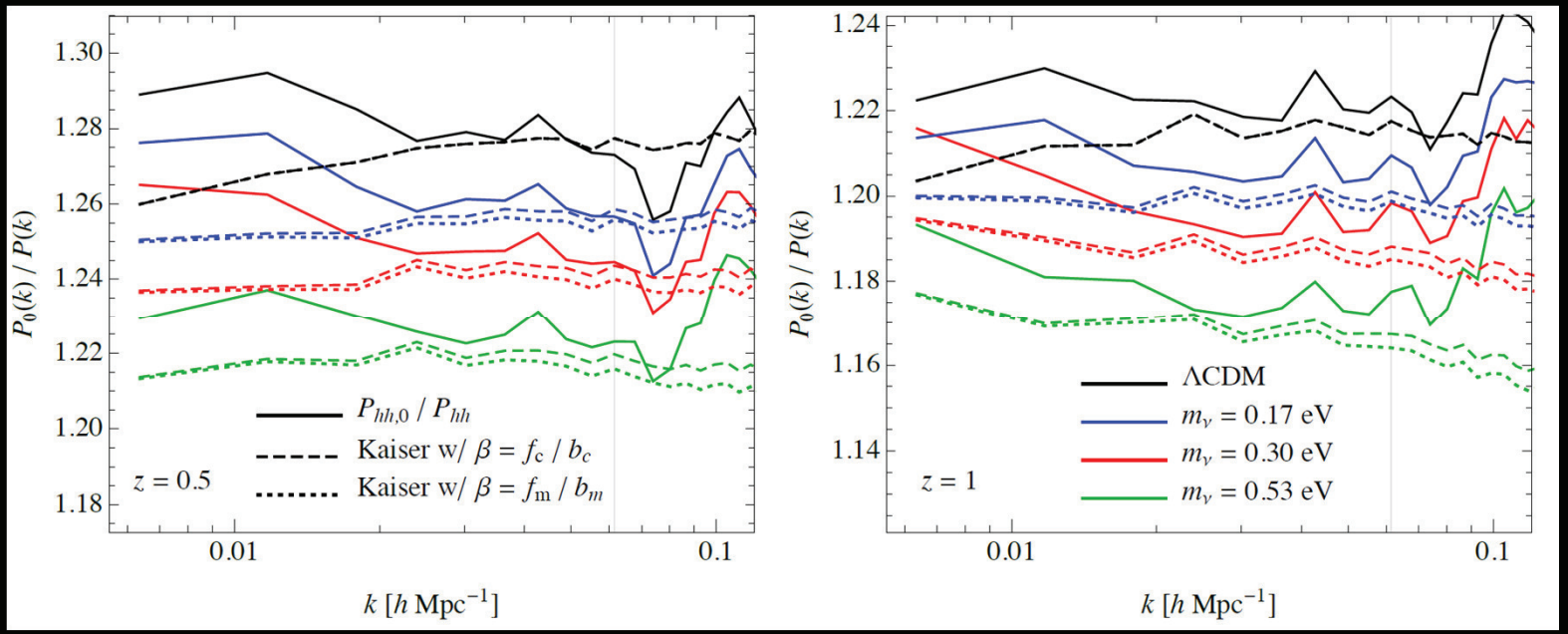

$$b_c = \sqrt{\frac{P_{hh}}{P_{cc}}}$$

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

**The $\sigma_{cc}$ prescription mitigates the ν-induced scale dependence 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.**

# Measurements in redshift space

## Castorina, CC et al in prep




$$P_{hh,s}(\vec{k}) = (1+\beta\mu^2)^2\, P_{hh}(k) = \sum_{l=0,2,4} P_{hh,\ell}\, L_\ell(\mu)$$

**$f_c$ and $\sigma_{cc}$ prescriptions work better than $f_m$ and $\sigma_{mm}$ (velocity bias effects are neglected)**

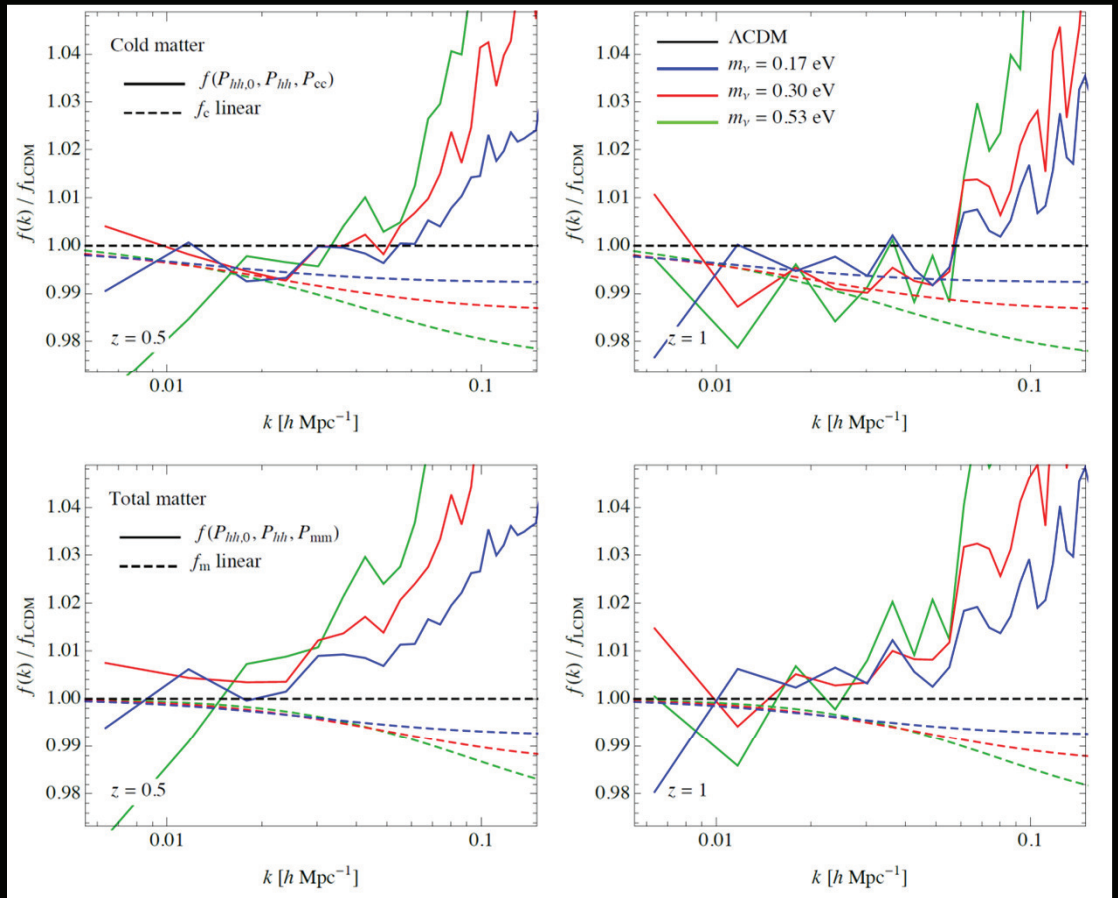
$$P_{hh,0}(k) = \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2\right) P_{hh}(k)$$

$$P_{hh,2}(k) = \left(\frac{4}{3}\beta + \frac{4}{7}\beta^2\right) P_{hh}(k)$$

$$P_{hh,4}(k) = \frac{8}{35}\beta^2 P_{hh}(k),$$

# The scale dependent growth-rate

**Using $b_m$ instead of $b_{cc}$ implies a systematic error on the determination of the growth rate at the level of 1-2%**




$$\beta \equiv f/b$$

$$f(a) \equiv \frac{d \ln D(a)}{d \ln a}$$

$$f(k) = \sqrt{\frac{P_{hh}(k)}{P_{cc}(k)}} \frac{1}{3} \left[ \sqrt{45 \frac{P_{hh,0}(k)}{P_{hh}(k)} - 20} - 5 \right]$$

**Castorina, CC et al in prep**

# Lensing and ISW-RS quantities

$$\phi(\hat{n}) = 2\int dD \frac{(D_s - D)}{DD_s}\Phi(D\hat{n}, D)$$

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

*D*= comoving distance from the observer

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

**Total ISW-RS effect (only late-ISW)**

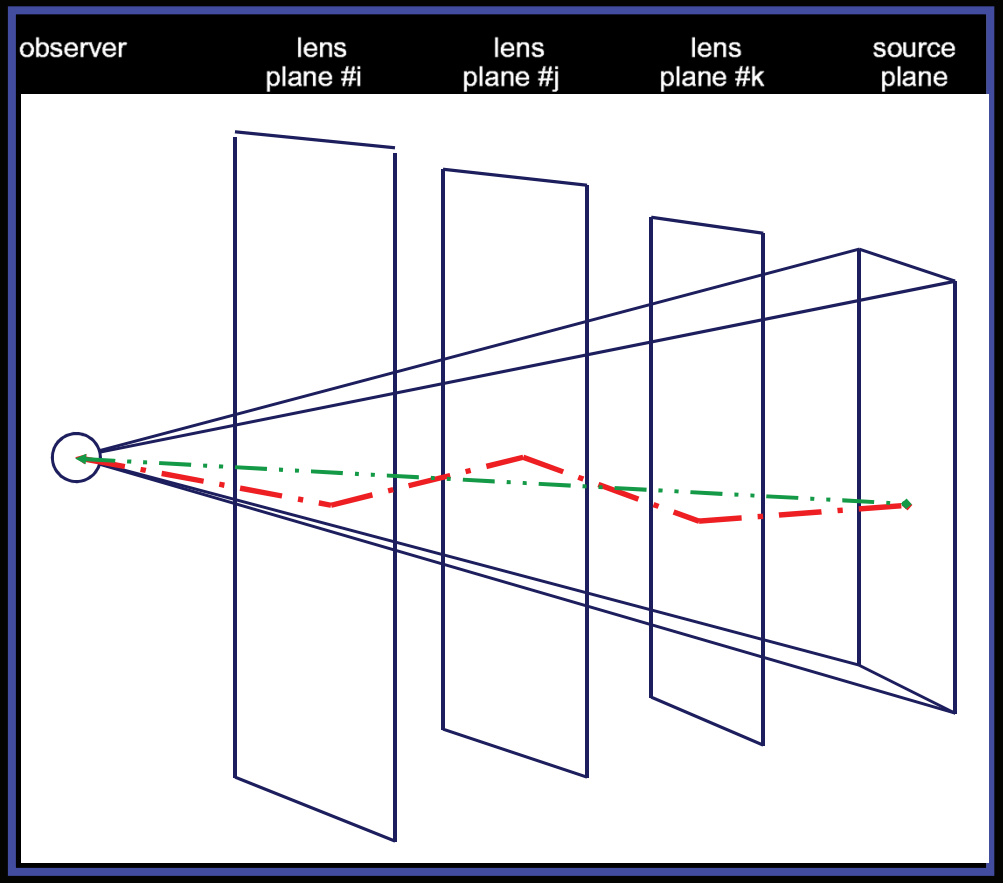
$$\widetilde{X}(\hat{\mathbf{n}}) = X(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$

$$X = T, Q, U$$

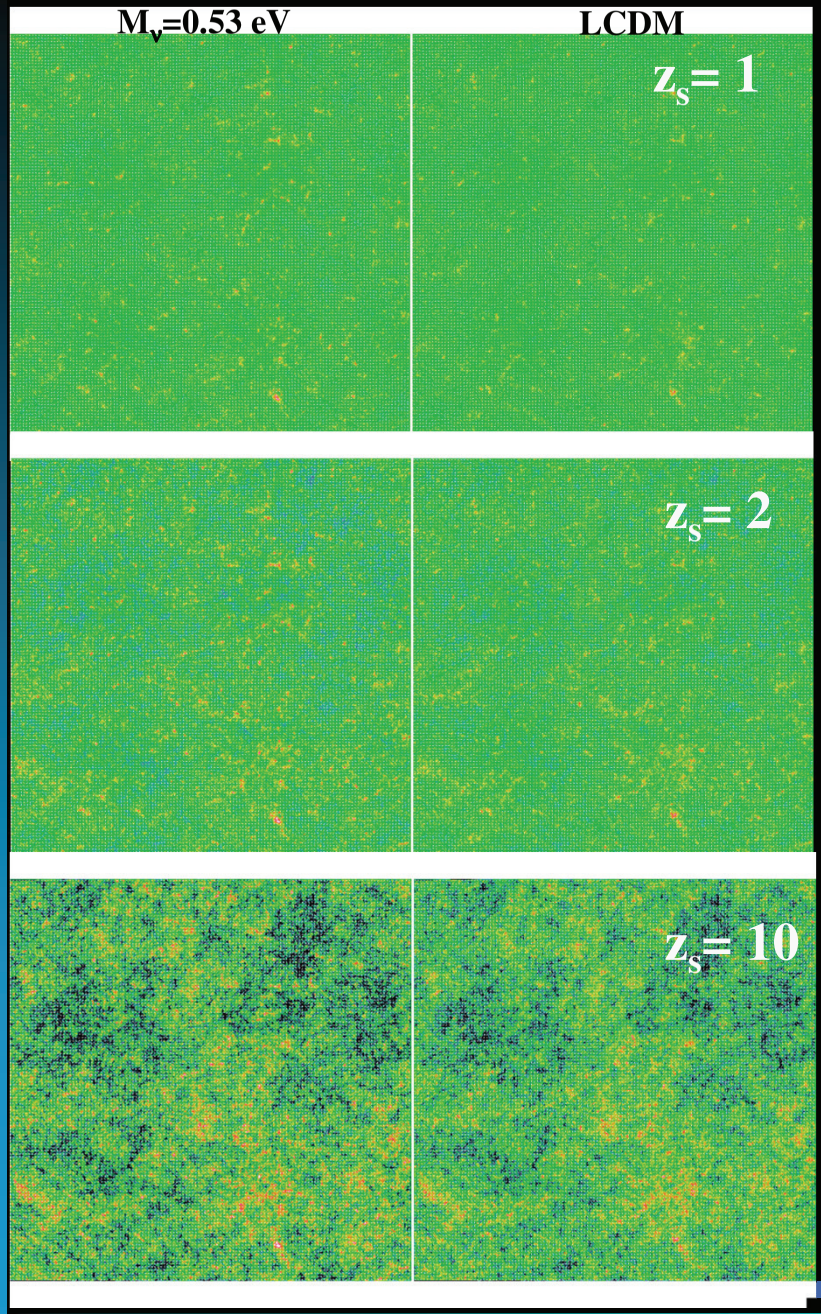
Gradients in the grav. potential generated by LSS cause deviations in the CMB photon propagation from LS to us:

points in a direction $\hat{n}$ actually come from points on the last scattering surface in a displaced direction $\hat{n}' = \hat{n} + \nabla\phi(\hat{n})$

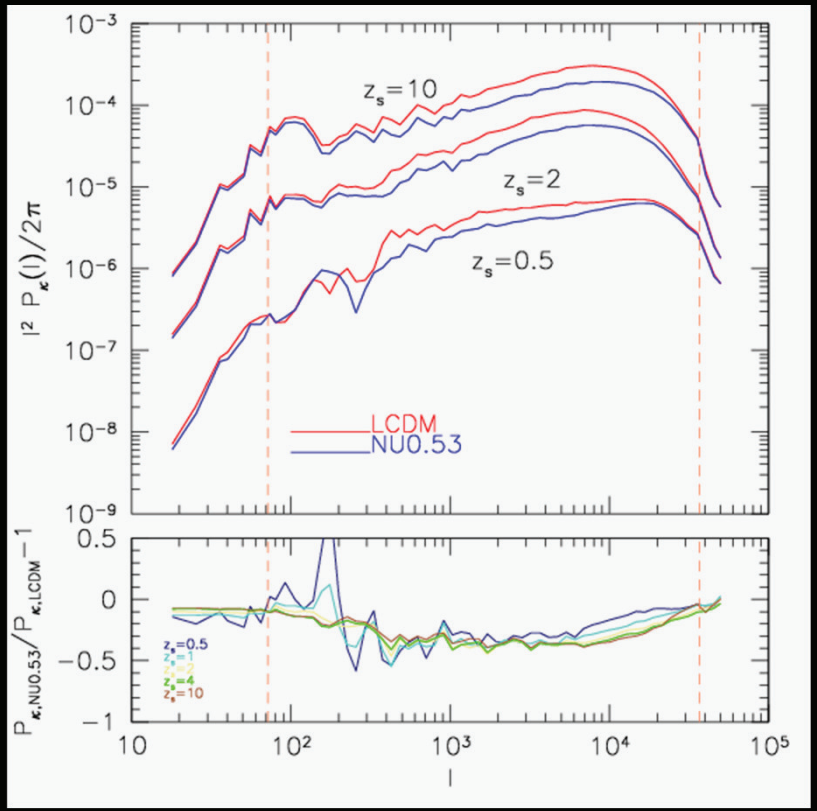
# Weak cosmological lensing and Born approximation



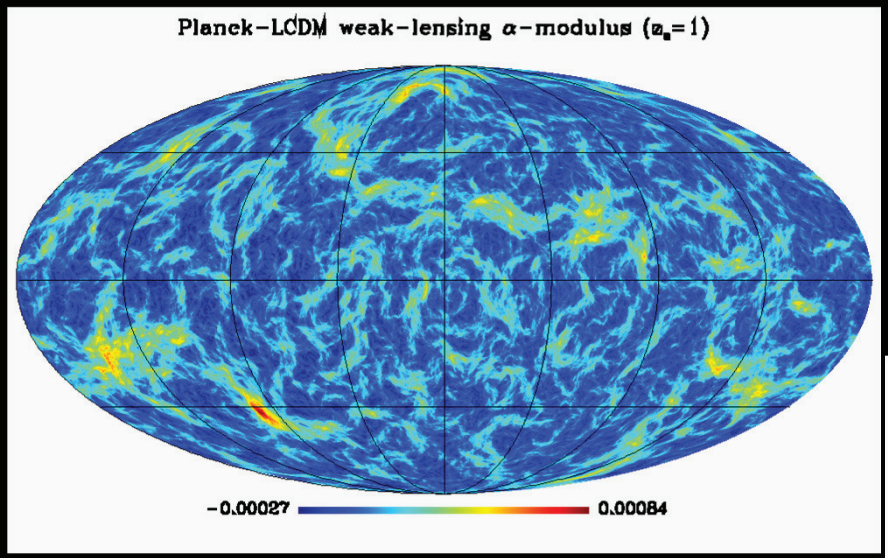

First Born approximation:
integration along the undeflected light geodesics.

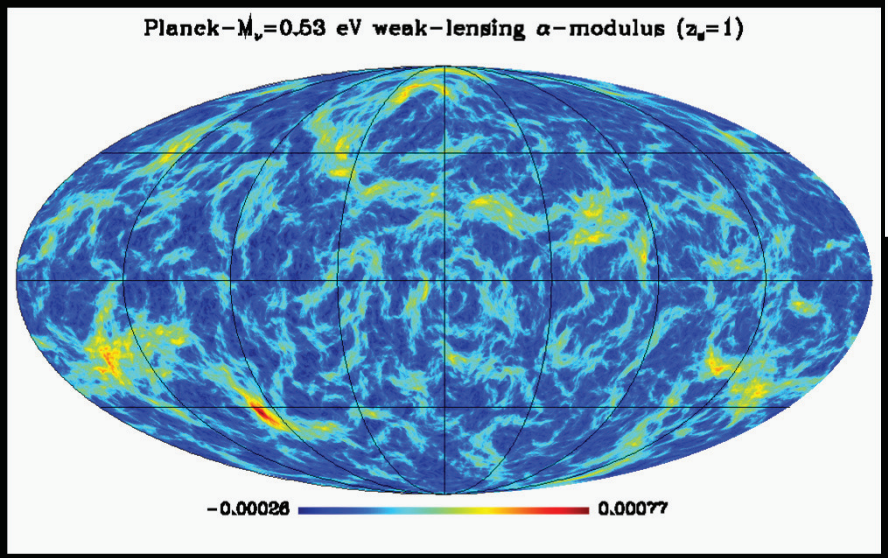


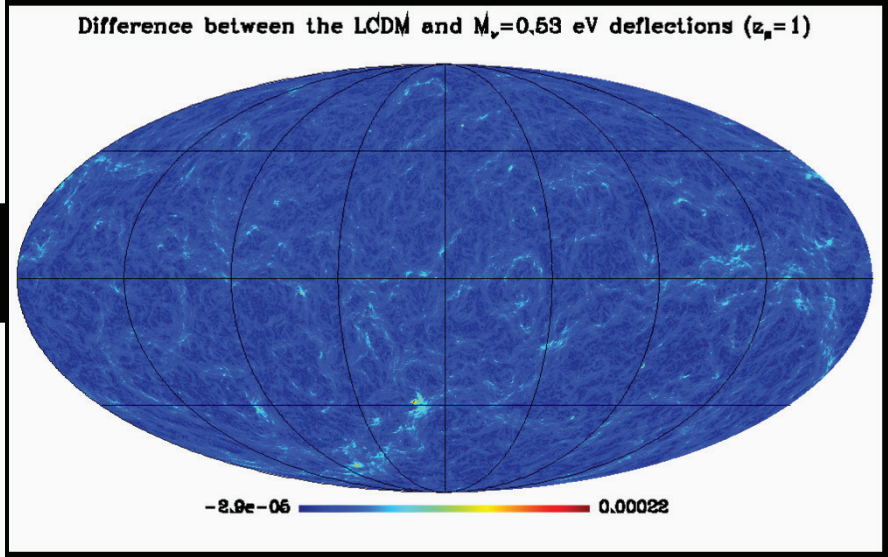

**5°x5° convergenge maps and power-spectra with different source redshift in fla-sky (from C. Giocoli)**



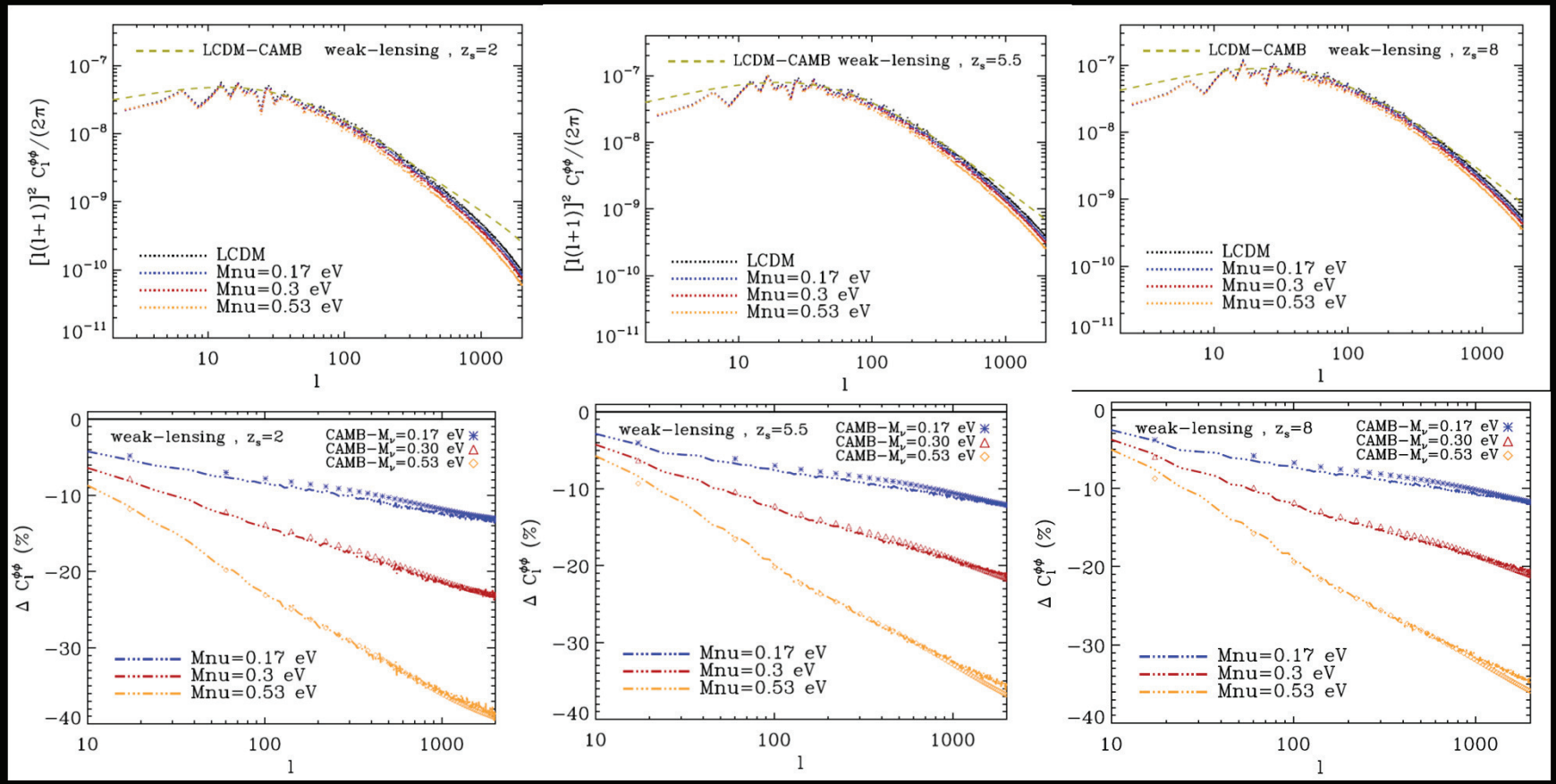
# Deflection angle maps for $z_s$=1 (CC et al. in prep)



# Weak-lensing angular power spectra at different redshifts

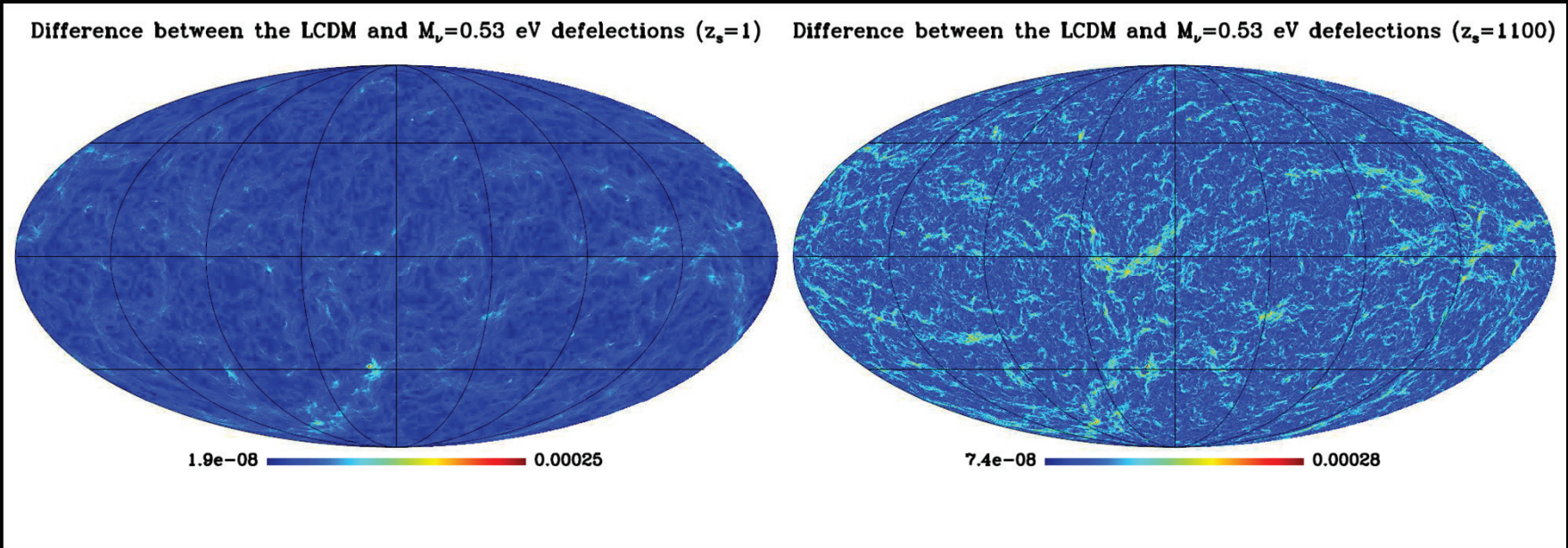



CC et al. in prep

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

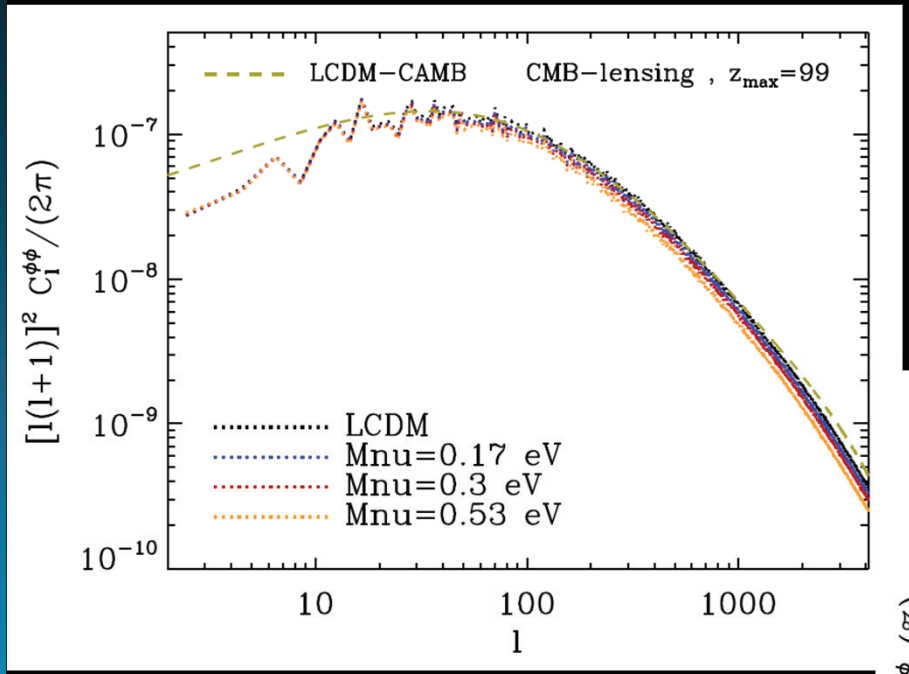
# CMB-lensing vs Weak-lensing

## CC et al. in prep

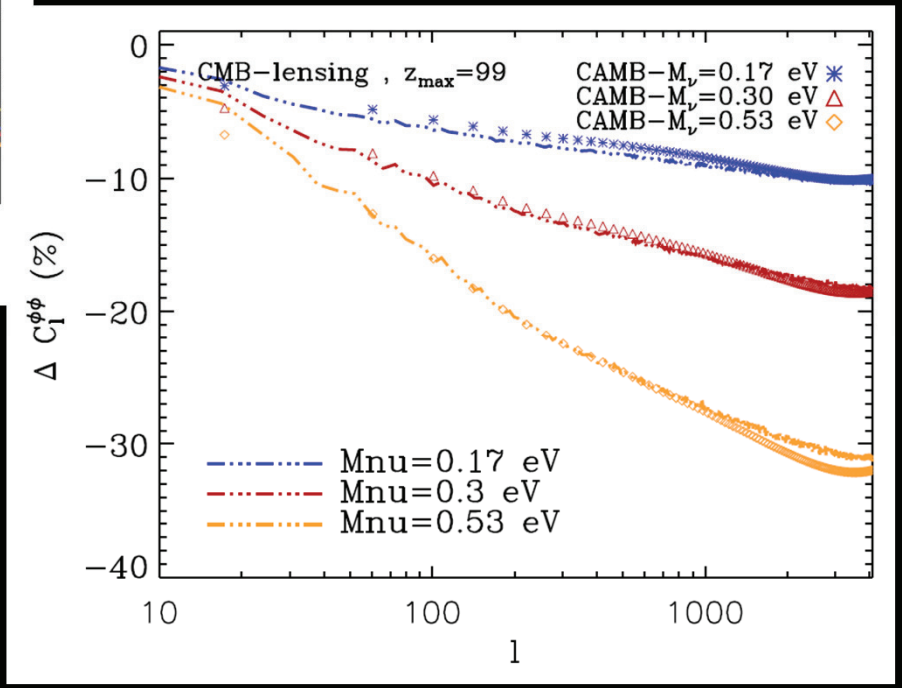



**As expected the effect increases with the source redshift**

# CMB-lensing angular power spectra

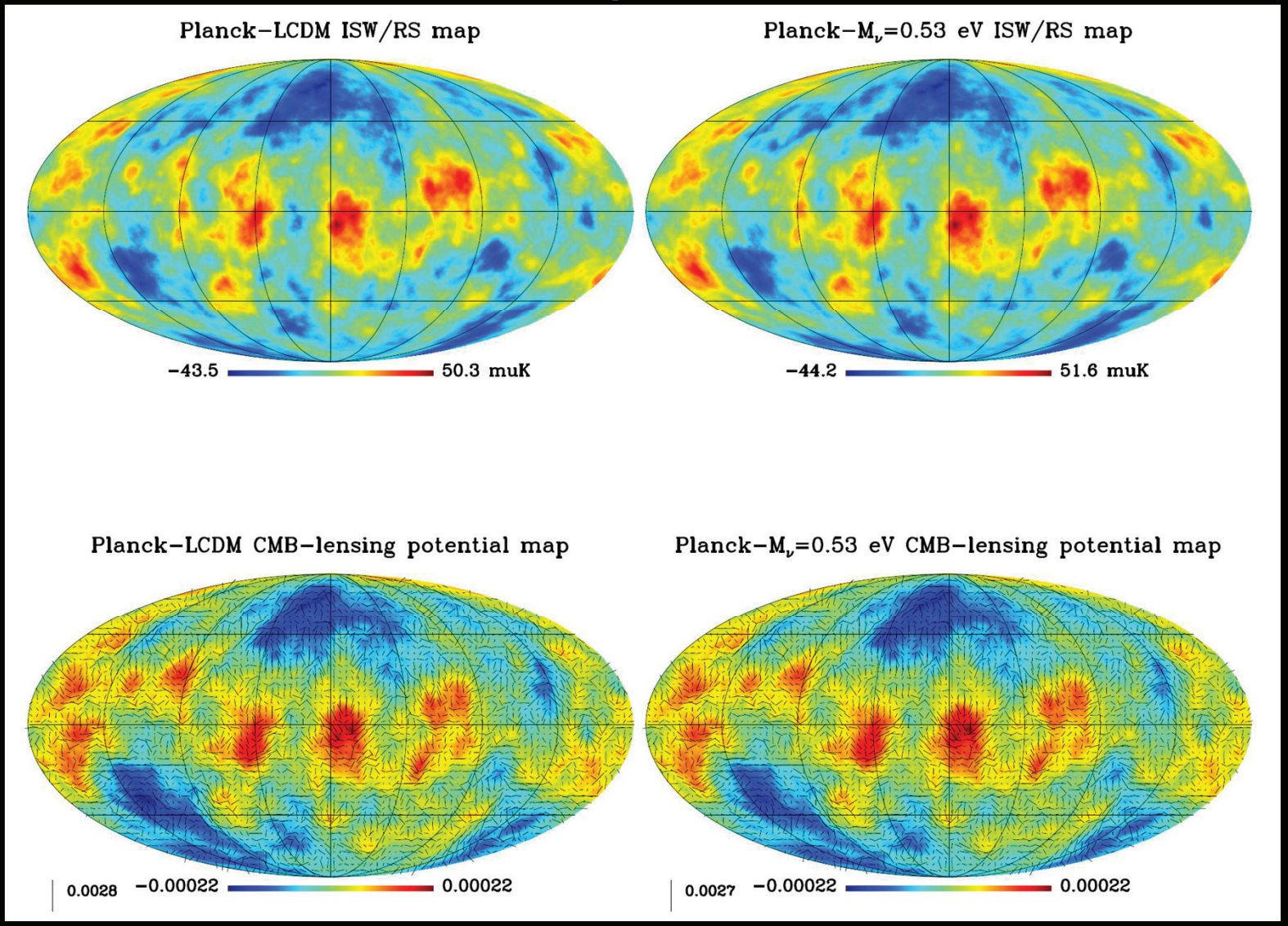



**Power suppression is less than in the weak-lensing case since there is the contribution from higher z**



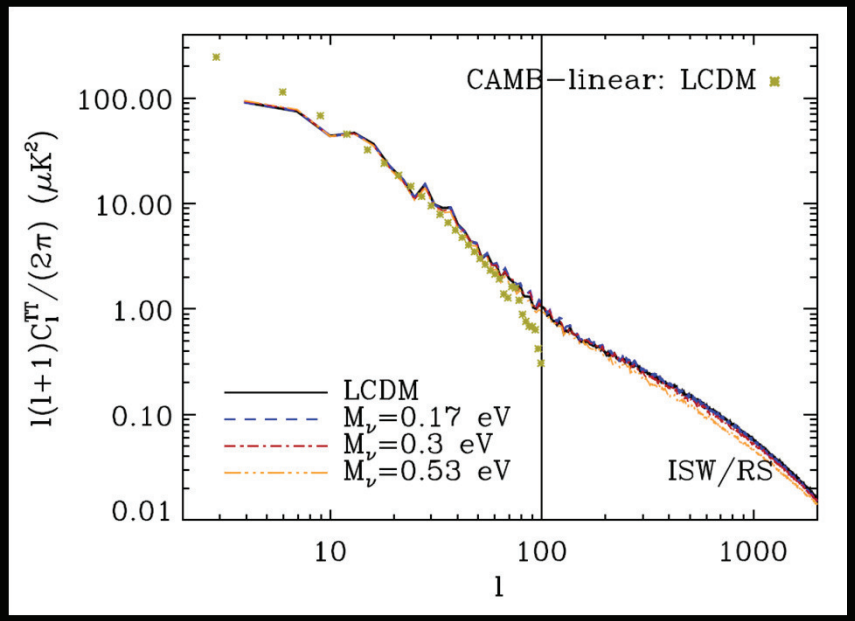

**CC et al. in prep**

# CMB-lensing vs ISW-RS



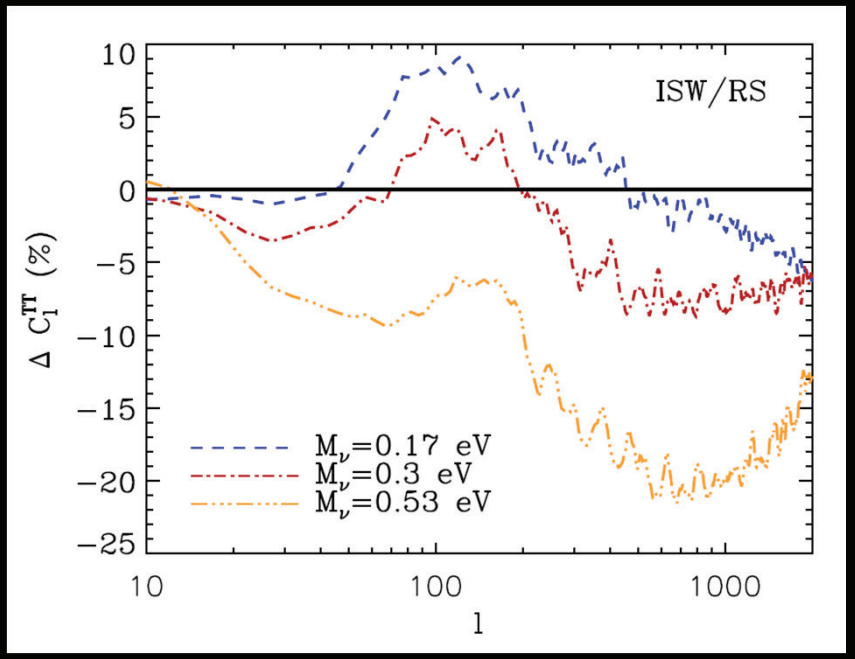

CC et al. in prep

# ISWRS angular power spectra

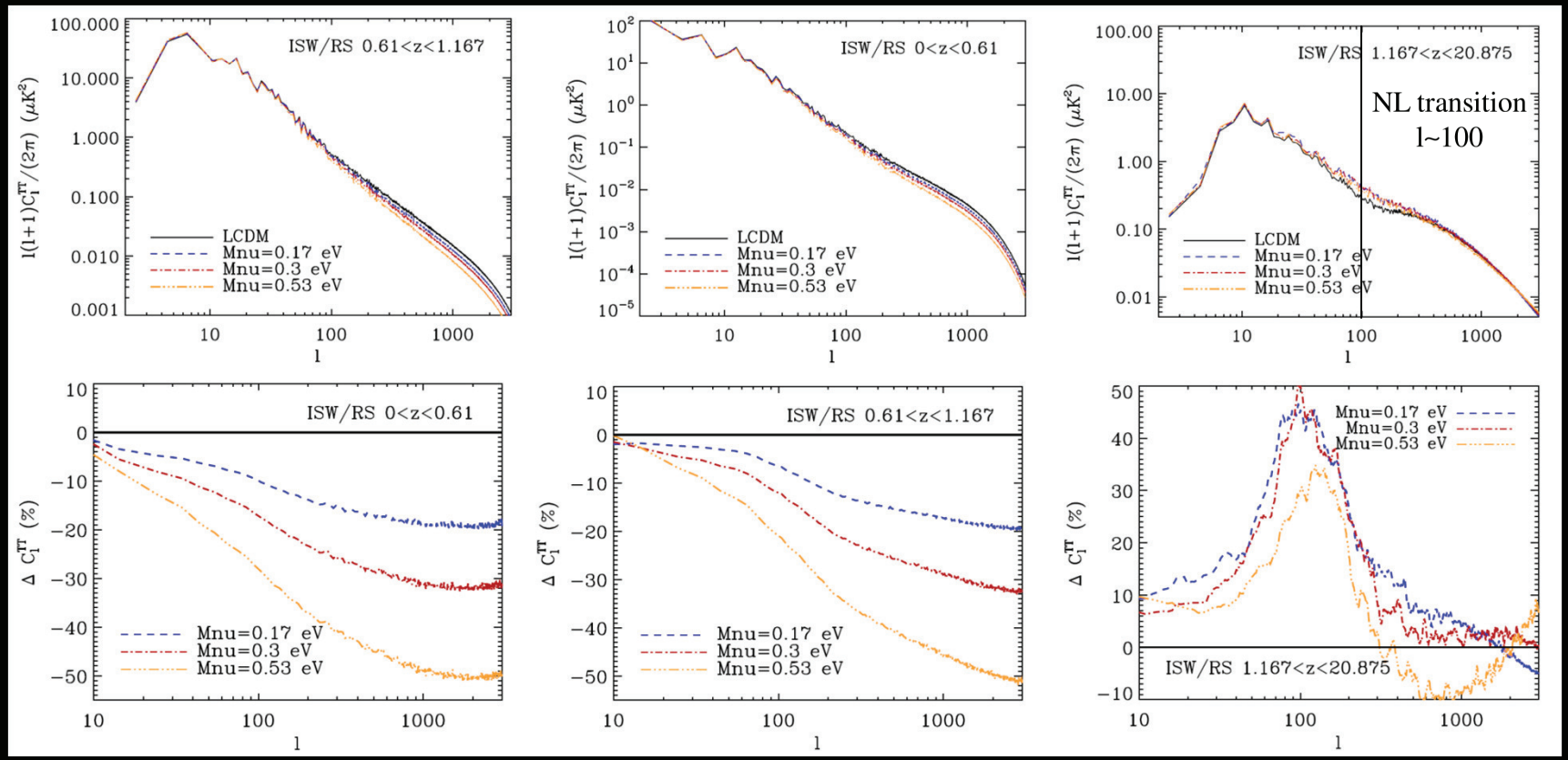



CC et al. in prep

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



# ISWRS angular power spectra at different redshifts

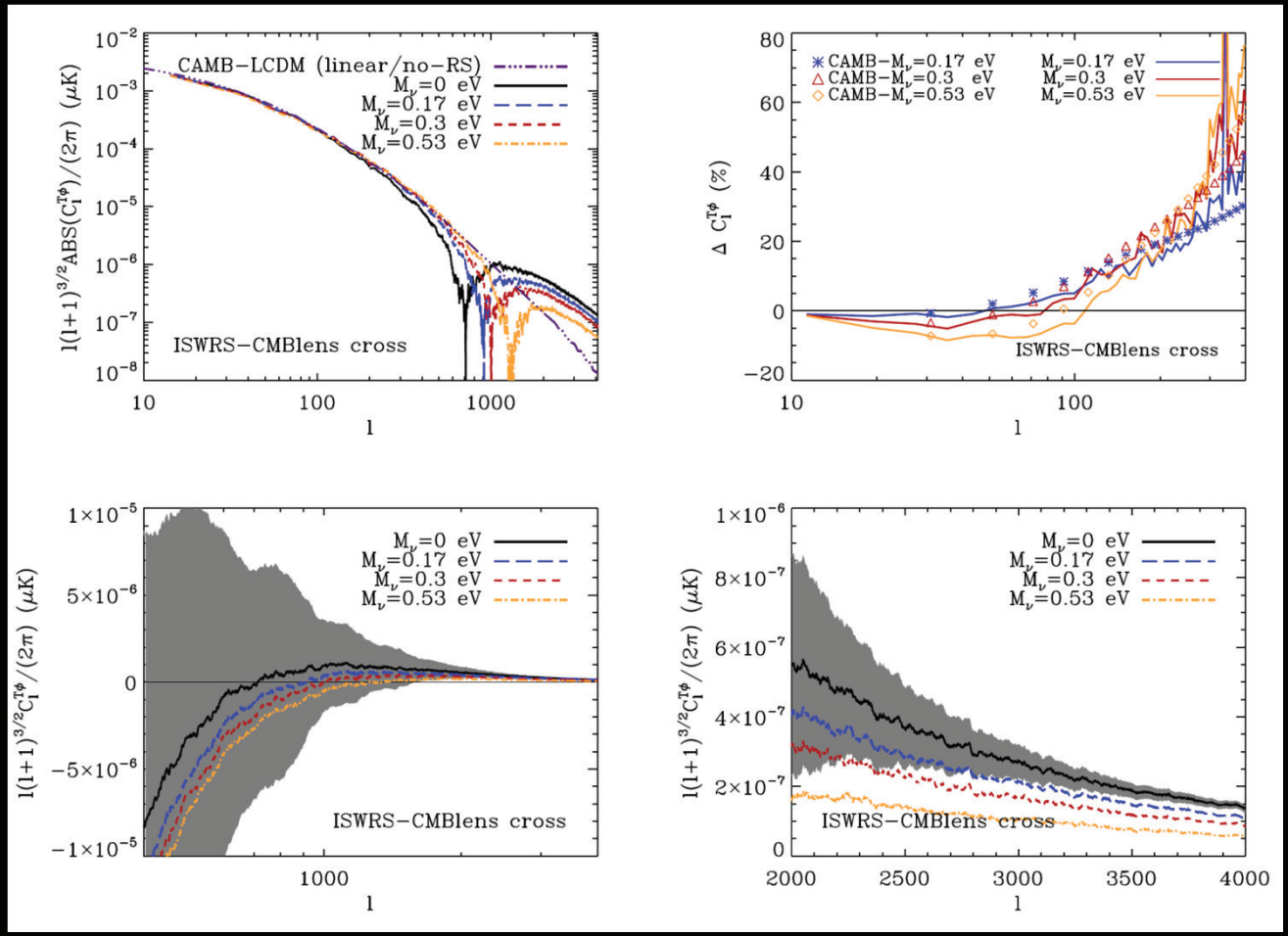



CC et al. in prep

**At redshifts non DE-dominated there is an excess of power**

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

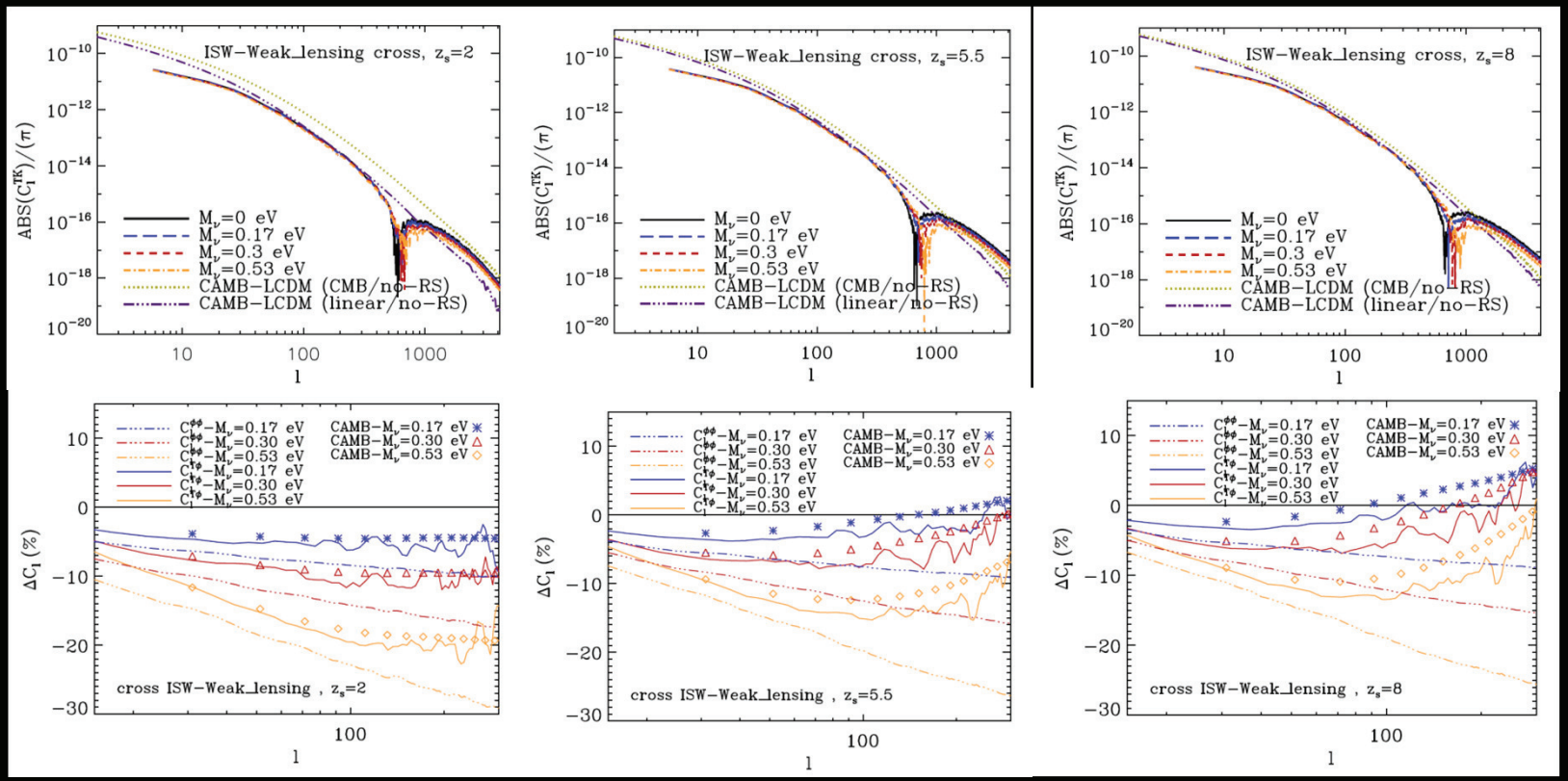
# ISWRS-CMBlens cross correlation




CC et al. in prep

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

# ISWRS-Weaklens cross correlation




CC et al. in prep

**Difference depends on the source redshift. Excess of power of the cross signal with respect to the auto-correlation signal.**

# Conclusions

- ✓ **Very large neutrino simulations for different probe combinations**
- ✓ **Previousli results on bias and MF recovered and confirmed**
- ✓ **New Halofit prescription to account for massive neutrinos**
- ✓ **Good behaviour of exiting PT approximations if applied to CDM alone.**
- ✓ **Detection of the scale dependent growth-rate at linear scales**
- ✓ **Suppression of the CMB/weak-lensing signals, depending on the neutrino mass and source redshifts**
- ✓ **Enhancement of power at the ISW-RS transition of about 10% due to neutrino free-streaming**
- ✓ **Enhancement of the $\phi$T cross-correlation in the case of the CMB lensing-potential, and for high redshift lensed sources, depending on the neutrino mass**
- ✓ **Suppression of $\phi$T cross-correlation for low median redshift surveys, but anyway larger than $\phi\,\phi$ auto-correlation.**