The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2419-4

Workshop on Large Scale Structure

30 July - 2 August, 2012

Non-linearities in the matter power spectrum: neutrinos and warm dark matter

M. Viel
INAF - OA di Trieste

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

A VIEW ON THE MATTER POWER AT MEDIUM SCALES

MATTEO VIEL

INAF and INFN Trieste

LSS Workshop @ ICTP – 30th July 2012

OUTLINE

- Neutrinos/warm dark matter impact at the linear order

- Neutrinos/warm dark matter in N-body/hydrodynamic simulations: methods

- Neutrinos/warm dark matter impact on cosmological structures

- Constraints on neutrinos and warm dark matter

NEUTRINOS

NEUTRINOS in the linear regime

Shift of the matter radiation equality
(CMB + BAO/SN constraints)

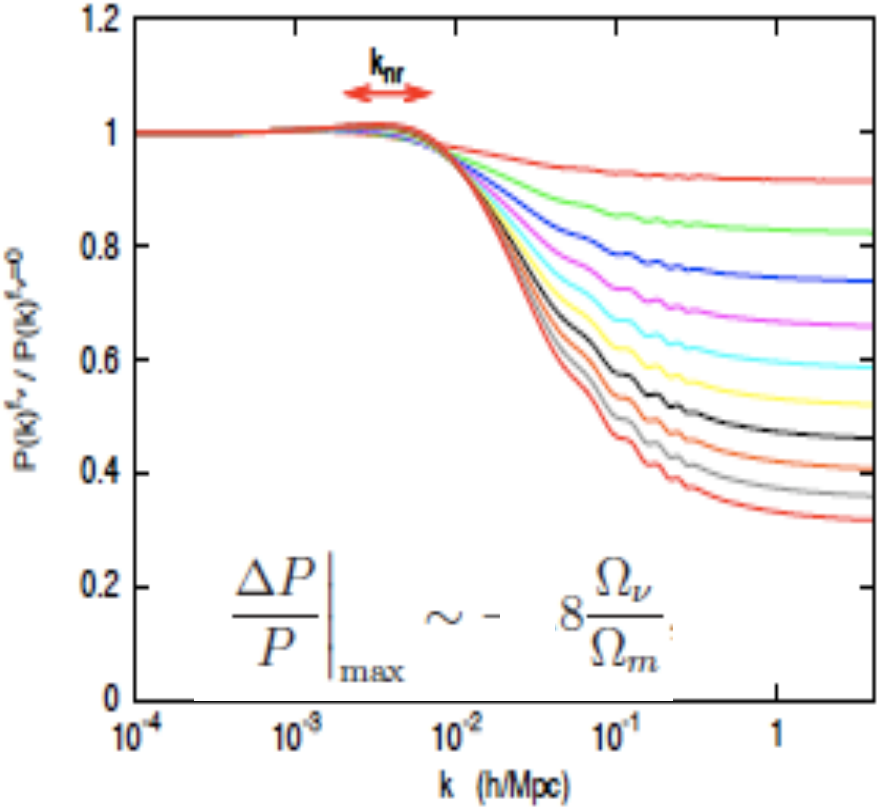
$$f_\nu = \frac{\Omega_\nu}{\Omega_m} = \frac{\Omega_\nu}{\Omega_{Baryons} + \Omega_{CDM} + \Omega_\nu}$$

$$a_{eq}^{f_\nu} = a_{eq}^{f_\nu = 0}(1 - f_\nu)^{-1}$$

$M_\nu < 0.6$ eV

Komatsu et al. 2011

Suppression of power in the linear regime
(Constraints from the LSS)



$M_\nu < 0.2{-}0.3$ eV

Lesgourgues & Pastor 2006

NEUTRINOS in the the non-linear regime: methods - I

- **NEUTRINO PARTICLES:** included in the simulations in the initial conditions with their momentum and clustering properties. Depending on the problem one could follow forces on neutrinos either on the particle mesh grid only or using the tree. This method is prone to Poisson noise.

- **FOURIER/GRID NEUTRINOS:** Neutrino clustering followed on the particle-mesh grid (code is interfaced with CAMB tables). Neutrino clustering kept at the linear level. Fast method.

- **HYBRID CODE:** that follows the neutrinos in momentum space (time consuming and applied to single objects)

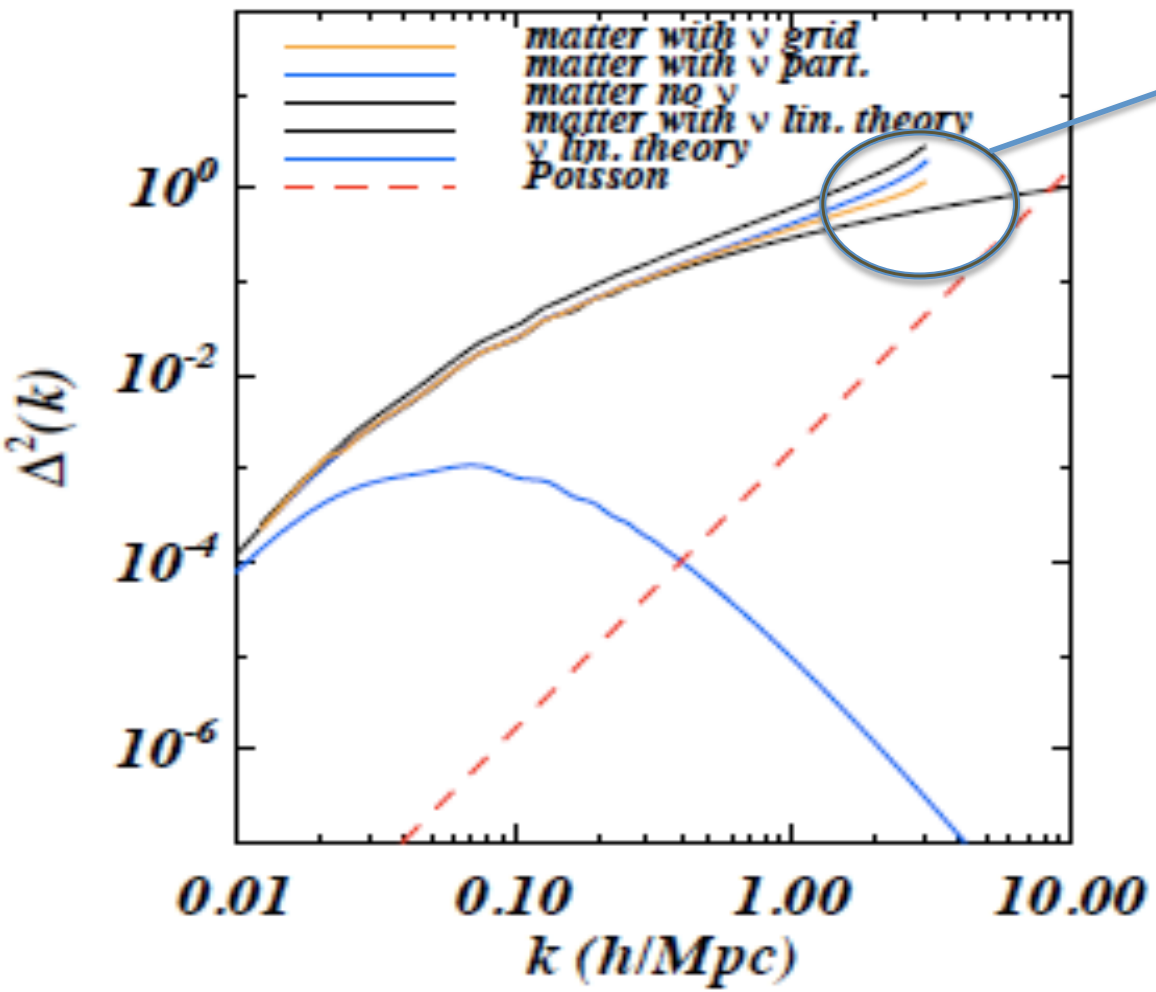
RECENT REFERENCES: Brandbyge et al. 2008 JCAP, 08, 20
Brandbyge et al. 2009 JCAP, 05, 002
Brandbyge & Hannestad 2010 JCAP, 09, 014
MV, Hahnelt & Springel 2010 JCAP, 06, 015
Bird, MV & Haehnelt 2012 MNRAS, 420, 2551
Wagner, Verde & Jimenez 2012 arXiv

Tools: high performance computational facilities

Neutrino universe simulations
(in order to appreciate non-linear effects):

default runs (with hydro):
~ 10 khrs (total wallclock time)

NEUTRINOS in the the non-linear regime: methods - II



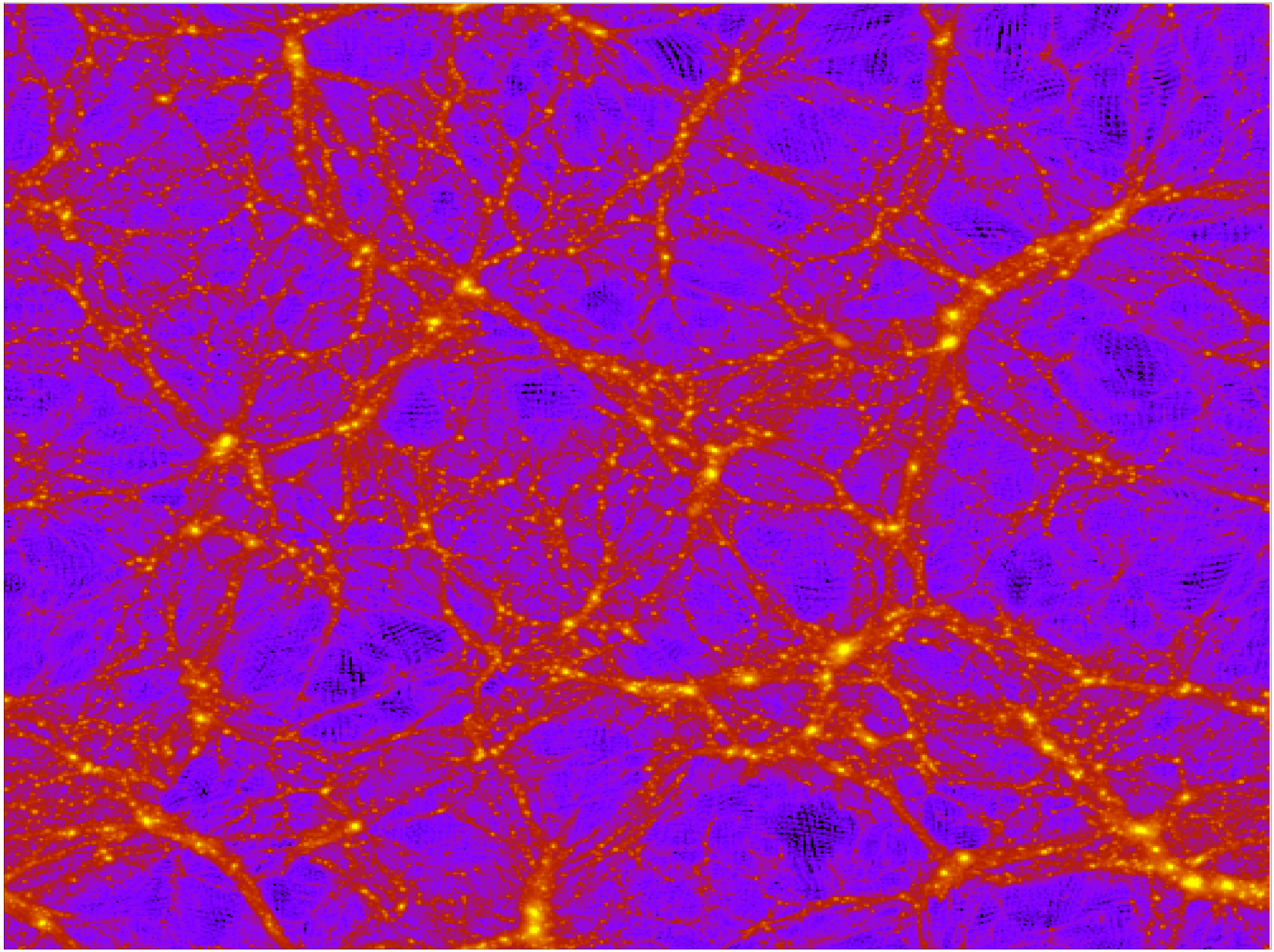
Methods differ

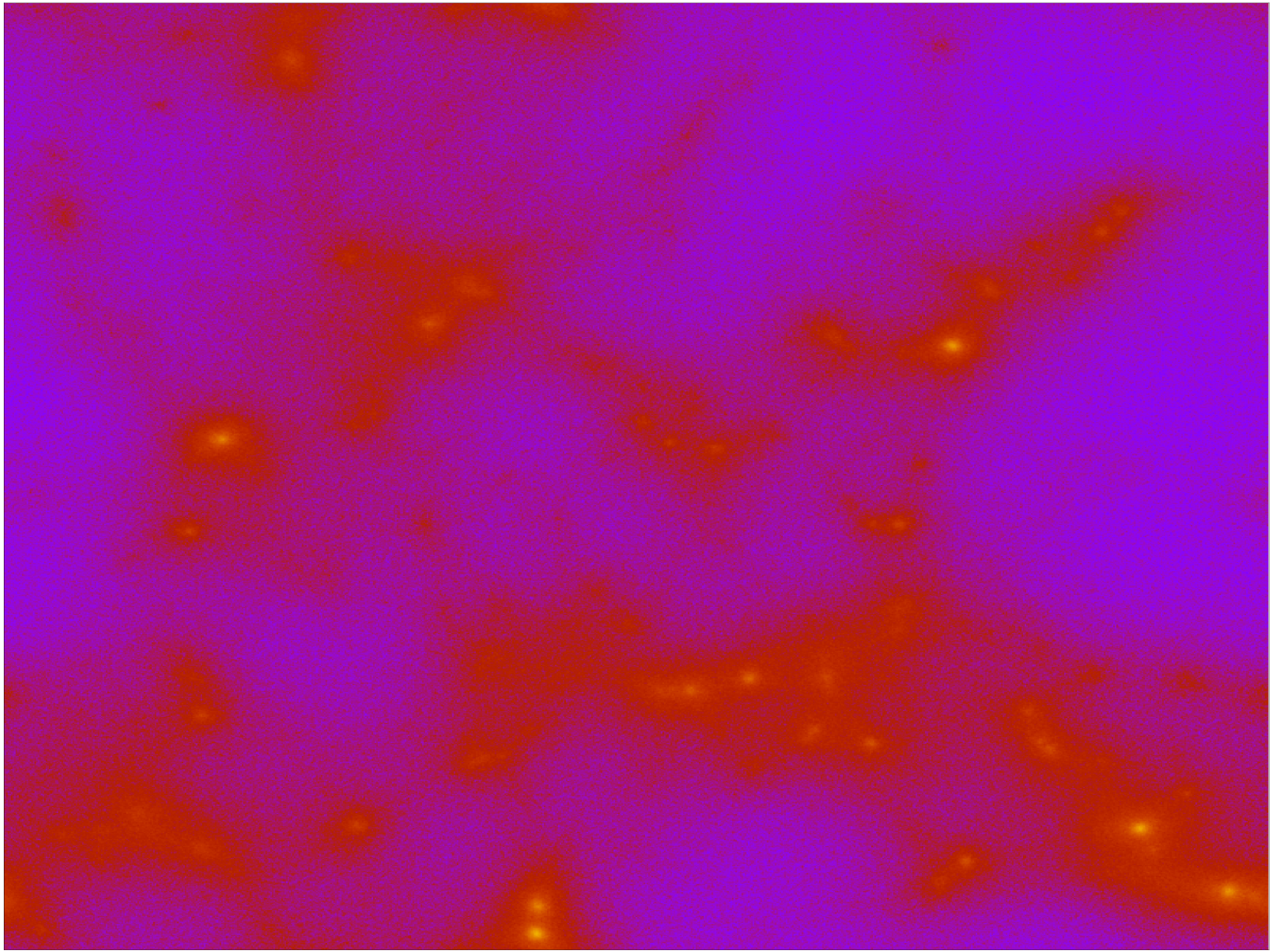
Matter power @ z = 3

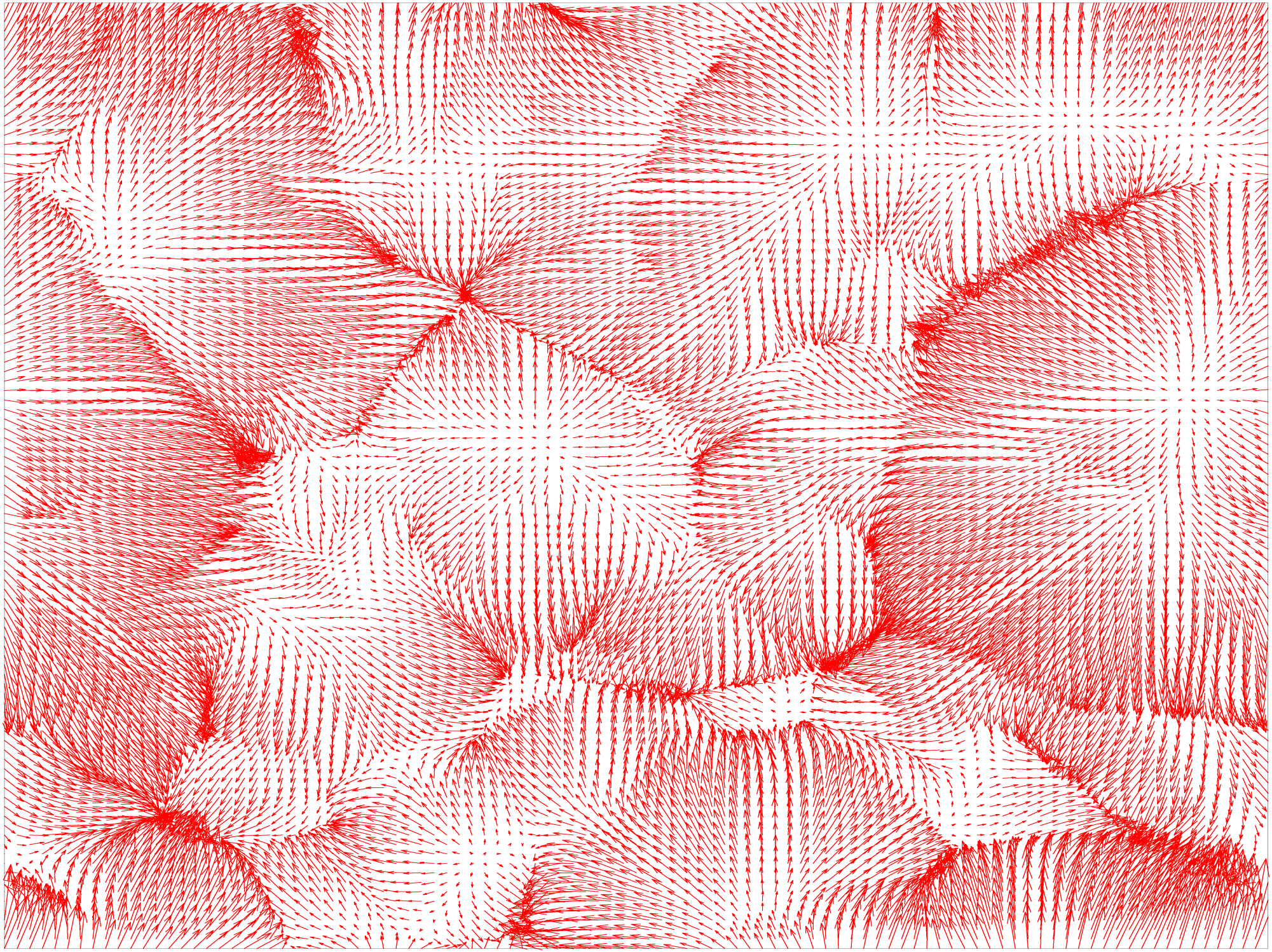
1) Significant non linear evolution at the smallest scales

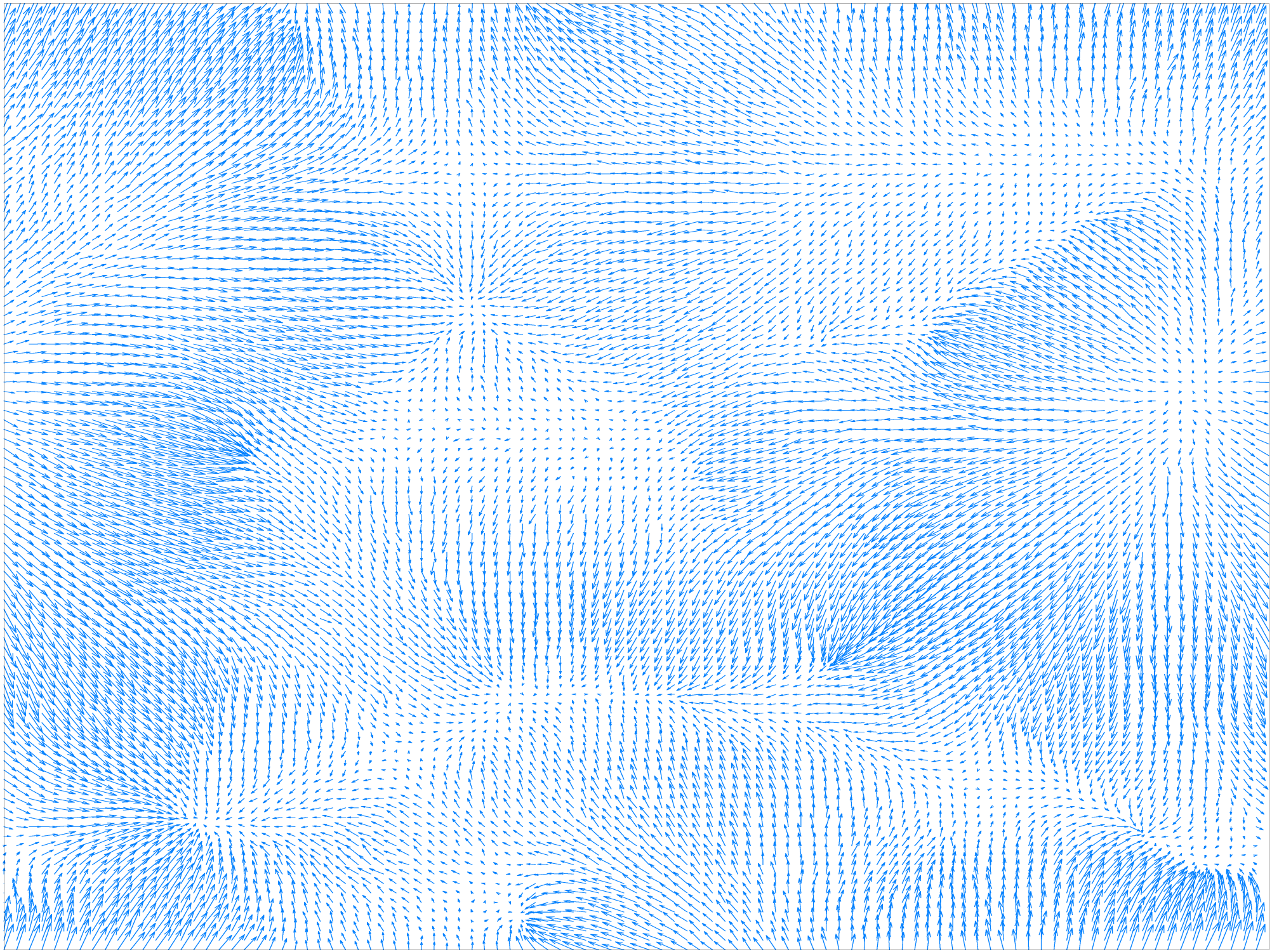
2) Percent level discrepancies between particle and grid methods

3) Poissonian contribution affects small scales

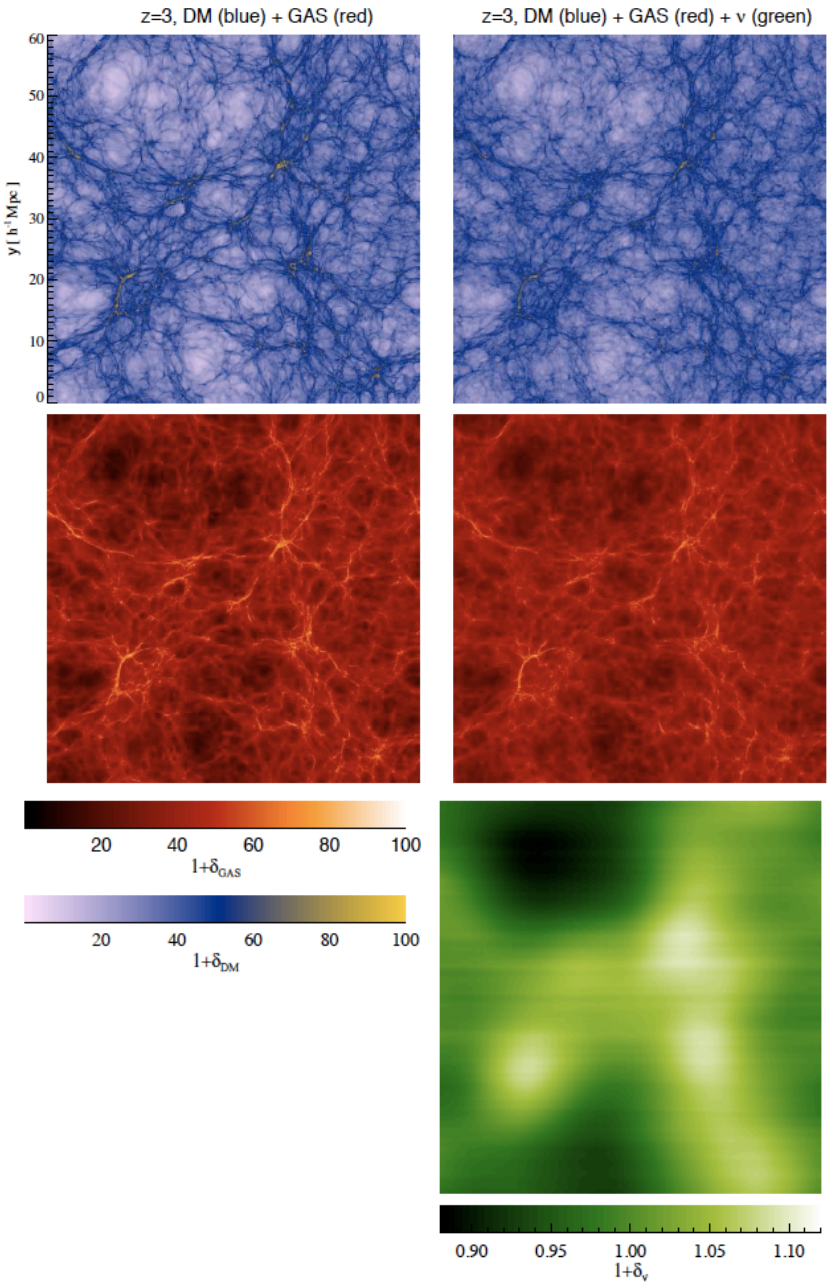








NEUTRINOS and the Intergalactic Medium (IGM)



TreeSPH code Gadget-III
follows DM, neutrinos, gas and star particles in a cosmological volume

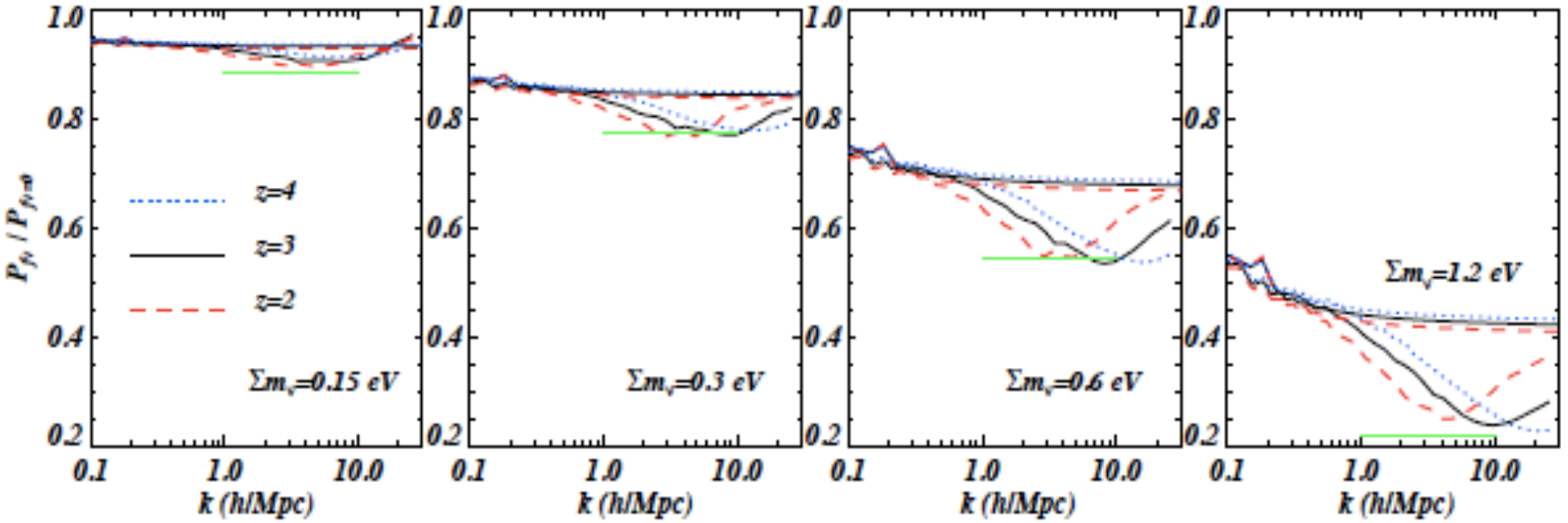
Since small scales are important we need to include baryons

$M_\nu < 0.9{-}1$ eV (2σ)

Viel, Haehnelt & Springel 2010, JCAP, 06 ,15

NEUTRINOS: impact on the non-linear matter power

Full hydro simulations: be aware that gas physics does impact at the <10 % level at scales k < 10 h/Mpc

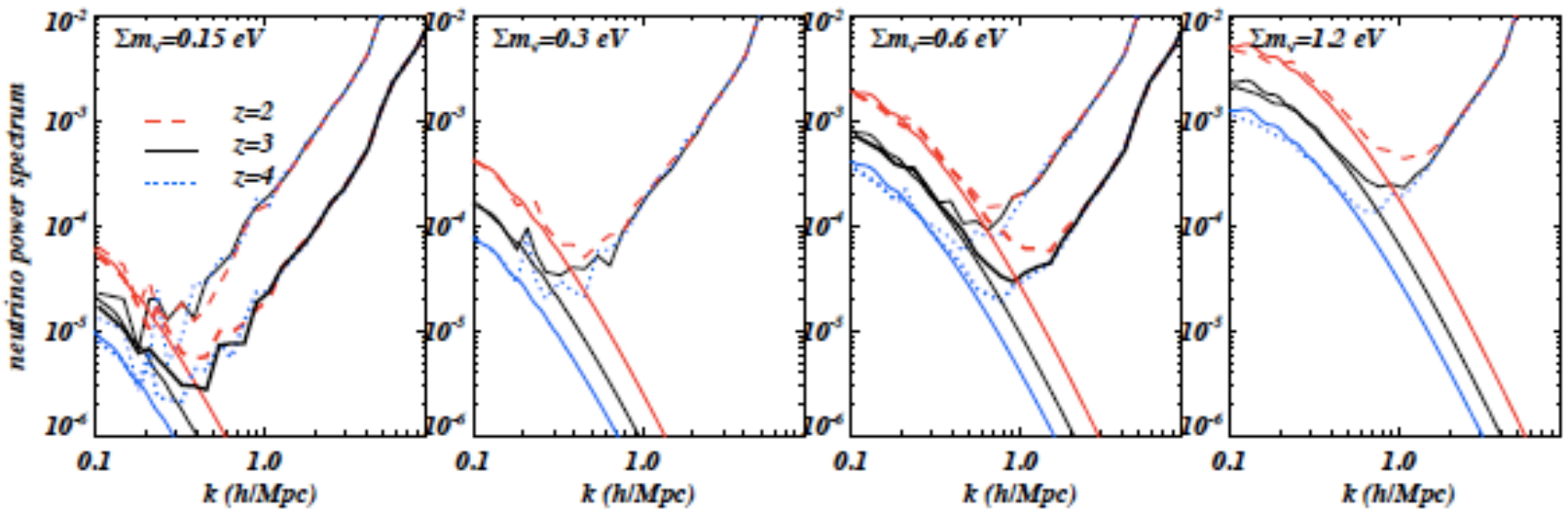


$$\left.\frac{\Delta P}{P}\right|_{\rm max} \sim -9.8\frac{\Omega_\nu}{\Omega_m}$$

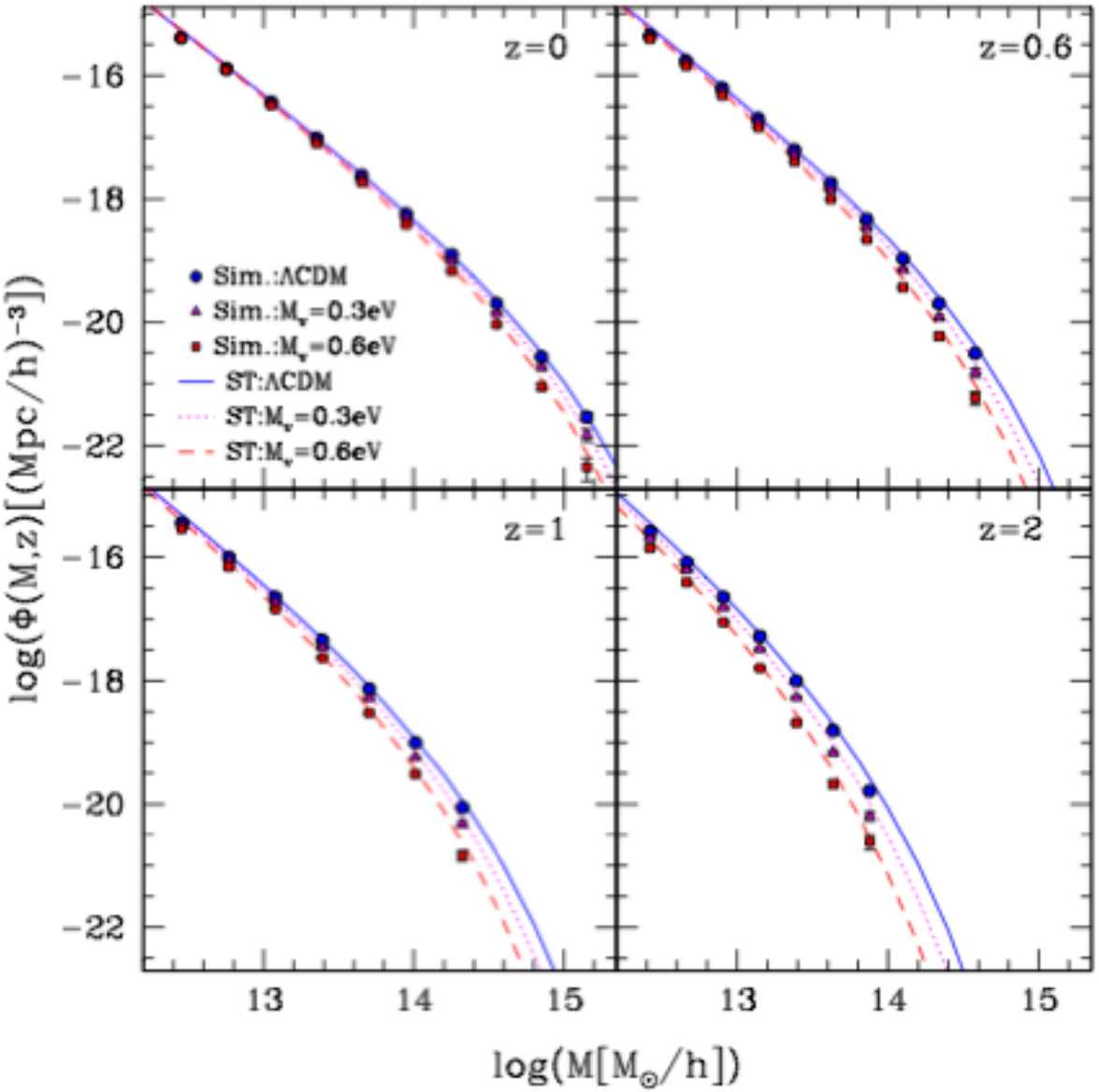
Viel, Haehnelt & Springel 2010, JCAP, 06 ,15

NEUTRINOS: the neutrino power spectrum

Increasing neutrino mass

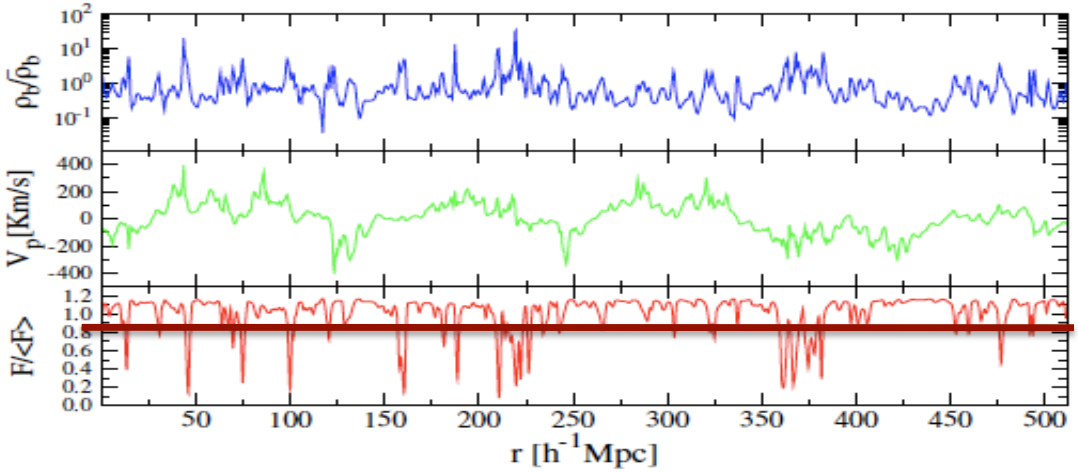


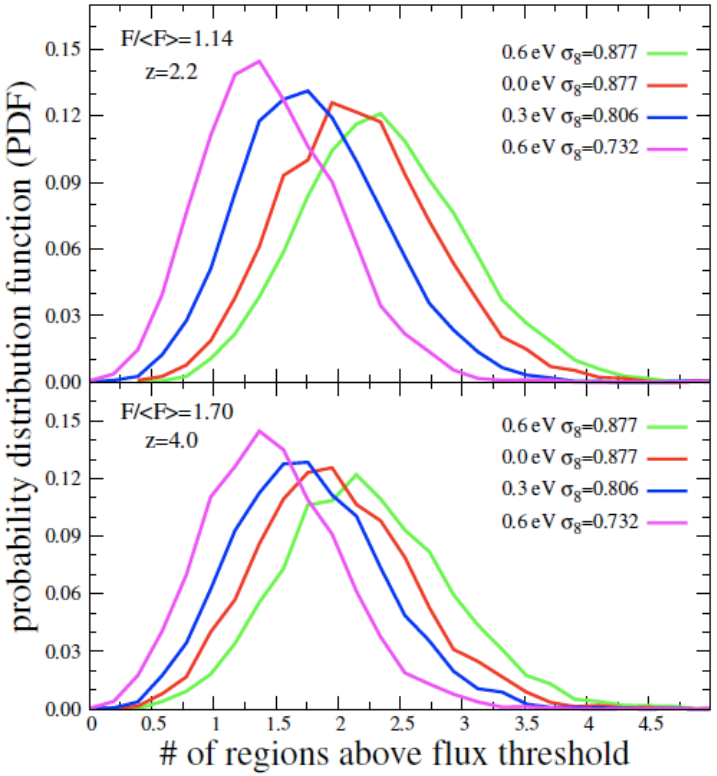
NEUTRINOS: halo mass functions



Marulli, Carbone, MV, Moscardini e Cimatti 2011, MNRAS, 418, 346

Neutrinos in hydro simulations: the distribution of high-z voids



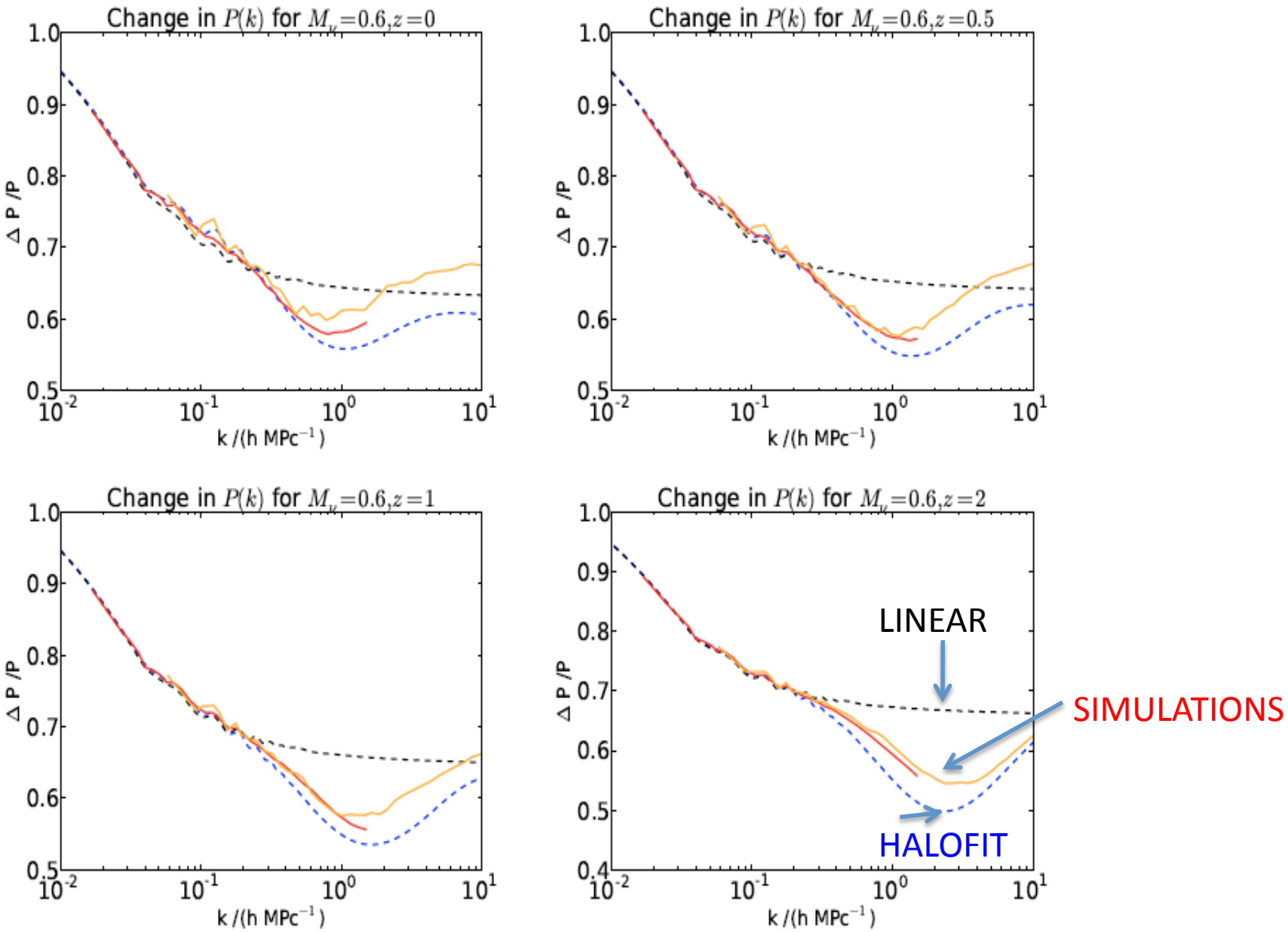


PDF of rare events does carry information
see e.g. Paranjape & Sheth 12

Navarro-Villaescusa, Vogelsberger, MV, Loeb 2012

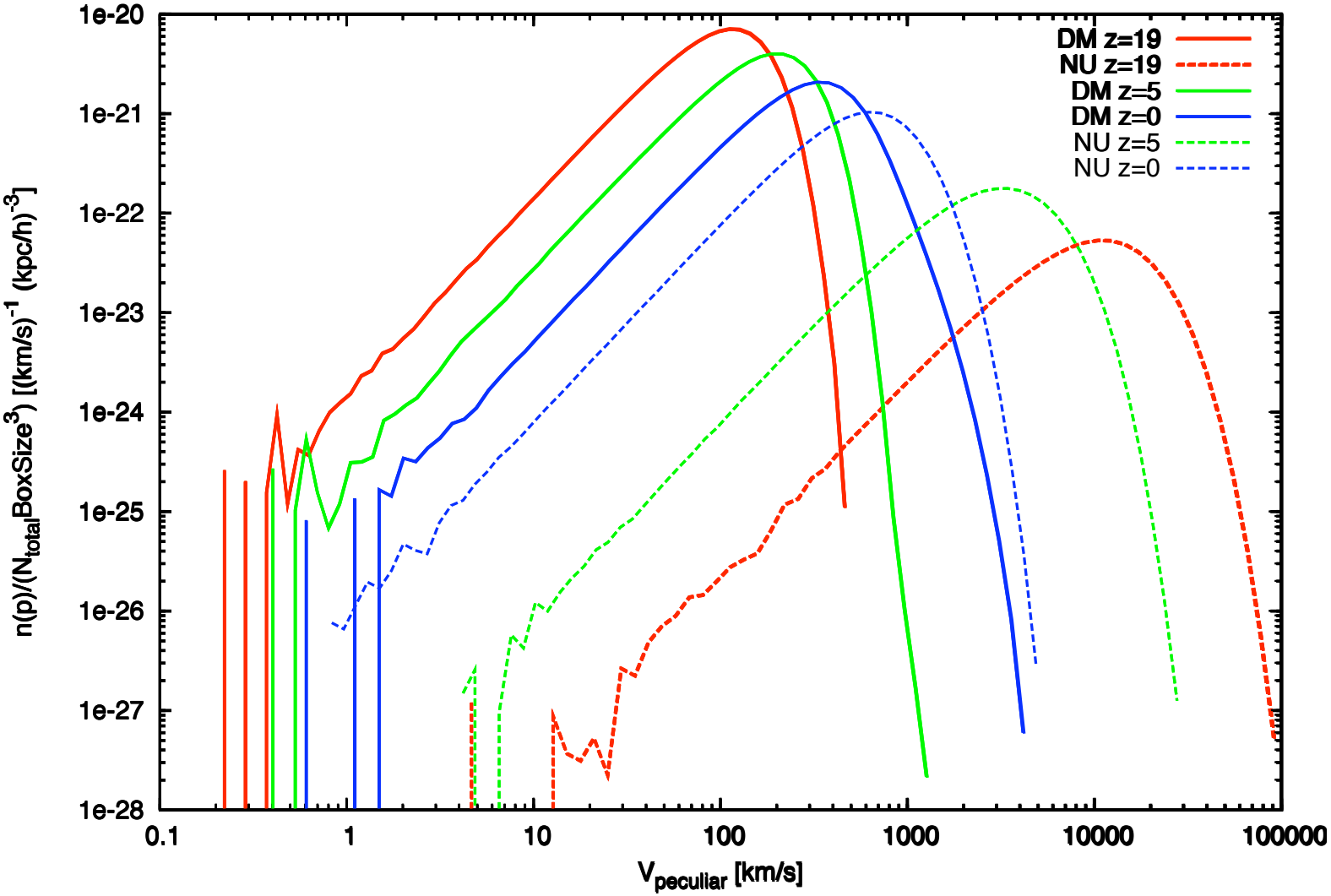
N-body simulations: non-linear regime

Bird, MV, Haehnelt 2012



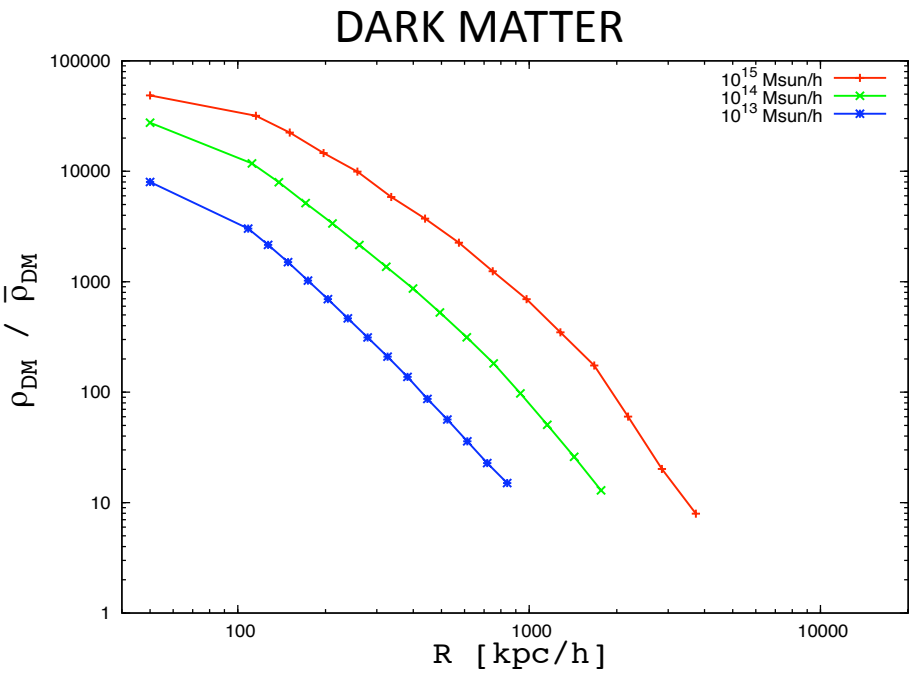
CAMB patches available @ http://www.sns.ias.edu/~spb / ← FIT TO THE SIMS

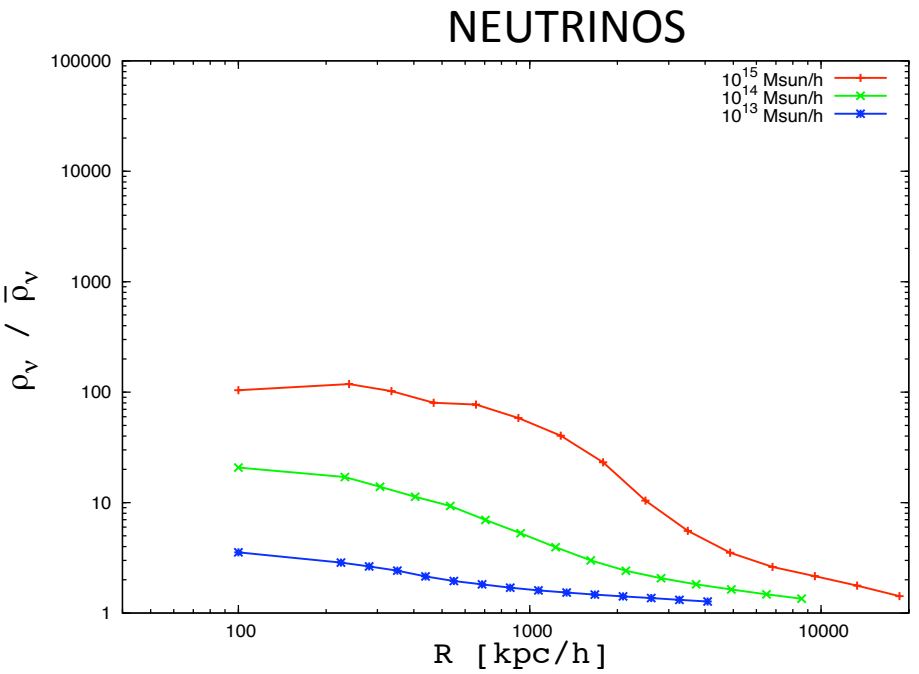
NEUTRINOS: peculiar velocity evolution of neutrinos and DM



Francisco Villaescusa-Navarro et al. 2012

NEUTRINOS: density profiles





Francisco Villaescusa-Navarro et al. 2012

NEUTRINOS: constraints

M_ν now in the range 0.05 – 0.3 eV

Tightest constraints from the SDSS Lyman−α forest (Seljak et al. 06): < 0.17-0.19 eV (2σ)

LSS constraints from SDSS LRGs M_ν < 0.26 eV (De Putter et al. 2012)

Constraints from CFHTLS+VIPERS reconstruction of the non-linear P(k): < 0.3 eV

95% C.L. $\sum m_\nu$ [eV]	Without HST Prior		With HST Prior	
	$\ell_{max} = 630$	$\ell_{max} = 960$	$\ell_{max} = 630$	$\ell_{max} = 960$
WMAP7	1.17		0.50	
WMAP7 + CFHTLS	0.64	0.43	0.41	0.29
WMAP7 + SDSS + CFHTLS	0.47	0.35	0.35	0.28
WMAP7 + SDSS + SN + CFHTLS	–	–	0.33	0.27

Xia, Granett, MV et al. 2012

NEUTRINOS: CFHTLS + VIPERS in harmonic space

Angular power spectrum C_l: $C_l = \langle |a_{lm}|^2 \rangle$

$$C_l = \frac{2}{\pi} \int \left[\int \phi(r) D_1(z)/D_1(\bar{z}) j_l(kr) r^2 dr \right]^2 P_k(\bar{z}) \frac{dk}{k}$$

Growth factor

Redshift distribution

Power spectrum

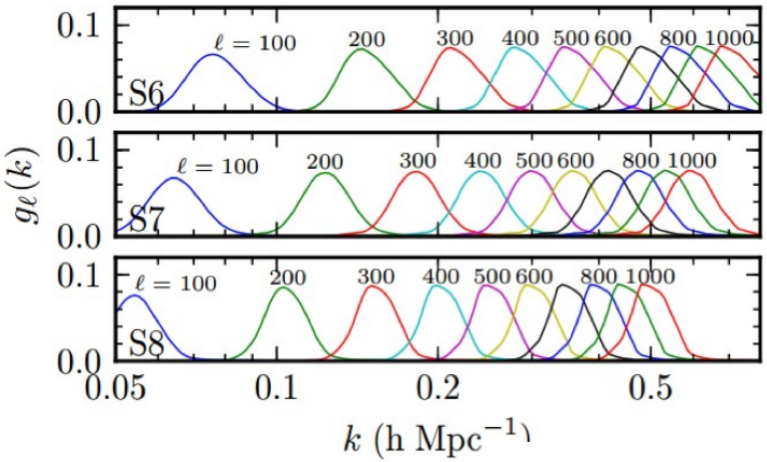
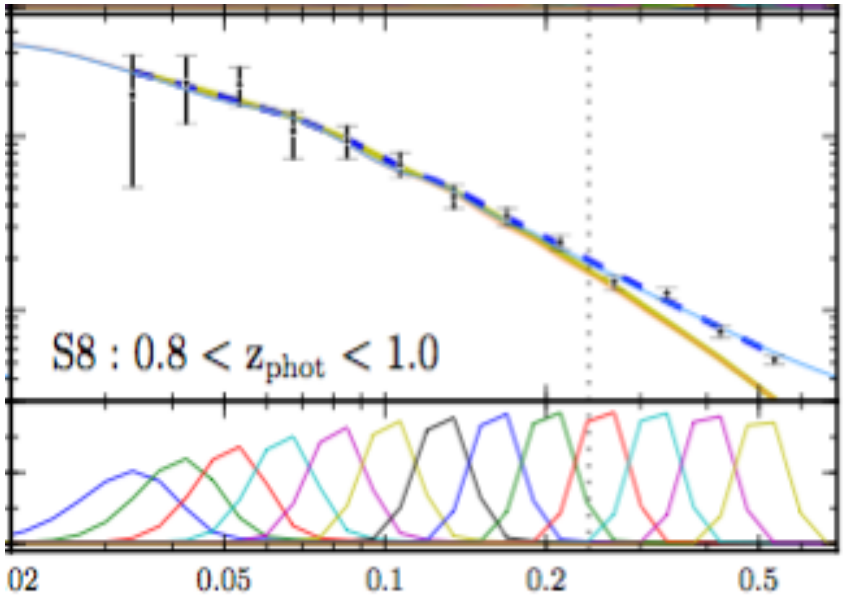
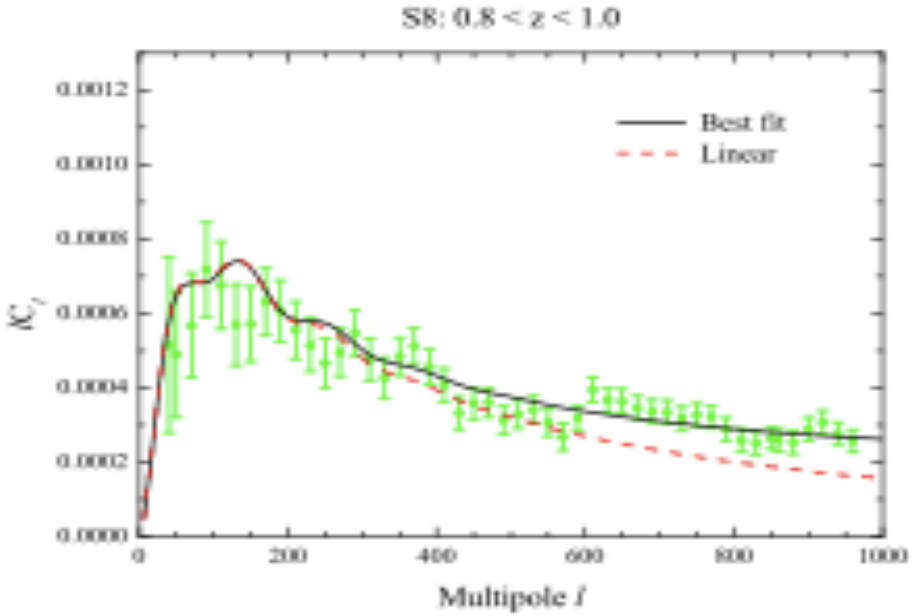


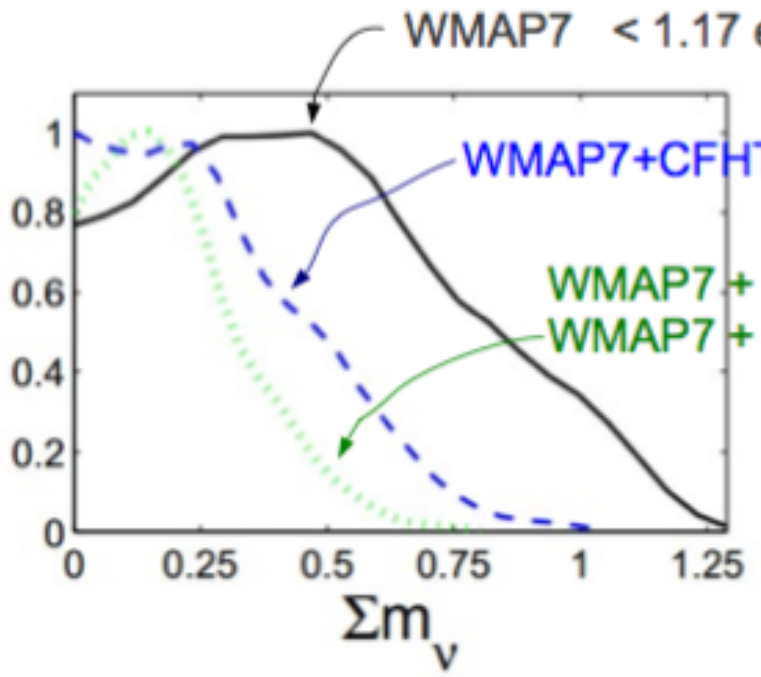
TABLE I: CFHTLS samples

Photo-z sample		$\bar{z}$	Scale (h/Mpc) $\ell = 630$	$\ell = 960$
S6	$0.5 < z_{phot} < 0.6$	0.557	0.43	0.65
S7	$0.6 < z_{phot} < 0.8$	0.687	0.36	0.55
S8	$0.8 < z_{phot} < 1.0$	0.839	0.31	0.47





NEUTRINOS: CFHTLS+VIPERS and neutrino masses

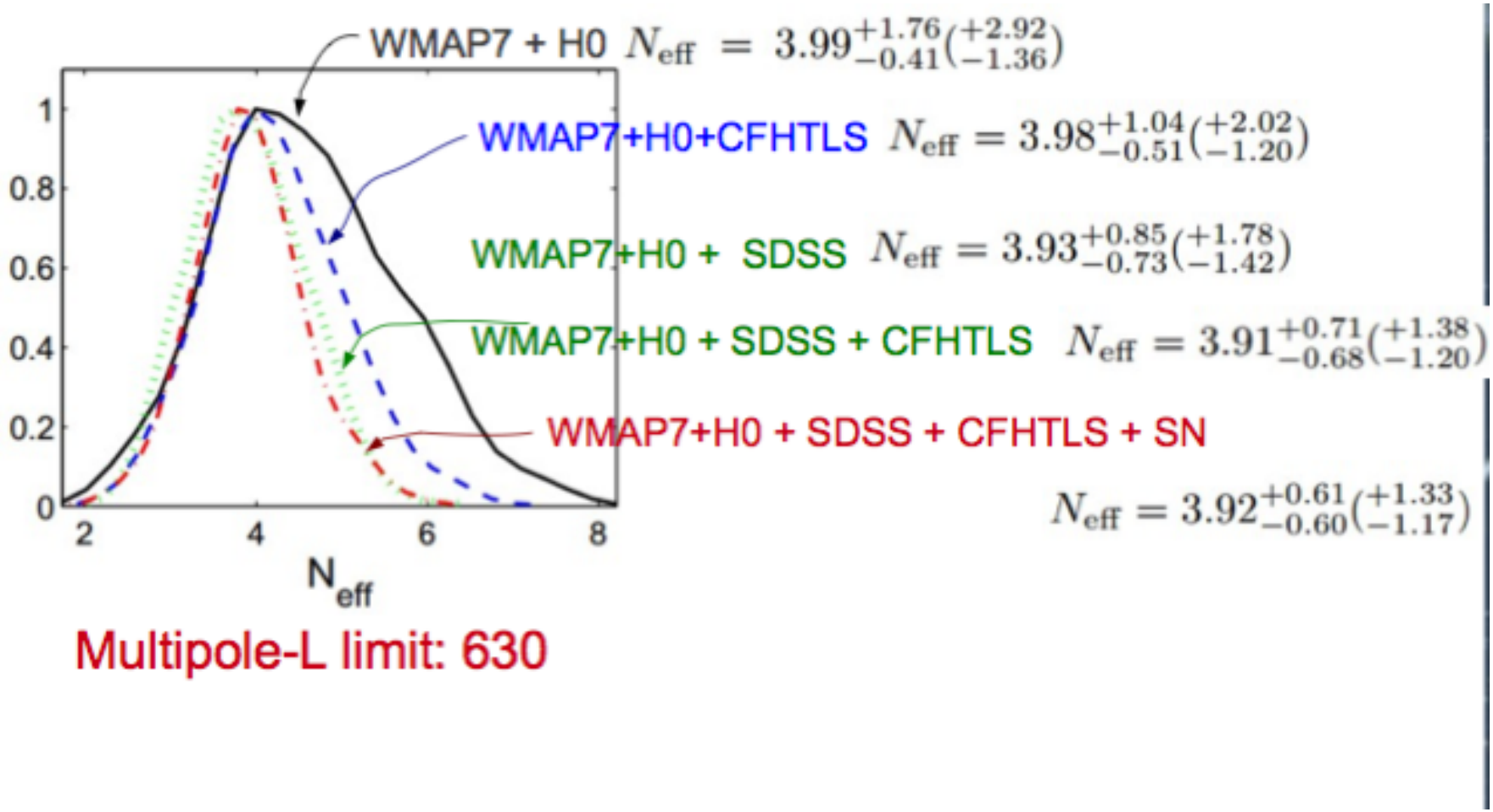


Adding H0 gives: < 0.41 eV (0.29 eV)
+ SN: < 0.33 eV (0.27 eV)

Multipole-L limit: 630 (960)

Xia, Granett, MV et al. 2012

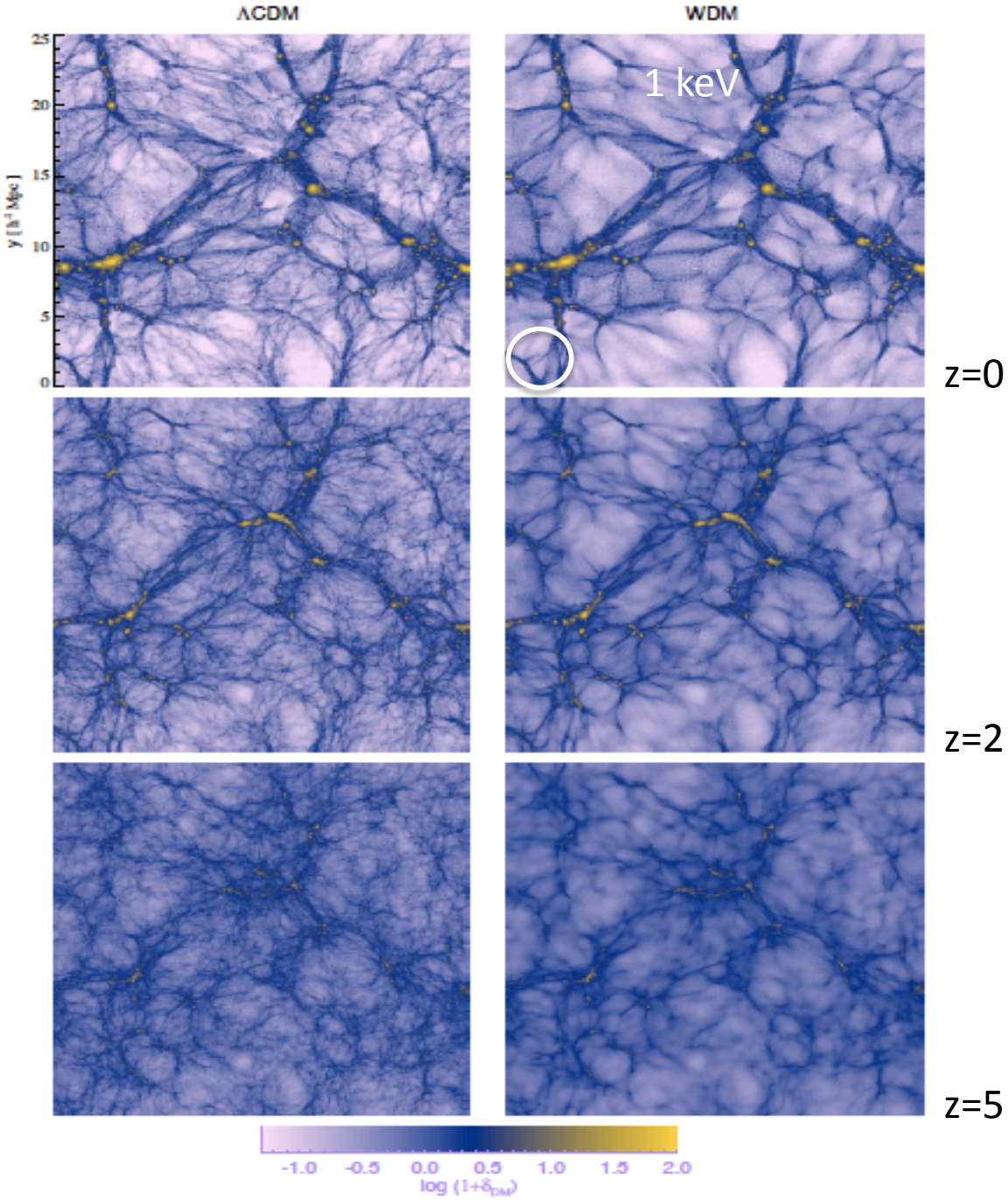
NEUTRINOS: Number of relativistic species



Xia, Granett, MV et al. 2012

WARM DARK MATTER

Warm Dark Matter and structure formation

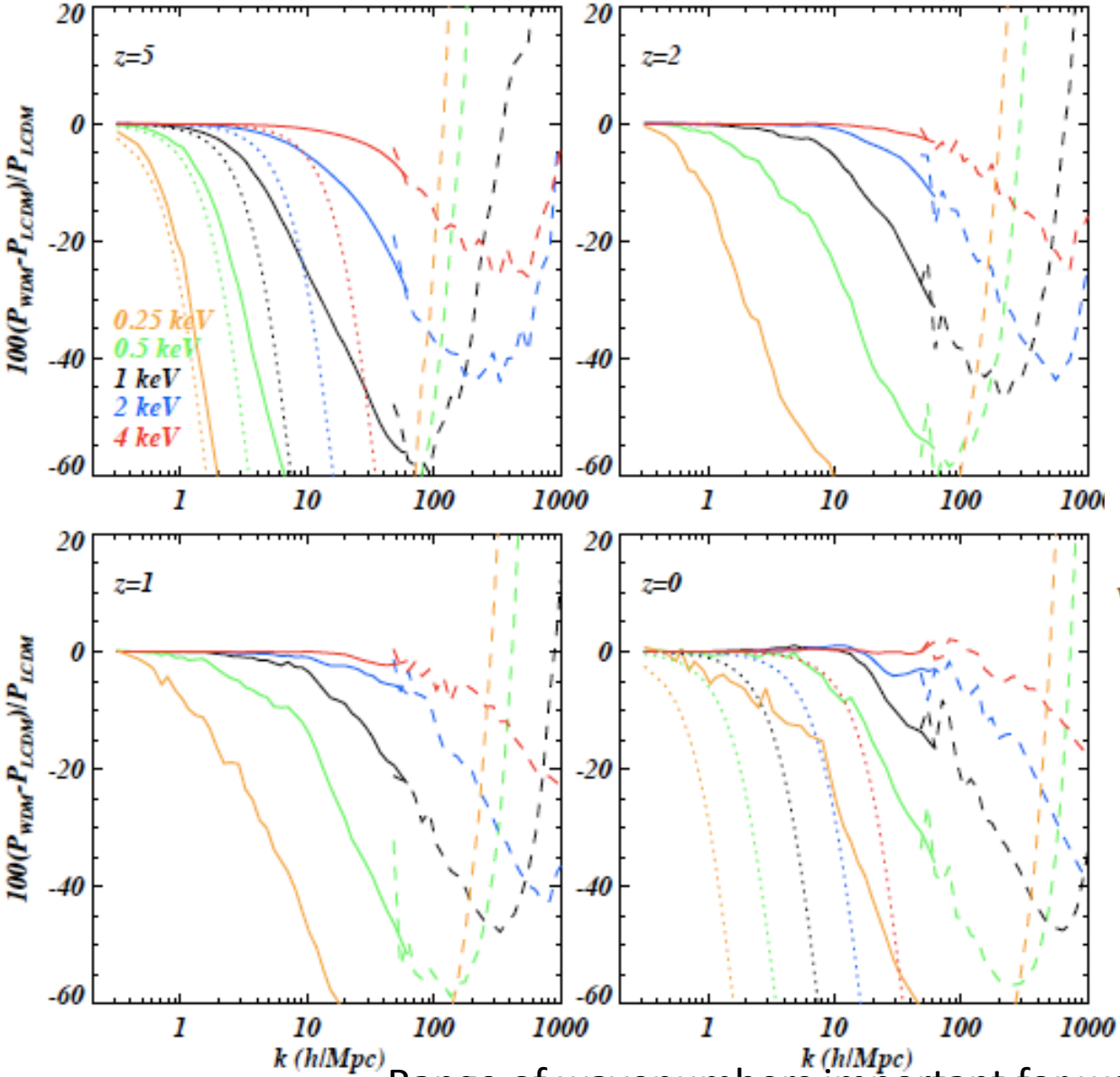


$k_{FS} \sim 5\, T_V/T_X\, (m_X/1\text{keV})\ \text{Mpc}^{-1}$

See Bode, Ostriker, Turok 2001
Abazajian, Fuller, Patel 2001
Avila-Reese et al. 2001
Boyarsky et al. 2009
Colin et al. 2008
Wang & White 2007
Gao & Theuns 2007
Abazajian et al. 2007
Lovell et al. 2009
Maccio' et al. 2012

Warm Dark Matter and non-linear power - II

MV, Markovic, Baldi & Weller 2012 MNRAS, 421, 50



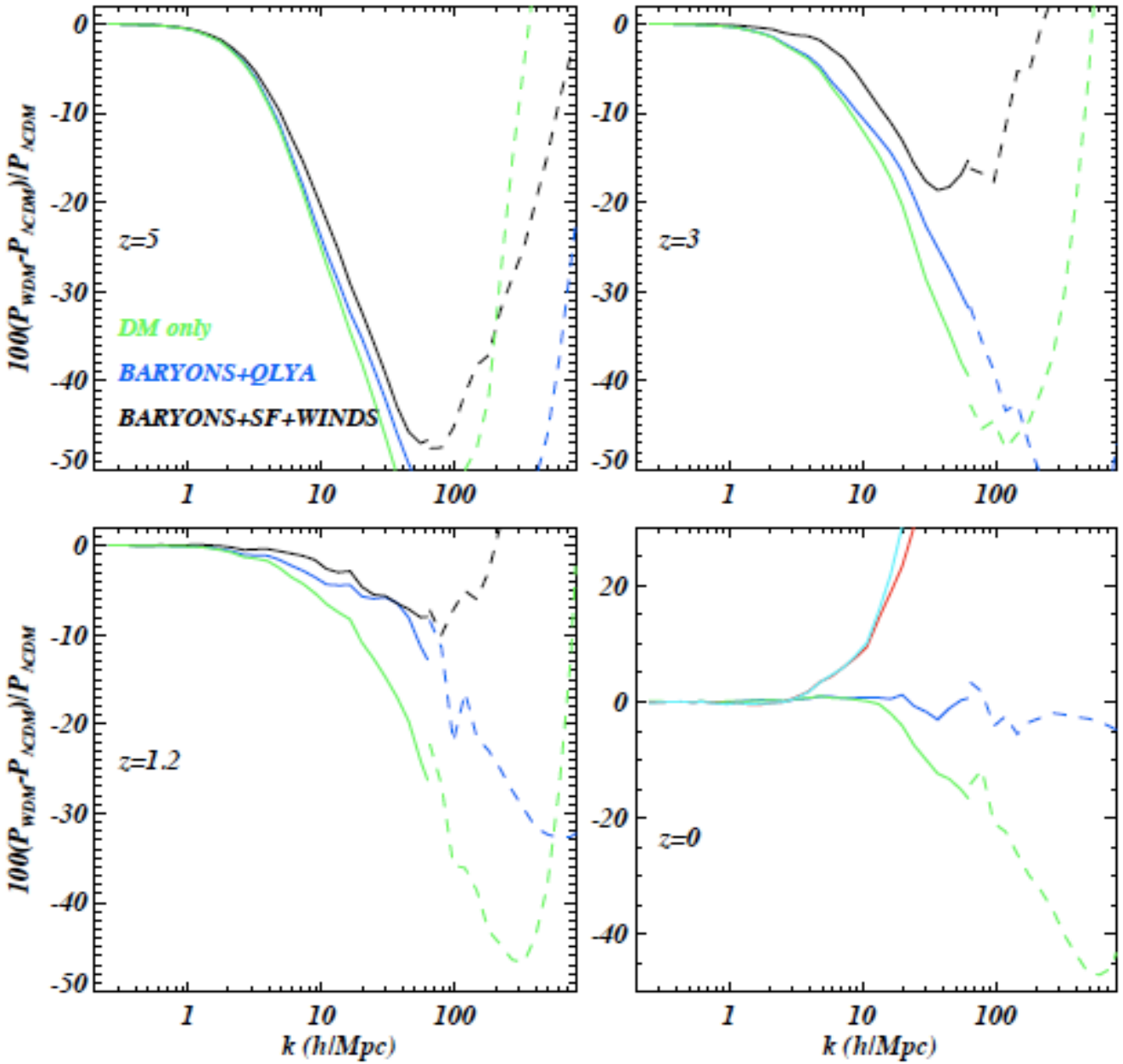
$$T^2_{\rm nl}(k) \equiv P_{\rm WDM}(k)/P_{\Lambda{\rm CDM}}(k) = (1+(\alpha\, k)^{\nu l})^{-s/\nu},$$

$$\alpha({\rm m_{WDM}}, z) = 0.0476 \left(\frac{1{\rm keV}}{\rm m_{WDM}}\right)^{1.85} \left(\frac{1+z}{2}\right)^{1.3},$$

with $\nu = 3$, $l = 0.6$ and $s = 0.4$.

Range of wavenumbers important for weak lensing tomography , IGM and small scale clustering of galaxies!

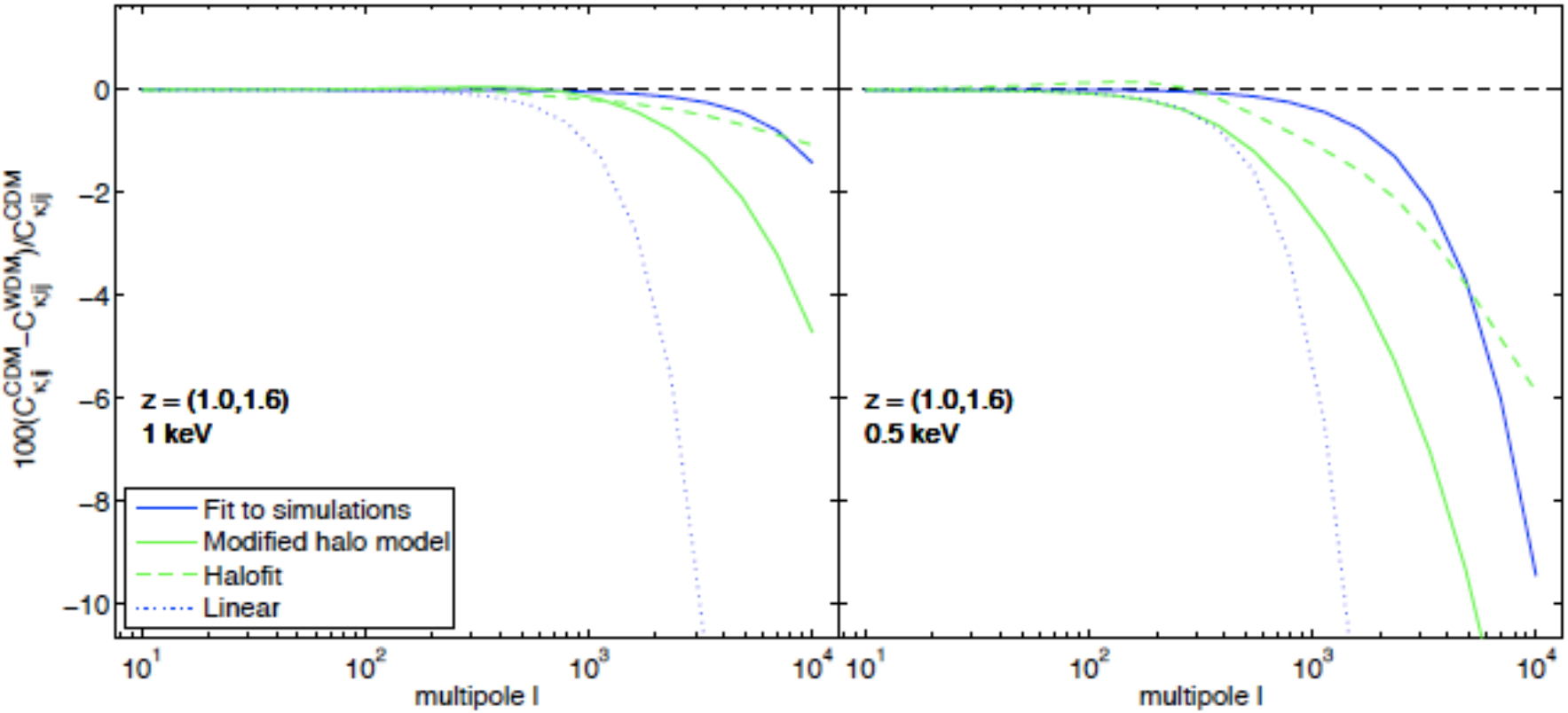
WDM and non-linear power - III: astrophysics



(see also Rudd et al. 08,
Guillet et al. 10
Van Daalen et al. 11,
Casarini et al. 11
Semboloni et al. 11)

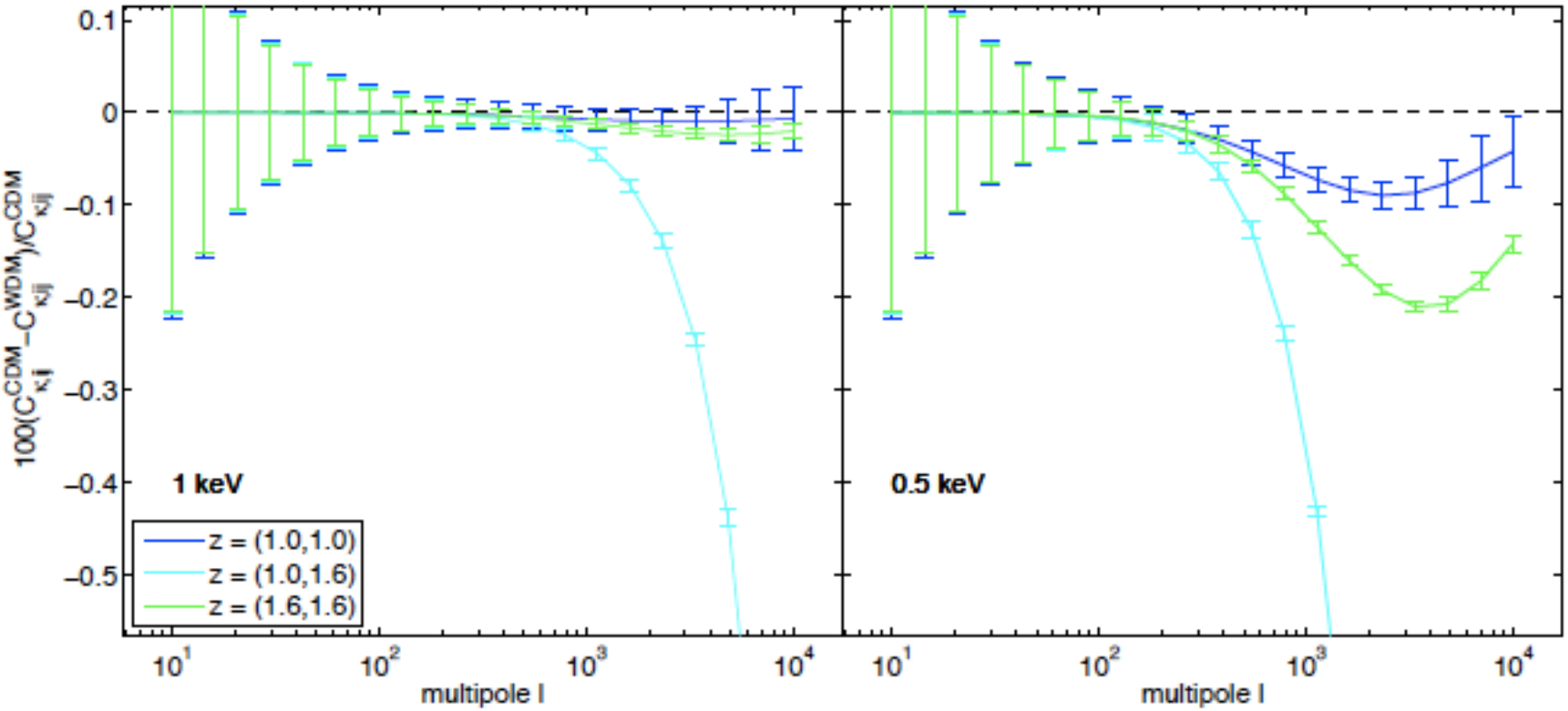
WDM and non-linear power: weak lensing - I

$$C_{ij}(l) = \int_0^{\chi_H} d\chi_1 W_i(\chi_1) W_j(\chi_1) \chi_1^{-2} P_{nl}\left(k = \frac{l}{\chi_1}, \chi_1\right) \qquad W_i(z_1) = \frac{4\pi G}{a_1(z_1)c^2} \rho_{m,0} \chi_1 \int_{z_1}^{z_{max}} n_i(z_s) \frac{\chi_{ls}(z_s, z_1)}{\chi_s(z_s)} dz_s$$



See Smith & Markovic 2011 for a comprehensive study of the halo model in WDM

WDM and non-linear power: weak lensing - II



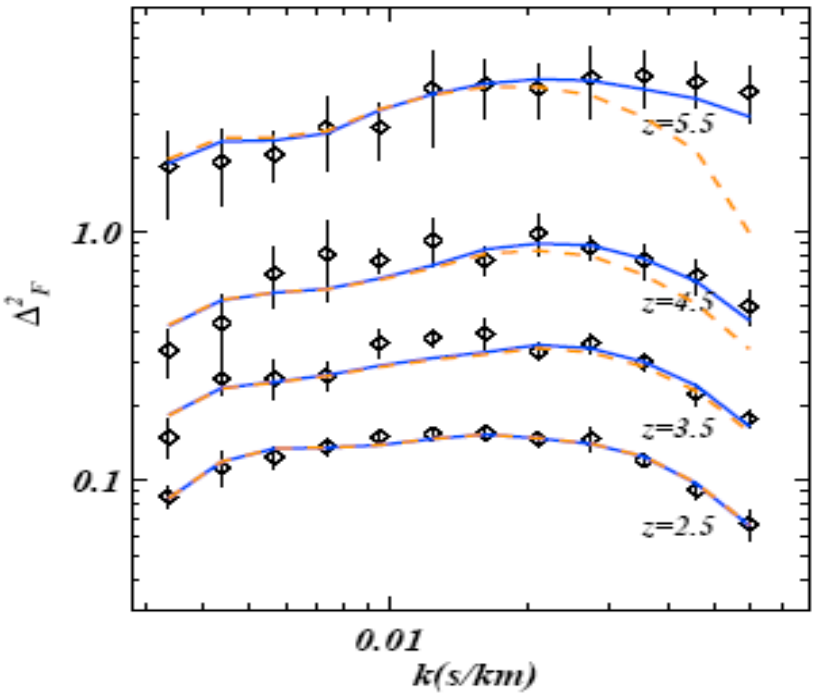
WDM constraints from LSS

Tightest constraints on mass of WDM particles to date:

$m_{WDM} > 4$ keV (early decoupled thermal relics)

$m_{sterile} > 28$ keV (standard scenario)

MV et al. 08
Seljak et al. 06



Boyarsky et al. 09

COLD + WARM DARK MATTER