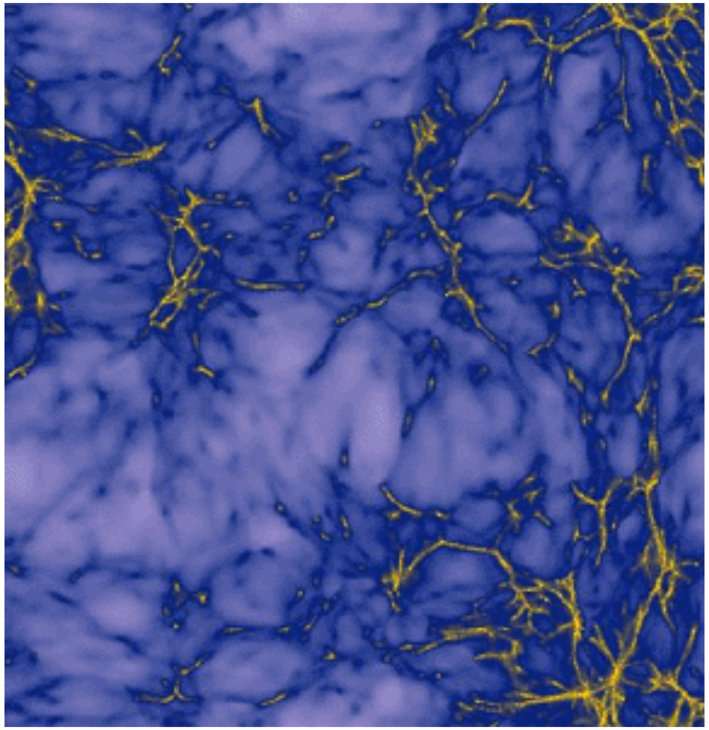
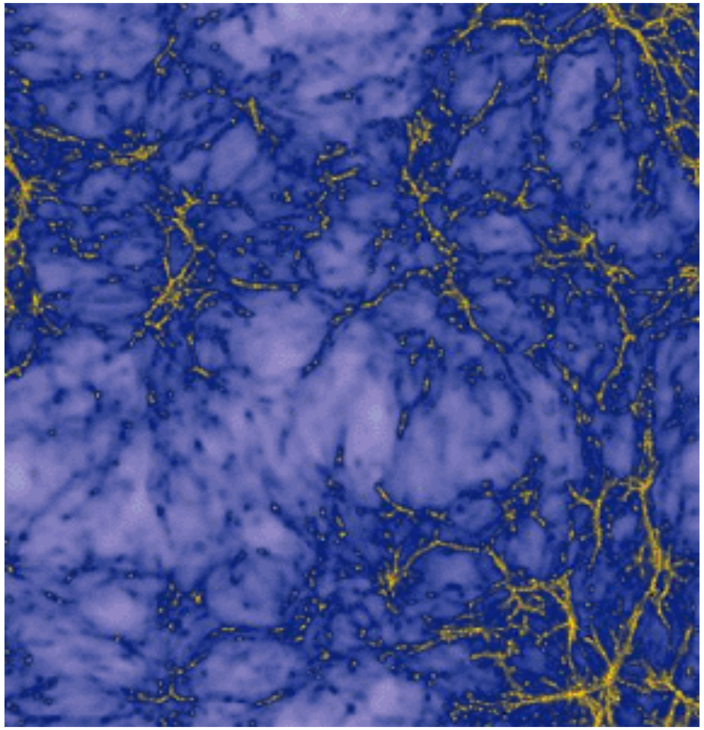
COSMOLOGICAL SIGNIFICANCE of the IGM

MATTEO VIEL

INAF and INFN
Trieste (Italy)





Bologna University Oct. 2011 – Lecture 2

OUTLINE: LECTURES

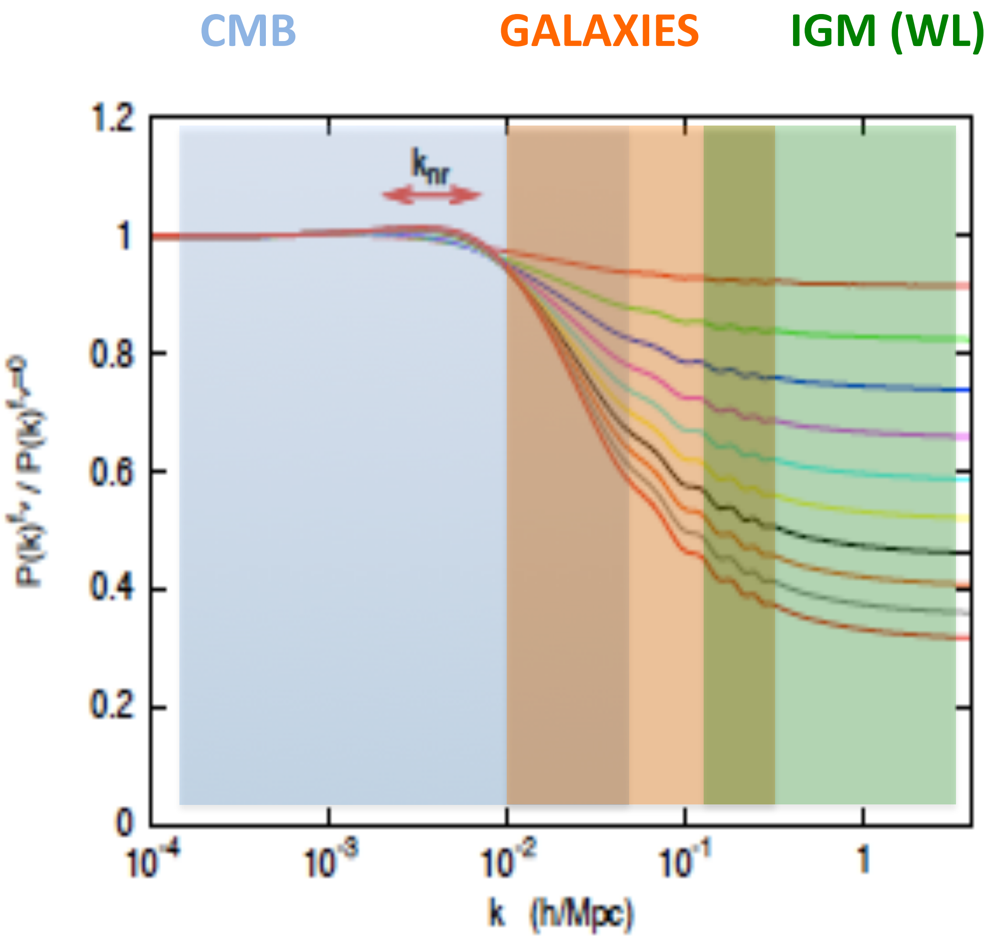
1. Physics of Lyman-alpha and its cosmological relevance

2. Lyman-alpha and fundamental physics

3. IGM/galaxy interplay

NEUTRINOS

EVOLUTION of LSS –I : dynamics in the linear regime

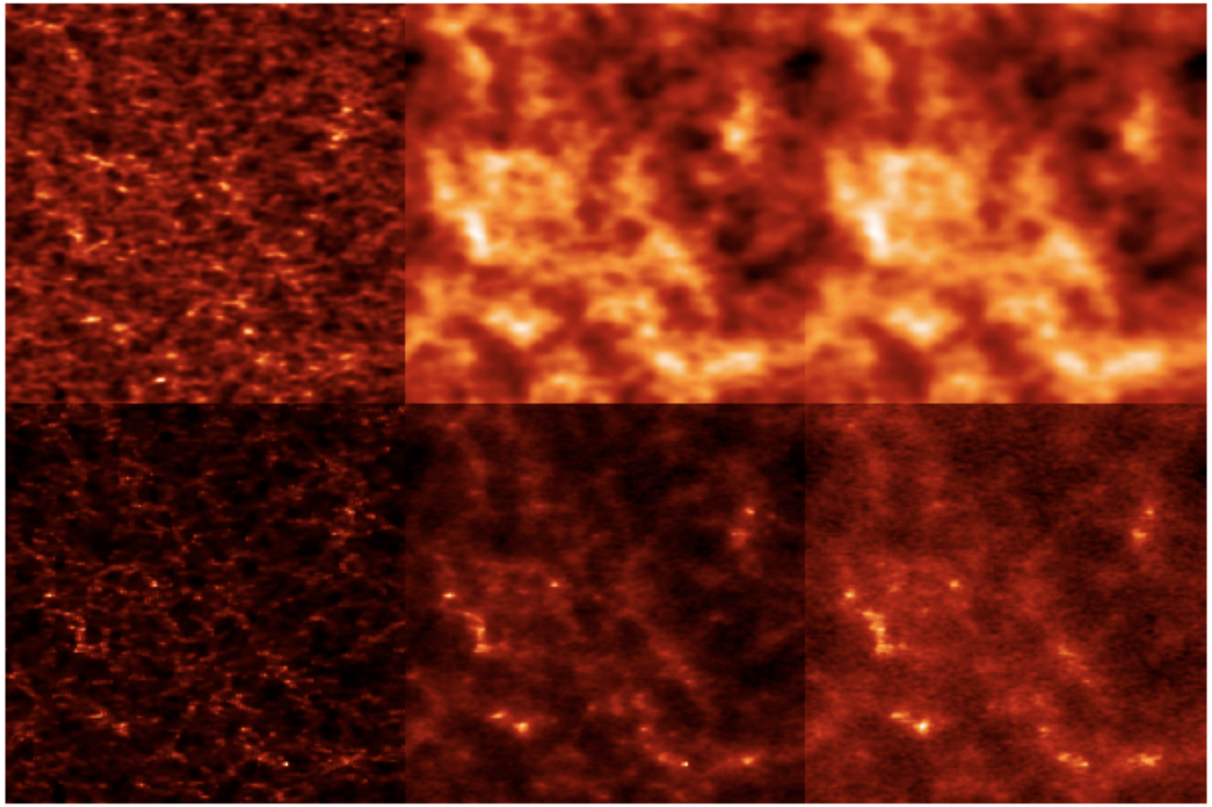


Effects in terms of matter clustering,
Hubble constant,
Energy density

(see Lesgourgues & Pastor 2006)

Different evolution in terms of **dynamics** and **geometry** as compared to massless neutrino universes

N-body simulations – I: particles



z=4

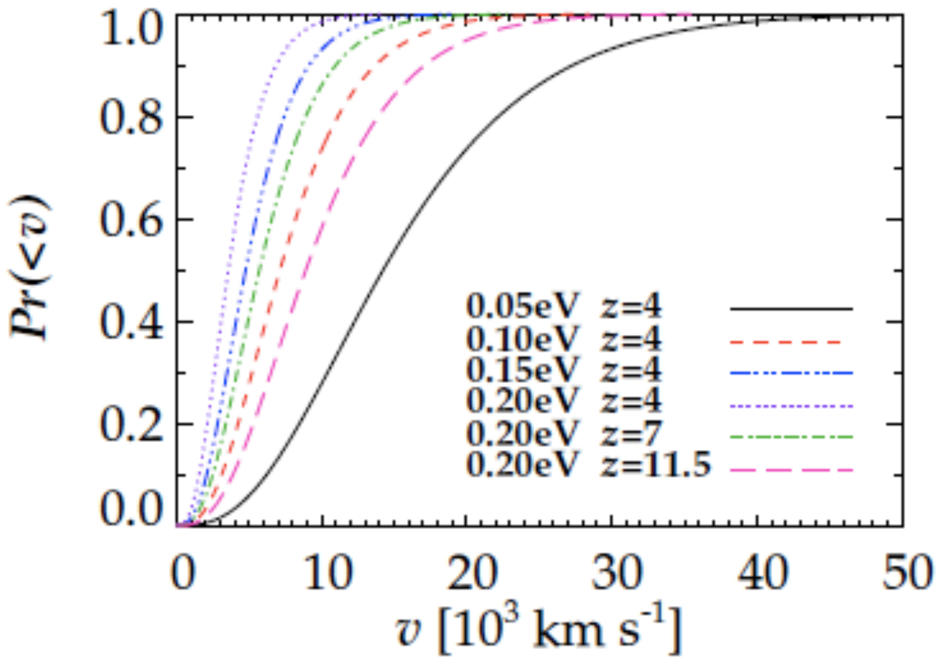
z=0

COLD DM NEUTRINOS 0.6 eV NEUTRINOS 0.3 eV

Brandbyge, Hannestad, Haugbolle, Thomsen 08

Simulation of neutrinos as an independent set of particles that interact gravitationally

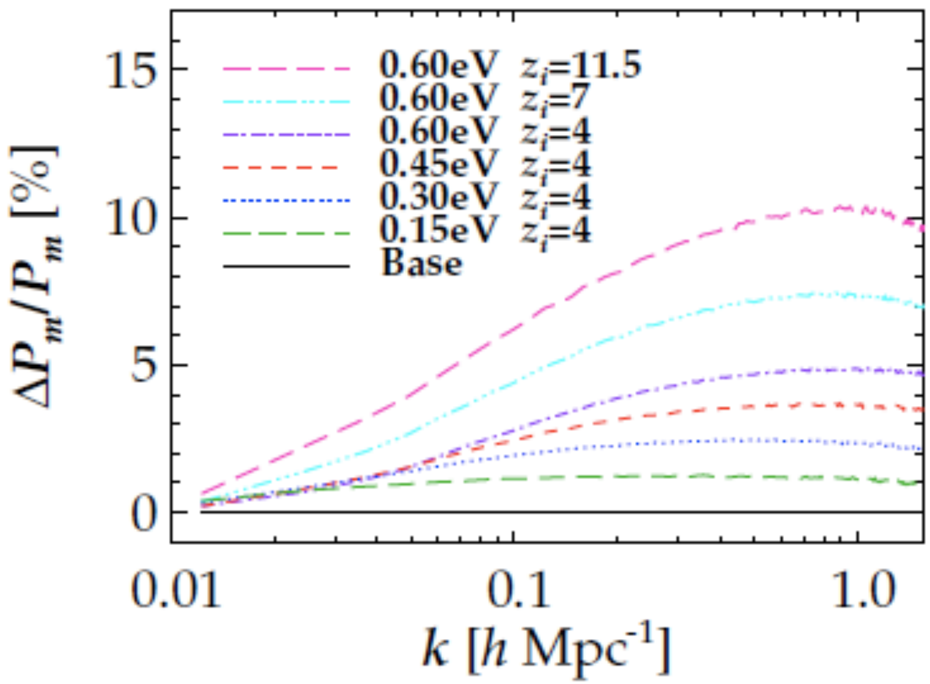
N-body simulations – II: neutrino velocities matter



$$T_\nu \simeq T_\gamma (4/11)^{1/3}$$

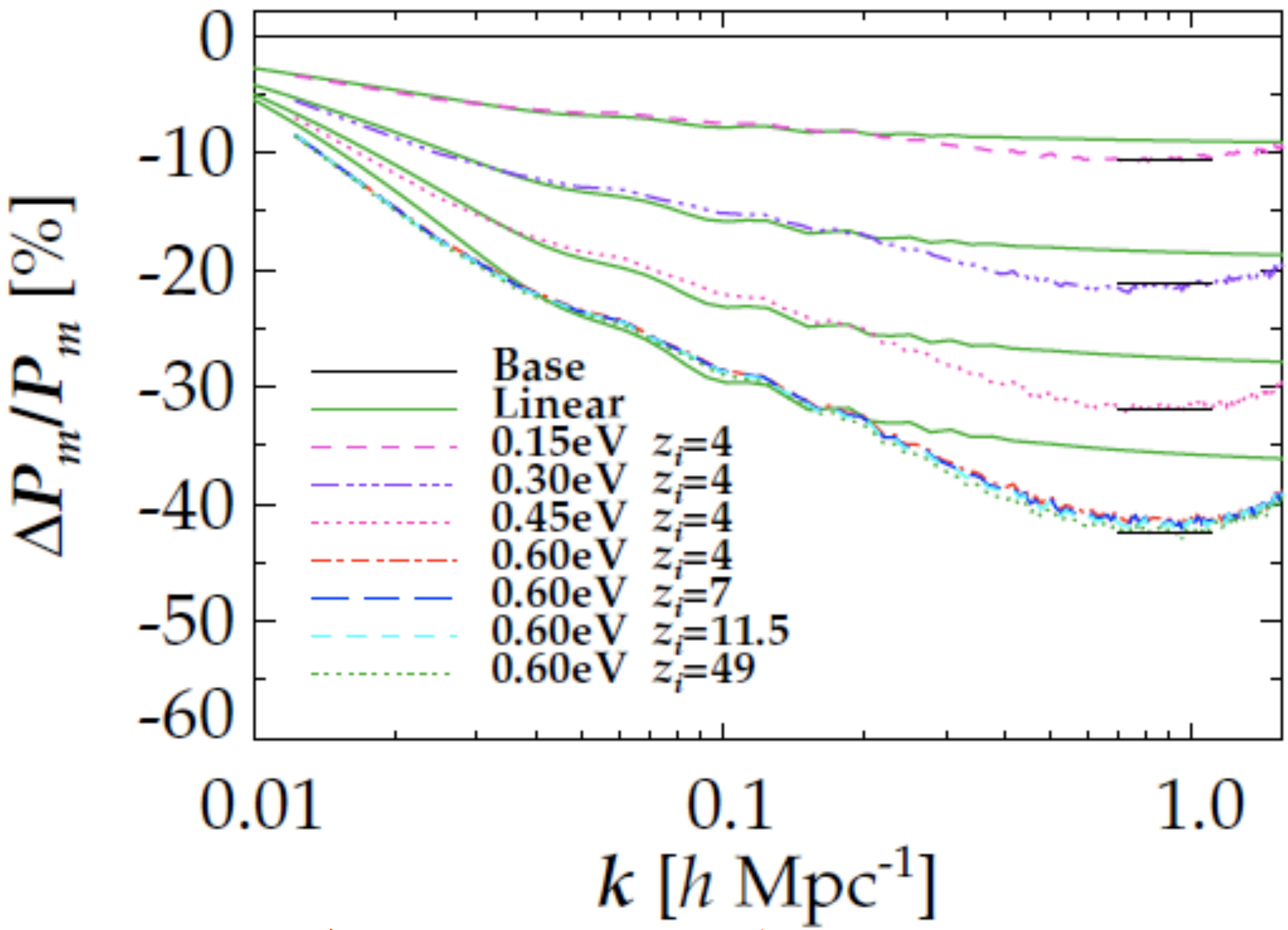
$$Pr(<p) = N \int_0^p \frac{p'^2}{e^{p'c/k_b T_\nu} + 1} dp'$$

Draw velocity from Fermi-Dirac distribution



Brandbyge et al 08

N-body simulations – III: effects in terms of non-linear power



Brandbyge et al 08

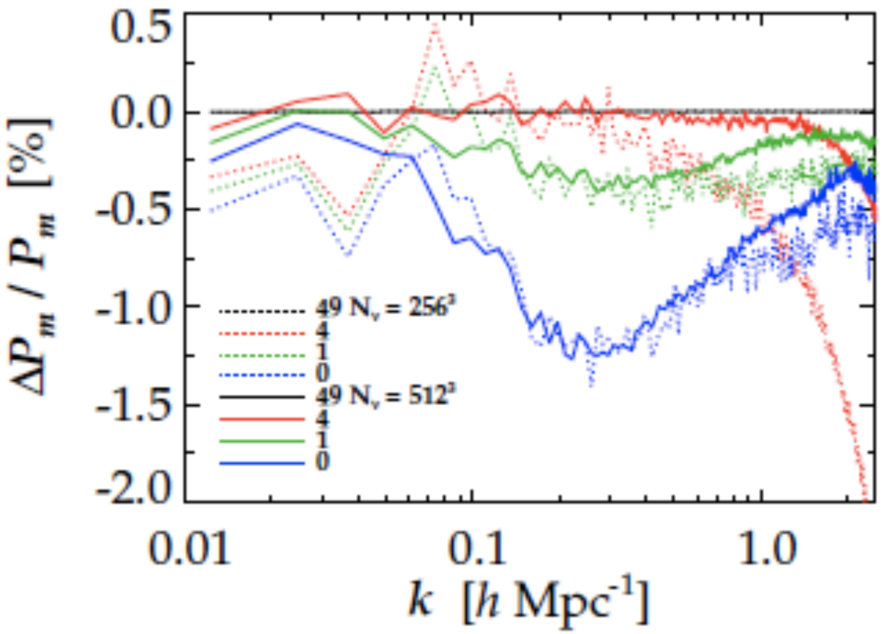
~~$\left.\frac{\Delta P}{P}\right|_{\max} \sim -8\frac{\Omega_\nu}{\Omega_m}$~~ → $\left.\frac{\Delta P}{P}\right|_{\max} \sim -9.8\frac{\Omega_\nu}{\Omega_m}$

N-body simulations – IV: mesh method

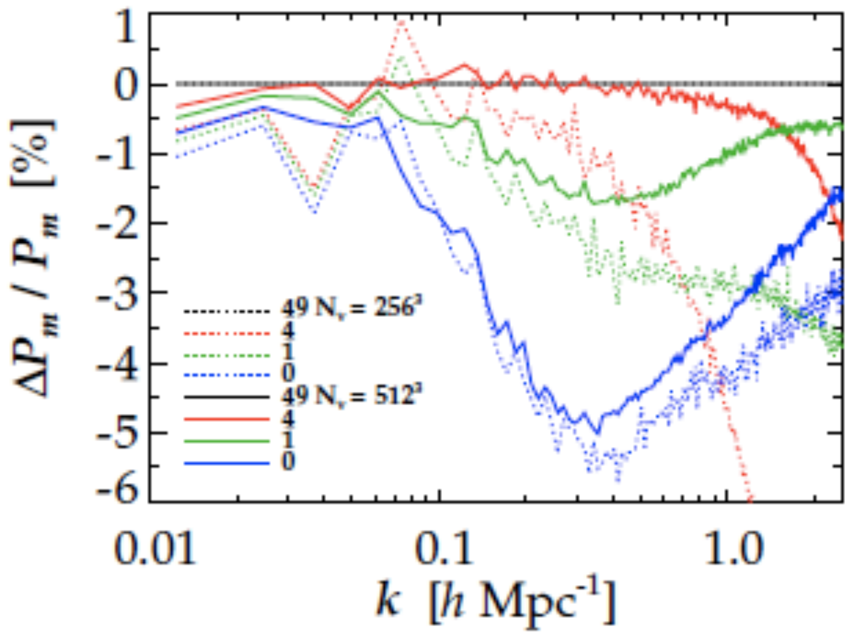
Computing the neutrino gravitational potential on the PM grid and summing up its contribution to the total matter gravitational potential – this is much faster!

COMPARISON GRID VS PARTICLES

M_ν =0.6 eV



M_ν = 1.2 eV



Brandbyge et al 08b

N-body simulations – V: a hybrid approach

$$f = f_0 + \frac{\partial f_0}{\partial T}\delta T = f_0(1+\Psi) \qquad f_0(q) = \frac{1}{e^{q/T}+1}$$

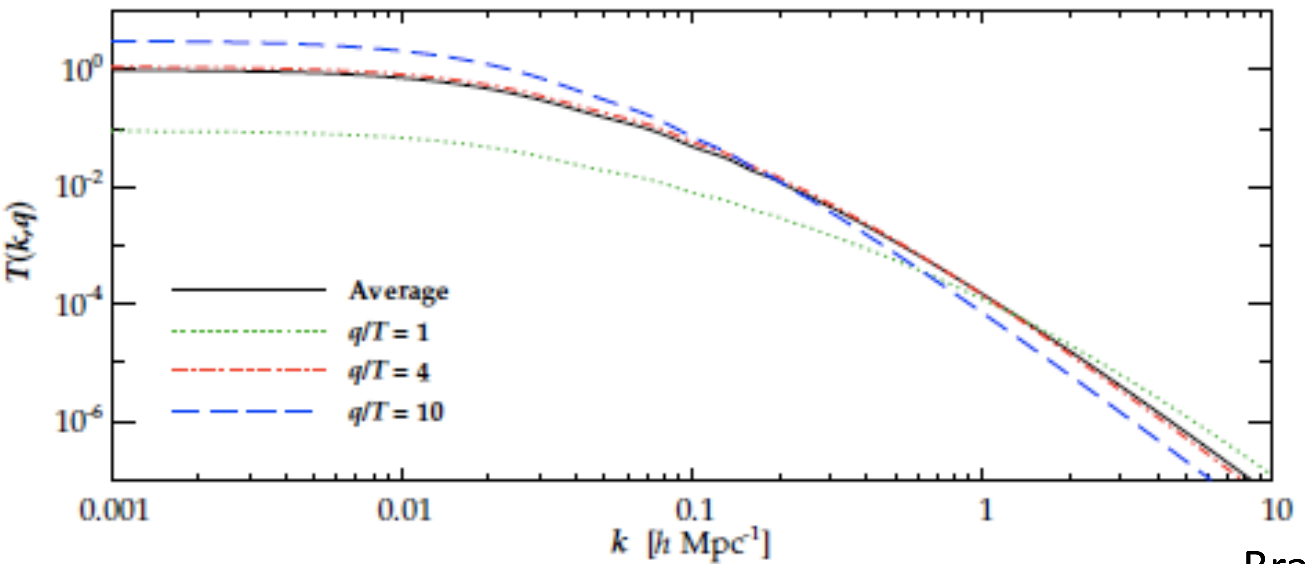
After neutrino decoupling CBE

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{dx^i}{d\tau}\frac{\partial f}{\partial x^i} + \frac{dq}{d\tau}\frac{\partial f}{\partial q} + \frac{dn_i}{d\tau}\frac{\partial f}{\partial n_i} = 0$$

$$\delta\rho_\nu(k) = 4\pi a^{-4}\int q^2 dq \epsilon f_0 \Psi_0 \qquad \epsilon = (q^2 + a^2 m^2)^{1/2}$$

Expansion of ψ in Legendre series

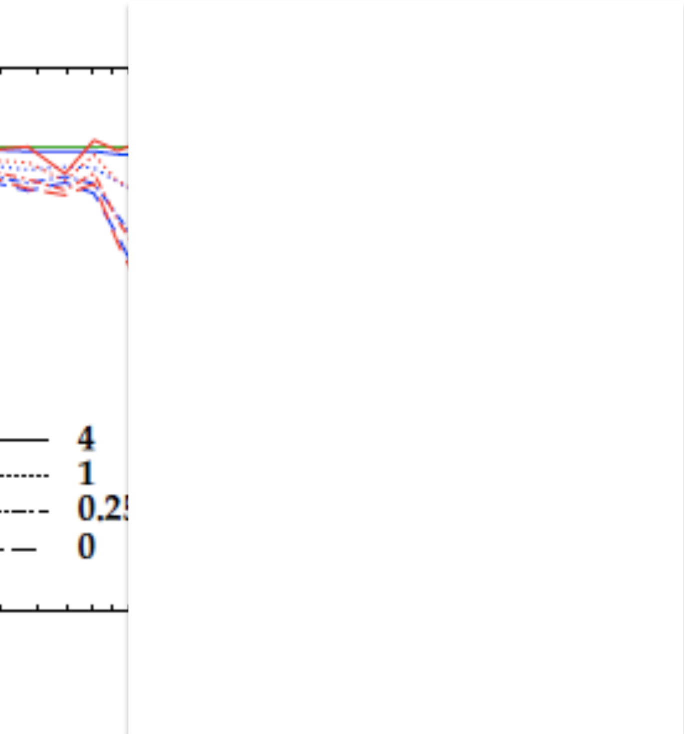
$$\dot\Psi_0 = -\frac{qk}{3\epsilon}\Psi_1 - \dot\phi\frac{d\ln f_0}{d\ln q},$$
$$\dot\Psi_1 = \frac{qk}{\epsilon}\left(\Psi_0 - \frac{2}{5}\Psi_2\right) - \frac{\epsilon k}{q}\psi\frac{d\ln f_0}{d\ln q},$$
$$\dot\Psi_l = \frac{qk}{\epsilon}\left(\frac{l}{2l-1}\Psi_{l-1} - \frac{l+1}{2l+3}\Psi_{l+1}\right),\ l \geq 2$$

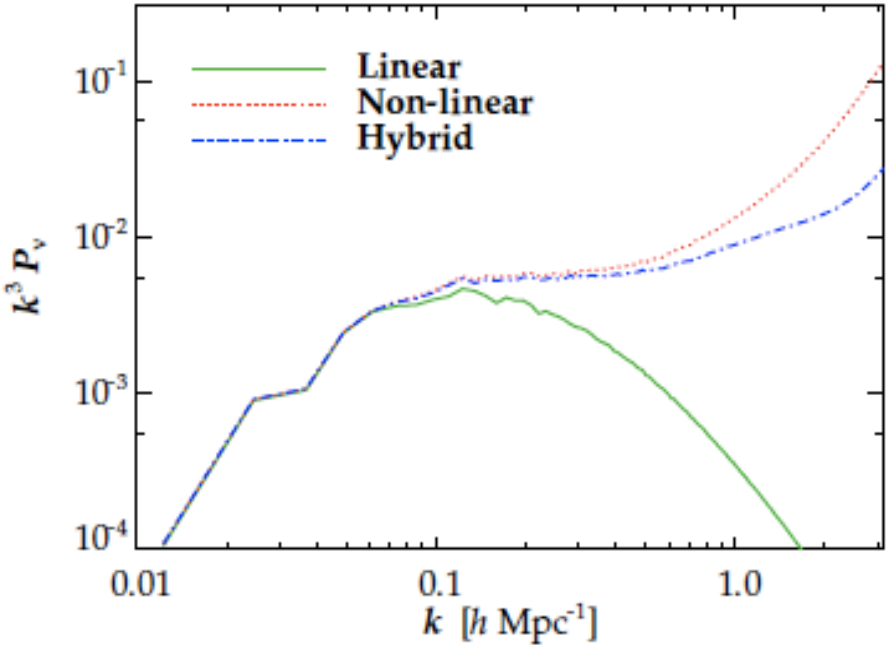


$$\Psi_0(k,q,z) = T(k,q,z)\Psi_0^I(k,q)$$

Brandbyge & Hannestad 09

N-body simulations – VI: comparison



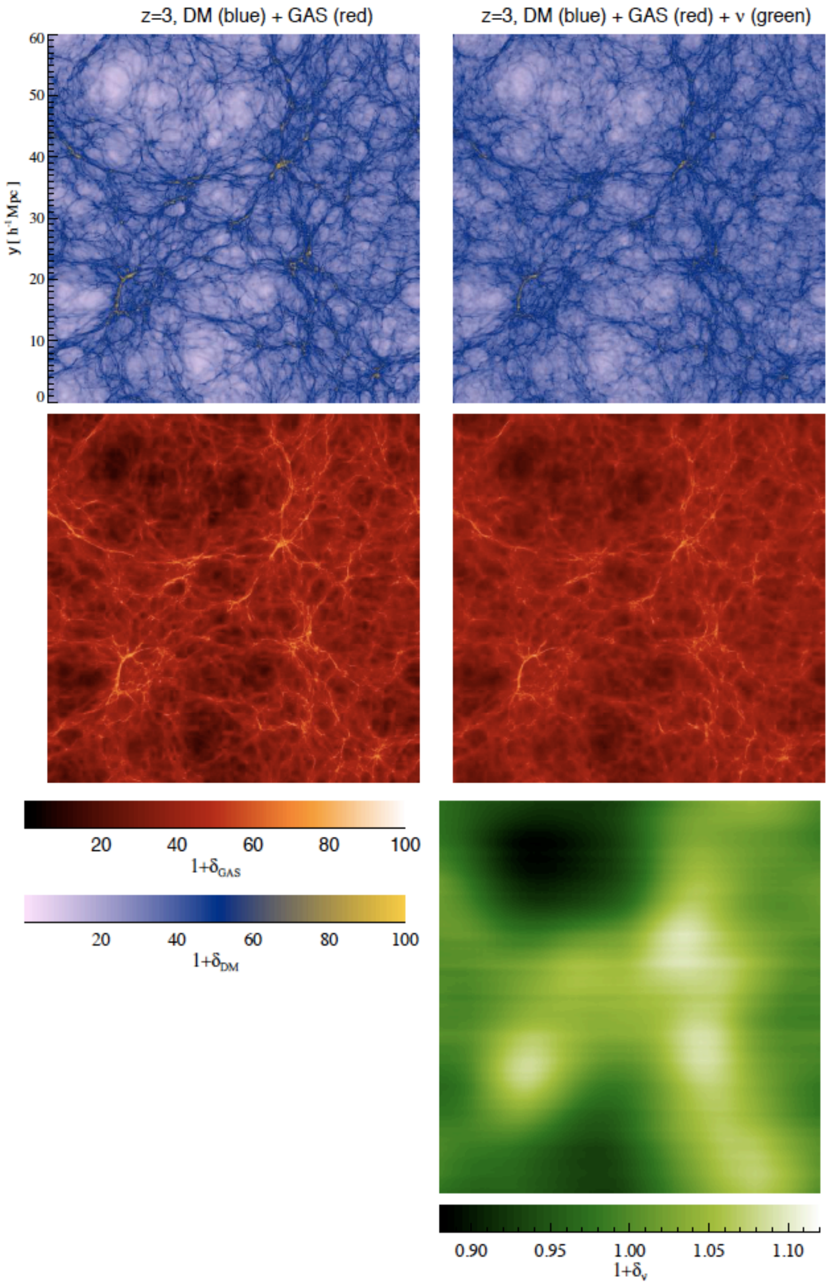


PARTICLES: accurate non-linear sampling but prone to shot-noise errors

GRID: fast and accurate but no phase mixing (i.e. non-linear regime suppression maybe it is less than it should be)

HYBRID: ideal for non-linear objects but memory demanding and prone to convergence issues

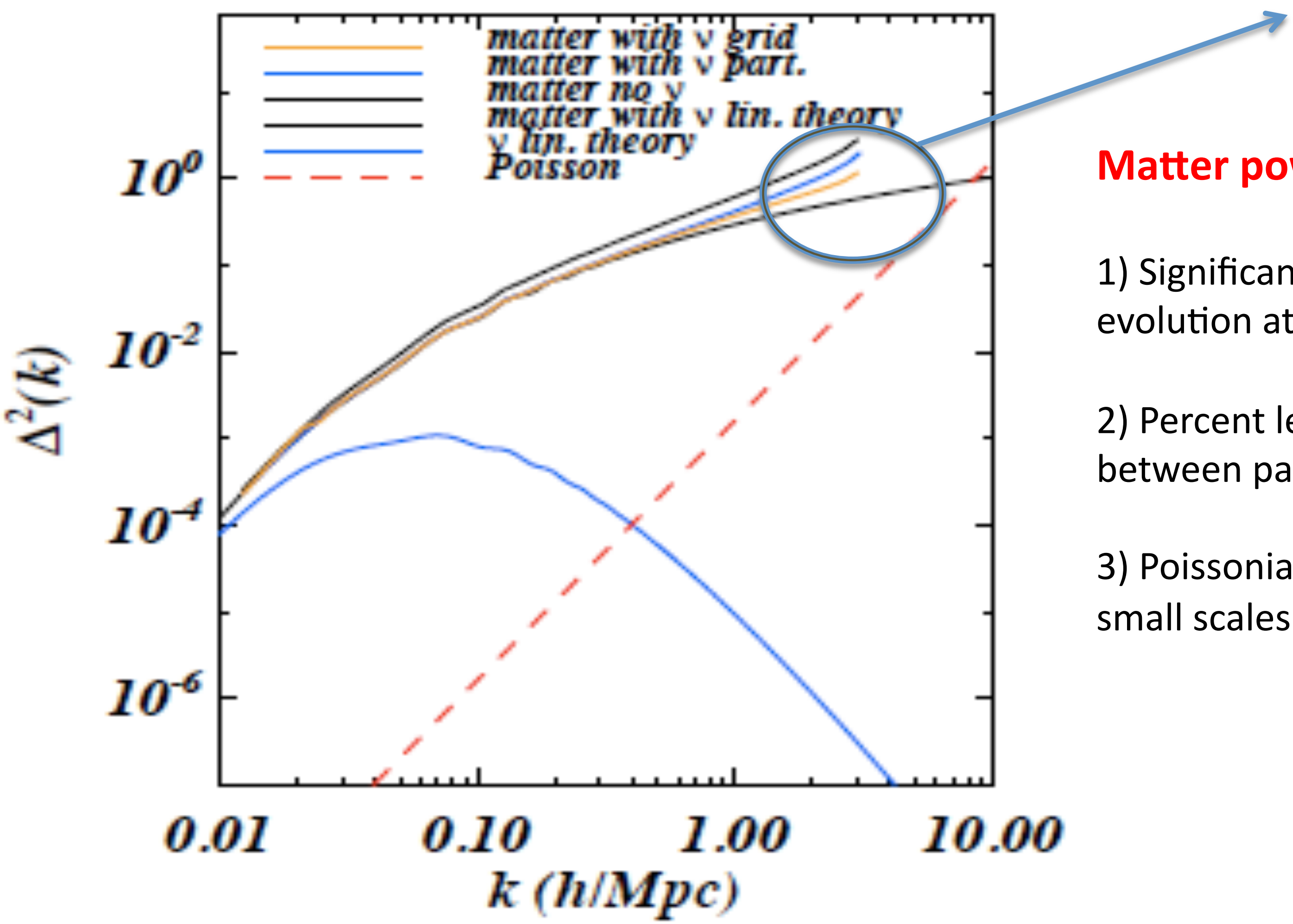
N-body + Hydro simulations – I: slices



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

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

SIMULATING NEUTRINOS in the IGM – II: methods



Methods differ

Matter power @ z = 3

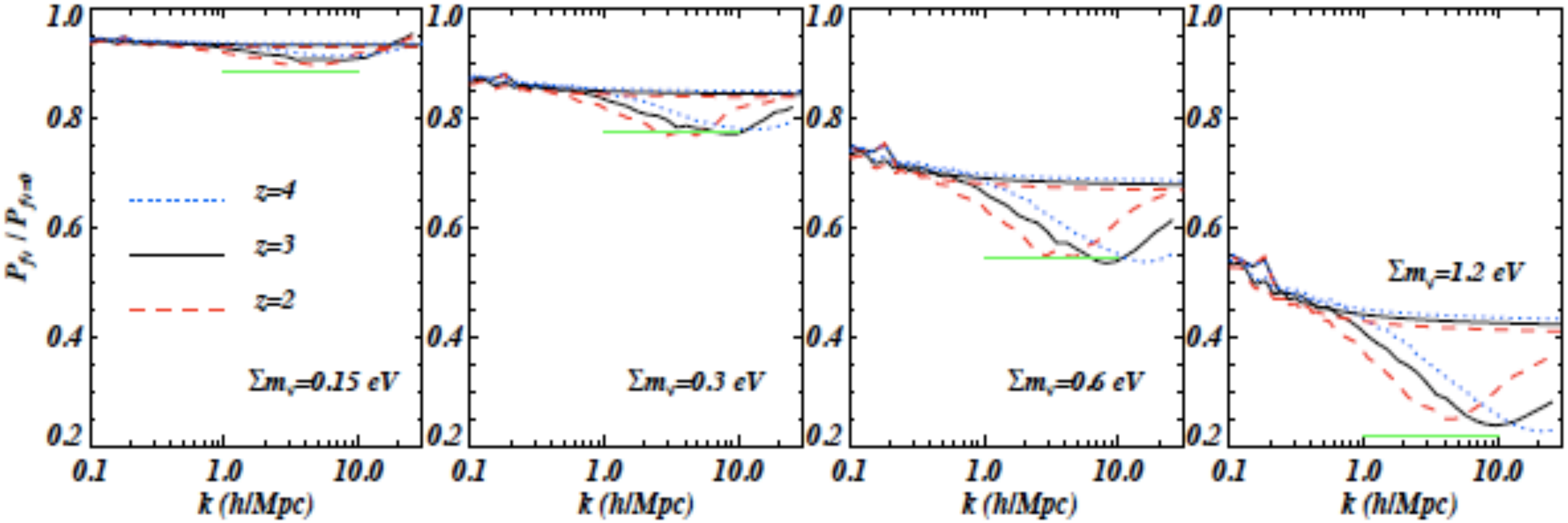
1) Significant non linear evolution at the smallest scales

2) Percent level discrepancies between particle and grid methods

3) Poissonian contribution affects small scales

Hydro simulations – III: redshift/scale dependence of non-linear power

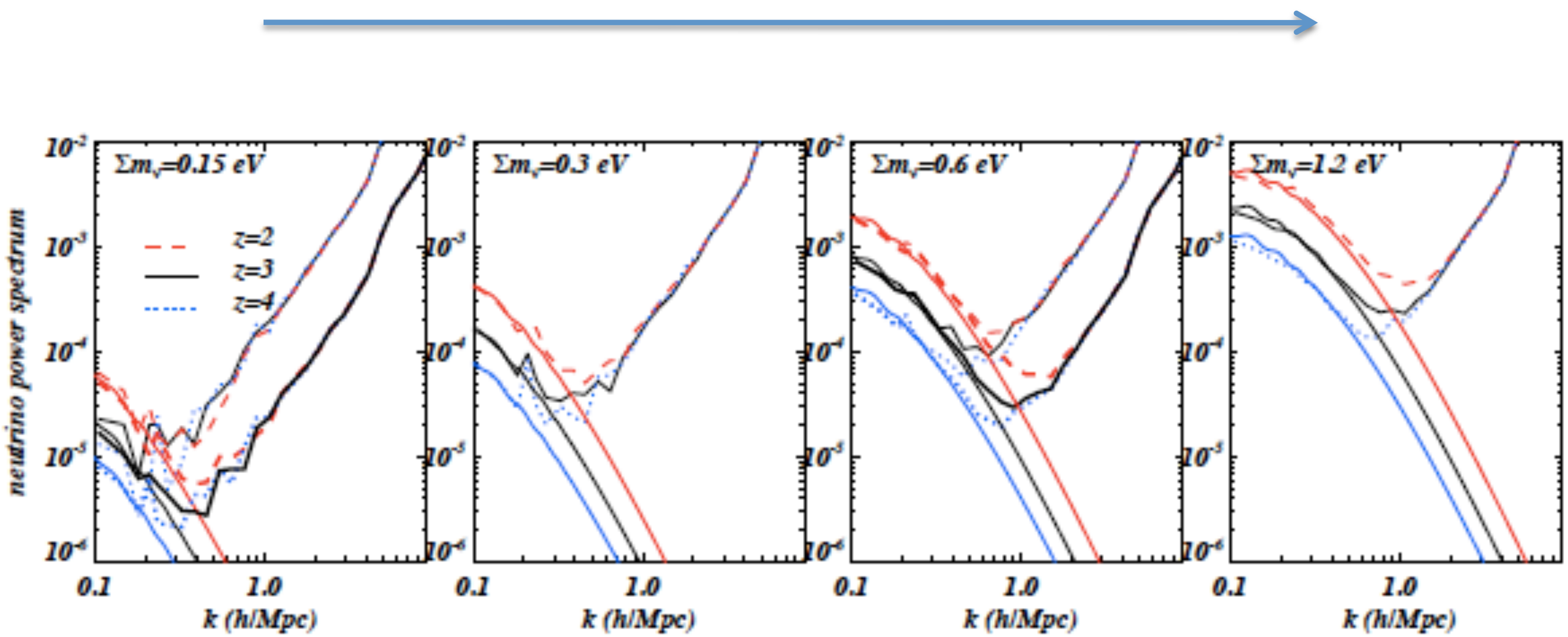
Full hydro simulations: gas physics does impact at the <10 % level at scales k < 10 h/Mpc



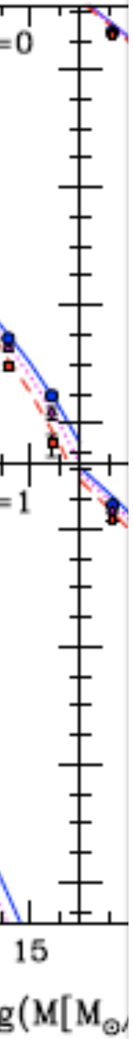
Viel, Haehnelt & Springel 2010, JCAP, 06 ,15

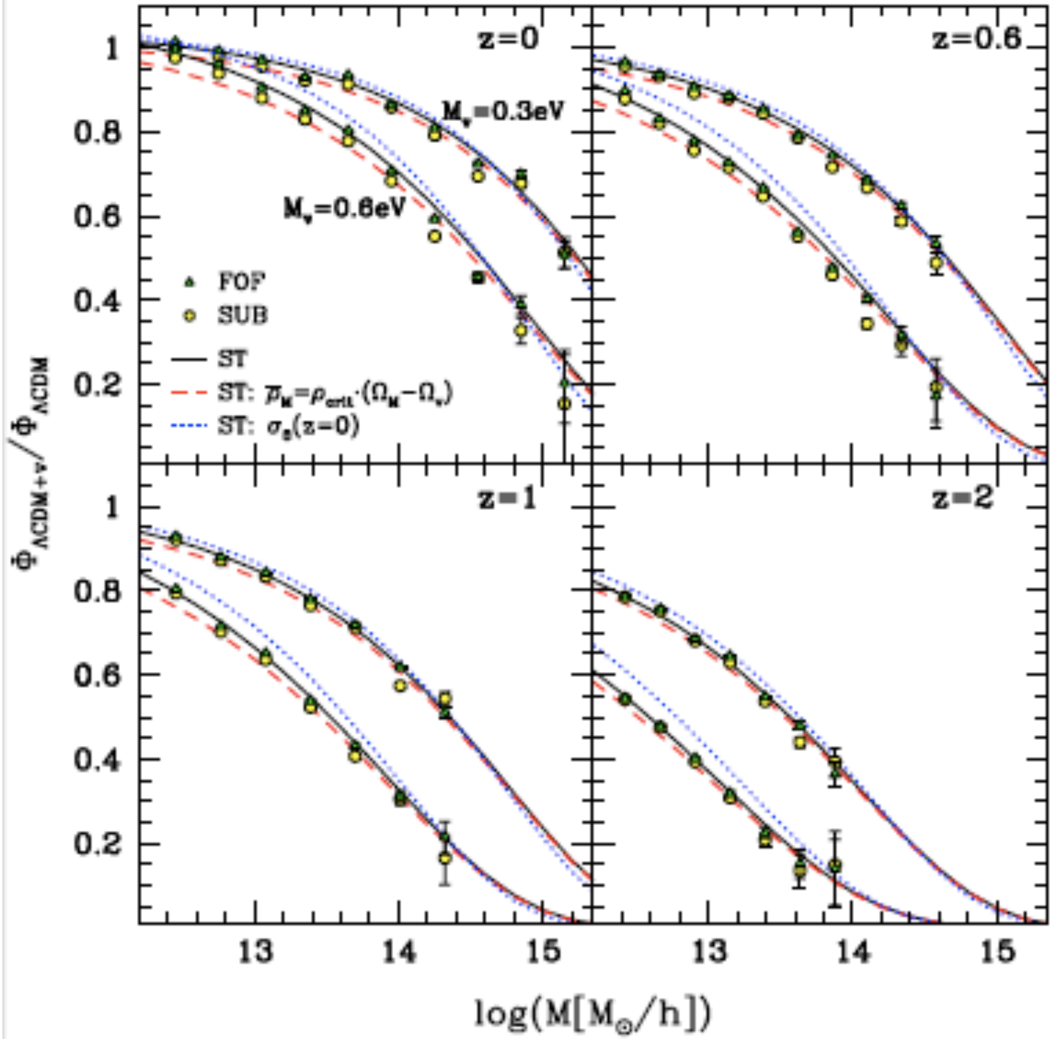
NEUTRINOS in the IGM – IV: impact on neutrino power spectrum

Increasing neutrino mass



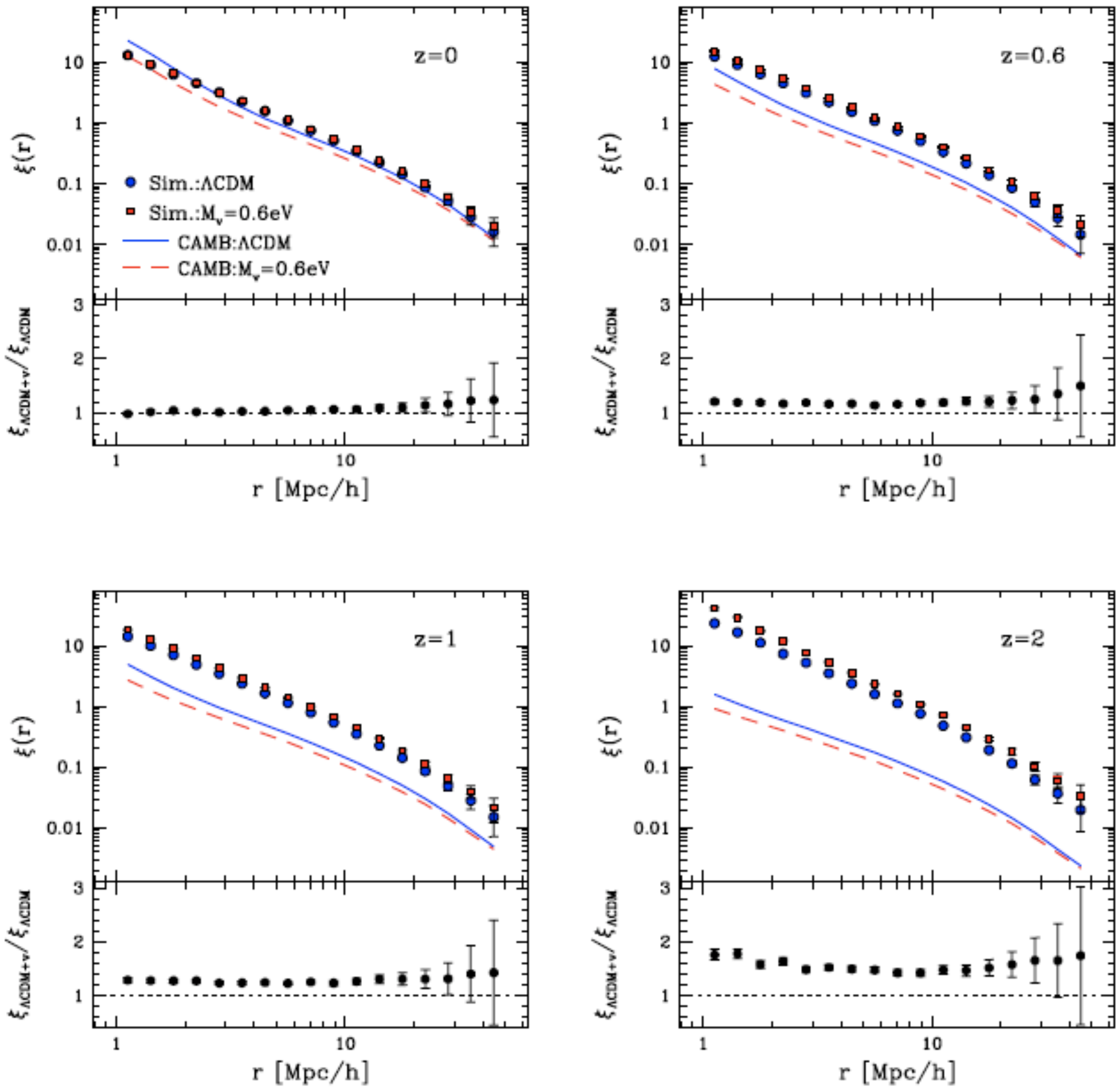
Hydro simulations – V: halo mass functions





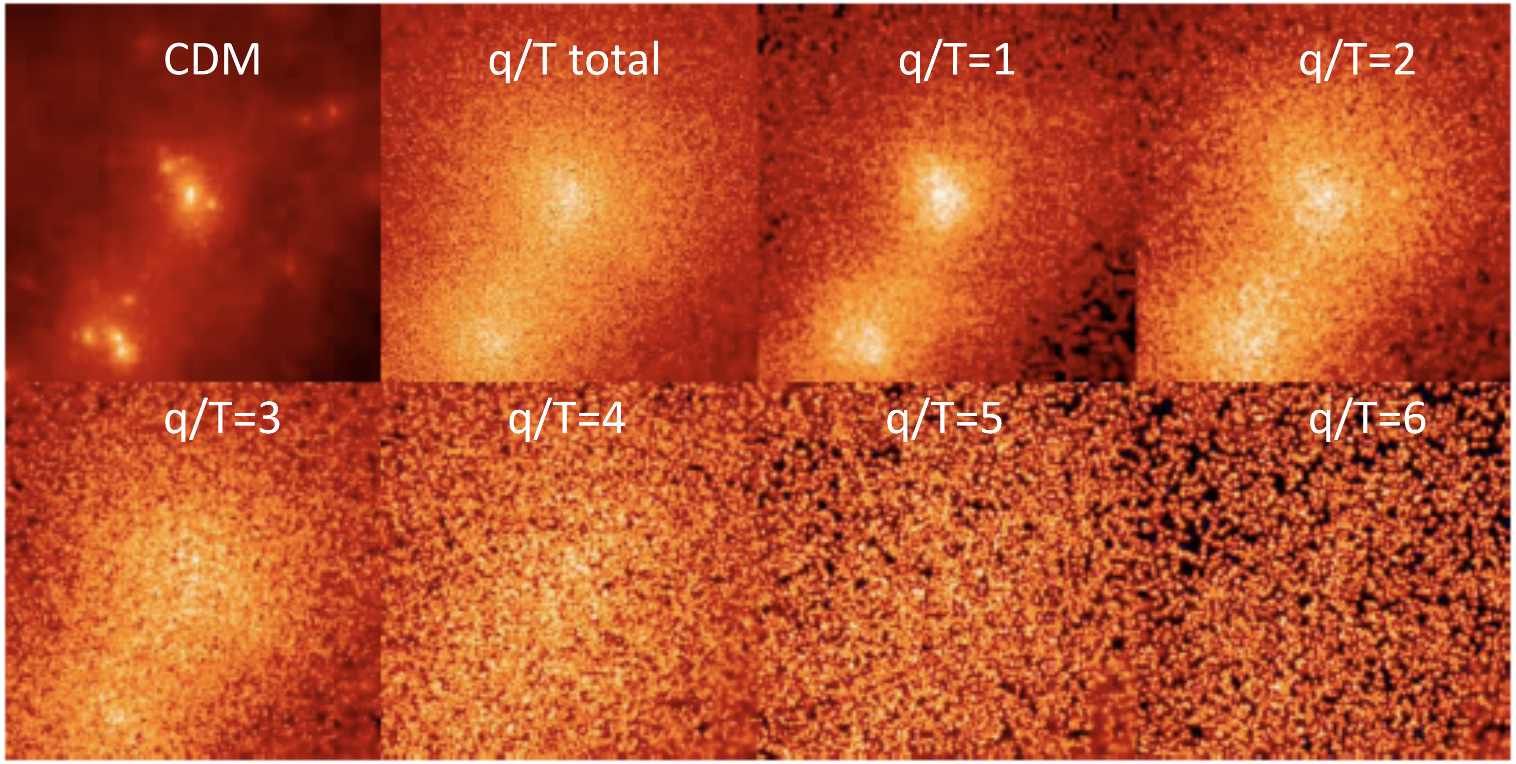
Marulli, Carbone, MV, Moscardini e Cimatti 2011 arxiv: 1103.0278

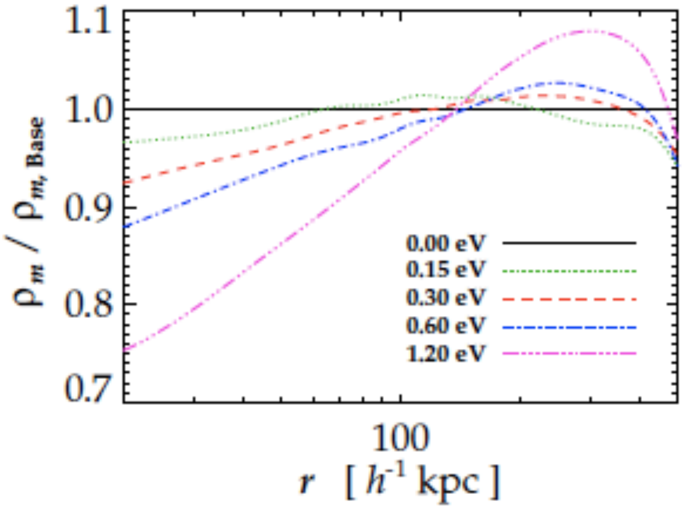
Hydro simulations – VI: matter and halo clustering



Marulli, Carbone, MV, Moscardini e Cimatti 2011 arxiv: 1103.0278, in press

N-body simulations – VII: halo density profile





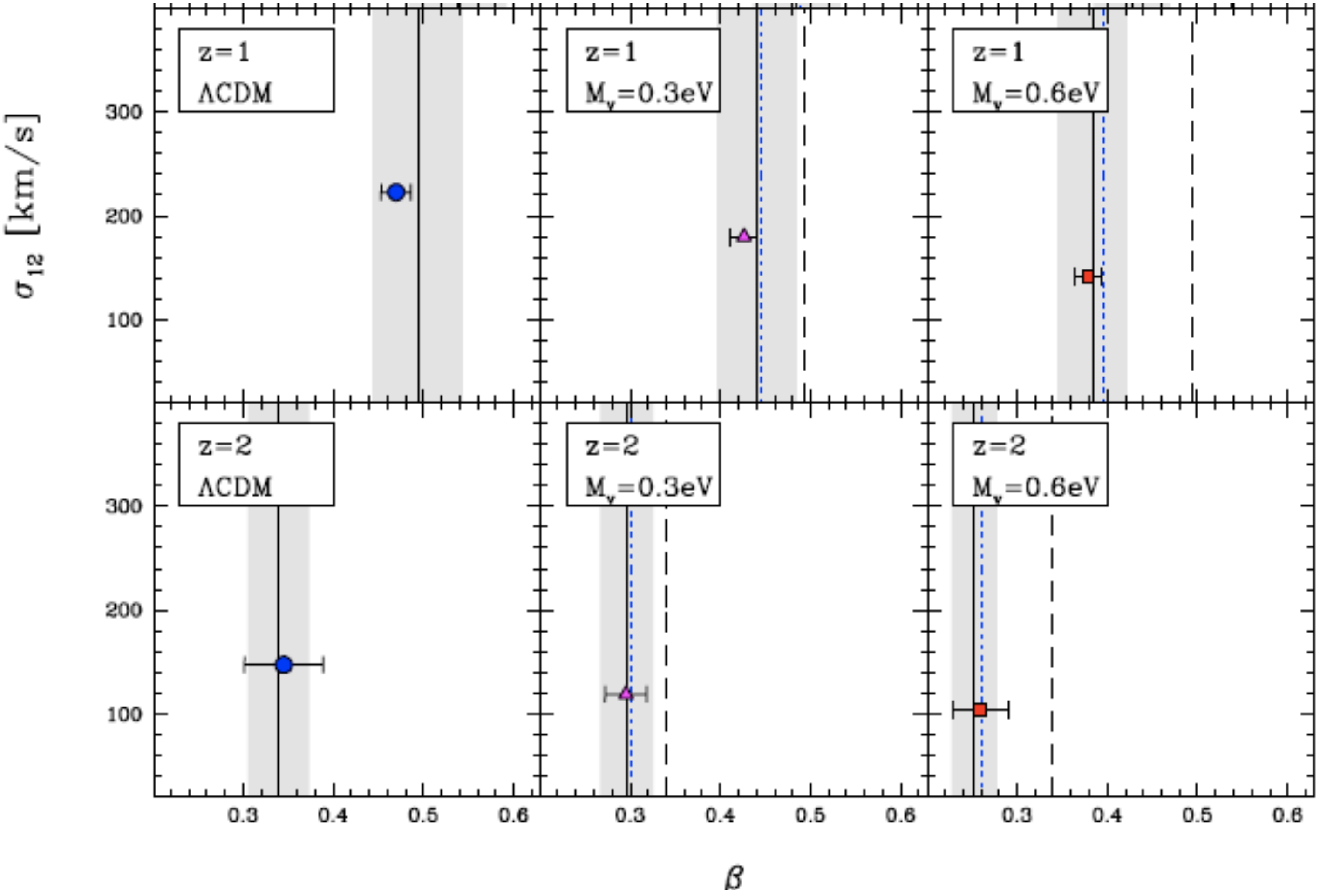
Brandbyge, Hannestad
Haugbolle, Wong 2010

Hydro simulations – VIII: redshift space distortions

$$\xi(s_\perp, s_\parallel) = \int_{-\infty}^{\infty} dv\, f(v)\, \xi(s_\perp, s_\parallel - v/H(z)/a(z))$$

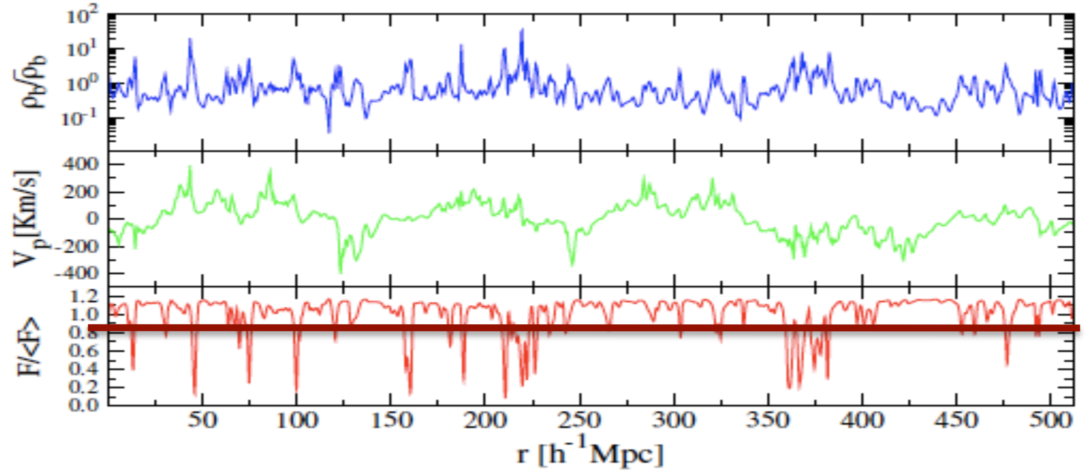
$$f_{\rm exp}(v) = \frac{1}{\sigma_{12}\sqrt{2}} \exp\left(-\frac{\sqrt{2}|v|}{\sigma_{12}}\right)$$

$$P(k) = (1+\beta\mu^2)^2 P_{\rm lin}(k)$$



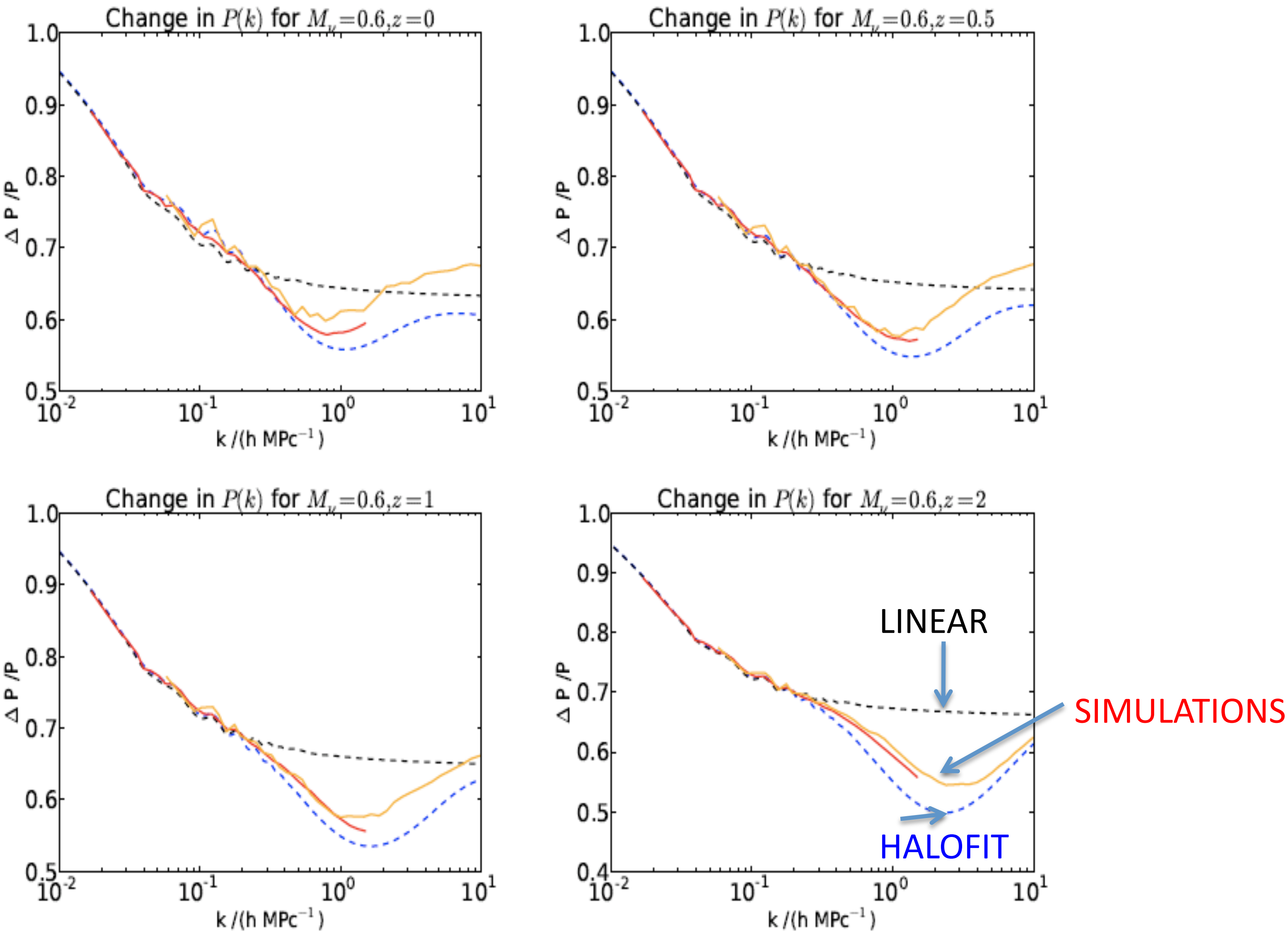
Marulli, Carbone, MV, Moscardini e Cimatti 2011 arxiv: 1103.0278

Hydro simulations – IX: the distribution of high-z voids



Navarro-Villaescusa, Vogelsberger, MV, Loeb 2011, arXiv: 1106.2543

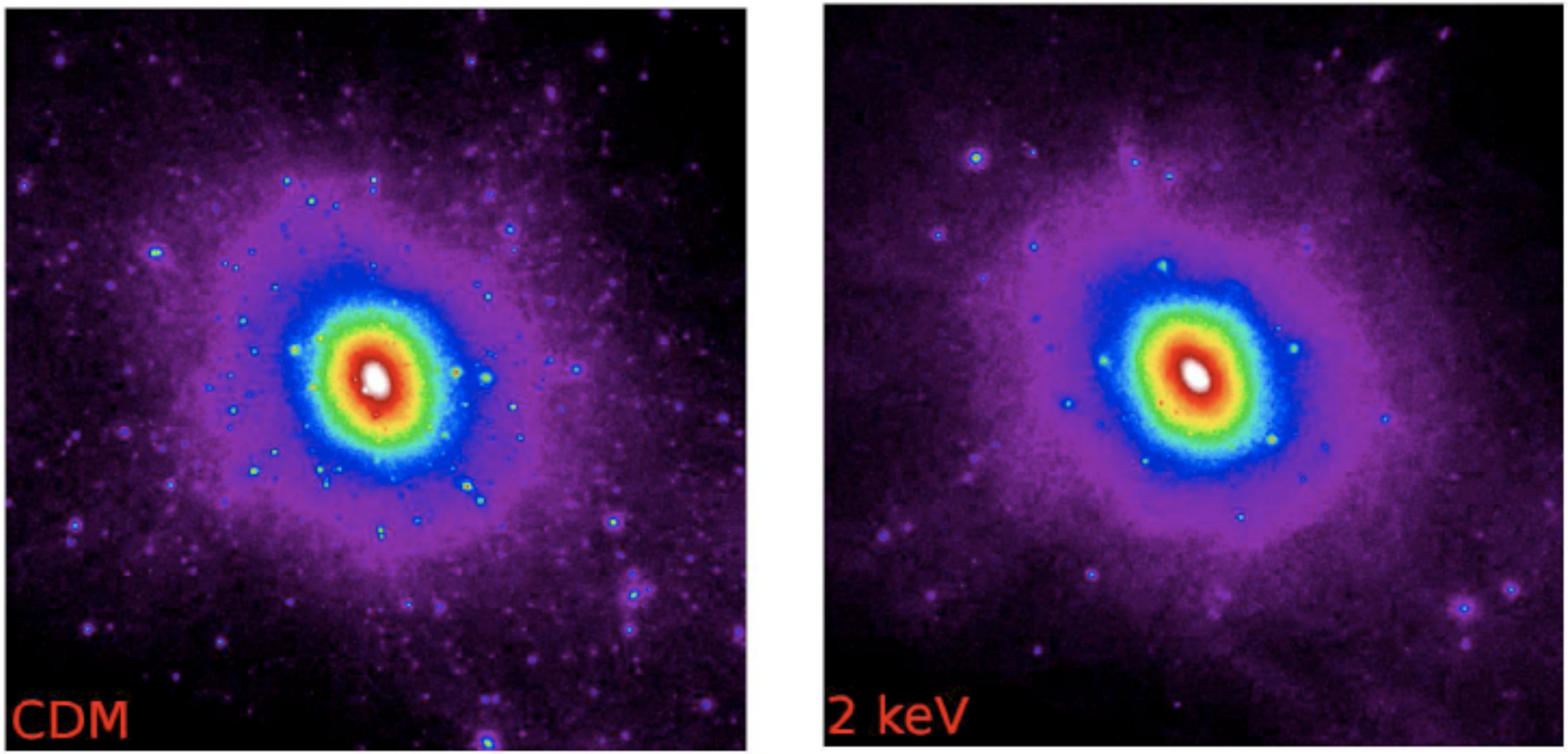
N-body simulations – X: very non-linear regime



Bird, MV, Haehnelt 11 (in prep.)

WARM DARK MATTER

FUNDAMENTAL PROPERTIES OF THE DARK MATTER: IMPACT ON HALOES



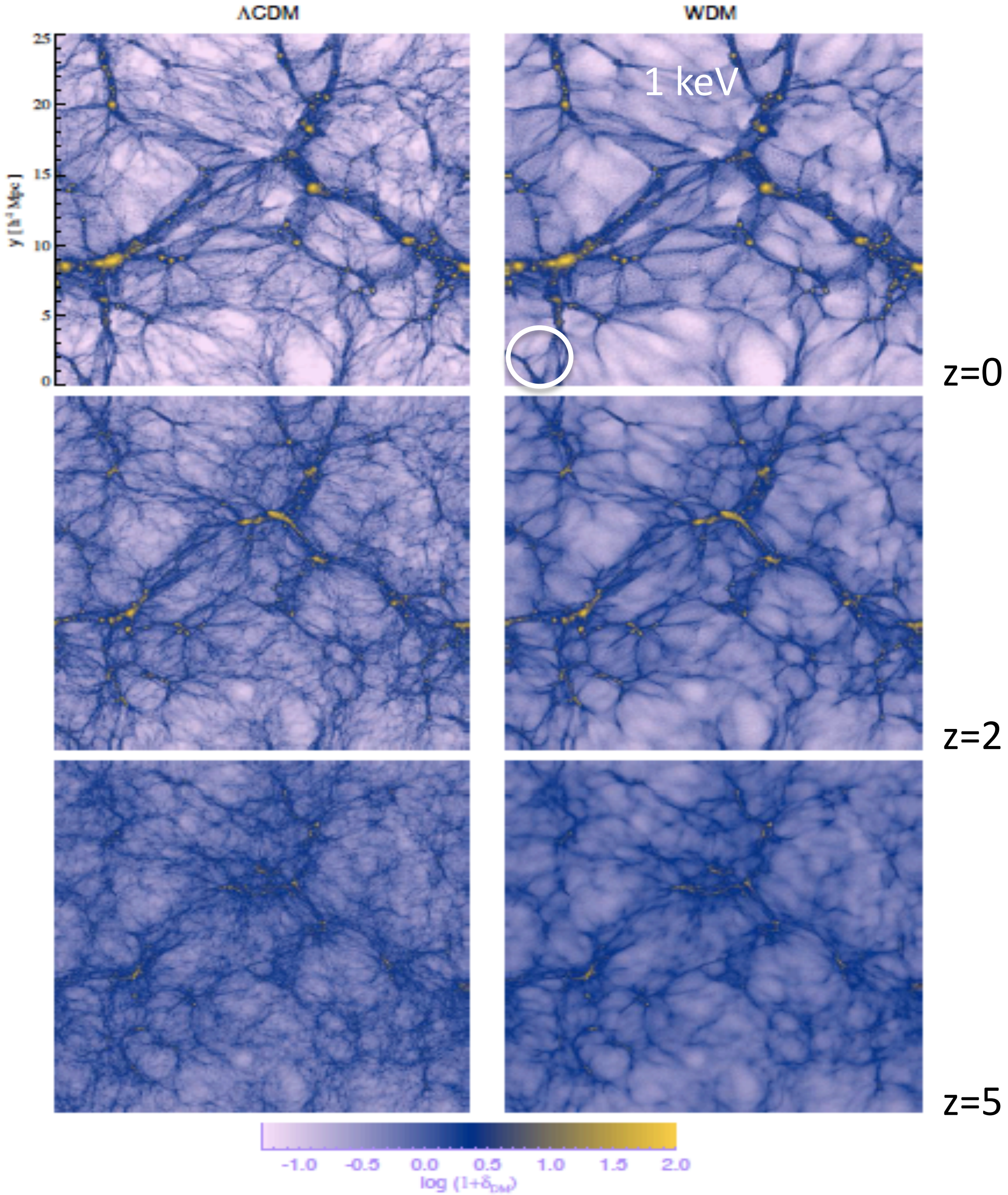
Polisensky & Ricotti 2010

See also Maccio' & Fontanot 2009 (application to galaxy formation)
Wang & White 2007 (numerical problems related to WDM/HDM sims.)
talks by Walker, Simon, Strigari, Koposov, Tikhonov etc...

Satellites no longer a problem: this is a success of ΛCDM numerical simulations (Frenk)

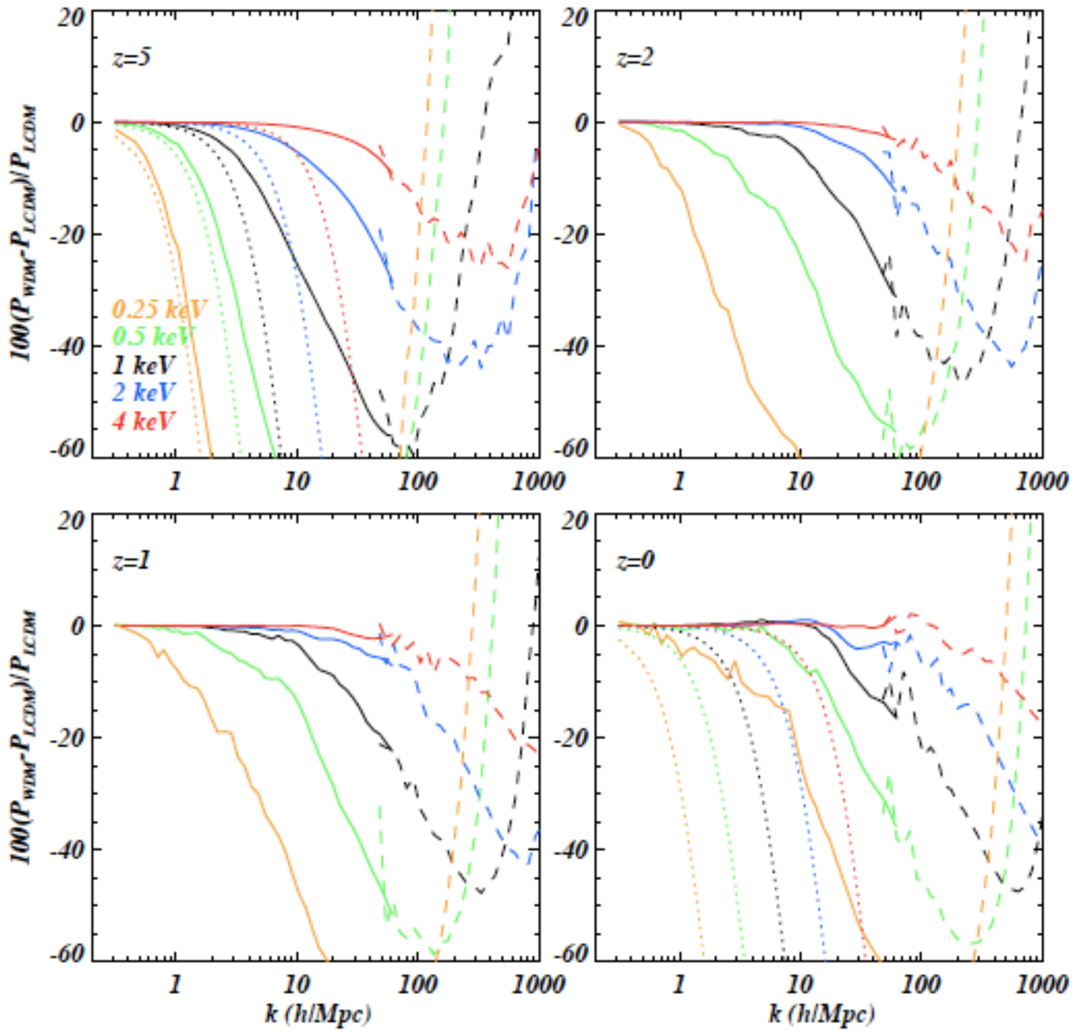
Warm Dark Matter and structure formation - I

$k_{FS} \sim 5\ T_\nu/T_x\ (m_x/1\text{keV})\ \text{Mpc}^{-1}$



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

Warm Dark Matter and non-linear power - II



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

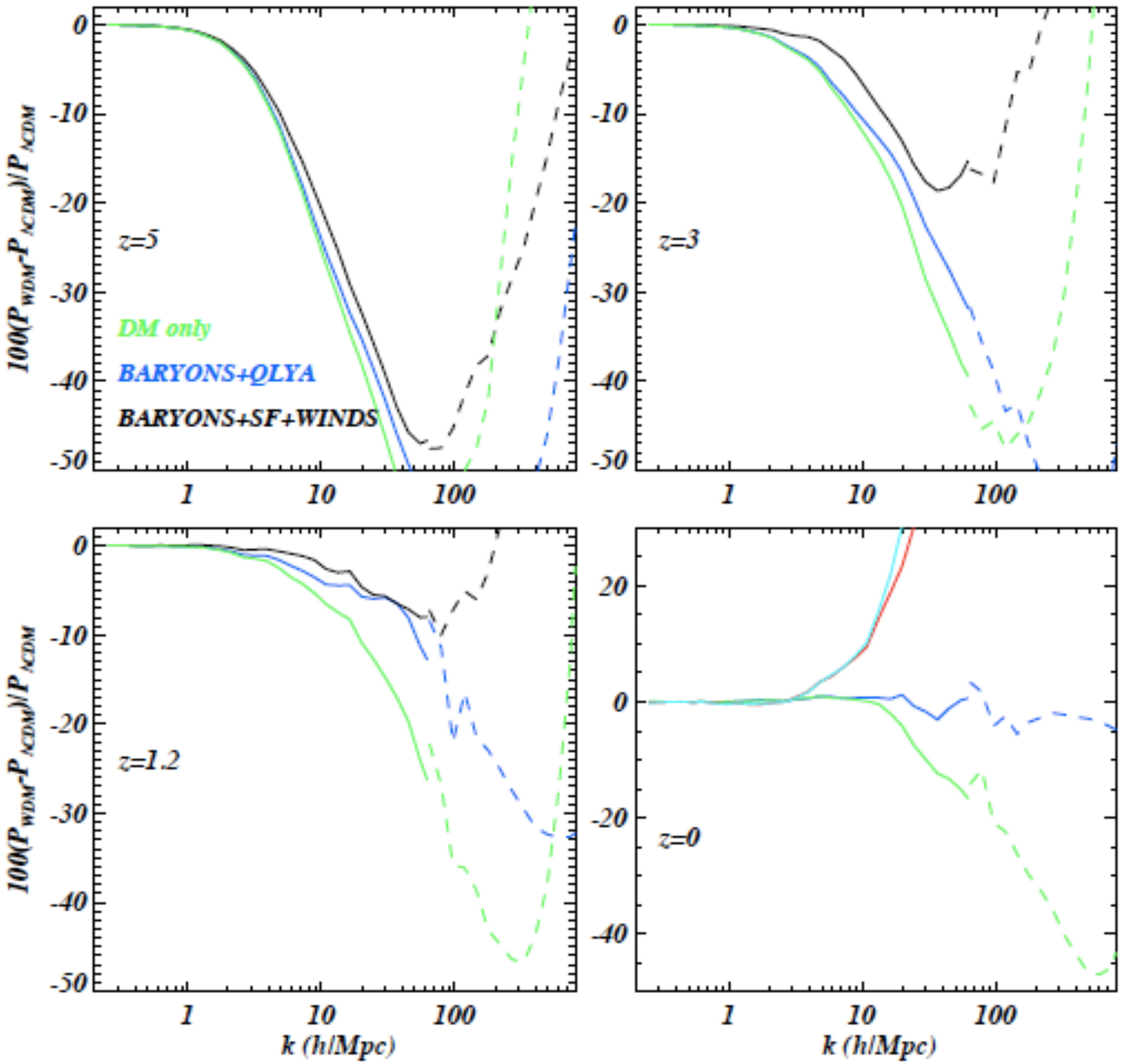
$$\alpha(m_{\rm WDM}, z) = 0.0476 \left(\frac{1{\rm keV}}{m_{\rm WDM}}\right)^{1.85} \left(\frac{1+z}{2}\right)^{1.3},$$

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

MV et al. 2011 (in prep.)

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

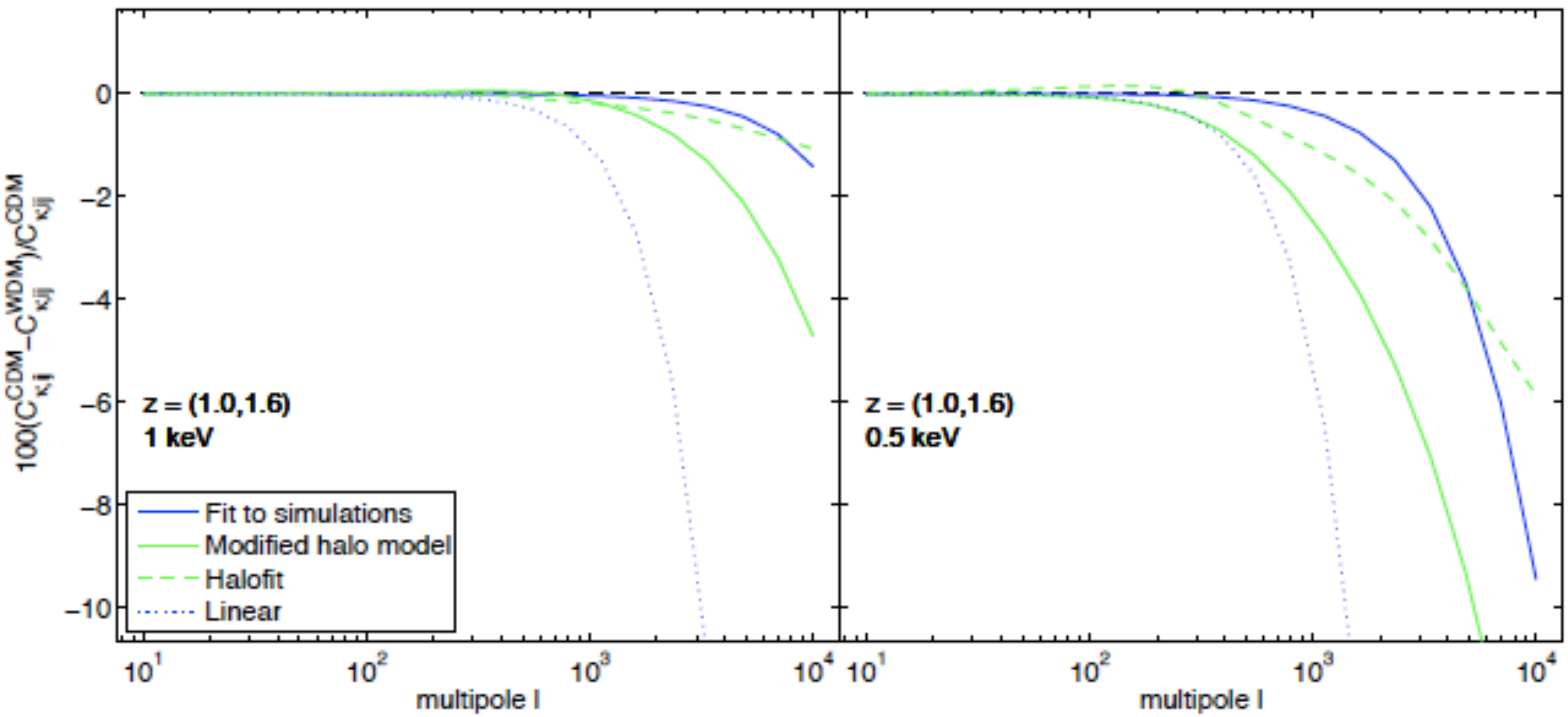
WDM and non-linear power - III: astrophysics



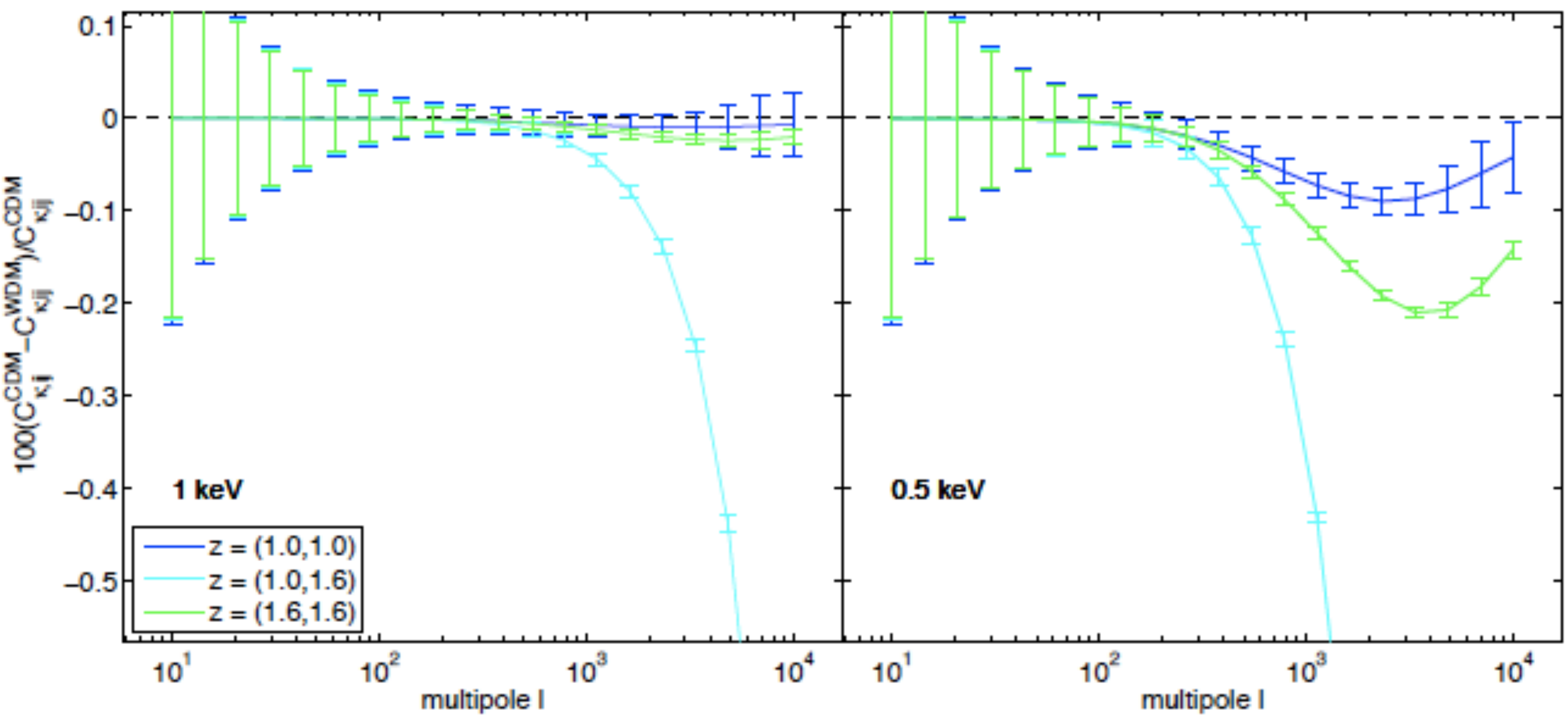
(see also Rudd et al. 08,
Guillet et al. 10
Van Daalen et al. 11,
Casarini et al. 11)

WDM and non-linear power - IV: weak lensing

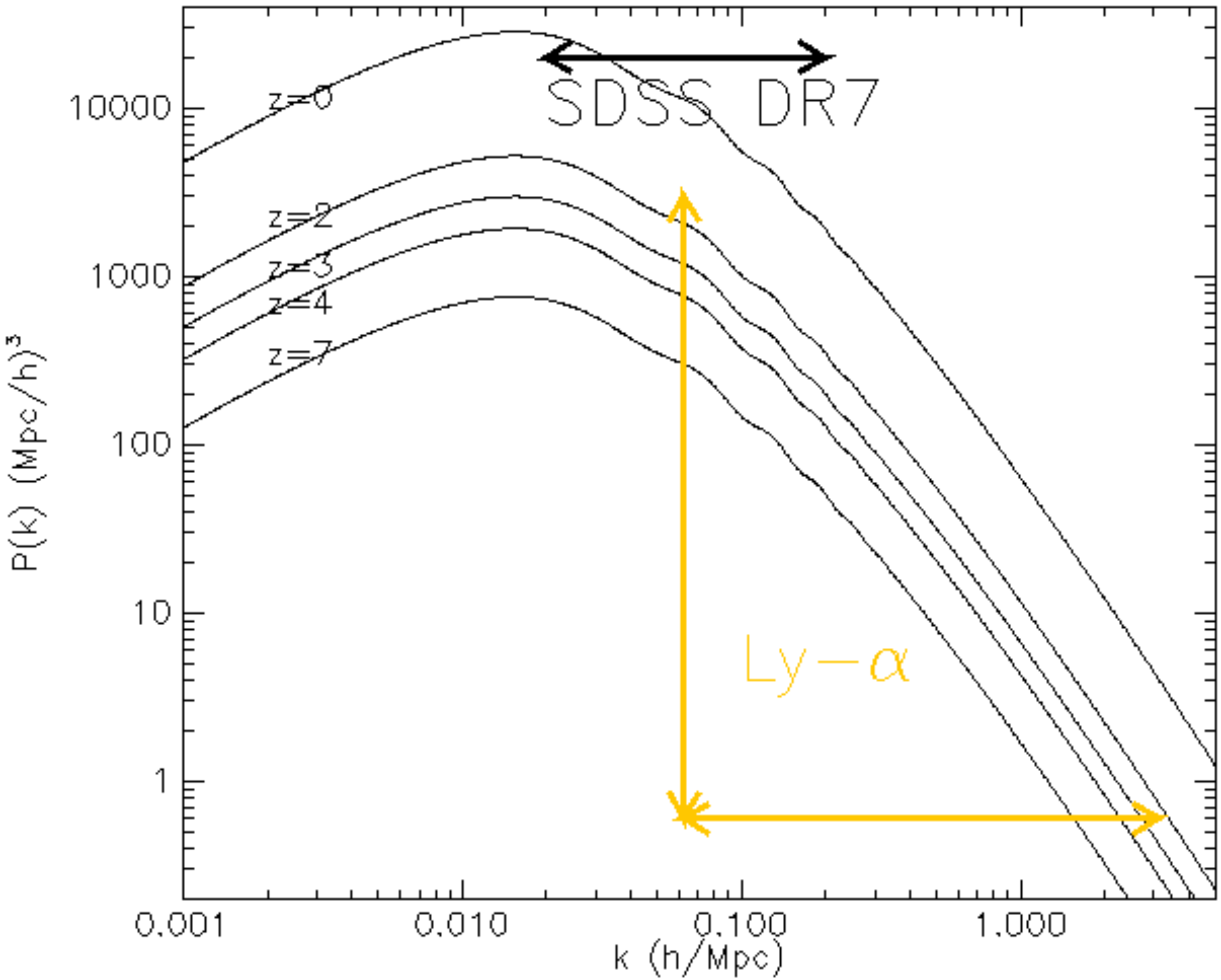
$$C_{ij}(l) = \int_0^{\chi_H} d\chi_l W_i(\chi_l) W_j(\chi_l) \chi_l^{-2} P_{nl}\left(k = \frac{l}{\chi_l}, \chi_l\right) \qquad W_i(z_l) = \frac{4\pi G}{a_l(z_l)c^2} \rho_{m,0} \chi_l \int_{z_l}^{z_{max}} n_i(z_s) \frac{\chi_{ls}(z_s, z_l)}{\chi_s(z_s)} dz_s$$



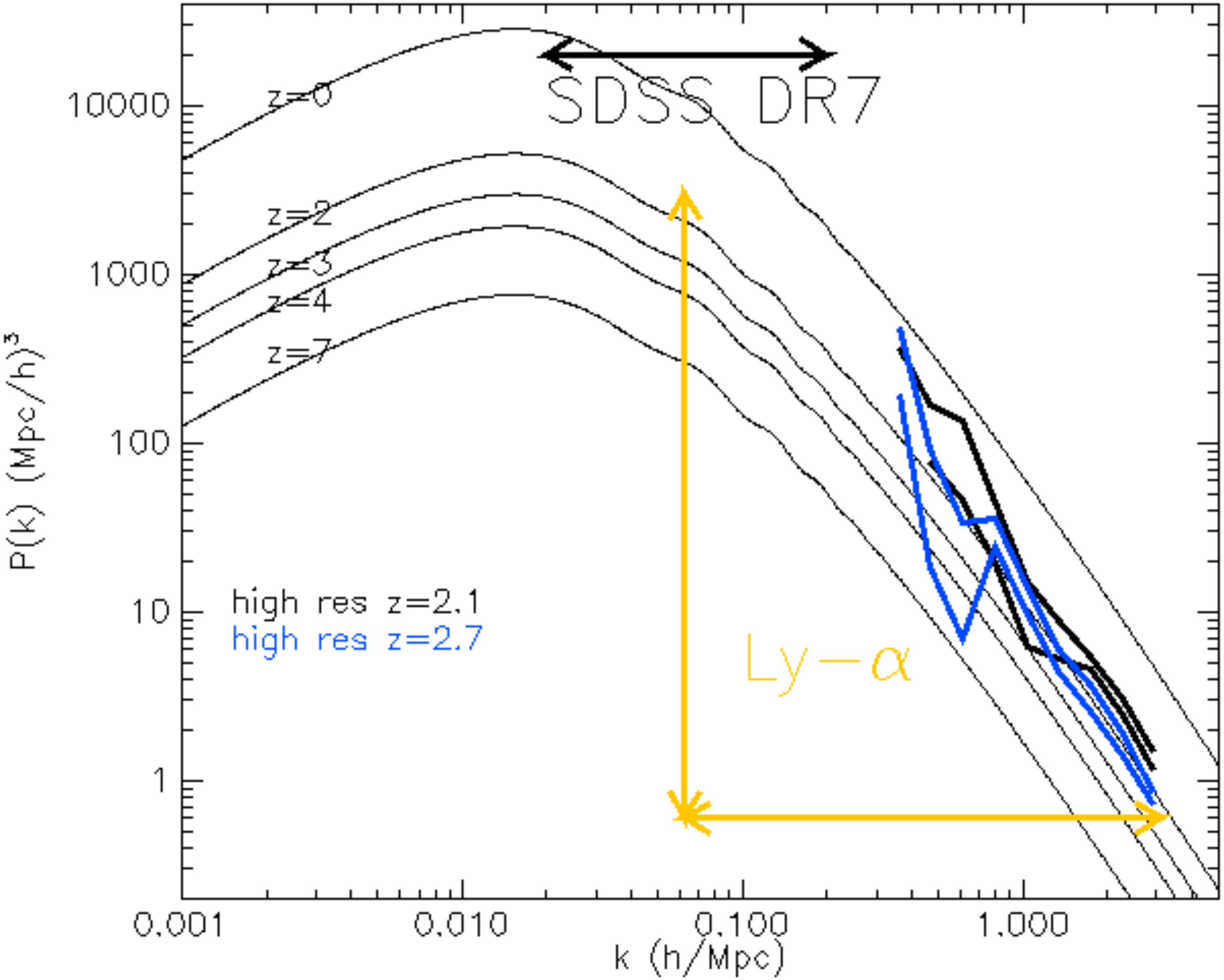
WDM and non-linear power - V: weak lensing



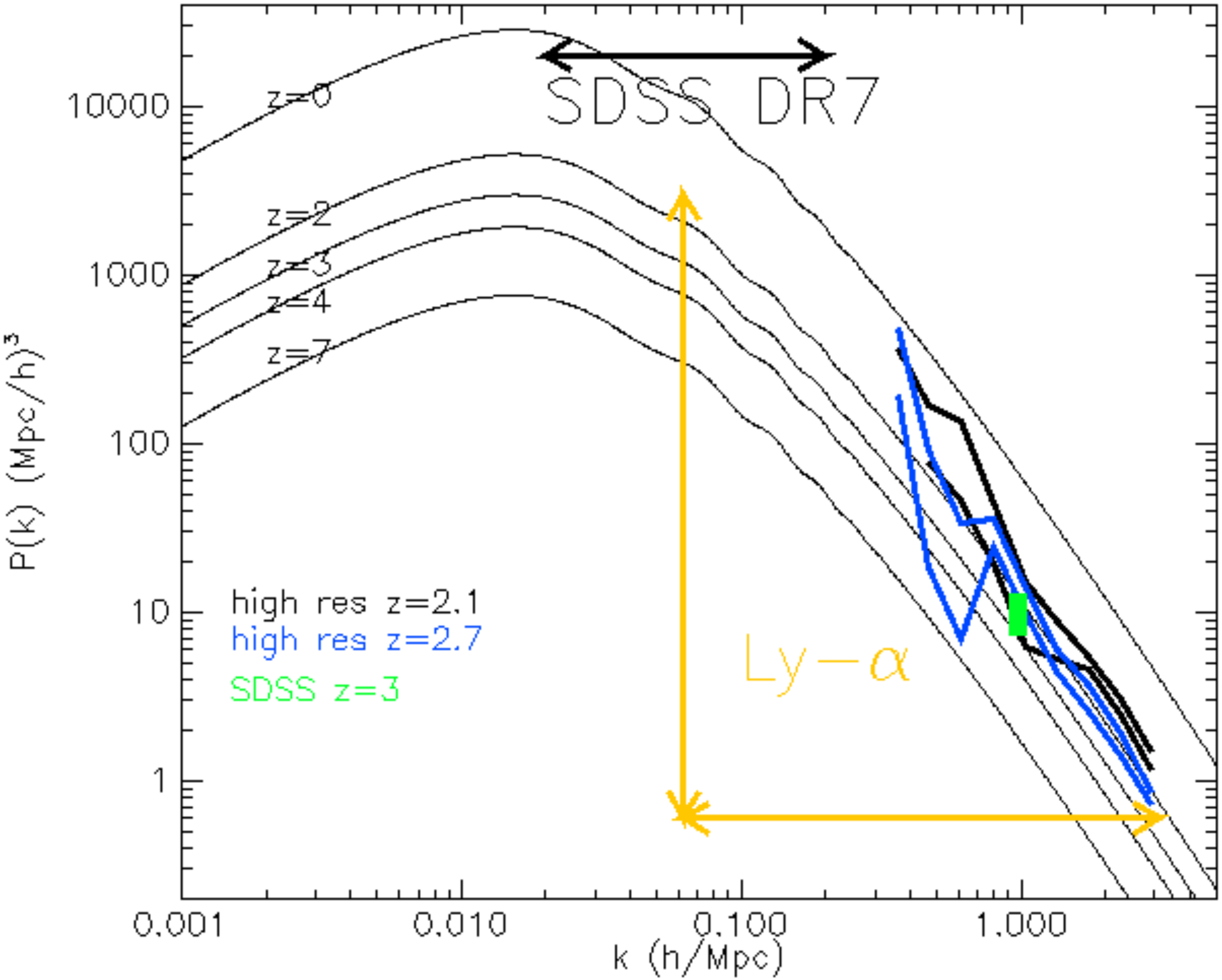
CONSTRAINTS from IGM data



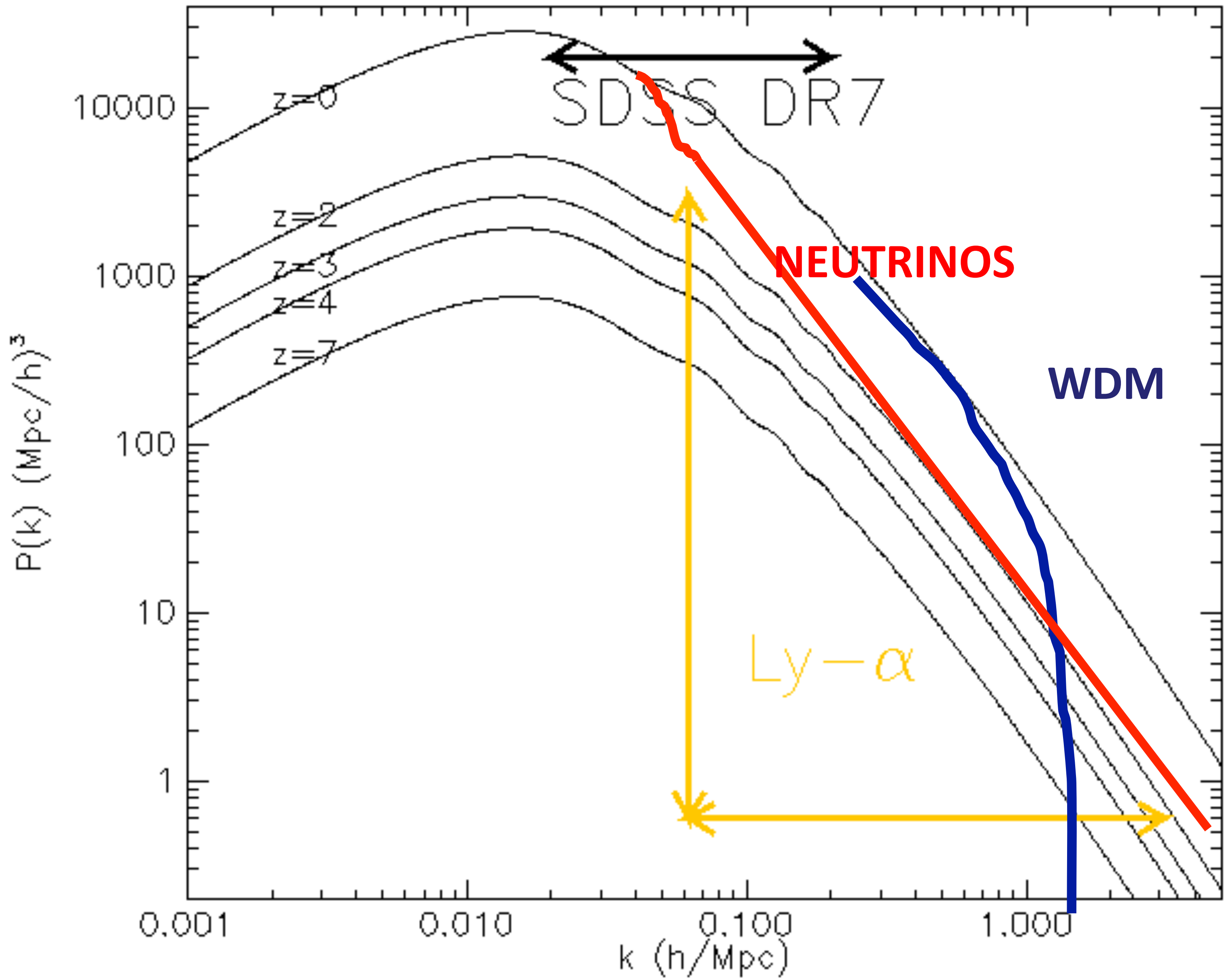
SDSS DR7
z=0
z=2
z=3
z=4
z=7
Ly−α
10000
1000
100
10
1
P(k) (Mpc/h)³
0.001
0.010
0.100
1.000
k (h/Mpc)



SDSS DR7
z=0
z=2
z=3
z=4
z=7
10000
1000
100
10
1
P(k) (Mpc/h)^3
high res z=2.1
high res z=2.7
Ly−α
0.001
0.010
0.100
1.000
k (h/Mpc)



SDSS DR7
z=0
z=2
z=3
z=4
z=7
10000
1000
100
10
1
P(k) (Mpc/h)^3
high res z=2.1
high res z=2.7
SDSS z=3
Ly−α
0.001
0.010
0.100
1.000
k (h/Mpc)



SDSS DR7
z=0
z=2
z=3
z=4
z=7
NEUTRINOS
WDM
Ly−α
10000
1000
100
10
1
P(k) (Mpc/h)^3
0.001
0.010
0.100
1.000
k (h/Mpc)

Summary (highlights) of results from the high-res and low-res data

Why Lyman-α ? Small scales
High redshift
Most of the baryonic mass is in this form
Quasars sample 75% of the age of the universe

1. Tightest constraints to date on neutrino masses and running of the spectral index

   Seljak, Slosar, McDonald JCAP (2006) 10 014

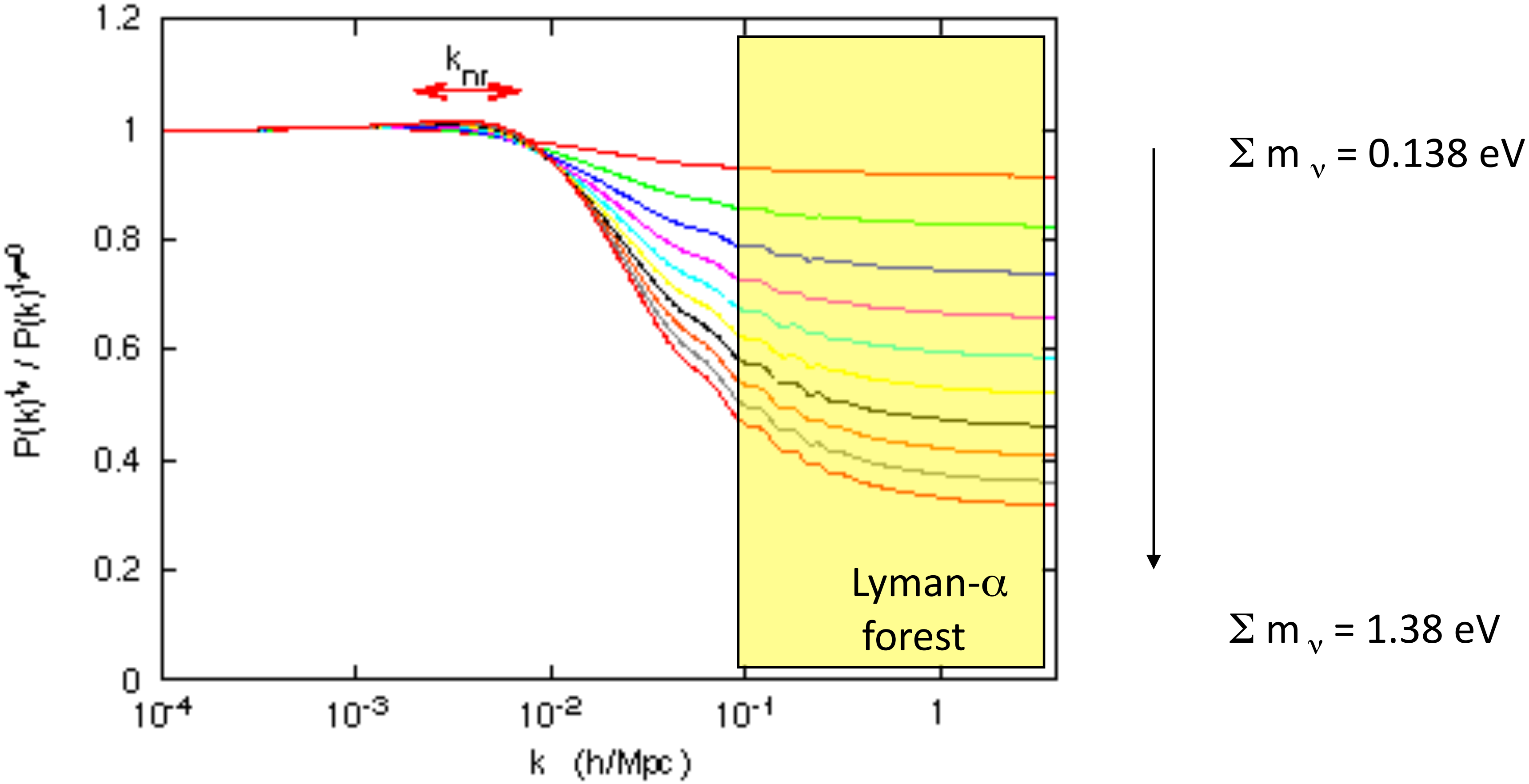
2. Tightest constraints to date on the coldness of cold dark matter

   MV et al., Phys.Rev.Lett. 100 (2008) 041304

Neutrinos – I: the linear effect

$$k_{nr} \simeq 0.018\, \Omega_m^{1/2} \left(\frac{m}{1\,\text{eV}}\right)^{1/2} h\,\text{Mpc}^{-1}$$

Lesgourgues & Pastor Phys.Rept. 2006, 429, 307

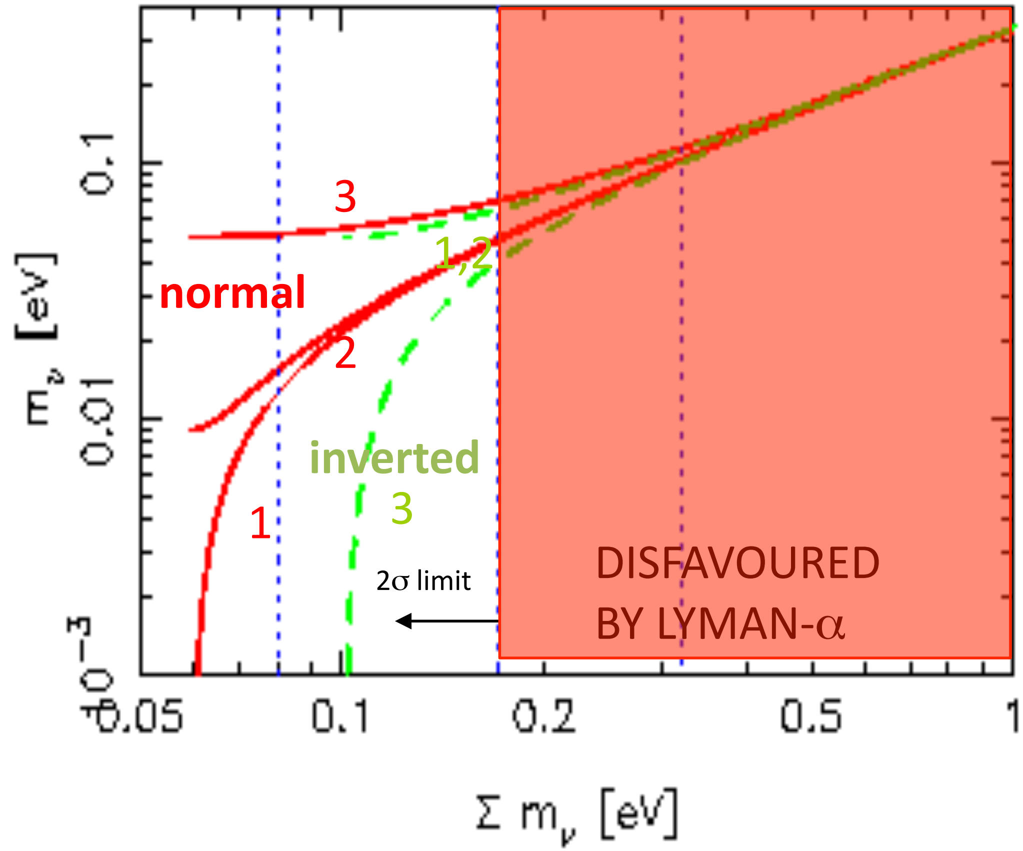


$$v_{th} \equiv \frac{\langle p \rangle}{m} \simeq \frac{3T_\nu}{m} = \frac{3T_\nu^0}{m}\left(\frac{a_0}{a}\right) \simeq 150(1+z)\left(\frac{1\,\text{eV}}{m}\right)\text{km}\,\text{s}^{-1}$$

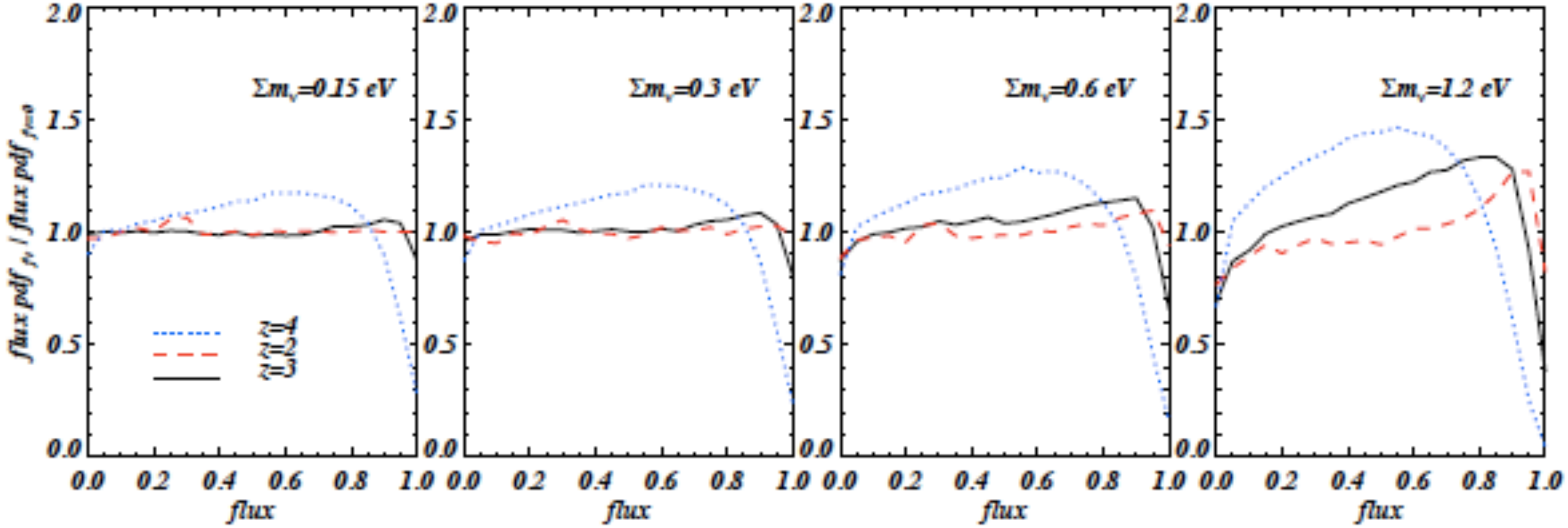
$$k_{FS}(t) = \left(\frac{4\pi G\bar{\rho}(t)a^2(t)}{v_{th}^2(t)}\right)^{1/2}, \qquad \lambda_{FS}(t) = 2\pi\frac{a(t)}{k_{FS}(t)} = 2\pi\sqrt{\frac{2}{3}}\frac{v_{th}(t)}{H(t)}$$

Neutrinos – II: constraints

Seljak, Slosar, McDonald, 2006, JCAP, 0610, 014



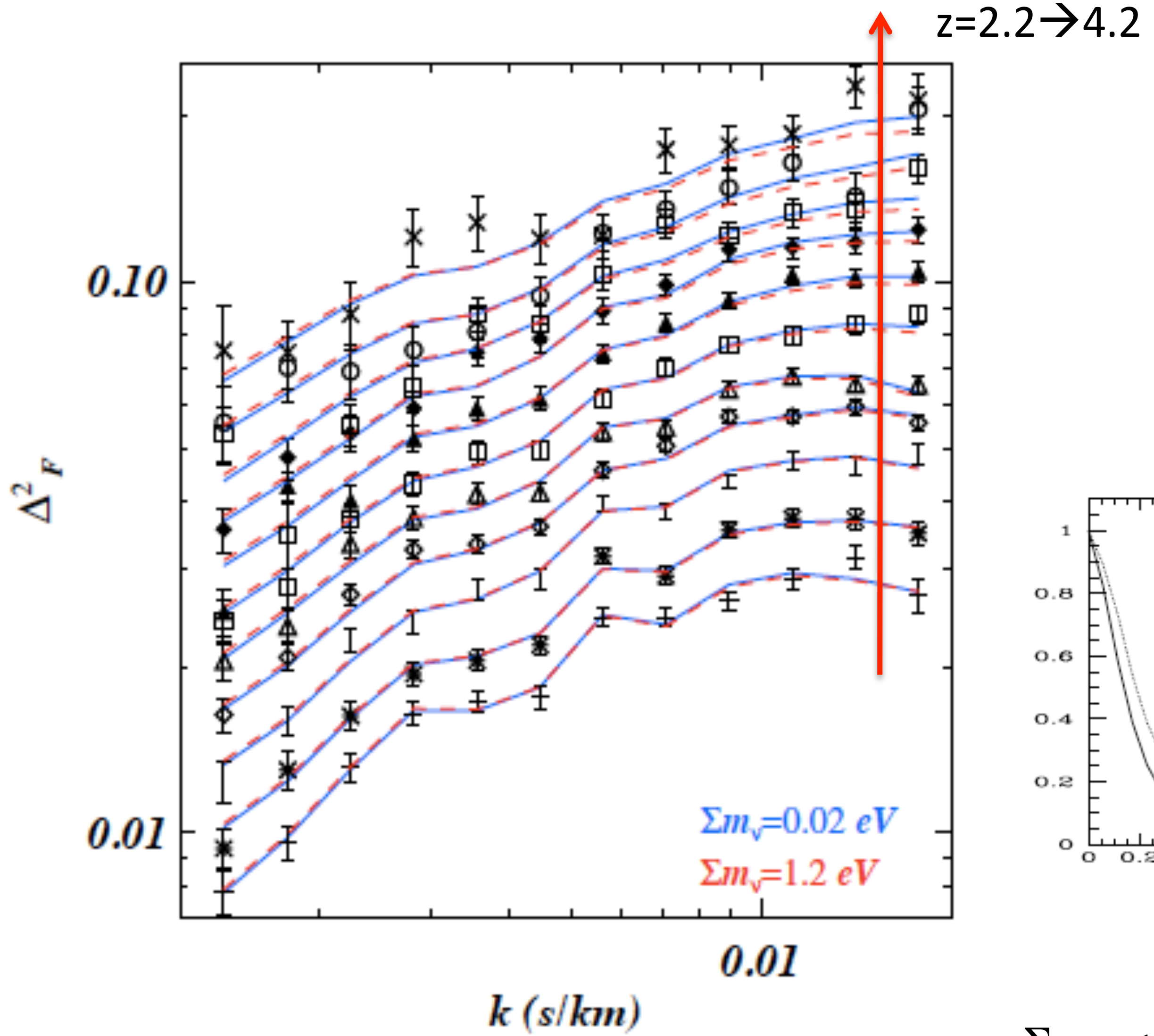
NEUTRINOS in the IGM – IV: impact on flux statistics



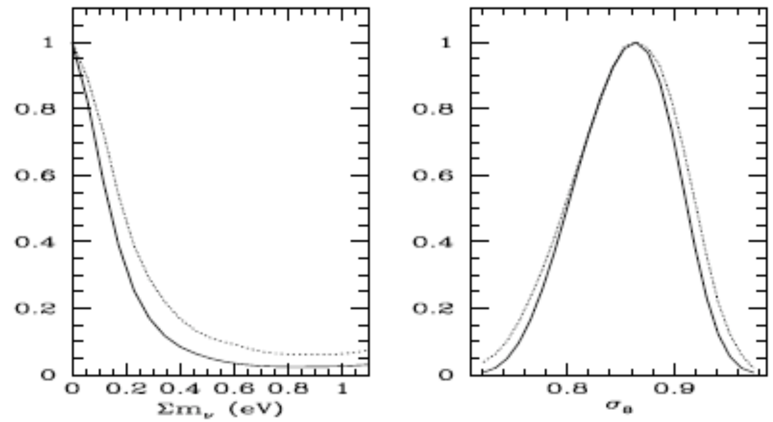
FLUX PDF

Increasing neutrino mass

NEUTRINOS in the IGM – IV: constraints from flux power



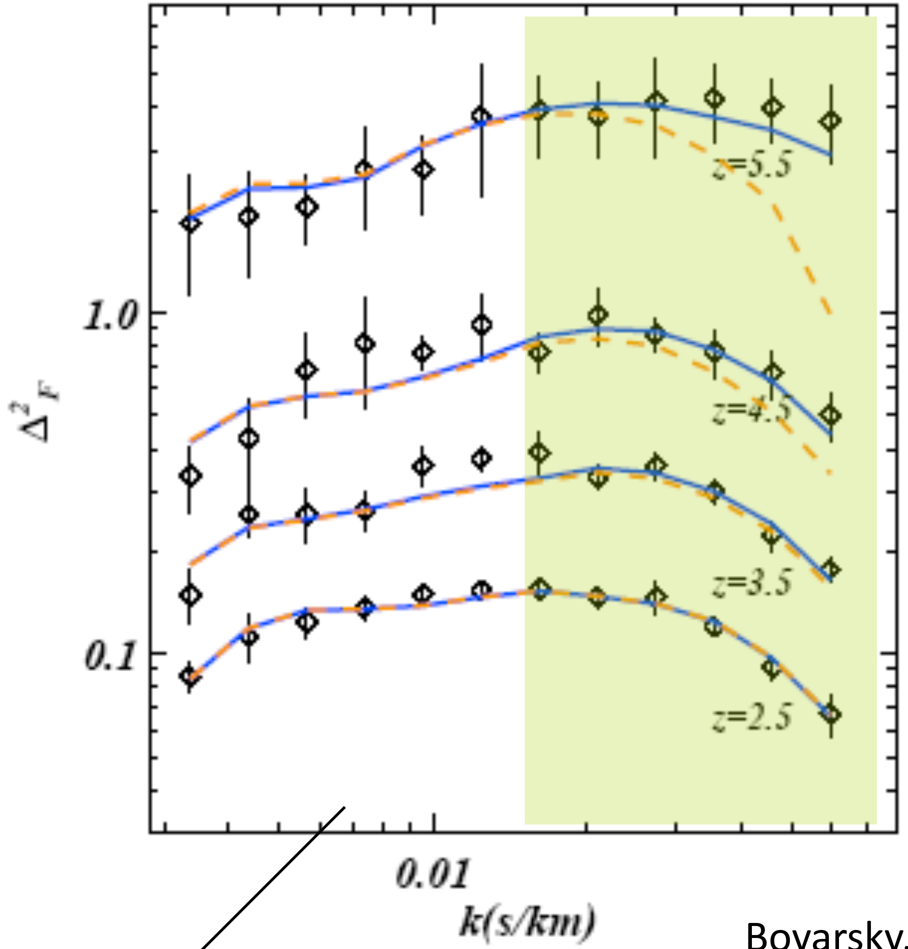
Impact on flux power is at the 5% level for ~ 1 eV



$\Sigma m_\nu < 0.9$ eV at the 2σ confidence level – SDSS alone

Warm Dark Matter and Lyman-α - I

SDSS + HIRES(Keck) Quasar spectra



SDSS range

MV et al., PRL 100 (2008) 041304

Tightest constraints on mass of WDM particles to date:

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

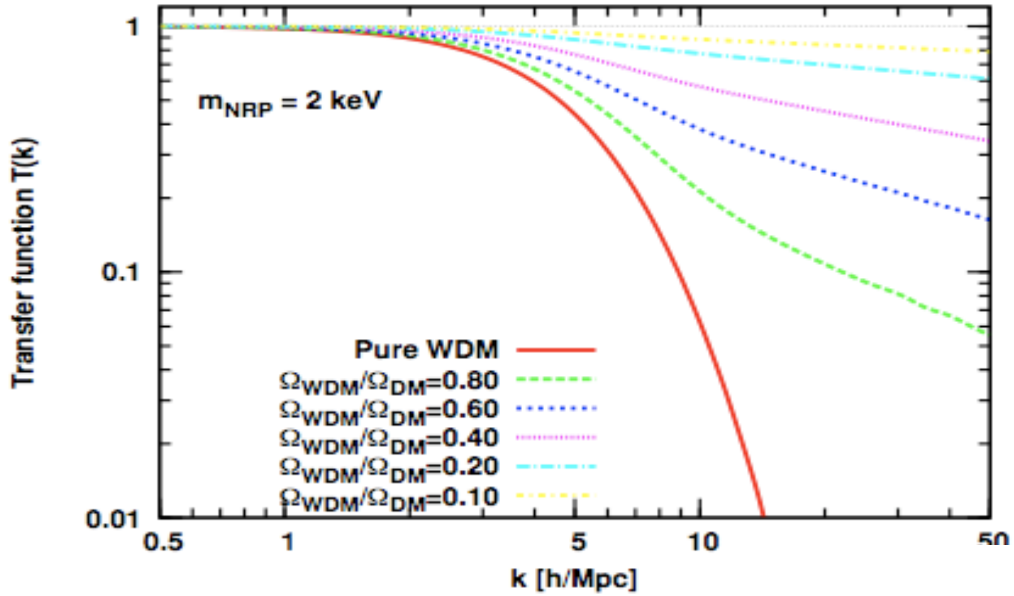
$m_{sterile}$ > 28 keV (standard scenario)

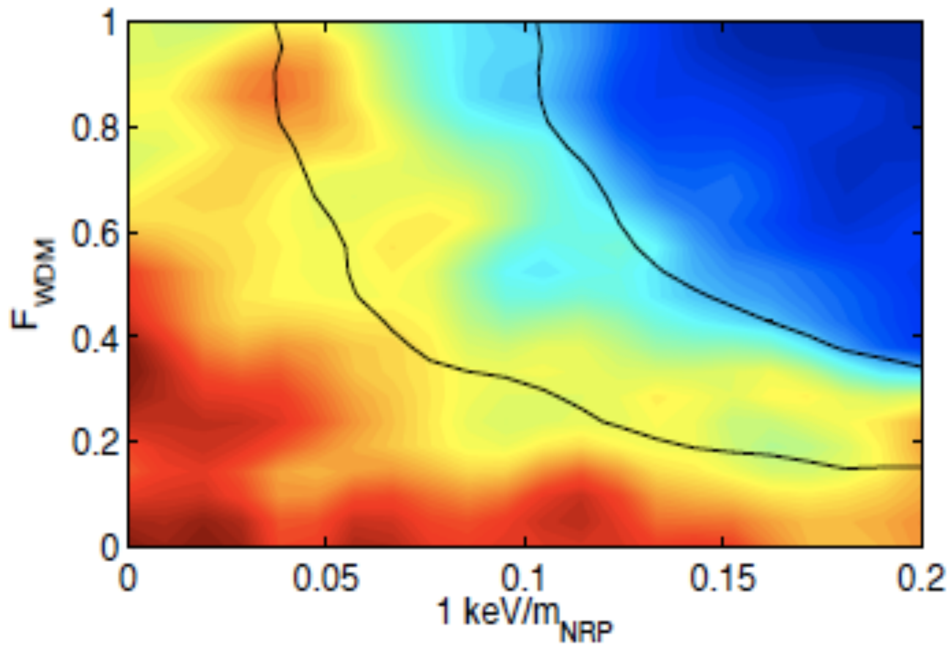
Note that this limit becomes much weaker (~**2 keV** in **RP mechanisms** or mixed cold+warm scenarios)

Boyarsky, Lesgourgues. Ruchayskiy, MV, 2009, PRL, 102,201304
Boyarsky, Lesgourgues, Ruchayskiy, MV, 2009, JCAP, 05, 012

MV, Lesgourgues, Haehnelt, Matarrese,
Riotto, PRD, 2005, 71, 063534 & PRL, 2006, 97, 071301

Lyman-α and sterile neutrinos - II

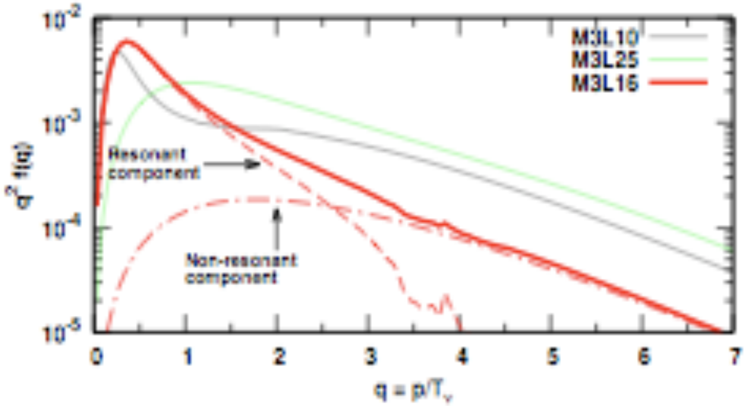


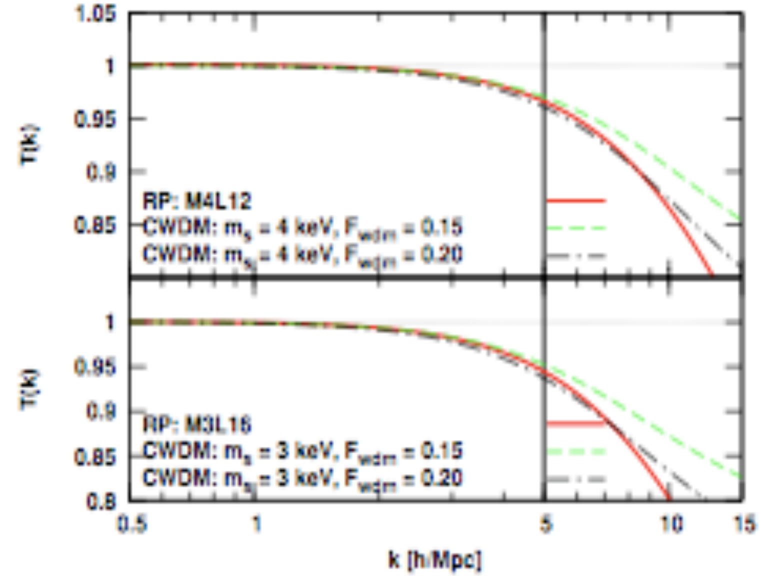


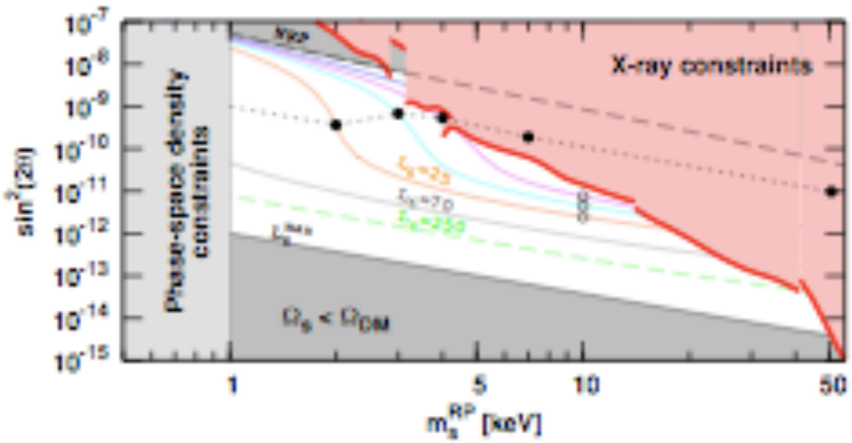
SDSS+WMAP5

Boyarsky, Lesgourgues, Ruchayskiy, Viel, 2009, JCAP, 05, 012– REVIEW!

Lyman-α and resonantly produced sterile neutrinos – III







Boyarsky, Lesgourgues. Ruchayski, Viel, 2009, PRL, 102, 201304

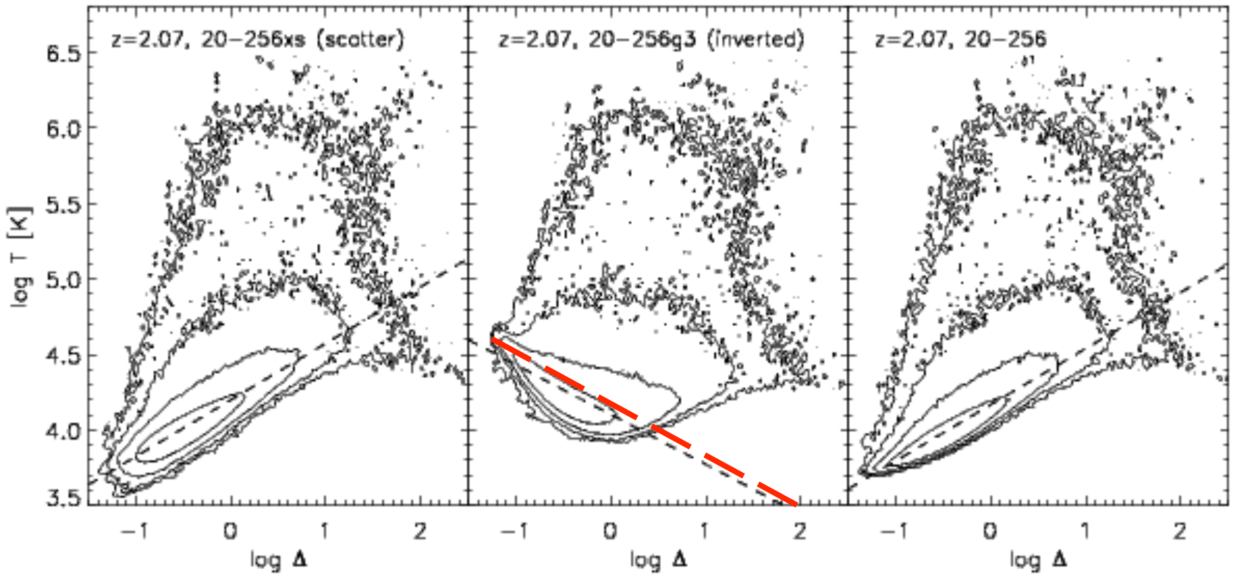
FLUX PDF

Fitting the flux probability distribution function-I

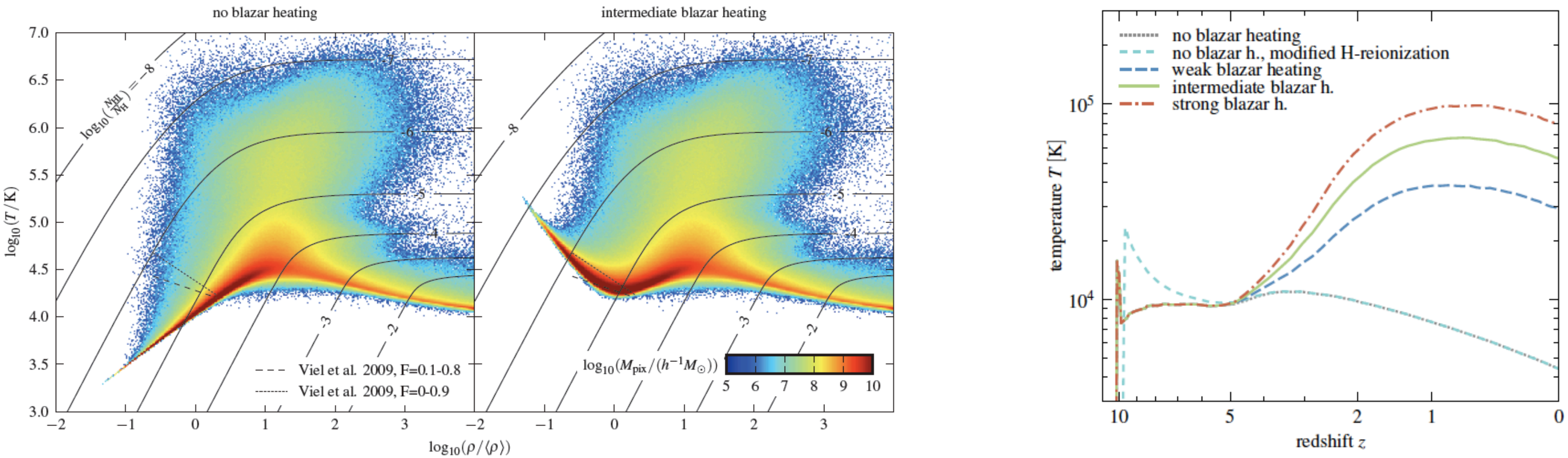
McDonald et al. 00, Desjacques et al. 04; Lidz et al. 06
Kim et al. 07; Bolton, MV, Kim, Haehnelt, Carswell (08); MV, Bolton et al. 09; McQuinn et al. 010

$T=T_0(1+\delta)^{\gamma-1}$

Inverted
equation of state
$\gamma<1$ means voids are
hotter than mean
density regions



Fitting the flux probability distribution function-II



Puchwein et al.

BAOs

Future perspectives : BAO

Importance of transverse direction:
MV et al 2002; White 2003;
McDonald & Eisenstein 2007;
Slosar et al. 2009

about 20 QSOs per square degree
with BOSS

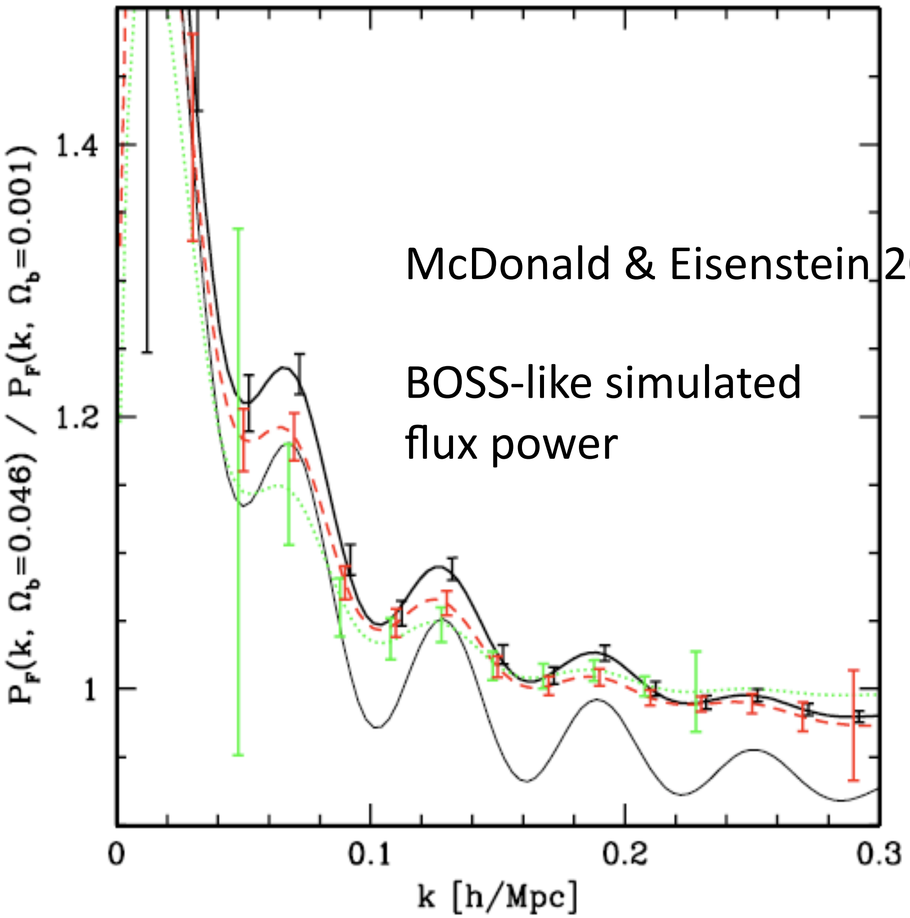
$$\psi_{\|}(k_{\|}|\mathbf{x}_{\perp}) \equiv \int \frac{d^2k_{\perp}}{(2\pi)^2} e^{i\mathbf{k}_{\perp}\cdot\mathbf{x}_{\perp}} \psi(k_{\|},\mathbf{k}_{\perp})$$

$$\langle \psi_{\|}(k_{\|}|\mathbf{x}_{\perp}) \psi_{\|}(k'_{\|}|\mathbf{x}_{\perp}+\mathbf{r}_{\perp}) \rangle = 2\pi \delta_D(k_{\|}+k'_{\|}) \pi(|k_{\|}||r_{\perp})$$

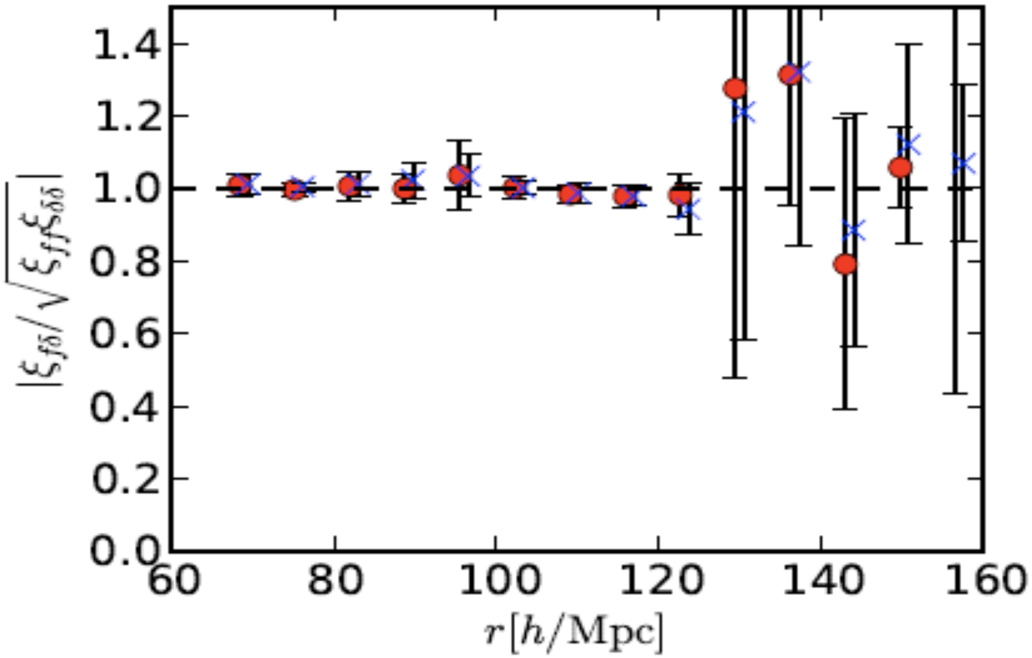
$$\pi(k|r_{\perp}) = \frac{1}{2\pi}\int_k^{\infty} dq q J_0(r_{\perp}\sqrt{q^2-k^2}) P(q)$$

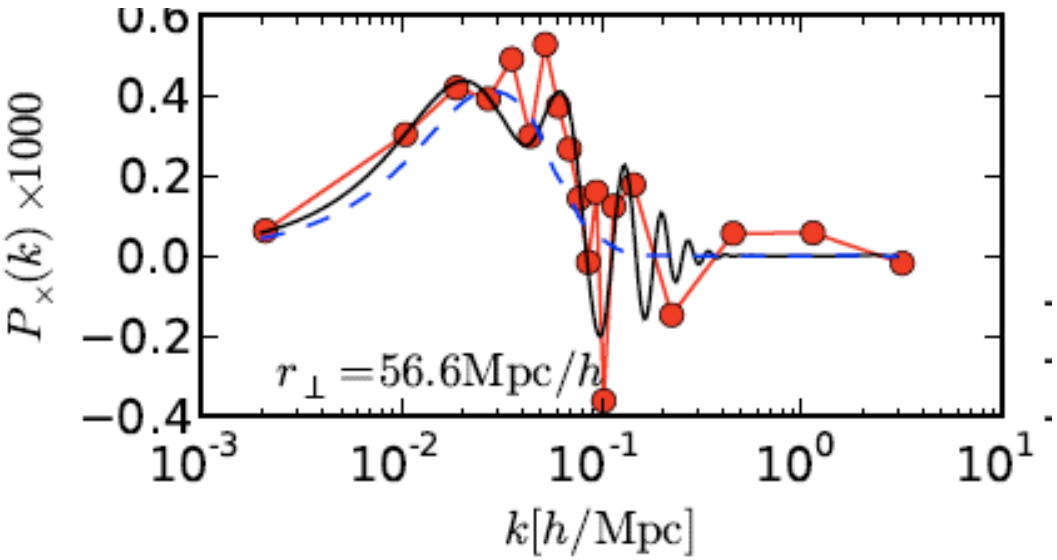
$$p(k) \equiv \pi(k|r_{\perp}=0) = \frac{1}{2\pi}\int_k^{\infty} dq q P(q)$$

$$P(k) = 2\pi \int_0^{\infty} dr_{\perp} r_{\perp} J_0(r_{\perp}\sqrt{k^2-q^2})\, \pi(q|r_{\perp})$$



BAOs in the Lyman-a forest: probing the transverse direction

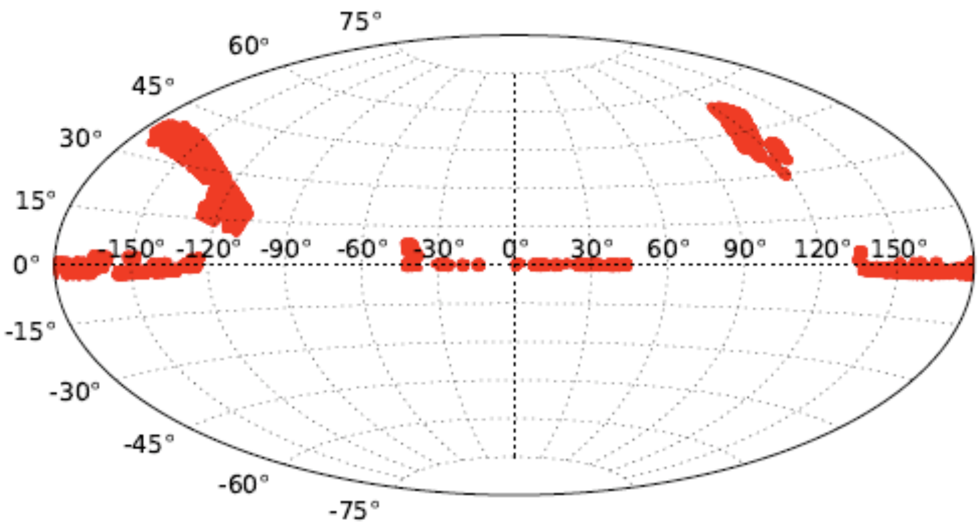




Importance of transverse direction:
MV et al 2002; White 2003;
McDonald & Eisenstein 2007;
Slosar et al. 2010

about 20 QSOs per square degree
with BOSS

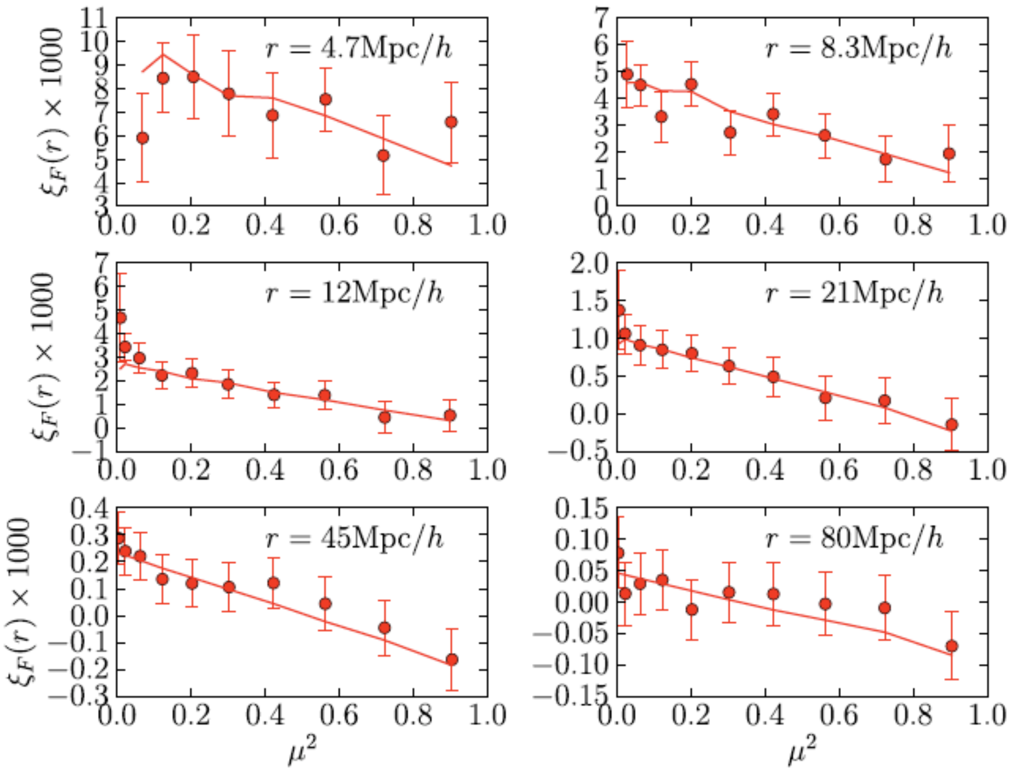
3D Correlations in BOSS 1yr data!



Slosar et al. 2011

$$P_F(k, \mu_k) = b^2 P_L(k)(1 + \beta \mu_k^2)^2$$

Estimates of b and β performed



COSMIC EXPANSION

Measuring the cosmic expansion?

$$1 + z(t_0, t_e) = \frac{a(t_0)}{a(t_e)} = \frac{a_0}{a}$$

$$dz = \frac{\partial z}{\partial t_0} dt_0 + \frac{\partial z}{\partial t_e} dt_e$$

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 136 SEPTEMBER 1962 NUMBER 2

THE CHANGE OF REDSHIFT AND APPARENT LUMINOSITY OF GALAXIES DUE TO THE DECELERATION OF SELECTED EXPANDING UNIVERSES

ALLAN SANDAGE

Mount Wilson and Palomar Observatories

Carnegie Institution of Washington, California Institute of Technology

(With an Appendix by G. C. McVittie, University of Illinois Observatory, Urbana)

Received February 2, 1962; revised April 13, 1962

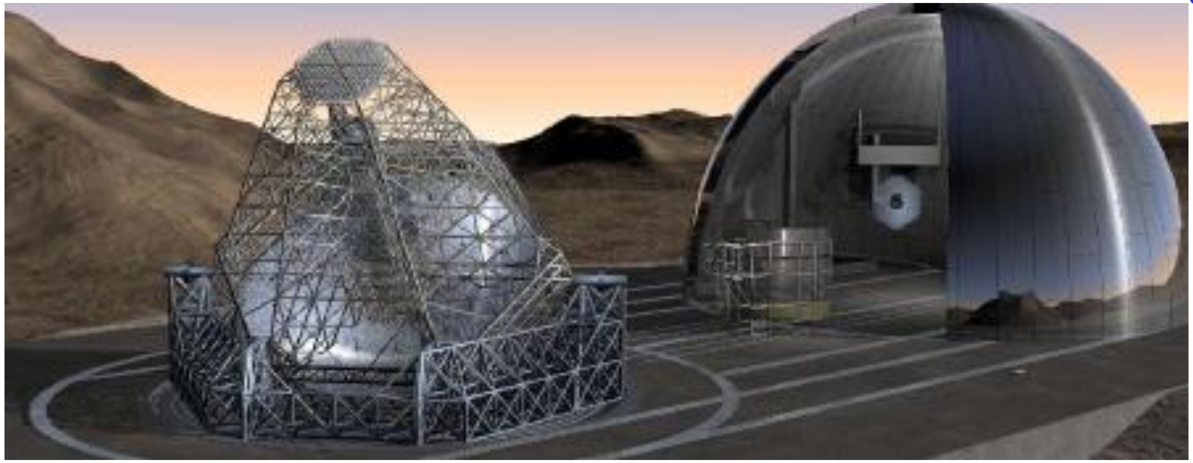
$$\dot{z} = \frac{dz}{dt_0} = \frac{\partial z}{\partial t_0} + \frac{\partial z}{\partial t_e}\frac{dt_e}{dt_0} = \frac{\dot{a}(t_0)}{a(t_e)} - \frac{\dot{a}(t_e)}{a(t_e)}\frac{a(t_0)}{a(t_e)}\frac{1}{1+z}$$

$$\dot{z} = (1 + z)H_0 - H(t_e)$$

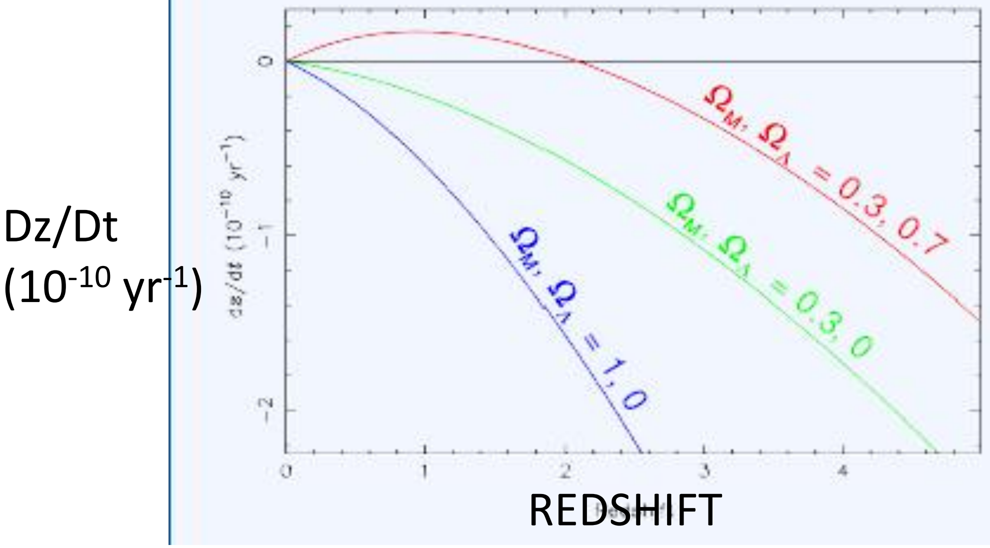
This is a fundamental quantity not related at all to the FRW equations….

COsmicDynamicEXperiment CODEX-I

Ultra-stable spectrograph



$$\frac{d}{dt_0}\left[1+z = \frac{a(t_0)}{a(t_e)}\right] \Rightarrow \frac{dz}{dt_0} = (1+z)\,H_0 - H(z)$$



ig. 1: dz/dt as a function of redshift for different cosmological parameters as indicated and $H_0 = 70$ km/s/Mpc.

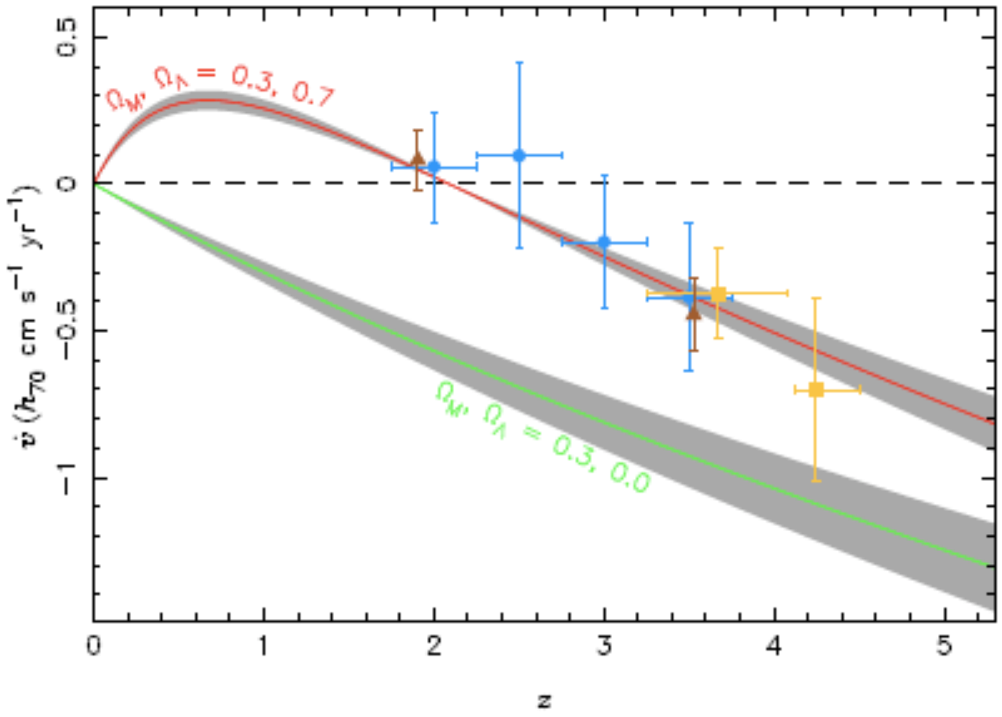
For $\Delta t = 10$ yr @ $z = 4$:

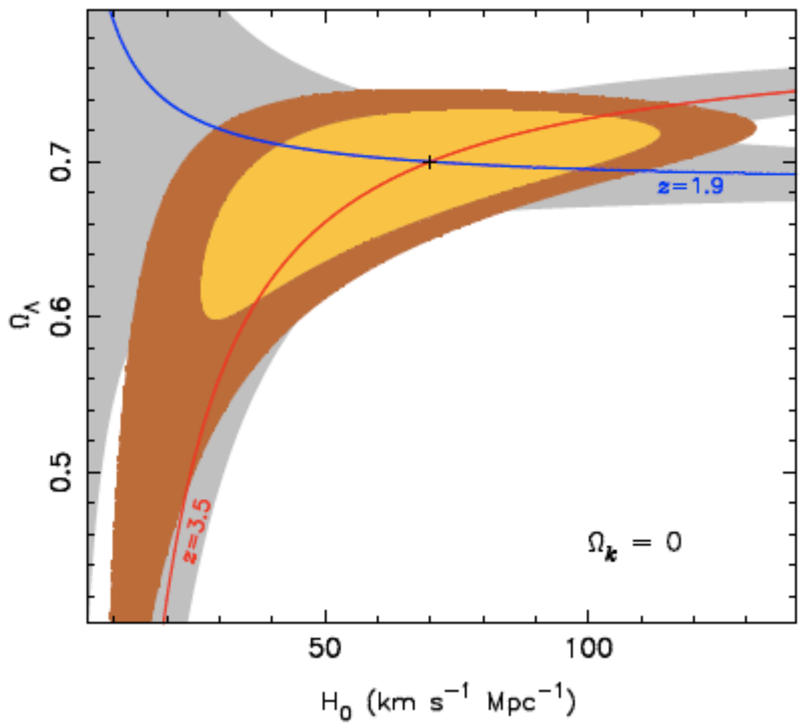
$\Delta z \sim 9 \times 10^{-10}$

$\Delta\lambda \sim 1 \times 10^{-6}$ Å

$\Delta v \sim 5.4$ cm/s

COsmicDynamicEXperiment CODEX - II

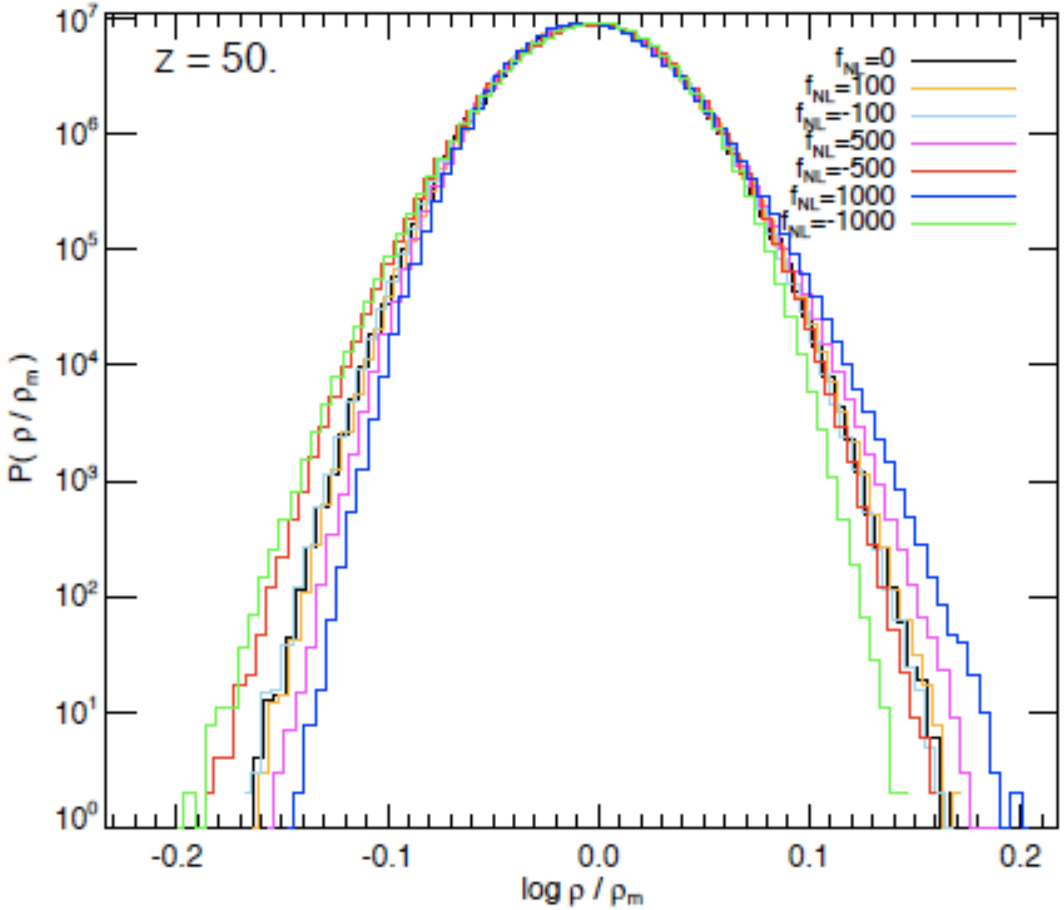




Liske et al. 2008, MNRAS, 386, 1192

NGs and CDE

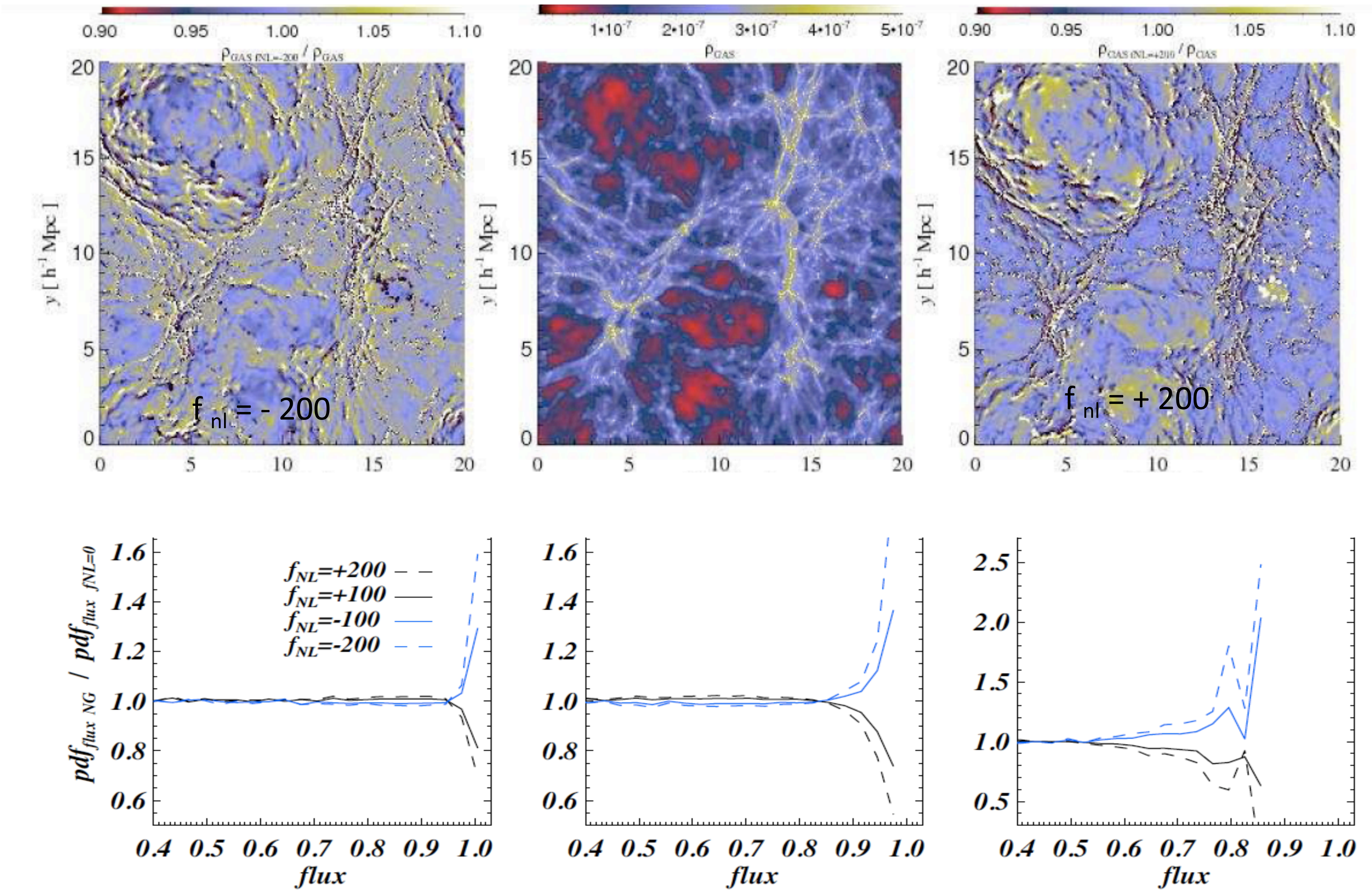
N-body simulation in NG scenario: the mass distribution



$$\Phi_{\rm NL} = f_{\rm NL}\left(\Phi_{\rm L}^2 - \langle \Phi_{\rm L}^2 \rangle\right)$$

Mathis et al. 04
Kang et al. 07
Grossi et al. 07,09
Hikage et al. 08
Desjacques et al. 08
Dalal et al. 08
Wagner et al. 10,11
Nishimichi et al. 10
etc........

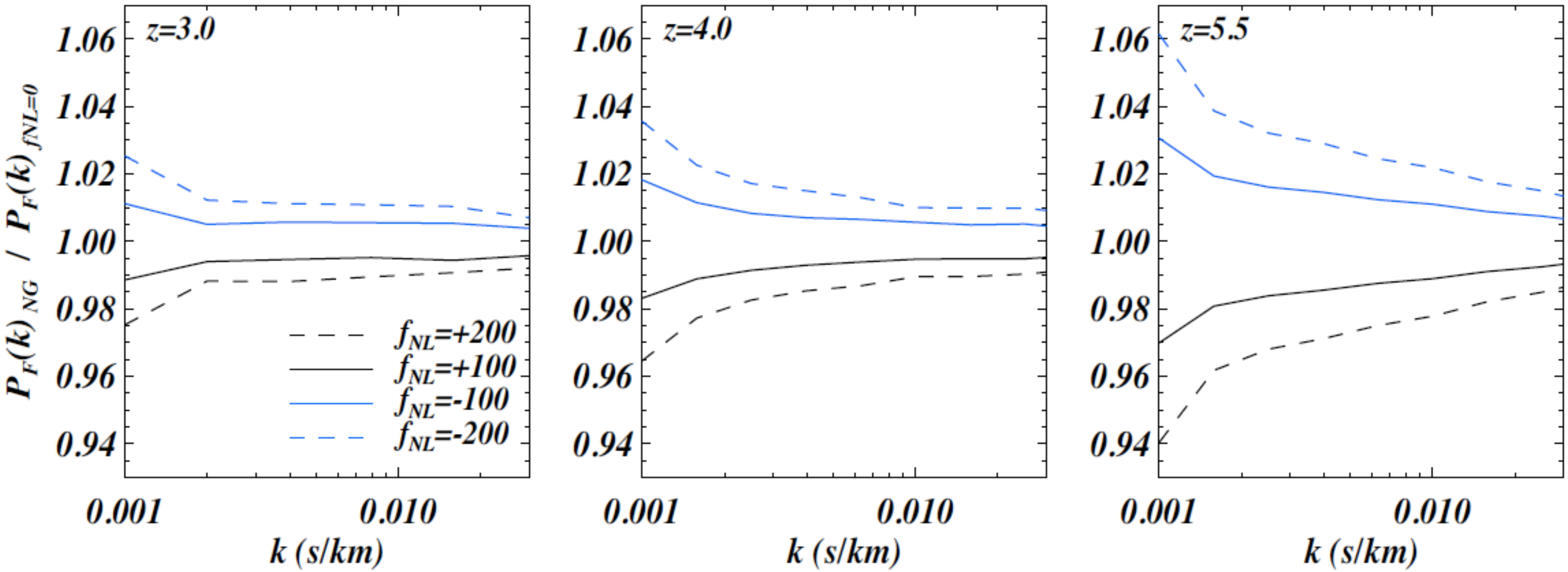
First hydrodynamical simulation in NG scenario



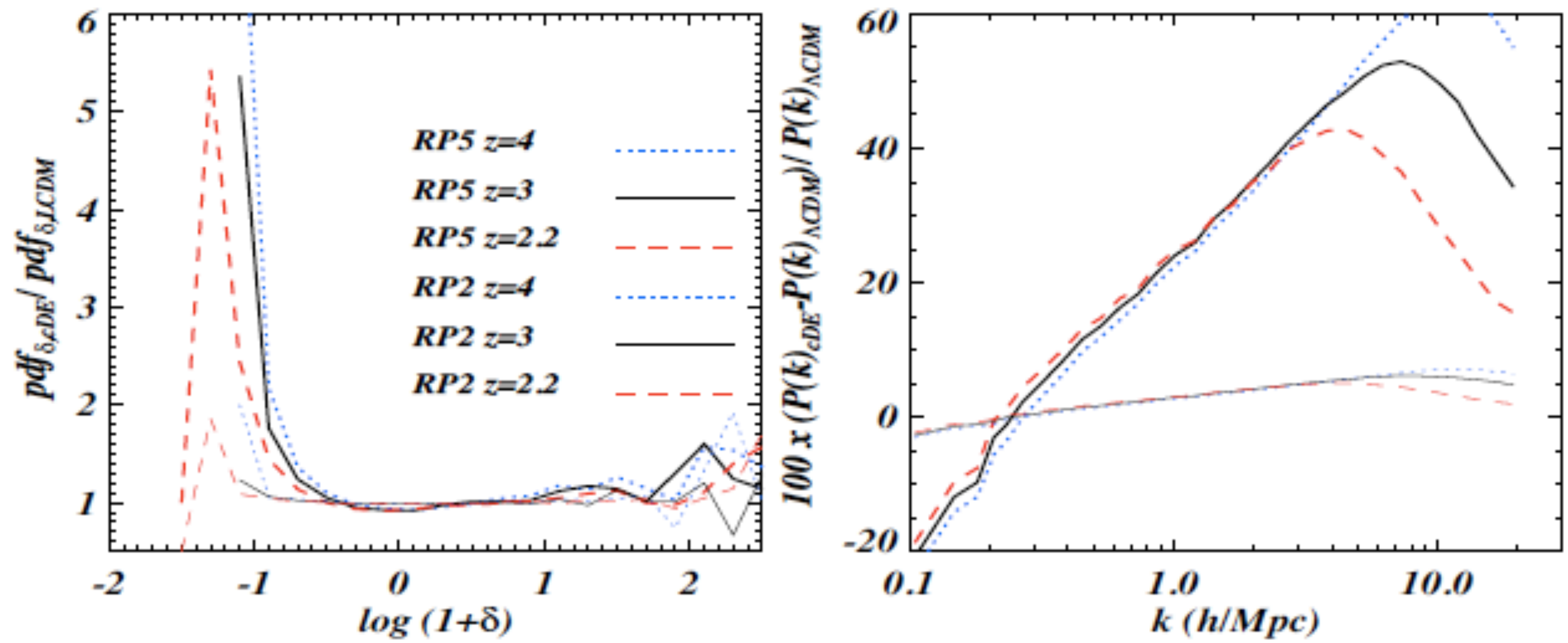
Viel, Branchini, Dolag, Grossi, Matarrese, Moscardini 2009, MNRAS, 393, 774

First hydrodynamical simulation in NG scenario: flux bispectrum

Local squeezed configuration $k_1 << k_2 \sim k_3$

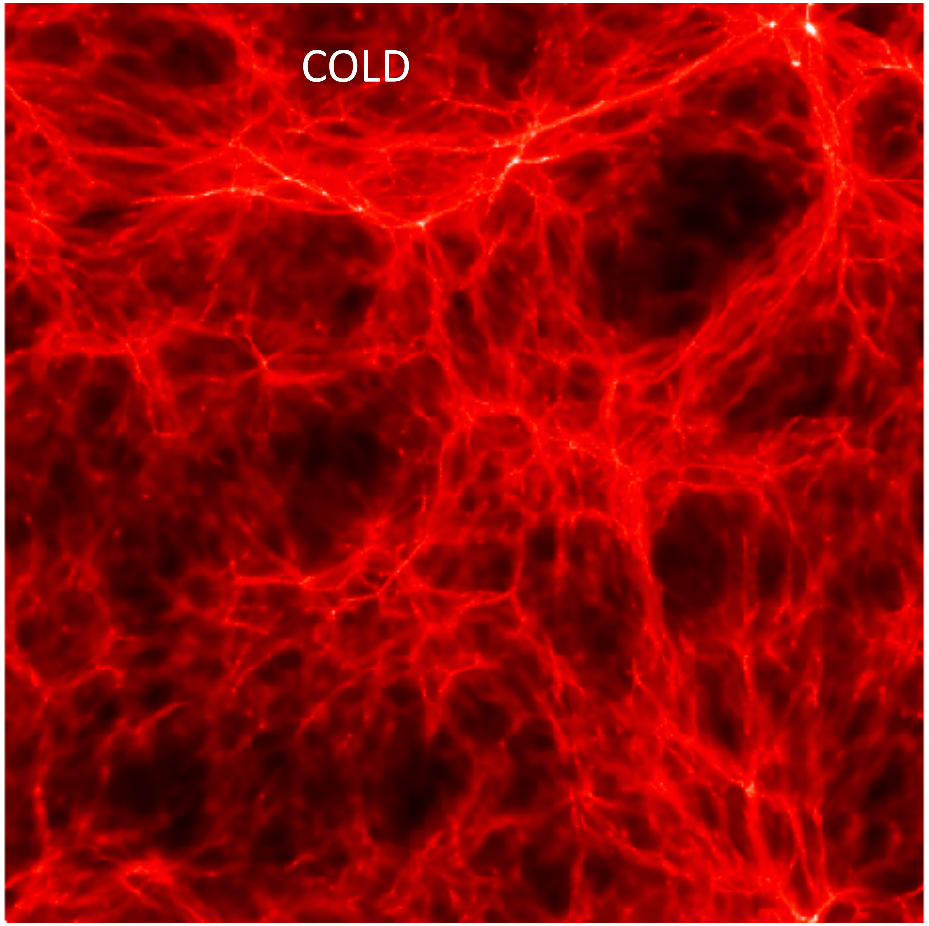


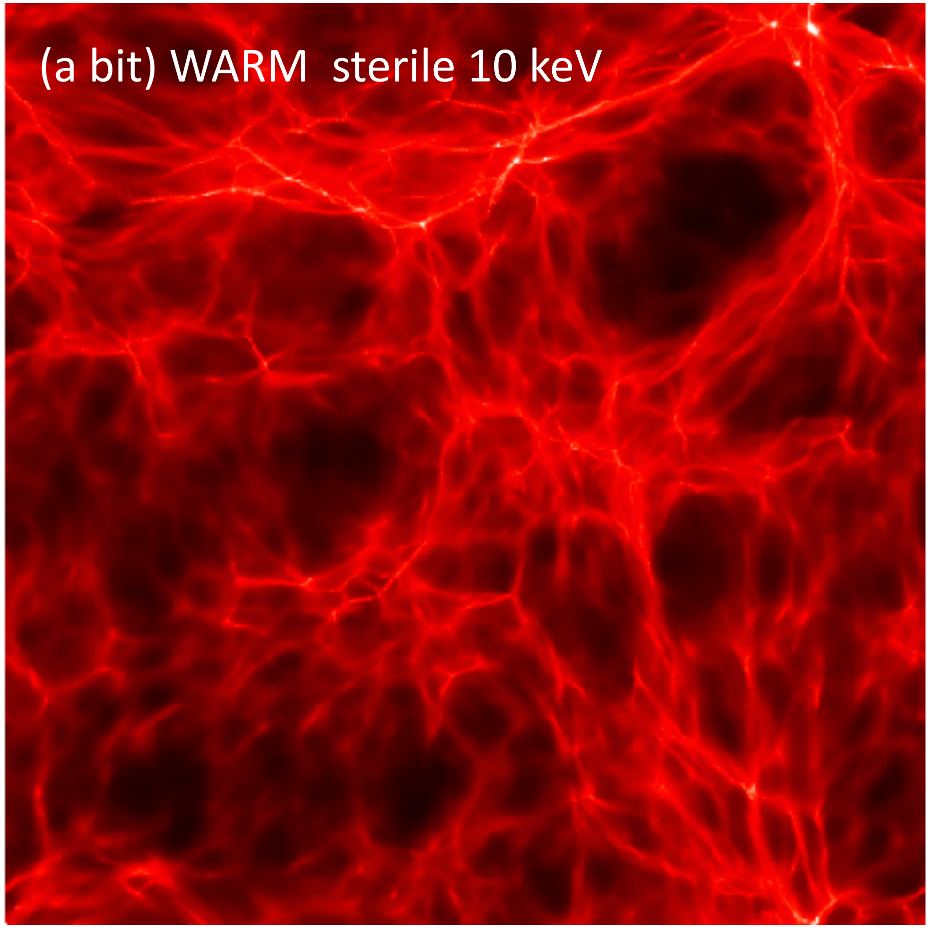
First hydrodynamical simulation in cDE scenario



Baldi & Viel 2010, MNRAS Lett, 409, 89 (cDE)

Little room for warm dark matter…… at least in the standard DW scenario
…the cosmic web is likely to be quite "cold"



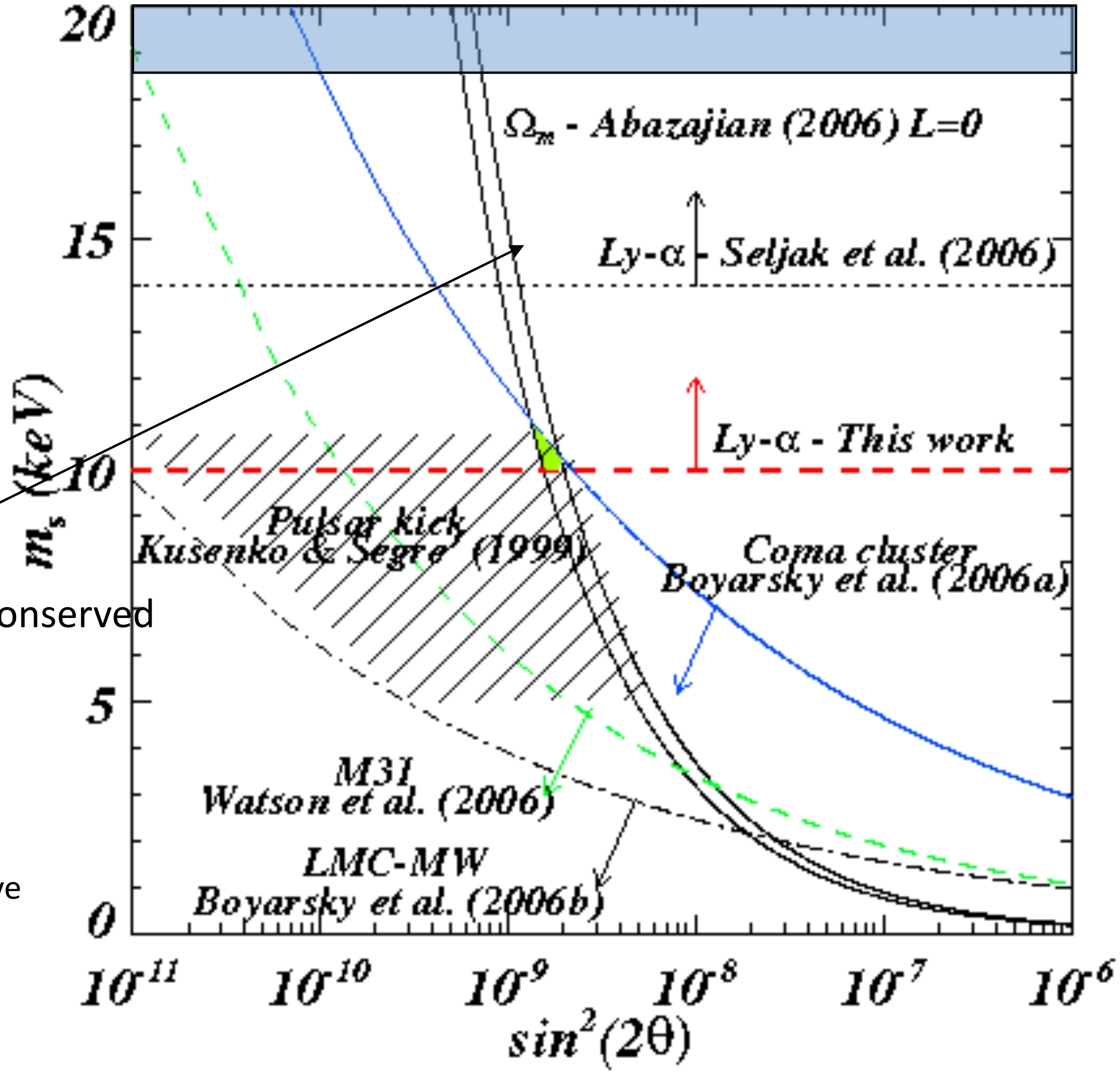


To constrain the sterile neutrino particle we need two parameters:

1) Neutrino mass $\mathbf{m_s}$

2) Mixing angle θ that describes the interaction between active and sterile neutrino families

Lyα-WDM VII: analysis with flux derivatives



$L_\nu = 0$

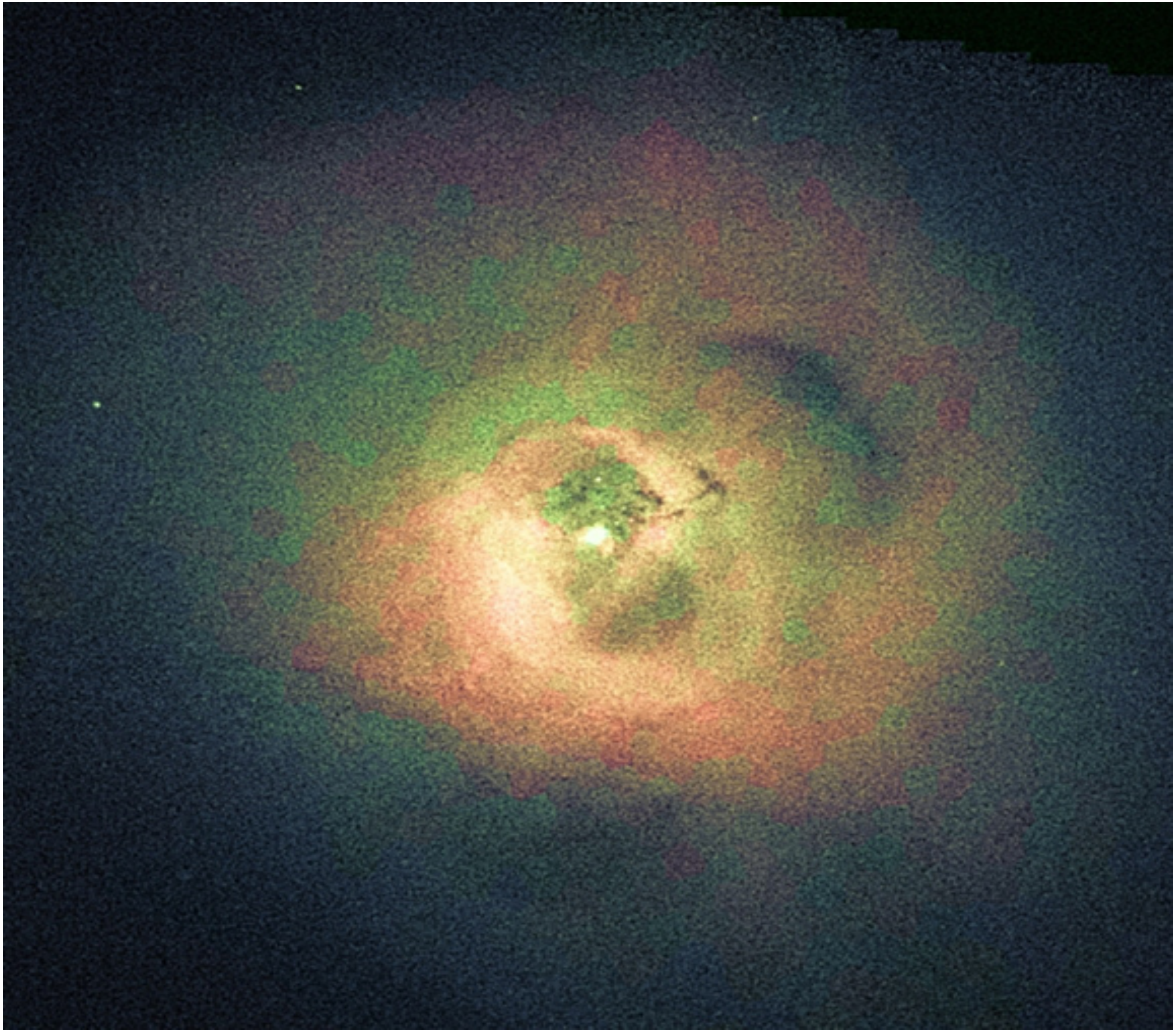
Leptonic number is conserved

Radiative decay channel at a
Rate that depends on its mass
And the mixing angle with active
Neutrinos

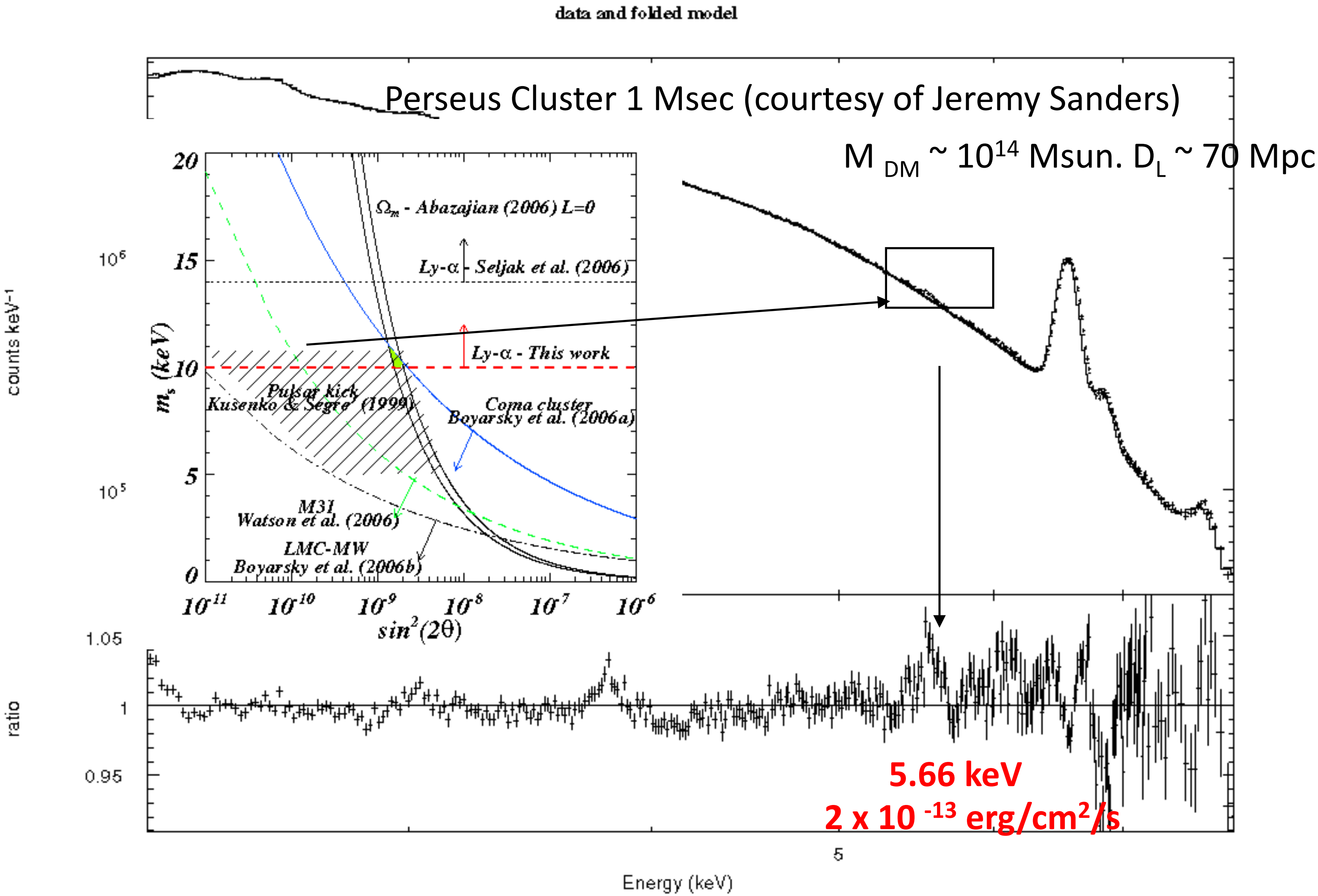
$\Gamma \sim \sin^2 2\theta \, m_{sterile}^5$

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, Phys.Rev.Lett., 2006, 97, 071301

Fabian, Sanders and coworkers…..



Decaying channel into photons and active neutrinos line with $E=m_s/2$ (X-band)



Line flux ~ 5×10^{-18} erg cm $^{-2}$ s $^{-1}$ $(D_L/1\mathrm{Mpc})^{-2}$ $(M_{DM}/10^{11} M_{sun})$ $(\sin^2 2\theta/10^{-10})$ $(m_s/1\mathrm{kev})^5$

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XMM-Newton reveals the origin of elements in galaxy clusters

10 May 2006

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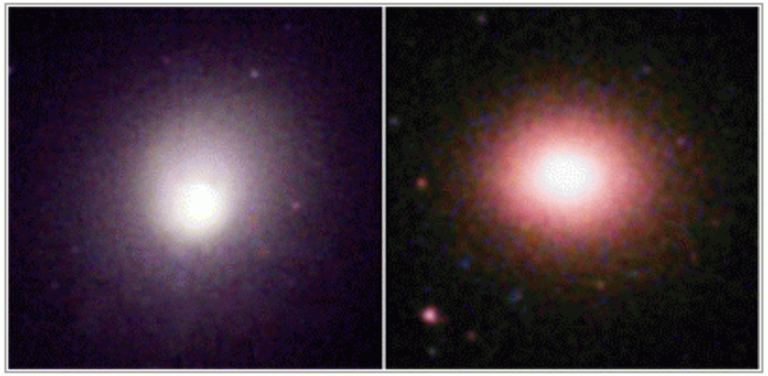

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These X-ray images of the clusters of galaxies 'Sersic 159-03' (right) and '2A 0335+096' (left) were taken by the European Photon Imaging Camera (EPIC) on-board ESA's XMM-Newton, in November 2002 and August 2003 respectively. Thanks to these observations, astronomers could determine the abundances of nine chemical elements in the clusters 'plasma' – a gas containing charged particles such as ions and electrons. These elements include oxygen, iron, neon, magnesium, silicon, argon, calcium, nickel, and - detected for the first time ever in a galaxy cluster - chromium. The distribution of silicon (produced by 'type Ia' and 'core collapse' supernova types) relative to iron (mainly produced by 'type Ia' supernovae) in these two clusters is very different, showing that they had a different evolution.

Credits: ESA and the XMM-Newton EPIC consortium

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- XMM-Newton overview

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5.66 keV !!!

CONCLUSIONS

- **Neutrinos** do impact on the LSS at a level which is very much constrained by present data sets. The effect is small and **systematic effects** should be addressed at an unprecedented level of precision. Modelling the power spectrum at the 1 % level at small scales is difficult: **relevant physical processes and numerics** should be modelled and under control.

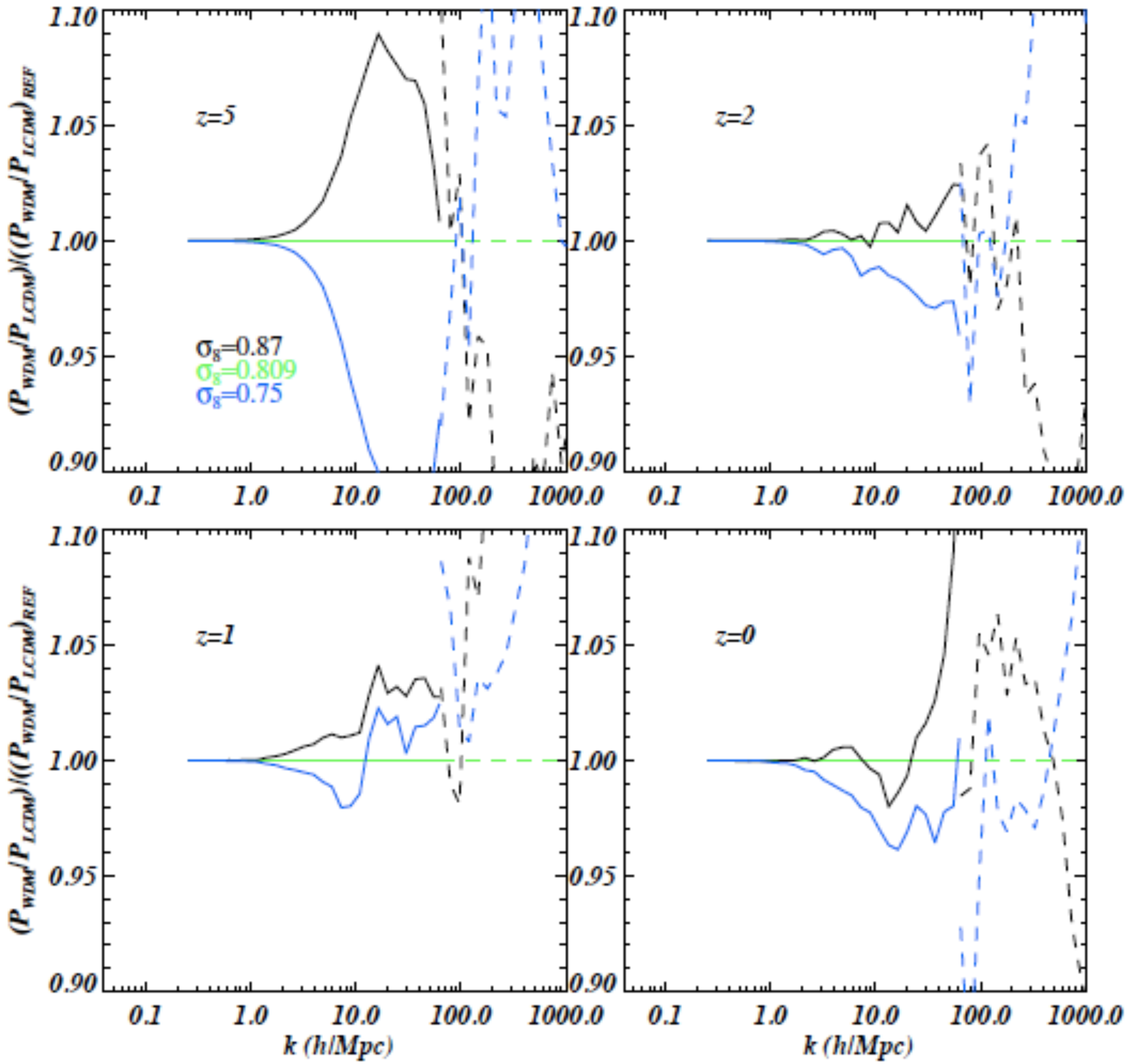
- Important role of the **IGM**, which is currently providing the tightest constraints on the mass (0.17 eV – 2σ upper limit); **weak lensing** and **galaxy redshift surveys** are likely to provide interesting results.

- **Coldness of cold dark matter** at small scales is a fundamental observable since possible deviations from the standard model can be measured or a candidate can show up. At present the constraints on the **sterile neutrinos** are tight (especially thanks to IGM data – but see also constraints from dwarf galaxies).

- **Flux PDF** statistics difficult to fit. Very sensitive to thermal state and systematics.

BACKUP SLIDES

WDM and non-linear power –III: amplitude of matter power



Little room for warm dark matter…… at least in the standard DW scenario
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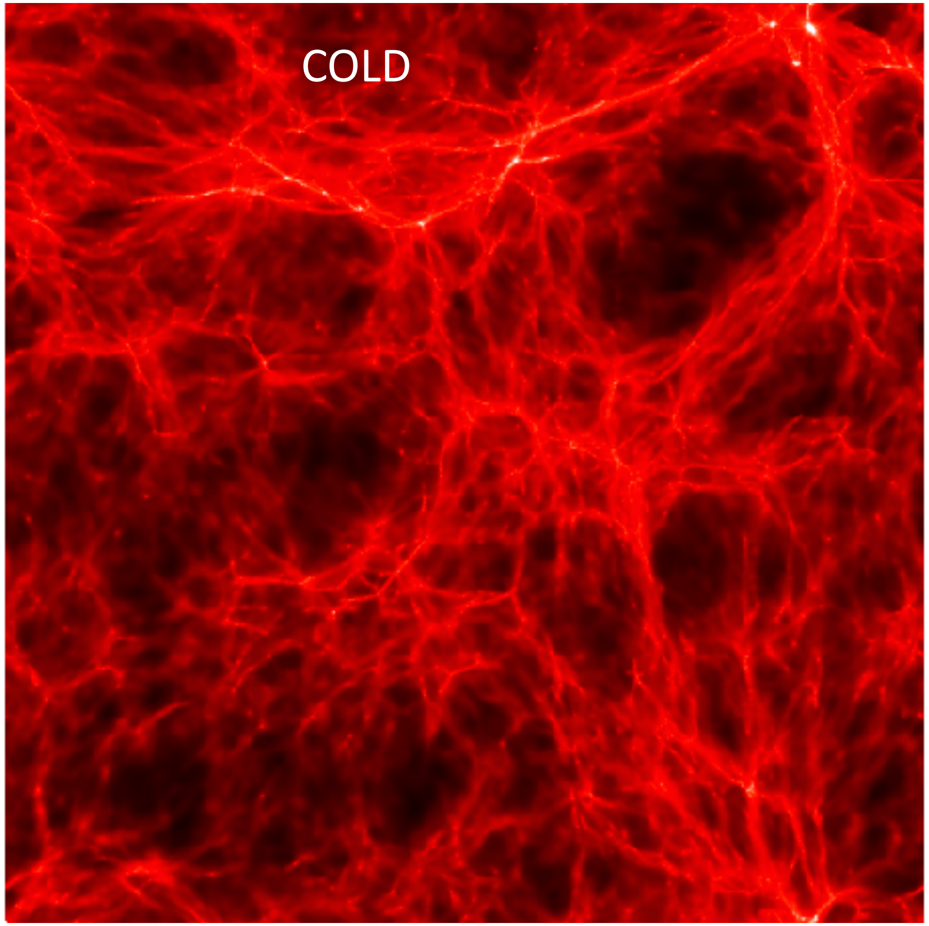
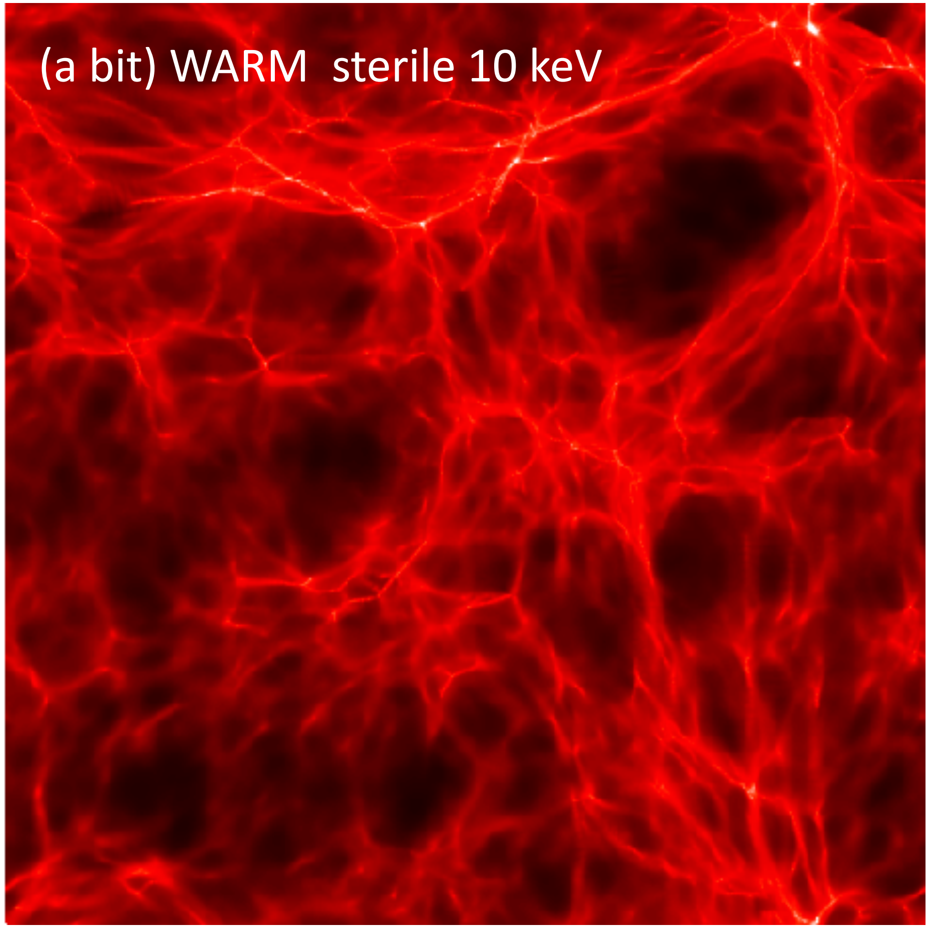
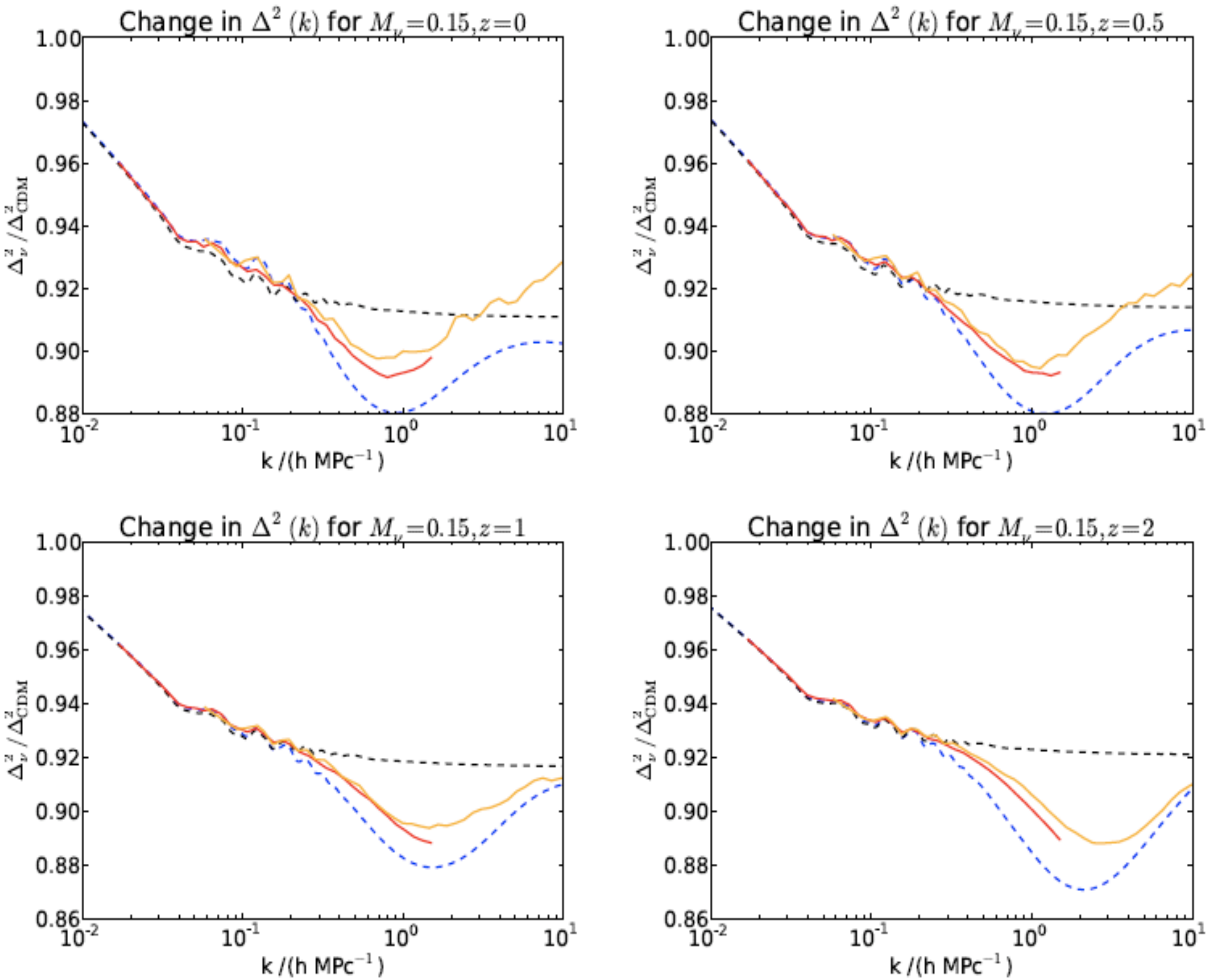




Hydro simulations – XII: very non-linear regime



Bird, MV, Haehnelt 11 (in prep.)

The interpretation: flux derivatives

Analysis of SDSS flux power

The flux power spectrum is a smooth function of k and z

Flux power

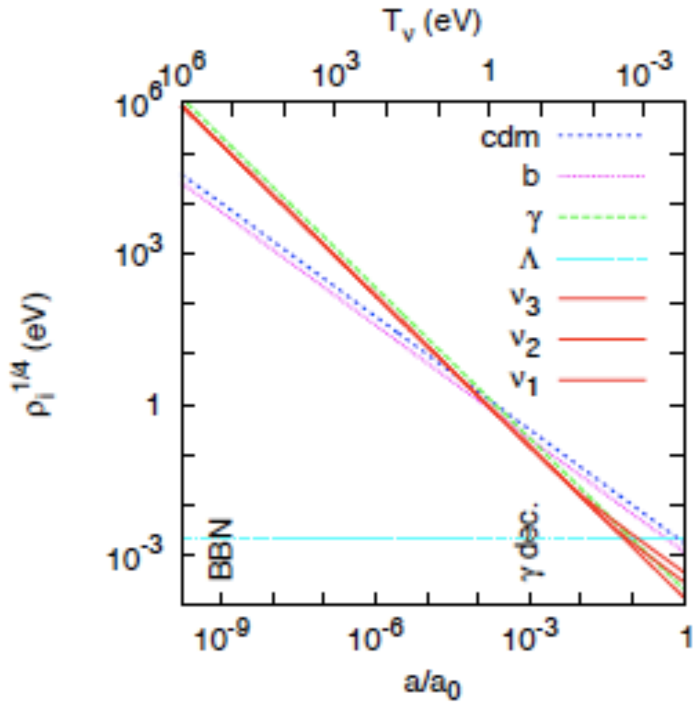
$$P_F(k, z; \mathbf{p}) = P_F(k, z; \mathbf{p}^0) + \sum_{i=1,N} \left. \frac{\partial P_F(k, z; p_i)}{\partial p_i} \right|_{\mathbf{p}=\mathbf{p}^0} (p_i - p_i^0)$$

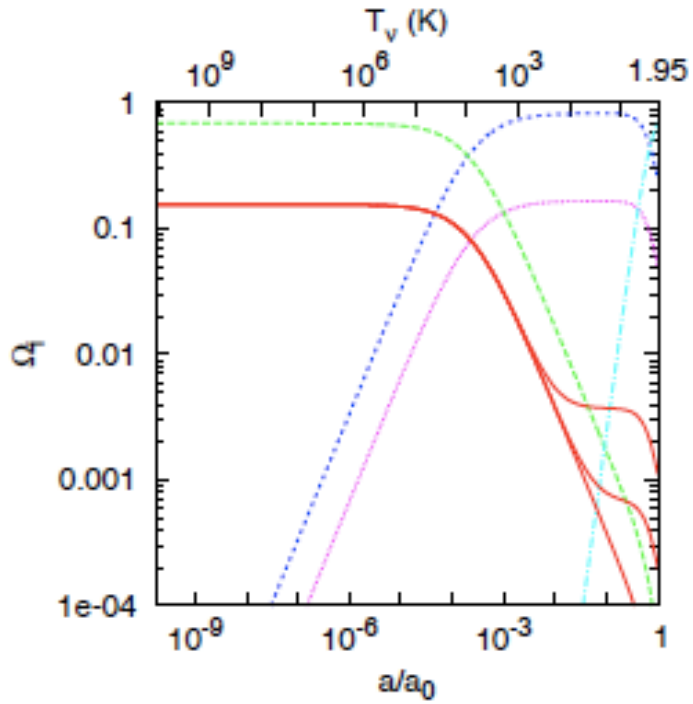
Best fit

p: astrophysical and cosmological parameters

but even resolution and/or box size effects if you want to save CPU time

EVOLUTION of LSS – III : background evolution





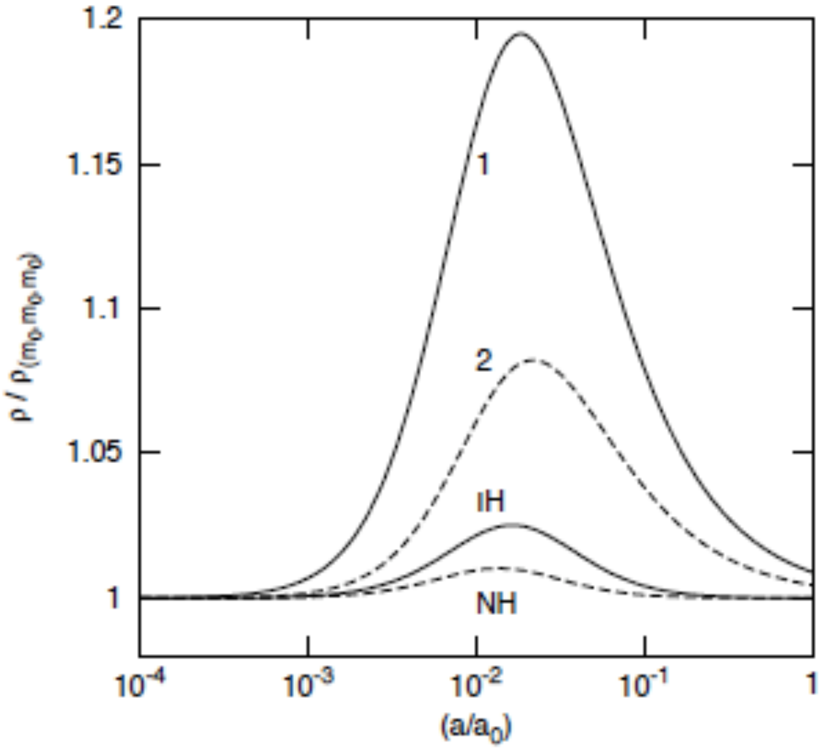
$$H(a) = H_0 \left[\frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2} + \frac{\Omega_\Lambda}{a^{3(1+w_{\rm eff}(a))}} \right]^{1/2}$$

$$\Omega_r = \Omega_\gamma \left(1 + 0.2271 N_{\rm eff}\right)$$

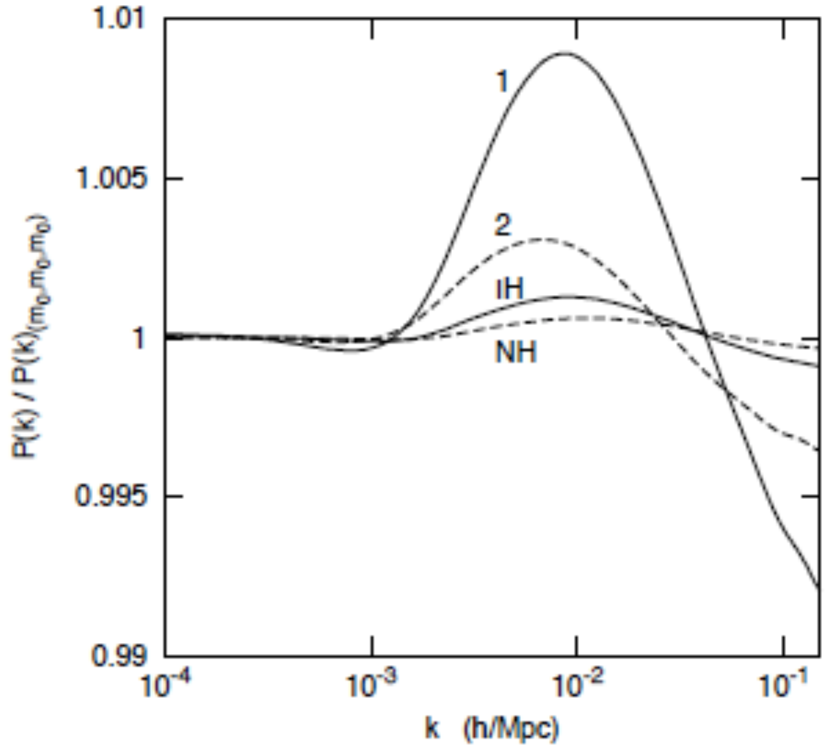
Note that the equation above is not exact
but it is a good approximation (e.g. Komatsu et al 11)

EVOLUTION of LSS - IV: individual neutrino masses do matter

Lesgourgues & Pastor 2006



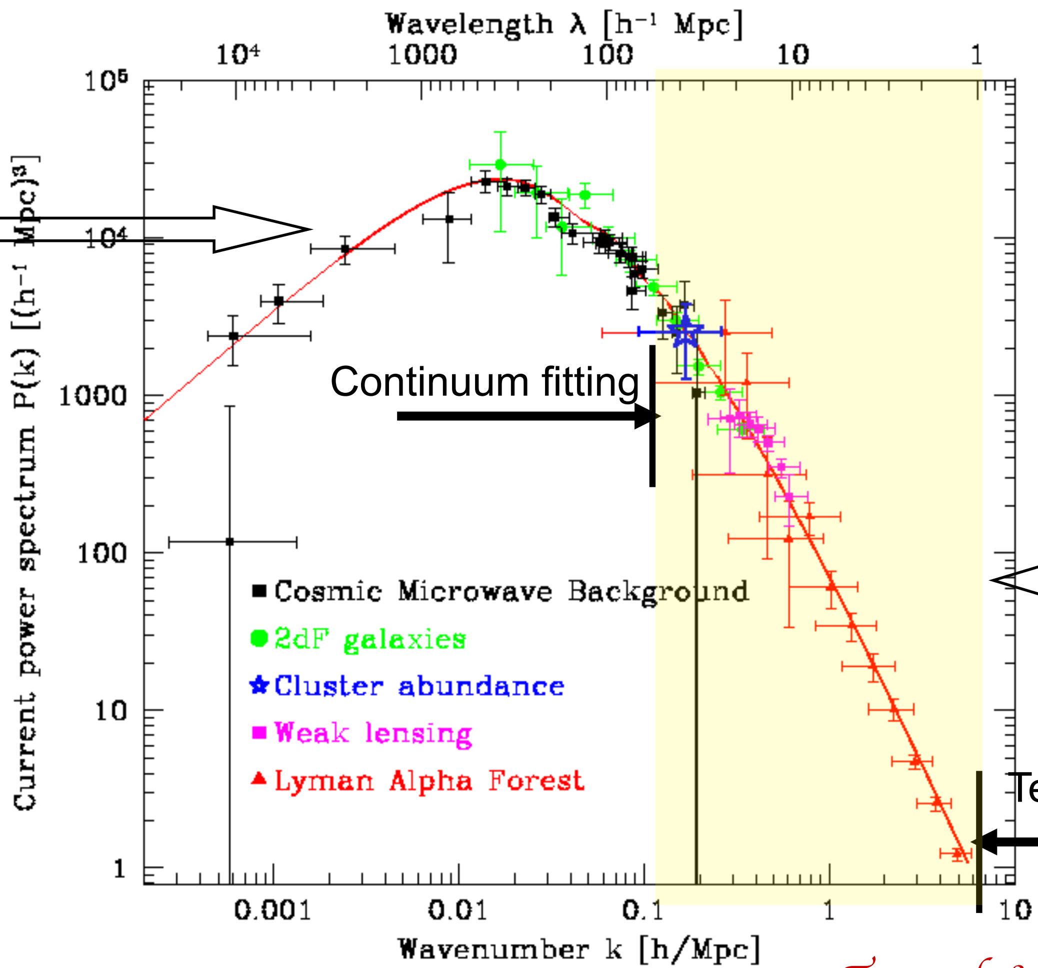
GEOMETRY



DYNAMICS

GOAL: the primordial dark matter power spectrum from the observed flux spectrum (filaments)

CMB physics
z = 1100
dynamics



Lya physics
z < 6
dynamics
+
termodynamics

Tegmark & Zaldarriaga 2002

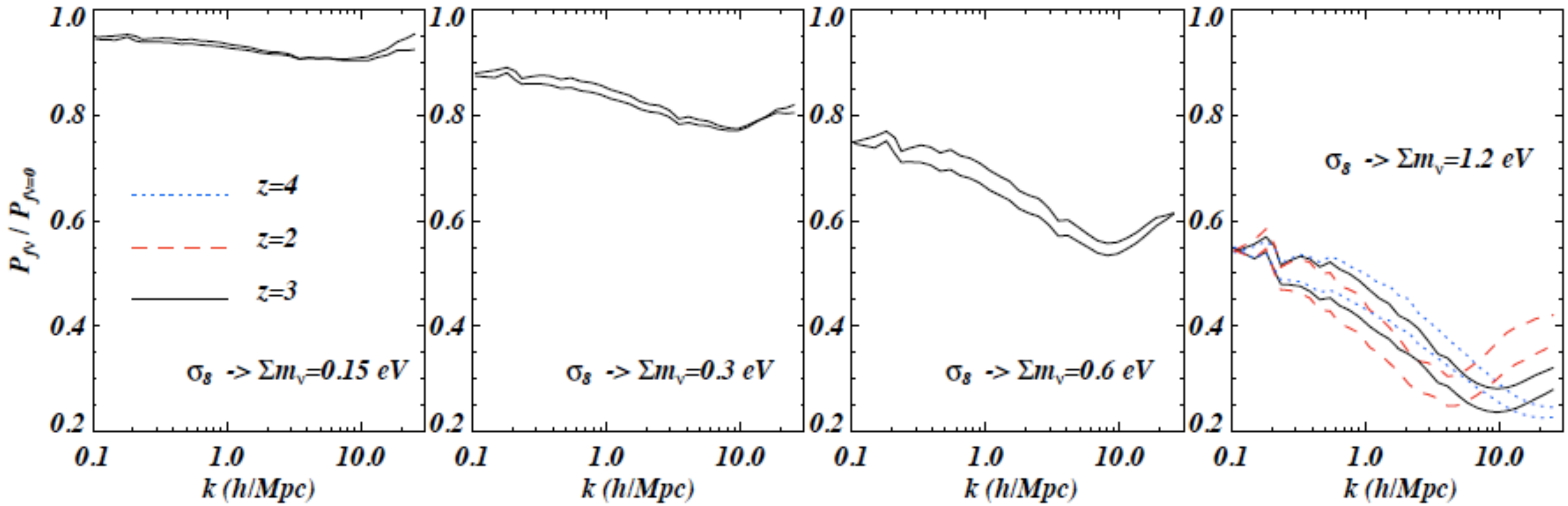
CMB + Lyman a ⇒ Long lever arm

Constrain spectral index and shape

Relation: $P_{FLUX}(k)$ - $P_{MATTER}(k)$??

NEUTRINOS in the IGM – III: impact on matter power (same σ_8)

Effect is of course smaller if P(k) is normalized at the forest scale



Increasing neutrino mass