Cosmology with the intergalactic medium

Matteo Viel *– INAF/OATs*
Helsinki Institute of Physics
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QUESTION

Why should we care about intergalactic medium cosmology?

QUANTITATIVE IGM COSMOLOGY

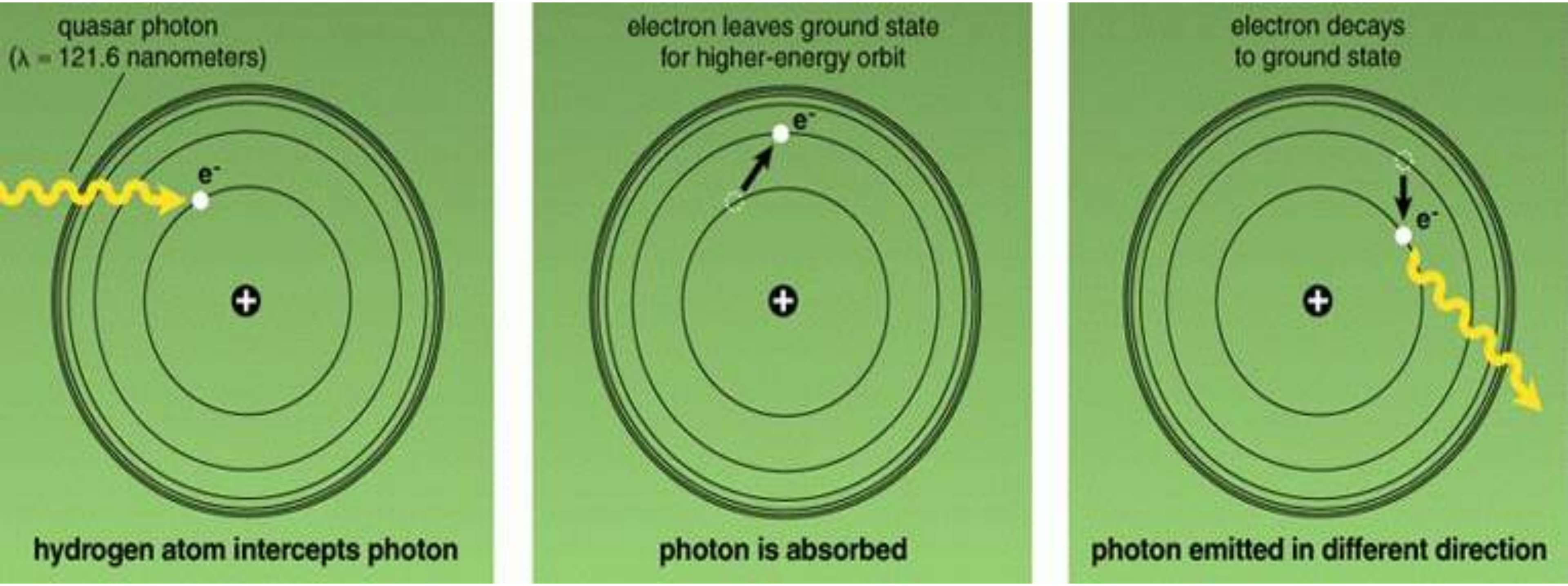
1) It probes the dynamical growth at the **smallest scales** (LCDM crisis? LCDM extensions?)

2) …but also **large scales** via BAO geometrical measurements (Lya-Lya or cross Quasar-Lya)

3) IGM sink and reservoir of baryons test bed for **galaxy formation** feedback models

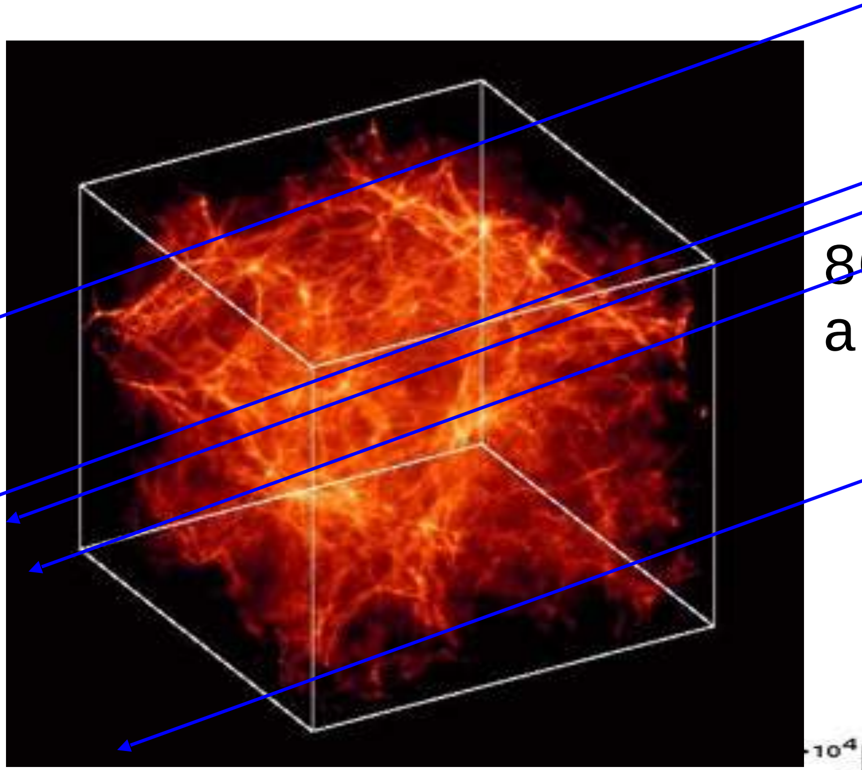
The Lyman-α forest

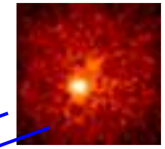
Lyman-α absorption is the main manifestation of the IGM



Tiny neutral hydrogen fraction after reionization…. But large cross-section

The Intergalactic Medium: Theory vs. Observations



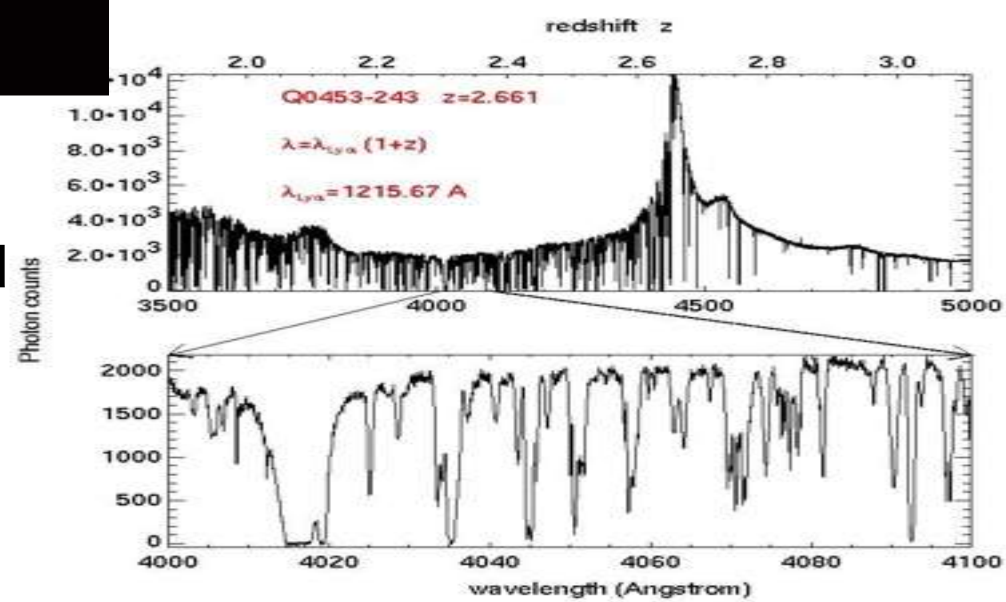


80% of the baryons at z=3 are in the **Lyman-α forest**

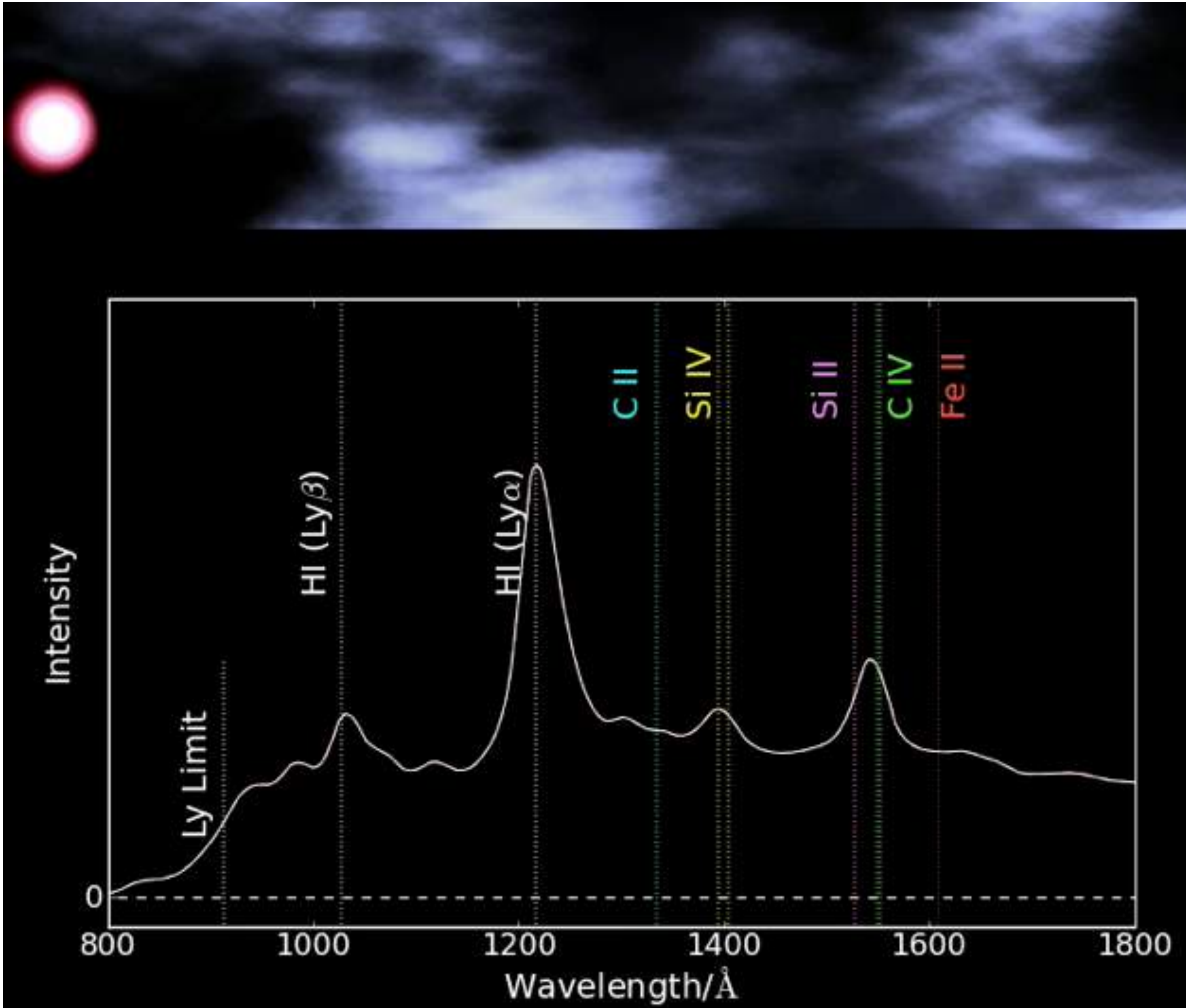
Bi & Davidsen (1997), Rauch (1998)
Review by Meiksin (2009)

baryons as tracer of the dark matter density field

$\delta_{IGM} \sim \delta_{DM}$



Croft+ 99,02
MV+ 04
McDonald+ 01,03



Intensity
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II
0
800
1000
1200
1400
1600
1800
Wavelength/Å

TOPIC	DATA	THEORY	RESULTS
BAOs	QSO Lya flux and coss correlation with QSOs 3D analysis – low res	Mocks	Clear detection, small tension with Planck
Cosmic neutrinos	IGM QSO Spectra low res 1D flux power	N-body/hydro sims	$\Sigma\ m_\nu < 0.12$ eV
Cold dark matter Coldness	IGM QSO Spectra high res 1D flux Power	N-body/hydro sims	$m_{WDM} > 3.3$ keV (thermal cross. sect.)
Low redshift Lyman-α forest	COS data at z=0.15	Hydro sims	HM01 background + "hot" gas

Two key *unique* aspects

$$P_{1D}(k) = \frac{1}{2\pi} \int_k^\infty P_{3D}(x) x dx$$

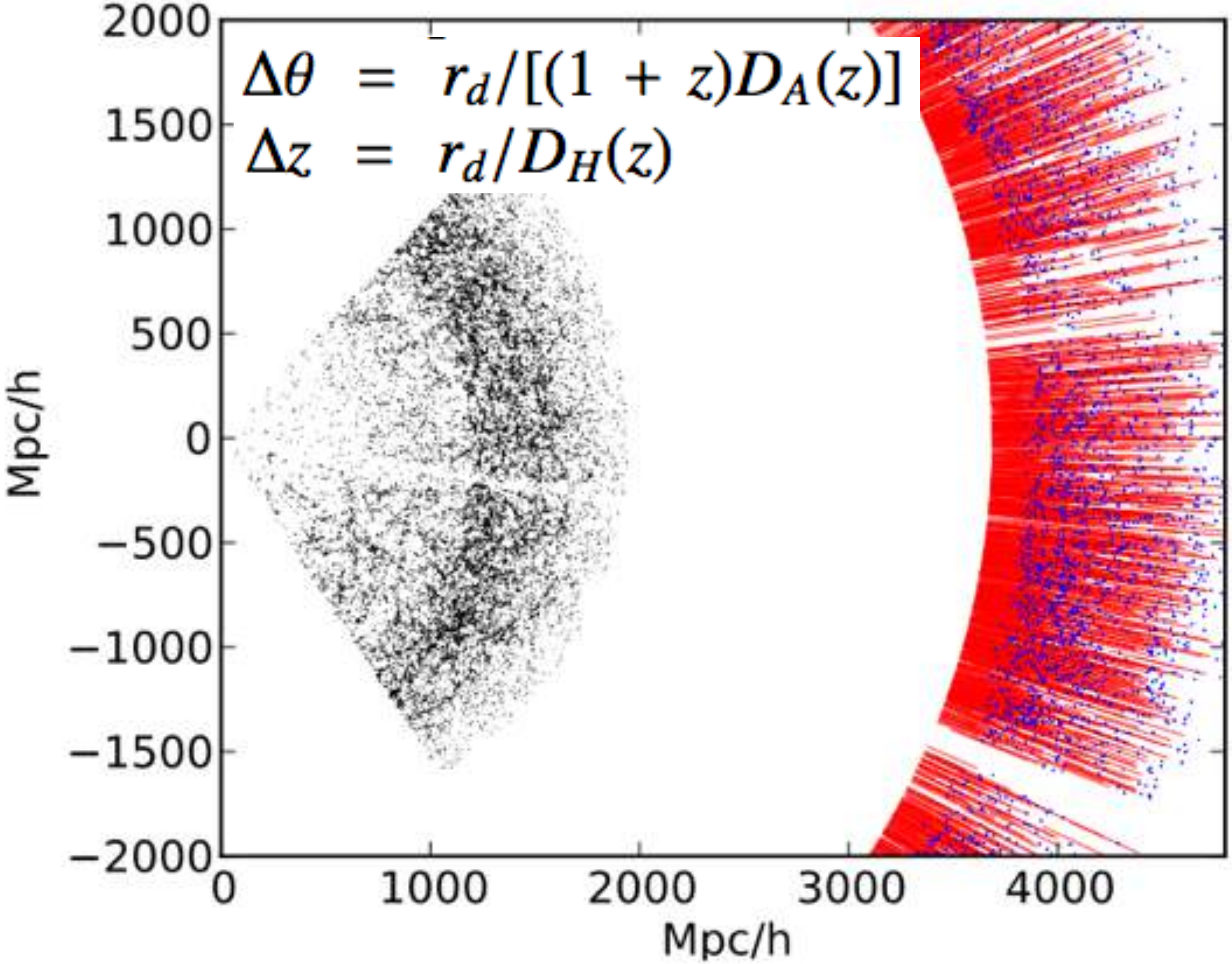
High redshift (and small scales):
possibly closer to linear behaviour

RESULTS FROM BOSS/SDSS-III

BAOs at z=2.3

SDSS- I

New regime to be probed with Lyman-α forest in 3D



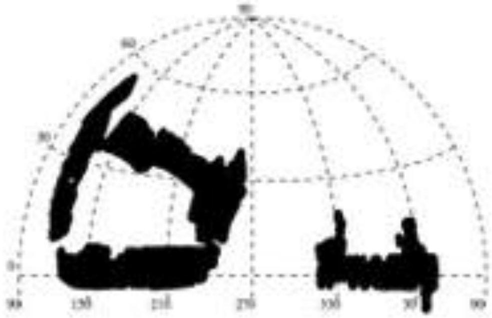
Slosar et al. 11
Busca et al. 13
Slosar et al. 13

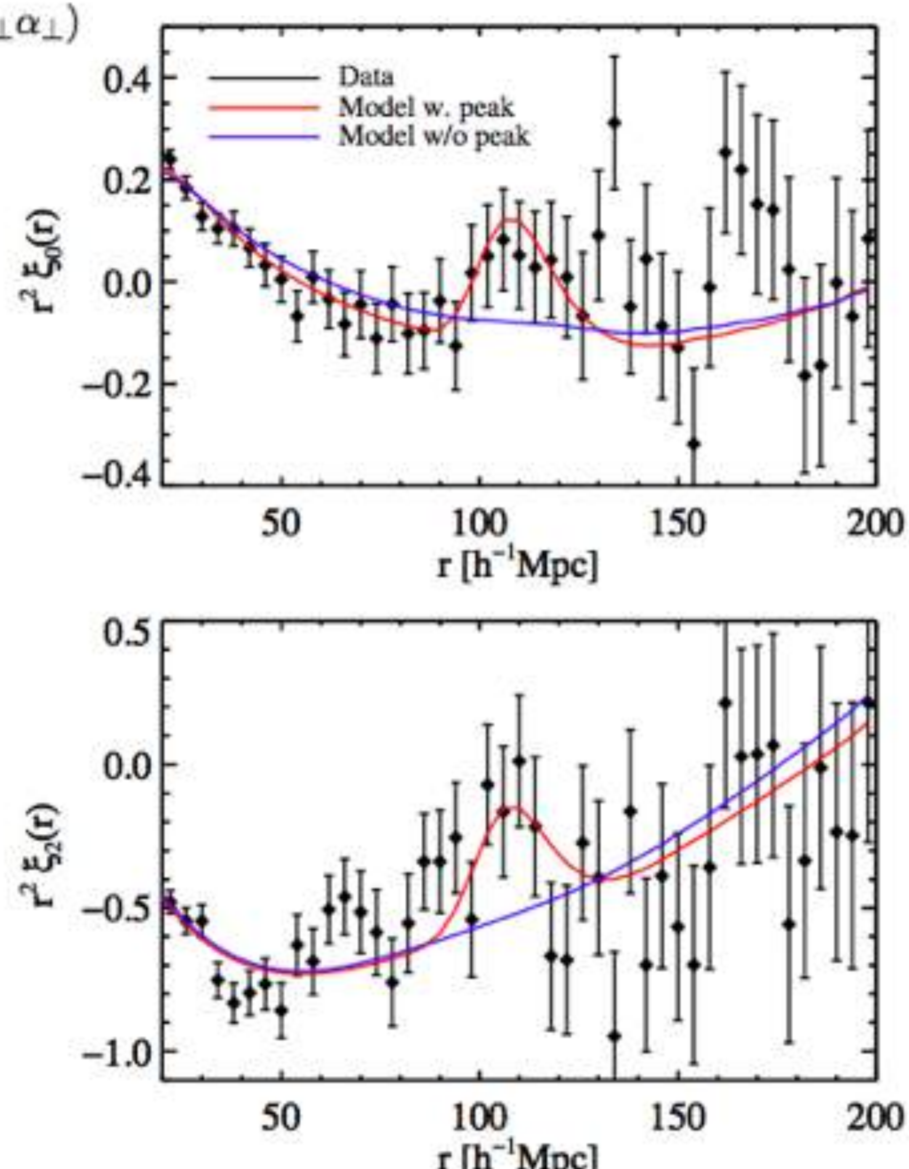
SDSS- II

Busca et al. 13

$$\xi_{\rm cosmo}(r_\parallel, r_\perp) = \xi_{\rm smooth}(r_\parallel, r_\perp) + a_{\rm peak} \cdot \xi_{\rm peak}(r_\parallel \alpha_\parallel, r_\perp \alpha_\perp)$$

$$\xi(r_\parallel, r_\perp) = \xi_{\rm cosmo}(r_\parallel, r_\perp, \alpha_\parallel, \alpha_\perp) + \xi_{\rm bb}(r_\parallel, r_\perp)$$



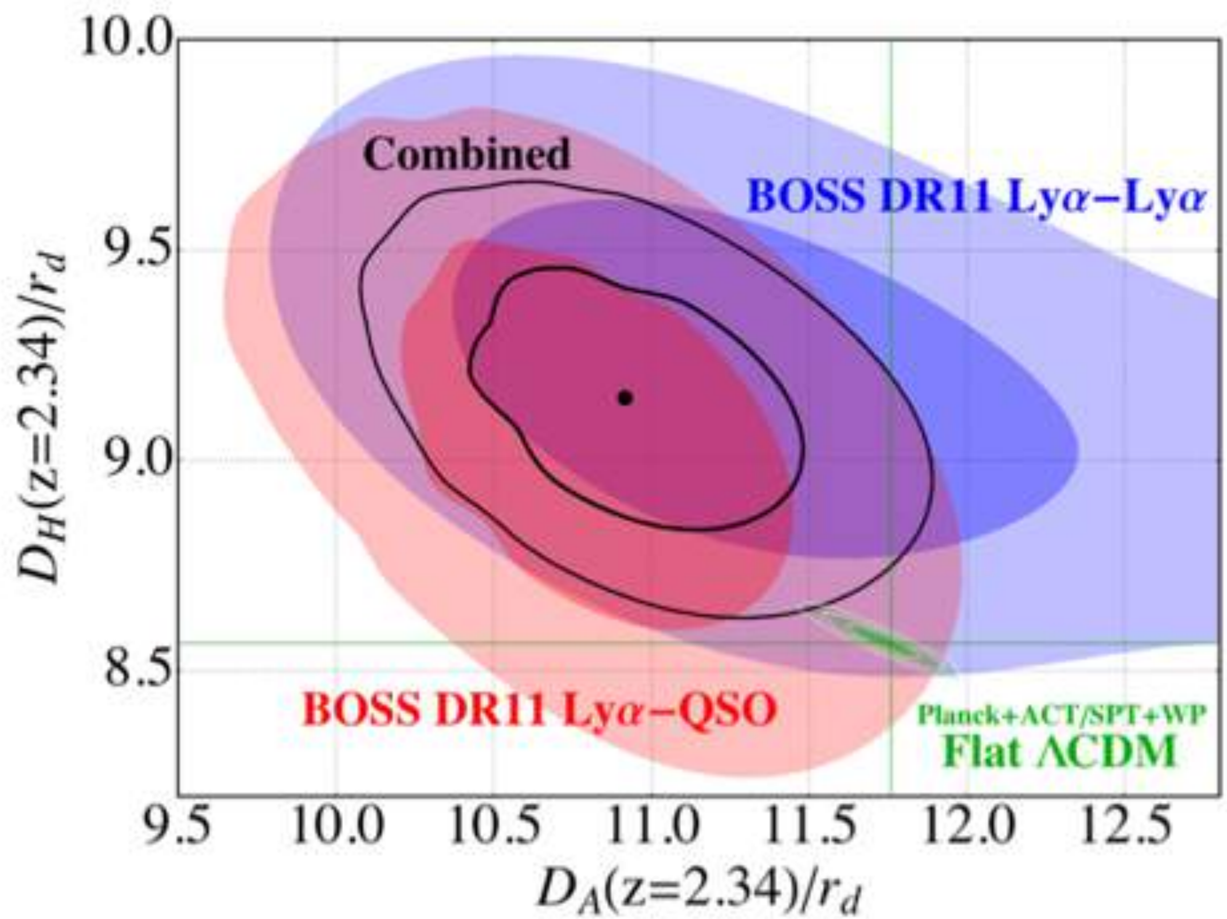


BAO feature detected at z=2.3
From 3000 deg^2, using 50000 QSOs
Significance of the detection at
around 3σ

SDSS-III

$$P_{qF}(\mathbf{k}) = b_q \left[1 + \beta_q \mu_k^2\right] b_F \left[1 + \beta_F \mu_k^2\right] \; P(k)$$

6% precision measurement of D_A/r_d
3% precision measurement of D_H/r_d



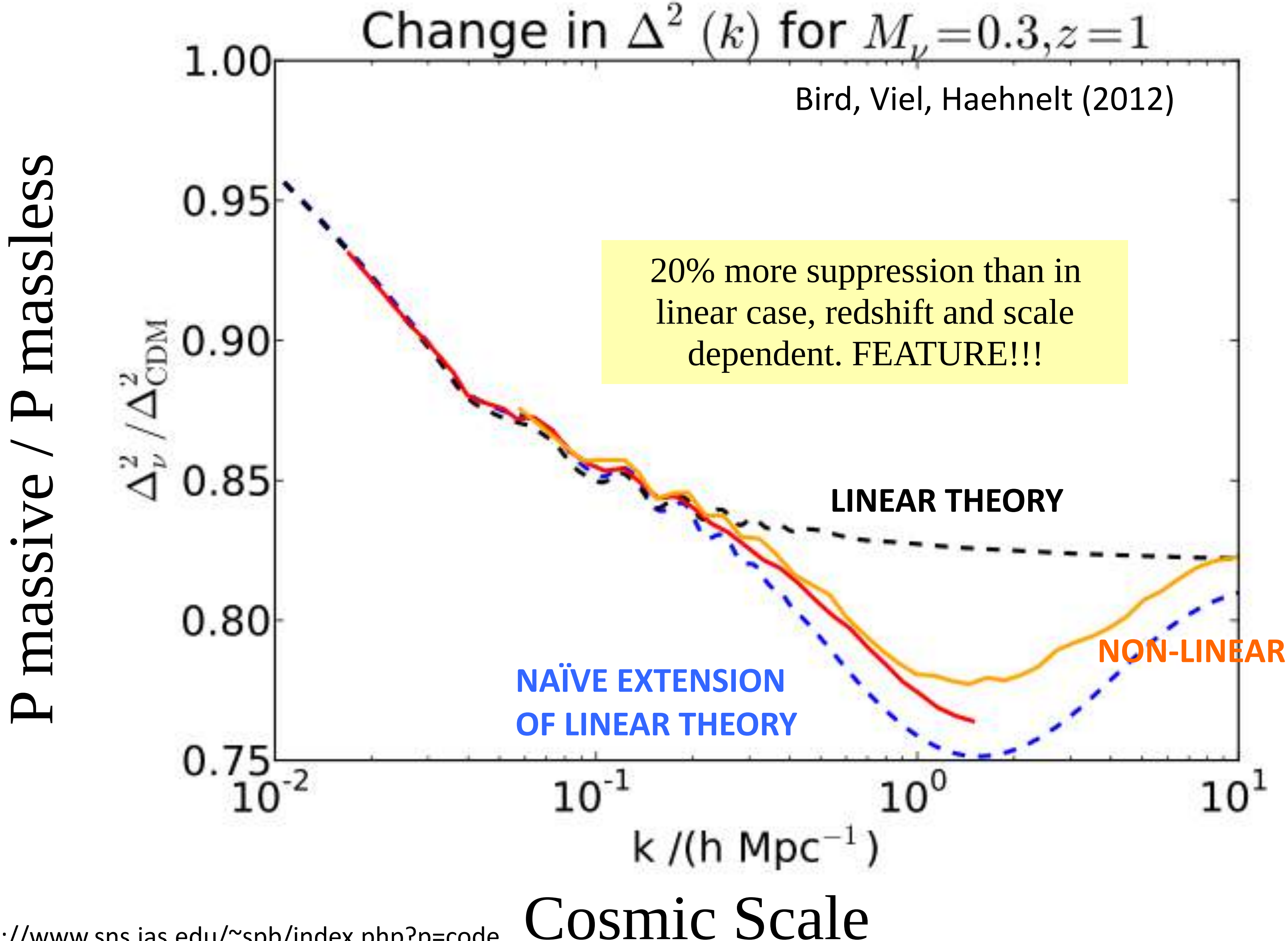
Delubac et al. 14

RESULTS FROM BOSS/SDSS-III

NEUTRINOS

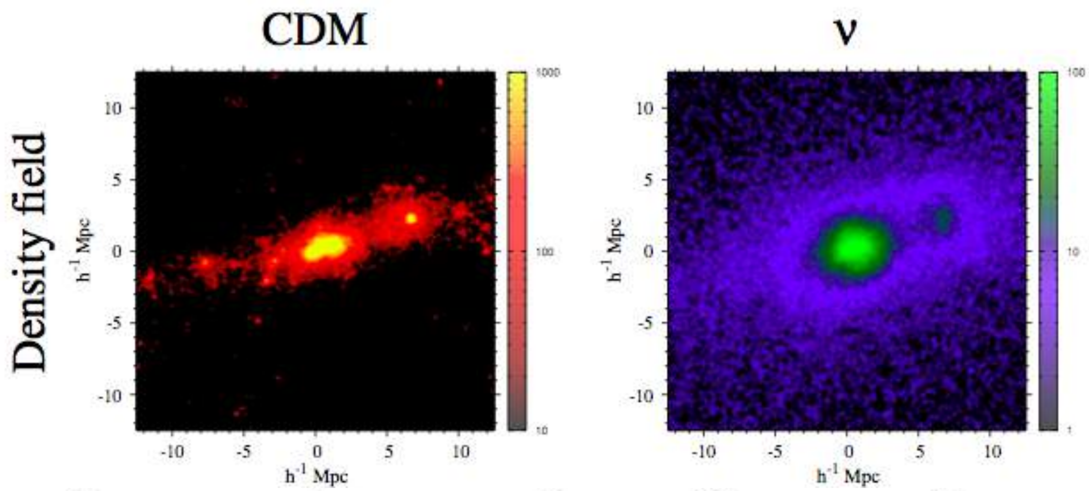
MASSIVE NEUTRINOS

COSMOLOGICAL NEUTRINOS : NON-LINEAR MATTER POWER

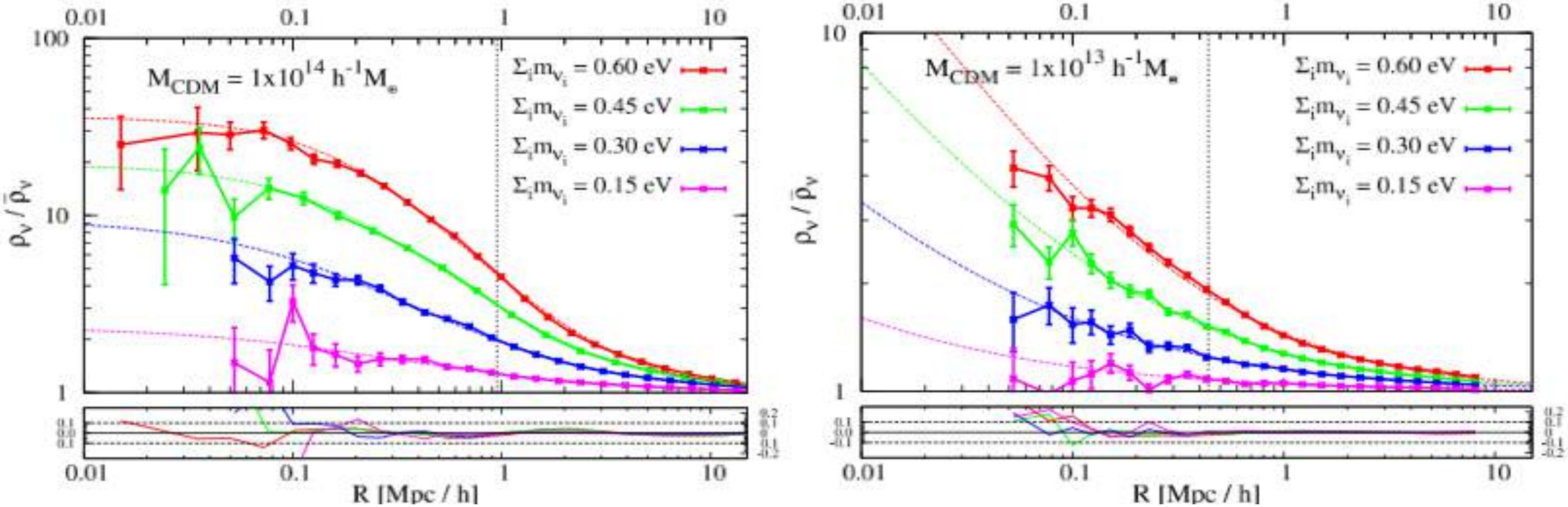


http://www.sns.ias.edu/~spb/index.php?p=code

THE NEUTRINO HALO?

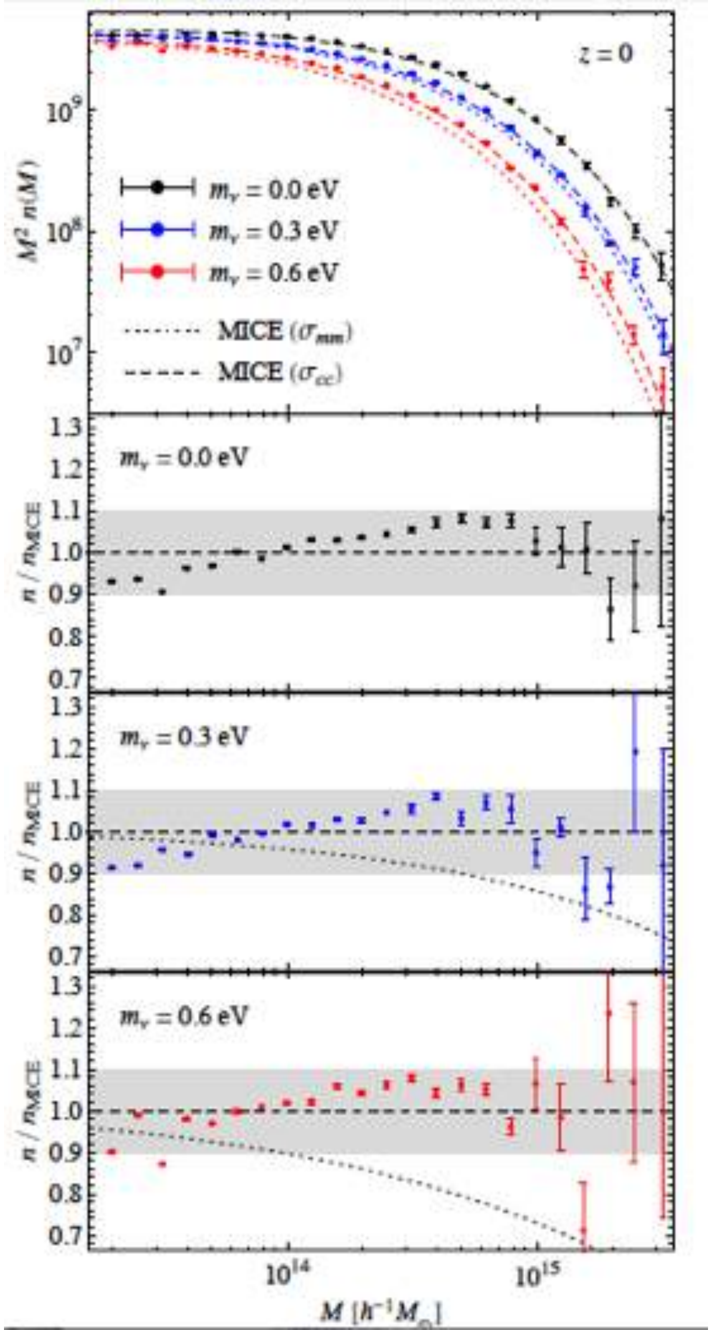


$$\delta_\nu(r) = \frac{\rho_\nu(r) - \bar{\rho}_\nu}{\bar{\rho}_\nu} = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$



Villaescusa-Navarro, Bird, Garay, Viel, 2013, JCAP, 03, 019
Marulli, Carbone, Viel+ 2011, MNRAS, 418, 346

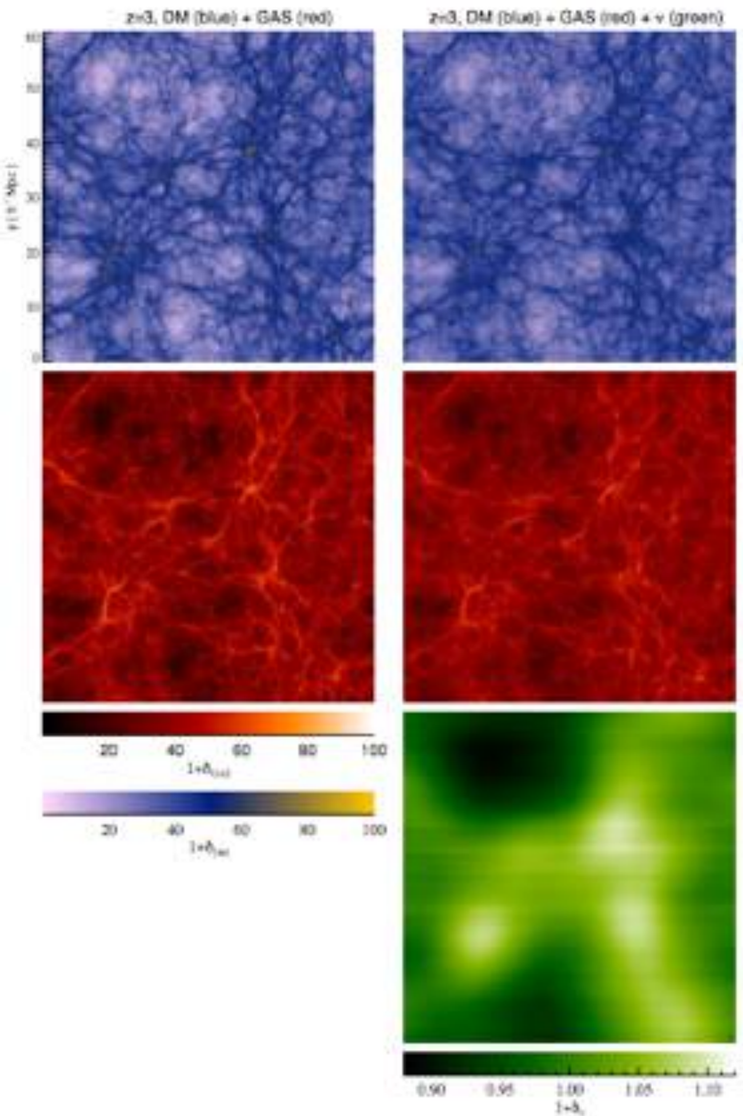
COSMOLOGICAL NEUTRINOS : MASS FUNCTION



Halo mass function in massive neutrino cosmologies is better described by the CDM field rather than the matter field. It becomes universal and bias becomes scale independent if CDM is used

Castorina+14
Costanzi+14

NEUTRINOS IN THE IGM



N-body + hydro sims

Neutrino induced non-linear suppression understood and reproduced also with simple halo modelling (**Massara+ 15**)

Degeneracies with s8 are present

Neutrino induced effects on RSD (Marulli+11), BAOs (Peloso+15), mass functions and bias (Castorina+14) investigated

FROM IGM ONLY:

$\Sigma m_{\nu} < 0.9$ eV(2σ)

Viel, Haehnelt, Springel 2010
Rossi+ 14, Villaescusa-Navarro+14

METHOD

DATA: thousands of low-res. Spectra for neutrino constraints. Few tens for cold dark matter coldness

SIMULATIONS: Gadget-III runs: 20 and 60 Mpc/h and (512^3,786^3,896^3)

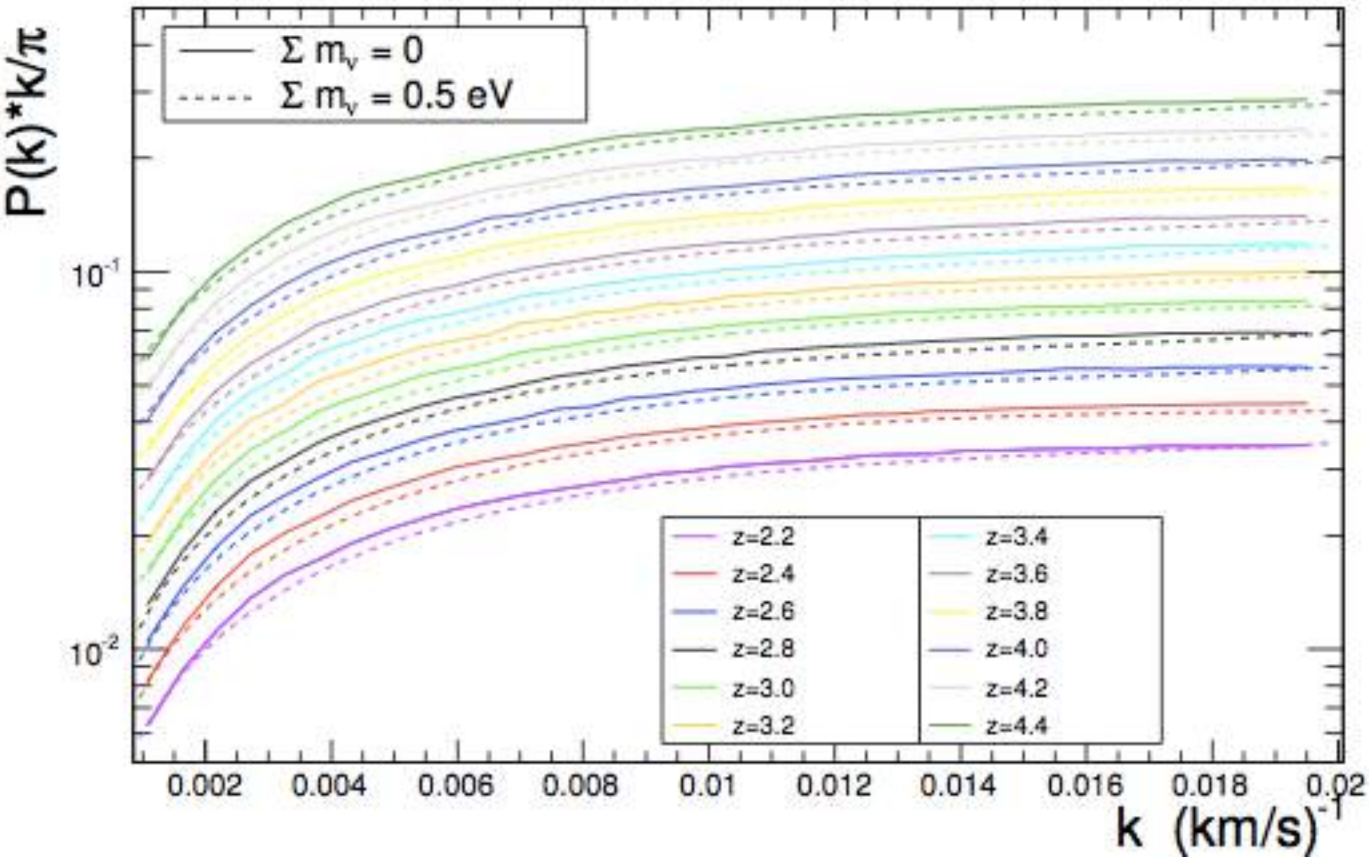
Cosmology parameters: σ_8, n_s, Ω_m, H_0, $m_{WDM,}$+ neutrino mass
Astrophysical parameters: z_{reio}, UV fluctuations, T_0, γ, $<F>$
Nuisance: resolution, S/N, metals

METHOD: Monte Carlo Markov Chains likelihood estimator
+ **very conservative assumptions** for the continuum fitting and error bars on the data

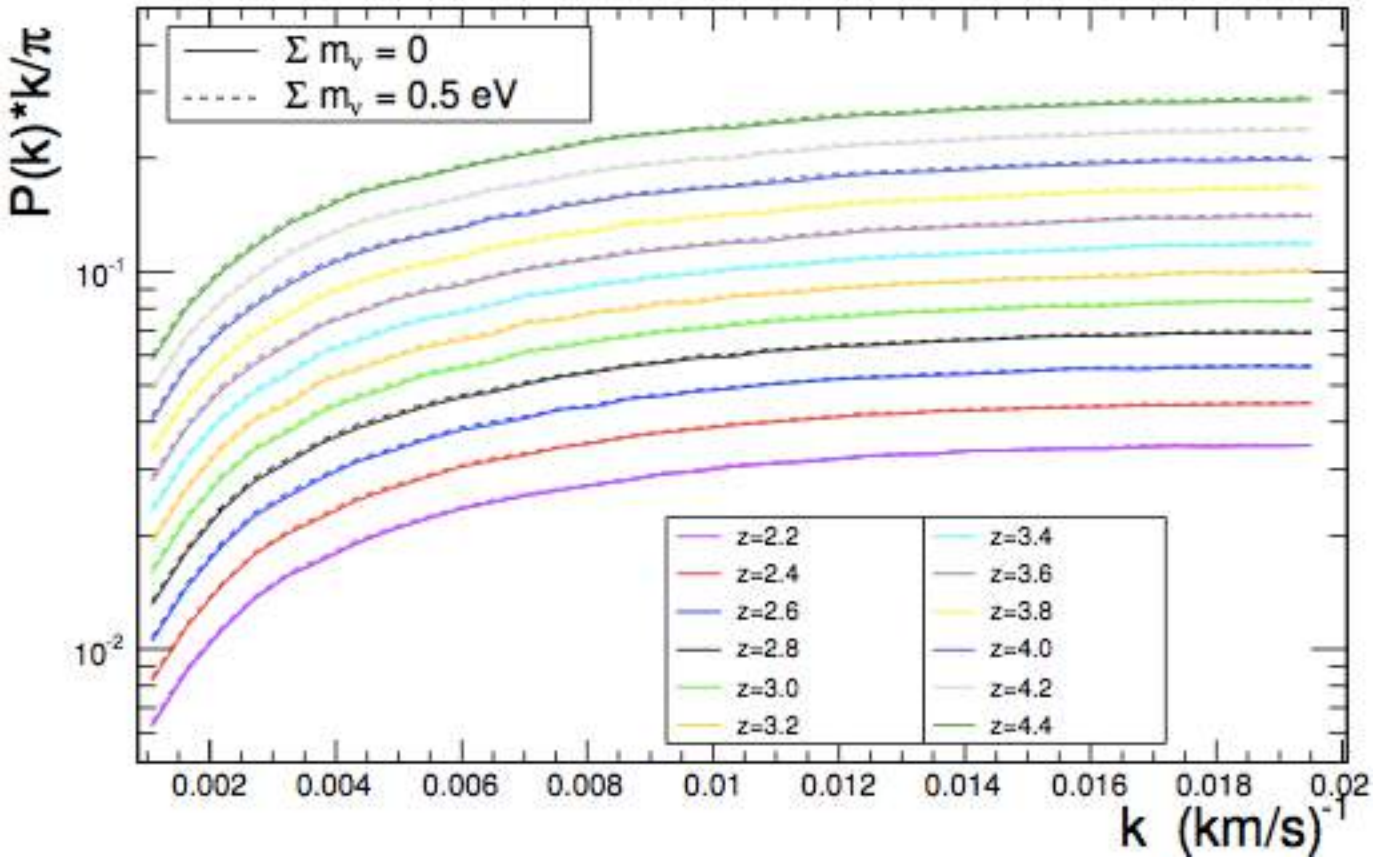
Parameter space: second order Taylor expansion of the flux power

$$P_F(k,z;\mathbf{p}) = P_F(k,z;\mathbf{p}^0) + \sum_i^N \frac{\partial P_F(k,z;p_i)}{\partial p_i}\bigg|_{\mathbf{p}=\mathbf{p}^0} (p_i - p_i^0)$$ + second order

NEUTRINO IMPACT - I



NEUTRINO IMPACT - II

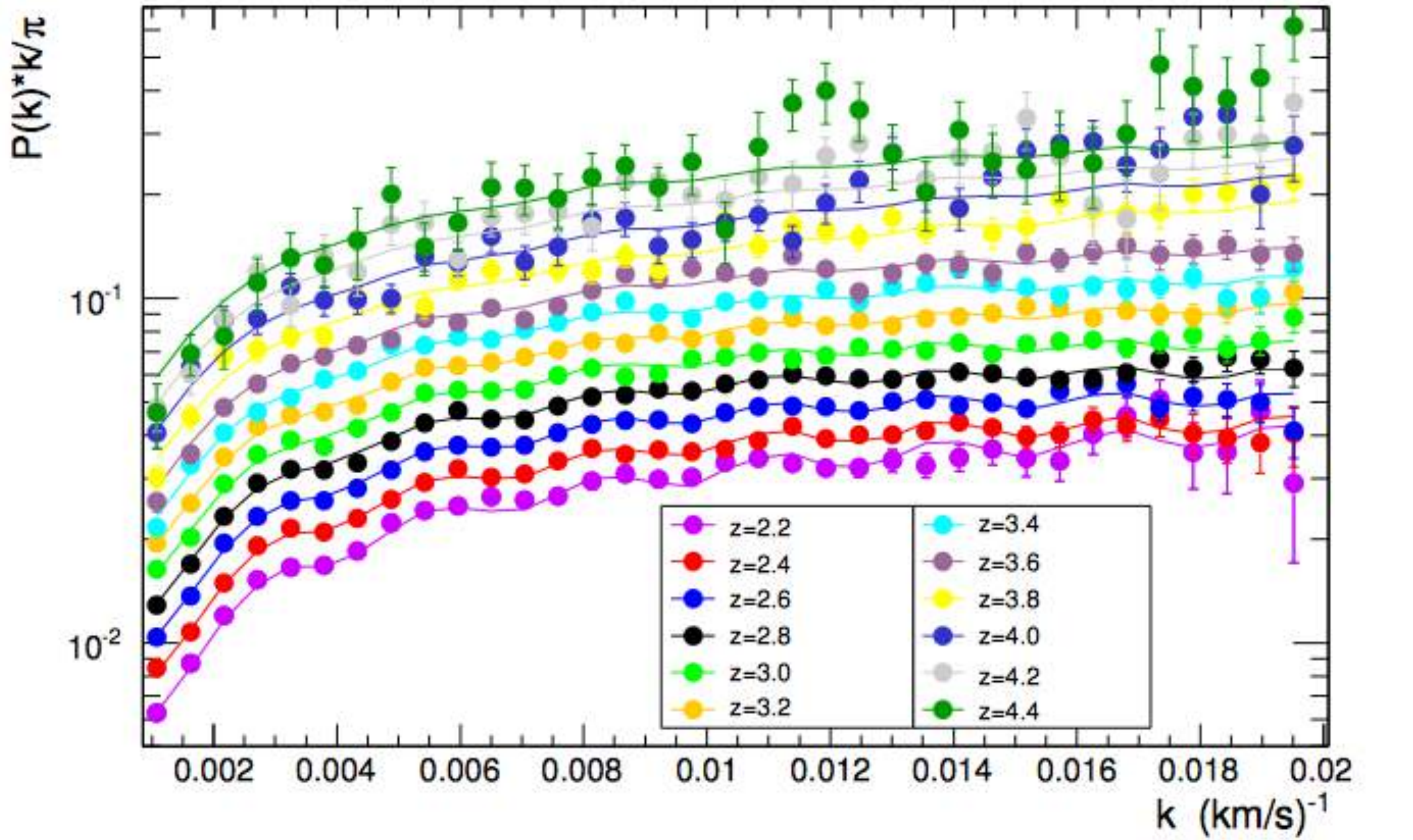


GROWTH OF STRUCTURES AT HIGH REDSHIFT

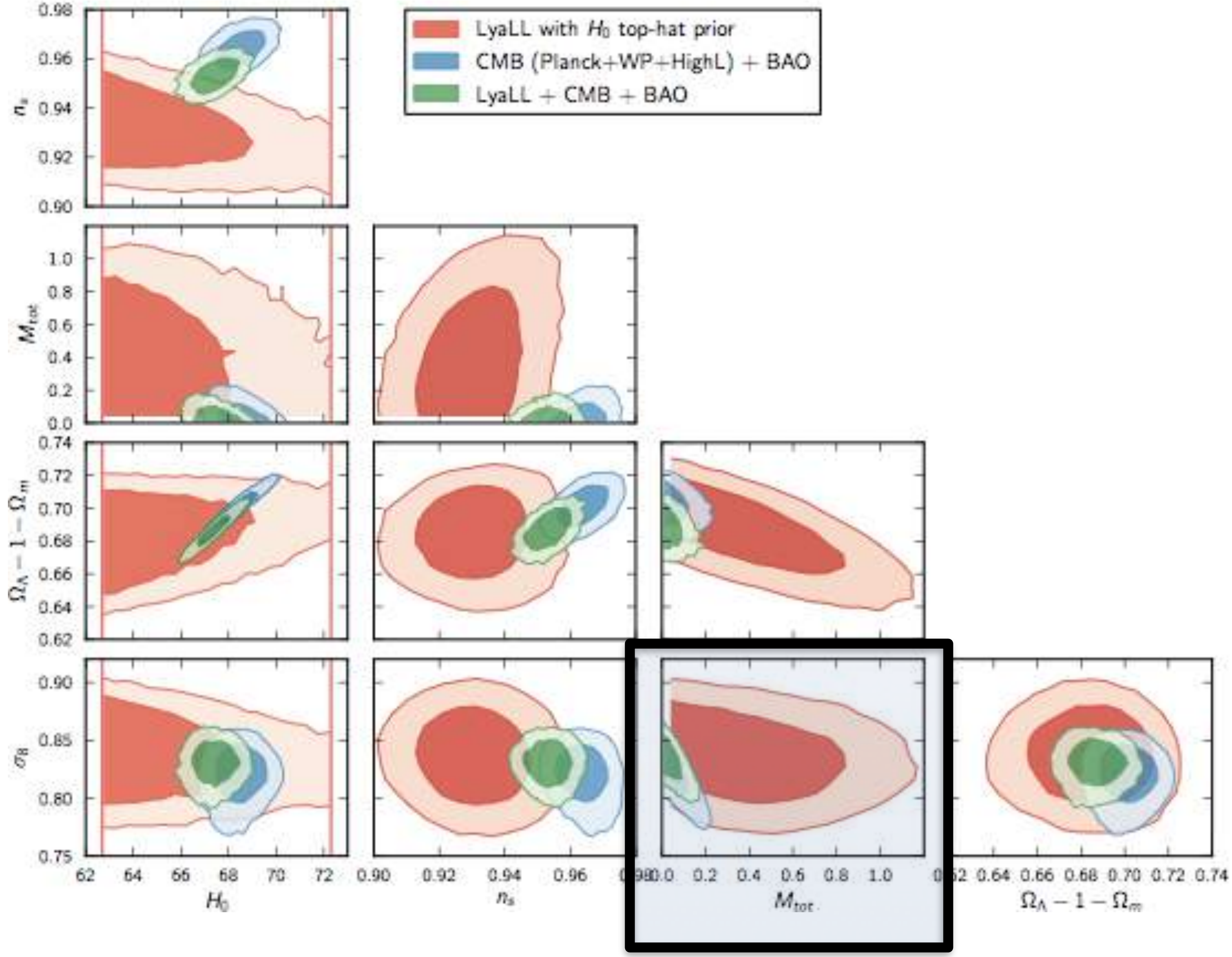
Constraint on neutrino masses from SDSS-III/BOSS Lyα forest and other cosmological probes

Nathalie Palanque-Delabrouille, Christophe Yèche, Julien Lesgourgues, Graziano Rossi, Arnaud Borde, Matteo Viel, Eric Aubourg, David Kirkby, Jean-Marc LeGoff, James Rich, Natalie Roe, Nicholas P. Ross, Donald P. Schneider, David Weinberg

1D Flux power spectrum evolution



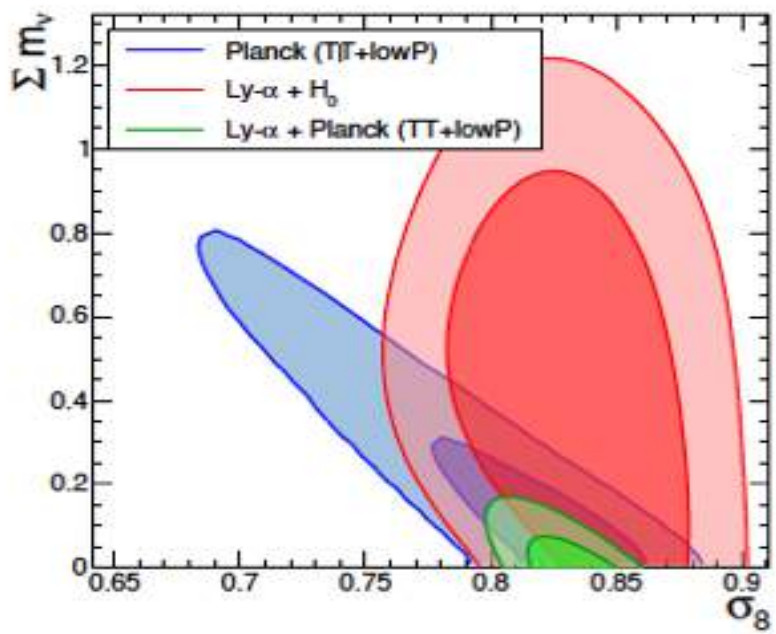
BAYESIAN ANALYSIS



UPDATE using Planck 15

Palanque-Delabrouille+ 2015

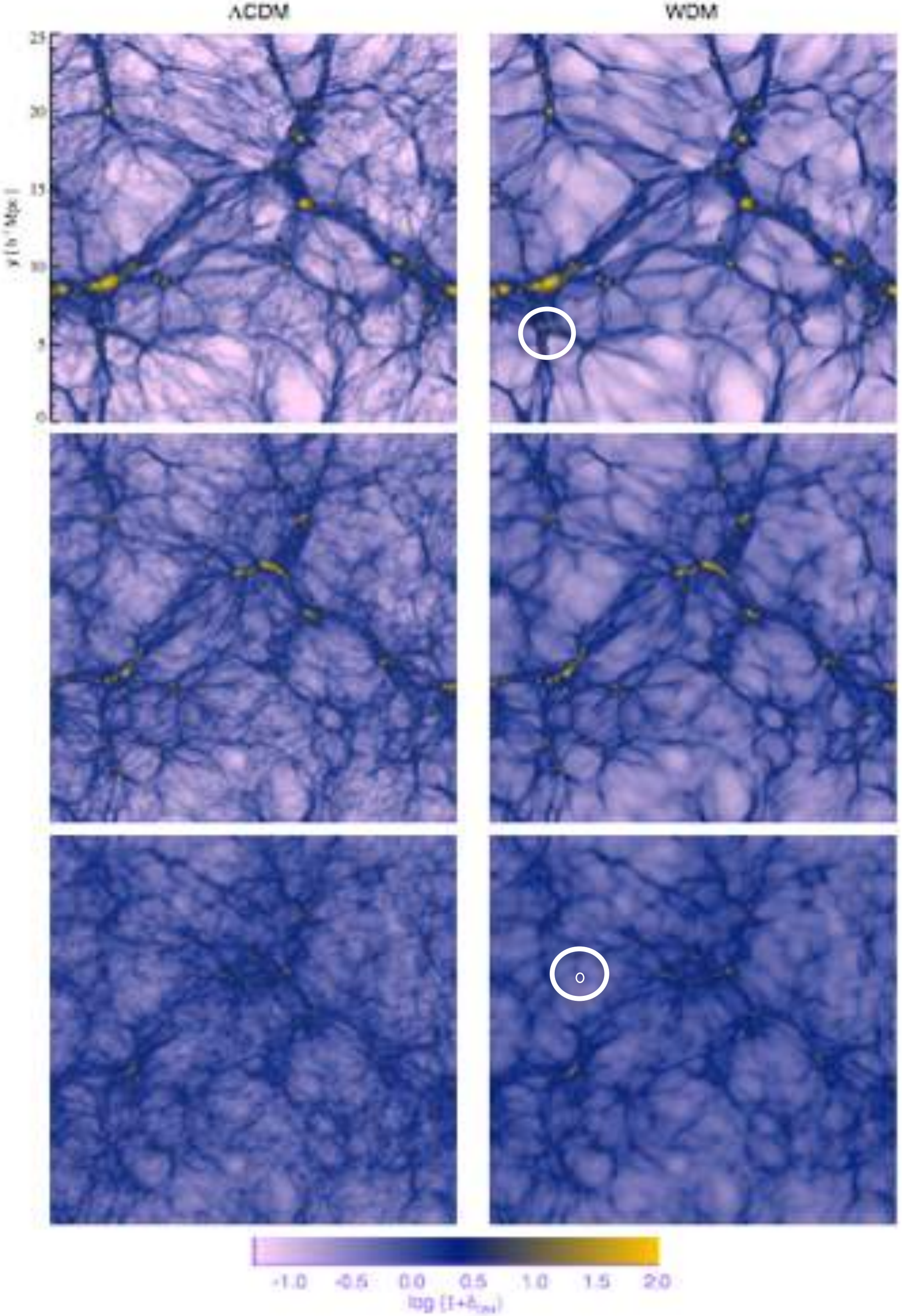
Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO	(4) Lyα + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014	0.311 ± 0.007
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1	67.7 ± 0.6
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)	< 0.12 (95% CL)
Reduced χ^2	0.99	1.04	1.05	1.05



COLDNESS OF COLD DARK MATTER

Viel, Becker, Bolton, Haehnelt, 2013, PRD, 88, 043502

THE COSMIC WEB in WDM/LCDM scenarios



z=0

$$\frac{T_x}{T_\nu} = \left(\frac{10.75}{g_*(T_D)}\right)^{1/3} < 1$$

$$k_{\rm FS} = \frac{2\pi}{\lambda_{\rm FS}} \sim 5\,{\rm Mpc}^{-1}\left(\frac{m_x}{1\,{\rm keV}}\right)\left(\frac{T_\nu}{T_x}\right)$$

$$\omega_x = \Omega_x h^2 = \beta\left(\frac{m_x}{94\,{\rm eV}}\right)$$

$$\beta = (T_x/T_\nu)^3$$

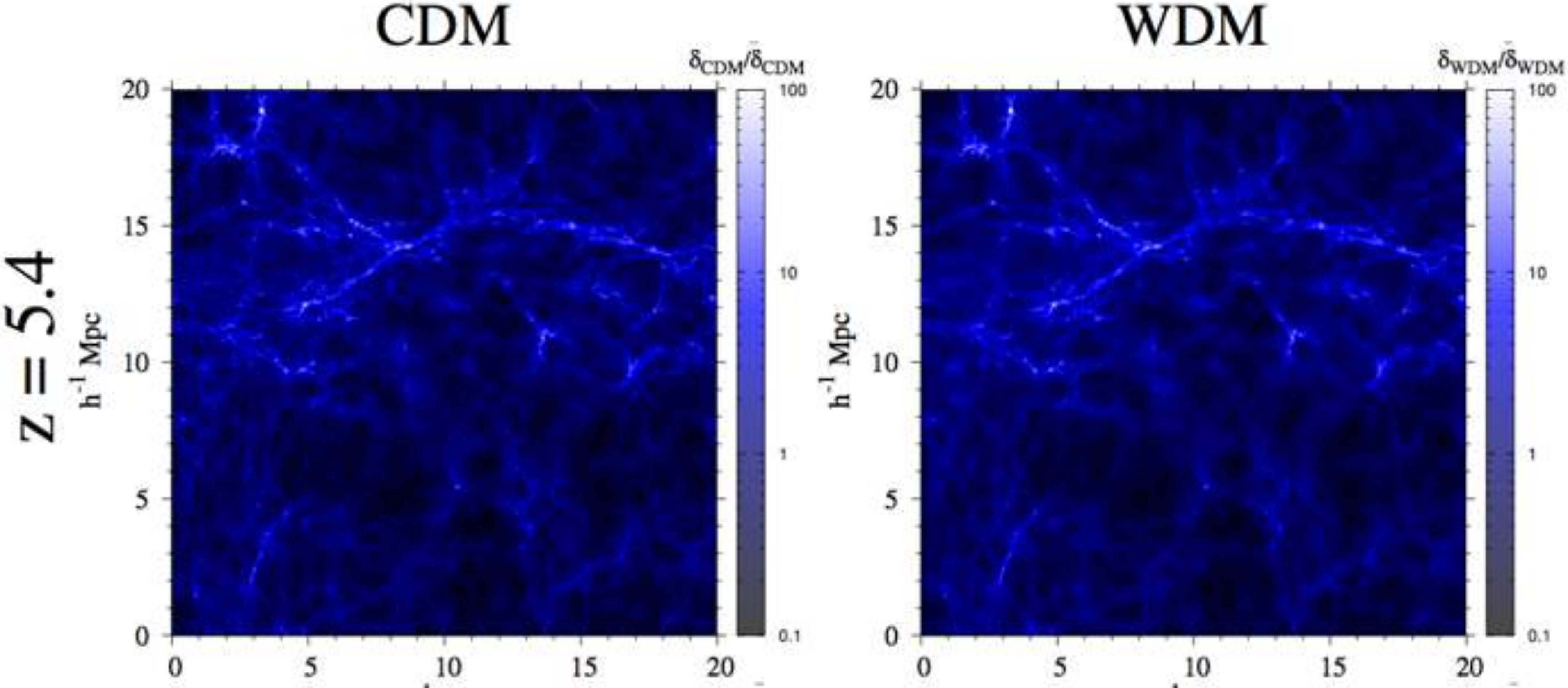
z=2

$$k_{\rm FS} \sim 15.6\frac{h}{\rm Mpc}\left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)^{4/3}\left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)^{1/3}$$

z=5

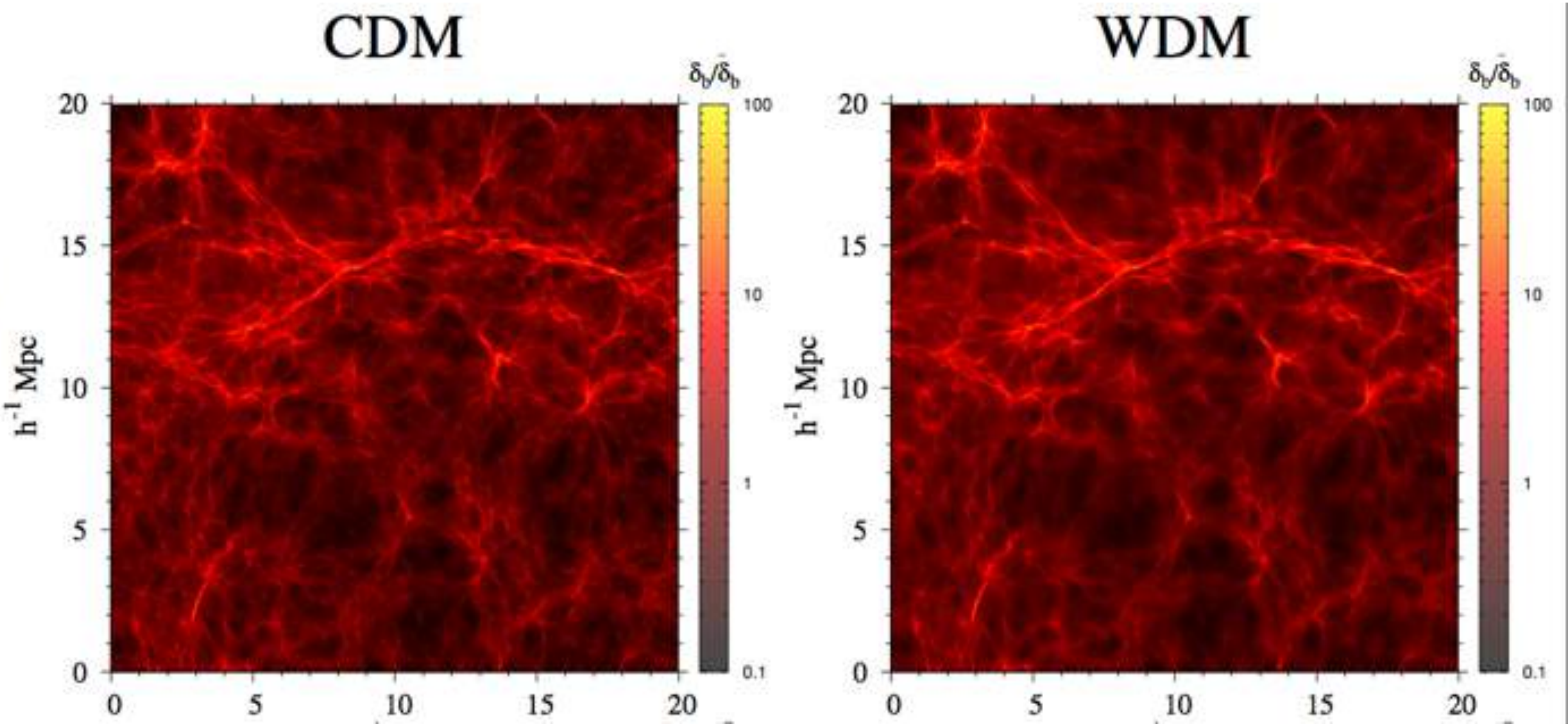
MV, Markovic, Baldi & Weller 2013
Markovic & MV, 2014

DARK MATTER DISTRIBUTION

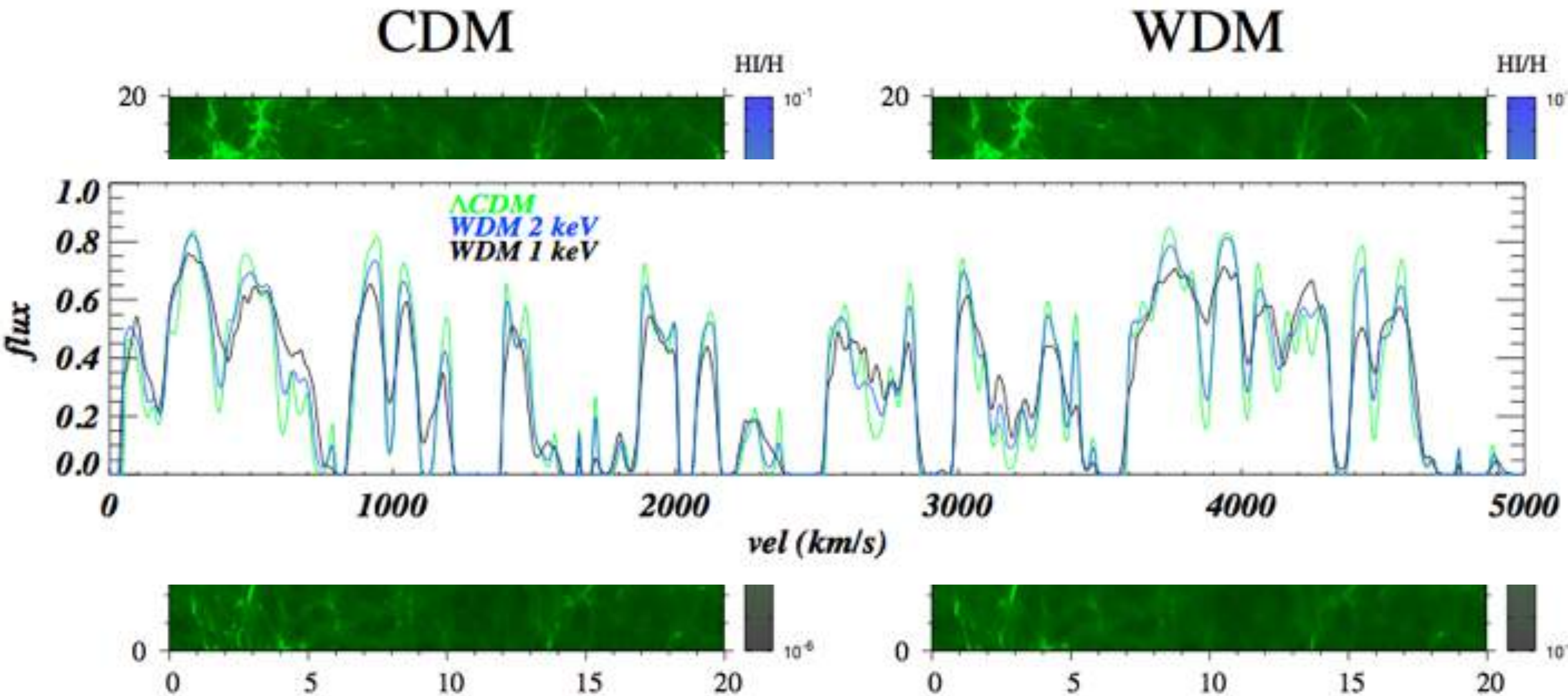


GAS DISTRIBUTION

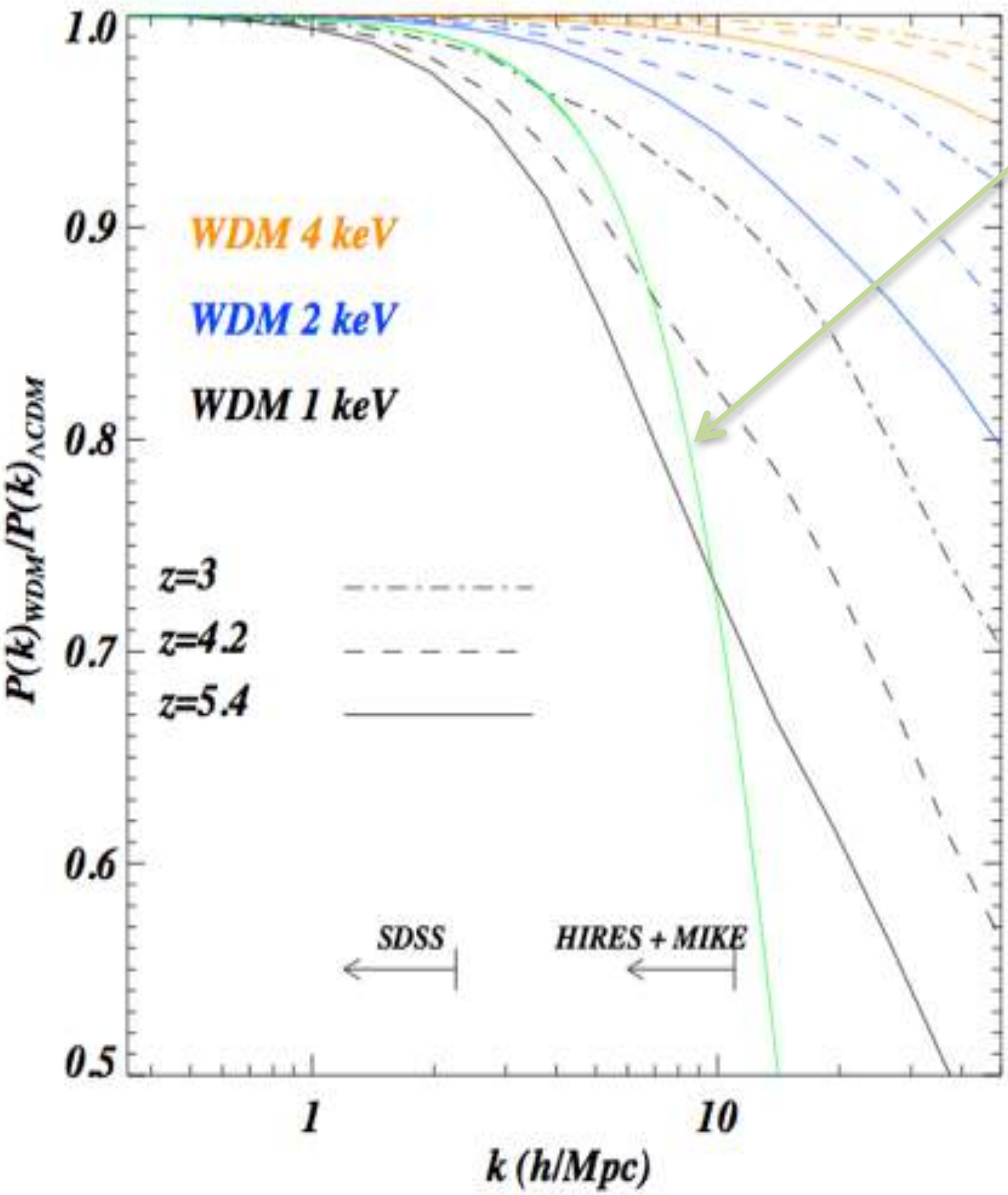
z = 5.4



HI DISTRIBUTION



THE WARM DARK MATTER CUTOFF IN THE MATTER DISTRIBUTION



Linear cutoff for WDM 2 keV

Linear cutoff is redshift independent

Fit to the non-linear cut-off

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

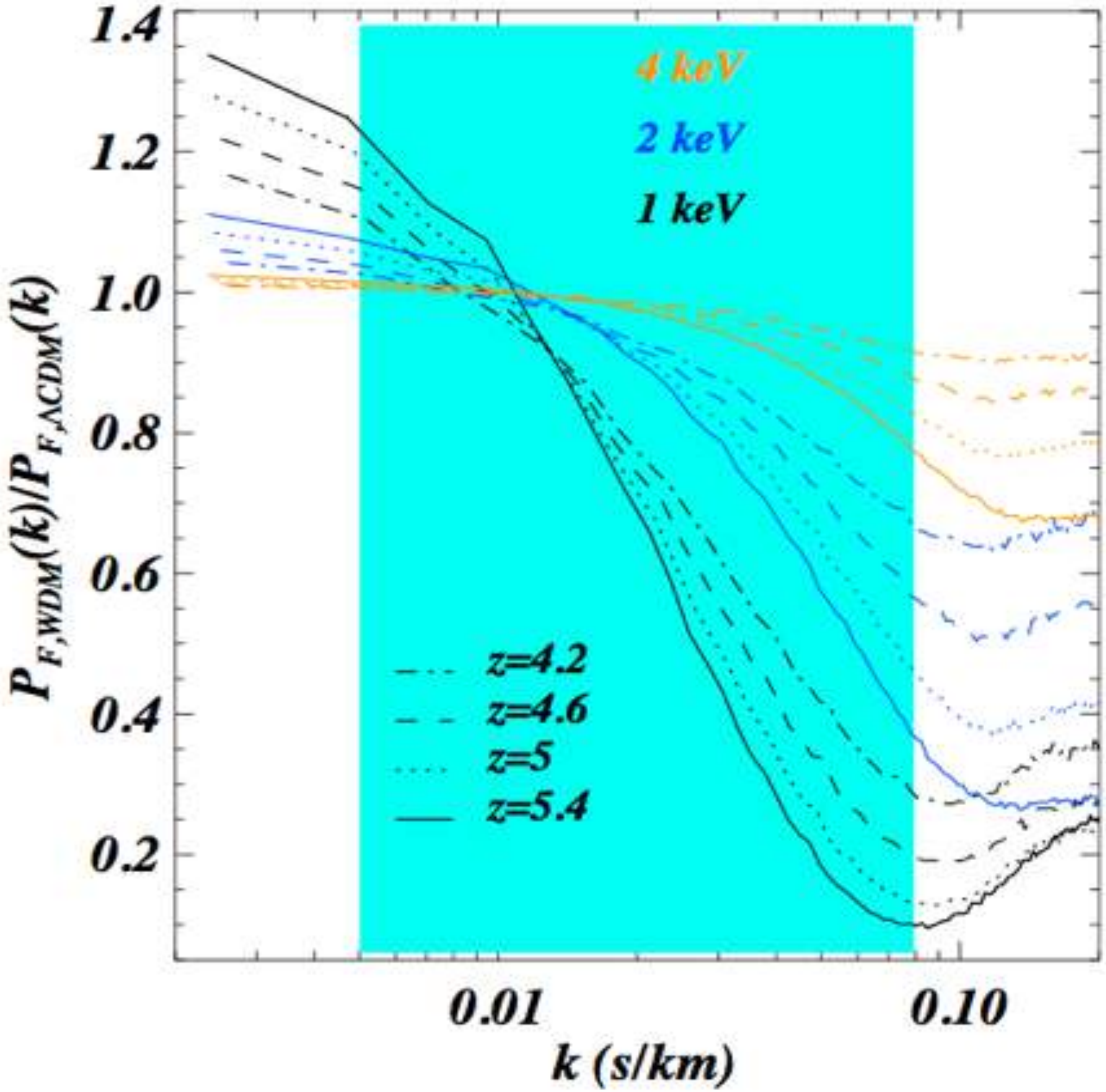
$$\alpha(m_{WDM}, z) = 0.0476 \left(\frac{1\text{keV}}{m_{WDM}}\right)^{1.85} \left(\frac{1+z}{2}\right)^{1.3},$$

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

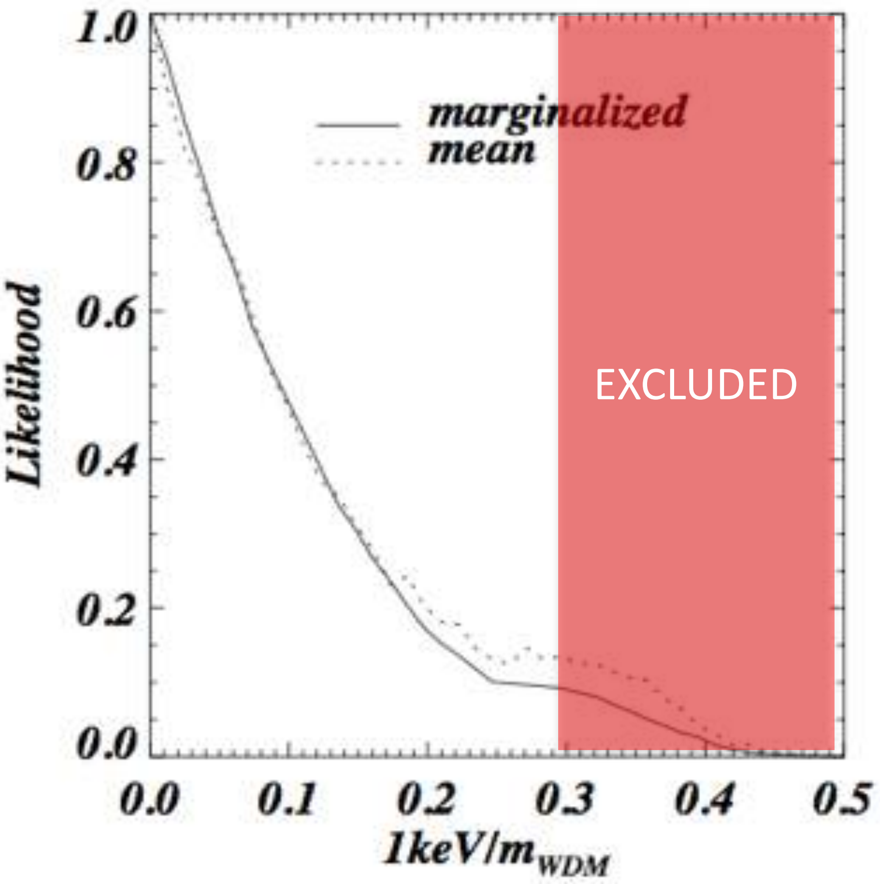
Viel, Markovic, Baldi & Weller 2013

THE HIGH REDSHIFT WDM CUTOFF

$\delta_F = F/\langle F\rangle - 1$



RESULTS FOR WDM MASS

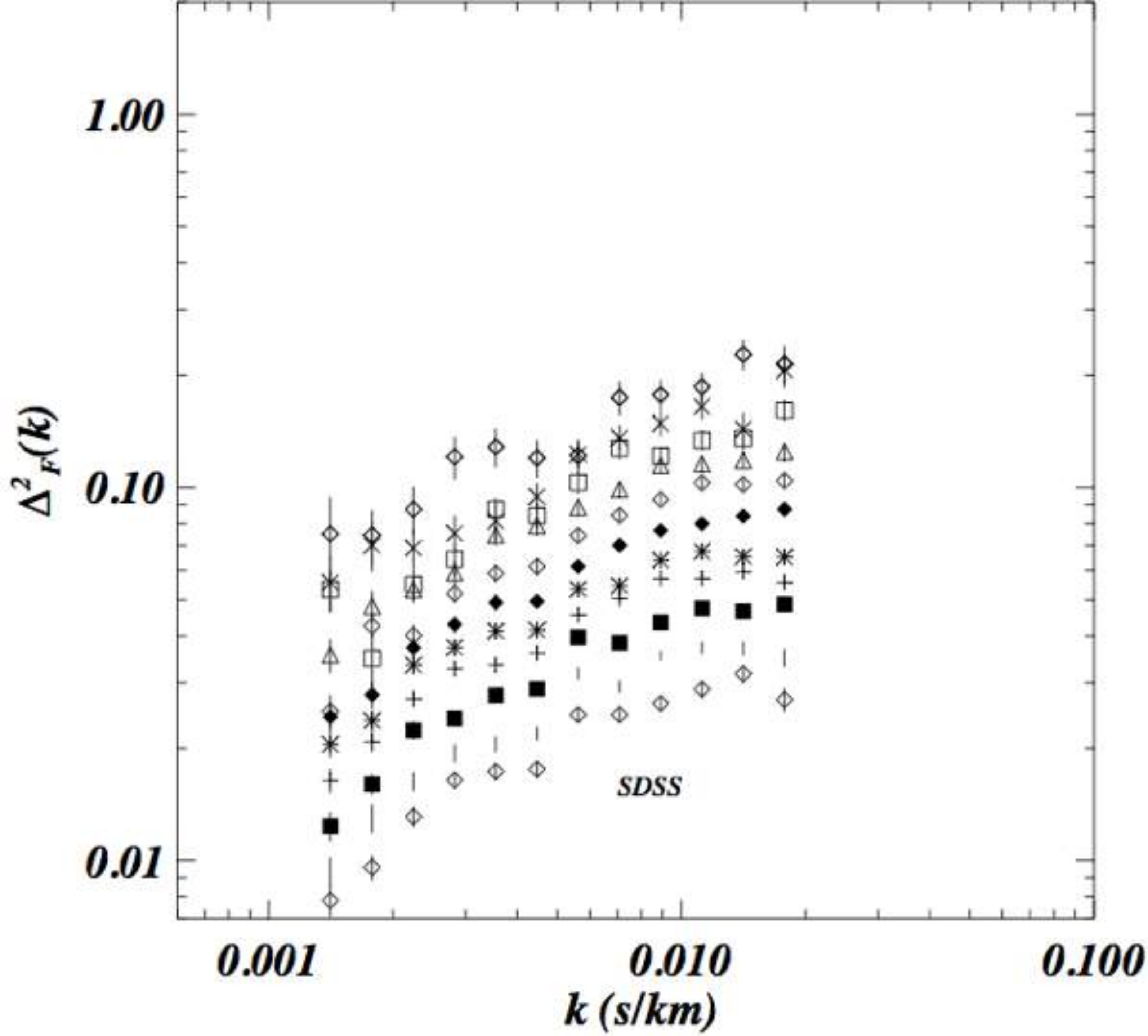


m > 3.3 keV (2σ)

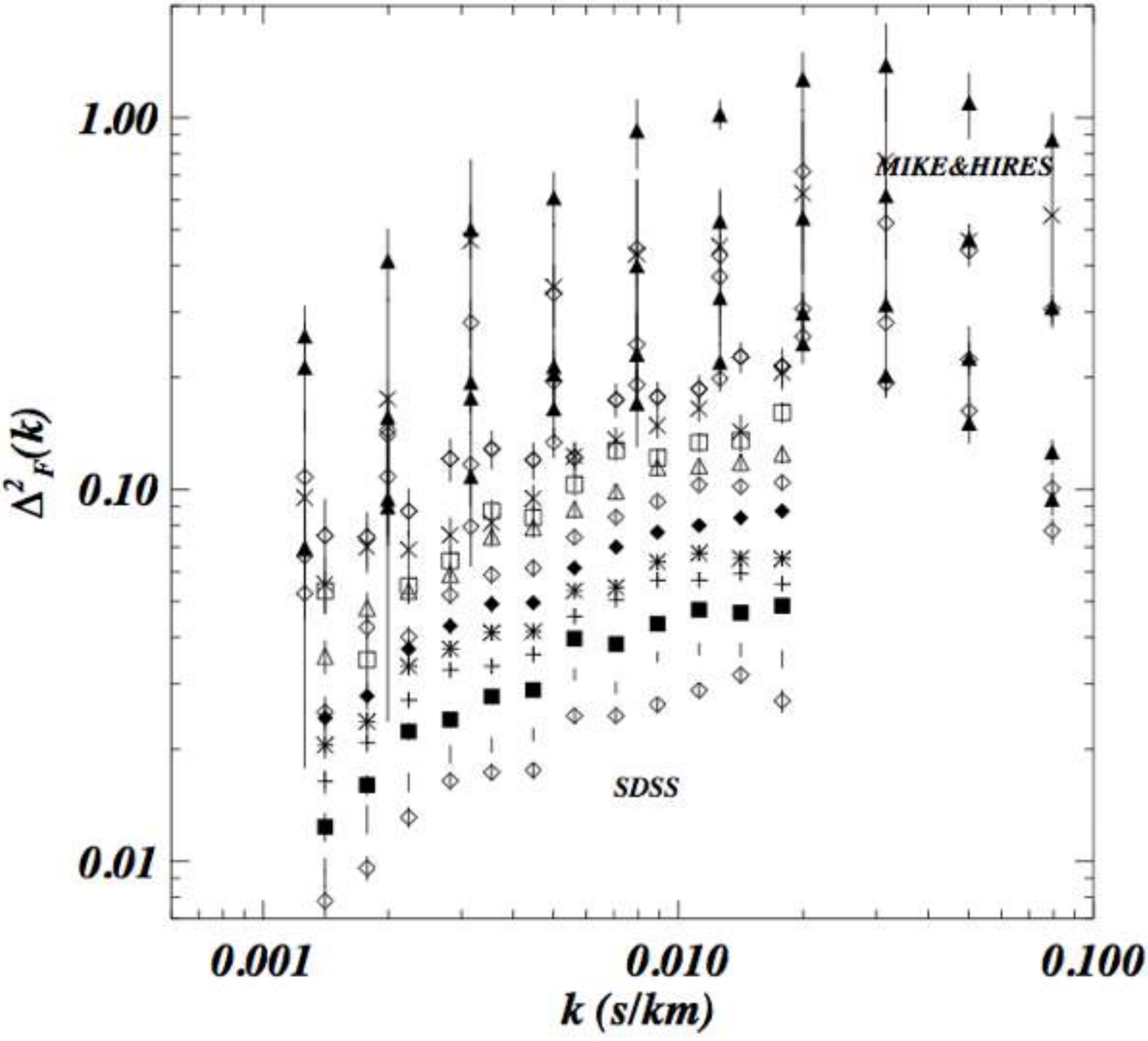
SDSS + MIKE + HIRES CONSTRAINTS

Joint likelihood analysis

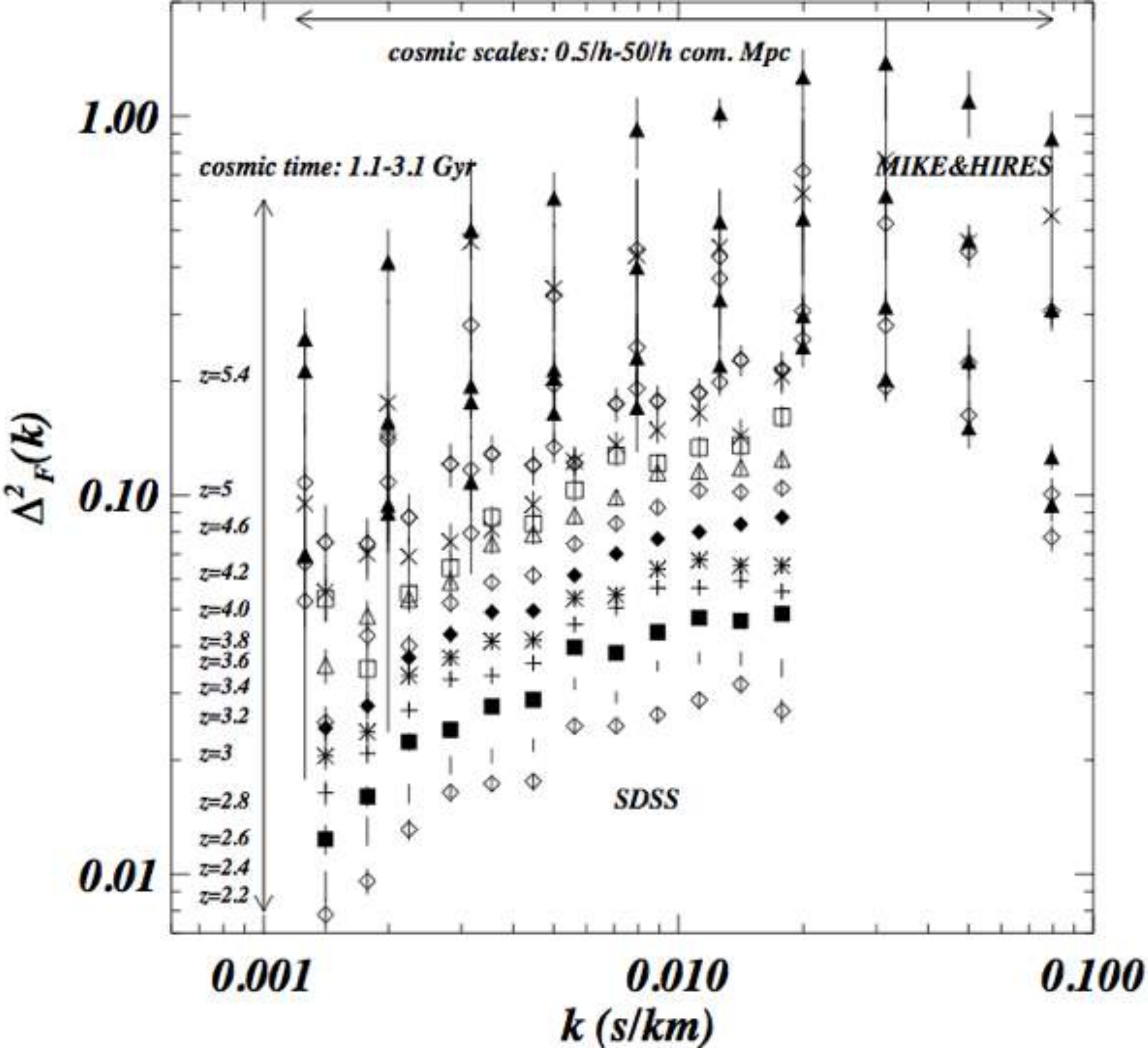
SDSS data from McDonald05,06 not BOSS



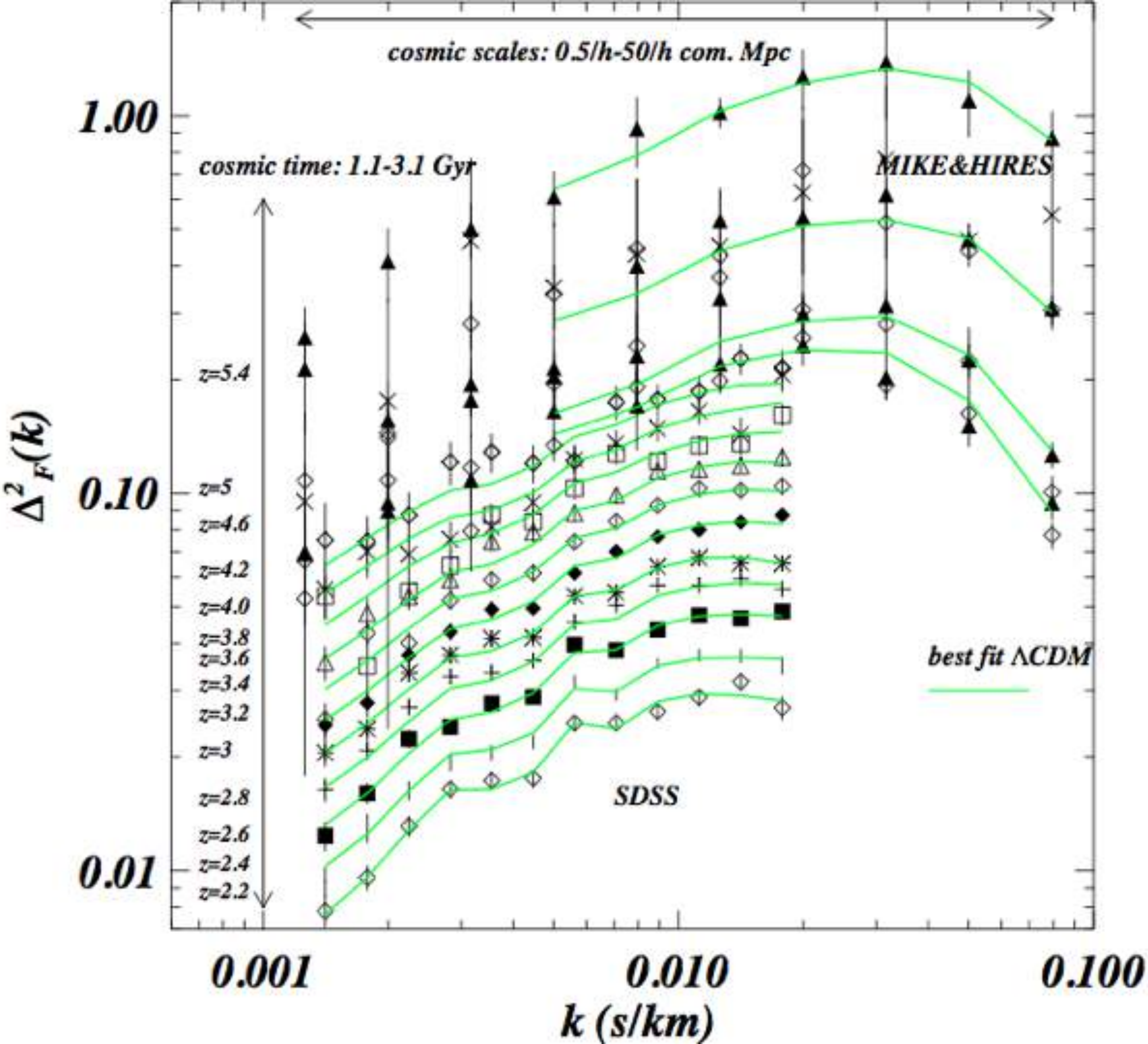
1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)



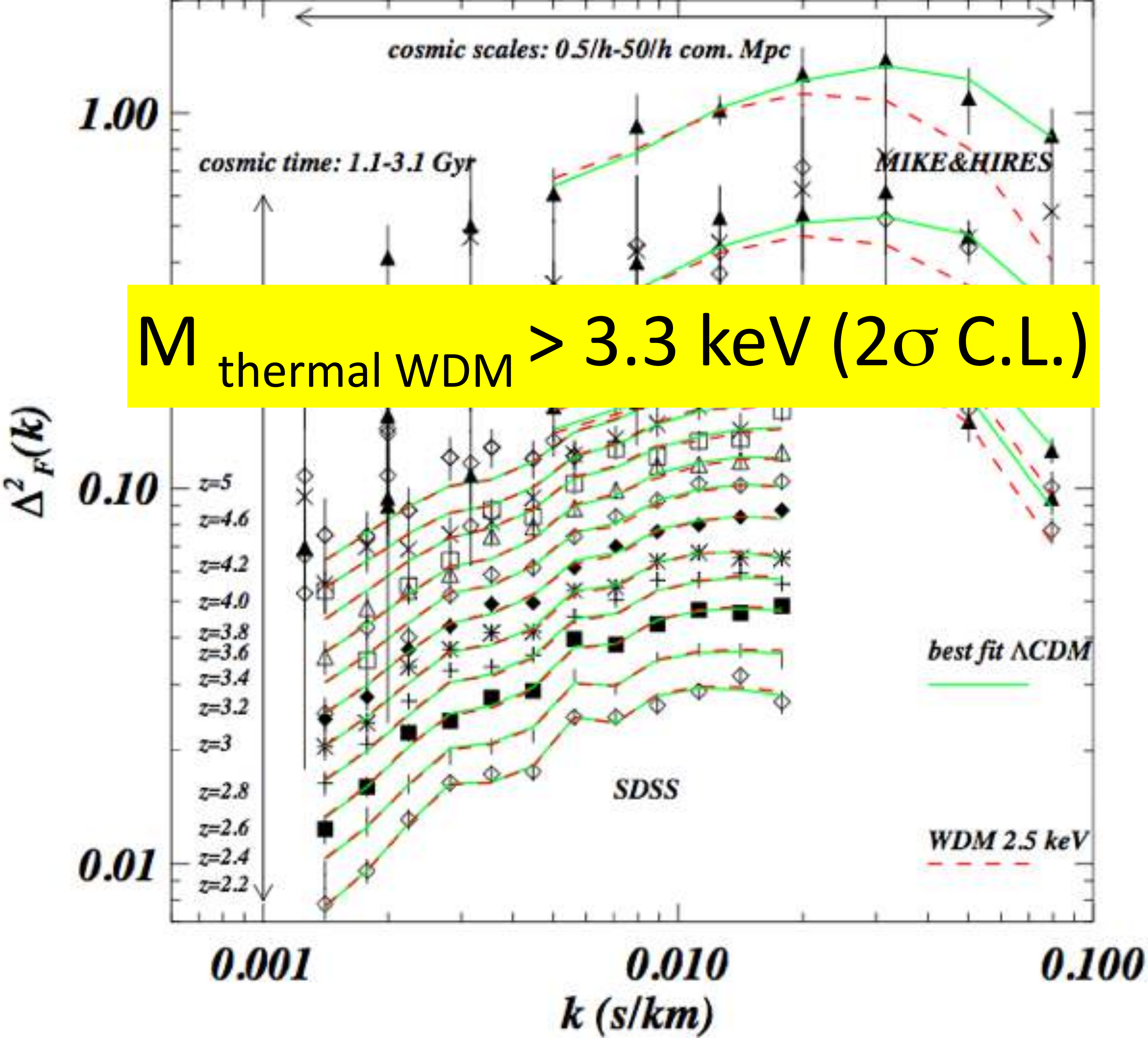
1.00
0.10
0.01
$\Delta^2_F(k)$
MIKE&HIRES
SDSS
0.001
0.010
0.100
k (s/km)



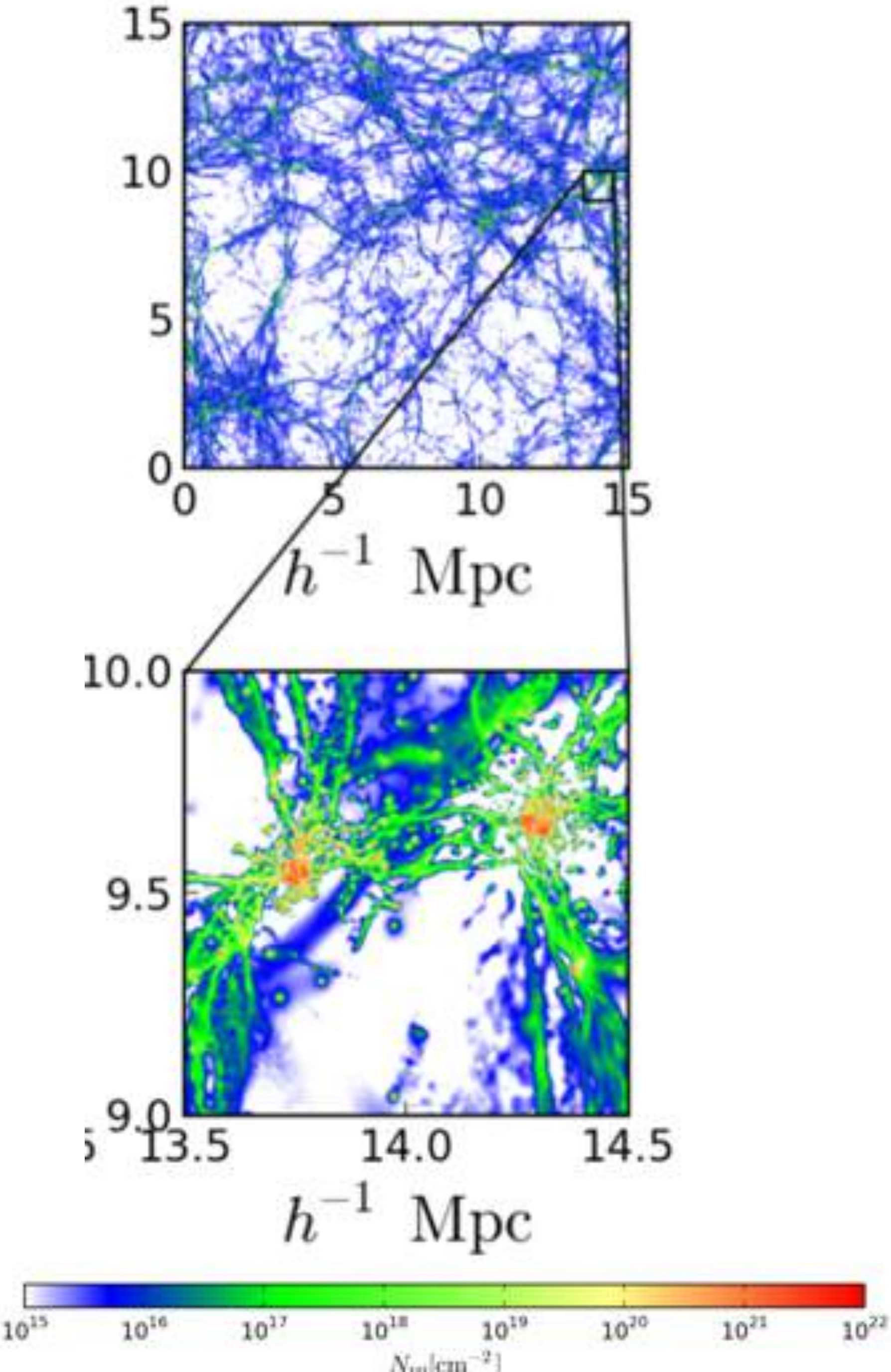
cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)


cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
best fit ΛCDM
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)

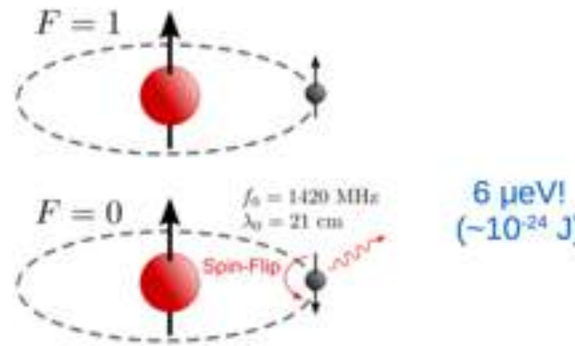
$M_{\text{thermal WDM}} > 3.3$ keV (2σ C.L.)



INTENSITY MAPPING: HI in emission



Proton-electron spin alignment in Hydrogen ground state
Rare "spin-flip" transition (~10^{-7} yr^{-1}) emits λ=21.1cm line



Could be the next LSS
tracer with SKA down
to z=0 from reionization era

WDM SUPPRESSION in 21cm INTENSITY MAPPING

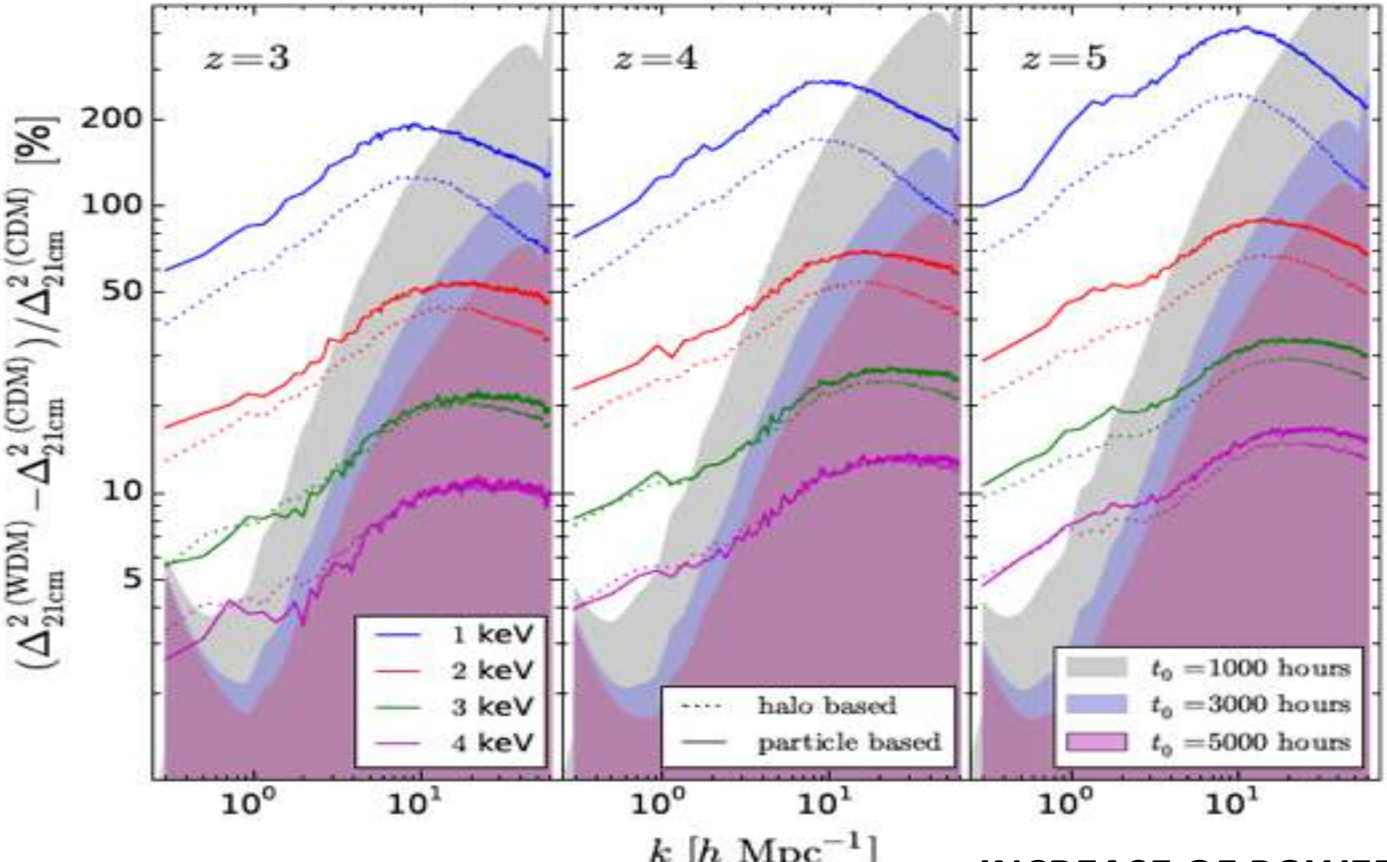
Carucci, Villaescusa, MV, Lapi 2015

$$\overline{\delta T_b}(z) = 23.88\ \bar{x}_{\rm HI}\left(\frac{\Omega_{\rm b}h^2}{0.02}\right)\sqrt{\frac{0.15}{\Omega_{\rm m}h^2}\frac{(1+z)}{10}}\ {\rm mK}$$

$$\delta T_b^s(\nu) = \overline{\delta T_b}(z)\left[\frac{\rho_{\rm HI}(\vec{s})}{\bar{\rho}_{\rm HI}}\right]$$

Contrary to Lyman-alpha forest HI in intensity mapping signal comes from haloes not filaments

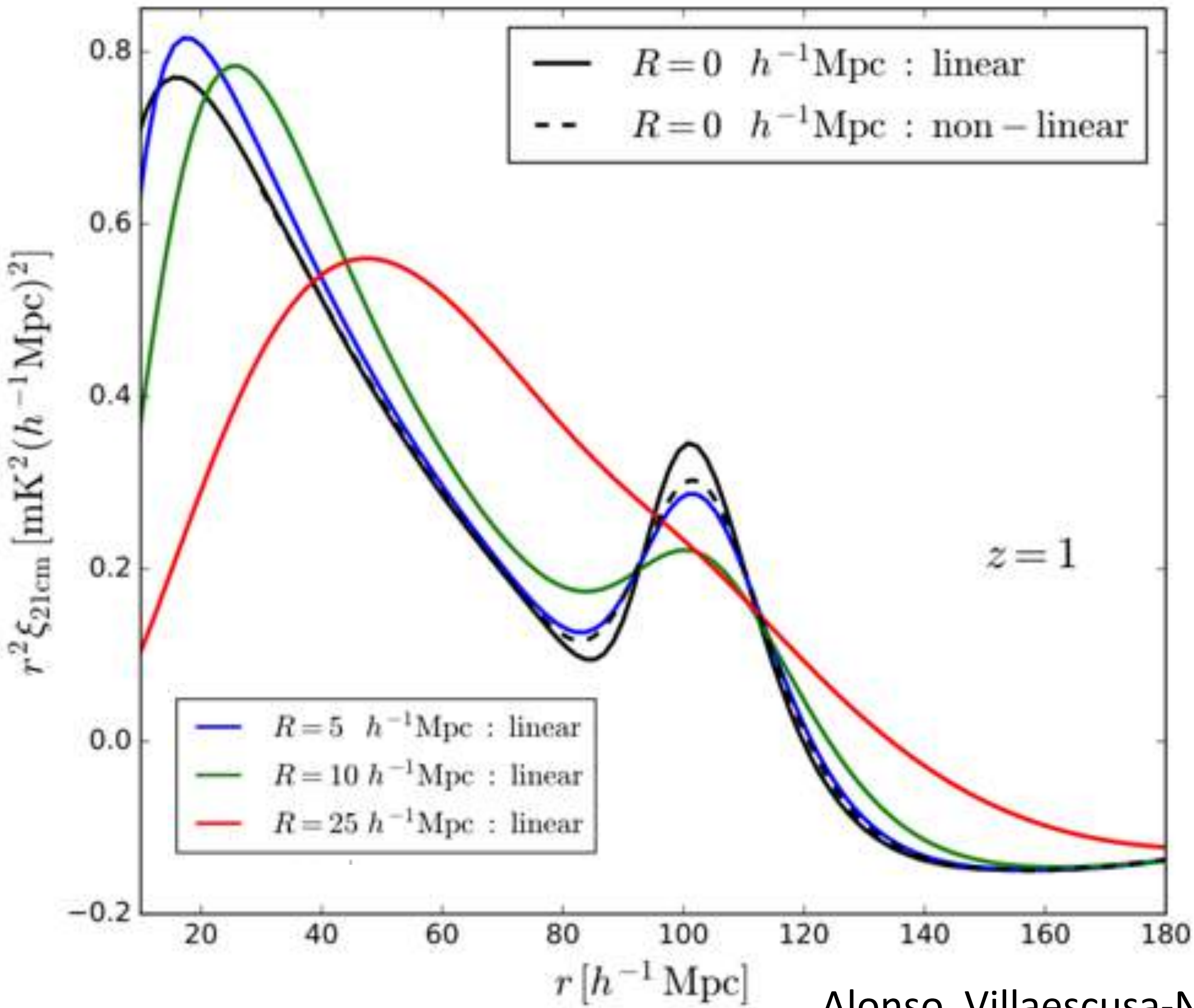
REALISTIC SKA forecasts



INCREASE OF POWER!!!

BAOs in intensity mapping

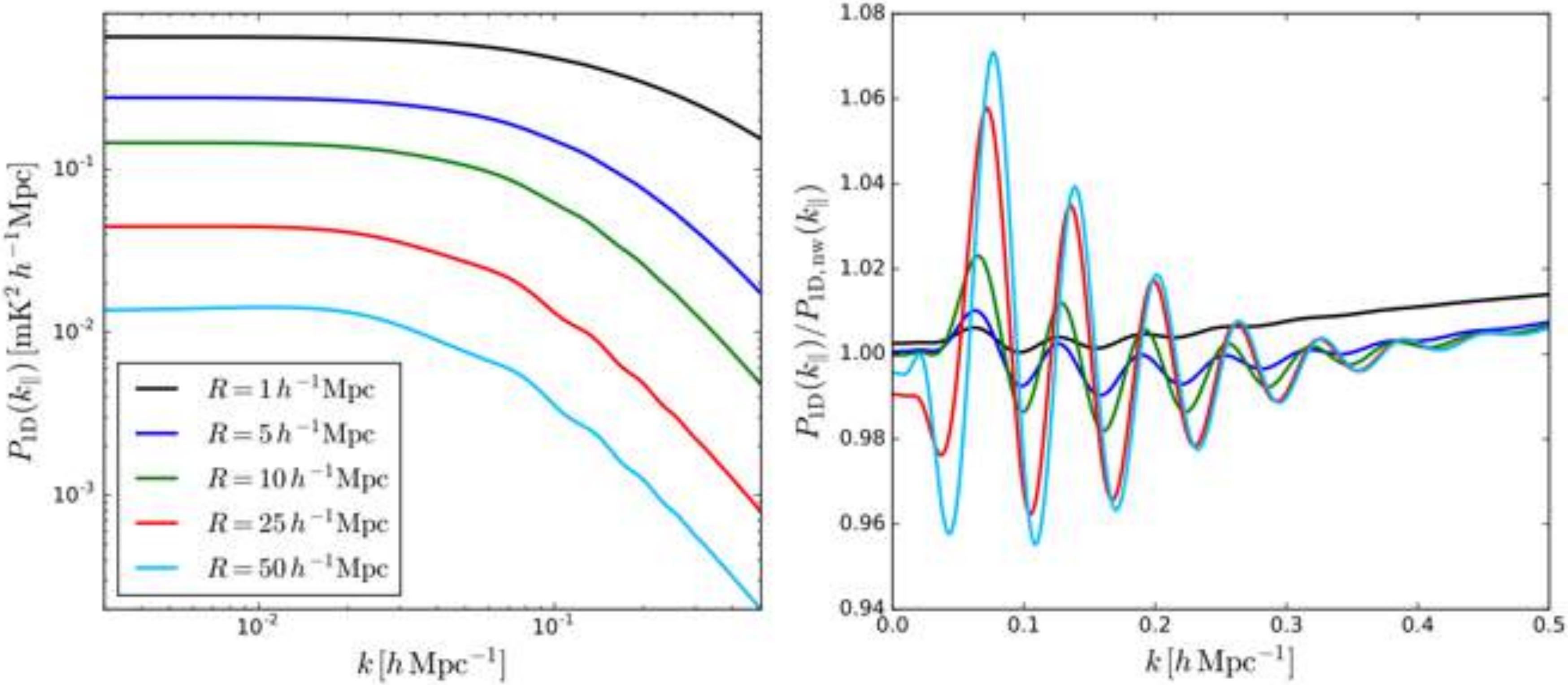
$$P_{21cm}(k,z) = b_{21cm}^2(z) P_m(k,z)$$



Alonso, Villaescusa-Navarro, MV 2016

BAOs in intensity mapping - II

$$\lim_{R\to\infty} P_{21\mathrm{cm,obs,1D}}(k_\parallel, z) = \frac{1}{4\pi R^2} P_{21\mathrm{cm}}(k_\parallel, z)$$

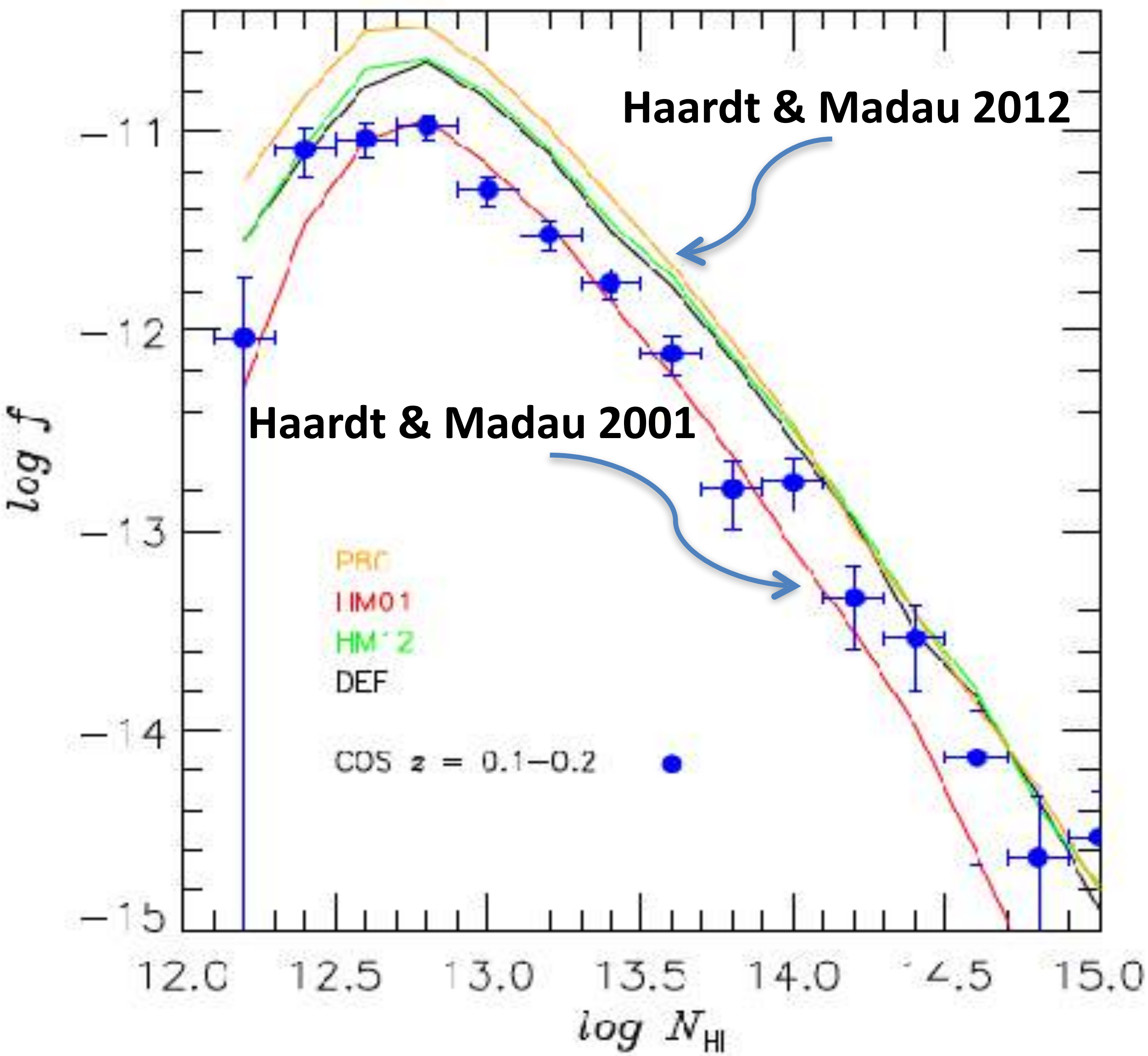


Realistic SKA forecast including foreground removal and treatment of noise show:
H(z) could be determined at z=0.6,1,1.6,2.5 with error of 2.4%,1.5%,1.9%,3.1%

Alonso, Villaescusa-Navarro, MV 2016

LOW REDSHIFT LY-ALPHA

Column density distribution of HI lines

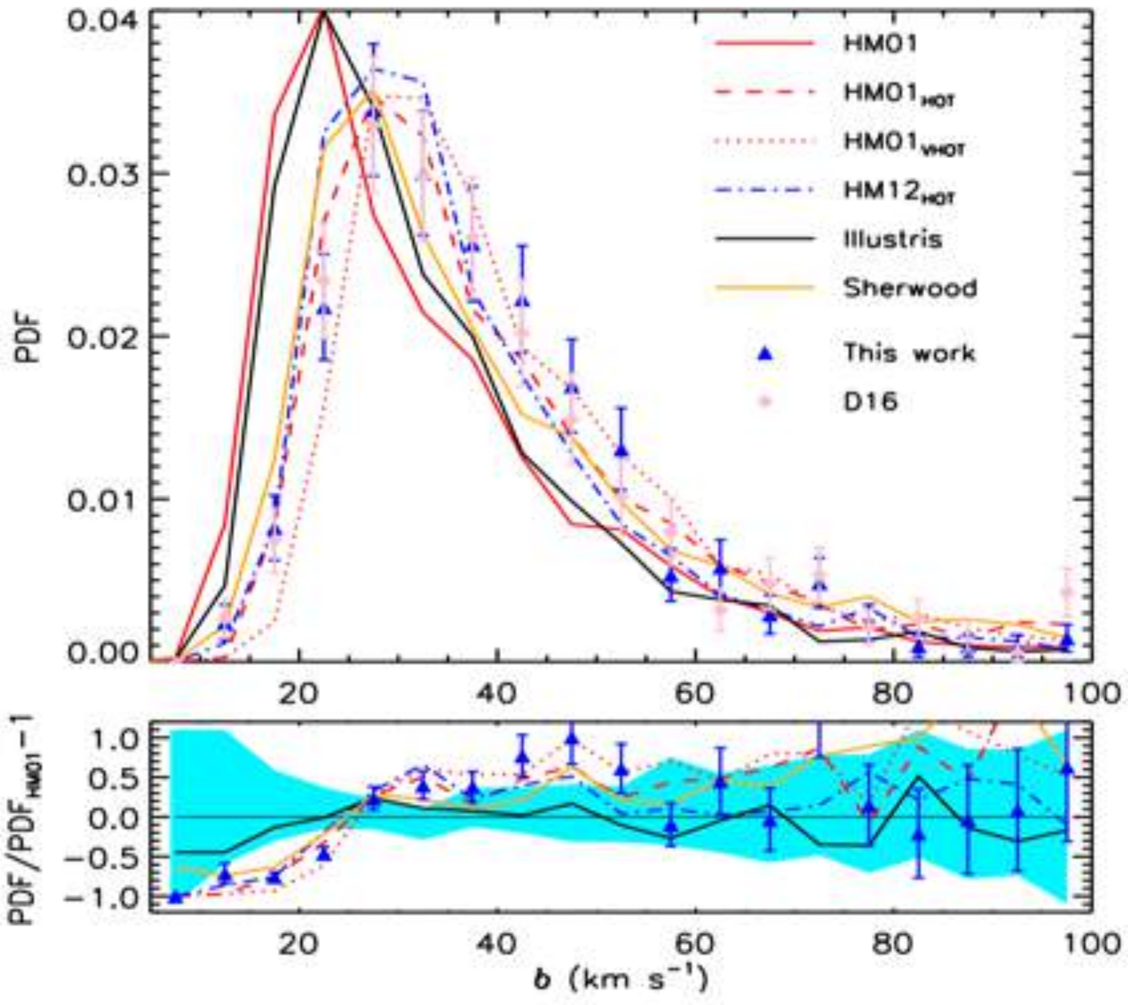


HI lines are probing CGM environments at z~0.1 with d~4-40

Photoionization equilibrium

Latest HM12 bacgkround results in number of lines that overpredict by ~3 compared to earlier models

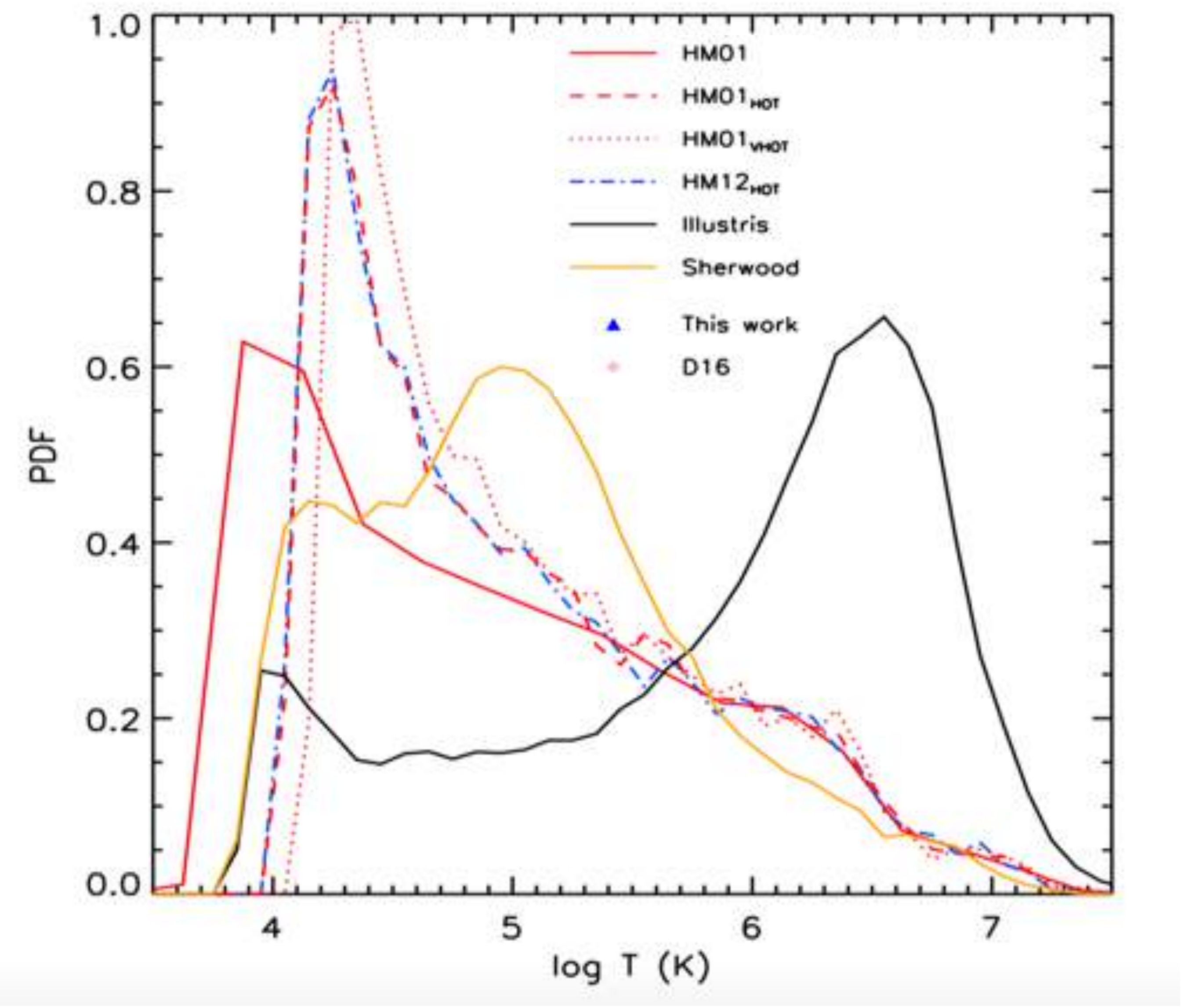
Line widths distribution



Line widths distribution very interesting:
on the low side even for somewhat extreme feedback models

Hotter CGM at low-z than obtained from the low-z evolution of hydro sims?

Line widths distribution-II



CONCLUSIONS

BAOs: clear detection, sytematics under control, tension with Planck (statistical fluctuations or systematics)?

NEUTRINOS:

no support for non zero neutrino masses from IGM data total neutrino mass <0.12 eV 2σ C.L.

WDM:

consistency with cold dark matter > 3.3 keV relics 2σ C.L.

LOW-z Lyman-alpha: exquisite UV thermometer