Cosmology with massive neutrinos: constraints and perspectives

Matteo Viel – INAF/OATS & INFN/TS

Neutrino Telescopes 2015 – Venice – 4th March 2015

MASSIVE NEUTRINOS

Summary

Cosmological neutrinos from linear theory to non-linearities

Introducing a ”new observable”: the Intergalactic Medium

Constraints on neutrino mass

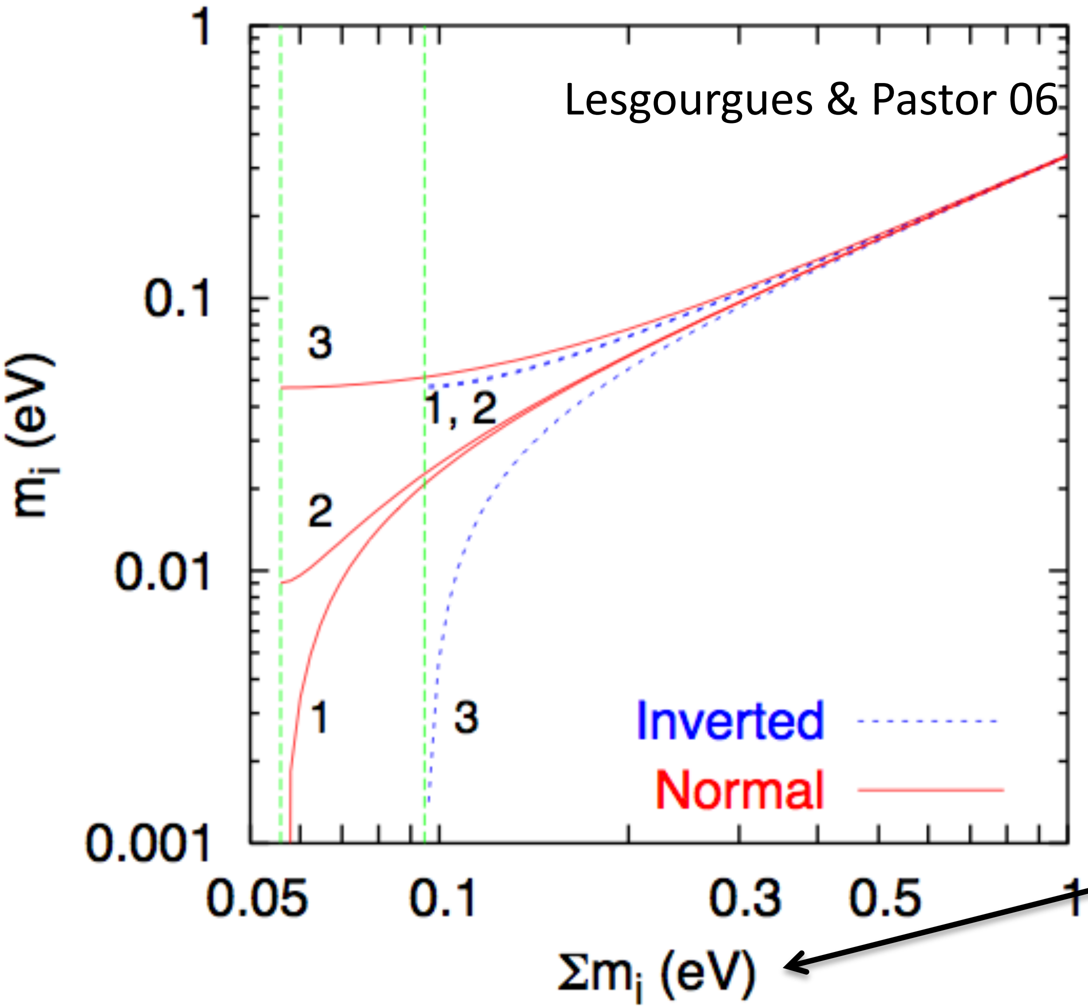
Constraints on cold dark matter coldness (e.g. keV sterile neutrinos)

Future perspectives

Conclusions

COSMOLOGICAL NEUTRINOS

COSMOLOGICAL NEUTRINOS - I: WHAT TO START FROM



COSMOLOGY

constraints on the sum of the neutrino masses

$$0.056\,(0.095)\ \text{eV} \lesssim \sum_i m_i \lesssim 6\ \text{eV}$$

COSMOLOGICAL NEUTRINOS - II: FREE-STREAMING SCALE

Neutrino thermal velocity

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

Neutrino free-streaming scale

$$k_{FS}(t) = \left(\frac{4\pi G\bar{\rho}(t)a^2(t)}{v_{\rm th}^2(t)}\right)^{1/2}$$

Scale of non-relativistic transition

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

THREE COSMIC EPOCHS

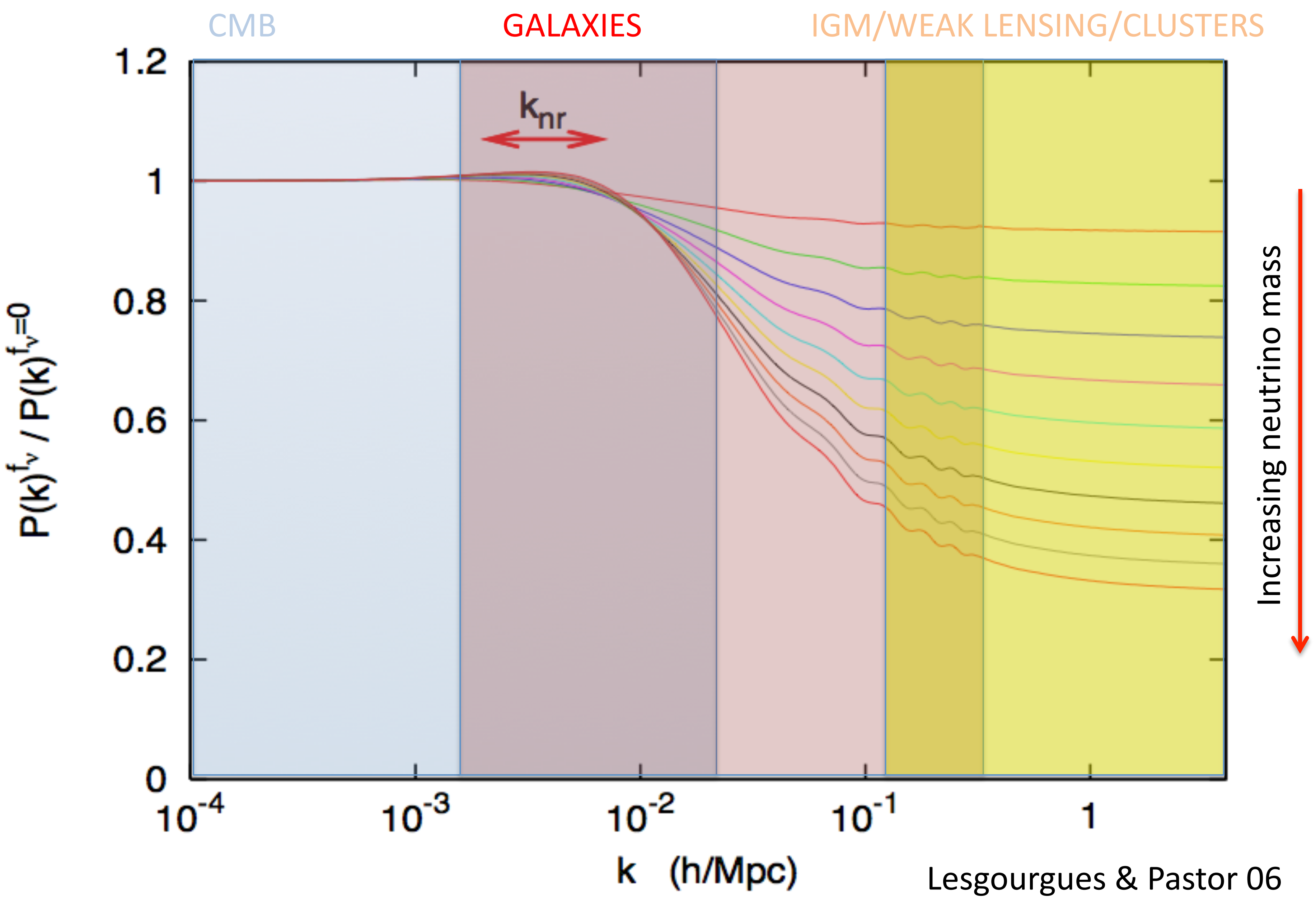
RADIATION ERA z>3400

MATTER RADIATION z<3400

NON-RELATIVISTIC TRANSITION z ~ 500
(for a 0.3 eV total mass)

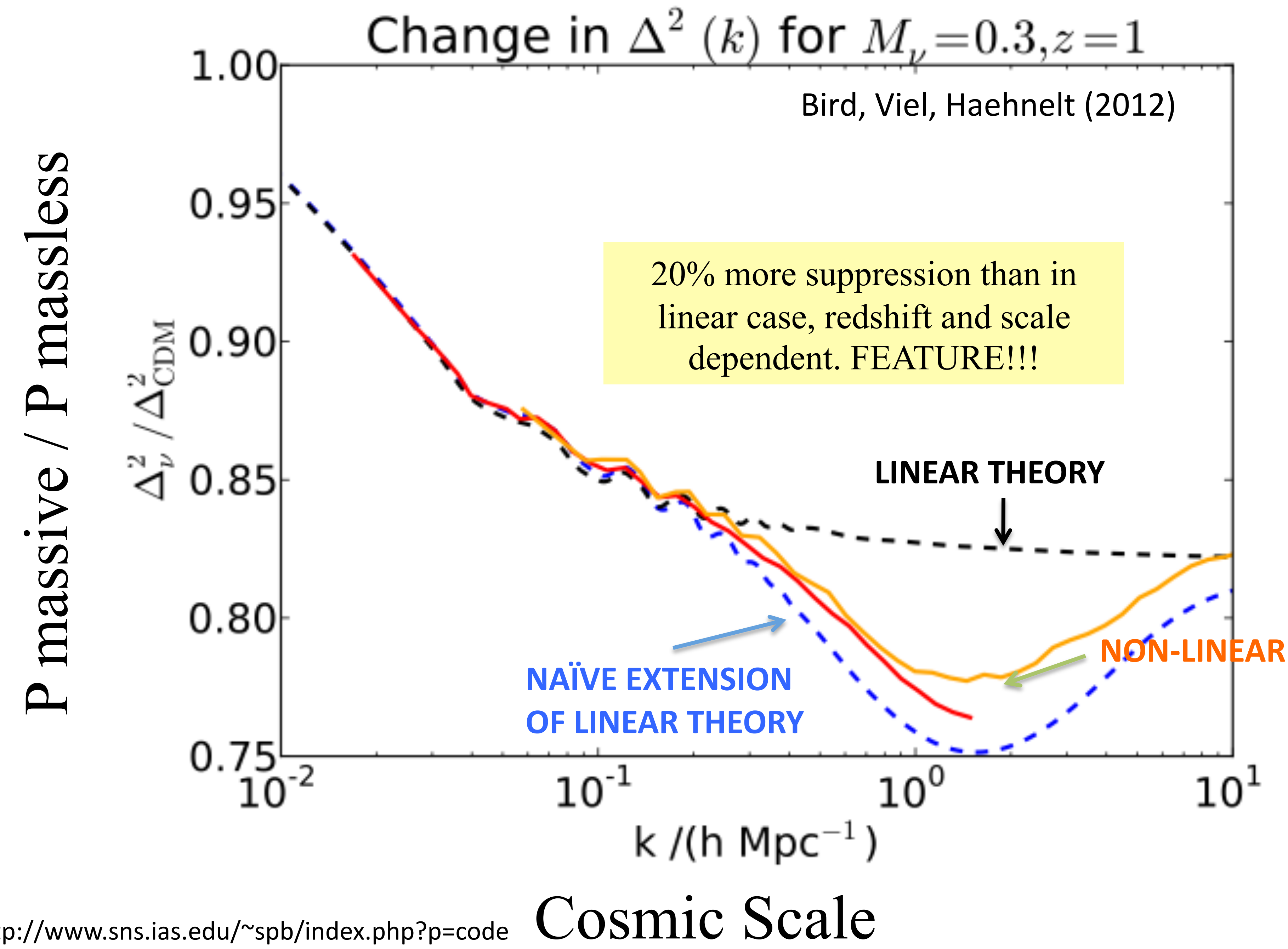
Below k_{nr} there is suppression in power at scales that are cosmologically important

COSMOLOGICAL NEUTRINOS - III: LINEAR MATTER POWER



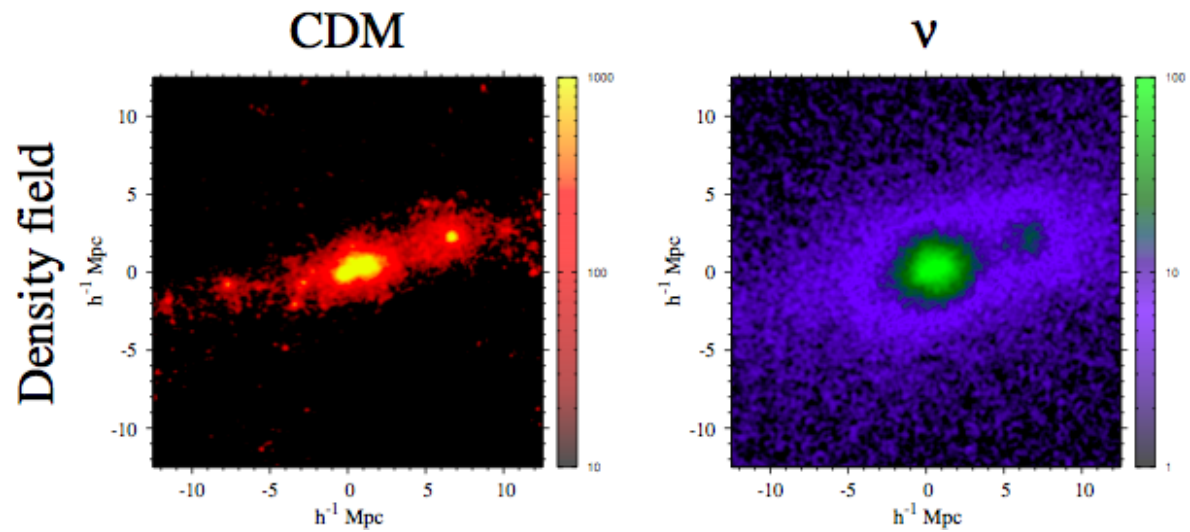
Lesgourgues & Pastor 06

COSMOLOGICAL NEUTRINOS: NON-LINEAR MATTER POWER

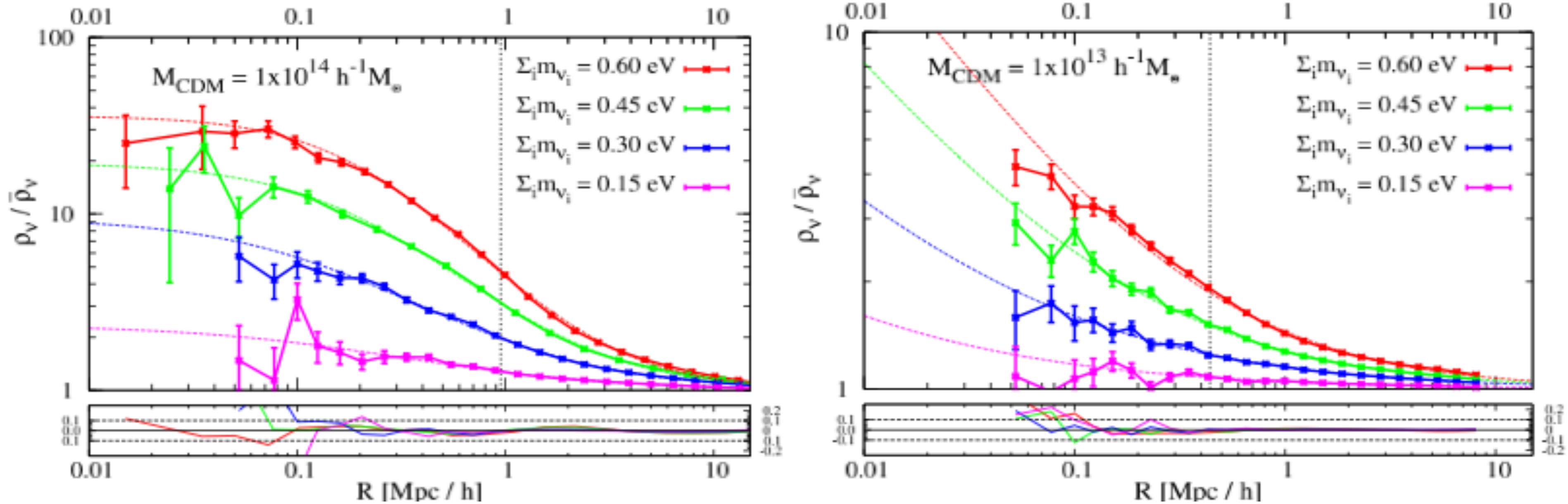


http://www.sns.ias.edu/~spb/index.php?p=code

CHARACTERIZING THE NEUTRINO HALO?



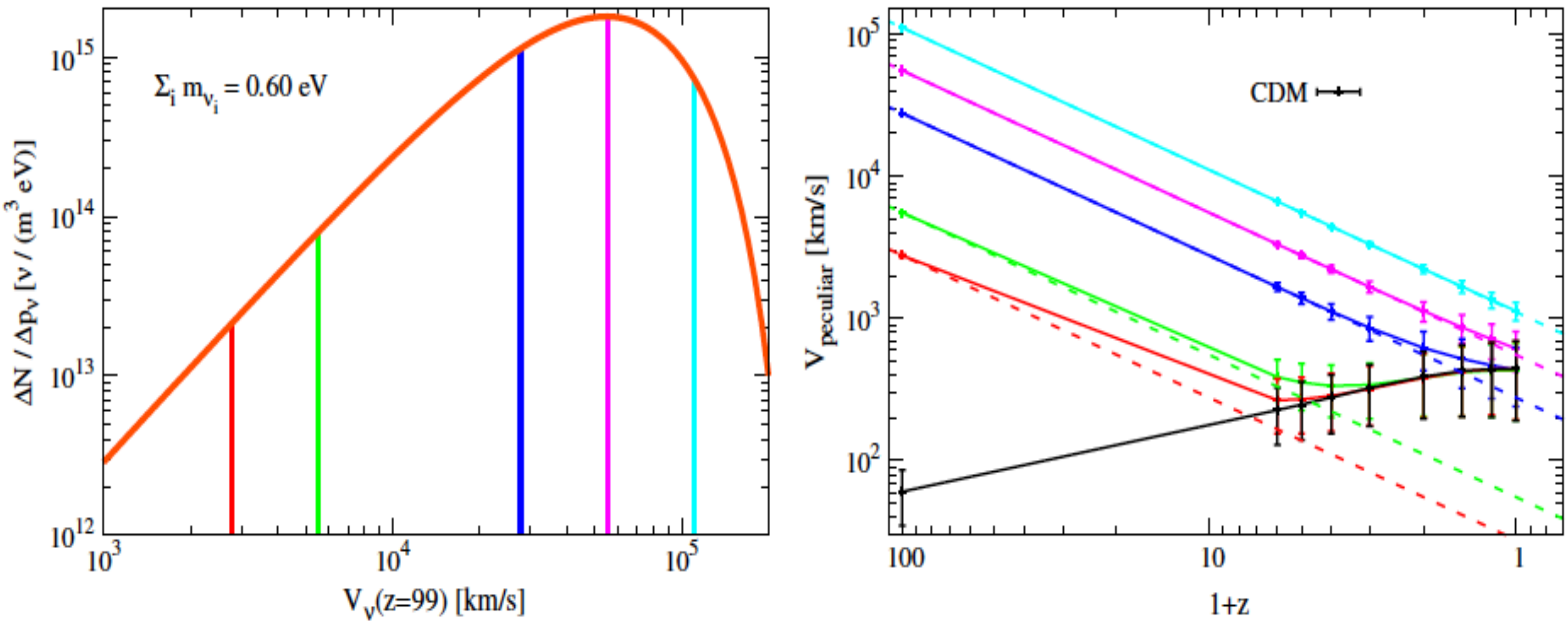
$$\delta_\nu(r) = \frac{\rho_\nu(r) - \bar{\rho}_\nu}{\bar{\rho}_\nu} = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$



Villaescusa-Navarro, Bird, Garay, Viel, 2013, JCAP, 03, 019

Marulli, Carbone, Viel+ 2011, MNRAS, 418, 346

CHARACTERIZING NEUTRINO PECULIAR VELOCITIES



Villaescusa-Navarro, Bird, Garay, Viel, 2013, JCAP, 03, 019

MODELLING NEUTRINOS WITHOUT N-BODY SIMULATIONS

$$P(k) = \left(\frac{\bar{\rho}_c}{\bar{\rho}}\right)^2 P_c(k) + 2\,\frac{\bar{\rho}_c \bar{\rho}_\nu}{\bar{\rho}^2}\,P_{c\nu}(k) + \left(\frac{\bar{\rho}_\nu}{\bar{\rho}}\right)^2 P_\nu(k)$$

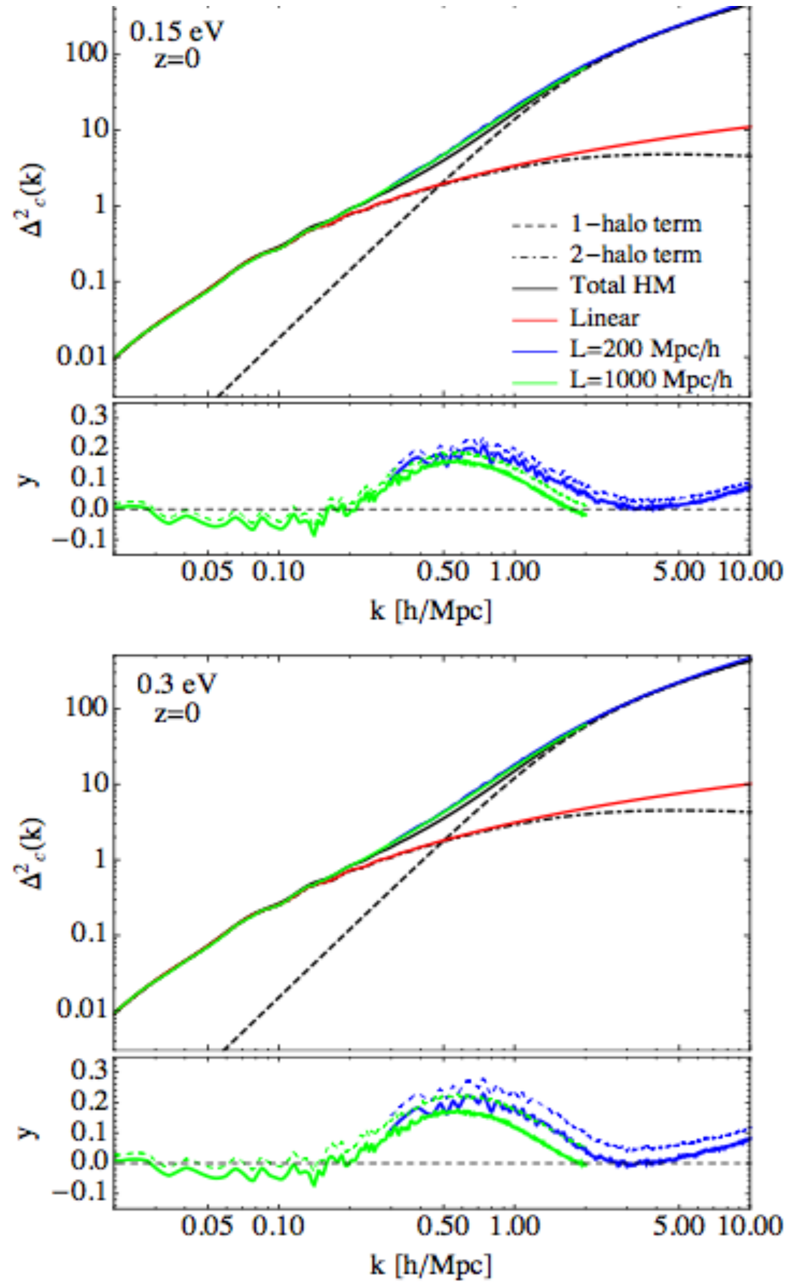
- Assumption: all matter within haloes 1h and 2h terms

- Simple modelling of non-linear power spectra (including cross-spectra)

- When used to predict ratios w.r.t. massless case it is as good as hydro/N-body to 2% level

- When used to compute actual power it suffers from limitation and it is good at the 20% level

NON LINEAR POWER SPECTRA



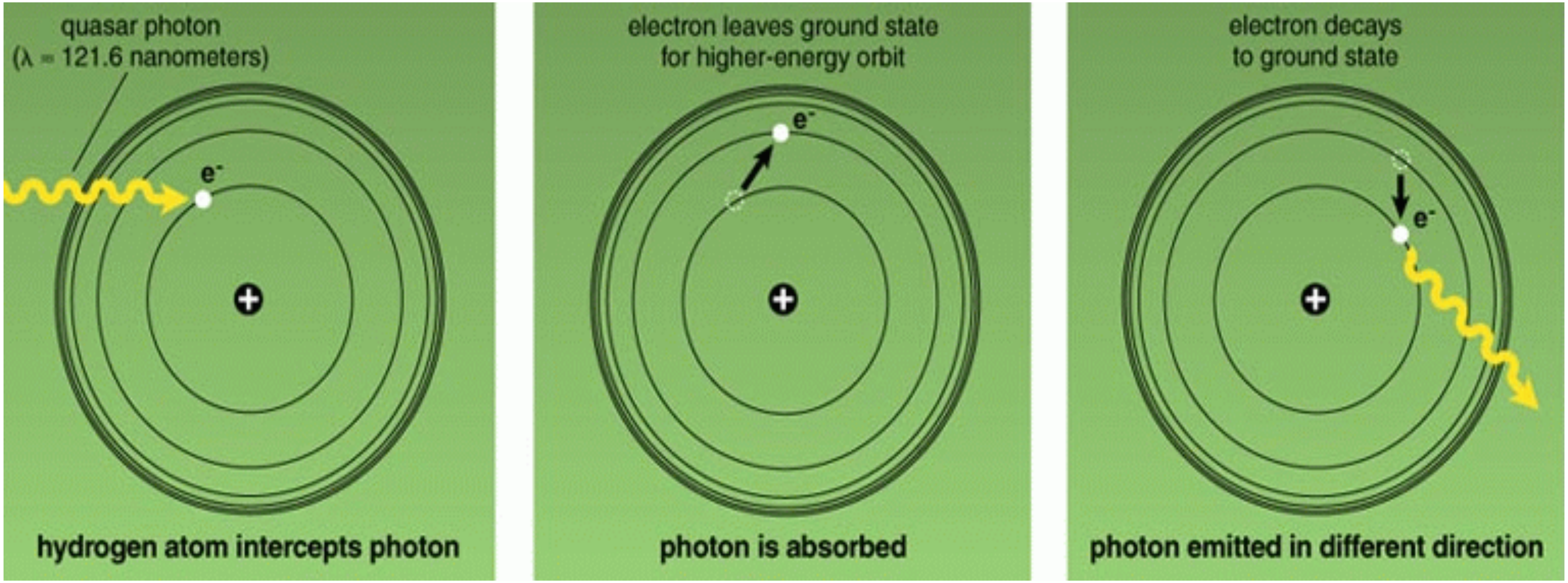
Massara, Villaescusa, MV (2014)

IGM

i.e. diffuse matter between galaxies

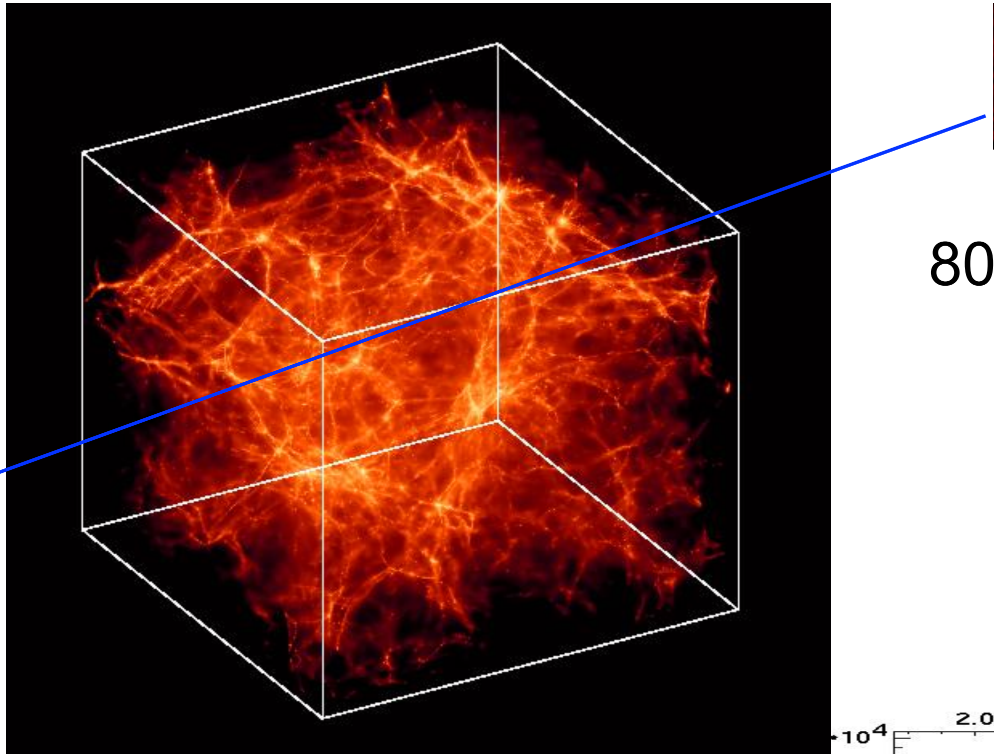
The Lyman-α forest

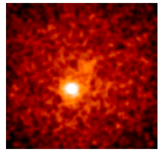
Lyman-α absorption is the main manifestation of the IGM

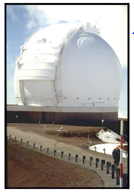


Tiny neutral hydrogen fraction after reionization…. But large cross-section

The Intergalactic Medium: Theory vs. Observations



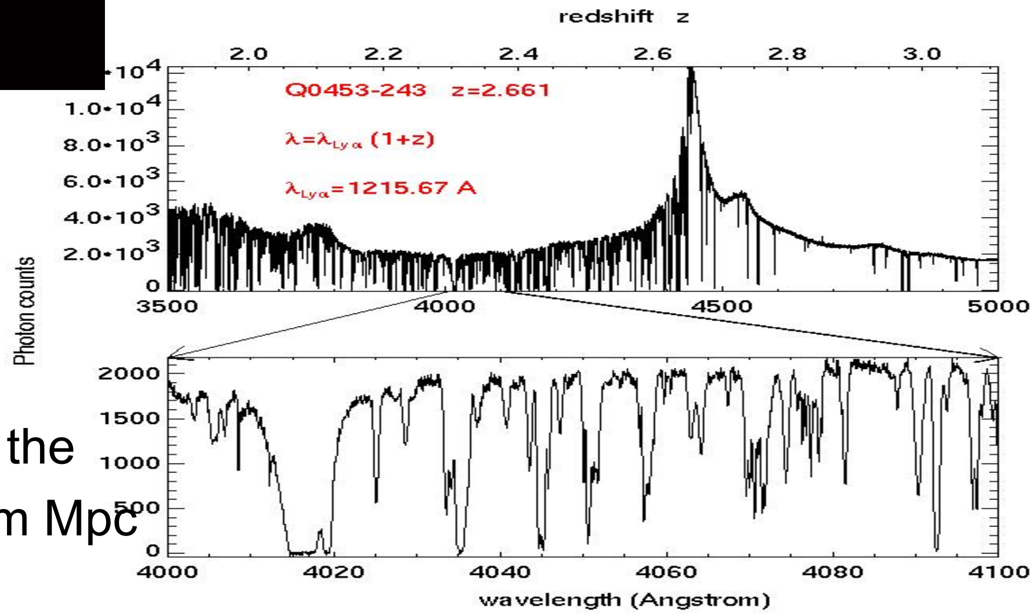




80 % of the baryons at z=3
are in the **Lyman-α forest**

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

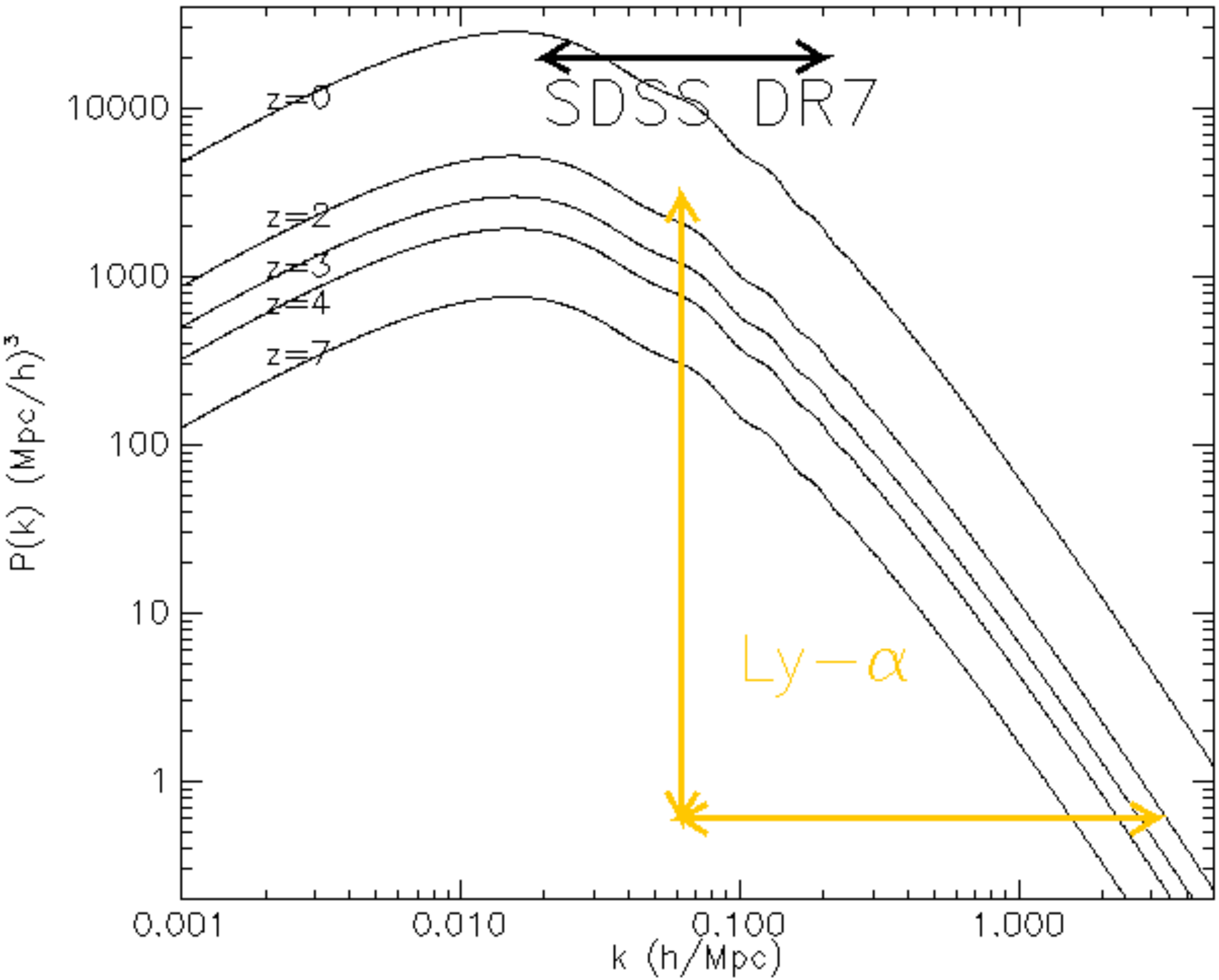
baryons as tracer of the dark matter density field



$\delta_{IGM} \sim \delta_{DM}$ at scales larger than the Jeans length ~ 1 com Mpc

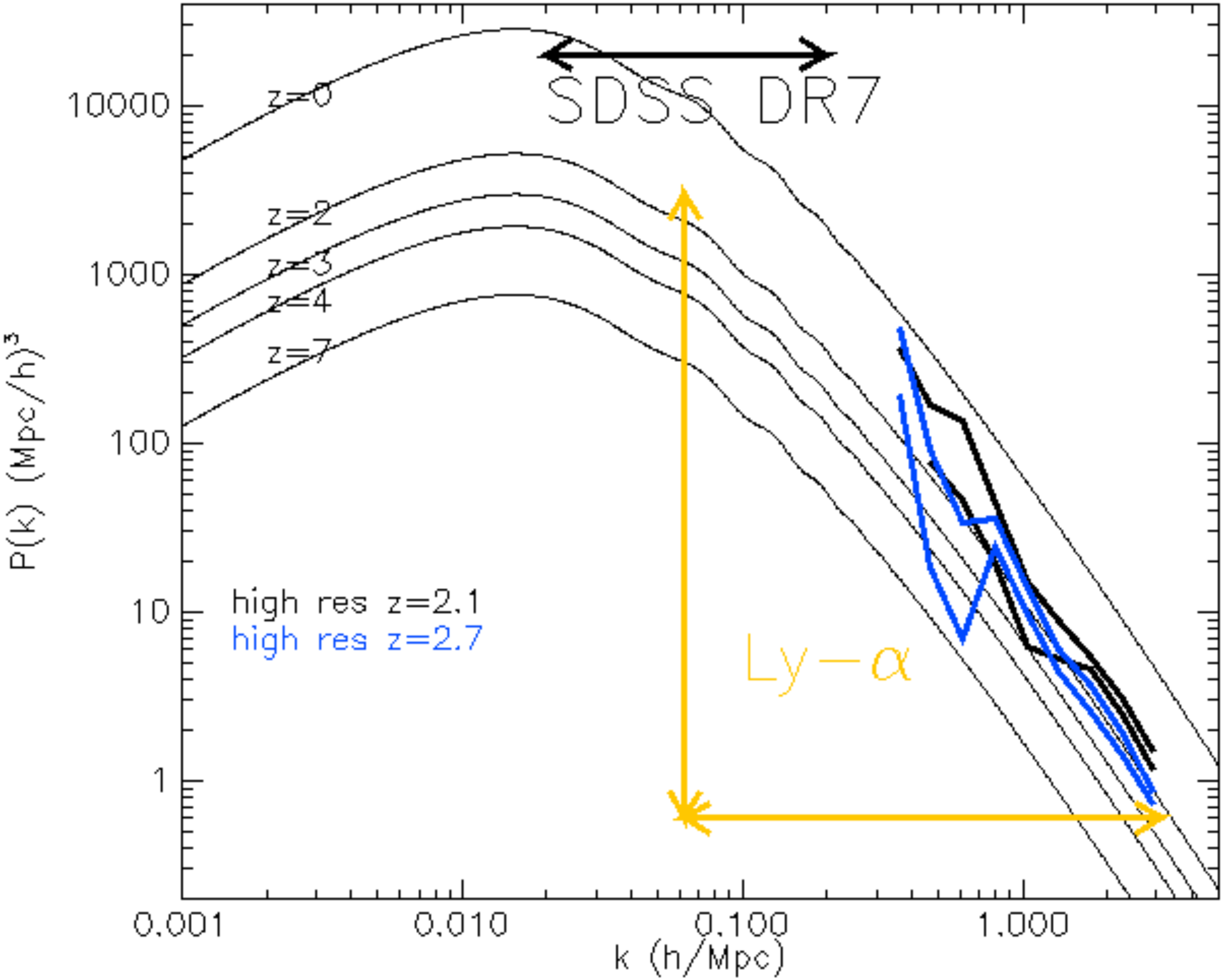
$\tau \sim (\delta_{IGM})^{1.6}\, T^{-0.7}$

DATA vs THEORY

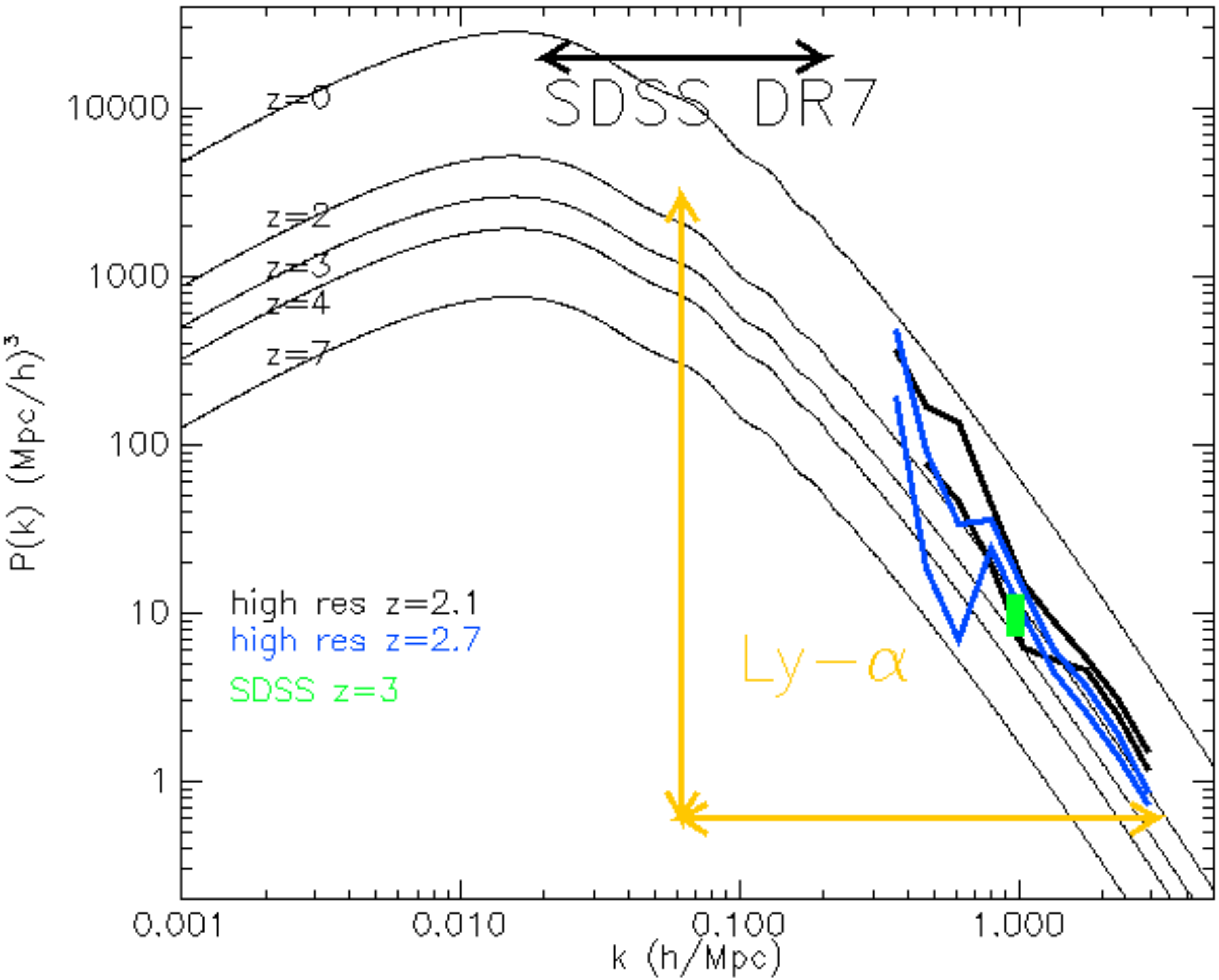


DATA vs THEORY

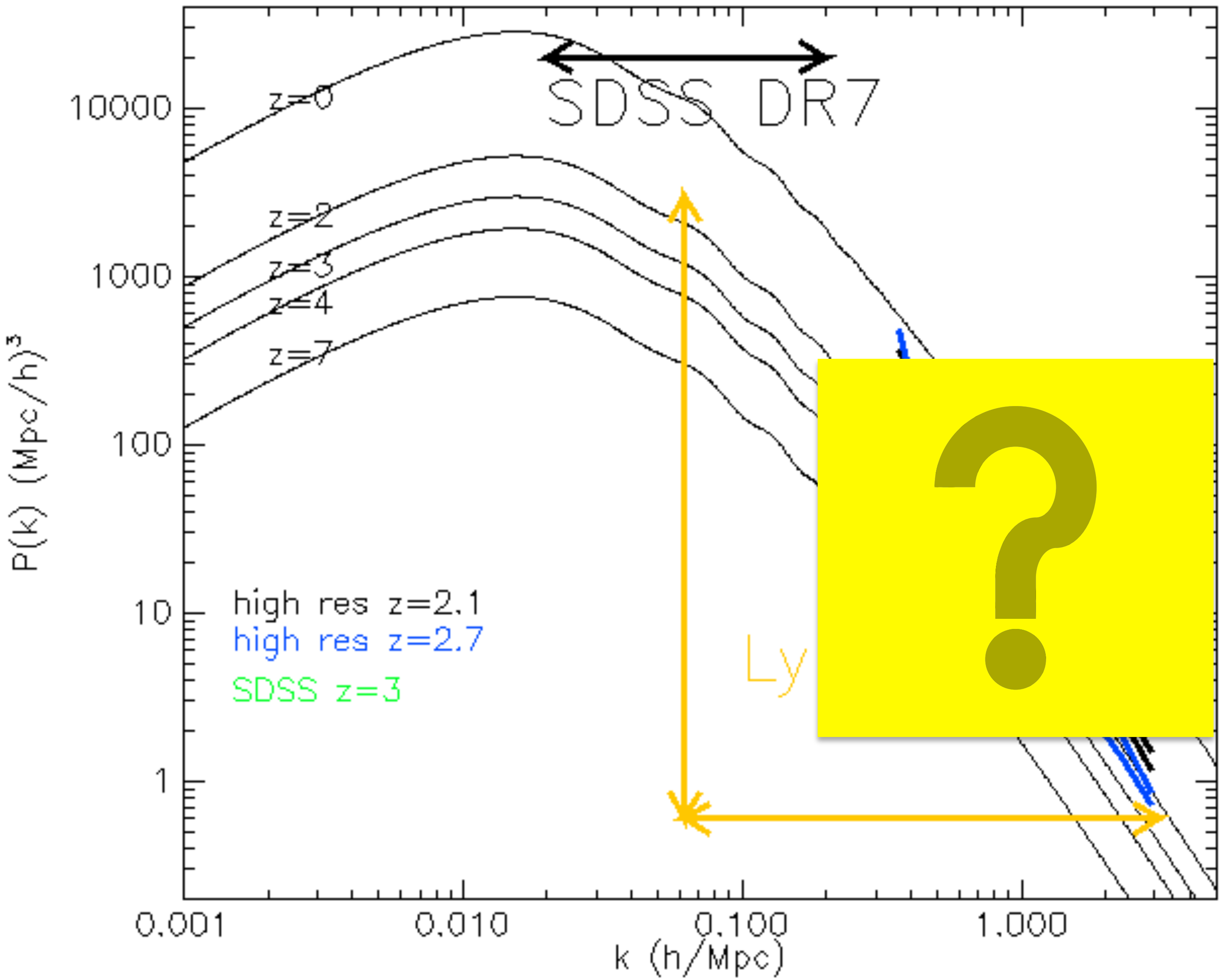
$P_{FLUX}(k,z) = bias^2(k,z) \times P_{MATTER}(k,z)$



DATA vs THEORY

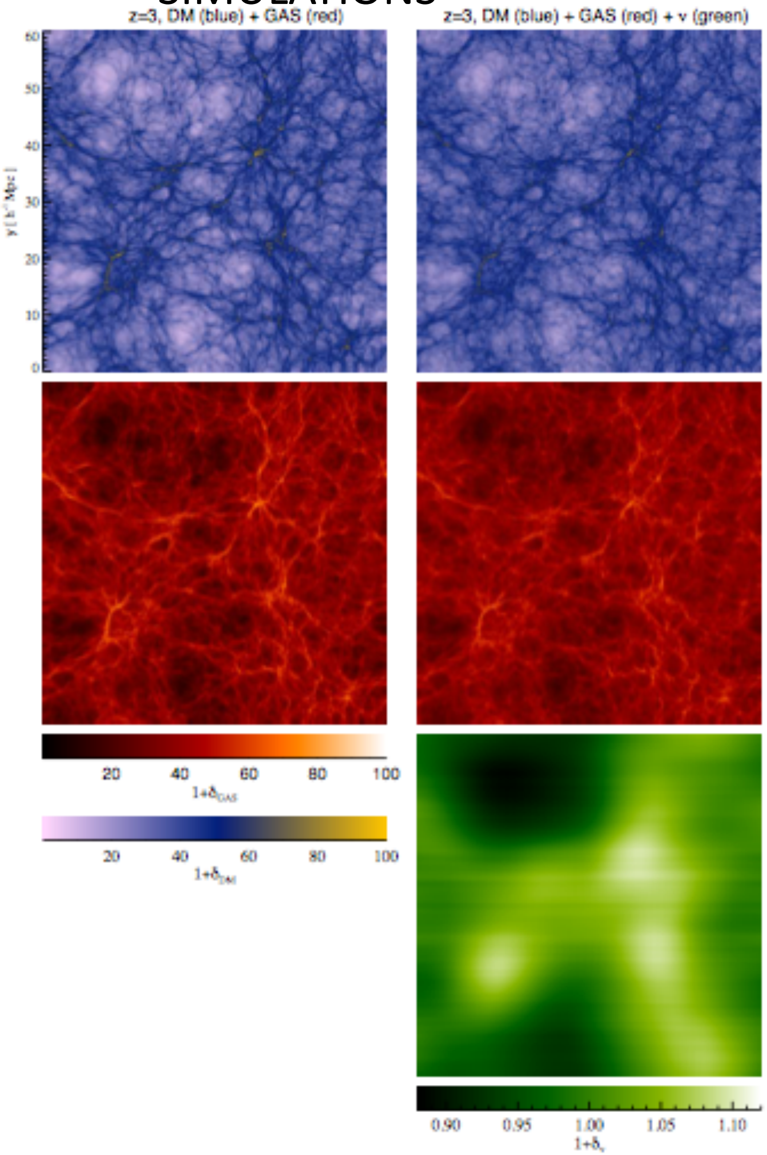


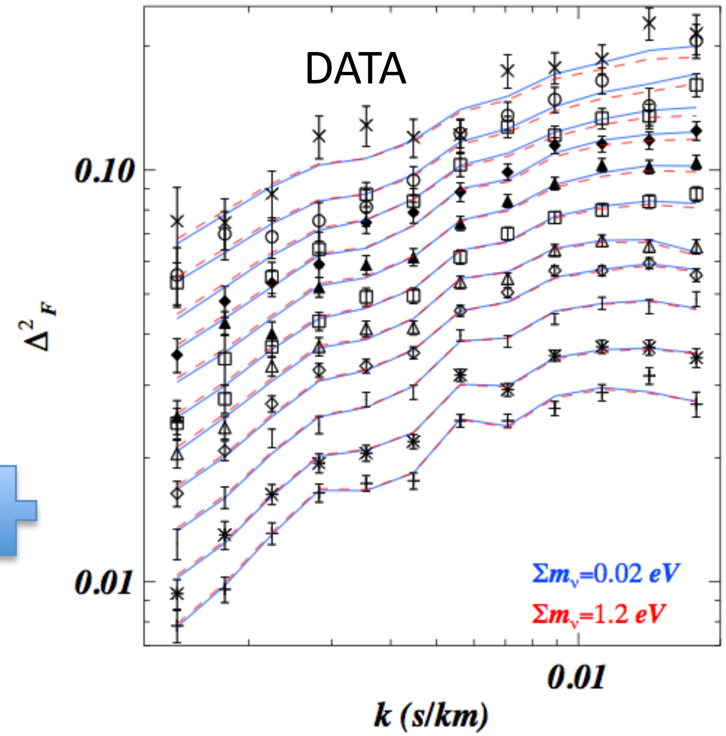
DATA vs THEORY



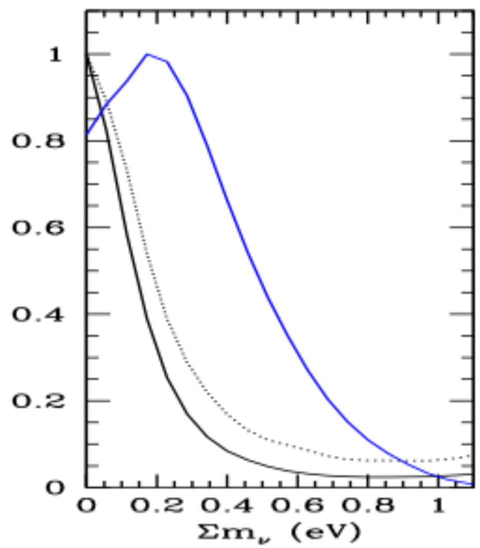
NEUTRINOS IN THE IGM

SIMULATIONS





CONSTRAINTS

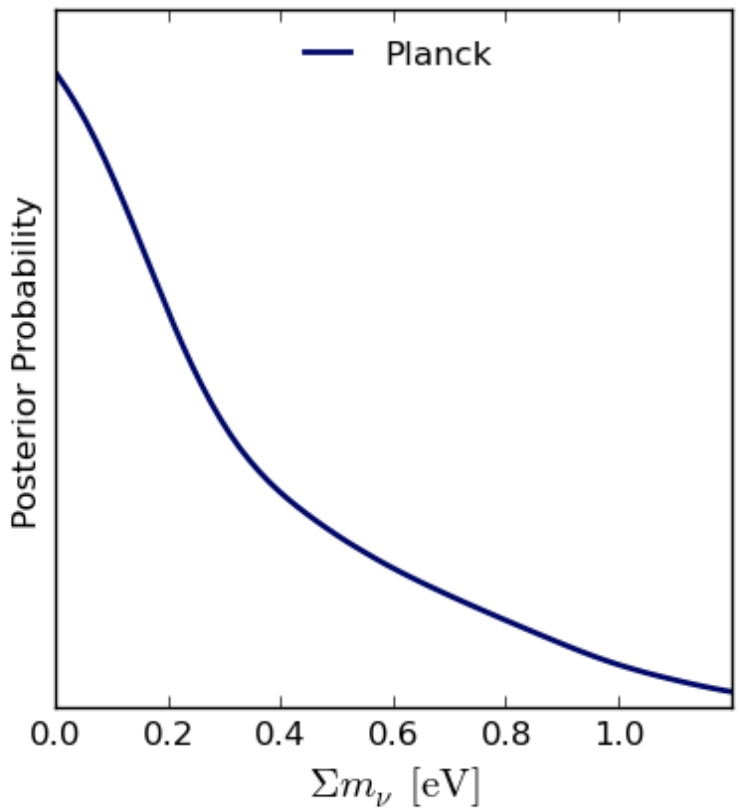


FROM IGM ONLY:

$\Sigma m_\nu < 0.9$ eV(2σ)

Viel, Haehnelt, Springel 2010

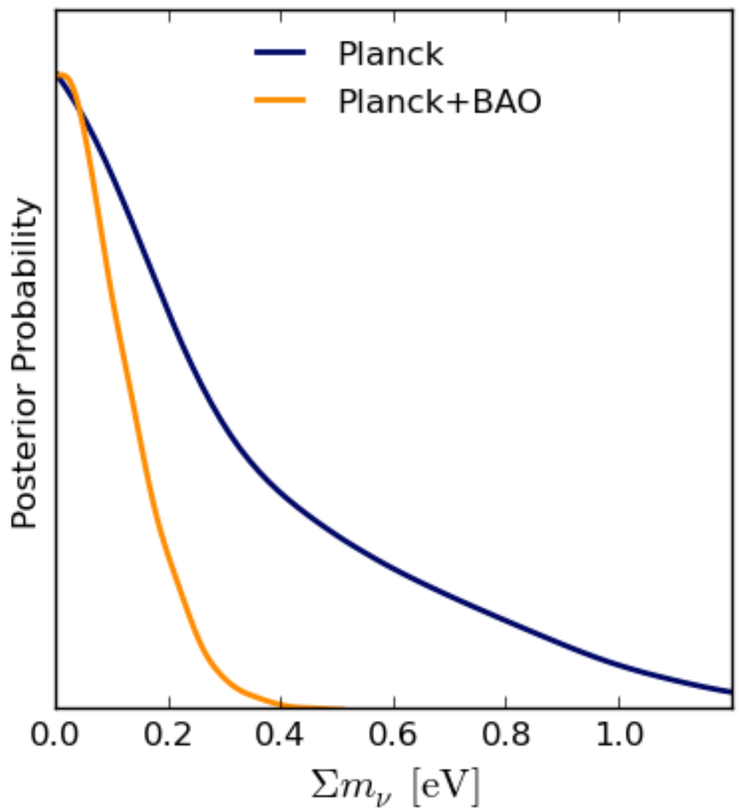
CONSTRAINTS on NEUTRINO MASSES FROM Planck: I



$\Sigma m_\nu < 0.93$ eV(2σ)

Costanzi+ 2014, JCAP

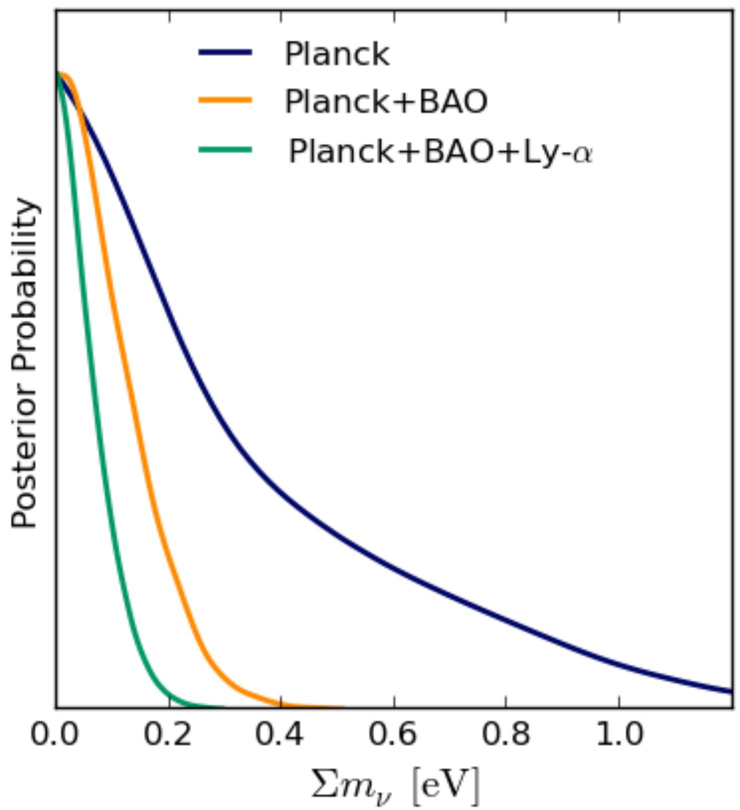
CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO: II



$$\Sigma m_\nu < 0.24 \text{ eV} (2\sigma)$$

Costanzi+ 2014

CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+old Lya: III



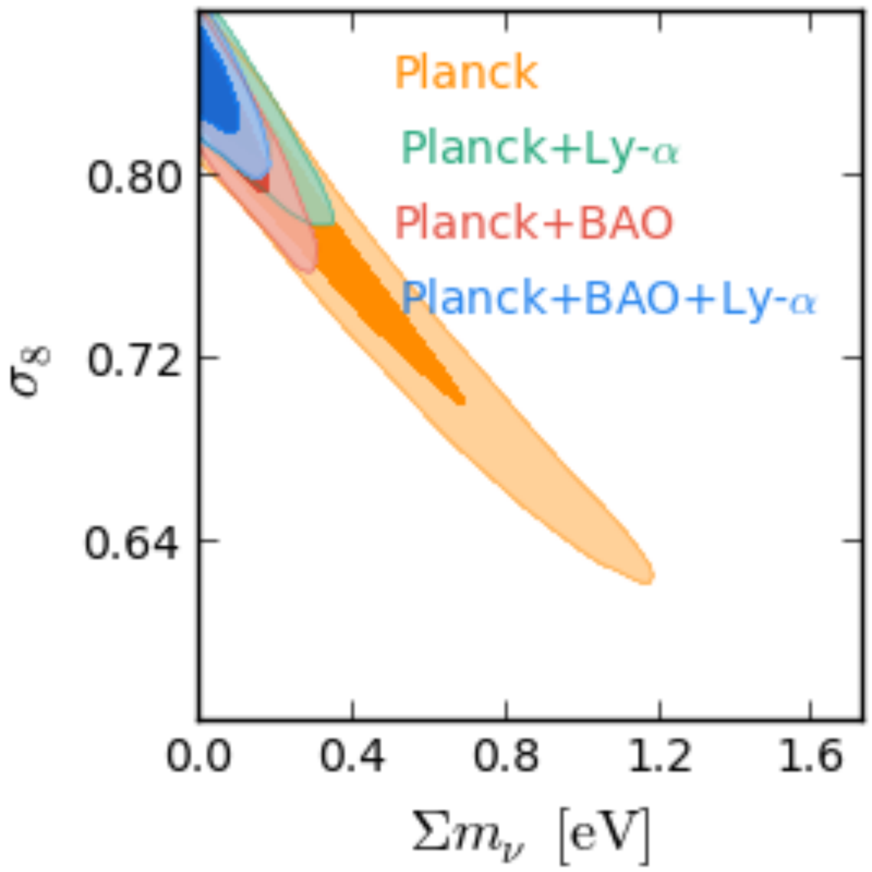
$\Sigma m_\nu < 0.14$ eV(2σ)

Costanzi+ 2014

CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+old Lya: IV

2σ upper limits

Planck:	$M_\nu < 0.93$ eV
Planck+Lya:	$M_\nu < 0.27$ eV
Planck+BAO:	$M_\nu < 0.24$ eV
Planck+BAO+Lyα:	$M_\nu < 0.14$ eV



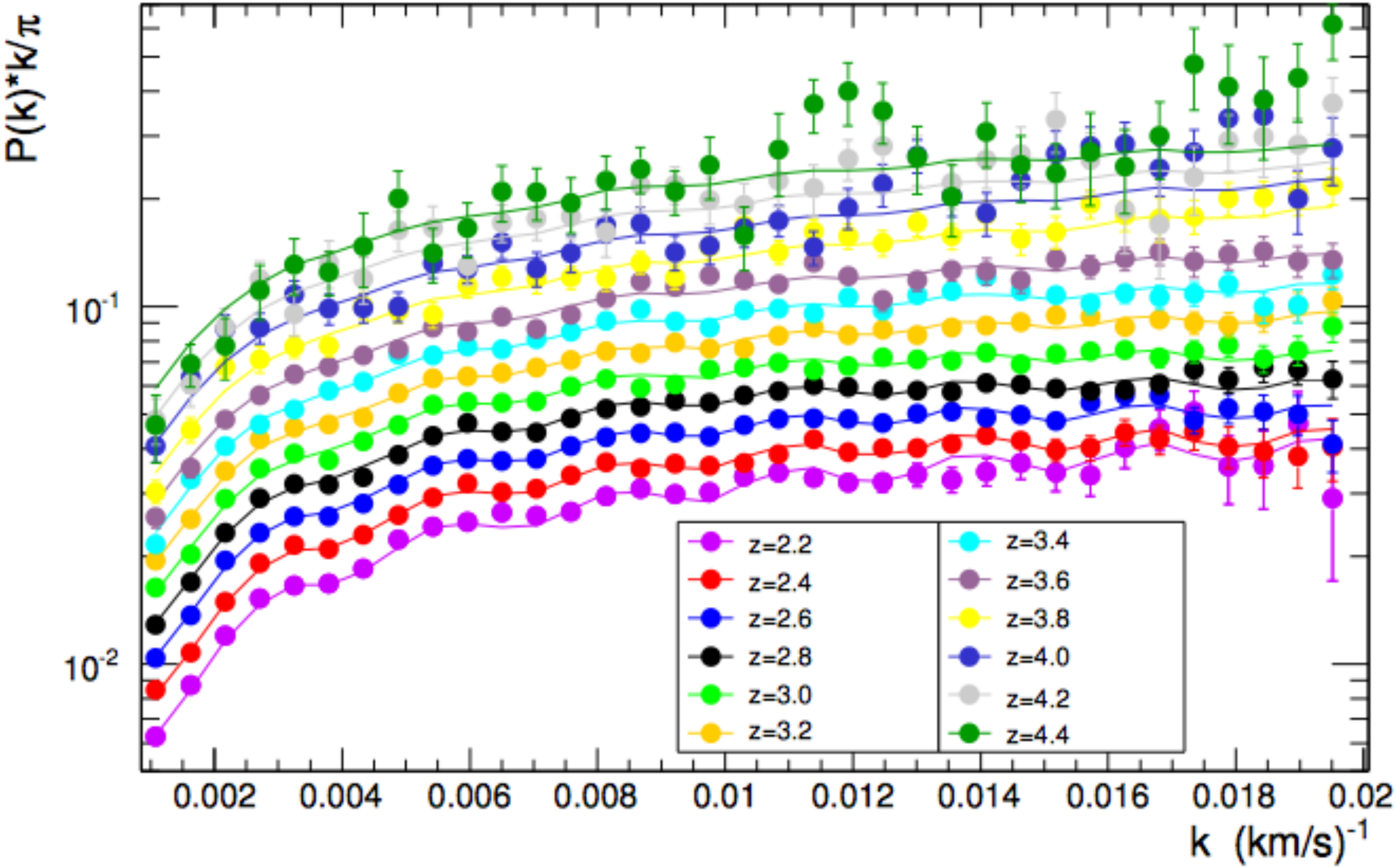
2 eV
29 eV
59 eV
.9 eV

Costanzi, Sartoris, MV, Borgani (2014)

GROWTH OF STRUCTURES AT HIGH REDSHIFT

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

Nathalie Palanque-Delabrouille,[a,b] Christophe Yèche,[a] Julien Lesgourgues,[c,d,e] Graziano Rossi,[a,f] Arnaud Borde,[a] Matteo Viel,[g,h] Eric Aubourg,[i] David Kirkby,[j] Jean-Marc LeGoff,[a] James Rich,[a] Natalie Roe,[b] Nicholas P. Ross,[k] Donald P. Schneider,[l,m] David Weinberg[n]



GRID OF HYDRODYNAMICAL SIMULATIONS

	Parameter	Central value	Range
Cosmological Parameters	n_s	0.96	± 0.05
	σ_8	0.83	± 0.05
	Ω_m	0.31	± 0.05
	H_0	67.5	± 5
Astrophysical Parameter	$T_0(z=3)$	14000	± 7000
	$\gamma(z=3)$..	1.3	± 0.3
	A^τ	0.0025	± 0.0020
	η^τ	3.7	± 0.4
Neutrino mass	$\sum m_\nu$ (eV)	0.0	0.4, 0.8

Astrophysics usually has a different redshift evolution compared to cosmology!

If my data cover a relatively wide redshift range then I can break the degeneracies

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)

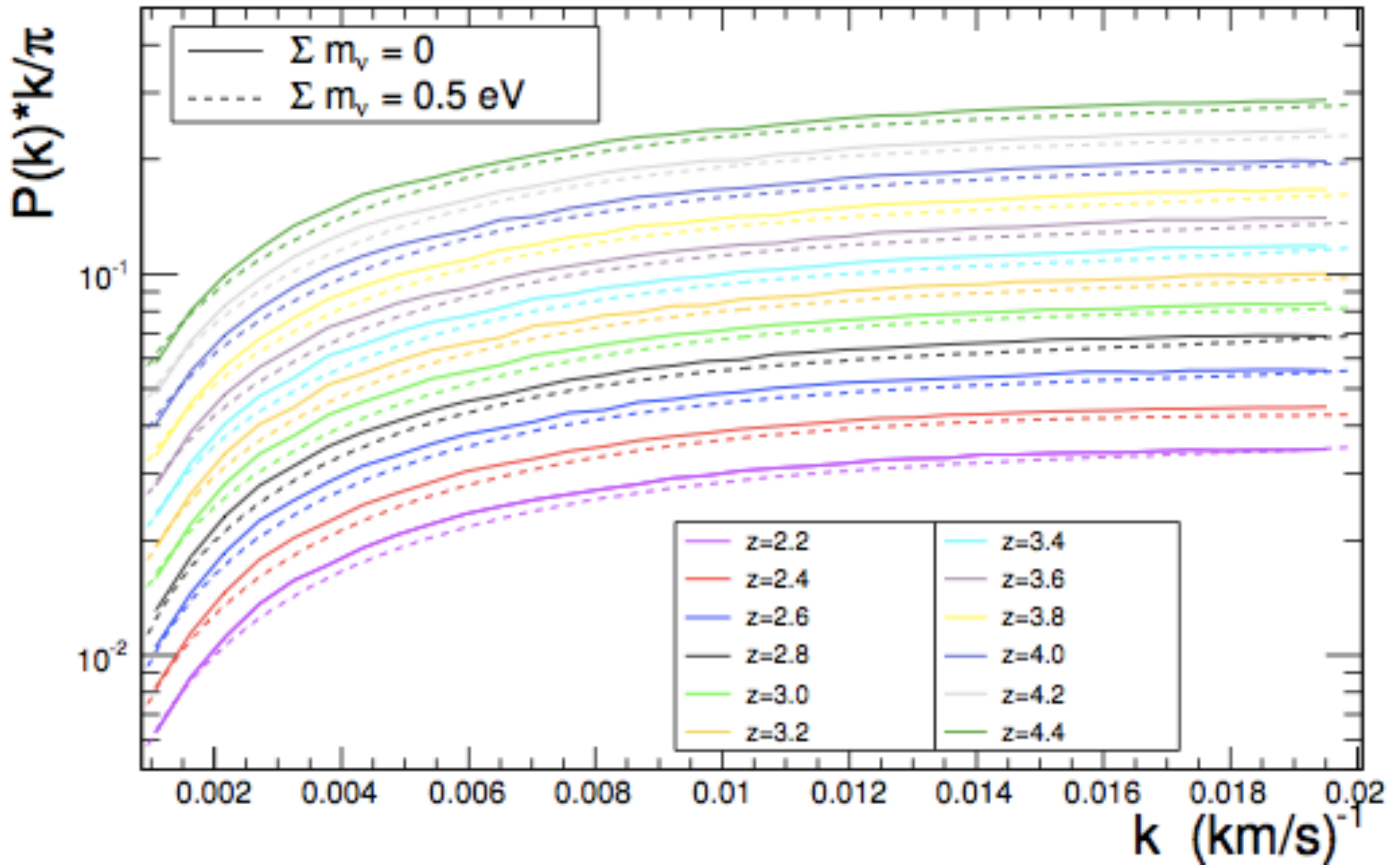
Cosmology parameters: σ_8, n_s, Ω_m, H_0, $m_{WDM,}$+ neutrino mass
Astrophysical parameters: z_{reio}, UV fluctuations, T_0, γ, $<F>$
Nuisance: resolution, S/N, metals

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

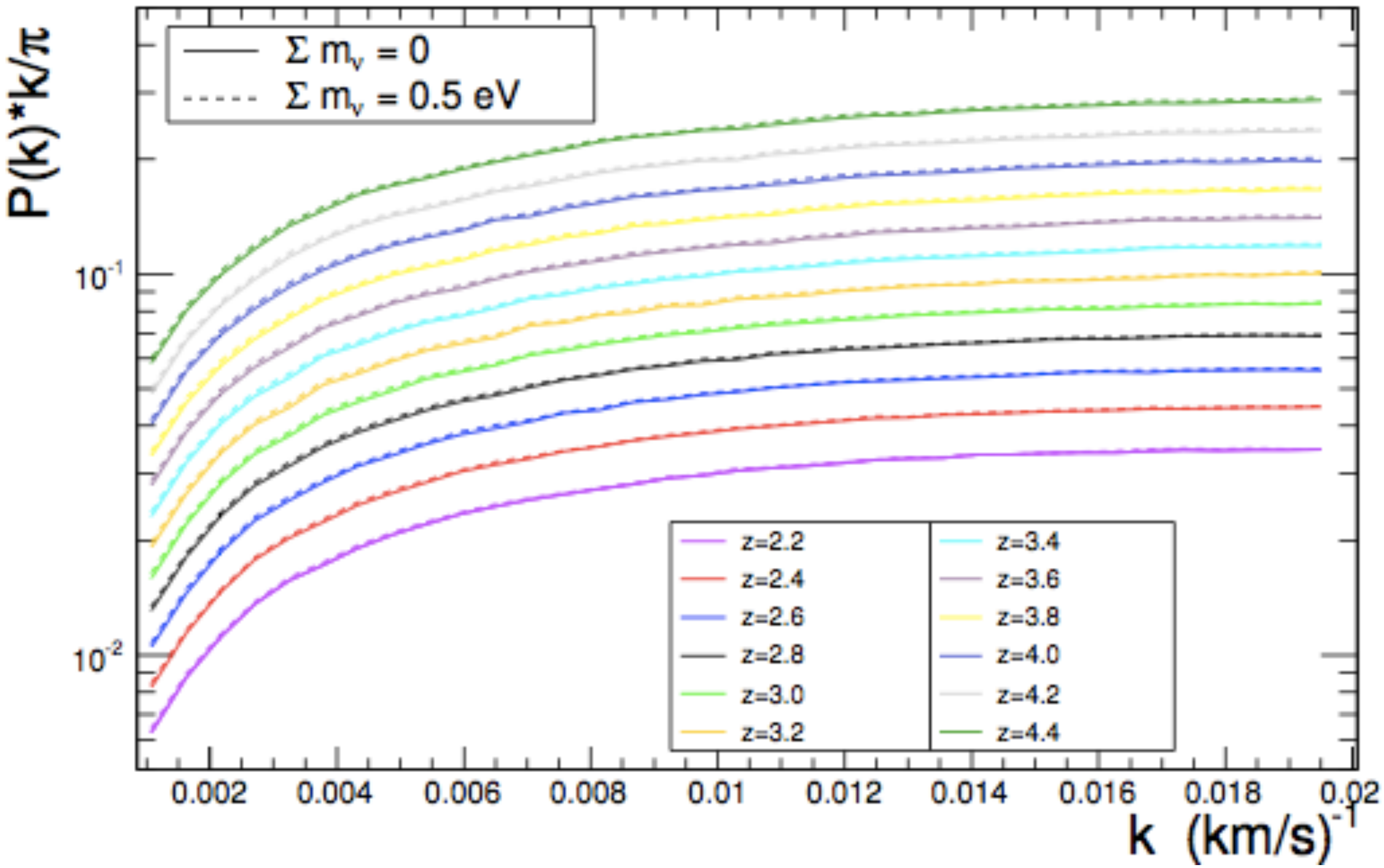
Parameter space: second order Taylor expansion of the flux power

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

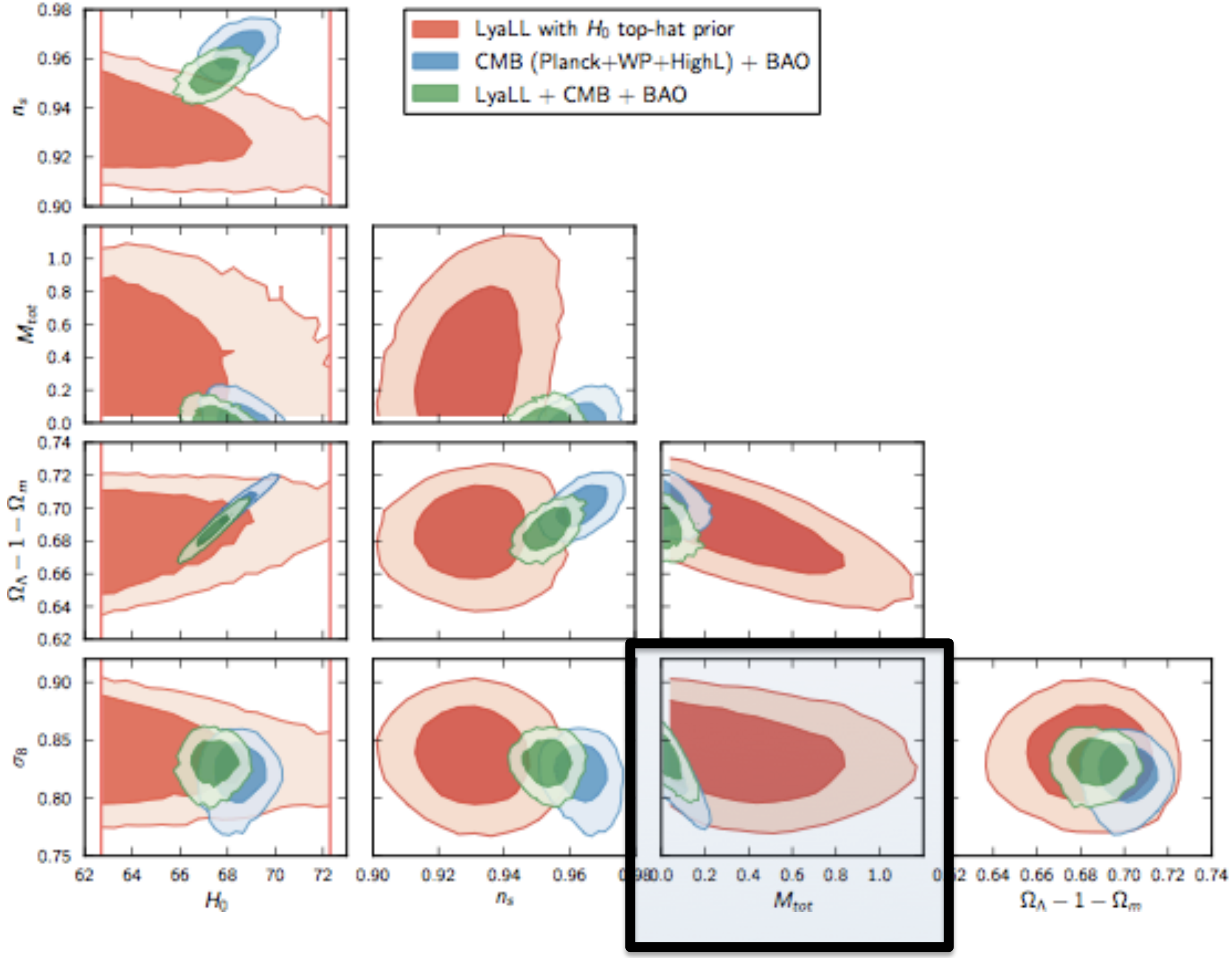
NEUTRINO IMPACT - I



NEUTRINO IMPACT - II



BAYESIAN ANALYSIS



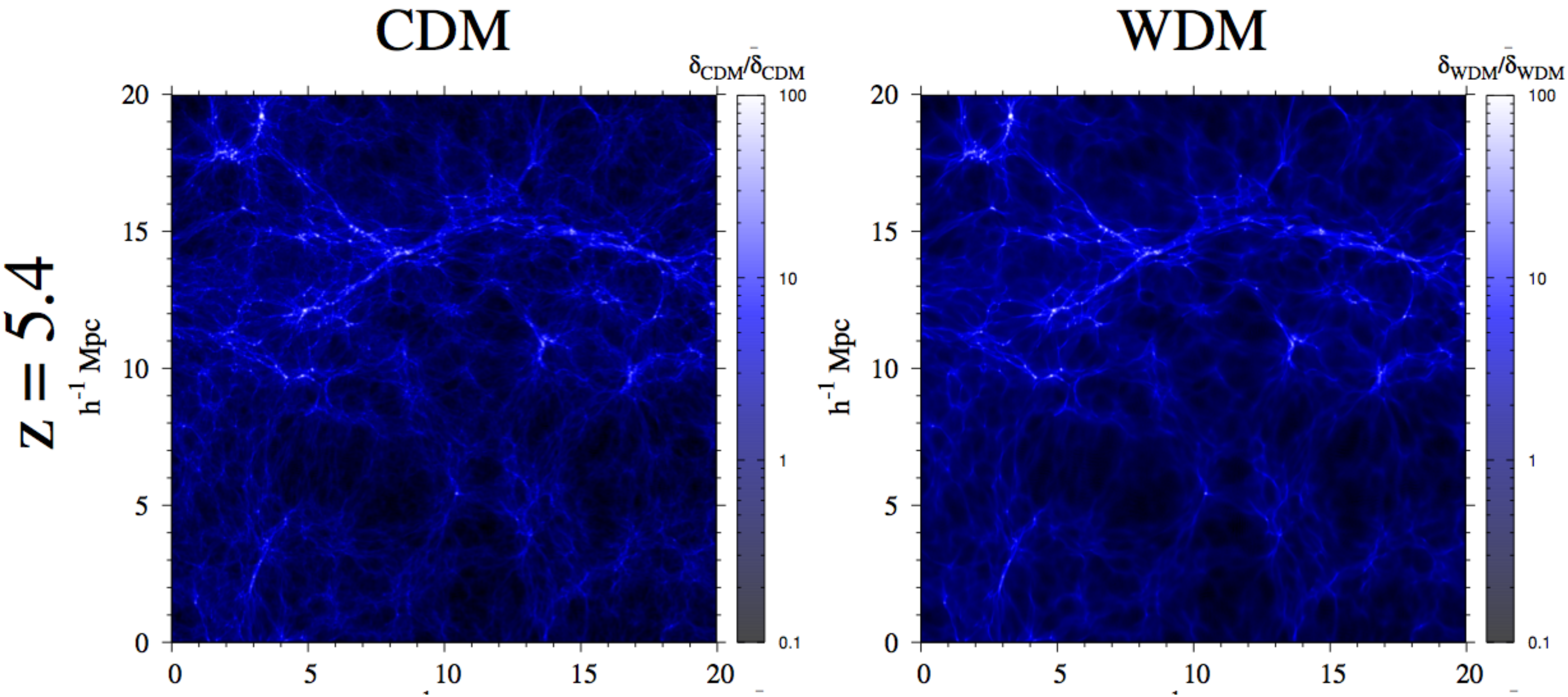
FINAL NUMBERS

Parameter	Lyα + H_0^{tophat} ($62.5 \le H_0 < 72.5$)	Lyα + CMB	Lyα + CMB + BAO	Lyα + CMB(A_L)
$10^9 A_s$	$3.2^{+0.5}_{-0.7}$	$2.20^{+0.05}_{-0.06}$	$2.20^{+0.05}_{-0.06}$	$2.18^{+0.05}_{-0.06}$
$10^2 \omega_b$	(fixed to 2.22)	2.20 ± 0.02	2.20 ± 0.02	2.22 ± 0.03
ω_{cdm}	$0.110^{+0.008}_{-0.013}$	$0.1200^{+0.0019}_{-0.0018}$	$0.1196^{+0.0015}_{-0.0014}$	0.1191 ± 0.002
τ_{reio}	(irrelevant)	$0.091^{+0.012}_{-0.013}$	$0.091^{+0.011}_{-0.013}$	$0.0871^{+0.012}_{-0.013}$
n_s	0.931 ± 0.012	0.953 ± 0.005	0.953 ± 0.005	$0.955^{+0.005}_{-0.006}$
H_0	< 70.9 (95%)	$67.2^{+0.8}_{-0.9}$	67.4 ± 0.7	$67.5^{+1.0}_{-1.1}$
$\sum m_\nu$ (eV)	< 0.98 (95%)	< 0.16 (95%)	< 0.14 (95%)	< 0.21 (95%)
A_L	(fixed to 1)	(fixed to 1)	(fixed to 1)	1.12 ± 0.10
σ_8	0.84 ± 0.03	$0.830^{+0.017}_{-0.013}$	$0.830^{+0.016}_{-0.012}$	$0.818^{+0.021}_{-0.014}$
Ω_m	$0.316^{+0.018}_{-0.021}$	0.316 ± 0.012	0.313 ± 0.009	0.312 ± 0.013

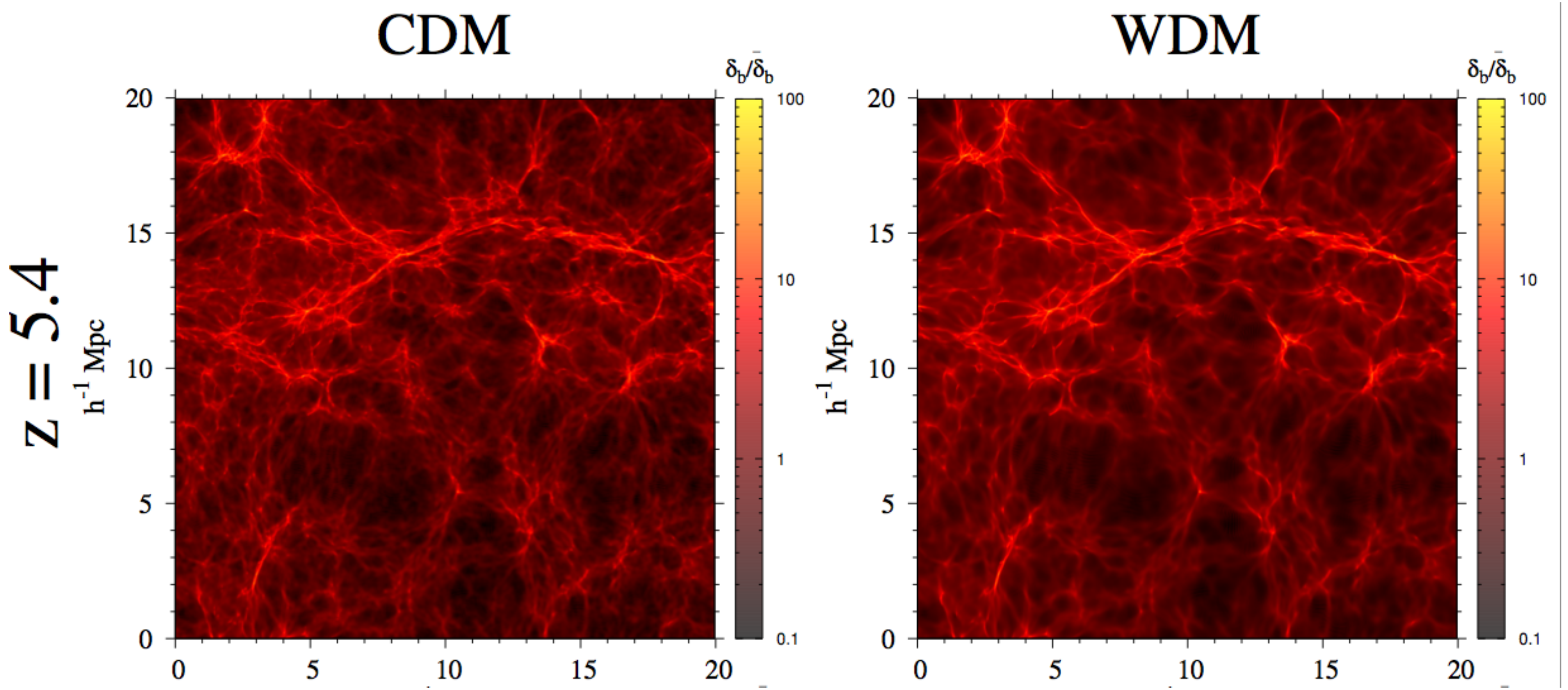
THE COLDNESS OF COLD DARK MATTER

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

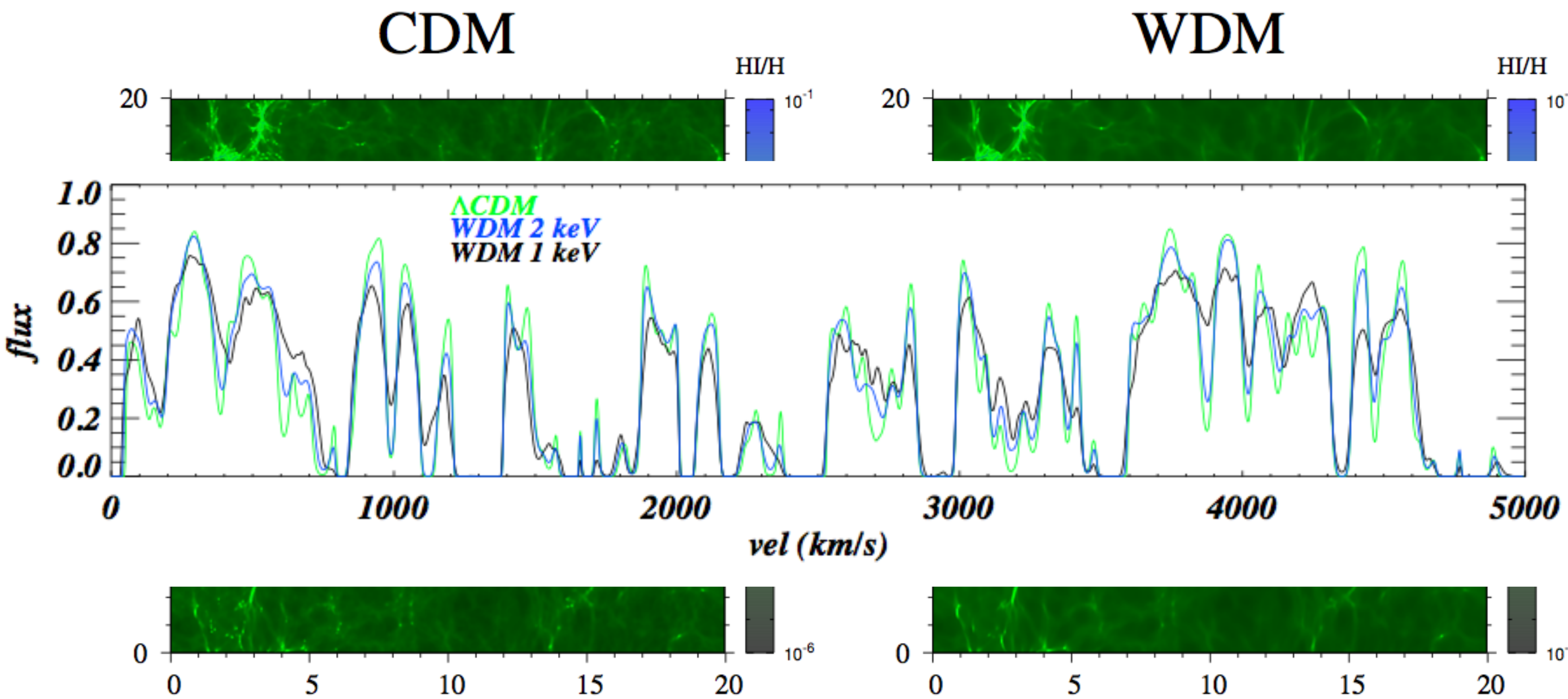
DARK MATTER DISTRIBUTION



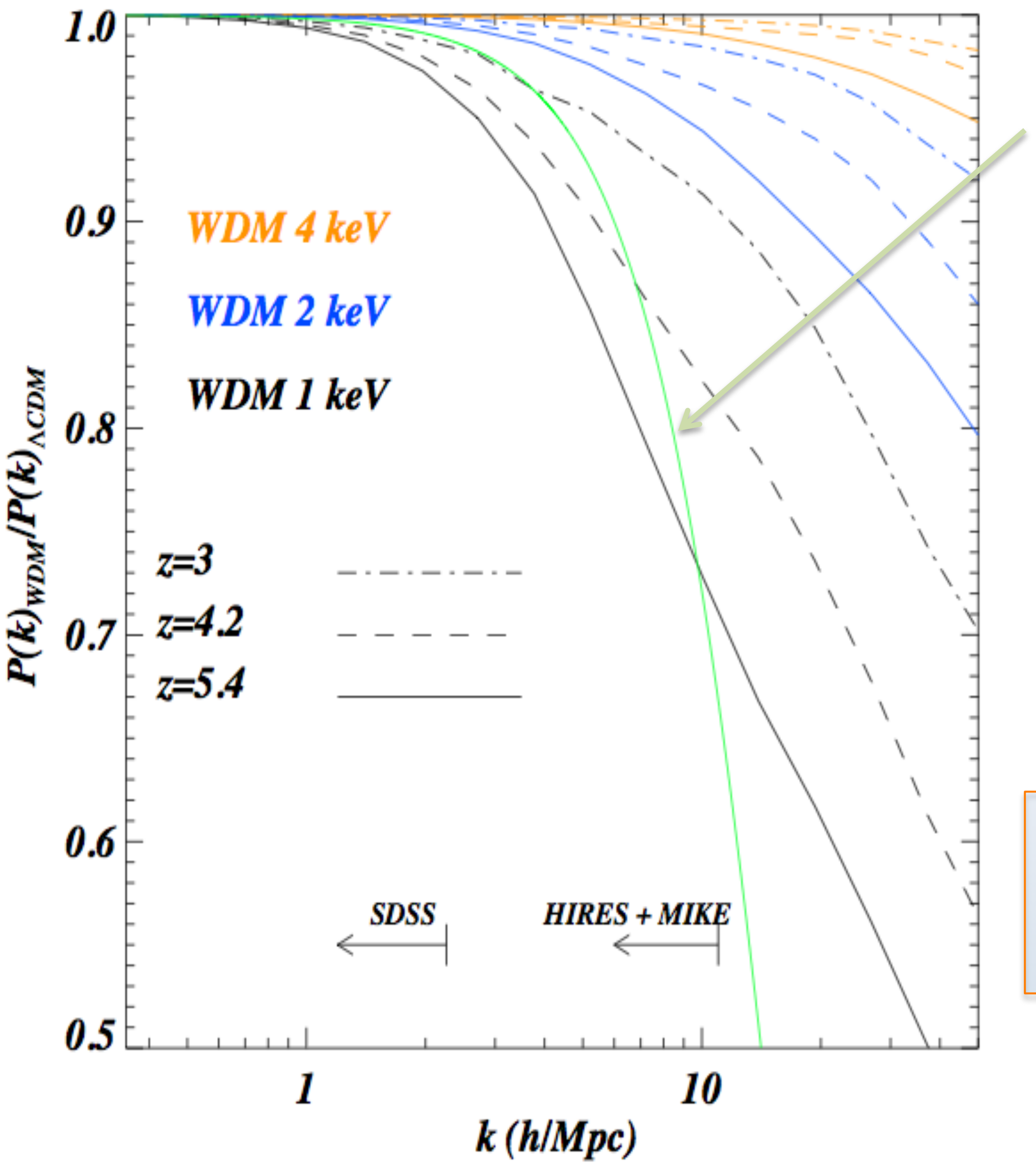
GAS DISTRIBUTION



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

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

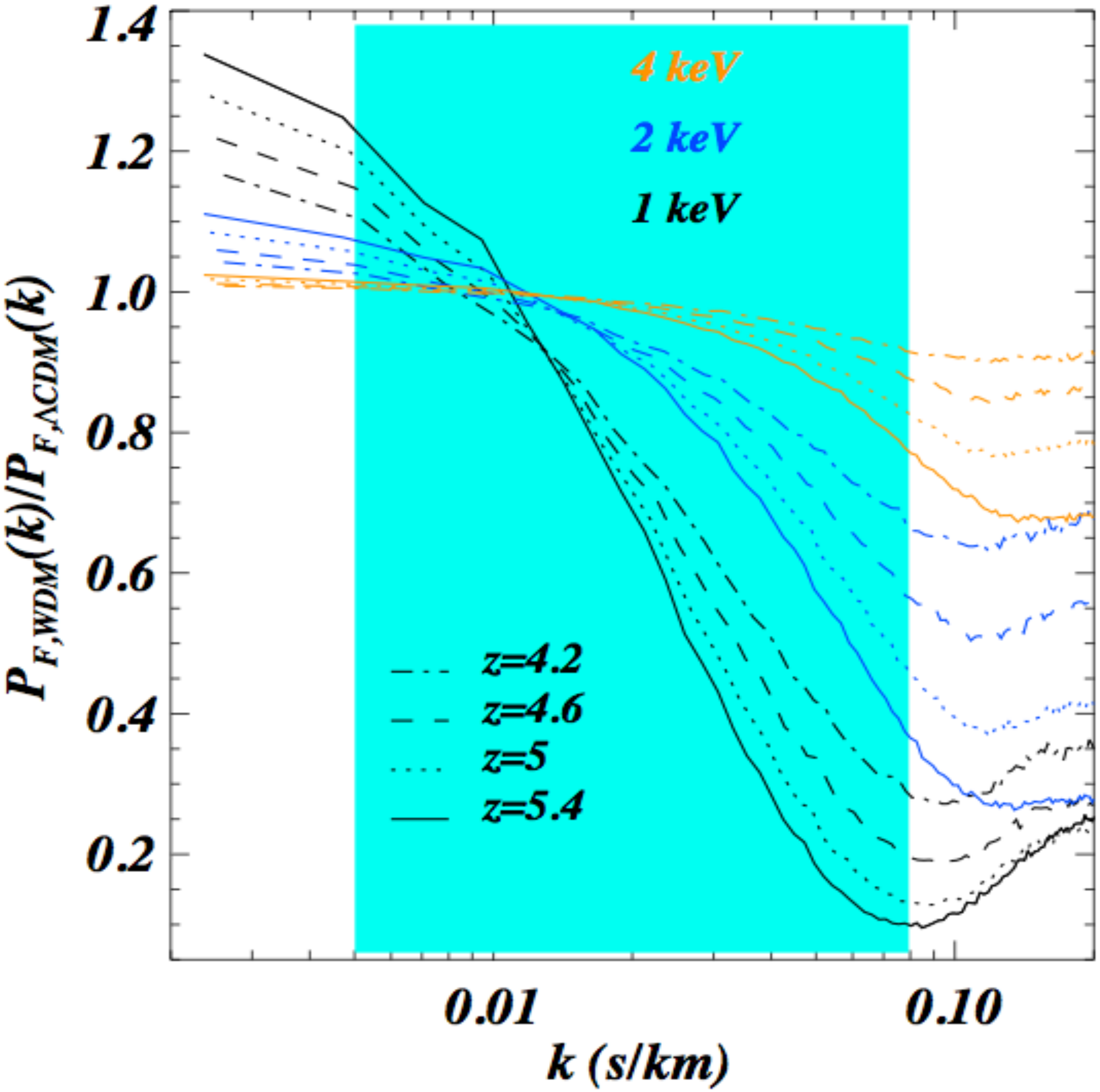
$$\alpha(\mathrm{m_{WDM}}, z) = 0.0476\left(\frac{1\mathrm{keV}}{\mathrm{m_{WDM}}}\right)^{1.85}\left(\frac{1+z}{2}\right)^{1.3},$$

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

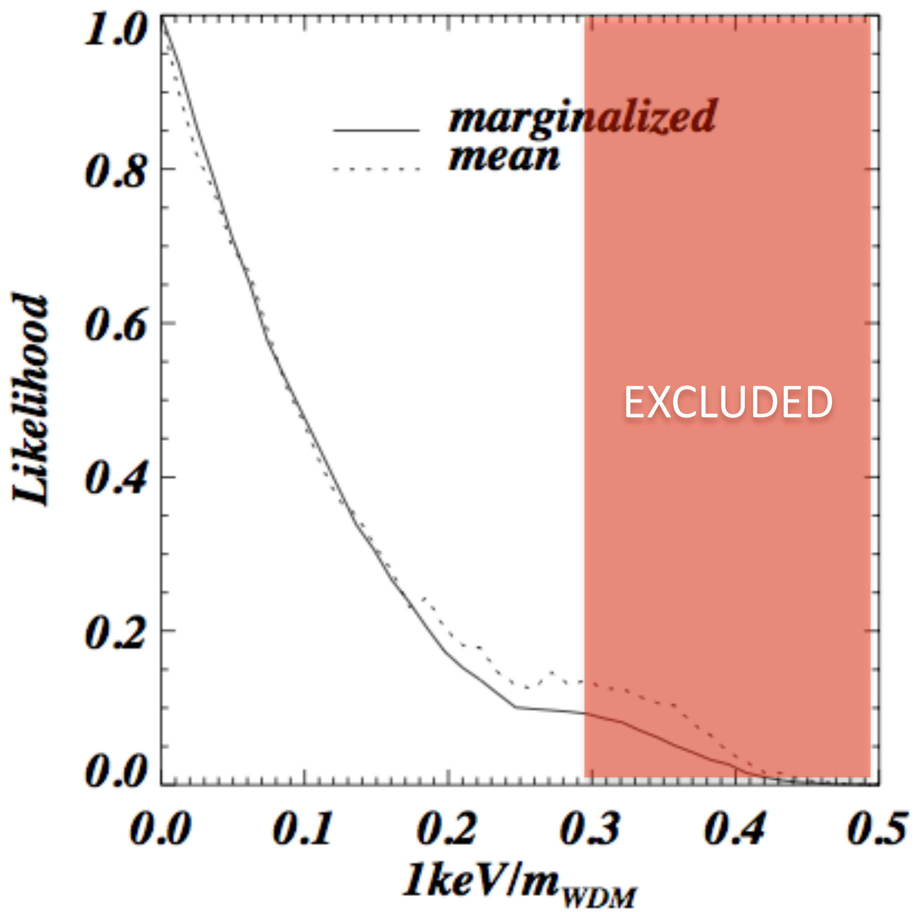
Viel, Markovic, Baldi & Weller 2013

THE HIGH REDSHIFT WDM CUTOFF

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



RESULTS FOR WDM MASS

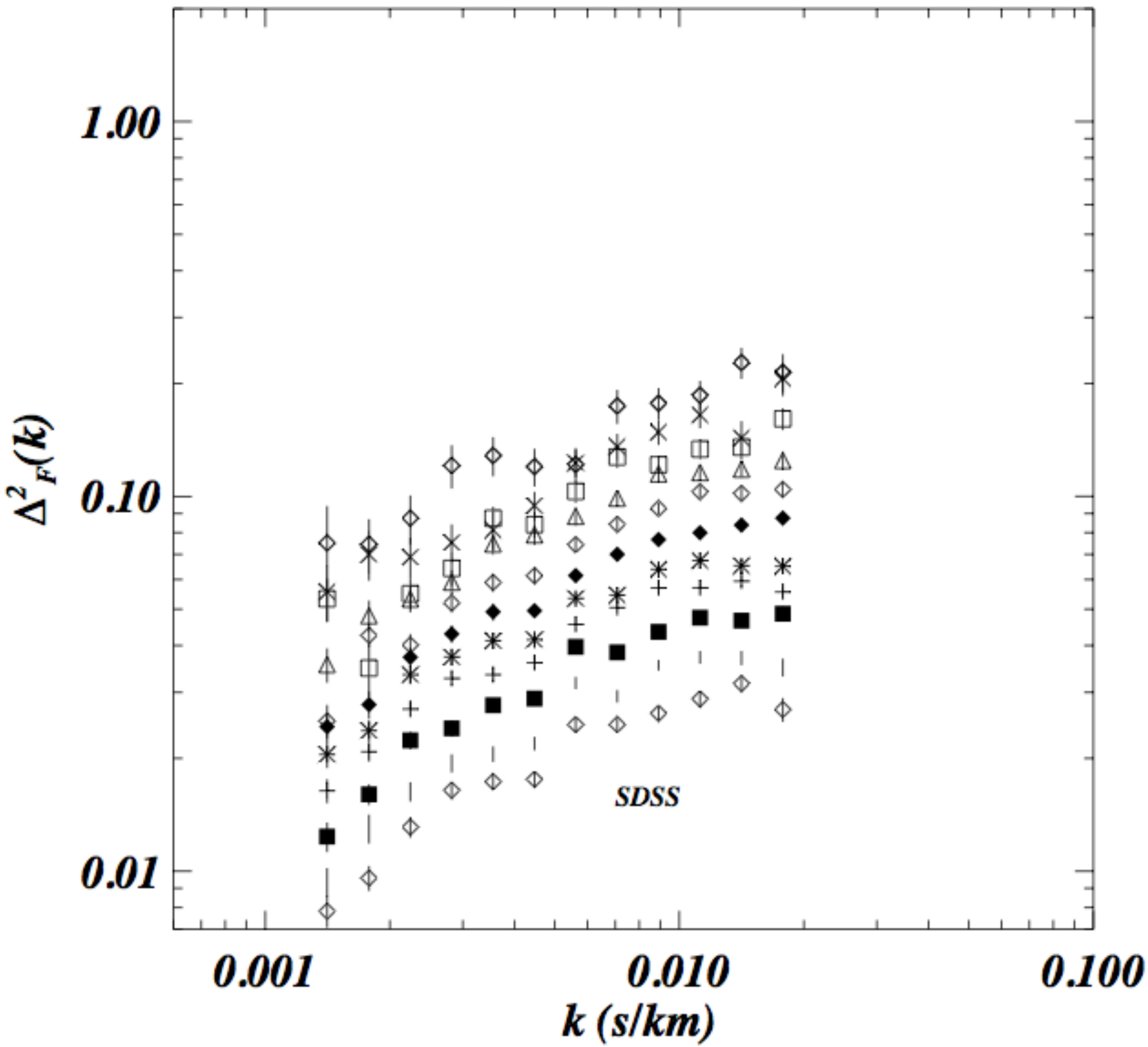


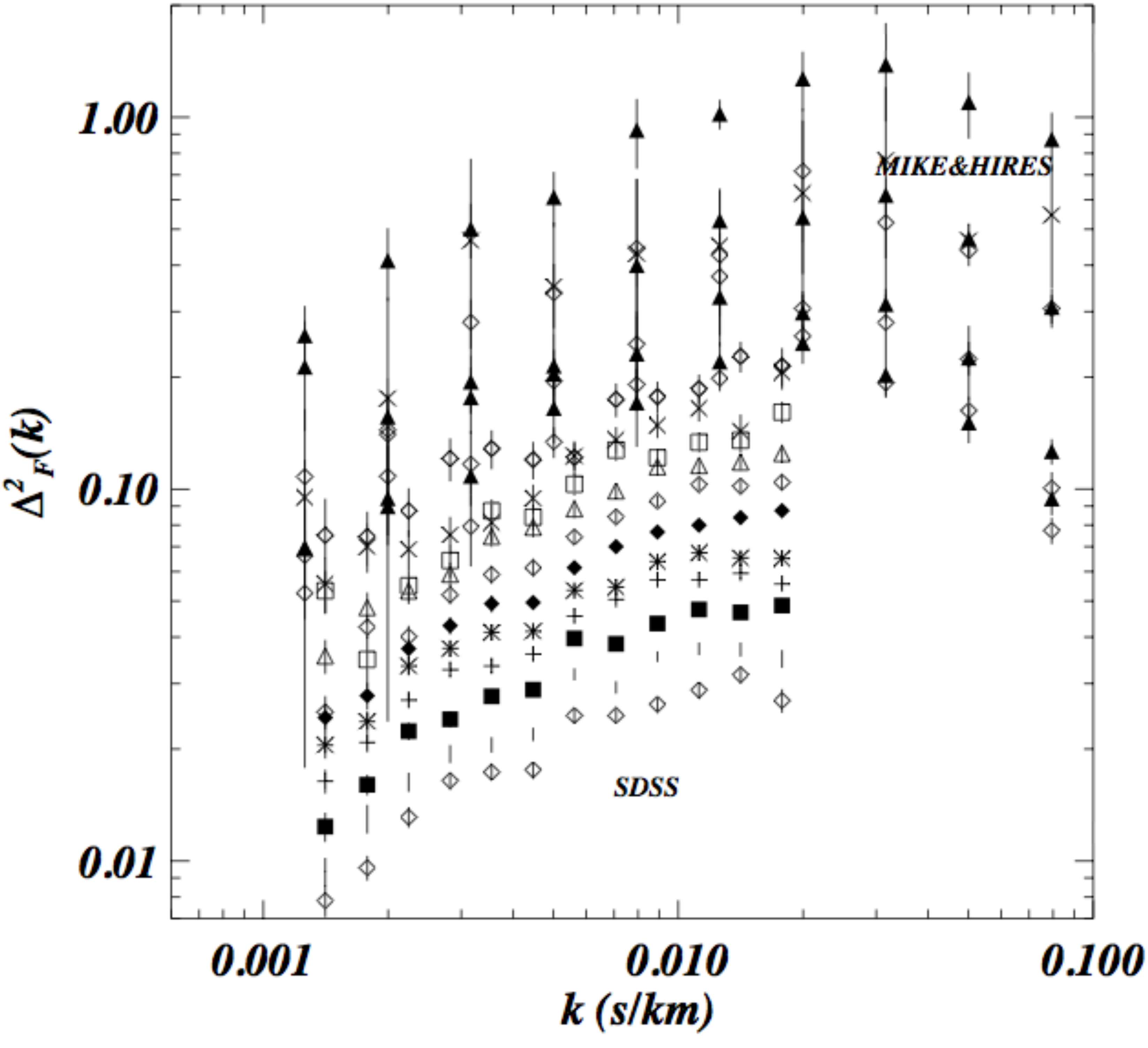
m > 3.3 keV (2σ)

SDSS + MIKE + HIRES CONSTRAINTS

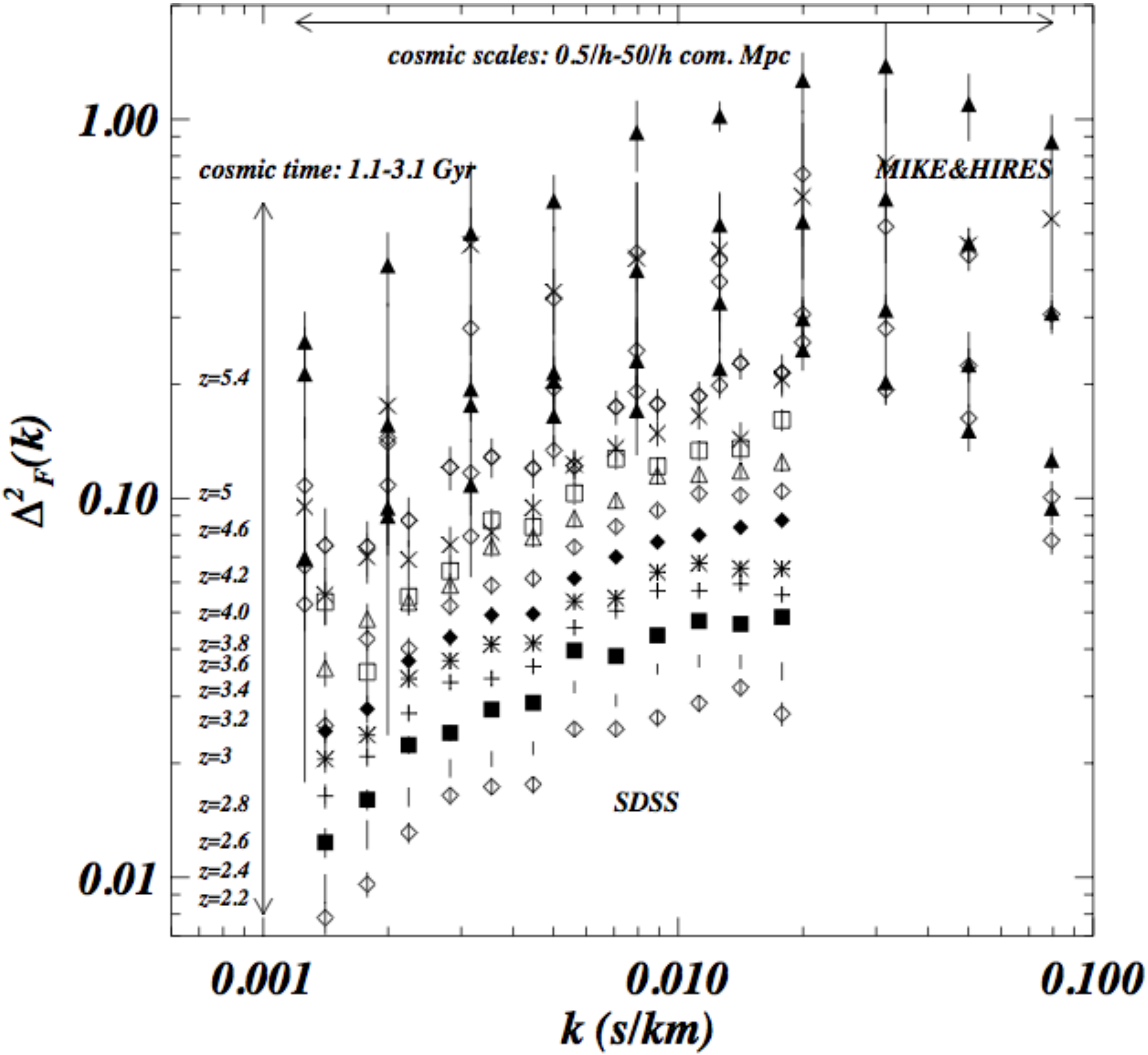
Joint likelihood analysis

SDSS data from McDonald05,06 not BOSS

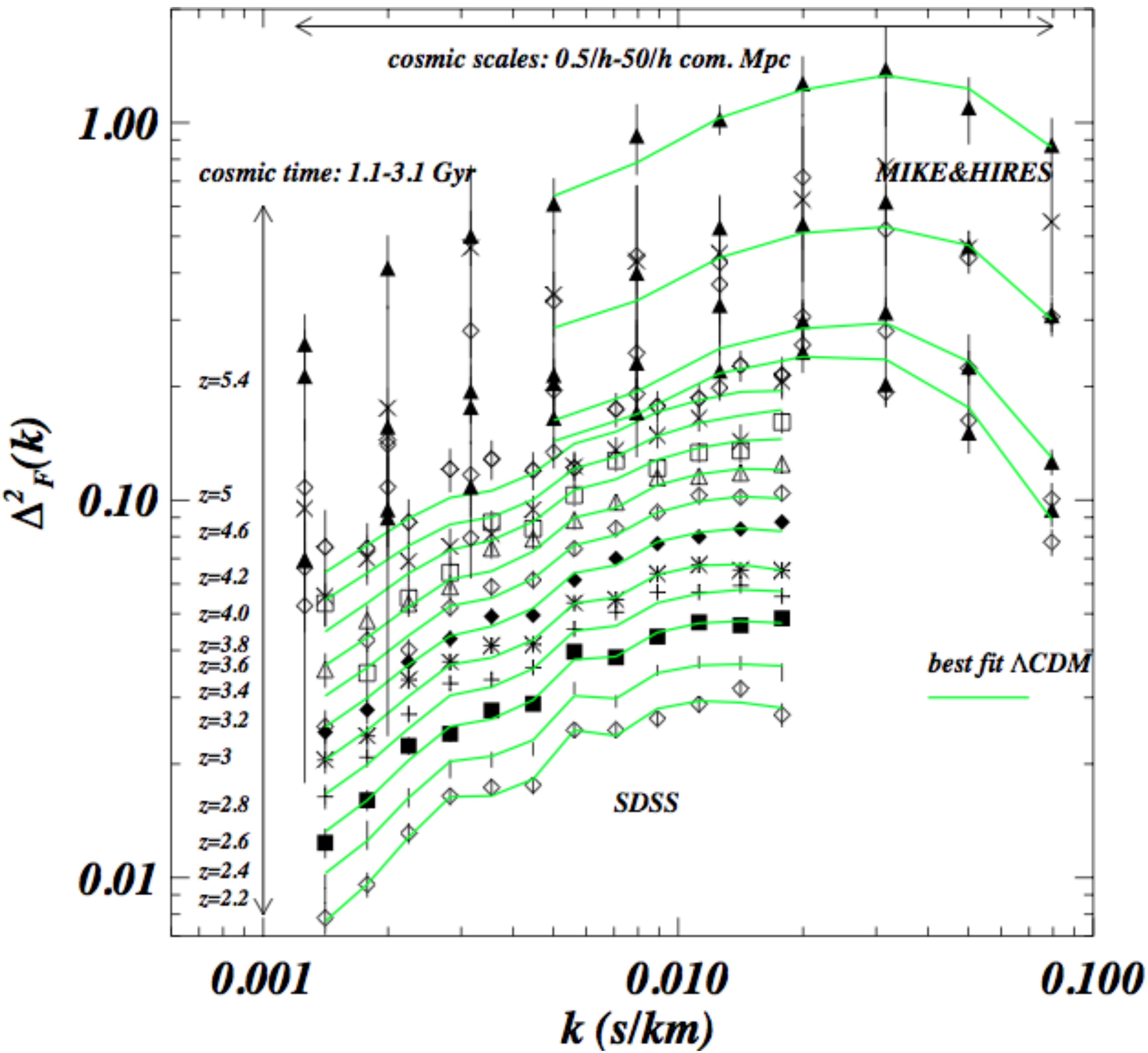

1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)



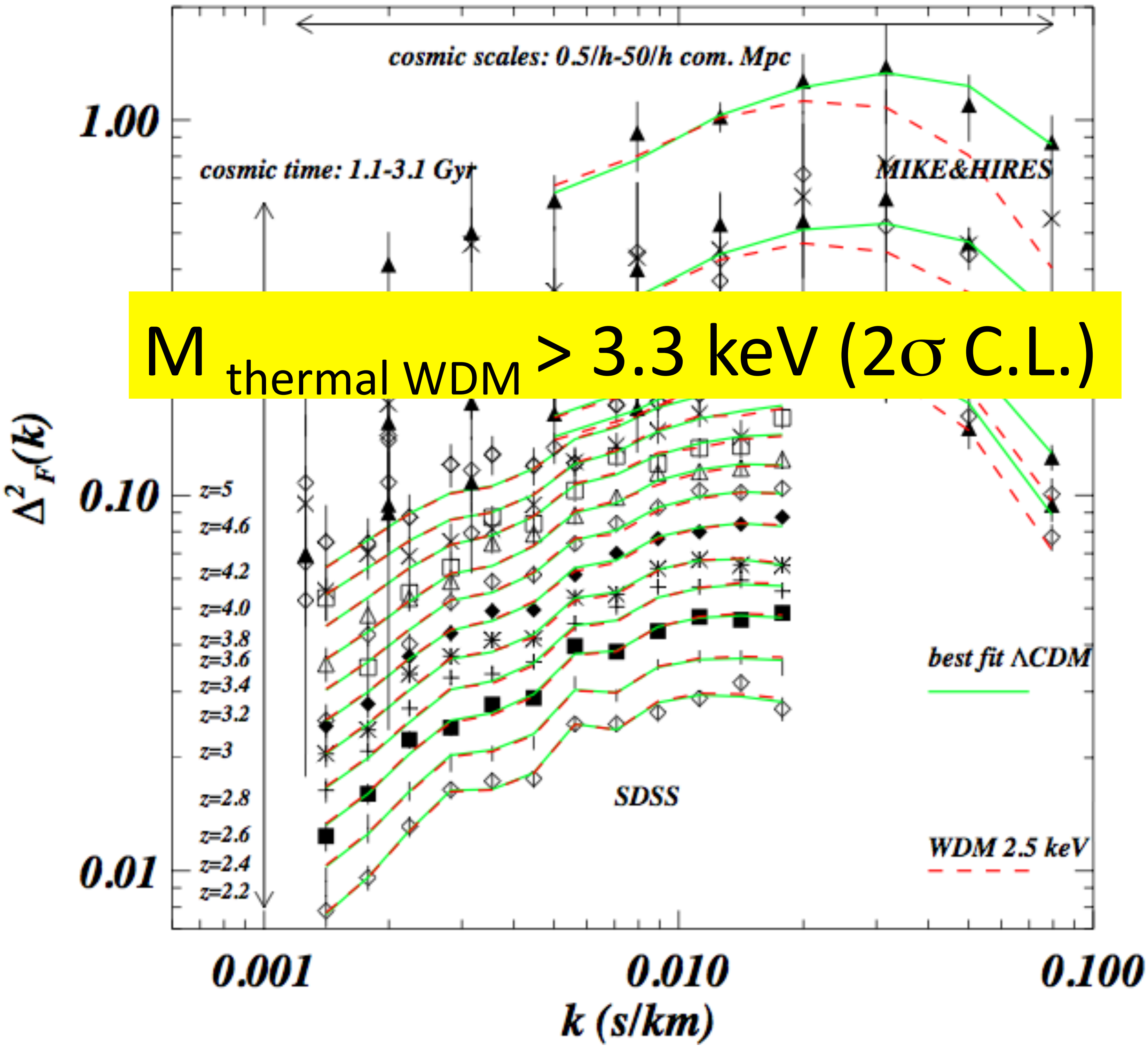
1.00
0.10
0.01
$\Delta^2_F(k)$
MIKE&HIRES
SDSS
0.001
0.010
0.100
k (s/km)



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)

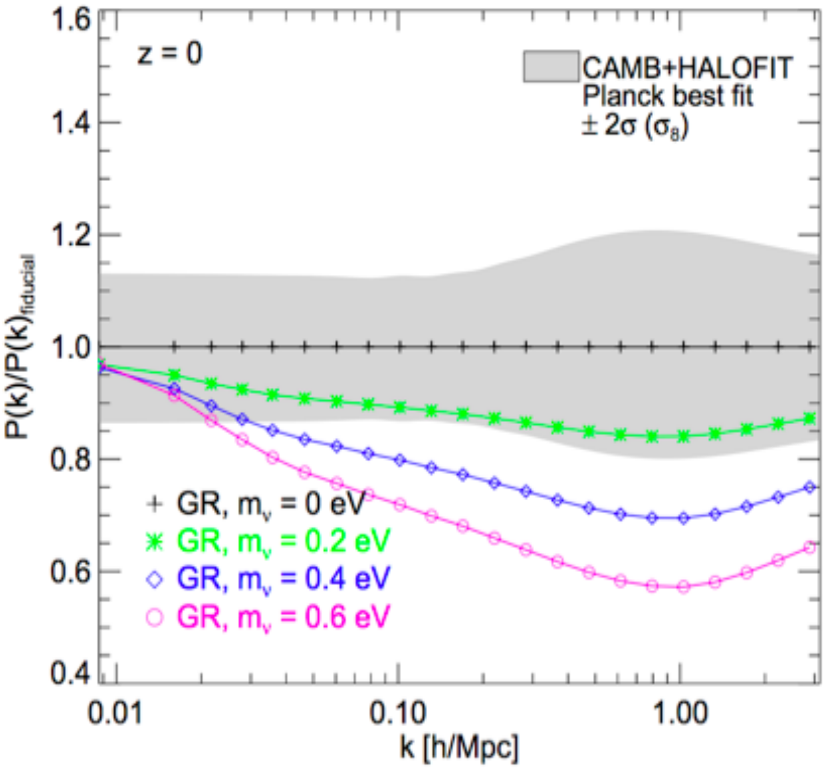


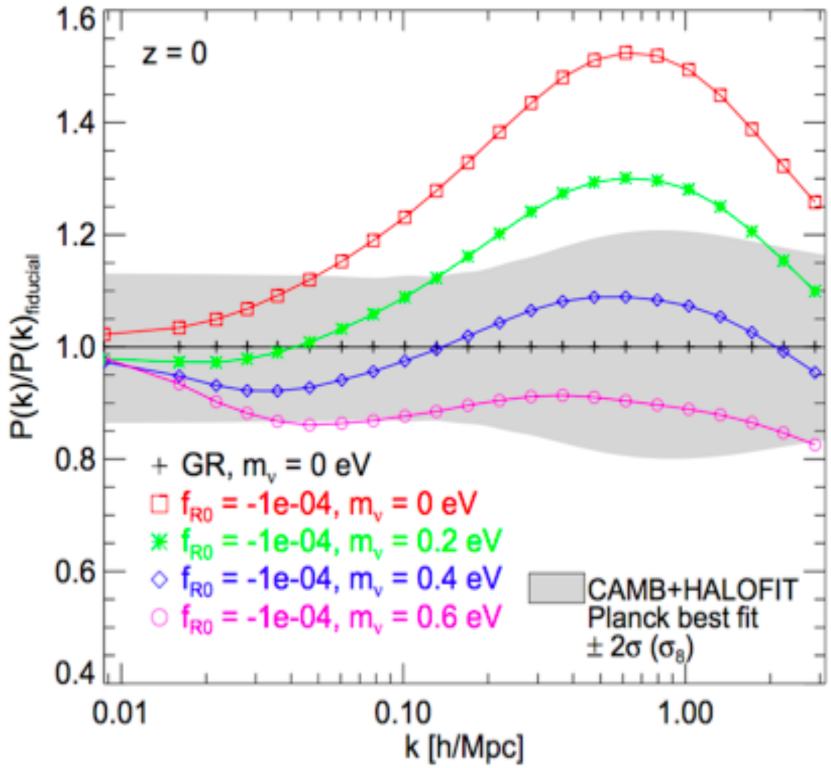
cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
best fit ΛCDM
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)



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

Cosmic Conspiracies?

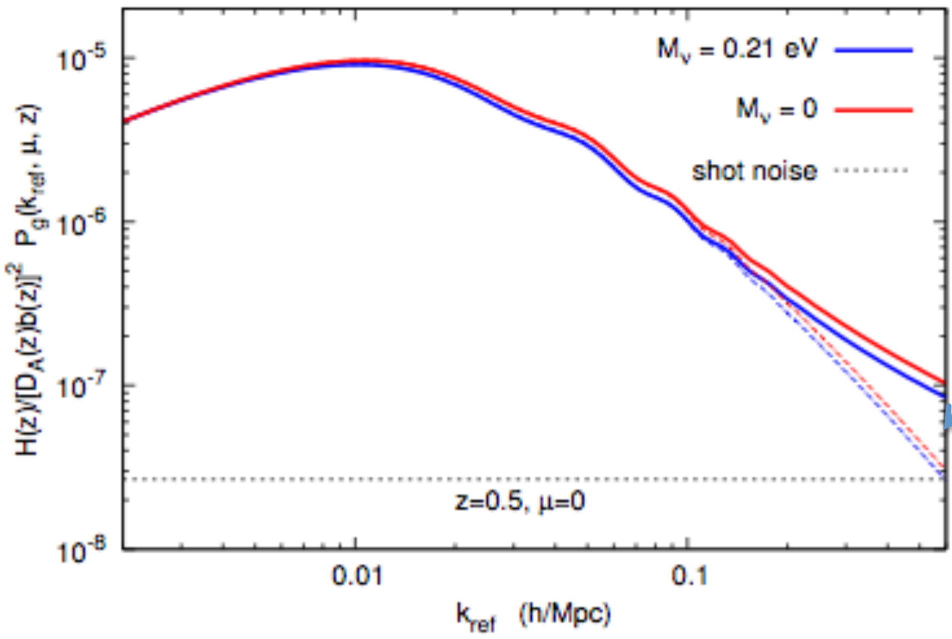


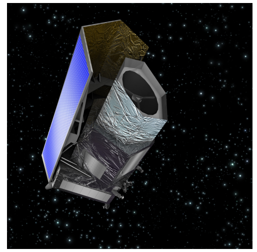


Baldi, Villaescusa-Navarro, Viel, Puchwein, Springel, Moscardini, 2014

MASSIVE NEUTRINO FORECASTS for Euclid

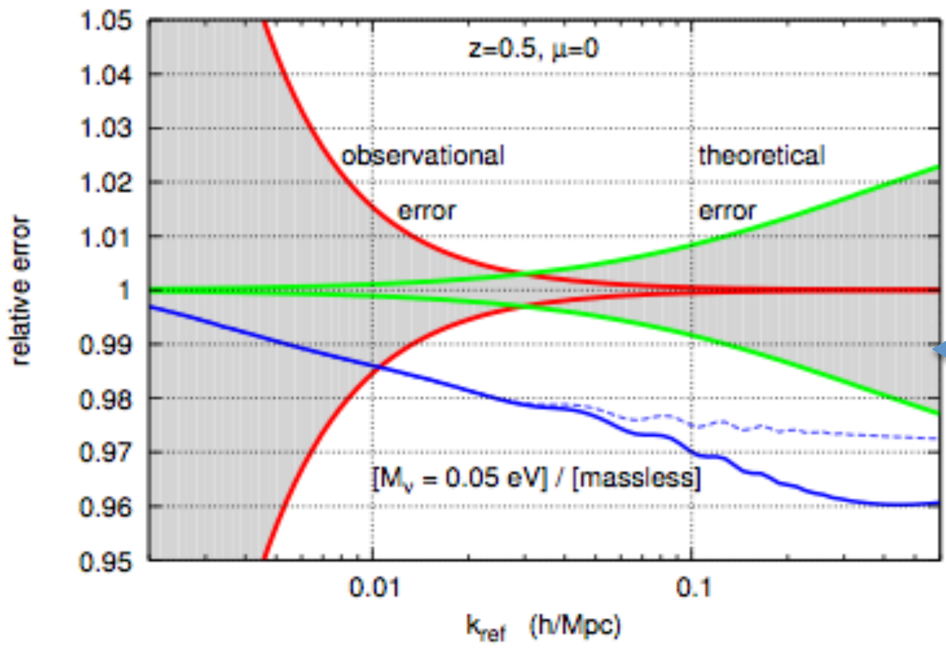
Audren, Lesgourgues, Bird, Haehnelt, MV 2013





Non-linearities

- $\sigma(M_\nu)$=18 meV → 5 meV when going from 0.1 to 0.6 h/Mpc
- with conservative errors the improvement is modest
- with realistic error could be 20%



Need to be modelled accurately

MASSIVE NEUTRINO FORECASTS for Euclid: II

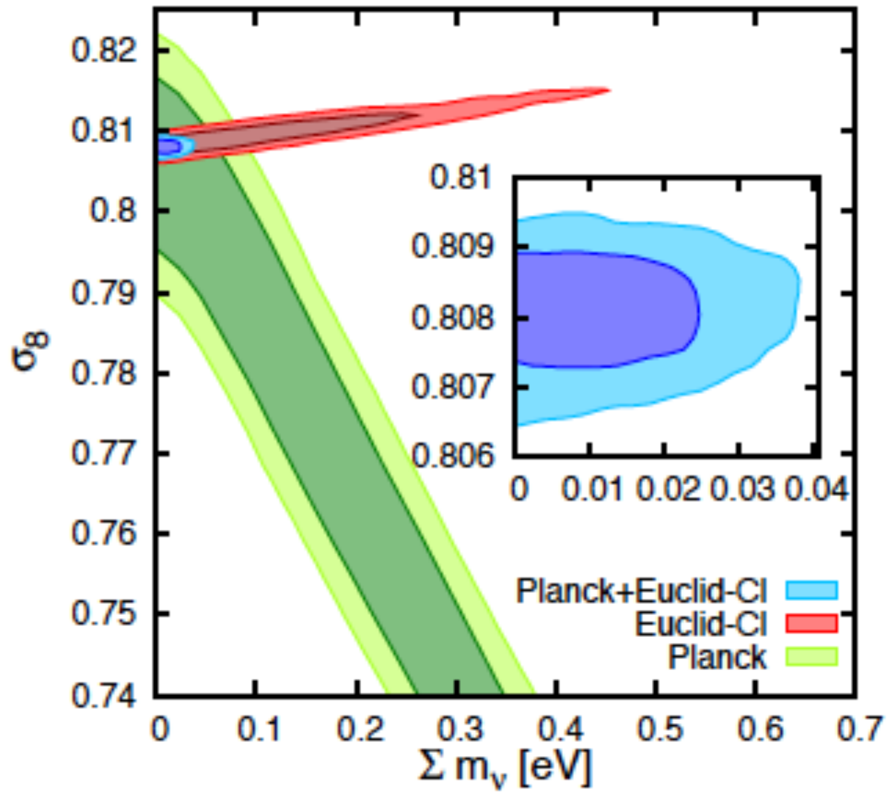
GALAXY POWER SPECTRUM

k_{max} (h/Mpc)	un. err.	co. err.	$3m_\nu = M_\nu$ (meV)
0.1	–	–	18
0.1	1/10	–	18
0.1	1/2	–	23
0.1	•	–	25
0.1	•	•	25
0.6	–	–	5.9
0.6	1/10	–	14
0.6	1/2	–	22
0.6	•	–	25
0.6	•	•	25

32 meV with cosmic shear (i.e. weak lensing)

CLUSTERS OF GALAXIES

Model		ΛCDM+m_ν			
Data		Planck	P^{cl}−only	Euclid-Cl	Euclid-Cl+Planck
$\sum m_\nu$ [eV]	68% CL	< 0.41	< 0.41	< 0.17	< 0.017
	95% CL	< 0.74	< 1.20	< 0.35	< 0.031



Costanzi, Sartoris, Xia, Biviano, Borgani, MV (2013)

CONCLUSIONS – NEUTRINOS

1D Lyman-α flux power provides the tightest constraints (<0.14 eV) on total neutrino mass.

Neutrino non-linearities modelled in the matter power spectrum. correlation function, density distribution of haloes, peculiar velocities, redshift space distortions. NEW REGIME!

Forecasting for Euclid survey: 14 meV error is doable but need to model the power spectrum to higher precision (possibly subpercent) and with physical input on the scale dependence of the effect.
Very conservative 20-30 meV

CONCLUSIONS – WARM DARK MATTER

High redshift Lyman-α disfavours thermal relic models with masses that are typically chosen to solve the small-scale crisis of ΛCDM

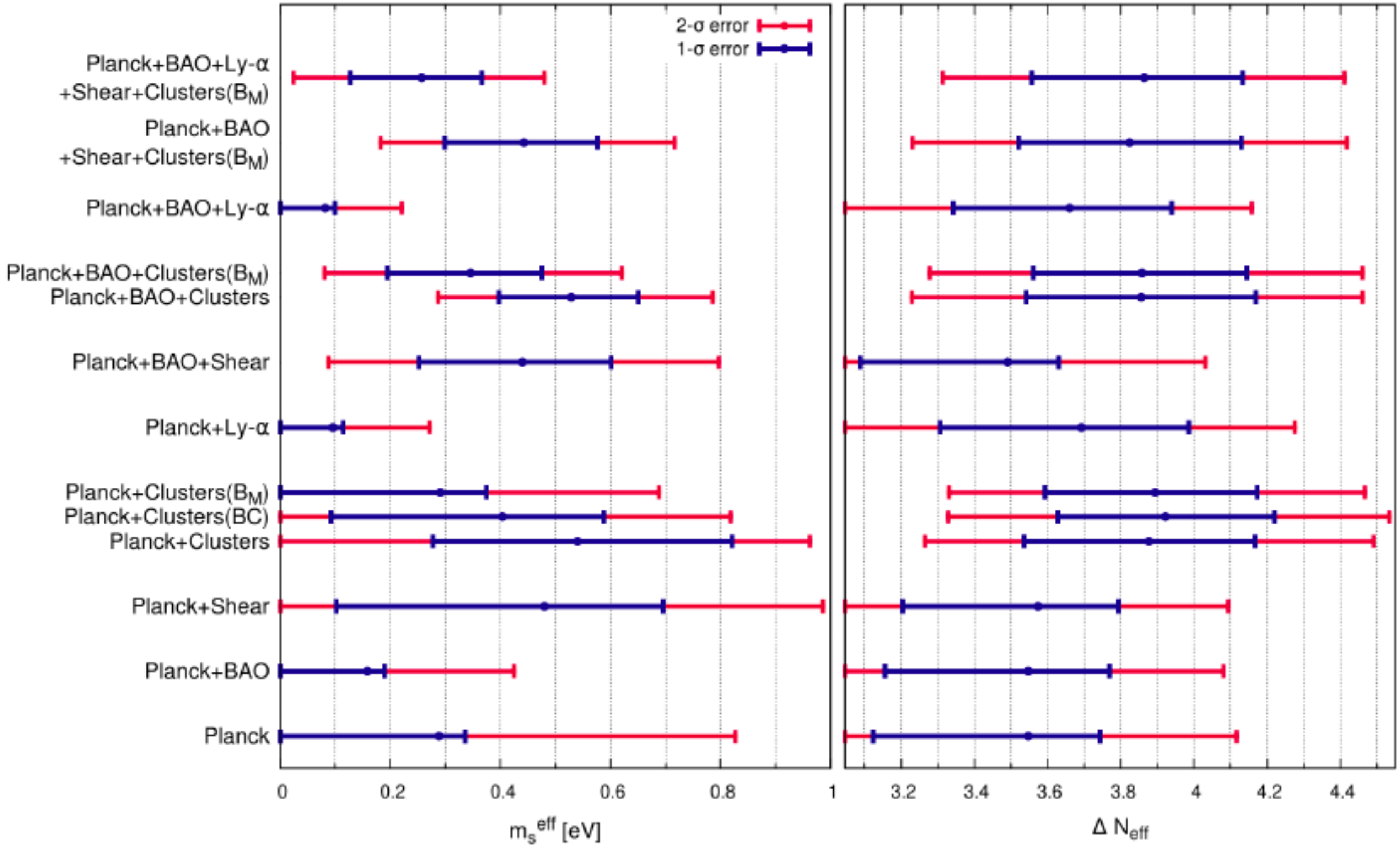
Models with 1 keV are ruled out at 9σ
2 keV are ruled out at 4σ
2.5 keV are ruled out at 3σ
3.3 keV are ruled out at 2σ

↓

1) free-streaming scale is $2\times10^{8} M_{\odot}/h$
2) at scales k=10 h/Mpc you cannot suppress more than 10% compared to ΛCDM

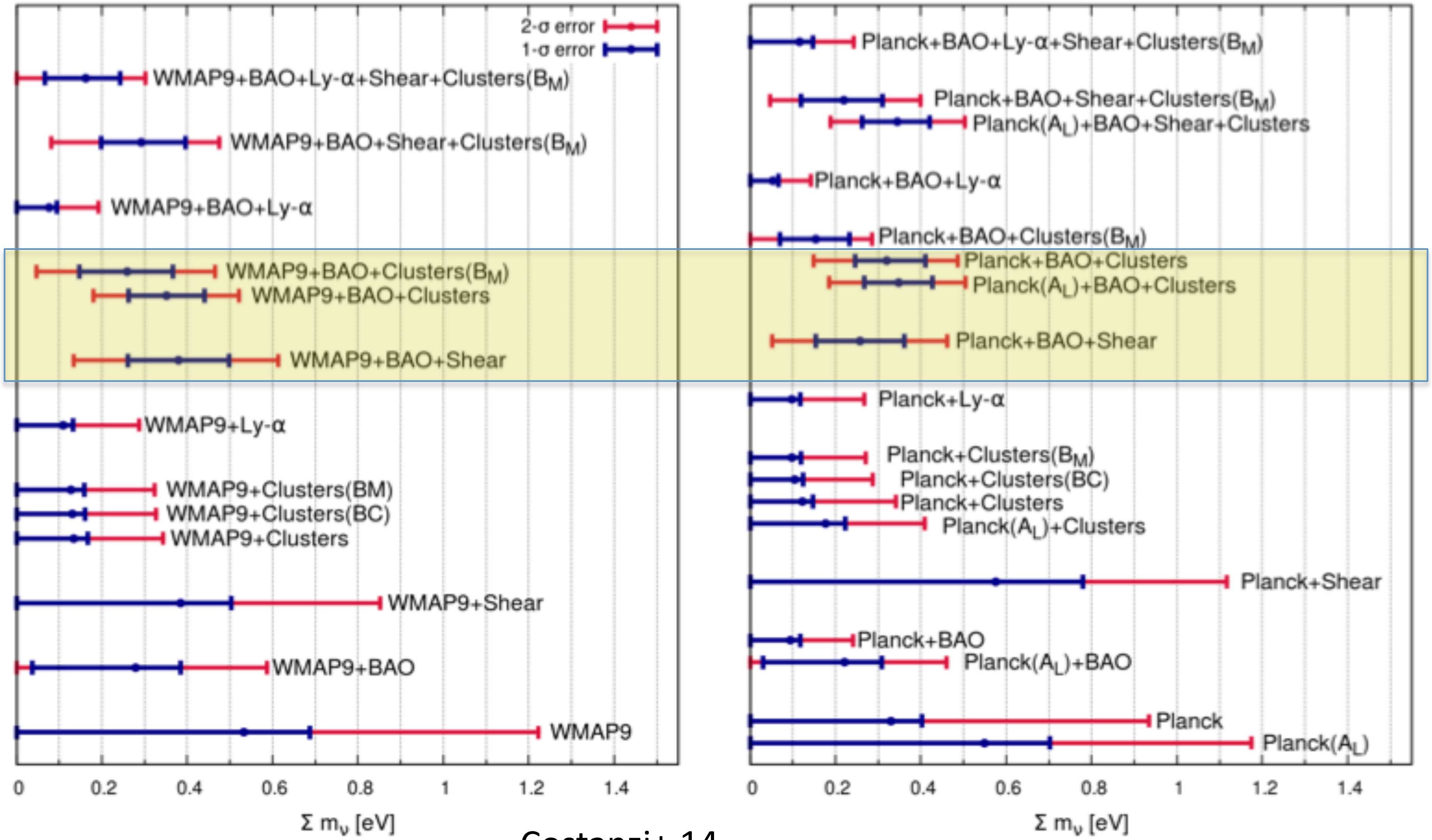
Of course they remain viable candidate for the Dark Matter (especially sterile neutrinos) but there are OBSERVATIONAL challenges

STERILES FROM COSMOLOGY



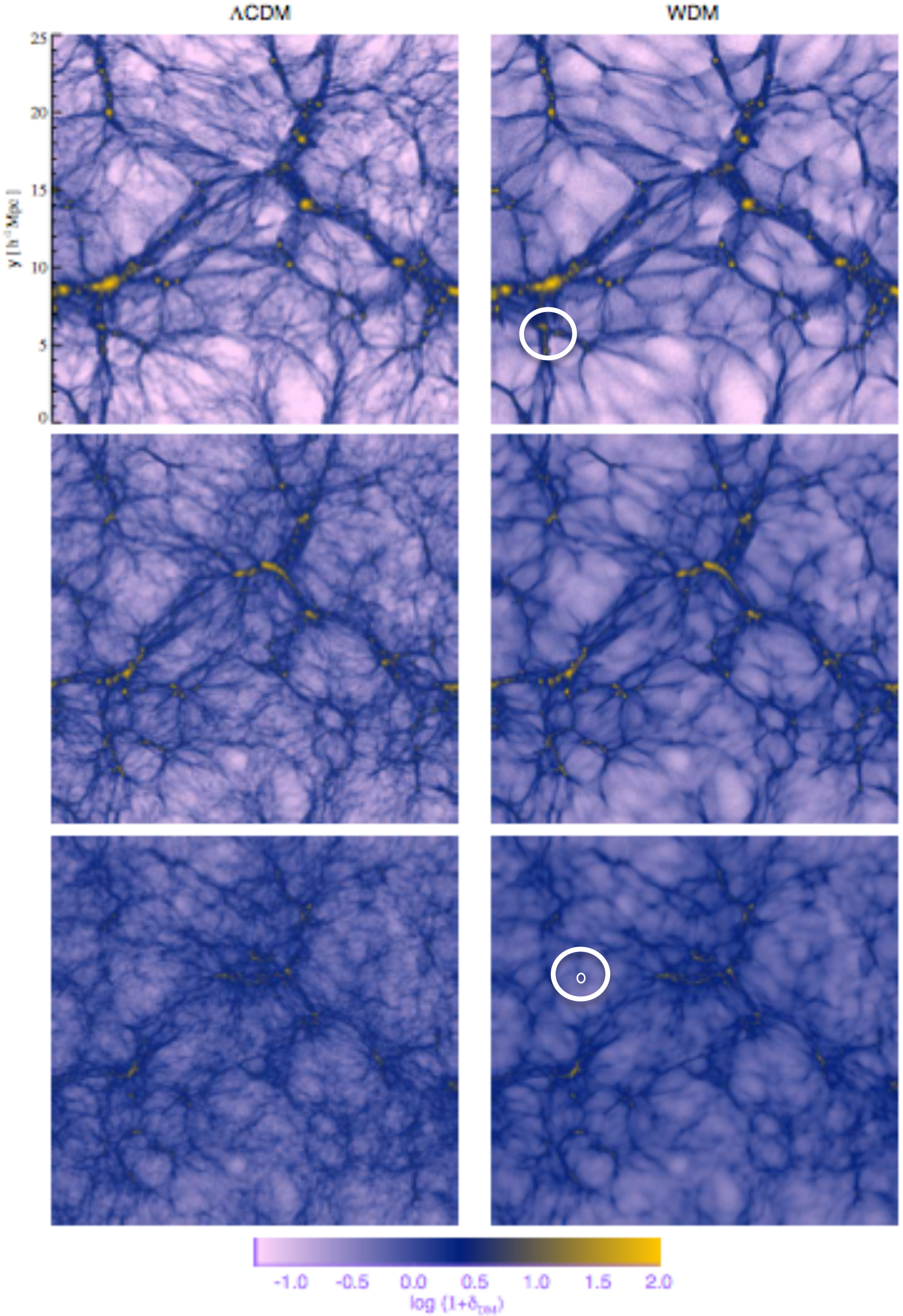
Costanzi+ 14

ACTIVE NEUTRINOS FROM COSMOLOGY



Costanzi+ 14

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

Viel, Markovic, Baldi & Weller 2013

IMPLICATIONS FOR STRUCTURE FORMATION

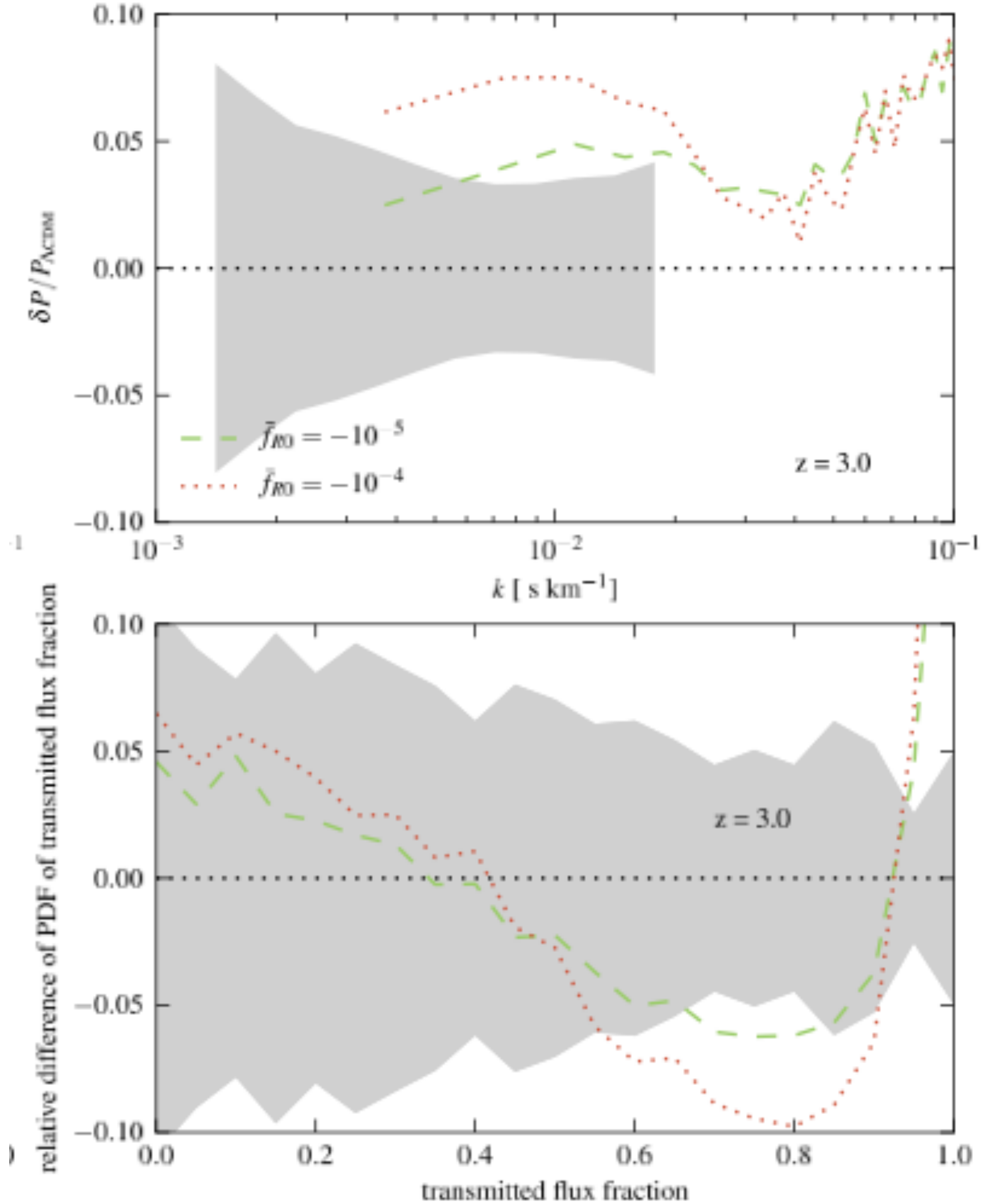
- Strong and weak lensing	Markovic et al. 13/Faadely & Keeton 12
- Galaxy formation	Menci et al 13, Kang et al. 13
- Reionization/First Stars	Gao & Theuns 07
- Dark Matter Haloes (mass functions)	Pacucci et al. 13
- Luminous matter properties	Polisensky & Ricotti 11, Lovell et al. 09
- Gamma-Ray Bursts	De Souza et al. 13
- HI in the local Universe	Zavala et al. 09
- Phase space density constraints	Shi et al. 13
- Radiative decays in the high-z universe	Boyarsky et al. 13

+ Lyman –α

Modified Gravity hydro results-I

Arnold, Puchwein & Springel 2015

- Small Impact on IGM statistics?



WHY LYMAN-α???

1) **ONE DIMENSIONAL**

$$\langle \tilde{F}_k^2 \rangle = \frac{1}{(2\pi)^2} \int dk_x \int dk_y \, P(k_x, k_y, k) = \frac{1}{2\pi} \int_k^{\infty} P(y) y \, dy$$

e.g. Kaiser & Peacock 91

2) **AND ALSO THREE DIMENSIONAL**

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

e.g. Viel et al. 02

3) **HIGH REDSHIFT**

Where you are possibly closer to primordial P(k)

...unfortunately non-linearities and thermal state of the IGM are quite important....