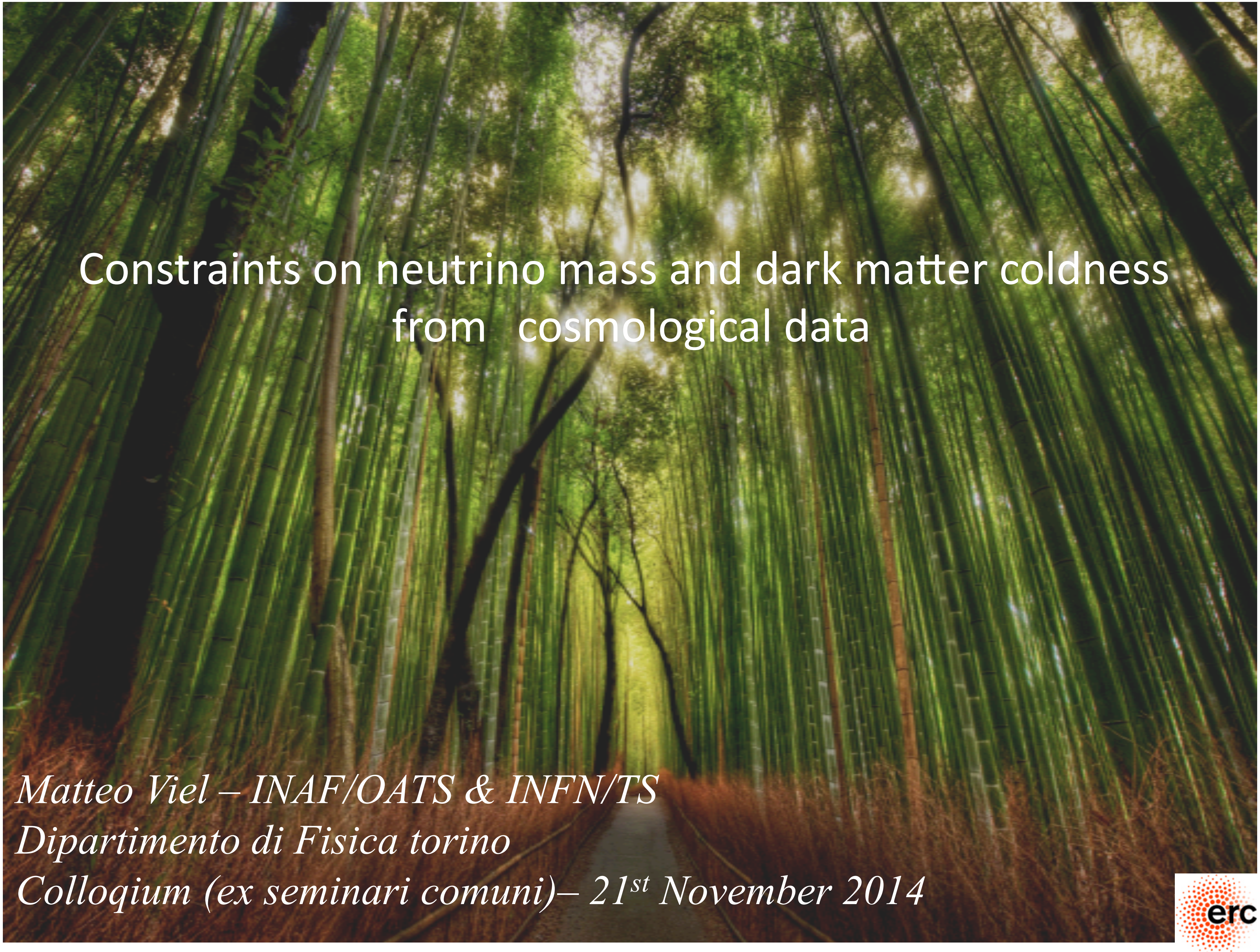


Constraints on neutrino mass and dark matter coldness from cosmological data

Matteo Viel – INAF/OATS & INFN/TS
Dipartimento di Fisica torino
Colloqium (ex seminari comuni)– 21st November 2014

OUTLINE

INTRO: the Intergalactic Medium and its main manifestation

TOOLS: Beyond linear theory with N-body/hydrodynamic simulations

DATA: State of the art observables at large and small scales

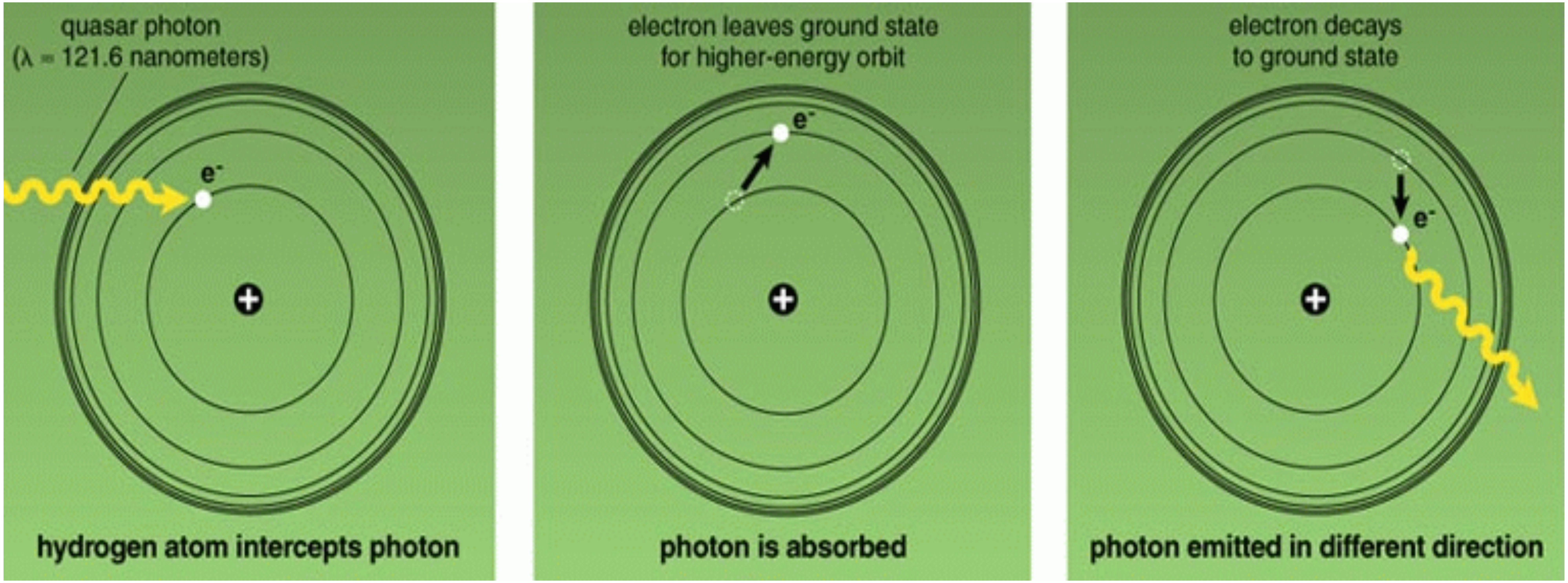
INTRO

Let’s learn:

- why atomic physics is important for intergalactic space
- baryons in intergalactic space are diffuse/low density
- physics of the IGM is relatively simple (at least at large scales)
- semi-analytical models can describe it well within 10% uncertainties or so

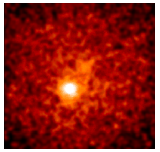
The Lyman-α forest

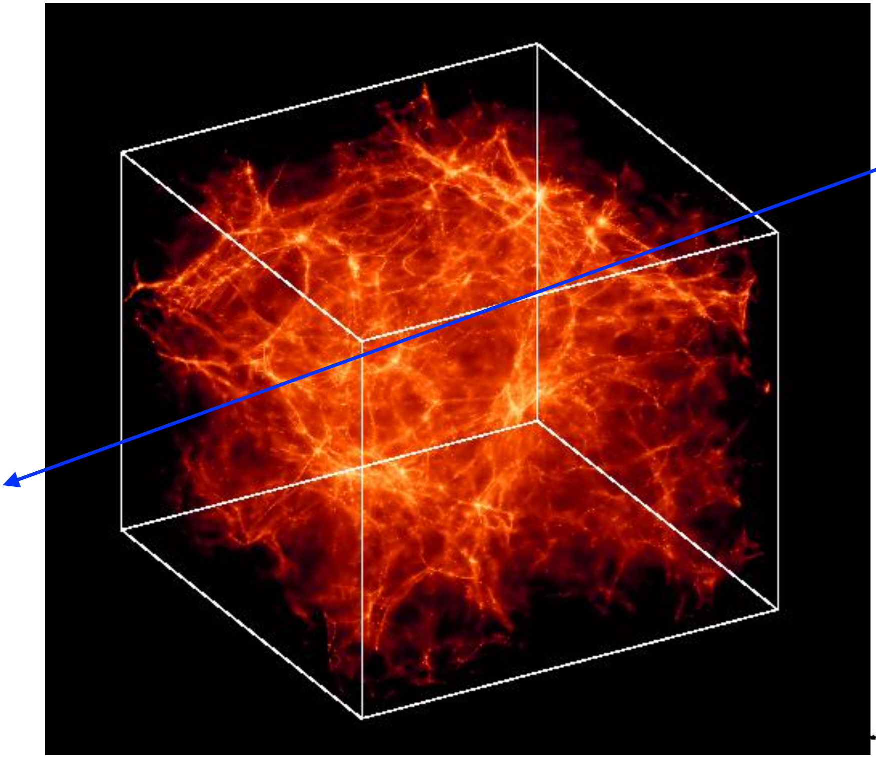
Lyman-α absorption is the main manifestation of the IGM

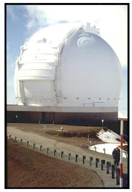


Tiny neutral hydrogen fraction after reionization…. But large cross-section

The Intergalactic Medium: Theory vs. Observations



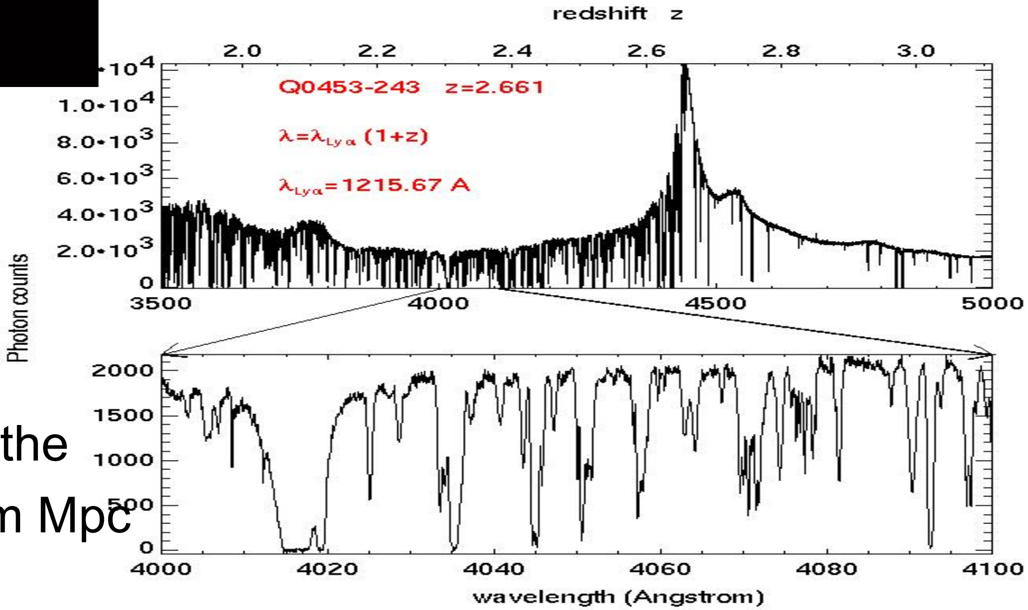




80 % of the baryons at z=3
are in the **Lyman-α forest**

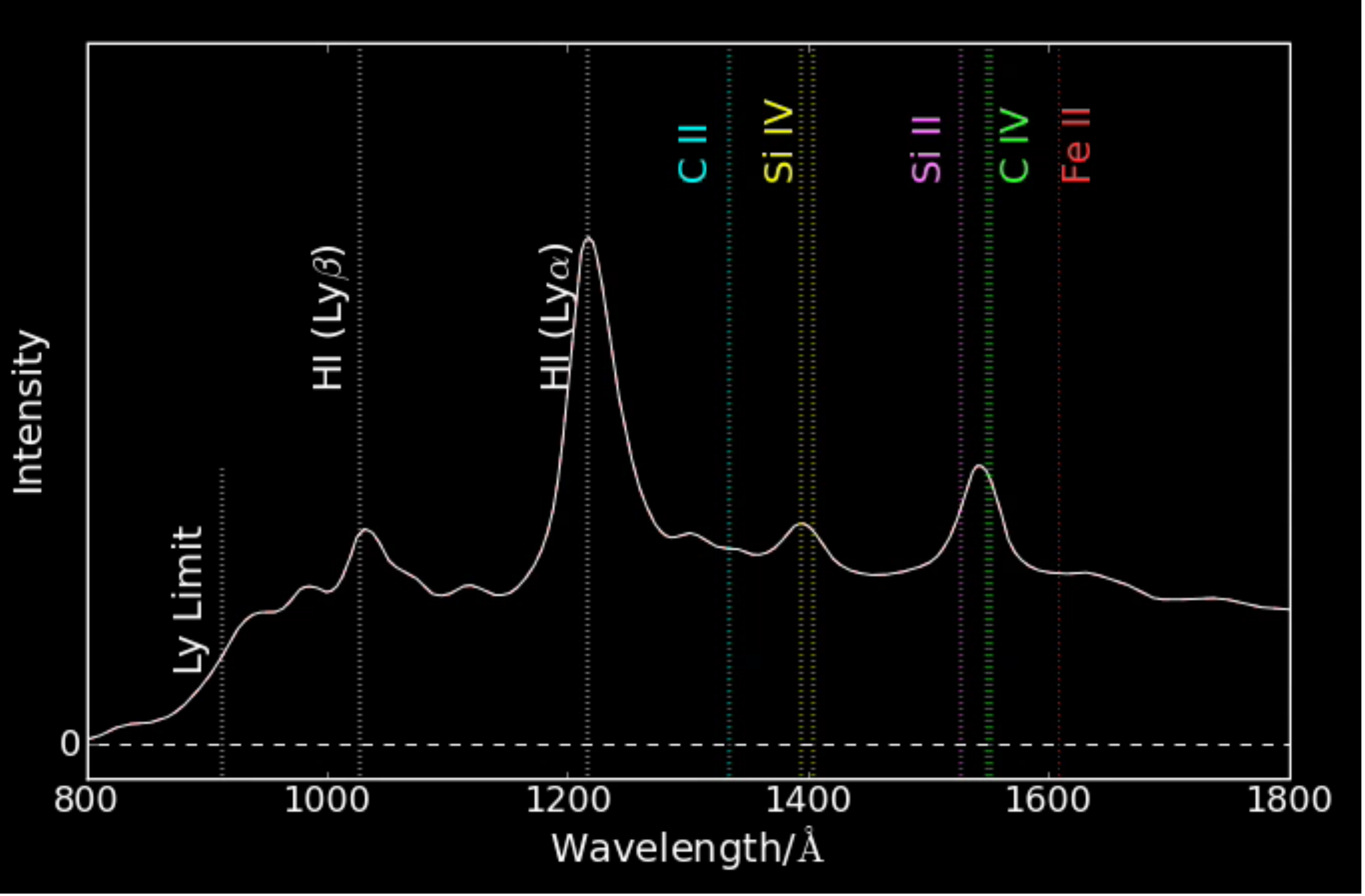
Bi & Davidsen (1997), Rauch (1998)
Review by Meiksin (2009)

baryons as tracer of the dark matter density field



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

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


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

Modelling the IGM – I: Physics

Dark matter evolution: linear theory of density perturbation +
Jeans length $L_J \sim \mathrm{sqrt}(T/\rho)$ + mildly non linear evolution

Hydrodynamic processes: mainly gas cooling
cooling by adiabatic expansion of the universe
heating of gaseous structures (reionization)

- photoionization by a uniform Ultraviolet Background
- Hydrostatic equilibrium of gas clouds

dynamical time = $1/\mathrm{sqrt}(G\,\rho)$ ~ **sound crossing time**= size /gas sound speed

↓

Size of the cloud: > 100 kpc
Temperature: ~ 10^4 K
Mass in the cloud: ~ $10^9\,M_\odot$
Neutral hydrogen fraction: 10^{-5}

In practice, since the process is mildly non linear you need numerical simulations
To get convergence of the simulated flux at the percent level (observed)

Modelling the IGM – II: Analytical models for the Ly-a forest

(Bi 1993, Bi & Davidsen 1997, Hui & Gnedin 1998,
Matarrese & Mohayaee 2002)

$$k_J^{-1}(z) \equiv H_0^{-1}\left[\frac{2\gamma k_B T_m(z)}{3\mu m_p \Omega_{0m}(1+z)}\right]^{1/2}$$

Jeans length

$$\delta_0^{\rm IGM}(\mathbf{k},z) = \frac{\delta_0^{\rm DM}(\mathbf{k},z)}{1+k^2/k_J^2(z)} \equiv W_{\rm IGM}(k,z)D_+(z)\delta_0^{\rm DM}(\mathbf{k})$$

Filtering of linear DM
density field

$$\mathbf{v}^{\rm IGM}(\mathbf{k},z) = E_+(z)\frac{i\mathbf{k}}{k^2}W_{\rm IGM}(k,z)\delta_0^{\rm DM}(\mathbf{k})$$

Peculiar velocity

$$n_{\rm IGM}(\mathbf{x},z) = \overline{n}_{\rm IGM}(z)\exp\left[\delta_0^{\rm IGM}(\mathbf{x},z) - \frac{\langle(\delta_0^{\rm IGM})^2\rangle D_+^2(z)}{2}\right]$$

Non linear density field

$$T(\mathbf{x},z) = \boxed{T_0(z)}\,(1+\delta^{\rm IGM}(\mathbf{x},z))^{\boxed{\gamma(z)}-1}$$

'Equation-of-state'

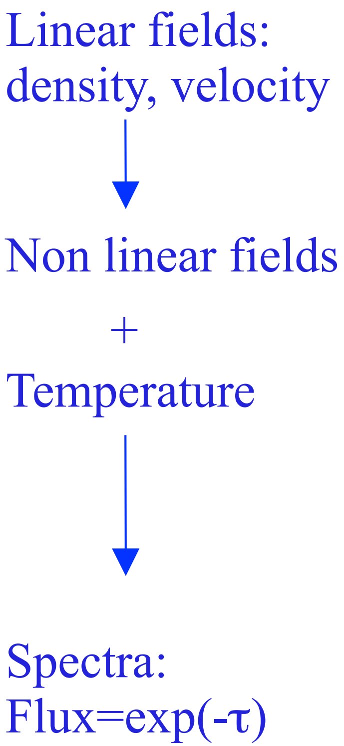
$$\boxed{\alpha(z,T(z))\,n_p n_e = J(z)n_{\rm HI}}\ ,$$

Neutral hydrogen
ionization equilibrium equation

$$\tau(u) = \frac{\sigma_{0,\alpha}\,c}{H(z)}\int_{-\infty}^{\infty} dy\, n_{\rm HI}(y)\,\mathcal{V}\left[u-y-v_{\parallel}^{\rm IGM}(y),\ b(y)\right]$$

Optical depth

Density Velocity Temperature



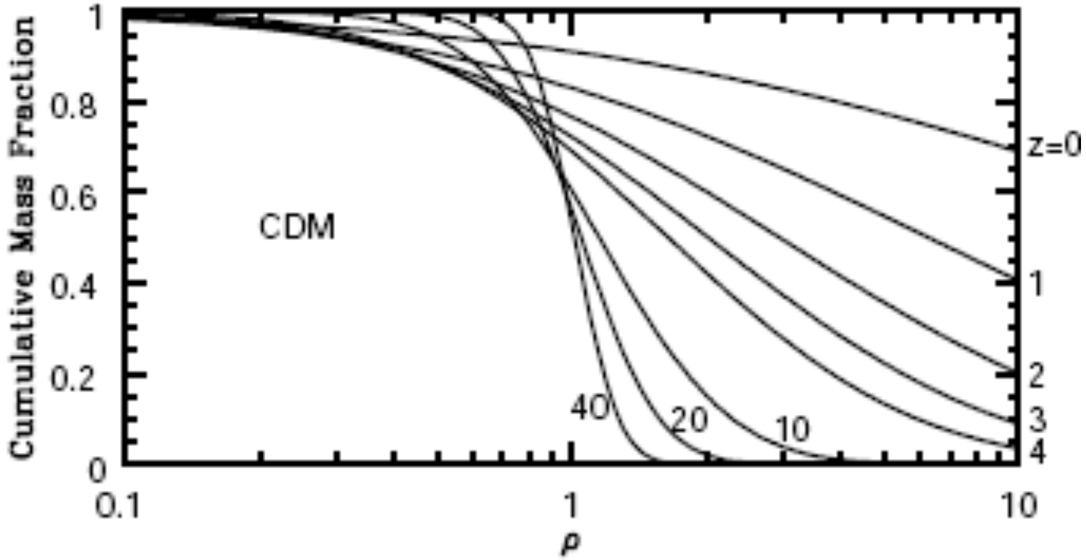
Linear fields:
density, velocity

Non linear fields
+
Temperature

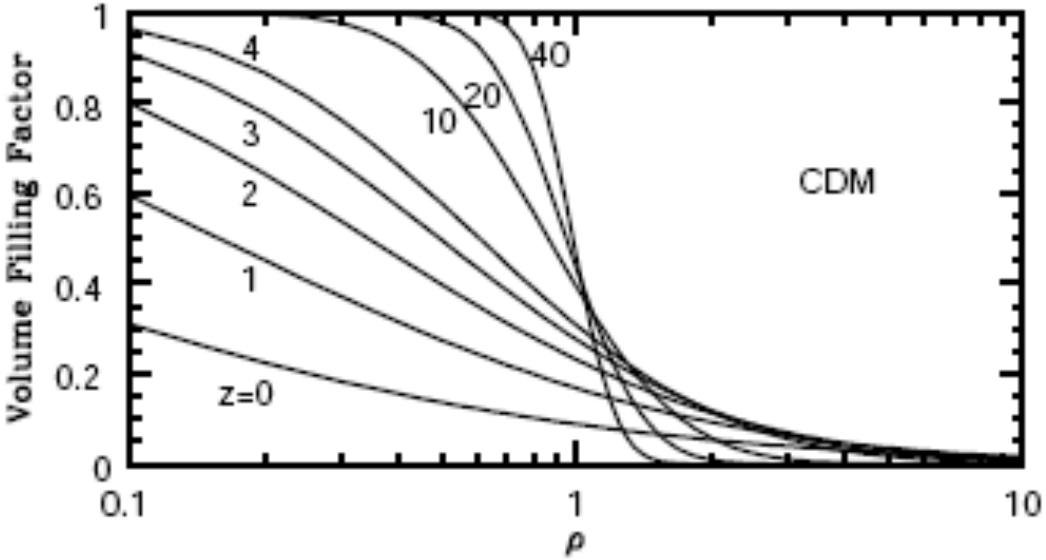
Spectra:
Flux=exp(-τ)

MV, Matarrese S., Mo HJ., Haehnelt M., Theuns T., 2002a, MNRAS, 329, 848

Modelling the IGM – III: IGM in a CDM universe



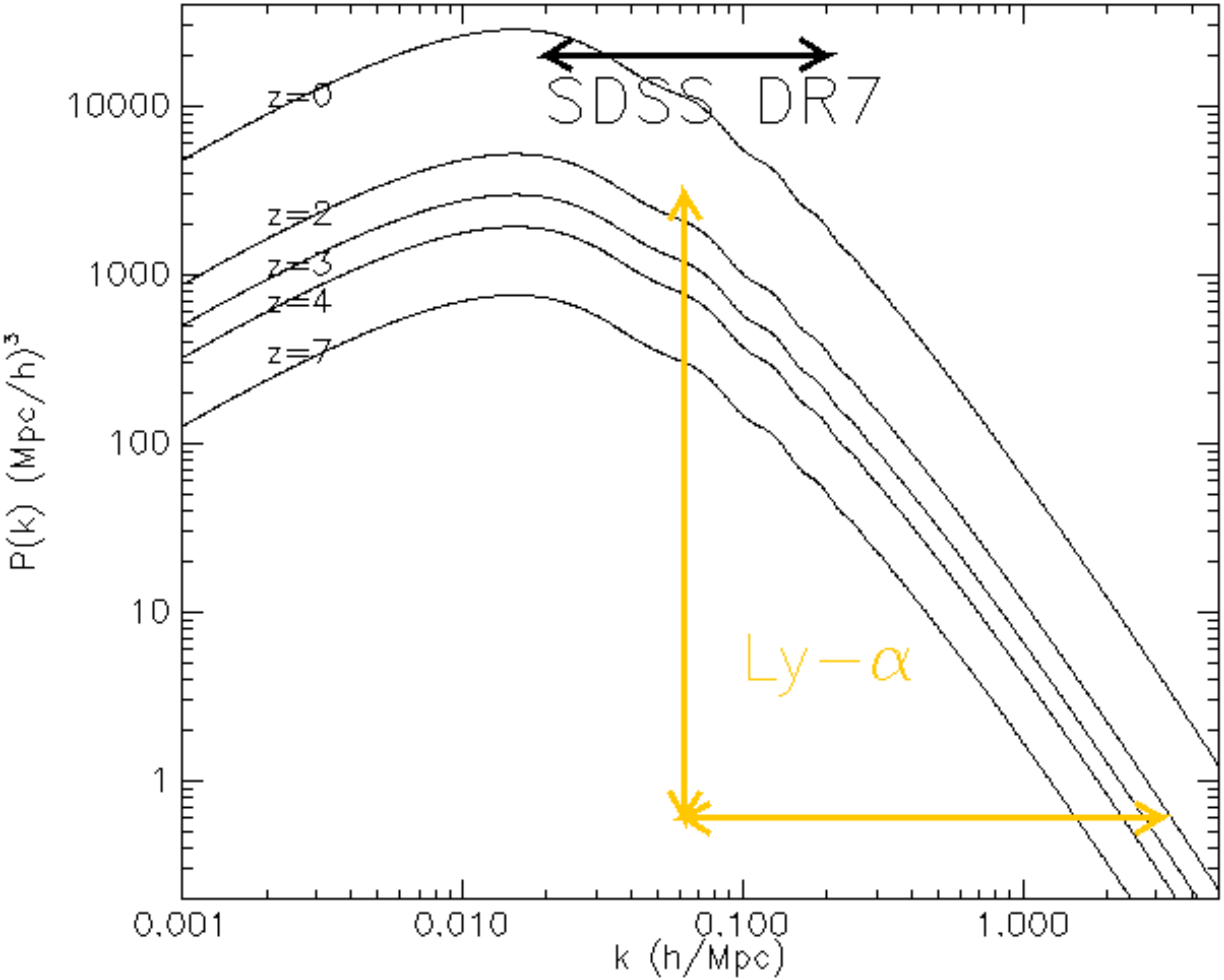
M (> ρ)



V (> ρ)

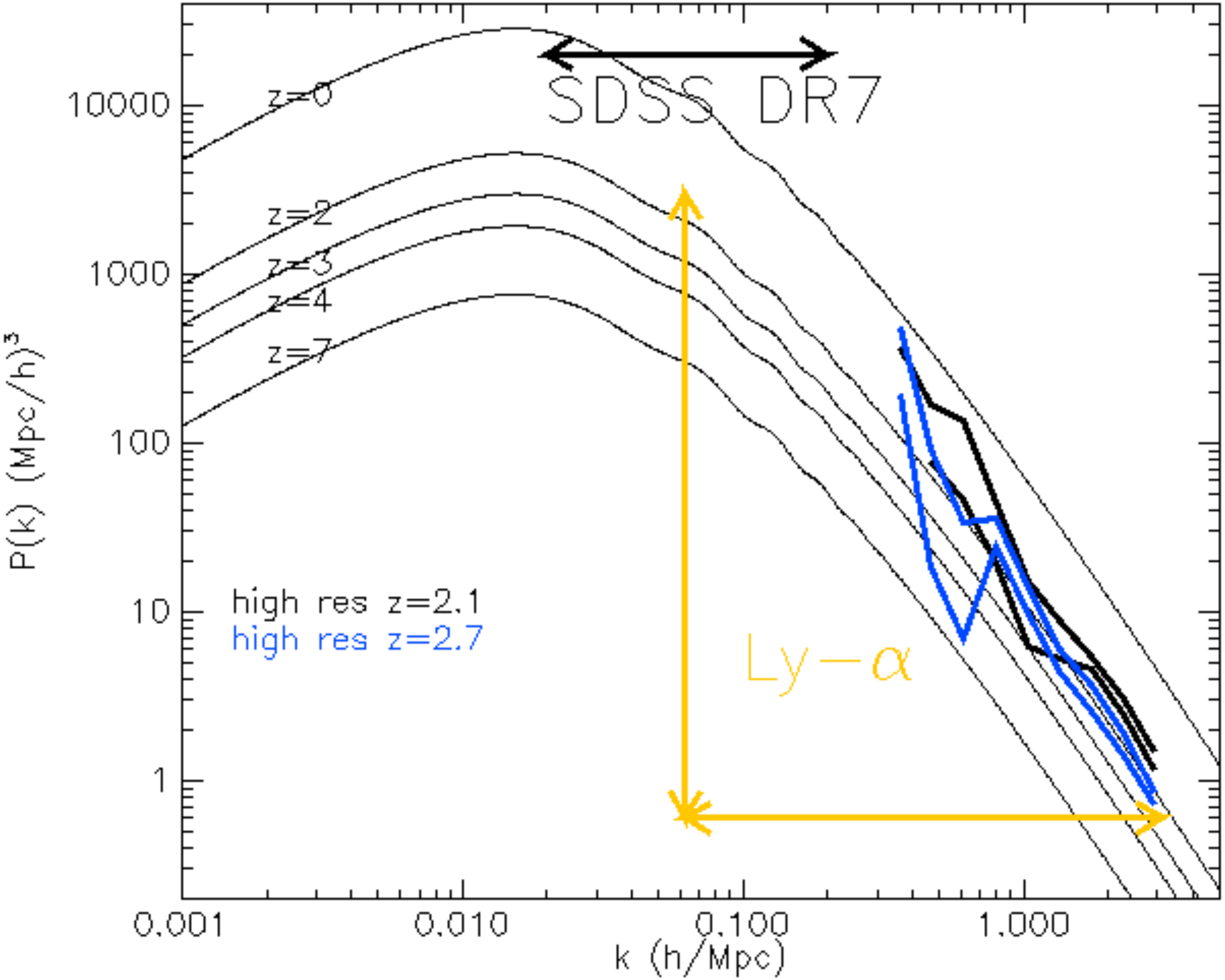
Bi & Davidsen 1997, ApJ, 479, 523

DATA vs THEORY

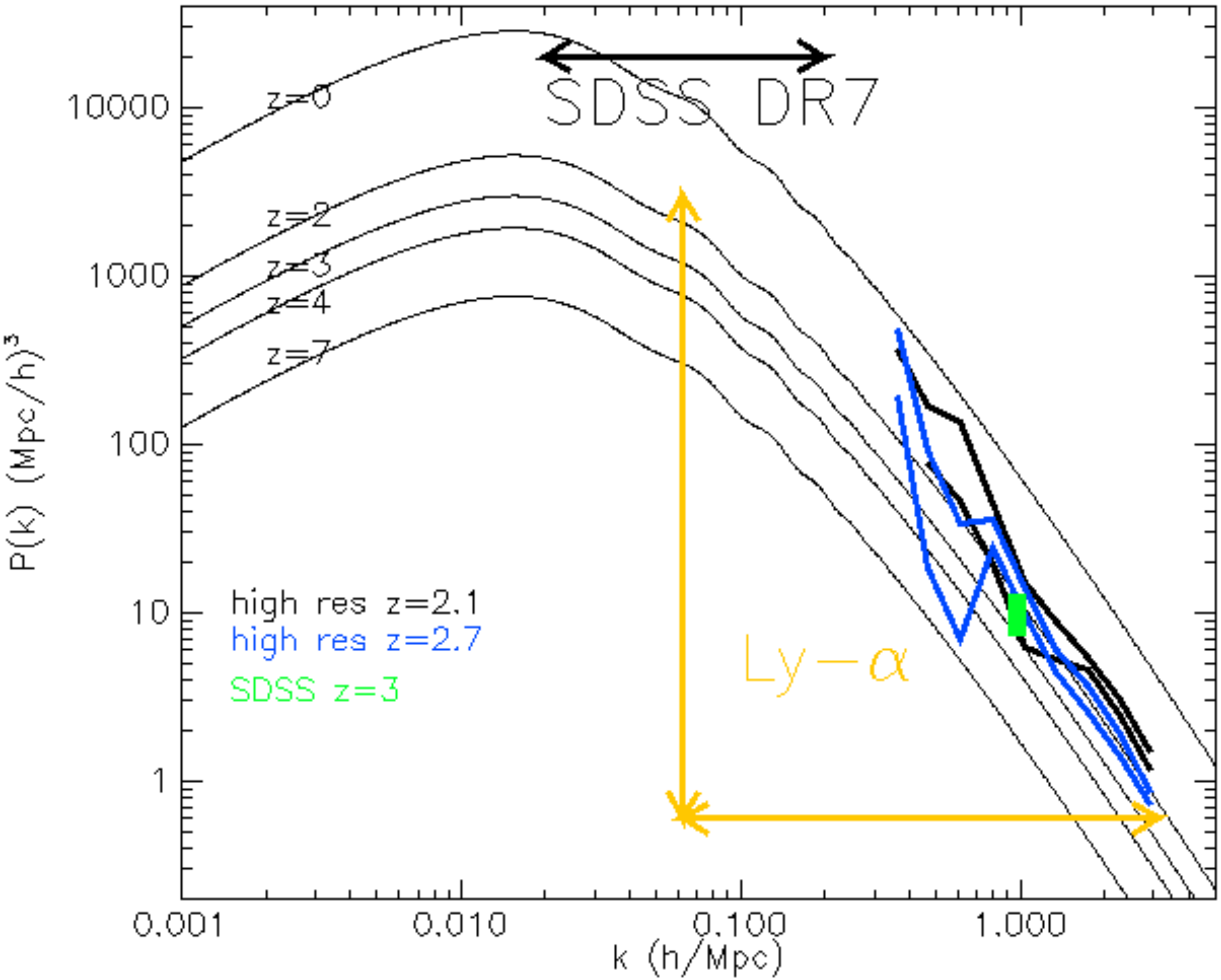


DATA vs THEORY

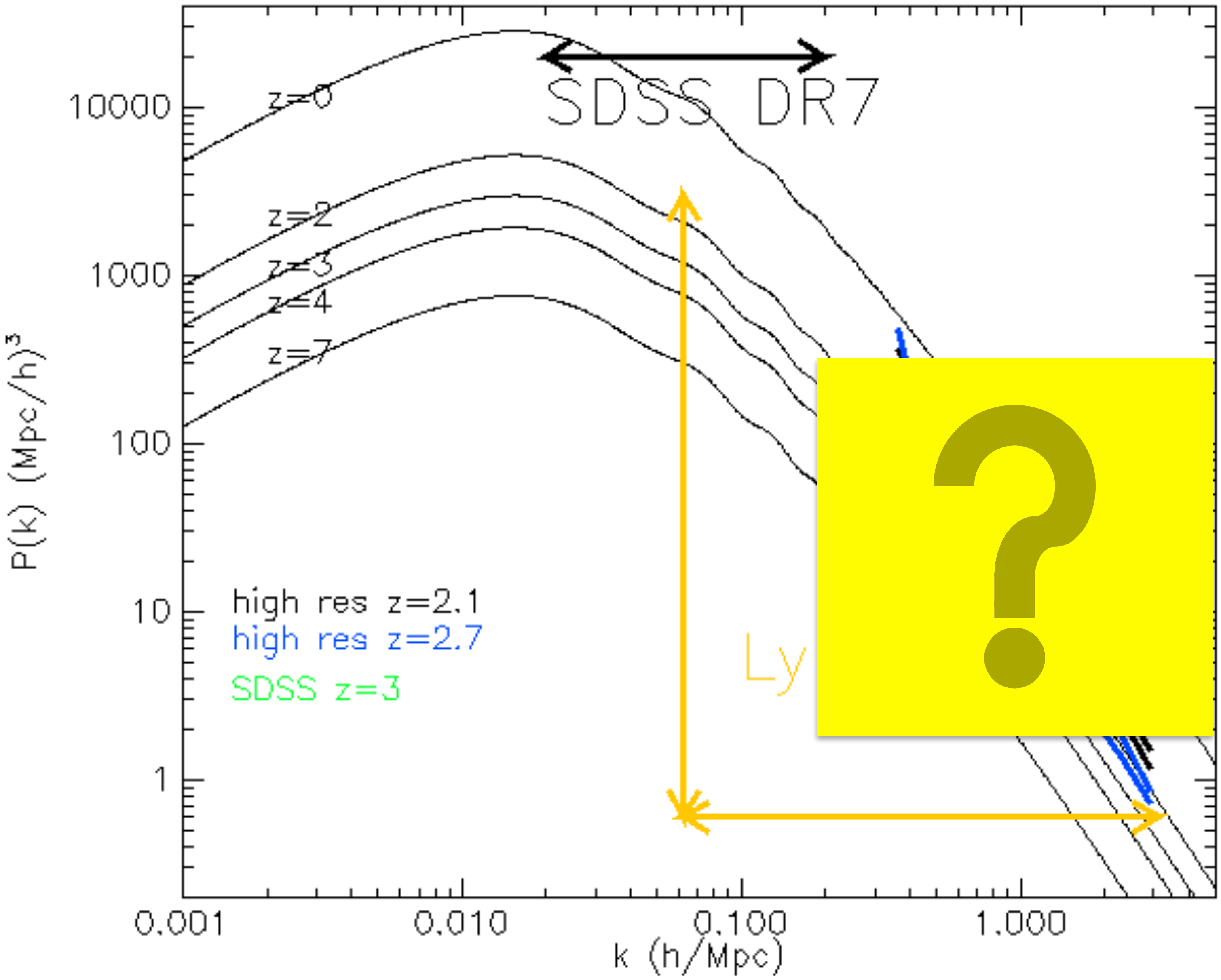
$$P_{\mathrm{FLUX}}(k,z) = \mathrm{bias}^2(k,z) \times P_{\mathrm{MATTER}}(k,z)$$



DATA vs THEORY



DATA vs THEORY



END OF INTRO

We have characterized *the physics of the IGM*
and we can now fully exploit the fact that:

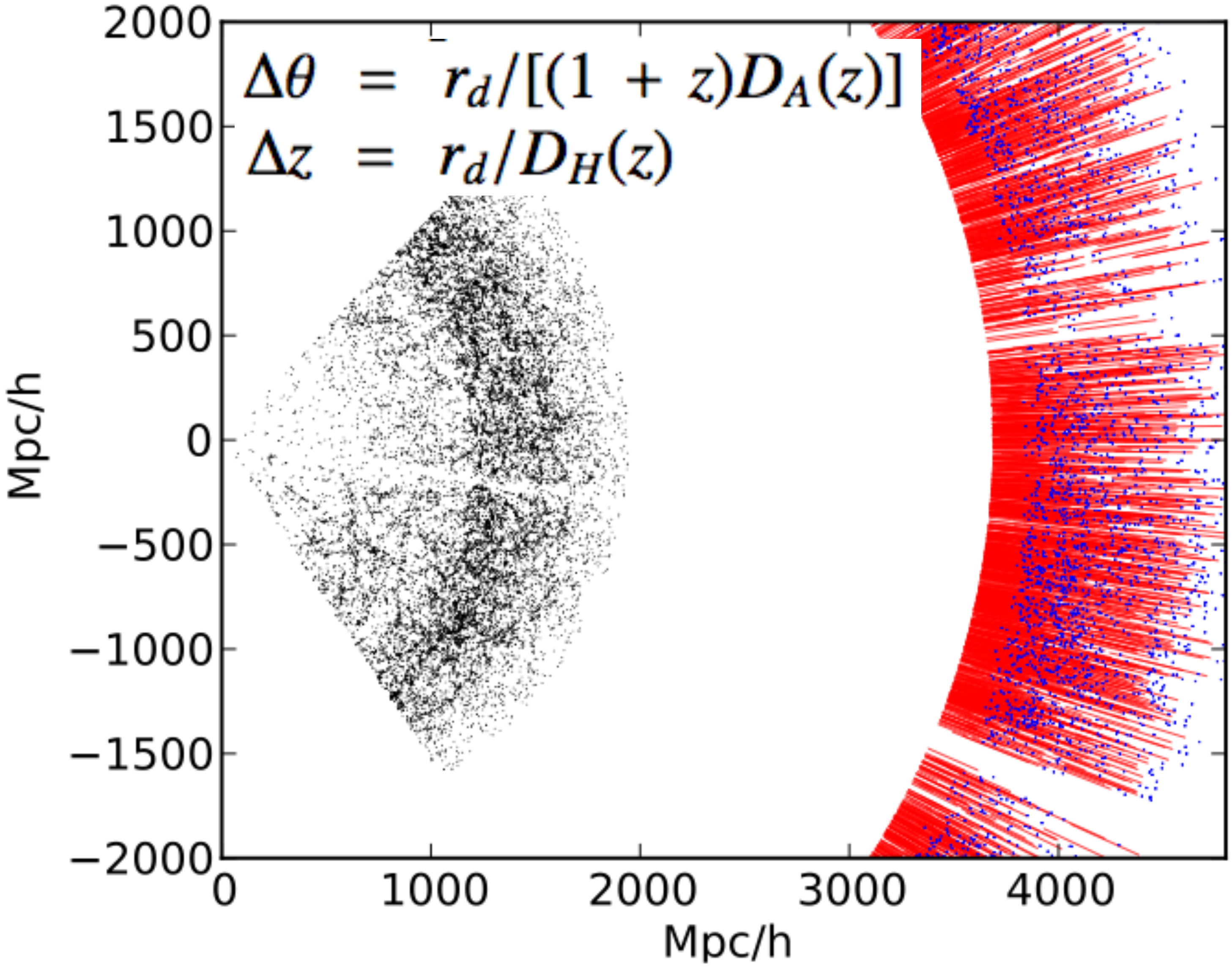
The IGM is a probe of matter fluctuations,
a laboratory for fundamental physics.
a sink (and a reservoir) for (of) galactic baryons

RESULTS FROM BOSS/SDSS-III

Geometrical and dynamical state of the Universe at $z = 2.3$

SDSS- I

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



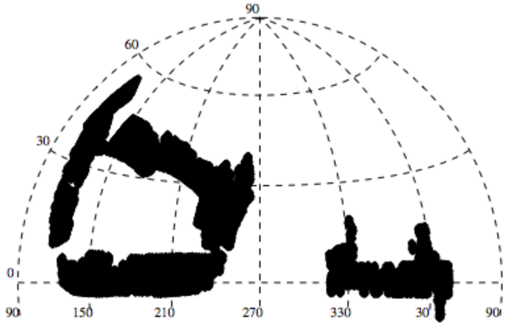
Slosar et al. 11
Busca et al. 13
Slosar et al. 13

SDSS- II

Busca et al. 13

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

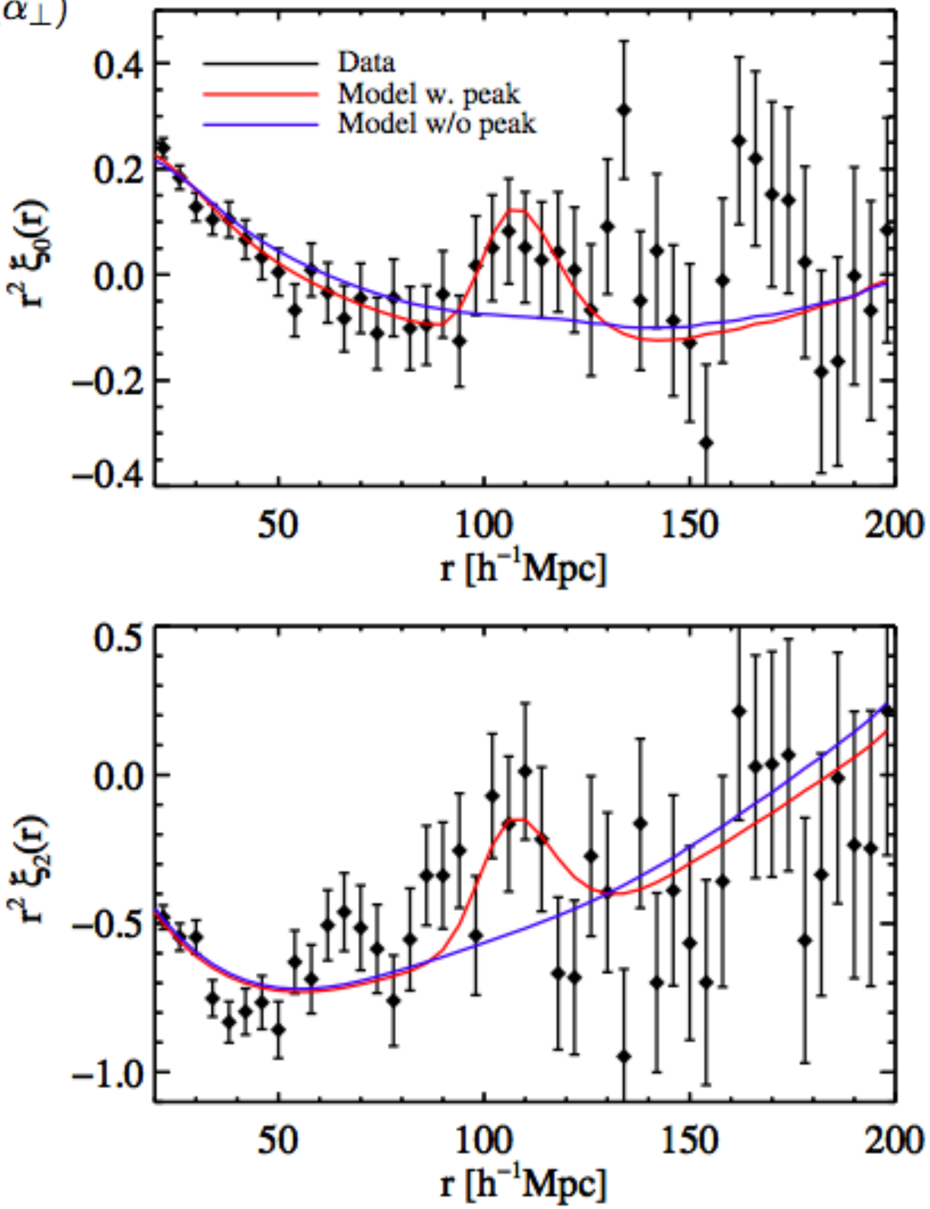
$$\xi(r_\parallel, r_\perp) = \xi_{\rm cosmo}(r_\parallel, r_\perp, \alpha_\parallel, \alpha_\perp) + \xi_{\rm bb}(r_\parallel, r_\perp)$$



BAO feature detected at z=2.3

From 3000 deg^2, using 50000 QSOs

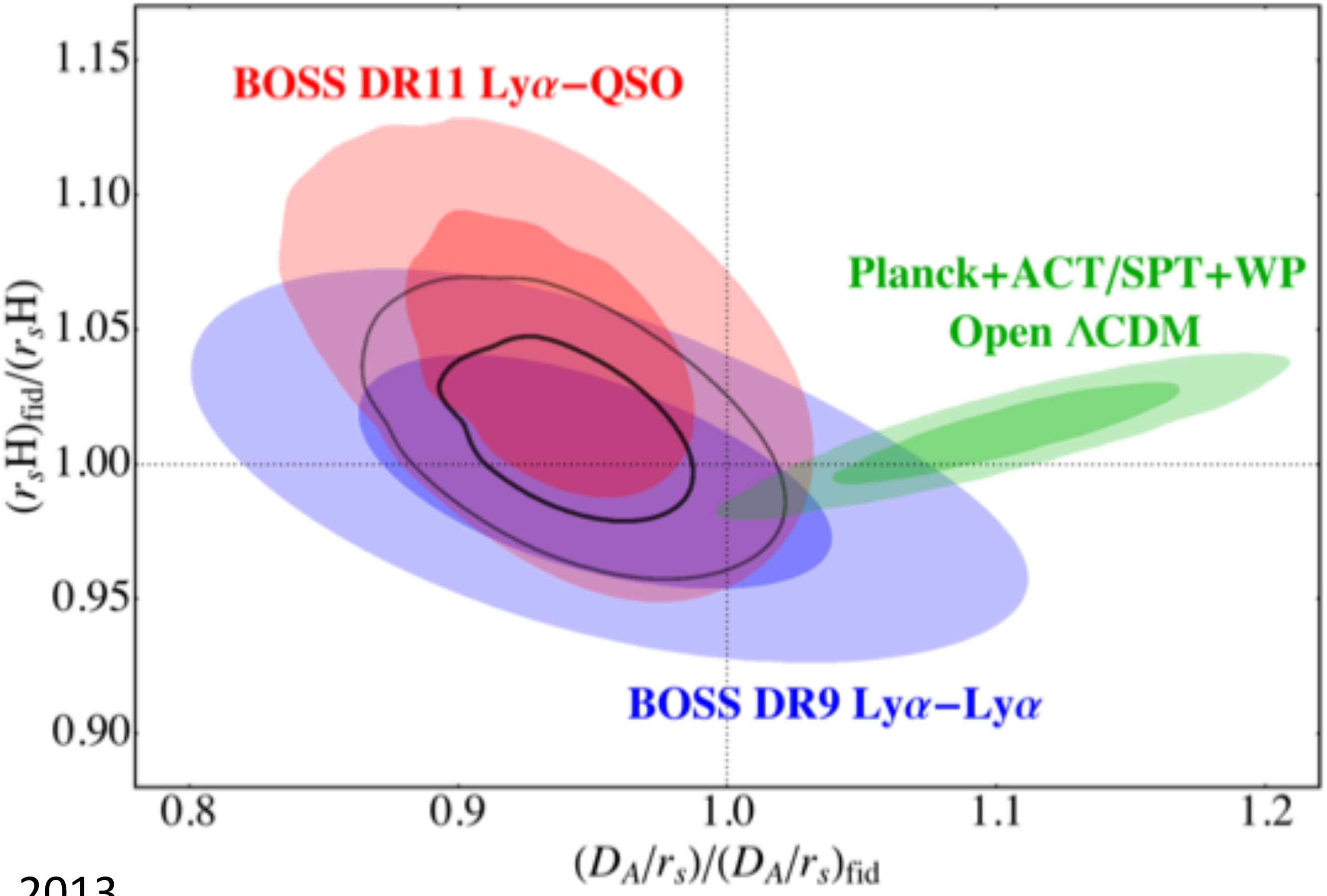
Significance of the detection at around 3σ



SDSS- III

3D cross-correlation between Lyman-α flux and quasars

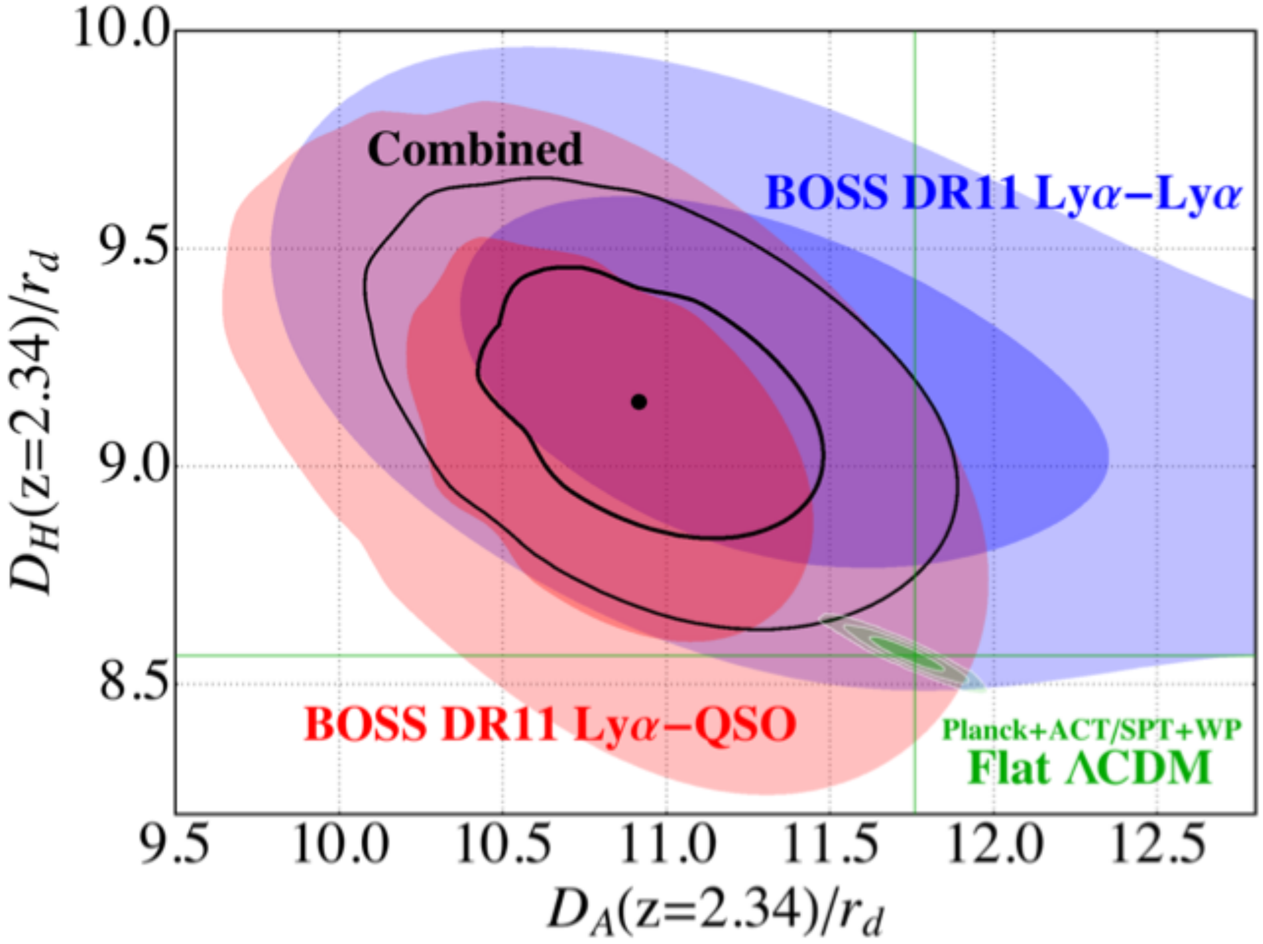
$$P_{qF}(\mathbf{k}) = b_q \left[1 + \beta_q \mu_k^2\right] b_F \left[1 + \beta_F \mu_k^2\right] \; P(k)$$



Font-Ribera et al. 2013

SDSS-IV

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



$$\frac{\rho_{\rm de}(z=2.34)}{\rho_{\rm de}(z=0)} = -1.2 \pm 0.8$$

!

Delubac et al. 14

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

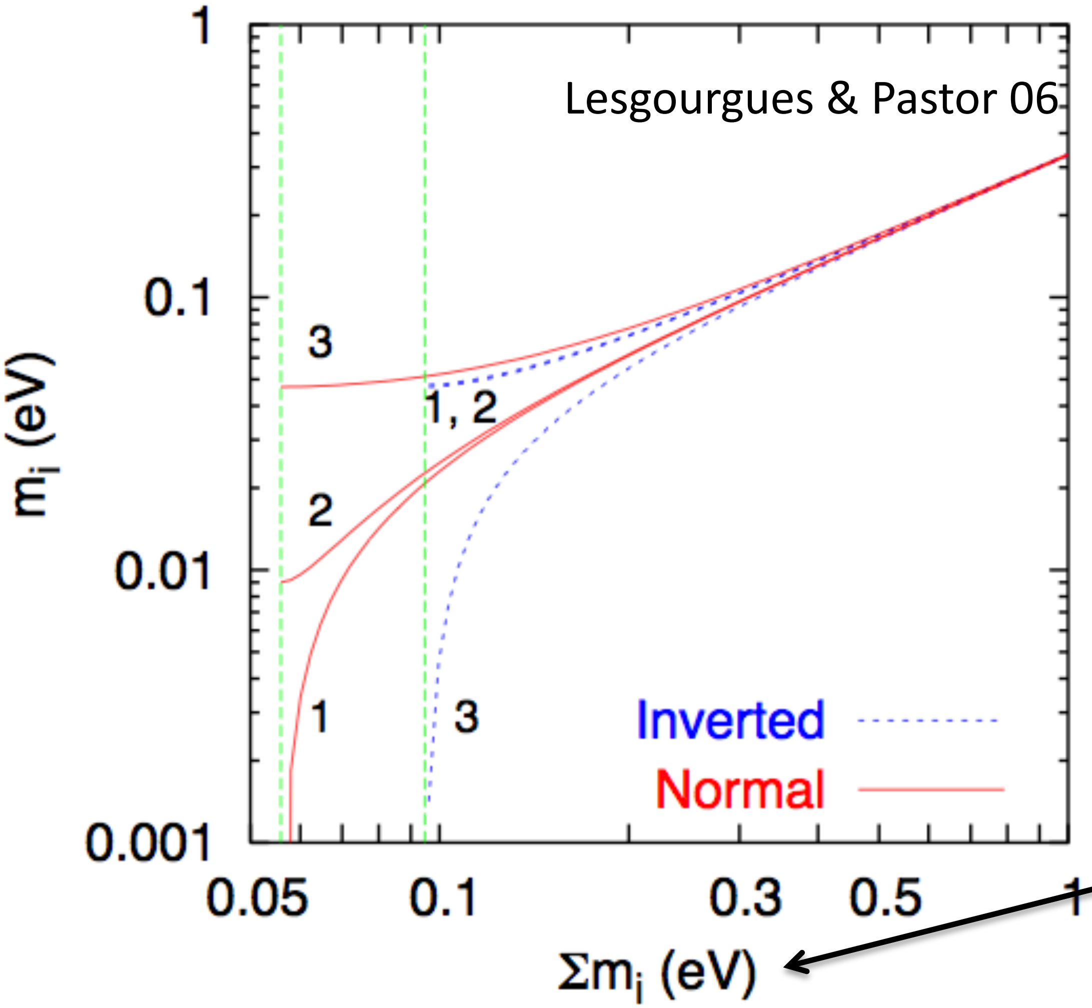
3) **HIGH REDSHIFT**

Where you are possibly closer to primordial P(k)

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

CONSTRAINTS ON 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

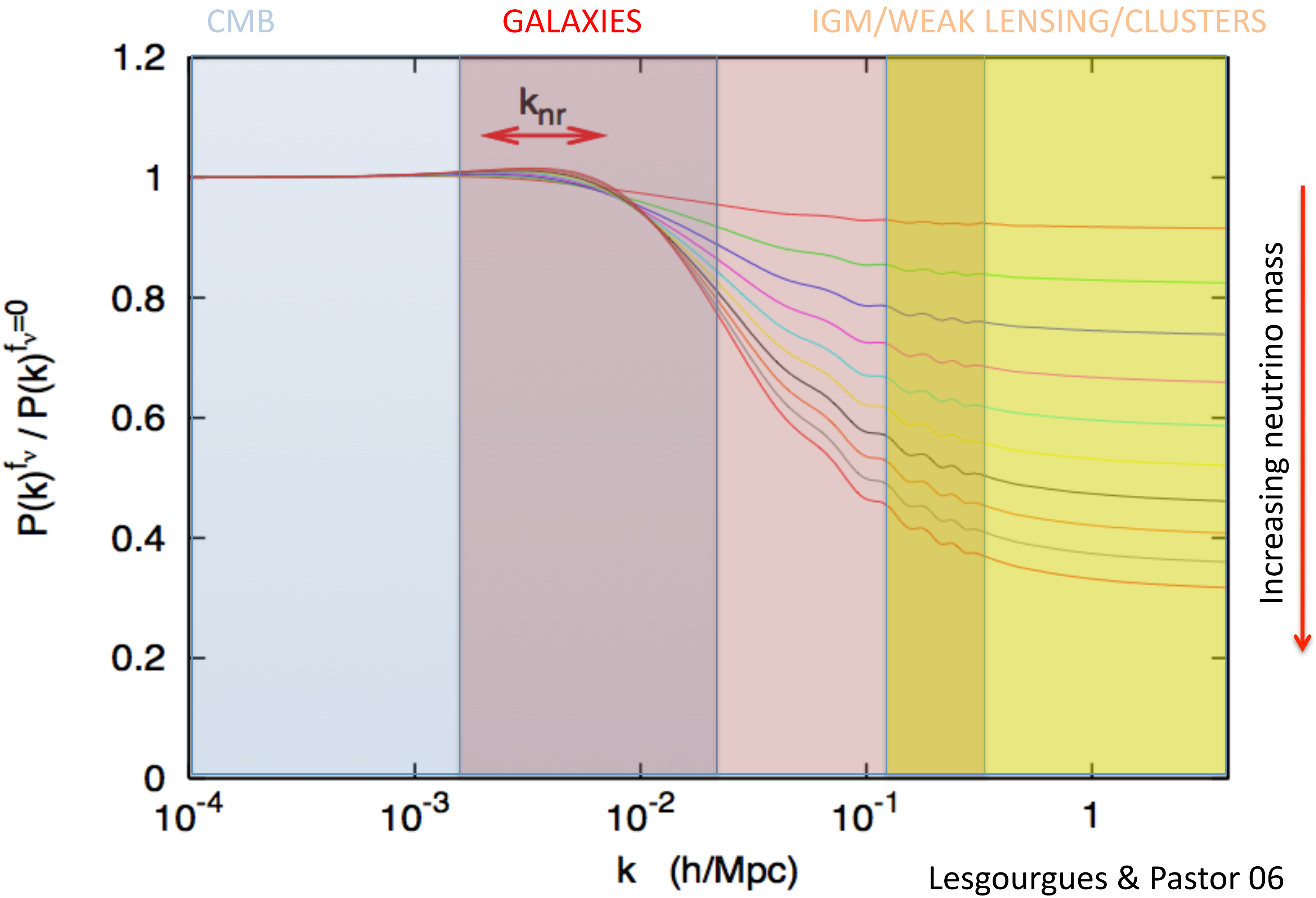
RADIATION ERA z>3400

MATTER RADIATION z<3400

NON-RELATIVISTIC TRANSITION z ~ 500

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

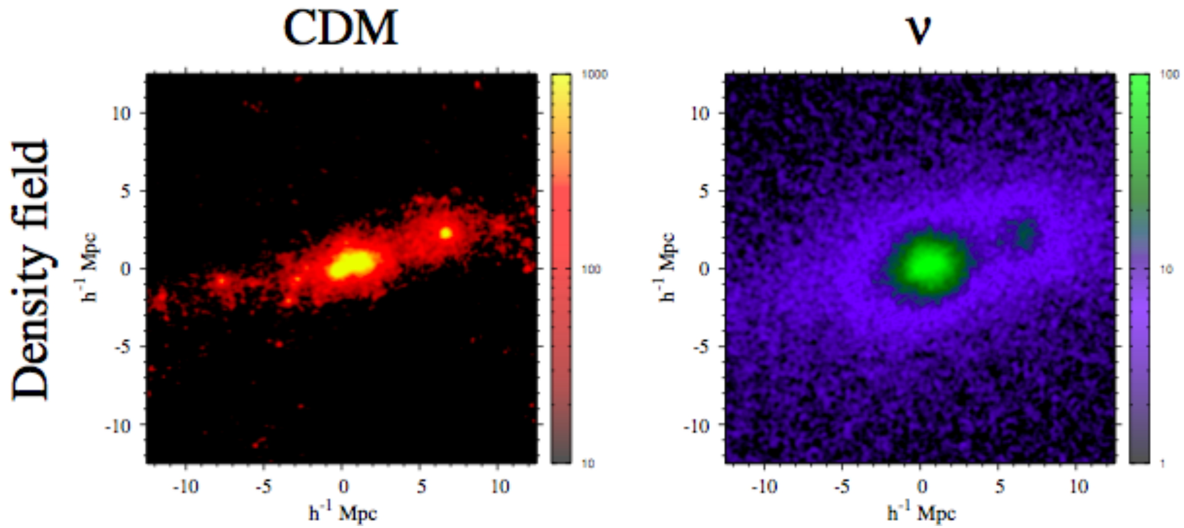
COSMOLOGICAL NEUTRINOS - III: LINEAR MATTER POWER



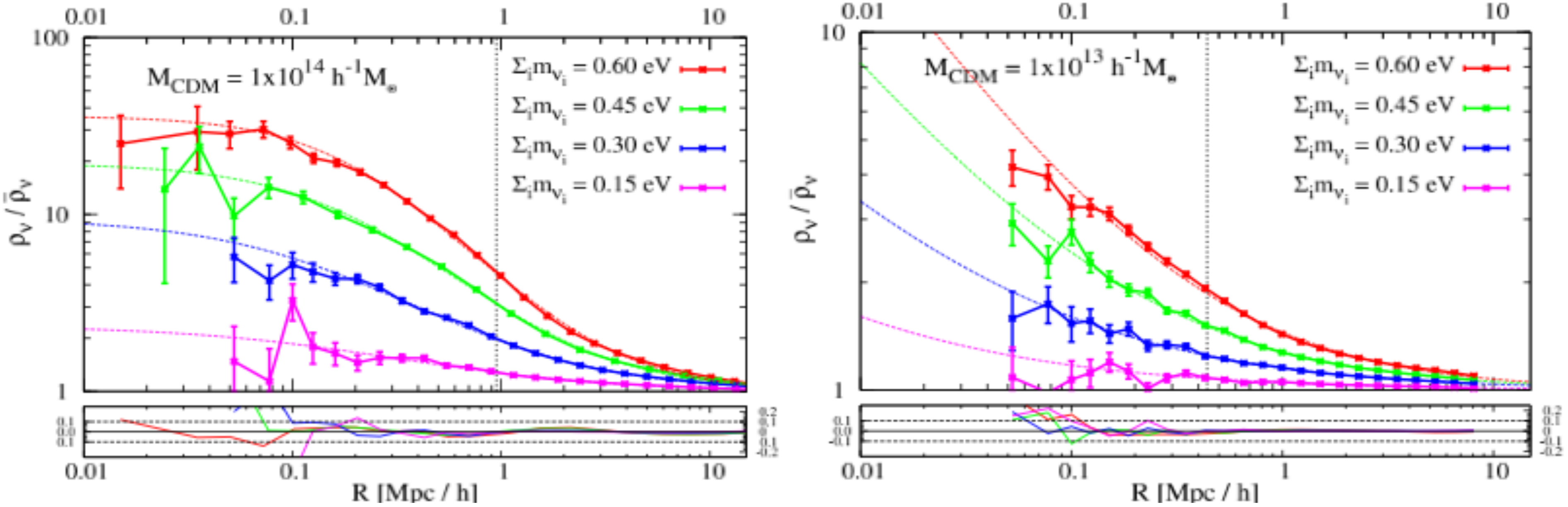
Lesgourgues & Pastor 06

MASSIVE NEUTRINOS

THE FUTURE: THE NEUTRINO HALO?

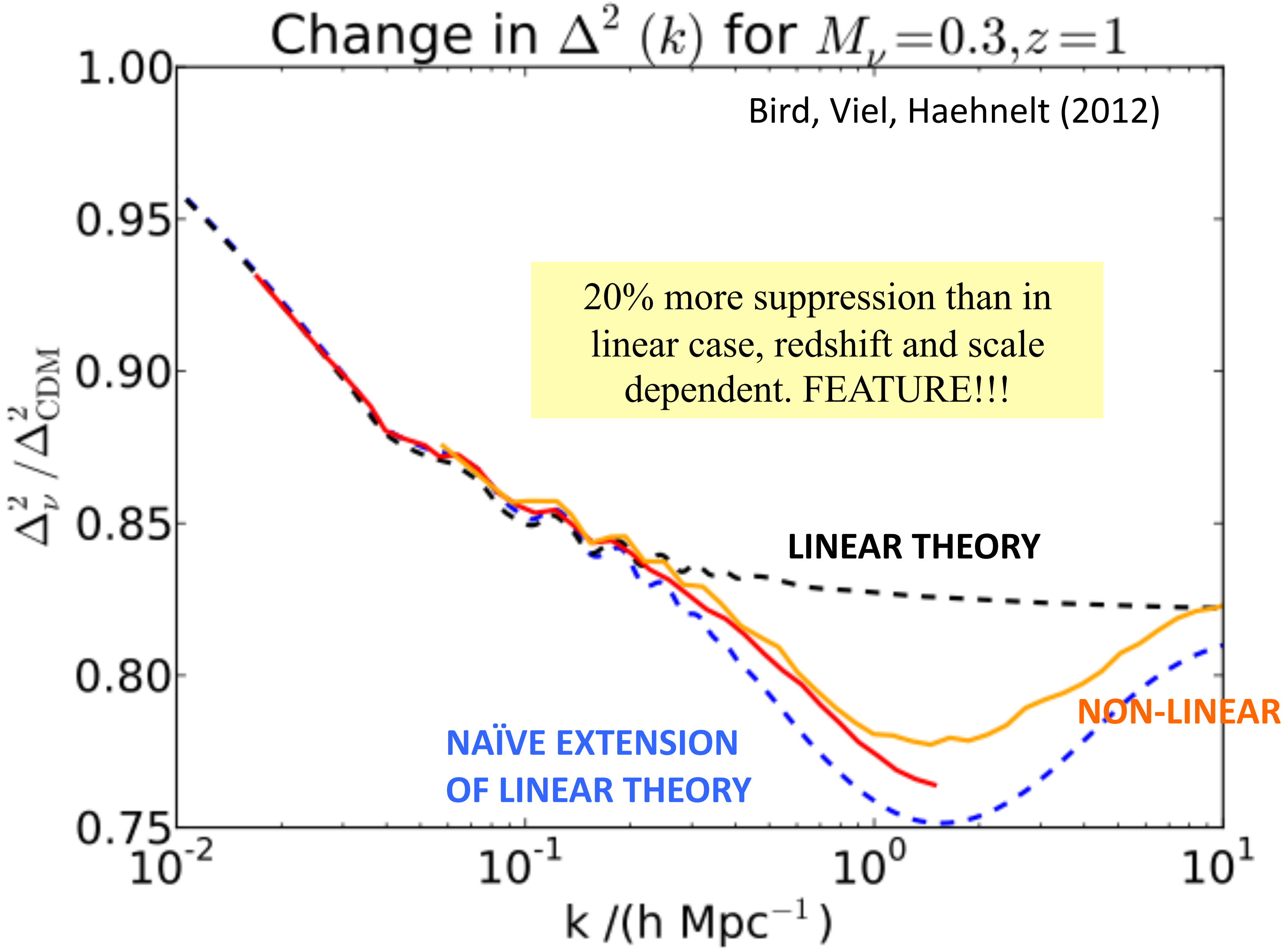


$$\delta_\nu(r) = \frac{\rho_\nu(r) - \bar{\rho}_\nu}{\bar{\rho}_\nu} = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$



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

COSMOLOGICAL NEUTRINOS : NON-LINEAR MATTER POWER



Bird, Viel, Haehnelt (2012)

20% more suppression than in linear case, redshift and scale dependent. FEATURE!!!

LINEAR THEORY

NAÏVE EXTENSION OF LINEAR THEORY

NON-LINEAR

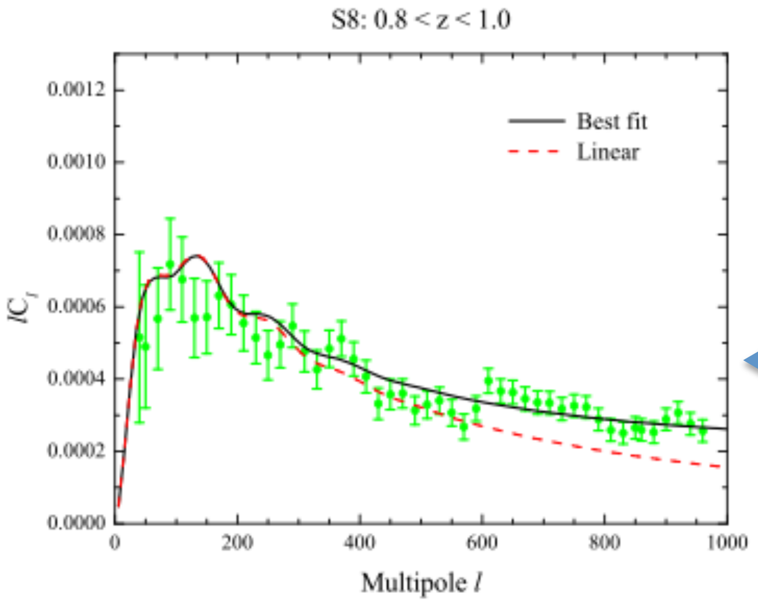
P massive / P massless

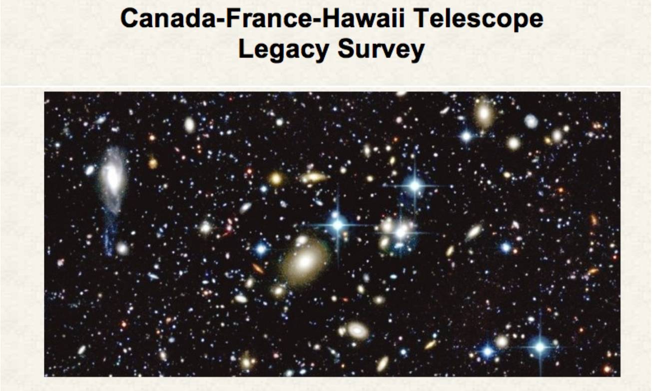
Cosmic Scale

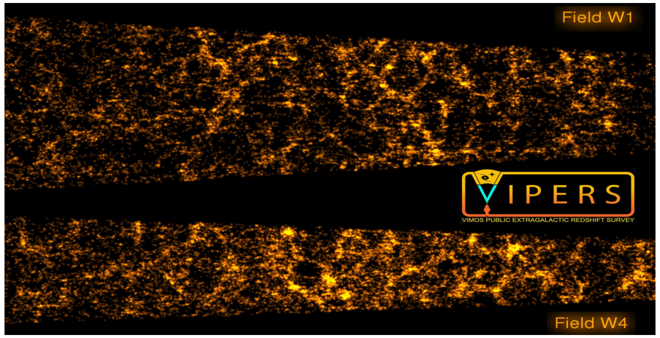
http://www.sns.ias.edu/~spb/index.php?p=code

CONSTRAINTS on NEUTRINO MASSES USING NON-LINEARITIES

Xia, Granett, Viel, Bird, Guzzo+ 2012 JCAP, 06, 010





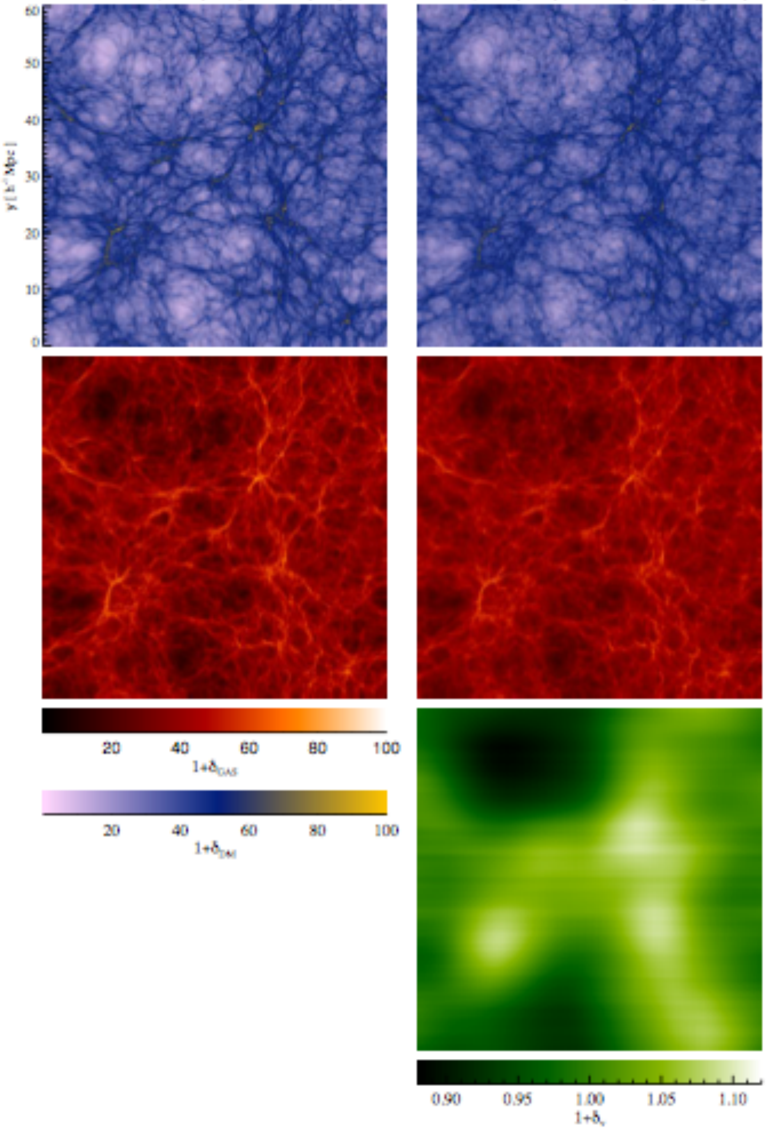


95% C.L. $\sum m_\nu$ [eV]	Without HST Prior		With HST Prior	
	$\ell_{\rm max} = 630$	$\ell_{\rm max} = 960$	$\ell_{\rm max} = 630$	$\ell_{\rm max} = 960$
WMAP7	1.17		0.50	
WMAP7 + CFHTLS	0.64	0.43	0.41	0.29
WMAP7 + SDSS + CFHTLS	0.47	0.35	0.35	0.28

If using just linear 0.43eV – Improvement is about 20% when extending to non-linear

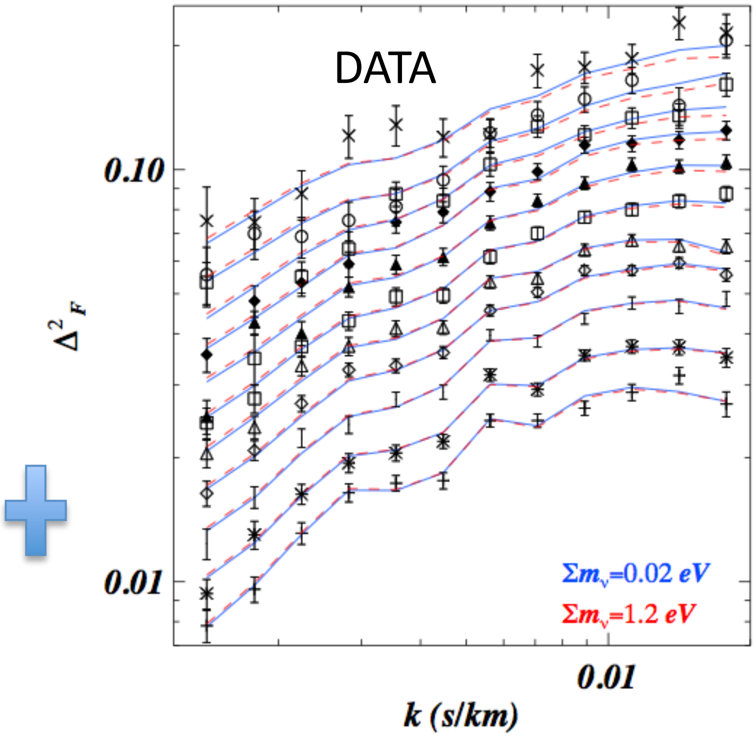
NEUTRINOS IN THE IGM

SIMULATIONS

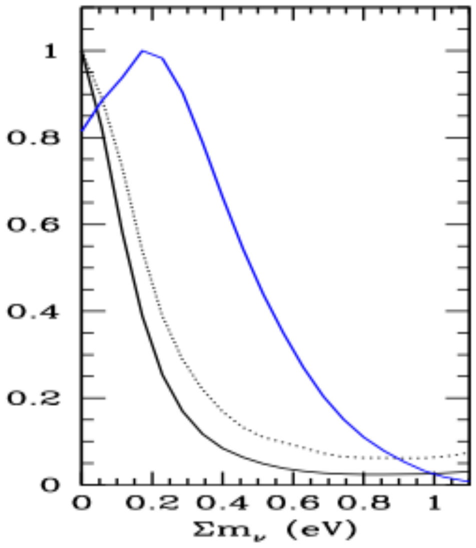


Viel, Haehnelt, Springel 2010

DATA



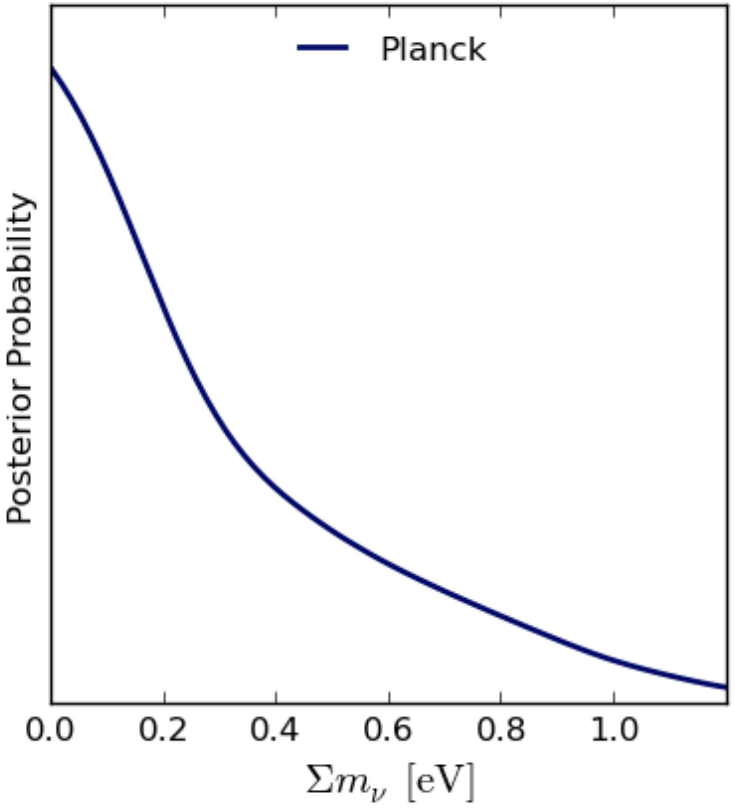
CONSTRAINTS



FROM IGM ONLY:

$\Sigma m_\nu < 0.9$ eV(2σ)

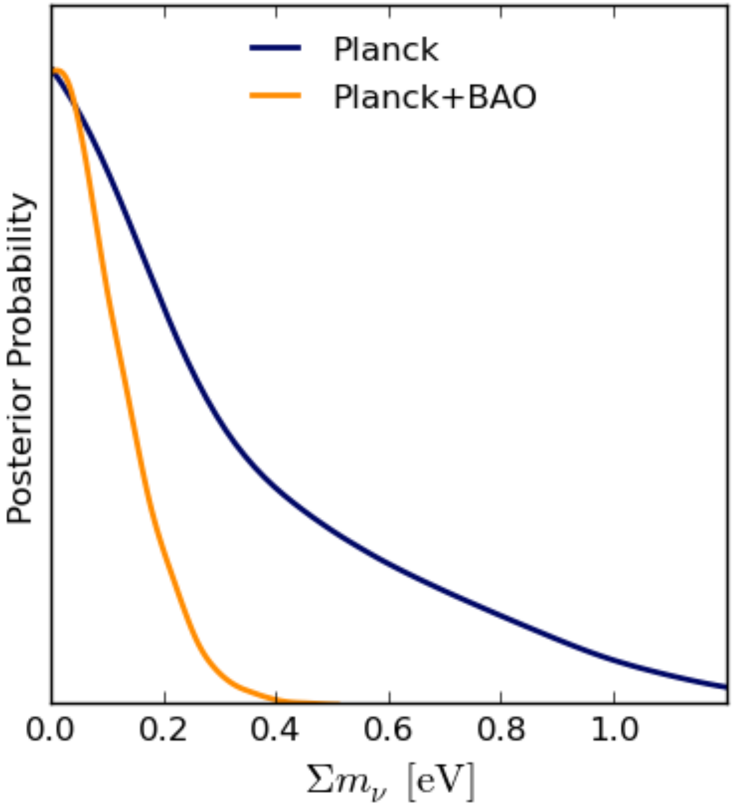
CONSTRAINTS on NEUTRINO MASSES FROM Planck: I



$$\Sigma m_\nu < 0.93 \text{ eV} (2\sigma)$$

Costanzi+ 2014, JCAP

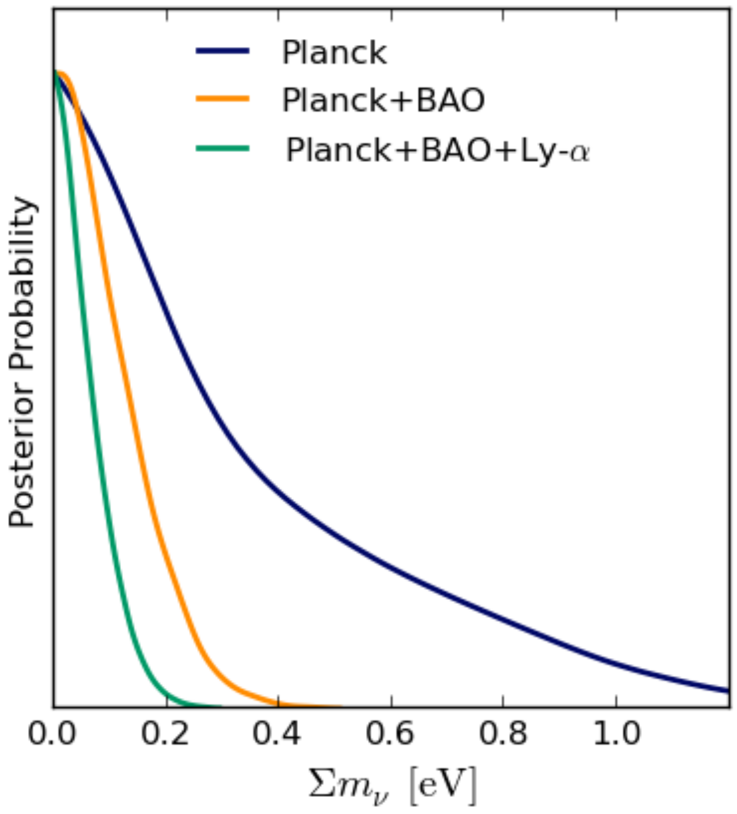
CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO: II



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

Costanzi+ 2014

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



$\Sigma m_\nu < 0.14$ eV(2σ)

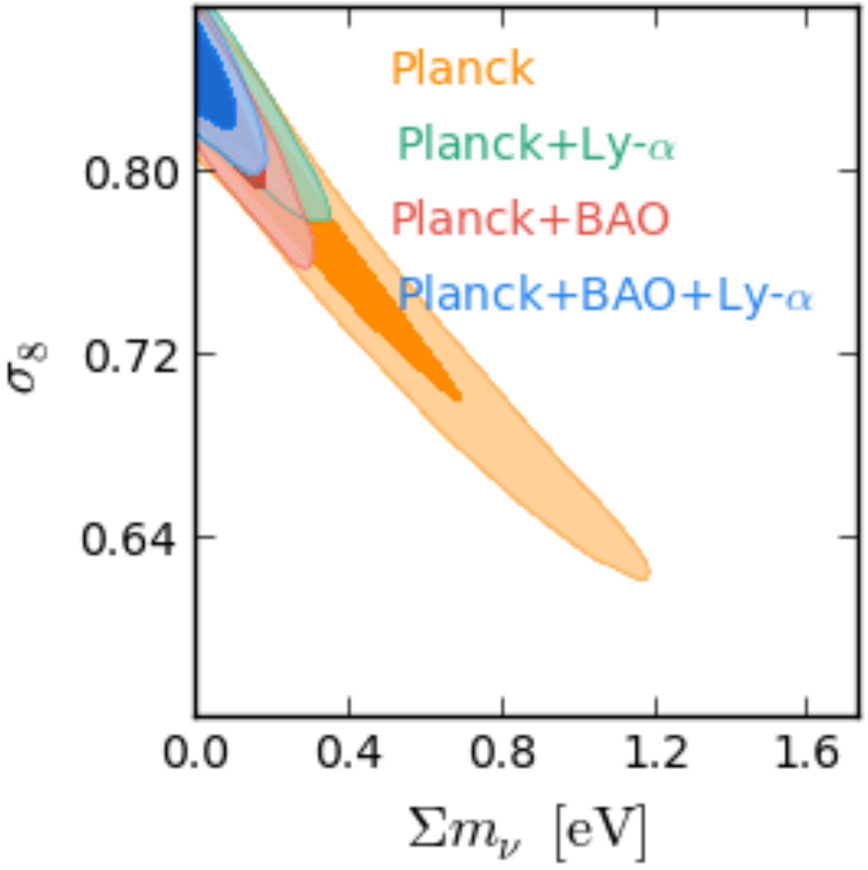
Costanzi+ 2014

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

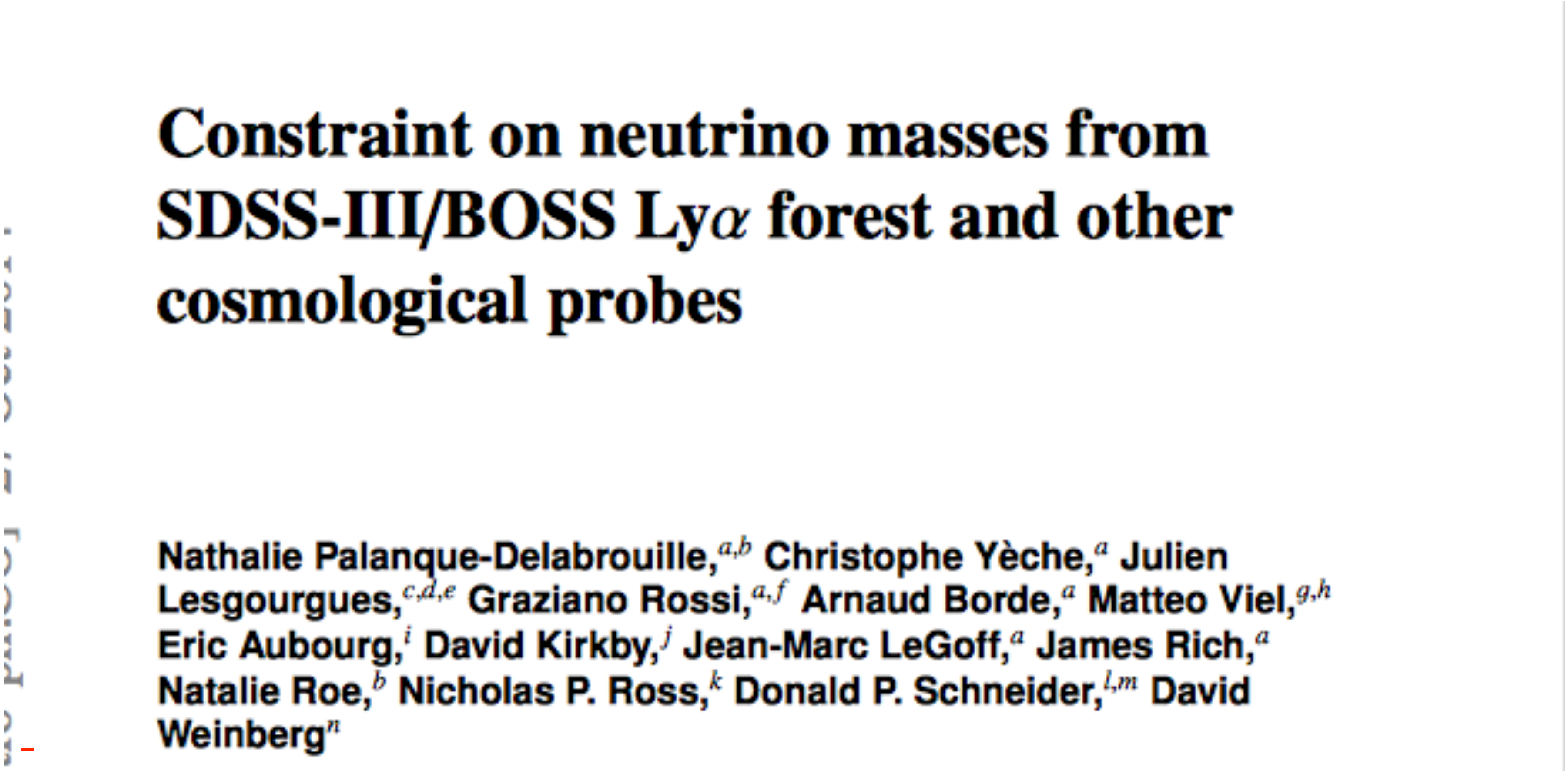
–



2 eV
29 eV
59 eV
19 eV

Costanzi, Sartoris, MV, Borgani 2014, JCAP in press

CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+ NEW Lya: I

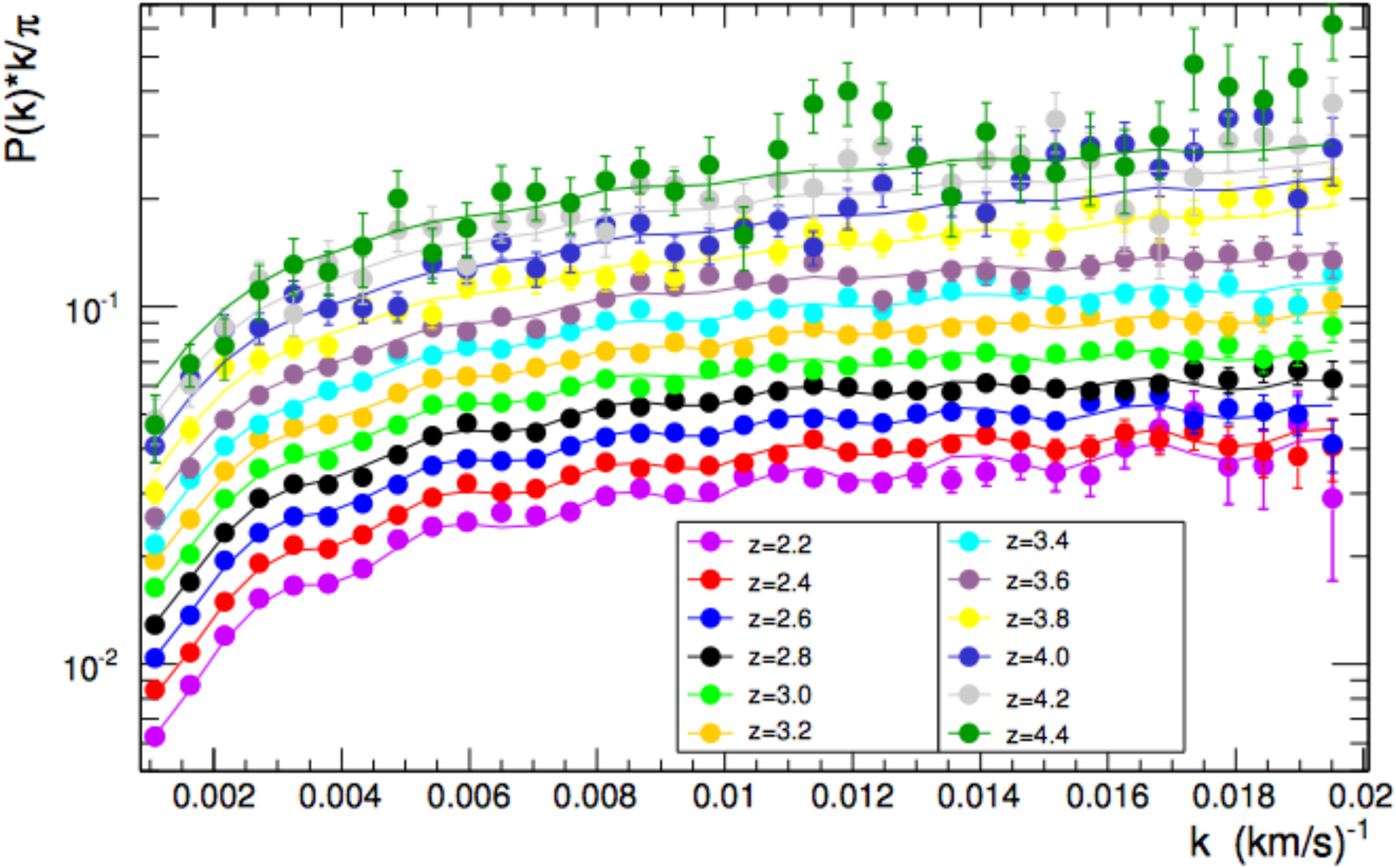


Constraint on neutrino masses from SDSS-III/BOSS Lyα forest and other cosmological probes

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]

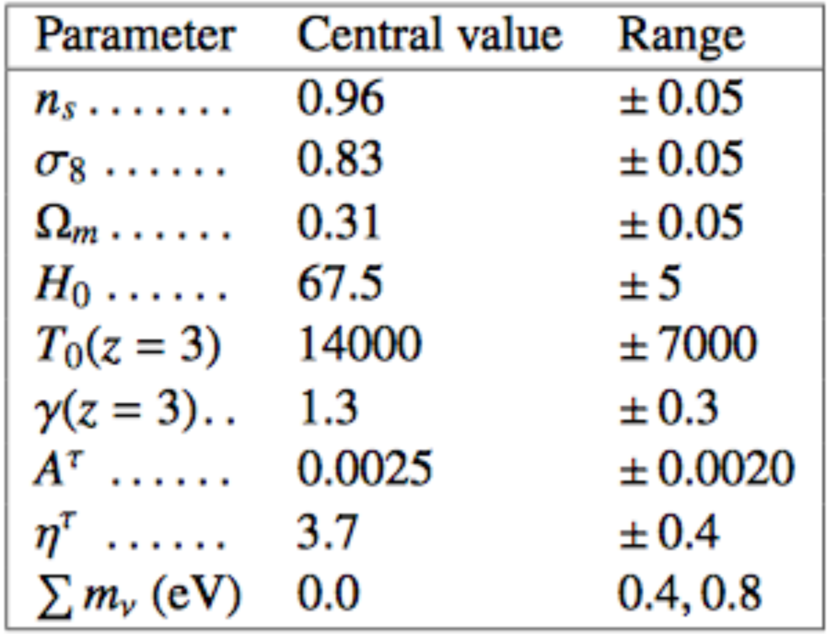
arXiv:1410.7244v1

CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+ NEW Lya: II



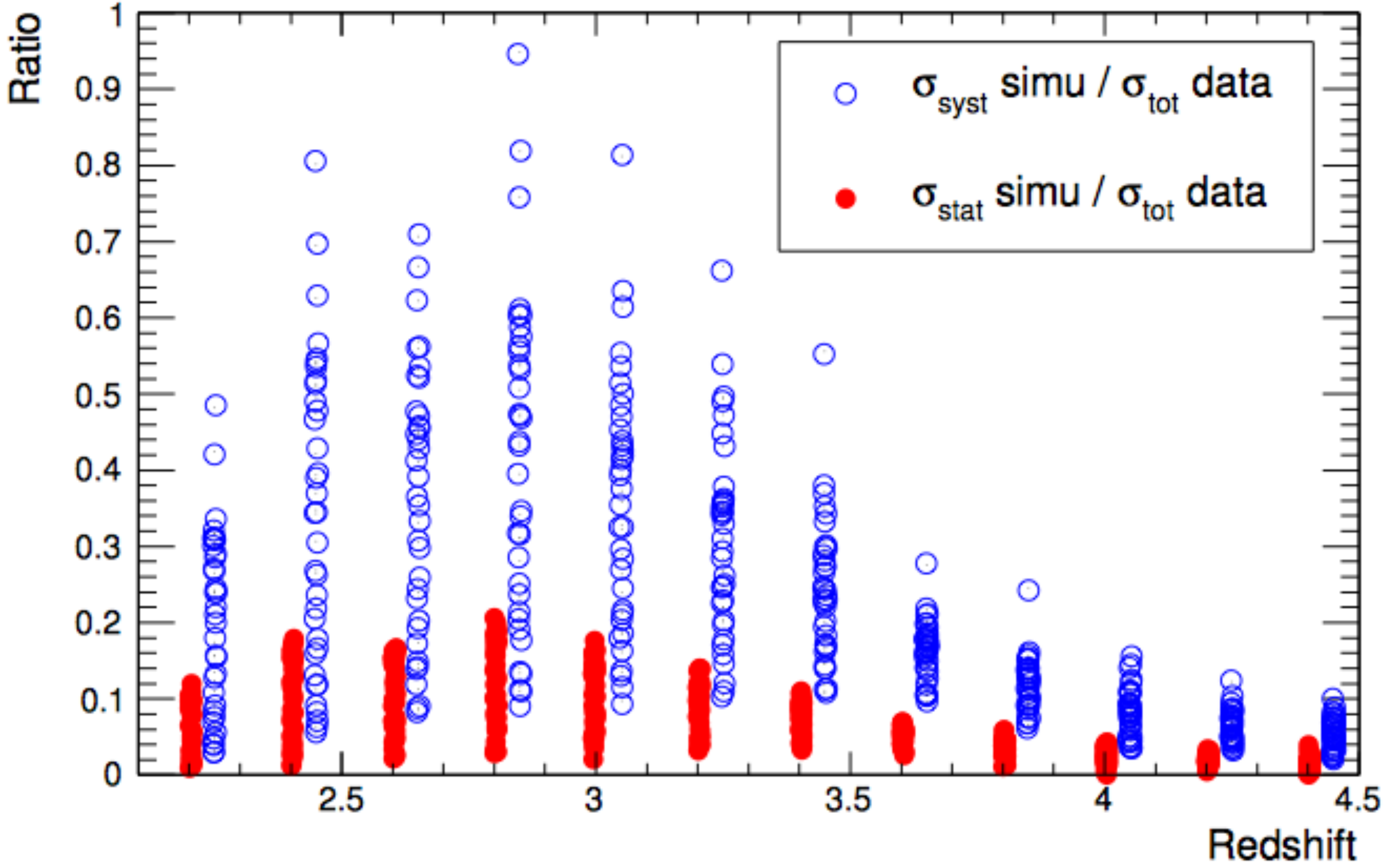
CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+ NEW Lya: III

Parameters varied



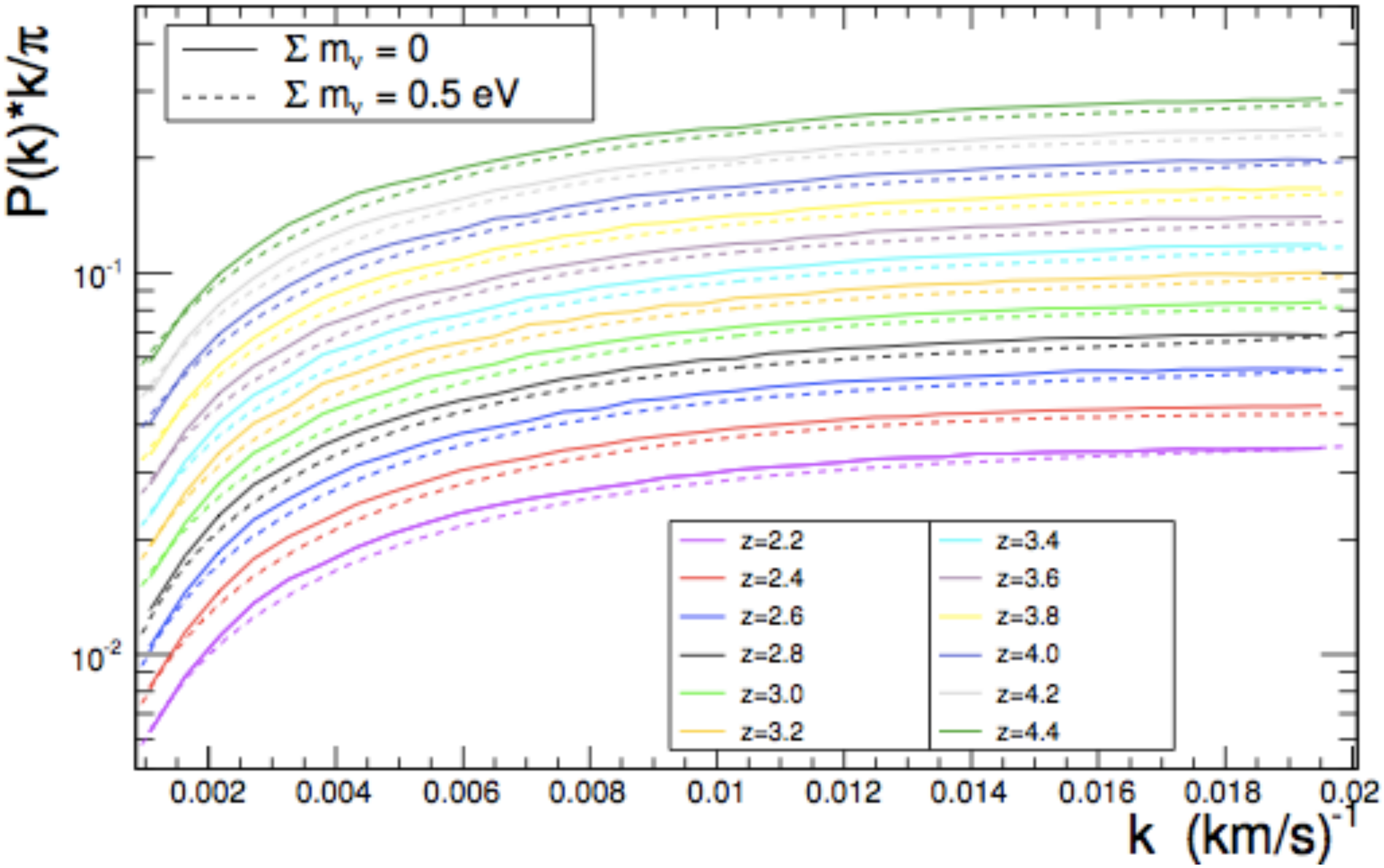
Parameter	Central value	Range
n_s	0.96	± 0.05
σ_8	0.83	± 0.05
Ω_m	0.31	± 0.05
H_0	67.5	± 5
$T_0(z = 3)$	14000	± 7000
$\gamma(z = 3)$..	1.3	± 0.3
A^τ	0.0025	± 0.0020
η^τ	3.7	± 0.4
$\sum m_\nu$ (eV)	0.0	0.4, 0.8

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



CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+ NEW Lya: V

Neutrino effect having fixed the amplitude at the CMB scale



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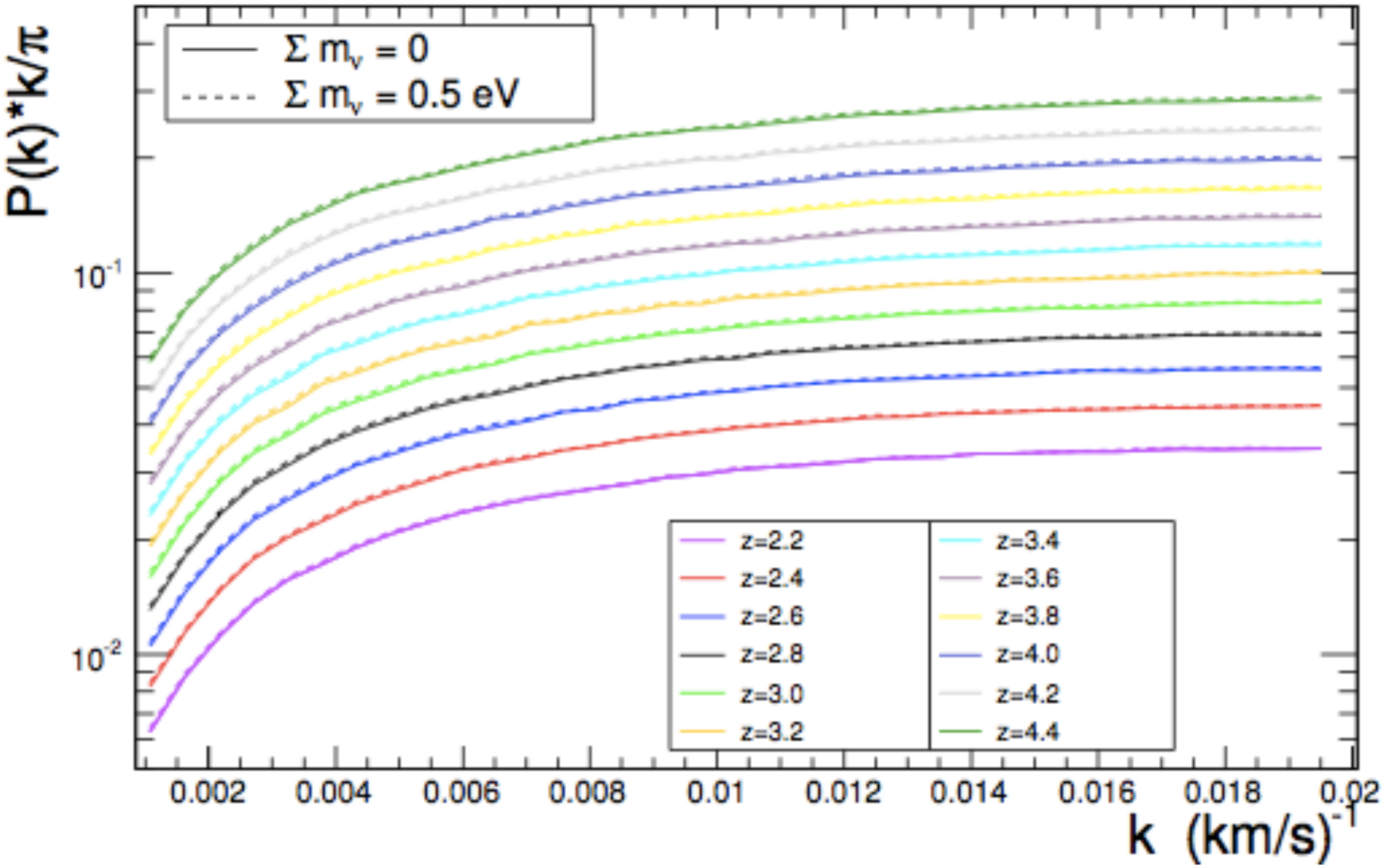
CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+ NEW Lya: VI

Neutrino effect having fixed the amplitude at the 8 Mpc/h



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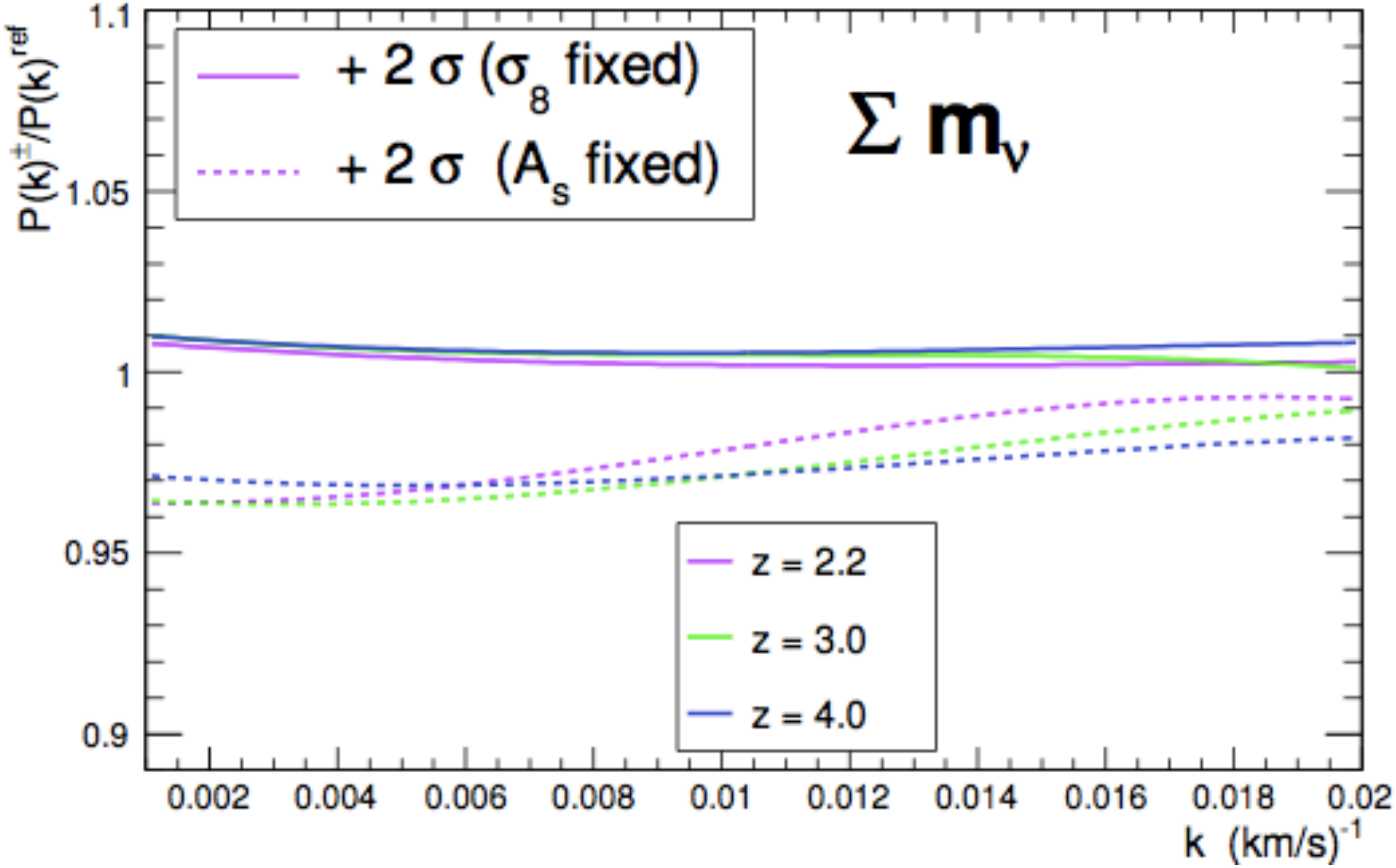
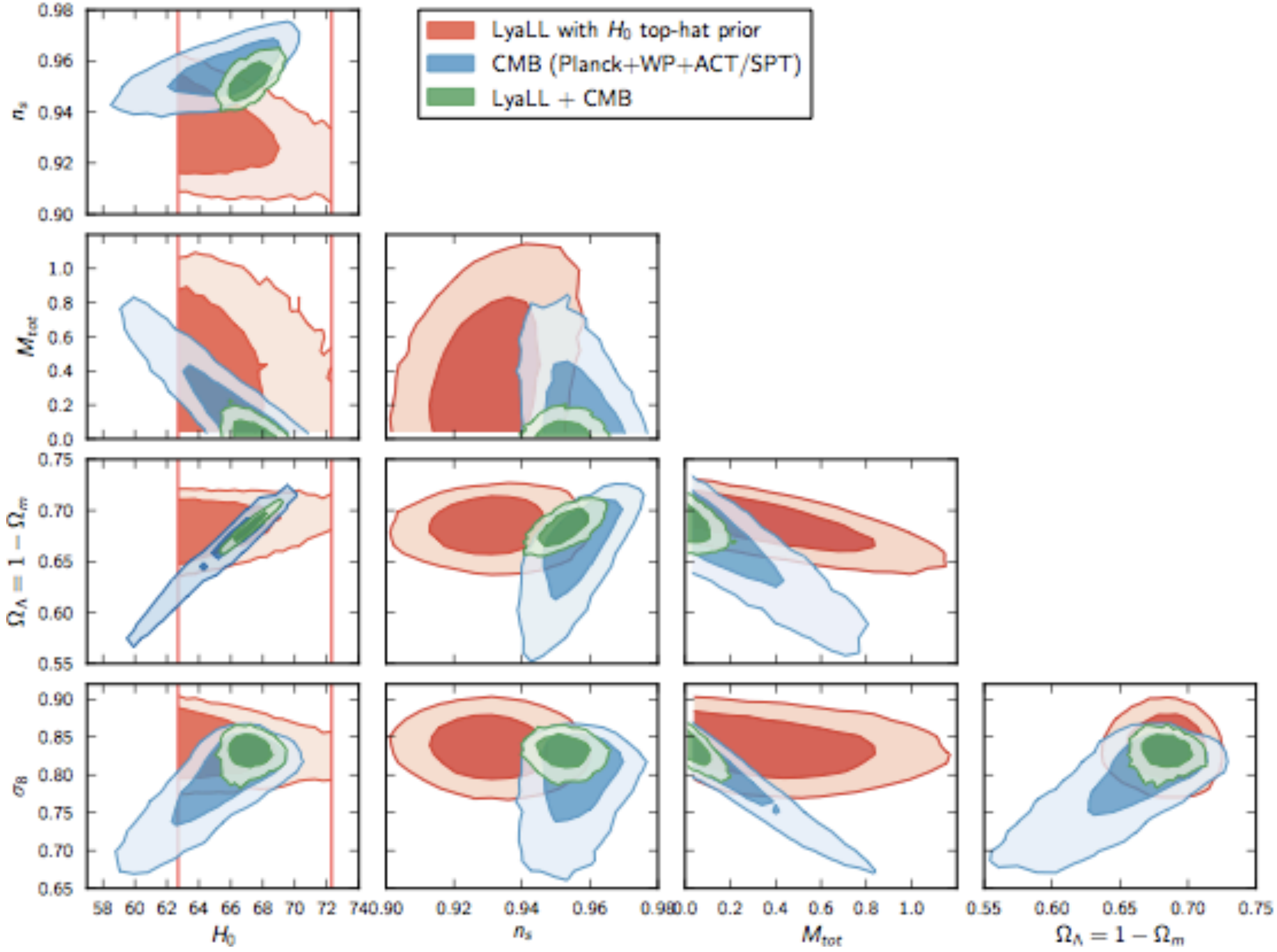
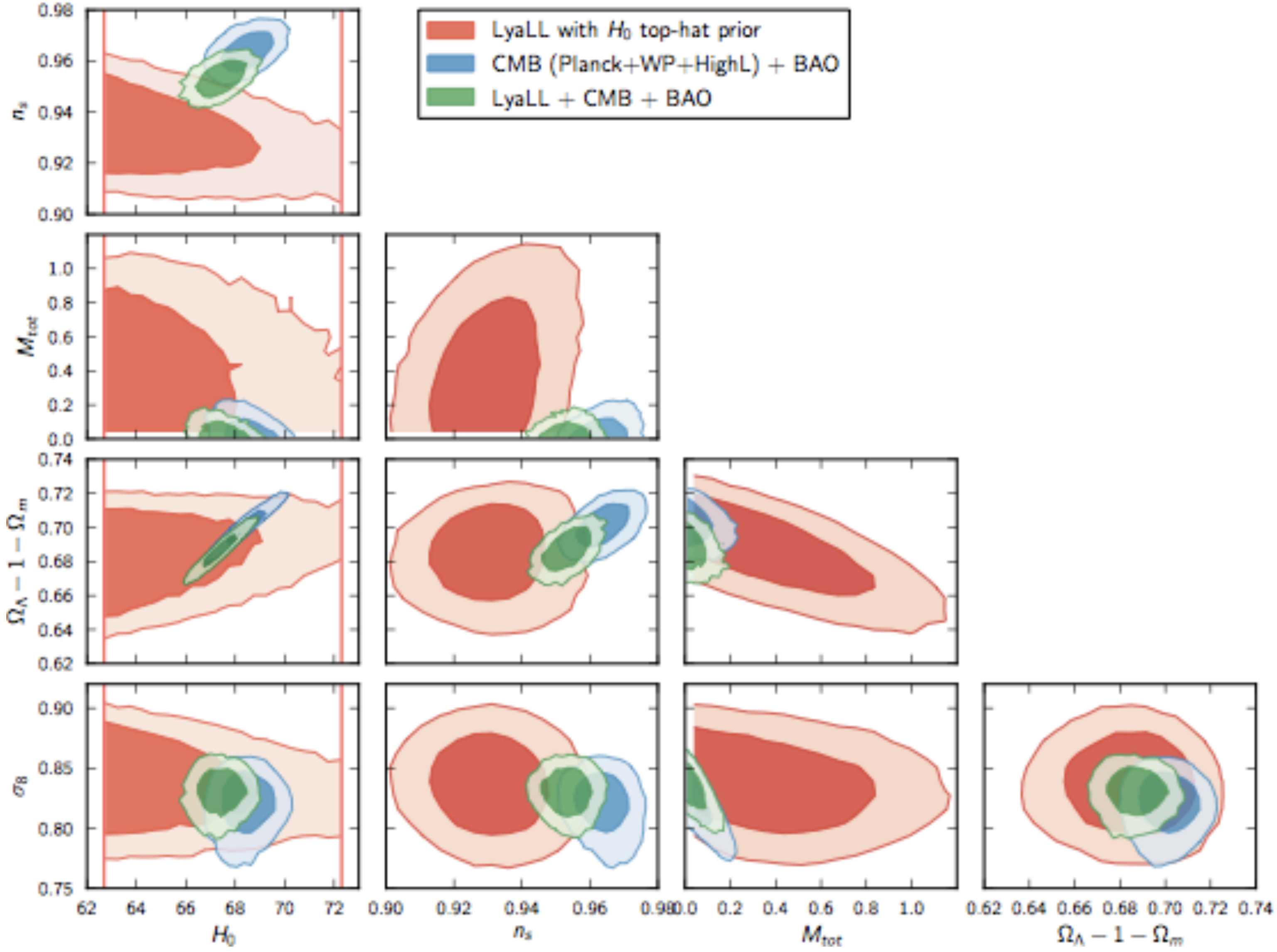
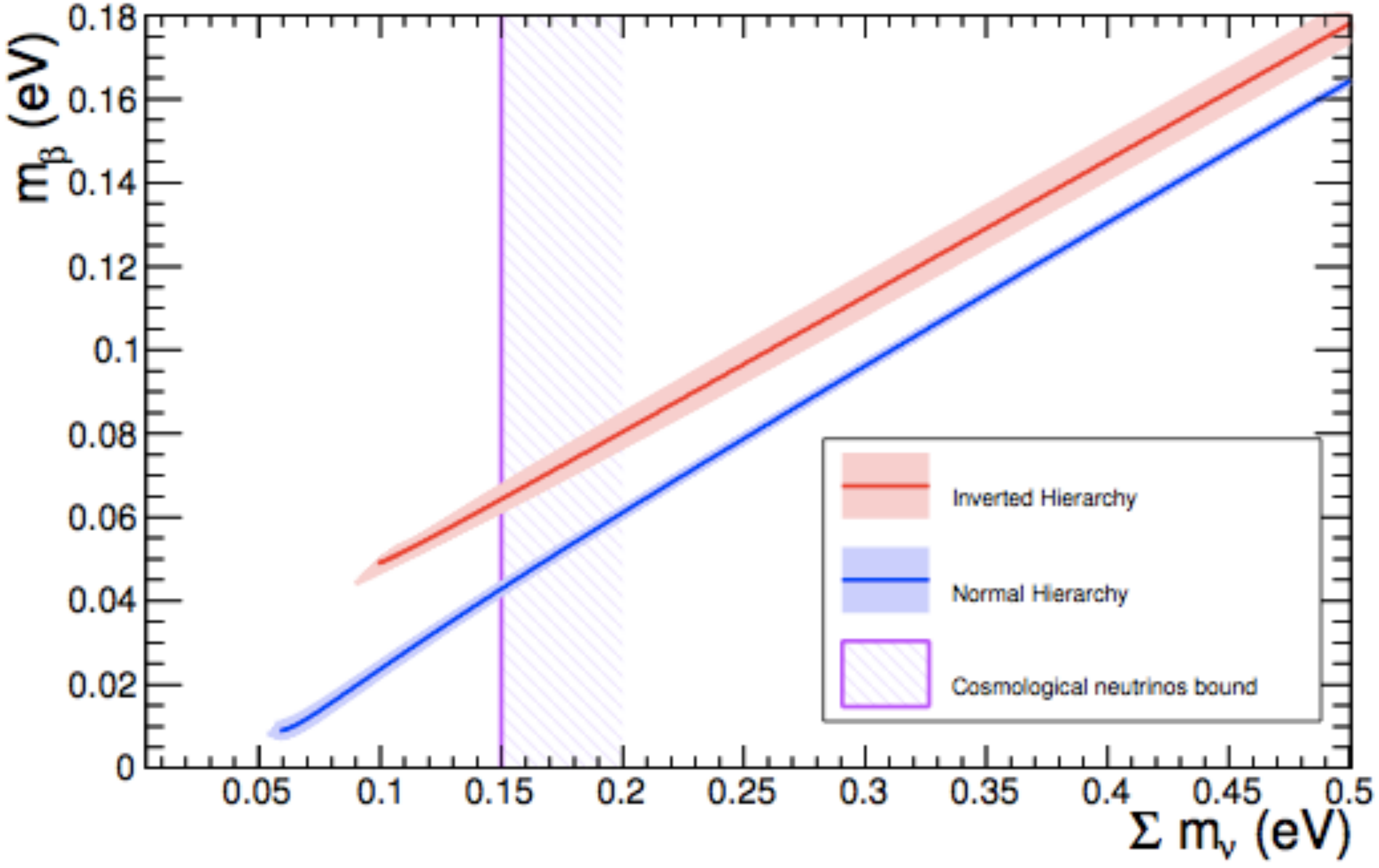
CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO+ NEW Lya: VII

This is the effect we are seeking….




LyaLL with H_0 top-hat prior
CMB (Planck+WP+ACT/SPT)
LyaLL + CMB
n_s
0.98
0.96
0.94
0.92
0.90
M_{tot}
1.0
0.8
0.6
0.4
0.2
0.0
$\Omega_\Lambda = 1 - \Omega_m$
0.75
0.70
0.65
0.60
0.55
σ_8
0.90
0.85
0.80
0.75
0.70
0.65
58
60
62
64
66
68
70
72
74
H_0
0.90
0.92
0.94
0.96
0.98
n_s
0.0
0.2
0.4
0.6
0.8
1.0
M_{tot}
0.55
0.60
0.65
0.70
0.75
$\Omega_\Lambda = 1 - \Omega_m$


LyaLL with H_0 top-hat prior
CMB (Planck+WP+HighL) + BAO
LyaLL + CMB + BAO
n_s
0.90
0.92
0.94
0.96
0.98
M_{tot}
0.0
0.2
0.4
0.6
0.8
1.0
$\Omega_\Lambda - 1 - \Omega_m$
0.62
0.64
0.66
0.68
0.70
0.72
0.74
σ_8
0.75
0.80
0.85
0.90
H_0
62
64
66
68
70
72



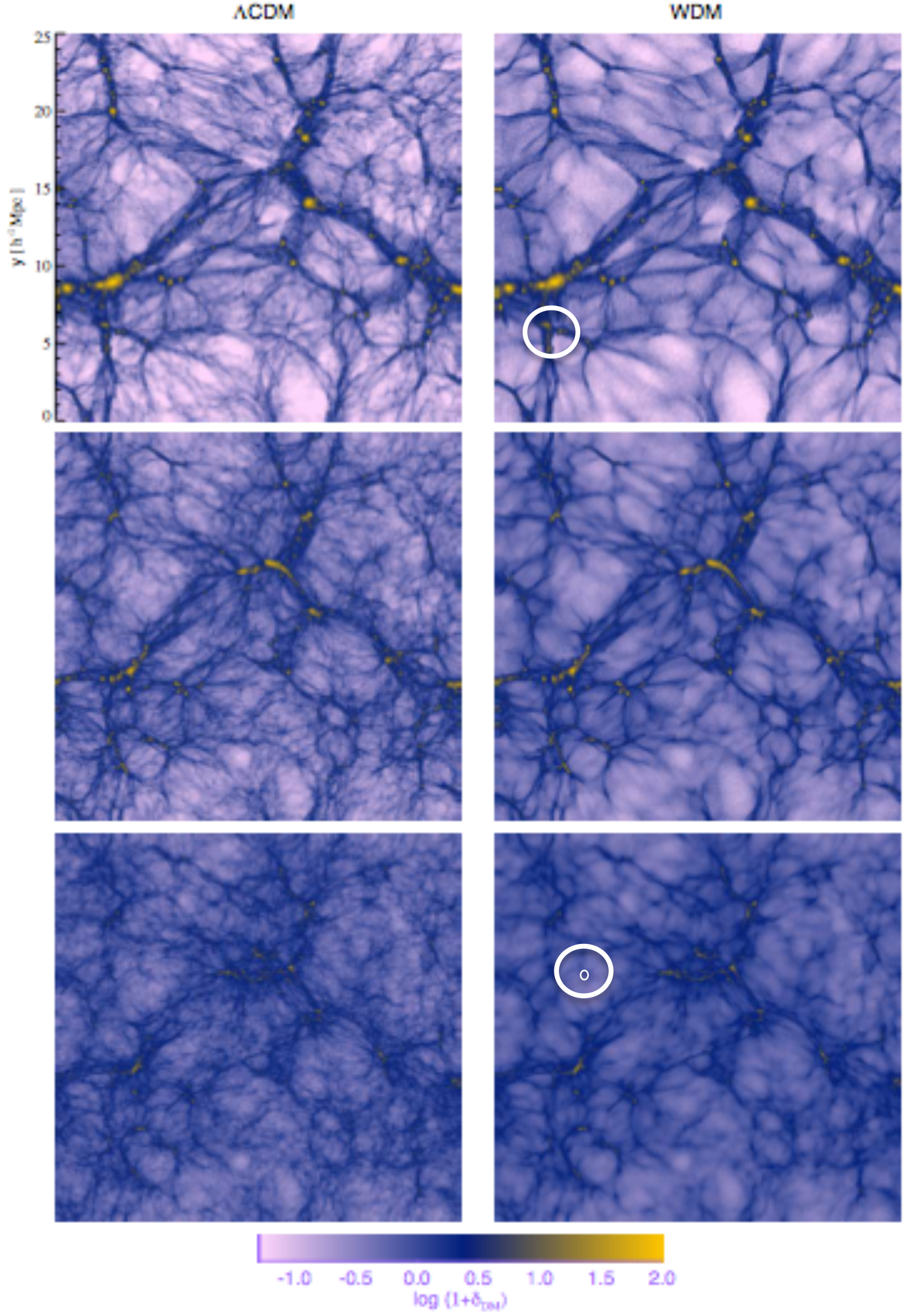
$M_\nu < 0.15$ eV Planck + Lya

$M_\nu < 0.14$ eV Planck + Lya + BAO

THE COLDNESS OF COLD DARK MATTER

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

THE COSMIC WEB in WDM/LCDM scenarios



z=0

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

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

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

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

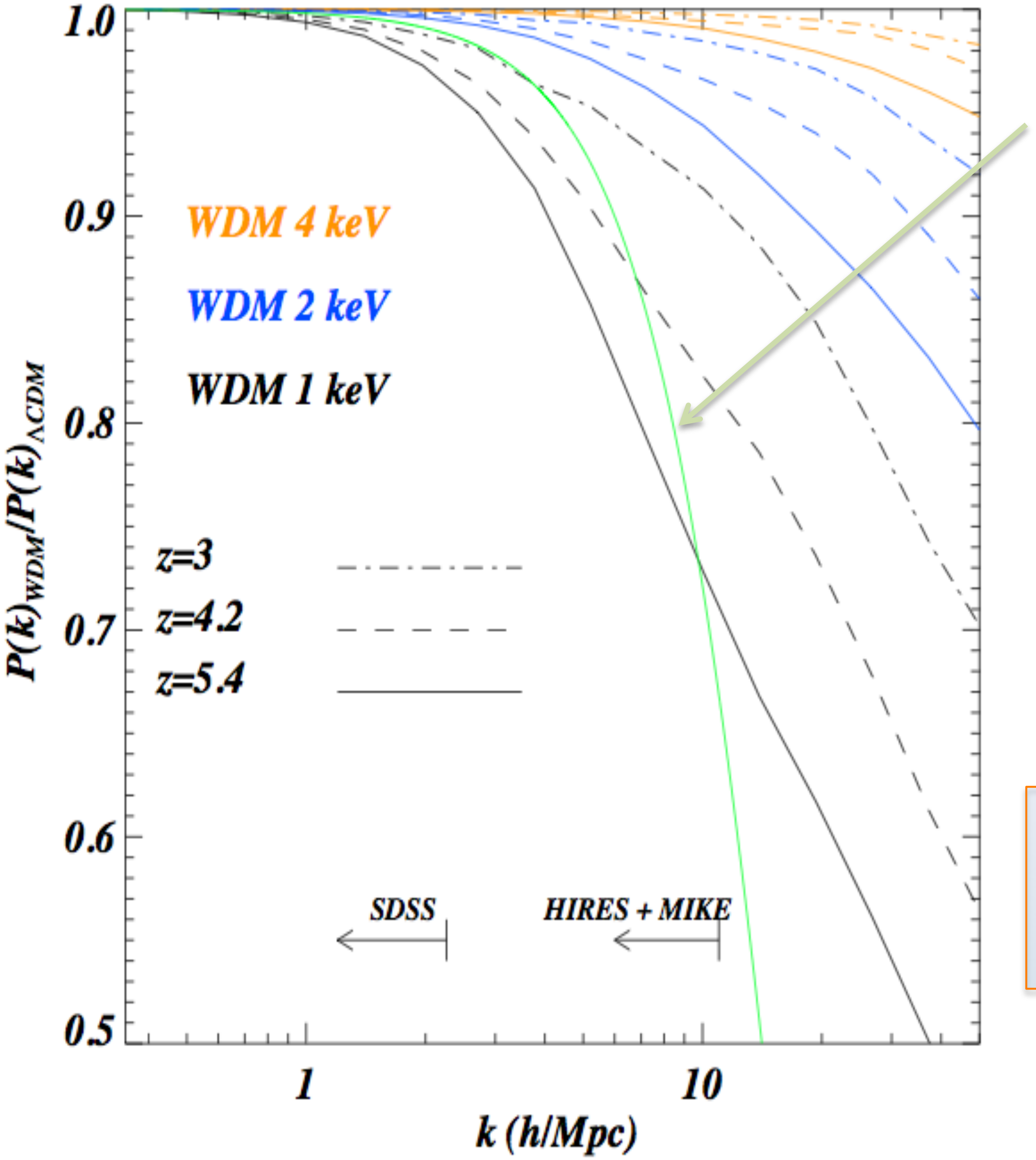
z=2

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

z=5

Viel, Markovic, Baldi & Weller 2013

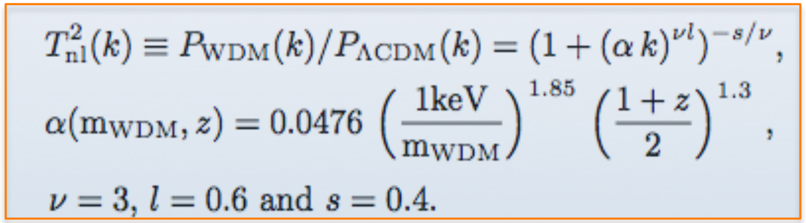
THE WARM DARK MATTER CUTOFF IN THE MATTER DISTRIBUTION



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

IMPLICATIONS FOR STRUCTURE FORMATION

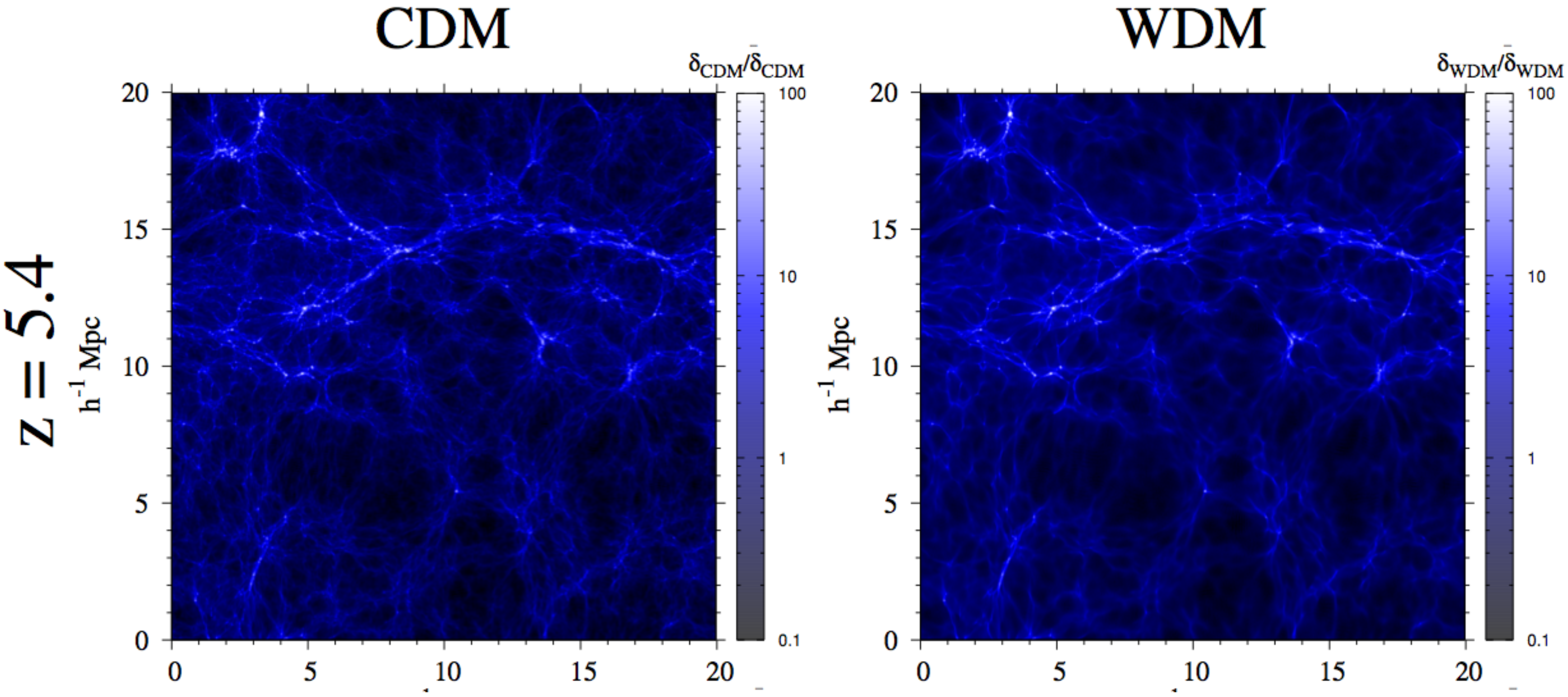
- Strong and weak lensing	Markovic et al. 13/Faadely & Keeton 12
- Galaxy formation	Menci et al 13, Kang et al. 13
- Reionization/First Stars	Gao & Theuns 07
- Dark Matter Haloes (mass functions)	Pacucci et al. 13
- Luminous matter properties	Polisensky & Ricotti 11, Lovell et al. 09
- Gamma-Ray Bursts	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

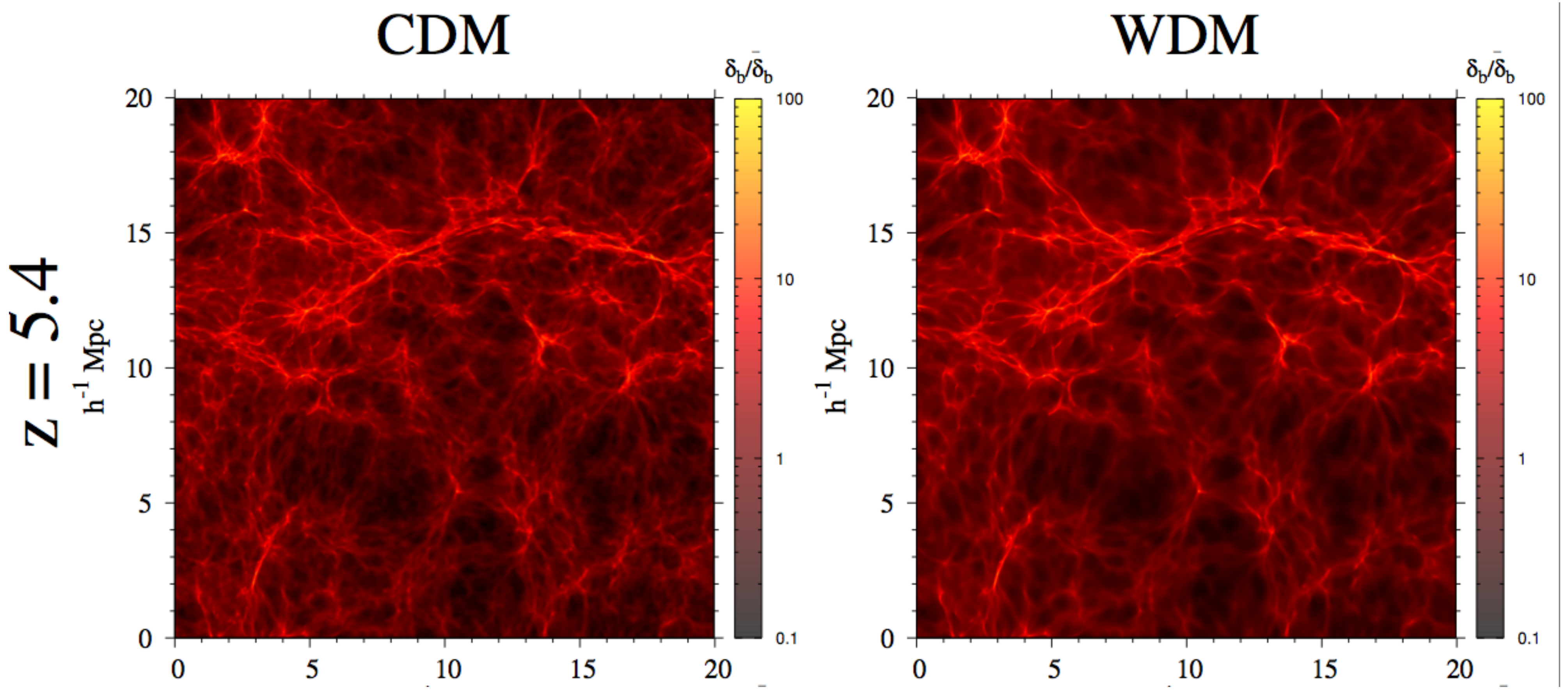
HISTORY OF WDM LYMAN-α BOUNDS

Narayanan et al.00	: $m > 0.75$ keV	Nbody sims + 8 Keck spectra Marginalization over nuisance not done
Viel et al. 05	: $m > 0.55$ keV (2σ)	Hydro sims + 30 UVES/VLT spectra Effective bias method of Croft et al.02
Seljak et al. 06	: $m > 2.5$ keV (2σ)	Hydro Particle Mesh method + SDSS grid of simulation for likelihood
Viel et al. 06	: $m > 2$ keV (2σ)	Fully hydro+SDSS Not full grid of sims. but Taylor expans.
Viel et al. 08	**: $m > 4.5$ keV (2σ)**	**SDSS+HIRES (55 QSOs spectra) Full hydro sims (Taylor expansion of the flux)**
Boyarsky et al. 09	: $m>2.2$ keV (2σ)	SDSS (frequentist+bayesian analysis) emphasis on mixed ColdWarmDM models

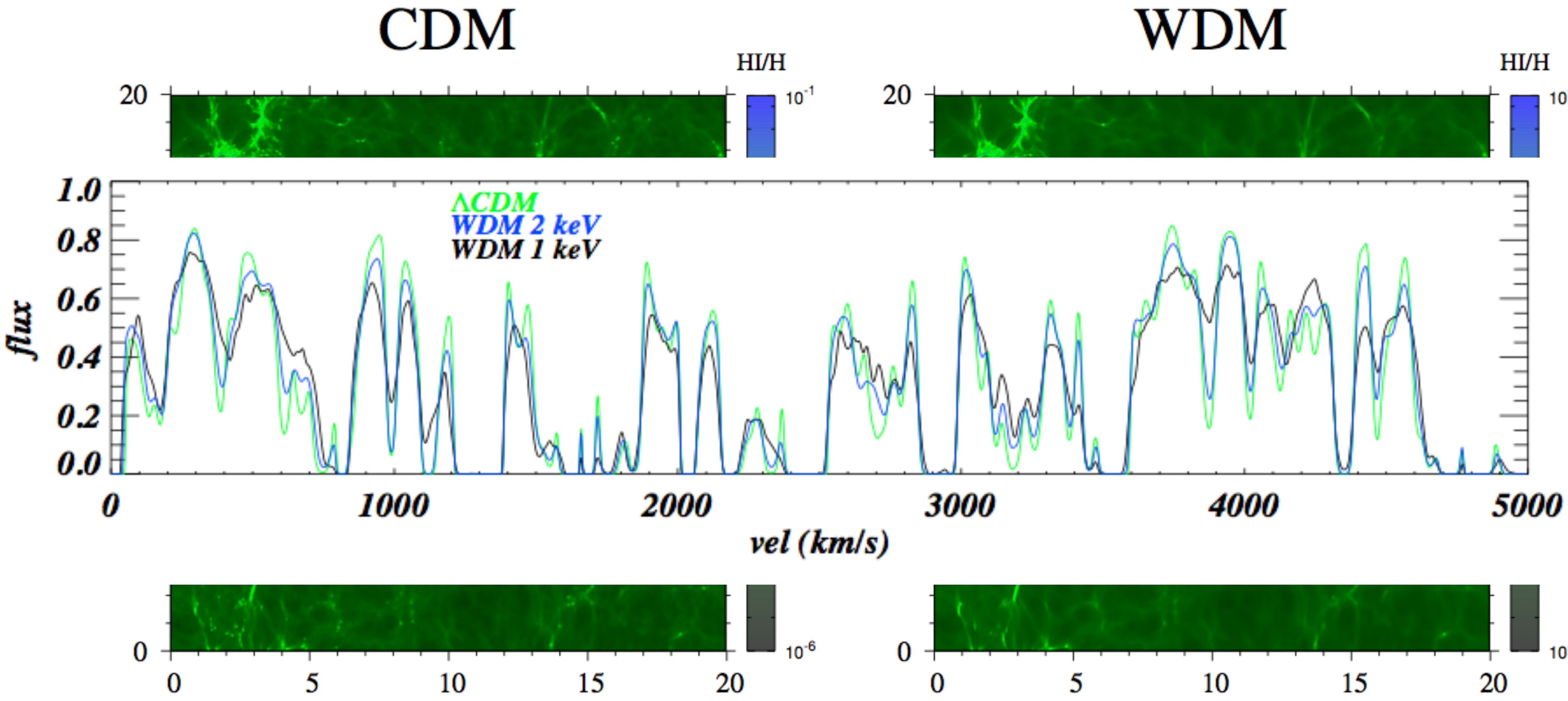
DARK MATTER DISTRIBUTION



GAS DISTRIBUTION



HI DISTRIBUTION



“Warm Dark Matter as a solution to the small scale crisis: new constraints from high redshift Lyman-α forest data” MV+ arXiv:1306.2314

DATA: 25 high resolution QSO spectra at $4.48<z_{em}<6.42$
from MIKE and HIRES spectrographs. Becker+ 2011

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}
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

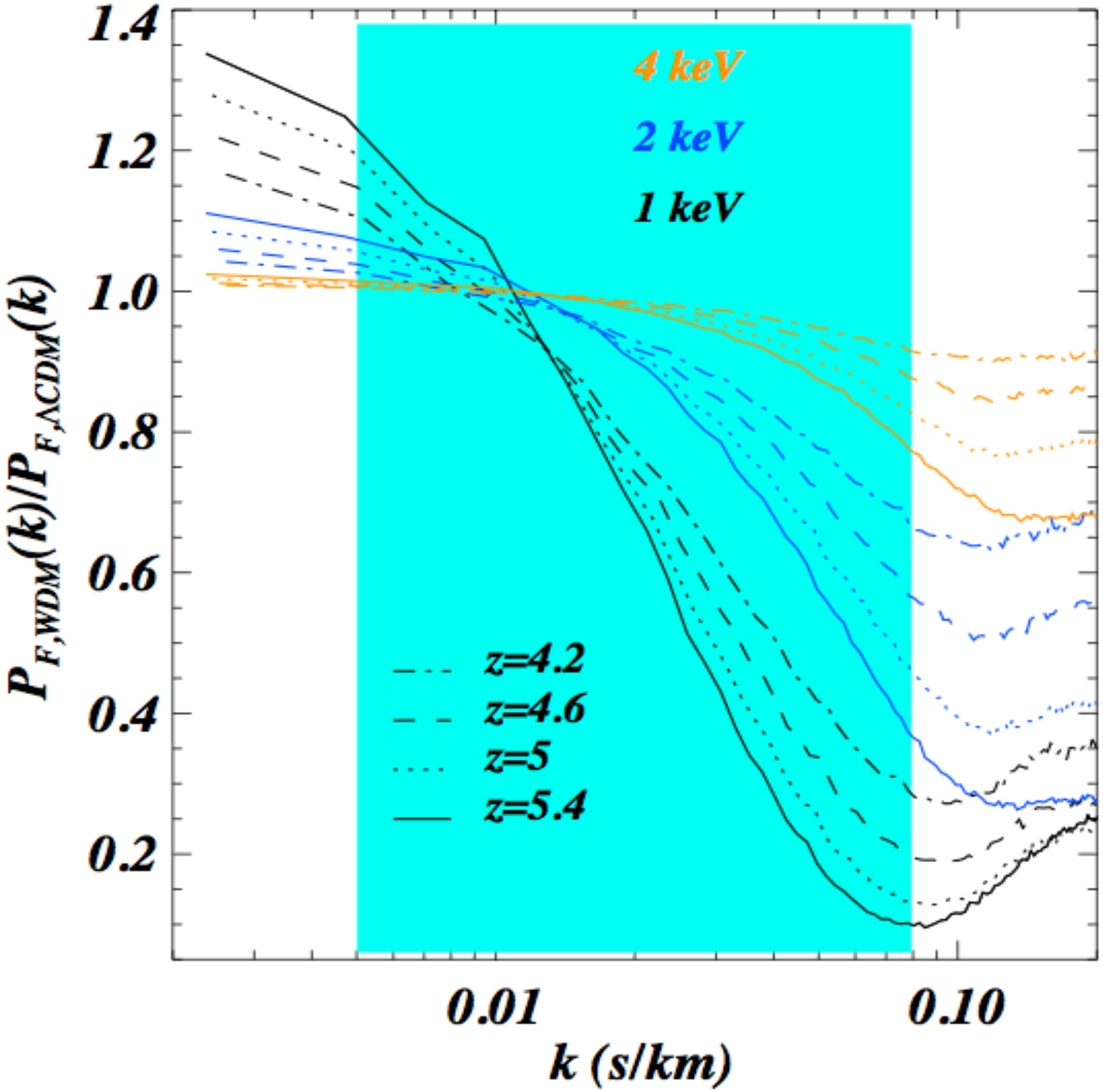
Parameter space: m_{WDM}, T_0, γ, <F> explored fully
Parameter space: : σ_8, n_s, Ω_m, H_0, UV explored with second order Taylor expansion of the flux power

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

\+ second order

THE HIGH REDSHIFT WDM CUTOFF

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



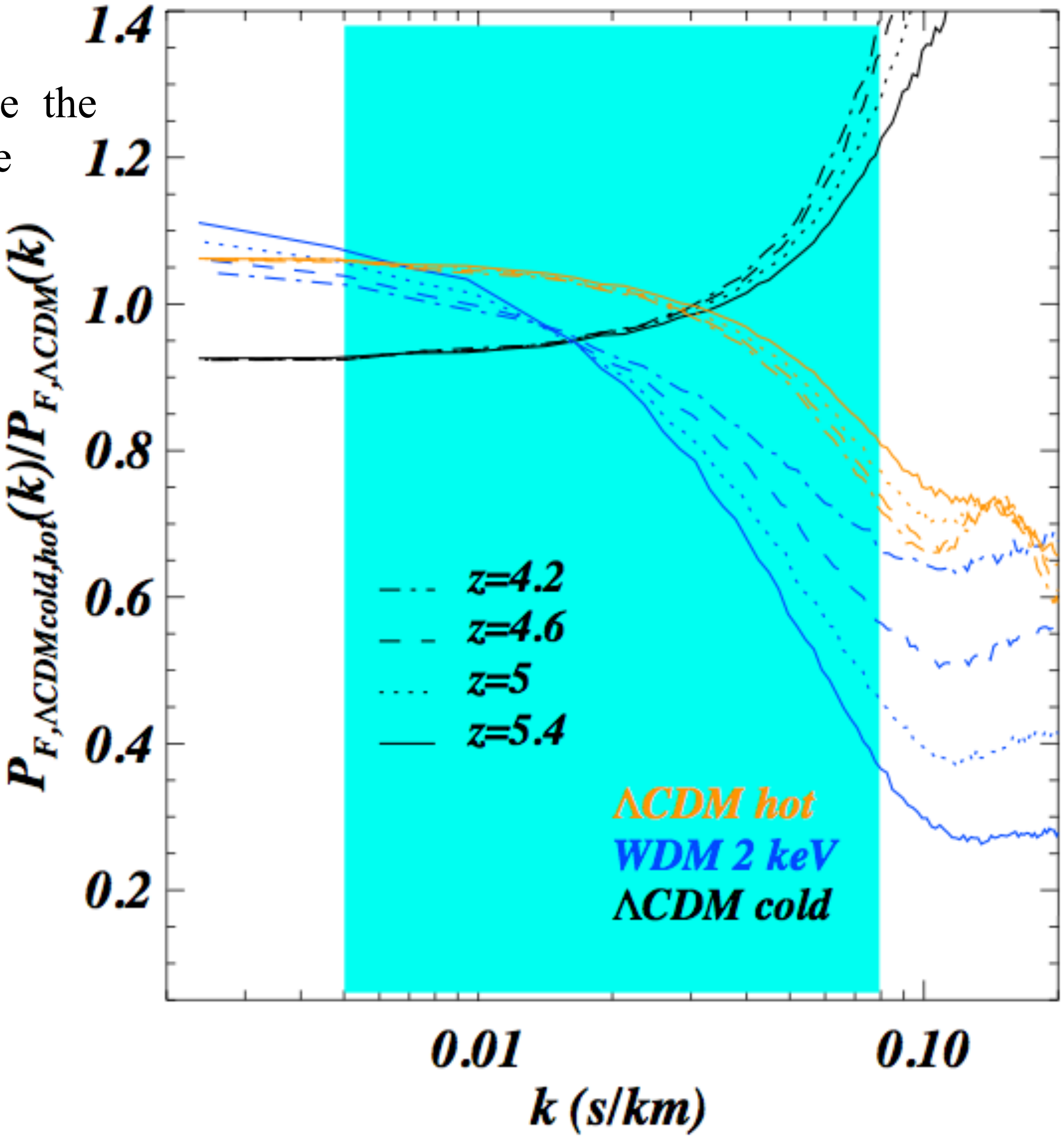
THE TEMPERATURE: T_0

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

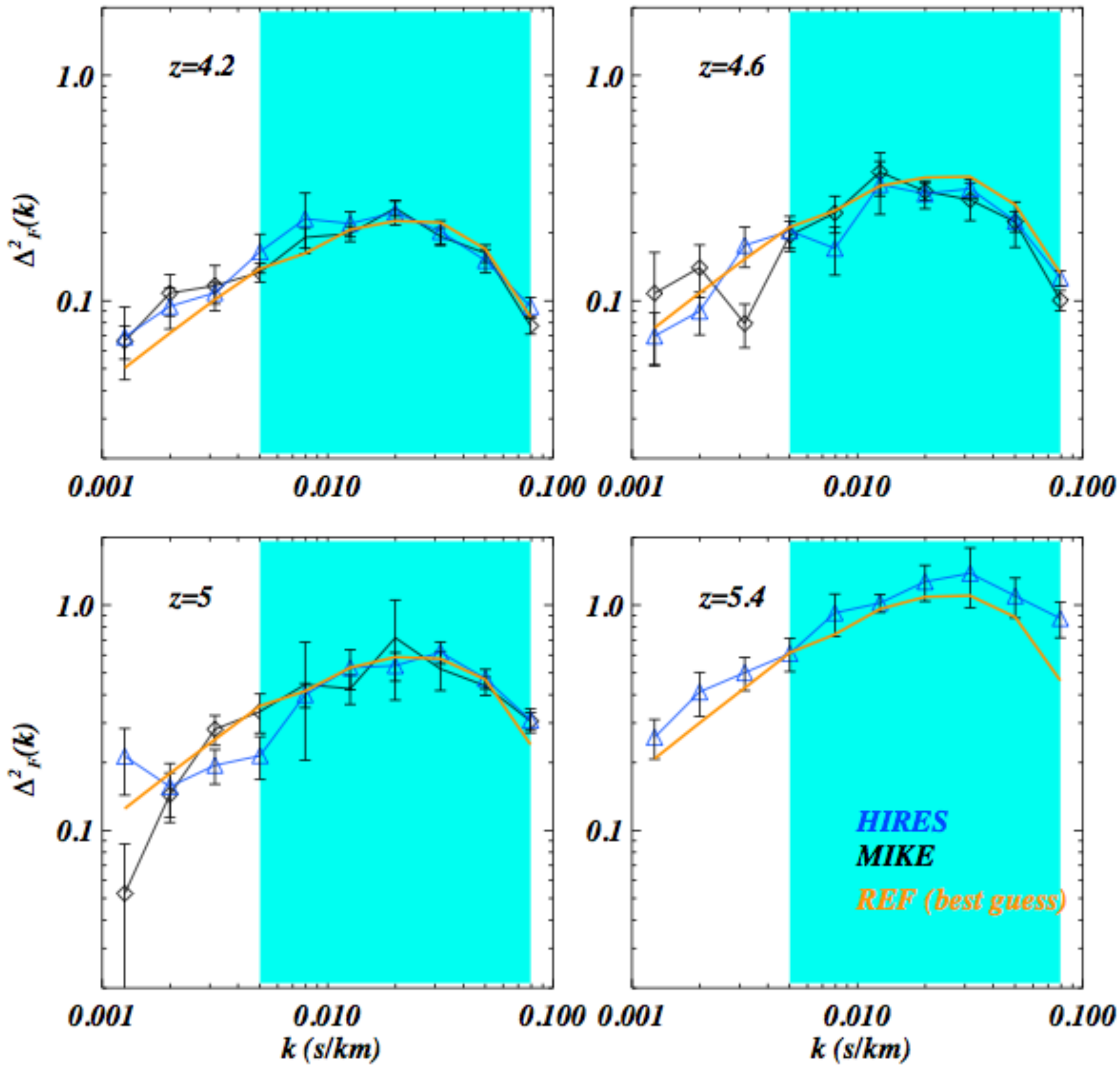
T_0 and γ describe the IGM thermal state

Hot + 3000 K
Cold – 3000 K

REF has 8300 K
at z=4.6

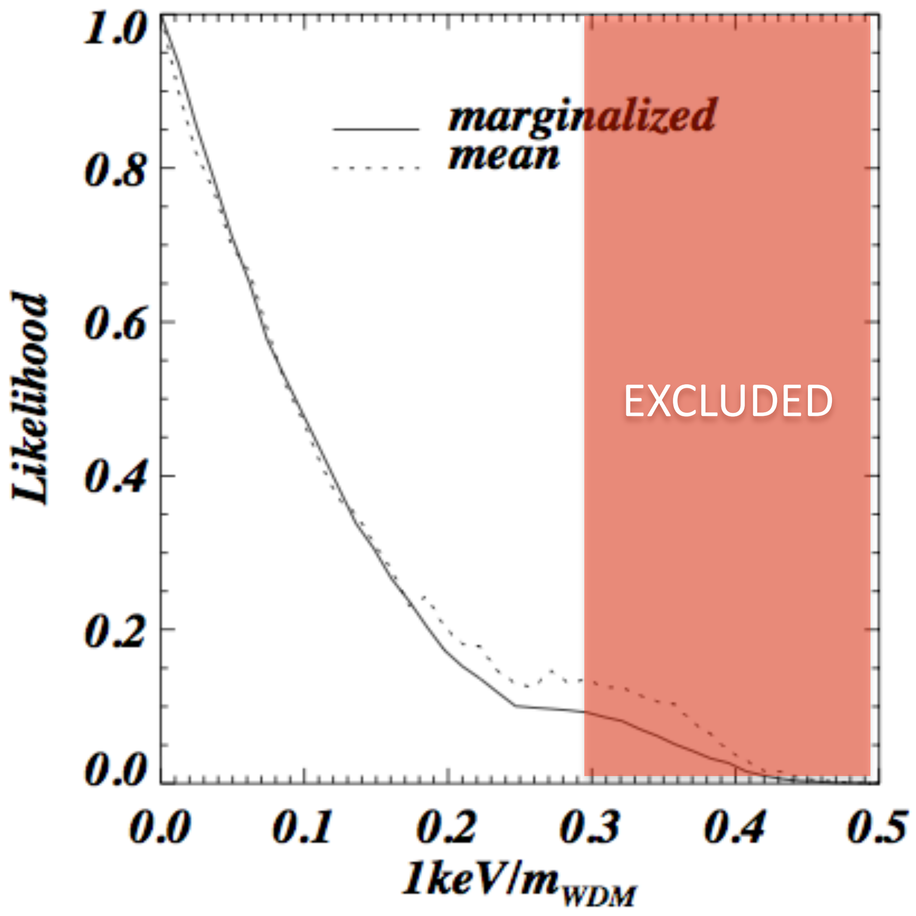


THE BEST GUESS MODEL



This is the starting
point of the MCMC
likelihood estimation
cosmology close
to Planck values

RESULTS FOR WDM MASS

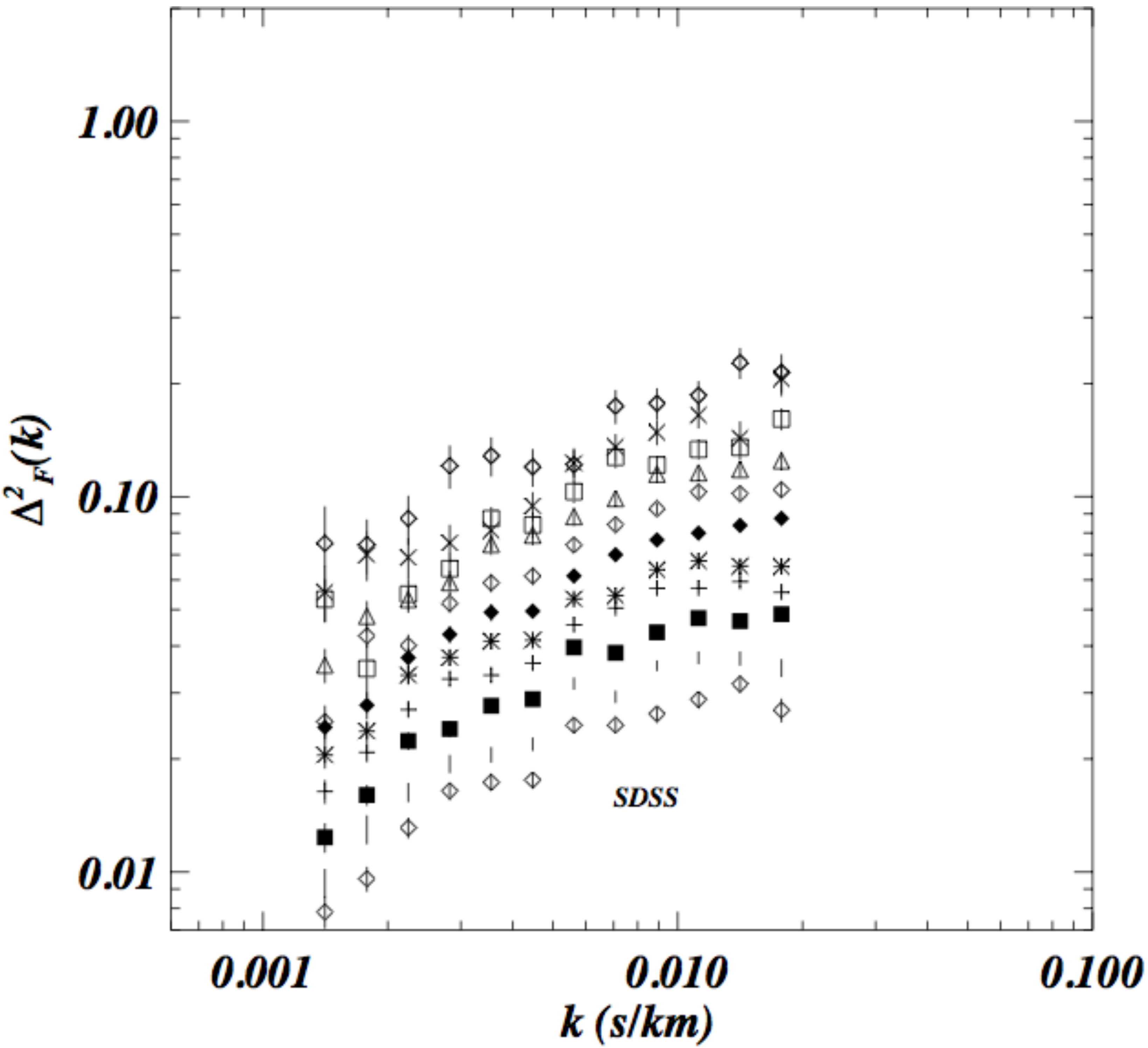


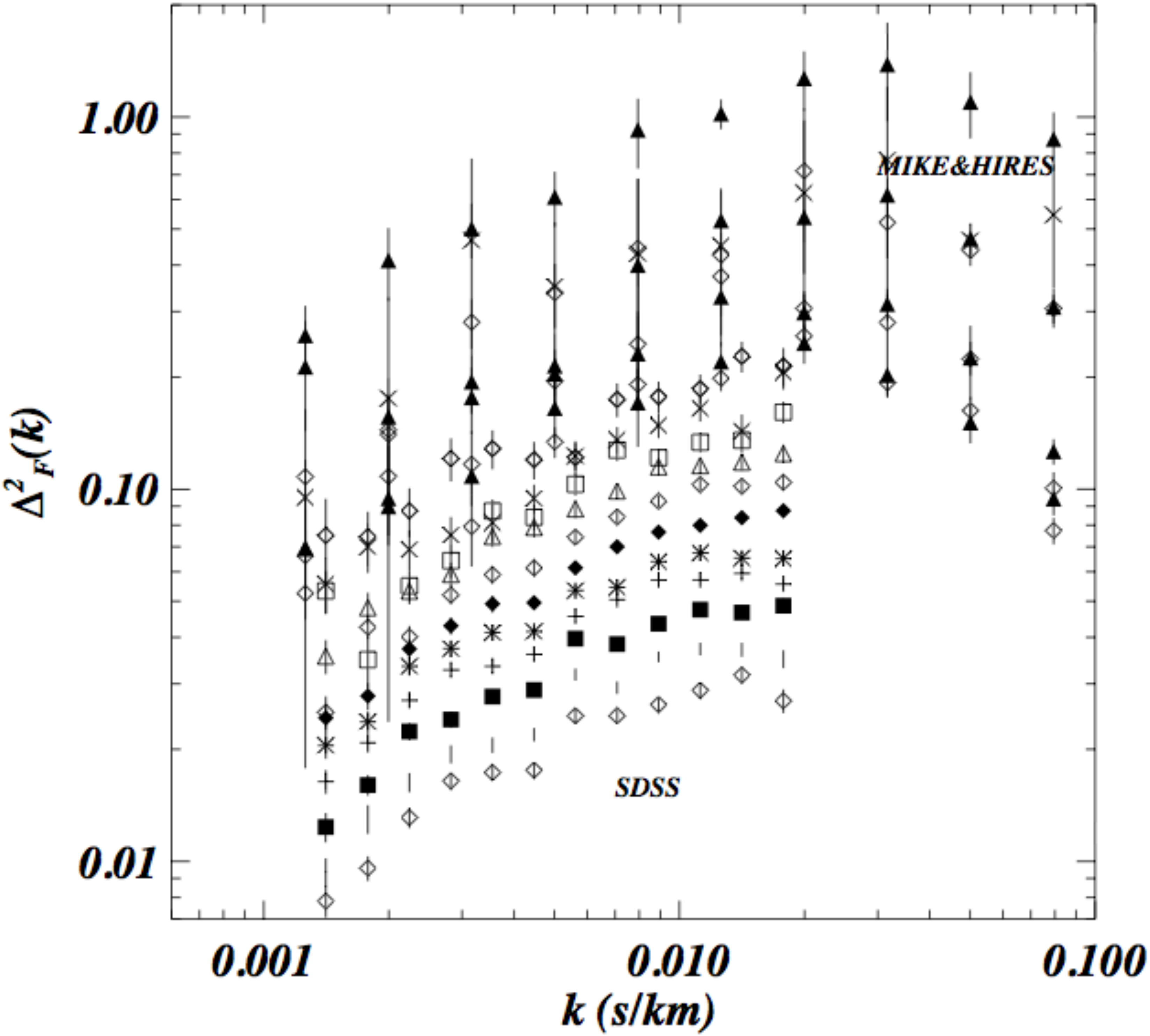
$m > 3.3$ keV (2σ)

SDSS + MIKE + HIRES CONSTRAINTS

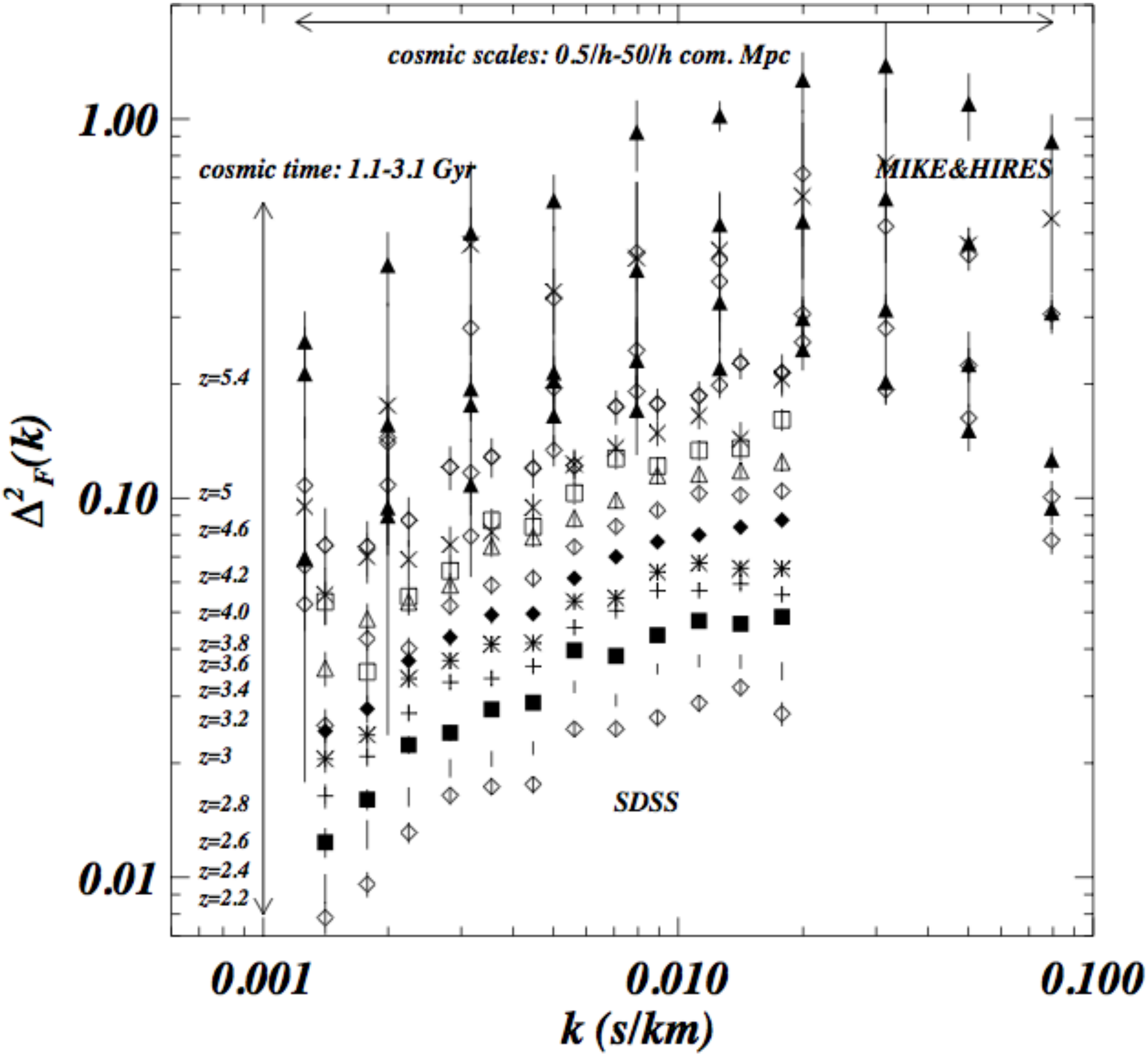
Joint likelihood analysis

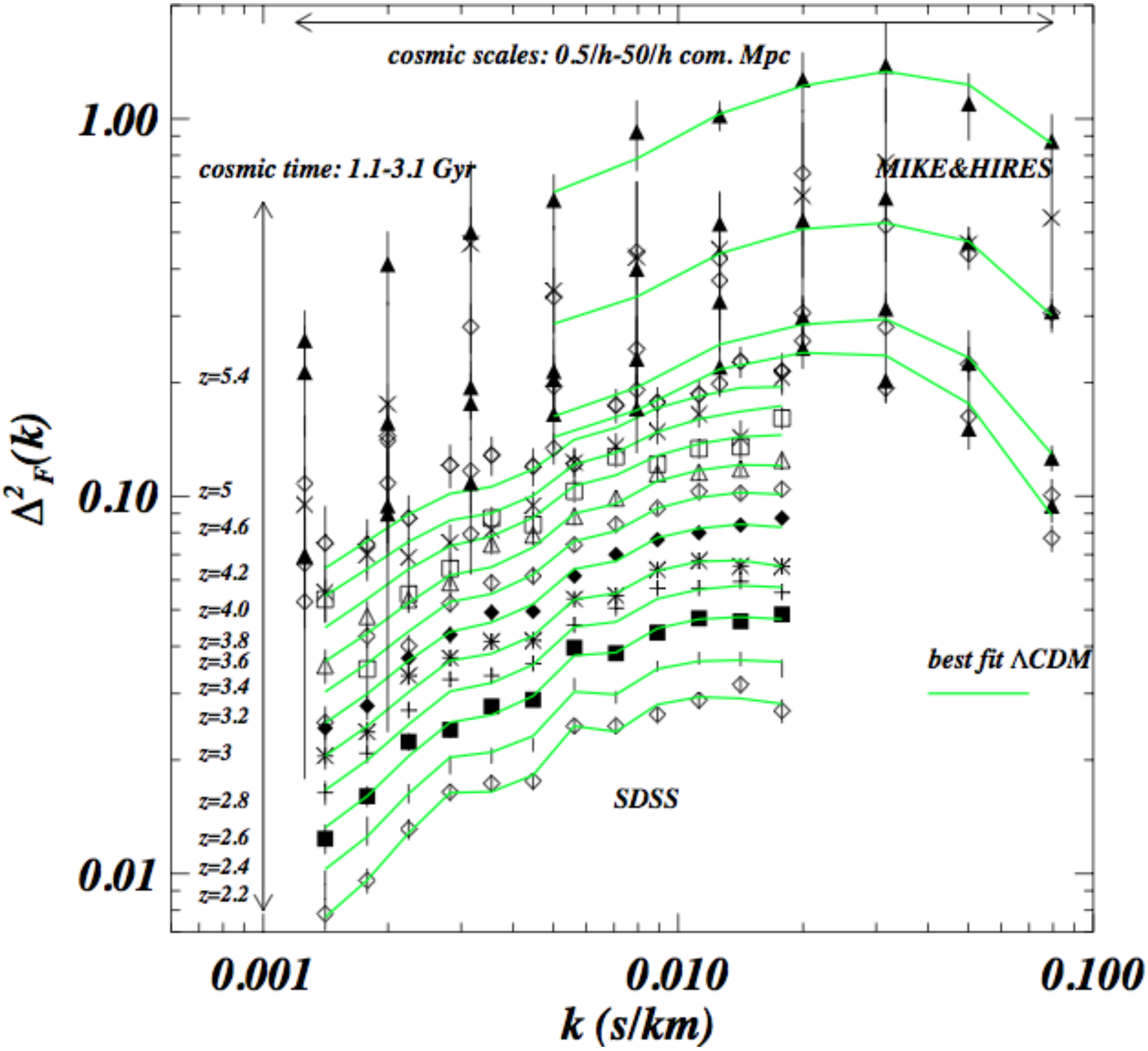
SDSS data from McDonald05,06 not BOSS

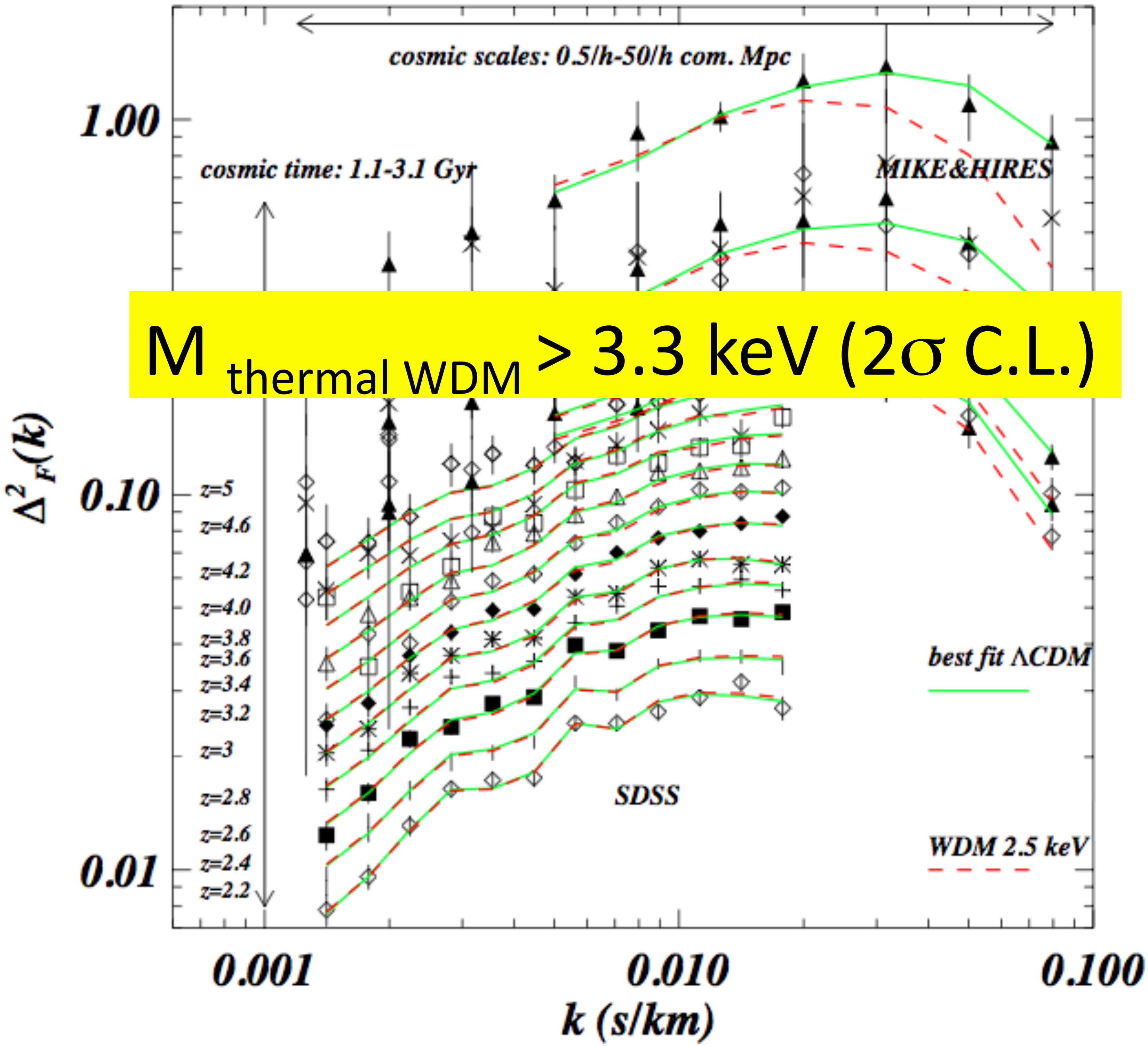

1.00
0.10
0.01
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)
SDSS



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


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
$\Delta^2_F(k)$
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
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.)

CONCLUSIONS – GEOMETRY and NEUTRINOS

Constraints on the geometry of the Universe via BAO measurements of Lyα and cross-correlations. Small tension with Planck.

Galaxy clustering data tend to give < 0.3 eV
CMB + BAO < 0.2 eV

1D Lyman-α flux power provides the tightest constraints (<0.14 eV) on total neutrino mass. Improved/checked with new methods, new data and new simulations: the result is <0.14 eV

CONCLUSIONS – NEUTRINO COSMOLOGY FUTURE

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 $2\text{x}10^8 M_\odot/h$
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