Neutrino masses from cosmological intergalactic data

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Webminar for Invisibles 27th January 2015

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

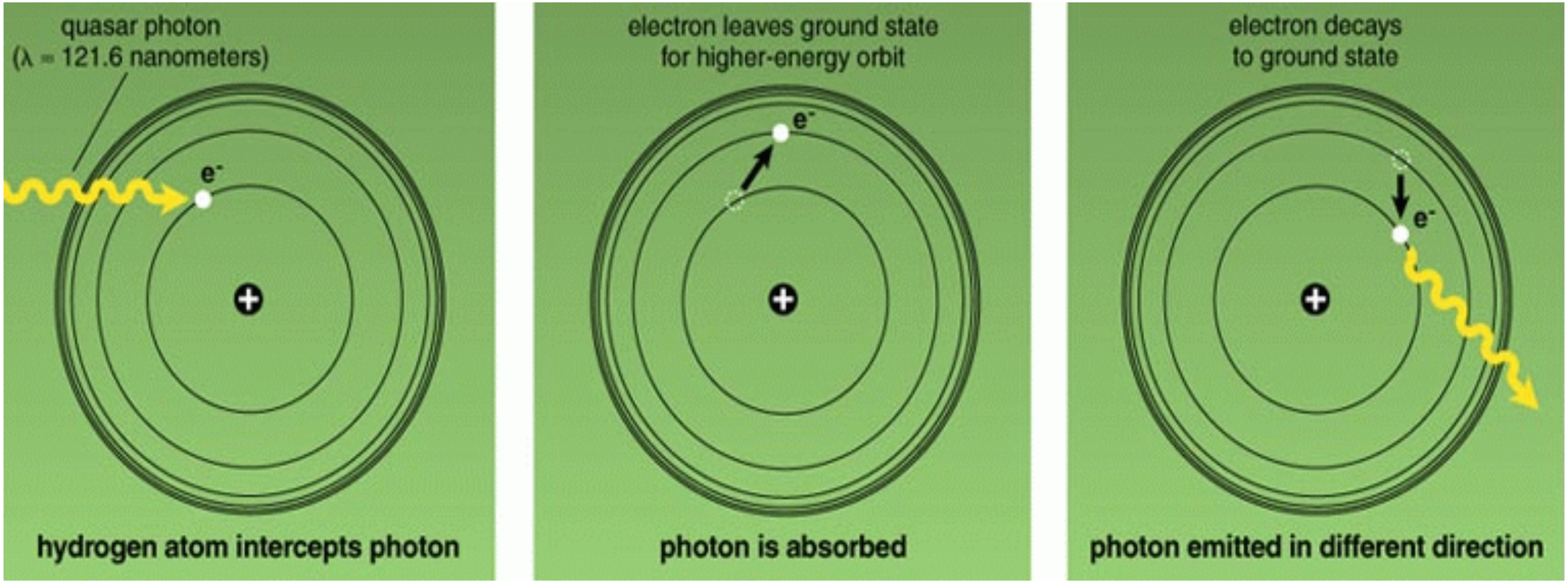
INTRO

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

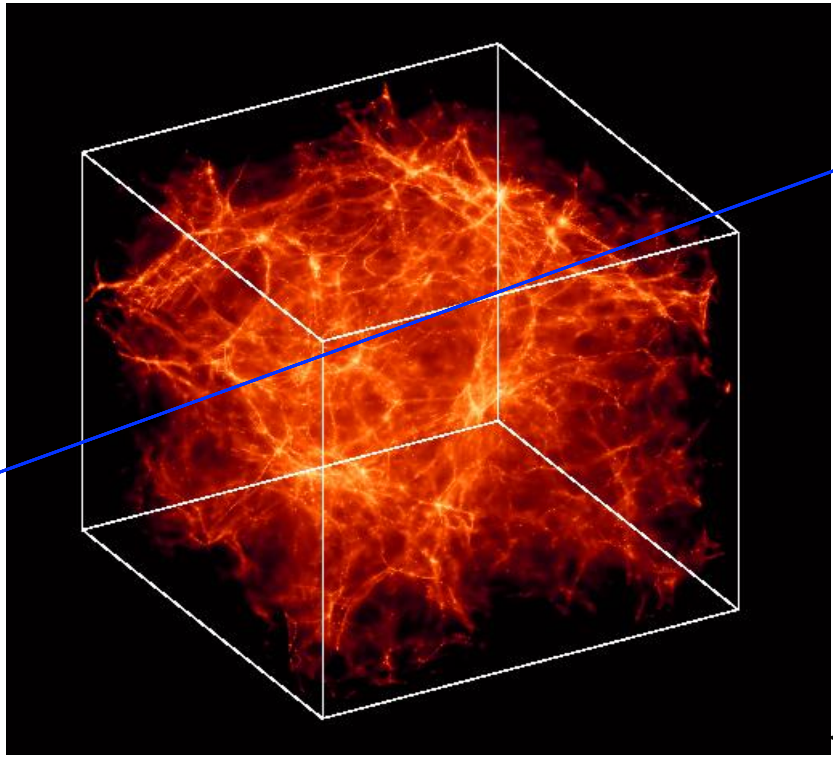
The Lyman-α forest

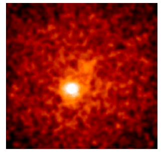
Lyman-α absorption is the main manifestation of the IGM

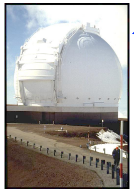


Tiny neutral hydrogen fraction after reionization…. But large cross-section

The Intergalactic Medium: Theory vs. Observations

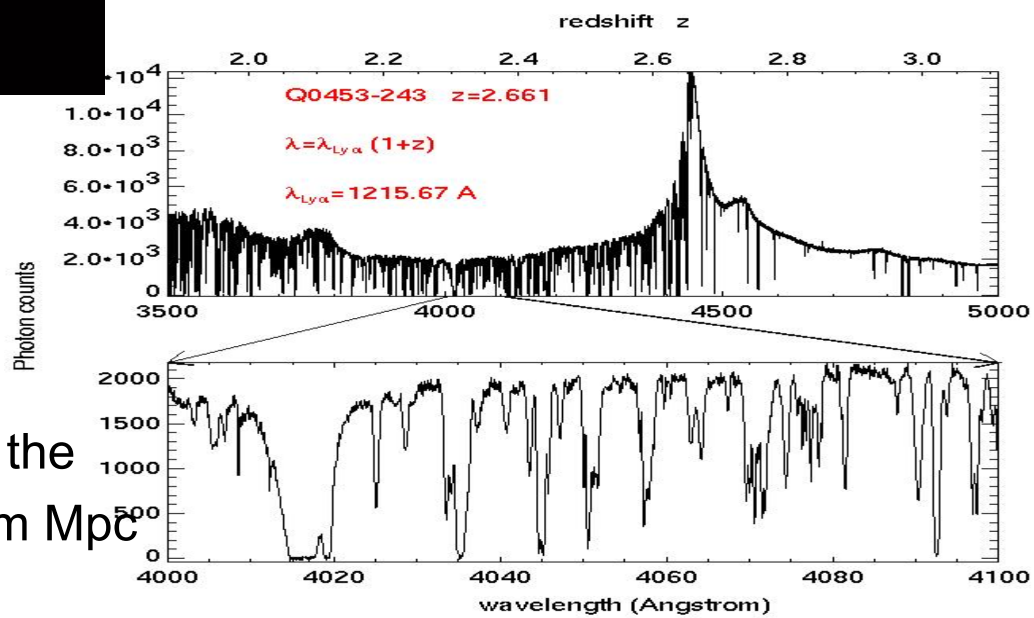






80 % of the baryons at z=3
are in the **Lyman-α forest**

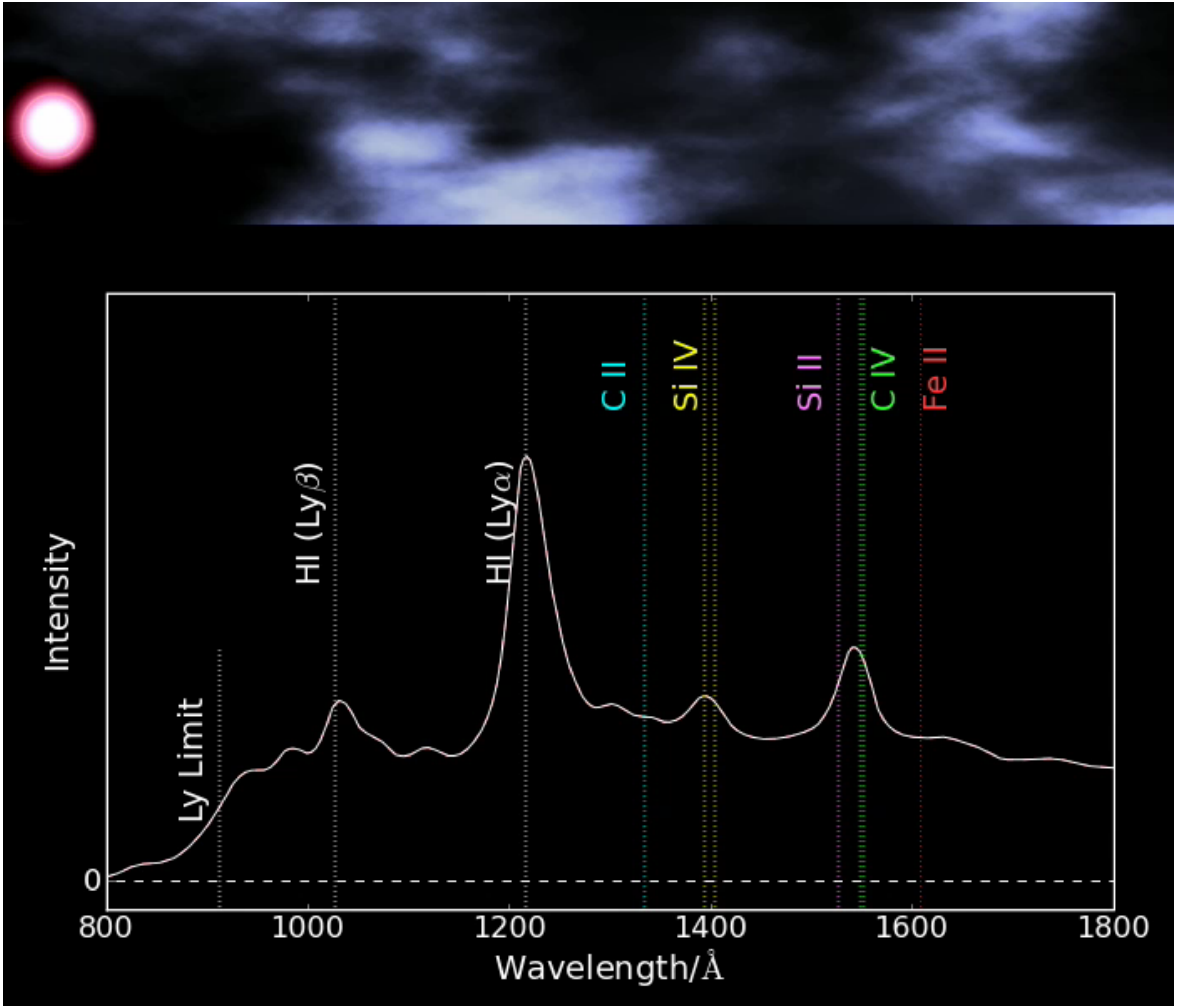
Bi & Davidsen (1997), Rauch (1998)
Review by Meiksin (2009)



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
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

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

+

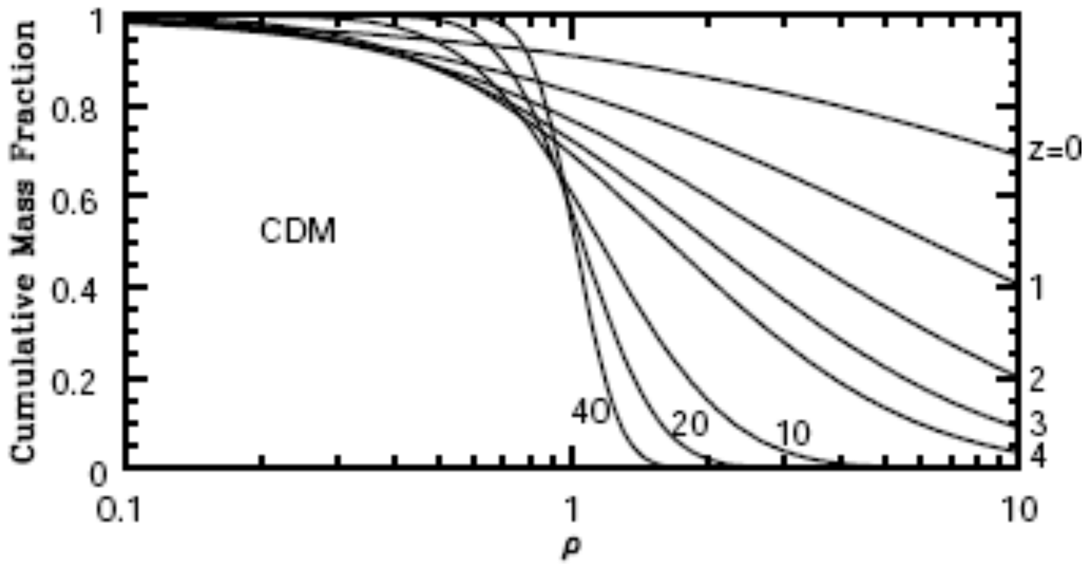
Temperature

↓

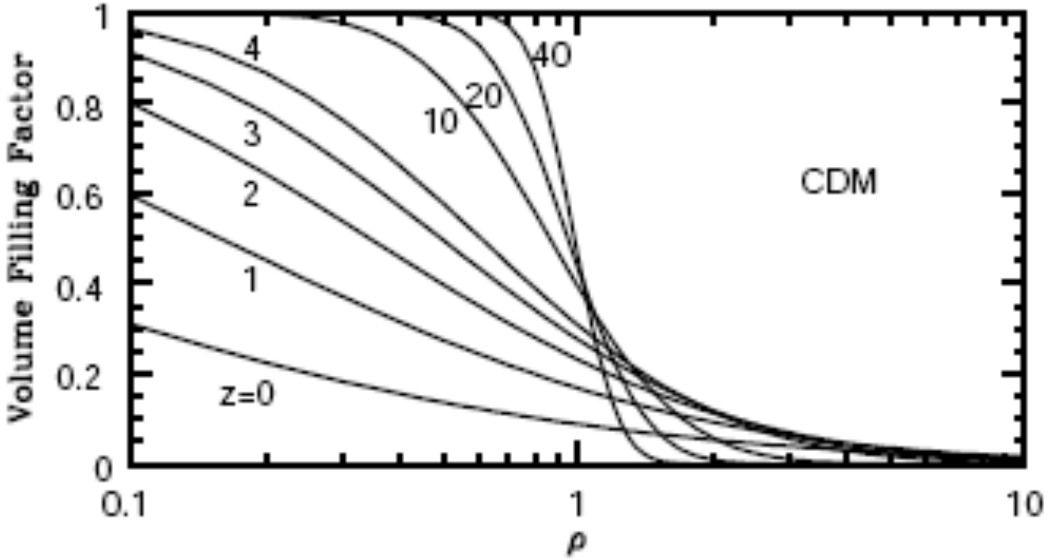
Spectra: Flux=exp(-τ)

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

Modelling the IGM – III: IGM in a CDM universe



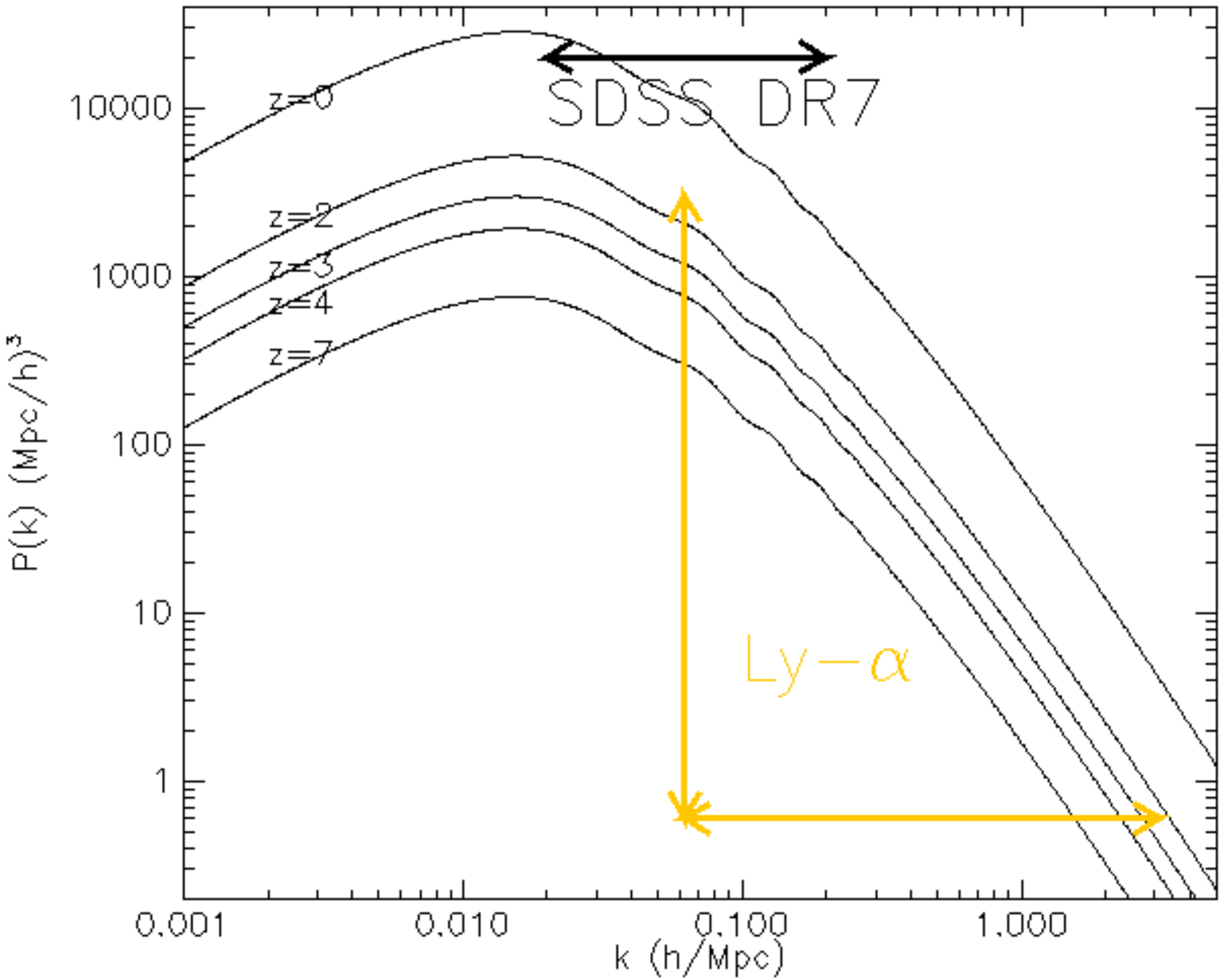
M (> ρ)



V (> ρ)

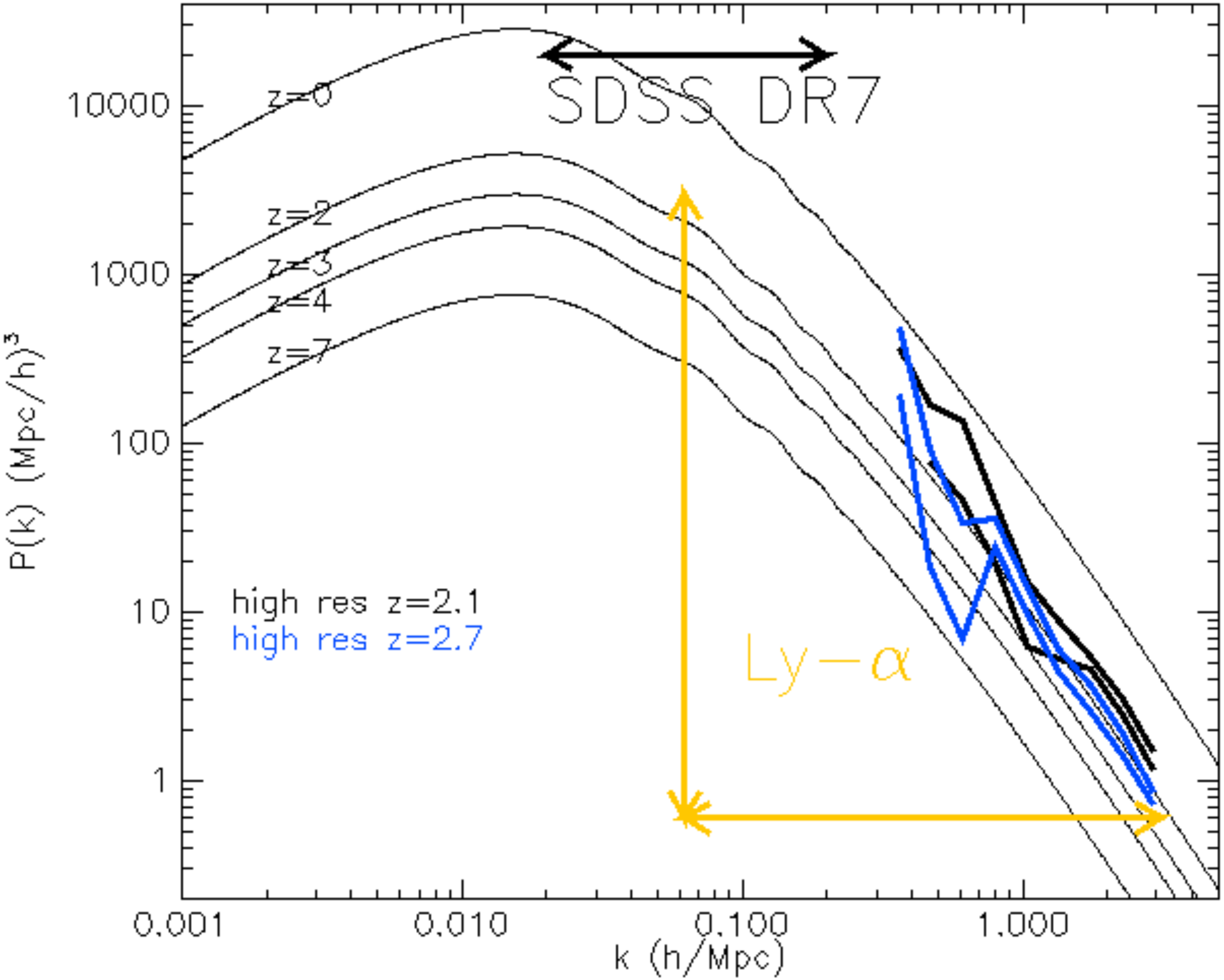
Bi & Davidsen 1997, ApJ, 479, 523

DATA vs THEORY

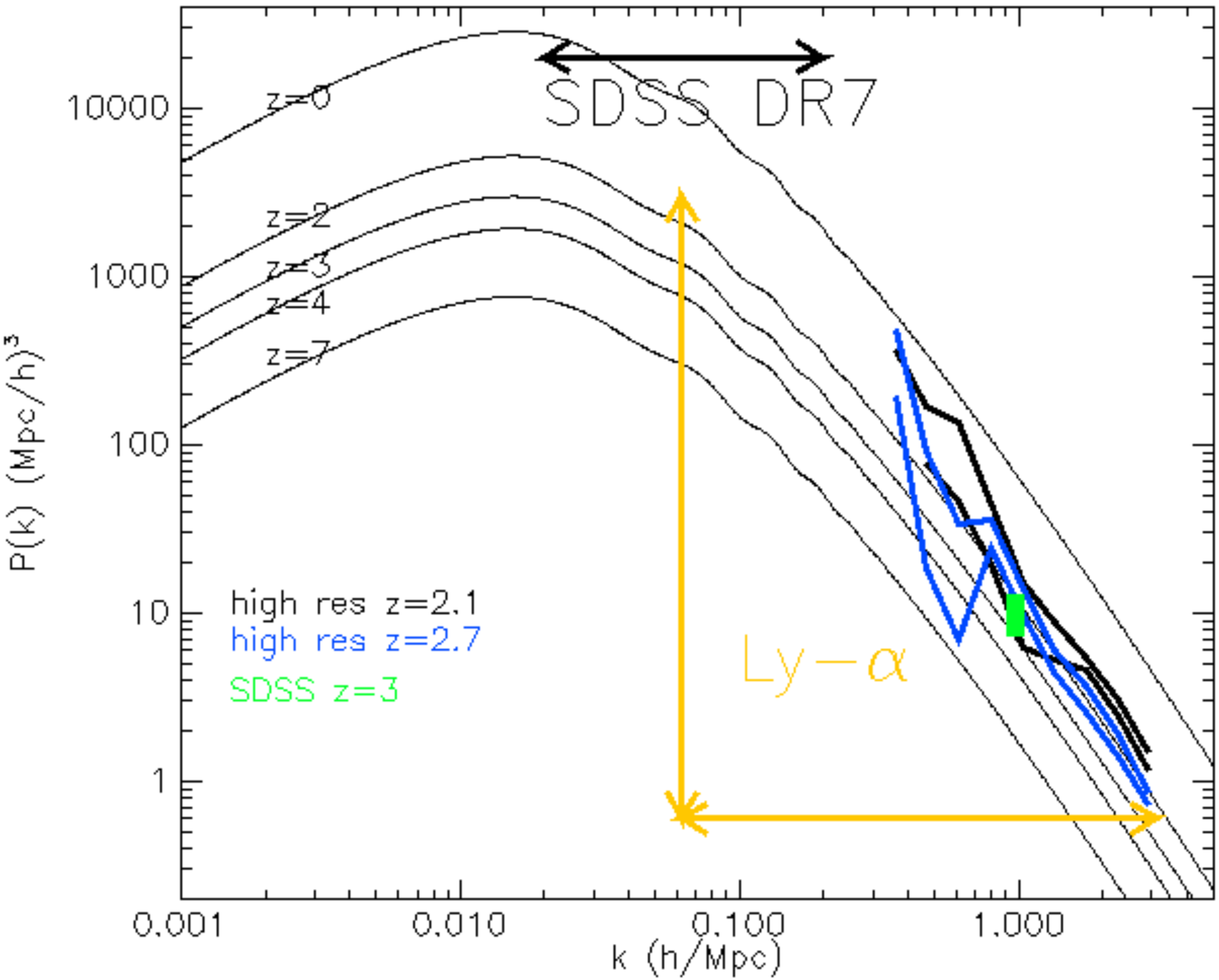


DATA vs THEORY

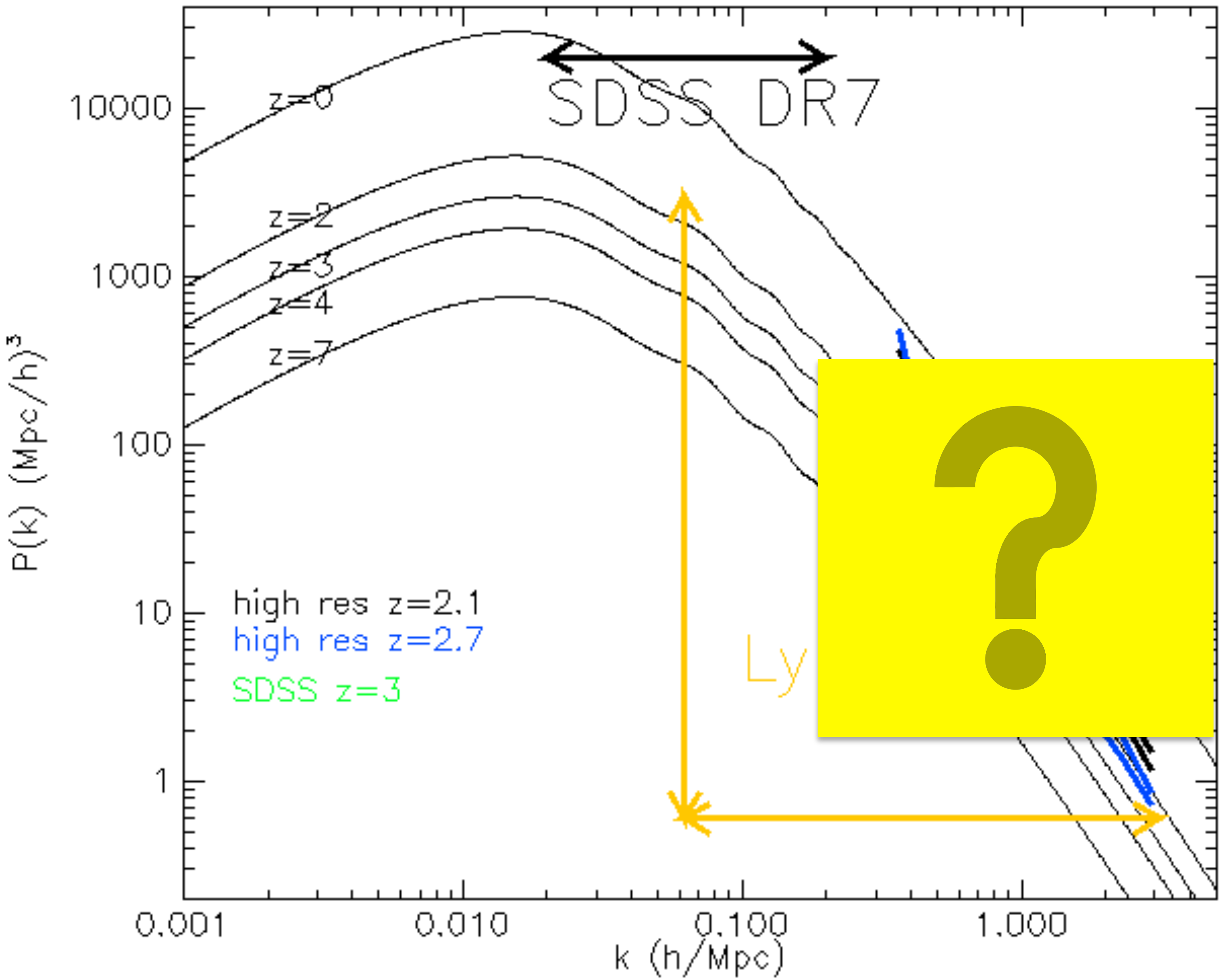
$$P_{FLUX}(k,z) = bias^2(k,z) \times P_{MATTER}(k,z)$$



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:

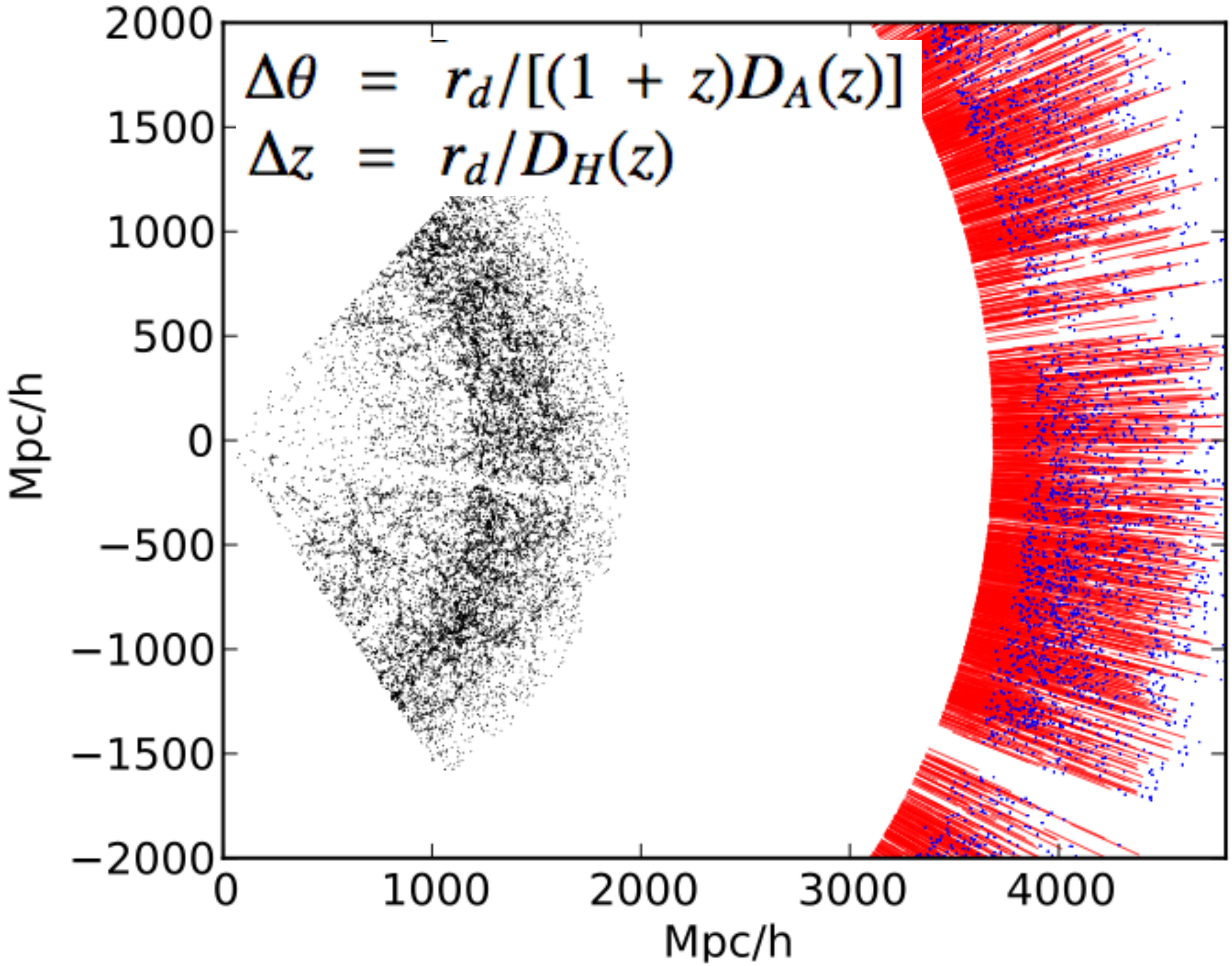
The IGM is a probe of matter fluctuations,
a laboratory for fundamental physics.
a sink (and a reservoir) for (of) galactic baryons

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



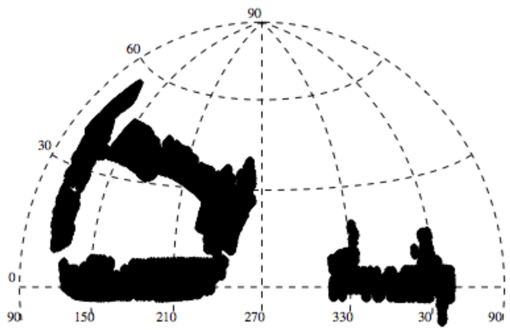
Slosar et al. 11
Busca et al. 13
Slosar et al. 13

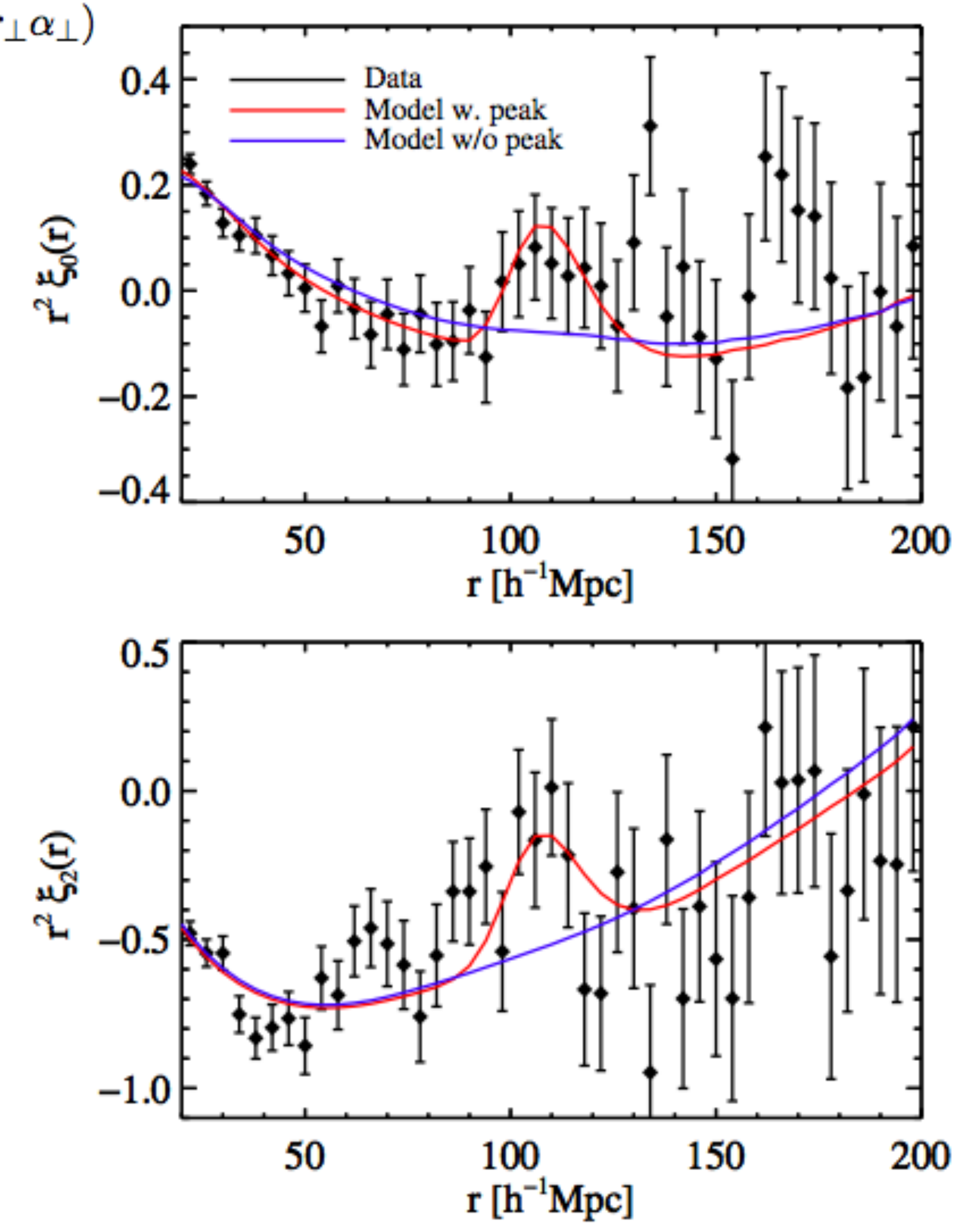
SDSS- II

Busca et al. 13

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

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



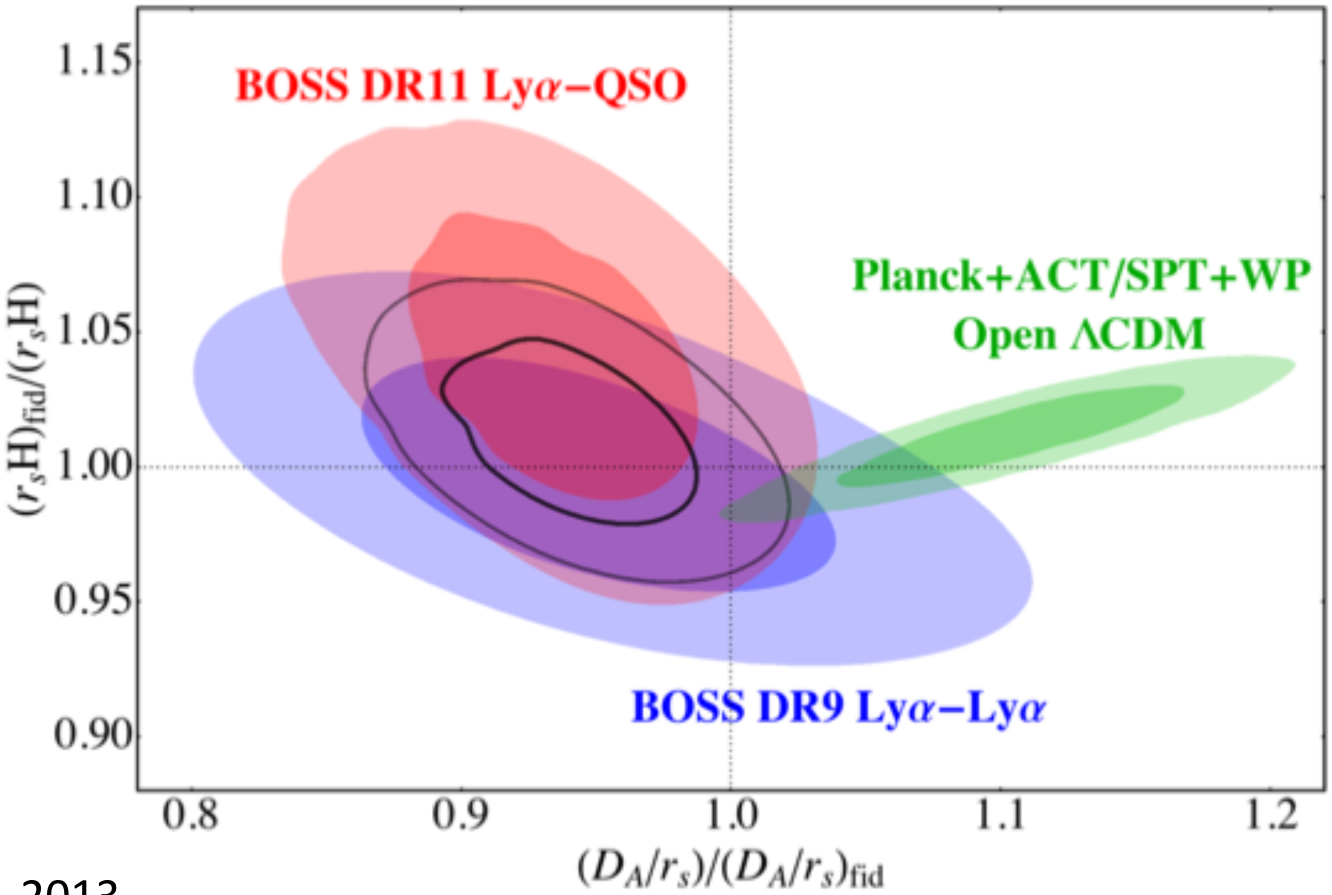


BAO feature detected at z=2.3
From 3000 deg^2, using 50000 QSOs
Significance of the detection at
around 3σ

SDSS- III

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

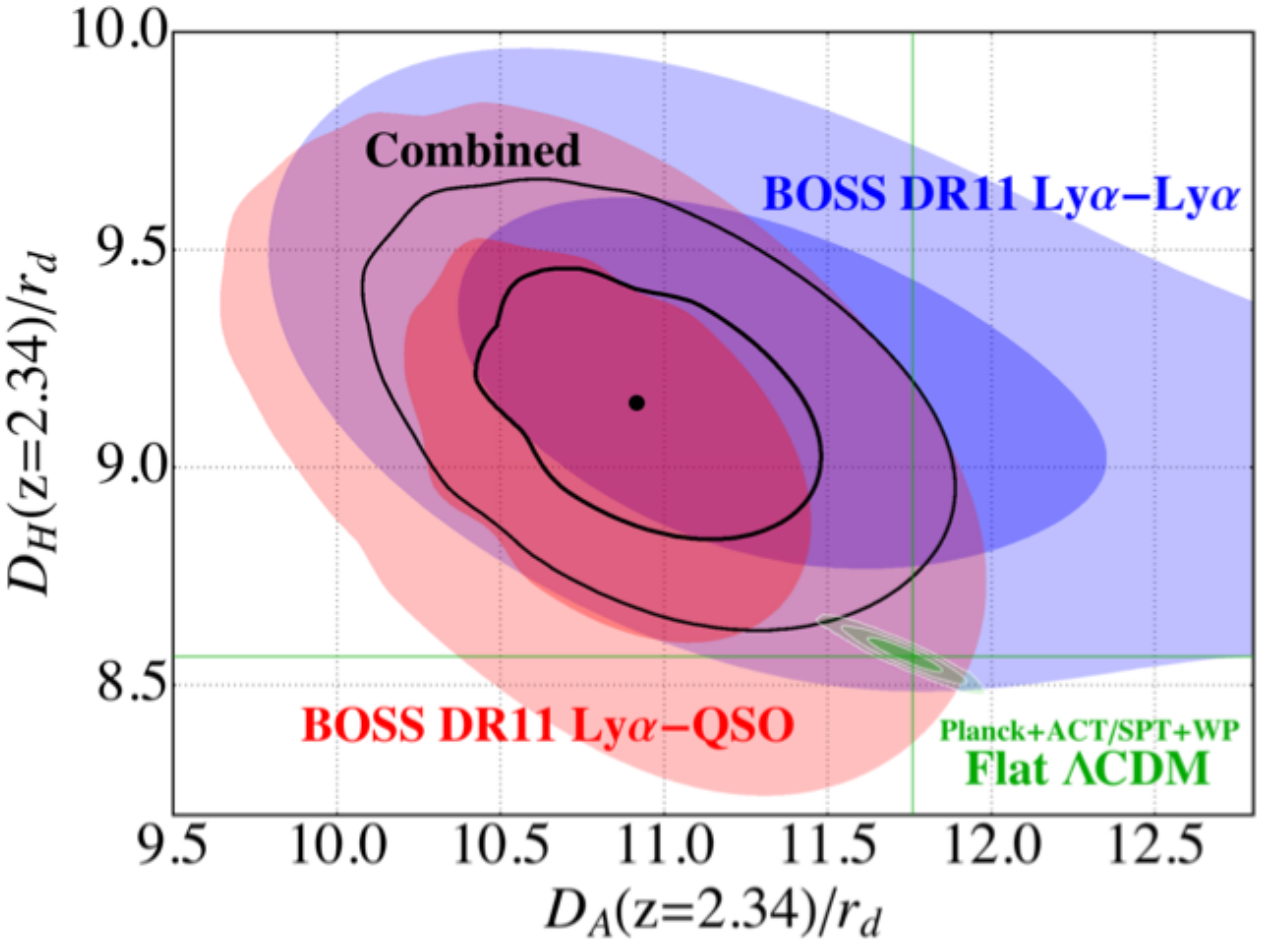
$$P_{qF}(\mathbf{k}) = b_q \left[1 + \beta_q \mu_k^2\right] b_F \left[1 + \beta_F \mu_k^2\right] \; P(k)$$



Font-Ribera et al. 2013

SDSS-IV

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

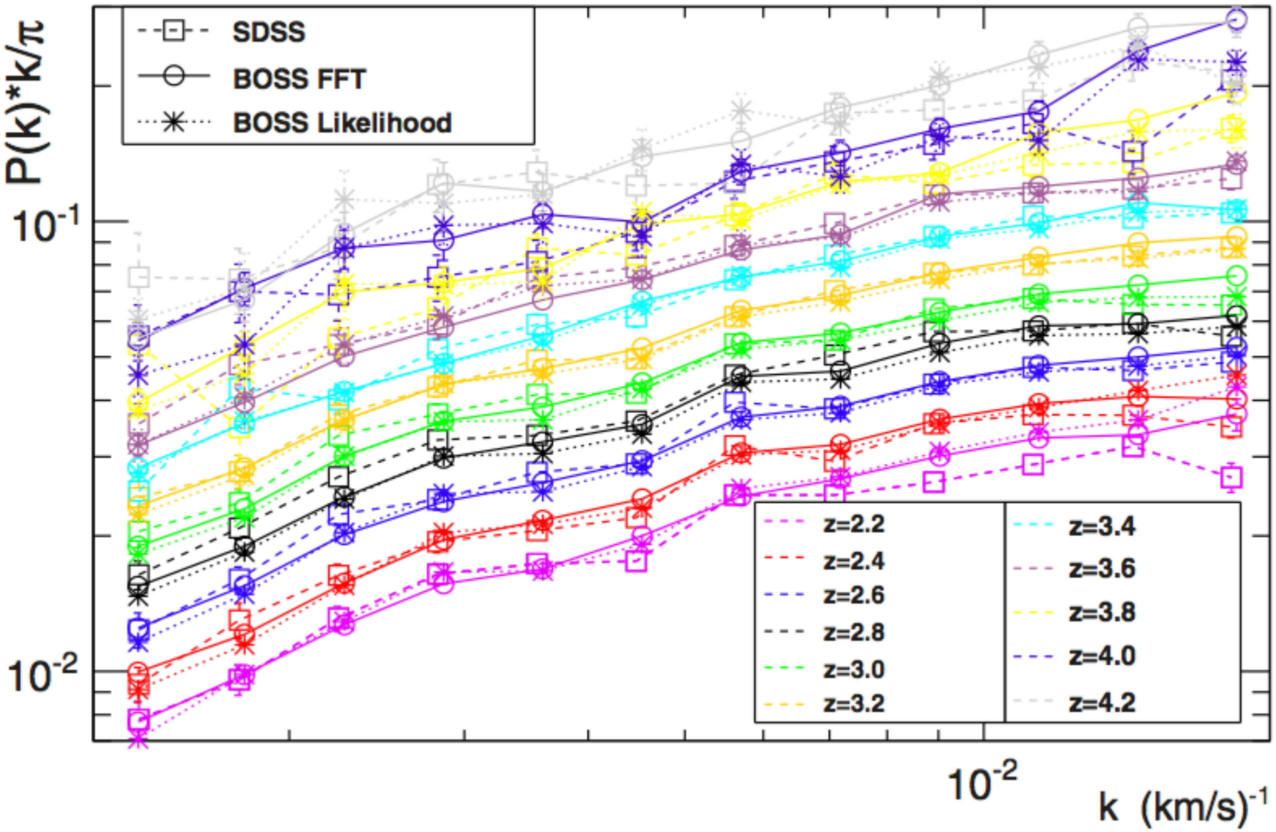


!

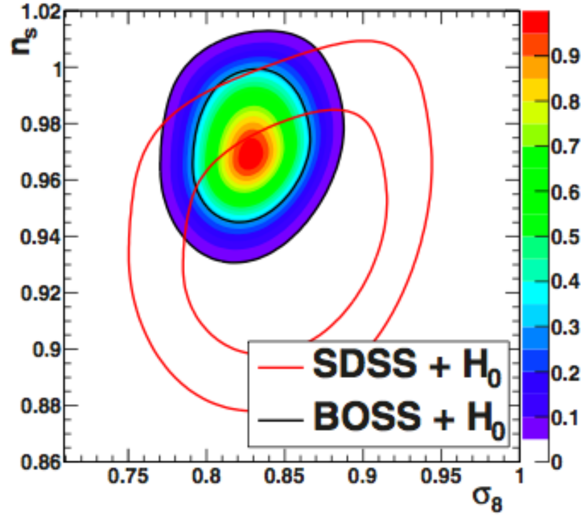
$$\frac{\rho_{\rm de}(z=2.34)}{\rho_{\rm de}(z=0)} = -1.2 \pm 0.8$$

Delubac et al. 14

<u>SDSS- IV</u> *1D Lyman-α flux power*



Palanque-Delabrouille et al. 2013



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

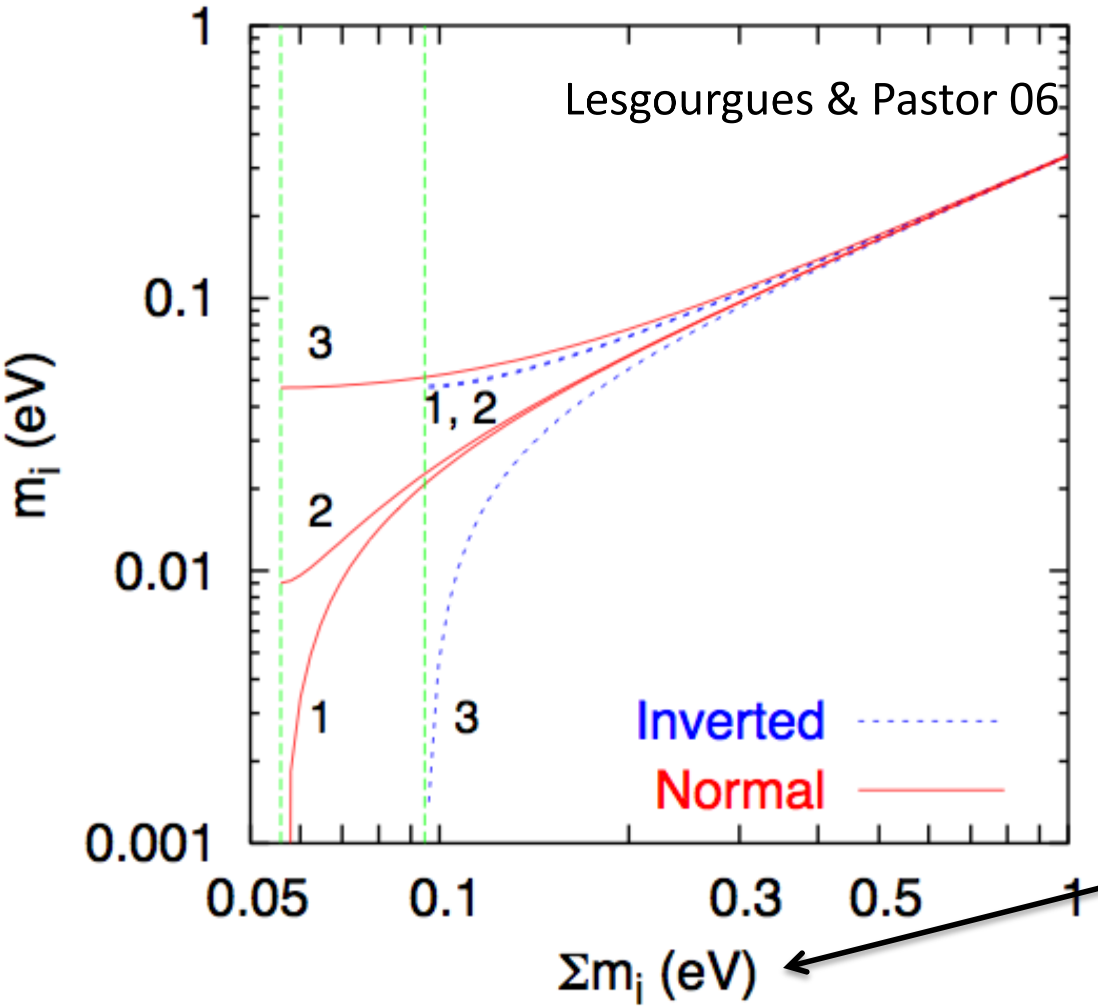
3) **HIGH REDSHIFT**

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

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

COSMOLOGICAL NEUTRINOS - II: FREE-STREAMING SCALE

Neutrino thermal velocity

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

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

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

THREE COSMIC EPOCHS

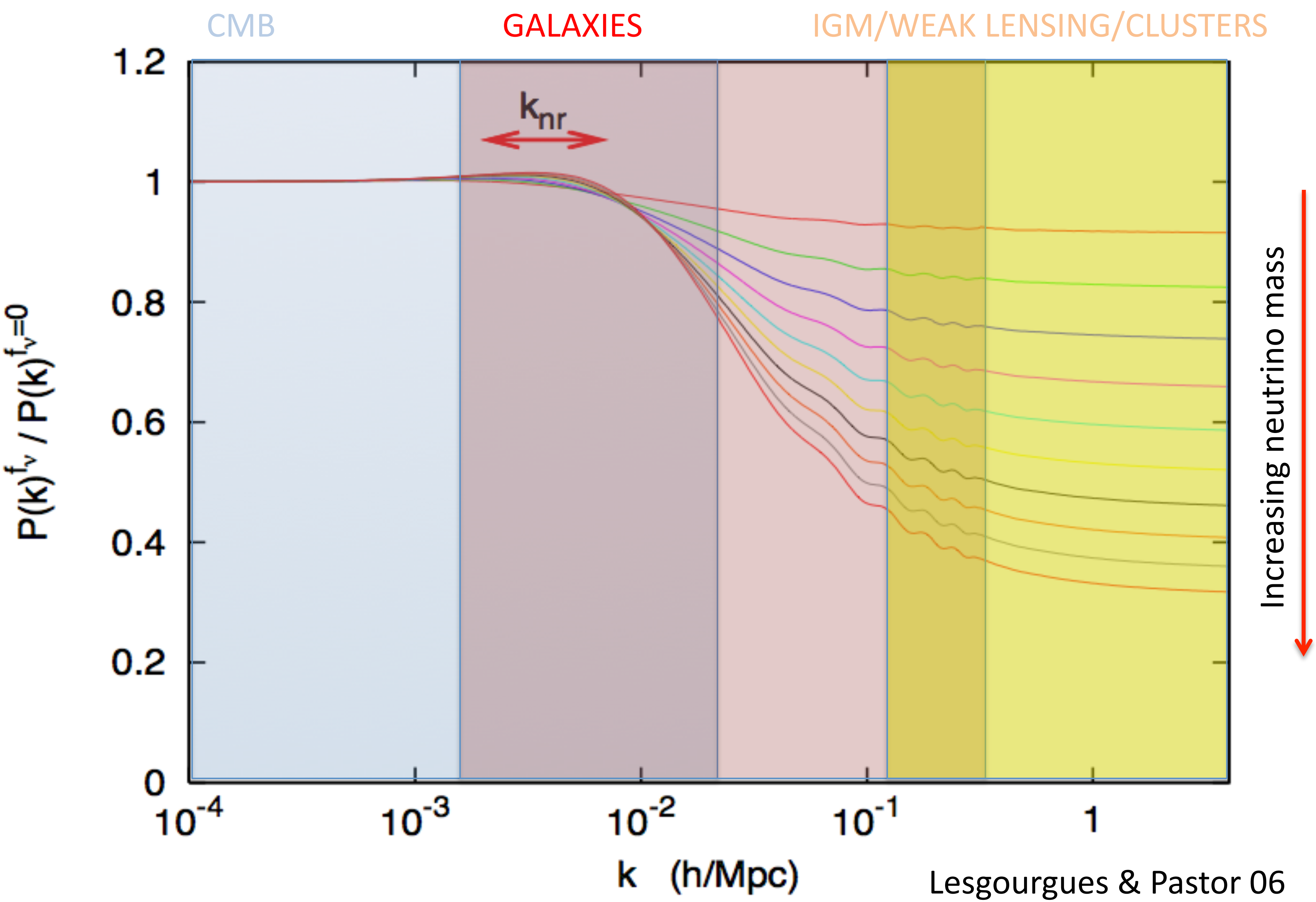
RADIATION ERA z>3400

MATTER RADIATION z<3400

NON-RELATIVISTIC TRANSITION z ~ 500

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

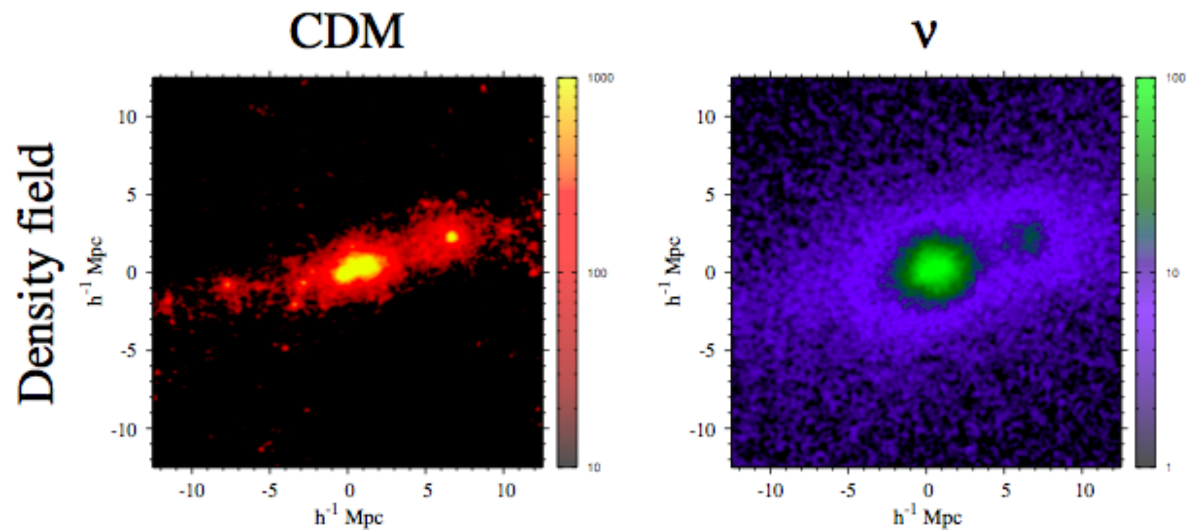
COSMOLOGICAL NEUTRINOS - III: LINEAR MATTER POWER



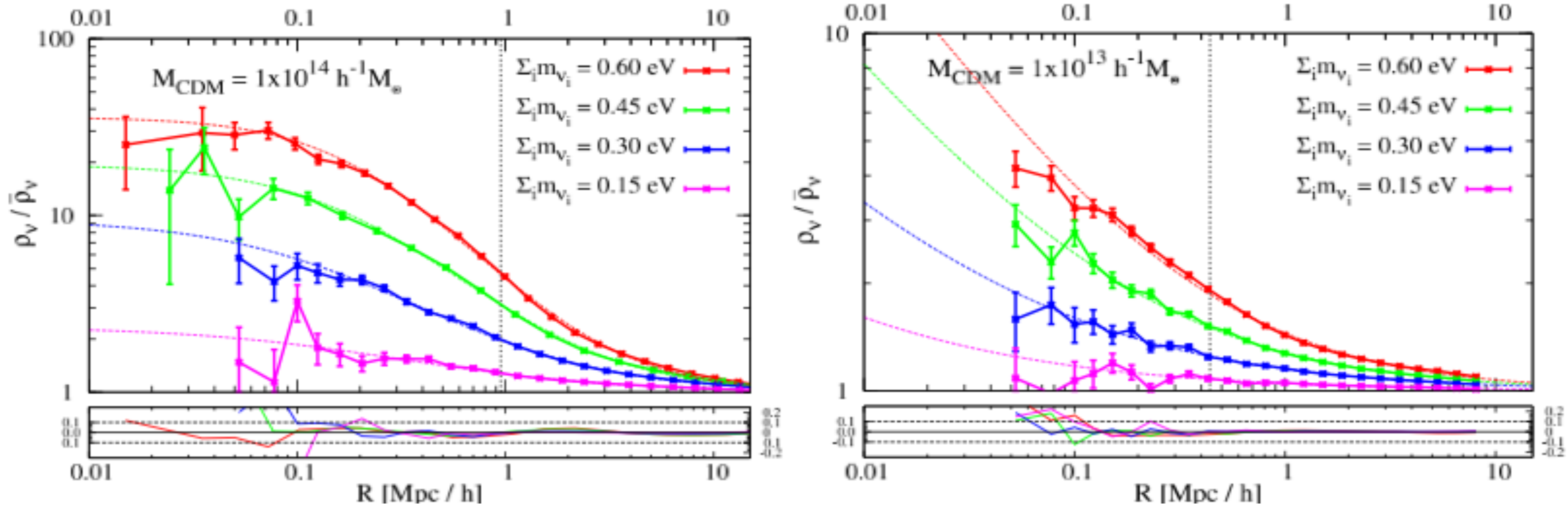
Lesgourgues & Pastor 06

MASSIVE NEUTRINOS

THE FUTURE: THE NEUTRINO HALO?

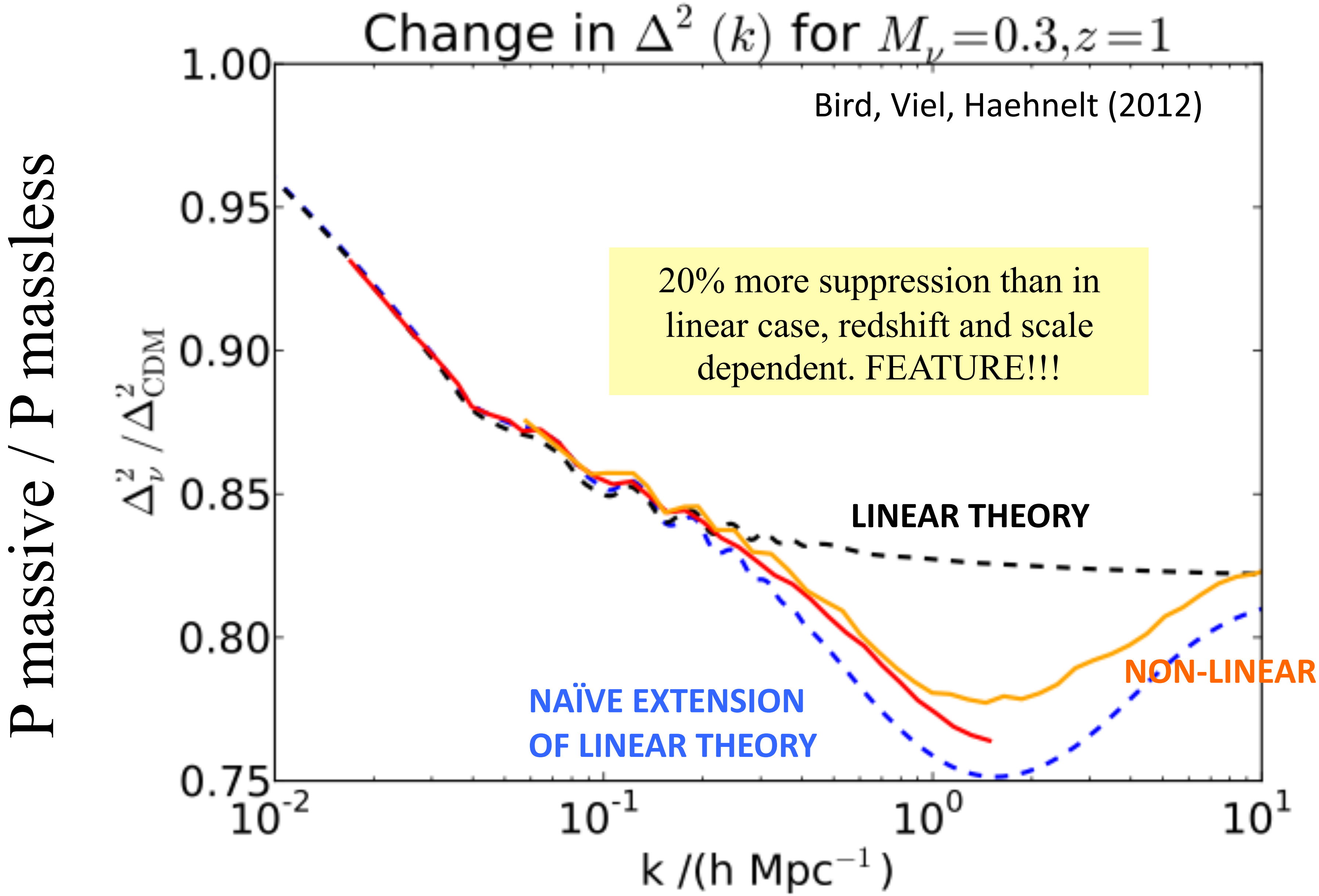


$$\delta_\nu(r) = \frac{\rho_\nu(r) - \overline{\rho}_\nu}{\overline{\rho}_\nu} = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$



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

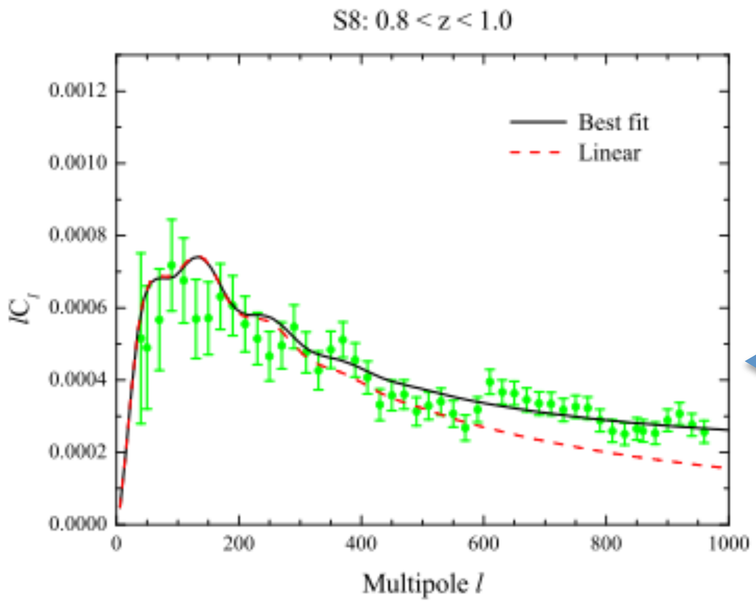
Marulli, Carbone, Viel+ 2011, MNRAS, 418, 346

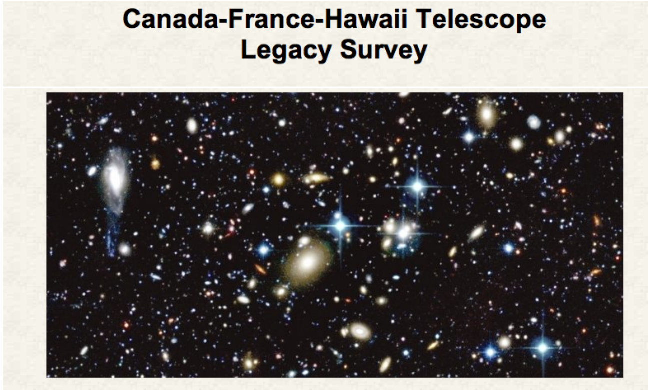


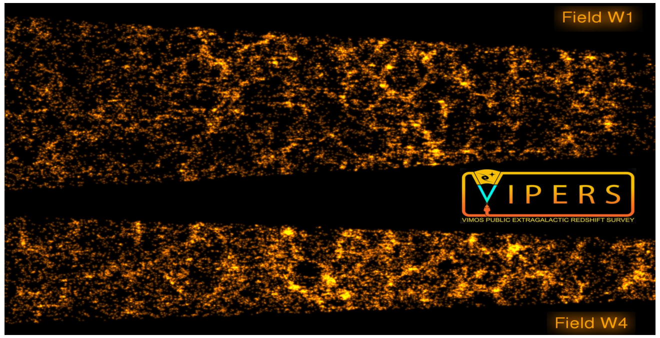
http://www.sns.ias.edu/~spb/index.php?p=code Cosmic Scale

CONSTRAINTS on NEUTRINO MASSES USING NON-LINEARITIES

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





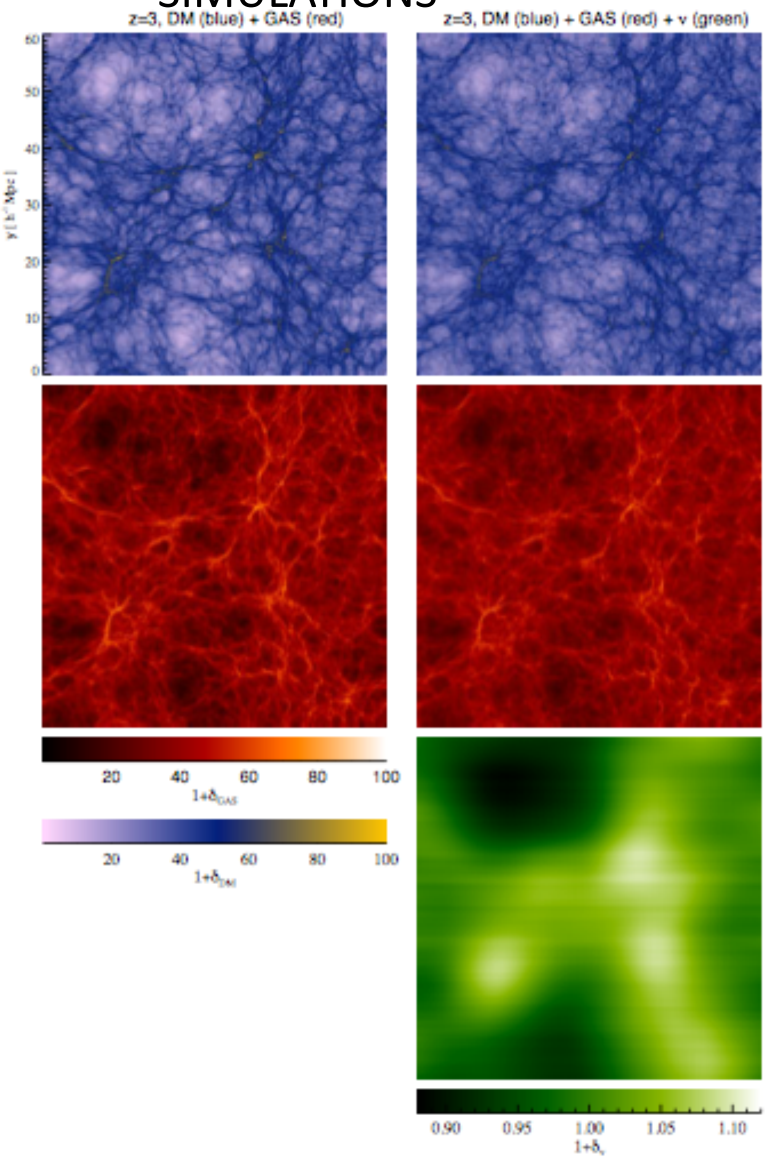


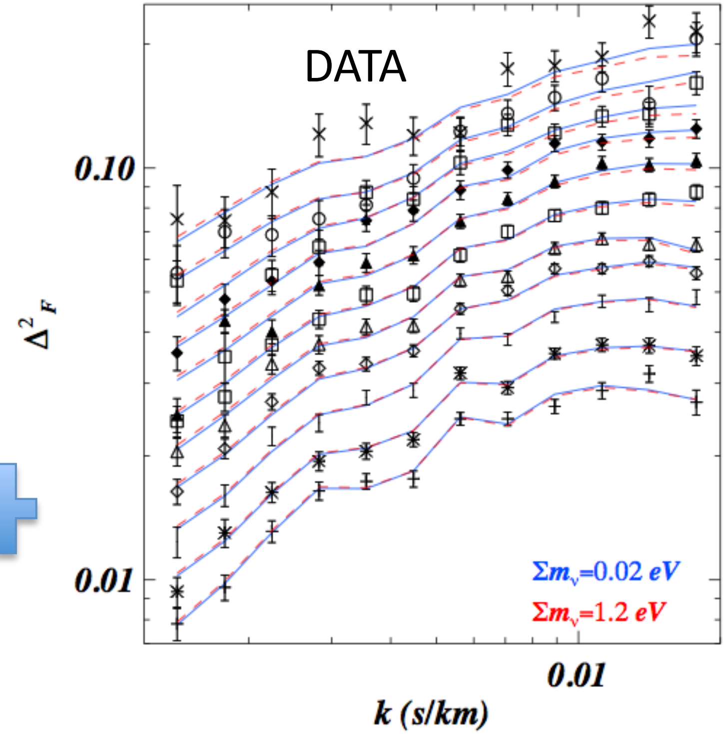
95% C.L. $\sum m_\nu$ [eV]	Without HST Prior		With HST Prior	
	$\ell_{max} = 630$	$\ell_{max} = 960$	$\ell_{max} = 630$	$\ell_{max} = 960$
WMAP7	1.17		0.50	
WMAP7 + CFHTLS	0.64	0.43	0.41	0.29
WMAP7 + SDSS + CFHTLS	0.47	0.35	$\boxed{0.35}$	$\boxed{0.28}$

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

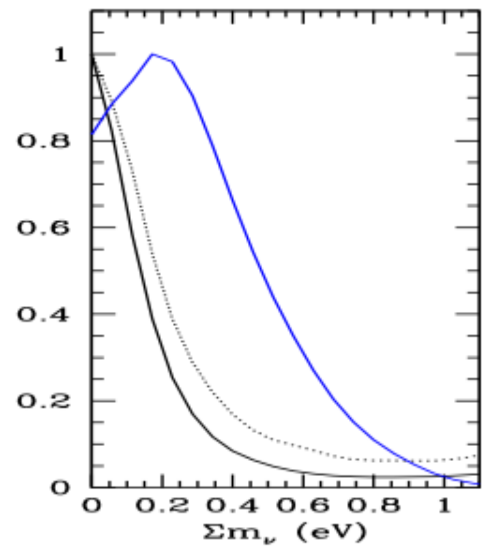
NEUTRINOS IN THE IGM

SIMULATIONS





CONSTRAINTS

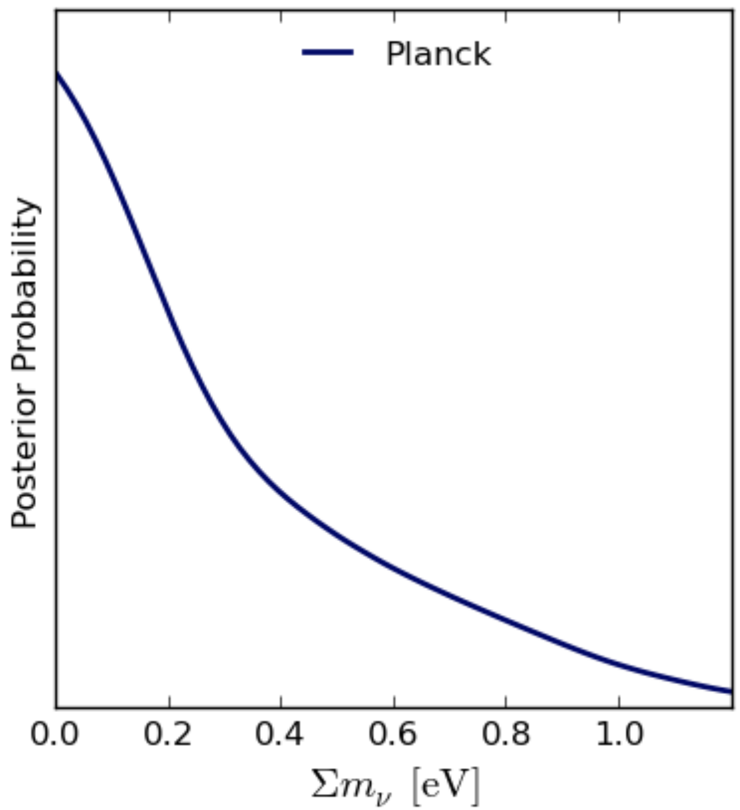


FROM IGM ONLY:

$\Sigma m_\nu < 0.9$ eV(2σ)

Viel, Haehnelt, Springel 2010

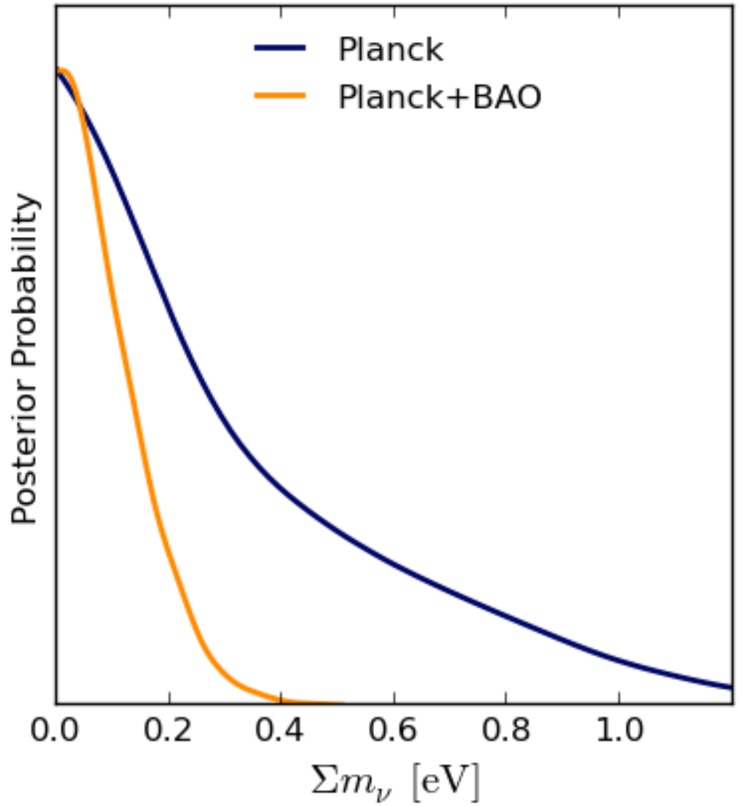
CONSTRAINTS on NEUTRINO MASSES FROM Planck: I



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

Costanzi+ 2014, JCAP

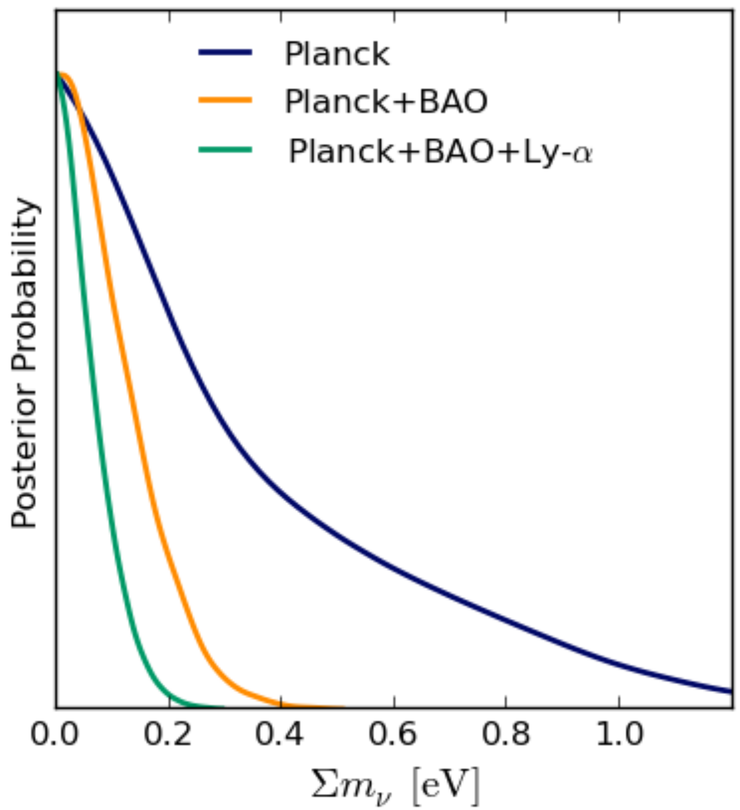
CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO: II



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

Costanzi+ 2014

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



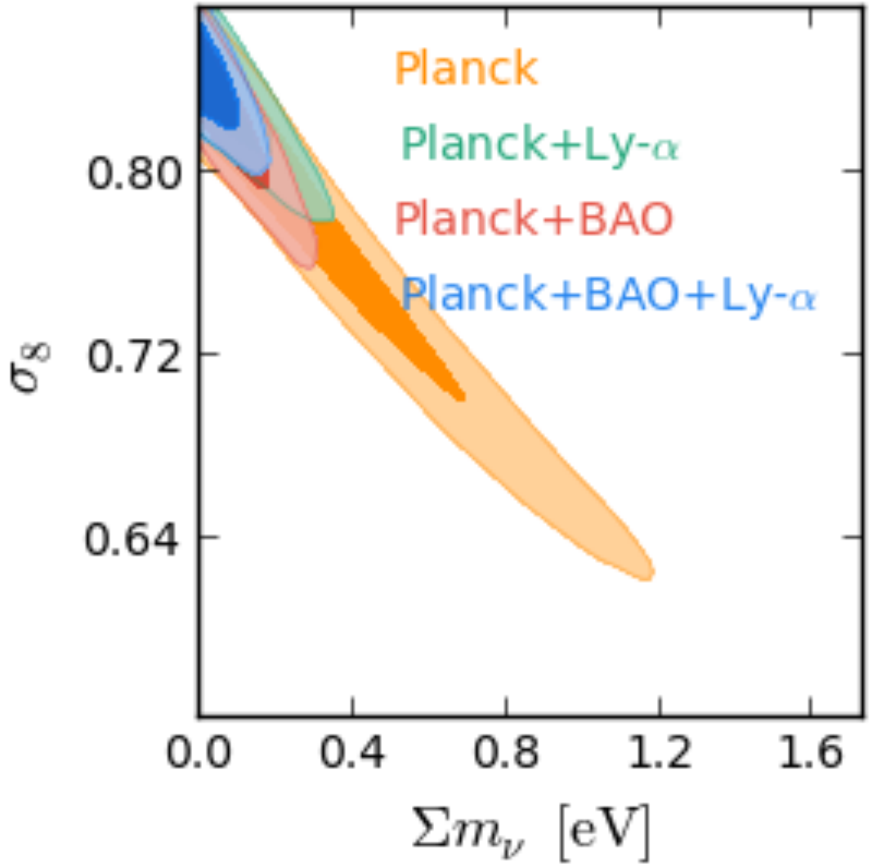
$$\Sigma m_\nu < 0.14 \text{ eV}(2\sigma)$$

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

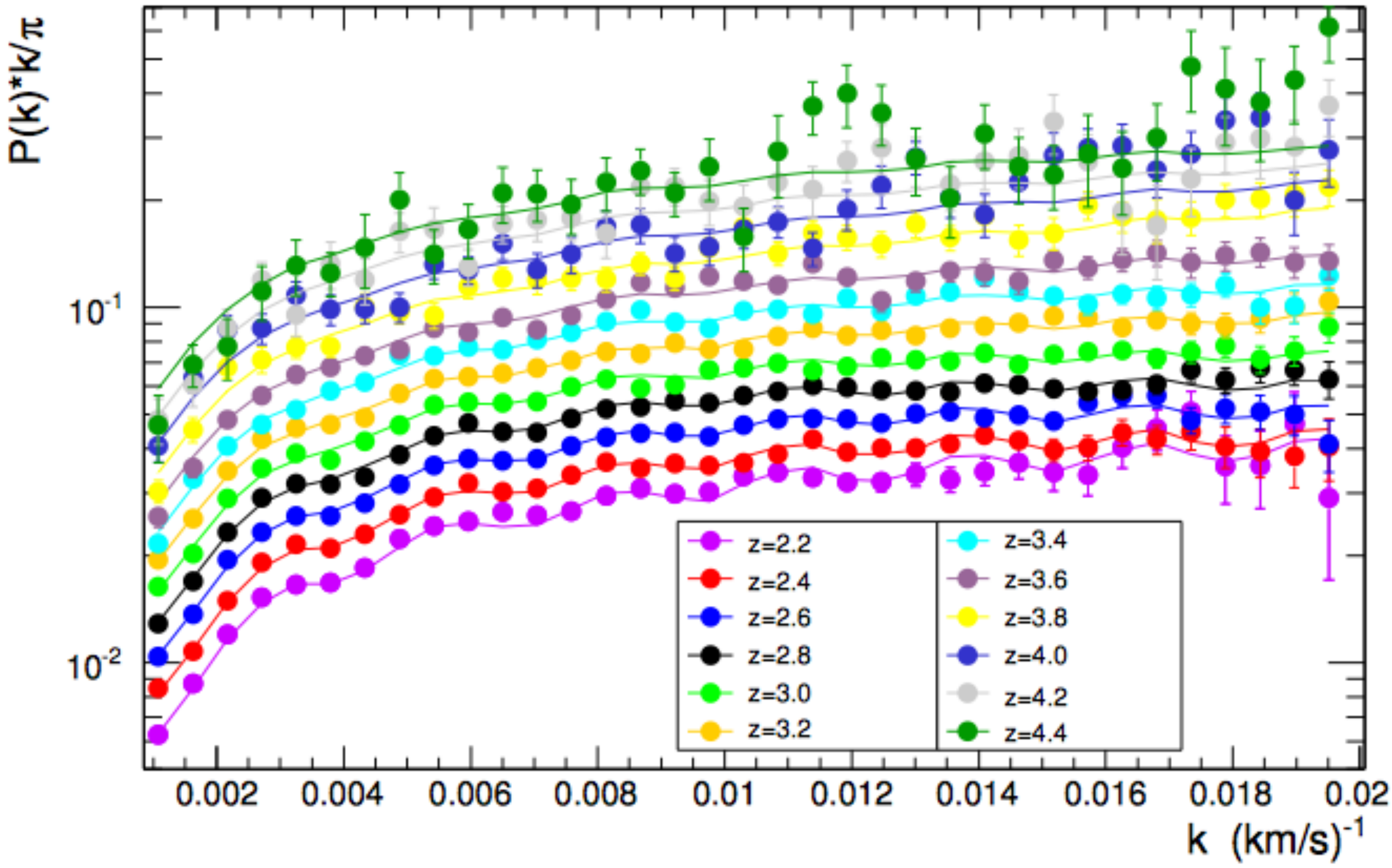
Costanzi, Sartoris, MV, Borgani 2014

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]

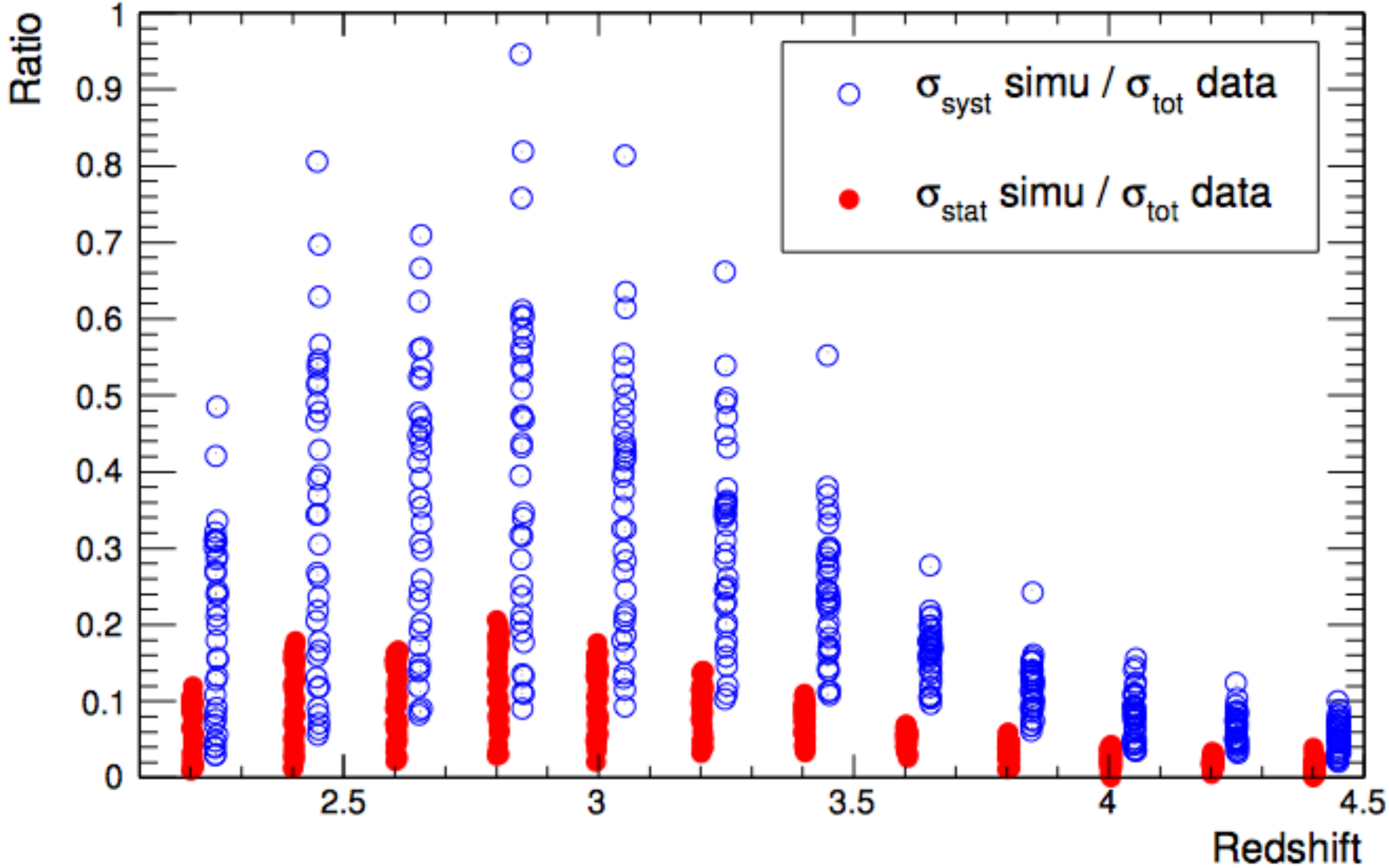
JCAP in press

arXiv:1410.7244v2

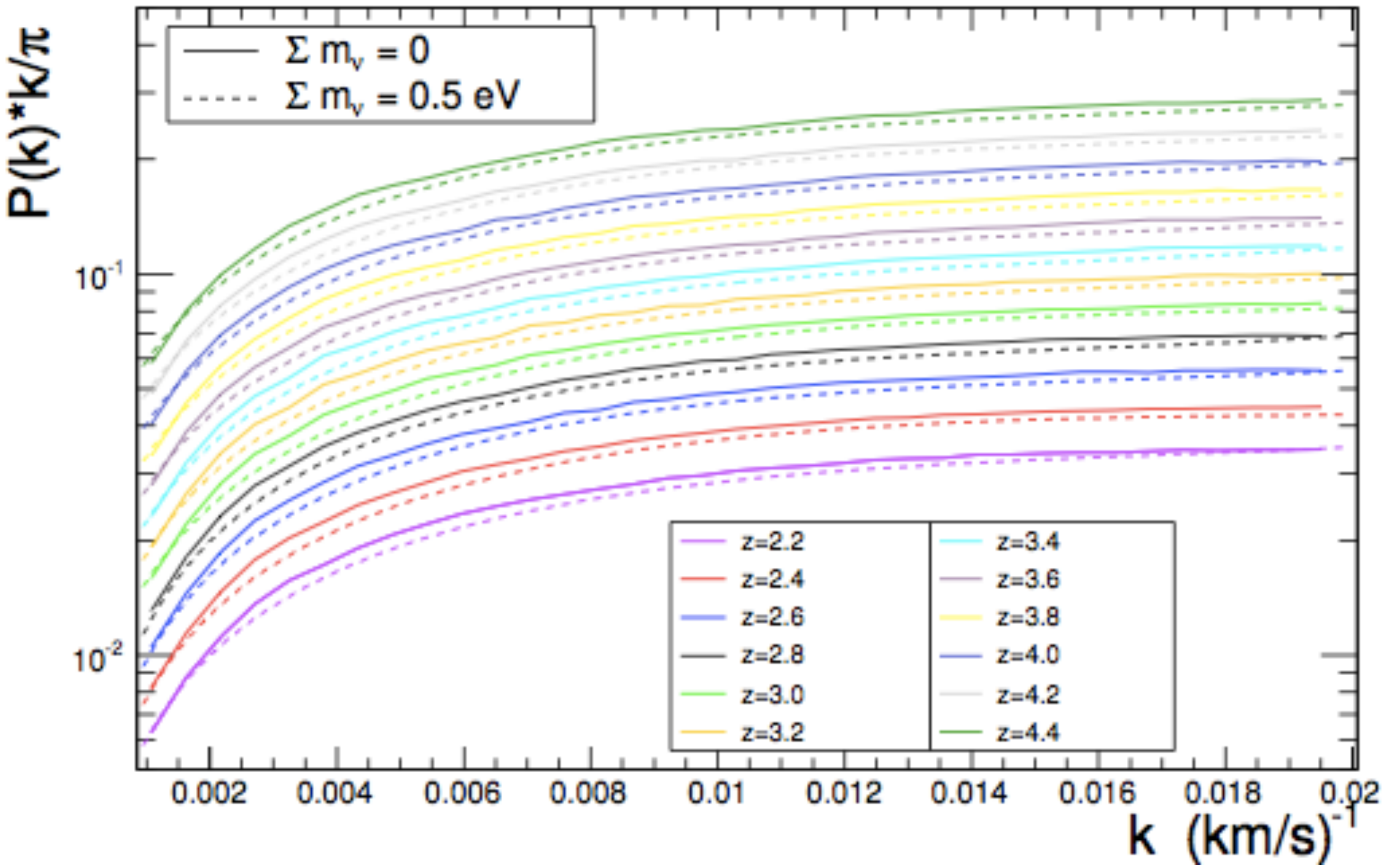


P(k)*k/π
10^-1
10^-2
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
k (km/s)^-1
z=2.2
z=2.4
z=2.6
z=2.8
z=3.0
z=3.2
z=3.4
z=3.6
z=3.8
z=4.0
z=4.2
z=4.4

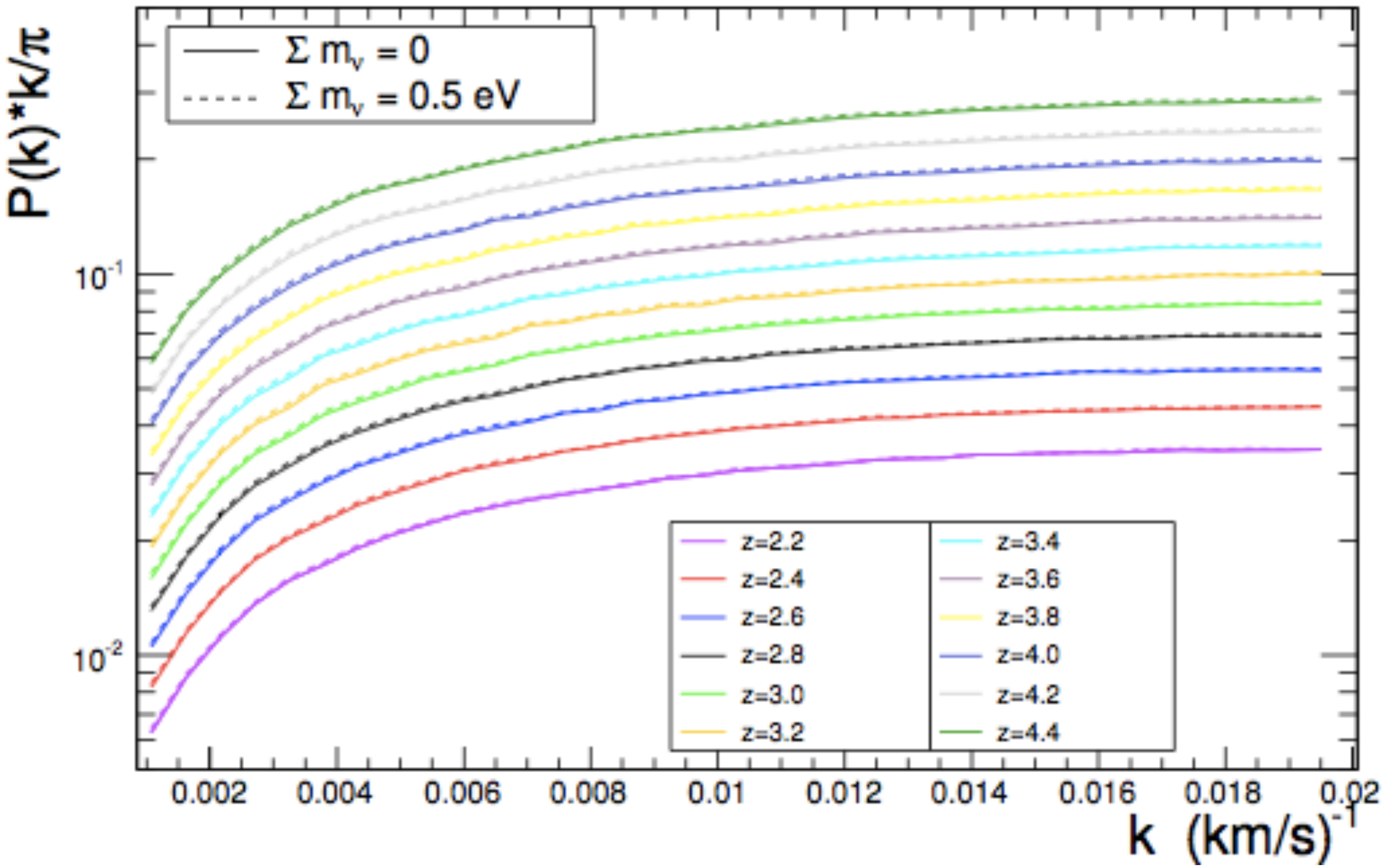
Parameter	Central value	Range
n_s	0.96	$\pm\,0.05$
σ_8	0.83	$\pm\,0.05$
Ω_m	0.31	$\pm\,0.05$
H_0	67.5	$\pm\,5$
$T_0(z=3)$	14000	$\pm\,7000$
$\gamma(z=3)$..	1.3	$\pm\,0.3$
A^τ	0.0025	$\pm\,0.0020$
η^τ	3.7	$\pm\,0.4$
$\sum m_\nu$ (eV)	0.0	0.4, 0.8



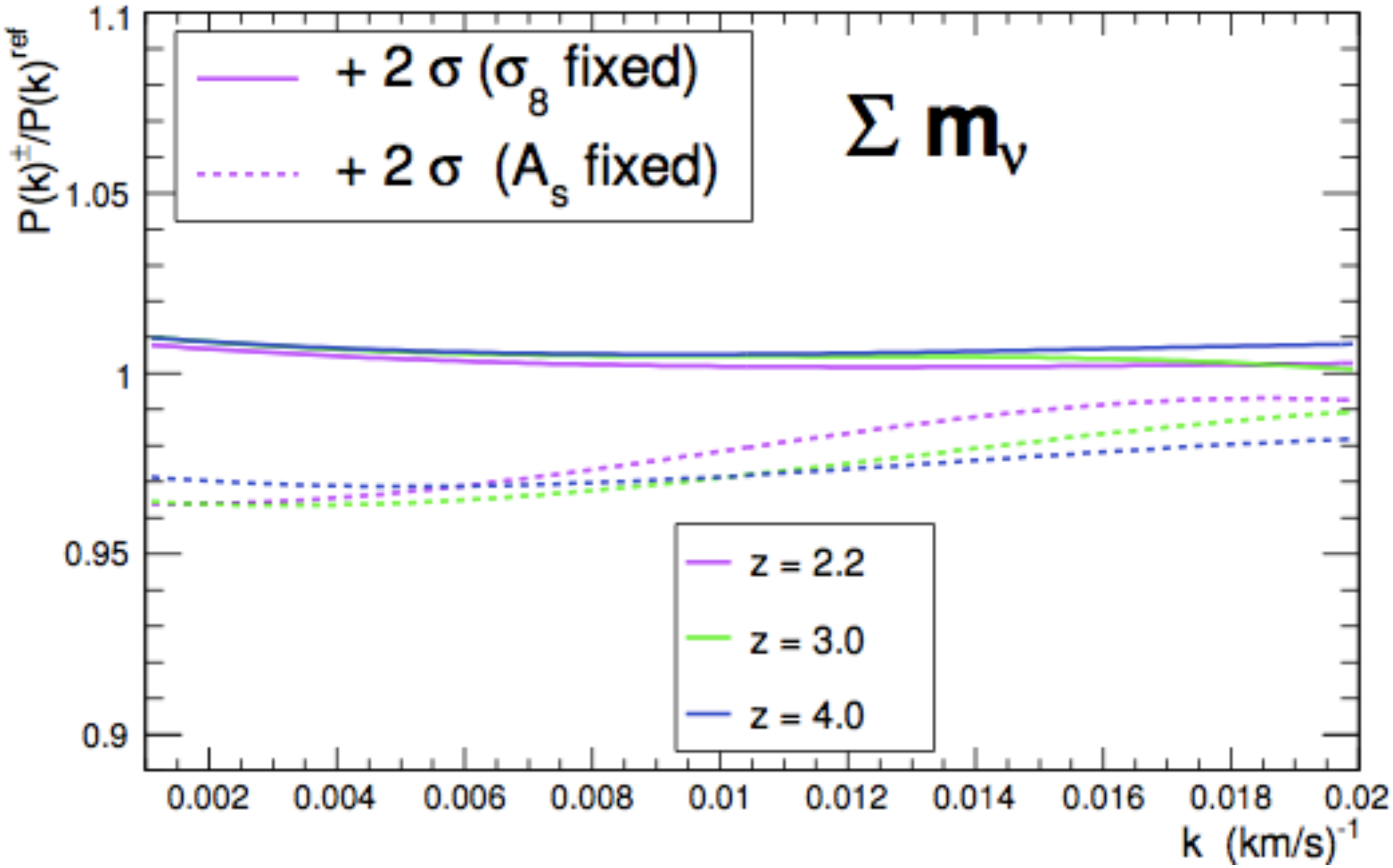
Ratio
Redshift
σ_{syst} simu / σ_{tot} data
σ_{stat} simu / σ_{tot} data
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2.5
3
3.5
4
4.5



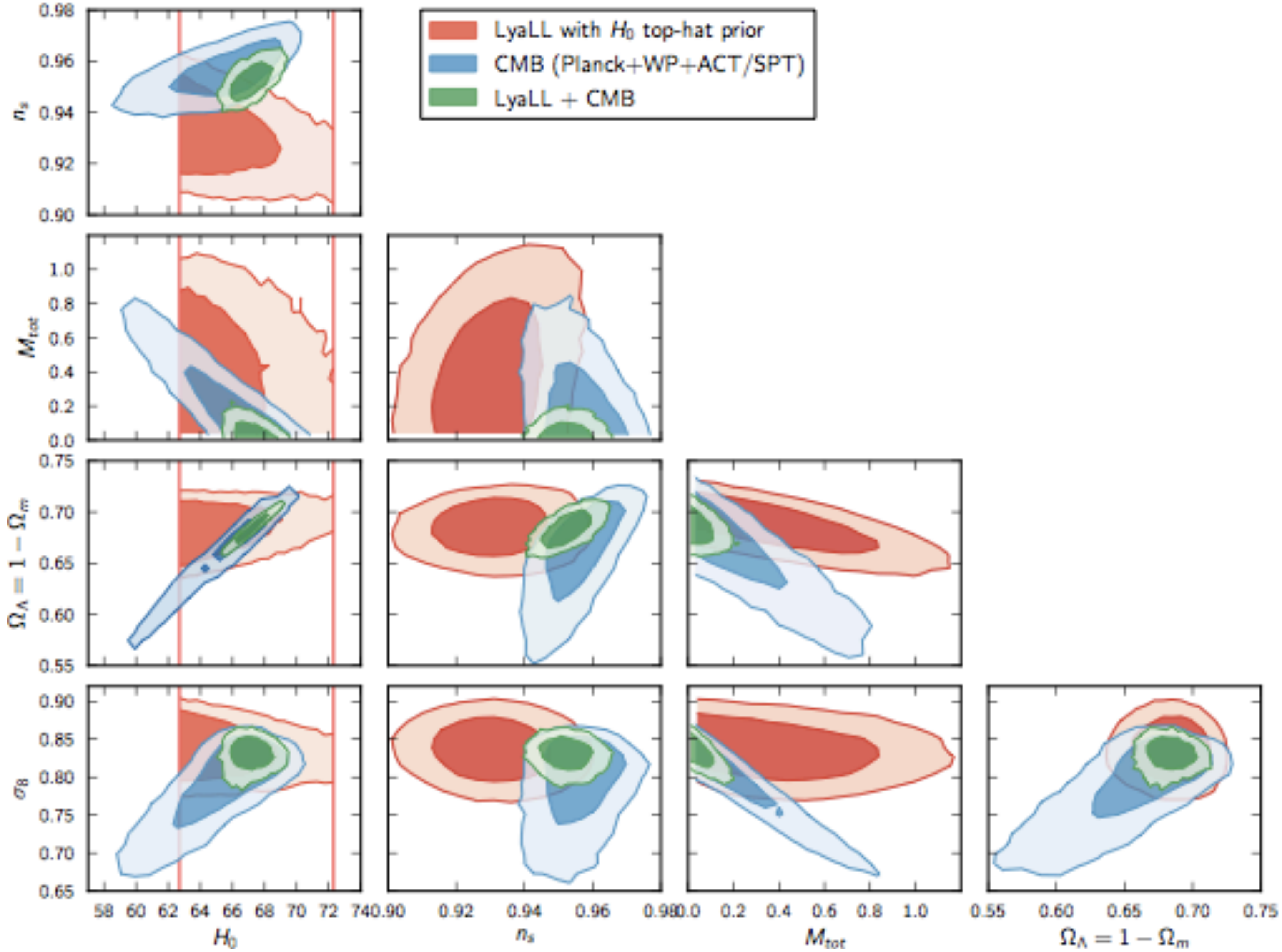
$\Sigma m_\nu = 0$
$\Sigma m_\nu = 0.5$ eV
P(k)*k/π
10^{-1}
10^{-2}
z=2.2
z=2.4
z=2.6
z=2.8
z=3.0
z=3.2
z=3.4
z=3.6
z=3.8
z=4.0
z=4.2
z=4.4
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
k (km/s)$^{-1}$

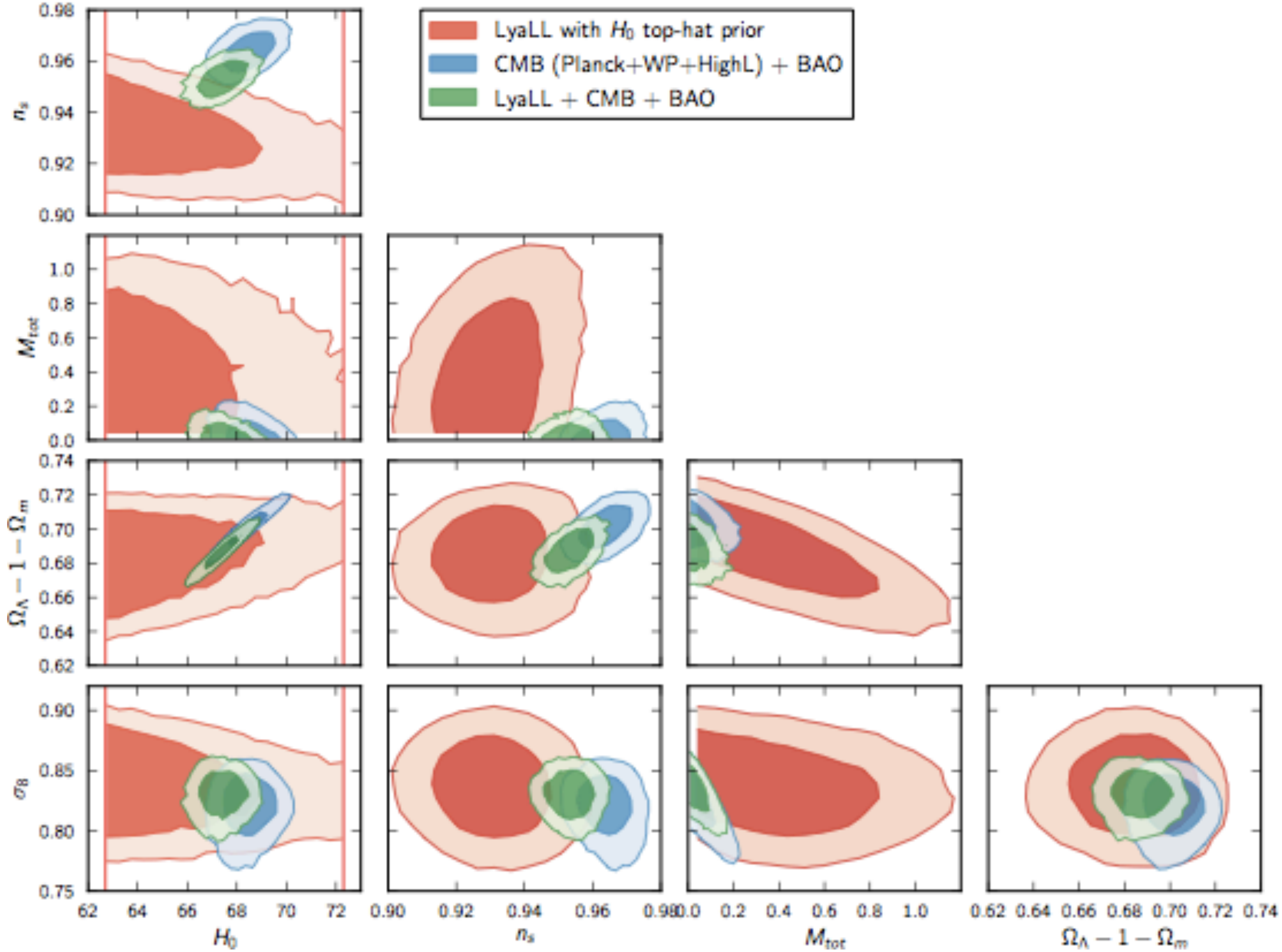


P(k)*k/π
10^{-1}
10^{-2}
Σ m_ν = 0
Σ m_ν = 0.5 eV
z=2.2
z=2.4
z=2.6
z=2.8
z=3.0
z=3.2
z=3.4
z=3.6
z=3.8
z=4.0
z=4.2
z=4.4
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
k (km/s)$^{-1}$



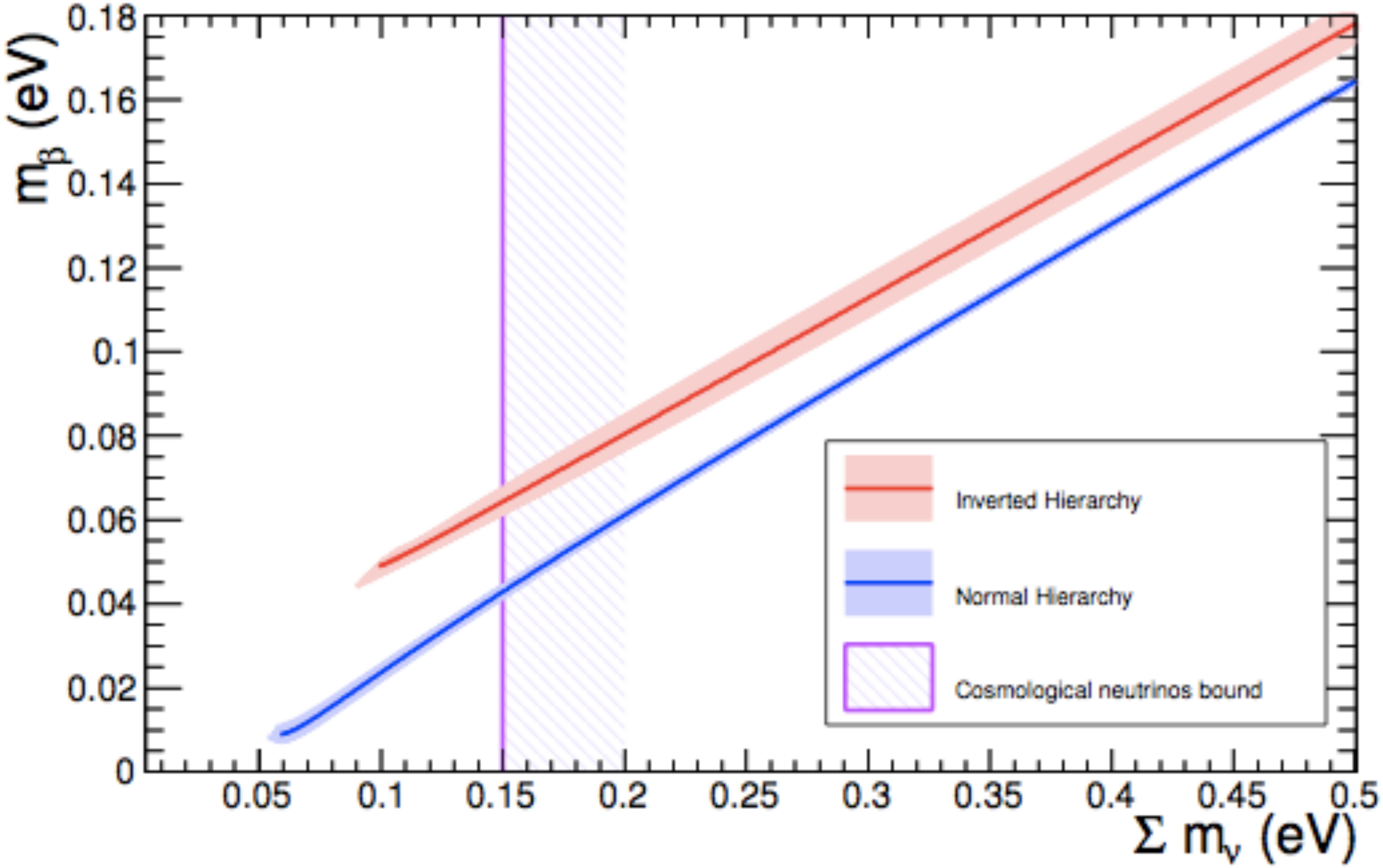
$P(k)^{\pm}/P(k)^{ref}$
1.1
1.05
1
0.95
0.9
$+2\sigma$ (σ_8 fixed)
$+2\sigma$ (A_s fixed)
$\Sigma\, m_\nu$
z = 2.2
z = 3.0
z = 4.0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
k $(km/s)^{-1}$


LyaLL with H_0 top-hat prior
CMB (Planck+WP+ACT/SPT)
LyaLL + CMB
n_s
M_{tot}
$\Omega_\Lambda = 1 - \Omega_m$
σ_8
H_0

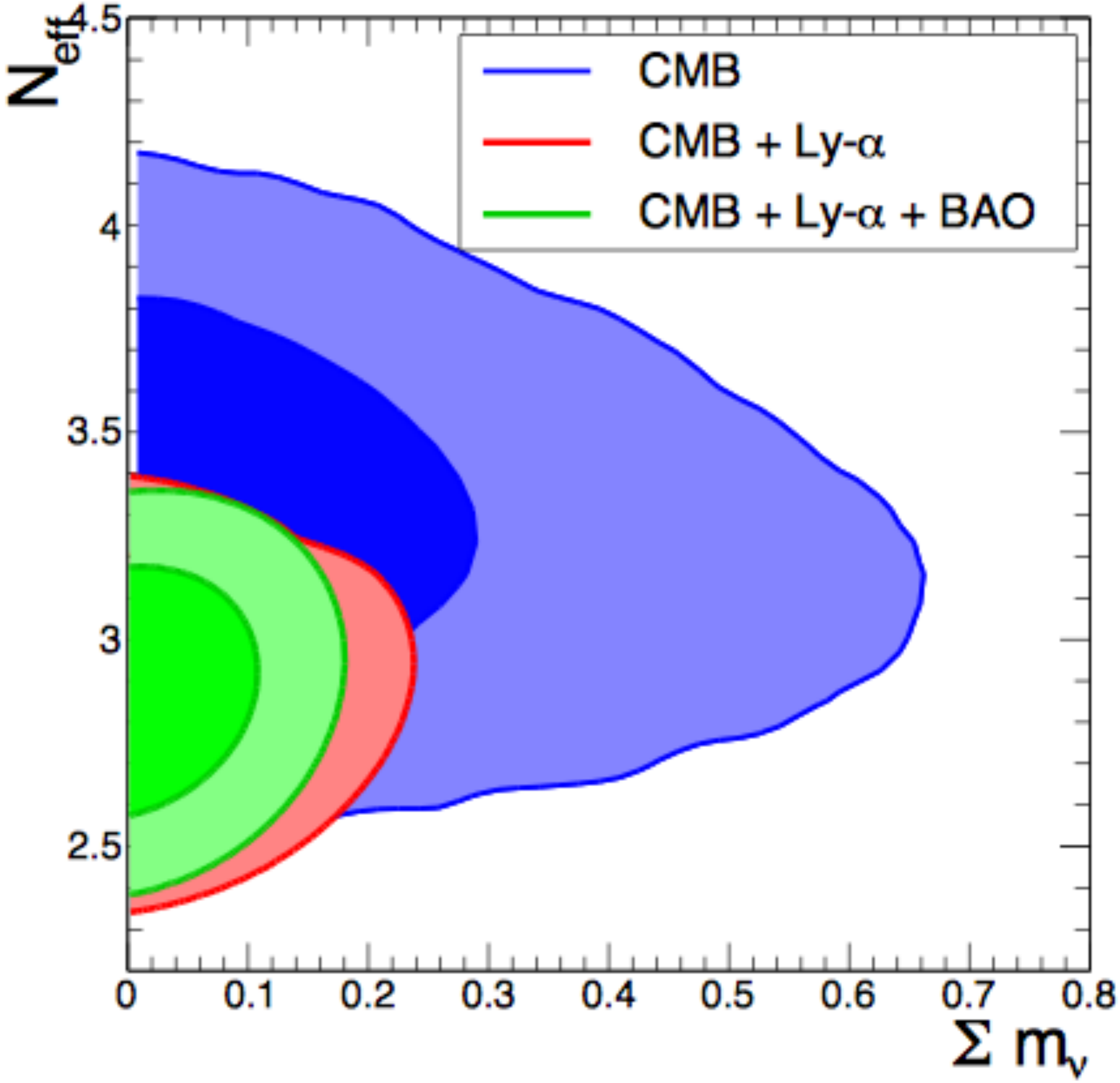


LyaLL with H_0 top-hat prior
CMB (Planck+WP+HighL) + BAO
LyaLL + CMB + BAO
n_s
M_{tot}
$\Omega_\Lambda - 1 - \Omega_m$
σ_8
H_0

Parameter	Lyα + H_0^{tophat} ($62.5 \leq H_0 < 72.5$)	Lyα + CMB	Lyα + CMB + BAO	Lyα + CMB(A_L)
$10^9 A_s$	$3.2^{+0.5}_{-0.7}$	$2.20^{+0.05}_{-0.06}$	$2.20^{+0.05}_{-0.06}$	$2.18^{+0.05}_{-0.06}$
$10^2 \omega_\mathrm{b}$	(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



m_β (eV)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
$\Sigma\, m_\nu$ (eV)
Inverted Hierarchy
Normal Hierarchy
Cosmological neutrinos bound



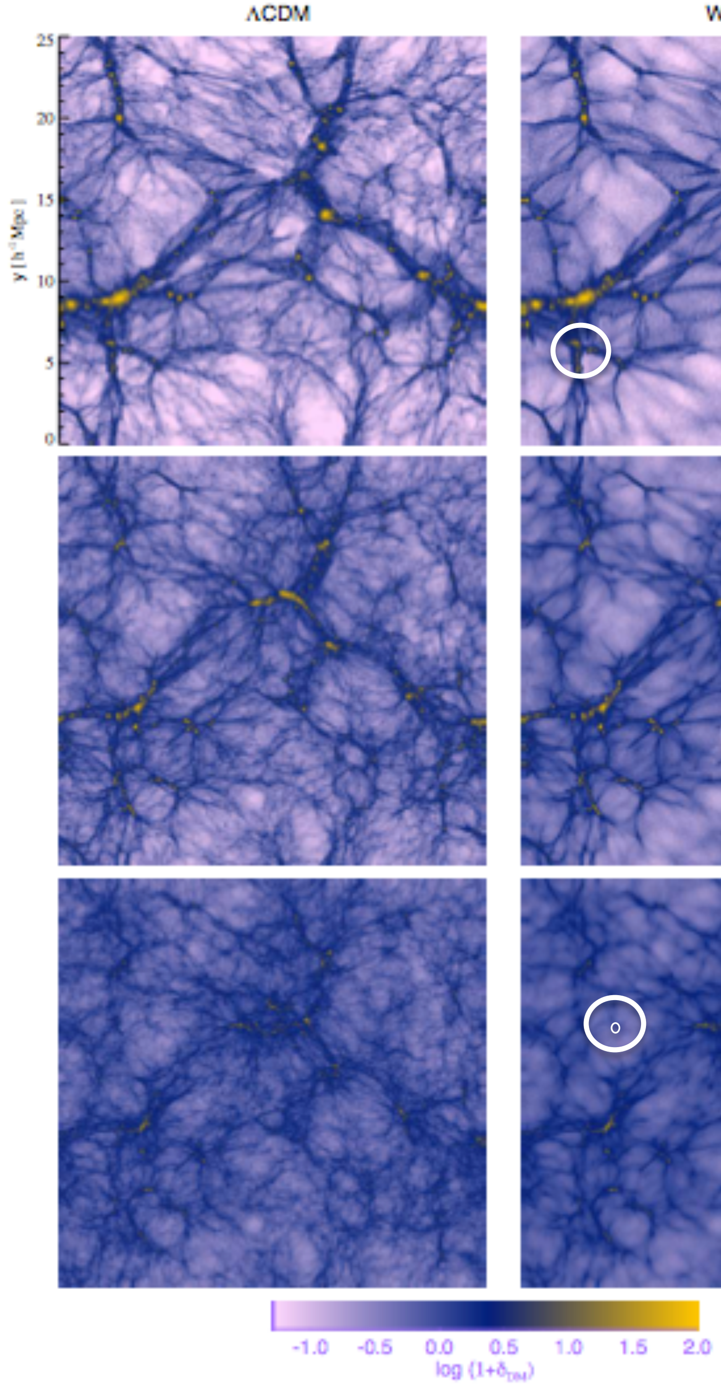
Rossi et al. arXiv 1412.6763

N_{eff}=2.88 ± 0.20

THE COLDNESS OF COLD DARK MATTER

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

THE COSMIC WEB in WDM/LCDM scenarios



z=0

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

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

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

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

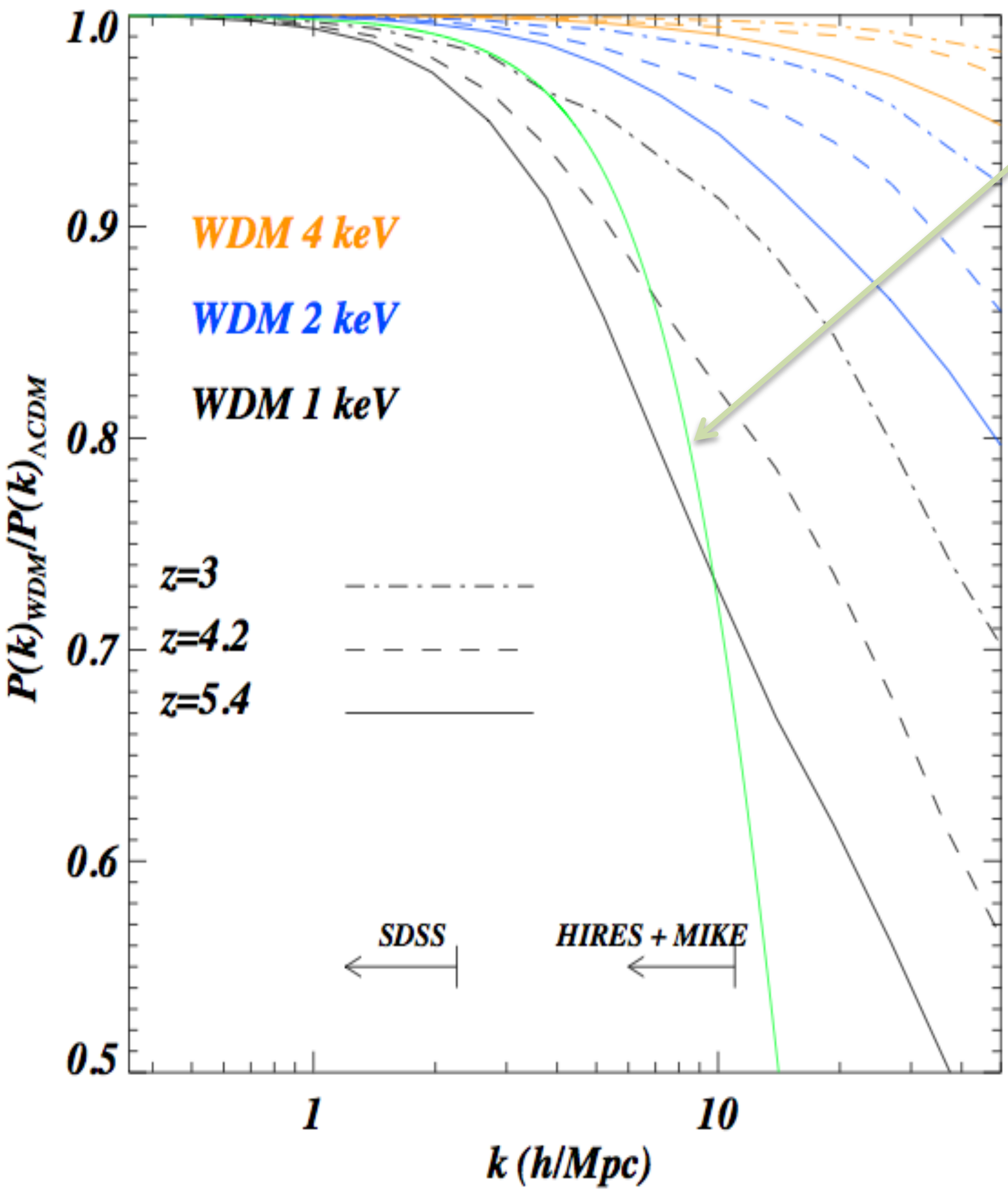
z=2

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

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

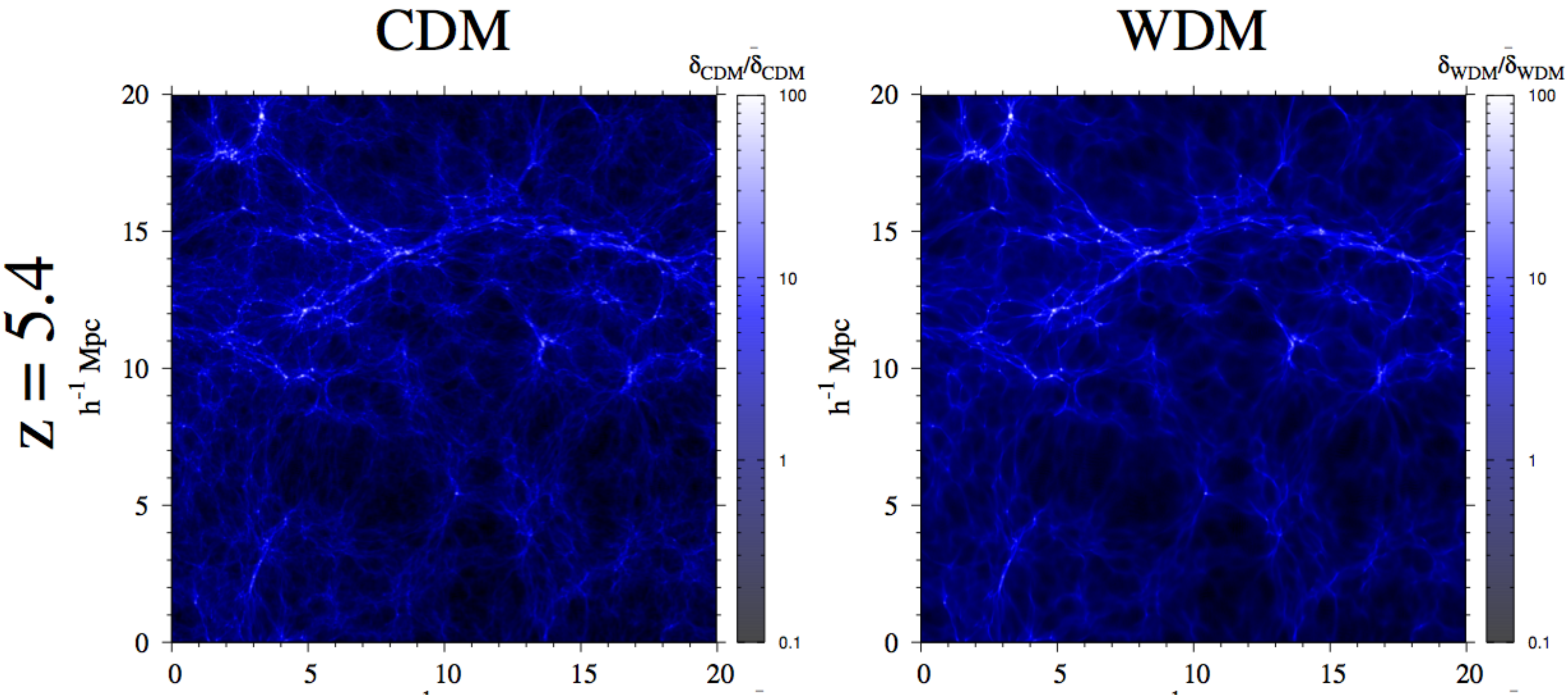
- Strong and weak lensing	Markovic et al. 13/Faadely & Keeton 12
- Galaxy formation	Menci et al 13, Kang et al. 13
- Reionization/First Stars	Gao & Theuns 07
- Dark Matter Haloes (mass functions)	Pacucci et al. 13
- Luminous matter properties	Polisensky & Ricotti 11, Lovell et al. 09
- Gamma-Ray Bursts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

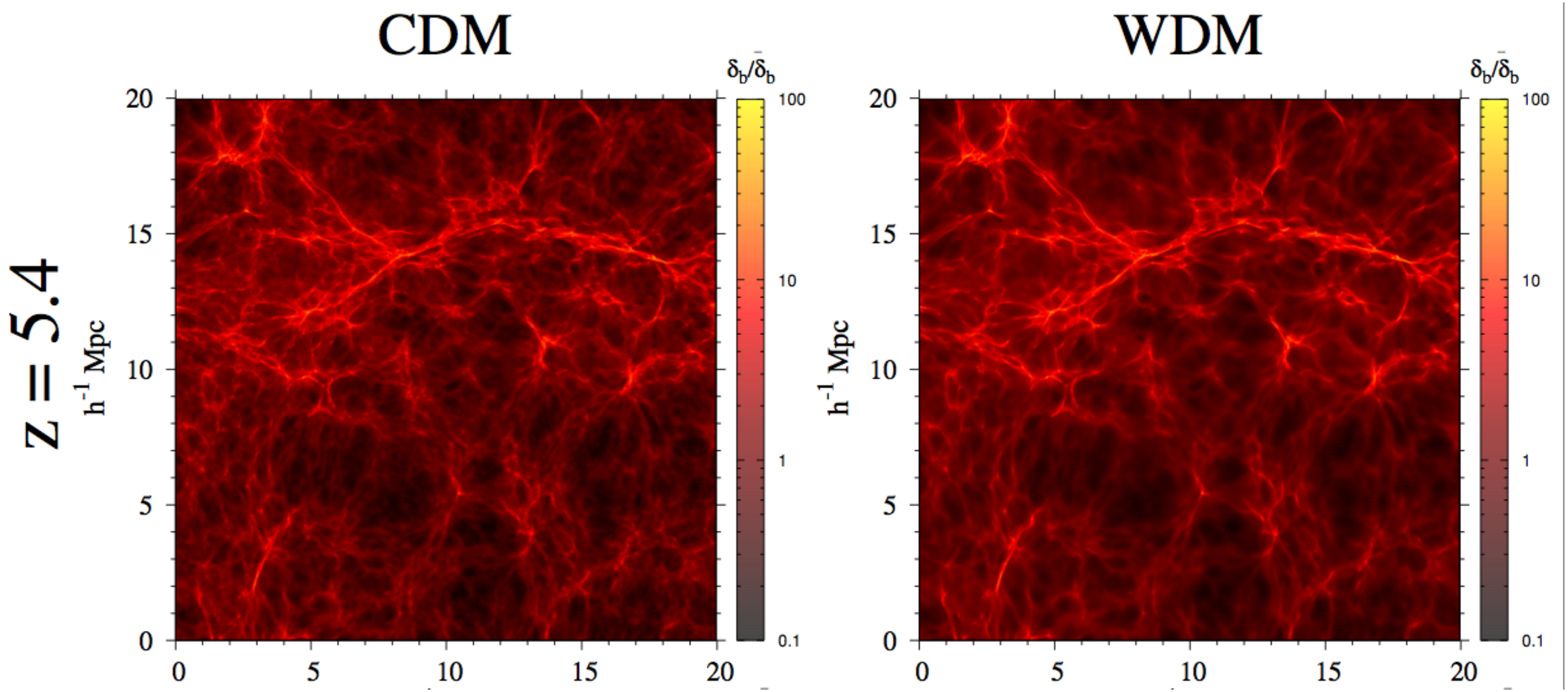
HISTORY OF WDM LYMAN-α BOUNDS

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

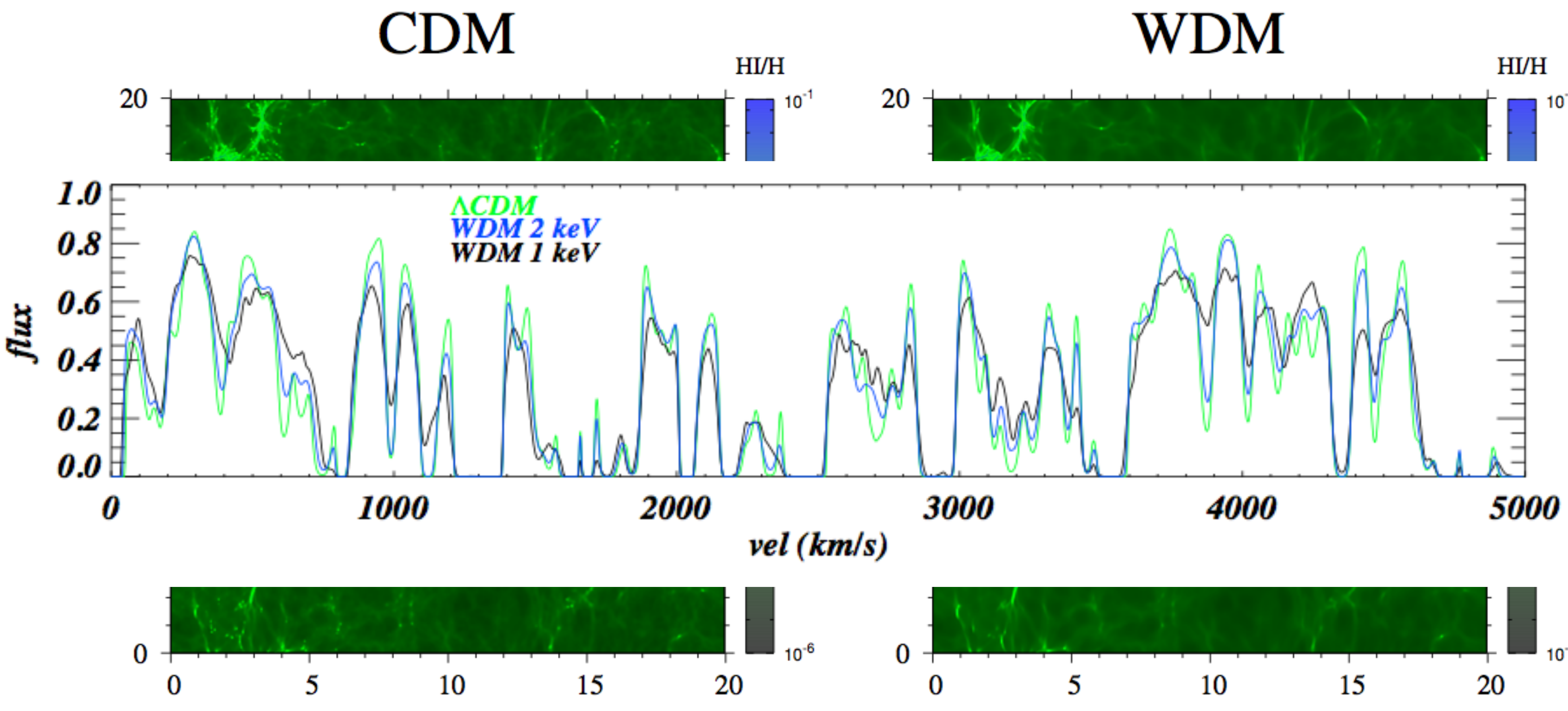
DARK MATTER DISTRIBUTION



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

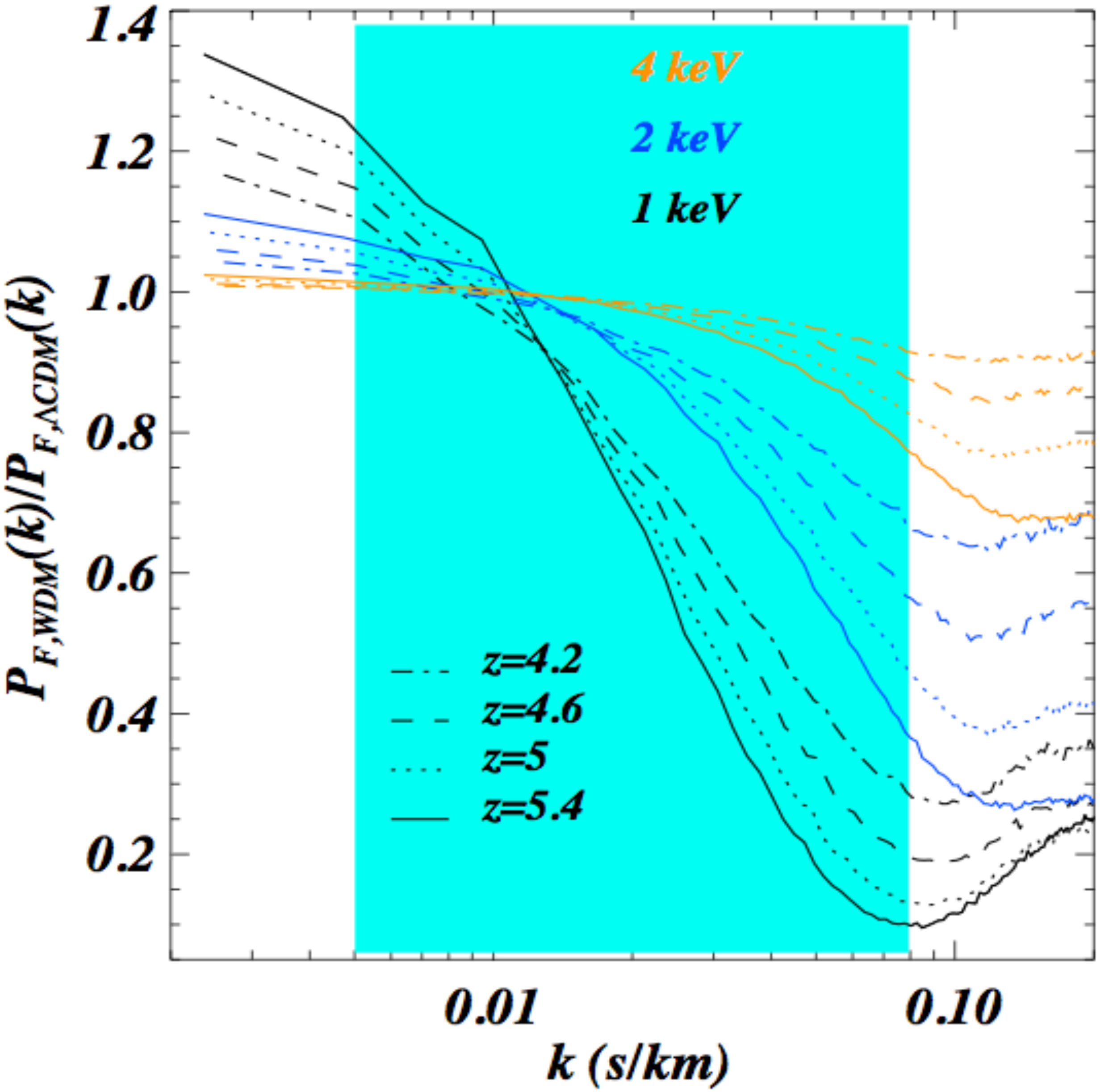
METHOD: Monte Carlo Markov Chains likelihood estimator + **very conservative assumptions** for the continuum fitting and error bars on the data

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

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



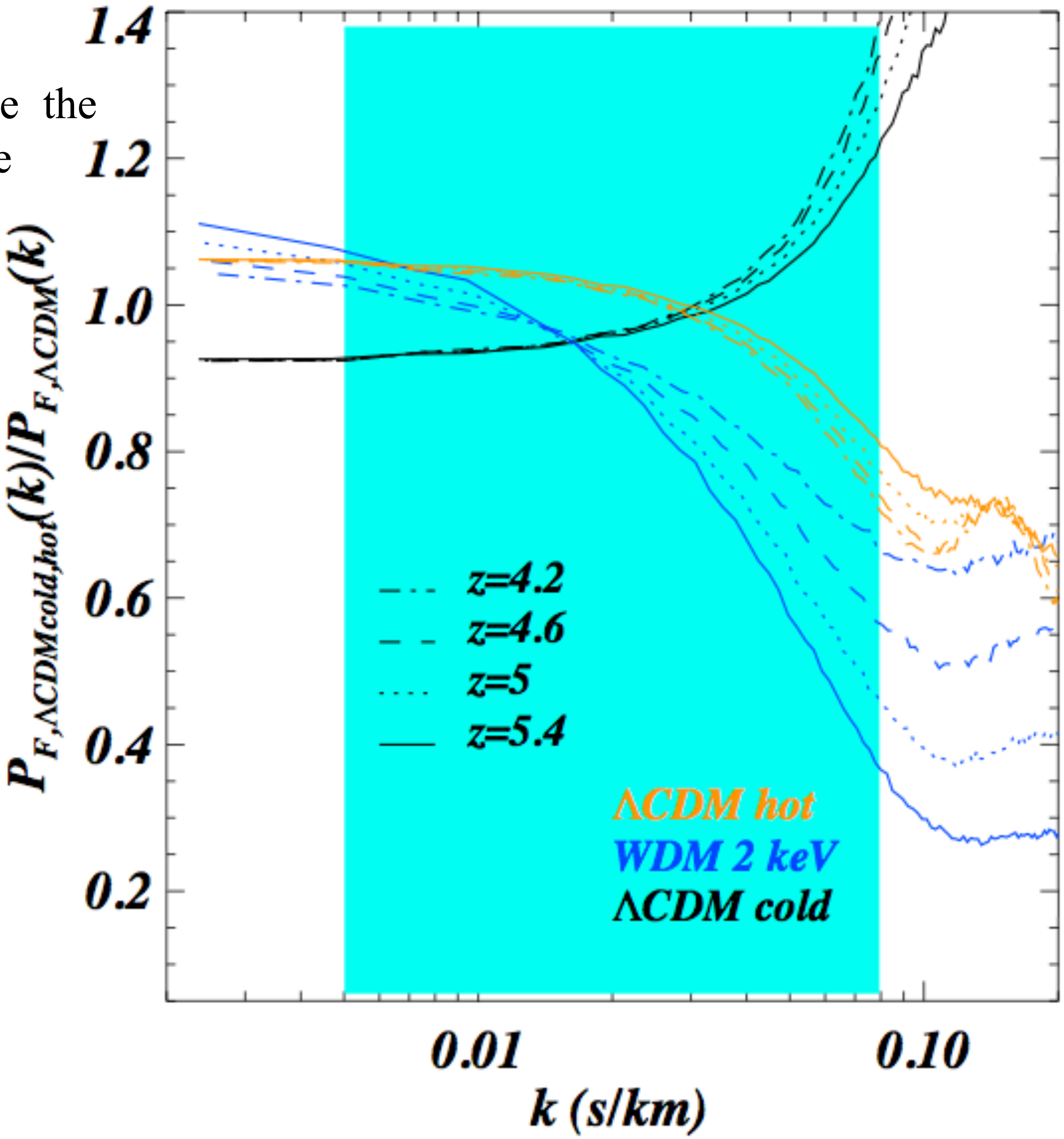
THE TEMPERATURE: T_0

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

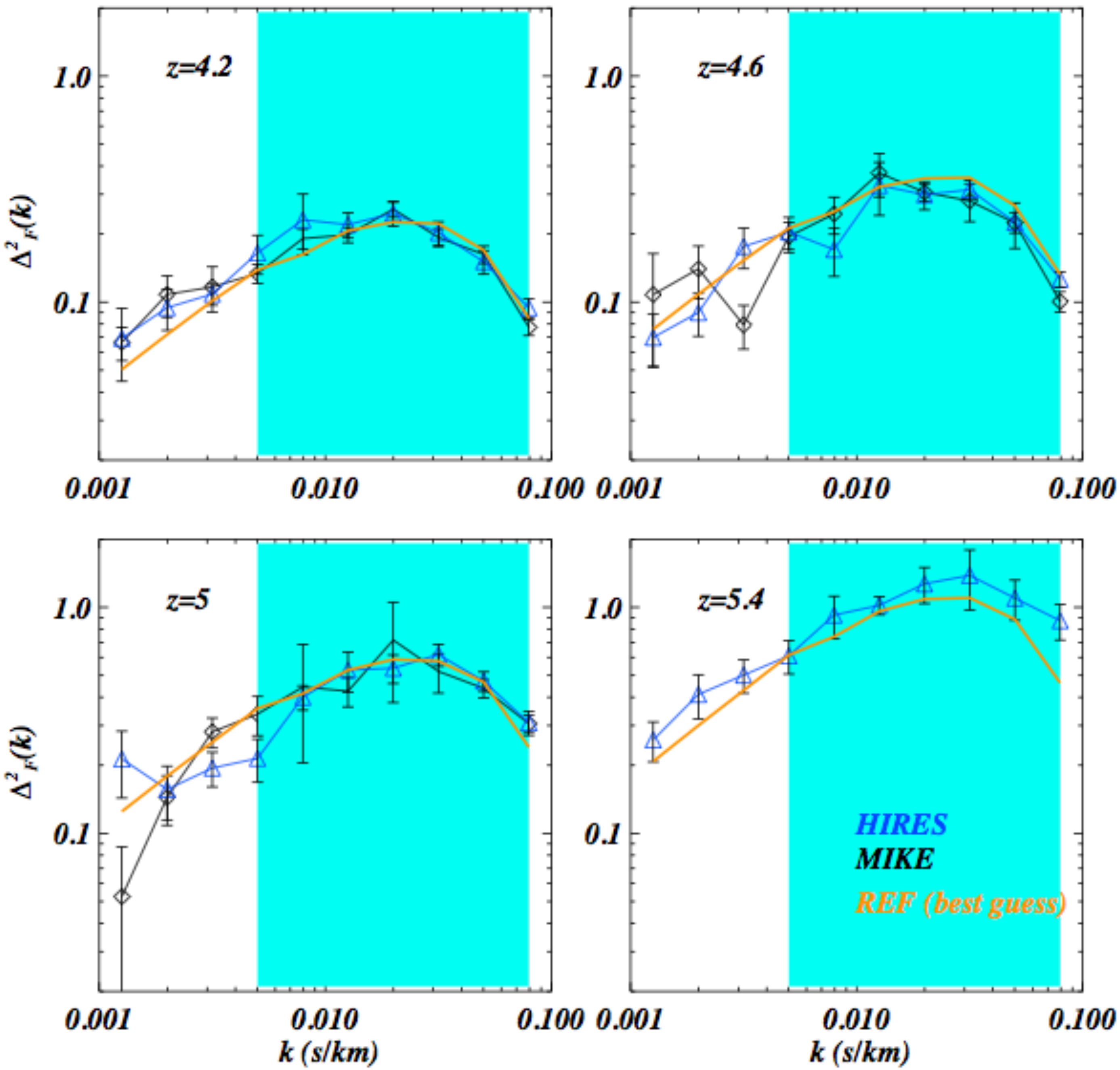
T_0 and γ describe the IGM thermal state

Hot + 3000 K
Cold – 3000 K

REF has 8300 K
at z=4.6

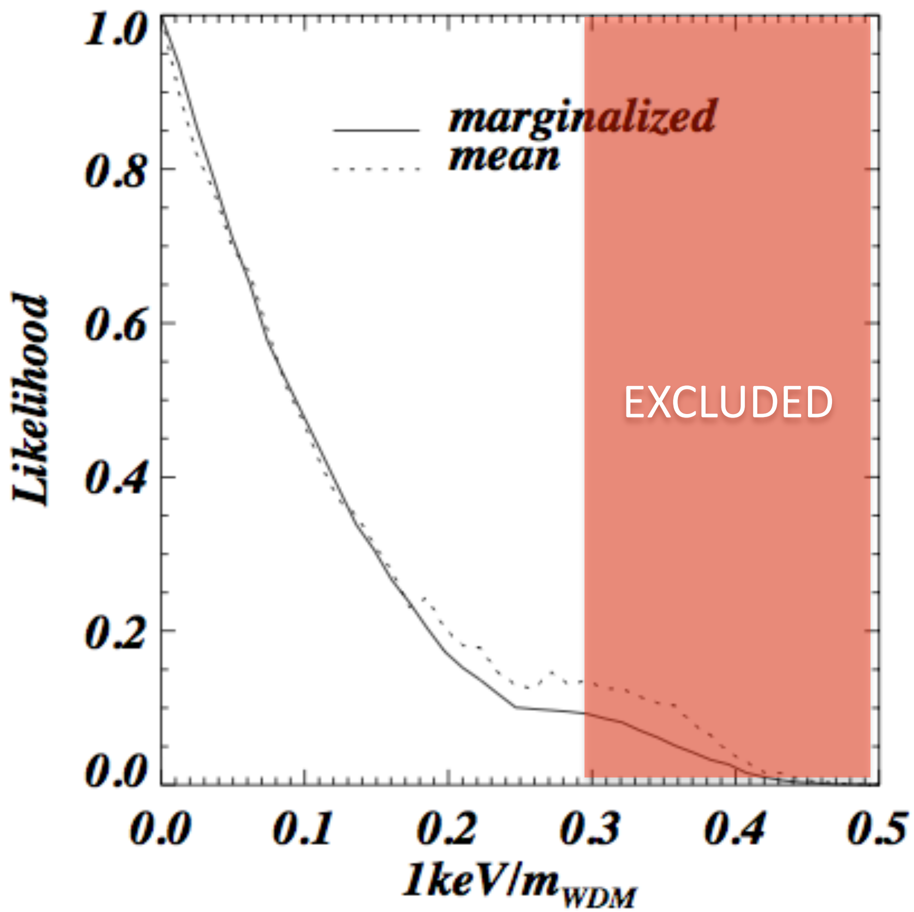


THE BEST GUESS MODEL



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

RESULTS FOR WDM MASS

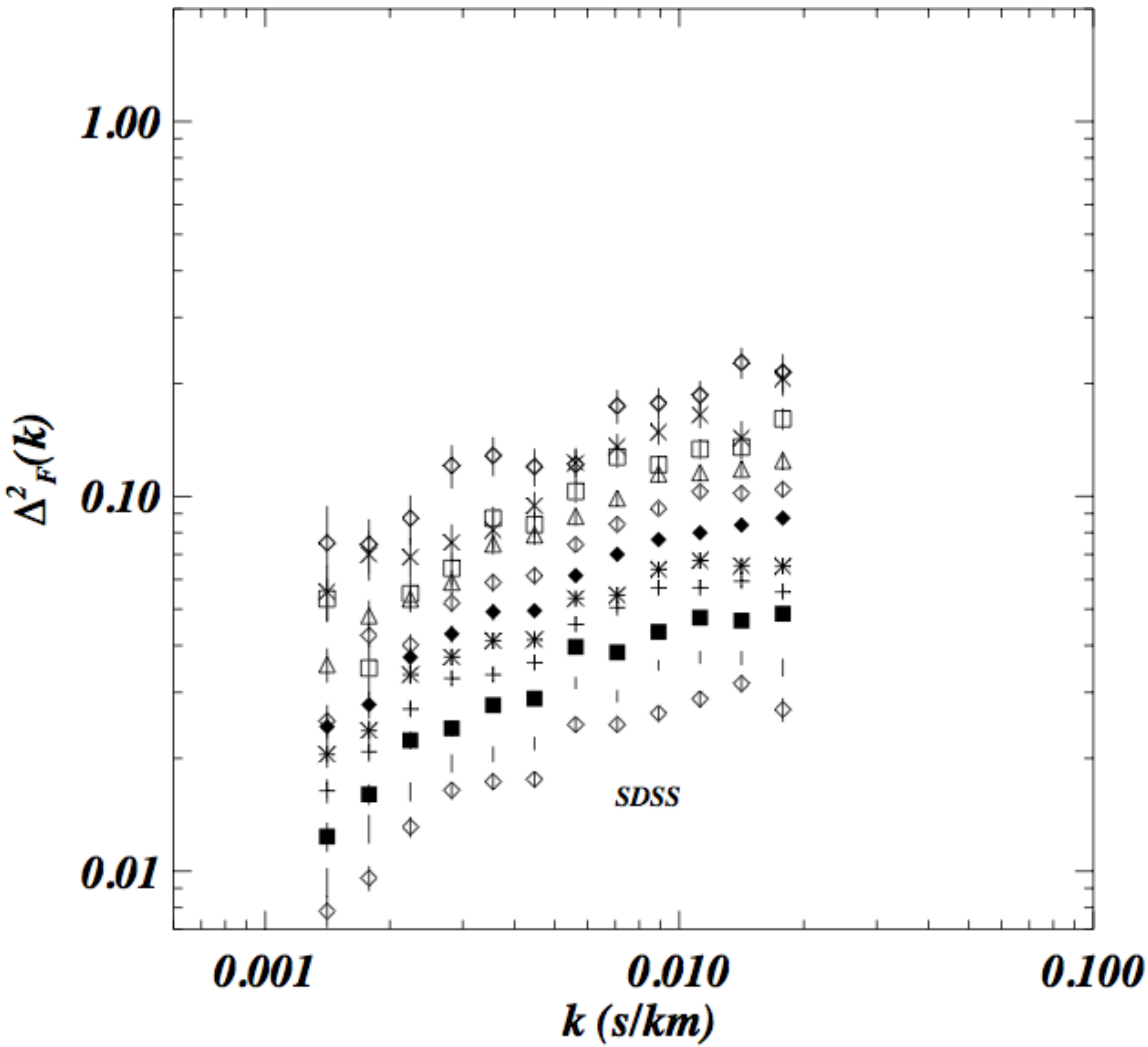


m > 3.3 keV (2σ)

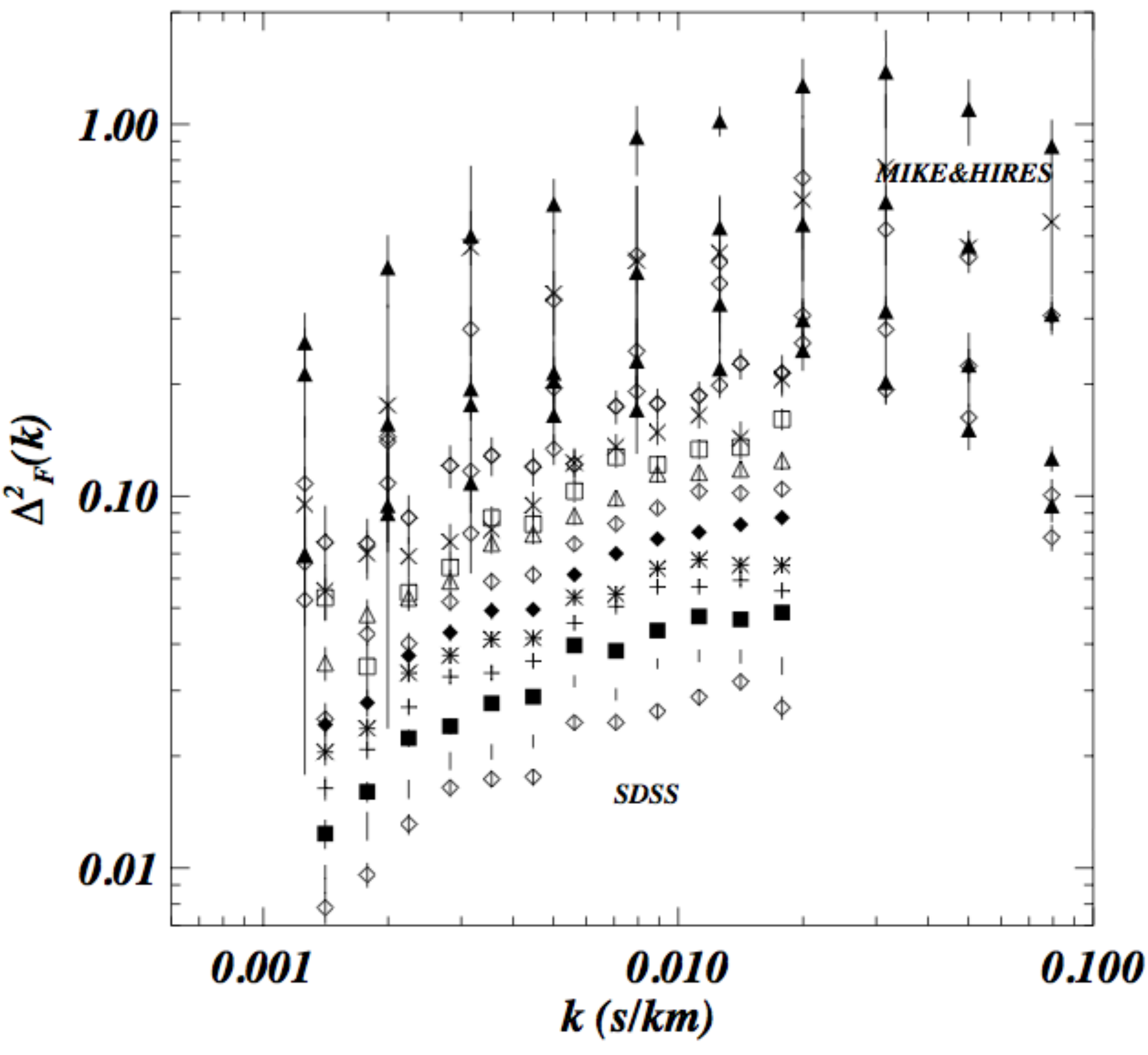
SDSS + MIKE + HIRES CONSTRAINTS

Joint likelihood analysis

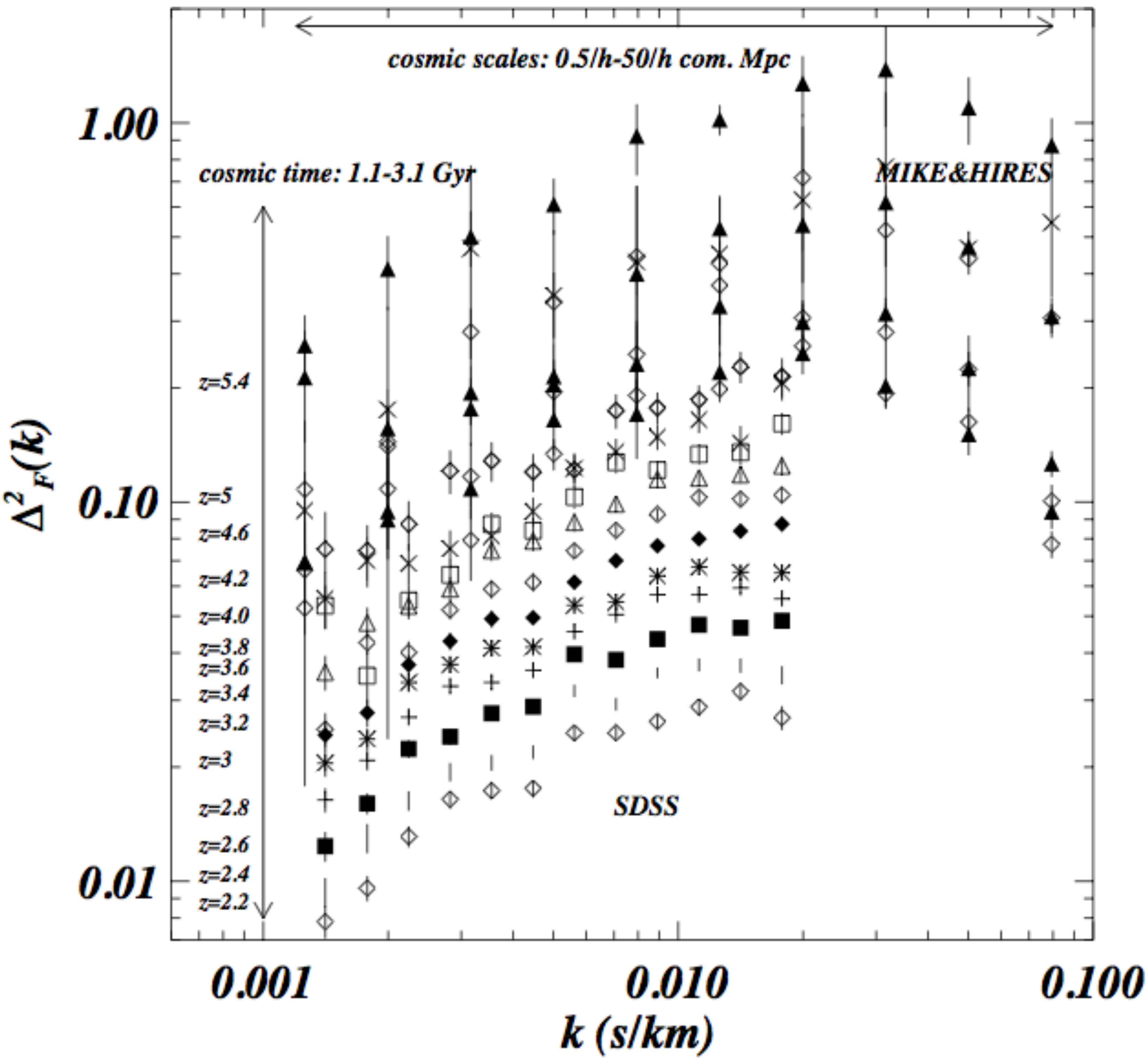
SDSS data from McDonald05,06 not BOSS



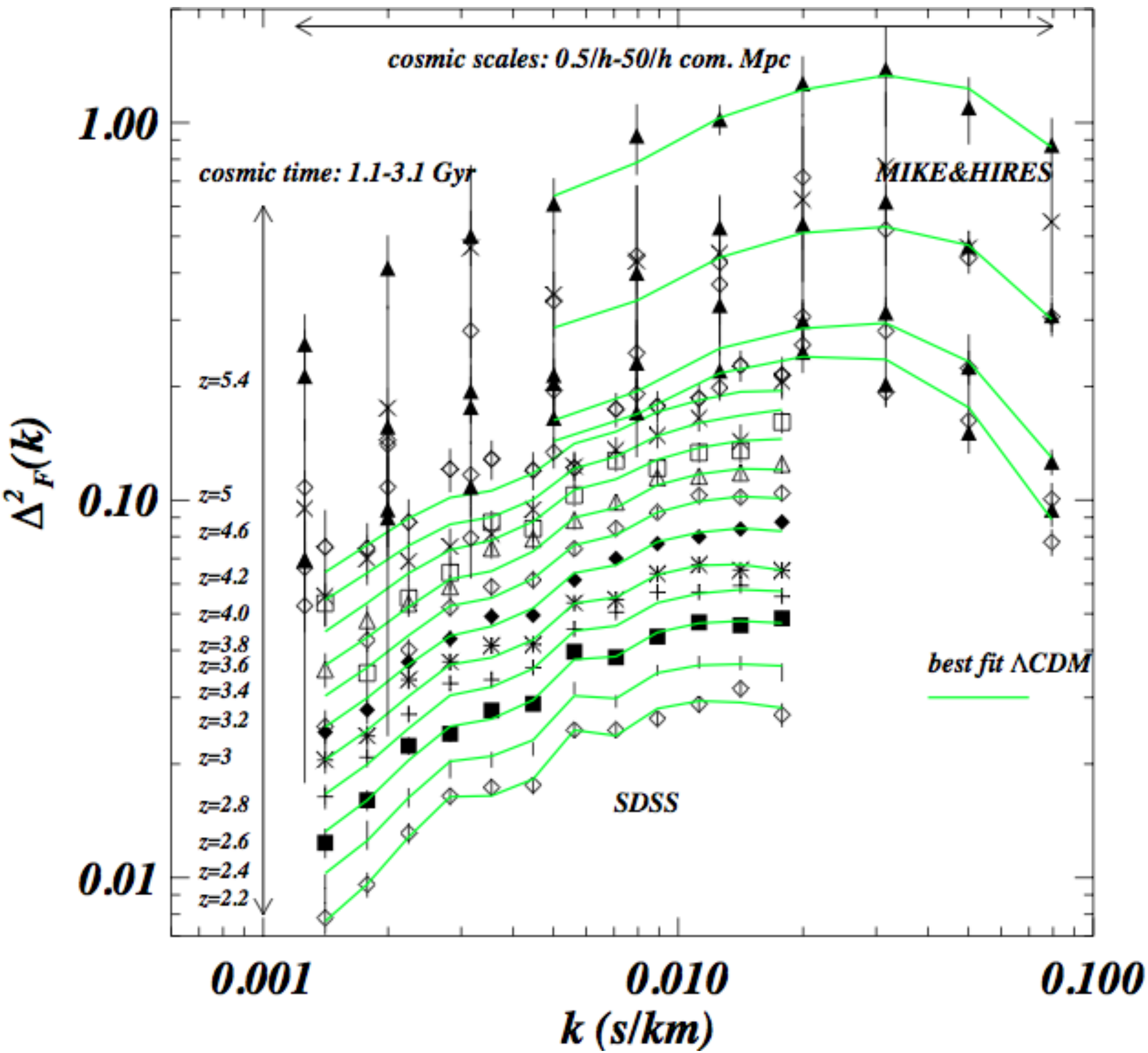
1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)



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

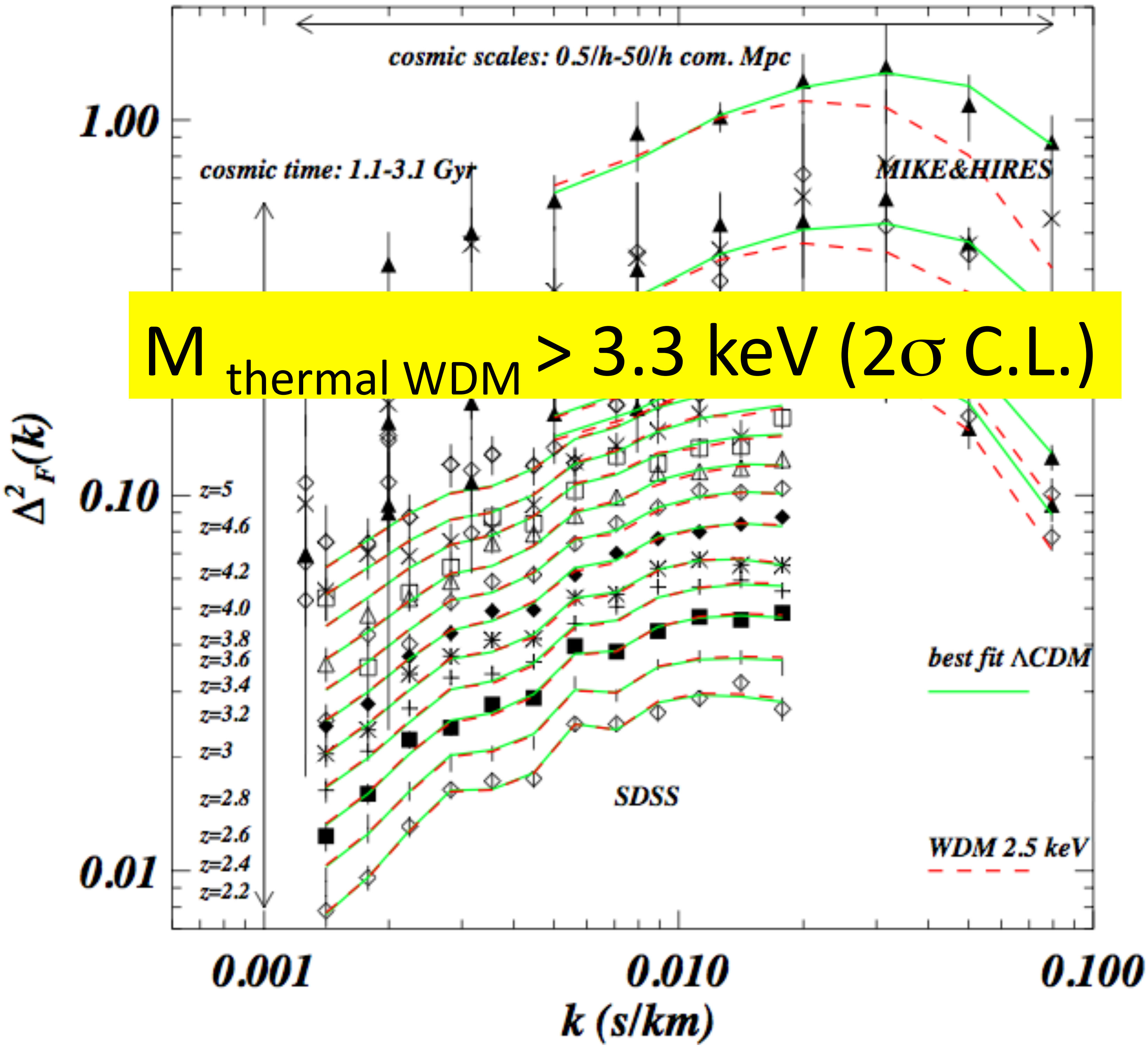


cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
1.00
0.10
0.01
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)



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 using old SDSS) on total neutrino mass. This was improved recently by using new SDSS/BOSS data with new methods 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

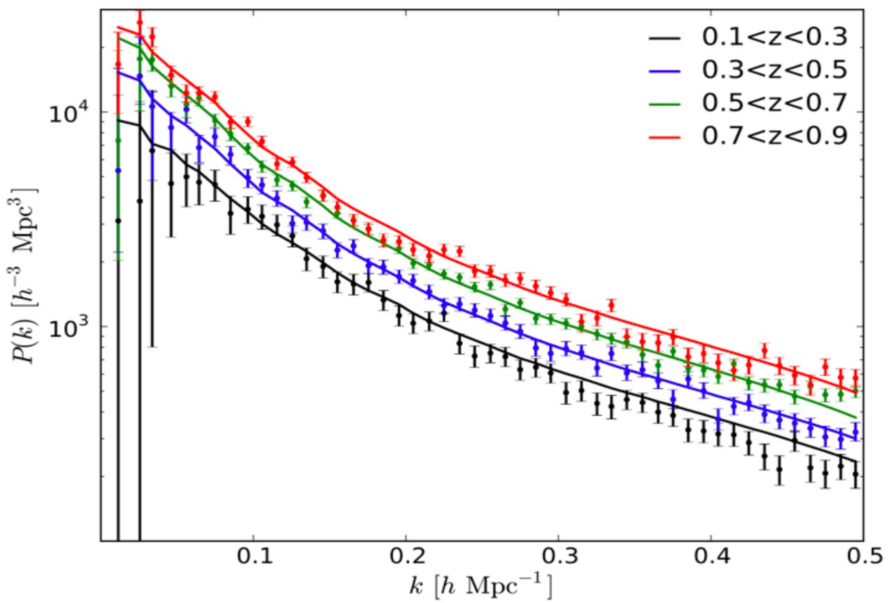
Models with 1 keV are ruled out at 9σ
2 keV are ruled out at 4σ
2.5 keV are ruled out at 3σ
3.3 keV are ruled out at 2σ

↓

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

TIGHTEST LIMITS PUBLISHED SO FAR



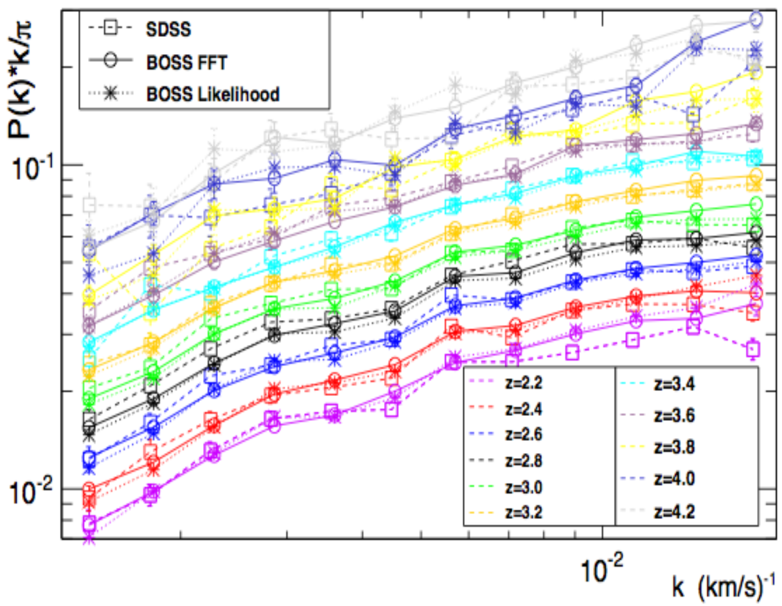
WiggleZ survey + Planck + HST + BAO

$\Sigma m_\nu < 0.18$ eV (2σ C.L.)

Riemer-Sorensen et al. 13

Beutler et al. 14

$\sum m_\nu = 0.34 \pm 0.14$ eV,



Intergalactic Medium data + CMB

$\Sigma m_\nu < 0.17$ eV (2σ C.L.)

Seljak et al. 06

Viel, Haehnelt & Springel 2010

IGM alone $\Sigma m_\nu < 0.9$ eV (2σ C.L.)

RESULTS FOR TEMPERATURE

$$\gamma^A(z) = \gamma^A[(1+z)/5.5)]^{\gamma^S_A} \qquad T^A_0(z) = T^A_0[(1+z)/5.5)]^{T^S_0}$$