Perspective of discoveries from Intergalactic Space

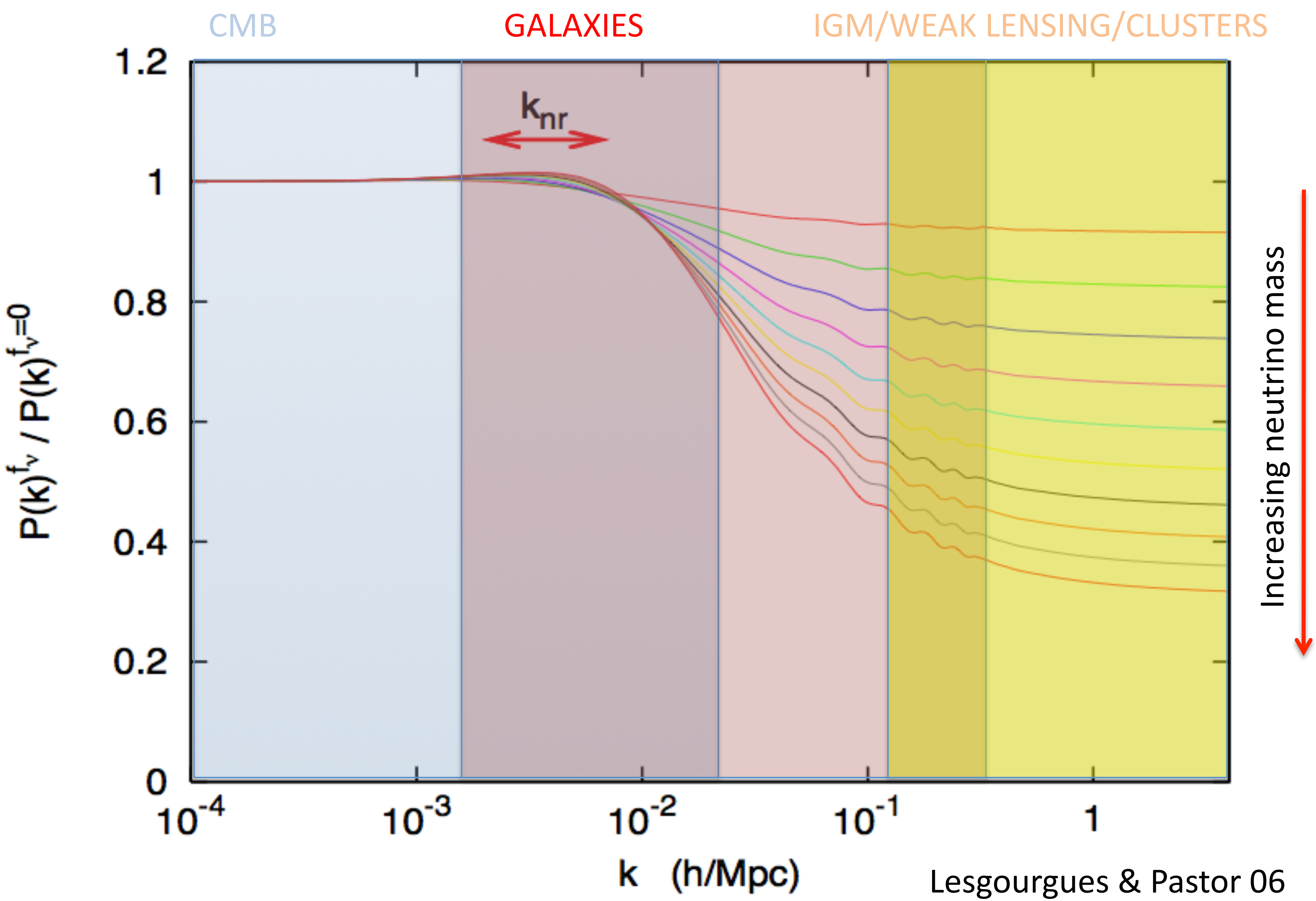
Matteo Viel – INAF/OATS & INFN/TS

Off-the-beaten-track workshop – ICTP Trieste - 14th April 2015

OFF-THE-BEATEN-TRACK
TOPIC #1:

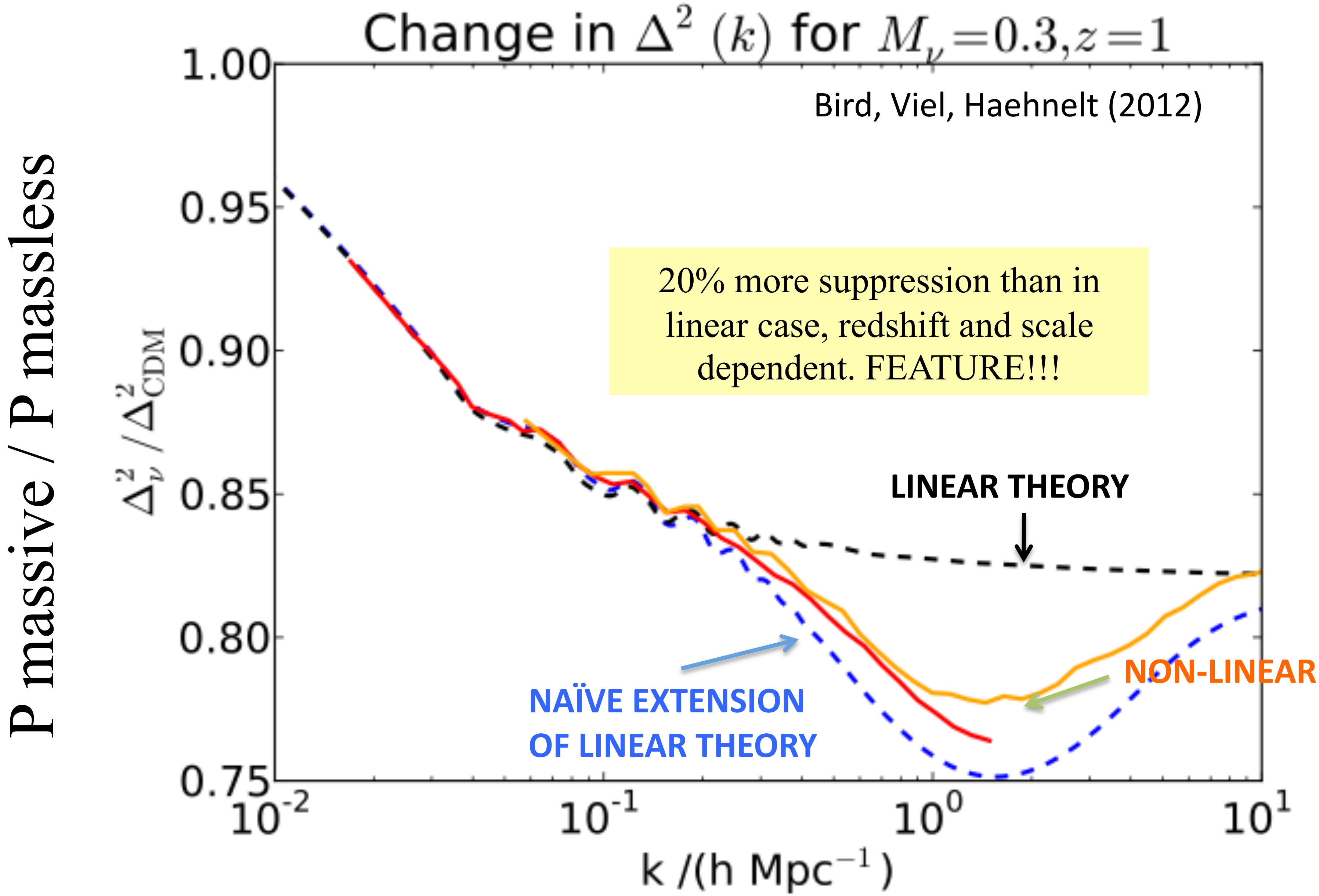
MASSIVE NEUTRINOS

COSMOLOGICAL NEUTRINOS - I: LINEAR MATTER POWER



Lesgourgues & Pastor 06

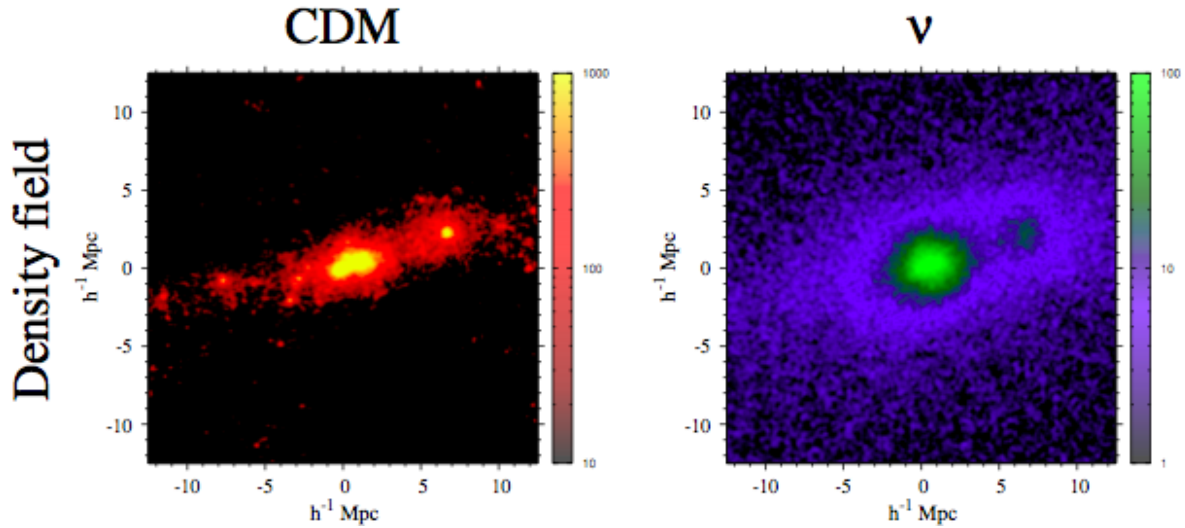
COSMOLOGICAL NEUTRINOS- II: NON-LINEAR MATTER POWER



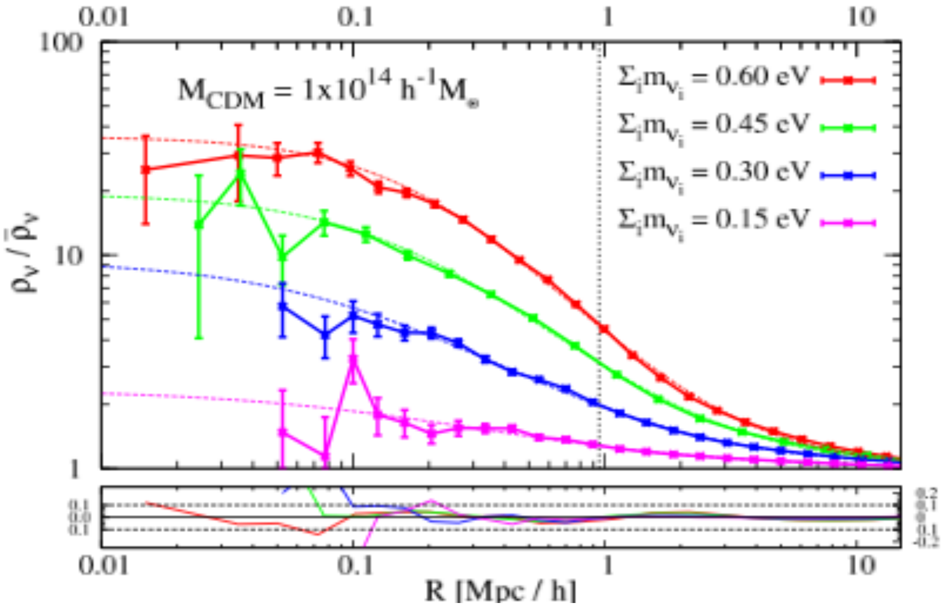
Cosmic Scale

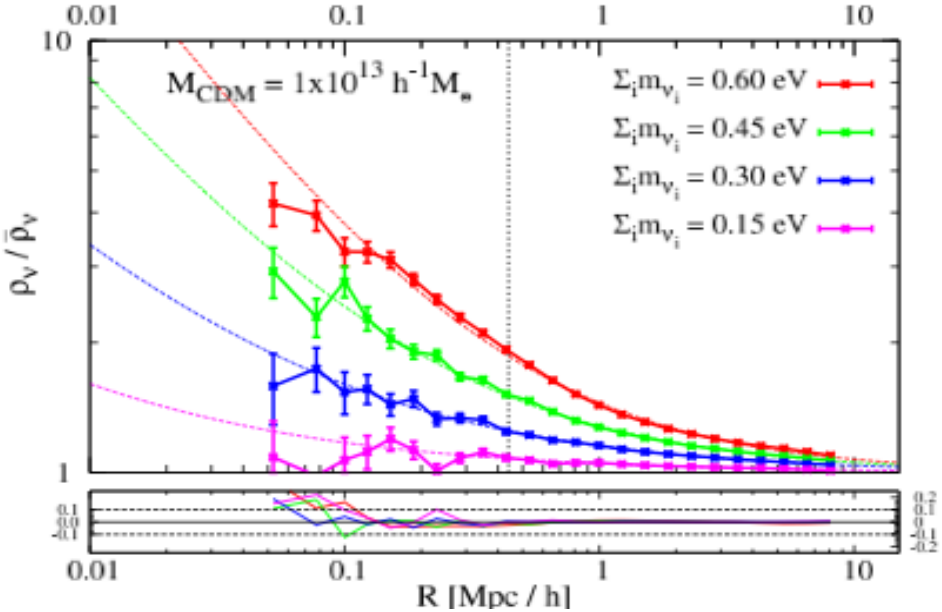
http://www.sns.ias.edu/~spb/index.php?p=code

COSMO NEUTRINOS –III: CHARACTERIZING 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

COSMO NEUTRINOS – IV: MODELLING NEUTRINOS *WITHOUT* N-BODY SIMS.

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

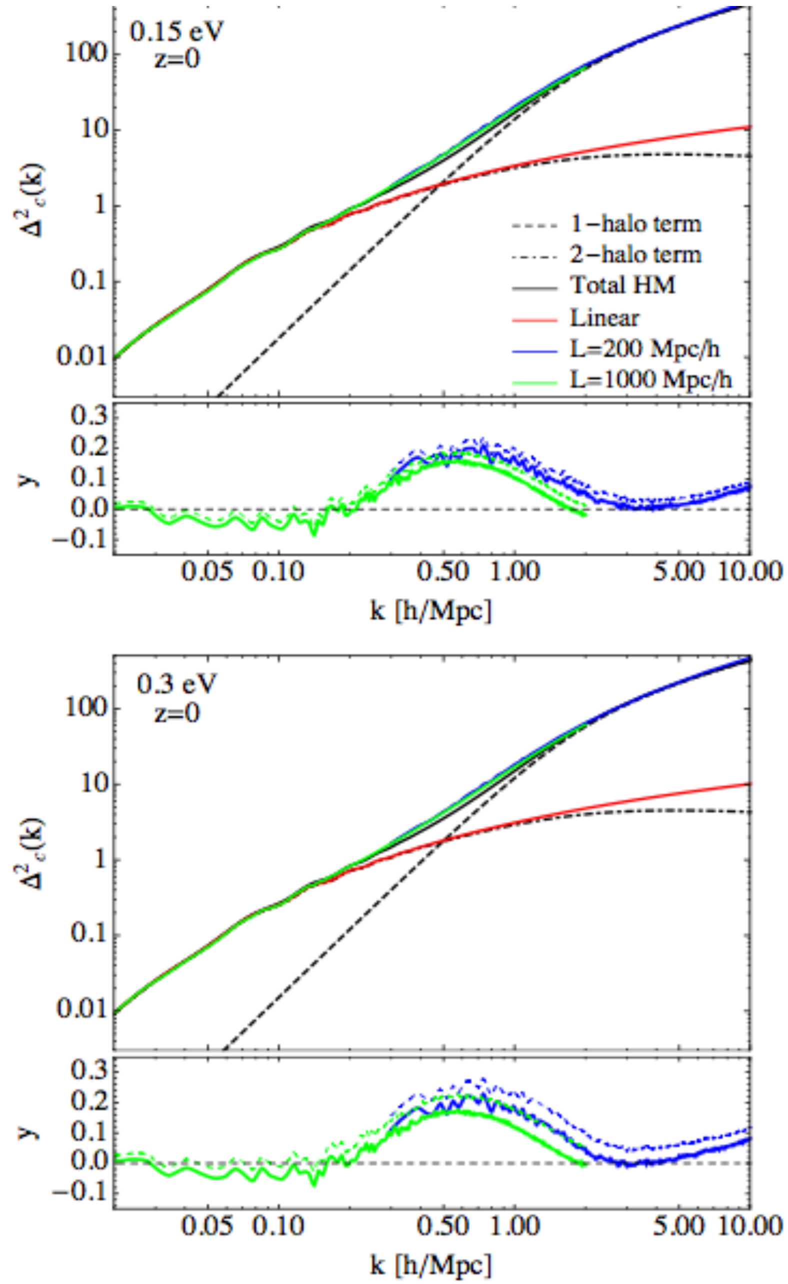
- Assumption: all matter within haloes 1h and 2h terms

- 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) – Castorina+ (2014) for bias and mass functions

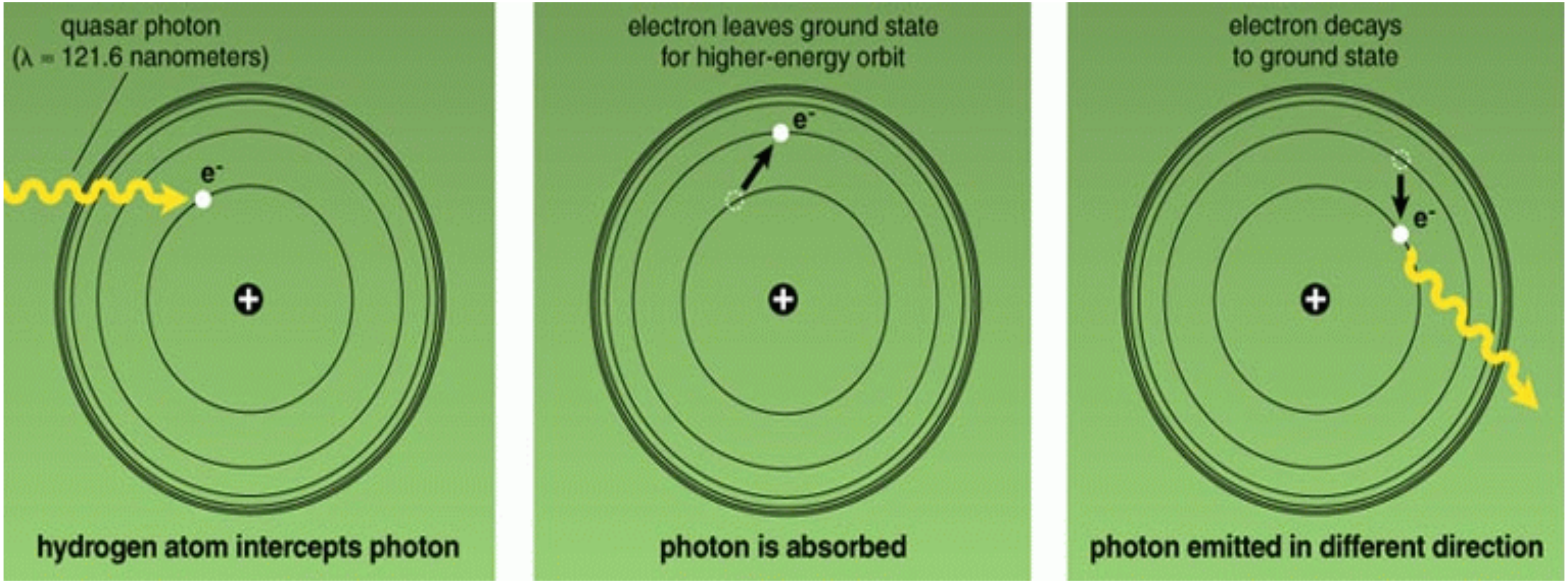
Intergalactic Medium (IGM)

i.e. diffuse matter between galaxies

i.e. an off-the-beaten-track observable

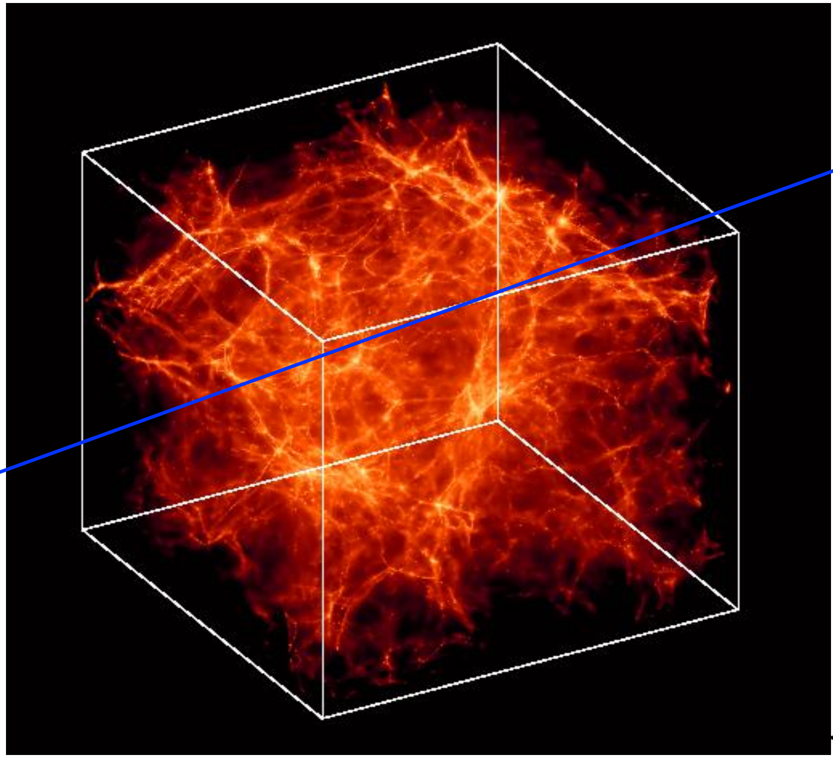
The Lyman-α forest

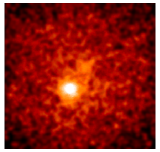
Lyman-α absorption is the main manifestation of the IGM

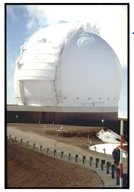


Tiny neutral hydrogen fraction after reionization…. But large cross-section

The Intergalactic Medium: Theory vs. Observations



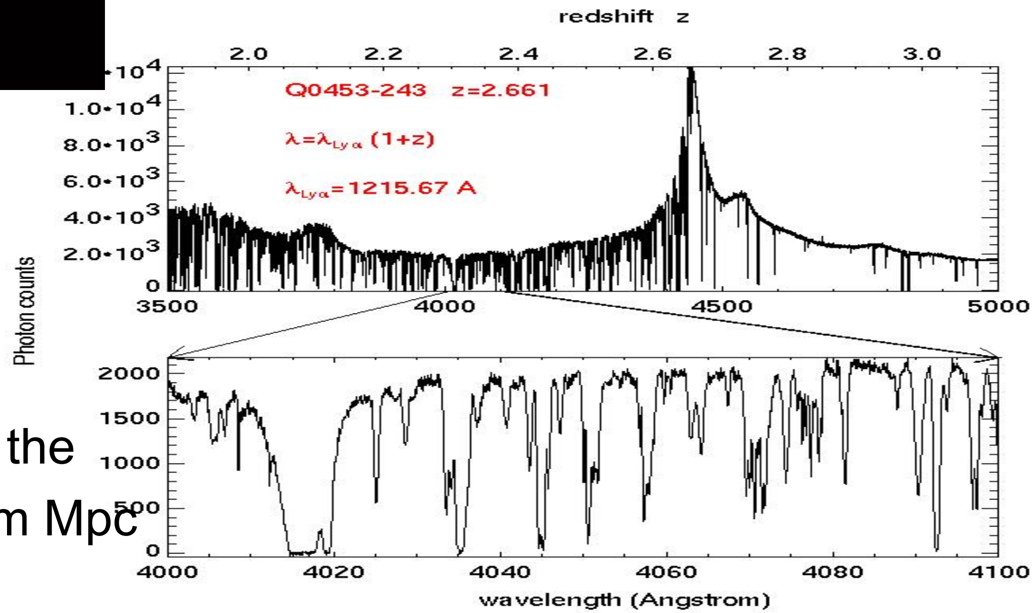




80 % of the baryons at z=3
are in the **Lyman-α forest**

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

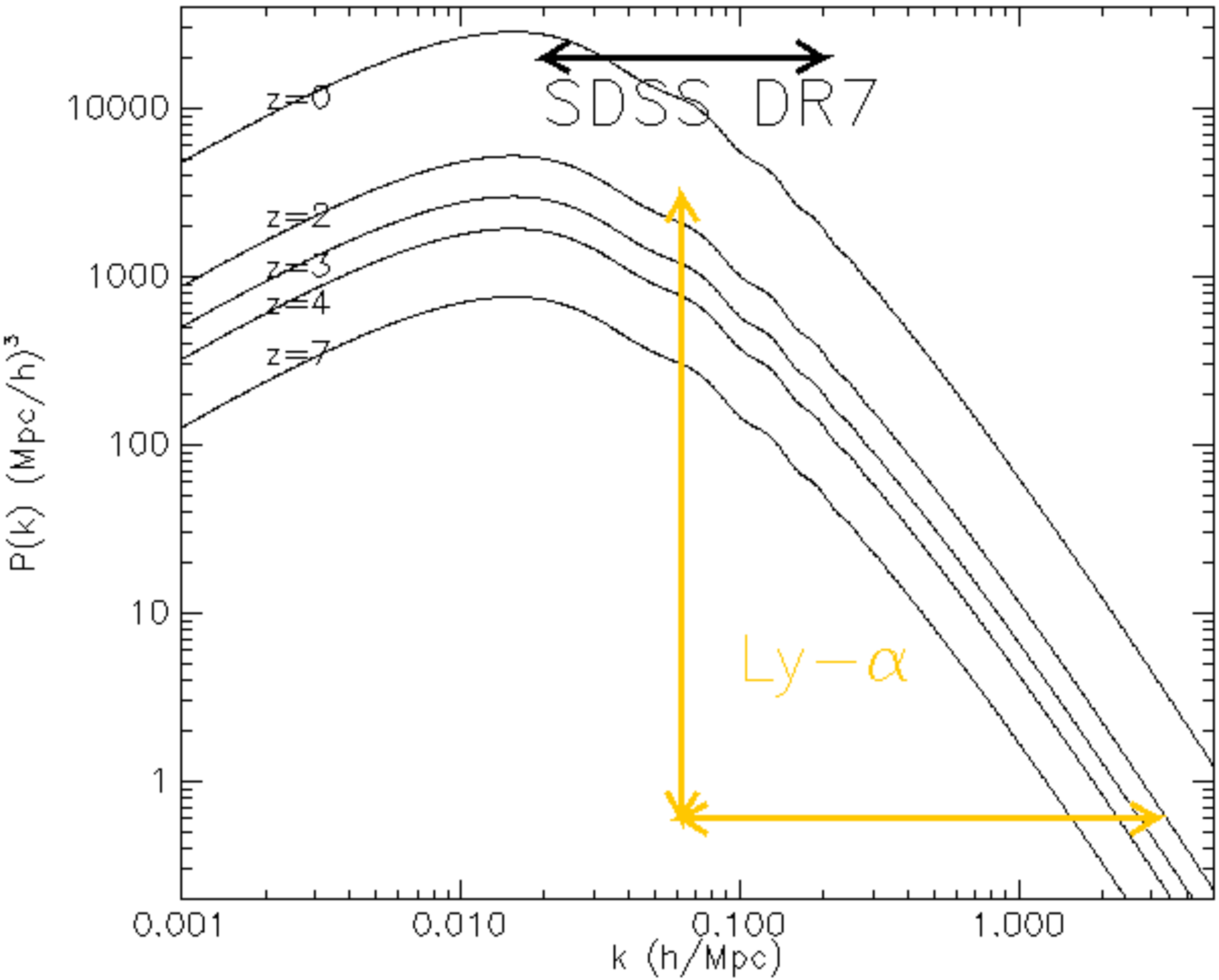
baryons as tracer of the dark matter density field



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

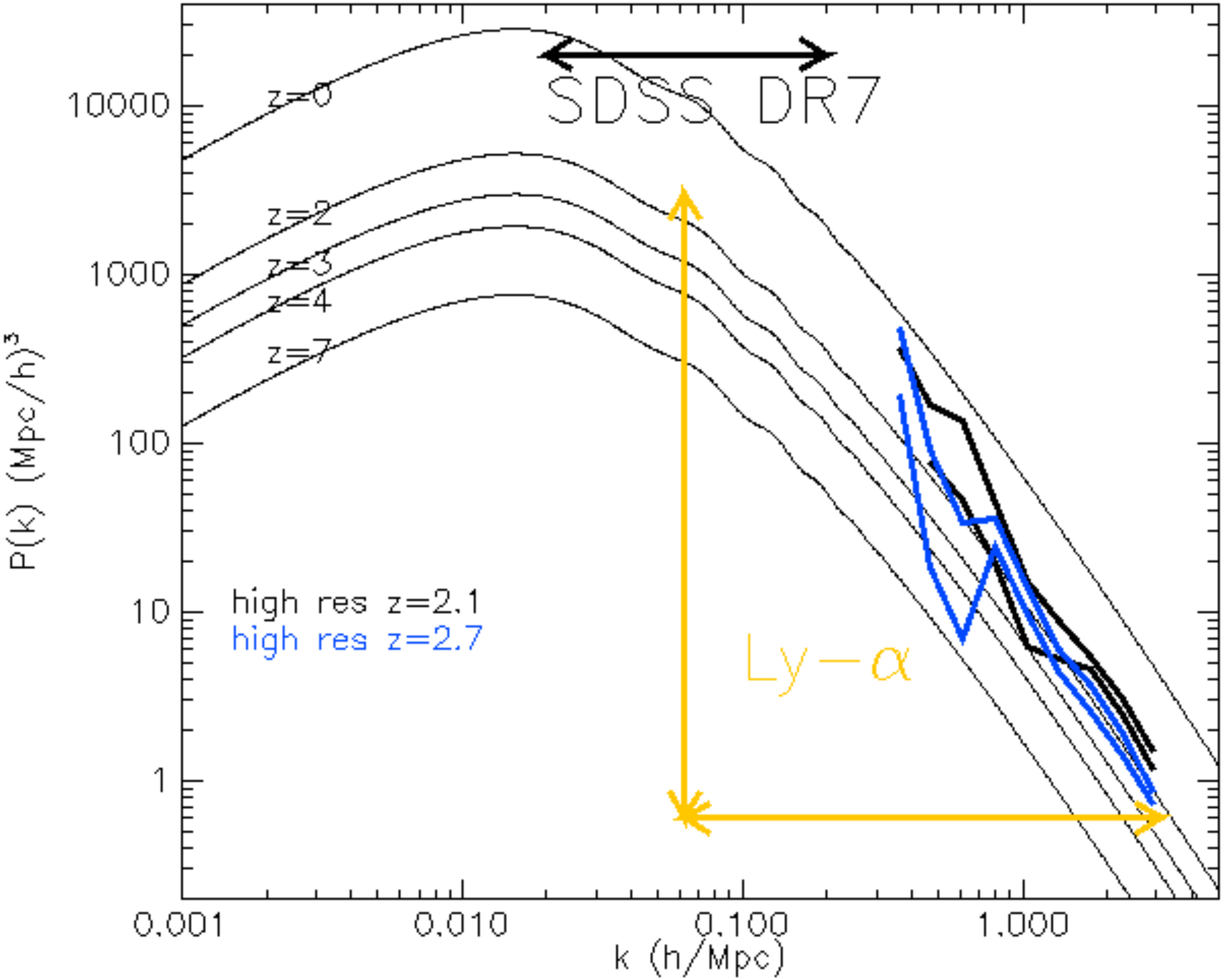
$\tau \sim (\delta_{IGM})^{1.6}\, T^{-0.7}$

DATA vs THEORY

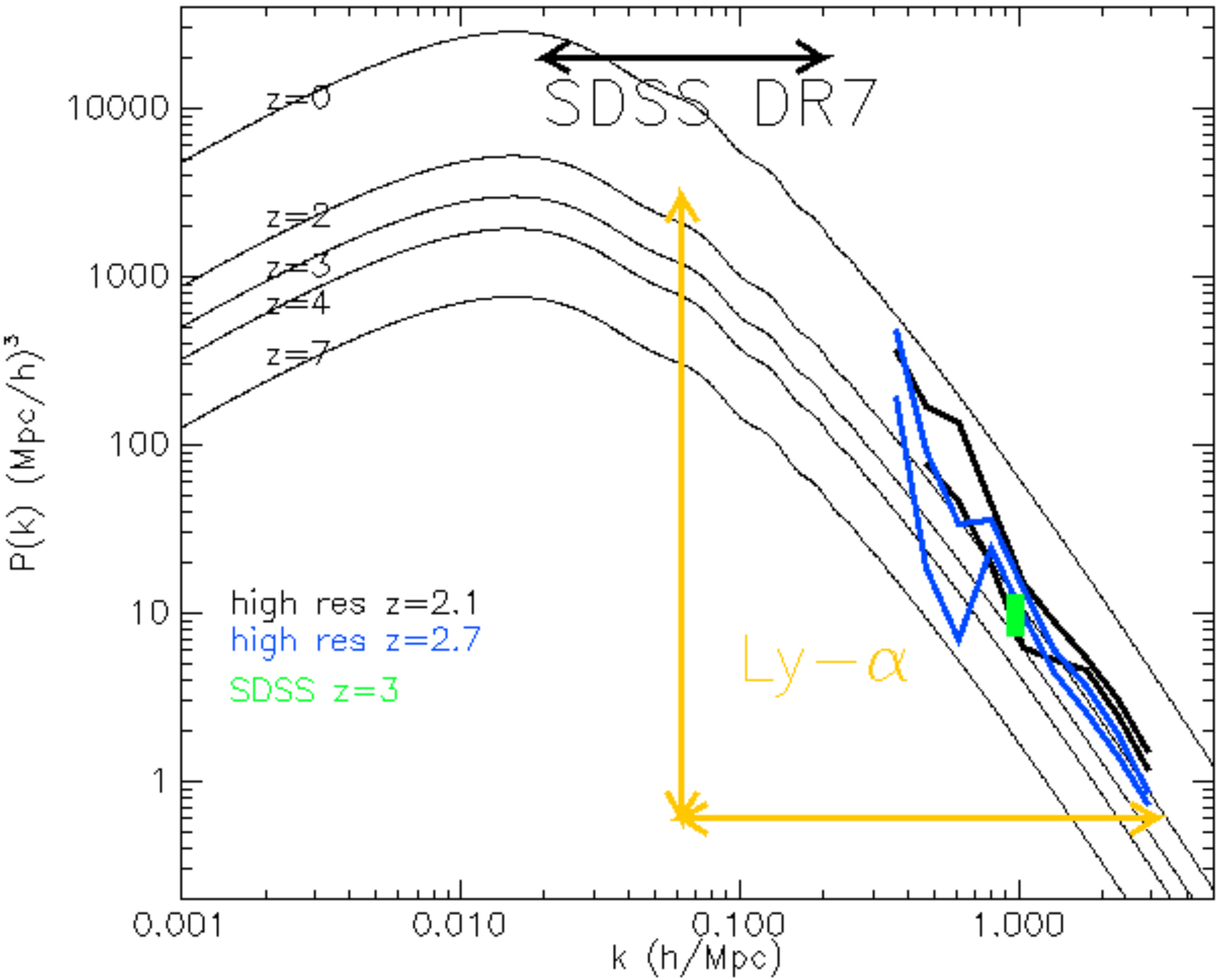


DATA vs THEORY

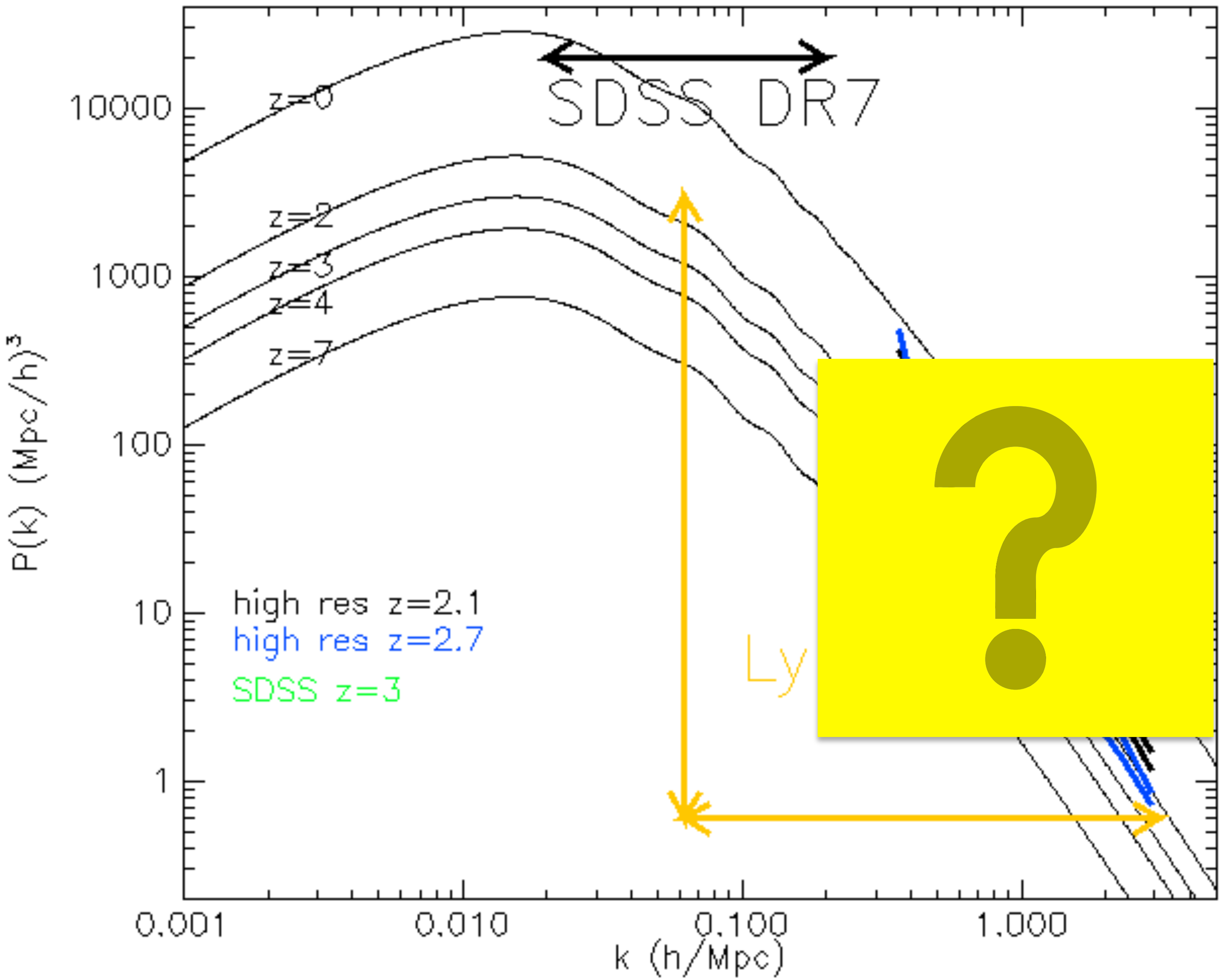
$$P_{FLUX}(k,z) = bias^2(k,z) \times P_{MATTER}(k,z)$$



DATA vs THEORY

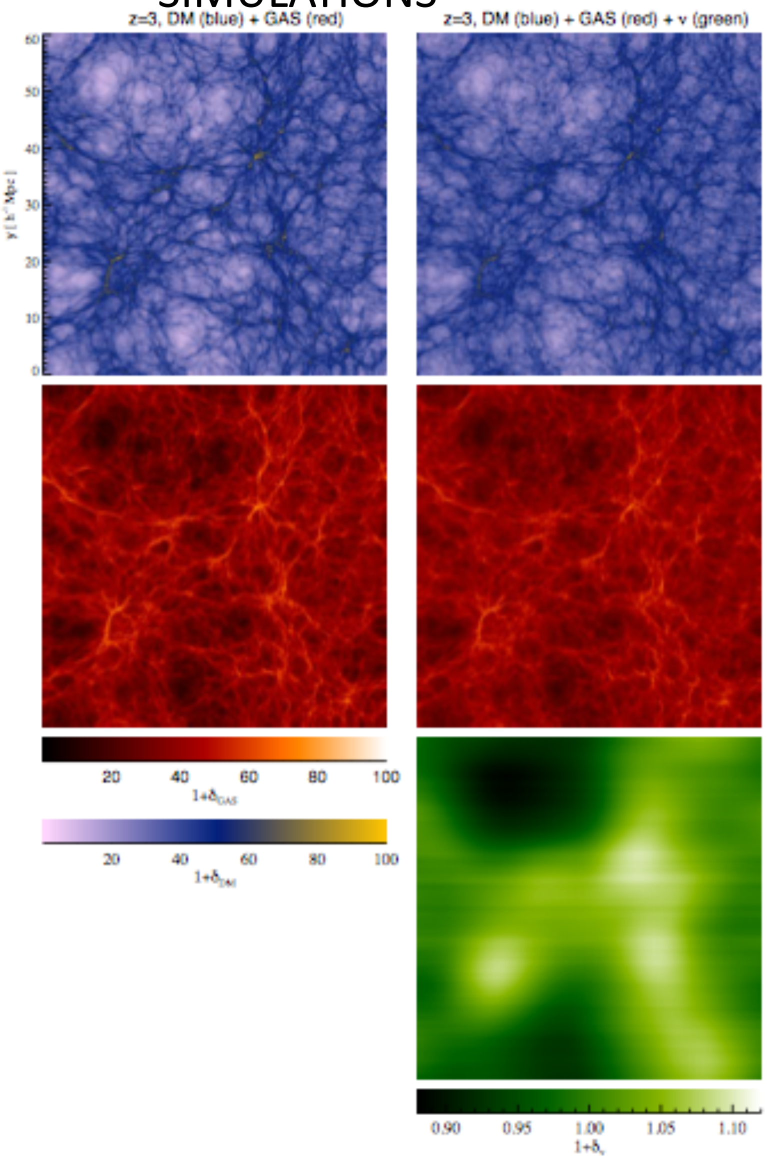


DATA vs THEORY

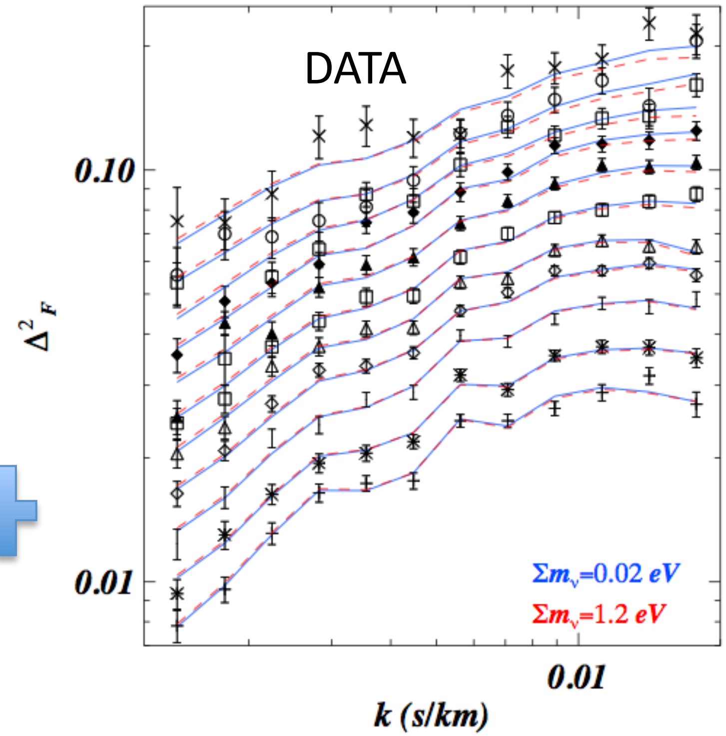


NEUTRINOS IN THE IGM

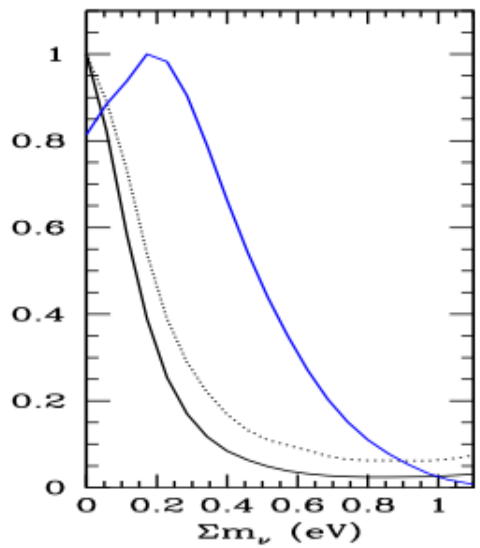
SIMULATIONS



DATA



CONSTRAINTS

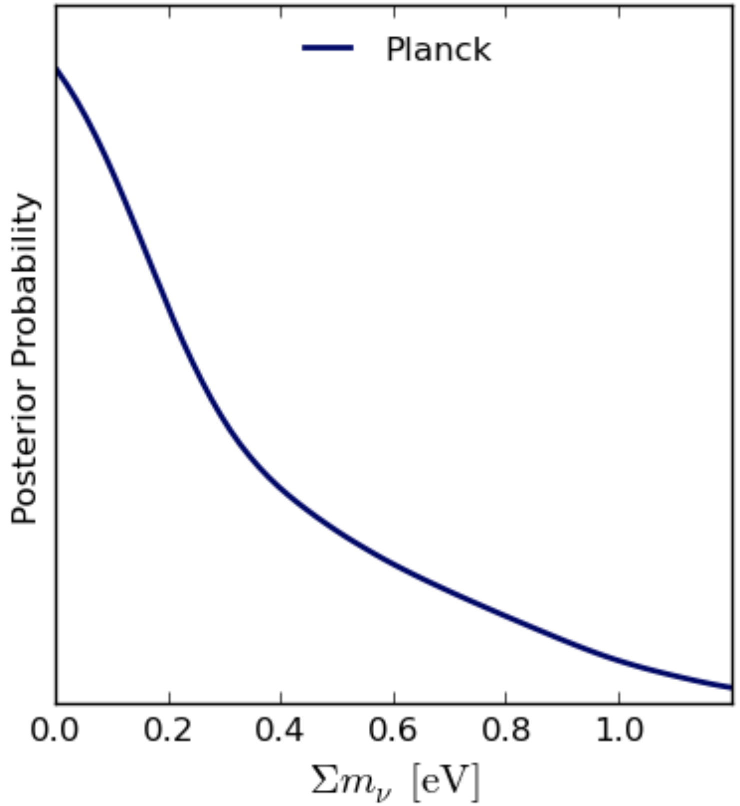


FROM IGM ONLY:

$\Sigma m_{\nu} < 0.9$ eV(2σ)

Viel, Haehnelt, Springel 2010

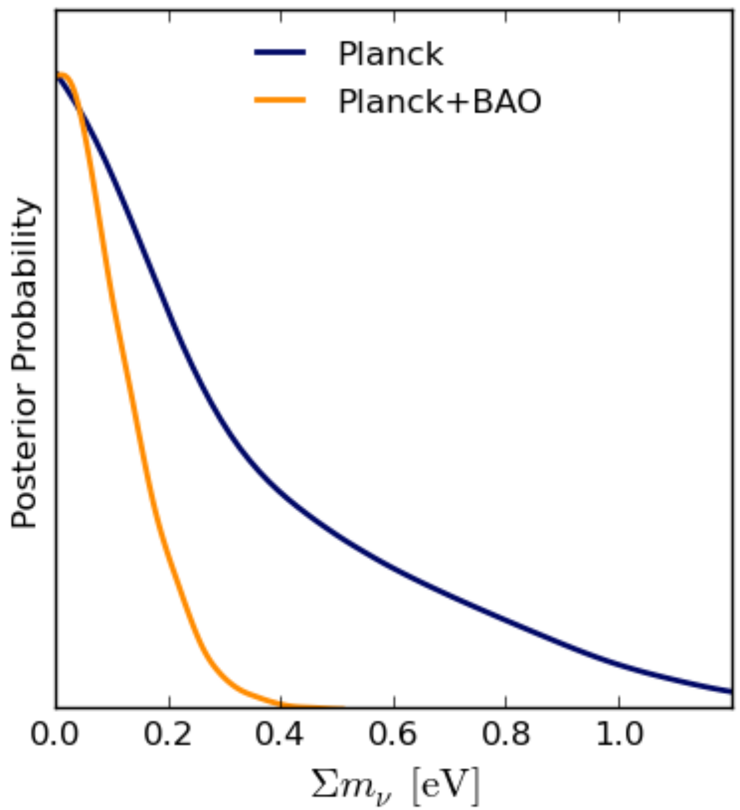
CONSTRAINTS on NEUTRINO MASSES FROM Planck: I



$\Sigma m_\nu < 0.93$ eV(2σ)

Costanzi+ 2014, JCAP

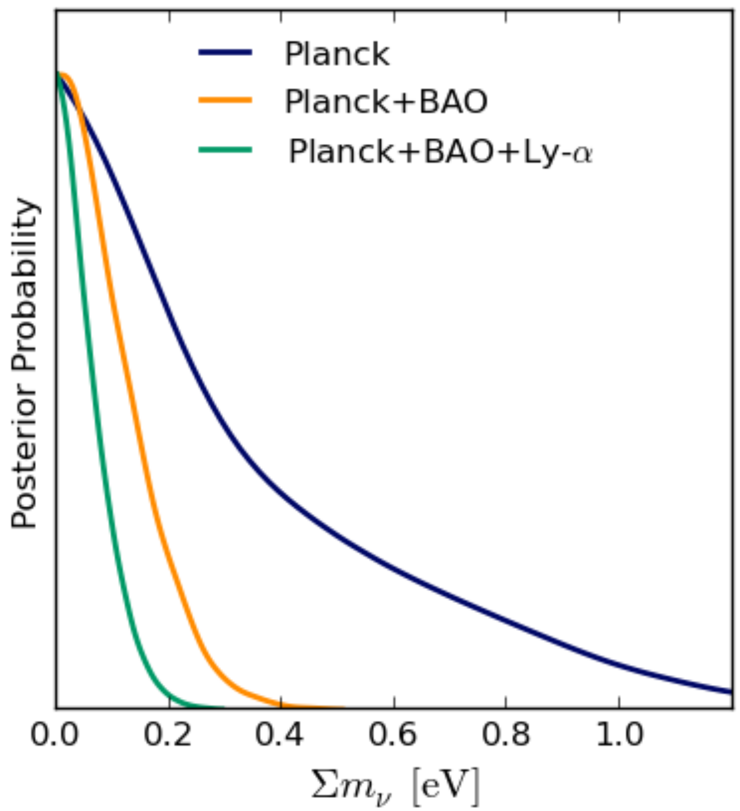
CONSTRAINTS on NEUTRINO MASSES FROM Planck+BAO: II



$\Sigma m_\nu < 0.24$ eV(2σ)

Costanzi+ 2014

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



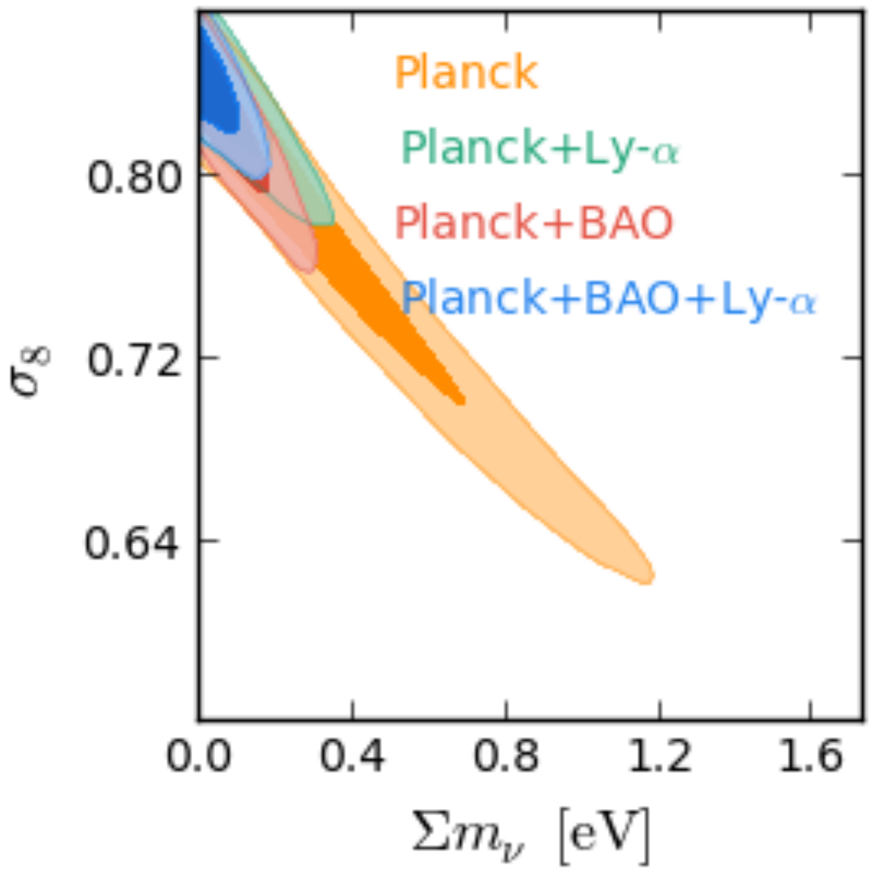
$$\Sigma m_\nu < 0.14 \text{ eV} (2\sigma)$$

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



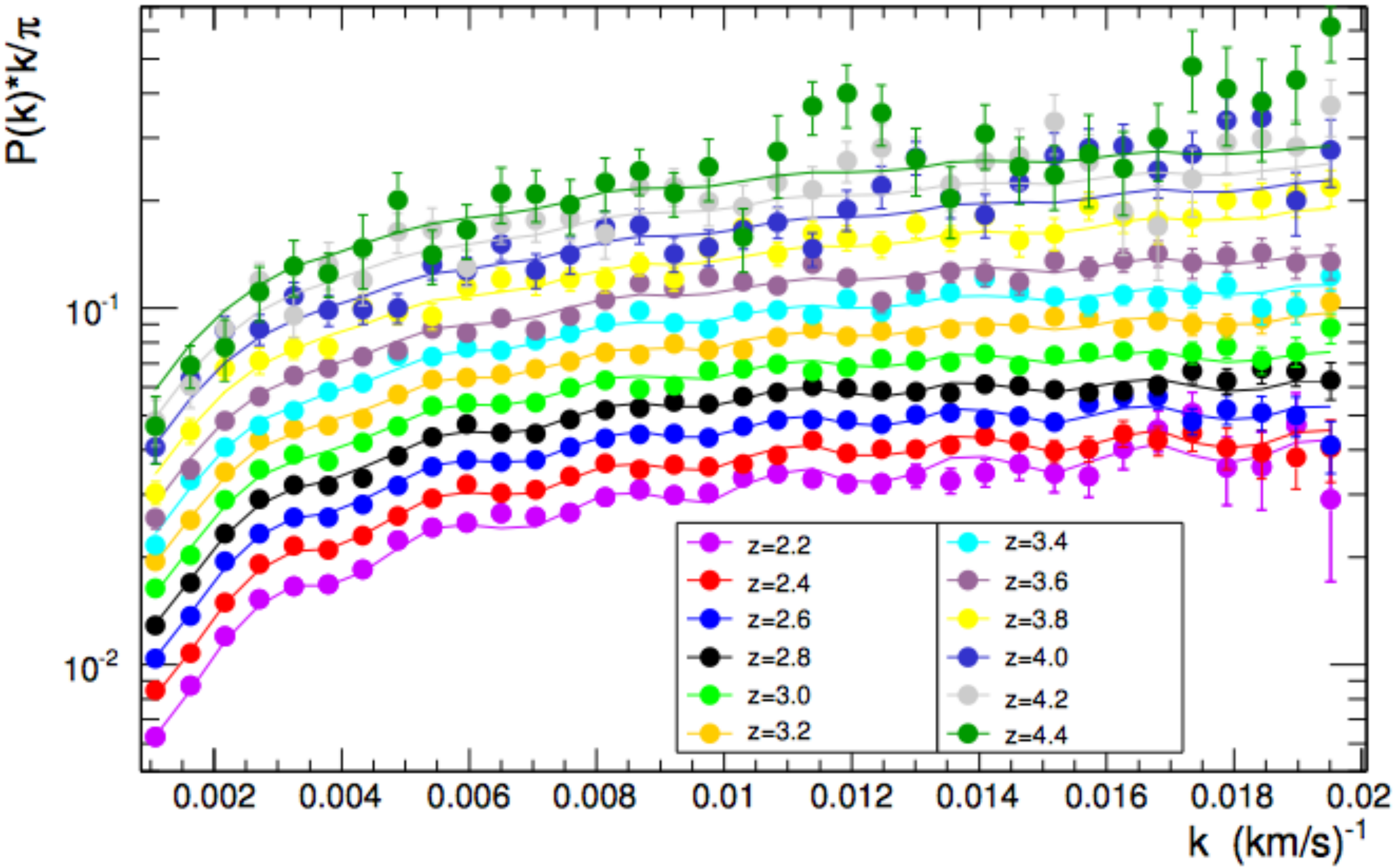
2 eV
29 eV
59 eV
.9 eV

Costanzi, Sartoris, MV, Borgani (2014)

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

Cosmological Parameters

Astrophysical Parameter

Neutrino mass

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

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)

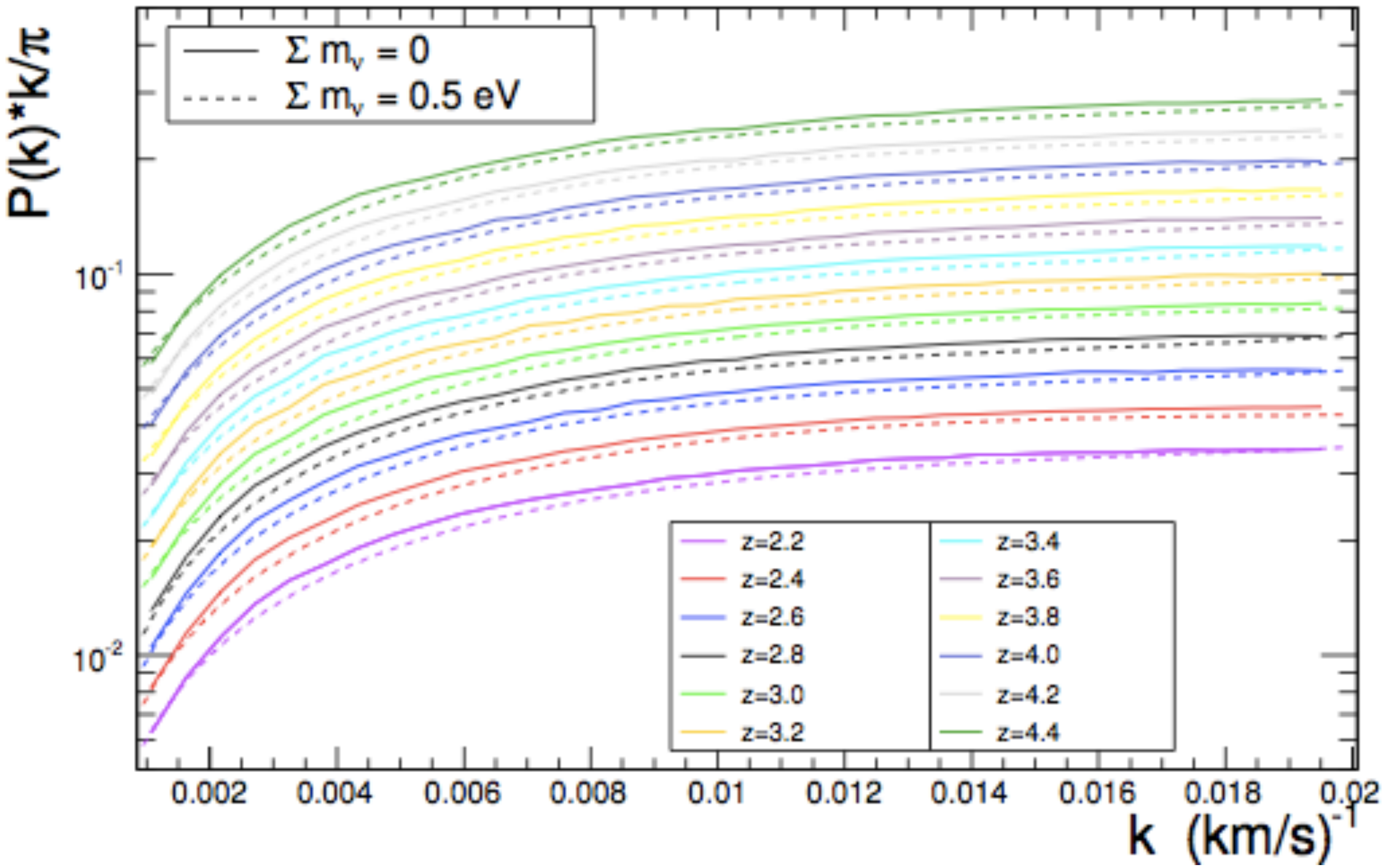
Cosmology parameters: σ_8, n_s, Ω_m, H_0, $m_{WDM,}$+ neutrino mass
Astrophysical parameters: z_{reio}, UV fluctuations, T_0, γ, $\langle F \rangle$
Nuisance: resolution, S/N, metals

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

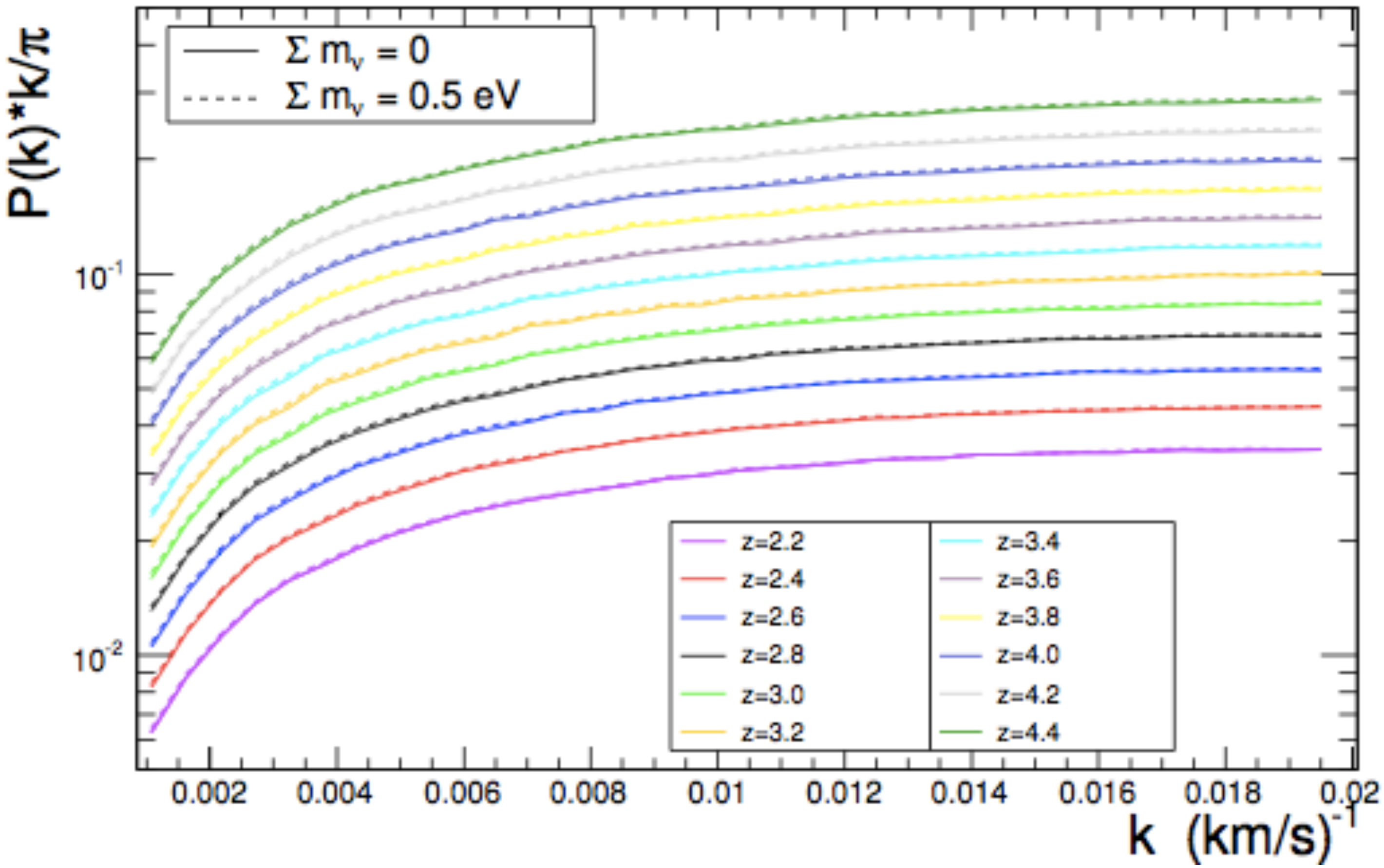
Parameter space: second order Taylor expansion of the flux power

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

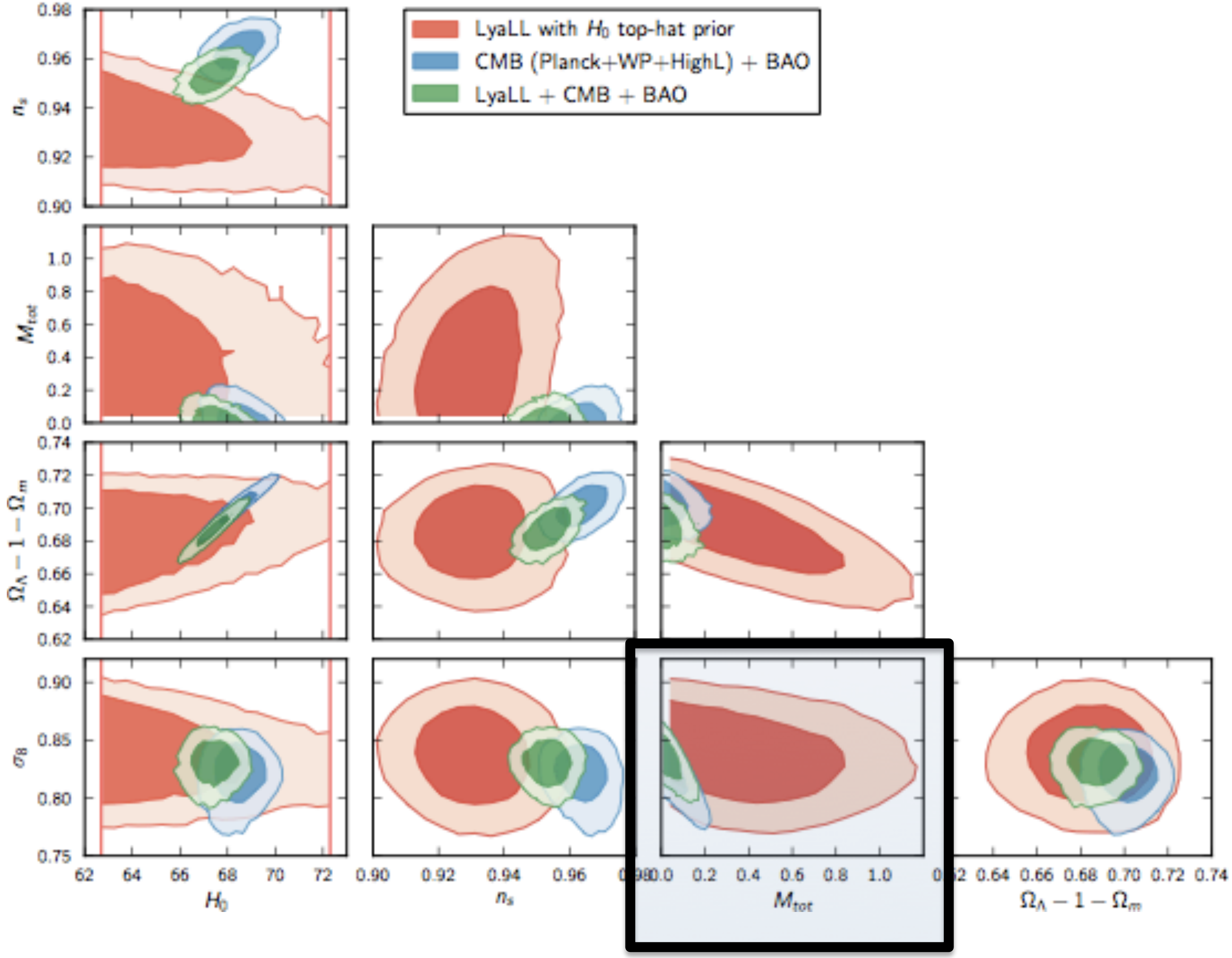
NEUTRINO IMPACT - I



NEUTRINO IMPACT - II



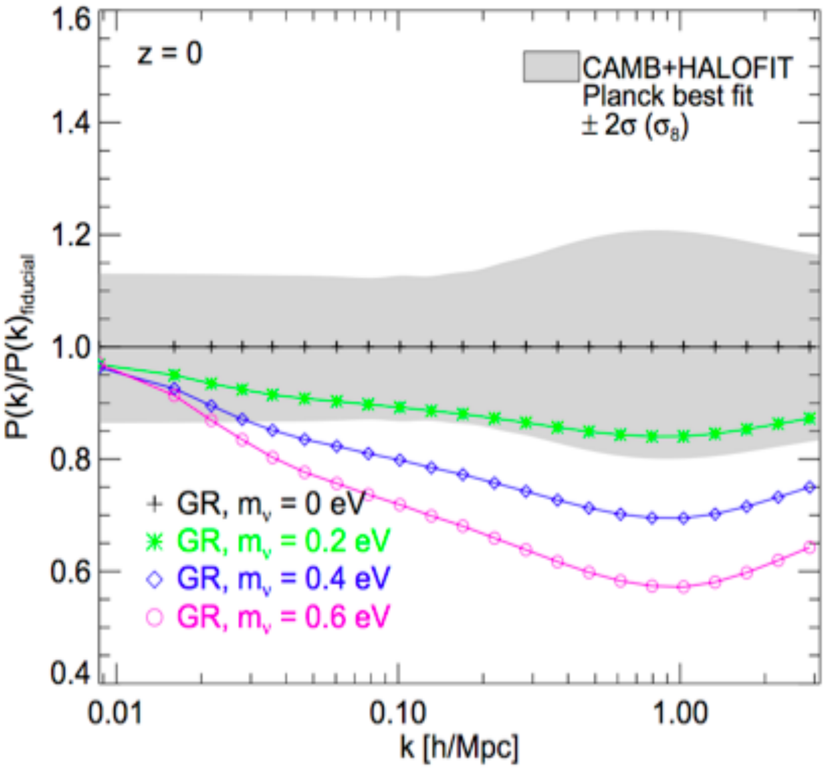
BAYESIAN ANALYSIS

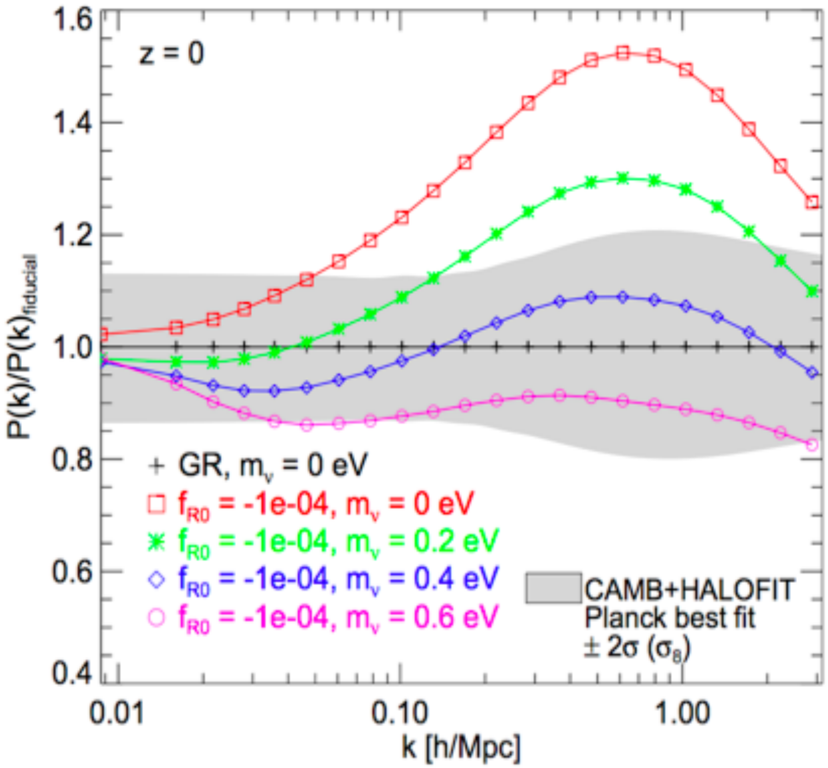


FINAL NUMBERS

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

Cosmic Conspiracies?





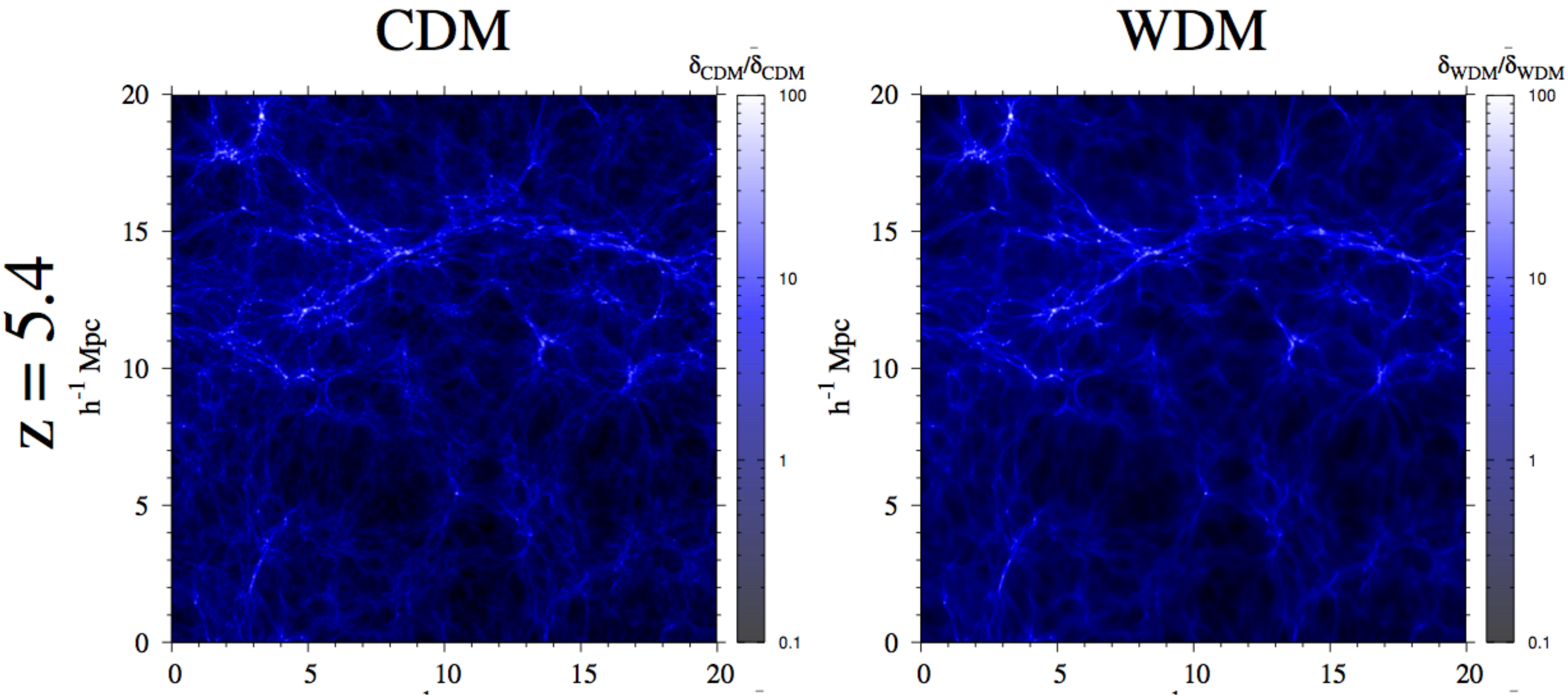
Baldi, Villaescusa-Navarro, Viel, Puchwein, Springel, Moscardini, 2014

OFF-THE-BEATEN-TRACK
TOPIC #2:

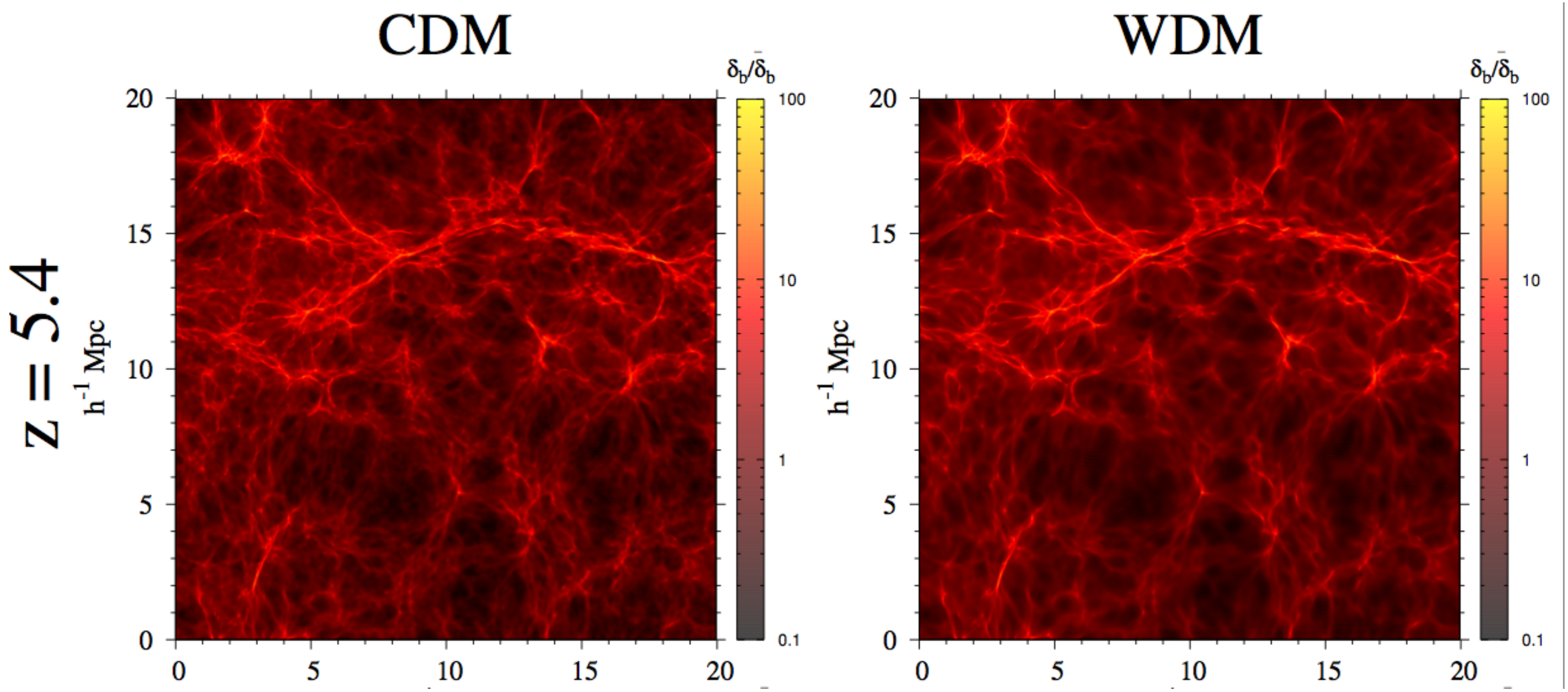
COLDNESS OF COLD DARK MATTER

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

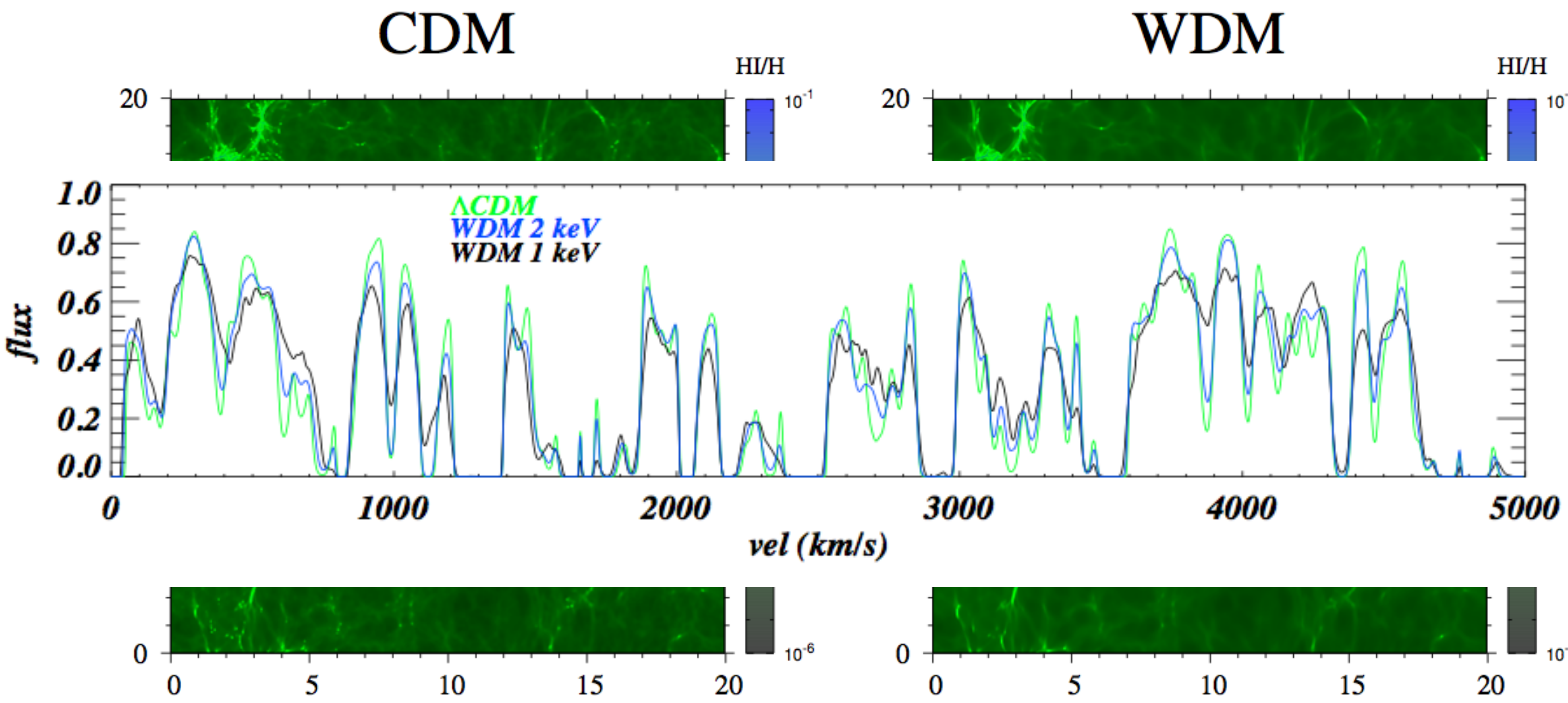
DARK MATTER DISTRIBUTION



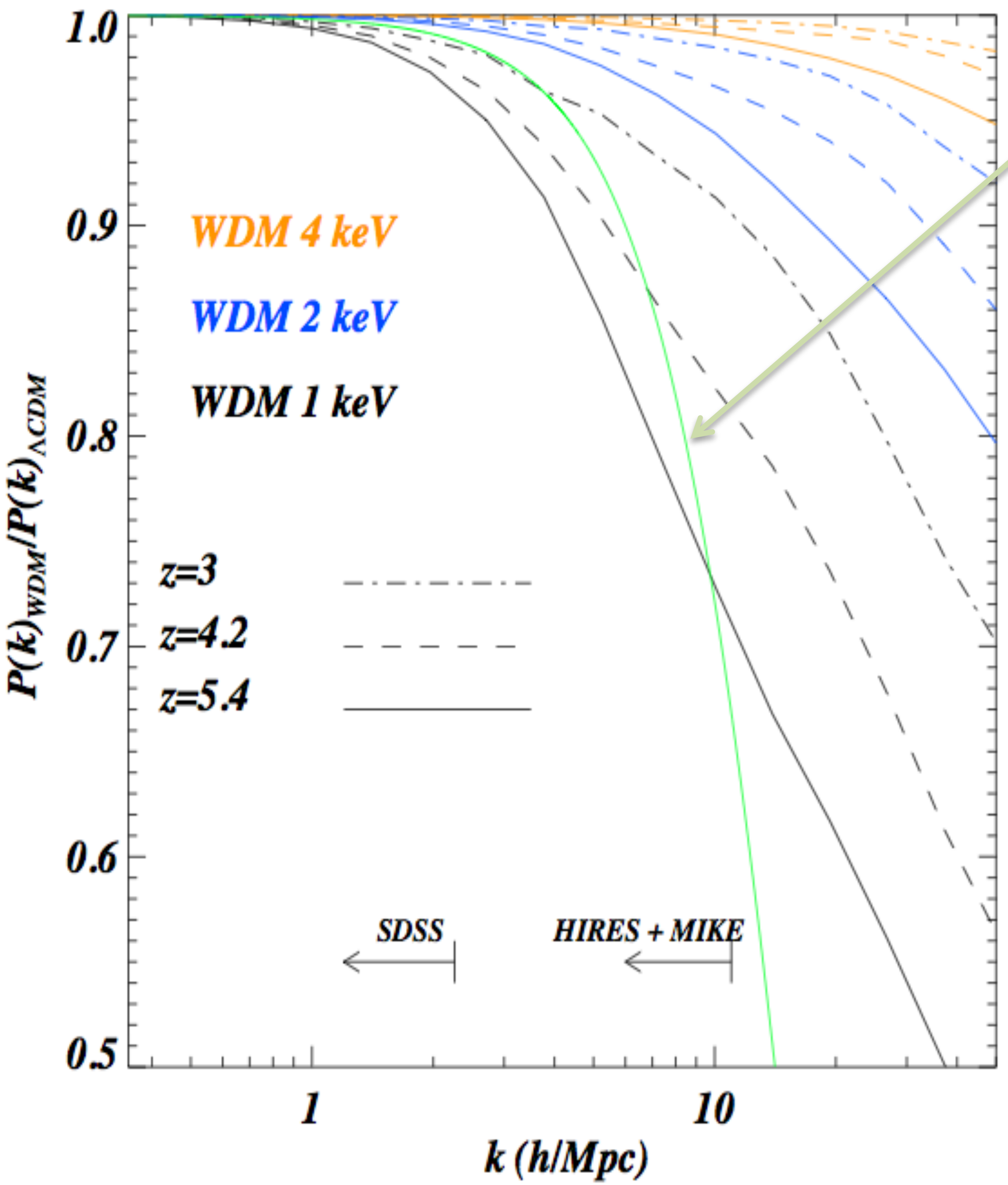
GAS DISTRIBUTION



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

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

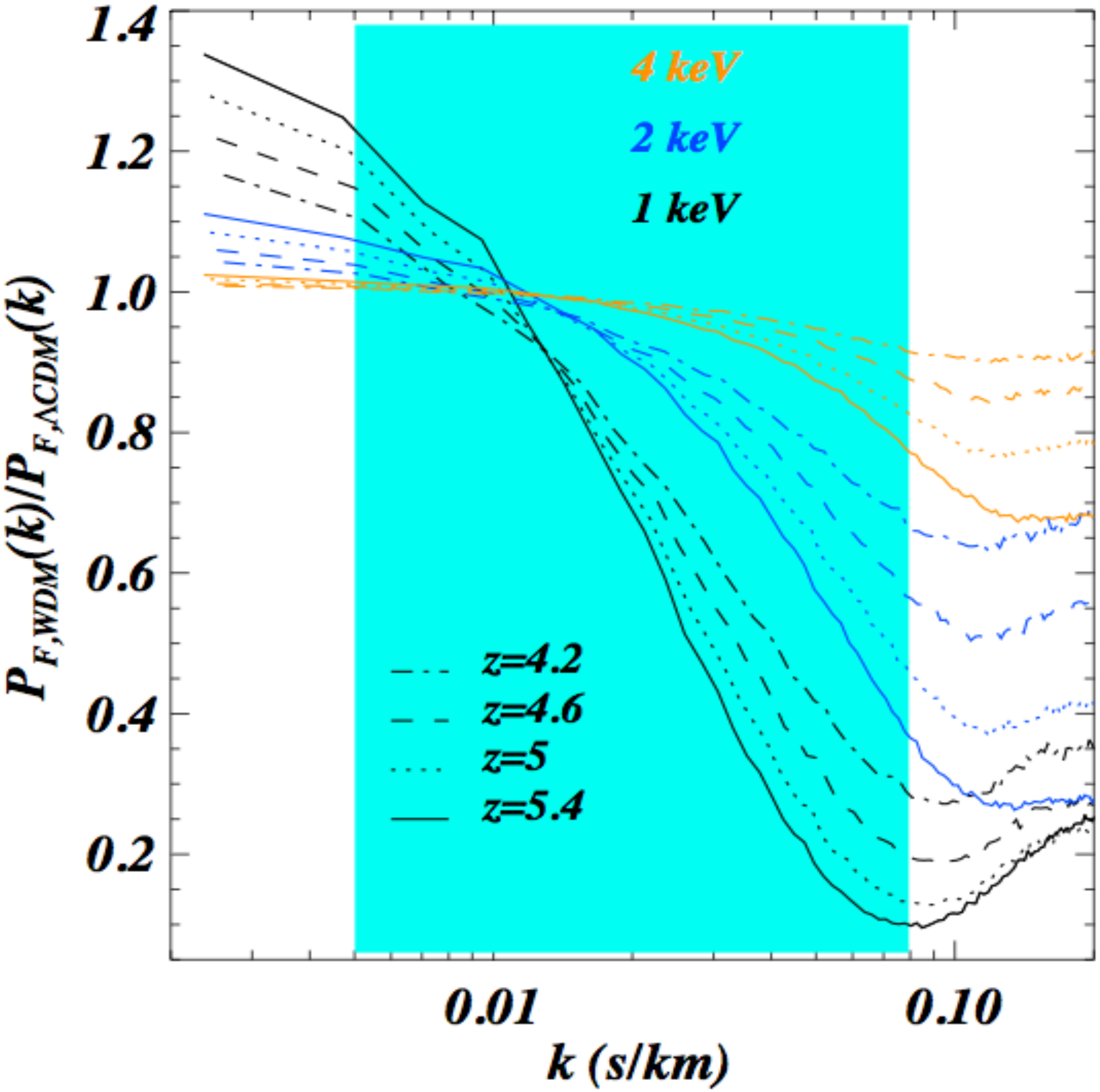
$$\alpha(m_{\rm WDM}, z) = 0.0476 \left(\frac{1{\rm keV}}{m_{\rm WDM}}\right)^{1.85} \left(\frac{1+z}{2}\right)^{1.3},$$

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

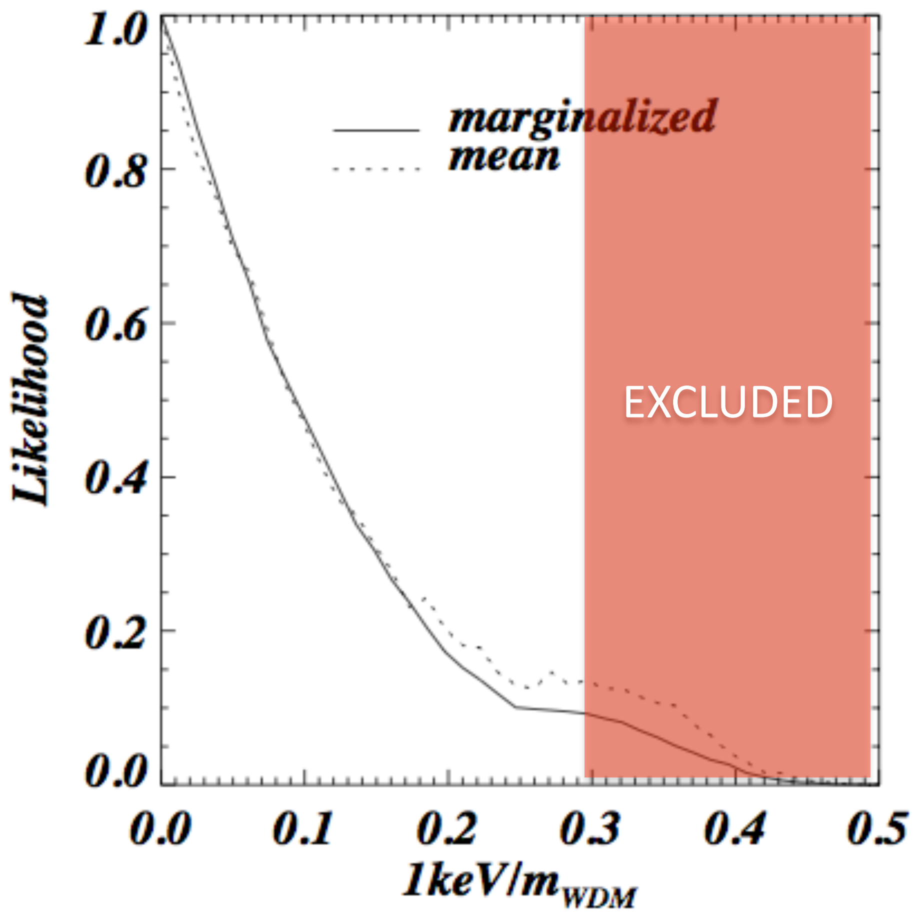
Viel, Markovic, Baldi & Weller 2013

THE HIGH REDSHIFT WDM CUTOFF

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



RESULTS FOR WDM MASS

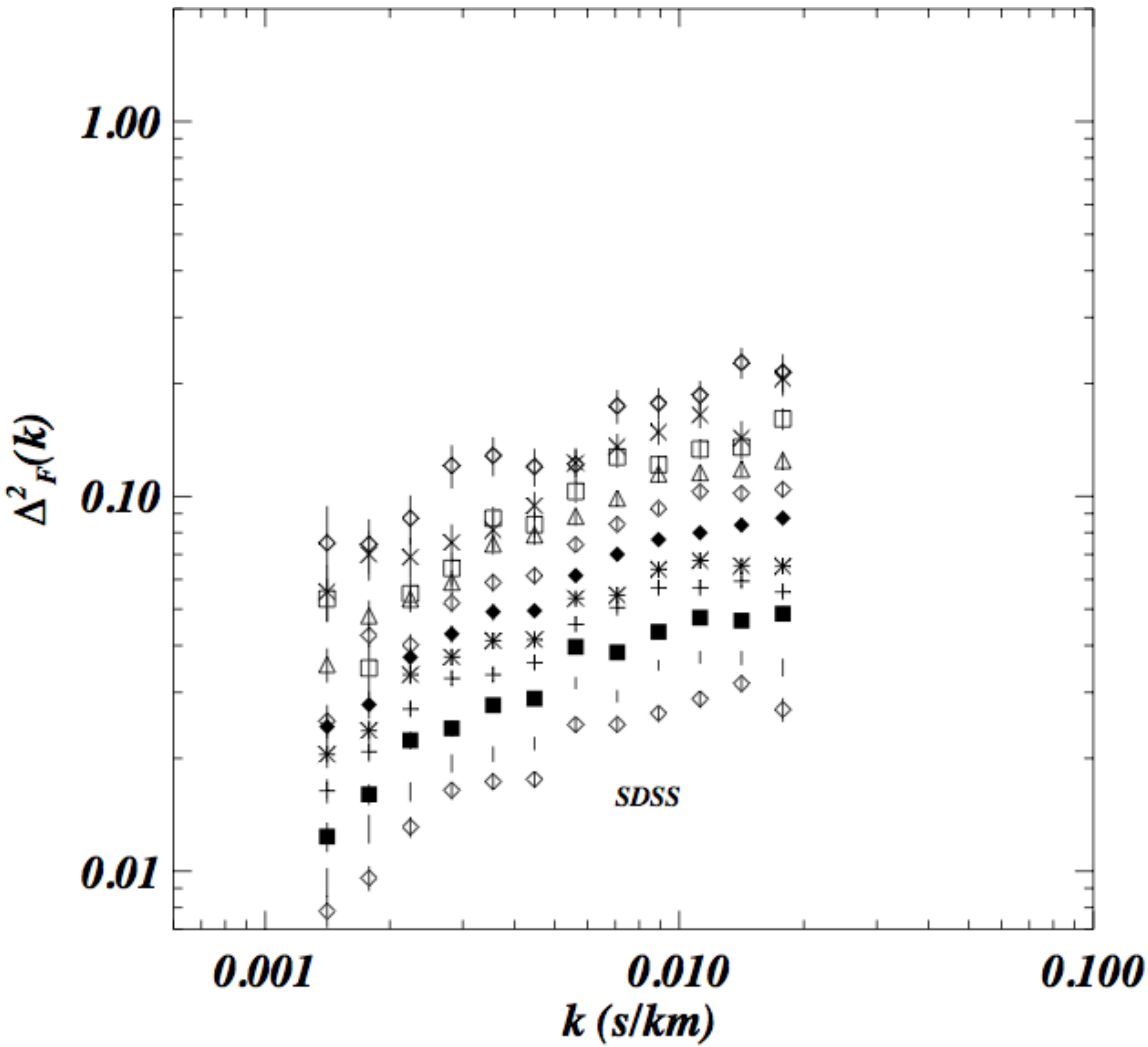


m > 3.3 keV (2σ)

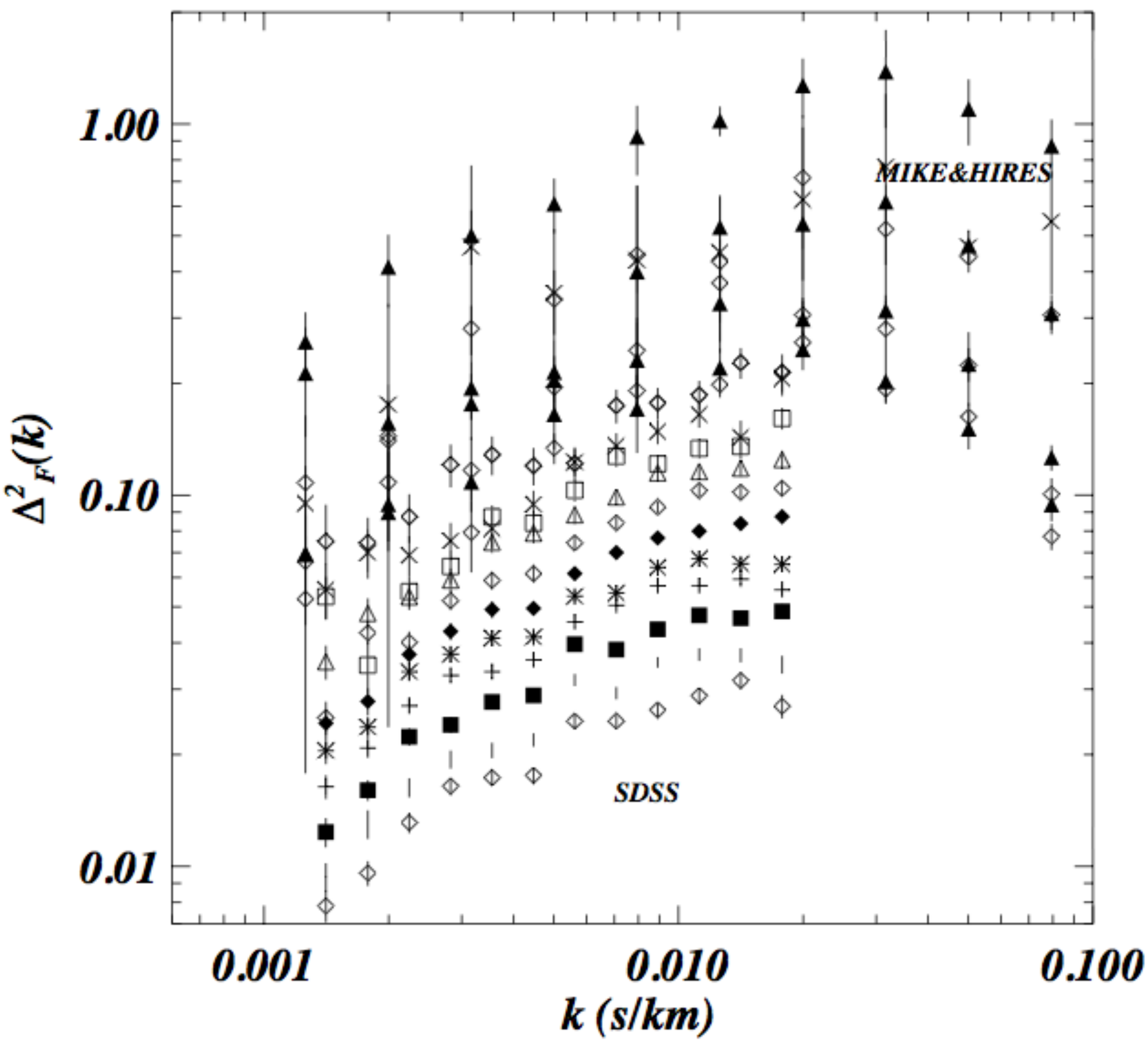
SDSS + MIKE + HIRES CONSTRAINTS

Joint likelihood analysis

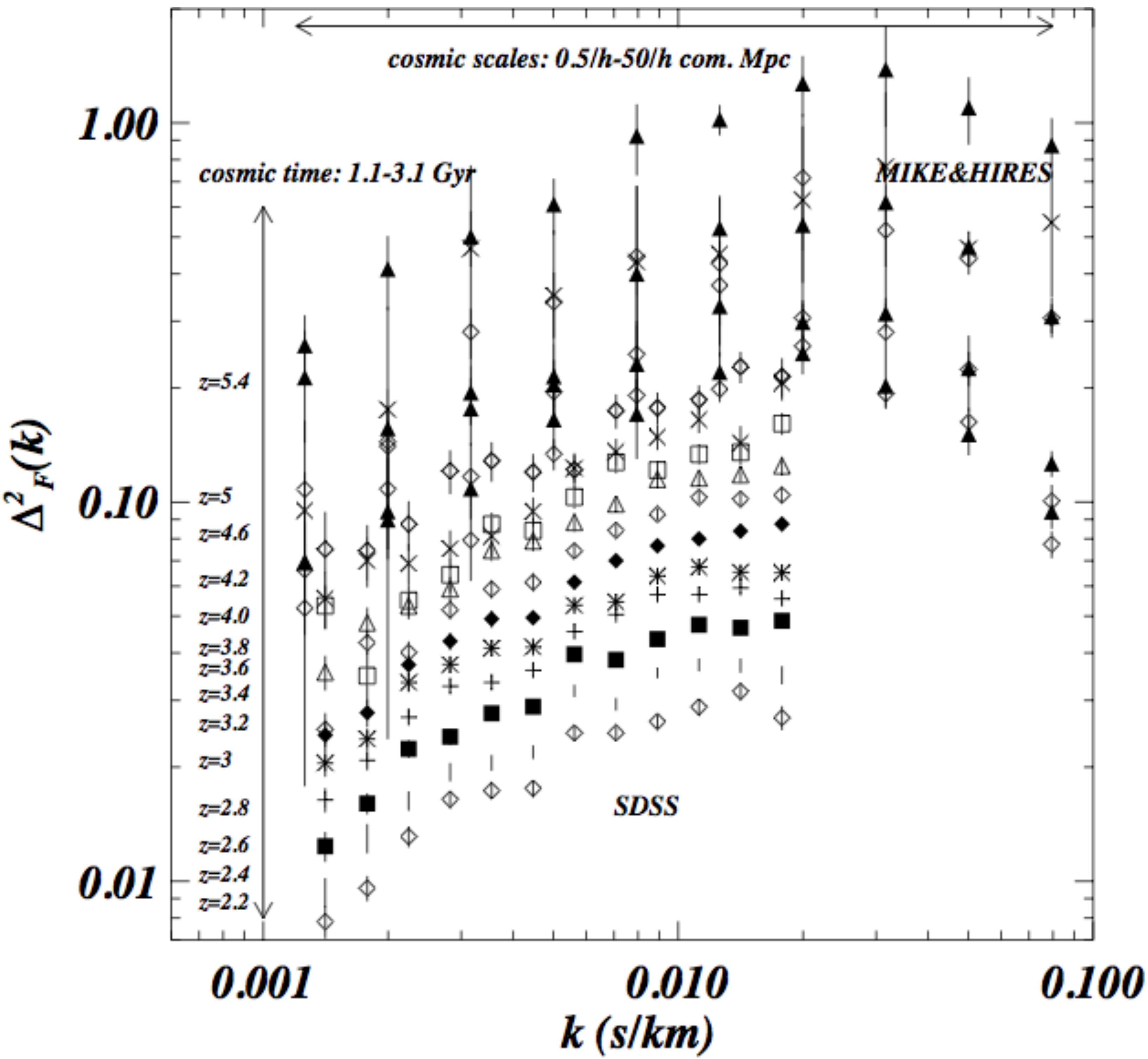
SDSS data from McDonald05,06 not BOSS



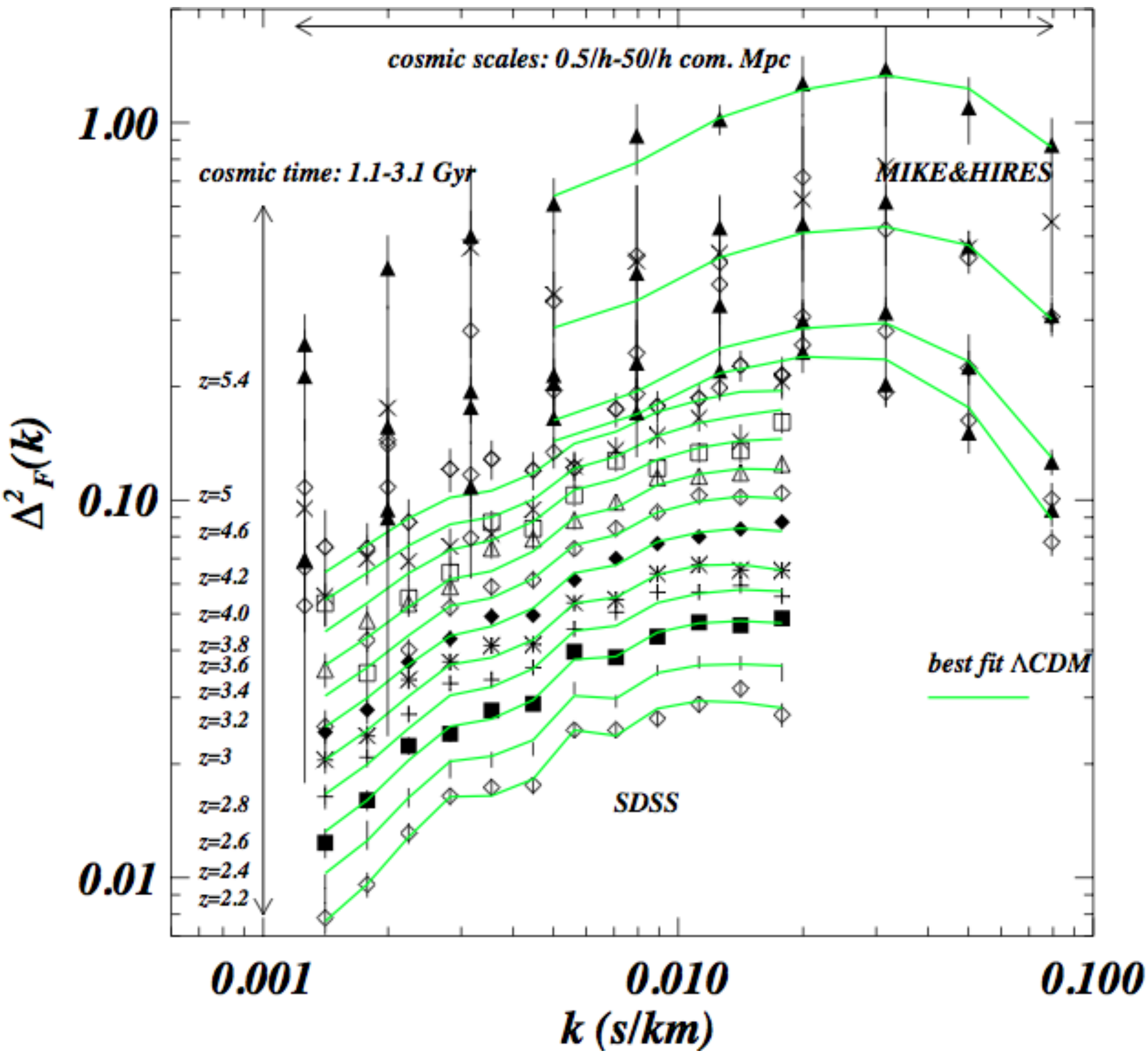
1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)



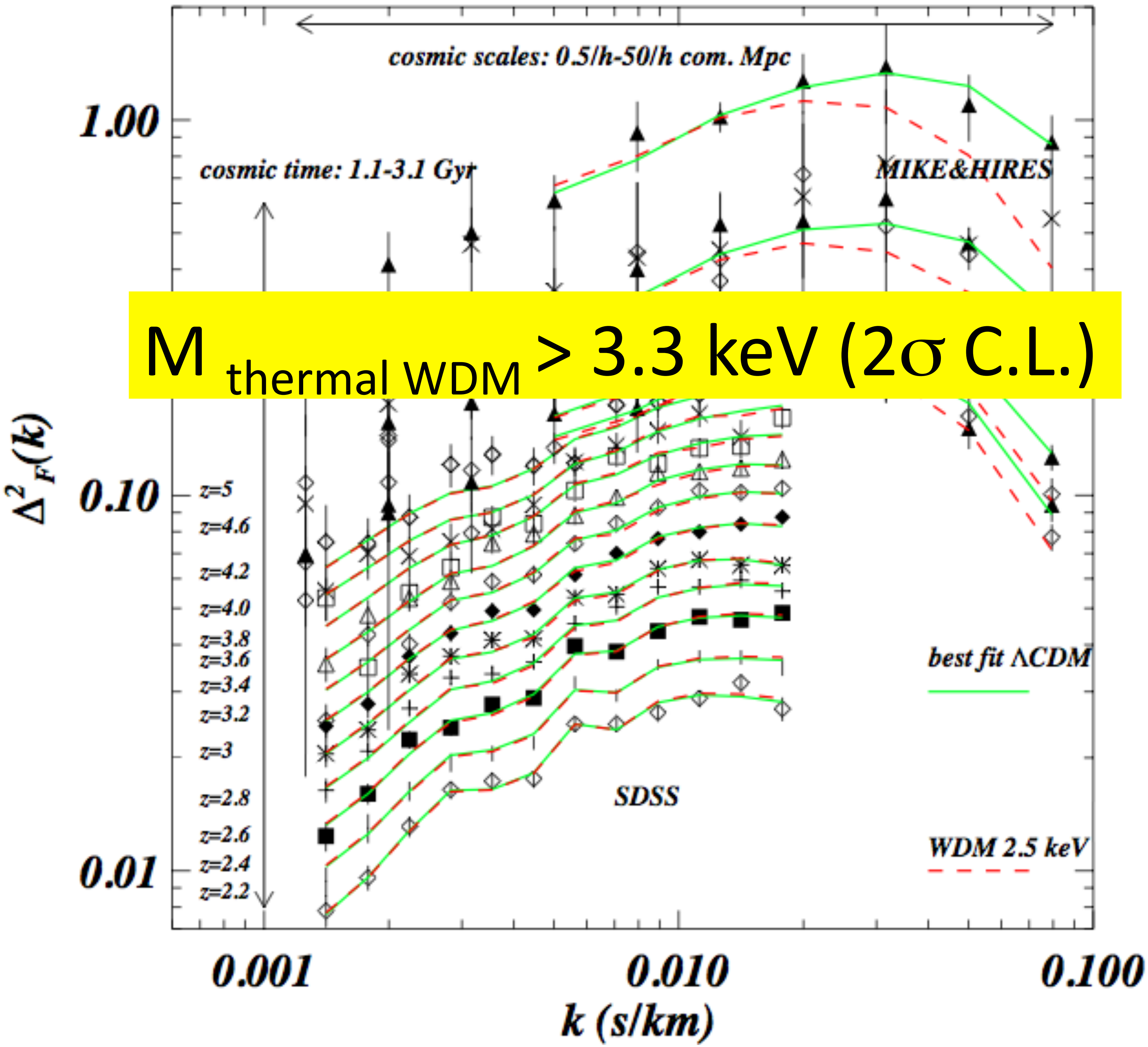
1.00
0.10
0.01
$\Delta^2_F(k)$
MIKE&HIRES
SDSS
0.001
0.010
0.100
k (s/km)



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.)



WDM SUPPRESSION in 21cm INTENSITY MAPPING

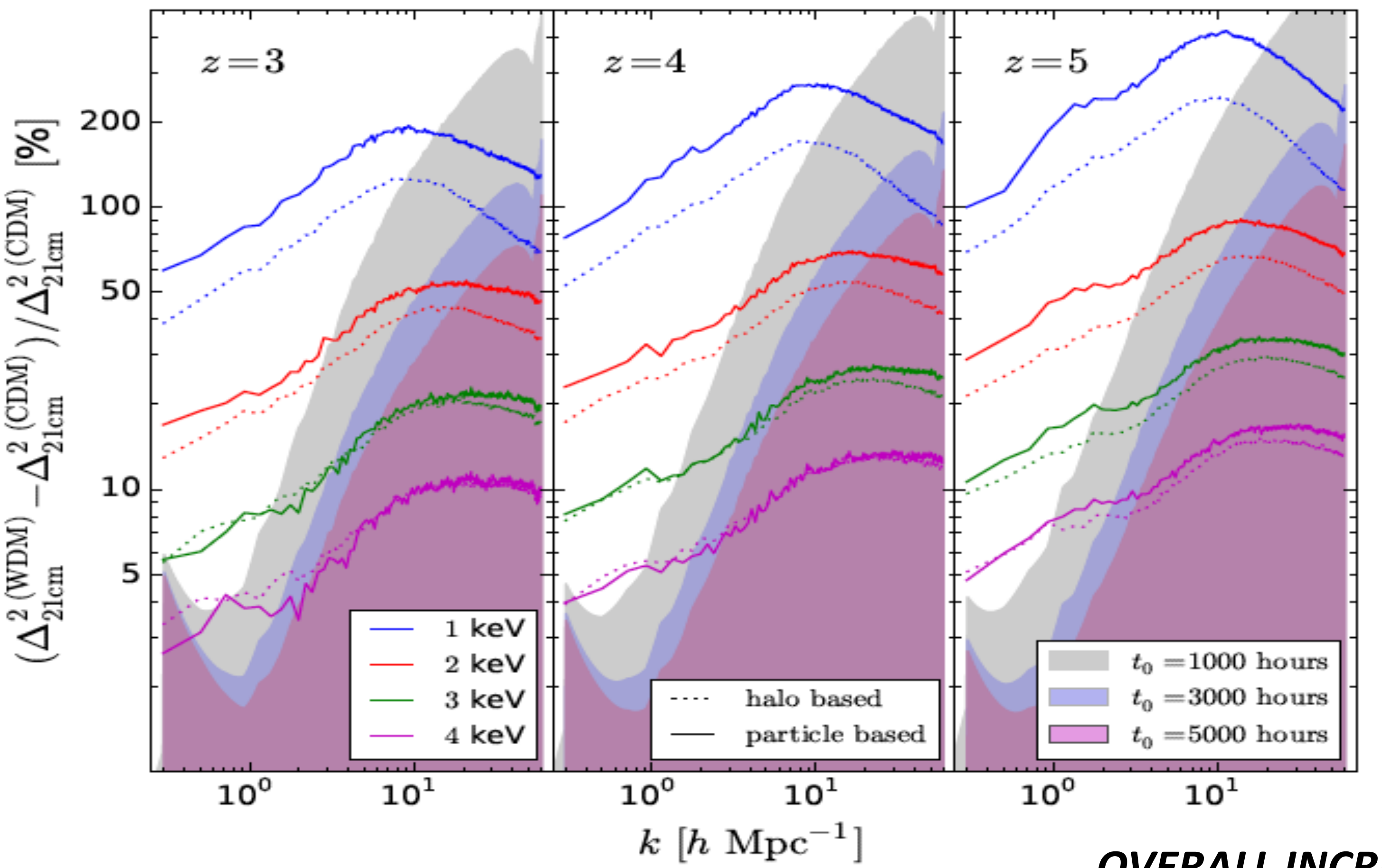
Carucci, Villaescusa, MV, Lapi 2015

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

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

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

REALISTIC SKA forecasts



OVERALL INCREASE OF POWER!!

OFF-THE-BEATEN-TRACK
TOPIC #3:

UNDERSTANDING
THE ISOTROPIC GAMMA RAY BACKGROUND
WITH CROSS-CORRELATION TECHNIQUES

See works by Ackermann+14 from Fermi collaboration
Fornasa, Sanchez-Conde 15
Xia, Cuoco, Branchini, Viel 2011
Ando 14, Ando+14

IGRB – I: Catalogs and Astrophysical models

TOMOGRAPHY OF THE *FERMI*-LAT γ-RAY DIFFUSE EXTRAGALACTIC SIGNAL VIA CROSS-CORRELATIONS WITH GALAXY CATALOGS

Jun-Qing Xia[1,2], Alessandro Cuoco[3,4,5], Enzo Branchini[6,7,8], and Matteo Viel[9,10]

ApJS, 2015, 217, 15

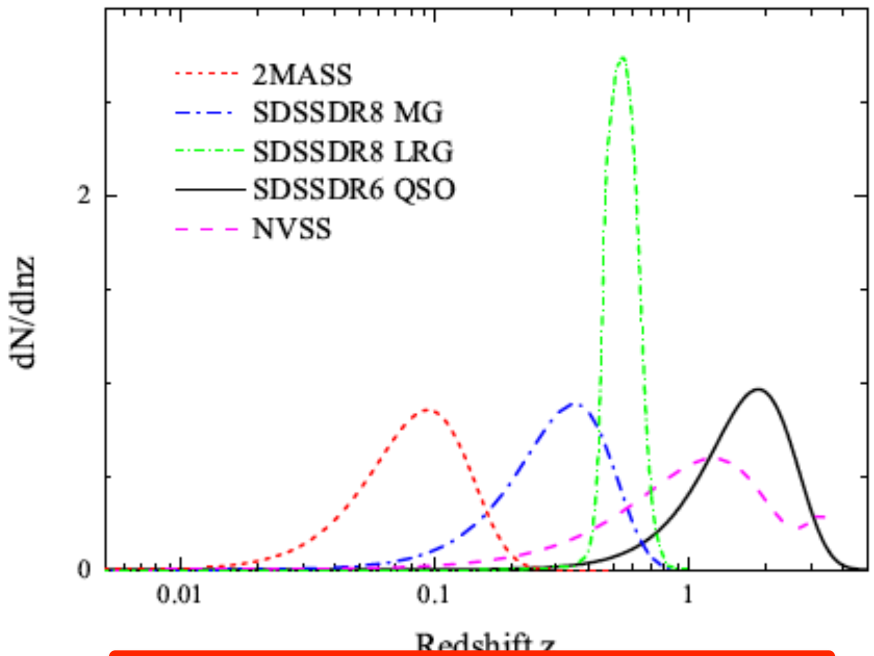
CATALOGS

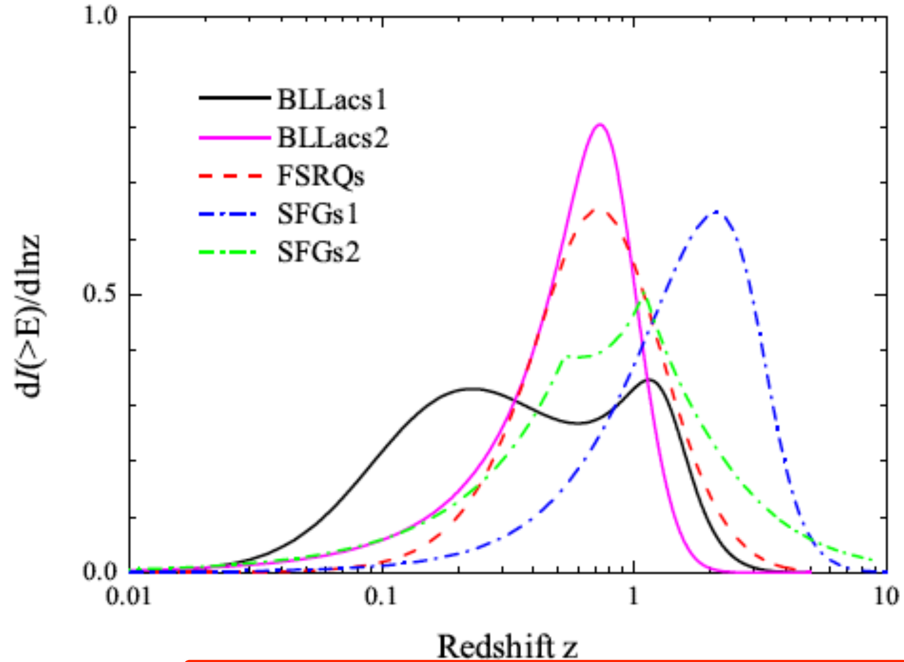
QSOs from SDSS DR6
Main galaxy sample SDSS DR8
Luminous Red Galaxies SDSS DR8
NVSS
2MASS

$$C_l^{I,j} = \frac{2}{\pi}\int k^2 P(k)[G_l^I(k)][G_l^j(k)]dk$$

SOURCES

BLLacs (2 models)
Star Forming Galaxies (2 models)
FSRQs
MAGNs also considered

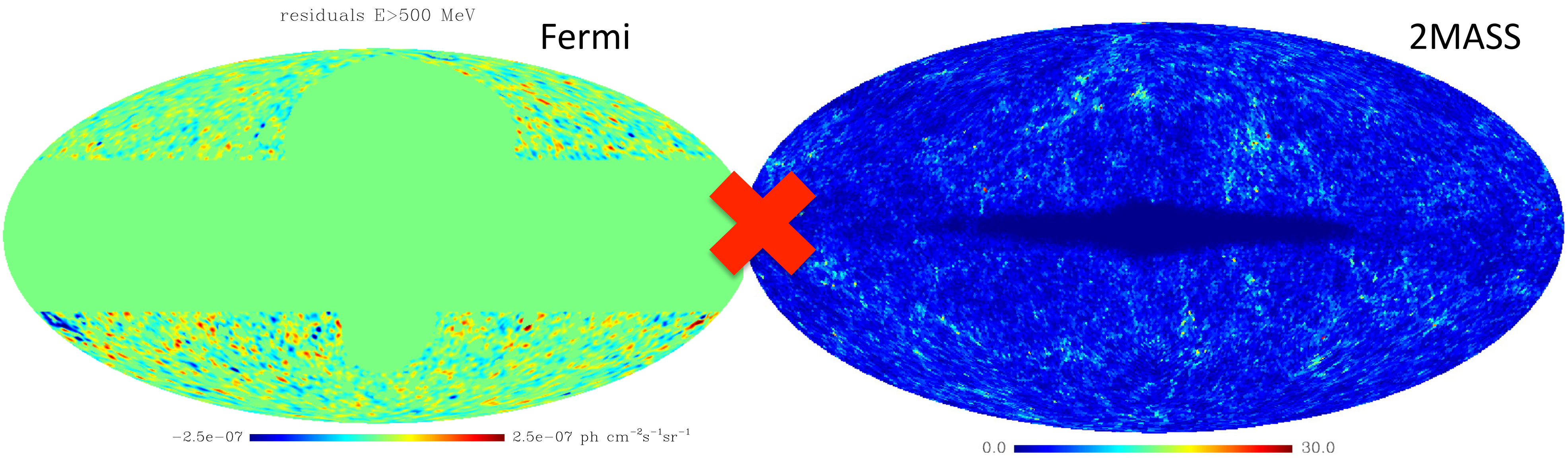


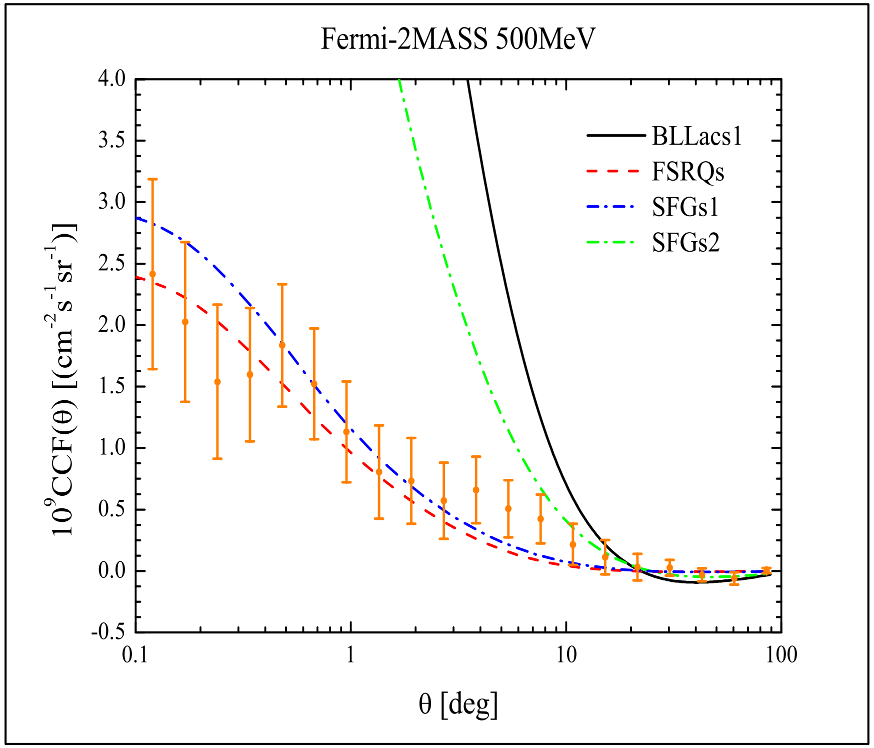


$$G_l^j(k) = \int \frac{dN(z)}{dz} b_j(z)D(z)j_l[k\chi(z)]dz,$$

$$G_l^I(k) = \int \rho_\gamma(z)b_\gamma(z)D(z)j_l[k\chi(z)]dz$$

IGRB – II: results from astro modelling





Cross-correlations detected:

2MASS: 3.5σ for θ<10° all energies

Main Galaxies: > 3σ at E>0.5,1 GeV

LRG: weak cross correlation

QSOs: 2-5σ

NVSS: strong cross corr. but likely to be syst.

Main Result:

Best fit when SFG are the main contributors 72^{+23}_{-37}% - Conclusions not sensitive to bias or dN/dz

BLLac contrib < 5%

FSRQs contrib < 10%

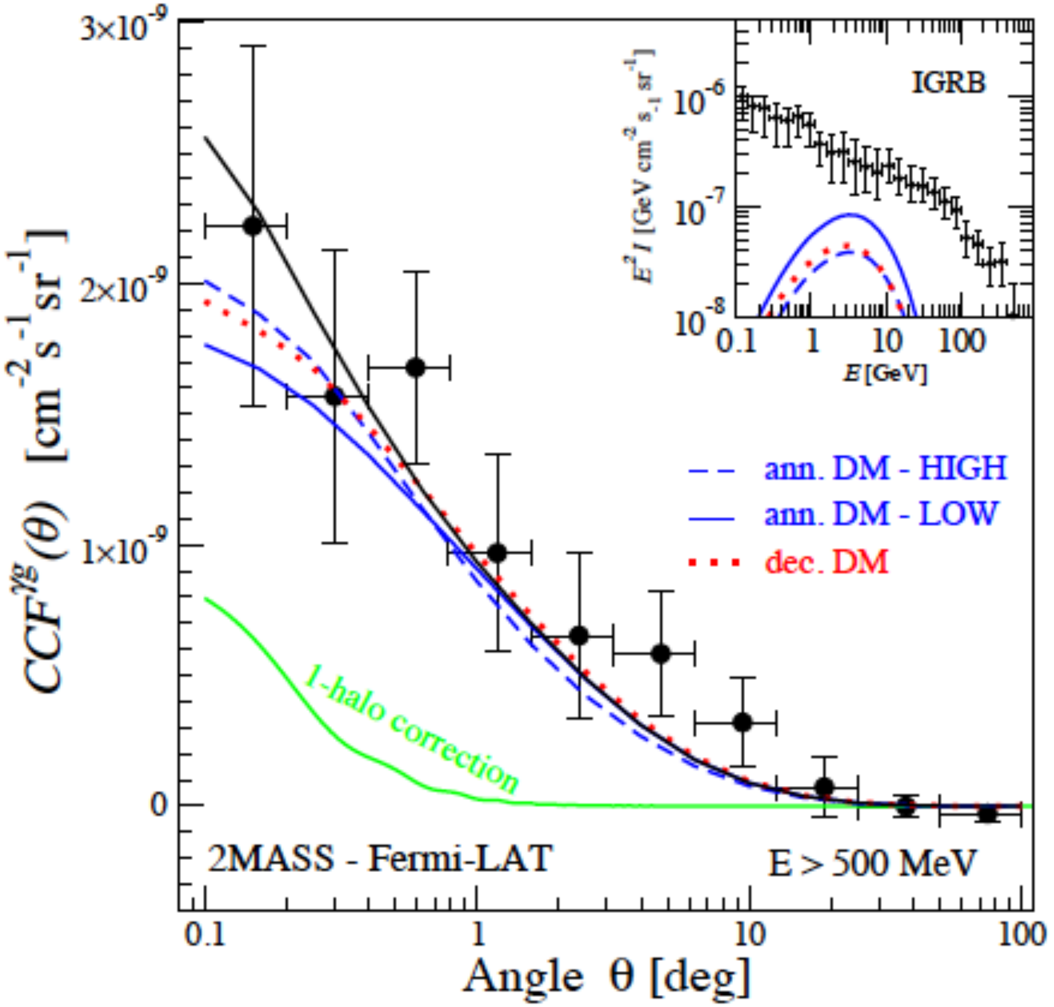
IGRB – III: dark matter contribution

Conservative assumption:
extra contribution due
to dark matter only

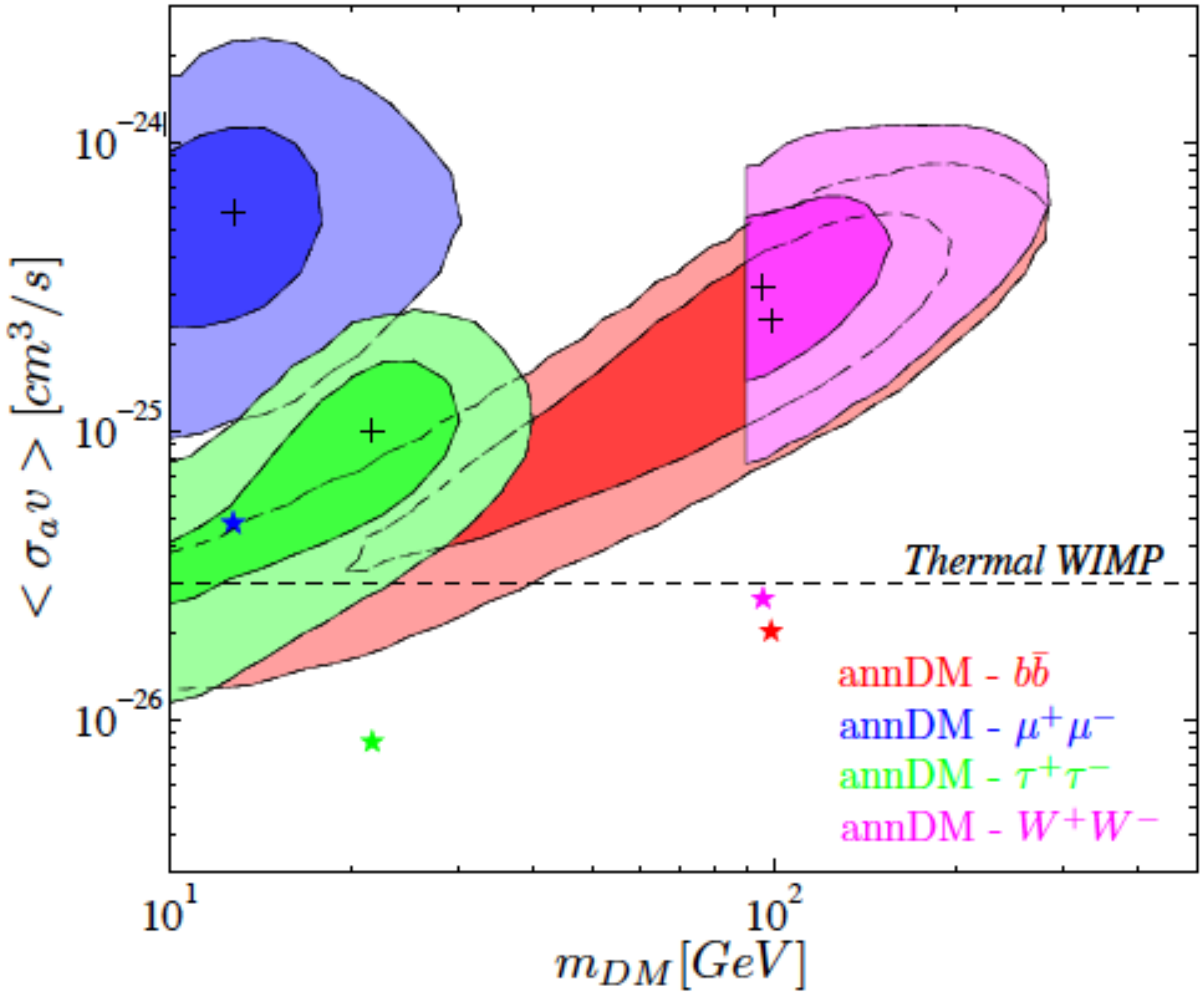
Annhil. $\propto \Omega_{DM}^2 \frac{\langle \sigma v \rangle}{2 m_x^2} \int \rho^2(z) D(z) j_l[k\chi(z)] dz$

Decay $\propto \Omega_{DM} \frac{\Gamma_D}{2 m_x}$

Regis, Xia, Cuoco, Branchini, Fornengo, MV, arXiv: 1503.05922

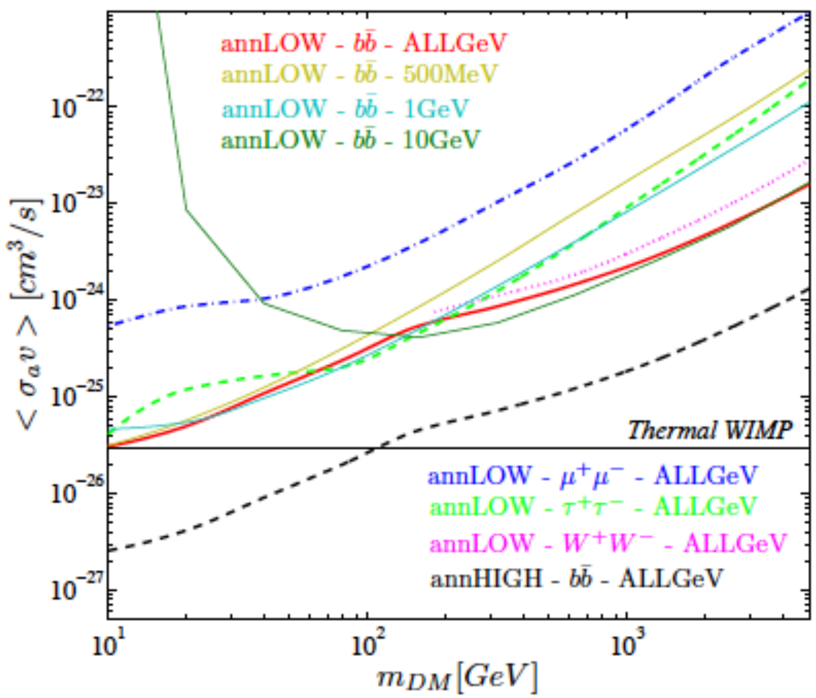


IGRB – IV: dark matter constraints

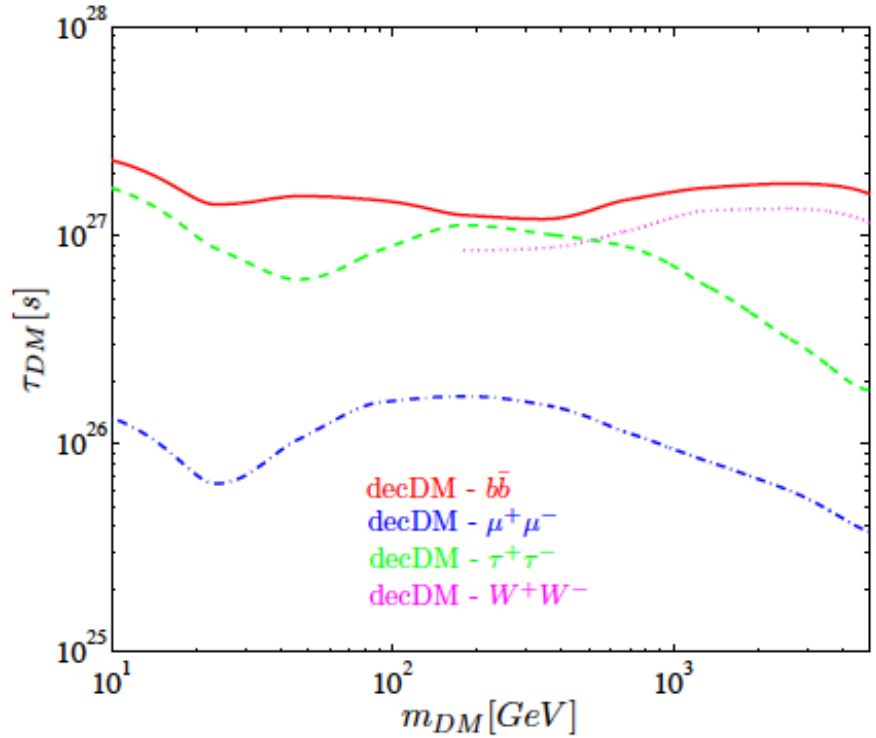


IGRB – IV: dark matter constraints

95% UPPER LIMITS ANNIHILATING DM



95% LOWER LIMITS DECAYING DM



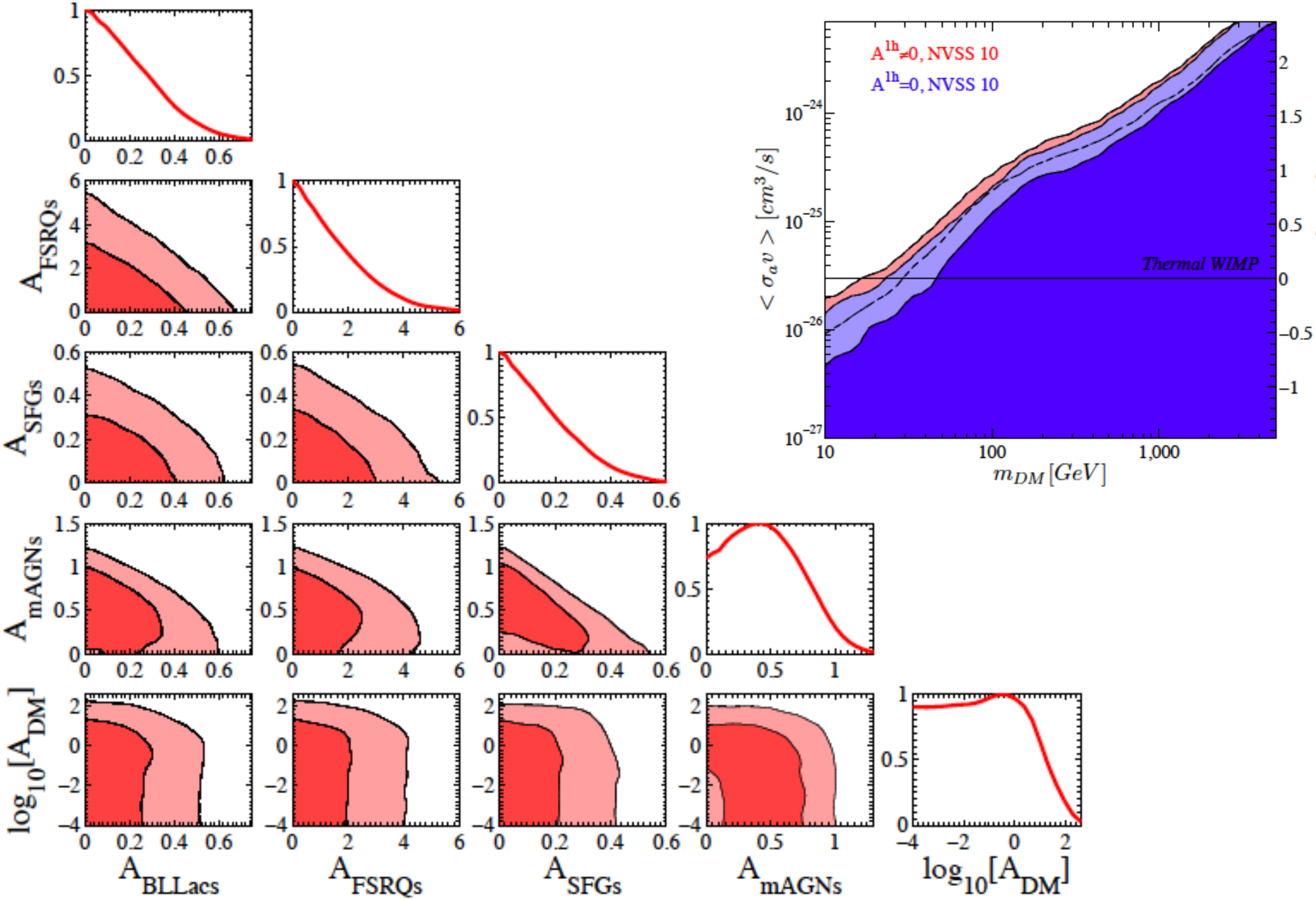
Cross-correlation significantly (>5 times) more constraining than other extragalactic probes like clusters or auto-correlation of the IGRB or IGRB energy spectrum

Adding DM improves the fits

With modest substructure boost thermal wimp cross sections up to few tens of GeV probed

IGRB – V: dark matter + full astro

Cuoco+ 2015



CONCLUSIONS

OFF-THE-BEATEN-TRACK NEUTRINOS:

no support for non zero neutrino masses from IGM data ***TiGHTEST CONSTRAINT***

total neutrino mass <0.14 eV 2σ C.L.

OFF-THE-BEATEN-TRACK WDM: ***TIGHTEST CONSTRAINT***

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

OFF-THE-BEATEN-TRACK IGRB: ***TIGHTEST CONSTRAINT***

astro+DM modelling that probes thermal cross section