The Power Spectrum at Small Scales

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MV

Ripples in the Cosmos Conference
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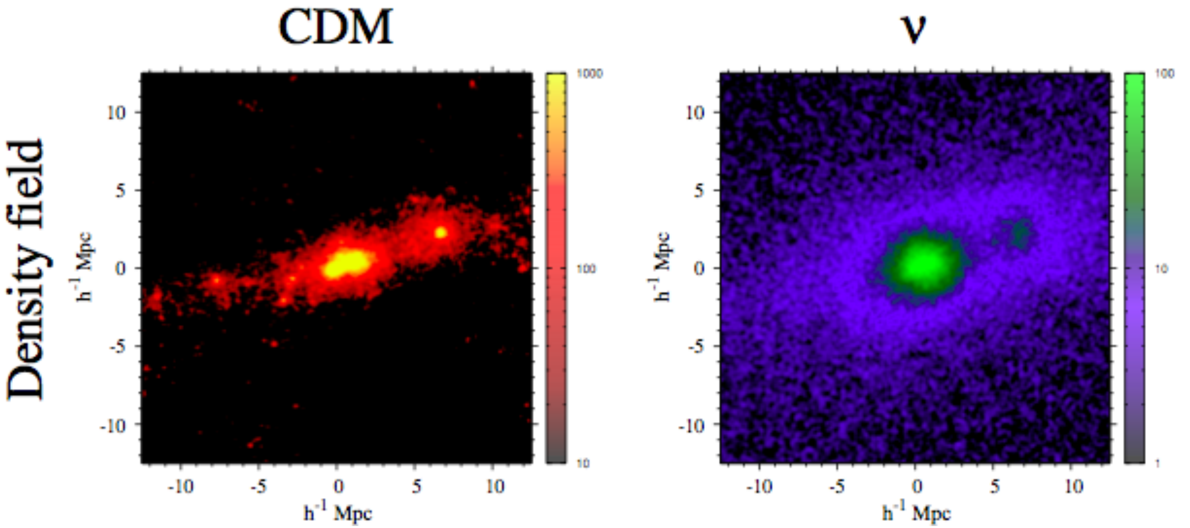
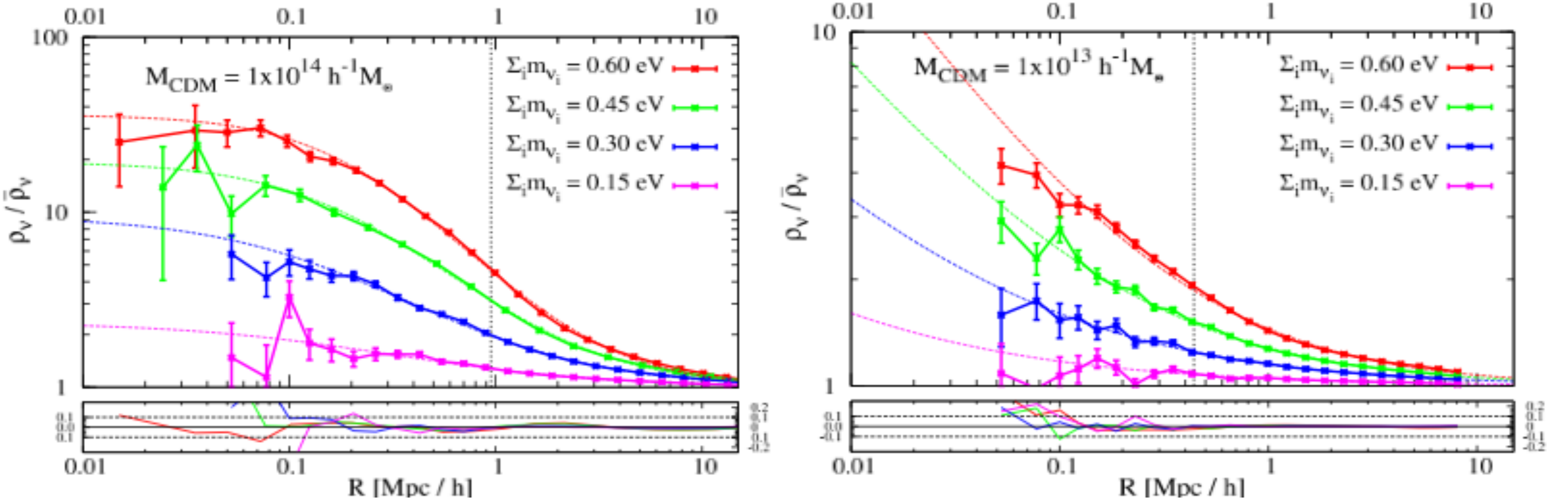
MASSIVE NEUTRINOS

THE NEUTRINO HALO



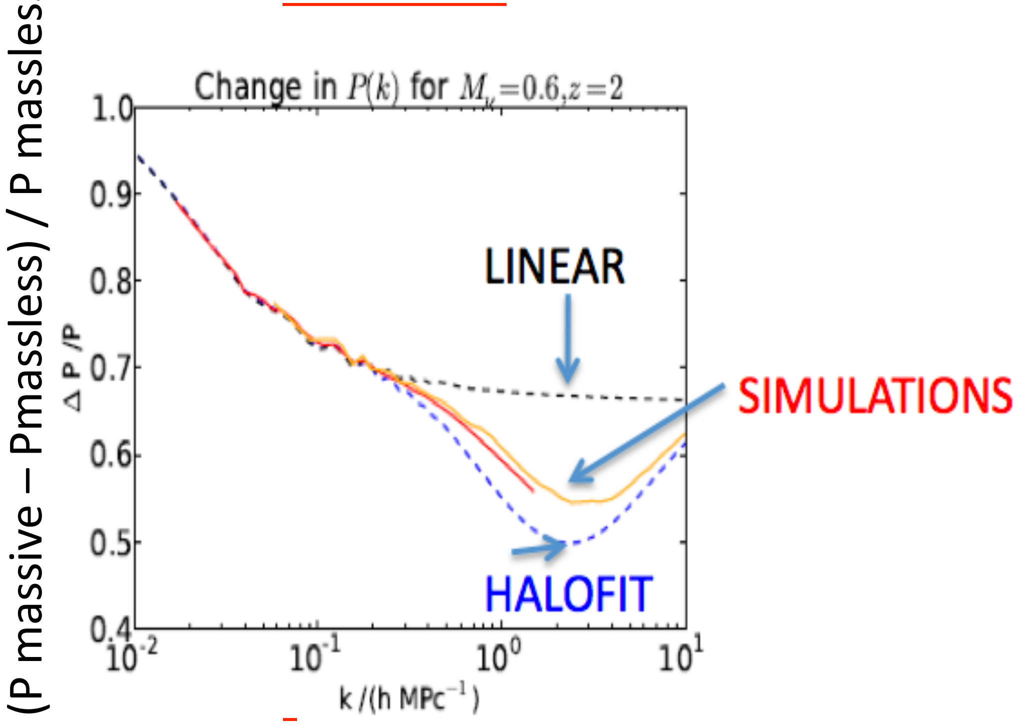
$$\delta_\nu(r) = \frac{\rho_\nu(r) - \bar{\rho}_\nu}{\bar{\rho}_\nu} = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$



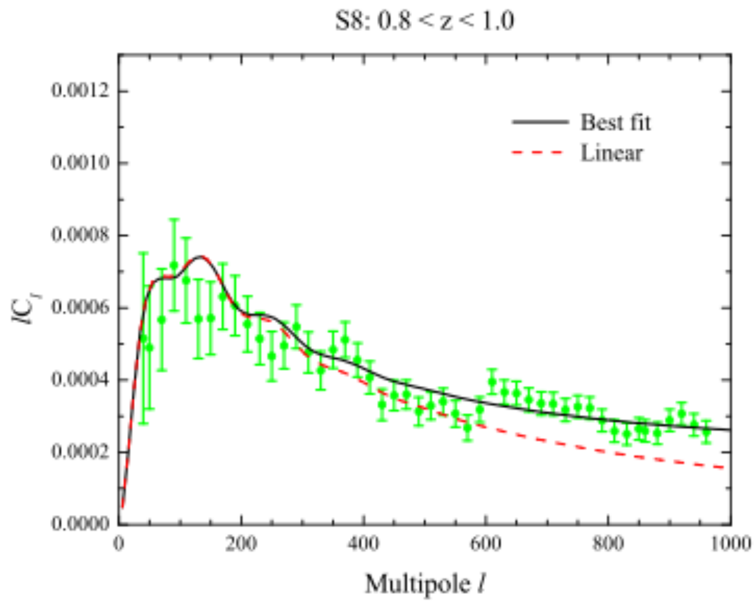
Villaescusa-Navarro, Bird, Garay, MV, 2013, JCAP, 03, 019

Marulli, Carbone, MV+, 2011, MNRAS, 418, 346 ← mass functions, redshift space dist.

THEORY



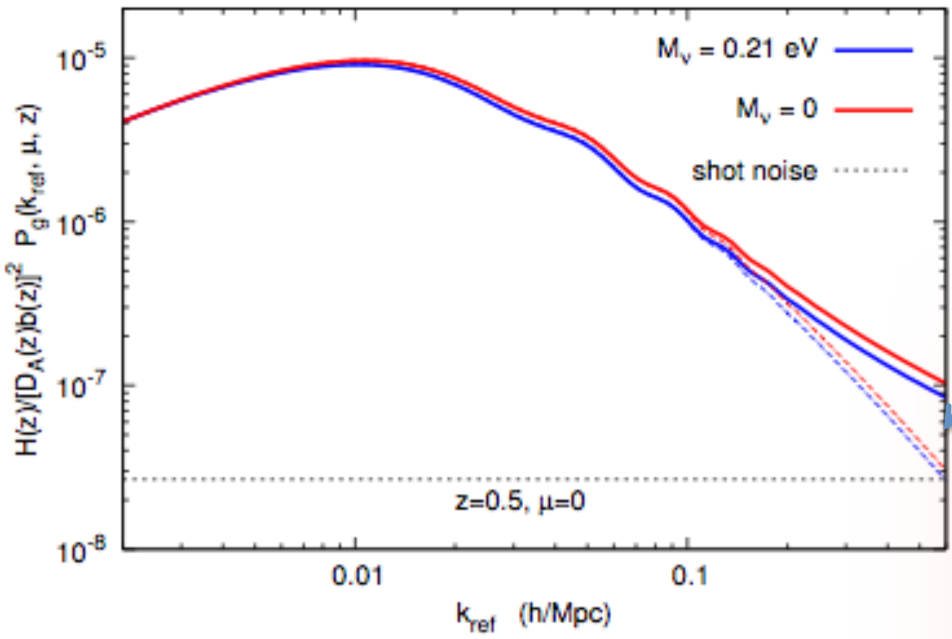
DATA: CFHTLS clustering



Granett et al. 2012; Xia, Granett, MV, Bird, Guzzo+ 2012 JCAP, 06, 010

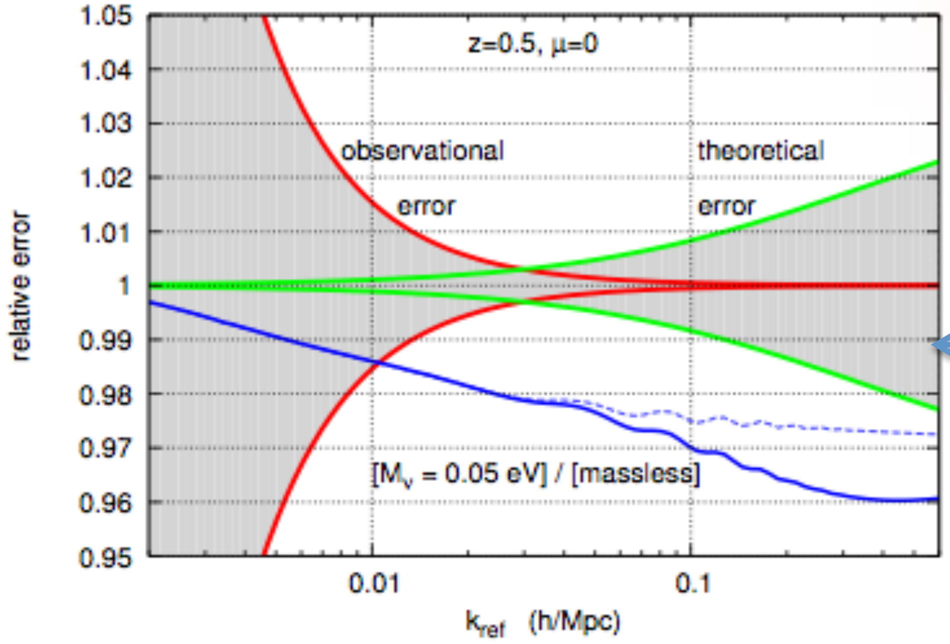
FORECASTS

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

e.g. **Henk Hoekstra talk**

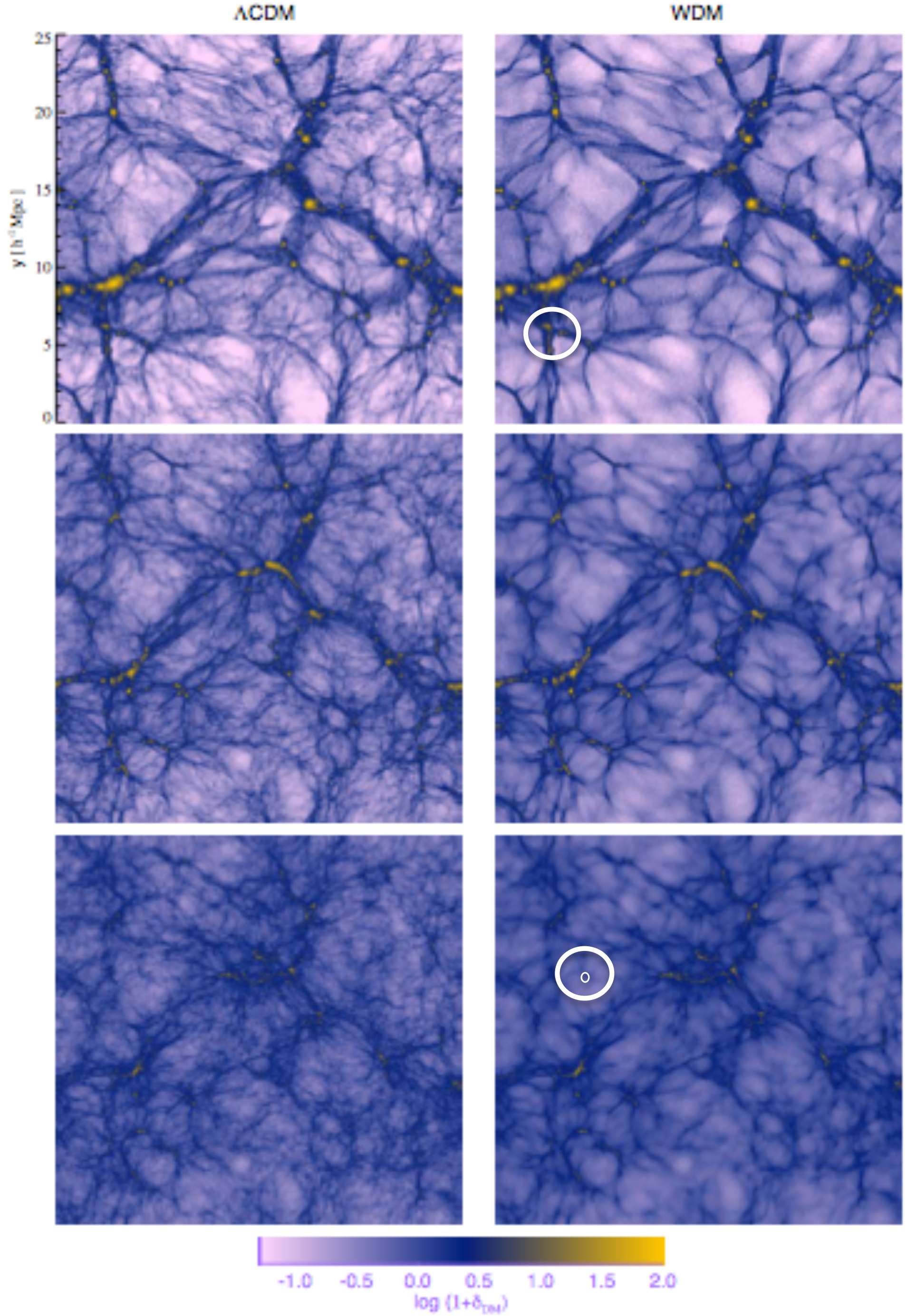
See also Costanzi et al. 2013 for clusters

COLDNESS OF COLD DARK MATTER

MV, Becker, Bolton, Haehnelt 2013, arXiv:1306.2314, PRD in press

Talks by Frenk, Lovell and Cole about WDM impact on LSS

THE COSMIC WEB in WDM/LCDM scenarios



z=0

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

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

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

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

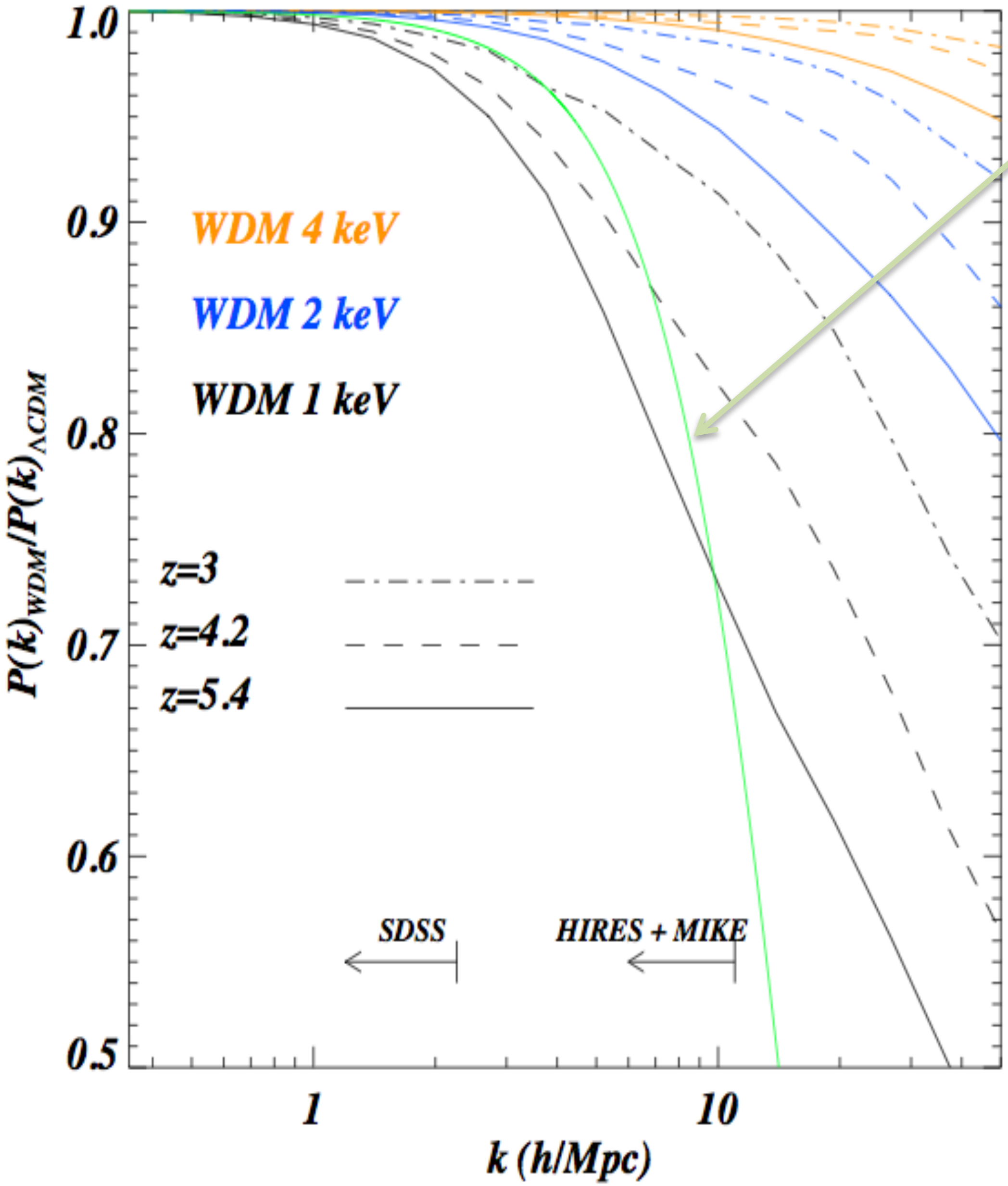
z=2

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

z=5

Viel, Markovic, Baldi & Weller 2013

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

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) HIGH REDSHIFT

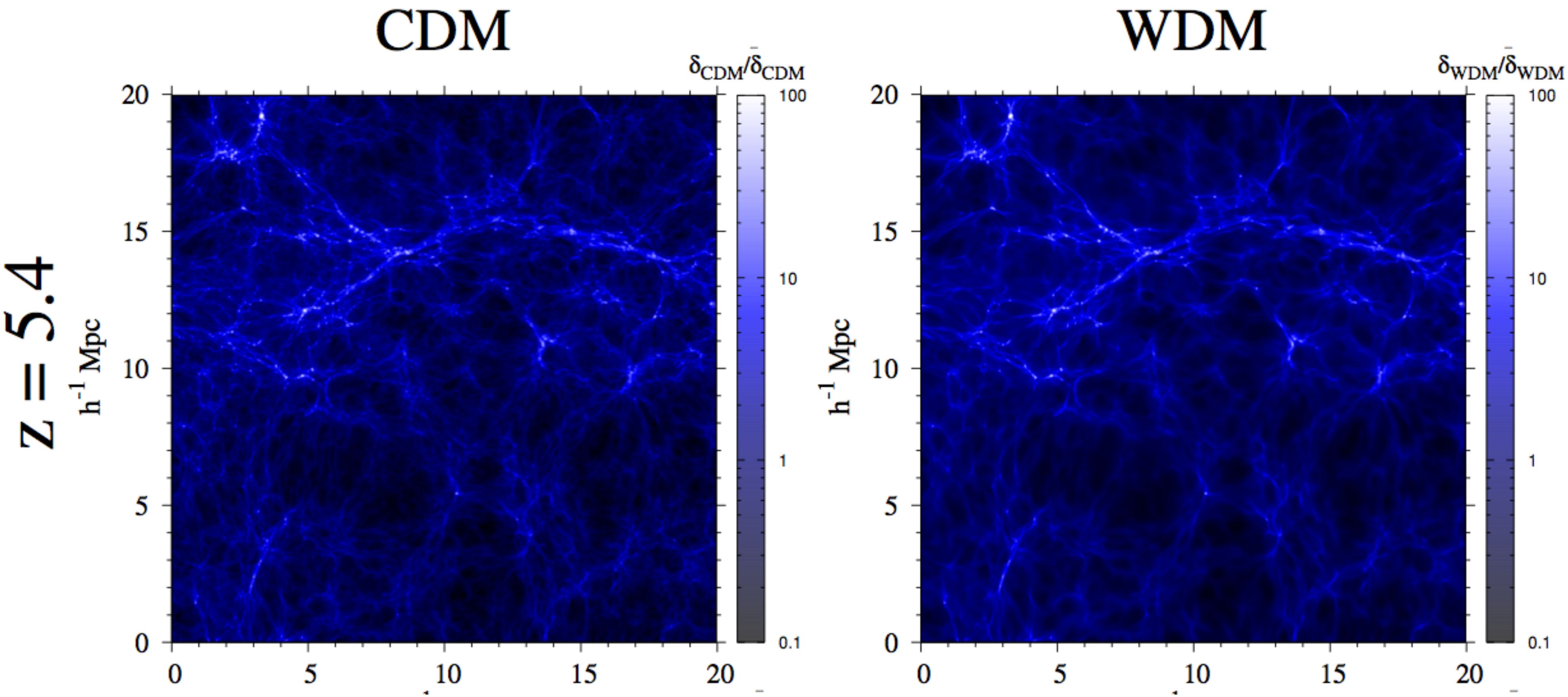
Where linear WDM cut-off is more prominent

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

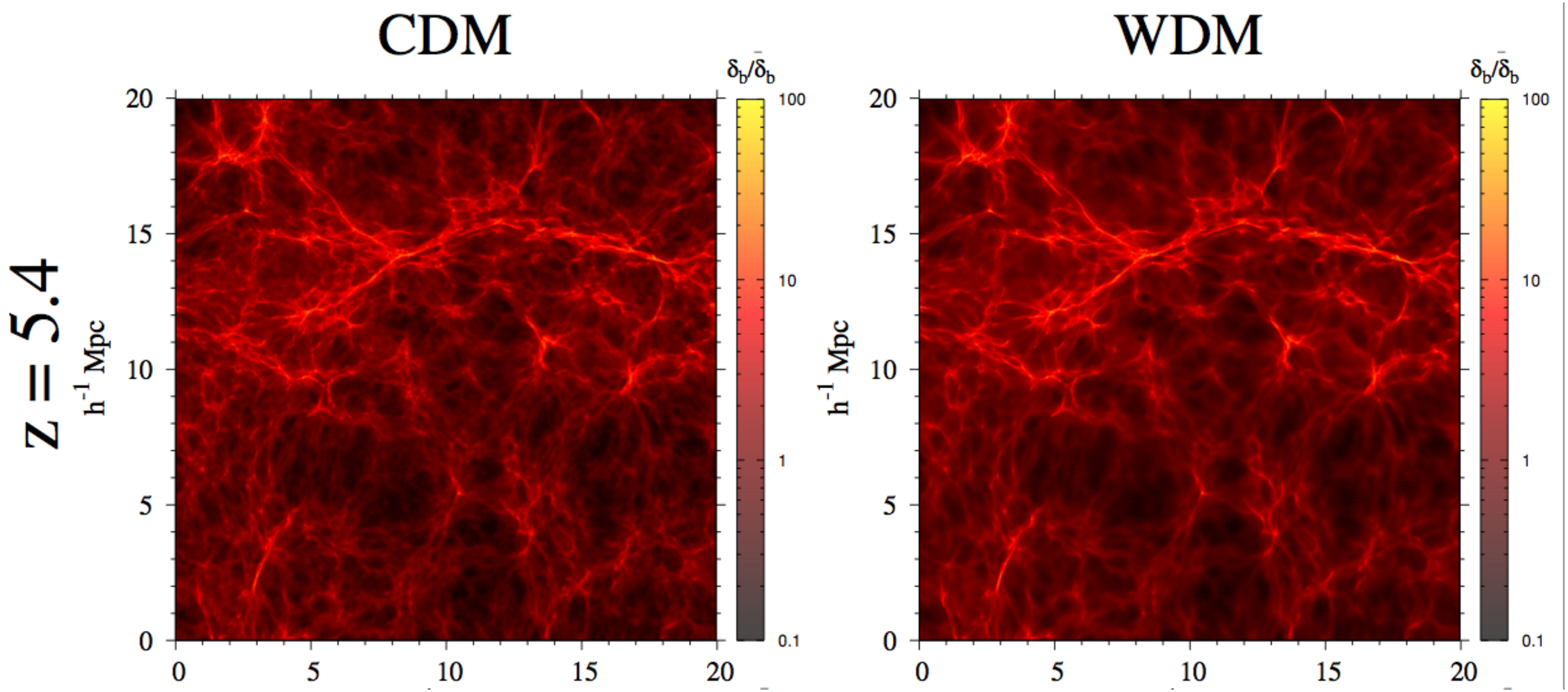
HISTORY OF WDM LYMAN-α BOUNDS

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

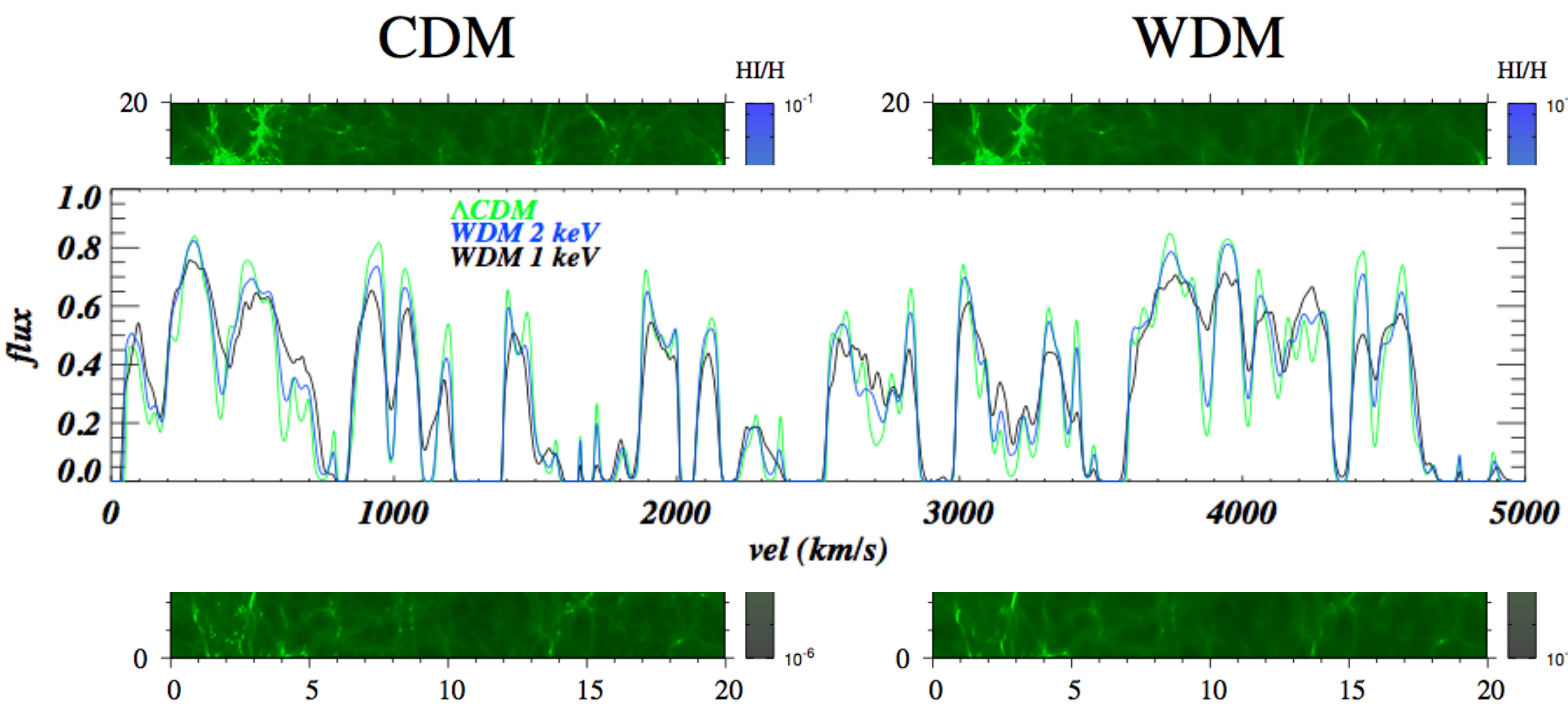
DARK MATTER DISTRIBUTION



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

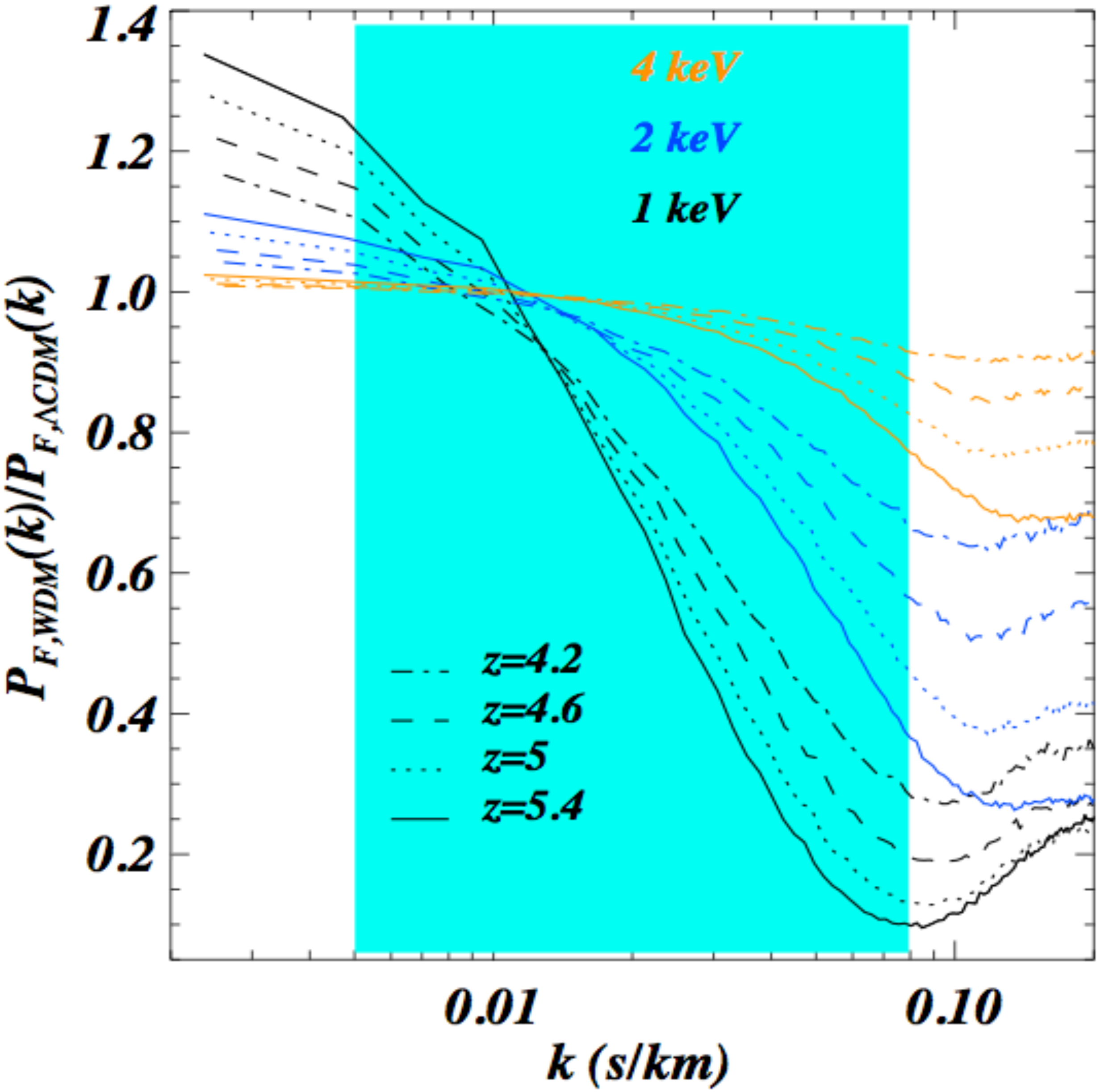
METHOD: Monte Carlo Markov Chains likelihood estimator
+ **very conservative assumptions** for the continuum fitting and error bars on the data

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

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

THE HIGH REDSHIFT WDM CUTOFF

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



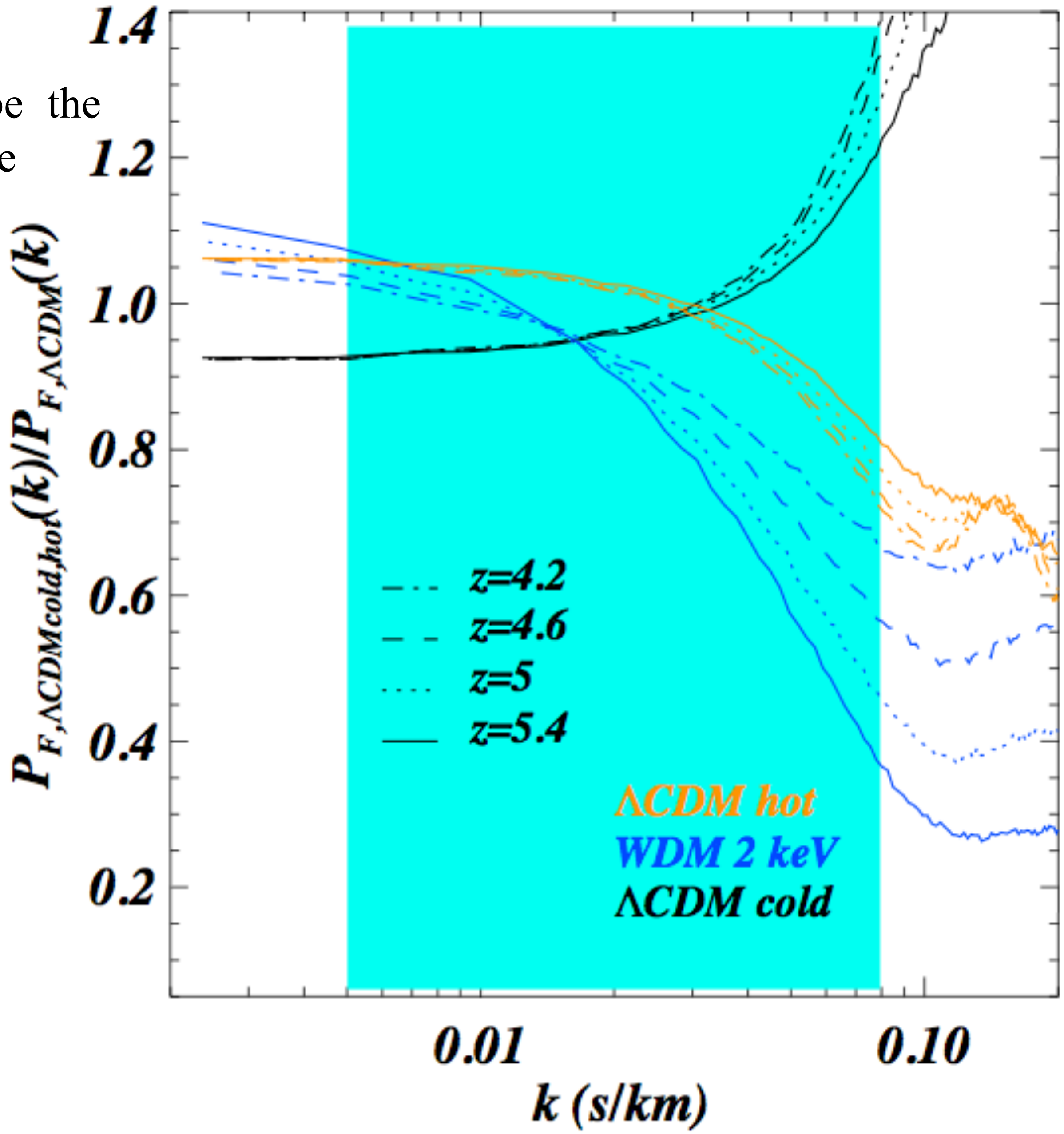
THE TEMPERATURE: T_0

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

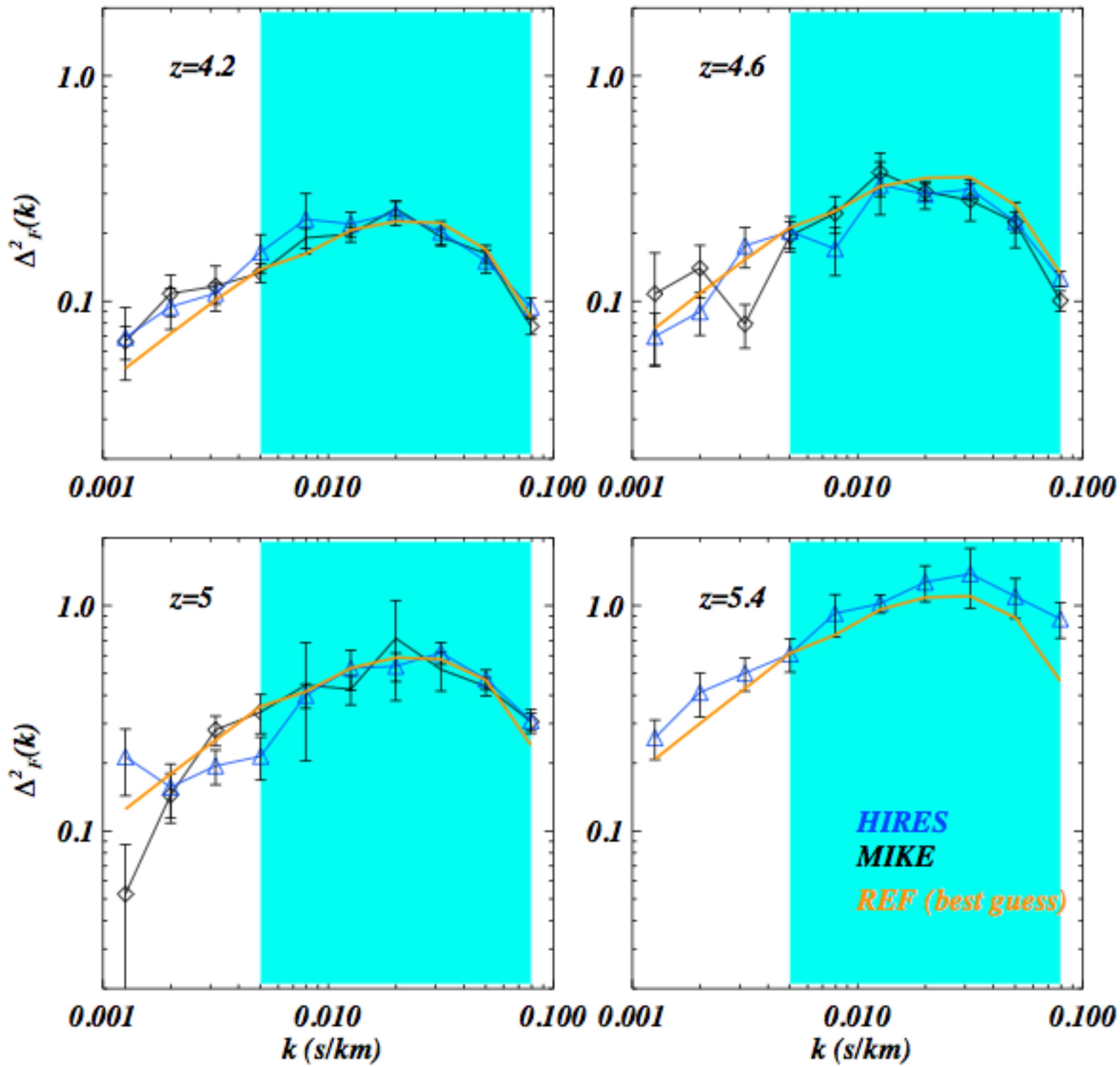
T_0 and γ describe the IGM thermal state

Hot + 3000 K
Cold – 3000 K

REF has 8300 K at z=4.6

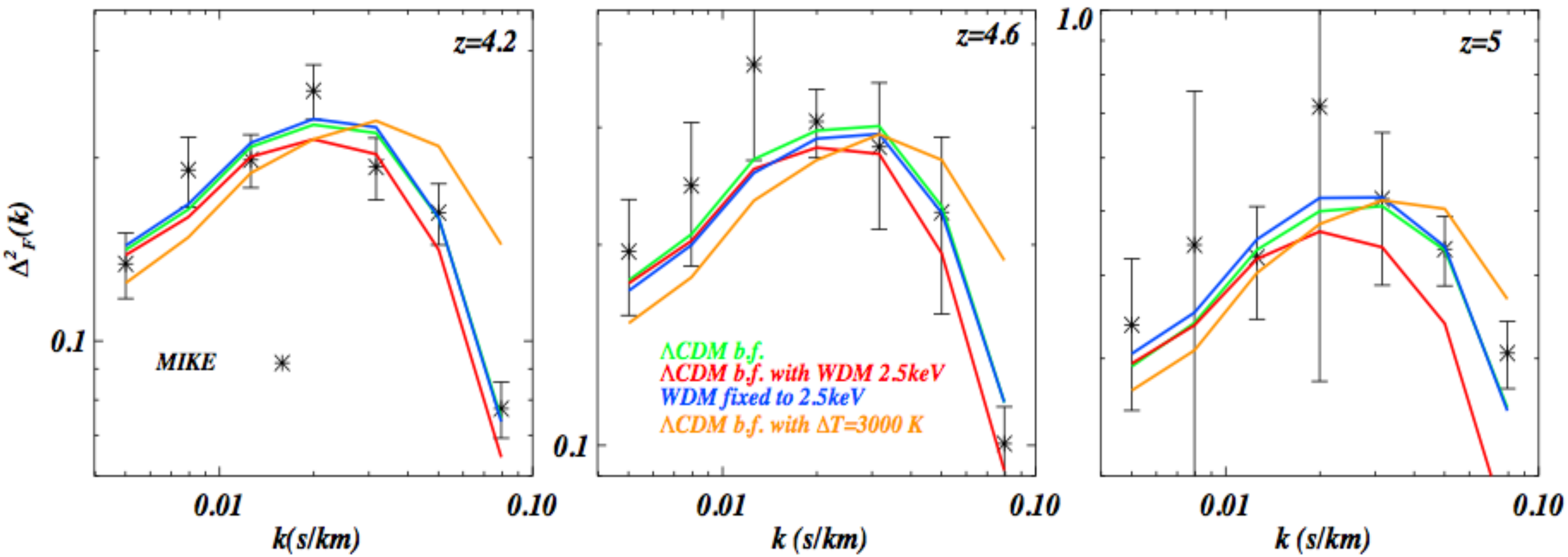


THE BEST GUESS MODEL

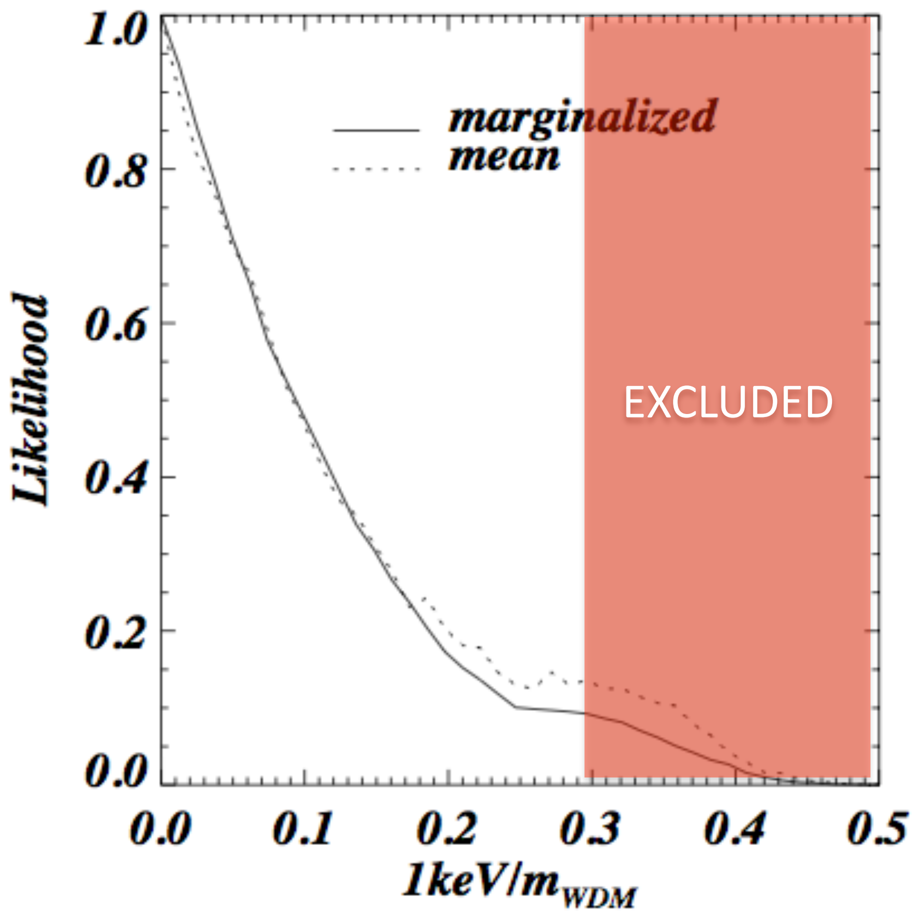


This is the starting point of the MCMC likelihood estimation cosmology close to Planck values

THE BEST FIT MODEL for MIKE



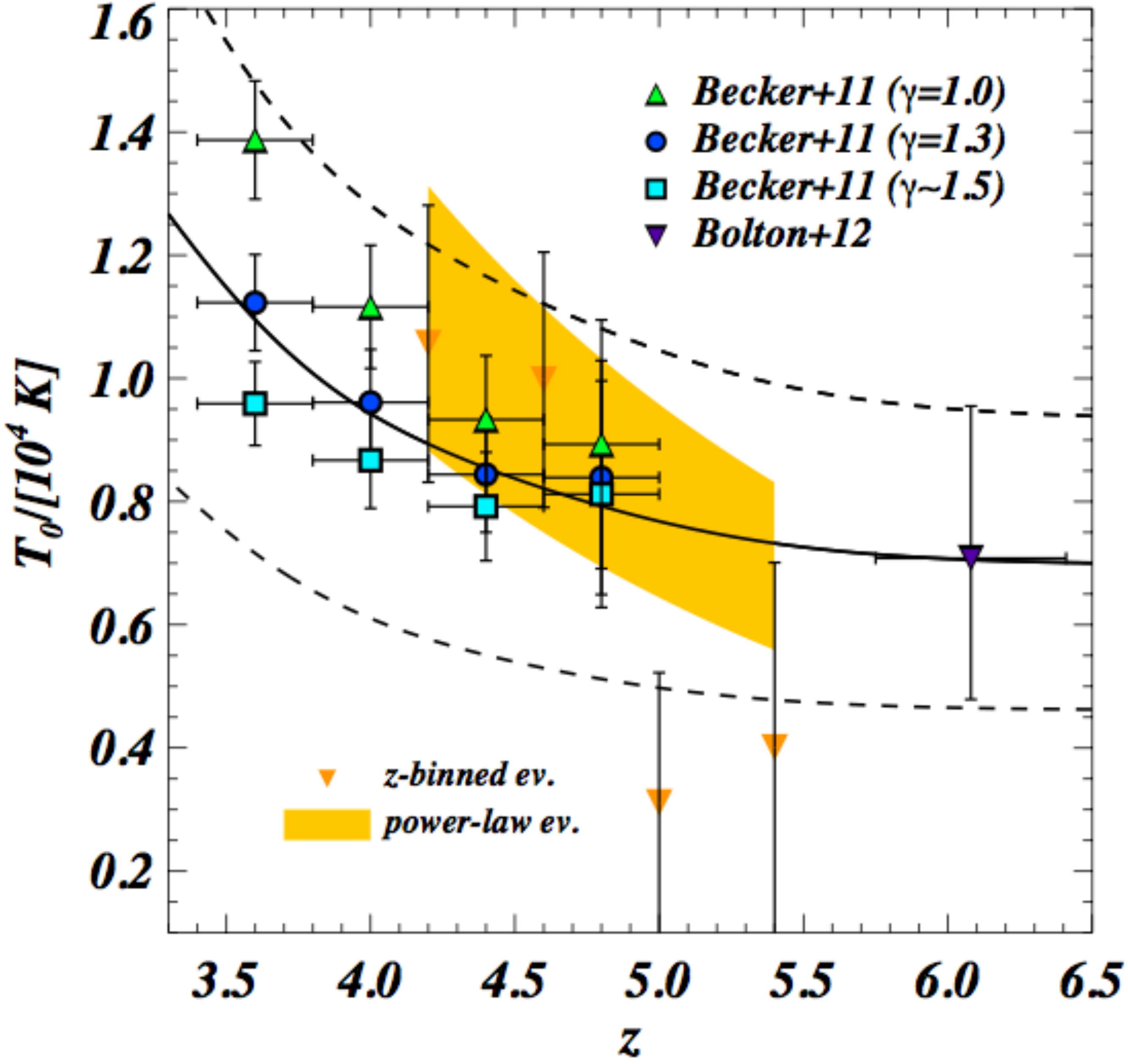
RESULTS FOR WDM MASS



m > 3.3 keV (2σ)

RESULTS FOR TEMPERATURE

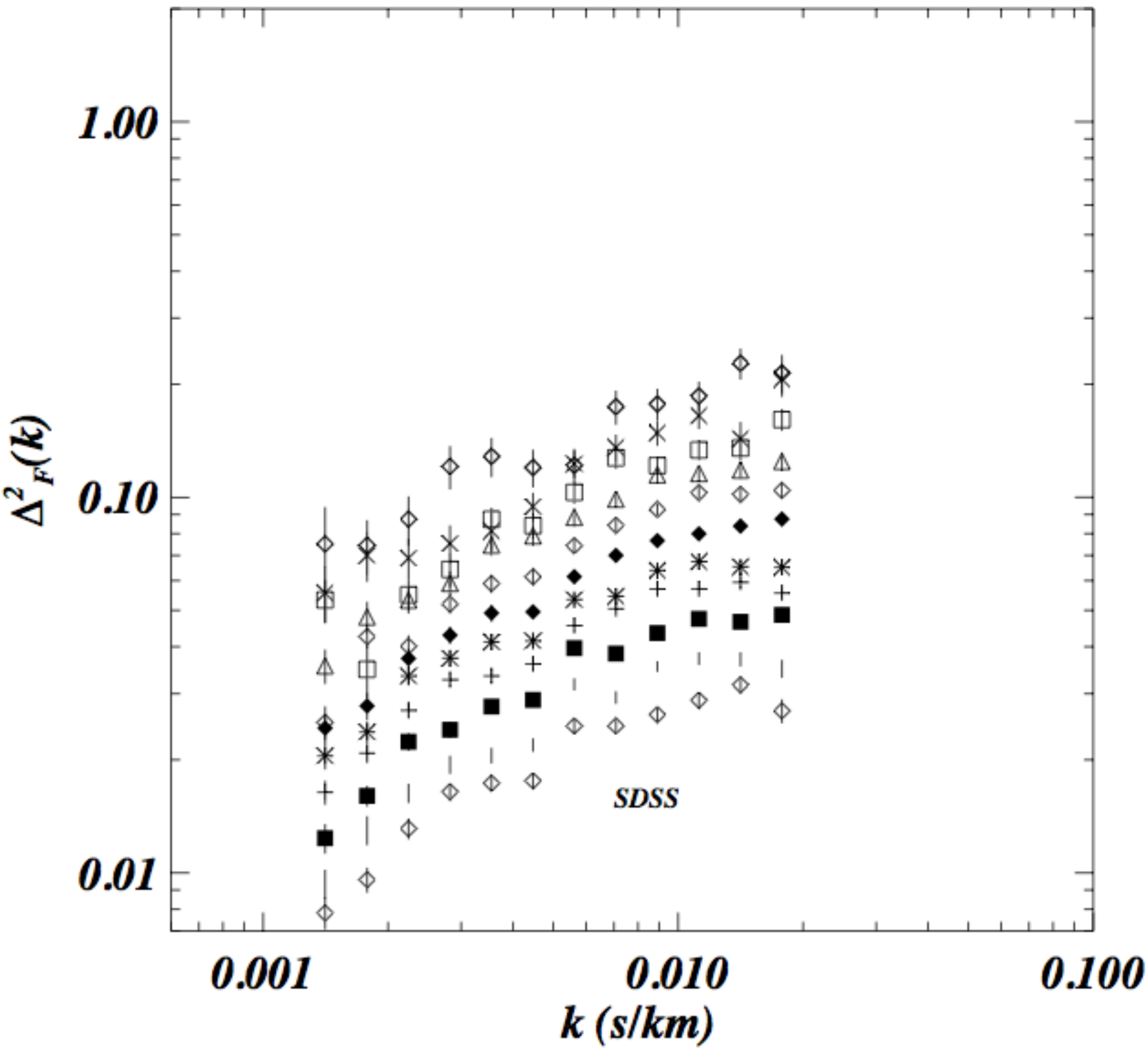
$$\gamma^A(z) = \gamma^A[(1+z)/5.5)]^{\gamma_A^S} \qquad T_0^A(z) = T_0^A[(1+z)/5.5)]^{T_0^S}$$



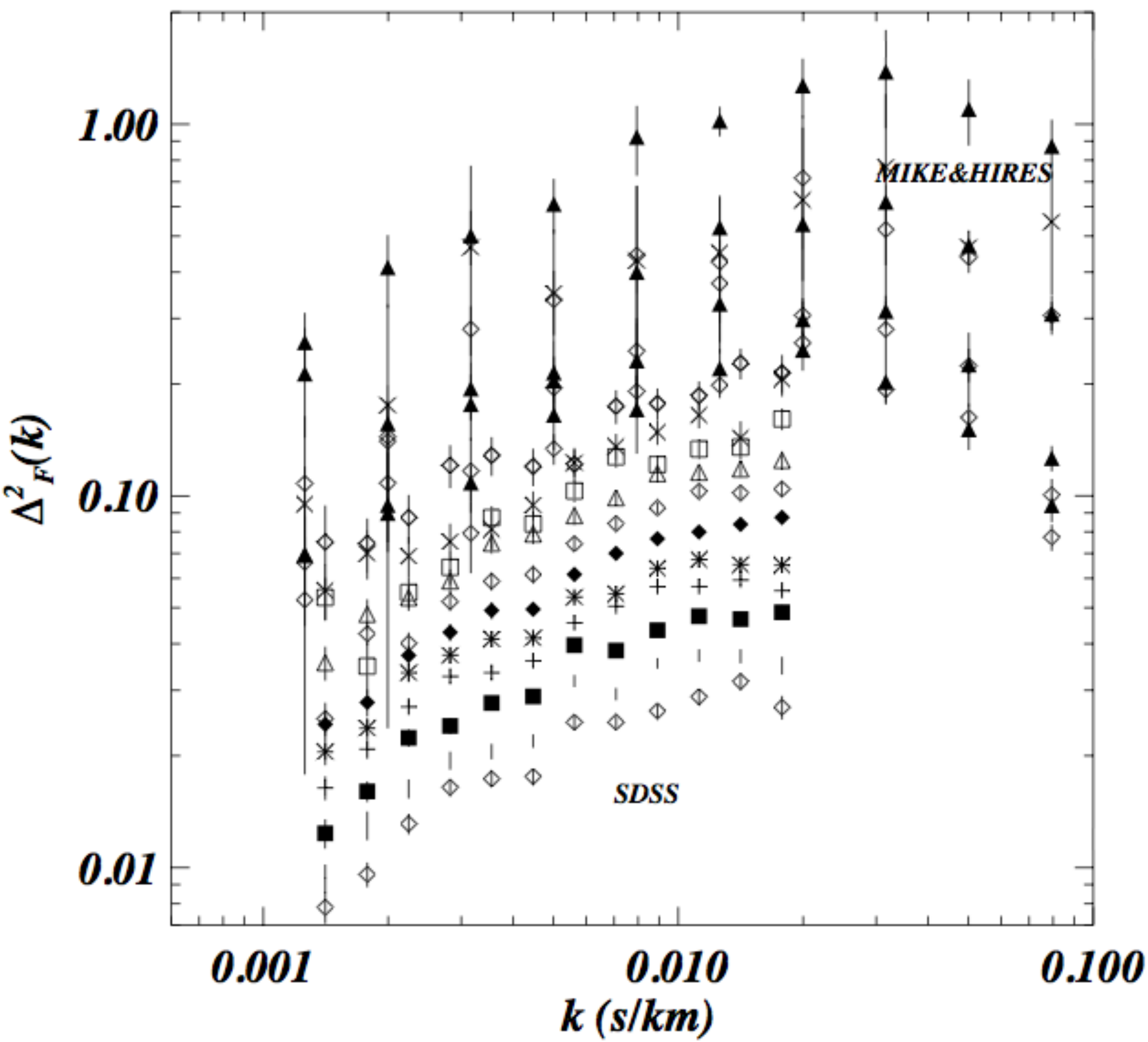
SDSS + MIKE + HIRES CONSTRAINTS

Joint likelihood analysis

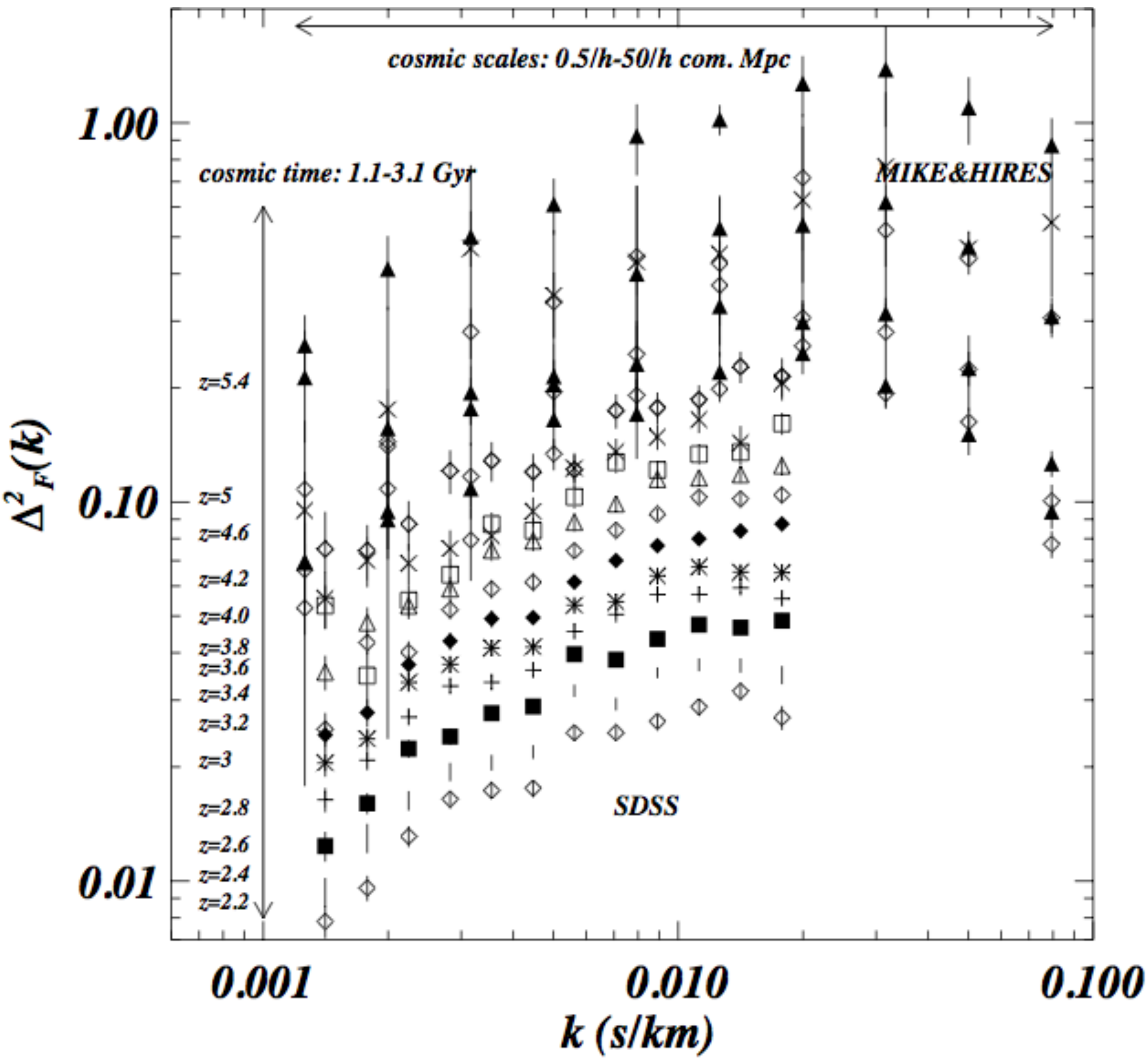
SDSS data from McDonald05,06 not BOSS



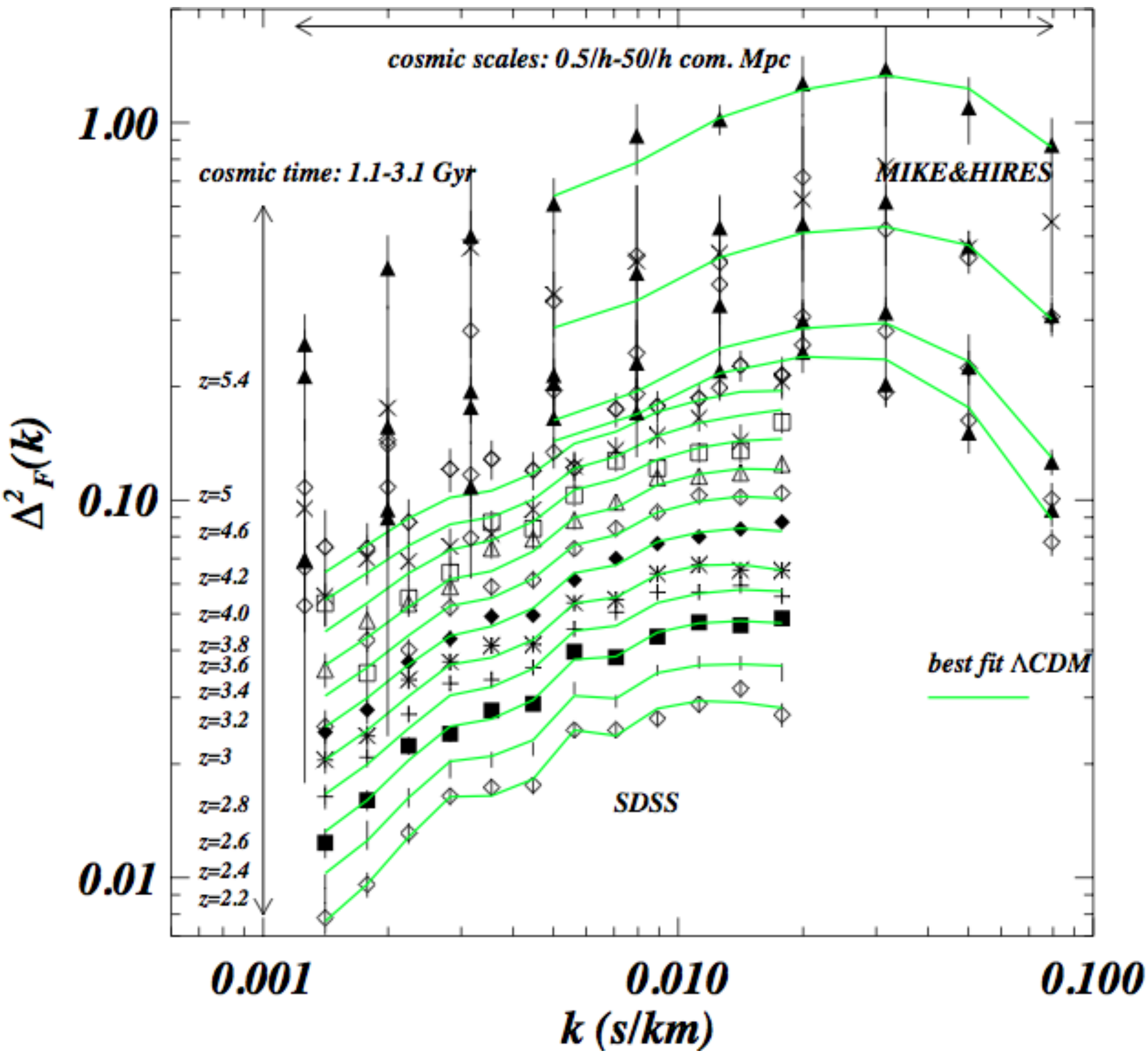
1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)

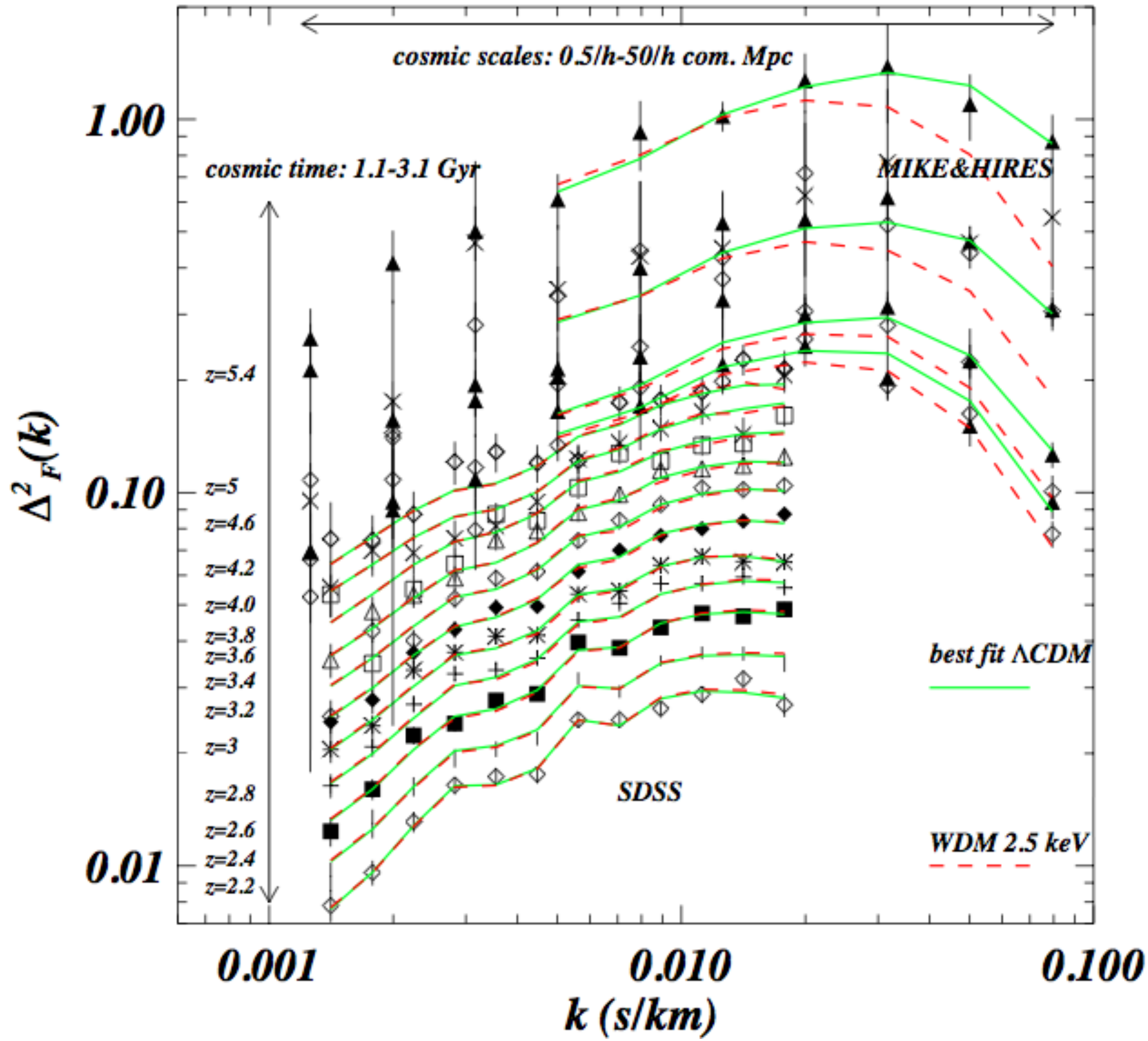


MIKE&HIRES
SDSS
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)



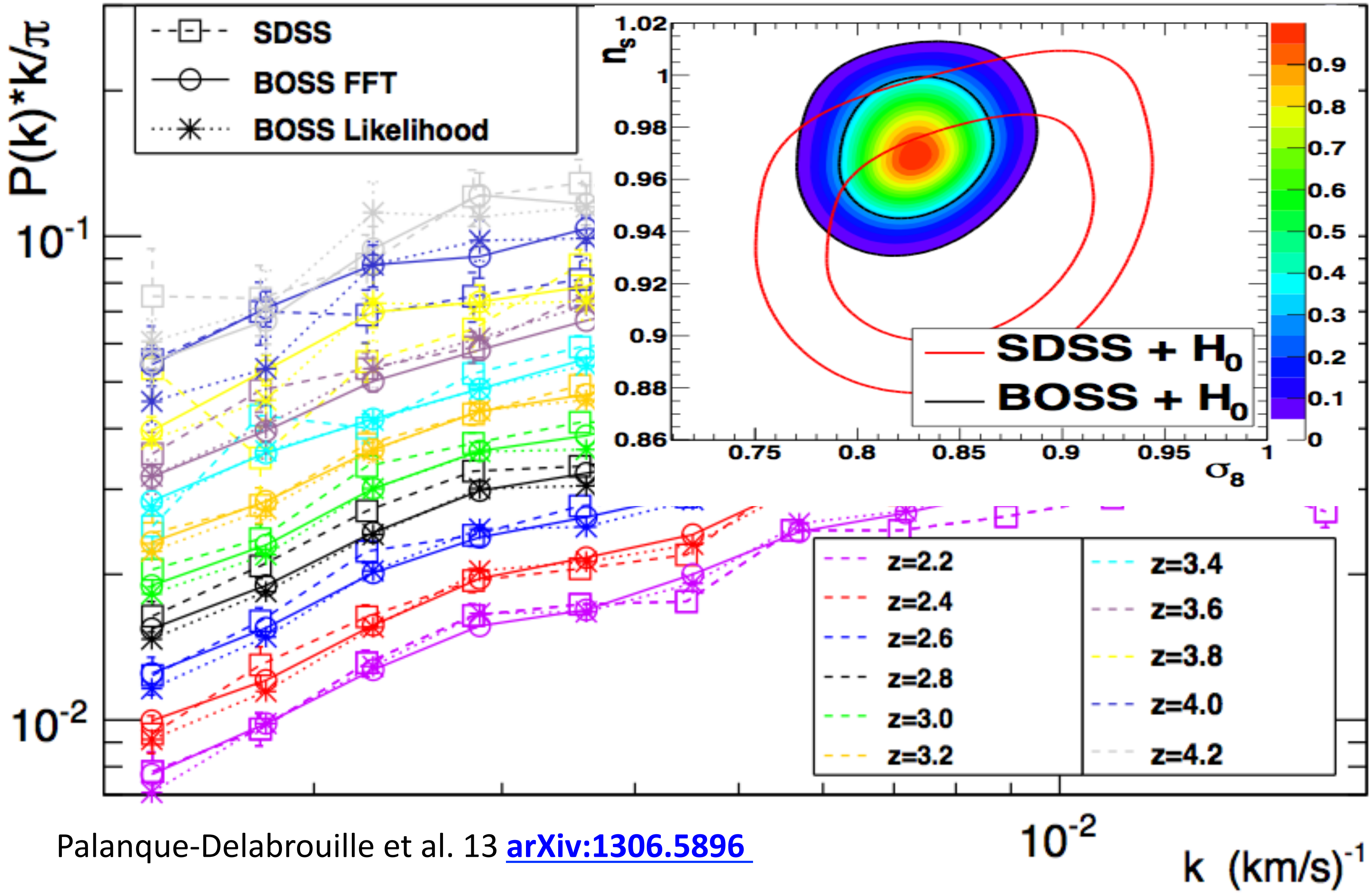
cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)


cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
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
best fit ΛCDM
SDSS
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
WDM 2.5 keV
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)

The one-dimensional Lyα forest power spectrum from BOSS



Palanque-Delabrouille et al. 13 arXiv:1306.5896

CONCLUSIONS - NEUTRINOS

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

CFHTLS data + VIPERS give 0.27 eV (2σ upper limit)

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

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

EXTRA SLIDES