The Coldness of Cold Dark Matter with the IGM

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OUTLINE

Introduction: small-scale crisis of cold dark matter

Warm Dark Matter implications for the Large Scale Structure

Constraints from the Lyman-α forest

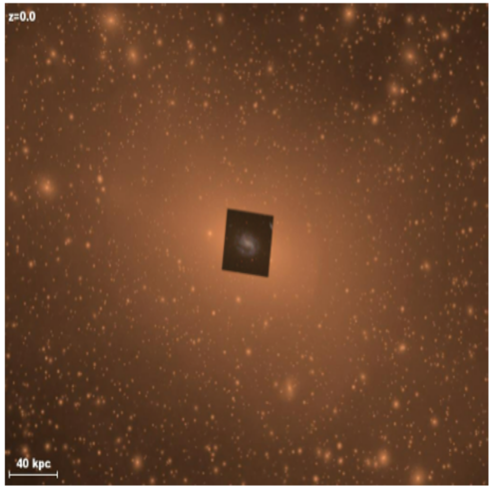
THE SMALL-SCALE CRISIS OF ΛCDM

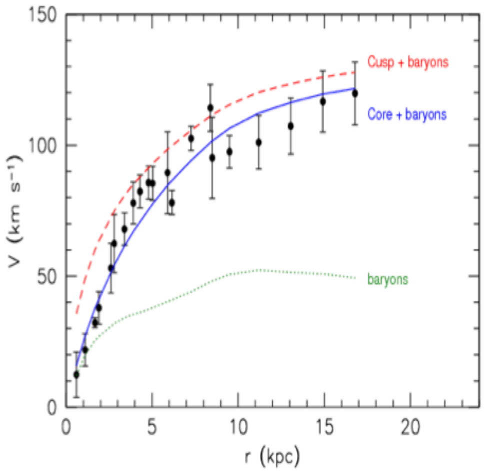
-Bode, Ostriker & Turok 01: number of satellites
profiles
clustering properties of dwarf galaxies

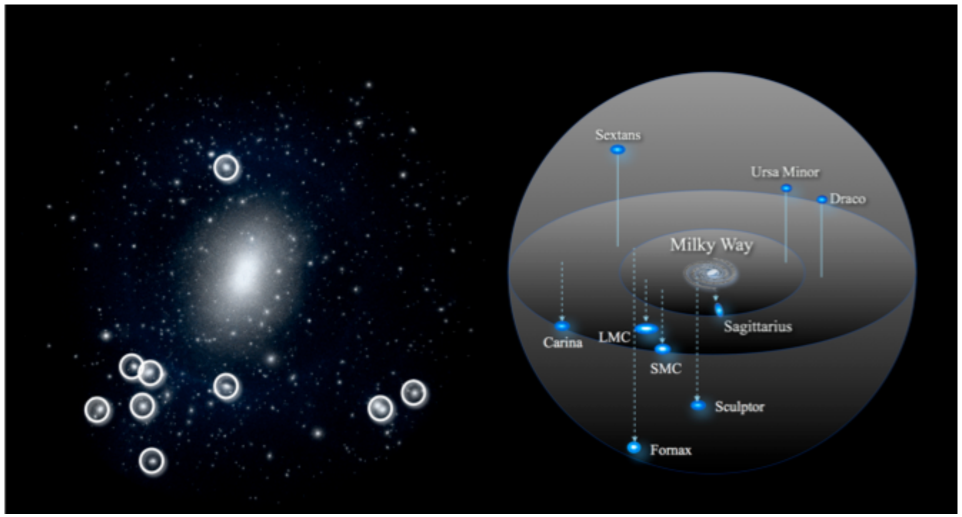
-Many more recent works on ΛCDM small-scale crisis

cusp/core

“too big to fail” problem (missing satellite)

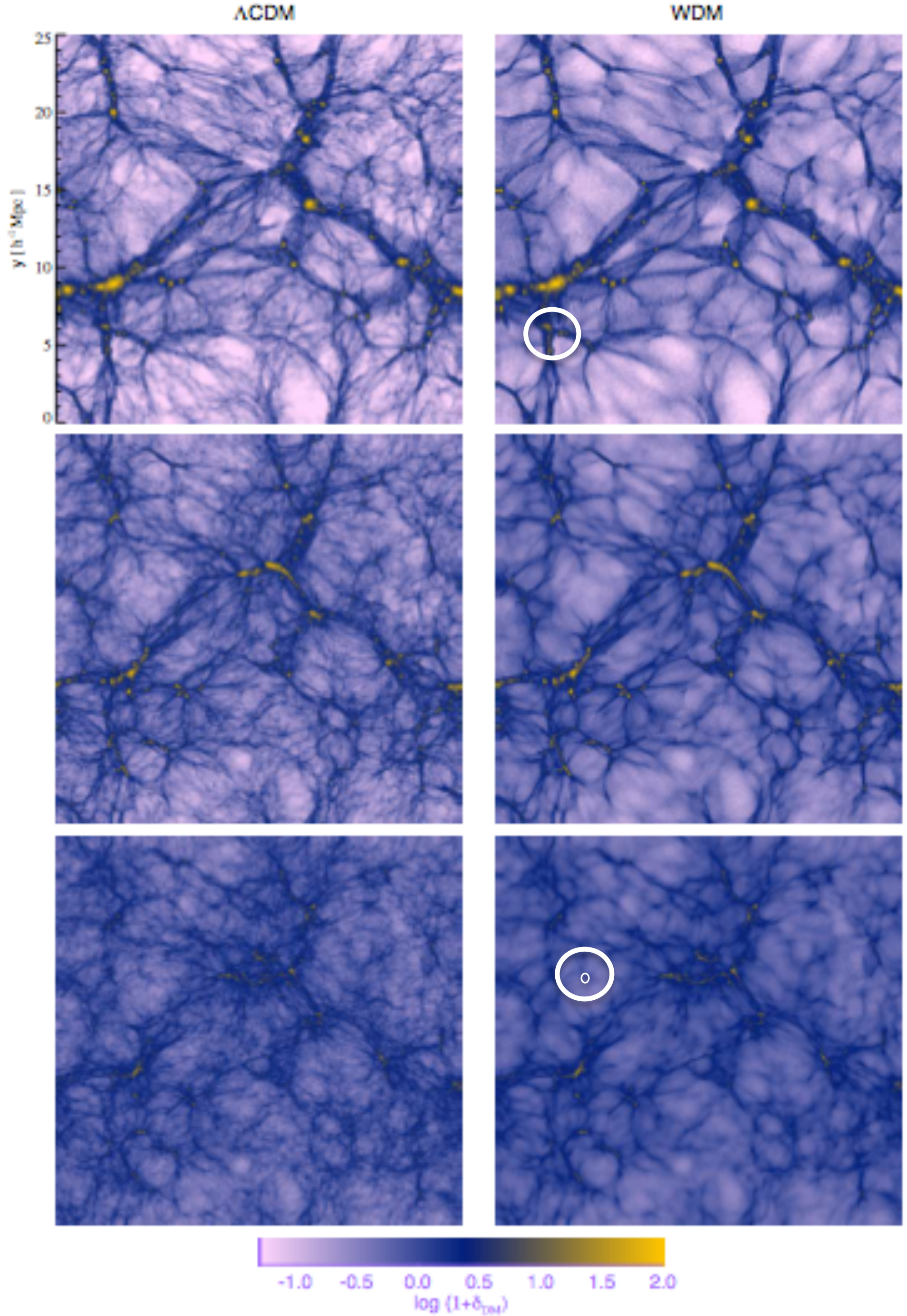






See recent Weinberg et al. arXiv:1306.0913

THE COSMIC WEB



z=0

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

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

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

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

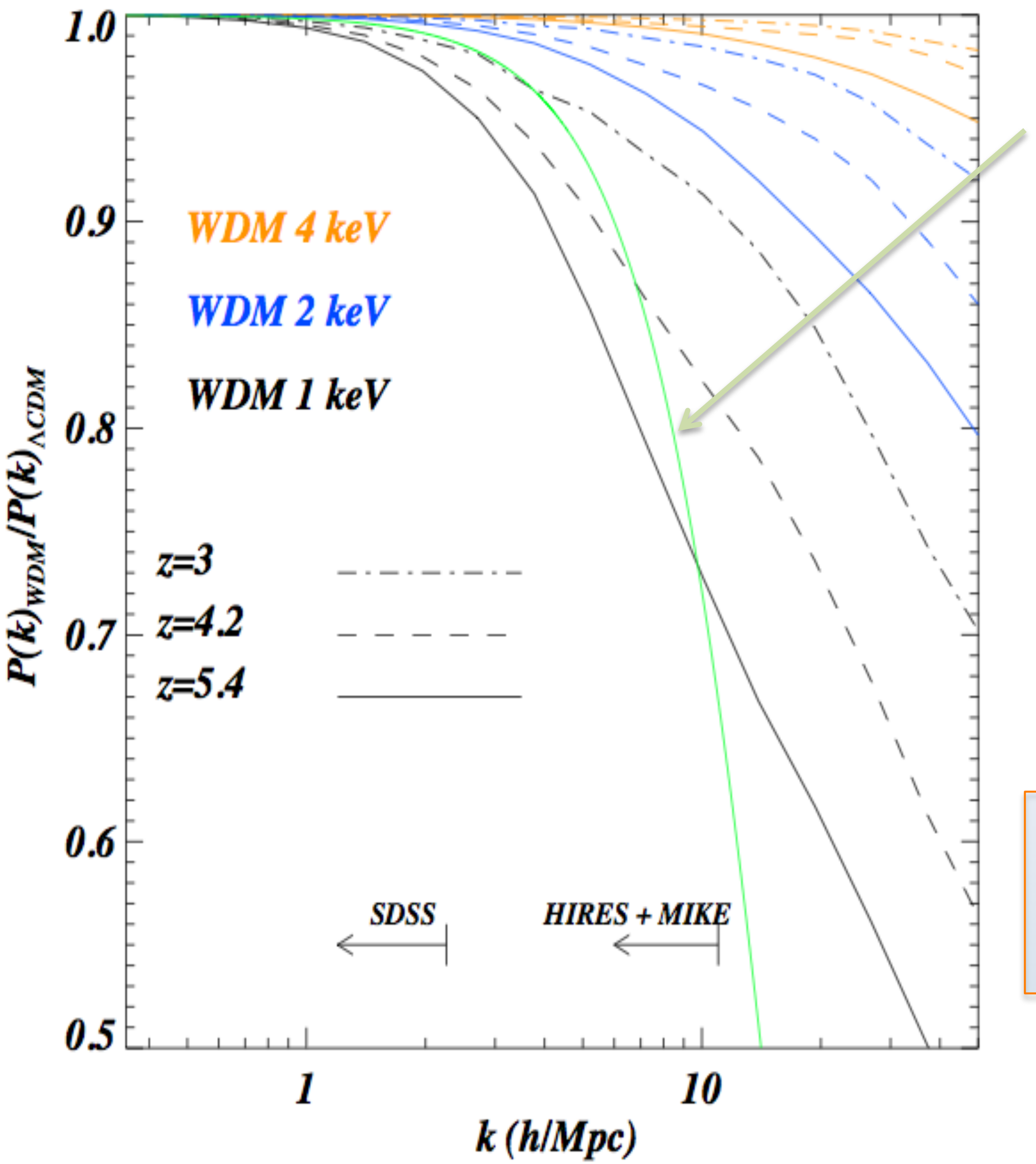
z=2

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

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

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

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

$\nu = 3$, $l = 0.6$ 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

QUESTION

Is the Lyman-α forest compatible with a cutoff in the matter power spectrum?

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**

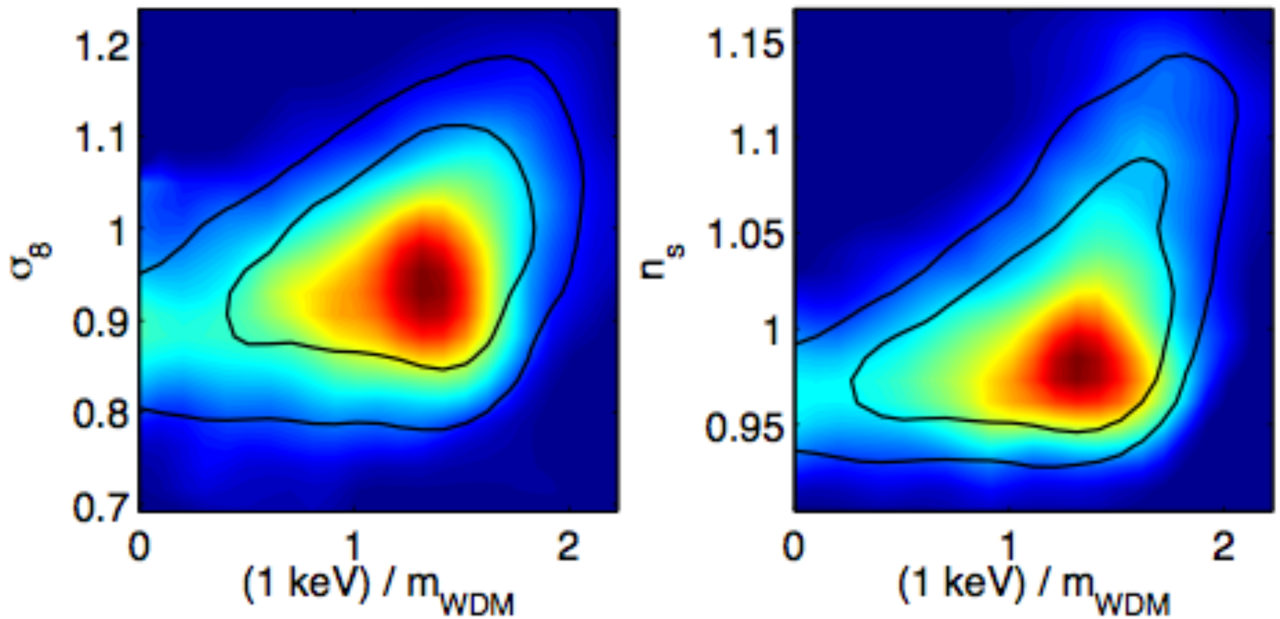
Where linear WDM cut-off is more prominent

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

CONSTRAINTS FROM UVES/VLT SPECTRA

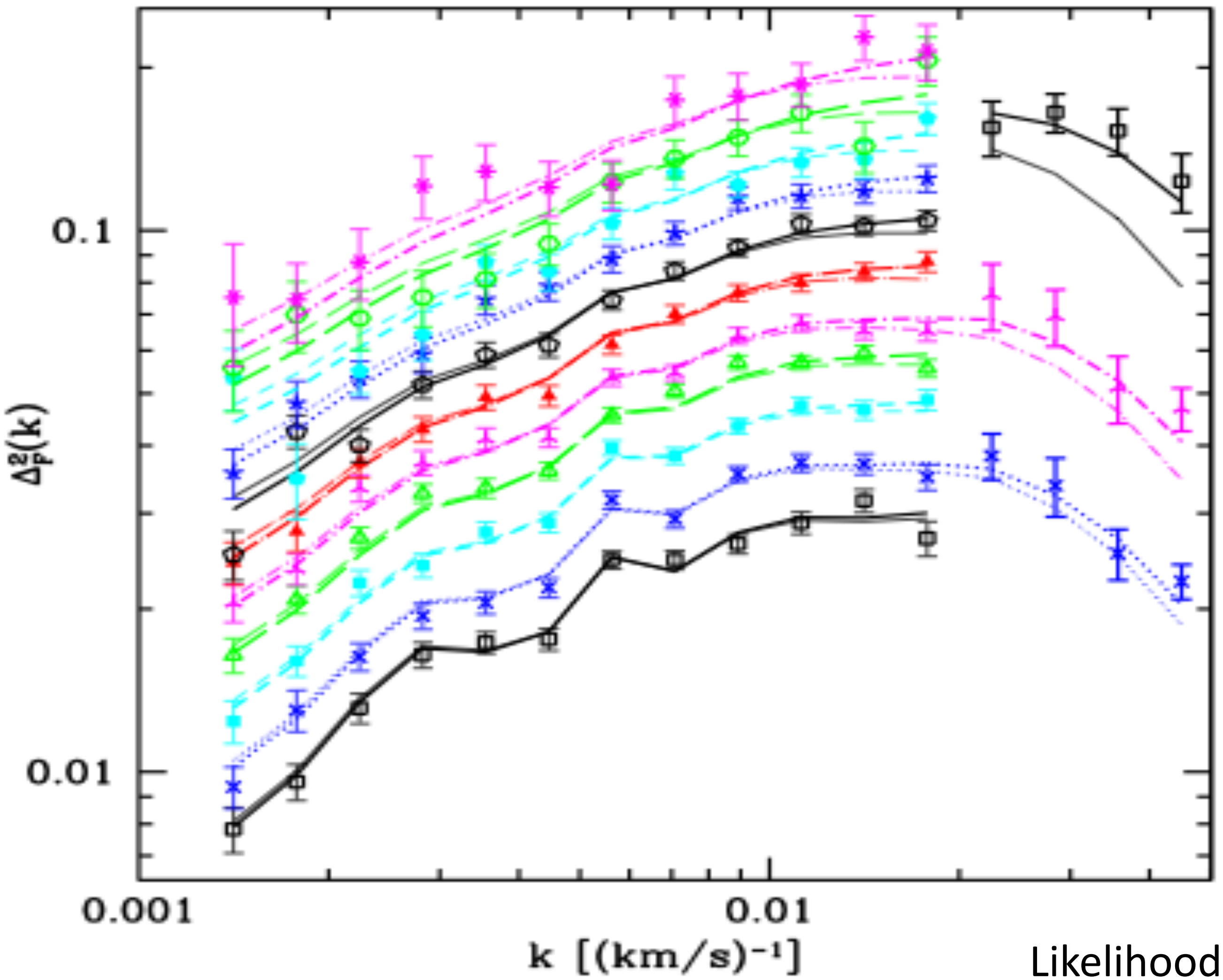
3D flux power spectrum $P_F(k)= b_{eff}(k,z)^2\ P(k)$



Degeneracies are present, z=2.12 and z=2.7 data analysed with the effective bias model of Croft et al. 02

MV + 2005, PRD, 71, 063534

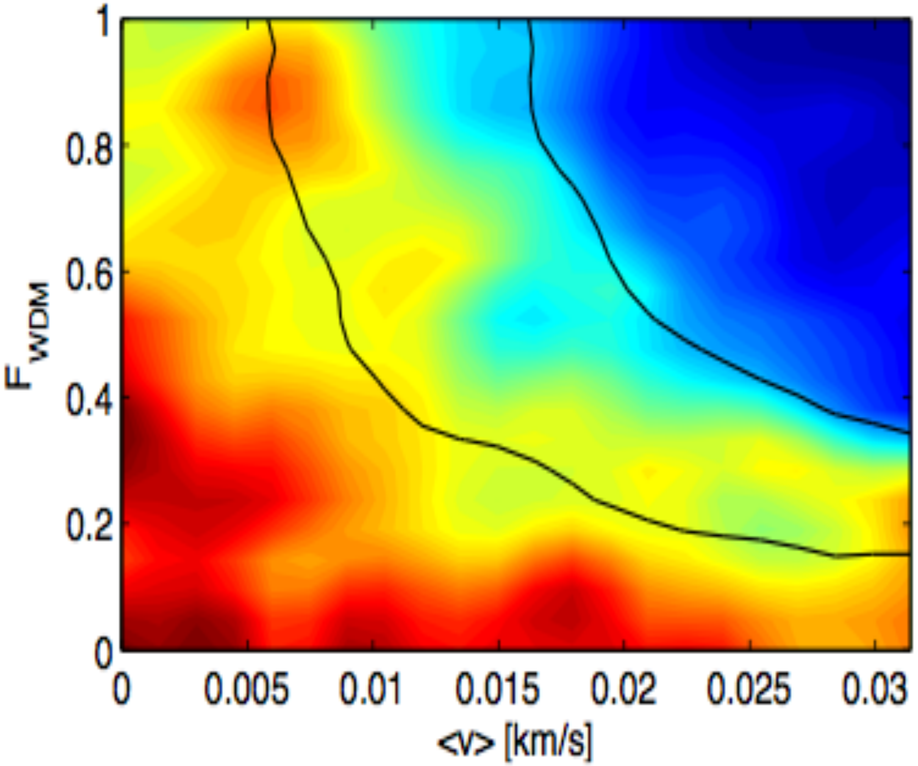
CONSTRAINTS FROM SDSS SPECTRA

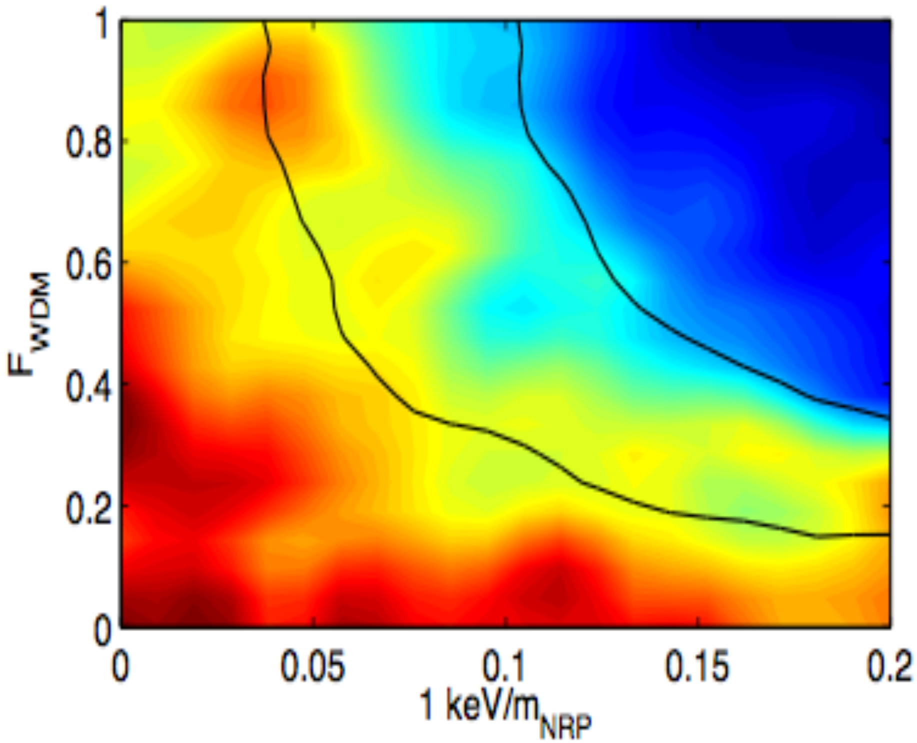


Likelihood sampling with HPM sims.

Seljak et al. 2006

CONSTRAINTS FROM SDSS vs UVES SPECTRA





m 1keV

m 2keV 1keV

Boyarsky, Ruchayasky, Lesguorgues, Viel, 2009, JCAP, 05, 012

"Warm Dark Matter as a solution to the small scale crisis: new constraints from high redshift Lyman-α forest data"

MV, Becker, Bolton, Haehnelt 2013, arXiv:1306.2314

DATA: 25 high resolution QSO spectra at $4.48<z_{em}<6.42$
from MIKE and HIRES spectrographs
Becker, Bolton, Haenelt, Sargent (2011)

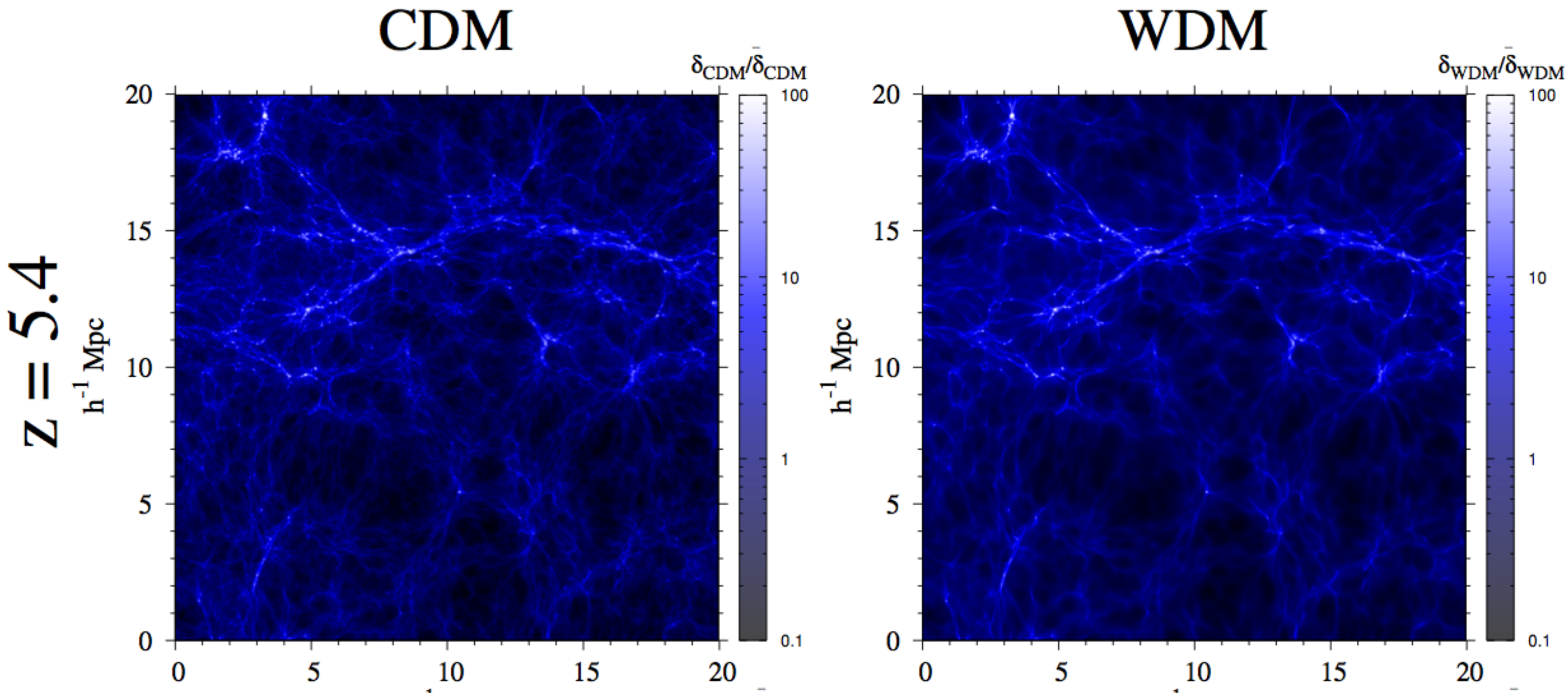
SIMULATIONS: Gadget-III
runs: 20 and 60 Mpc/h and $(512^3, 786^3, 896^3)$
Cosmology parameters: σ_8, n_s, Ω_m, H_0, m_{WDM}
Astrophysical parameters: z_{reio}, UV fluctuations, T_0, γ, $<F>$
Nuisance: resolution, S/N, metals

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

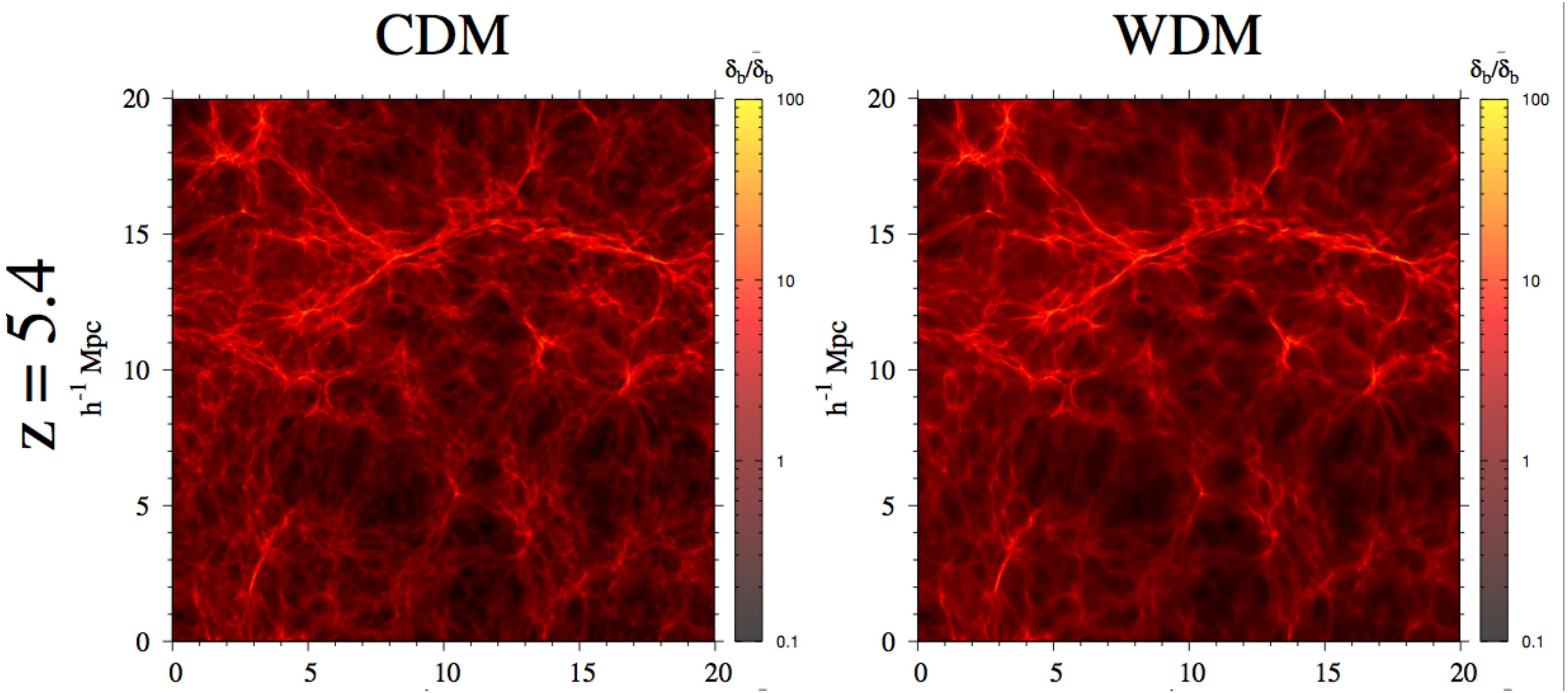
Parameter space: m_{WDM}, T_0, γ, $<F>$ explored fully
Parameter space: : σ_8, n_s, Ω_m, H_0, UV explored with second order Taylor expansion of the flux power

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

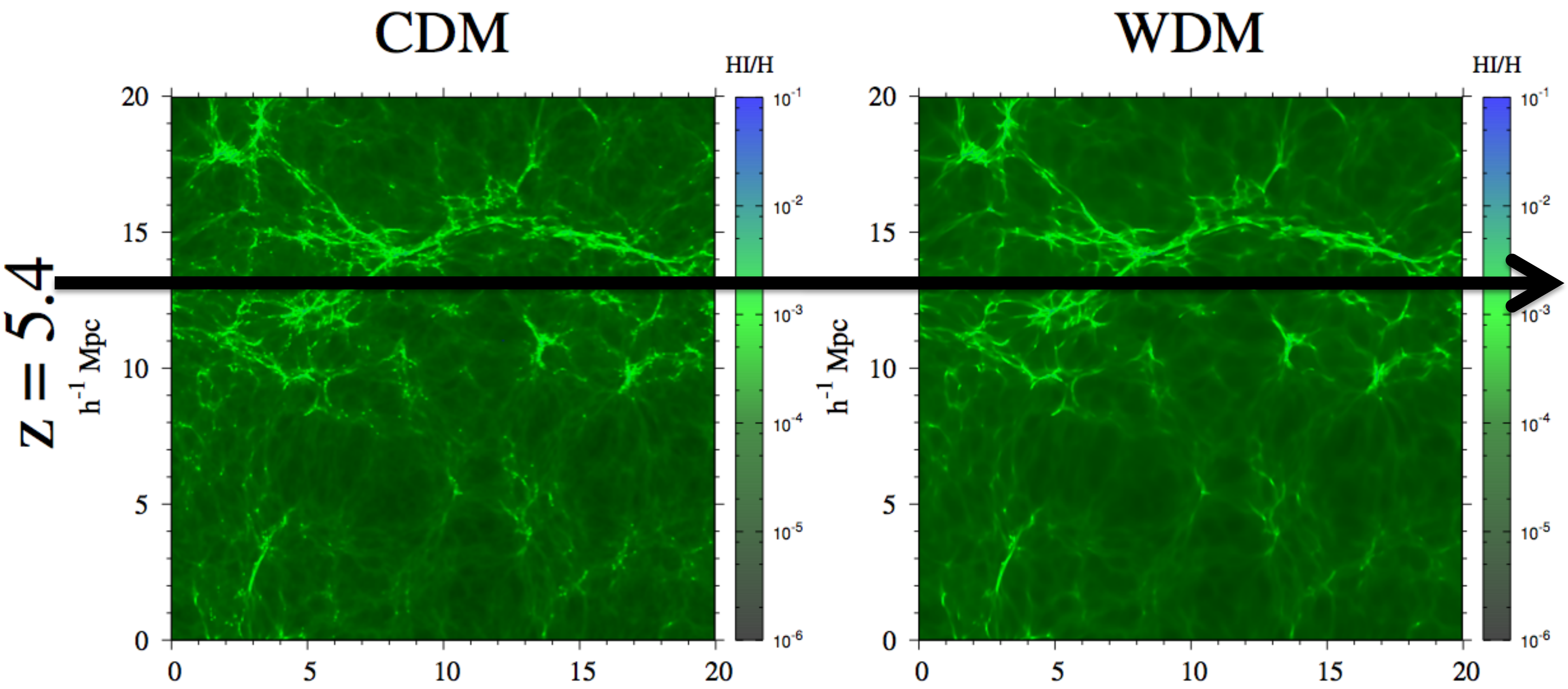
DARK MATTER DISTRIBUTION

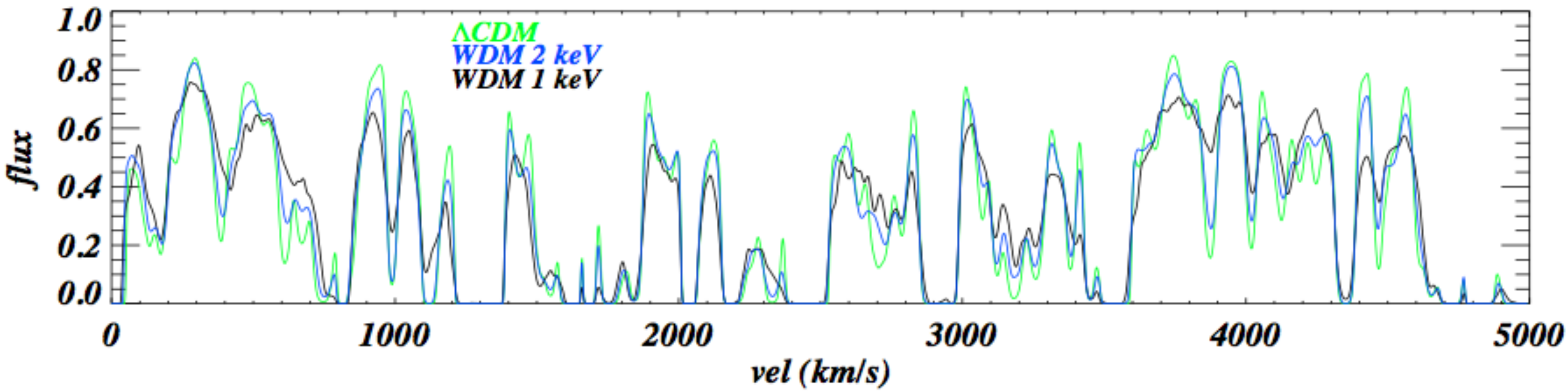


GAS DISTRIBUTION



HI DISTRIBUTION

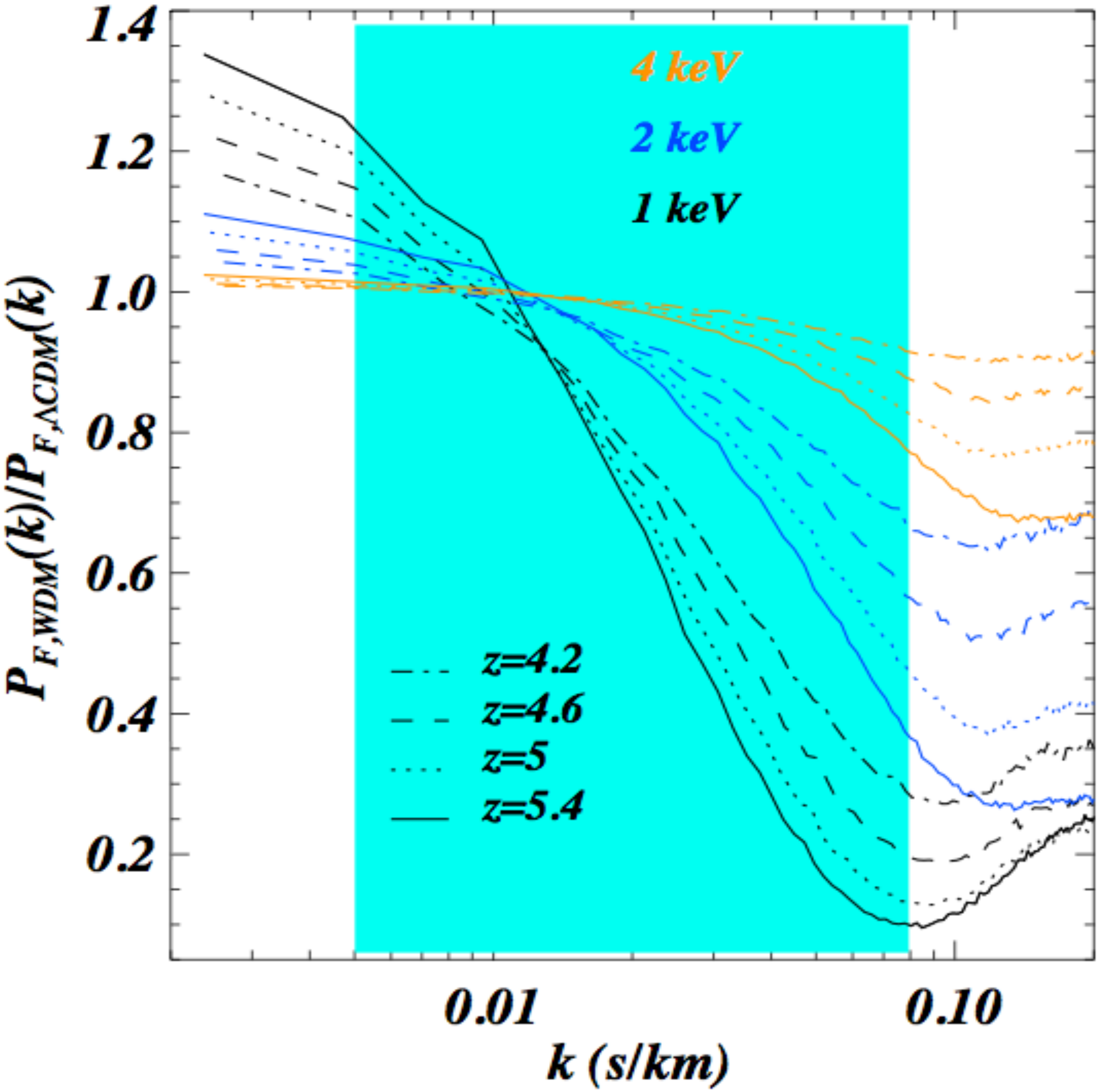




ΛCDM
WDM 2 keV
WDM 1 keV
1.0
0.8
0.6
0.4
0.2
0.0
flux
0
1000
2000
3000
4000
5000
vel (km/s)

THE HIGH REDSHIFT WDM CUTOFF

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

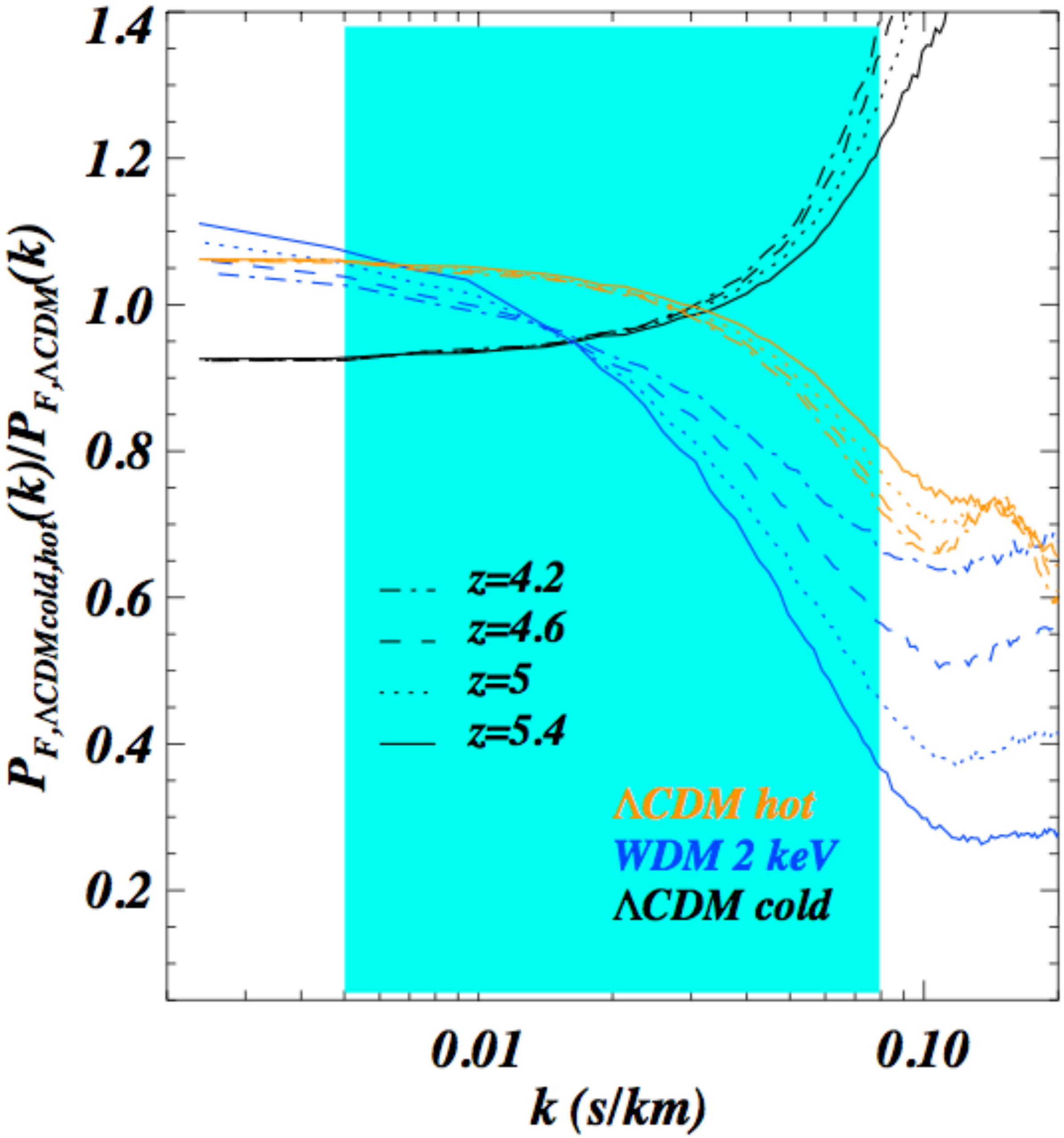


THE TEMPERATURE: T_0

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

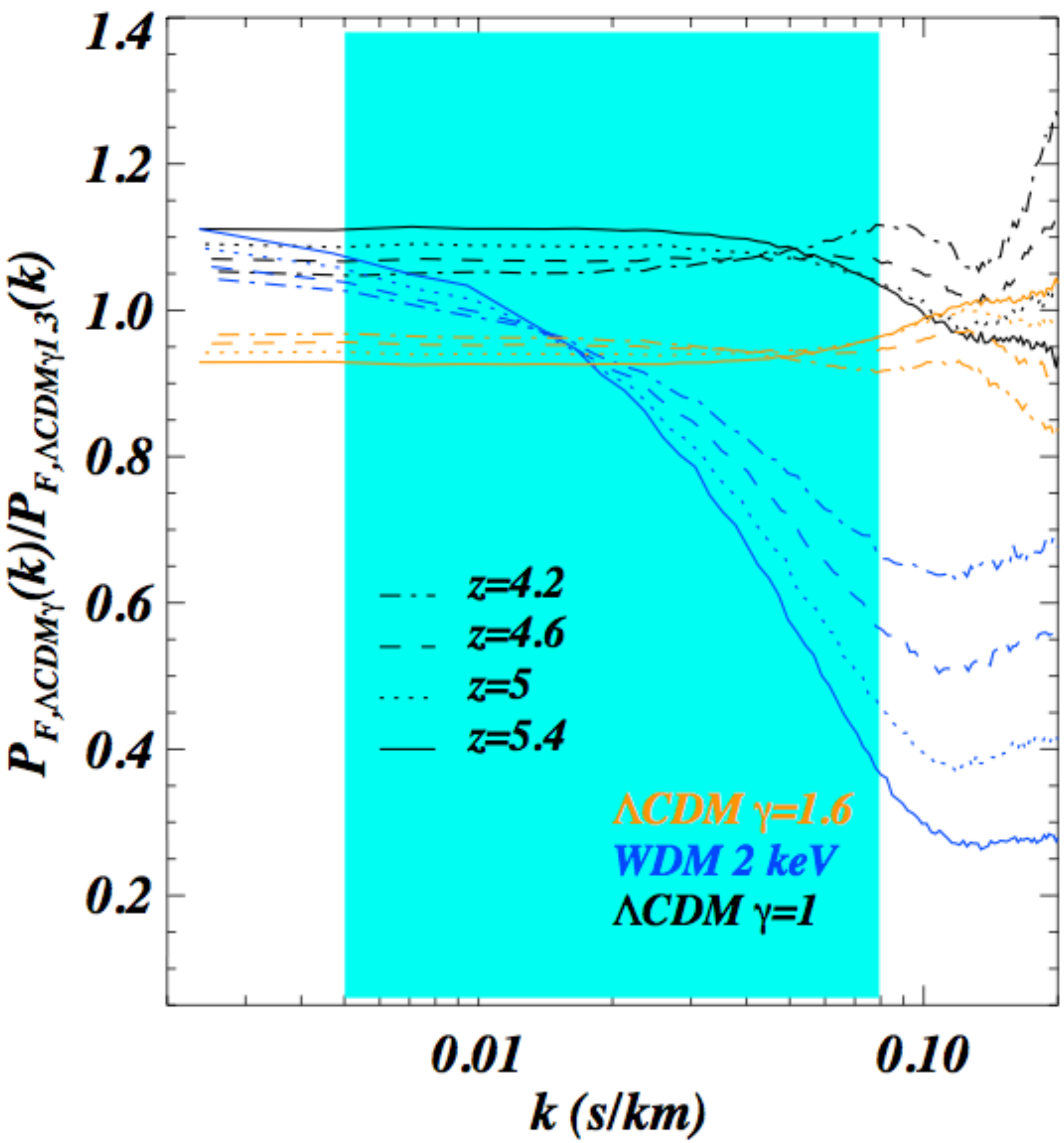
Hot + 3000 K
Cold – 3000 K

REF has 8300 K
at z=4.6

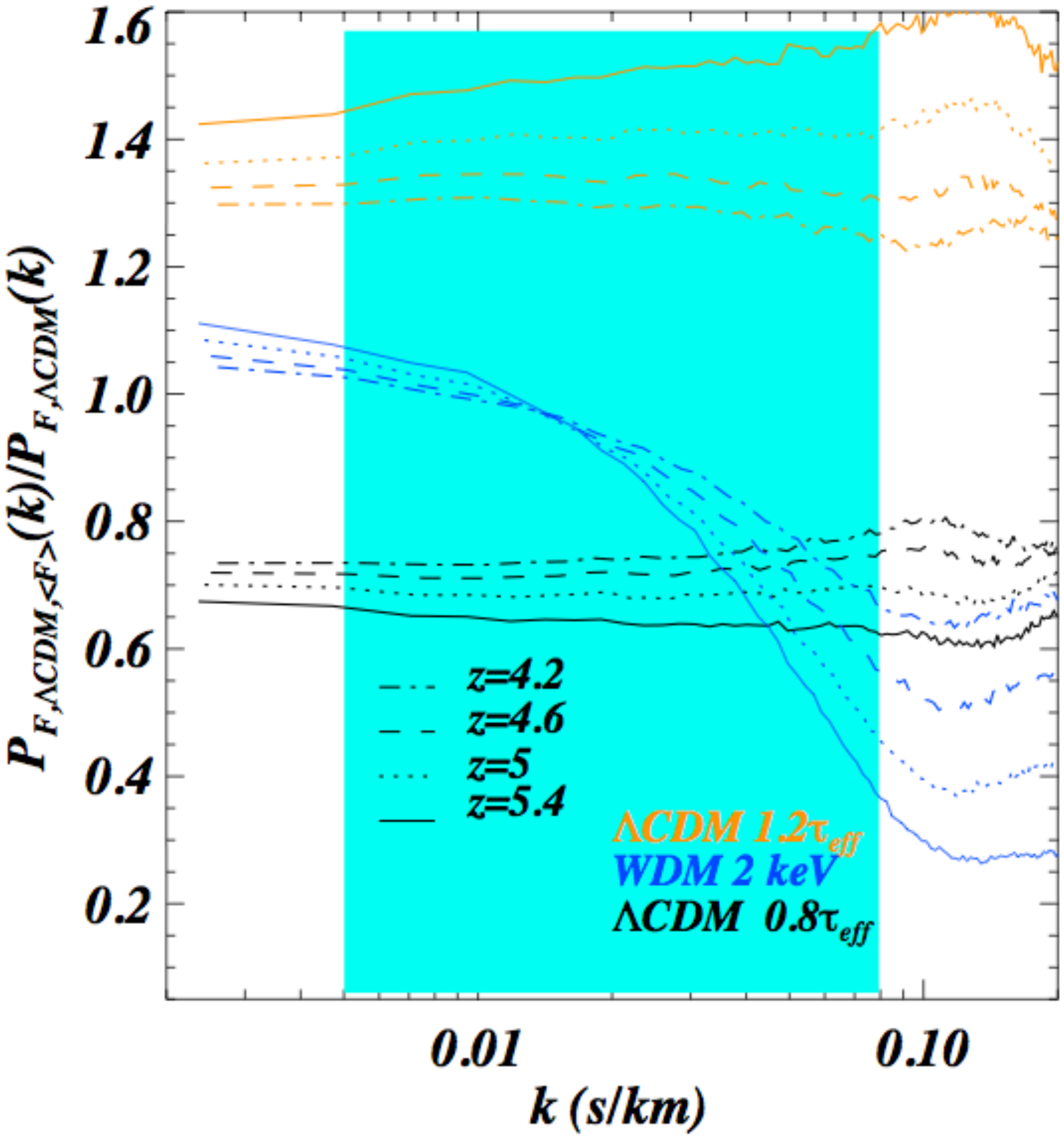


THE TEMPERATURE: γ

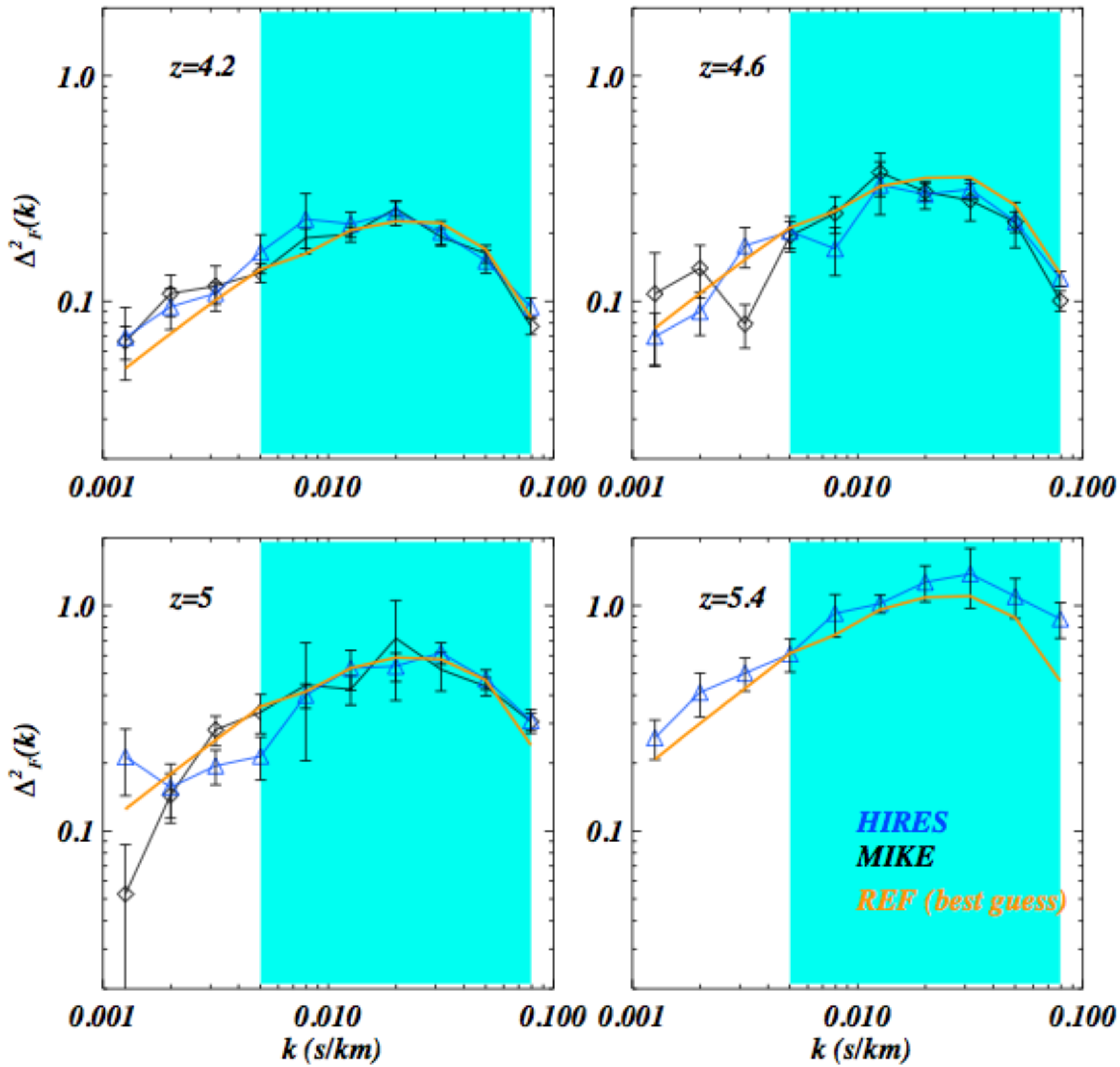
$T=T_0(1+\delta)^{\gamma-1}$



THE MEAN FLUX LEVEL

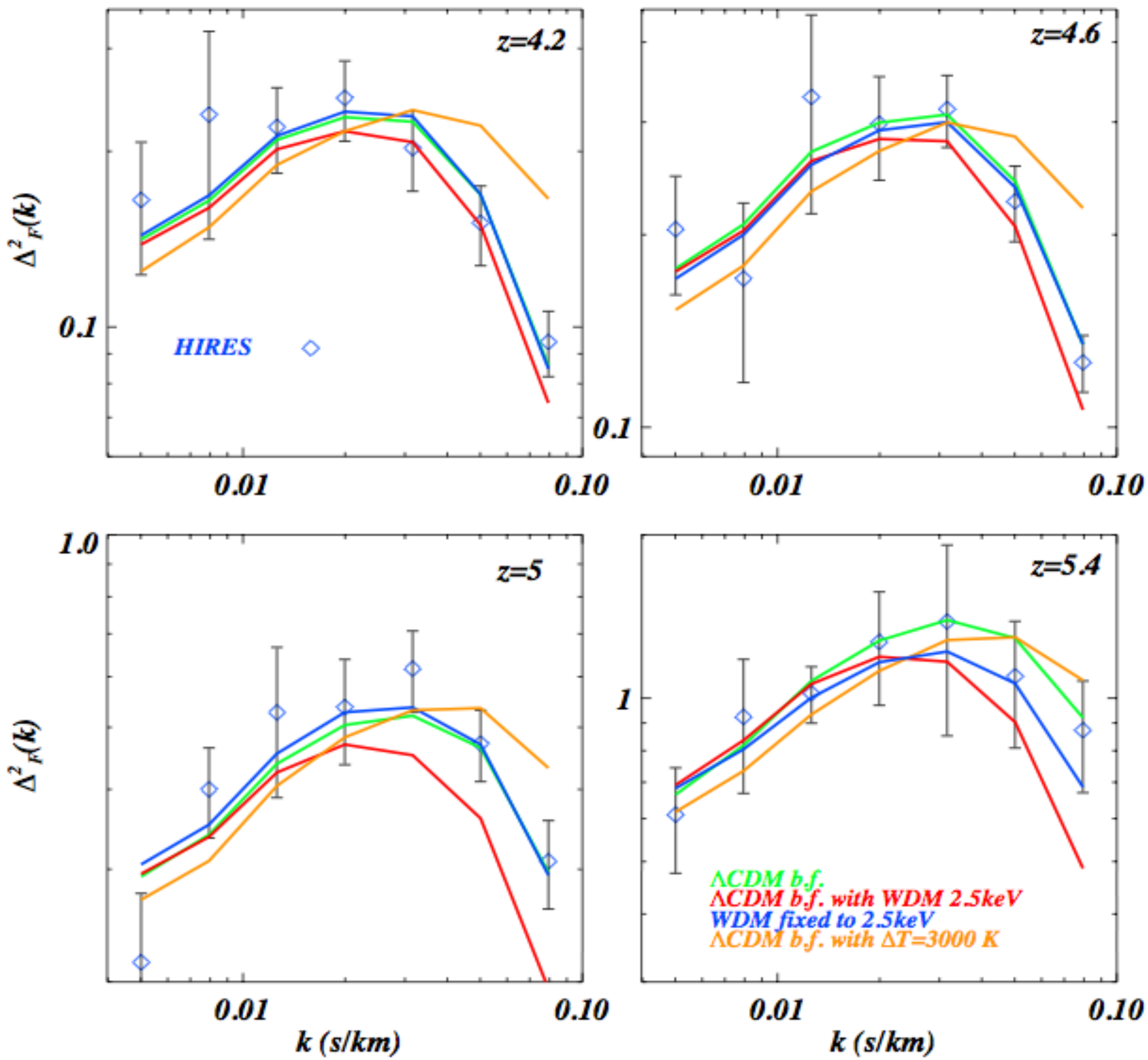


THE BEST GUESS MODEL

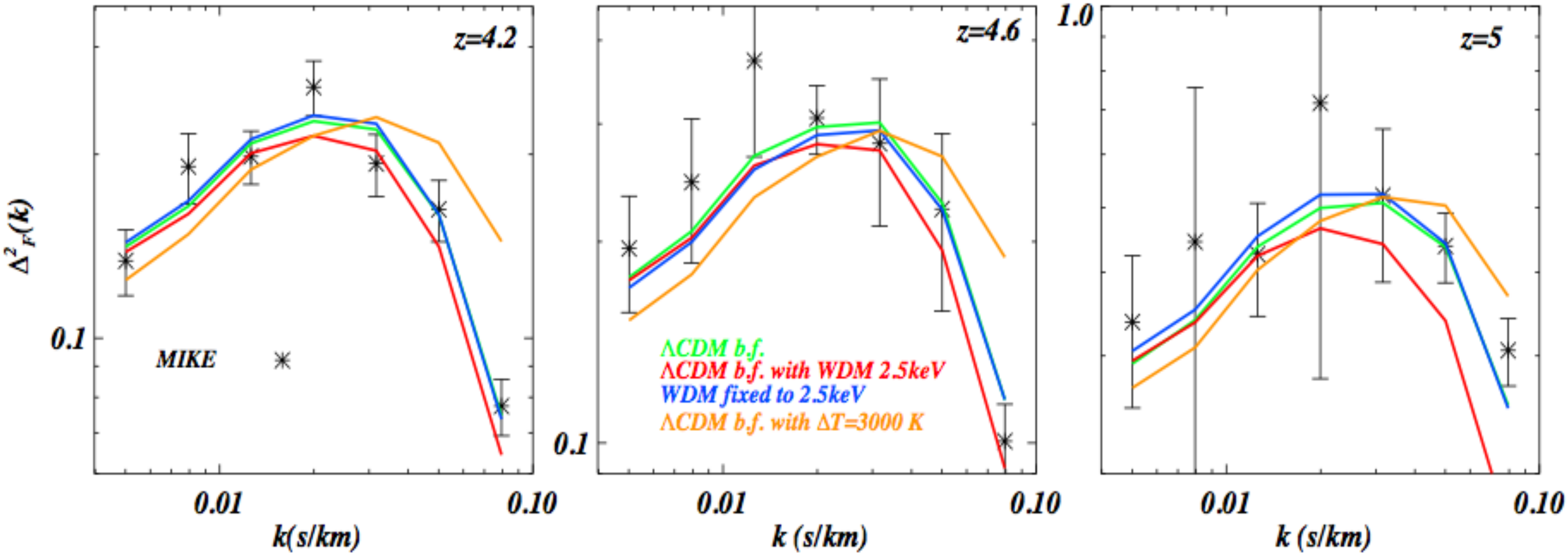


This is the starting point of the MCMC likelihood estimation cosmology close to Planck values

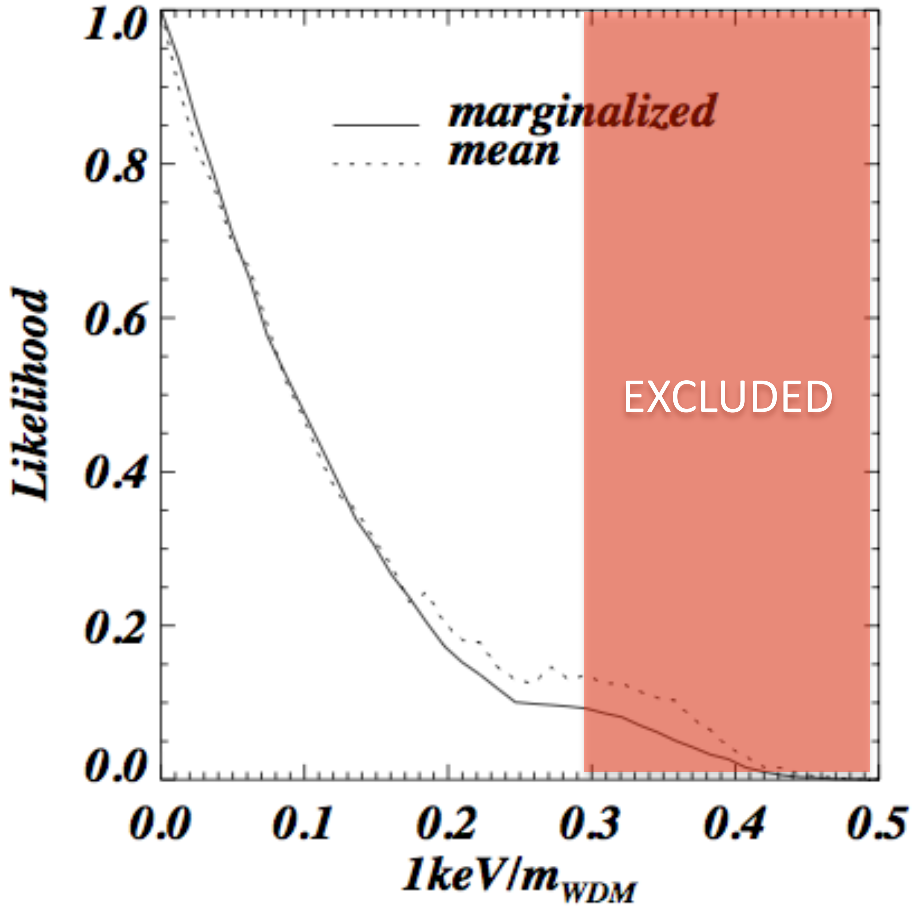
THE BEST FIT MODEL for HIRES



THE BEST FIT MODEL for MIKE



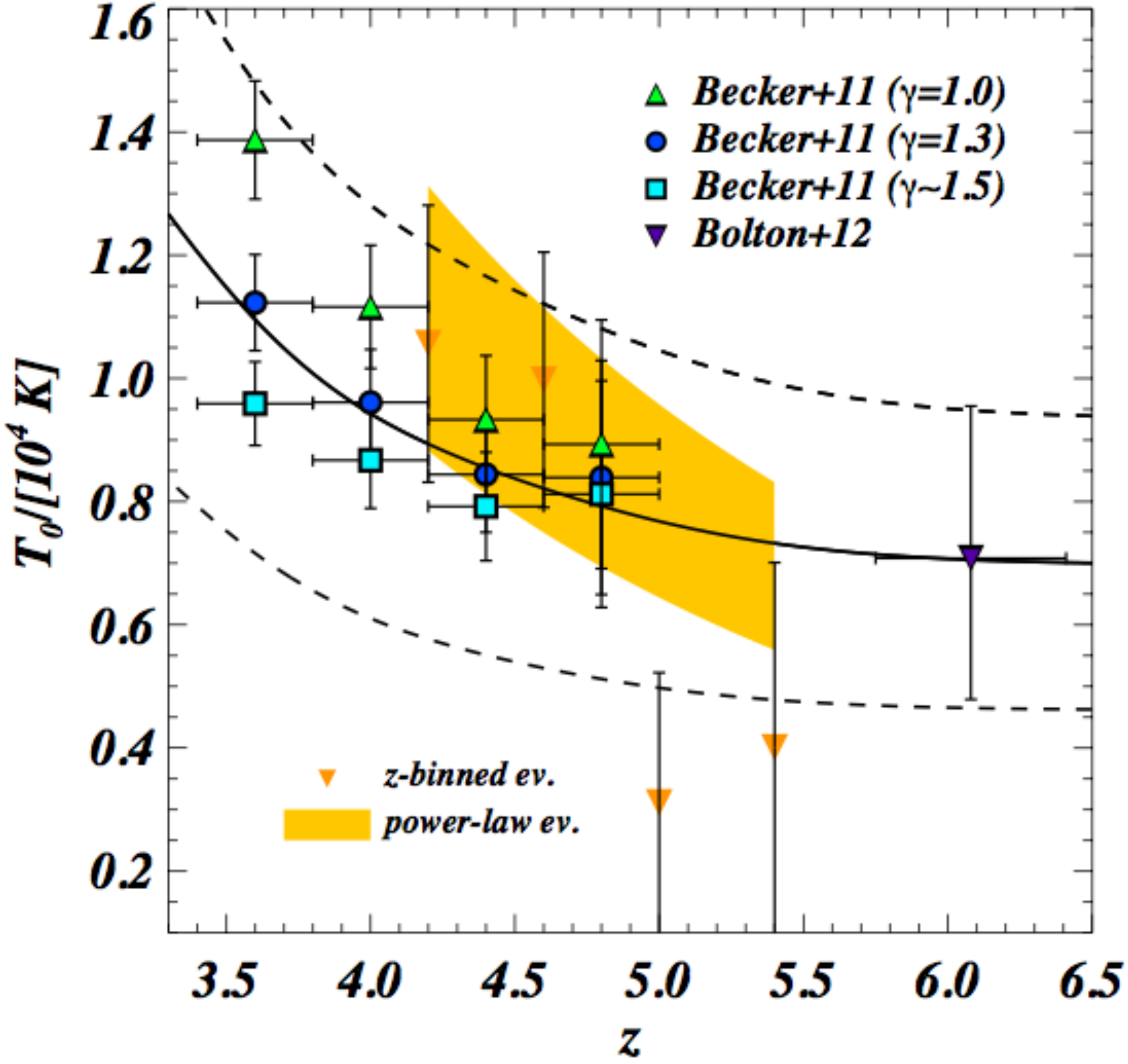
RESULTS FOR WDM MASS



m > 3.3 keV (2σ)

RESULTS FOR TEMPERATURE

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



SUMMARY OF RESULTS

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

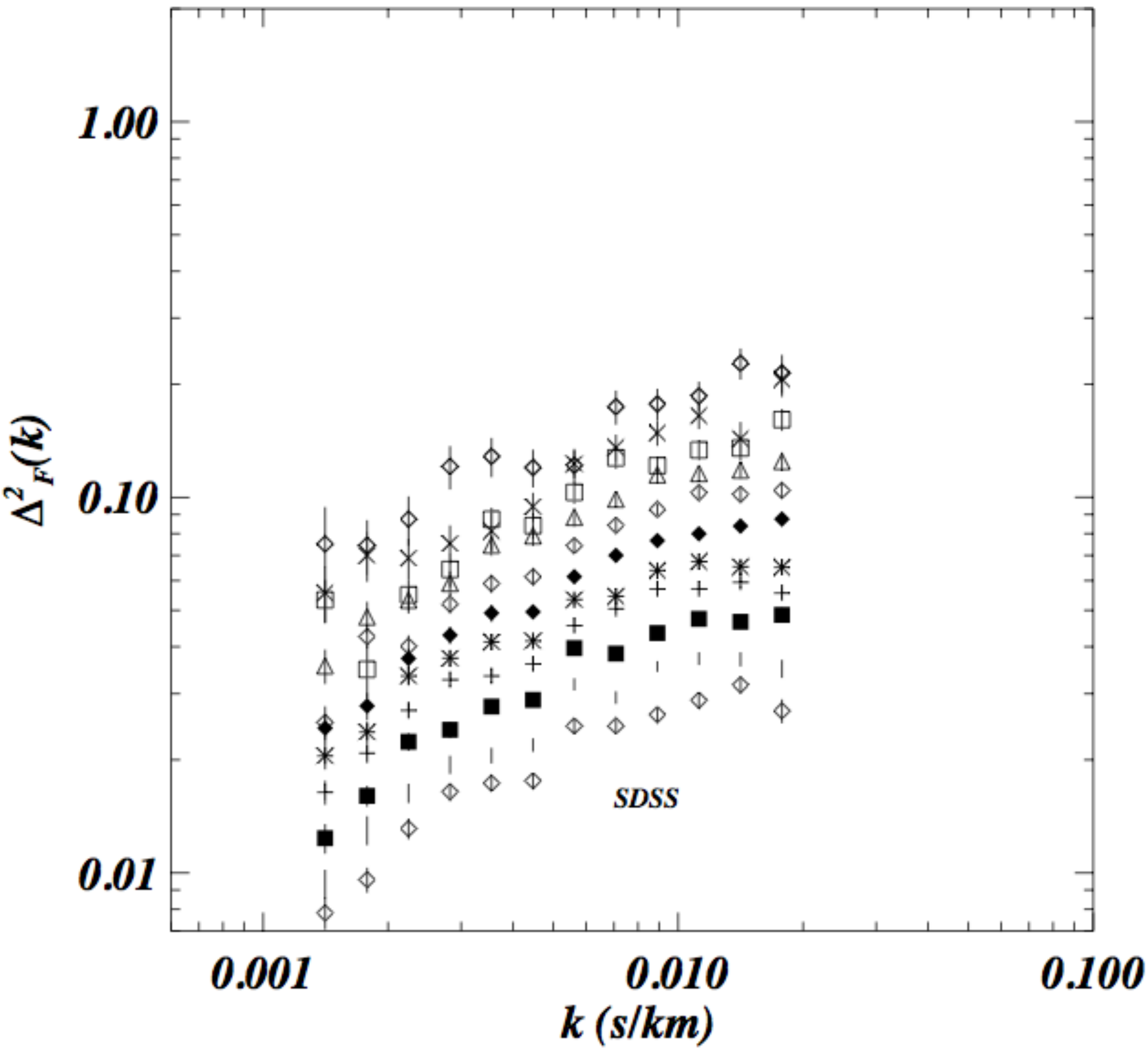
parameter	(1σ)	(2σ)	best fit
n_s	$[0.942, 0.97]$	$[0.928, 0.984]$	0.957
σ_8	$[0.806, 0.856]$	$[0.781, 0.881]$	0.822
Ω_m	$[0.265, 0.331]$	$[0.234, 0.362]$	0.298
$\tau_{\rm eff}^A(z=4.2)$	$[1.04, 1.16]$	$[0.98, 1.22]$	1.16
$\tau_{\rm eff}^A(z=4.6)$	$[1.19, 1.33]$	$[1.12, 1.4]$	1.32
$\tau_{\rm eff}^A(z=5)$	$[1.76, 1.96]$	$[1.66, 2.05]$	1.91
$\tau_{\rm eff}^A(z=5.4)$	$[2.72, 3.06]$	$[2.55, 3.21]$	3.09
$\gamma^A(z=4.5)$	$[1.38, 1.54]$	$[1.09, 1.65]$	1.64
$\gamma^S(z=4.5)$	$[-0.76, 1.1]$	$[-2, 2.3]$	-0.15
$T_0^A(z=4.5)(10^3)$ K	$[9.1, 10.4]$	$[7.8, 11.6]$	9.2
$T_0^S(z=4.5)(10^3)$ K	$[-3, -2.05]$	$[-3, -1.1]$	-2.5
$f_{\rm UV}$	$[0-1]$	$[0-1]$	0.18
$z_{\rm reio}$	$[5-11]$	$[5-16.4]$	11.2
$1\ {\rm keV}/m_{\rm WDM}$	$[0-0.12]$	$[0-0.3]$	0.03

model	(1σ)	(2σ)	best fit	χ^2/d.o.f.
REF.	> 8.3 keV	> 3.3 keV	33 keV	34/37
REF. w/o 30%	> 11.1 keV	> 4.5 keV	100 keV	48/37
REF. w/o covmat	> 7.7 keV	> 3.1 keV	14.3 keV	33.2/37
REF. + SDSS	> 7.2 keV	> 3.3 keV	42 keV	183.3/170

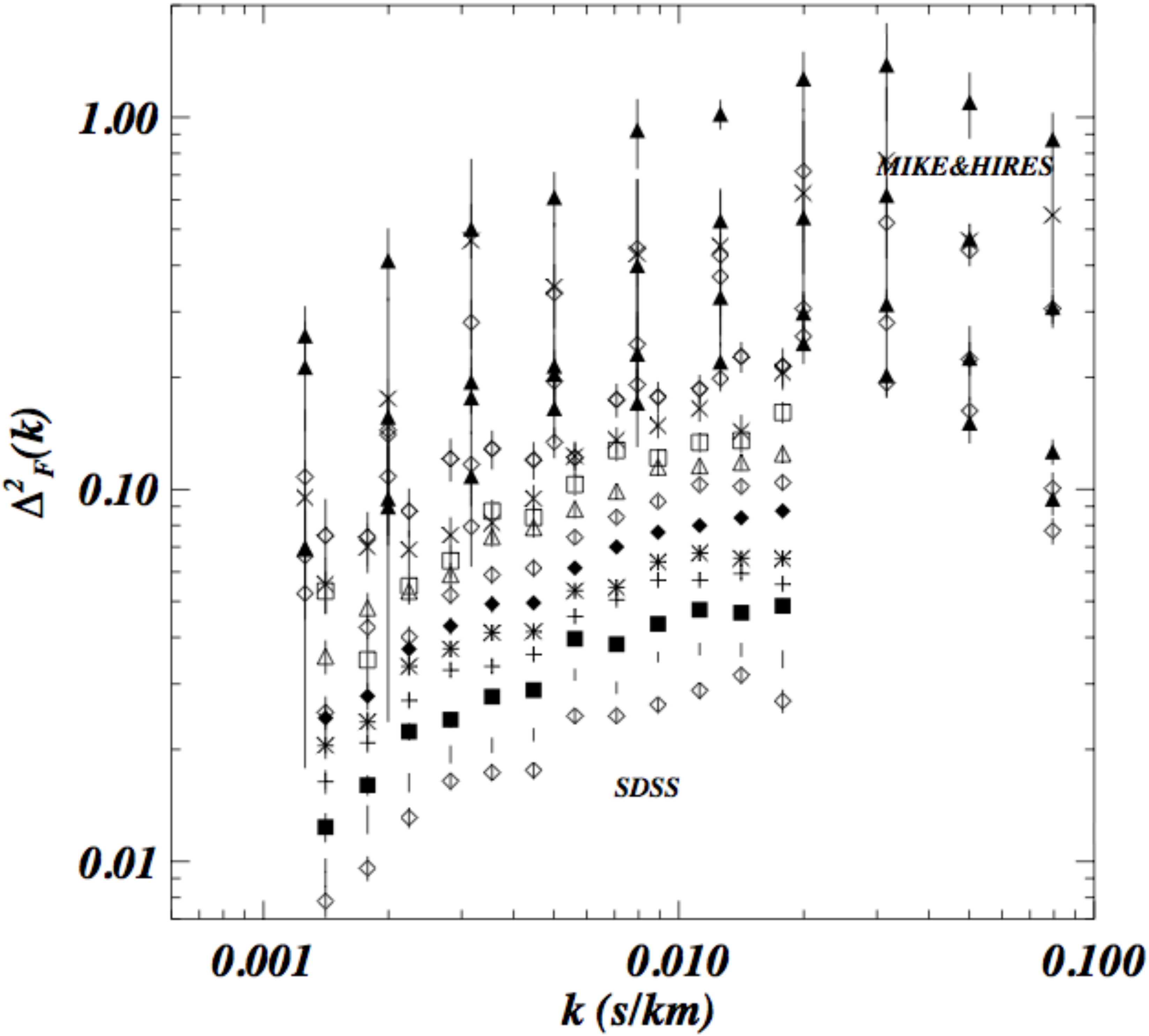
SDSS + MIKE + HIRES CONSTRAINTS

Joint likelihood analysis

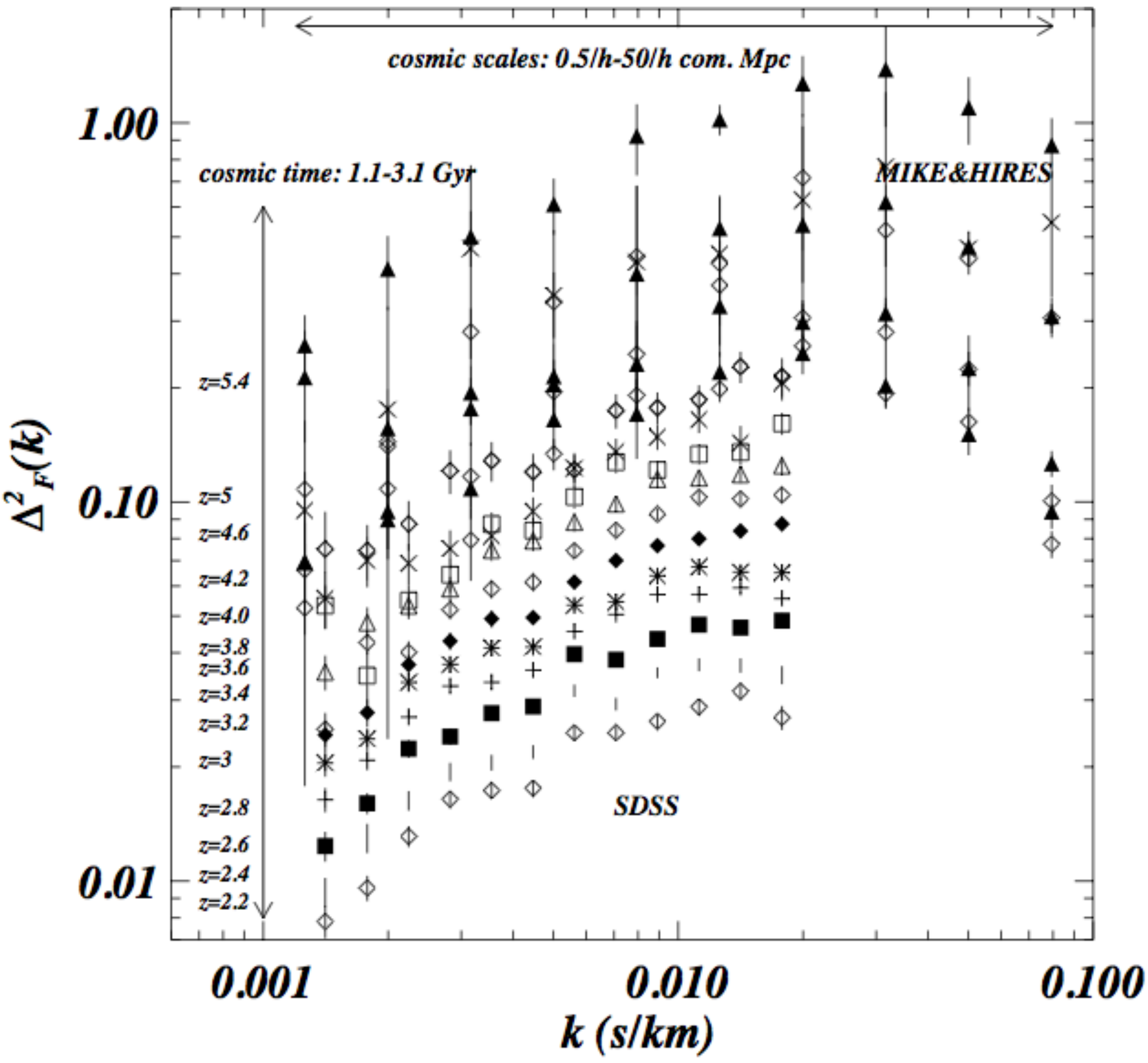
SDSS data from McDonald05,06 not BOSS



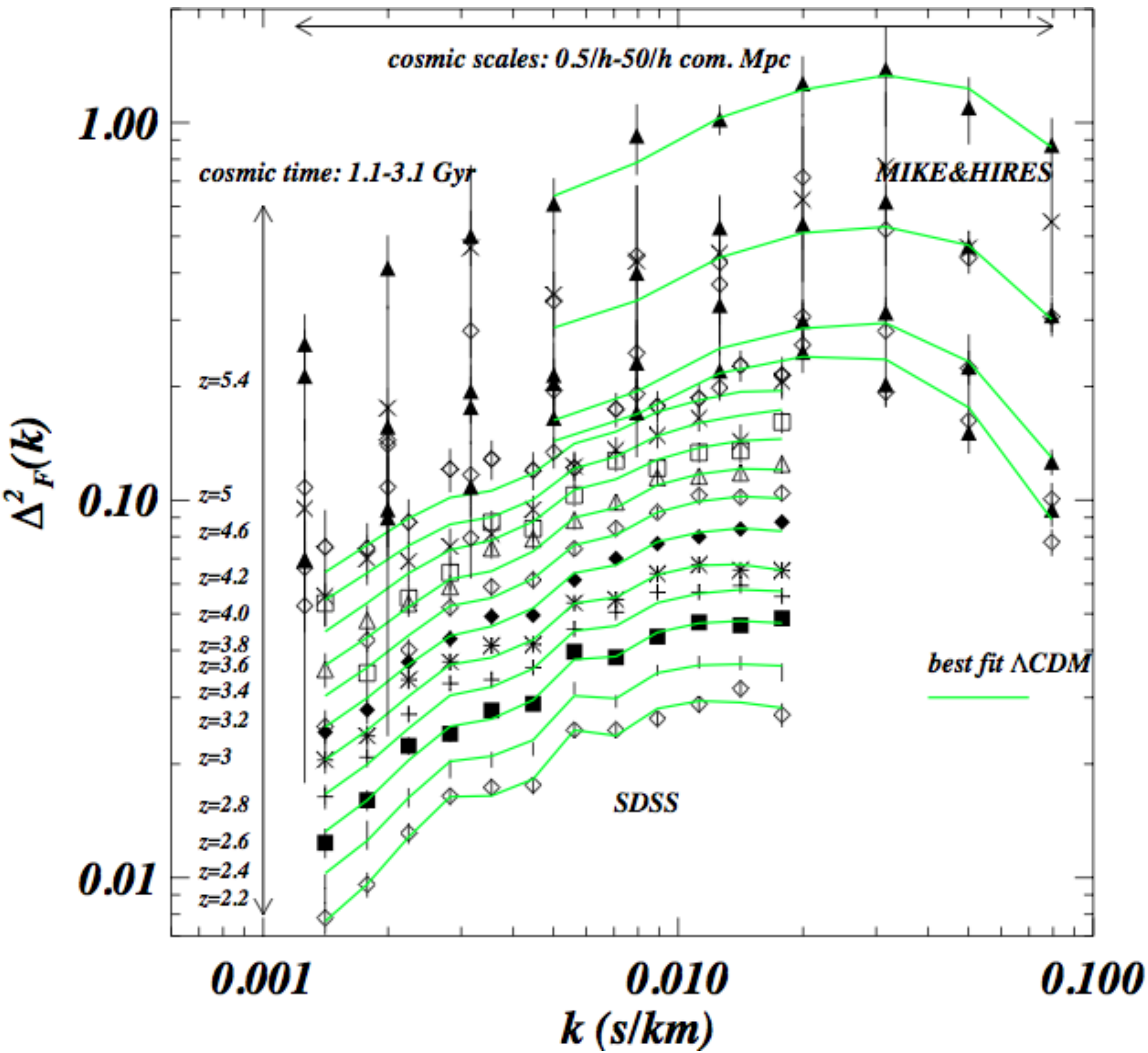
1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)



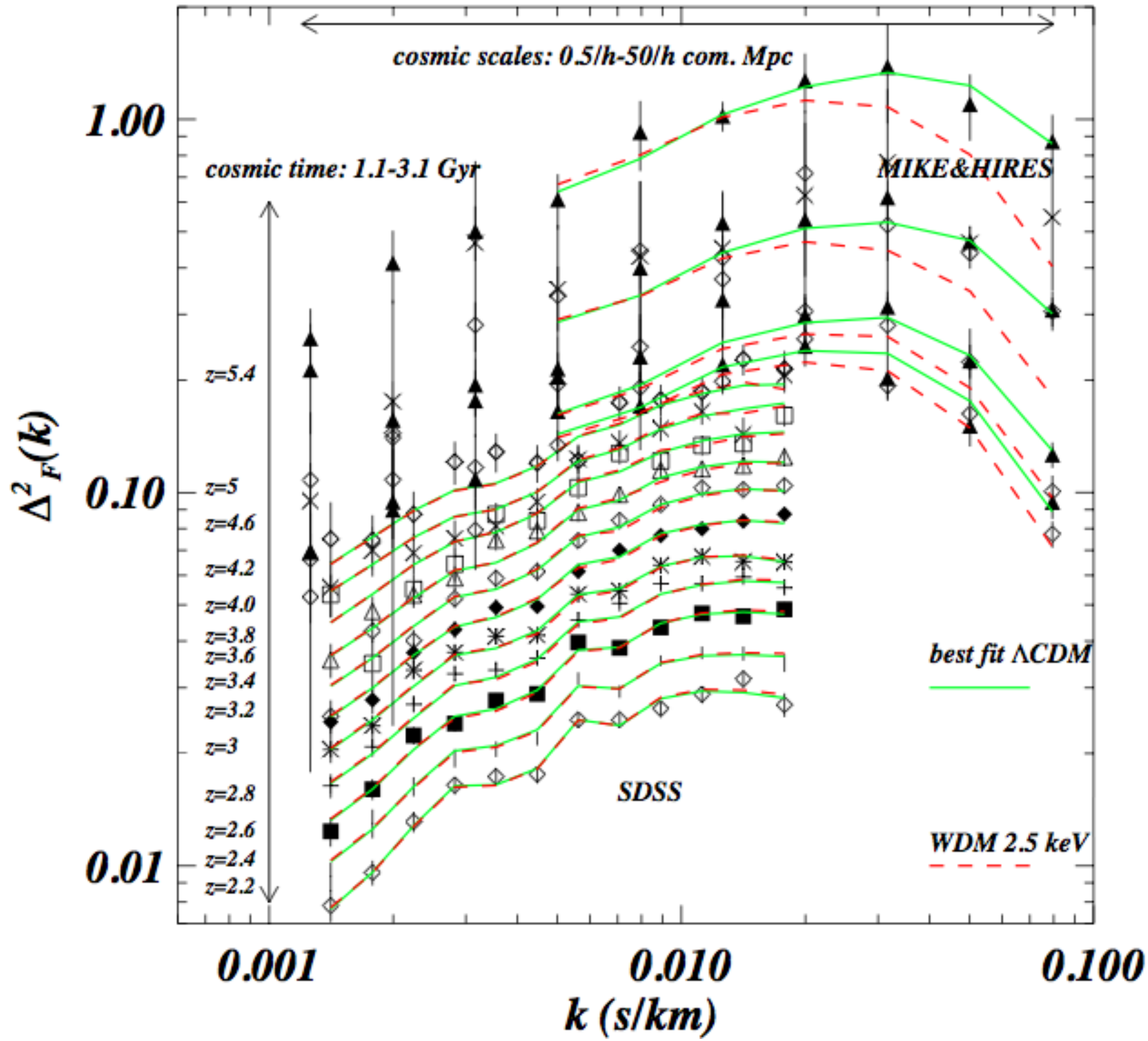
MIKE&HIRES
SDSS
1.00
0.10
0.01
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)



cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
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)

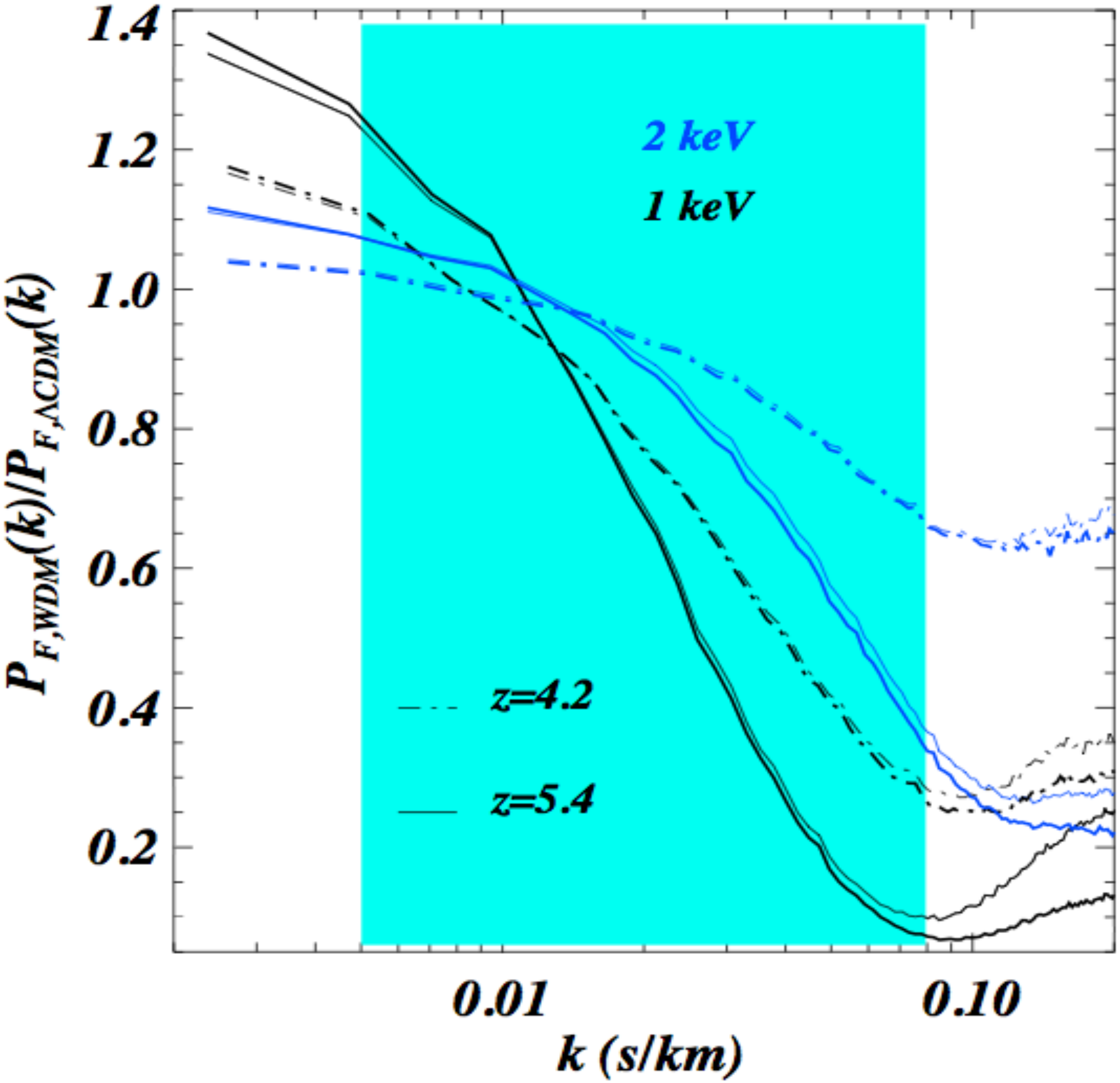


cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
best fit ΛCDM
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)



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)

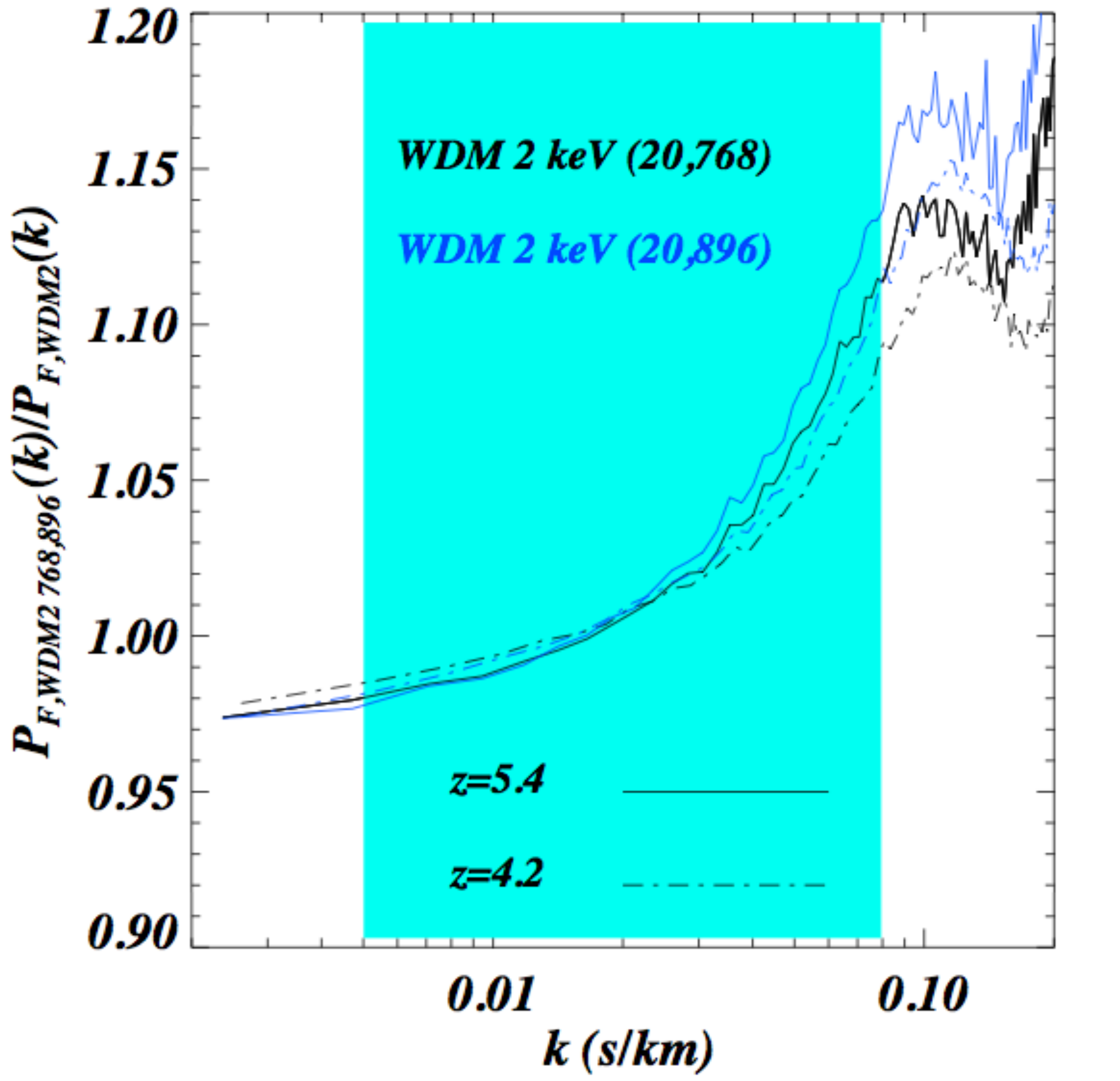
SYSTEMATICS: NUMERICAL CONVERGENCE – I



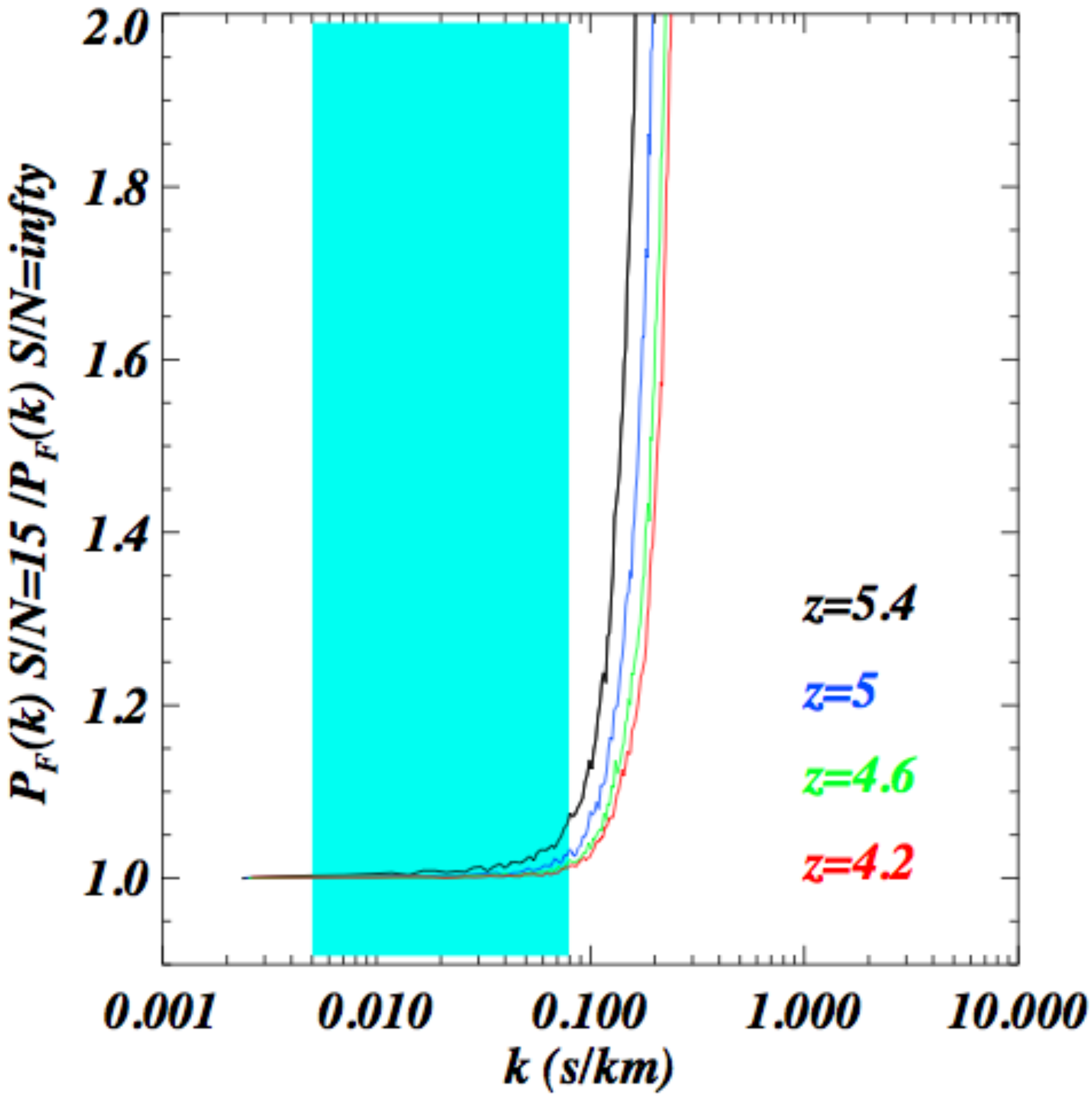
20 Mpc/h,512^3

20 Mpc/h,768^3

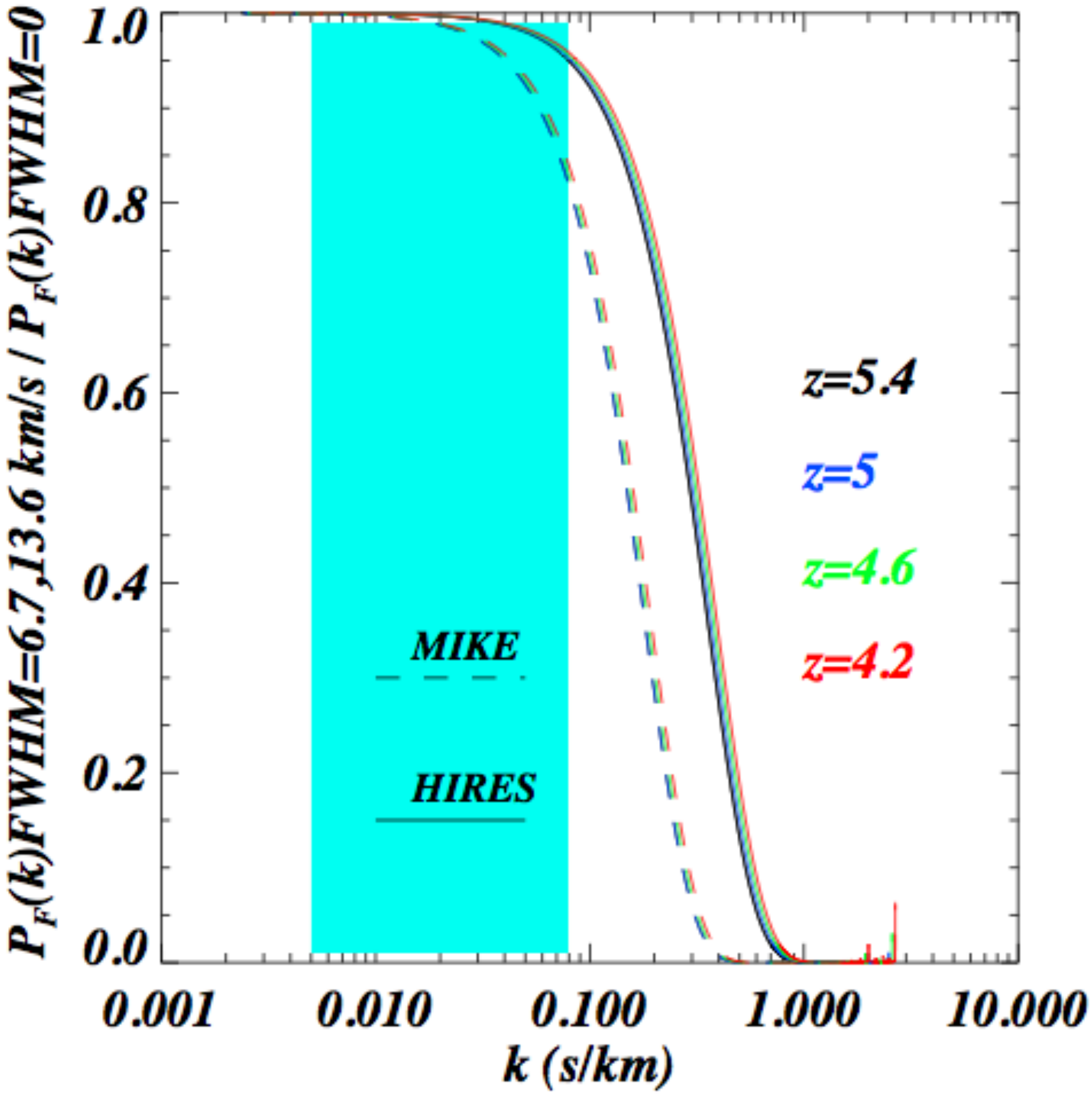
SYSTEMATICS: NUMERICAL CONVERGENCE – II



SYSTEMATICS: SIGNAL-TO-NOISE RATIO

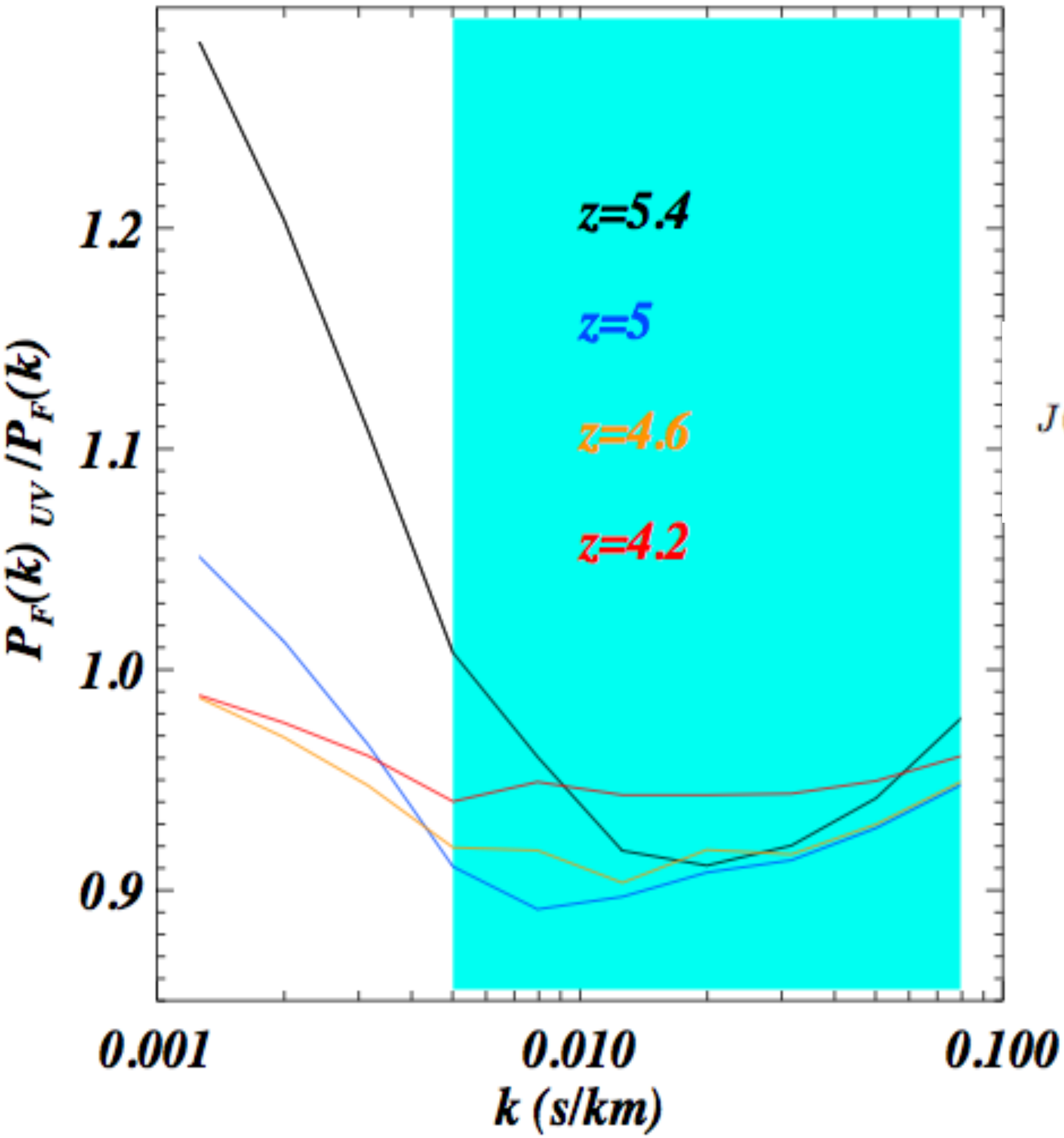


SYSTEMATICS: INSTRUMENTAL RESOLUTION



SYSTEMATICS: UV FLUCTUATIONS

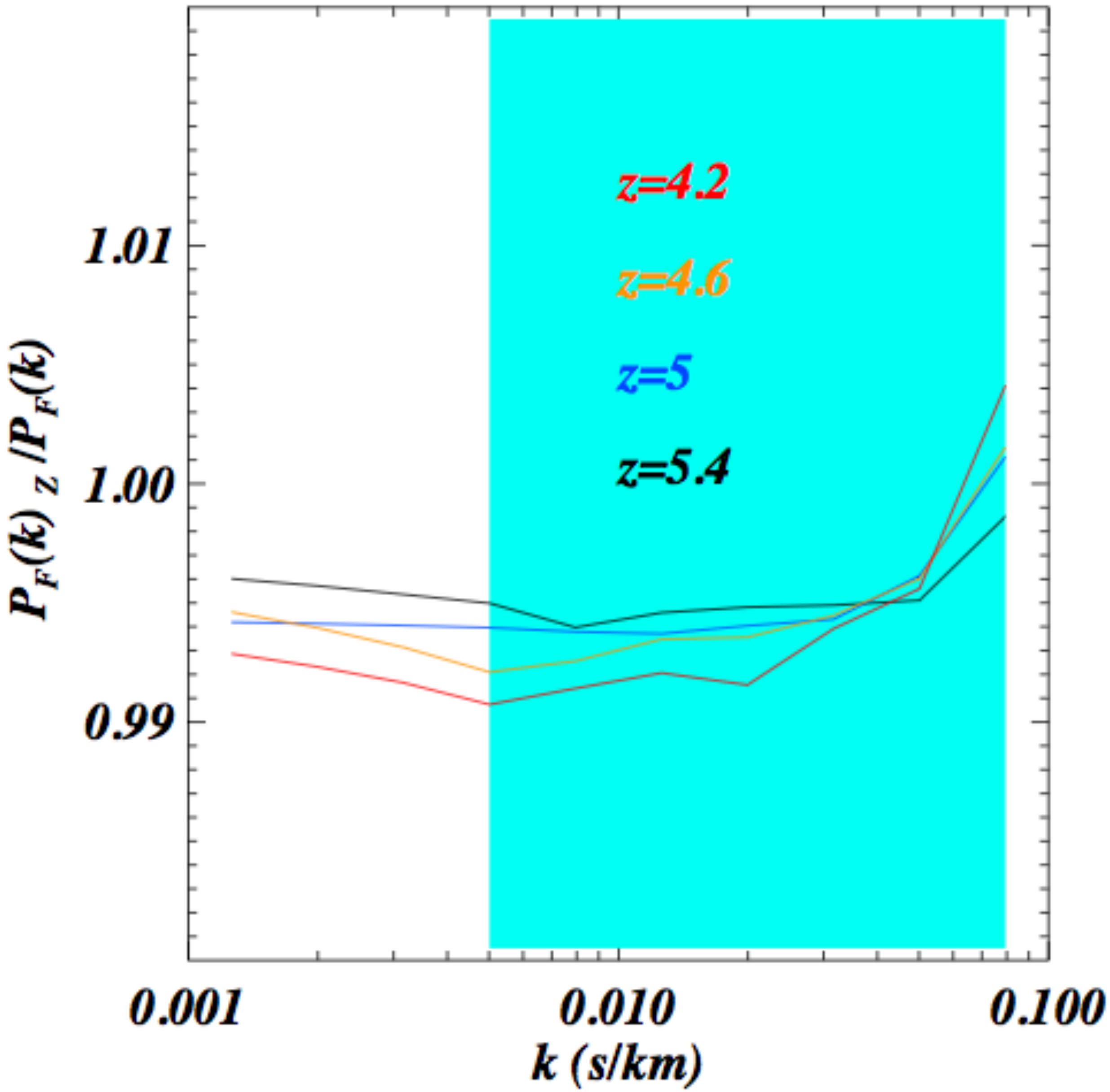
as in Bolton, J. S., & Viel, M. Mon. Not. Roy. Astron. Soc., 414, 241 (2011)



$$J(\mathbf{r},\nu) = \frac{1}{4\pi}\sum_{i=1}^{N}\frac{L_i(\mathbf{r}_i,\nu)}{4\pi|\mathbf{r}_i-\mathbf{r}|^2}e^{-\frac{|\mathbf{r}_i-\mathbf{r}|}{\lambda_{\rm HI}}}\left(\frac{\nu}{\nu_{\rm HI}}\right)^{-3(\beta-1)}$$

Produced by QSOs with $M_B < -22$

SYSTEMATICS: METAL CONTAMINATIONS



CIV
MgII
SiIV
at lower redshift

SUMMARY OF SYSTEMATIC EFFECTS

syst. eff.	$\sigma(P_\mathrm{F})/P_\mathrm{F}$	Notes
data res.	$< 5 - 15\%$	corrected
data S/N	$< 3\%$	corrected
num. res.	$< 5\%$	corrected
metals	$< 1\%$	neglected
mean flux	$\sim 30\%$	marginalized
thermal history	$\sim 30\%$	marginalized
UV	$< 10\%$	marginalized

Continuum: unimportant at the scales considered
Astrophysics (e.g. feedback from Galactic winds): unimportant at the redshifts considered

CONCLUSIONS

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

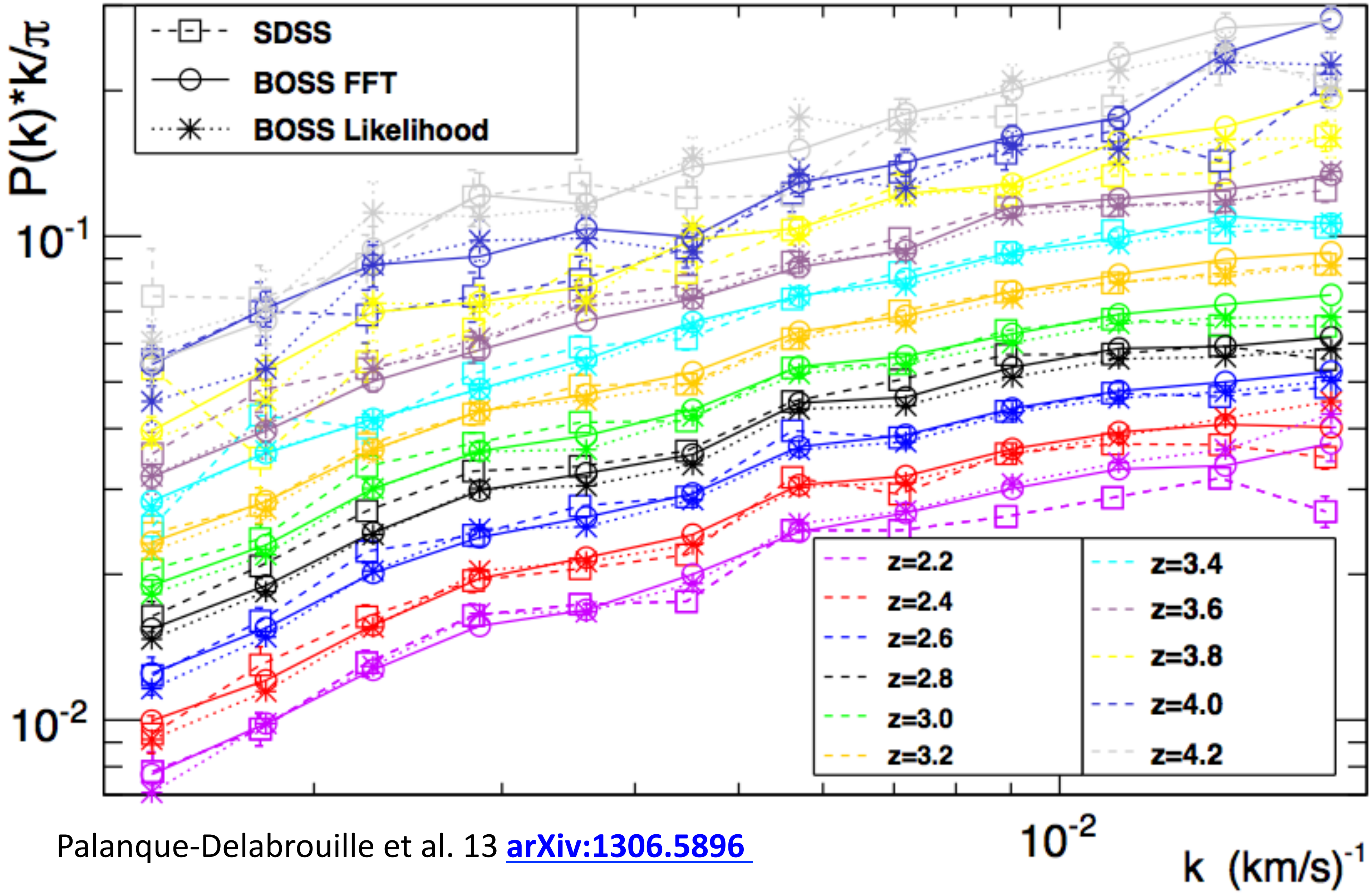
Models with 1 keV are ruled out at 9σ
2 keV are ruled out at 4σ
2.5 keV are ruled out at 3σ
3.3 keV are ruled out at 2σ

↓

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

The one-dimensional Lyα forest power spectrum from BOSS



Palanque-Delabrouille et al. 13 arXiv:1306.5896