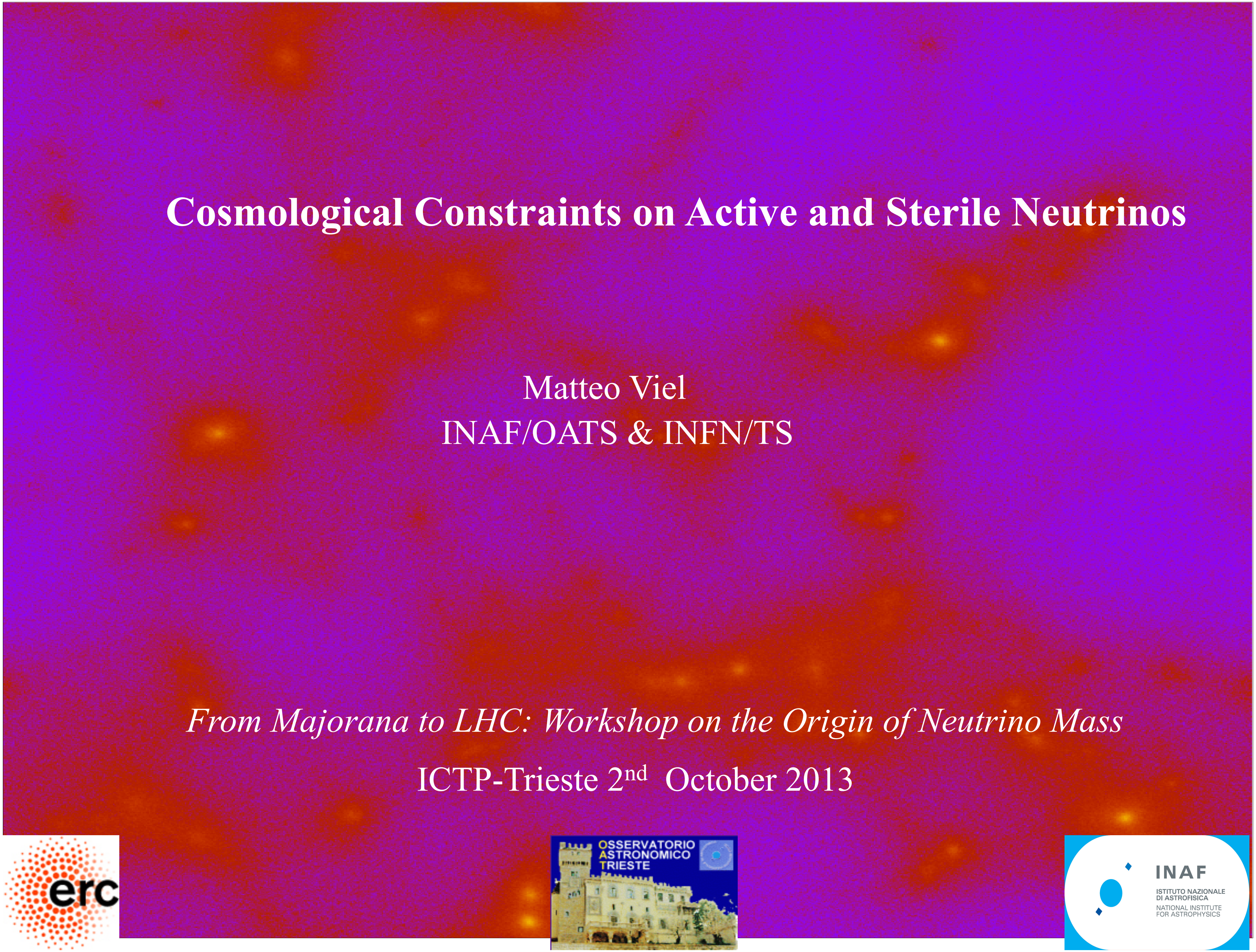


Cosmological Constraints on Active and Sterile Neutrinos

Matteo Viel
INAF/OATS & INFN/TS

From Majorana to LHC: Workshop on the Origin of Neutrino Mass

ICTP-Trieste 2nd October 2013

OUTLINE

THEORY: Effect of massive neutrinos and warm dark matter on the LSS/SSS

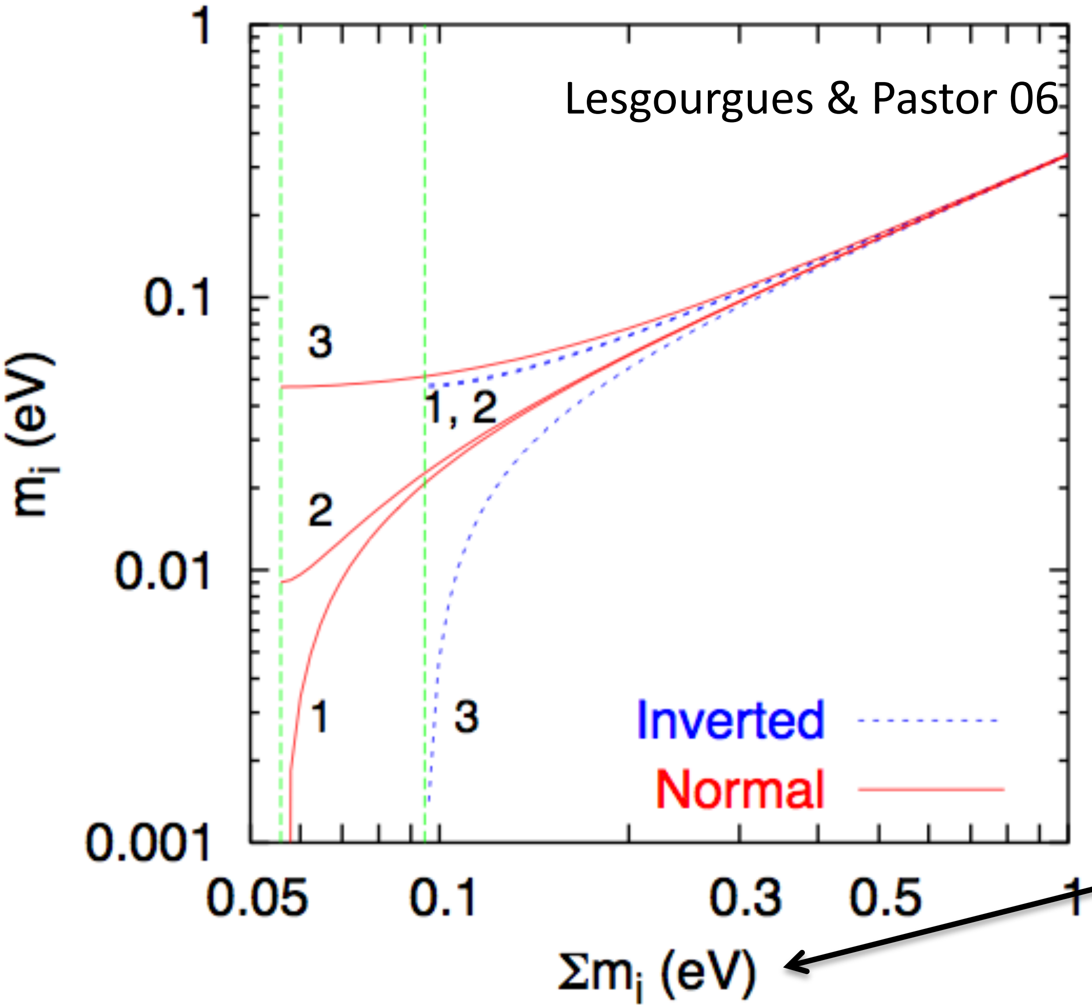
Matter Power Spectrum as traced by: galaxies
cluster number counts
weak lensing
intergalactic matter

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

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

CONSTRAINTS: on neutrino masses and on coldness of cold dark matter

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

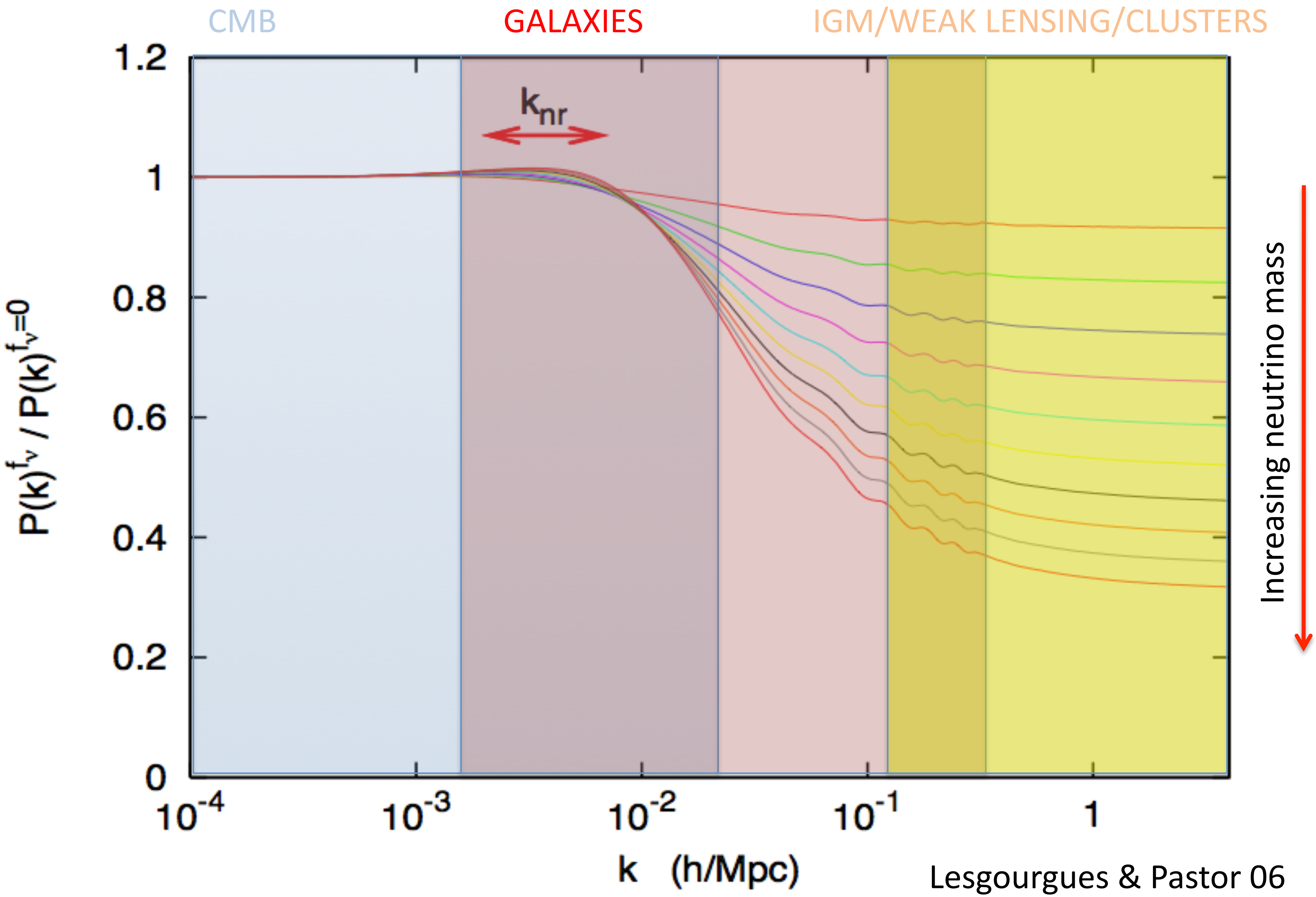
RADIATION ERA z>3400

MATTER RADIATION z<3400

NON-RELATIVISTIC TRANSITION z ~ 500

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

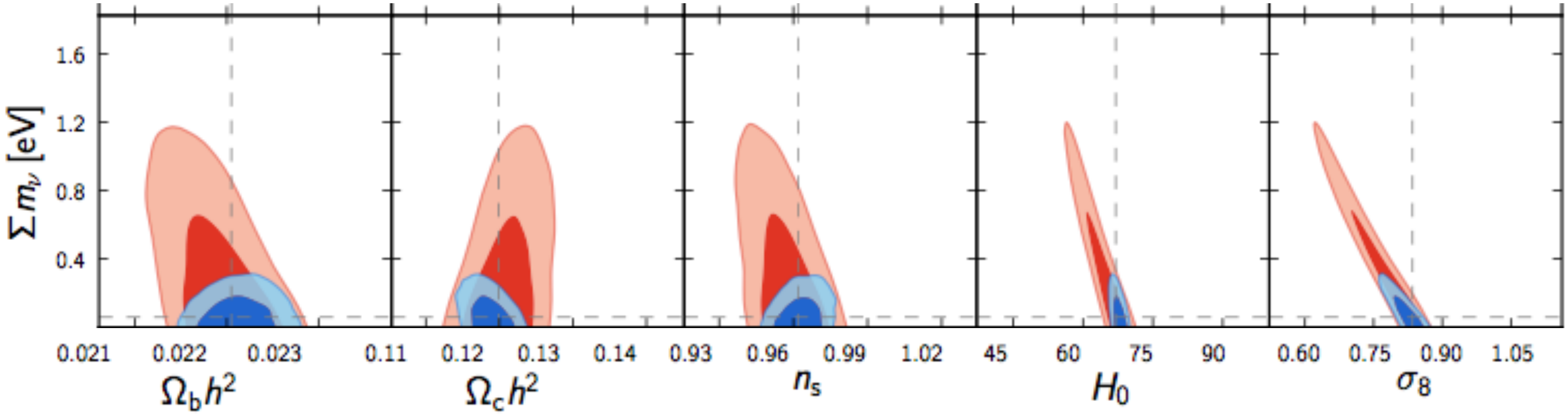
COSMOLOGICAL NEUTRINOS - III: LINEAR MATTER POWER



Lesgourgues & Pastor 06

CMB CONSTRAINTS on NEUTRINO MASS FROM PLANCK

Planck collaboration paper XVI



$\Sigma m_\nu < 0.247$ eV (2σ) from Planck + WMAP pol. + BAO

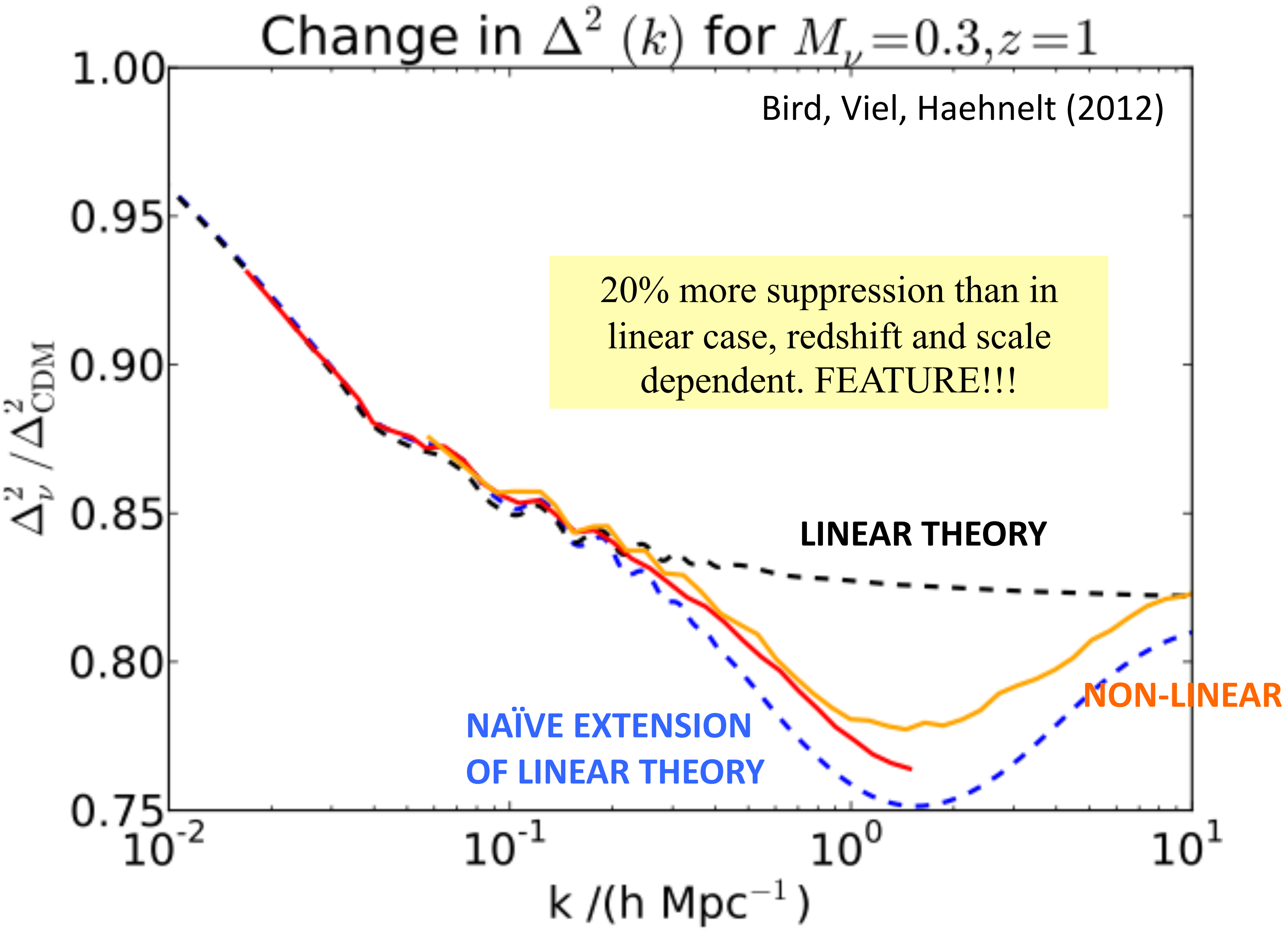
$\Sigma m_\nu < 0.93$ eV (2σ) from Planck + WMAP pol.

Main results:

Planck strongly improves constraints for neutrino masses
Planck TT spectrum prefers a lensing amplitude $A_L=1.2$
Inclusion of lensing TTTT weakens the constraints by 20%
Best constraints when adding also highL experiments and it is 0.23 eV

MASSIVE NEUTRINOS

COSMOLOGICAL NEUTRINOS : NON-LINEAR MATTER POWER



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

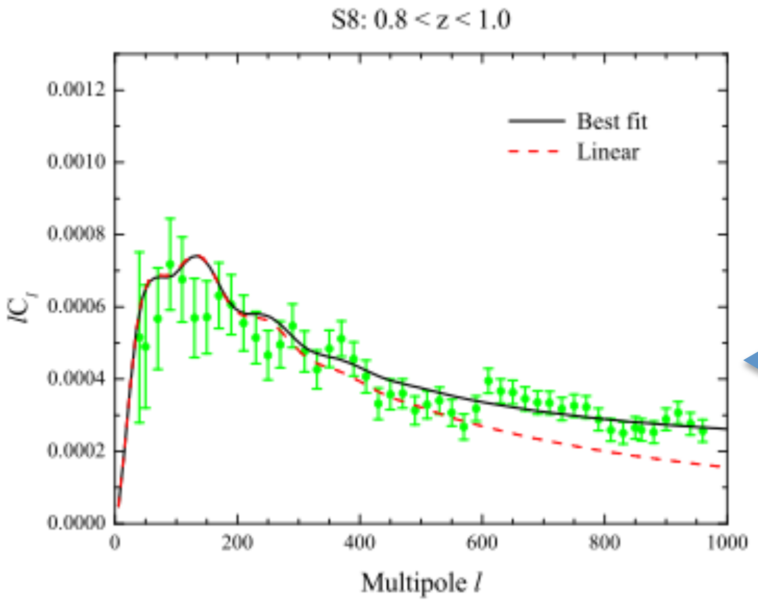
P massive / P massless

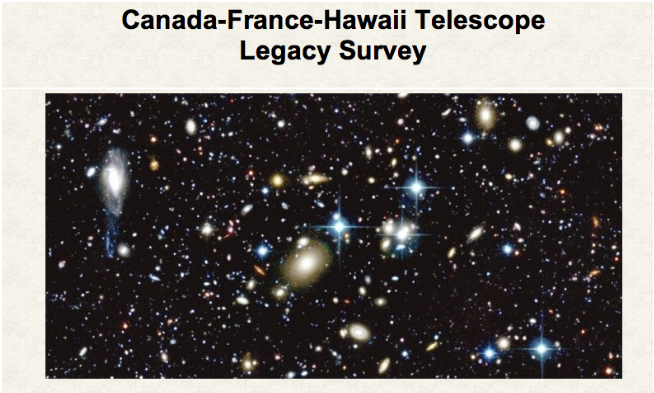
Cosmic Scale

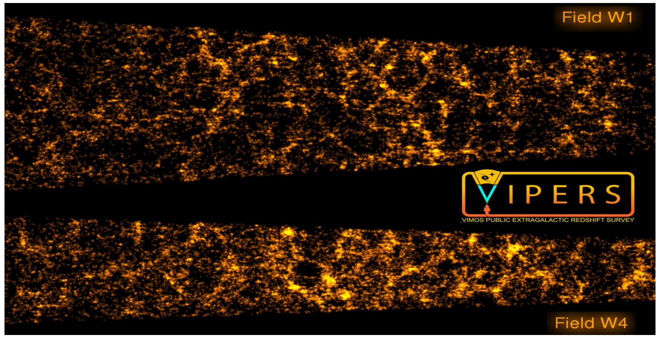
http://www.sns.ias.edu/~spb/index.php?p=code

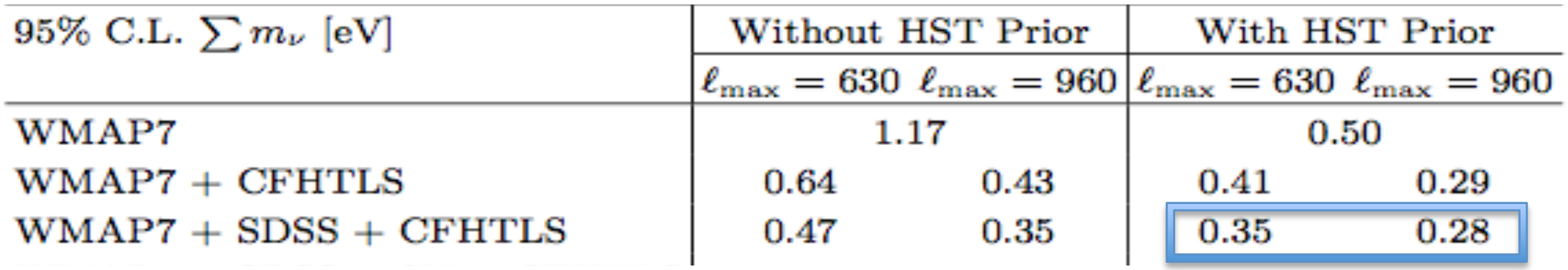
CONSTRAINTS on NEUTRINO MASSES USING NON-LINEARITIES

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







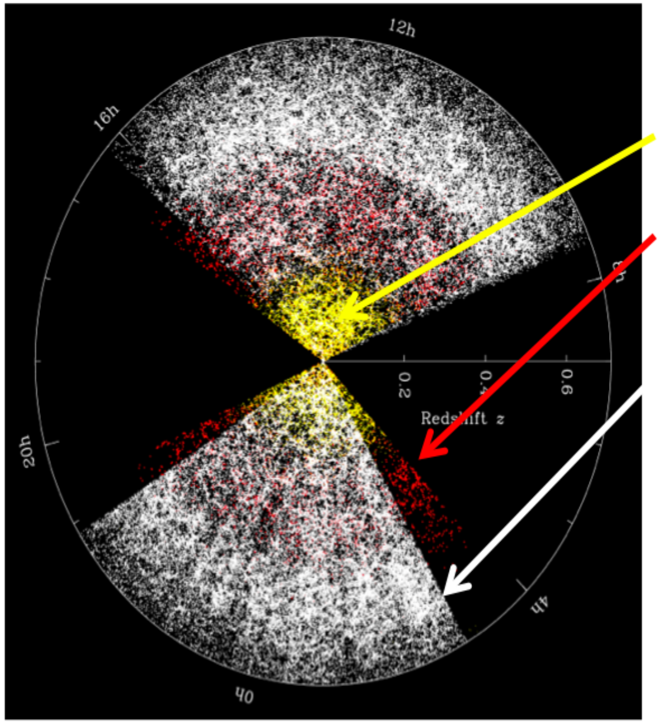


95% C.L. $\sum m_\nu$ [eV]	Without HST Prior		With HST Prior	
	$\ell_{\rm max} = 630$	$\ell_{\rm max} = 960$	$\ell_{\rm max} = 630$	$\ell_{\rm max} = 960$
WMAP7	1.17		0.50	
WMAP7 + CFHTLS	0.64	0.43	0.41	0.29
WMAP7 + SDSS + CFHTLS	0.47	0.35	0.35	0.28

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

CONSTRAINTS ON MASSIVE NEUTRINOS FROM LSS CLUSTERING - I

Zhao et al. 13 using SDSS galaxy clustering sample

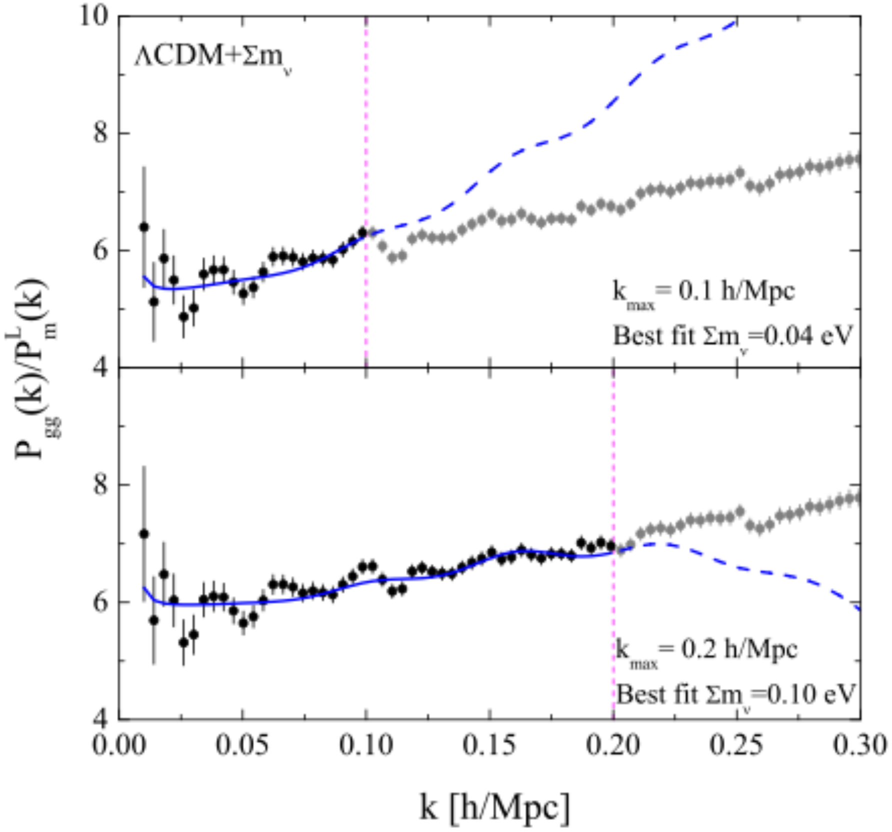


SDSS-II main galaxies

SDSS-II LRGs

BOSS CMASS galaxies

Image credit: Blanton



$$\Sigma\, m_{\nu} < 0.\,340\ \mathrm{eV}\quad (2\sigma)$$

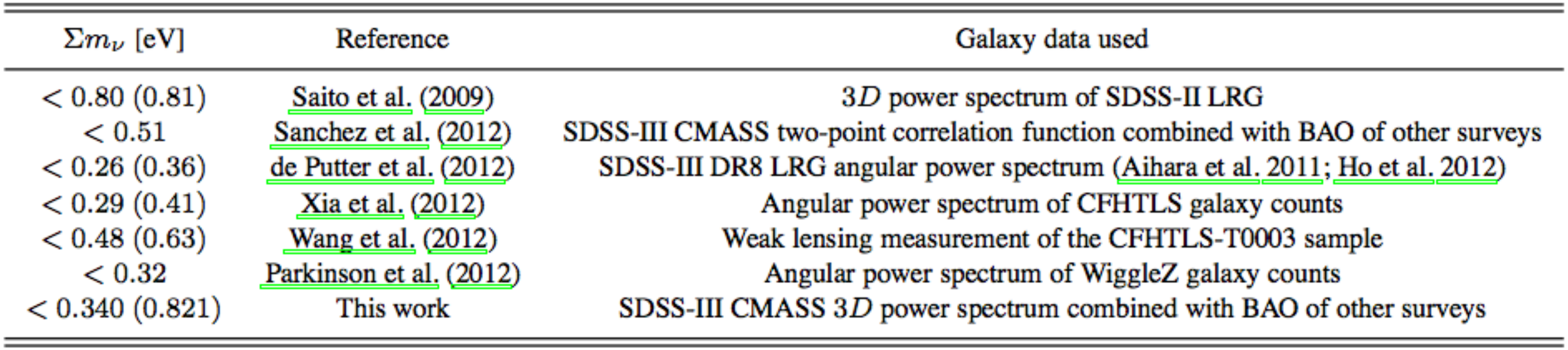
Note the tricky bits:

model relation between galaxies and matter (bias, which model of bias)

model the signal in redshift space

model neutrino induced non-linearities

CONSTRAINTS ON MASSIVE NEUTRINOS FROM LSS CLUSTERING - II

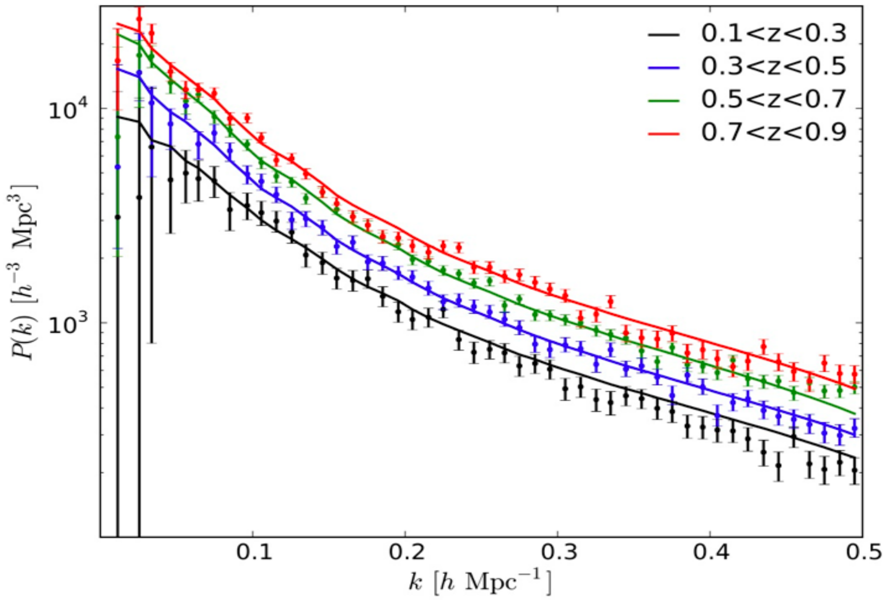


Σm_ν [eV]	Reference	Galaxy data used
< 0.80 (0.81)	Saito et al. (2009)	$3D$ power spectrum of SDSS-II LRG
< 0.51	Sanchez et al. (2012)	SDSS-III CMASS two-point correlation function combined with BAO of other surveys
< 0.26 (0.36)	de Putter et al. (2012)	SDSS-III DR8 LRG angular power spectrum (Aihara et al. 2011; Ho et al. 2012)
< 0.29 (0.41)	Xia et al. (2012)	Angular power spectrum of CFHTLS galaxy counts
< 0.48 (0.63)	Wang et al. (2012)	Weak lensing measurement of the CFHTLS-T0003 sample
< 0.32	Parkinson et al. (2012)	Angular power spectrum of WiggleZ galaxy counts
< 0.340 (0.821)	This work	SDSS-III CMASS $3D$ power spectrum combined with BAO of other surveys

VARIETY OF CONSTRAINTS FROM LSS GALAXY CLUSTERING

- In 10 years constraints greatly improved from 1.7 eV to 0.3 eV (conservative)
- Most aggressive constraints are below the 0.2 eV level
- Modelling bias is tricky (typically you marginalize over) and some systematics are uncertain
- If you complicate the minimal standard ΛCDM then constraints become much weaker (by a factor ~1.5)

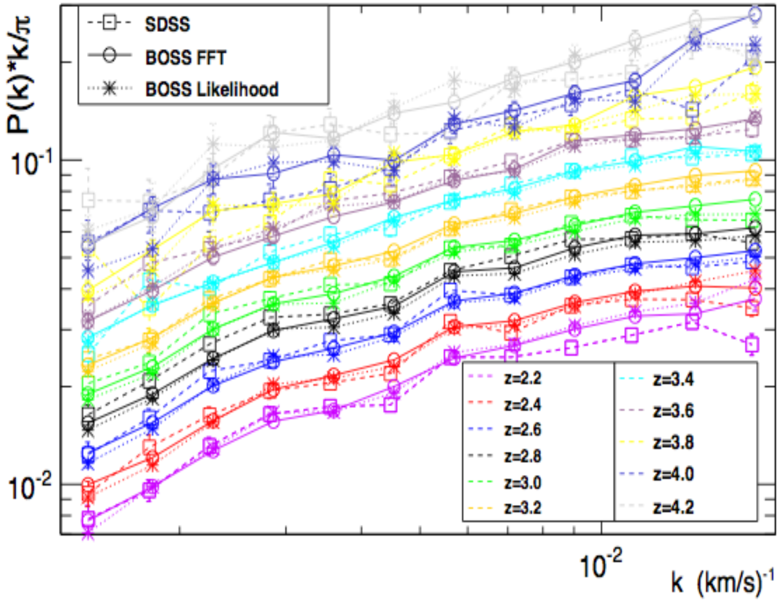
TIGHTEST LIMITS PUBLISHED SO FAR



WiggleZ survey + Planck + HST + BAO

$\Sigma m_\nu < 0.14$ eV (2σ C.L.)

Riemer-Sorensen et al. 13



Intergalactic Medium data + CMB

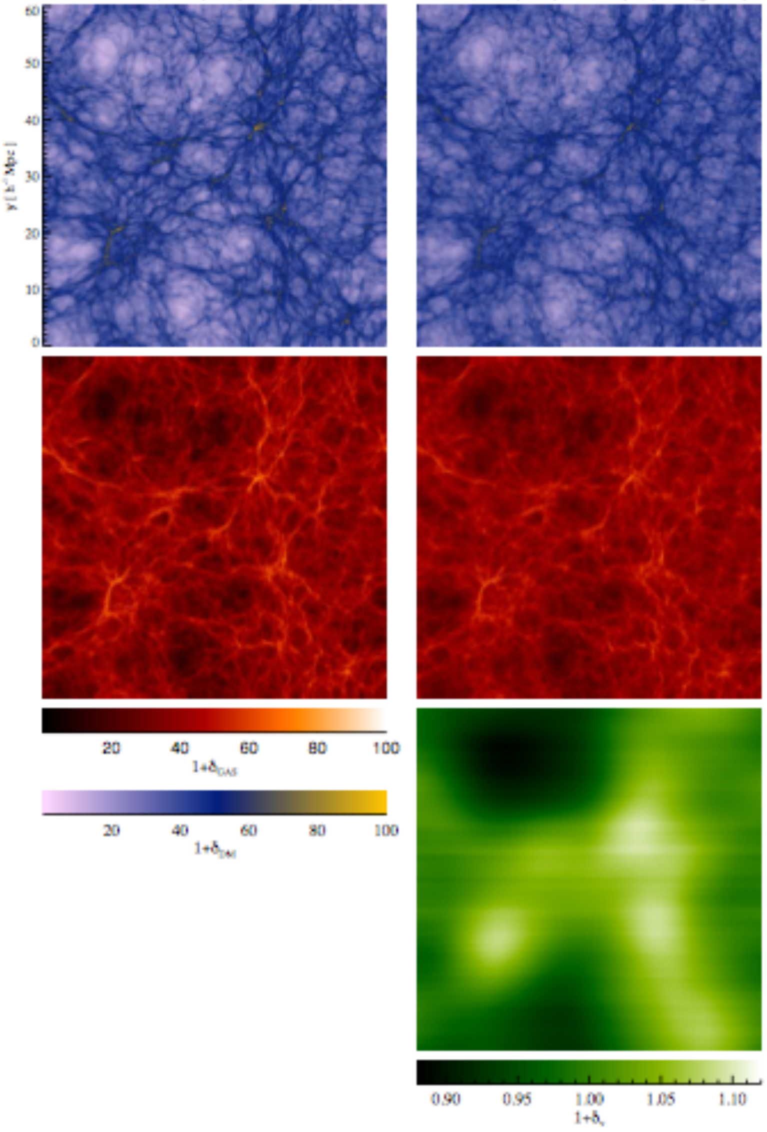
$\Sigma m_\nu < 0.17$ eV (2σ C.L.)

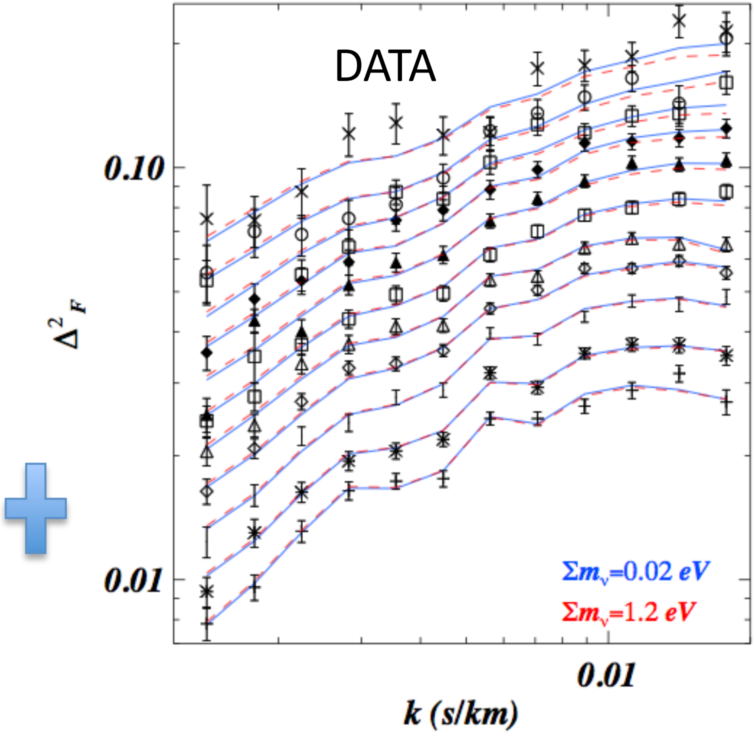
Seljak et al. 06

Viel, Haehnelt & Springel 2010
IGM alone $\Sigma m_\nu < 0.9$ eV (2σ C.L.)

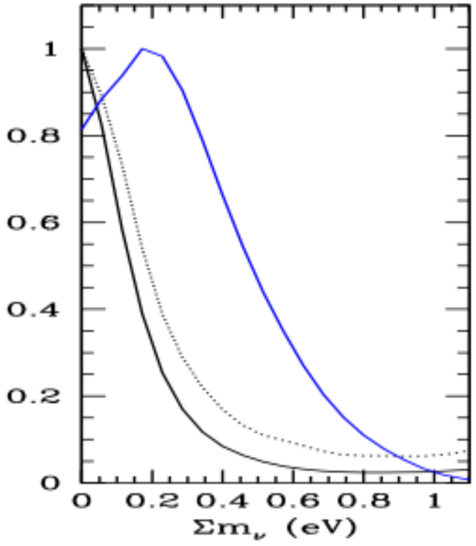
NEUTRINOS IN THE IGM

SIMULATIONS





CONSTRAINTS



$\Sigma m_\nu < 0.9$ eV (2σ)

Viel, Haehnelt, Springel 2010

THE BRIGHT FUTURE OF COSMOLOGICAL NEUTRINOS

FORECASTING-I

Carbone et al. 11

Euclid-like survey (comparison between different spectr. survey strategies)
Fisher Matrix approach
Clear detection of cosmological neutrinos if M_ν>0.1 eV
If masses are below then you need CMB priors

Carbone et al. 12

Euclid-like Cluster catalogue from number counts and power spectrum (photom.)
Fisher Matrix approach
$\sigma(M_\nu)$~0.9 eV (most conservative with varying w)
$\sigma(M_\nu)$~0.08eV with Planck priors
$\sigma(M_\nu)$~0.04eV with Planck priors and nuisance under control

Hamann et al. 13

Euclid-like photometric galaxy+cosmic shear
Monte Carlo Markov Chains
Minimum mass 0.06eV detected at the 1.5-2.5σ level (marginalizing over galaxy bias)
Clustering + WL breaks degeneracies between neutrino mass, matter density and H0
Not sensitive to the exact spectrum of the masses

Basse et al. 13

Euclid-like galaxy power spectrum+cosmic shear+cluster number counts
$\sigma(M_\nu)$~0.01eV (even when varying w!)

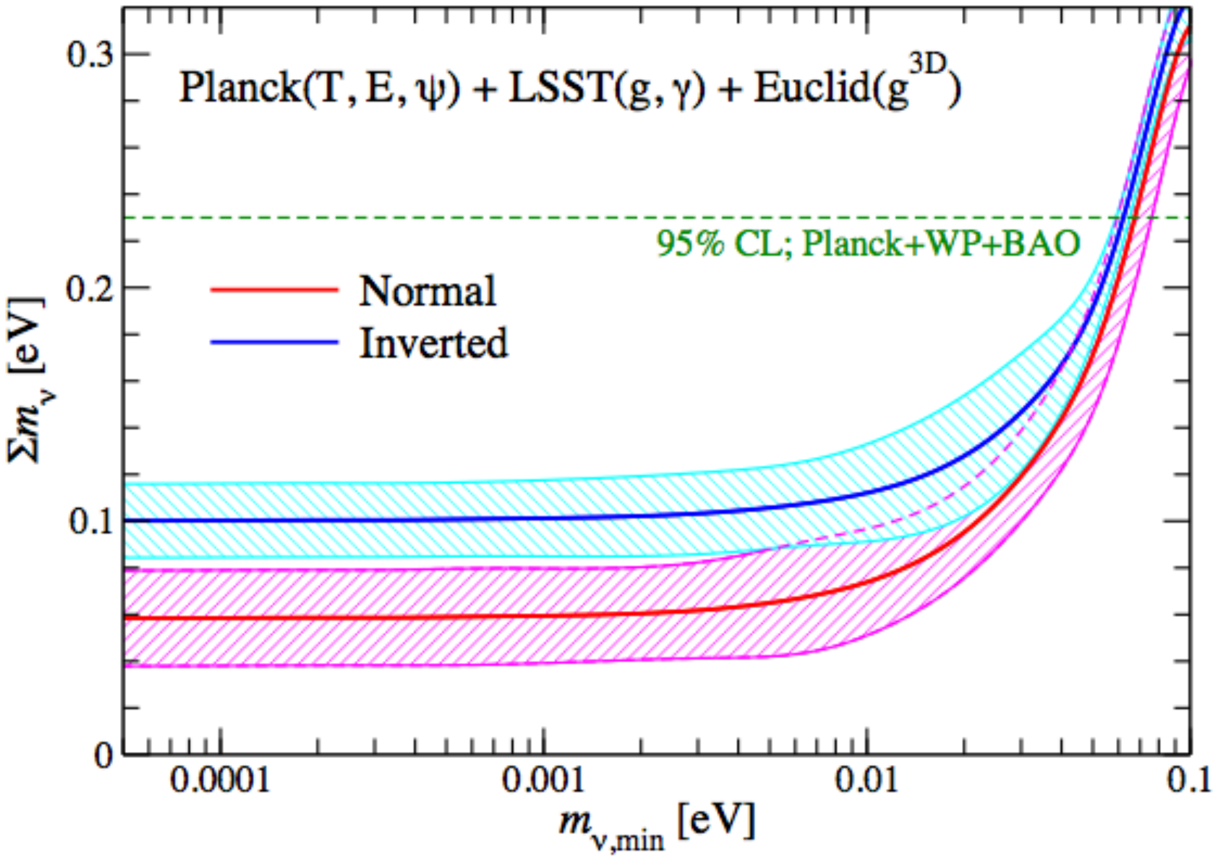
FORECASTING-II

Takeuchi & Kadota – today arXiv

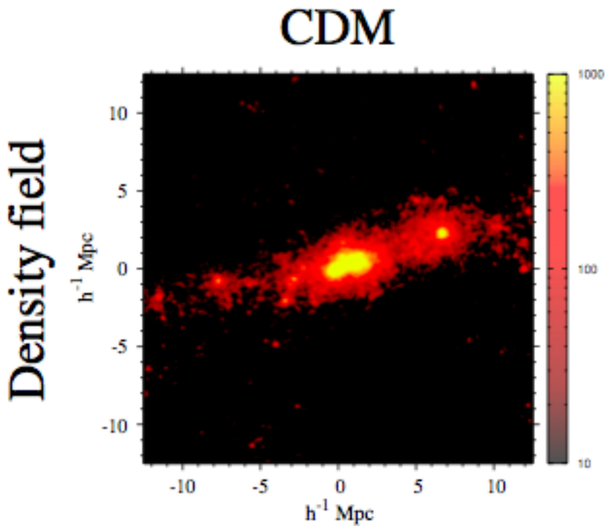
Euclid-like + LSST surveys + CMB + CMB lensing

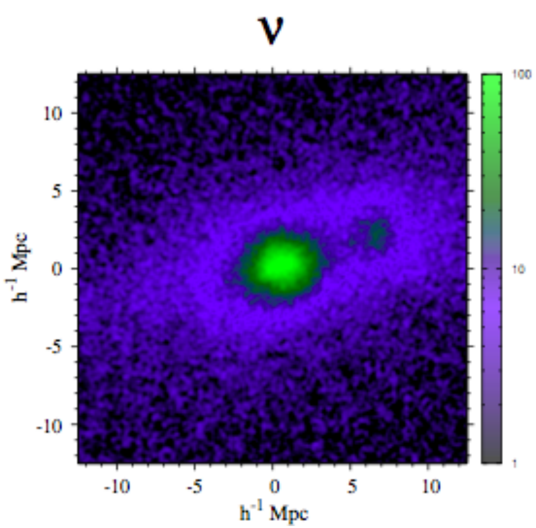
Fisher Matrix approach

$\sigma(M_\nu)$~0.02eV

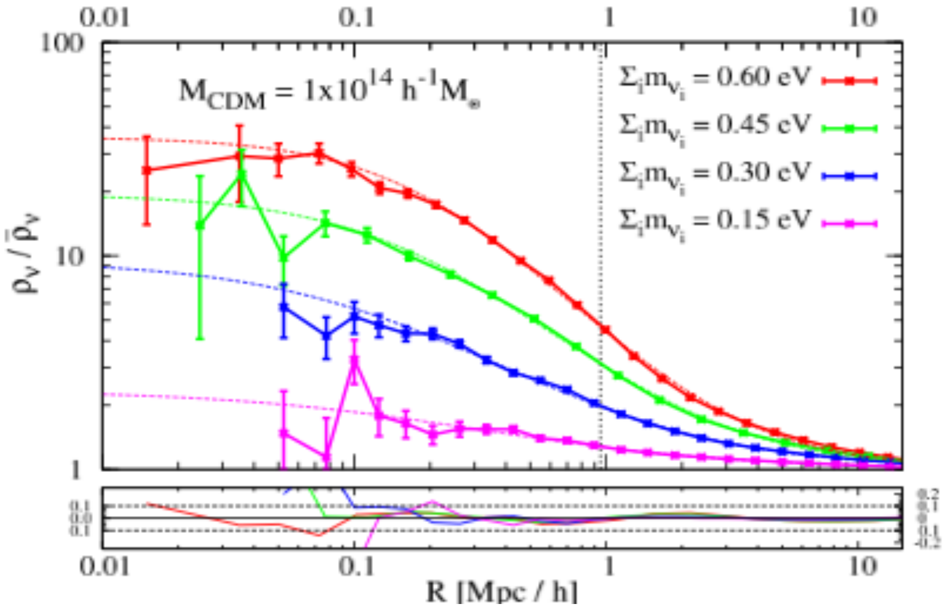


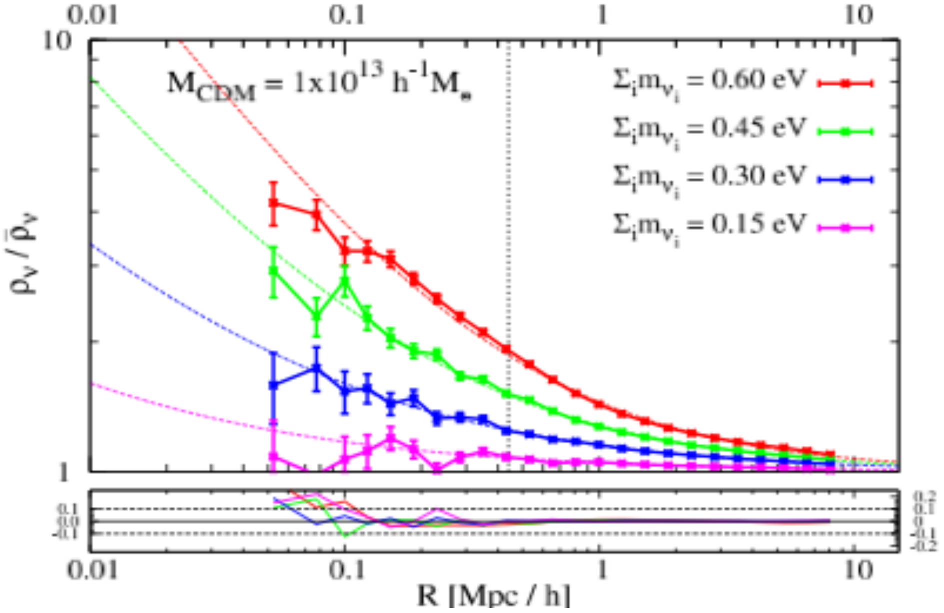
THE FUTURE: THE NEUTRINO HALO?





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

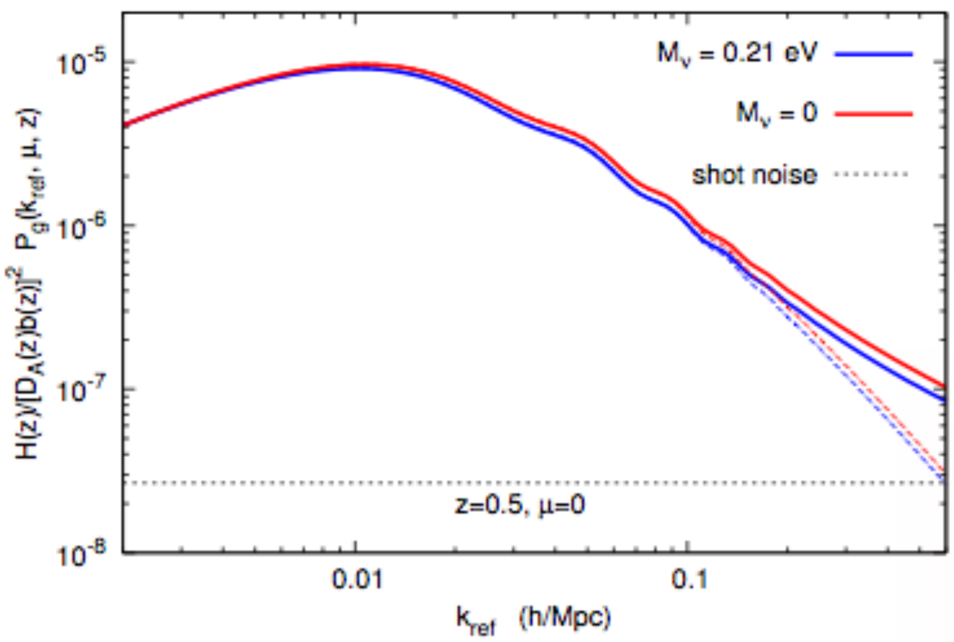




Villaescusa-Navarro, Bird, Garay, Viel, 2013, JCAP, 03, 019
Marulli, Carbone, Viel+ 2011, MNRAS, 418, 346

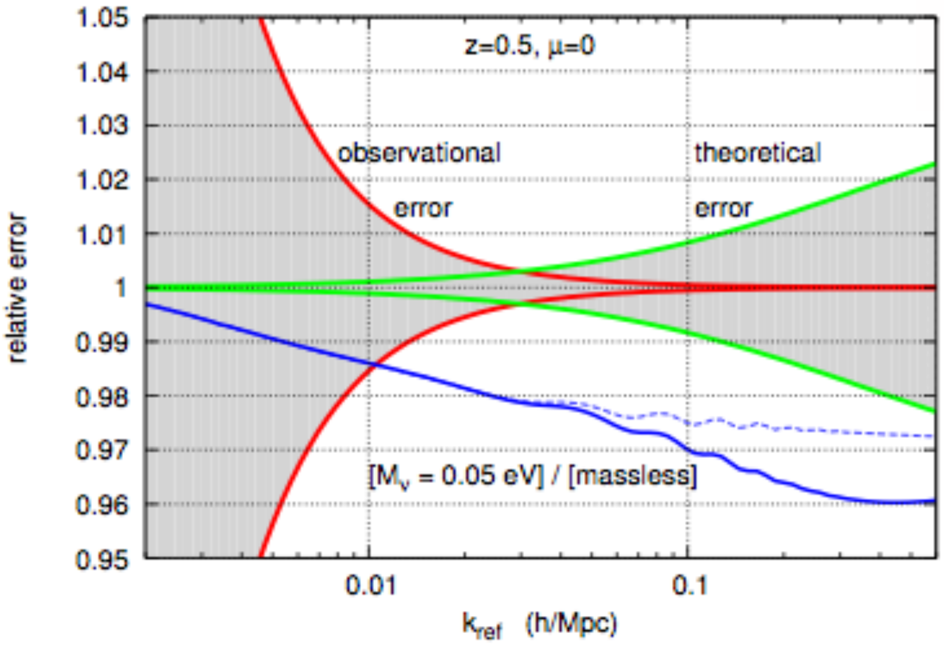
THE FUTURE: CLUSTERING FROM EUCLID GALAXIES and WEAK LENSING

Audren, Lesgourgues, Bird, Haehnelt, Viel 13



Non-linearities

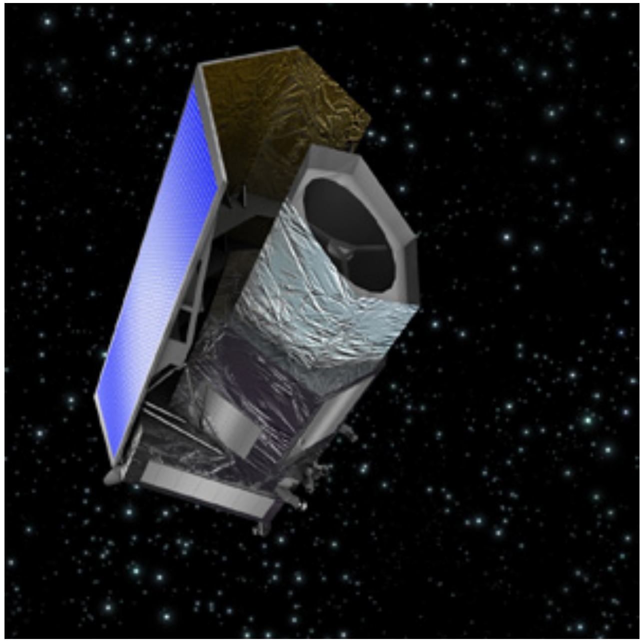
- $\sigma(M_\nu)$=18 meV → 5 meV when going from 0.1 to 0.6 h/Mpc
- with conservative errors the improvement is modest
- with realistic error could be 20%

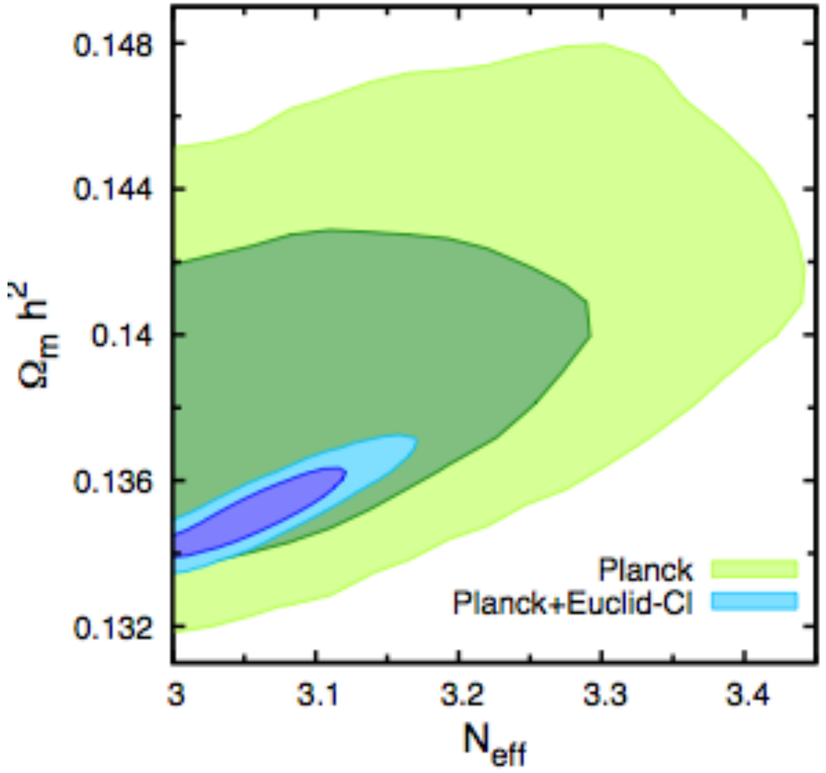


Need to be modelled accurately

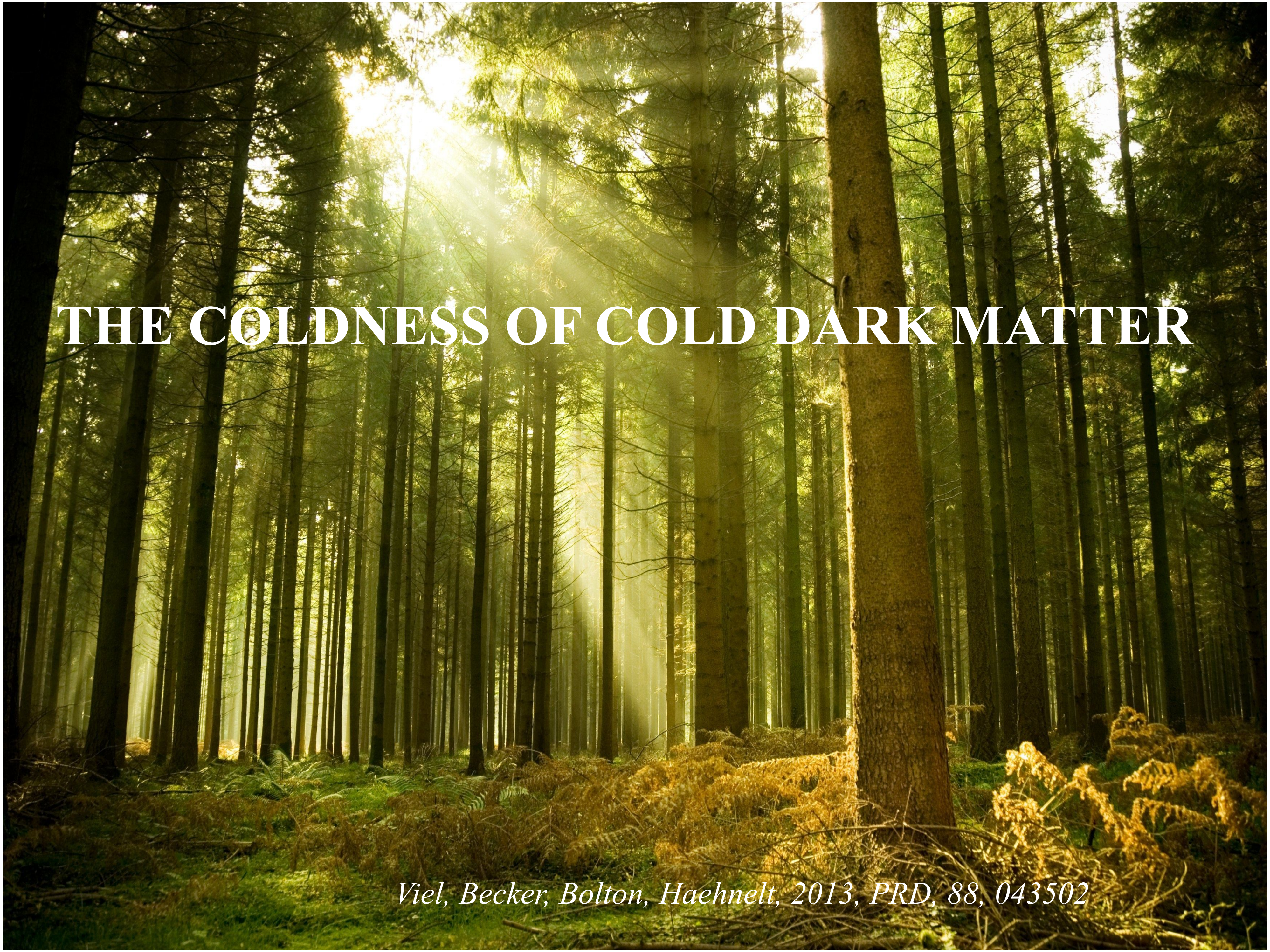
THE FUTURE: CLUSTERING and NUMBER COUNTS FROM EUCLID CLUSTERS

Costanzi, Sartoris, Xia, Biviano, Borgani, Viel 13





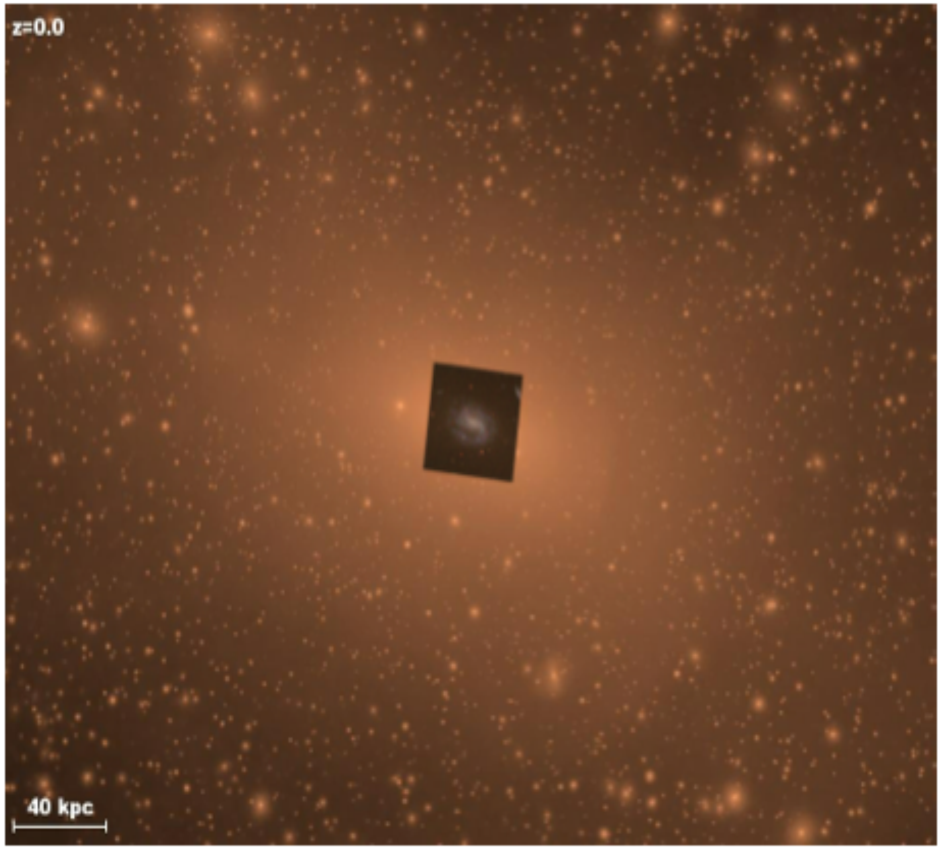
Model		ΛCDM+m_ν			
Data		Planck	P^{cl}−only	Euclid-Cl	Euclid-Cl+Planck
$\sum m_\nu$ [eV]	68% CL	< 0.41	< 0.60	< 0.17	< 0.017
	95% CL	< 0.74	< 1.37	< 0.35	< 0.031

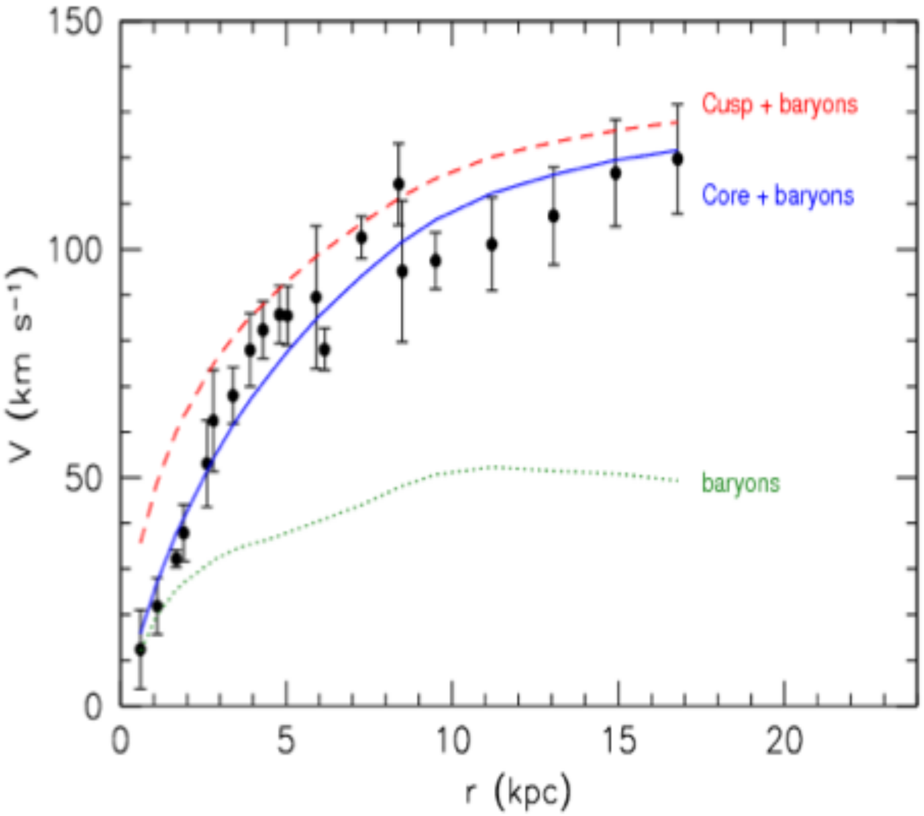


THE COLDNESS OF COLD DARK MATTER

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

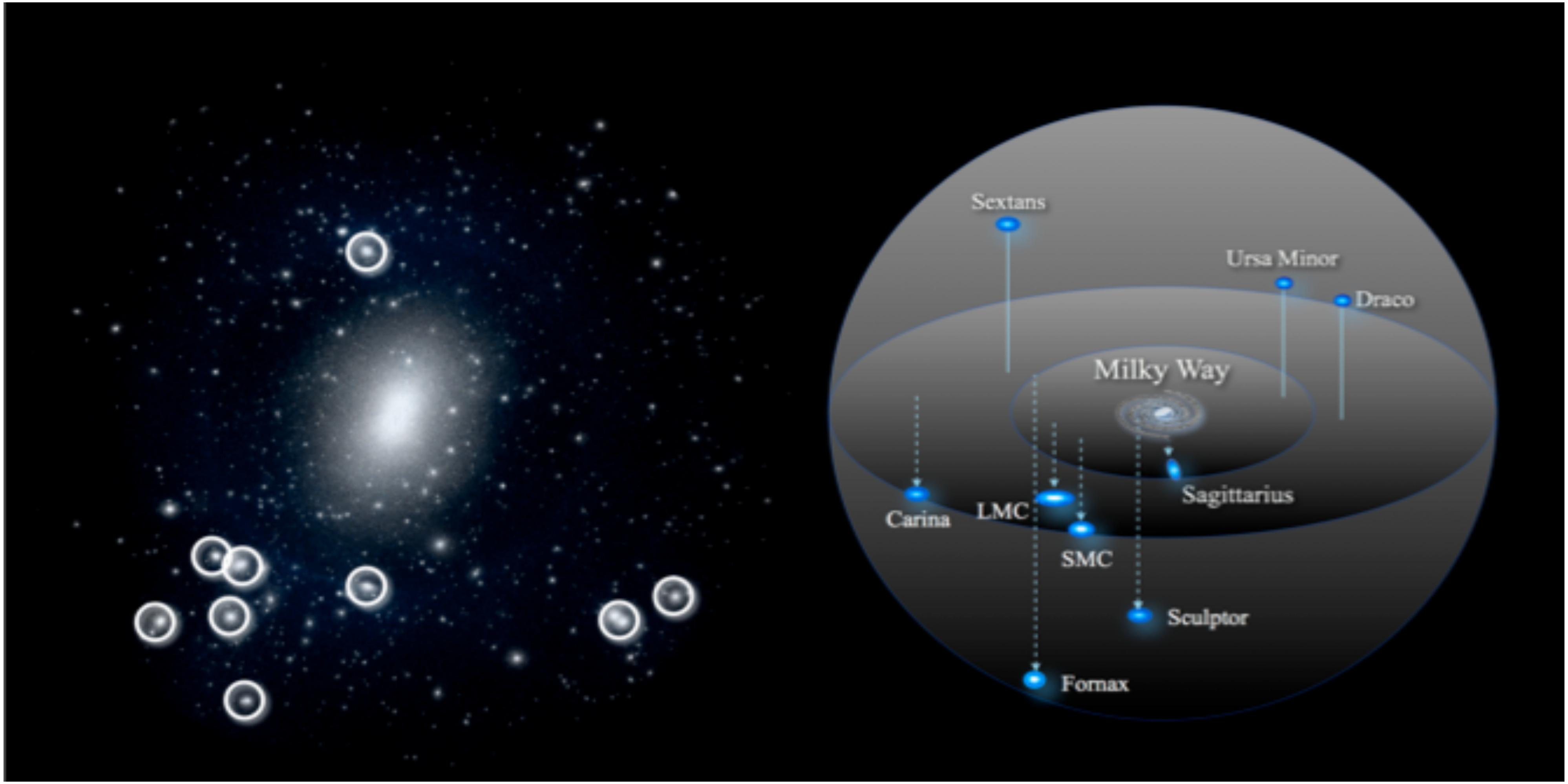
THE SMALL-SCALE CRISIS OF ΛCDM: CUSP/CORE





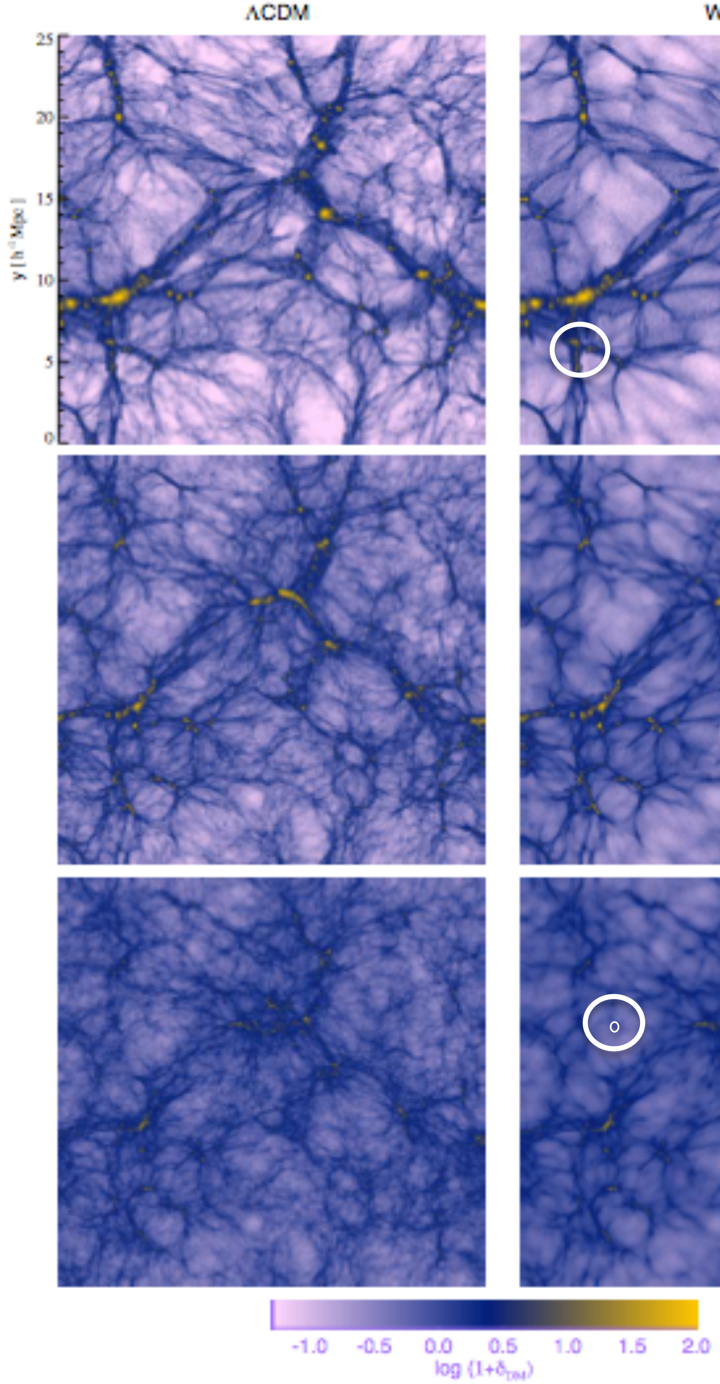
See recent Weinberg et al. arXiv:1306.0913

THE SMALL-SCALE CRISIS OF ΛCDM: TOO BIG TO FAIL



See recent Weinberg et al. arXiv:1306.0913

THE COSMIC WEB in WDM/LCDM scenarios



z=0

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

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

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

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

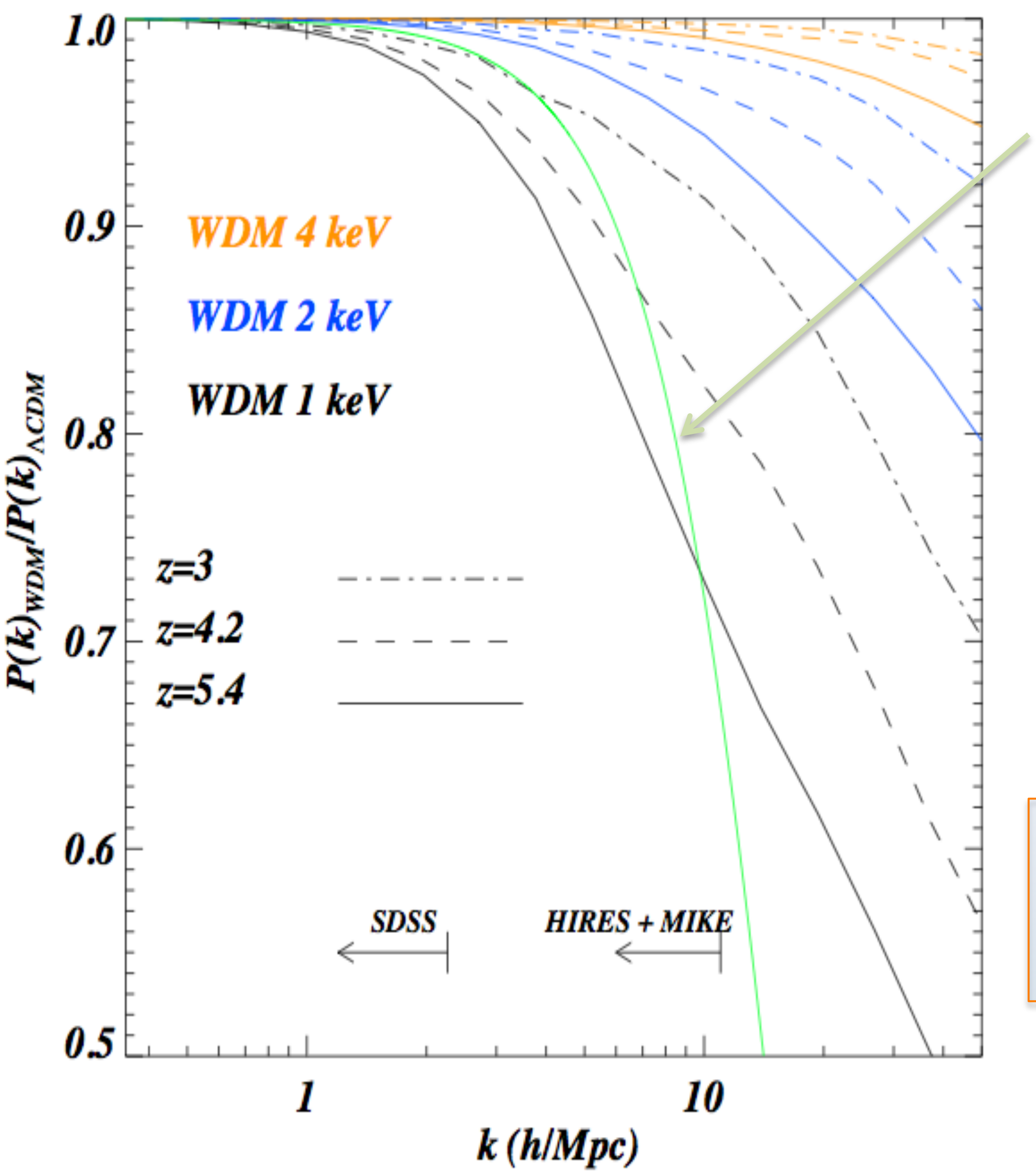
z=2

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

z=5

Viel, Markovic, Baldi & Weller 2013

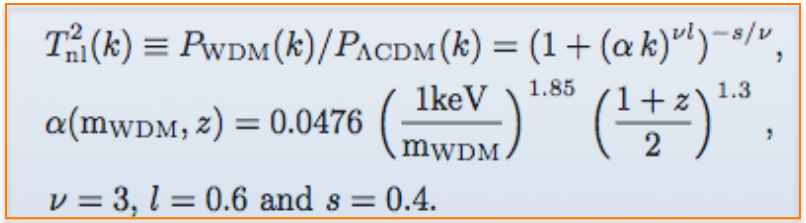
THE WARM DARK MATTER CUTOFF IN THE MATTER DISTRIBUTION



Linear cutoff for WDM 2 keV

Linear cutoff is redshift independent

Fit to the non-linear cut-off



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

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

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

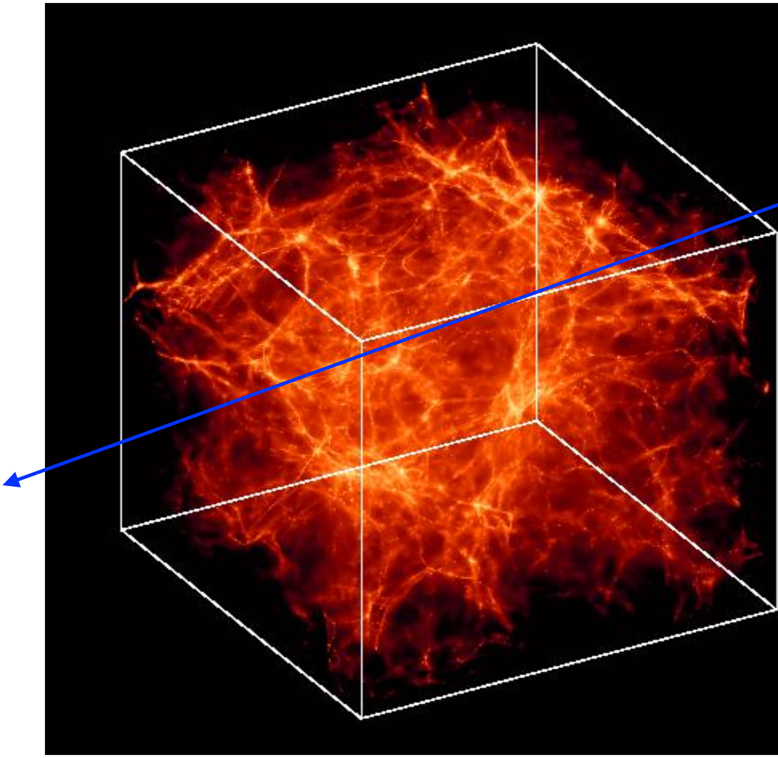
Viel, Markovic, Baldi & Weller 2013

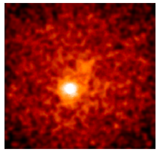
IMPLICATIONS FOR STRUCTURE FORMATION

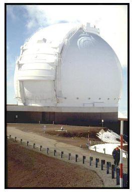
- Strong and weak lensing	Markovic et al. 13/Faadely & Keeton 12
- Galaxy formation	Menci et al 13, Kang et al. 13
- Reionization/First Stars	Gao & Theuns 07
- Dark Matter Haloes (mass functions)	Pacucci et al. 13
- Luminous matter properties	Polisensky & Ricotti 11, Lovell et al. 09
- Gamma-Ray Bursts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

The Intergalactic Medium: Theory vs. Observations







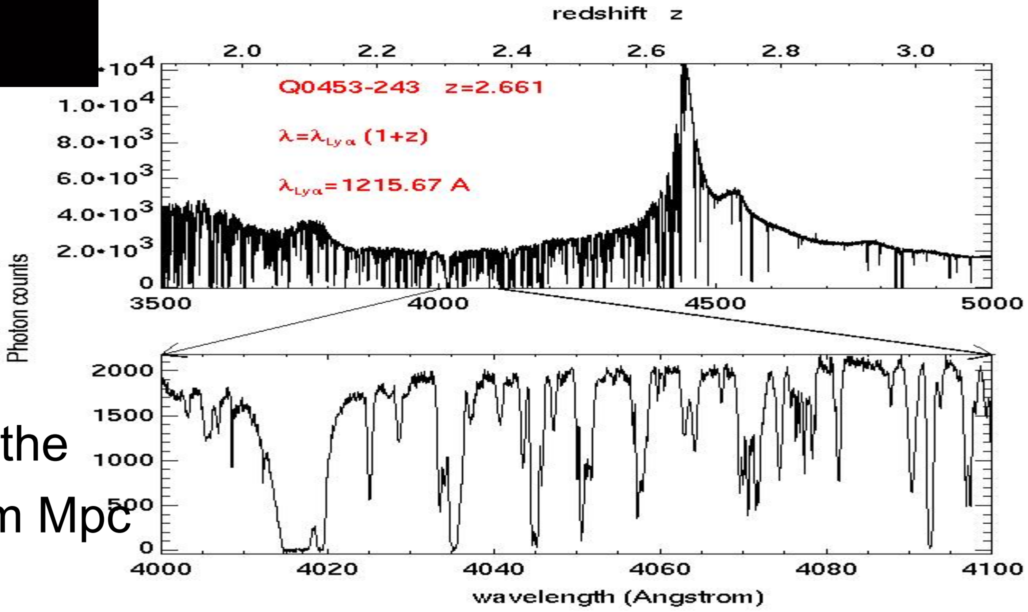
80 % of the baryons at z=3
are in the **Lyman-α forest**

Bi & Davidsen (1997), Rauch (1998)

baryons as tracer of the dark matter density field

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

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



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

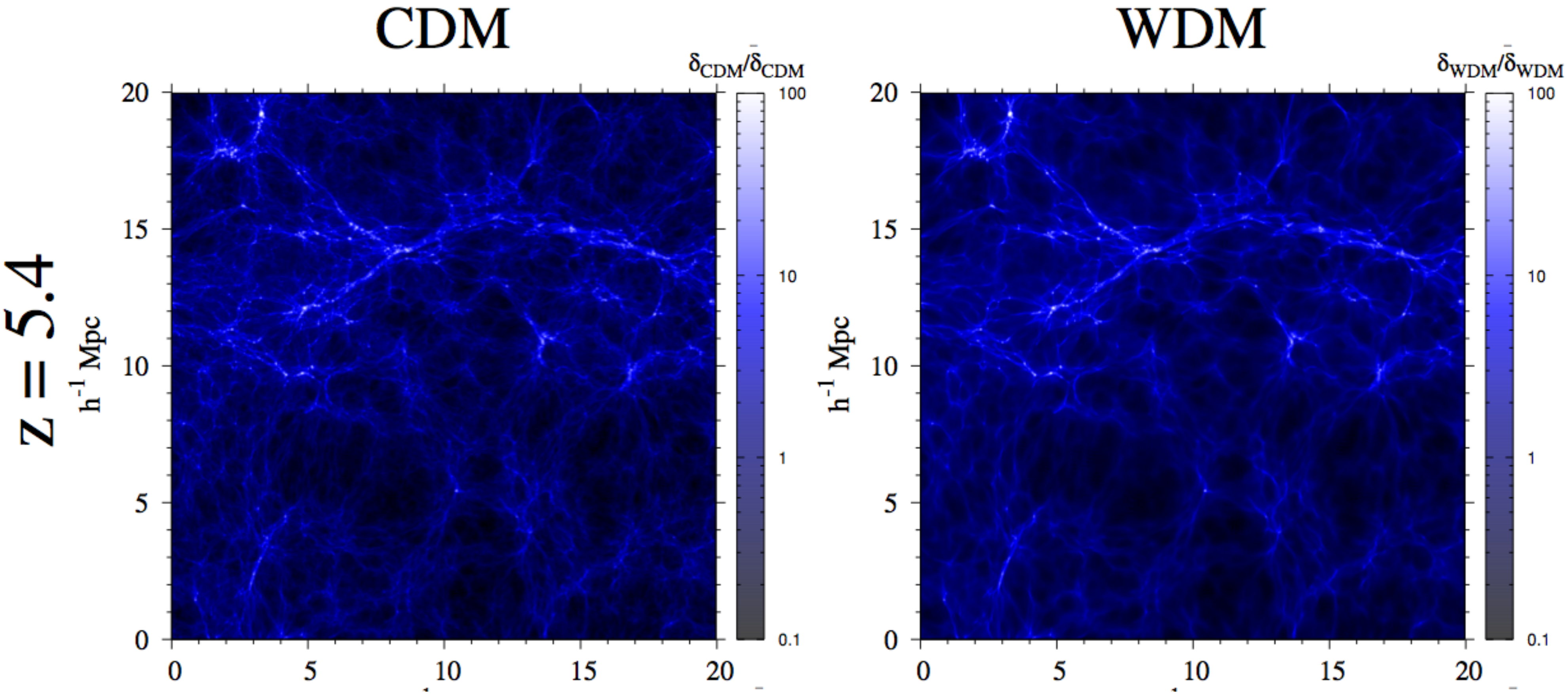
Where linear WDM cut-off is more prominent

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

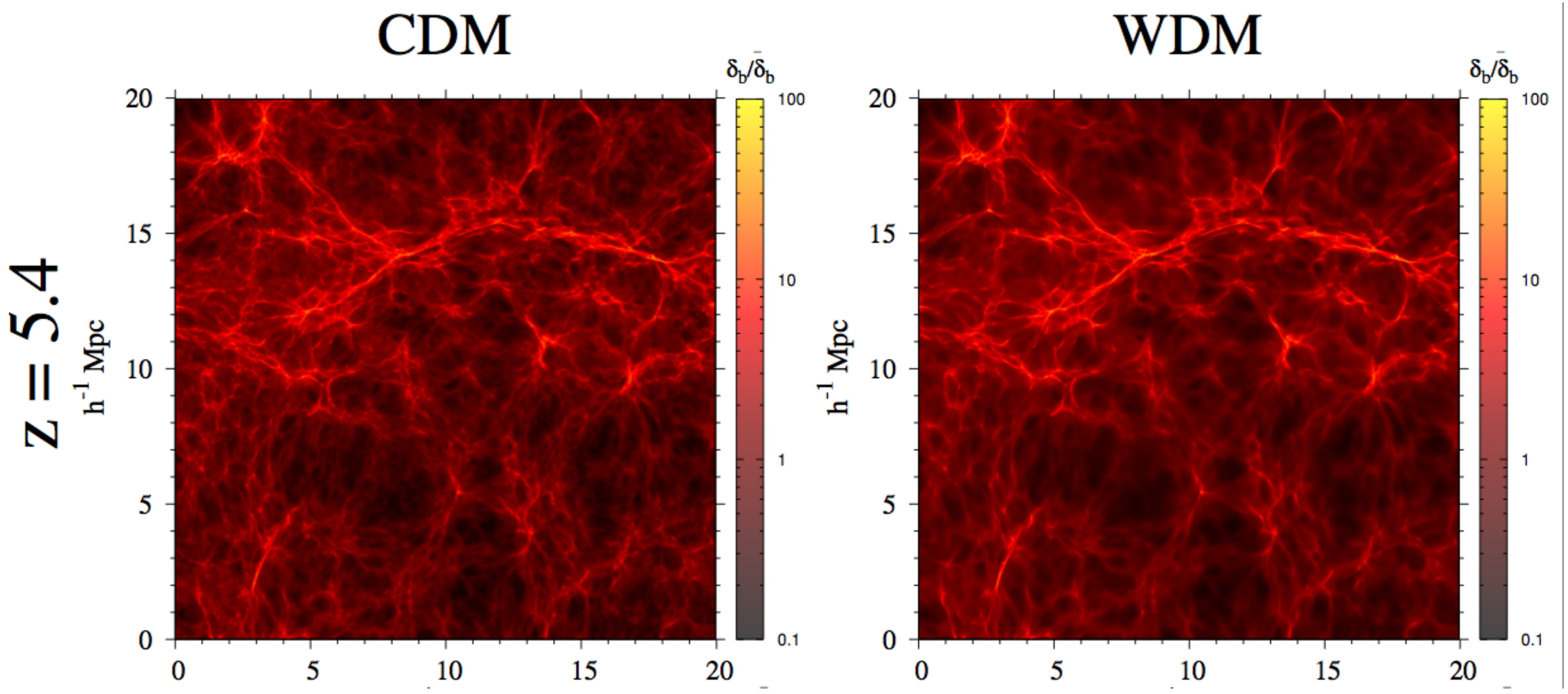
HISTORY OF WDM LYMAN-α BOUNDS

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



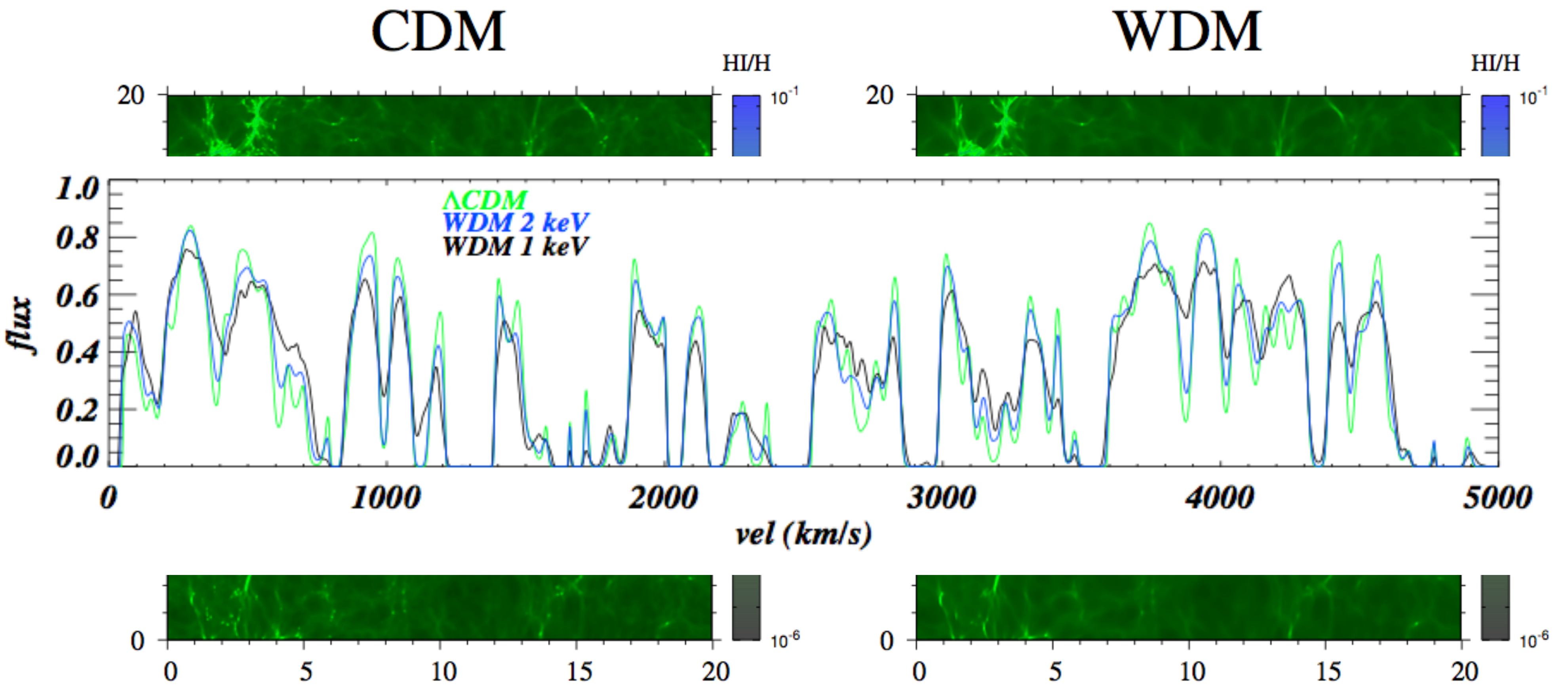
GAS DISTRIBUTION



CDM

WDM

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

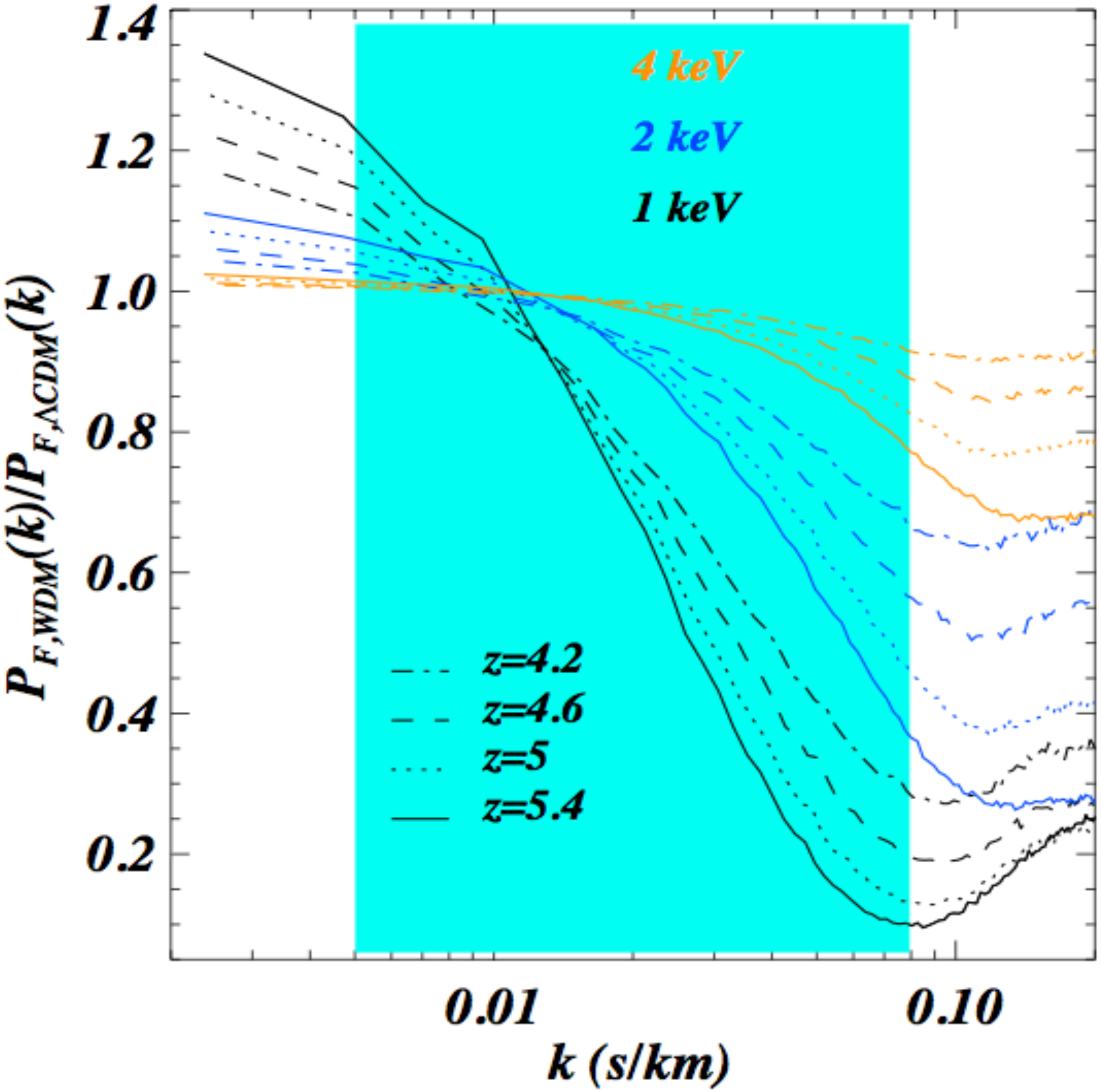
Parameter space: m_{WDM}, T_0, γ, <F> explored fully
Parameter space: : σ_8, n_s, Ω_m, H_0, UV explored with second order Taylor expansion of the flux power

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

+ second order

THE HIGH REDSHIFT WDM CUTOFF

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



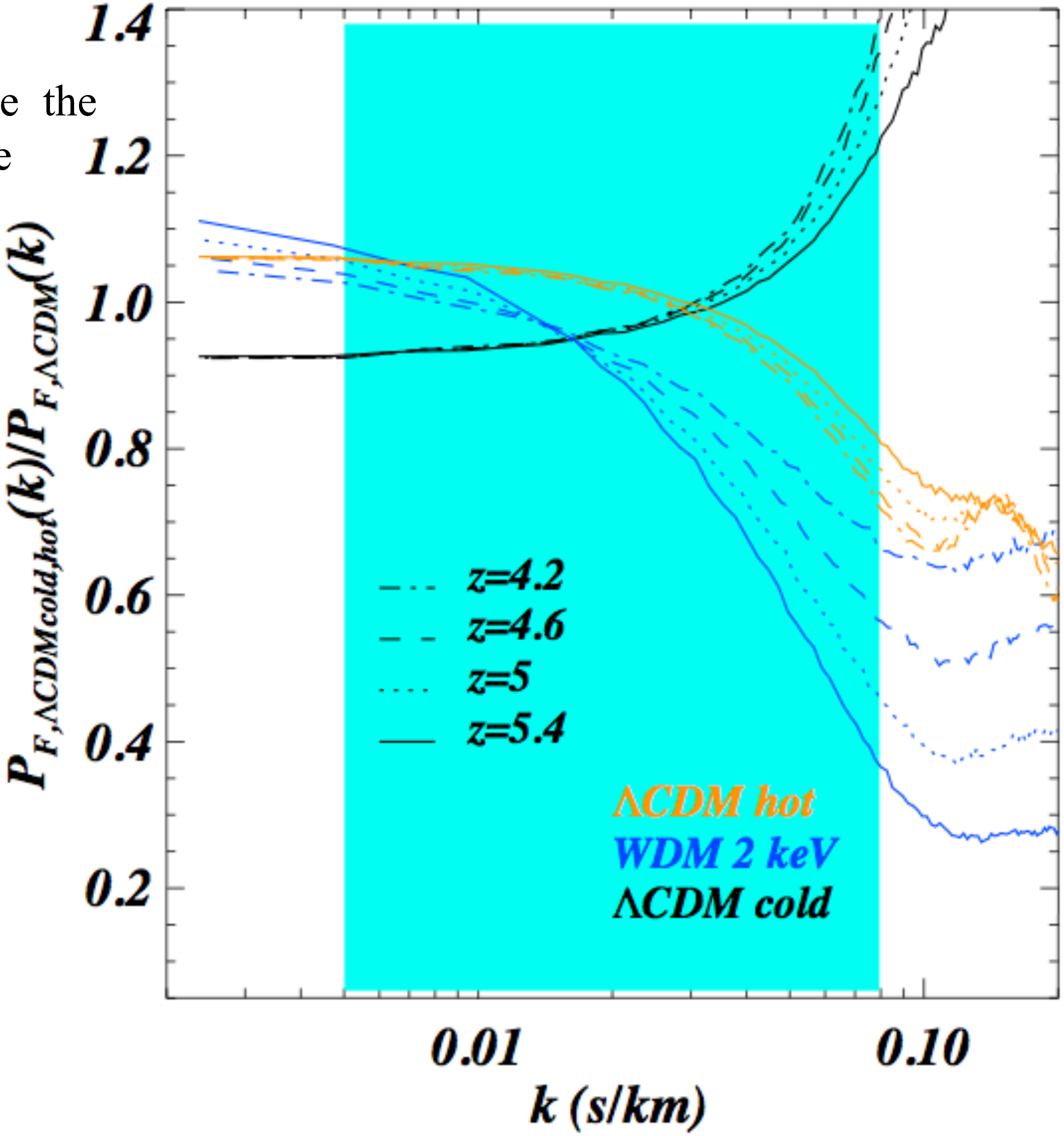
THE TEMPERATURE: T_0

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

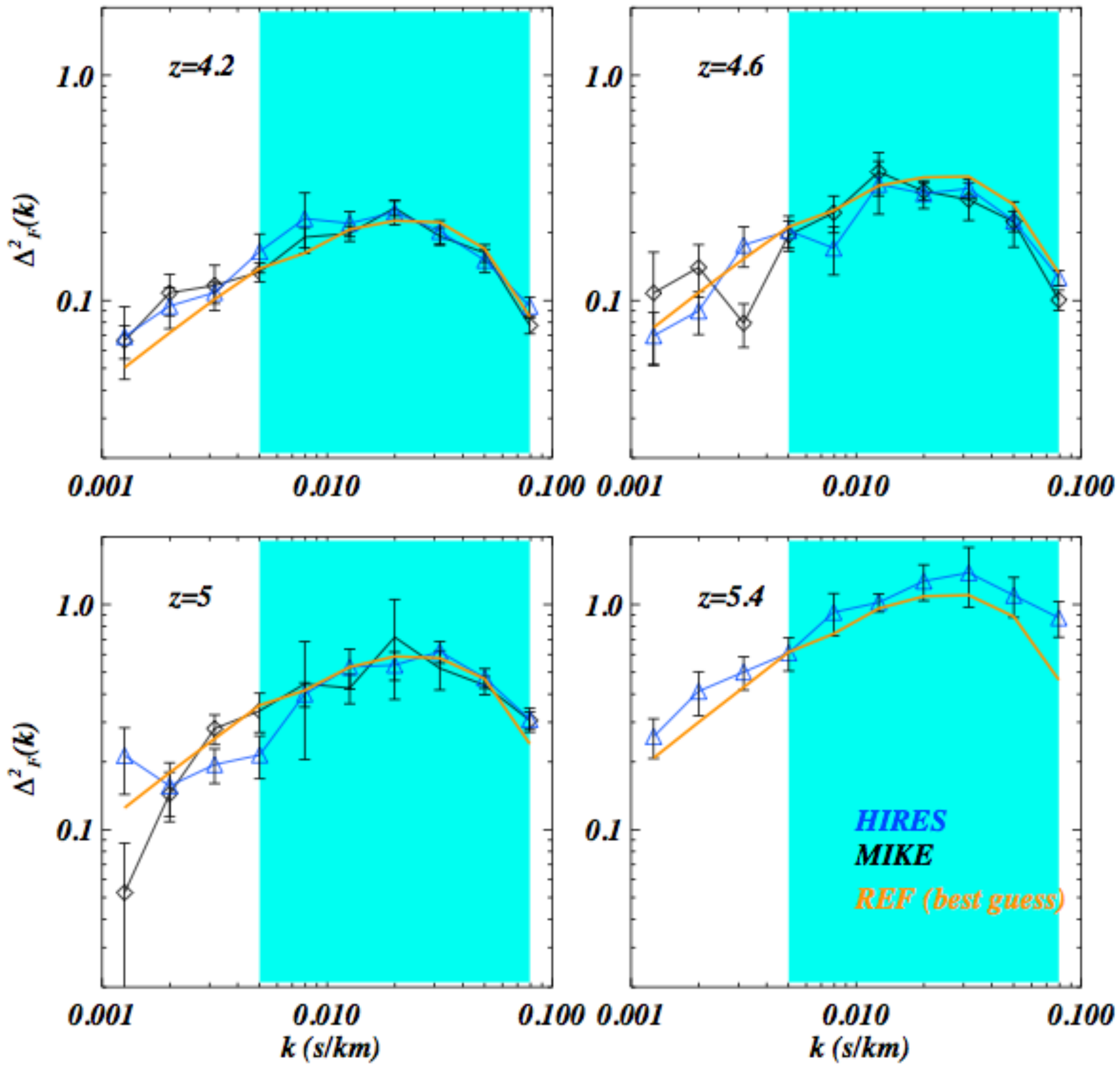
T_0 and γ describe the IGM thermal state

Hot + 3000 K
Cold – 3000 K

REF has 8300 K
at z=4.6

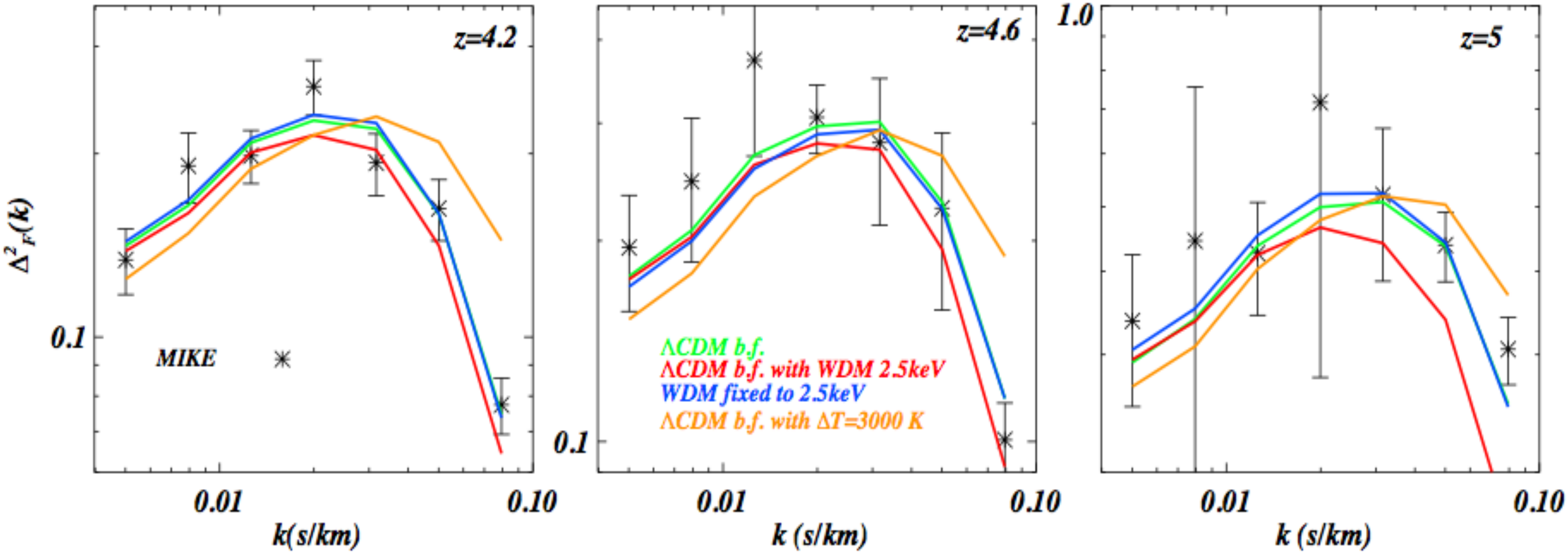


THE BEST GUESS MODEL

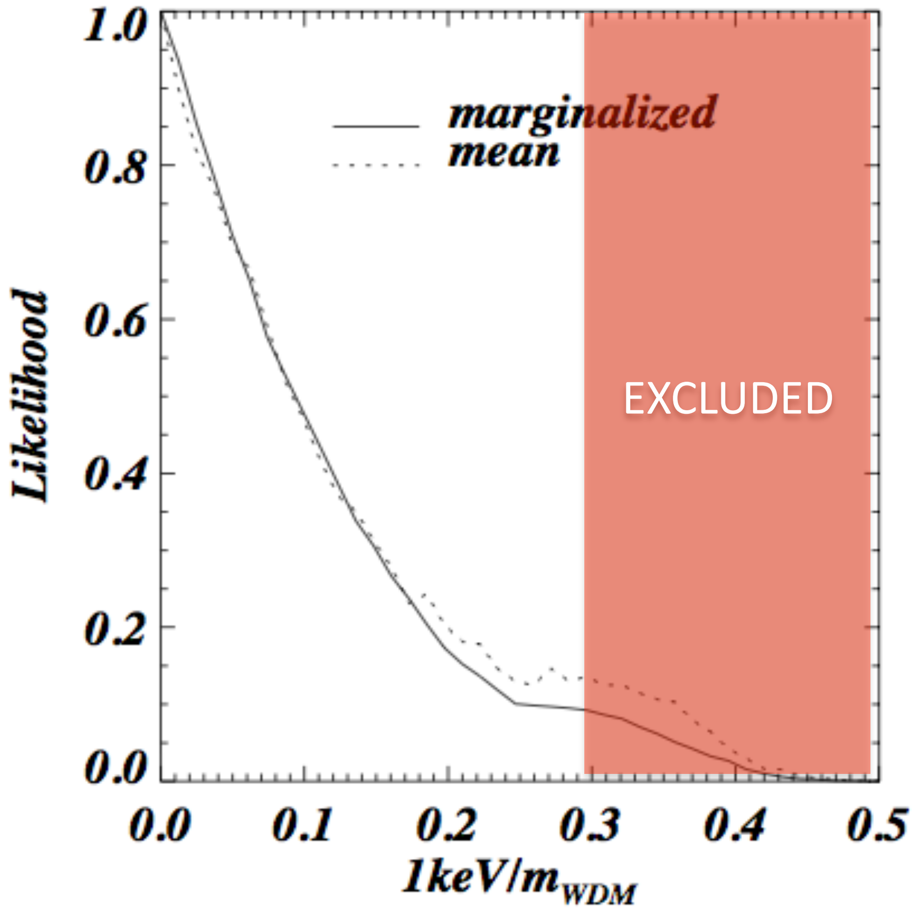


This is the starting point of the MCMC likelihood estimation cosmology close to Planck values

THE BEST FIT MODEL for MIKE



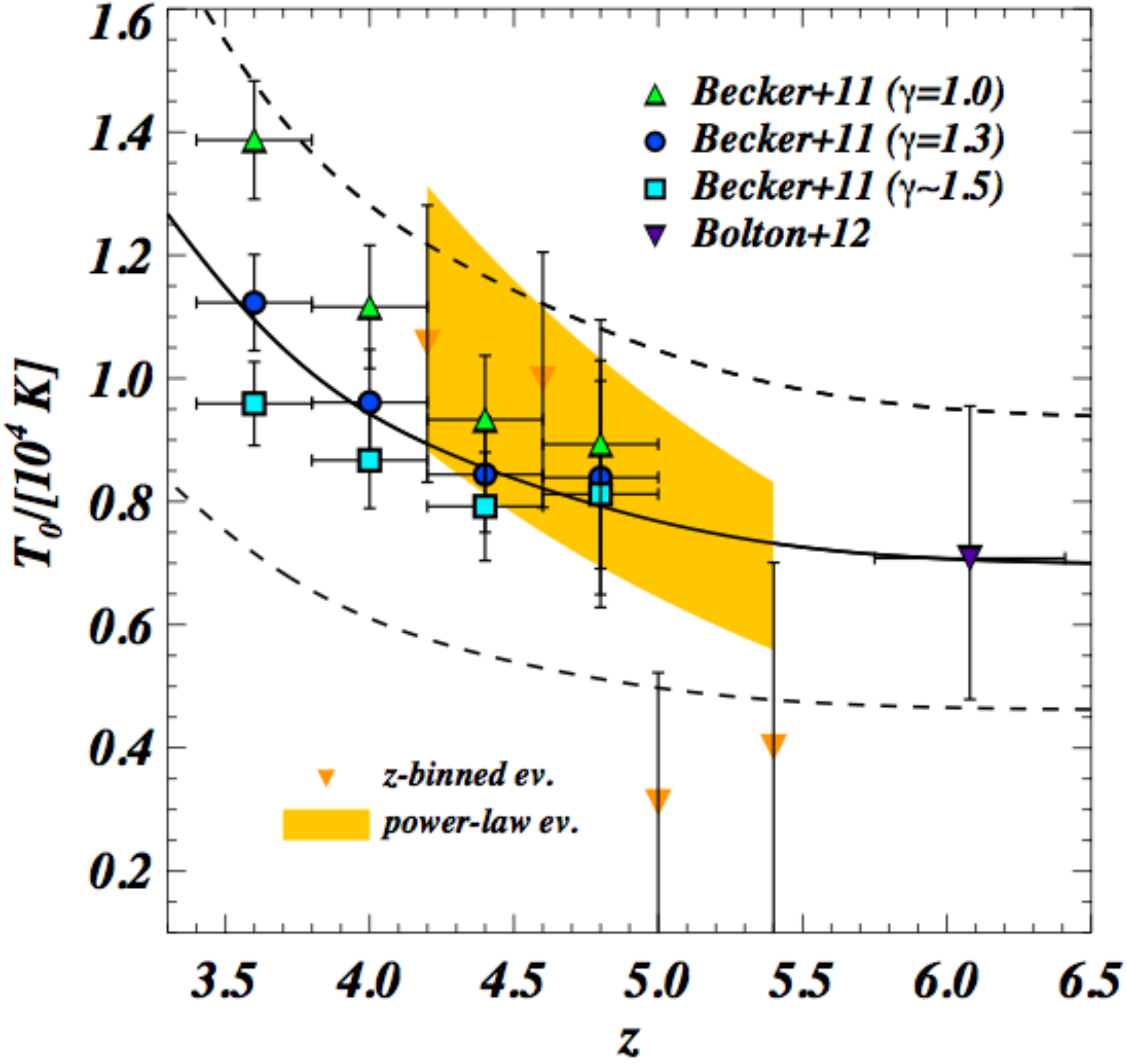
RESULTS FOR WDM MASS



$m > 3.3$ keV (2σ)

RESULTS FOR TEMPERATURE

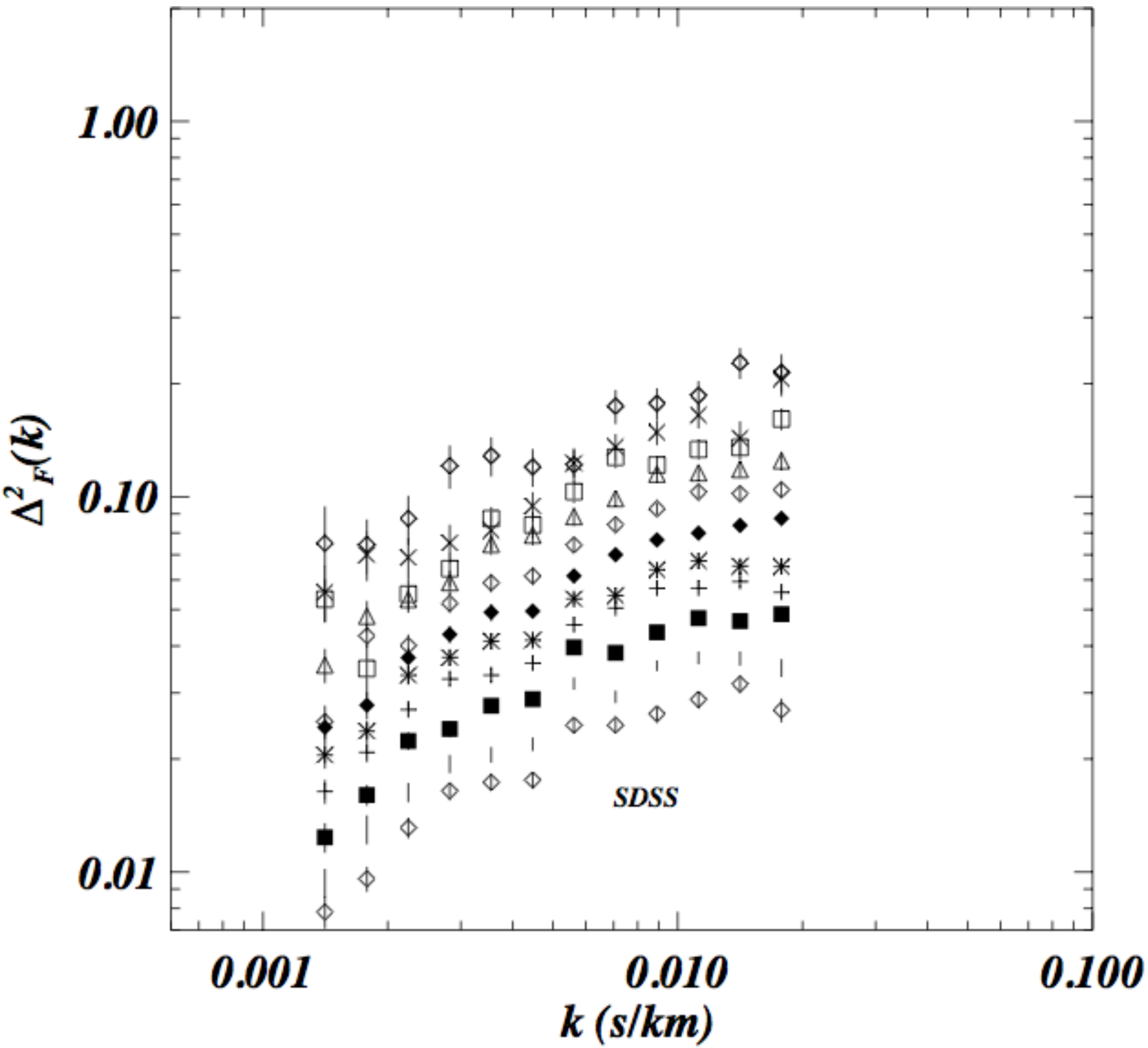
$$\gamma^A(z) = \gamma^A[(1+z)/5.5]^{\gamma_A^S} \qquad T_0^A(z) = T_0^A[(1+z)/5.5]^{T_0^S}$$

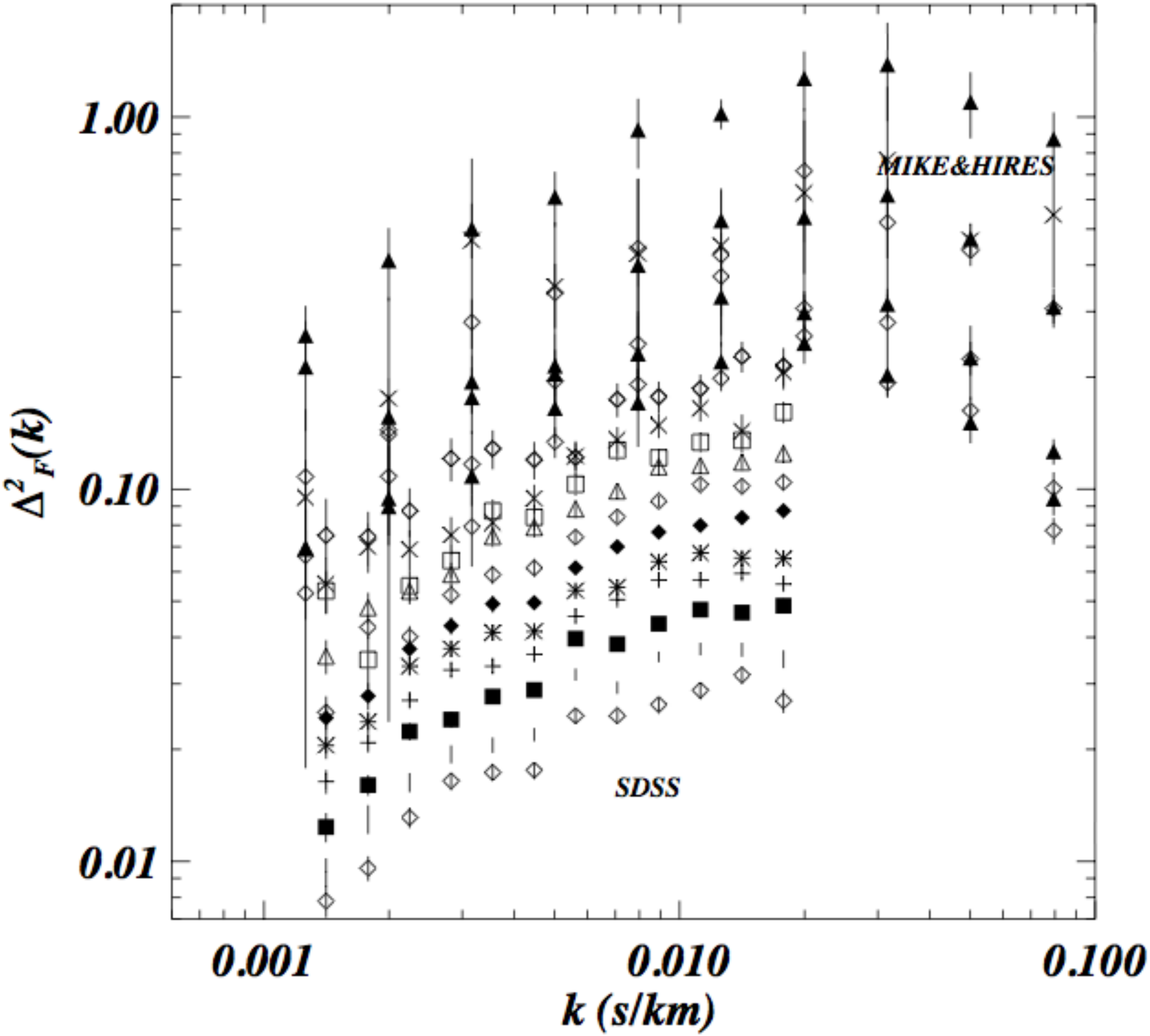


SDSS + MIKE + HIRES CONSTRAINTS

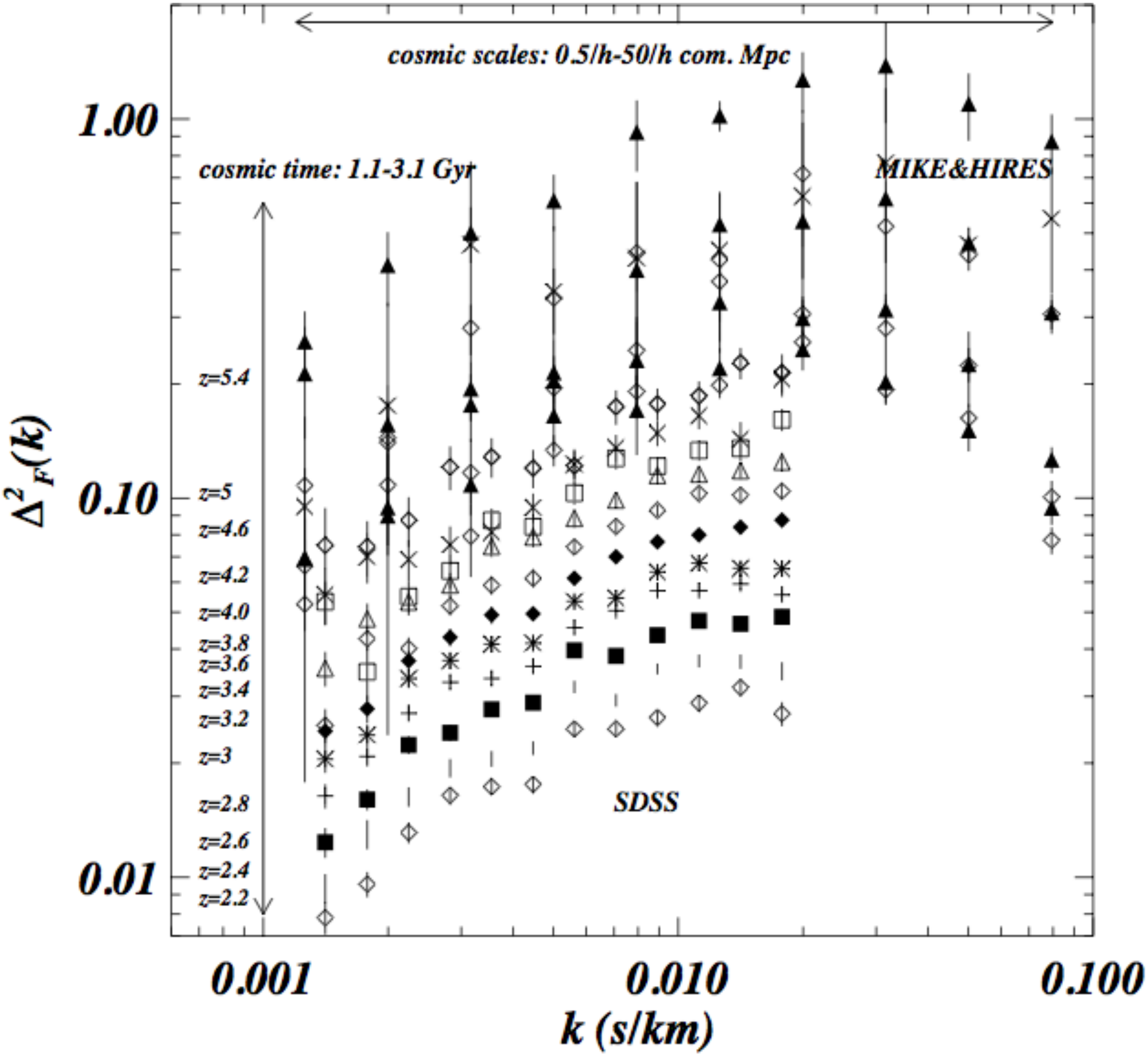
Joint likelihood analysis

SDSS data from McDonald05,06 not BOSS

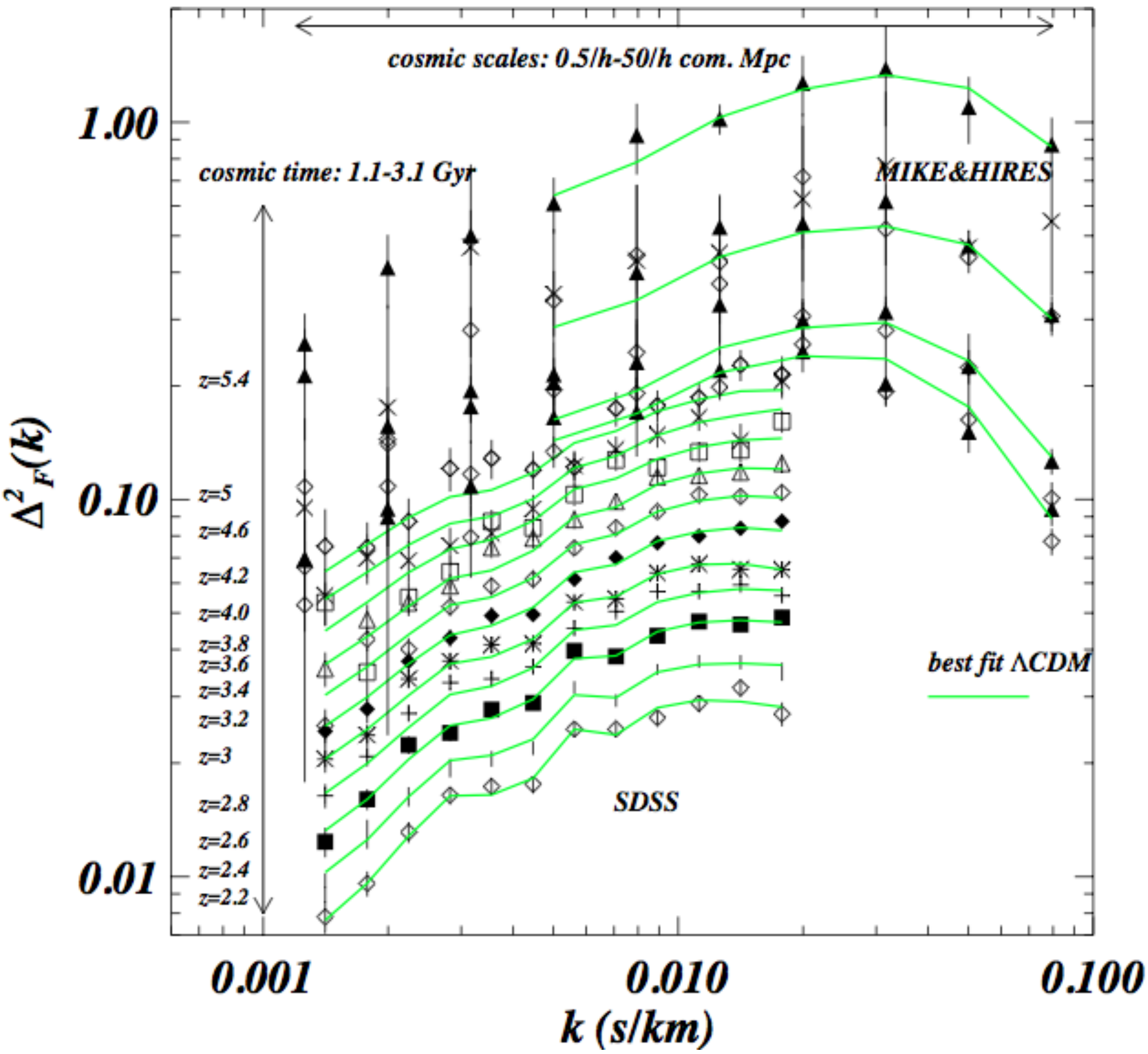

1.00
0.10
0.01
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)
SDSS

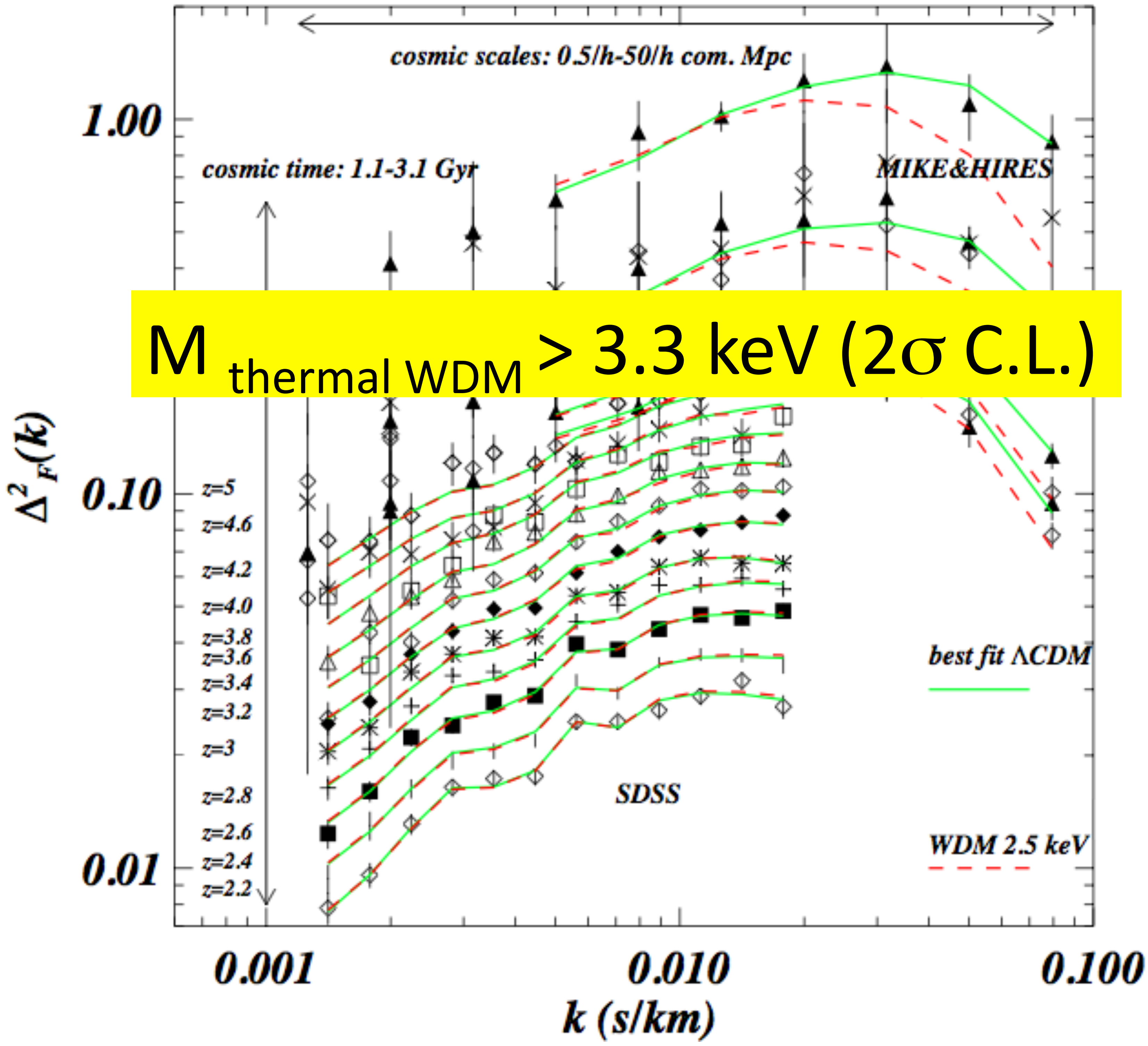


$\Delta^2_F(k)$
1.00
0.10
0.01
0.001
0.010
0.100
k (s/km)
MIKE&HIRES
SDSS



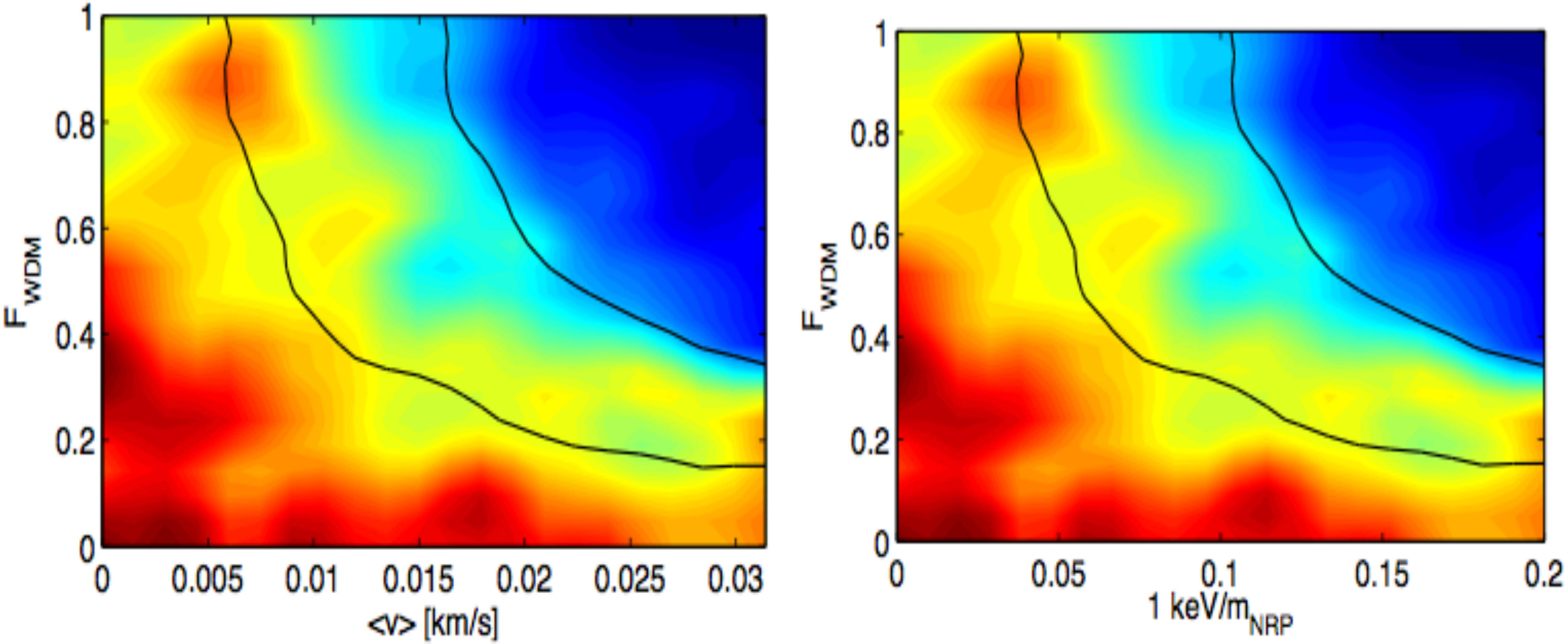
cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)


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
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)



$M_{\mathrm{thermal\ WDM}} > 3.3$ keV (2σ C.L.)

CONSTRAINTS FROM SDSS vs UVES SPECTRA

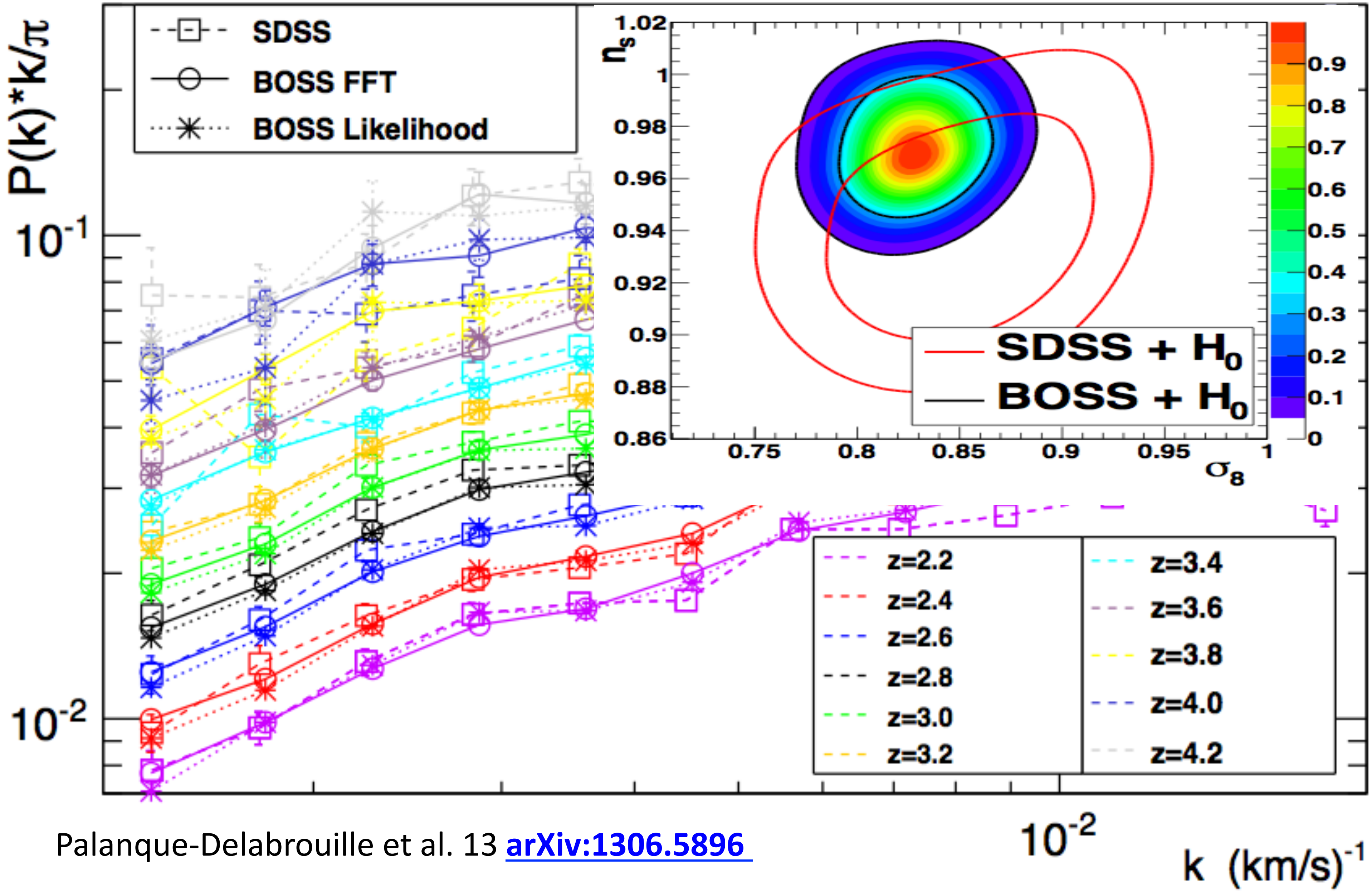


m 1keV

m 2keV 1keV

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

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!

Galaxy clustering data give <0.3 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.
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 $2x10^8 M_\odot/h$
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