Structure formation in WDM

Matteo Viel – *HAP meeting 2015*

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HALO FORMATION IN WARM DARK MATTER MODELS

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ABSTRACT

Discrepancies have emerged between the predictions of standard cold dark matter (CDM) theory and observations of clustering on subgalactic scales. Warm dark matter (WDM) is a simple modification of CDM in which the dark matter particles have initial velocities due either to their having decoupled as thermal relics or to their having been formed via nonequilibrium decay. We investigate the nonlinear gravitational clustering of WDM with a high-resolution *N*-body code and identify a number of distinctive observational signatures. Relative to CDM, halo concentrations and core densities are lowered, core radii are increased, and large halos emerge with far fewer low-mass satellites. The number of small halos is suppressed, and those present are formed by "top-down" fragmentation of caustics, as part of a "cosmic web" connecting massive halos. Few small halos form outside this web. If we identify small halos with dwarf galaxies, then their number, spatial distribution, and formation epoch appear in better agreement with the observations for WDM than they are for CDM.

3 putative tensions:

1) Number of satellites
2) Cores in dwarfs
3) Voids

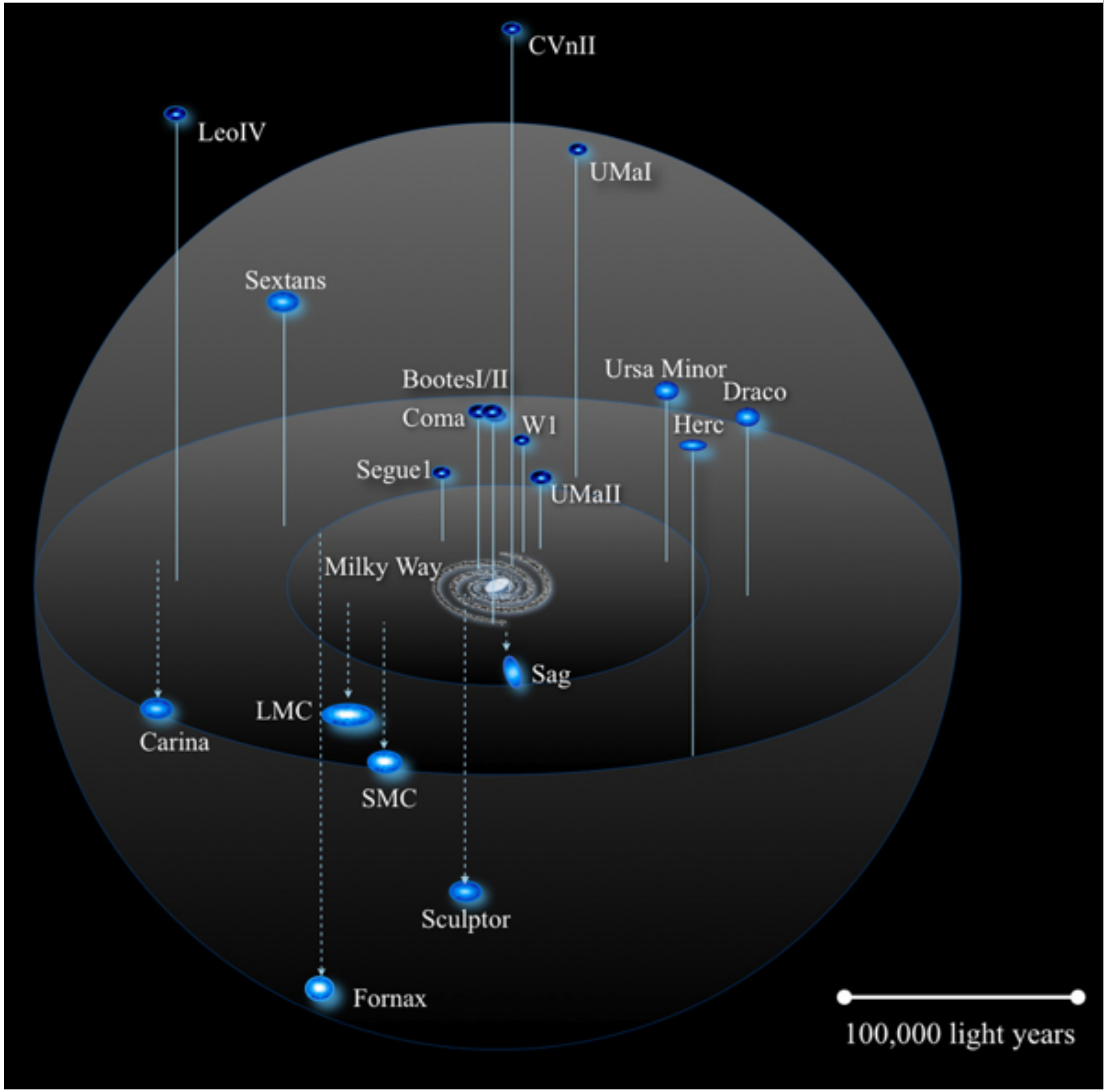
See also Colombi+96, Colin+01, Hogan&Dalcanton 00, Sommer-Larsen&Dolgov01

WDM STRUCTURE FORMATION

Generic features of WDM scenarios:

- Lower core densities
- Reduction of small mass haloes
- Suppression of satellites
- Emptier voids (debatable once galaxy mocks are done)
- Late formation of low mass haloes
- Suppression of halo formation at high redshift and somewhat faster evolution at lower redshifts
- Enhanced bias of WDM haloes with respect to CDM (small effect)
- Regimes in which a top-down scenario of structure form. could be in place

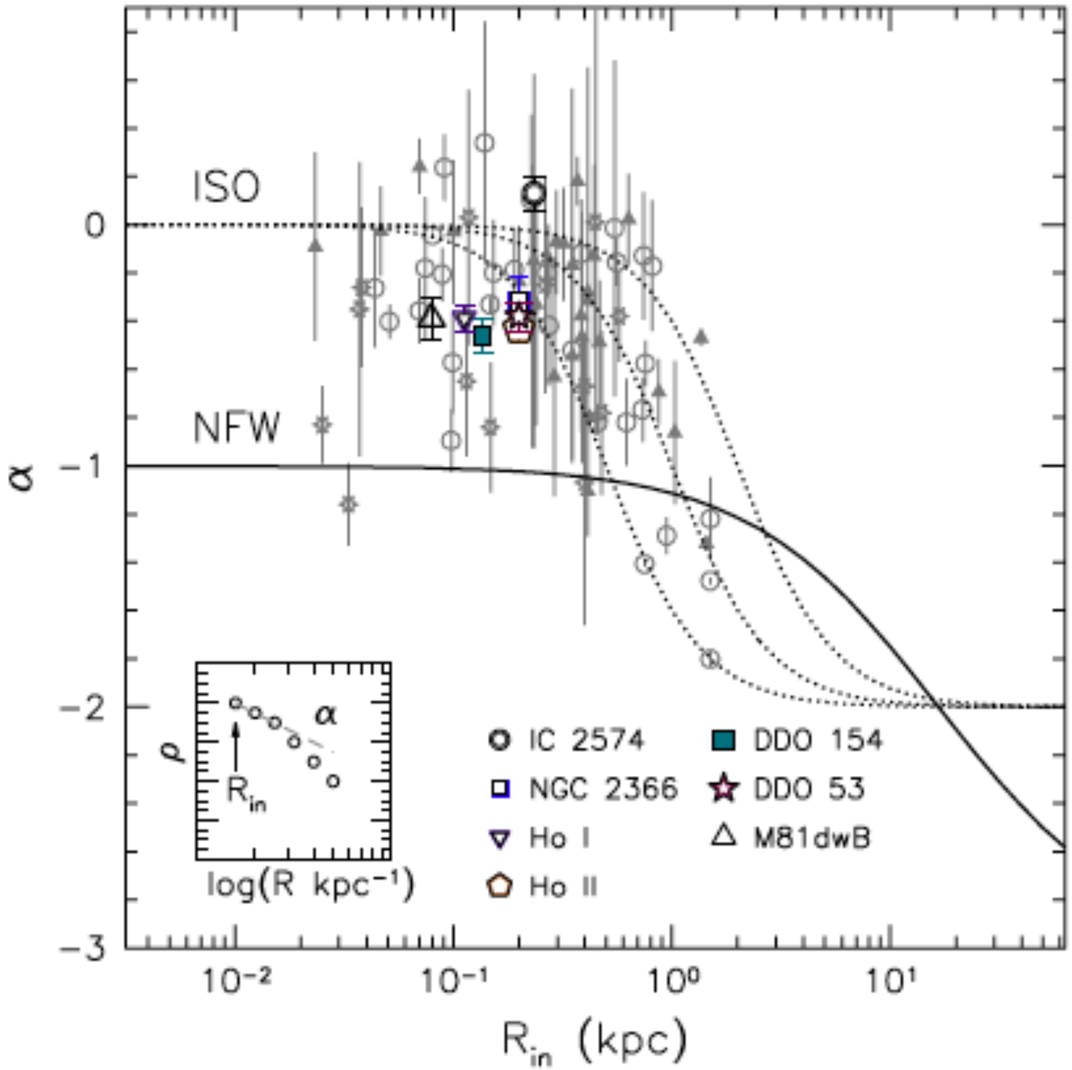
Satellites



Canis Major Dwarf	1.5	8	Irr	2003
Sagittarius Dwarf	2	20	E	1994
Large Magellanic Cloud	4	48.5	SBm	prehistoric
Small Magellanic Cloud	2	61	Irr	prehistoric
Ursa Major II Dwarf	0.2	30	dG D	2006
Ursa Minor Dwarf	0.4	60	dE4	1954
Draco Dwarf	0.7	80	dE0	1954
Sculptor Dwarf	0.8	90	dE3	1937
Sextans Dwarf Spheroidal	0.5	90	dE3	1990
Carina Dwarf Spheroidal	0.5	100	dE3	1977
Ursa Major I Dwarf	-	100	dG D	2005
Fornax Dwarf	0.6	140	dE2	1938
Leo II	0.7	210	dE0	1950
Leo I	0.5	250	dE3	1950
Leo IV	0.3	160	dSph	2006
Leo V	0.08	180	dSph	2007
Leo T	0.34	420	dSph/dIrr	2006
Boötes I	0.3	60	dSph	2006
Boötes II	0.1	42	dSph	2007
Boötes III	1	46	dSph?	2009
Coma Berenices	0.14	42	dSph	2006
Segue 2	0.07	35	dSph	2007
Canes Venatici I	2	220	dSph	2006
Canes Venatici II	0.3	155	dSph	2006
Hercules	0.7	135	dSph	2006
Pisces II	0.12	180	dSph	2010
Reticulum II	-	30	dSph	2015 [6][7]
Eridanus II	-	380	dSph	2015 [6] [7]
Horologium	-	100	dSph?	2015 [6] [7] [a]
Pictoris	-	115	dSph?	2015 [6] [7] [a]
Phoenix II	-	100	dSph?	2015 [6] [7] [a]
Kim 2/Indus I	-	100	dSph?	2015 [8] [6] [7] [a]
Grus	-	120	dSph	2015 [6]
Eridanus III	-	90	dSph?	2015 [6] [7] [a]
Tucana II	-	70	dSph	2015 [6] [7]

Dwarfs

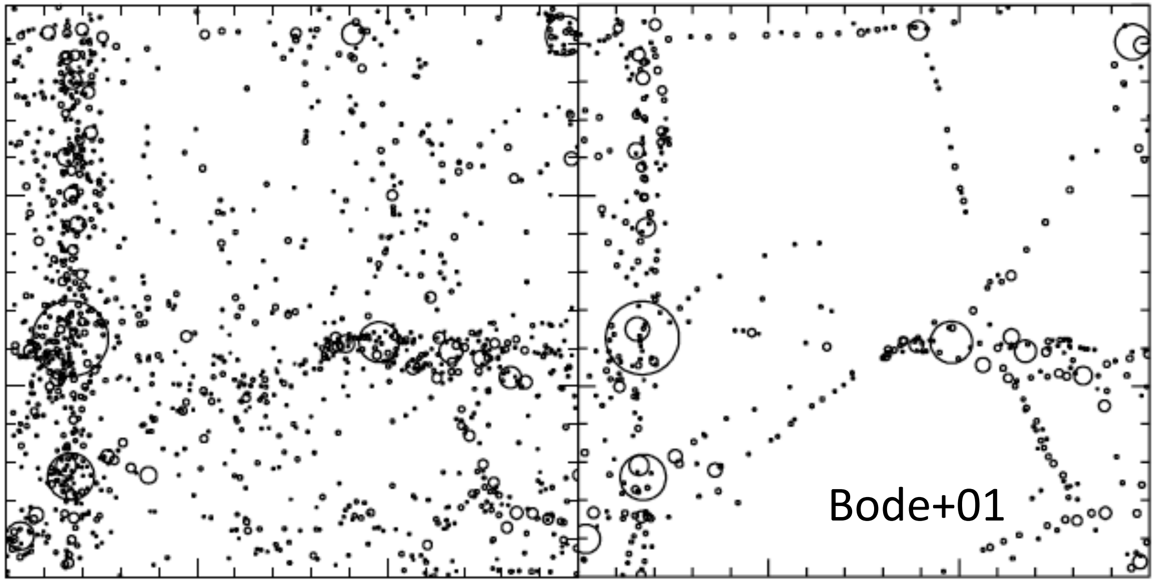
Pontzen&Governato14

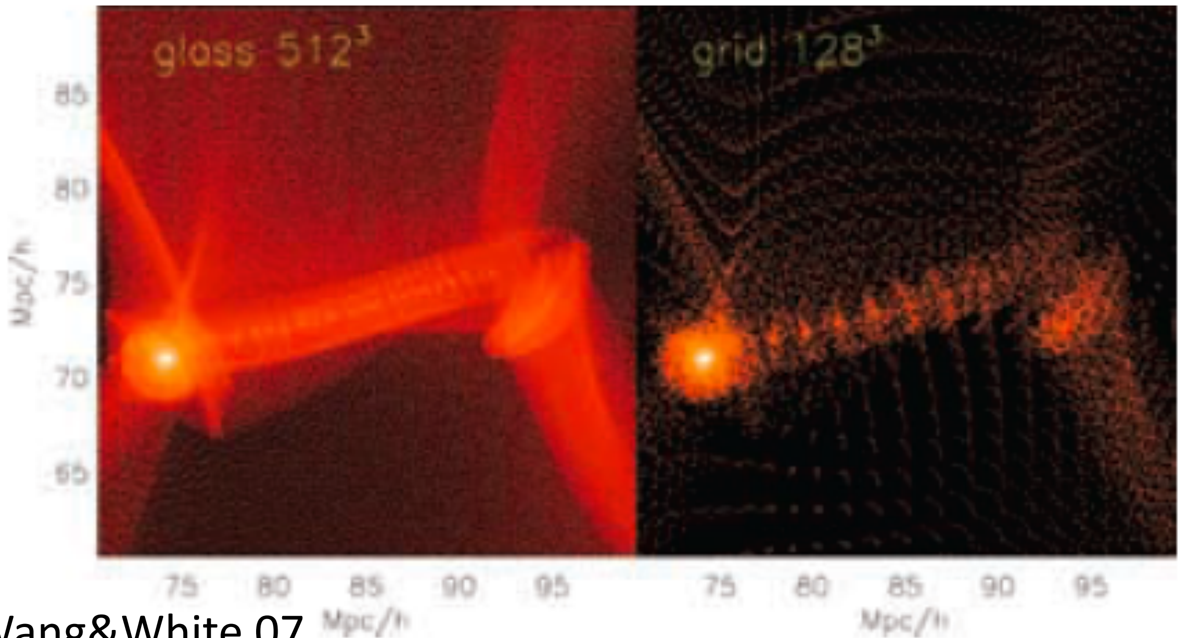


- Innermost properties are in a region dominated by stars and baryons (feedback is crucial)

- Observations are difficult refined models (which follow e.g. different stellar population) do not exclude NFW for some Putative cored dwarfs e.g. Strigari+15

Voids





Wang&White 07

Void phenomenon
(Peebles 2001)

- Dwarf galaxies avoid voids
- Dwarfs in voids and near voids are a fair representation of the void population

- In WDM spurious numerical fragmentation should be taken into account

- In ΛCDM properties could be matched with semi-analytical models (e.g. Tinker & Conroy 08)

SMALL SCALE CRISIS of CDM

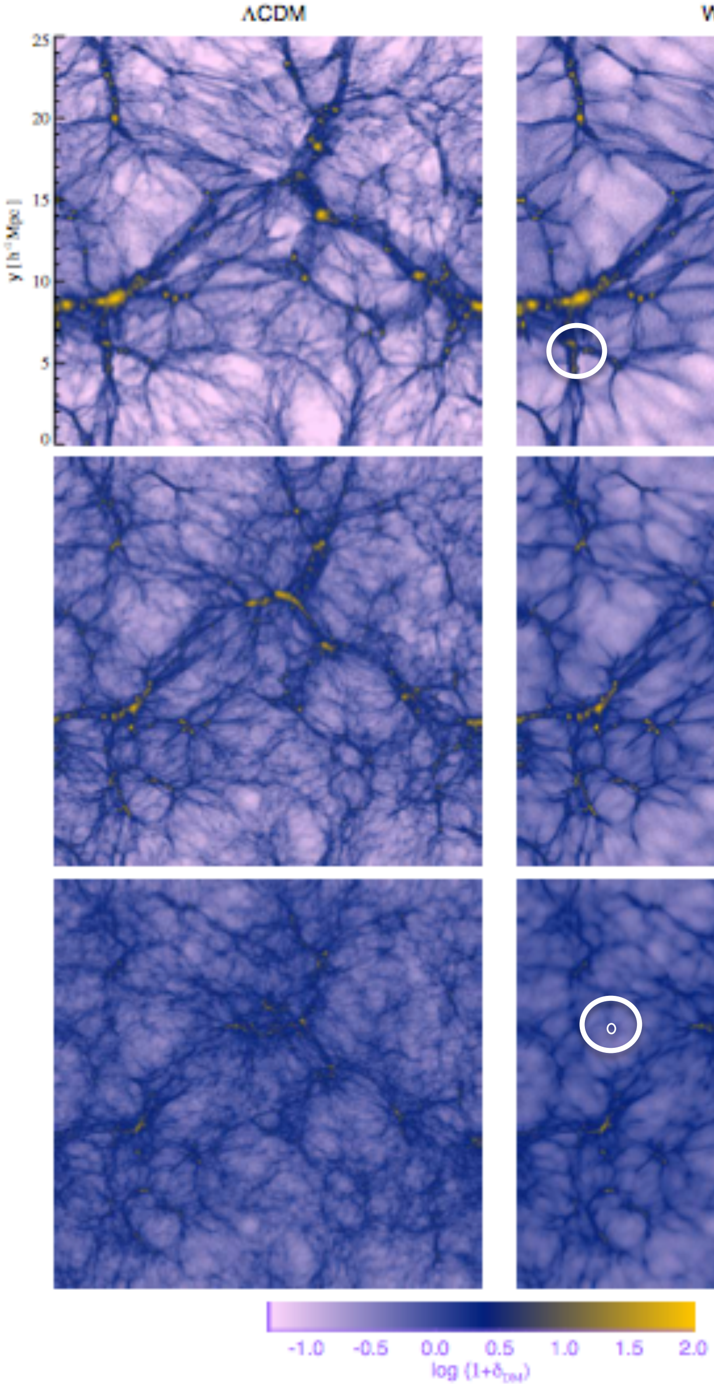
The small scale problems of ΛCDM have now a more modern/precise characterization

i.e. “too-big-to-fail” or “inner mass deficit”

Namely: the dynamical properties of the observed MW satellites are at odds with those of the most massive sub-haloes in MW simulations, which are **too dense** compared to reality

See Boylan-Kolchin+11, Oman+15

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

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

z=5

Viel, Markovic, Baldi & Weller 2013

Structure formation – I

$$T_{\rm WDM}(k) = \left[\frac{P_{\rm lin}^{\rm WDM}}{P_{\rm lin}^{\rm CDM}}\right]^{1/2} = \left[1 + (\alpha k)^{2\mu}\right]^{-5/\mu}$$

$$\alpha = 0.049 \left[\frac{m_{\rm WDM}}{\rm keV}\right]^{-1.11} \left[\frac{\Omega_{\rm WDM}}{0.25}\right]^{0.11} \left[\frac{h}{0.7}\right]^{1.22}$$

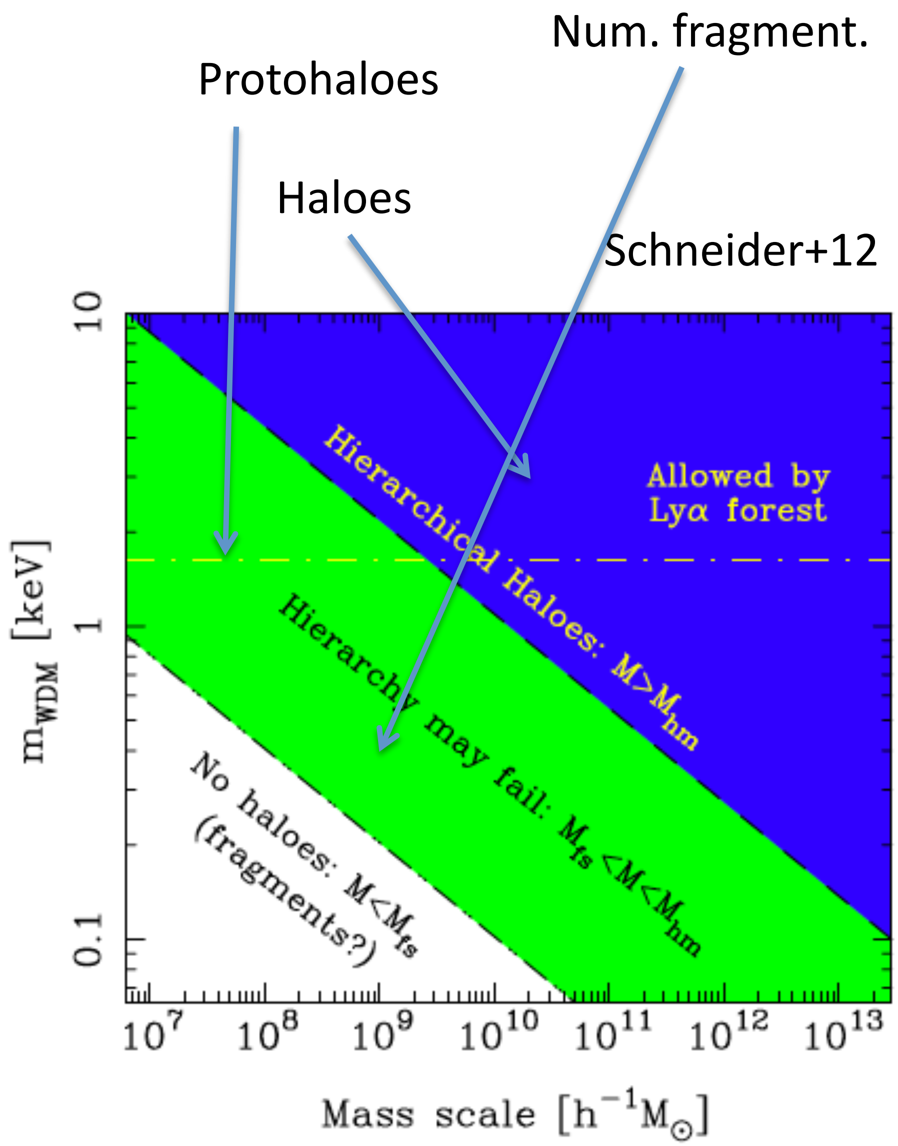
$$\alpha \equiv \lambda_{\rm fs}^{\rm eff}$$

Free streaming mass

$$M_{\rm fs} = \frac{4\pi}{3}\bar{\rho}\left(\frac{\lambda_{\rm fs}^{\rm eff}}{2}\right)^3$$

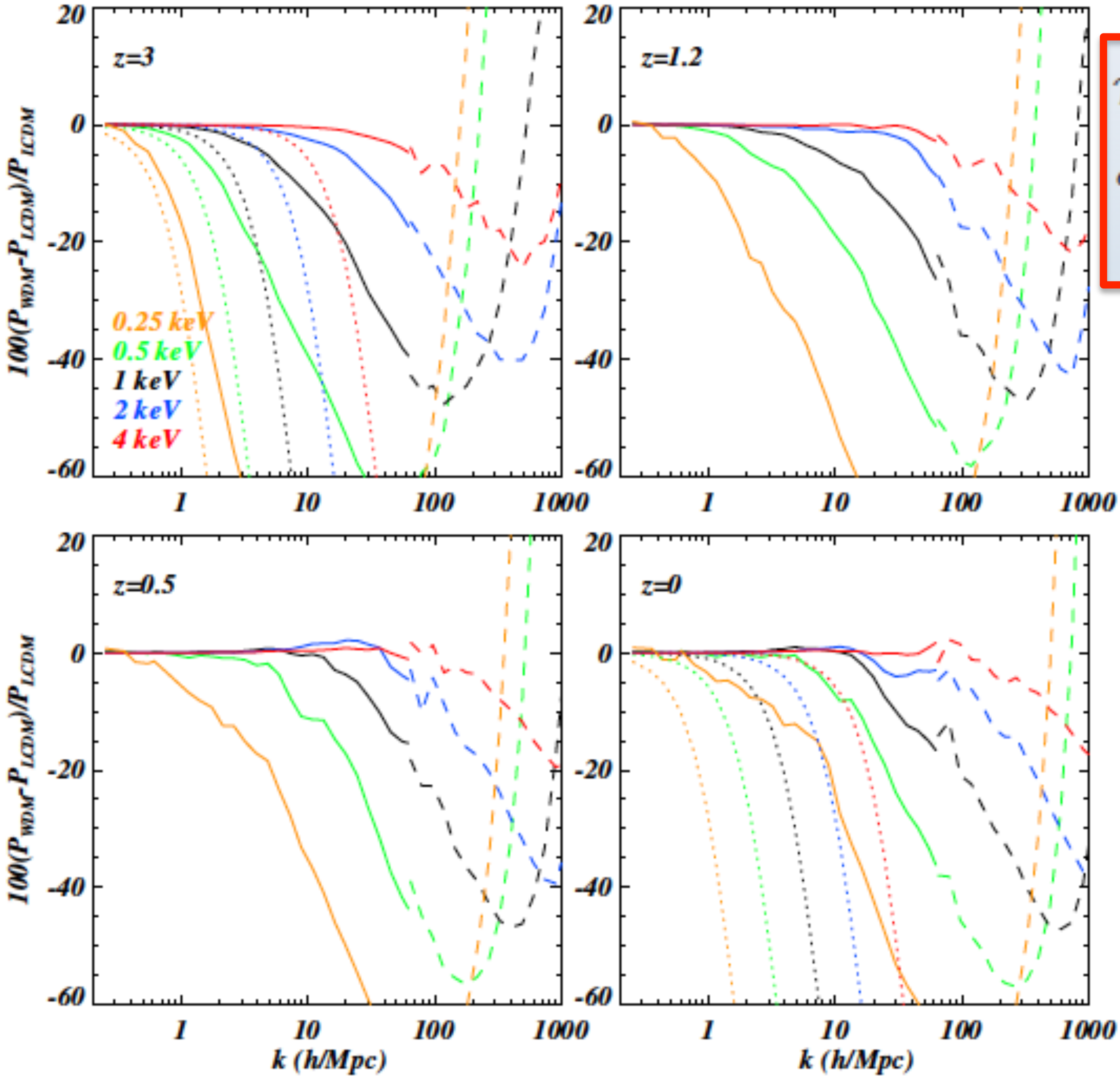
Half mode mass

$$M_{\rm hm} = \frac{4\pi}{3}\bar{\rho}\left(\frac{\lambda_{\rm hm}}{2}\right)^3 \approx 2.7 \times 10^3 M_{\rm fs}$$



Structure formation – II

Markovic&Viel 13
Viel+13



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

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

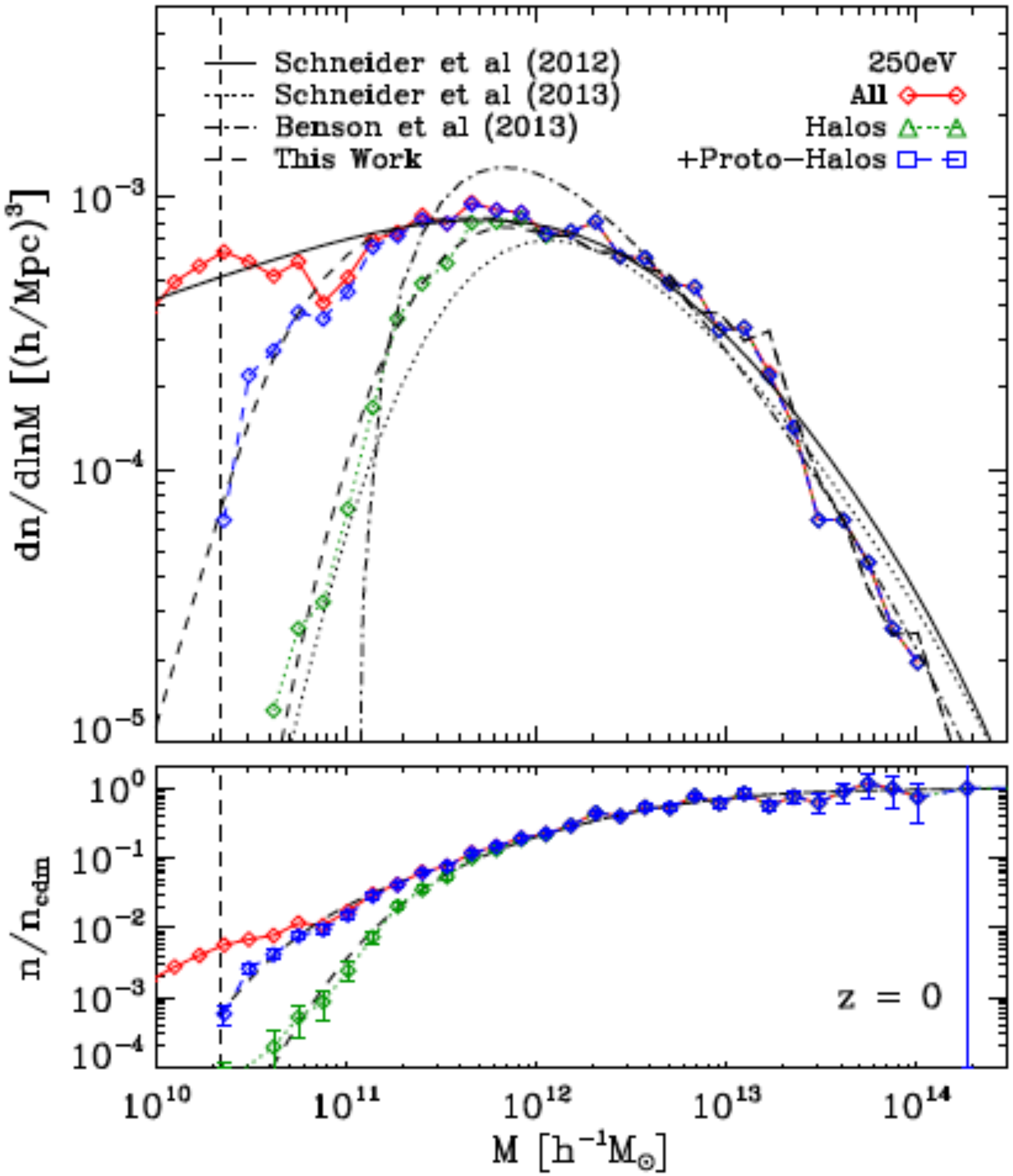
$$\nu = 3,\ l = 0.6 \text{ and } s = 0.4$$

- Non linear evolution tends to erase primordial differences in a redshift dependent way

- Simple analytical fits or WDM halo models (Smith&Markovic 11) that could be used for weak lensing forecasts

- Astrophysical effects at small scales should be taken into account

MASS FUNCTIONS

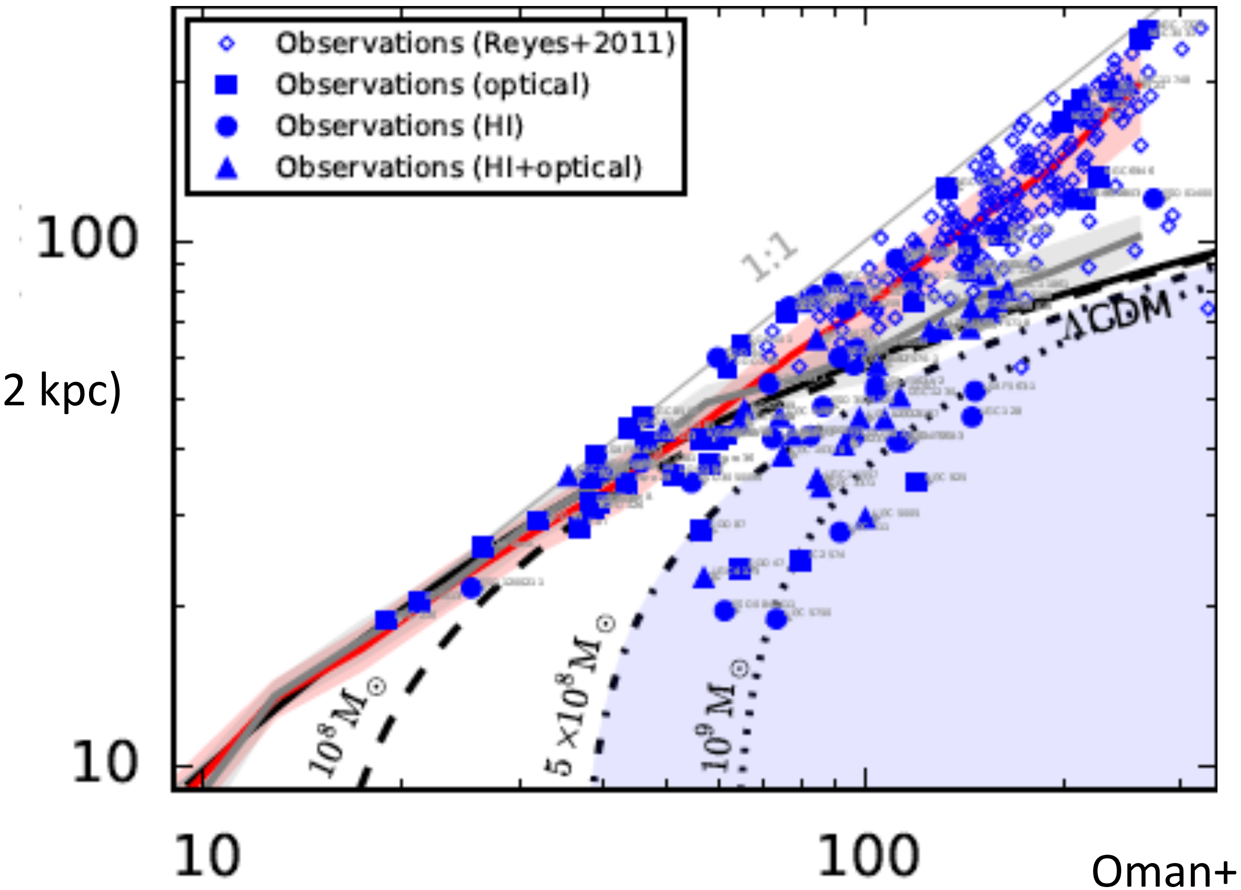


- Spurious fragmentation induced by force resolution which is very large and produces noise at approx. the size of the mean linear inter-particle spacing

- Several methods to get rid of this in an effective way: coding or removal "by hand" Angulo+14, Hahn&Angulo15, Lovell +12

MOVING TO SMALLER SCALES: DWARFS

V_{circ} (2 kpc)

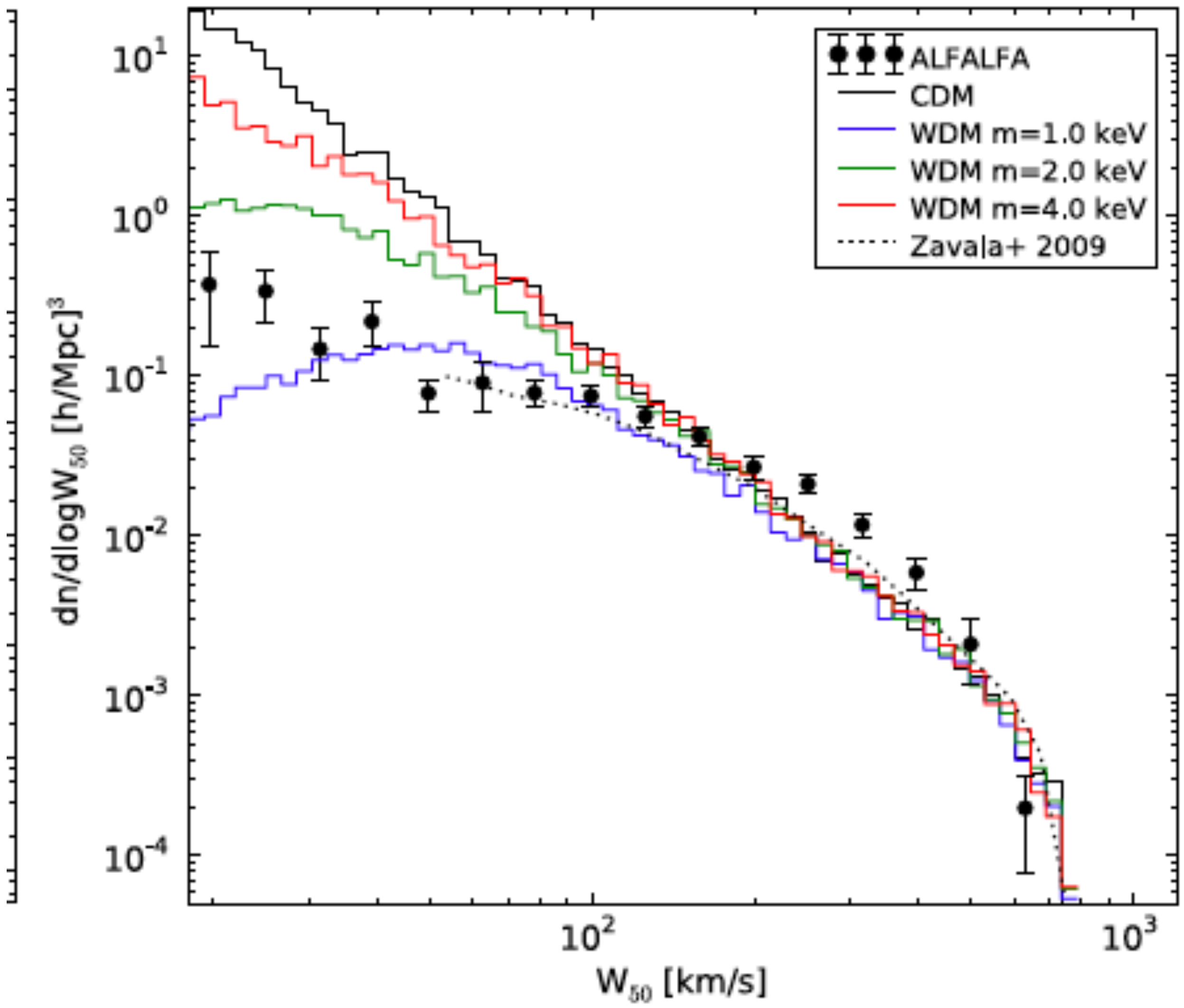


Oman+15

V_{max}

- Large scatter at fixed Vmax in data -- much less in sims.
- Less mass in the inner parts

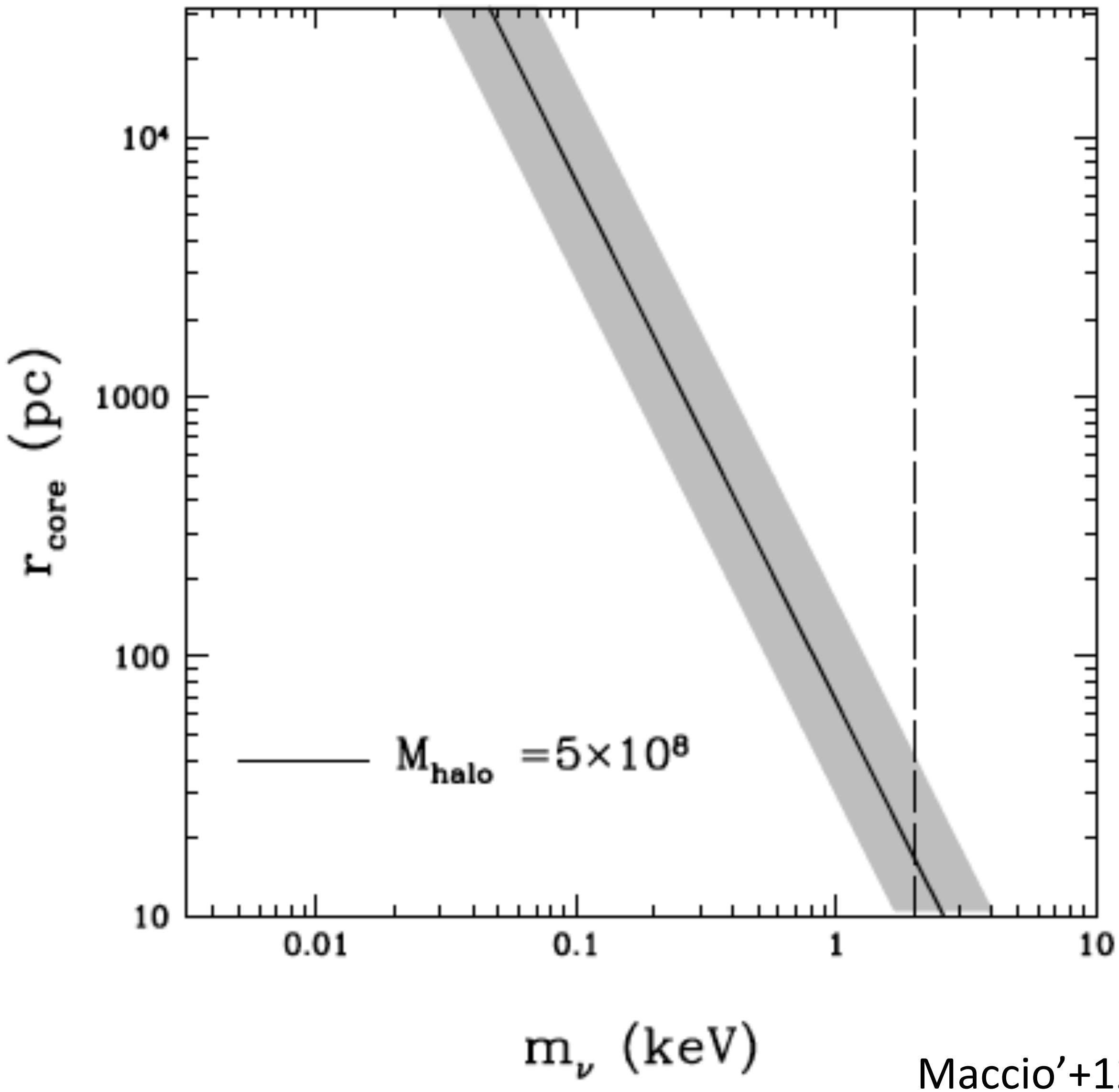
HI MASS FUNCTION



- Velocity width function of the HI component (W50 related to Vmax and then to mass)

Schneider+14

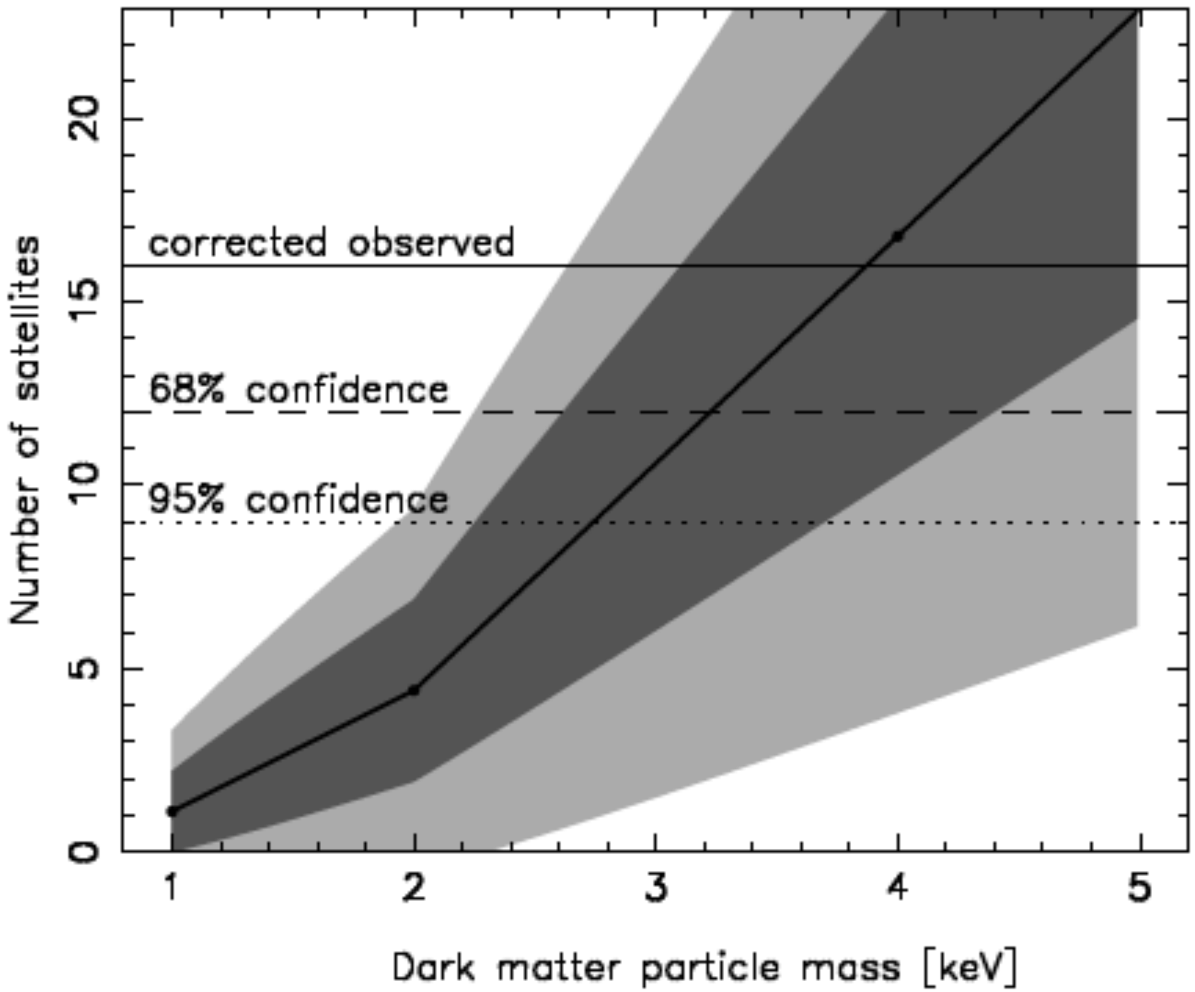
CORE RADIUS



Maccio'+12

- Observed core (if any) at the kpc scale (for massive dwarfs)
- This result could also be obtained with simple semi-analtyical models (Villaescusa-Navarro & Dalal 11)
- To form a kpc size core (for a very massive dwarf) 0.1 keV needed which make difficult to form the haloes themselves

MISSING SATELLITES

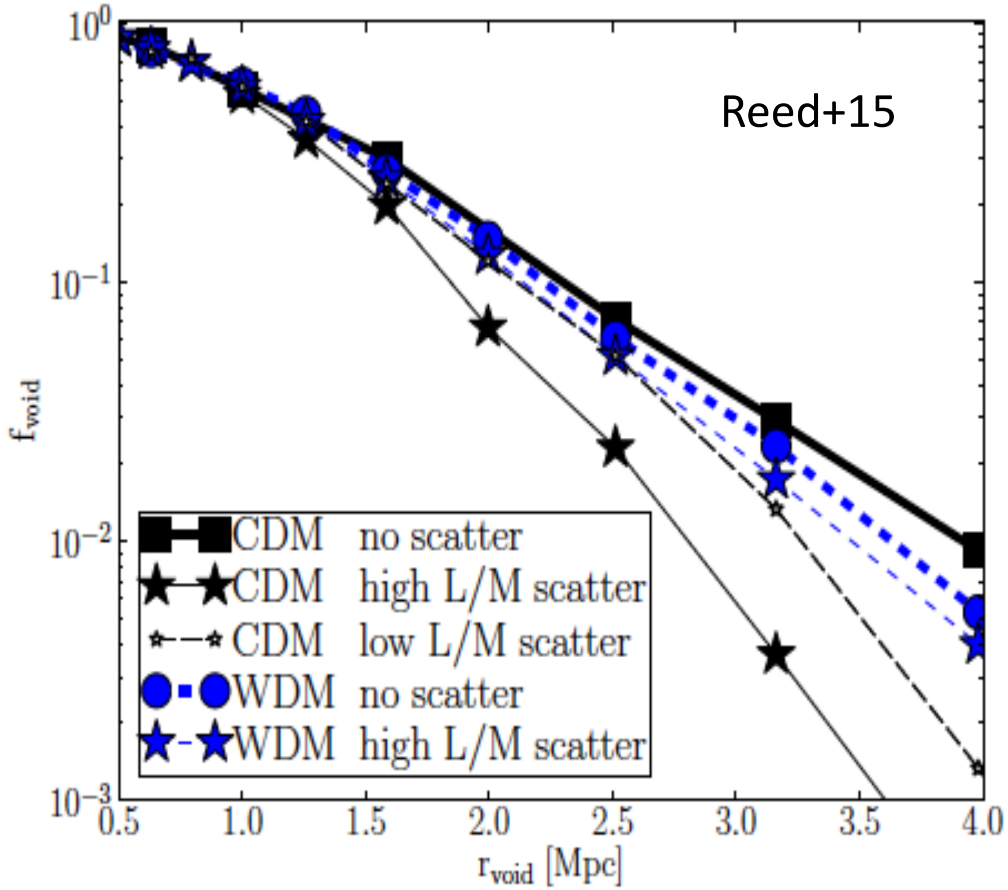


- Number of satellites can be reproduced only if DM is relatively cold – this is obtained from N-body high-resolution sims.

$m_{WDM} > 2.3$ keV (2σ C.L.)

Polisensky&Ricotti 11

MOVING TO GALAXY FORMATION



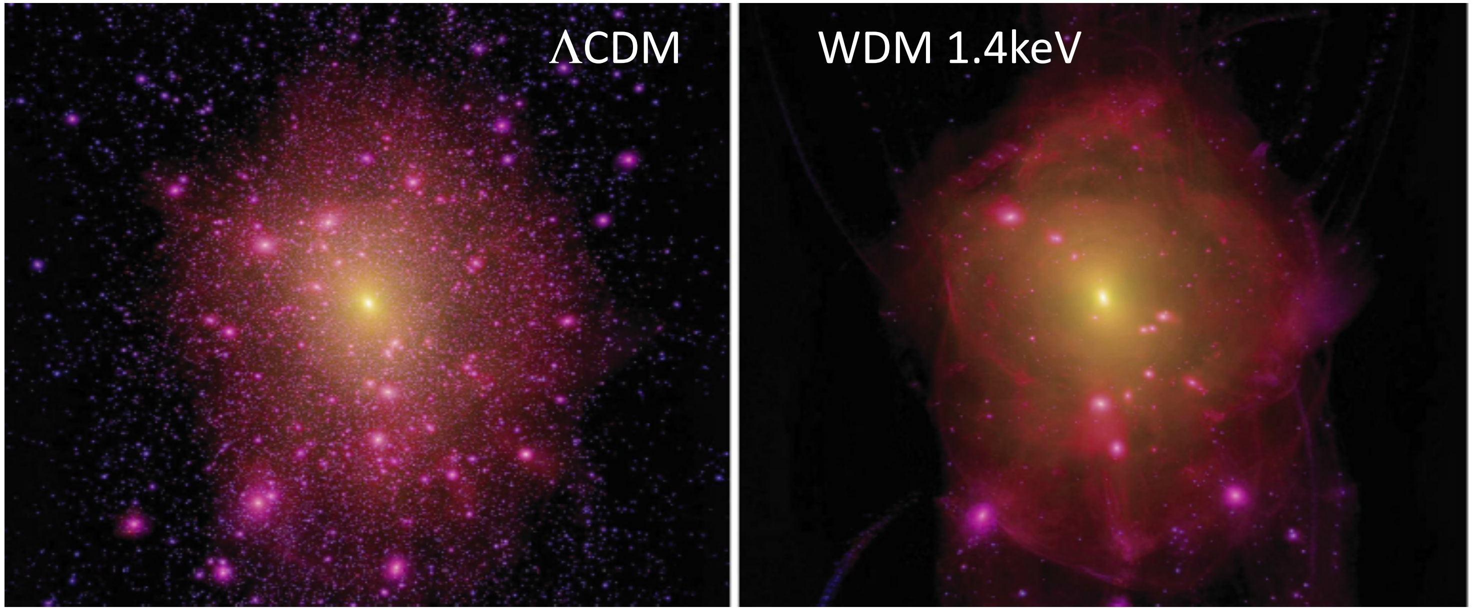
- one-to-one matching between Vc (circular velocity proxy for mass) and galaxy luminosity – mass limit to avoid spurious haloes

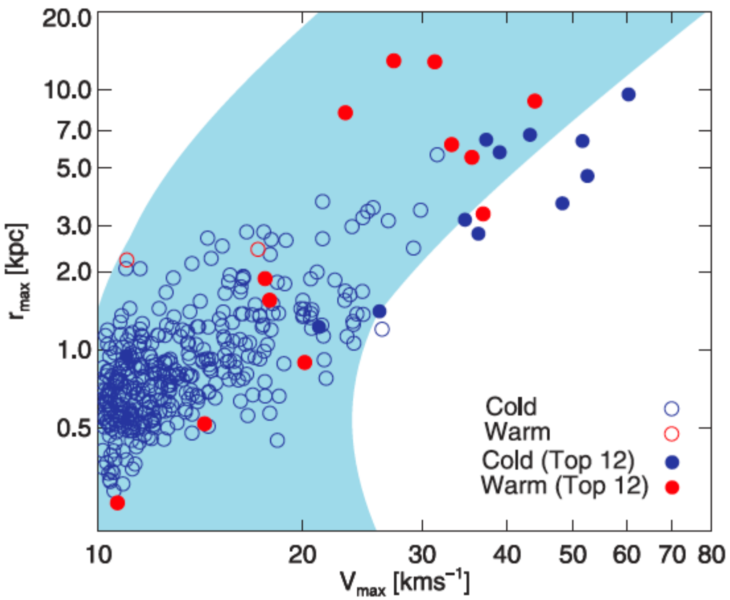
- very similar clustering properties (for a 2keV WDM) to CDM: WDM suppression does not feel the environment, even if WDM haloes are more biased than CDM

- when considering **scatter** in the luminosity-Vc relation things can change things: in LCDM some small DM halo can host a bright dwarf, reducing the number of empty voids

SIMULATIMG MW SATELLITES

Lovell+12

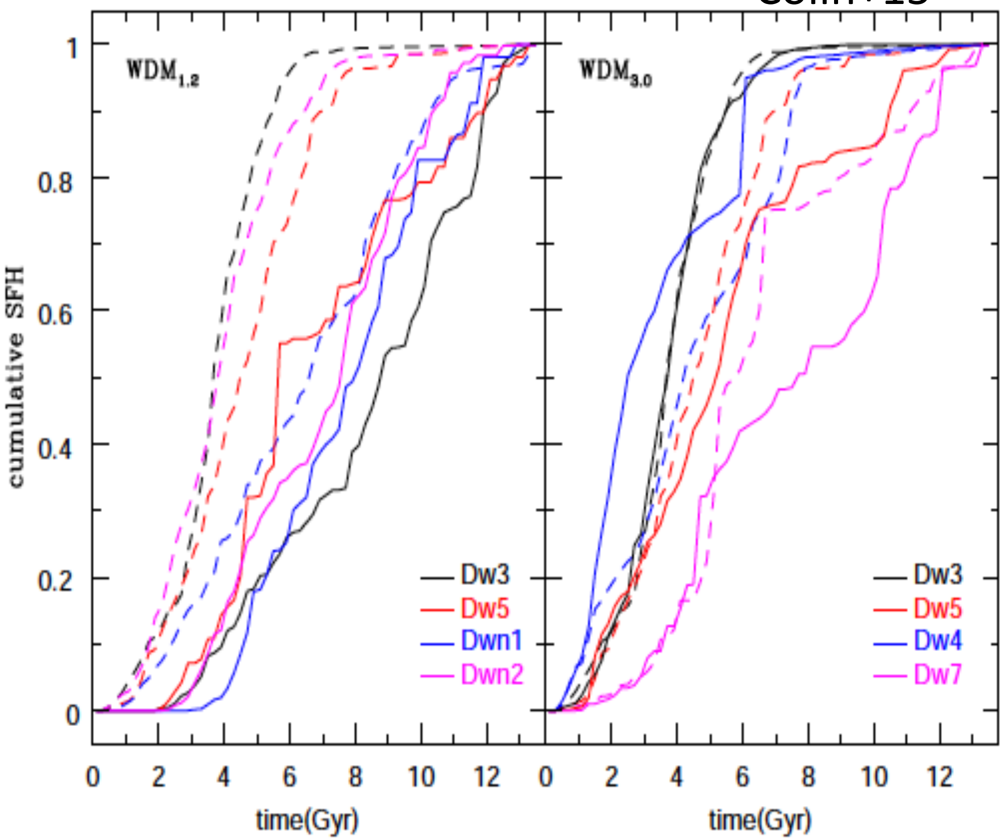




WDM with this mass seems to alleviate significantly the “too-big-to-fail” problem

SIMULATING DWARFS

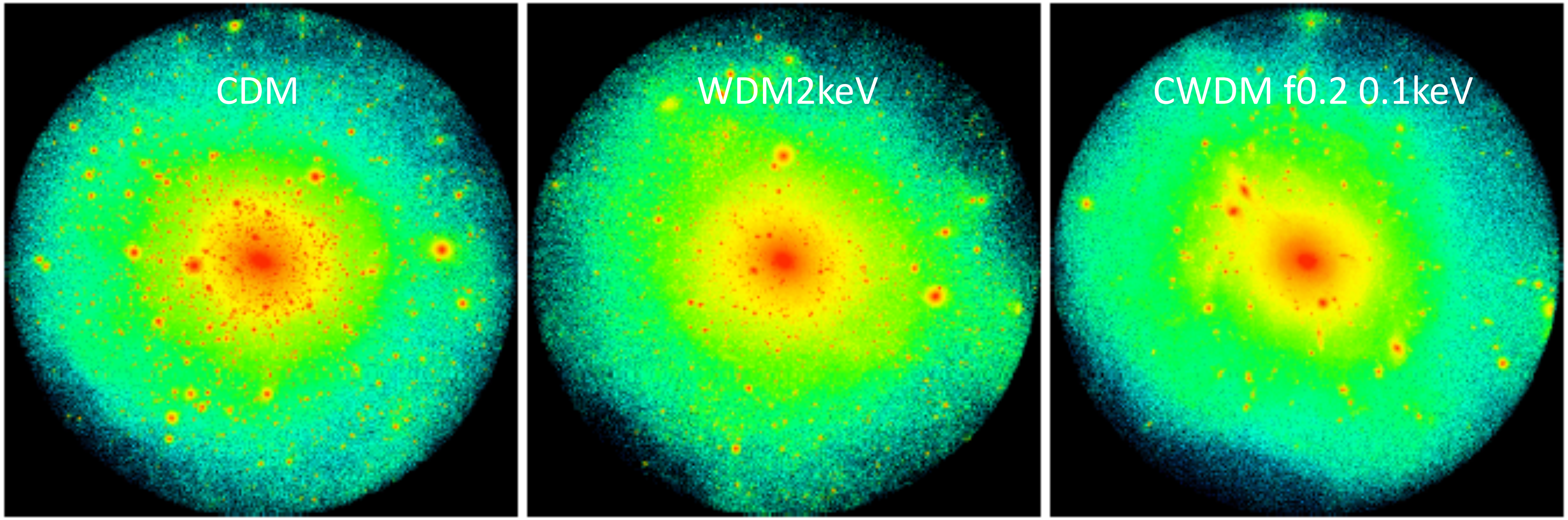
Colin+15



- fitering mass is $2\text{x}10^{10}\ M_{\odot}/h$ (1.2keV): shallow velociy profiles, late assembly of mass and stars, less concentrated and more extended star distribution – Disk like structures

- Virtually no differences (both in properties and evolution) for filtering masses corresponding to 3 keV

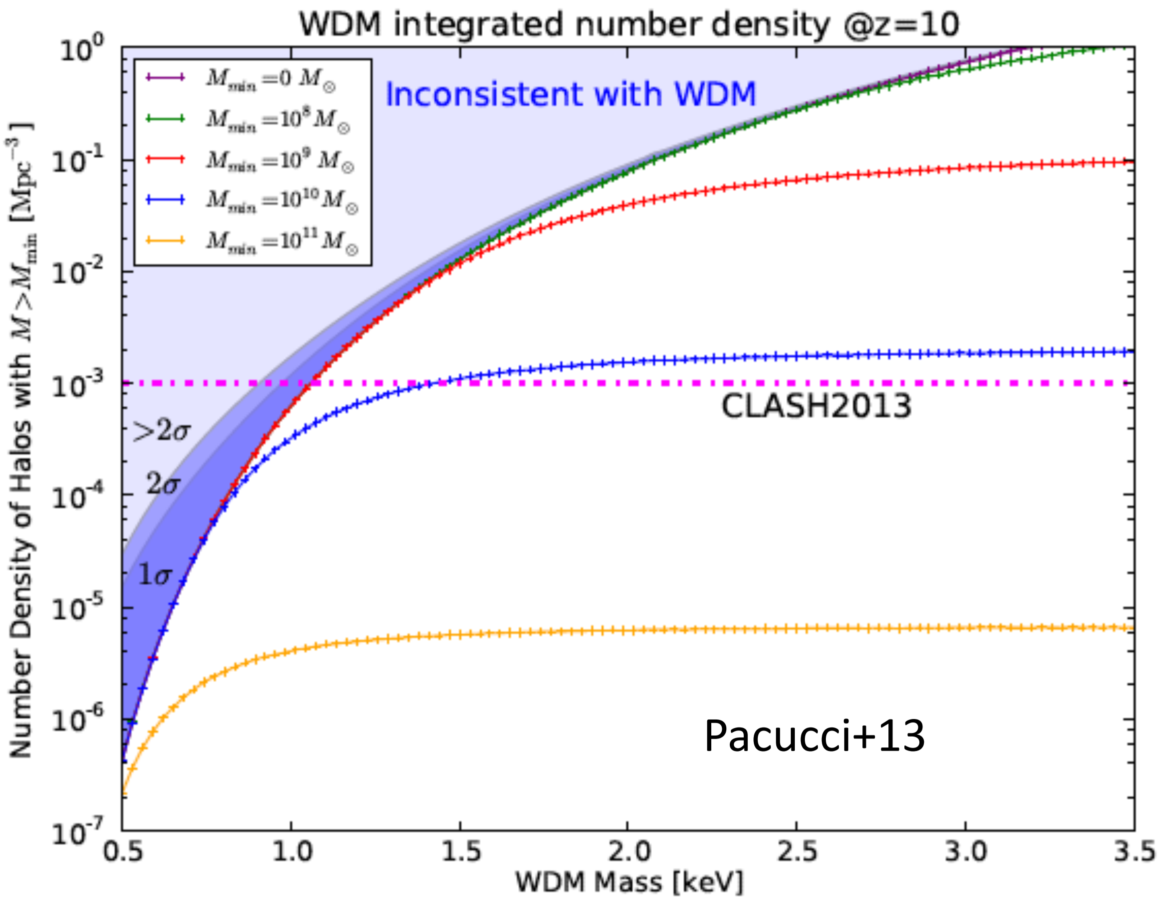
Mixed Dark Matter models



- Possibly flat cores and reduced innermost density
- Local mean WDM density differ from cosmic average, especially for extreme models – depends on mass and not on fraction

Anderdhalen+13

Model independent constraints from the high redshift universe – I



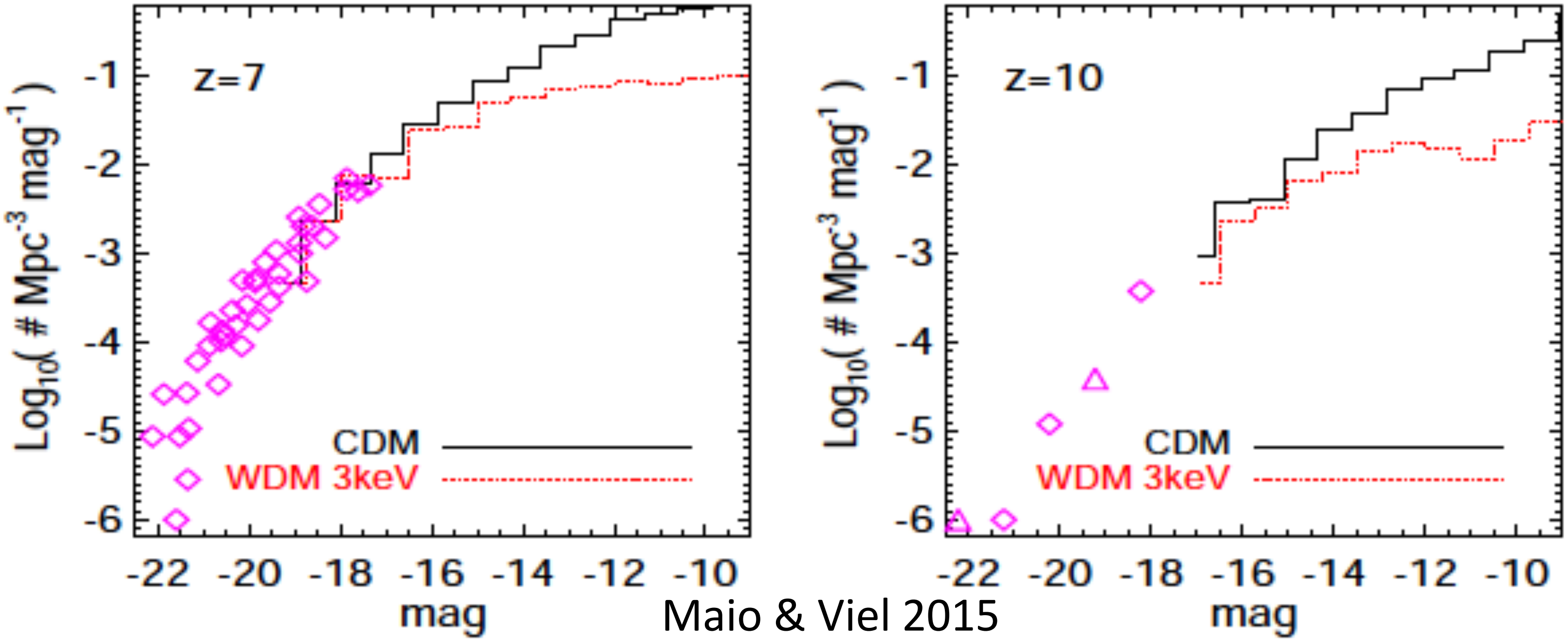
- Model independent bound:
  theory uses just the mass function of WDM
  Observations: exploit large (lensed) high redshift volumes

- Ultra-conservative limit

> 0.9 keV (2σ C.L.)

Model dependent constraints from the high redshift universe – I

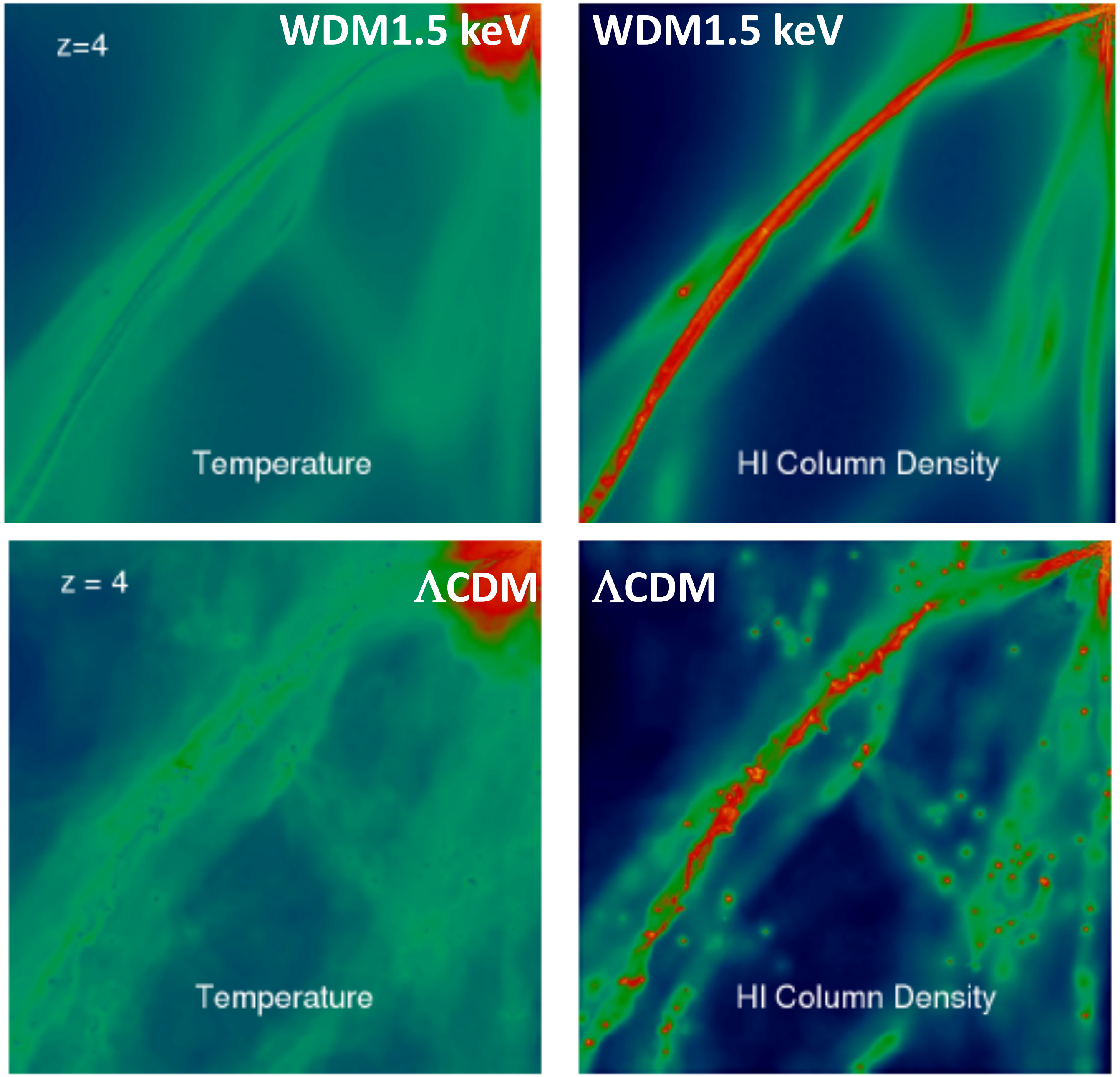
LUMINOSITY FUNCTION



Maio & Viel 2015

- WDM structures below 10^8 $M_\odot$ are less abundant by a factor 10 in the first Gyr
- Onset of star formation delayed by $\Delta z=6$
- Number of star forming galaxies is lower by a factor 10(100) at z=7 (15)

Model dependent constraints from the high redshift universe – II

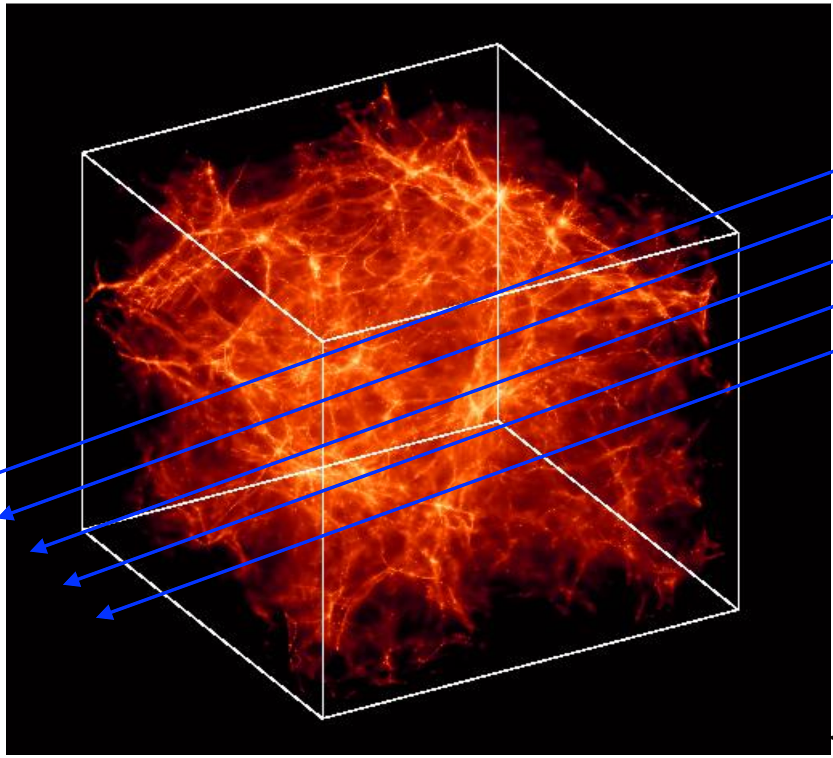


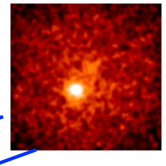
- Dense and large filaments in WDM at high redshift
- Significant star formation happening within these filaments
- Stringy pattern still surviving at later stage possibly affecting correl. properties of HI absorbers (especially strong systems)

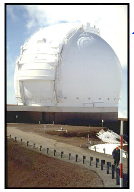
Gao, Theuns, Springel 15

IGM

The Intergalactic Medium: Theory vs. Observations







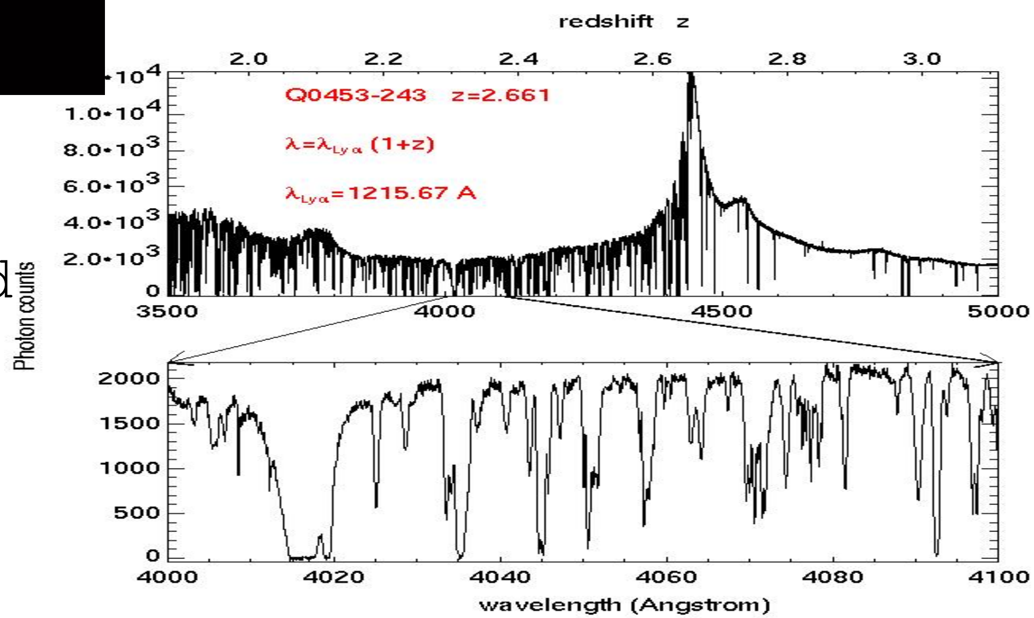
80% of the baryons at z=3 are in the **Lyman-α forest**

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

baryons as tracer of the dark matter density field

$\delta_{IGM} \sim \delta_{DM}$

Croft+ 99,02
MV+ 04
McDonald+ 01,03



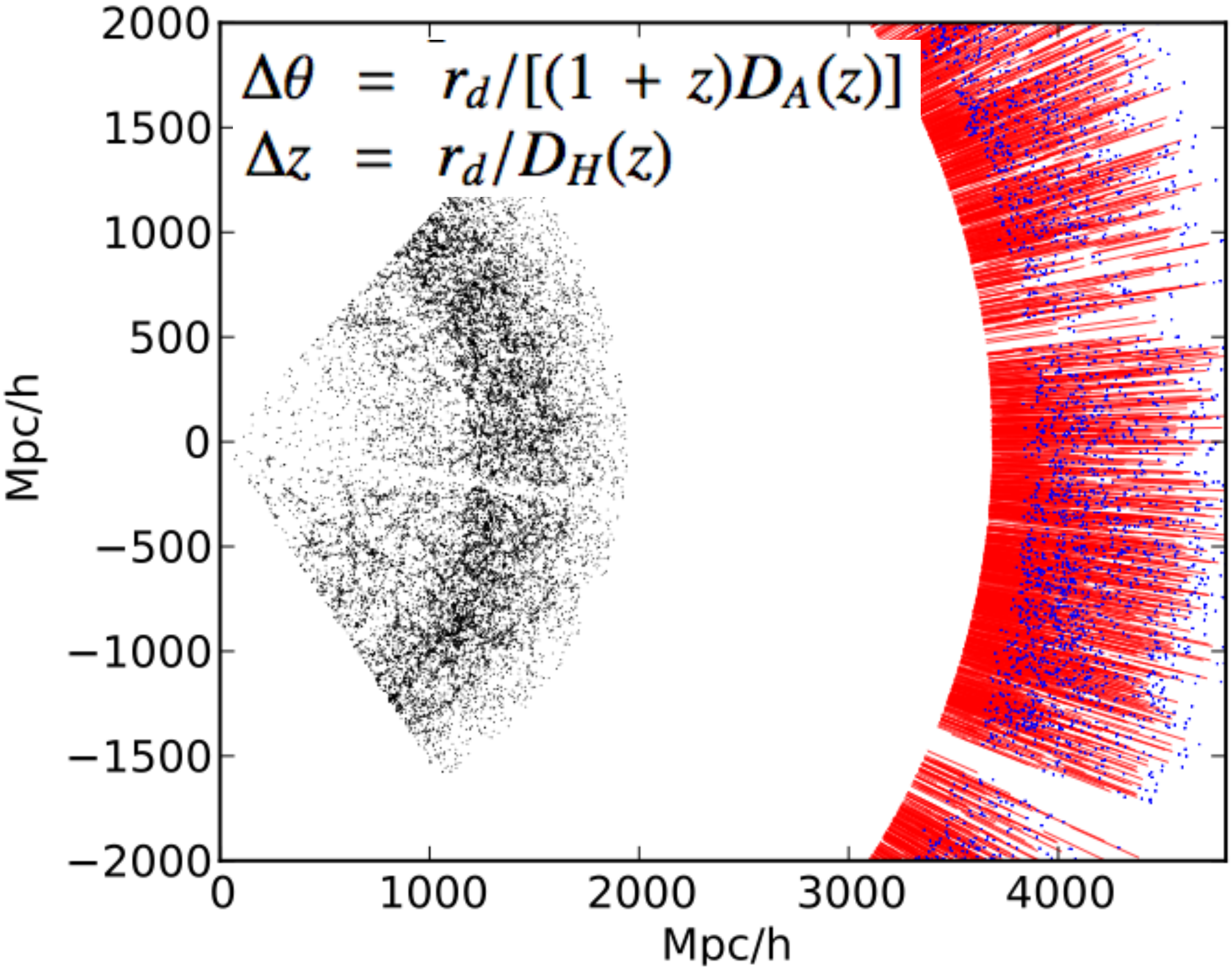
RESULTS FROM BOSS/SDSS-III

BAOs at z=2.3

@COSMO15: Cieplak talk

<u>**SDSS- I**</u>

New regime to be probed with Lyman-α forest in 3D



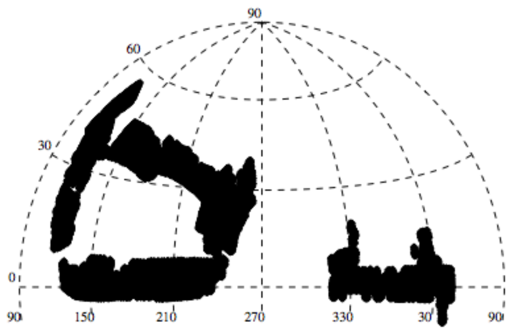
Slosar et al. 11
Busca et al. 13
Slosar et al. 13

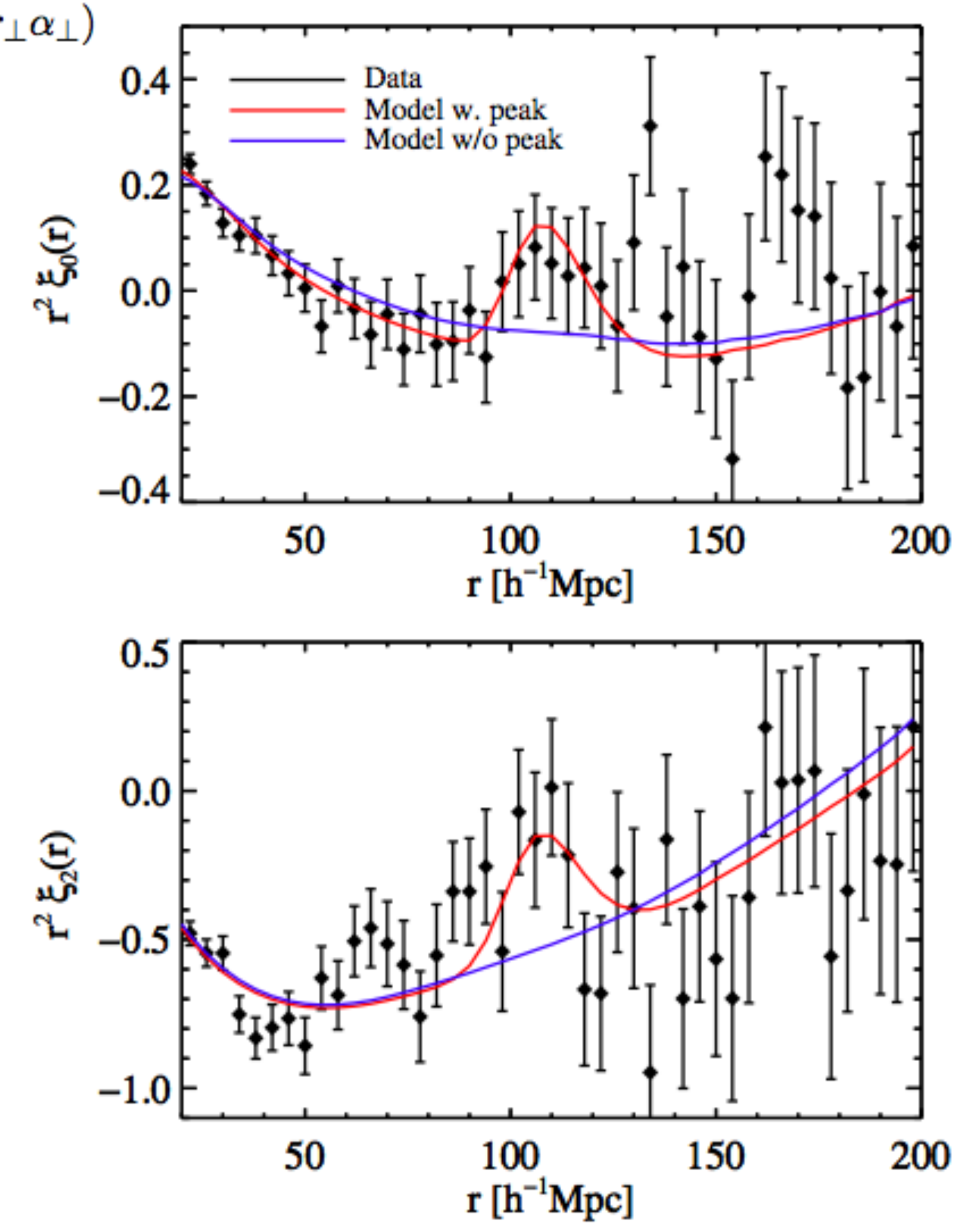
SDSS- II

Busca et al. 13

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

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





BAO feature detected at z=2.3

From 3000 deg^2, using 50000 QSOs

Significance of the detection at around 3σ

COLDNESS OF COLD DARK MATTER

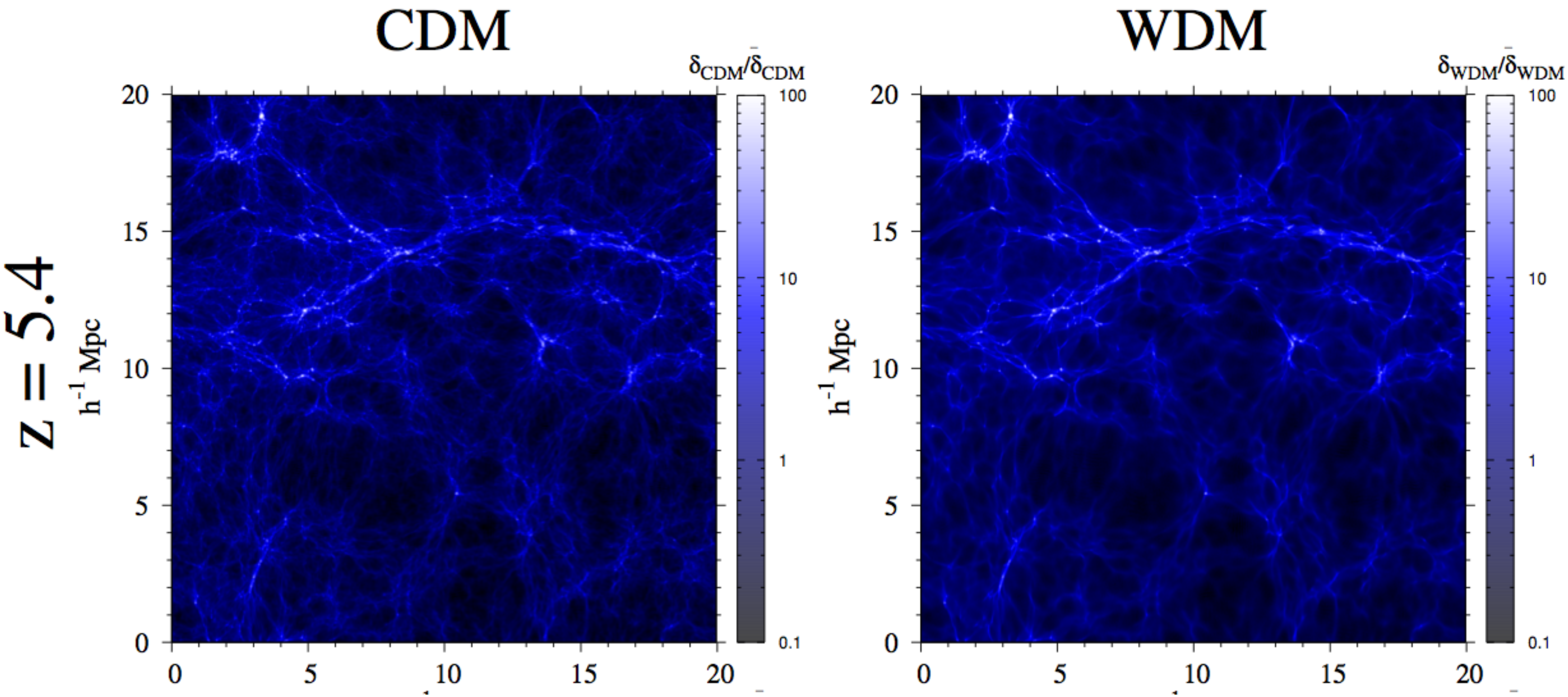
Viel, Becker, Bolton, Haehnelt, 2013, PRD, 88, 043502

... Garzilli’s talk in the parallel session …

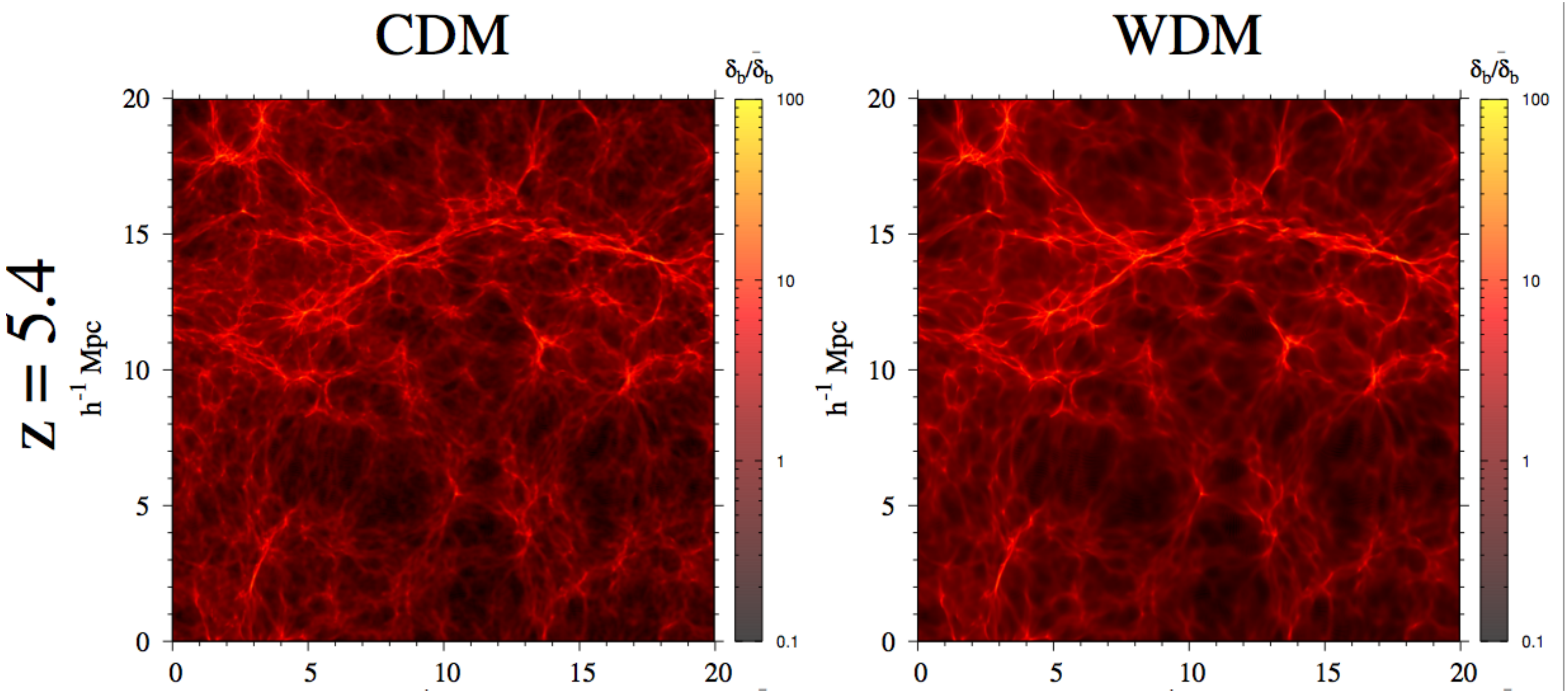
HISTORY OF WDM LYMAN-α BOUNDS

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

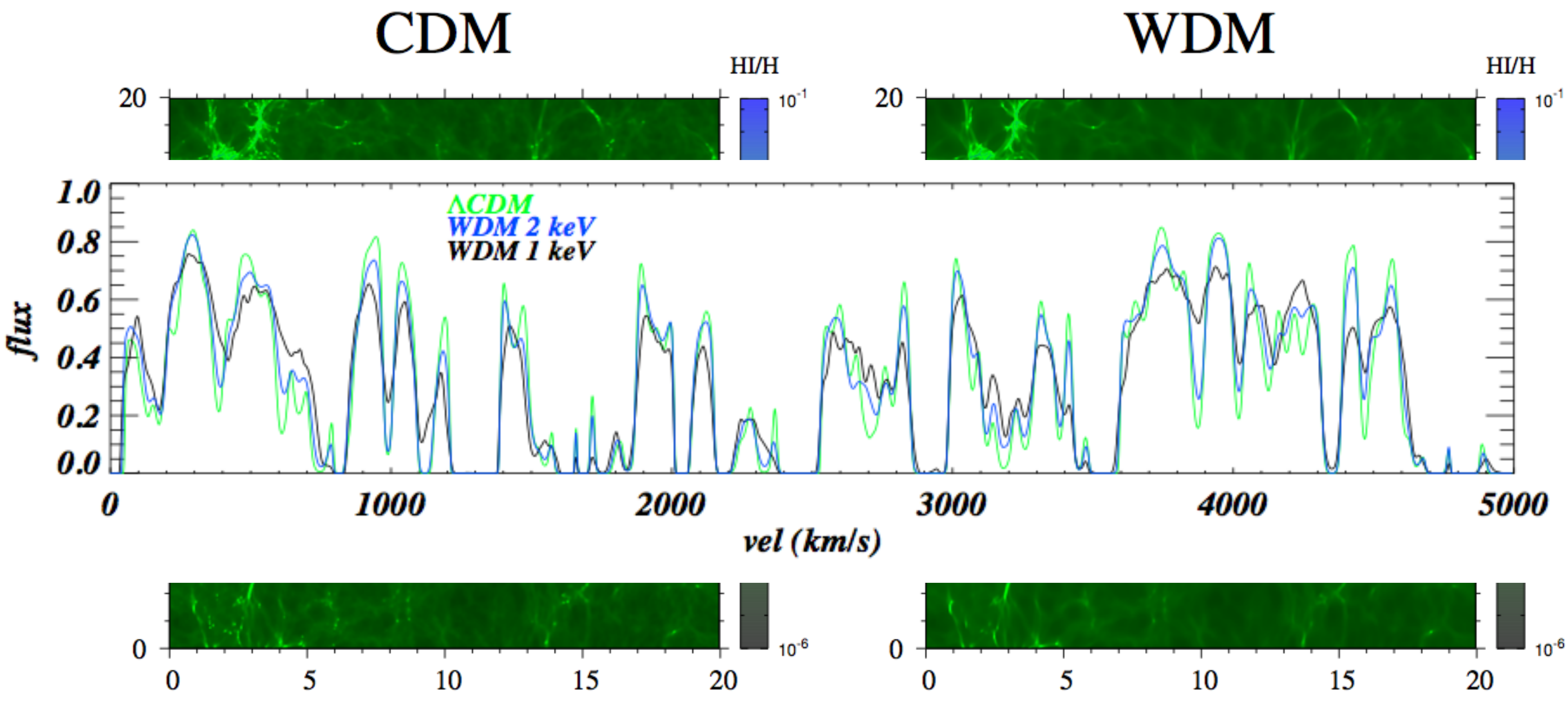
DARK MATTER DISTRIBUTION



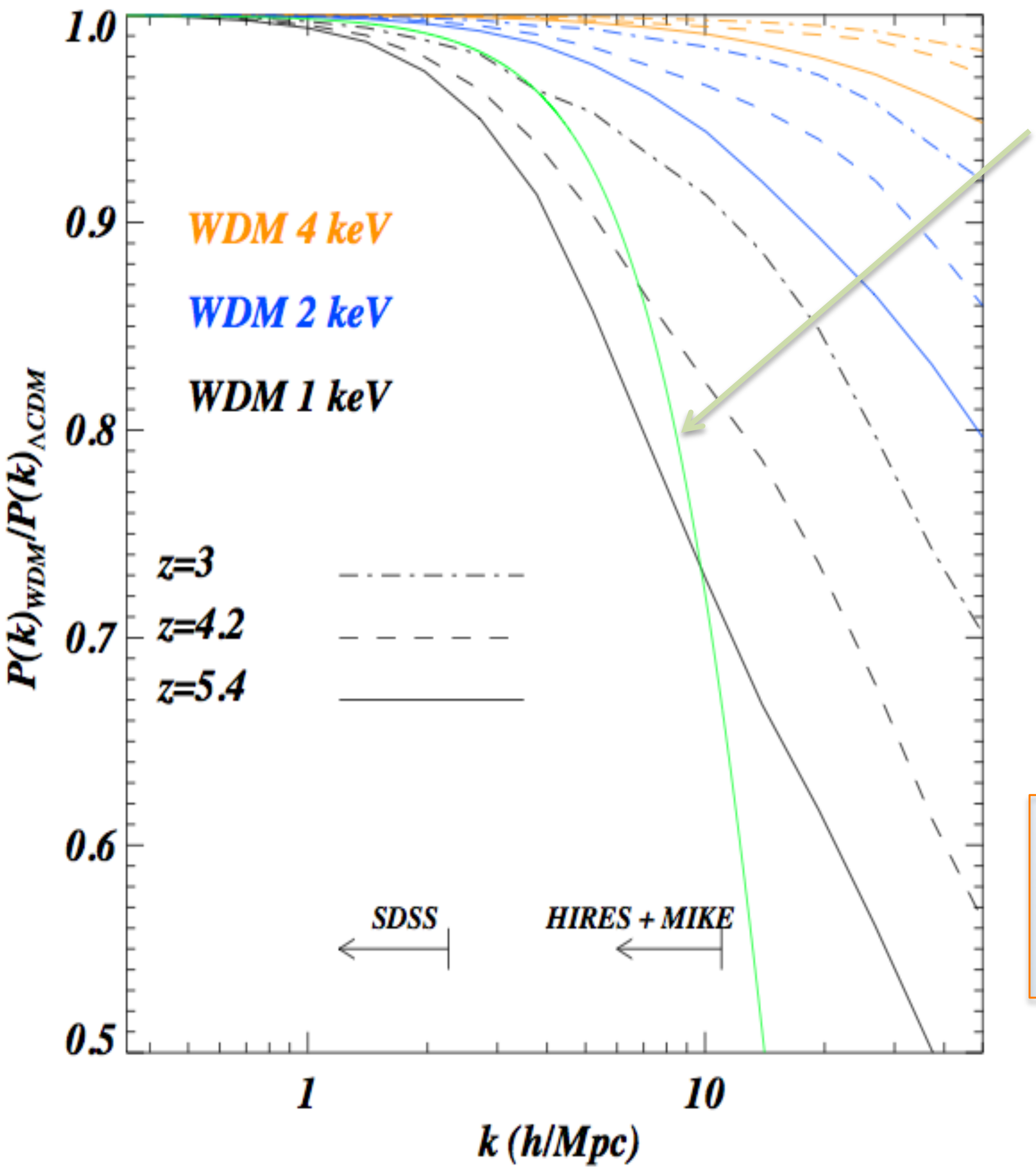
GAS DISTRIBUTION



HI DISTRIBUTION



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

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

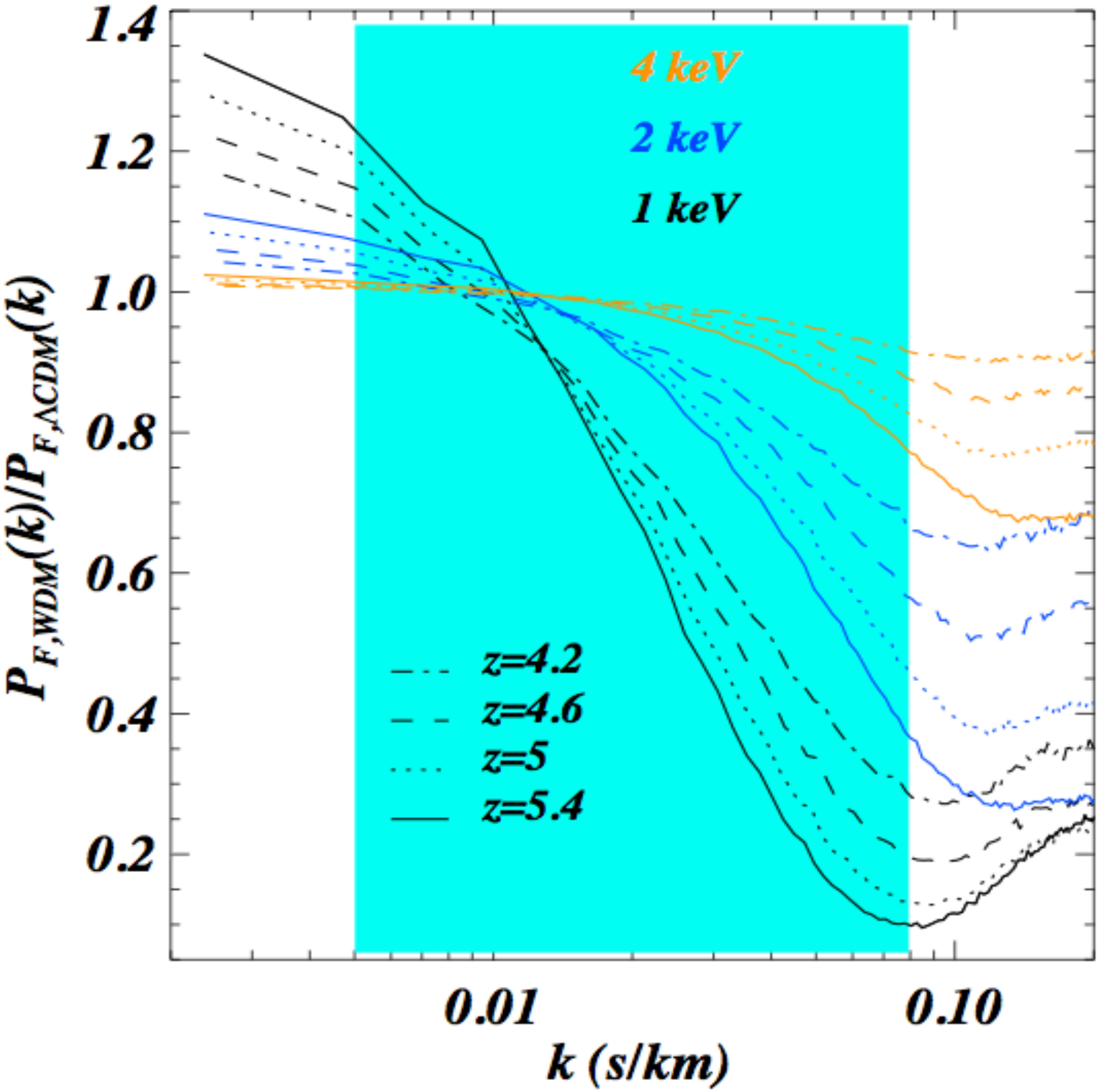
$$\alpha(m_{\rm WDM}, z) = 0.0476 \left(\frac{1{\rm keV}}{m_{\rm WDM}}\right)^{1.85} \left(\frac{1+z}{2}\right)^{1.3},$$

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

Viel, Markovic, Baldi & Weller 2013

THE HIGH REDSHIFT WDM CUTOFF

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



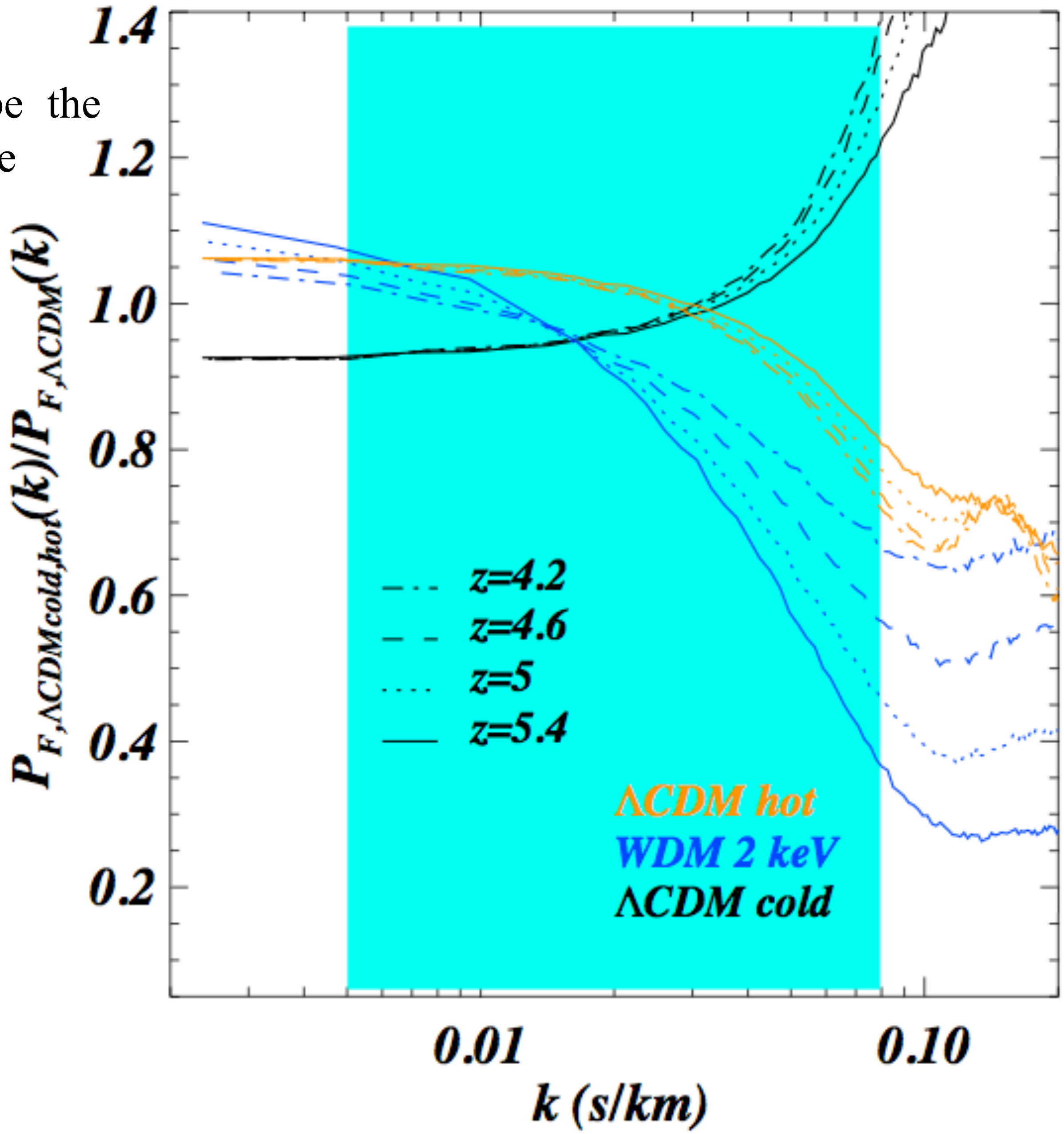
THE TEMPERATURE: T_0

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

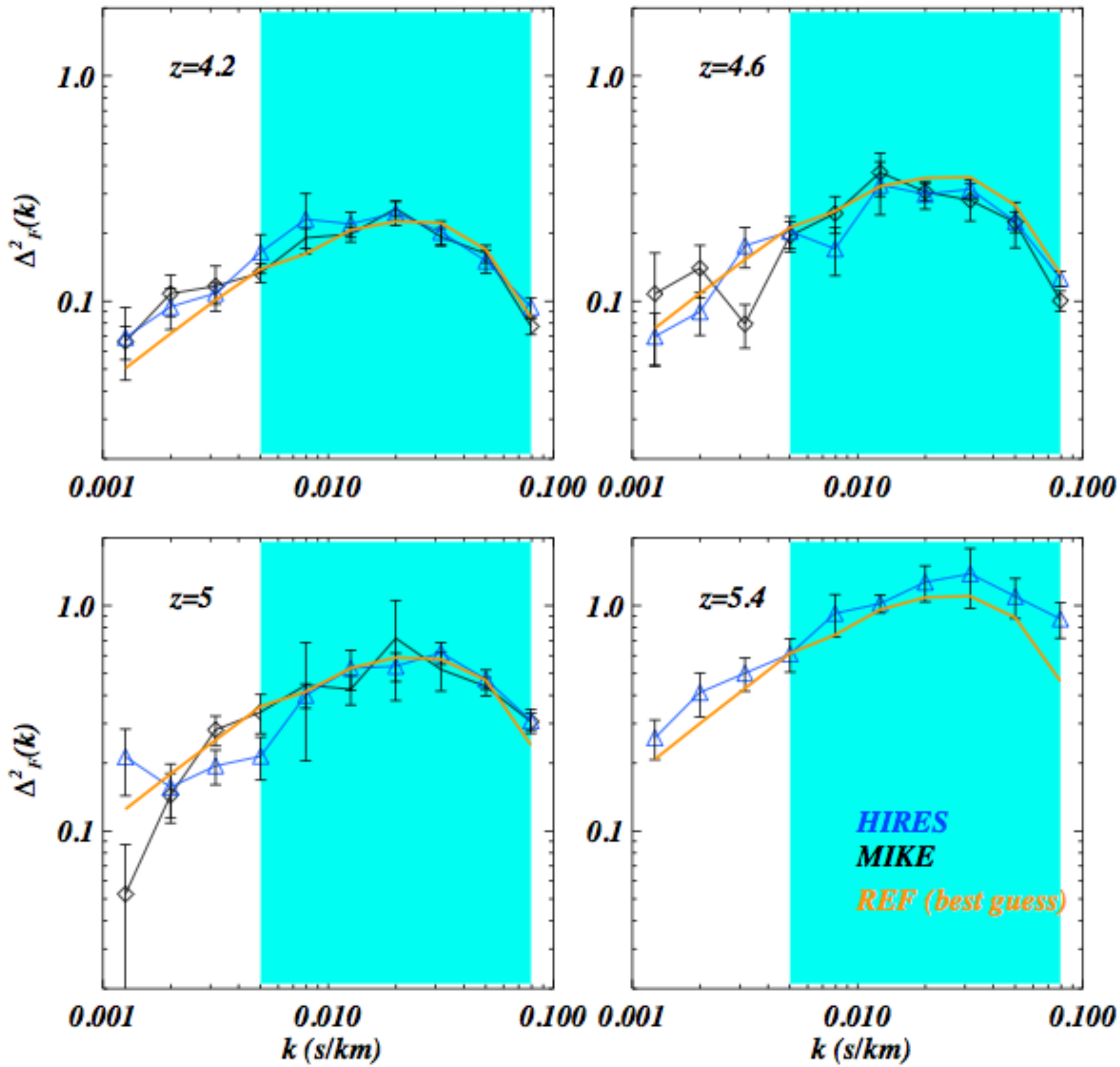
T_0 and γ describe the IGM thermal state

Hot + 3000 K
Cold – 3000 K

REF has 8300 K
at z=4.6

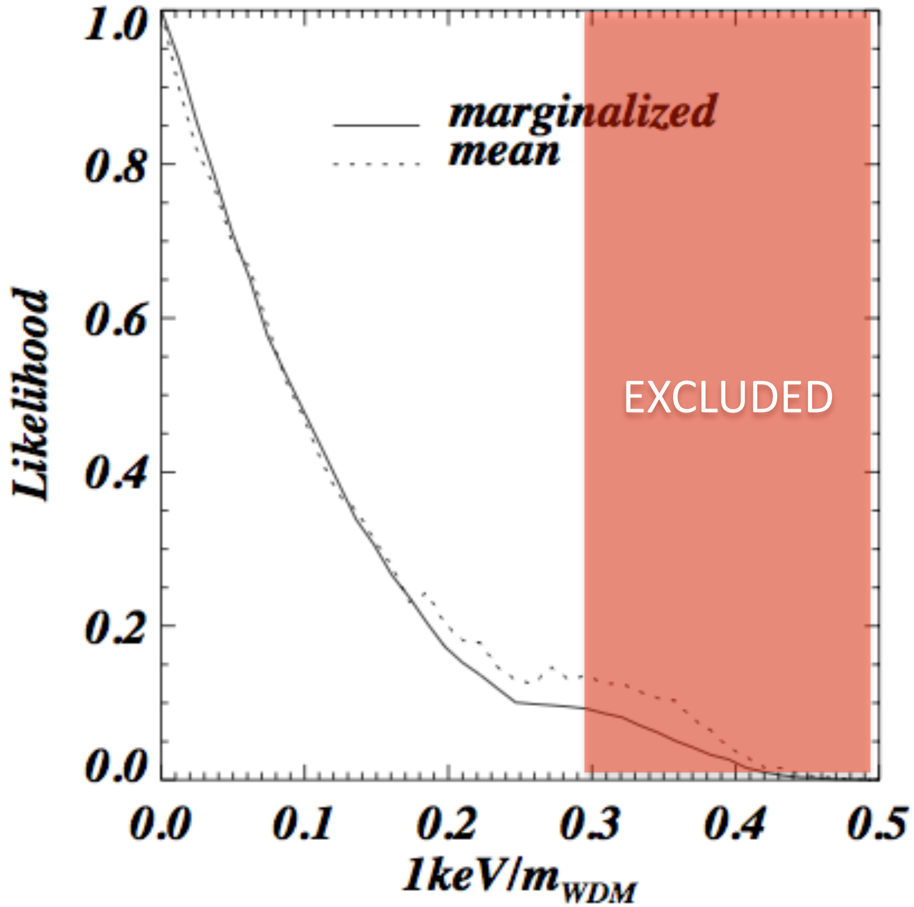


THE BEST GUESS MODEL



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

RESULTS FOR WDM MASS

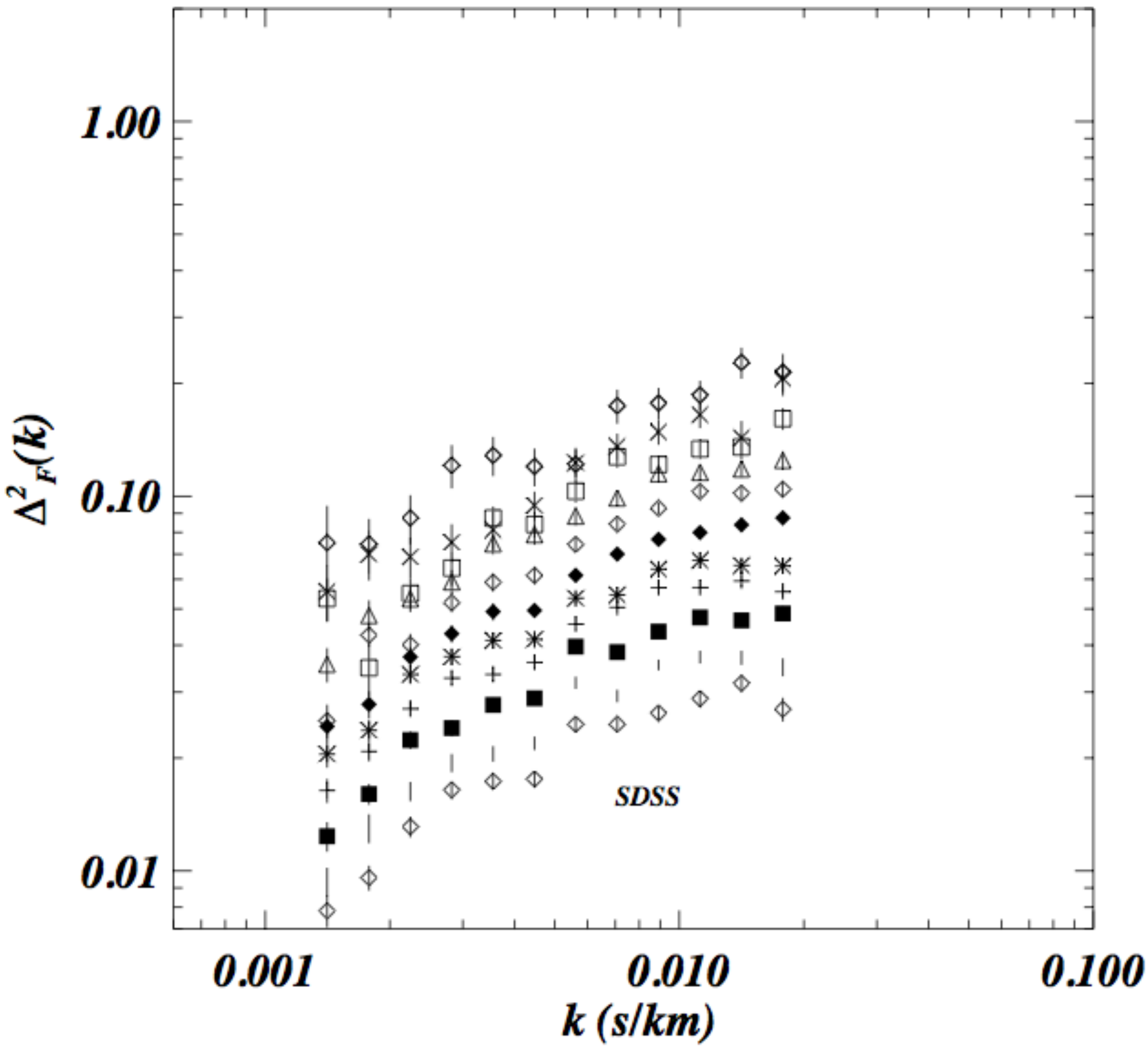


m > 3.3 keV (2σ)

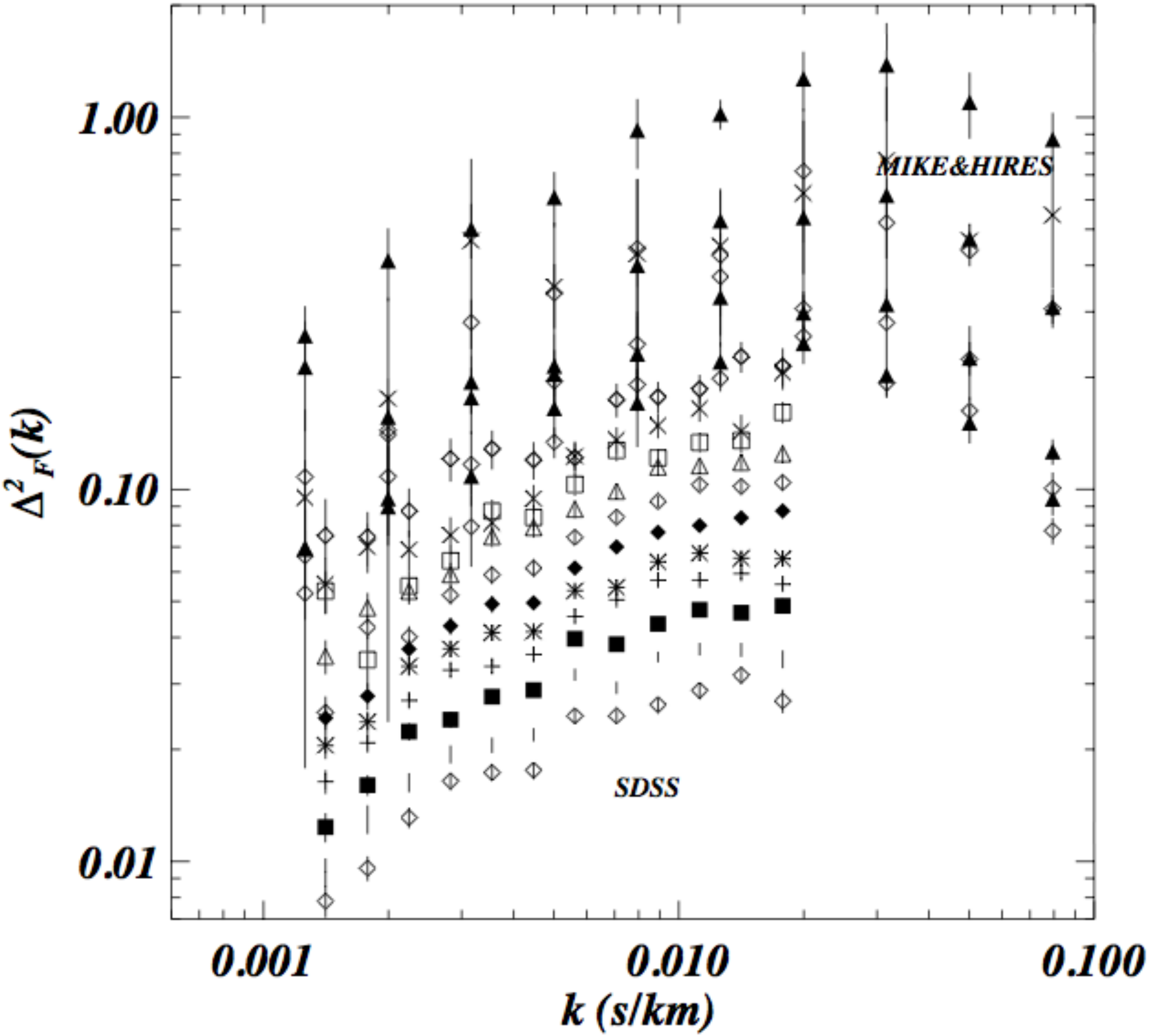
SDSS + MIKE + HIRES CONSTRAINTS

Joint likelihood analysis

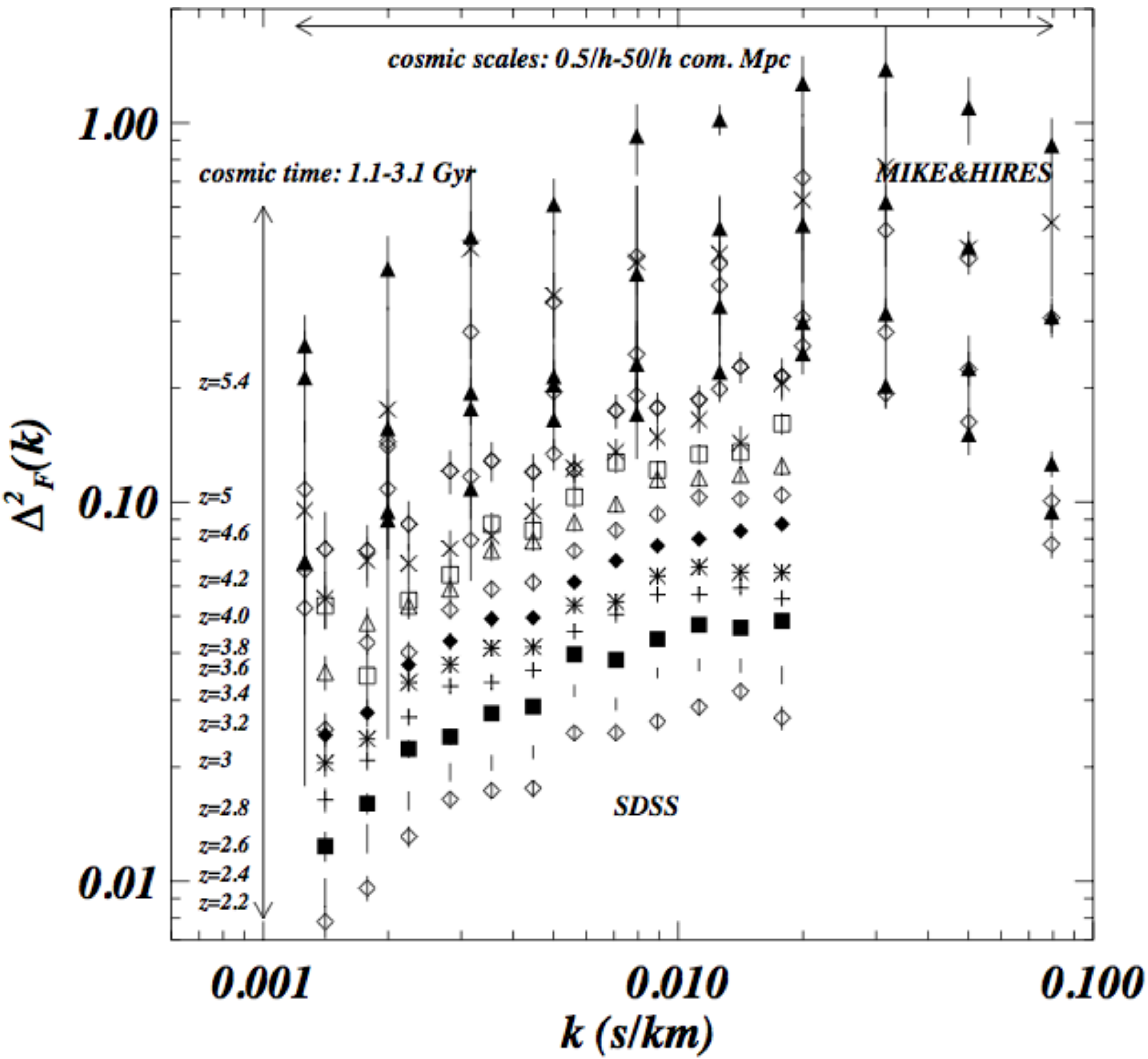
SDSS data from McDonald05,06 not BOSS



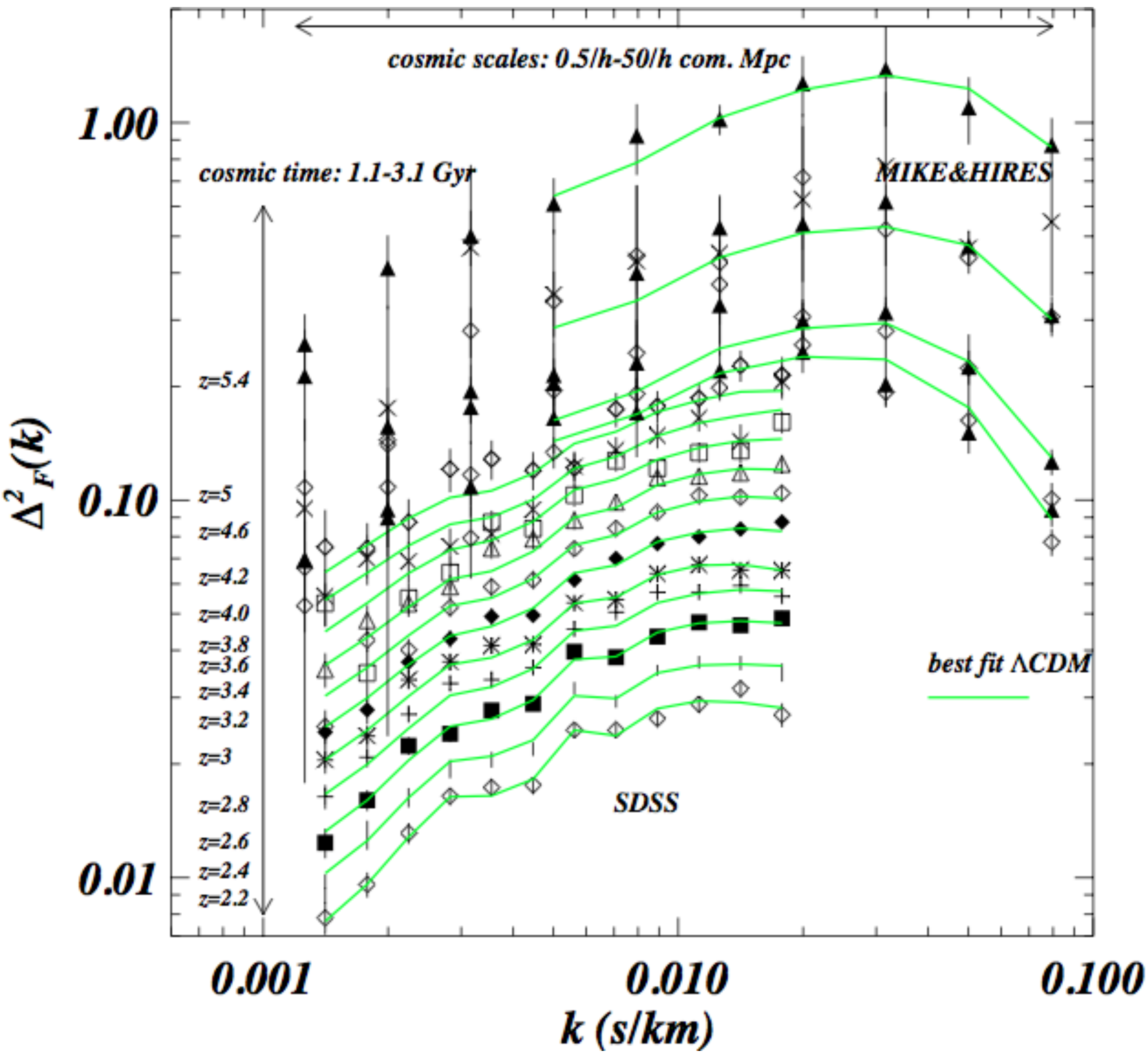
1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)

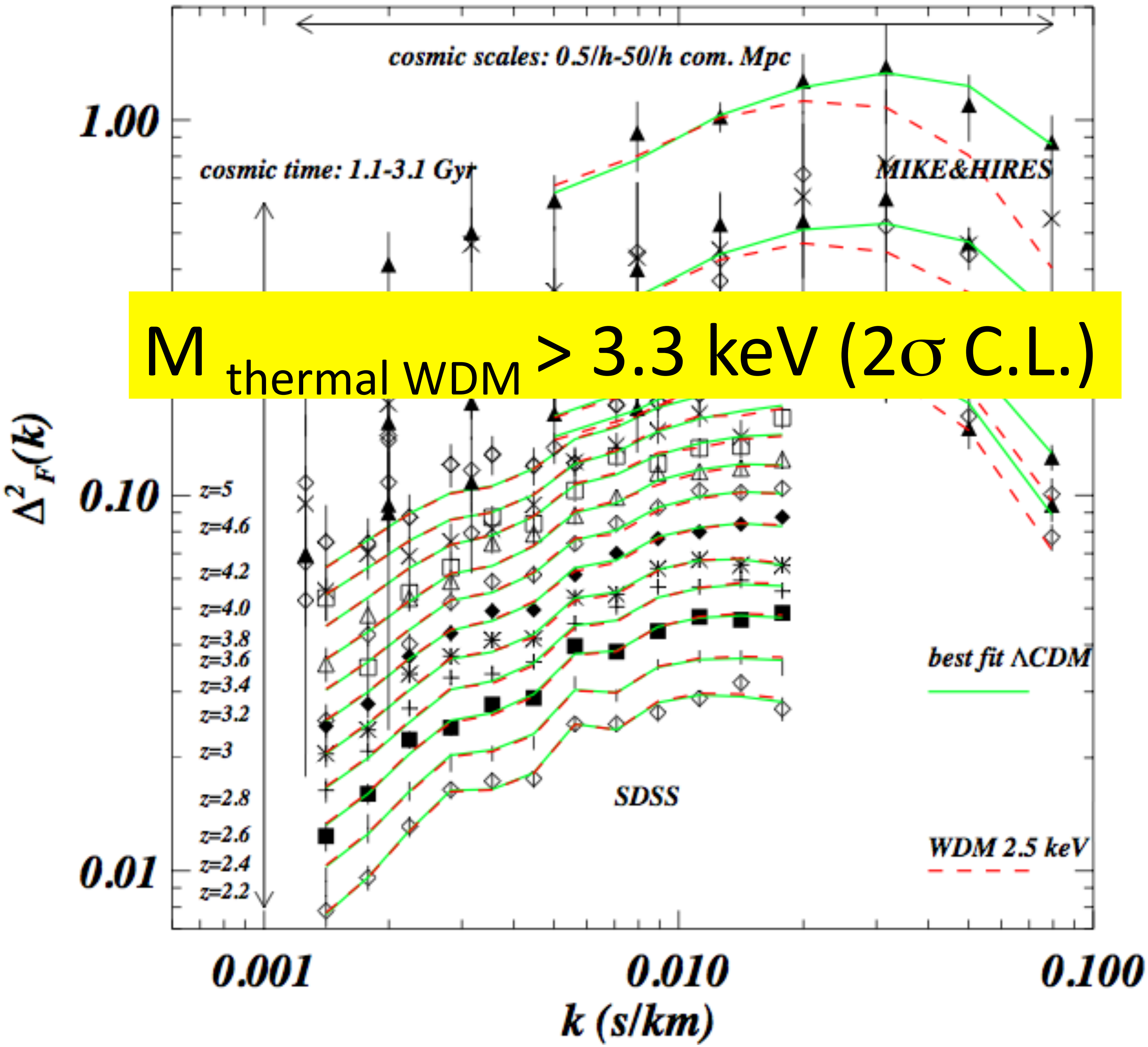


1.00
0.10
0.01
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)
MIKE&HIRES
SDSS



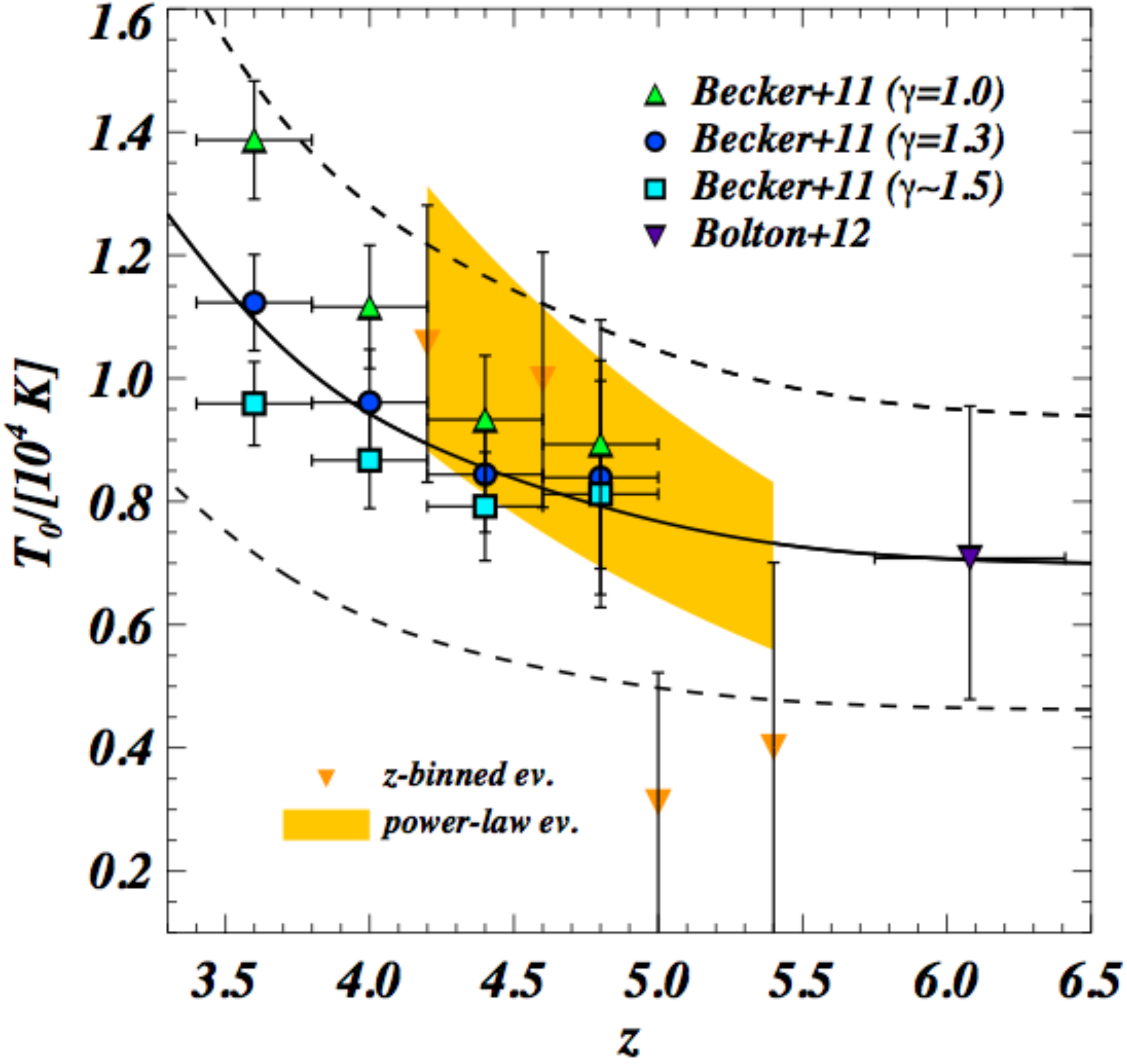
cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)


cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
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
$\Delta^2_F(k)$
0.001
0.010
0.100
k (s/km)

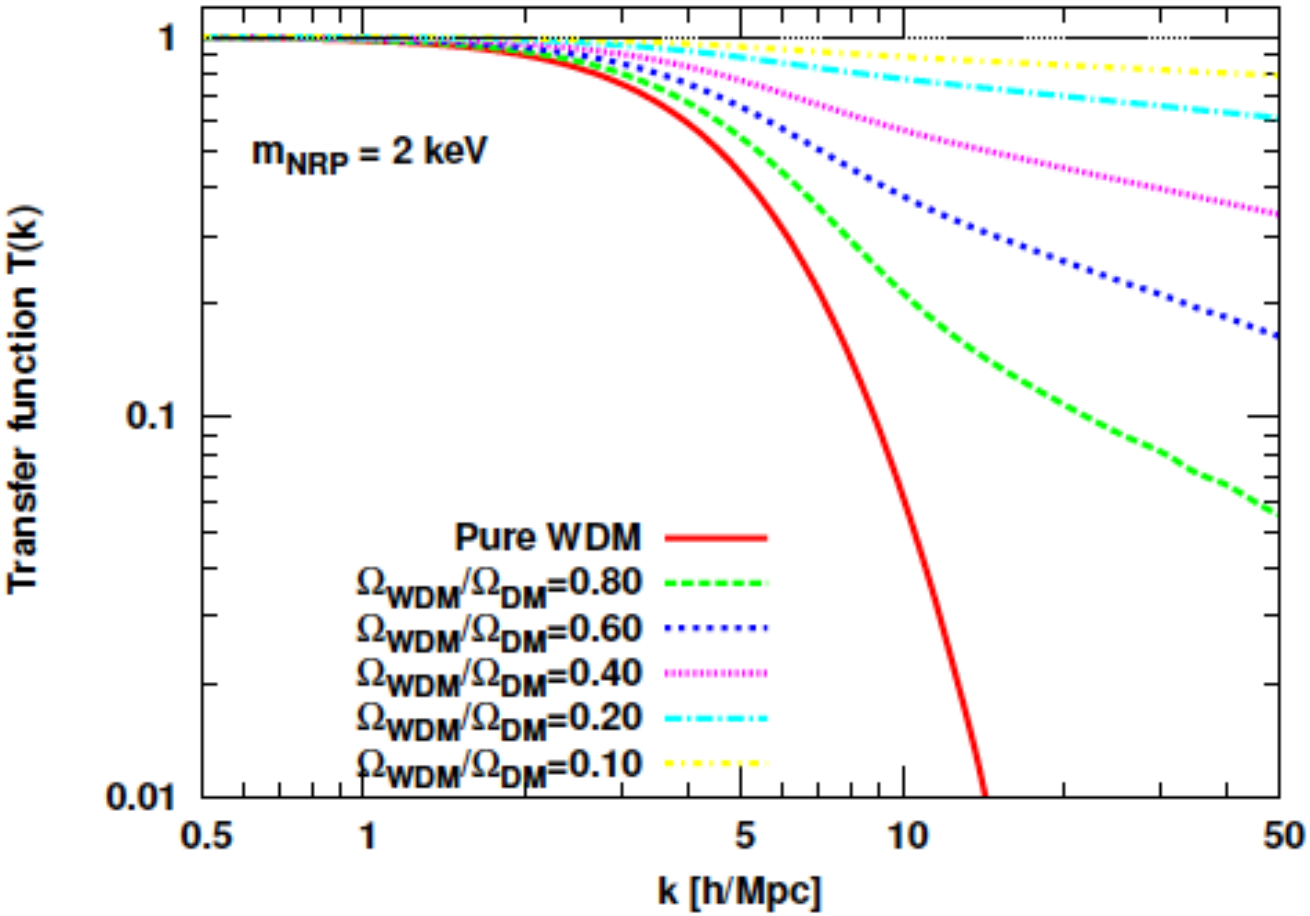

cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
M thermal WDM > 3.3 keV (2σ C.L.)
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
SDSS
best fit ΛCDM
WDM 2.5 keV
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)

RESULTS FOR TEMPERATURE

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

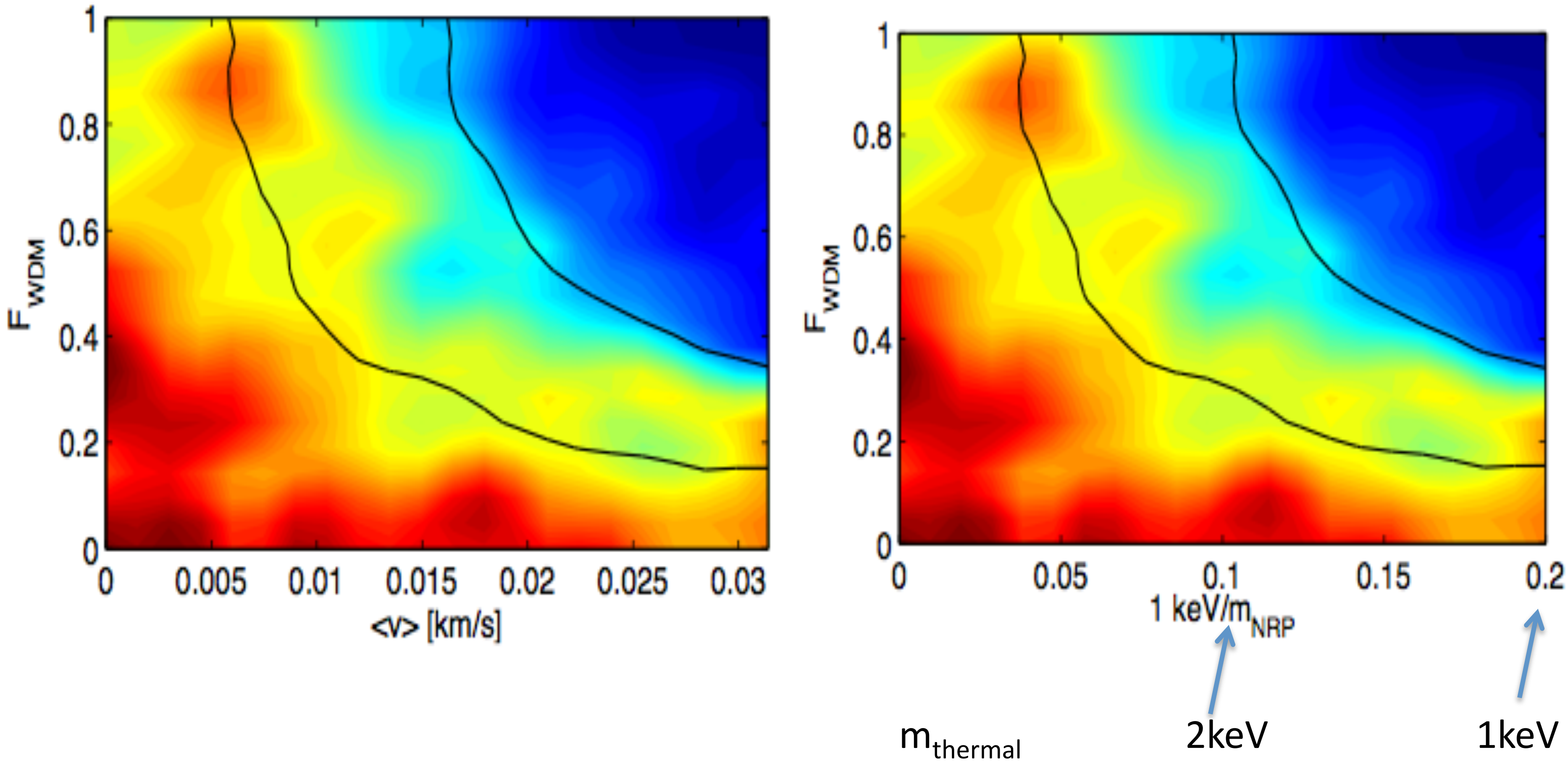


CWDM models



Boyarsky, Ruchasky, Lesgourgues, Viel 09

CONSTRAINTS FROM SDSS DATA ON COLD+WARM DM MODELS



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

WDM SUPPRESSION in 21cm INTENSITY MAPPING

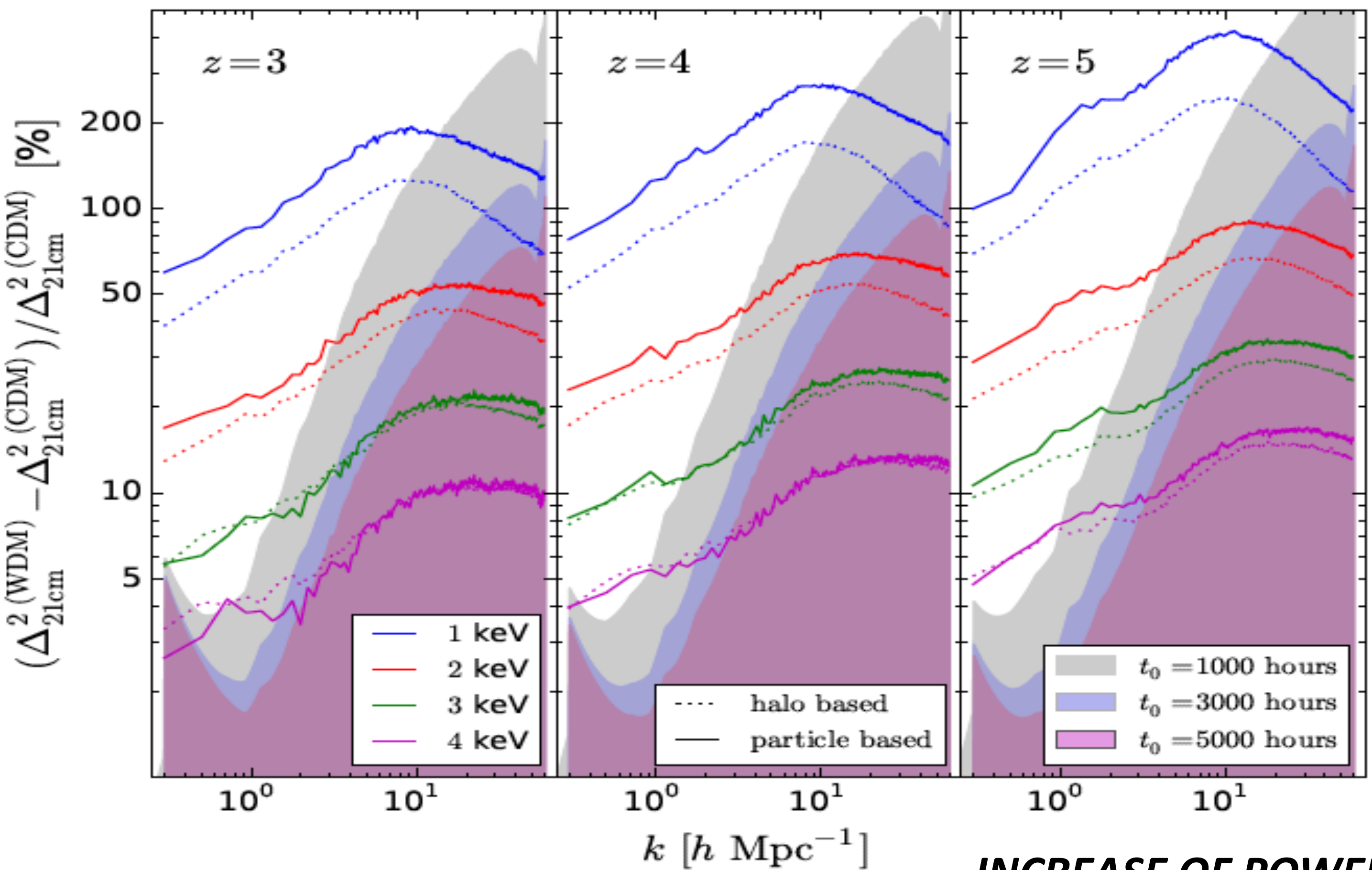
Carucci, Villaescusa, MV, Lapi 2015

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

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

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

REALISTIC SKA forecasts



INCREASE OF POWER!!!

CONCLUSIONS

- WDM could solve some putative tensions of CDM at small scales:

1) Reduces the number of satellites
2) Alleviate the "too-big-to fail" problem

- 2) Is however reached by having a relatively low mass that does not fit Lyman-alpha forest constraints

- WDM does not form cores in dwarfs

- CWDM models could relax all the bounds

- Of course WDM remains a very interesting DM candidates (e.g. sterile neutrino)