WARM DARK MATTER

Or if you prefer.. How cold is cold dark matter?

PROLOGUE

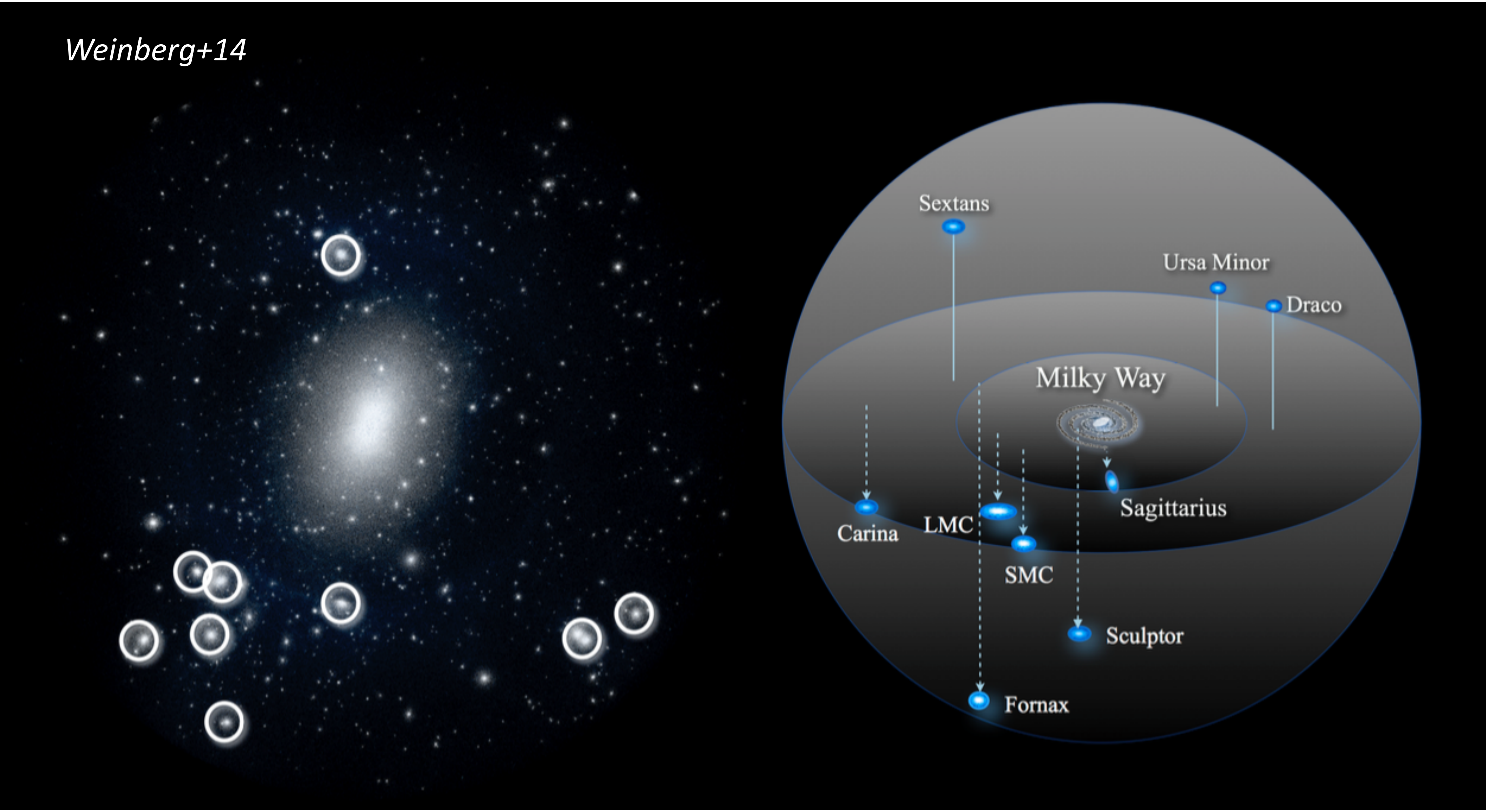
CMB data + some external data set support a consistent picture in favour of the 6 parameter LCDM, with CDM and baryonic matter needed at > 80 sigmas.

Tensions are present: most notably CMB/WL, CMB H0/H0 from SNIa. *Systematics? New physics?*

DATA: At small scales we can constrain the free streaming of the dark matter if it is in a regime probed by data: IGM data and Dwarf galaxies are the two best probes of the small scale structure.

THEORY: Either cold (SUSY like) or warm (sterile neutrinos, fuzzy dark matter) predict different shapes for the linear matter power.

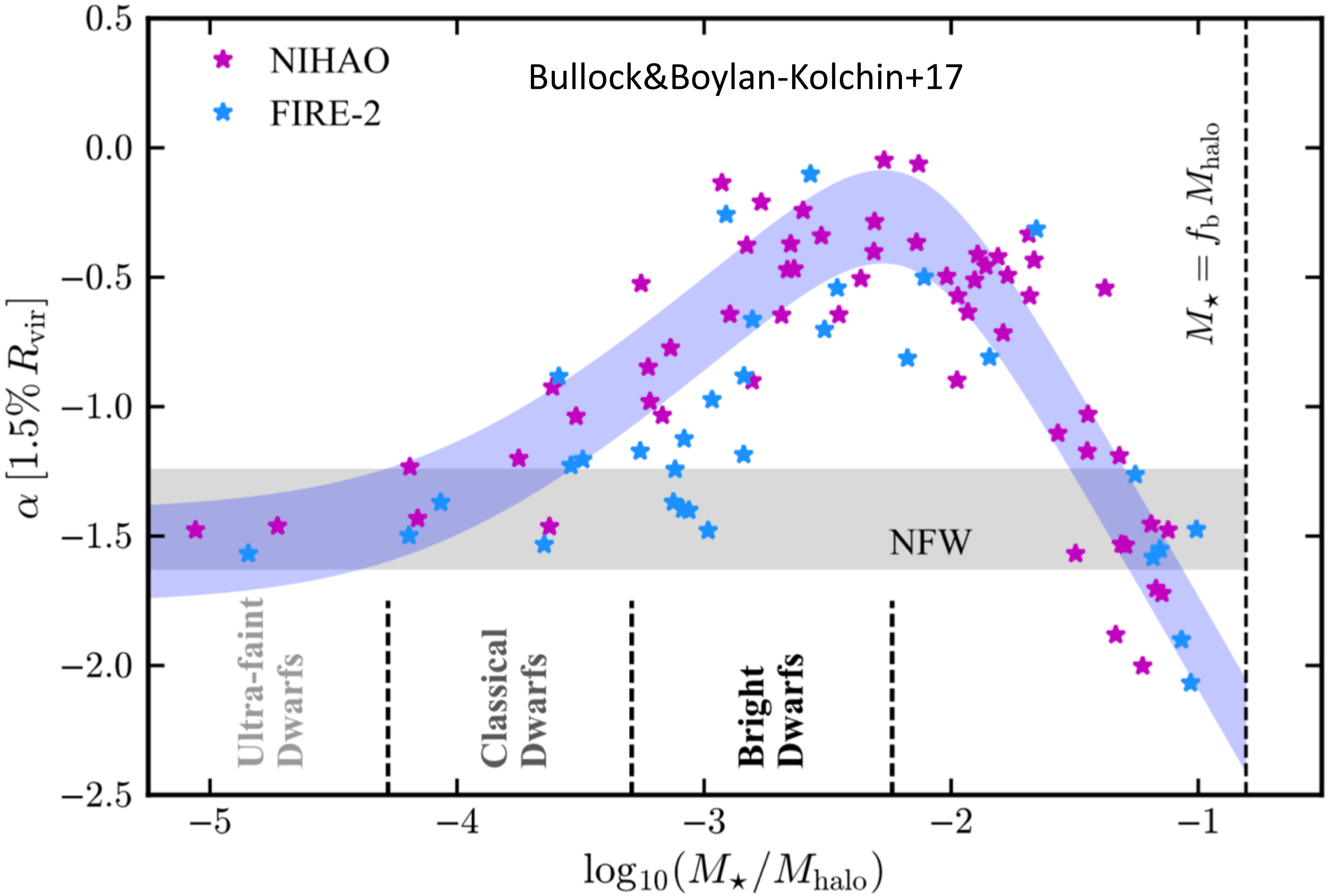
ΛCDM model: small scales problems?



1) Too big to fail problem
2) Missing satellite problem
3) Cusp-core problem

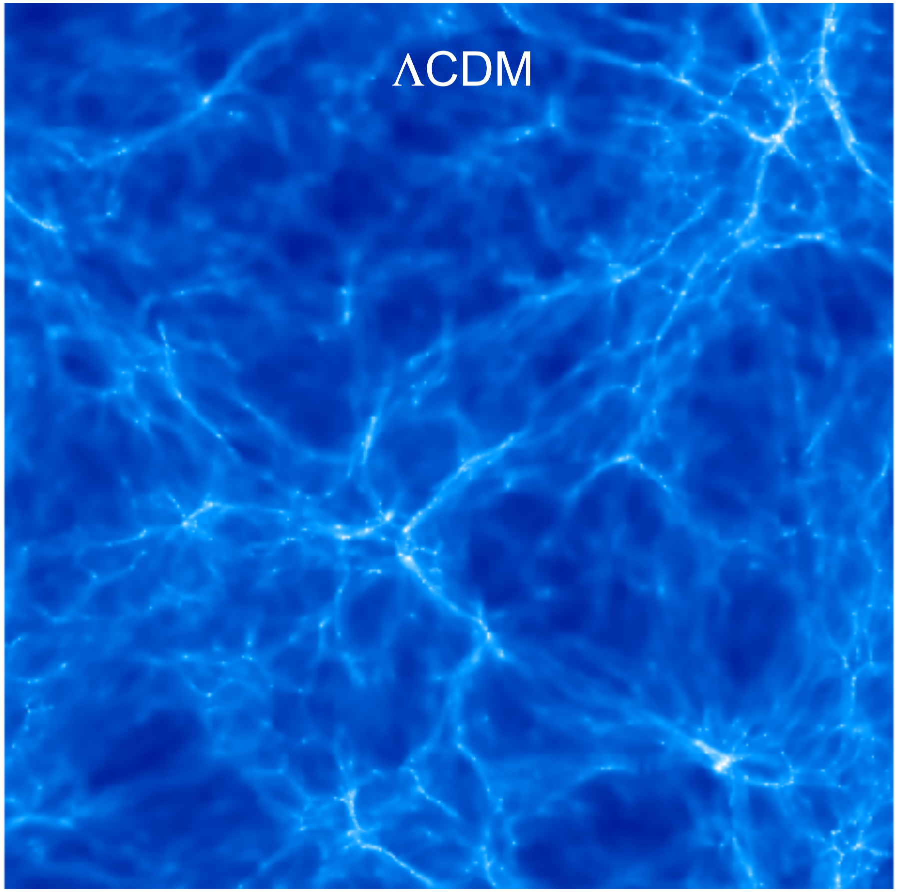
Note that baryonic physics (e.g. galactic feedback) could also solve the tension. Contrived to have DM perfectly mimicking baryons (different z-evolution?)

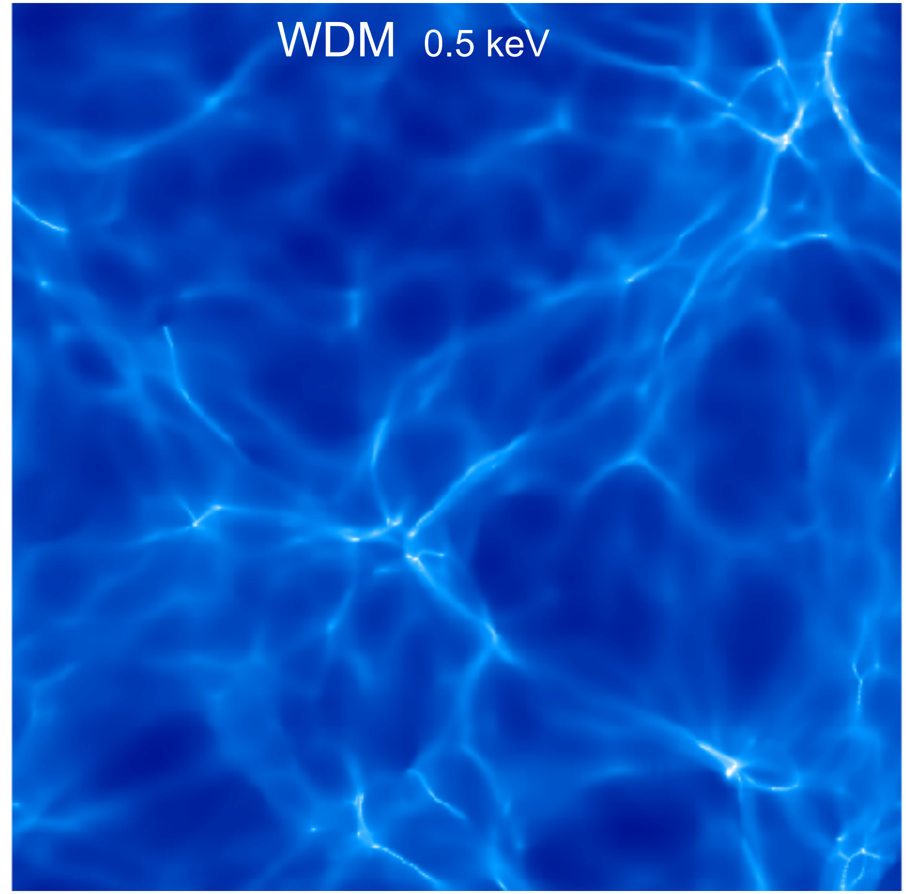
ΛCDM model: core/cusps with feedback



Hydro simulation in LCDM with feedabck predict cored profile for bright dwarfs 10^7–10^9 M★, and cuspy for classical (10^5–10^7 M★)and ultra-faint Dwarfs (10^2–10^5 M★)

Lyman-α and Warm Dark Matter - I





30 comoving Mpc/h z=3

In general

$k_{FS} \sim 5\, T_\nu/T_x\, (m_x/1\mathrm{keV})\ \mathrm{Mpc}^{-1}$

Set by relativistic degrees of freedom at decoupling

See Bode, Ostriker, Turok 2001
Abazajian, Fuller, Patel 2001

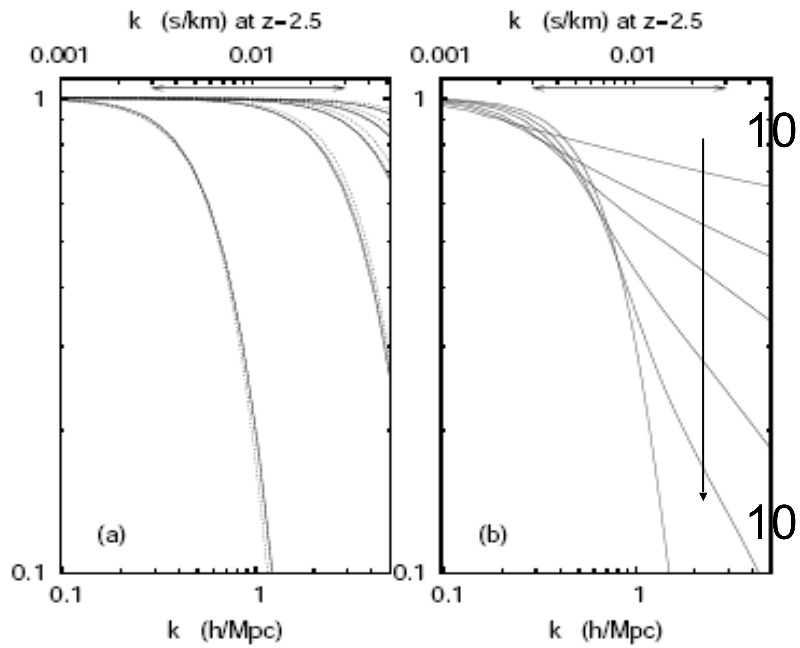
MV, Lesgourgues, Haehnelt, Matarrese, Riotto, PRD, 2005, 71, 063534

Lyman-α and Warm Dark Matter - II

$P(k) = A\, k^n\, T^2(k)$

$[P(k)_{WDM}/P(k)_{CDM}]^{1/2}$

$$\frac{T_x}{T_\nu} = \frac{10.75^{1/3}}{g(T_D)^{1/3}}$$



10 eV

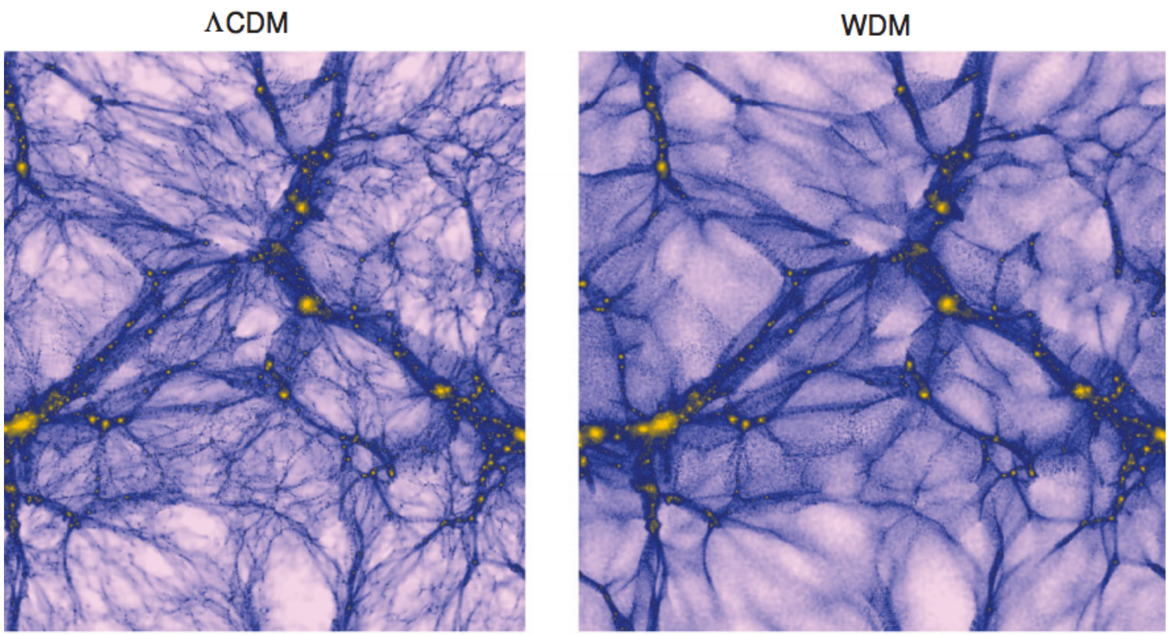
100 eV

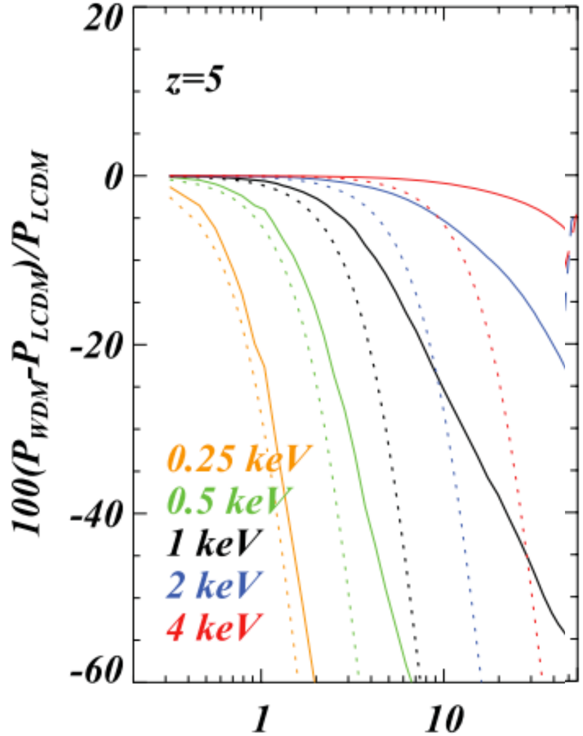
Light gravitino contributing to a fraction of dark matter

Warm dark matter

MV, Lesgourgues, Haehnelt, Matarrese, Riotto, PRD, 2005, 71, 063534

Solution to small scale crisis: Make Dark Matter Warm

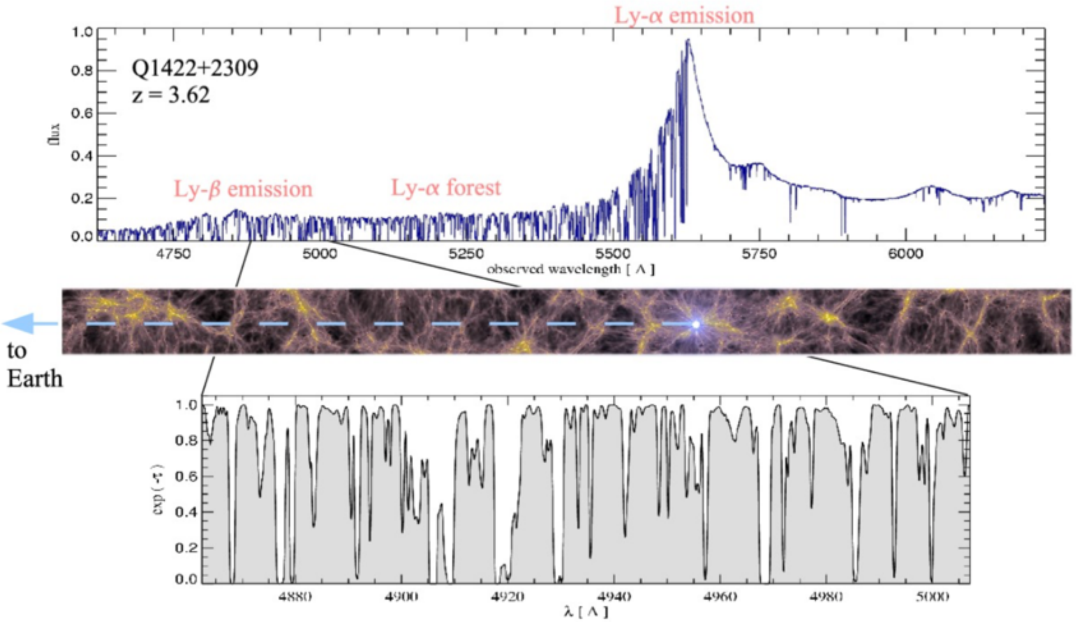




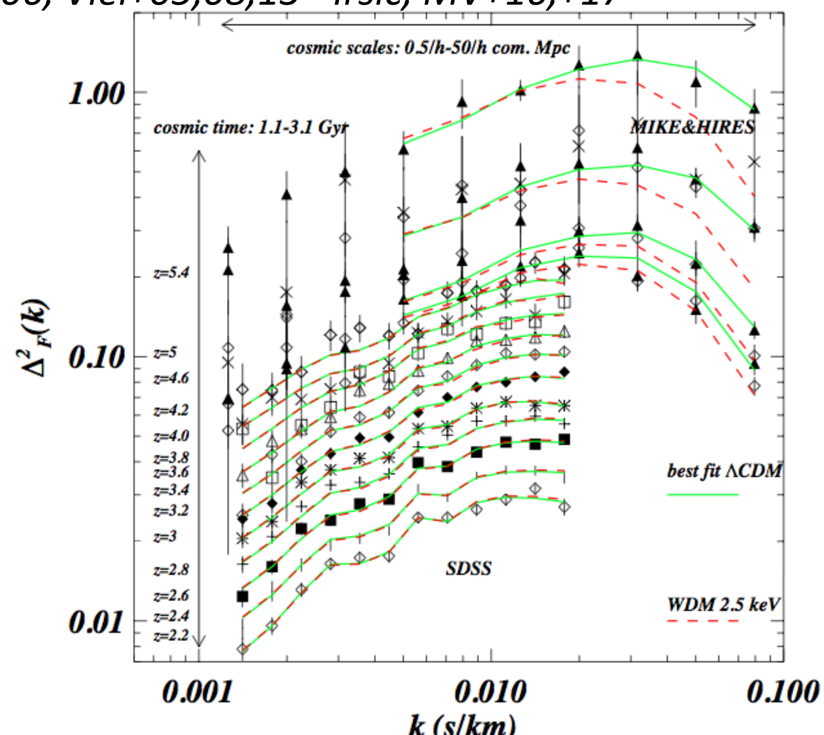
Viel+12

- Cold dark matter is collisionless: zero pressure (thermal velocities).
- Warm dark matter has non zero **thermal velocities** thus non zero pressure (Jeans scale below which perturbations cannot grow).
- Generic prediction is thus a scale and redshift dependent **lack of power** (at non linear level).
- Strong link to **particle physics** and minimal extensions of the standard models: sterile neutrinos?
- **Impact on structure formation could be dramatic BUT baryon physics** can also play a role.

Warm Dark Matter Constraints

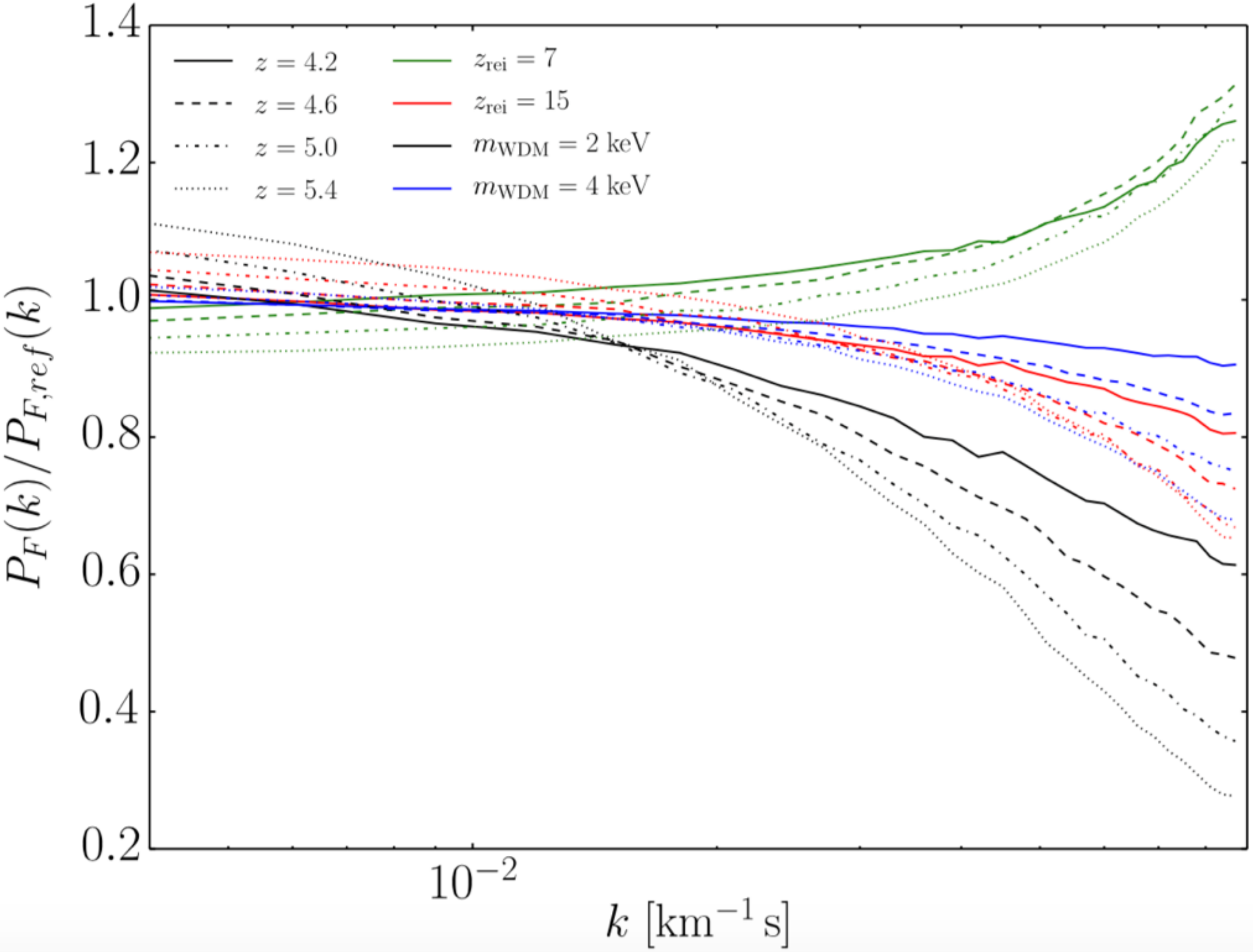


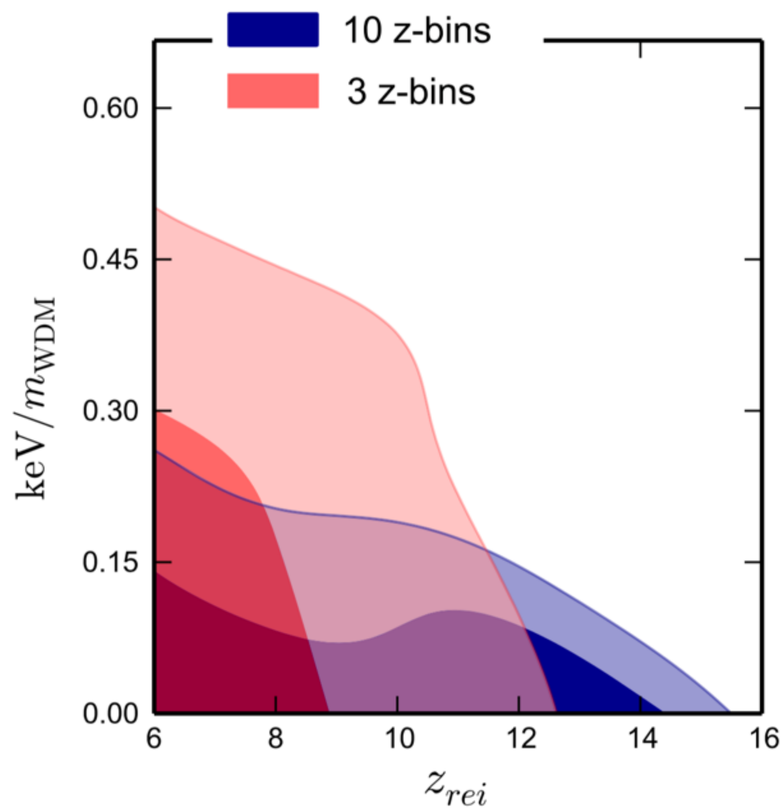
Seljak+06, Viel+05,08,13 - Irsic, MV+16,+17



- **Intergalactic medium:** filaments at low density (outside galaxies) - distances spanned 0.1-100 Mpc/h
- Lyman-alpha forest its the main manifestation of the IGM
- High redshift observable, 1D projected power
- Tight constraints on:
  thermal warm dark matter
  sterile neutrinos
  ultralight boson dark matter
- **Results:** masses typically advocated to solve the small scale crisis are at odds with Lyman-alpha forest. Impact on structure formation not distinguishable from LCDM. **Cosmic web is cold.**
- Mixed C+W Dark matter?
  Redshift dependence?
  Note: *other astro signatures*

New Results on WDM - I: effect of reionization

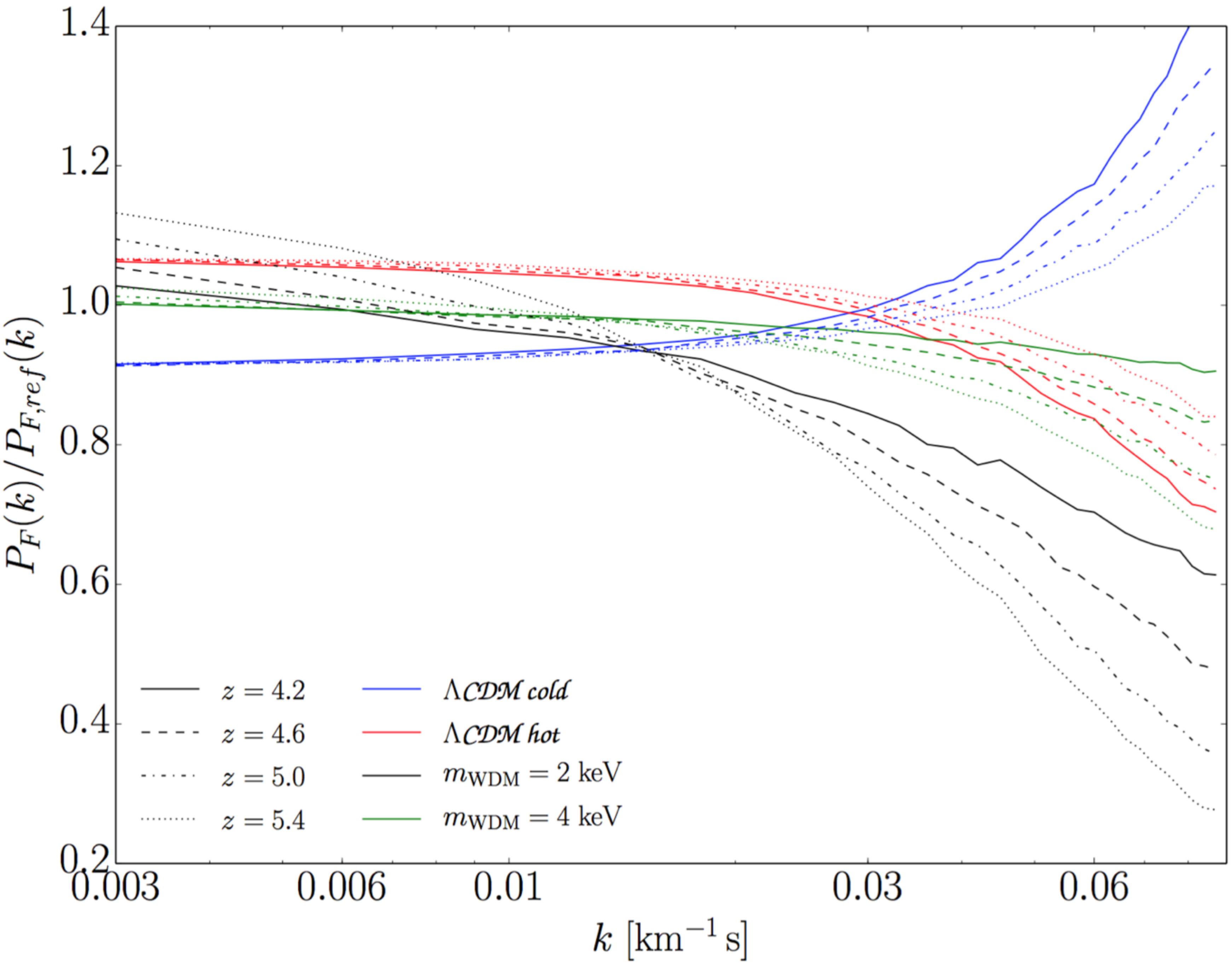




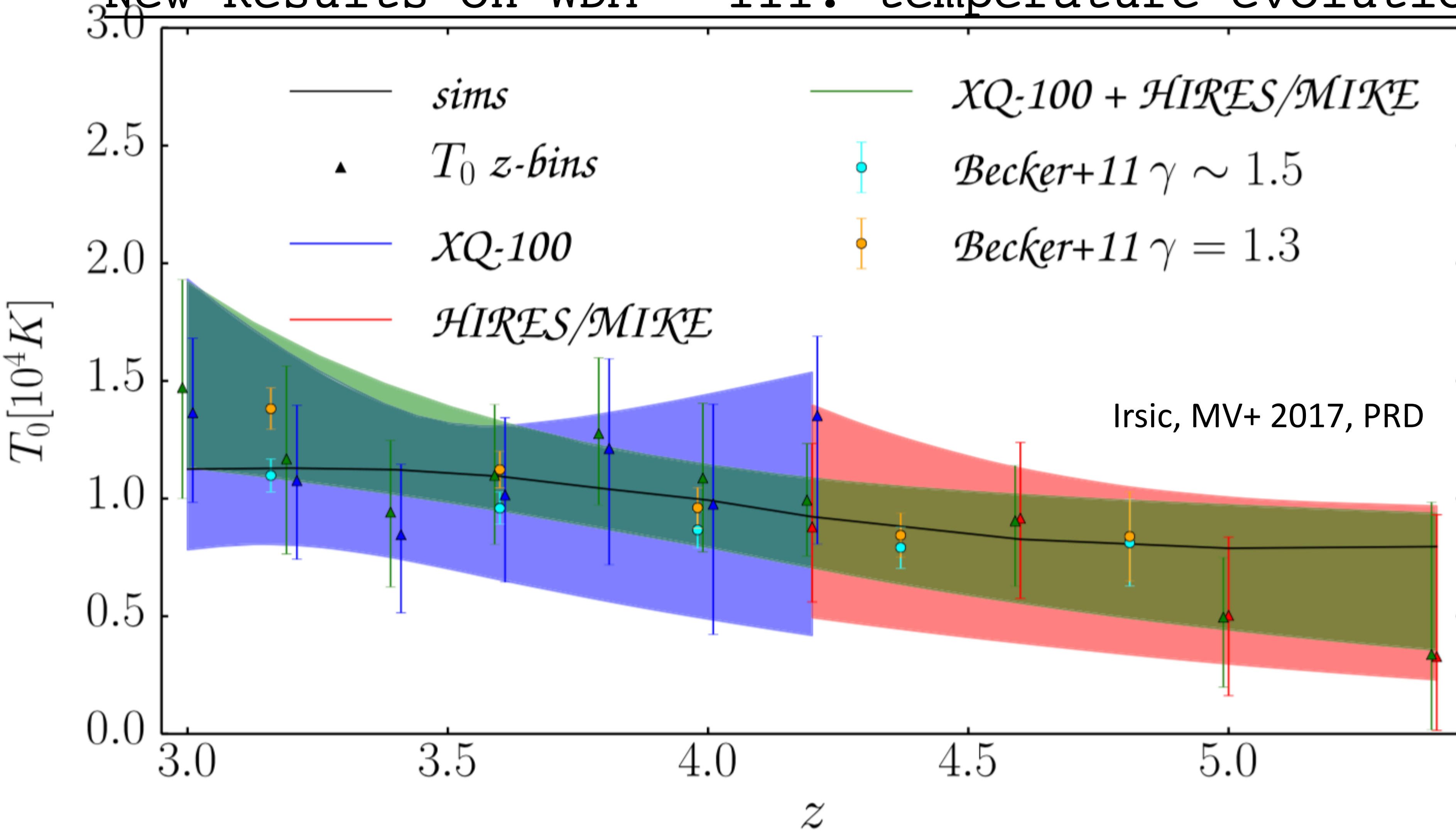
- New "**hot topic**" prompted also by low tau values of Planck: reionization redshift is low.

- Cutoff/smoothing in the power spectrum is thermal (1D) and due to pressure (3D) or WDM (3D). Pressure smoothing is sensitive to the integrated thermal history and thus to reionization redshift.

New Results on WDM - II: effect of temperature



New Results on WDM - III: temperature evolution



- Thermal history is the main nuisance. It is marginalized over but still quite sensitive to priors.
- For reference case $T_{IGM}(z)$ assumed to be a power-law (motivated by IGM physics), having this assumption lifted weakens the combined constrained to 3.5 keV.
- Key-aspect here: **wide redshift range** that allows to break degeneracies between WDM cutoff, Jeans pressure, filtering scale (all suppress power but differently in z).

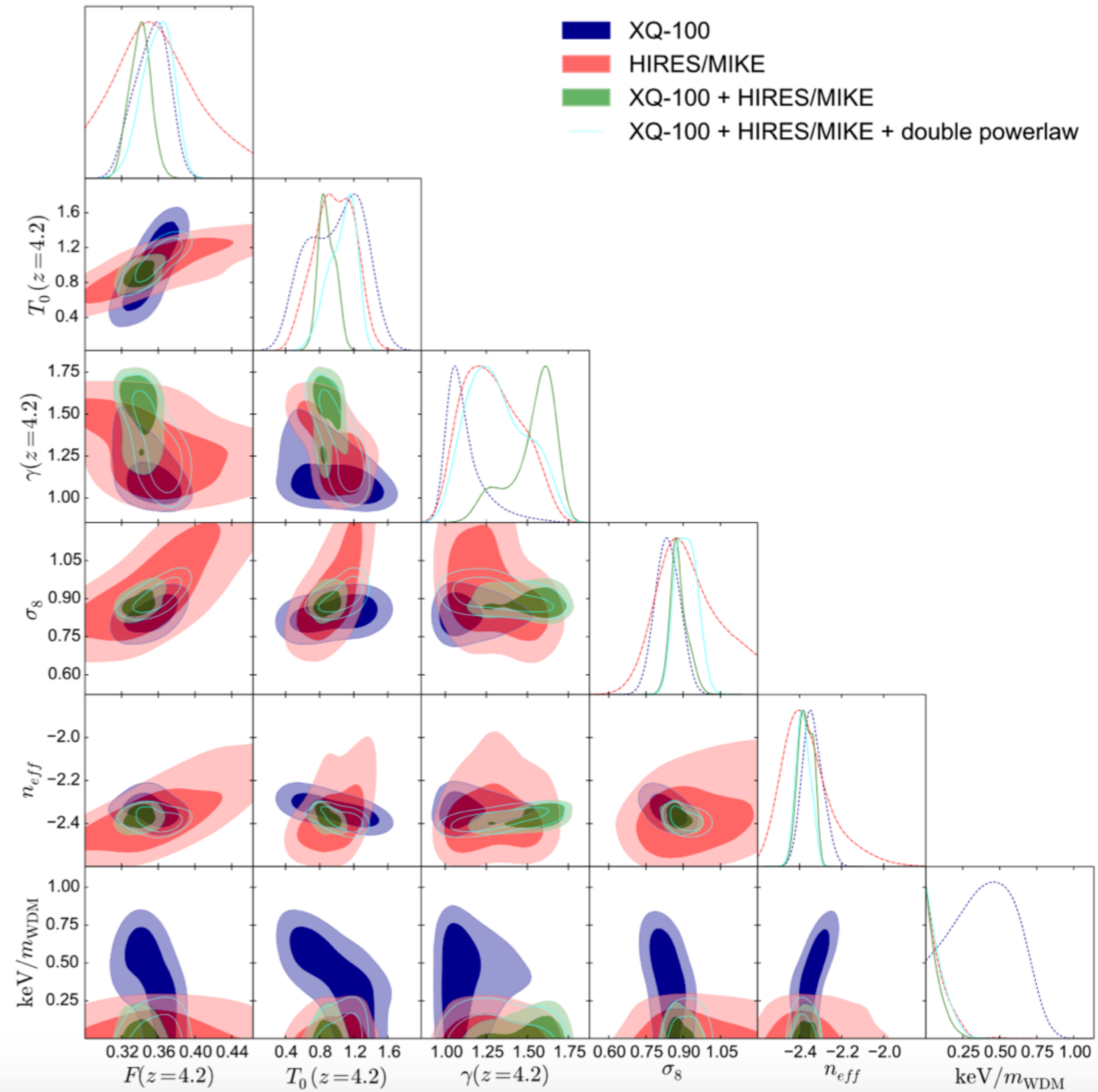
New Results on WDM - IV: thermal relic mass

Parameter	XQ-100	HIRES/MIKE	Combined
$m_{\rm WDM}$ [keV]	>1.4	>4.1	>5.3
σ_8	[0.75, 0.92]	[0.75, 1.32]	[0.83, 0.95]
$n_{\rm eff}$	[−2.42, −2.25]	[−2.53, −2.11]	[−2.43, −2.32]
$T^A(z_p)$ [10^4 K]	[0.73, 1.27]	[0.46, 1.12]	[0.74, 1.06]
$T^S(z_p)$	[−4.39, 1.89]	[−4.78, −1.80]	[−3.22, −0.82]
$\gamma^A(z_p)$	[1.12, 1.45]	[1.08, 1.52]	[1.23, 1.69]
$\gamma^S(z_p)$	[−1.89, 0.17]	[−1.18, 1.77]	[−0.07, 1.81]
$z_{\rm rei}$	[6.5, 15.66]	[6.26, 14.88]	[6.25, 13.43]
$f_{\rm UV}$	[0.06, 0.96]	[0.05, 0.96]	[0.05, 0.94]
χ^2/d.o.f.	134/124	33/40	185/173

- Tight limit (5.3 keV) is prior dominated. Relaxing the priors on temperature evolution **5.3 --> 3.5 keV** for the combined data set.

- At such high redshifts astrophysical effects (feedback) are not a problem. But UV and temperature fluctuations due to **inhomogeneous reionization could be.** For UV template fitting, for temperature no effect considered (Trac+12) show that the effect is at large scale and negligible at z<4.5.

New Results on WDM - V: consistency checks



Complementarity of the data sets is important and allows to break degeneracies

Scalar Dark Matter - I

$$\nabla_\mu \nabla^\mu \phi = m^2 \phi, \quad G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

KG and Einstein equations

$$T^{\phi}_{\mu\nu} = g_{\mu\nu}\left(-\frac{1}{2}\partial_\rho\phi\partial^\rho\phi - \frac{1}{2}m^2\phi^2\right) + \partial_\mu\phi\partial_\nu\phi.$$

Energy momentum tensor for the scalar field

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Phi)d\boldsymbol{x}^2$$

Metric

$$\phi = \frac{1}{\sqrt{2m}}\left(\varphi e^{-imt} + \varphi^* e^{imt}\right)$$

Oscillating field

$$i\left(\dot{\varphi} + \frac{3}{2}H\varphi\right) = -\frac{\partial^2\varphi}{2a^2m} + m\Phi\varphi,$$

Dropping higher order and averaging over one oscillating period: Schrodinger type eq.

$$\rho_\phi \equiv m\varphi\varphi^*, \quad v_i \equiv \frac{\partial_i\{\arg(\varphi)\}}{am} = -\frac{i}{2am}\left(\frac{\partial_i\varphi}{\varphi} - \frac{\partial_i\varphi^*}{\varphi^*}\right)$$

Defining density and velocities of the fluid

$$\dot{v}_i + Hv_i + \frac{v_j\partial_j v_i}{a} = -\frac{\partial_i\Phi}{a} + \frac{1}{2a^3m^2}\partial_i\left(\frac{\partial^2\sqrt{\rho_\phi}}{\sqrt{\rho_\phi}}\right)$$

Euler eq. NOTE the pressure term

$$\dot{\rho}_\phi + 3H\rho_\phi + \frac{\partial_i(\rho_\phi v_i)}{a} = 0.$$

Continuity

Hui+16 for a review, Mocz & Succi 15 for SPH implementation, Marsh+15 for sims.

Scalar Dark Matter - II

$$\delta_{\rm m} = F\delta_\phi + (1-F)\delta_{\rm c}$$

$$\ddot{\delta}_{\phi\boldsymbol{k}} + 2H\dot{\delta}_{\phi\boldsymbol{k}} + \frac{c_s^2 k^2}{a^2}\delta_{\phi\boldsymbol{k}} - \frac{3}{2}H^2\delta_{\rm m\boldsymbol{k}} = 0,$$

$$\ddot{\delta}_{\rm c\boldsymbol{k}} + 2H\dot{\delta}_{\rm c\boldsymbol{k}} - \frac{3}{2}H^2\delta_{\rm m\boldsymbol{k}} = 0.$$

Linear perturbation theory in CDM+scalar field model

$$c_s^2 \equiv \frac{k^2}{4a^2m^2}, \qquad \frac{k_{\rm J}}{a} = \sqrt{Hm},$$

Sound speed of scalar DM and Jeans scale definition

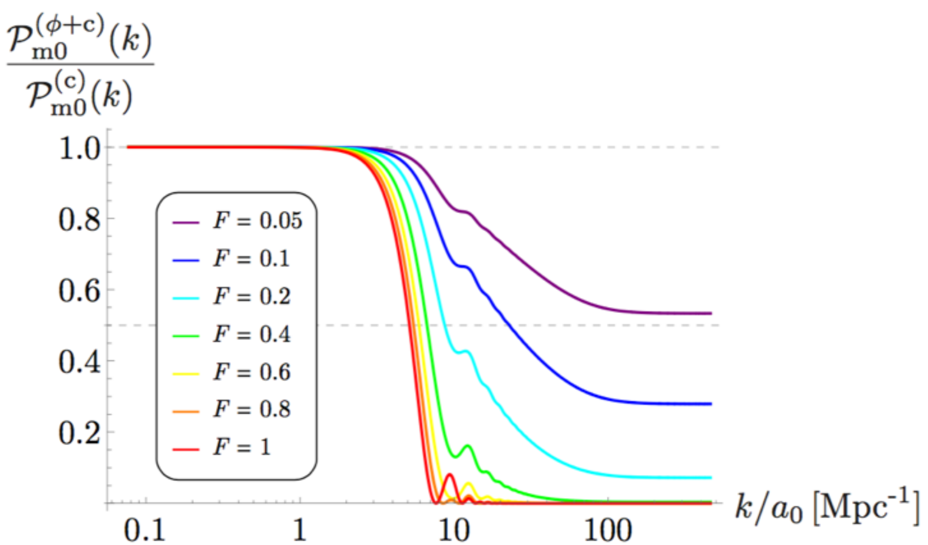
$$\frac{k_{\rm Jeq}}{a_0} = \frac{a_{\rm eq}}{a_0}\sqrt{H_{\rm eq}m} \approx 7\,{\rm Mpc}^{-1}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{1/2}$$

At $k<k_J$ no pressure

At $k>k_J$ pressure and oscillations
no growth

Comoving Jeans $k_J \sim a^{1/4}$ in MD

Important quantity is k_J at equival.

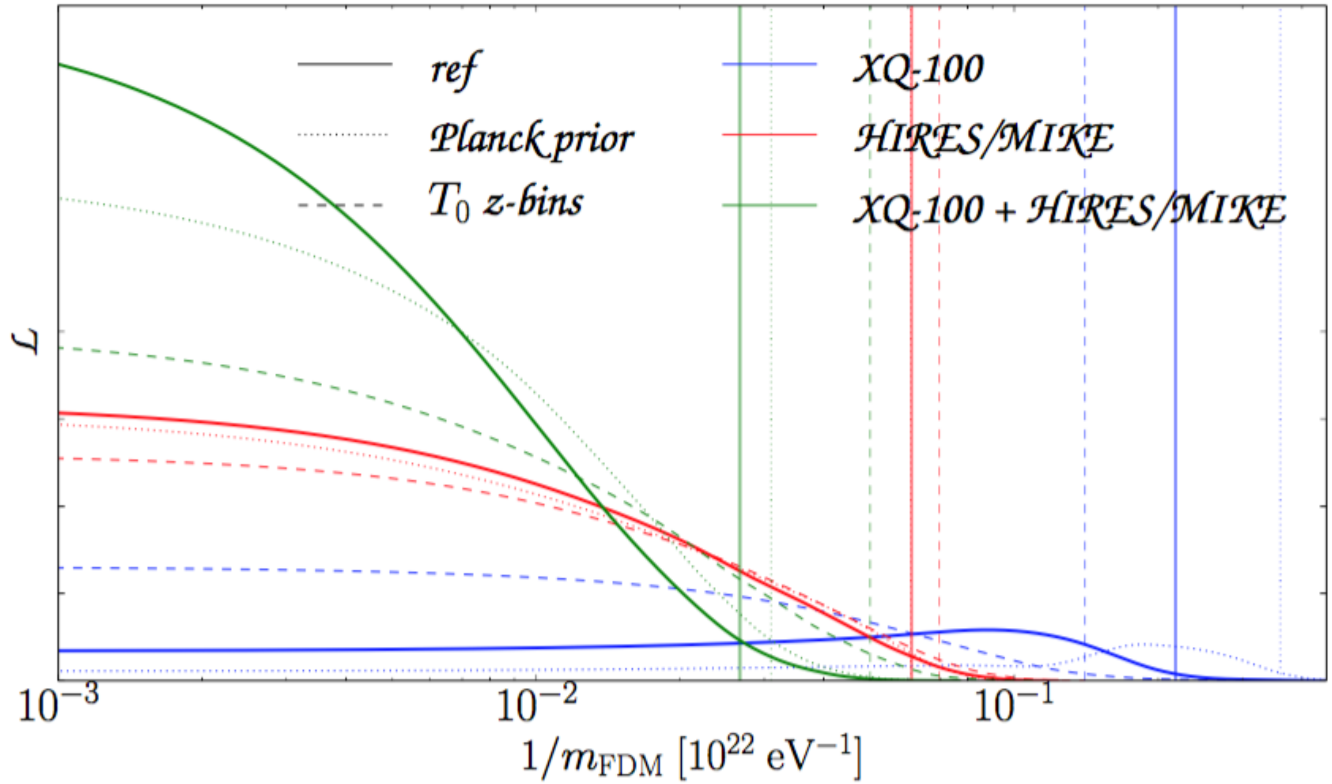


Plateau is set by FDM fraction

Cutoff scale set by FDM mass

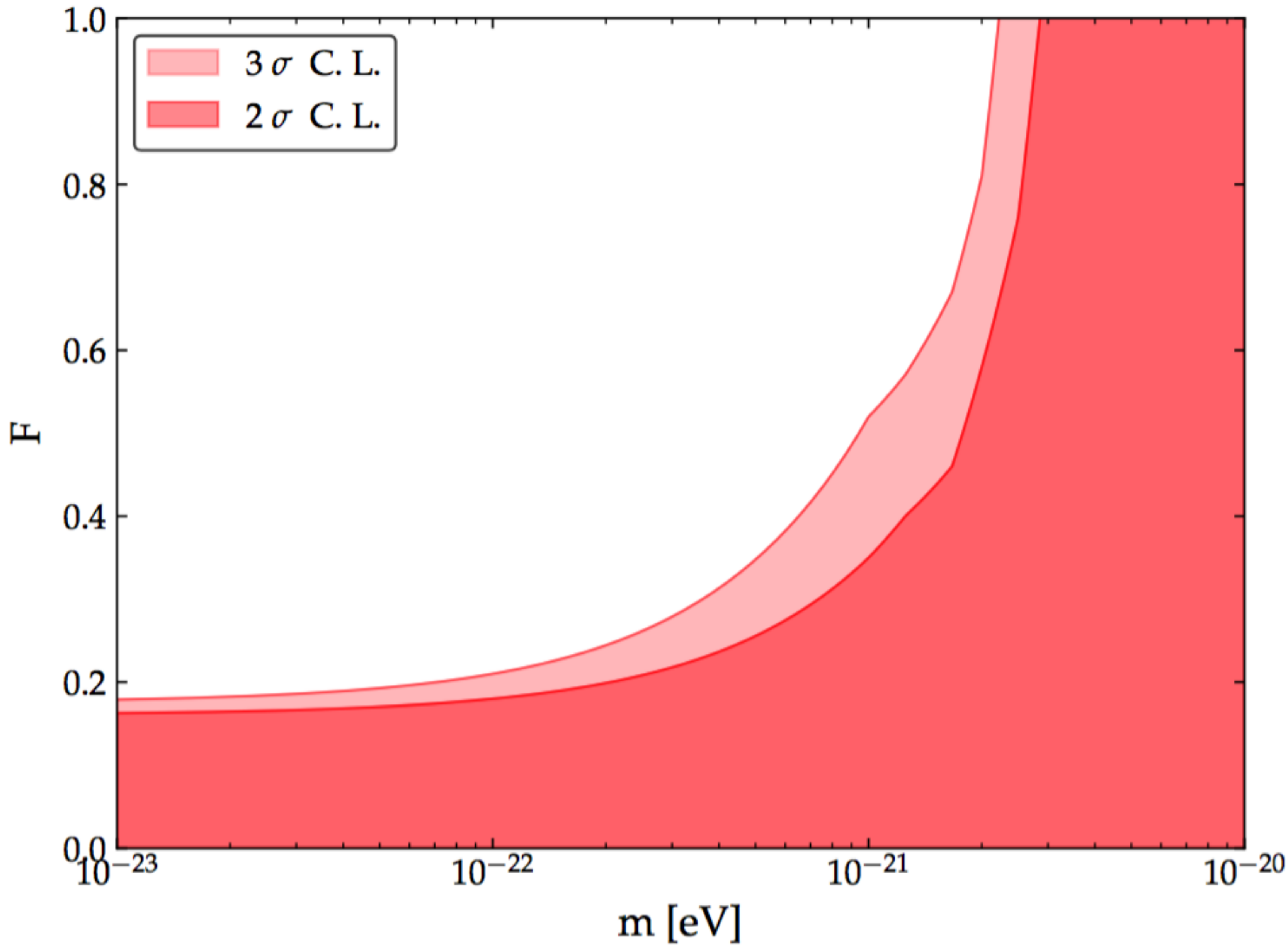
Constraints on Fuzzy (Scalar) Dark Matter

Irsic, MV+ 2017, PRL



$m_{\rm FDM}$ [10^{-22}eV]	XQ-100	HIRES/MIKE	Combined
ref.	4.5	16.4	37.5
Cov. $\times$ 1.3	3.9	16.3	34.9
Planck priors	2.7	16.5	32.2
$T_0(z)$ bins	7.1	14.3	20.0
$\chi^2/d.o.f.$ (ref.)	134/124	33/40	187/173

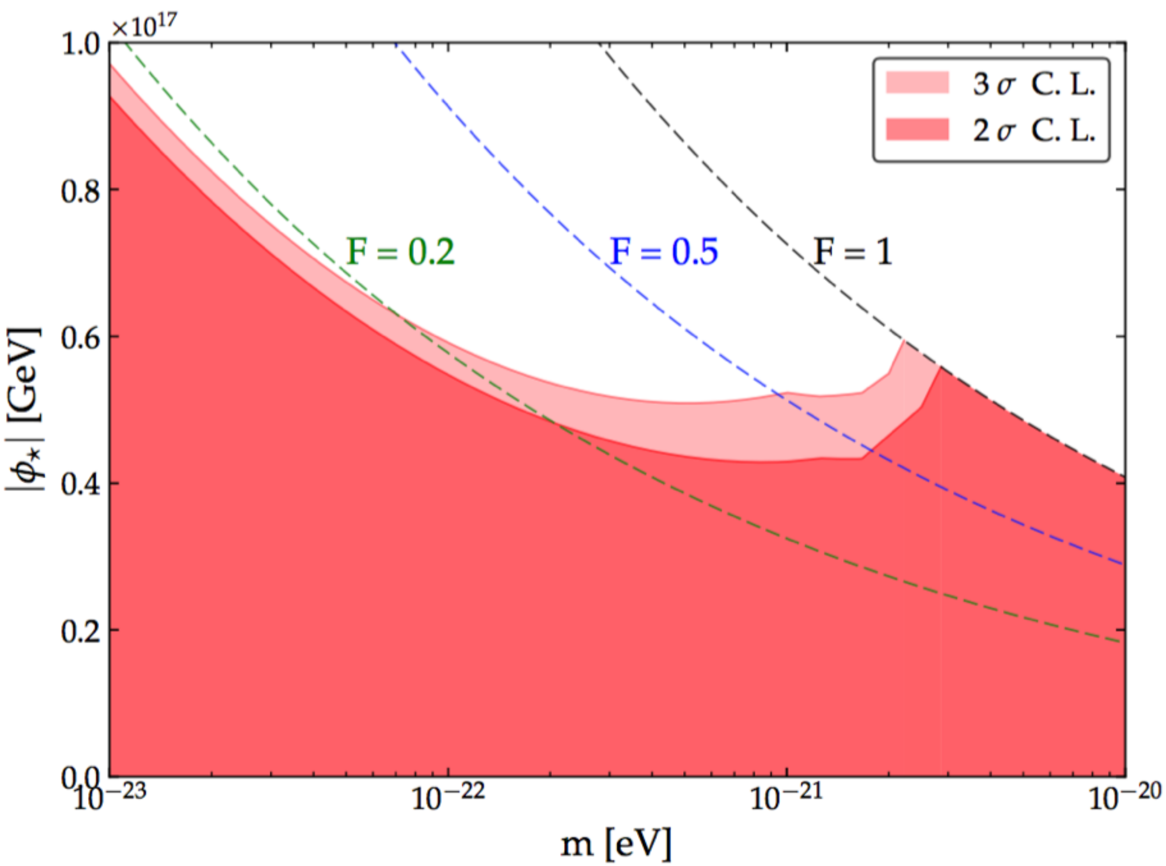
Constraints on Fuzzy (Scalar) Dark Matter in mixed CDM+FDM models



Scalar Dark Matter as a fluid

$$F \equiv \frac{\Omega_\phi}{\Omega_c} \approx 0.6 \left(\frac{g_{*osc}}{3.36}\right)^{3/4} \left(\frac{g_{s*osc}}{3.91}\right)^{-1} \left(\frac{\phi_\star}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}.$$

Kobayashi+17



- Scalar fields with small masses motivated by string theory. Could be the DM.
- Scalar behaves like CDM except at scales smaller than its De Broglie wavelength –> suppression.

Klein Gordon equation describes the field evolution: scalar stays frozen at its initial value at H>>m and behaves as pressureless matter at H<<m.

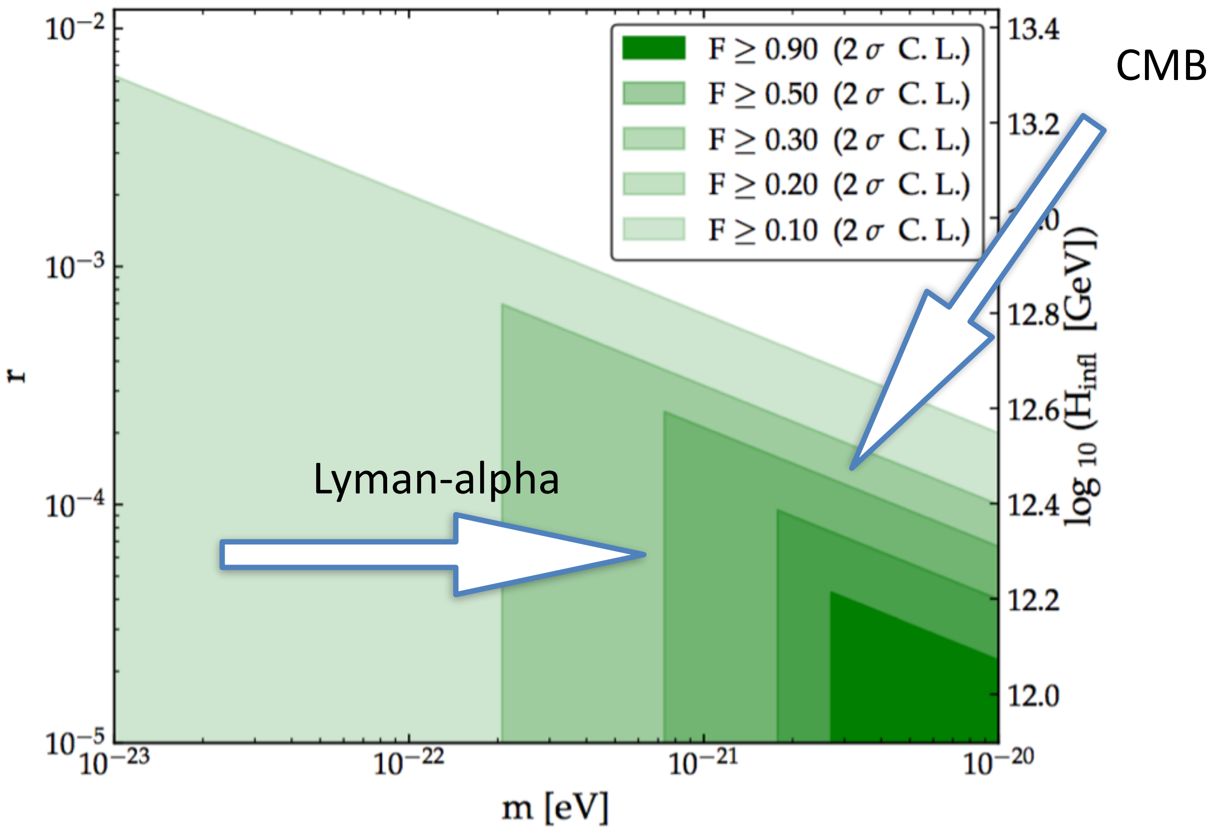
Scalar starts oscillating in the radiation era.

FDM fraction could be casted as a function of mass and initial value of the scalar field

Upper limits on scalar field.

Scalar Dark Matter as a fluid: perturbations

$$r(k_{\rm piv}) < 4 \times 10^{-4} \left(\frac{g_{*\rm osc}}{3.36}\right)^{-3/2} \left(\frac{g_{s*\rm osc}}{3.91}\right)^{2} \left(\frac{m}{10^{-22}\,\rm eV}\right)^{-1} \left(\frac{\phi_\star}{10^{17}\,\rm GeV}\right)^{-2}$$



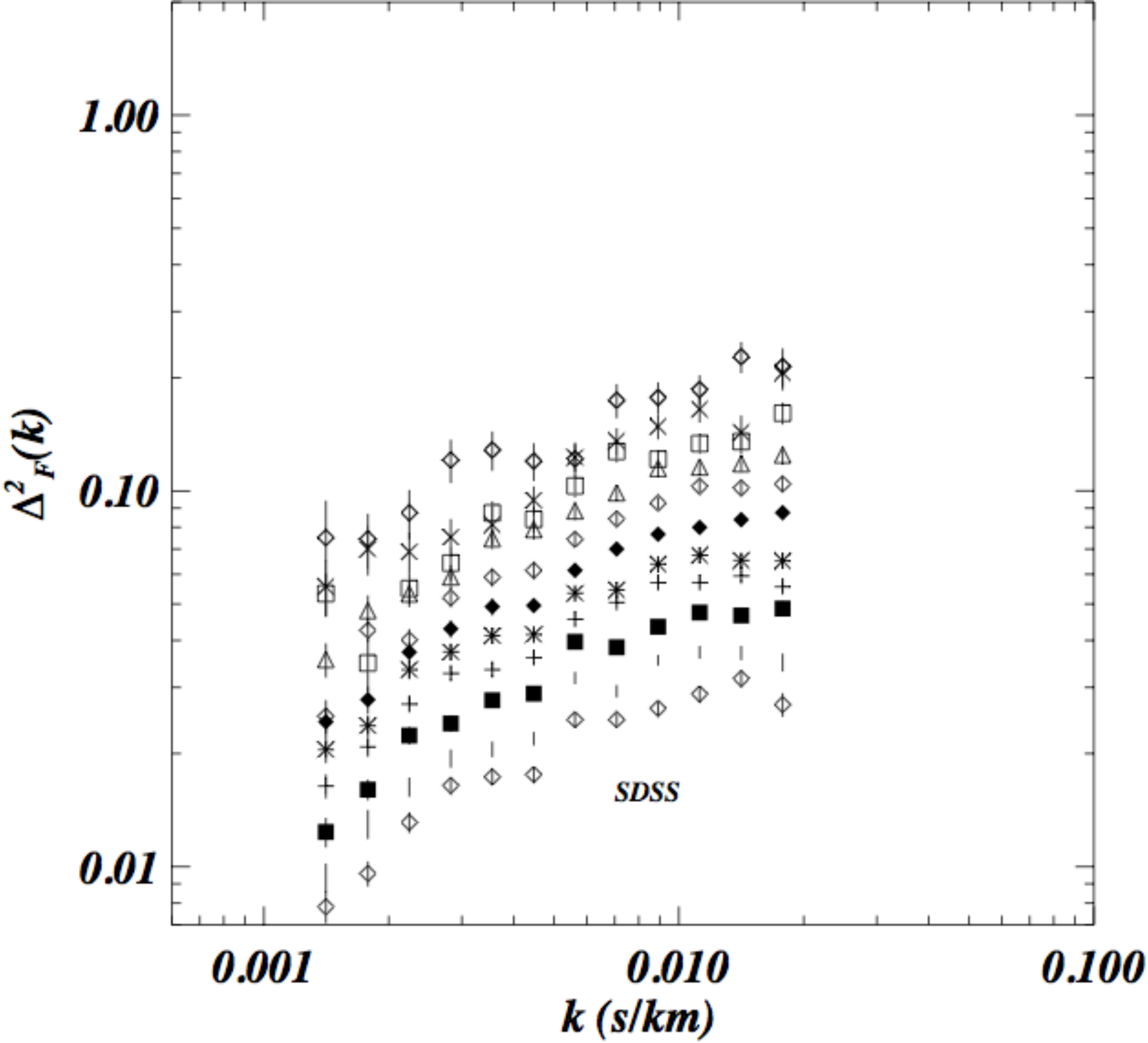
- Scalar field will have super horizon fluctuations during inflation which will depend on the initial field value.
- Isocurv. perturbations will be produced (constrained by Planck upper bound). This will set a limit on the inflation scale, a limit on the Hubble rate when k=0.05/Mpc leaves the horizon and a **limit on tensor to scalar ratio.**

Kobayashi, Murgia + 17

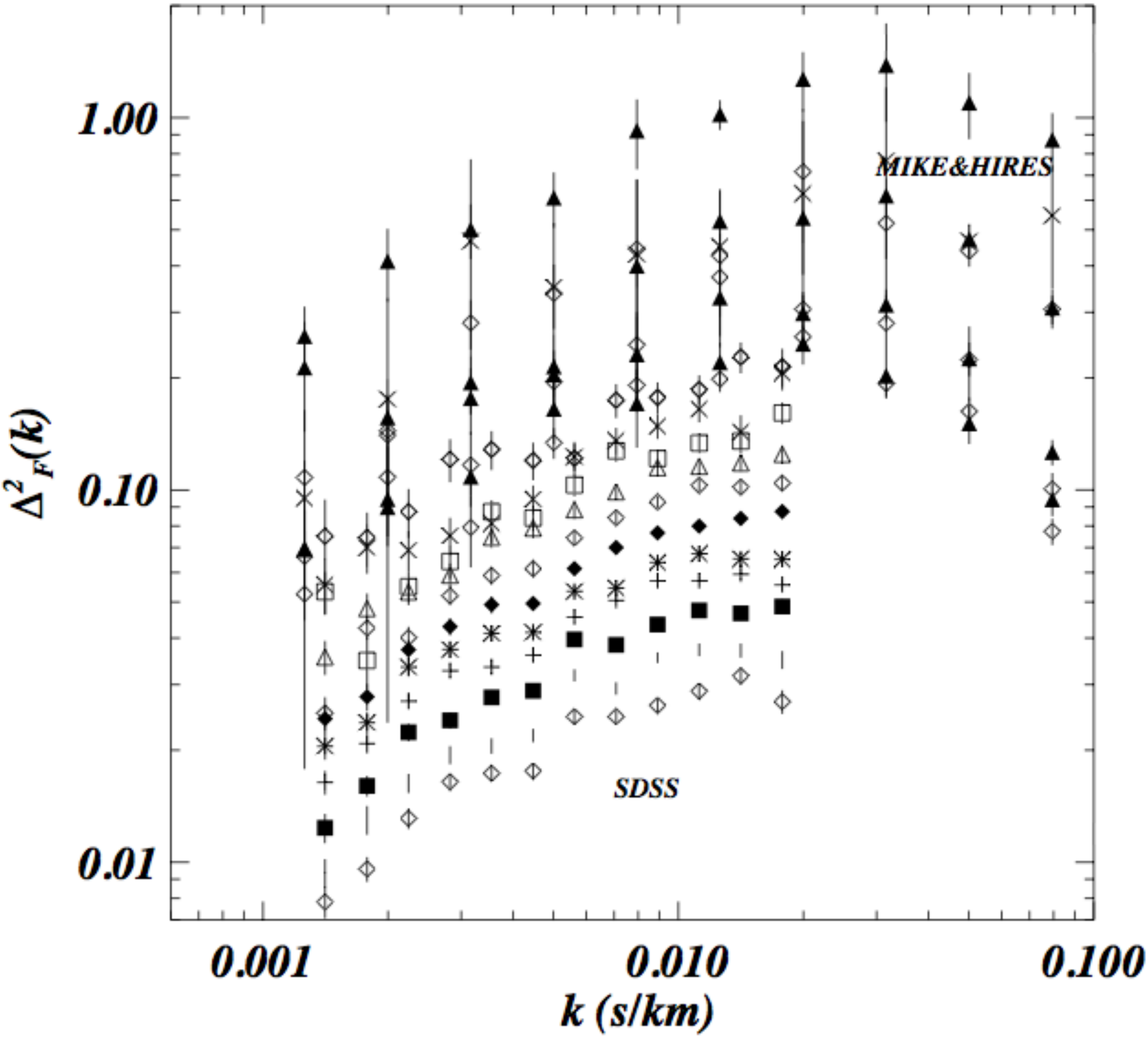
SDSS + MIKE + HIRES CONSTRAINTS

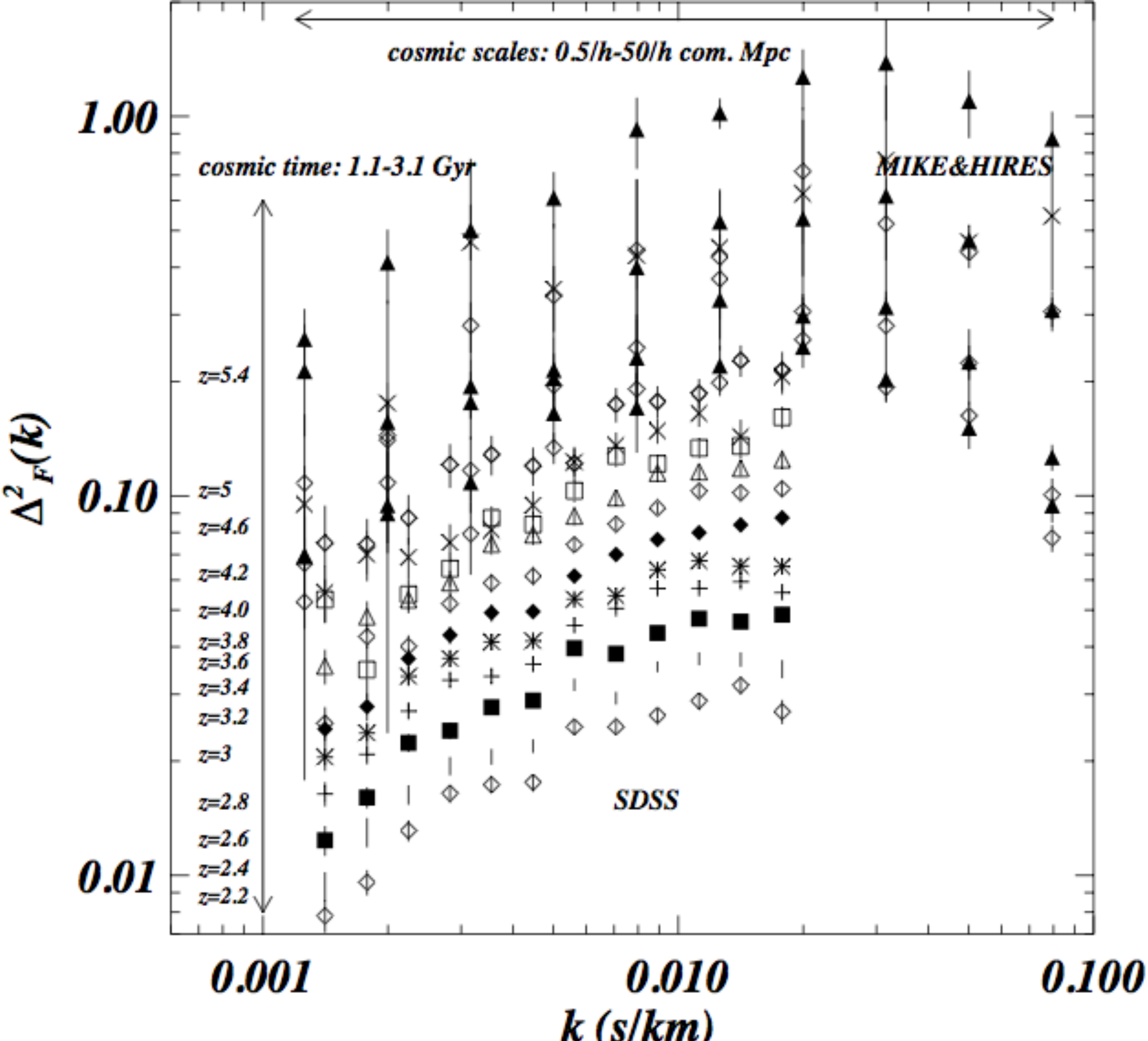
Joint likelihood analysis

SDSS data from McDonald05,06 not BOSS

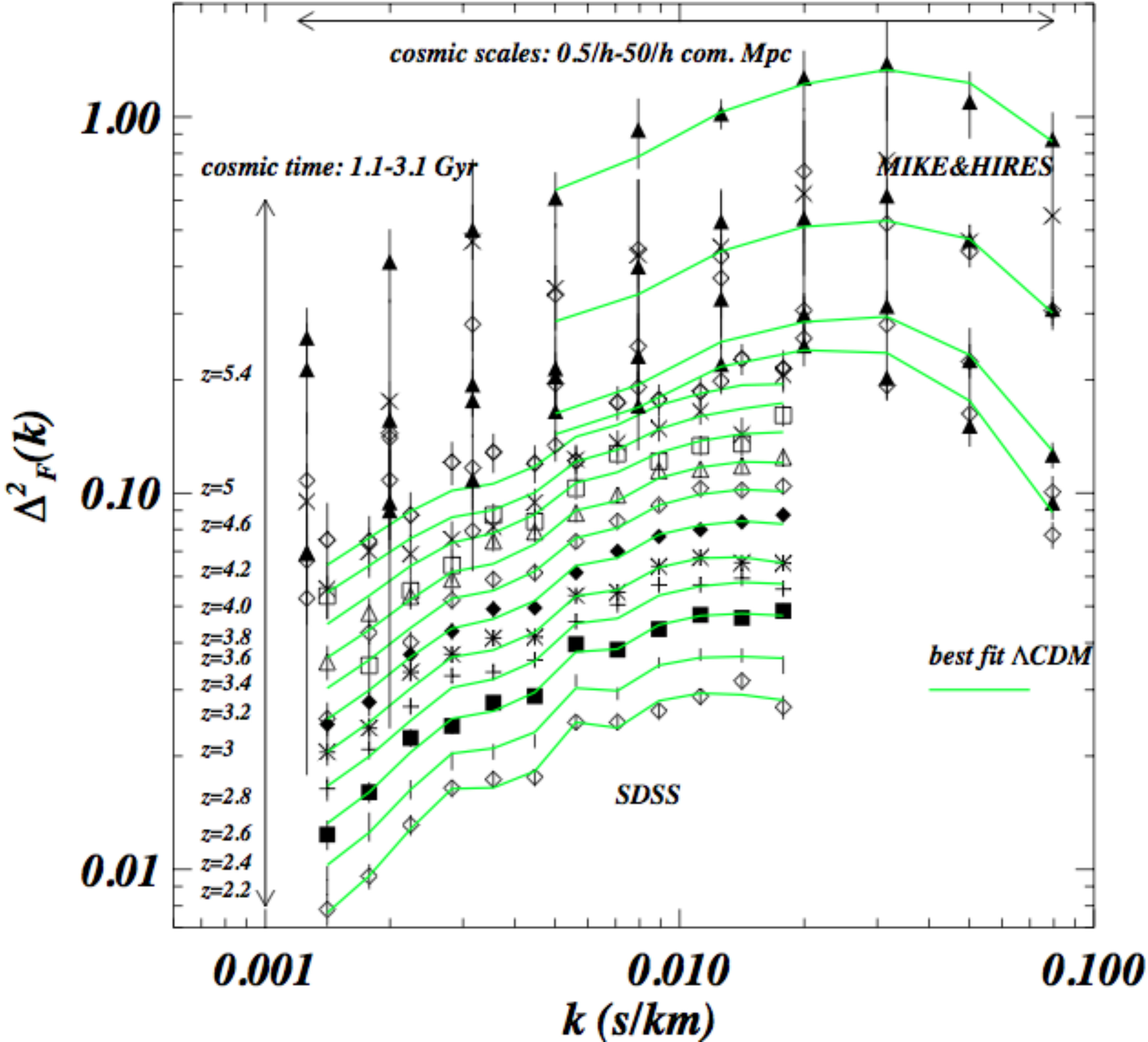


1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)

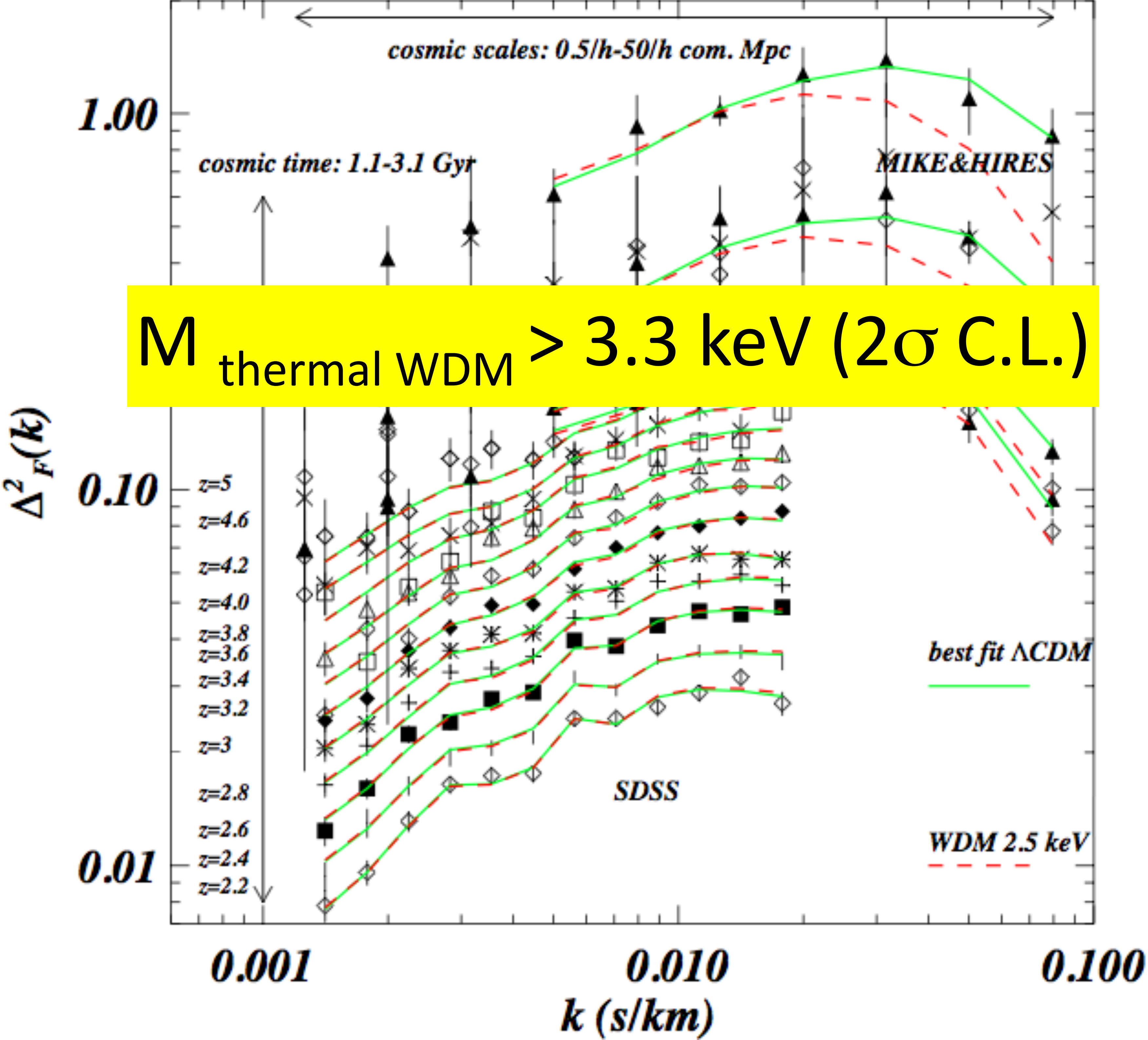

1.00
0.10
0.01
0.001
0.010
0.100
k (s/km)
MIKE&HIRES
SDSS



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



M $_{\text{thermal WDM}}$ > 3.3 keV (2σ C.L.)

Summary

- LCDM has putative problems at small scales could be addressed by baryon physics but also by modifying DM nature

- Topic is interesting per se, even without invoking the "crisis" argument: DM properties at small scales.

- IGM constraints from a new compilation of medium res. + high res; unprecedented tight constraints mainly prior driven

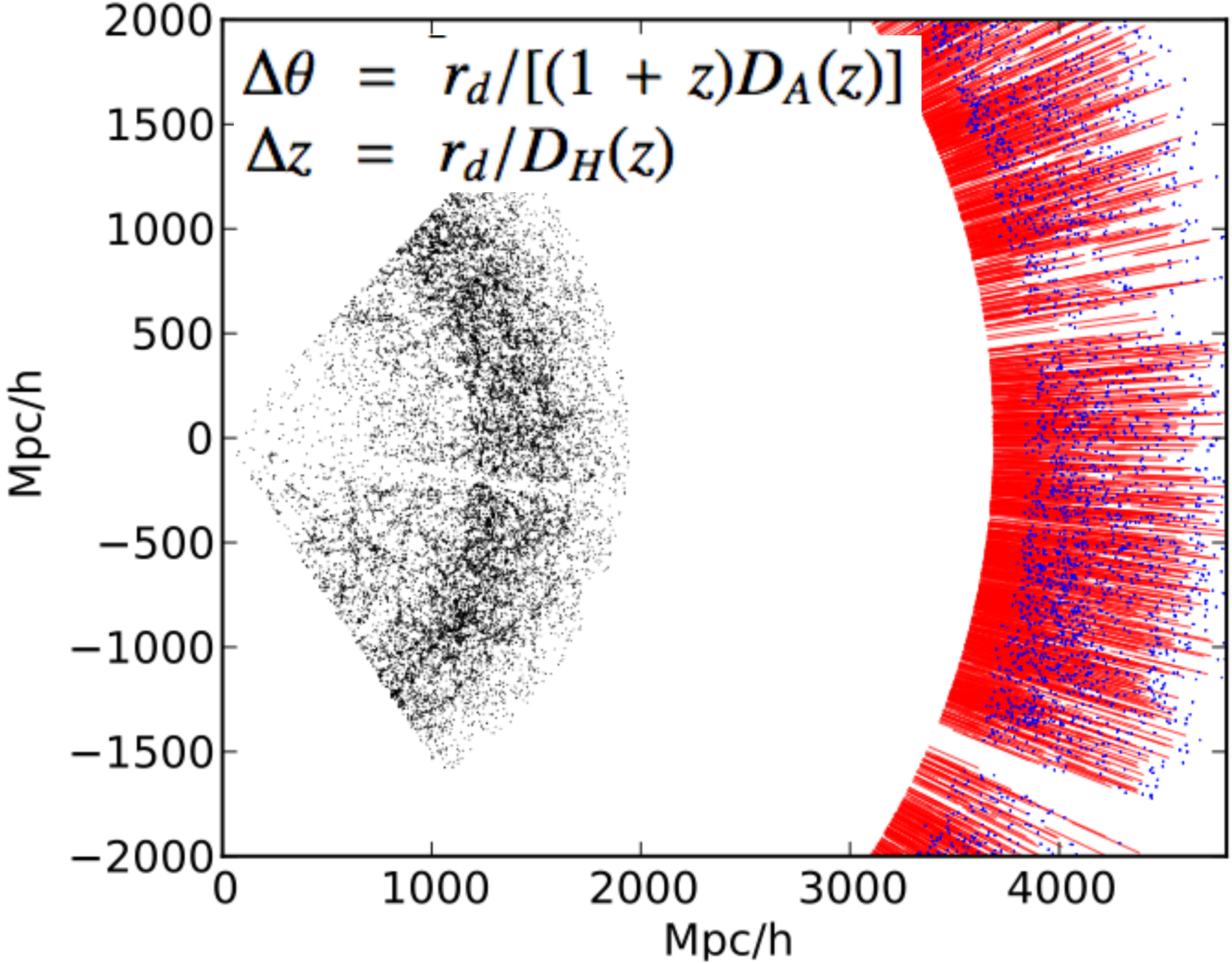
- Fuzzy scalar dark matter also "ruled out": numbers invoked for solving the crisis are too warm for cosmic web of gas at high-z

RESULTS FROM BOSS/SDSS-III

BAOs at z=2.3

SDSS- I

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



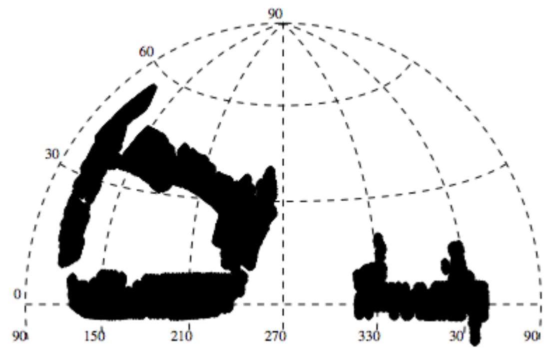
Slosar et al. 11
Busca et al. 13
Slosar et al. 13

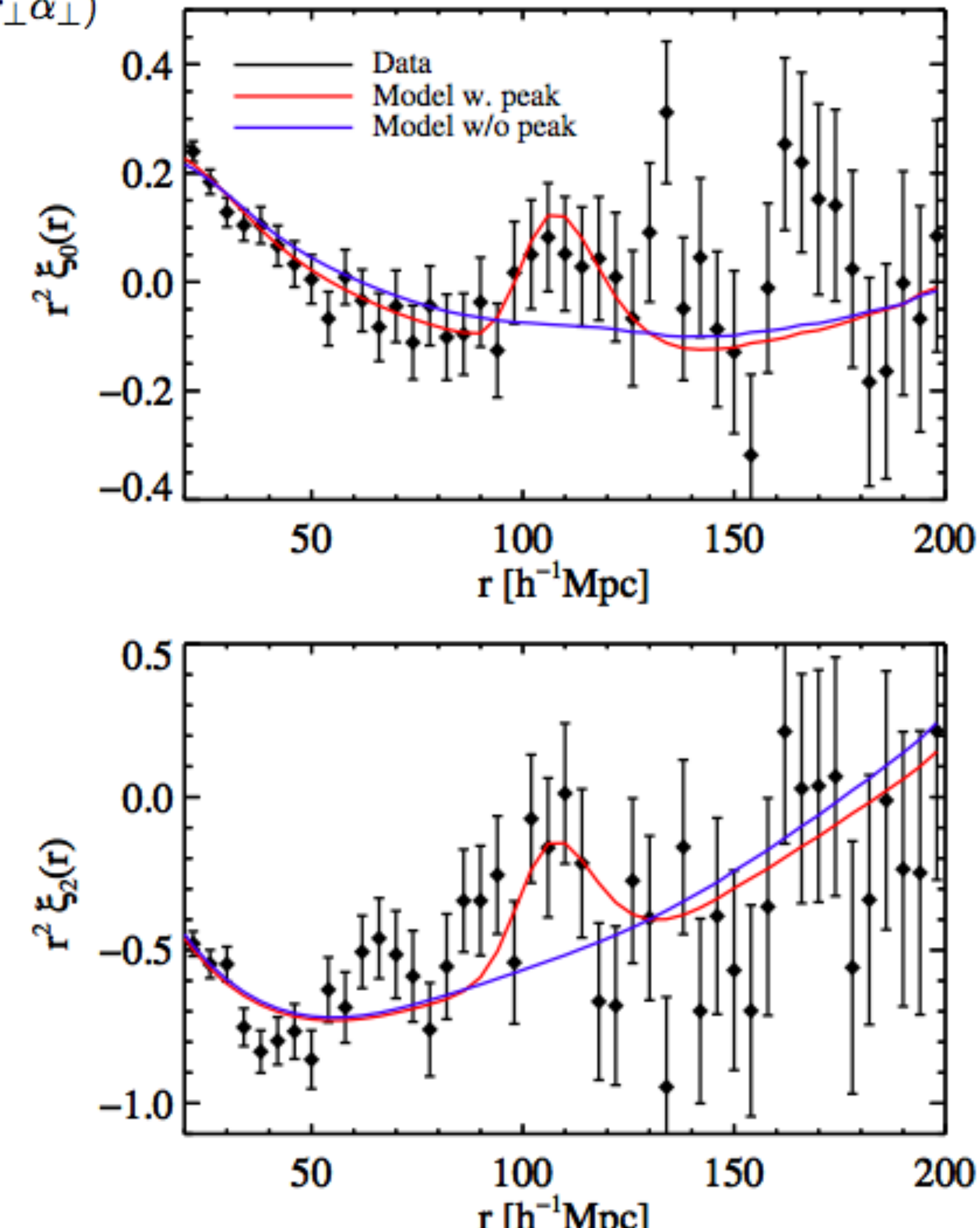
SDSS- II

Busca et al. 13

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

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



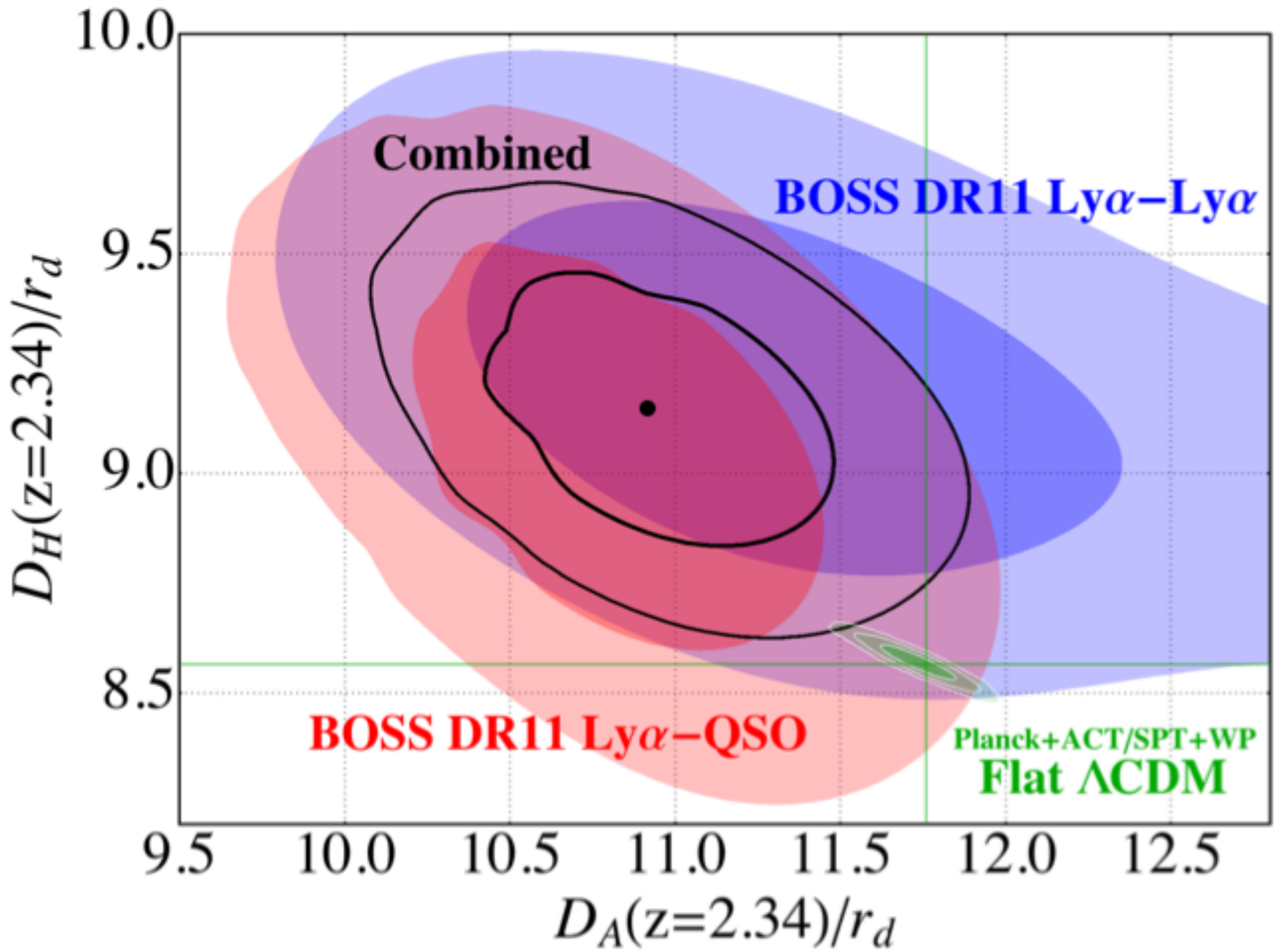


BAO feature detected at z=2.3
From 3000 deg^2, using 50000 QSOs
Significance of the detection at around 3σ

SDSS-III

$$P_{qF}(\mathbf{k}) = b_q \left[1 + \beta_q \mu_k^2\right] b_F \left[1 + \beta_F \mu_k^2\right] P(k)$$

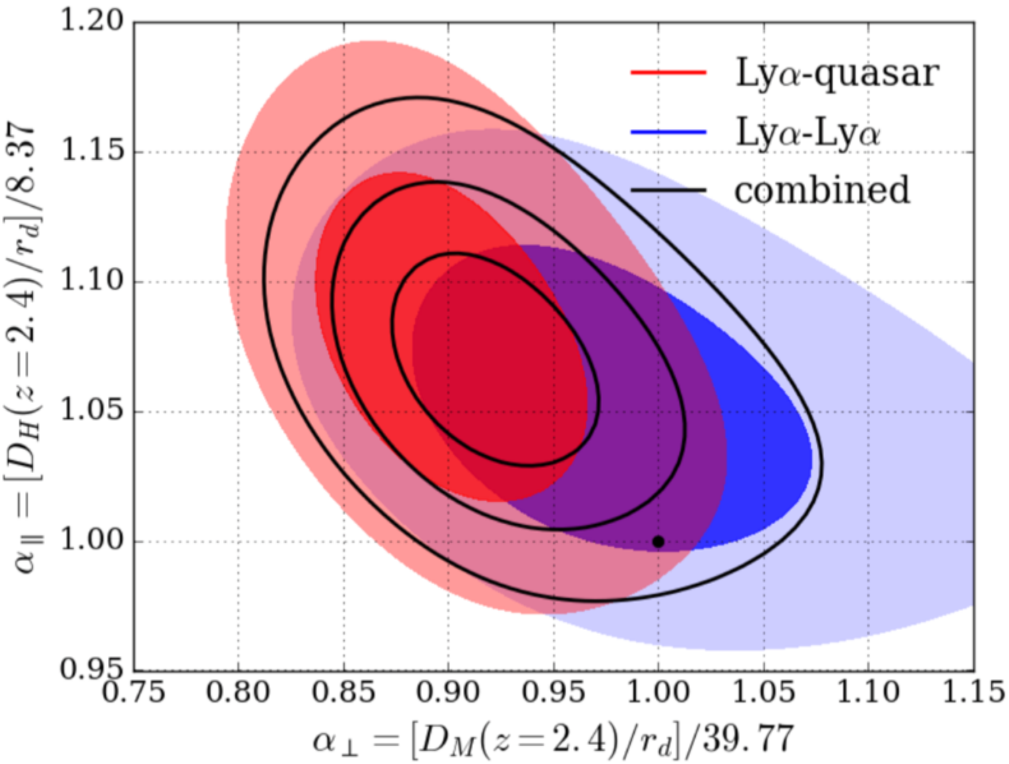
6% precision measurement of D_A/r_d
3% precision measurement of D_H/r_d

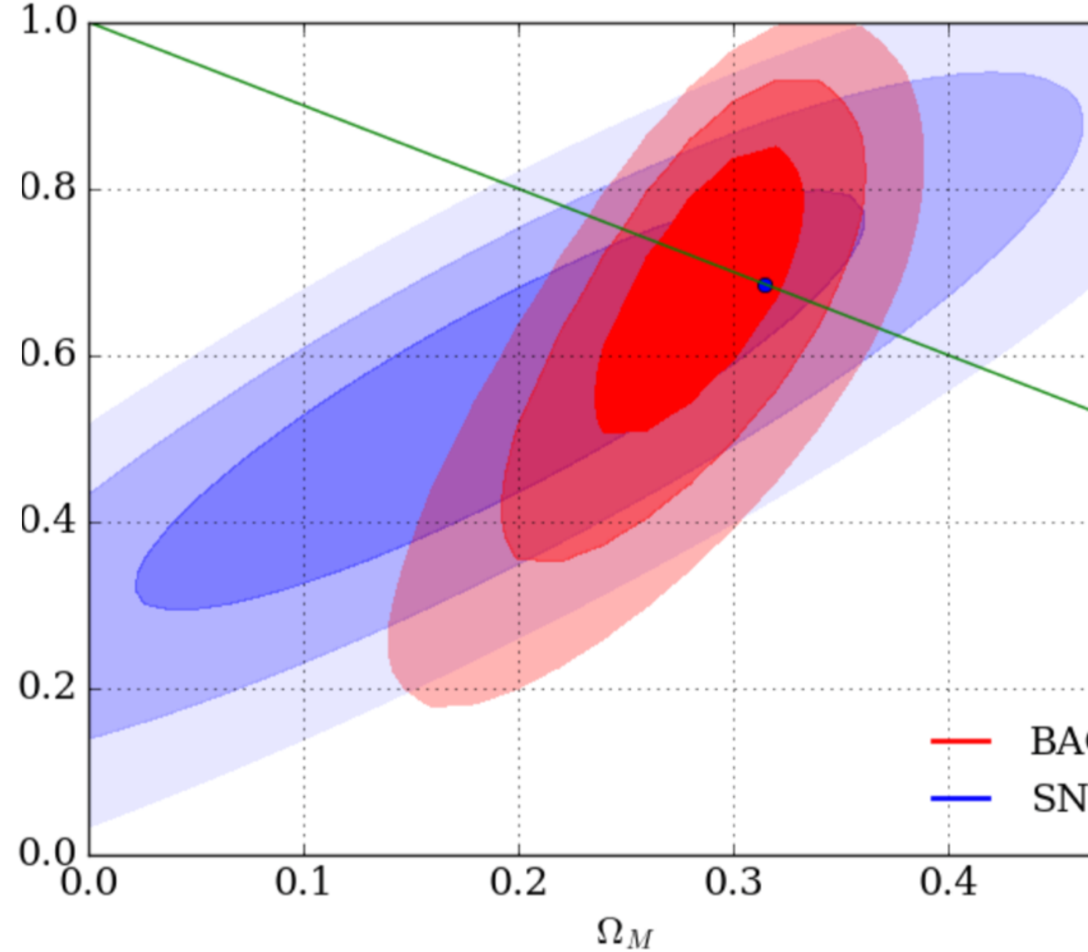


Delubac et al. 14

Latest SDSS results

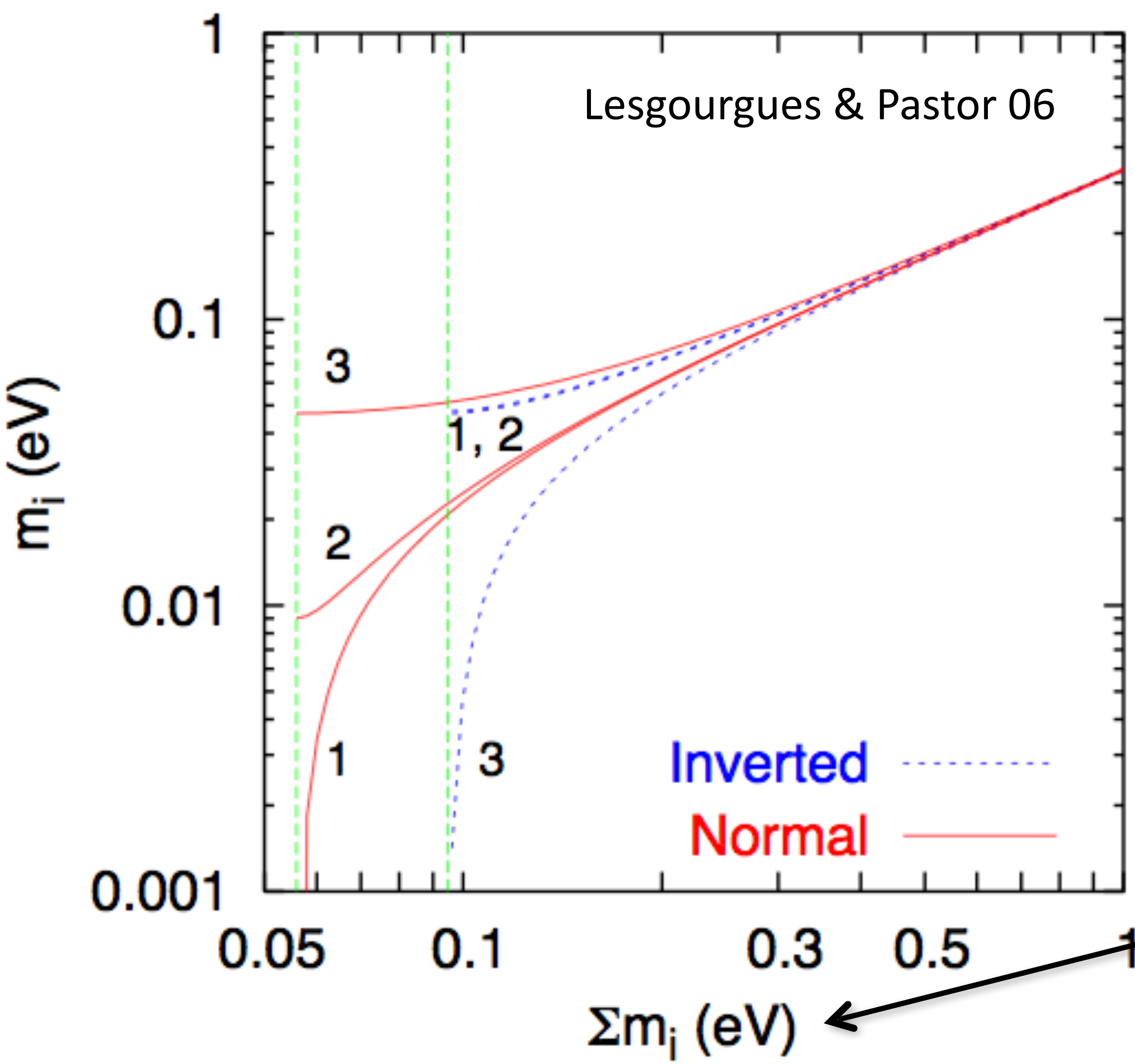
du Mas de Bourboux+ 17





COSMOLOGICAL NEUTRINOS

COSMOLOGICAL NEUTRINOS - I: STARTING POINT



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

$$k_{FS}(t) = \left(\frac{4\pi G\bar{\rho}(t)a^2(t)}{v_{\rm th}^2(t)}\right)^{1/2}$$

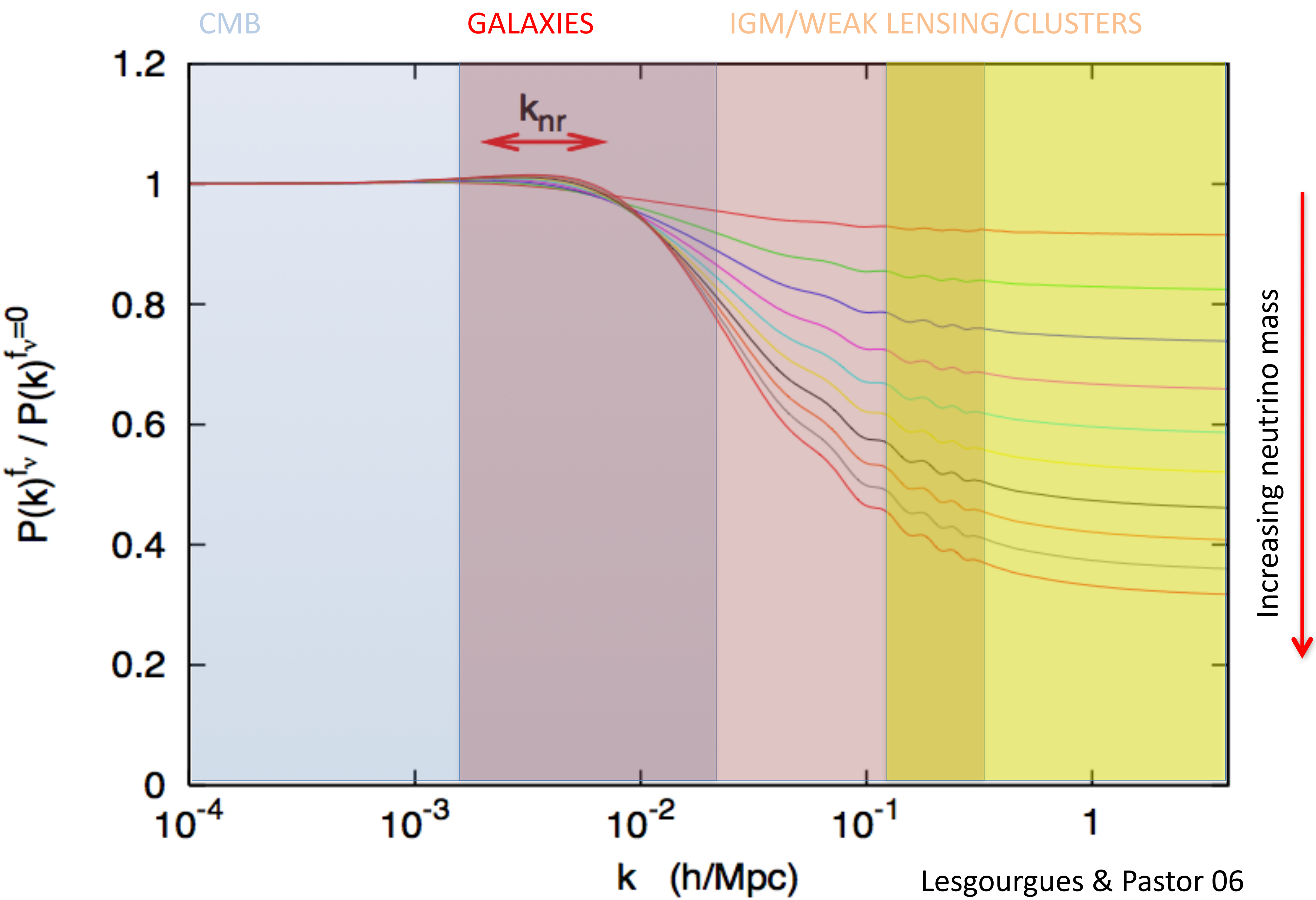
Scale of non-relativistic transition

$$k_{\rm nr} \simeq 0.018\;\Omega_{\rm m}^{1/2}\left(\frac{m}{1\,{\rm eV}}\right)^{1/2} h\,{\rm Mpc}^{-1}$$

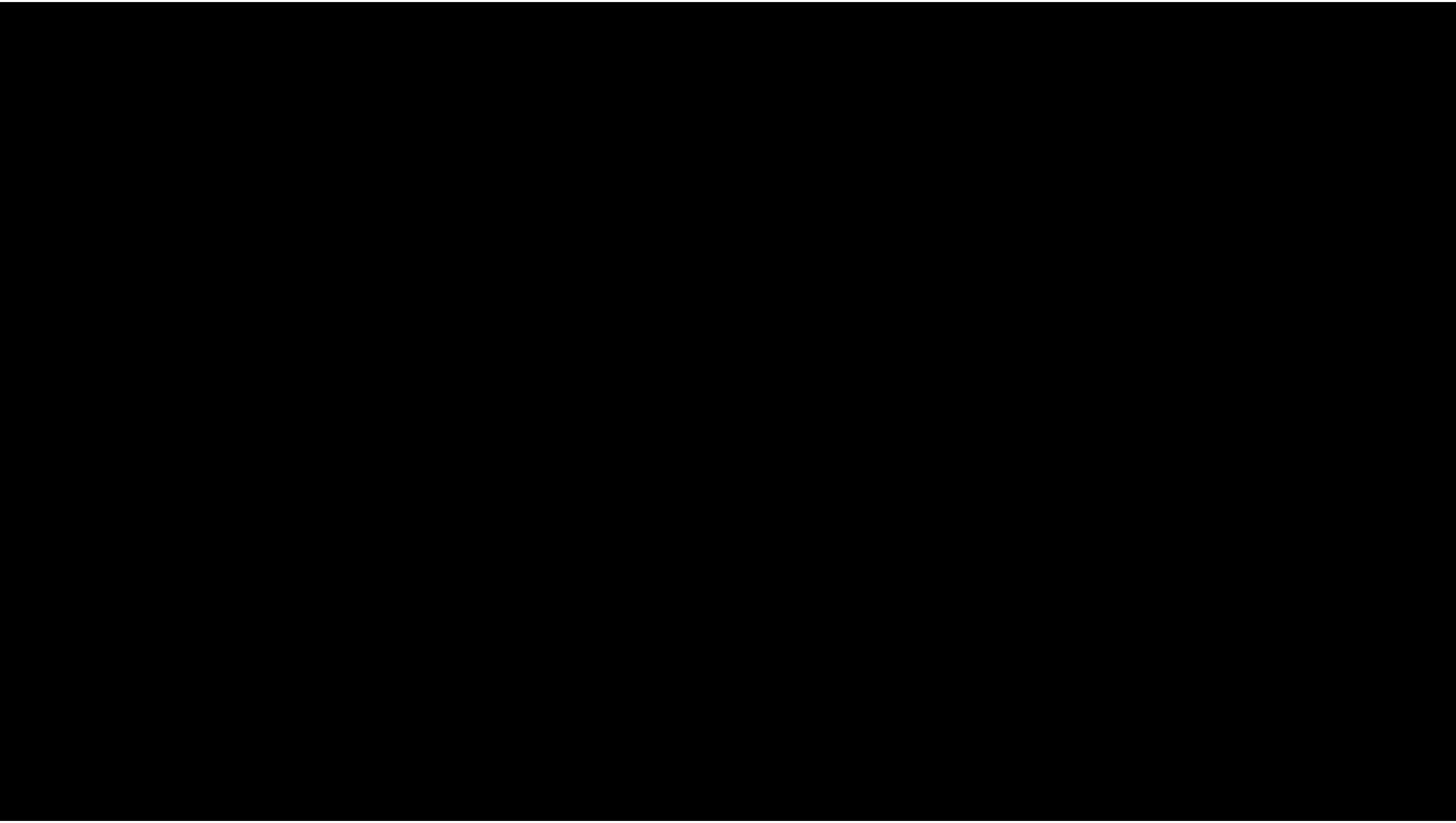
THREE COSMIC EPOCHS	RADIATION ERA z>3400
	MATTER RADIATION z<3400
	NON-RELATIVISTIC TRANSITION z ~ 500

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

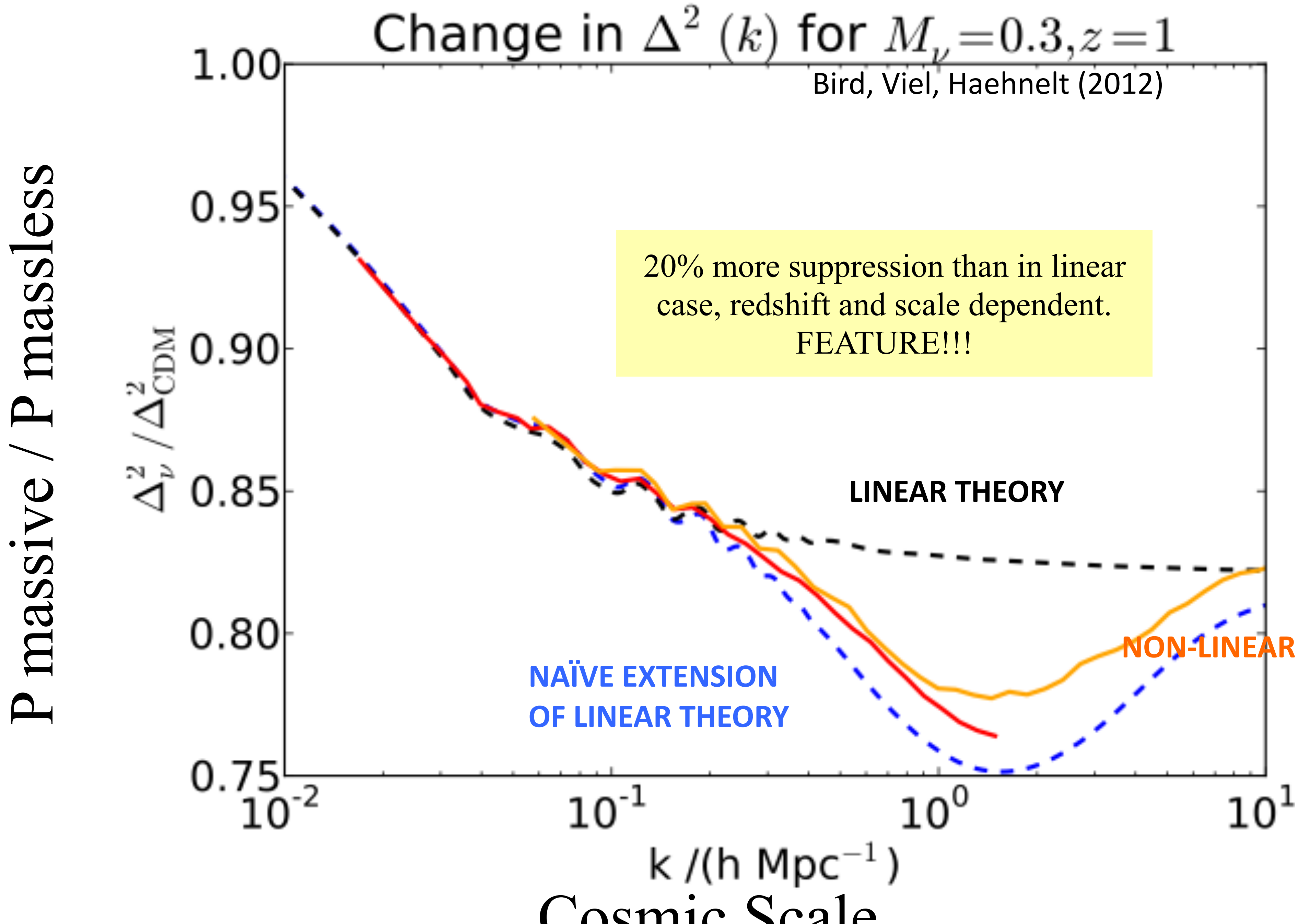
COSMOLOGICAL NEUTRINOS - III: LINEAR MATTER POWER



Lesgourgues & Pastor 06

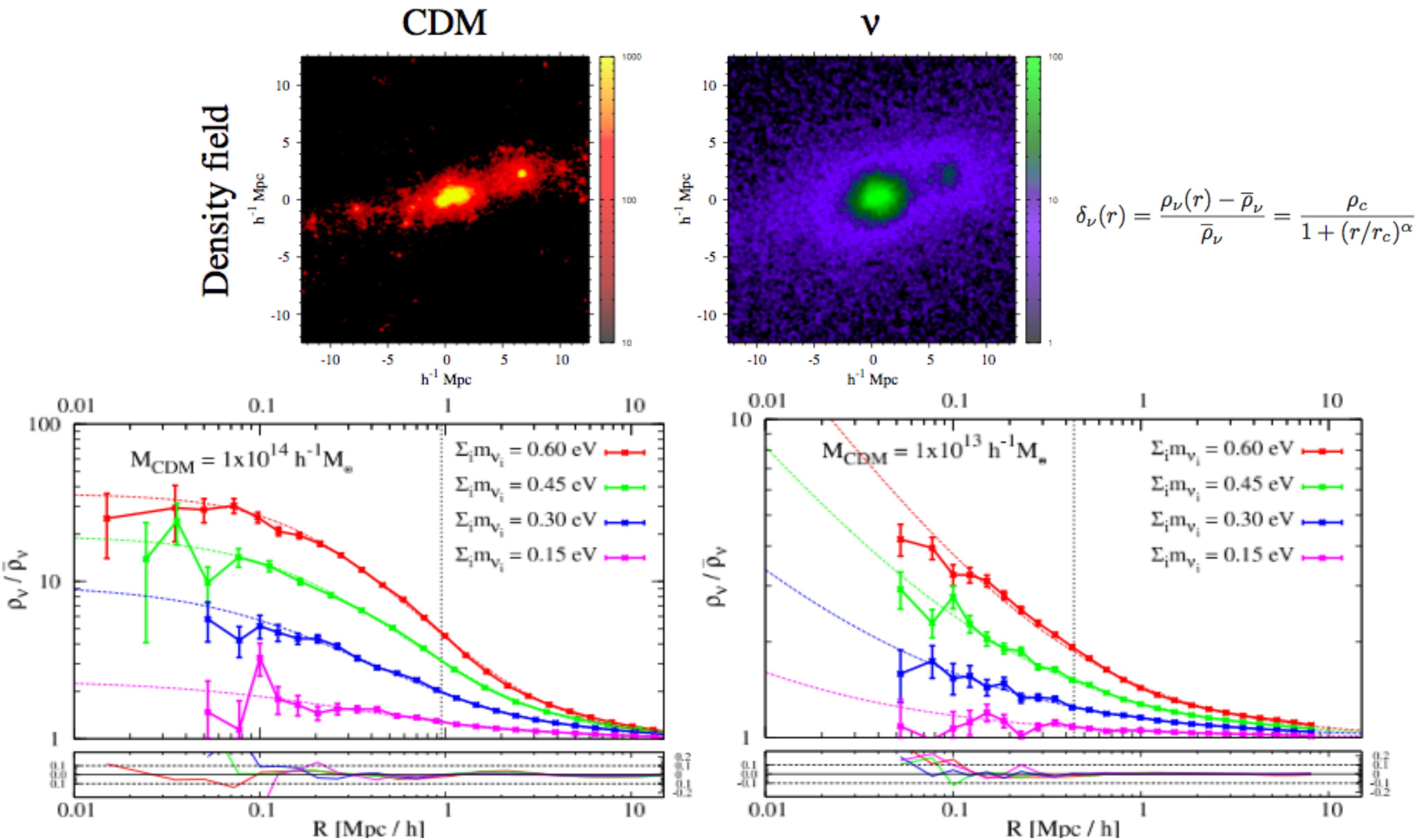


COSMOLOGICAL NEUTRINOS: NON-LINEAR MATTER POWER



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

COSMO NEUTRINOS –III: CHARACTERIZING 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, Viel, 2013, JCAP, 03, 019
Marulli, Carbone, Viel+ 2011, MNRAS, 418, 346

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

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

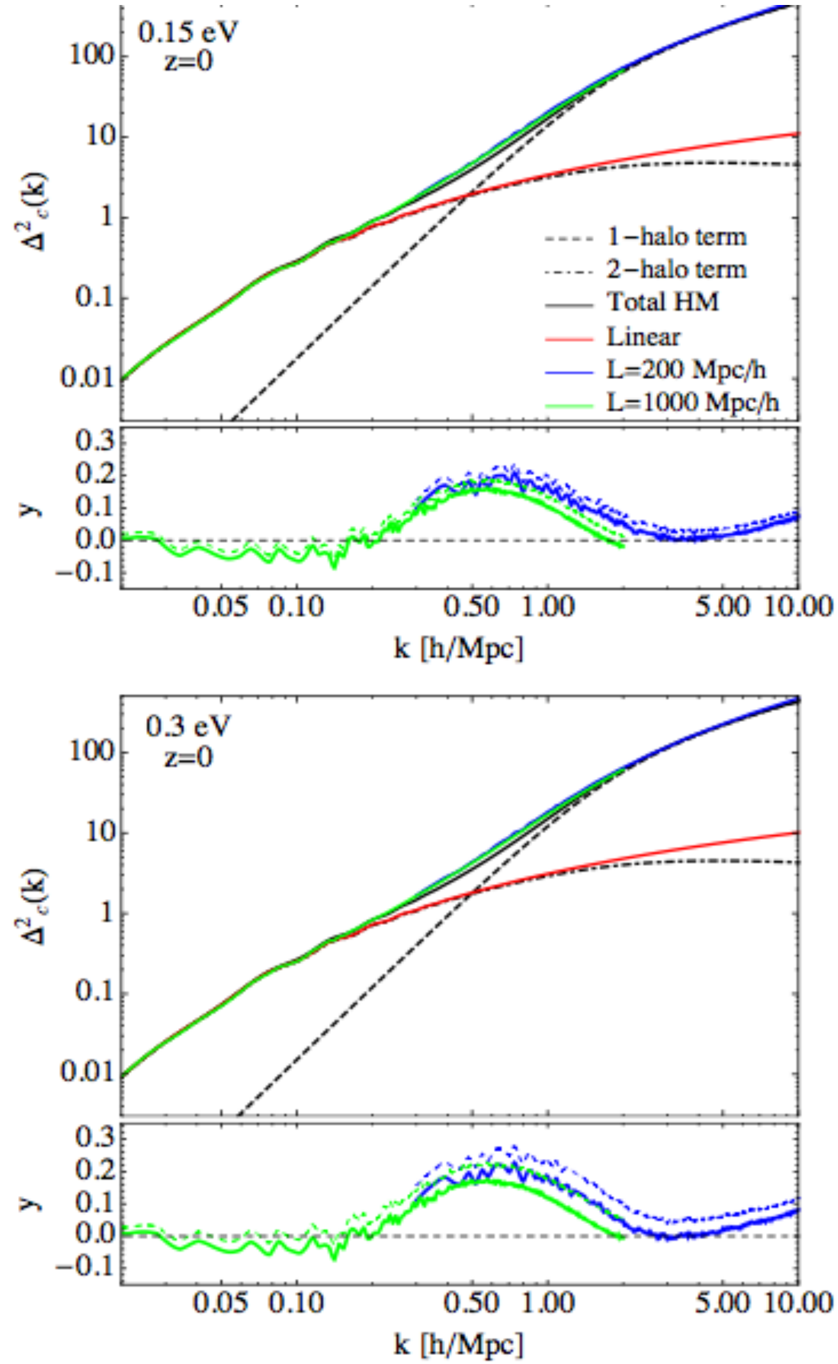
- Assumption: all matter within haloes 1h and 2h terms

- 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

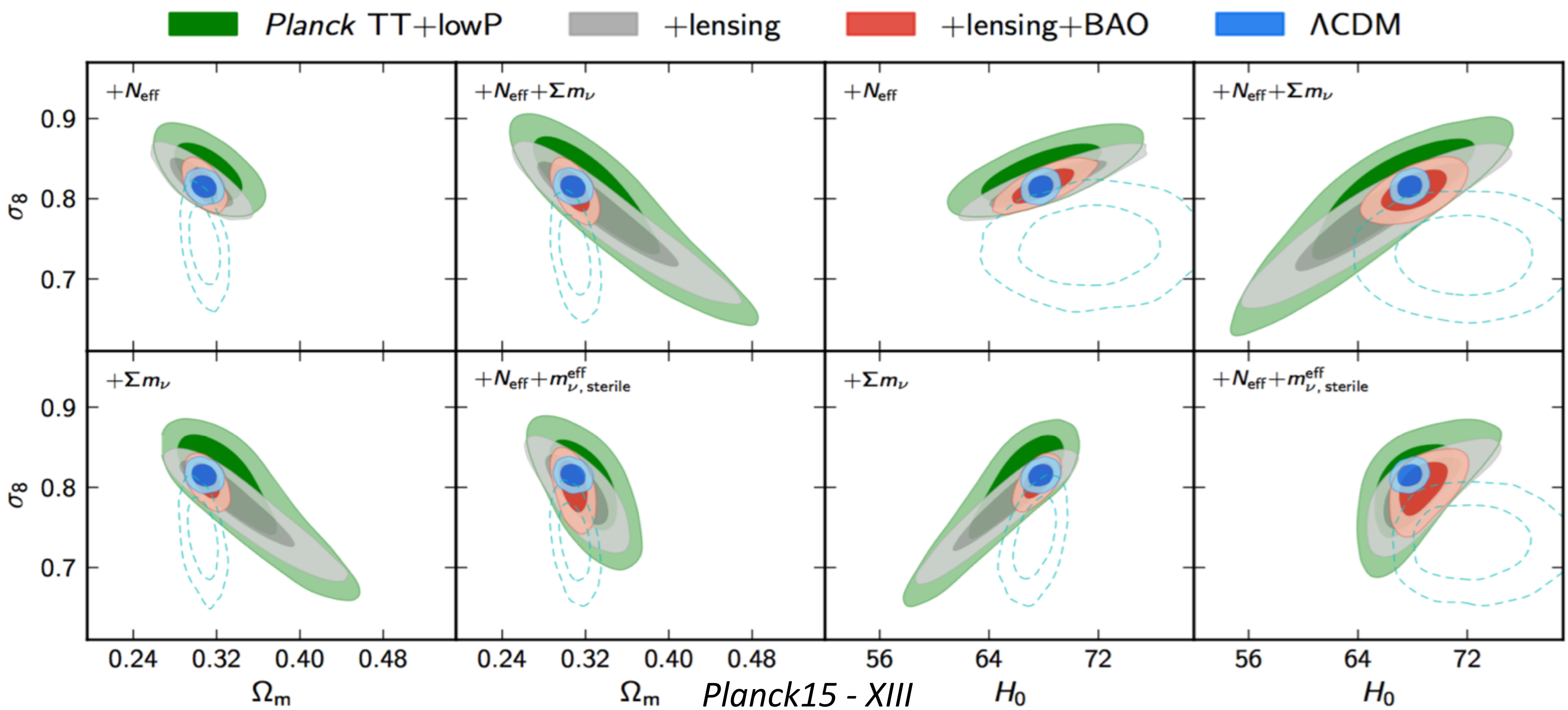
- When used to compute actual power it suffers from limitation and it is good at the 20% level

NON LINEAR POWER SPECTRA



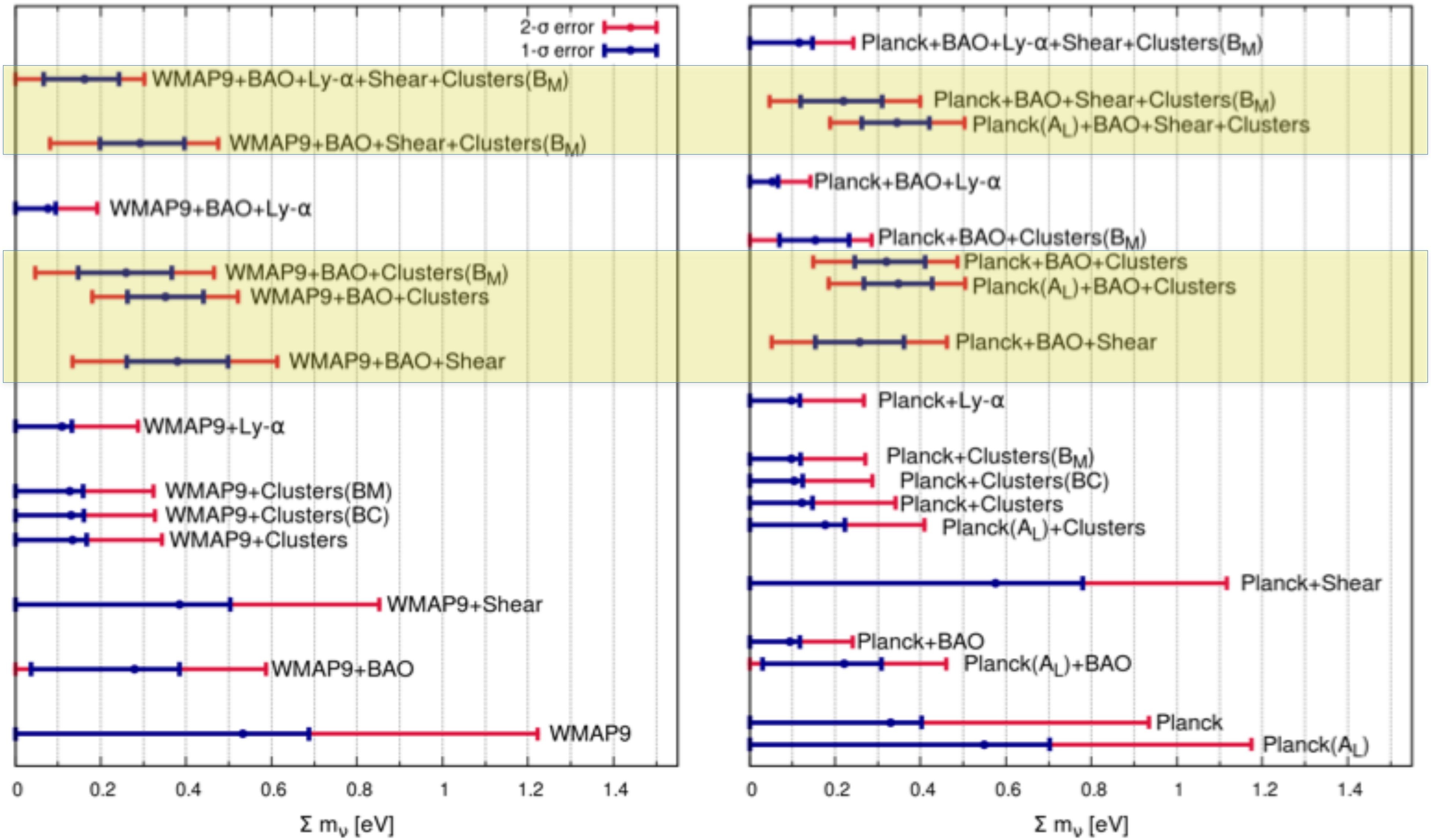
Massara, Villaescusa, MV (2014) – Castorina+ (2014) for bias and mass functions

Departing from LCDM using neutrinos is difficult



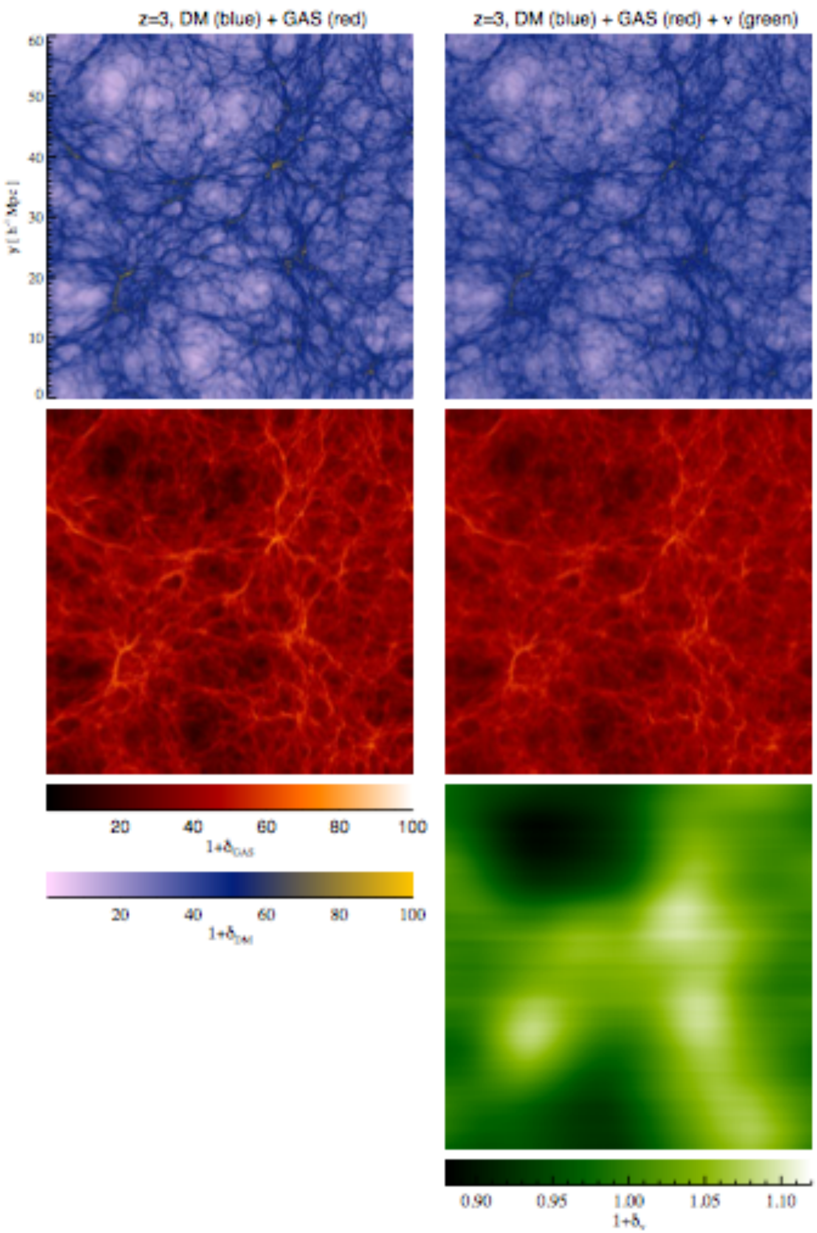
Planck15 - XIII

Claims of non zero neutrino mass 0.3 ± 0.1 eV appear to be a compromise to reconcile low σ_8 values suggested by weak lensing and/or cluster number counts – some is true for the sterile sector.



2-σ error
1-σ error
WMAP9+BAO+Ly-α+Shear+Clusters(BM)
WMAP9+BAO+Shear+Clusters(BM)
WMAP9+BAO+Ly-α
WMAP9+BAO+Clusters(BM)
WMAP9+BAO+Clusters
WMAP9+BAO+Shear
WMAP9+Ly-α
WMAP9+Clusters(BM)
WMAP9+Clusters(BC)
WMAP9+Clusters
WMAP9+Shear
WMAP9+BAO
WMAP9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Σ mν [eV]
Planck+BAO+Ly-α+Shear+Clusters(BM)
Planck+BAO+Shear+Clusters(BM)
Planck(AL)+BAO+Shear+Clusters
Planck+BAO+Ly-α
Planck+BAO+Clusters(BM)
Planck+BAO+Clusters
Planck(AL)+BAO+Clusters
Planck+BAO+Shear
Planck+Ly-α
Planck+Clusters(BM)
Planck+Clusters(BC)
Planck+Clusters
Planck(AL)+Clusters
Planck+Shear
Planck+BAO
Planck(AL)+BAO
Planck
Planck(AL)
Σ mν [eV]

NEUTRINOS IN THE IGM



N-body + hydro sims

Neutrino induced non-linear suppression understood and reproduced also with simple halo modelling (**Massara+ 15**)

Degeneracies with s8 are present

Neutrino induced effects on RSD (Marulli +11), BAOs (Peloso+15), mass functions and bias (Castorina+14) investigated

FROM IGM ONLY:

$\Sigma m_\nu < 0.9$ eV(2σ)

Viel, Haehnelt, Springel 2010
Rossi+ 14, Villaescusa-Navarro+14

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)

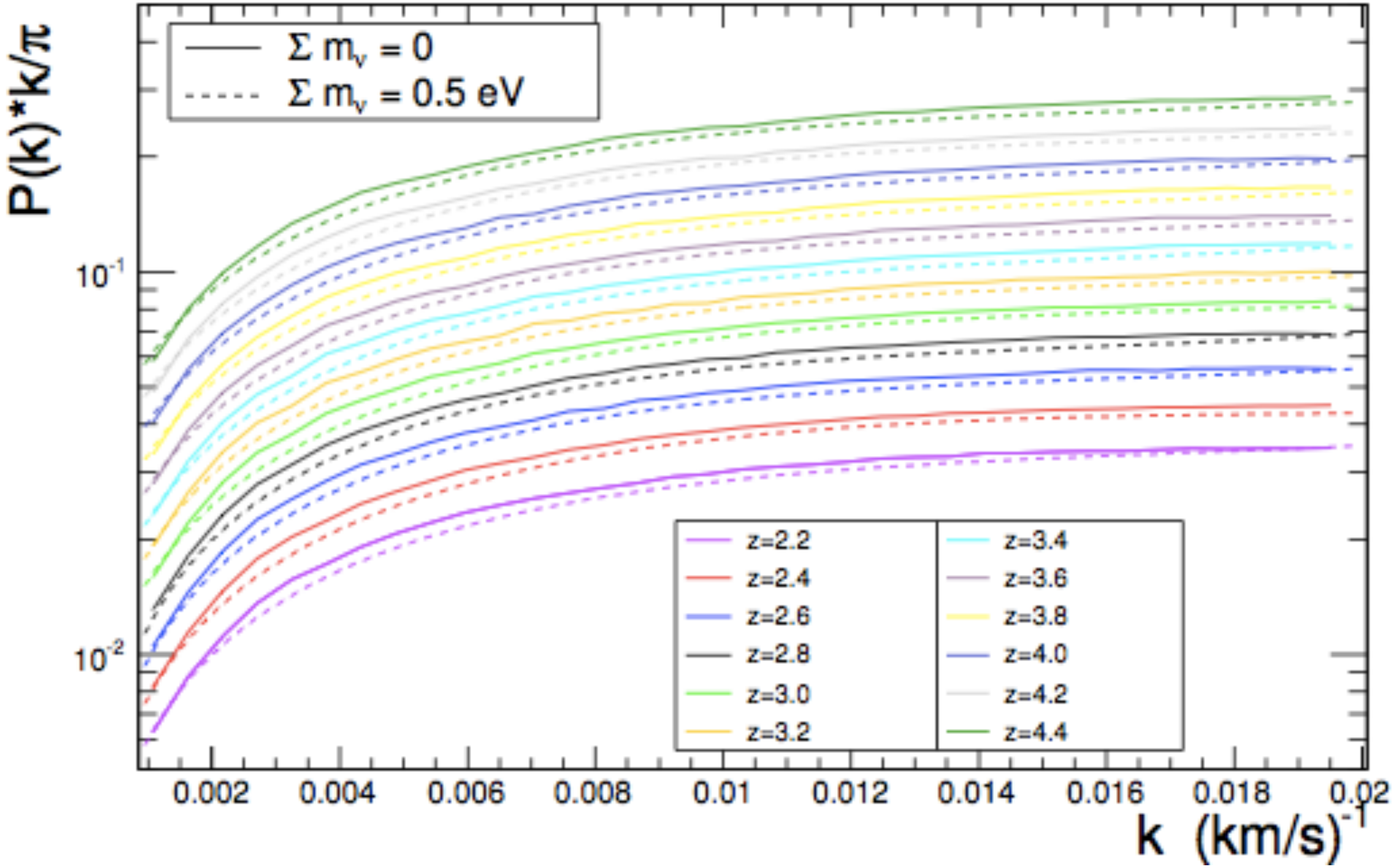
Cosmology parameters: σ_8, n_s, Ω_m, H_0, m_{WDM}, + neutrino mass
Astrophysical parameters: z_{reio}, UV fluctuations, T_0, γ, <F>
Nuisance: resolution, S/N, metals

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

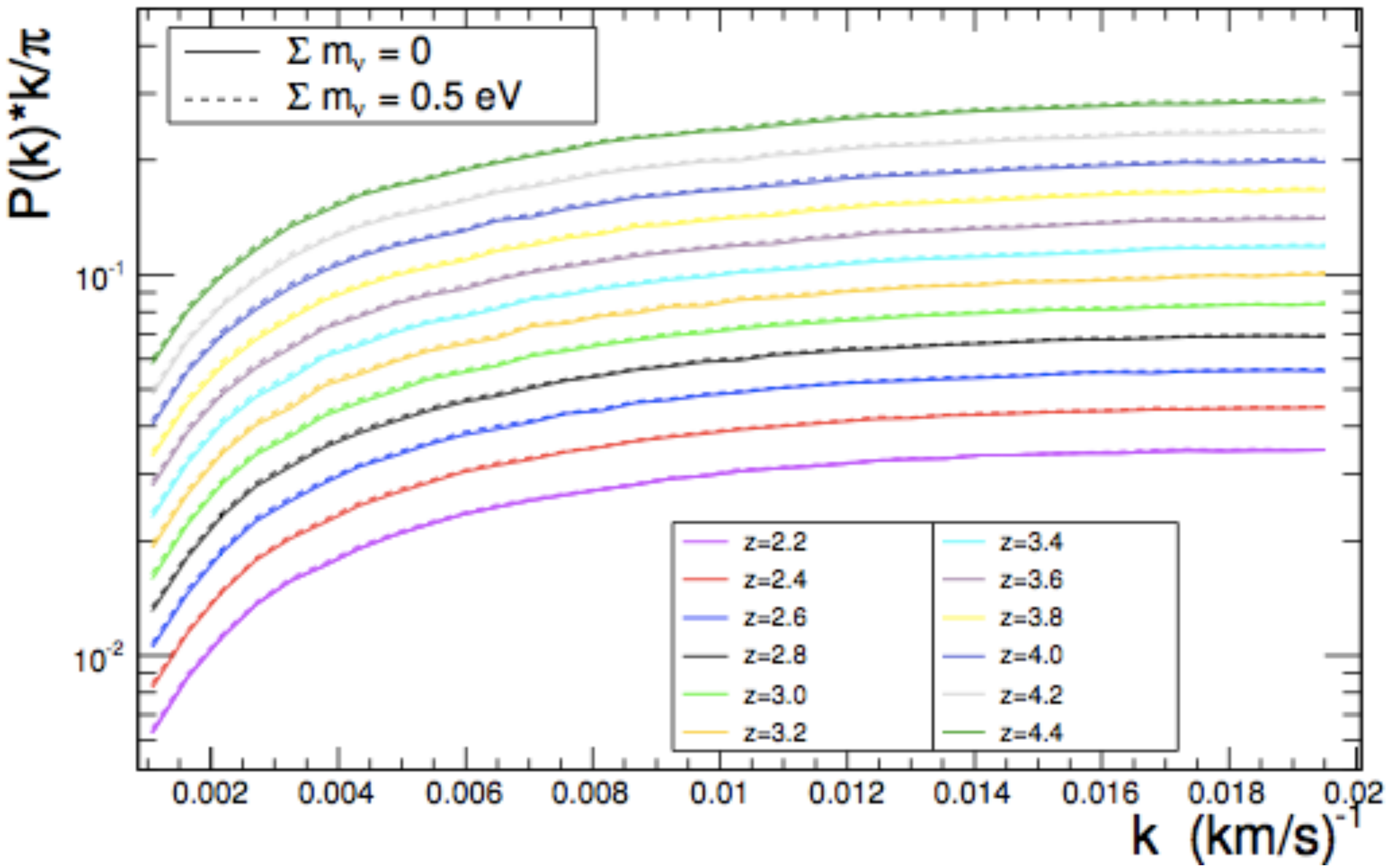
Parameter space: second order Taylor expansion of the flux power

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

NEUTRINO IMPACT - I



NEUTRINO IMPACT - II

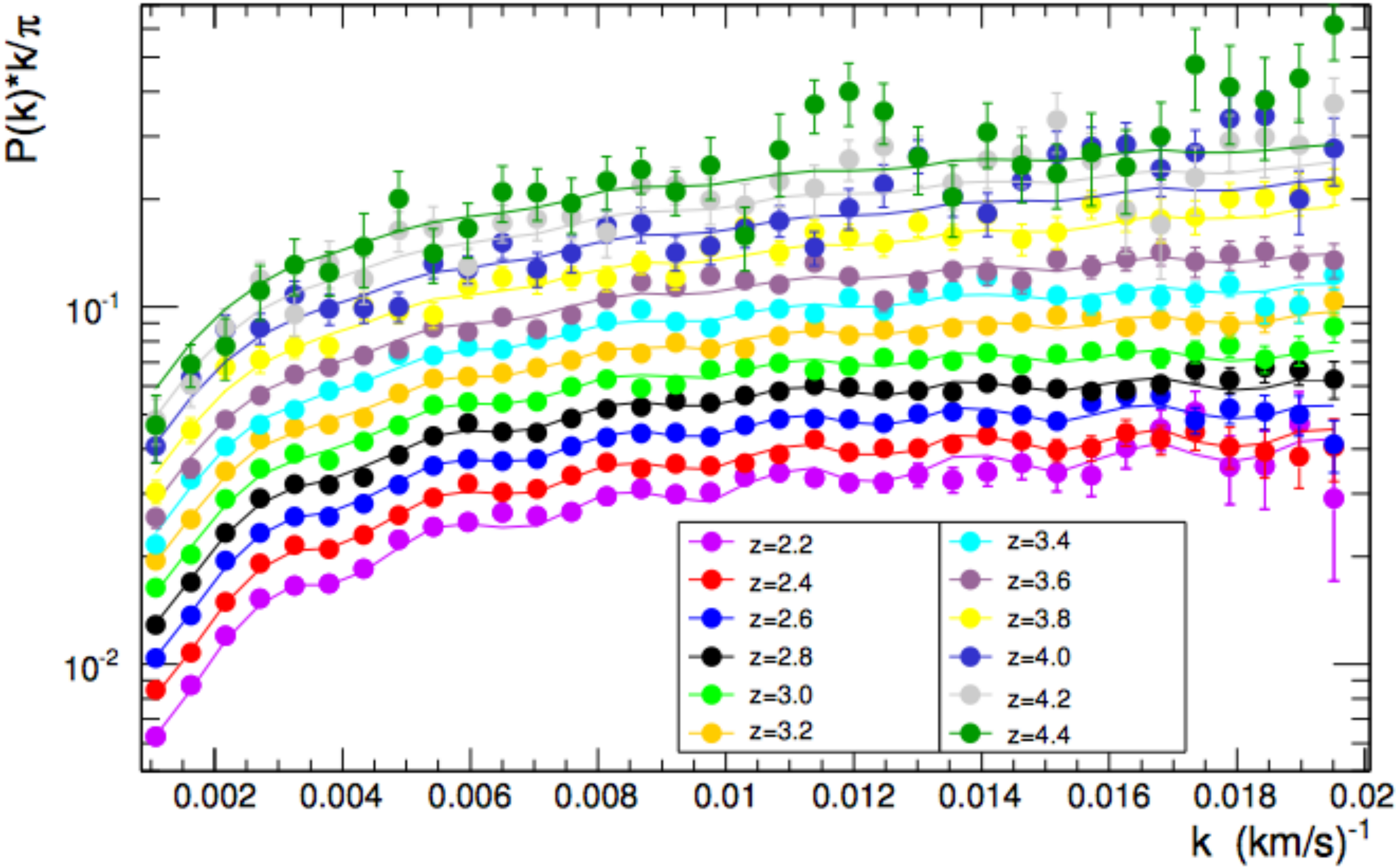


GROWTH OF STRUCTURES AT HIGH REDSHIFT

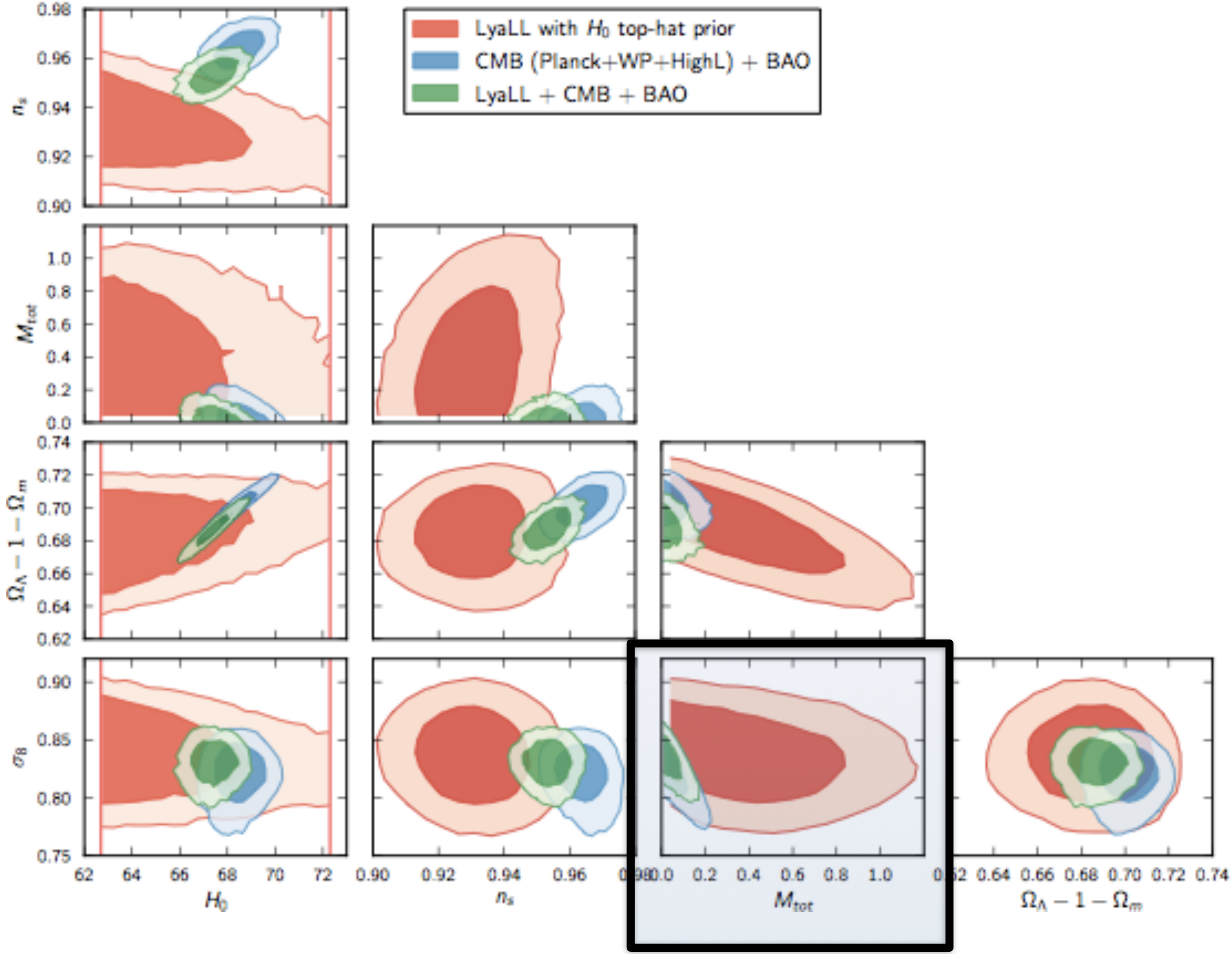
Constraint on neutrino masses from SDSS-III/BOSS Lyα forest and other cosmological probes

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]

1D Flux power spectrum evolution



BAYESIAN ANALYSIS



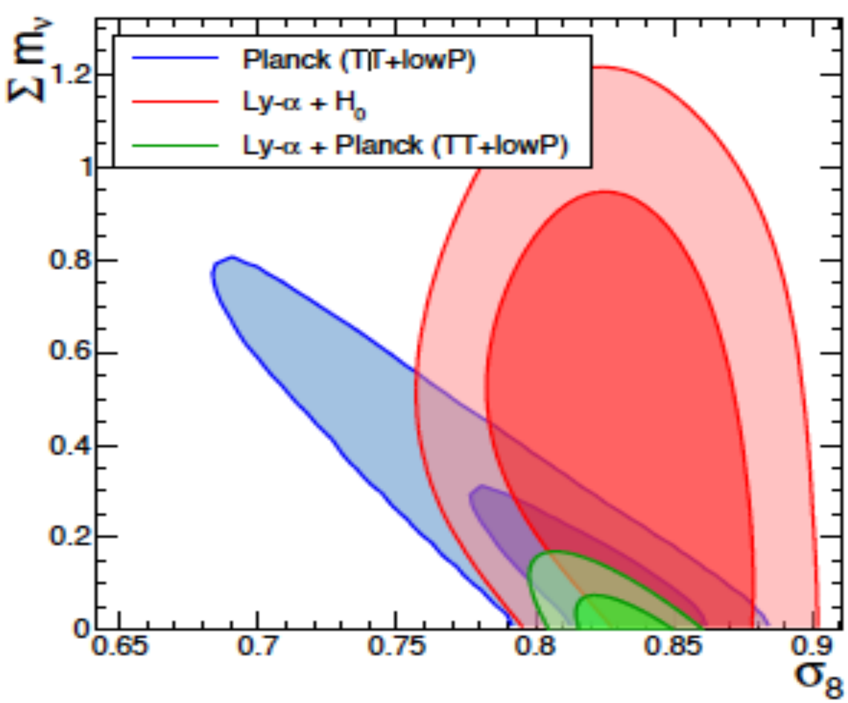
FINAL NUMBERS

Parameter	Lyα + $H_0^{\rm tophat}$ ($62.5 \le H_0 < 72.5$)	Lyα + CMB	Lyα + CMB + BAO	Lyα + CMB(A_L)
$10^9 A_s$	$3.2^{+0.5}_{-0.7}$	$2.20^{+0.05}_{-0.06}$	$2.20^{+0.05}_{-0.06}$	$2.18^{+0.05}_{-0.06}$
$10^2 \omega_{\rm b}$	(fixed to 2.22)	2.20 ± 0.02	2.20 ± 0.02	2.22 ± 0.03
$\omega_{\rm cdm}$	$0.110^{+0.008}_{-0.013}$	$0.1200^{+0.0019}_{-0.0018}$	$0.1196^{+0.0015}_{-0.0014}$	0.1191 ± 0.002
$\tau_{\rm reio}$	(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	$0.830^{+0.017}_{-0.013}$	$0.830^{+0.016}_{-0.012}$	$0.818^{+0.021}_{-0.014}$
$\Omega_{\rm m}$	$0.316^{+0.018}_{-0.021}$	0.316 ± 0.012	0.313 ± 0.009	0.312 ± 0.013

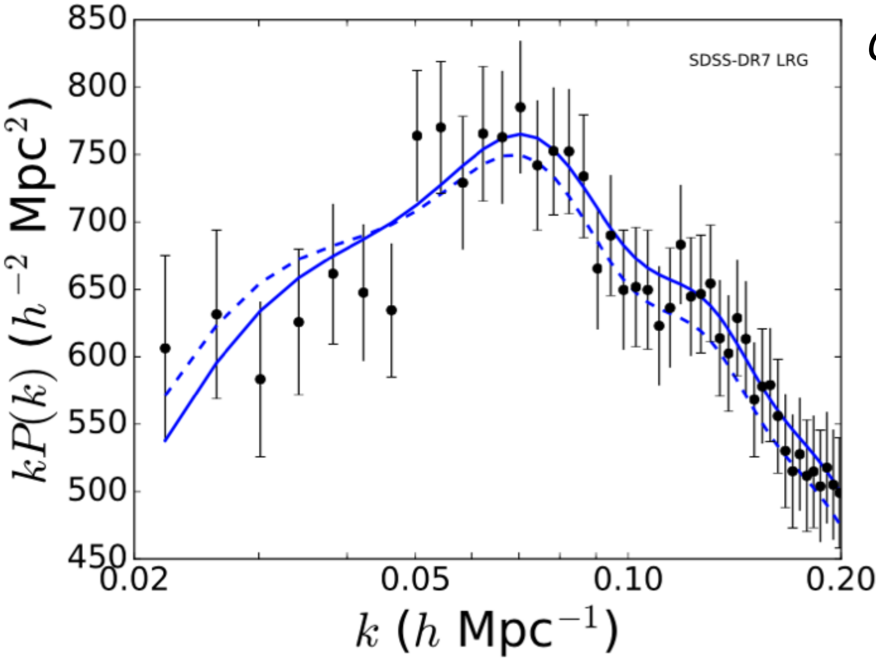
UPDATE using Planck 15

Palanque-Delabrouille+15 arxiv: 1506.05976

Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO	(4) Lyα + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014	0.311 ± 0.007
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1	67.7 ± 0.6
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)	< 0.12 (95% CL)
Reduced χ^2	0.99	1.04	1.05	1.05



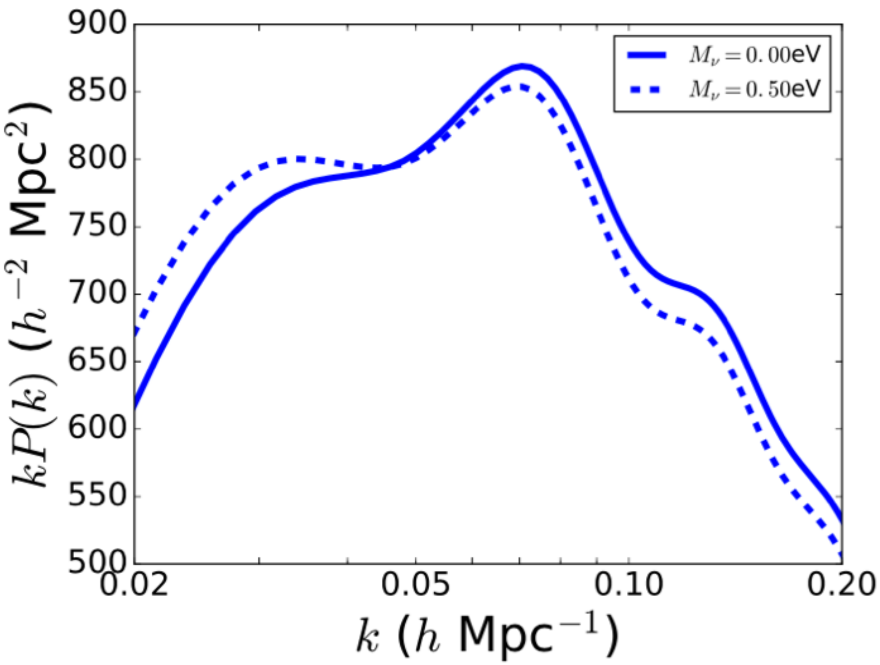
Constraints from galaxy clustering



Cuesta+16

•Galaxy clustering offers independent constraints that mainly exploit the shape

•Notice: galaxy bias Pgal=b^2 x Pmatter marginalized over but some assumptions on the bias b(k,z) model must be made



Parameter	CMB15+LRG+BAO
$100\ \omega_b$	$2.236^{+0.014}_{-0.014}$
$\omega_{\rm cdm}$	$0.1183^{+0.0012}_{-0.0011}$
n_s	$0.9677^{+0.0042}_{-0.0045}$
$\tau_{\rm reio}$	$0.083^{+0.016}_{-0.017}$
$ln(10^{10}A_s)$	$3.097^{+0.031}_{-0.034}$
H_0	$68.06^{+0.55}_{-0.55}$
σ_8	$0.831^{+0.016}_{-0.015}$
M_ν [eV]	< 0.13

THE LOW REDSHIFT EVOLUTION OF THE LYMAN-ALPHA FOREST

OUTLINE

- Comparison between high-redshift and low-redshift neutral hydrogen
- Low-redshift cosmic web in HI: properties from sims
- Comparison with COS data
- Consequences in terms of Galaxy/IGM interplay
- Summary

taken mainly from the following 3 papers:

Bolton+ MNRAS, 464, 1 (2017)
Viel+ MNRAS L., 467, 86 (2017)
Nasir+ MNRAS, in press, eprint arXiv:1706.04790

INTRO

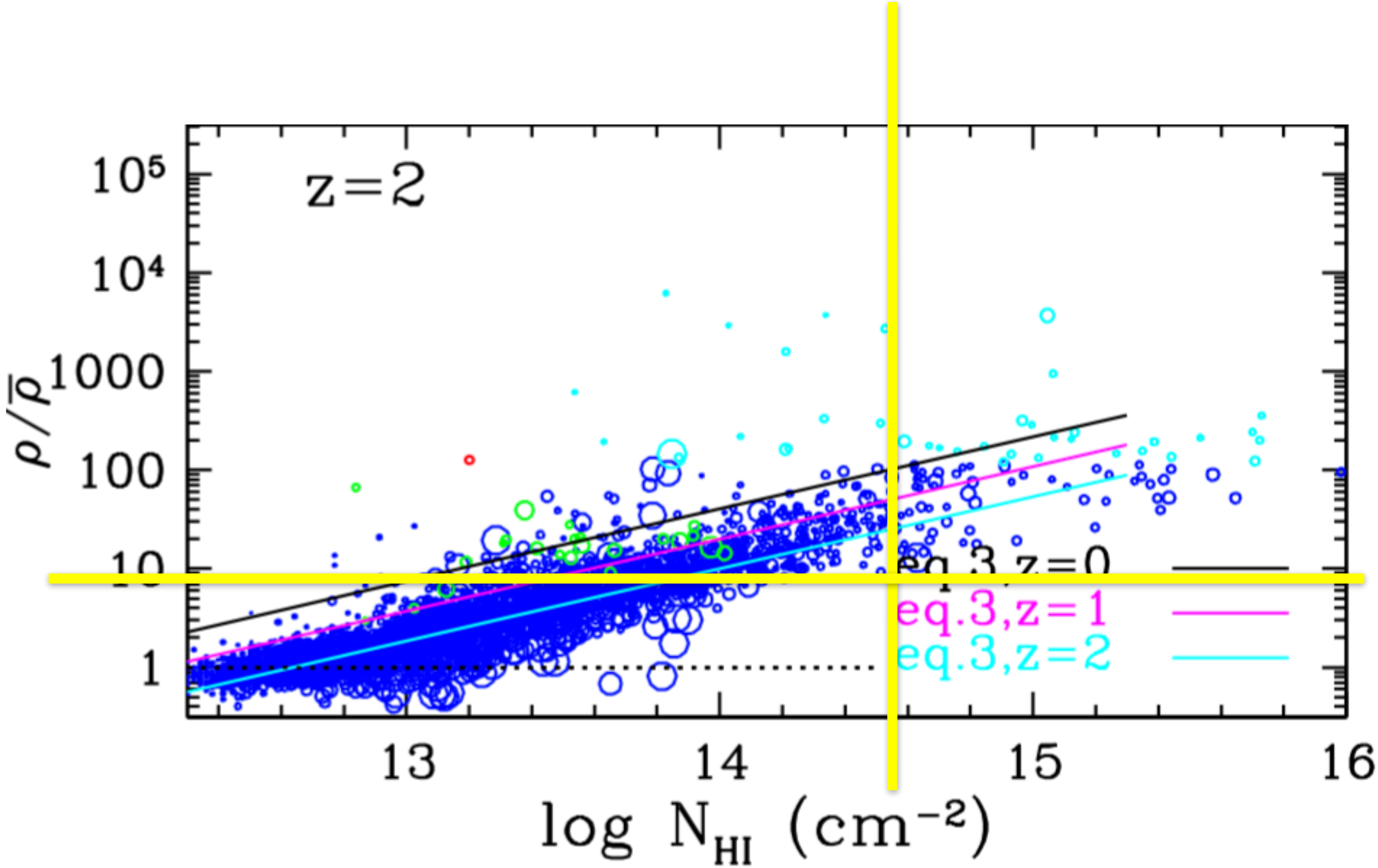
In general the Lyman-α flux in the local universe is a complicated non-linear function that depends on UV background, IGM temperature, underlying density field, peculiar velocities.

The bias between flux and matter evolves strongly with redshift and the same Lyman-α line **traces different environments at different cosmic times.**

$$\delta_{\rm H} \equiv \frac{\rho}{\bar{\rho}_{\rm H}} \sim 20 \left[\frac{N_{\rm H\,I}}{10^{14}\ {\rm cm}^{-2}} \right]^{0.7} 10^{-0.4z}$$

Theuns et al. 98
Dave’ et al. 1999,2010
Schaye 2001

Gas densities vs column densities



Dave' et al. 2010

The link between the low-redshift and high-redshift forest

Low-redshift forest

~30% of the baryons reside in it and fills a significant but smaller (compared to high z) fraction of the volume of the Universe

Quite non-linear regime

Photoionized by QSOs and galaxies

feedback probe/UV probe
Baryons studies/CGM
Cosmological use mainly prevented by too low statistics

High-redshift forest

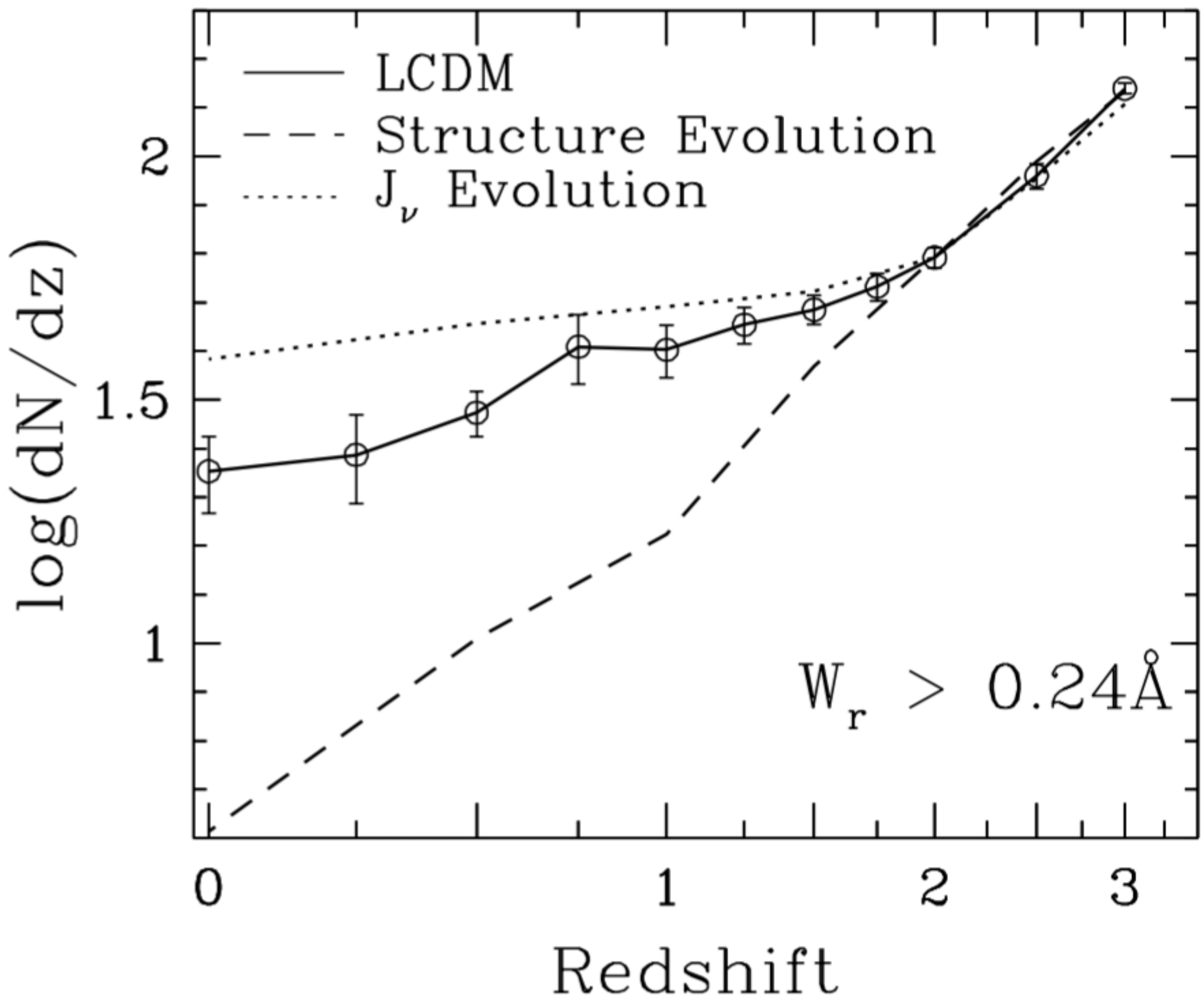
Most of the baryons (80% in mass) reside in it and fills a significant part of the volume of the Universe

Mildly non-linear regime:
Optical depth in HI "faithful" tracer of underlying matter field

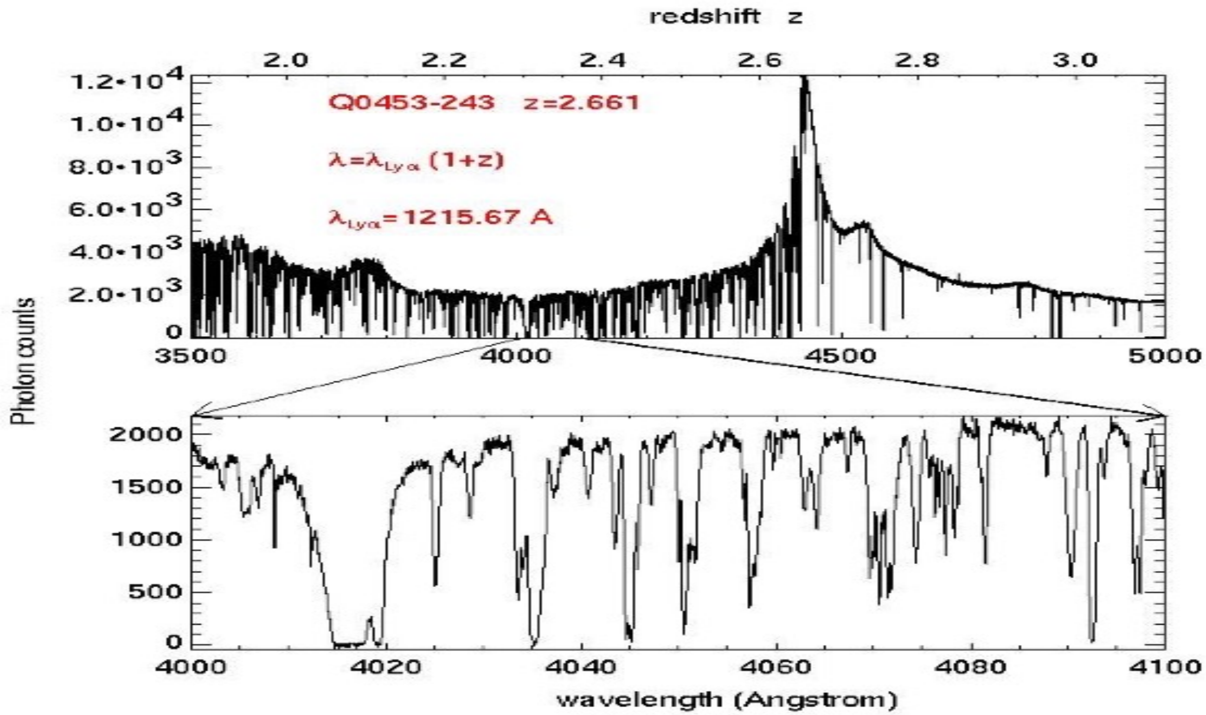
Photoionized by QSOs and galaxies

Cosmological probe (matter clustering)
Galaxy/IGM interplay

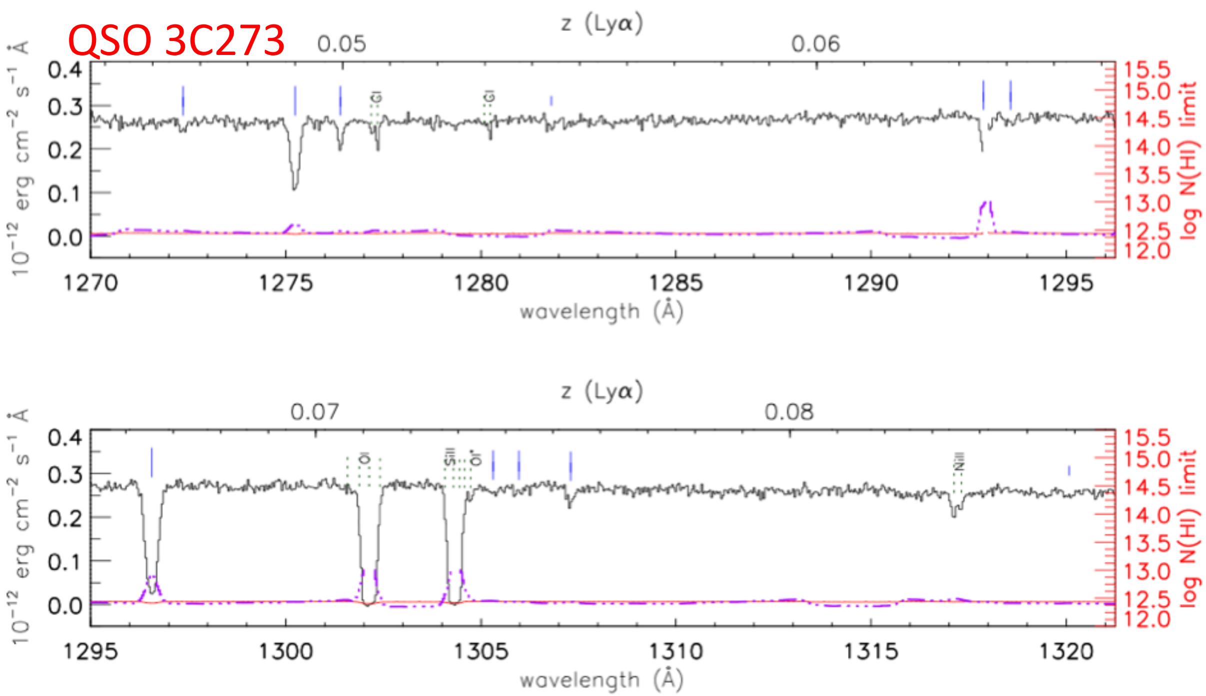
Redshift evolution in LCDM context



Dave'+99,10

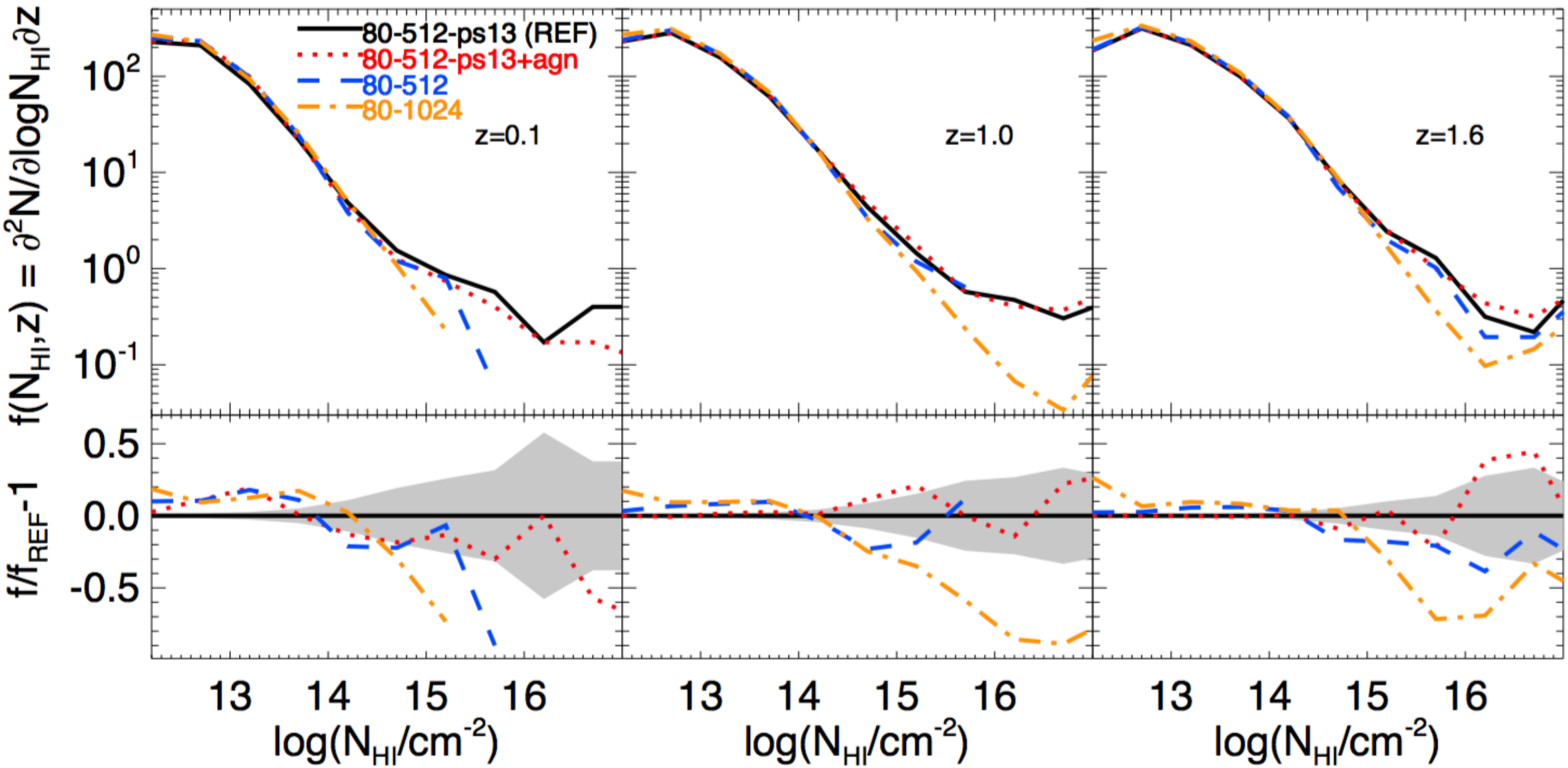


Kim et al. 2004



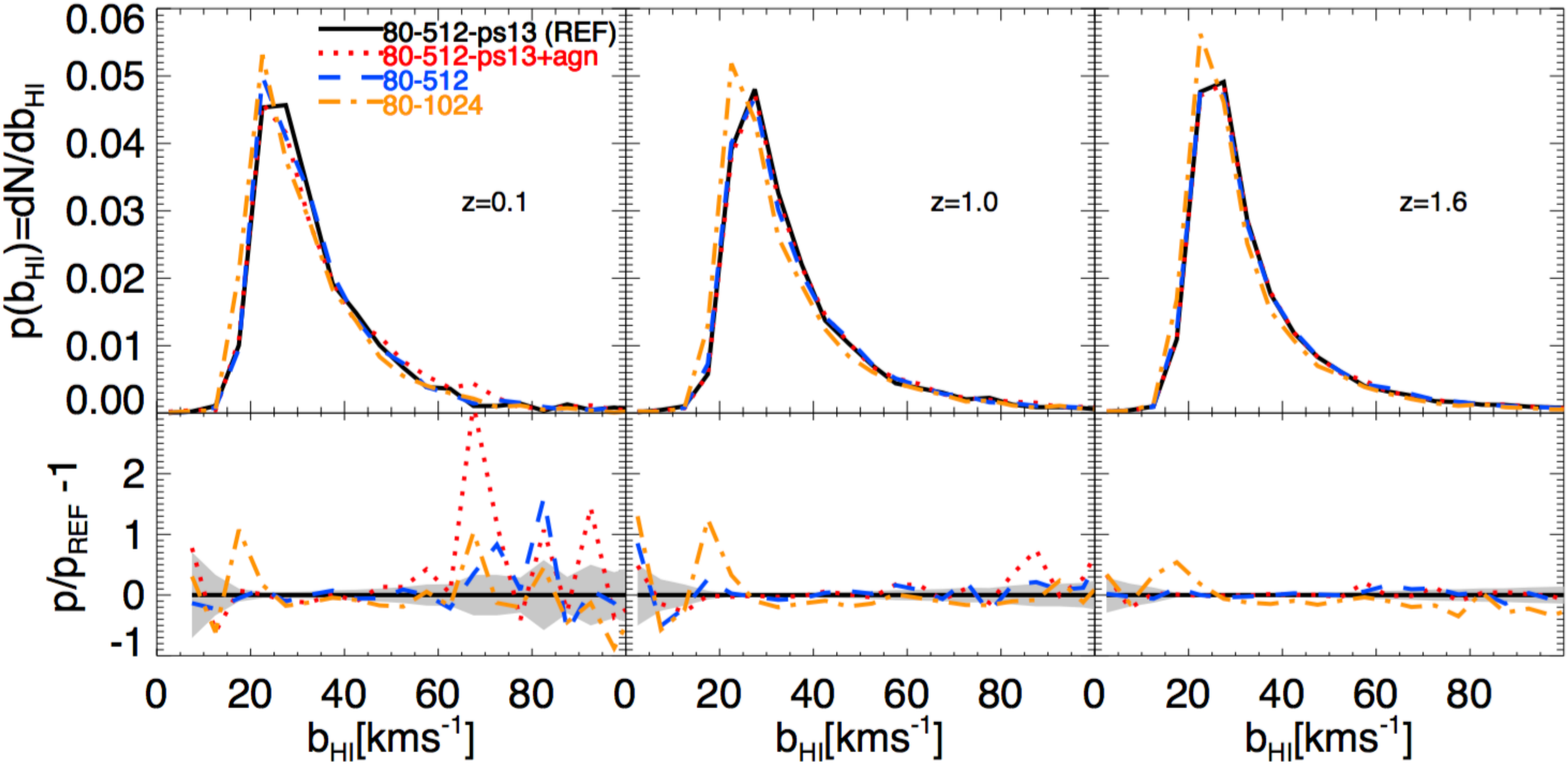
Williger et al. 2010

Sherwood Simulations: column density distribution



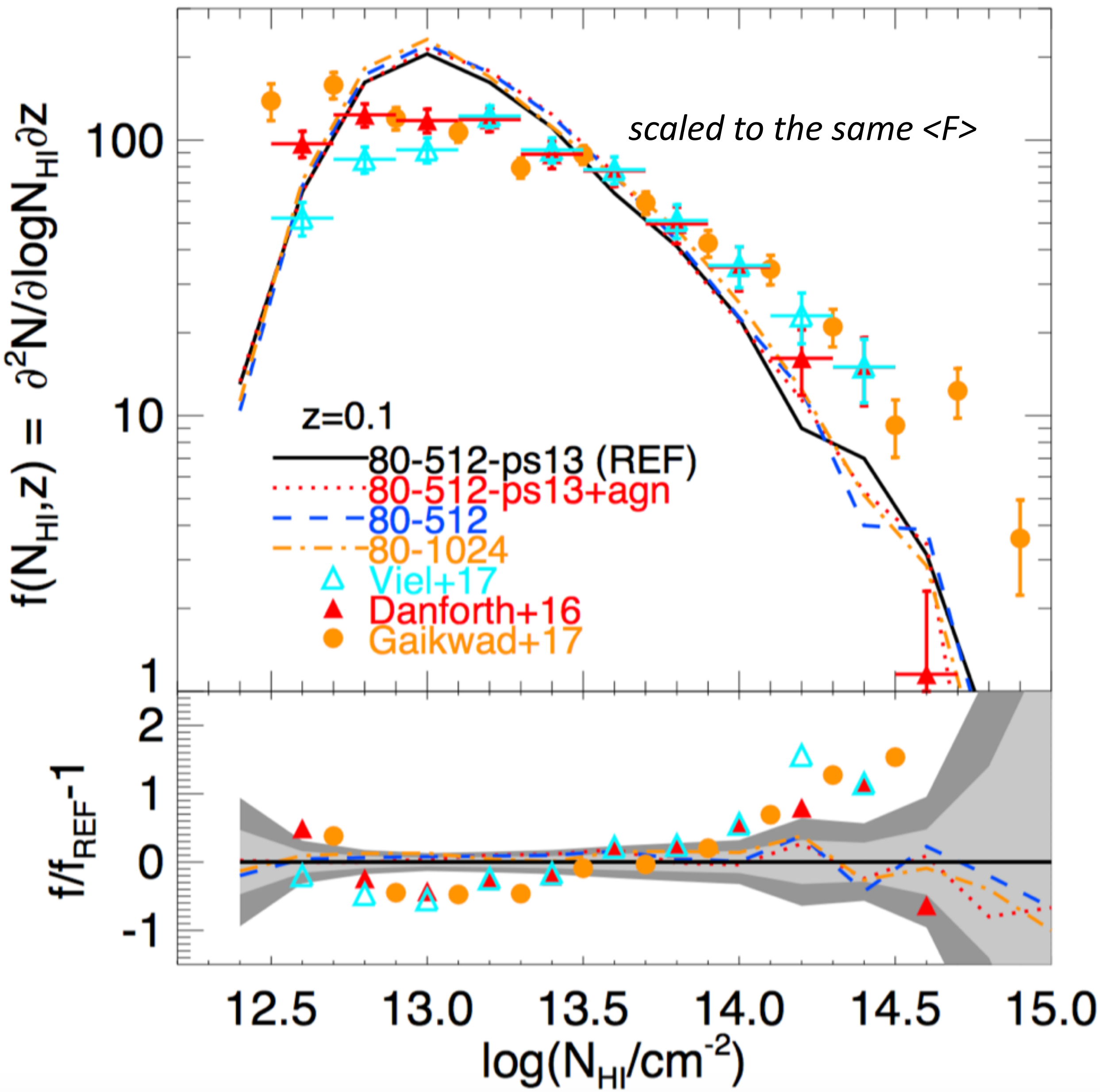
- CDDF at high resolution S/N=50 and FWHM=6.7 km/s
- Feedback does play a small role for strong systems
- QLYA: fewer systems because of missing cold gas and for missing outflows (that increase the EWs)

Sherwood Simulations: line width distribution



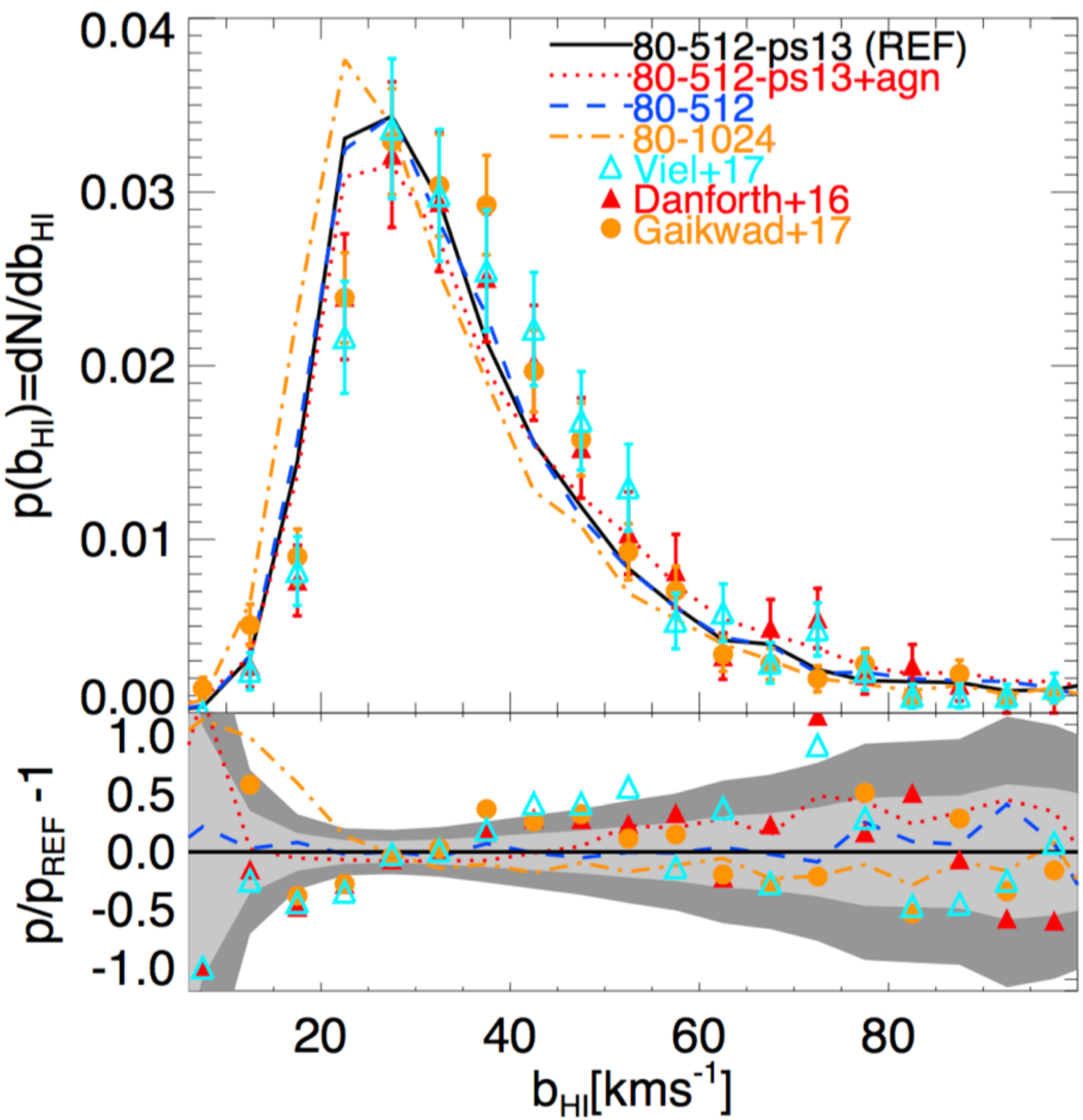
- Note the poor numerical convergence at low values < 30 km/s
- Similar results than those of Tepper-Garcia+12 using OWLS sims

CDDF: comparison with data



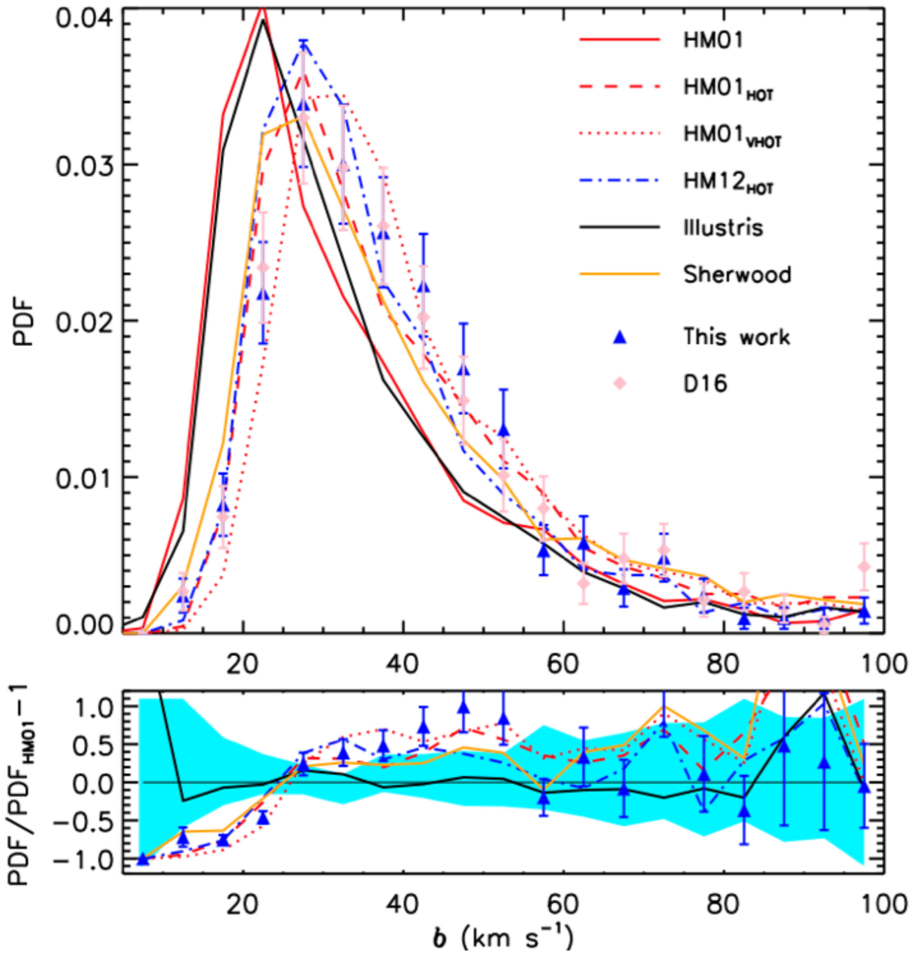
- Simulations are numerically converged but poor noise modelling at 10^{13} makes agreement not good (factor 2).
- Narrow range in which sims and data are in agreement $10^{13.2-14}$.
- Including or not AGN feedback does not impact on HI CDDF (no consensus on this since it depends on sub-grid modelling) - see Gurvich+17.
- Tepper-Garcia+12 compared with Lehner+07 (FUSE) and found better agreement at > 10^{14} but applying the same cuts we get very similar results.
- Simulations have shallower slope than observations.

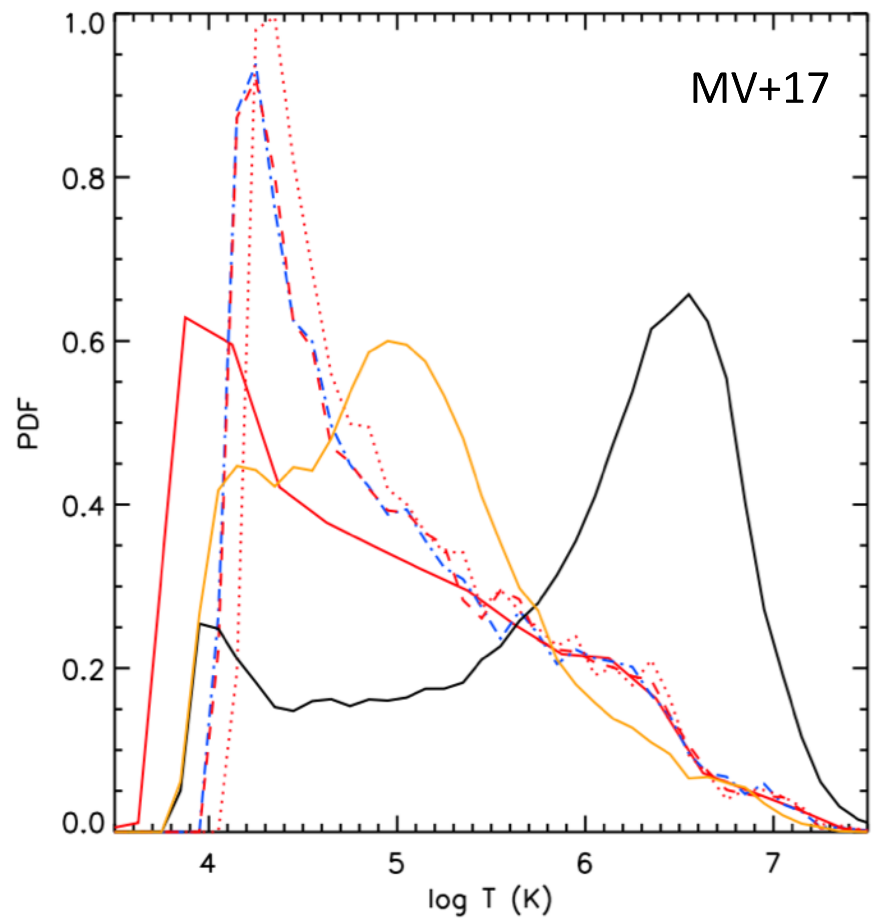
Line widths: comparison with data



- **Discrepancy present** in the range 40-70 km/s and also in the range 15-25 km/s.
- Numerical convergence not perfectly achieved - likely that this makes the problem worse.
- AGN feedback increases <b> by 2 km/s.
- In Dave'+10 better agreement but COS LSF not properly modelled.

Line widths: comparison with data and T-rho diagram

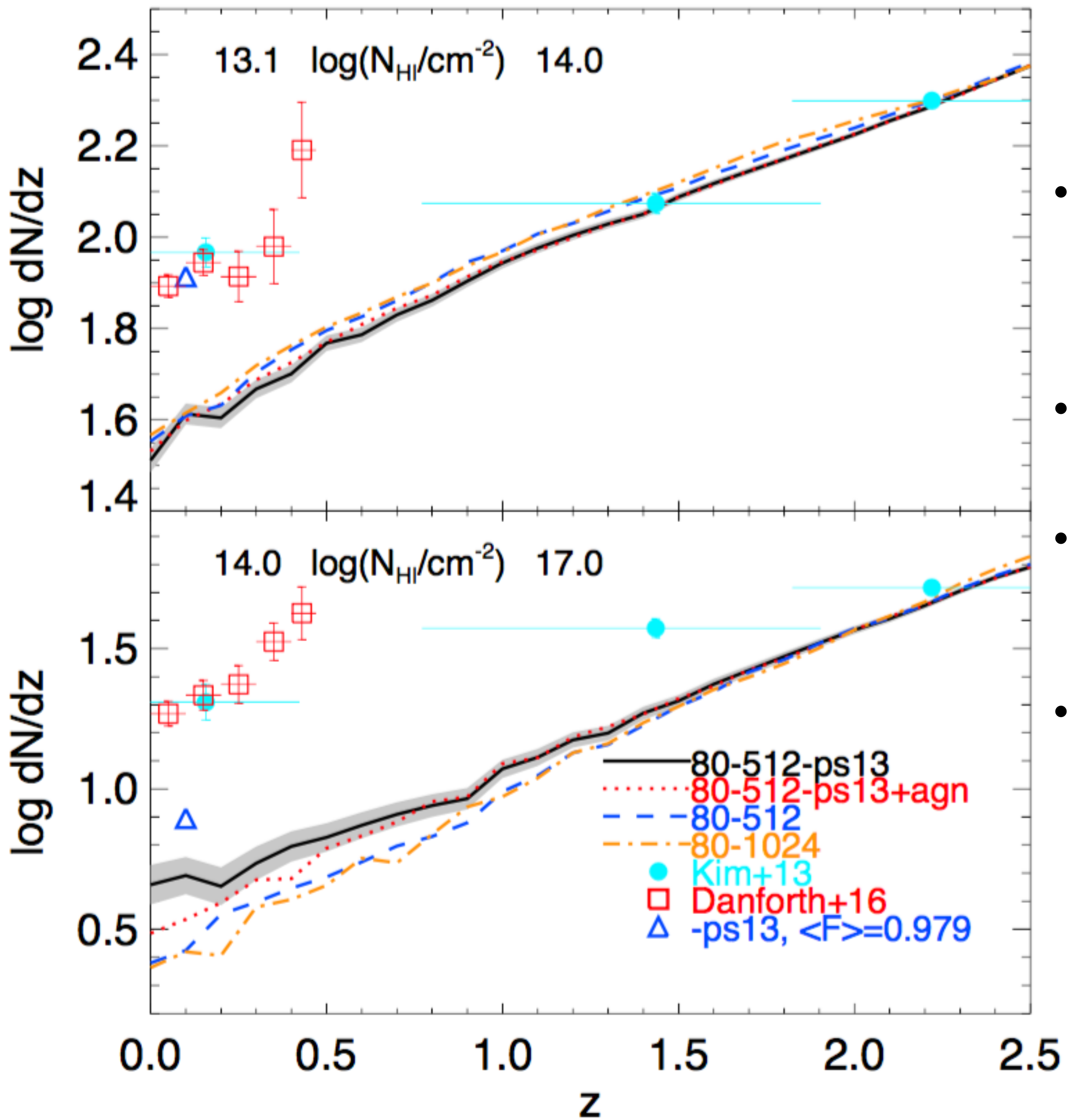




- Gas too cold?
- Gas too hot? (and thereby collisionaly ionized)
- Overall powerful diagnostic tool for feedback models

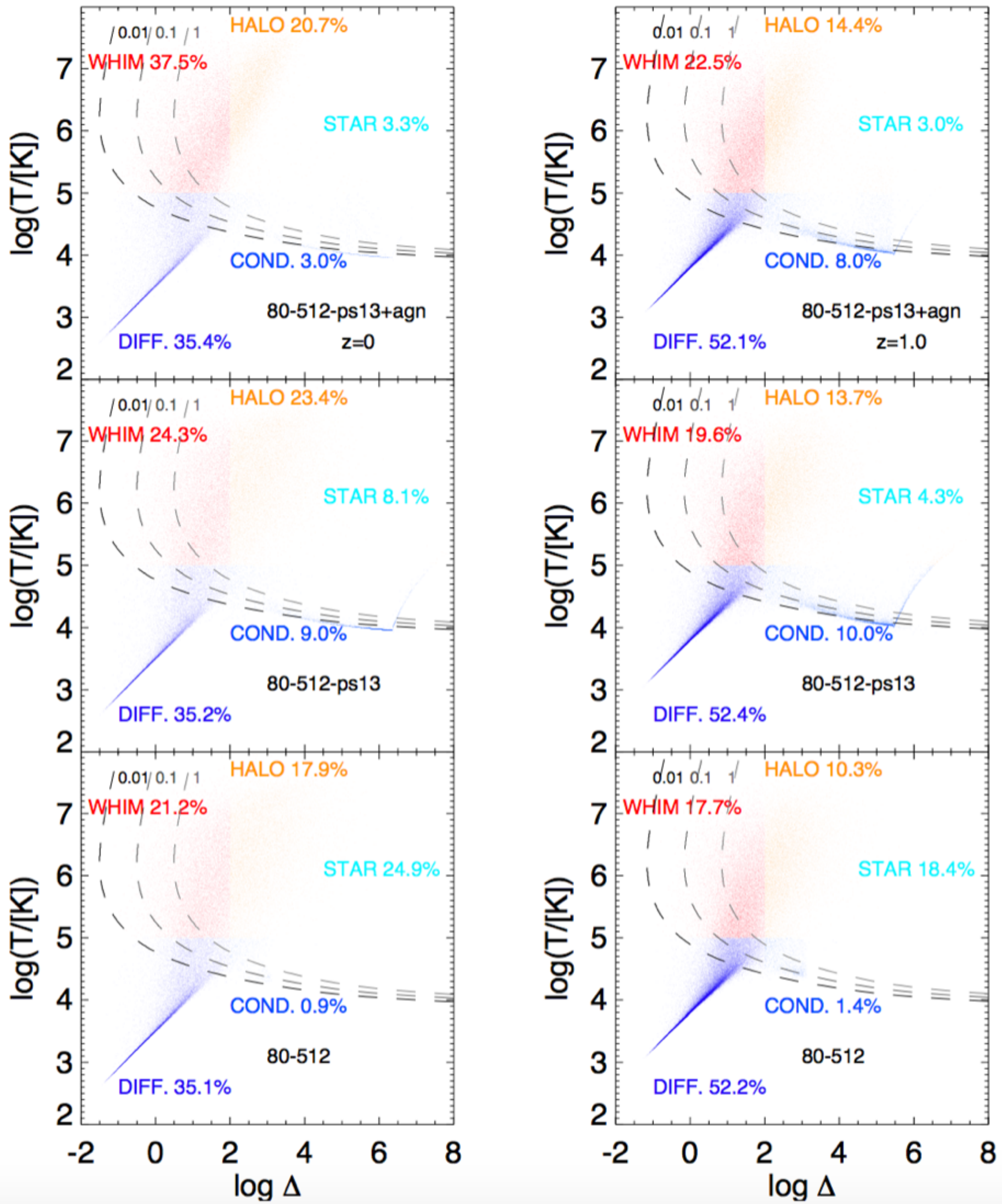
Solving the discrepancy by having hotter gas at *Δ* =4-40
HeII photionization rates thus UVB harder at z>2? or fine-tuned feedback?
or turbulent component?

dN/dz evolution



- High column density systems somewhat more sensitive to star formation and/or feedback.
- All models fail to predict dN/dz at z<1.5.
- Rescaling the mean flux improves the situation but only slightly so.
- This suggests that simulations are not capturing the saturated systems (as for the CDDF).

Gas phases



Diffuse: $\rho < \rho_{th}$ and $T < T_{th}$
WHIM: $\rho < \rho_{th}$ and $T > T_{th}$
Hot halo: $\rho > \rho_{th}$ and $T > T_{th}$
Condensed: $\rho > \rho_{th}$ and $T < T_{th}$

$T_{th} = 10^5$ K
$\rho_{th}(z)$ = 97, 65, 62 at z=0.1,1,1.6

- WHIM fraction increases for AGN models (e.g. Tornatore+10).
- ps13 model similar to momentum driven model (Dave'+10).
- Results in broad agreement with the BAL analysis of Tepper-Garcia+12.

SUMMARY

- High redshift photoionized cosmic web exploited for cosmological studies mainly cold dark matter coldness or neutrino constraints. Simulations show a consistent picture in which astrophysics does not play a major role.

- Low redshift cosmic web addresses UVB evolution and galaxy IGM/ interplay. Numerical convergence more difficult to achieve.

- Simulations have more problems here: high column density systems, low b-parameters systems, dN/dz when compared with COS data.

- No photon underproduction crisis present.

- Feedback is important but only if the T-rho diagram is significantly modified (e.g. Illustris simulation). Other less aggressive schemes impact much less.

FINAL REMARKS

IGM powerful and now mature cosmological observables that exploits small scales and high redshifts

Particularly useful when combined to other largest scales probes and very constraining for neutrino masses and warm dark matter

Systematics need to be pinned down more importantly continuum fitting for 3D studies and temperature evolution/astrophysics for 1D

Low redshift evolution important for UV nature and feedback

FUTURE DIRECTIONS

eBOSS and DESI will extend the number of QSOs by another factor 10 or so: BAO studies and cross-correlation studies (Miralda-Escude’ et al.) will be very important in the near future.

ESPRESSO and WEAVE also quite important in extending the number of high res. QSOs.

E-ELT high res. spectrograph will probably allow to beat down systematics and perform the expansion test.

Unique view on the high redshift Universe: surprises in DE evolution? MG?

Sinergies with other observables will be crucial: Intensity Mapping at high z, galaxy clustering, CMB lensing, etc.

Full 3D topological reconstruction of the cosmic web mandatory: new statistical tools to be developed.