COSMOLOGICAL SPECTROSCOPY OF THE HIGH REDSHIFT UNIVERSE: STATUS & PERSPECTIVES

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OUTLINE

1- INTRODUCTION: THE LYMAN–α FOREST

2- RESULTS IN TERMS OF LARGE SCALE STRUCTURE

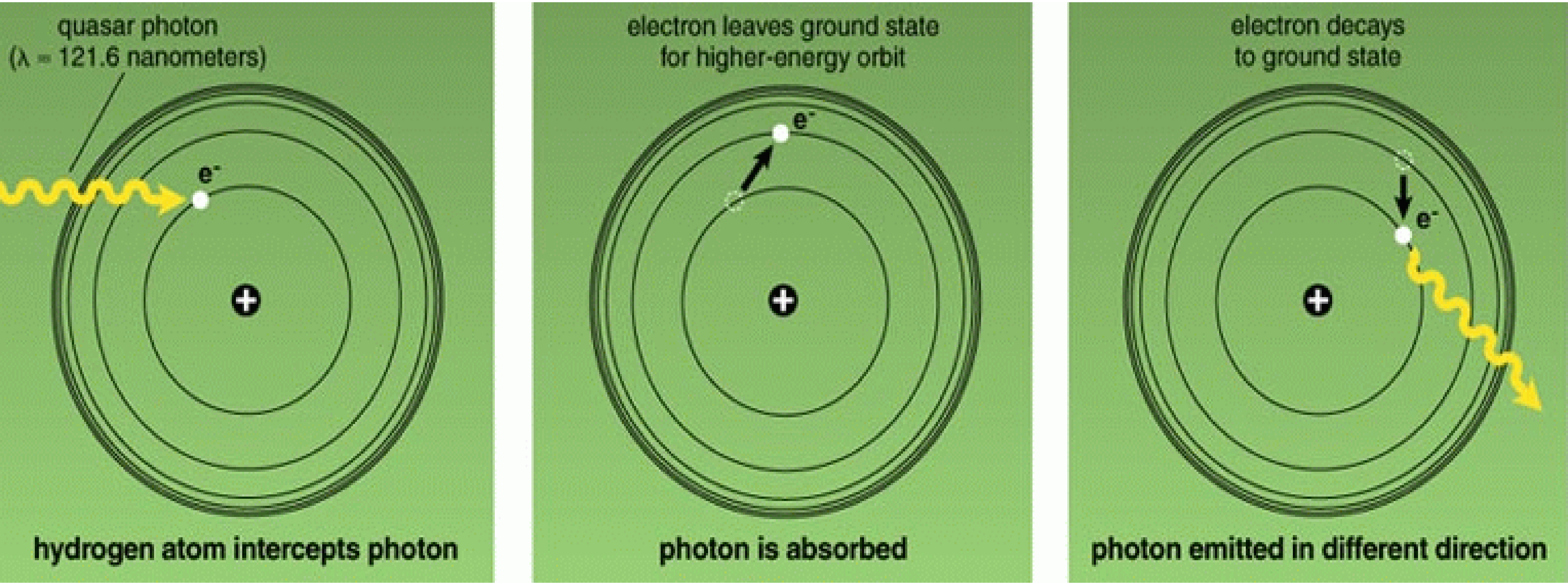
3- RESULTS IN TERMS OF FUNDAMENTAL PHYSICS

4- RESULTS IN TERMS OF GALAXY/IGM INTERPLAY

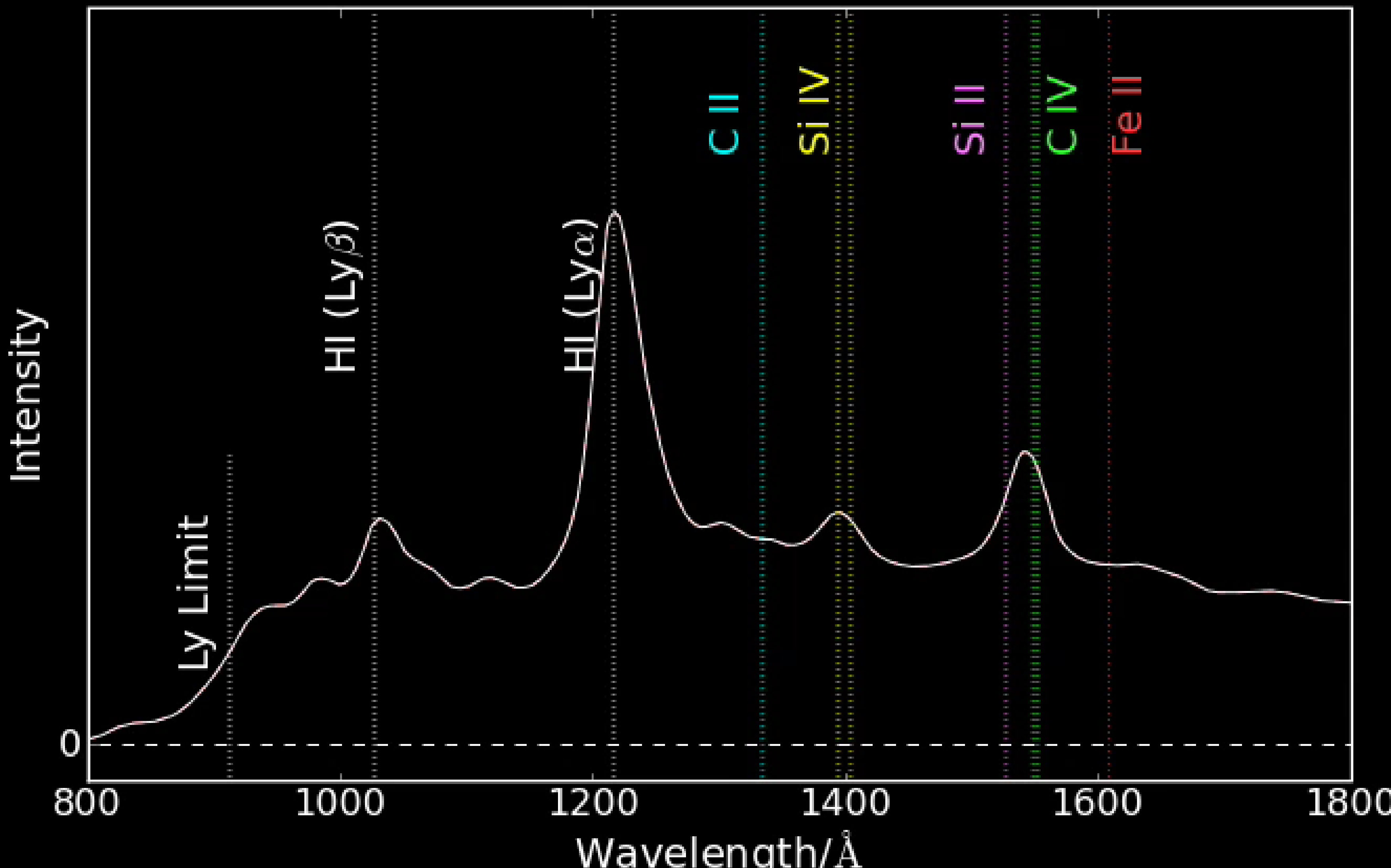
5- PERSPECTIVES

INTRO

Lyman-α absorption is the main manifestation of the IGM

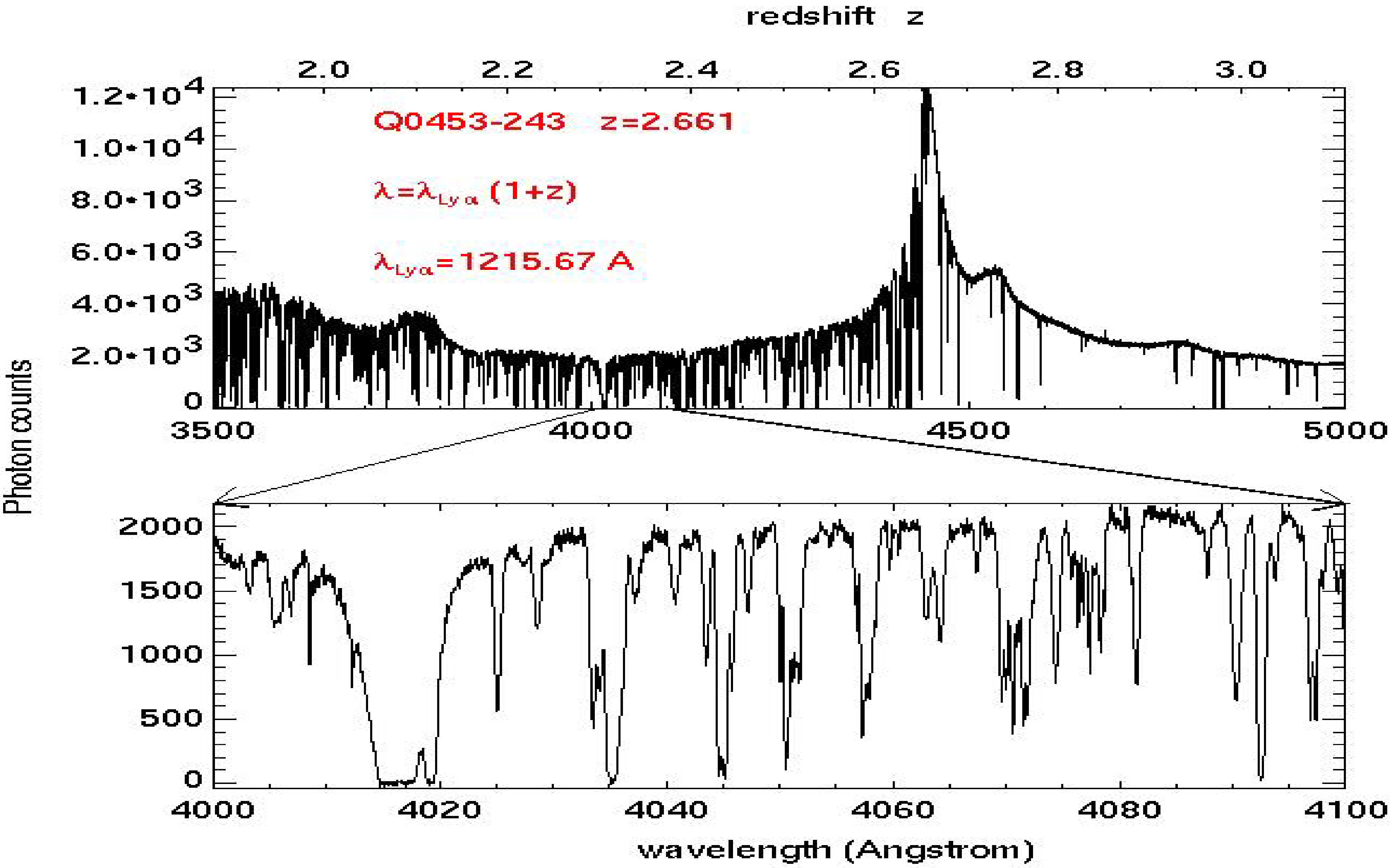


Tiny neutral hydrogen fraction after reionization…. But large cross-section

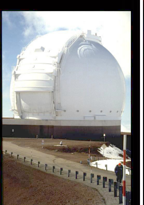


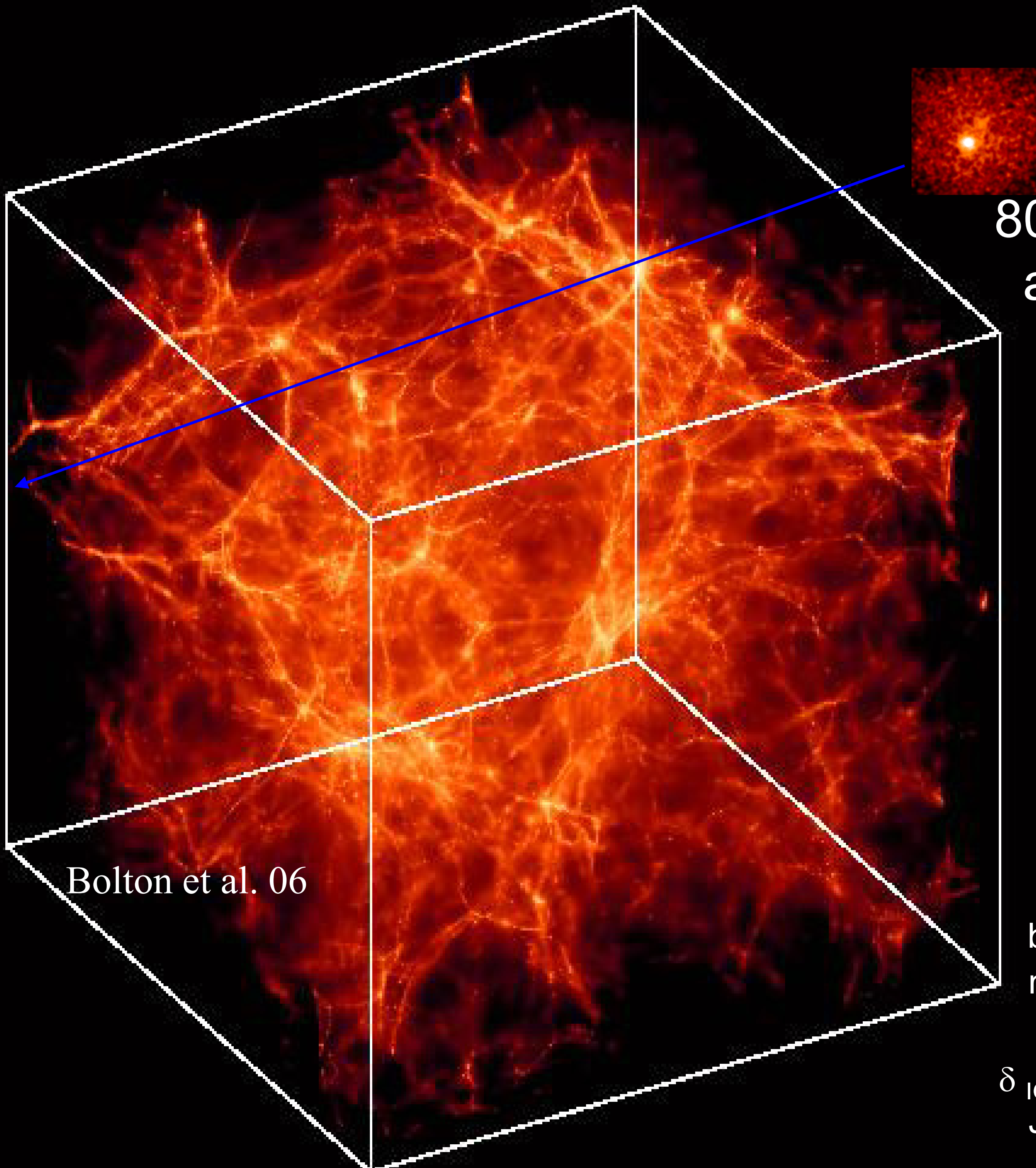
Intensity
Wavelength/Å
0
800
1000
1200
1400
1600
1800
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II

DATA: high resolution spectrum



THEORY: GAS in a ΛCDM universe





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

Bi & Davidsen (1997)
Rauch (1998, review)
Meiksin (2009, review)

baryons as tracer of the dark matter density field

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

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

BRIEF HISTORICAL OVERVIEW of the Lyman-α forest

'ISOLATED' CLOUDS

PROBES OF THE JEANS SCALE

- Gunn & Peterson (1965): a unifom IGM at redshift 2 is very highly ionized, to avoid very large HI opacity;

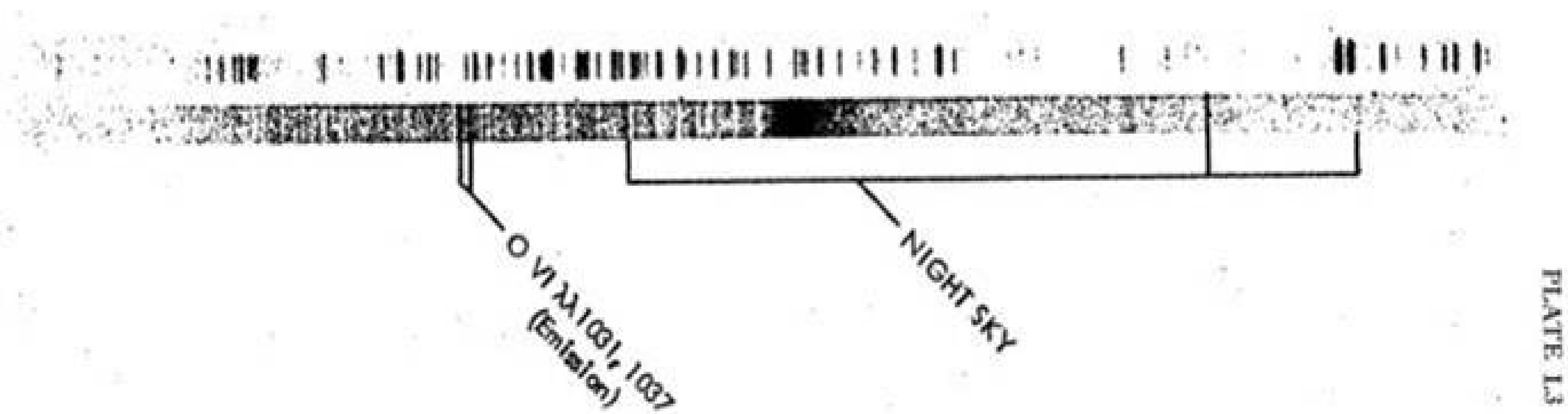


FIG. 1.—A spectrogram illustrating the numerous absorption lines in 4C 05.34. The strong emission line in the center is Lα. The O VI emission lines and several airglow features are also indicated. The comparison spectrum is He + Ar + Ne.

LYNDS (see page L73)

v

discrete clouds, reproduced most of the observations;

NETWORK OF FILAMENTS

COSMOLOGICAL PROBES

- N-body + Hydro simulations (Cen et al. 1994), semi analytical models (Bi et al., 1993).

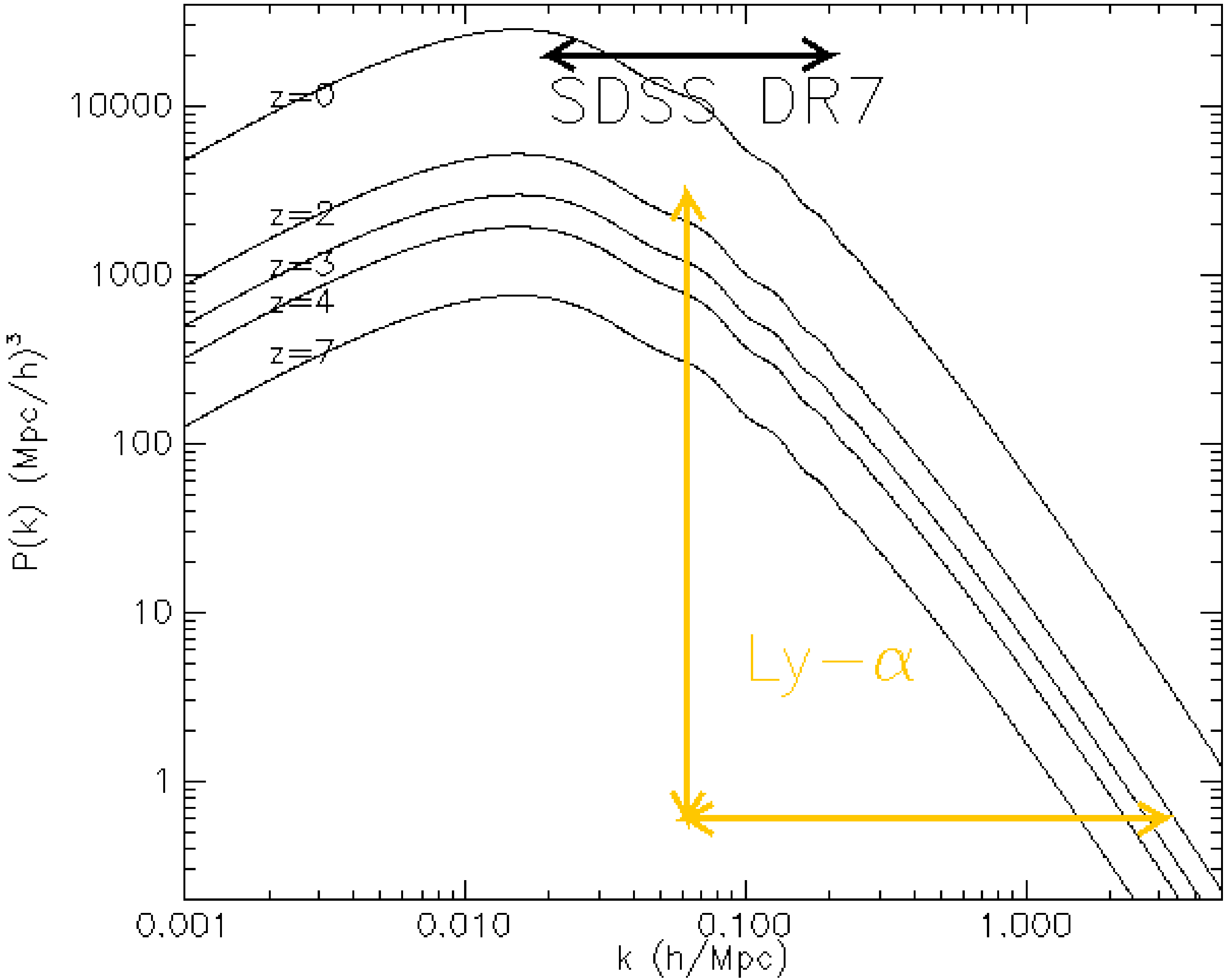
Tools to investigate the Lyman-α forest

Discrete fields: statistics of lines fitted with Voigt profile
examples: Doppler parameters, column density distribution functions

Continuous fields: transmitted flux
examples: mean flux, flux probability distribution function, **flux power** and bispectrum

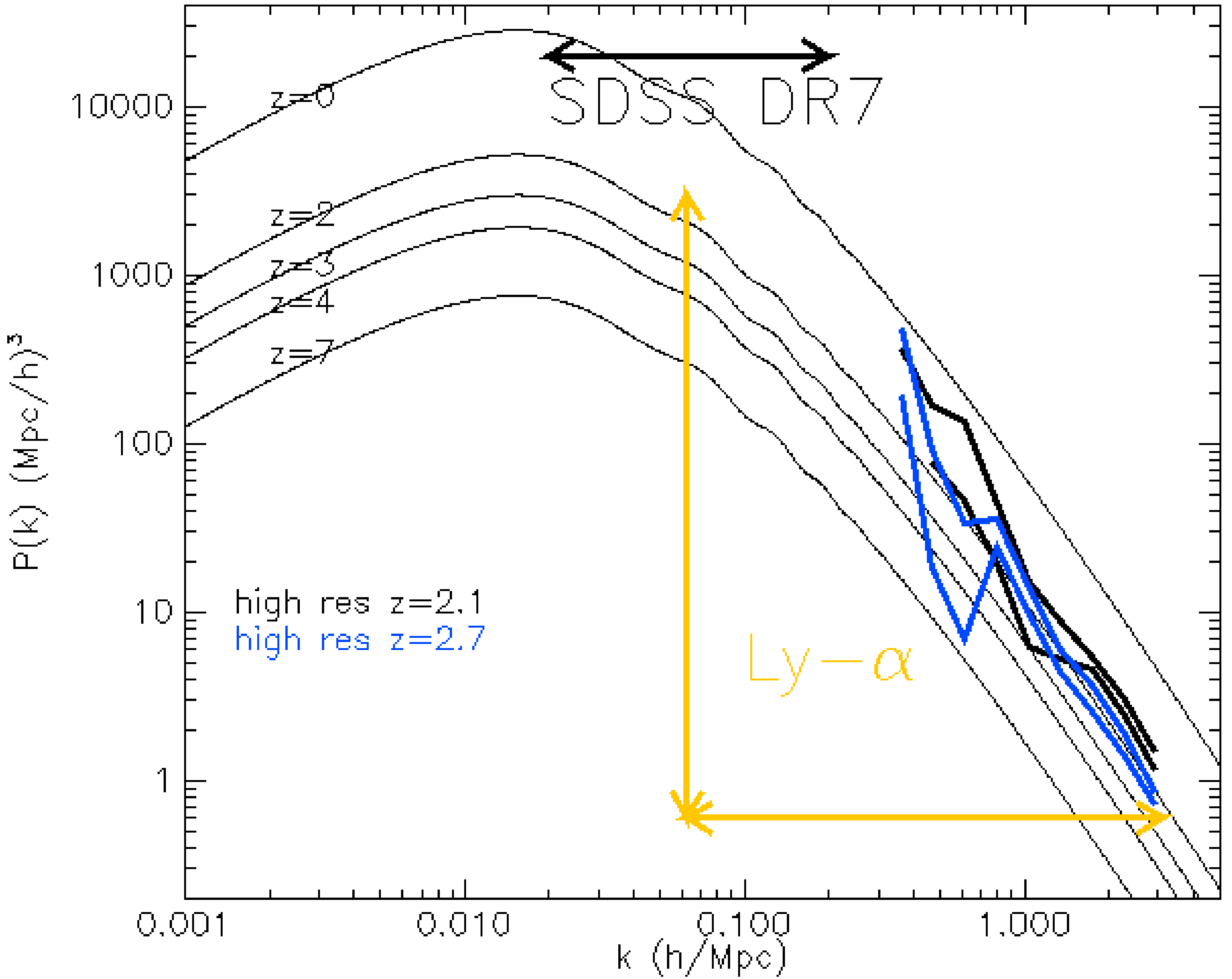
Other statistics: wavelets, pixel optical depth techniques etc.

DATA vs THEORY

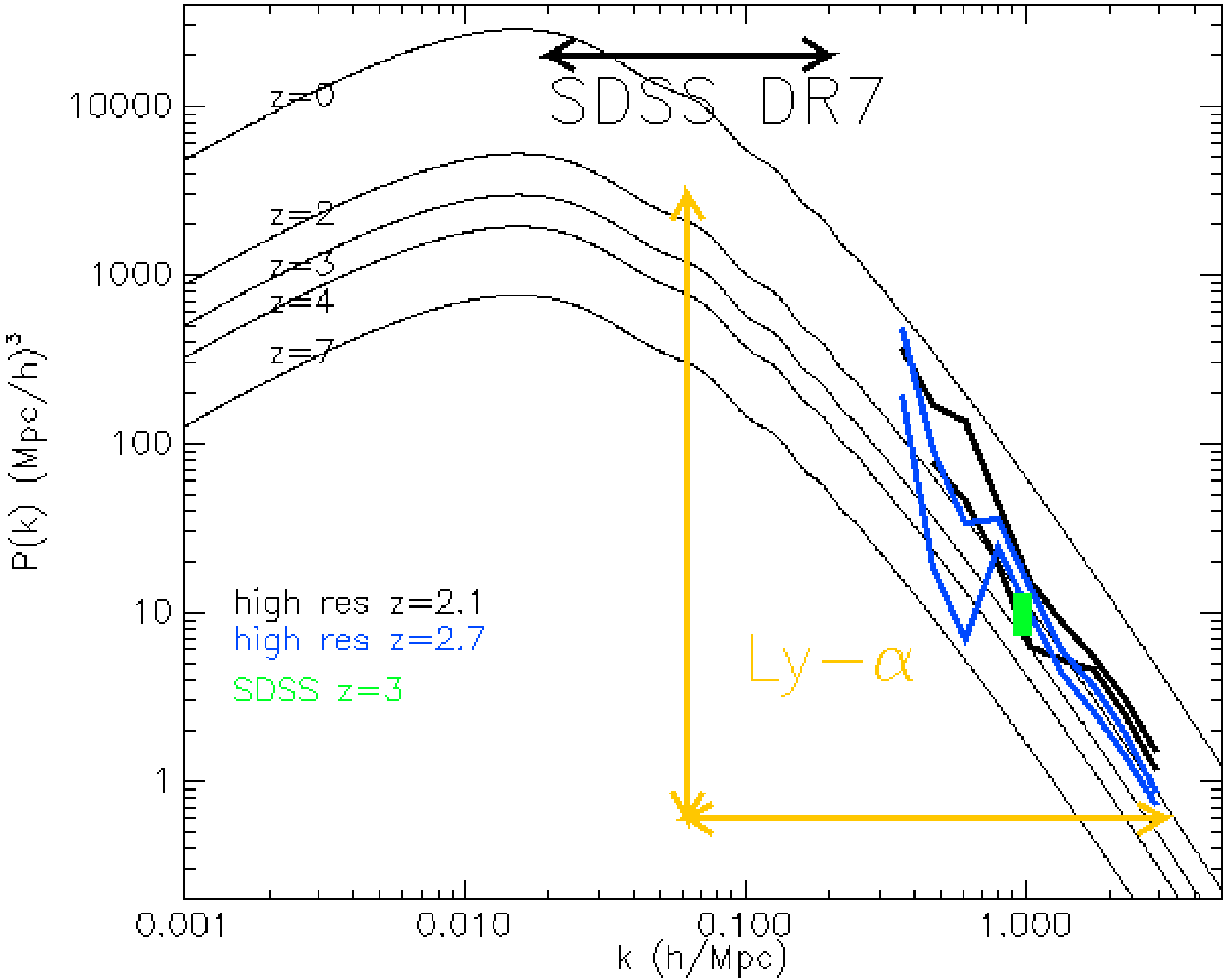


DATA vs THEORY

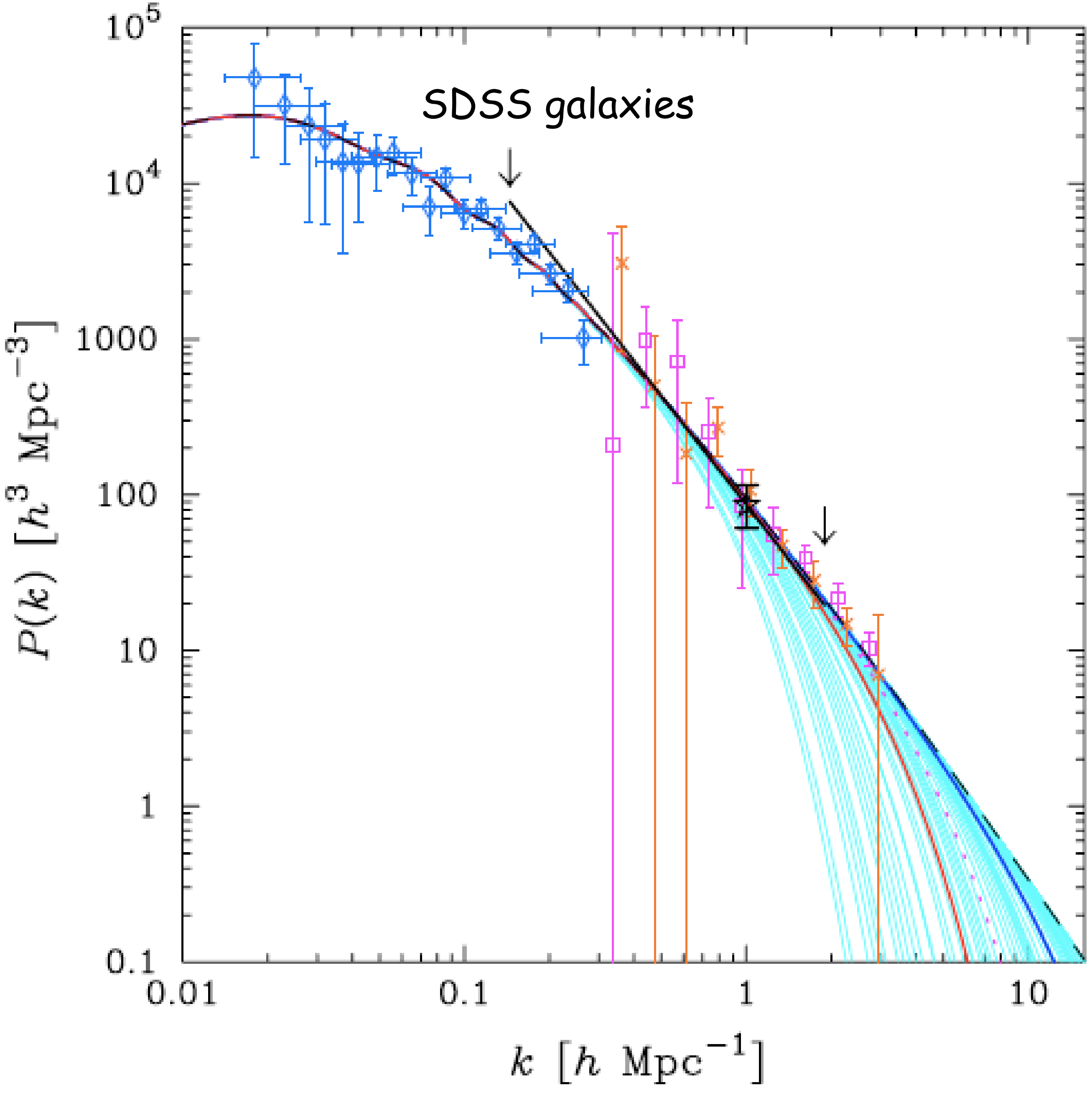
$$P_{FLUX}(k,z) = bias^2(k,z) \times P_{MATTER}(k,z)$$



DATA vs THEORY



FUNDAMENTAL PROPERTIES OF THE DARK MATTER: IMPACT ON CLUSTERING



Abazajian 2006

DARK MATTER cutoff

Depending on the scale:

Hot 100 Mpc
Warm Mpc
Cold << 1 Mpc

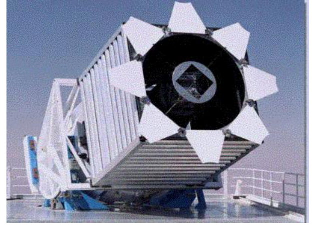
Outline

in collaboration with: **Haehnelt, Bolton, Carswell, Kim, Springel**
Becker, Rauch, Lesgourgues, Boyarsky,
Ruchaysky, Matarrese, Riotto, Sargent, etc.

- What data we got — The data sets
- How we used them — Theoretical framework
- What we achieved — Results

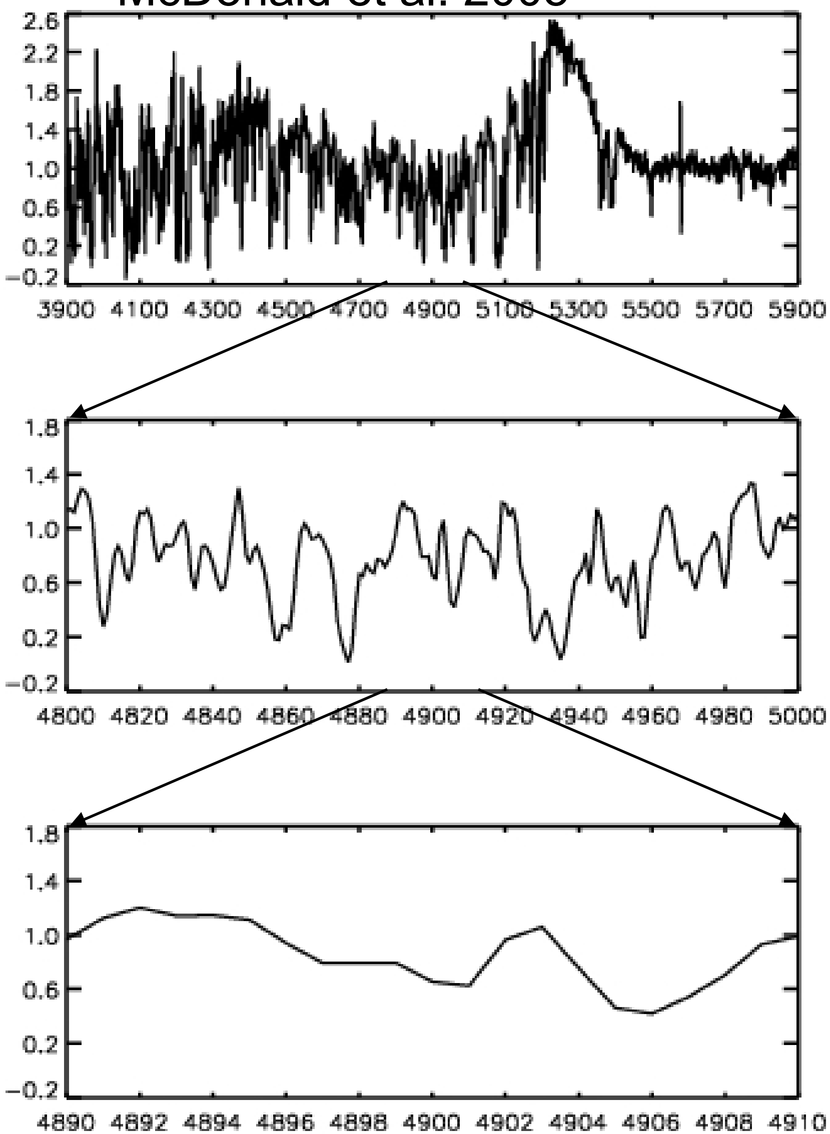
Why Lyman-α ? Small scales
High redshift
Most of the baryonic mass is in this form
Quasars sample 75% of the age of the universe

The data sets

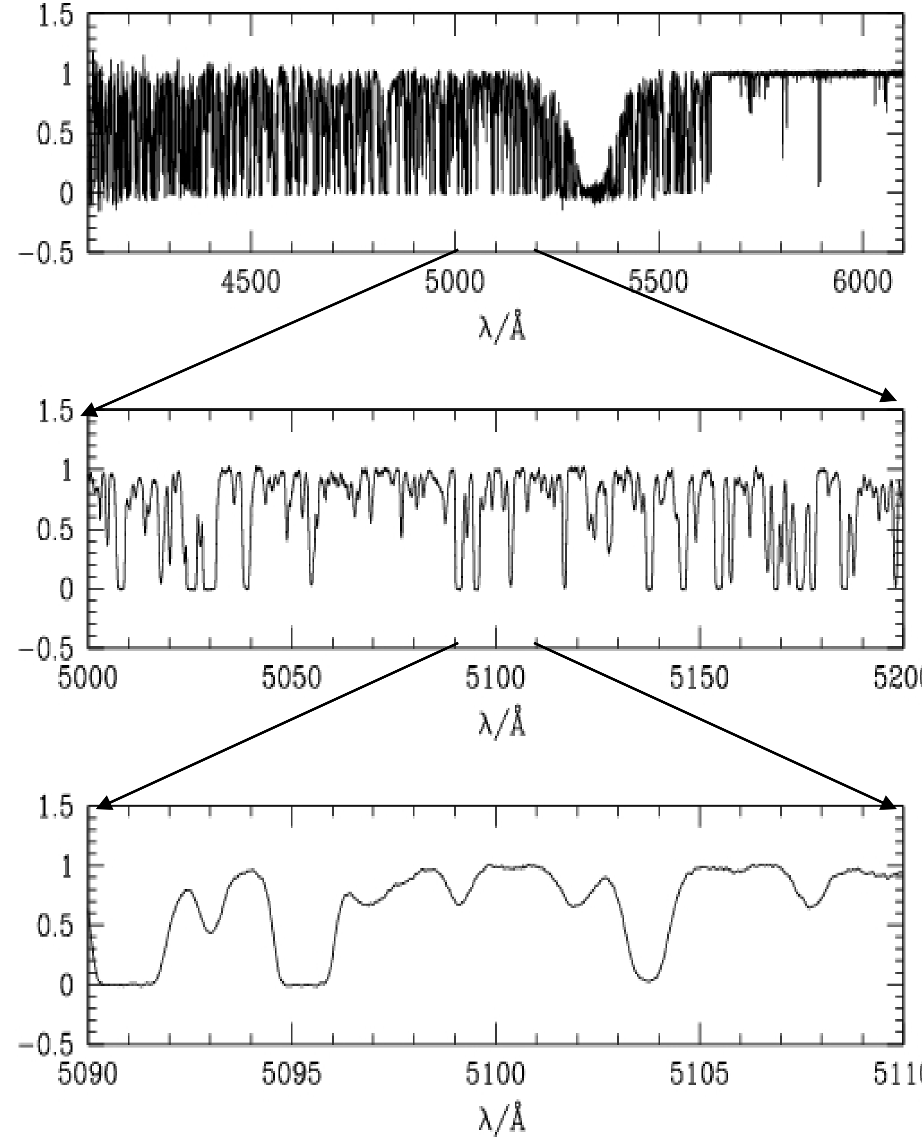


SDSS vs LUQAS

McDonald et al. 2005



Kim, MV et al. 2004



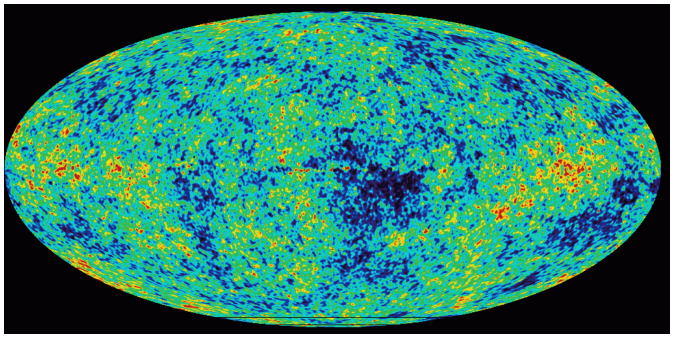
SDSS — LUQAS

3035 LOW RESOLUTION LOW S/N vs 30 HIGH RESOLUTION HIGH S/N

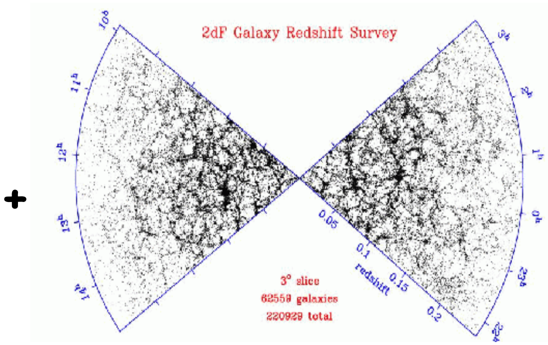
The interpretation: full grid of sims - I

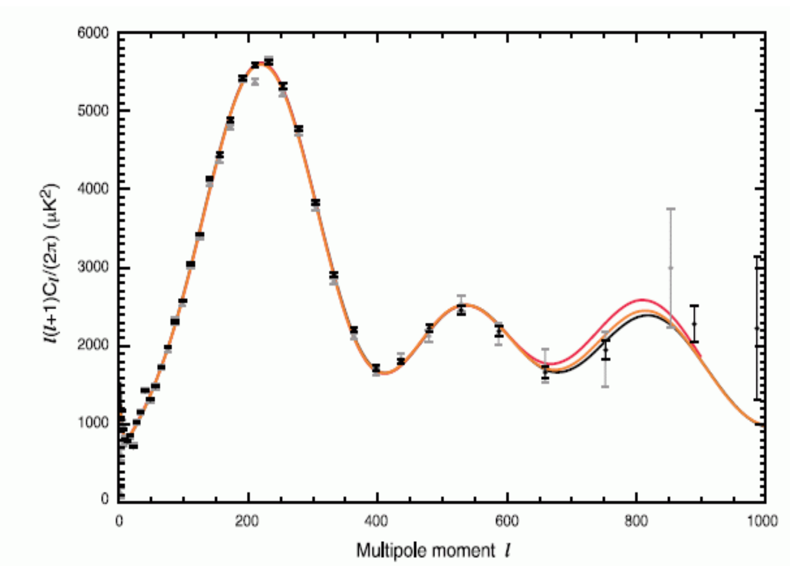
SDSS power analysed by forward modelling motivated by the huge amount of data with small statistical errors

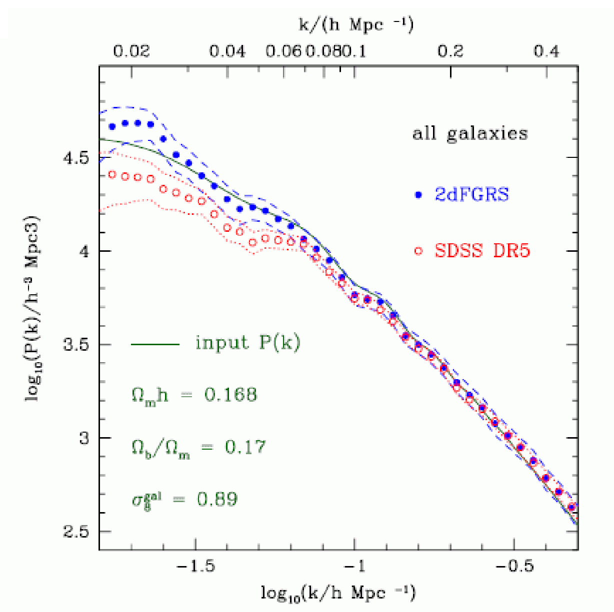
CMB: Komatsu et al. (09) Galaxy P(k): Sanchez & Cole (07)



+







z=4.2

z=2.2

Cosmological parameters + e.g. bias +

The interpretation: full grid of sims - II

McDonald et al. 05

We vary 34 parameters, 3 of which are fixed for our primary result but varied for consistency checks. We give a summary before defining each in detail. In parentheses we give the actual number of parameters for each type:

Parameters $\Delta_L^2(k_p, z_p)$, $n_{\rm eff}(k_p, z_p)$, and $\alpha_{\rm eff}(k_p, z_p)$ (3).—Standard linear power spectrum amplitude, slope, and curvature on the scale of the Lyα forest, assuming a typical ΛCDM-like universe. Parameter $\alpha_{\rm eff}(k_p, z_p)$ is fixed to -0.23 for the main result.

Parameters g' and s' (2).—Modifiers of the evolution of the amplitude and slope with redshift, to test for deviations from the expectation for ΛCDM. Fixed for main result.

Parameters $\bar{F}(z_p)$ and ν_F (2).—Mean transmitted flux normalization and redshift evolution.

Parameters $T_{i=1\ldots3}$ and $\tilde{\gamma}_{i=1\ldots3}$ (6).—Temperature-density relation parameters, including redshift evolution.

Parameter $x_{\rm rei}$ (1).—Degree of Jeans smoothing, related to the redshift and temperature of reionization.

Parameters $f_{\rm Si\,III}$ and $\nu_{\rm Si\,III}$ (2).—Normalization and redshift evolution of the Si III–Lyα cross-correlation term.

Parameters $\epsilon_{n,i=1\ldots11}$ (11).—Freedom in the noise amplitude in the data in each SDSS redshift bin.

Parameter α_R (1).—Freedom in the resolution for the SDSS data.

Parameter $A_{\rm damp}$ (1).—Normalization of the power contributed by high-density systems.

Parameters $a_{\rm NOSN}$ and $a_{\rm NOMETAL}$ (2).—Admixture of corrections from the NOSN and NOMETAL hydrodynamic simulations.

Parameters $A_{\rm UV}$ and $\nu_{\rm UV}$ (2).—Normalization and redshift evolution of the correction for fluctuations in the ionizing background.

Parameter $x_{\rm extrap}$ (1).—Freedom in the extrapolation of our small simulation results to low k.

Tens of thousands of models
Monte Carlo Markov Chains

- Cosmology
- Cosmology
- Mean flux
- $T=T_0\,(1+d)^{g-1}$
- Reionization
- Metals
- Noise
- Resolution
- Damped Systems
- Physics
- UV background
- Small scales

The interpretation: flux derivatives - III

Independent analysis of SDSS power

The flux power spectrum is a smooth function of k and z

Flux power

$$P_F(k, z; \mathbf{p}) = P_F(k, z; \mathbf{p}^0) + \sum_{i=1,N} \left. \frac{\partial P_F(k, z; p_i)}{\partial p_i} \right|_{\mathbf{p} = \mathbf{p}^0} (p_i - p_i^0)$$

Best fit

p: astrophysical and cosmological parameters

but even resolution and/or box size effects if you want to save CPU time

RESULTS

POWER SPECTRUM AND NEUTRINOS

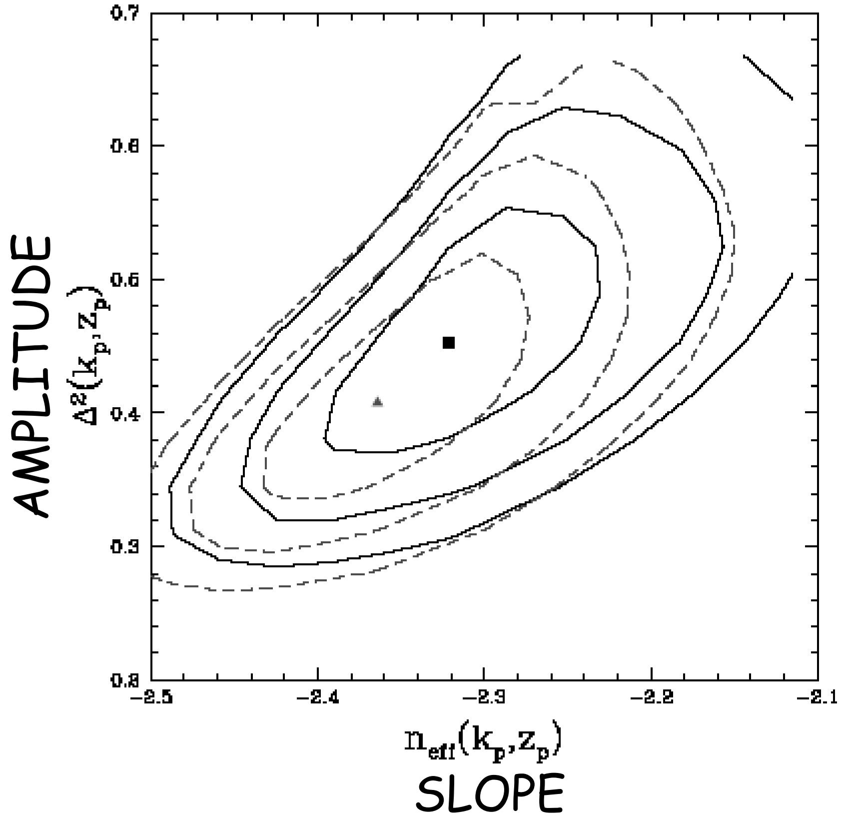
Results Lyman-α only with full grid: amplitude and slope

$$\Delta^2_L(k,\ z) \simeq \left[\frac{D(z)}{D(z_p)}\right]^2 \Delta^2_L(k_p,\ z_p) \quad \times \left[\frac{k}{k_\star(z)}\right]^{3+n_{\rm eff}(k_p,z_p)+(1/2)\alpha_{\rm eff}(k_p,z_p)\,\ln[k/k_\star(z)]}$$

χ^2 likelihood code distributed with COSMOMC

McDonald et al. 05

Croft et al. 98,02   40% uncertainty
Croft et al. 02   28% uncertainty
Viel et al. 04   29% uncertainty
McDonald et al. 05   14% uncertainty

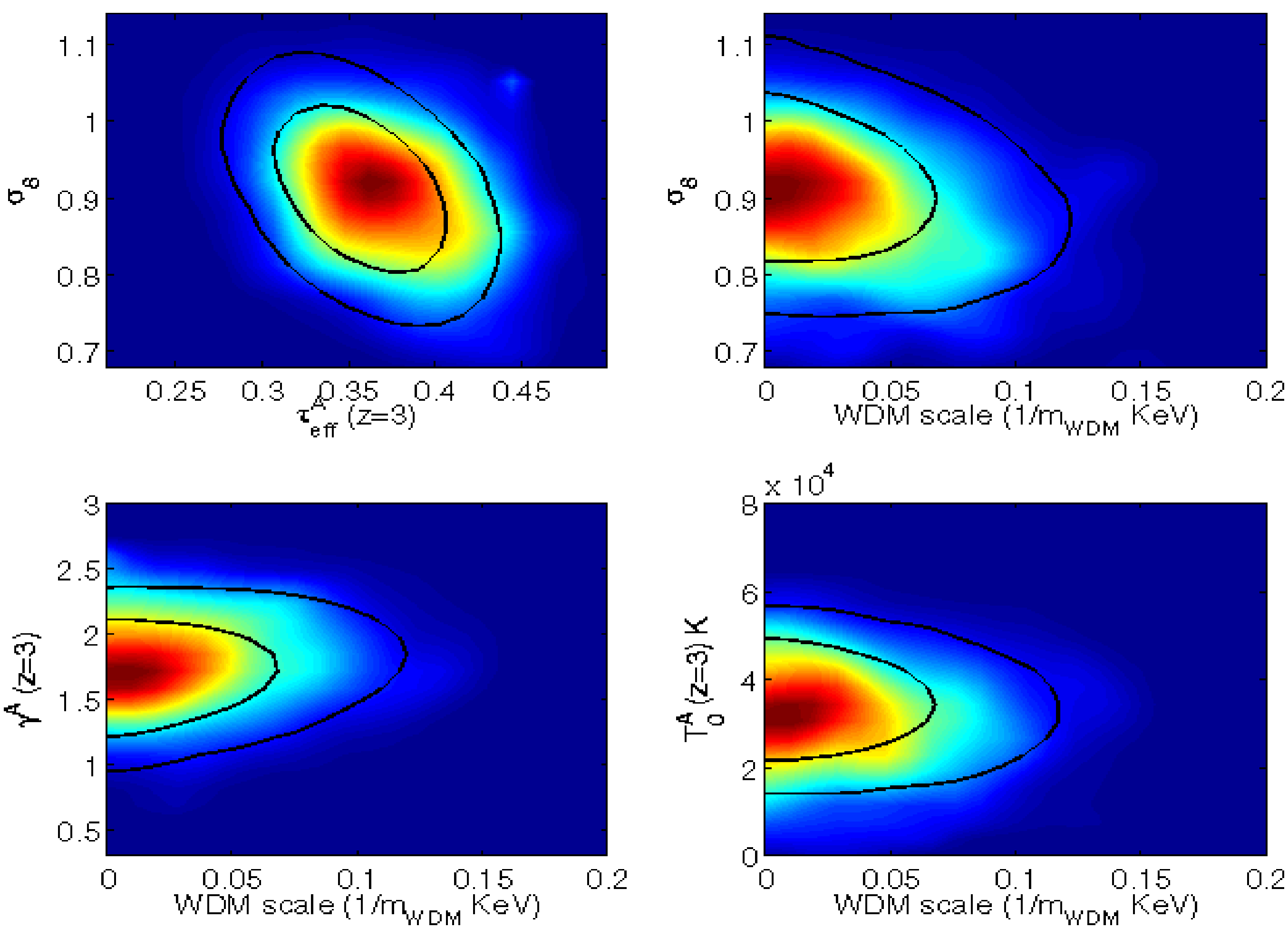


Redshift z=3 and k=0.009 s/km corresponding to ~7 comoving Mpc/h

Results Lyman-α only with flux derivatives: correlations

Fitting SDSS data with GADGET-2
this is SDSS Ly-α only

FLUX DERIVATIVES



SDSS data only

$\sigma_8 = 0.91 \pm 0.07$
$n = 0.97 \pm 0.04$

Summary (highlights) of results

1. Competitive constraints in terms of cosmological parameters (in particular shape and curvature of the power spectrum)

   Lesgourgues, MV, Haehnelt, Massey (2007) JCAP 11 008

2. Tightest constraints to date on neutrino masses and running of the spectral index

   Seljak, Slosar, McDonald JCAP (2006) 10 014

3. Tightest constraints to date on the coldness of cold dark matter

   MV et al., Phys.Rev.Lett. 100 (2008) 041304

Lyman-α forest + Weak Lensing + WMAP 5yrs

Lesgourgues, MV, Haehnelt, Massey, 2007, JCAP, 8, 11

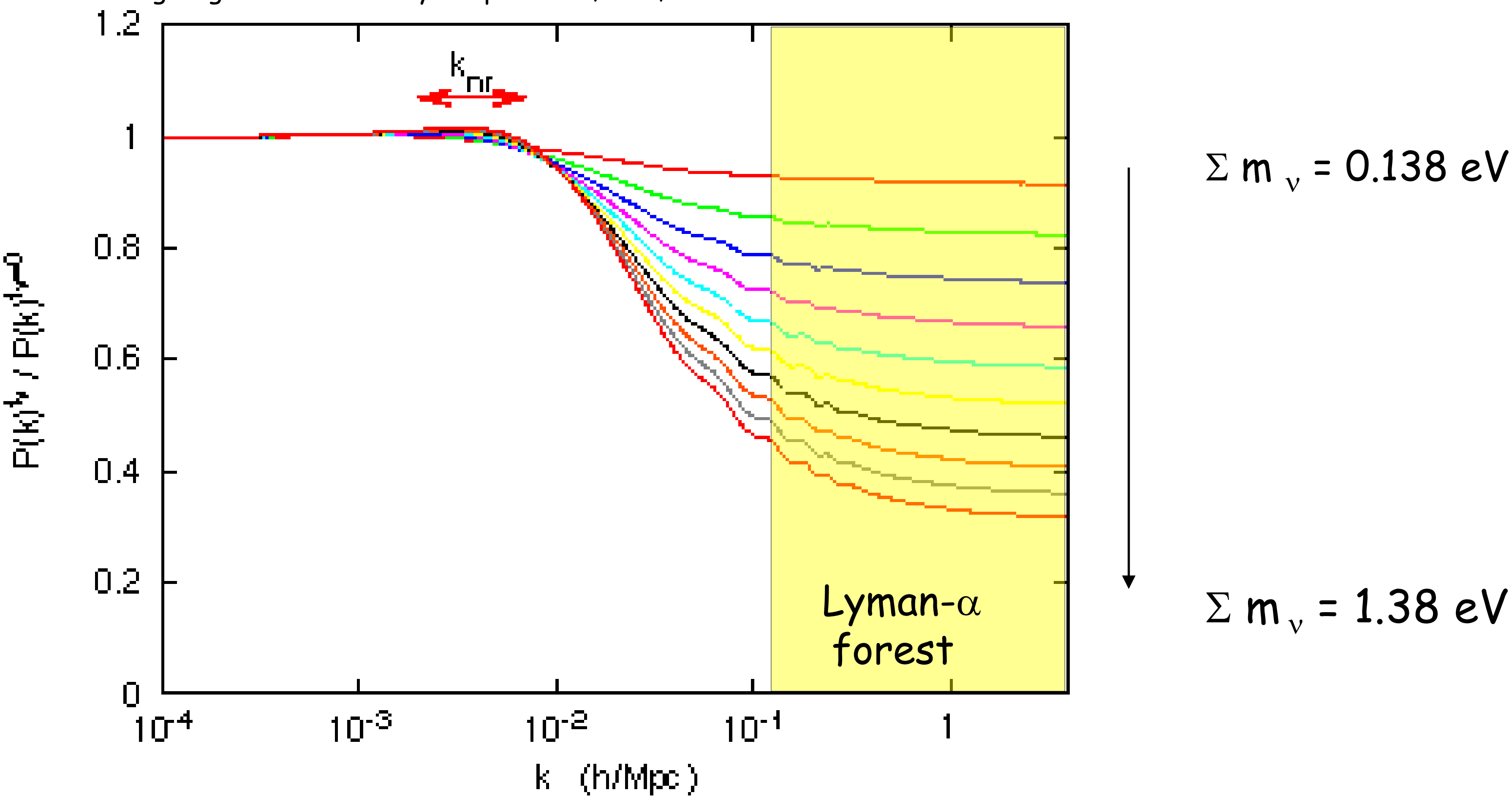
	WL+WMAP3+Lyα VHS	WL+WMAP3+Lyα SDSS-d
σ_8	0.822 ± 0.032	0.800 ± 0.023
n_s	0.960 ± 0.016	0.971 ± 0.011
Ω_{0m}	0.282 ± 0.026	0.247 ± 0.016
h	0.700 ± 0.022	0.730 ± 0.016
τ	0.094 ± 0.028	0.109 ± 0.026

$|dn/d\ln k| < 0.021$

Active neutrinos –I: linear theory

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

Lesgourgues & Pastor Phys.Rept. 2006, 429, 307

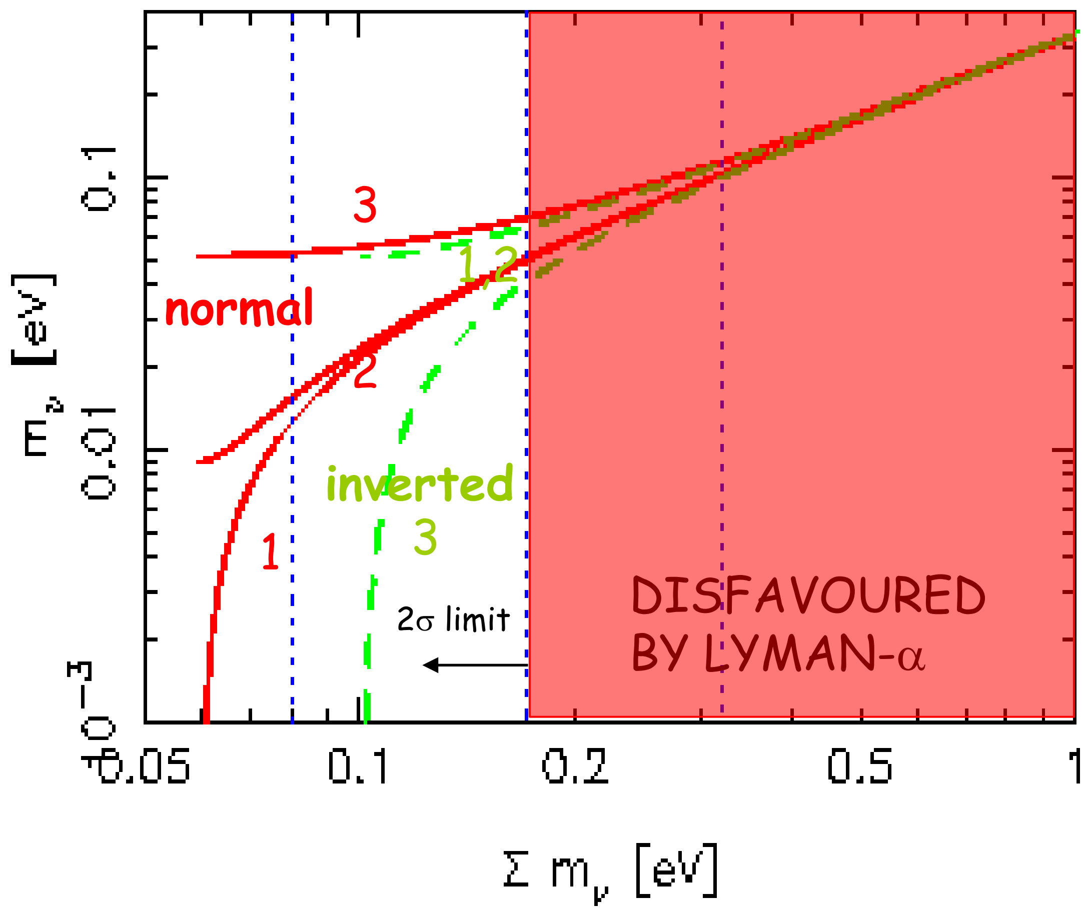


$$v_{th} \equiv \frac{\langle p \rangle}{m} \simeq \frac{3T_\nu}{m} = \frac{3T_\nu^0}{m}\left(\frac{a_0}{a}\right) \simeq 150(1+z)\left(\frac{1\,\mathrm{eV}}{m}\right)\mathrm{km\,s^{-1}}$$

$$k_{FS}(t) = \left(\frac{4\pi G \bar{\rho}(t) a^2(t)}{v_{th}^2(t)}\right)^{1/2}, \qquad \lambda_{FS}(t) = 2\pi \frac{a(t)}{k_{FS}(t)} = 2\pi \sqrt{\frac{2}{3}} \frac{v_{th}(t)}{H(t)}$$

Active neutrinos –II: constraints from Ly-α

Seljak, Slosar, McDonald, 2006, JCAP, 0610, 014



Tight constraints because data are marginally compatible

$\Sigma m\nu$ (eV) < 0.17 (95 %C.L.), < 0.19 eV (Fogli et al. 08)

r < 0.22 (95 % C.L.)

running = -0.015 ± 0.012

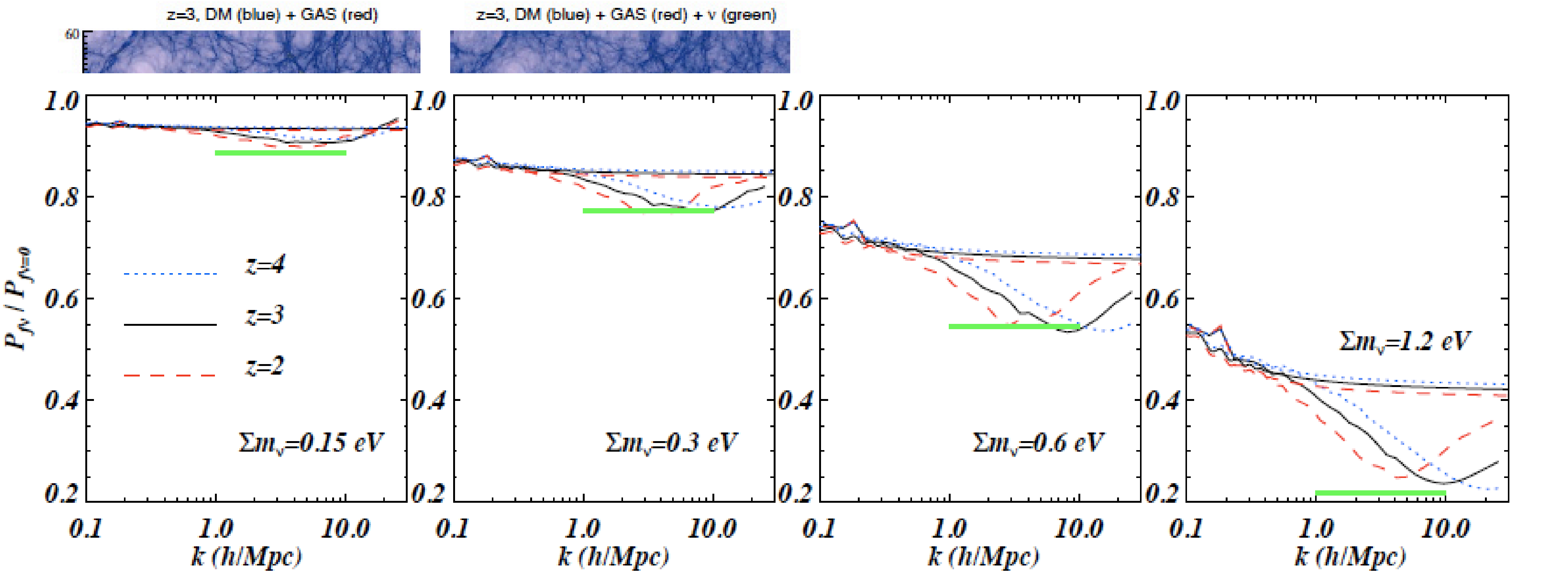
Neff = 5.2 (3.2 without Ly α)

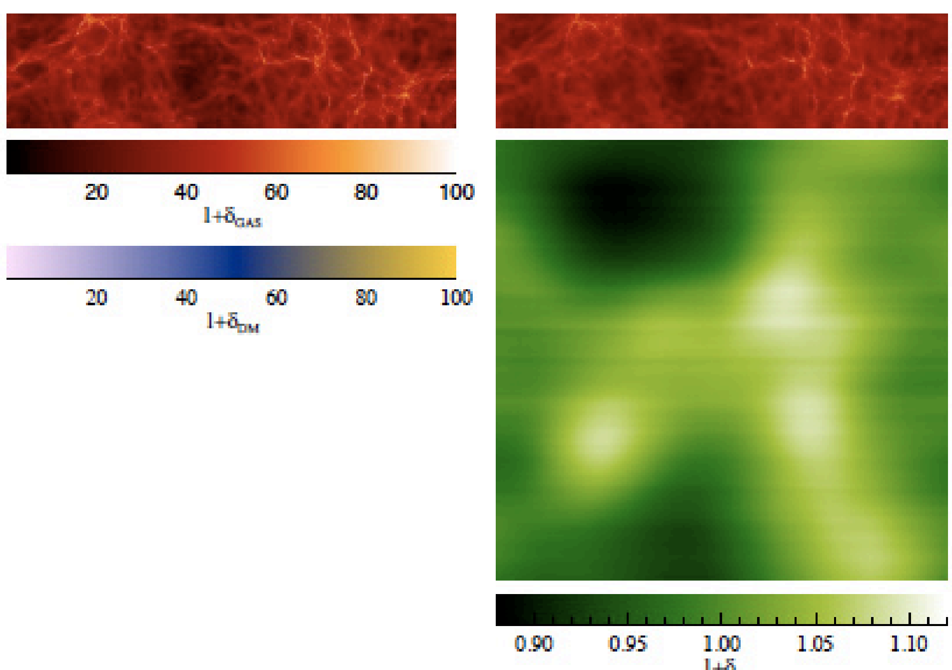
CMB + SN + SDSS gal+ SDSS Ly-α

Goobar et al. 06 get upper limits 2-3 times larger

for forecasting see Gratton, Lewis, Efstathiou 2007

Active neutrinos – III: non linear evolution





Viel, Haehnelt, Springel, 2010
JCAP, 06, 015

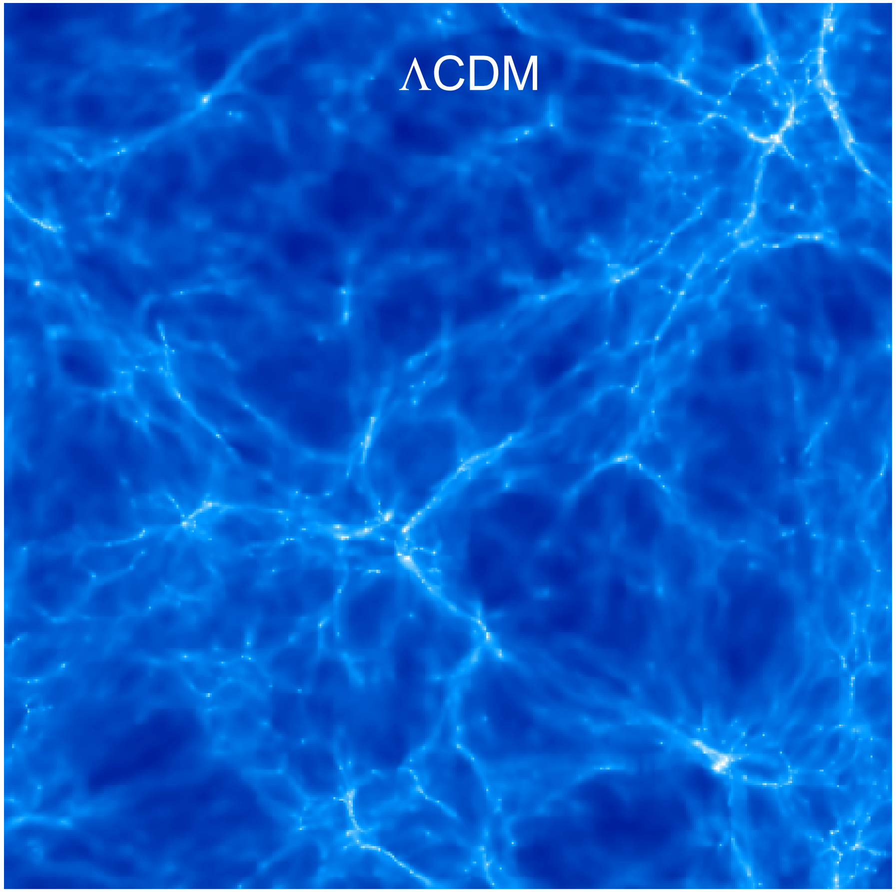
See also Brandbyge, Hannestad
et al. 2007,2008,2009

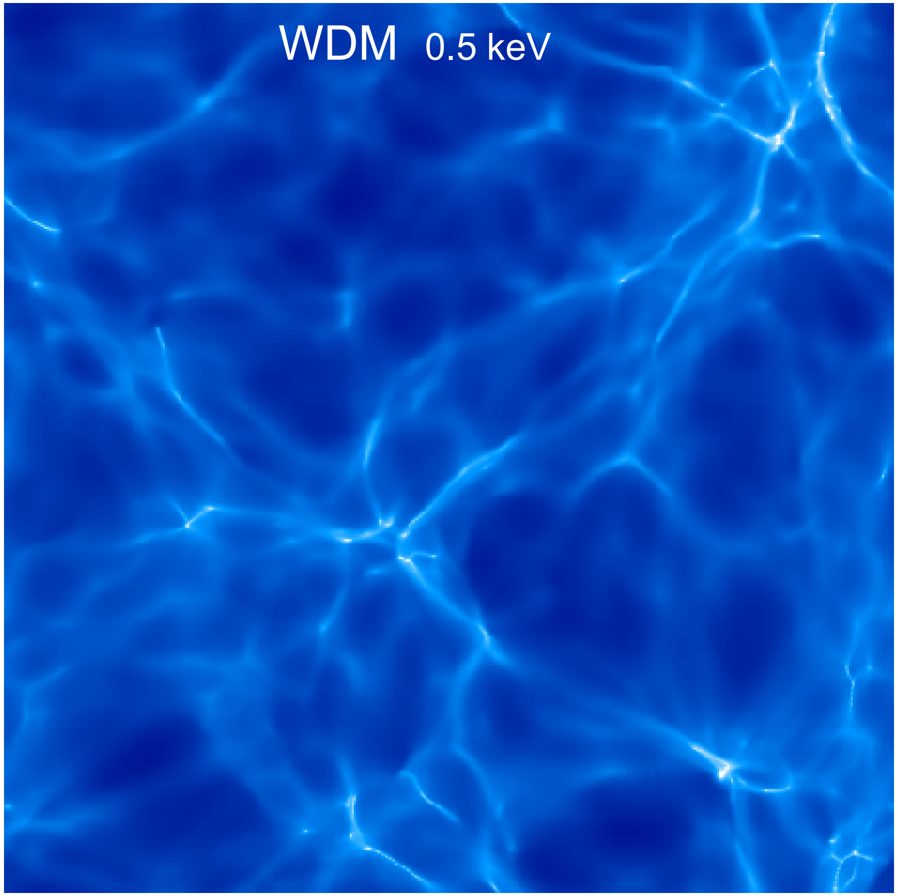
RESULTS

WARM DARK MATTER

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

Lyman-α and Warm Dark Matter - I





30 comoving Mpc/h z=3

In general

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

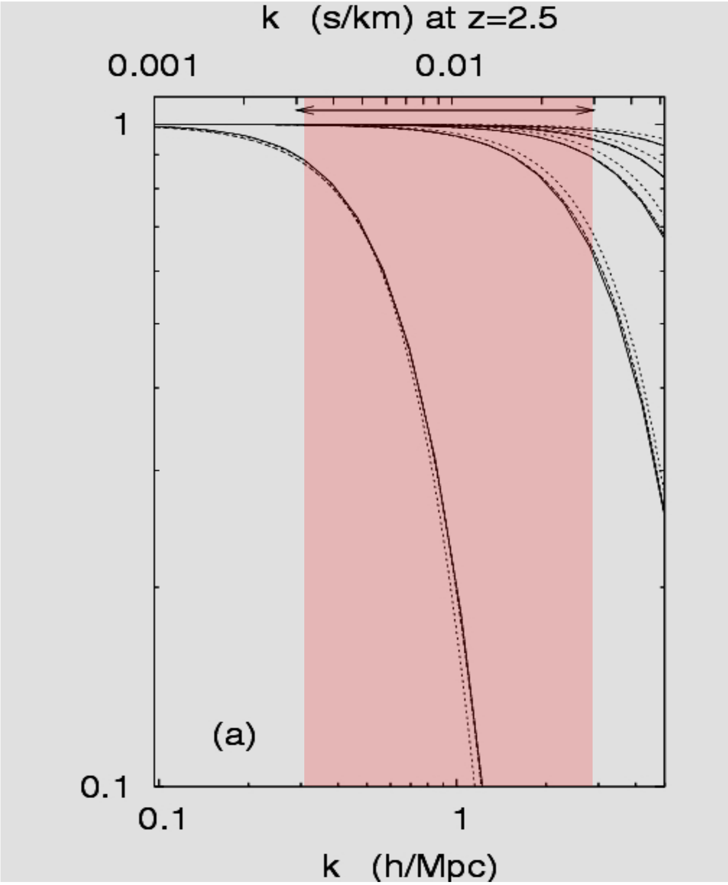
Set by relativistic degrees of freedom at decoupling

See Colombi, Dodelson, Widrow, 1996
Colin, Avila-Reese, Valenzuela 2000
Bode, Ostriker, Turok 2001
Abazajian, Fuller, Patel 2001
Abazajian 2006
Abazajian & Koushiappas 2006
Wang & White 2007
Colin, Avila-Reese, Valenzuela 2008
Tikhonov et al. 2009

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

Lyman-α and Warm Dark Matter - II

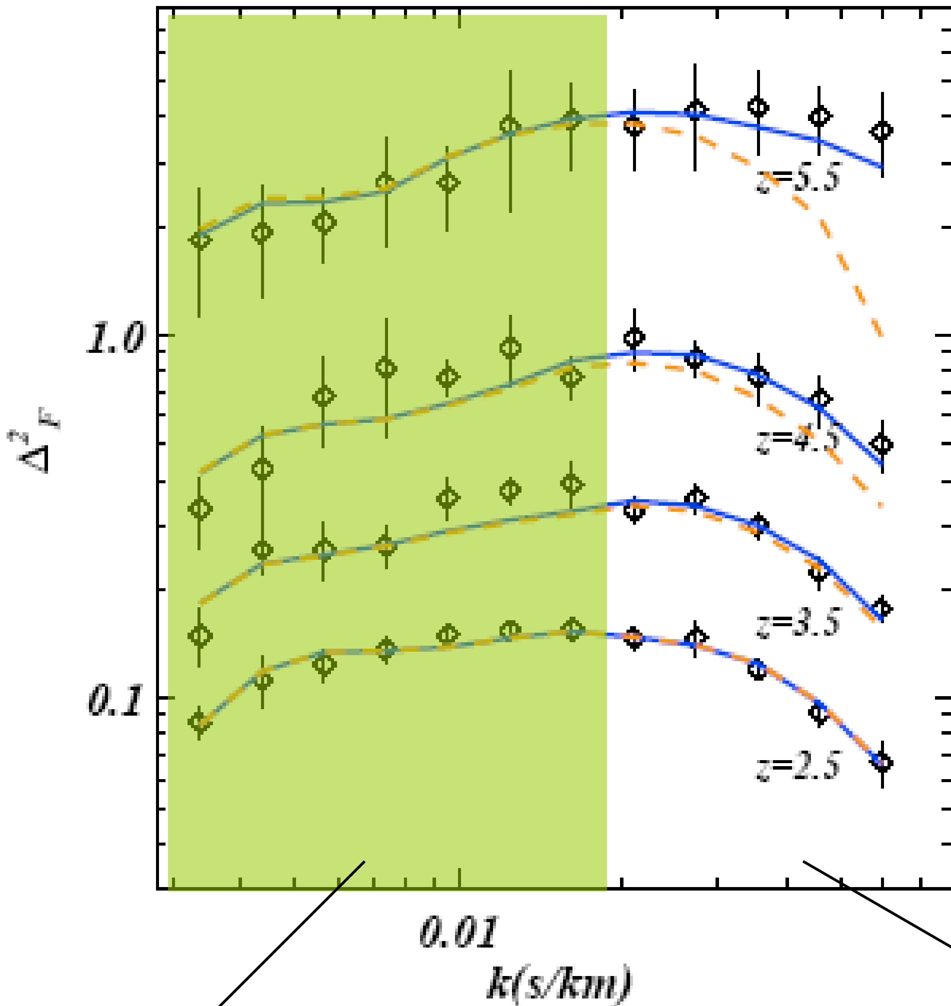
[P (k) WDM/P (k) CDM]$^{1/2}$



1.4 keV
1keV
0.7 keV
0.4 keV
0.1 keV

Lyman-α and Warm Dark Matter - III

MV, Becker, Bolton, Haehnelt, Rauch, Sargent, Phys.Rev.Lett. 100 (2008) 041304



SDSS range

Completely new small scale regime

SDSS + HIRES data

(SDSS still very constraining!)

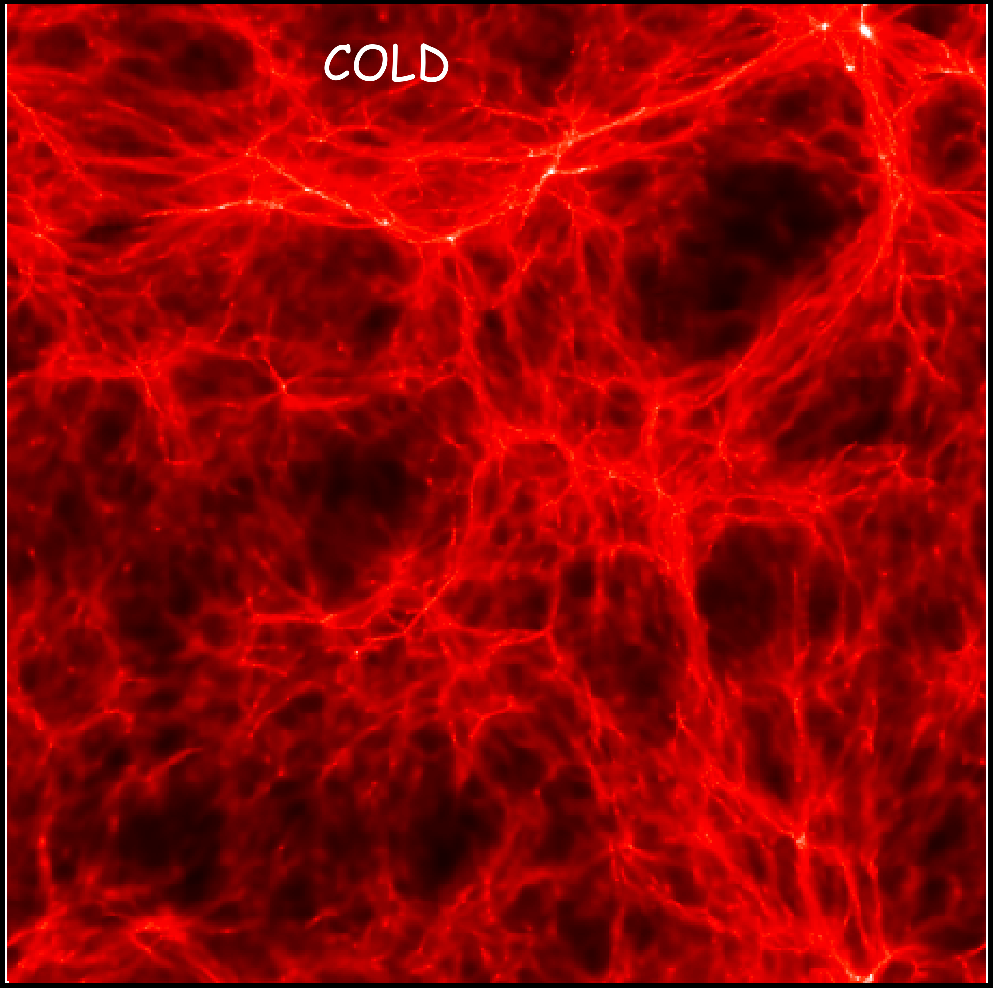
Tightest constraints on mass of WDM particles to date:

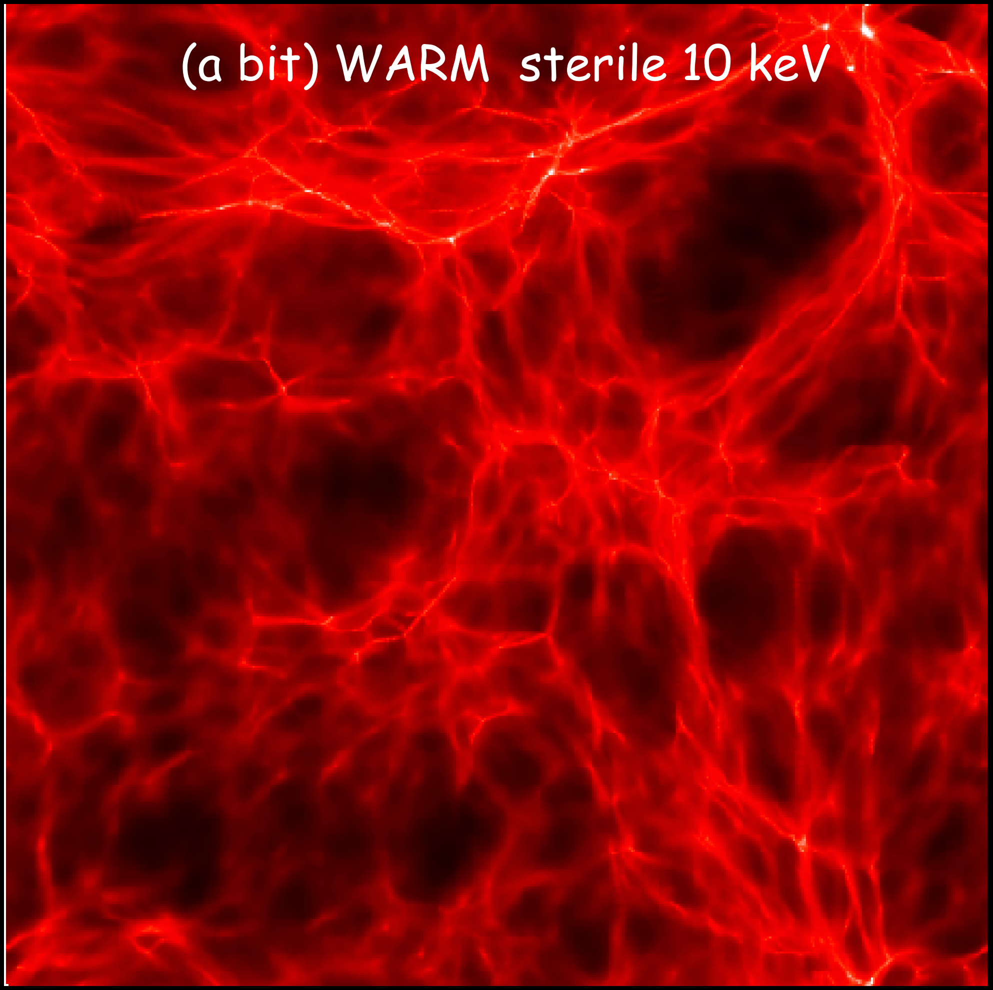
m_{WDM} > 4 keV (early decoupled thermal relics)

$m_{sterile}$ > 28 keV (standard Dodelson-Widrow mechanism)

Little room for standard warm dark matter scenarios……

… the cosmic web is likely to be quite "cold"

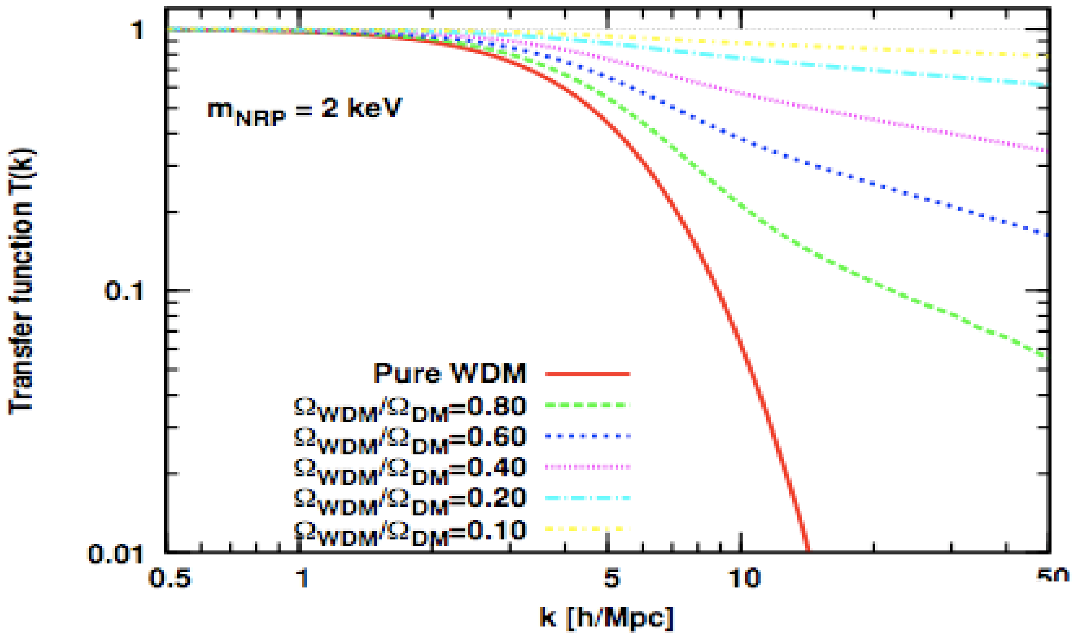




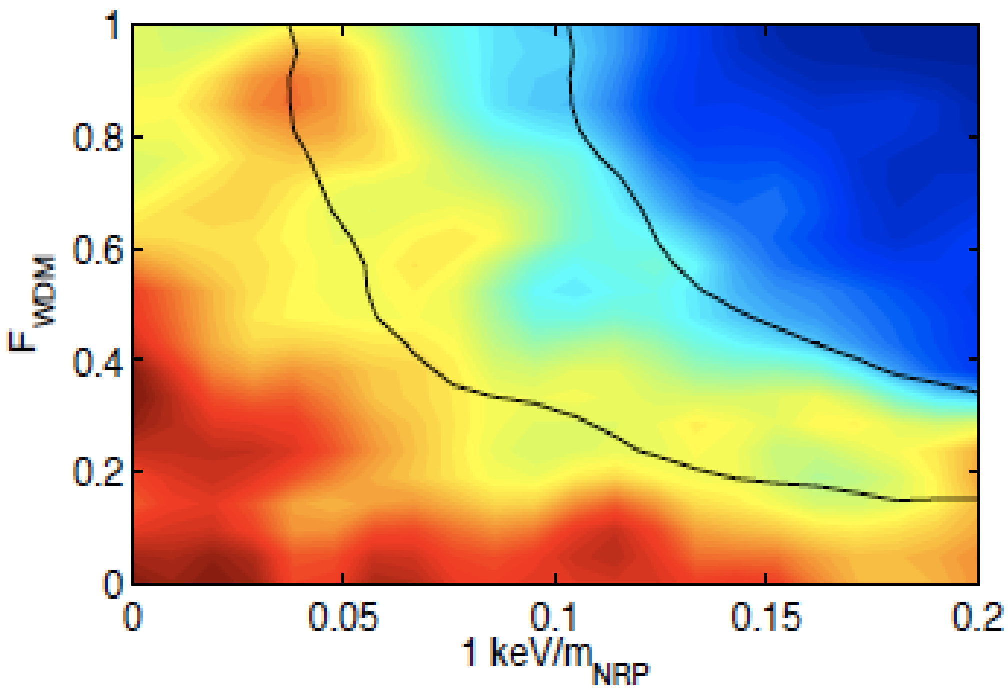
or in terms of halo masses...

$$M_{\rm FS} \approx 2.6 \times 10^{10}\ M_\odot/h\ \left(\frac{\Omega_m h^2}{0.14}\right)\left(\frac{\rm keV}{m_\nu}\right)^3\left(\frac{\langle p/T\rangle}{3.15}\right)^3$$

Lyman-α and Cold+Warm Dark Matter - I

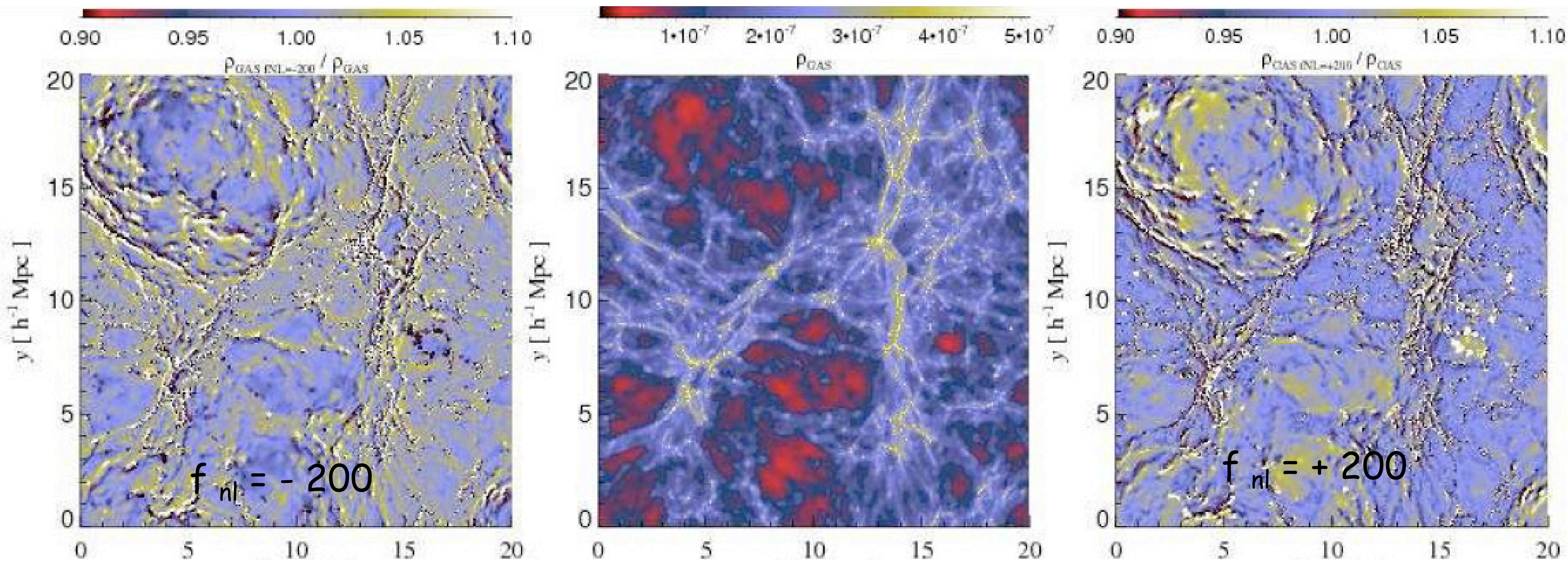


SDSS+WMAP5



further constraints
non gaussianities
DM-DE couplings...

First hydrodynamical simulation in NG scenario

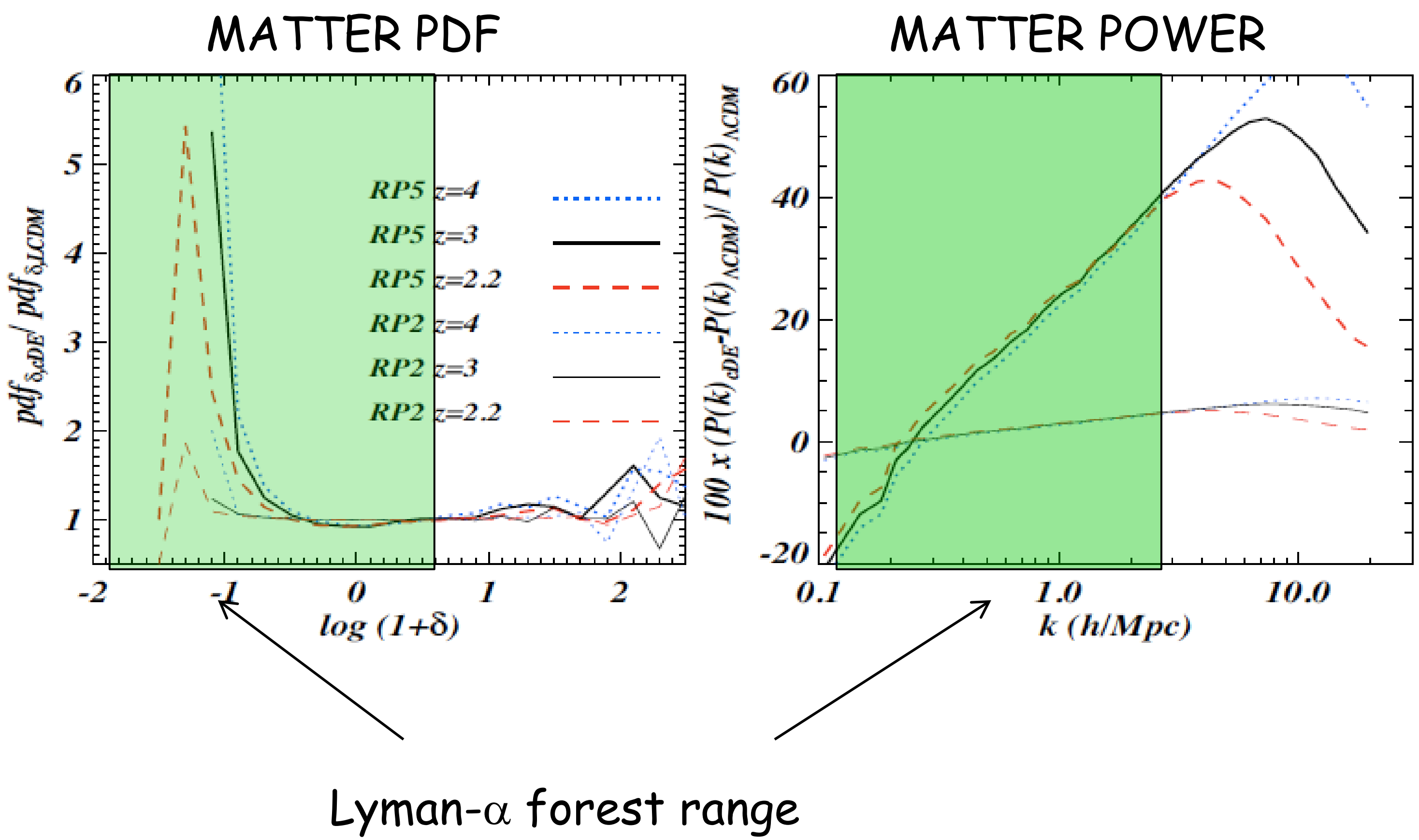


Viel, Branchini, Dolag, Grossi, Matarrese, Moscardini 2009, MNRAS, 393, 774

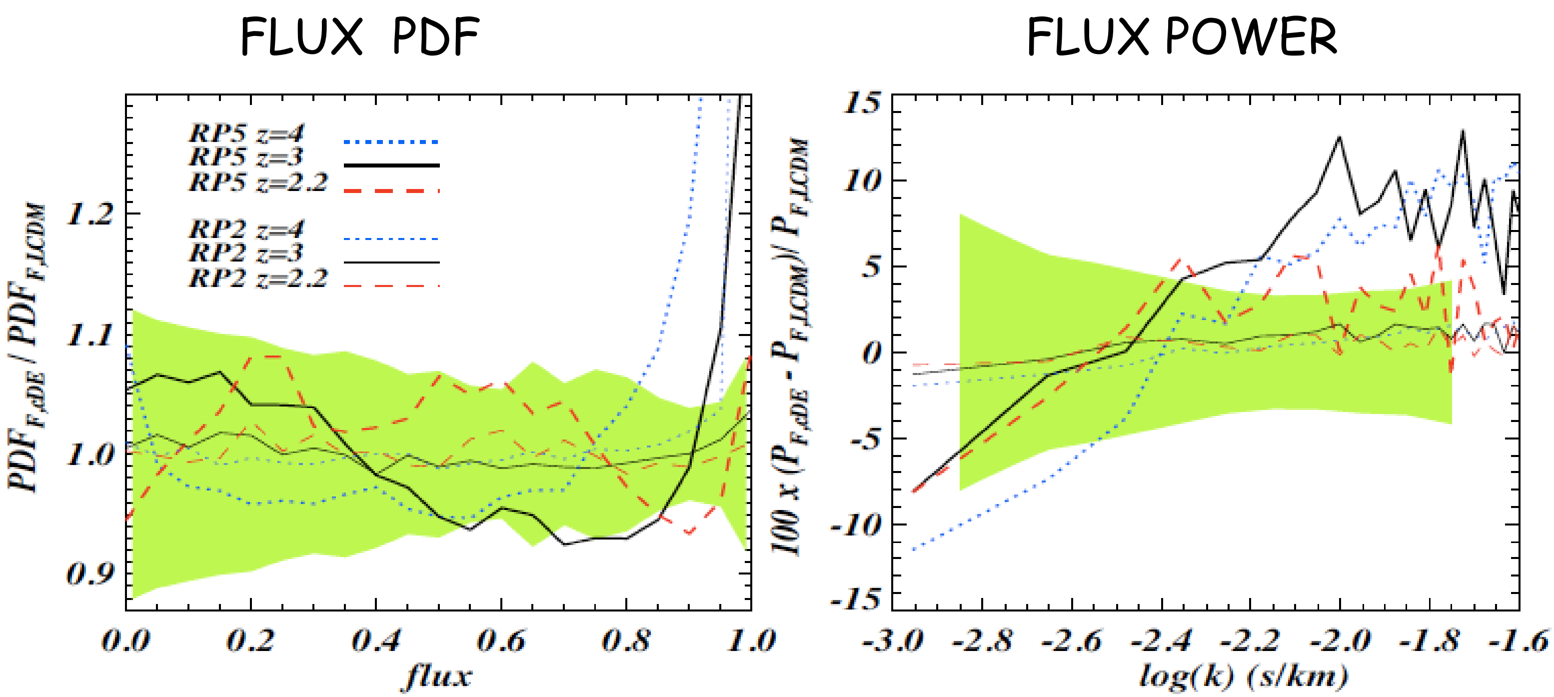
Hydro simulation for coupled dark energy cosmologies - I

Wetterich 95, Amendola 00,
Pettorino & Baccigalupi 08
Wintergest & Pettorino 010
Baldi & Pettorino 010
Maccio' et al 04, Li & Barrow 010

$$\rho_c' + 3\mathcal{H}\rho_c = -\beta\phi'\rho_c$$
$$\rho_\phi' + 3\mathcal{H}\rho_\phi = +\beta\phi'\rho_c$$



Hydro simulation of coupled dark energy: impact on flux - II

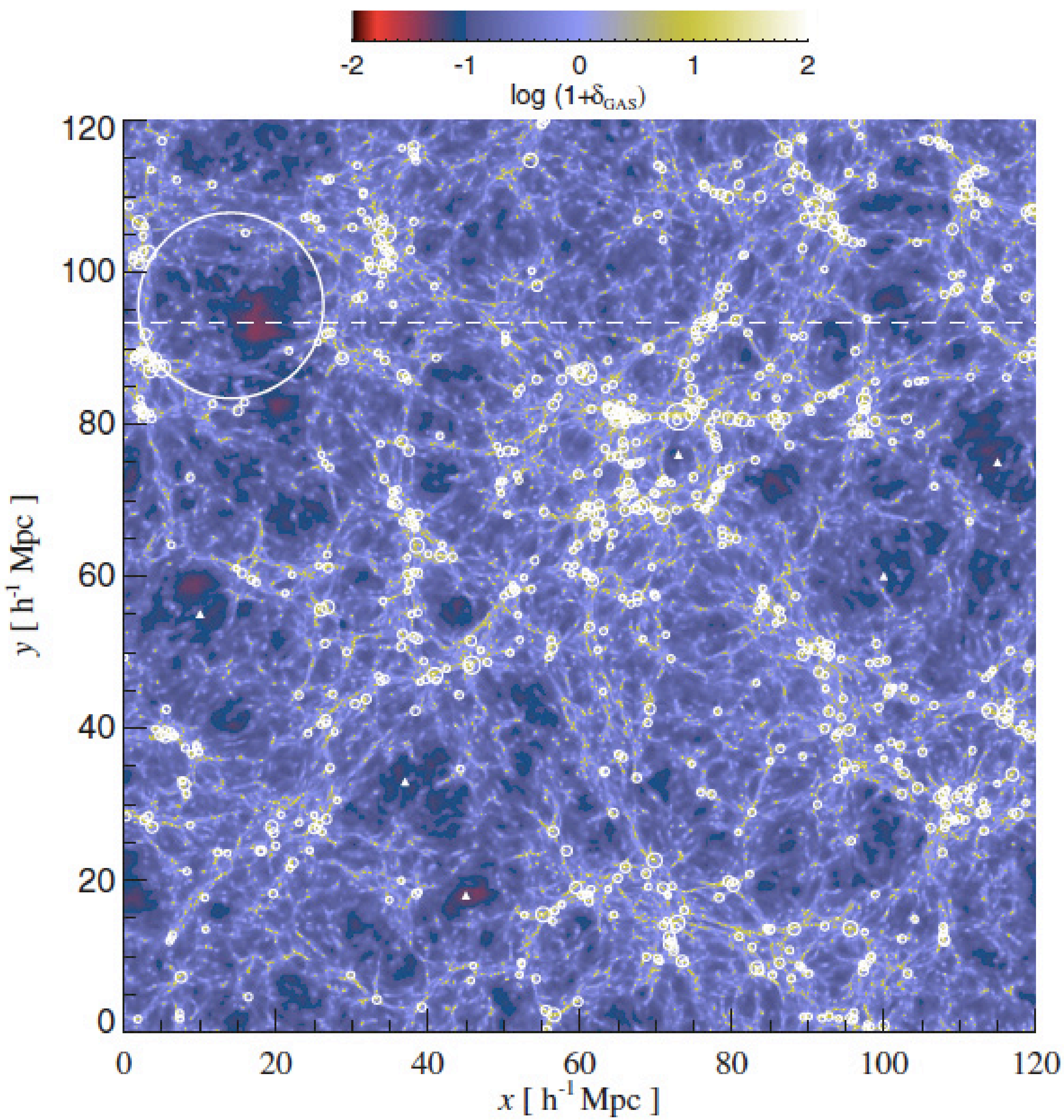


$\beta < 0.1\text{-}0.15$ (2σ C.L.)

Baldi & MV 2010

IGM-GALAXY INTERPLAY

Galaxies and the IGM – I: questions



MV, Colberg & kim 2010

Fundamental questions on the IGM Galaxy interplay:

1)How and when the IGM becomes metal enriched?

2)Are galaxies capable of modifying the physical state of the IGM around them via gravitational or astrophysical effects?

3)What is the low-redshift evolution of the cosmic web?

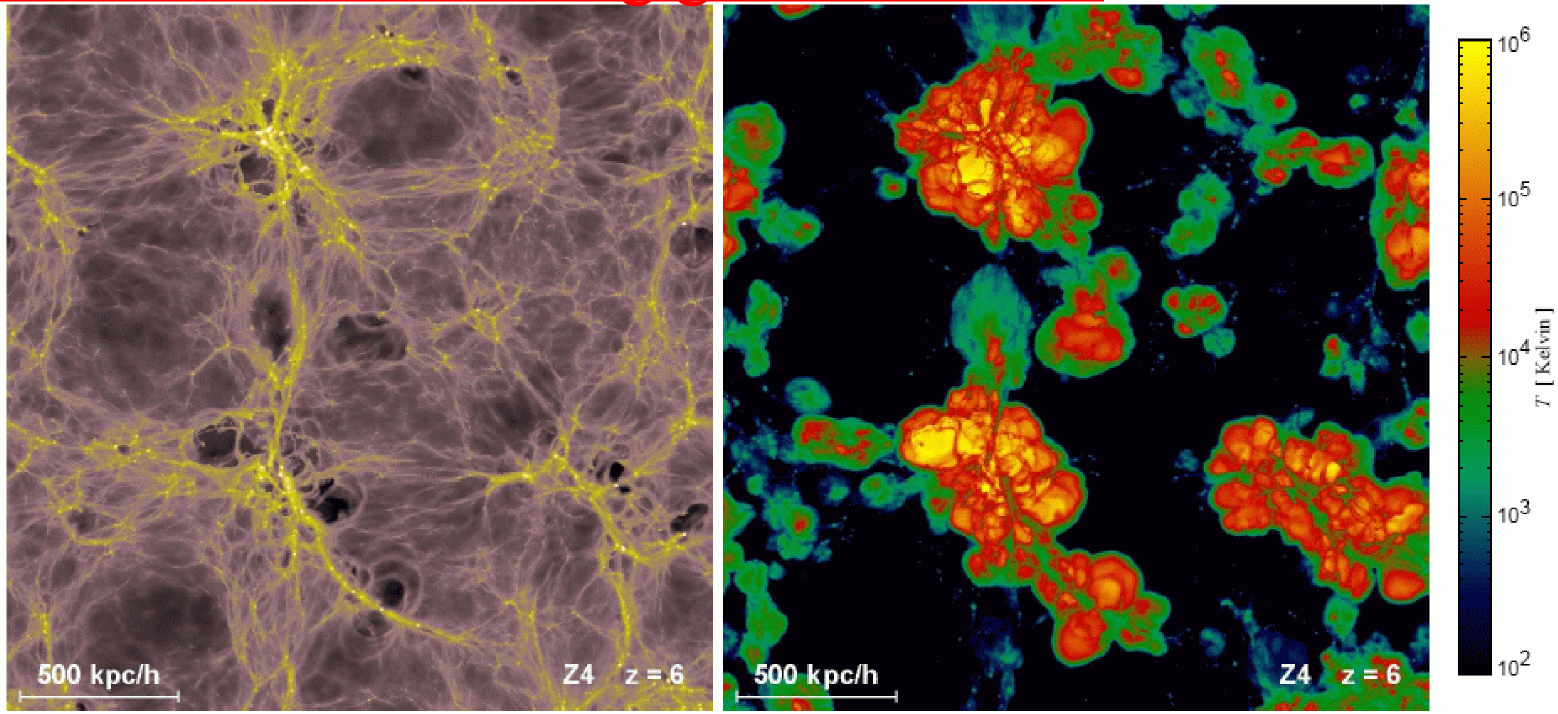
4) What is the nature of the ionizing sources during cosmic time?

5) To what extent galaxies trace the matter distribution at high redshift?

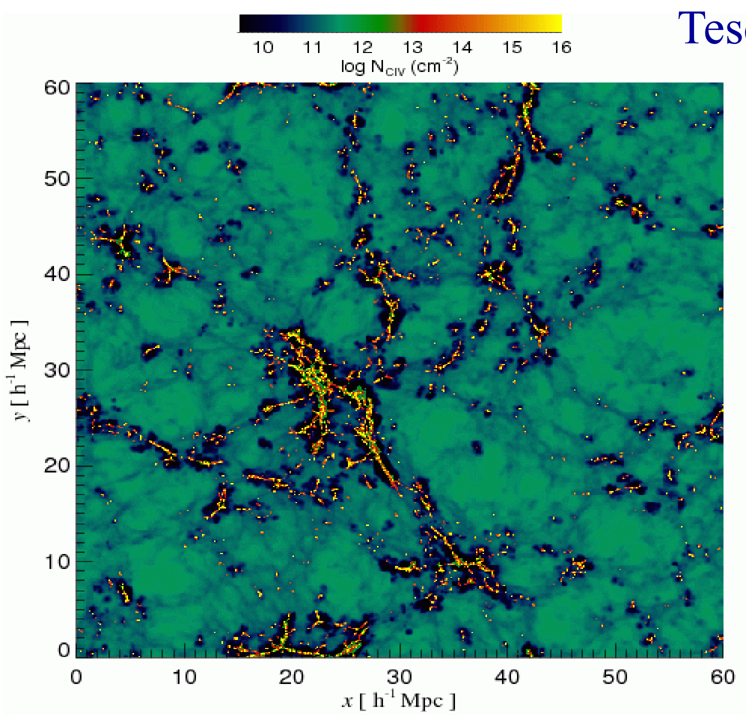
Galaxies and the IGM – II: simulating galactic winds

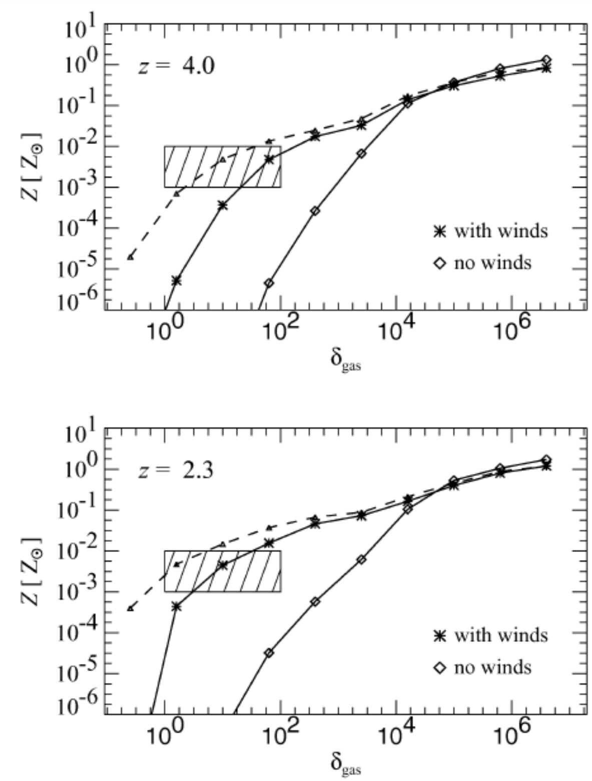
Springel & Hernquist 2002
Springel & Hernquist 2003

(Dave', Cen, Kawata, Theuns, Schaye etc.)



Tescari, MV et al. 2010

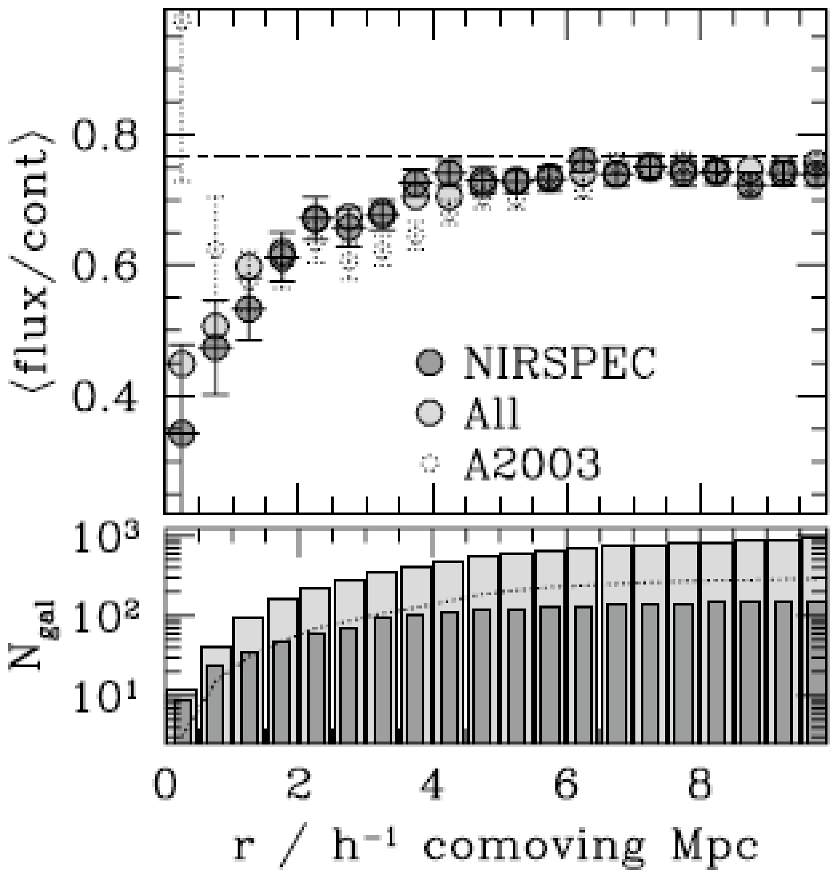


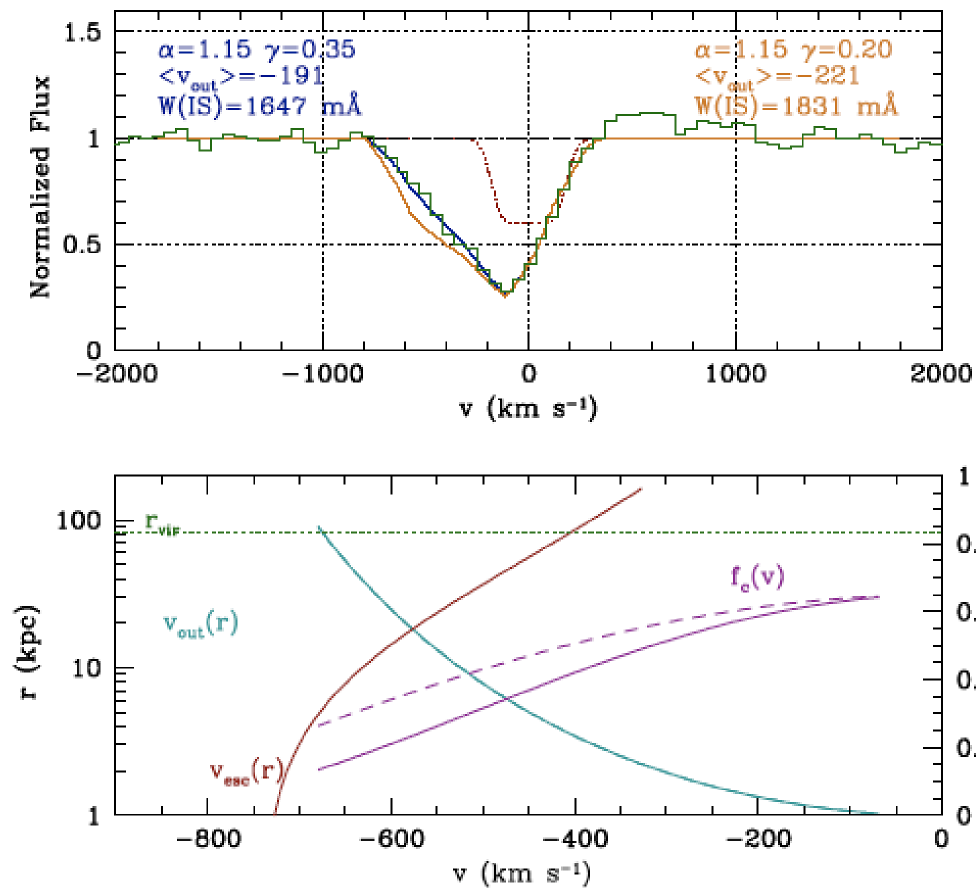


Galaxies and the IGM – III: observational results

$$a(r) = Ar^{-\alpha}$$

$$f_c(r) \propto r^{-\gamma}$$





Adelberger et al. 2005

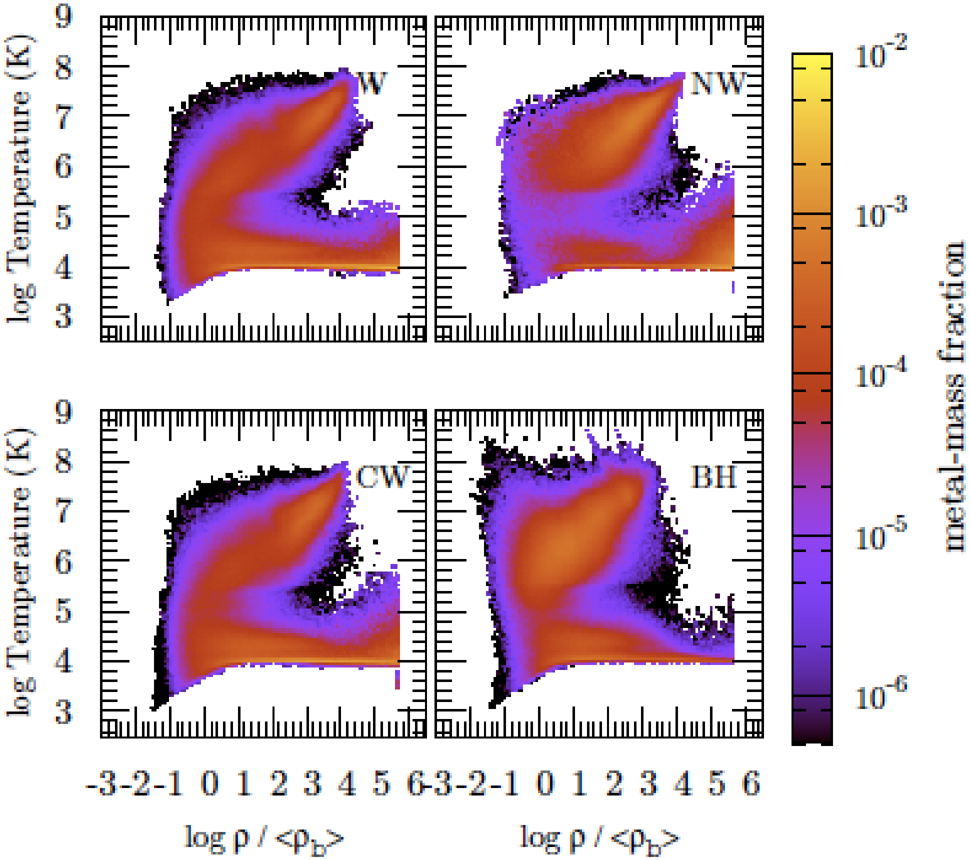
Background QSOs and foreground galaxies

Steidel et al. 2010

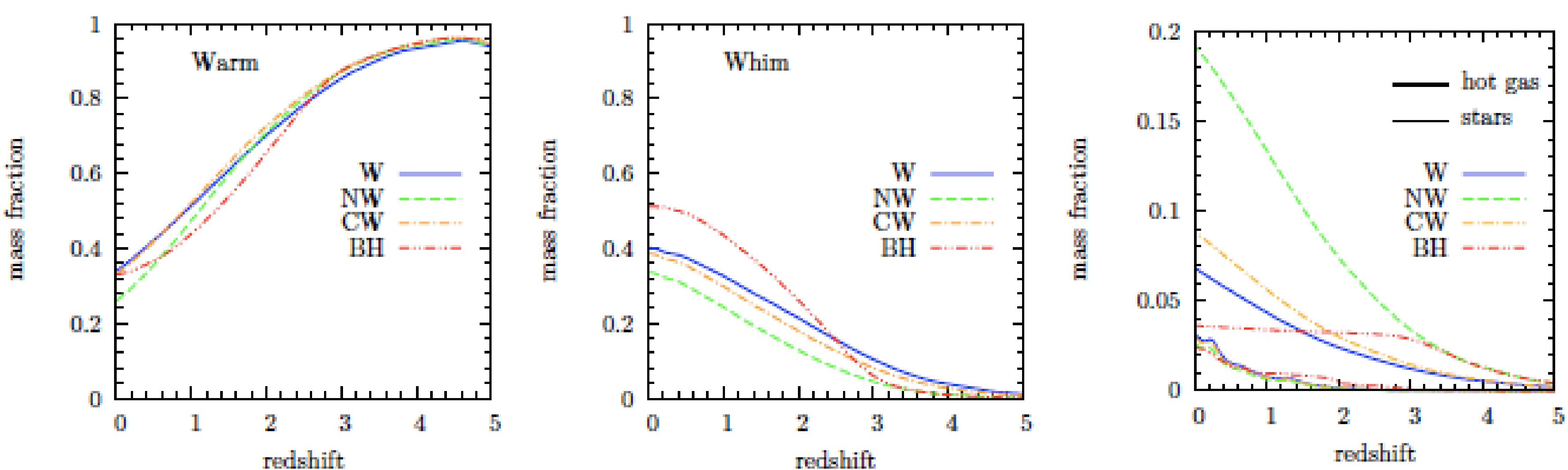
Background galaxies and foreground galaxies

Observational support for galacitc outflows at high redshift

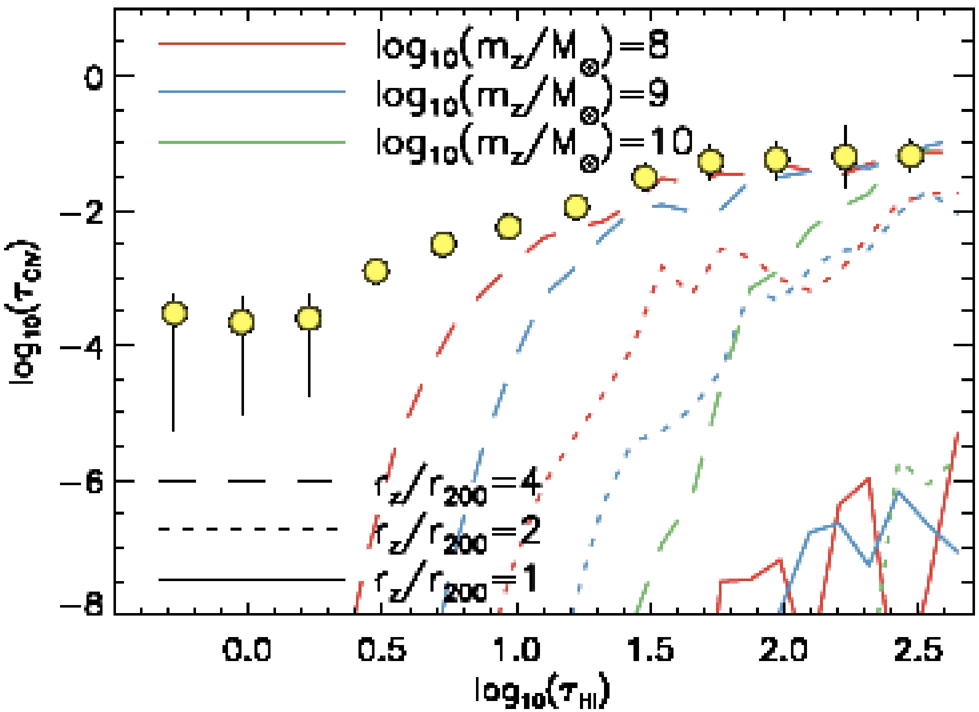
Galaxies and the IGM – IV: low redshift evolution and feedback



Tornatore, Borgani, Viel & Springel 2010

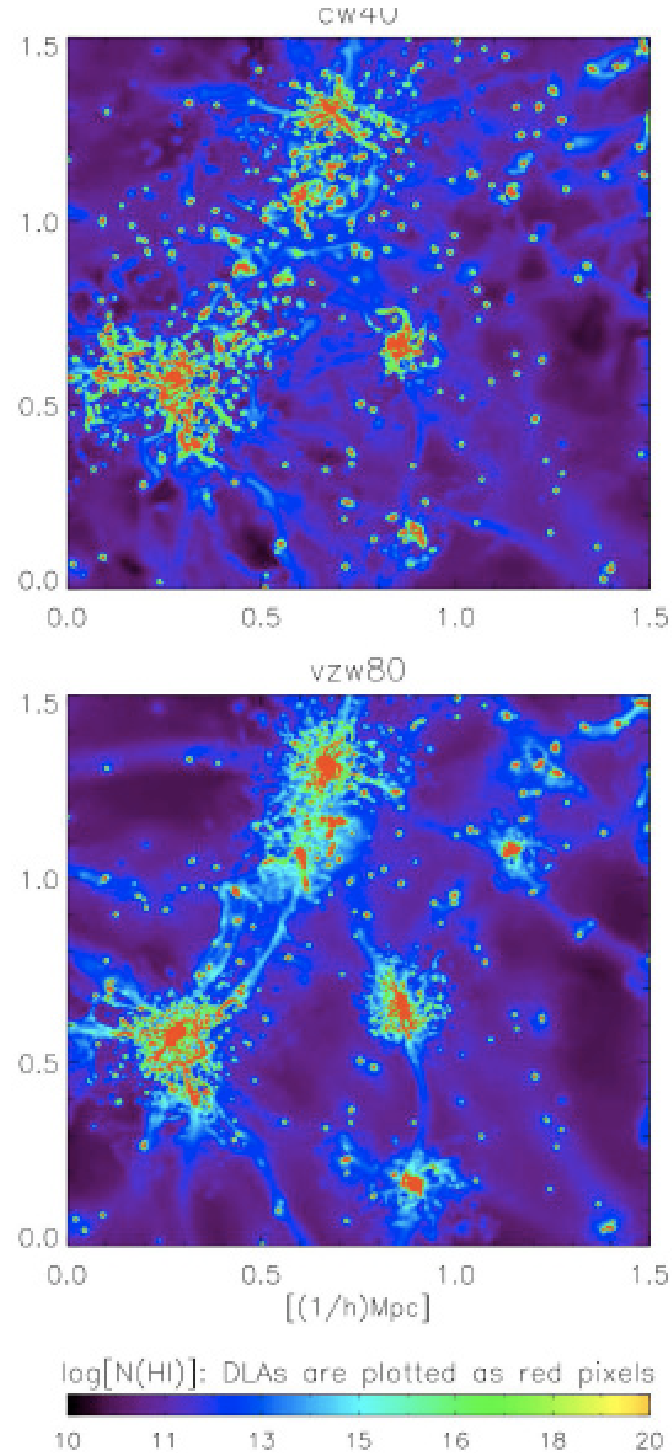


Galaxies and the IGM – IV: IGM metallicity



Booth et al. 2010
Schaye and co-workers

Hong et al. 2010
(Cen et al. 2010,
Dave' and co-workers,
Tescari, MV et al 09, 10



THE FUTURE

COSMIC EXPANSION

&

BAOs

Measuring the cosmic expansion?

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 136 SEPTEMBER 1962 NUMBER 2

THE CHANGE OF REDSHIFT AND APPARENT LUMINOSITY OF GALAXIES DUE TO THE DECELERATION OF SELECTED EXPANDING UNIVERSES

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
(With an Appendix by G. C. McVITTIE, University of Illinois Observatory, Urbana)

Received February 2, 1962; revised April 13, 1962

$$1 + z(t_0, t_e) = \frac{a(t_0)}{a(t_e)} = \frac{a_0}{a}$$

$$dz = \frac{\partial z}{\partial t_0} dt_0 + \frac{\partial z}{\partial t_e} dt_e$$

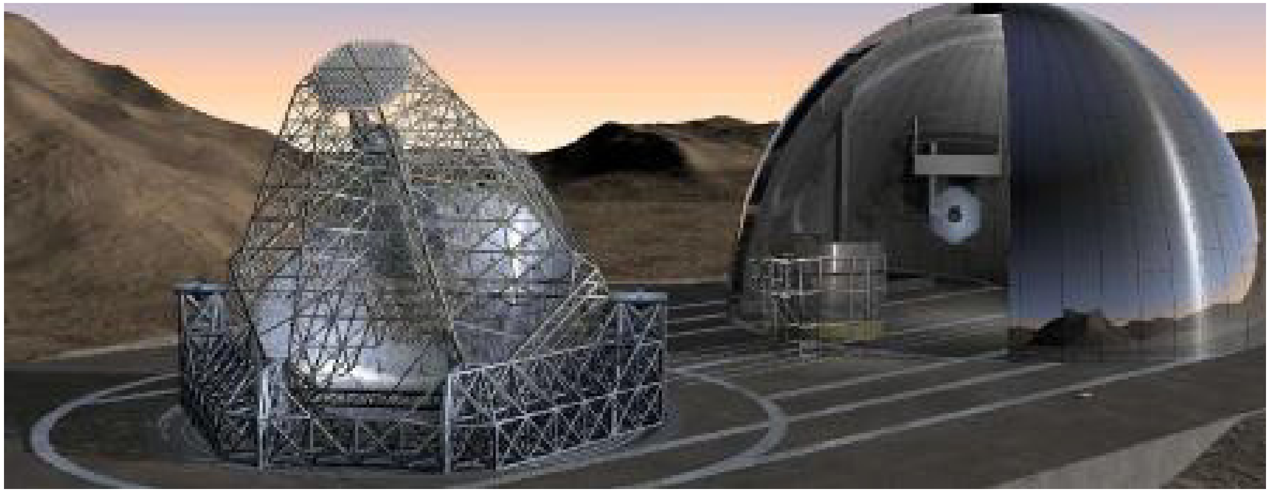
$$\dot{z} = \frac{dz}{dt_0} = \frac{\partial z}{\partial t_0} + \frac{\partial z}{\partial t_e}\frac{dt_e}{dt_0} = \frac{\dot{a}(t_0)}{a(t_e)} - \frac{\dot{a}(t_e)}{a(t_e)}\frac{a(t_0)}{a(t_e)}\frac{1}{1+z}$$

$$\dot{\mathbf{z}} = (\mathbf{1} + \mathbf{z})\mathbf{H}_0 - \mathbf{H}(\mathbf{t}_e)$$

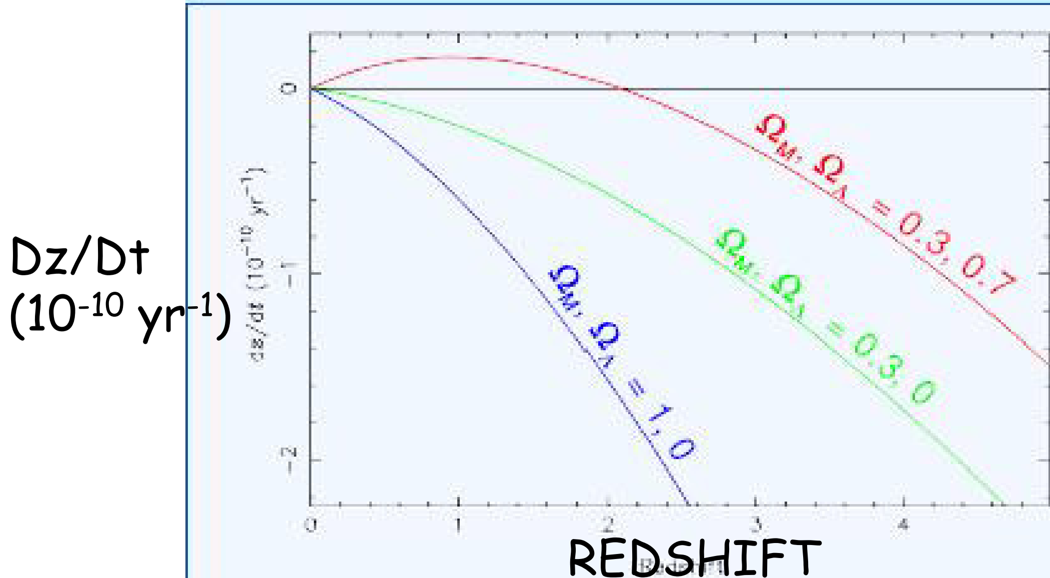
This is a fundamental quantity not related at all to the FRW equations….

COsmicDynamicEXperiment CODEX-I

Ultra-stable spectrograph



$$\frac{d}{dt_0}\left[1+z = \frac{a(t_0)}{a(t_e)}\right] \Rightarrow \frac{dz}{dt_0} = (1+z)\,H_0 - H(z)$$



dz/dt as a function of redshift for different cosmological parameters as indicated and H_0 = 70 km/s/Mpc.

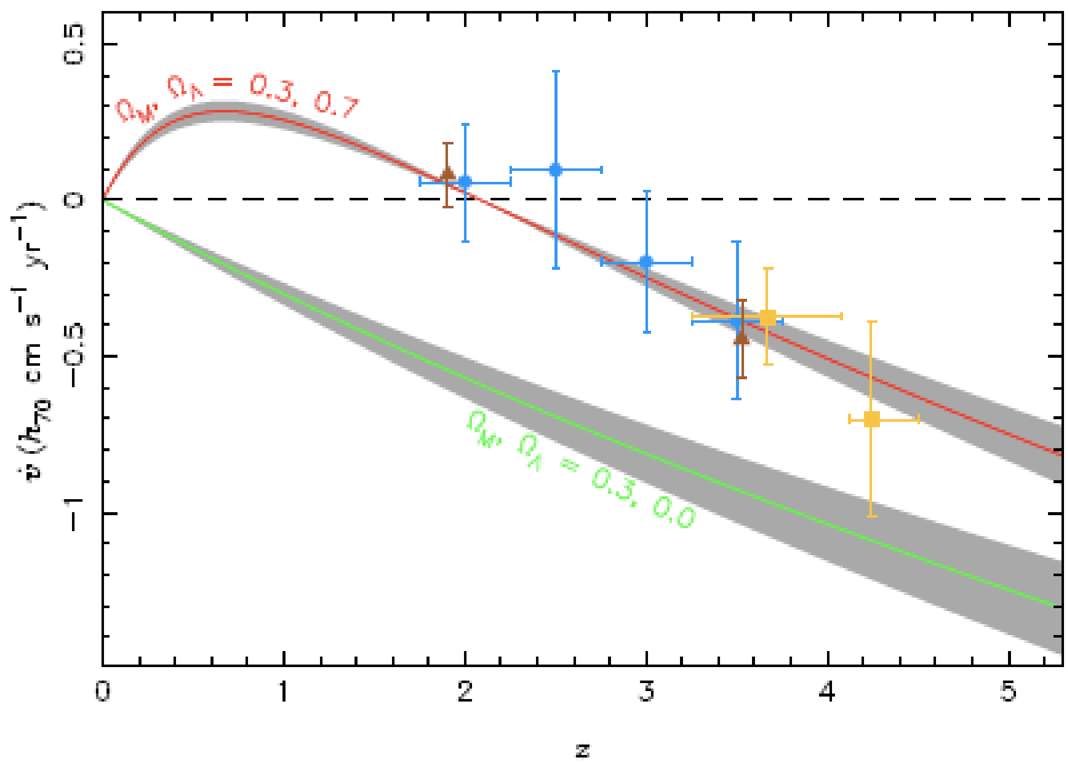
For Δt = 10 yr @ z = 4:

$\Delta z \sim 9 \times 10^{-10}$

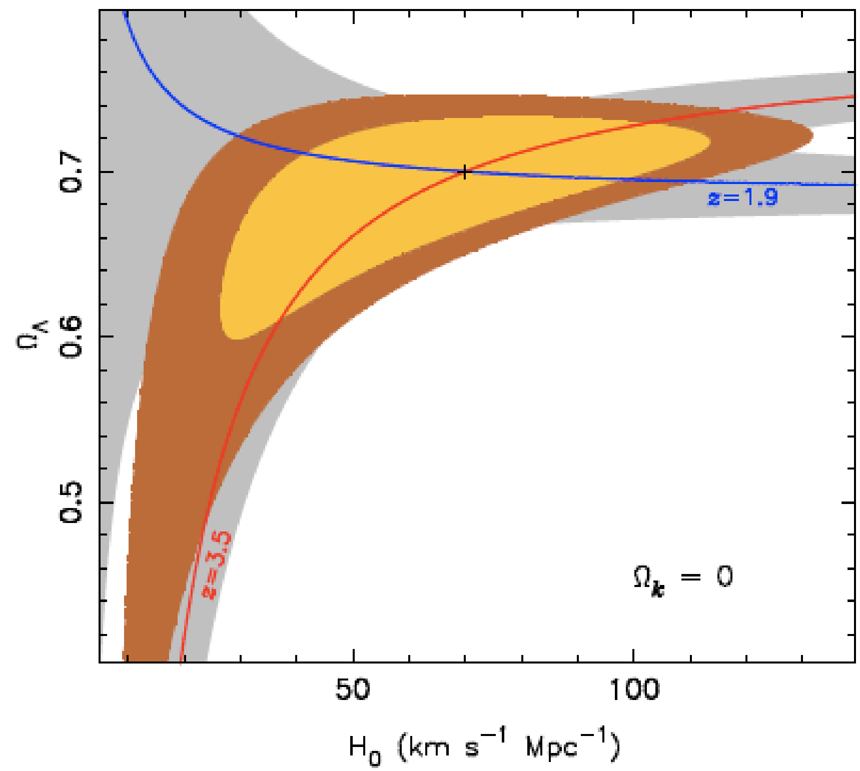
$\Delta\lambda \sim 1 \times 10^{-6}$ Å

$\Delta v \sim 5.4$ cm/s

COsmicDynamicEXperiment CODEX - II

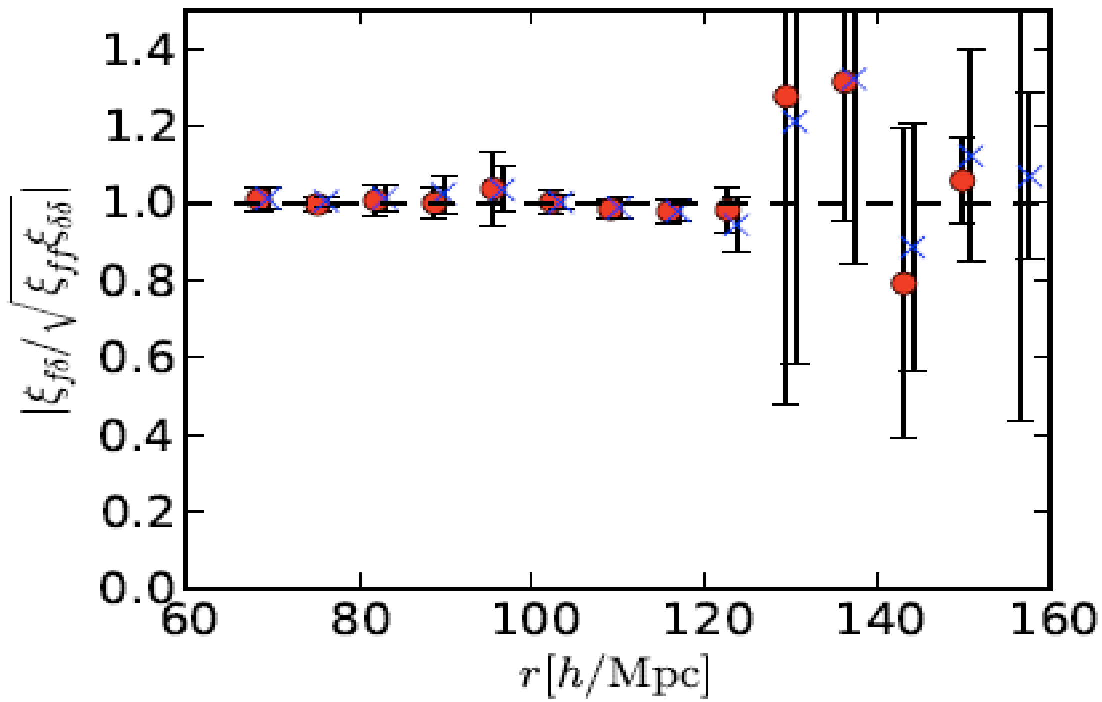


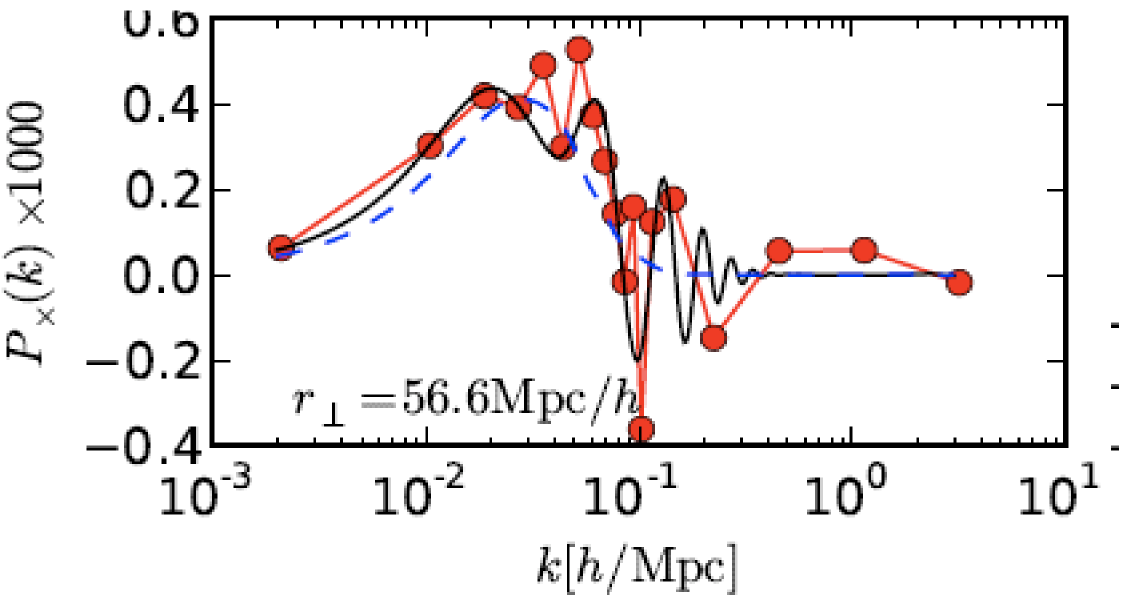
Liske et al. 2008, MNRAS, 386, 1192



Another scientific goal:
Real-time mapping of gravitational potentials:
Amendola et al. 2008
Quercellini et al. 2010

BAOs in the Lyman-a forest: probing the transverse direction





Importance of transverse direction:
MV et al 2002; White 2003;
McDonald & Eisenstein 2007;
Slosar et al. 2010

about 20 QSOs per square degree
with BOSS

SUMMARY

- Lyman-α forest is an important cosmological probe at a unique range of scales and redshifts in the structure formation era

-For fundamental physics great QUANTITATIVE progress in the last few years:

m_{WDM} = 0.5 keV → 2 keV → 4 keV (2σ lower limits)
$m_{STERILE}$ = 2 keV → 12 keV → 28 keV (2σ lower limits)
Σm_{ν} = 1eV → 0.19 eV (2σ upper limits)

- Current limitations are more theoretical (more reliable simulations are needed for example for neutrino species) than observational and statistical errors are smaller than systematic ones

-Tension with the CMB still present. Systematic errors not fully under control. But this is unlikely to affect the results above. Importance of cross-correlations of different observables in the SDSS-III/LHC era.

- Mechanism of metal enrichment not understood. Simulated winds do not look like real ones.

cosmoIGM: ERC Starting Grant – 2010 (4 postdocs + SDSS)
Email: viel@oats.inaf.it

COSMOLOGY

IGM as a tracer of the large scale structure of the universe: tomography of IGM structures; systematic/statistical errors; sinergies with other probes – IGM unique in redshift and scales

cosmoIGM

IGM as a probe of fundamental physics: dark matter at small scale; neutrinos; coldness of dark matter; fundamental constants; cosmic expansion

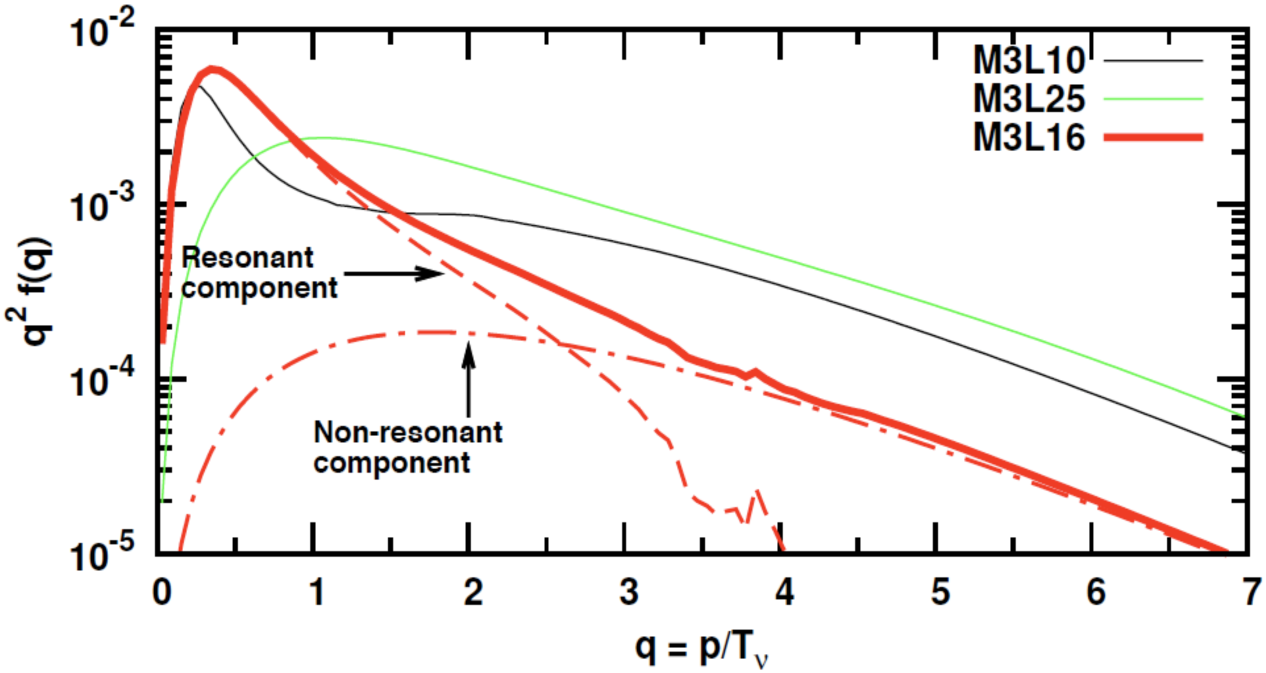
PARTICLE PHYSICS

Galaxy/IGM interplay: metal enrichment and galactic feedback; impact on the cosmic web and metal species; the UV background; the temperature of the IGM

GALAXY FORMATION

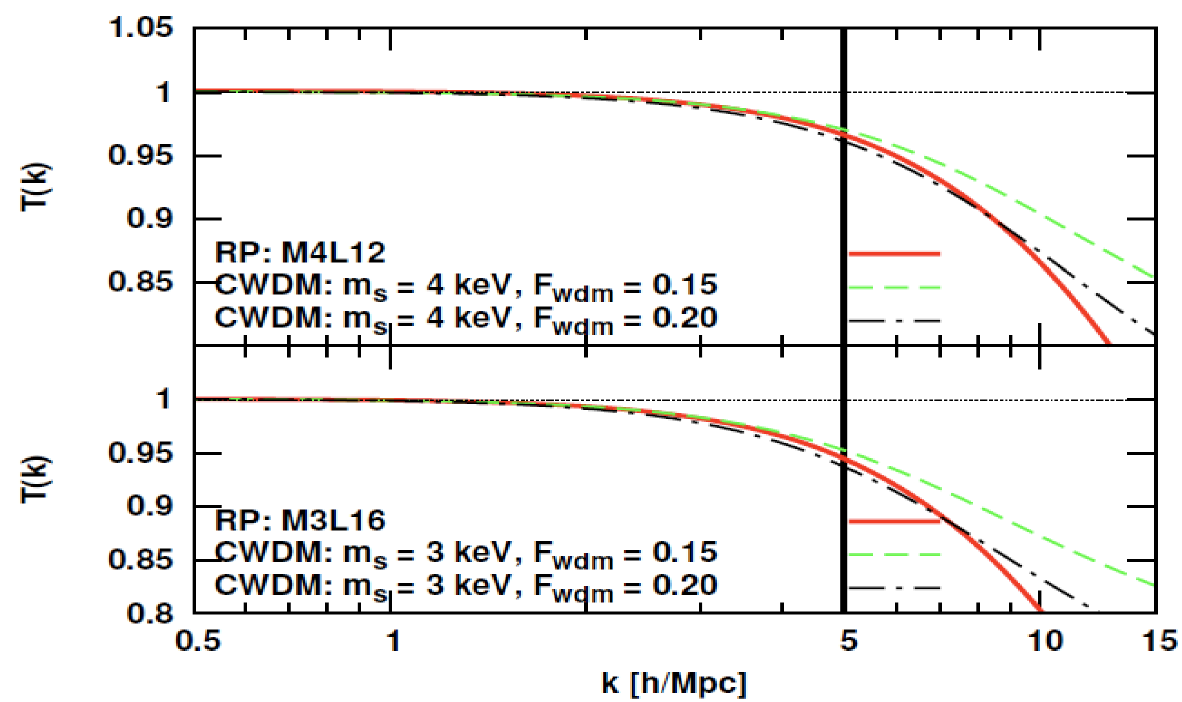
THE END

Lyman-α and resonantly produced sterile neutrinos - I



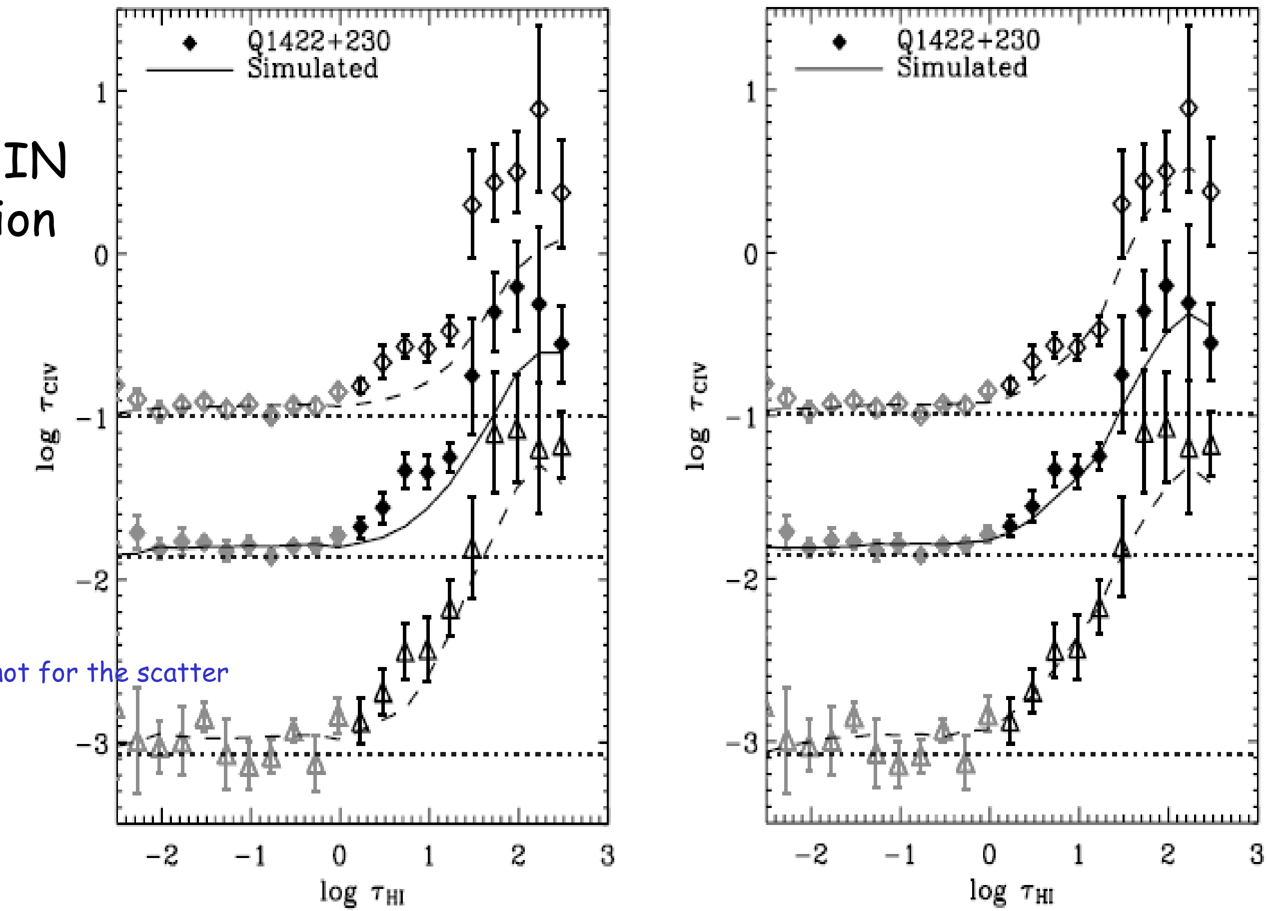
$L=10^6\,(n\,\nu_e\ - n\,\underline{\nu_e}\,)/s$

Mass sterile = 3 keV



Observations: the POD technique-II

NO SCATTER IN THE Z-ρ relation



SCATTER IN THE Z-ρ relation

Good fit to the median but not for the scatter

FIG. 5.—Comparison of the optical depth statistics of observed and simulated spectra using the metal distribution measured from the observations. From top to bottom the three sets of data points are the 84th (*open diamonds*), 69th (*solid diamonds*), and 50th (*triangles*) percentiles of the recovered C IV optical depth as a function of $\tau_{\rm H\,I}$ for Q1422+230. For clarity, the 84th and 69th percentiles have been offset by +1.0 and +0.5 dex, respectively. The curves in the left-hand panel are for a simulation in which each particle was given the median metallicity measured from the observations, $[{\rm C/H}] = -3.12 + 0.90(\log\delta - 1.0)$. The simulation can fit the observed median $\tau_{\rm C\,IV}$ (χ^2 probability $Q = 0.21$), but not the observed $\tau_{\rm C\,IV}(\tau_{\rm H\,I})$ for the other percentiles ($Q < 10^{-4}$). The curves in the right-hand panel are for a simulation that has the same median metallicity, but which includes scatter. The simulation cube was divided into 10^3 cubic sections, and all particles in each section were given a metallicity of $[{\rm C/H}] = -3.12 + s + 0.90(\log\delta - 1.0)$, where s, which is the same for all particles in the subvolume, is drawn at random from a lognormal distribution with mean 0 and variance $\sigma = 0.81$ dex as measured from the observations. The simulation provides an acceptable fit to all percentiles (from top to bottom, $Q = 0.33$, 0.69, and 0.90).

Schaye et al., 2003, ApJ, 596, 768

RESULTS "NEW" WARM DARK MATTER MODEL

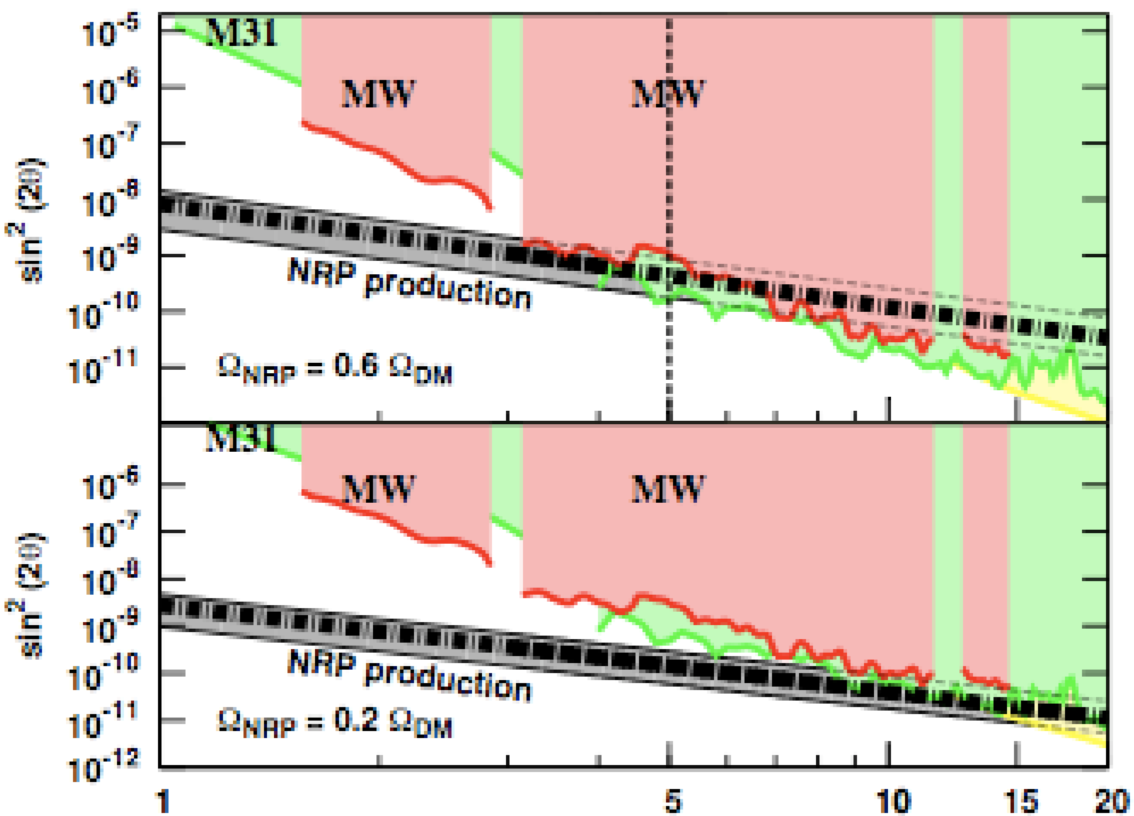
(sterile neutrino)

Mixed Cold and Warm models: Boyarsky, Lesgourgues, Ruchayskiy, Viel, 2009, JCAP, 05, 012 → REVIEW!

Shi & Fuller 1999 model:
Boyarsky, Lesgourgues, Ruchayskiy, Viel, 2009, Phys.Rev.Lett, 102, 201304

Lyman-α and Cold+Warm Dark Matter - II

X-ray flux ~ $\theta^2 M_{sterile}^{\ 5}$

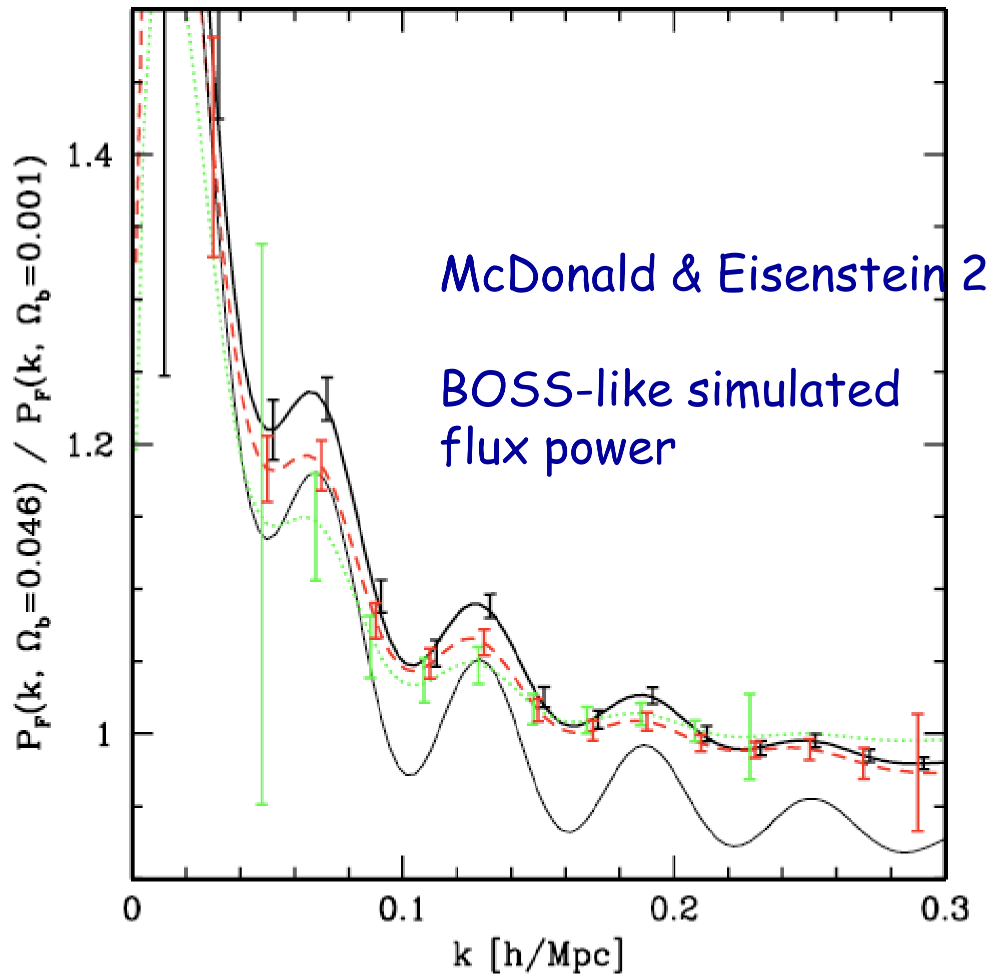


For m > 5 keV any fraction of WDM < 0.6 is allowed – frequentist analysis 99.7% C.L.
For m > 5 keV any fraction of WDM < 0.35 is allowed – bayesian analysis 95% C.L.

Future perspectives : BAO

Importance of transverse direction:
MV et al 2002; White 2003;
McDonald & Eisenstein 2007;
Slosar et al. 2009

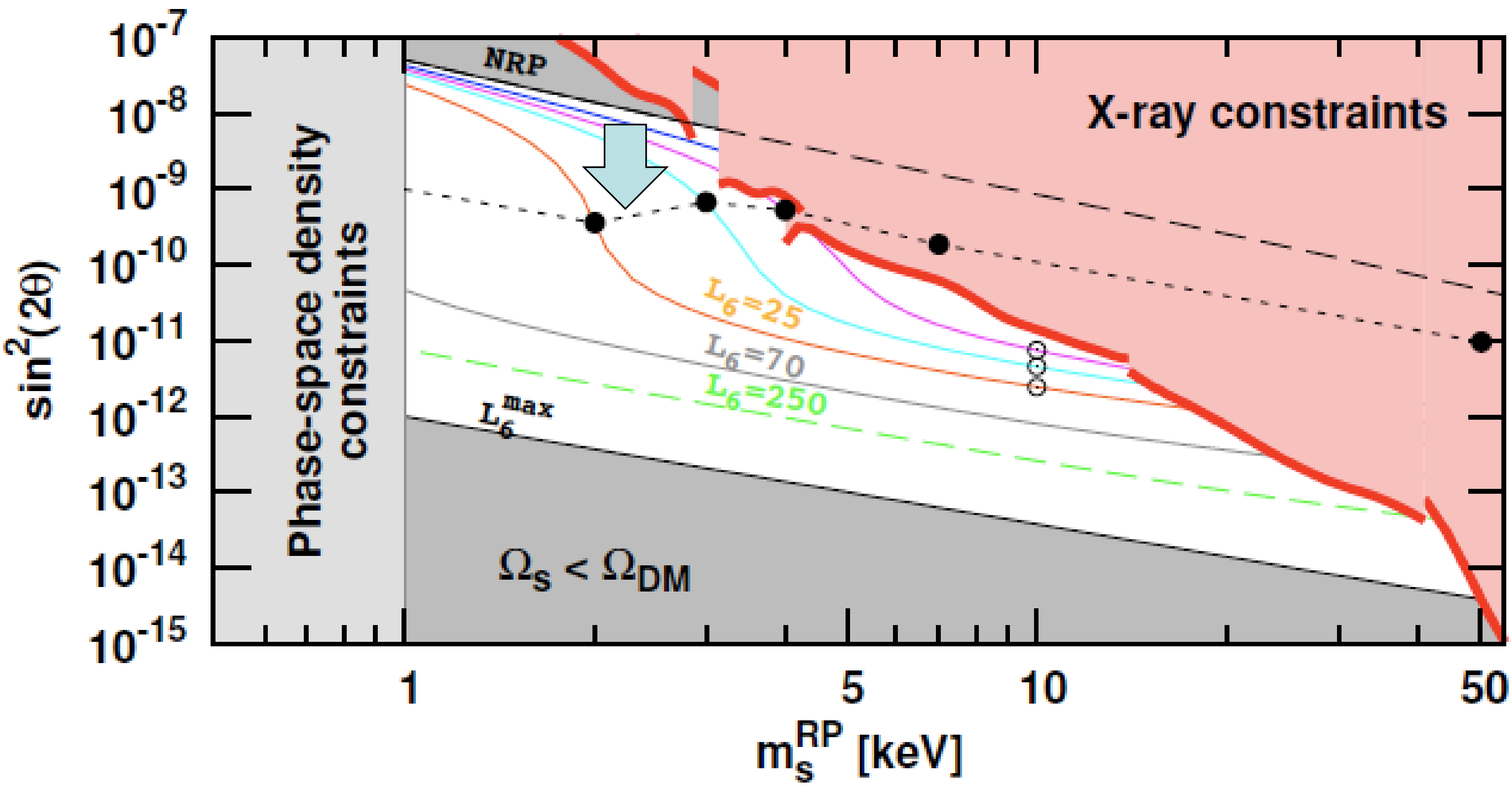
about 20 QSOs per square degree
with BOSS



McDonald & Eisenstein 2007

BOSS-like simulated flux power

Lyman-α and resonantly produced sterile neutrinos - II



Opening up a new (more physically motivated window) for $m_{sterile} > 2$ keV

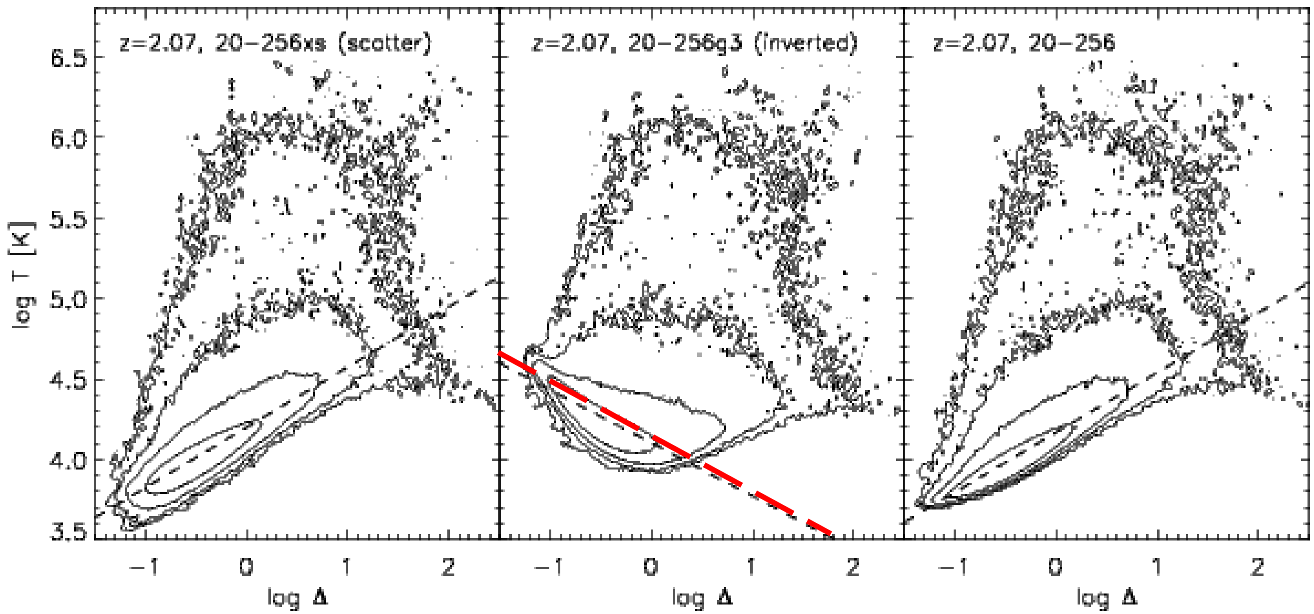
SYSTEMATICS

Fitting the flux probability distribution function

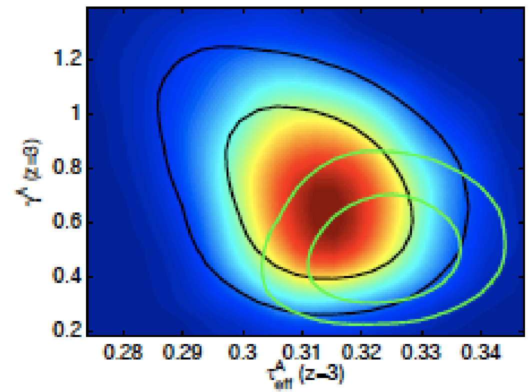
Bolton, MV, Kim, Haehnelt, Carswell (08)

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

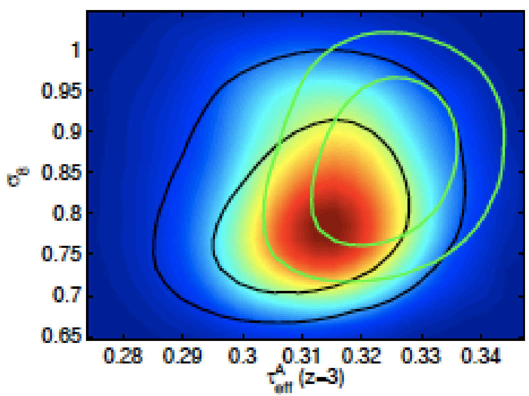
Inverted equation of state $\gamma<1$ means voids are hotter than mean density regions



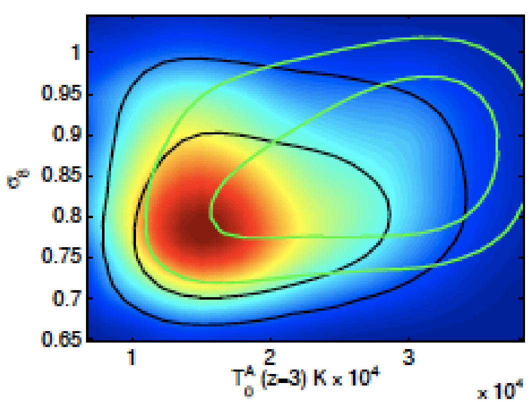
Fitting the flux probability distribution function-II



1) Fitting all flux statistics at once (see Desjacques & Nusser 07) will make clear at which level we are affected by systematics



2) However, already from the flux PDF (one point statistics) there are very interesting constraints on thermal state of the IGM and on some cosmological parameters



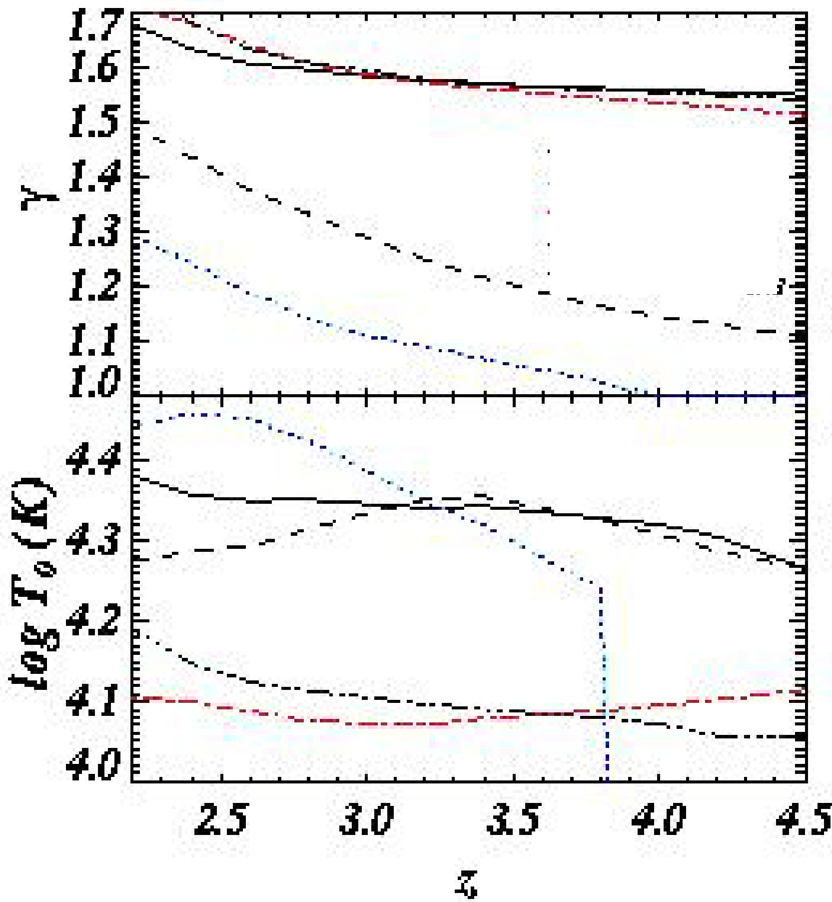
3) Flux power prefers a higher temp. than the flux pdf alone: joint constraints reasonable and still prefers a high σ_8 than the CMB alone

Viel, Bolton, Haehnelt, 2009, MNRAS

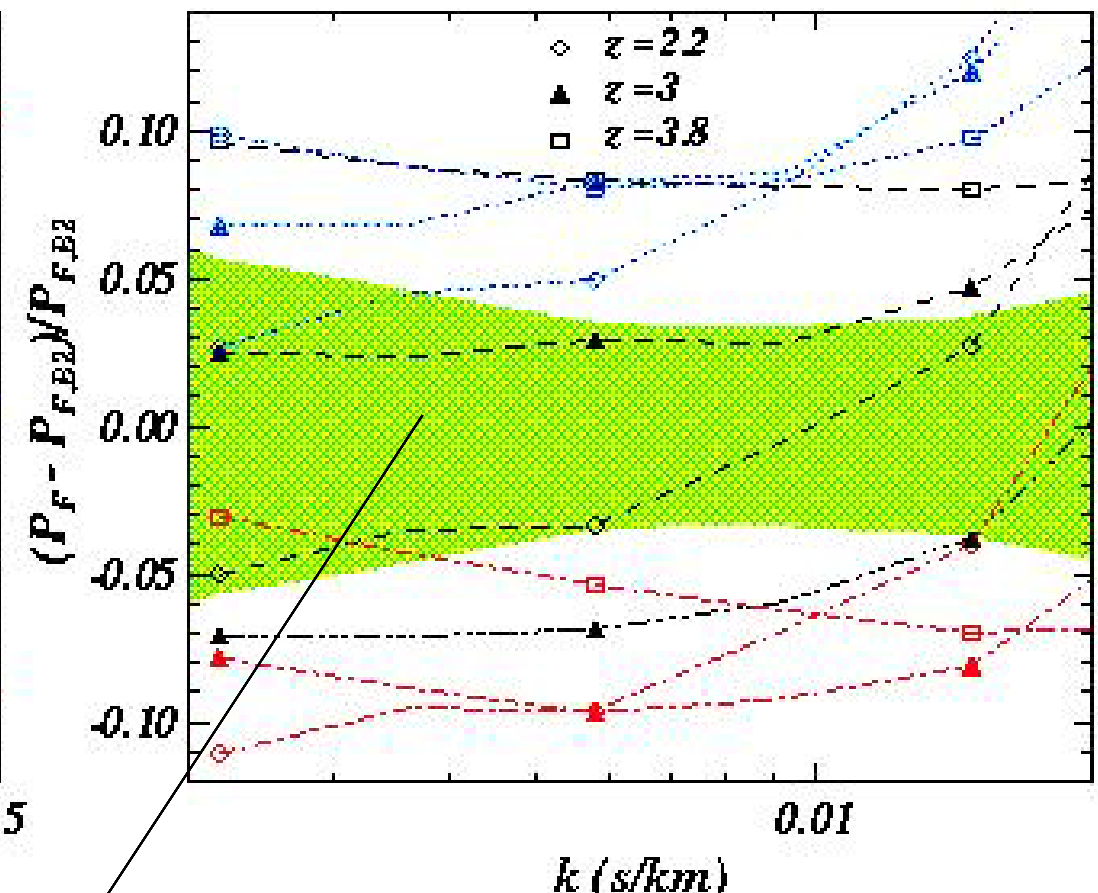
Systematics: Thermal state

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

Thermal histories



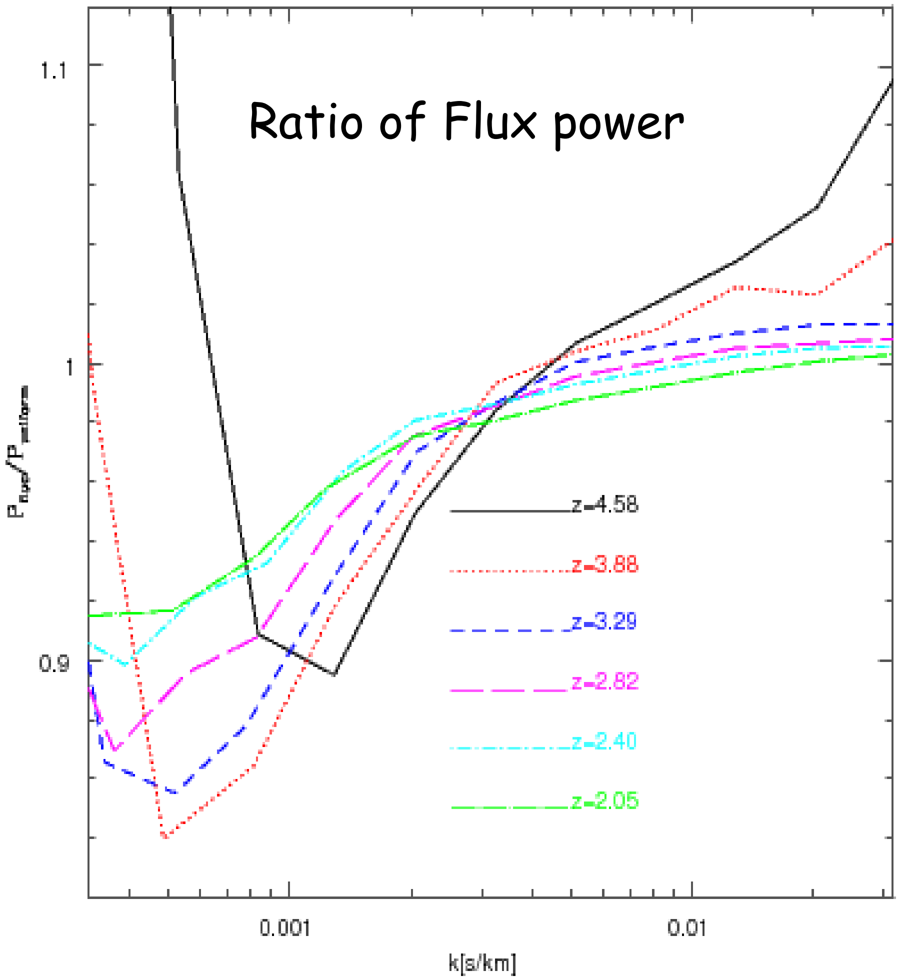
Flux power fractional differences



Statistical SDSS errors on flux power

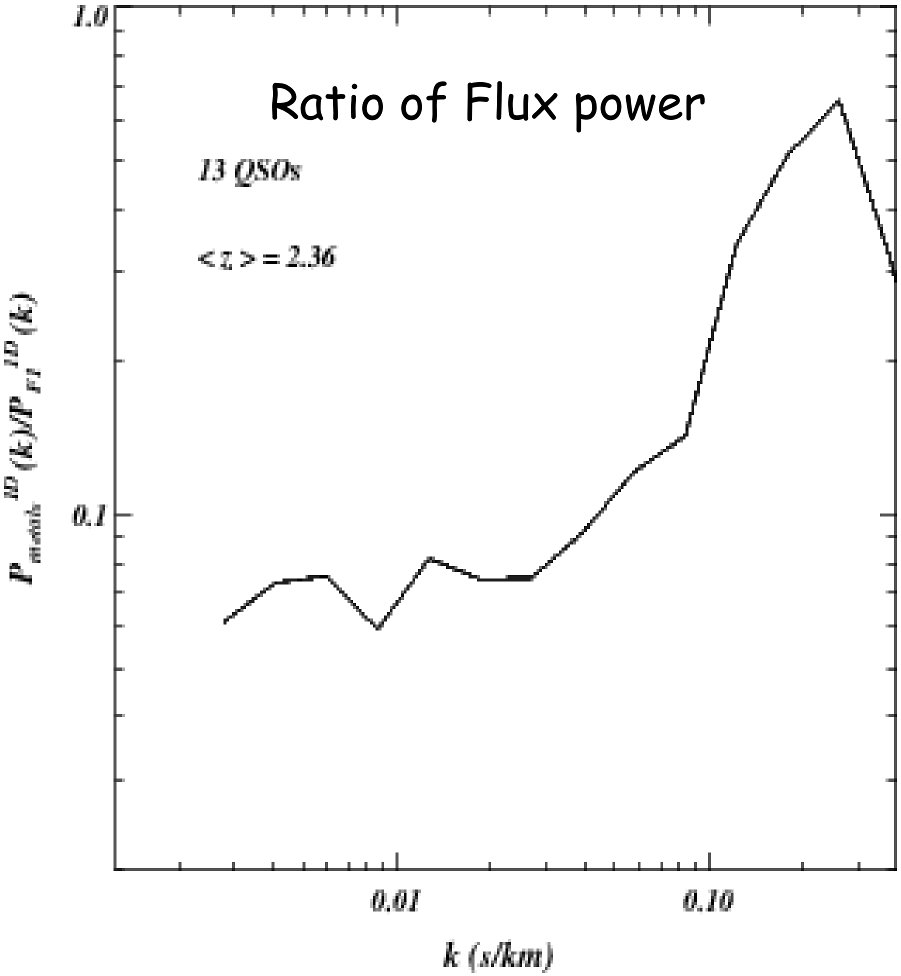
Systematics: UV fluctuations and Metals

UV fluctuations from Lyman Break Galaxies



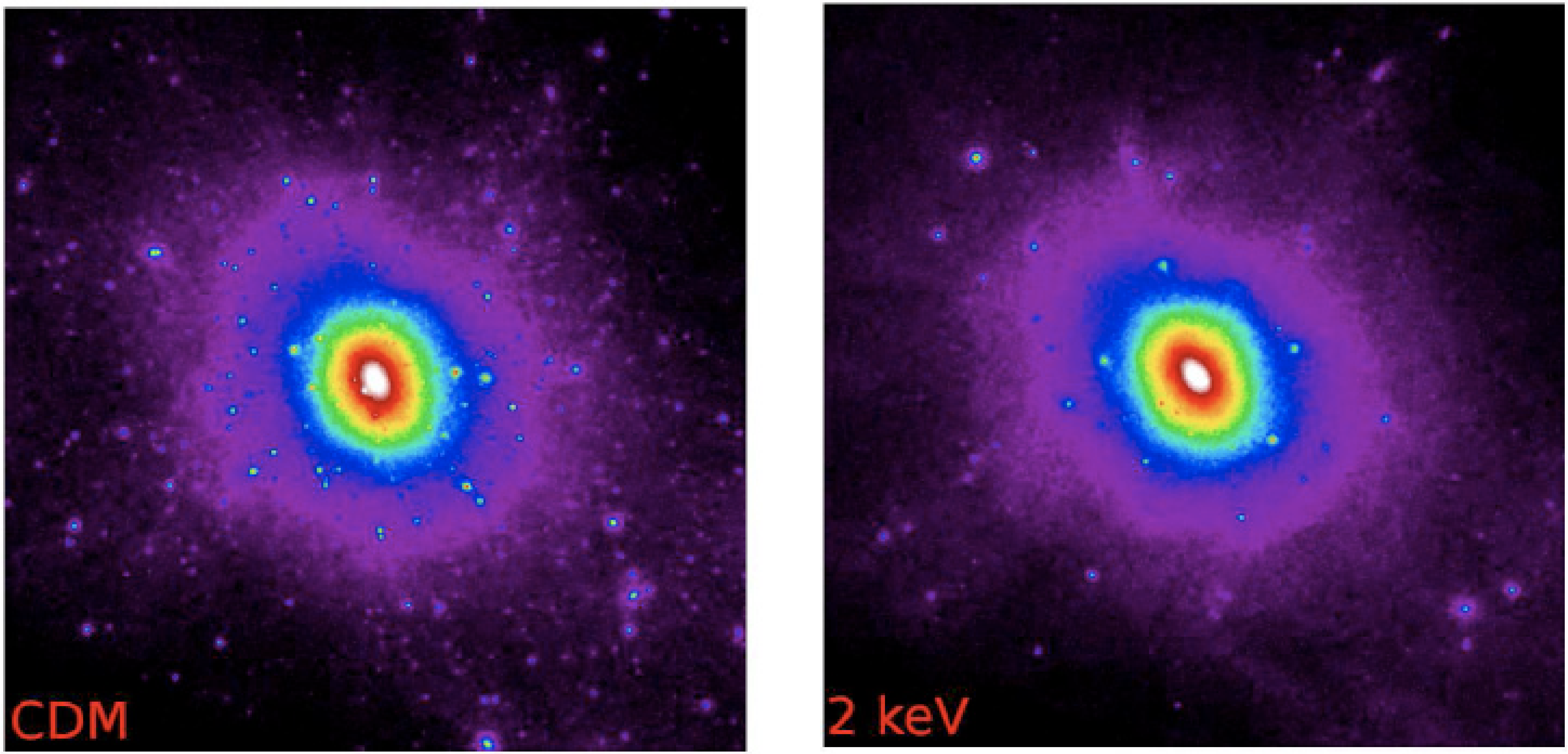
McDonald, Seljak, Cen, Ostriker 2004
Croft 2006
Lidz et al. 2007

Metal contribution



Kim, MV, Haehnelt, Carswell, Cristiani (2004)

FUNDAMENTAL PROPERTIES OF THE DARK MATTER: IMPACT ON HALOES



Polisensky & Ricotti 2010

See also Maccio' & Fontanot 2009 (application to galaxy formation)
Wang & White 2007 (numerical problems related to WDM/HDM sims.)
talks by Walker, Simon, Strigari, Koposov, Tikhonov etc...

Satellites no longer a problem: this is a success of ΛCDM numerical simulations (Frenk)