COSMOLOGICAL SIGNIFICANCE of the IGM

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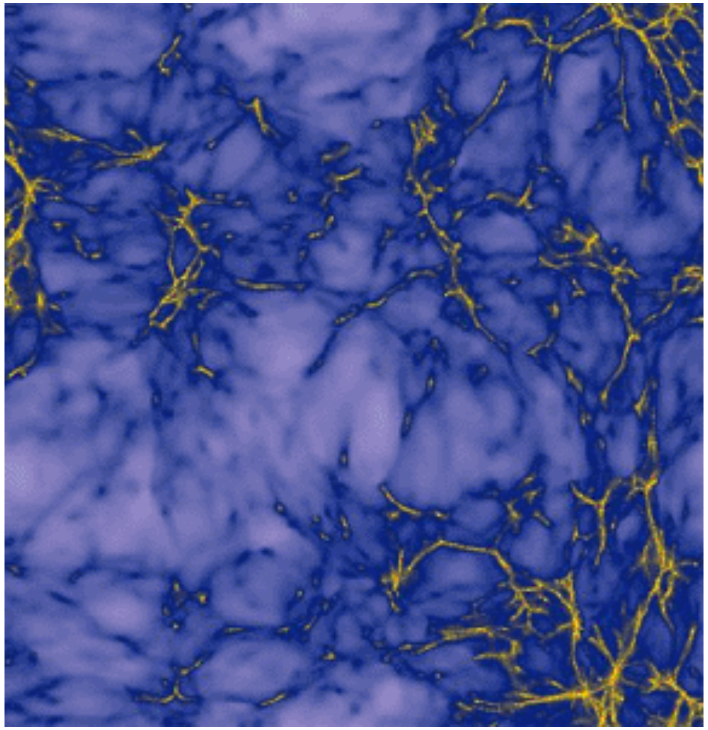
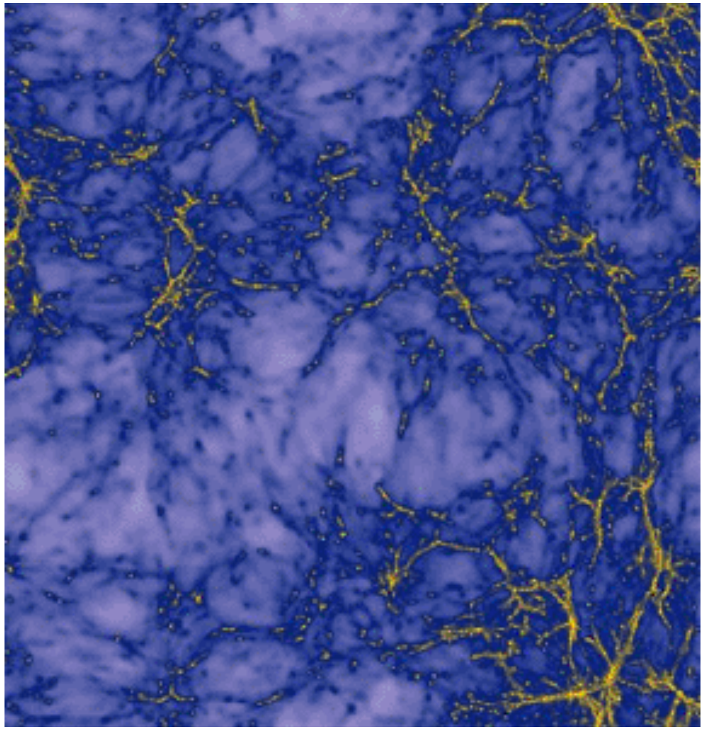




Bologna University Oct. 2011 – Lecture 1

OUTLINE: LECTURES

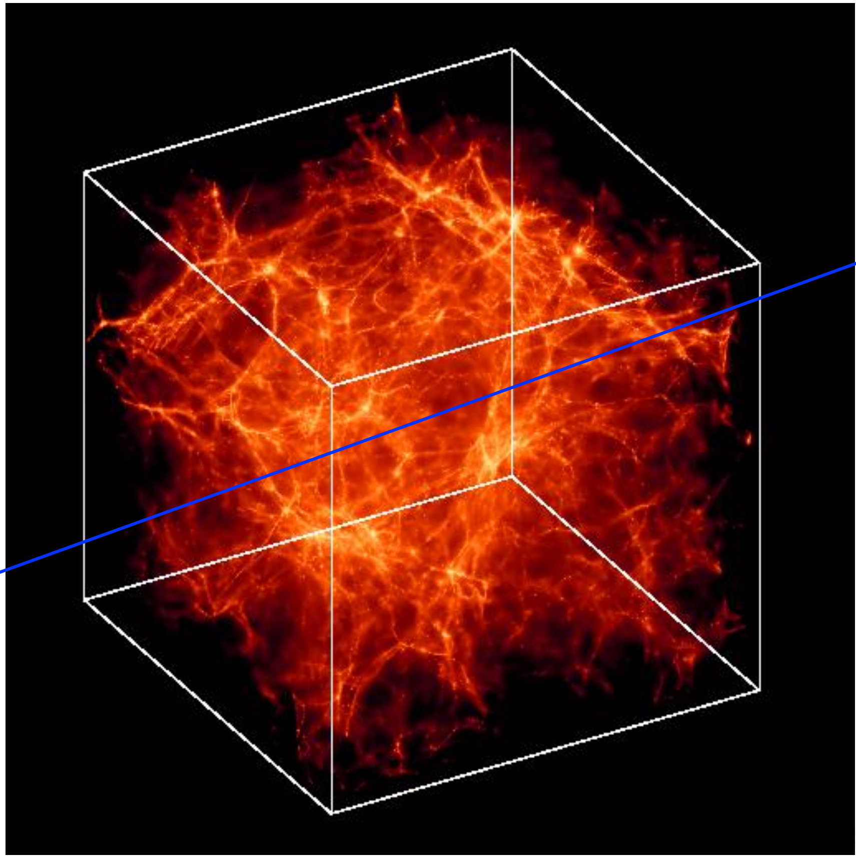
1. Physics of Lyman-alpha and its cosmological relevance

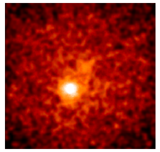
1. Lyman-alpha and fundamental physics

2. IGM/galaxy interplay

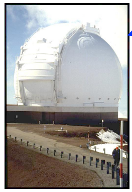
BASICS

IGM: baryonic (gaseous) matter (not in collapsed objects) that lies between galaxies



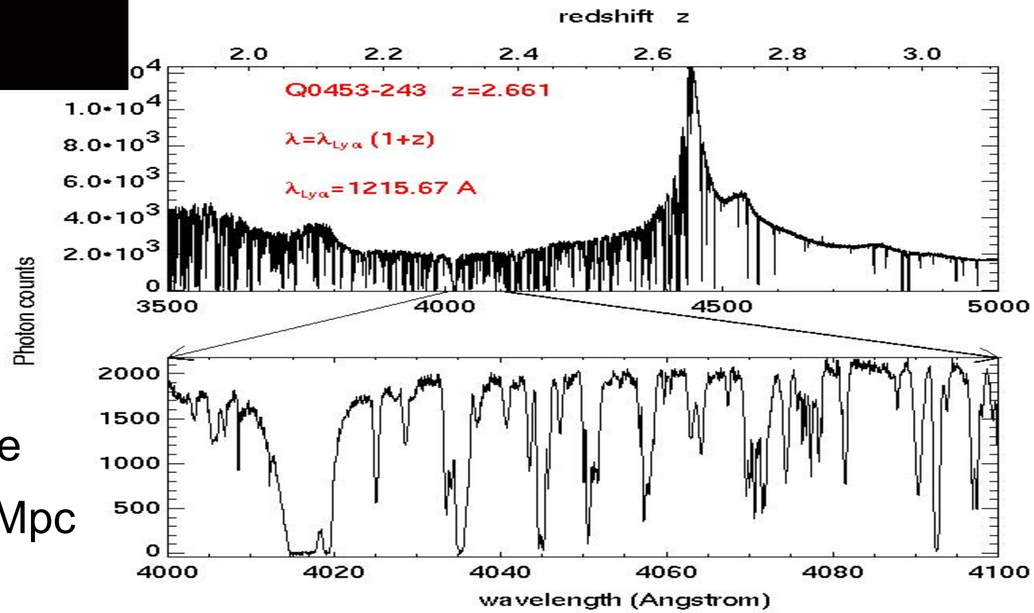


80 % of the baryons at z=3
are in the Lyman-α forest



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

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

BRIEF HISTORICAL OVERVIEW of the Lyman-α forest

‘ISOLATED’ CLOUDS

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

PROBES OF THE JEANS SCALE

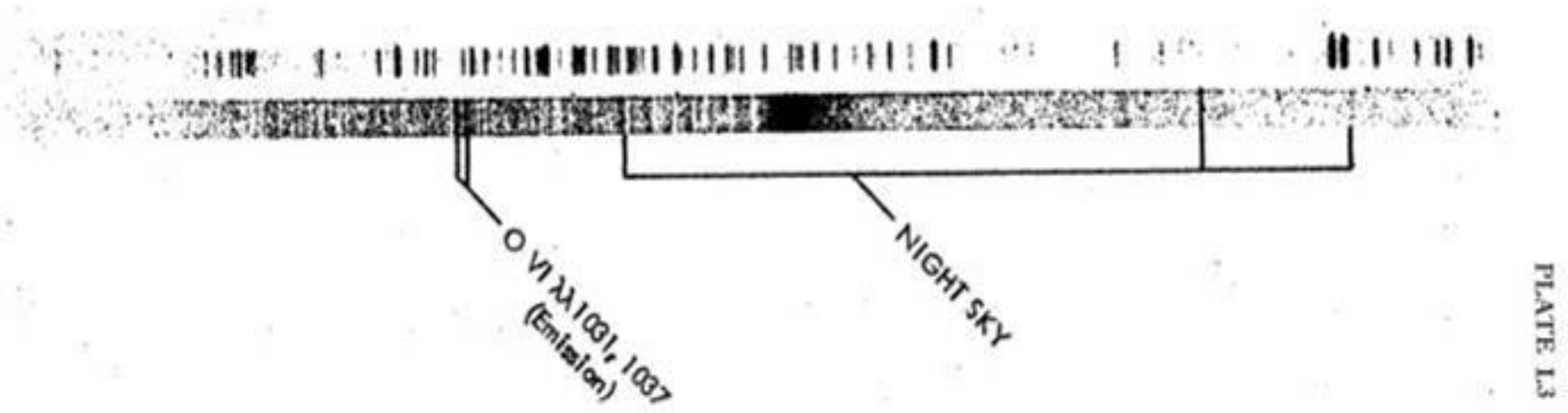


FIG. 1.—A spectrogram illustrating the numerous absorption lines in 4C 05.34. The strong emission line in the center is Lα. The O VI emission lines and several airglow features are also indicated. The comparison spectrum is He + Ar + Ne.

LYNDS (see page L73)

V

V

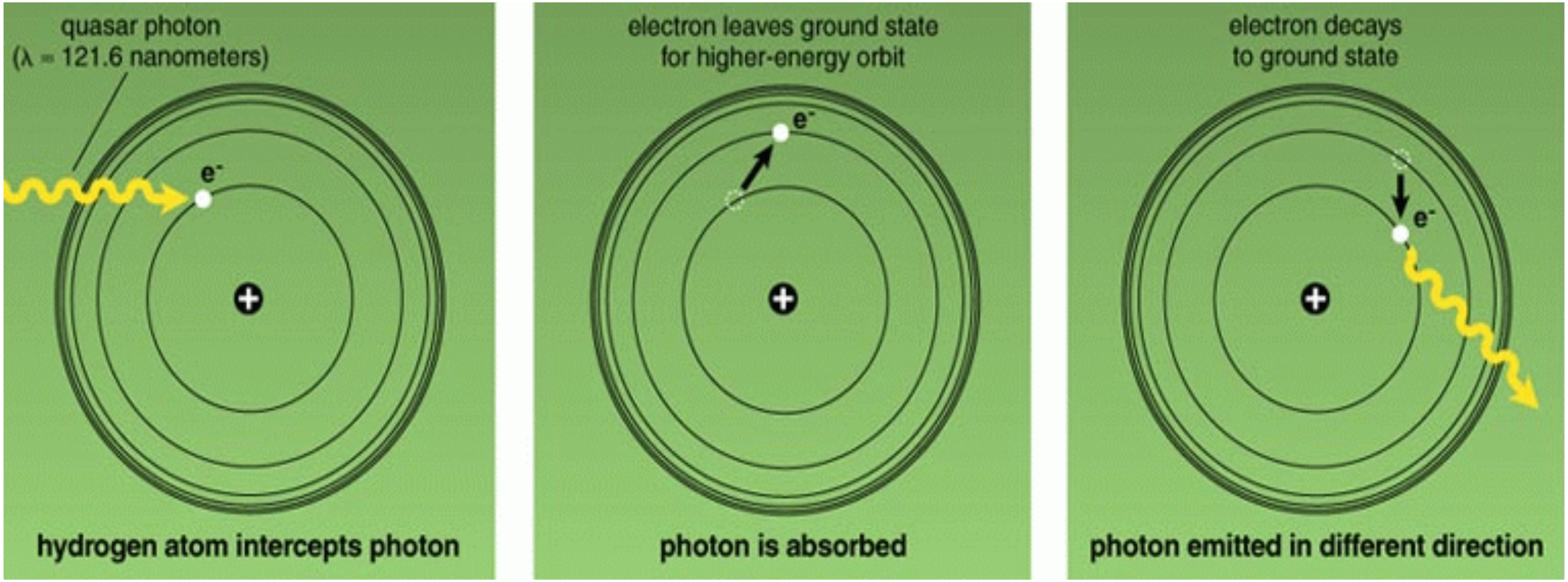
discrete clouds, reproduced most of the observations;

NETWORK OF FILAMENTS

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

COSMOLOGICAL PROBES

Lyman-α absorption is the main manifestation of the IGM



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

Modelling the IGM

Dark matter evolution: linear theory of density perturbation +
Jeans length $L_J \sim \mathrm{sqrt}(T/\rho)$ + mildly non linear evolution

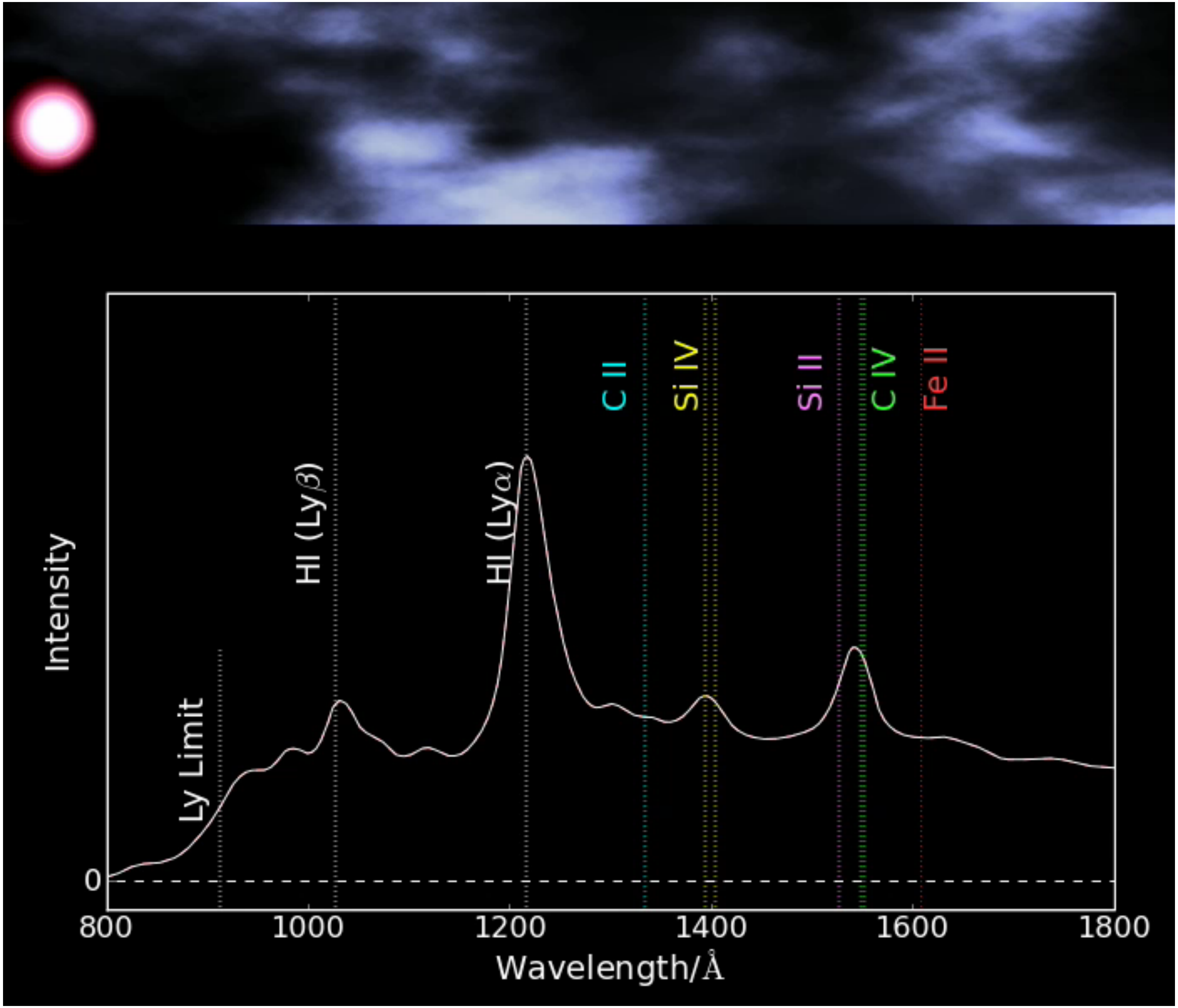
Hydrodynamical processes: mainly gas cooling
cooling by adiabatic expansion of the universe
heating of gaseous structures (reionization)

- photoionization by a uniform Ultraviolet Background
- Hydrostatic equilibrium of gas clouds

dynamical time = $1/\mathrm{sqrt}(G\,\rho)$ ~ sound crossing time= size /gas sound speed

Size of the cloud: > 100 kpc
Temperature: ~ 10^4 K
Mass in the cloud: ~ 10^9 M sun
Neutral hydrogen fraction: 10^{-5}

In practice, since the process is mildly non linear you need numerical simulations
To get convergence of the simulated flux at the percent level (observed)



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

INTRO: modelling the IGM at the 10% level - I

THE ASTROPHYSICAL JOURNAL, 479:523–542, 1997 April 20

EVOLUTION OF STRUCTURE IN THE INTERGALACTIC MEDIUM AND THE NATURE OF THE LYα FOREST

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ABSTRACT

We have performed a detailed statistical study of the evolution of structure in a photoionized intergalactic medium (IGM) using analytical simulations to extend the calculation into the mildly nonlinear density regime found to prevail at $z = 3$. Our work is based on a simple fundamental conjecture: that the probability distribution function of the density of baryonic diffuse matter in the universe is described by a lognormal (LN) random field. The LN distribution has several attractive features and follows plausibly from the assumption of initial linear Gaussian density and velocity fluctuations at arbitrarily early times. Starting with a suitably normalized power spectrum of primordial fluctuations in a universe dominated by cold dark matter (CDM), we compute the behavior of the baryonic matter, which moves slowly toward minima in the dark matter potential on scales larger than the Jeans length. We have computed two models that succeed in matching observations. One is a nonstandard CDM model with $\Omega = 1$, $h = 0.5$, and $\Gamma = 0.3$, and the other is a low-density flat model with a cosmological constant (LCDM), with $\Omega = 0.4$, $\Omega_\Lambda = 0.6$, and $h = 0.65$. In both models, the variance of the density distribution function grows with time, reaching unity at about $z = 4$, where the simulation yields spectra that closely resemble the Lyα forest absorption seen in the spectra of high-z quasars. The calculations also successfully predict the observed properties of the Lyα forest clouds and their evolution from $z = 4$ down to at least $z = 2$, assuming a constant intensity for the metagalactic UV background over this redshift range. *However, in our model the forest is not due to discrete clouds, but rather to fluctuations in a continuous intergalactic medium.* At $z = 3$, typical clouds with measured neutral hydrogen column densities $N_{\rm H\,I} = 10^{15.3}$, $10^{13.5}$, and $10^{11.5}$ cm^{-2} correspond to fluctuations with mean total densities approximately 10, 1, and 0.1 times the universal mean baryon density. Perhaps surprisingly, fluctuations whose amplitudes are less than or equal to the mean density still appear as "clouds" because in our model more than 70% of the volume of the IGM at $z = 3$ is filled with gas at densities below the mean value.

Dark matter evolution and baryon evolution -I

linear theory of density perturbation +
Jeans length $L_J \sim sqrt(T/\rho)$ + mildly non linear evolution

$$x_b \equiv \frac{1}{H_0}\left[\frac{2\gamma k T_m}{3\mu m_p \Omega(1+z)}\right]^{1/2}$$

Jeans length: scale at which gravitational forces and pressure forces are equal

$$\delta_0(x) \equiv \frac{1}{4\pi x_b^2}\int \frac{\delta_{\rm DM}(x_1)}{|x-x_1|} e^{-|x-x_1|/x_b} dx_1$$

$$\delta_0(k) \equiv \frac{\delta_{\rm DM}(k)}{1+x_b^2 k^2},$$

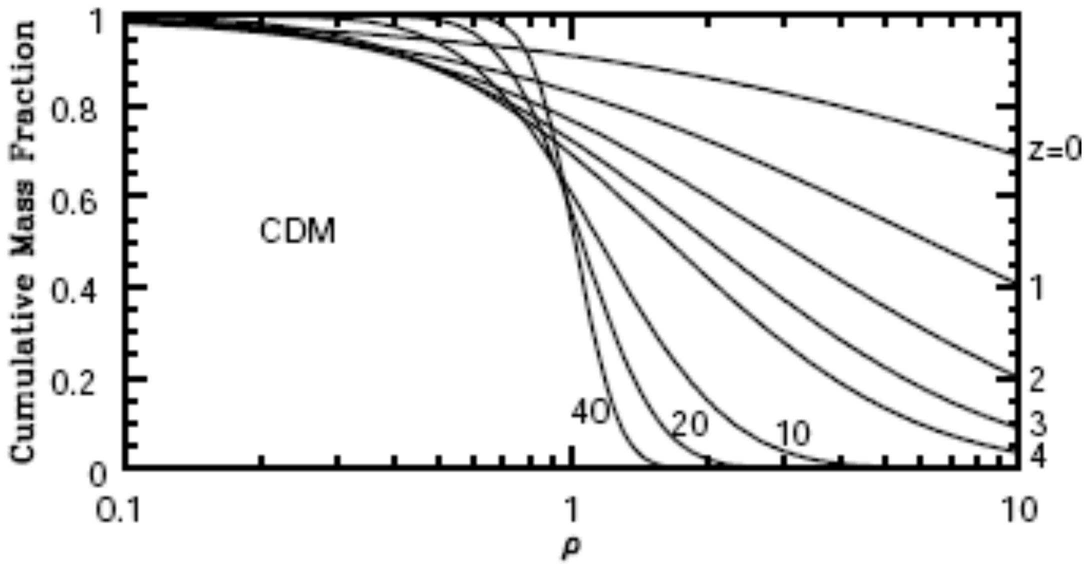
Density contrast in real and Fourier space

$$n(x) = n_0 \exp\left[\delta_0(x) - \frac{\langle \delta_0^2 \rangle}{2}\right]$$

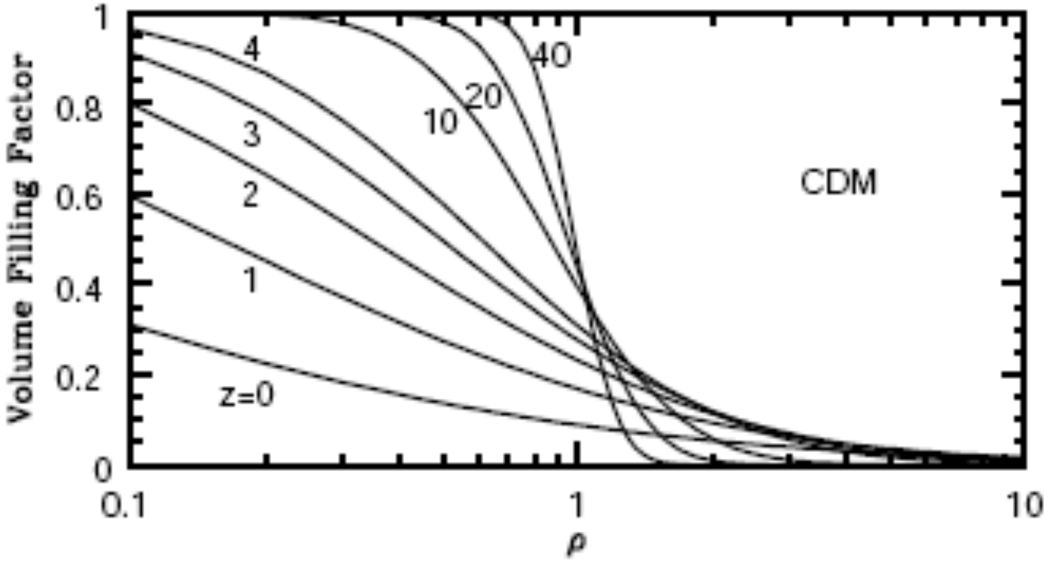
Non linear evolution lognormal model

Bi & Davidsen 1997, ApJ, 479, 523

Dark matter evolution and baryon evolution –II



M (> ρ)



V (> ρ)

Bi & Davidsen 1997, ApJ, 479, 523

Dark matter evolution and baryon evolution –III (more precisely)

$$\frac{d^2\delta_X}{dt^2} + 2H\frac{d\delta_X}{dt} = 4\pi G\bar{\rho}(f_X\delta_X + f_b\delta_b),$$

$$\frac{d^2\delta_b}{dt^2} + 2H\frac{d\delta_b}{dt} = 4\pi G\bar{\rho}(f_X\delta_X + f_b\delta_b) - \frac{c_S^2}{a^2}k^2\delta_b,$$

Dark matter-baryon fluid
X is DM
b is baryonic matter

Gravity term

pressure term (at large scales → 0)

$c_s^2 = dP/d\rho$

$T=\rho^{\gamma-1}$

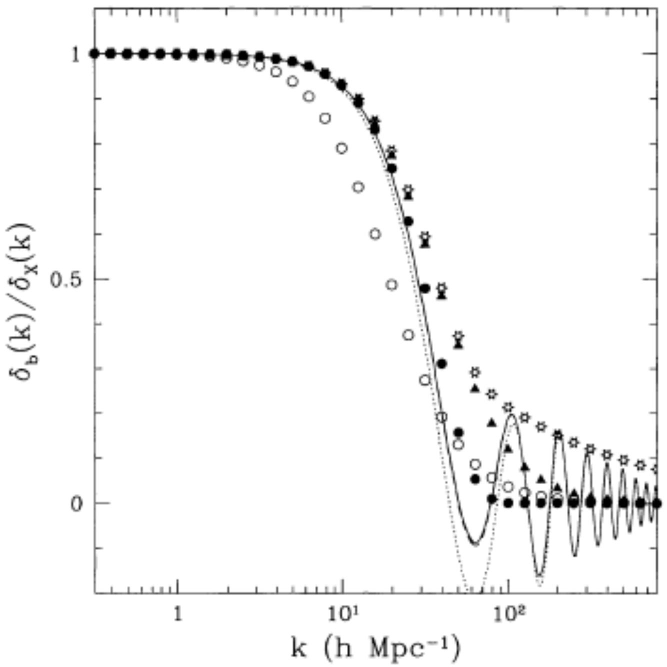
Polytropic gas

if T ~ 1/a and f_b = 0 then we get the Bi & Davidsen result

Better filter is $\exp(-k^2/k_F^2)$

Instead of $1+(k/k_J)^2$

But note that k_F depends on the whole thermal history



Hui & Gnedin 1998, MNRAS, 296, 44

Ionization state -I

Photoionization equilibrium UV background by QSO and galaxies

$$J(\nu) = J_{21}(\nu_0/\nu)^m \times 10^{-21} \mathrm{erg\,s^{-1}Hz^{-1}cm^{-2}sr^{-1}}$$

$\Gamma_{-12} = 4 \times J_{21}$

$$\Gamma_{\gamma i}(z) = \int_{\nu_i}^{\infty} \frac{4\pi J(\nu,z)\sigma_i(\nu)}{h\nu}\,d\nu$$

Photoionization rates

$$\mathrm{H\,I} + \mathrm{H\,II} = 1$$

+

$$\frac{d\mathrm{H\,I}}{dt} = \alpha_{\mathrm{H\,II}}\, n_e \mathrm{H\,II} - \mathrm{H\,I}\,(\Gamma_{\gamma \mathrm{H\,I}} + \Gamma_{e\mathrm{H\,I}}\, n_e)$$

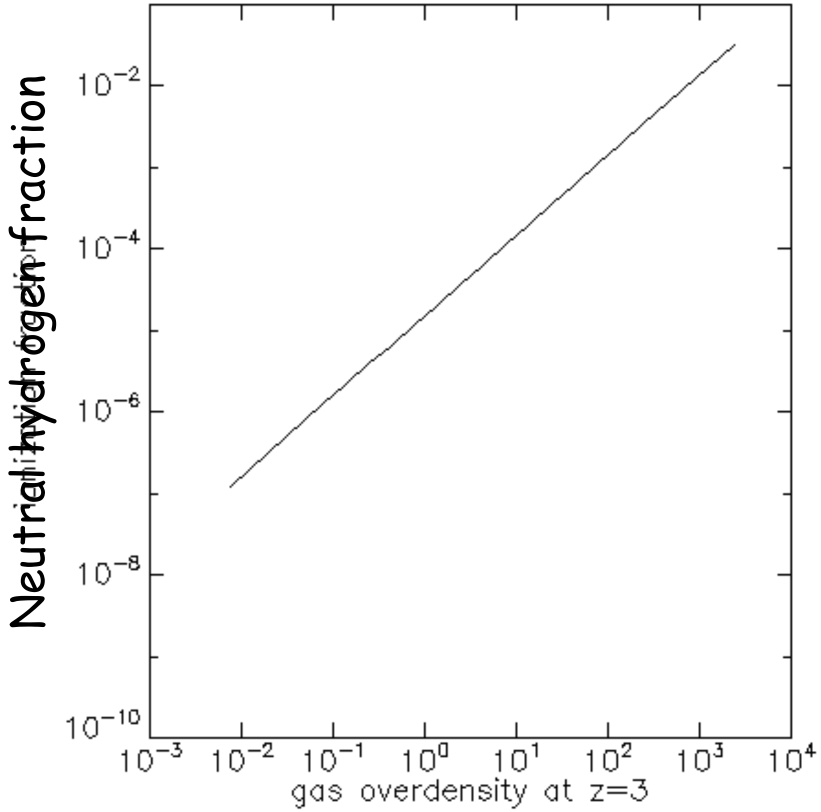
Recombination rates

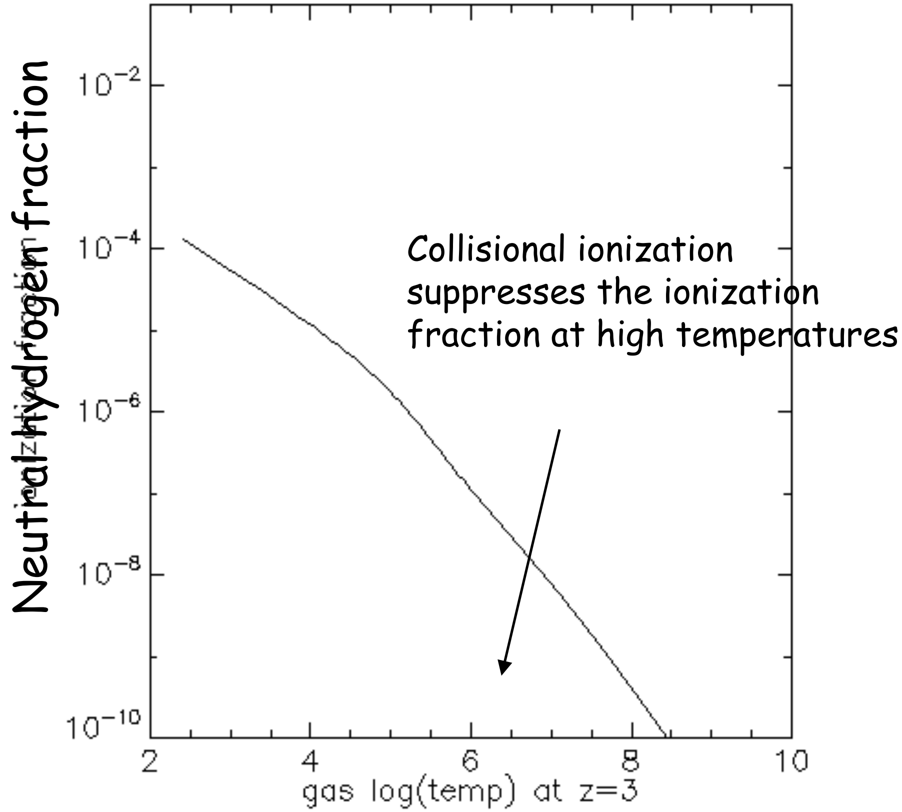
Photoionization rate

Collisional ionization rate

Theuns et al., 1998, MNRAS, 301, 478

Ionization state –II

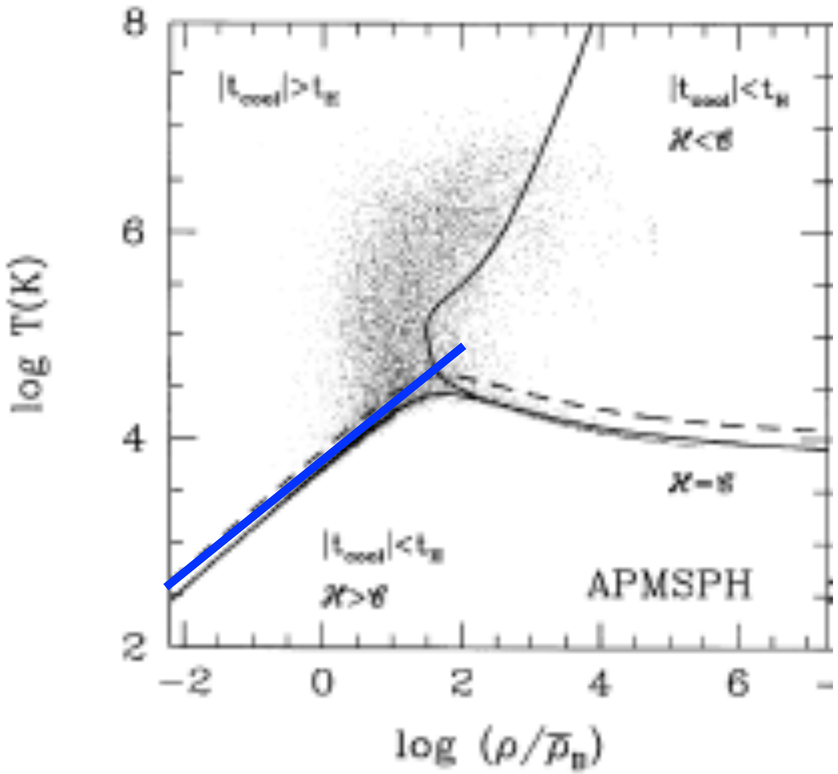




$$n_{\rm HI}(\mathbf{x},z) \approx 10^{-5}\, \overline{n}_{\rm IGM}(z) \left(\frac{\Omega_{0b}h^2}{0.019}\right) \left(\frac{\Gamma_{-12}}{0.5}\right)^{-1} \left(\frac{T(\mathbf{x},z)}{10^4{\rm K}}\right)^{-0.7} \left(\frac{1+z}{4}\right)^3 (1+\delta_{\rm IGM}(\mathbf{x},z))^2$$

Viel, Matarrese, Mo et al. 2002, MNRAS, 329, 848

Thermal state - I



Tight power-law relation is set by the equilibrium between photo-heating and adiabatic expansion

$$\epsilon_{\gamma i}(z) = \int_{\nu_i}^{\infty} \frac{4\pi J(\nu,z)\sigma_i(\nu)(h\nu - h\nu_i)}{h\nu}\,\mathrm{d}\nu$$

$$\mathcal{H} = \left(\mathrm{H\,I}\,\epsilon_{\gamma\mathrm{H\,I}} + \mathrm{He\,I}\,\epsilon_{\gamma\mathrm{He\,I}} + \mathrm{He\,II}\,\epsilon_{\gamma\mathrm{He\,II}}\right)/n_{\mathrm{H}}$$

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

Theuns et al., 1998, MNRAS, 301, 478

Semi-analytical models for the Ly-a forest

(Bi 1993, Bi & Davidsen 1997, Hui & Gnedin 1998, Matarrese & Mohayaee 2002)

$$k_J^{-1}(z) \equiv H_0^{-1}\left[\frac{2\gamma k_B T_m(z)}{3\mu m_p \Omega_{0m}(1+z)}\right]^{1/2}$$ Jeans length

$$\delta_0^{\rm IGM}(\mathbf{k},z) = \frac{\delta_0^{\rm DM}(\mathbf{k},z)}{1+k^2/k_J^2(z)} \equiv W_{\rm IGM}(k,z)D_+(z)\delta_0^{\rm DM}(\mathbf{k})$$ Filtering of linear DM density field

$$\mathbf{v}^{\rm IGM}(\mathbf{k},z) = E_+(z)\frac{i\mathbf{k}}{k^2}W_{\rm IGM}(k,z)\delta_0^{\rm DM}(\mathbf{k})$$ Peculiar velocity

$$n_{\rm IGM}(\mathbf{x},z) = \overline{n}_{\rm IGM}(z)\exp\left[\delta_0^{\rm IGM}(\mathbf{x},z) - \frac{\langle(\delta_0^{\rm IGM})^2\rangle D_+^2(z)}{2}\right]$$ Non linear density field

$$T(\mathbf{x},z) = \boxed{T_0(z)}\,(1+\delta^{\rm IGM}(\mathbf{x},z))^{\boxed{\gamma(z)}-1}$$ 'Equation-of-state'

$$\boxed{\alpha(z,T(z))\,n_p n_e = J(z) n_{\rm HI}}\ ,$$ Neutral hydrogen ionization equilibrium equation

$$\tau(u) = \frac{\sigma_{0,\alpha}\,c}{H(z)}\int_{-\infty}^{\infty} dy\, n_{\rm HI}(y)\,\mathcal{V}\left[u-y-v_{\parallel}^{\rm IGM}(y),\ b(y)\right]$$ Optical depth

Density Velocity Temperature

Linear fields: density, velocity

↓

Non linear fields

+

Temperature

↓

Spectra: Flux=exp(-τ)

MV, Matarrese S., Mo HJ., Haehnelt M., Theuns T., 2002a, MNRAS, 329, 848

Lyman-α forest – I (small clouds)

$$t_{\rm dyn} \equiv \frac{1}{\sqrt{G\rho}} \sim 1.0 \times 10^{15}\ {\rm s}\left(\frac{n_{\rm H}}{1\ {\rm cm}^{-3}}\right)^{-1/} \times \left(\frac{1-Y}{0.76}\right)^{1/2}\left(\frac{f_g}{0.16}\right)^{1/2}$$

$$t_{\rm sc} \equiv \frac{L}{c_s} \sim 2.0 \times 10^{15}\ {\rm s}\left(\frac{L}{1\ {\rm kpc}}\right)T_4^{-1/2}\left(\frac{\mu}{0.59}\right)^{1/2}$$

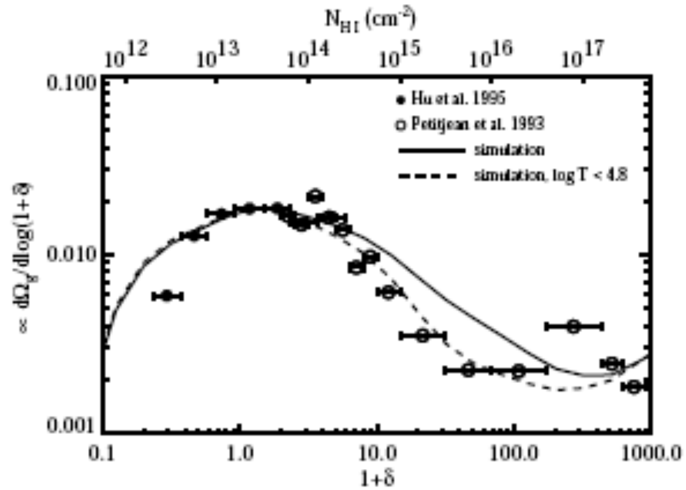
For overdense absorbers typically $t_{dyn} \sim t_{sc}$ sets a jeans length

$$dP/dr = -G\rho M/r^2 \qquad P \sim c_s^2\,\rho \qquad c_s^2\,\rho/L \sim G\rho^2 L$$

$$L_J \equiv \frac{c_s}{\sqrt{G\rho}} \sim 0.52\ {\rm kpc}\ n_{\rm H}^{-1/2}\ T_4^{1/2}\left(\frac{f_g}{0.16}\right)^{1/2}$$

If $t_{sc} \gg t_{dyn}$ then the cloud is Jeans unstable and either fragments
or if $v \gg c_s$ shocks to the virial temperature

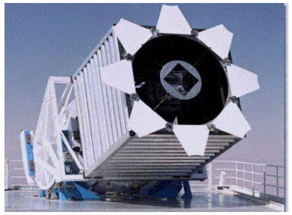
If $t_{dyn} \gg t_{sc}$ the cloud will expand or evaporates and equilbrium will be restored
in a time t_{sc}



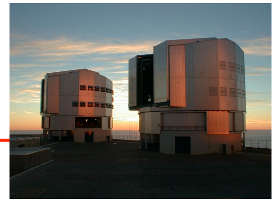
Simple scaling arguments (Schaye 2001, ApJ, 559, 507)

END OF IGM BASICS

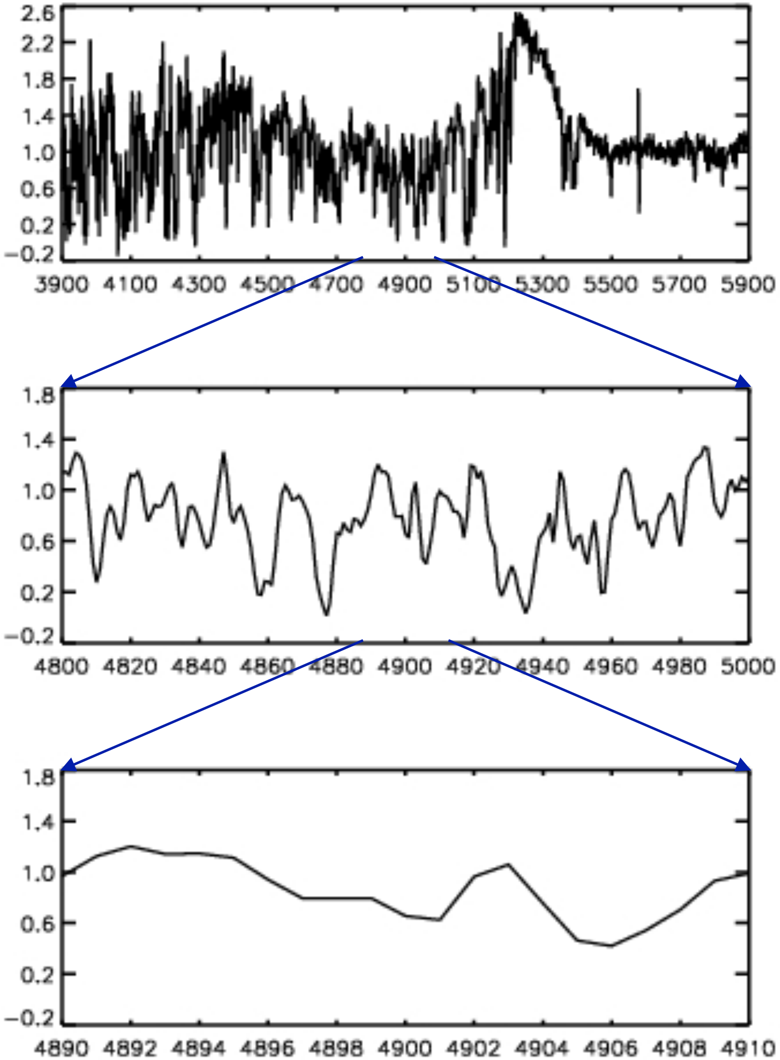
More in A.Meiksin's review 2009 arXiv:0711.3358



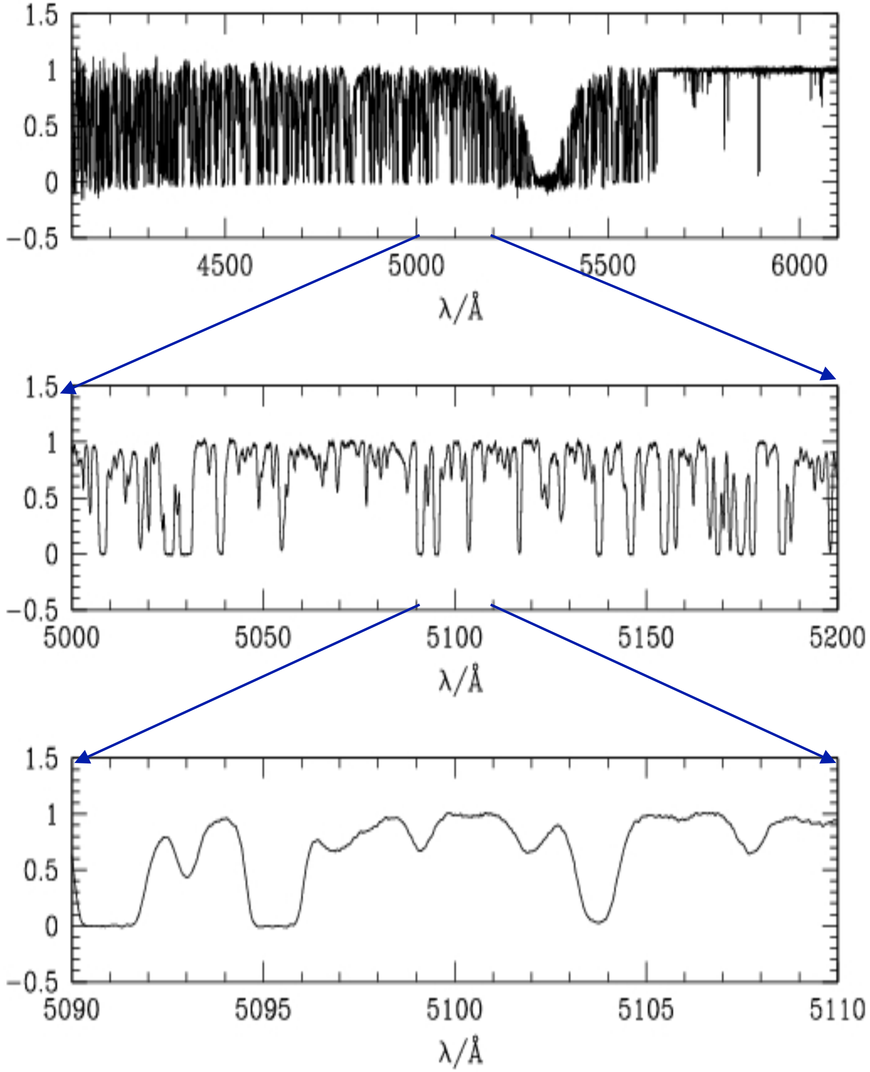
SDSS vs LUQAS



McDonald et al. 2006



Kim, MV et al. 2004, MNRAS, 347, 355



SDSS

3000 LOW RESOLUTION LOW S/N

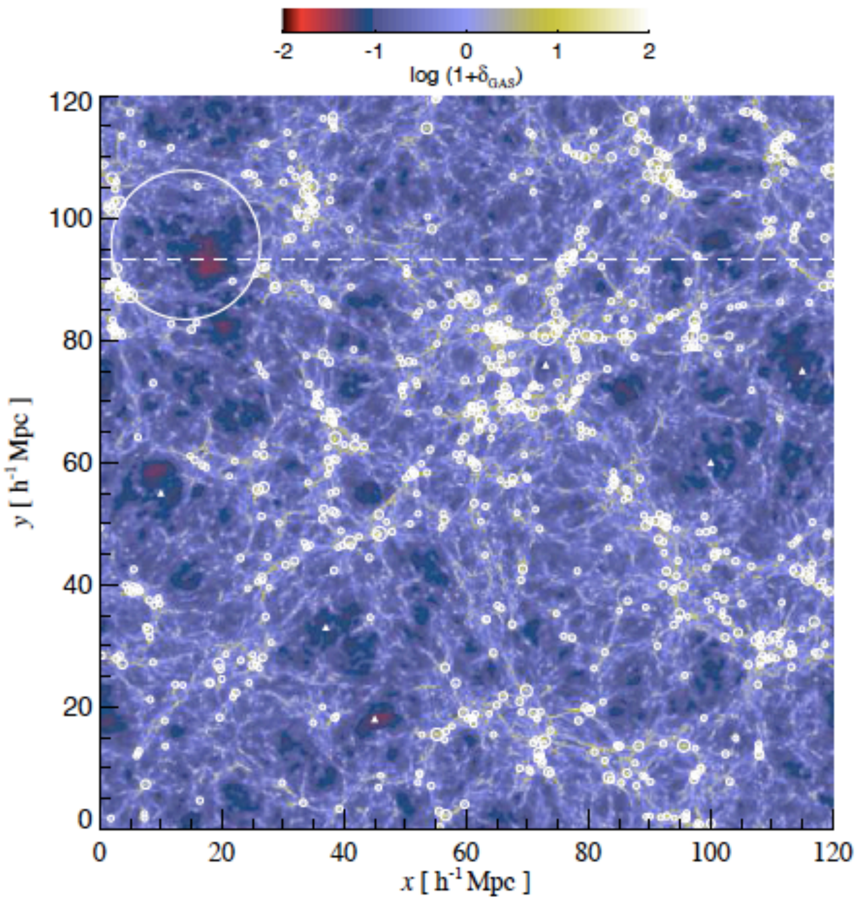
LUQAS

30 HIGH RESOLUTION HIGH S/N

STATISTICS OF DENSITY (or FLUX) FIELDS

0-pt, 1-pt, 2-pt, 3-pt,……. n-pt statistics of the density field
Ideally one would like to deal with $\delta_{\text{DARK MATTER}}$
in practice $\delta_{\text{ASTROPHYSICAL OBJECTS (galaxies,HI, etc...)}}$

0-pt: calculate the mean density
1-pt: calculate probability distribution function (pdf)
2-pt: calculate correlations between pixels at different distances (powerspectrum)
3-pt: calculate correlations in triangles (bispectrum)



Viel, Colberg, Kim 2008

The power spectrum P(k)

$$\delta(\mathbf{x}) \equiv \frac{\rho(\mathbf{x}) - \langle\rho\rangle}{\langle\rho\rangle}$$

Density contrast

$$\xi(\mathbf{r}) \equiv \langle \delta(\mathbf{x}) \cdot \delta(\mathbf{x}+\mathbf{r}) \rangle$$

$$\xi = \left\langle \sum_{\mathbf{k}} \sum_{\mathbf{k}'} \delta_{\mathbf{k}} \delta^*_{\mathbf{k}'} \, e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{x}} \, e^{-i\mathbf{k}\cdot\mathbf{r}} \right\rangle$$

$$\xi(\mathbf{r}) = \frac{V}{(2\pi)^3} \int |\delta_{\mathbf{k}}|^2 e^{-i\mathbf{k}\cdot\mathbf{r}} \, d^3k$$

Correlation function

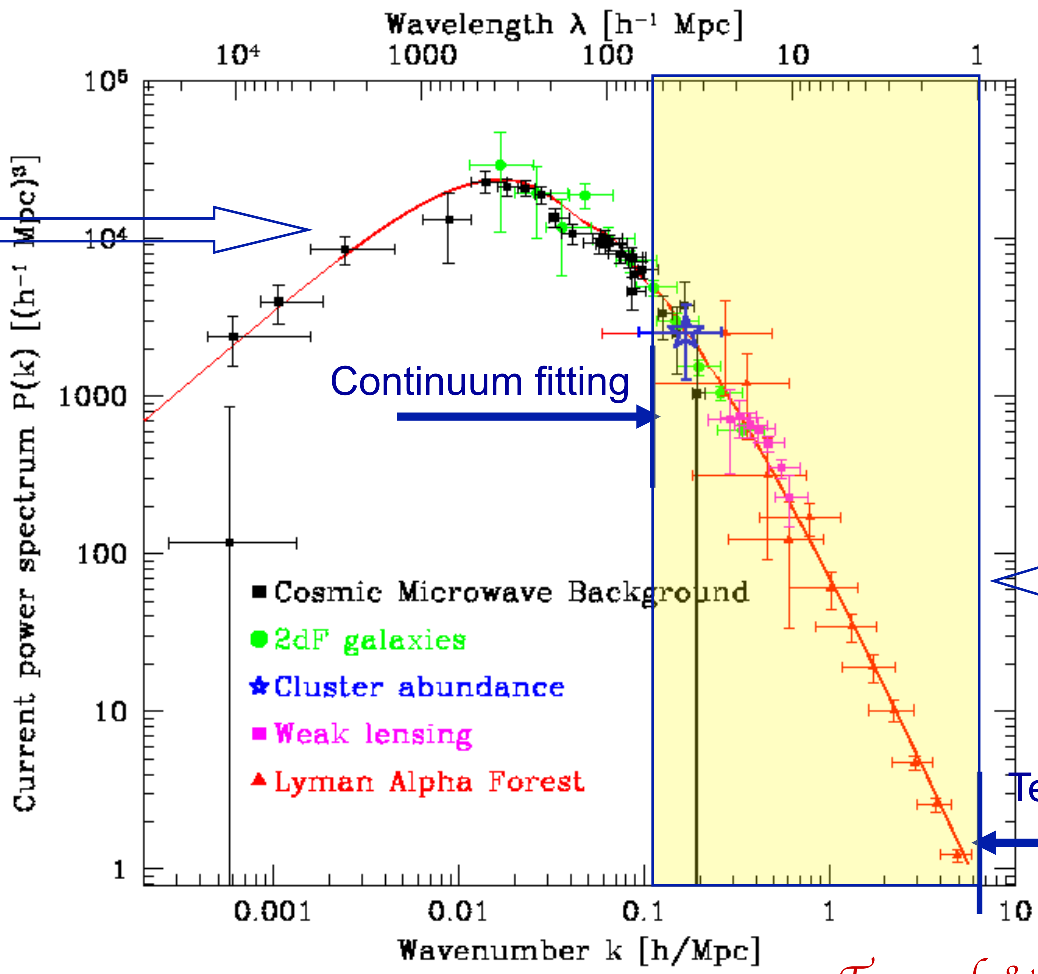
$$dP = n[1 + \xi(\mathbf{r})]dV$$

Power spectral density of *A*

$$\left\langle A(\vec{k}) A^*(\vec{k}') \right\rangle = P_A(k) \delta^3_{\mathrm{D}}(\vec{k} - \vec{k}')$$

GOAL: the primordial dark matter power spectrum from the observed flux spectrum (filaments)

CMB physics
z = 1100
dynamics



Tegmark & Zaldarriaga 2002

Lya physics
z < 6
dynamics
+
termodynamics

Temperature, metals, noise

CMB + Lyman a ⟹ Long lever arm

Relation: $P_{FLUX}(k)$ - $P_{MATTER}(k)$??

Constrain spectral index and shape

OUTLINE

1 - IGM basics

2- Technical part: from $P_F(k)$ to $P_{matter}(k)$

Several methods have been used to recover the linear matter power spectrum
From the flux power:

- "Analytical" Inversion Nusser et al. (99), Pichon et al. (01), Zaroubi et al. (05) "OLD"

- The effective bias method pioneered by Croft (98,99,02) and co-workers "OLD"

- Modelling of the flux power by McDonald, Seljak and co-workers (04,05,06) NEW!
  Jena,Tytler et al. (05,06)

3- Some recent results

Tightest constraints on Warm Dark Matter particle masses with SDSS and High-z High-res High signal-to-noise QSO spectra

Lyman-α with active and sterile neutrinos

“Analytical” methods

Voigt profile pec. Vel. Doppler par.

$$\text{Flux} = \exp(-\tau(w)) = \sigma_0 \frac{c}{H(z)} \int_{-\infty}^{\infty} n_{\rm H\,I}(x)\, \mathcal{H}[w - x - v_{\rm p}(x), b(x)]\, {\rm d}x.$$

Neutral hydrogen density

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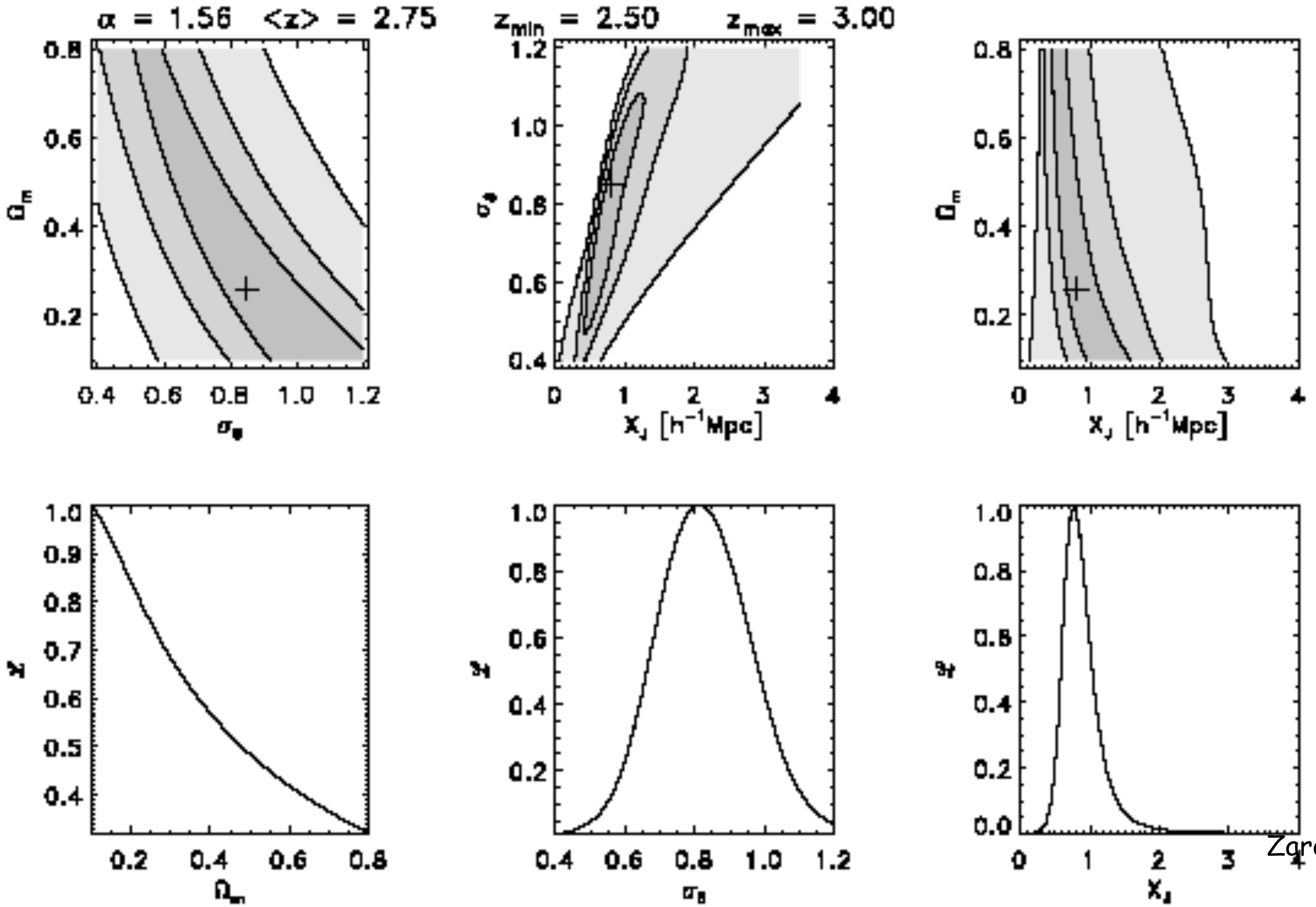

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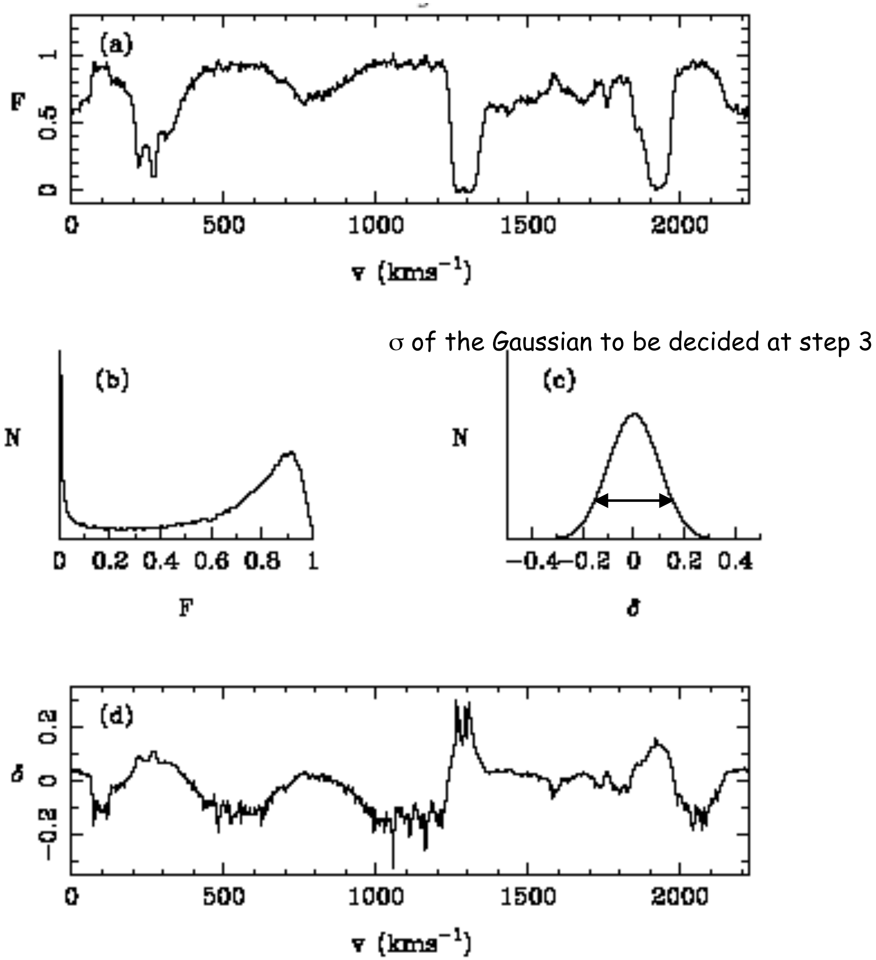
Zaroubi et al. 05

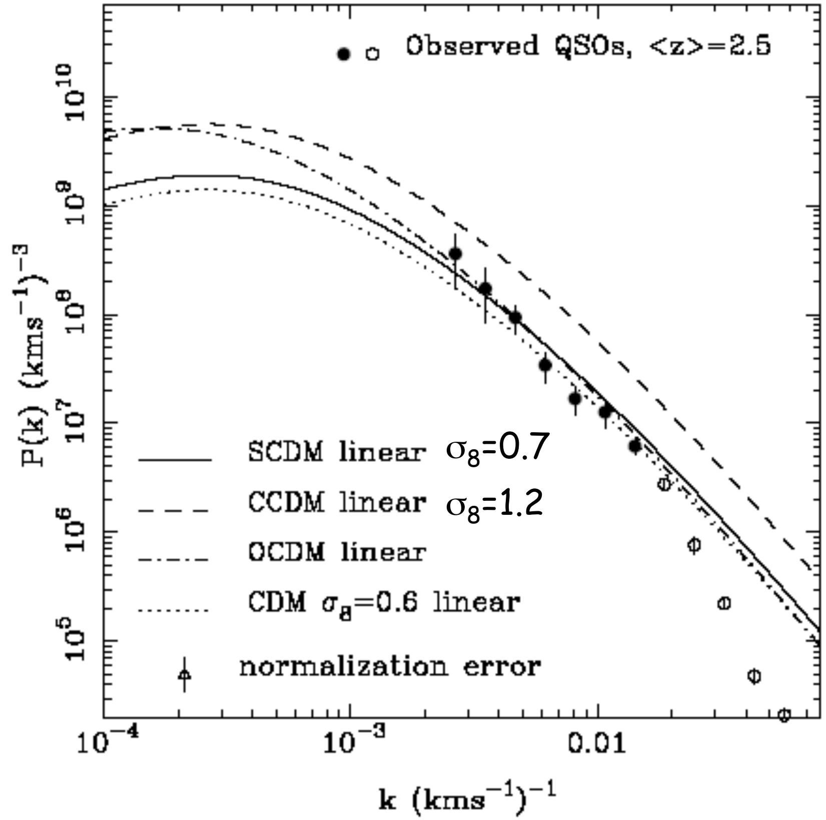
THE EFFECTIVE BIAS METHOD - I

Croft et al. 1998, Croft et al. 1999

1- Convert flux to density pixels: $F=\exp(-A\rho^{\beta})$ – Gaussianization (Weinberg 1992)
2- Measure $P_{1D}(k)$ and convert to $P_{3D}(k)$ by differentiation to obtain shape
3- Calibrate $P_{3D}(k)$ amplitude with (many) simulations of the flux power

$$P_F(k) = b^2 P(k)$$

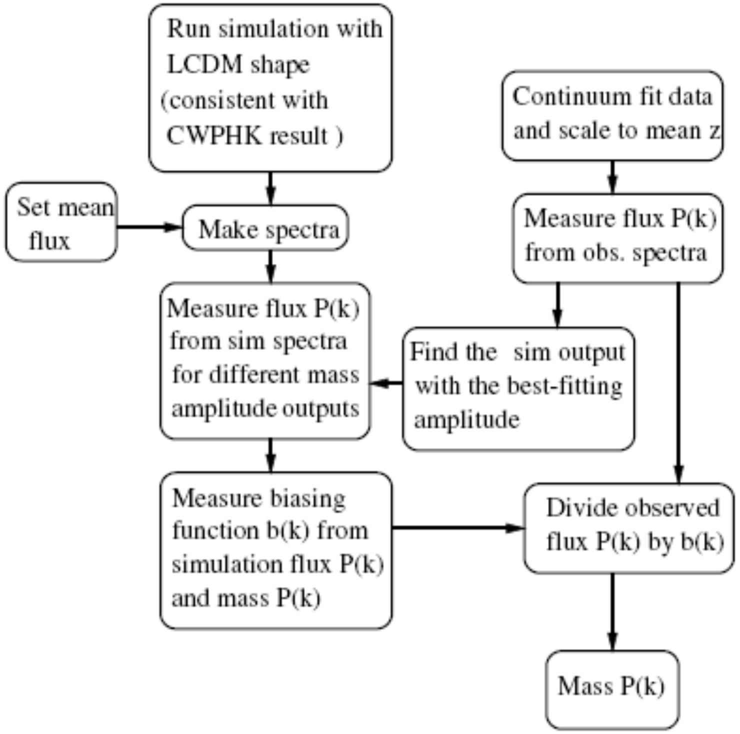




RESULTS:
P(k) amplitude and slope measured at 4-24 comoving Mpc/h and z=2.5, 40% error on the amplitude consistency with n=1 and open models

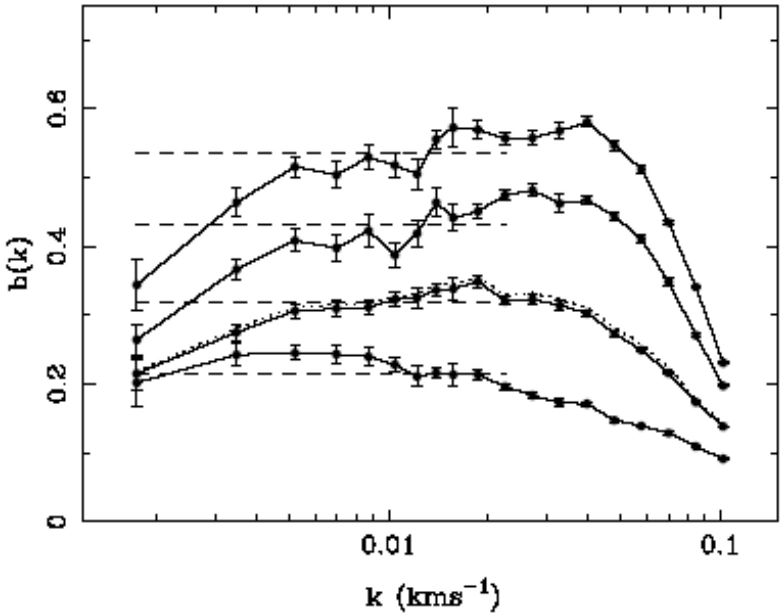
THE EFFECTIVE BIAS METHOD - II

Croft et al. 2002



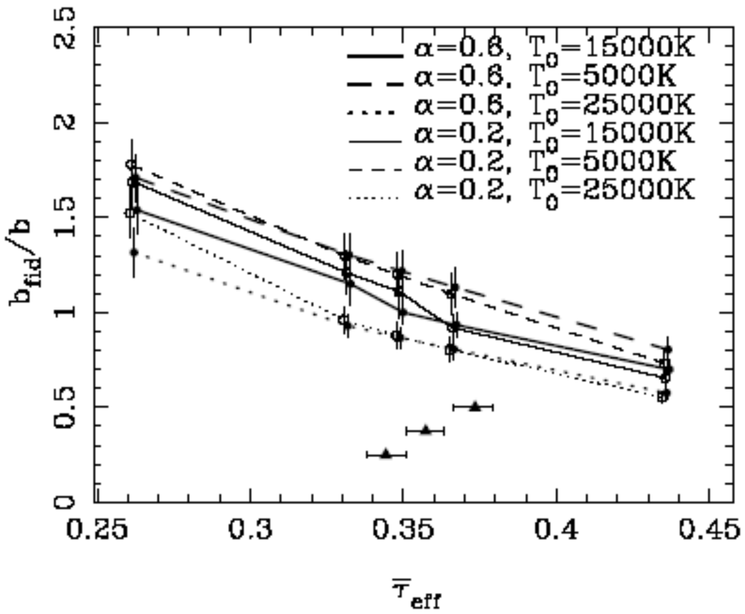
$$P_F(k) = b^2(k)\,P(k)$$

Scale and z dependent



THE EFFECTIVE BIAS METHOD - III

Croft et al. 2002

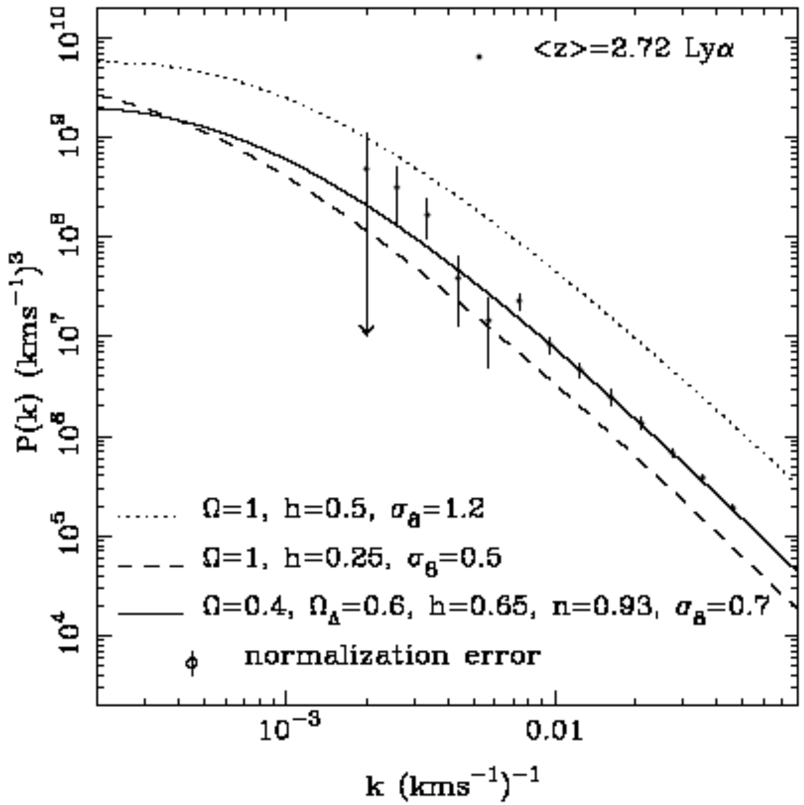


$$\frac{b_{\rm fid}}{b} = \left(\frac{\overline{\tau}_{\rm eff}}{0.349}\right)^{C_\tau}\quad C_\tau = -1.7$$

$$\frac{b_{\rm fid}}{b} = \left(\frac{1+T_0/15000\ {\rm K}}{2}\right)^{C_T}\quad C_T = -0.5$$

No dependency on γ: $T = T_0(1+\delta)^{\gamma-1}$

RESULTS →



THE EFFECTIVE BIAS METHOD - IV

Gnedin & Hamilton 2002

Critical assessment of the effective bias method by Gnedin & Hamilton (02)

$P_F\,(k) = b^2\,[k,P(k)]\;P(k)$

$$\Delta P_{\mathrm{F}}(k) = \sum_{k'} b^2(k,k')\Delta P_{\mathrm{L}}(k')$$

Systematic errors

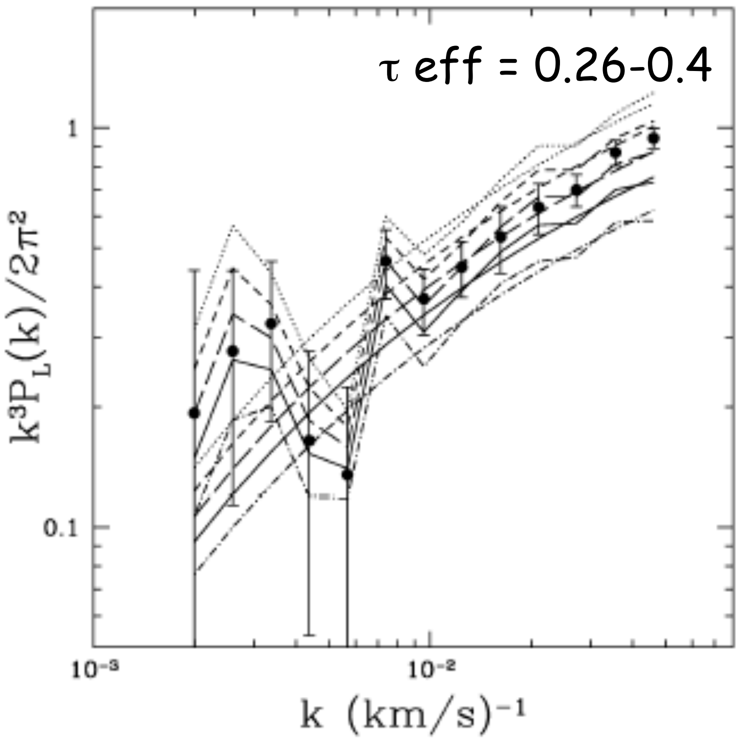
$$P_{\mathrm{L}}^{\mathrm{obs}}(k) = P_{\mathrm{L}}^{\mathrm{fct}}(k) Q_\Omega Q_T Q_\tau,$$

where

$$Q_\Omega \approx \left(\frac{2.4}{1+1.4 f_3}\right)^2,$$

$$Q_T = 20\,000\ \mathrm{K}/T_0,$$

$$Q_\tau = (0.349/\tau)^{0.75},$$

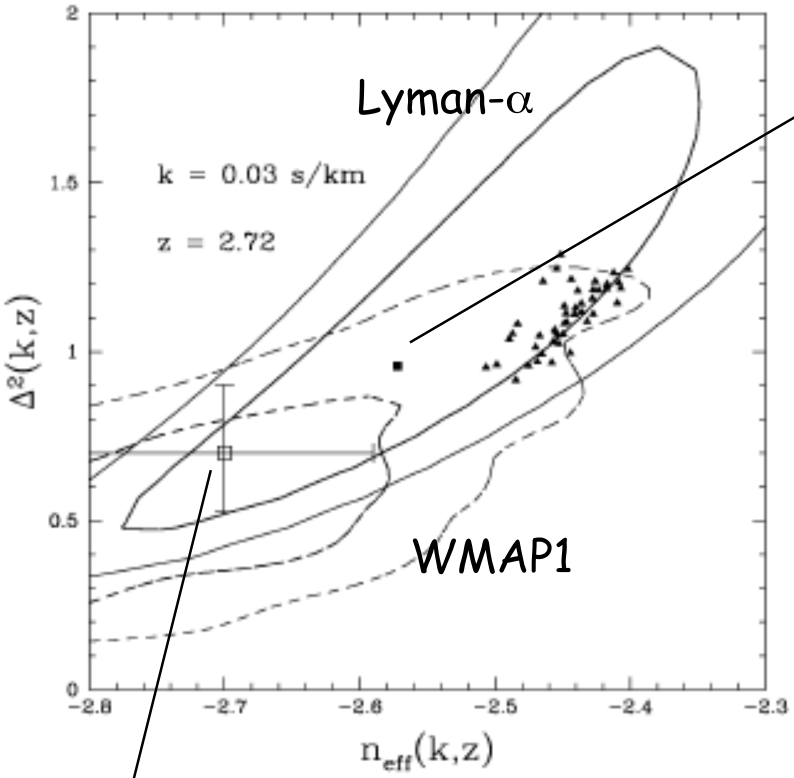


RESULTS: Croft et al. 02 method works (missing physics, bias function, smoothing by peculiar velocities) but this is mainly due to the fact that statistical errors are large and comparable to systematic errors

THE EFFECTIVE BIAS METHOD and WMAP

Verde et al. (03)
Seljak, McDonald & Makarov (03)

Croft et al. 02 revisited



Croft et al. 02

Evidence for running is smaller
if a more conservative range
For the effective optical depth
Is taken

τ eff = 0.305 – 0.349

Value from
High res spectra

Value from
Low res. spectra

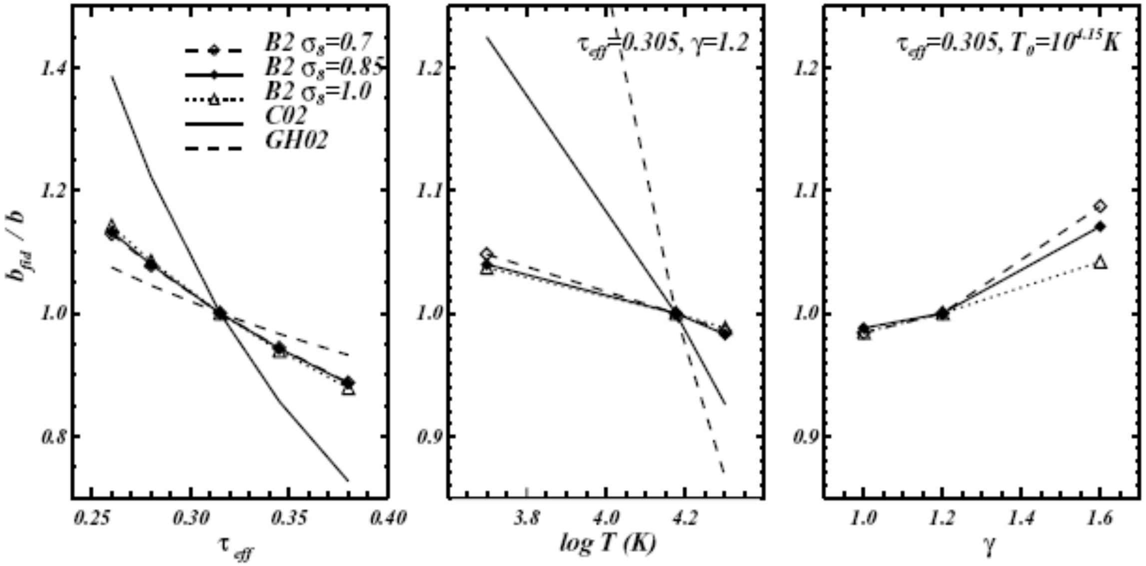
THE EFFECTIVE BIAS METHOD, WMAP + a new QSO sample- I

Viel, Haehnelt & Springel (04)

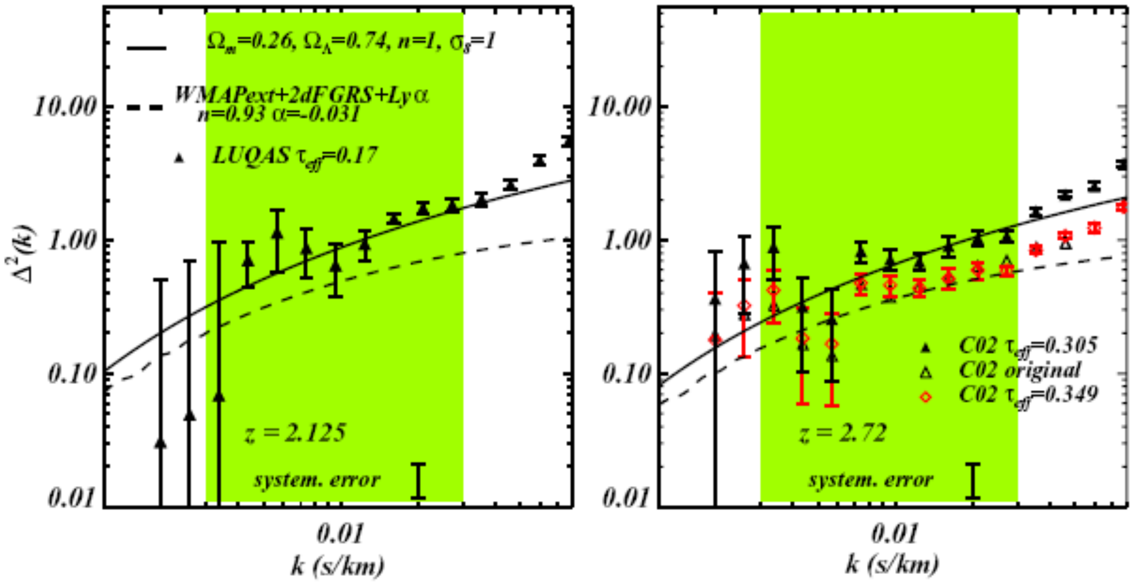
-New sample at <z>=2.125

-Full grid of hydro simulations with GADGET

BIAS FUNCTION



LINEAR POWER SPECTRUM



THE EFFECTIVE BIAS METHOD - SUMMARY

Viel, Haehnelt & Springel (04)

Many uncertainties which contribute more or less equally
(statistical error seems not to be an issue!)

ERRORS	CONTRIB. to R.M.S FLUCT.
Statistical error	4%
Systematic errors	~ 15 %
$\tau_{eff}(z=2.125)=0.17 \pm 0.02$	8 %
$\tau_{eff}(z=2.72) = 0.305 \pm 0.030$	7 %
$\gamma = 1.3 \pm 0.3$	4 %
$T_0 = 15000 \pm 10000$ K	3 %
Method	5 %
Numerical simulations	8 %
Further uncertainties	5 %

THE EFFECTIVE BIAS METHOD, WMAP + a new QSO sample-II

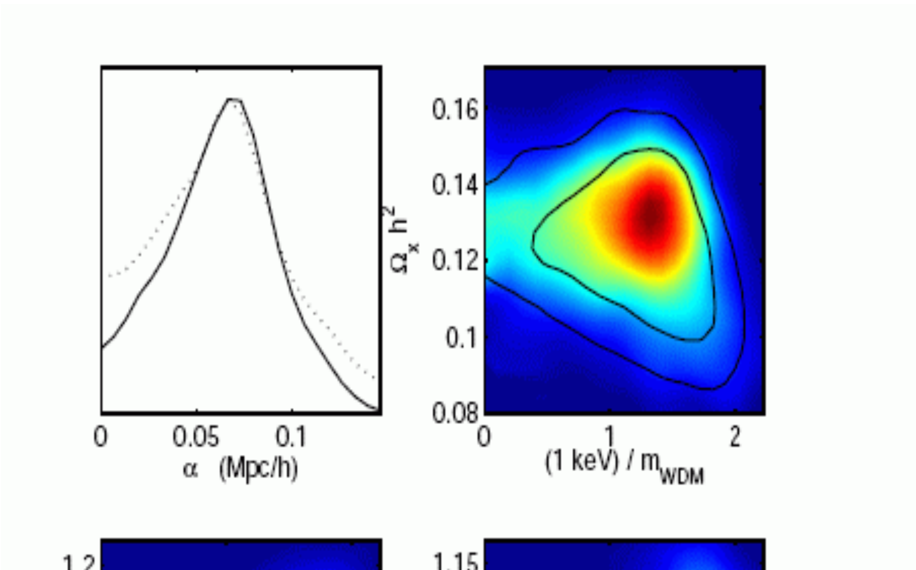
Viel, Haehnelt & Weller (04) – Viel, Haehnelt & Lewis (06)

RESULTS: good agreement with WMAP1, agreement with WMAP3 as well
but the VHS data set is not constraining any more many parameters
constraints on WDM particles presented in

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

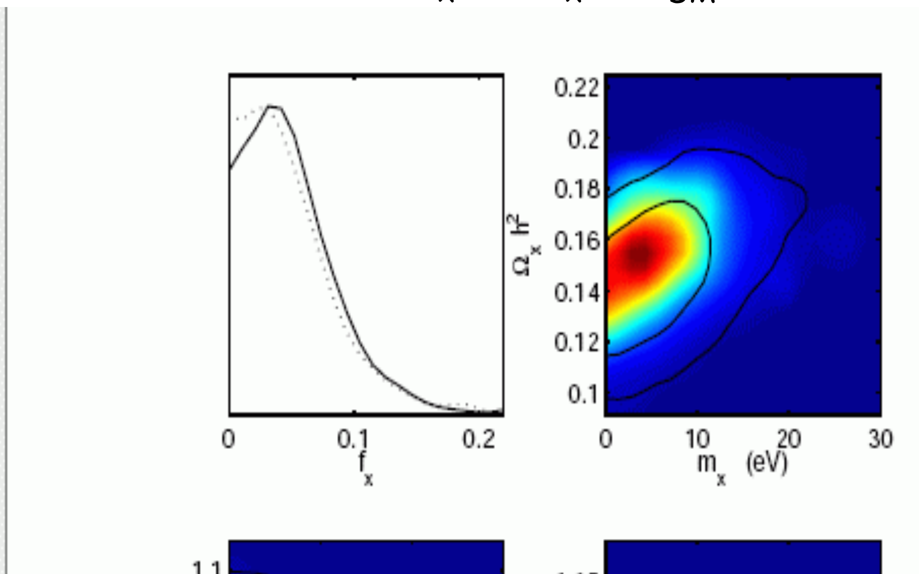
WARM DARK MATTER

α sets the transition scale



(light) GRAVITINO

f_x is Ω_x / Ω_{DM}

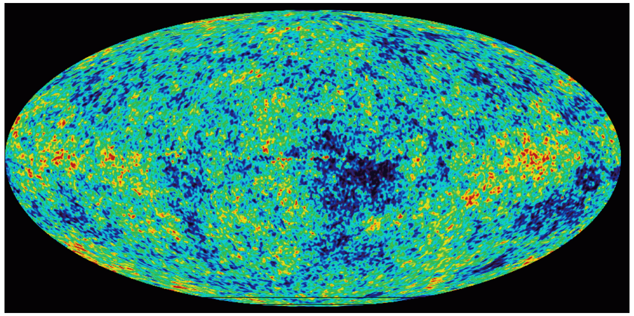


FORWARD MODELLING OF THE FLUX POWER

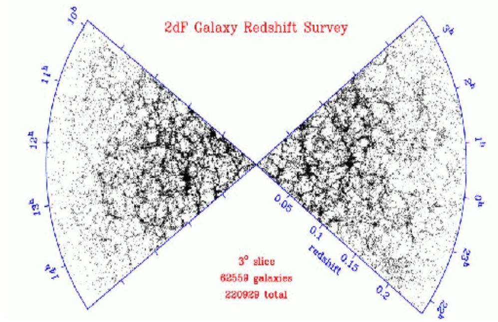
The interpretation: full grid of simulations

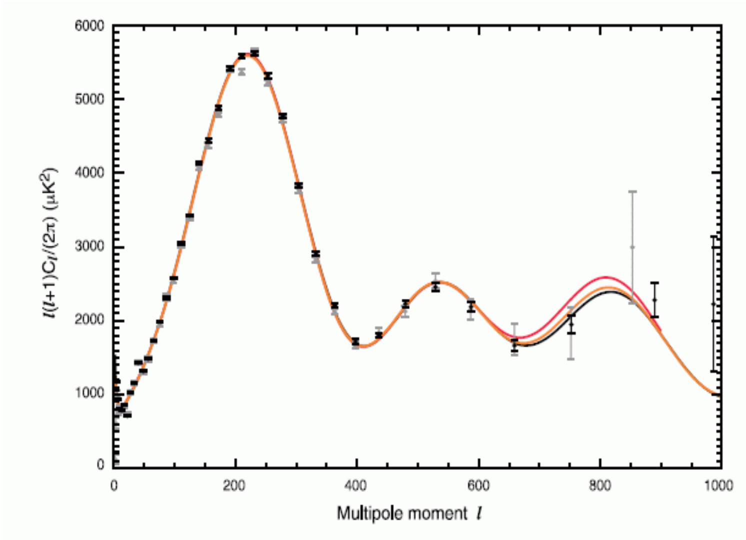
SDSS power analysed by forward modelling motivated by the huge amount of data with small statistical errors

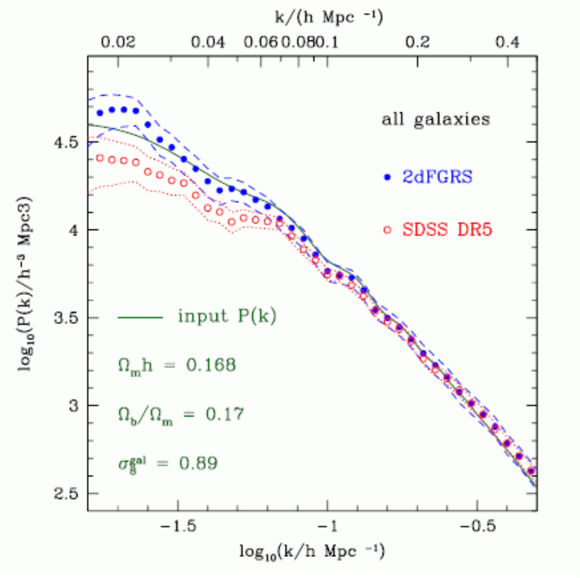
CMB: Spergel et al. (05) Galaxy P(k): Sanchez & Cole (07)



+







Cosmological parameters + e.g. bias

MODELLING FLUX POWER – II: Method

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
- $T=T_0\,(1+\delta)^{\gamma-1}$
- Reionization
- Metals
- Noise
- Resolution
- Damped Systems
- Physics
- UV background
- Small scales

MODELLING FLUX POWER – III: Likelihood Analysis

McDonald et al. 05

TABLE 2

EFFECT OF MODIFICATIONS OF THE FITTING PROCEDURE ON THE INFERRED LINEAR POWER SPECTRUM AND ITS ERRORS

Variant[a]	Δ_L^2	$n_{\rm eff}$	χ^{2b}	$\Delta\chi^{2c}$
Standard fit	0.452 ± 0.072	-2.321 ± 0.069	185.6	0.0
No hydrodynamic corrections	0.377 ± 0.041	-2.284 ± 0.046	191.8	4.0
Fixed extrapolation	0.456 ± 0.071	-2.303 ± 0.058	185.9	0.2
Fixed to FULL	0.453 ± 0.070	-2.322 ± 0.063	185.4	0.0
Fixed to NOSN	0.435 ± 0.059	-2.262 ± 0.054	187.9	1.9
Fixed to NOMETAL	0.394 ± 0.048	-2.374 ± 0.055	188.3	1.3
No $L = 40\ h^{-1}$ Mpc simulations	0.439 ± 0.065	-2.328 ± 0.069	190.0	0.1
$\Omega_m = 0.4$, HS transfer function	0.454 ± 0.074	-2.307 ± 0.067	187.6	0.1
No damping wings (DWs)	0.366 ± 0.042	-2.398 ± 0.050	188.7	1.8
DW power known to 10%	0.452 ± 0.071	-2.321 ± 0.067	185.6	0.0
Randomly located DW	0.435 ± 0.070	-2.333 ± 0.067	186.8	0.1
No UVBG fluctuations	0.446 ± 0.067	-2.338 ± 0.049	187.4	0.2
Strong attenuation UVBG	0.452 ± 0.072	-2.320 ± 0.067	185.1	0.0
Galaxy-based UVBG	0.452 ± 0.069	-2.346 ± 0.059	187.4	0.3
$\bar{F}$ errors times 2	0.452 ± 0.077	-2.321 ± 0.071	184.9	0.0
$\bar{F}$ errors times $\frac{1}{2}$	0.455 ± 0.062	-2.320 ± 0.066	188.2	0.0
Fix $\bar{F}$ to best	0.452 ± 0.030	-2.321 ± 0.048	185.6	0.0
TDR errors times 2	0.530 ± 0.106	-2.299 ± 0.078	180.4	0.8
TDR errors times $\frac{1}{2}$	0.455 ± 0.055	-2.305 ± 0.065	192.0	0.0
Schaye TDR	0.524 ± 0.059	-2.307 ± 0.072	195.4	1.4
HIRES P_F errors times 2	0.493 ± 0.086	-2.276 ± 0.081	153.8	0.9
HIRES P_F errors times $\frac{1}{2}$	0.442 ± 0.070	-2.335 ± 0.053	292.1	0.1
SDSS P_F errors times $\frac{1}{2}$	0.468 ± 0.053	-2.301 ± 0.033	584.3	0.1
Fix nuisance parameters to best	0.452 ± 0.010	-2.321 ± 0.012	185.6	0.0
Include Croft/Kim, no background subtraction	0.355 ± 0.051	-2.366 ± 0.054	313.3	2.9
Include Croft & Kim	0.408 ± 0.064	-2.364 ± 0.063	215.9	0.4
Drop bad Croft z	0.411 ± 0.064	-2.366 ± 0.064	206.1	0.3
Add Kim only	0.466 ± 0.082	-2.318 ± 0.076	178.7	0.1
Standard with HIRES background subtraction	0.503 ± 0.094	-2.305 ± 0.081	161.9	0.6

NOTE.—Here $z_p = 3.0$ and $k_p = 0.009$ s km^{-1}.

[a] The meaning of each variant is explained in § 3.5.

[b] Standard χ^2 for the fit, for ~161 degrees of freedom, plus 20–24 for Kim et al. (2004a), plus 44–65 for Croft et al. (2002) (see details in § 3.6).

[c] The $\Delta\chi^2$ between the variant best-fit amplitude and slope and the standard best-fit values (essentially unrelated to χ^2 for the fit).

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

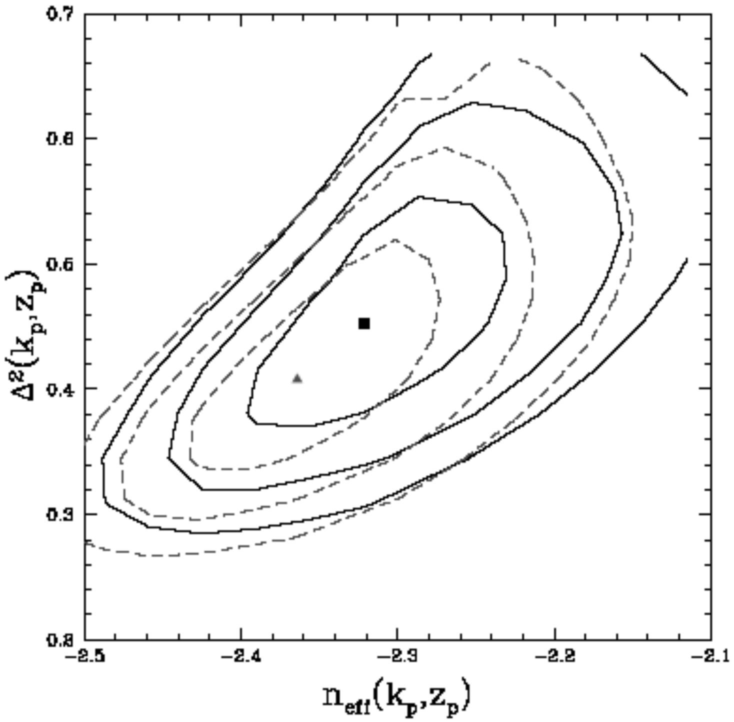
$$\Delta_L^2(k,\,z) \simeq \left[\frac{D(z)}{D(z_p)}\right]^2 \Delta_L^2(k_p,\,z_p) \quad \times \left[\frac{k}{k_\star(z)}\right]^{3+n_{\rm eff}(k_p,z_p)+(1/2)\alpha_{\rm eff}(k_p,z_p)\,\ln[k/k_\star(z)]}$$

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

AMPLITUDE



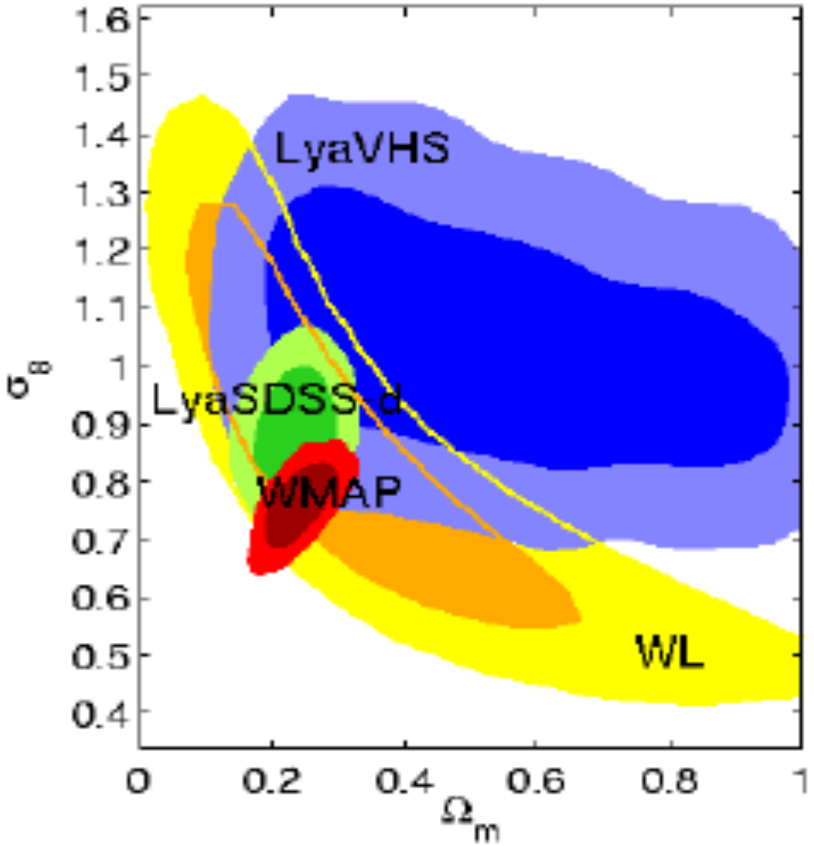
SLOPE

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

Lyman-α forest + Weak Lensing + WMAP 3yrs

VHS-LUQAS: high res Ly-a from (Viel, Haehnelt, Springel 2004)
SDSS-d: re-analysis of low res data SDSS (Viel & Haehnelt 2006)
WL: COSMOS-3D survey Weak Lensing (Massey et al. 2007) 1.64 sq degree
public available weak lensing COSMOMC module
http://www.astro.caltech.edu/~rjm/cosmos/cosmomc/

AMPLITUDE



MATTER DENSITY **SPECTRAL INDEX**

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

Lyman-α forest + Weak Lensing + WMAP 3yrs

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

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

WMAP 5yrs

WMAP5only Dunkley et al. 08

$\sigma_8 = 0.796 \pm 0.036$
$n_s = 0.963 \pm 0.015$
$\Omega_m = 0.258 \pm 0.030$
$h = 71.9 \pm 2.7$
$\tau = 0.087 \pm 0.017$
$dn/d\ln k = -0.037 \pm 0.028$

WMAP5+BAO+SN Komatsu et al. 08

$\sigma_8 = 0.817 \pm 0.026$
$n_s = 0.960 \pm 0.014$
$h = 70.1 \pm 1.3$
$\tau = 0.084 \pm 0.016$

with Lyman-α factor 2 improvements on the running

FORWARD MODELLING OF THE FLUX POWER:

A DIFFERENT APPROACH

Flux Derivatives - I

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

McDonald et al. 05: fine grid of (calibrated) HPM (quick) simulations
Viel & Haehnelt 06: interpolate sparse grid of full hydrodynamical (slow) simulations

Both methods have drawbacks and advantages:

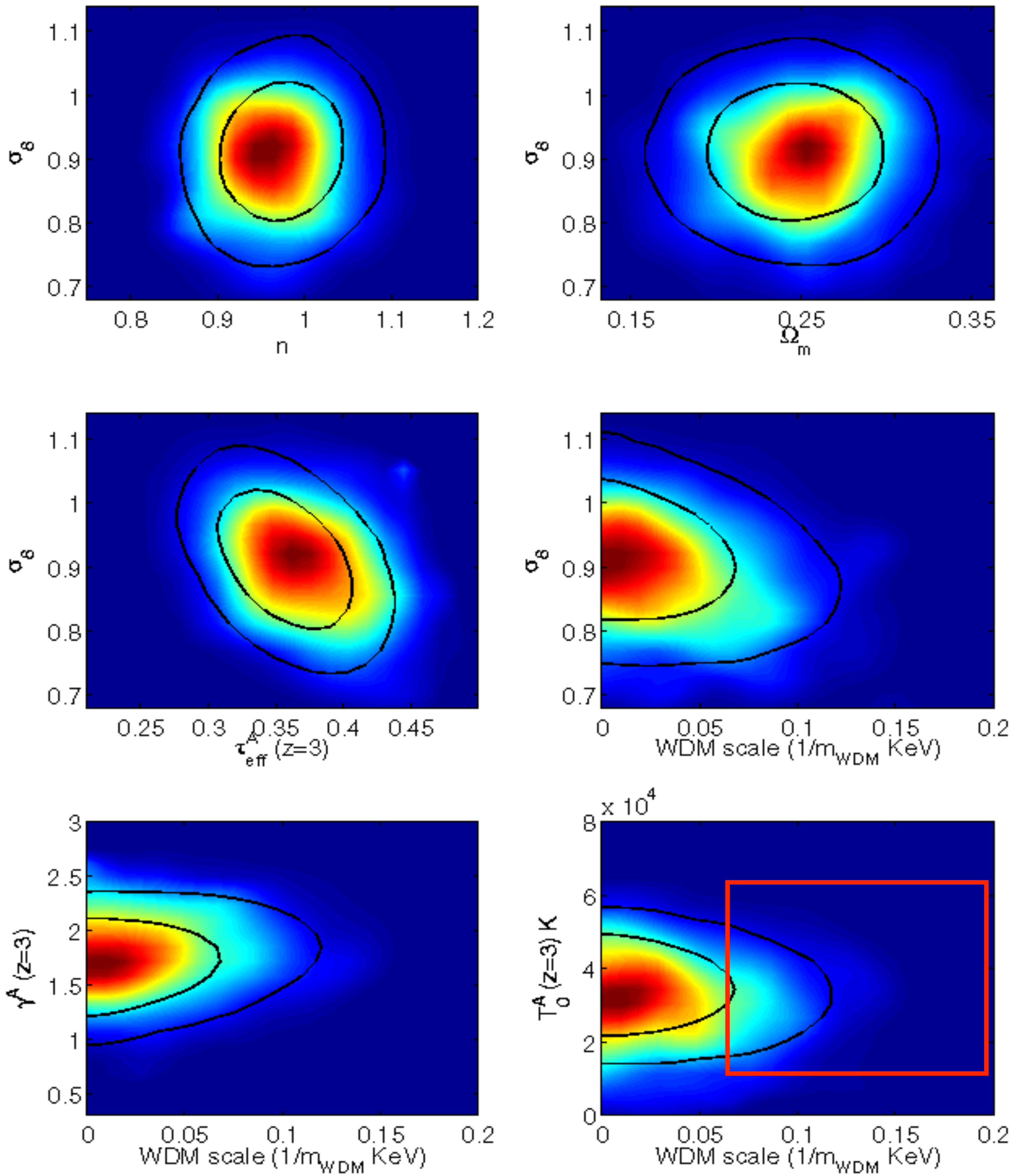
1- McDonald et al. 05 better sample the parameter space
2- Viel & Haehnelt 06 rely on hydro simulations, but probably error bars are underestimated

Flux power

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

p: astrophysical and cosmological parameters

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



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

FLUX DERIVATIVES method
of lecture 2

M sterile neutrino > 10 KeV
95 % C.L.

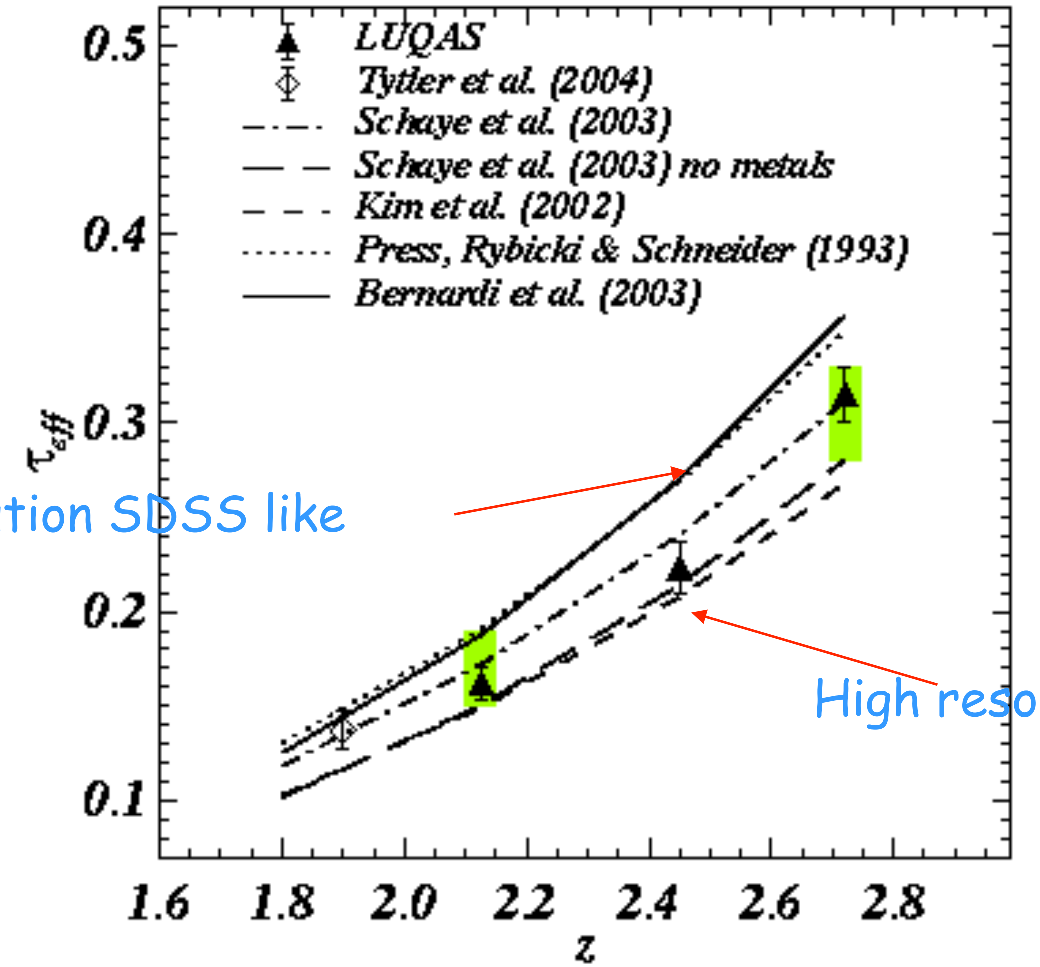
SDSS data only

σ_8 = 0.91 ± 0.07
n = 0.97 ± 0.04

SYSTEMATICS

Systematics I: Mean flux

Effective optical depth



Low resolution SDSS like spectra

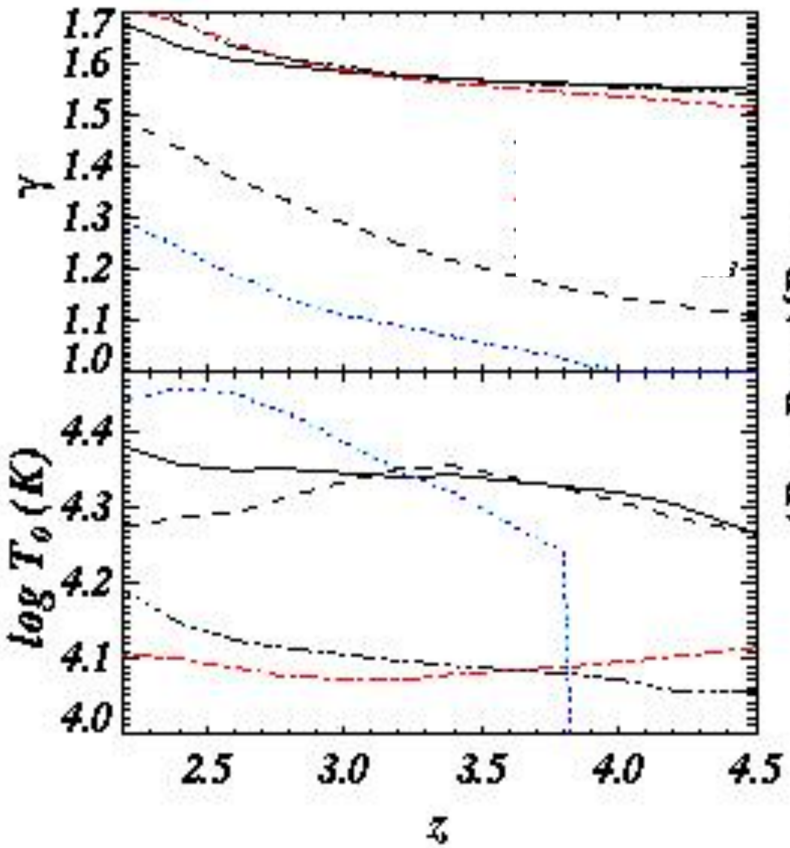
High resolution UVES like spectra

$\langle F \rangle = \exp(-\tau_{eff})$ Power spectrum of $F/\langle F \rangle$

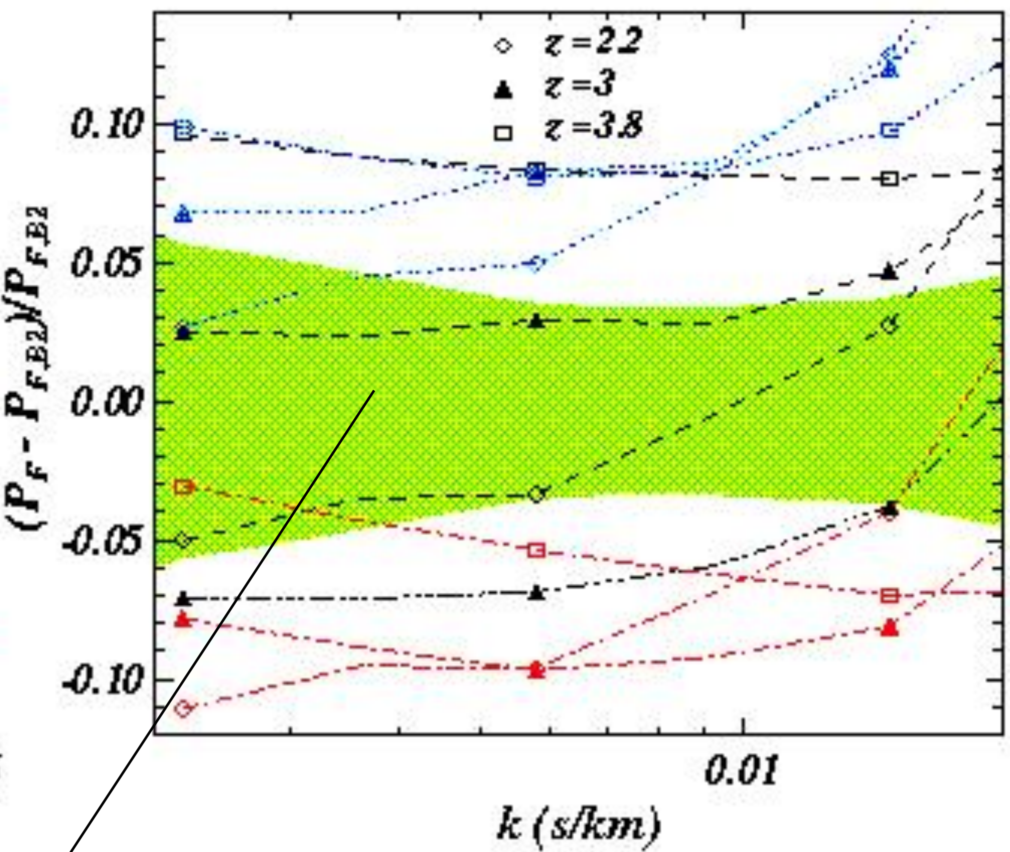
Systematics II: Thermal state

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

Thermal histories



Flux power fractional differences



Statistical SDSS errors on flux power

Systematics III: Numerical modelling HPM simulations

$$\frac{dv}{dt} + Hv = -\nabla\phi - \frac{1}{\rho}\nabla P,$$

equation of motion for gas element

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

$$\frac{dv}{dt} + Hv = -\nabla\psi$$

where

$$\psi = \phi + \mathcal{H},$$

and $\mathcal{H}$, called *the specific enthalpy*, is

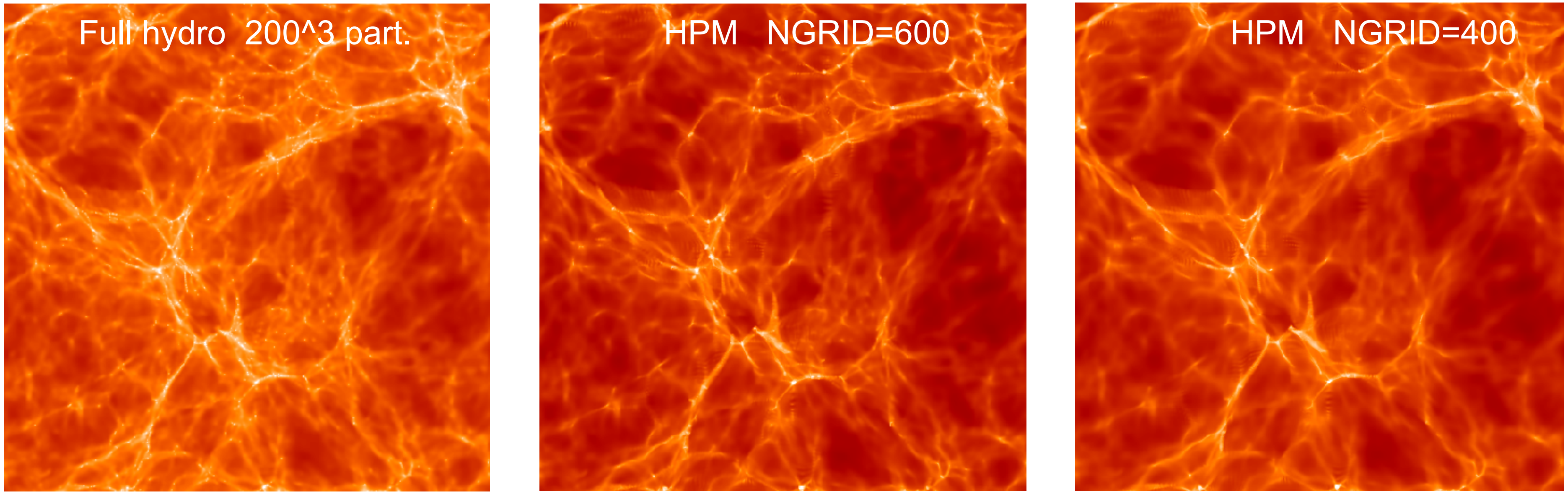
$$\mathcal{H}(\rho) = \frac{P(\rho)}{\rho} + \int_1^\rho \frac{P(\rho')}{\rho'}\frac{d\rho'}{\rho'}.$$

We thus conclude that the HPM approximation can be successfully used to model the Lyman-alpha forest when a 10-15% accuracy is sufficient.

Gnedin & Hui 1998

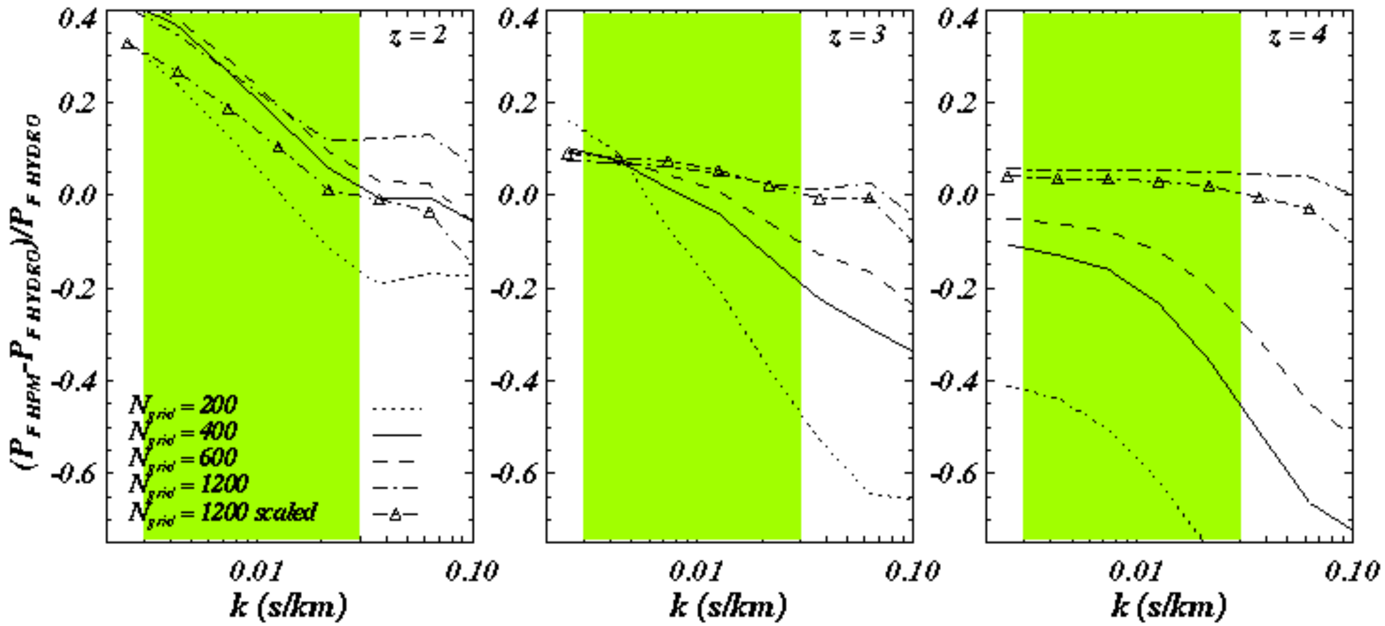
Other similar techniques agree with the statement above
Meiksin & White 2001

Systematics IV: Numerical modelling HPM simulations



MV, Haehnelt, Springel (2006)

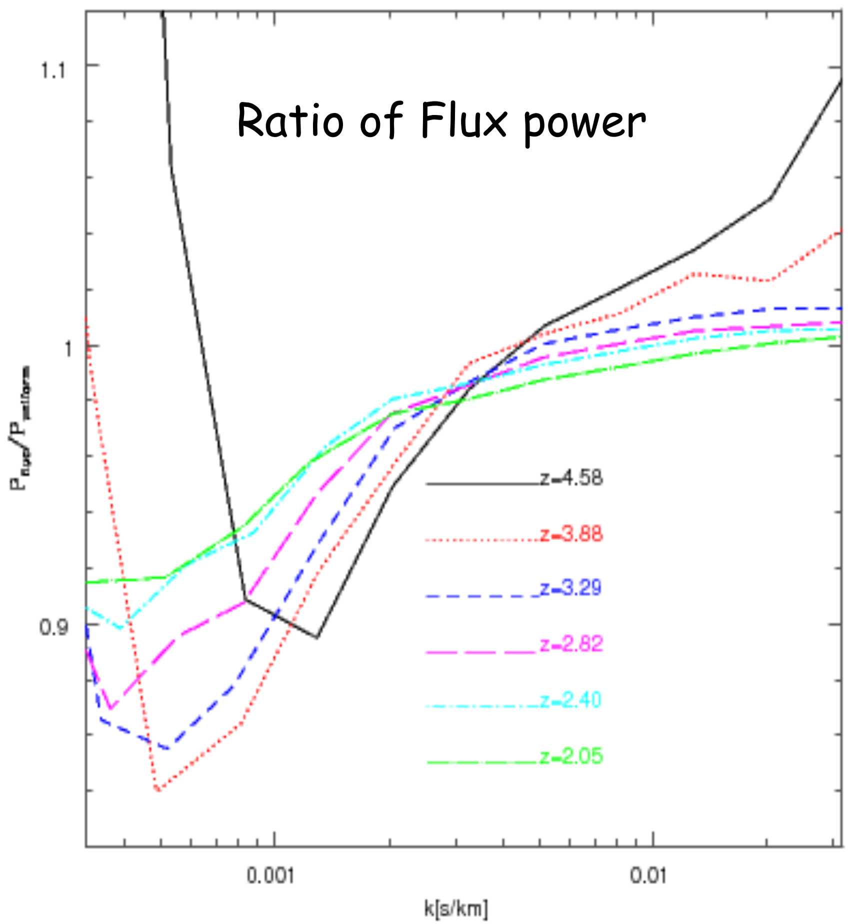
FLUX POWER



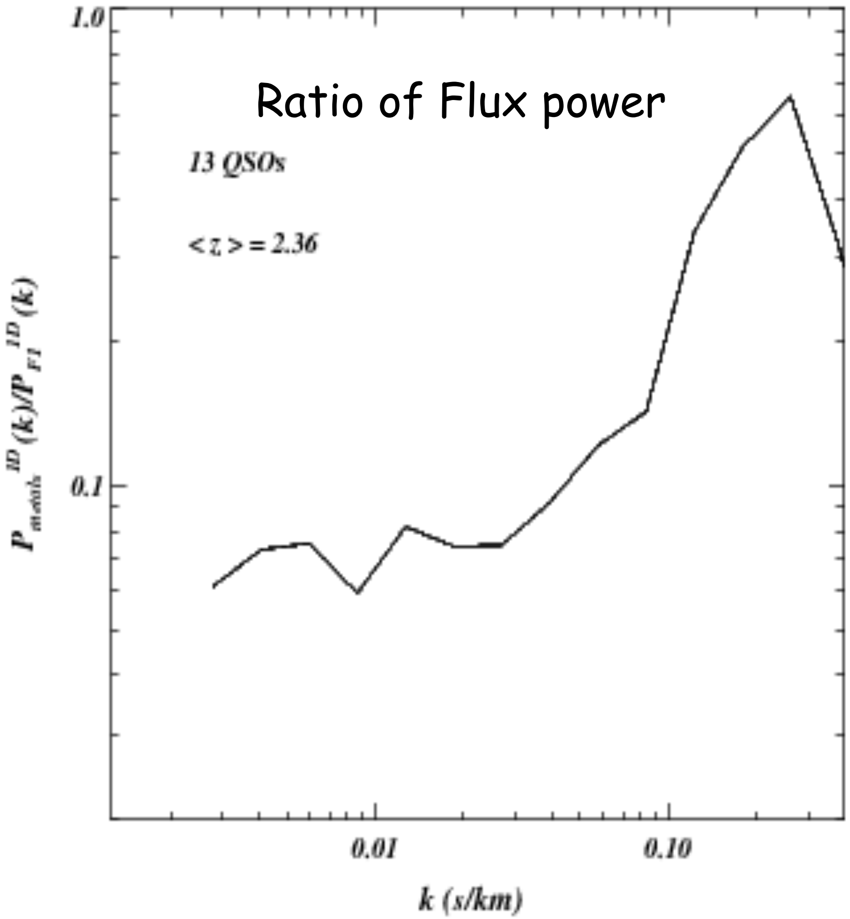
Systematics IV: UV fluctuations and Metals

UV fluctuations from Lyman Break Galaxies

Metal contribution



McDonald, Seljak, Cen, Ostriker 2004

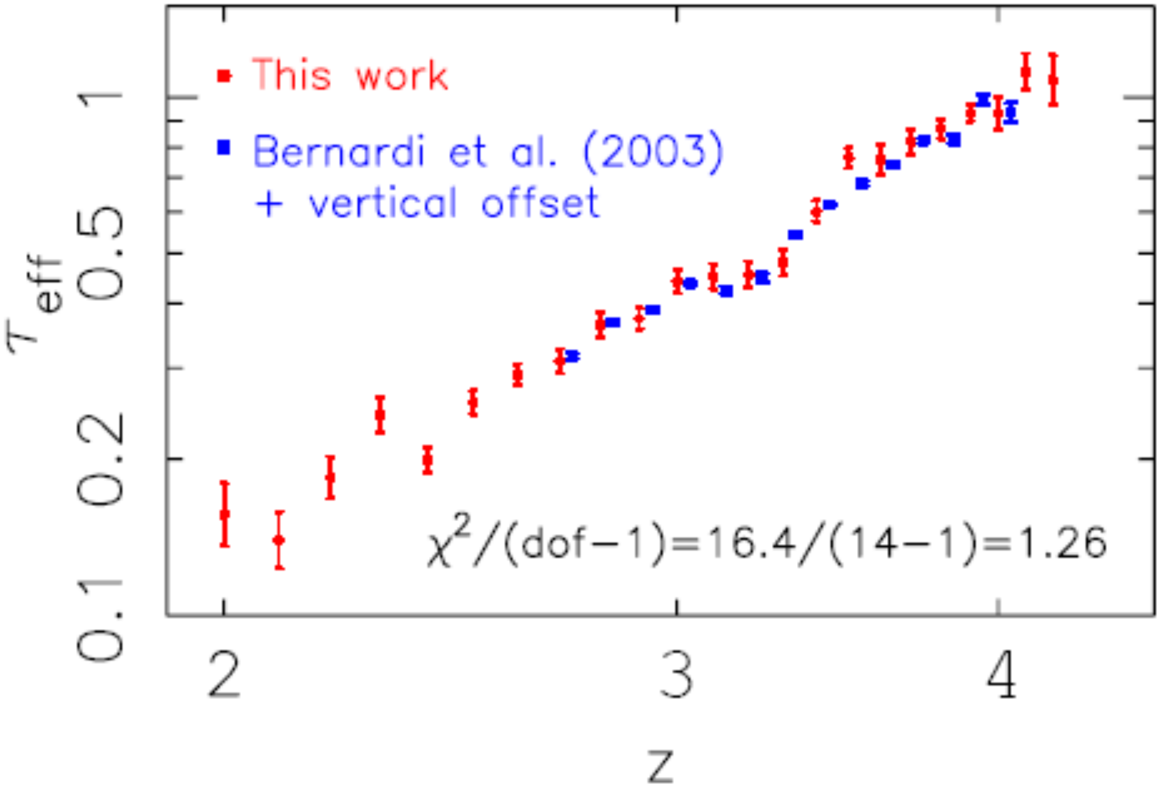


Kim, MV, Haehnelt, Carswell, Cristiani (2004)

NEW RESULTS
for
SIMPLER STATISTICS ?

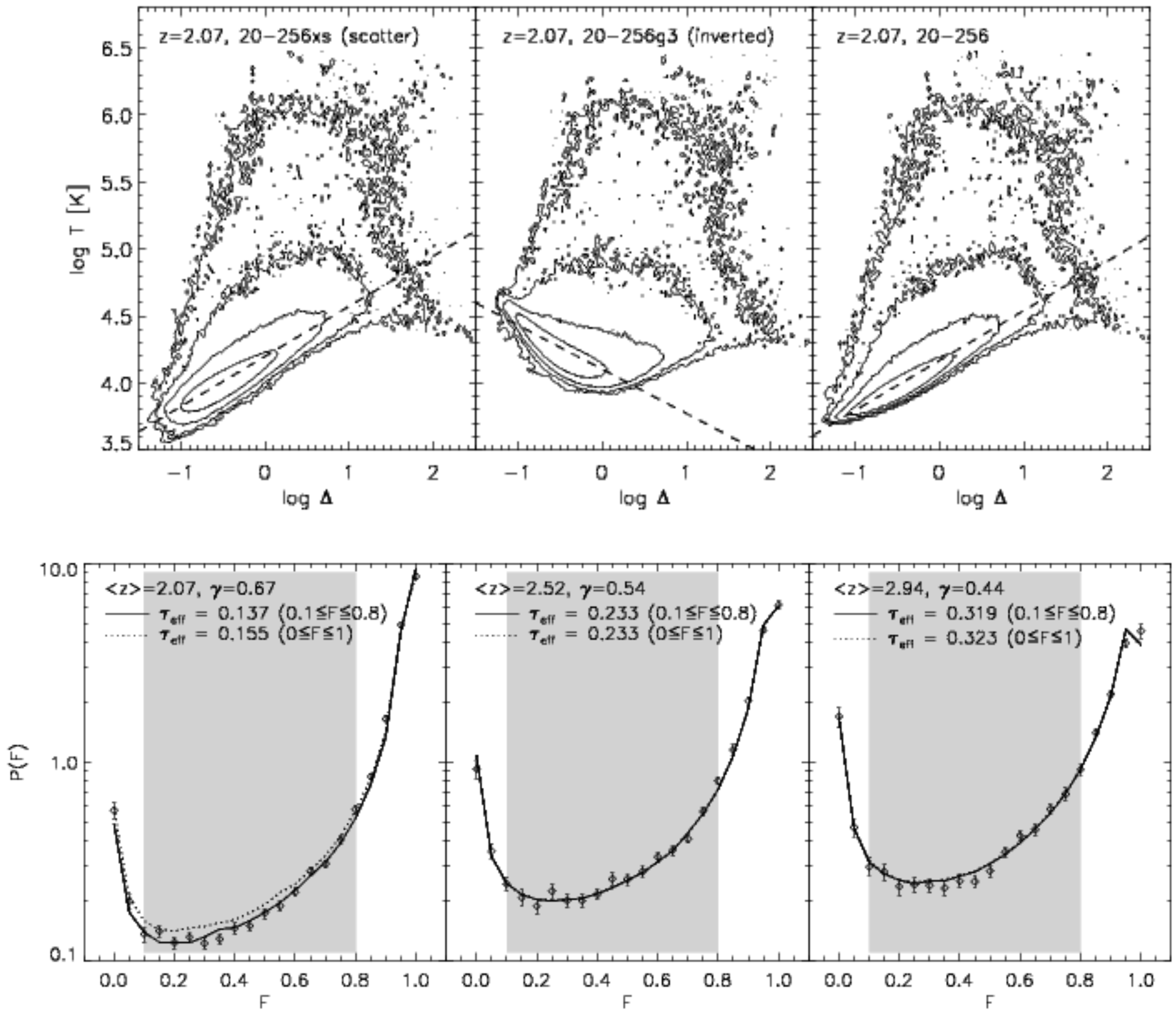
Fitting the mean flux evolution -I

Faucher-Giguere et al. (07)



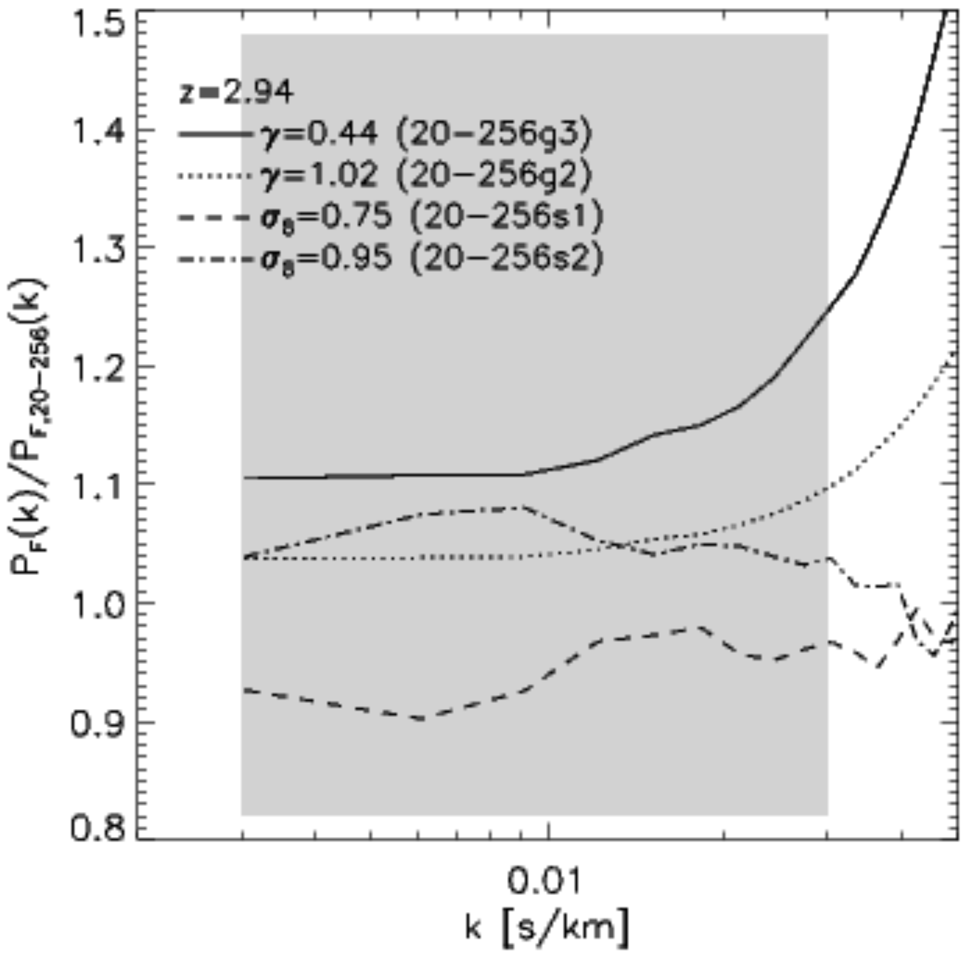
Fitting the flux probability distribution function

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

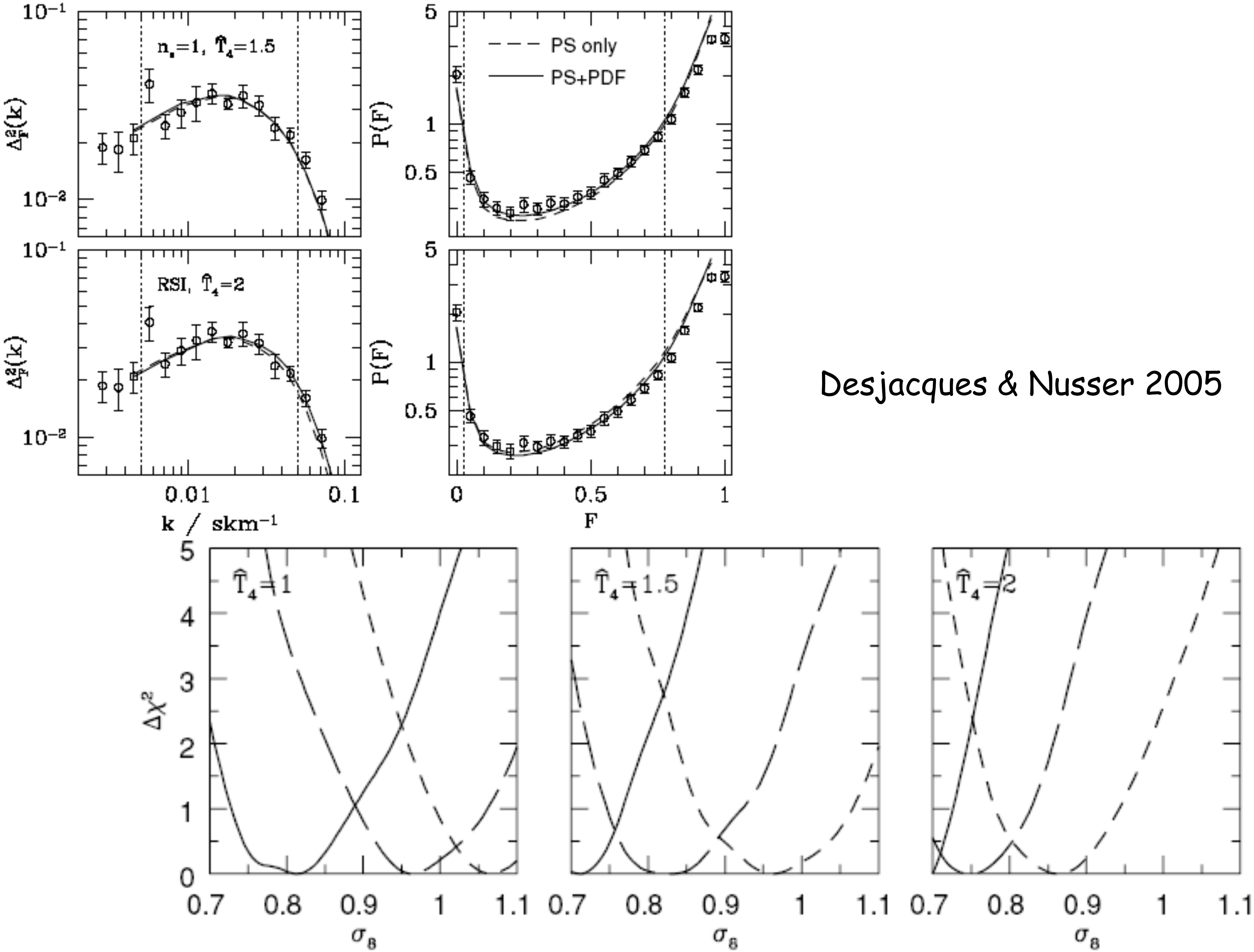


Fitting the flux probability distribution function-II

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



Fitting all the IGM statistics ?



Desjacques & Nusser 2005

SUMMARY

-Simple physics of the IGM and its main manifestation: the Lyman-a forest.

- Methods to recover the underlying matter power and quantifying the impact of nuisance parameters (temperature, DLAs… etc.)

- Quantitative cosmology is possible and main limitations are due to systematics: Lyman-a is a measurement of matter power at small scales

- Flux power is the main observable but lower order statistics carry precious information which could be more difficult to interpret (flux PDF and mean flux evolution)

SOME
RECENT RESULTS

RESULTS

WARM DARK MATTER

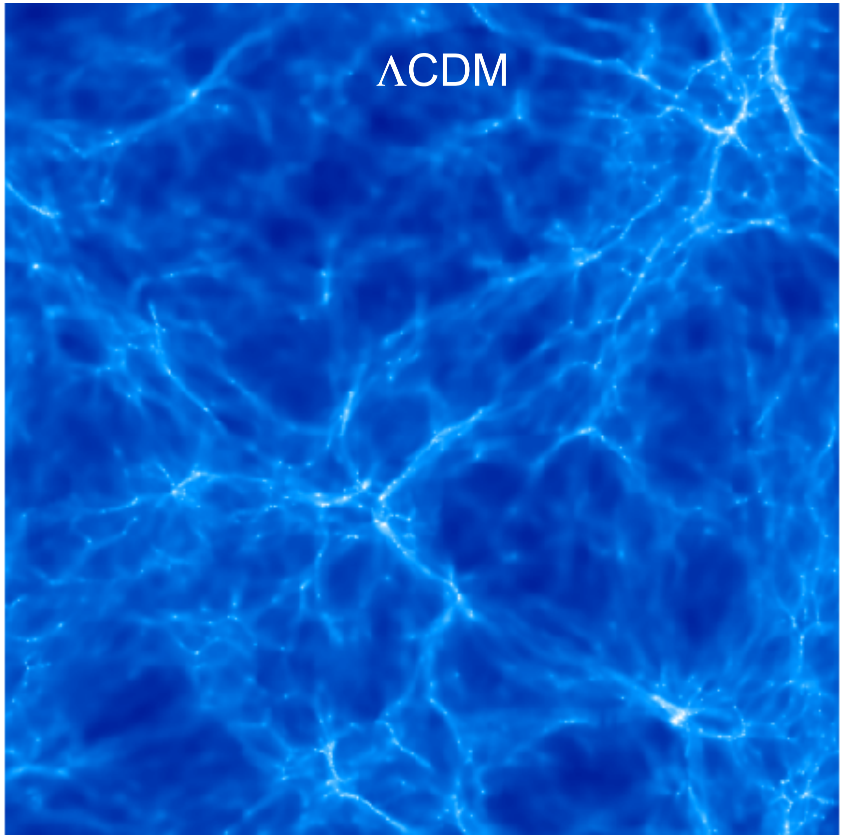
Or if you prefer.. How cold is cold dark matter?

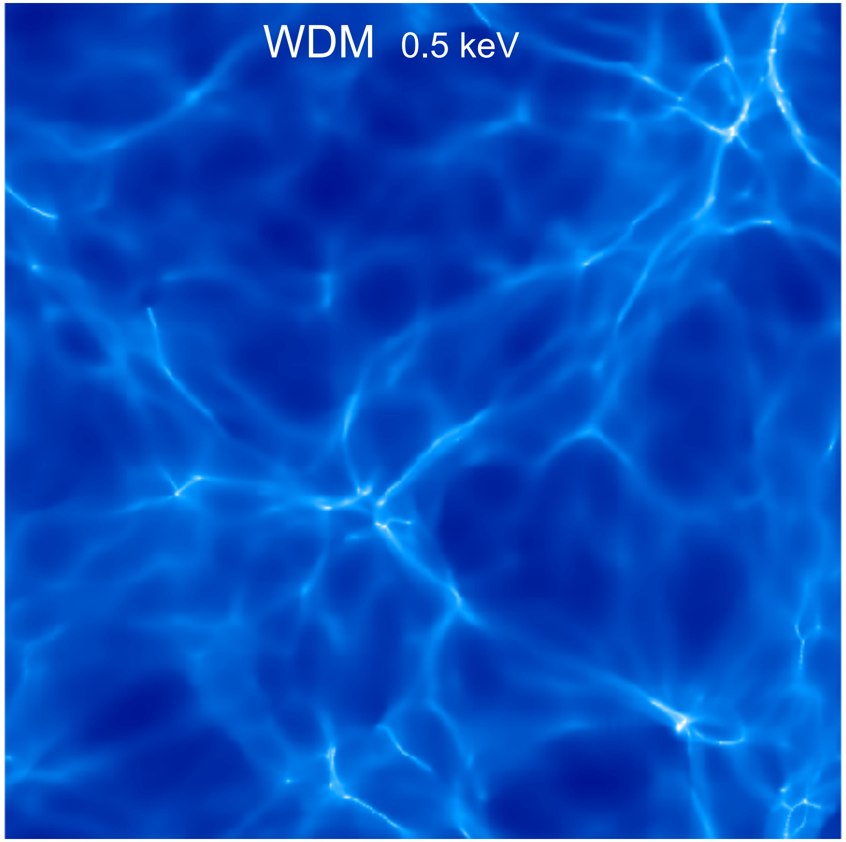
(Some) Motivations

- Some problems for cold dark matter at the small scales: 1- too **cuspy cores**, 2- too **many satellites**, 3- **dwarf galaxies** less clustered than bright ones (e.g. Bode, Ostriker, Turok 2001)

Although be aware that 1- **astrophysical processes** can act as well to alleviate these problems (feedback); 2- number of **observed satellites** is increasing (SDSS data); 3- galaxies along filaments in warm dark matter sims is probably a **numerical artifact**

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

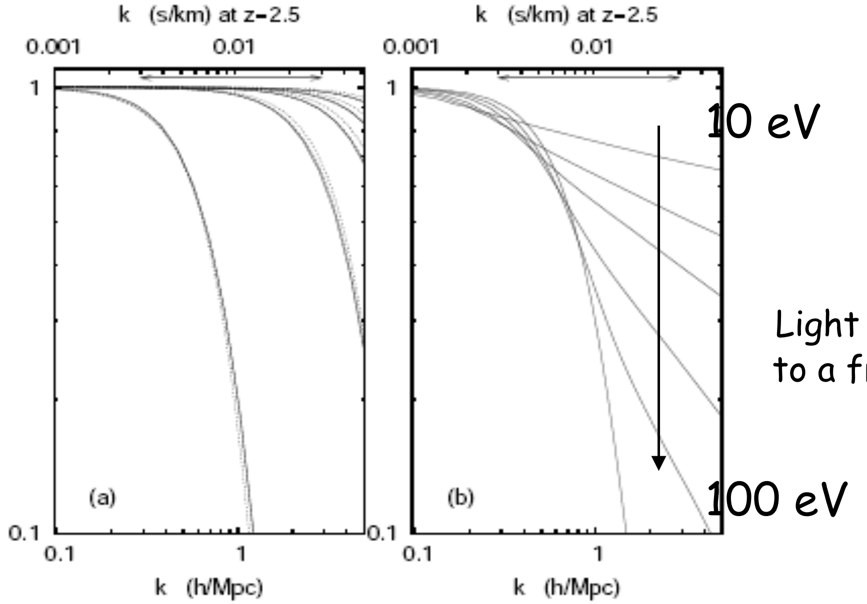
MV, Lesgourgues, Haehnelt, Matarrese, Riotto, PRD, 2005, 71, 063534

Lyman-α and Warm Dark Matter - II

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

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

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



Light gravitino contributing to a fraction of dark matter

Warm dark matter

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

Lyman-α and Warm Dark Matter - III

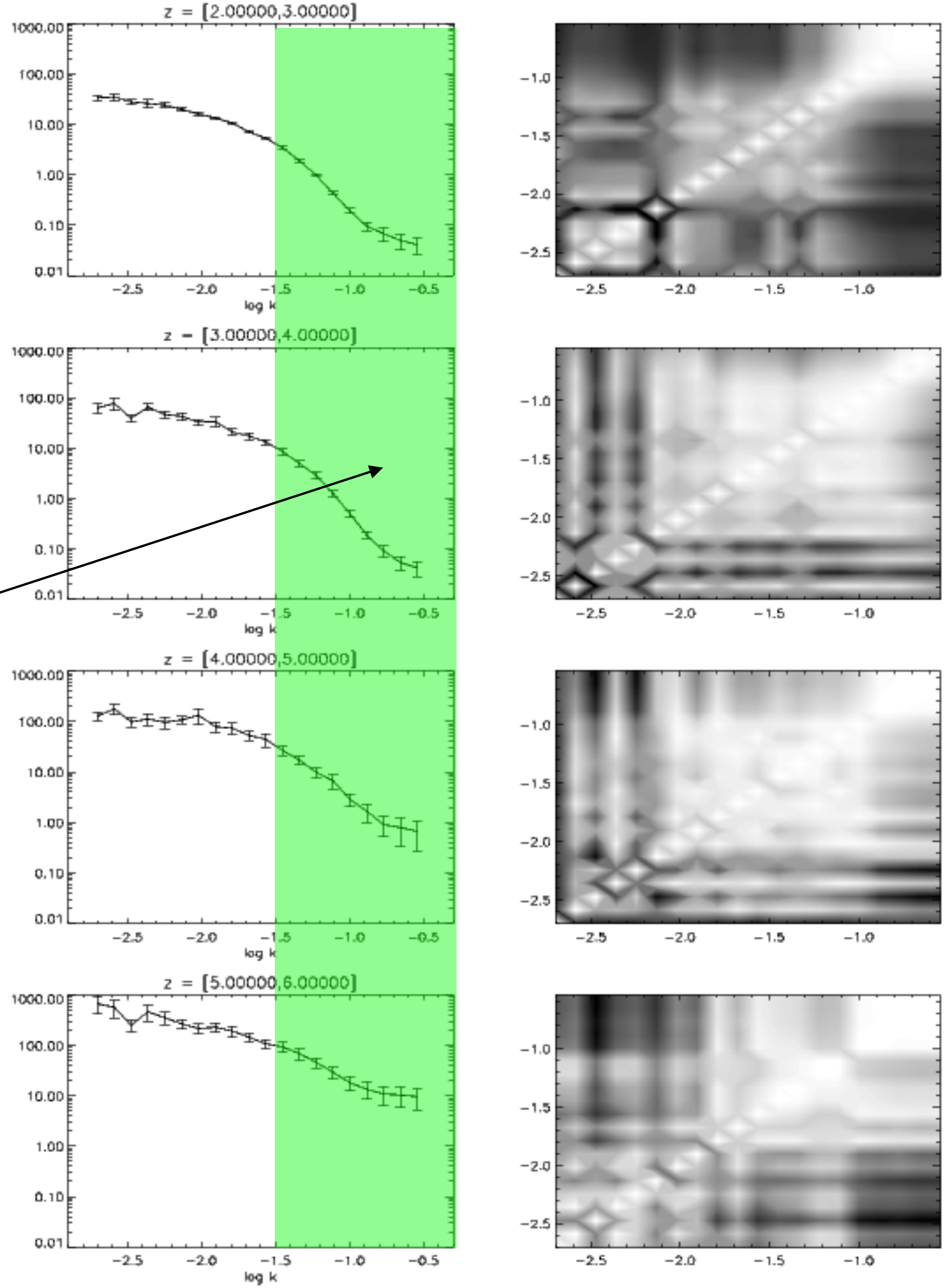
55 HIRES spectra QSOs z=2-6.4
from Becker, Rauch, Sargent (2006)

Masking of DLAs and metal lines associated to the DLAs, or identified from other lines outside the forest (so there could be still some metal contamination)

Unexplored part of the flux power spectrum which is very sensitive to:

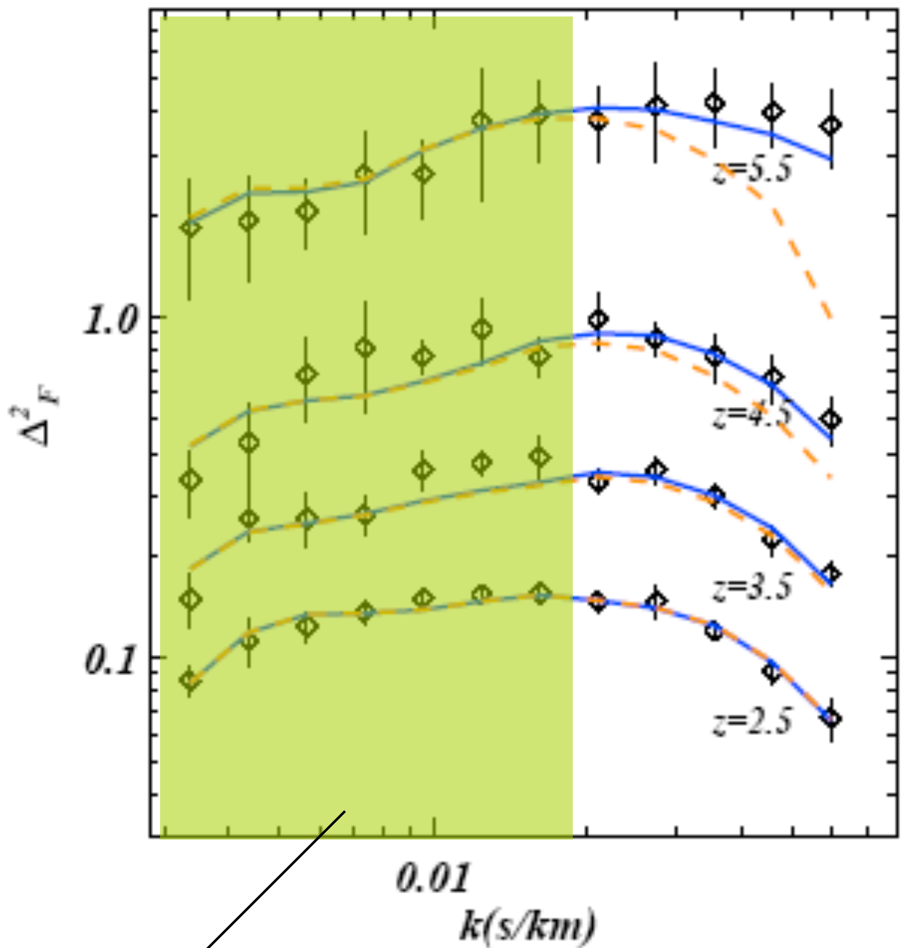
Temperature,
Metals,
Noise,
Galactic winds,
Ionizing fluctuations,
Damping wings….
…and maybe more

Power Spectrum **Covariance Matrix**



Lyman-α and Warm Dark Matter - IV

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



SDSS range

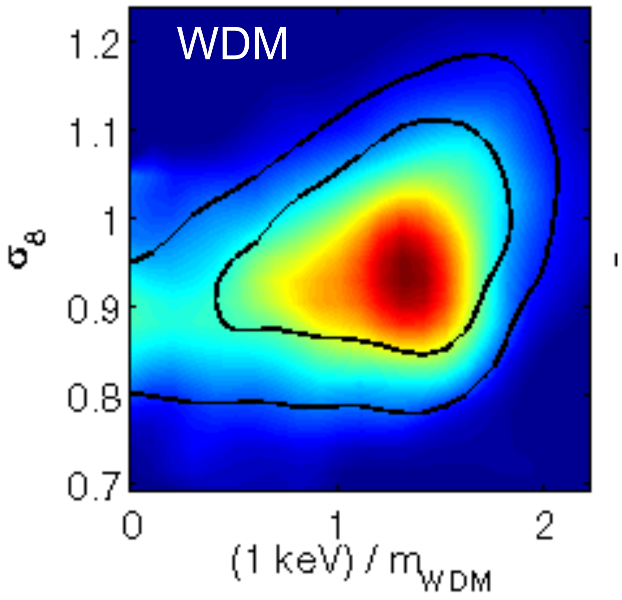
SDSS + HIRES data

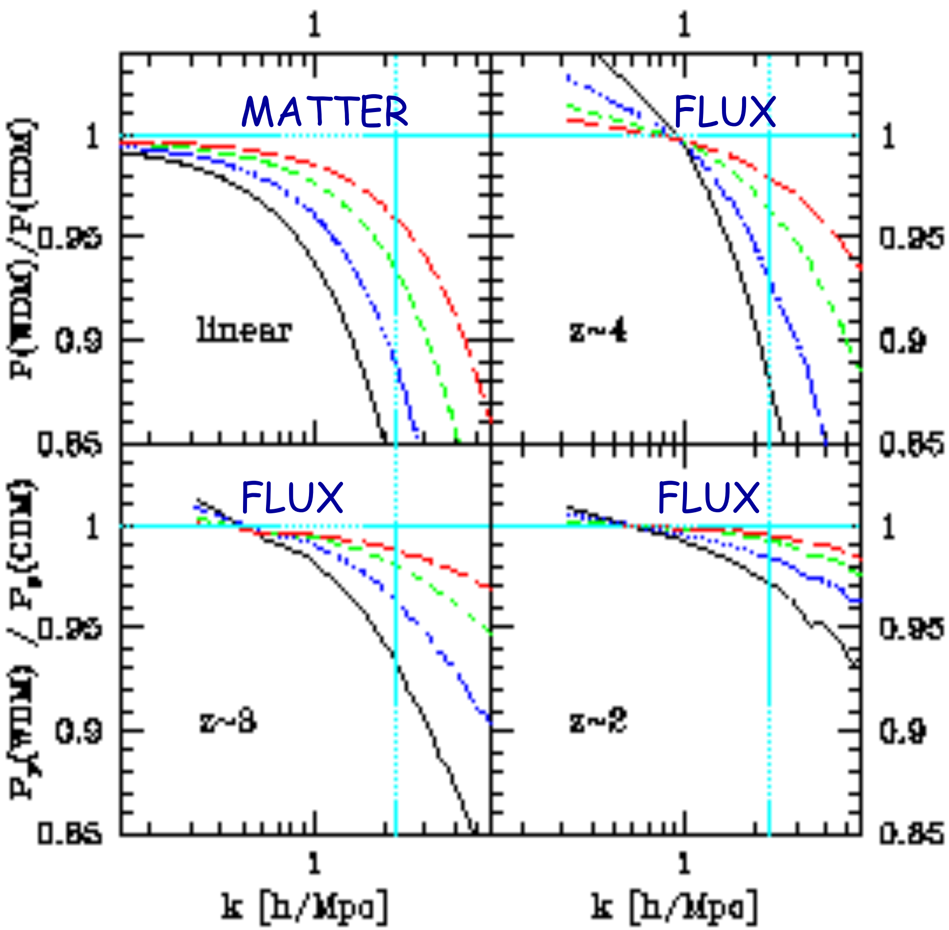
Tightest constraints on mass of WDM particles to date:

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

$m_{sterile} > 28$ keV

Lyman-α and Warm Dark Matter - V





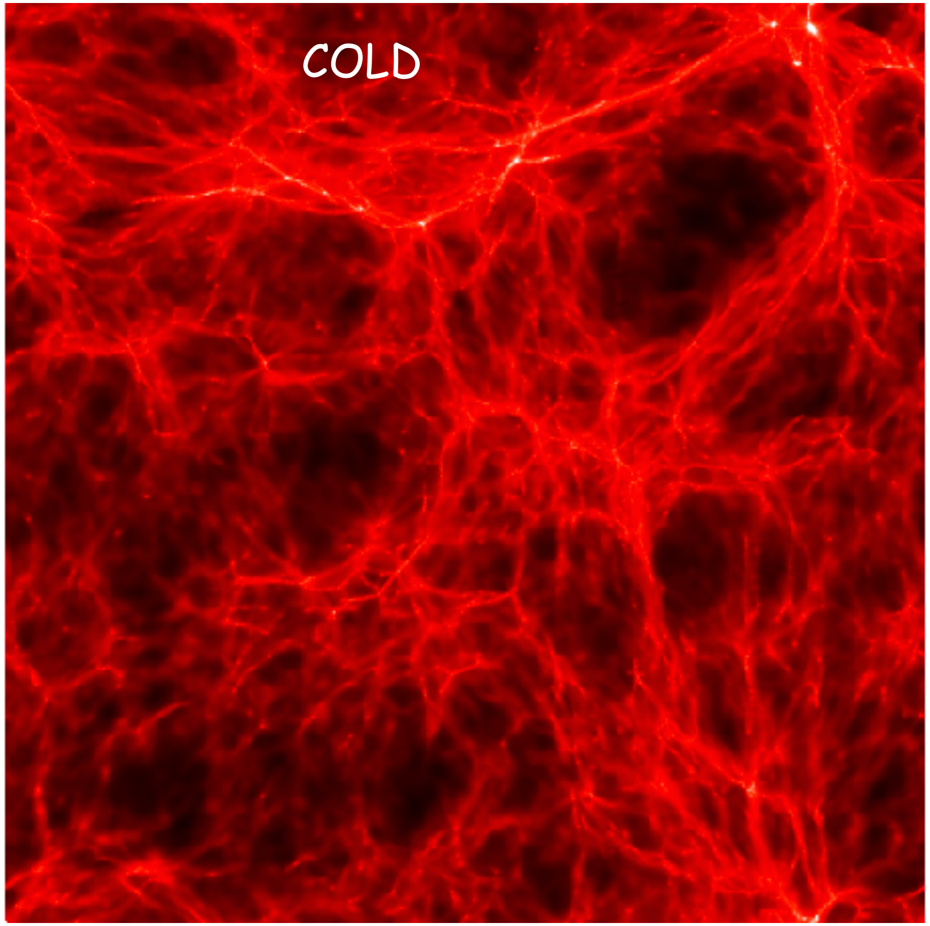
m_{WDM} > 550 eV thermal
> 2keV sterile neutrino

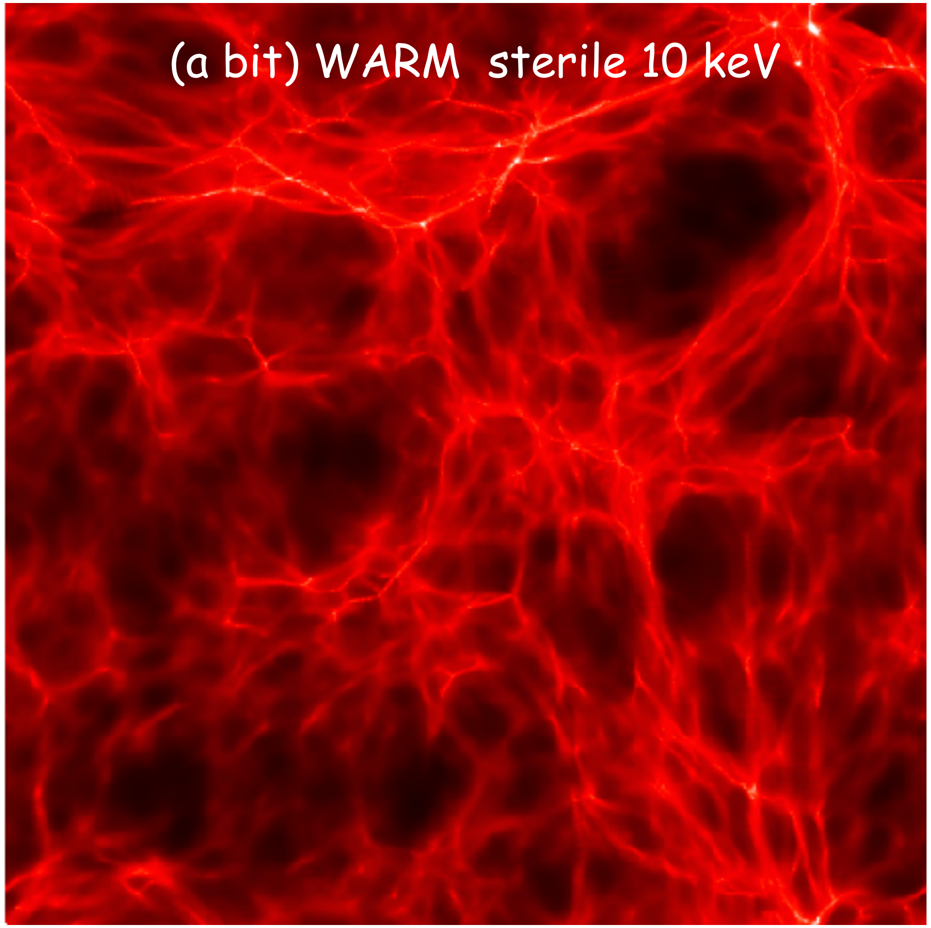
Viel et al. (2005)from high-res z=2.1 sample

m_{WDM} > 1.5-2 keV thermal
> 10-14 keV sterile neutrino

Seljak, Makarov, McDonald, Trac, PhysRevLett, 2006, 97, 191303
MV, Lesgourgues, Haehnelt, Matarrese, Riotto, PhysRevLett, 2006, 97, 071301

Little room for warm dark matter…… at least in the standard DW scenario
…the cosmic web is likely to be quite "cold"



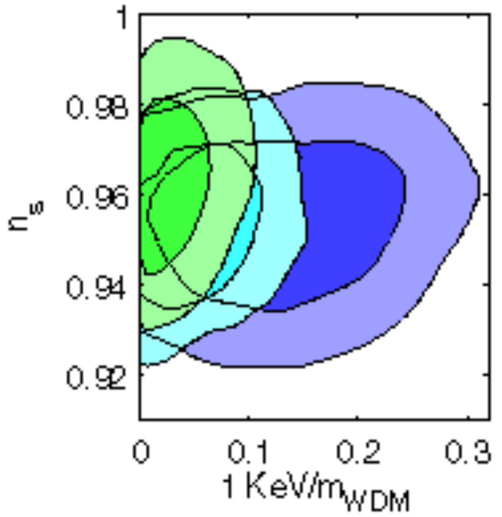


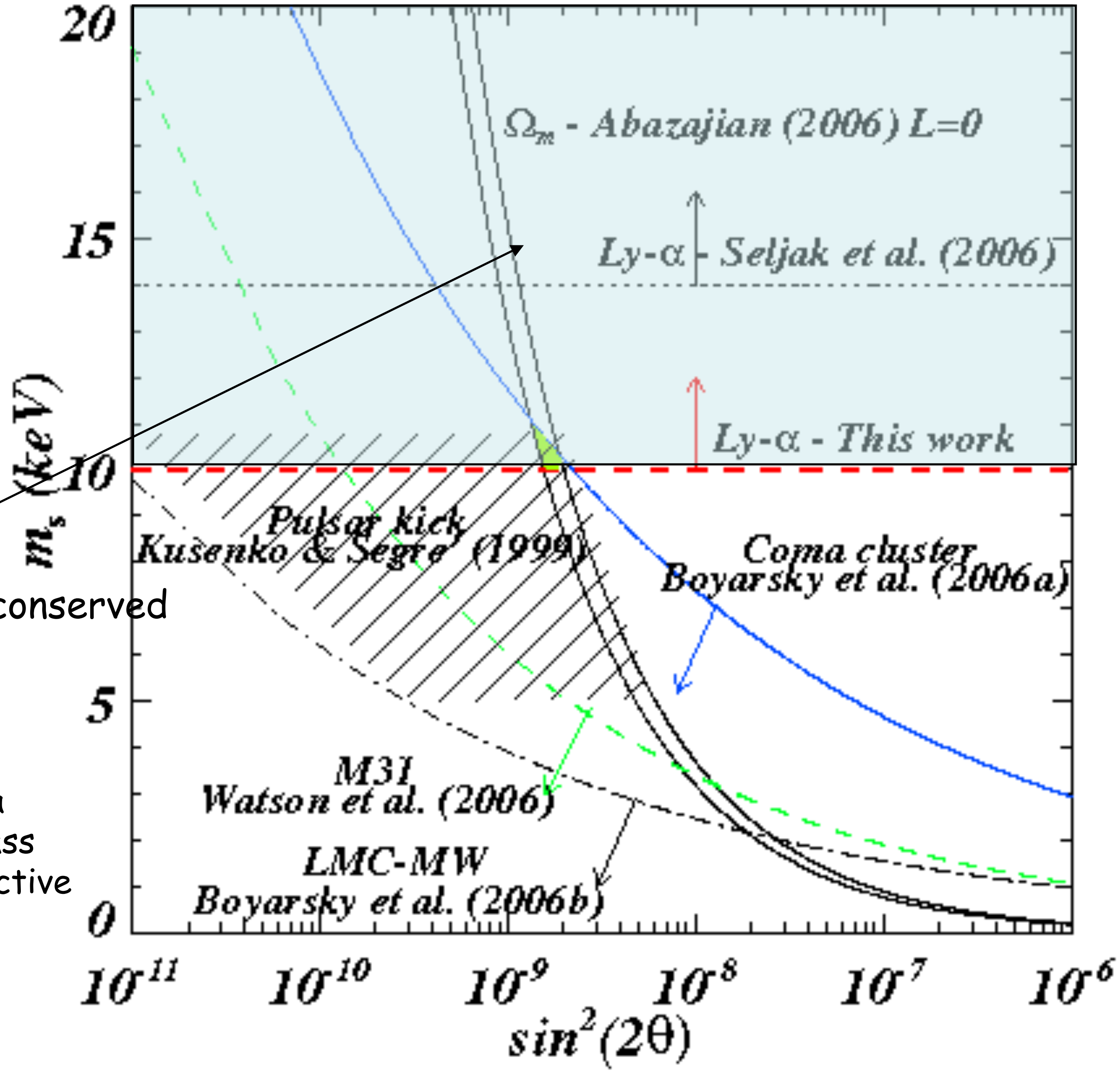
To constrain the sterile neutrino particle we need two parameters:

1) Neutrino mass m_s

2) Mixing angle θ that describes the interaction between active and sterile neutrino families

Lyα-WDM VII: analysis with flux derivatives





$L_\nu = 0$

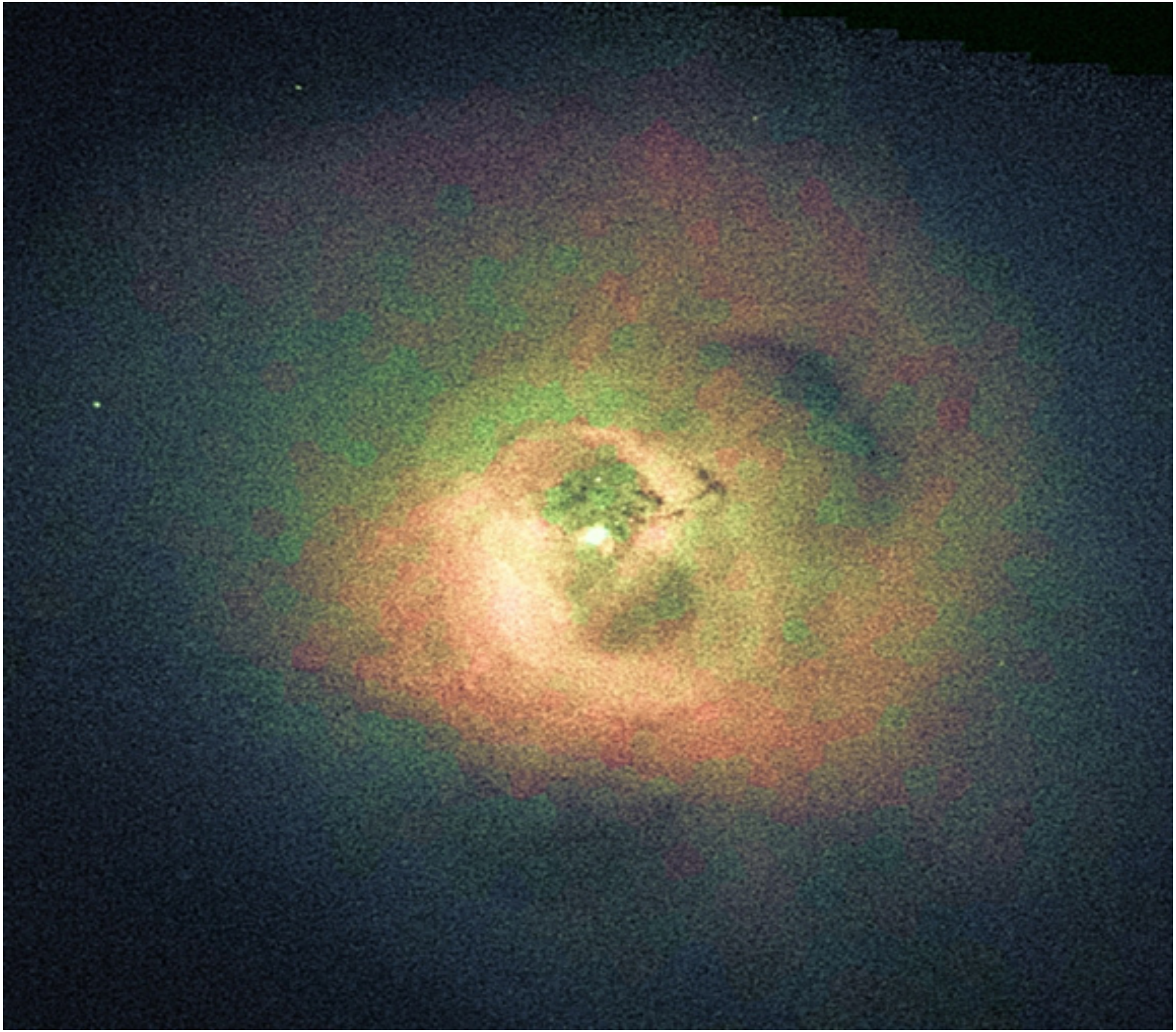
Leptonic number is conserved

Radiative decay channel at a
Rate that depends on its mass
And the mixing angle with active
Neutrinos

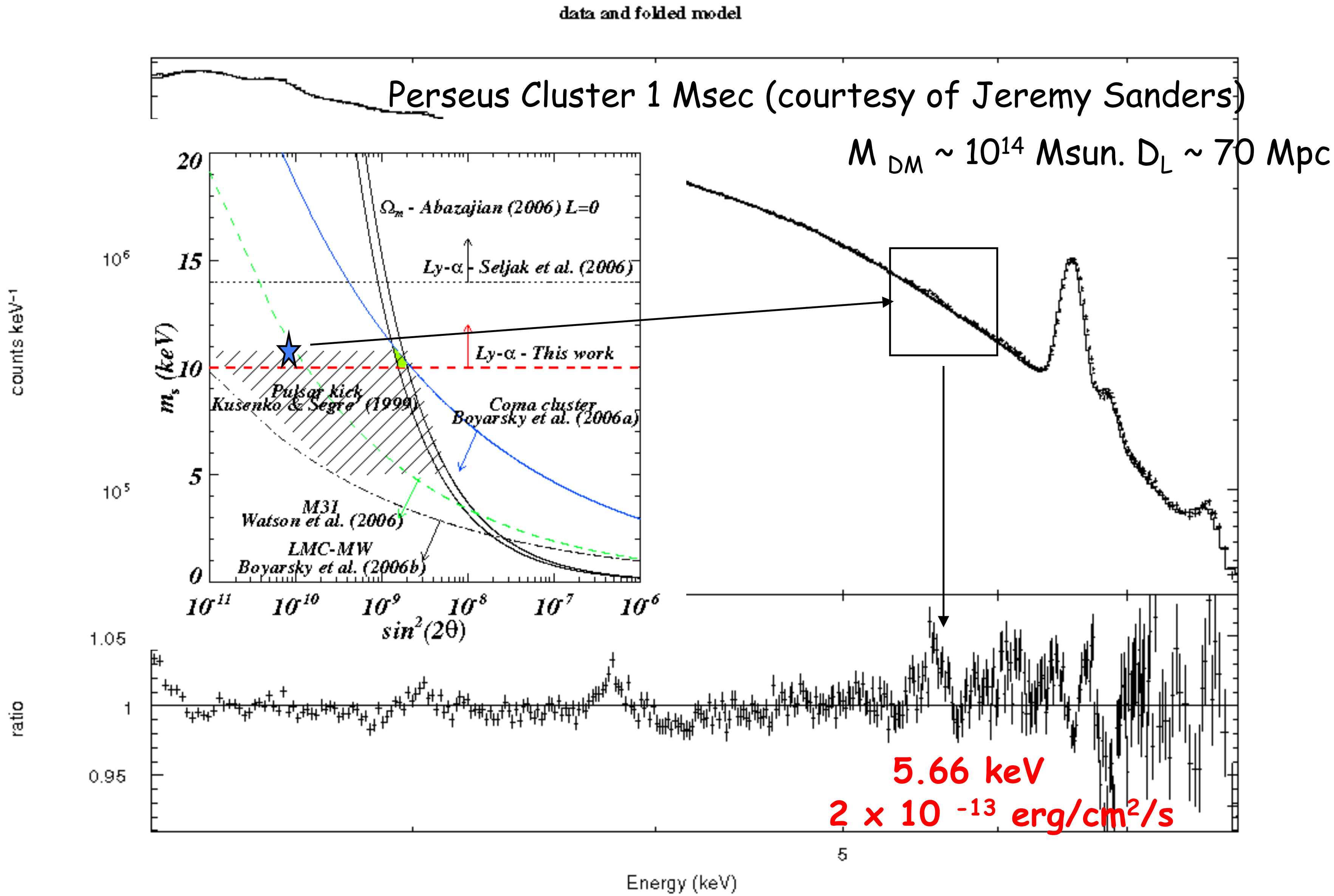
$\Gamma \sim \sin^2 2\theta\, m_{sterile}^5$

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, Phys.Rev.Lett., 2006, 97, 071301

Fabian, Sanders and coworkers…..



Decaying channel into photons and active neutrinos line with $E=m_s/2$ (X-band)



Line flux ~ 5×10^{-18} erg cm $^{-2}$ s $^{-1}$ $(D_L/1\text{Mpc})^{-2}$ $(M_{DM}/10^{11}\, M_{sun})$ $(\sin^2 2\theta/10^{-10})$ $(m_s/1\text{kev})^5$

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XMM-Newton reveals the origin of elements in galaxy clusters

10 May 2006

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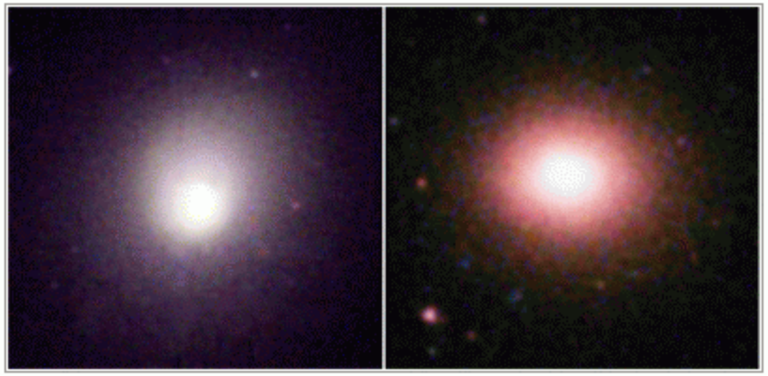

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These X-ray images of the clusters of galaxies 'Sersic 159-03' (right) and '2A 0335+096' (left) were taken by the European Photon Imaging Camera (EPIC) on-board ESA's XMM-Newton, in November 2002 and August 2003 respectively. Thanks to these observations, astronomers could determine the abundances of nine chemical elements in the clusters 'plasma' – a gas containing charged particles such as ions and electrons. These elements include oxygen, iron, neon, magnesium, silicon, argon, calcium, nickel, and - detected for the first time ever in a galaxy cluster - chromium. The distribution of silicon (produced by 'type Ia' and 'core collapse' supernova types) relative to iron (mainly produced by 'type Ia' supernovae) in these two clusters is very different, showing that they had a different evolution.

Credits: ESA and the XMM-Newton EPIC consortium

5.66 keV !!!

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$\Delta E_{line} = v_{virial} \, E/c$ ~ 50 eV for a galaxy cluster 5 eV for a galaxy for E=5keV

Note that the EDGE Low Energy Telescope will be at < 3(1.6) keV with a resolution of 1 eV
So if the sterile neutrino is more massive than 10 keV it might not be seen by EDGE

$\Delta E_{Xraybackground} \sim E$

SENSITIVITY of DETECTION ~ $1/\sqrt{(\Delta E)}$, $\sqrt{(A\ eff)}$, $\sqrt{FOV}$,

Note that both clusters and dwarf galaxies are about 1deg^2 in the sky having a larger field of view will not improve things dramatically

See Boyarsky, den Herder, Neronov, Ruchayskiy, 2006, astro-ph/0612219

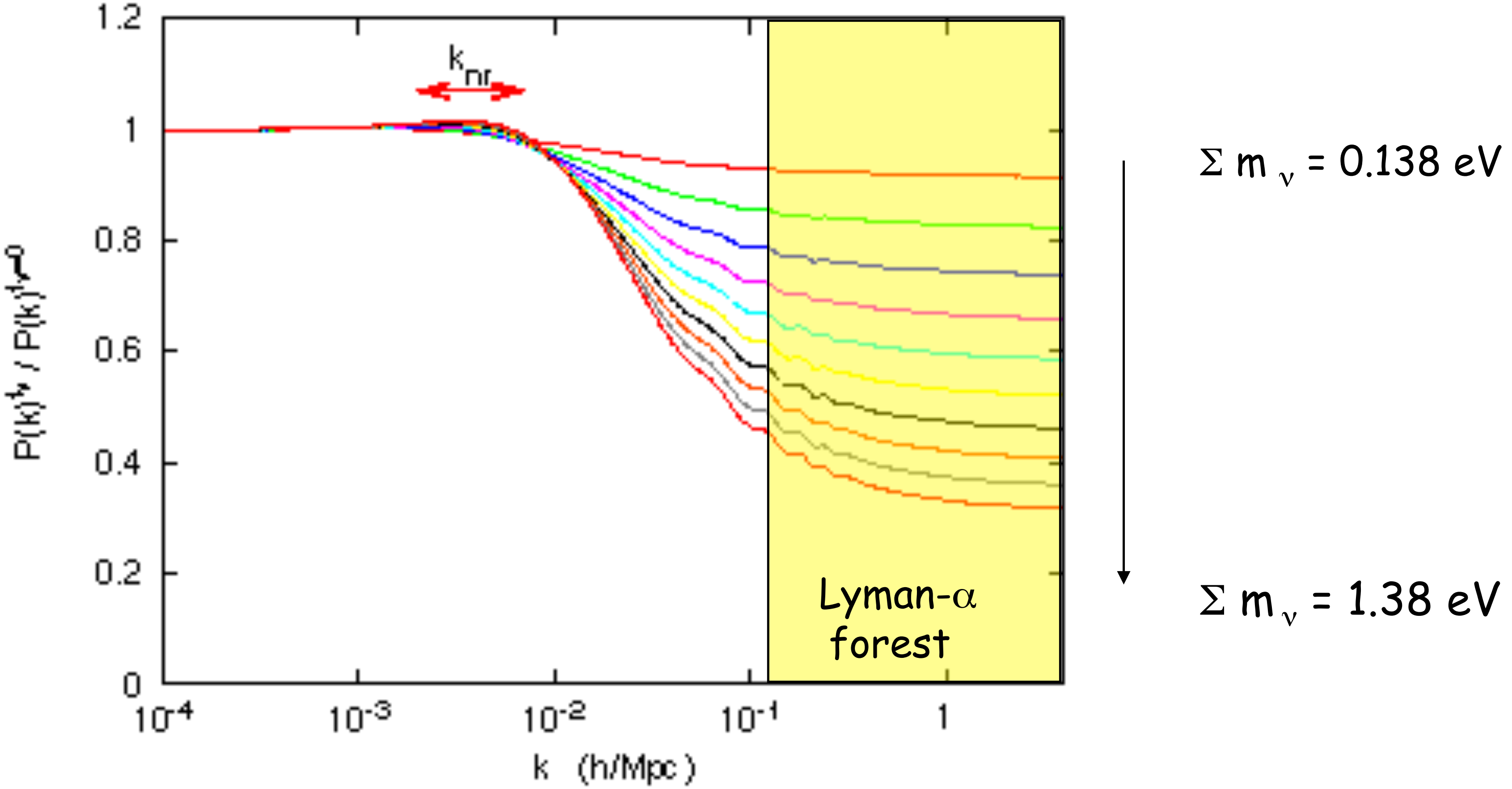
RESULTS

NEUTRINOS

Active neutrinos - I

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

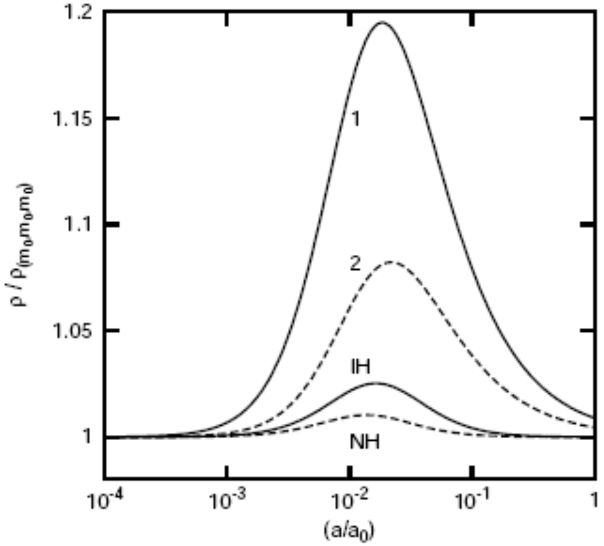
Lesgourgues & Pastor Phys.Rept. 2006, 429, 307

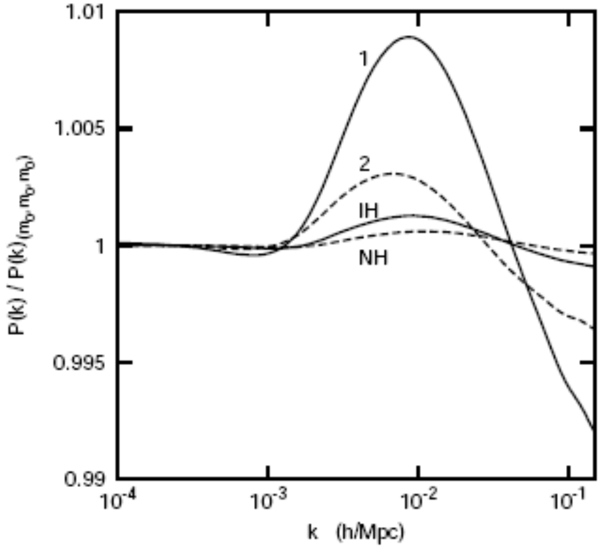


$$v_{th} \equiv \frac{\langle p\rangle}{m} \simeq \frac{3T_\nu}{m} = \frac{3T_\nu^0}{m}\left(\frac{a_0}{a}\right) \simeq 150(1+z)\left(\frac{1\,\mathrm{eV}}{m}\right)\mathrm{km\,s^{-1}}$$

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

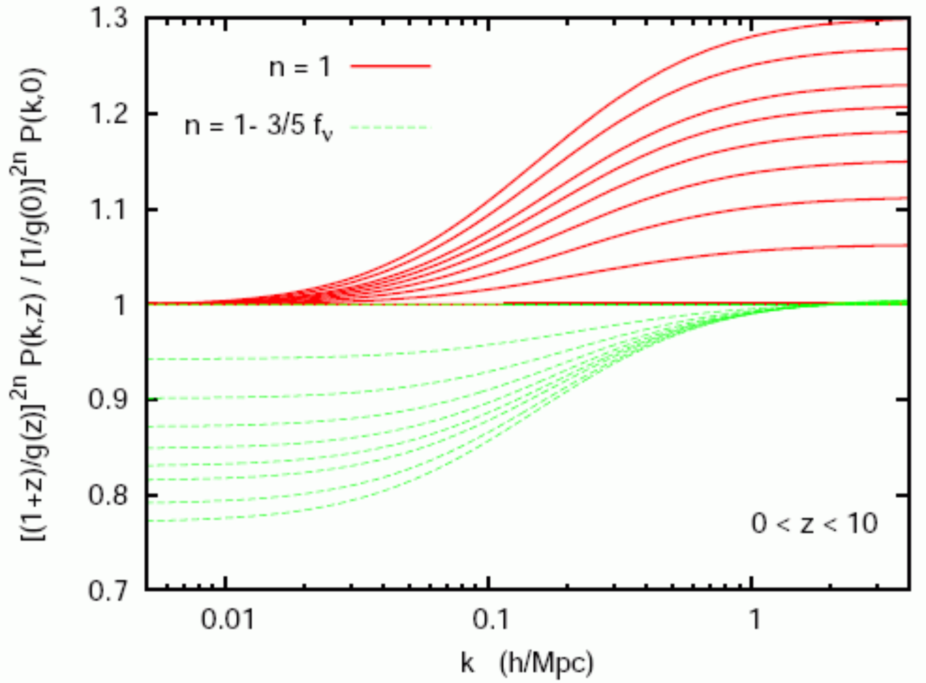
Active neutrinos -II





$$P(k,z)^{f_\nu=0} = \left(\frac{g(z)}{(1+z)\,g(0)}\right)^2 P(k,0)^{f_\nu=0}$$

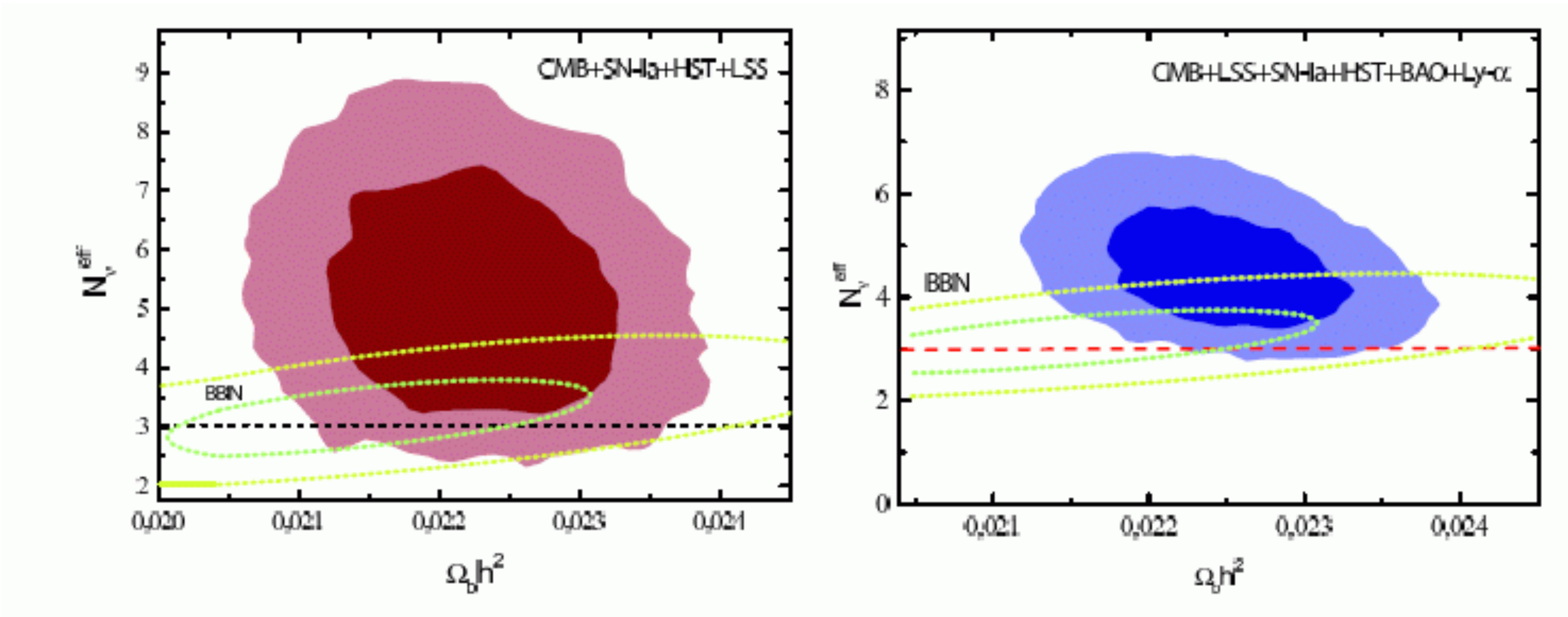
$$P(k,z) = \begin{cases} \left(\dfrac{g(z)}{(1+z)g(0)}\right)^2 P(k,0) & \text{for} \quad aH < k < k_{\rm nr} \\ \left(\dfrac{g(z)}{(1+z)g(0)}\right)^{2-6/5\,f_\nu} P(k,0) & \text{for} \quad k \gg k_{\rm nr} \end{cases}$$



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

Active neutrinos - III

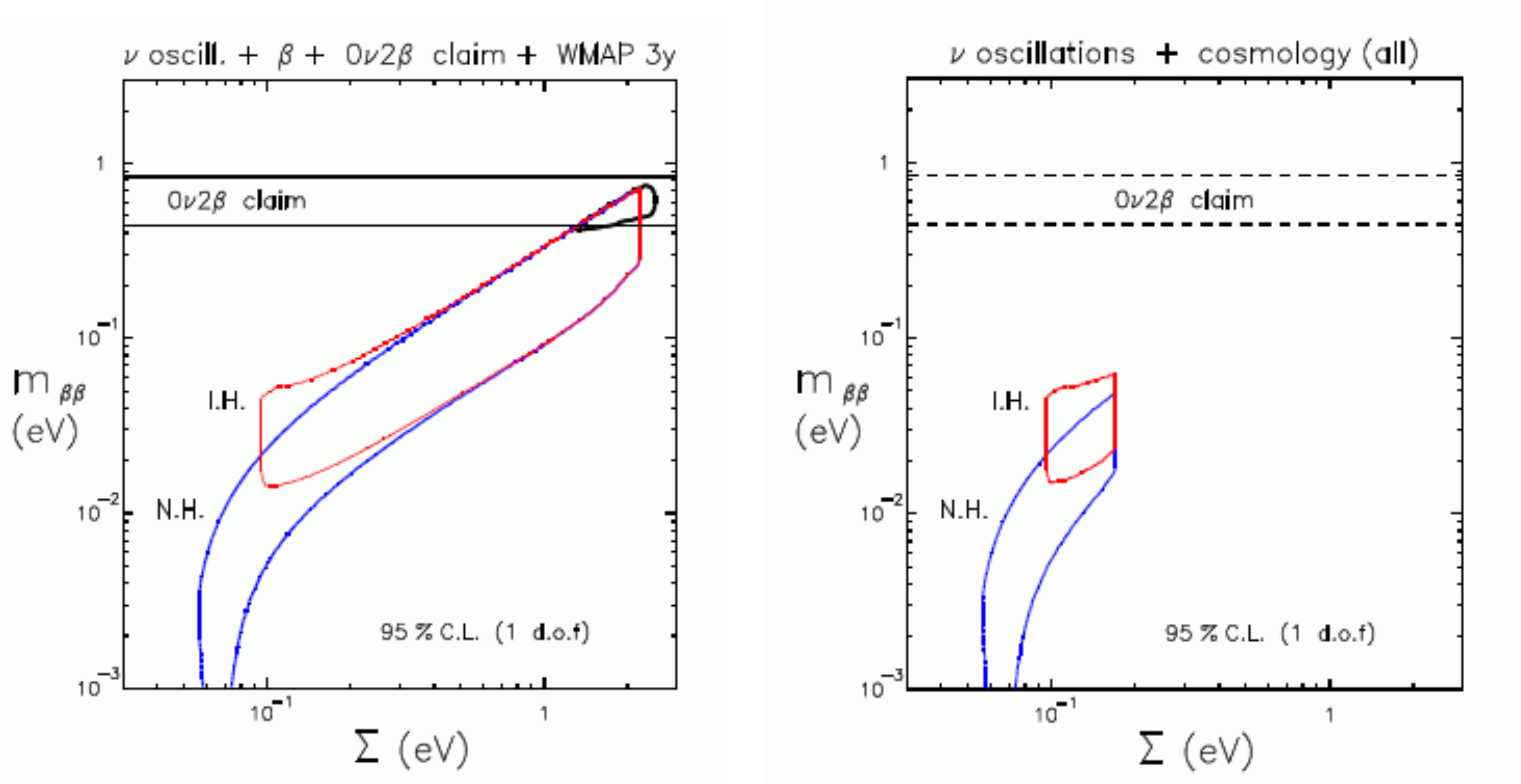
H(z) depends on the energy density
Different H(z) changes the freezing temperature of the neutron to proton ratio
and changes element abundances ^{4}He



$$H^2 = \frac{8\pi G}{3}(\rho_\gamma + \rho_{\rm cdm} + \rho_{\rm b} + \rho_\nu + \rho_\Lambda)$$

Mangano, Melchiorri, Mena, Miele, Slosar, JCAP, 2007, 0703, 006

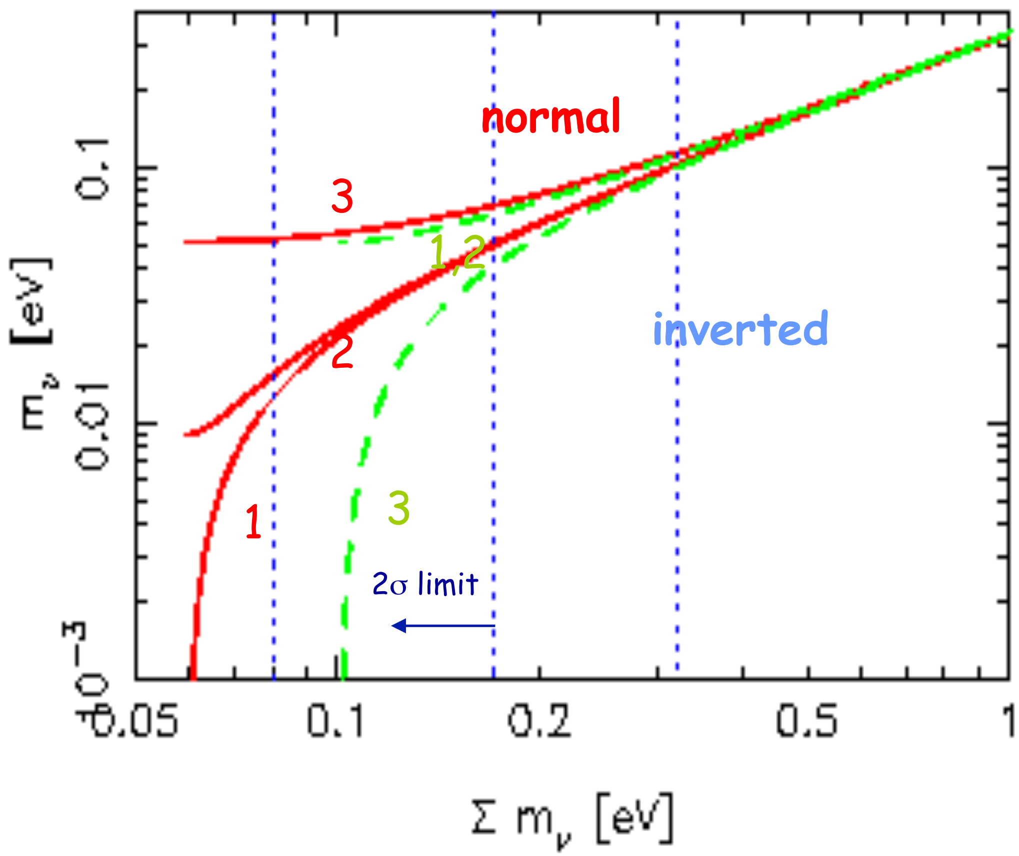
Active neutrinos -VII



Fogli, Lisi, Marrone, Melchiorri, Palazzo, Serra, Silk, Slosar, PhysRevD, 2007, 75, 0533001

Active neutrinos - VIII

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……

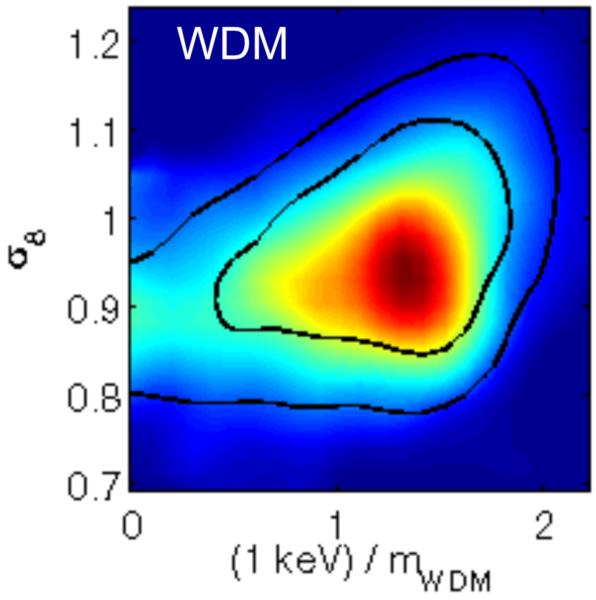
for forecasting see Gratton, Lewis, Efstathiou 2007

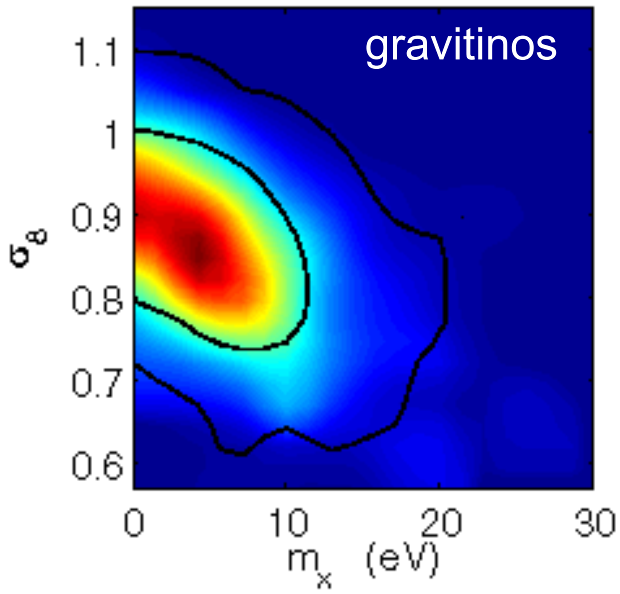
SUMMARY

IGM is an important laboratory to test fundamental physics

- IGM cosmology basics extracting and interpreting the flux power
- Temperature and nature of the dark matter (Cold dark matter and Warm dark matter candidates)
- Effects of neutrinos on the matter power spectrum

Cosmological implications: WDM and/or gravitinos- IV





m_{WDM} > 550 eV

> 2keV sterile neutrino

m_{grav} < 16 eV

	ΛWDM	ΛCWDM
$\Omega_x h^2$	0.124 ± 0.015	0.149 ± 0.019
$\Omega_B h^2$	0.024 ± 0.001	0.024 ± 0.001
h	0.72 ± 0.06	0.71 ± 0.06
τ	0.18 ± 0.09	0.17 ± 0.08
σ_8	0.96 ± 0.08	0.86 ± 0.09
n	1.01 ± 0.04	1.00 ± 0.04
α (Mpc/h)	0.06 ± 0.03	—
f_x	—	0.05 ± 0.04

Set limits on the scale of Supersymmetry breaking

$\Lambda_{susy} < 260$ TeV