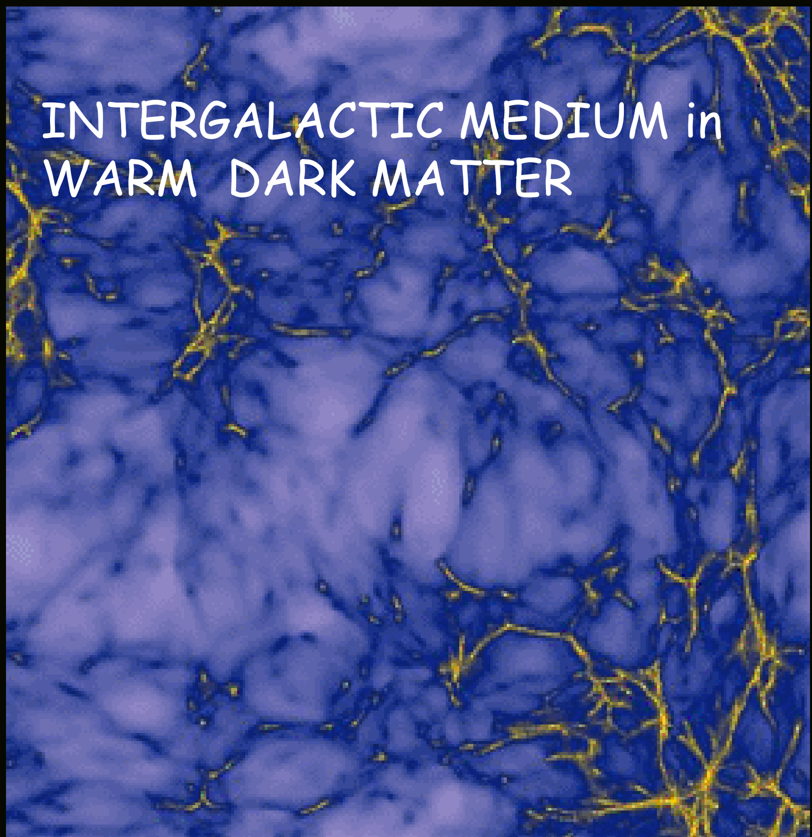
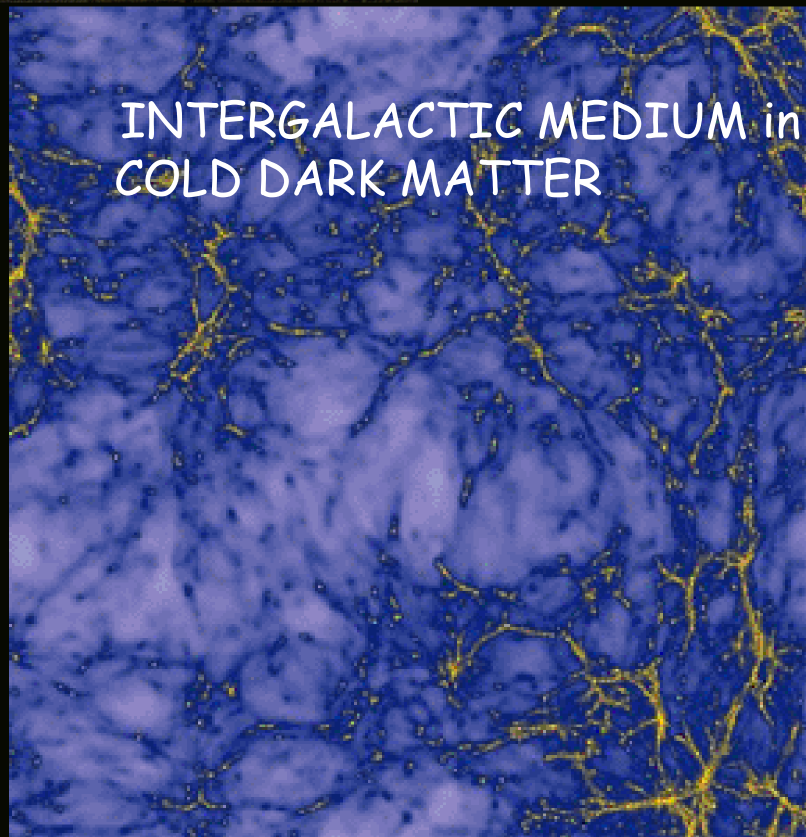
COSMOLOGY AND FUNDAMENTAL PHYSICS WITH HI (in the Lyman-α forest)

MATTEO VIEL

INAF-OATS
and INFN-TS





20 Mpc/h

HI survival through cosmic time – Abbazia di Spineto, Siena (Italy) – 15th June 2007

PLAN OF THE TALK

- Lyman-α forest and cosmological parameters

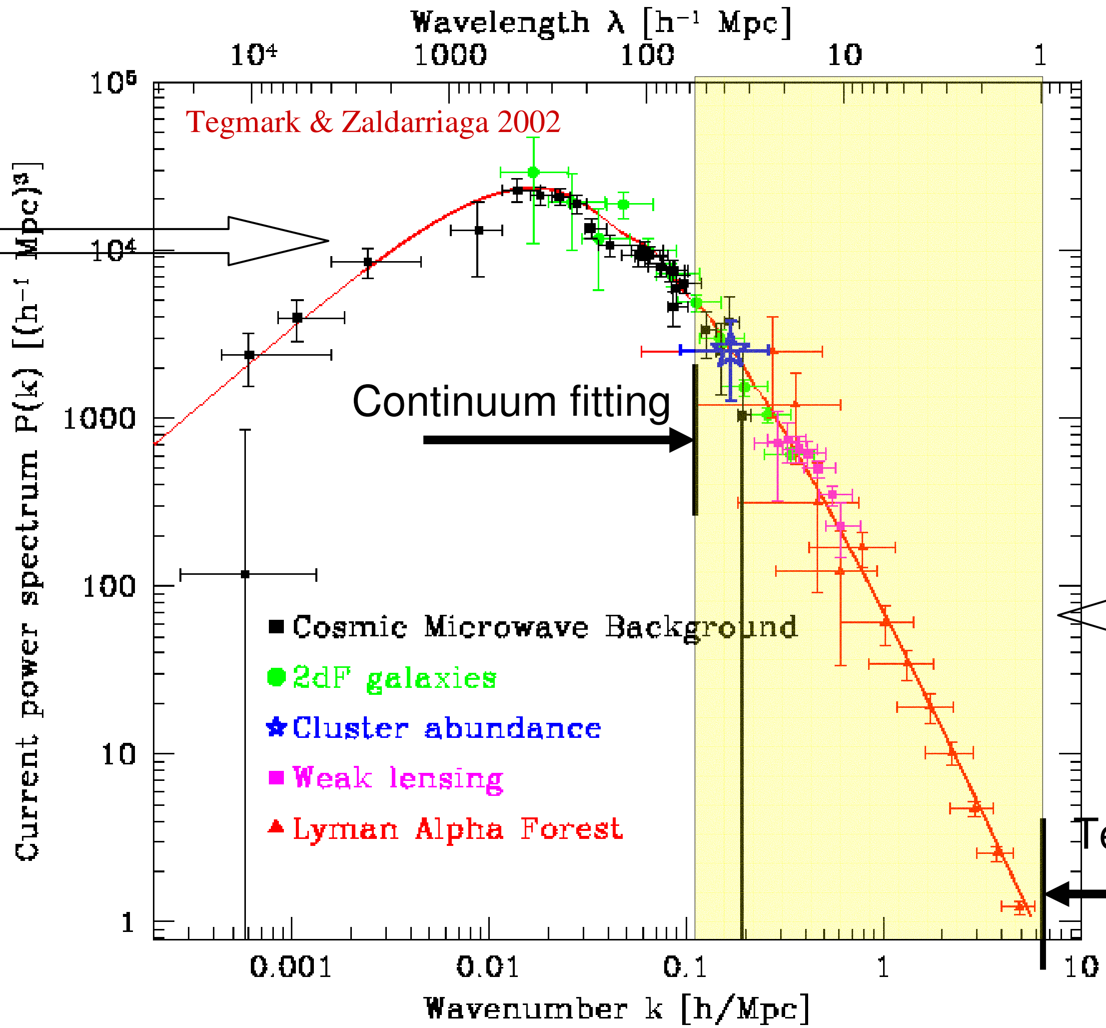
  σ_8 – n (amplitude and slope of the powerspectrum)
  WMAP and large scale structure (Weak Lensing)

- Lyman-α forest and fundamental physics

  active neutrinos (hot dark matter – radiation)
  sterile neutrinos (warm dark matter)

GOAL: the primordial dark matter power spectrum from the observed flux spectrum

CMB physics
z = 1100
dynamics



Lyα physics
z < 6
dynamics
+
termodynamics

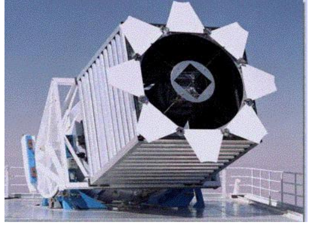
Temperature, metals, noise

CMB + Lyman α ⟹ Long lever arm

Constrain spectral index and shape

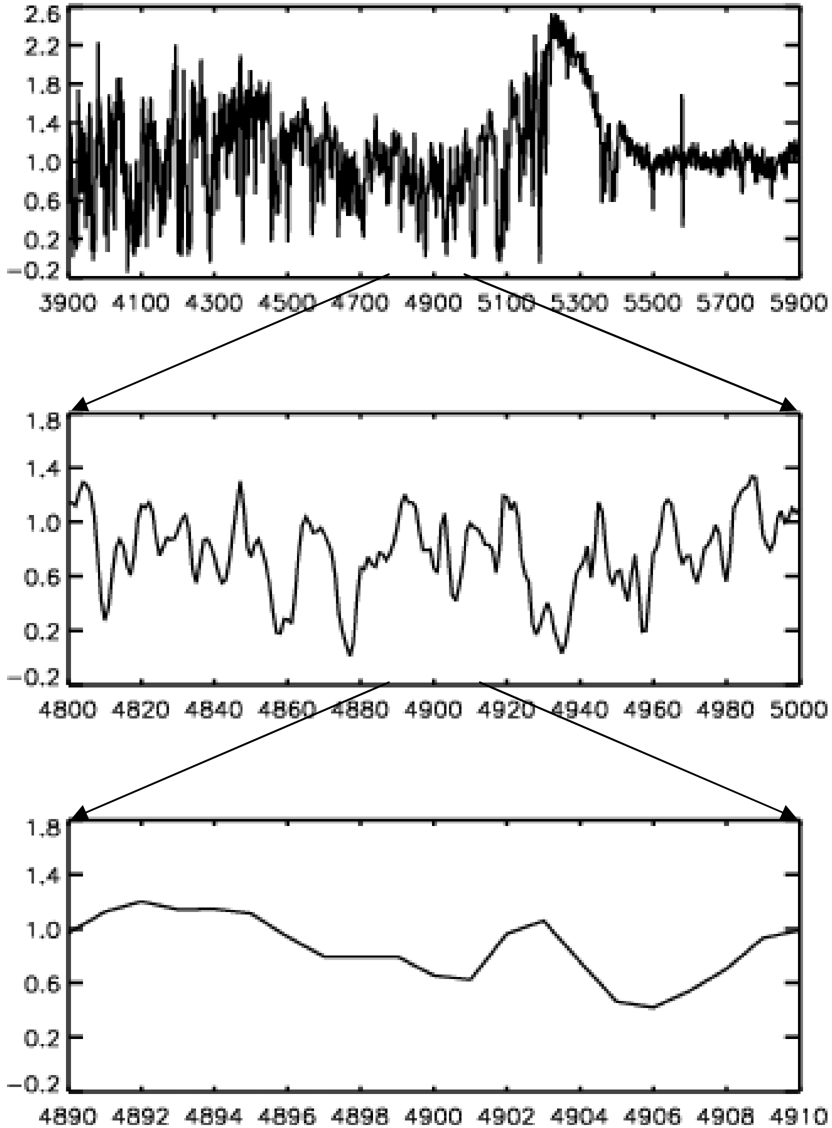
Relation: $P_{FLUX}(k)$ - $P_{MATTER}(k)$

DATA

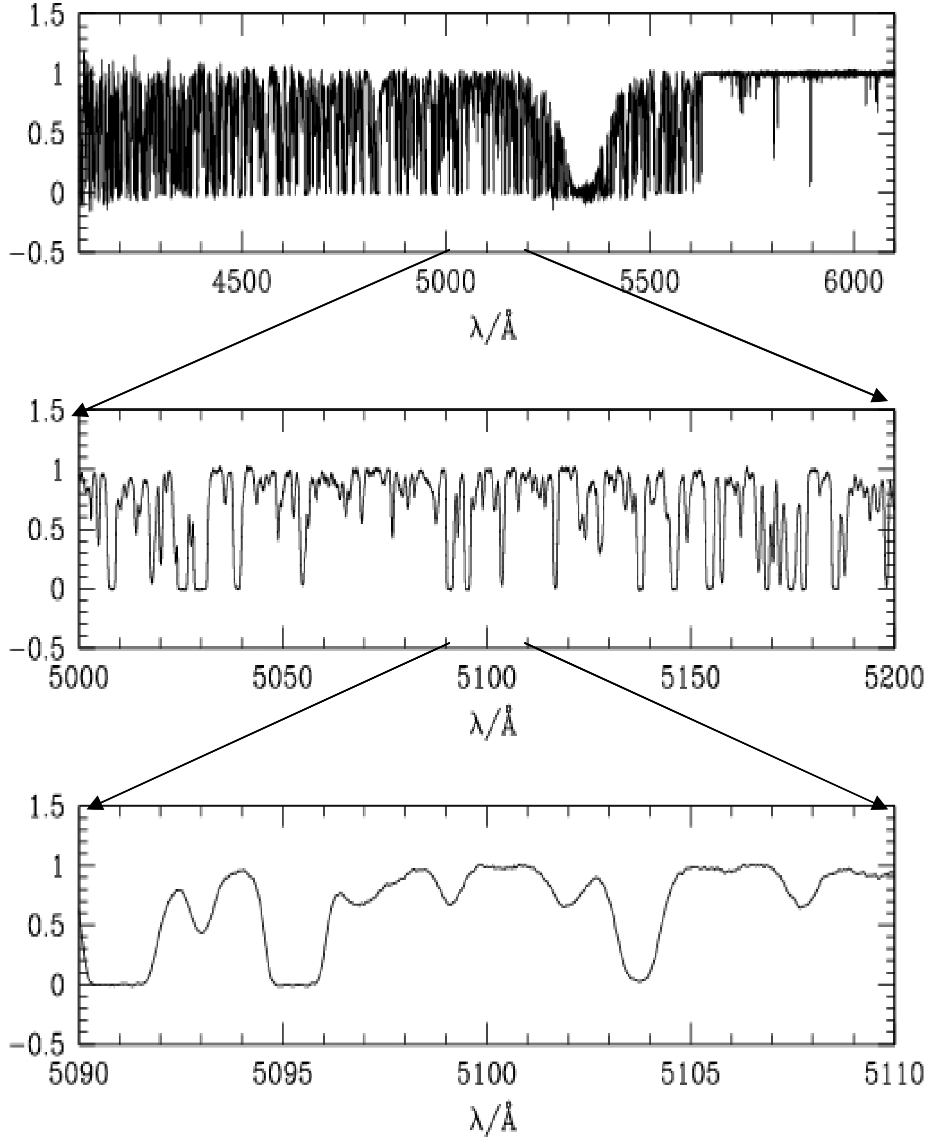


SDSS vs LUQAS

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

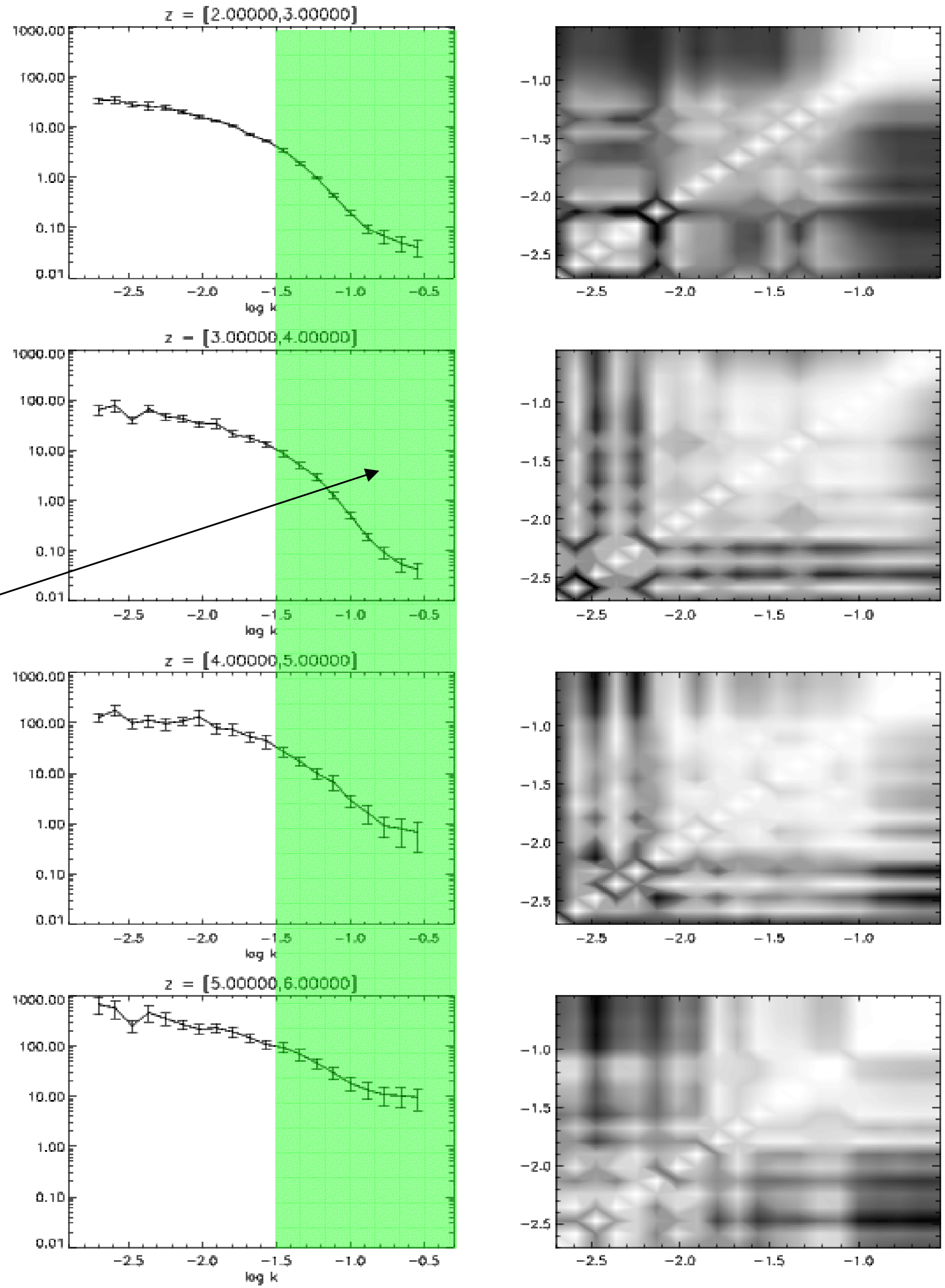
55 HIRES spectra QSOs z=2-6.4
from Becker, Rauch, Sargent (2006)

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



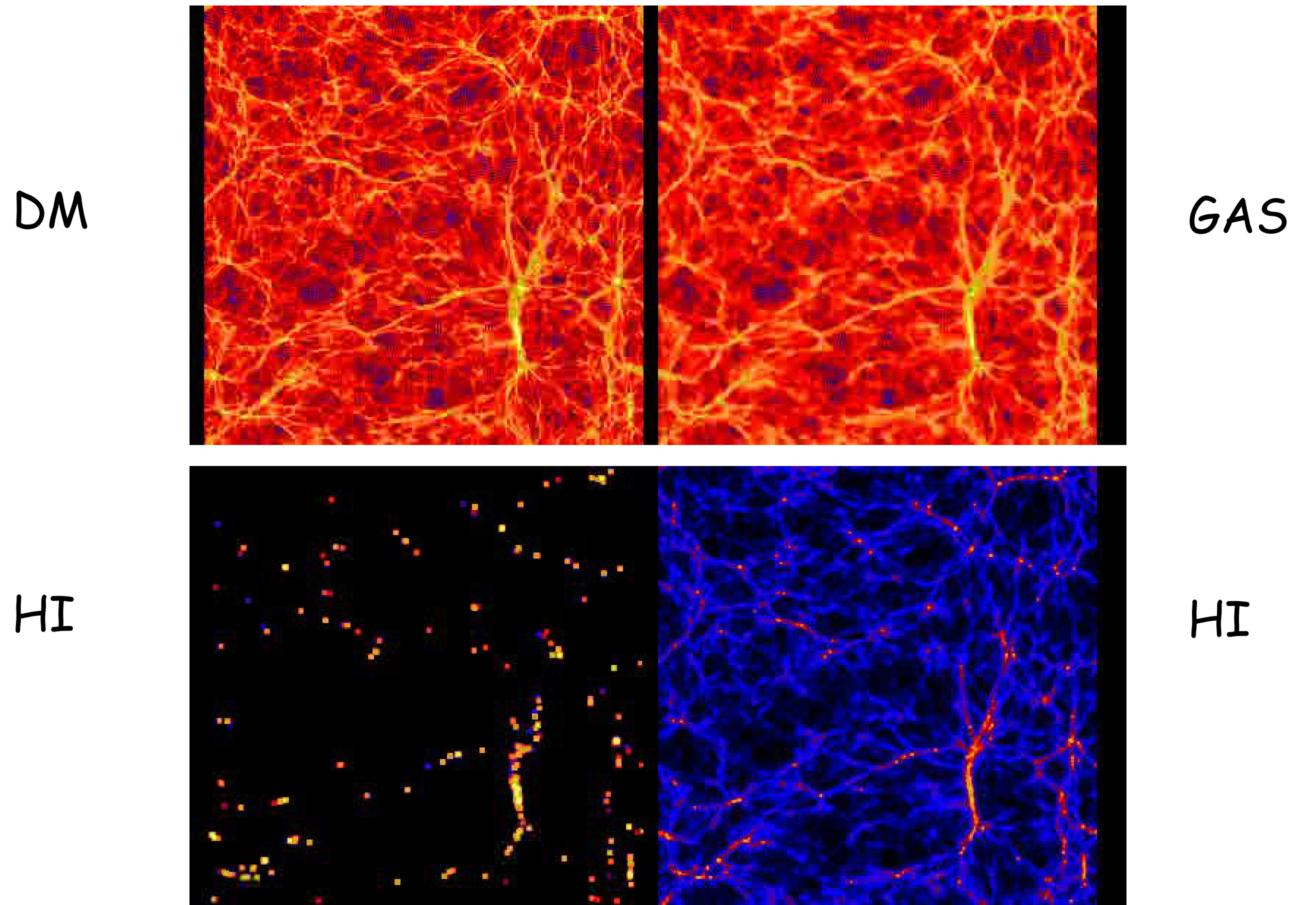
METHOD

Modelling the Lyman-α forest flux power

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



COSMOLOGICAL PARAMETERS

	LUQAS	SDSS
DATA	30 high res z~2.1 QSO spectra + 53 Croft et al. 2002 spectra	3000 QSO spectra z>2.2
THEORY: SIMULATIONS	full hydro simulations	HPM `calibrated' sims (approximately hydro)
THEORY: METHOD	3D flux Inversion $P_F = b^2(k)\,P(k)$	1D flux direct modelling
ADVANTAGES	band power	large redshift range
DRAWBACKS	only z=2.1 (and 2.72) and larger error bars	34 parameters modelling

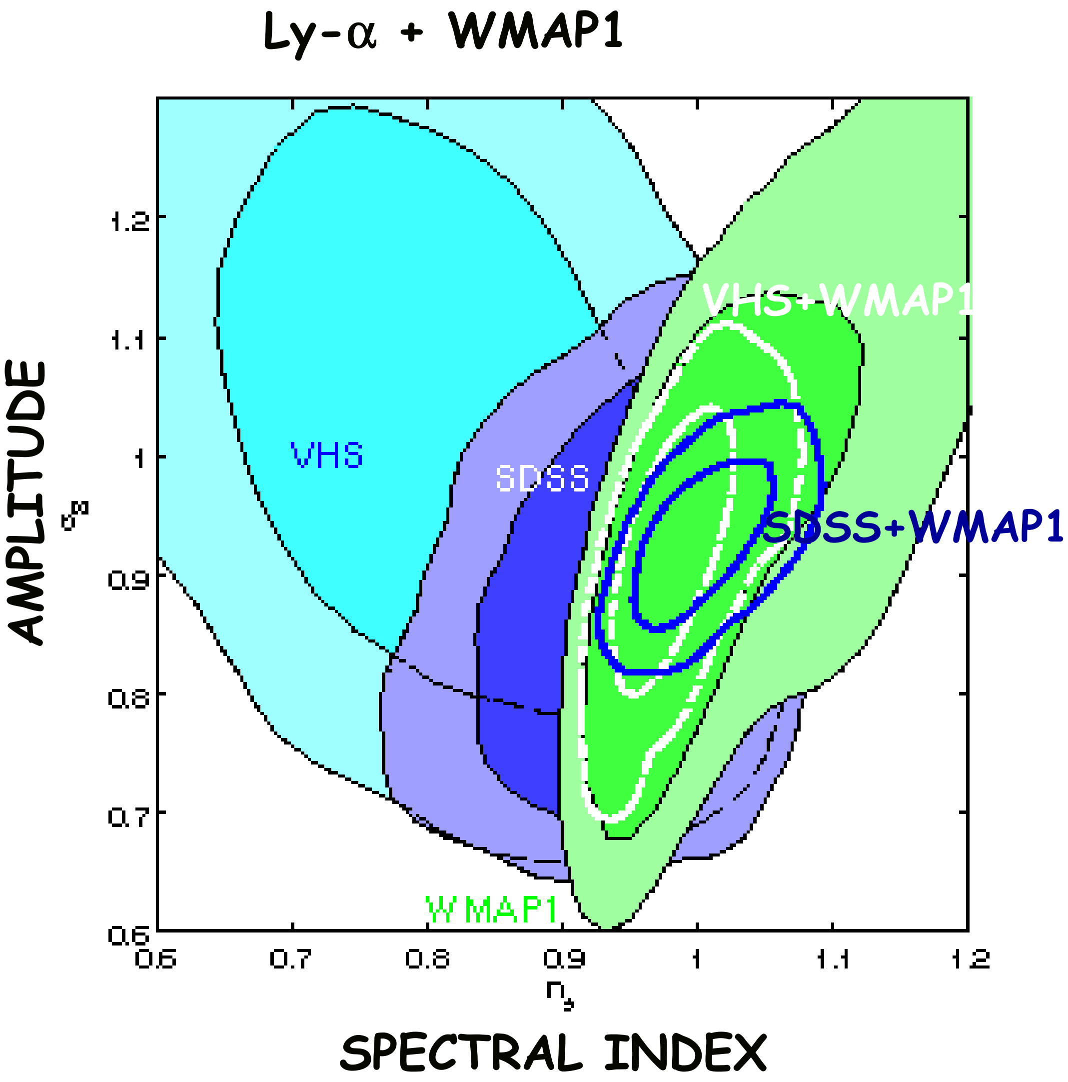
RESULTS

no running, scale invariant, `high' power spectrum amplitude

$dn/d\ln k = 0$, $n = 1$, $\sigma_8 = 0.9$

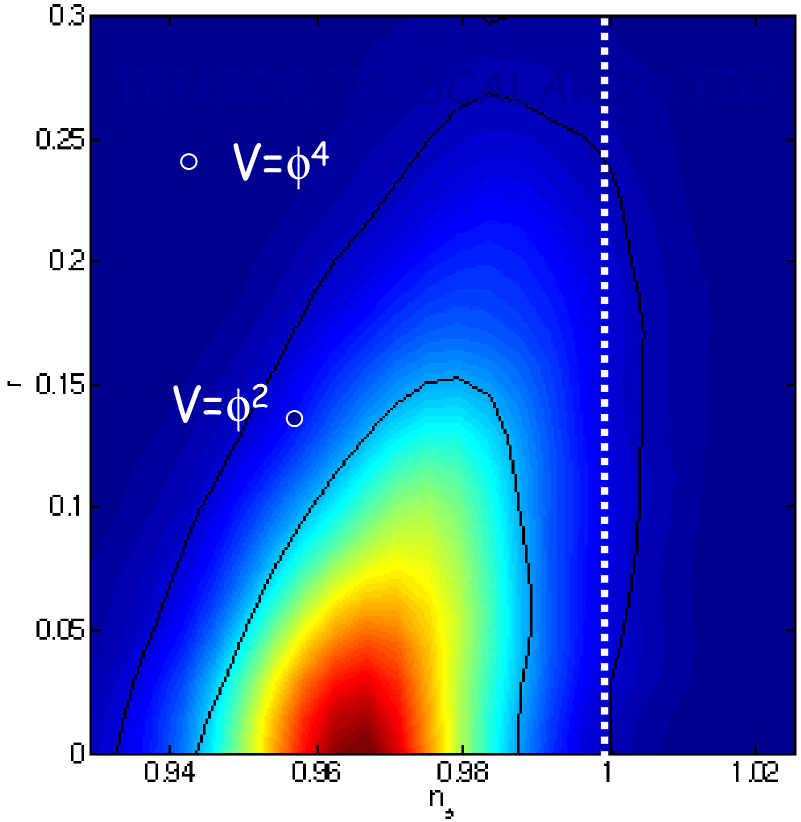
Lyman-α forest + CMB-I : SLOPE AND AMPLITUDE

VHS: high res Ly-a from Viel, Haehnelt, Springel 2004
SDSS: low res Ly-a from McDonald, Seljak et al. 2006



Viel , Haehnelt, Lewis, 2006, MNRAS, 370, 51L

Lyman-α forest + CMB – II: TESTING INFLATION



Signature of gravitational waves (tensors)
And inflation

n, r and dn/dlnk are related to the inflaton potential and its derivatives

$\Sigma m\nu$ (eV) < 0.68 (95 %C.L.)

r < 0.55 (95 % C.L.)

running = -0.055 ± 0.03

WMAP3 only

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

LY-α and WEAK LENSING

Weak Lensing - the COSMOS survey - I

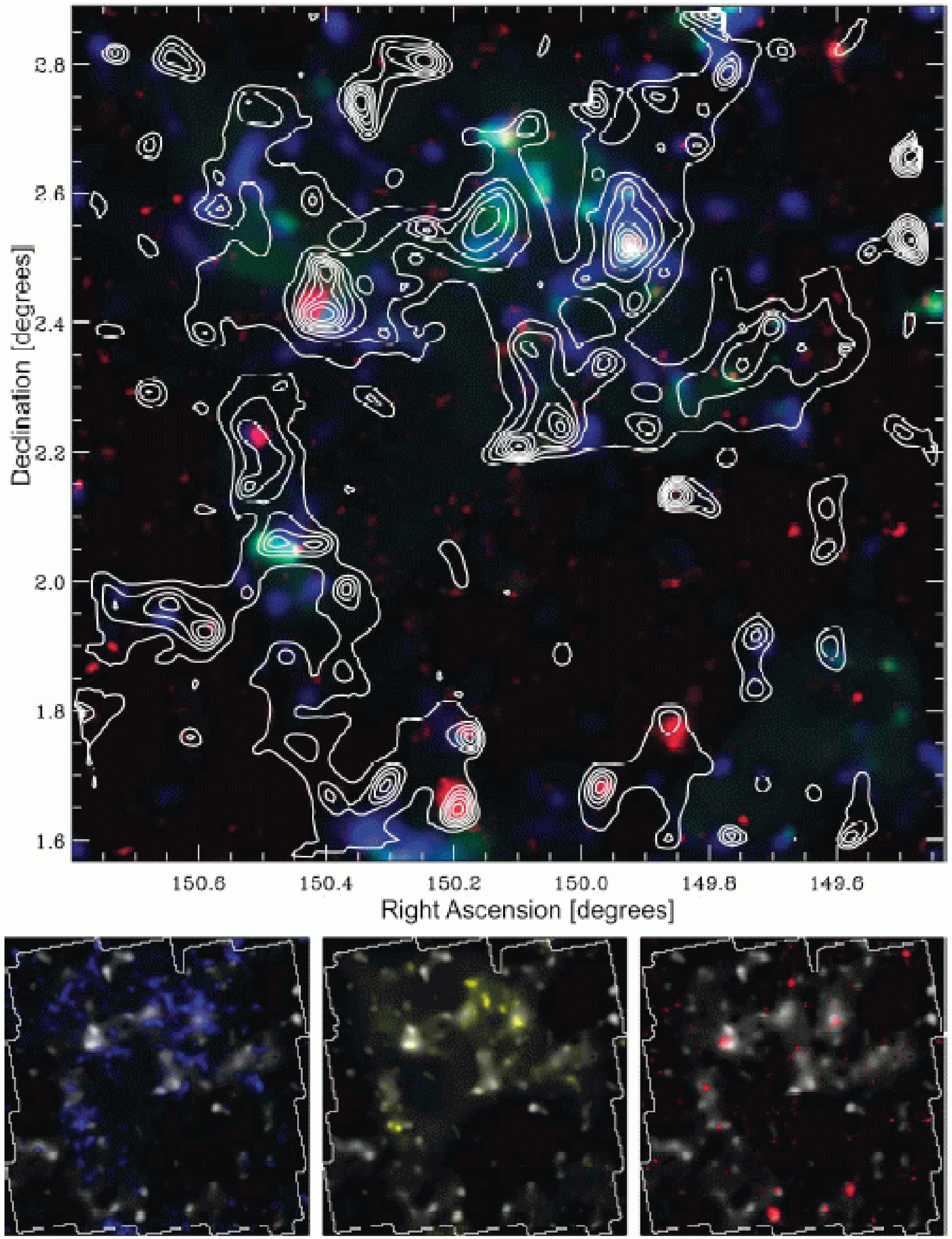


Figure 3 | Comparison of baryonic and non-baryonic large-scale structure. The total projected mass from weak lensing, dominated by dark matter, is shown as contours in panel **a** and as a linear grey scale in panels **b**, **c** and **d**. Independent baryonic tracers comprise (i) stellar mass (blue, colour scale peaks at 2.3×10^{11} M_{sun} deg^{-2} within Δz=0.1), (ii) galaxy number density (yellow, peak at 1.4×10^{5} deg^{-2} within Δz=0.1) seen in optical and near-IR light (adjusted to the redshift sensitivity function of the lensing mass), and (iii) hot gas (red, peak at 2.6×10^{-14} $erg/s/cm^2/arcmin^2$) seen in x-rays after removal of point sources.

Massey et al., 2007, Nature, 445, 286

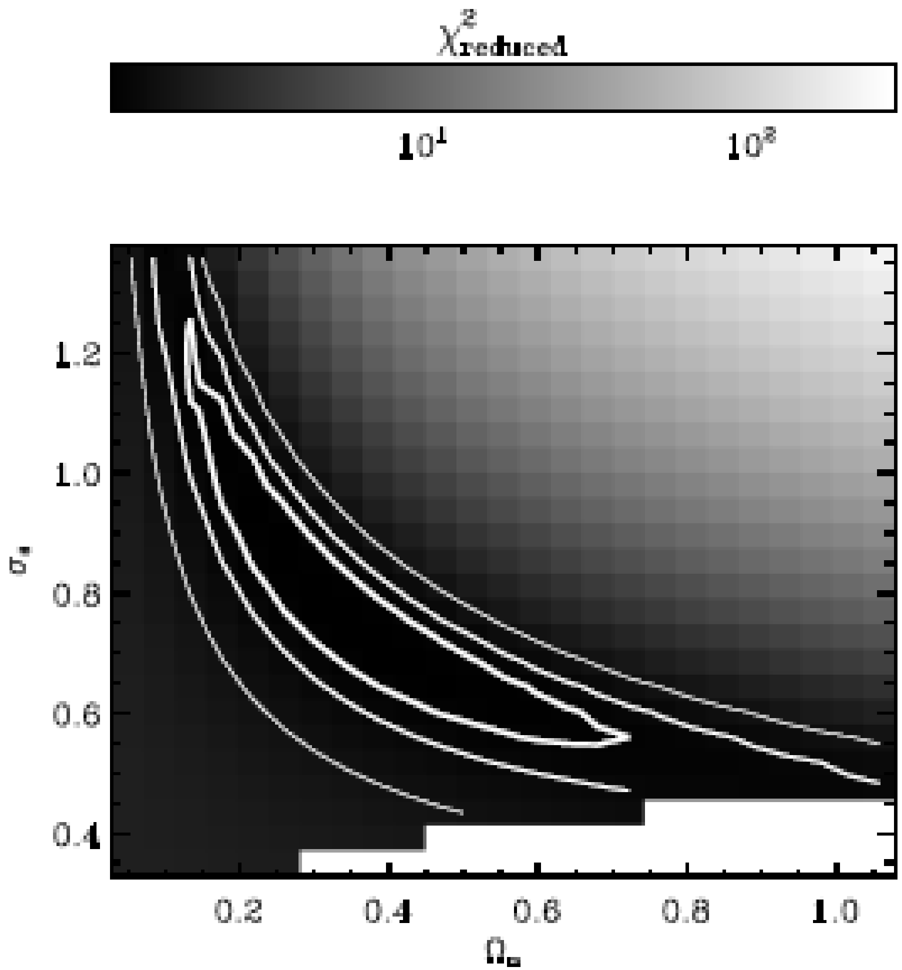
Weak Lensing - the COSMOS survey - II

$$C_1(\theta) = \langle\, \gamma_1^r(\mathrm{r})\, \gamma_1^r(\mathrm{r}+\theta)\,\rangle$$
$$C_2(\theta) = \langle\, \gamma_2^r(\mathrm{r})\, \gamma_2^r(\mathrm{r}+\theta)\,\rangle$$

$$C_1(\theta) = \frac{1}{4\pi}\int_0^\infty C_\ell^\gamma\ [\mathrm{J}_0(\ell\theta)+\mathrm{J}_4(\ell\theta)]\ \ell\ \mathrm{d}\ell$$
$$C_2(\theta) = \frac{1}{4\pi}\int_0^\infty C_\ell^\gamma\ [\mathrm{J}_0(\ell\theta)-\mathrm{J}_4(\ell\theta)]\ \ell\ \mathrm{d}\ell$$

$$g(\chi) = 2\int_\chi^{\chi_h} \eta(\chi')\,\frac{D_A(\chi)D_A(\chi'-\chi)}{D_A(\chi')}\,a^{-1}(\chi)\,\mathrm{d}\chi'$$

$$C_\ell^\gamma = \frac{9}{16}\left(\frac{H_0}{c}\right)^4 \Omega_m^2 \int_0^{\chi_h}\left[\frac{g(\chi)}{D_A(\chi)}\right]^2 P(k,\chi)\,\mathrm{d}\chi$$



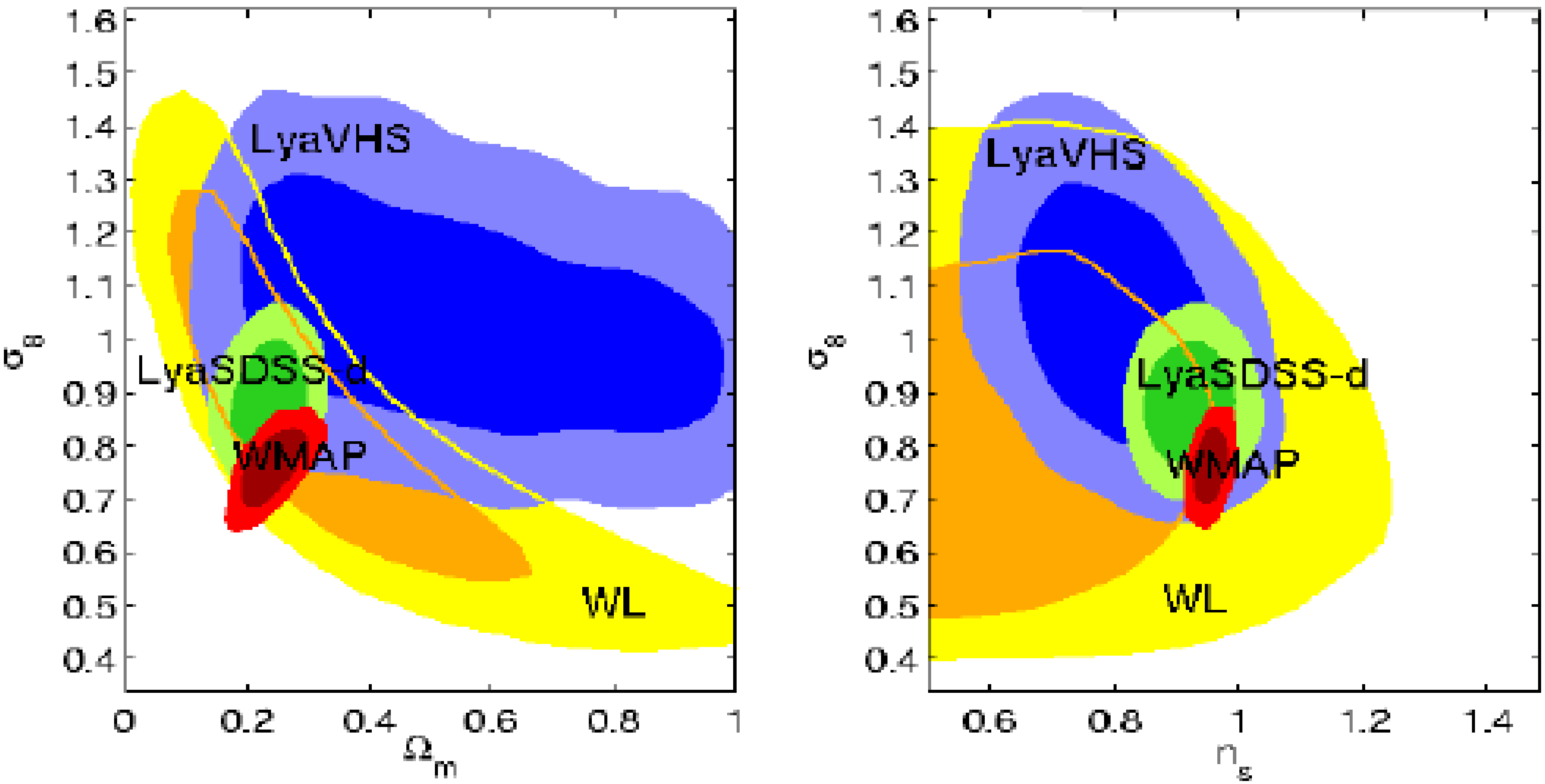
Cosmology (crucial to model non linear corrections!)

Massey et al., 2007, arXiv: astro-ph/0701480

Lyman-α forest + Weak Lensing + WMAP3

VHS: high res Ly-a from Viel, Haehnelt, Springel 2004
SDSS-d: re-analysis of SDSS with flux derivatives (Viel & Haehnelt 2006)
WL: COSMOS survey Weak Lensing (Massey et al. 2007)

AMPLITUDE



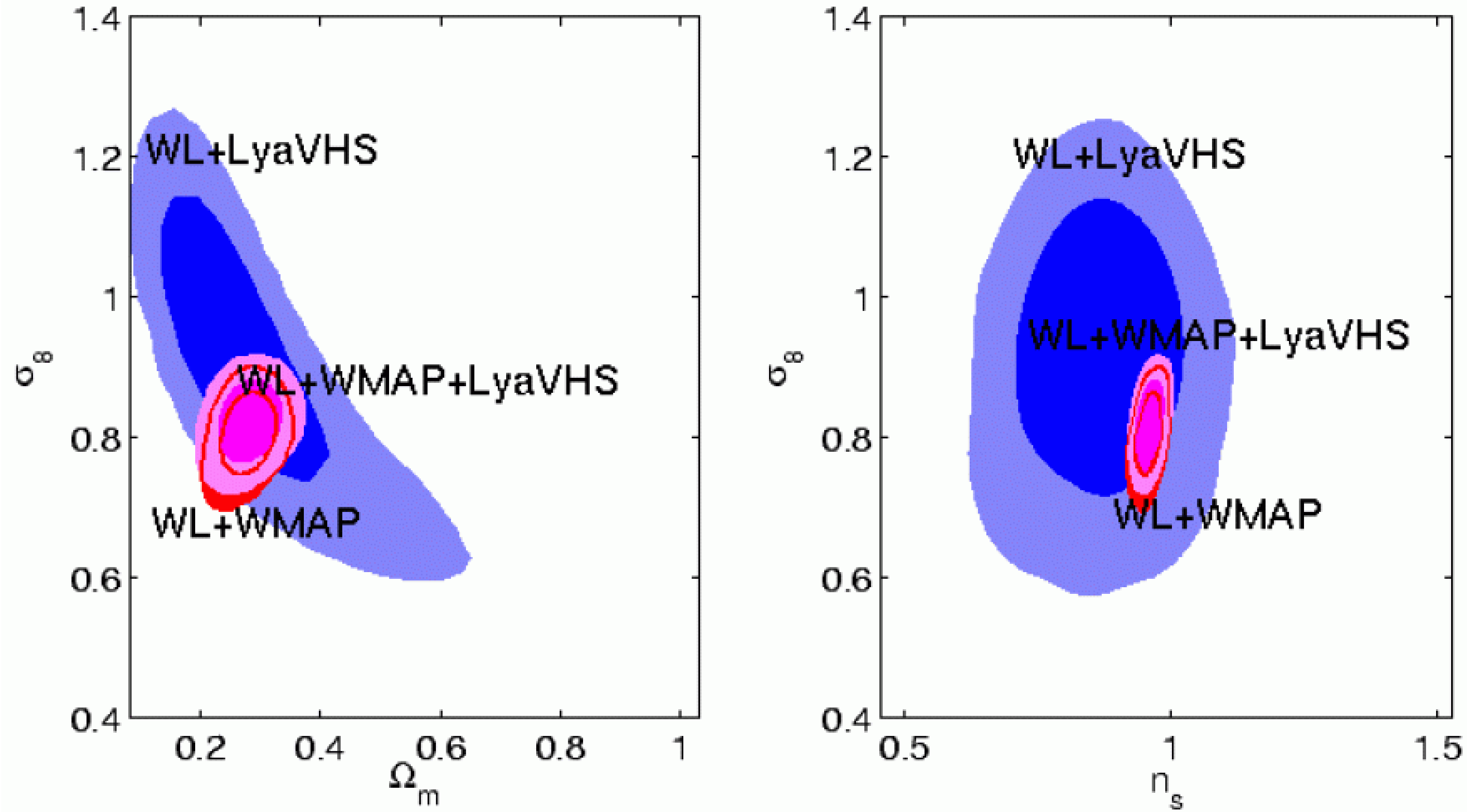
MATTER DENSITY **SPECTRAL INDEX**

Viel , Haehnelt, Lewis, 2006, MNRAS, 370, 51L
Lesgourgues, MV, et al. (2007)

Lyman-α forest + Weak Lensing + WMAP3-II

VHS: high res Ly-a from Viel, Haehnelt, Springel 2004
WL: COSMOS survey Weak Lensing (Massey et al. 2007)

AMPLITUDE



MATTER DENSITY

SPECTRAL INDEX

Viel , Haehnelt, Lewis, 2006, MNRAS, 370, 51L
Lesgourgues, MV, et al. 2007, in preparation

Table II: Summary of the constraints on σ_8, n_s, Ω_{0m}, h and τ for the combination of CMB, weak lensing and Lyα forest data. The quoted values are the mean and 68% confidence limits.

	WL+WMAP3+VHS	WL+WMAP3+SDSS	WL+WMAP3+SDSS-d
σ_8	0.82 ± 0.04	0.85 ± 0.02	0.80 ± 0.02
n_s	0.96 ± 0.02	0.97 ± 0.02	0.97 ± 0.01
Ω_{0m}	0.28 ± 0.03	0.29 ± 0.03	0.25 ± 0.02
h	0.70 ± 0.03	0.70 ± 0.02	0.73 ± 0.02
τ	0.10 ± 0.03	0.10 ± 0.03	0.11 ± 0.02

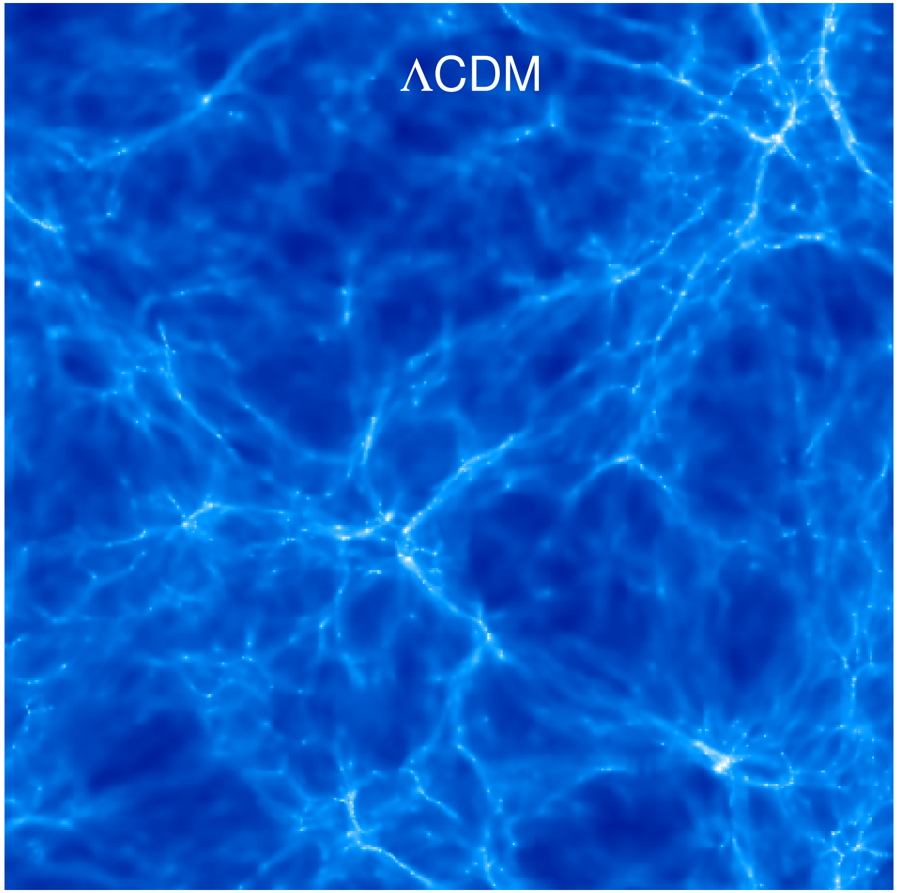
HOW COLD
IS
COLD DARK MATTER ?

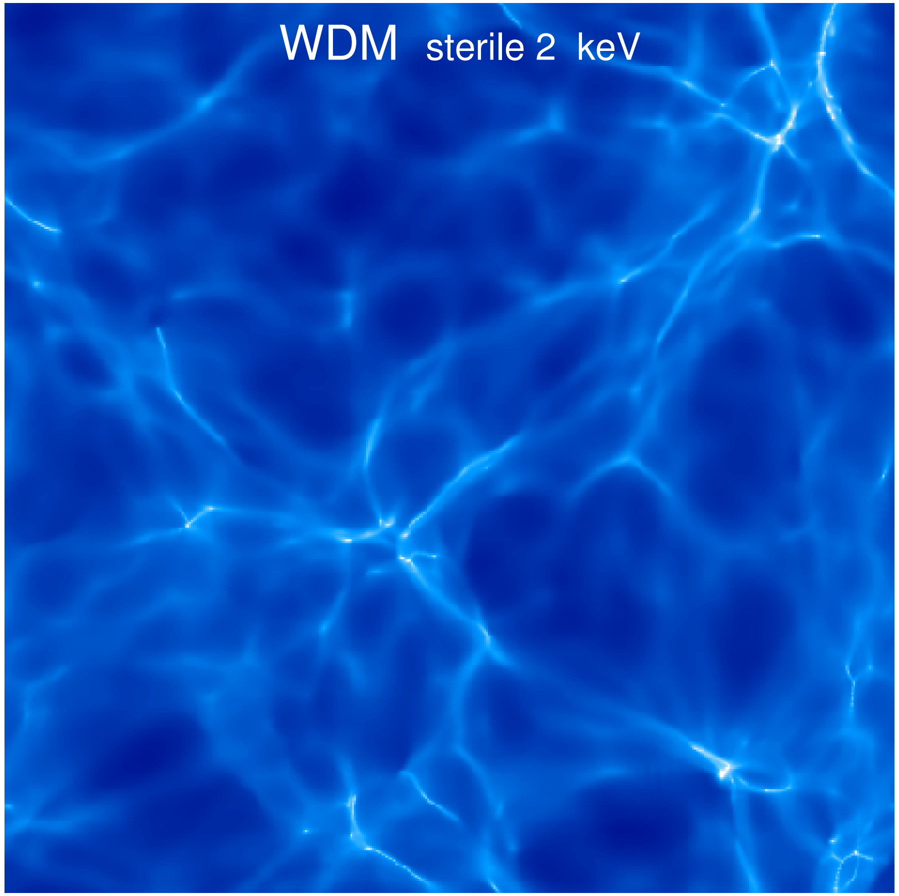
(Some) Motivations

★ 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





30 comoving Mpc/h z=3

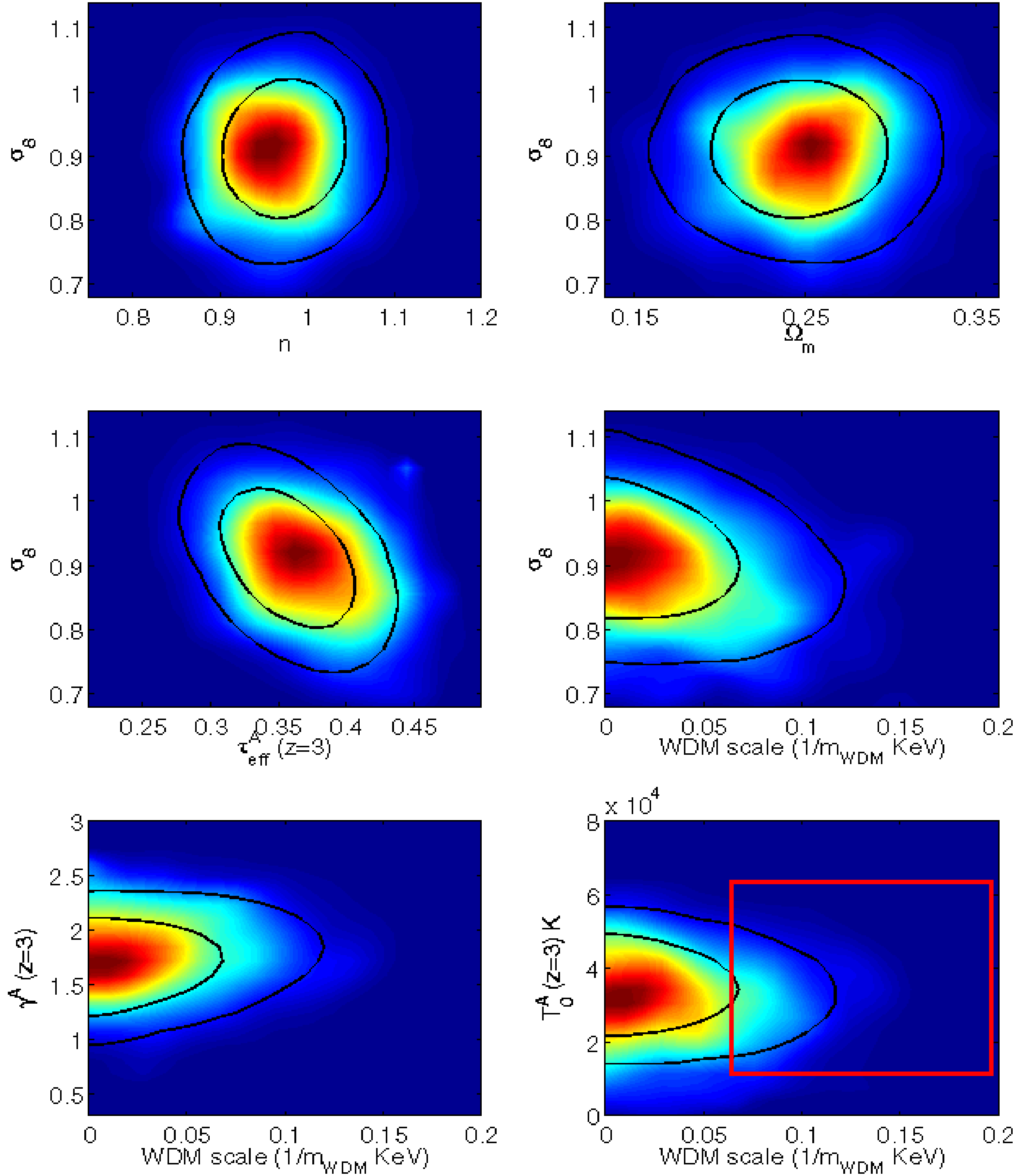
See Bode, Ostriker, Turok 2001
Abazajian, Fuller, Patel 2001

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

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



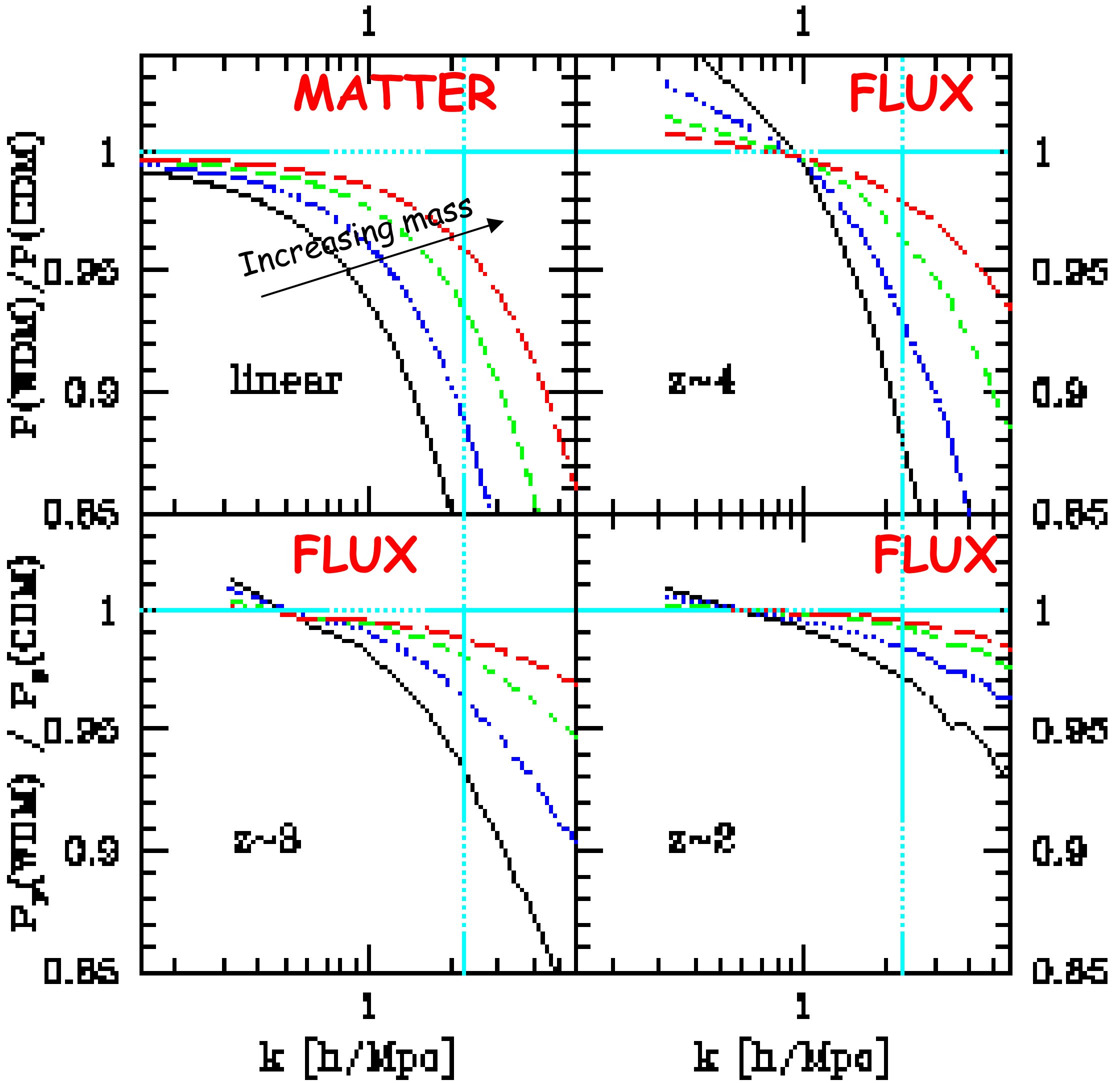
Fitting SDSS data with GADGET-2
this is SDSS Ly-α only !!

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

SDSS data only

σ_8 = 0.91 ± 0.07
n = 0.97 ± 0.04

Lyman-α and Warm Dark Matter

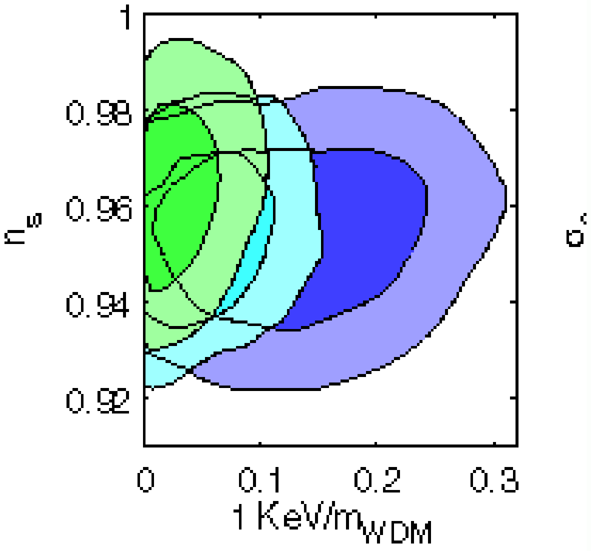


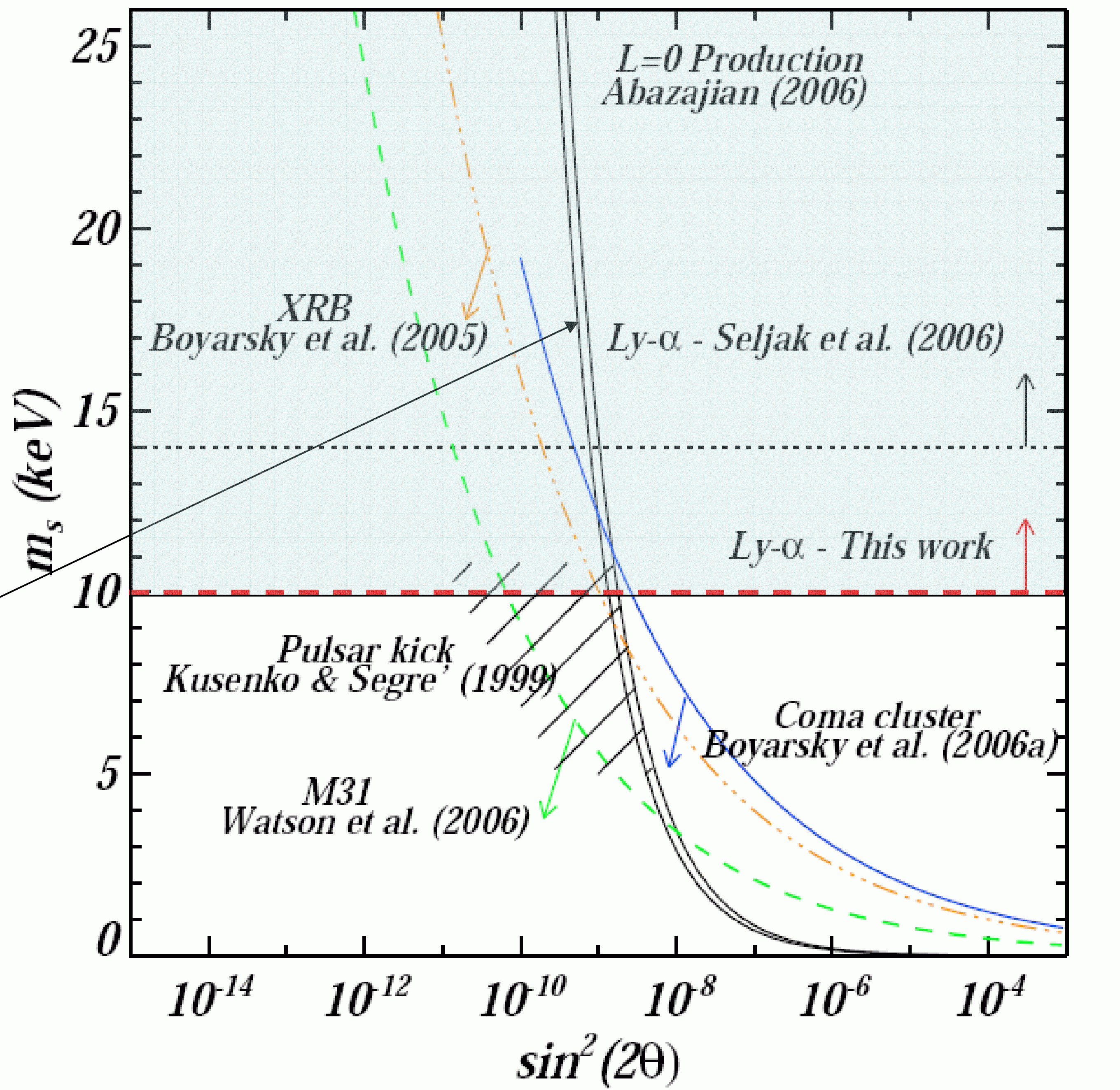
Seljak et al. 2006

m $_{WDM}$ > 2 keV thermal

> 14 keV sterile neutrino

Lyα-WDM: new analysis of the SDSS data





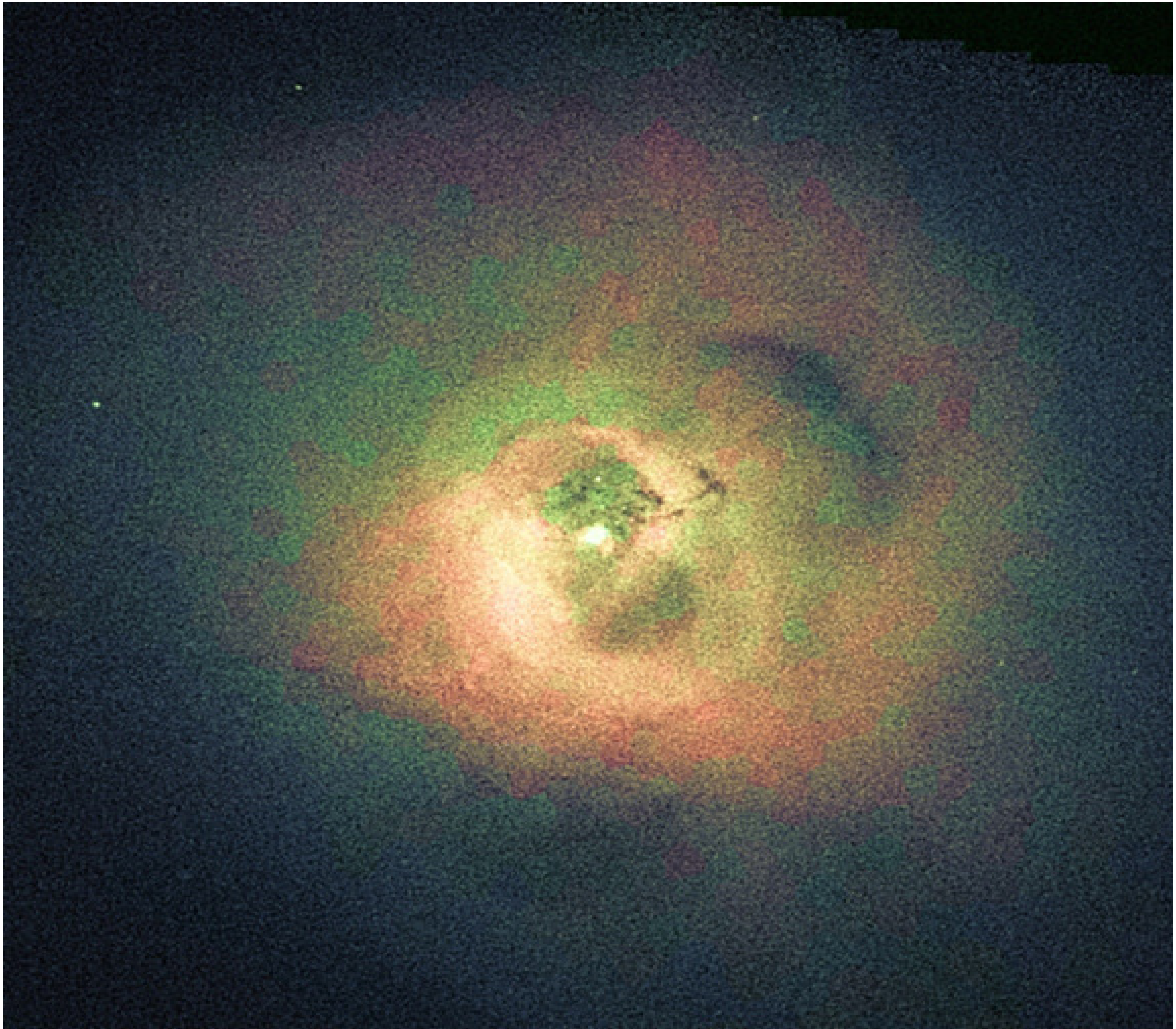
$L_\nu = 0$

Leptonic number is conserved: this is tl standard case

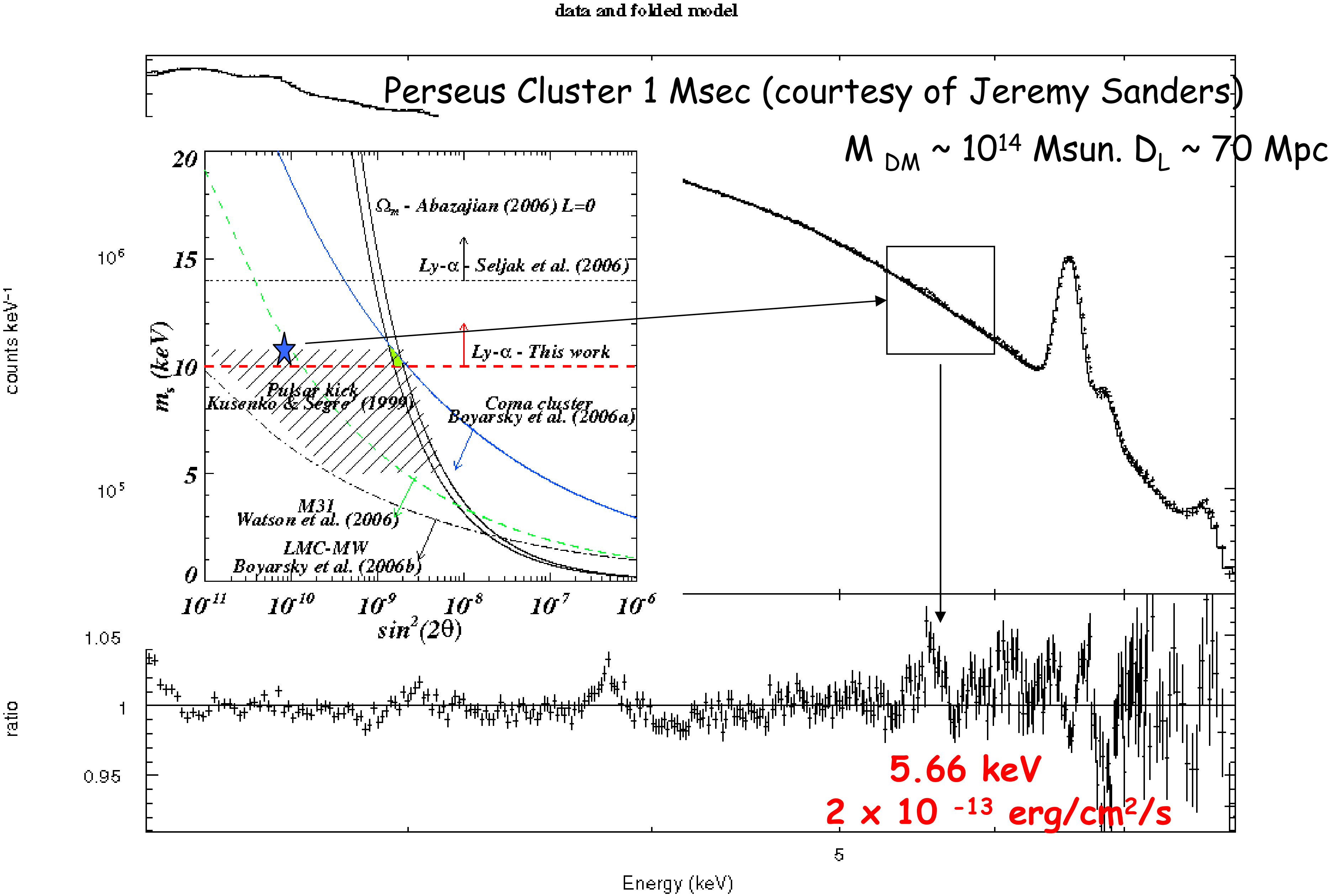
Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, Phys.Rev.Lett., 2006, 97, 071301

X-RAY DETECTABILITY
OF
STERILE NEUTRINOS

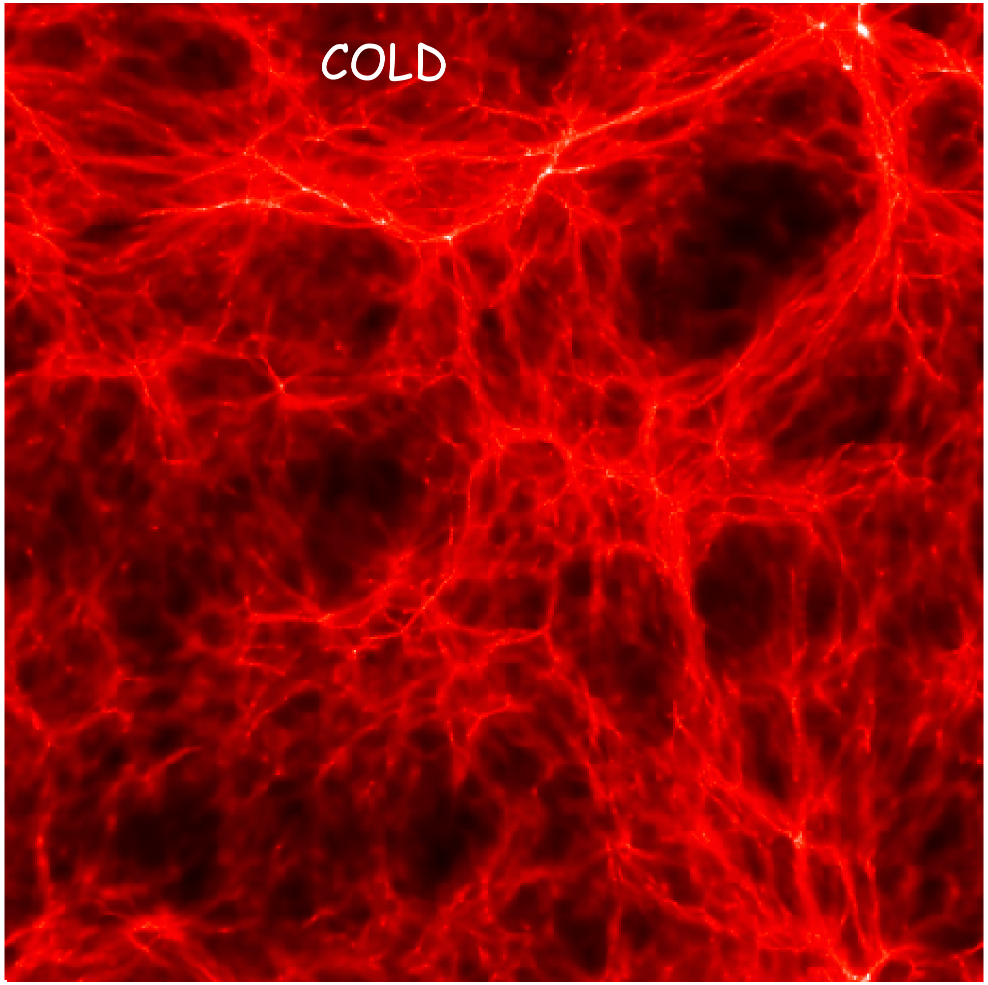
Fabian, Sanders and coworkers.....

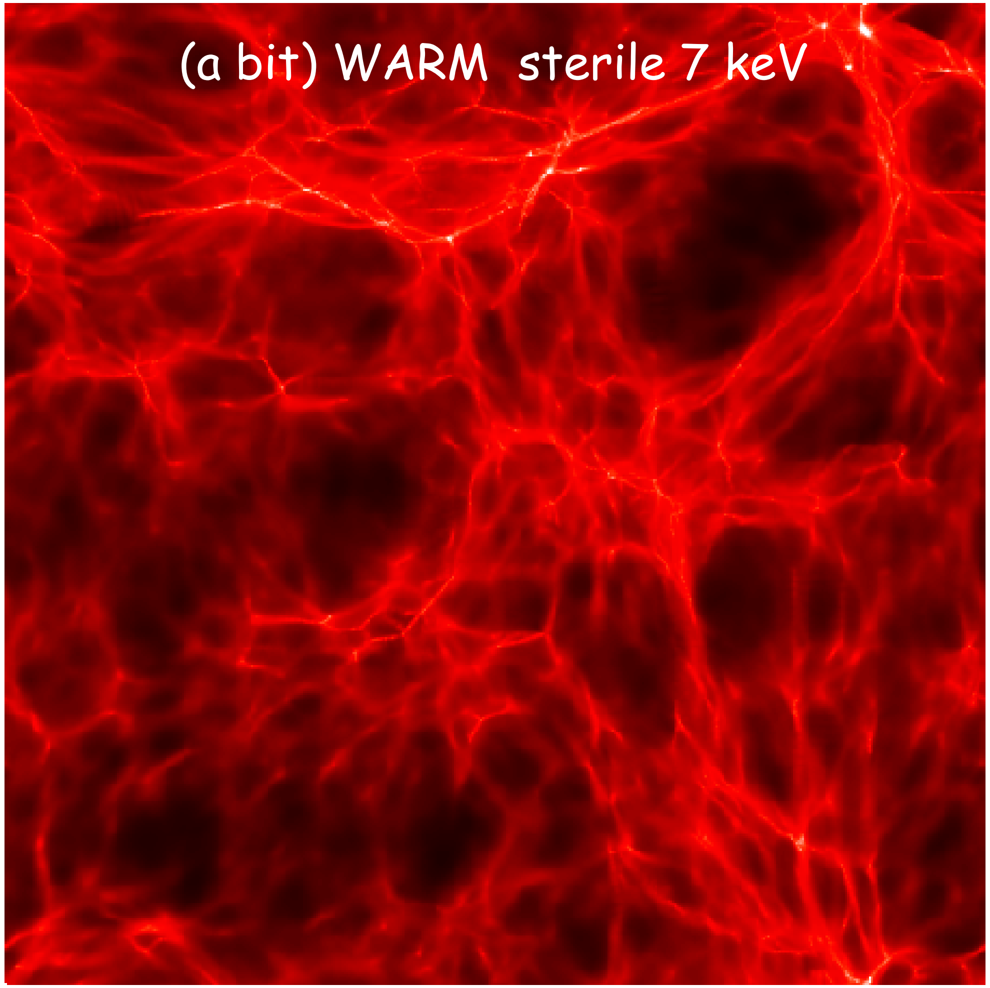


Decaying channel into photons and active neutrinos line with $E=m_s/2$ (X-band)



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



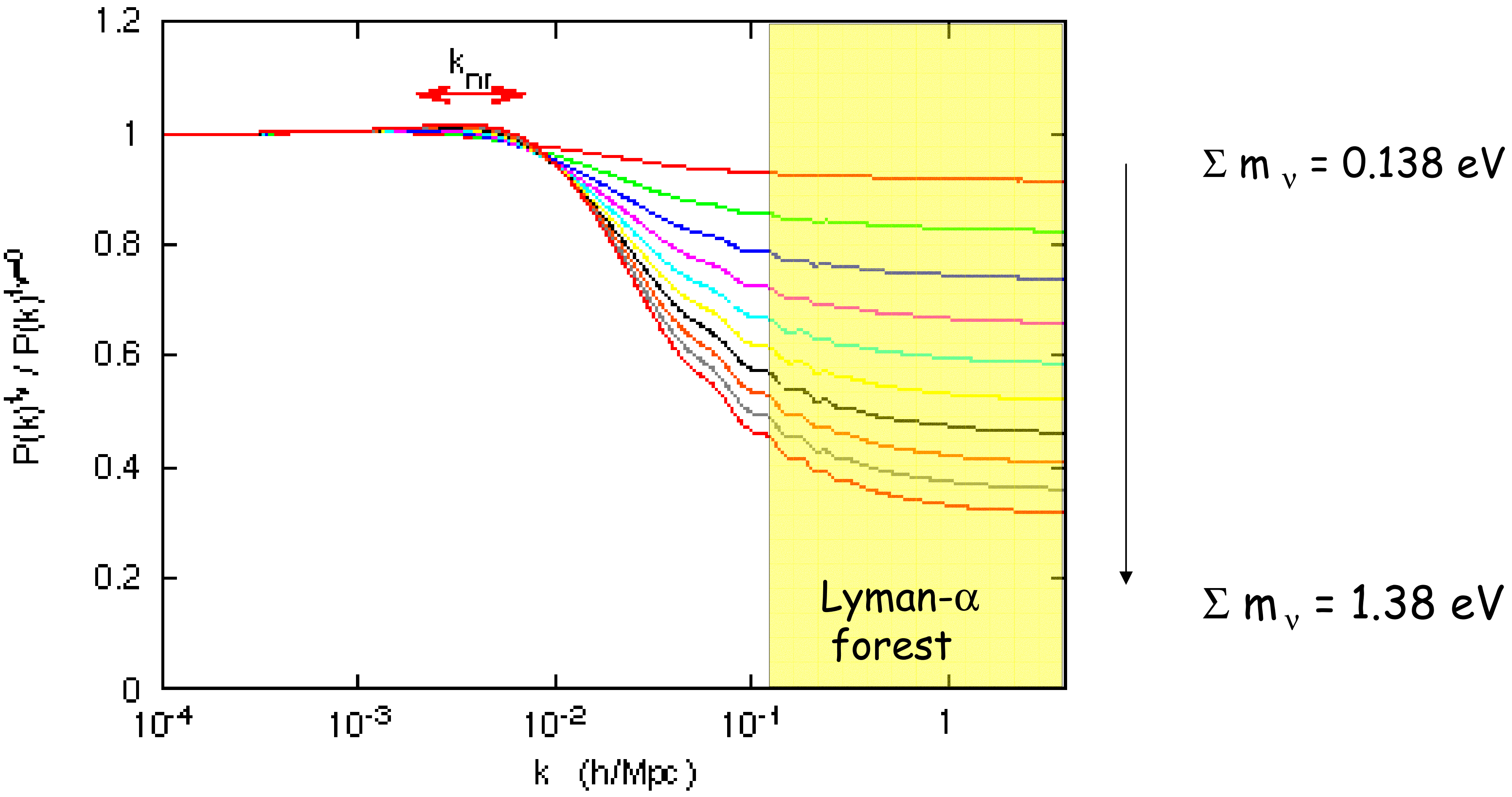


For the impact on 21 cm, thermal and reionization history
see Valdes, Ferrara, Mapelli, Ripamonti (2007)
Mapelli, Ferrara, Pierpaoli (2006) etc.

RESULTS

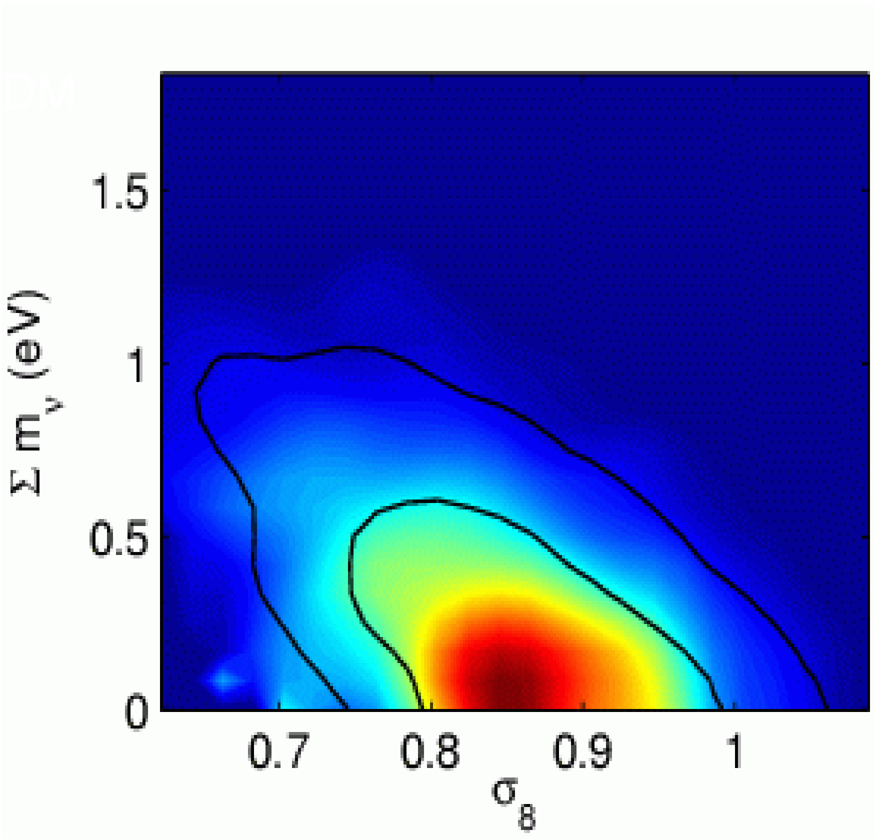
ACTIVE

Active neutrinos - I



Lesgourgues & Pastor 2006

Active neutrinos and Lyman-α II: VHS data

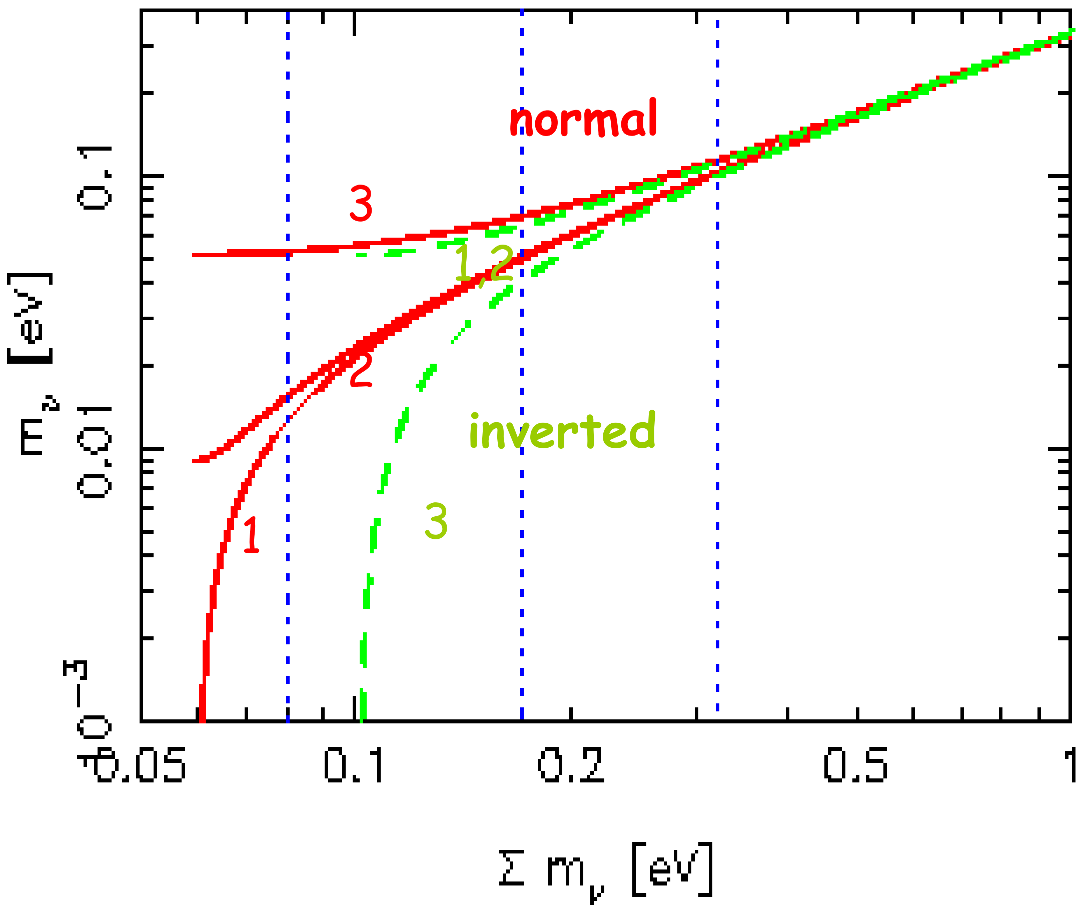


Σmν (eV) < 1 eV (95 % C.L.)
WMAP1 + 2dF + LYα

Good agreement with the latest Tegmark et al. results.....

Active neutrinos and Lyman-α III : SDSS

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



Tight constraints because data
Are marginally compatible

$\Sigma m\nu$ (eV) < 0.17 (95 %C.L.)

r < 0.22 (95 % C.L.)

running = -0.020 ± 0.12

CMB + SN + SDSS gal+ SDSS Ly-α

Goobar et al. (aph/0602155) get upper limits 2-3 times larger……

SUMMARY

- Lyman-α forest is a complementary measurement of the matter power spectrum and can be use to constrain cosmology together with the CMB
  <u>There are no other observables at the forest scales and redshifts</u>

- Tight constraints on active neutrinos and warm dark matter candidates

- All(?) the possible systematics are under control: there is really significant
  Power at these scales and redshifts
  (Weak lensing data support this)

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

Note that the **EDGE (NASA proposal)** 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

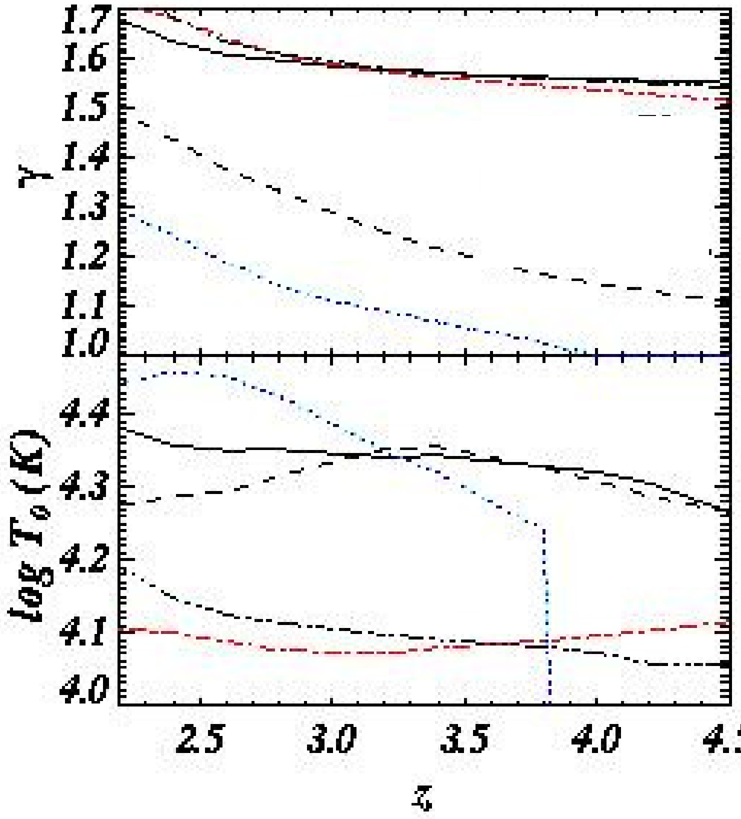
See Boyarsky, den Herder, Neronov, Ruchayskiy, 2006, astro-ph/0612219

SYSTEMATICS

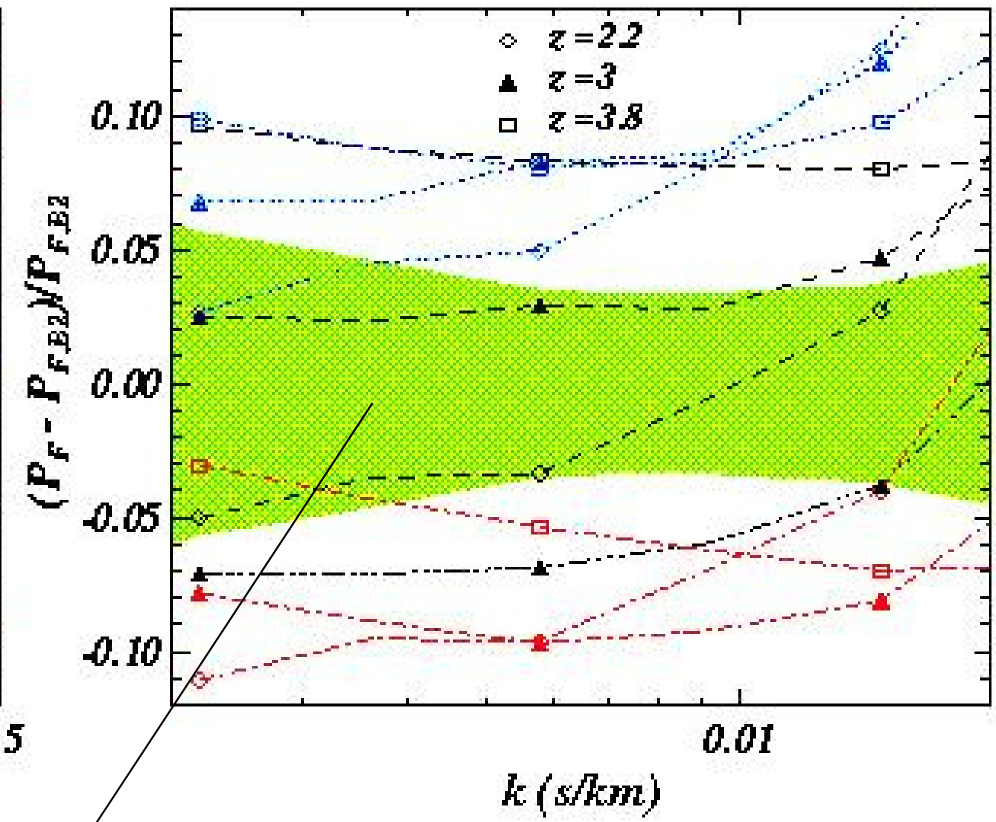
Systematics: Thermal state

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

Thermal histories



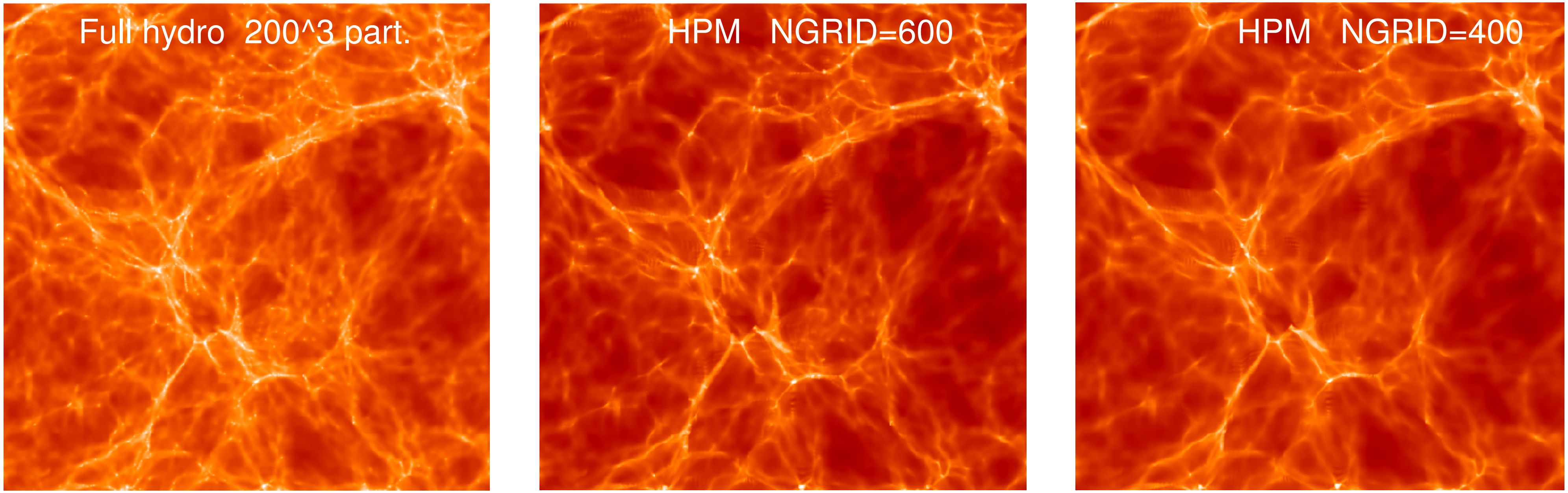
Flux power fractional differences



Viel & Haehnelt 2006

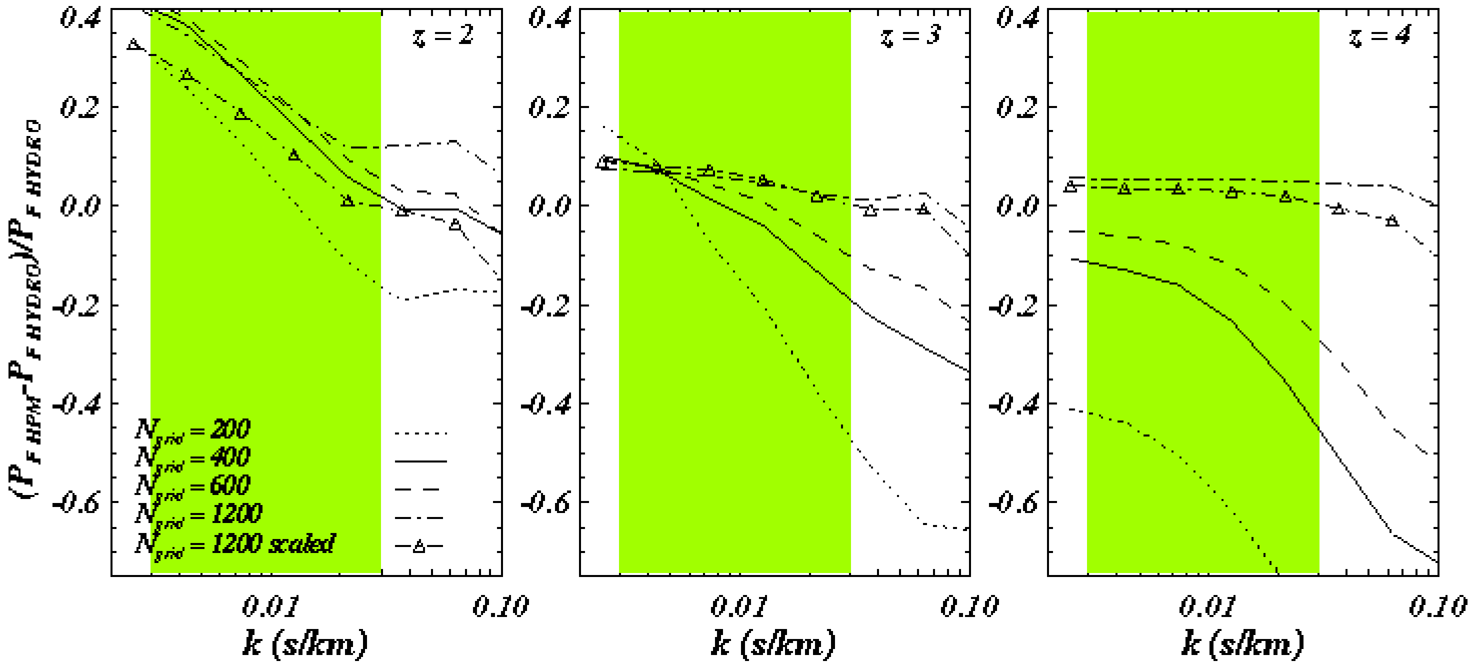
Statistical SDSS errors on flux power

Systematics: Hydrodynamical simulations



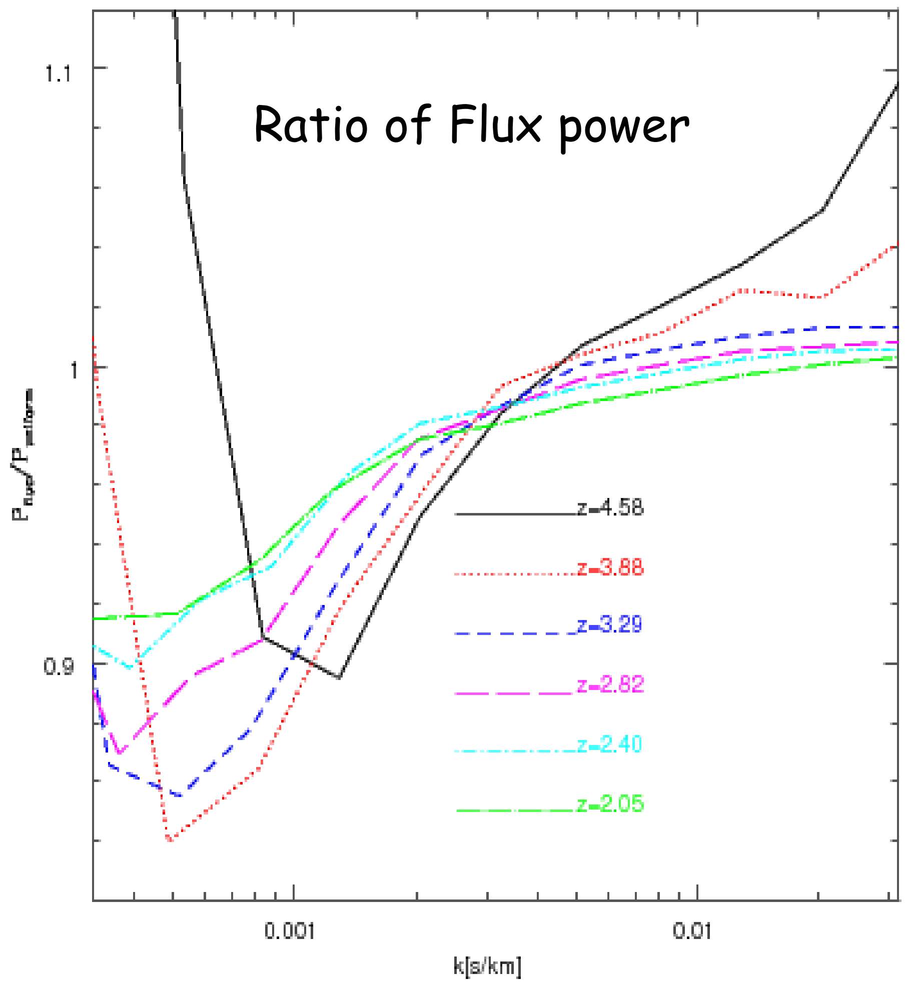
MV, Haehnelt, Springel (2006)

FLUX POWER



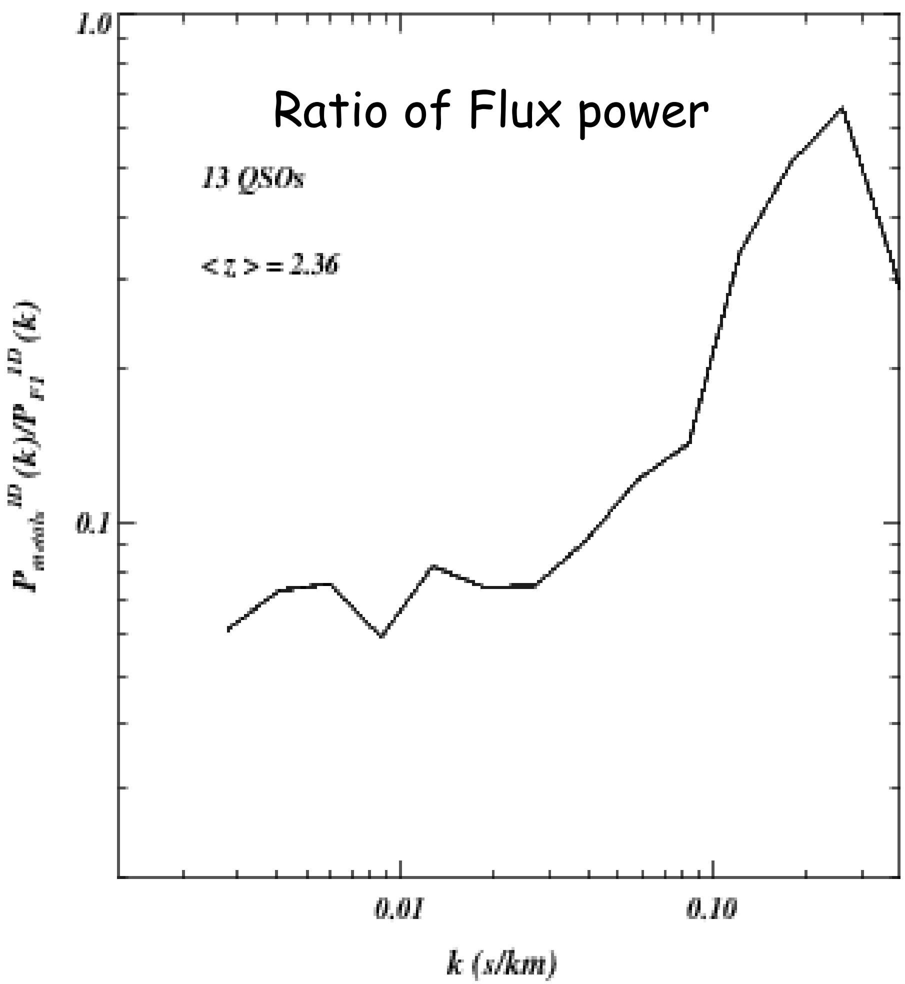
Systematics: UV fluctuations and Metals

UV fluctuations from Lyman Break Galaxies



McDonald, Seljak, Cen, Ostriker 2004

Metal contribution



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

BRIEF HISTORICAL OVERVIEW of the Lyman-α forest

- Gunn & Peterson (1965): a uniform IGM at redshift 2 is very highly ionized, to

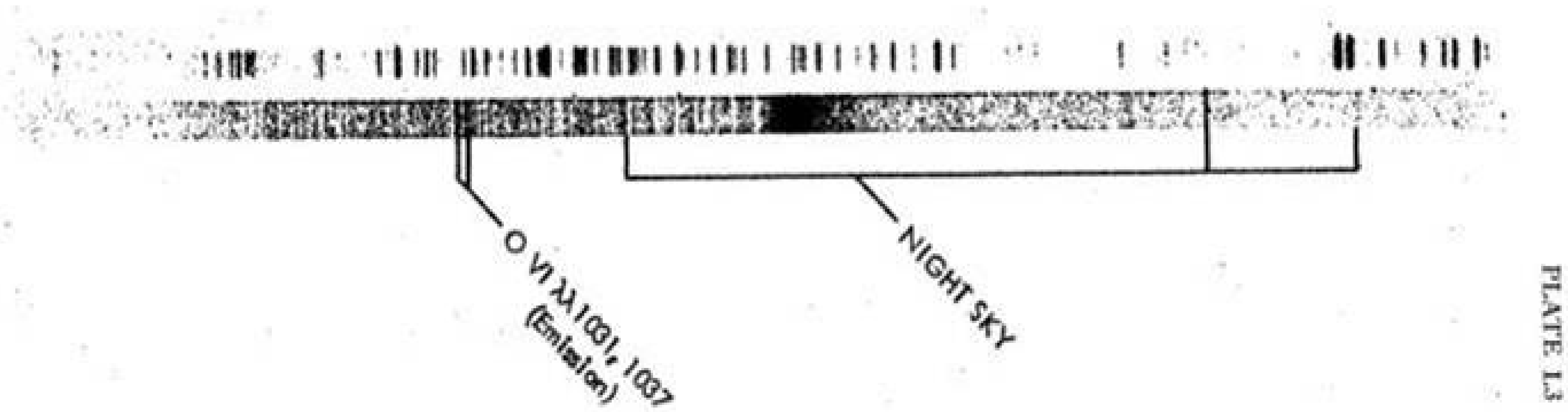


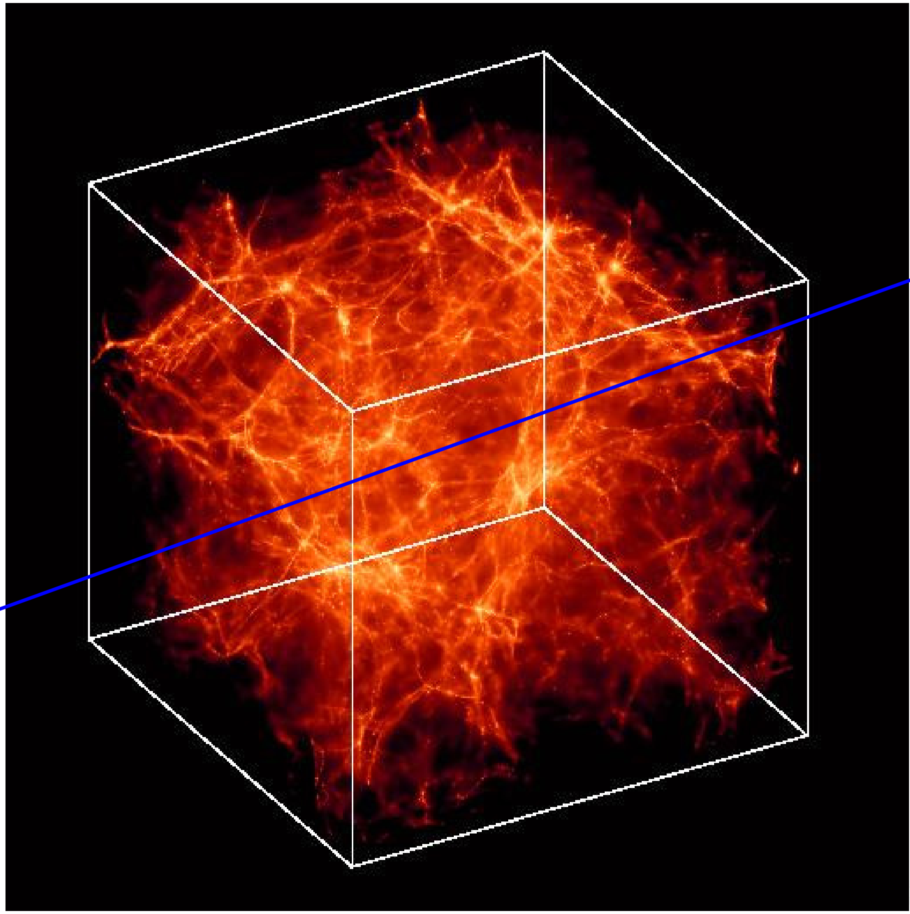
FIG. 1.—A spectrogram illustrating the numerous absorption lines in 4C 05.34. The strong emission line in the center is Lα. The O VI emission lines and several airglow features are also indicated. The comparison spectrum is He + Ar + Ne.

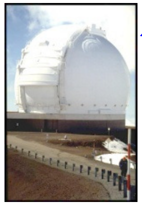
LYNDS (see page L73)

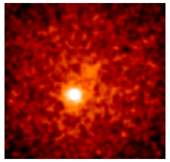
- McGill (1991), Bi (1992) considered an evolution of the IGM in cold dark matter models and found that a "median-fluctuated" medium, instead of discrete clouds, reproduced most of the observations;
- N-body + Hydro simulations (Cen et al. 1994), semi analytical models (Bi et al., 1993).

NETWORK OF FILAMENTS

COSMOLOGICAL PROBES



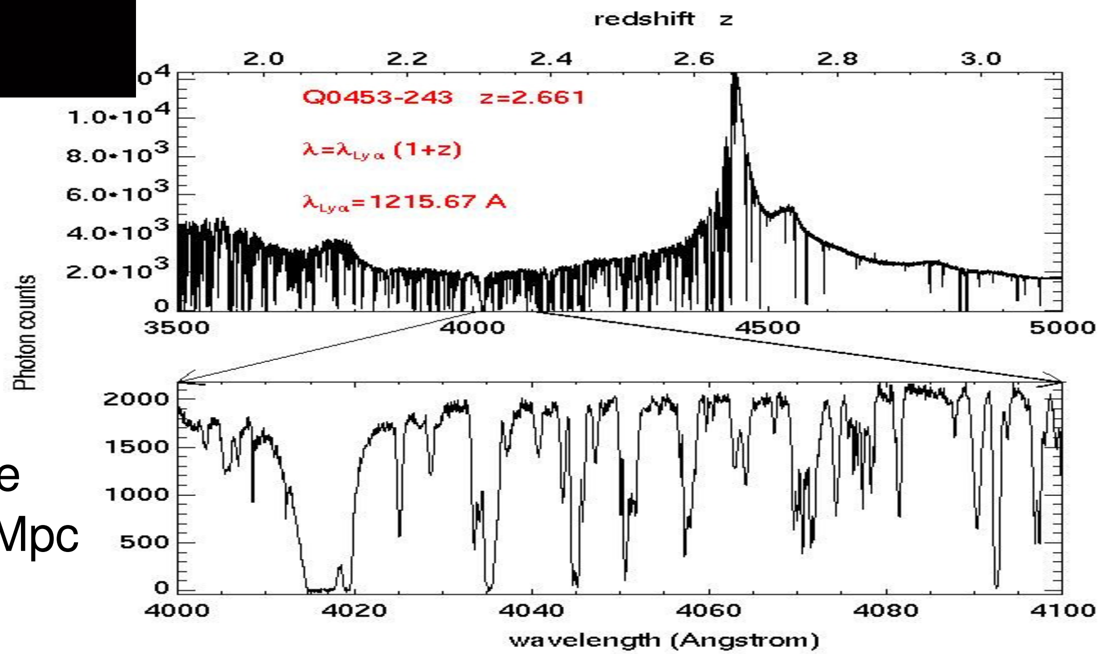




80 % of the baryons at z=3
are in the Lyman-α forest

Bi & Davidsen (1997), Rauch (1998)

baryons as tracer of the dark matter density field

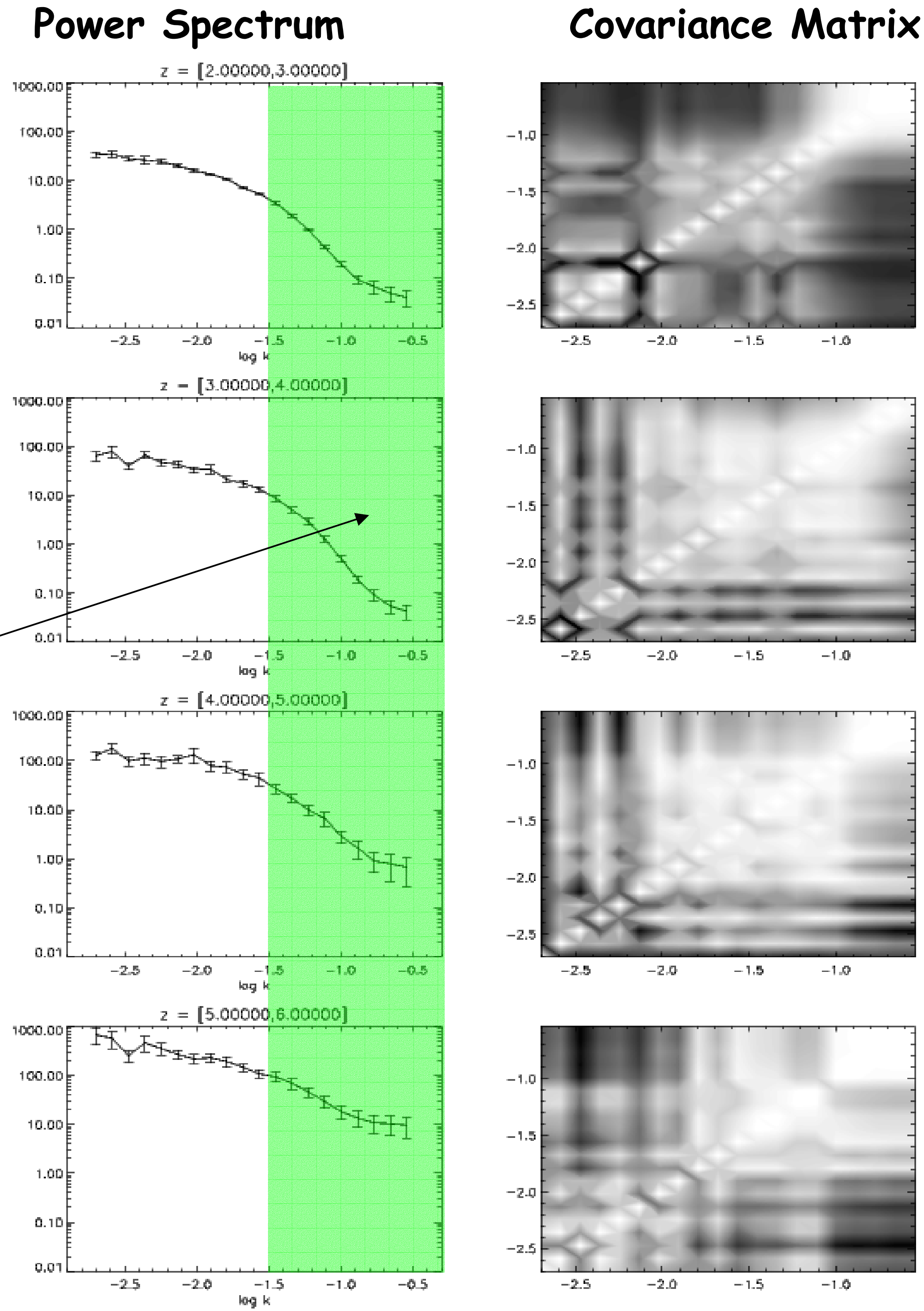


$\delta_{\mathrm{IGM}} \sim \delta_{\mathrm{DM}}$ at scales larger than the Jeans length ~ 1 com Mpc

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

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

Multimedia
ESA Multimedia gallery
Podcasting
National galleries
Media Centre
Press Releases
Information Notes
ESA Television
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XMM-Newton reveals the origin of elements in galaxy clusters

10 May 2006

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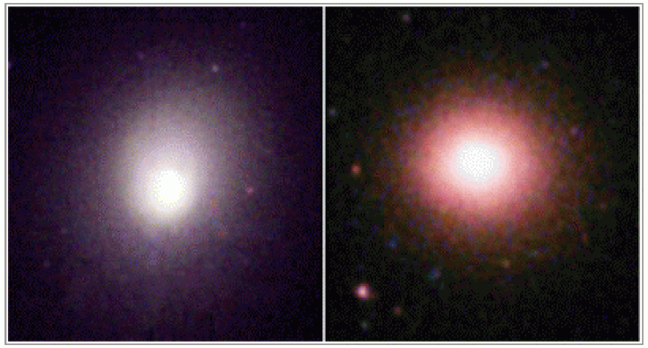

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These X-ray images of the clusters of galaxies 'Sersic 159-03' (right) and '2A 0335+096' (left) were taken by the European Photon Imaging Camera (EPIC) on-board ESA's XMM-Newton, in November 2002 and August 2003 respectively. Thanks to these observations, 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

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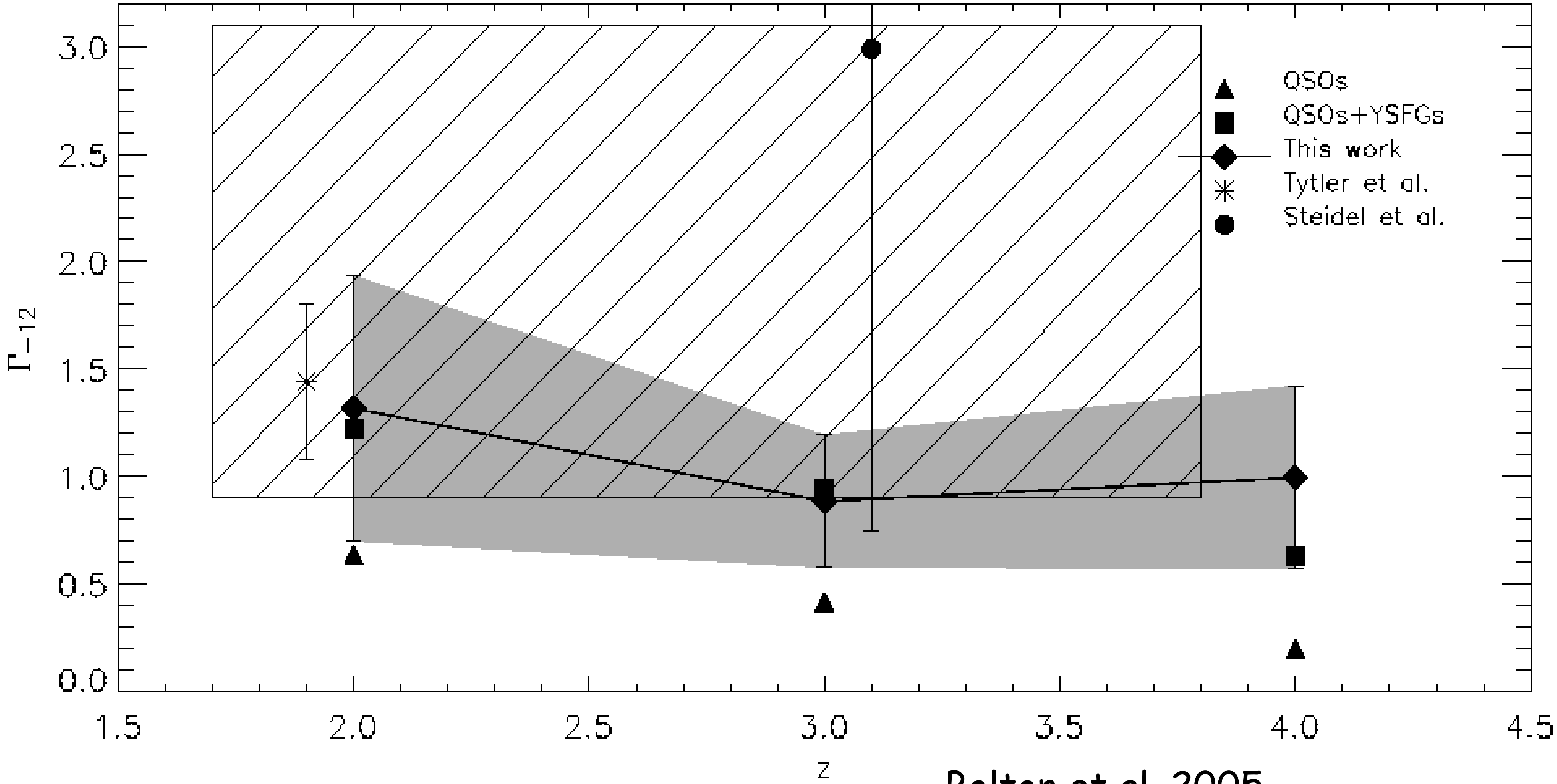
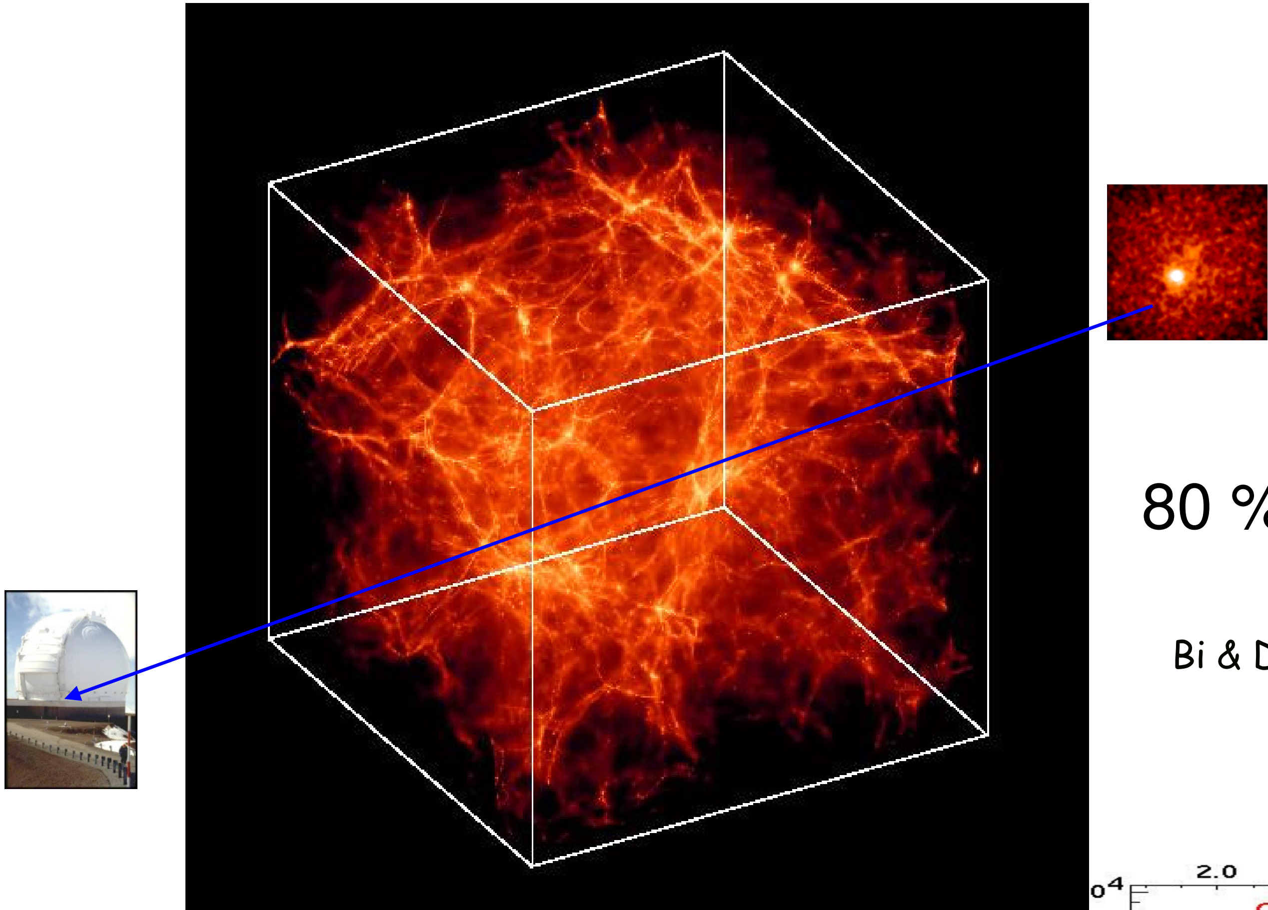
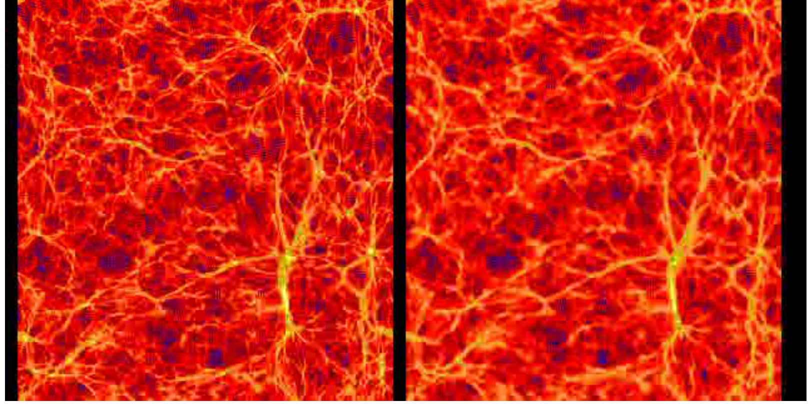
Systematics: Ionization state

Fluctuations in the UV background seem to be not important and the ionization Rate follows a smooth evolution



Bolton et al. 2005



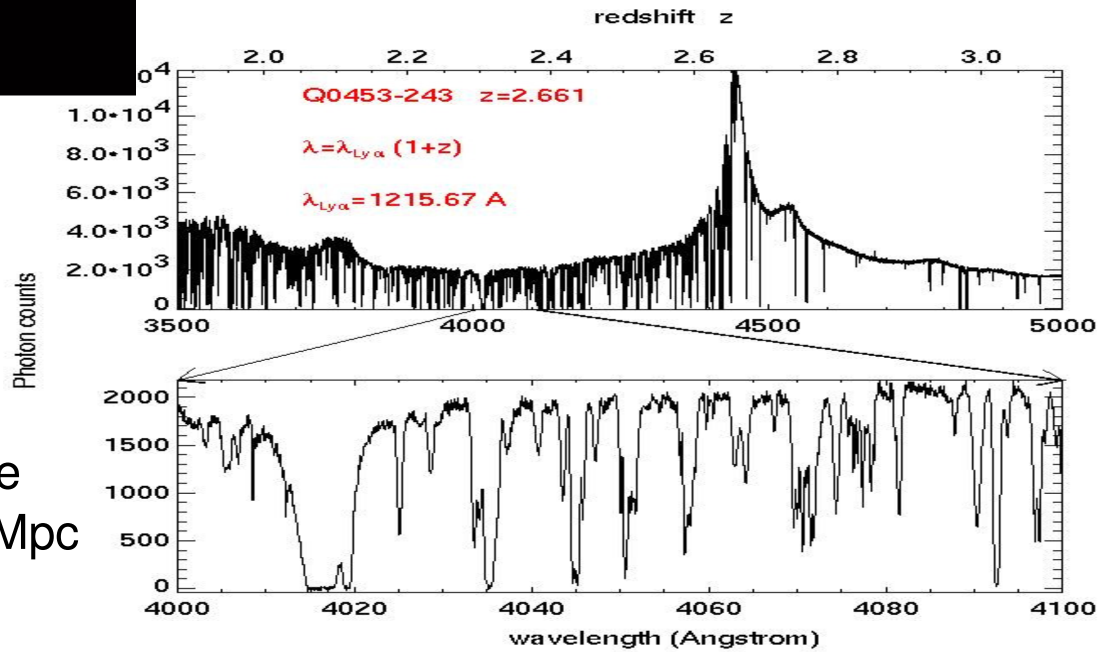


Physics of the simulations is simple: dark matter,
Gas cooling, photoionization heating, star formation

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

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

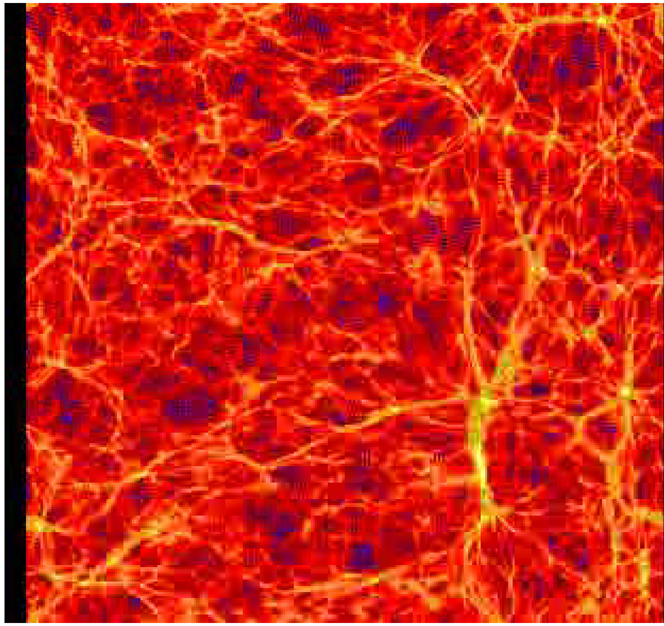
INTRO

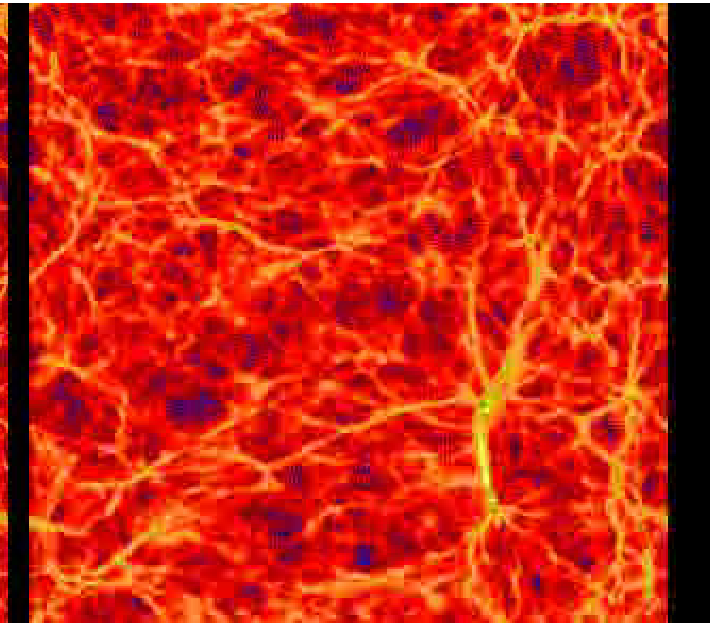
$\Omega_m = 0.26$ $\Omega_\Lambda = 0.74$ $\Omega_b=0.0463$ $H_0 = 72$ km/sec/Mpc - 60 Mpc/h $2\mathrm{x}400^3$ GAS+DM

2.5 com. kpc/h softening length

GADGET –II code COSMOS computer – DAMTP (Cambridge)

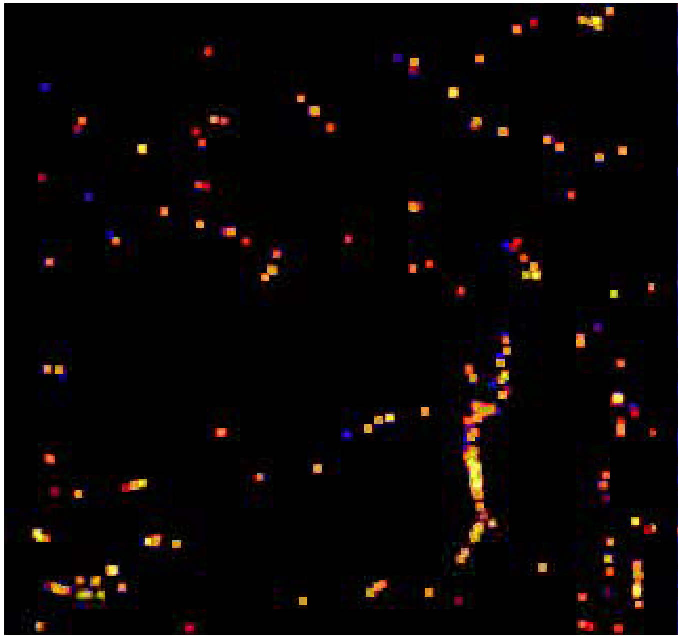
DM

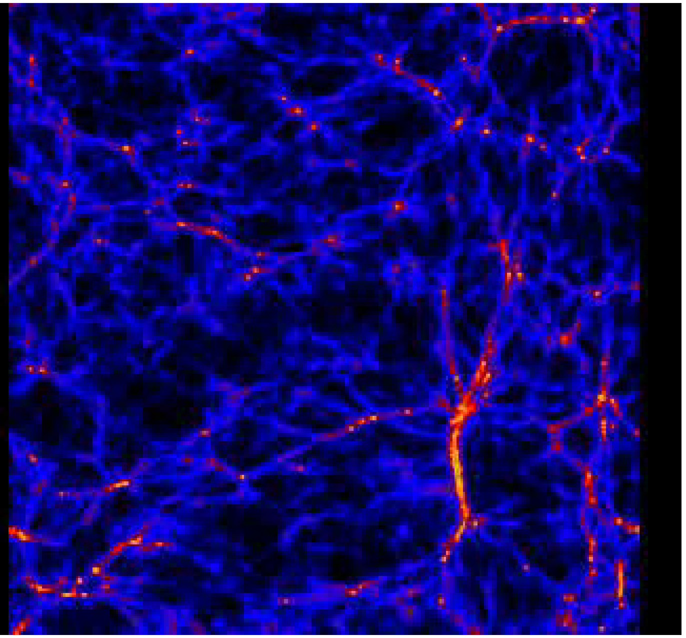




GAS

STARS





NEUTRAL HYDROGEN

Weak Lensing and Lyman-α - II

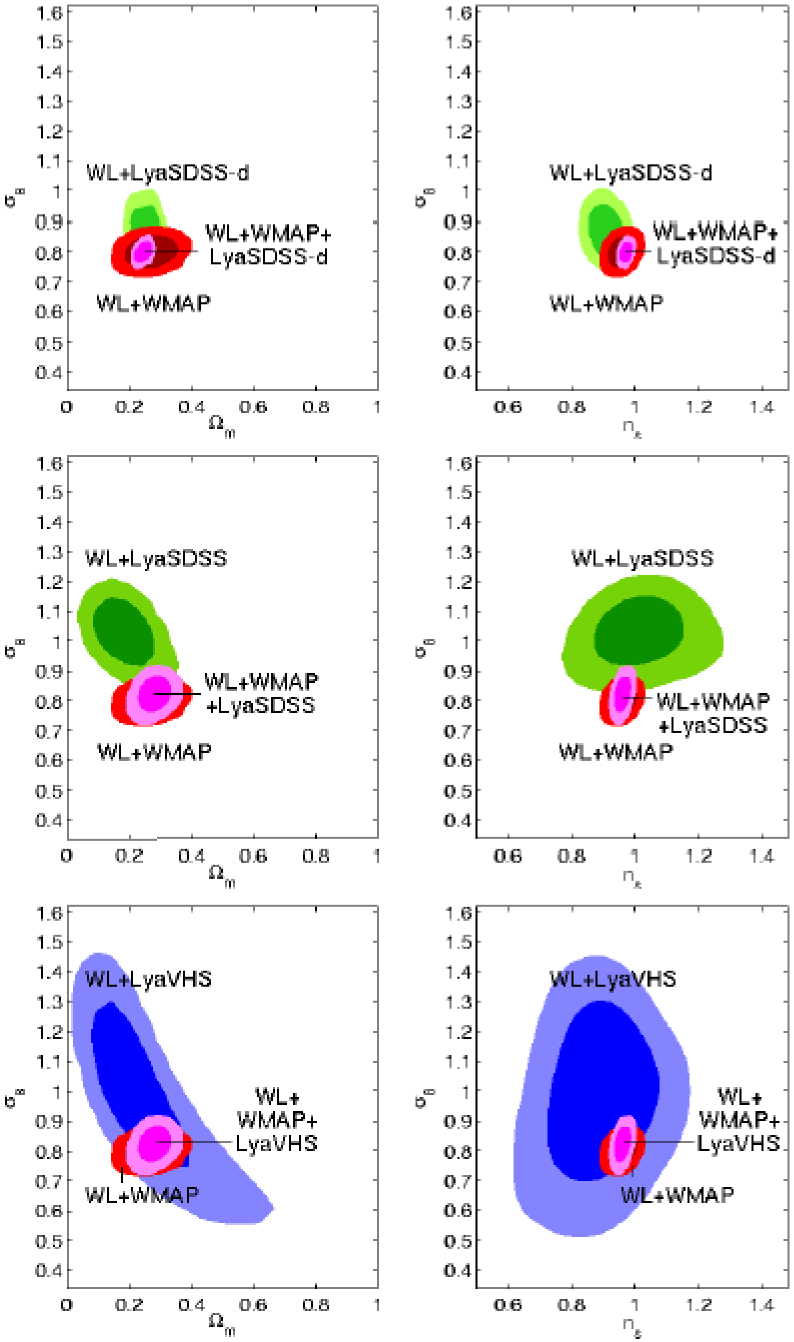


Table I: Summary of the constraints on σ_8, n_s, Ω_{0m}, h and τ, for the minimal 6-parameter ΛCDM model and various data sets. The quoted values are the mean and 68% confidence limits.

	WL	Lya VHS	Lya SDSS	Lya SDSS-d	WMAP3	WL+WMAP3	WL+Lya VHS	WL+Lya SDSS	WL+Lya SDSS-d
σ_8	0.84 ± 0.22	1.04 ± 0.16	0.89 ± 0.11	0.87 ± 0.07	0.76 ± 0.05	0.80 ± 0.04	0.98 ± 0.19	1.02 ± 0.07	0.87 ± 0.05
n_s	0.75 ± 0.18	0.81 ± 0.10	0.95 ± 0.07	0.98 ± 0.03	0.95 ± 0.02	0.96 ± 0.02	0.89 ± 0.11	1.02 ± 0.09	0.91 ± 0.03
Ω_{0m}	0.35 ± 0.20	0.55 ± 0.23	0.43 ± 0.25	0.21 ± 0.04	0.24 ± 0.03	0.27 ± 0.03	0.25 ± 0.12	0.19 ± 0.05	0.25 ± 0.03
h	0.77 ± 0.15	0.71 ± 0.13	0.67 ± 0.14	0.75 ± 0.08	0.73 ± 0.03	0.71 ± 0.03	0.82 ± 0.14	0.78 ± 0.14	0.84 ± 0.07
τ	–	–	–	–	0.09 ± 0.03	0.09 ± 0.03	–	–	

Table II: Summary of the constraints on σ_8, n_s, Ω_{0m}, h and τ for the combination of CMB, weak lensing and Lyα forest data. The quoted values are the mean and 68% confidence limits.

	WL+WMAP3+VHS	WL+WMAP3+SDSS	WL+WMAP3+SDSS-d
σ_8	0.82 ± 0.04	0.85 ± 0.02	0.80 ± 0.02
n_s	0.96 ± 0.02	0.97 ± 0.02	0.97 ± 0.01
Ω_{0m}	0.28 ± 0.03	0.29 ± 0.03	0.25 ± 0.02
h	0.70 ± 0.03	0.70 ± 0.02	0.73 ± 0.02
τ	0.10 ± 0.03	0.10 ± 0.03	0.11 ± 0.02

Table III: Summary of the constraints on σ_8, n_s, Ω_{0m}, h and τ for the combination of CMB, weak lensing and Lyα forest data for the case with a running spectral index. The quoted values are the mean and 68% confidence limits.

	WL+WMAP3+VHS	WL+WMAP3+SDSS	WL+WMAP3+SDSS-d
σ_8	0.81 ± 0.04	0.85 ± 0.03	0.82 ± 0.02
n_s	0.96 ± 0.02	0.98 ± 0.02	0.97 ± 0.02
Ω_{0m}	0.30 ± 0.03	0.30 ± 0.03	0.26 ± 0.02
h	0.68 ± 0.02	0.69 ± 0.03	0.72 ± 0.02
τ	0.09 ± 0.04	0.11 ± 0.03	0.13 ± 0.03
n_{run}	-0.028 ± 0.018	-0.023 ± 0.013	-0.007 ± 0.021

Lesgourgues, Viel, Haehnelt, Massey, 2007

Modelling Lyman-α absorptions:

Dark matter evolution: linear theory of density perturbation +
Jeans length $L_J \sim sqrt(T/\rho)$ + 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 = $1/sqrt(G \rho)$ ~ 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}

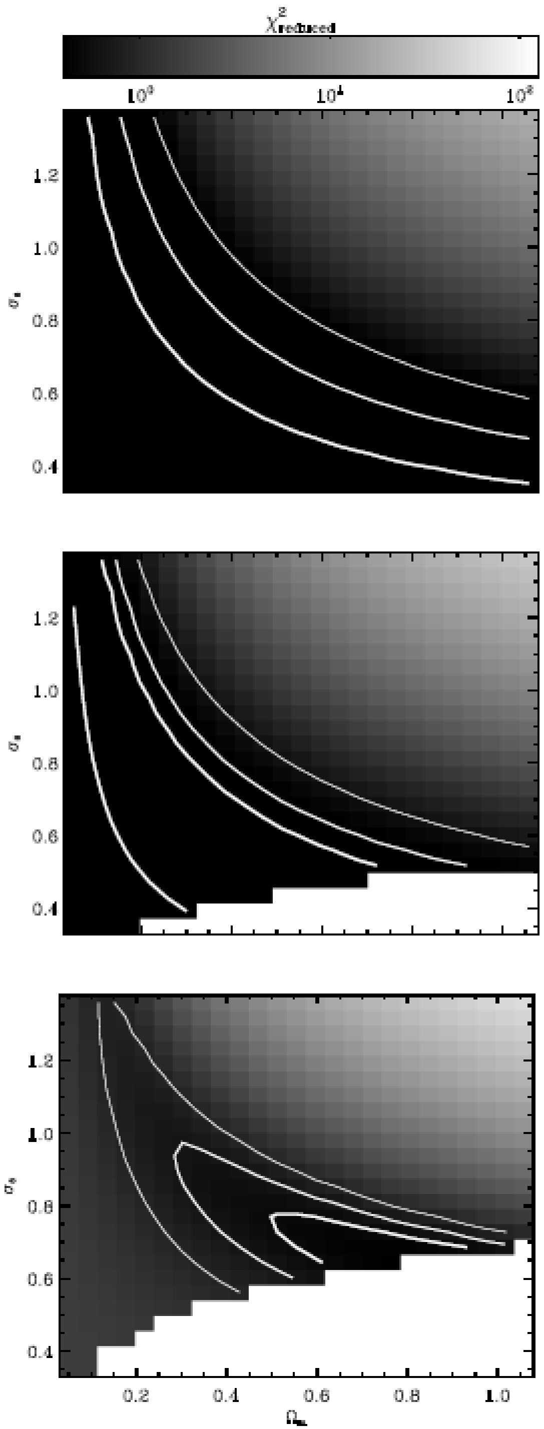
In practice, since the process is mildly non linear you need numerical simulations
To get convergence of the simulated flux at the percent level (observed)

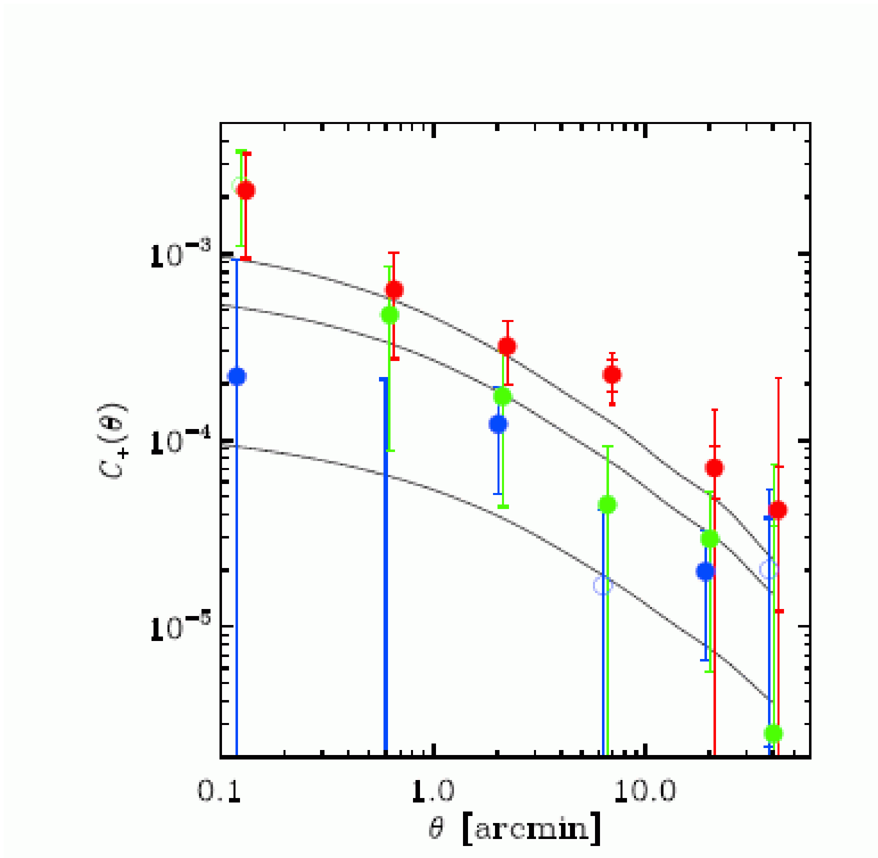
Weak Lensing - the COSMOS survey - III

z = 0.1 - 1

z = 1 - 1.4

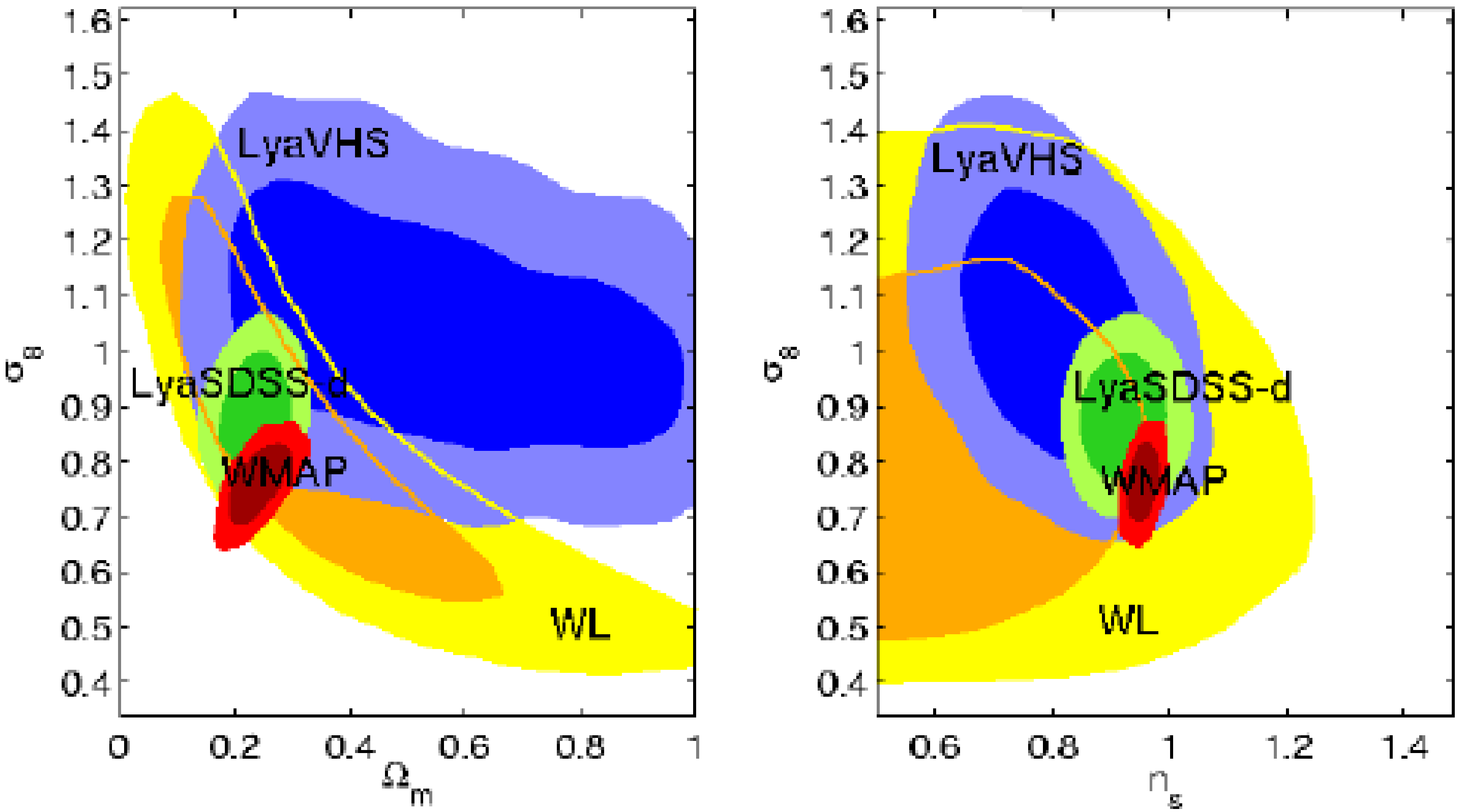
z = 1.4 -3





Massey et al., 2007, arXiv: astro-ph/0701480

Weak Lensing and Lyman-α - I



Lesgourgues, Viel, Haehnelt, Massey, 2007