The intergalactic medium as a cosmological tool

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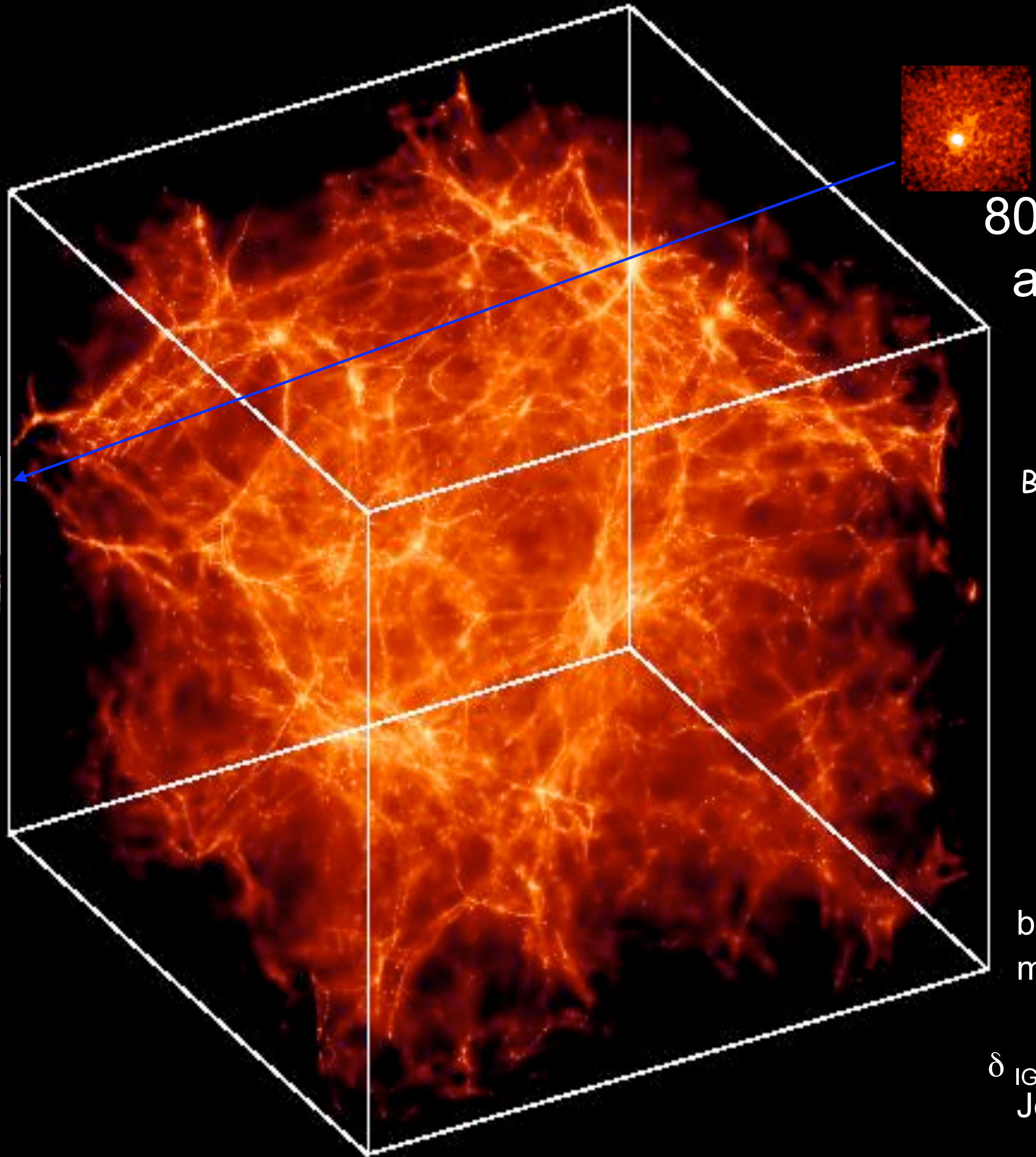
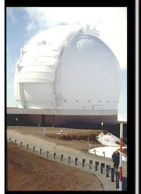
INAF & INFN – Trieste

GGI-Florence 10th February 2009

THEORY: GAS in a ΛCDM universe





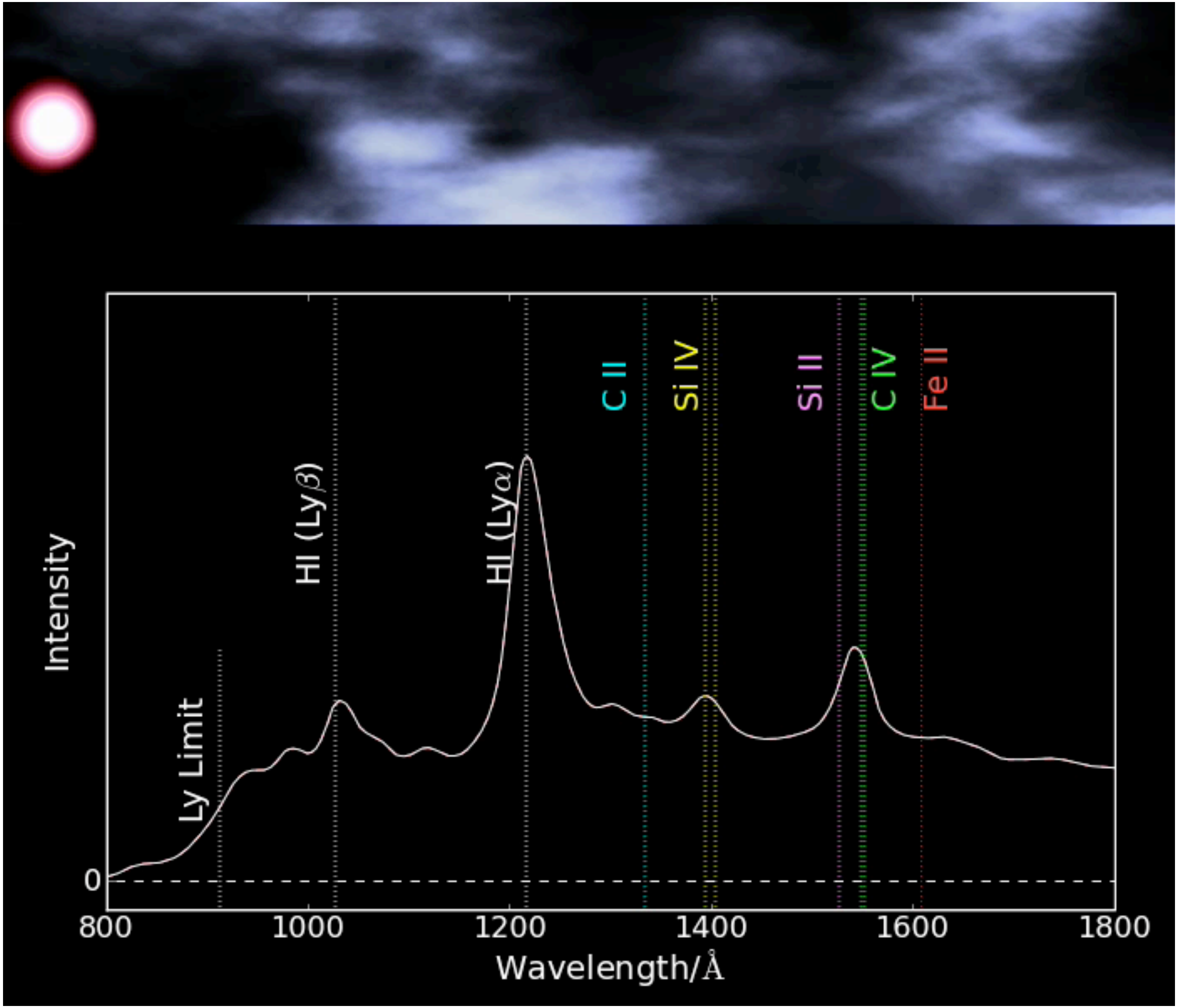
80 % of the baryons at z=3 are in the Lyman-α forest

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

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

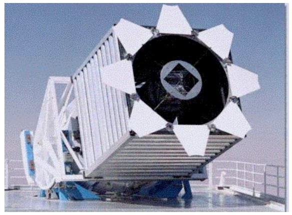

Intensity
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II
0
800
1000
1200
1400
1600
1800
Wavelength/Å

Outline

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

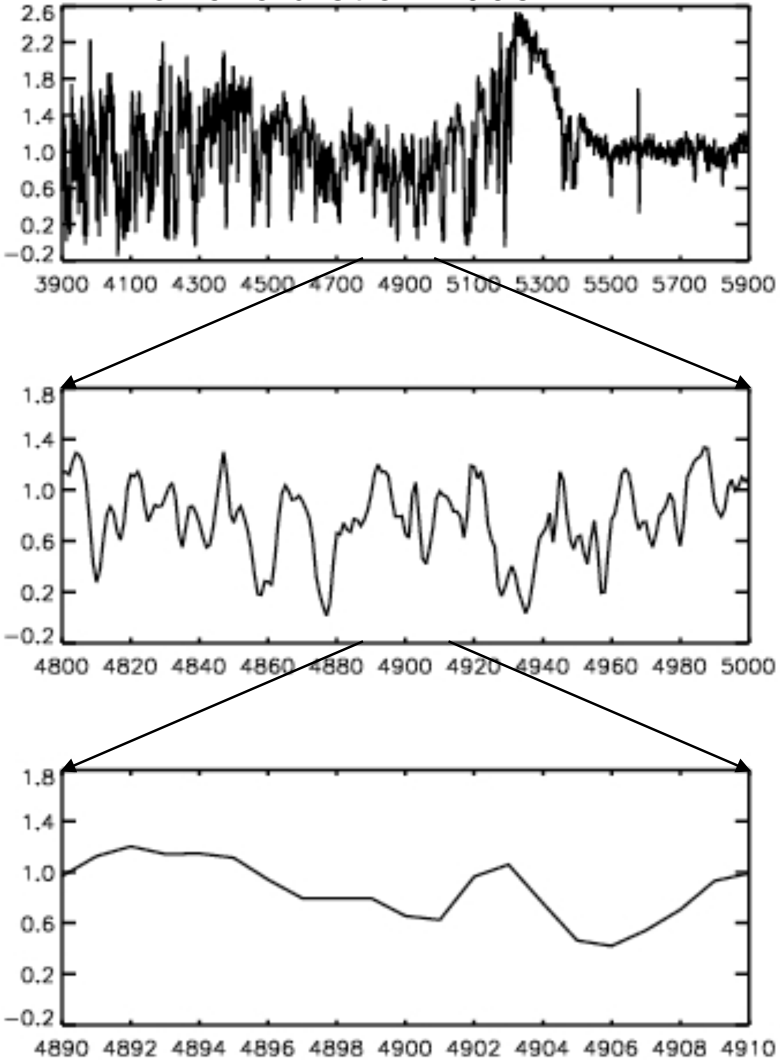
Why Lyman-α ? Small scales
high redshift
Most of the baryonic mass is in this form
Quasars sample 75% of the age of the universe

The data sets

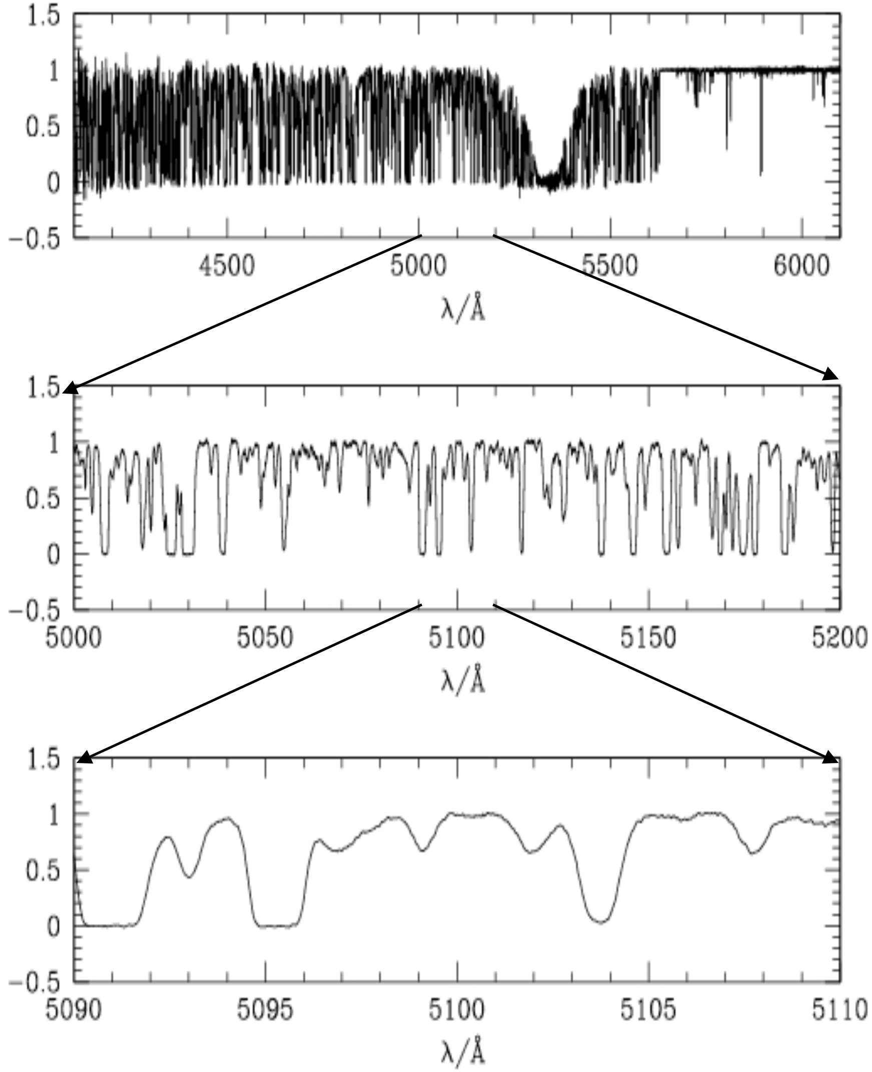


SDSS vs LUQAS

McDonald et al. 2005



Kim, MV et al. 2004



SDSS

3035 LOW RESOLUTION LOW S/N

vs

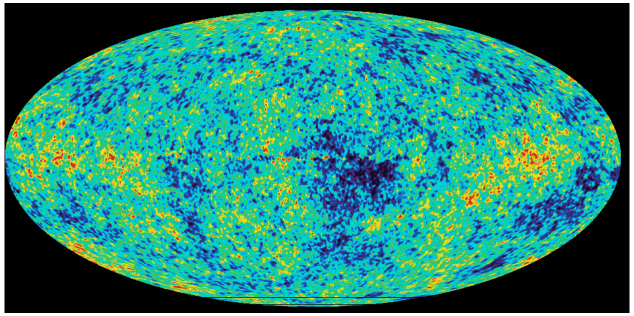
LUQAS

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: Spergel et al. (05) | Galaxy P(k): Sanchez & Cole (07) | Flux Power: McDonald (05)



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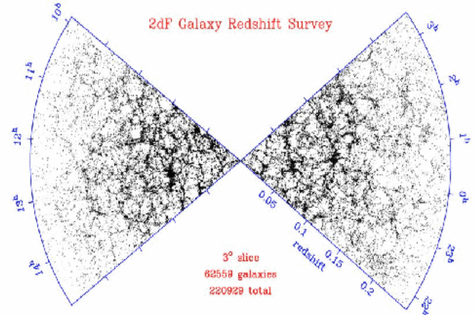

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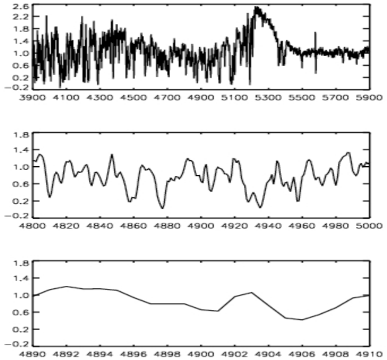
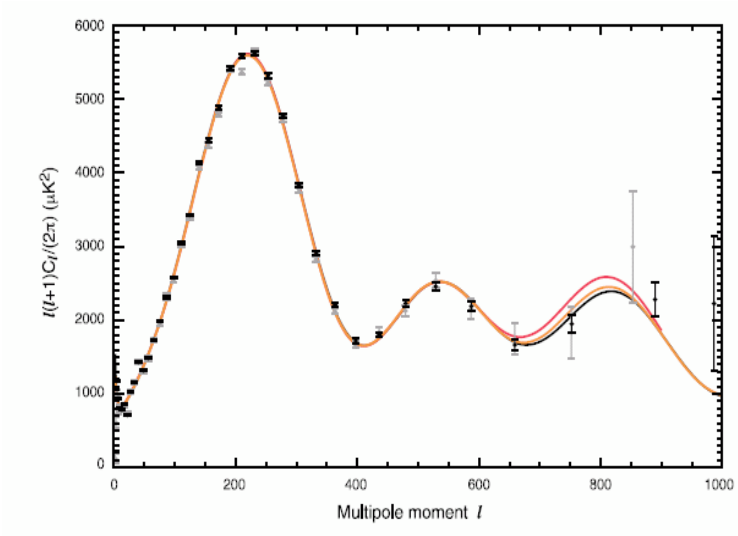
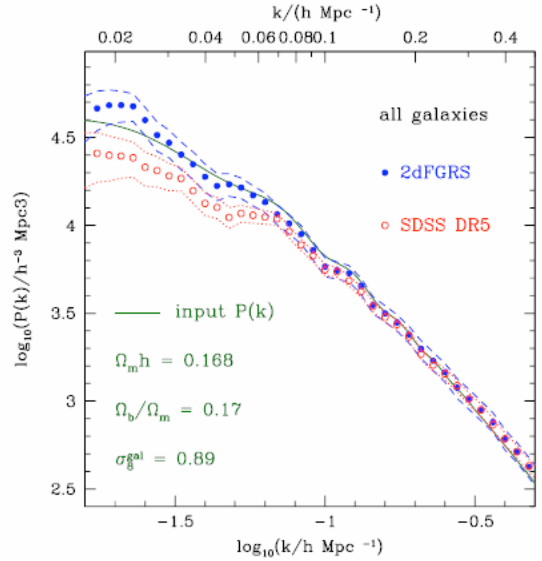
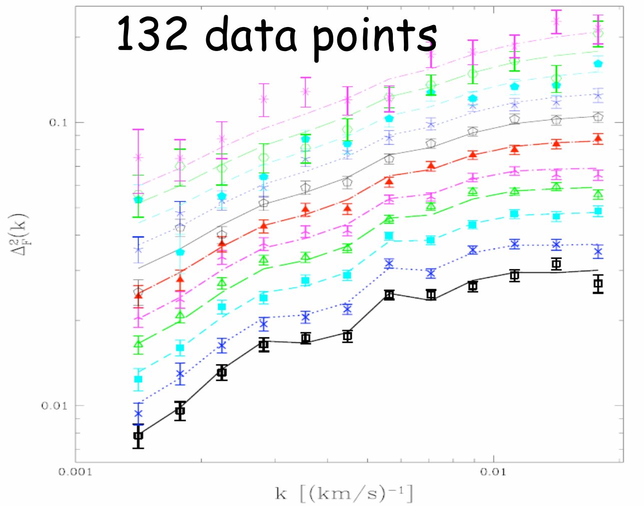








Cosmological parameters + e.g. bias + Parameters describing IGM physics

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

McDonald et al. 05: fine grid of (calibrated) HPM (quick) simulations

Viel & Haehnelt 06: interpolate sparse grid of full hydrodynamical (slow) simulations

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

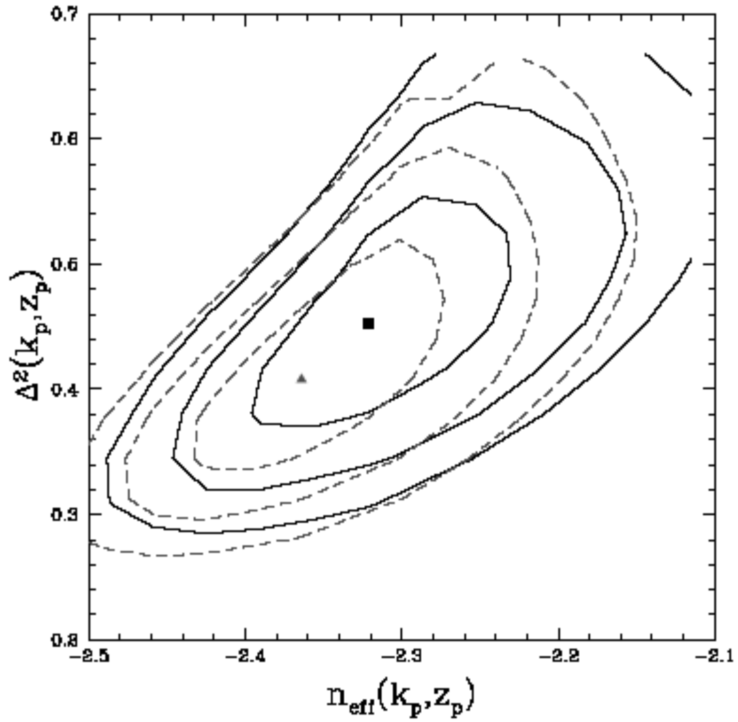
$$\Delta_L^2(k,\ z) \simeq \left[\frac{D(z)}{D(z_p)}\right]^2 \Delta_L^2(k_p,\ z_p) \quad \times \left[\frac{k}{k_\star(z)}\right]^{3+n_{\rm eff}(k_p,z_p)+(1/2)\alpha_{\rm eff}(k_p,z_p)\,\ln[k/k_\star(z)]}$$

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

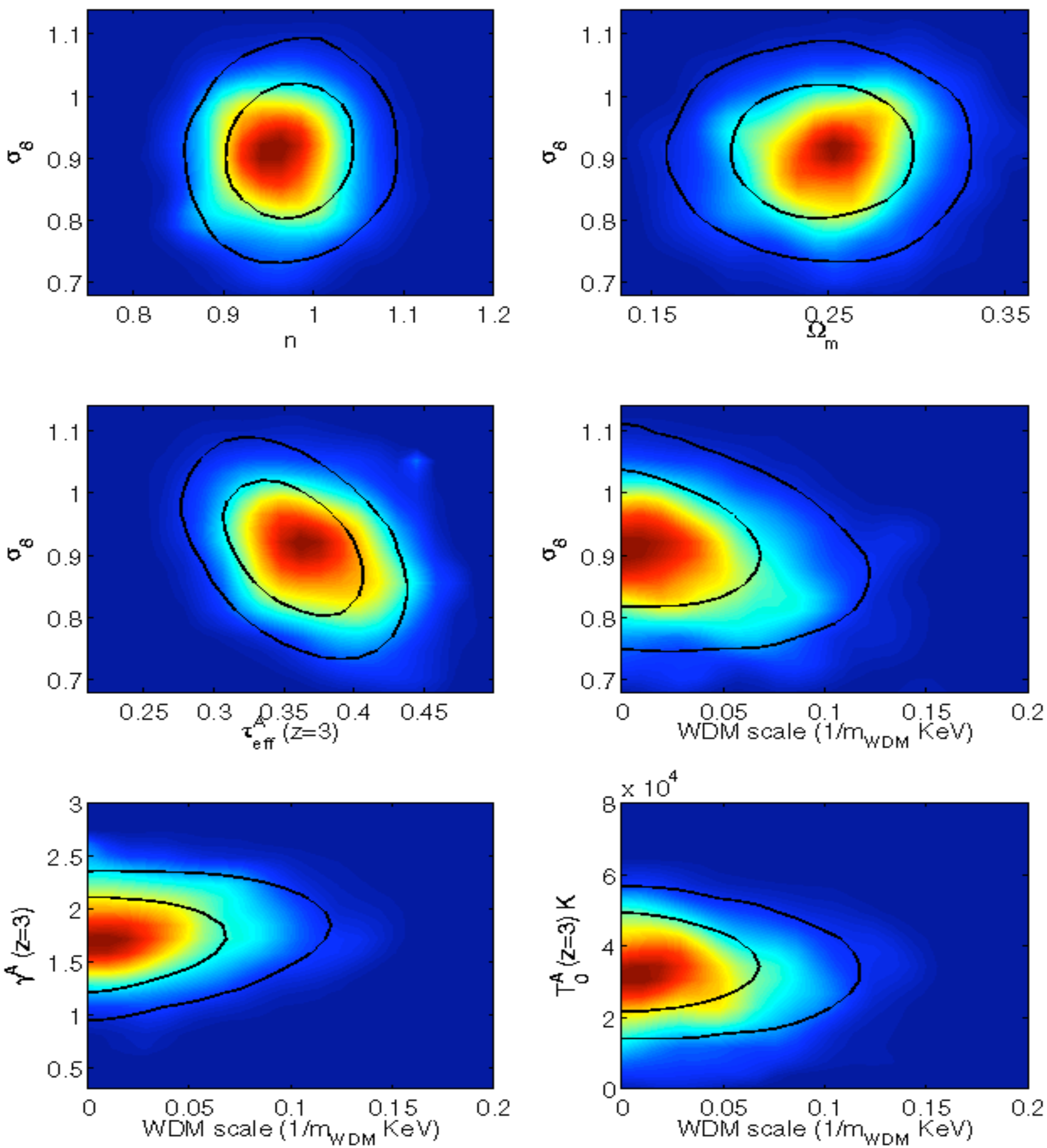
AMPLITUDE



SLOPE

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

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

σ_8 = 0.91 ± 0.07
n = 0.97 ± 0.04

Summary (highlights) of results

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

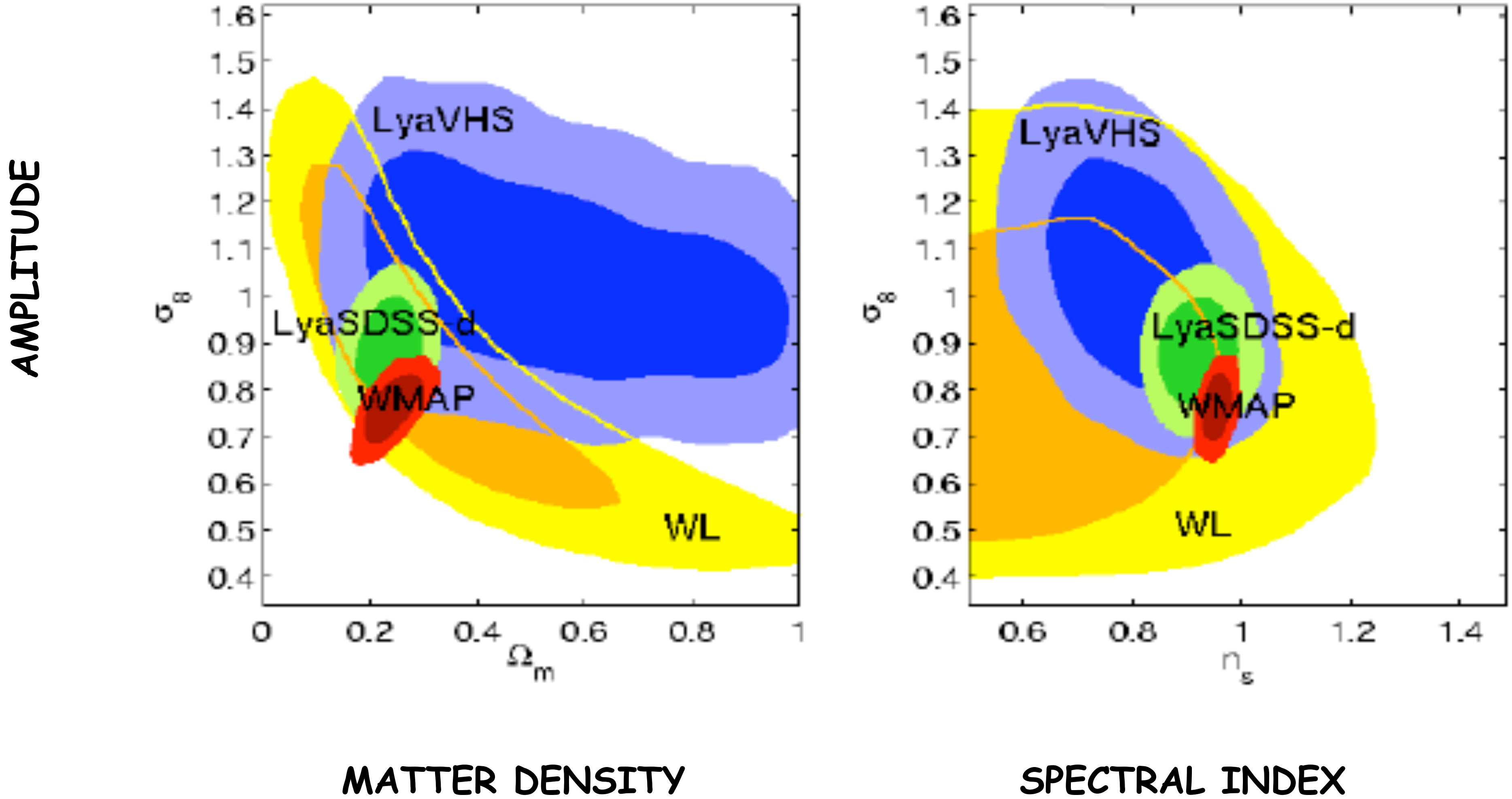
   Seljak, Slosar, McDonald JCAP (2006) 10 014

2. 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 3yrs

VHS: 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/



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

σ_8 = 0.796 ± 0.036
n_s = 0.963 ± 0.015
Ω_m= 0.258 ± 0.030
h = 71.9 ± 2.7
τ= 0.087 ± 0.017
dn/dlnk= -0.037 ± 0.028

WMAP5+BAO+SN Komatsu et al. 08

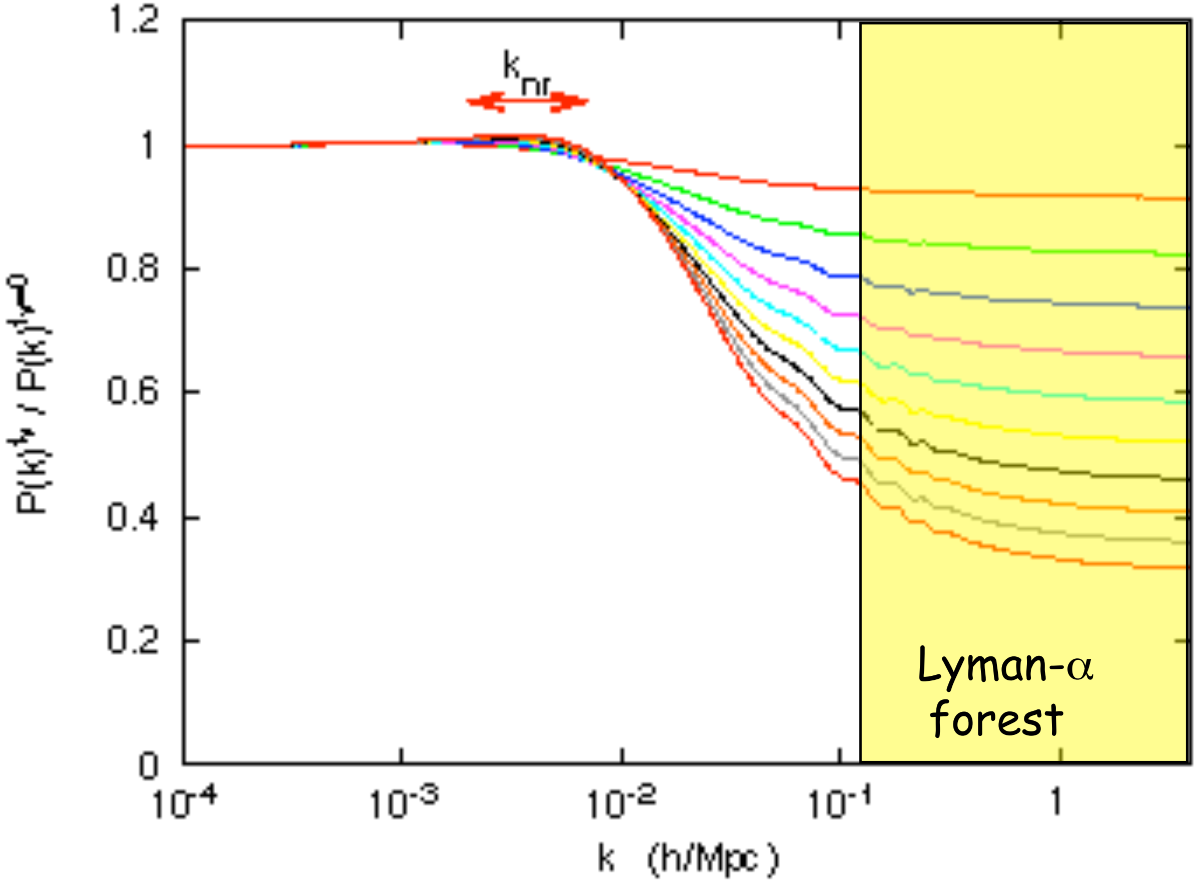
σ_8 = 0.817 ± 0.026
n_s = 0.960 ± 0.014
h = 70.1 ± 1.3
τ = 0.084 ± 0.016

with Lyman-α factor 2 improvements on the running

Active neutrinos - I

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

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

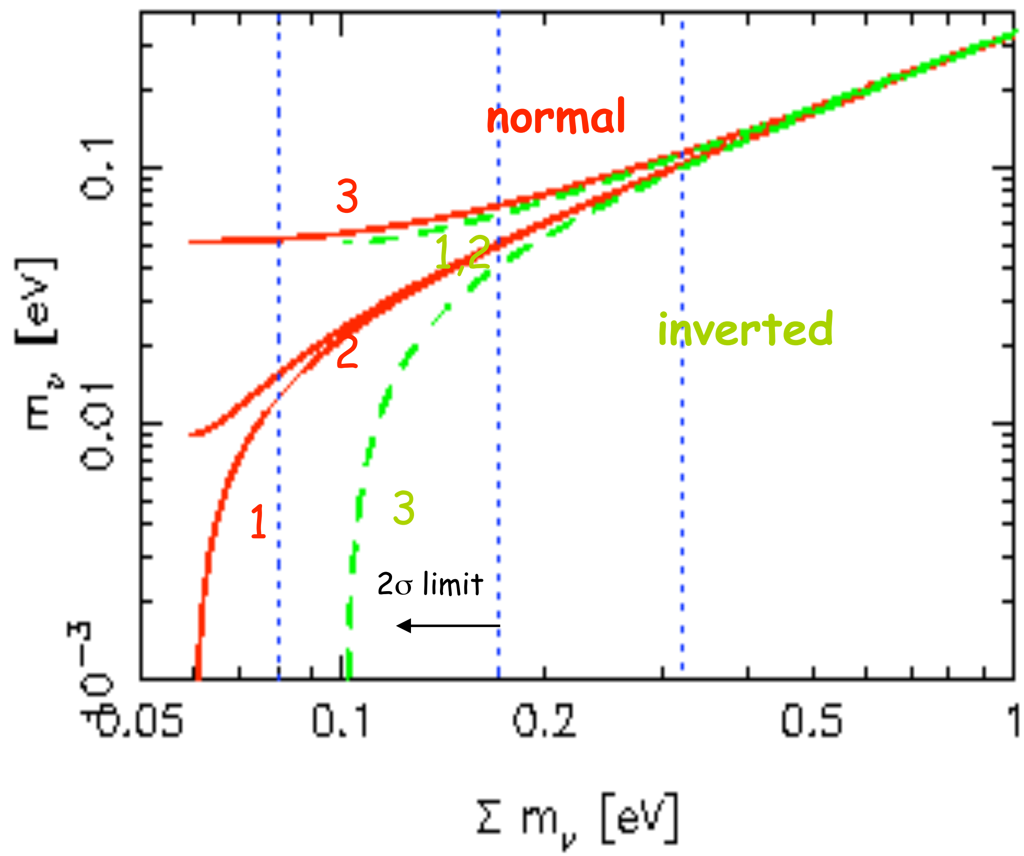


Σm_ν = 0.138 eV

Σm_ν = 1.38 eV

Active neutrinos - II

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……

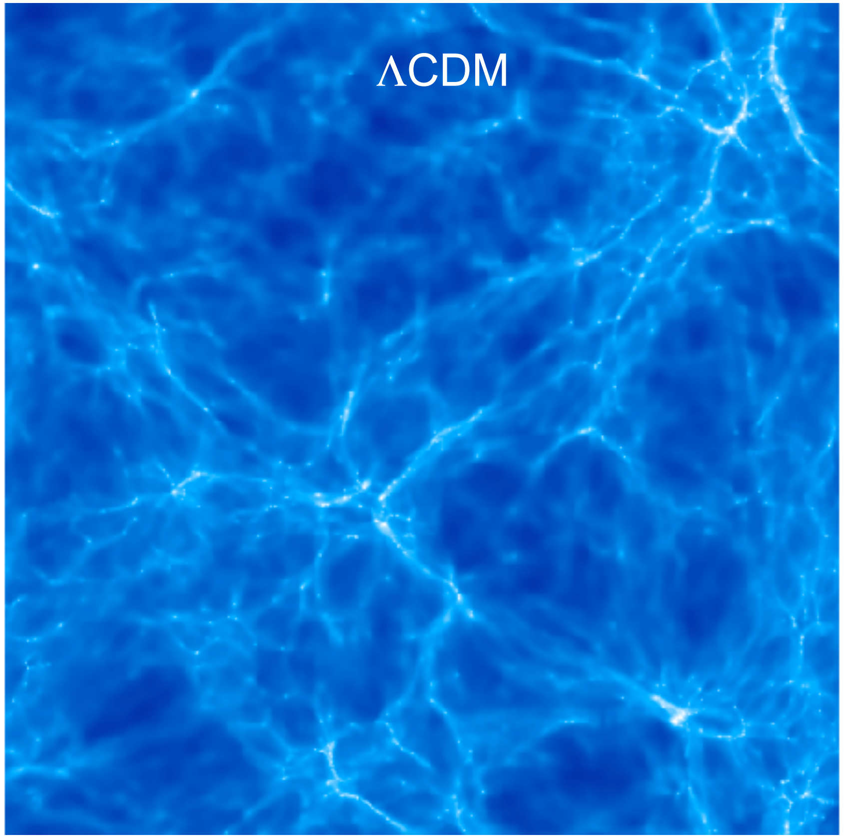
for forecasting see Gratton, Lewis, Efstathiou 2007

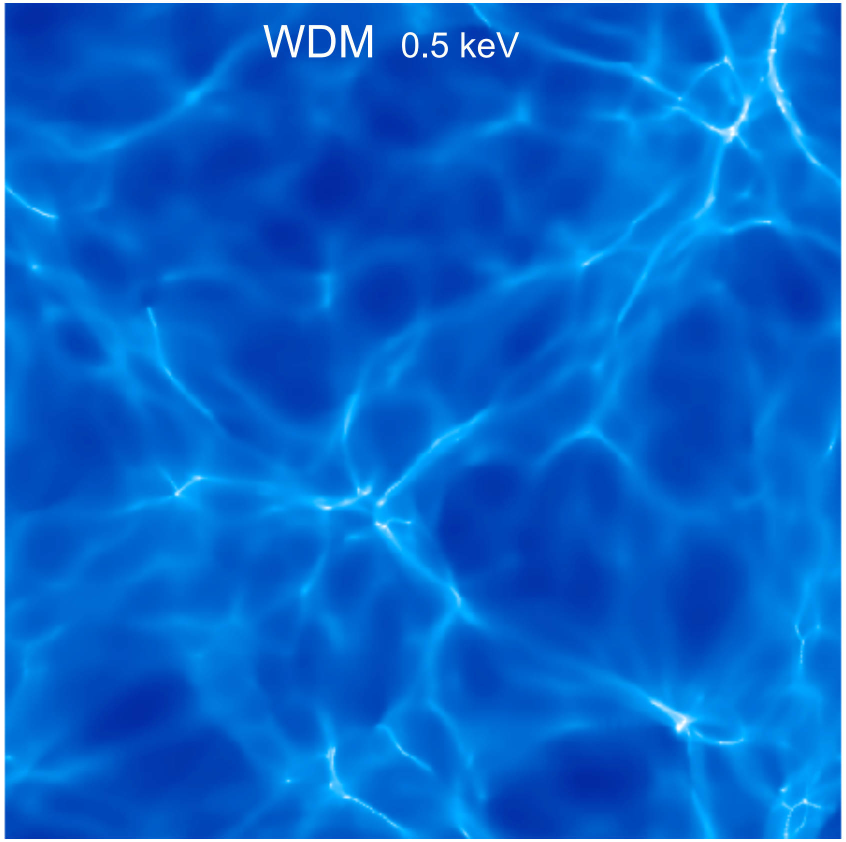
RESULTS

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

m_{WDM} > 0.5 (2.5) keV from VHS, SDSS
m_s > 2 (14) keV from VHS, SDSS

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

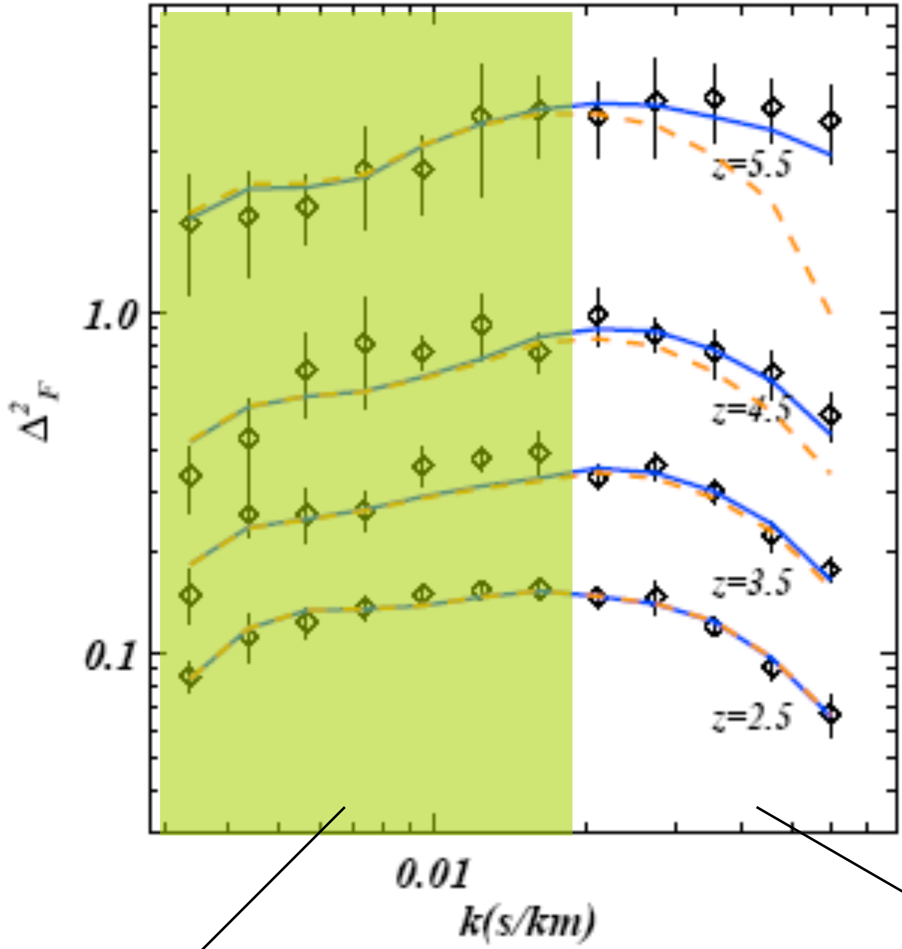
See (for numerical studies):

- Colombi, Dodelson, Widrow, 1996
- Colin, Avila-Reese, Valenzuela 2000
- Bode, Ostriker, Turok 2001
- Abazajian, Fuller, Patel 2001
- Wang & White 2007
- Colin, Avila-Reese, Valenzuela 2008

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

Lyman-α and Warm Dark Matter - II

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



SDSS range

Completely new small scale regime

SDSS + HIRES data

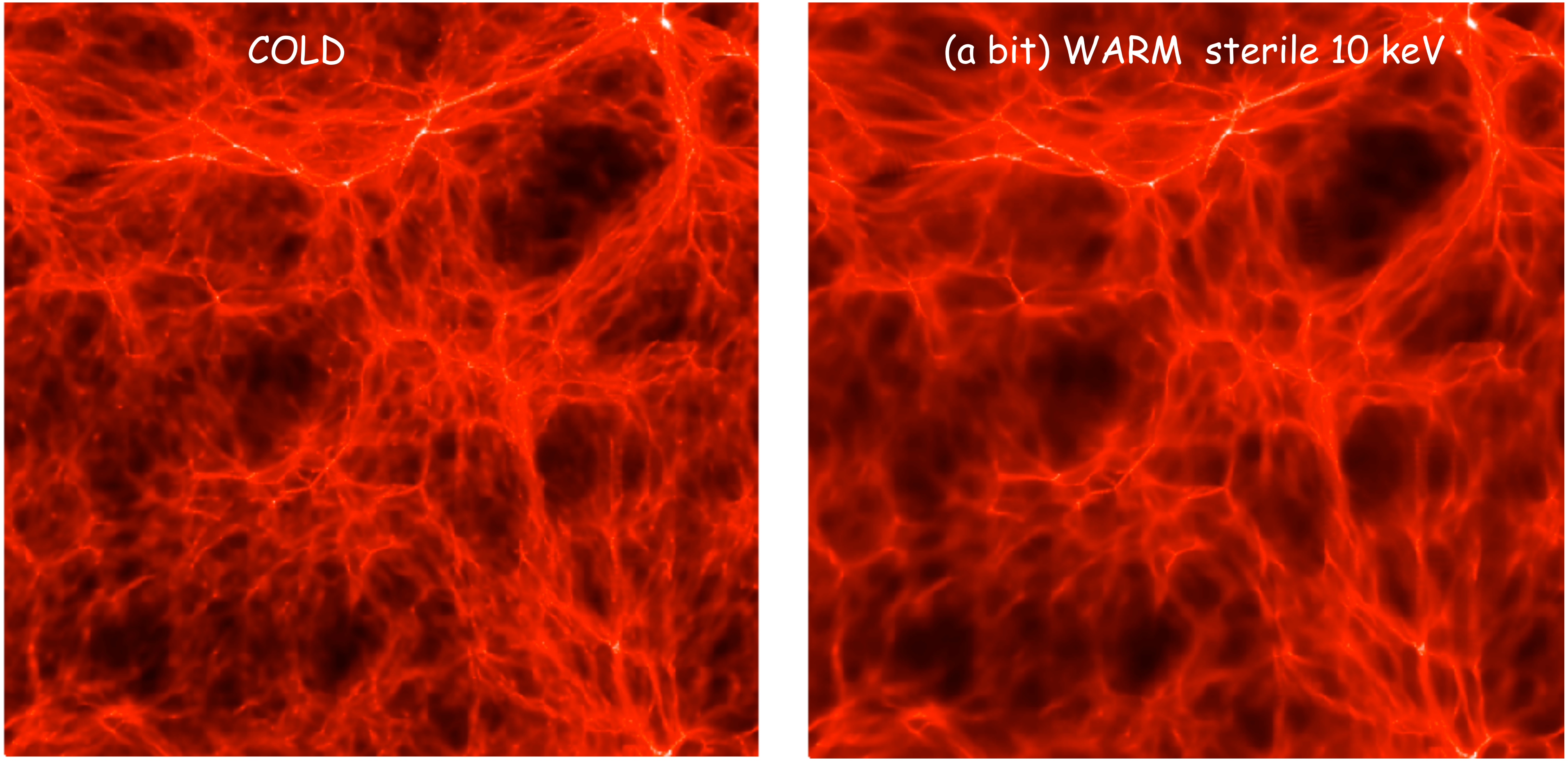
(SDSS still very constraining!)

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)

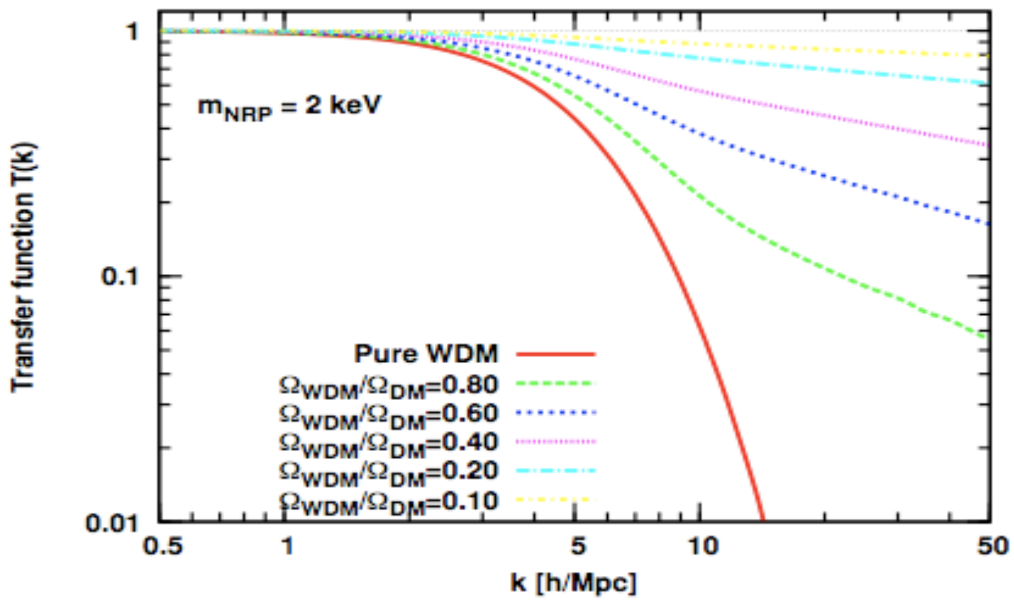
Little room for standard warm dark matter scenarios……
… the cosmic web is likely to be quite "cold"



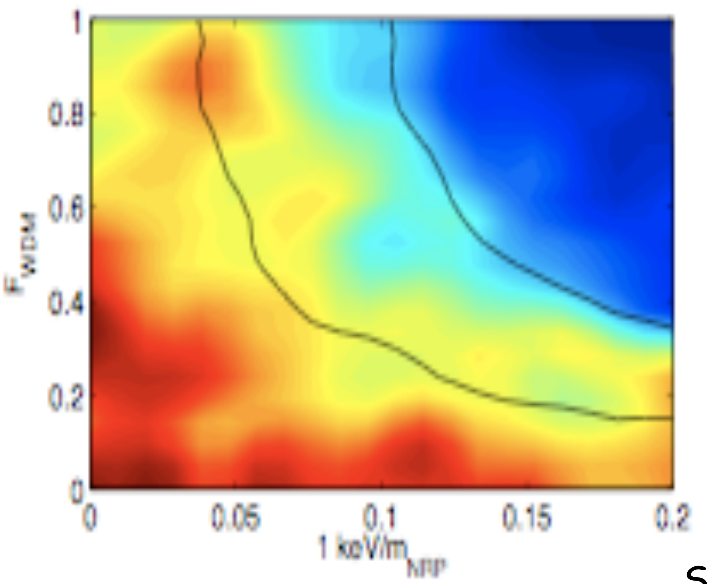
RESULTS
NEW WARM DARK MATTER MODEL
(sterile neutrino)

REVIEW Boyarsky, Lesgourgues, Ruchayskiy, Viel, 2008, arxiv: 0812.0010
Boyarsky, Lesgourgues, Ruchayskiy, Viel, 2008, arxiv: 0812.3256

Lyman-α and Cold+Warm Dark Matter - I



SDSS+WMAP5



Pure ΛWDM: m > 9.5 keV (frequentist)
m > 12 keV (Bayesian)

CWDM: F < 0.40 any mass (frequentist)
F < 0.35 any mass (Bayesian)

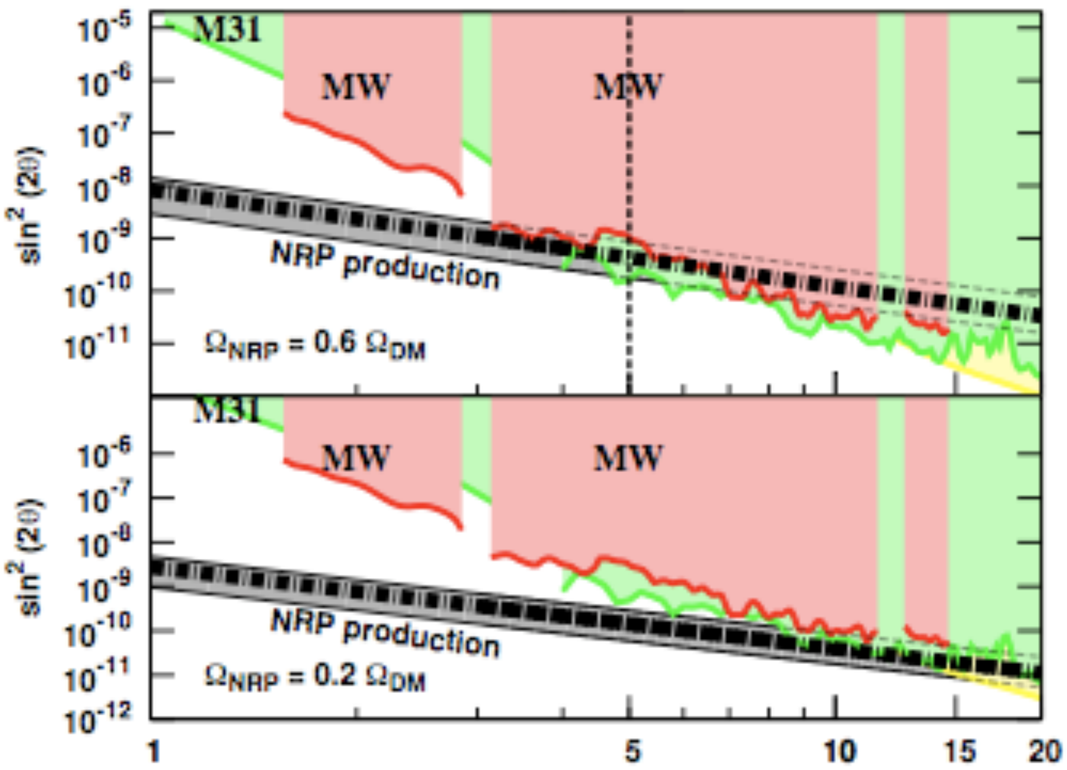
See also Palazzo, Cumberbatch, Slosar, Silk et al. (2007)

Lyman-α and Cold+Warm Dark Matter - II

$$F_{DM} = \frac{M_{DM}^{fov}\Gamma}{4\pi D_L^2}\frac{E_\gamma}{M_1} \simeq 6.38 \left(\frac{M_{DM}^{fov}}{10^{10}M_\odot}\right)\left(\frac{\mathrm{Mpc}}{D_L}\right)^2 \times \sin^2(2\theta_1)\left[\frac{M_1}{\mathrm{keV}}\right]^5 \frac{\mathrm{keV}}{\mathrm{cm}^2\cdot \mathrm{sec}}$$

60% of WDM

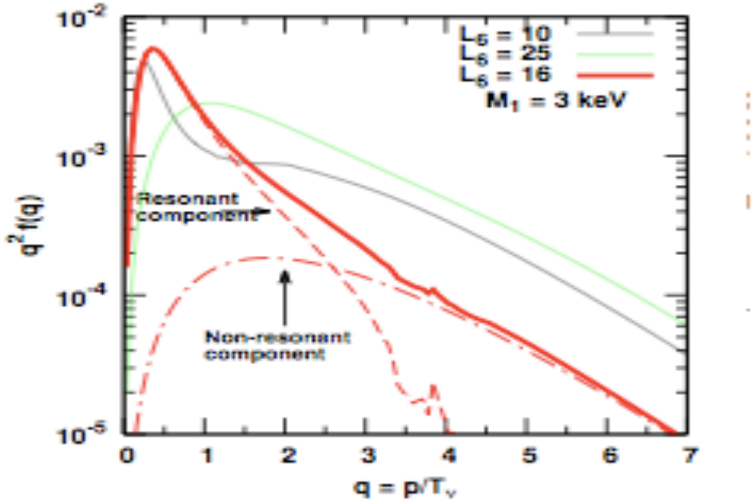
20% of WDM

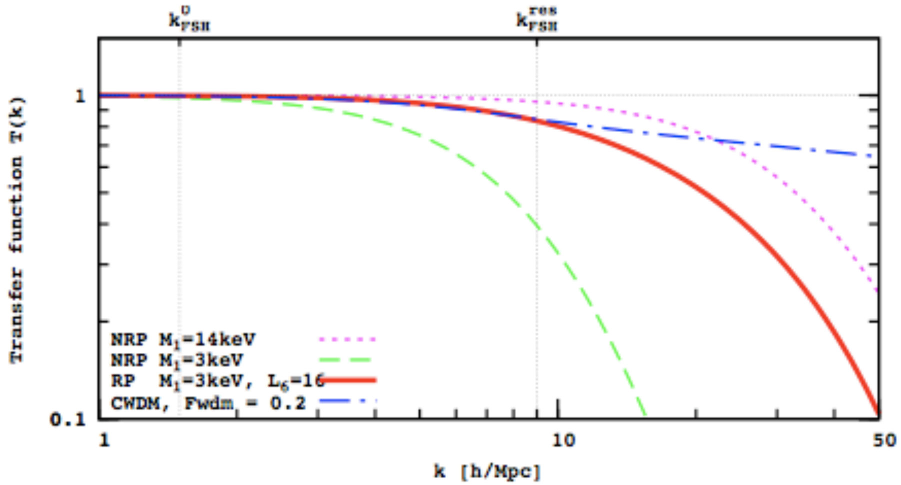


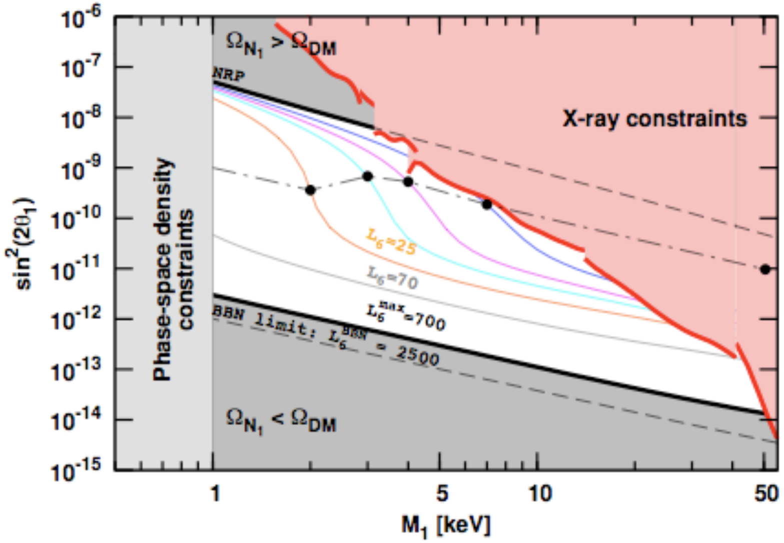
Note that for F>0.6 Ly-α bounds are in conflict with X-ray observations at 3 σ !

Lyman-α and resonantly produced sterile neutrinos - I

Shi & Fuller (1999), Asaka, Kusenko, Laine, Shaposhnikov etc.







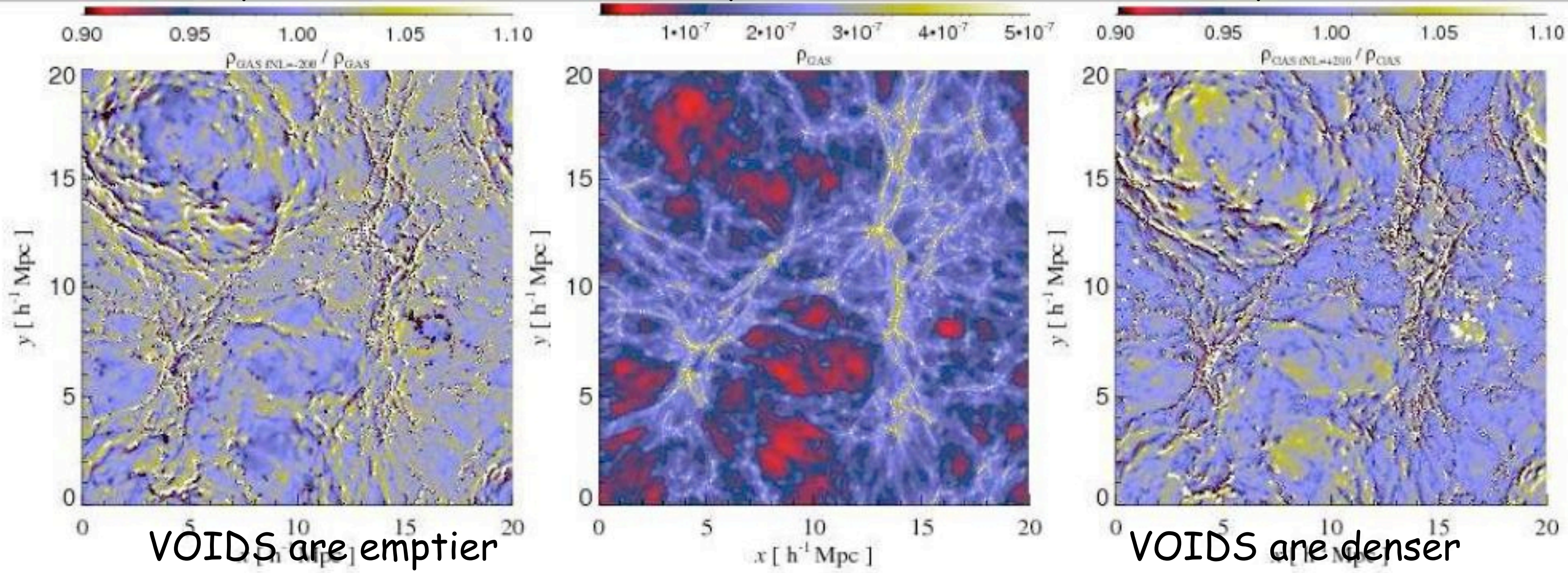
In this scenario
also the 28 keV DW sterile
neutrino can be accomodated

For m $_{RP}$ > 2 keV there is a least one value of Lepton asymmetry for which sterile are the dark matter and satisfy any astrophysical constraints

PRIMORDIAL Non Gaussianities in the IGM

First hydrodynamical simulation in NG scenario

f nl = - 200 | f nl = 0 | f nl = + 200



VOIDS are emptier

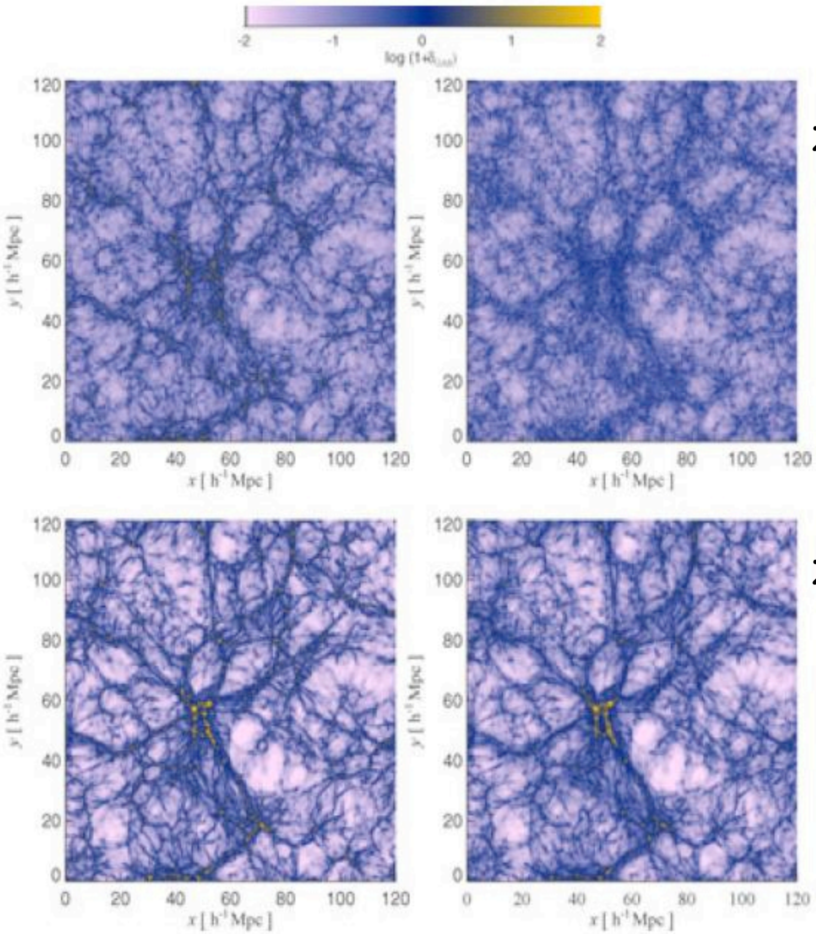
VOIDS are denser

MV, Branchini, Dolag, Grossi, Matarrese, Moscardini 2009, MNRAS

SINERGIES of IGM with other astrophysical and cosmological probes

In the standard ΛCDM scenario ….

Astrophysics: Low-redshift evolution



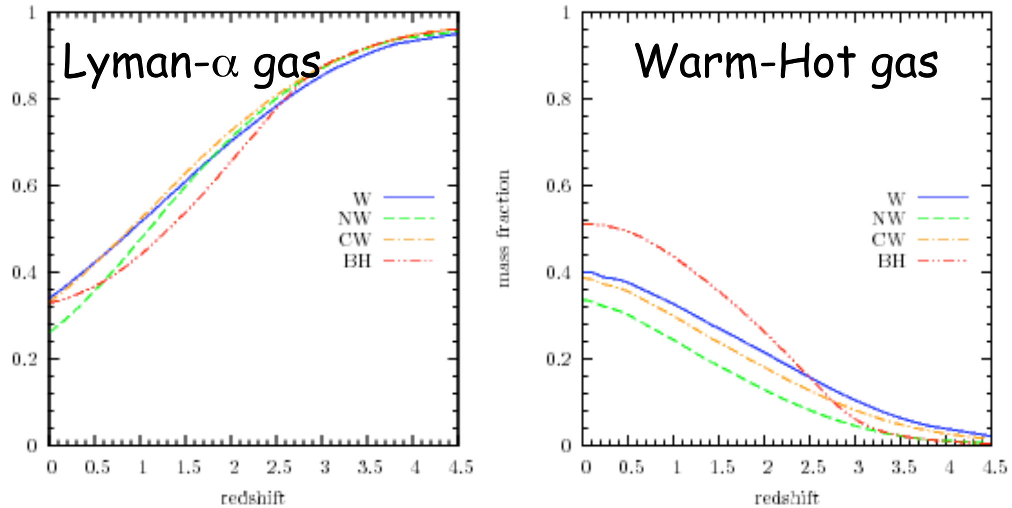
z = 3

Density dependent heating mechanism
DM annihilation-like

z = 0

Borgani & MV, 2008

Tornatore, Borgani, MV, in prep



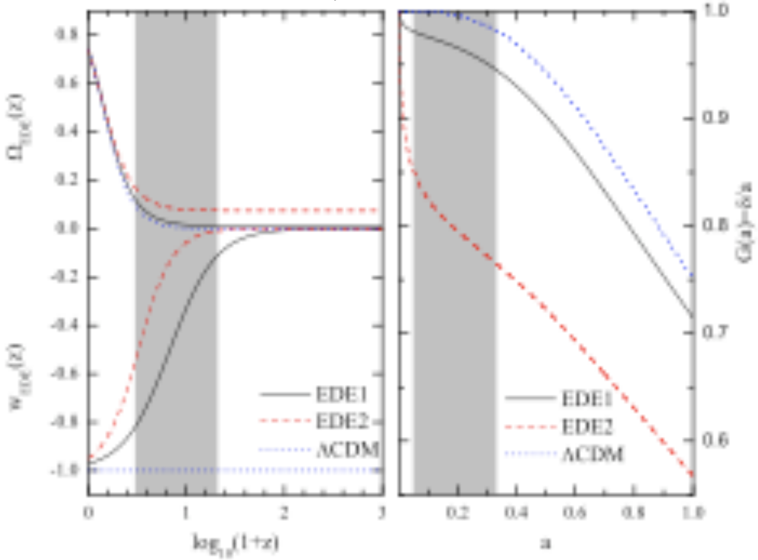
Different feedback recipes: AGN, winds

Cosmology: high redshift probes

Improvement by a factor 20 on Ω_{DE} (lss) when Using Lya and GRBs

Ω_{DE} (z)

w(z)



Parameter	WMAP5+BAO+SN		+GRB+Lyα		+GRB+GFLyα	
	Mean	BestFit	Mean	BestFit	Mean	BestFit
w_0	< -0.906	-0.972	< -0.952	-0.999	< -0.958	-0.997
C	< 2.711	1.858	< 2.613	1.628	< 2.245	0.152
Ω_m	0.261 ± 0.014	0.258	0.283 ± 0.014	0.279	0.275 ± 0.014	0.274
σ_8	0.748 ± 0.049	0.734	0.842 ± 0.022	0.863	0.836 ± 0.024	0.846
$\Omega_{EDE}(z_{lss})$	< 0.0228	0.0064	< 0.0029	1.77×10^{-6}	< 0.0014	1.71×10^{-9}
$\Omega_{EDE,sf}$	0.0643 ± 0.0076	0.0672	0.0540 ± 0.0029	0.0529	0.0546 ± 0.0024	0.0543
γ	–	–	0.622 ± 0.139	0.552	–	–

Xia & MV **arXiv:0901.0605**

SUMMARY

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

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

- Need to fit all the IGM statistics at once (mean flux + flux pdf + flux power + flux bispectrum + …).

-Tension with the CMB is partly lifted (σ_8 went a bit up). Still very constraining for what happens at those scales: running (inflation), neutrinos, warm dark matter candidates …

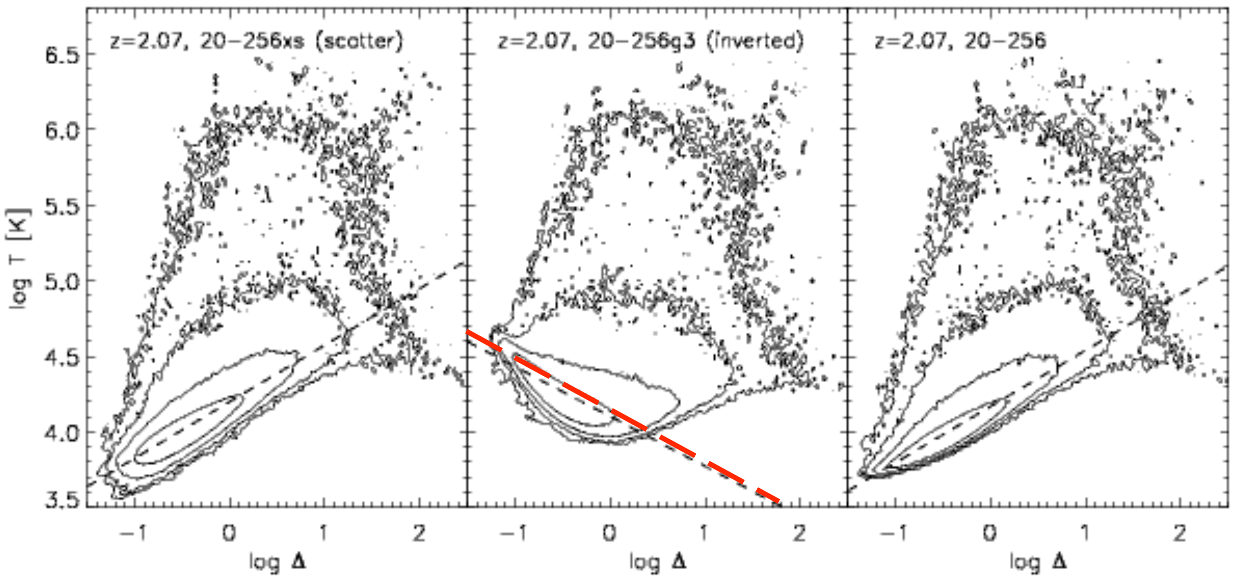
- IMPORTANCE of SINERGIES with cosmology and astrophysics

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



Flux probability distribution function