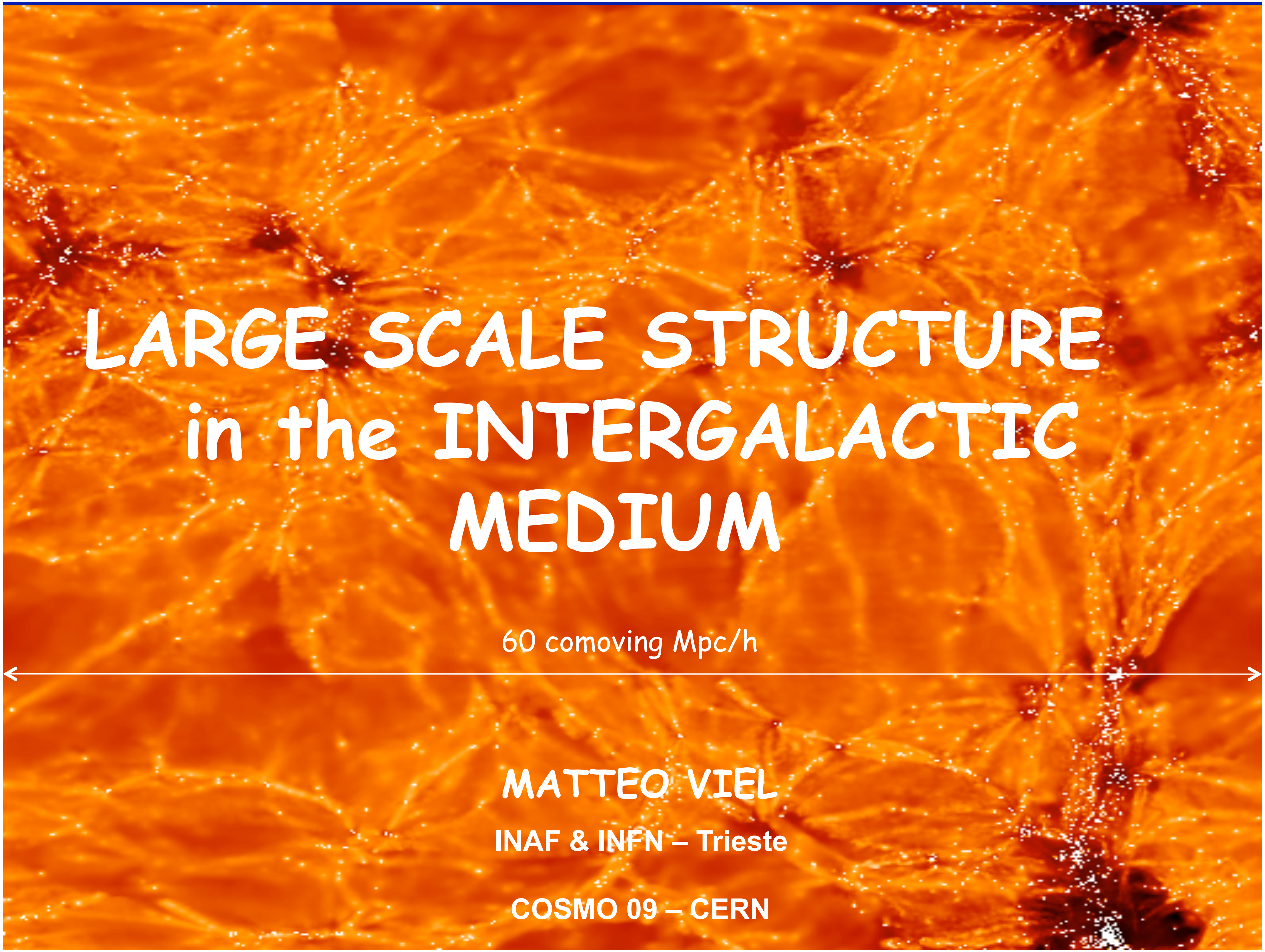


LARGE SCALE STRUCTURE in the INTERGALACTIC MEDIUM

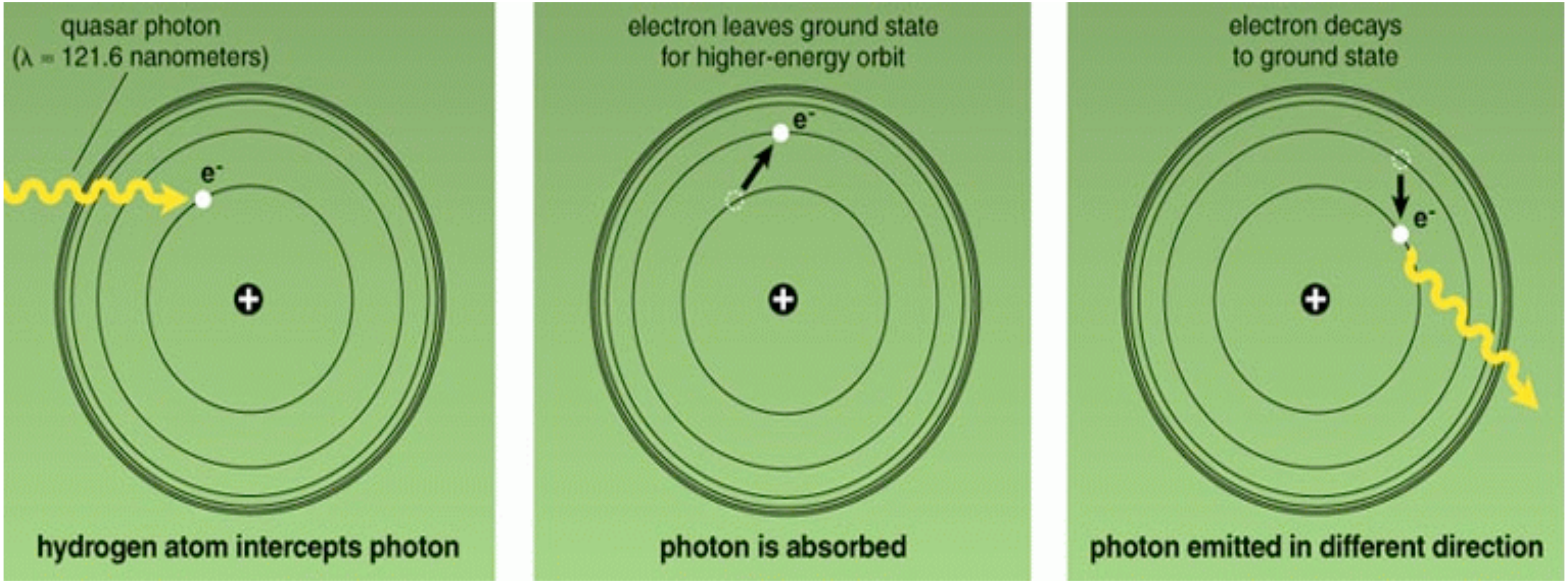
MATTEO VIEL

INAF & INFN – Trieste

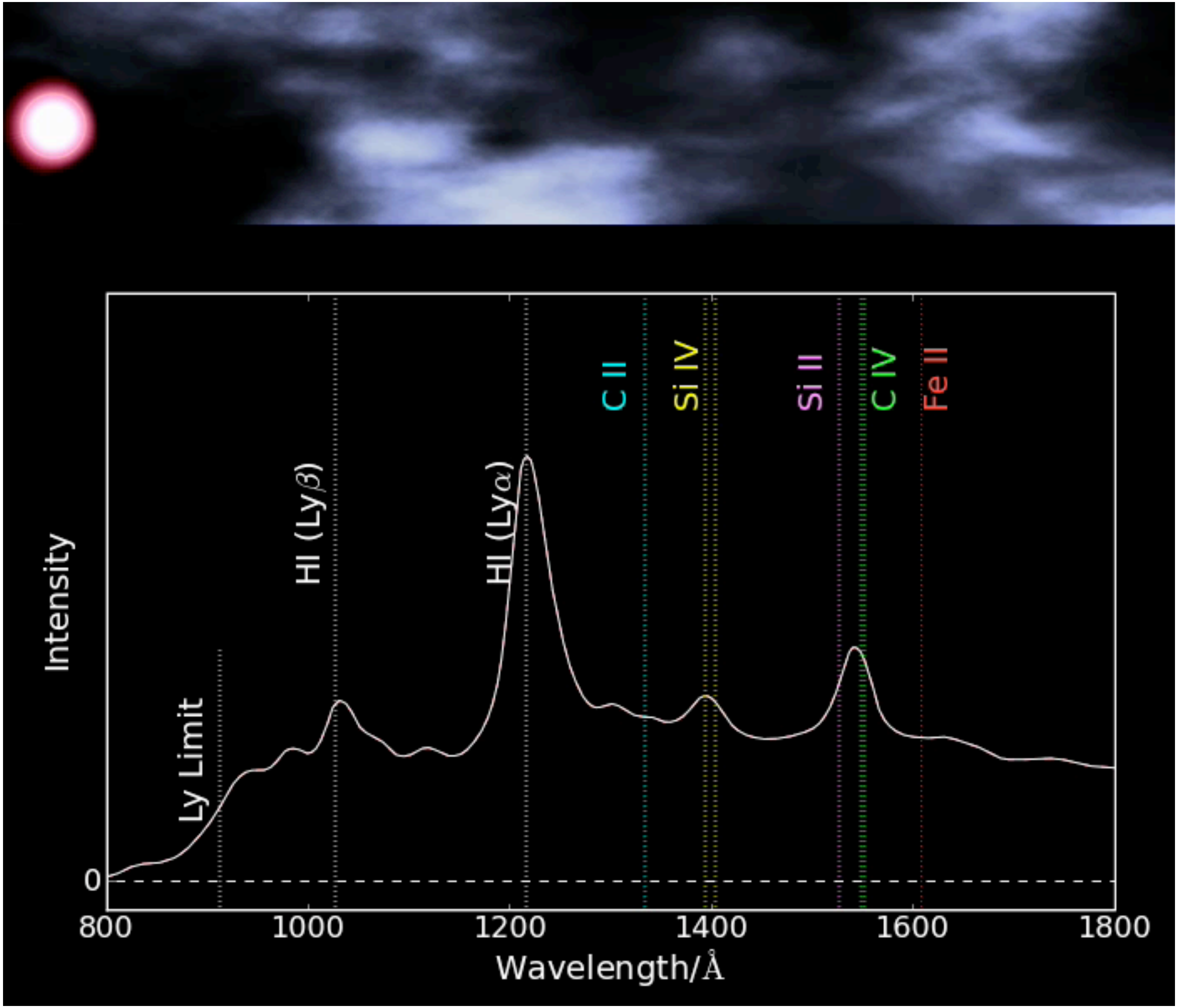
COSMO 09 – CERN

INTRO

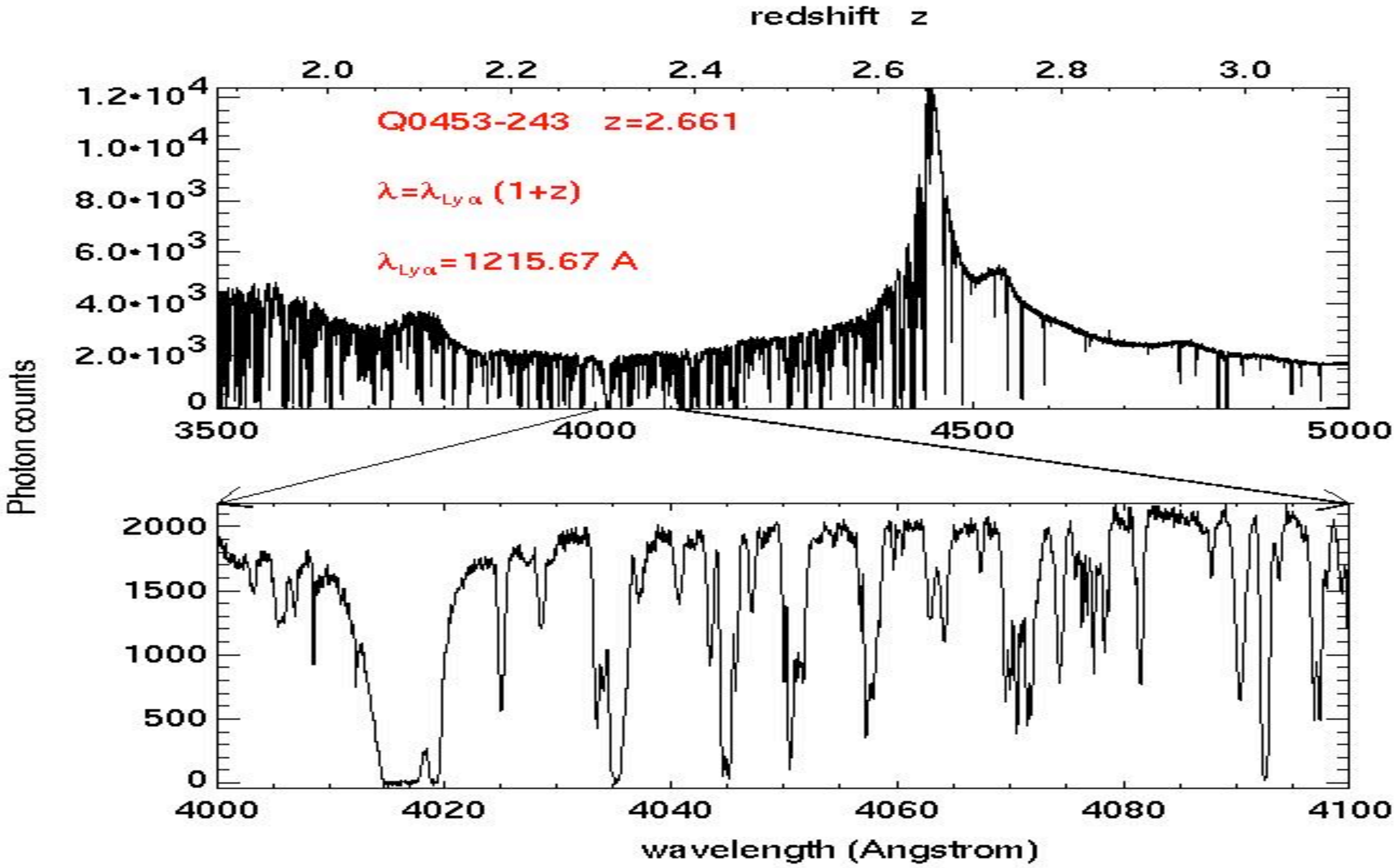
Lyman-α absorption is the main manifestation of the IGM



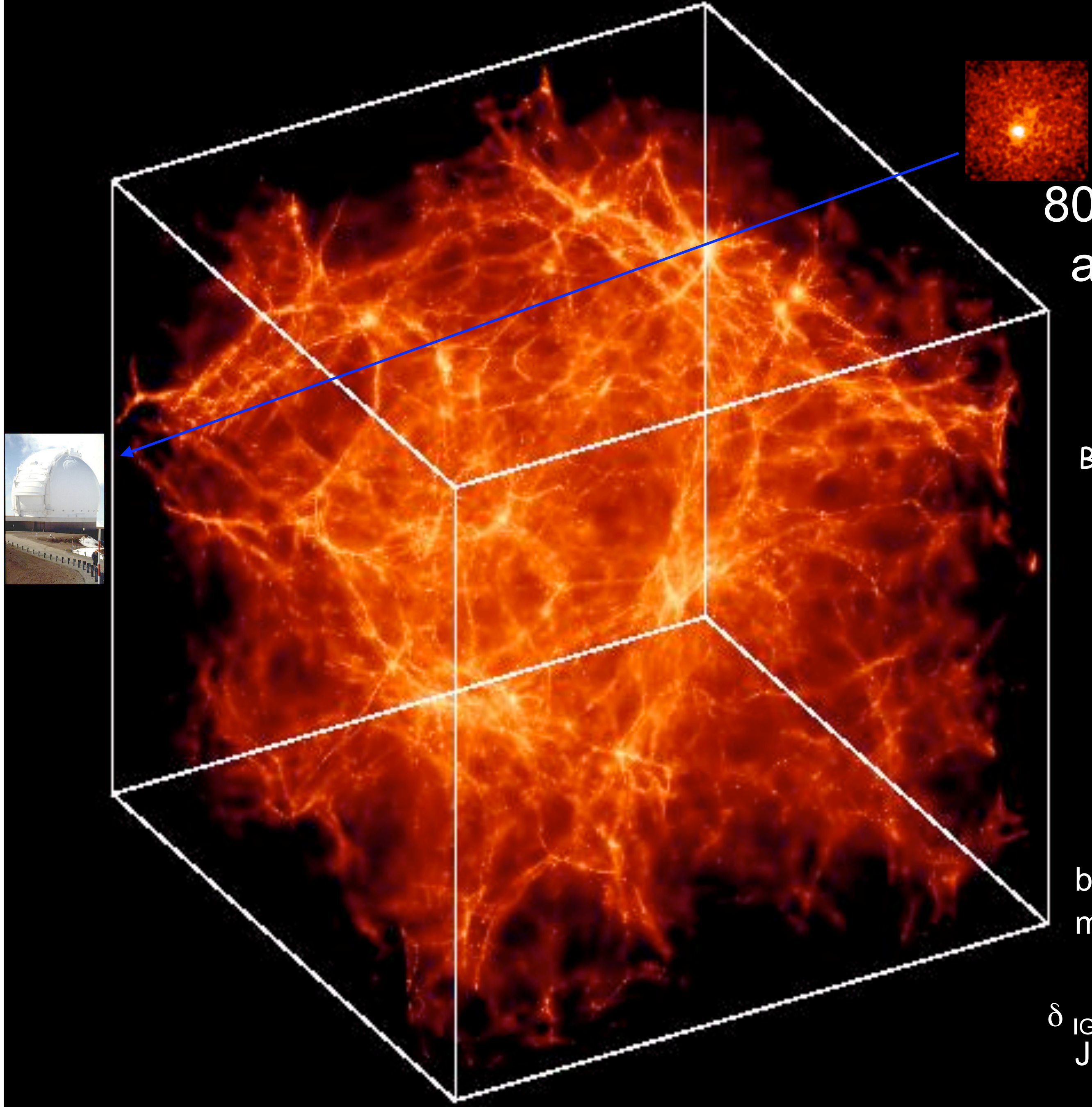
Tiny neutral hydrogen fraction after reionization…. But large cross-section


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

DATA: high resolution spectrum



THEORY: GAS in a ΛCDM universe



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

Bi & Davidsen (1997), Rauch (1998)

baryons as tracer of the dark matter density field

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

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

BRIEF HISTORICAL OVERVIEW
of the Lyman-α forest

'ISOLATED' CLOUDS

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

PROBES OF THE JEANS SCALE

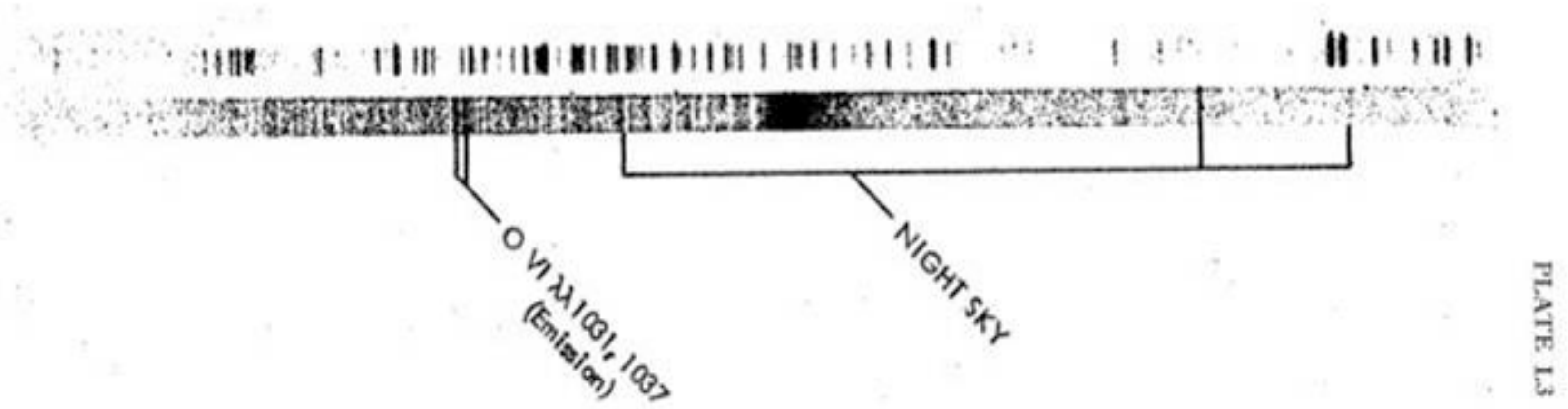


FIG. 1.—A spectrogram illustrating the numerous absorption lines in 4C 05.34. The strong emission line in the center is Lα. The O VI emission lines and several airglow features are also indicated. The comparison spectrum is He + Ar + Ne.

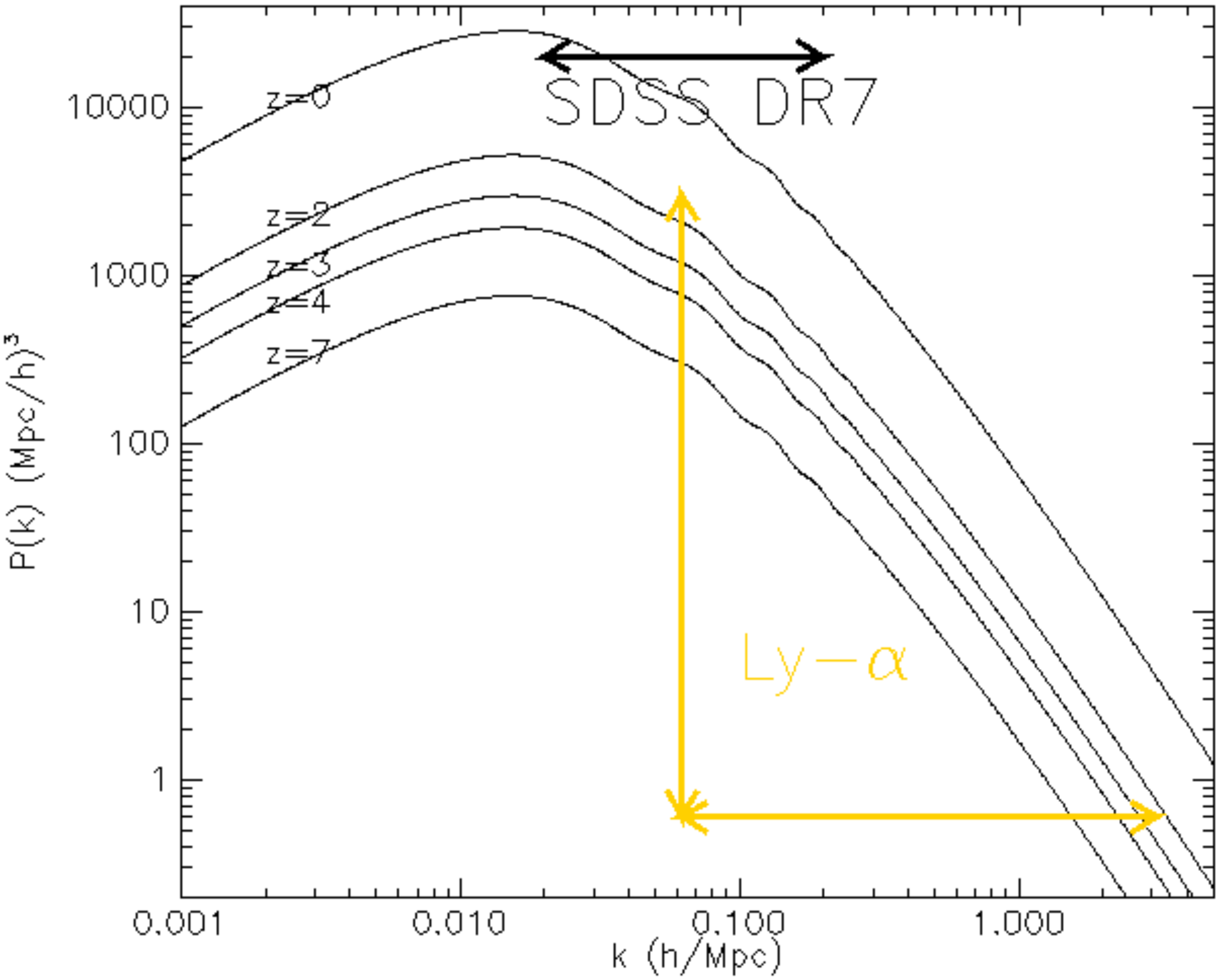
LYNDS (see page L73)

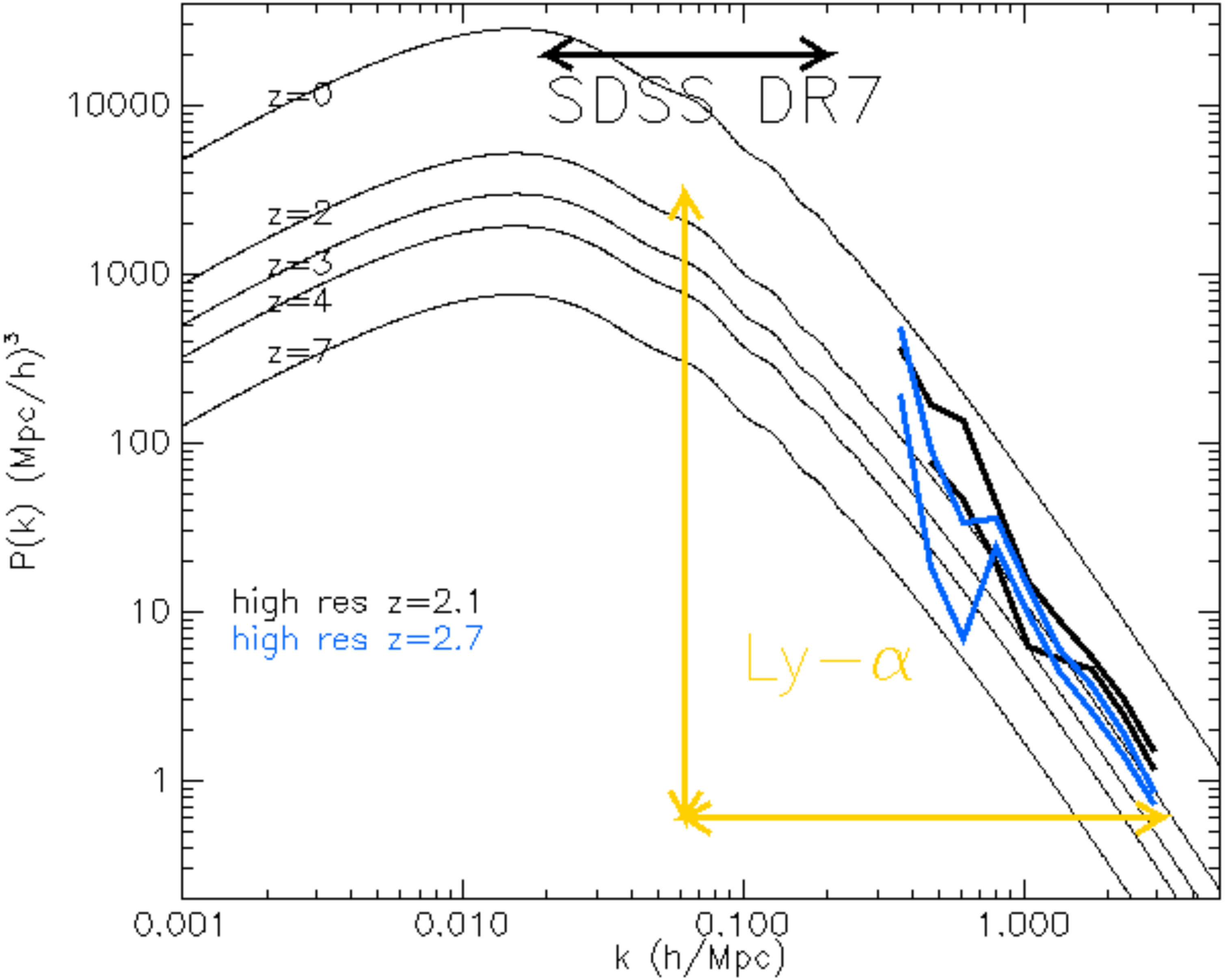
discrete clouds, reproduced most of the observations;

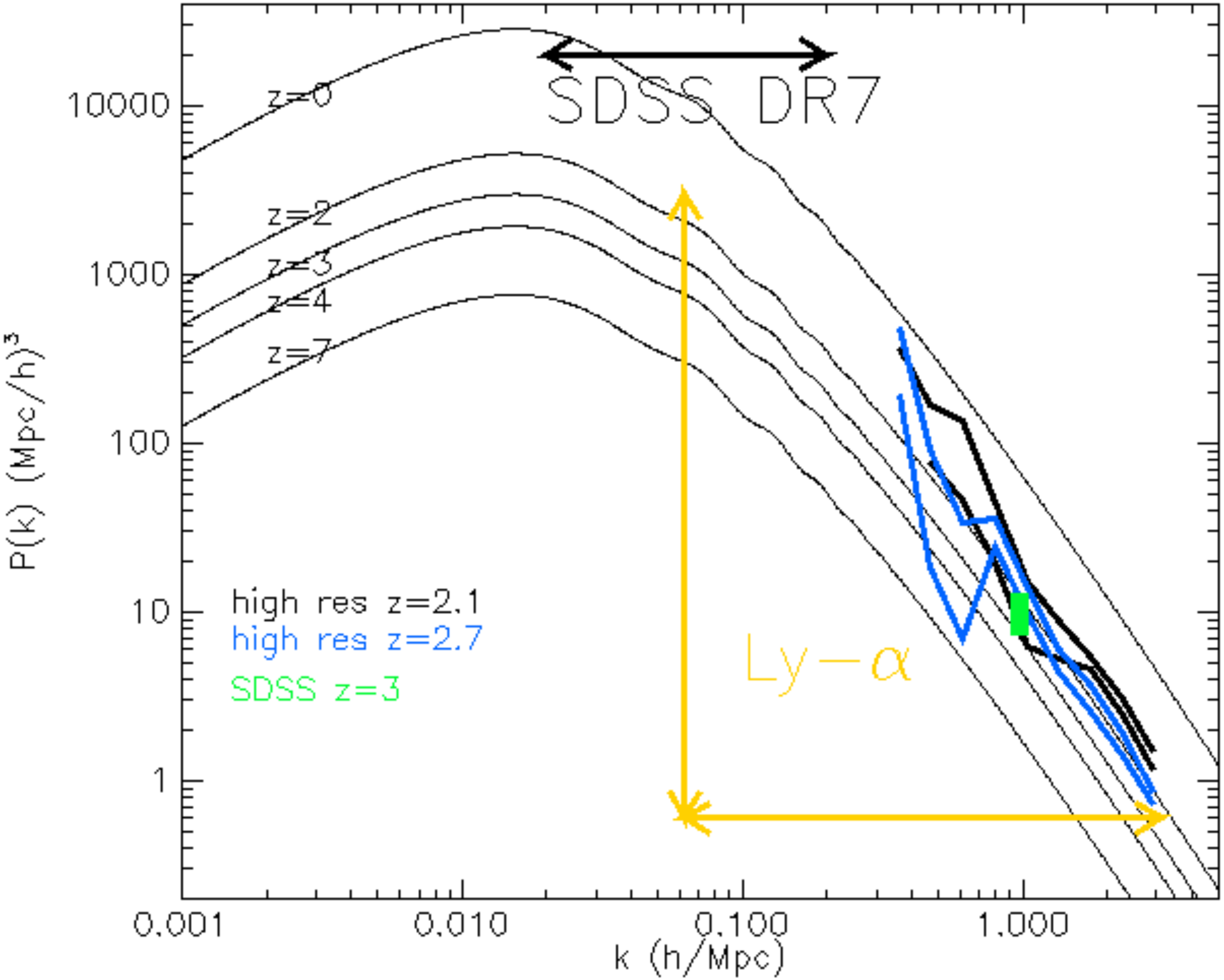
NETWORK OF FILAMENTS

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

COSMOLOGICAL PROBES


SDSS DR7
Ly−α
z=0
z=2
z=3
z=4
z=7
10000
1000
100
10
1
0.001
0.010
0.100
1.000
P(k) (Mpc/h)^3
k (h/Mpc)


SDSS DR7
z=0
z=2
z=3
z=4
z=7
high res z=2.1
high res z=2.7
Ly−α
10000
1000
100
10
1
0.001
0.010
0.100
1.000
P(k) (Mpc/h)^3
k (h/Mpc)

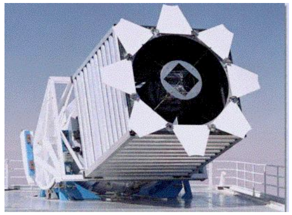

SDSS DR7
z=0
z=2
z=3
z=4
z=7
Ly−α
high res z=2.1
high res z=2.7
SDSS z=3
P(k) (Mpc/h)³
10000
1000
100
10
1
0.001
0.010
0.100
1.000
k (h/Mpc)

Outline

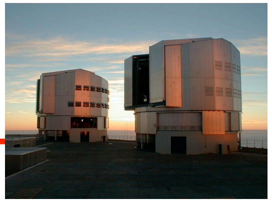
- What data we got	The data sets
- How we used them	Theoretical framework
- What we achieved	Results

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

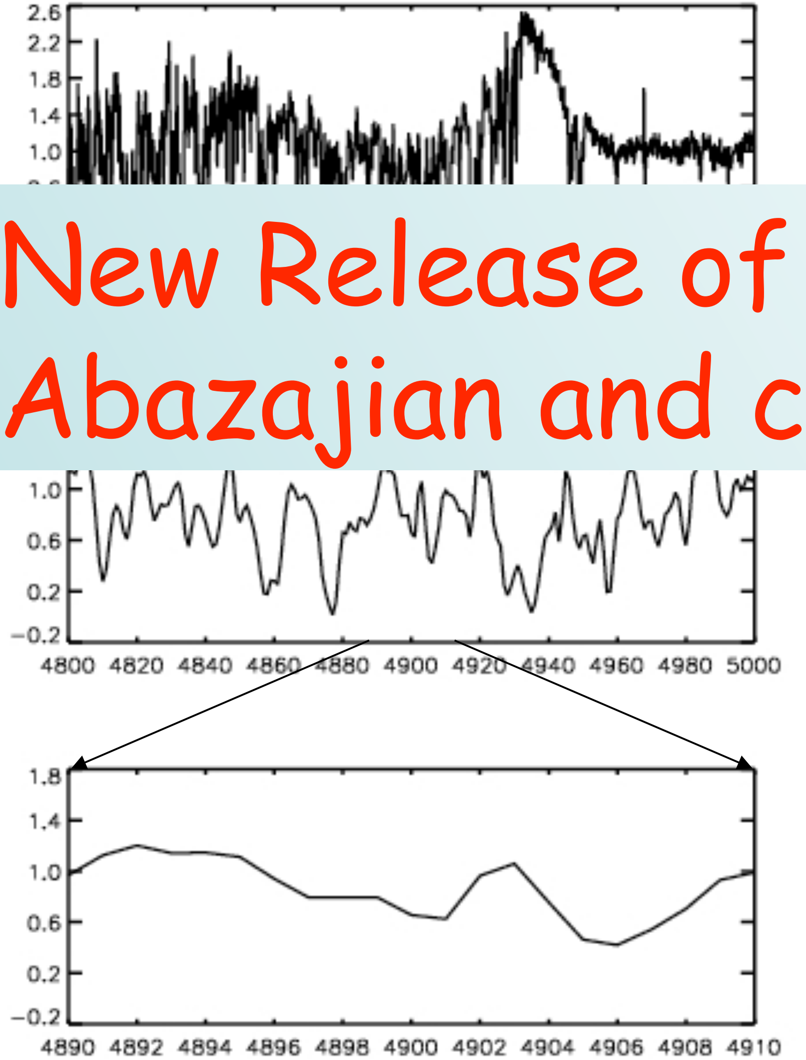
The data sets



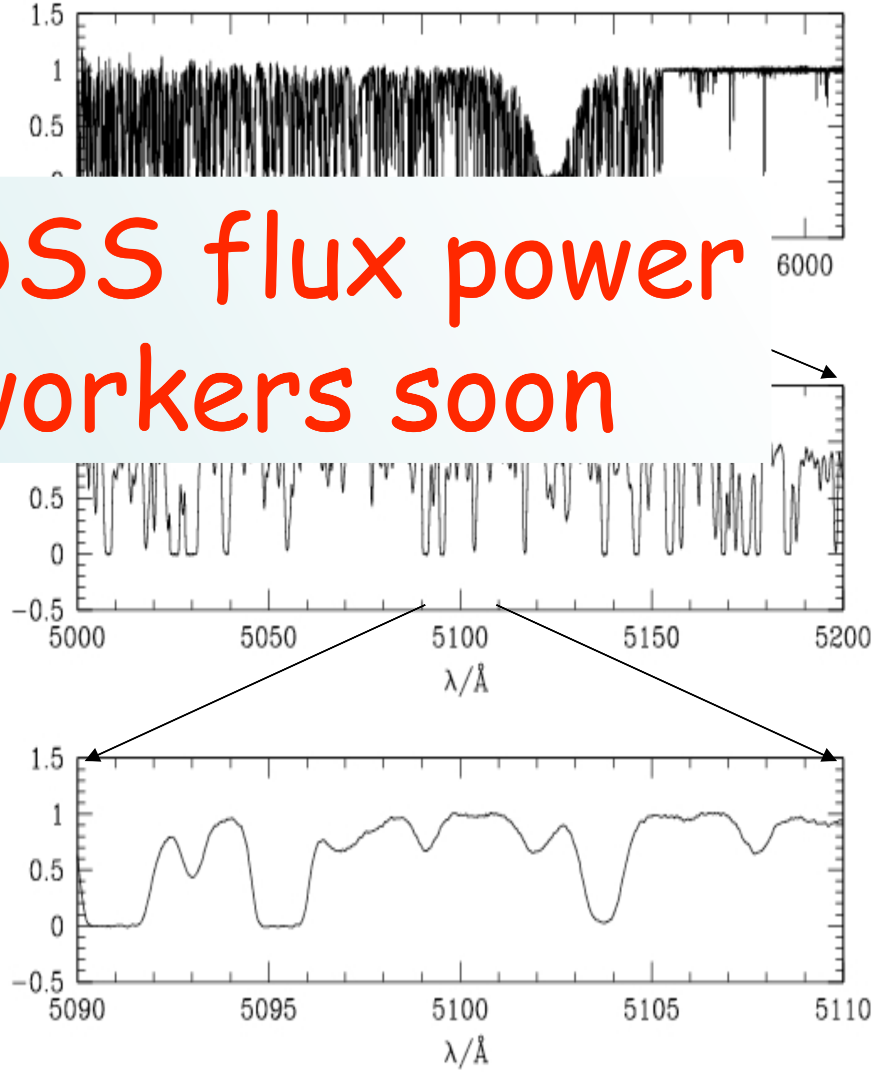
SDSS vs LUQAS



McDonald et al. 2005



Kim, MV et al. 2004



New Release of SDSS flux power
Abazajian and co-workers soon

SDSS
3035 LOW RESOLUTION LOW S/N vs

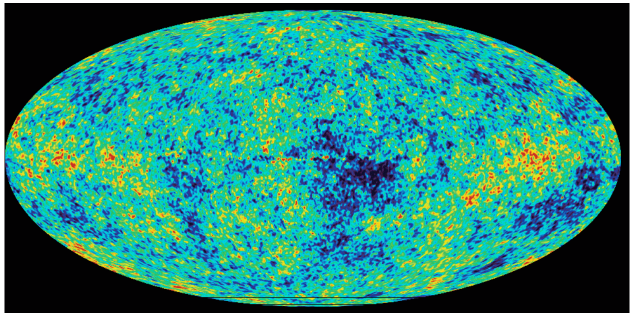
LUQAS
30 HIGH RESOLUTION HIGH S/N

The interpretation: full grid of sims - I

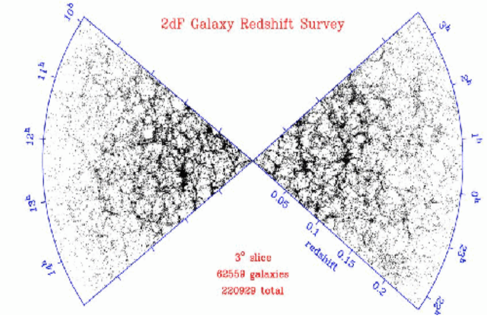
SDSS power analysed by forward modelling motivated by the huge amount of data with small statistical errors

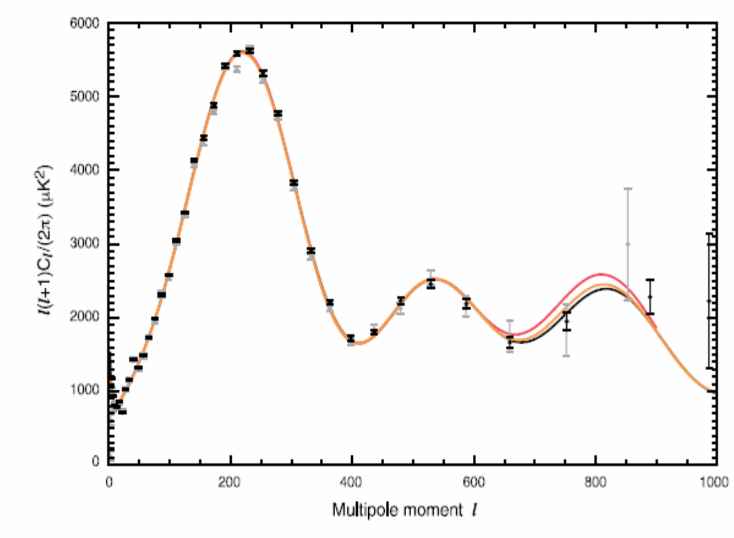
CMB: Spergel et al. (05)

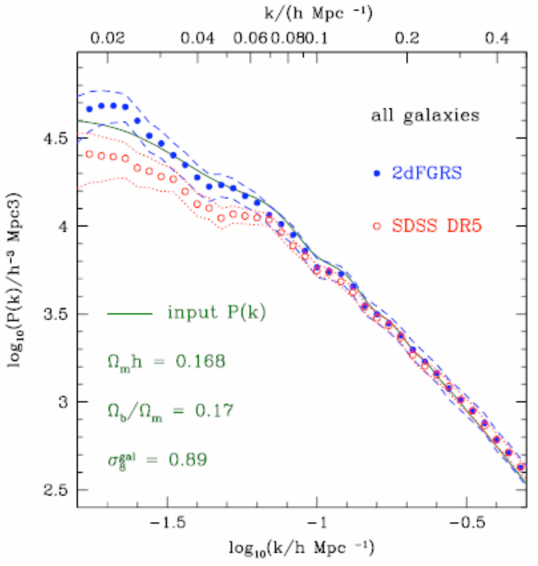
Galaxy P(k): Sanchez & Cole (07)



+







z=4.2

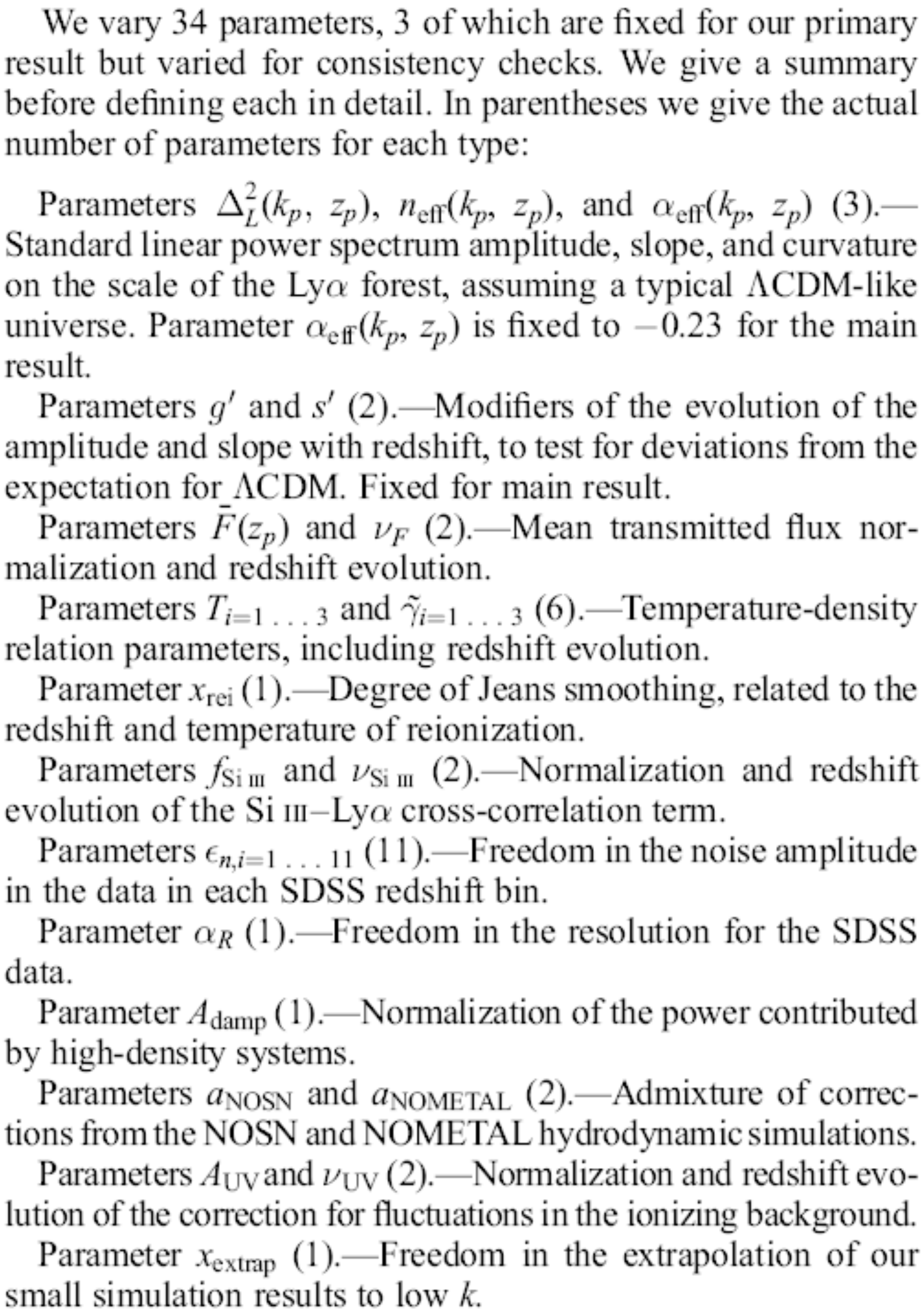
z=2.2

Cosmological parameters + e.g. bias

The interpretation: full grid of sims - II

McDonald et al. 05

Tens of thousands of models
Monte Carlo Markov Chains



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 $T_{i=1\,...\,3}$ and $\tilde{\gamma}_{i=1\,...\,3}$ (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 $\epsilon_{n,i=1\,...\,11}$ (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.

- 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

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

RESULTS

POWER SPECTRUM AND NEUTRINOS

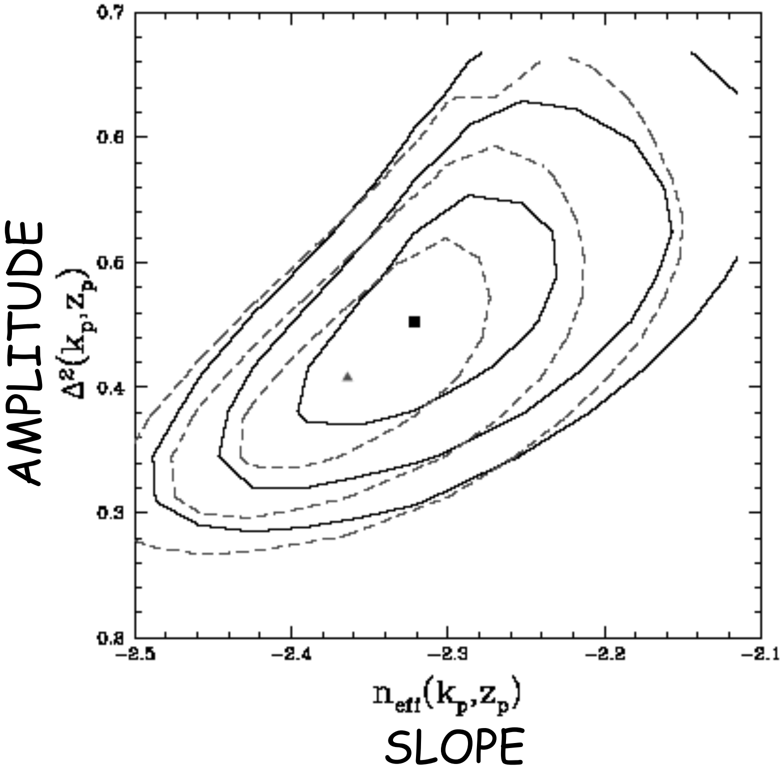
Results Lyman-α only with full grid: amplitude and slope

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

χ^2 likelihood code distributed with COSMOMC

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

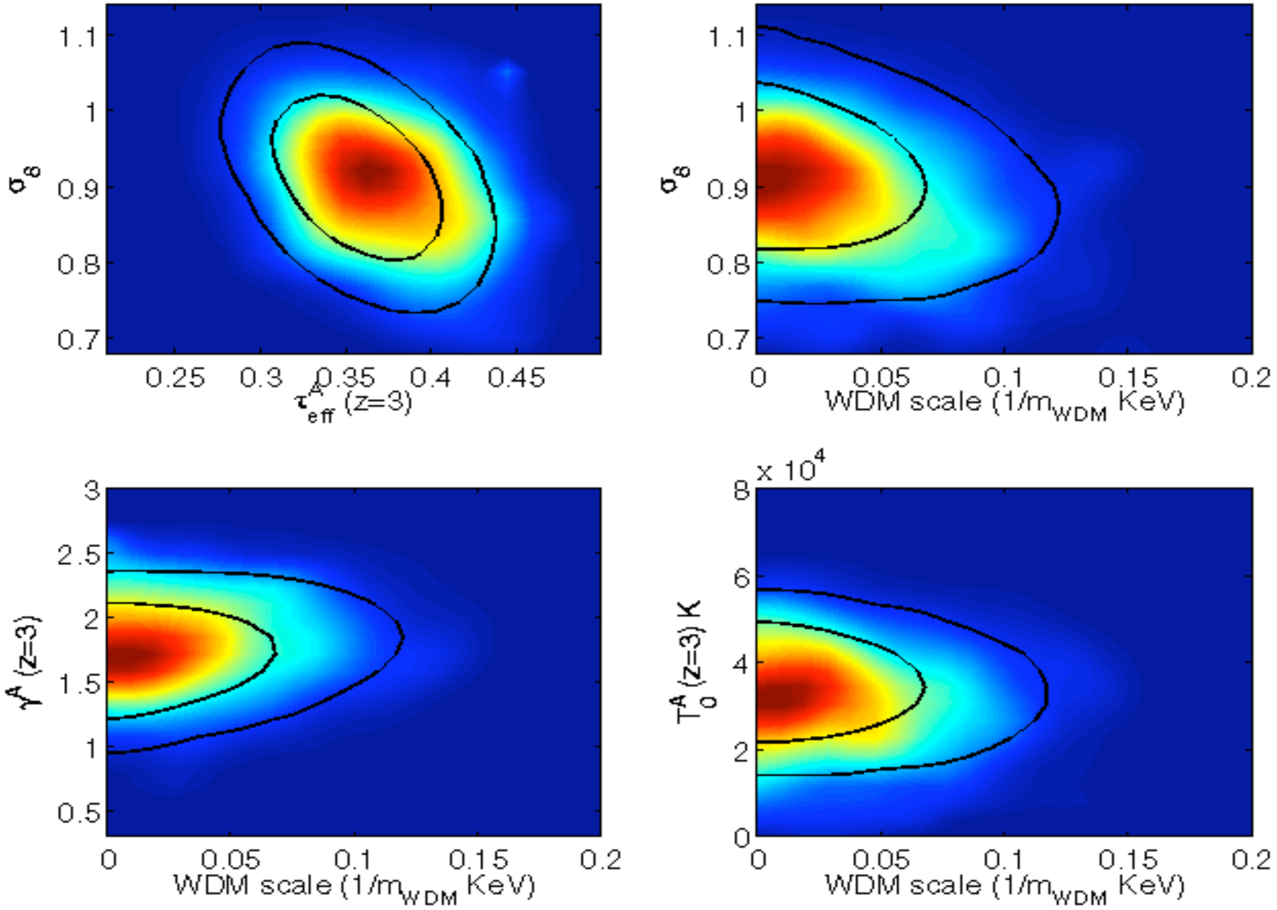
McDonald et al. 05



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

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

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

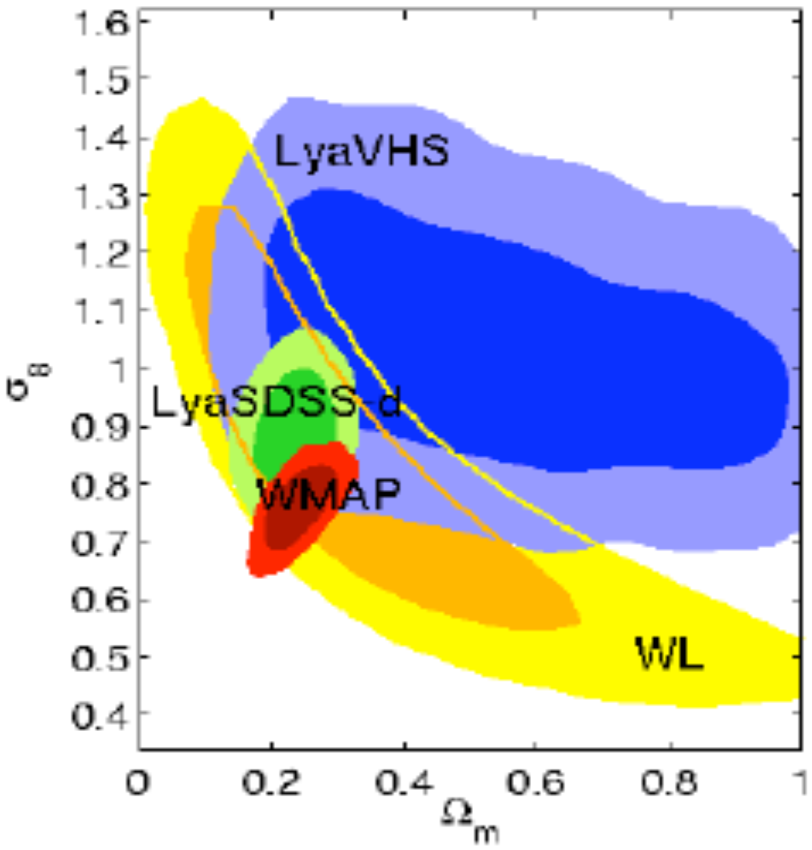
   Seljak, Slosar, McDonald JCAP (2006) 10 014

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

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

Lyman-α forest + Weak Lensing + WMAP 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



AMPLITUDE

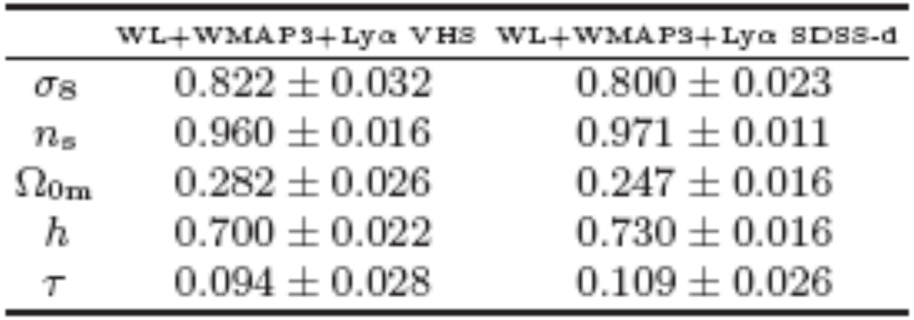
MATTER DENSITY

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



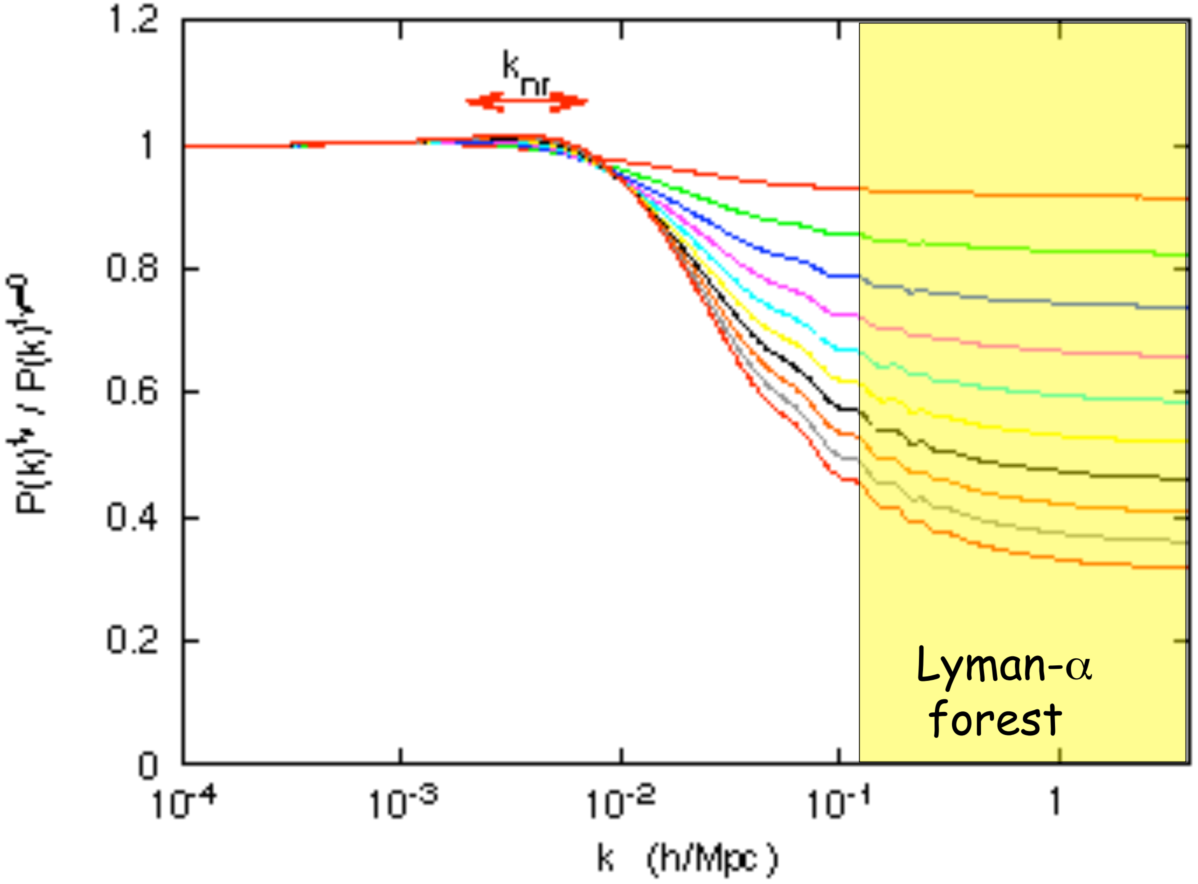
	WL+WMAP3+Lyα VHS	WL+WMAP3+Lyα SDSS-d
σ_8	0.822 ± 0.032	0.800 ± 0.023
n_s	0.960 ± 0.016	0.971 ± 0.011
Ω_{0m}	0.282 ± 0.026	0.247 ± 0.016
h	0.700 ± 0.022	0.730 ± 0.016
τ	0.094 ± 0.028	0.109 ± 0.026

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

Active neutrinos - I

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

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



$\Sigma\, m_\nu$ = 0.138 eV

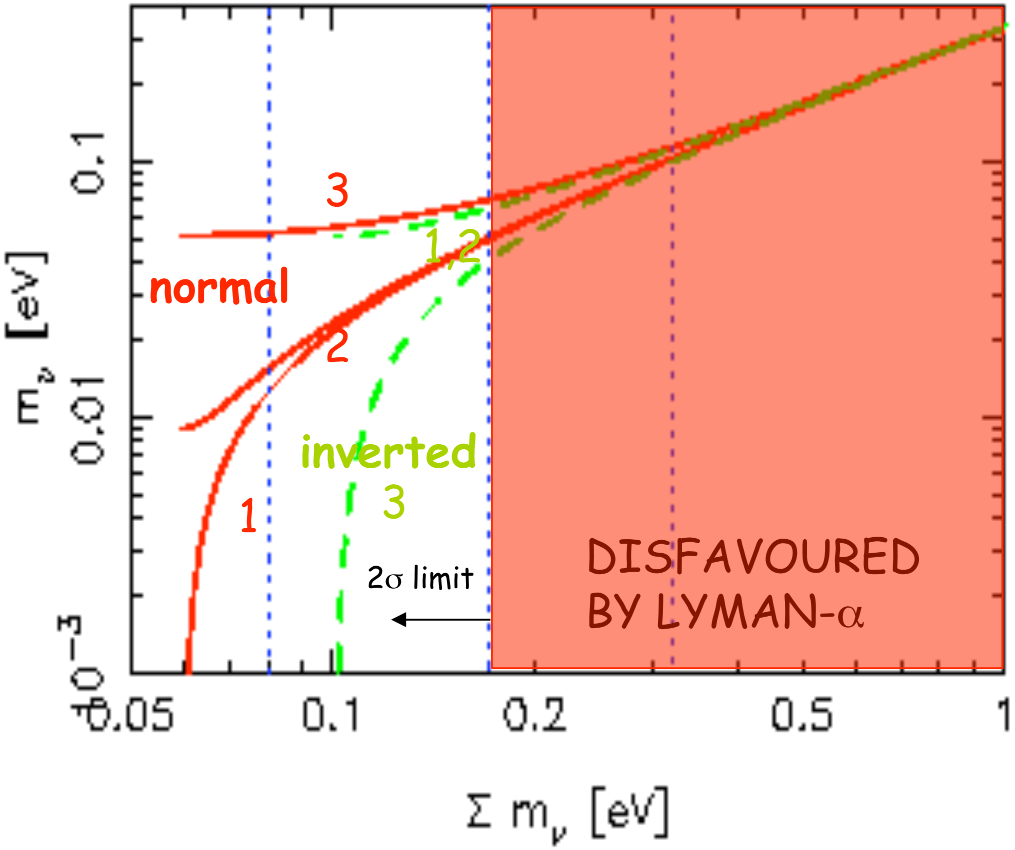
$\Sigma\, m_\nu$ = 1.38 eV

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

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

Active neutrinos - II

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



Tight constraints because data
are marginally compatible

Σmν (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……

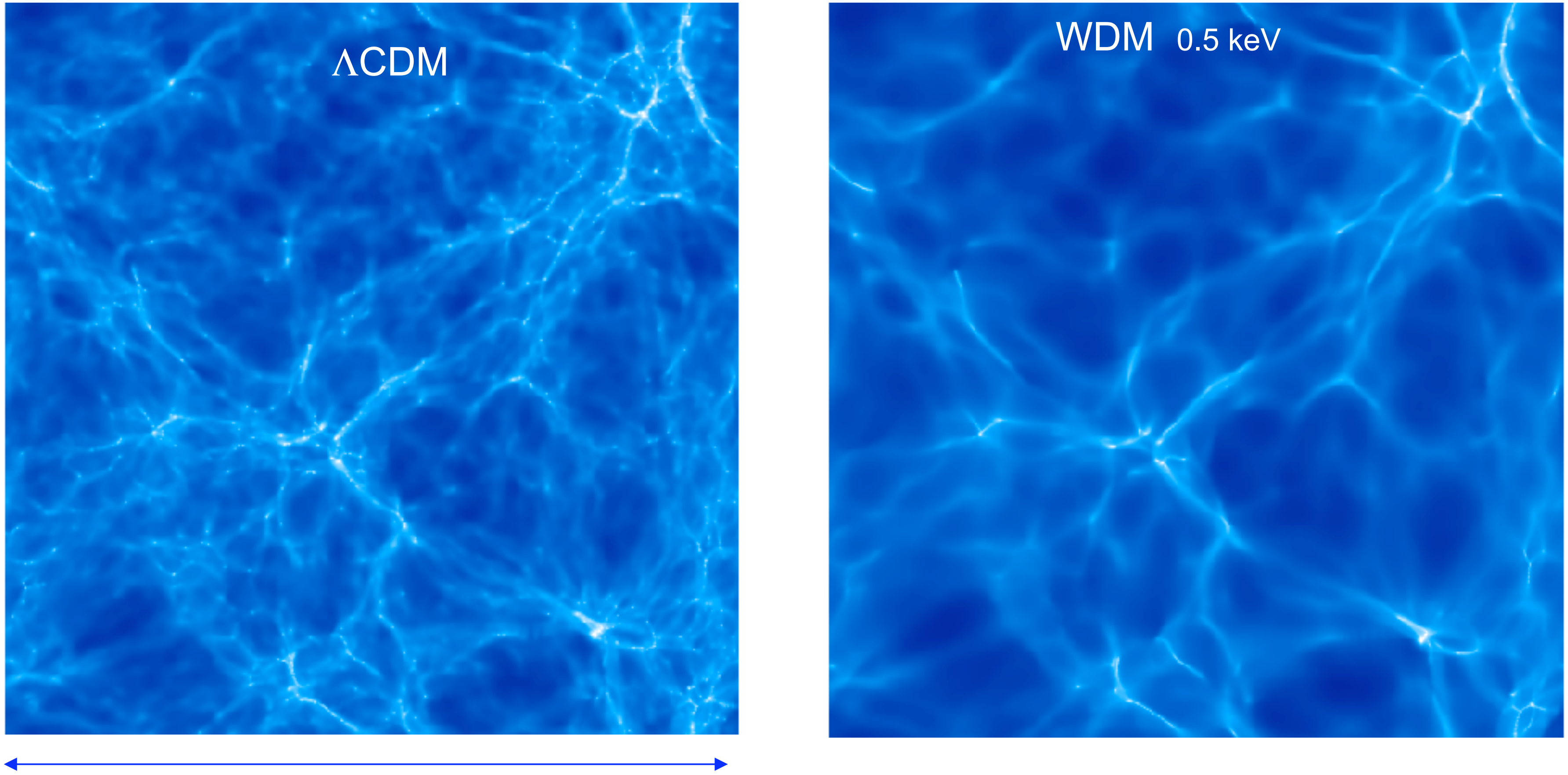
for forecasting see Gratton, Lewis, Efstathiou 2007

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

In general

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

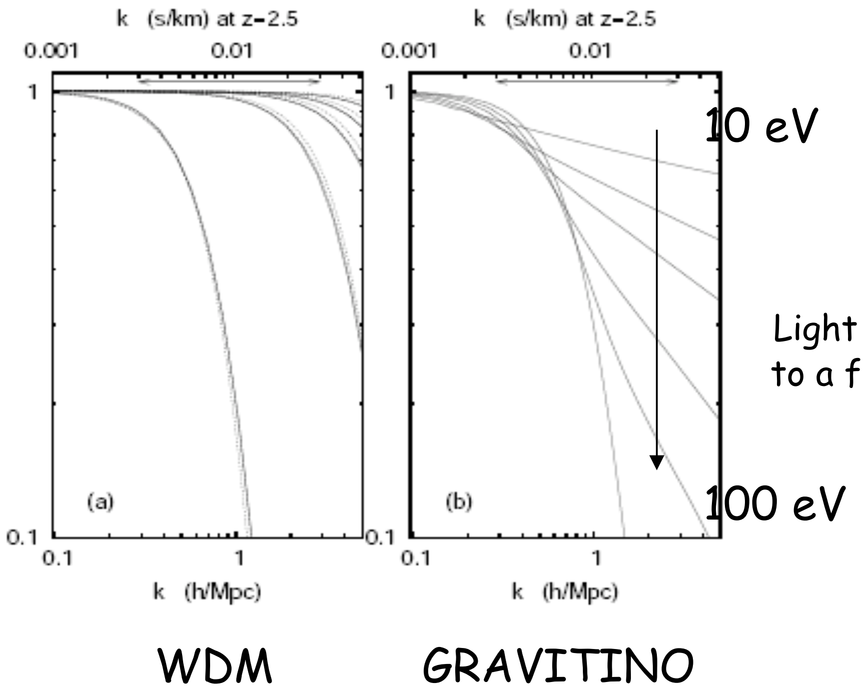
Set by relativistic degrees of freedom at decoupling

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

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

Lyman-α and Warm Dark Matter - II

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



Light gravitino contributing
to a fraction of dark matter

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

$m_{gravitino} < 16$ eV ($2\,\sigma$ C.L.)
(or any particle with
$g(T_D)$~90-100)
From high res. Lyman-a data

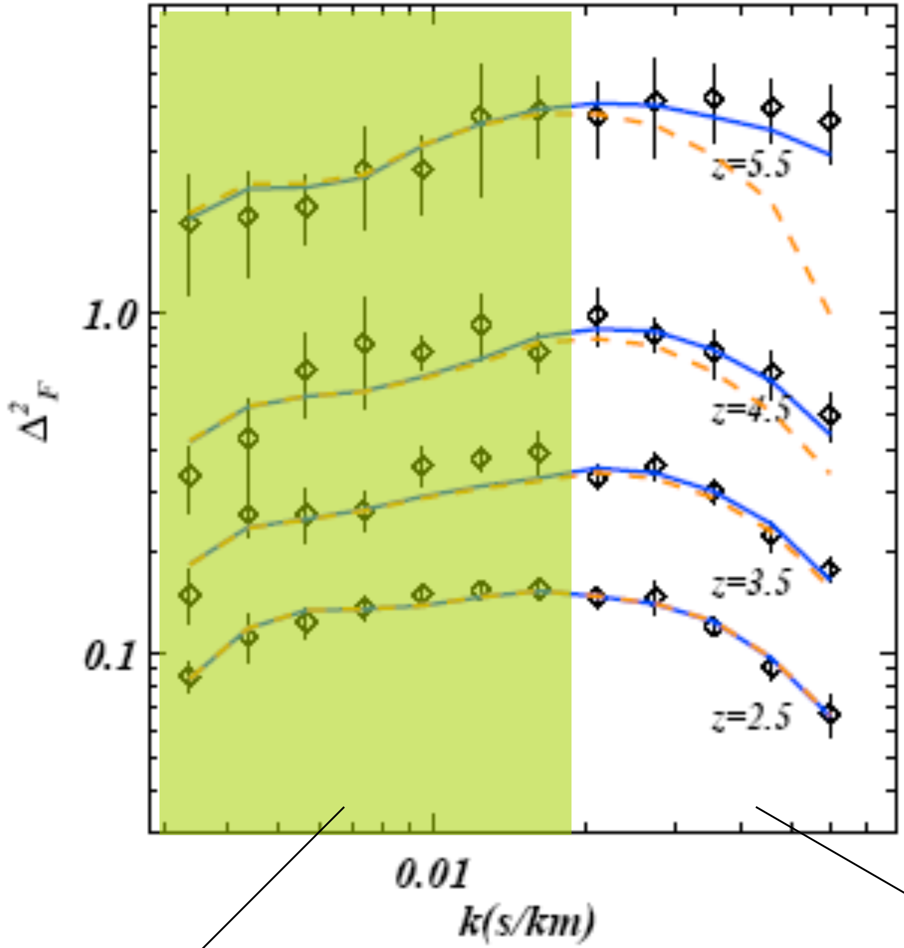
If the gravitino is the LSP then the susy breaking scale is limited from above

$\Lambda_{susy} < 260$ TeV

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

Lyman-α and Warm Dark Matter - III

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



SDSS + HIRES data

(SDSS still very constraining!)

Tightest constraints on mass of WDM particles to date:

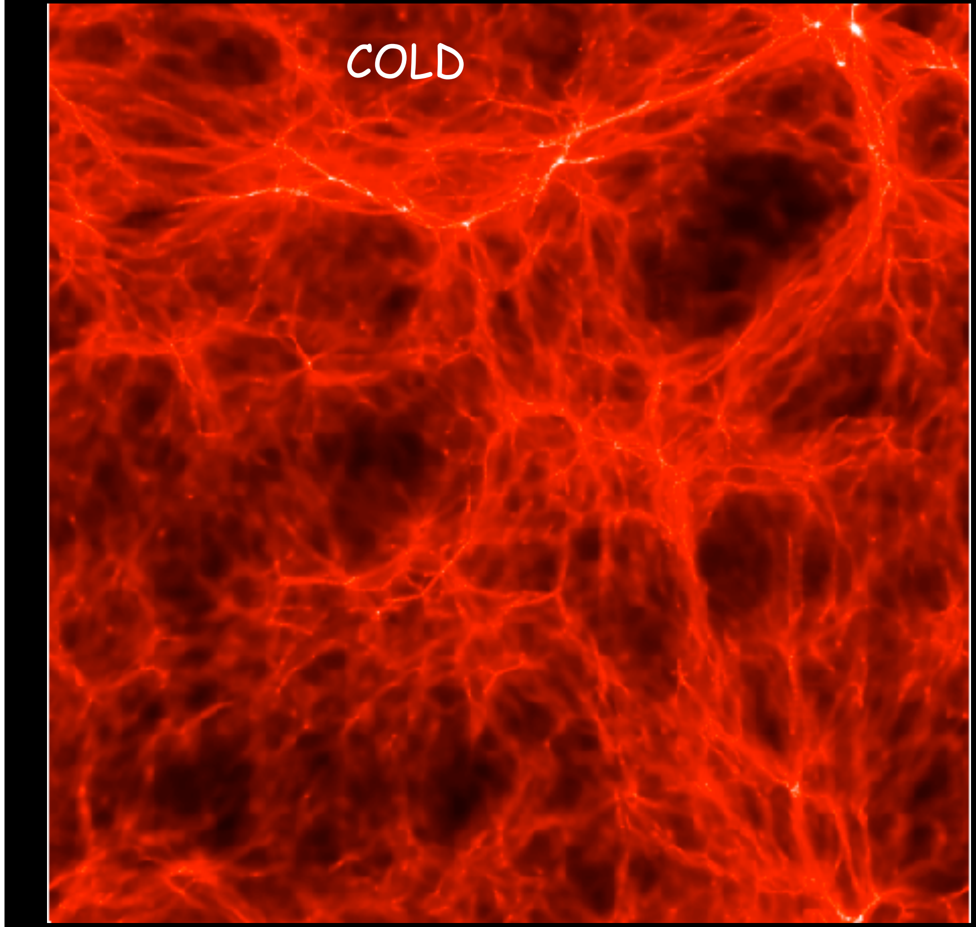
m $_{\mathrm{WDM}}$ > 4 keV (early decoupled thermal relics)

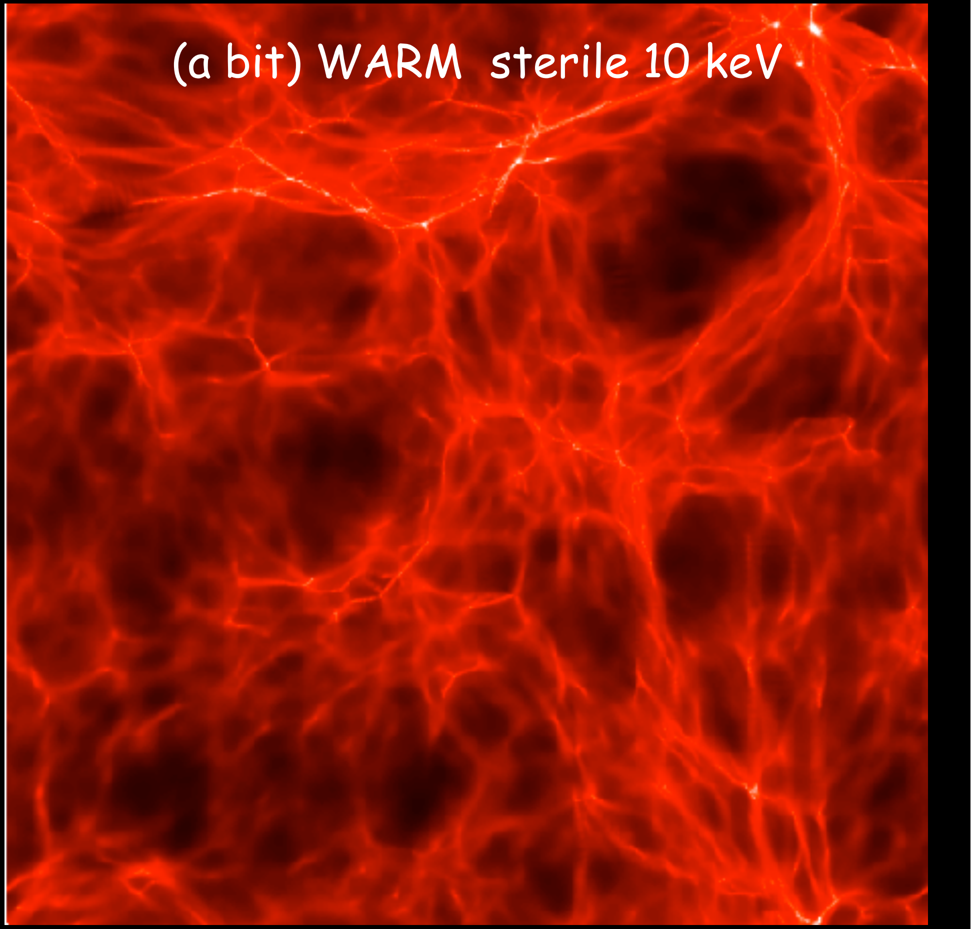
m $_{\mathrm{sterile}}$ > 28 keV (standard Dodelson-Widrow mechanism)

SDSS range

Completely new small scale regime

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


COLD


(a bit) WARM sterile 10 keV

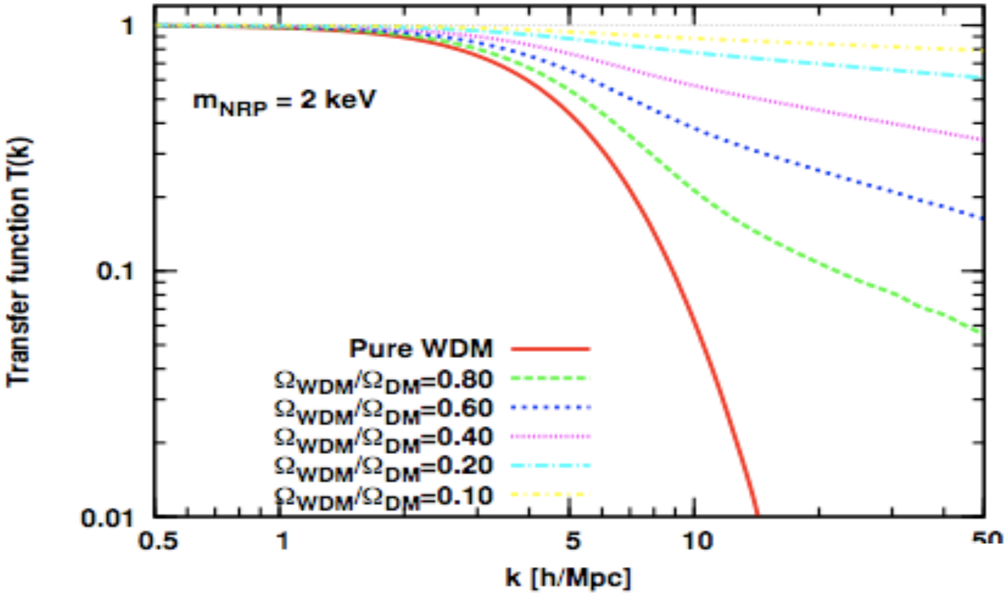
RESULTS NEW WARM DARK MATTER MODEL

(sterile neutrino)

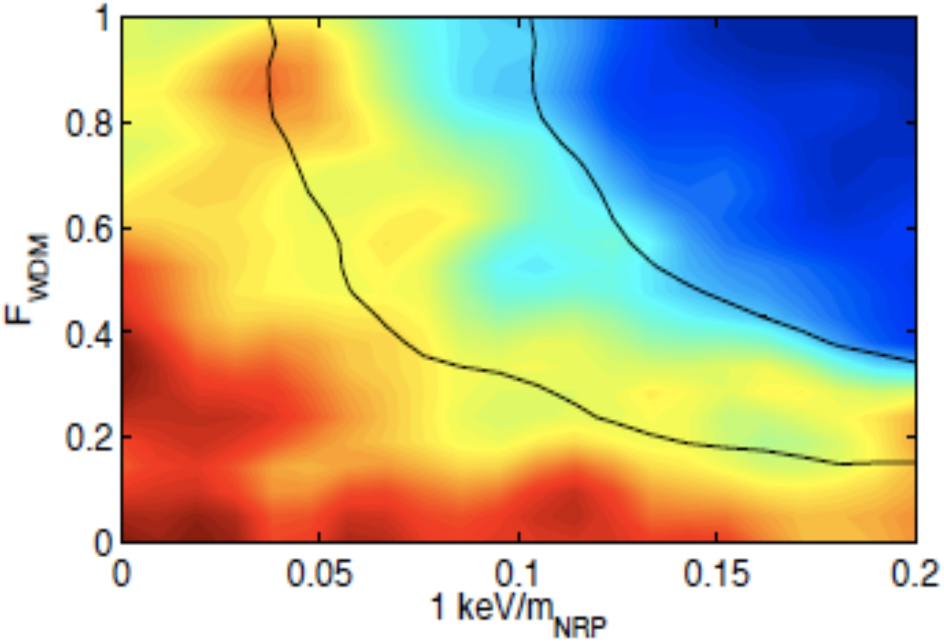
Mixed Cold and Warm models: Boyarsky, Lesgourgues, Ruchayskiy, Viel, 2009, JCAP, 05, 012

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

Lyman-α and Cold+Warm Dark Matter - I

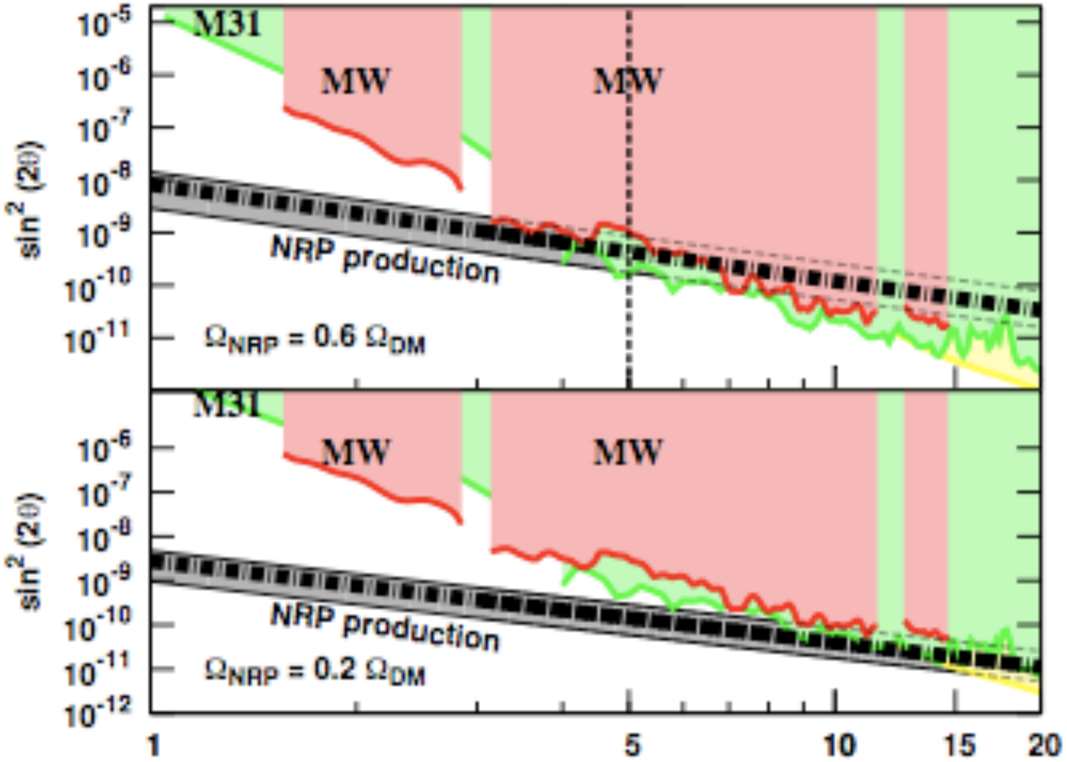


SDSS+WMAP5



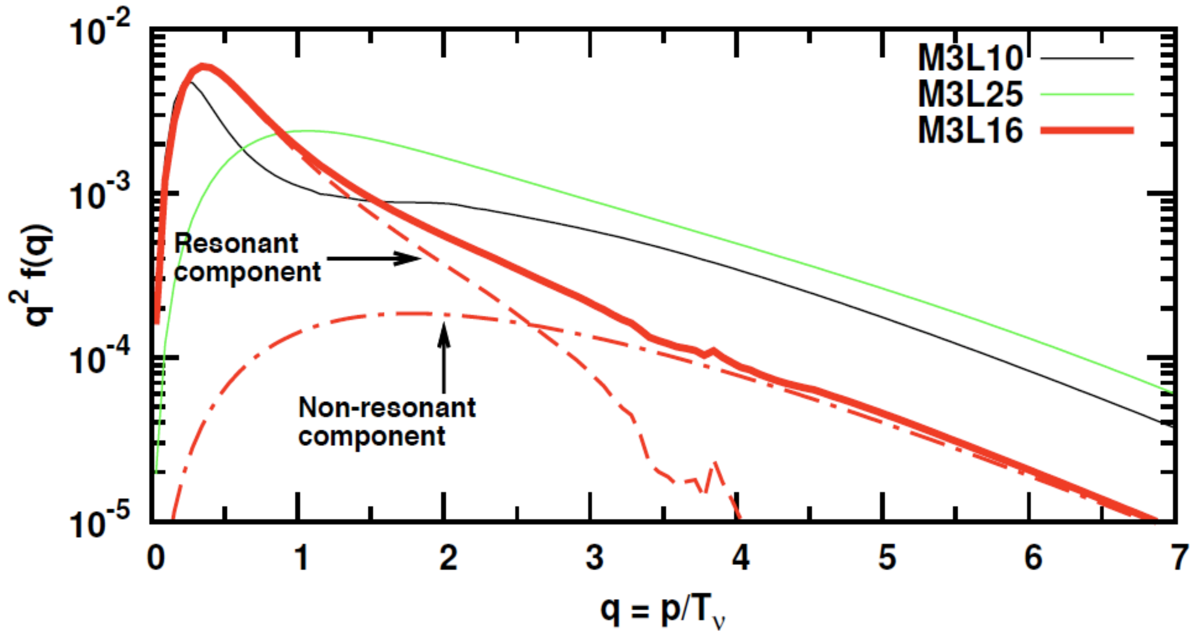
Lyman-α and Cold+Warm Dark Matter - II

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



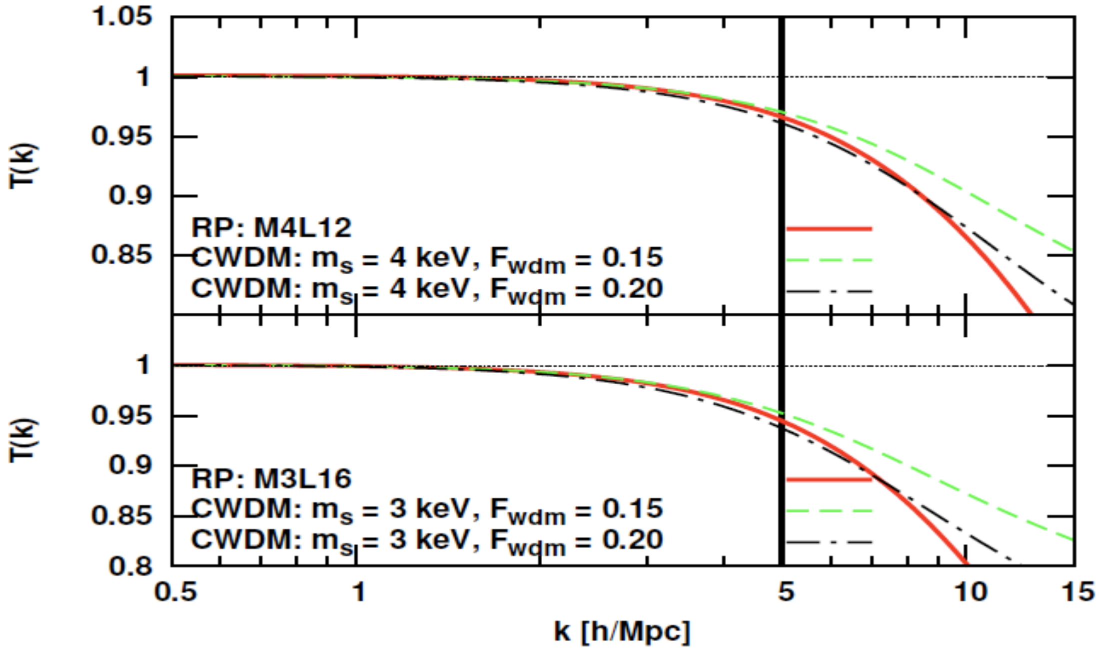
For m > 5 keV any fraction of WDM < 0.6 is allowed – frequentist analysis 99.7% C.L.
For m > 5 keV any fraction of WDM < 0.35 is allowed – bayesian analysis 95% C.L.

Lyman-α and resonantly produced sterile neutrinos - I

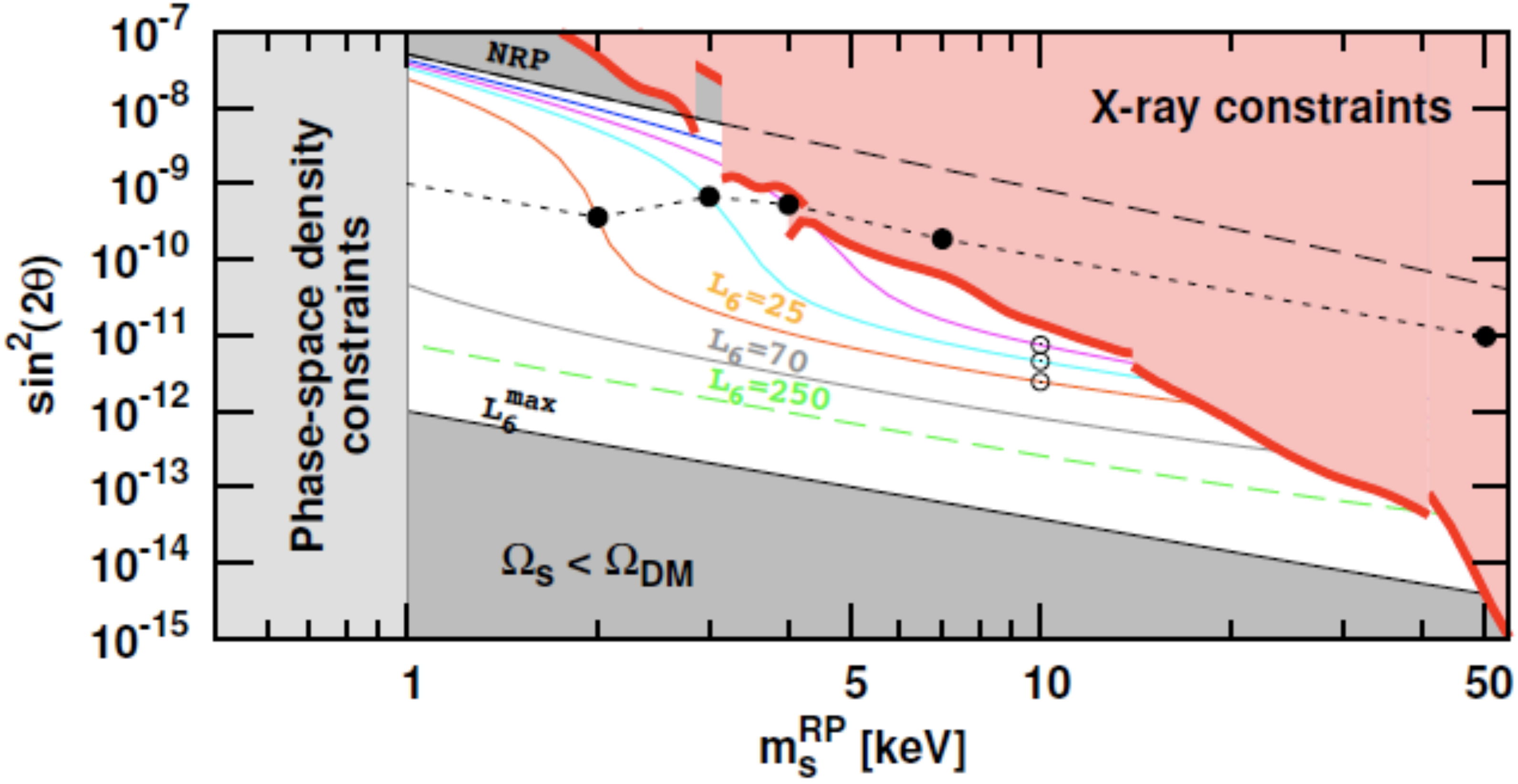


$L=10^6 (n\,\nu_e - n\,\underline{\nu_e})/s$

Mass sterile = 3 keV

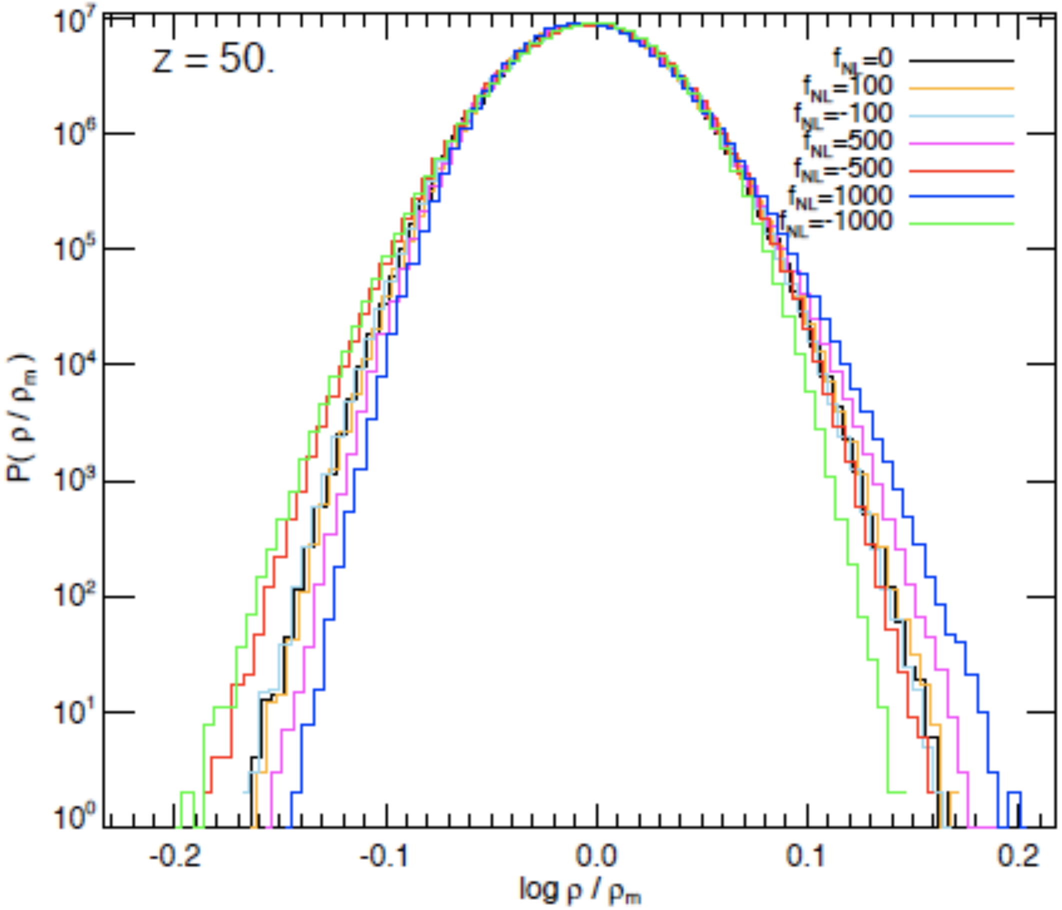


Lyman-α and resonantly produced sterile neutrinos - II



PRIMORDIAL Non Gaussianities in the IGM

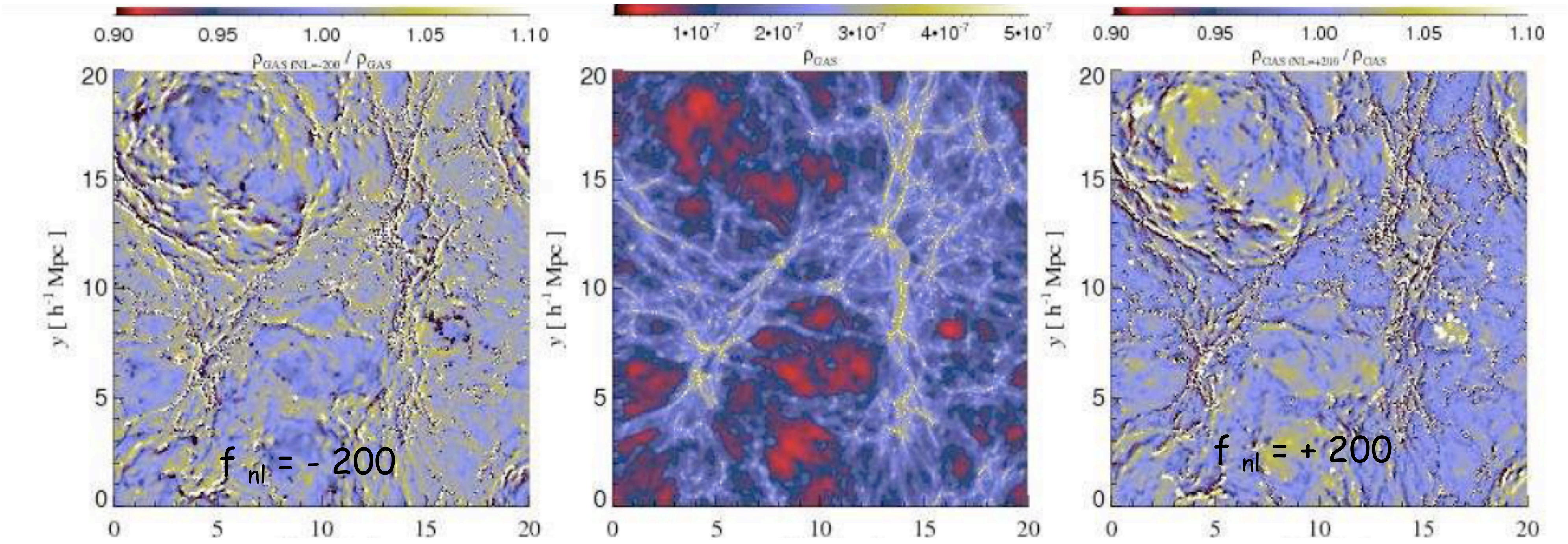
N-body simulation in NG scenario: the mass distribution



$$\Phi_{\rm NL} = f_{\rm NL}\left(\Phi_{\rm L}^2 - \langle\Phi_{\rm L}^2\rangle\right)$$

Mathis et al. 04
Kang et al. 07
Grossi et al. 07,09
Hikage et al. 08
Desjacques et al. 08

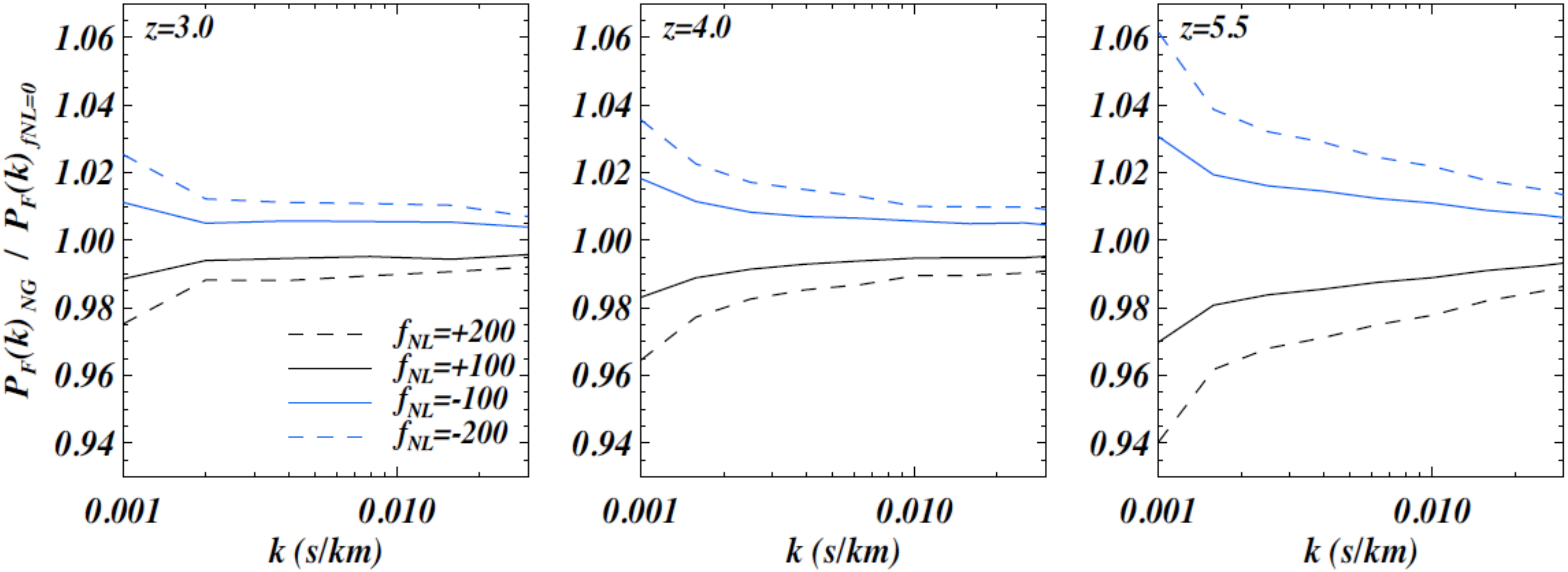
First hydrodynamical simulation in NG scenario



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

First hydrodynamical simulation in NG scenario: flux bispectrum

Local squeezed configuration $k_1 \ll k_2 \sim k_3$



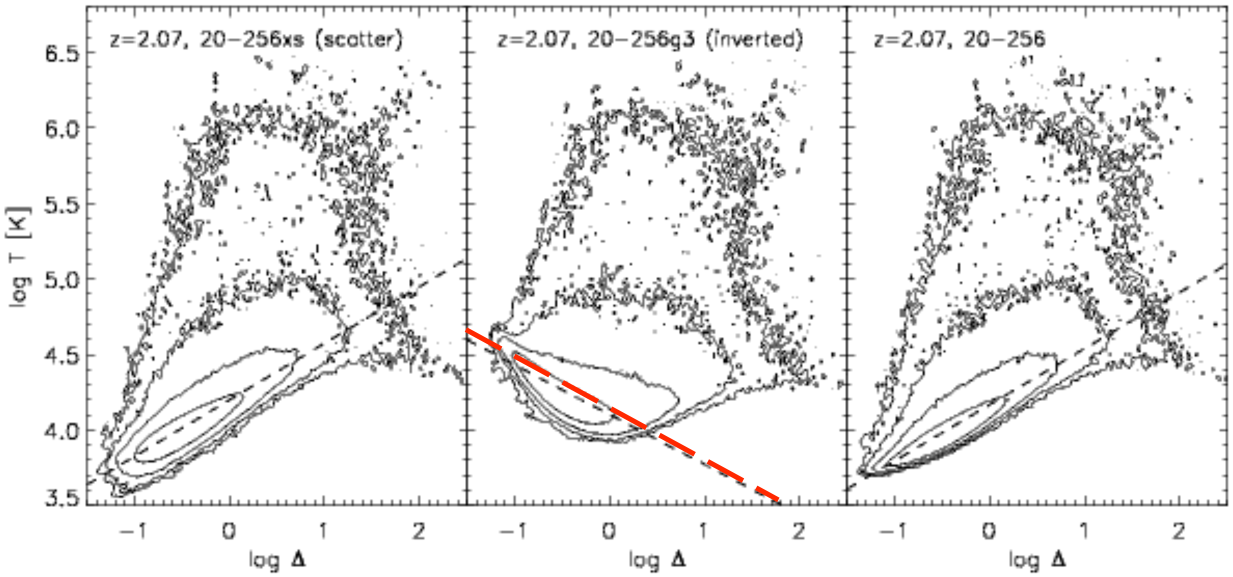
SYSTEMATICS

Fitting the flux probability distribution function

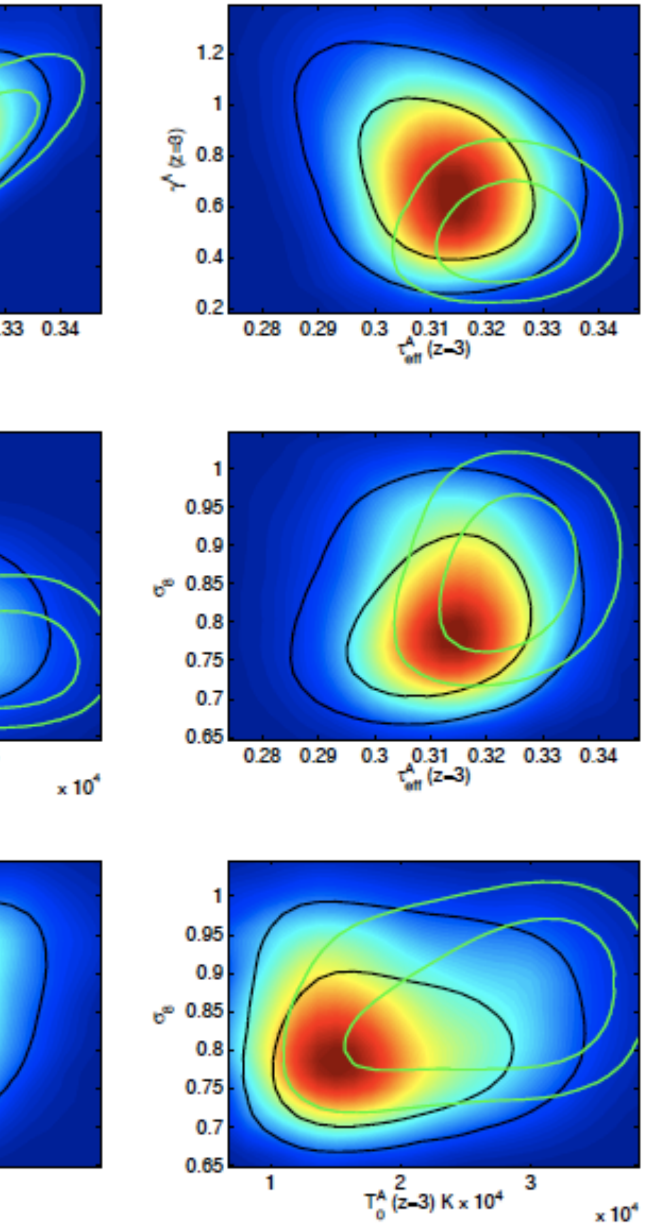
Bolton, MV, Kim, Haehnelt, Carswell (08)

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

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



Fitting the flux probability distribution function-II



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

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

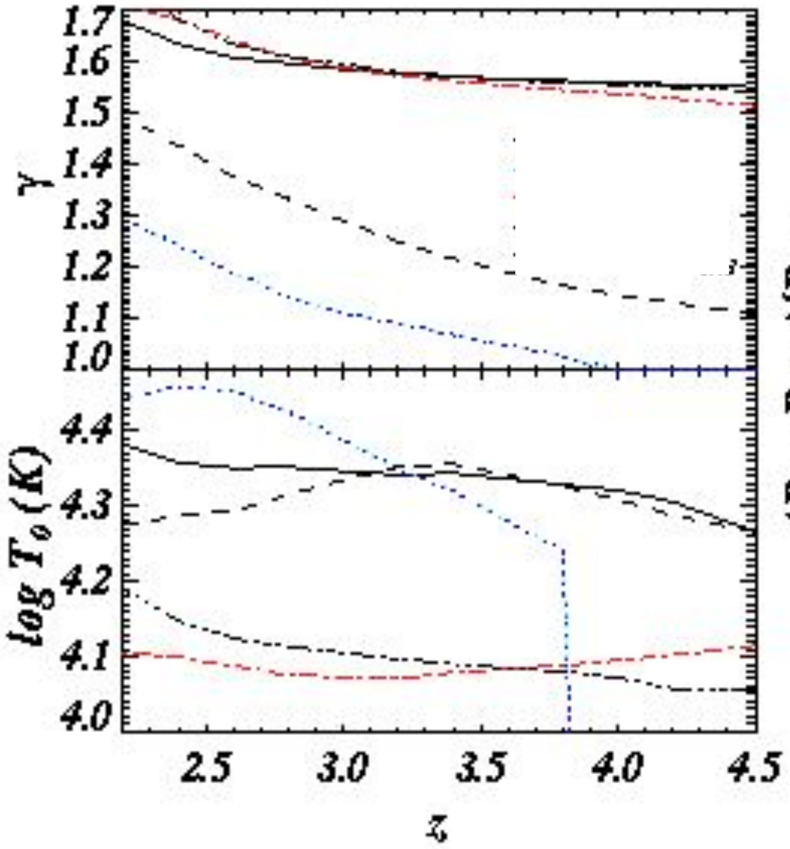
3) Flux power prefers a higher temp.
than the flux pdf alone: joint constraints
reasonable and still prefers a high σ_8
than the CMB alone

Viel, Bolton, Haehnelt, 2009, MNRAS

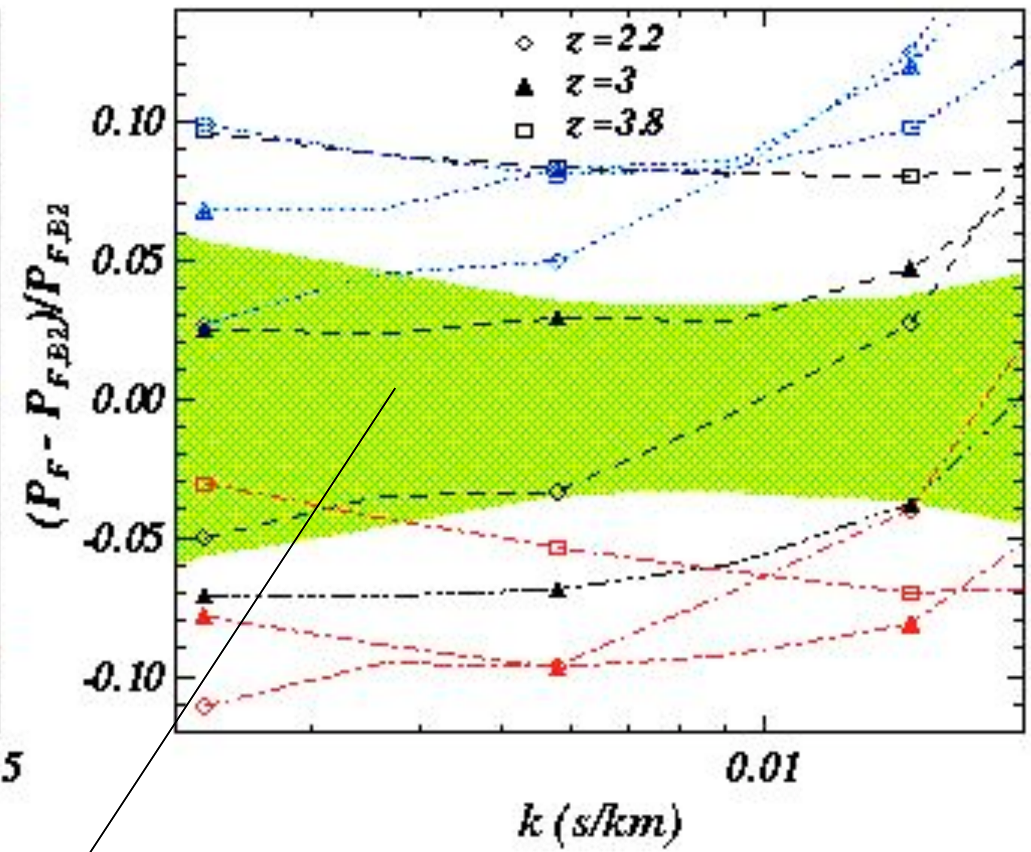
Systematics: Thermal state

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

Thermal histories



Flux power fractional differences

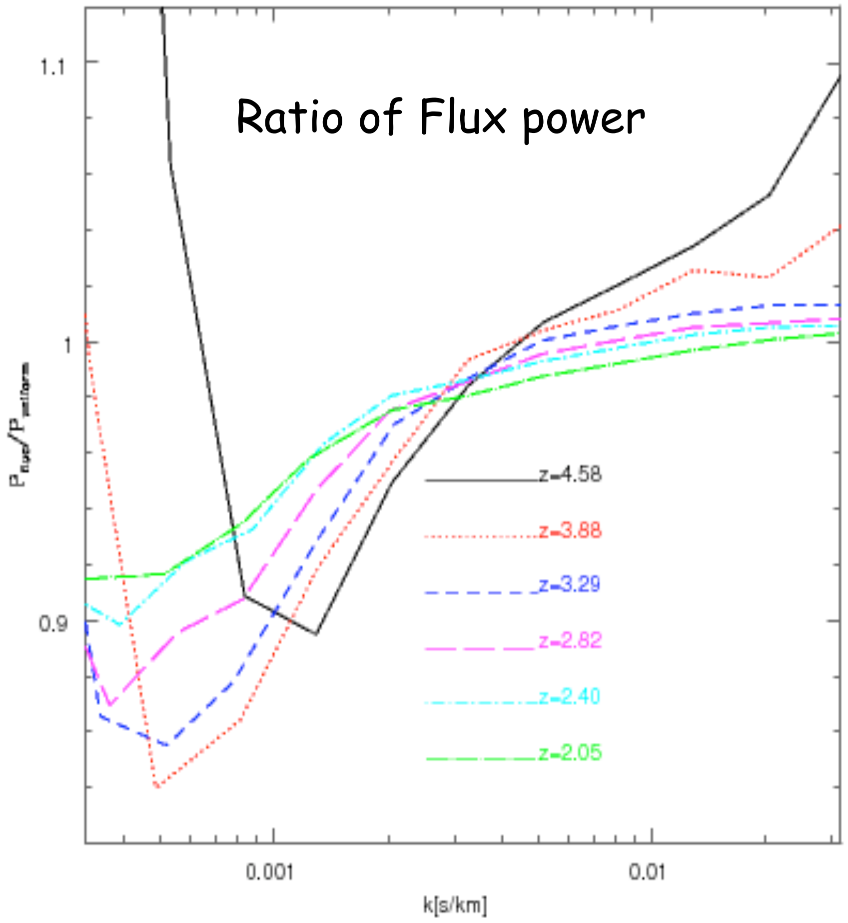


Statistical SDSS errors on flux power

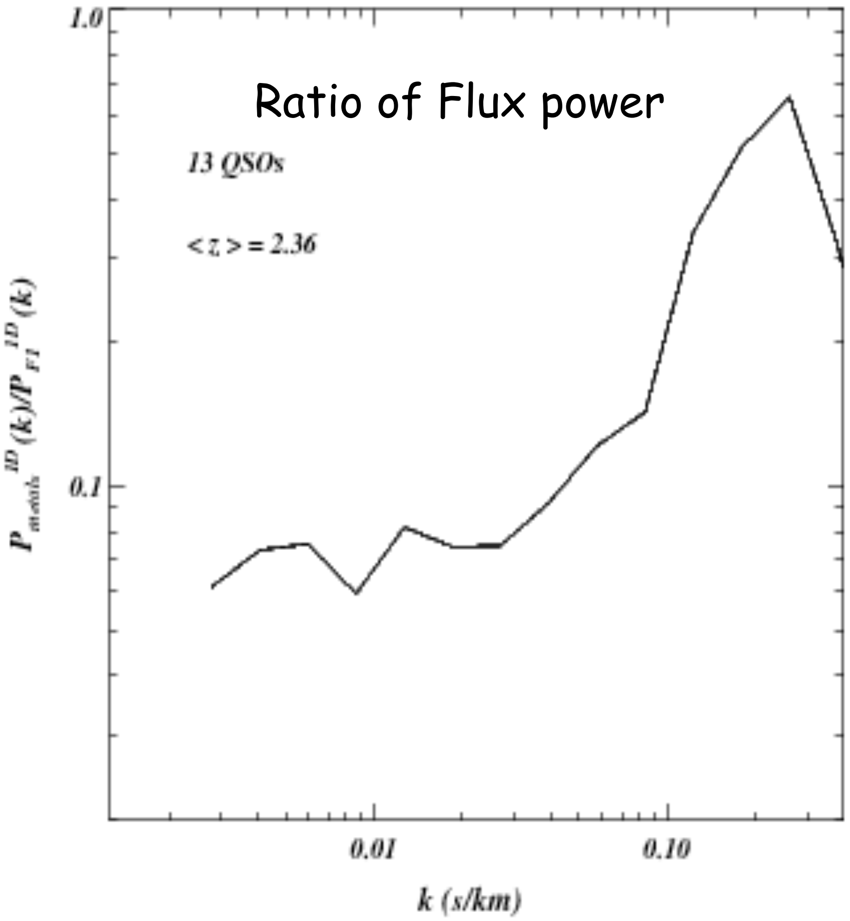
Systematics: UV fluctuations and Metals

UV fluctuations from Lyman Break Galaxies

Metal contribution


Ratio of Flux power

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


Ratio of Flux power

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

FUTURE

Future perspectives

BOSS (or SUPERBOSS) – SDSS III
150,000 (1,000,000) QSO spectra → tailored for BAO and P(k) studies

X-Shooter (taking data now) spectrograph
Medium resolution between SDSS and high res → at least 100 QSO spectra needed to improve constraints

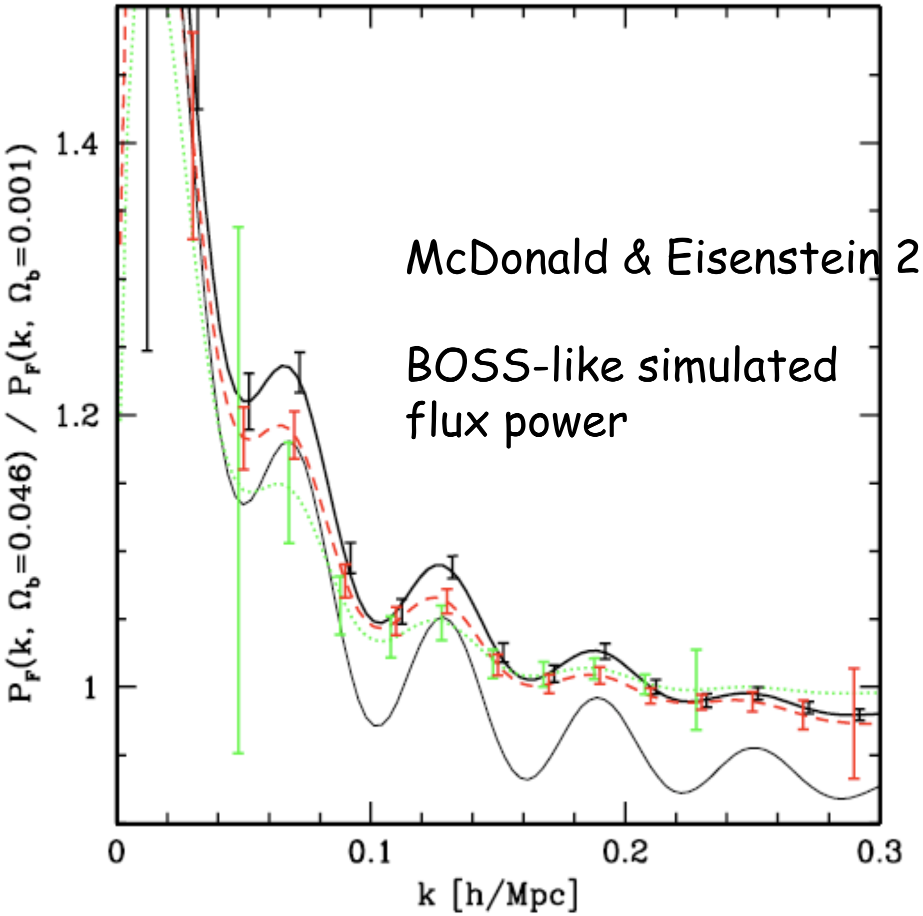
Independent analysis of thermal state using different statistics and constraints both on astrophysics and cosmological probes (e.g. Vallinotto, Xia's talks) at both HIGH and low redshift

E-ELT era: measuring the cosmic expansion

Future perspectives : BAO

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

about 20 QSOs per square degree
with BOSS



McDonald & Eisenstein 2007

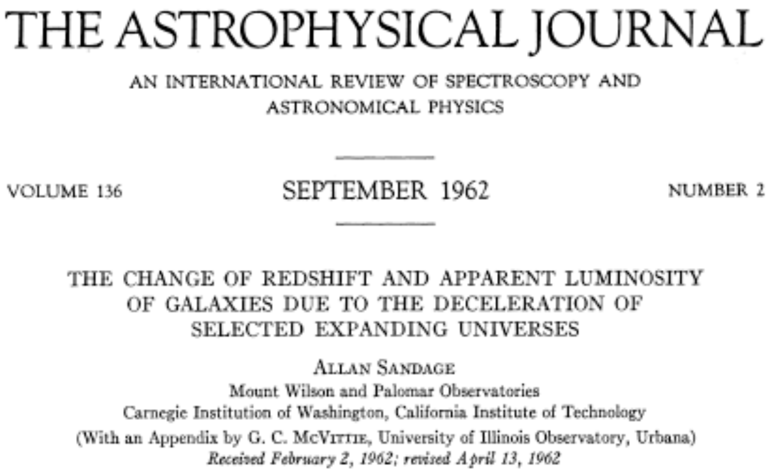
BOSS-like simulated
flux power

COSMIC EXPANSION

Measuring the cosmic expansion?

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

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



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME 136 SEPTEMBER 1962 NUMBER 2

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

Allan Sandage
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
(With an Appendix by G. C. McVittie, University of Illinois Observatory, Urbana)
Received February 2, 1962; revised April 13, 1962

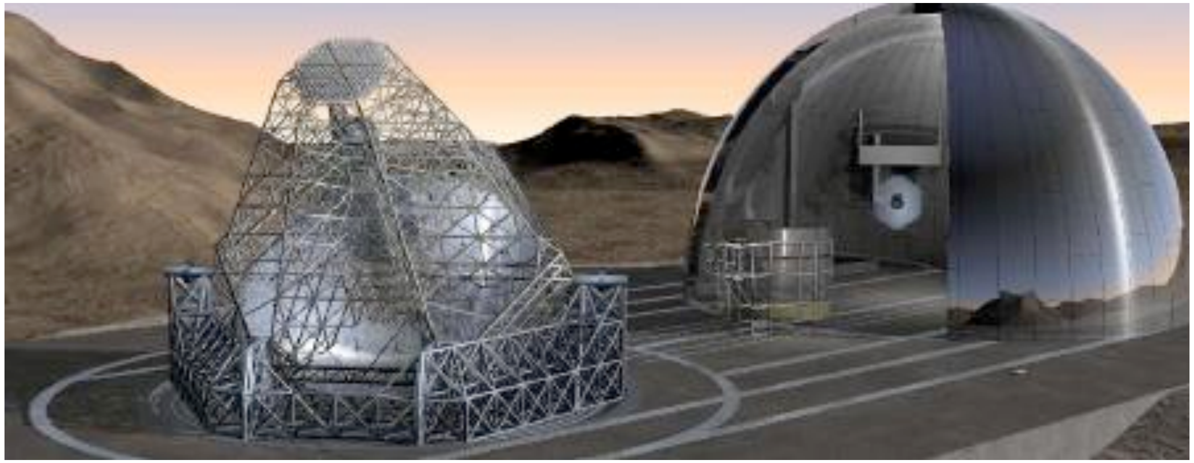
$$\dot{z} = \frac{dz}{dt_0} = \frac{\partial z}{\partial t_0} + \frac{\partial z}{\partial t_e}\frac{dt_e}{dt_0} = \frac{\dot{a}(t_0)}{a(t_e)} - \frac{\dot{a}(t_e)}{a(t_e)}\frac{a(t_0)}{a(t_e)}\frac{1}{1+z}$$

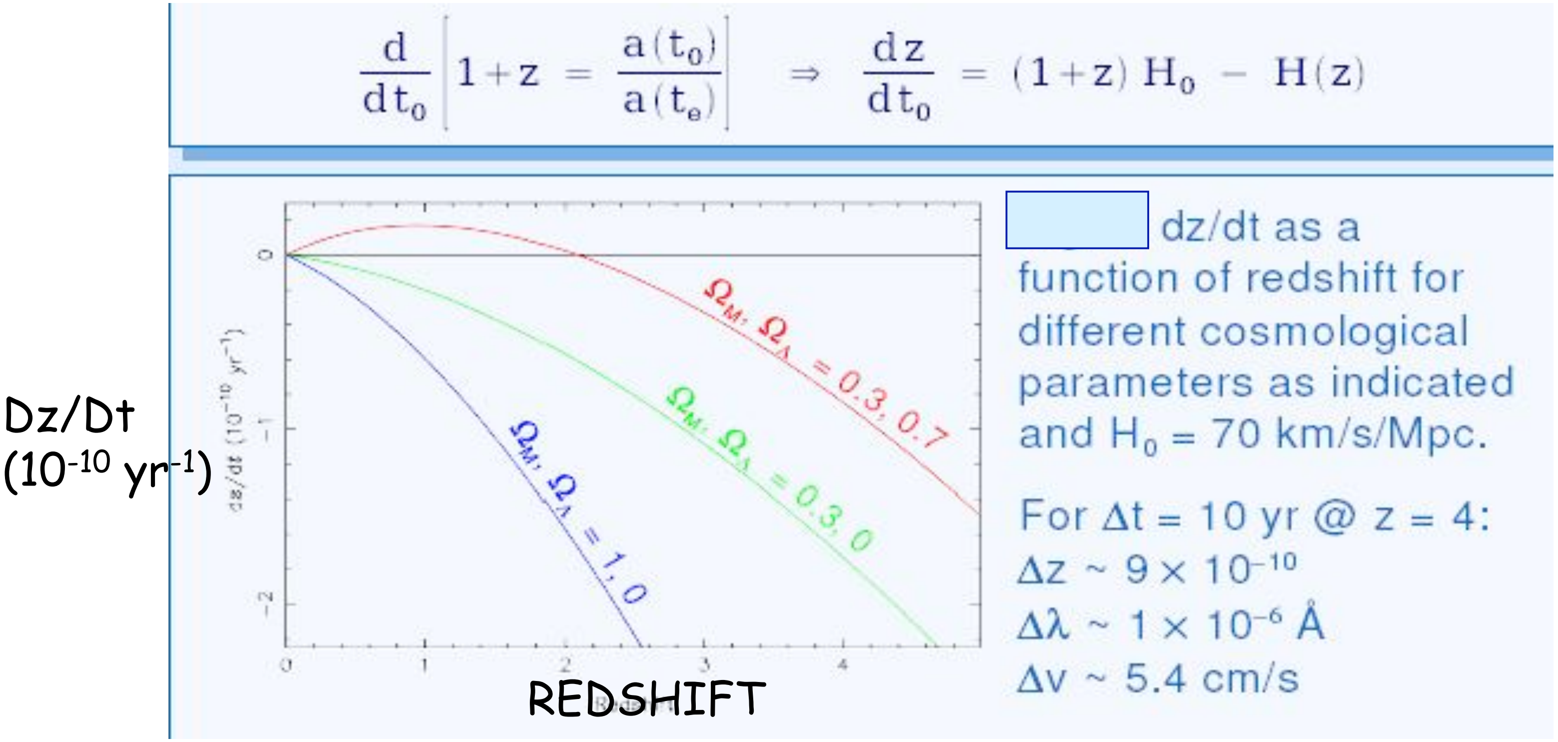
$$\dot{z} = (1 + z)H_0 - H(t_e)$$

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

COsmicDynamicEXperiment CODEX-I

Ultra-stable spectrograph





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

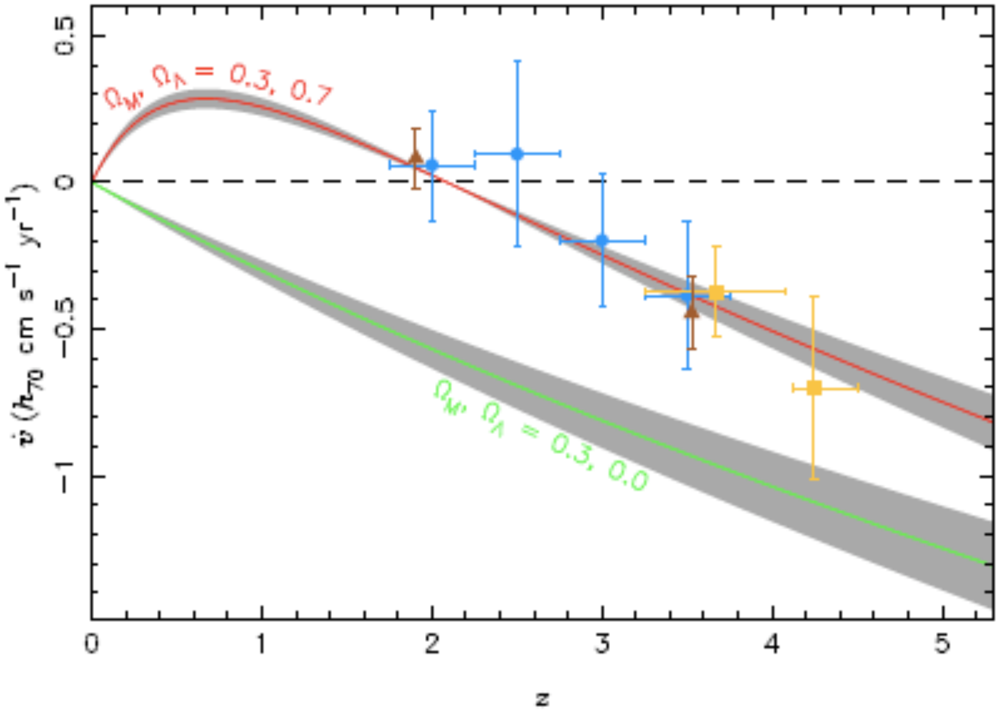
Dz/Dt (10^{-10} yr^{-1})

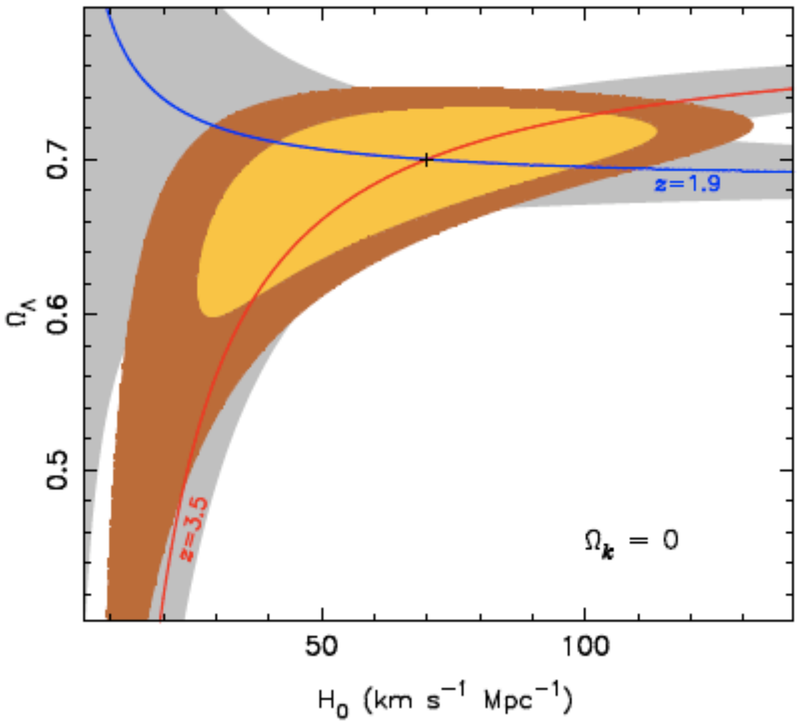
REDSHIFT

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

For Δt = 10 yr @ z = 4:
$\Delta z \sim 9 \times 10^{-10}$
$\Delta\lambda \sim 1 \times 10^{-6}$ Å
$\Delta v \sim 5.4$ cm/s

COsmicDynamicEXperiment CODEX - II





Liske et al. 2008, MNRAS, 386, 1192

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 more theoretical (more reliable simulations are needed for example for neutrino species) than observational 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 + …) to beat down systematics

-Tension with the CMB is still there. Very constraining for what happens at those scales: running (inflation), neutrinos, warm dark matter candidates … IMPORTANCE of SINERGIES with cosmology and astrophysics and cross-correlations of observables in the SDSS-3 era