# OBSERVATIONAL and QUANTITATIVE COSMOLOGY WITH THE IGM

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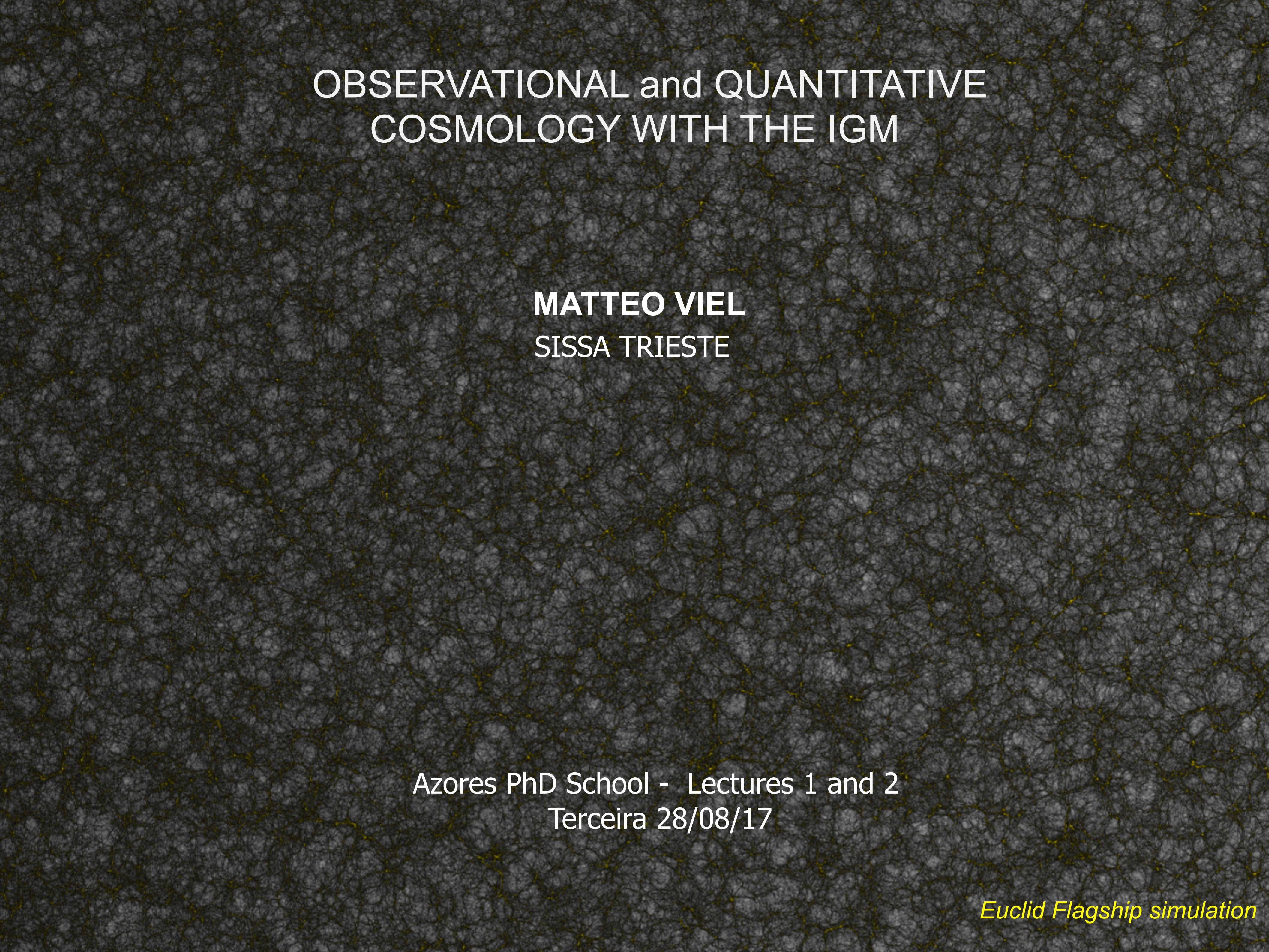
Azores PhD School - Lectures 1 and 2
Terceira 28/08/17



*Euclid Flagship simulation*

# GOALS and OUTLINE

**GOALS**

1) provide a clear understanding of why the IGM can be used to do quantitative cosmology

2) provide you with the state-of-the-art in this field

3) highlight possible pathways to future developments

**OUTLINE**

1) Physics of the Intergalactic Medium
2) What can we learn from the use of different transmitted flux statitistics

TEST CASES: 3) WARM DARK MATTER
4) NEUTRINOS
5) LOW-z FOREST

# BASICS

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

differently from galaxies:

does not “shine”, tipically samples overdensities delta = [-1,10],
forms a network of filaments called the “cosmic web” with clustering pattern/topology that needs to be characterized
usually pixels are used and not “objects"

**CGM:** circum galactic medium (is closer to galaxies) thereby possibly more affected by astrophysics

*Key question for us is: if and how well the IGM traces the underlying gravitational potential.*

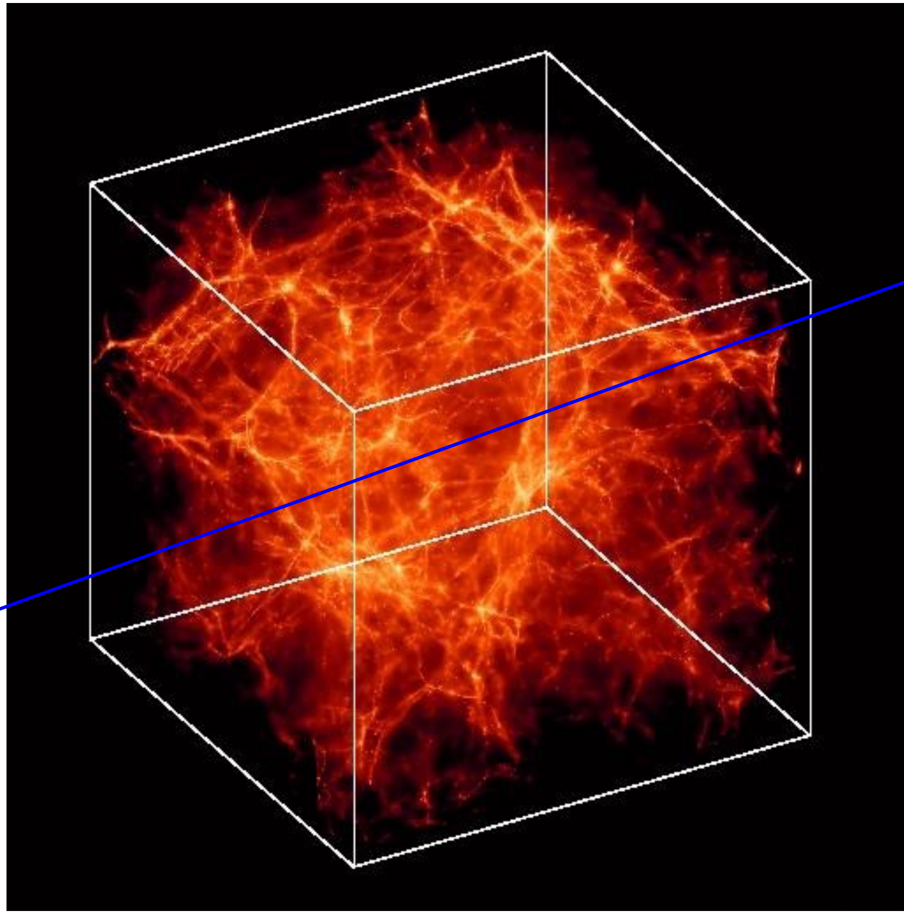
# SOME REFERENCES

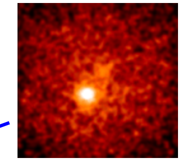
**1) MODEL BUILDING:**
Bi & Davidsen 1997,
"Evolution of Structure in the Intergalactic Medium and the Nature of the Ly$\alpha$ Forest”, ApJ, 479, 523

**2) MORE ON OBSERVATIONS:**
Rauch, 1998, “The Lyman-alpha forest in the spectra of QSOs”, ARA&A, 32, 267

**3) RECENT REVIEWS (include sims and recent data sets):**
Meiksin, 2009, “The Physics of the IGM”, Progress Reports, 81, 1405

McQuinn, 2016, “The Evolution of the Intergalactic Medium“, ARA&A, 54,313

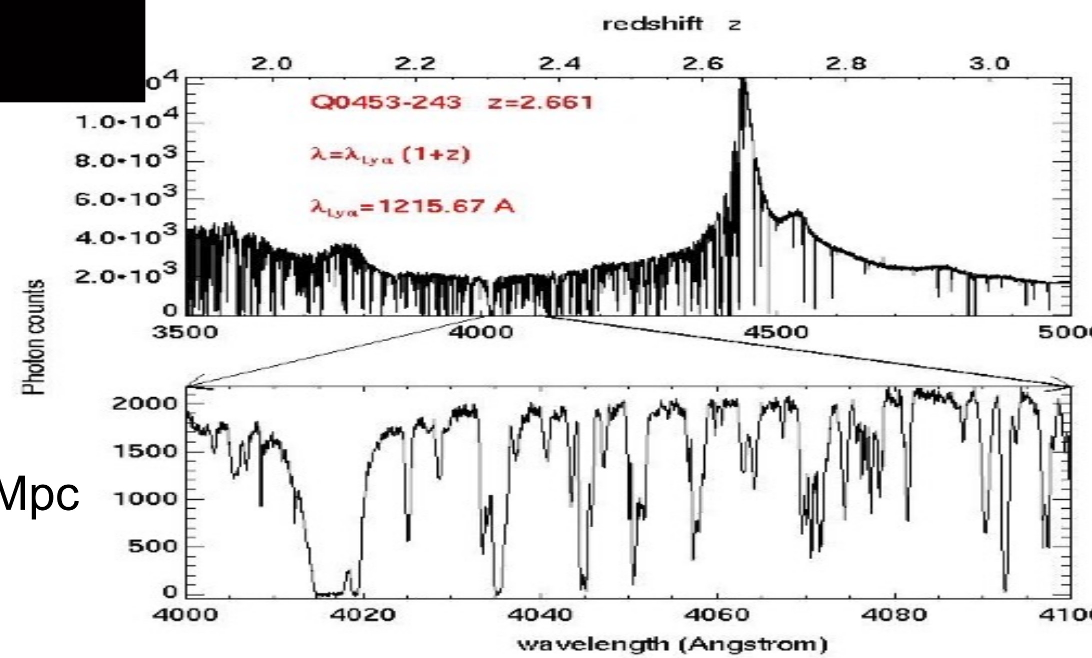




80 % of the baryons at z=3 are in the Lyman-$\alpha$ forest

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

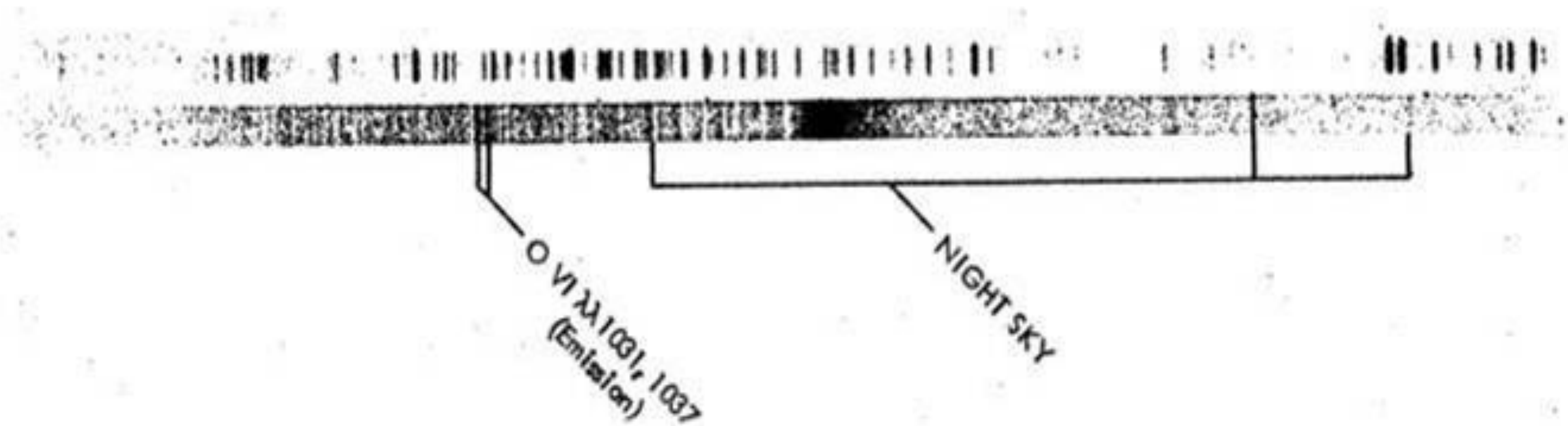



PLATE L3

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

## More recent milestones

**DATA:** early 90s: advent of high res spectroscopy (UVES, Keck)

[1998-2002] Croft, Weinberg+: first quantitative use of the Lyman-alpha forest for cosmology.

[1998-2004] better understanding of physics of the IGM (Hui, Gnedin, Meiksin, White)

[2004] Viel+: usage of UVES to complement Croft's work with better sims to cover the parameter space.

[2005-06] SDSS-II results (McDonald, Seljak…): excellent synergy with CMB abd other probes demonstrated (constraints on inflation and neutrinos).

[2007-now] systematic use of QSO spectra for DM nature at small scales (Viel+).

[2013] BAO detected in the Lyman-alpha forest 3D correlation by BOSS (SDSS-III) from low resolution.

# 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)

# Lyman-$\alpha$ forest (small clouds)

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

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

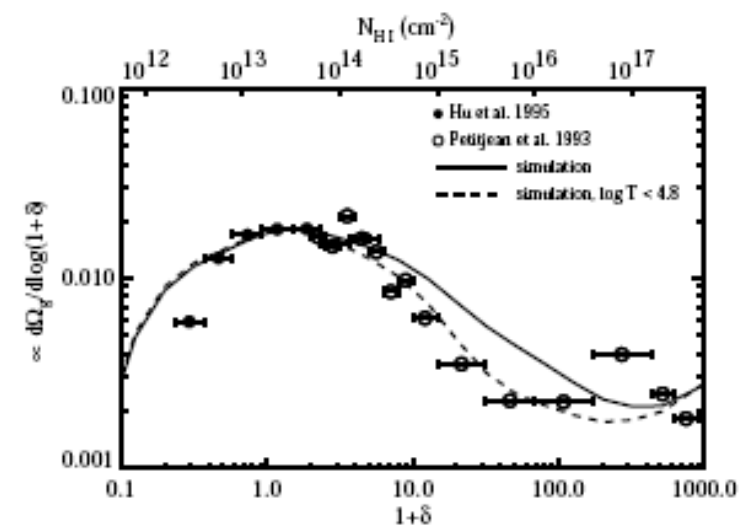
$$t_{\rm sc} \equiv \frac{L}{c_s} \sim 2.0 \times 10^{15}\ {\rm s} \left(\frac{L}{1\ {\rm kpc}}\right) T_4^{-1/2} \left(\frac{\mu}{0.59}\right)^{1/2}$$

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

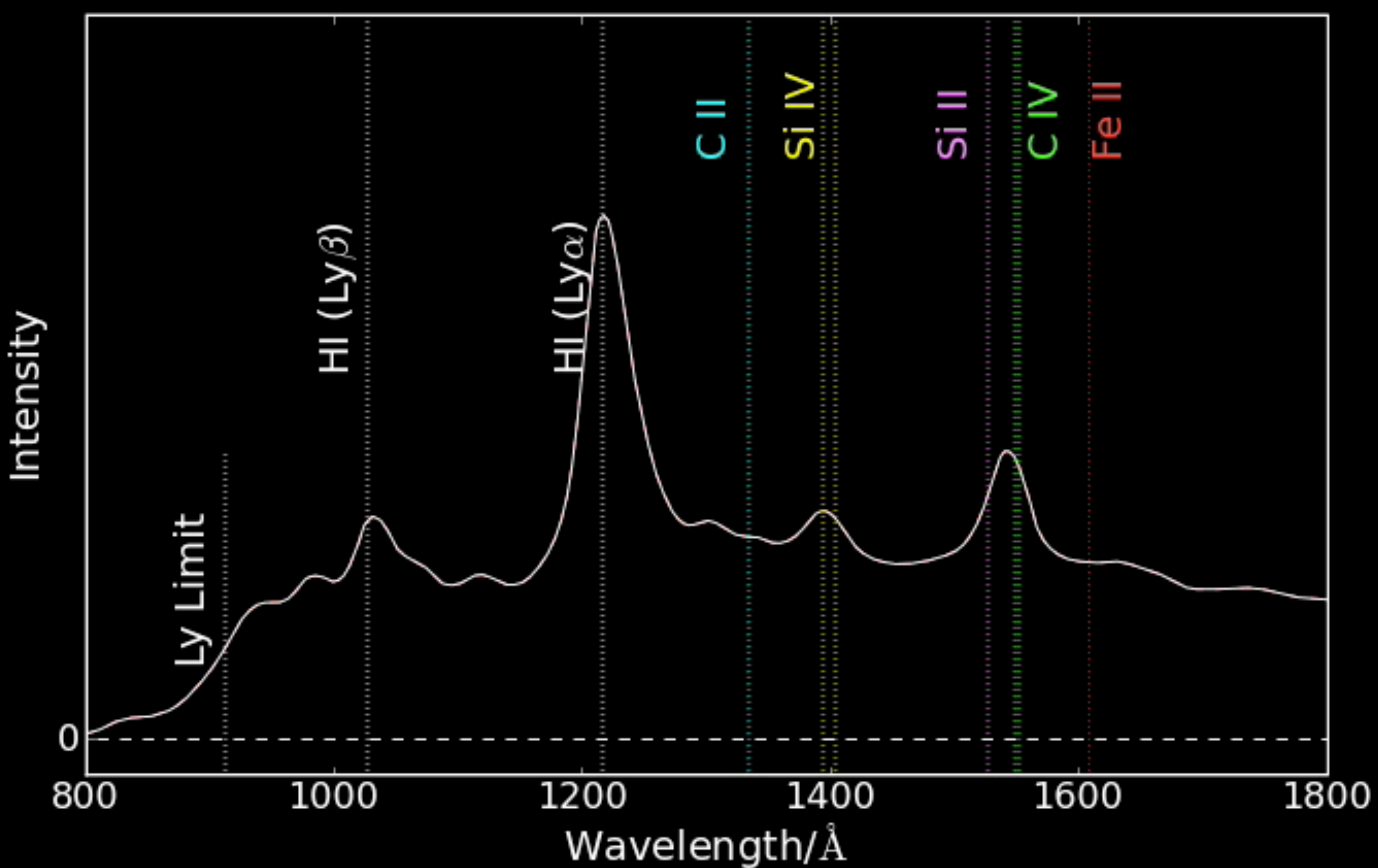
$$L_J \equiv \frac{c_s}{\sqrt{G\rho}} \sim 0.52\ {\rm kpc}\ n_{\rm H}^{-1/2}\, T_4^{1/2} \left(\frac{f_g}{0.16}\right)^{1/2}$$

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

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




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



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

## Dark matter evolution and baryon evolution –I

linear theory of density perturbation +

Jeans length $L_J \sim \mathrm{sqrt}(T/\rho)$ + 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

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

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

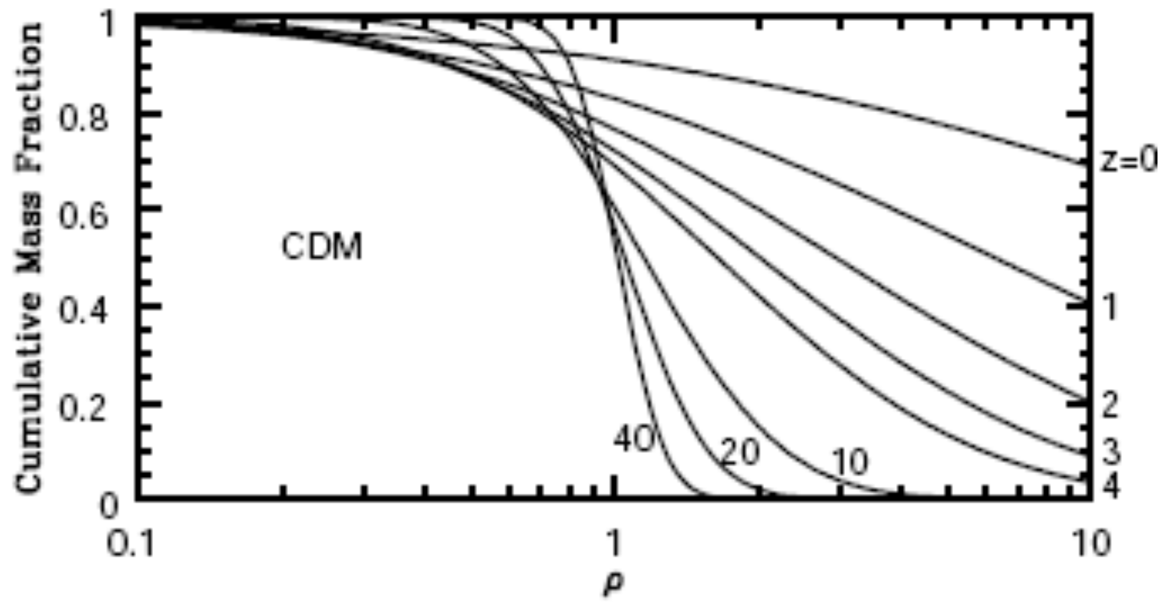
Density contrast in real and Fourier space

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

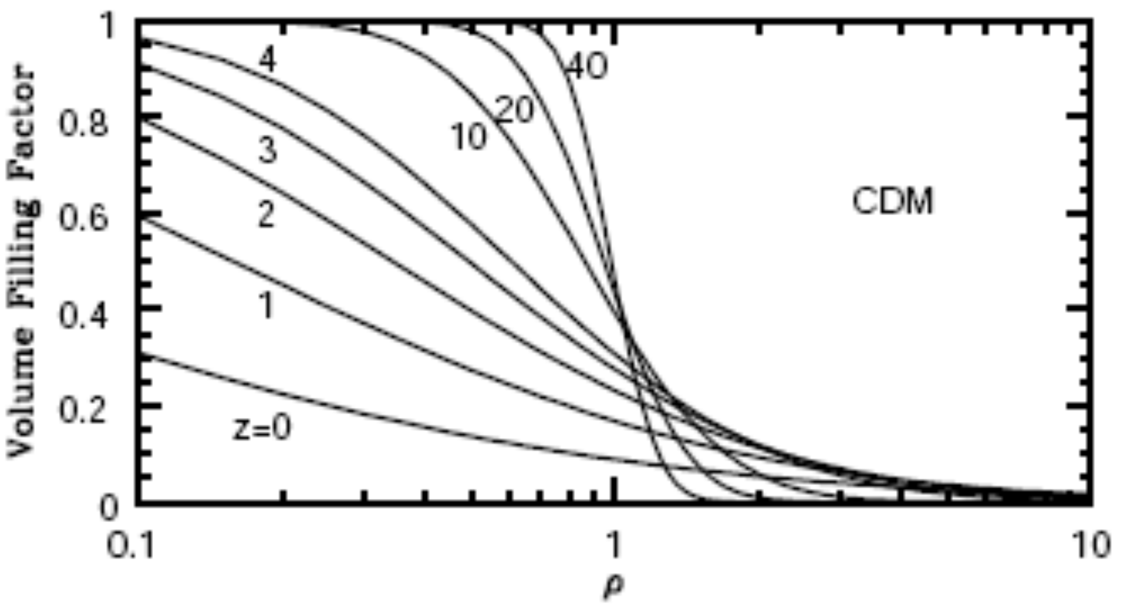
Non linear evolution lognormal model

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

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

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

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

Gravity term

pressure term (at large scales → 0)

$c_s^2 = dP/d\rho$

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

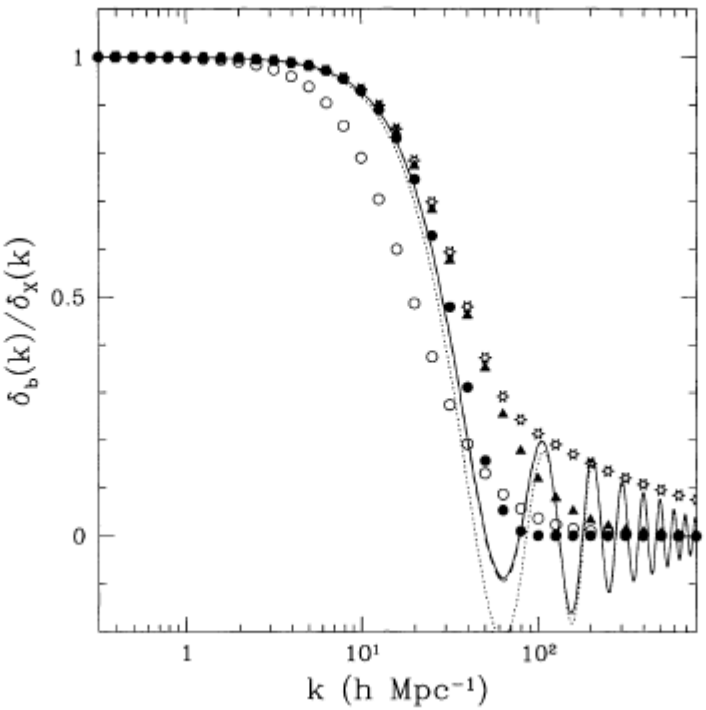
Polytropic gas

if $T \sim 1/a$ 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

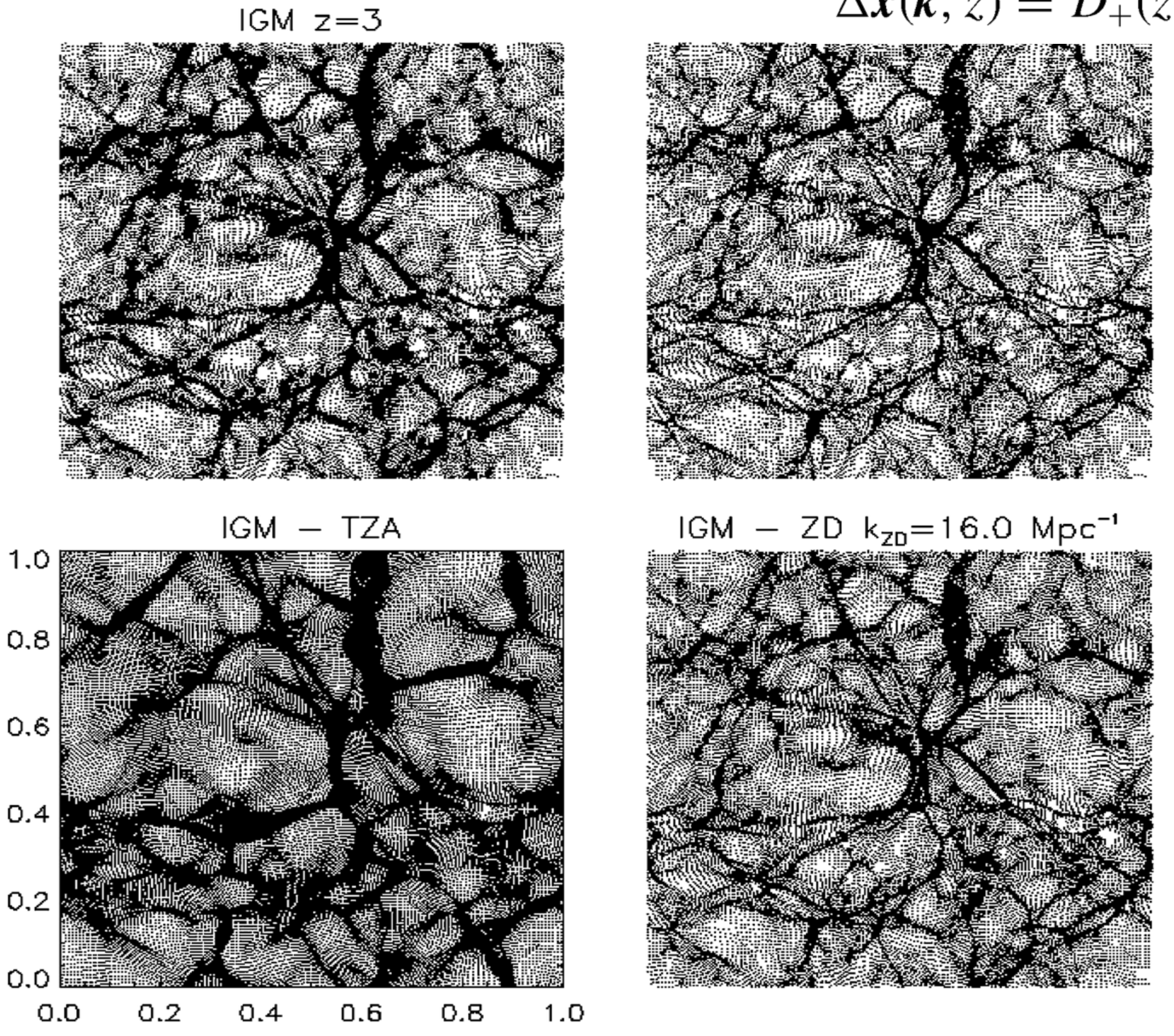



Hui & Gnedin 1998, MNRAS, 296, 44

# LINEAR THEORY OF DENSITY FLUCTUATIONS

$$\Delta \boldsymbol{x}(\boldsymbol{q}, z) = D_+(z)[\nabla_{\boldsymbol{q}} \psi_{\mathrm{IGM}}(\boldsymbol{q}, z) - \nabla_{\boldsymbol{q}} \phi_{\mathrm{DM}}(\boldsymbol{q})]$$

$$\Delta \boldsymbol{x}(\boldsymbol{k}, z) = D_+(z)[W_{\mathrm{IGM}} - 1] i \boldsymbol{k} \phi_{\mathrm{DM}}(\boldsymbol{k}).$$




Viel et al. 2002

# Ionization state – I

Photoionization equilibrium  UV background by QSO and galaxies

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

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

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

Photoionization rates

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

+

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

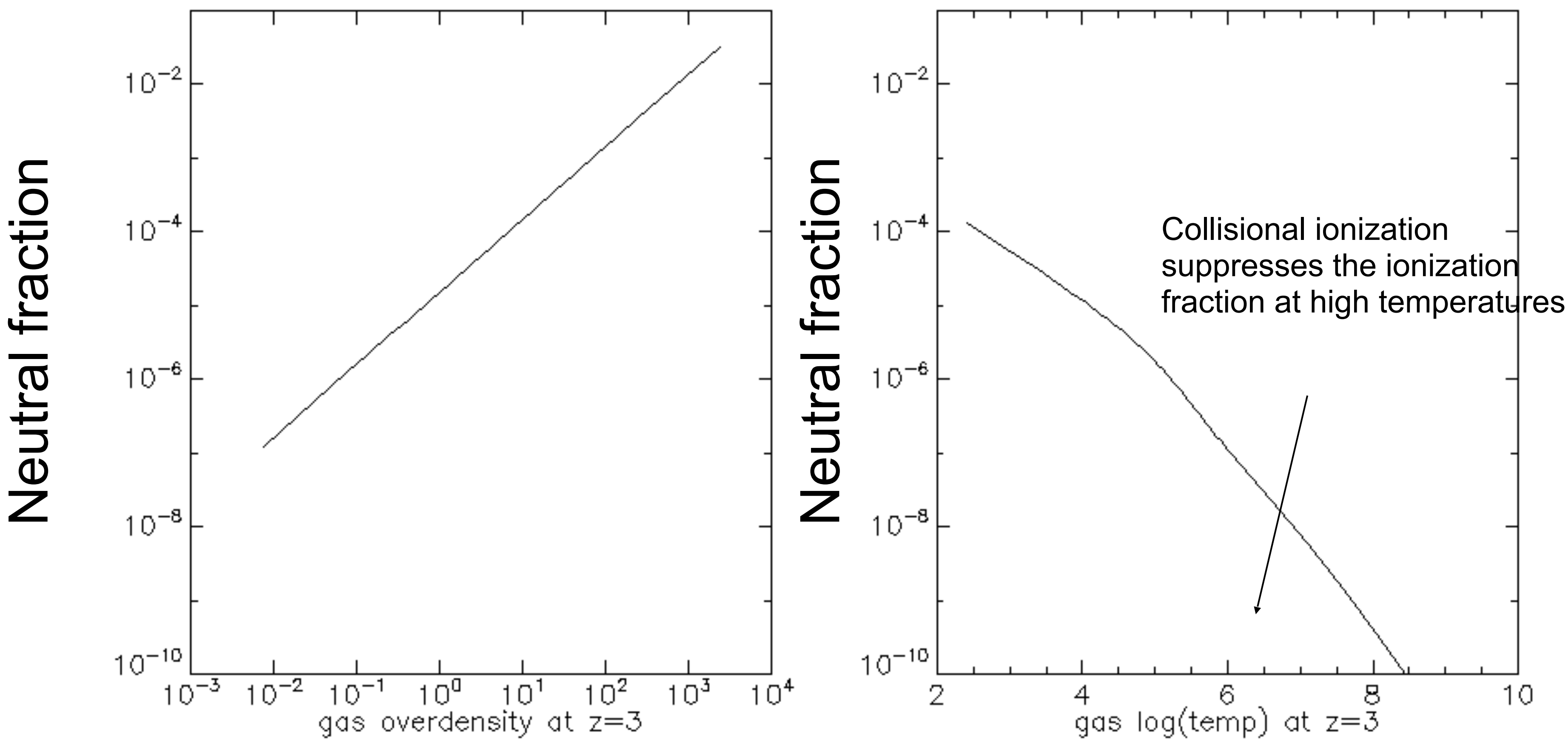
Recombination rates

Photoionization rate

Collisional ionization rate

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

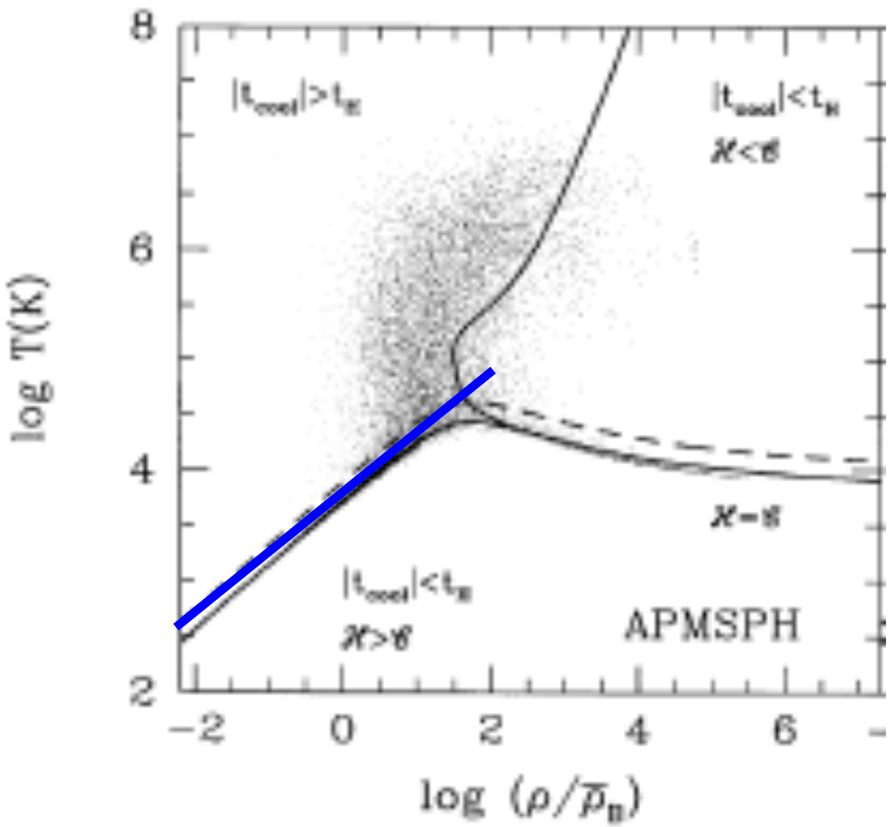
# Ionization state – II




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

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

# Thermal state




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

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

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

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

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

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

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

# The transmitted flux

Now my observable is the transmitted flux on a pixel-by-pixel basis, i.e. a continouos field, the key assumption is that it still contains some info on the underlying density field (gas+dark matter), however, the relation is non linear and in principle difficult to model

*Statistical properties of the flux can be investigated like*

1) **<F>:** important for measuring Omega baryons or UV amplitude

2) **Flux PDF** (1 point function, i.e. histogram of F values): important for…?

3) **1D flux power:** important for cosmological parameters and small scale power

4) **3D flux power:** important for BAO detection

5) **Flux bispectrum:** important for non gaussianities

*Note that also corresponding real space quantities could be used*

# HOW TO GO FROM FLUX TO DENSITY ?

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"

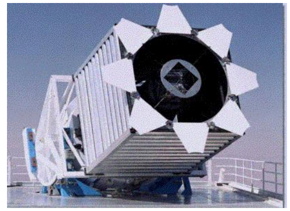
- The effective bias method pioneered by Croft (98,99,02) and co-workers "OLD"

- Modelling of the flux power by McDonald, Seljak and co-workers (04,05,06) **NEW**
  Jena,Tytler et al. (05,06)
  Viel+13,+11 - Irsic+17

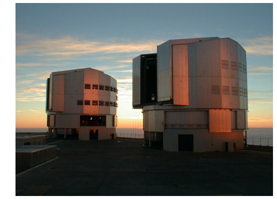
In practice it is now state-of-the-art to rely on hydro sims.
(Bolton+17, Lukic+16 etc.)

Hydro simulations set-up is tailored to the **scientific problem** under investigation and to the **data set** used.

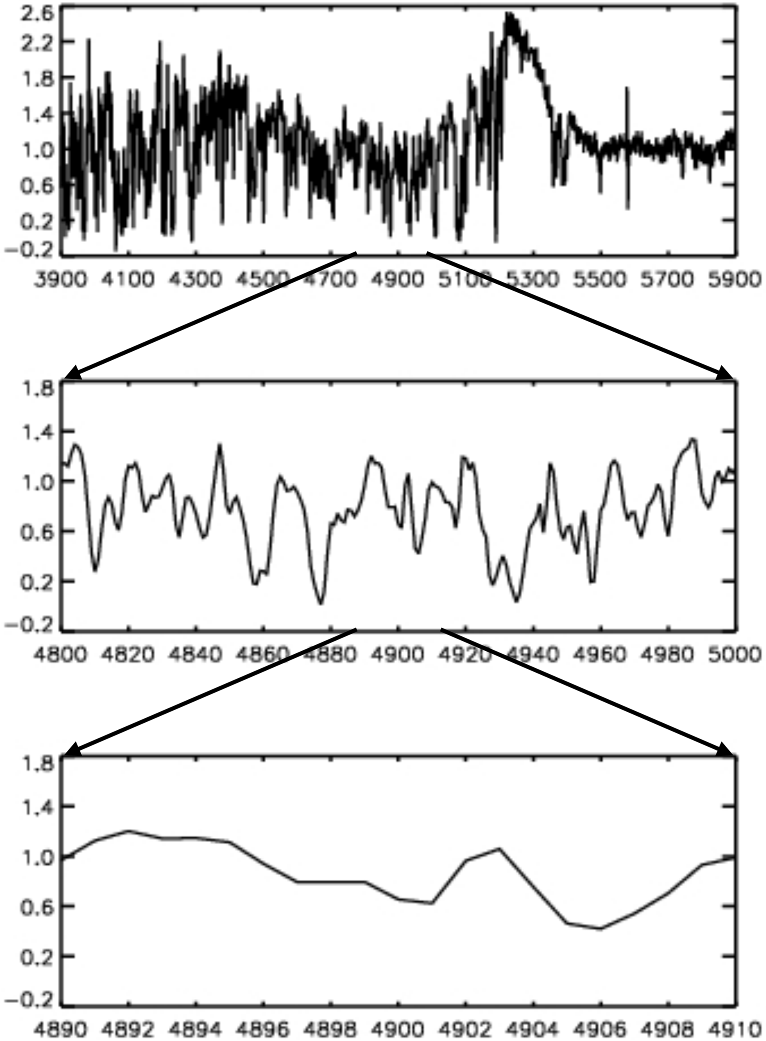
# The data sets



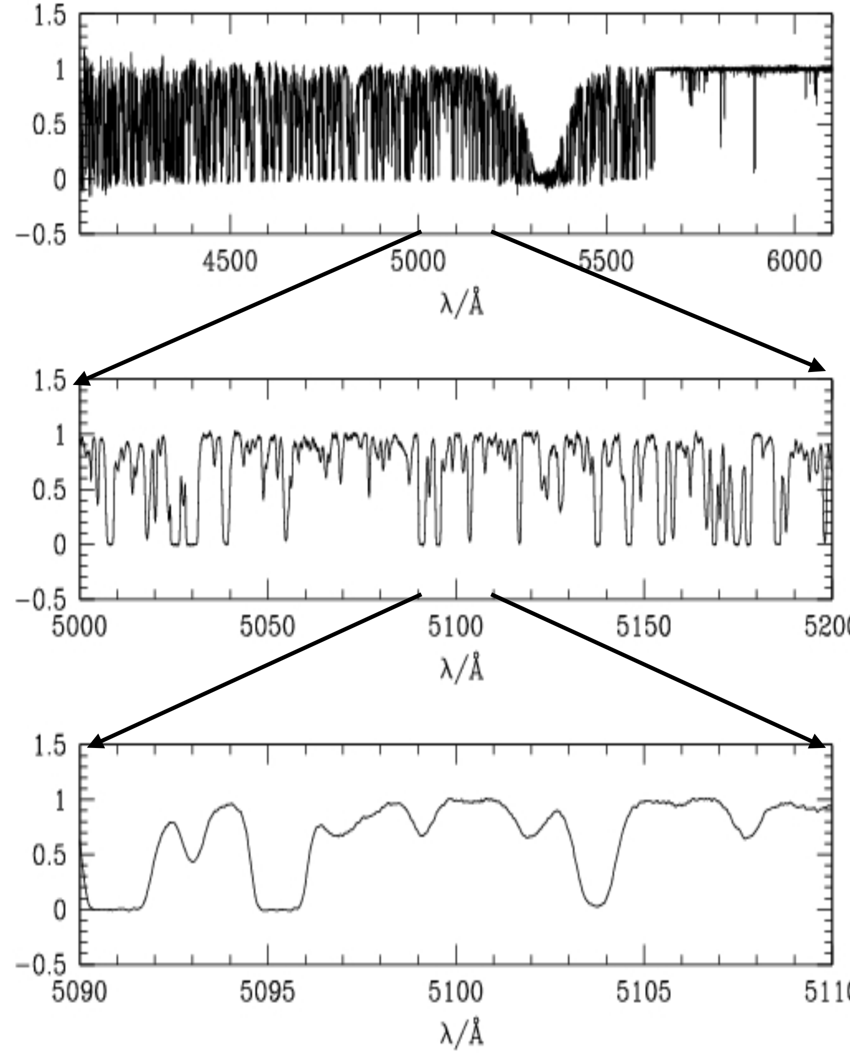
SDSS vs UVES



McDonald et al. 2005



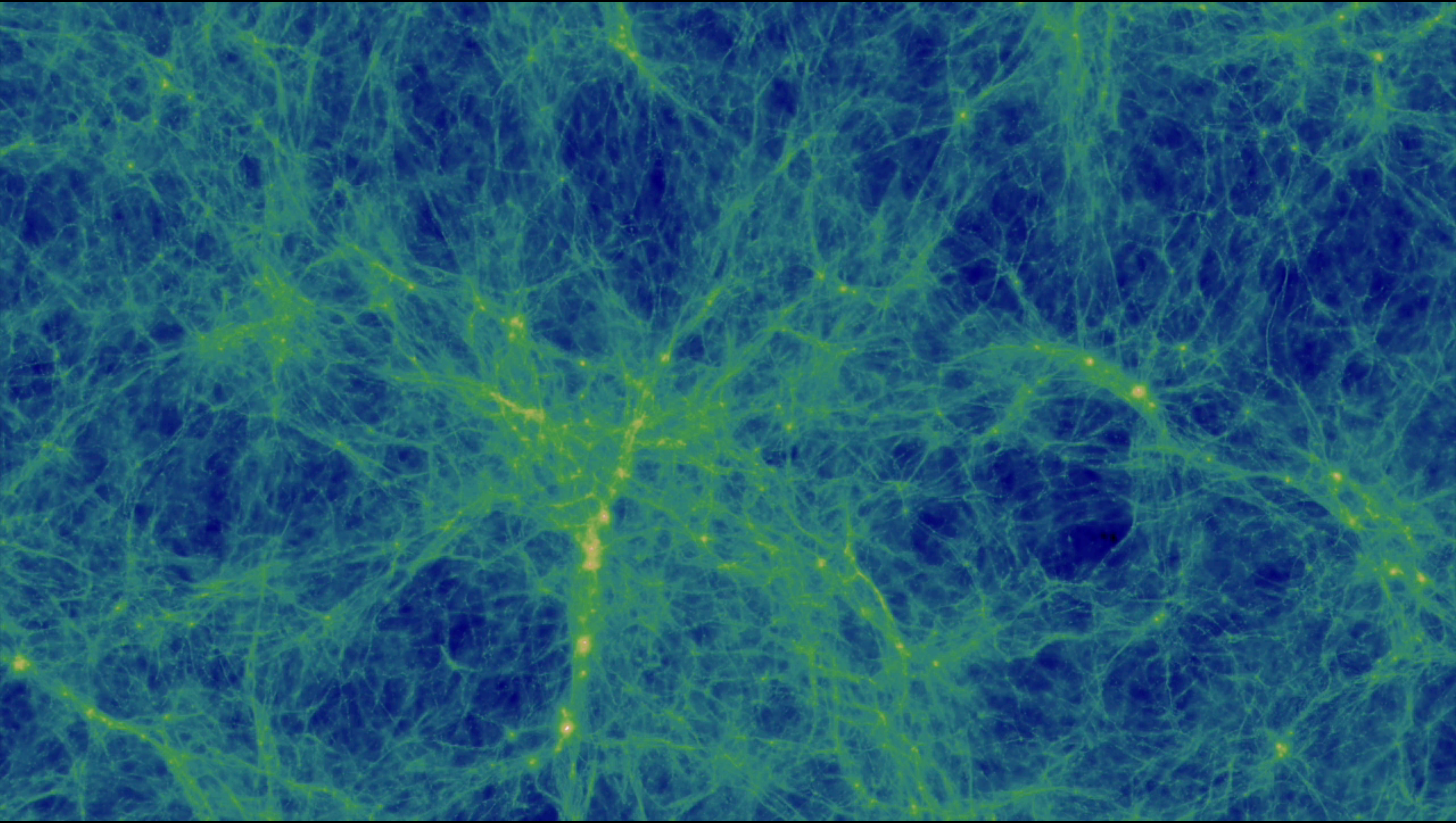

Kim, MV+ 2004




SDSS
~$10^4$ LOW RESOLUTION LOW S/N

vs

UVES/KECK etc.
~$10^2$ HIGH RESOLUTION HIGH S/N



Bolton+17, Sherwood simulation suite (PRACE: 15 CPU Mhrs)


Density
Temperature
z=49.0
HI fraction
Peculiar velocity

# Two key *unique* aspects

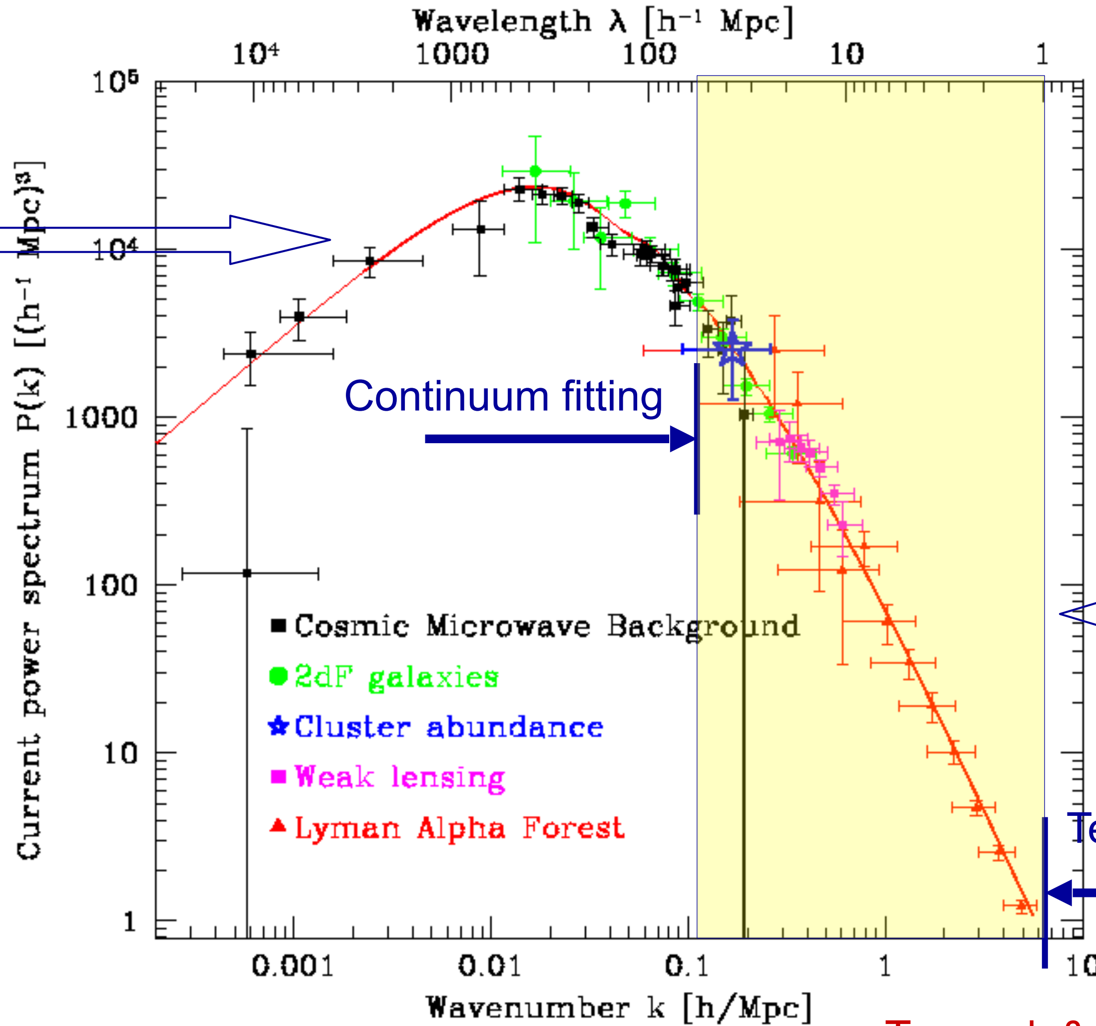
$$P_{1D}(k) = \frac{1}{2\pi} \int_k^\infty P_{3D}(x) x dx$$

High redshift (and small scales):
possibly closer to linear behaviour

# END OF IGM BASICS

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

CMB physics
z = 1100
dynamics




Continuum fitting

Lya physics
z < 6
dynamics
+
termodynamics

Temperature, metals, noise

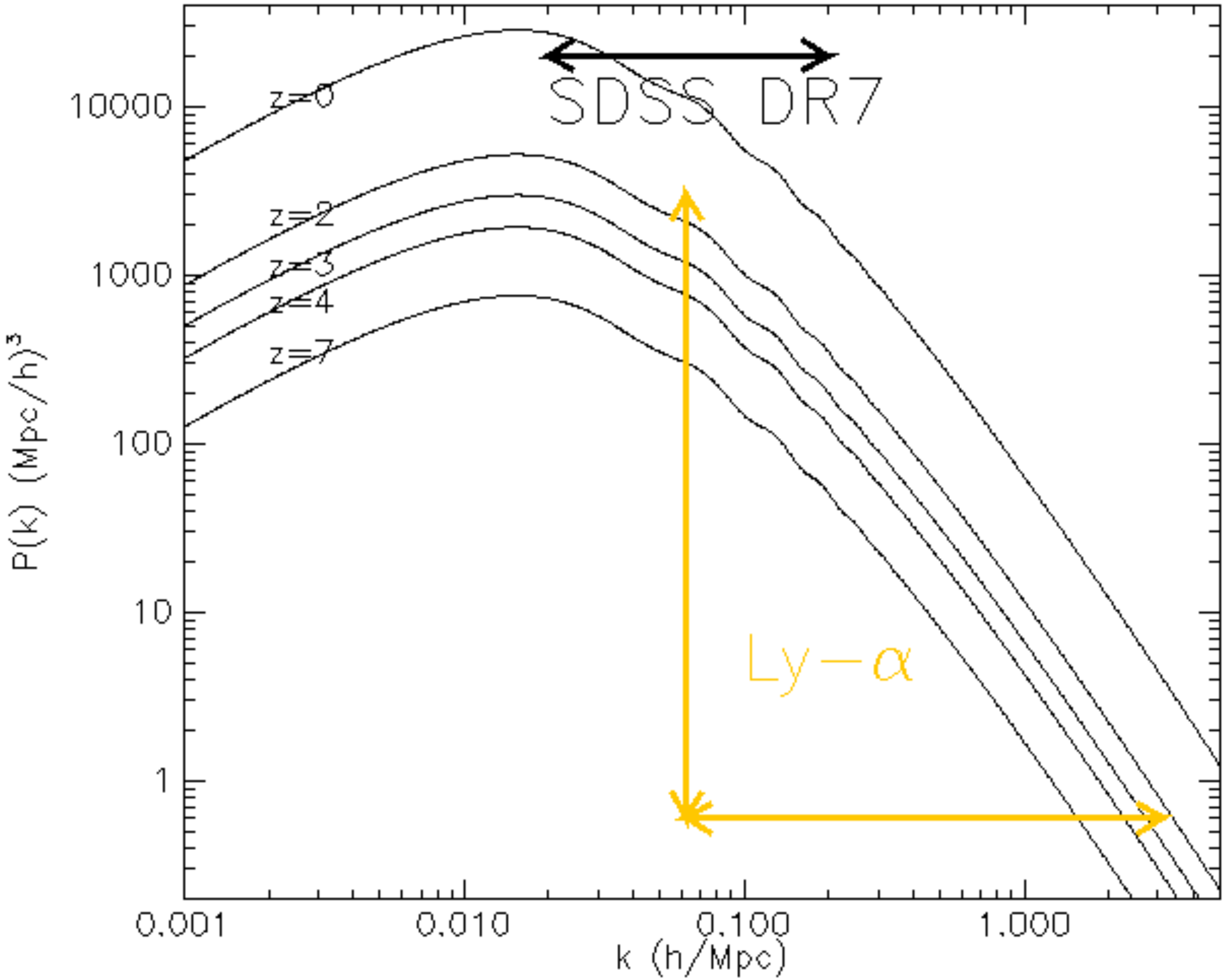
Tegmark & Zaldarriaga 2002

CMB + Lyman a → Long lever arm

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

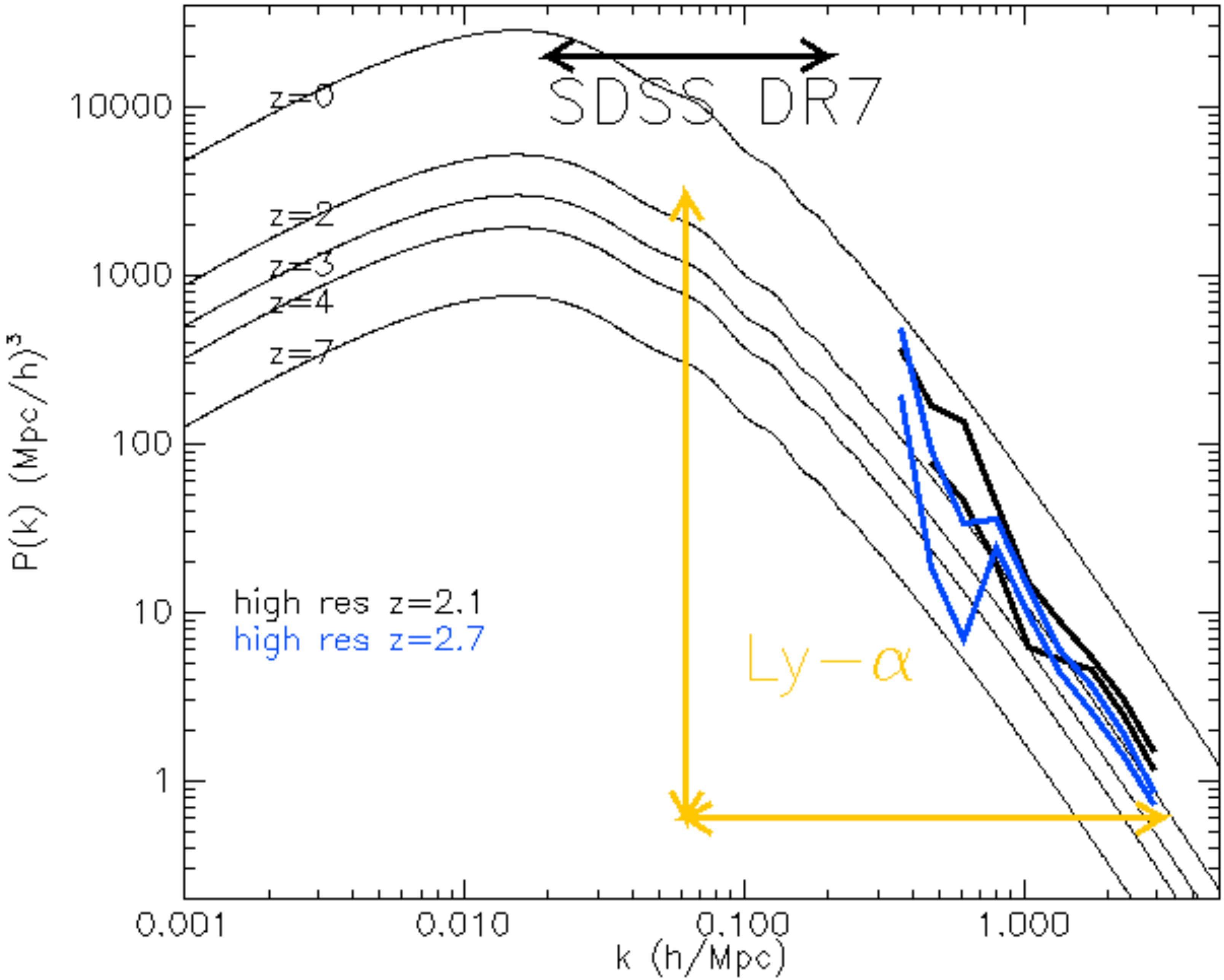
Constrain spectral index and shape

## DATA vs THEORY

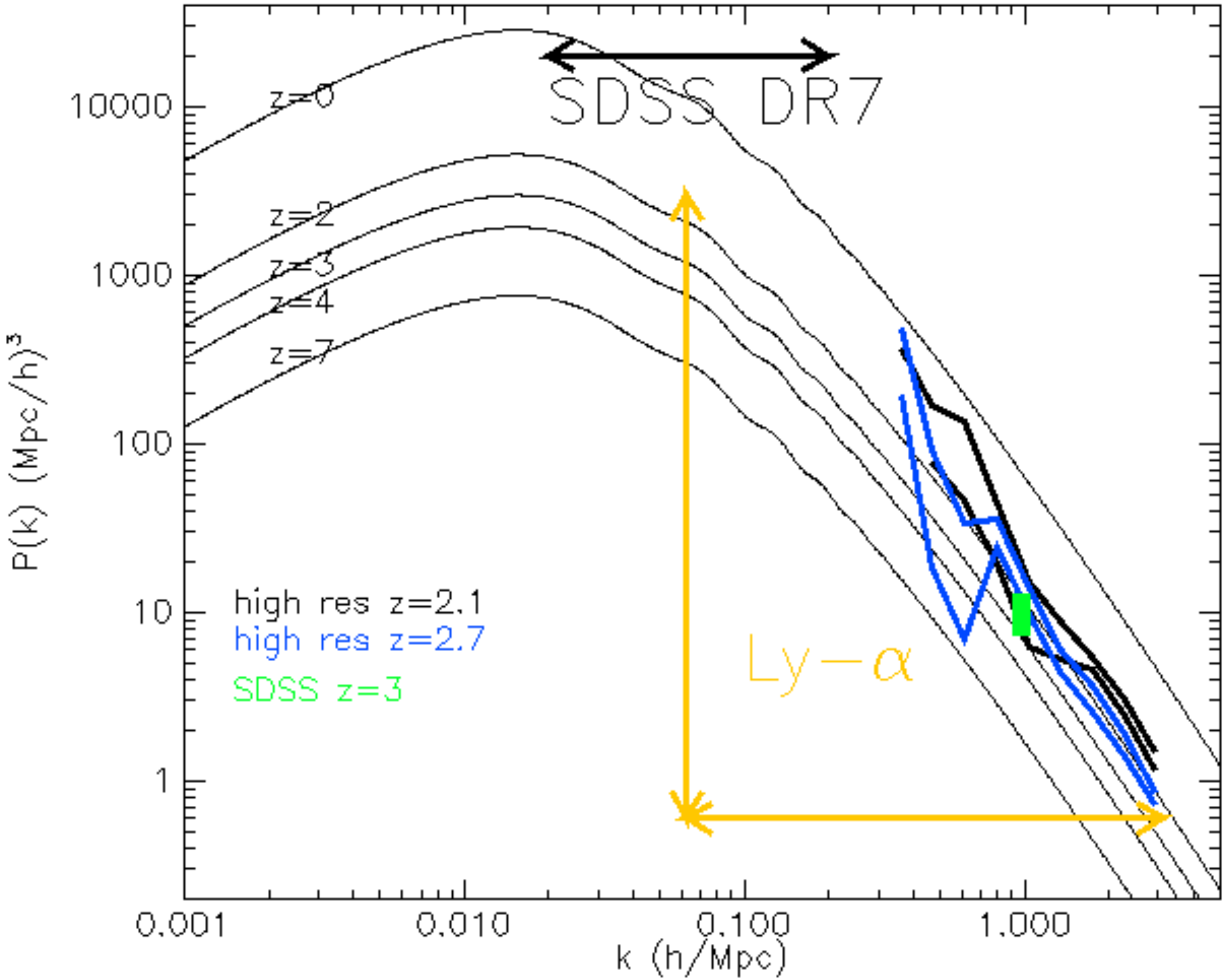


## DATA vs THEORY

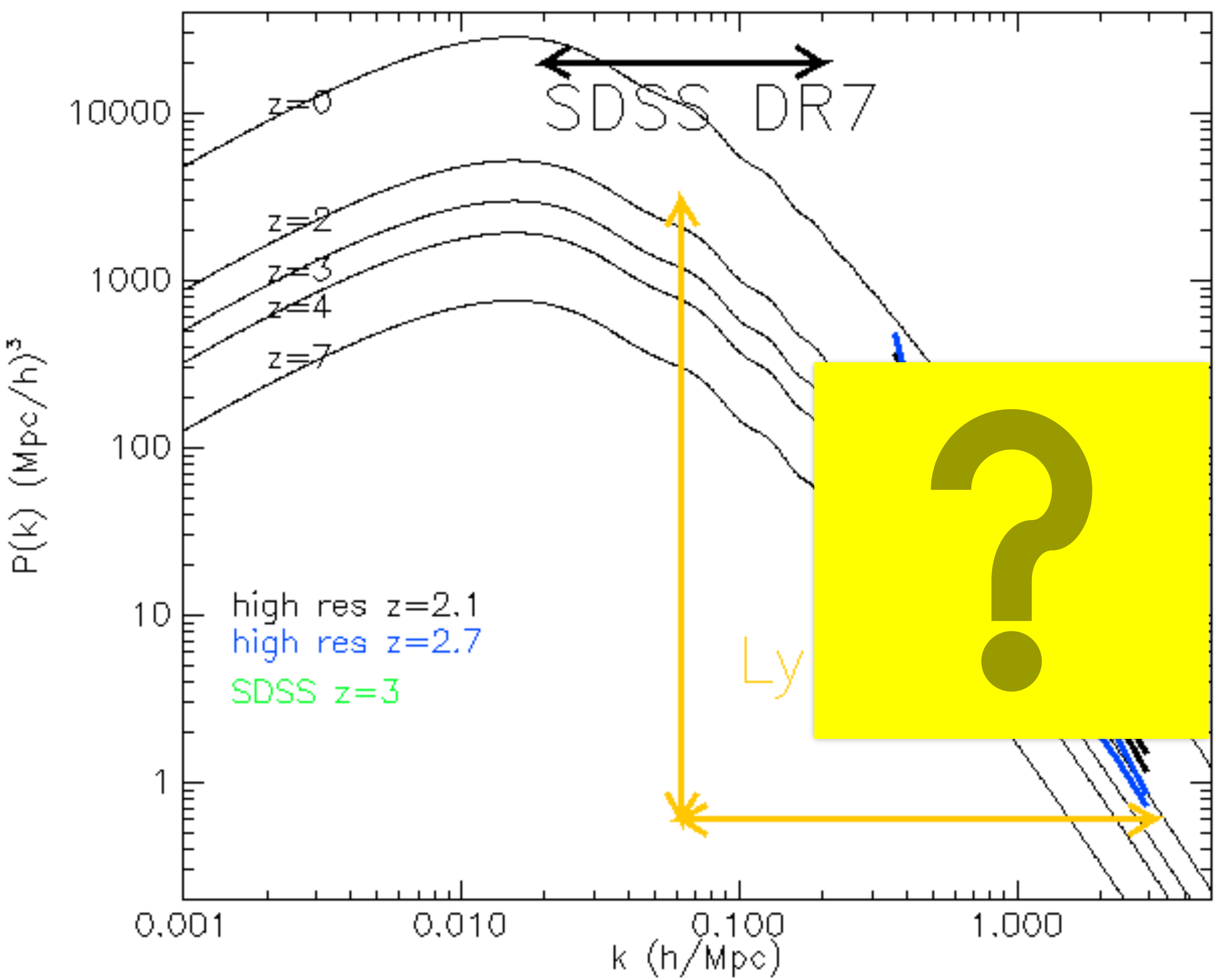
$$P_{FLUX}(k,z) = bias^2(k,z) \times P_{MATTER}(k,z)$$



## DATA vs THEORY



**DATA vs THEORY**



# THE EFFECTIVE BIAS METHOD - I

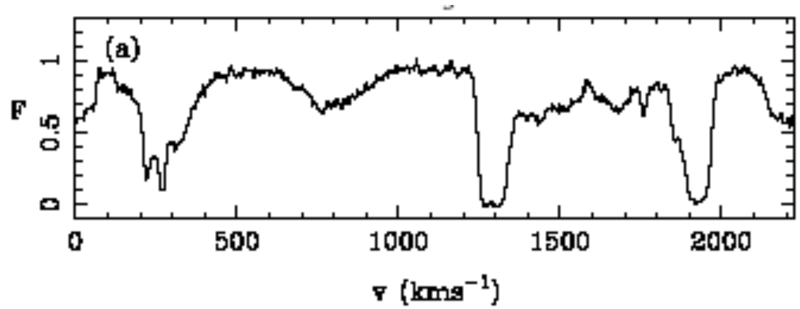
Croft et al. 1998, Croft et al. 1999

1- Convert flux to density pixels: F=exp(-A$\rho^{\beta}$) – Gaussianization (Weinberg 1992)

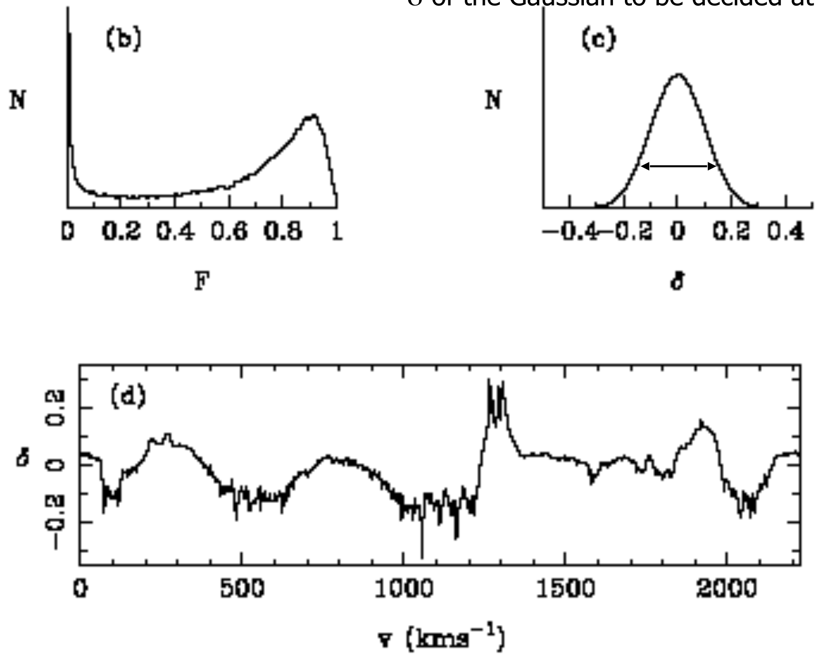
2- Measure $P_{1D}$(k) and convert to $P_{3D}$(k) by differentiation to obtain shape

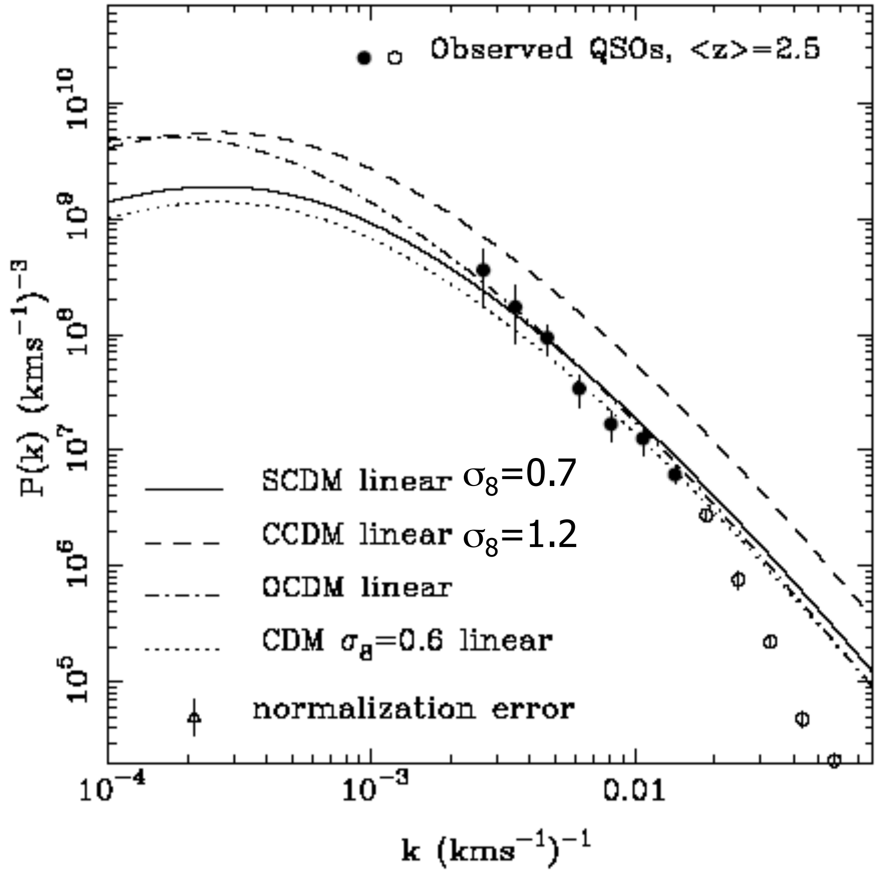
3- Calibrate $P_{3D}$(k) amplitude with (many) simulations of the flux power

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




σ of the Gaussian to be decided at step 3



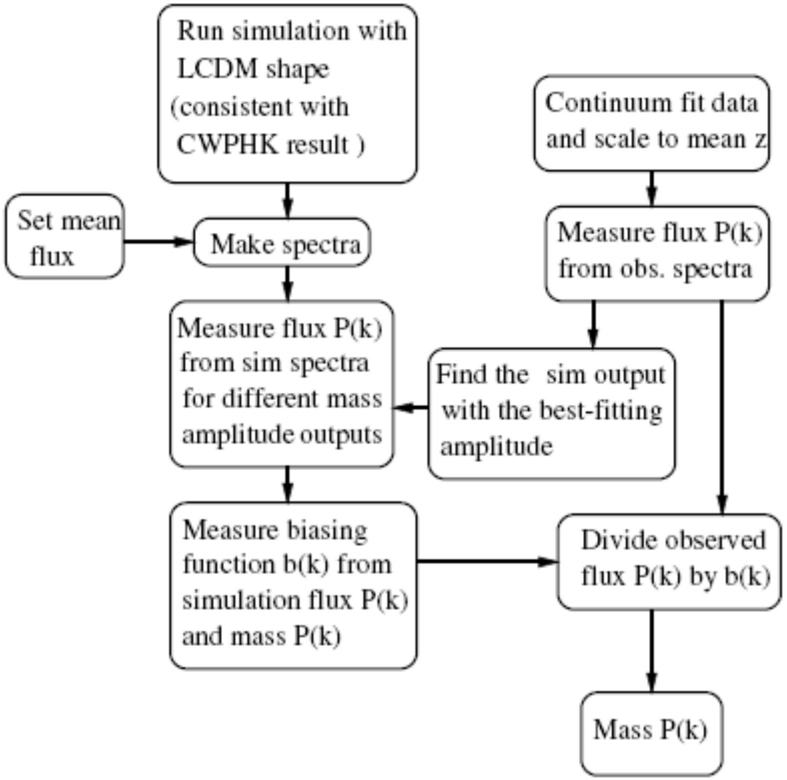




RESULTS:

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

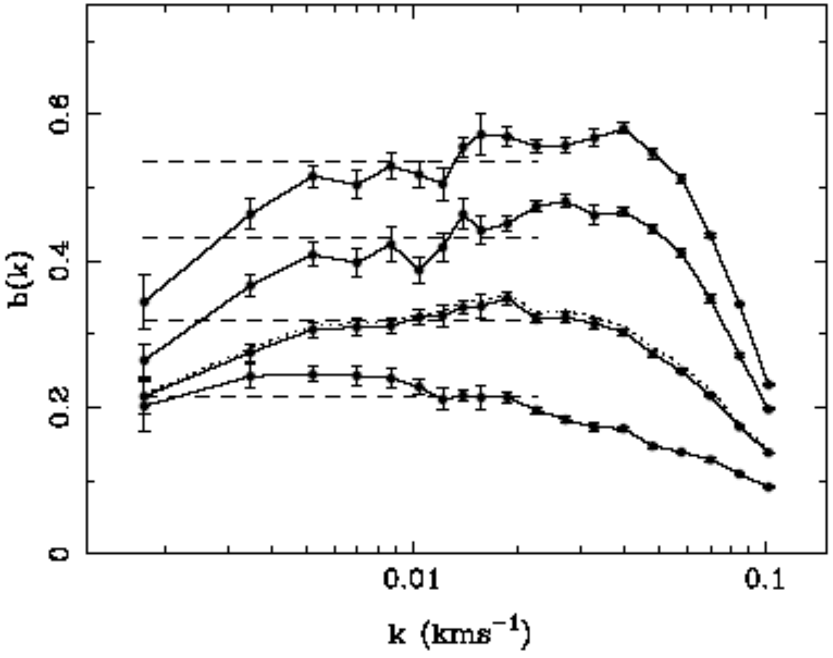
# THE EFFECTIVE BIAS METHOD - II

Croft et al. 2002



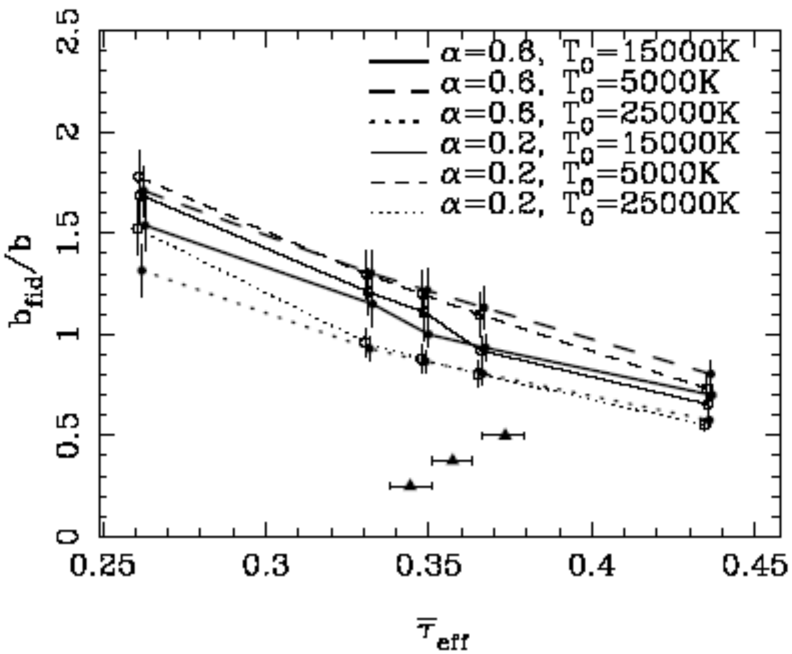

$$P_F(k) = b^2(k)\, P(k)$$

Scale and z dependent



# THE EFFECTIVE BIAS METHOD - III

Croft et al. 2002

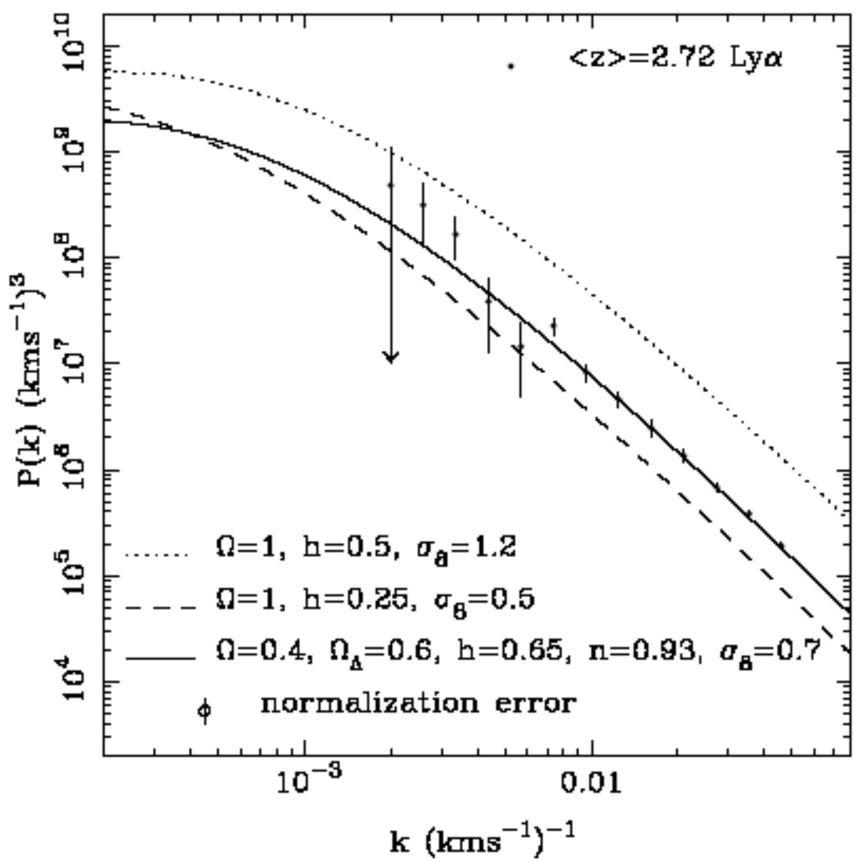



$$\frac{b_{\rm fid}}{b} = \left(\frac{\overline{\tau}_{\rm eff}}{0.349}\right)^{C_\tau} \quad C_\tau = -1.7$$

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

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

RESULTS →



# THE EFFECTIVE BIAS METHOD - IV

Gnedin & Hamilton 2002

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

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

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

Systematic errors

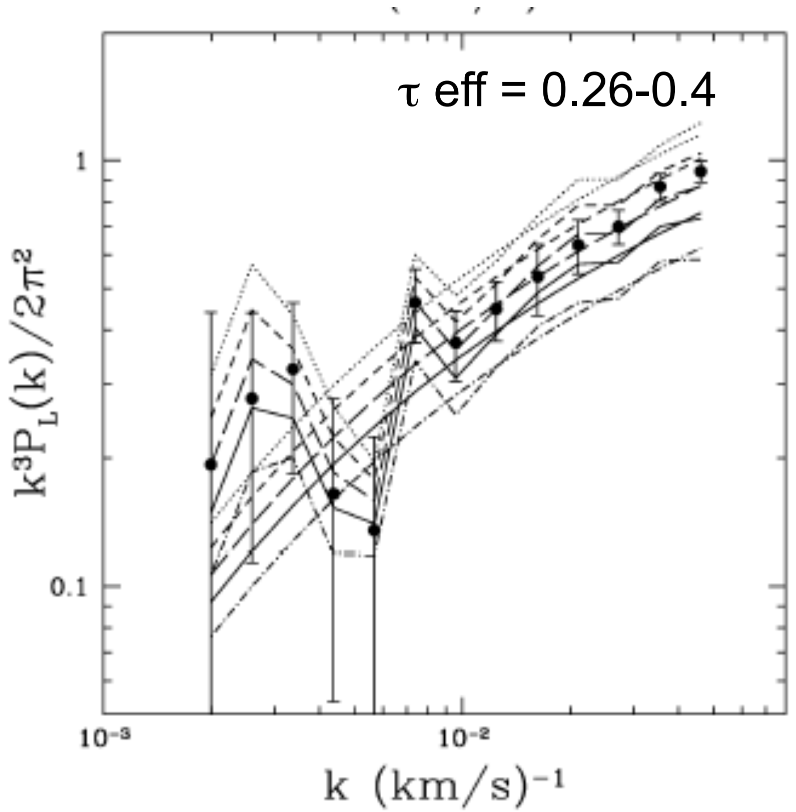
$$P_{\rm L}^{\rm obs}(k) = P_{\rm L}^{\rm fct}(k) Q_\Omega Q_T Q_\tau,$$

where

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

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

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

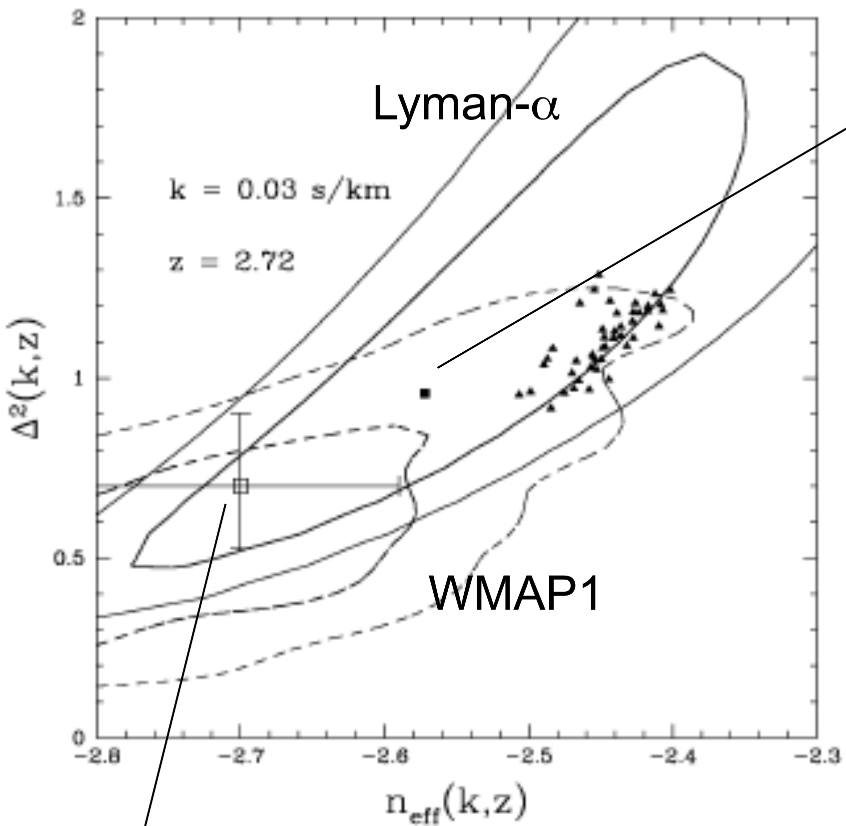



RESULTS: Croft et al. 02 method works (missing physics, bias function, smoothing by peculiar velocities) but this is mainly due to the fact that statistical errors are large and comparable to systematic errors

# 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

$\tau$ eff = 0.305 – 0.349

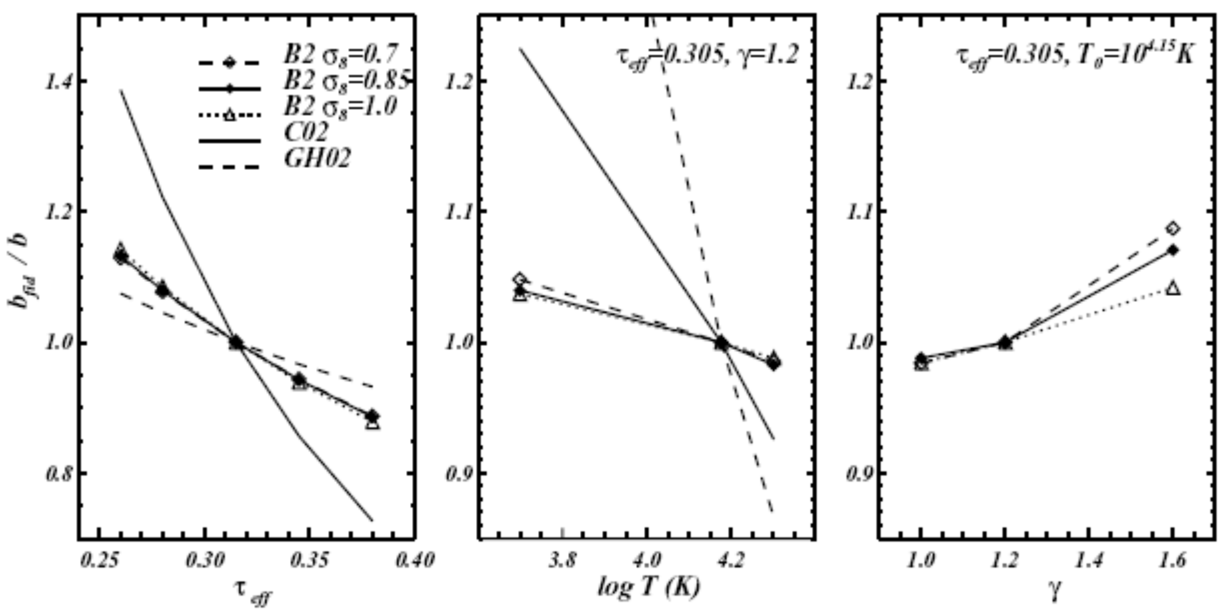
Value from
High res spectra

Value from
Low res. spectra

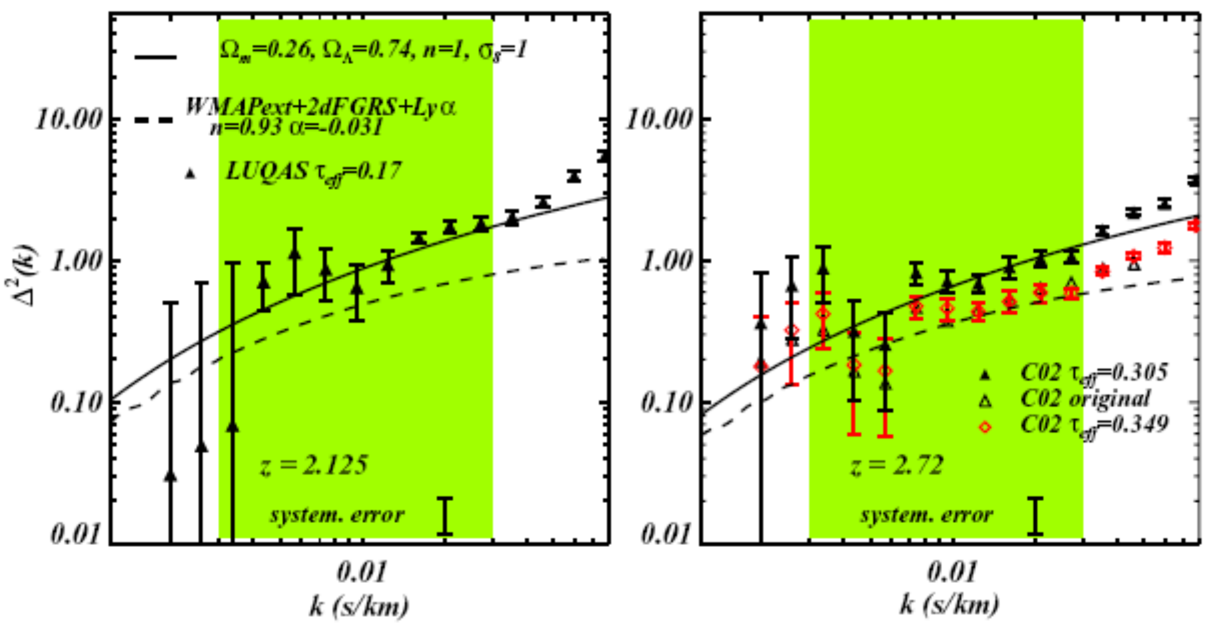
# THE EFFECTIVE BIAS METHOD, WMAP + a QSO sample (LUQAS)

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!)

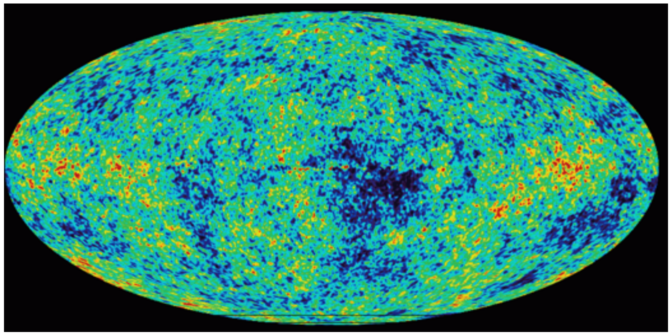
| ERRORS | CONTRIB. to R.M.S FLUCT. |
| --- | --- |
| Statistical error | 4% |
| Systematic errors | ~ 15 % |
| $\tau_{eff}(z=2.125)=0.17 \pm 0.02$ | 8 % |
| $\tau_{eff}(z=2.72) = 0.305 \pm 0.030$ | 7 % |
| $\gamma = 1.3 \pm 0.3$ | 4 % |
| $T_0 = 15000 \pm 10000$ K | 3 % |
| Method | 5 % |
| Numerical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

# FORWARD MODELLING OF THE FLUX POWER

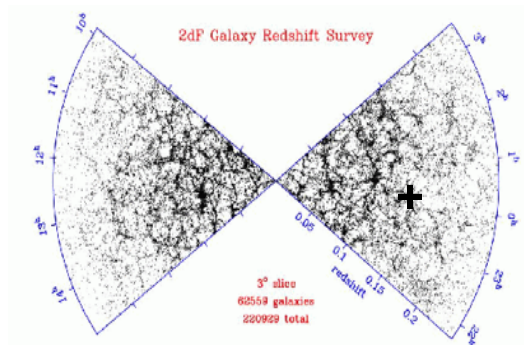
# The interpretation: full grid of simulations

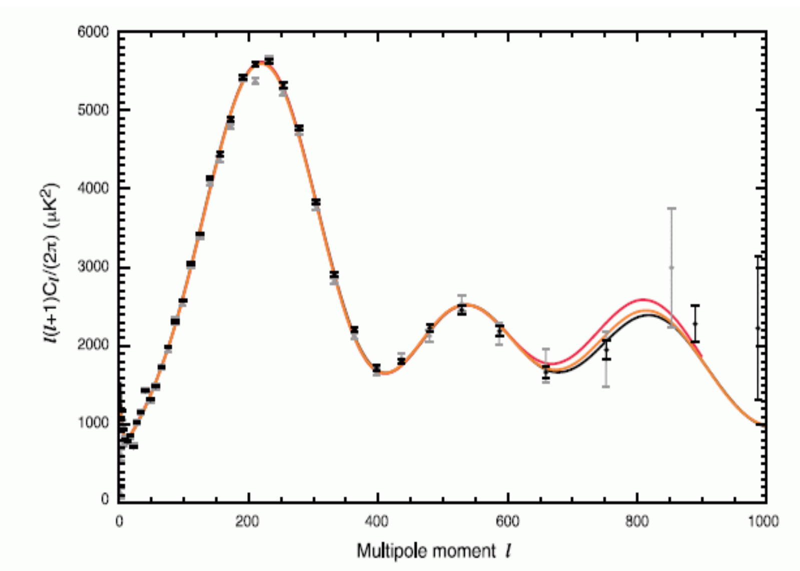
SDSS power analysed by forward modelling motivated by the huge amount of data with small statistical errors

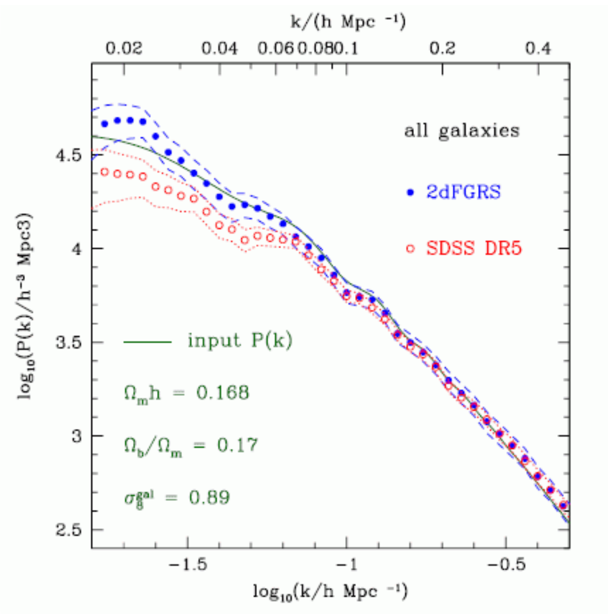
CMB: Spergel et al. (05)    Galaxy P(k): Sanchez & Cole (07)



+




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 $\Delta^2_L(k_p, z_p)$, $n_{\rm eff}(k_p, z_p)$, and $\alpha_{\rm eff}(k_p, z_p)$ (3).—Standard linear power spectrum amplitude, slope, and curvature on the scale of the Ly$\alpha$ forest, assuming a typical $\Lambda$CDM-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 $\Lambda$CDM. Fixed for main result.

Parameters $\bar{F}(z_p)$ and $\nu_F$ (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–Ly$\alpha$ cross-correlation term.

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

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

# Results Lyman-$\alpha$ only with full grid: amplitude and slope

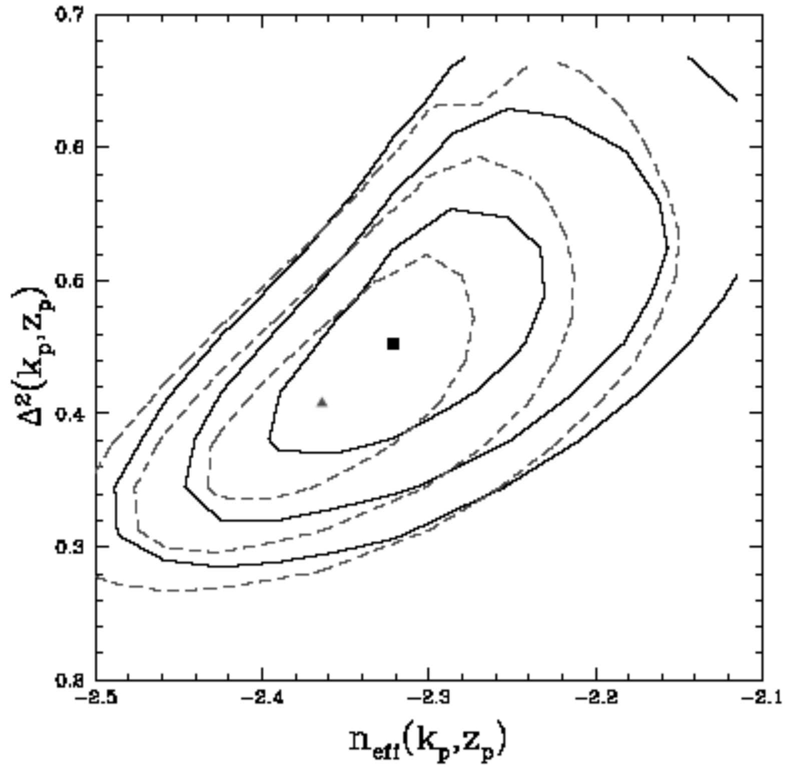
$$\Delta_L^2(k,\ z) \simeq \left[\frac{D(z)}{D(z_p)}\right]^2 \Delta_L^2(k_p,\ z_p) \quad \times \left[\frac{k}{k_*(z)}\right]^{3+n_{\rm eff}(k_p,z_p)+(1/2)\alpha_{\rm eff}(k_p,z_p)\ \ln[k/k_*(z)]}$$

$\chi^2$ 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

# FORWARD MODELLING OF THE FLUX POWER:

# A DIFFERENT APPROACH

# Flux Derivatives

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:

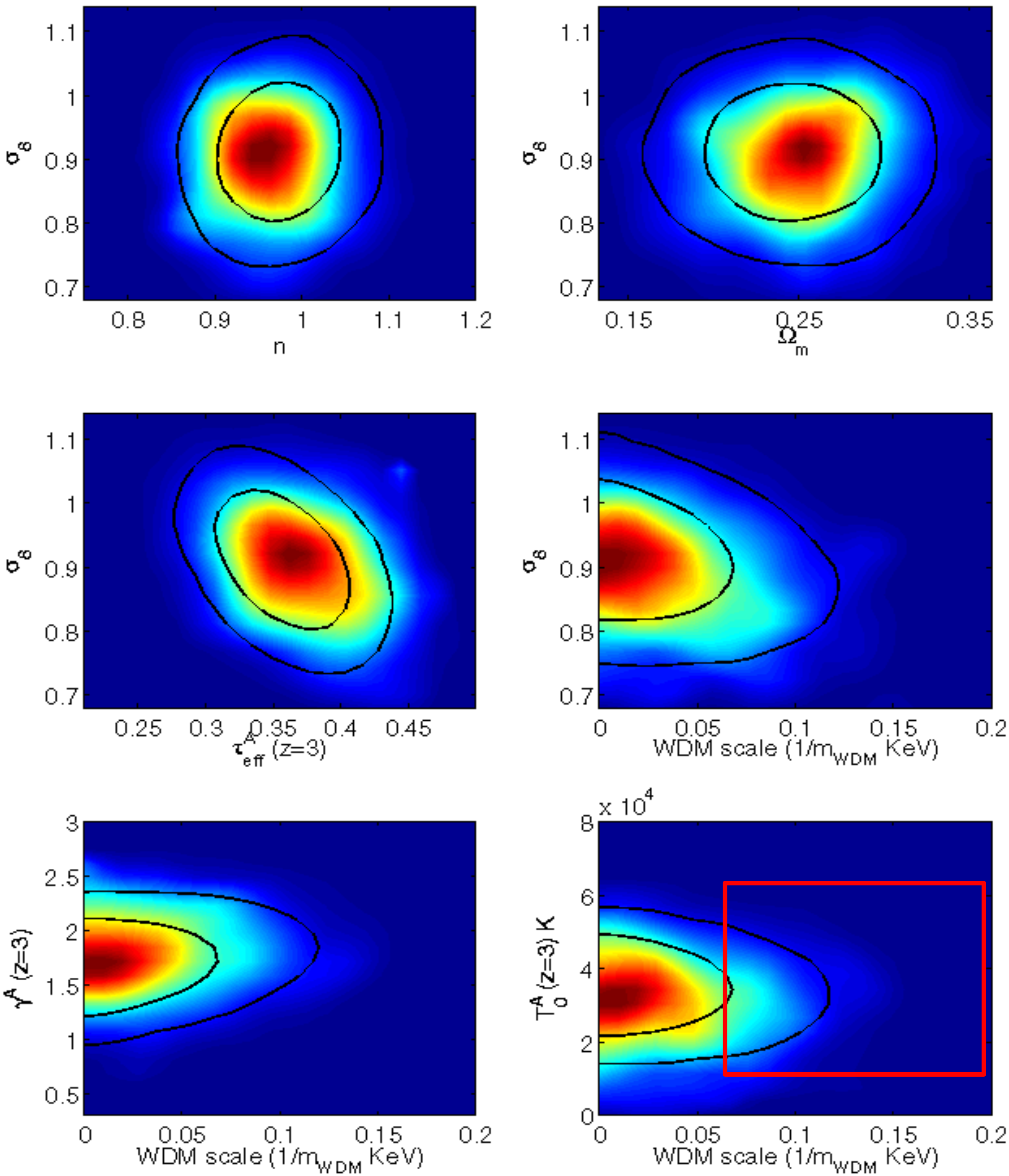
1- McDonald et al. 05 better sample the parameter space with poor sims
2- Viel & Haehnelt 06 rely on hydro simulations, but probably error bars are underestimated
3- Palanque-Delabrouille+15,+16 (new BOSS data) uses method 2

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-$\alpha$
only !!

FLUX DERIVATIVES method
of lecture 2

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

SDSS data only

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