9/29/04

Simulating The Intergalactic Medium

Tom Theuns

Craig Booth
Claudio Dalla Vecchia

SNS ASTROPHYSICS

Joop Schaye & Anthony Aguirre

Emmanuel Rollinde, Srianand

Tae-Sun Kim, Michael Rauch, W Sargent, P Petitjean, H Chand,
S Zaroubi, M Viel, S Kay

Specials of the day:

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Introduction: the IGM seen in quasar spectra

continuum fitting and the problem of echelle spectrographs

Hydrogen transitions, the Lya forest, and metal lines

Theoretical Paradigm / Numerical Modelling

What goes into the simulations? What comes out? Codes.

Photo-ionisation heating

The Pixel Optical Depth method: a new way for analysing QSO spectra

Applications : - metal pollution, the UV background

18 hour Keck spectrum of quasar 1422+231

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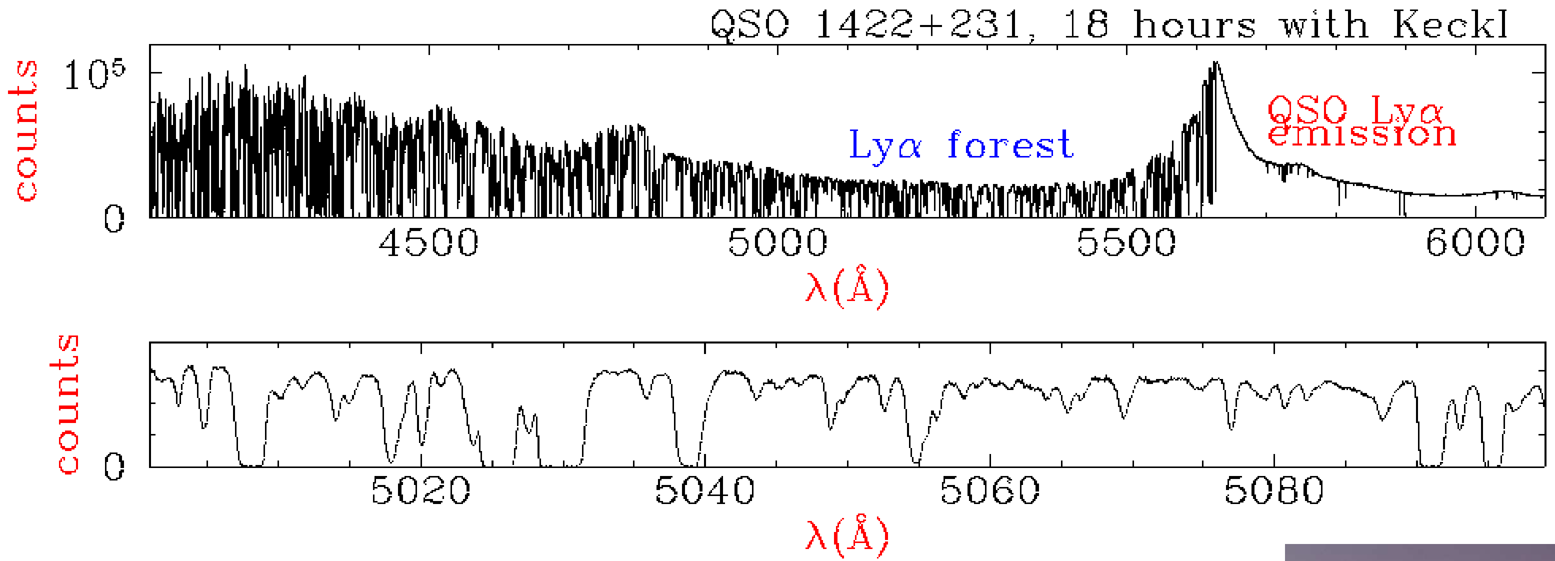

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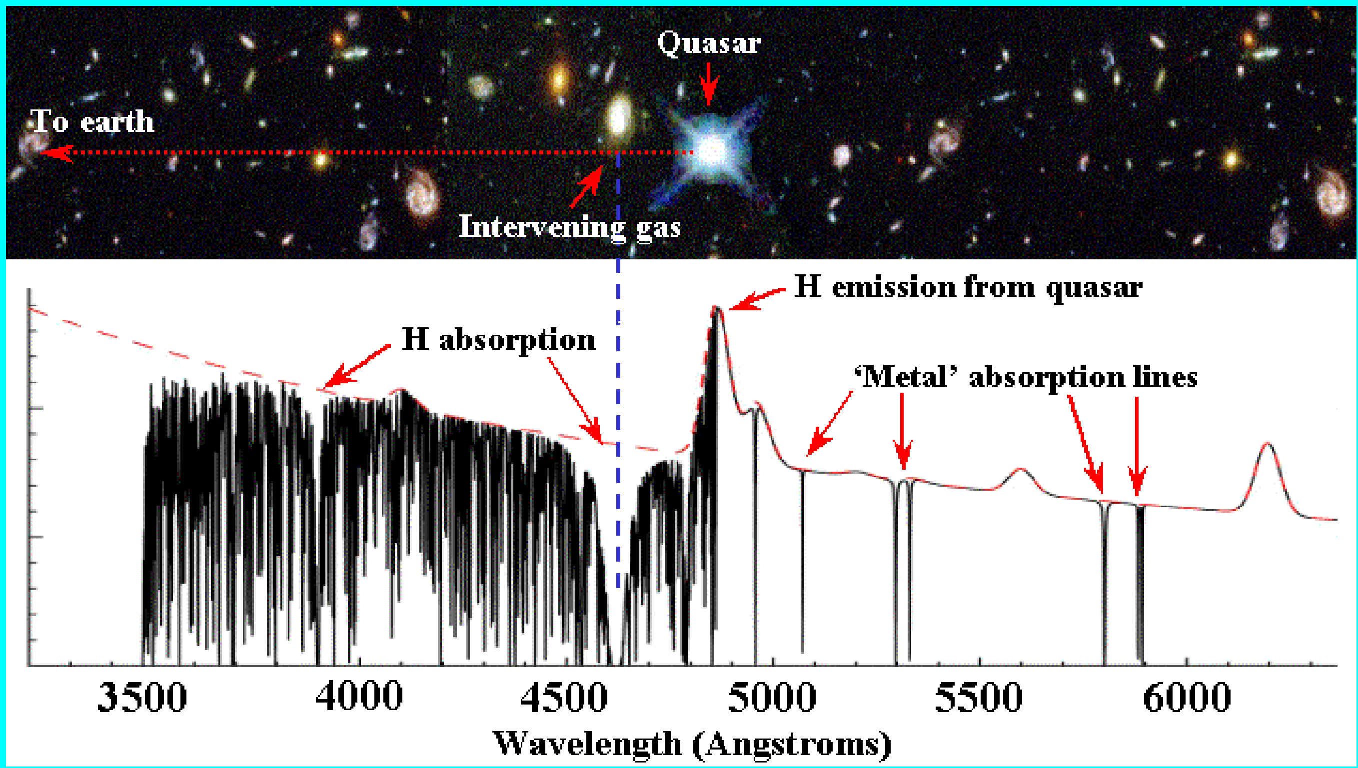
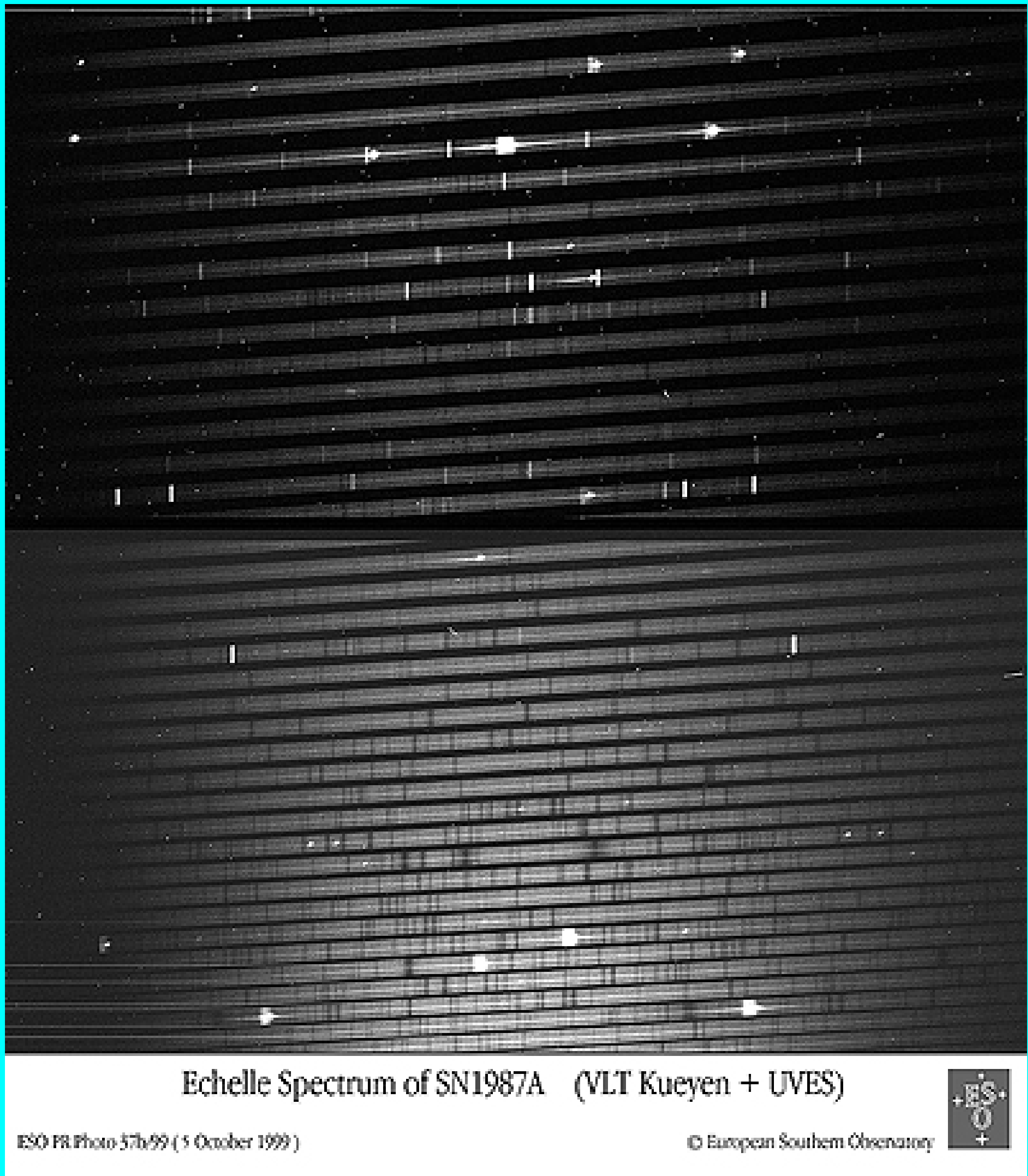
What are all these absorption lines? The old paradigm



What is an echelle spectrograph?



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Data reduction and The Art of Continuum Fitting

$$\exp(-\tau) \equiv \text{Transmission} = \frac{\text{Observed Flux}}{\text{Emitted Flux}}$$

What is the shape of the intrinsic QSO spectrum (i.e. Emitted Flux)?

How do you take into account the varying sensitivity of the CCD?

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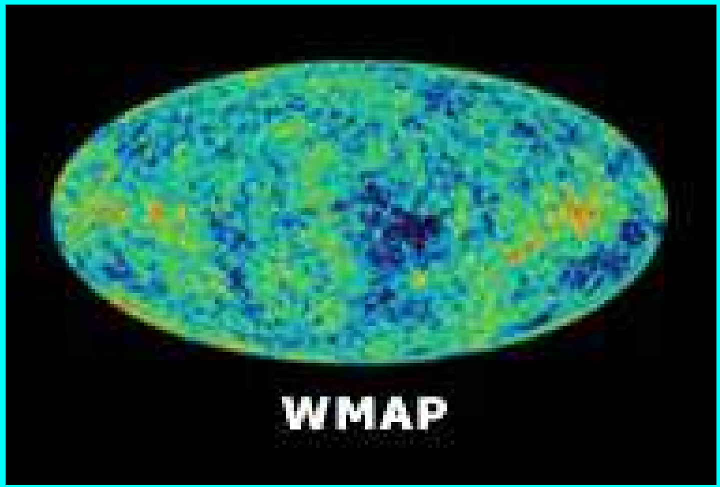
Theoretical paradigm

Structure formation (ΛCDM)

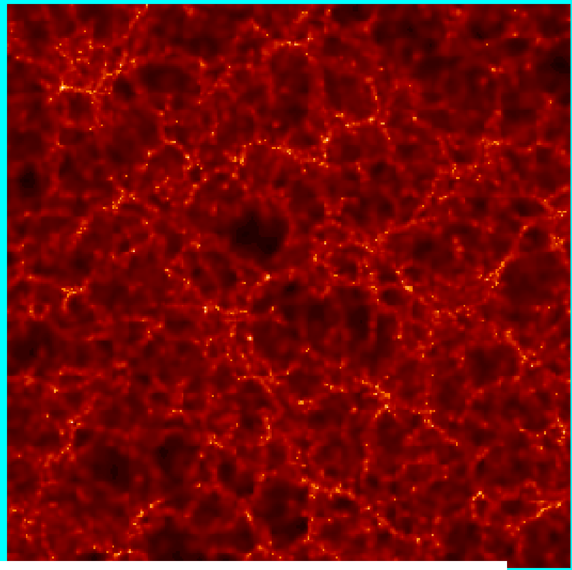
Ionising radiation

Ingredients:

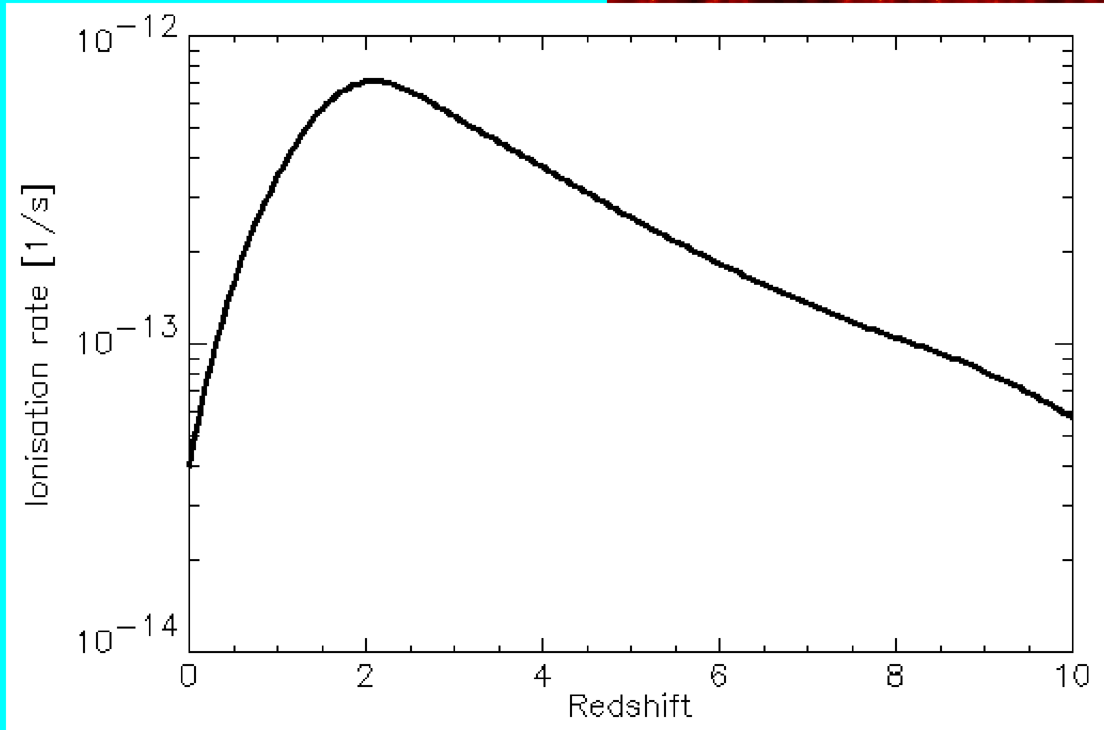
Structure formation



Gravity



Ionising background



Gas physics: photo-ionisation 9/29/04

$$\Gamma = \int_{\nu_0}^{\infty} \frac{J(\nu)}{h\nu}\,\sigma(\nu)\,d\nu$$

$$\epsilon = \int_{\nu_0}^{\infty} \frac{J(\nu)}{h\nu}\,\sigma(\nu)\,(h\nu - h\nu_0)\,d\nu$$

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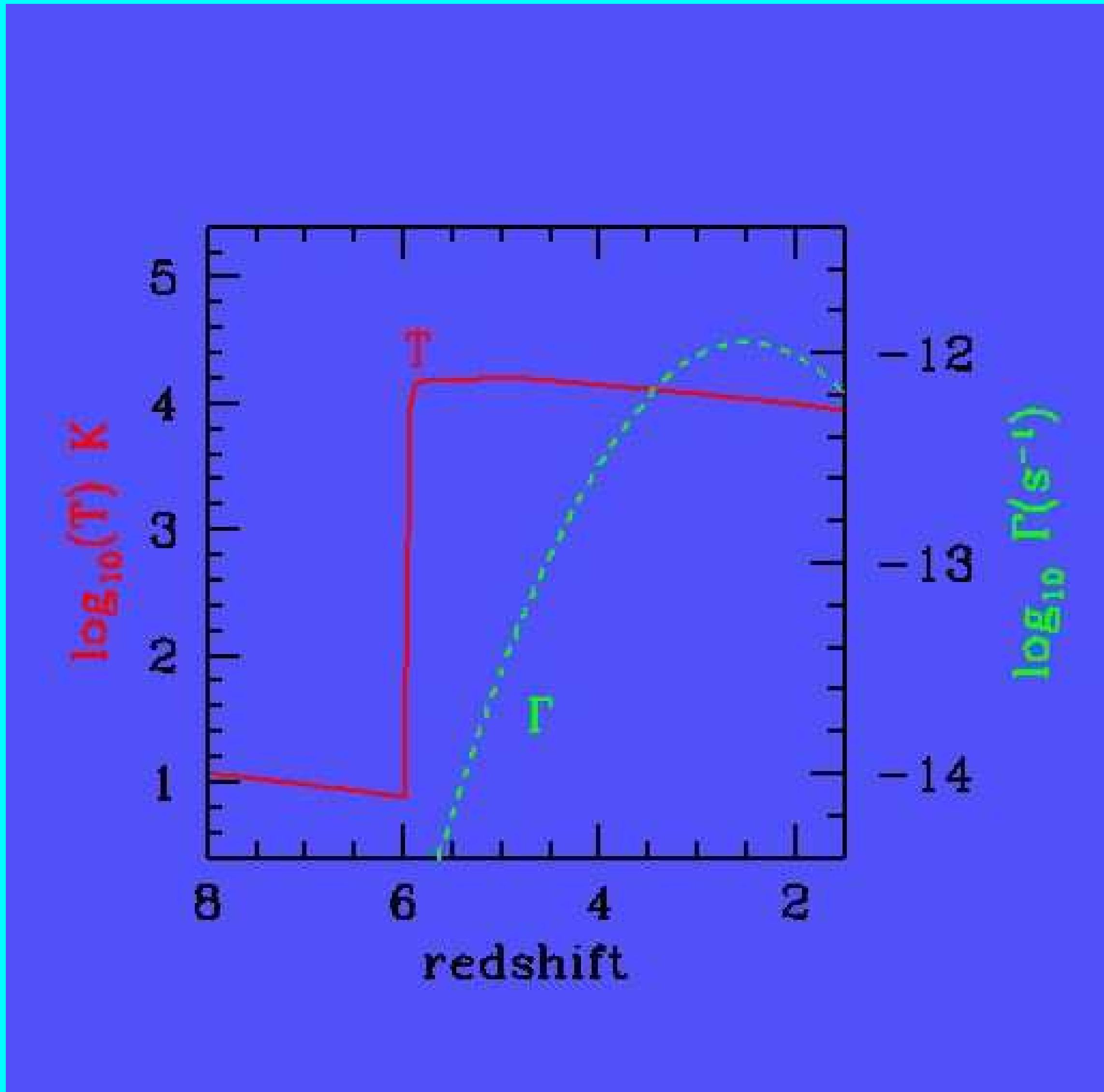

An imposed UV-background heats and ionizes the Intergalactic Medium

$$\Gamma = \int_{\nu_0}^{\infty} \frac{J(\nu)}{h\nu}\, \sigma(\nu)\, d\nu$$

$$\epsilon = \int_{\nu_0}^{\infty} \frac{J(\nu)}{h\nu}\, \sigma(\nu)\, (h\nu - h\nu_0)\, d\nu$$

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$$\frac{dn}{dt} = \alpha\, \rho^2 - \Gamma\, n$$

$$\rho\, \frac{dT}{dt} = \epsilon\, n$$

$$\Gamma = \int_{\nu_0}^{\infty} \frac{J(\nu)}{h\nu}\,\sigma(\nu)\,d\nu$$

$$\epsilon = \int_{\nu_0}^{\infty} \frac{J(\nu)}{h\nu}\,\sigma(\nu)\,(h\nu - h\nu_0)\,d\nu$$

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$$\frac{dn}{dt} = \alpha\,\rho^2 - \Gamma\,n$$

$$\rho\,\frac{dT}{dt} = \epsilon\,n$$

$$\frac{n}{\rho} = \frac{\alpha}{\Gamma}\rho$$

$$\frac{dT}{dt} = \epsilon\,\frac{n}{\rho} = \frac{\alpha\epsilon}{\Gamma}\rho$$

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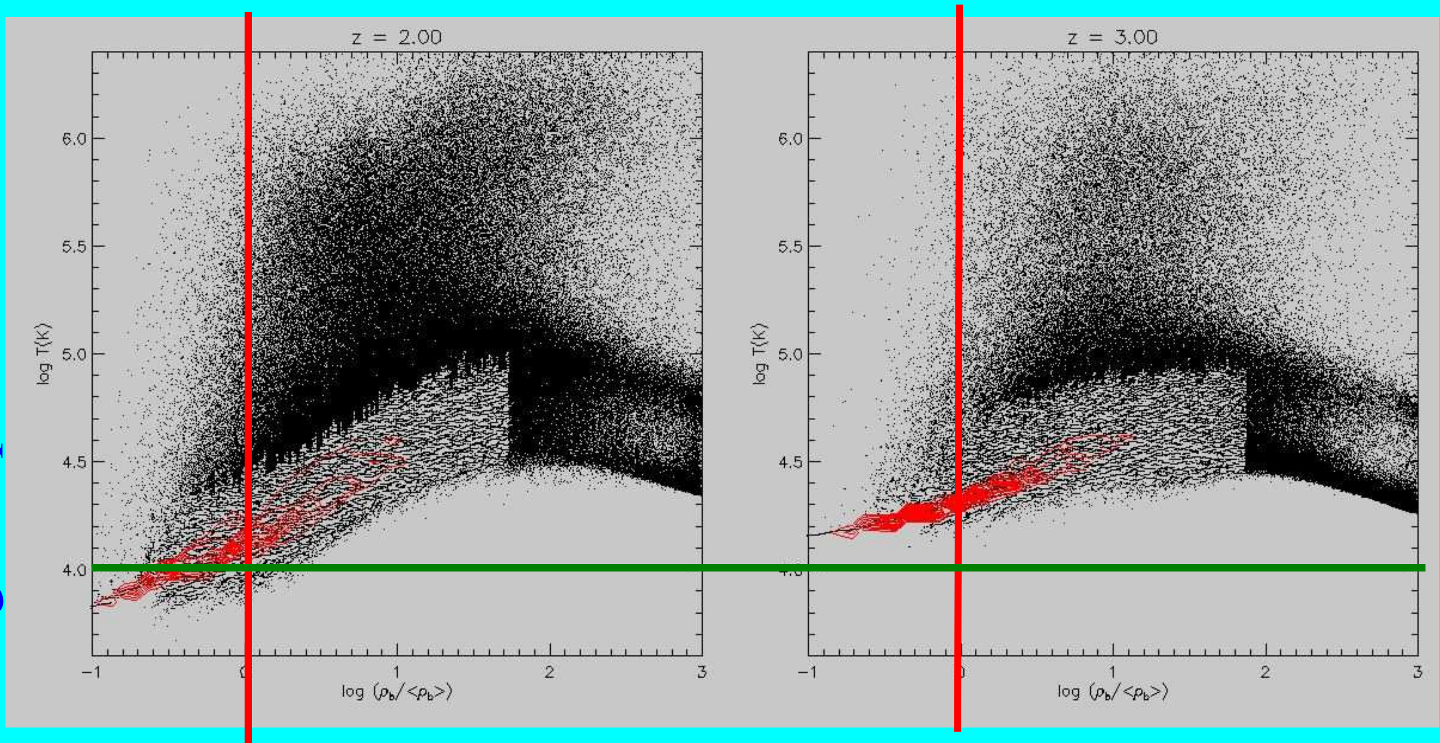
Redshift z=2 Redshift z=3

Log Temperature (K)



10000K

Log density/mean density

... introducing a power-law temperature-density relation

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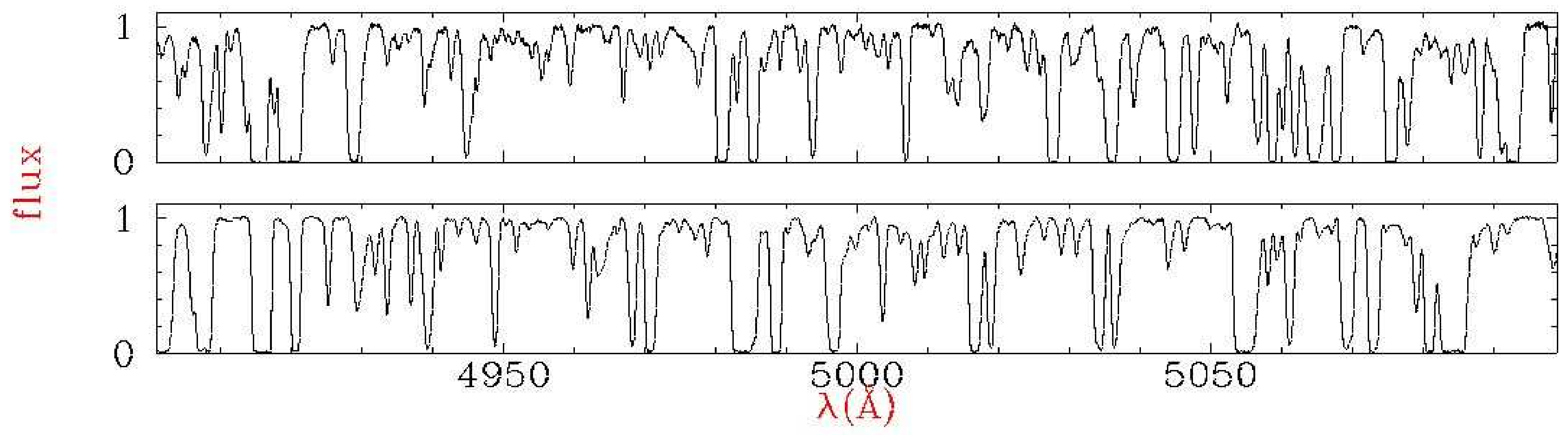
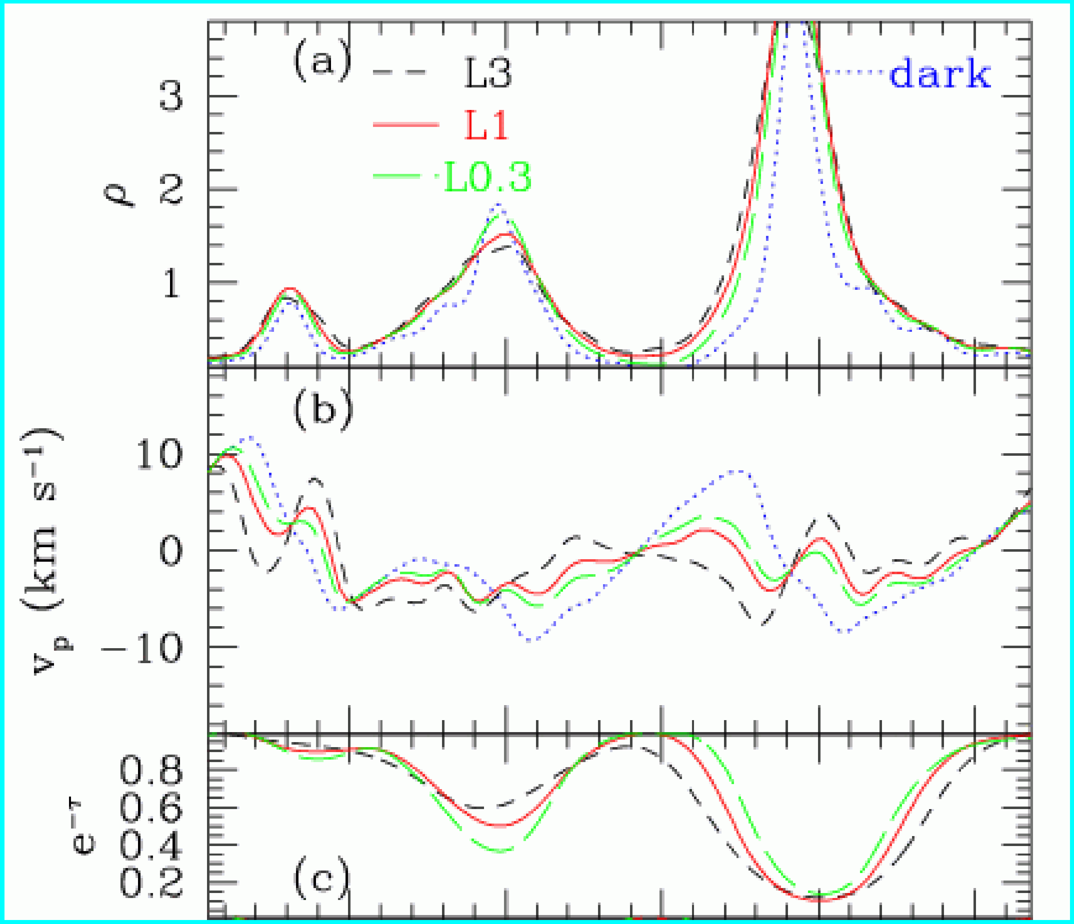
The simulated forest looks very much like the observed one





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The photo-ionised gas is also heated, and therefore spills out of the potential wells of the filaments

TT, Schaye & Haehnelt '00

Data analysis: line fitting.

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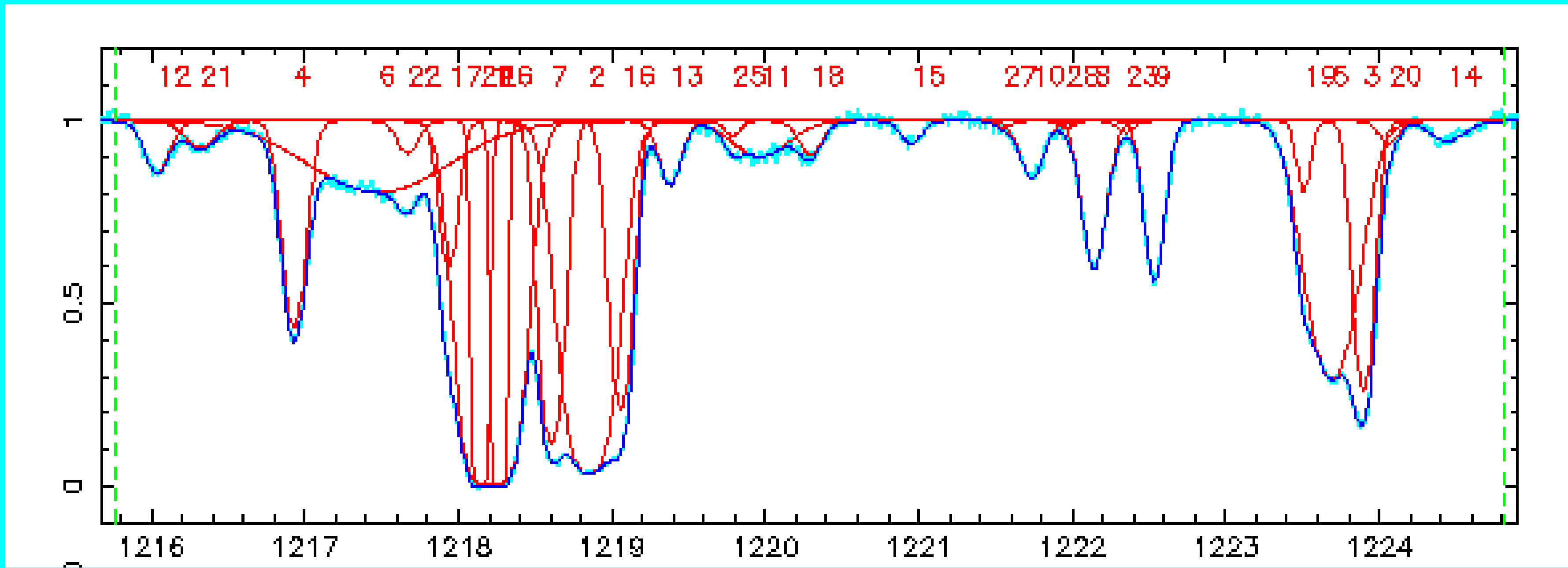

Each line is 'fitted' as a blend of Voigt profiles

Each Voigt profile has (1) position,
(2) width 'b' (km/s),
(3) column density N (neutral/cm^2)

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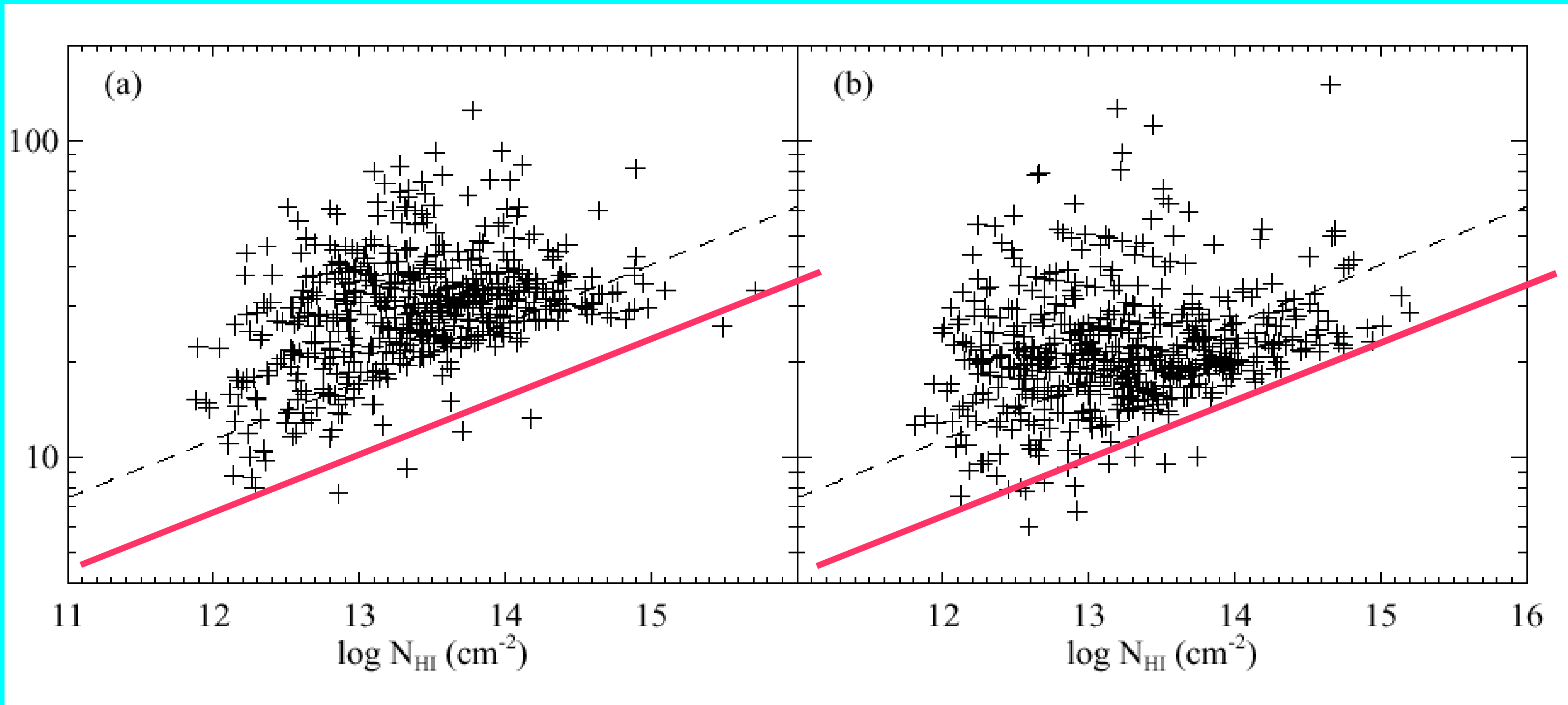
There is a relation between the line-widths and the temperature of the gas.



Unfortunately, line-fitting is rather ill defined ...

Schaye, TT, Leonard, Efstathiou '99

Comparison simulations and data suggest Helium reionisation causes the lines to widen around z=3.4

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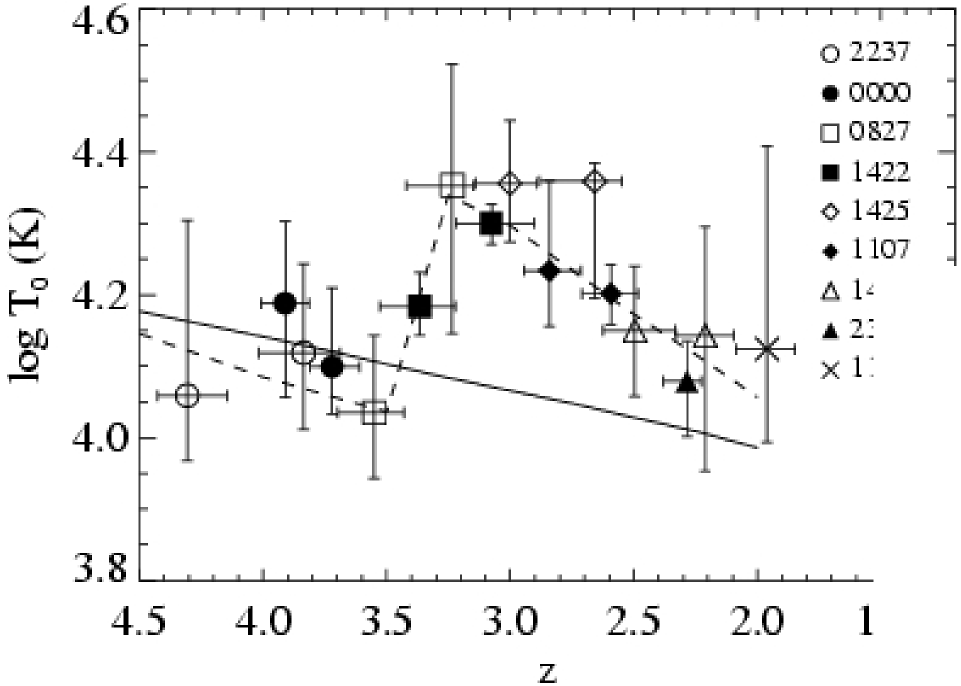
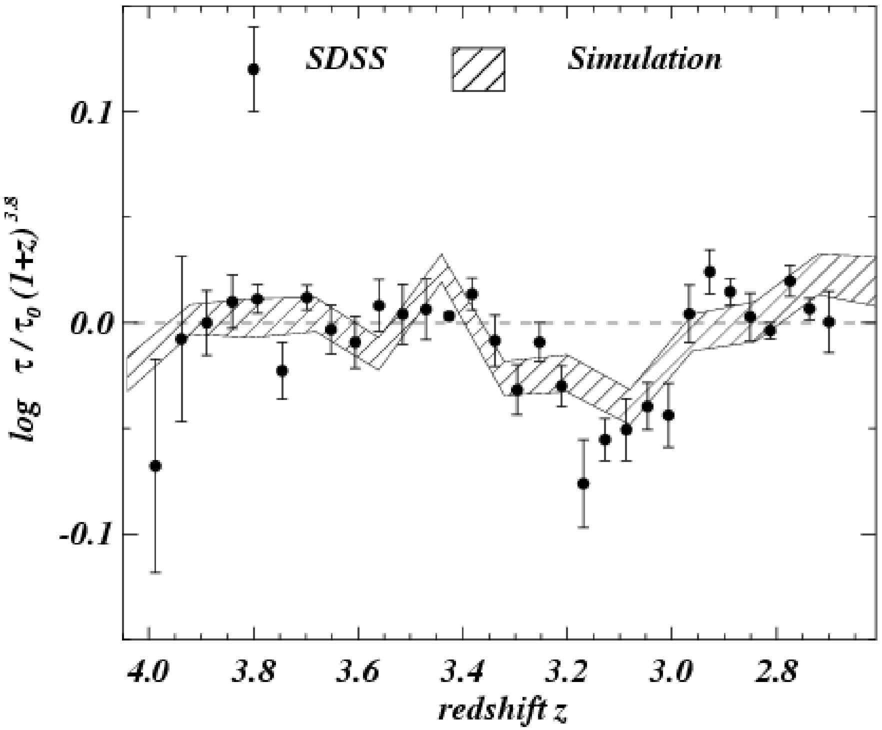


Schaye, TT, Rauc, Efstathiou, & Sargent '00



This has also an observable effect on the mean flux.

TT et al. 2002

A new way to analyse spectra: the Pixel Optical Depth method)

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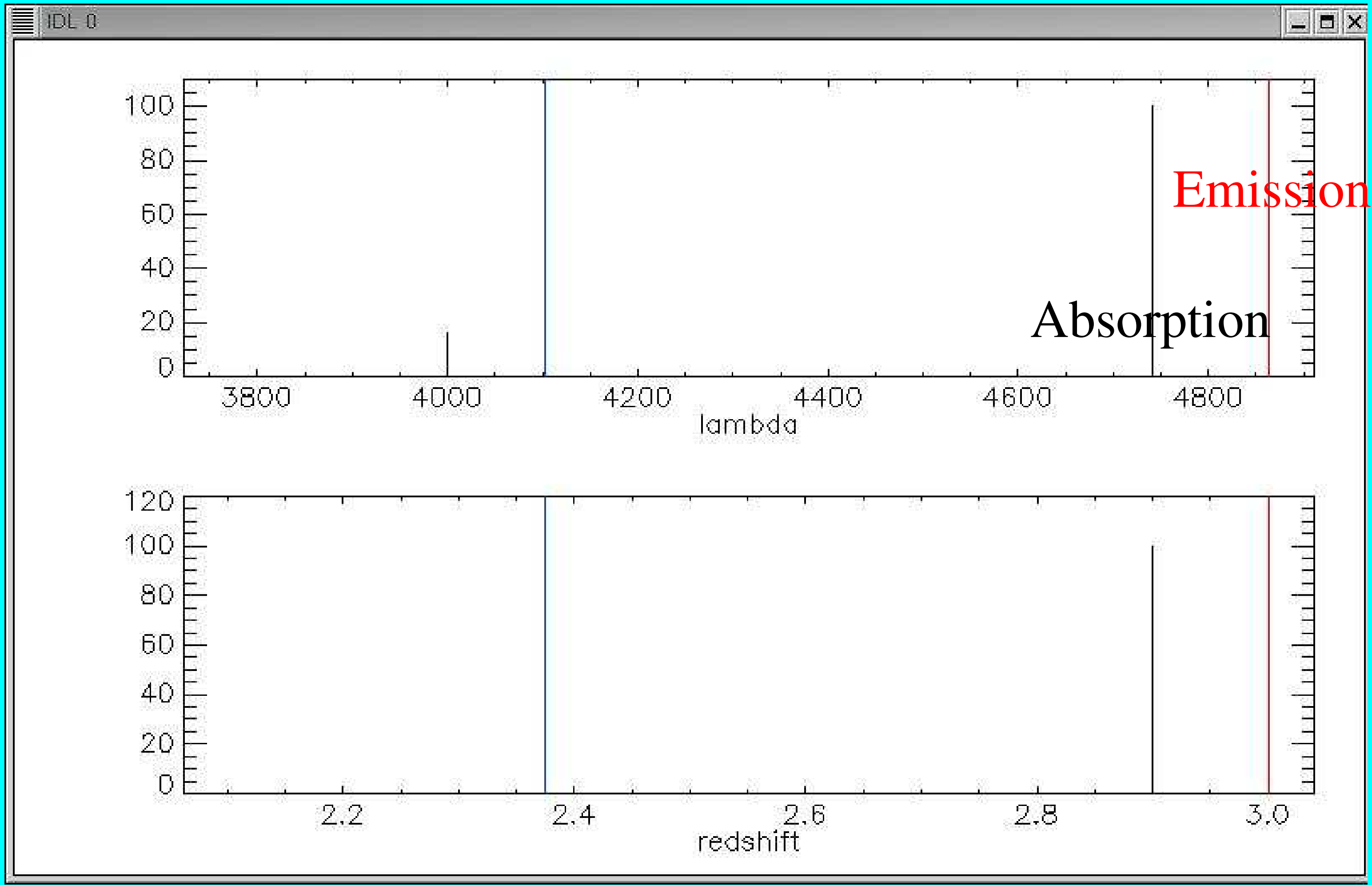
Suppose you observe a quasar at redshift 3.0 ....



Lyman β

Lyman α

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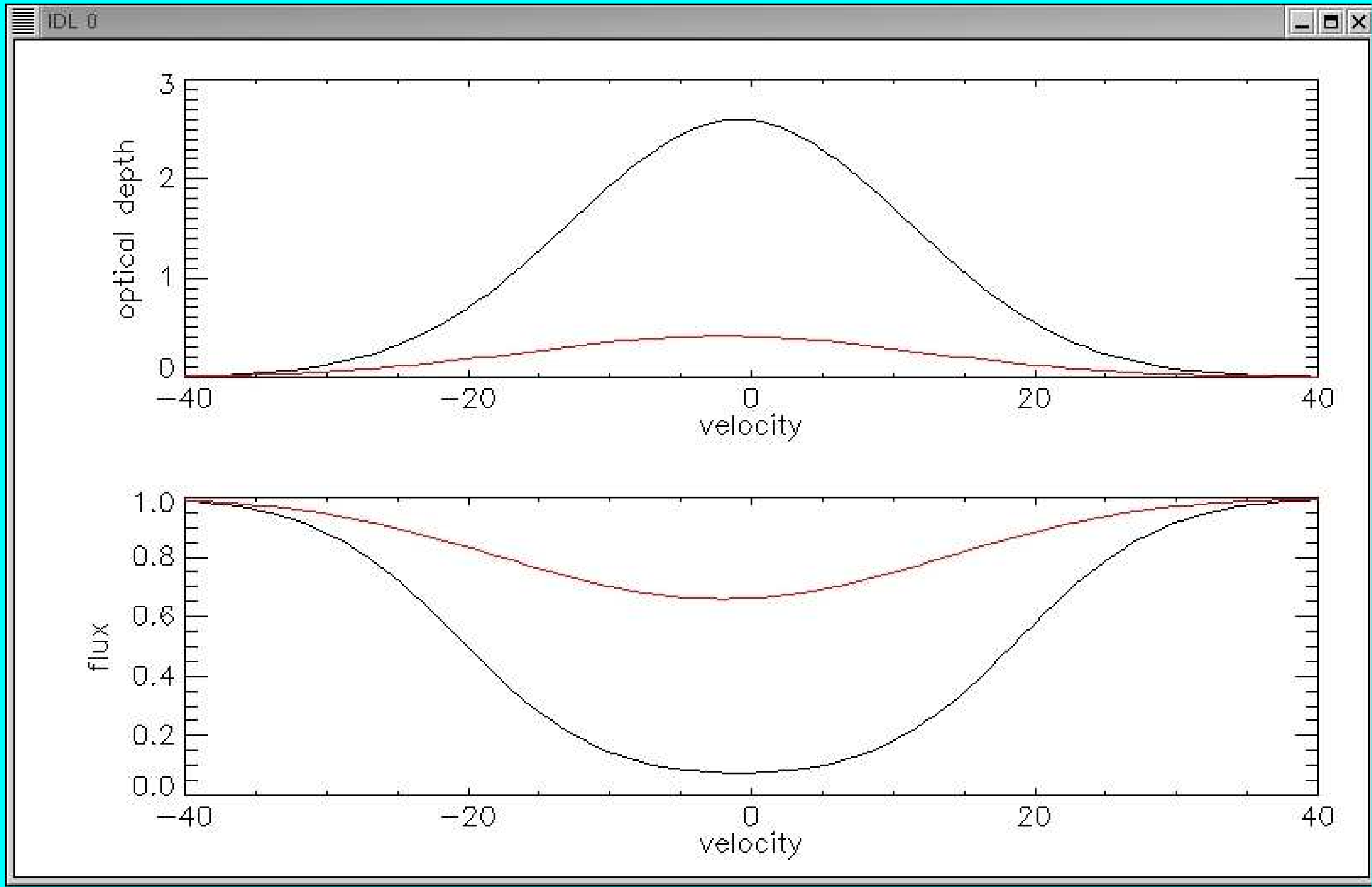
For gas at given temperature, the line will be thermally broadened



$\exp(-\tau)$ is the fraction of light you'll observe

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So because of broadening, τ and ρ cannot be one-to-one related: there has to be some scatter.

Alternatively, consider that we are smoothing the density field on the scale of the Jeans length.

However: if τ is large, we cannot determine it accurately: here is where the pixel optical depth comes into its own: we use the higher order transitions.

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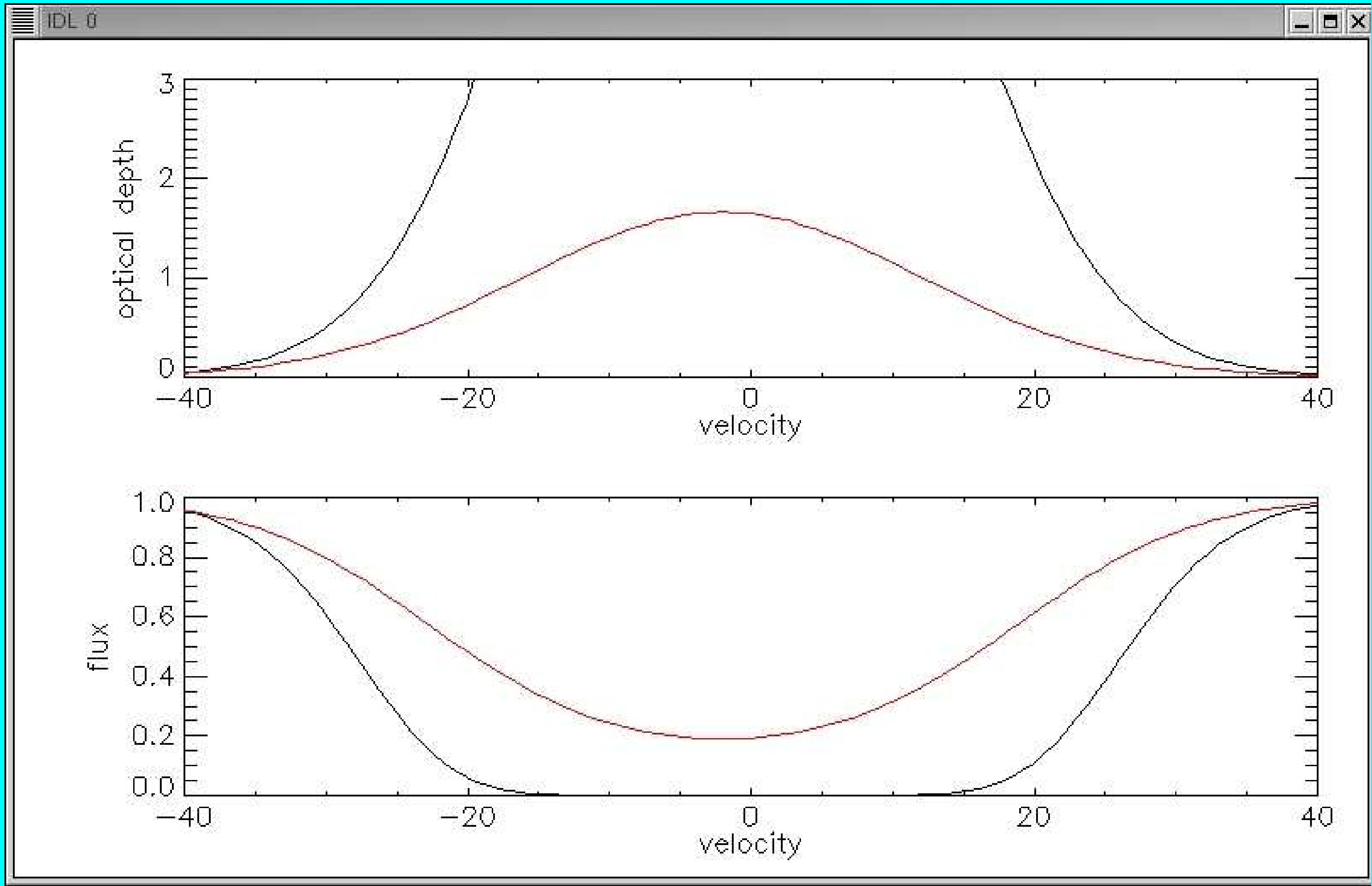
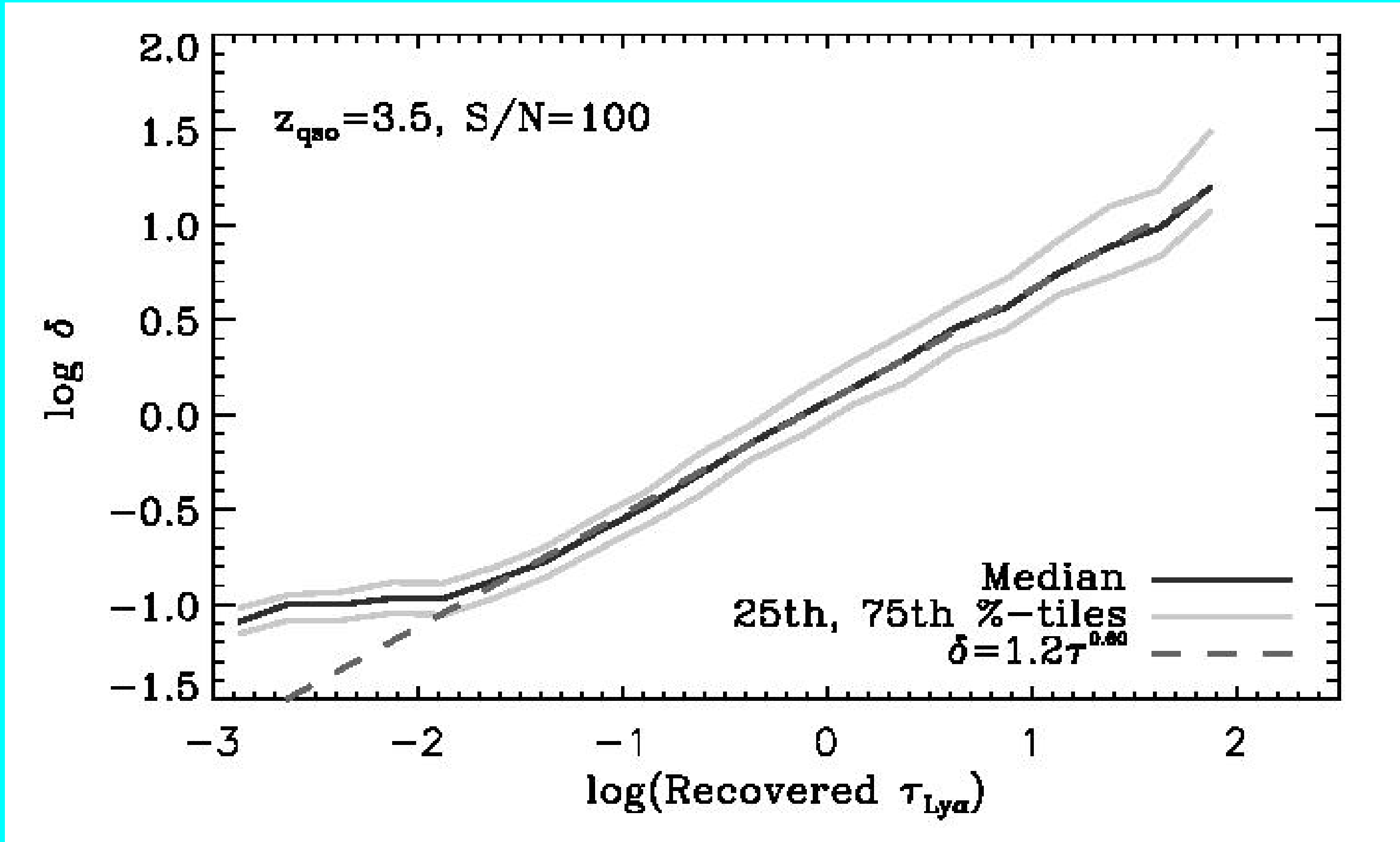


In this strong line, we cannot measure the lyman α optical depth, but we can measure lyman β!

From realistic simulations: 9/29/04

Over-density of gas



Recovered optical depth (from higher order lines)

Aguirre, Schaye, TT '02

Summarising:

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The POD can accurately recover $\tau(\lambda)$

Can use simulations that include:

evolution of S/N with λ

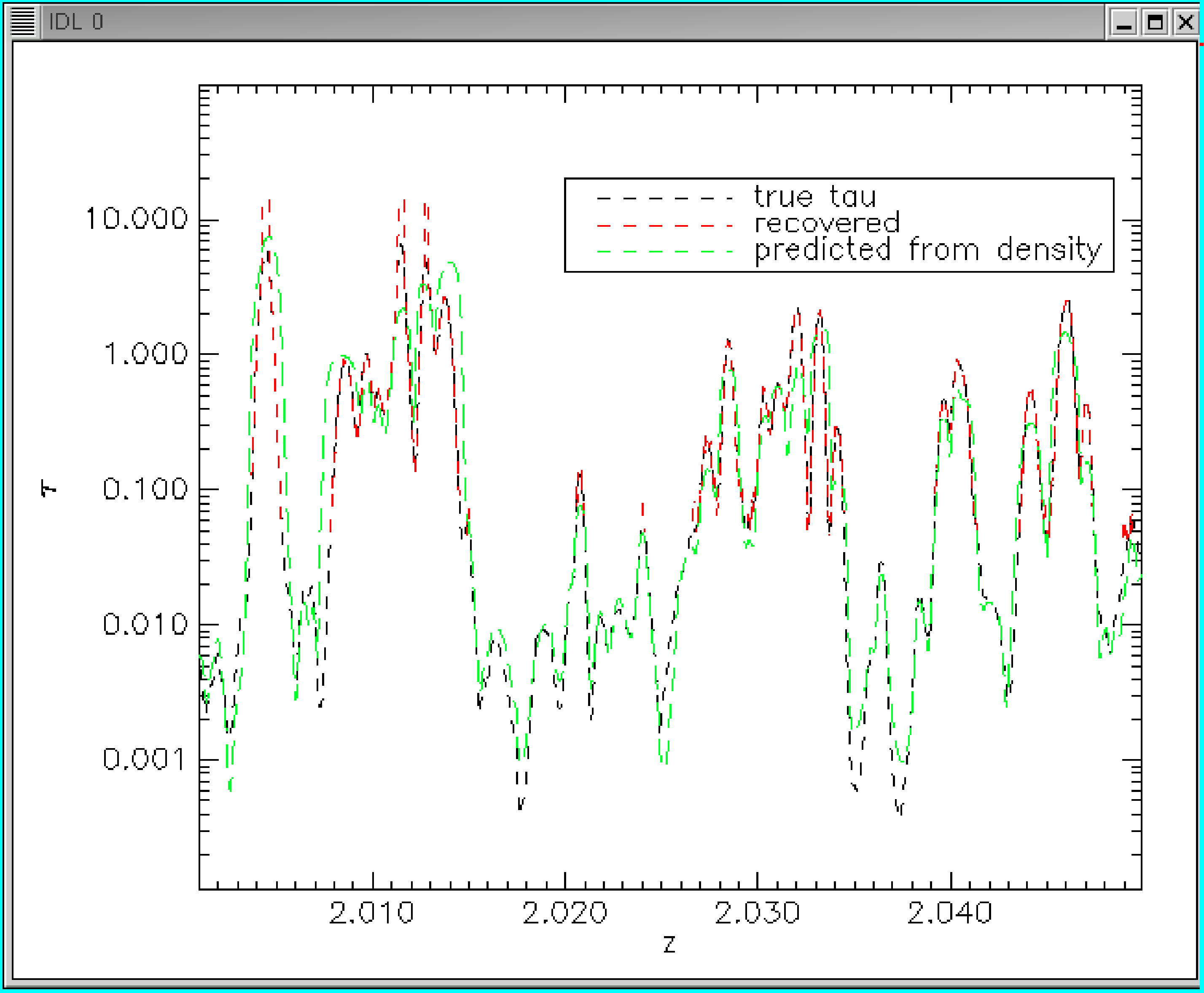
actual wave-length covarage of particular spectrum

to try new methods for analysis of spectra

However: optical depth at given λ *does not* refer to unique position in space

- thermal broadening
- peculiar velocities

Illustration of recovery procedure.



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In equations:

$$\begin{aligned}
\Delta &\equiv \rho/\langle\rho\rangle \\
\tau &= \tau_0\,\Delta^{1/(1+\beta)} \\
\tau_0 &= 0.206\,(\frac{\Omega_b h^2}{0.02})^2\,\frac{X}{0.24}\,\frac{X+0.5Y}{0.88}\,\frac{\alpha(T)}{\alpha(T=10^4K)}\,\frac{1}{\Gamma_{12}}\,\frac{H(2)}{H(z)}\,(\frac{1+z}{3})^6 \\
T &= T_0\,\Delta^{\gamma-1} \\
1/(1+\beta) &\equiv 2-0.7(\gamma-1)
\end{aligned}$$

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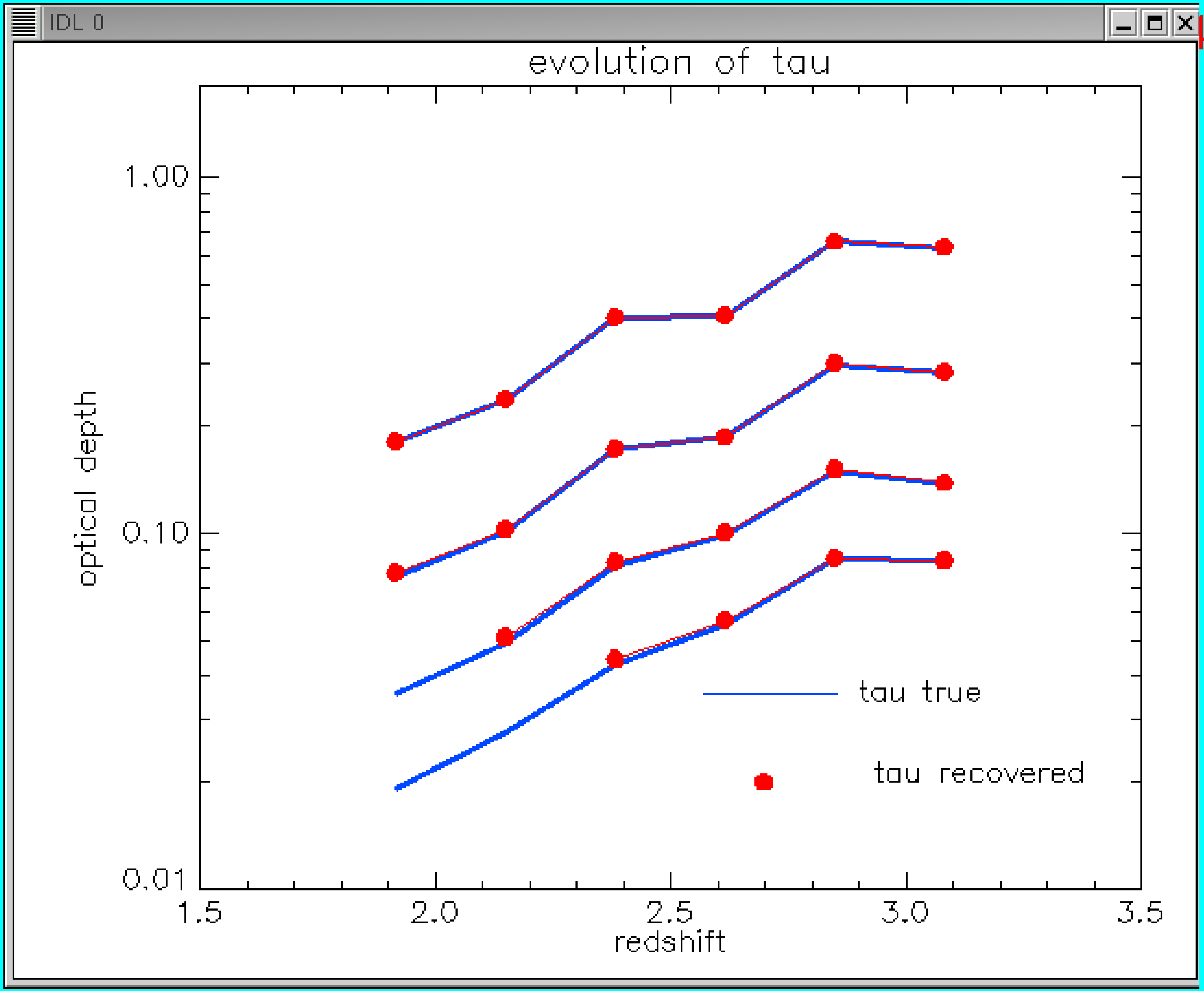
MODEL-INDEPENDENT INSIGHTS INTO THE NATURE OF THE Lyα FOREST AND THE DISTRIBUTION OF MATTER IN THE UNIVERSE

JOOP SCHAYE
School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton NJ 08540; schaye@ias.edu
Received 2001 April 16 ; accepted 2001 June 1

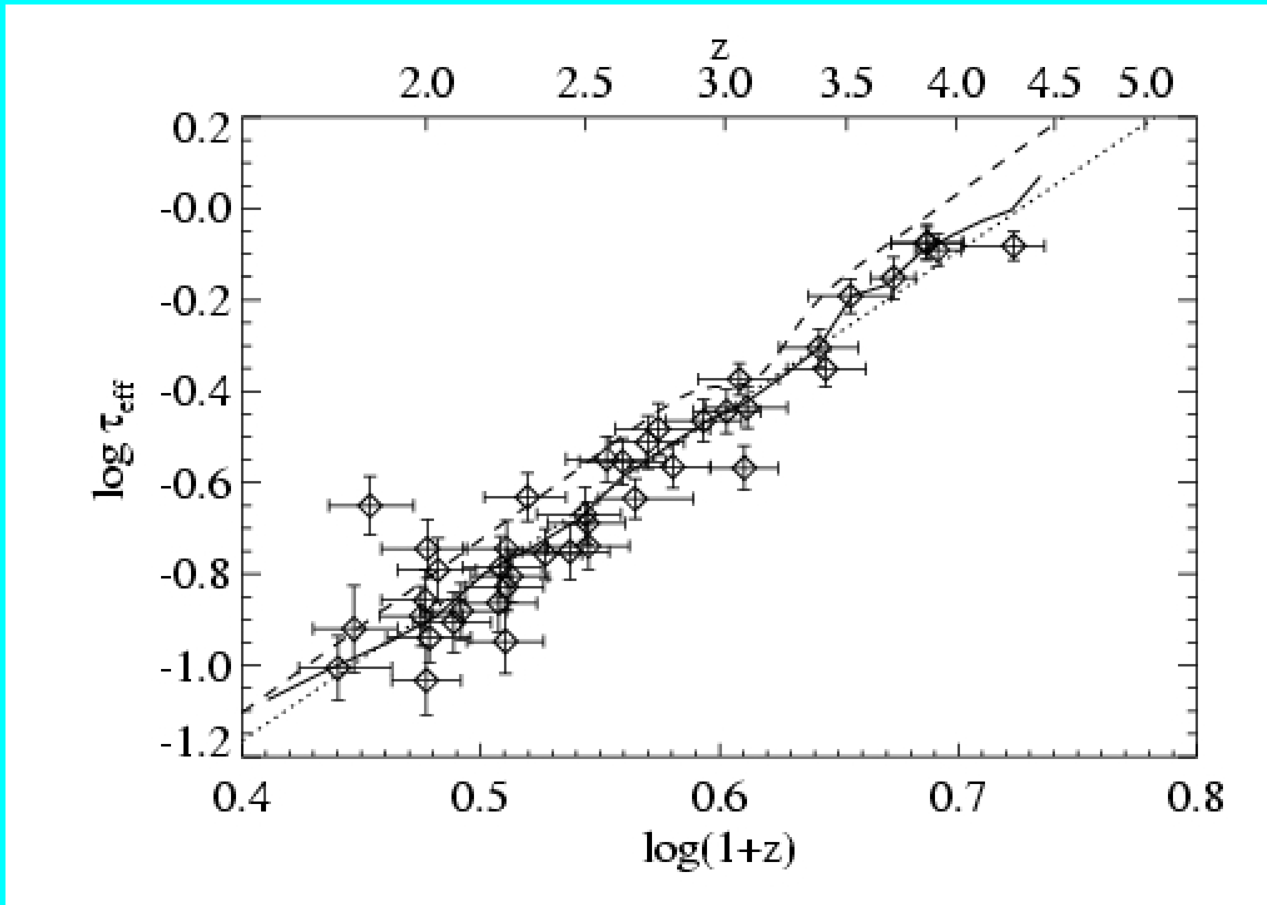
The POD allows us in principle to interprete the Lyman-α forest directly, *without* having to calibrate against simulations.

Recovery of the optical depth evolution



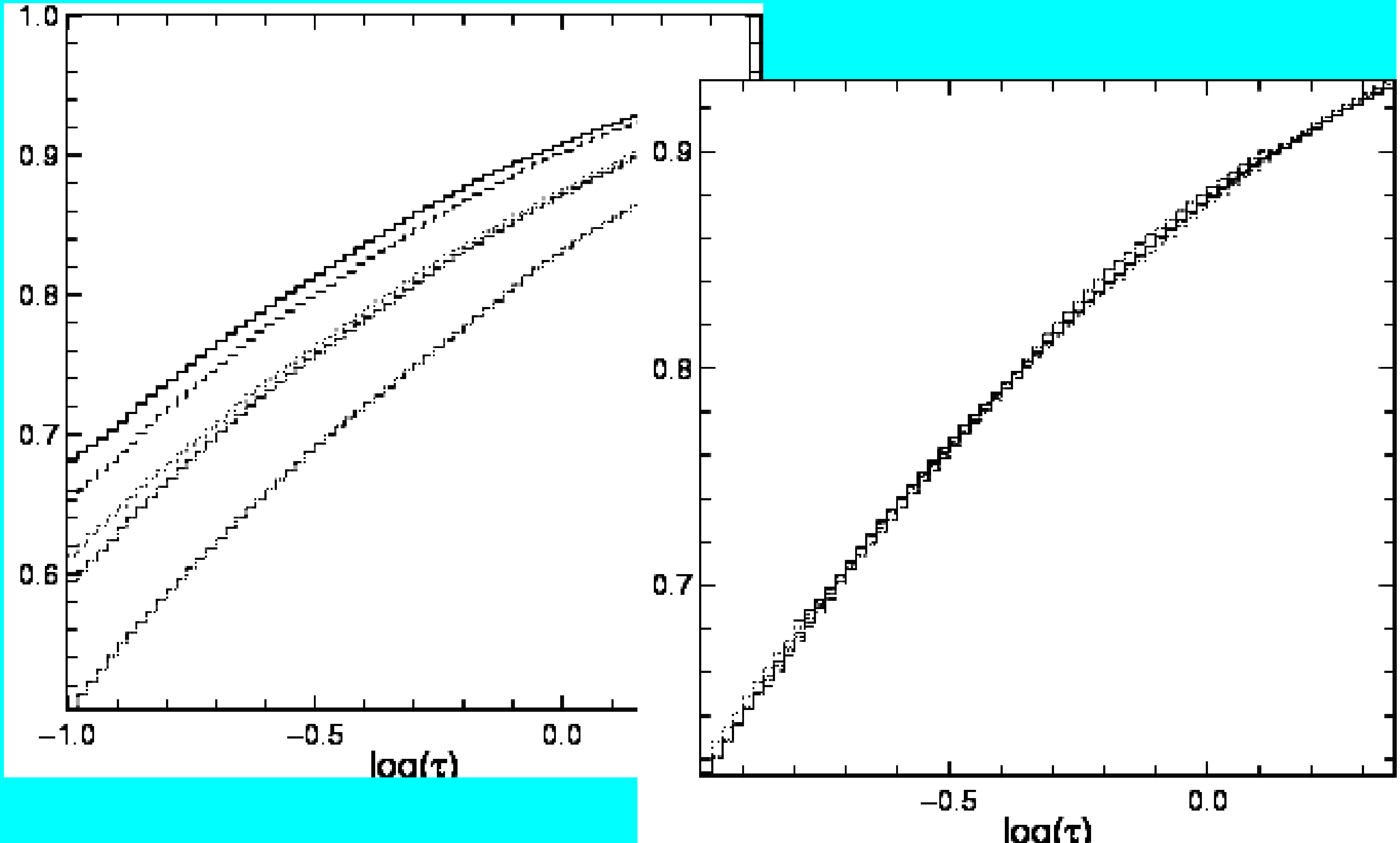
Contrast this with what is usually used:

$$\langle F \rangle = \exp(-\tau_{\rm eff}) = \langle \exp(-\tau) \rangle$$



Schaye et al '03

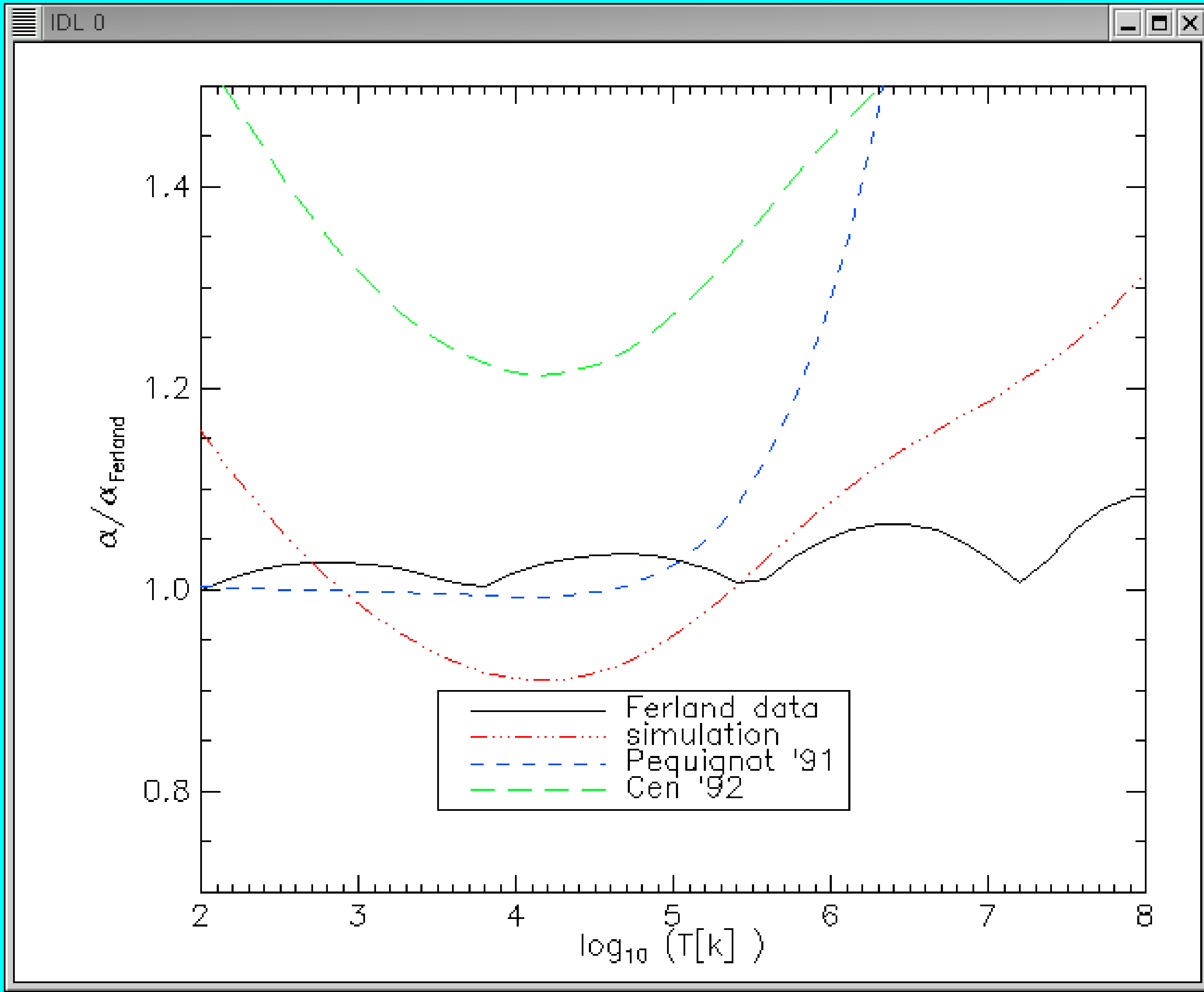
Optical depth PDF at different z



And scaled to the same z

Rollinde, Srianand, TT, Petitjean & Chand '04

Precision cosmology?



Hydrogen recombination coefficient as function of Temperature

Quasar spectra also contain metal lines.

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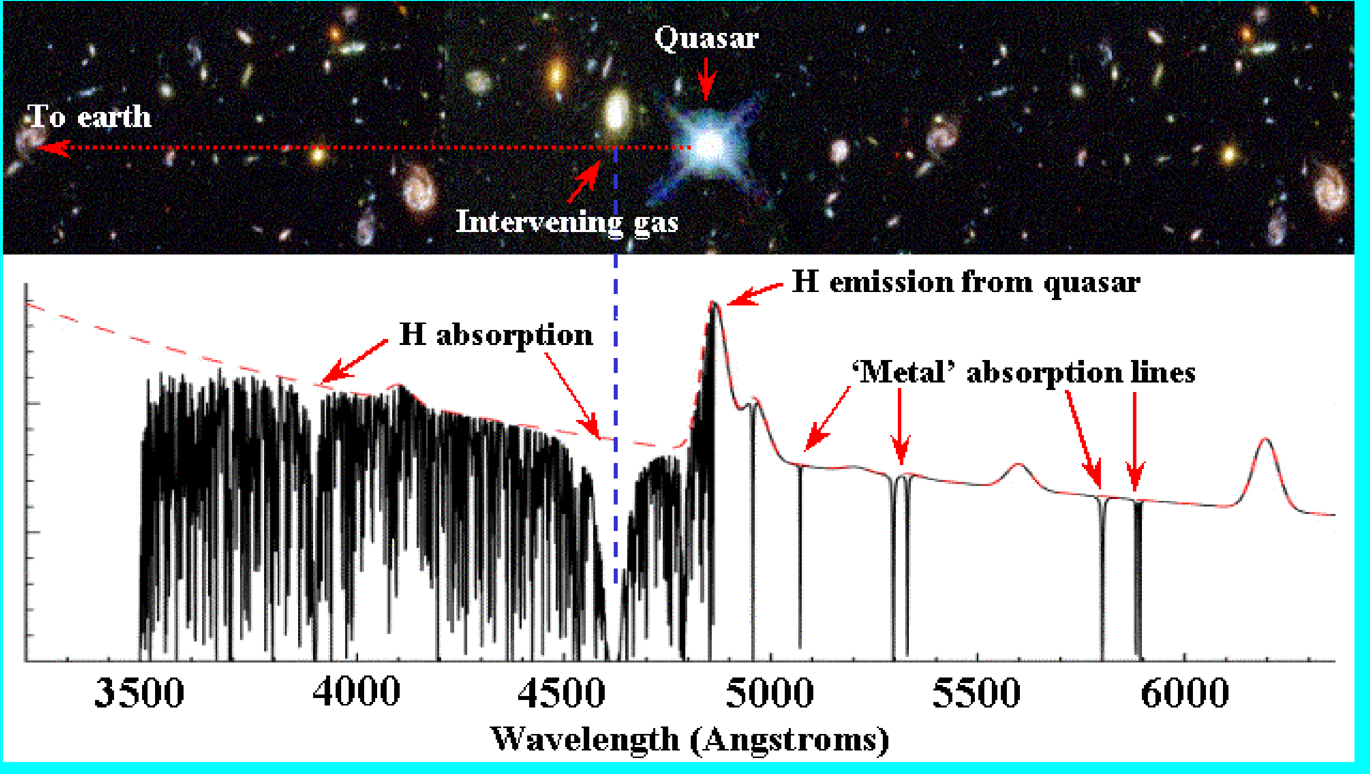
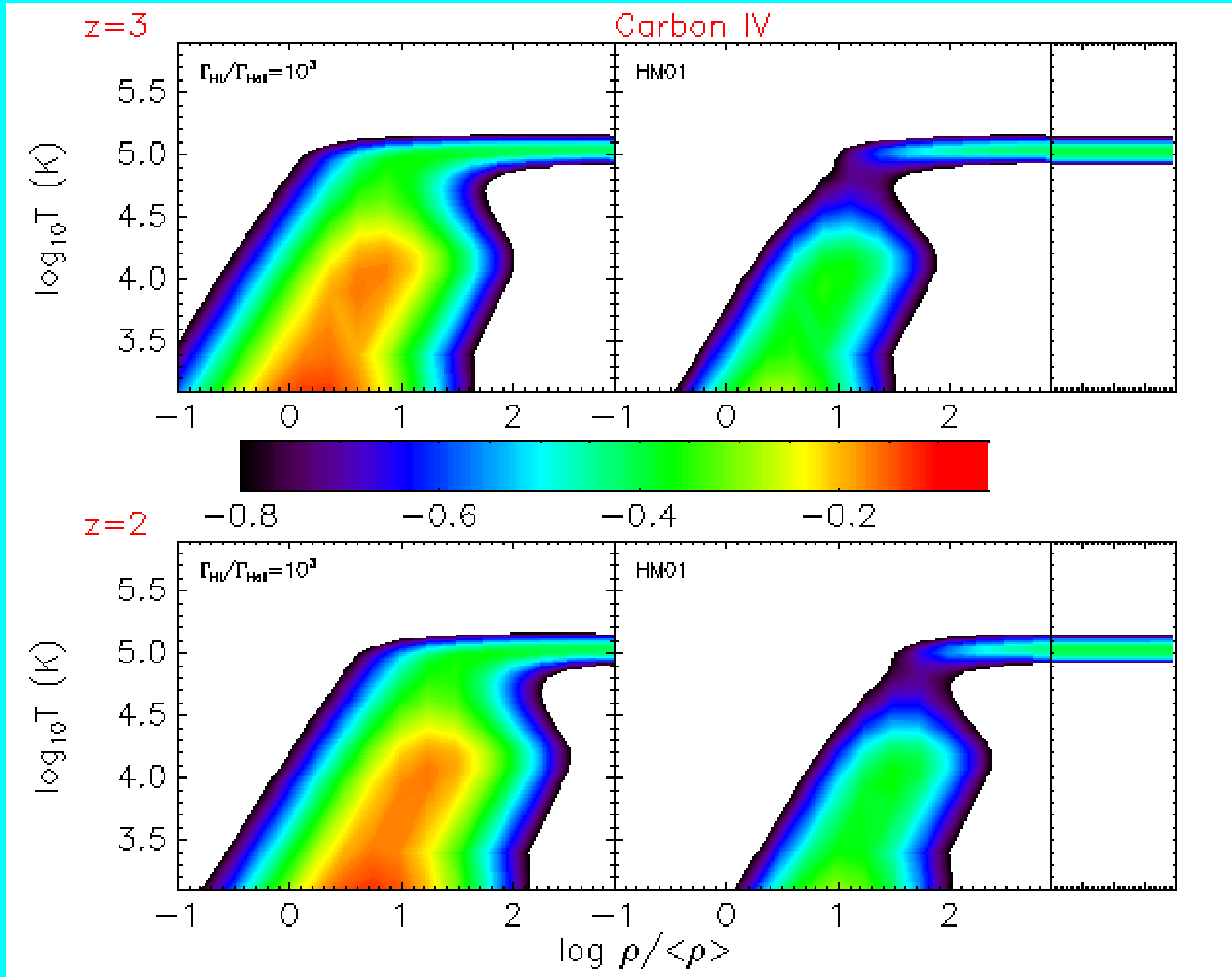


How many? How do they get there?



CIV fraction as function of density and temperature
Local sources? (Schaye 2004)

Because the simulated spectra look like the observed ones, we can use them to learn about the biases in recovering metals

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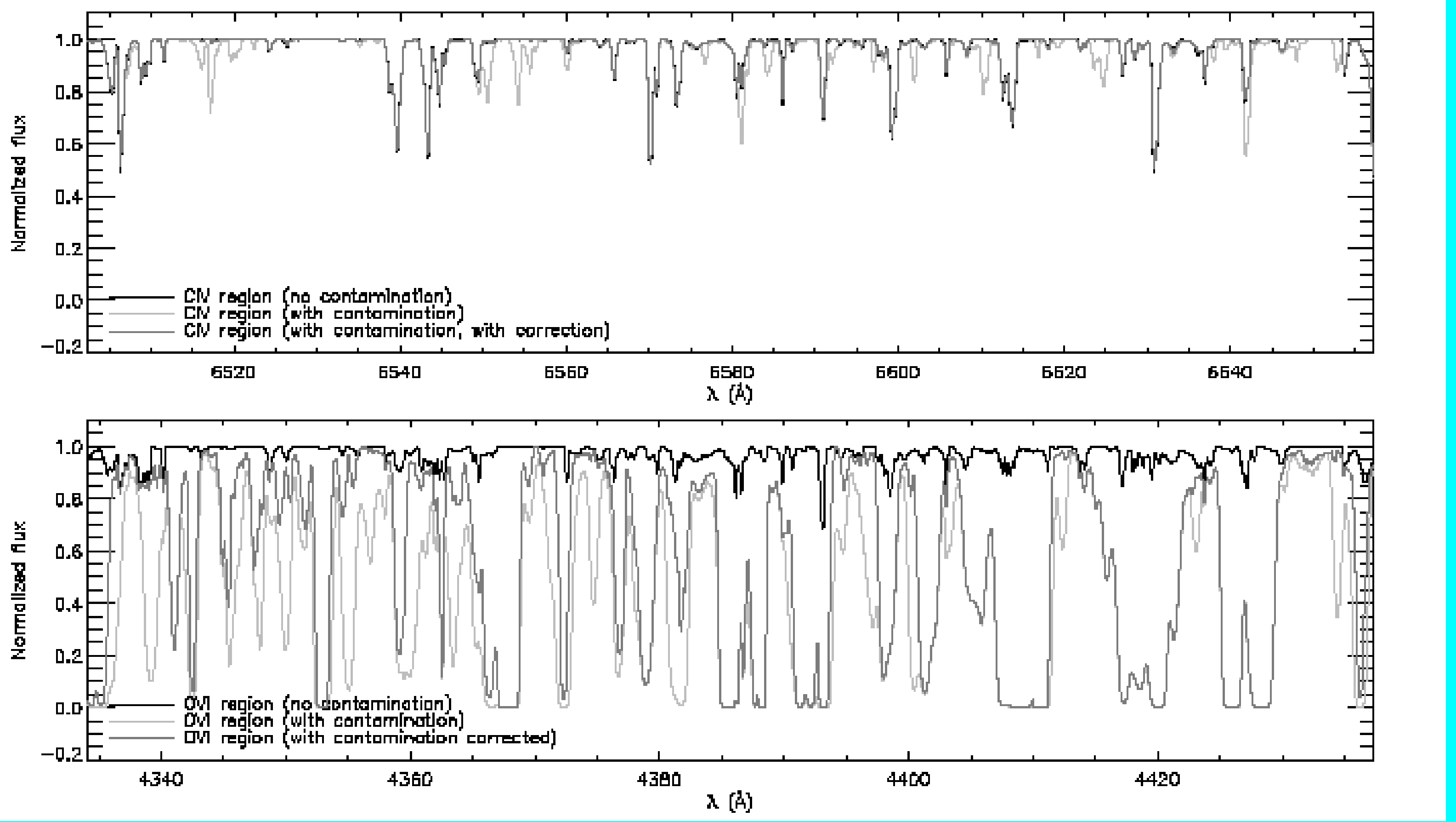
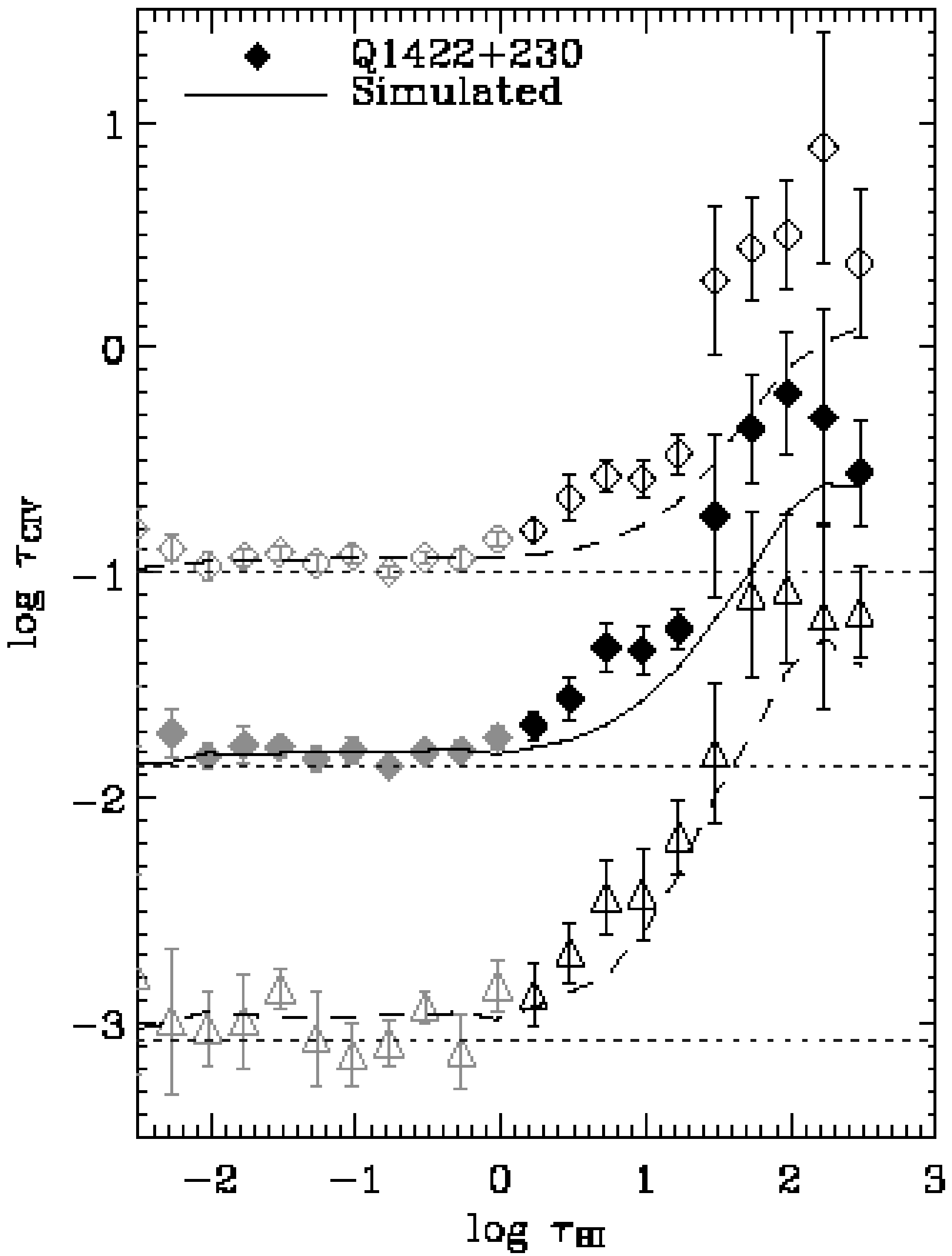


Best fit uniform metal distribution



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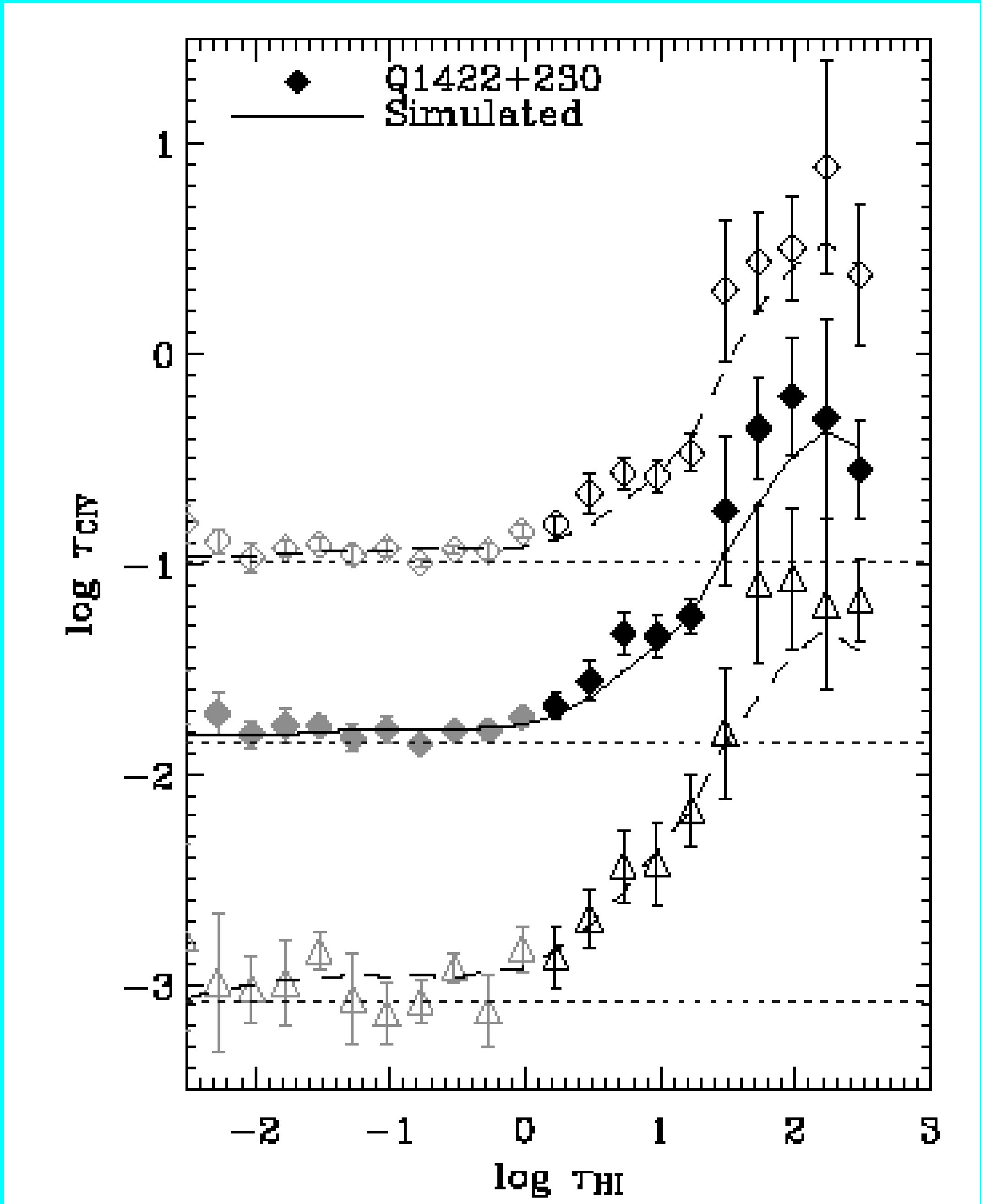
Schaye et al '03

Best fit metal distribution with scatter



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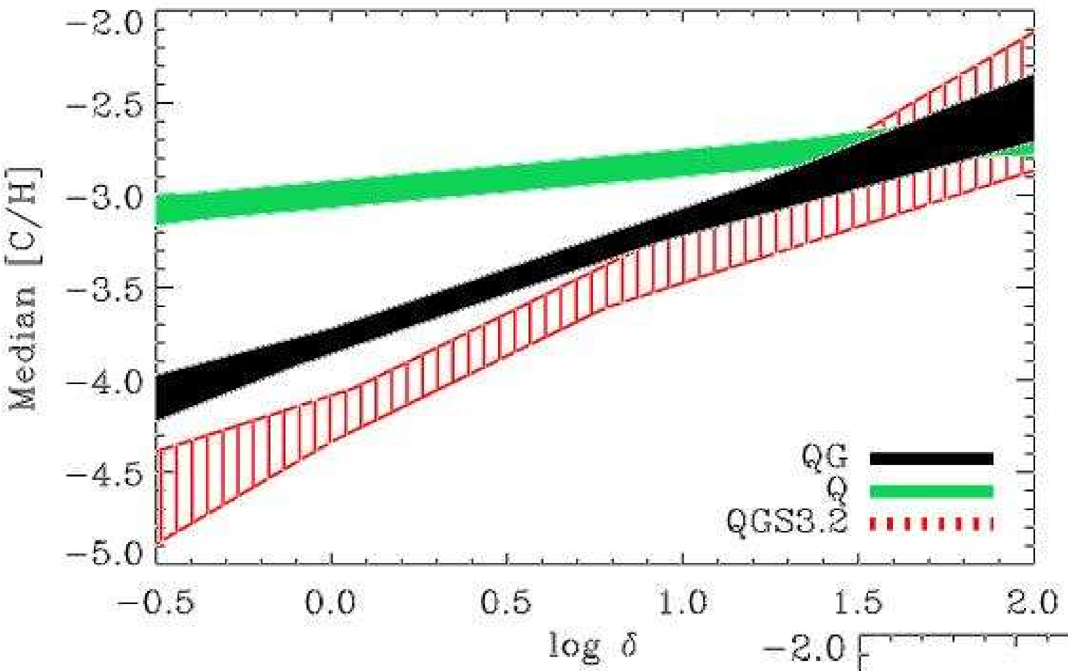
Schaye et al '03

Evolution of C abundance



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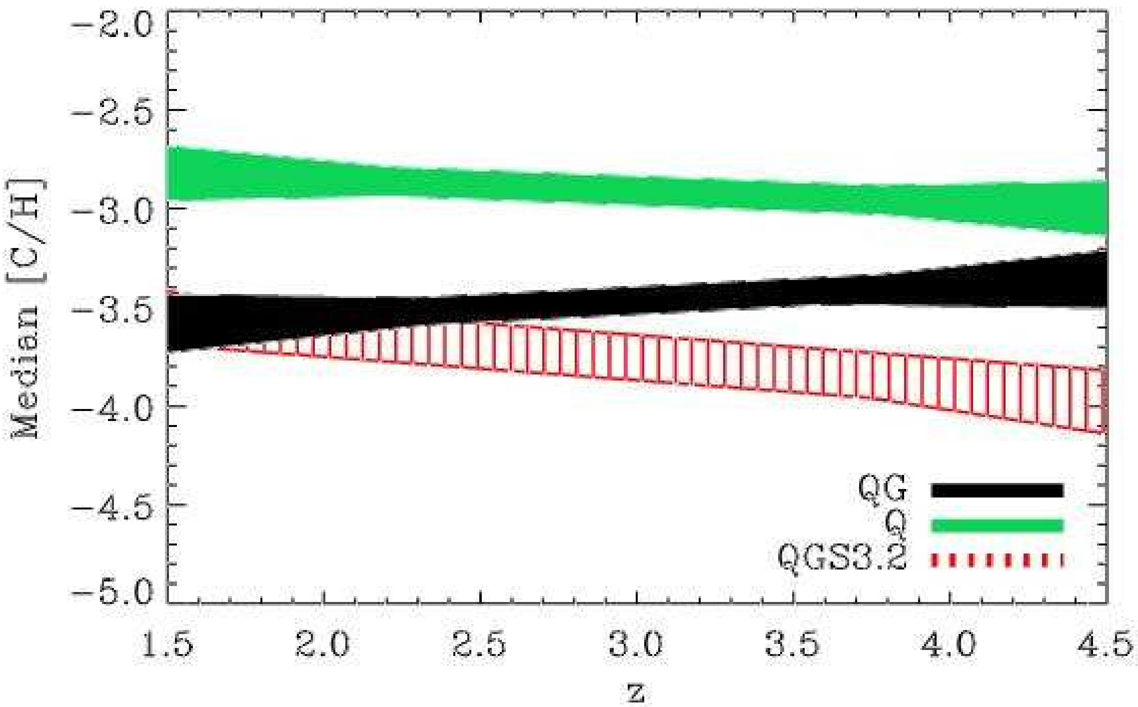
Biggest uncertainty: shape of UV-background

δ=3

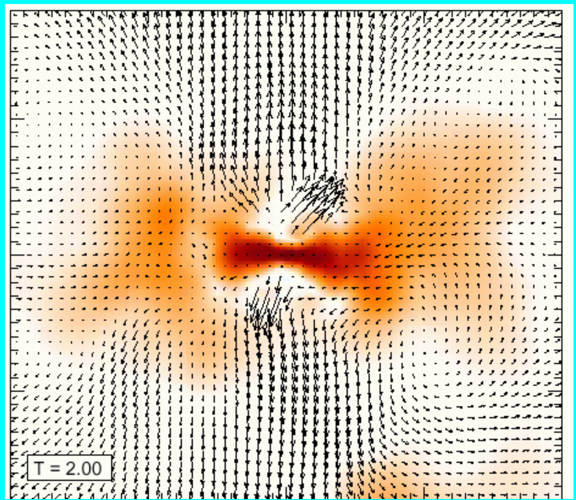
Redshift = 3

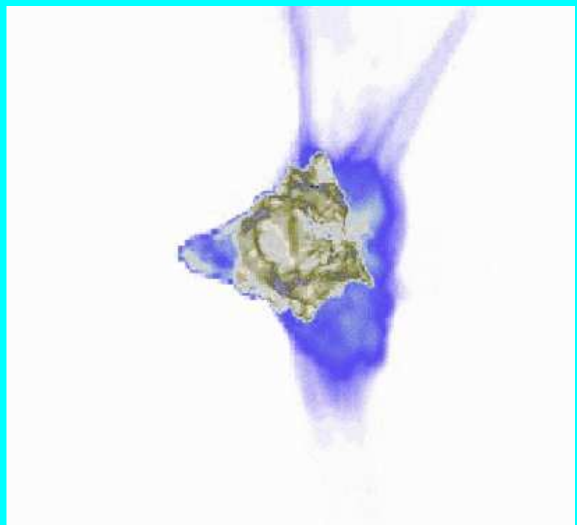


Schaye et al '03

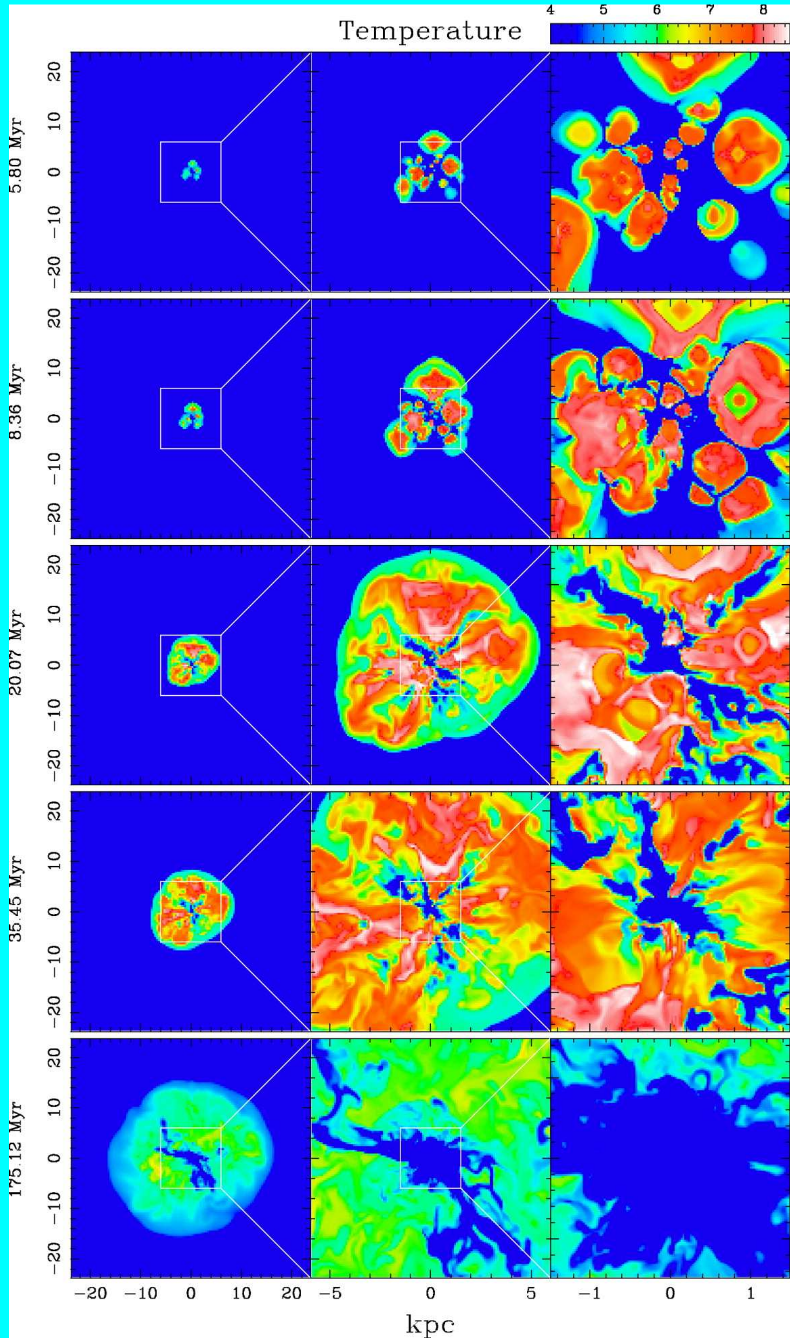
How and when did metals enter the IGM?

Springel & Hernquist 2002



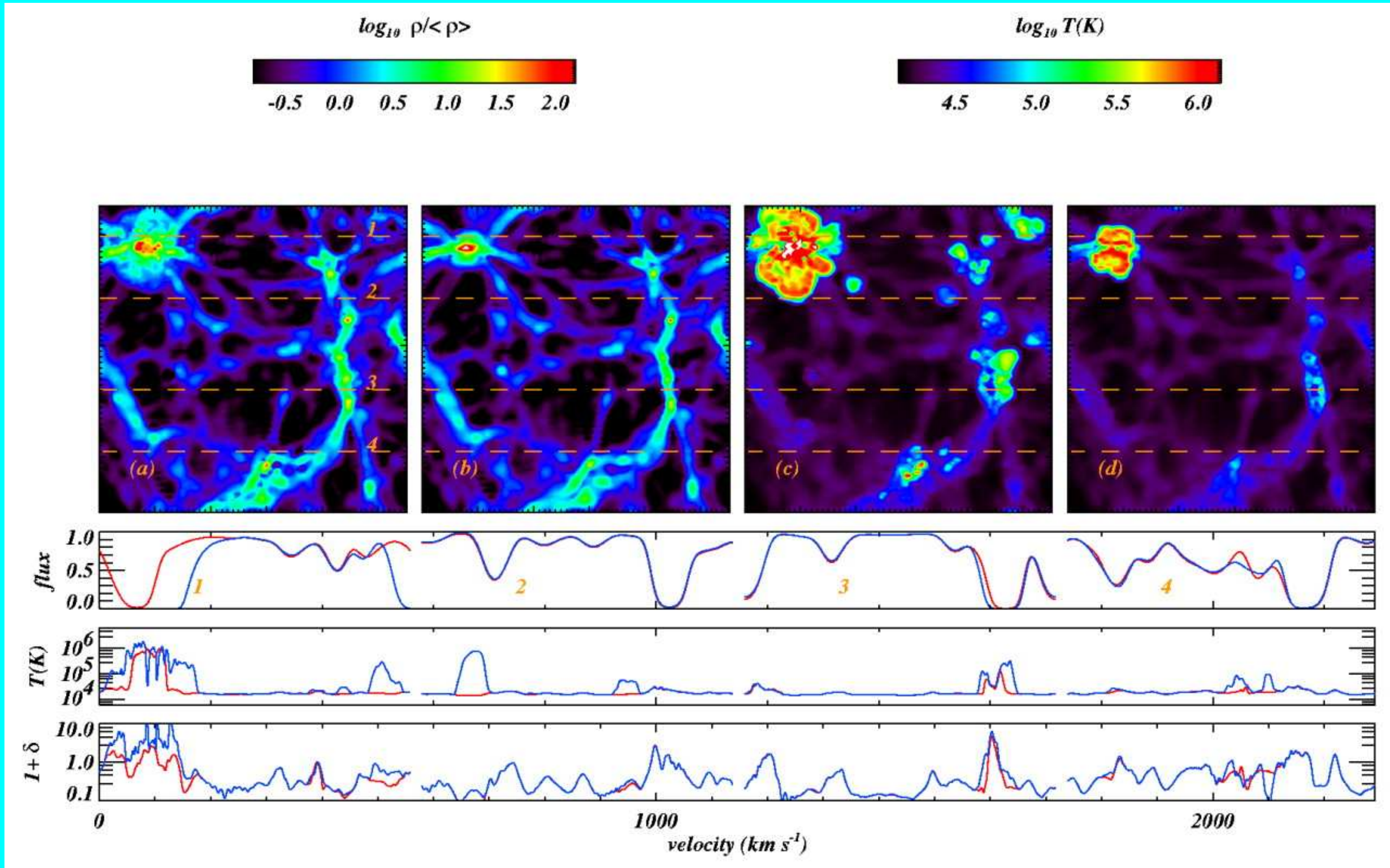


Abel et al '00



Mori, Ferrara & Madau '02

Simulations include reionization of HI, HeI, HeII, and metal enriched galactic winds



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TT et al '02

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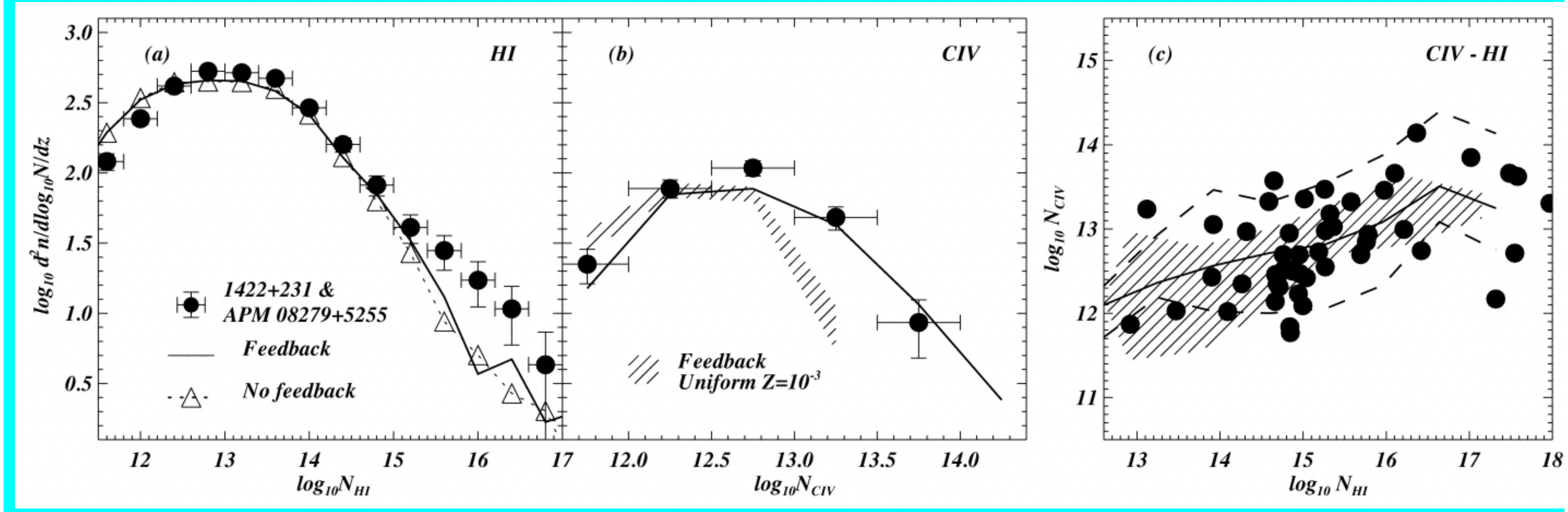
These winds have little effect on the Lya forest



But produce a CIV forest that looks similar to the observed, as they tend to expand perpendicular to the filaments.

But may be the effect of galaxies on the IGM is more dramatic?

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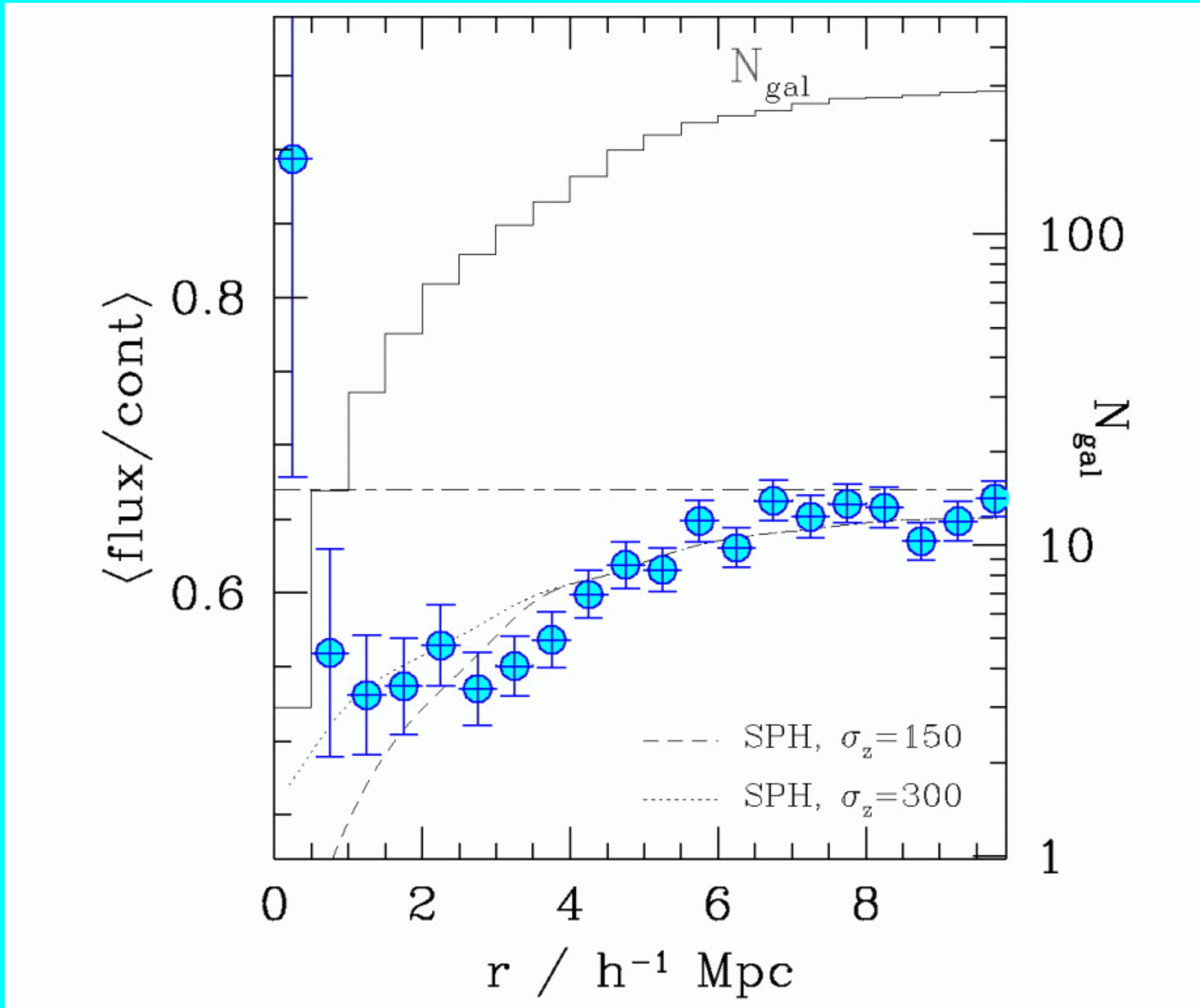
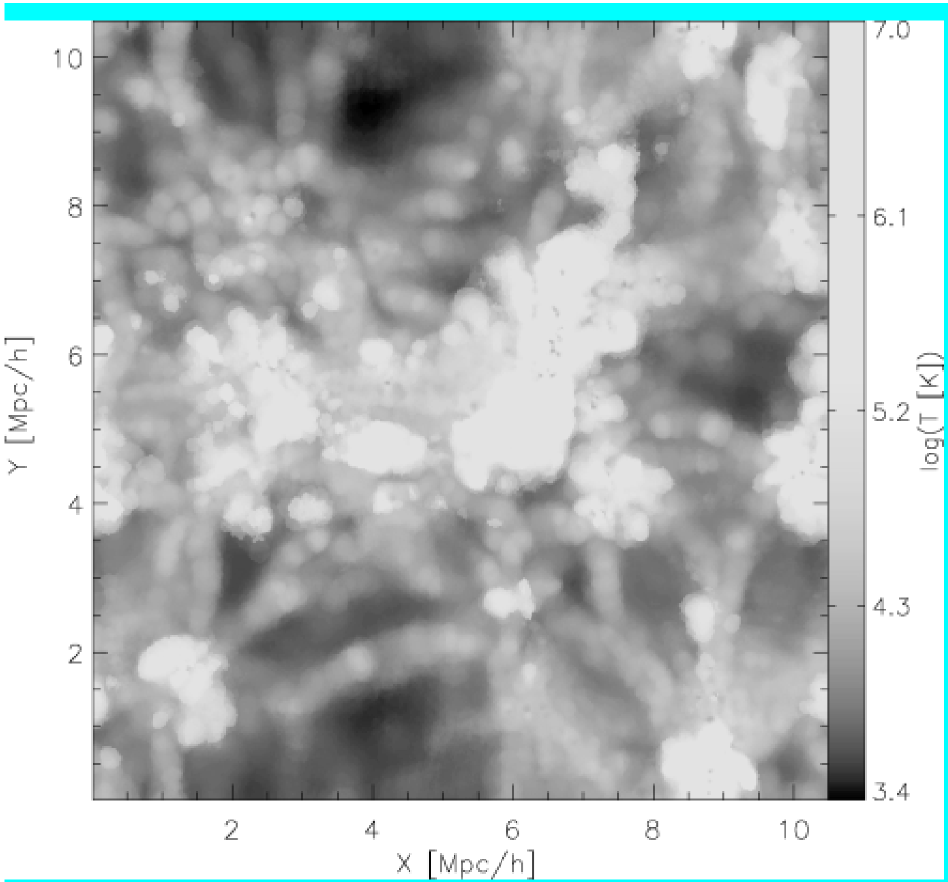


Adelberger '03



Bruscoli et al '03

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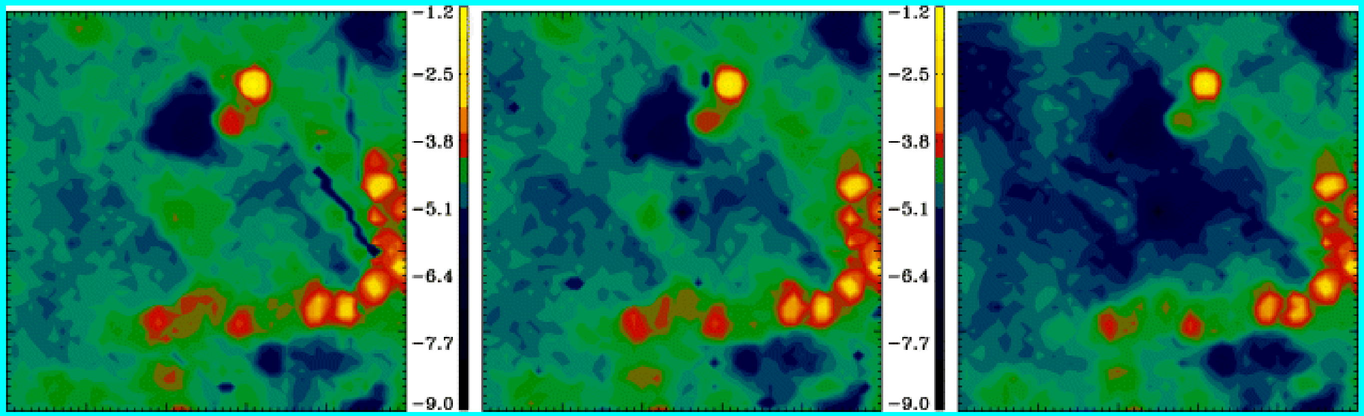
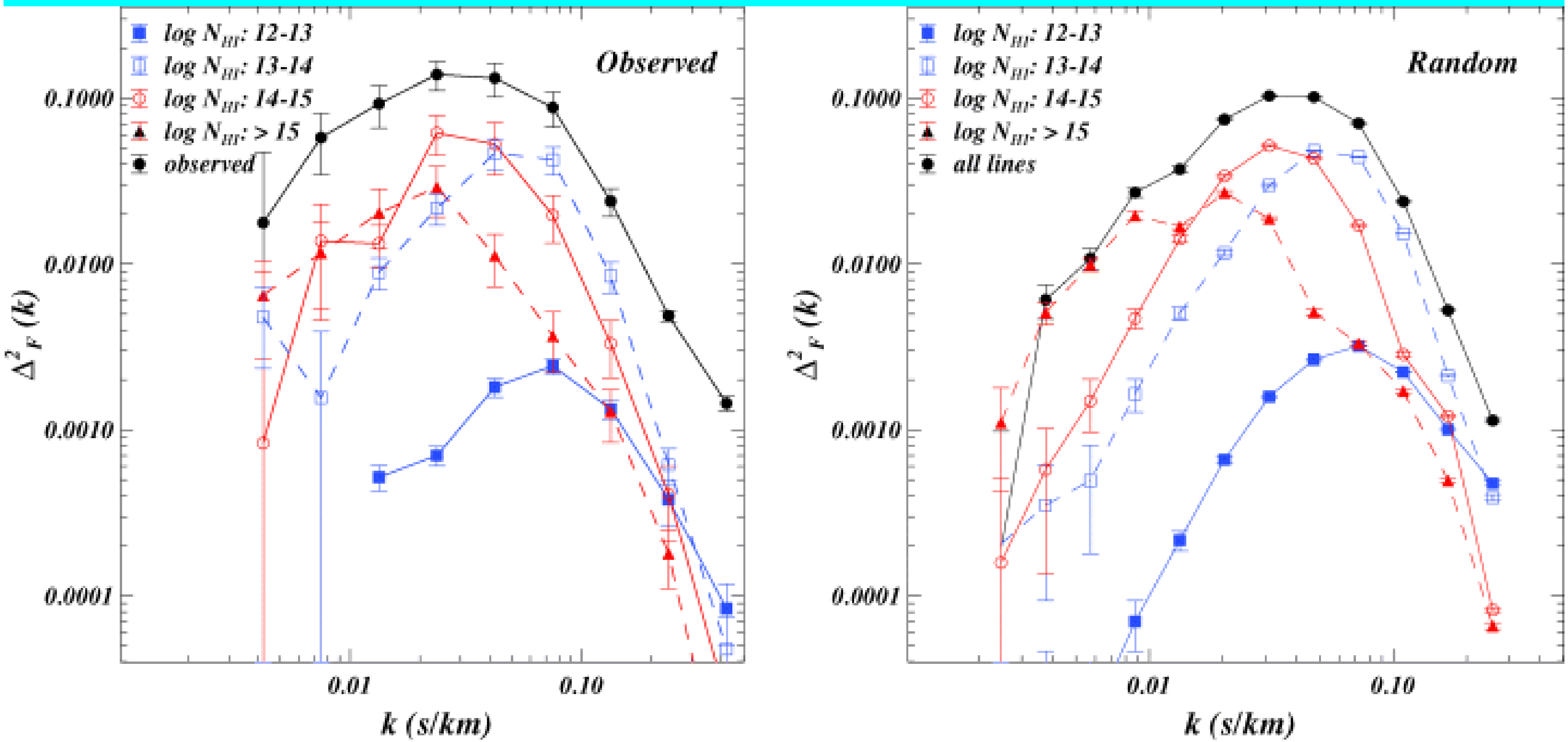
These results are not easy to reproduce ..

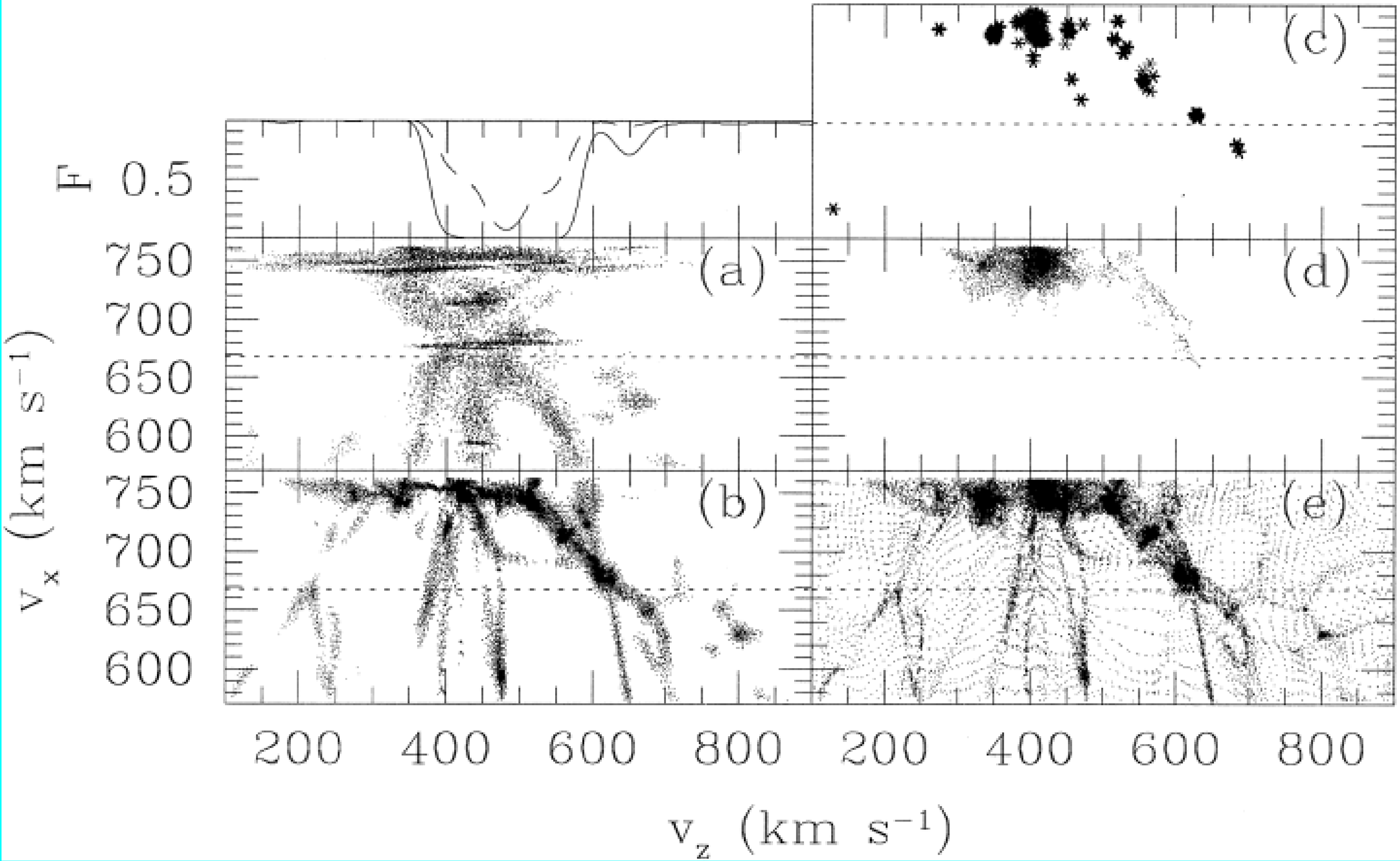


Maselli et al '04



The effect of winds could be important for cosmology as well

Viel et al '04



Winds could potentially destroy or produce strong lines.
Since these lines are usually fitted, we lose most of the information contained in the substructure TT, Mo & Schaye '01

Simulating galactic winds

FLASH: AMR/MPI

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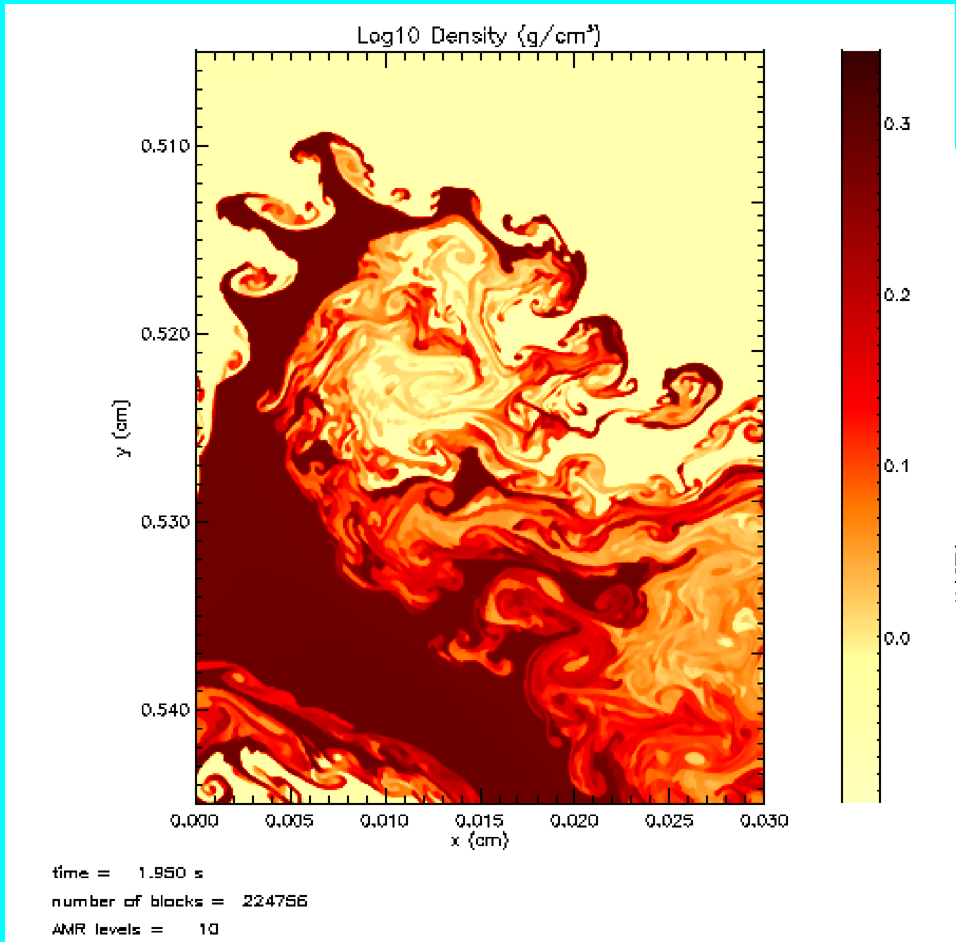

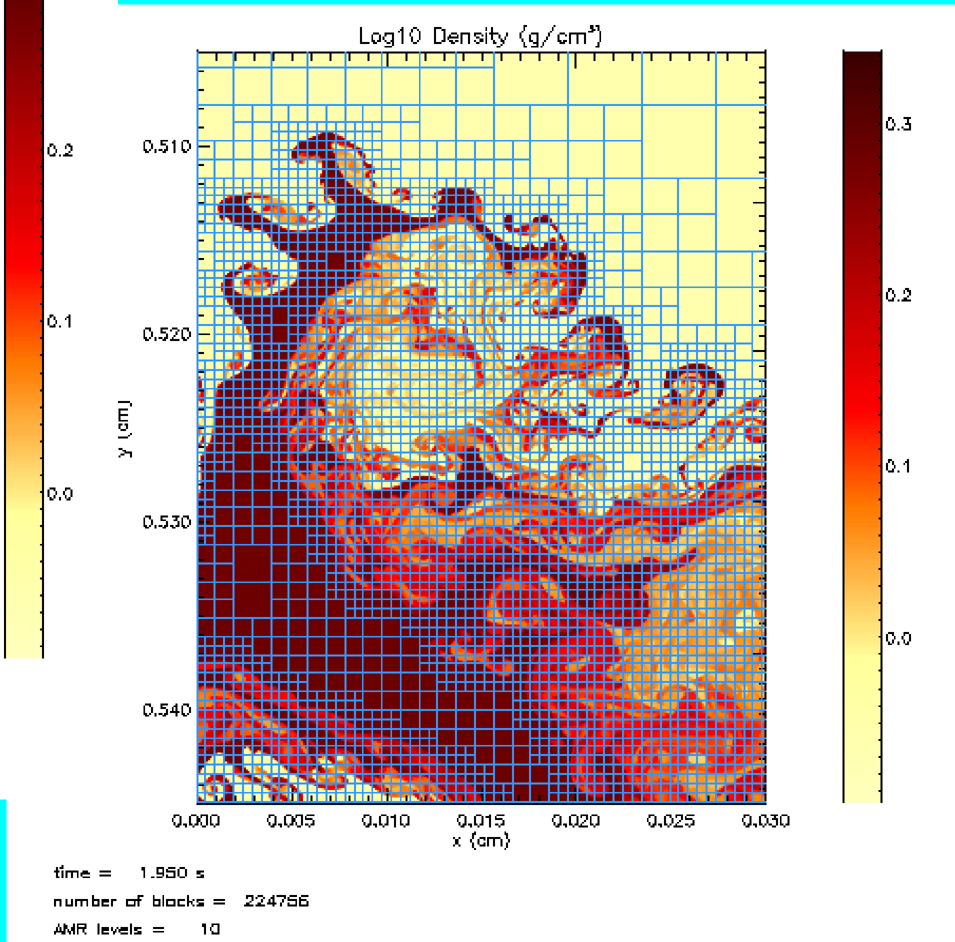

A new toy: the 512 processor SUN computer of the ICC

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ICC

With Craig Booth, Claudio Dalla Vecchia, Richard Bower

Formation of the Santa Barbara cluster.

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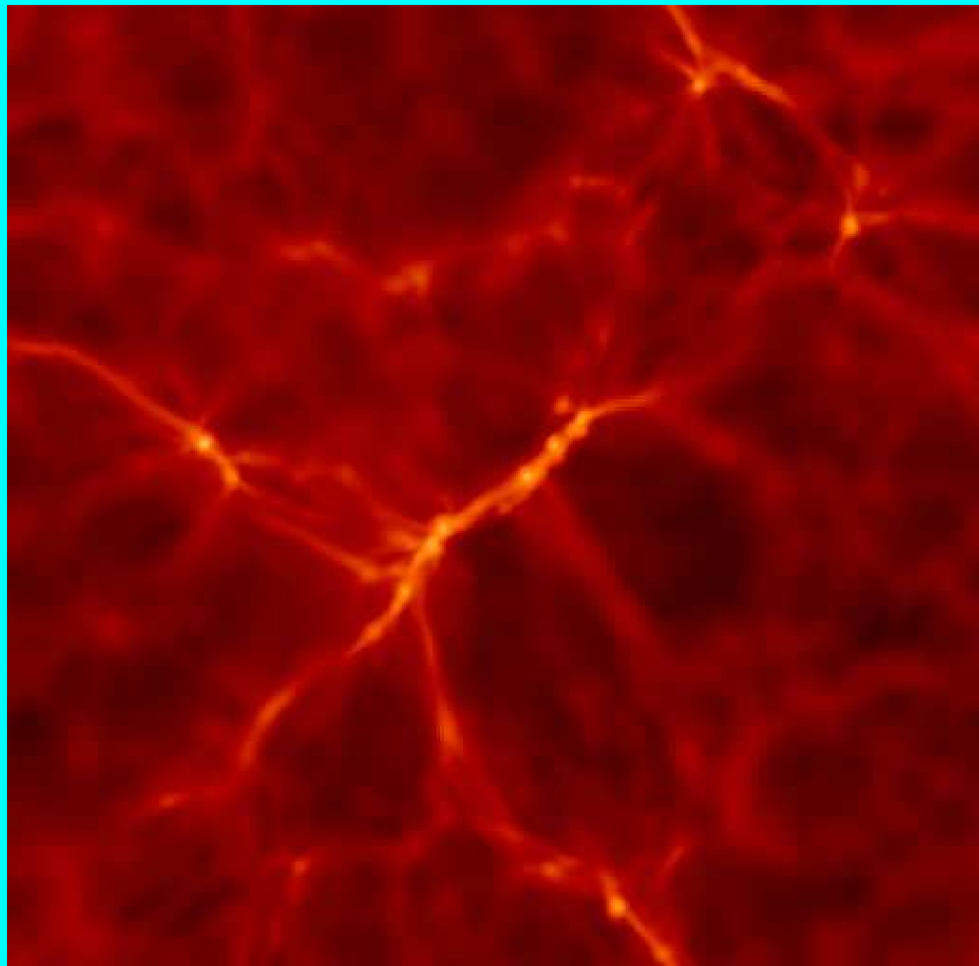

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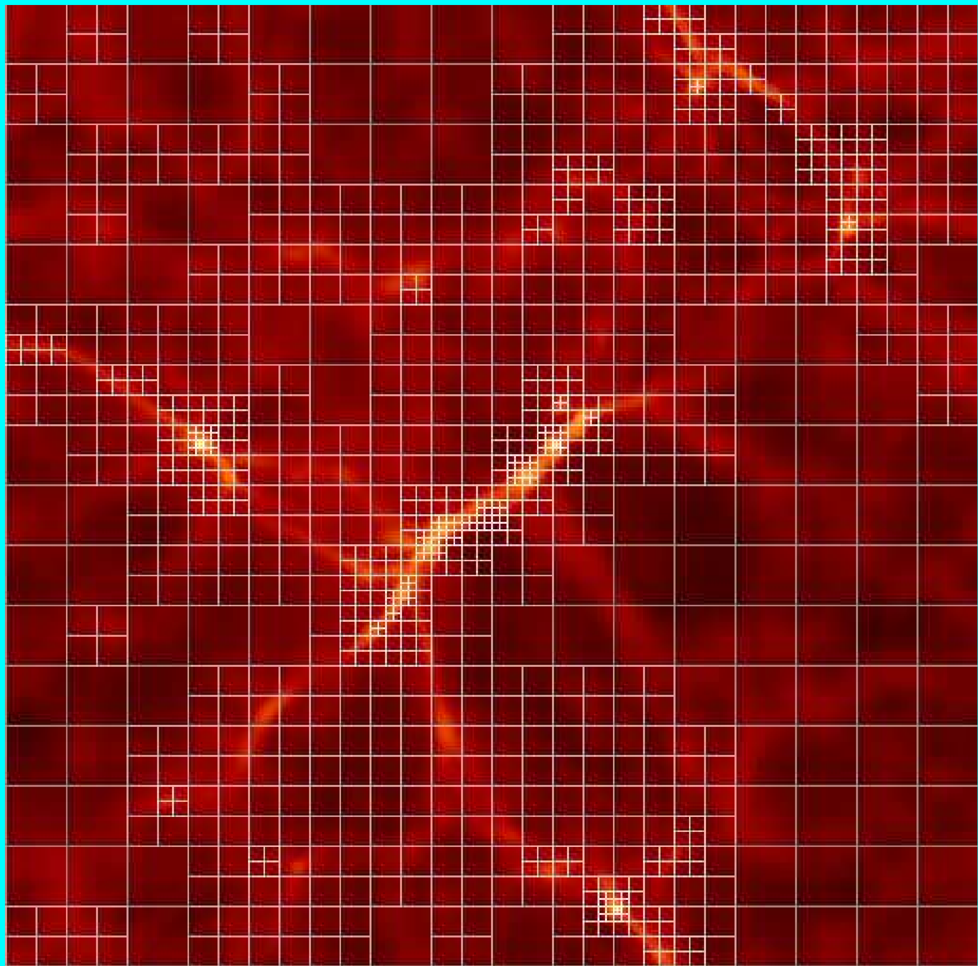

For all you simulators: Multi-resolution Gaussian random fields

The friendly face of Ed

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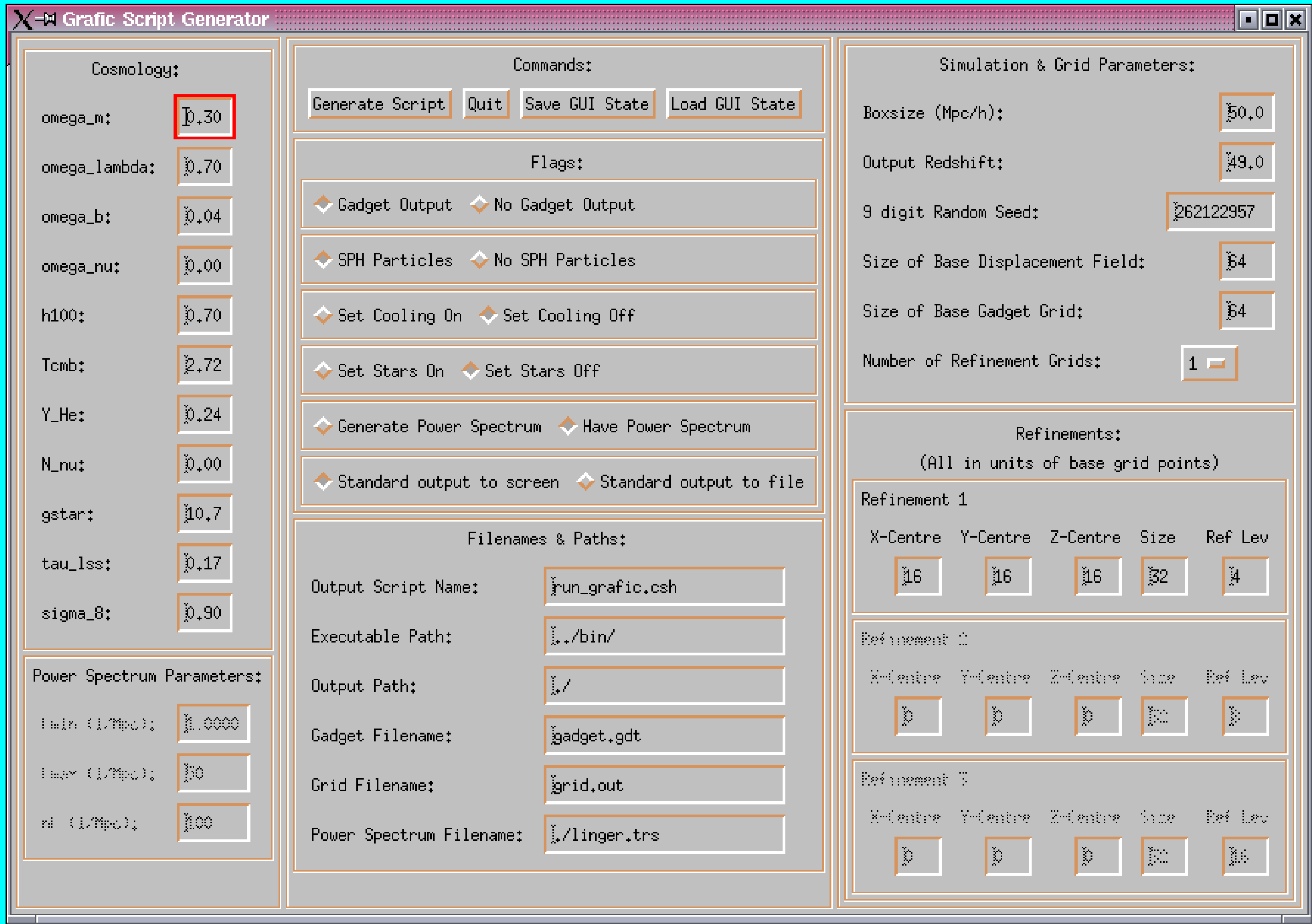
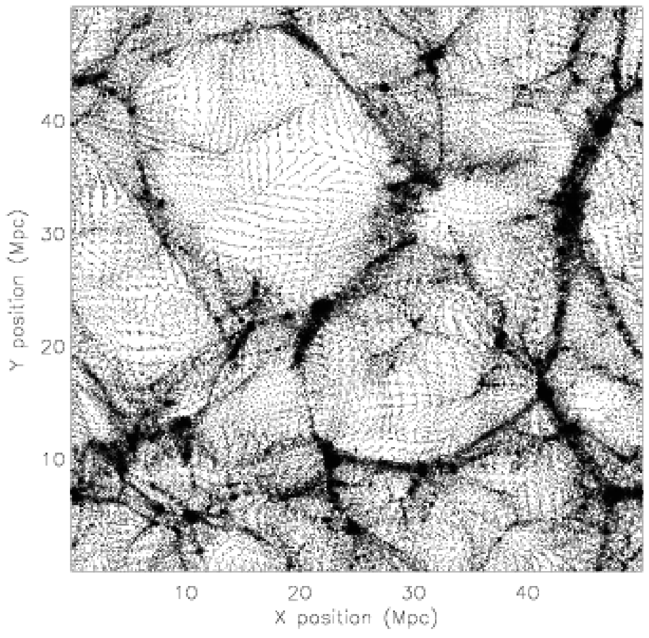


The friendly interface to Grafic II



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30
20
10
Y position (Mpc)
10
20
30
40
X position (Mpc)

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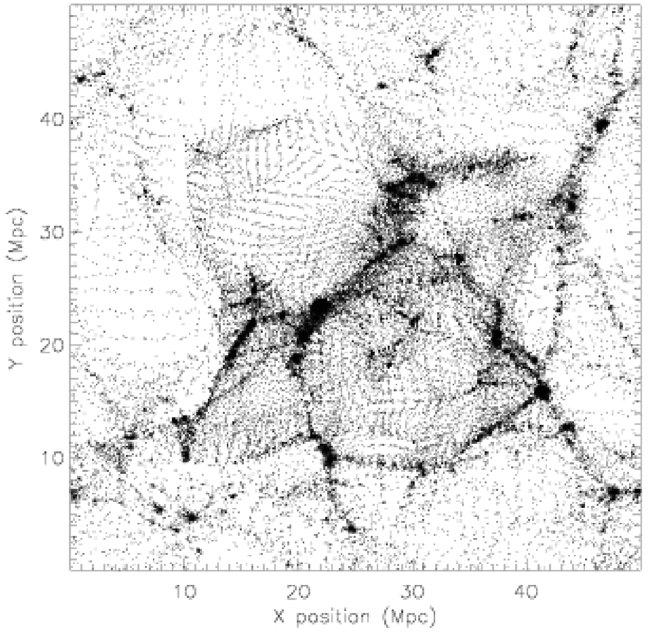

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30
20
10
Y position (Mpc)
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40
X position (Mpc)

Thank you, any questions?