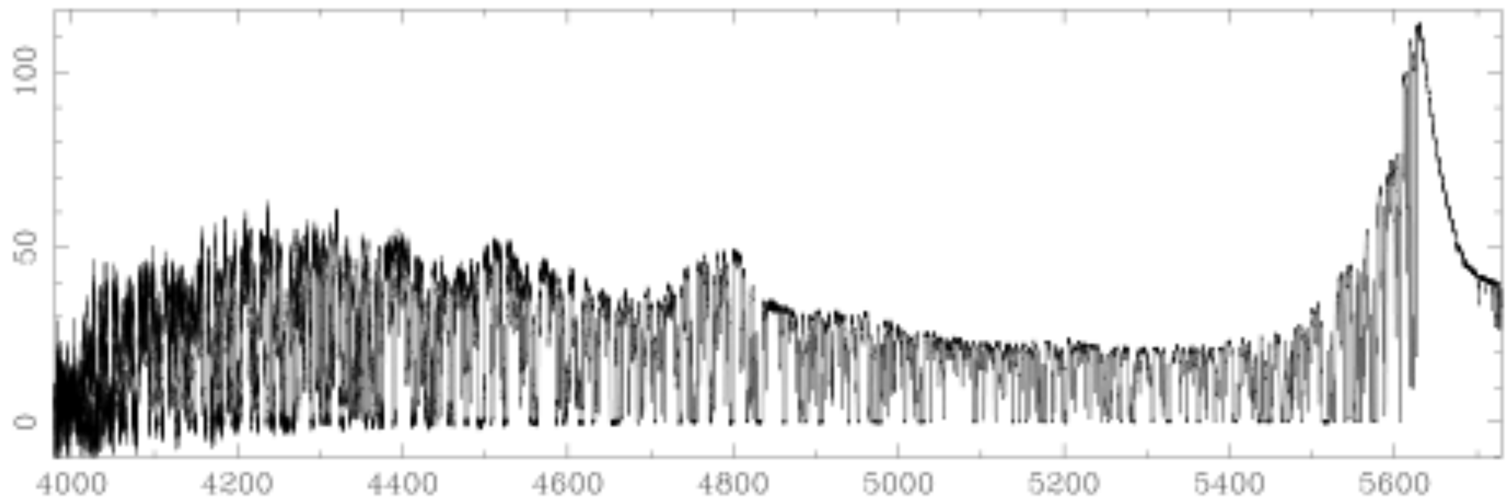
Modeling the Ly-α forest

Paradigm successes and challenges



QSO 1422+23

Orientation: distances & redshifts

z	λ_α	$\Delta\chi$	$d\lambda/d\chi$	$dv/d\chi$
2.0	3657	575	1.11	91
2.5	4255	546	1.37	97
3.0	4863	518	1.66	102

The basic observations

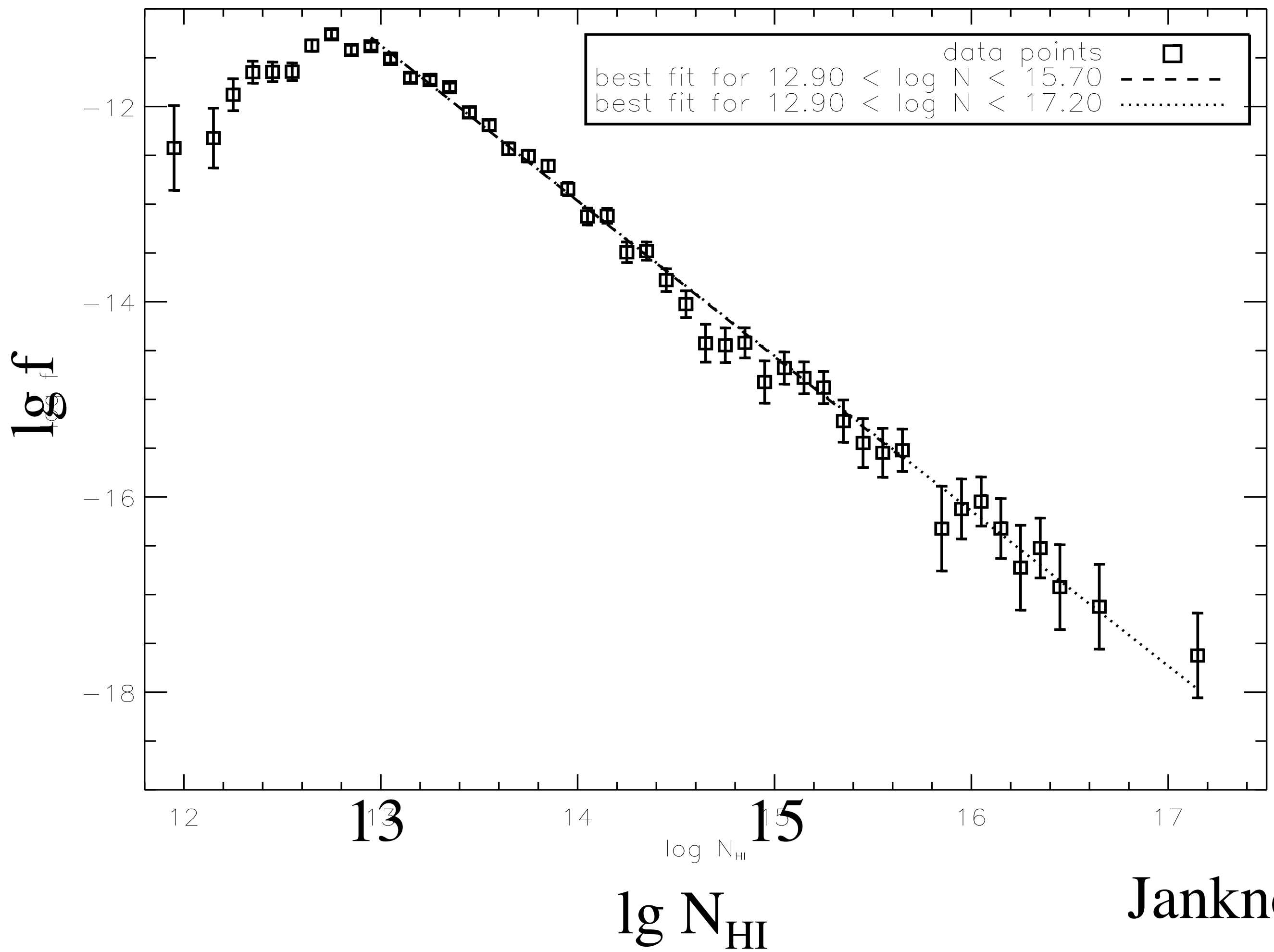
- Observations of the Ly-α forest go back to the 70s and early 80s when the basic properties were established.
- Low resolution spectra provide mean flux or distributions of equivalent widths.
- High resolution spectra provide column densities (N_{HI}) and doppler parameters (b).

$N_{HI} < 10^{12}$ cm^{-2}	Not currently observable
$10^{12} < N_{HI} < 10^{17}$ cm^{-2}	Ly-α forest
$10^{17} < N_{HI} < 10^{20}$ cm^{-2}	Lyman limit systems
$10^{20} < N_{HI}$	Damped Ly-α systems

Power laws everywhere

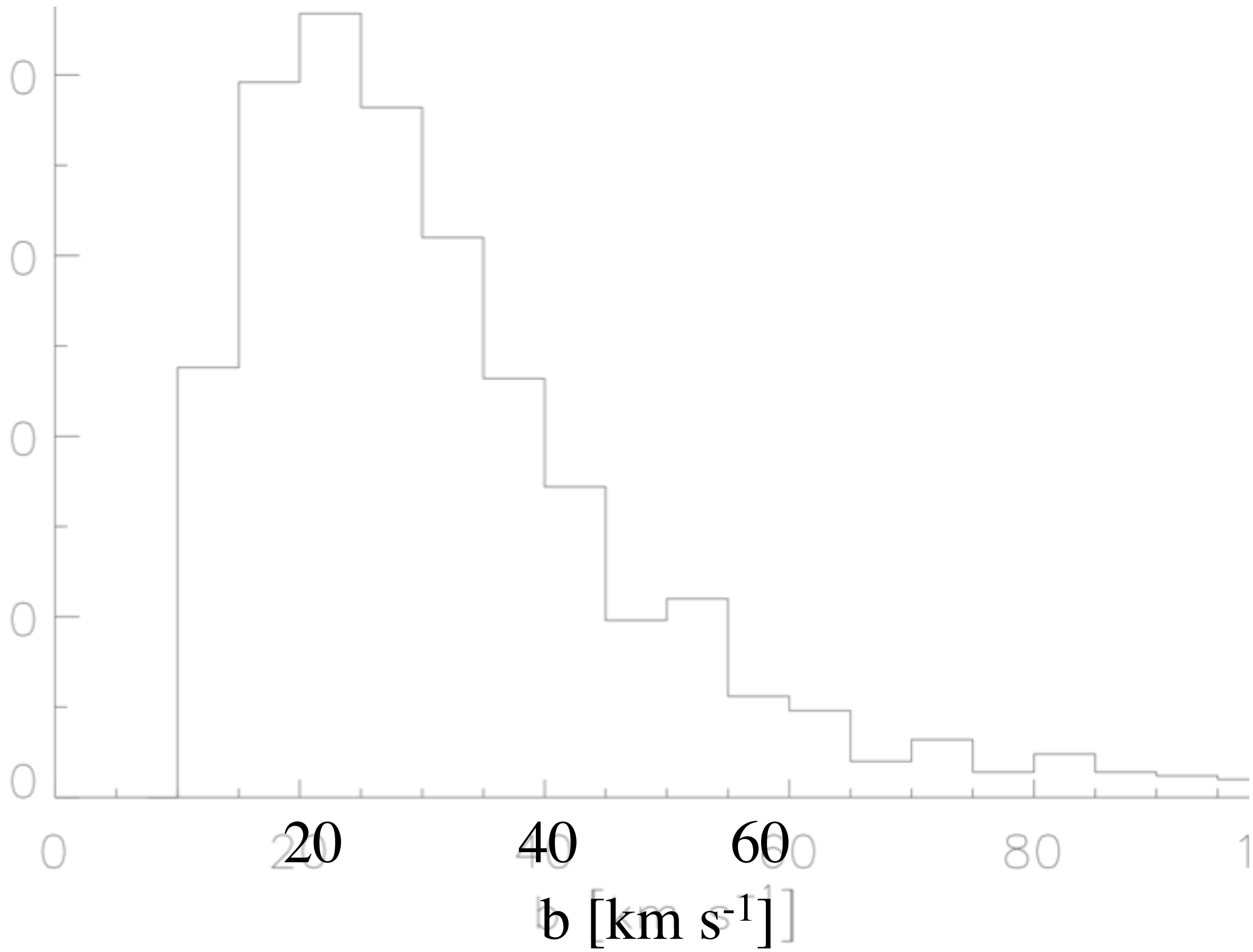
- Equivalent width distribution
  - $d^2N/dWdz \sim e^{-W/W^*} (1+z)^\gamma$
  - $W_* \sim 0.27$A and $1.5<\gamma<3$
- Column density distribution
  - $dN/dN \sim N^{-1.5}$ $12<\log N<22$!!!
    - (Some evidence for "break", e.g. Prochaska++10)
  - Slight steepening above logN=14
- *b* distribution
  - Gaussian of mean ~ 30km/s, width 10km/s
  - *b* decreases to higher *z*
- Absorbers are weakly clustered

Column density distribution



Janknecht++06

Doppler parameter



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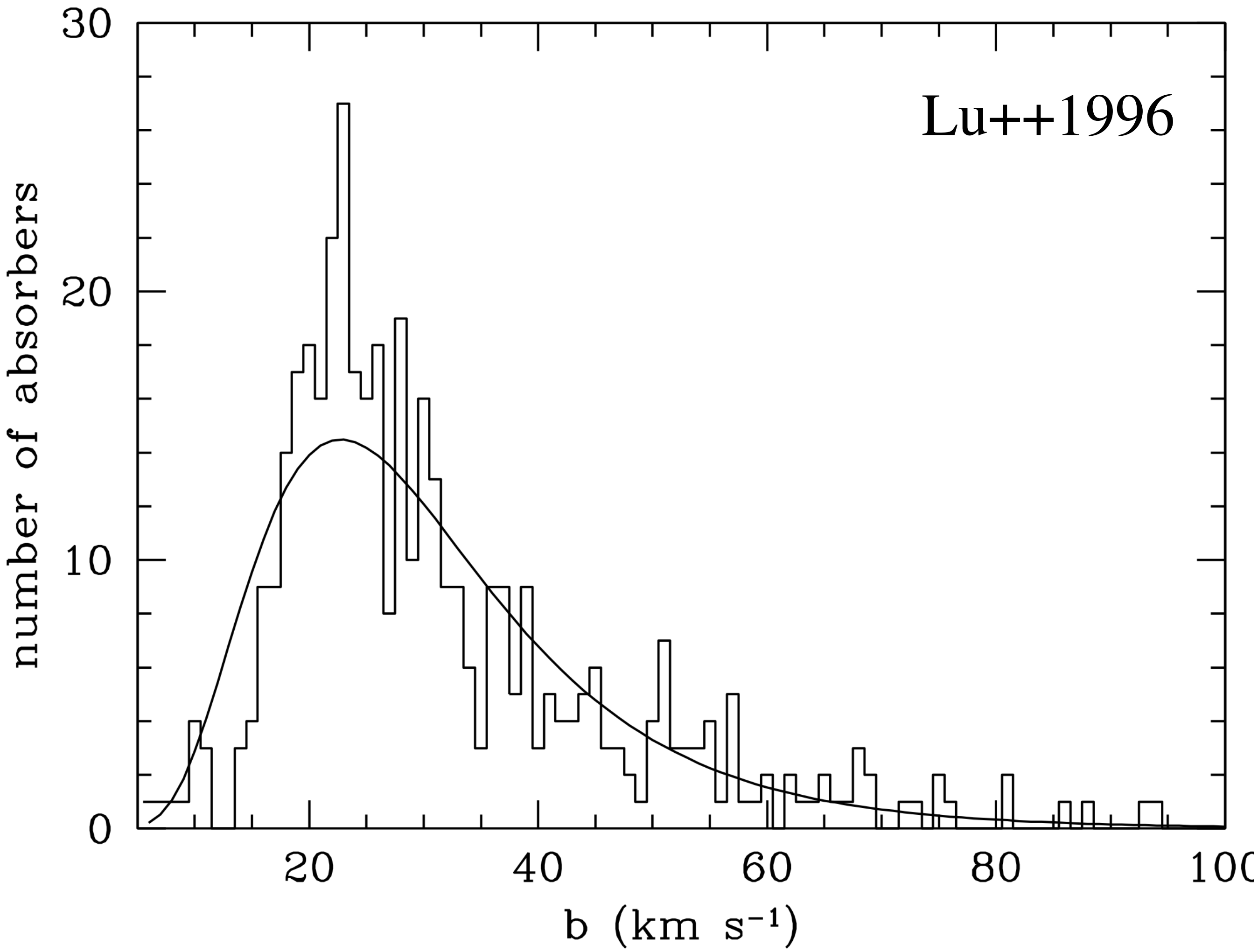
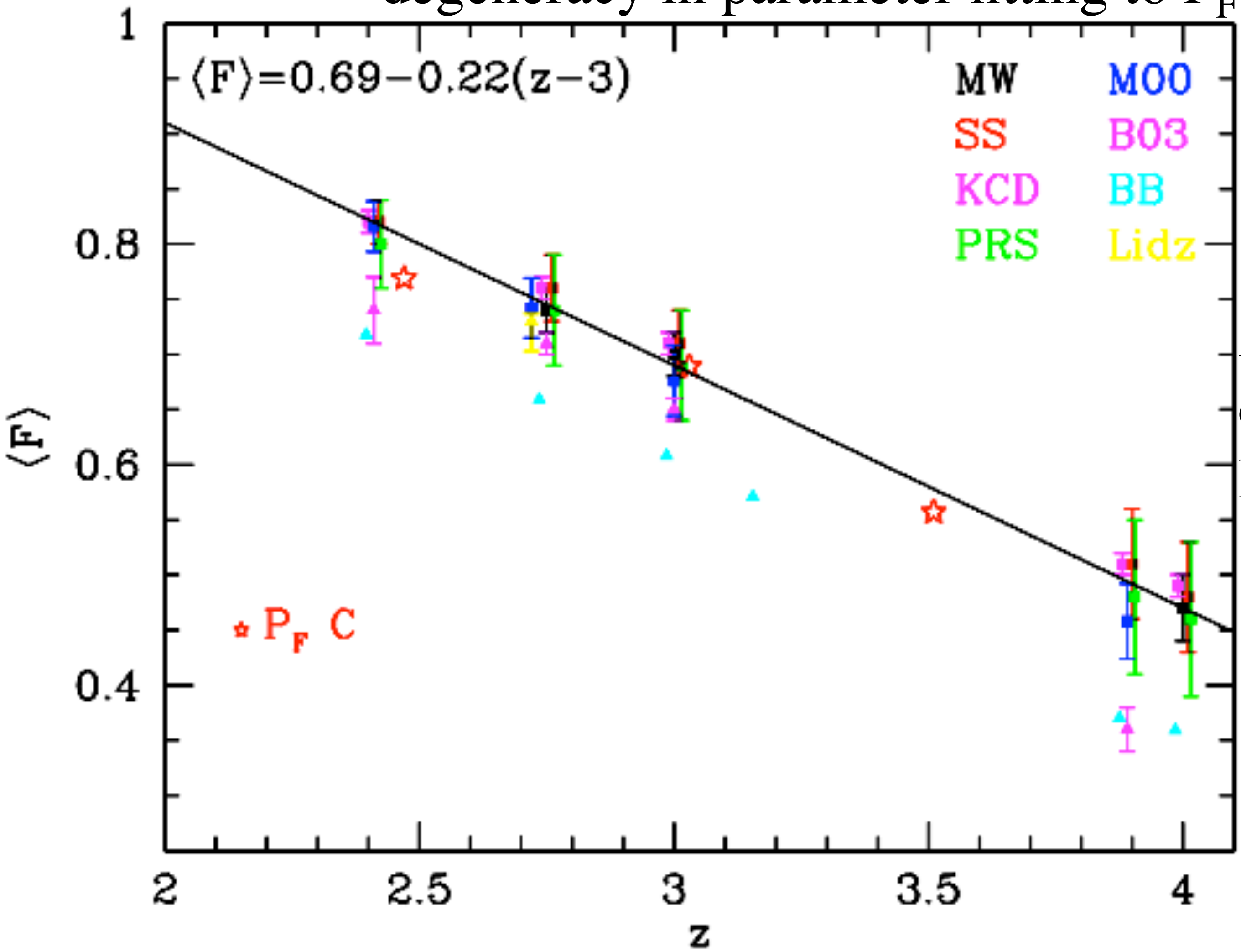
Doppler parameter



Lognormal distribution provides a reasonable fit.

Mean flux

Used to fix τ normalization in the FGPA, removes a major degeneracy in parameter fitting to $P_F(k)$



A compilation of data from the literature.

Interpretation

- But the entire framework for *interpreting* these observations has changed dramatically in "recent" years.
- No longer discuss (spherical) halos, shock, pressure or gravity confined clouds, minihalos etc.
- Now we discuss continuous density fields - the flux is a 1D, non-linear map of the density field (in redshift space).
- Much of the structure of the IGM can be understood as a consequence of the spatial coherence and properties of the "cosmic web".
- Beware misleading language and toy model concepts!

Old “theories” of the Lyα forest

- Pressure-confined intergalactic gas clouds
  - Sargent et al. 1980; Ostriker & Ikeuchi 1983
- Gravitationally-confined dark matter minihalos
  - Ikeuchi 1986; Rees 1986
- Caustics and sheets
  - McGill 1990; Miralda-Escude & Rees 1993; Meiksin 1994
- Extended gaseous disks
  - Salpeter 1993; Charlton et al. 1993, 1994

Cosmic web

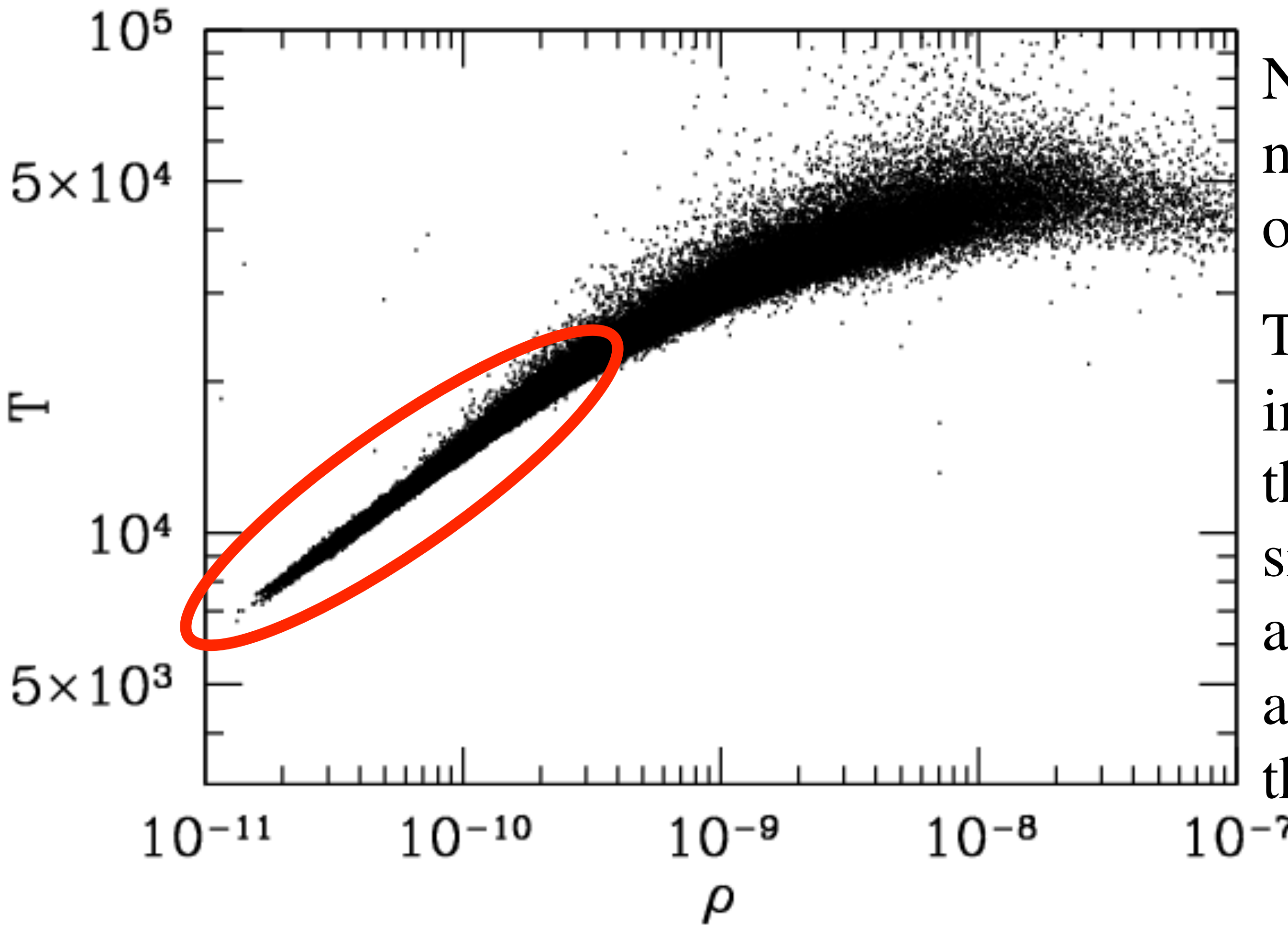
- IGM is the main baryonic reservoir for z>2
  - Galaxies are "flotsam"
- Hierarchy of structure
  - Sheets for $N_{HI}<10^{14}$ cm^{-2}
  - Filaments for $N_{HI}\sim10^{15}$ cm^{-2}
  - Clouds for $N_{HI}>10^{16}$ cm^{-2}
    - Topology depends on overdensity!
- Smaller lines come from cold but low density material -- Hubble expansion dominates the broadening!
- Basic properties of the forest depend very weakly on cosmology or indeed hydrodynamics!

FGPA

- Physics of the forest is straightforward.
  - Gas making up the IGM is in photo-ionization (but not thermal) equilibrium with a (uniform?) ionization field which results in a tight ρ-T relation for the absorbing material: $T = T_0\ (\rho/\rho_0)^{\gamma-1}$
    - Expect $\gamma \sim 1$ at reionization to ~1.5 at late time and $T_0 \sim 2.\ 10^4$K
  - The HI density is proportional to a power of the baryon density.
    - For $z<5$, $x_e \sim 1$ so $n_e \sim n_p \sim n_b$ thus $n_{HI} \sim \alpha(T)\ n_b^2/\Gamma \sim n_b^p$
  - Since pressure forces are sub-dominant, the gas traces the dark matter on scales of 0.1-10 Mpc/h.
  - The structure in the QSO spectrum thus traces, in a calculable way, the fluctuations in the matter density along the line-of-sight to the QSO. The Ly-α forest arises from overdensities ~ 1.

$$\tau(u) \propto \int dx \left[\frac{\rho(x)}{\bar{\rho}}\right]^2 T(x)^{-0.7} \frac{e^{-(u-u_0)^2/b^2}}{b} \quad \text{with} \quad b = \sqrt{2k_B T/m_{\rm H}}$$

ρ-T relation



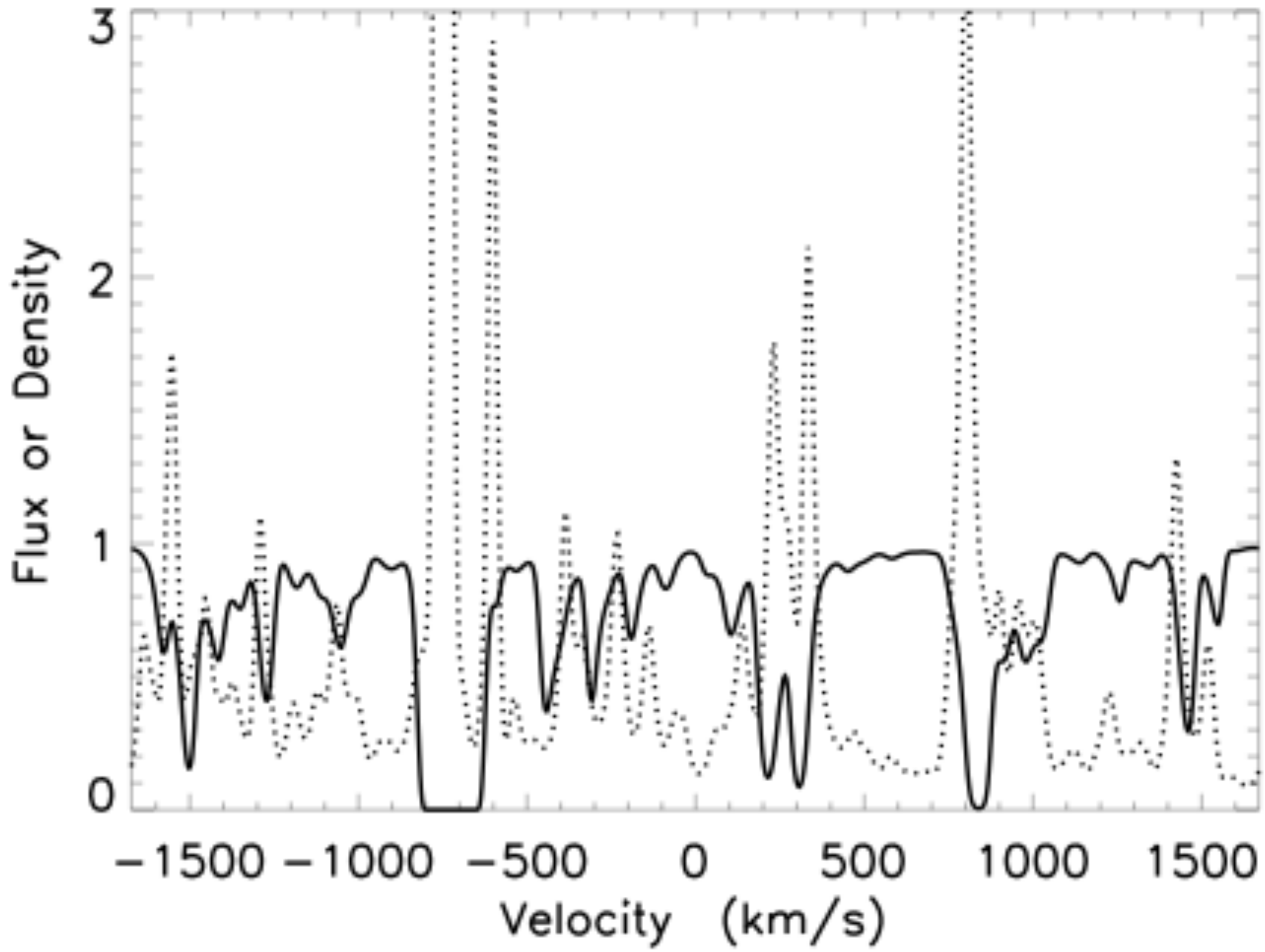
Neither ρ nor T is an observable!

There are indications that simulations and theory are getting this wrong.

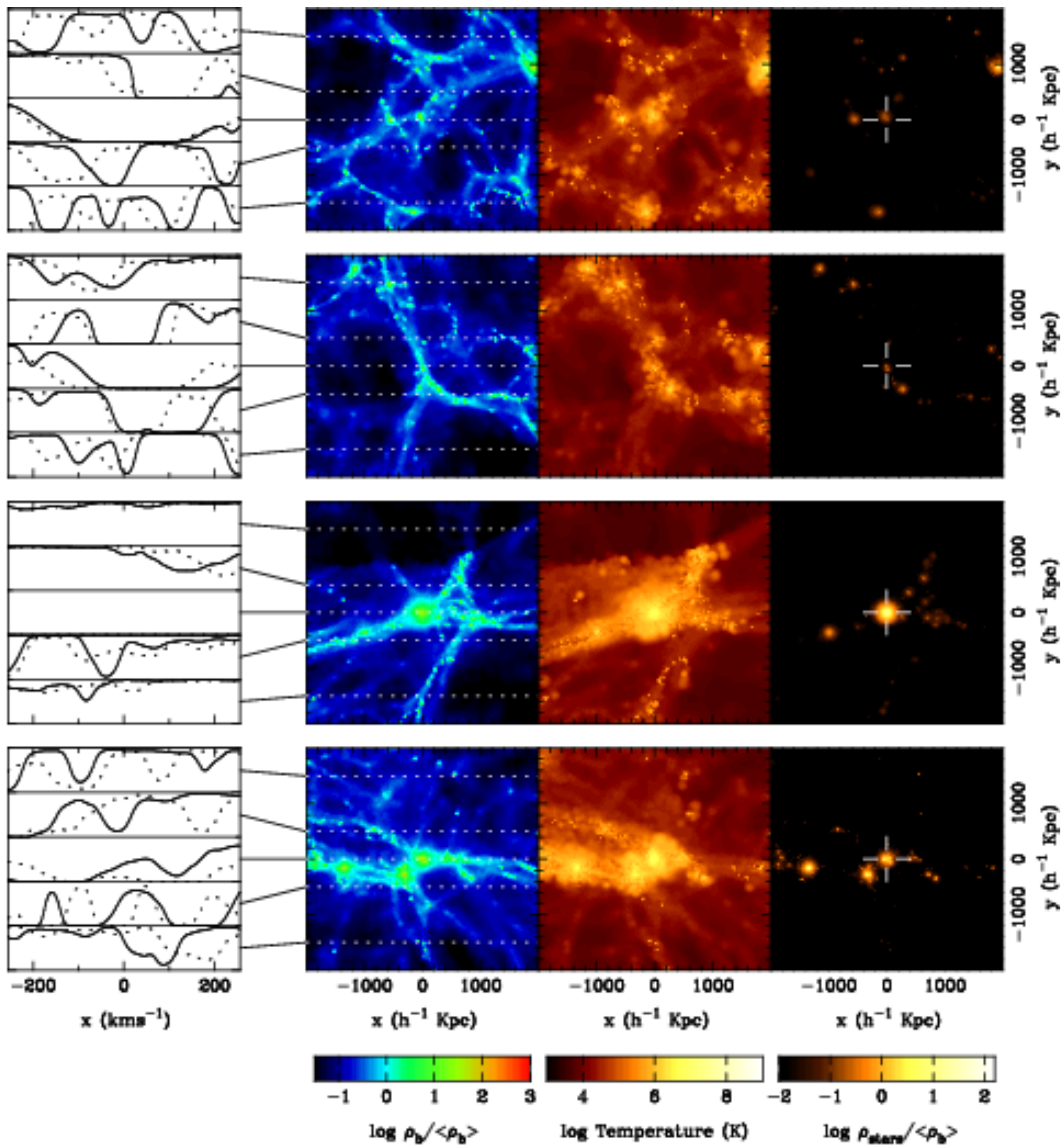
Stochasticity

- It is actually possible to constrain the amount of scatter in ρ-T, or "extra" physics, using properties of the forest.
- Gravitational clustering predicts a certain pattern of non-Gaussianity which is not mimicked by non-gravitational effects.
- Currently limited by the amount of publicly available Ly-α data, but scatter seems to be consistent with hydrodynamic effects.
  - Fang & White (2004)
  - Existing measurements provide very poor constraints on the types of scatter one might most expect theoretically.
- Being able to do 3D measurements of the forest could significantly improve this!
  - White++10, McQuinn++10

Spectrum '=' density

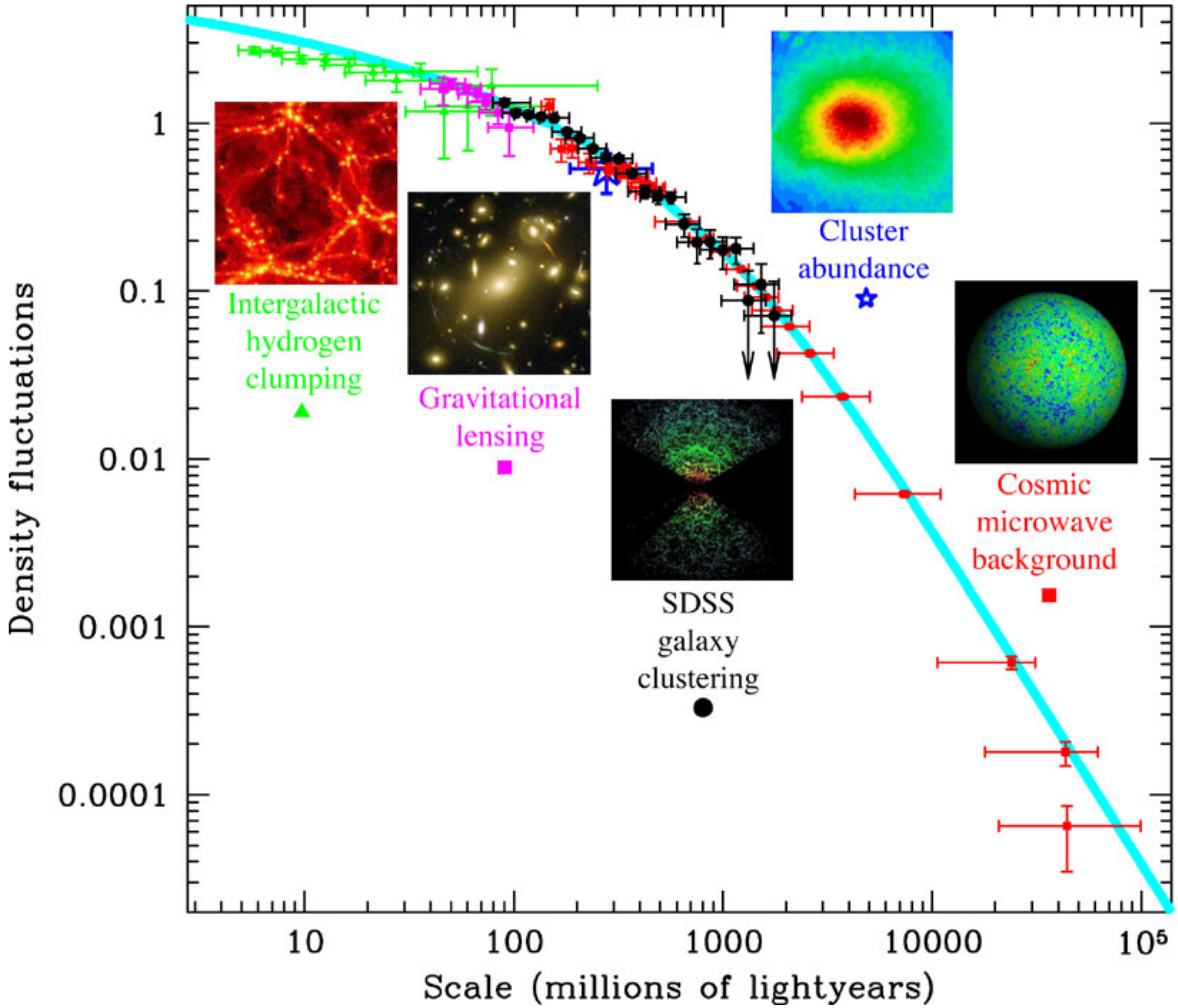


Galaxy-IGM connection



Croft++02

The power spectrum

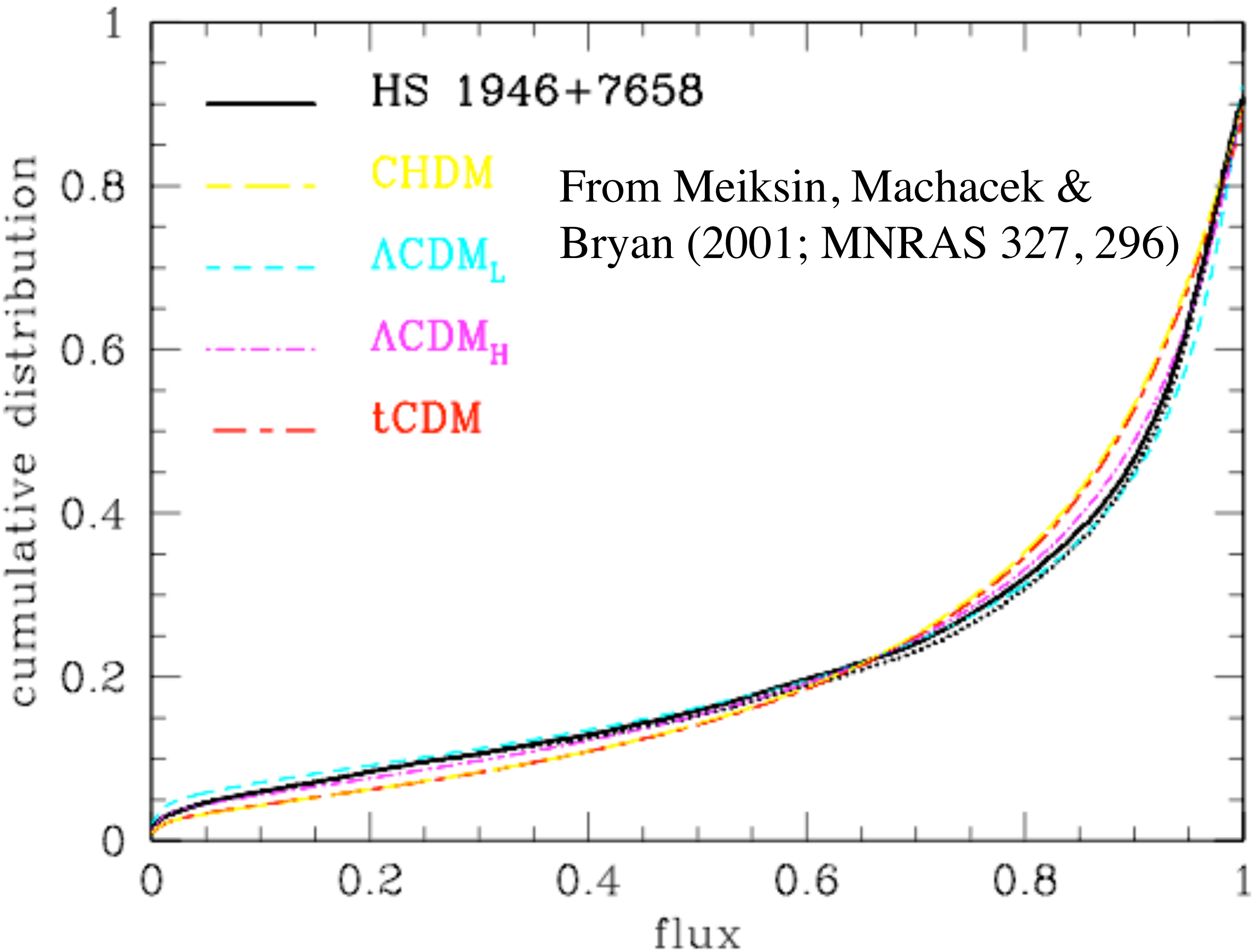


From Max Tegmark

Theory and observation

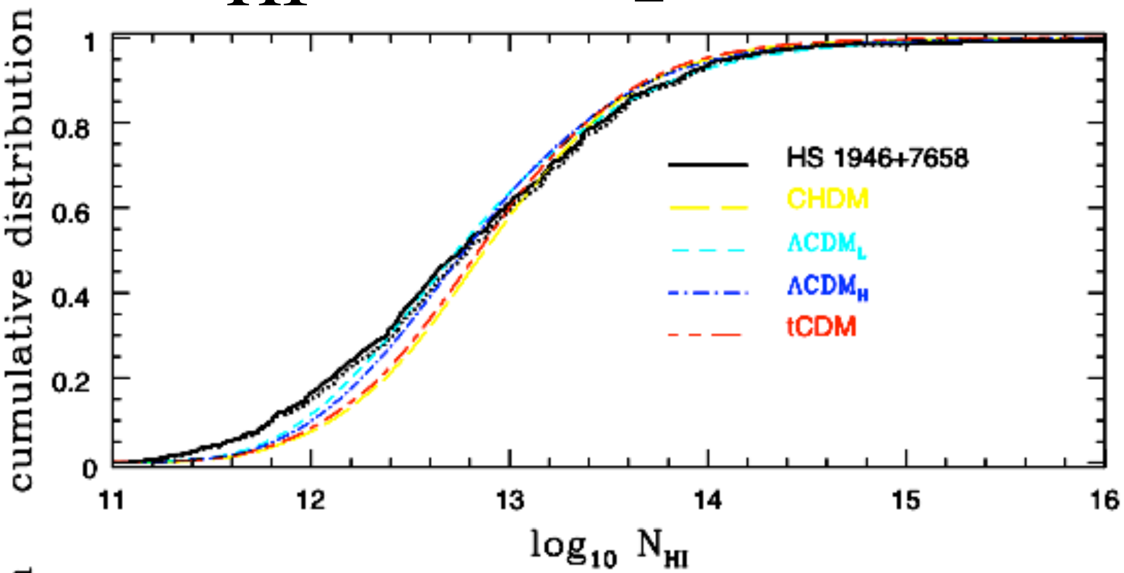
- Agree surprisingly well!
- Column density distribution shows good agreement.
- Flux histograms agree quite well with data.
- Non-Voigt line shapes predicted by simulations seen in observational data.
- Redshift evolution of absorbers agrees well with data - at both high and low column density!
- Large coherence length explained by filaments.
- Low level of clustering agrees with data.
- “Predicted” high baryon density we have now.

Flux distribution



From Meiksin, Machacek & Bryan (2001; MNRAS 327, 296)

N_{HI} and *b*-parameter distribution



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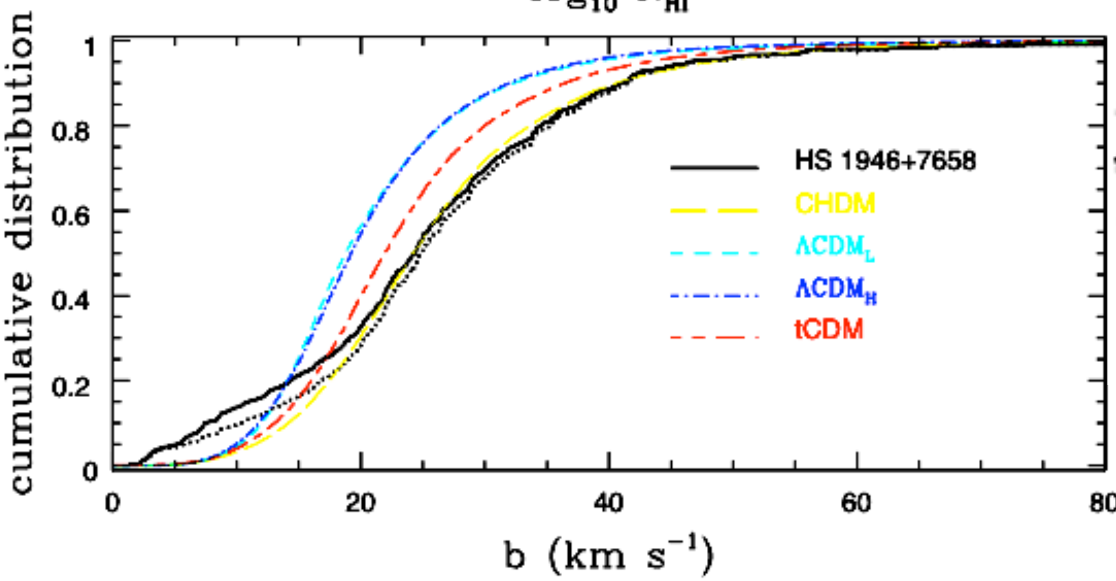
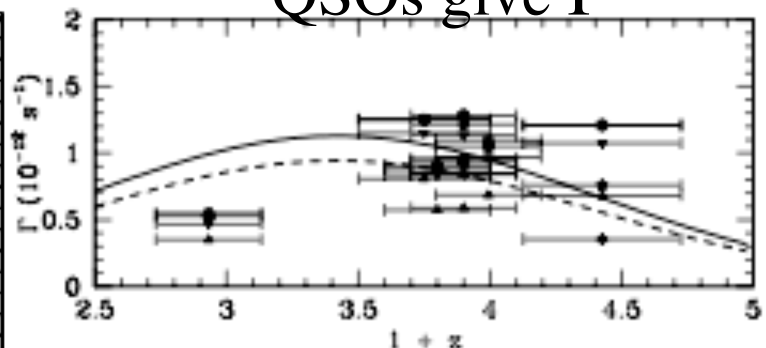
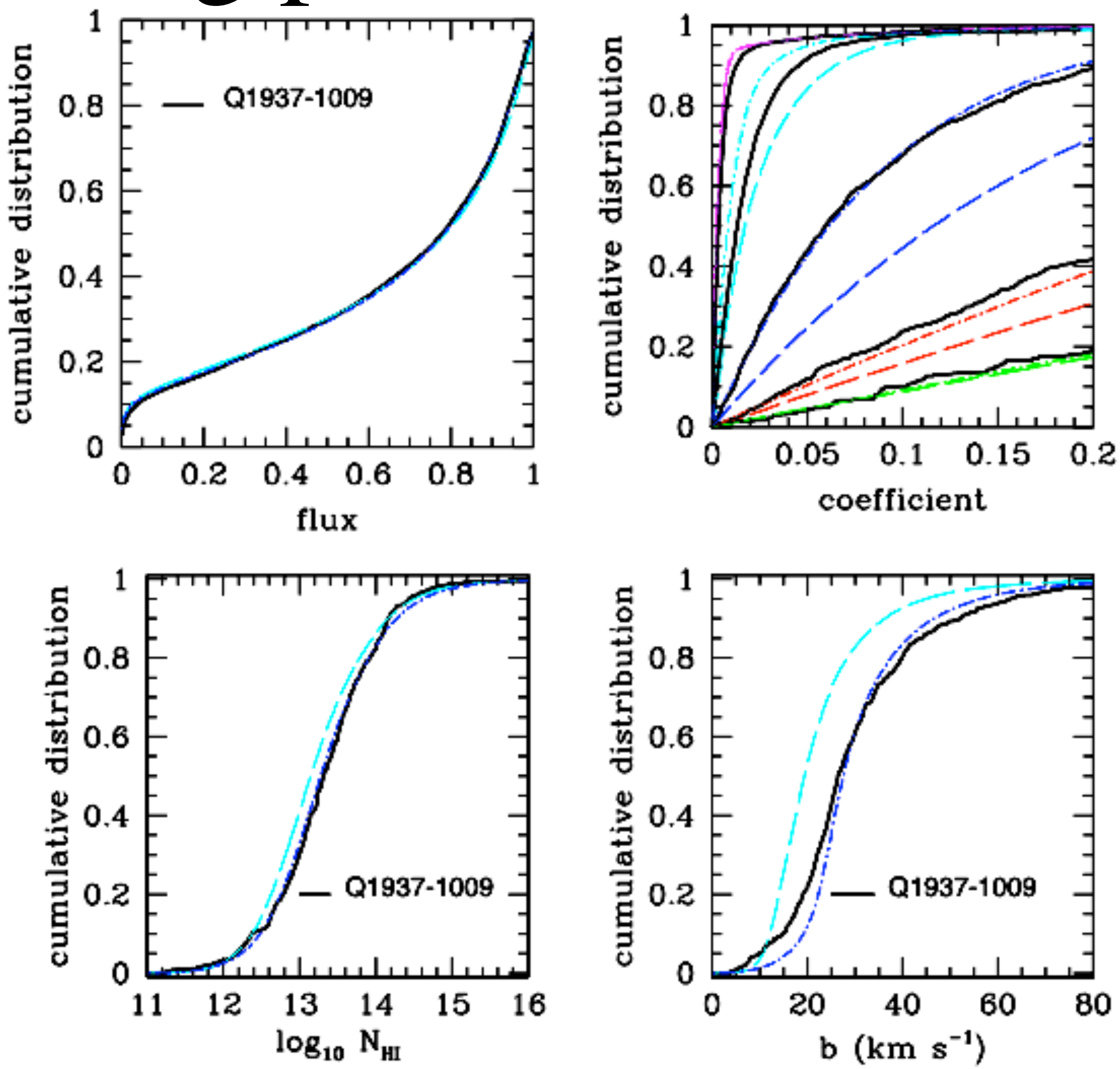


QSOs give Γ



Outstanding problems

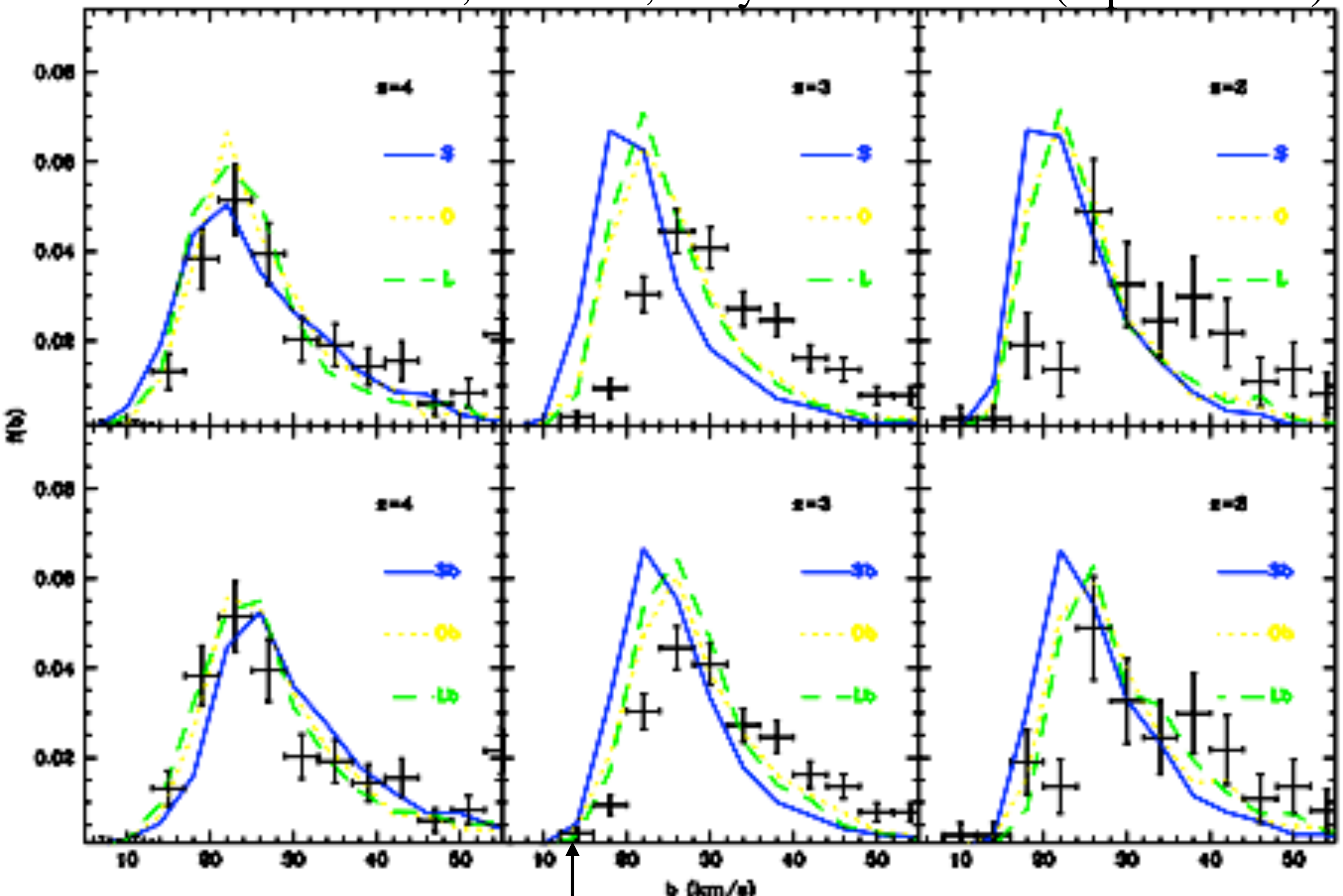
- Doppler parameter mismatch
  - *b* gets smaller as resolution increases.
  - Higher z_{re} means lower T_0 at z~3.
  - Higher $\Omega_b h^2$ makes lines broader but maybe not enough.
  - HeII reionization heats gas in underdense regions by x2



Lines broadened by 12km/s (dot-dashed)

High baryon density

Theuns, Leonard, Shaye & Efstathiou (a-p/9812141)



Low ω_b

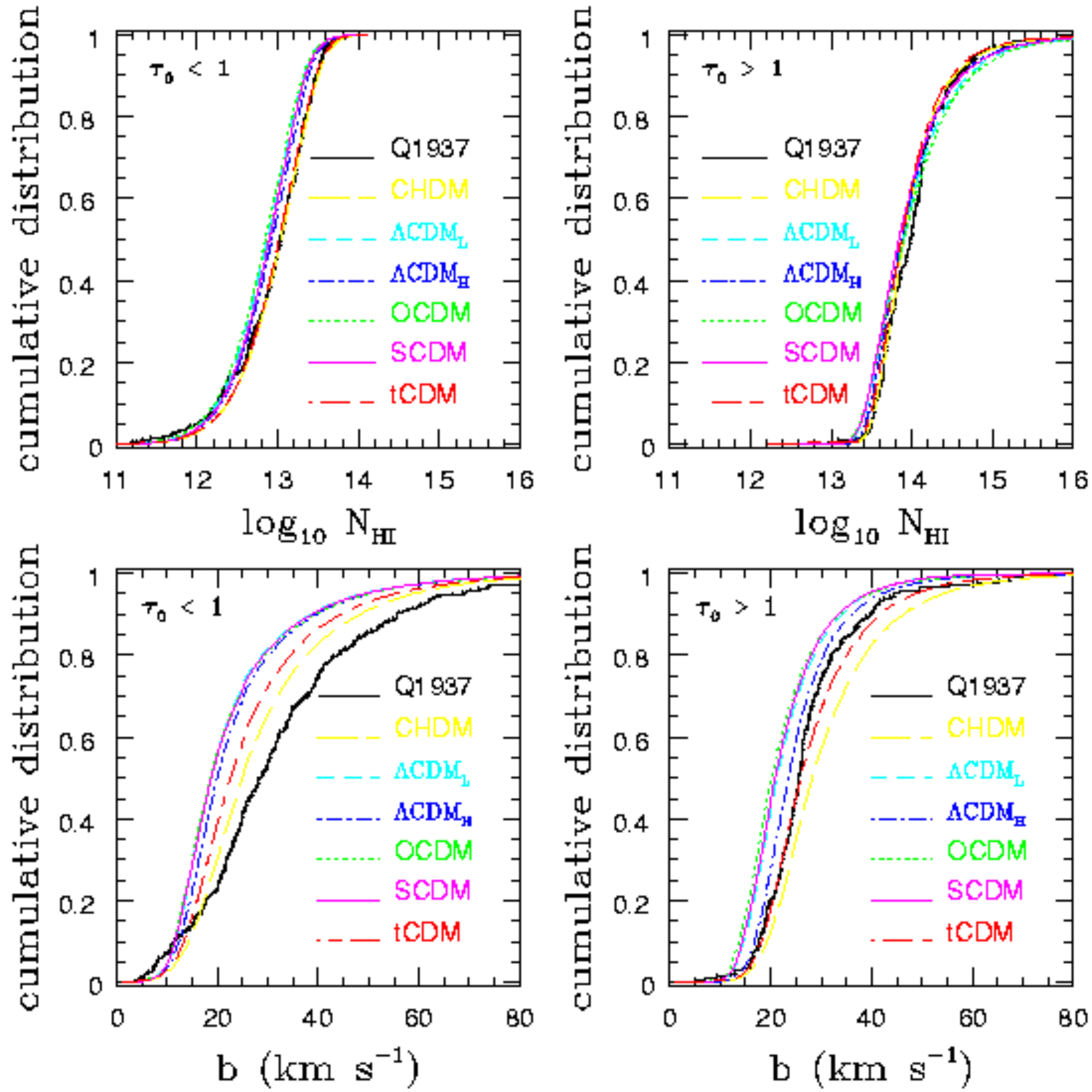
High ω_b

Low *b* cutoff is a probe of T_0 (?!)

Where is the problem?

- Hit diminishing returns in increasing ω_b from 2% to 2.4%
- The higher baryon density ΛCDM models do "okay" for the lines optically thick at line center.
- The thin lines are the problem!
- In simulations these come from low density gas - which retain memory of initial temp.
  - Radiative transfer or QSO heating will help

Thin vs thick lines

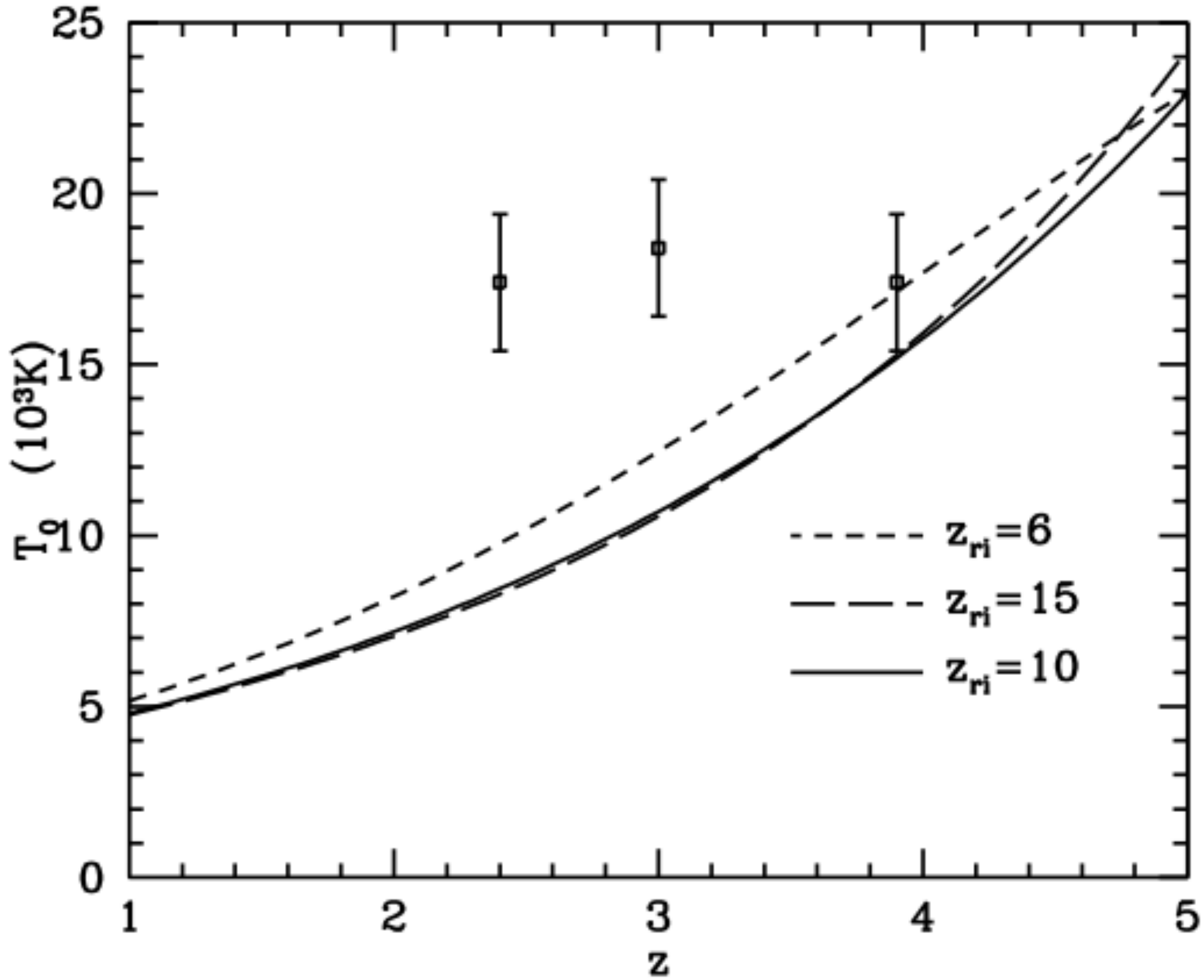


Meiksin, Bryan & Machacek (2001)

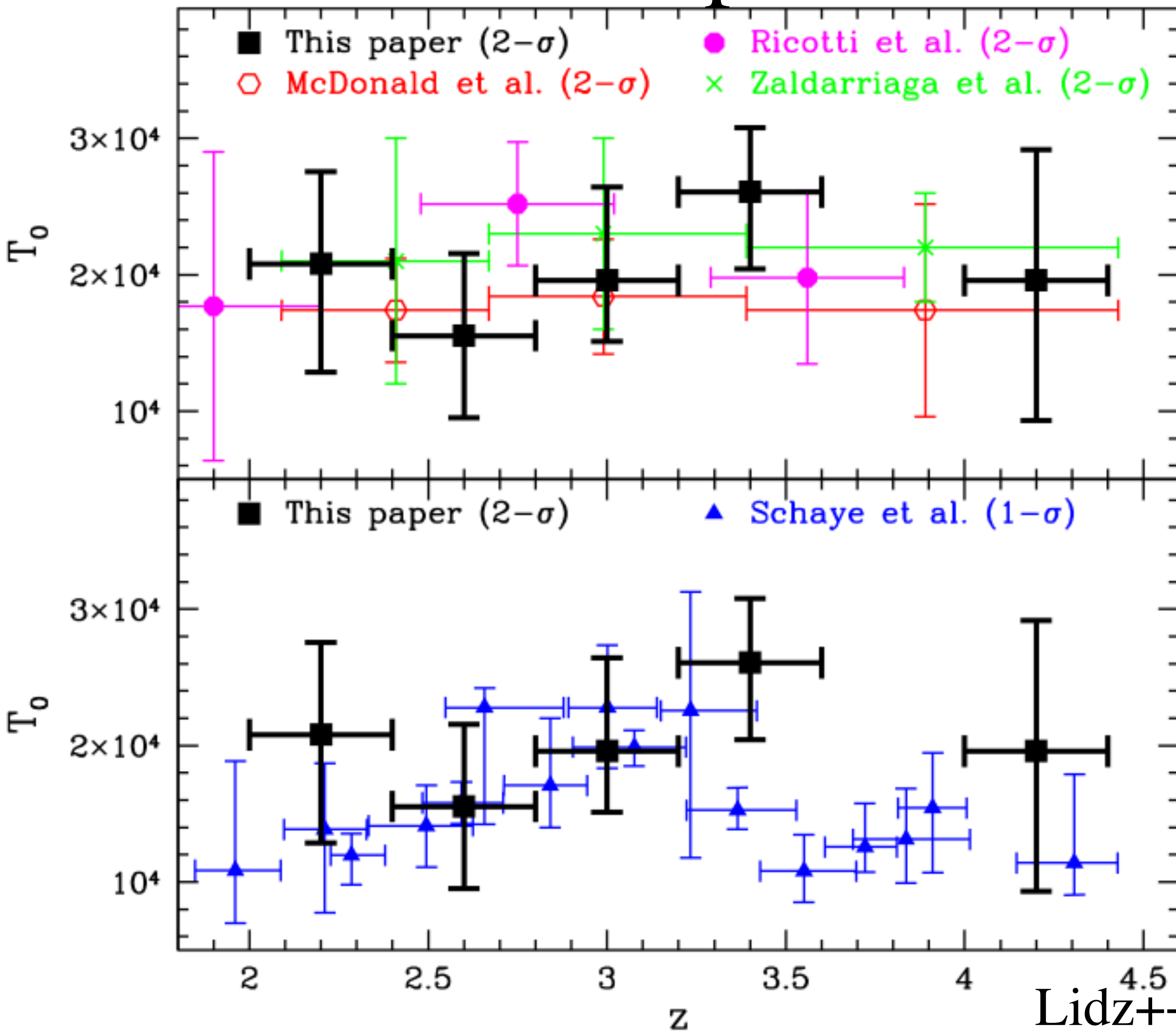
IGM temperature?

- Based on a high reionization redshift, we would expect the IGM temperature to be fairly low (at mean density).
- Measurements by McDonald, done by comparing observed spectra to a hydro simulation, give:
  - T_0=17,400; 18,400 and 17, 400 K (+/- 2000K) at z=3.9, 3.0 and 2.4

IGM temperature



IGM temperature

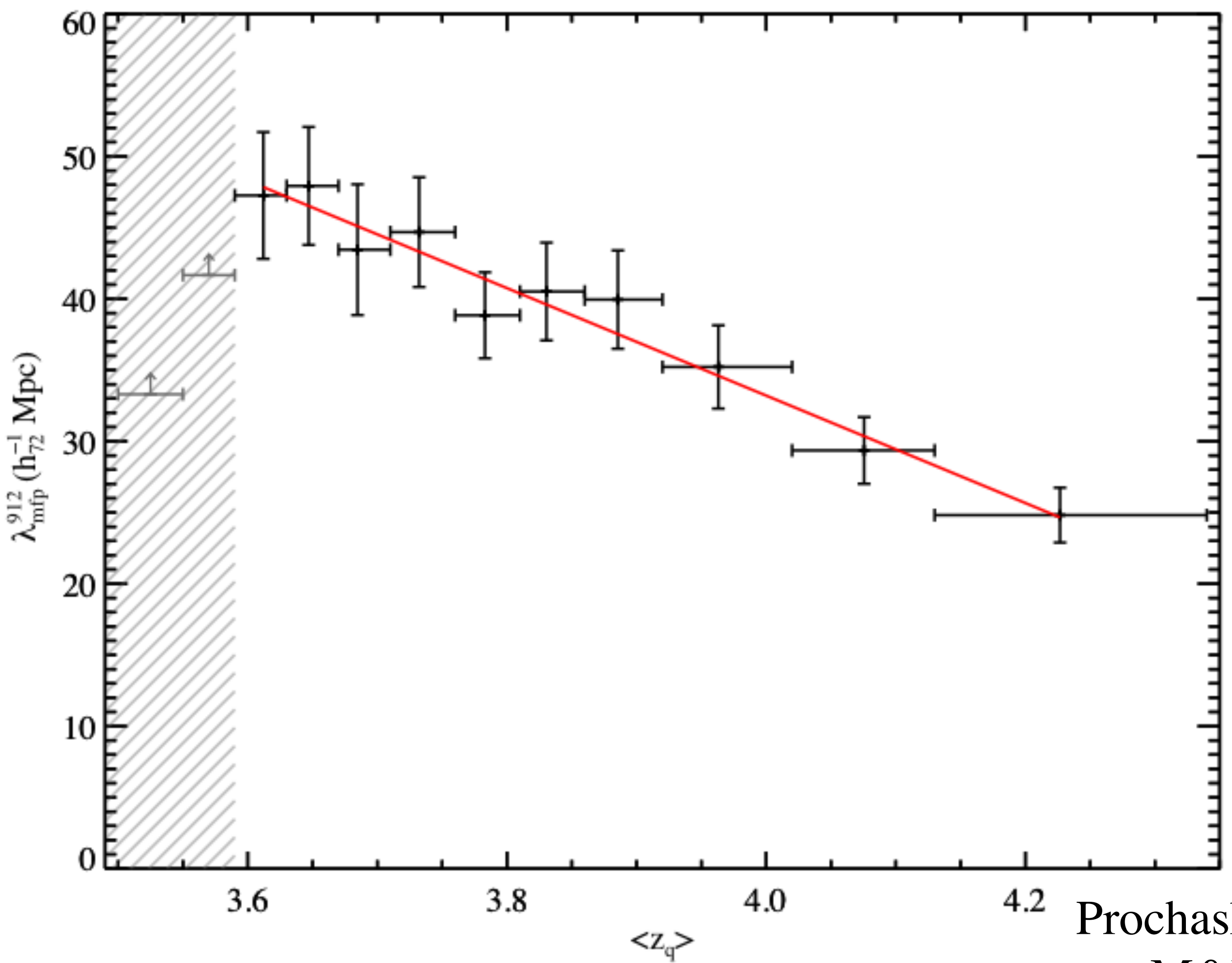


Lidz++10

Ionization rate

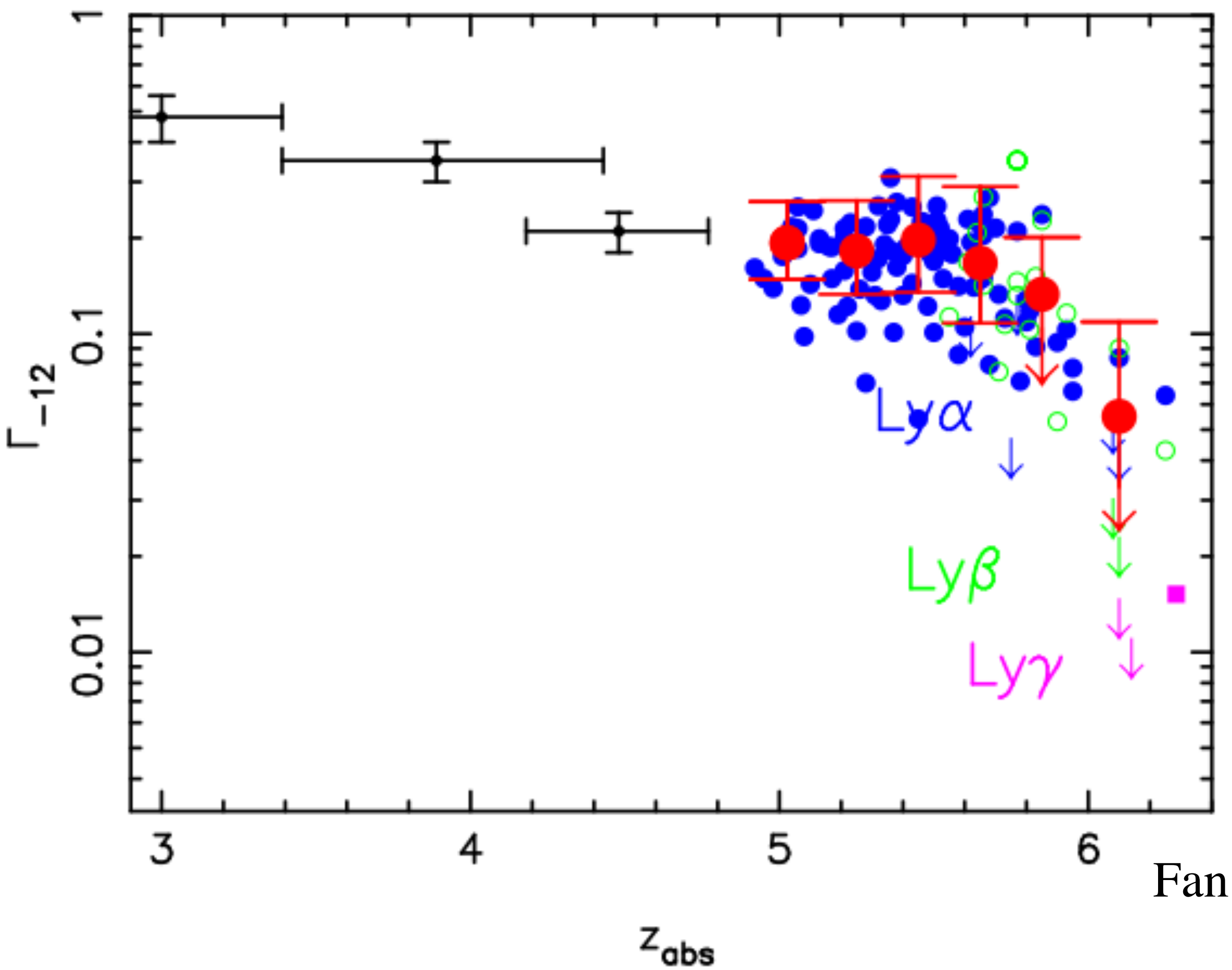
- Values of Γ_{-12} required to fit data with hydro simulations of ΛCDM cosmologies are ~4x larger than those in EdS models.
- Recent compilation by Prochaska++09.
- Require extra radiation above that due to QSOs at z<4 at about factor of 2 level.

Ionizing background



Prochaska++09
see M&W04 for lower *z*s.

Evolution of Γ_{-12}



Fan et al. (2006)

Outstanding problems

- Effects of radiative transfer
  - Heating of the IGM
    - Abel & Haehnelt (1999; ApJ 520, L13)
  - Effect on DLAS and LLS??
- Reionization - when and how?
- HeII
  - Why is there so much scatter in HeII Ly-α optical depth at z~3?
  - Why are HeII linewidths the *same* as the HI widths?
    - Very underdense regions where thermal broadening not dominant?
- Metal lines (almost no theory)
  - Metal enrichment is ubiquitous.
- DLAs and LLS
  - Little detailed theory, a lot of observation.
    - Beware interpretation based on simplified models!
  - Possible abundance mismatch between sim and obs.
    - Gardner et al. (astro-ph/9911343)
- Galaxy-IGM connection, effects on environment?
  - Adelberger et al. (2003; ApJ, 584, 45)

Extra physics?

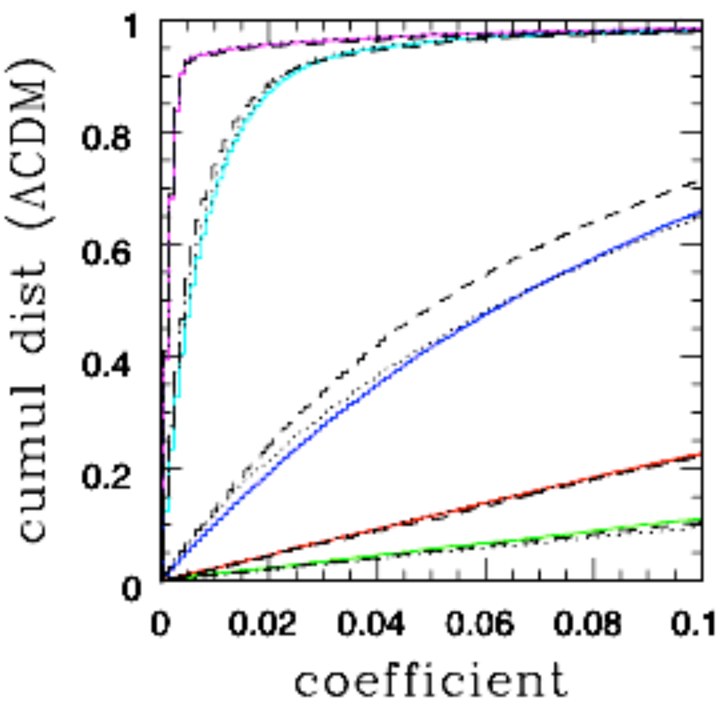
- Hydrodynamics.
- Fluctuating ionization field.
- Fluctuating mean temperature.
- HeII reionization
- Stellar feedback (SN ejecta, winds, …)
- Radiative transfer.

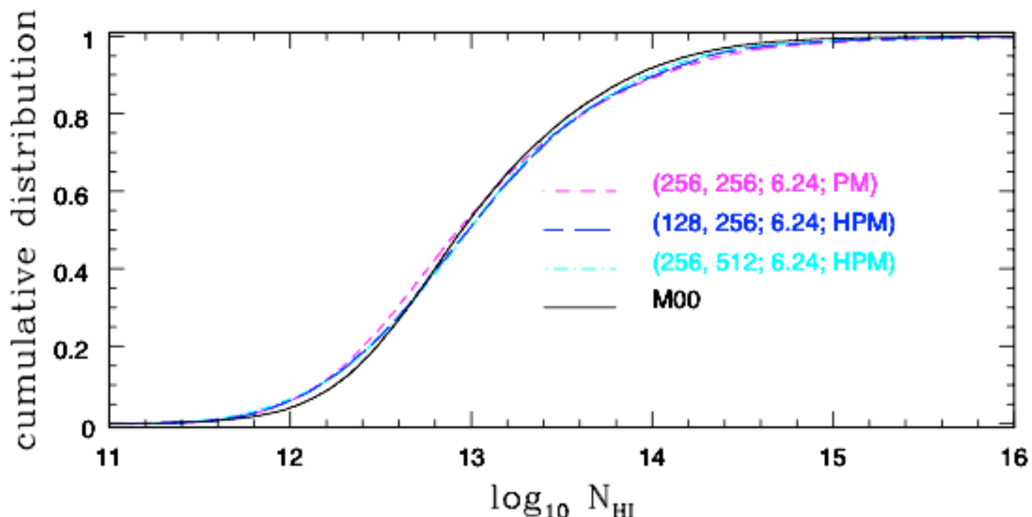
Hydrodynamics?

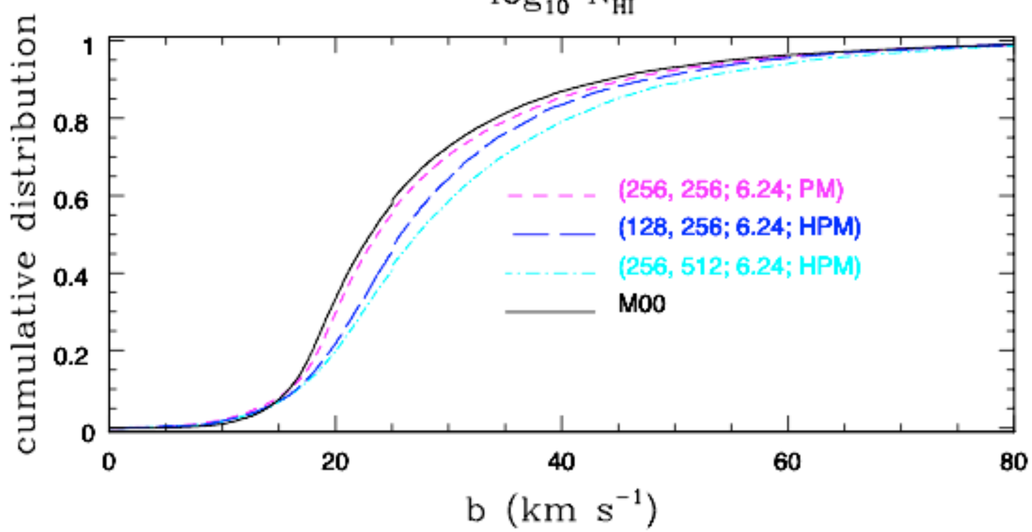
Comparing FGPA schemes to full hydrodynamic simulations

Wavelet coefficients

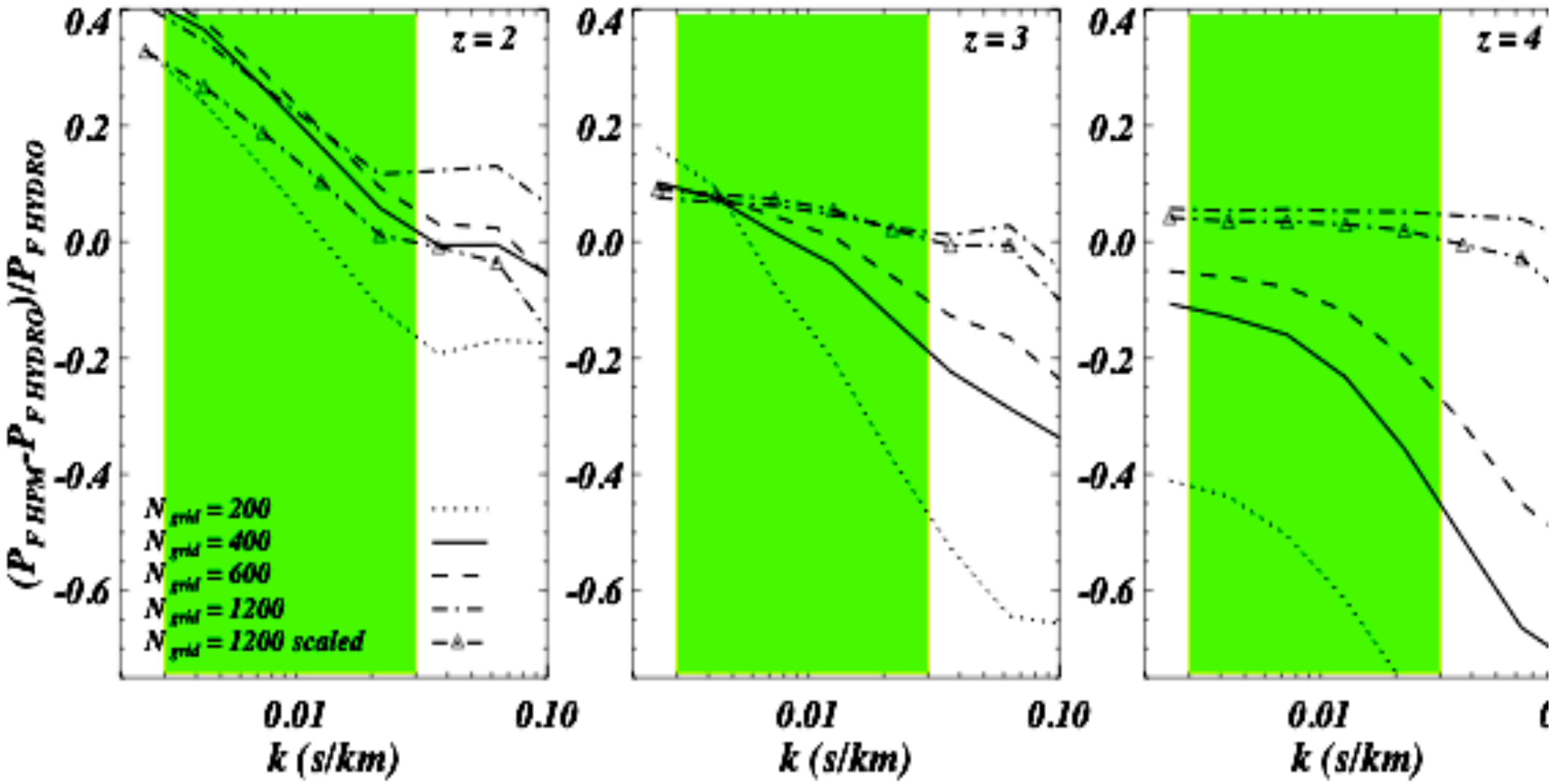
Solid: Hydro
Dotted: PM
Dashed: HPM







Hydrodynamics II



Viel, Haehnelt & Springel (2005)

HeII reionization

- Many of the problems alluded to above would be (at least partly) mitigated by HeII reionization at z~3ish.
- There are several lines of (tentative) evidence that this could be happening.
- QSOs near break of LF contribute most photons.
  - Faint-end slope would have to be very wrong to change this.
  - Consistent with HeII Lyα forest intensity fluctuations (rare objects).
  - Integration of LF + extrapolation to FUV gives few HeII ionizing photons by z~3 … just what you need.
- Optical QSOs (Type I) most important.
  - E~100eV photons important – little HI column allowed.
  - Photons E>1keV not absorbed in Hubble length at z~2-3.

Conclusions

- Basic picture appears to be correct.
  - IGM traces "cosmic web".
  - Dominant properties set by dark matter skeleton and photo-ionization equilibrium.
- Level of agreement between different types of simulations and simulations with observations is O(10%) for a large number of (1- and 2-point) statistics of the forest.
  - A major problem seems to be temperature of IGM (role of RT, HeII, …) and the Doppler parameter distribution.
  - Can often change physics inputs to better match one set of observational statistics at the cost of "breaking" the agreement somewhere else.
- Improvements in theory and observation are expected to occur over the next few years which will maintain LyαF as one of our premier cosmological probes.