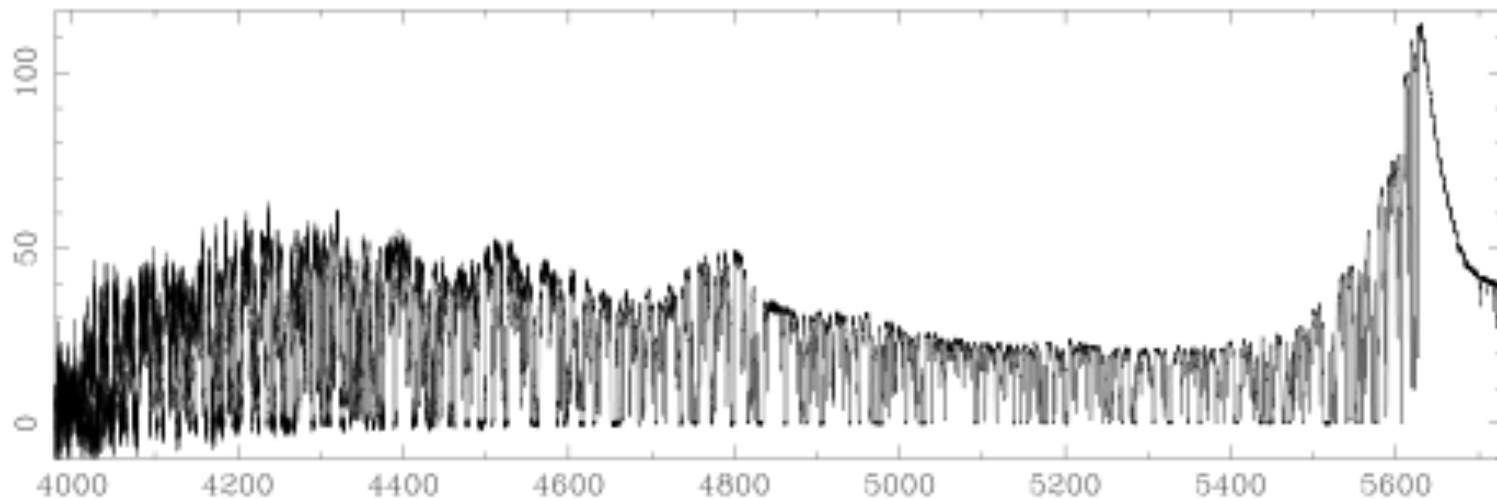


Modeling the Ly- α forest

Paradigm successes and challenges



QSO 1422+23

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).

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

Power laws everywhere

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

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!

Cosmic web

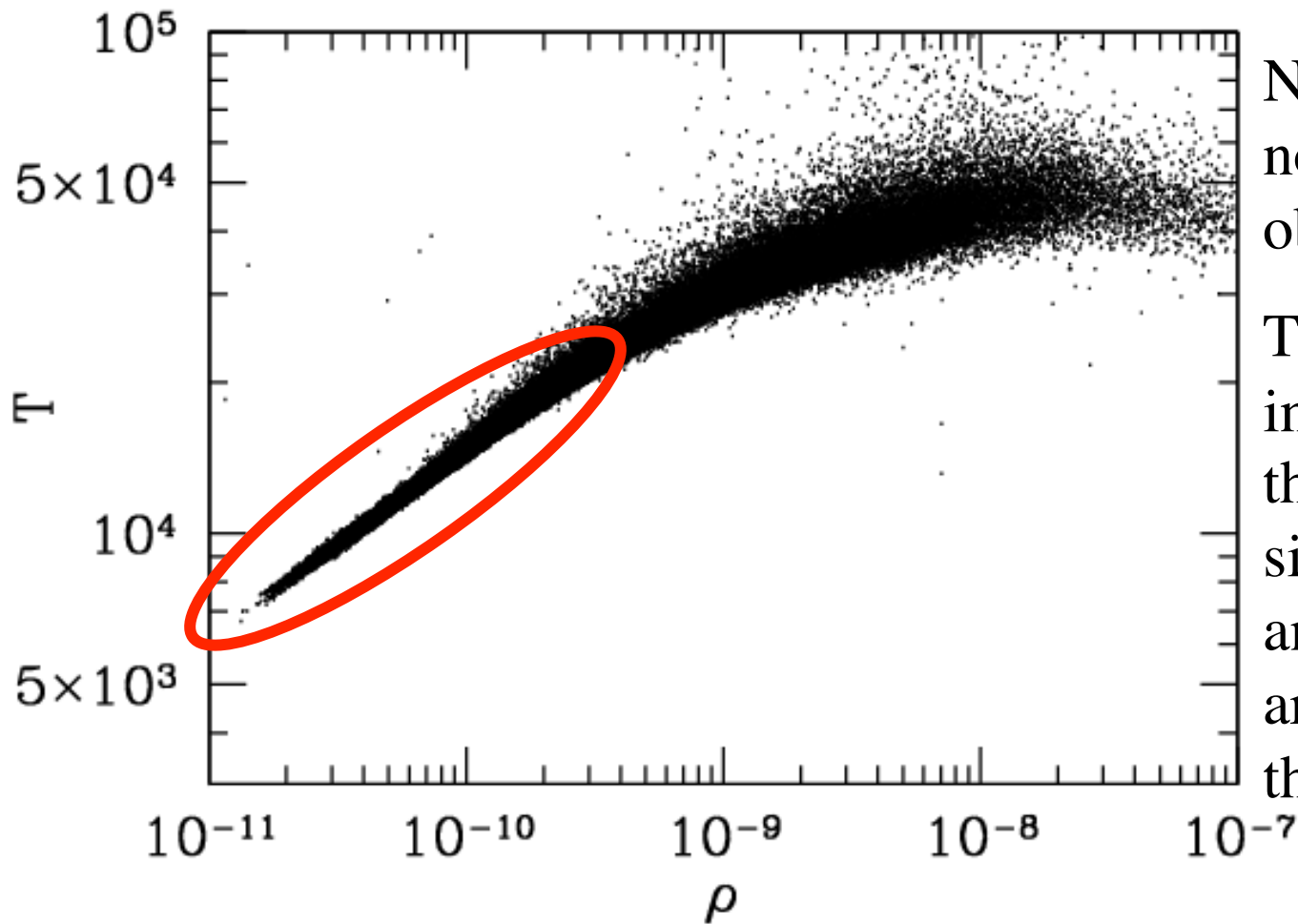
- IGM is the main baryonic reservoir for $z > 2$
 - Galaxies are “flotsam”
- Hierarchy of structure
 - Sheets for $N_{\text{HI}} < 10^{14} \text{ cm}^{-2}$
 - Filaments for $N_{\text{HI}} \sim 10^{15} \text{ cm}^{-2}$
 - Clouds for $N_{\text{HI}} > 10^{16} \text{ cm}^{-2}$
- Smaller lines come from cold 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 $T_0 \sim 2 \cdot 10^4 \text{K}$
 - 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 $n_{\text{HI}} \sim \alpha(T) n_b^2 / \Gamma \sim n_b^p$
 - 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 .

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

ρ -T relation



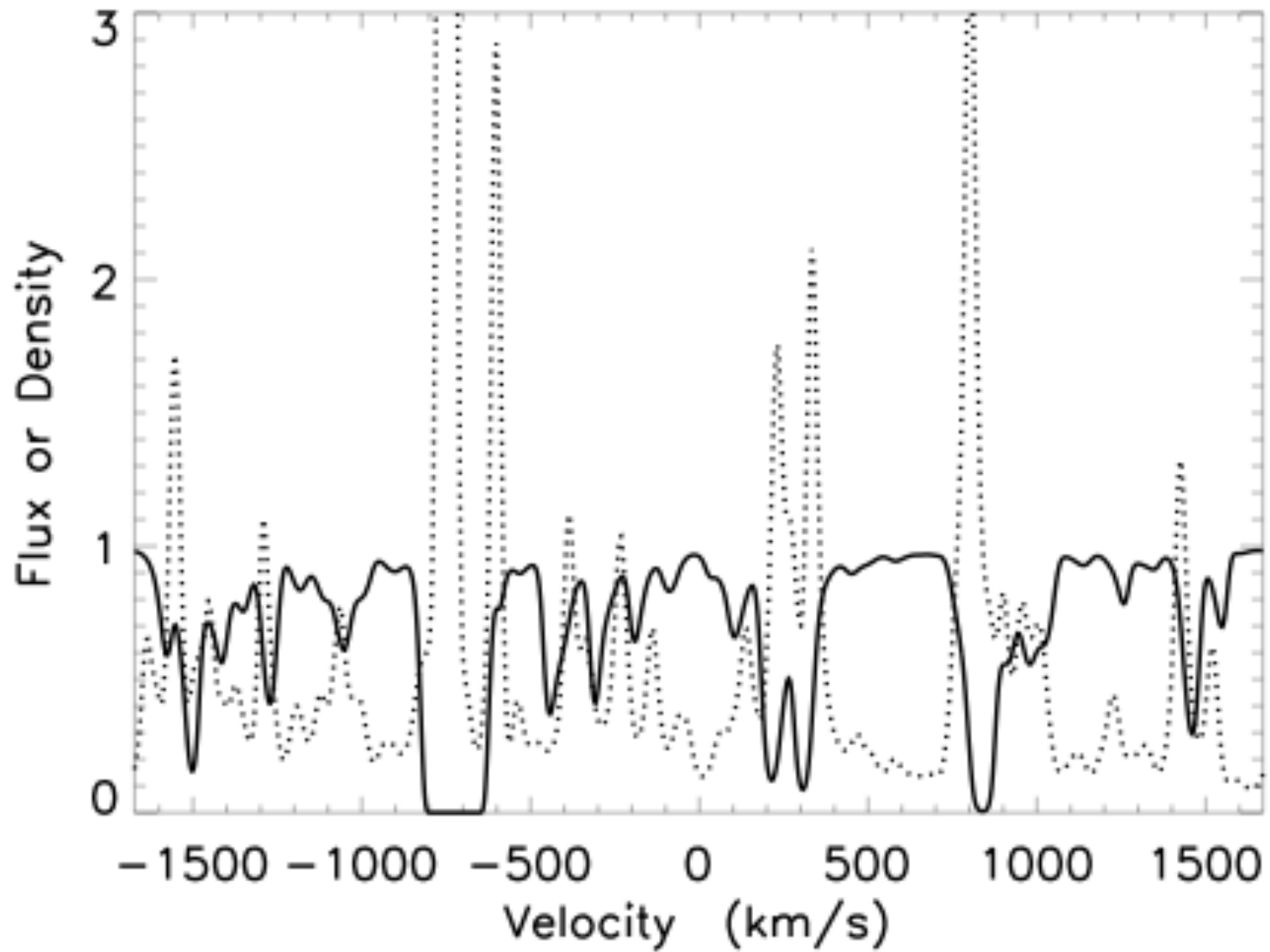
Neither ρ
nor T is an
observable!

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

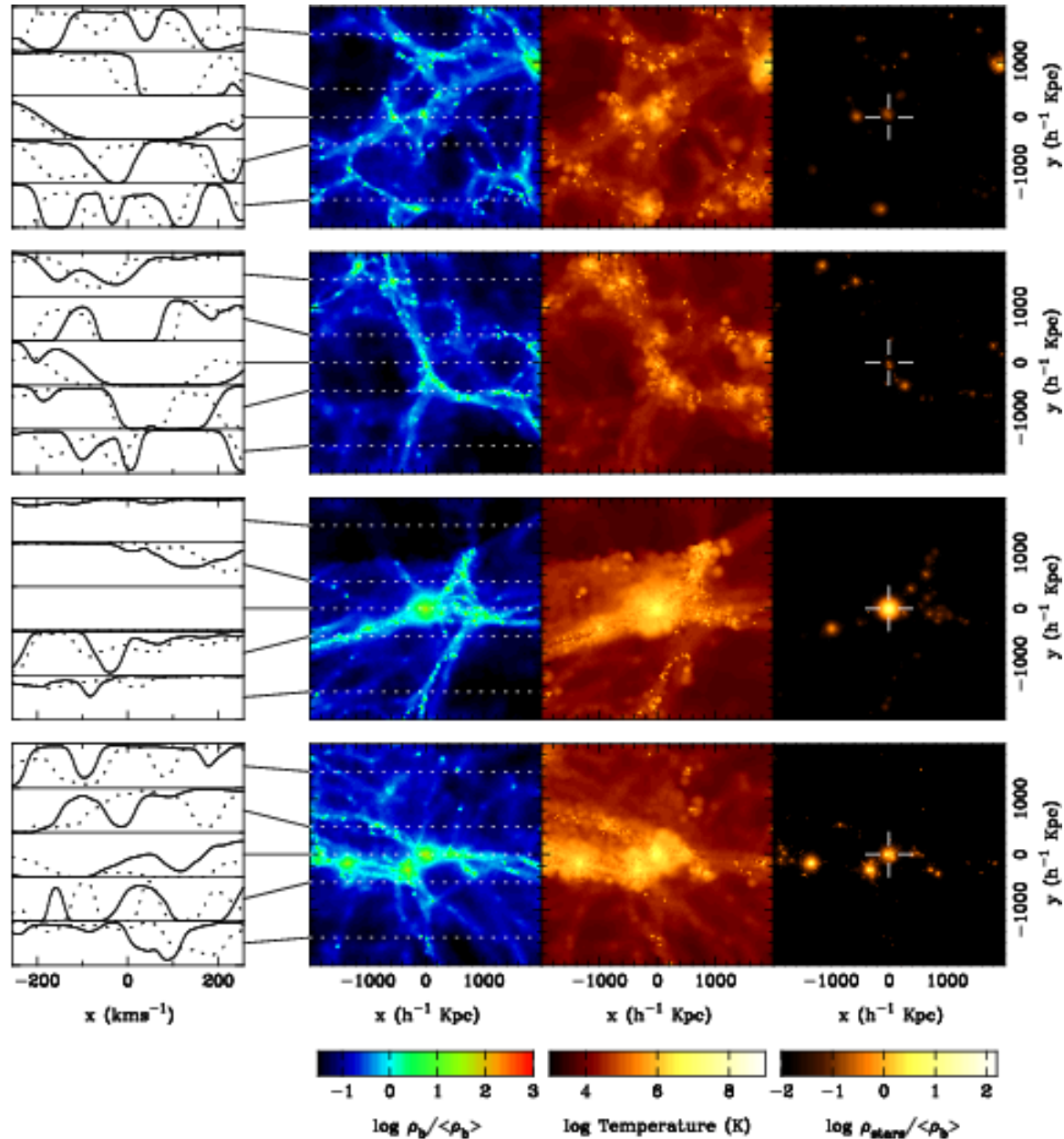
Stochasticity

- 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; ApJ, 606, L9)

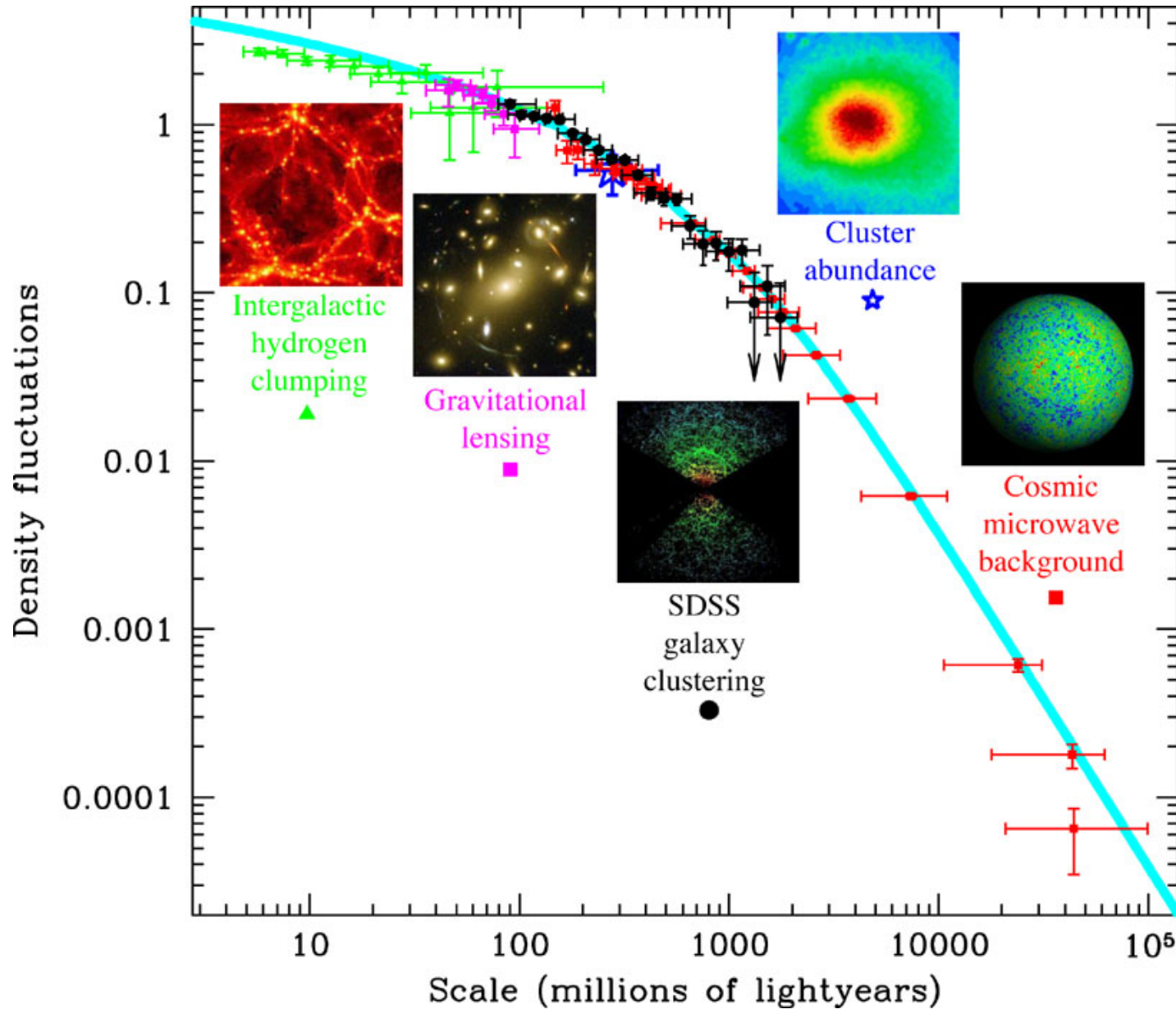
Spectrum '=' density



Galaxy-IGM connection



The power spectrum

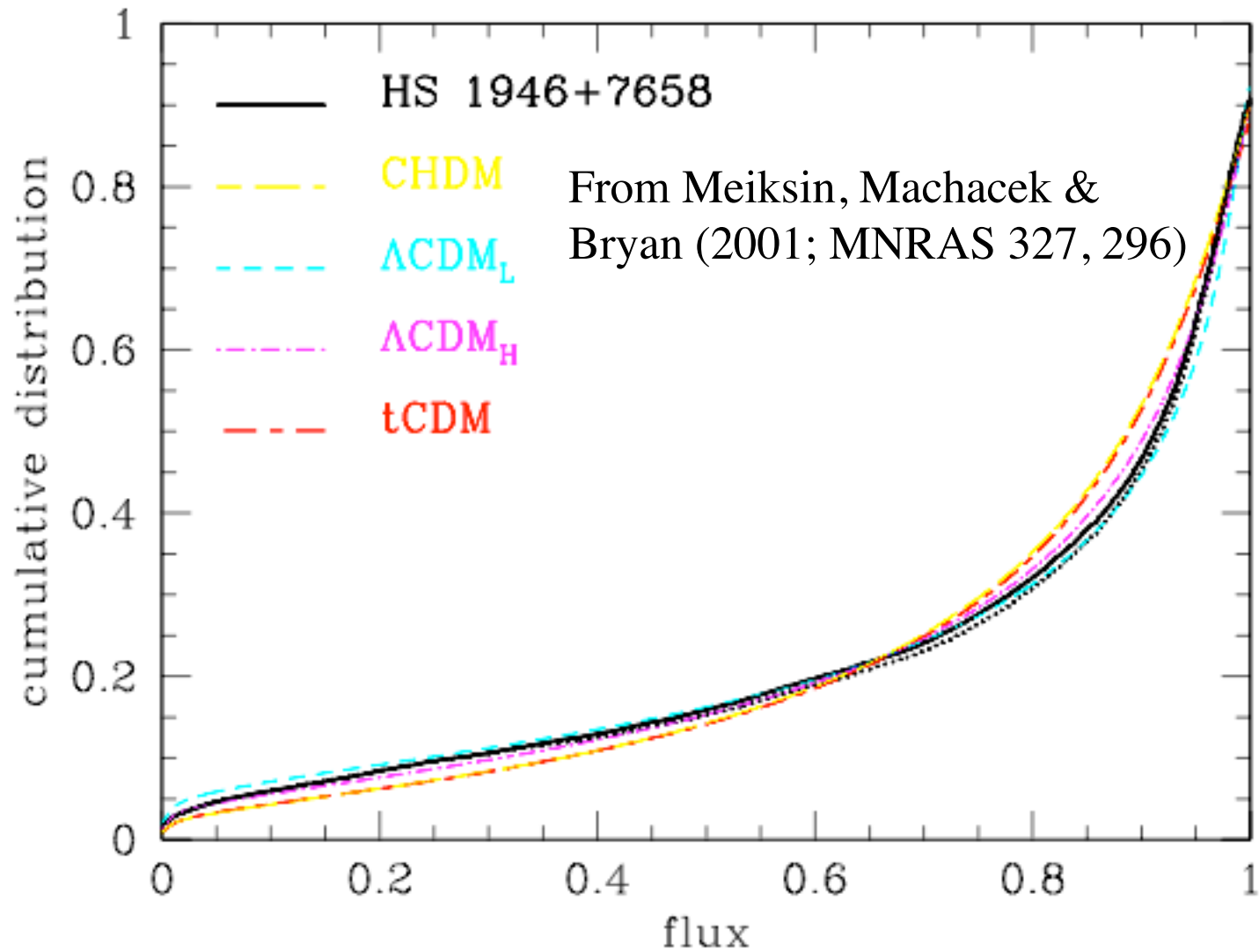


From Max Tegmark

Theory and observation

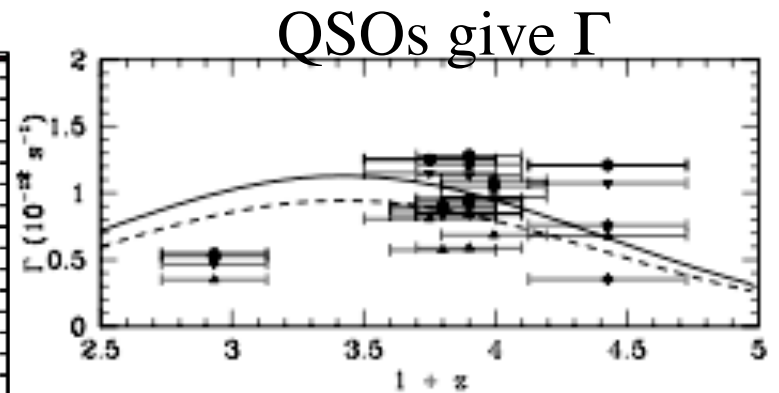
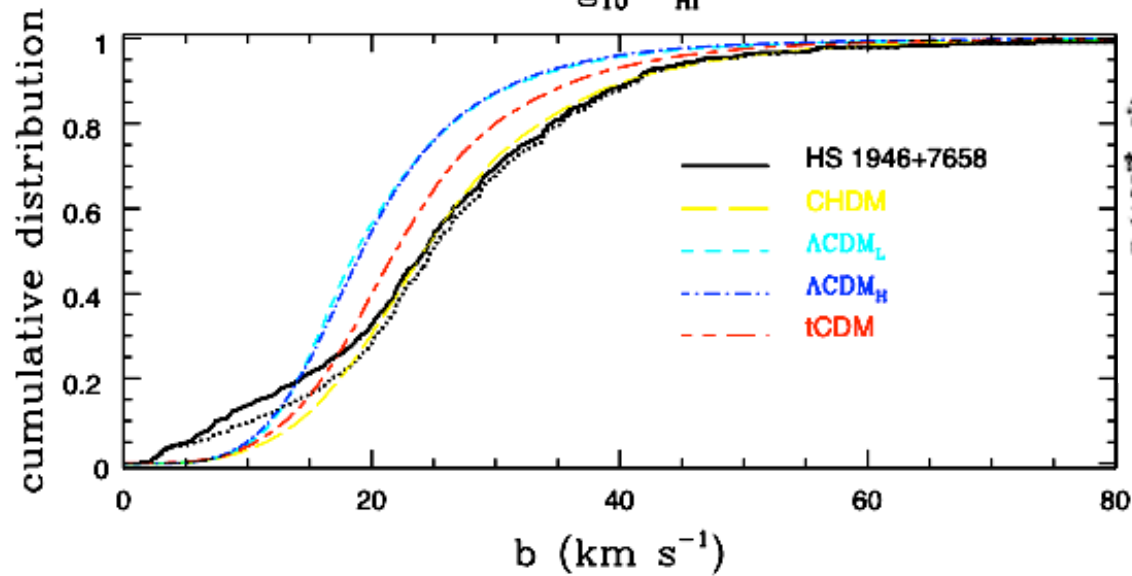
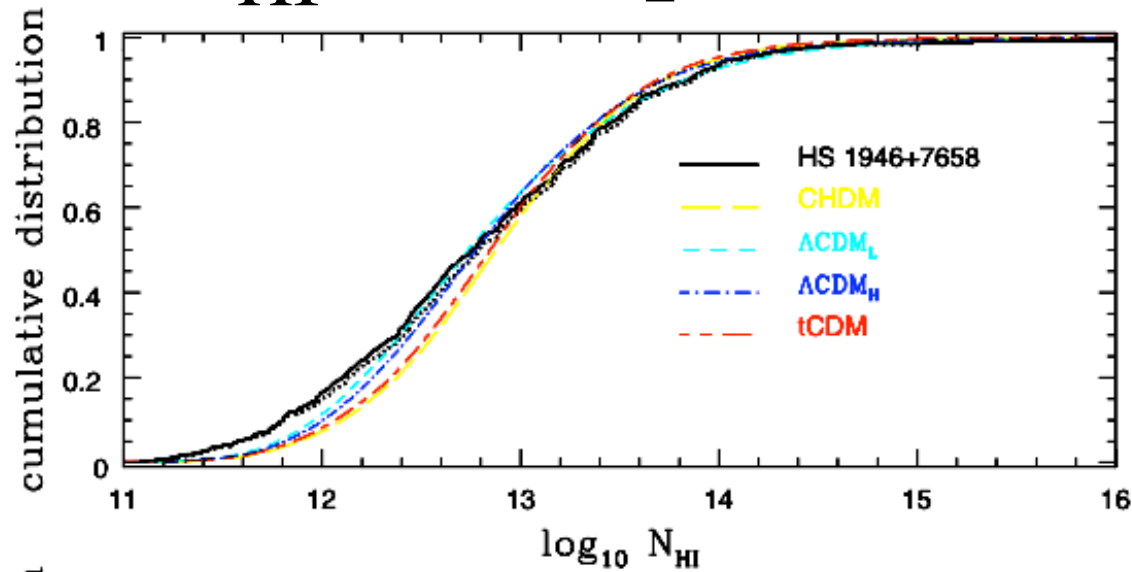
- Agree surprisingly well!
- Column density distribution shows good agreement.
- Flux histograms agree quite well with data.
- Non-Voigt line shapes predicted by simulations seen in observational data.
- Redshift evolution of absorbers agrees well with data - at both high and low column density!
- Large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

Flux distribution



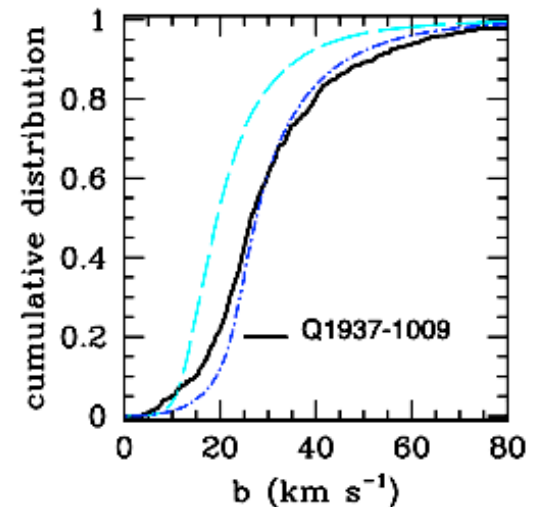
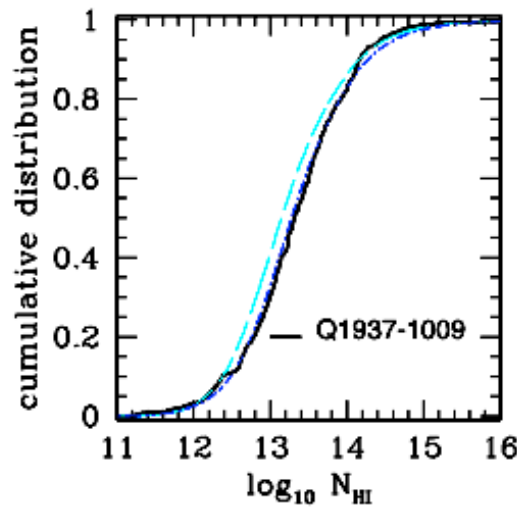
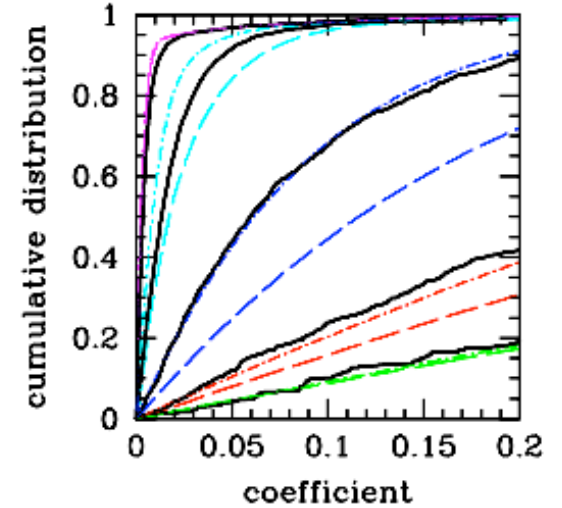
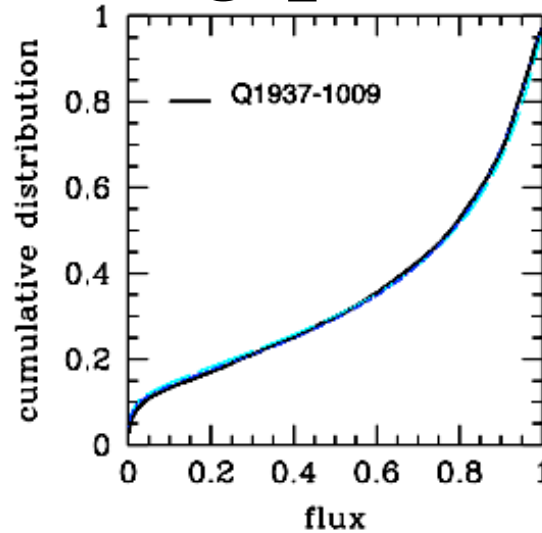
N_{HI} and b -parameter distribution

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



Outstanding problems

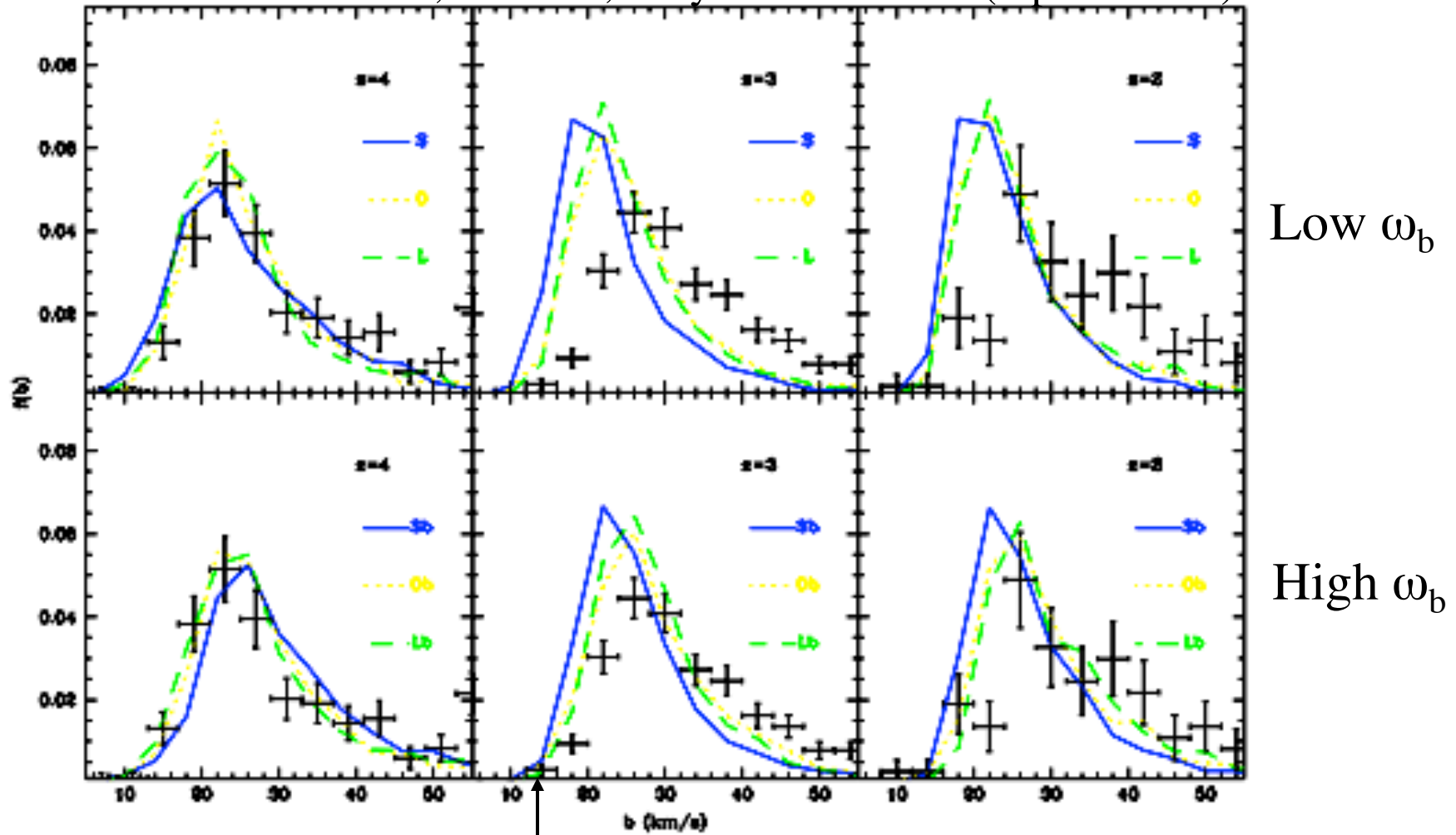
- Doppler parameter mismatch
 - b gets smaller as resolution increases.
 - Higher z_{re} means lower T_0 at $z \sim 3$.
 - Higher $\Omega_b h^2$ makes lines broader but maybe not enough.
 - HeII reionization heats gas in underdense regions by $\times 2$



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

High baryon density

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



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

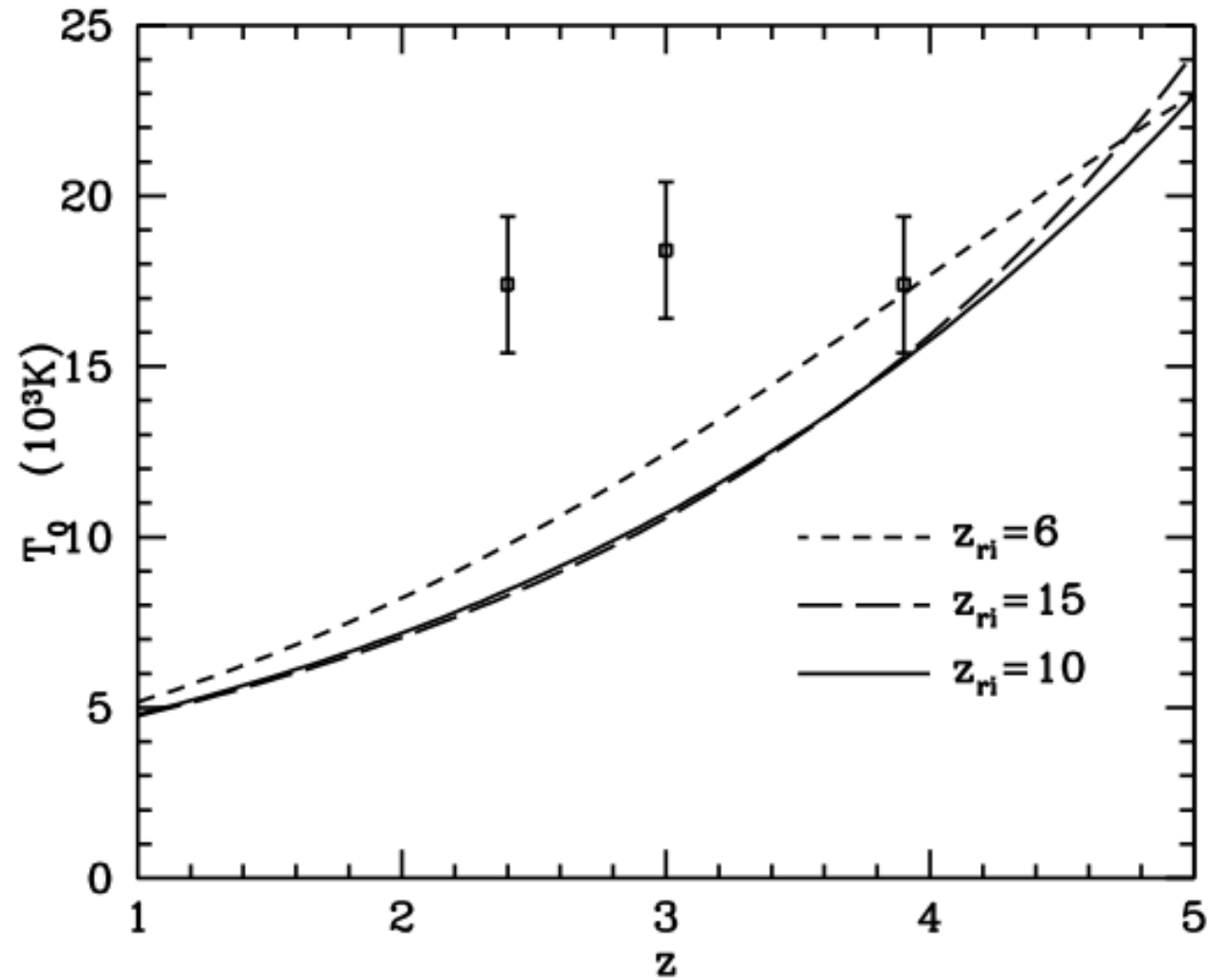
Where is the problem?

- Hit diminishing returns in increasing ω_b from 2% to 2.4%
- The higher baryon density Λ CDM 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

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
 - Would be interesting to revisit this ... a large amount of work has been done, but things are getting better all of the time.

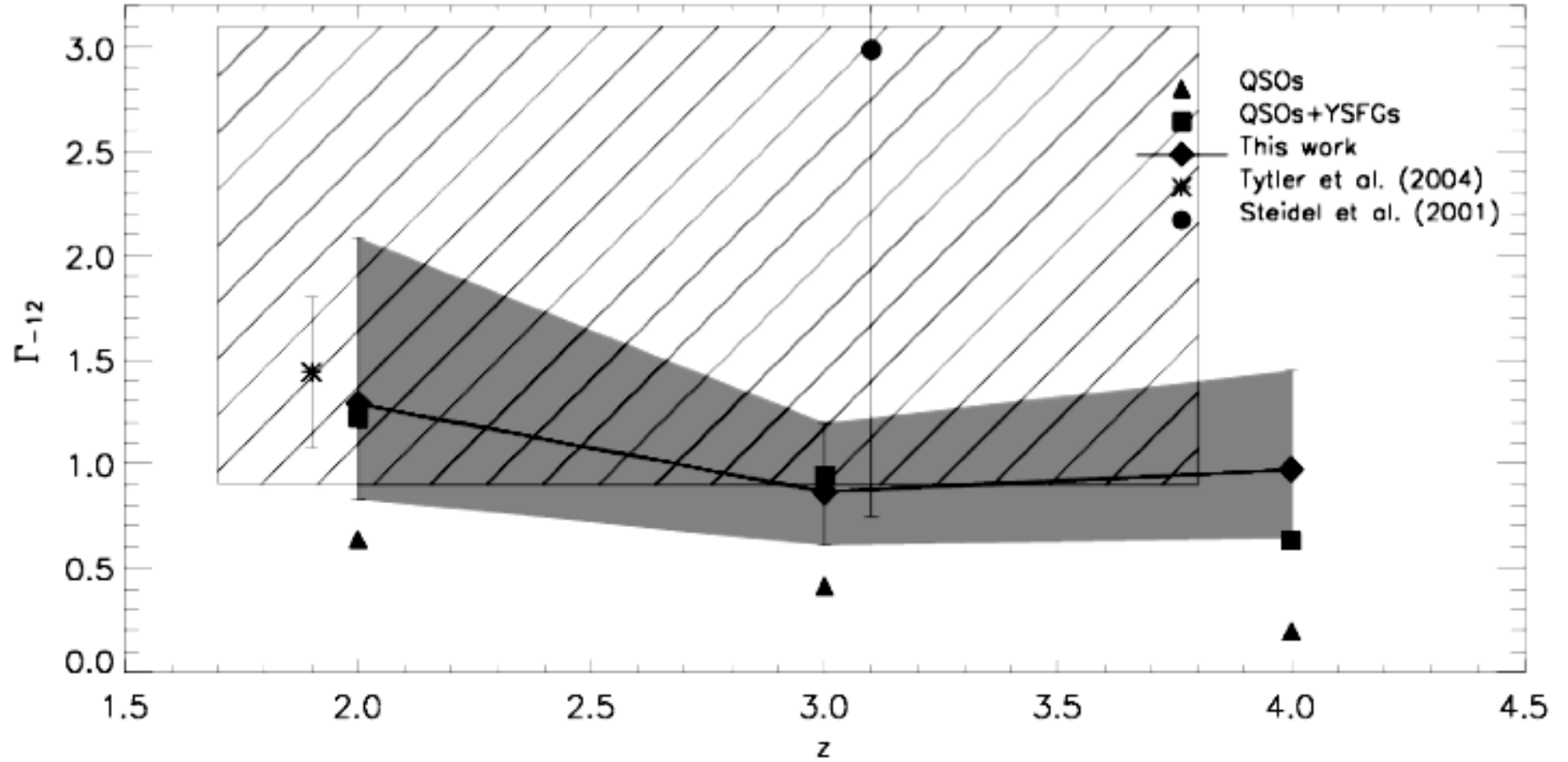
IGM temperature



Ionization rate

- Values of Γ_{-12} required to fit data with hydro simulations of Λ CDM cosmologies are $\sim 4x$ larger than those in EdS models.
- Recent compilation by Bolton et al. (2005)
- Require extra radiation above that due to QSOs at $z < 4$ at about factor of 2 level.

Evolution of Γ_{-12}



Bolton et al. (2005)

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 $z \sim 3$?
 - Why are HeII linewidths the *same* as the HI widths?
- Metal lines (almost no theory)
- 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
- Stellar feedback (SN ejecta, winds, ...)
- Radiative transfer

Hydrodynamics?

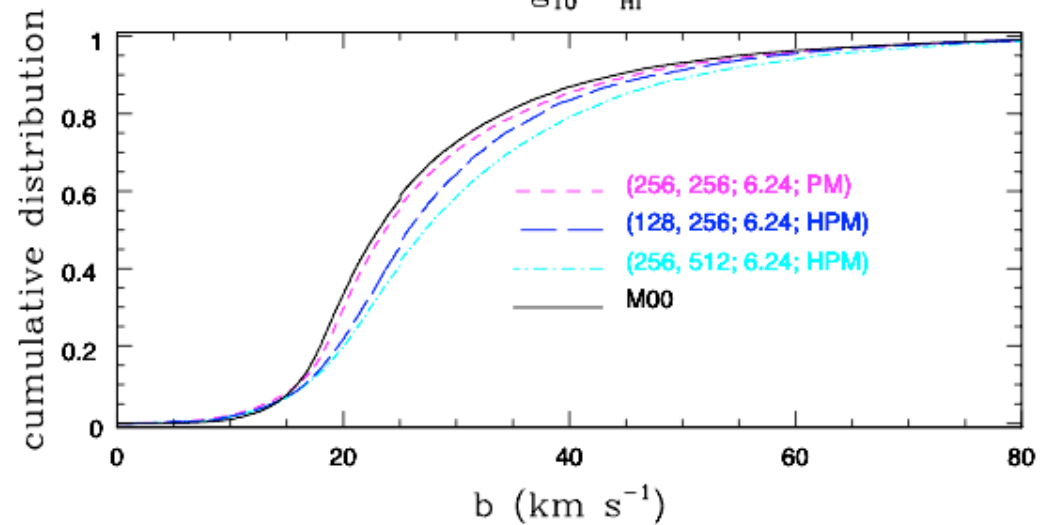
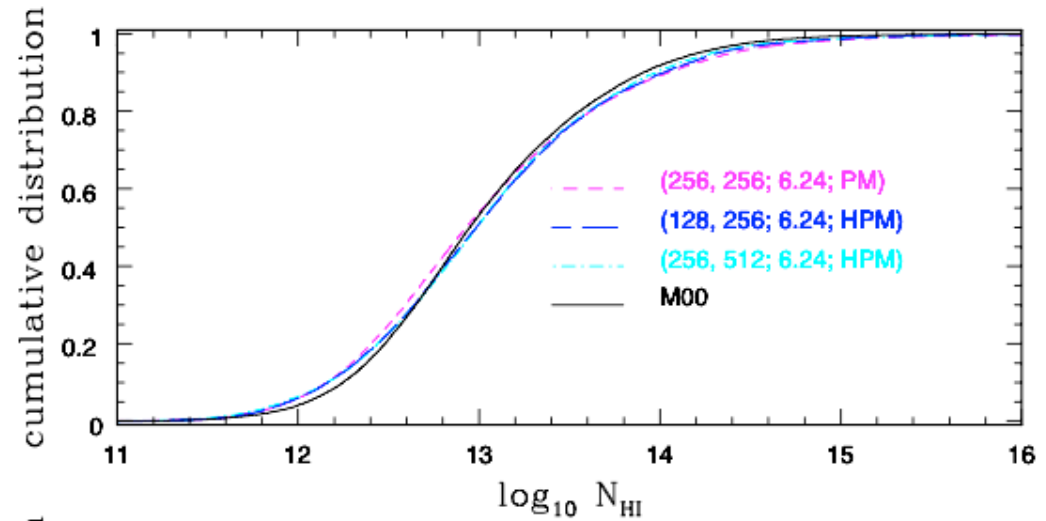
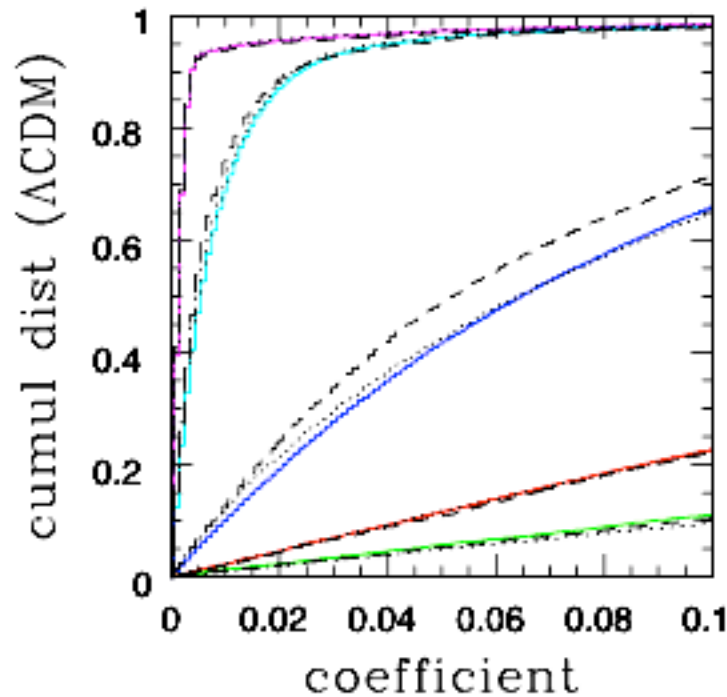
Comparing FGPA schemes to full hydrodynamic simulations

Wavelet coefficients

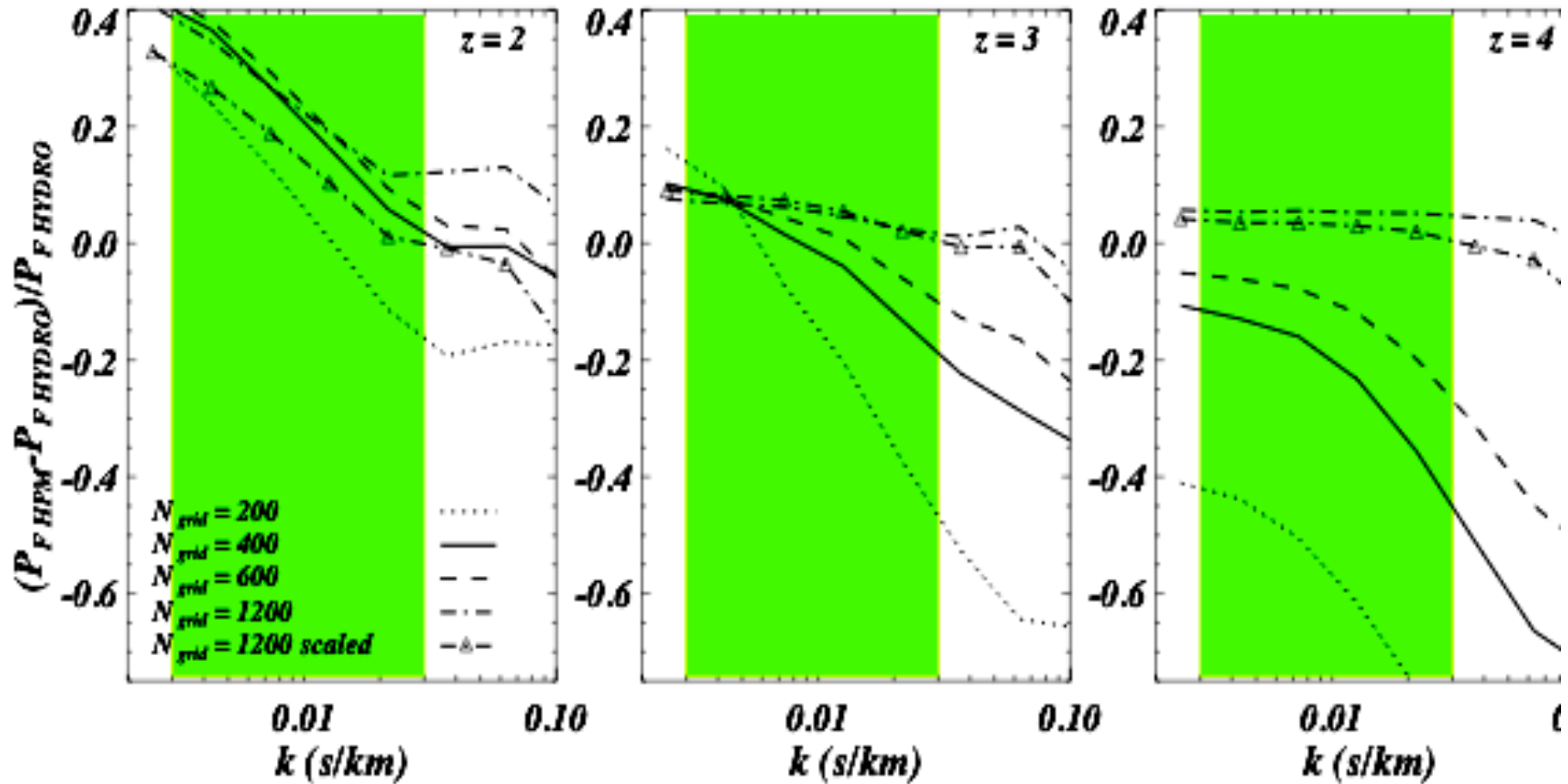
Solid: Hydro

Dotted: PM

Dashed: HPM

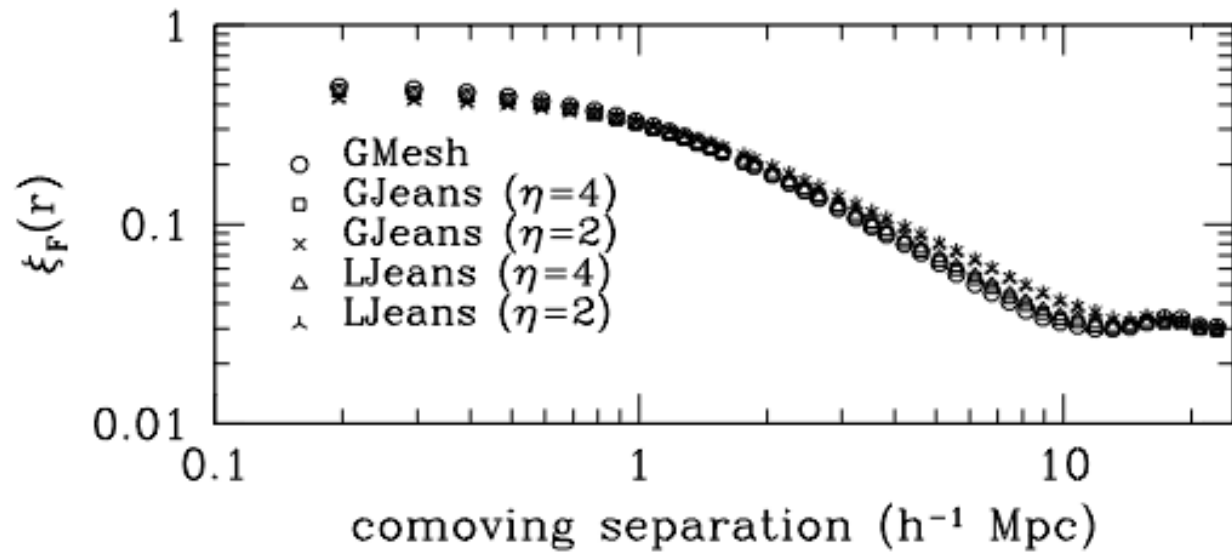
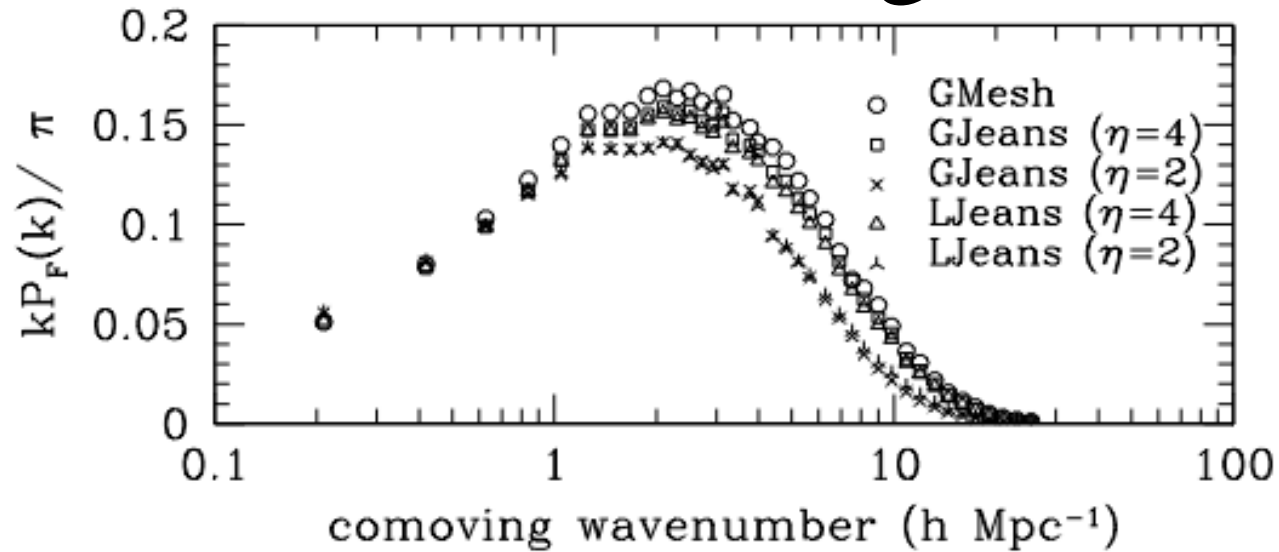


Hydrodynamics II

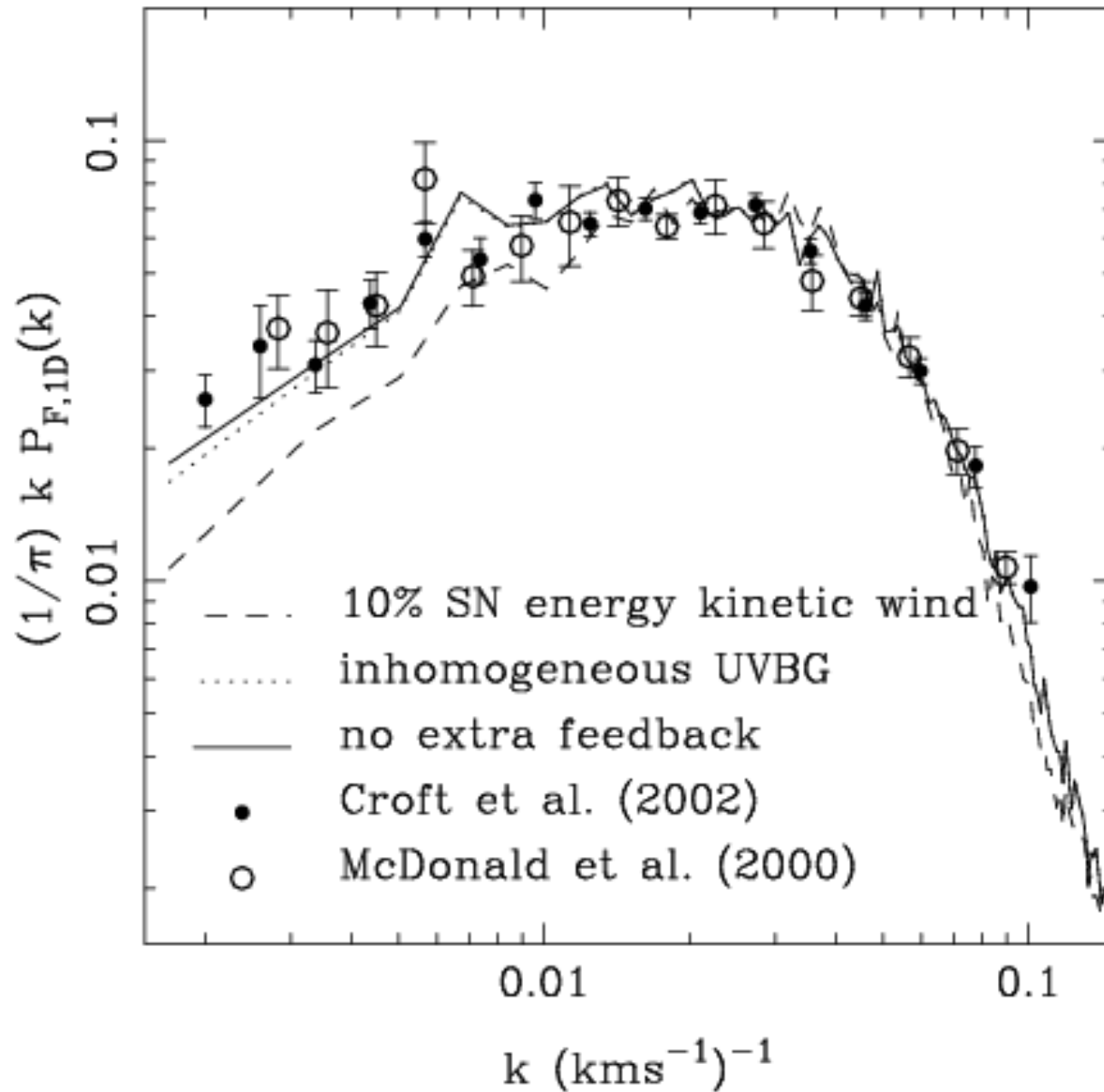


Viel, Haehnelt & Springel (2005)

Smoothing?

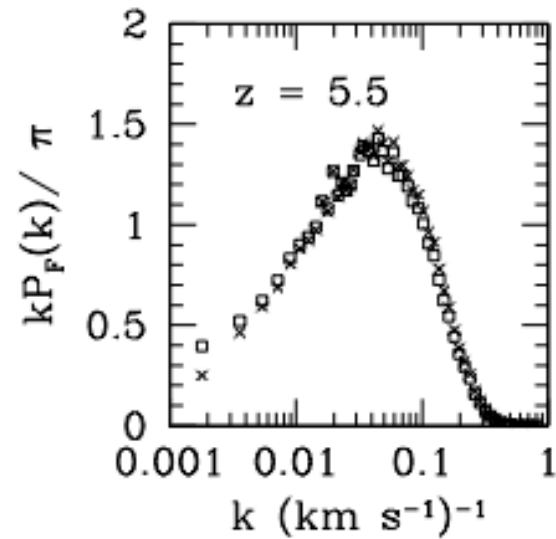
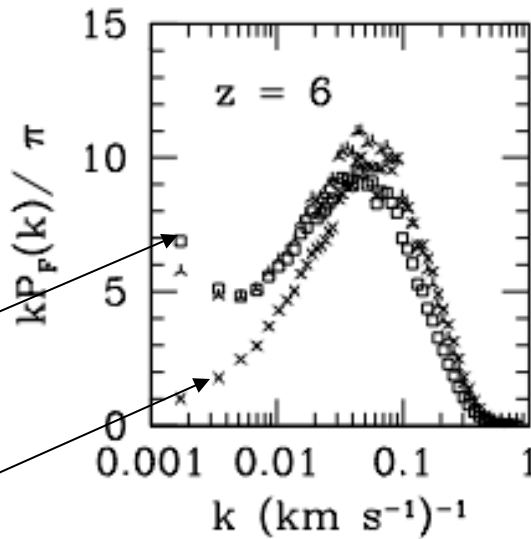


Effect of winds on Ly- α P(k)

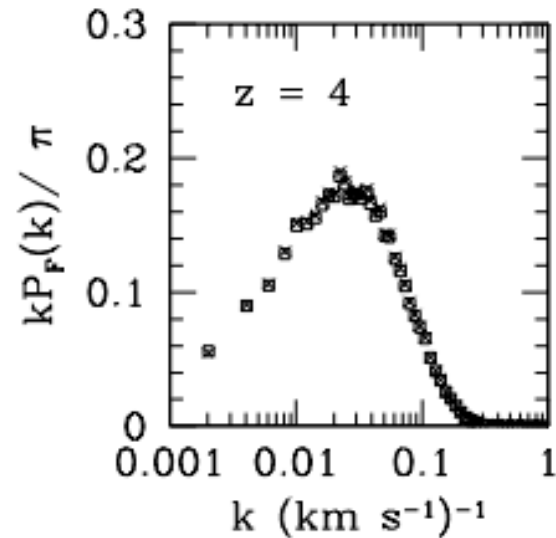
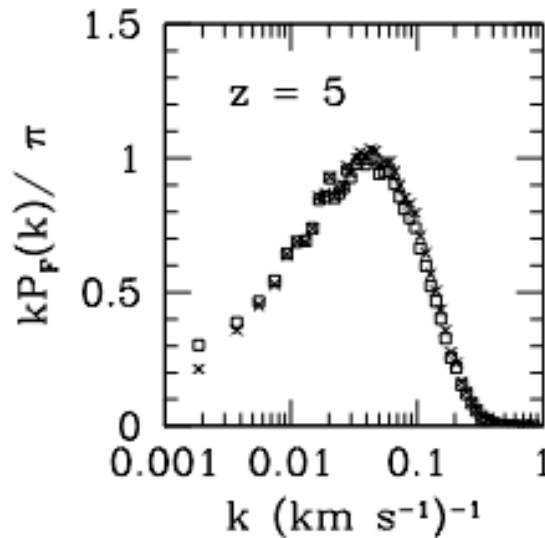


Effect of fluctuating J on P(k)

With δJ



No δJ



Conclusions

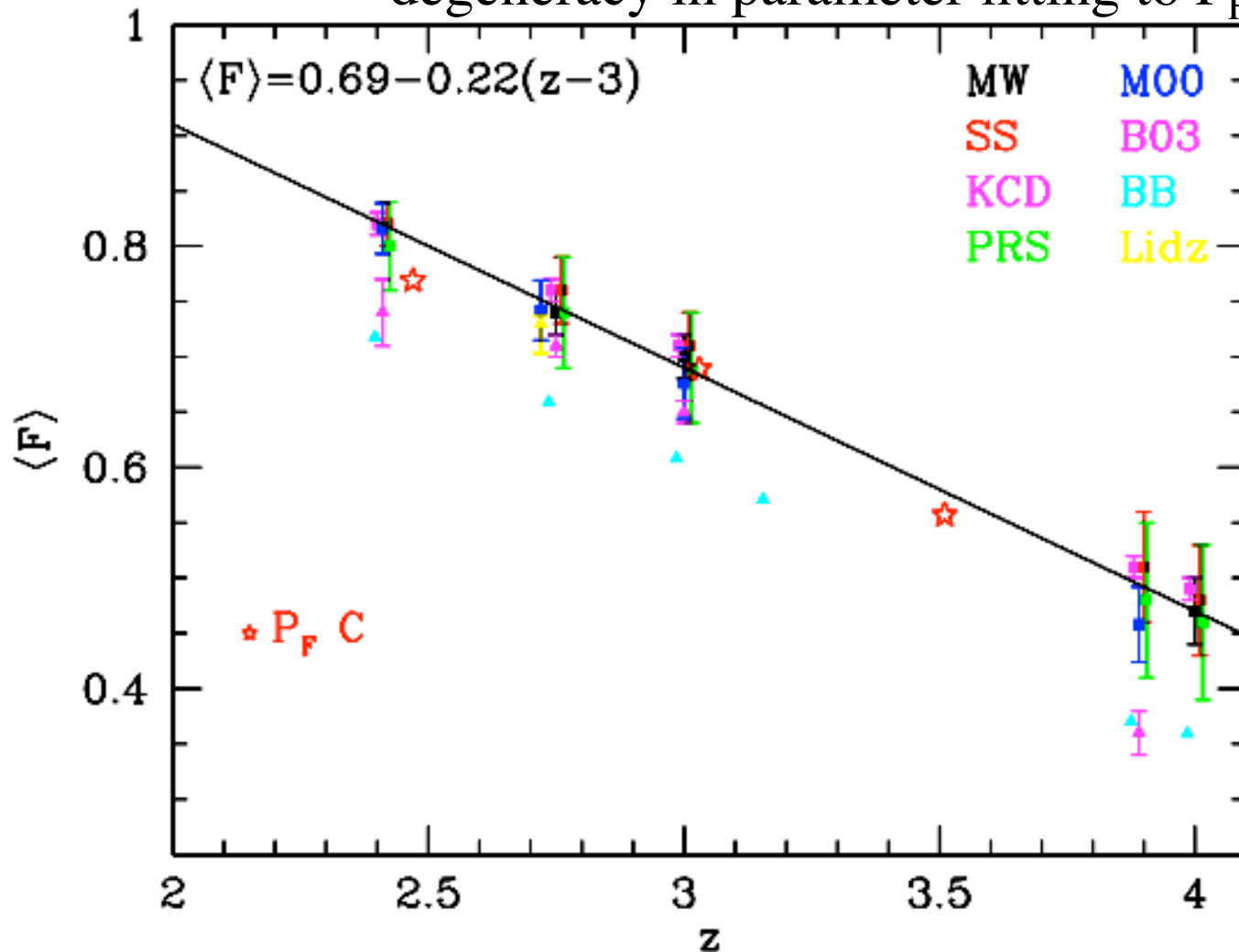
- Basic picture appears to be correct. IGM traces “cosmic web”.
- Dark matter only methods agree with hydro at 10% level. Roughly level of agreement with observations.
- Major problem seems to be temperature of IGM (role of RT, HeII, ...).

Analyzing spectra

- The mean flux
 - Use $\langle F \rangle$ to fix normalization of τ
- Continuum fitting [Observe $e^{-\tau(z)} \times \text{QSO}(z)$]
 - By-hand continuum fitting
 - Trend removal (polynomial fitting)
 - Length of segment, order of polynomial?
 - Dividing by a smooth spectrum.
 - What is “best” smoothing length?
- Data chunking
- Excising high column density systems
- Treating metal line systems

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.