Probing the Tail End of Reionization,
or

How I Learnt to Stop Worrying and Love the Lyman Series

Peng Oh
UCSB

Talk outline: from Alpha to Gamma

α Radiative Transfer in a Clumpy, Dusty Medium: Can Equivalent Widths be enhanced?

β, γ How Universal is the Gunn-Peterson Trough at z~6?

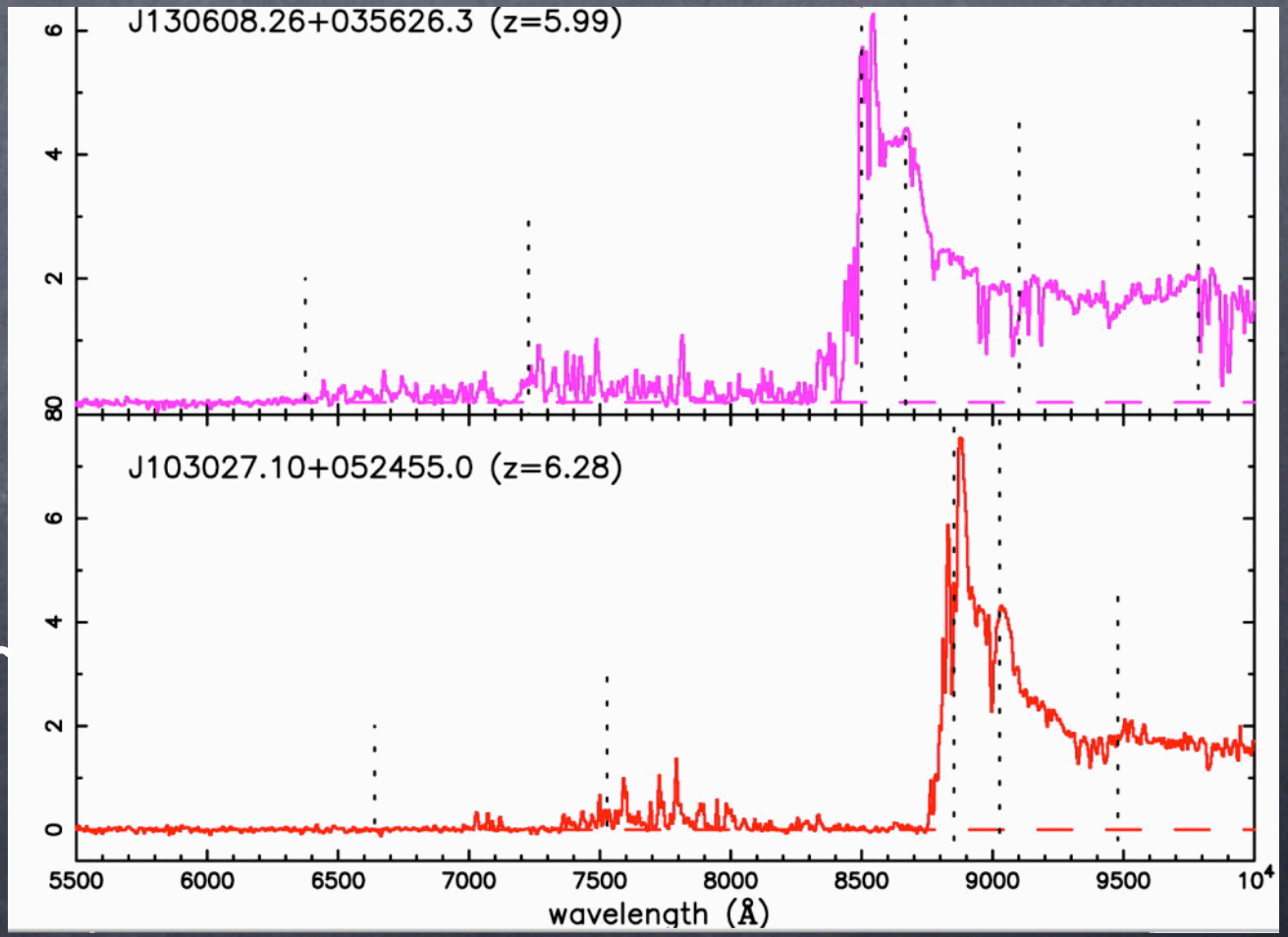
Ly-alpha Radiative Transfer in an Clumpy Dusty Medium

Hansen & Oh 2004, in prep

Ly-alpha is often our ONLY probe of high-z galaxies/QSOs....

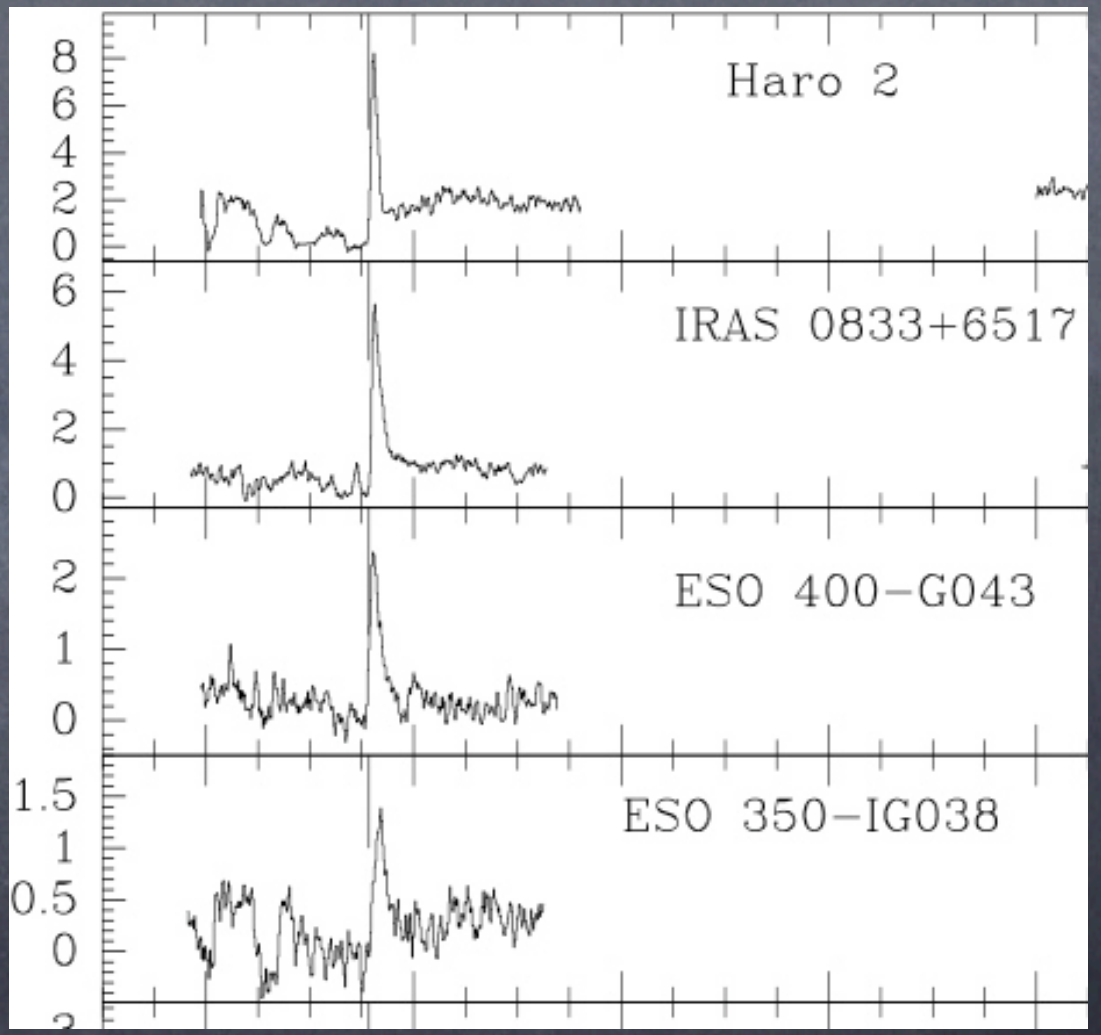
Image = Astronomy
Spectra= Physics
Look at line:
1. Shape
2. Equivalent width
3. Offset from other lines

Becker et al 2001



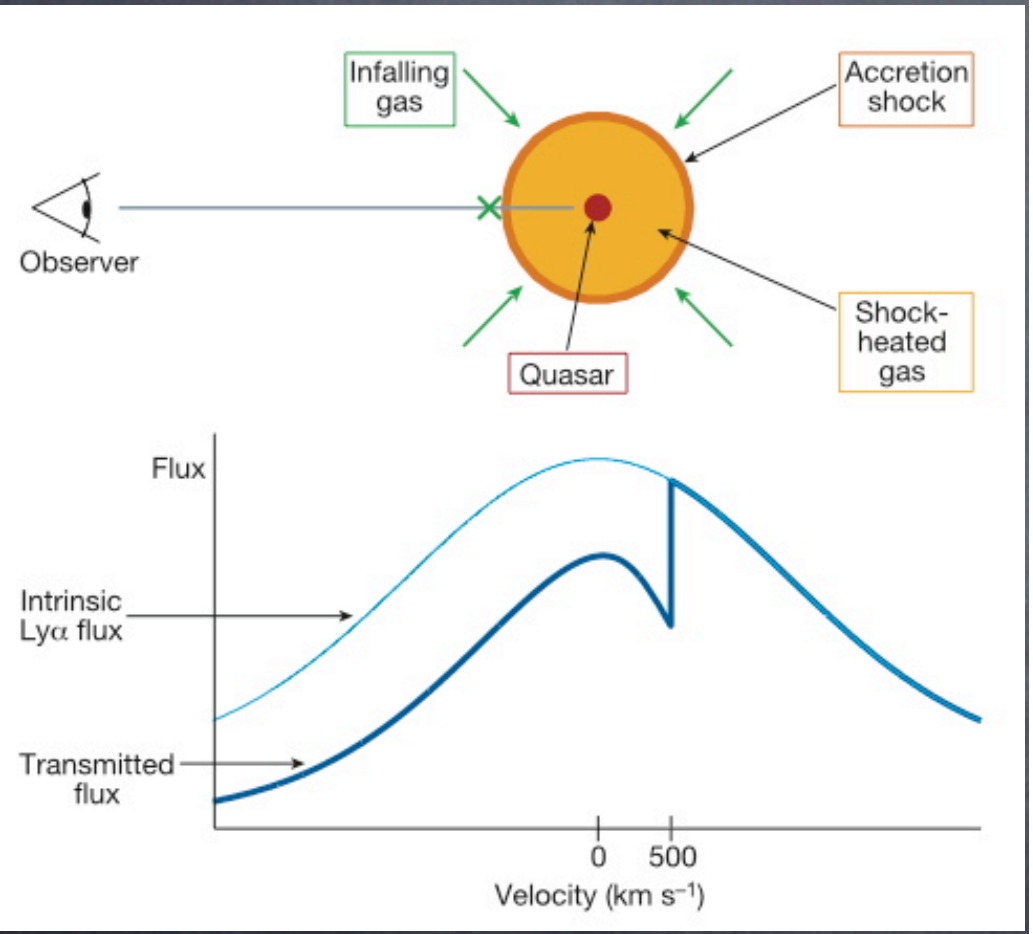
...and is used to infer winds

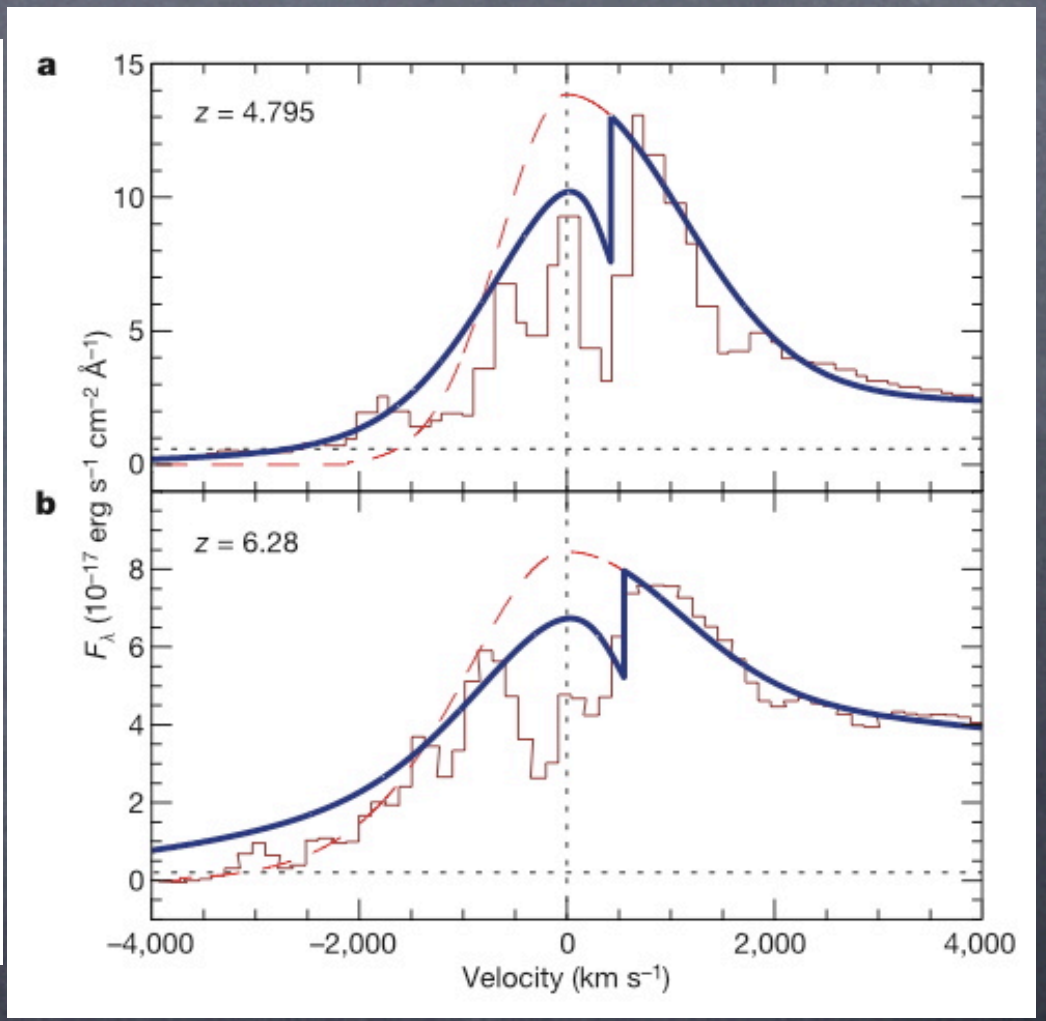
P Cygni profiles
Offset wrt other metal lines



Kunth et al 1998

...accretion shocks

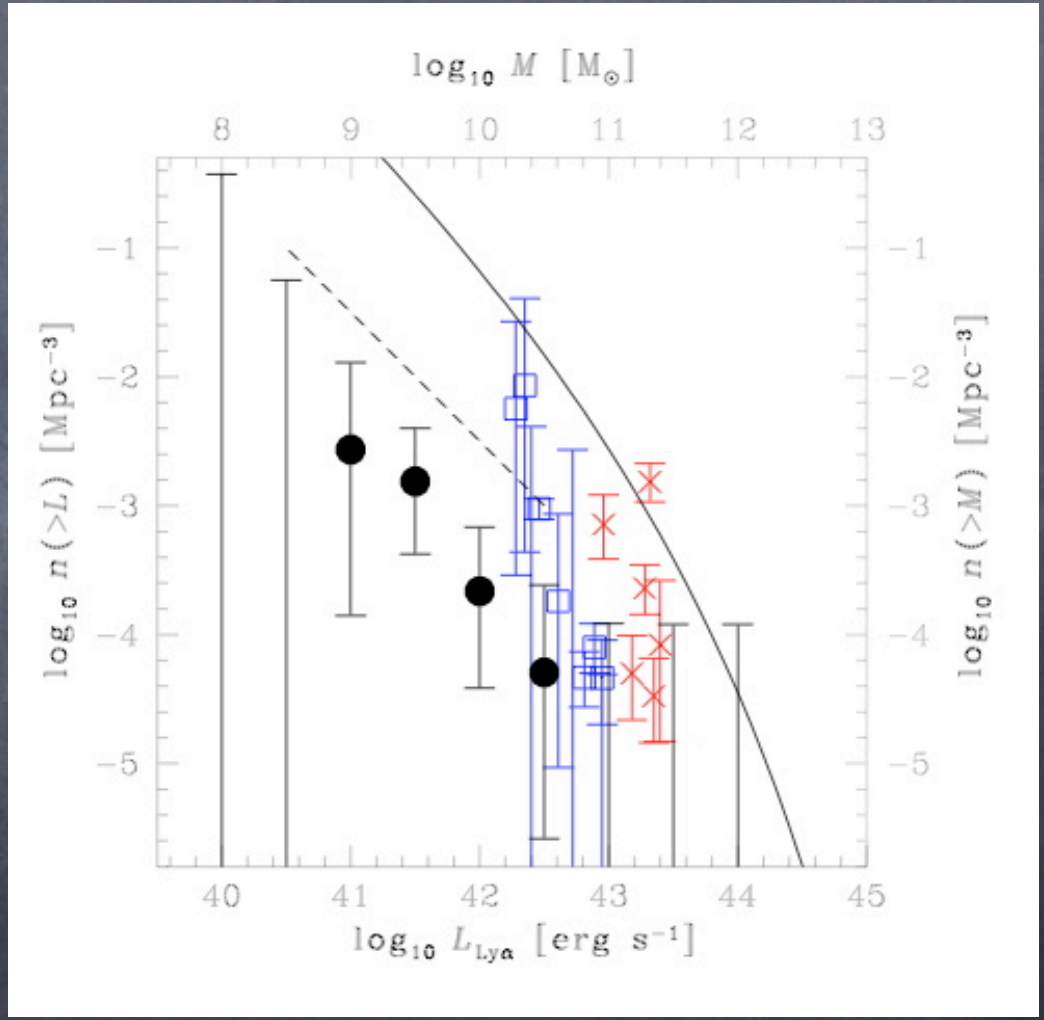




Barkana & Loeb 2003

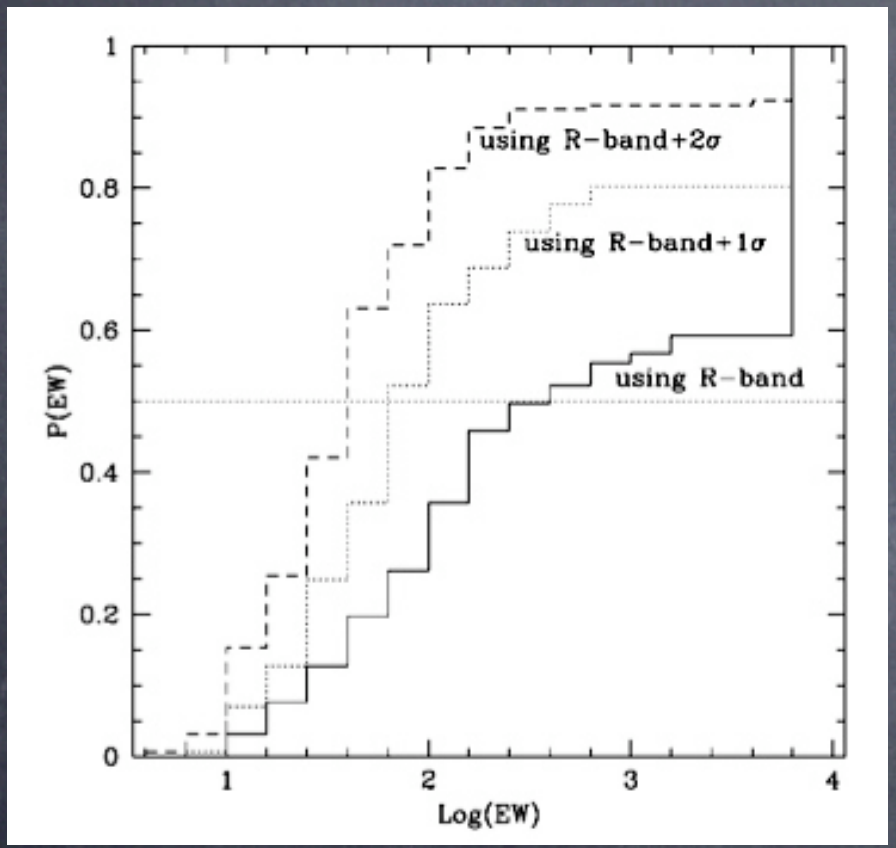
...constrain the epoch of reionization...

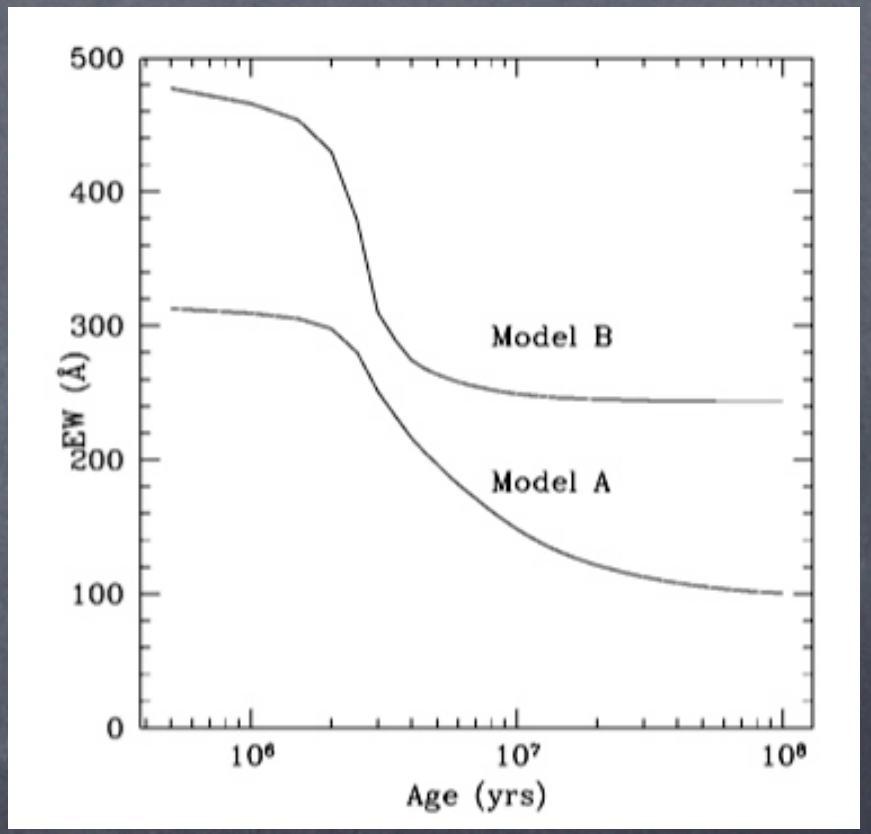
Low luminosity tail should be suppressed after reionization



Santos et al 2004

...possible Pop III stars at high-z



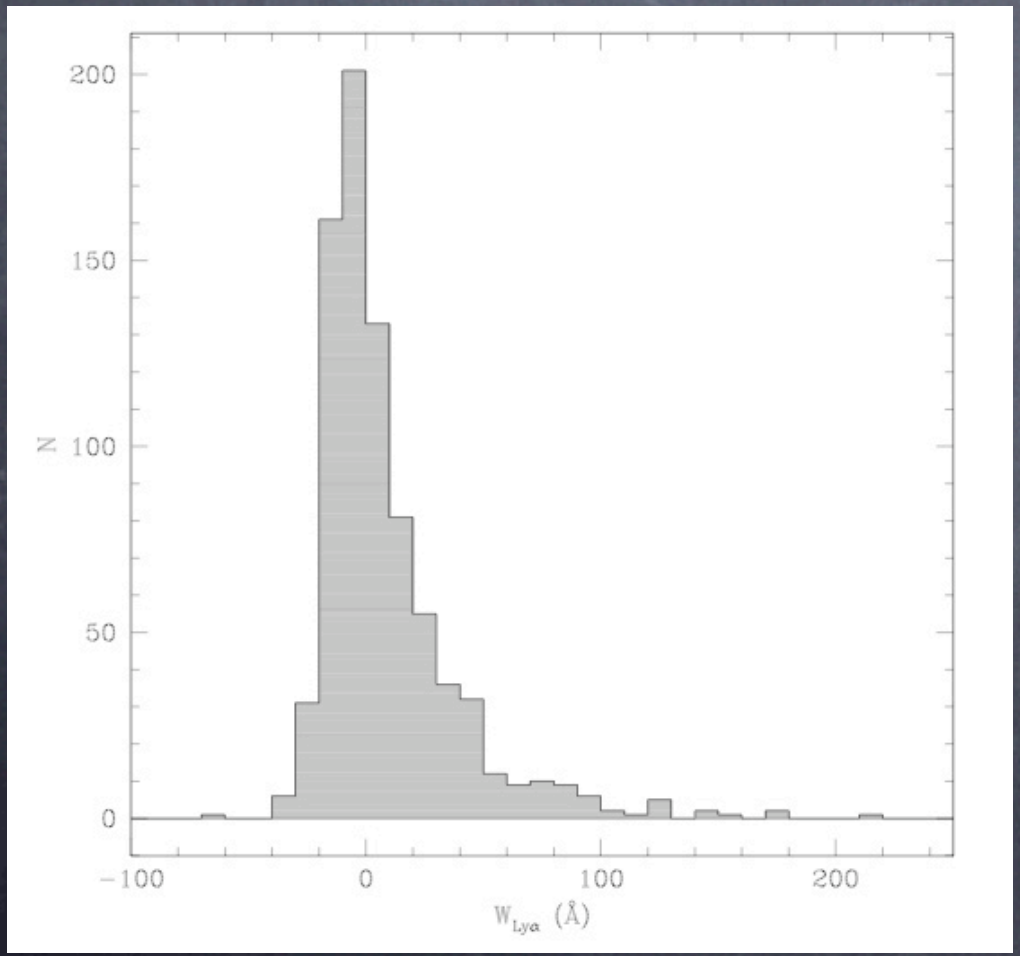


Malhotra & Rhoads 2002

> 60% of sources have EW > 240 Angstroms

Note: no X-ray emission or high ionization lines seen

CAUTION: Ly-alpha properties show HUGE dispersion

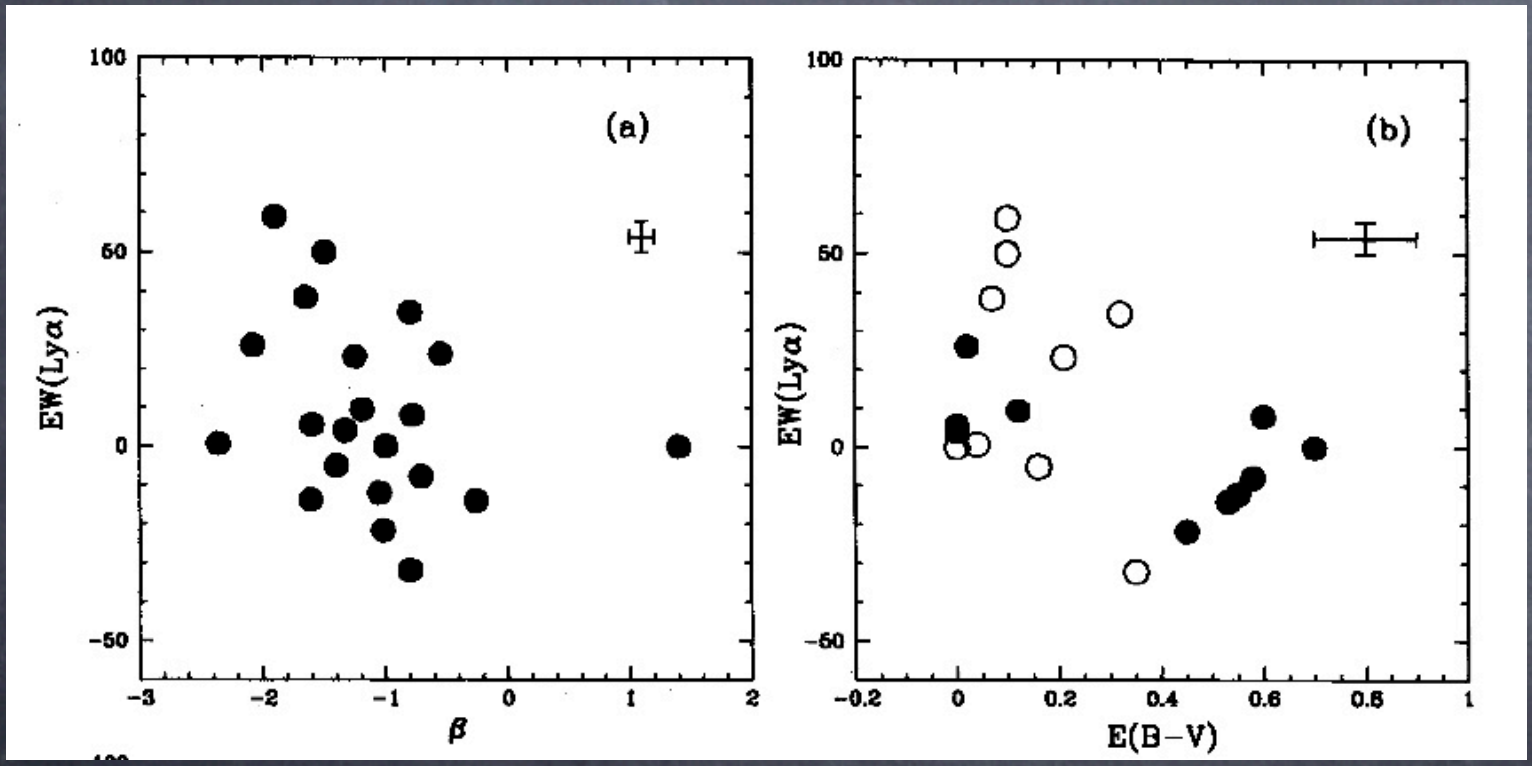


Radiative transfer within ISM is at LEAST as important as transfer within IGM

Let's understand what we're looking at!

Shapley et al 2004

Won't dust just kill the Ly-alpha EW?

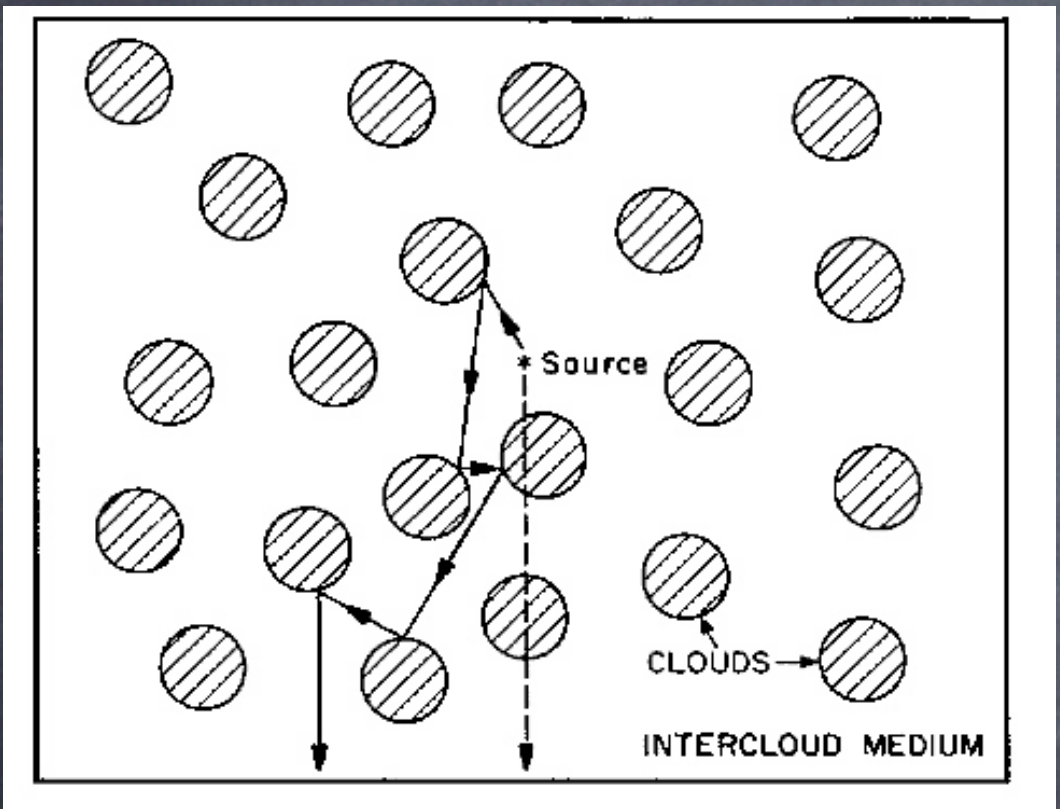


No--Ly-alpha EW appears to be decoupled from the dust content

Giavalisco et al 1996

Also: bright SCUBA sources w/ high Ly-alpha EW... (Chapman & Blain 2003)

Not if the ISM is clumpy



Preferential extinction of continuum possible in multi-phase medium (Neufeld 1991)

Amazingly, there has been no detailed study of resonance line radiative transfer in a clumpy, dusty medium

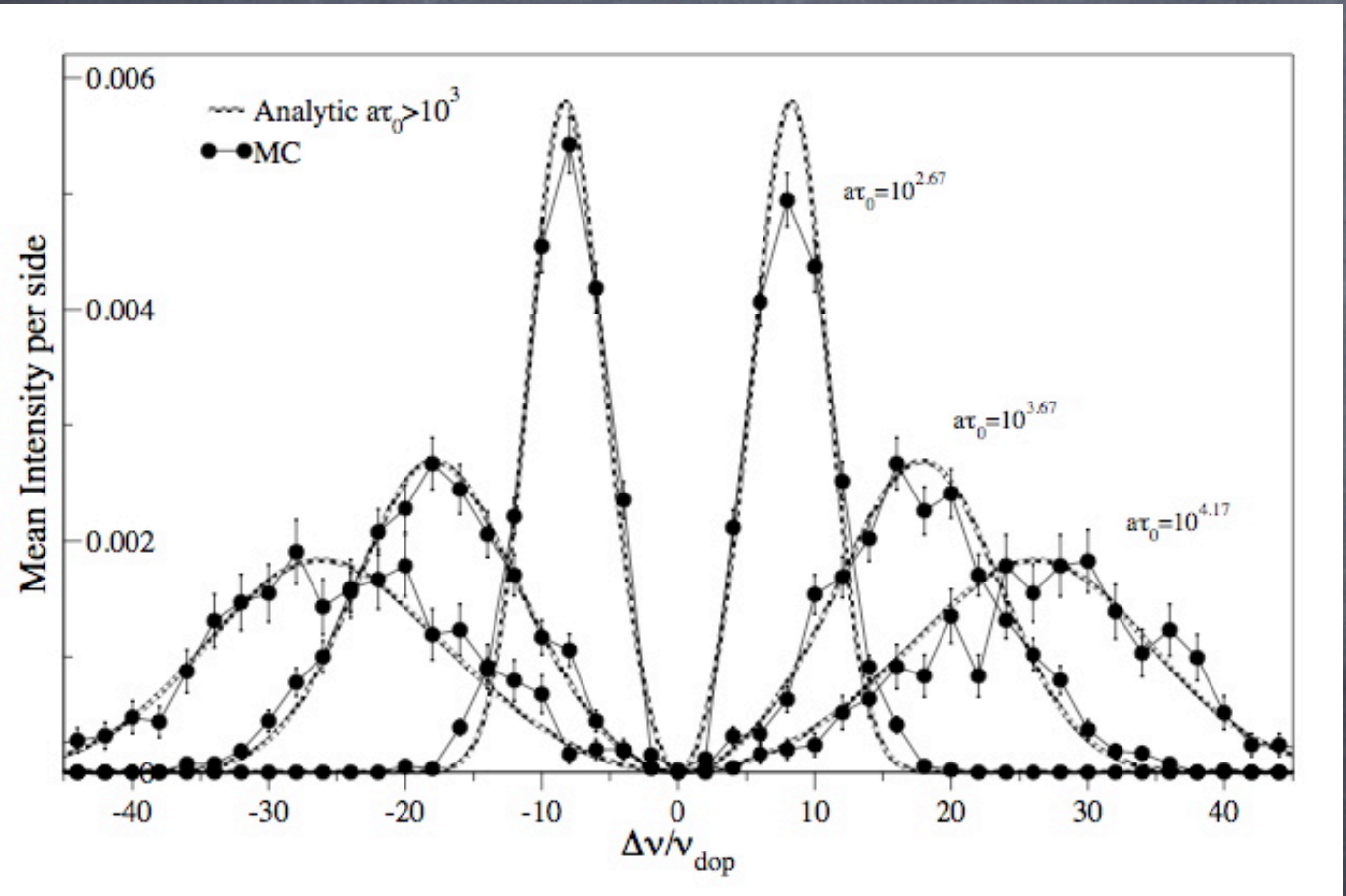
Is Ly-alpha escape controlled by kinematics or geometry?

1. Outflows alone can never give an EW above the intrinsic value

2. Test: velocity offset between Ly-alpha and metal lines

3. Different line-shape profiles

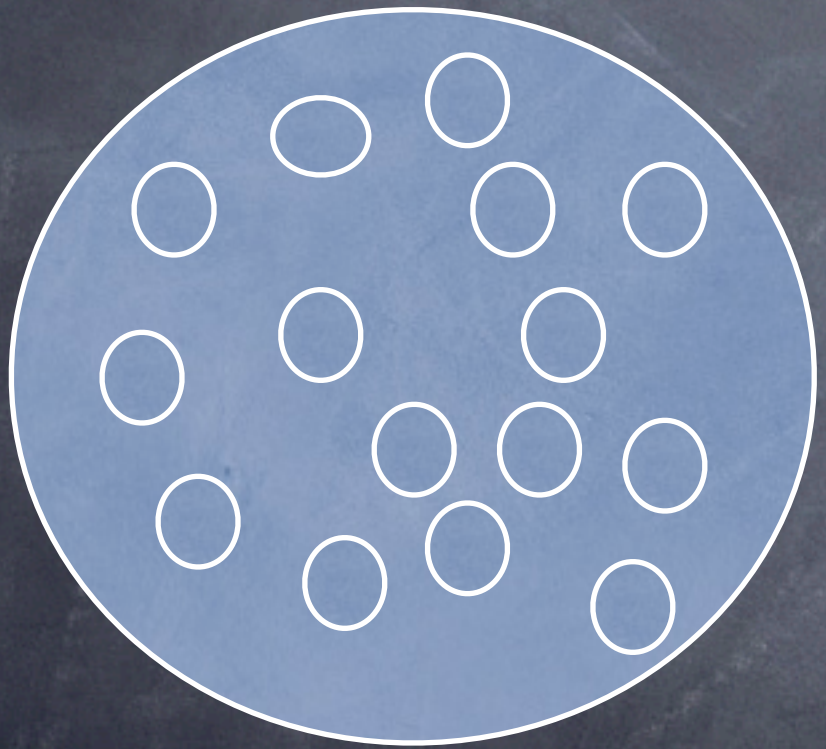
Test this with a Monte-Carlo RT code...

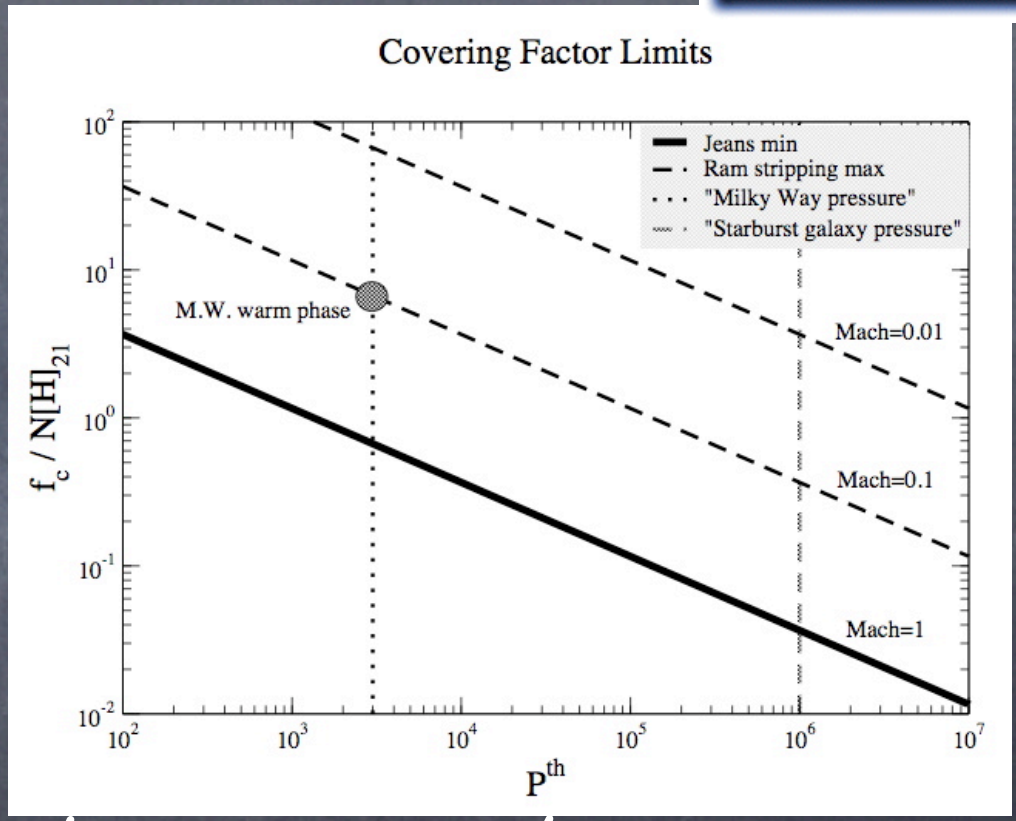


Just Photon Pinball...

1. Choose Frequency
2. Choose Direction
3. Choose Optical Depth

Consider a spherical galaxy...



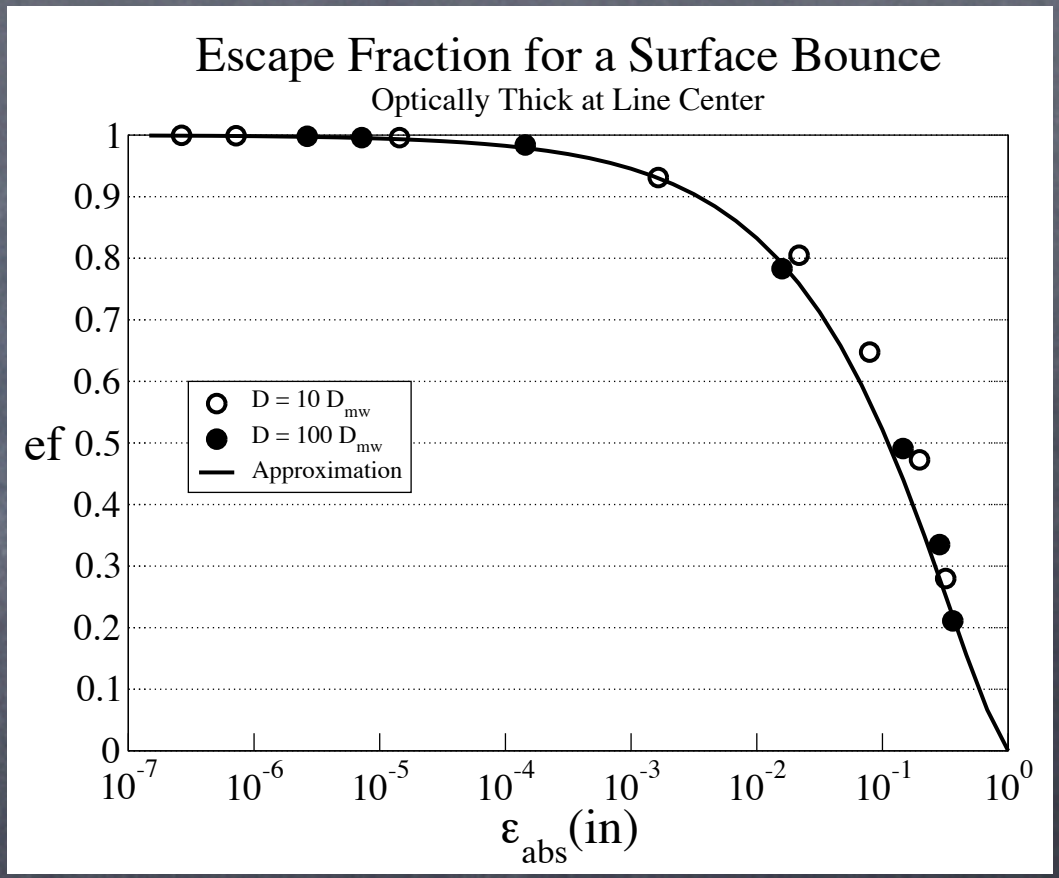


Not so crazy: cloud size/shape doesn't really matter for highly optically thick clouds

Only the cloud covering fraction fc~few matters

Monte-Carlo on Speed: "Mega-Grains"

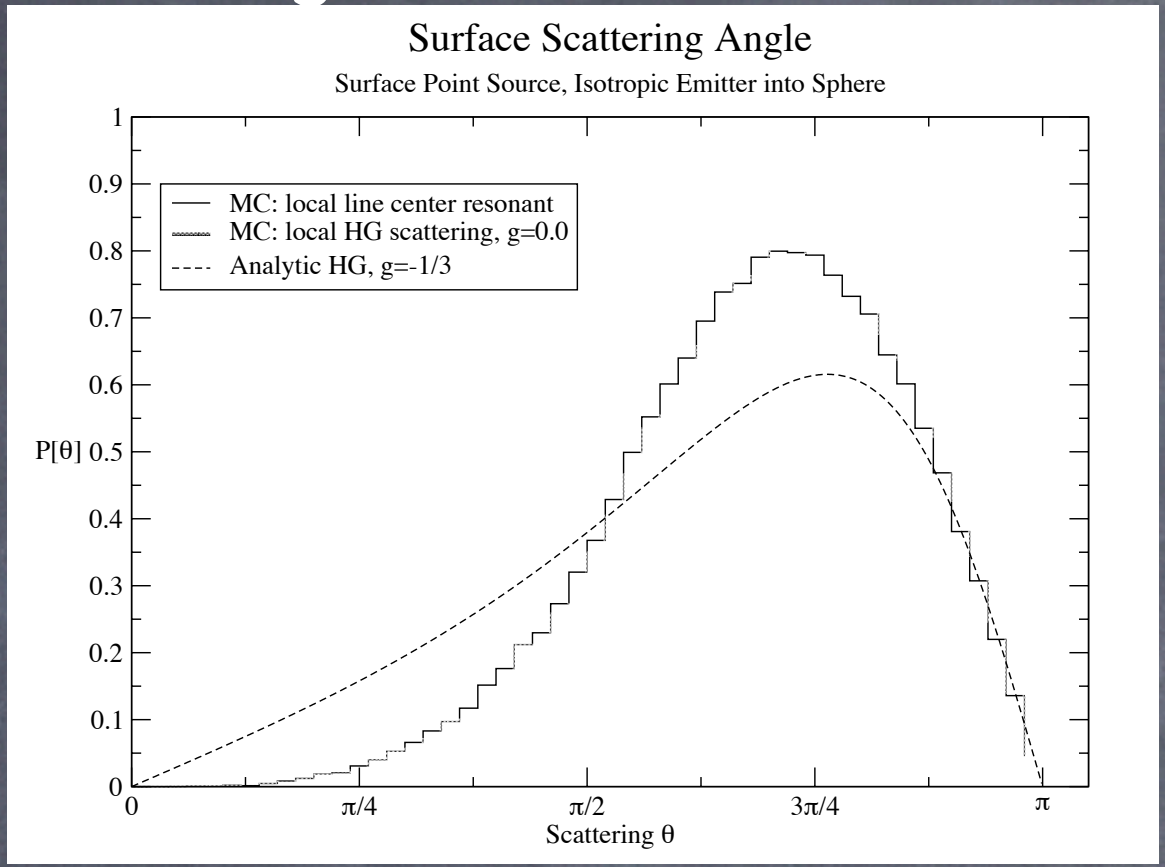
Treat each cloud as a single particle capable of scattering/ absorbing particles



Characterize by:

a) Albedo

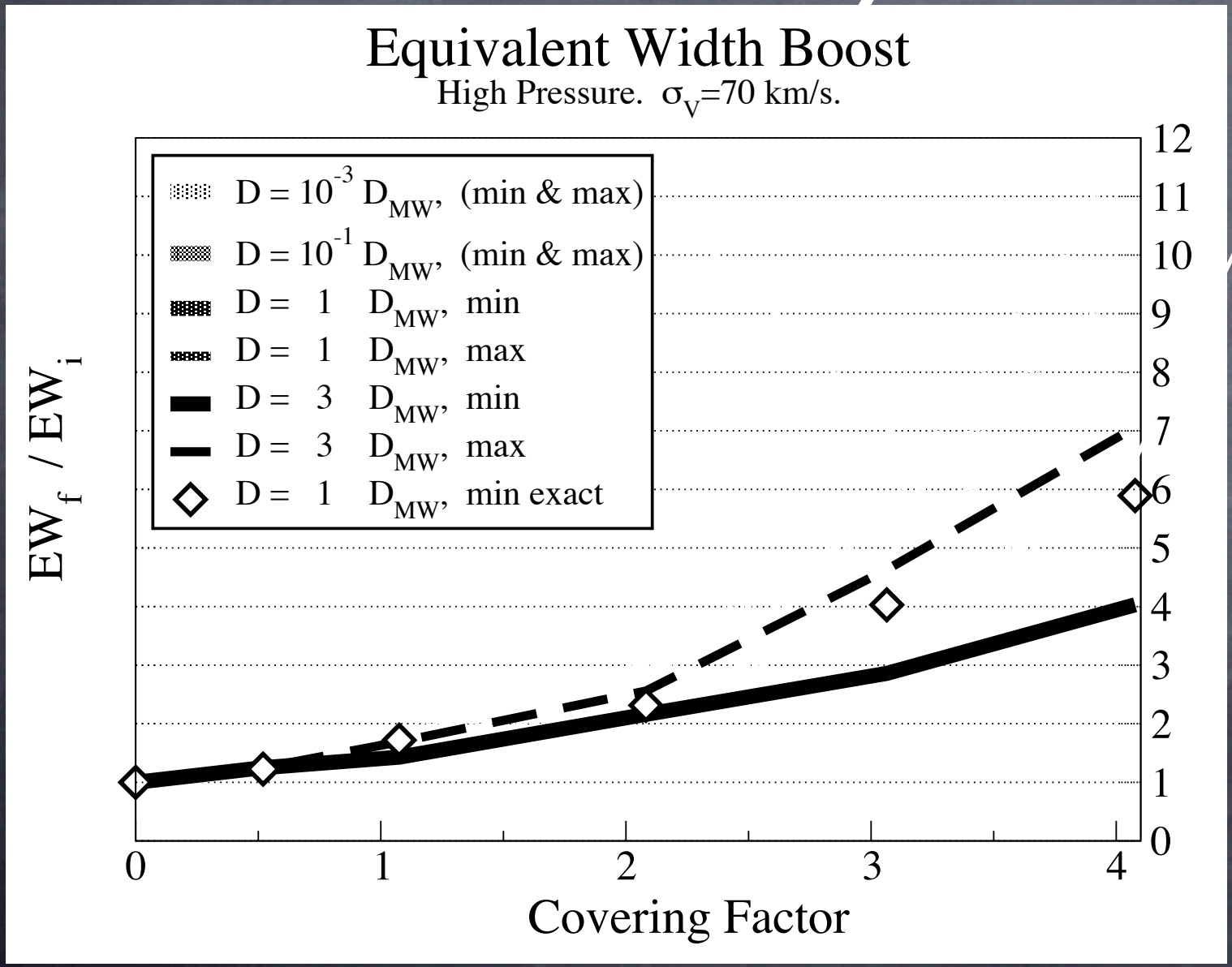
b) Scattering Phase Function



c) Frequency Redistribution---coherent scattering is good approximation

d) Effects of cloud velocity---turns out to be negligible

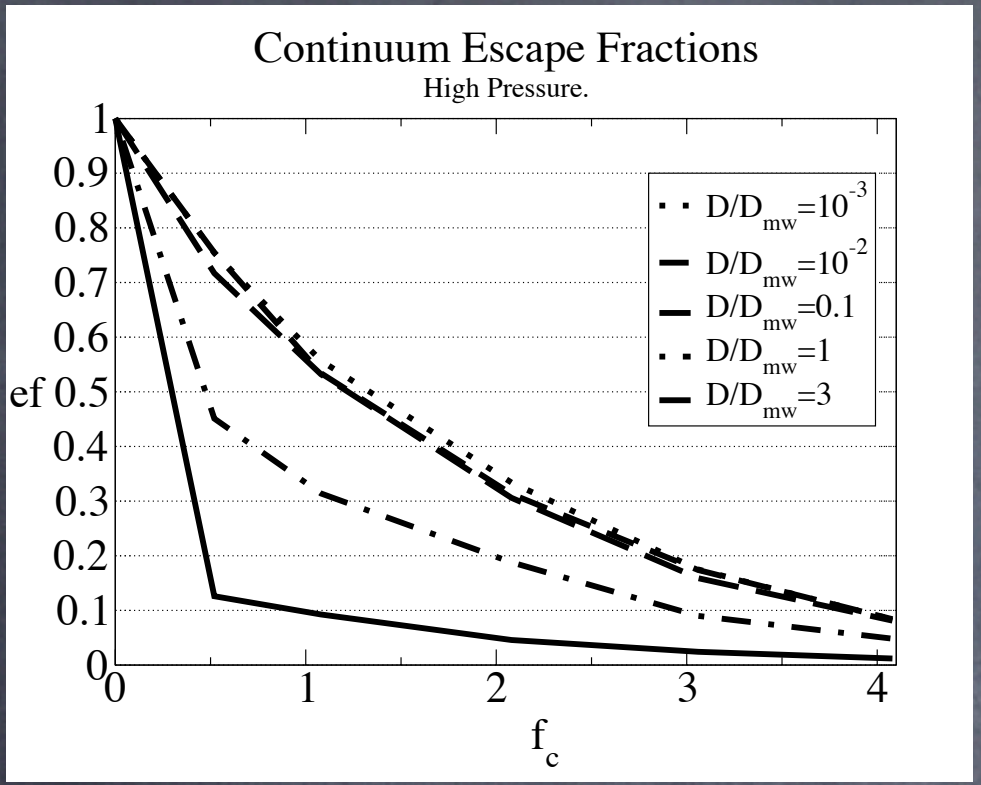
EW boost of ~few is easy...

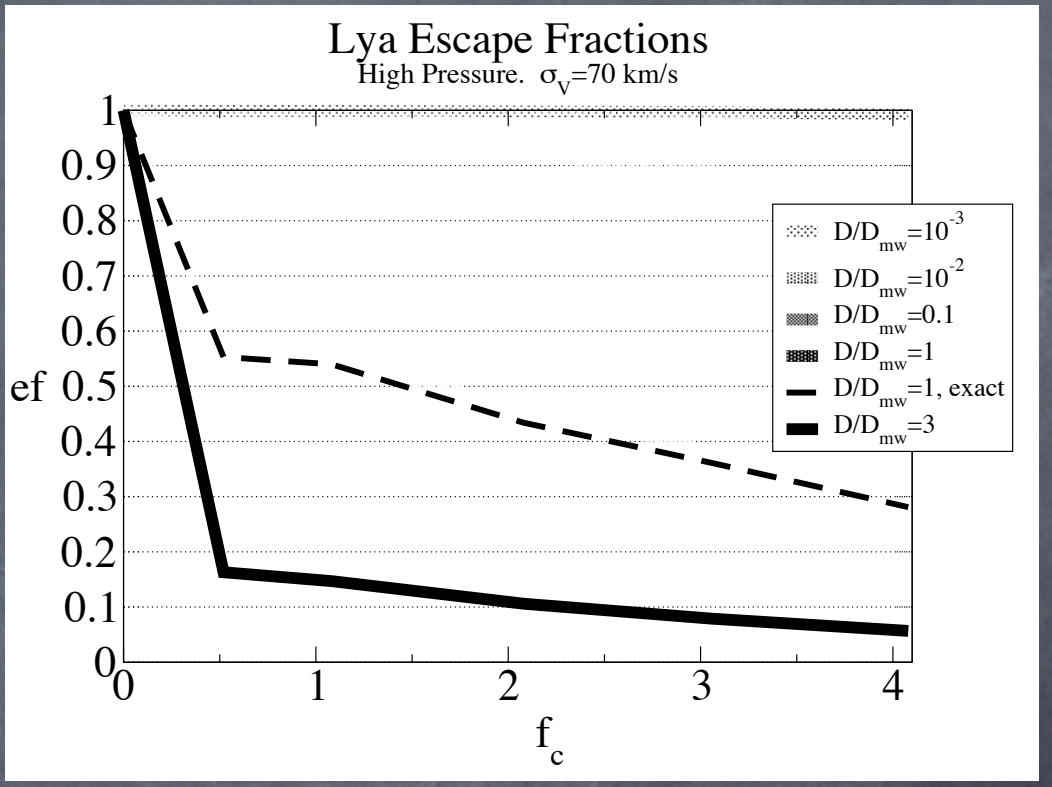


Agreement between exact + fast MC is v. good

Amazingly, the boost is higher in lower metallicity systems...

....why?





Continuum: albedo independent of metallicity

N.B. Monte-Carlo for continuum is exact

Ly-alpha: albedo increases strongly with metallicity

Test: compare Ly-alpha w/ Balmer lines

Future work

- Effects of cloud topology/porosity. Viewing angle/geometrical effects. Do RT in numerical simulations...
- Ly-alpha "blobs" at z=3....also no continuum seen. Model Ly-alpha line profiles, polarization...
- Radiation pressure from Ly-alpha photon trapping...

How universal is the Gunn-Peterson trough at z~6?

How neutral is the Universe at z~6?

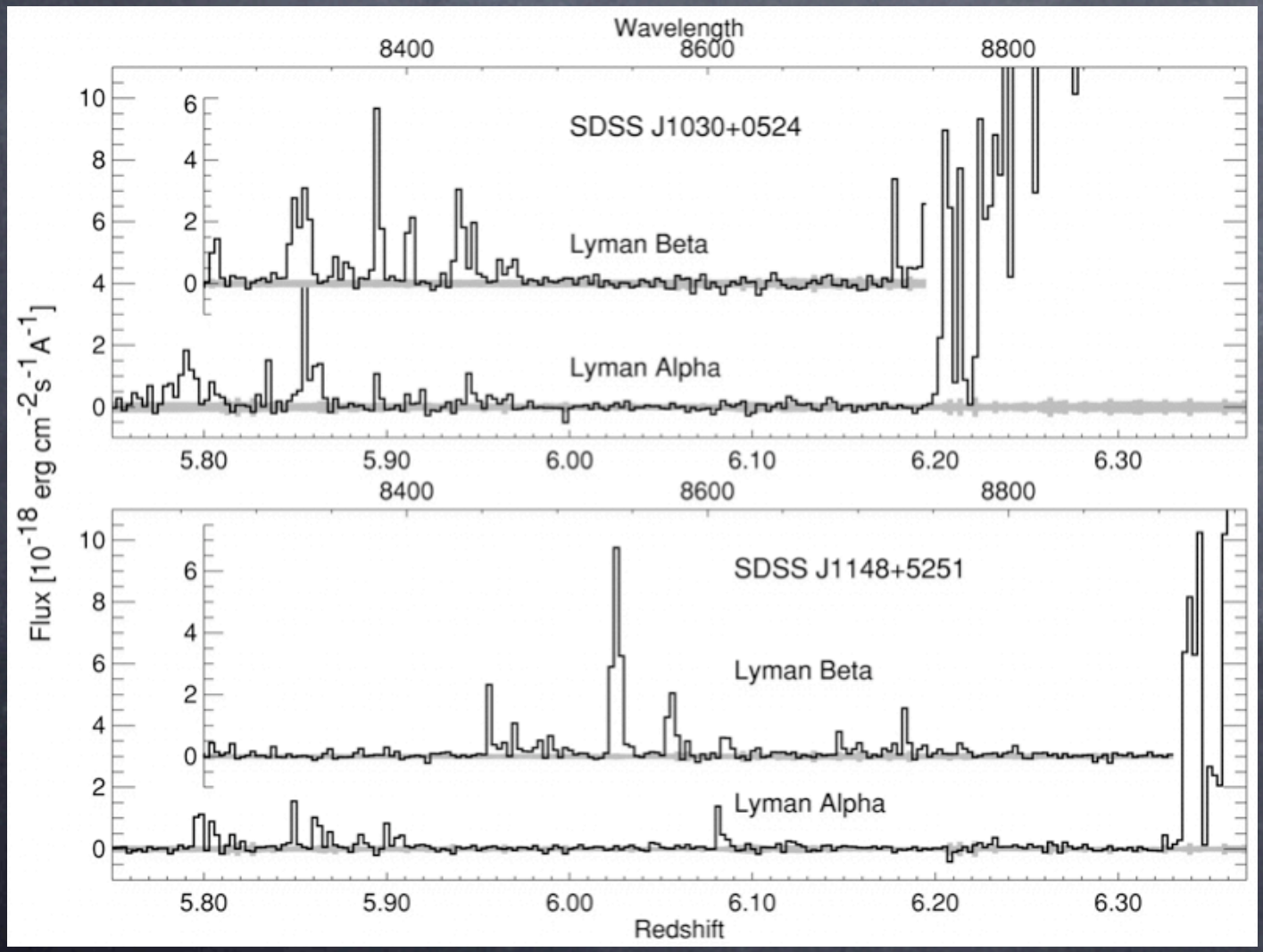
- No flux in Ly-alpha, Ly-beta troughs: $x_{HI} < 10^{-3}$

Two arguments that $x_{HI} \sim 0.2$

1) Small size of QSO HII regions (Wyithe & Loeb 2004)

2) Indirect test for Gunn-Peterson damping wing: smooth rather than fluctuating opacity (Meisinger & Haiman 2004)

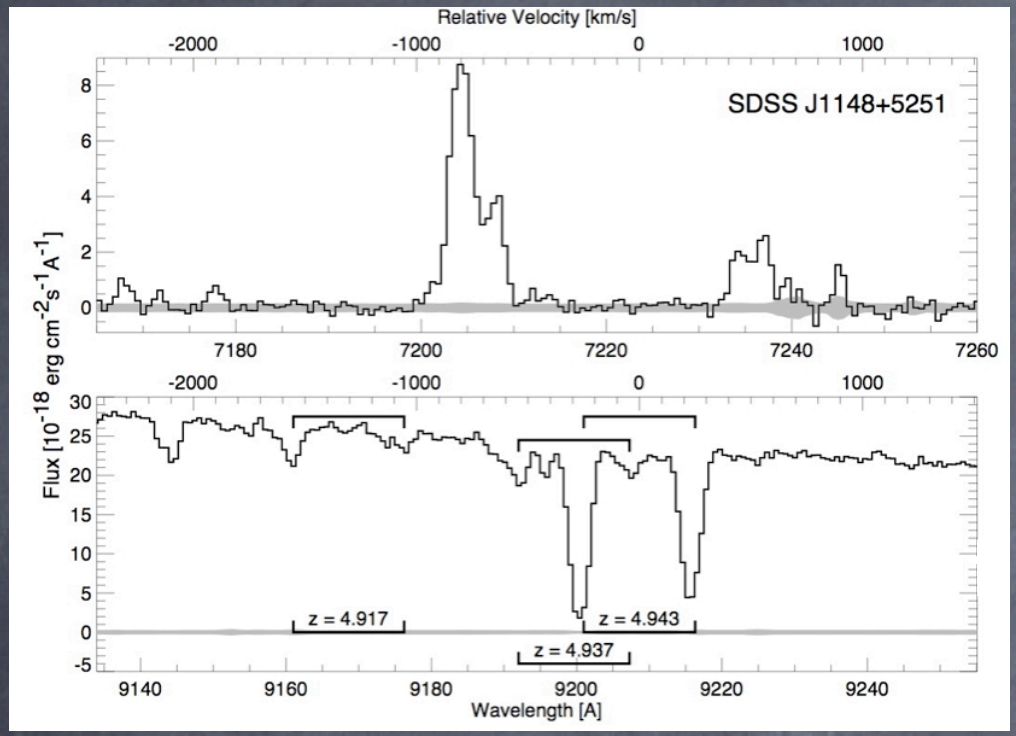
But how universal are the Gunn-Peterson troughs...?



Transmission gaps or intervening galaxies??

White et al 2003

The Case for an Interloper



White et al 2004

- Ly-alpha emission + CIV absorption seen at z=4.94
- Flux seen in both Ly-alpha + Ly-beta troughs, but flux ratios wrong: too much flux seen in Ly-alpha trough

Flux ratios are OK...

$$\tau_{\rm eff} = \int \exp[-\tau(\Delta)] P(\Delta) d\Delta$$

$$\tau_\alpha/\tau_\beta = 6.24 \rightarrow \sim 3$$

$$\tau_\alpha/\tau_\gamma = 17.93 \rightarrow \sim 5-6$$

Ratio reduced further by fluctuating radiation field, esp self-shielding systems

$$\tau \propto \Delta^\beta, \beta > 2$$

Error bars must include variance in foreground transmission

The Unjustly Neglected Lyman-Gamma Trough

- Absorption from Ly-alpha(z=5),Ly-beta(z=5.9), Ly-gamma(z=6.3)
- Can put bound on Ly-beta(z=5.9) from Ly-alpha(z=5.9)....
- Lyman gamma trough should have minimal continuum contamination from interloper: flux absorbed by z=4.9 Ly-alpha forest
- Instead, find fluxes in Ly-gamma and beta troughs are comparable
- Transmission gap!!

Oh & Furlanetto 2004

- Note: spikes can't transmission gap in z~5 forest---galaxy isn't bright enough

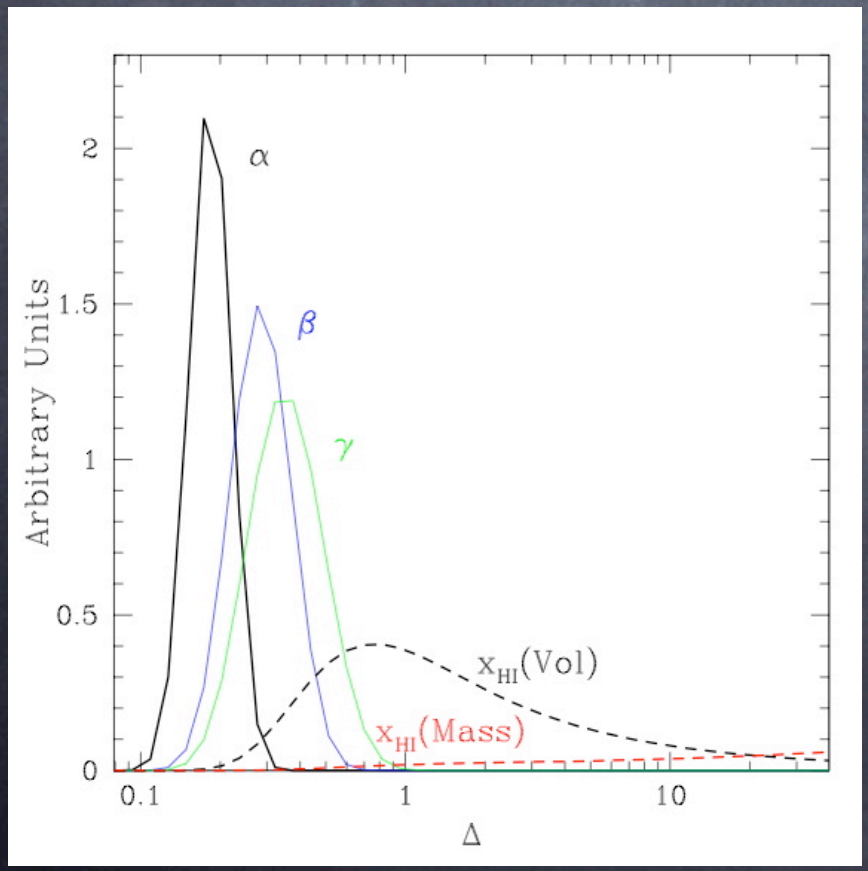
- Strongest constraint on optical depth from Ly-gamma trough: $\tau_{\rm eff} < 14.5 (2\sigma)$

IGM still highly transparent along this line of sight....

If other line of sight is significantly neutral, ---> large sample variance in reionization redshift...

...don't believe claims about neutral fraction!

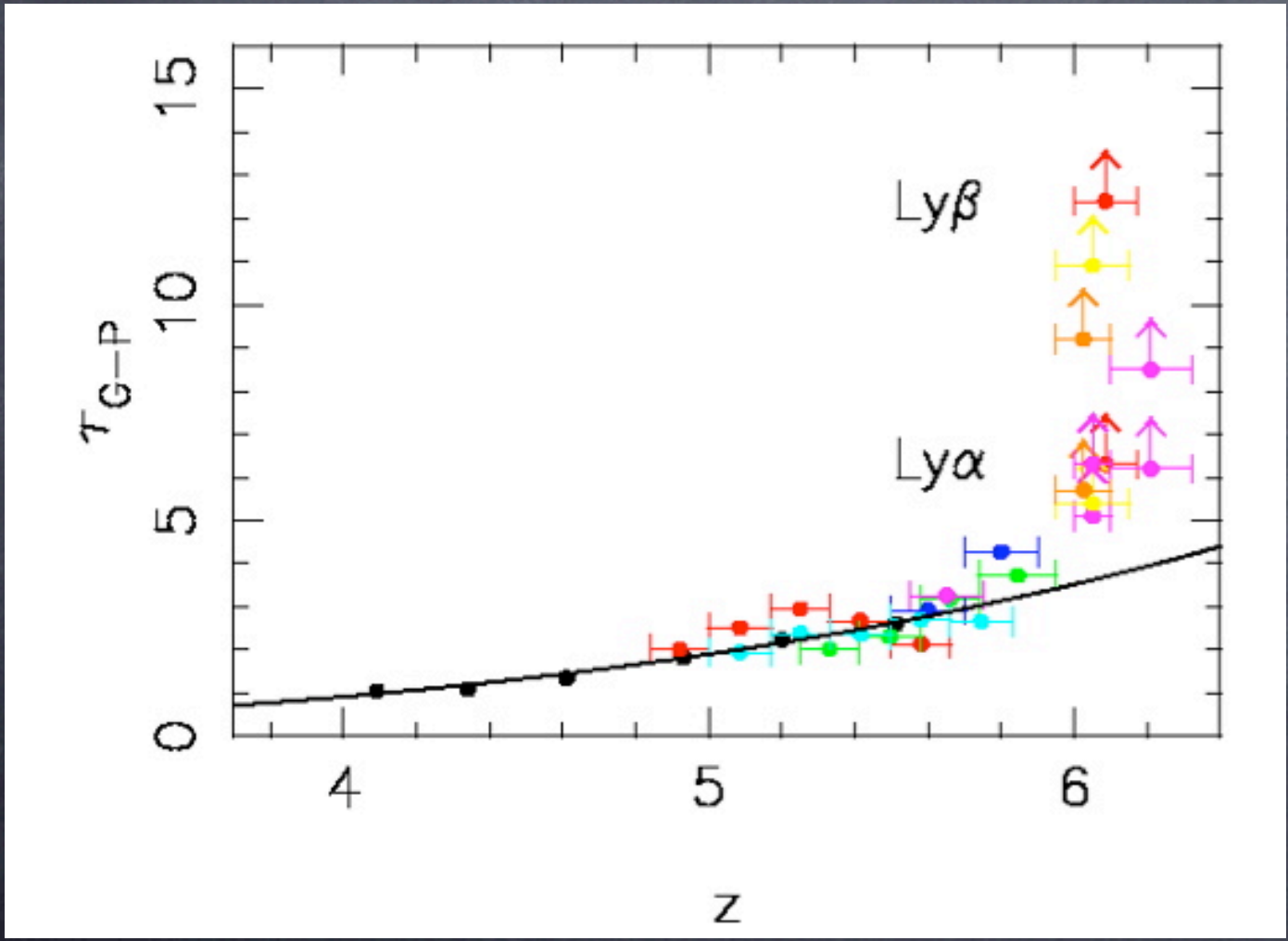
Can't infer $\langle x_{HI} \rangle \propto \langle \tau \rangle$ from $\langle \exp(-\tau) \rangle$ unless we know $P(\tau)$ very well



But before overlap, radiation field highly non-uniform...relation between τ and Δ is complicated...

Anyhow, very different parts of the integrand contribute...

...all we know is that there is a jump in tau...

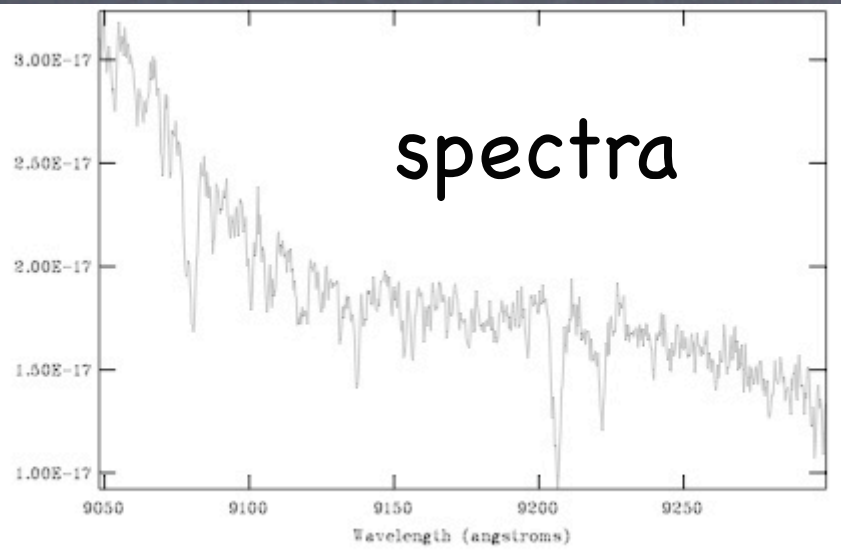


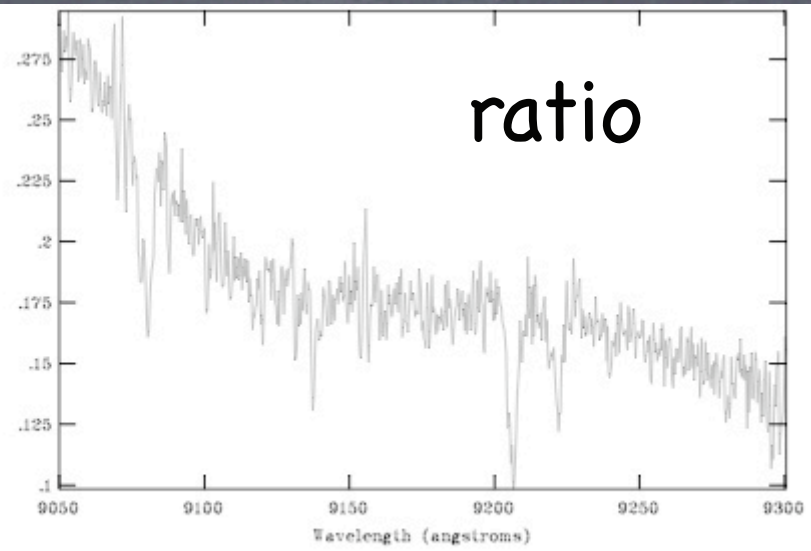
Fan 2004

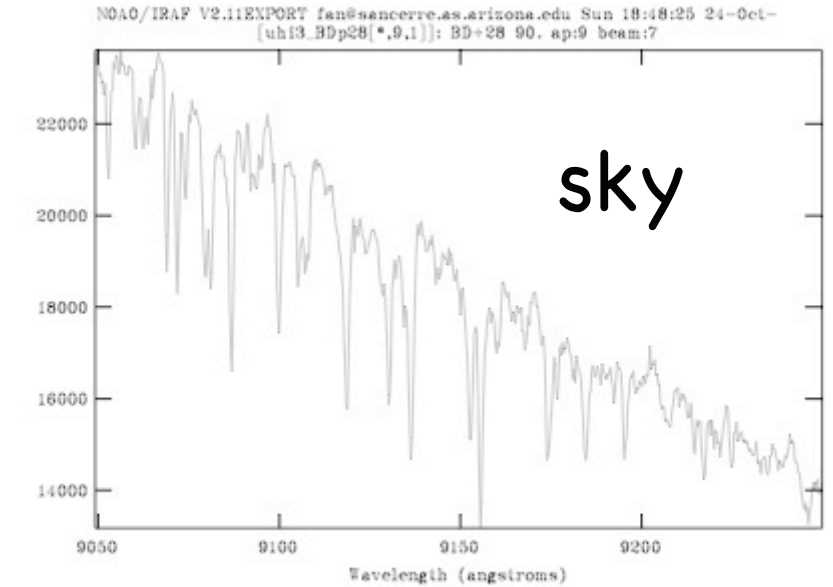
Does this mean tau keeps on increasing to ~10^5??

...so some cautionary notes:

- relation between different taus and x_HI is highly uncertain
- Reionization doesn't have to be phase-change like...it could be modulated by Lyman-limit systems
- Want some probe of the forest during this optically thick era...telling us x_HI, and the abundance of LLS...

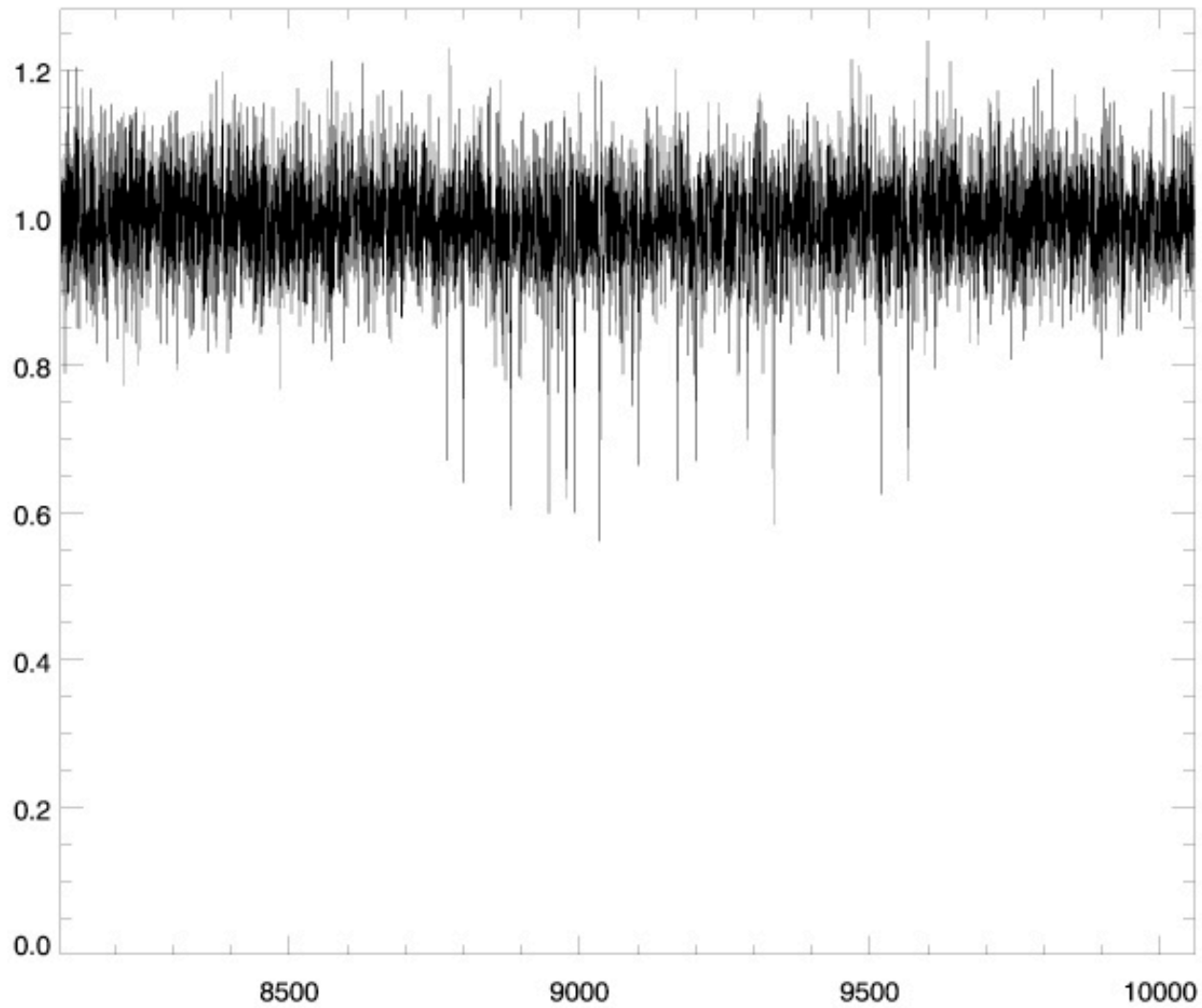






Courtesy of Xiaohui Fan

Unfortunately, the sky is full of nasty lines there...
A good standard star calibration is needed!



w/ J. Prochaska &
P. Madau

...and more simulations/modelling...
Note: frequency of OI lines places limit on abundance of Lyman limit systems/photon mfp

Summary

- In an inhomogeneous medium, continuum photons can be preferentially extinguished, boosting Ly-alpha equivalent widths
- There is probably flux transmission in the GP trough of the z=6.41 SDSS quasar. Either the universe is still highly ionized at z~6, or there is significant cosmic variance in the reionization epoch...