Spectral Signatures of Early Galaxy Formation

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Audience Participation Game

Answer the question...

...get me off the stage!

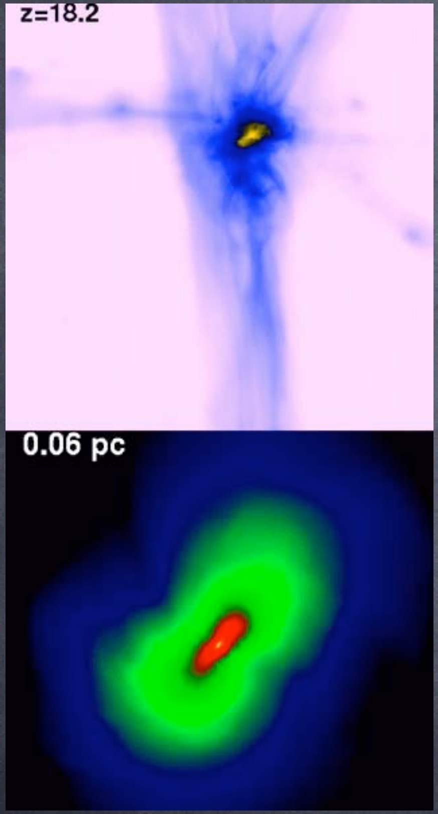
and go home early...

The $64,000 question is...

How do we know **EMPIRICALLY** that the early universe was truly metal-free?

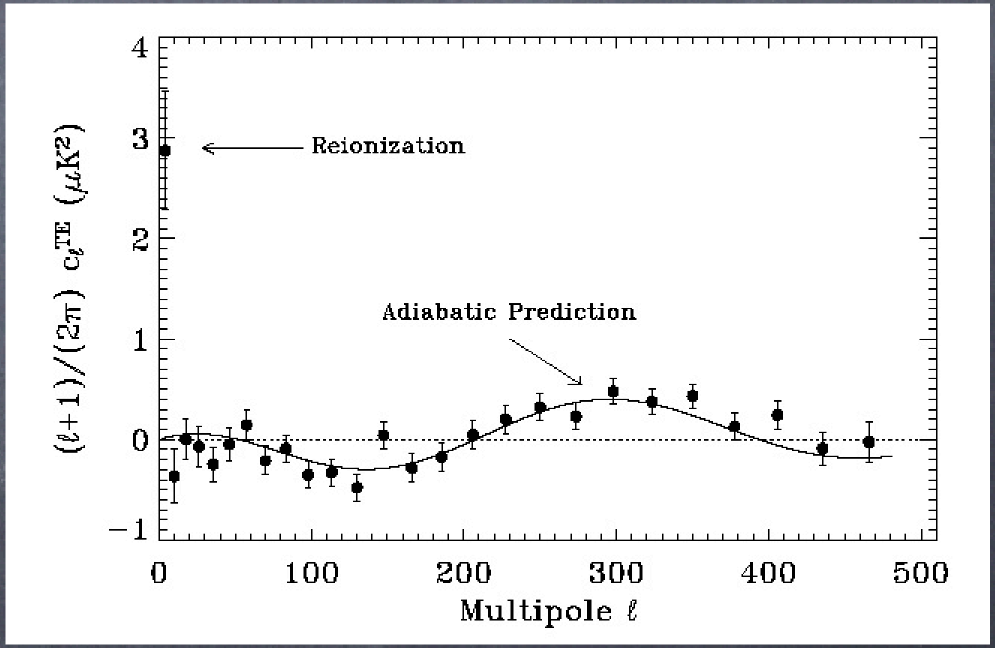
it's just an article of faith...

What if Nature was playing head-games with us?



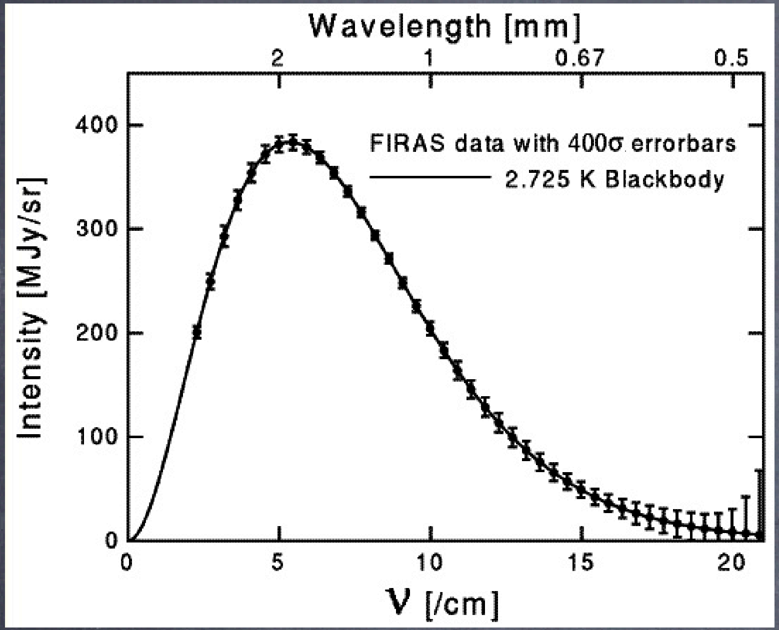
Lay waste to years of careful work on metal-free chemistry and star formation!

Easily explain high WMAP tau!



Make enemies! Impress friends and family!

How would CMB change?



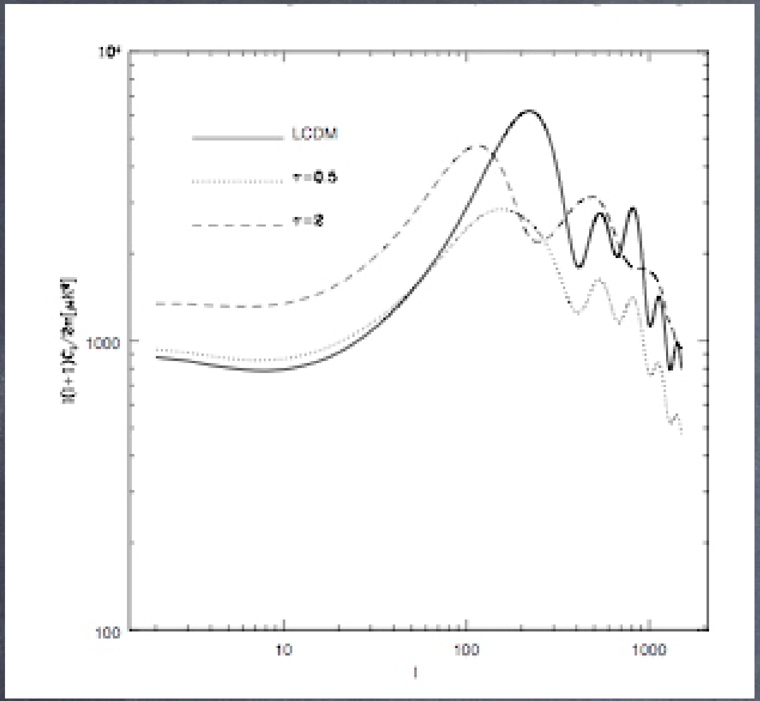
No net spectral distortion of CMB (it's all in LTE!)

So either:

1) Rescattering of CMB anistropies

2) Change recombination history

New anisotropies?



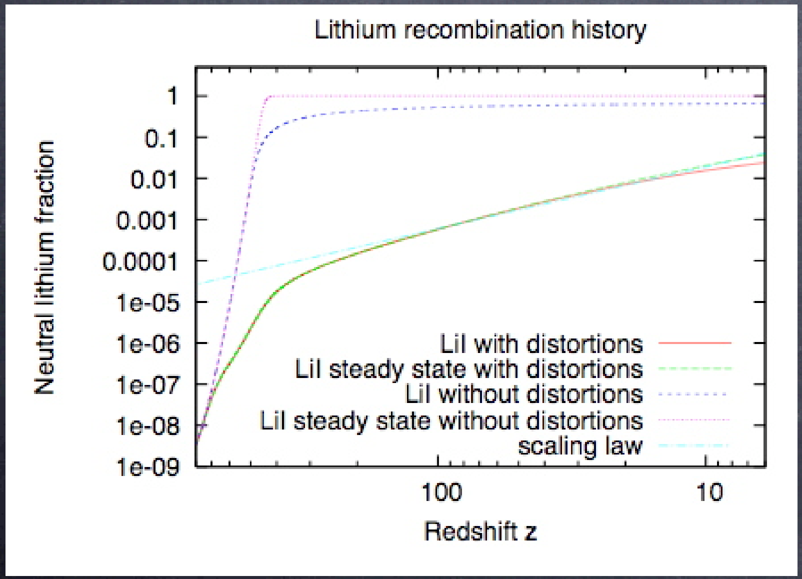
E.g. Lithium rescattering

(Loeb 2001, Zaldarriaga & Loeb 2002)

but:

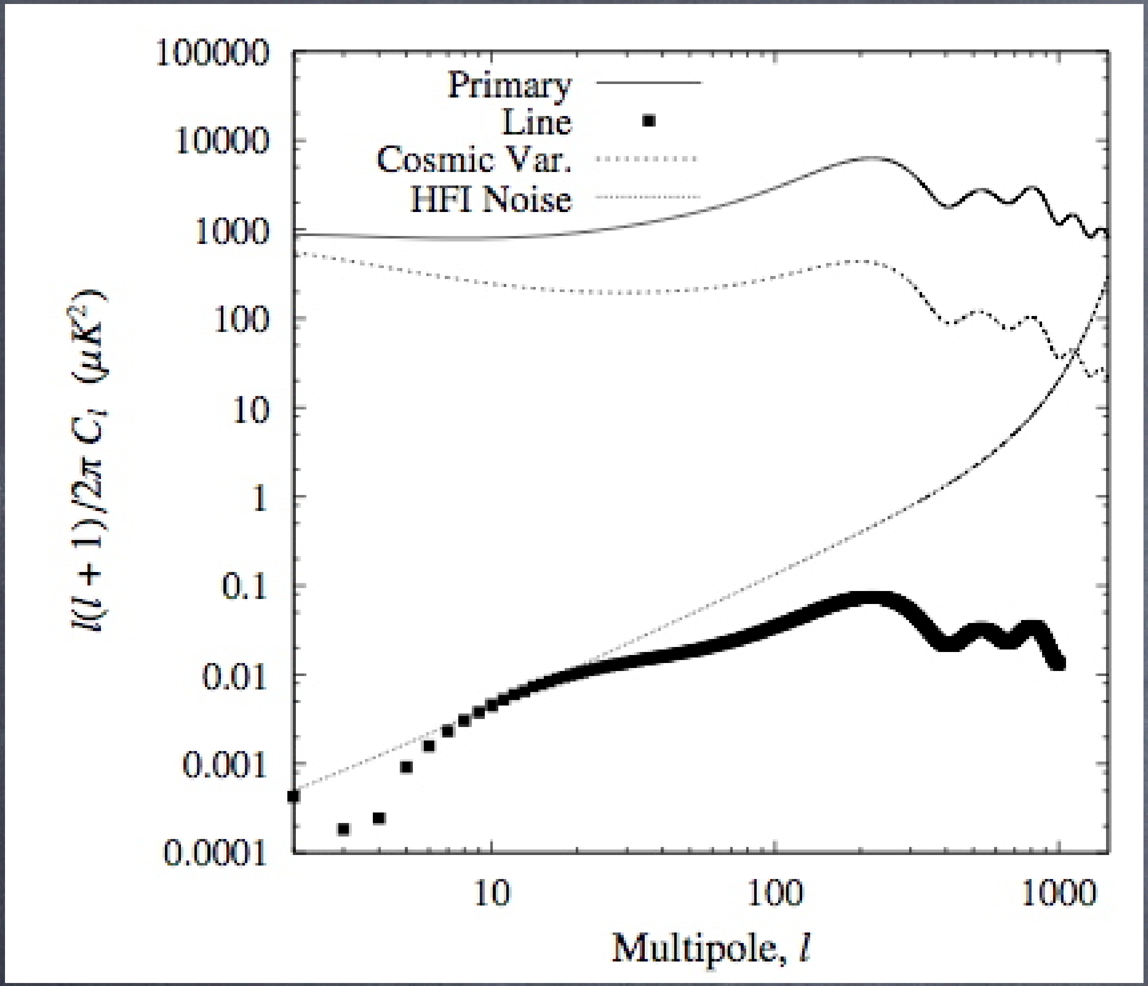
1) Other elements (e.g. C, Si, O) don't have such low freq lines

2) actually, doesn't work for Li either



Ly-alpha from H recombinations keeps Li ionized

Switzer & Hirata 2005



Basu et al 2004

can try to look for fine structure lines...

but this is a very small signal

many foreground issues

Change recombination history?

CMB is not pure BB…there's a Ly-alpha "bump" which delays recombination

Can "get rid" of this by having Ly-alpha photons photo-ionize metals

Or via charge-exchange reactions w/ OI

Can only constrain abundance of metals to 1 part in 10^4!

basic reason:

rate at which destroy Ly-alpha photons=ionization rate=recombination rate

Rate at which ly-alpha photons produced given by ionized H fraction = 1.e-4 at end of recombination

so only an appreciable effect for large amount of metals...

Any ideas, email me!

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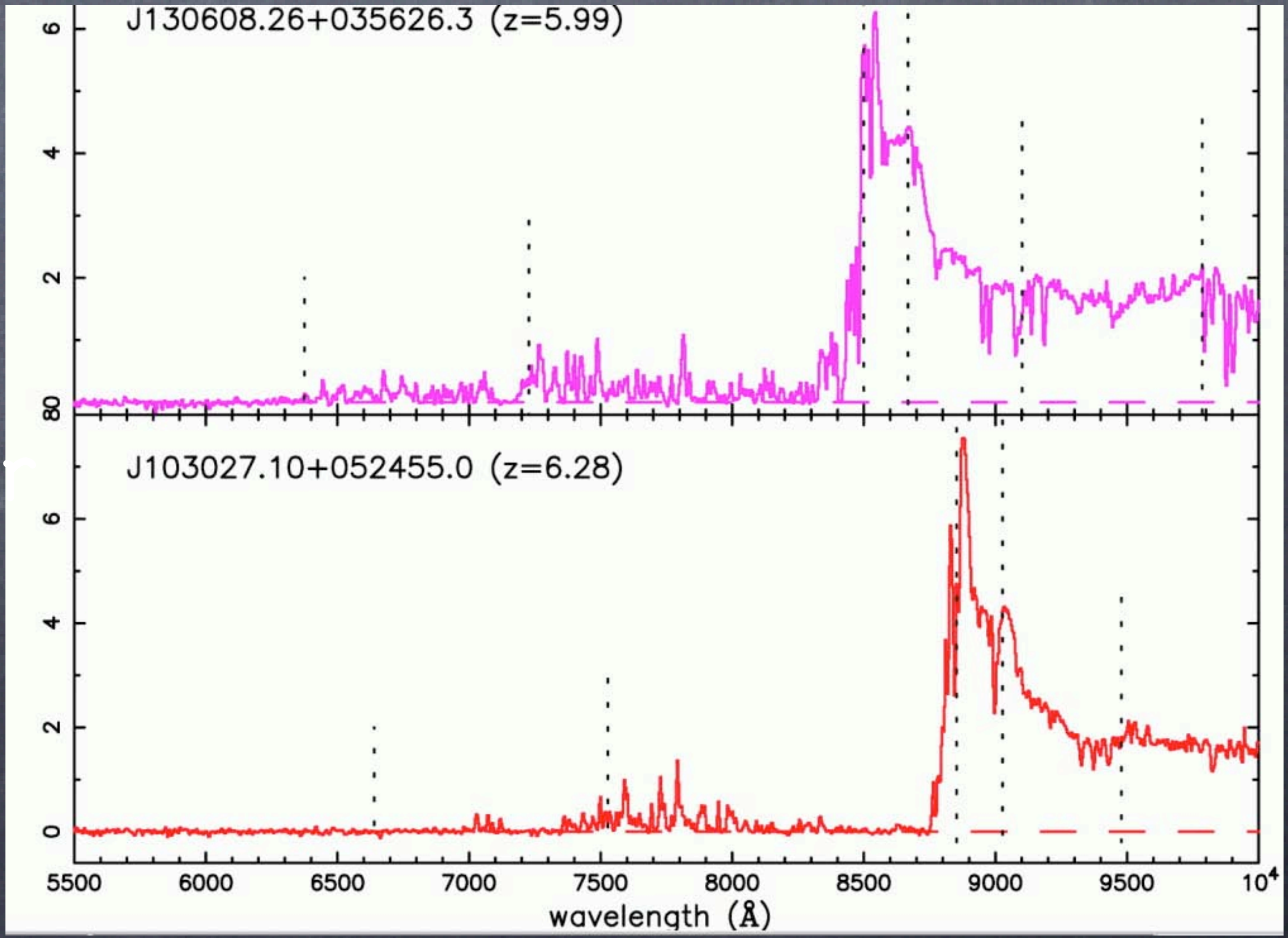
Smoke and Mirrors: Ly-alpha Radiative Transfer in a Dusty, Multi-phase Medium

Hansen & Oh (2005)

astro-ph/0507586

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

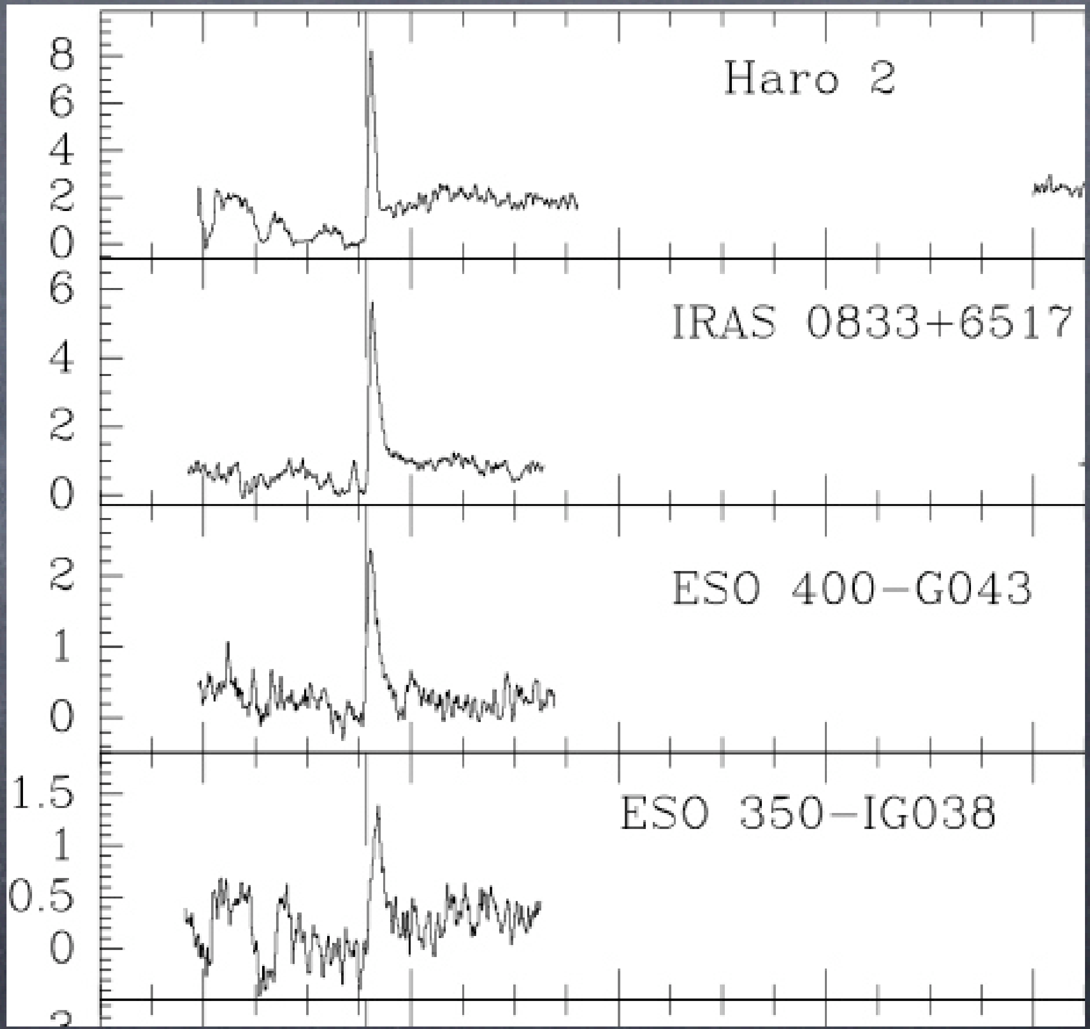
Look at line:
1. Shape
2. Equivalent width
3. Offset from other lines



Becker et al 2001

…and is used to infer winds

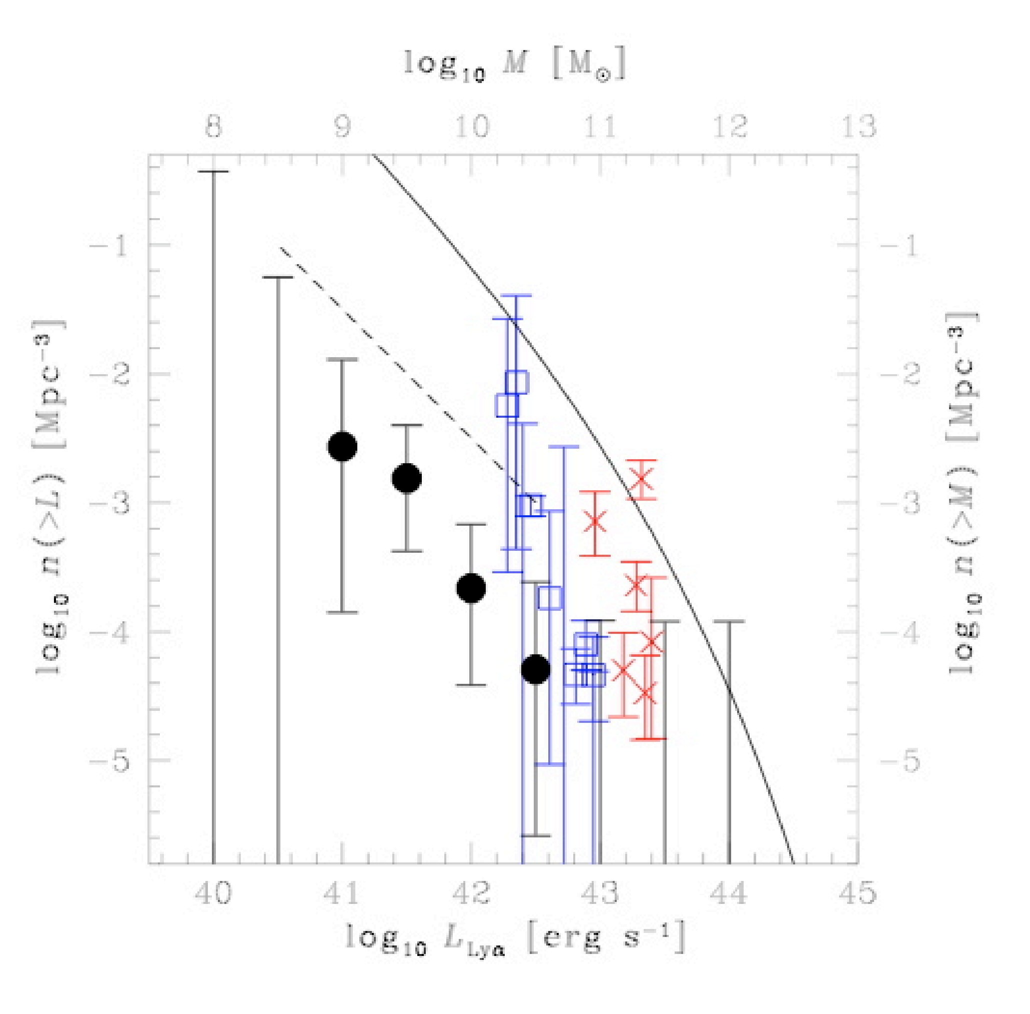
P Cygni profiles
Offset wrt other metal lines



Kunth et al 1998

...constrain the epoch of reionization...

Low luminosity tail should be suppressed after reionization



Santos et al 2004

...and much more...

Isn't this a solved problem?

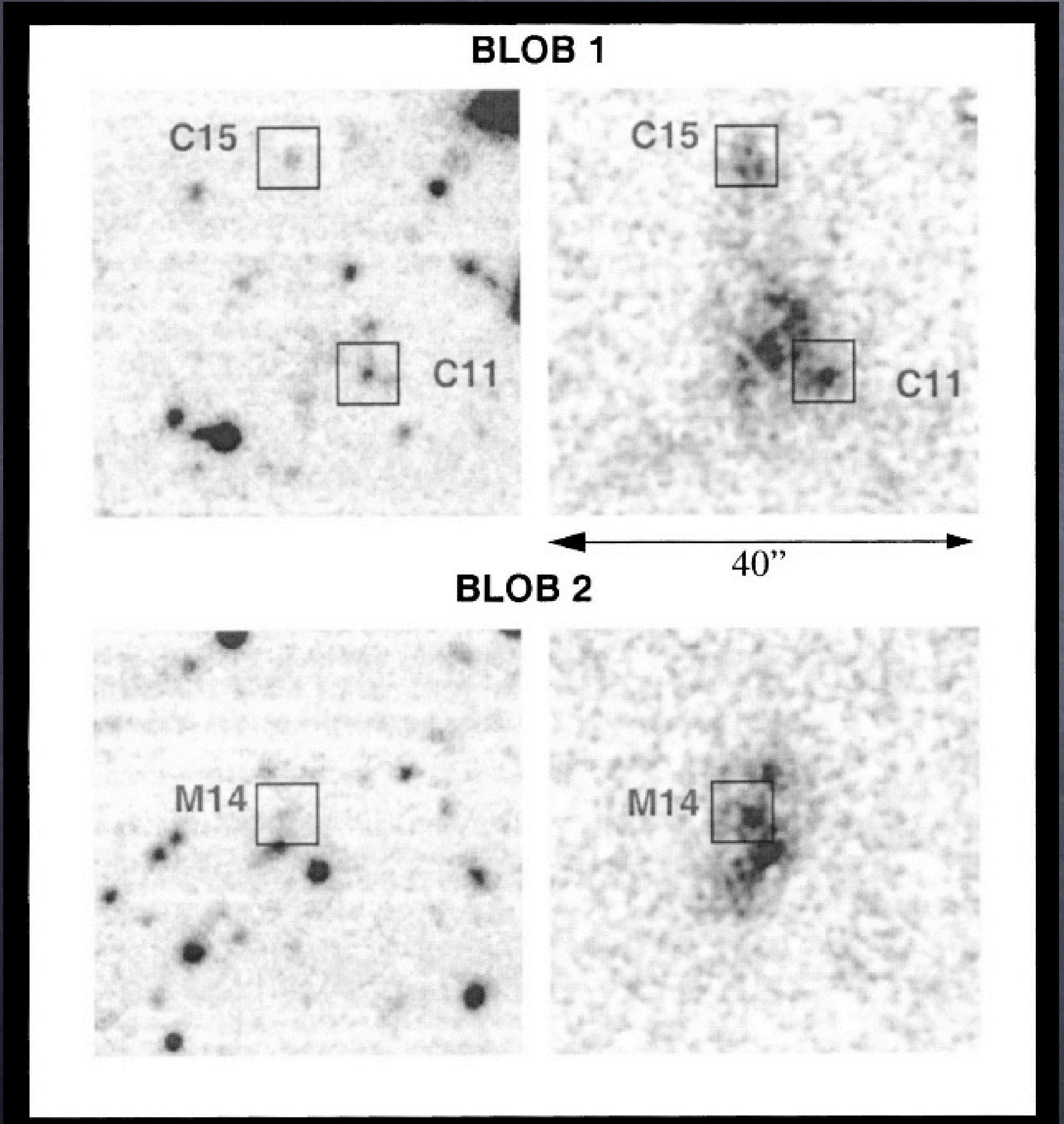
Many, many classic papers on Ly-alpha transfer...

How often are complications modelled?

1. Kinematics ---Yes
2. Dust --- Sometimes
3. Multi-phase structure --No

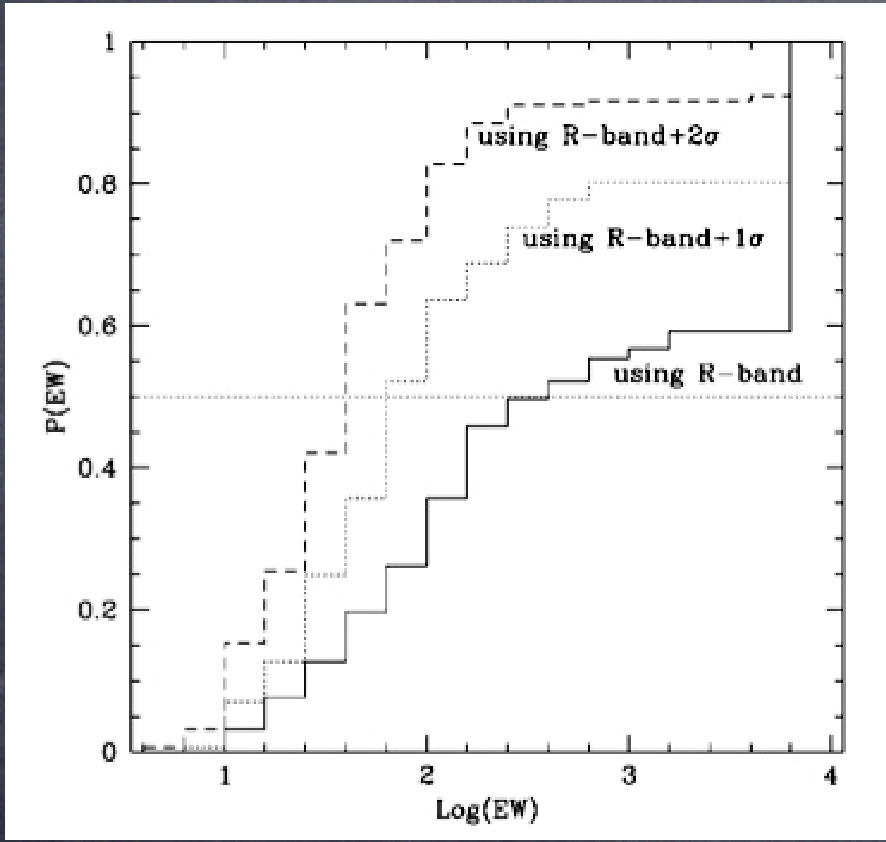
Why should we care?

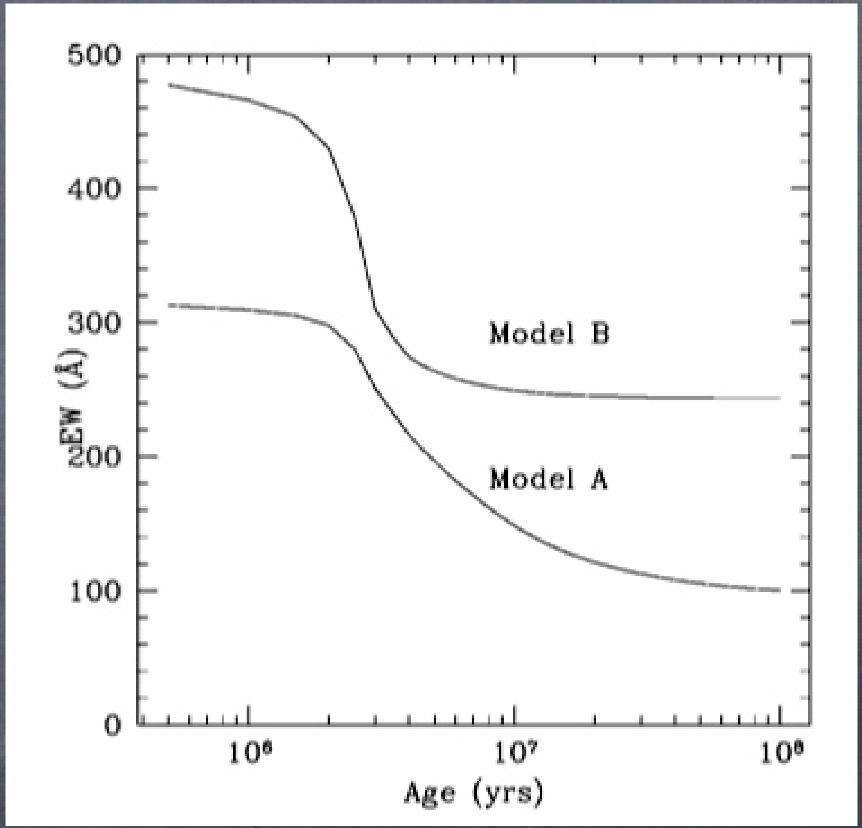
What's going on here?



Steidel et al (2000)

Are these really Pop III stars at high-z??



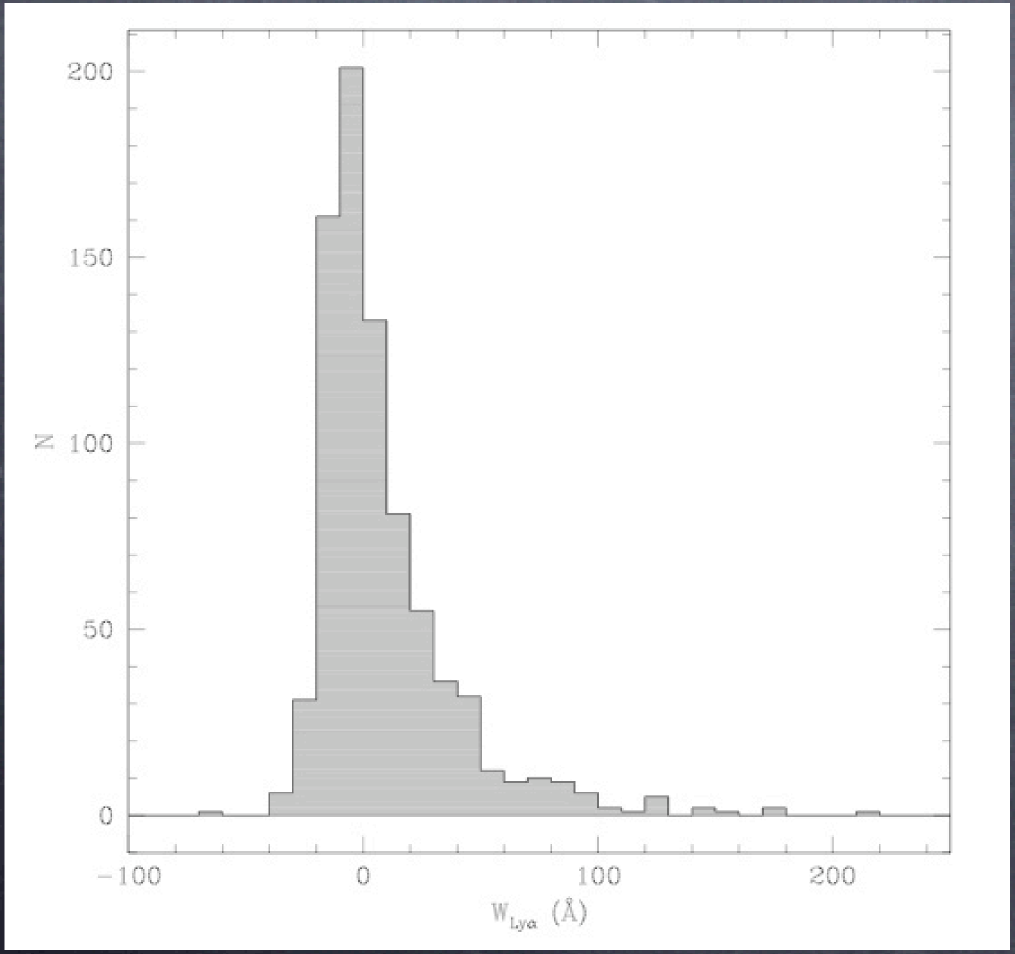


Malhotra & Rhoads 2002

> 60% of sources have EW > 240 Angstroms

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

Ly-alpha properties of LBGs show HUGE dispersion

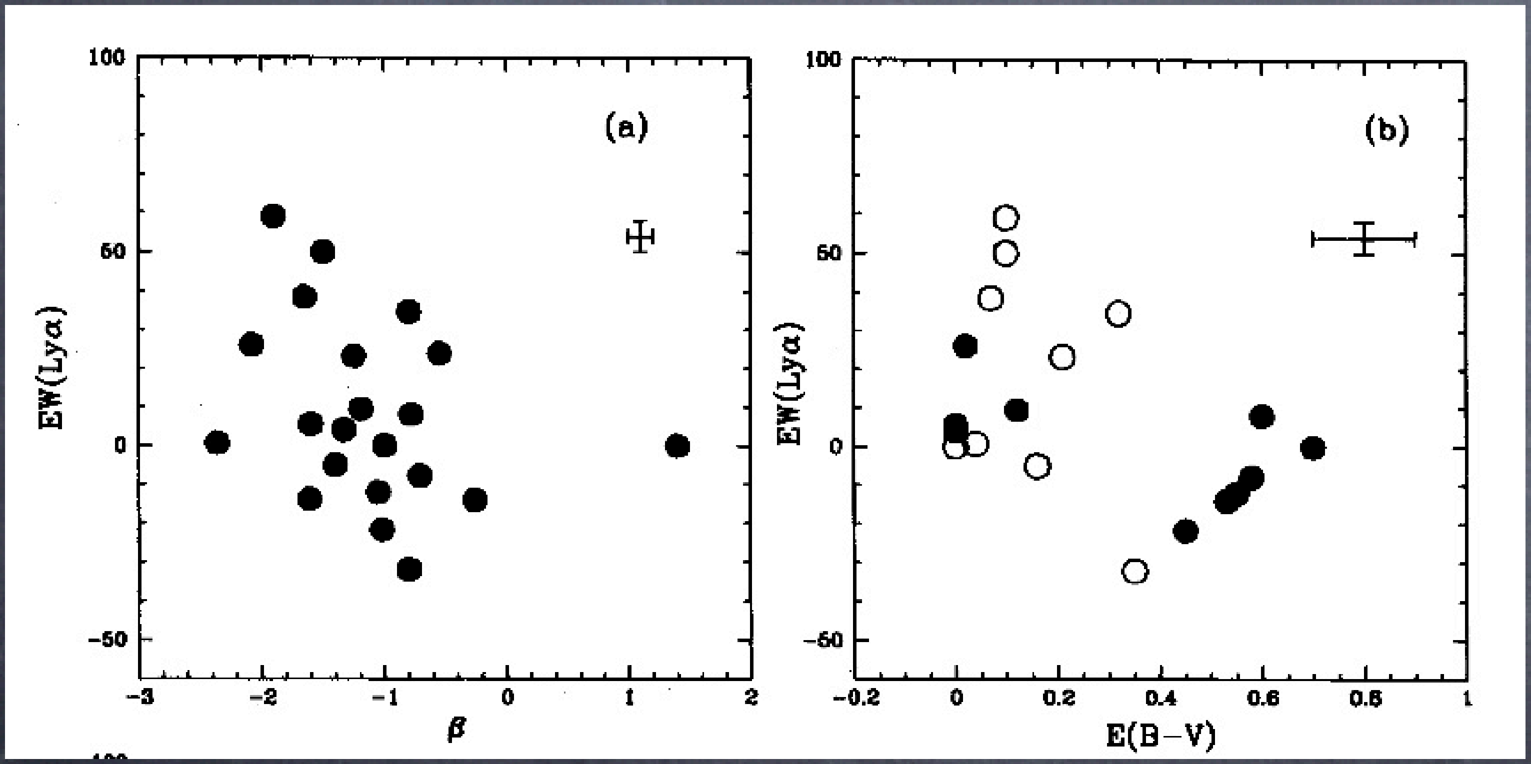


Radiative transfer within ISM is at LEAST as important as transfer within IGM

Let's understand what we're looking at!

Shapley et al 2004

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

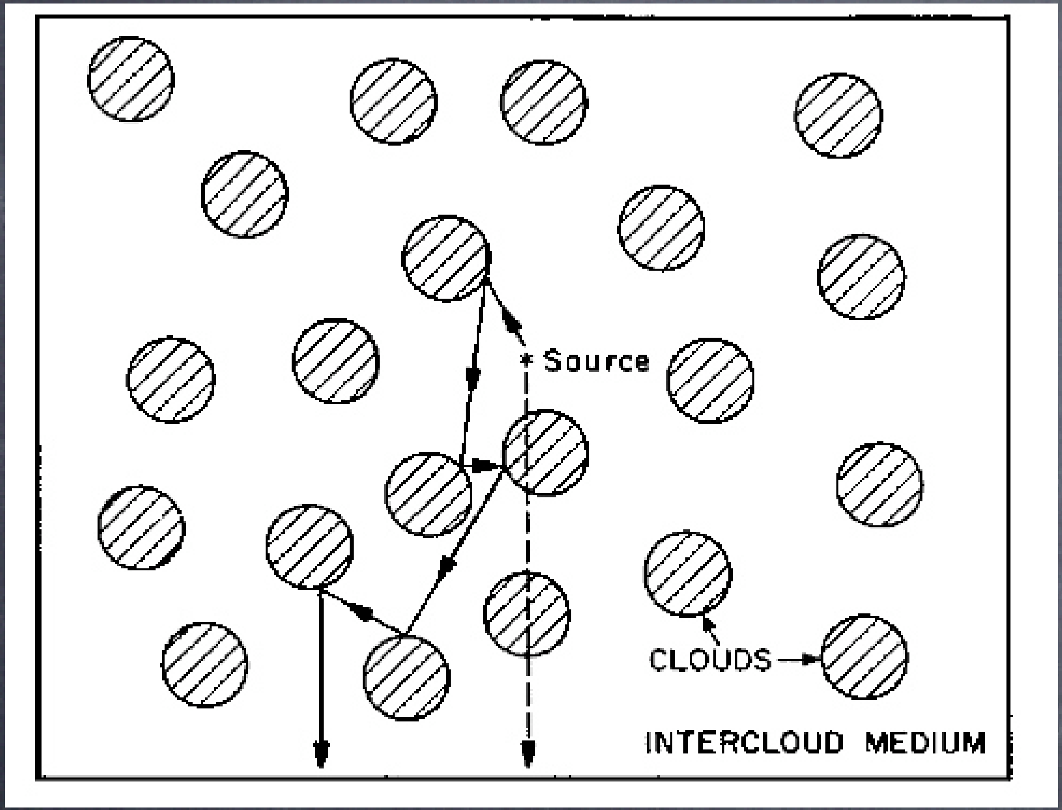


No--Ly-alpha EW appears to be decoupled from the dust content

Giavalisco et al 1996

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

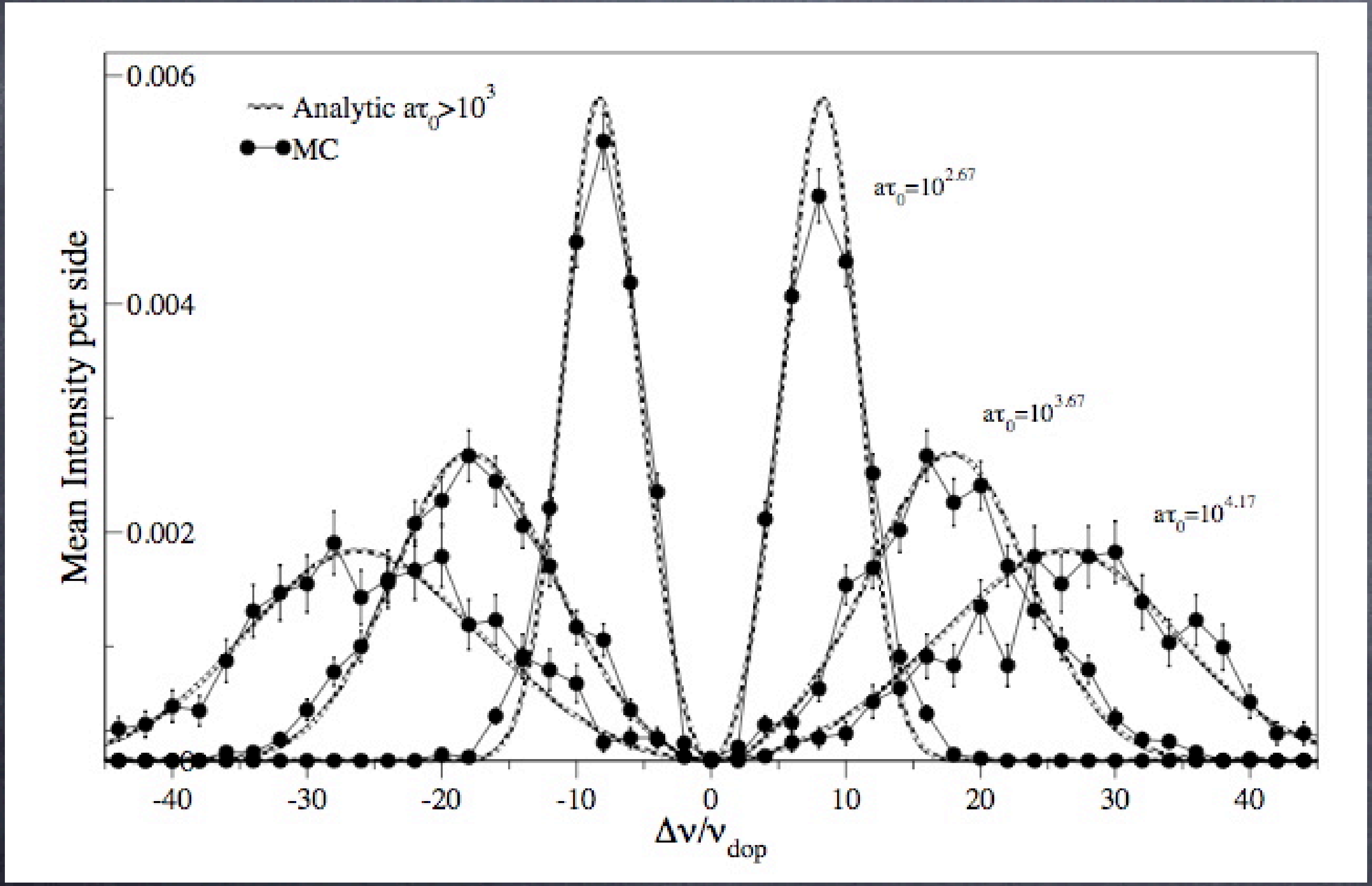
Not if the ISM is clumpy



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

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



Just Photon Pinball...

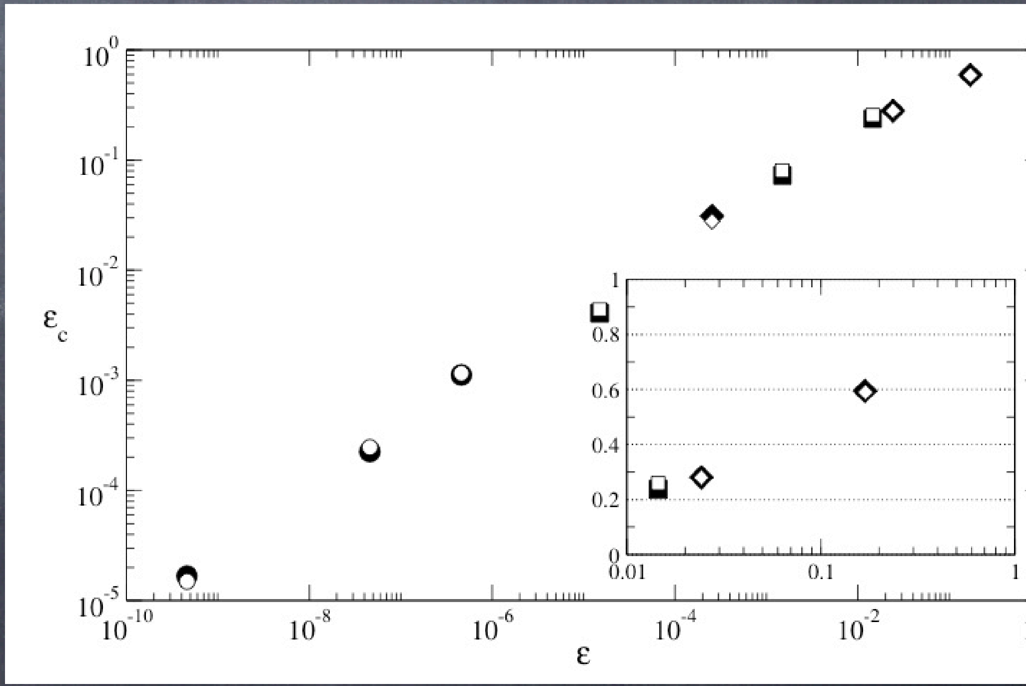
1. Choose Frequency
2. Choose Direction
3. Choose Optical Depth

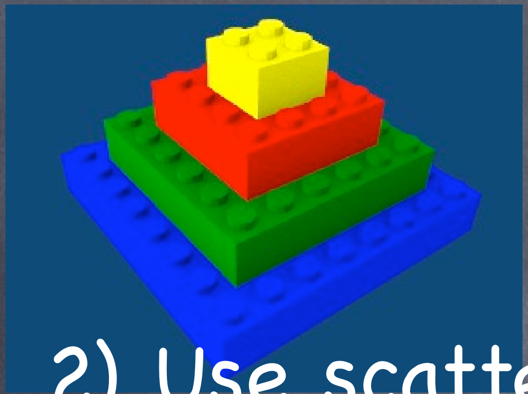
The Need for Speed

Conventional Monte Carlo solves the same problem
over and over and over again....very slow.....

Overcome this (with speed-up ~million) in two ways:

1) Ignore scattering in Doppler core (adaptation of Ahn et al 2002)





2) Use scattering surfaces as Lego blocks --- figure out their properties and use them again and again

Treat cold, dusty phase as flat absorbing mirror.

Check:

a) Sudden jump in photon mean free path

b) Mfp << density scale height, radius of curvature

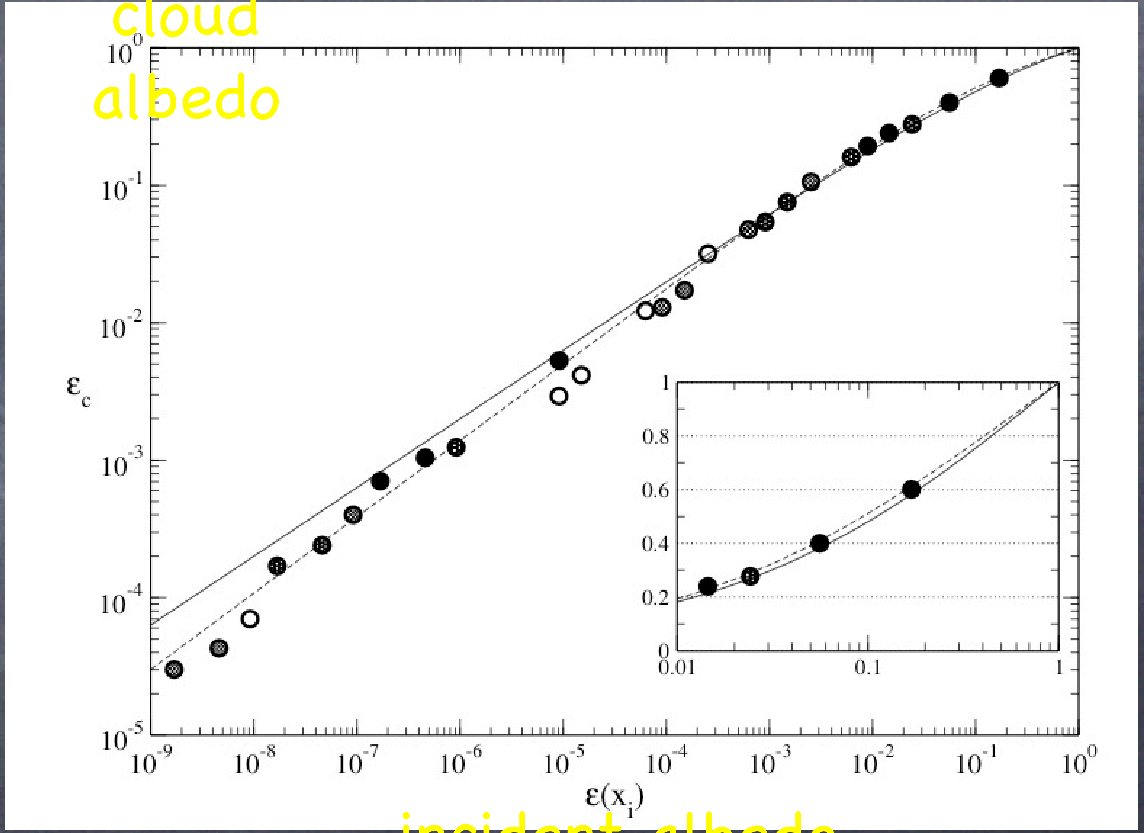
Monte Carlo on Speed

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

Characterize by:

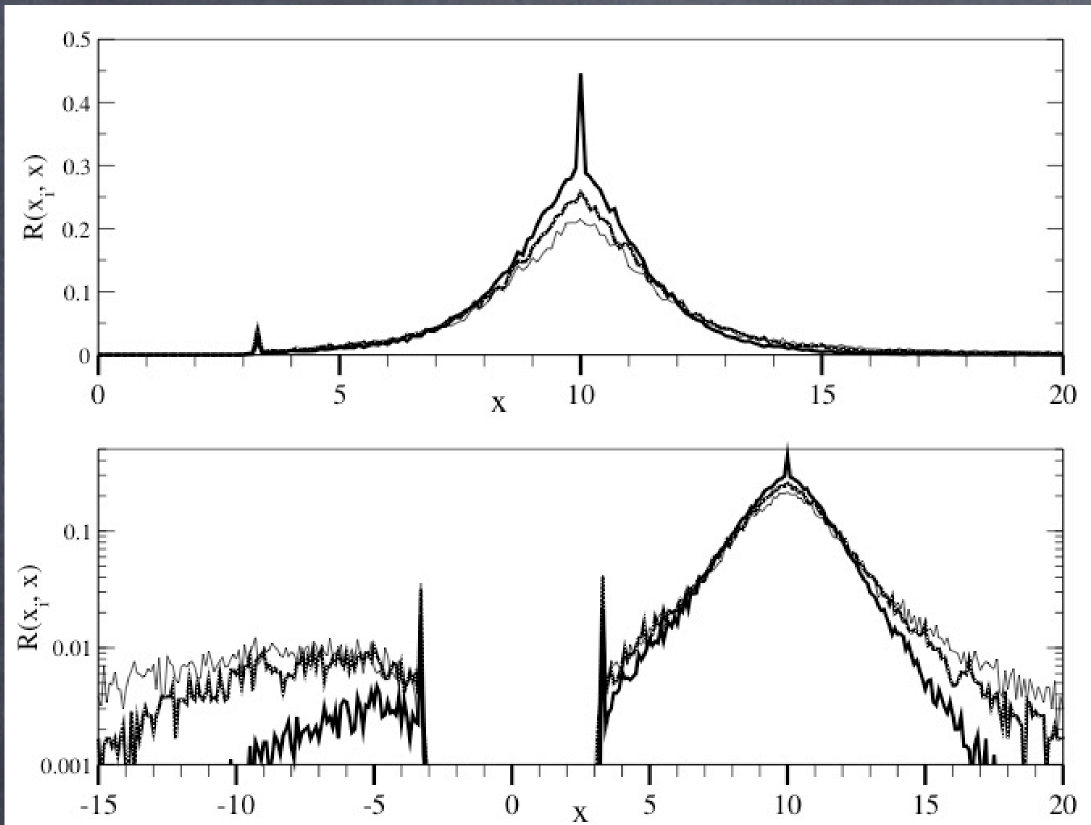
a) Albedo

$$\epsilon_c \approx \frac{3{\epsilon_i}^{5/9}}{1 + 2{\epsilon_i}^{1/2}}$$



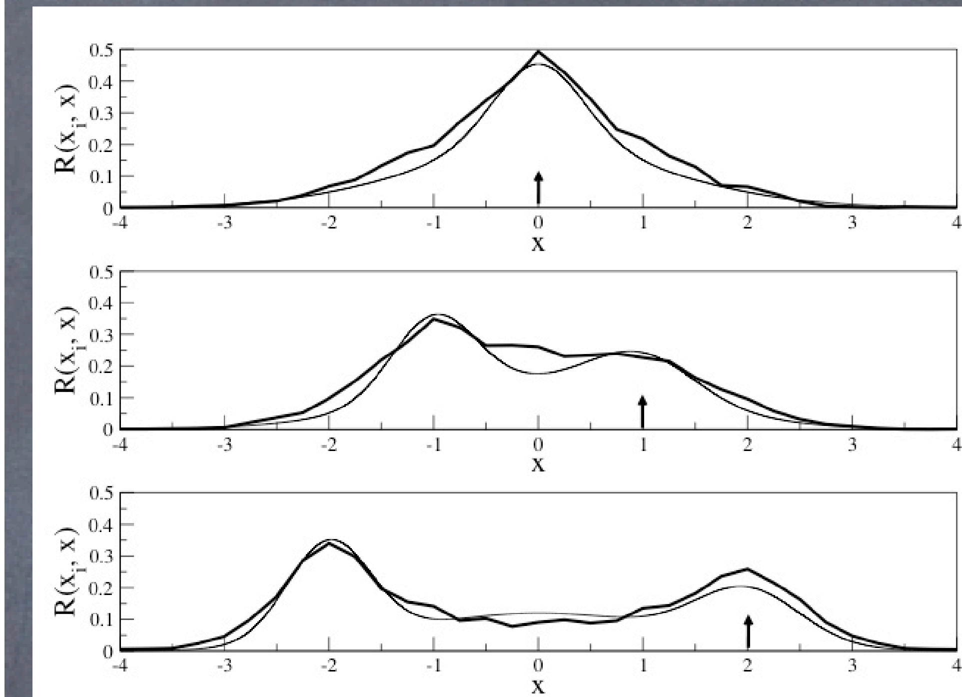
Depends only on albedo evaluated at incident frequency! (no separate temp/dust/freq dependence)

Frequency Redistribution



$$R(x_i, x; \alpha) = \frac{3\sqrt{\alpha}}{\pi} \frac{x^2 \tilde{x}_i^2}{\alpha \tilde{x}_i^4 + (x^3 - \tilde{x}_i^3)^2} \, .$$

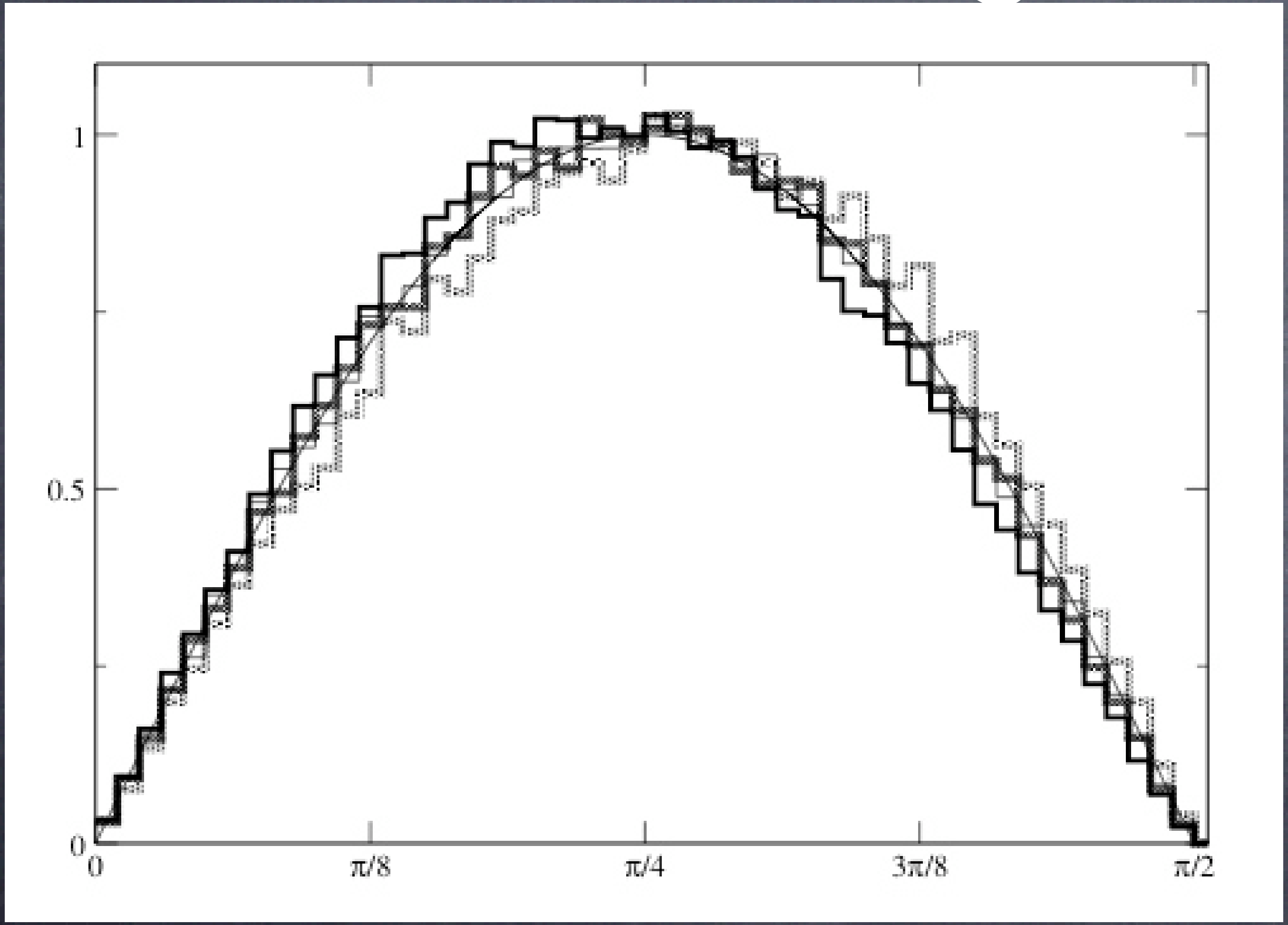
Line Wing



Doppler Core

(Almost) independent of dust content!

Distribution of exiting angles



$$D_{ss}(\theta) = \sin 2\theta$$

As expected from photons that escape isotropically from tau=1 photosphere

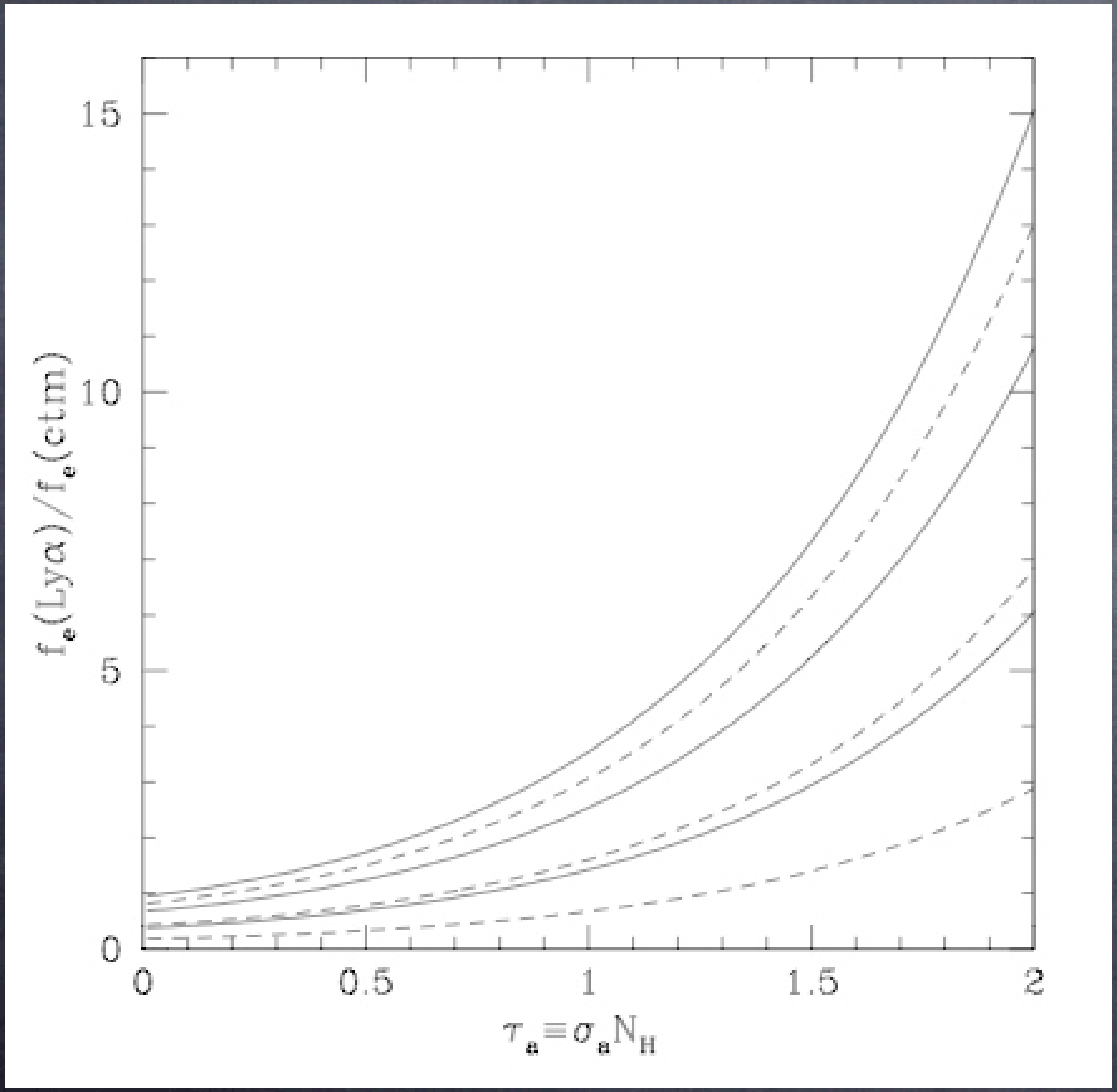
No dependence on incident angle, frequency, or dust content

Effect of Surface Motion

- Just perform Dopper boost into/out of rest frame of surface

These rules are all that's needed to perform very fast multi-phase radiative transfer!

EW boost of ~few is easy...

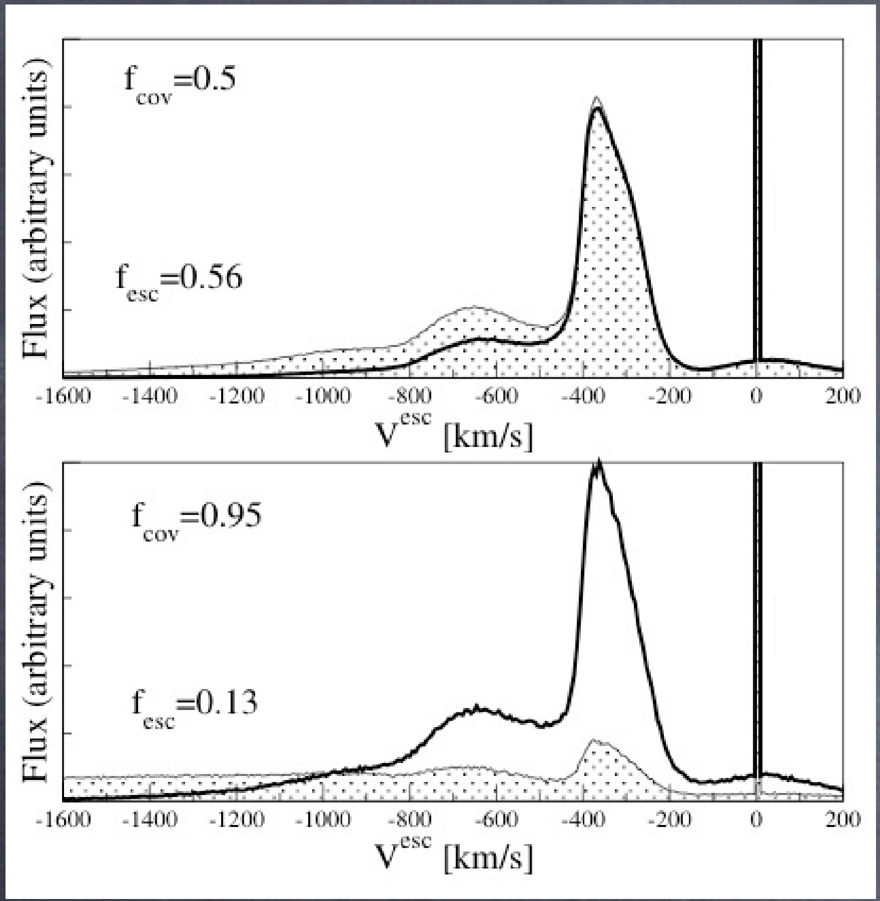


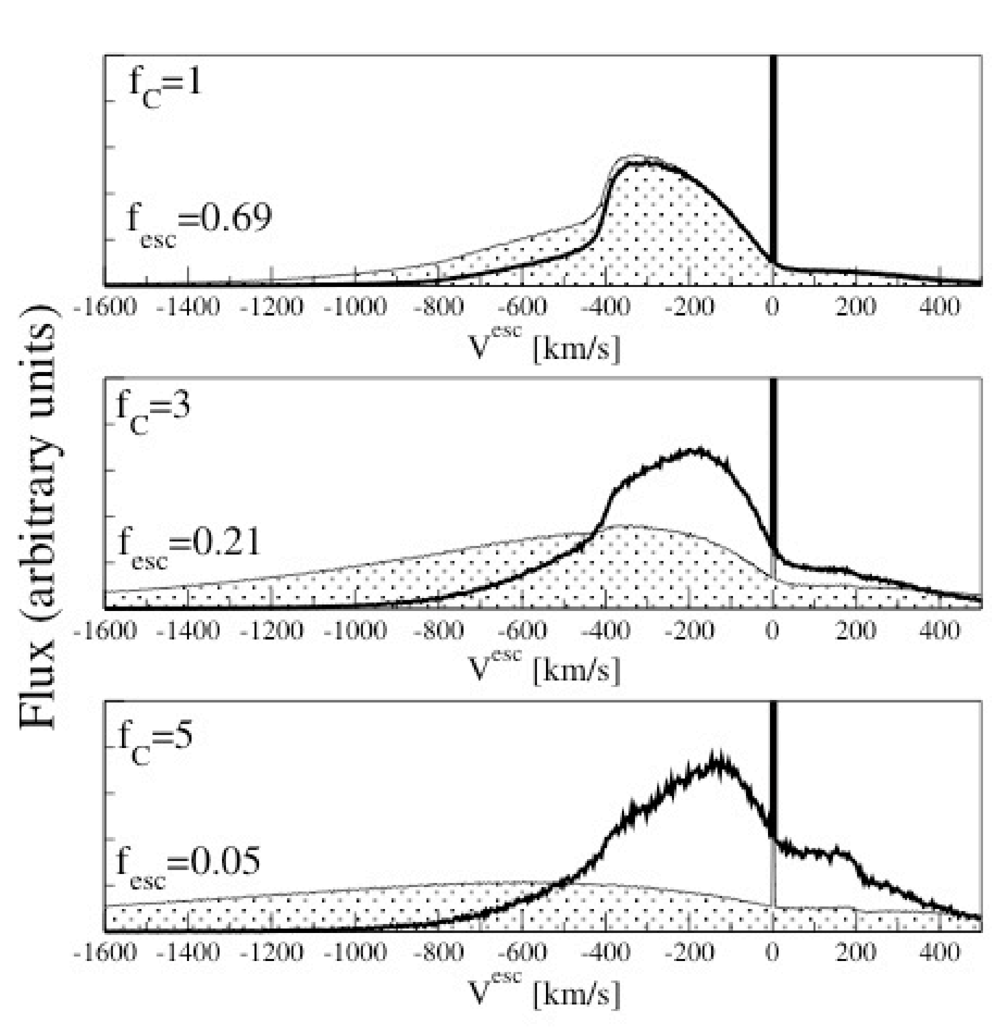
Agreement between exact + fast MC is v. good

EW boost peaks when clouds become optically thick in dust

Test: compare Ly-alpha with Balmer lines

Multi-phase Outflows





Asymmetric line shape

Line widths ~ few times outflow speed

Photons escape more easily, profile more sharply peaked than in homogeneous outflow

Analytic Multi-Phase Radiative Transfer

Can estimate escape fraction and number of scatters analytically!!

Escape fraction = $$\frac{1}{\cosh\left(\sqrt{2\epsilon\mathcal{N}_0}\right)}$$

Number of scatters= $$(1-\epsilon)\mathcal{N}_0\,\frac{\tanh\left(\sqrt{2\epsilon\mathcal{N}_0}\right)}{\sqrt{2\epsilon\mathcal{N}_0}}$$

ϵ albedo at escape frequency is function of N_o

So need just one parameter:

N_o : number of scatters if no absorption

N_o is purely geometric

Frequency independent for very optically thick scattering surfaces

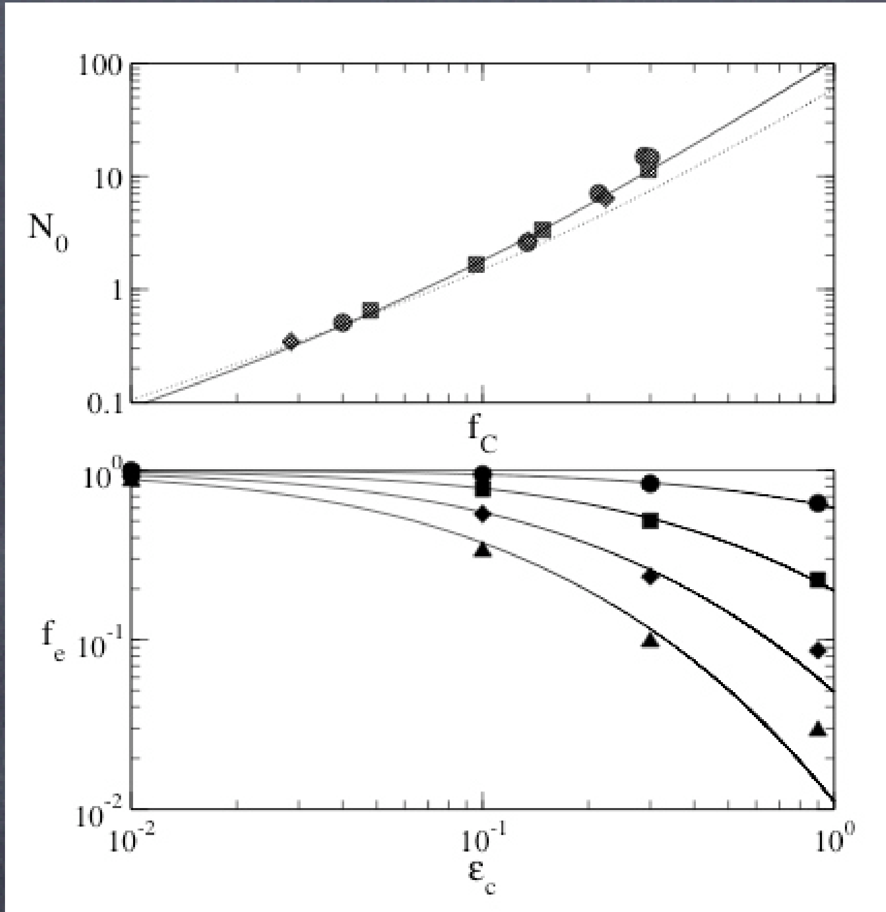
We've found fitting formula for generic astrophysical situations by running Monte-Carlos....

$$\mathcal{N}_0 = \frac{3}{5} f_C{}^2 + f_C$$

Randomly oriented surfaces

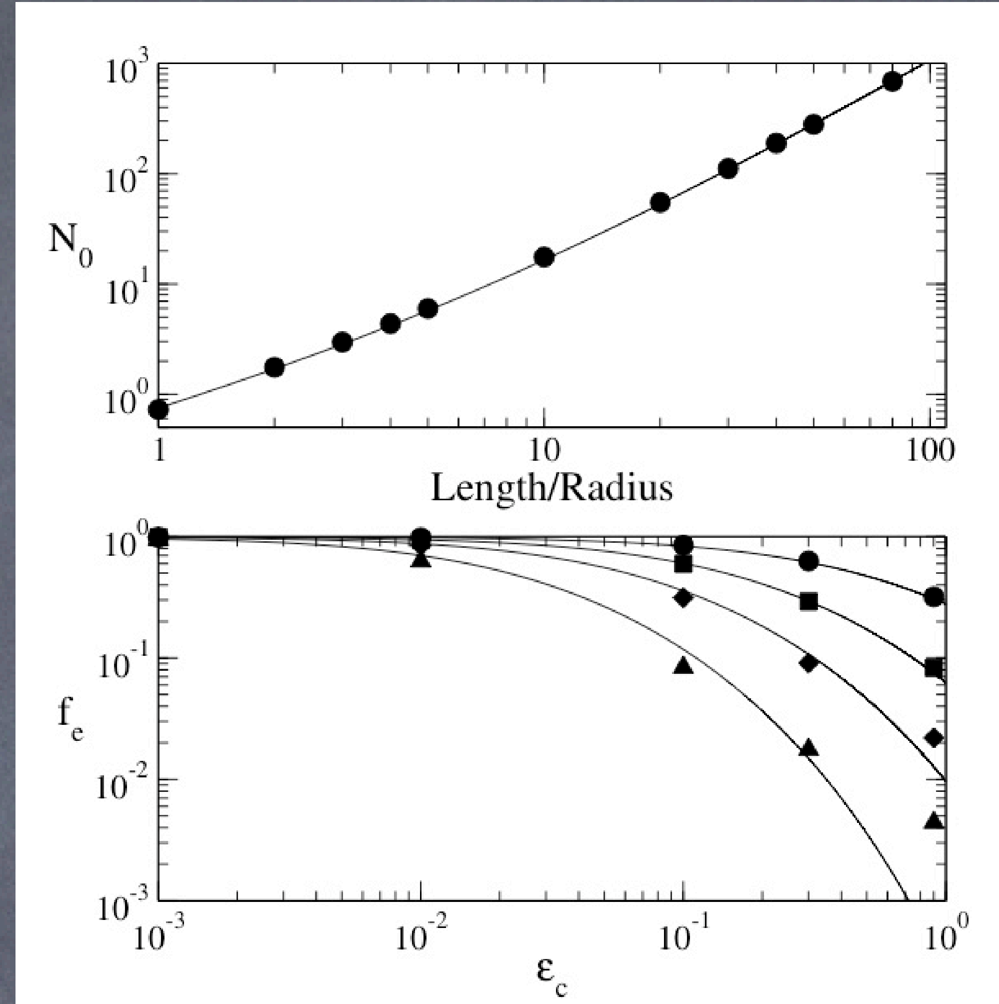
$$\mathcal{N}_0 \approx f_{\rm cov}/(1 - f_{\rm cov})$$

Shell with holes



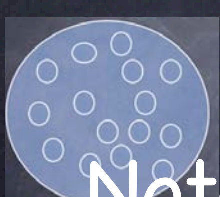
$$\mathcal{N}_0 = {f_C}^2 + \frac{4}{5} f_C$$

Random spheres



$$\mathcal{N}_0 = \frac{1}{10}(L/R)^2 + \frac{13}{20}(L/R)$$

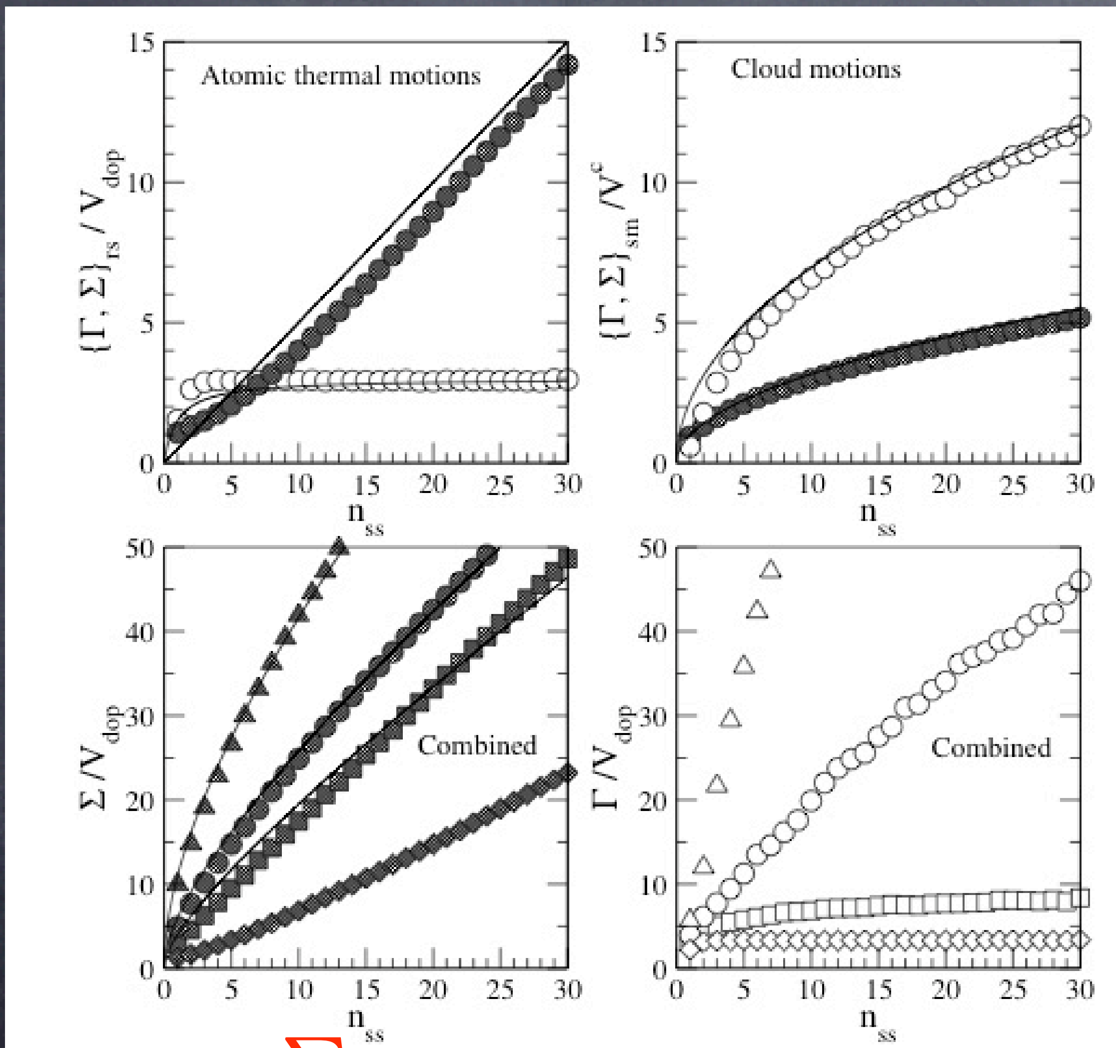
Tube with holes



Note: independent of size distribution of spheres!

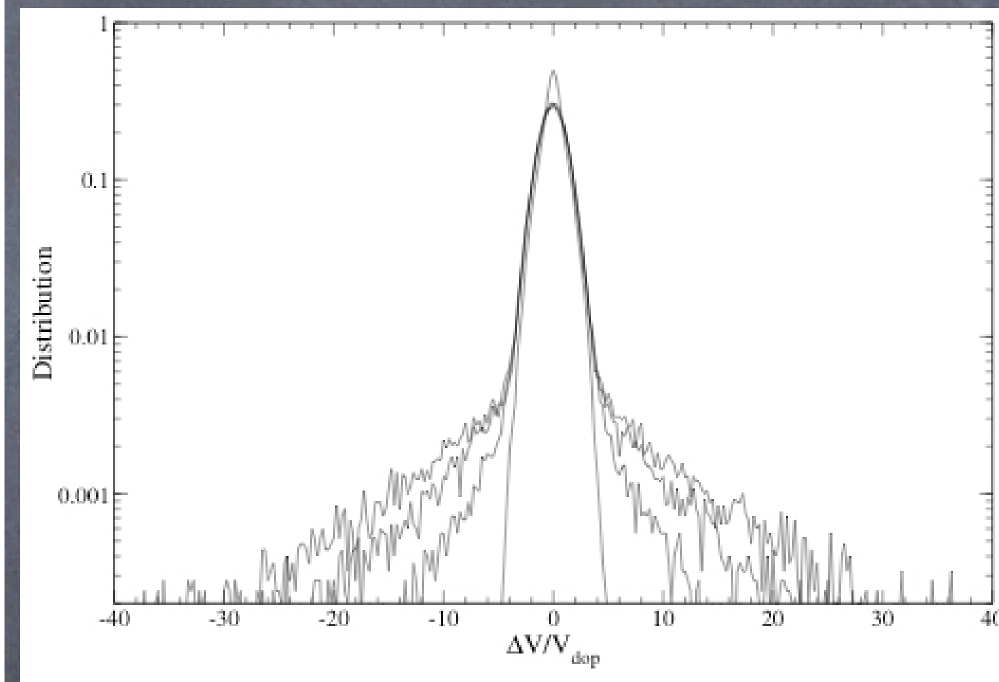
Escape Frequency

What is characteristic line width after repeated scattering?



$\Sigma \propto n_{ss}$

Atomic motions only

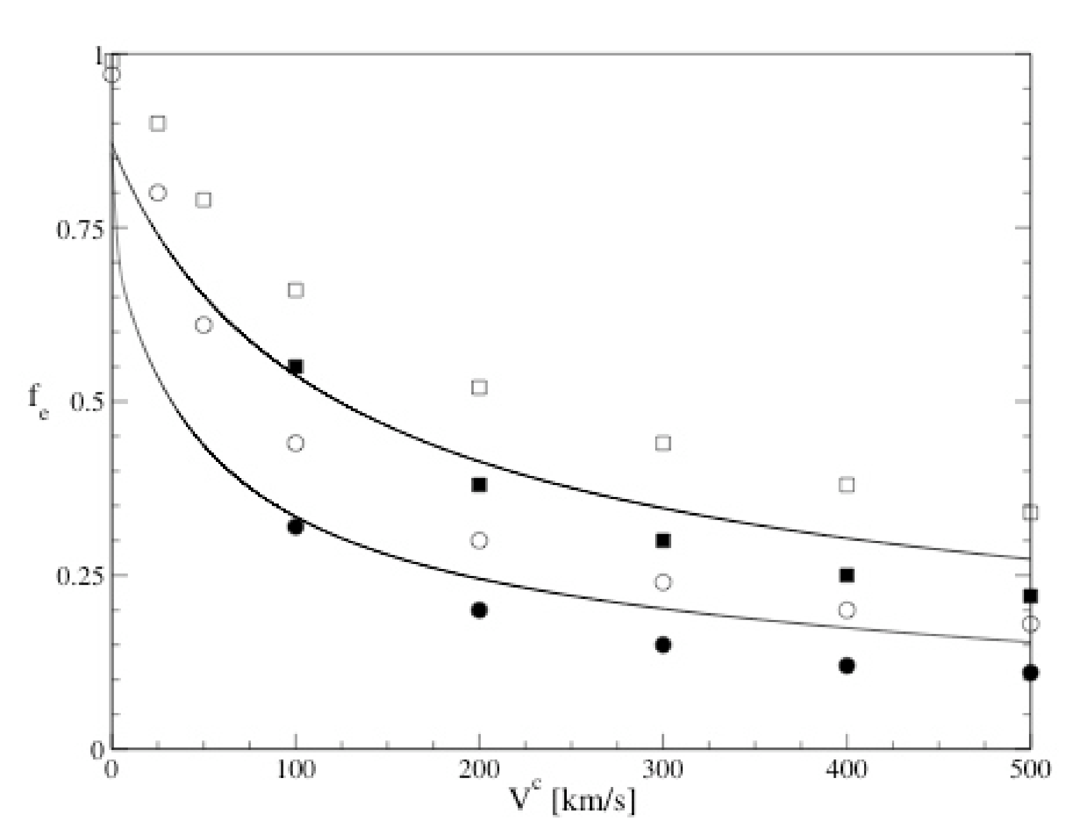


If no cloud motions, core "thermalizes", with non-gaussian tail...

If V_surface > 100 km s^-1, then no saturation

Analytic Escape Fractions with Cloud Motion

Solve for number of surface scatterings iteratively to estimate escape frequency



Bottom line

- Technical Advances
  - Surface scattering quantified for 1st time....we think!
  - An ultra-fast adaption of Monte-Carlo transfer suitable for multi-phase numerical simulations
  - Analytic formulae for escape fraction/line width, based on geometric quantity N_o
- Astronomy Results
  - Large boost of Ly-alpha equivalent widths in multi-phase, dusty medium
  - Multi-phase outflow: asymmetric line profile, line width ~ (several) x flow speed

Many future applications possible....