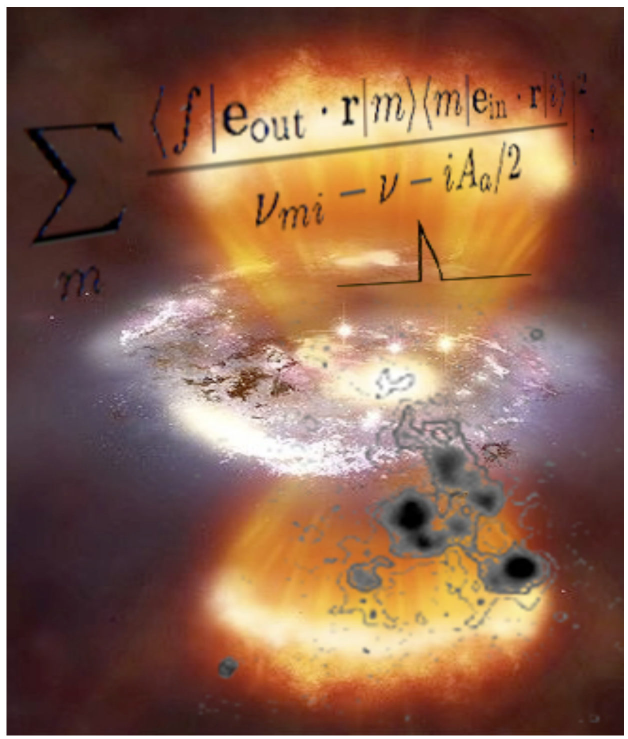
Mark Dijkstra, Austin, March 2010

Seeing Through the Trough: Detecting Lyman Alpha from Early Generations of Galaxies ‘

Mark Dijkstra (ITC)
collaborators: Stuart Wyithe, Avi Loeb, Adam Lidz, Zoltan Haiman



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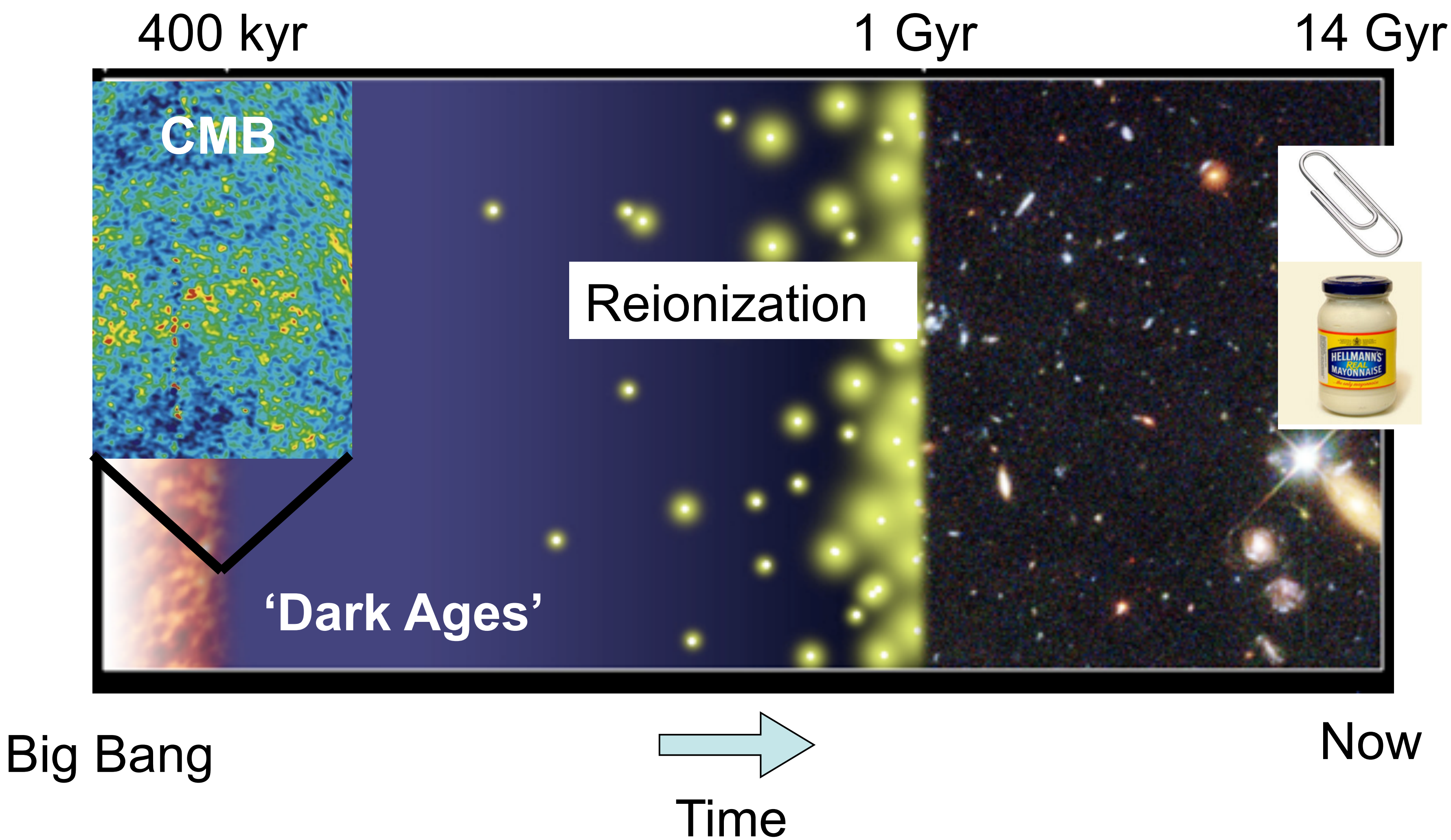
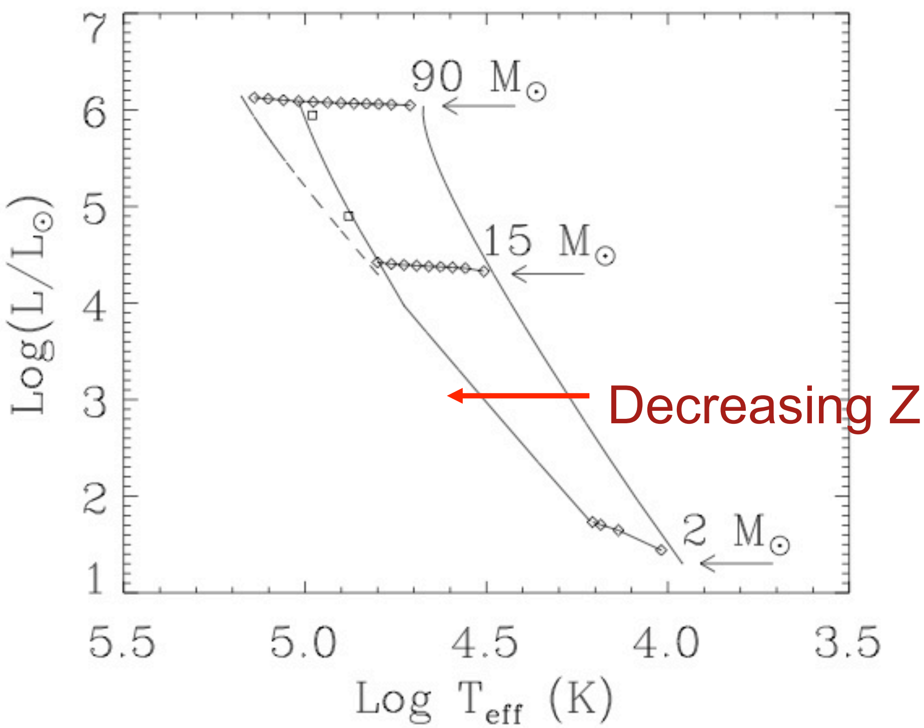
Schematic History of the Universe



Lyα From 'First' Galaxies

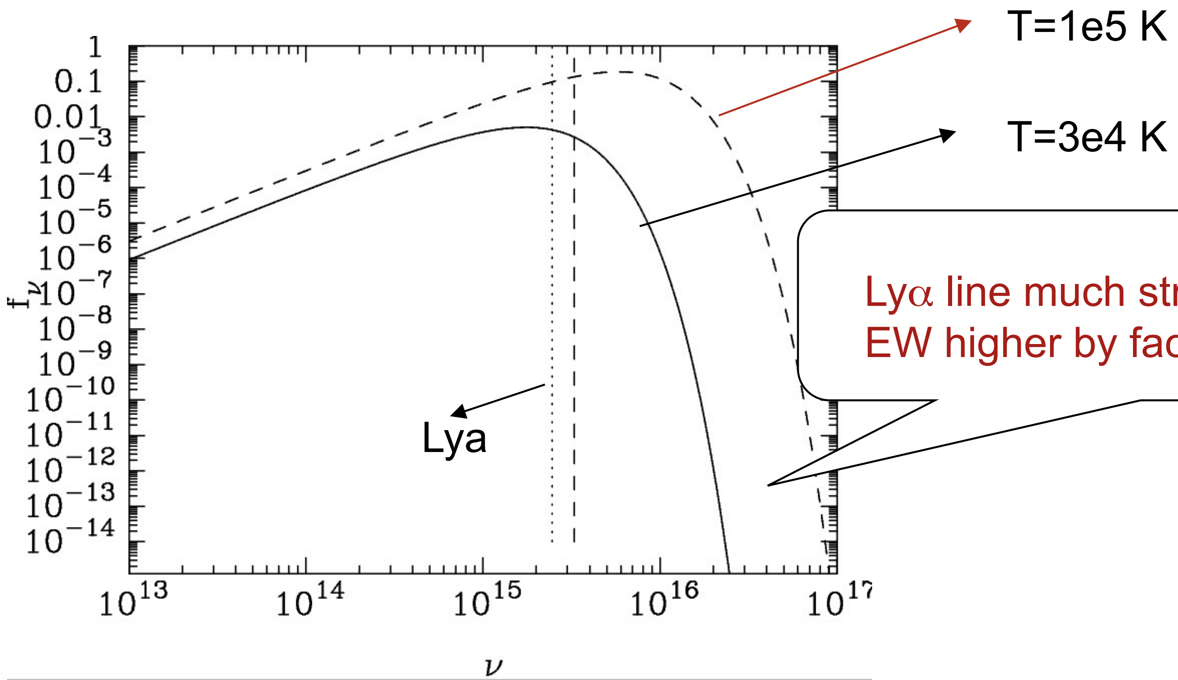
- First generation of galaxies: lower metallicity=hotter stars.



Tumlinson & Shull `00

Lyα From First Galaxies

- Hotter stars produce more ionizing radiation-> Stronger nebular emission from HII regions around hotter stars.
- ~0.6-0.7 Lya photons / recombination-> more Lyα



Lyα line much stronger at higher z, EW higher by factor of ~ 15:

Lyα From First Galaxies

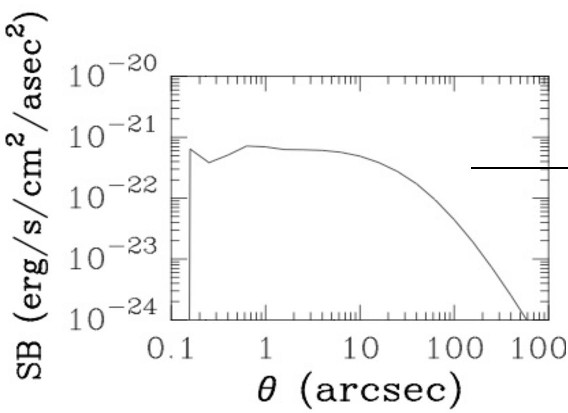
- Lyα line emission most robust predicted spectral feature of first generation of galaxies (e.g. TS00, Bromm+01,Schaerer ‘02,’03, Johnson+09).
- EW~1500 A (restframe).
- Lyα luminosity ~ 20% of bolometric luminosity.
- Hα flux lower by factor of ~ 8 (deeper in IR).
- HeII Hα (λ= 1640 A) flux can be comparable to HI Hα, but this depends sensitively on stellar initial mass function (Johnson+09).
- Can we detect Lyα line?

Lyα From First Galaxies

- Can we detect Lyα line?
- First galaxies surrounded by neutral intergalactic medium. Optical depth to Lya is ~ Gunn-Peterson (GP) optical depth.

$$\tau_{\rm GP,0} \approx 7.30 \times 10^5 x_{\rm HI} \left(\frac{1+z}{10}\right)^{3/2}$$

- Note: observed flux not suppressed by exp(-τ_{GP}), instead Lya scatters and observable is large (angular radius ~10-20") faint halos (Loeb & Rybicki '99):



→ SB < 1e-21(L_α/1e43 erg/s) erg/s/cm^2/arcsec^2

No.

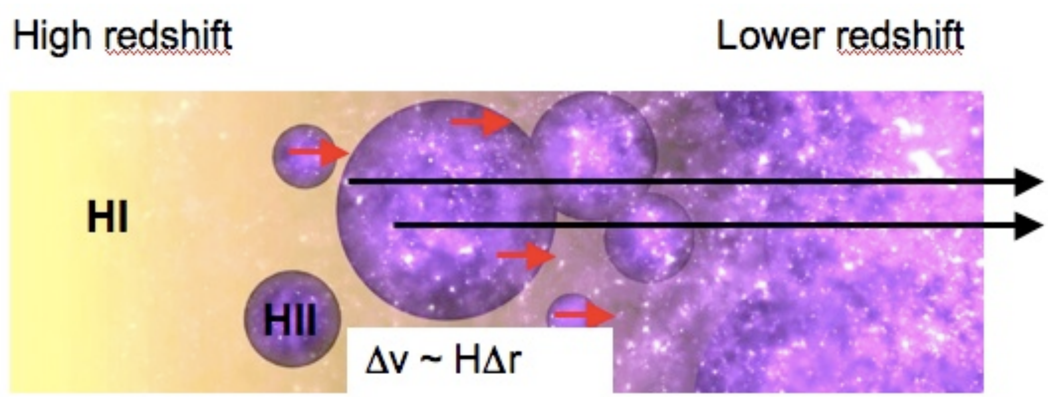
Lyα From the First Galaxies

- But….GP optical depth reduces quickly with wavelength:

$$\tau_{\rm GP}(\Delta v) \approx 2.3\Big(\frac{\Delta v}{600\ {\rm km\ s^{-1}}}\Big)^{-1}\Big(\frac{1+z}{10}\Big)^{3/2}$$

- The GP-optical depth is smaller for photons that first enter neutral intergalactic medium with some velocity off-set Δv (redward of line center).

- This is why Lya may be detected from galaxies that reside in large HII regions during later stages of the EoR, and why Lya emitting galaxies probe the EoR.



Lyα From the First Galaxies

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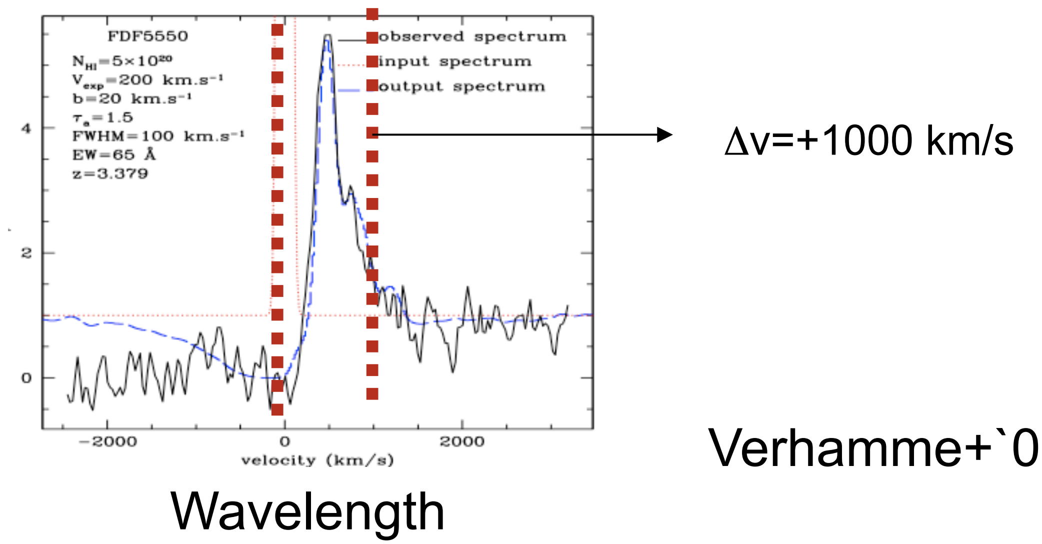
$$\tau_{\rm GP}(\Delta v) \approx 2.3\Big(\frac{\Delta v}{600\ {\rm km\ s^{-1}}}\Big)^{-1}\Big(\frac{1+z}{10}\Big)^{3/2}$$

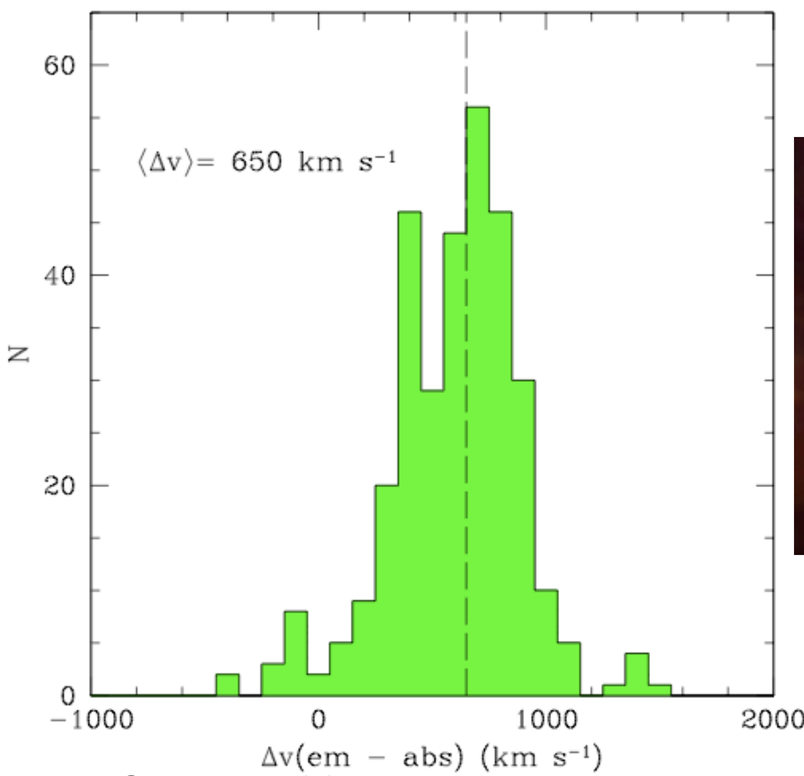
- We know observationally that Lya emission lines are asymmetric, and--**most importantly**-- can contain flux at Δv >> 500 km/s.



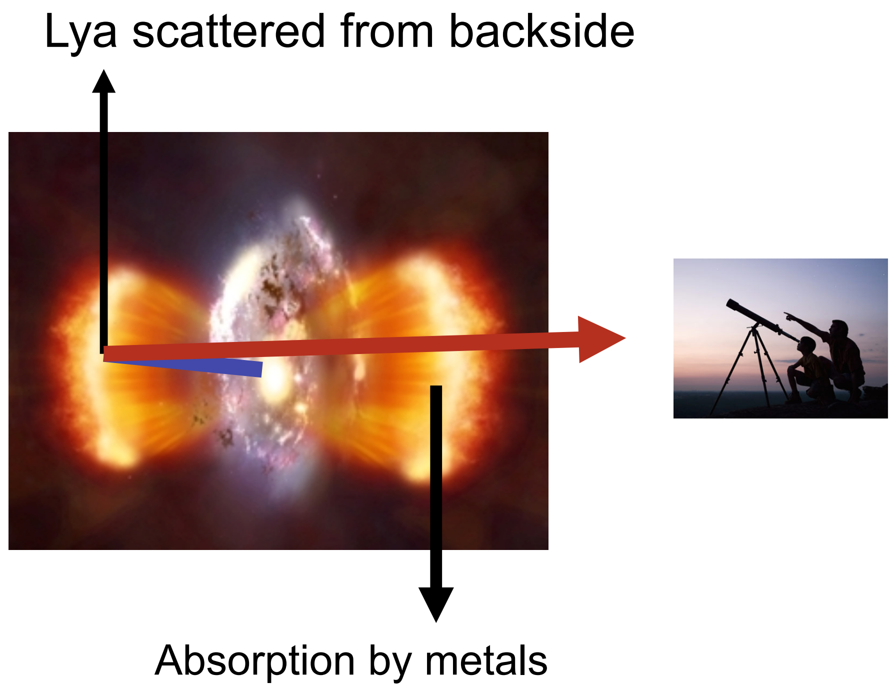
Verhamme+`08

Lyα From the First Galaxies

- Off set attributed to outflowing winds. Winds appear present in *all* galaxies (e.g. Steidel+10, arxiv 1003.).

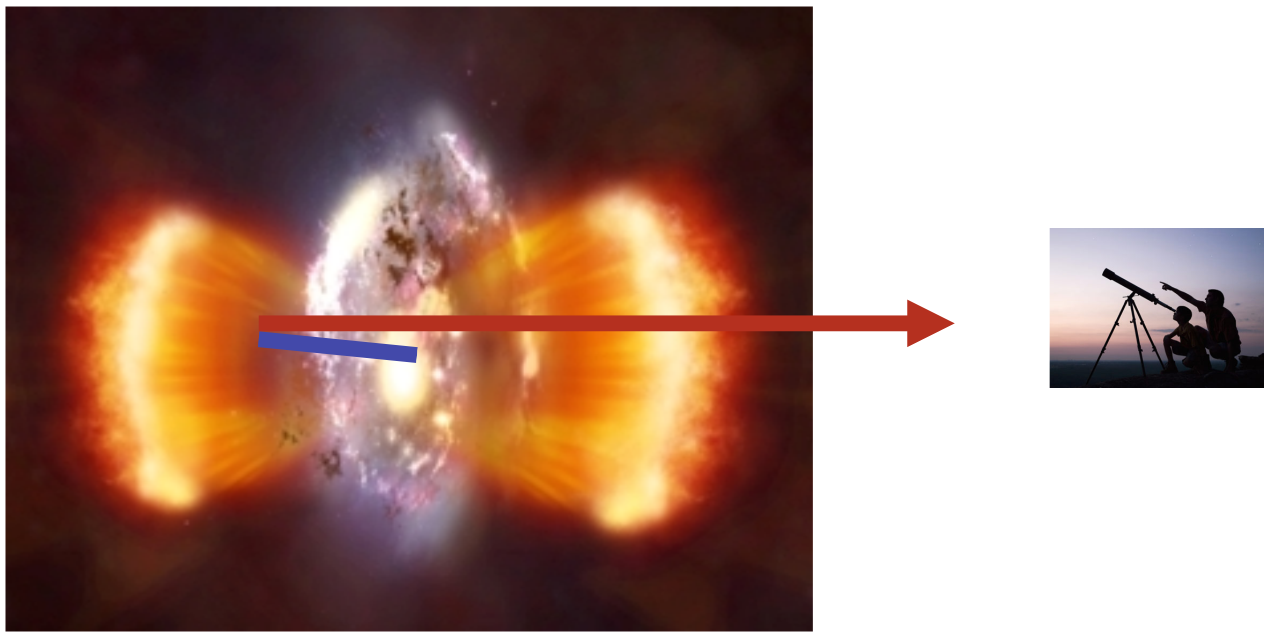


Shapley+03



Lyα From the First Galaxies

- Off set attributed to outflowing winds. Winds appear present in *all* high-z galaxies (e.g. Steidel+10, arxiv 1003.0679). Outflows Doppler boost Lya photons out of resonance, and as a result, escapes more easily.



- Observations of *local starburst galaxies* indicate that Lya escape fraction strongly regulated by outflows (more so than dust!, Kunth+98, Atek+08).

Lyα From the First Galaxies

- Lya line shape in observed galaxies (z=0-5) can be reproduced using spherical shells of outflowing HI gas, with column density N_{HI} and outflow speed v_{shell} .
(see Verhamme+08,Schaerer & Verhamme+08,Vanzella+10.)

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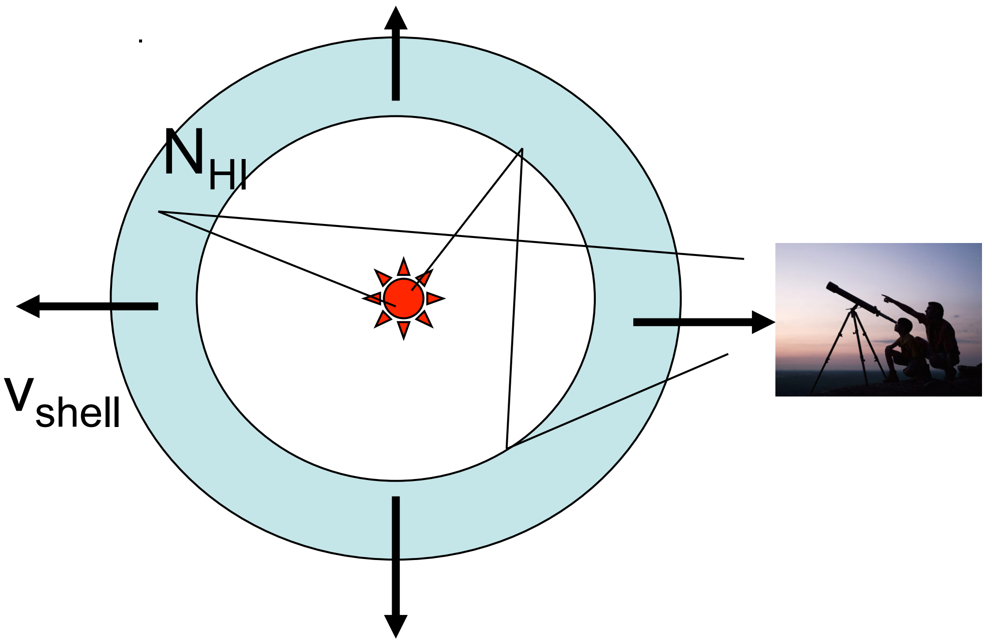
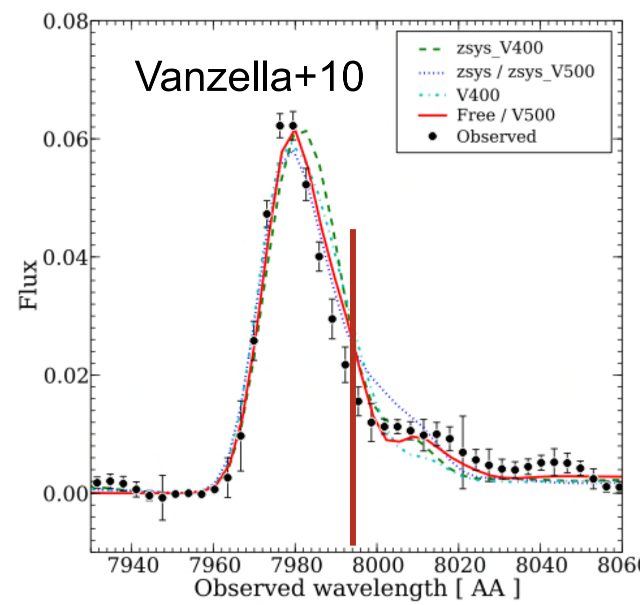




'Backscattering' transforms originally Gaussian emission line into a redshifted (few hundred km/s) Lya emission line. There can be flux at |v|> 1000 km/s.

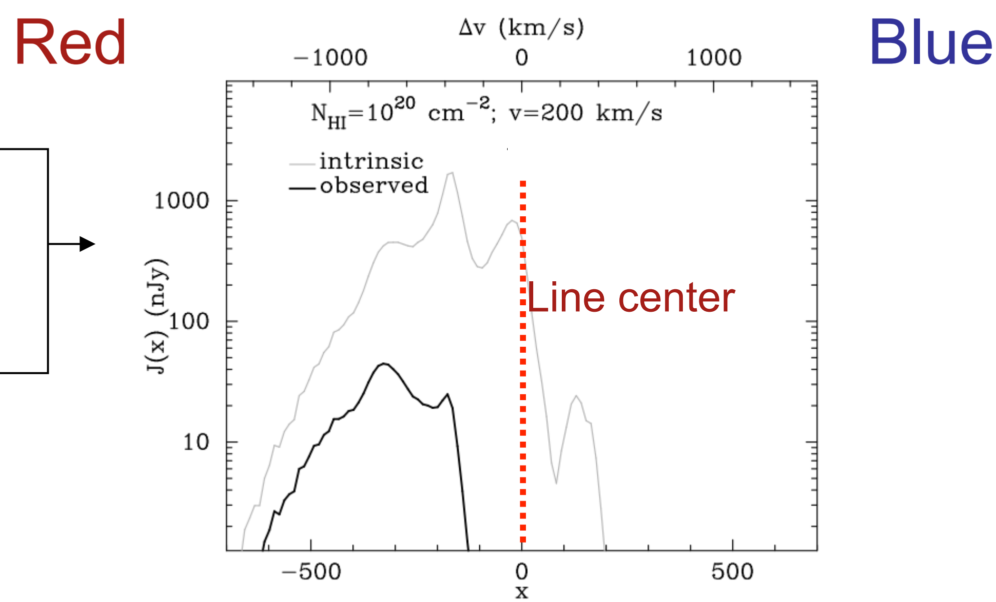
Lyα From the First Galaxies

- Observations at z<6 typically require log N_{HI} = 19-22 and v_{shell}=0-500 km/s (Verhamme+08).
- Compute Lya spectrum emerging from Lya source surrounded by spherical shell with column density log N_{HI} = 20-21 and outflow speed v_{shell}=0-200 km/s. We used the MC RT code 'McHammer' (D et al '06). Assume no dust.
- Compute what fraction is transmitted through neutral IGM.

Example:

z=10, v_{shell}=200 km/s,

log N_{HI} = 20



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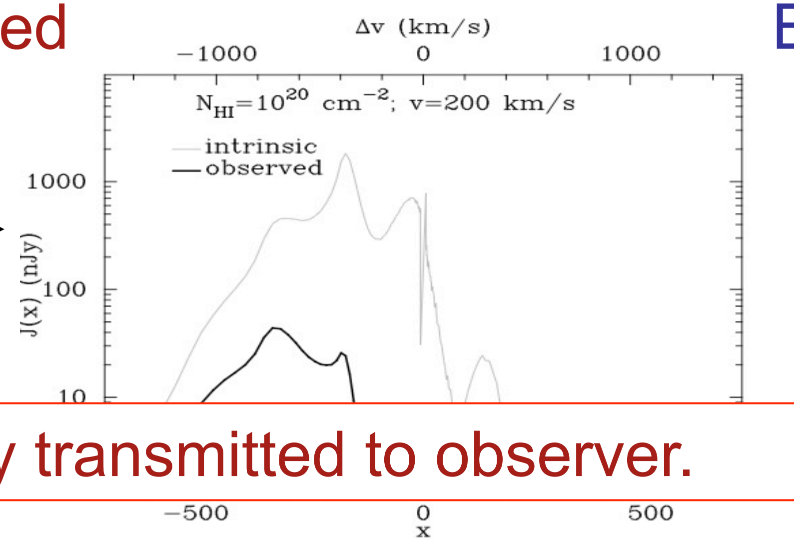
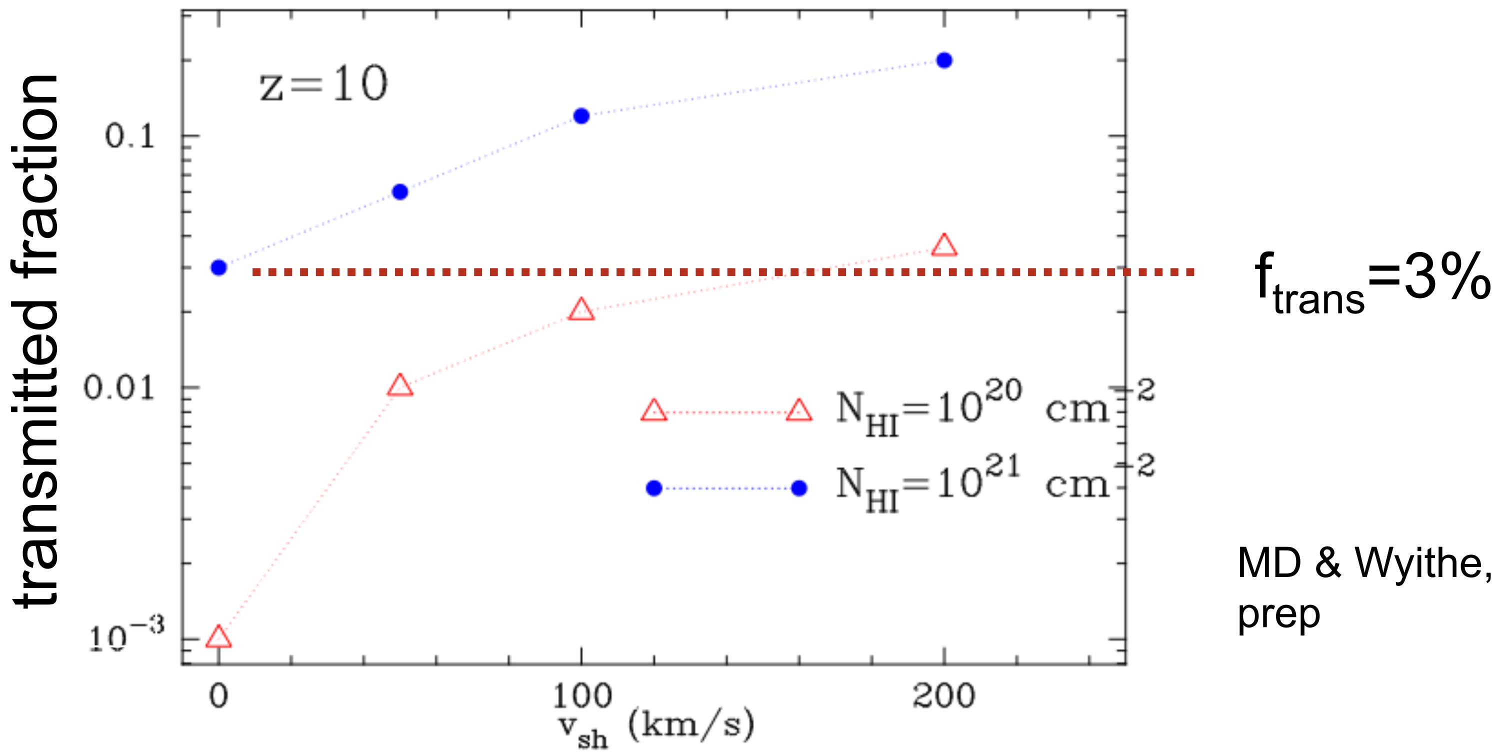


4% directly transmitted to observer.

Lyα From the First Galaxies

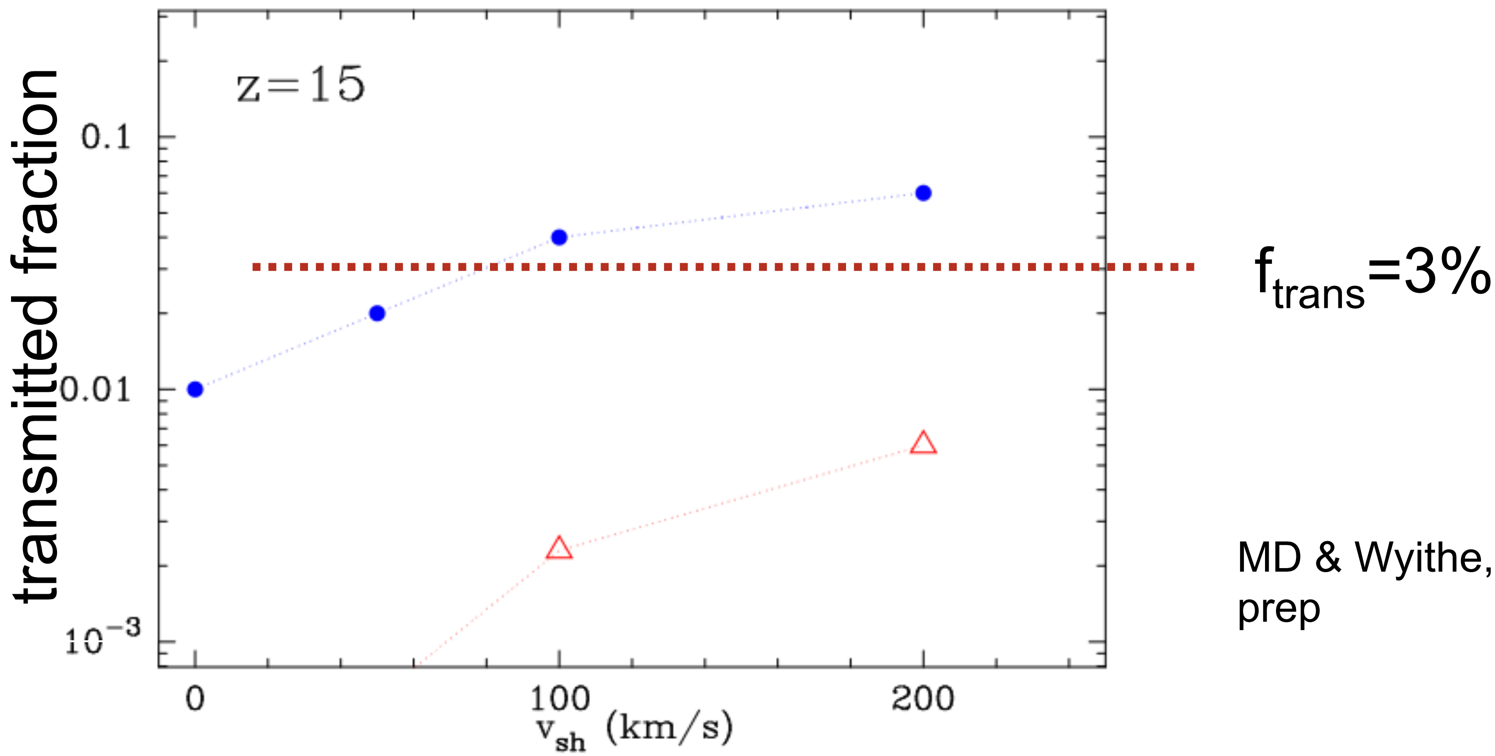
- Directly transmitted fraction f_{trans} as a function of N_{HI} and v_{shell} . .



MD & Wyithe, in prep

Lyα From the First Galaxies

- Consider a suite of models with different N_{HI} and $v_{shell.}$



MD & Wyithe, in prep

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Lyα From the First Galaxies

- It may be possible to directly transmit f_{trans}> 3% of Lyα flux directly to observer **through fully neutral IGM** at z=10-15 (without HII `bubbles'!).

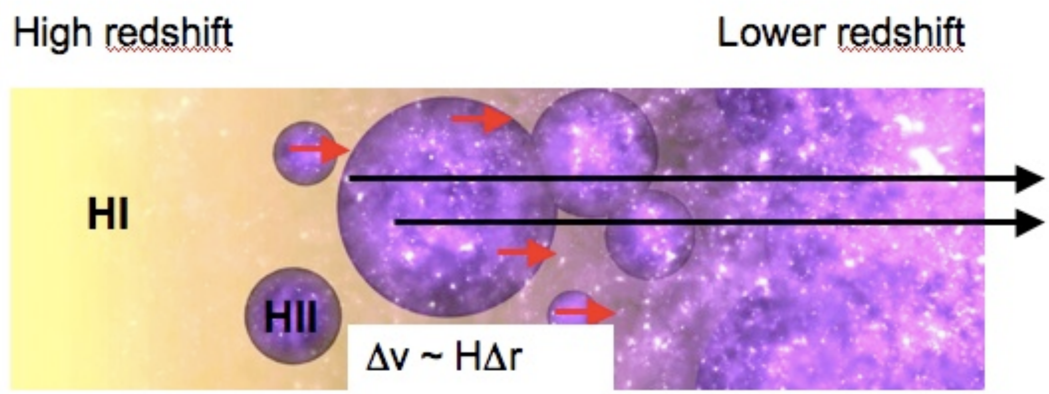
- Translates to observed restframe EW~45(f_{trans}/0.03)(EW_{int}/1500) A -> Strong LAEs.

- Lyα provides opportunity for spectroscopic confirmation.

  – E.g. SFR~ 1M_{sun} /yr, -> Lya luminosity ~1e43 erg/s. The flux at z=10 S~2e-19(f_{trans}/0.03) erg/s/cm^2 , while continuum flux density at ~ 1216+ is ~ 3 nJy.
  – Line flux: NIRSPEC, R=1000, integration time 1e5 s, S/N ~3
  – Continuum NIRCAM wide filter, same integration time, S/N~2.

LAEs During (and after) the EoR

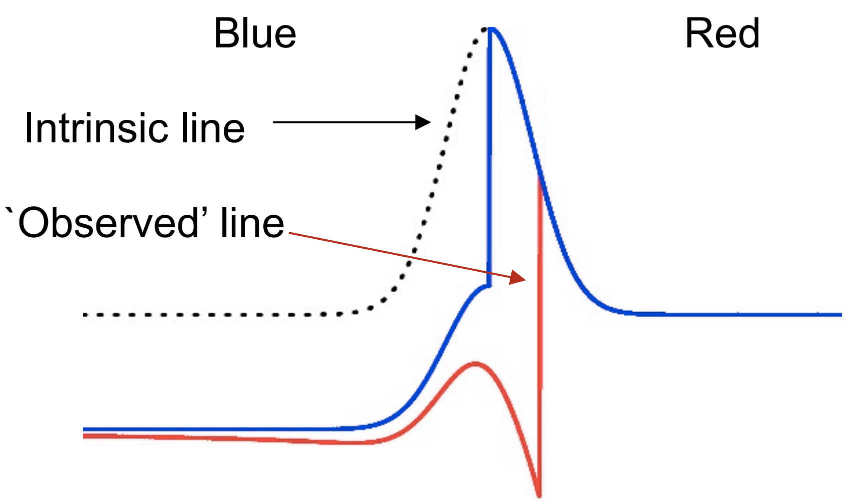
- Outflows affect the detectability of LAEs during and even after reionization.

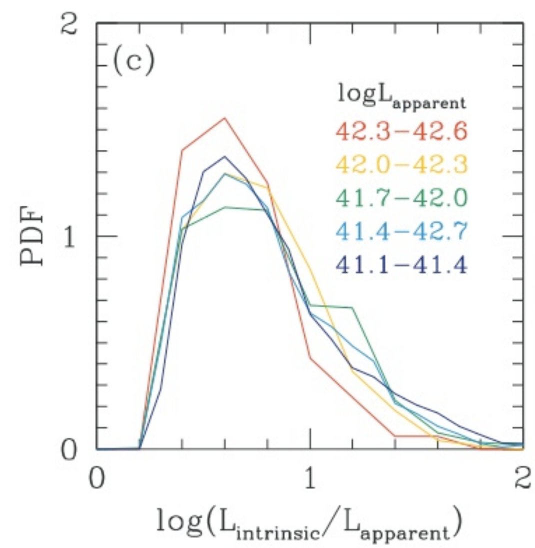


- Without outflows, even **the ionized IGM** can be quite opaque to Lya.

The Opacity of Ionized IGM to Lyα photons.

- Infall of denser intergalactic gas ($r>r_{vir}$) onto massive DM halos can strongly suppress observed Lya flux.

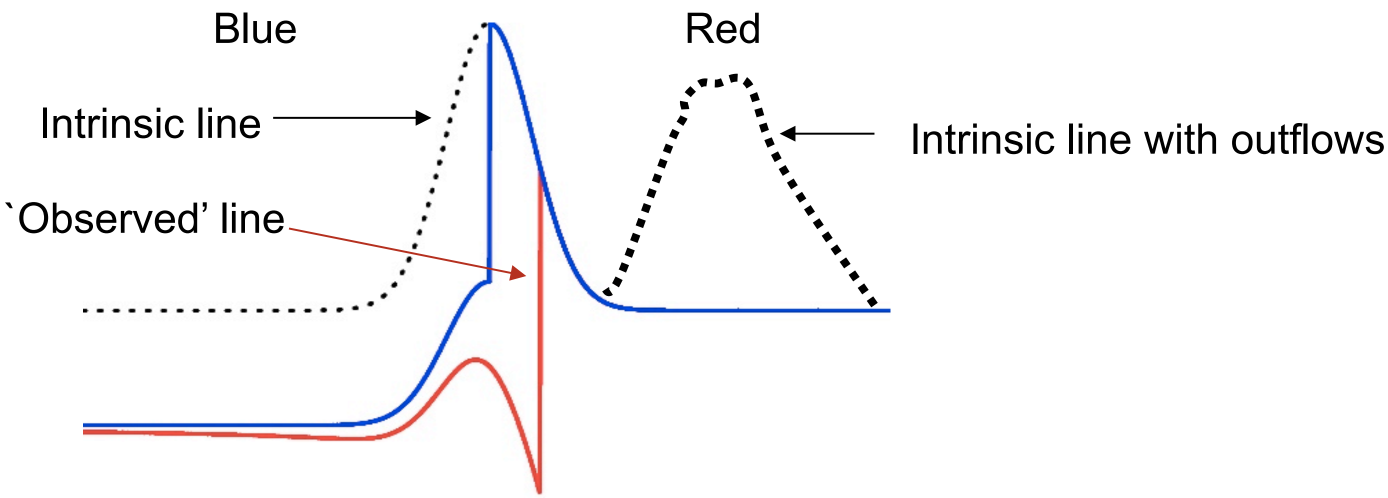




- IGM transmits 10-30% of emitted flux (D, Lidz & Wyithe +07, also see Iliev+08, Dayal+10, Zheng+10).

The Opacity of Ionized IGM to Lyα photons.

- Outflows shift `intrinsic’ line to frequencies where ionized IGM has smaller impact.



- I.e. because of outflows in ISM, subsequent transfer in IGM is uncertain.

What do LAEs Presently say on the EoR?

- Observed number density of LAEs drops suddenly beyond z=6?

Cum. Number density

Log (Lya Luminosity)

- 89 LAEs observed at z=5.7 (Shimasaku+06, blue squares),
- 57 LAEs observed at z=6.5 (Kashikawa+06, red circles)

Restframe UV LF remains constant!

What do LAEs Presently say on the EoR?

- Why does observed number density of LAEs drops suddenly beyond z=6?

Cum. Number density

Log (Lya Luminosity)

- For galaxies of a given restframe UV flux density, their corresponding measured Lya flux from galaxies at z=6.5 is lower than at z=5.7 (Kashikawa+06).
- Additional opacity in IGM at z=6.5 provides natural explanation. Opacity evolution may be attributed to re yithe '07).

To be continued…..

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Conclusions

- The first galaxies were strong Lyα emitters (LAEs). Restframe EW~ 1500 A. Lyα luminosity can be 20% of bolometric luminosity.
- Outflows may cause a few percent or more of the emitted Lyα radiation can be observed from galaxies at z>>6 to be detected *even through a fully neutral IGM*.
- Only a few per cent transmission may facilitate the detection/spectroscopic confirmation of z >> 6 galaxies.
- Understanding outflows and their impact on Lya is crucial when assessing the impact of IGM (as well as of dust) on Lya emission line.
- Lya line shape alone not enough to observationally constrain outflow properties. Polarization provides additional constraints (D & Loeb ‘08, Ahn & Lee ‘98).

Appendix

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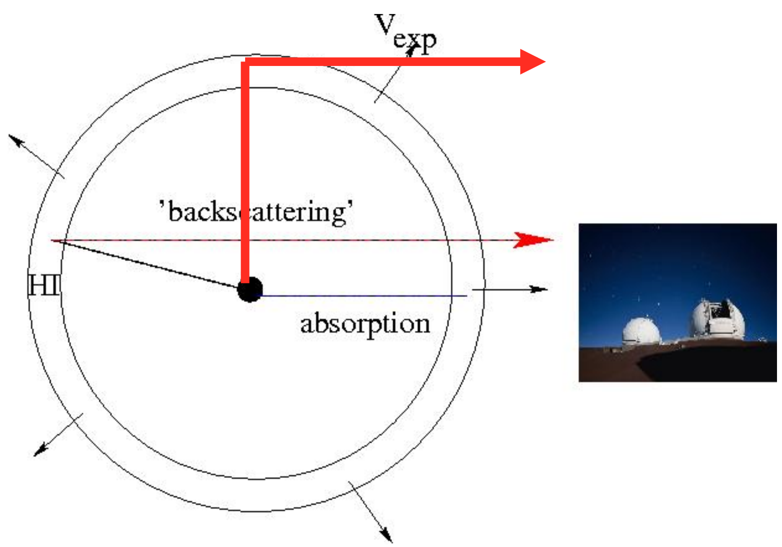
III: Polarization of Scattered Lya

- Scattered photons can appear polarized to an observer (electric vectors of photons have some preferred directions).
- Consider photon whose path is indicated with



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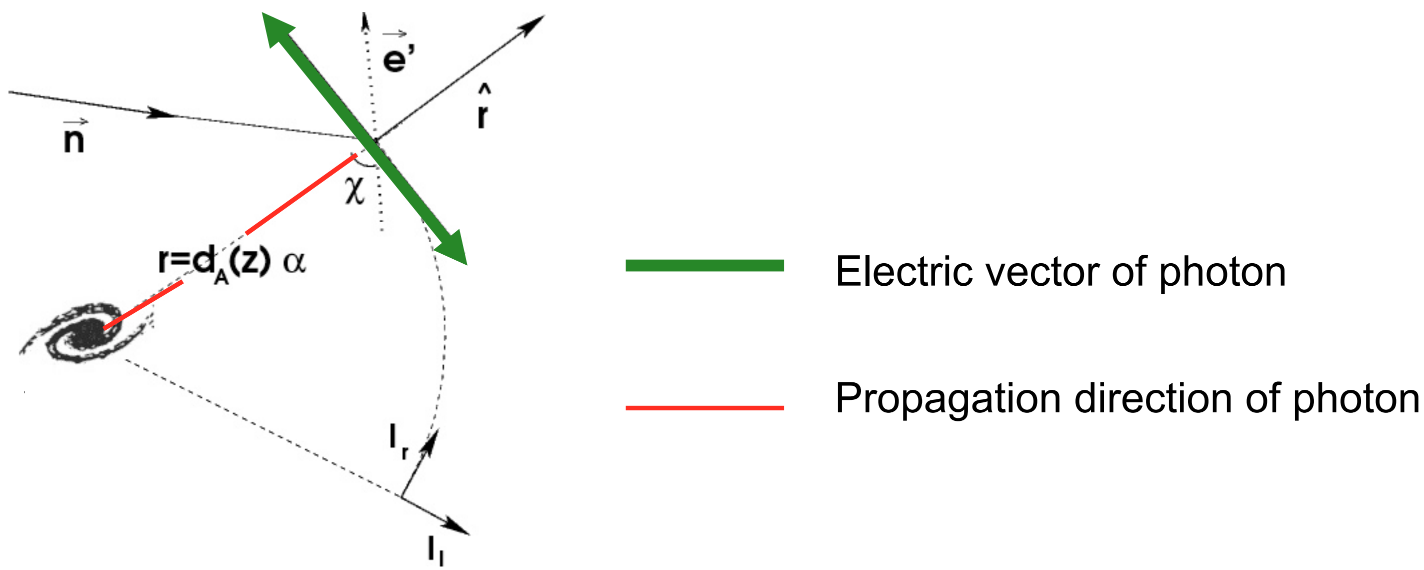


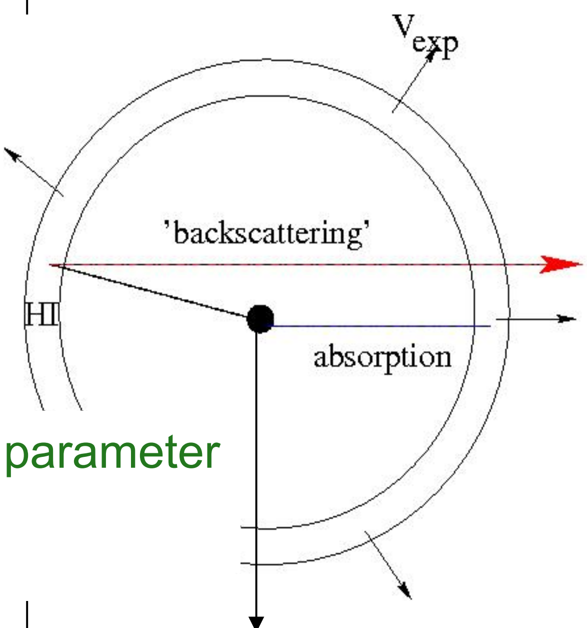
- Lya scattering can in practise be described accurately by Rayleigh scattering, for which scattering by θ deg, results in $100[\sin^2\theta/(1+\cos^2\theta)]$ % polarization.

III: Polarization of Scattered Lya

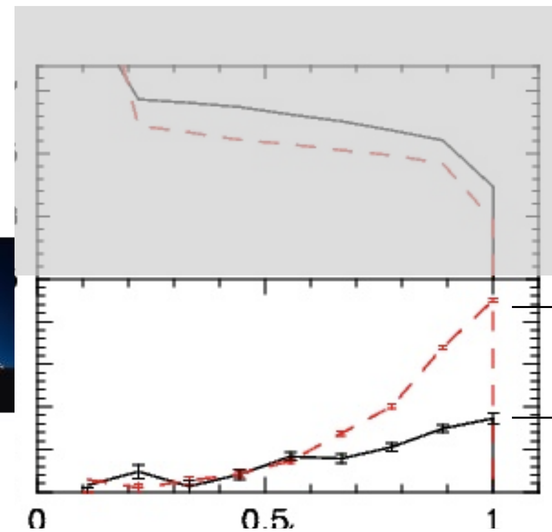
- Compute polarization of backscattered Lya radiation using a Monte-Carlo radiative transfer code (D & Loeb '08, also see Lee & Ahn '98). In this code:
  - the trajectories of individual photons are simulated as they scatter off H atoms (microphysics of scattering is accurate)
  - can attach a polarization vector to each photon, and
  - compute observed quantities such as the Lya spectrum, surface brightness profile, and the polarization
- Polarization quantified as $P=|I_l-I_r|/(I_l+I_r)$. Single photon contributes $\cos^2\chi$ to I_l and $\sin^2\chi$ to I_r (Rybicki & Loeb 99).
- Apply Monte-Carlo code to a central Lya emitting source, completely surrounded by a thin, single, expanding shell of HI gas (as in Verhamme+06,08). Free parameters are N_{HI} and v_{exp}.

III: Polarization of Scattered Lya

- Lya can reach high levels of polarization (~40%, D & Loeb '08)



Impact parameter



45%

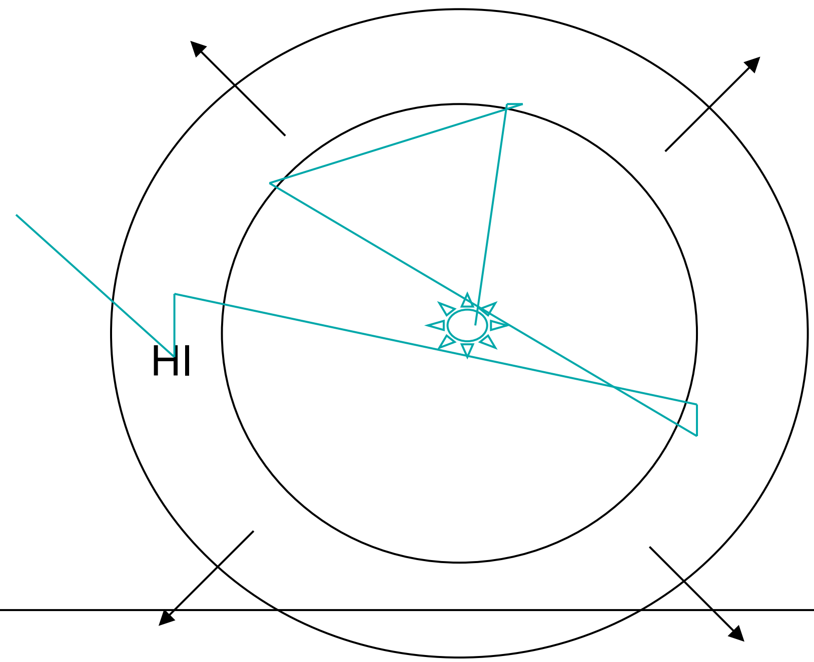
18%

Impact parameter

- Polarization depends on N_{HI} and v_{sh}, and therefore provides additional constraints on scattering medium (frequency dependence of polarization also constrains sign of v_{sh} , see D & Loeb '08).

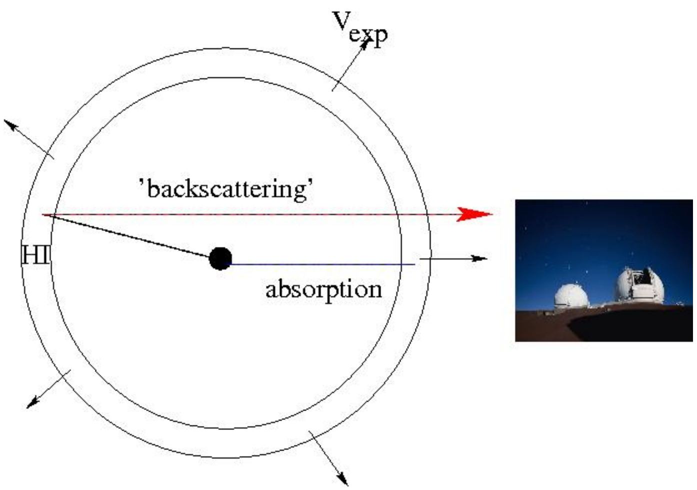
Discussion.

- This mechanism is affected by dust, but not eliminated.
  - Photons that are most effectively trapped interior to the shell scatter mostly on the surface and 'see' little dust.

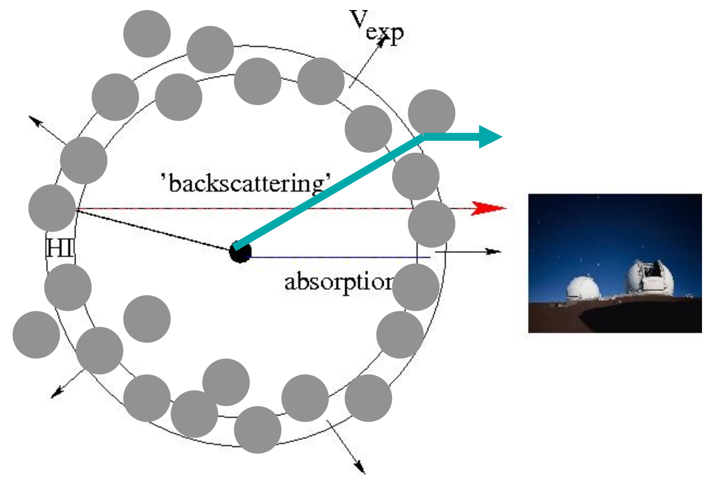


Discussion.

- This mechanism is affected when the covering factor of HI gas is << 100% and/or by clumpiness of the outflow



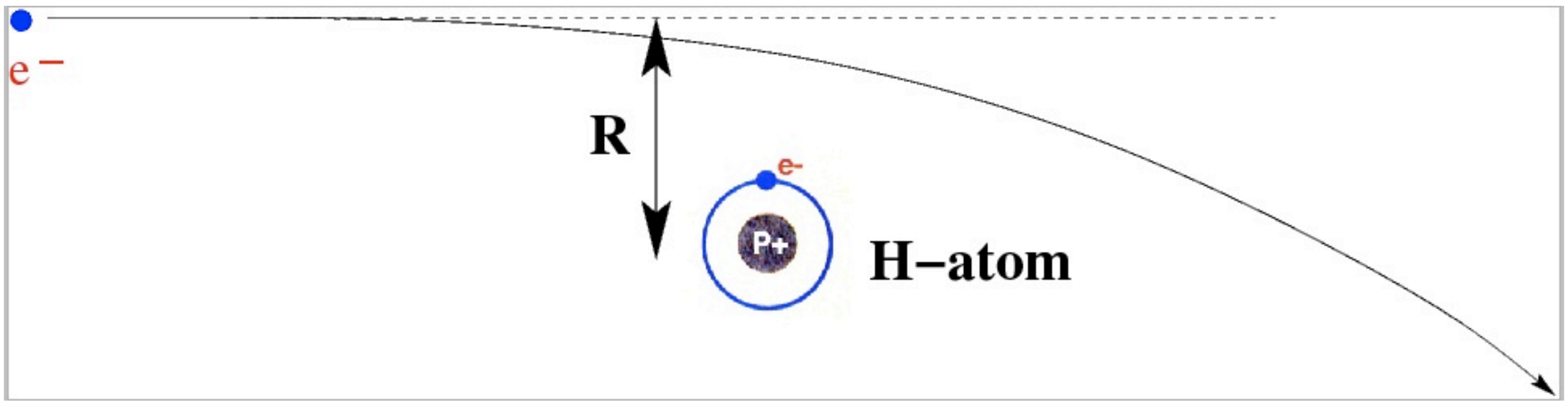
VS



Detailed structure of outflow determines how much our results are affected.

Introduction: Lyα from Collisions

- Lyα: n=2->n=1 (groundstate) transition of atomic hydrogen λ=1216 A; ΔE = 10.2 eV ~1e5 K.
- Collisional excitation following `impact' by electron.



- Collisional excitation rate depends on n_e, n_{HI}, and T, and must be computed quantum mechanically (e.g. Scholz+91, Aggarwal+91)
- Very important in partially neutral gas (> 1 part neutral in 10^3 !) at T > 1e4 K.

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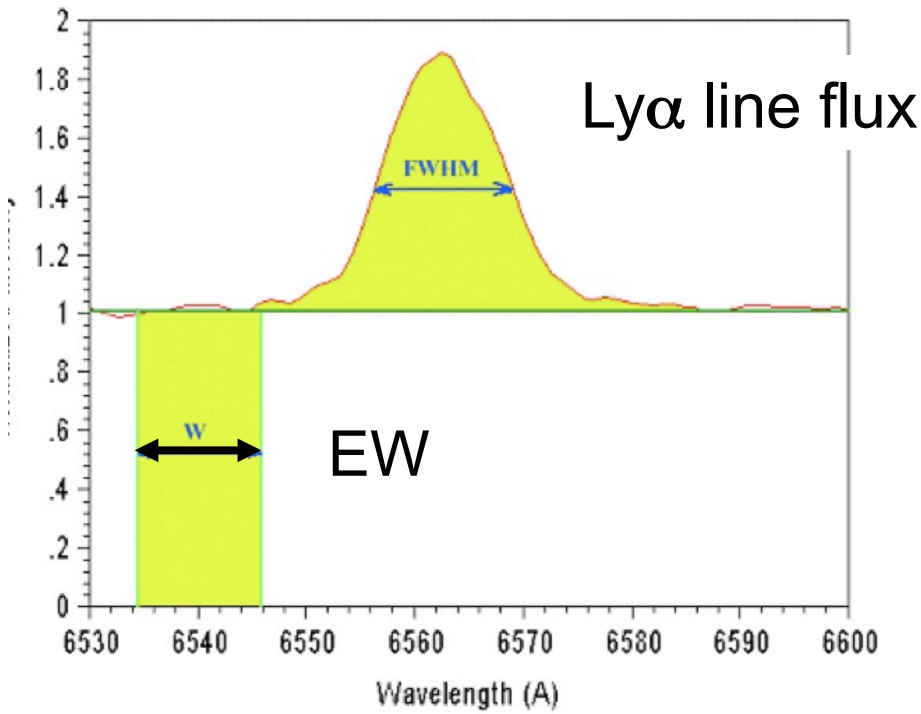
Introduction: Equivalent Width

Observationally, galaxy is ‘Lyman Alpha Emitter’ if restframe EW ≥ 20 A

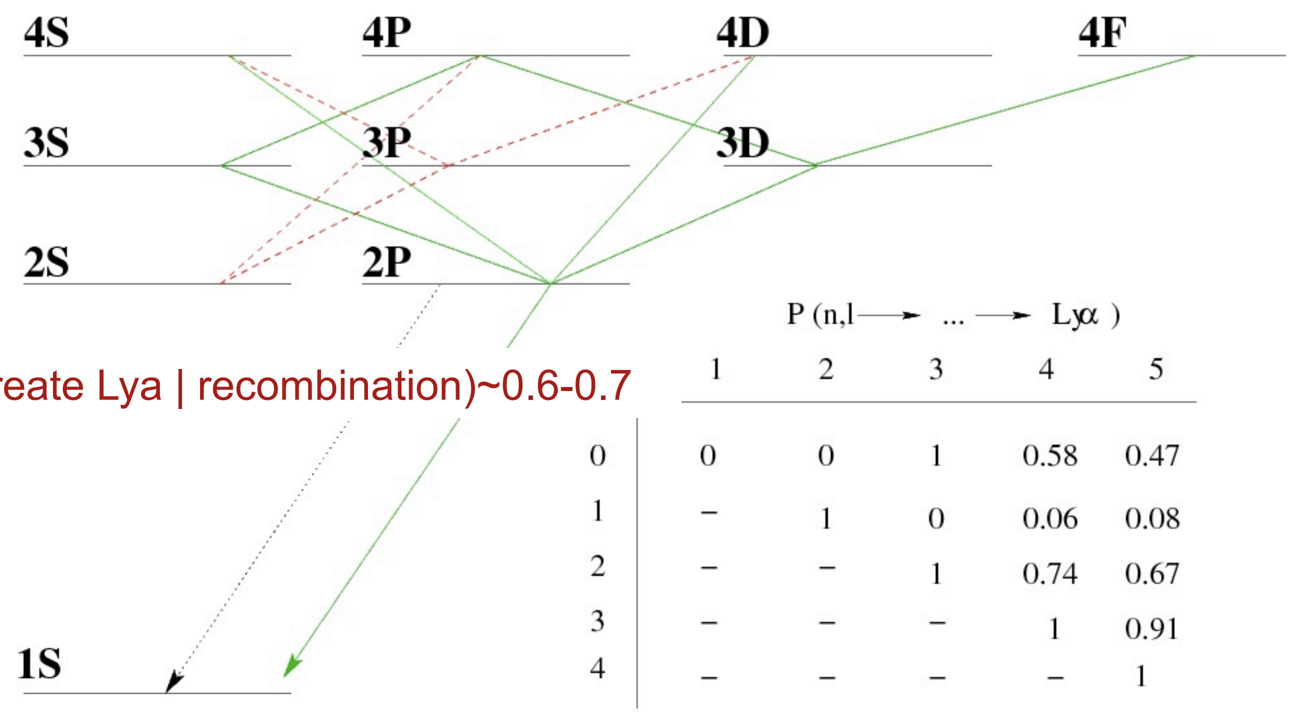


$EW \sim 0.5 * FWHM * f_{peak,\nu} / f_{con,\nu}$.

FWHM ~ 1-2 A, EW~ 20-400 A. Line flux density ~ 10 -100 cont. flux density

Introduction: Lyα from recombination.

- Radiative cascades following recombination into H level n,l



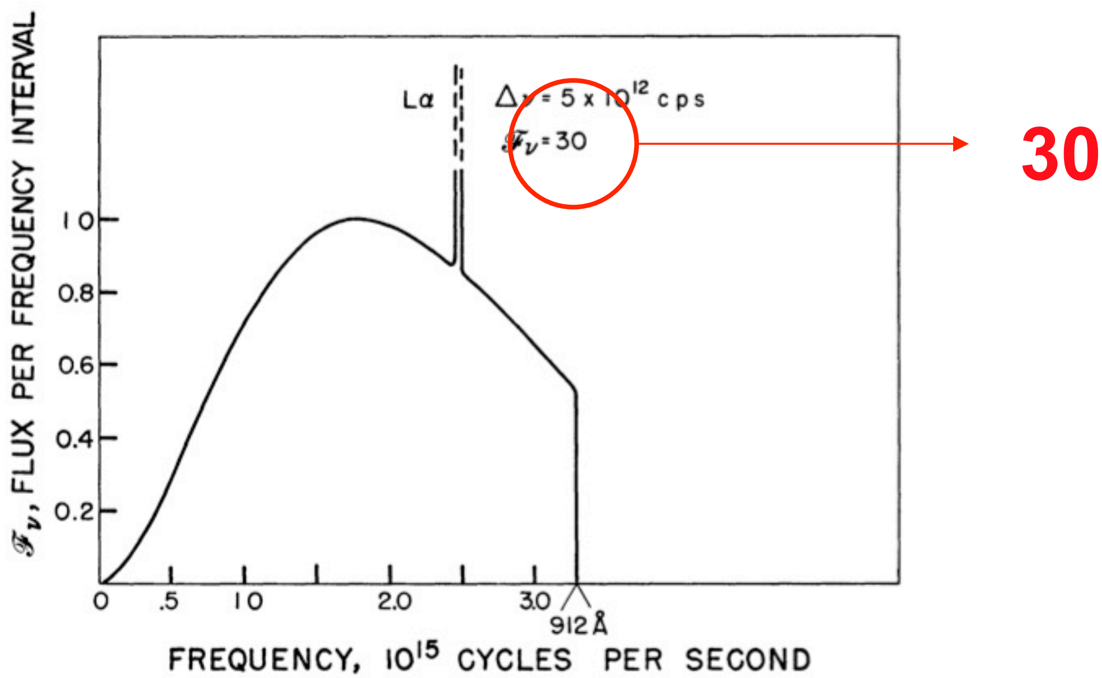
P(create Lya | recombination)~0.6-0.7

P (n,l ⟶ ... ⟶ Lyα)

	1	2	3	4	5
0	0	0	1	0.58	0.47
1	–	1	0	0.06	0.08
2	–	–	1	0.74	0.67
3	–	–	–	1	0.91
4	–	–	–	–	1

Introduction: Lyα from recombination..

- Star forming galaxies can emit a substantial fraction (~10%) of their bolometric luminosity in the Lyman Alpha line.

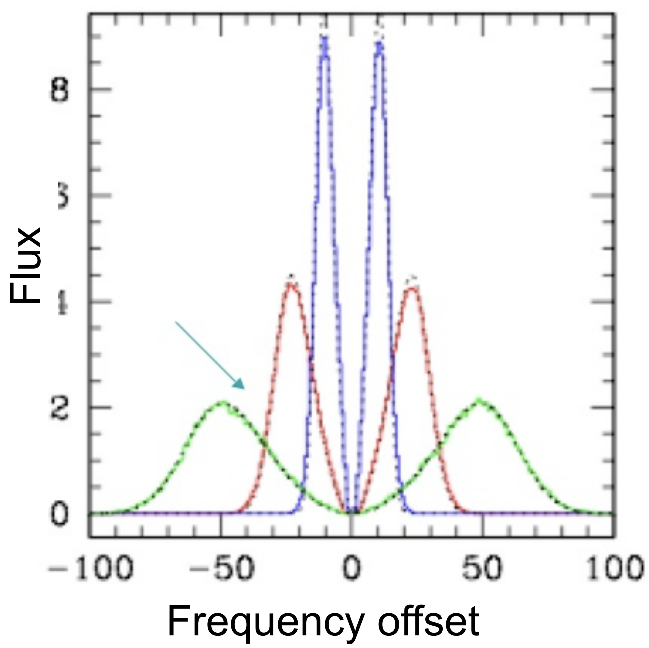


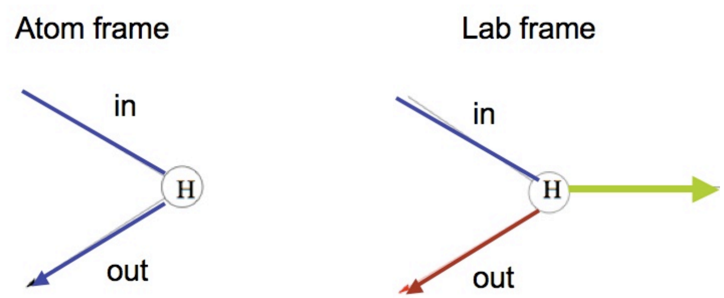
Partridge & Peebles ‘67

Introduction: Radiative Transfer in 1 slide

- Following absorption -reemission occurs instantly -> 'scattering'.

- As Lyα scatters through real space, it diffuses in frequency space. Further from line center, Lyα photons escape easier from very opaque media.

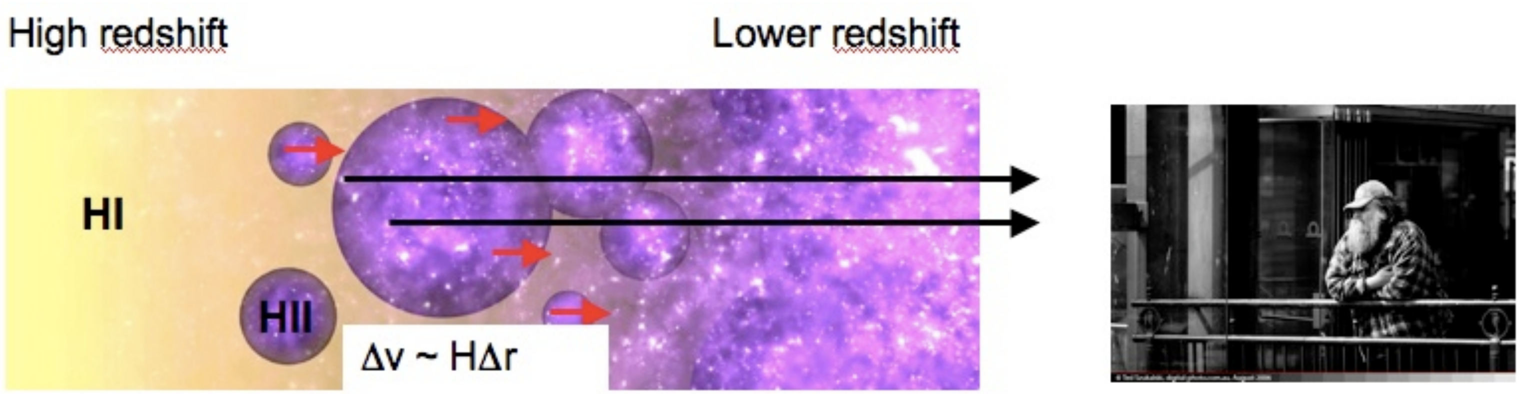




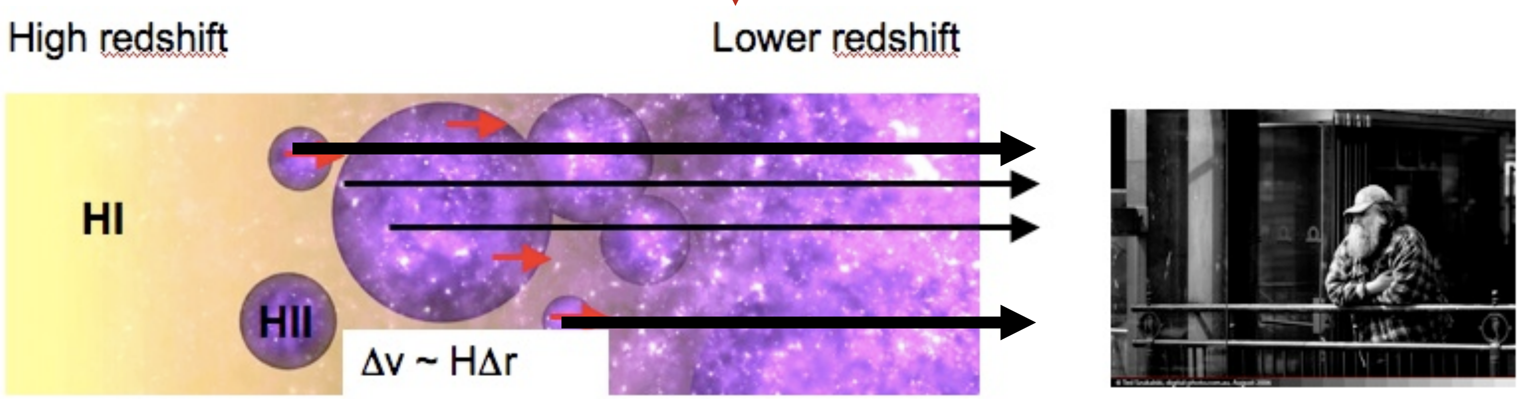
For uniform static slab/sphere

$\Delta v = \pm 160 (N_{HI}/1e20)^{1/3} (T/1e4)^{1/6}$ km/s

Lyα From the First Galaxies



HI Outflows



+ Δv_{int}

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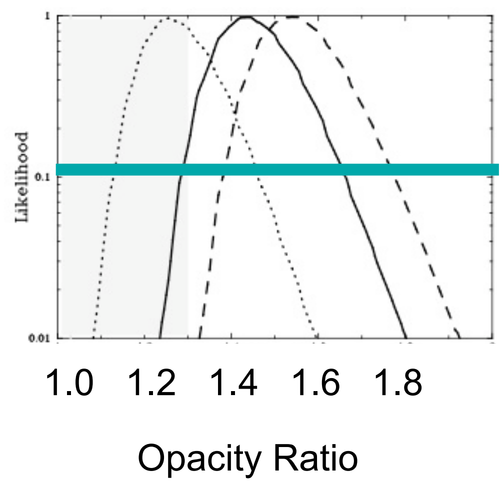
What do LAEs Presently Say About Reionization?

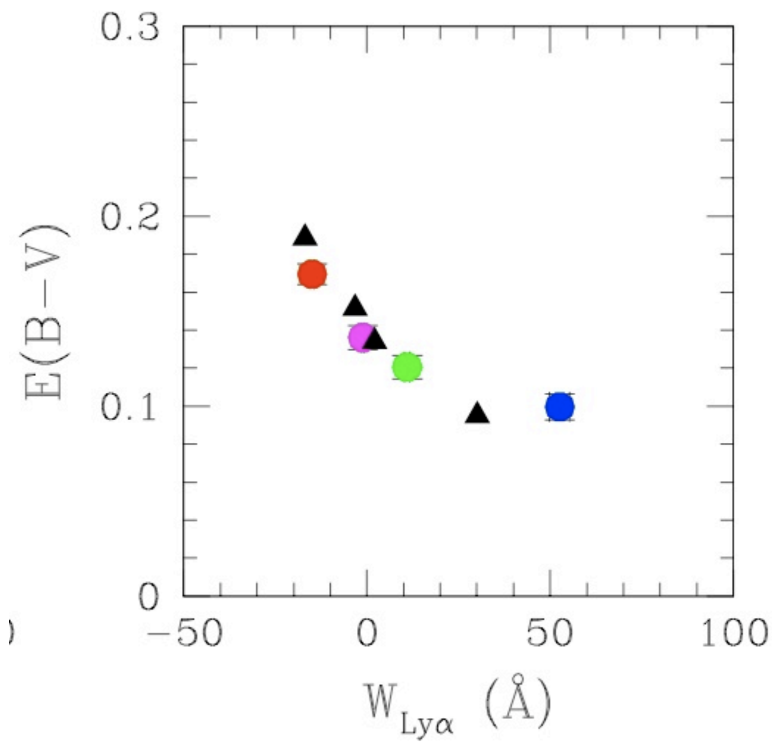
- Observations imply we receive ~ 10-80% (~95% CL) less Lya photons per restframe UV continuum photon from z=6.5 compared to z=5.7 (D, Wyithe & Haiman+07).
- Why?
  - Evolution in f_esc? (Because Llya ~ [1-fesc]).
  - Dust?
  - Both These effects involve a detailed understanding of galaxies at z
  - Less Lya is transmitted through IGM?



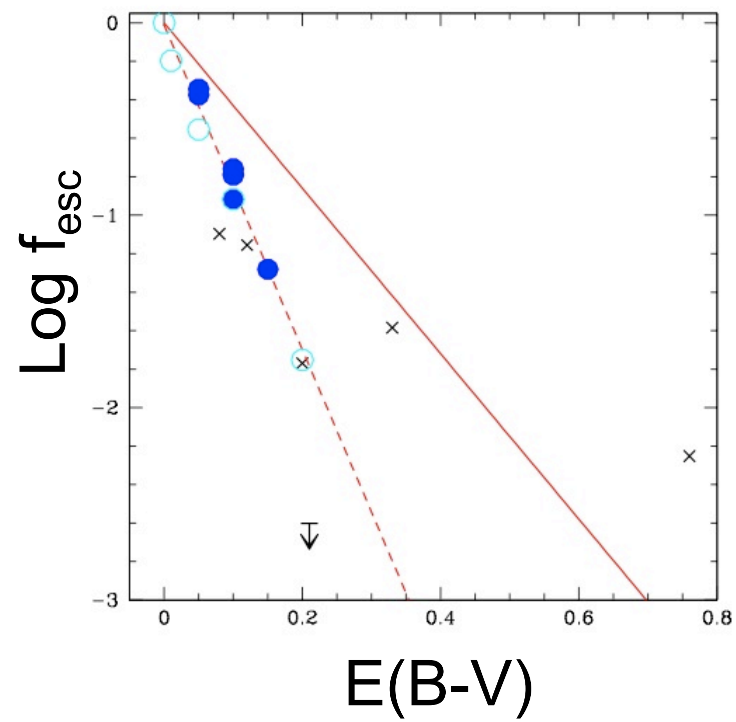
- Gas densities evolve as $(1+z)^3$; $n_{HI} \sim (1+z)^6$. (Re)Ionized gas can be significantly more opaque at z=6.5 than at z=5.7.
- But ionized IGM less relevant when winds are strong. Require neutral patches of IGM??

Dust.

- Dust quenches Lya flux from galaxies.



Shapley+03



Verhamme+08

Dust.

- But no one-to-one relation between dust content and Lya escape fraction.
- Dusty galaxies can be strong Lya emitters (Ono+10, arxiv 0911.2544).
- Blue galaxies can emit no Lya at all (Kunth+98).
  `We …find that the velocity structure of the neutral gas in these galaxies is the driving factor that determines the detectability of Lyalpha in emission.'
- Galaxies become bluer towar nuation is less important (Bouwens+10)