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GRBs in the early universe – probes of reionization

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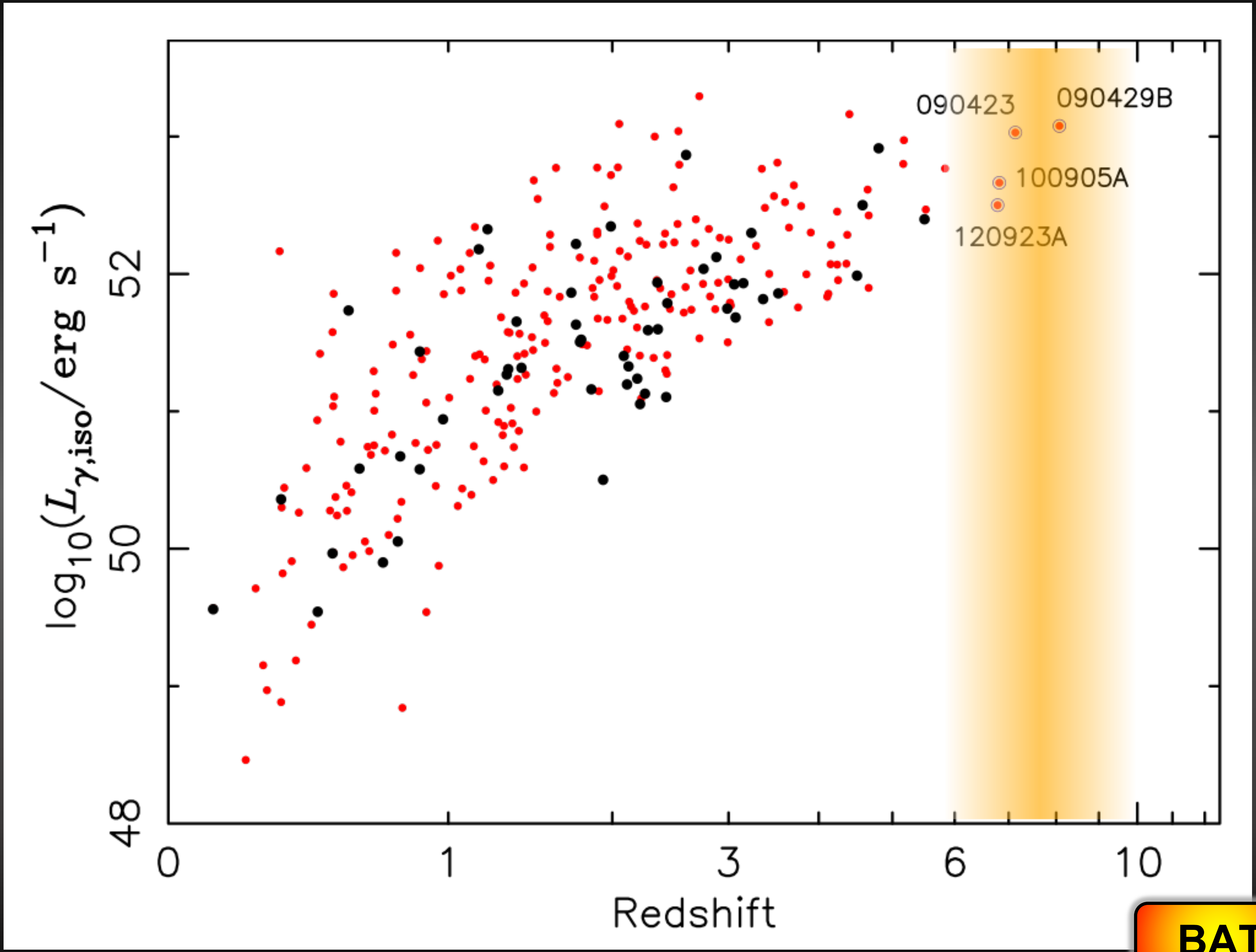
Swift GRBs span most of cosmic history

- Visible to very high redshift (detectable in wide-field gamma/X-ray monitors)
- Trace star formation
- Bright afterglow power-law spectra make ideal backlights.
- Only intrinsically brightest bursts detectable at high-*z* with current technology, so rather rare.



BAT

GRBs @ high-z

Thanks to this extreme brightness, provide powerful complementary probe of star formation and galaxy evolution in the era of reionization (and potentially beyond).

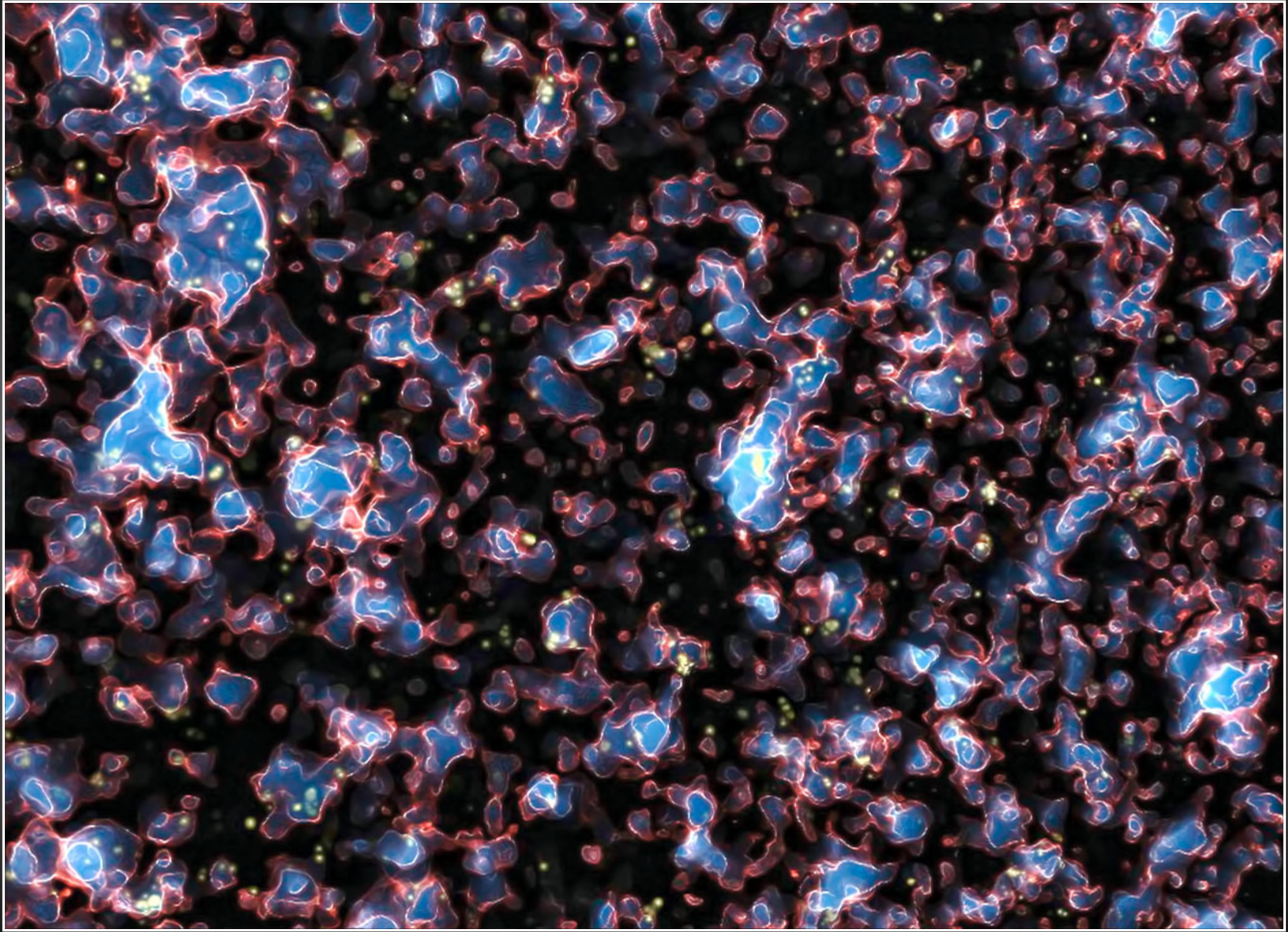
Some key issues:

- Star formation rate density at high redshifts
- Nature of primordial galaxies
- Escape fraction of ionizing radiation
- Timeline and topology of reionization
- Cosmic chemical evolution

Reionization of the intergalactic medium

The intergalactic medium went from being completely neutral to completely ionized, largely in the era between z=10 and z=6.

Assumed that ionized bubbles grow and ultimately fill whole of universe.



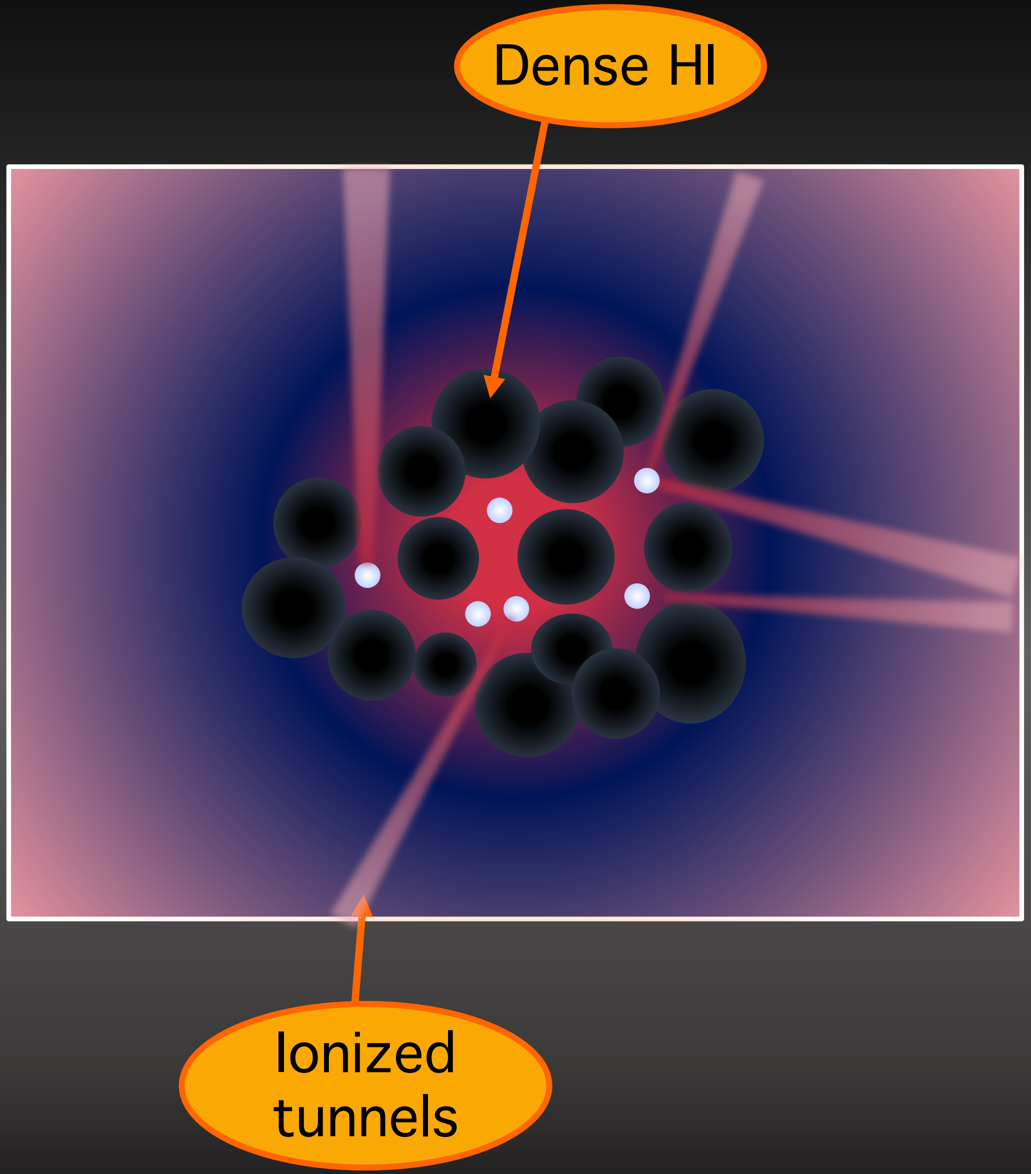
Ionizing escape fraction

To decide whether radiation from stars was largely responsible for reionization, we need to know at z~8:

- Massive star formation rate density
- Typical spectra
- *Escape fraction of ionizing radiation*

If escape fraction is not reasonably high (>~10%) at z>6 then becomes hard to envisage reionization being driven primarily by stars.

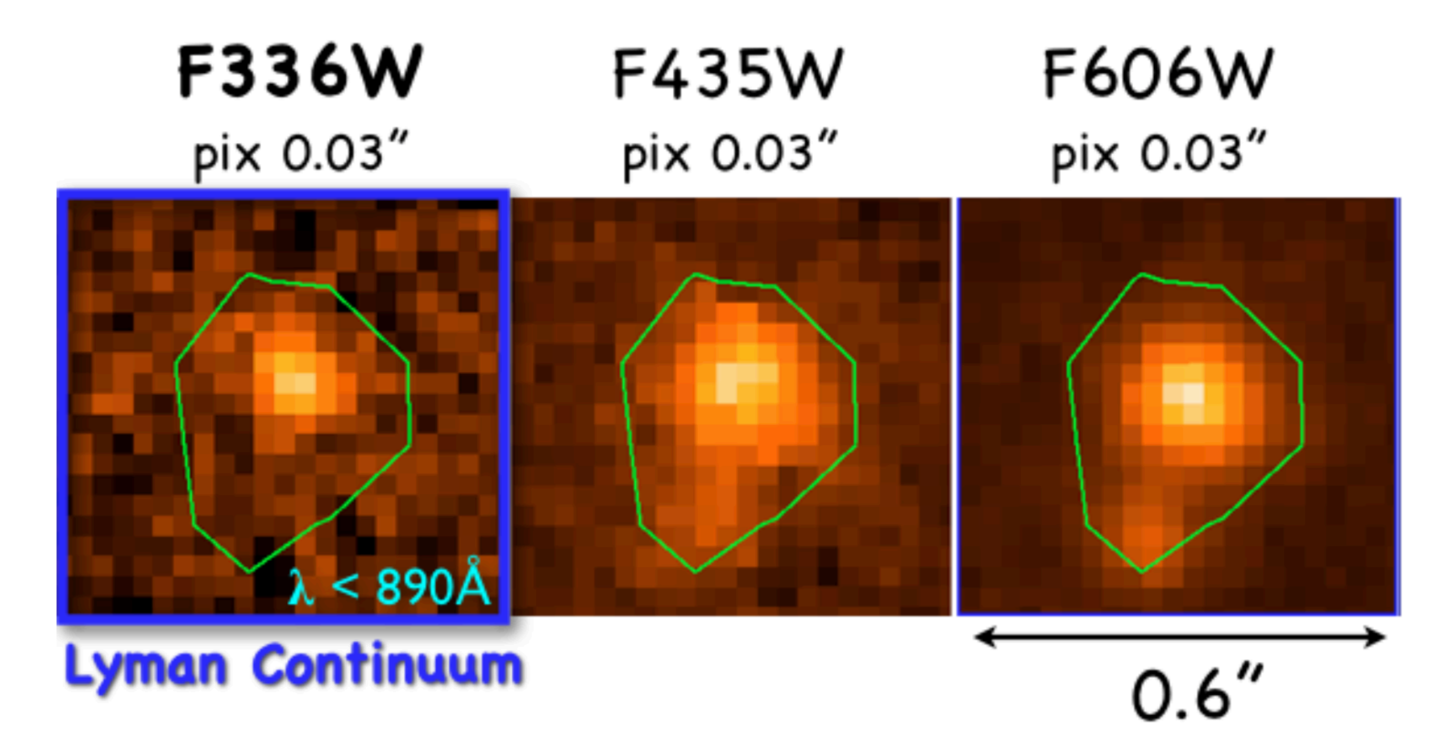
Very hard to measure directly!



Traditional approach

Studies at z~2-3 generally find low values of <~few %, although some exceptional systems.

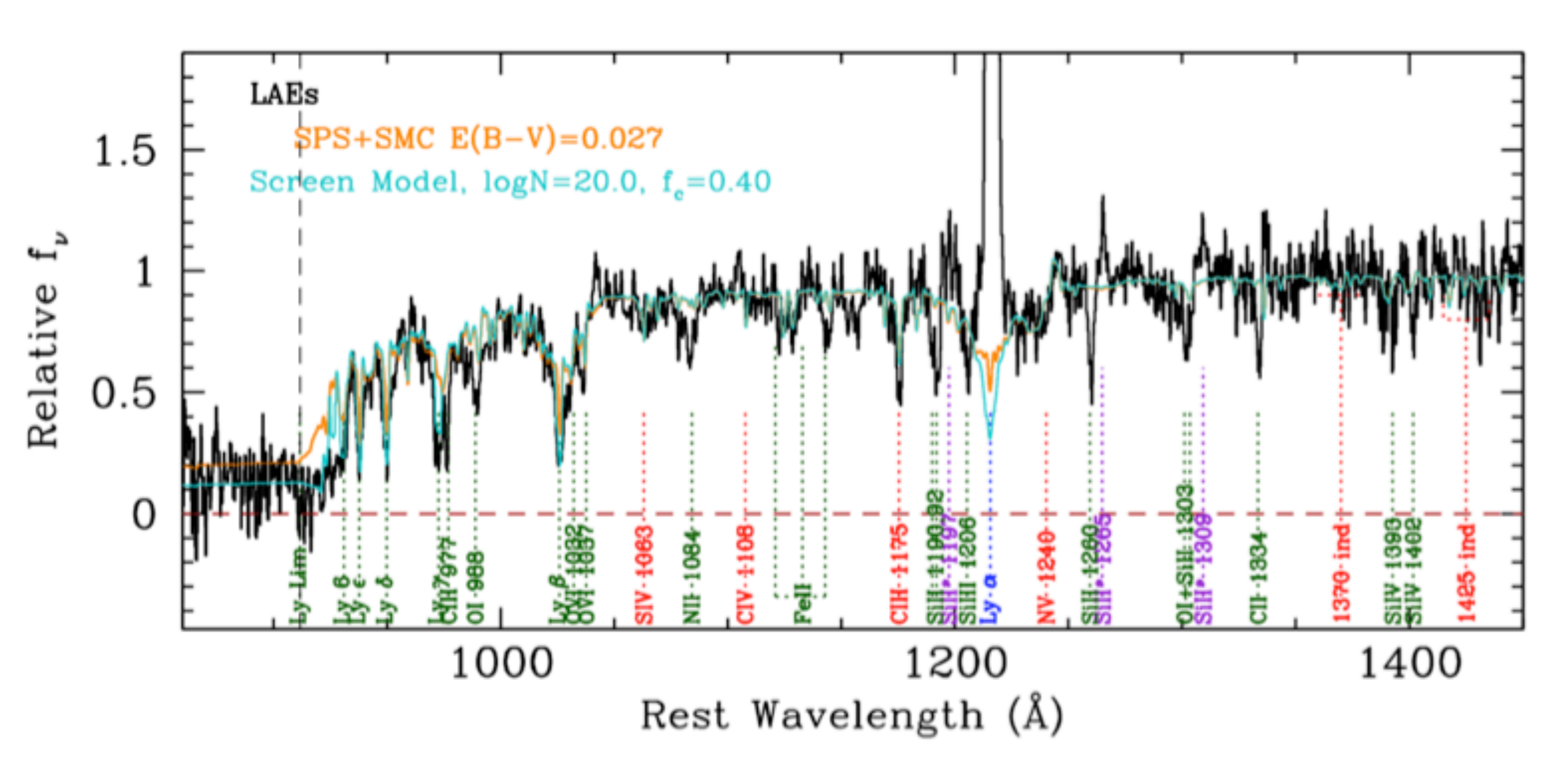
Weak constraints for (dominant population) of faint galaxies.



e.g. Vanzella et al. 2016 – z=3.2 galaxy, fesc>0.5

Traditional approach

- Important recent spectroscopic study by Steidel et al. 2018 of z~3 LBG galaxy sample.
- Stacked spectra show significant Lyman continuum, particularly when restricted to strong Ly-a emitters.

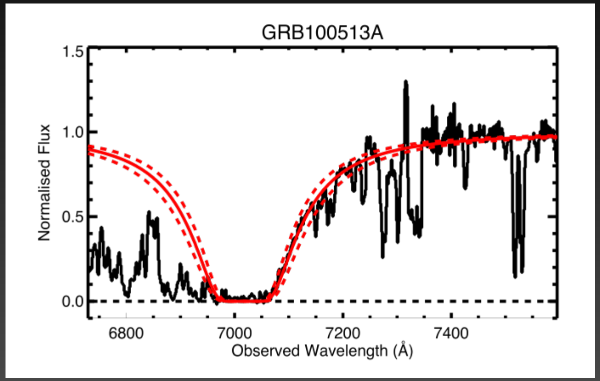


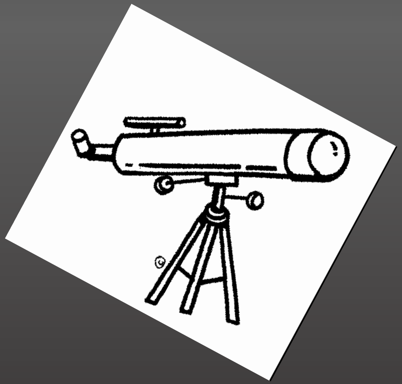
Overall escape fraction f_{esc} ~9%, consistent with requirements for reionization.

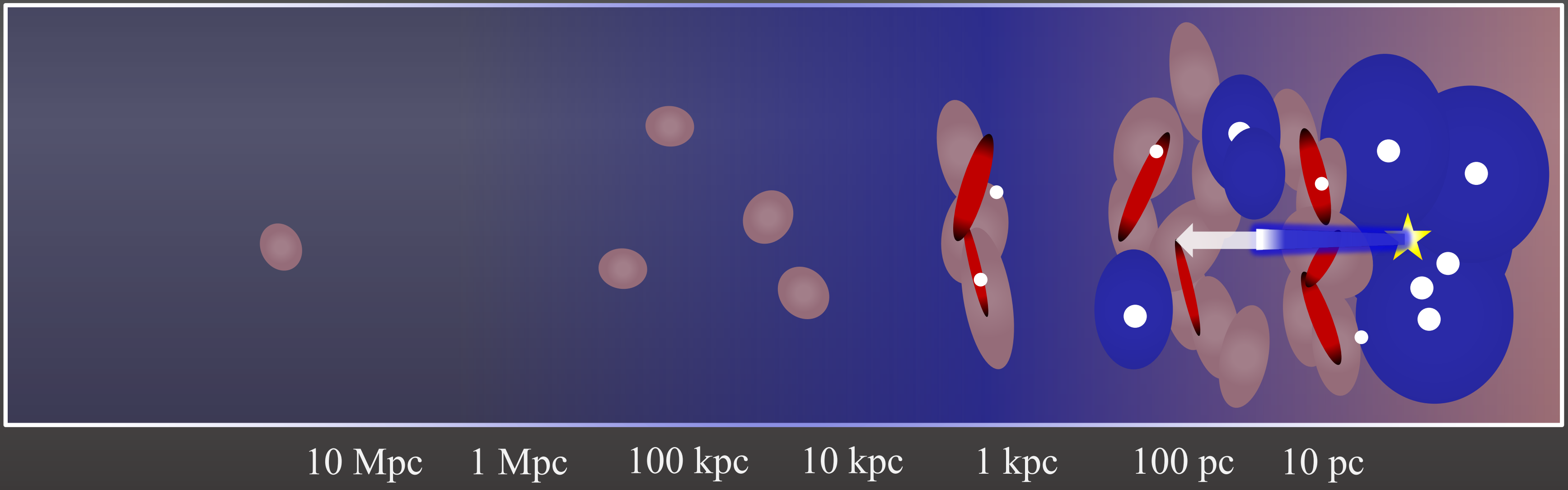
Evidence of increasing f_{esc} with decreasing galaxy luminosity.

GRB approach

- Use GRBs to measure HI column, and hence infer opacity to ionizing radiation.
- Can be applied at all redshifts, up to reionization era, and all galaxies.
- Just relies on atomic physics, but only samples one sight line – so need to assume a sample of GRBs is representative of the sight lines to massive stars.



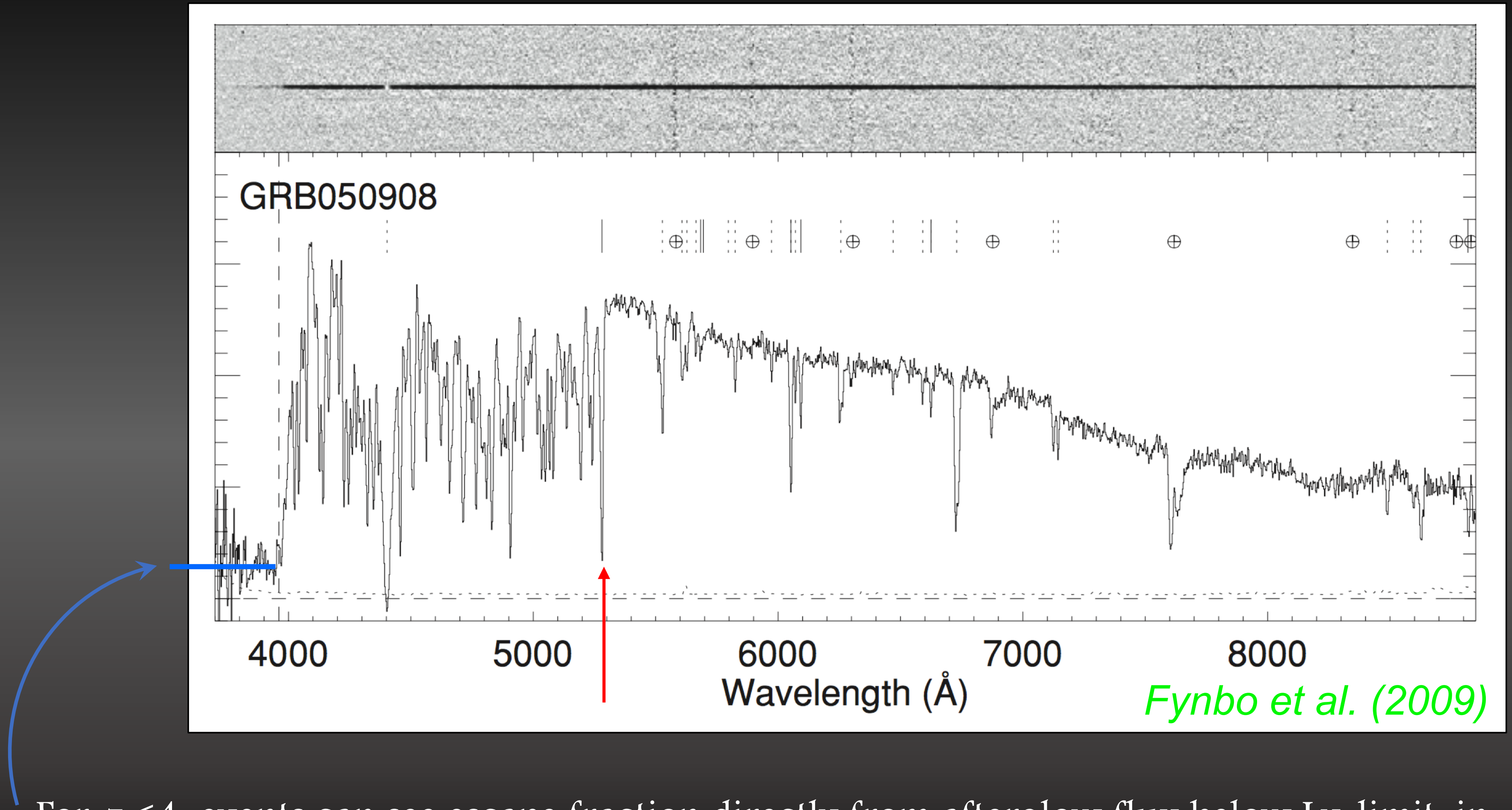




In fact GRB itself may ionize local environment, so measured HI column is lower limit.

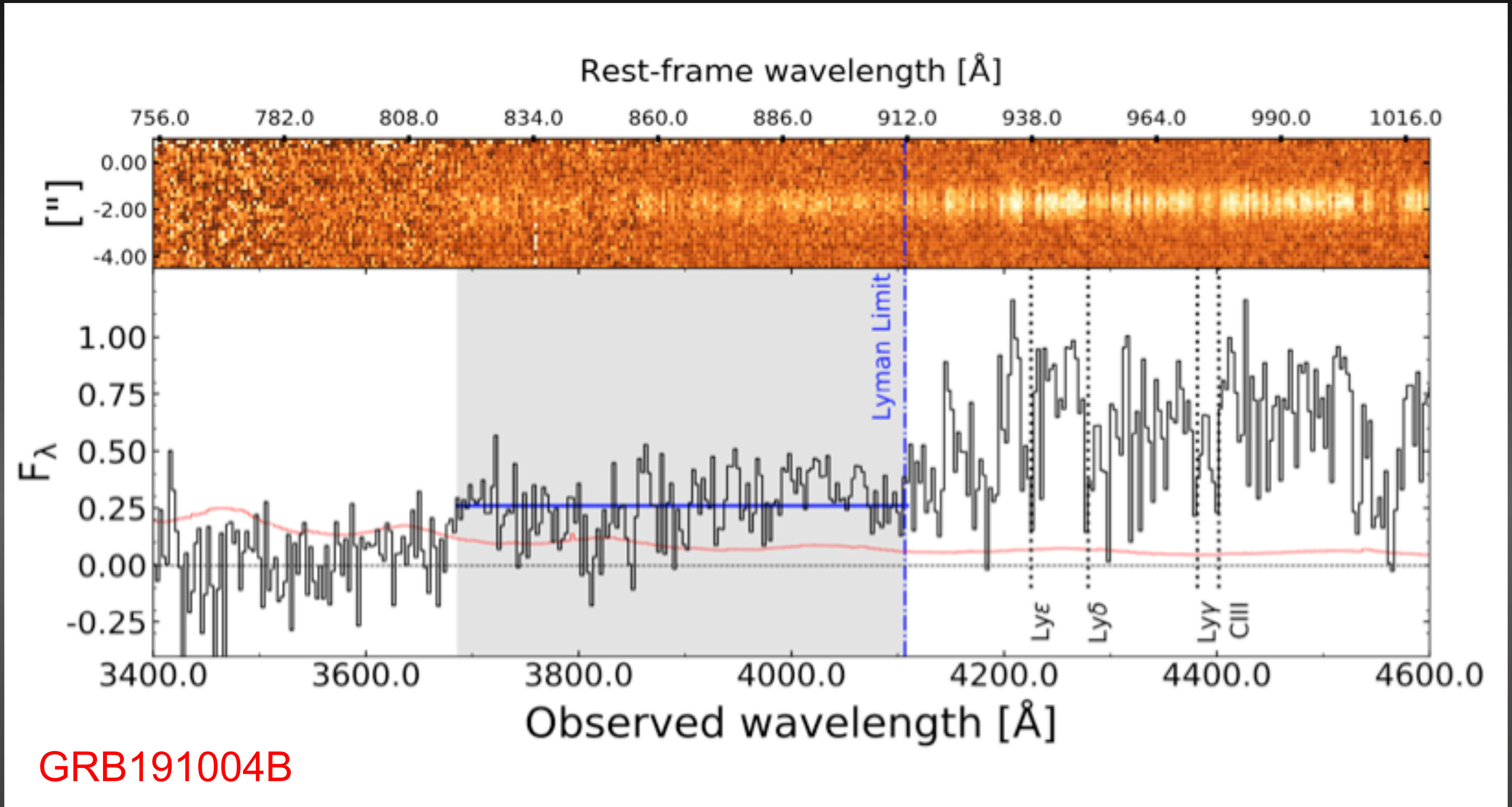
Absorbing gas typically at several 10s to 100s pc

Low column systems are rare!



For $z < 4$ events can see escape fraction directly from afterglow flux below Ly-limit, in addition to inferring from Ly-alpha line.

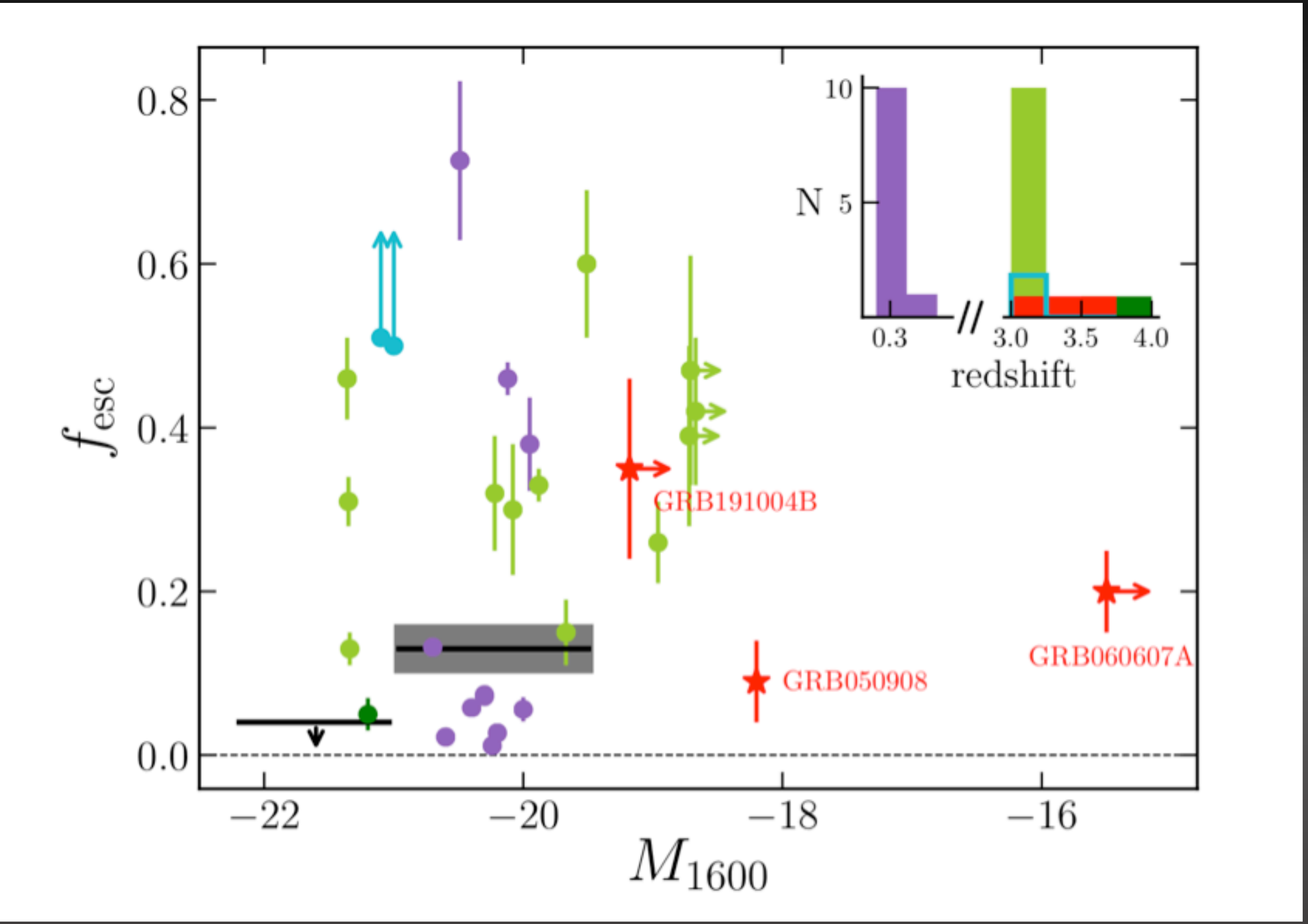
Low column systems are rare!



Vielfaure et al. 2020 present new analysis of three GRBs where this comparison can be made, finding broad consistency between the methods.

GRB 191004B is only case where Ly-a emission seen from host, but small statistics limit search for any trend of f_{esc} with Ly-a.

Host population



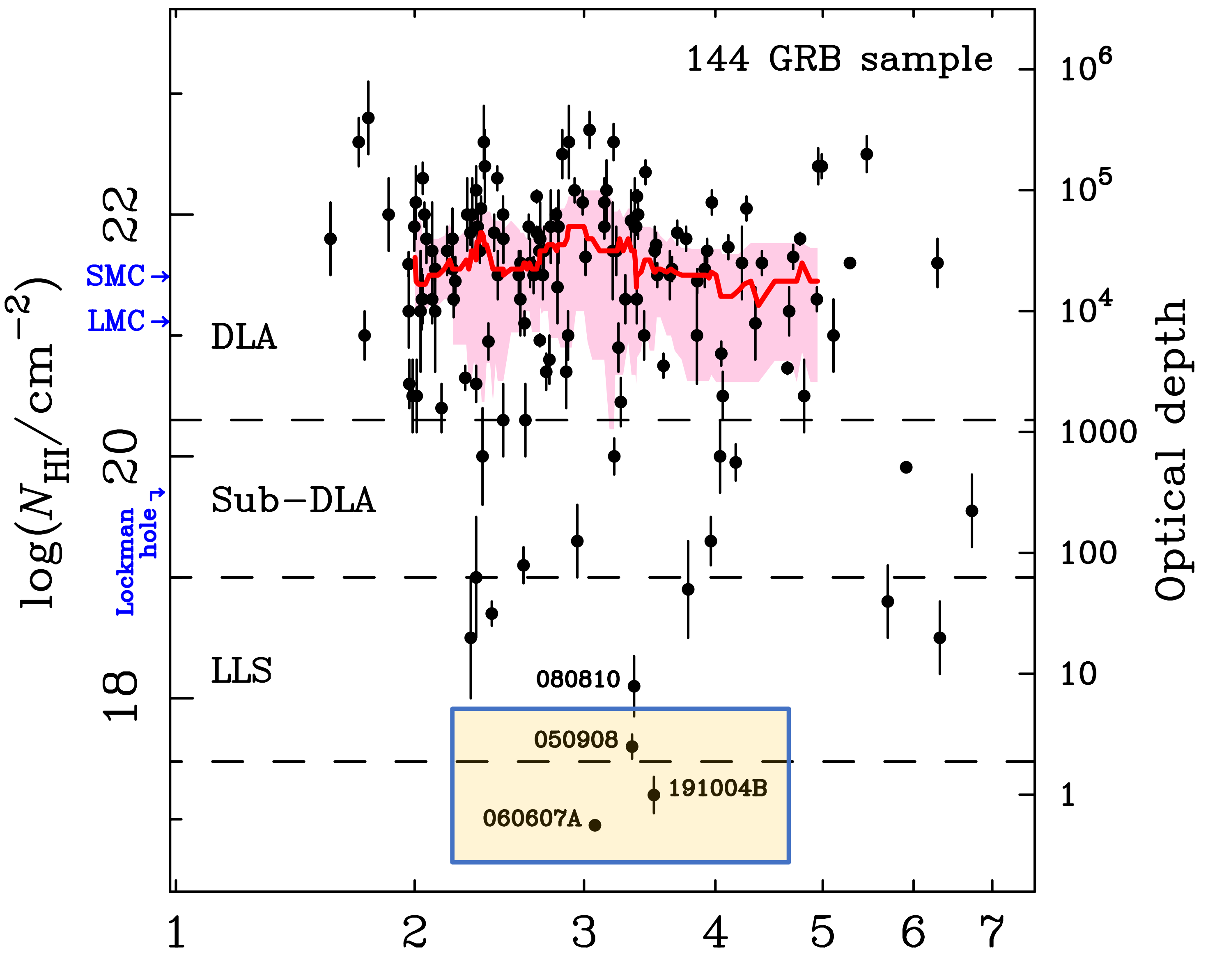
GRB hosts probe fainter absolute magnitudes than galaxy studies (too faint for individual host Ly-continuum detection). Single lines of sight to GRBs unlikely to be representative in individual cases, but powerful approach for samples.

Host population

Large majority of sight-lines are opaque to EUV (as we are from position of the Sun in the MW!).

Overall provides upper limit to escape fraction for *these stellar pops* of <2 %. (Intriguingly, around z~3, consistent with the f_{esc}~10% found by Steidel et al.)

(In principle dust column can also be well constrained from afterglow observations.)

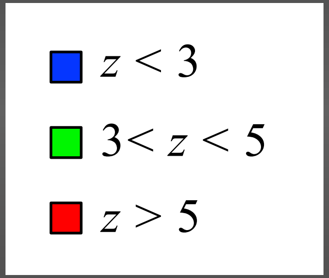


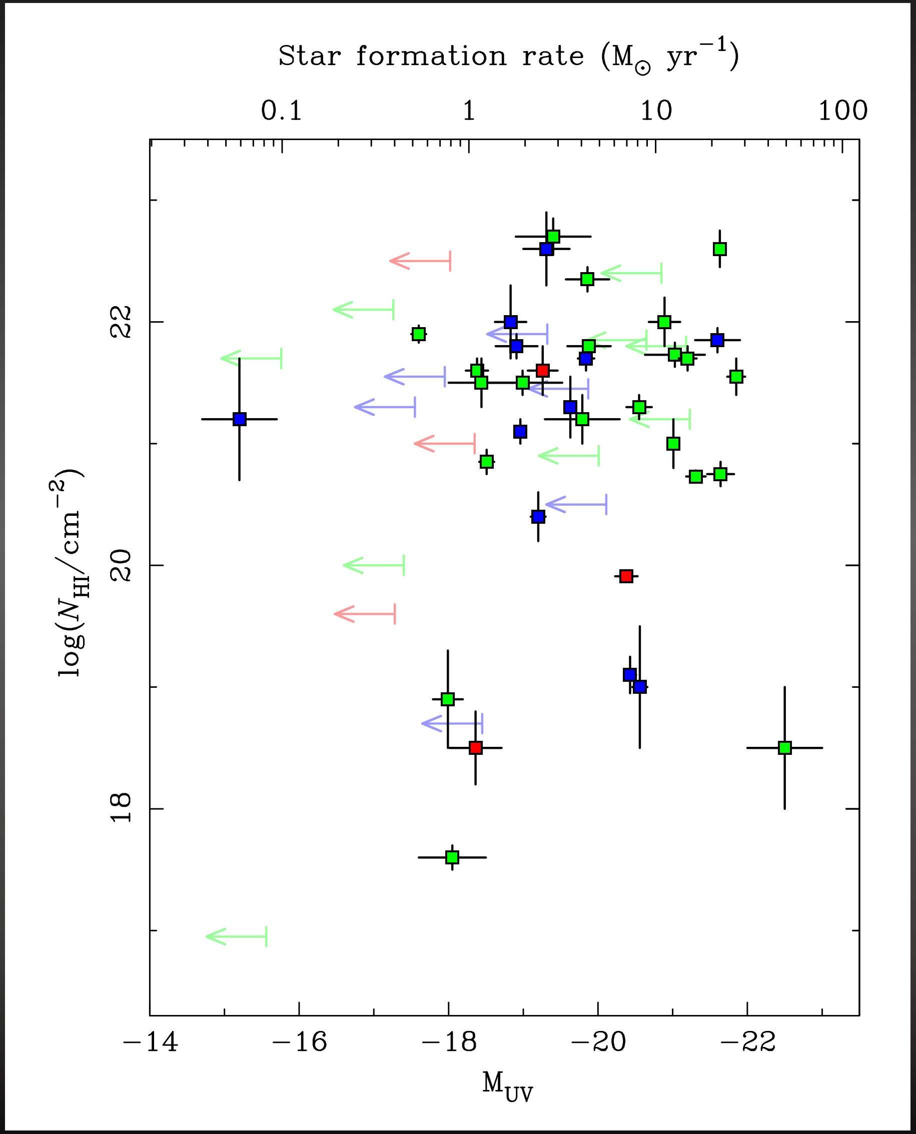
NT et al. (2019)

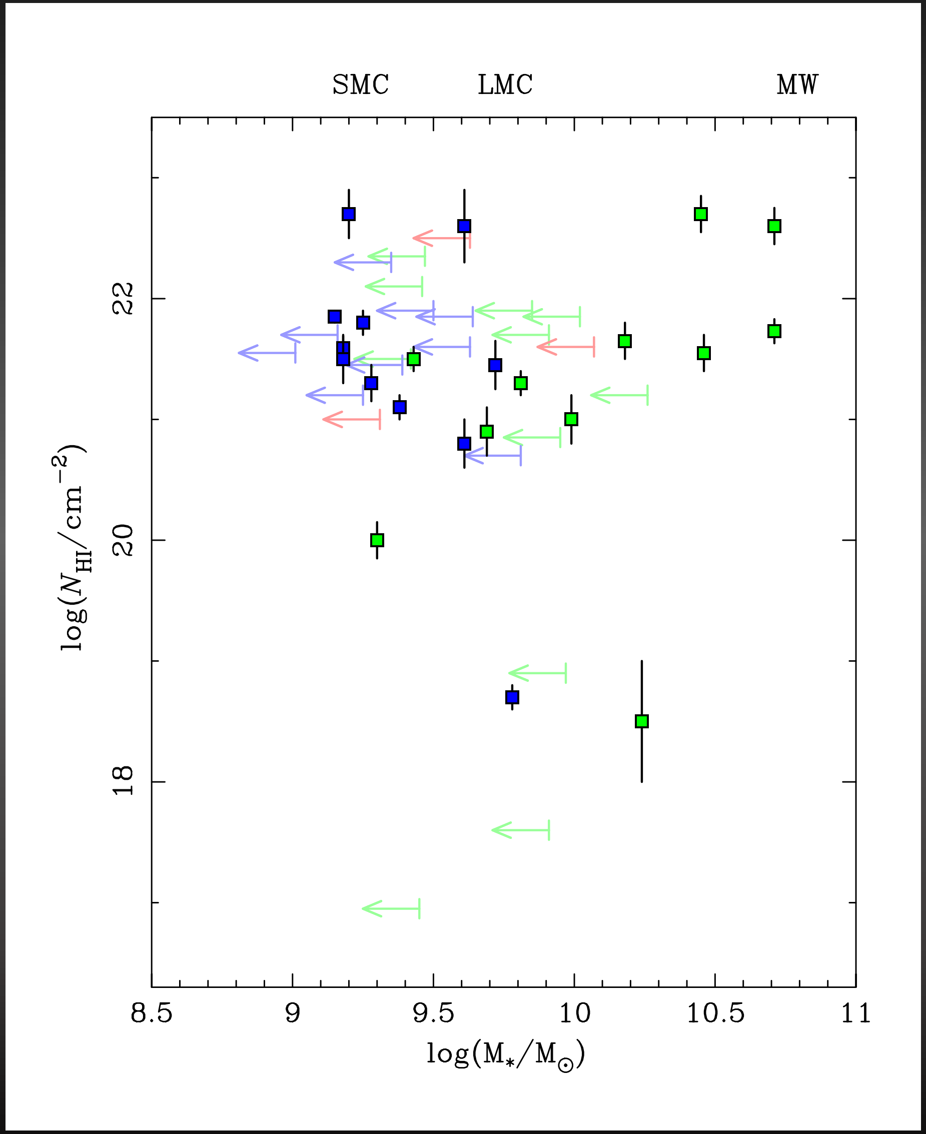
Vielfaure et al. (2020)

No clear trend with host UV magnitude (proxy for star formation rate).

Nor with stellar mass

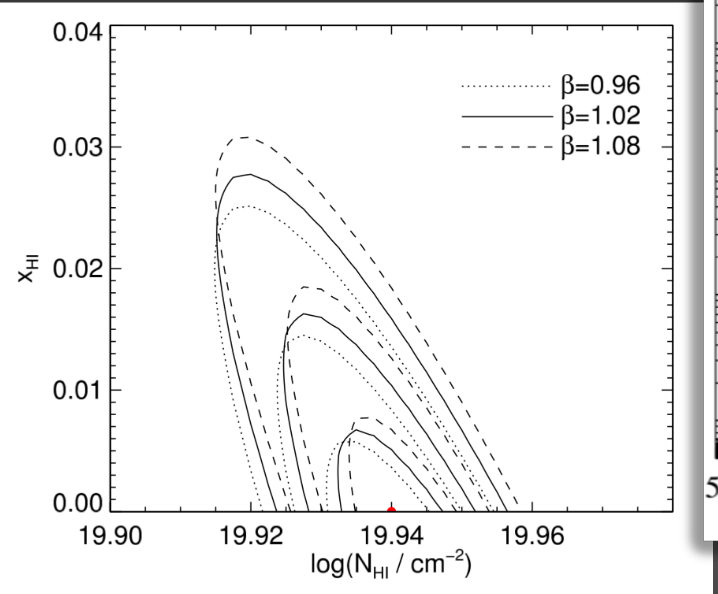


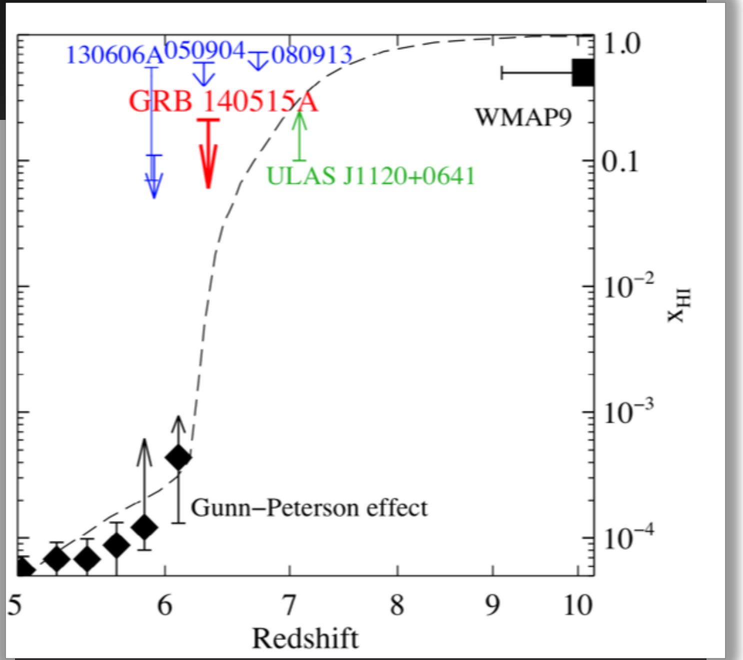


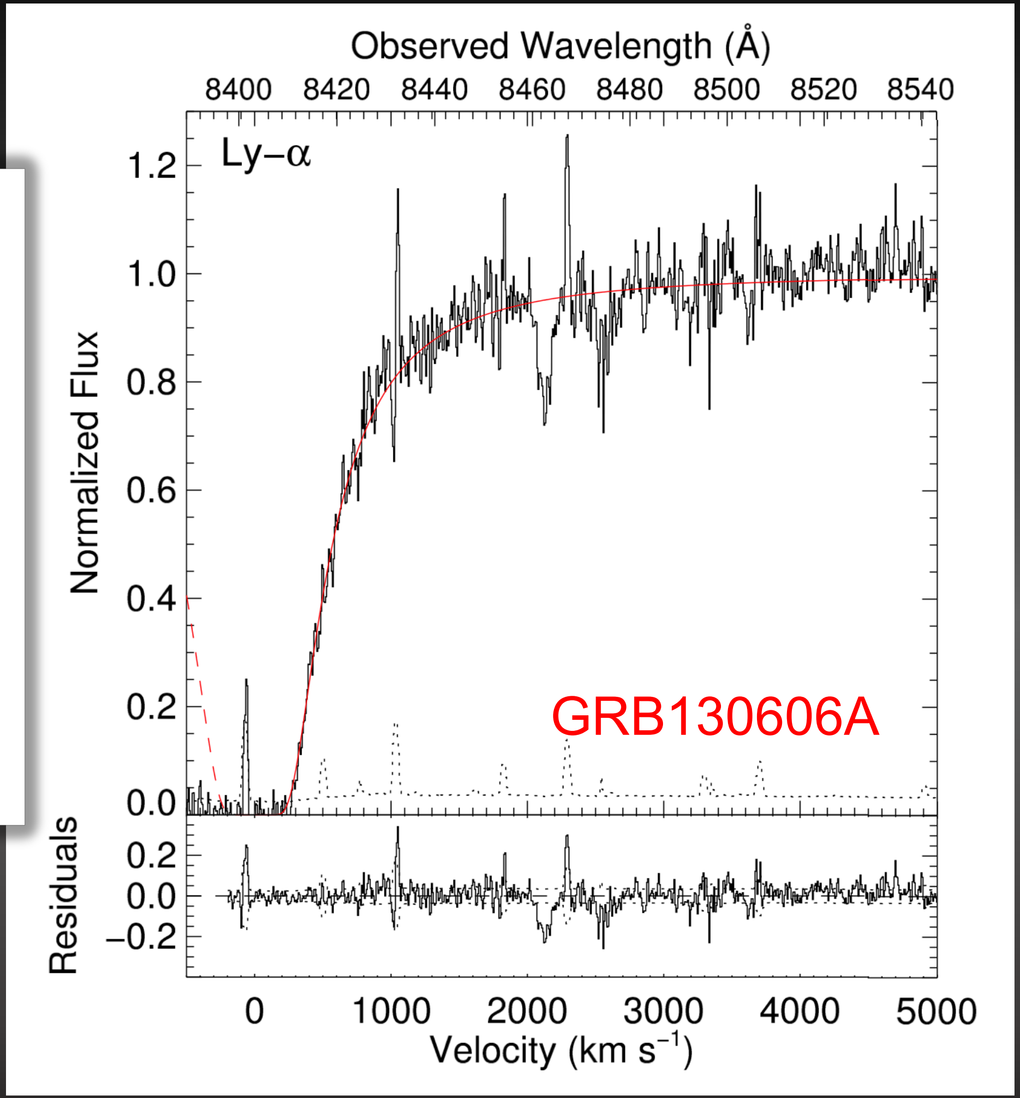


GRB 130606A (poster child)

Bright well-studied afterglow







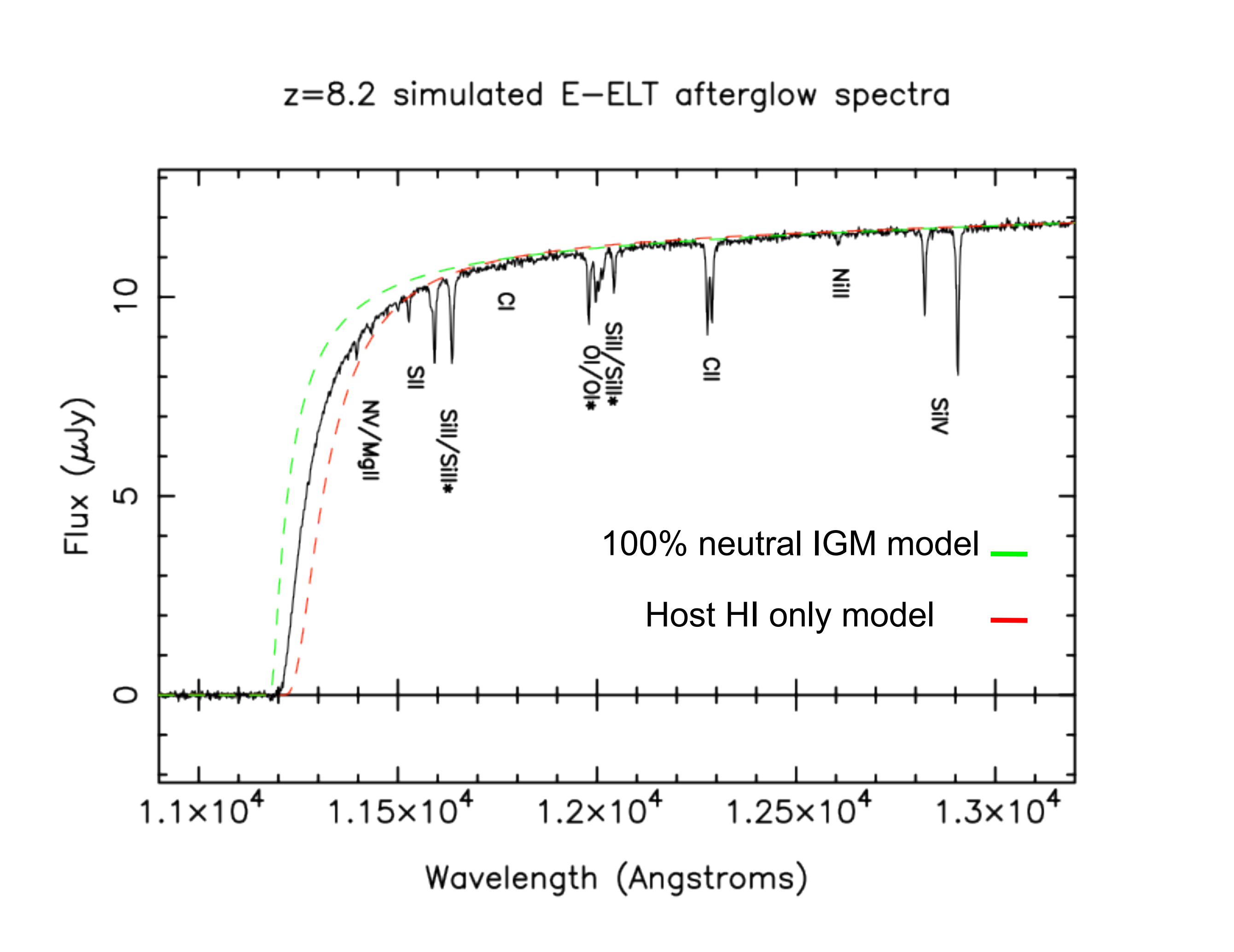
VLT spectrum well fit by host only (low column) absorption, although note Totani+16 showed that different choice of continuum can result in few percent neutral IGM being preferred.

Hartoog+2015 (also Castro-Tirado+2013; Chornock+2013)

Reionization: constraining demand

Classical route to measure IGM neutral fraction, based on red damping wing of Ly-alpha absorption line in high-z sources *(Miralda-Escude 1998)*

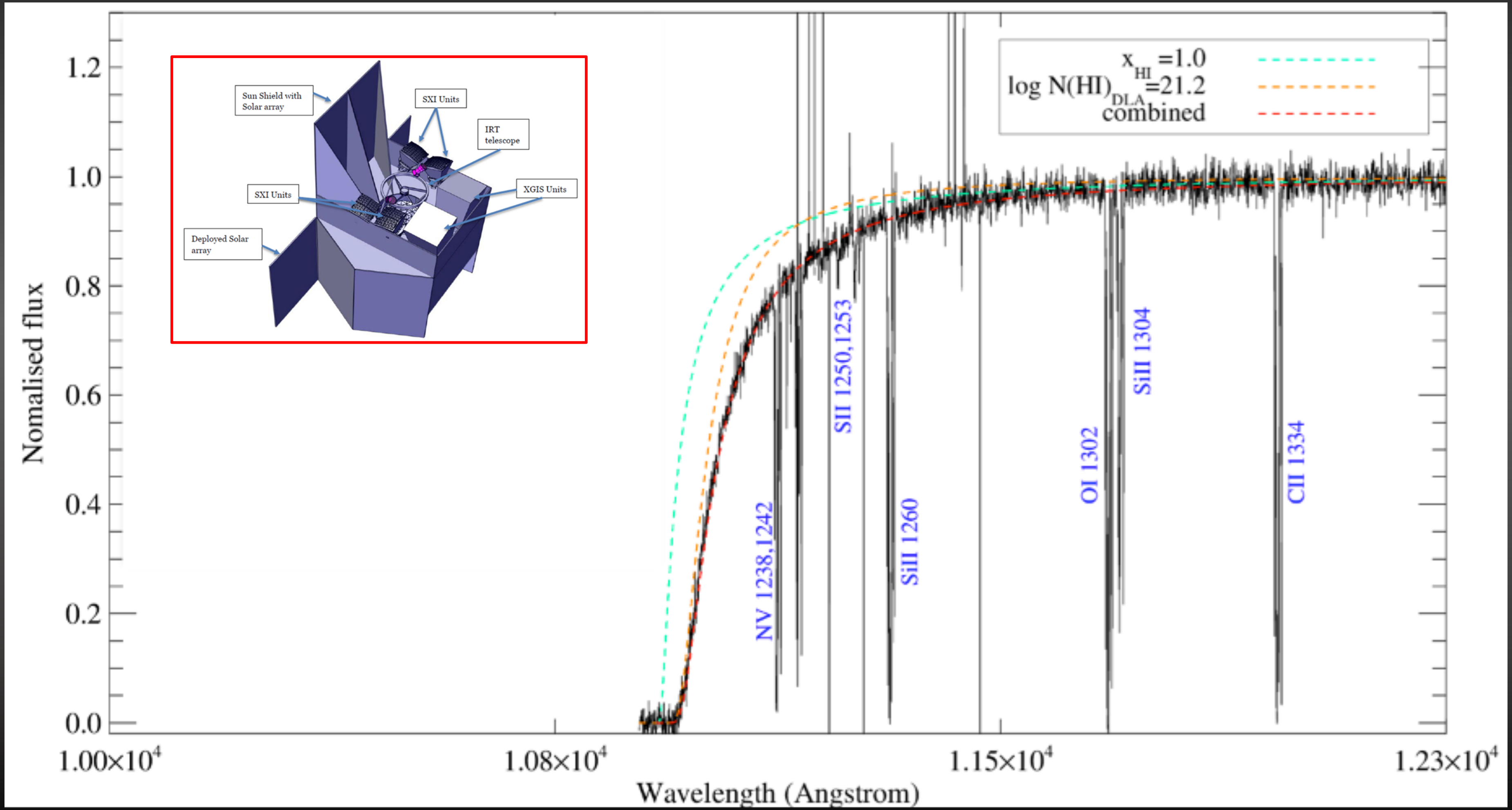
Barkana & Loeb 2003: For GRBs can decompose host and IGM contributions, with good S/N spectra and knowledge of systemic redshift. (Still hard if host NH is high)



McQuinn et al. 2008: effects of local ionized bubble can also be probed.
Many sight-lines required to map environment-dependent progress of reionization.

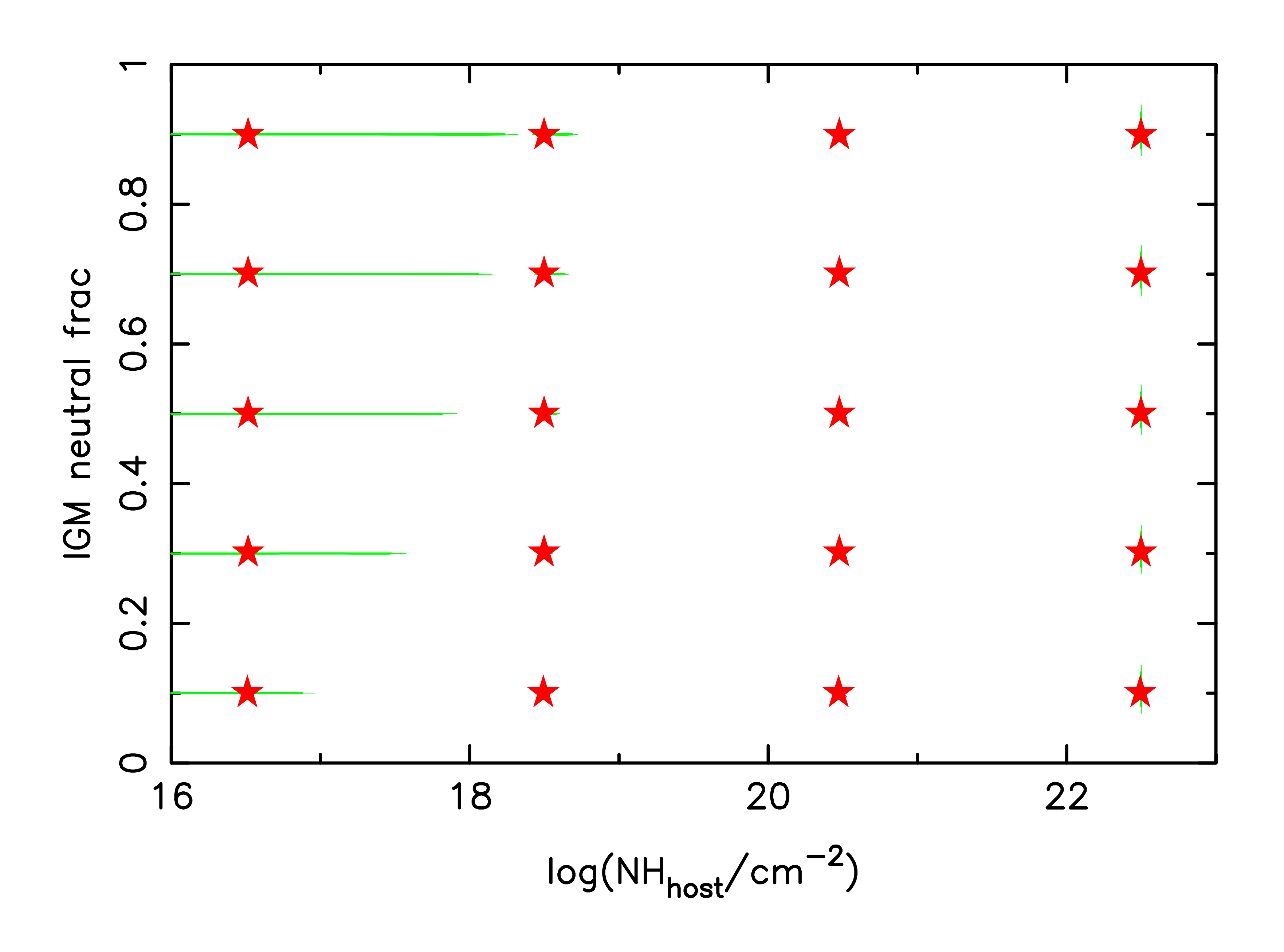
THESEUS era

- In future, benefit from powerful new spectroscopic facilities e.g. ELT, TMT, GMT, SCORPIO, Athena…
- Greatly increased rate of discovery THESEUS (see Giancarlo's talk)



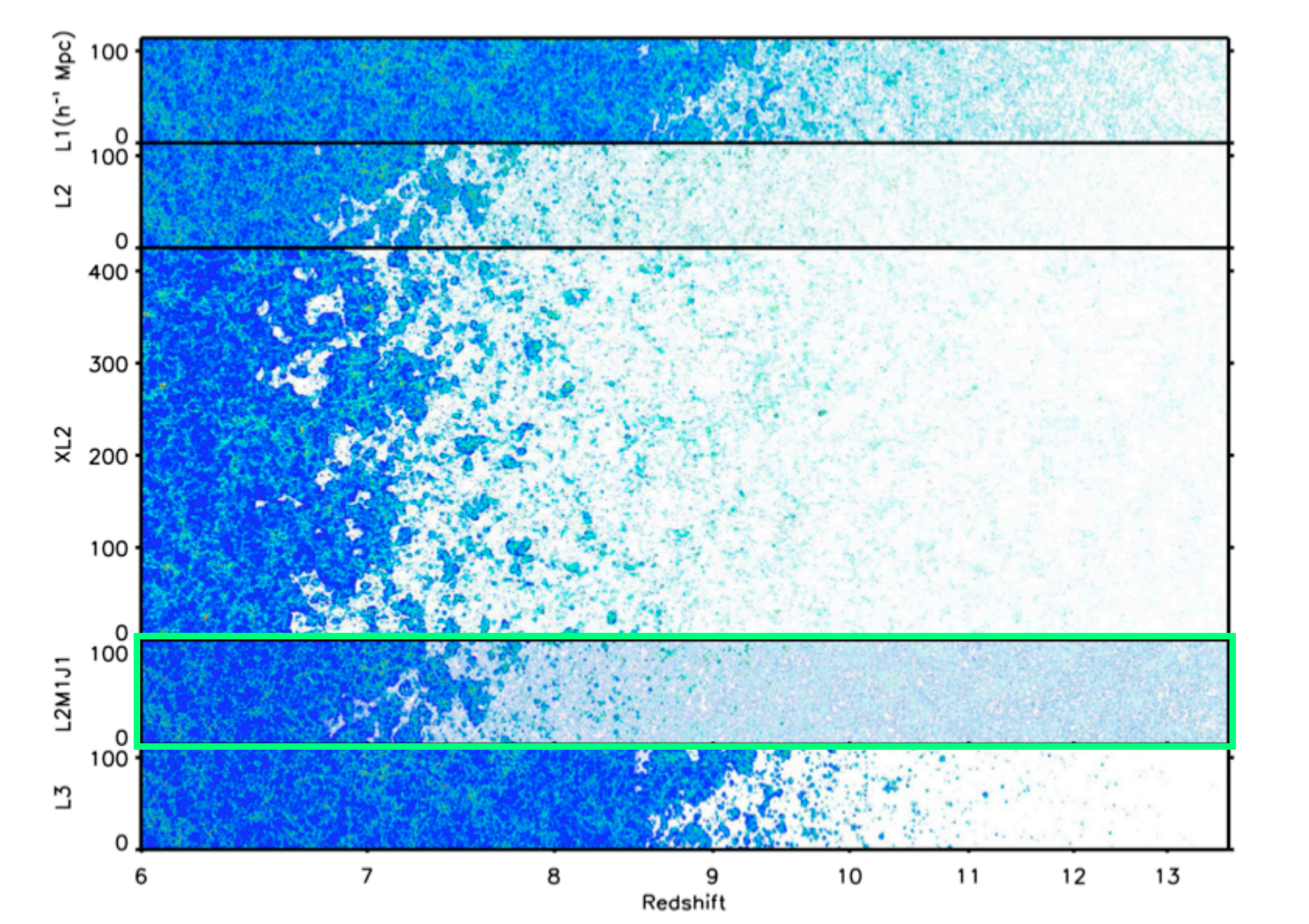
L. Christensen

Decomposing NH



Distinguishing reionization models

CMB studies fix era, but not good at timeline or topology.



Park+2013

Timescale and topology of reionization depends on nature of the dominant sources. E.g. a significant contribution from mini-halos expected to lead to a longer and smoother process due to self-regulation (i.e. SF quickly shut down in mini-halos in already ionized regions)

Conclusions

- GRB spectroscopy provides unique window on star-forming galaxies and ISM/IGM in high redshift universe.
- Difficult to reconcile the observed low escape fraction of ionizing radiation (<2%) from z<6 GRB *locations* with the requirement to reionize the intergalactic medium (~10%). ie. seems to require rapid evolution in galaxy population to z~8, and is problematic even at z~3-5. Get-outs?
  1. maybe more EUV radiation can be produced at t >10 Myr (e.g. from binaries) after strong bursts of star formation clears gas from galaxies?
  2. maybe, especially during reionization, much SF is in very small galaxies which are more easily cleared of neutral gas?
- New spectroscopic facilities will provide much better constraints in the Theseus era. Samples of several tens of GRBs at z>6 will check for evolution in HI column distribution.
- The same spectroscopy will probe the average IGM neutral fraction proximate to each burst, and hence the timeline and topology of reionization.