Sexten/Sesto Workshop - 2023

Exploring the reionization era with GRBs

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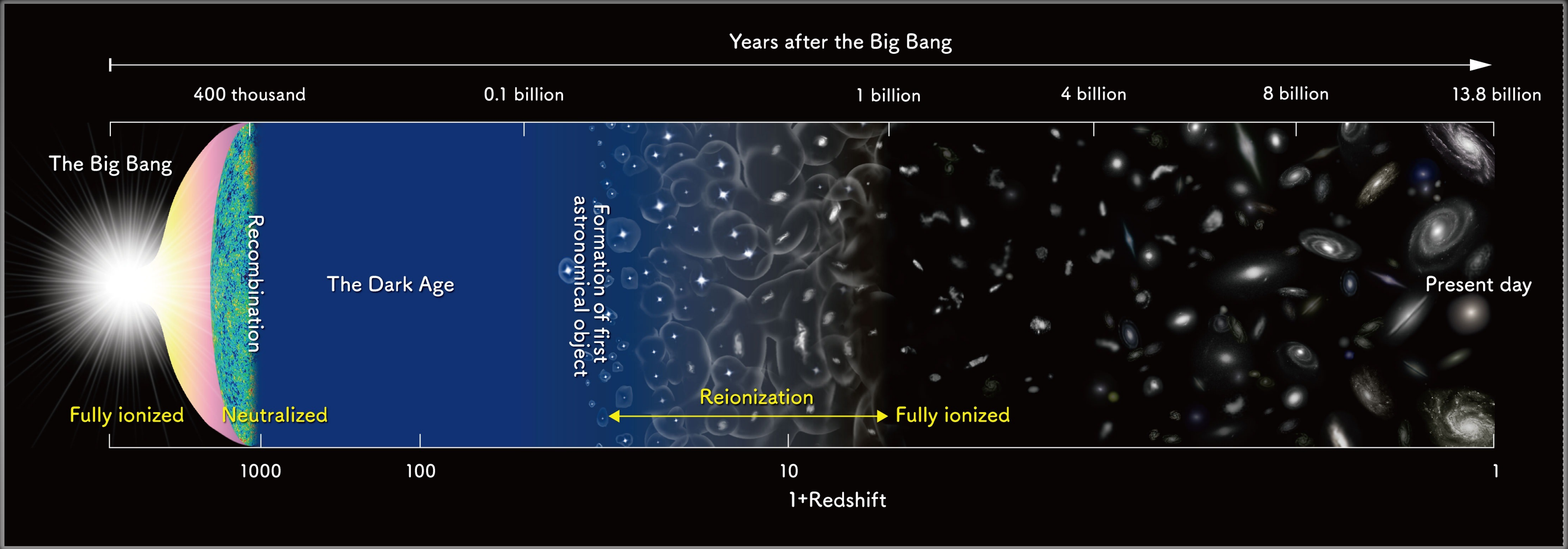
The epoch of reionization & before



What was the timeline?

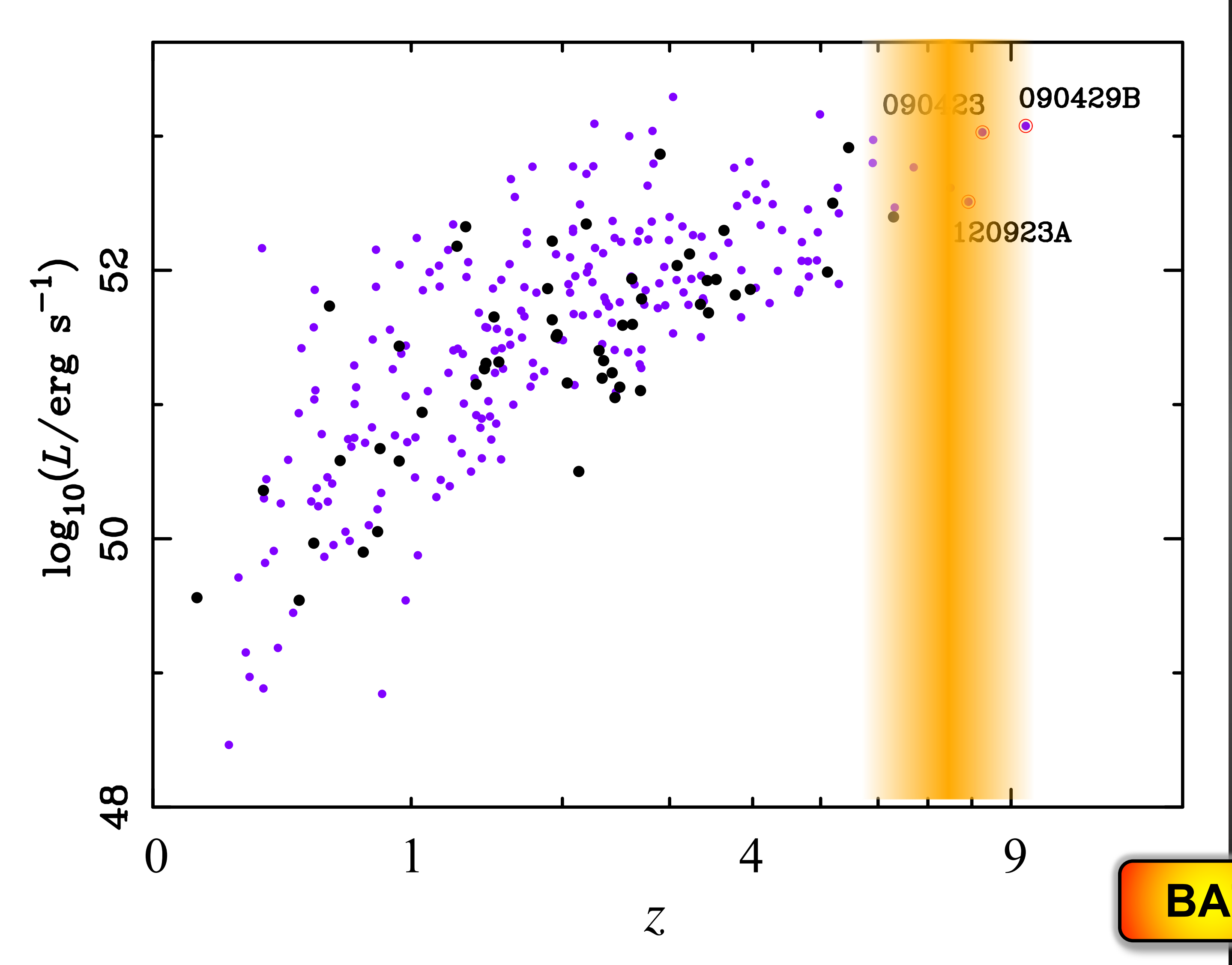
What sources were responsible?

How did the chemical elements build up?

What modes of star formation?

Swift GRBs span most of cosmic history

- Detectable to very high redshift with wide-field gamma/X-ray monitors.
- But with current technology only the intrinsically brightest GRBs found in era of reionization, so rather rare.



BAT

GRBs @ high-z

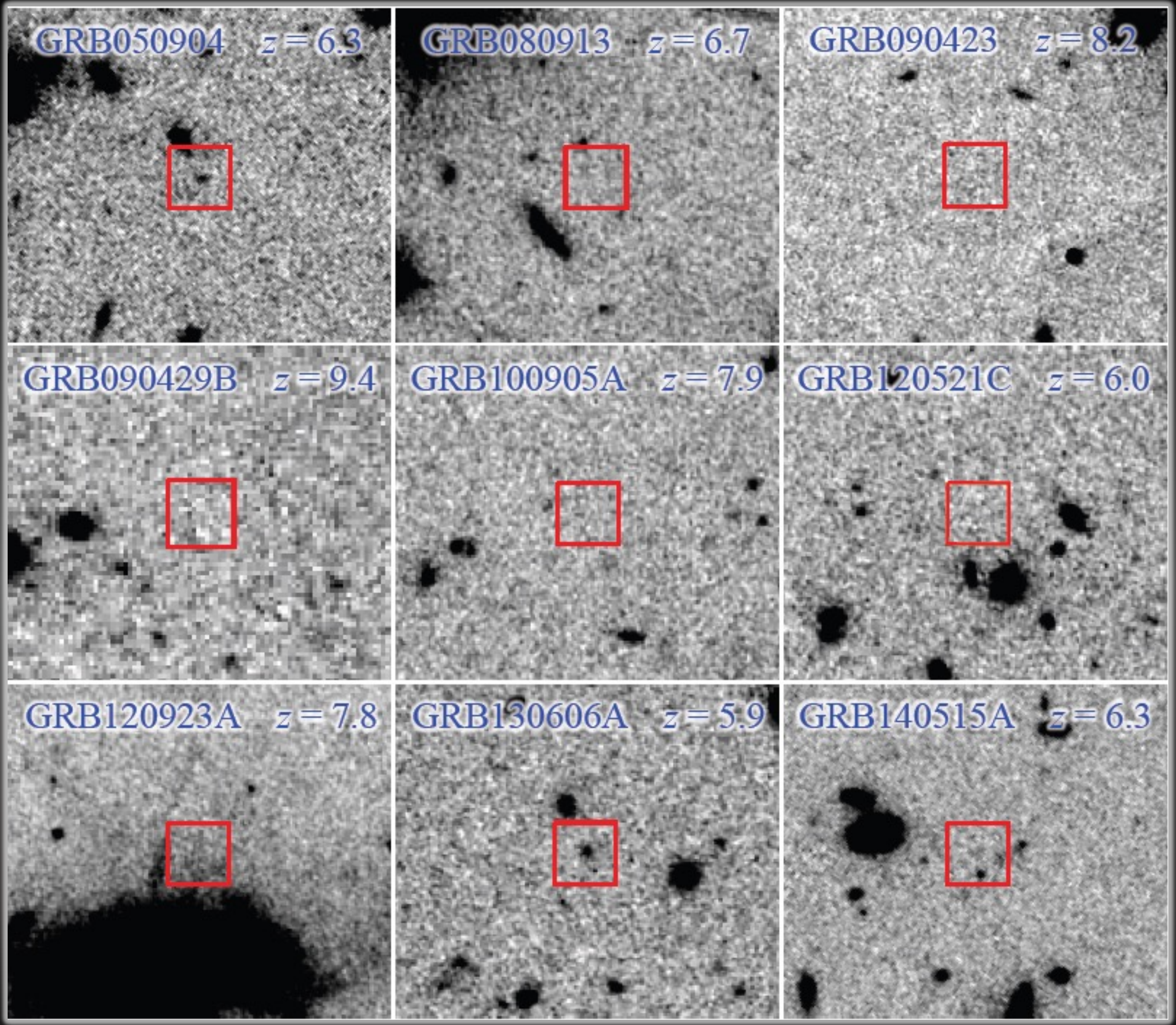
Thanks to this extreme brightness, provide powerful complementary probe of star formation and galaxy evolution over cosmic history, out to the era of reionization.

Allow us to address some key issues:

- Star formation rate density at high redshifts
- Nature of early galaxies
- Escape fraction of ionizing radiation
- Timeline and topology of reionization
- Dust and cosmic chemical evolution
- IGM probes

High-z GRB hosts

Sample the whole star-forming galaxy luminosity function using both detected and undetected hosts.

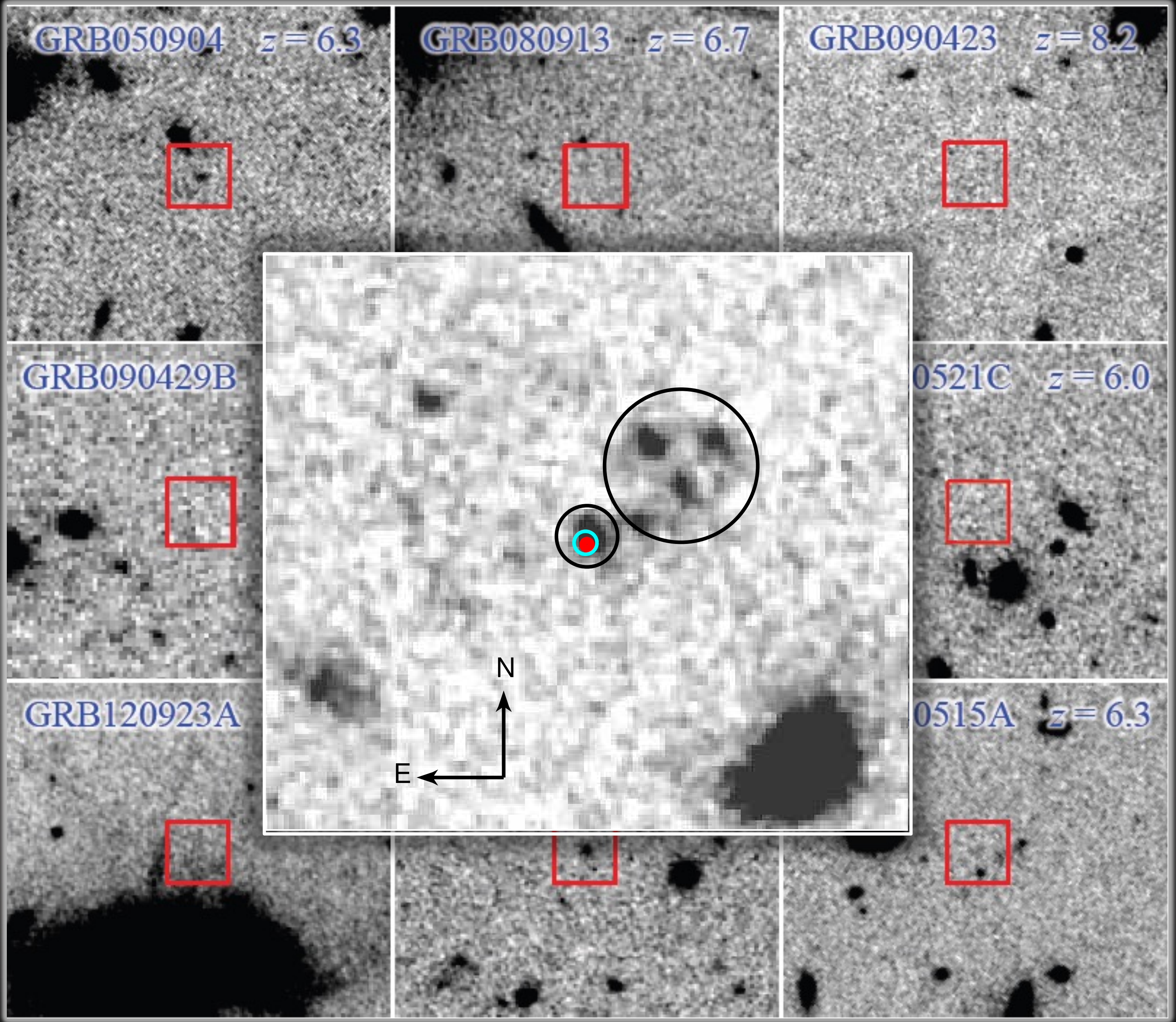


NT+12, McGuire+2016

High-z GRB hosts

Sample the whole star-forming galaxy luminosity function using both detected and undetected hosts.

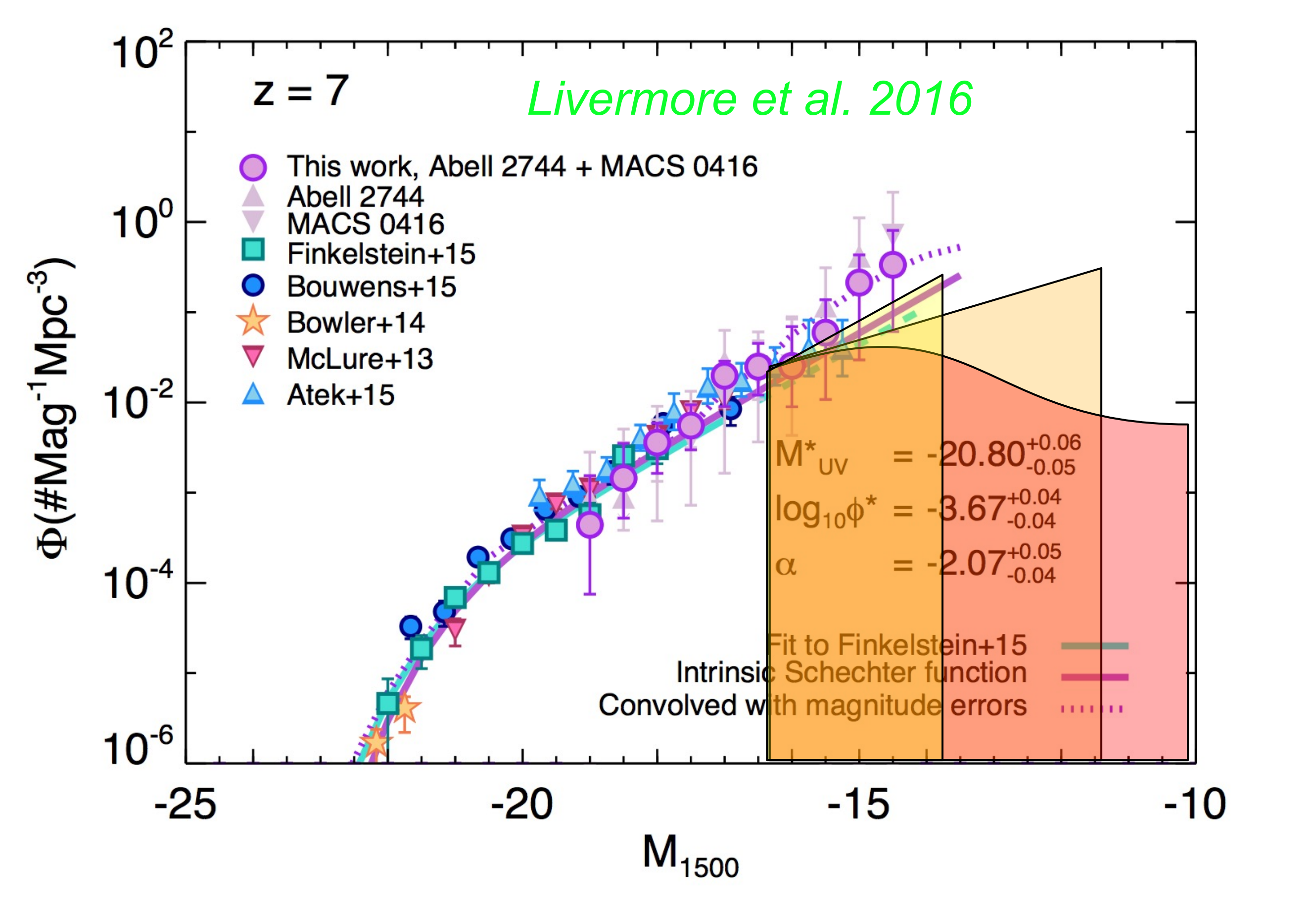
Host of GRB 210905A (Rossi et al. 2022, Saccardi et al. 2022) at z=6.3 is a brighter, and potentially large more complex system.



NT+12, McGuire+2016

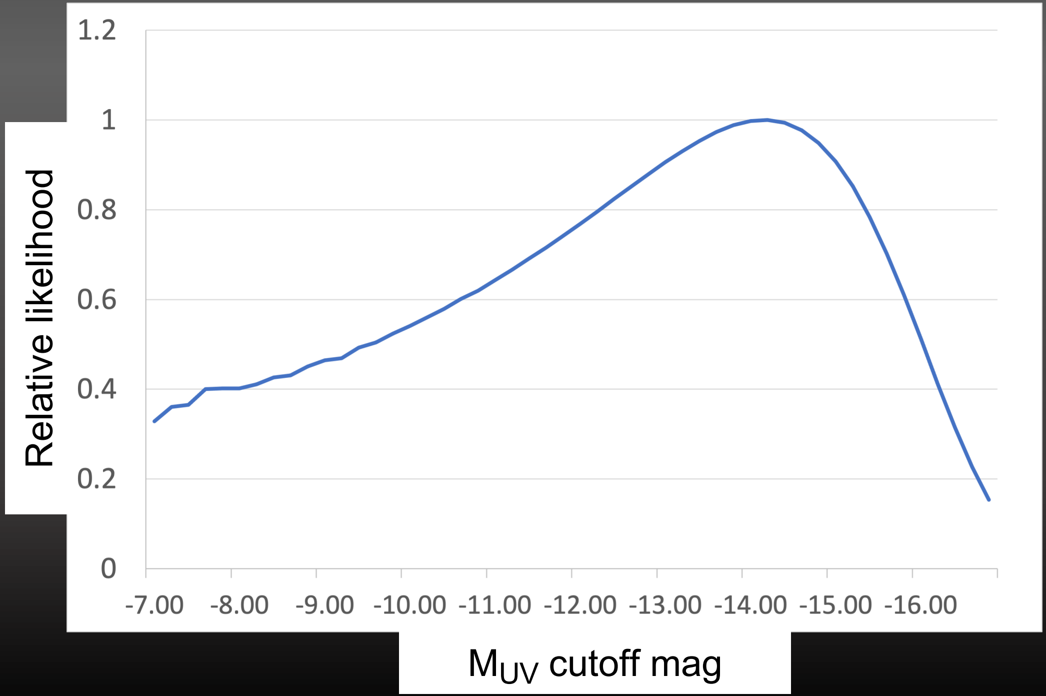
Constraining the galaxy LF

Ultimately seeking to quantify amount of star formation in unseen galaxies.



Assume *GRB rate ~ SFR ~ UV*

Results from small current z>~6 sample are consistent with steep faint-end slope of (Schechter) galaxy LF down to M_{UV} ~ -14



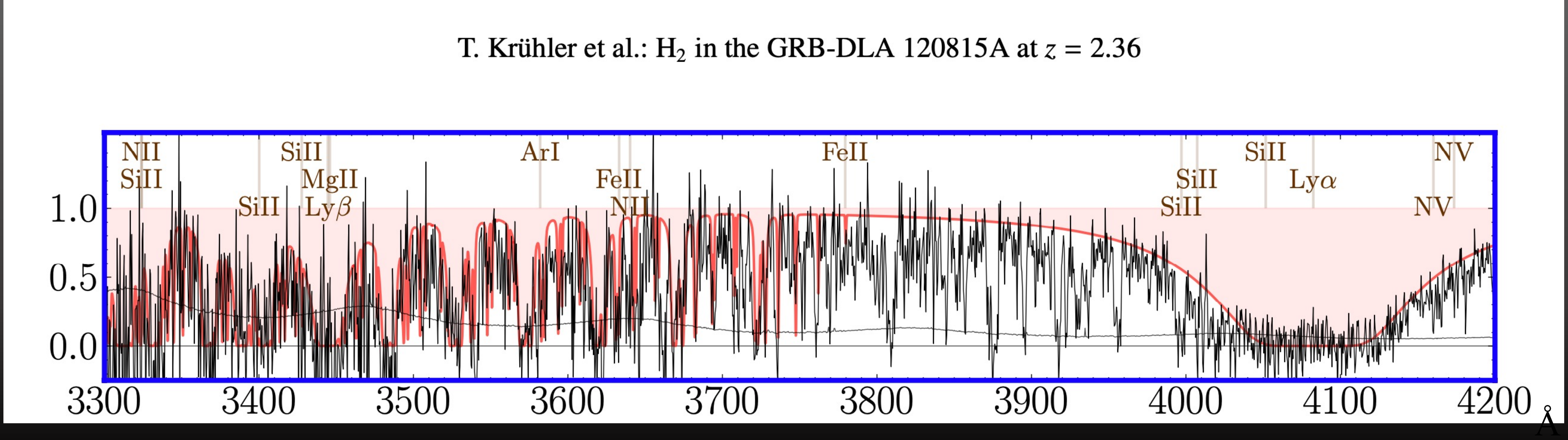
GRB host limits can be very deep since knowledge of position allows us to look for low-significance detections (and we don't need deep veto filters).

Afterglow spectroscopy

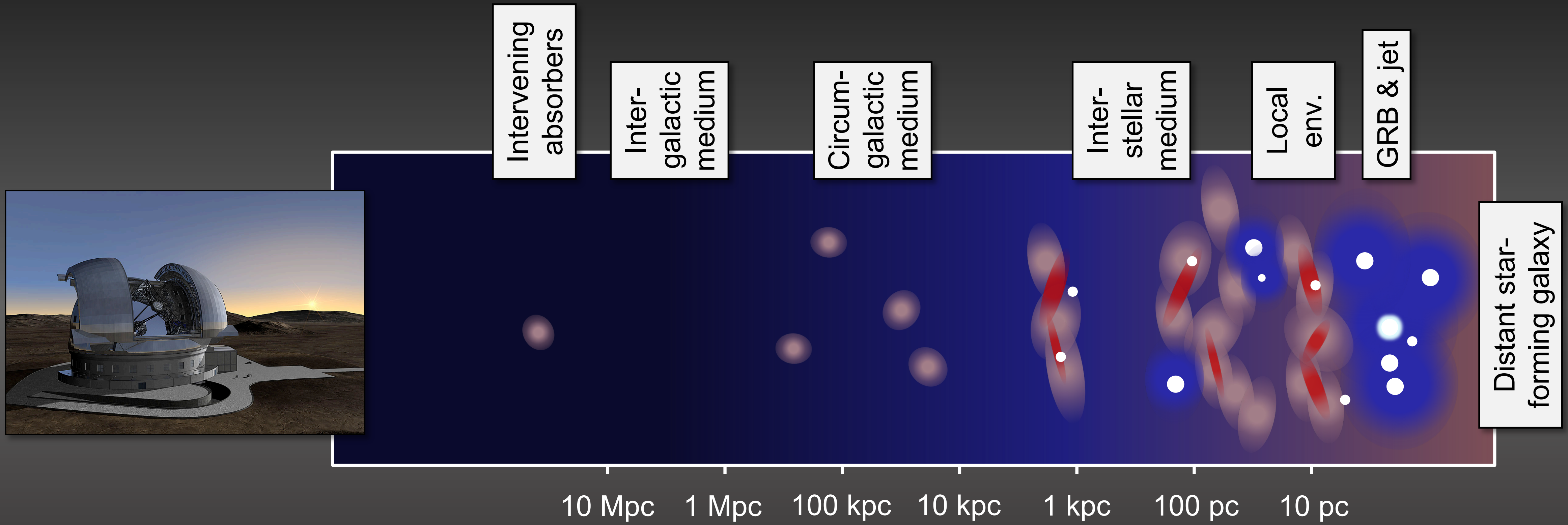
Provides unprecedented information about host ISM and intervening IGM.

Bright, smooth (power-law) continuum backlight:

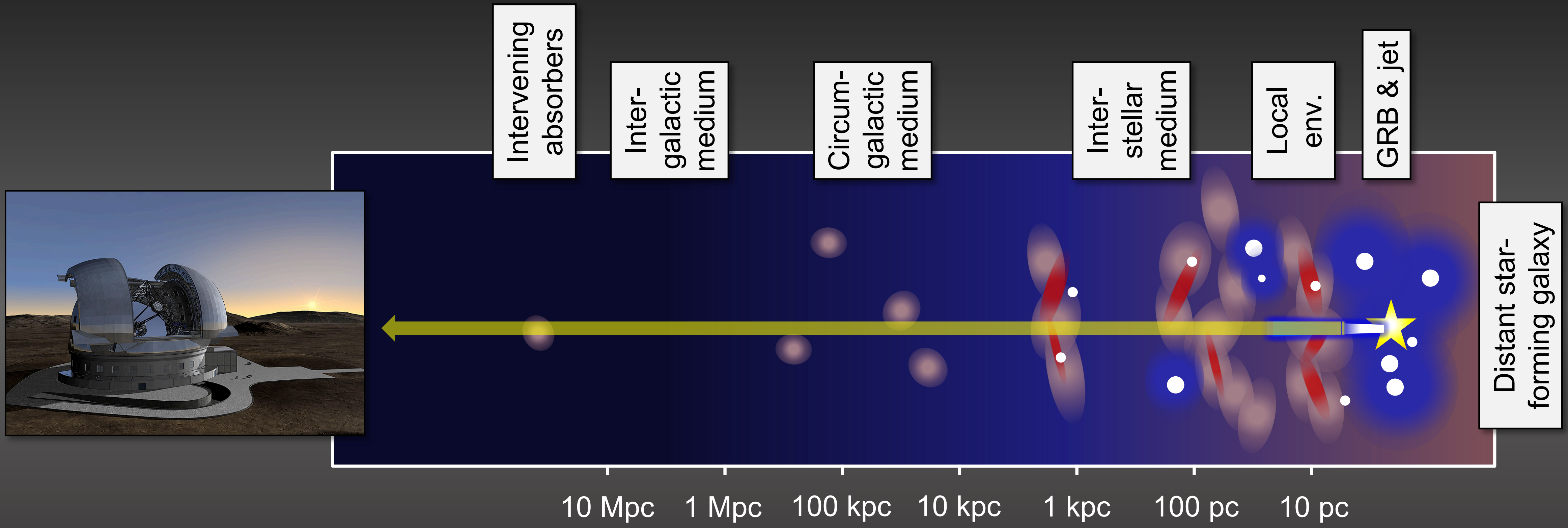
- Metal species – abundances, kinematics, ionization states
- HI column density in host and IGM
- Dust, molecules etc.



What we are seeing

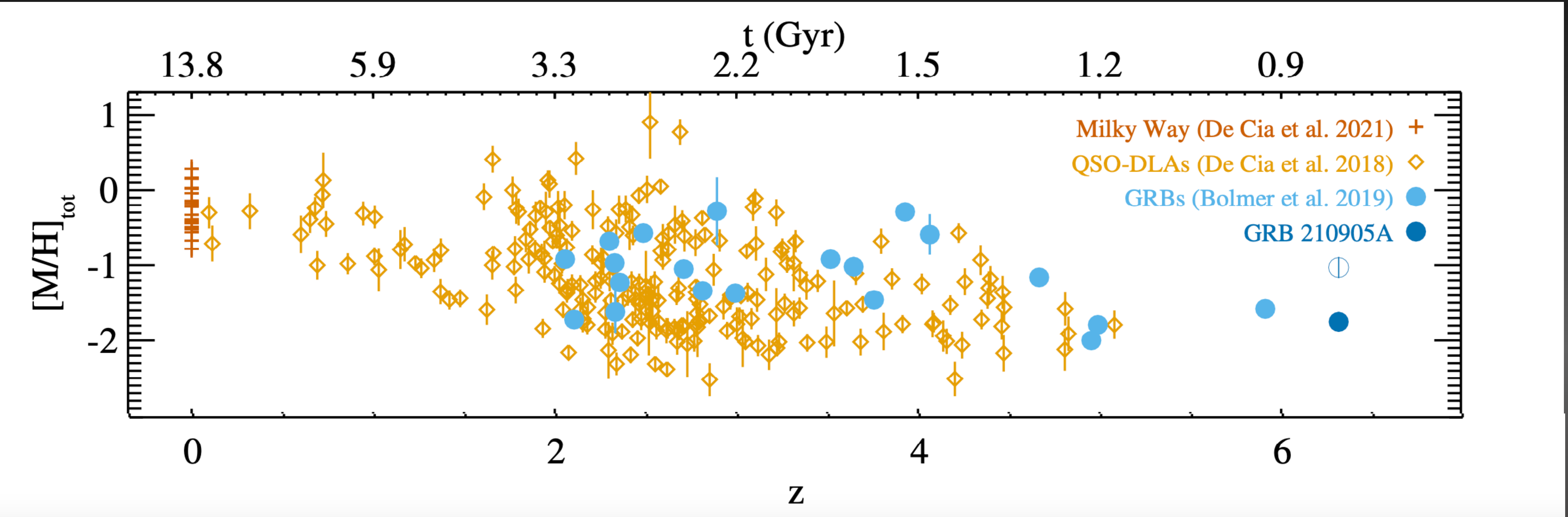


What we are seeing



Cosmic chemical evolution

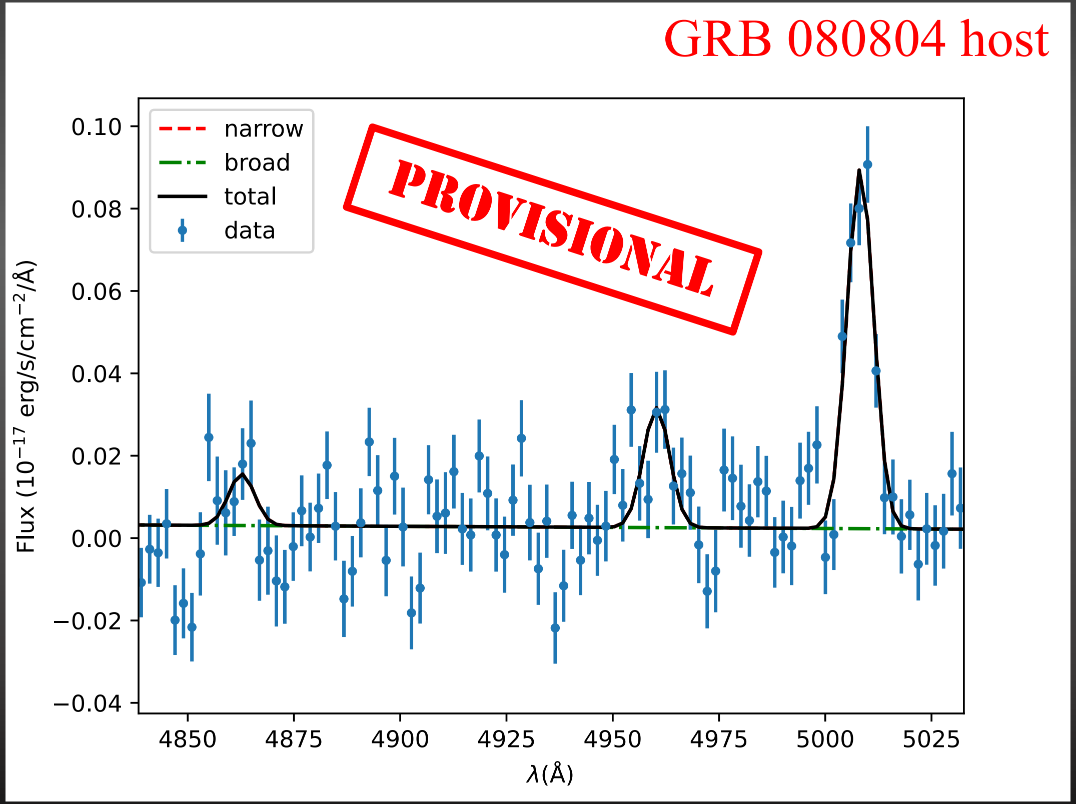
See Saccardi talk

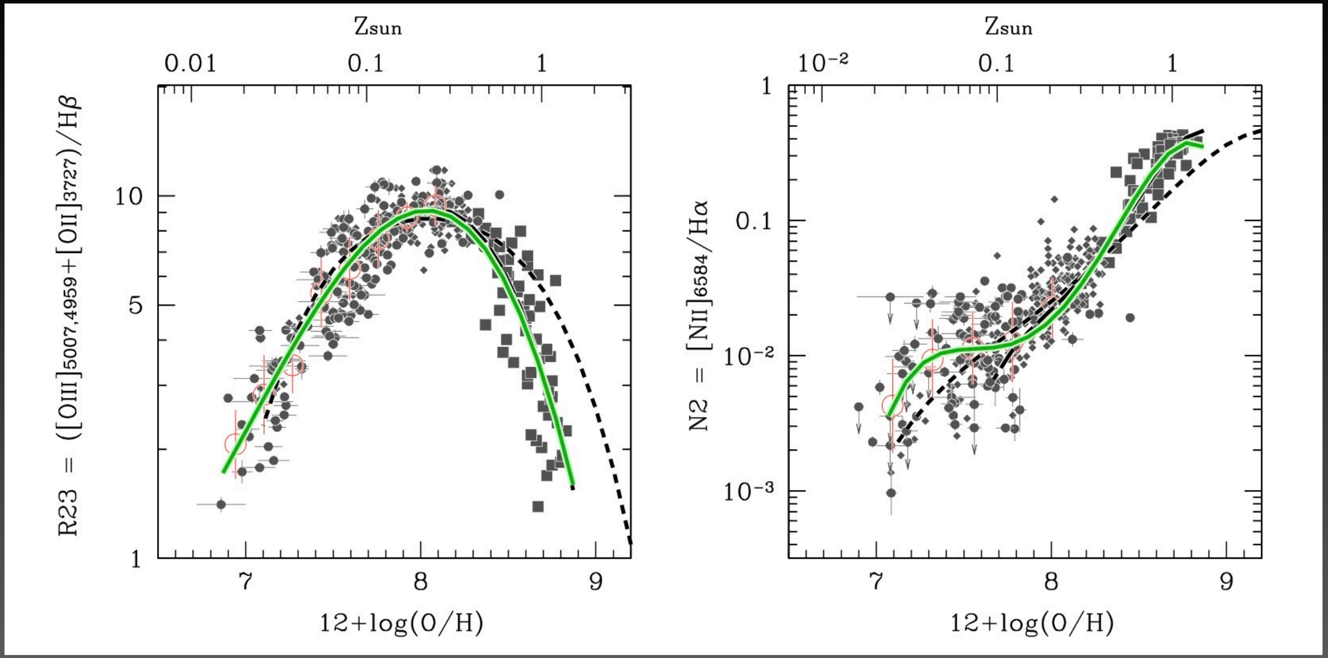


Opportunity to "calibrate" emission line metallicity indicators against our absorption measures!

Cosmic chemical evolution

Schady et al. cycle 1 *JWST* programme – 10 hosts

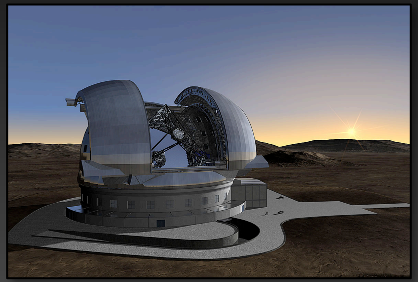


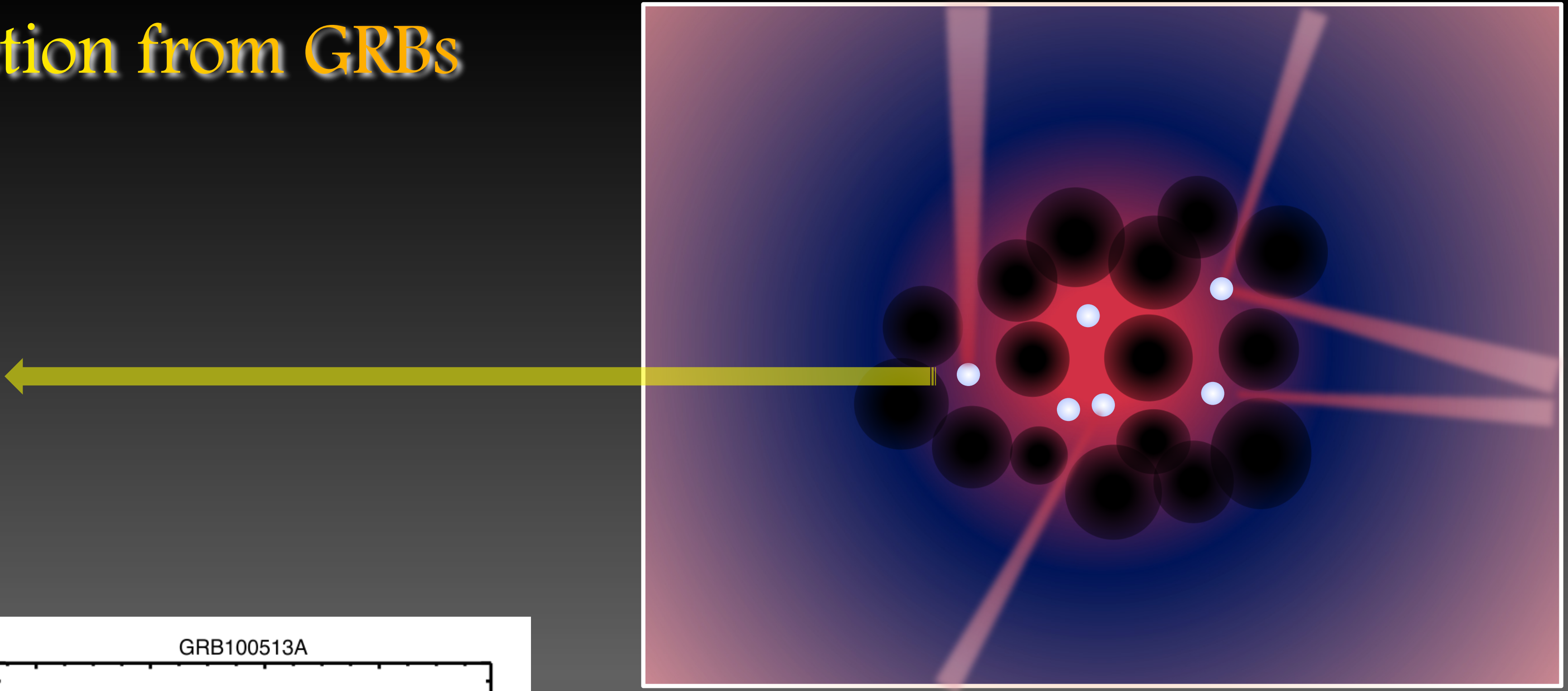


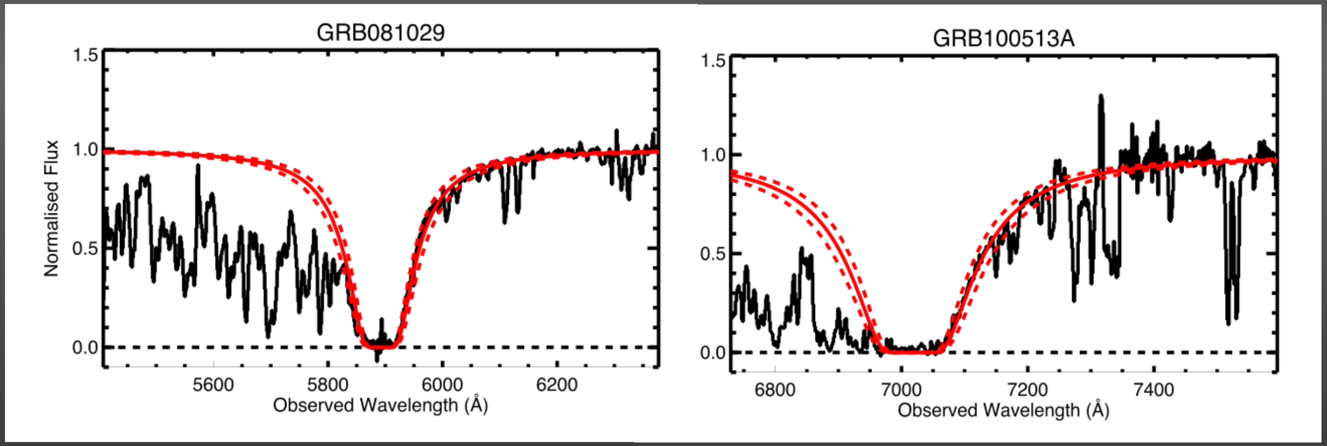
Important because emission line measures:

- are rather crude, especially for faint galaxies, and require calibration, typically with brighter (usually lower redshift) systems.
- obviously biased to the brightest ionized star forming regions, and not necessarily a good tracer of the prior enrichment.

Ionizing escape fraction from GRBs





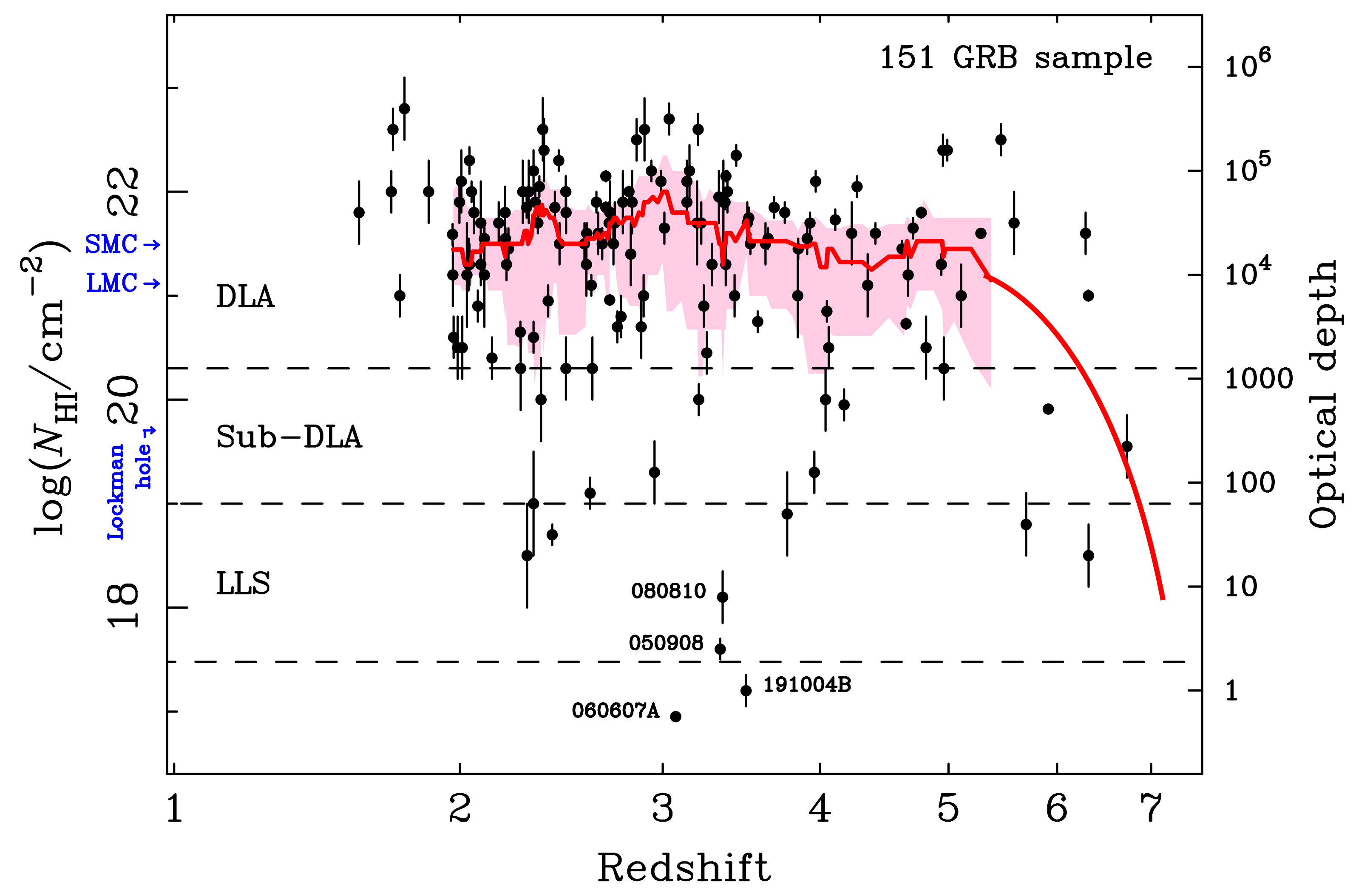


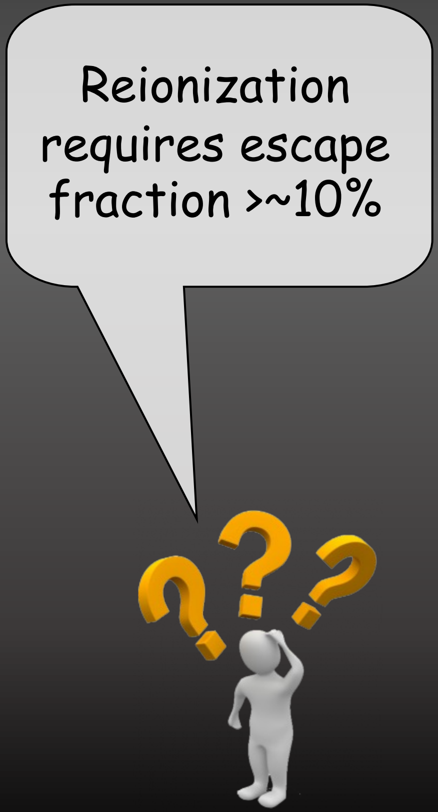
Directly measure N(HI) from Ly-a damping wing fit to afterglow spectra => f_{esc}.

(Hydrogen) ionizing radiation very easily blocked by neutral H. If massive stars responsible for reionization, there need to be some sight-lines to massive stars that are largely free of HI.

HI column density evolution

NT et al. (2019) - updated





High column densities seen in optical spectra of most 2<z<5 GRBs suggest escape fractions for *these stellar pops* of < 2 %.

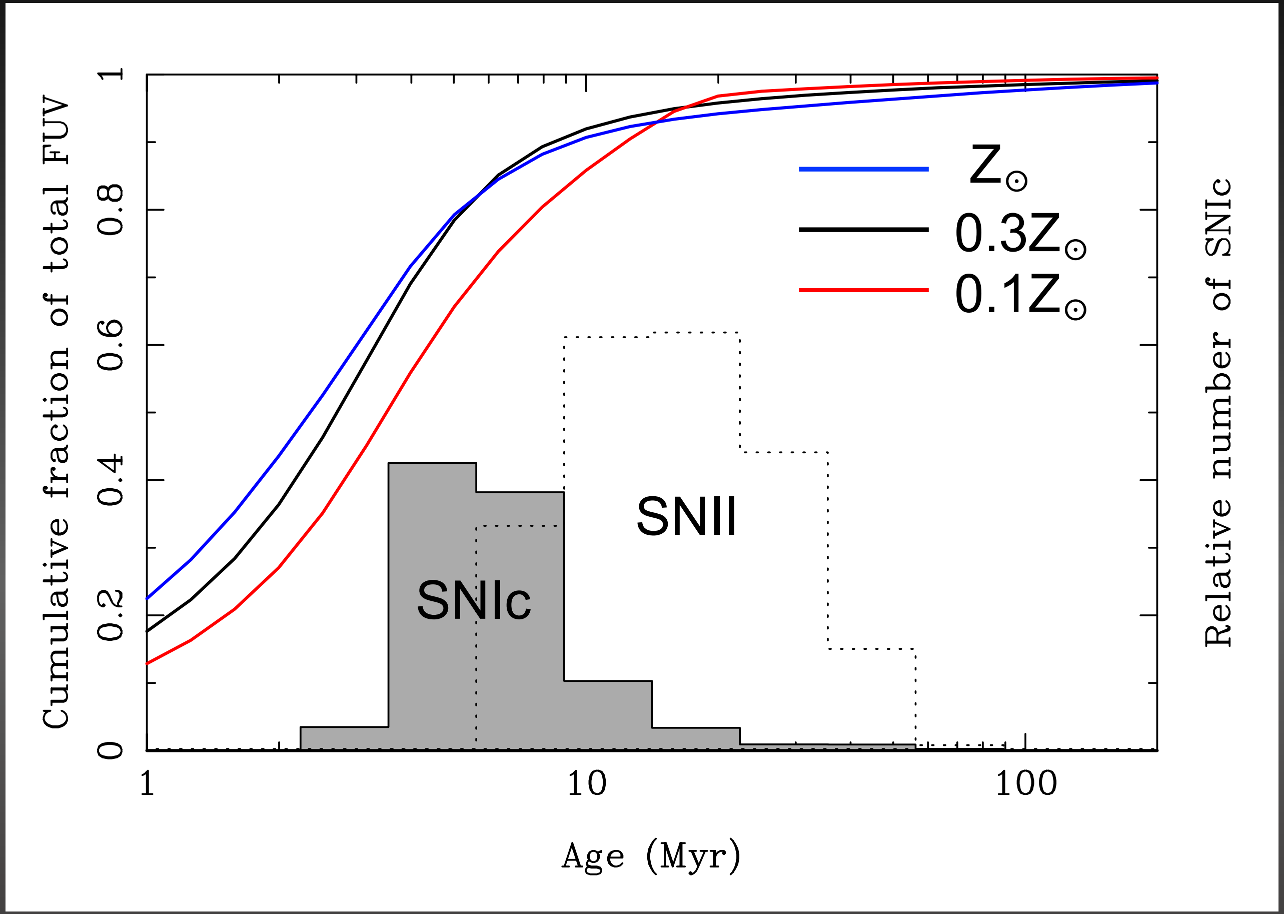
HI column density evolution

Single burst stellar population synthesis, based on binary evolution BPASS-2 models (Stanway & Eldridge 2016) – most production is $t < 10$ Myr, consistent with typical GRB progenitor lifetimes (and SNIc).

Thus, reionization by stars seems to require rapid evolution in galaxy population to z~8, and is problematic even at z~3-5.

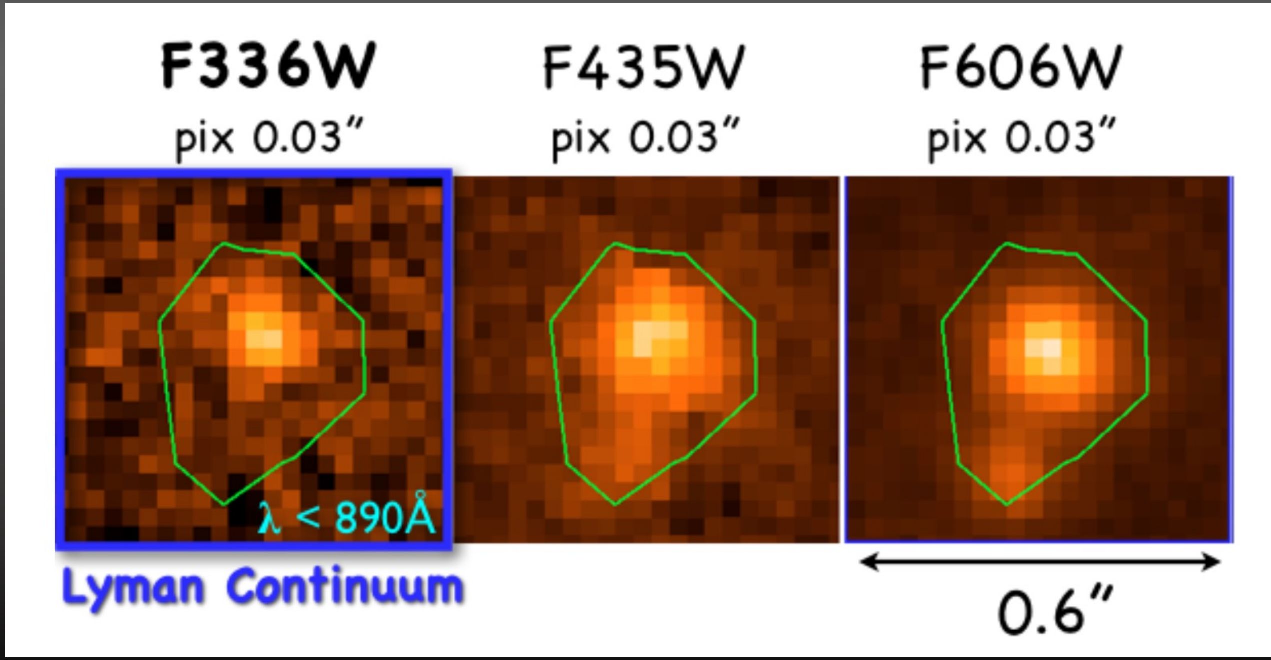
e.g during reionization, much SF is in very small galaxies which are more easily cleared of neutral gas?

Or, 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?



Tension with classical approach?

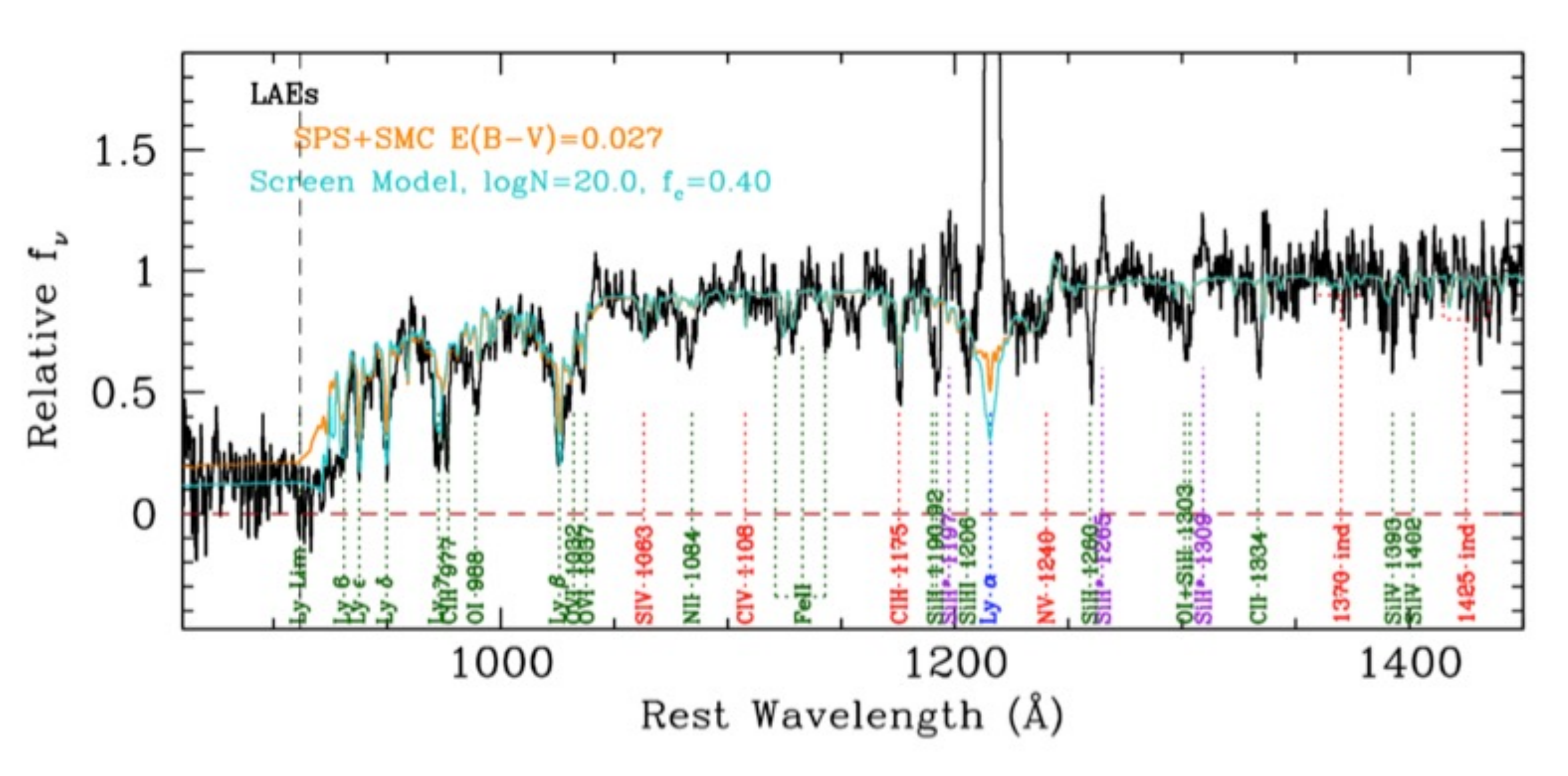
- Search directly for emission below the Lyman limit (EUV) and compare to λ~1500 Å (FUV).
- Need to know/model underlying spectrum.
- Need to account for IGM absorption (only tractable at z<~4).
- Required intrinsically bright targets (bias?), and prone to confusion by lower redshift sources on line-of-sight.



e.g. Vanzella et al. 2016
z=3.2 galaxy, f_{esc}>0.5

Tension with classical approach?

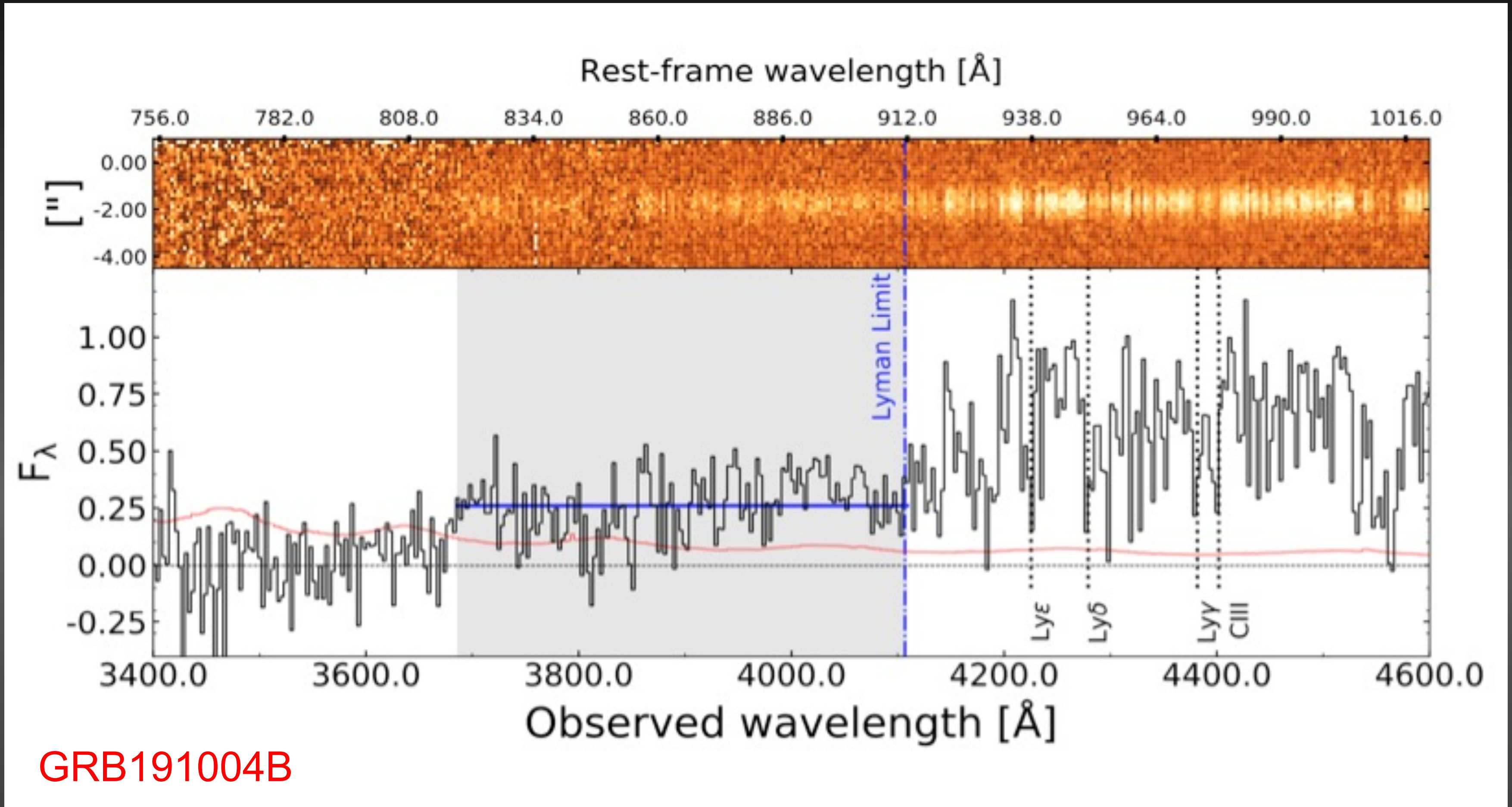
- Steidel et al. 2018 z~3 LBG galaxy sample: stacked spectra show significant Lyman continuum, particularly when restricted to strong Ly-a emitters.



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

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

Low column systems are rare!

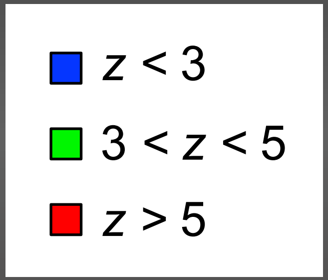


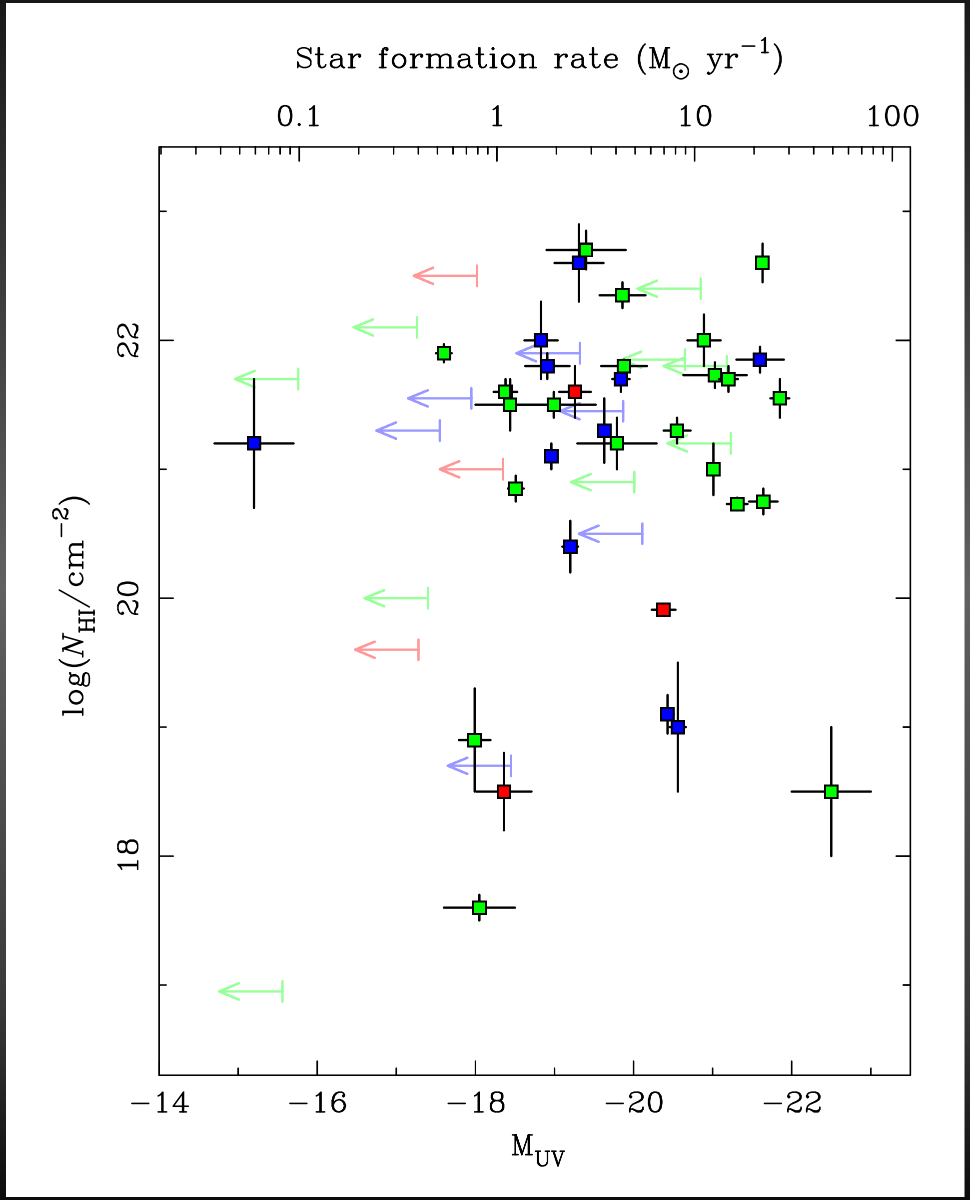
Vielfaure et al. 2020 anaysed three ($z \sim 3$) GRBs where this comparison can be made, finding broad validation of the method.

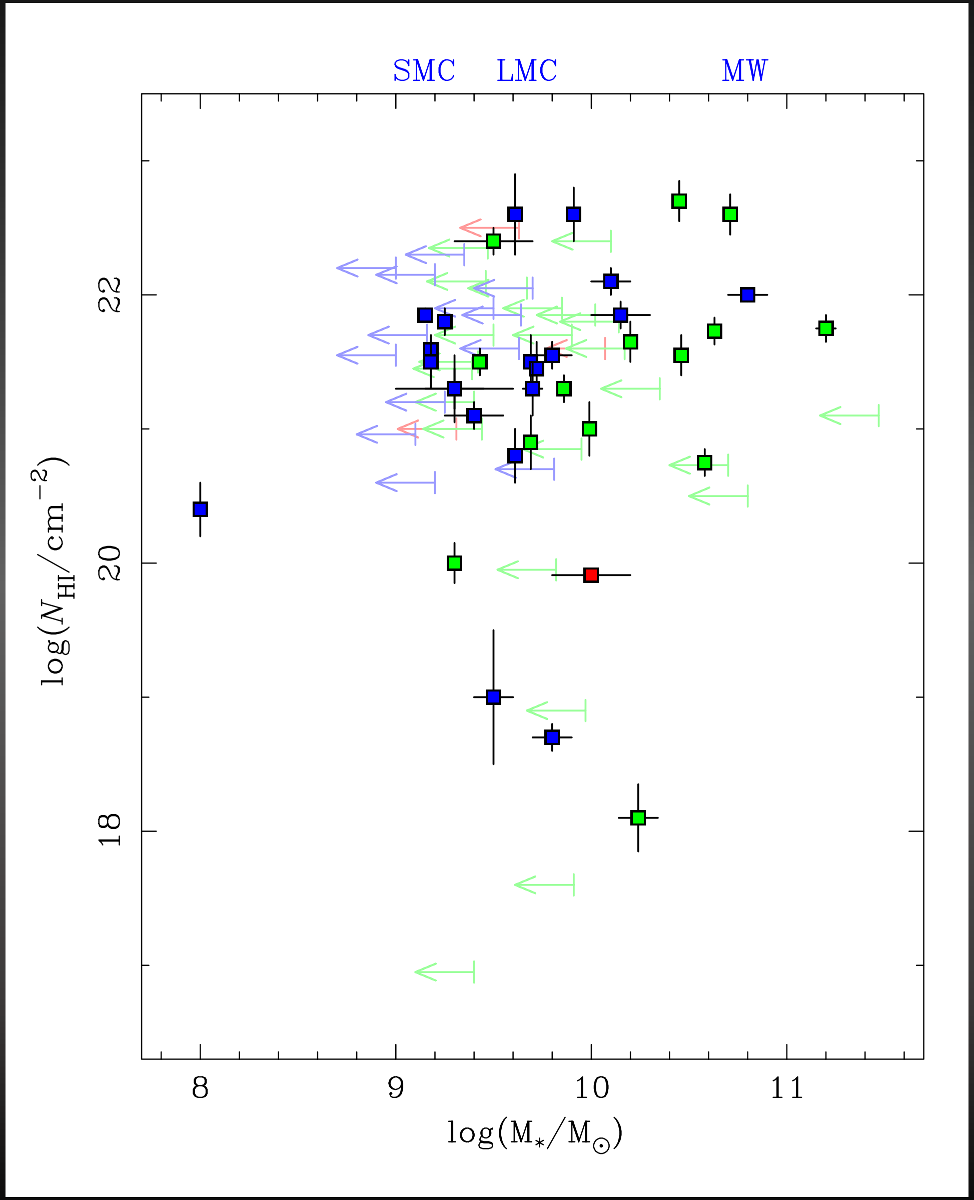
GRB 191004B is only case where Ly-a emission seen from host, but small statistics limit search for any trend of f_{esc} with Ly-a.

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

Nor with stellar mass

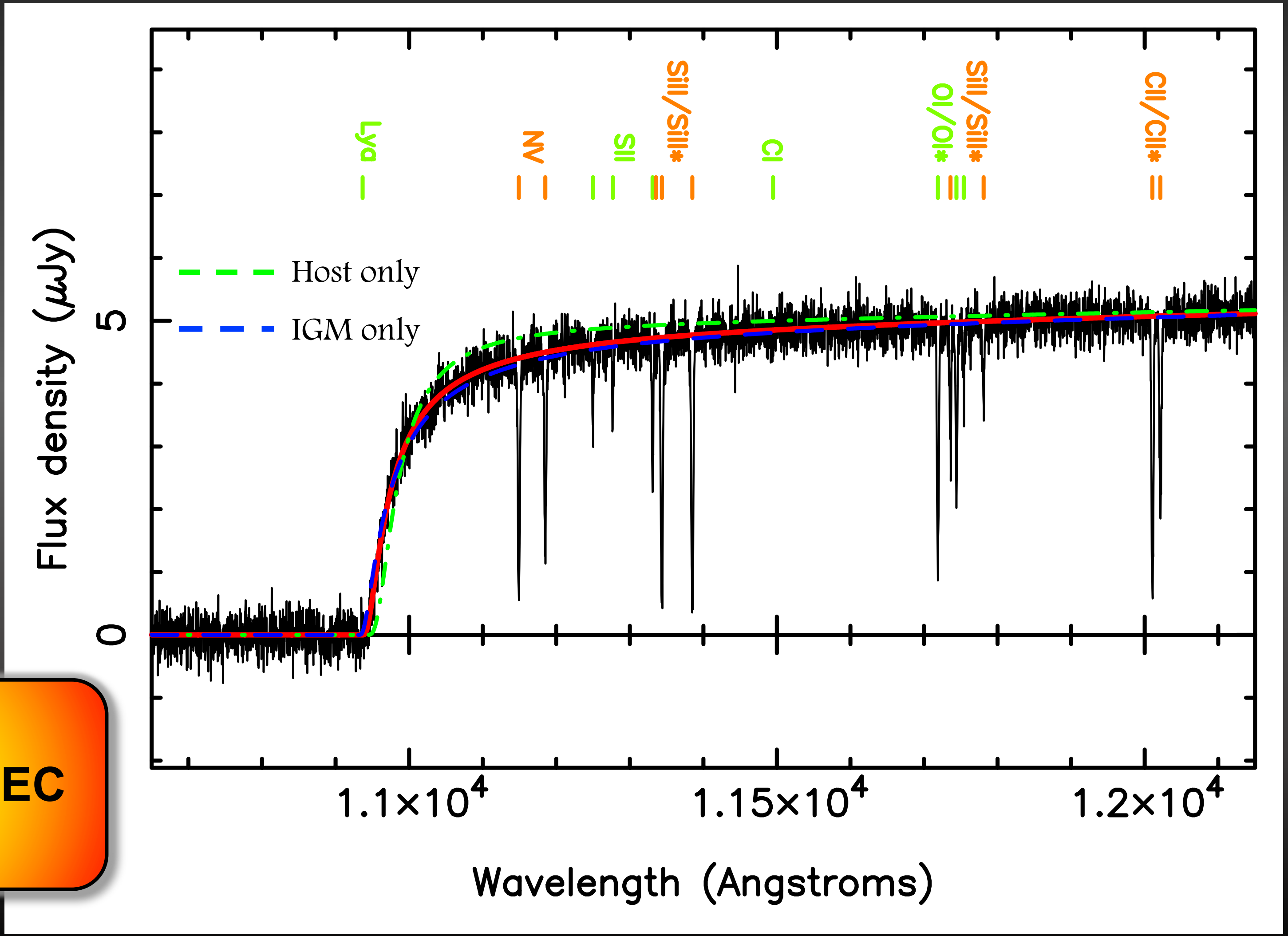






Reionization: constraining demand

Technically, obtaining host N(HI) at high-z requires decomposition of host and IGM contributions to Ly-alpha damping wing, with good S/N spectra (and ideally knowledge of systemic redshift from metal lines).



With JWST, potential for high S/N even a few days post-burst: this example is a rather typical afterglow (H_{AB}~22; 5 hr exposure)

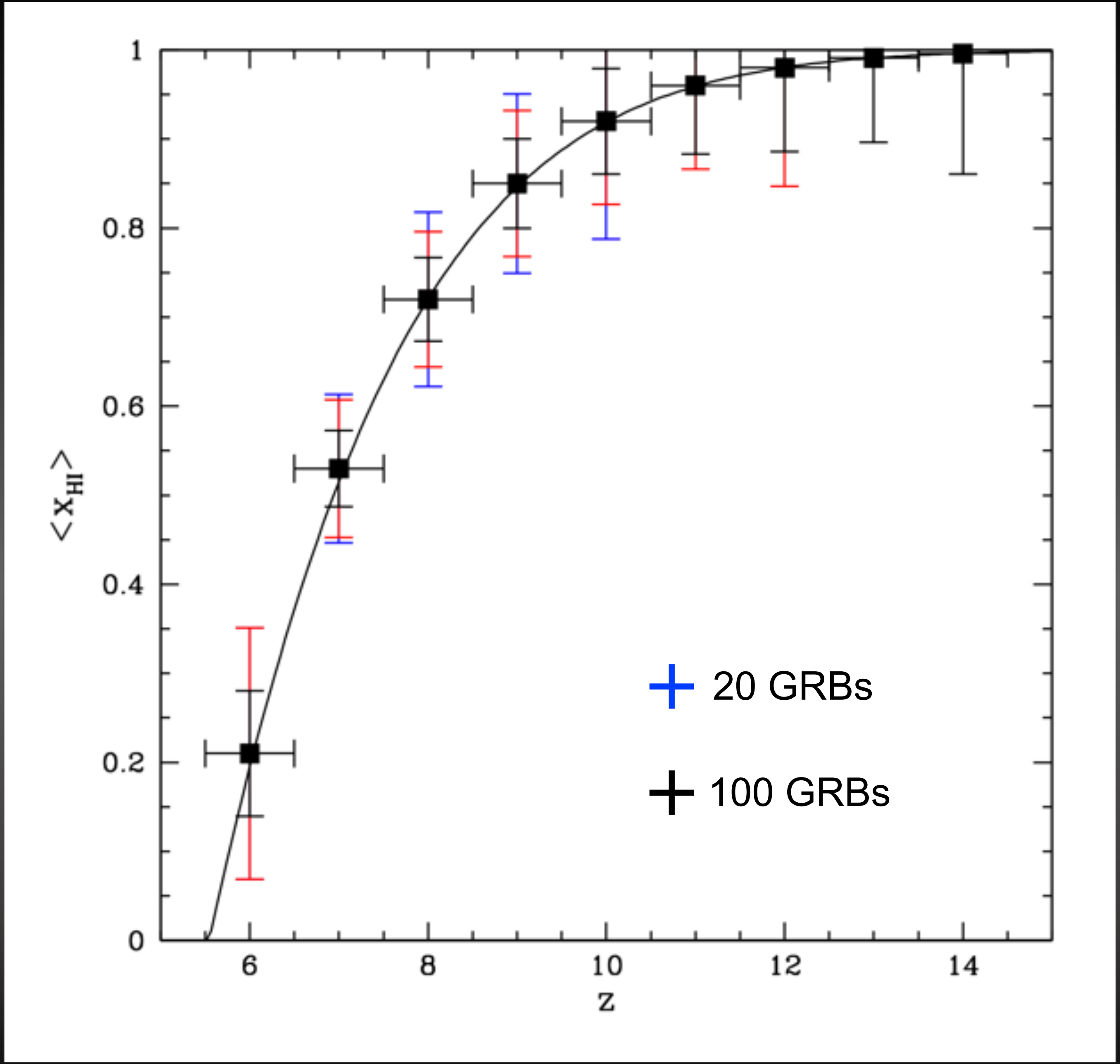
Simulated JWST/NIRSPEC spectrum

Time-line of reionization

The evolution of the neutral fraction (X_{HI}) of the IGM can be quantified with a sample of high-z GRB afterglows.

Lidz et al. 2021 – simulated GRBs in EoR. In early phases, small numbers of GRBs compensated by lower "cosmic variance" of the universe.

GRBs, being produced in typical (small) galaxies, produce a more representative view.



Conclusions

- GRBs offer an independent route to establishing the rate of star formation, dust and metal enrichment through cosmic history.
- JWST (and subsequently 30m scopes) nIR afterglow spectroscopy provides unique window on star-forming galaxies and ISM/IGM in high redshift universe.
- Currently difficult to reconcile the observed low escape fraction of ionizing radiation (<2%) from $z < 5$ GRB *locations* with the requirement to reionize the intergalactic medium (~10%). ie. seems to require rapid evolution in galaxy population to $z \sim 8$, or fine tuning of timescales such that star formation is very bursty (even in lower redshift GRB hosts) *and* very high escape fractions arise after typical GRBs have exploded.
- The same spectroscopy will probe the average IGM neutral fraction proximate to each burst, and hence the timeline and topology of reionization, and emission properties of hosts.
- Future missions, such as THESEUS, required to build significantly larger high-z samples.