THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Future Constraints on the Reionization History from GRB Afterglows

Nicholas White (GWU), Tzu-Ching Chang (JPL), Adam Lidz (UPenn), Alex Kann* (Goethe University Frankfurt), Andrew Levan (Radboud Univ) & the *Gamow Explorer* team

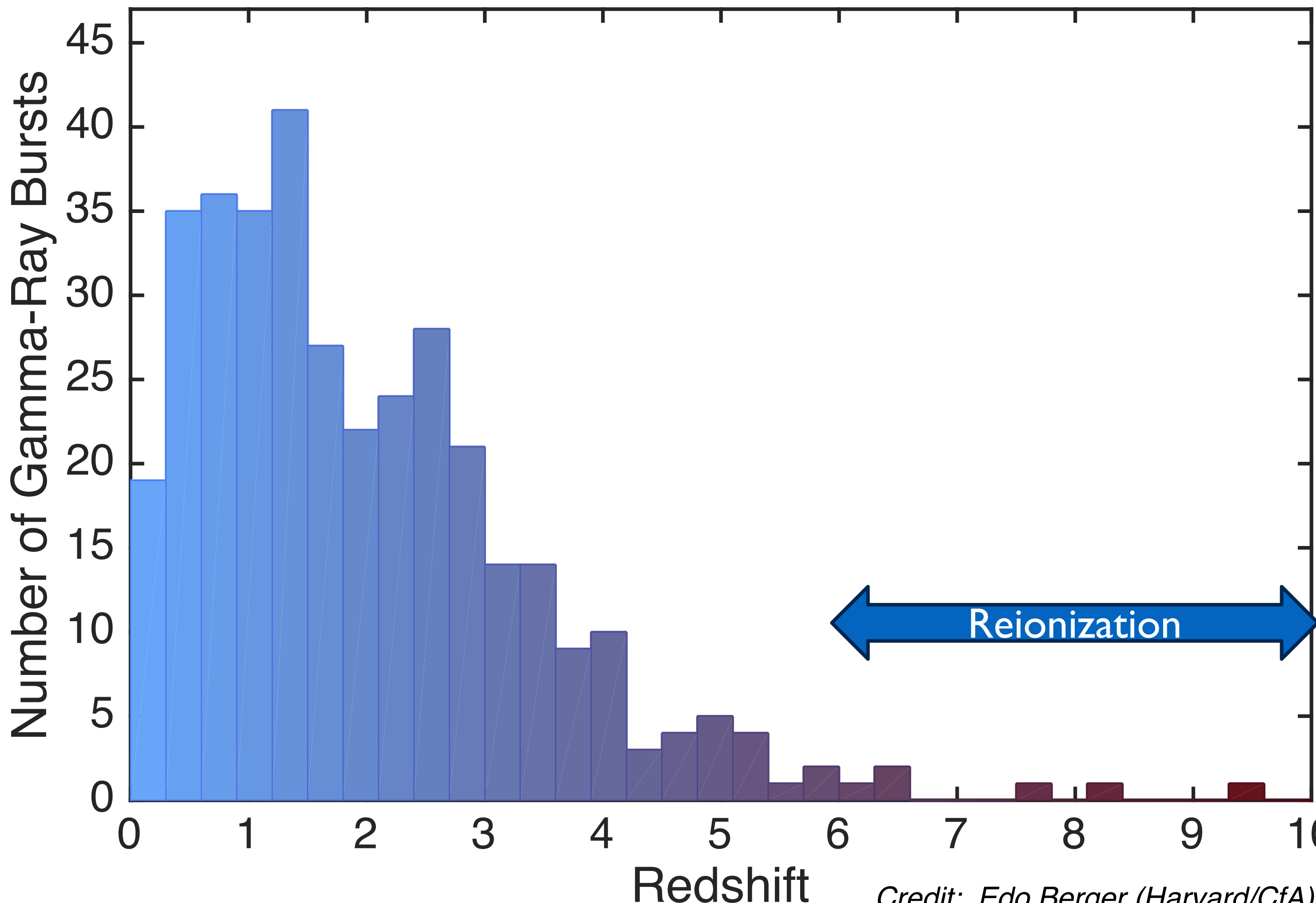
Based on
Lidz et al., 2021, ApJ 917, 58
https://arxiv.org/abs/2105.02293
Kann et al., 2024, A&A, in press
https://arxiv.org/pdf/2403.00101

* Alex Kann passed away March 2023

11th Fermi Symposium Sept 12, 2024

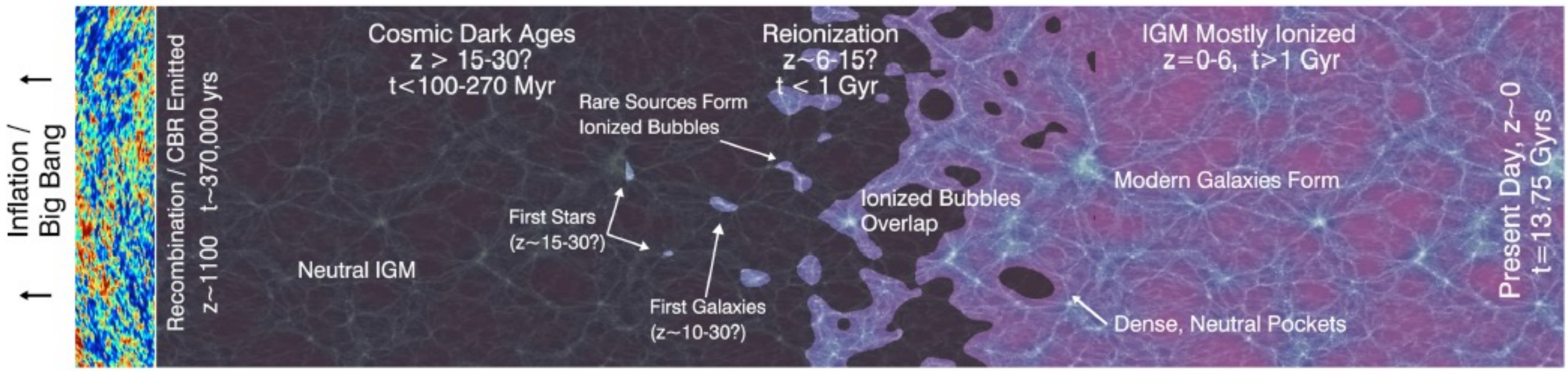
Redshift Distribution of LGRBs

Mostly Swift + ground follow up determined *redshift*



Credit: Edo Berger (Harvard/CfA)

Epoch of Reionization



Robertson+ 2010

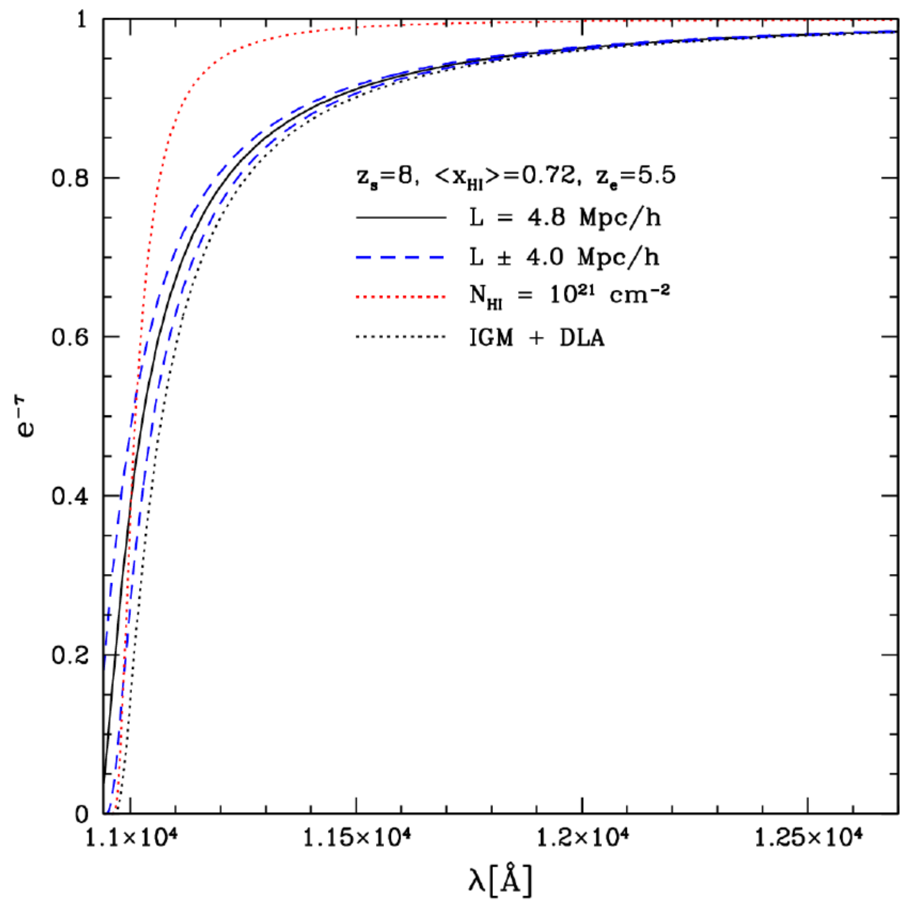
- When？(Fraction of volume in ionized phase versus redshift)
- How？ (Bubble Sizes)
- Who？ (Properties of Ionizing Sources)

GRB afterglows probe the ionization state of the IGM during reionization

Key signature is Ly-α red-side damping wing (Miralda-Escudé 1998). In a significantly neutral universe, IGM damping wing optical depth leads to absorption far redward of Ly-α at source redshift:

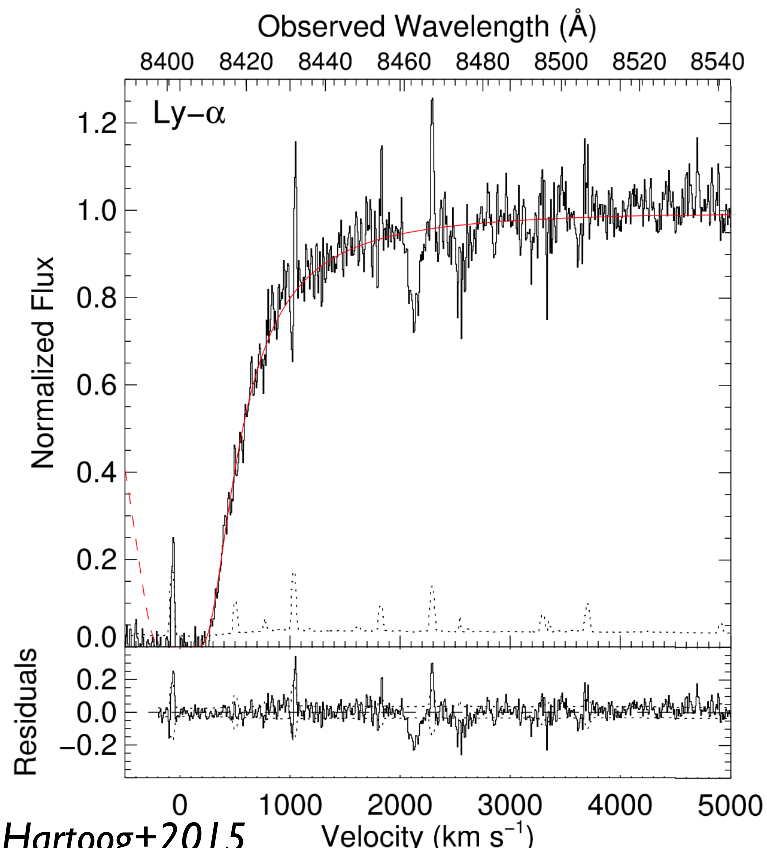
$$\lambda \geq \lambda_\alpha(1 + z_s)$$

At e.g. z ~ 8 expect larger neutral fraction, shorter mean distance from GRB host to neutral gas, and smaller scatter which makes the damping wing stronger, less confusion with host DLA

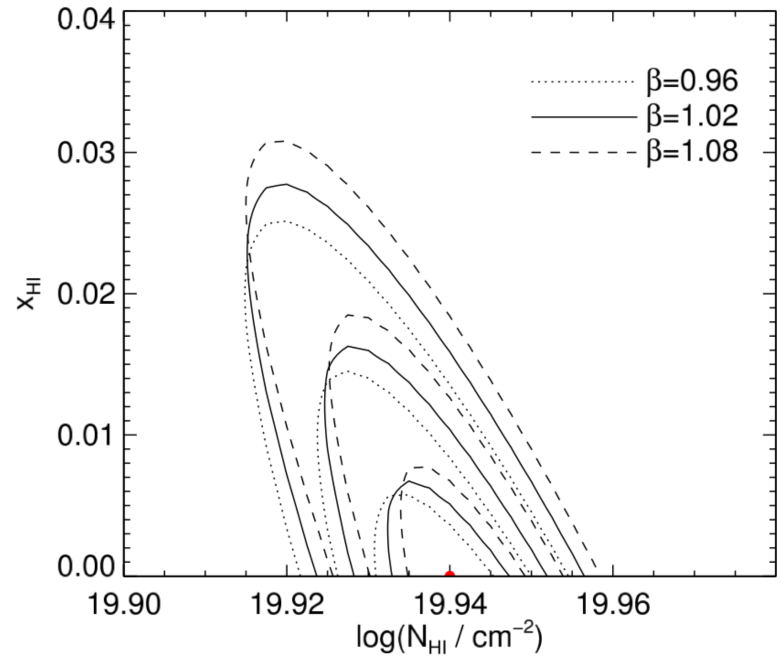


See also *Barkana & Loeb 2003, McQuinn et al. 2008*

GRB 130606A @ z ~ 5.91



Hartoog+2015



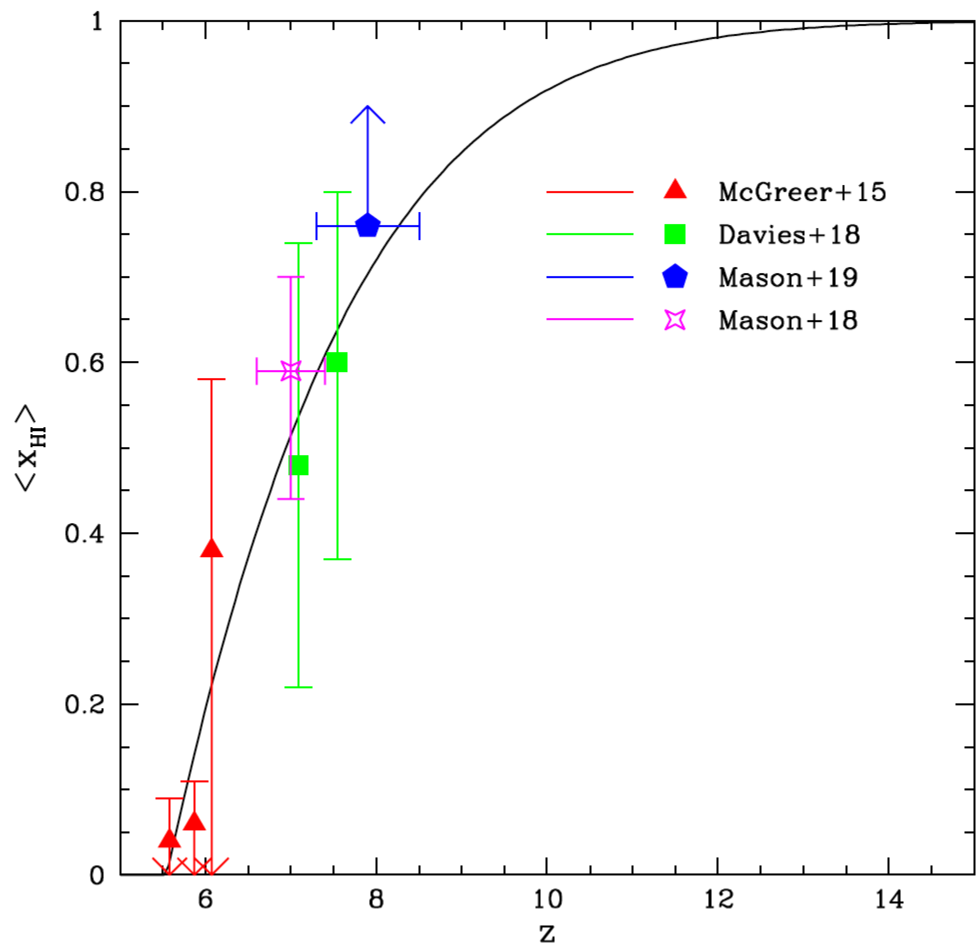
VLT spectrum Ly–α red wing well fit by host only (low column) absorption, and nearly fully ionised IGM

Fisher matrix forecasts

- Damping-wing feature in each afterglow spectrum described by three parameter model.
  - N_{HI} : column density of neutral hydrogen from local host galaxy.
  - L : size of ionized bubble around GRB host galaxy.
  - $\langle x_{HI} \rangle$: average neutral fraction, approximated as uniform outside host bubble.
- Forecast $\langle x_{HI} \rangle$ errors, marginalized over L, N_{HI}.

Fiducial ionization history

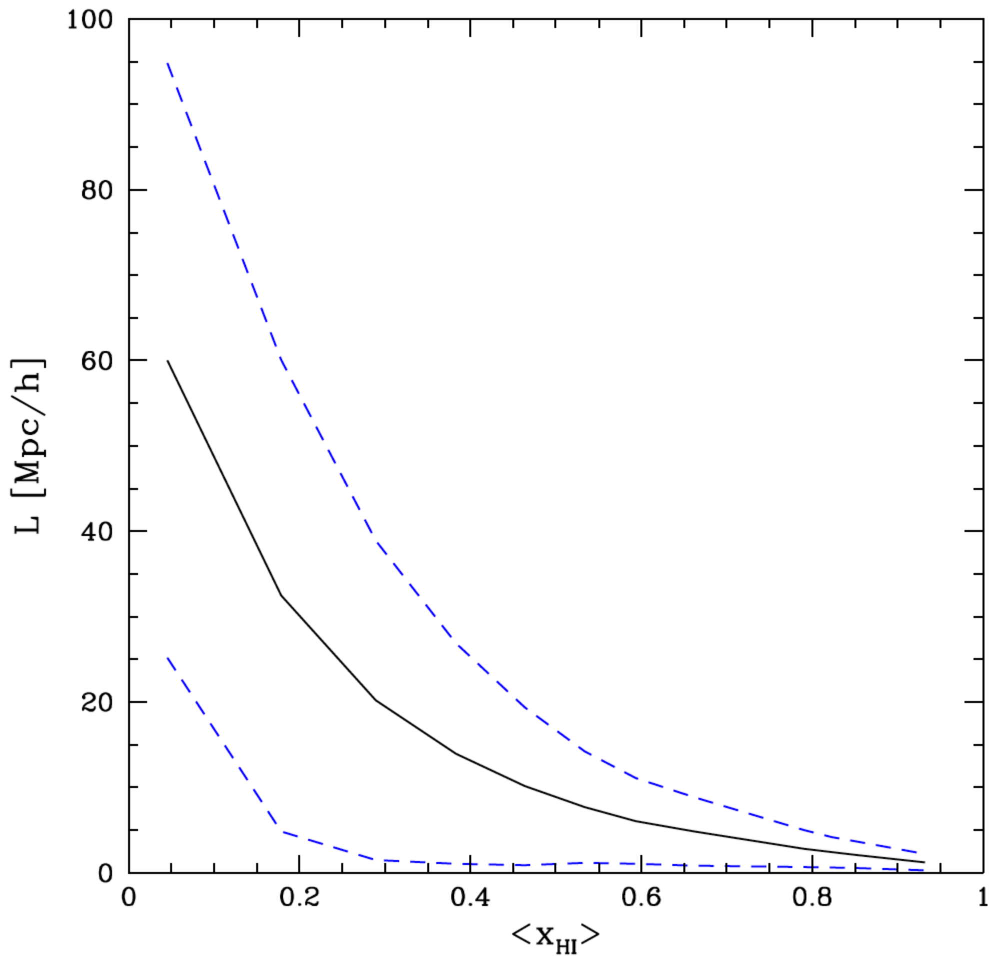
- Neutral fraction evolution model assumed.
- Consistent with current constraints.



Lidz+ 2021

Bubble size distribution

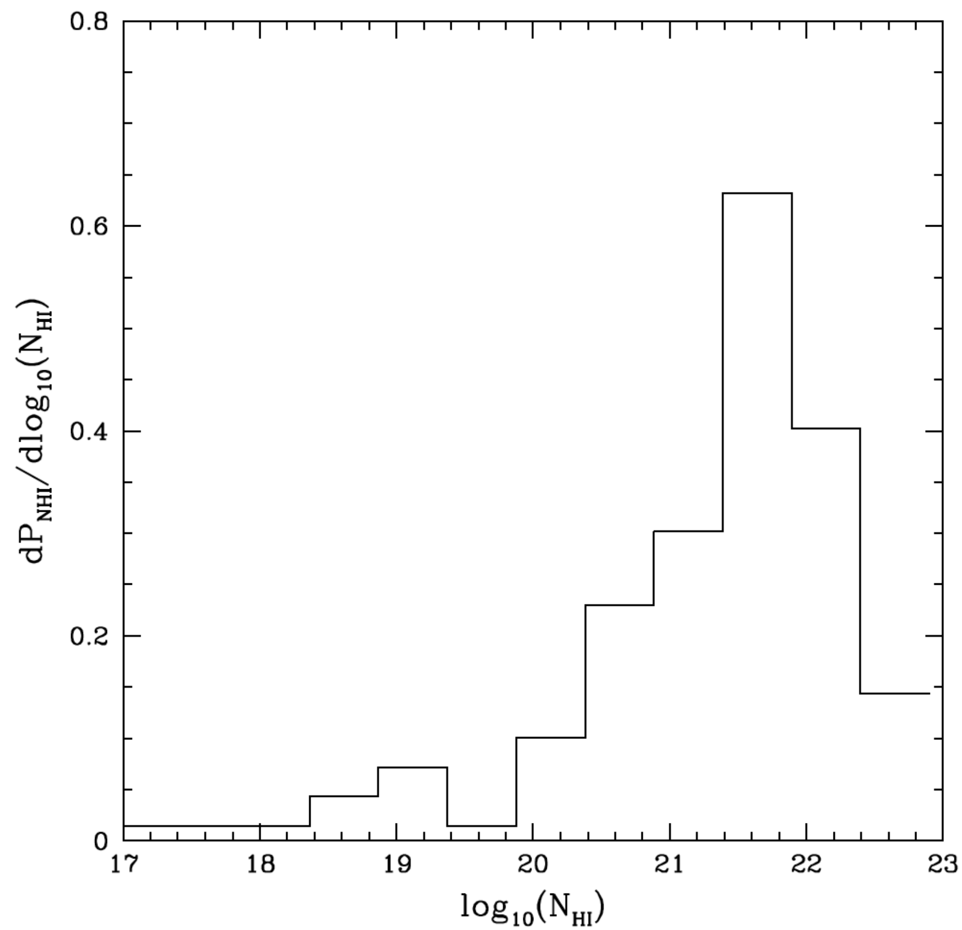
- Distance from GRB host to first neutral region extracted from reionization simulations (McQuinn+2007).
- Partly accounts for patchiness of reionization process.



Lidz+ 2021

Assumed Host Galaxy N_{HI} Distribution

- Empirical: from current GRB afterglow measurements, mostly at lower redshifts (Tanvir+2019).
- May be pessimistic assumption because escape fraction likely increases with redshift.

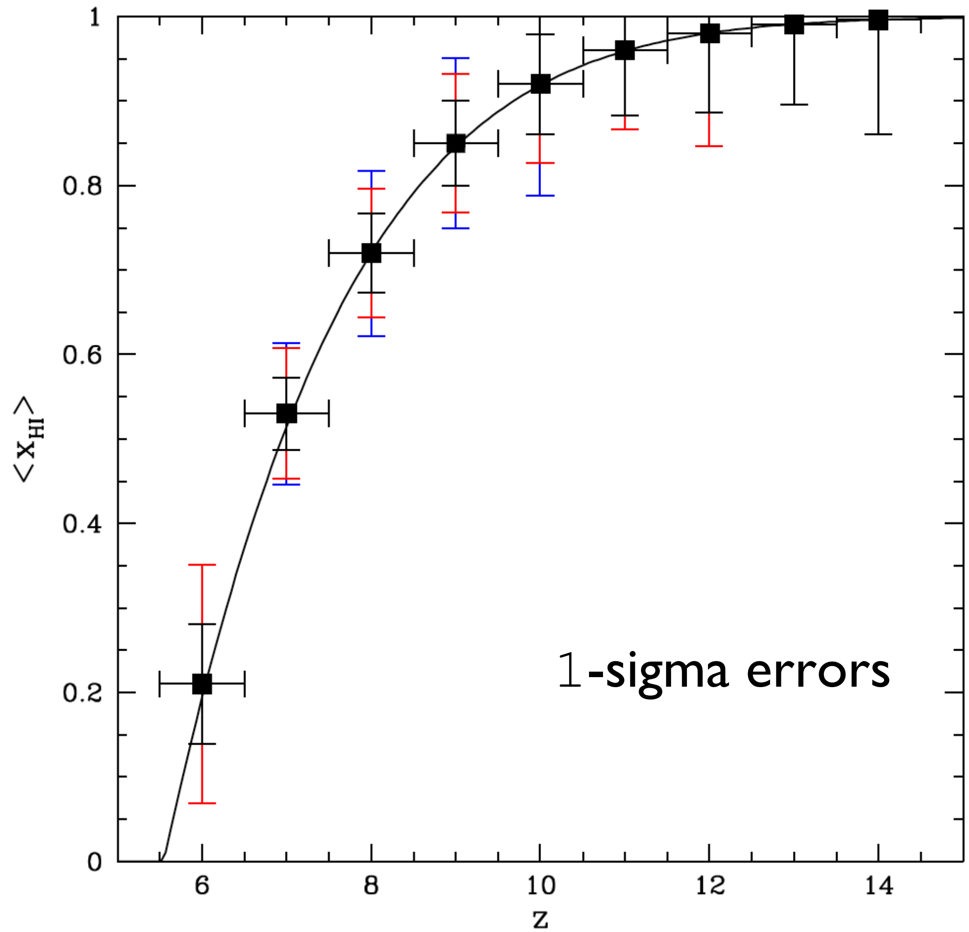


Lidz+ 2021

Forecasted constraints on reionization

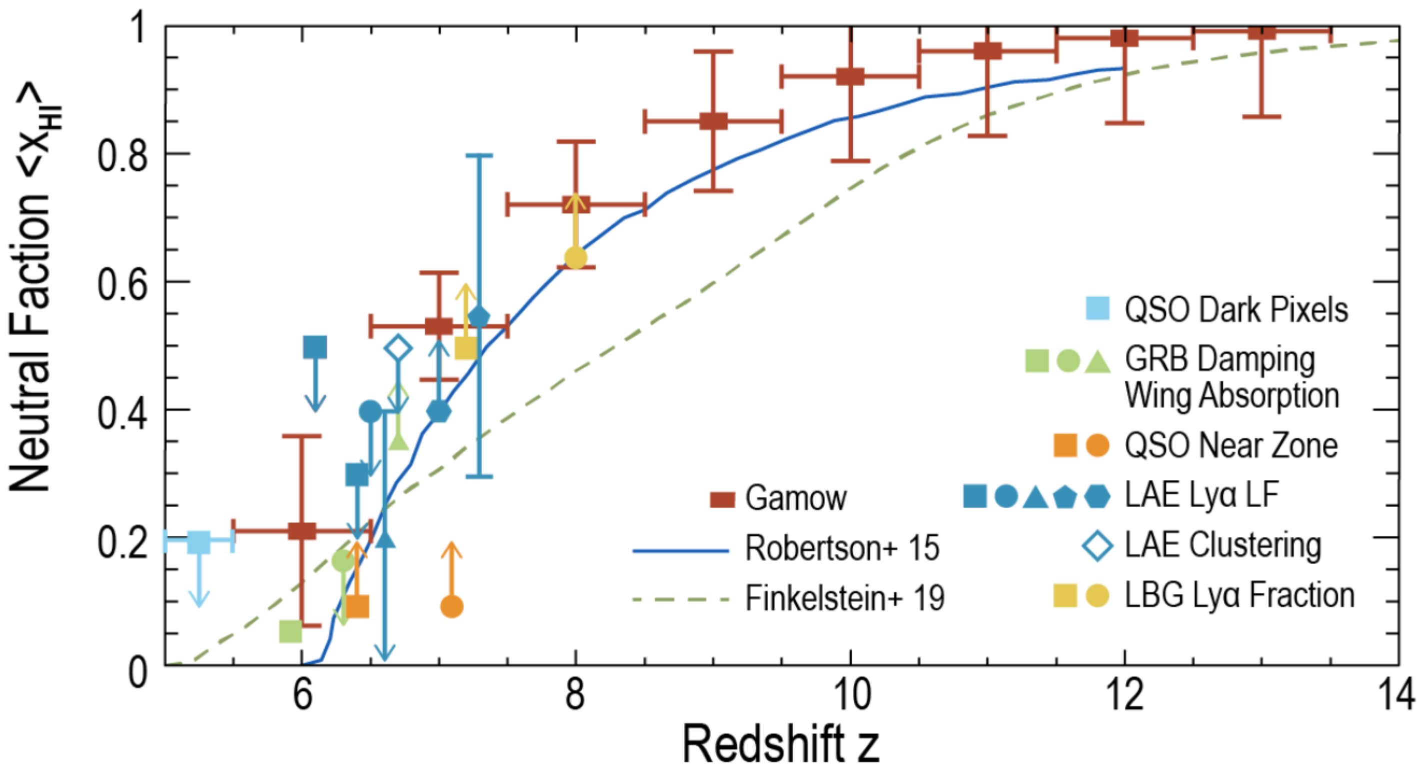
Each spectra assumed to have SNR=20 per R=3,000 resolution element at the continuum.

- Blue: 20 z > 6 GRBs
- Red: 31 z > 6 GRBs
- Black: 80 z > 6 GRBs



Lidz + 2021

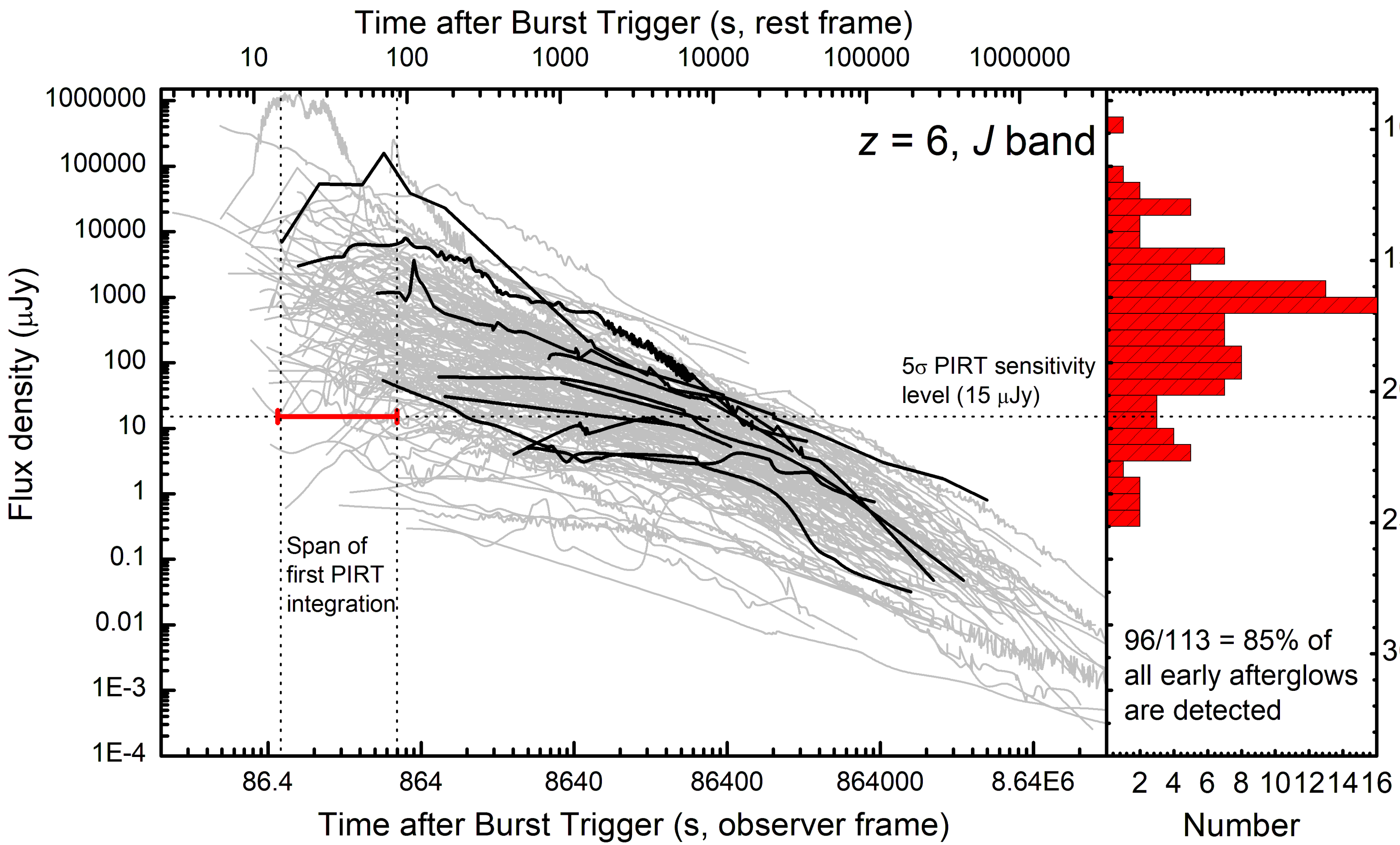
Reionization Constraints



High-z GRBs provide competitive constraints on the reionization history, that sample typical galaxies out to the highest redshifts

Follow up Spectroscopy Requirements

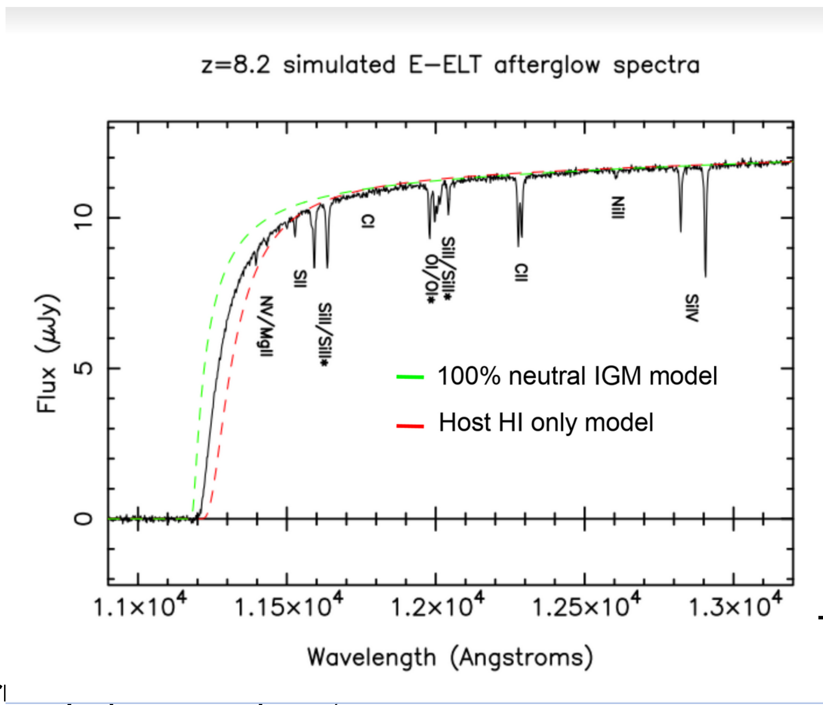
Predicted IR afterglow brightness by Kann et al (2024) based on 140 observed afterglows transformed to a common J-band *z* of 6



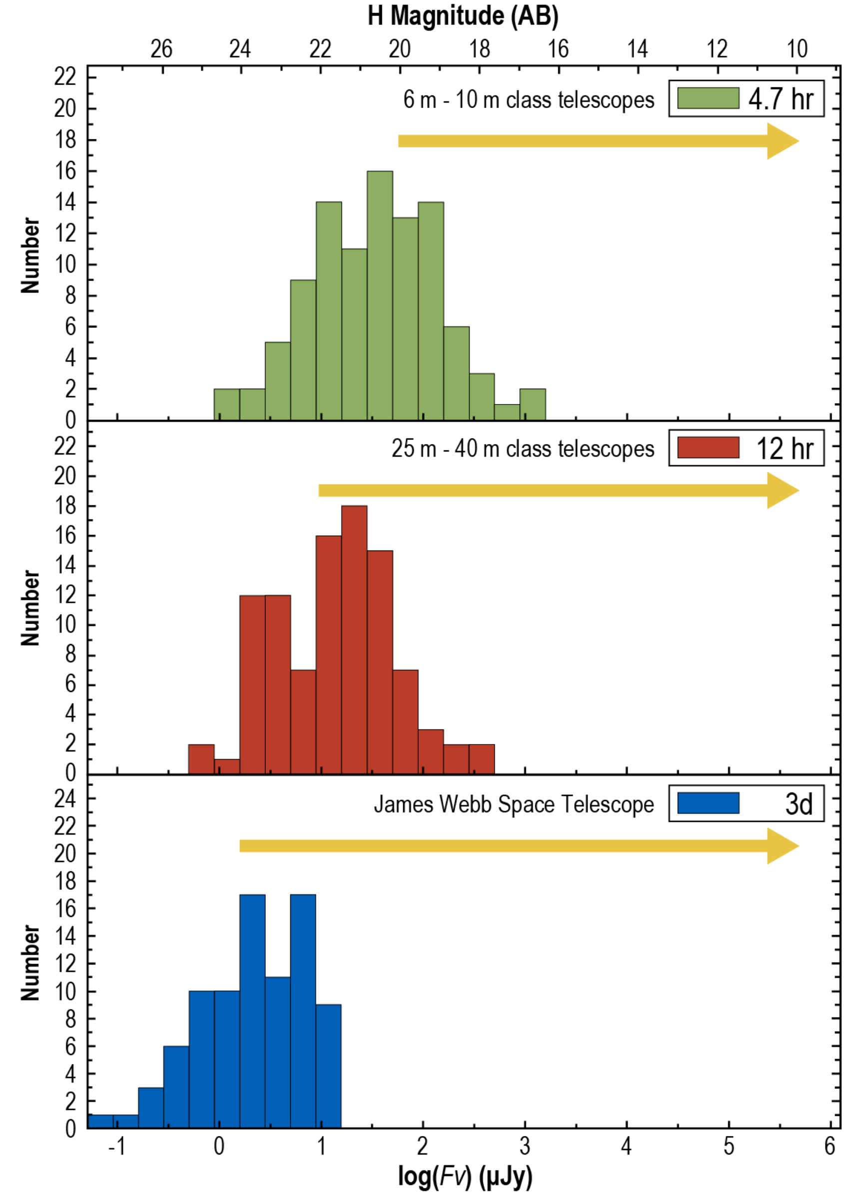
Follow up Spectroscopy Requirements

Afterglow must be bright enough to obtain NIR R > 2500 spectroscopy with SNR of >20

- Ground using 6 to 10m telescopes (Magellan, Keck, GTC, Gemini, VLT) within hours
- Ground ELTs within 12 to 24 hr
- Space JWST 2-3 days – disruptive TOO



Tanvir



z = 8

Kann et al (2024)

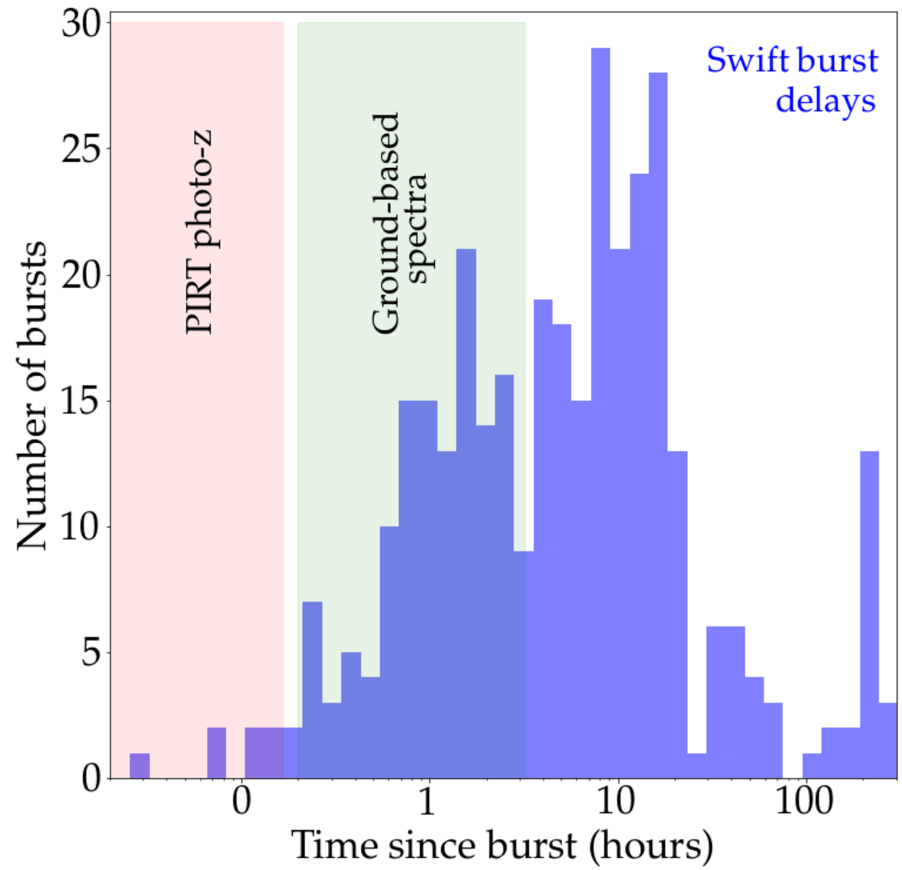
Delays in obtaining redshifts for GRBs in the *Swift* era

Swift follow-up retrieves only one third of GRB redshift!

Of that only Swift UVOT redshift determinations are within the window required to trigger follow-up NIR spectroscopy

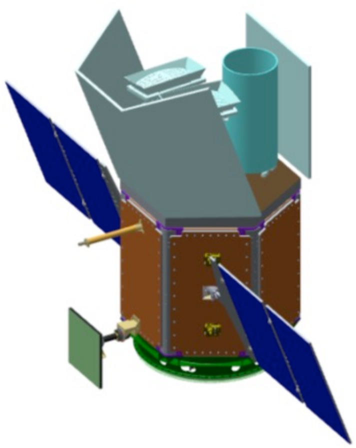
The response times required for an initial photo-z redshift determination and R > 2500 NIR spectroscopy are indicated

An onboard photo-z telescope essential to rapidly recover >80% of redshifts

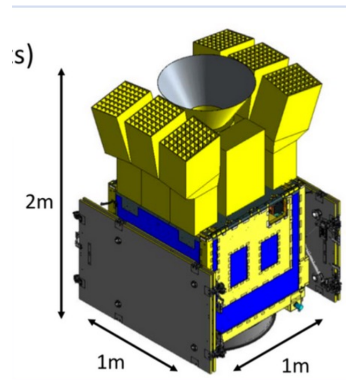


Compiled by Andrew Levan and published in Kann et al (2024)

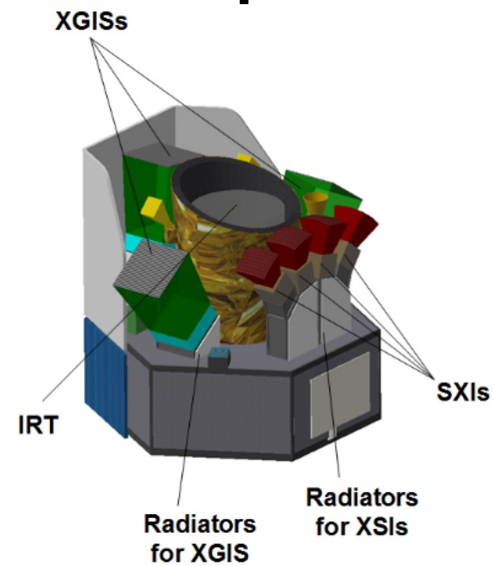
Future High-z GRB Mission Proposals



Gamow Explorer
White+20



Hi-Z GUNDAM
Yonetaku+14

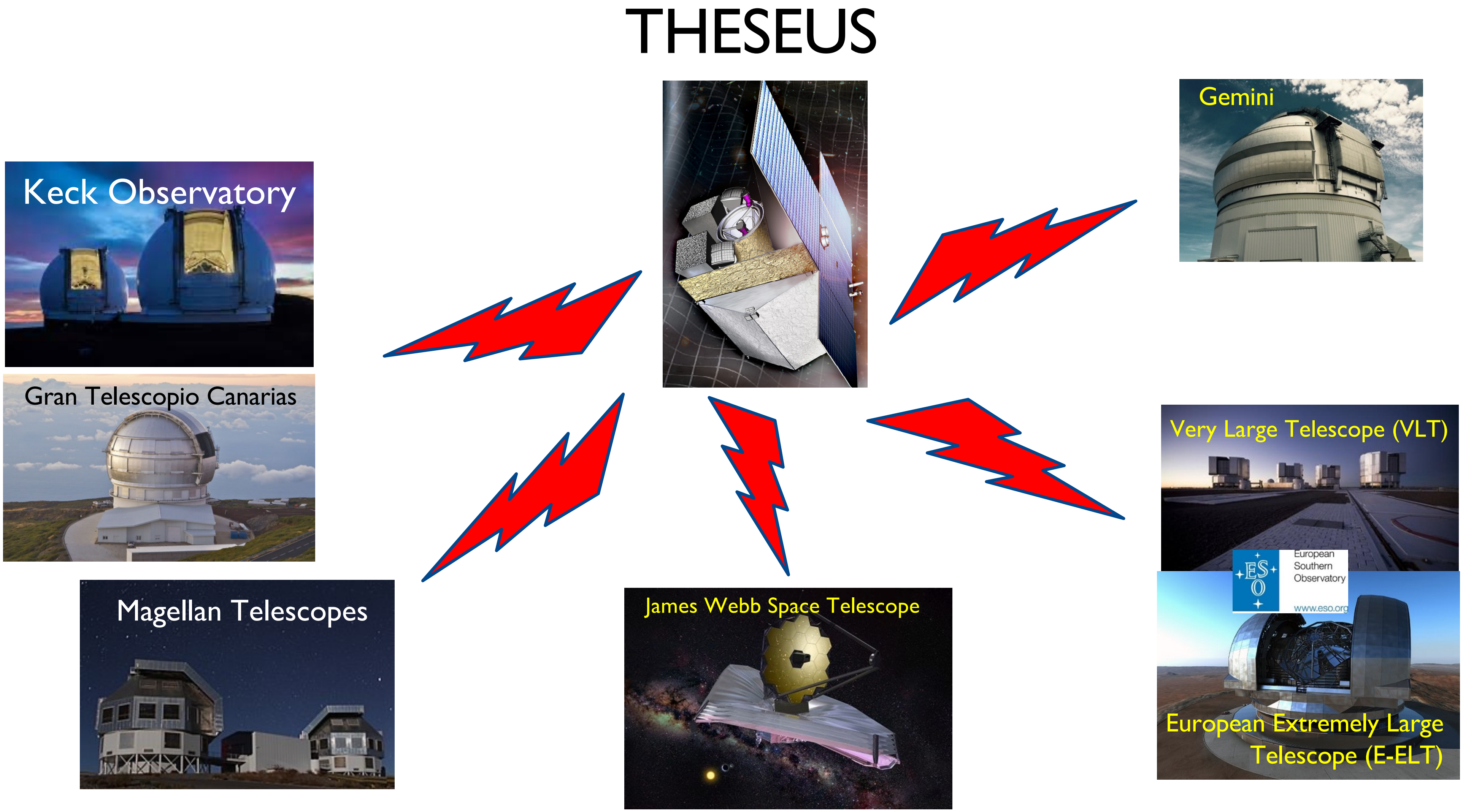


THESEUS
Amati+17

GRB Missions proposed to ESA (THESEUS), JAXA (Hi-Z Gundam), and NASA (Gamow Explorer) optimized for rapidly identifying high redshift GRBs using onboard IR telescope

Rapid follow-up by large telescopes is critical to catch the afterglow when it is at its brightest!

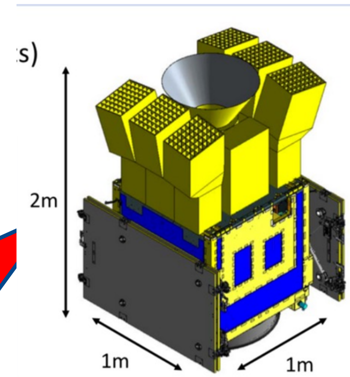
Follow-up Observations



>6m aperture NIR R>2500 resolution spectroscopy

Follow-up Observations

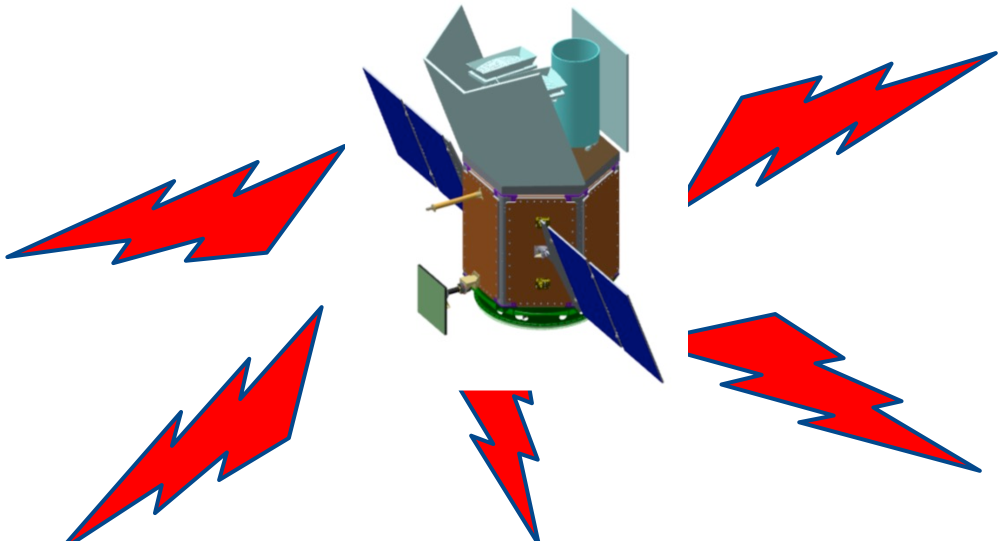
HiZ Gundam



>6m aperture NIR R>2500 resolution spectroscopy

Follow-up Observations

Gamow



>6m aperture NIR R>2500 resolution spectroscopy

GRBs Complement other Reionization Probes

Like dark energy or the Hubble constant there are many complimentary & independent ways to make the required measurements!

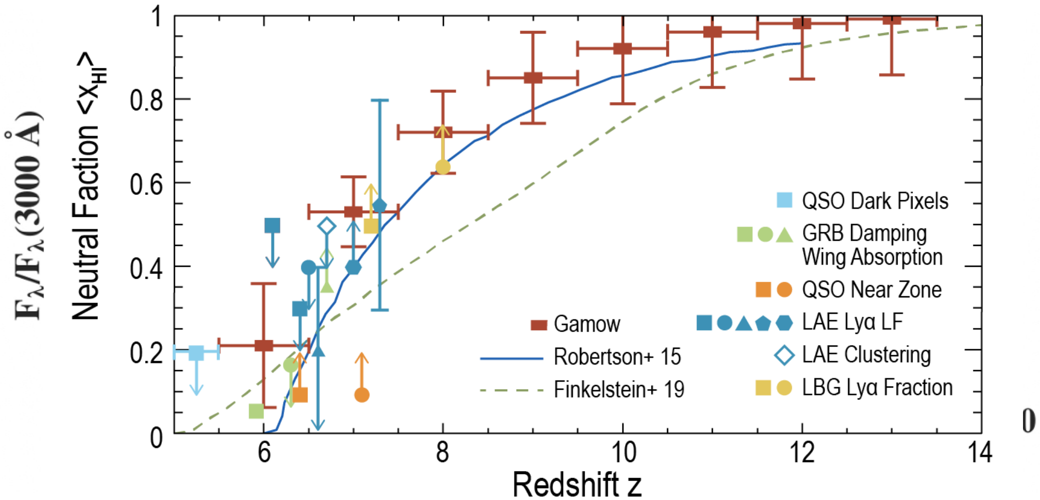
- GRBs have simpler unabsorbed continuum than quasar backlights, probe less-biased regions, access higher redshifts ($z \gtrsim 9$).
- Stacked measurements of Lyman-break galaxies (e.g. from JWST, Umeda+ 23): greater abundance than GRBs, access to high redshifts, but continuum-fitting uncertainties, DLA contamination
- Lyman-α Luminosity functions probe source counts, but not ionization state of intergalactic medium
- Redshifted 21 cm emission measurements are complimentary, but grapple with strong foreground contamination plus instrument challenges, with so far no signal detected
- CMB optical depth gives only integral constraint. Kinetic Sunyaev-Zel'dovich effect requires exquisite component separation.

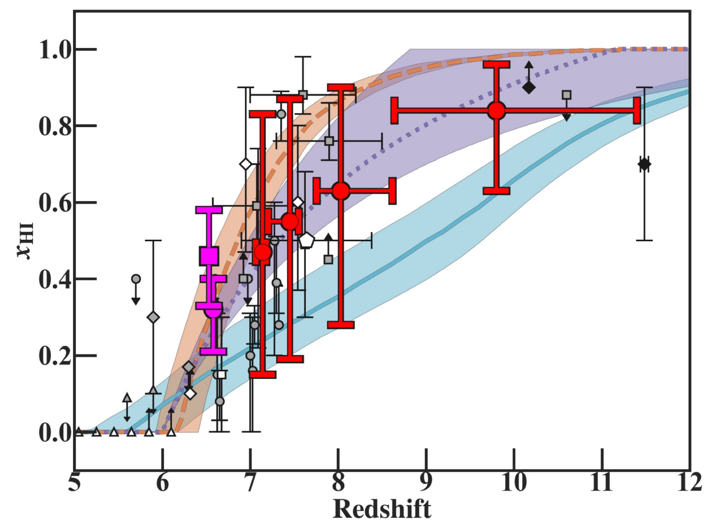
Summary

- GRBs have featureless simple power law continuum compared to quasar backlights, probe less-biased regions and potentially access higher redshifts z >~ 9
- Same spectra also measure many metal absorption lines, constraining chemical enrichment history in lower mass galaxies, plus also directly measure escape fraction from host galaxy
- Requires future GRB missions optimized to maximize number of high redshift GRBs, with an onboard photo-z IR telescope to provide rapid (within ~1000s) high-z GRB alerts to trigger large (>6m) NIR spectrographs

Backup

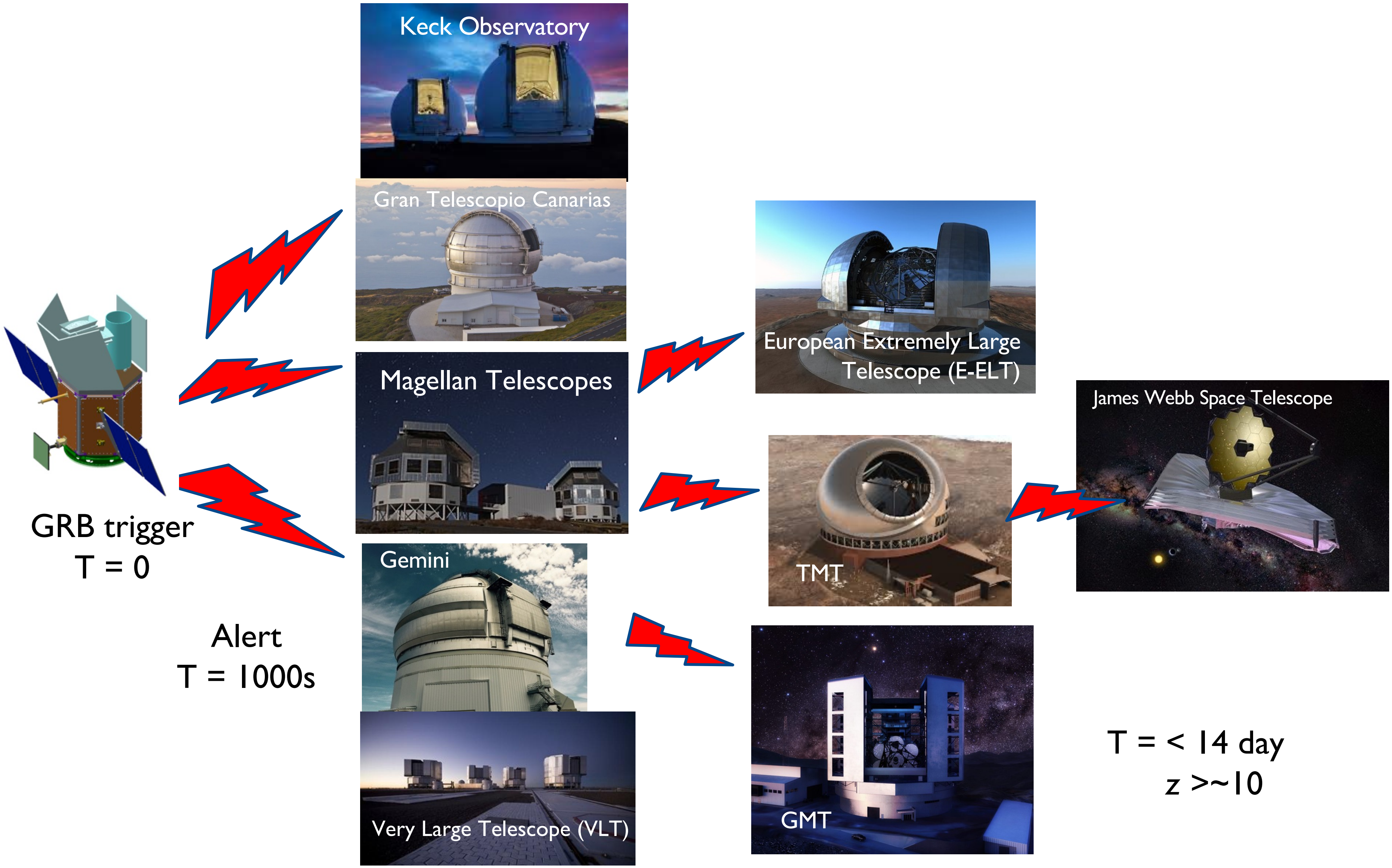
JWST Lyα Damping Wing in 26 Bright Continuum Galaxies





- Umeda et al (2023) construct 4 composite spectra from 26 individual JWST PRISM spectra binned by redshift, and find a clear evolution of spectral flattening towards high redshift
- The redshift evolution indicates reionization history, consistent with CMB measurements, but no constraint on speed of reionization
- Individual GRB JWST spectra are 100-1000 times brighter (2-3 days after GRB trigger), providing a precise measurement for individual galaxies to distinguish between reionization models

Follow up Spectroscopy Strategy



Follow up Spectroscopy Requirements

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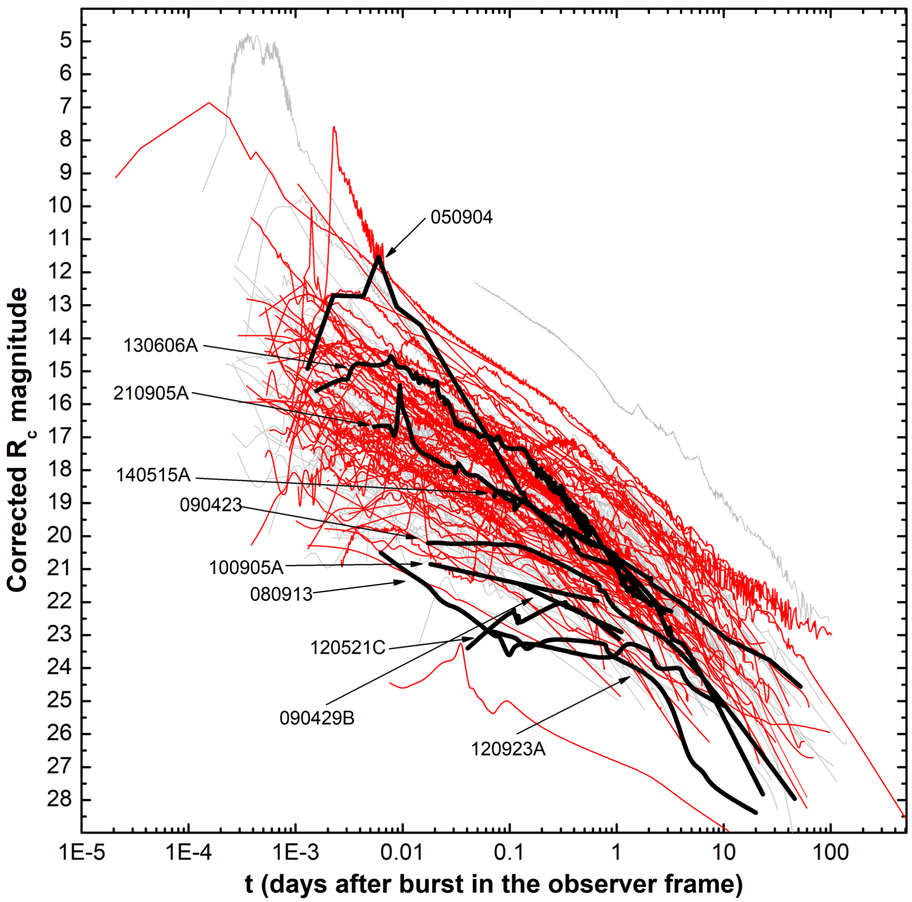
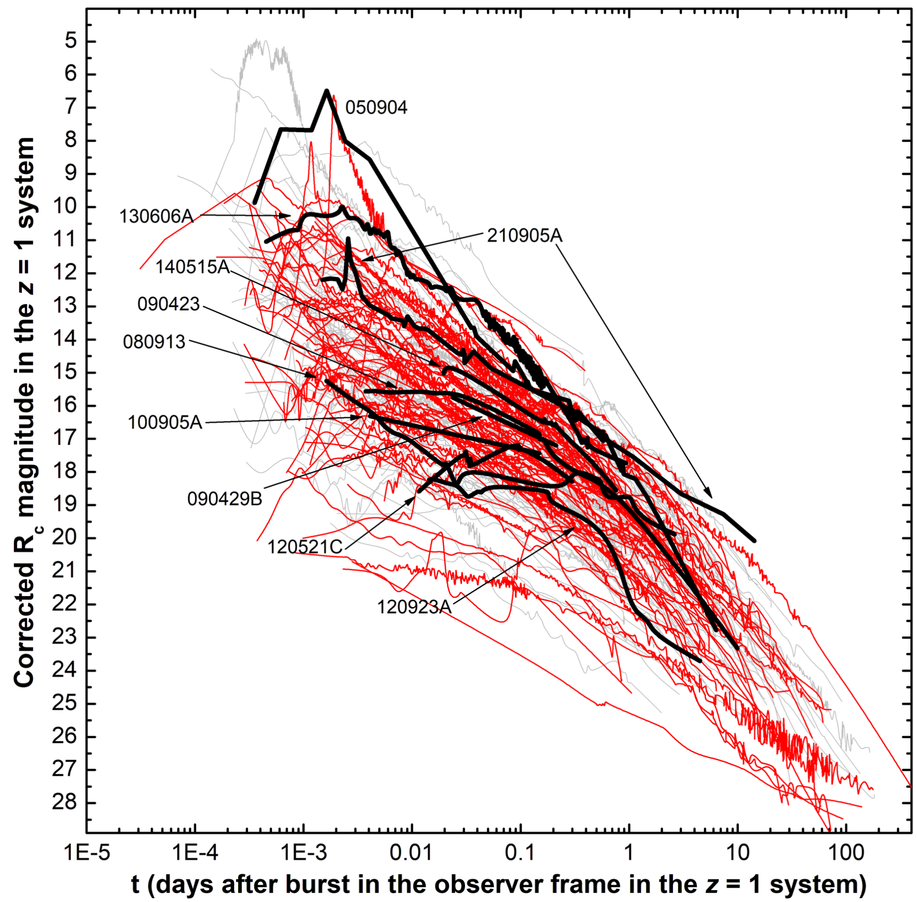
Observer frame



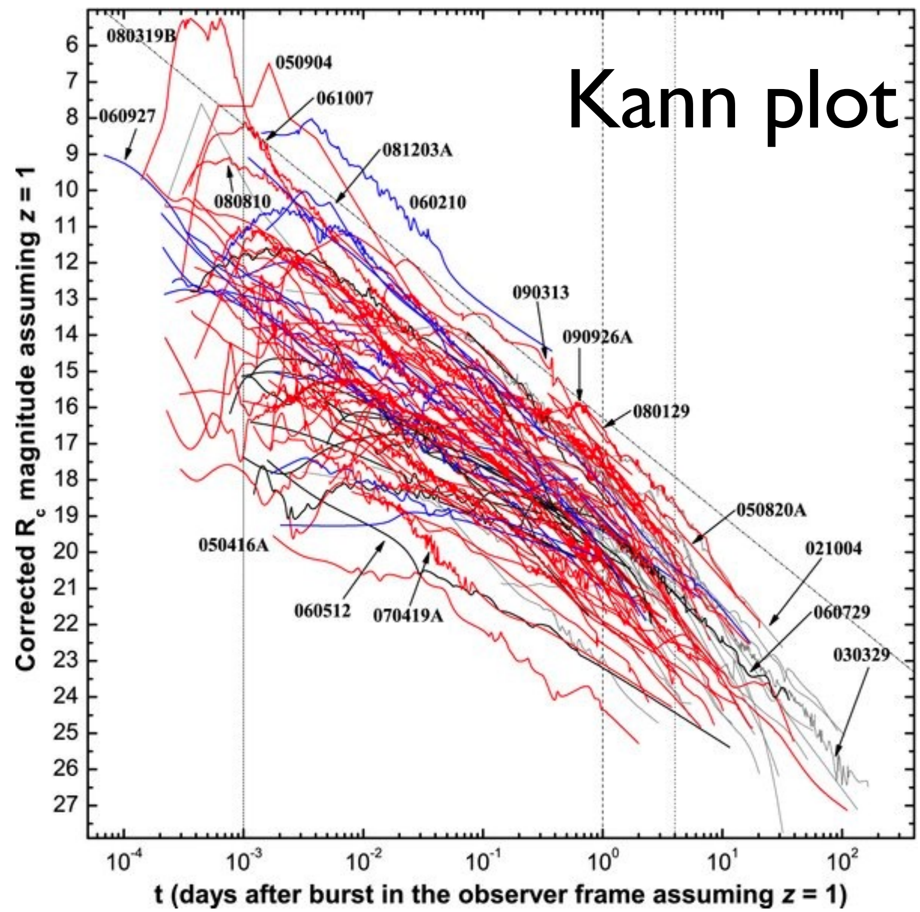
Transformed to z = 1



Kann et al (2024)

In Memoriam: Alex Kann

A key member of the GRB Community, he is greatly missed



Kann et al. 2010, Astrophysical Journal, Vol 720, p 1513

Unexpectedly passed away March 10, 2023
at the age of 46

See Hessian Cluster ELEMENTS in Memoria