Lecture 2

GRBs as Tools

Overview

- Beaming in GRBs and the Standard Universal Energy
- Using GRBs as Standard Candles
  - The Amati Relation (and pseudo-z)
  - The Ghirlanda Relation
  - The Variability-Luminosity Relation
  - Spectral Lags and the Lag-Luminosity Relation
- GRBs to probe star-formation and star-forming galaxies
- GRBs to understand cosmic dust
- Some notable GRBs

Previously on Batman...

- Gamma-ray bursts are short intense bursts of γ-rays. They do not originate from the earth or the sun.
- GRBs are highly-relativistic phenomena
- GRBs are isotropically distributed on the sky and are non-Euclidean.
- They come in at least two flavours (long and short)
- Long GRBs originate from galaxies at "cosmological" distances. Extremely energetic explosions. Synchrotron radiation from highly relativistic electrons?
- Collimation: opening angles few degrees. There are many more GRBs than those we see.
- Long GRBs connected to supernovae! (type Ic)
- Not all GRBs associated with observable SNe
- GRBs can be seen to the greatest distances

Collimation in GRBs and the Standard Universal Energy

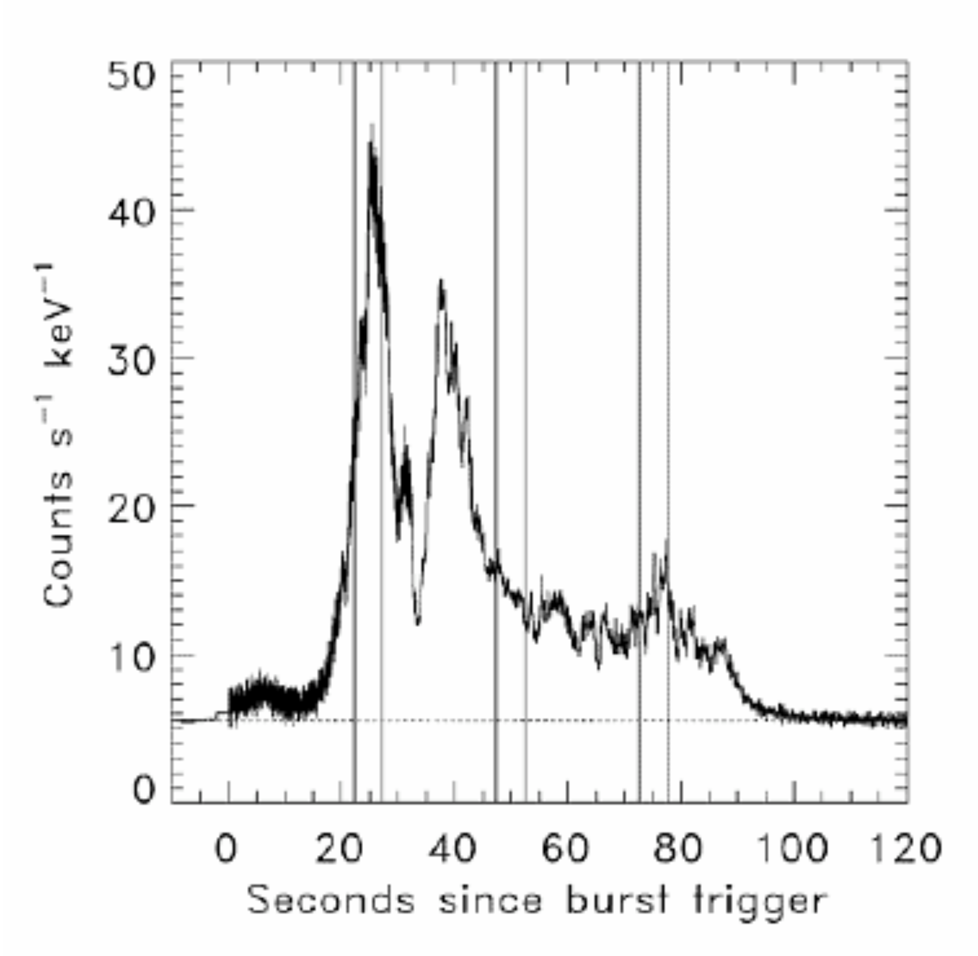
JETS AND THE JET-BREAK

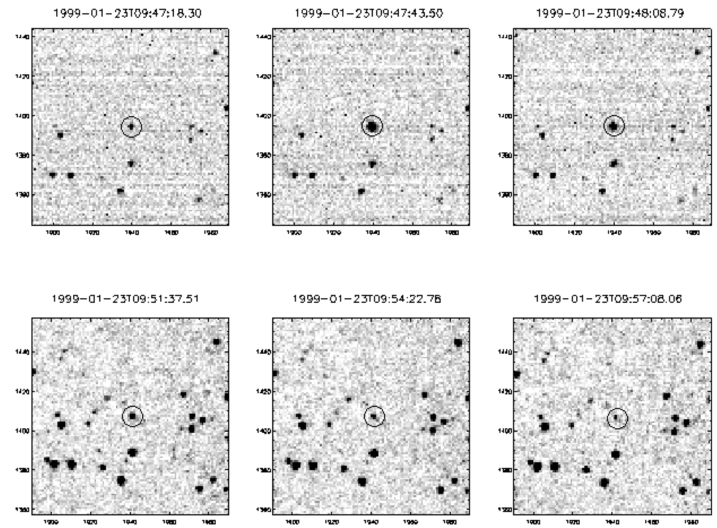
Jets in GRBs

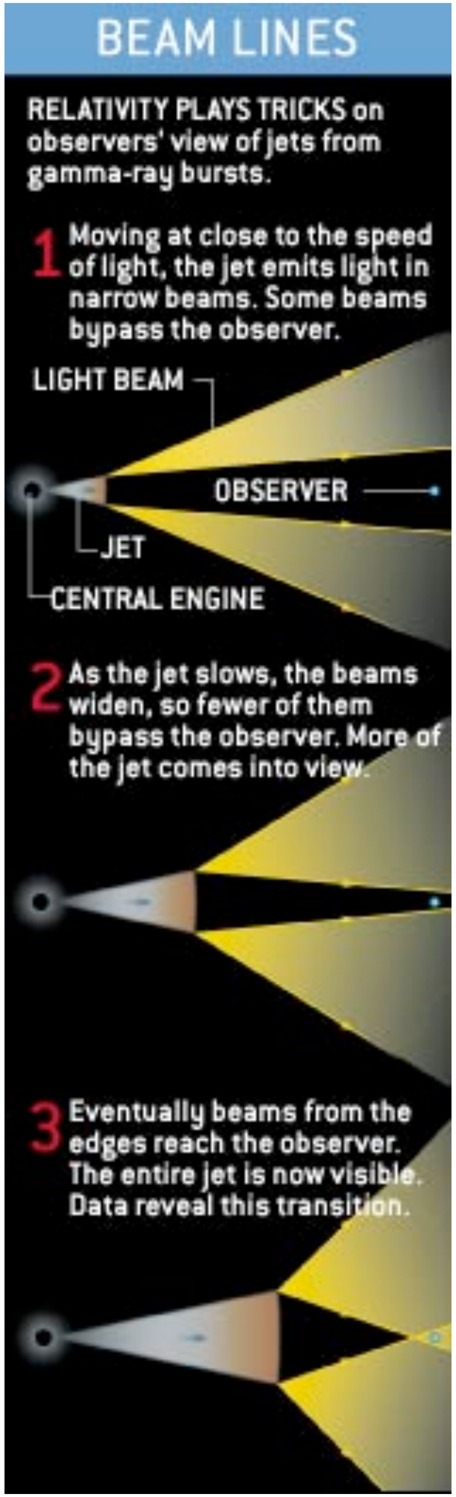
- GRBs are ultra-relativistic
- Bursts must be relativistically beamed
- Equivalent isotropic energy release in Gamma-rays can be as high as 10^{54} ergs, so total energy release likely much lower
- Collapsar model suggests collimation → jets
- Many astrophysical sources have jets

GRB990123: Brightest burst

Jan 23 09:46:56 (1999)

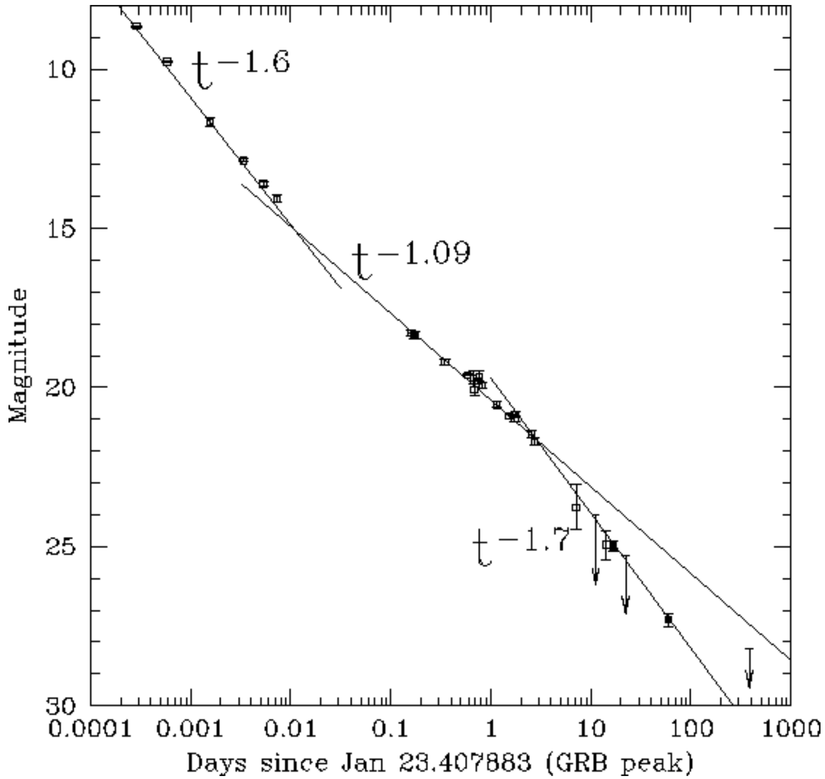






The Jet Break

$E_{iso} = 4.5 \times 10^{54}$ erg

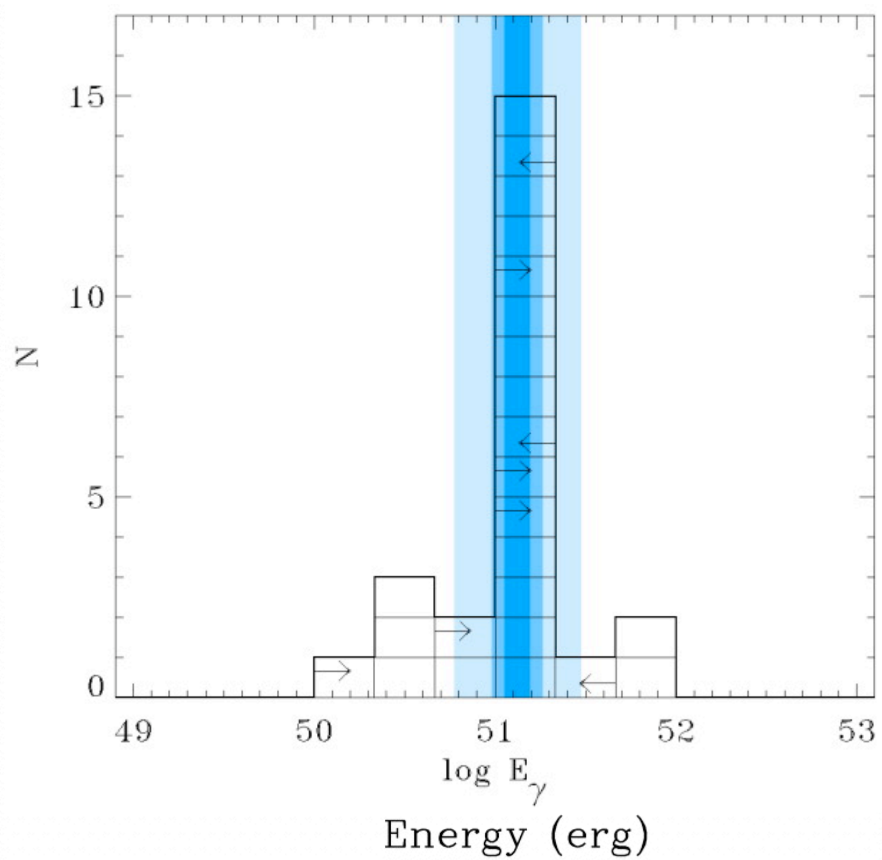


More than rest-energy of the sun!

Beaming solves the energy problem, but at the expense of increasing the rate by factor ~100-500!

A Standard Universal Energy?

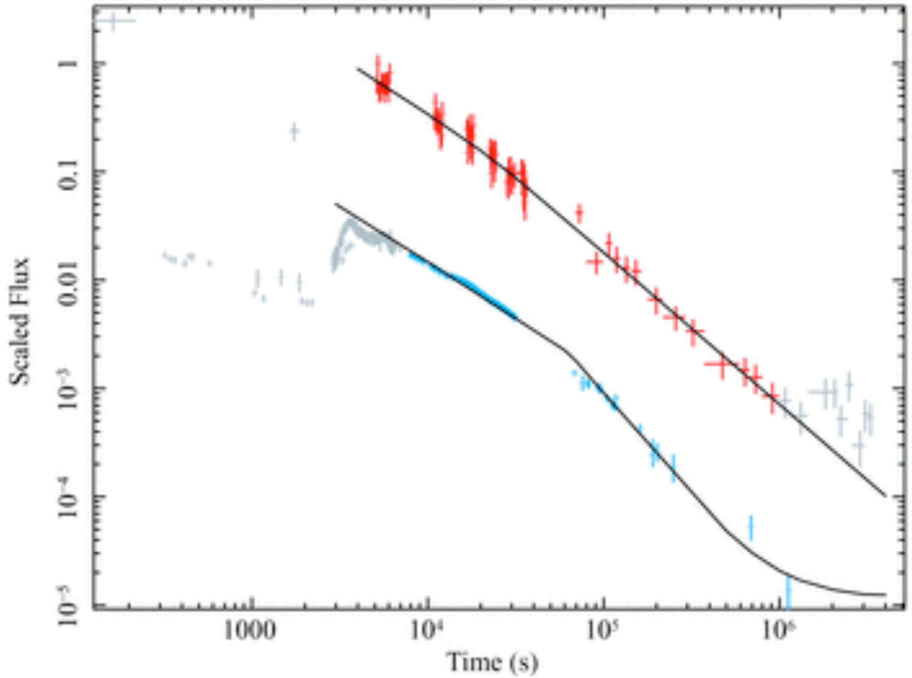
Bloom et al. 2003
Frail et al. 2001



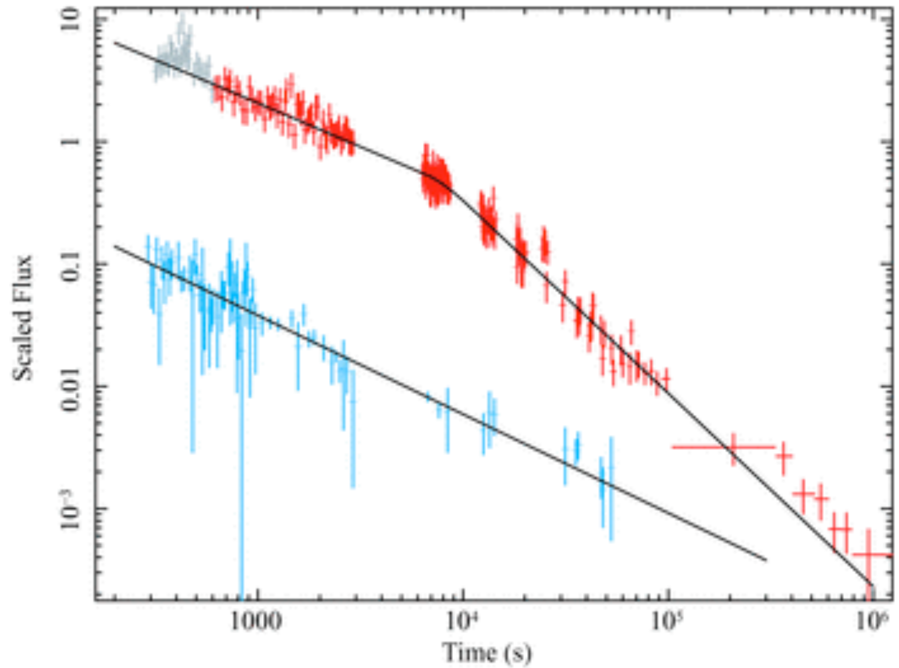
- Using the timing of breaks observed in GRB afterglow lightcurves, we can work out the opening angles of the jets (making some assumptions on density etc.)
- Frail, Bloom and Kulkarni found a single universal energy of 1.3FOE.

Are lightcurve breaks really 'jet breaks'?

Optical breaks – no X-ray



X-ray breaks – no optical

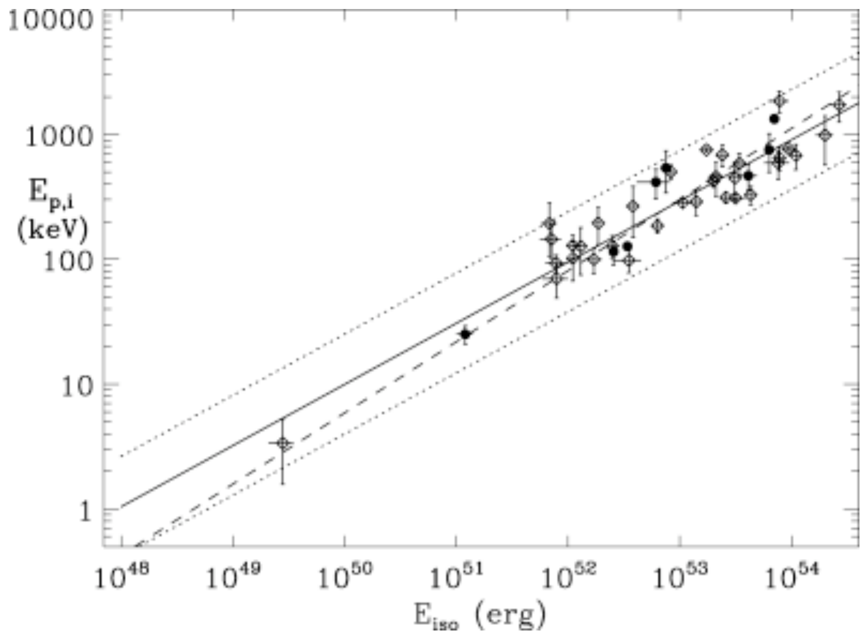


…and why it doesn't work

GRBS AS STANDARD CANDLES

The Amati Relation

Amati et al. 2006

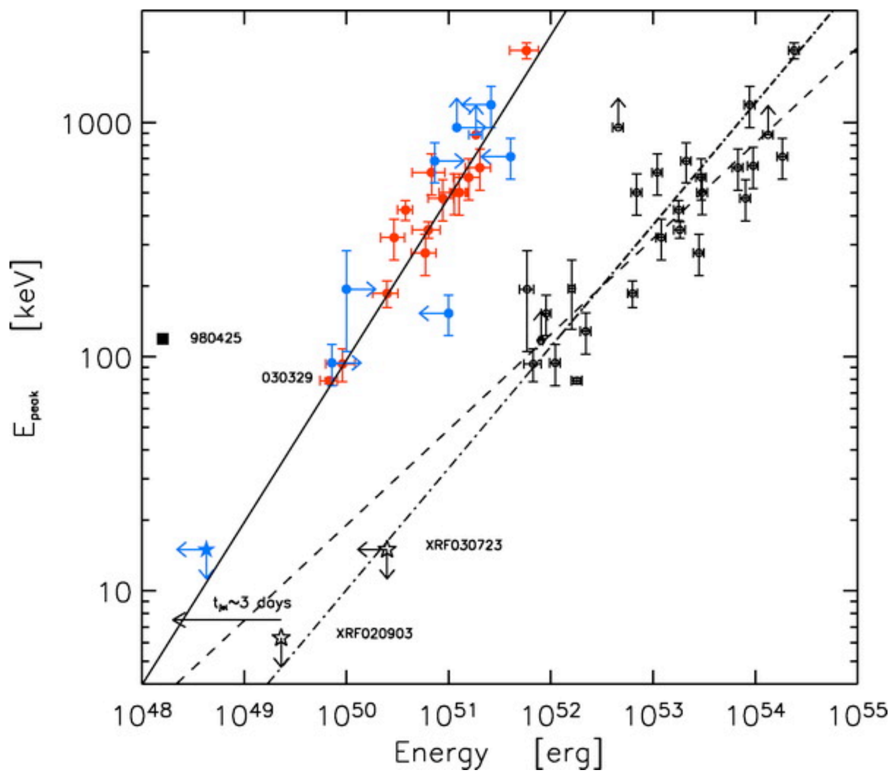


Amati relation and Atteia et al.'s pseudo-z

- The 'Amati-relation' is a correlation between equivalent isotropic energy release and restframe spectral peak (E_{peak}).
- (A related note is the pseudo-z, a redshift indicator, (<z> +/– 1) which primarily relies on this correlation. It is highly unreliable: e.g. GRB060927 pseudo-z = 2.37 ± 0.75; measured *z* = 5.47)

The Ghirlanda Relation

Ghirlanda + Amati

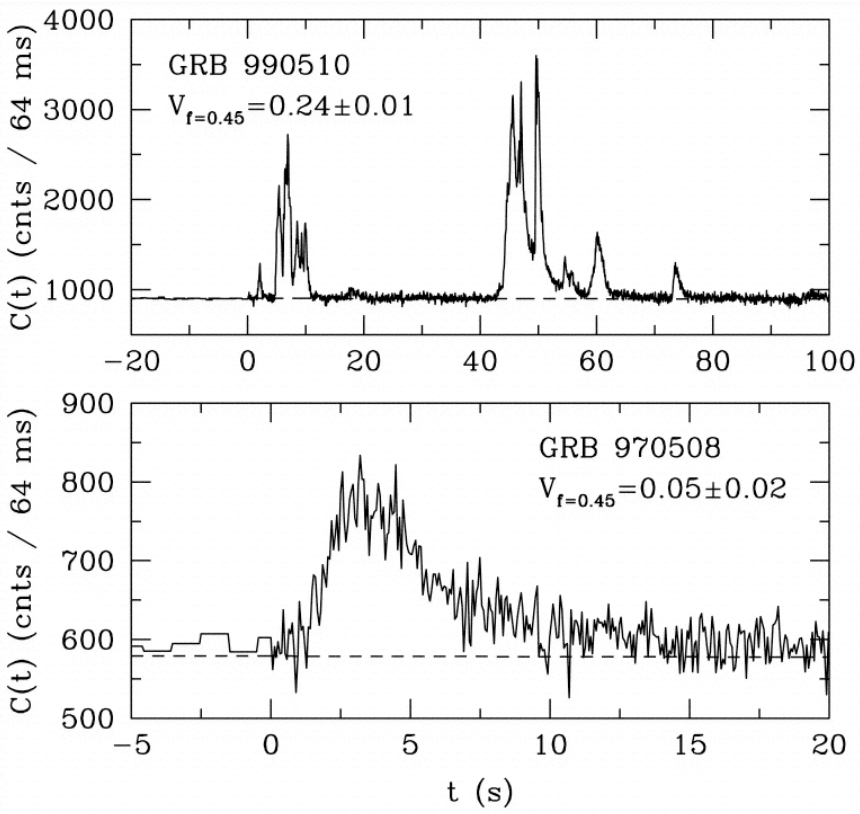


Cosmology?

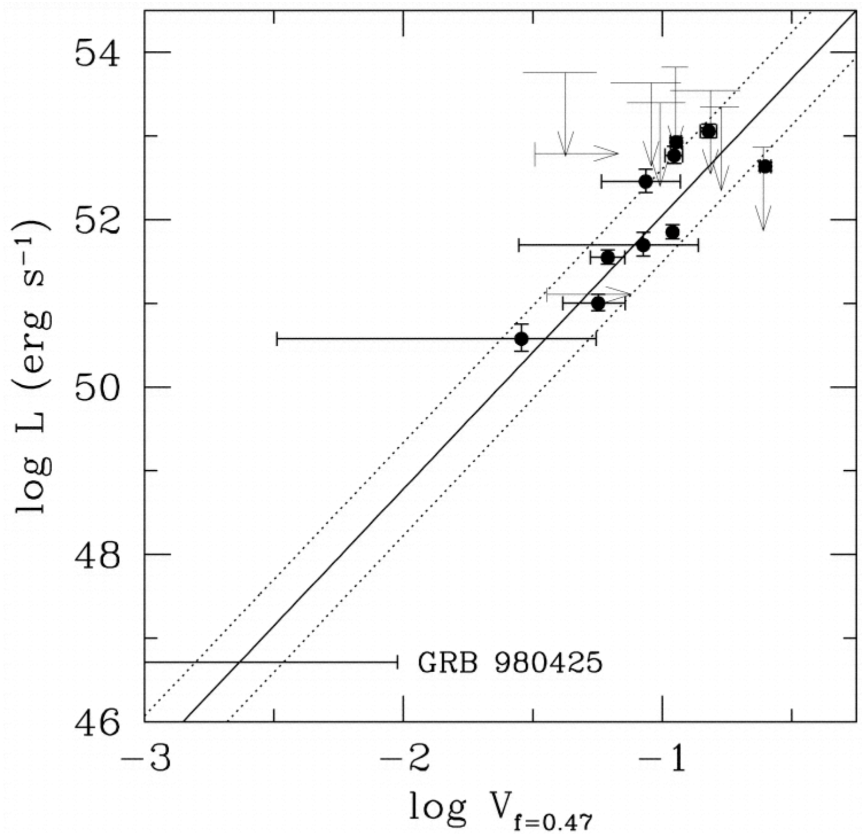
- Correct apparent isotropic energy for beaming – tight correlation between spectral peak and bolometric energy. (Compare with Frail et al. single standard energy!)
- Can do cosmology with this – but fraught with problems
  – Are lightcurve breaks really jet breaks?
  – Do we really know the density structures in these bursts?
  – Selection effects of GRB triggers.

Variability-Luminosity Relation

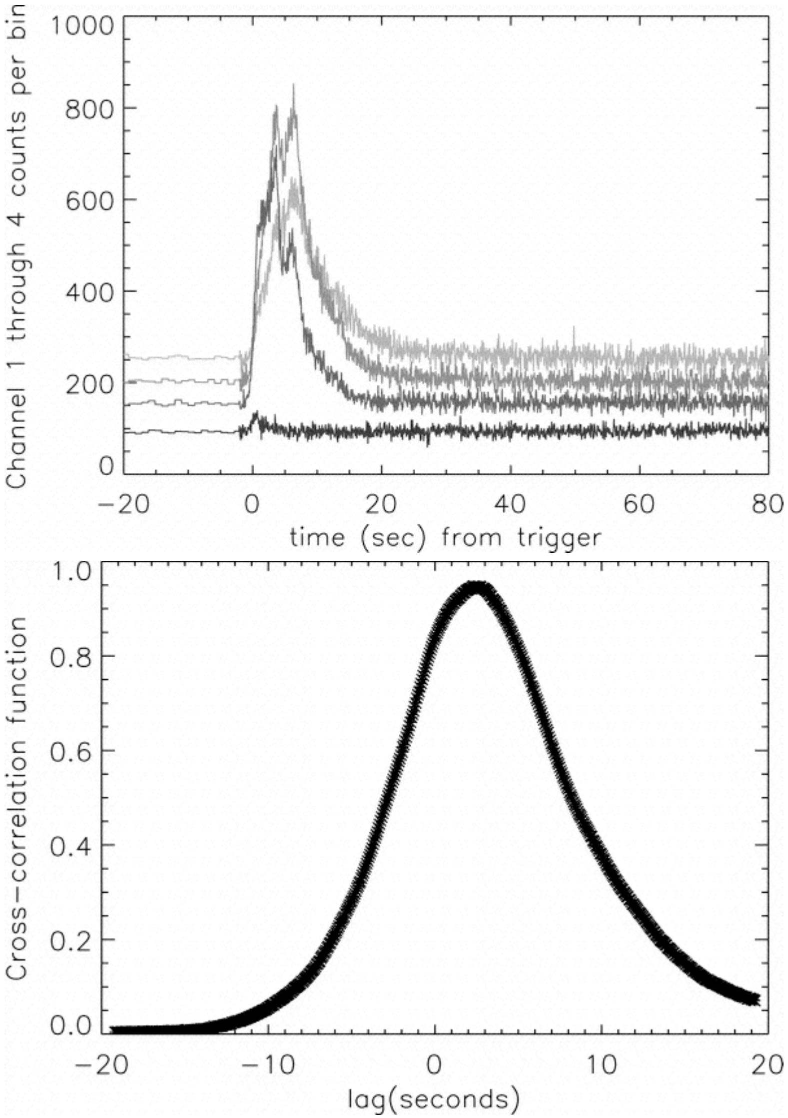
High-variability → low-luminosity



Correlation → Redshift indicator?



Spectral Lags in GRBs

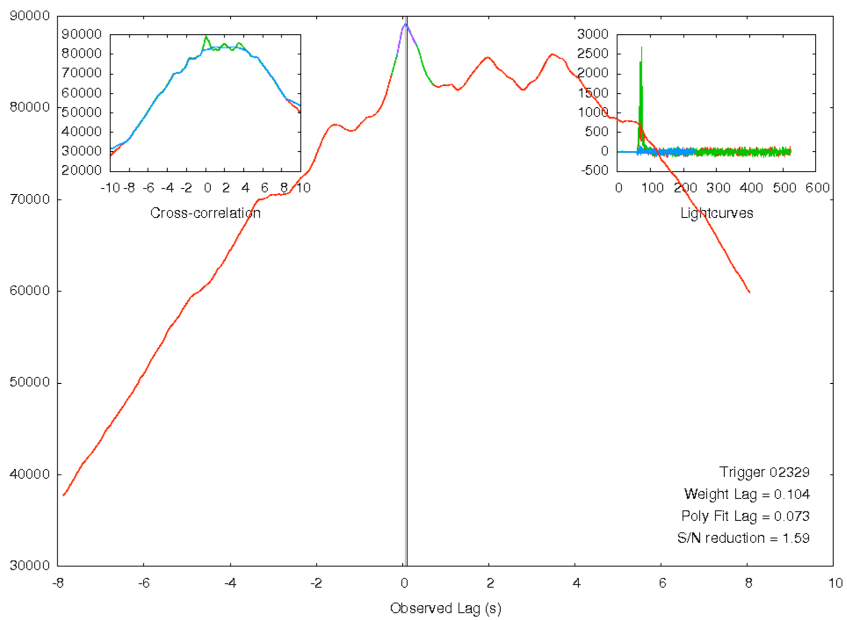


Lags

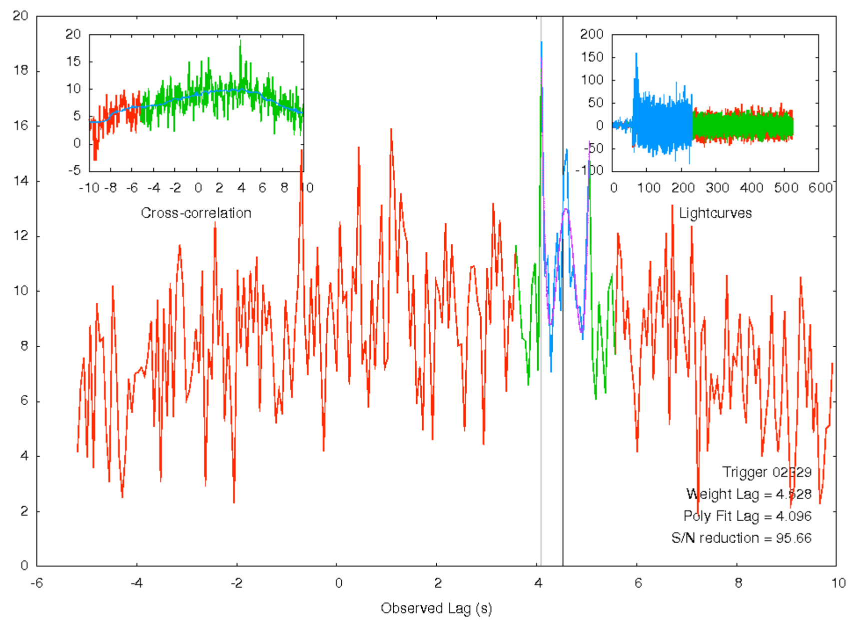
- Time lag between the arrival times of different energy bands.
- Measured by difference in arrival time of peaks.
- Practically uses peak of CCF of lightcurves in two energy bands.

A difficult measurement

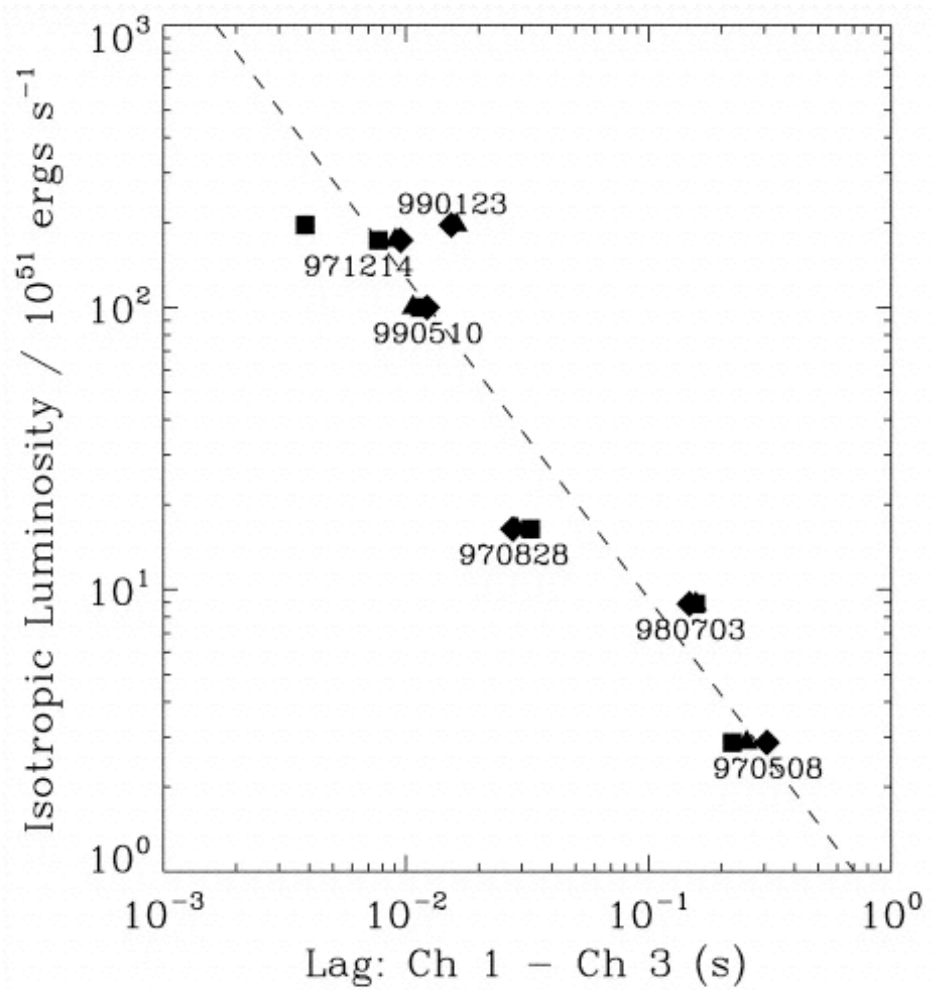
High S/N



Low S/N (same burst)

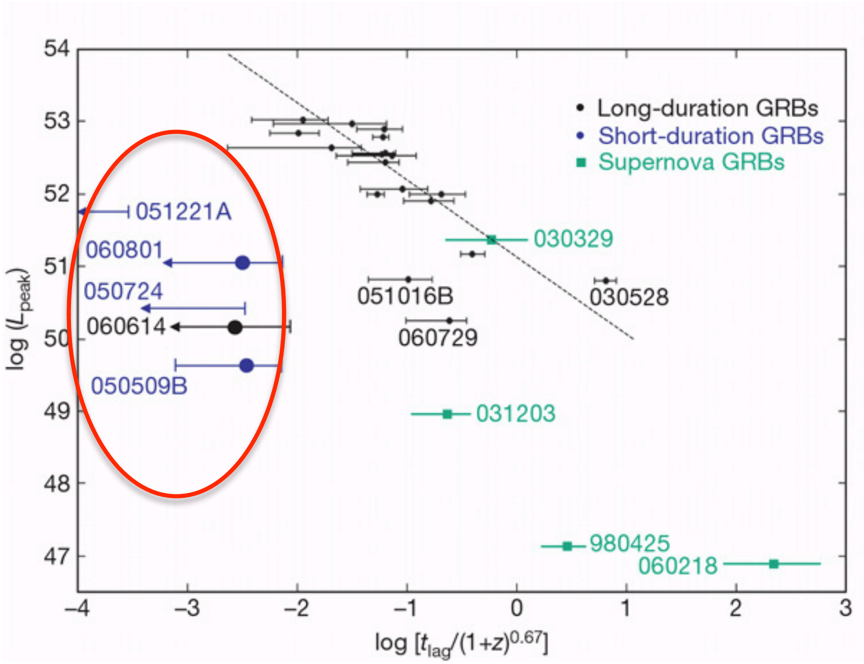


Lag-Luminosity Relation

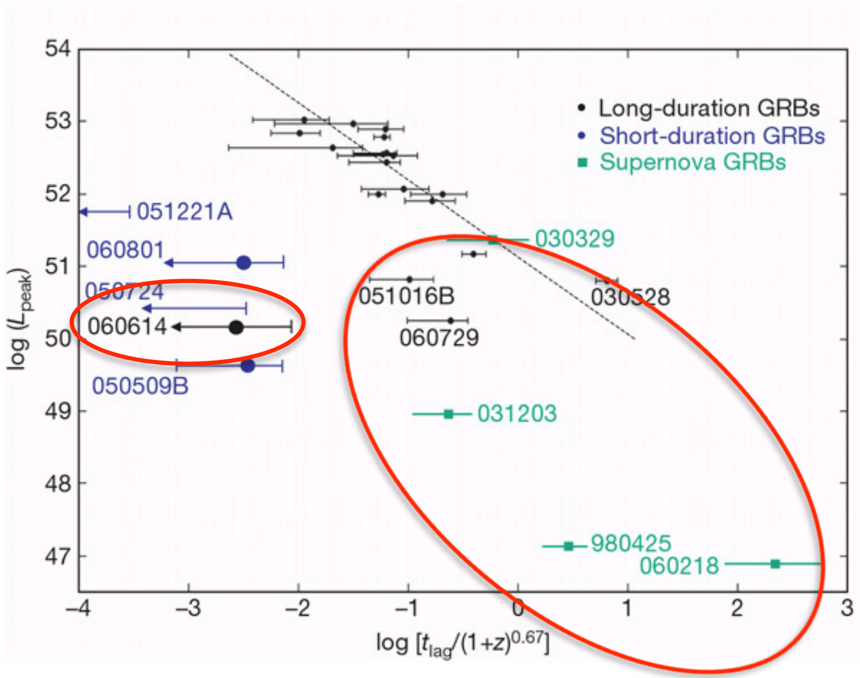


Problems with Lag-Luminosity

Short GRBs have 0 lag.



But Long GRBs do not always follow the correlation



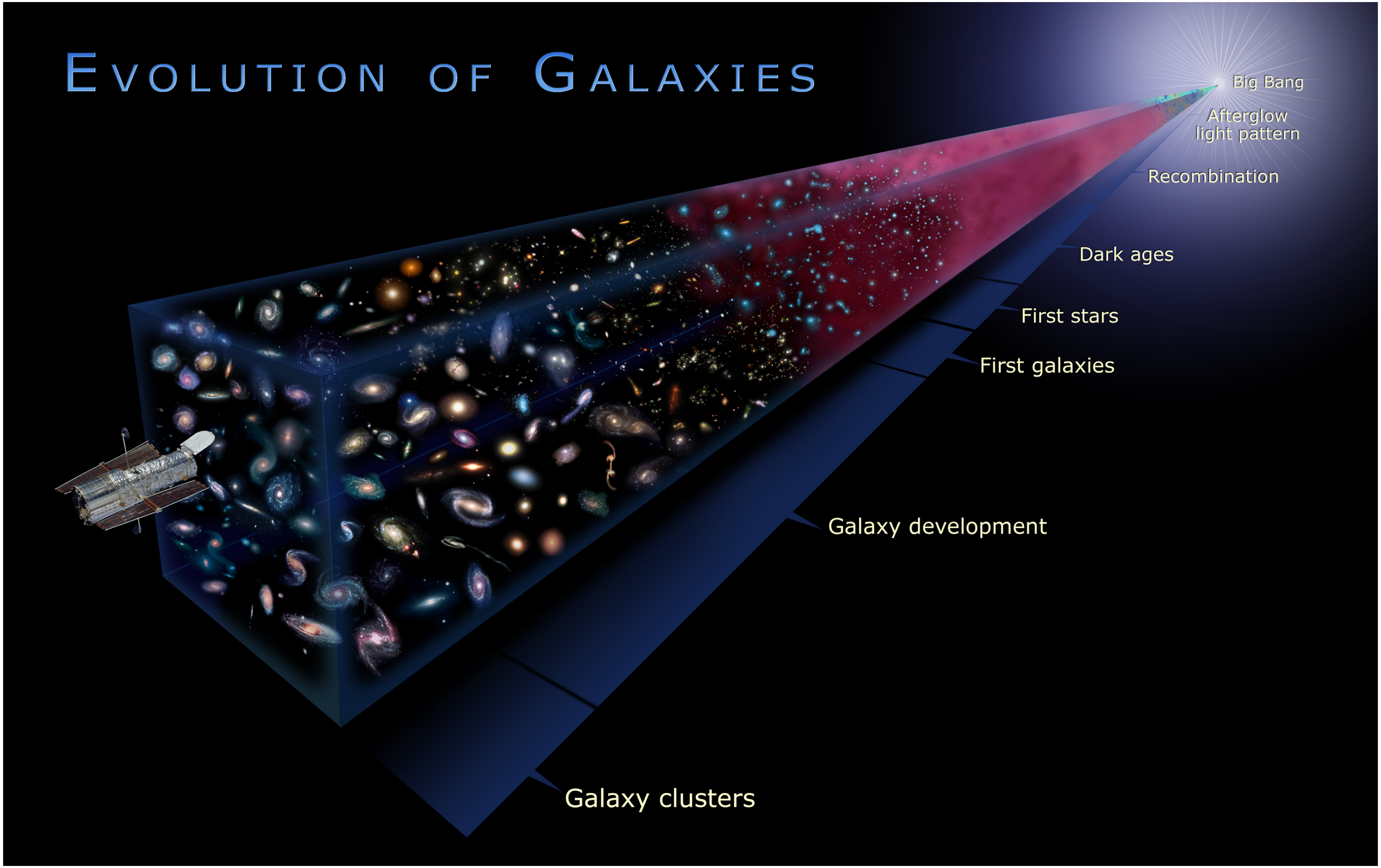
What are spectral lags?

Lags

- Unknown
- Zero-lag/lag: binary merger vs. core collapse?
- Lags are properties of individual pulses

GRBs to probe cosmic star-formation and star-forming galaxies

STAR-FORMATION


Evolution of Galaxies
Big Bang
Afterglow light pattern
Recombination
Dark ages
First stars
First galaxies
Galaxy development
Galaxy clusters

Star Formation using GRBs

- The Host Galaxies of GRBs
  - Emission properties
  - Absorption properties

- Gamma-rays and X-rays independent of obscuration
- GRB independent of host galaxy luminosity
  - Great tool for looking at massive SF

Mon. Not. R. Astron. Soc. **294,** L13–L17 (1998)

Gamma-ray bursts from stellar remnants: probing the Universe at high redshift

Ralph A. M. J. Wijers,★ Joshua S. Bloom,† Jasjeet S. Bagla and Priyamvada Natarajan
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA

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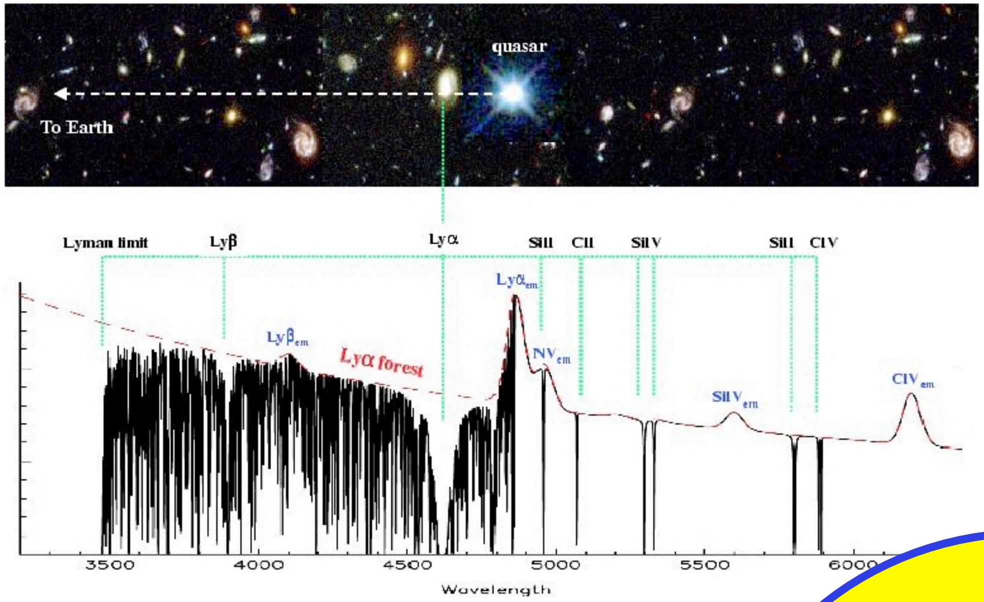
ABSTRACT

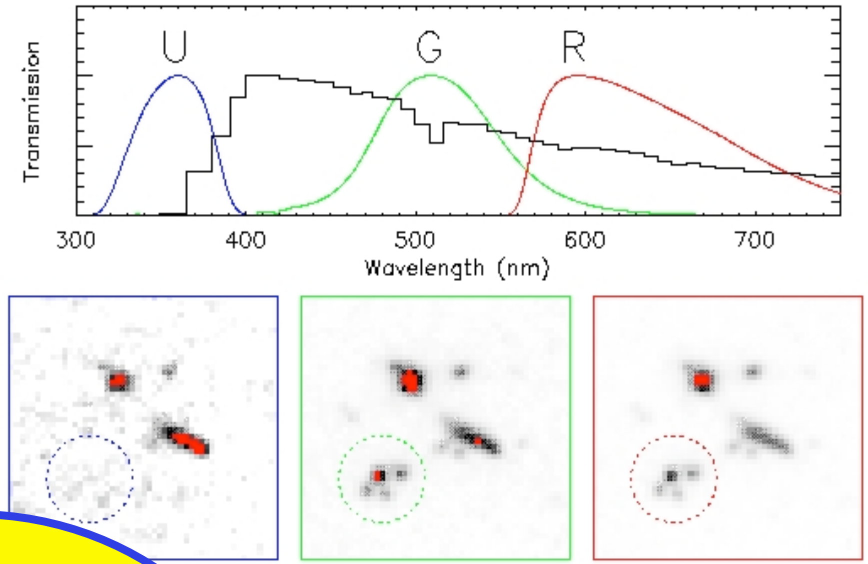
A gamma-ray burst (GRB) releases an amount of energy similar to that of a supernova explosion, which combined with its rapid variability suggests an origin related to neutron stars or black holes. Since these compact stellar remnants form from the most massive stars not long after their birth, GRBs should trace the star formation rate in the Universe; we show that the GRB flux distribution is consistent with this. Because of the strong evolution of the star formation rate with redshift, it follows that the dimmest known bursts have $z \sim 6$, much above the value usually quoted and beyond the most distant quasars. This explains the absence of bright galaxies in well-studied GRB error boxes. The increased distances imply a peak luminosity of 8.3×10^{51} erg s^{-1} and a rate density of 0.025 per million years per galaxy. These values are 20 times higher and 150 times lower, respectively, than are implied by fits with non-evolving GRB rates. This means either that GRBs are caused by a much rarer phenomenon than mergers of binary neutron stars, or that their gamma-ray emission is often invisible to us due to beaming. Precise burst locations from optical transients will discriminate between the various models for GRBs from stellar deaths, because the distance between progenitor birth place and burst varies greatly among them. The dimmest GRBs are then the most distant known objects, and may probe the Universe at an age when the first stars were forming.

Key words: binaries: close – stars: formation – cosmology: theory – early Universe – gamma-rays: bursts.

Damped Ly-α Absorbers



Lyman-break galaxies

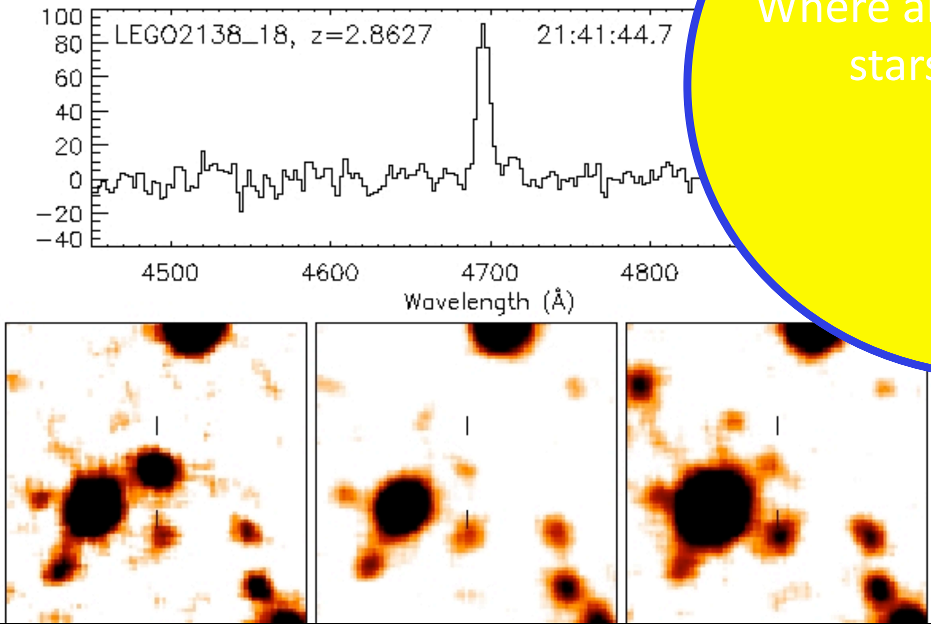


GRBs as probes

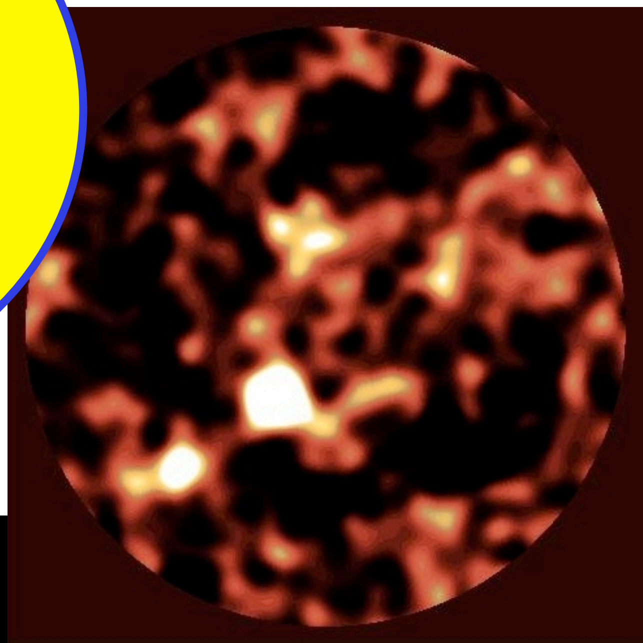
Where are the massive stars at high z

?

Lyman-α galaxies

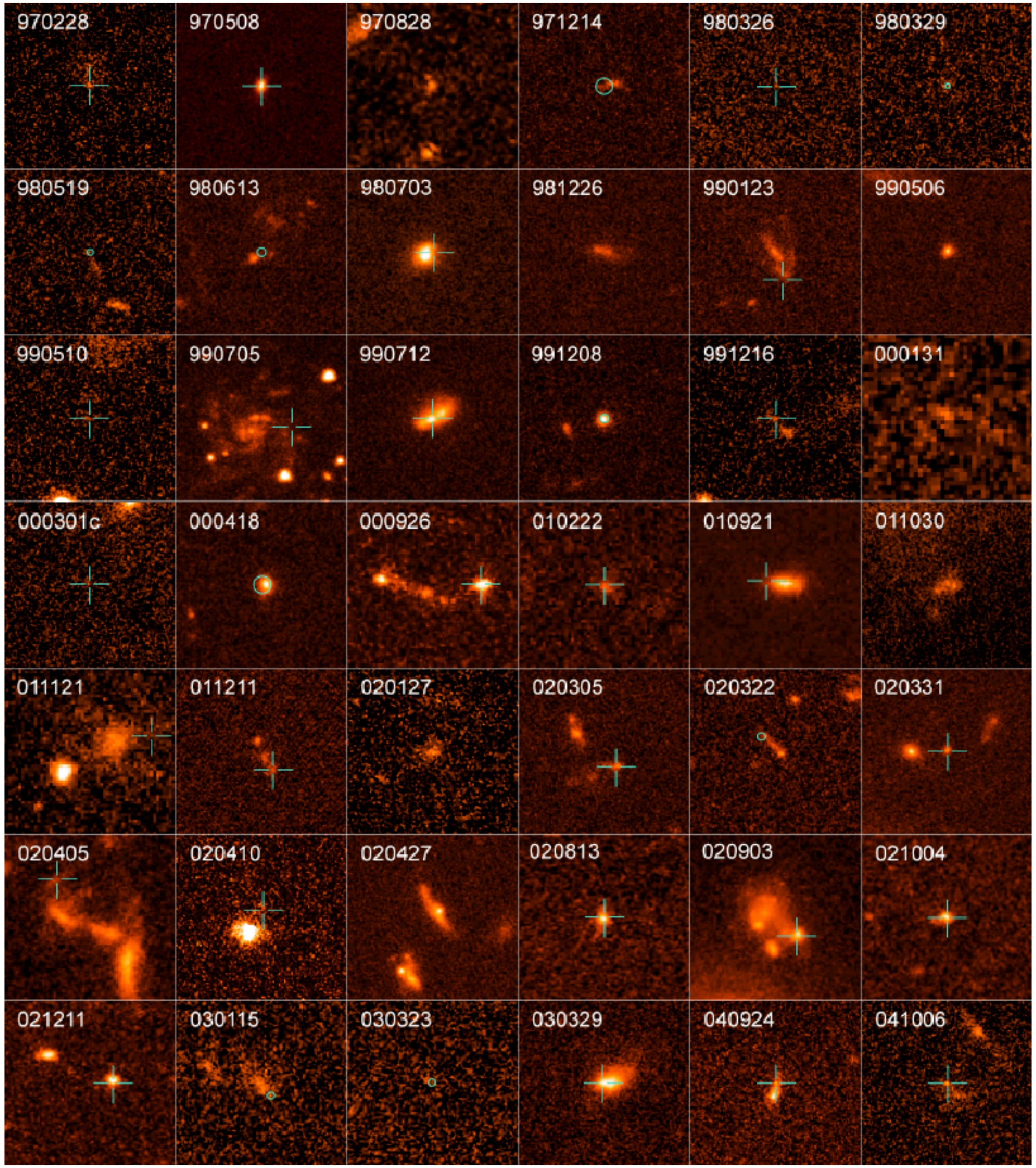


Dusty starbursts



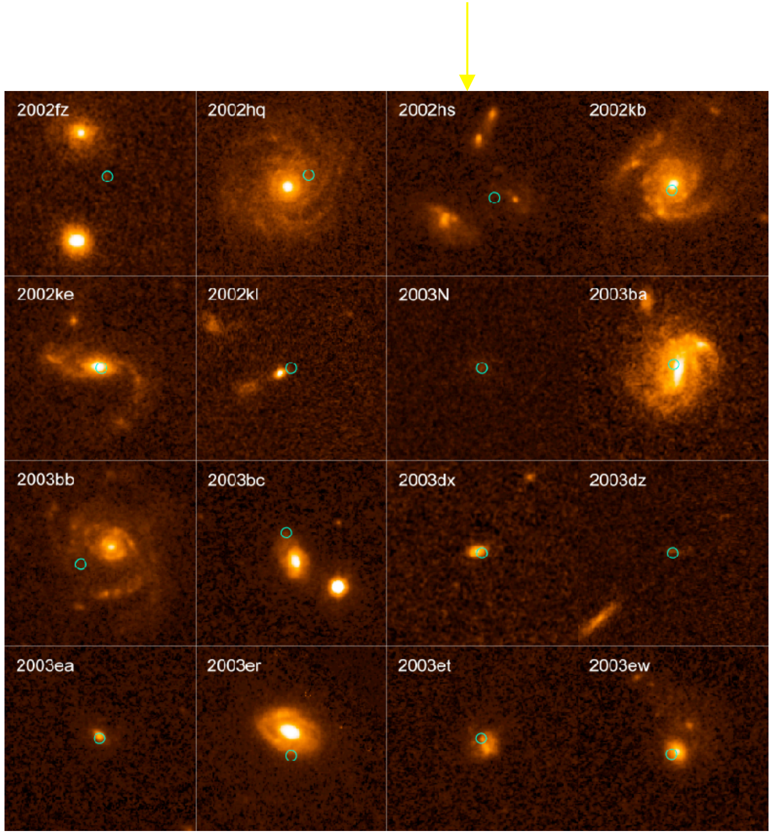
Small, blue thing

OPTICAL/UV PROPERTIES OF HOSTS



Different locations

- GRBs follow ~Light²
- ccSN follow the light
- SN hosts are brighter

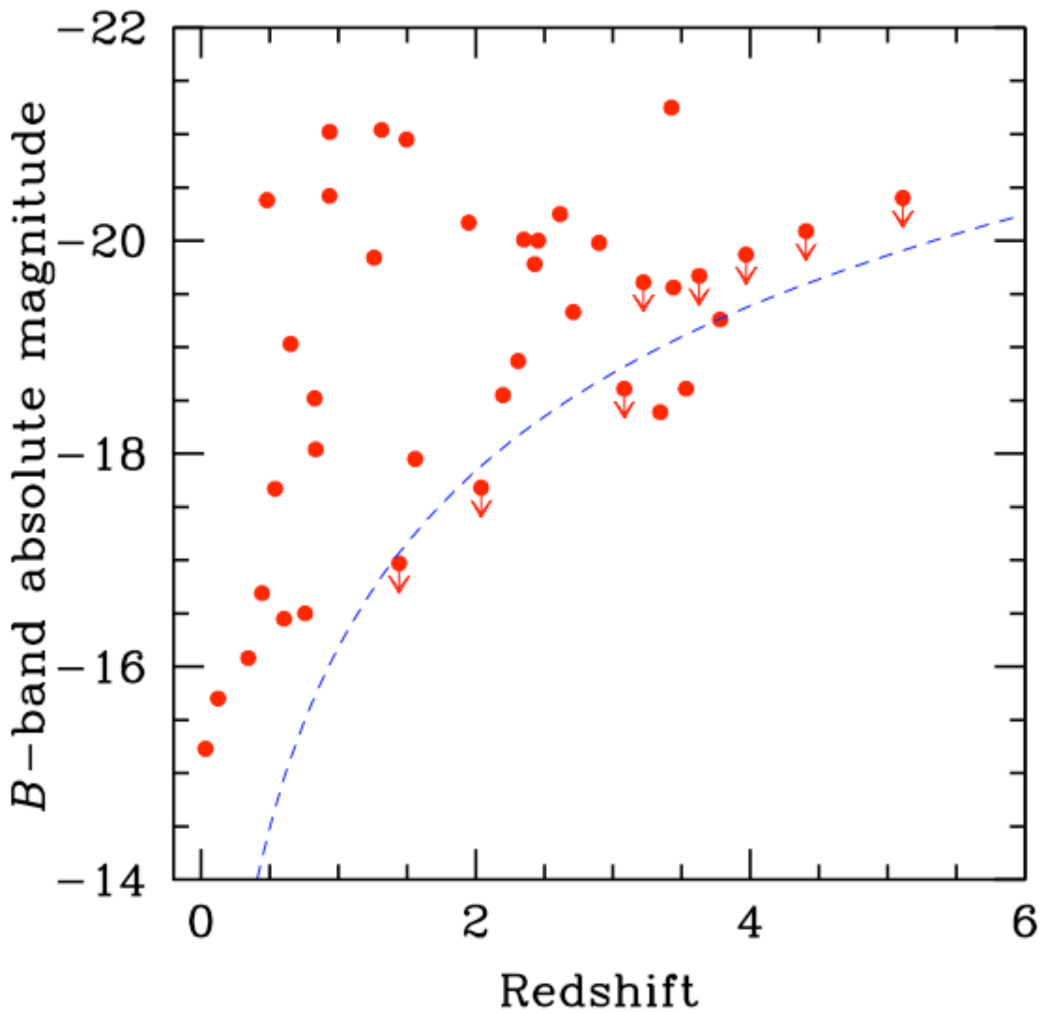


Fruchter et al. 2006

Luminosities of the hosts

Broad range of host luminosities.

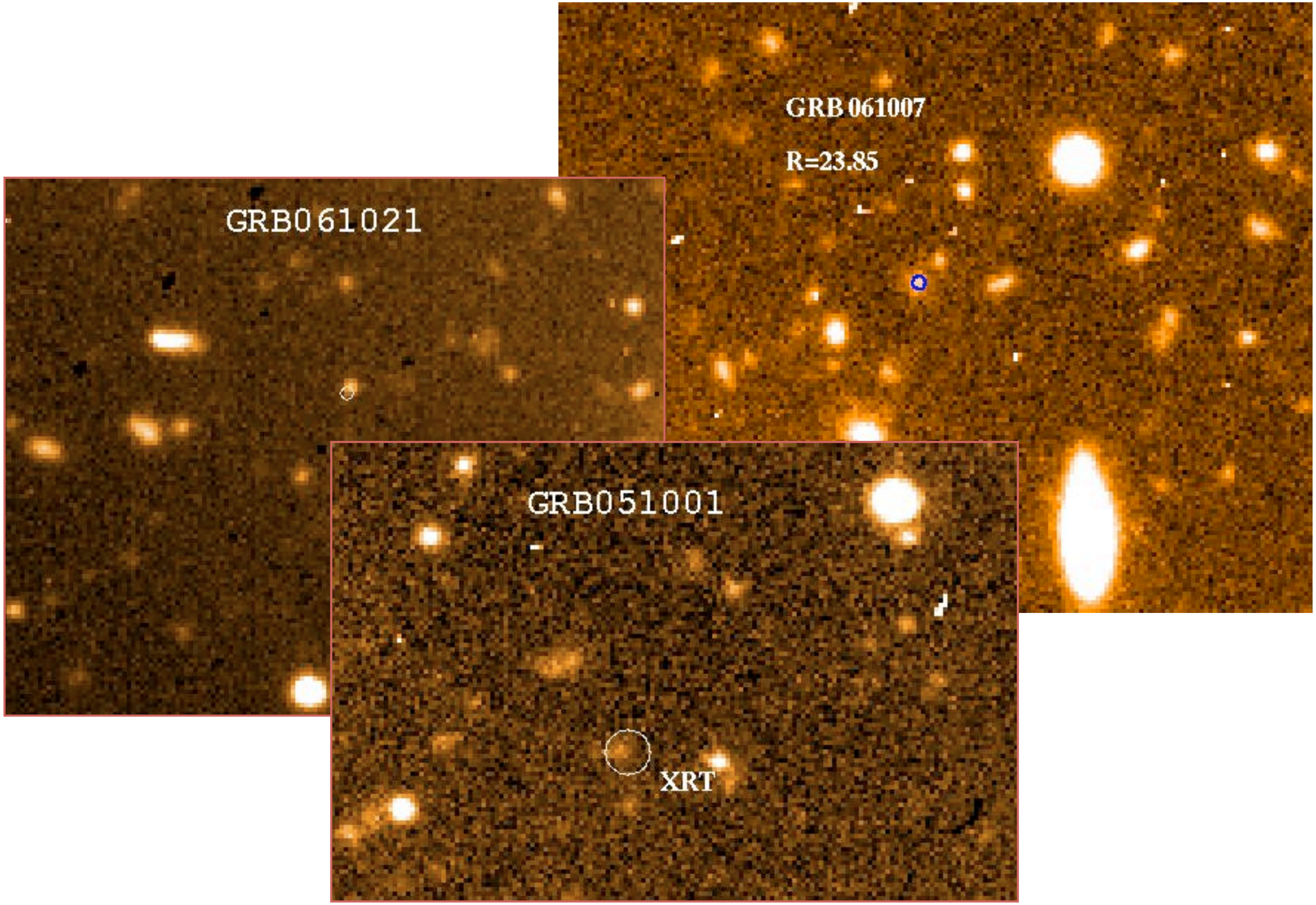
Predominantly blue R-K colours



80% detection rate

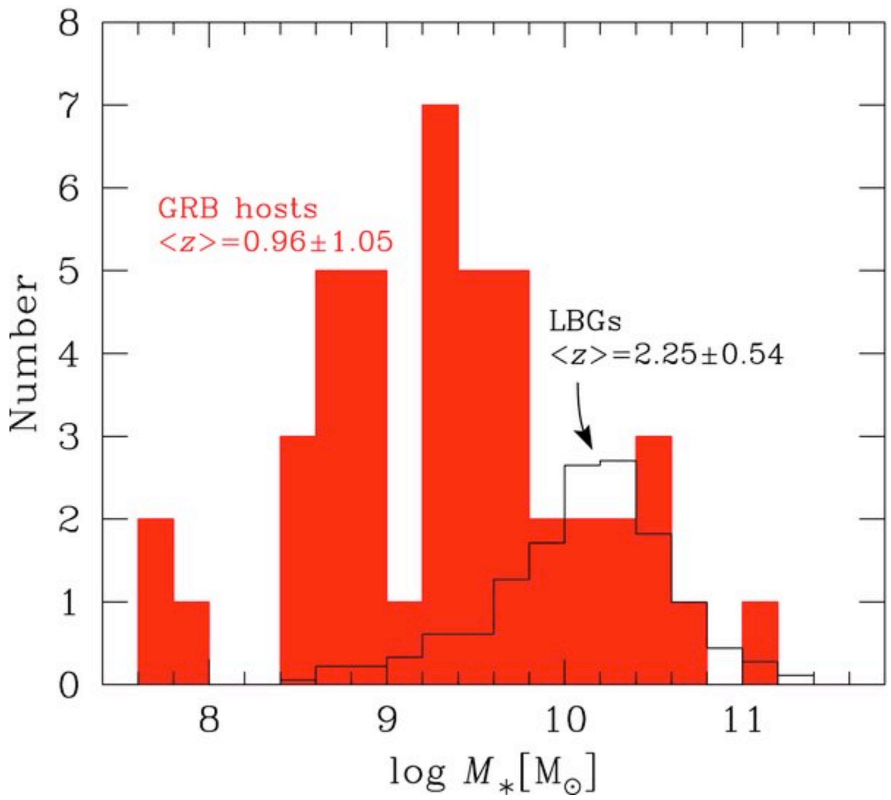
44 bursts with redshifts,
36 hosts detected

Hosts galaxies

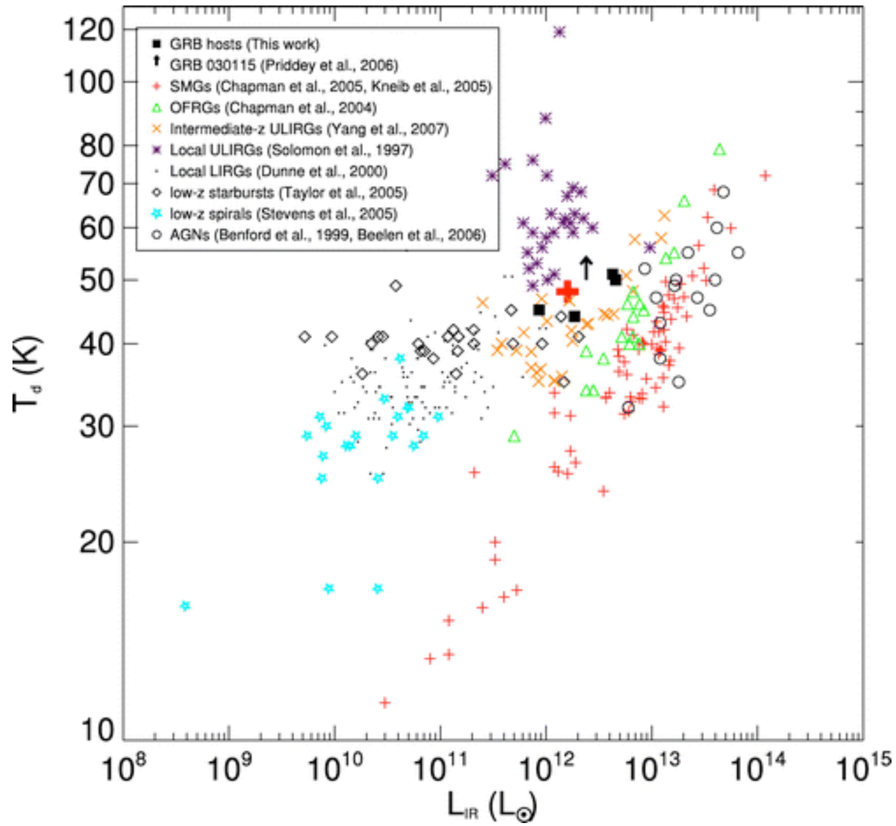


IR/Sub-mm properties of Hosts

NIR stellar masses suggest GRB hosts have relatively modest stellar masses

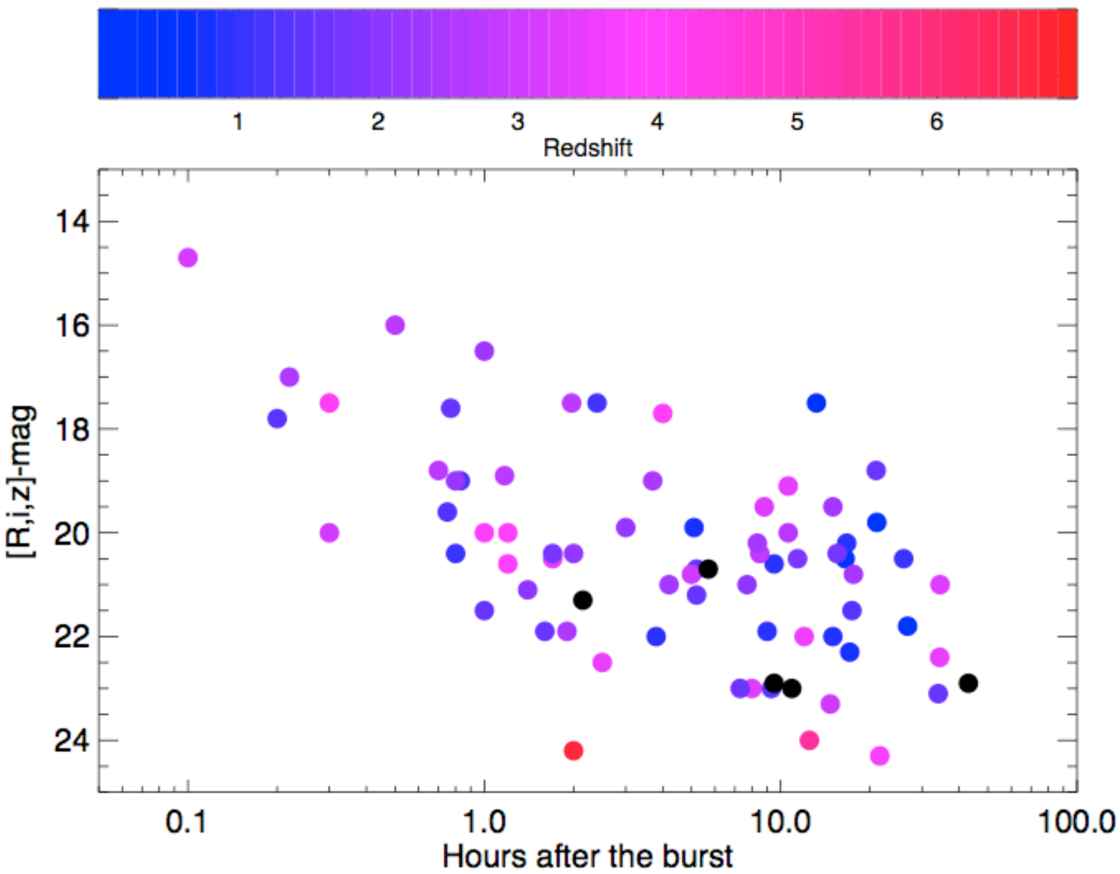


MIR and sub-mm observations suggest hot & young galaxies



BIAS!

- BUT!
  - Selection effects because we require an optical/UV afterglow to get the redshift



Redshifts from Optical Afterglow Spectroscopy

Building a complete sample

So far: ∃ but not ∀

frequent, accurate reliable

Building a complete sample – X-ray selection

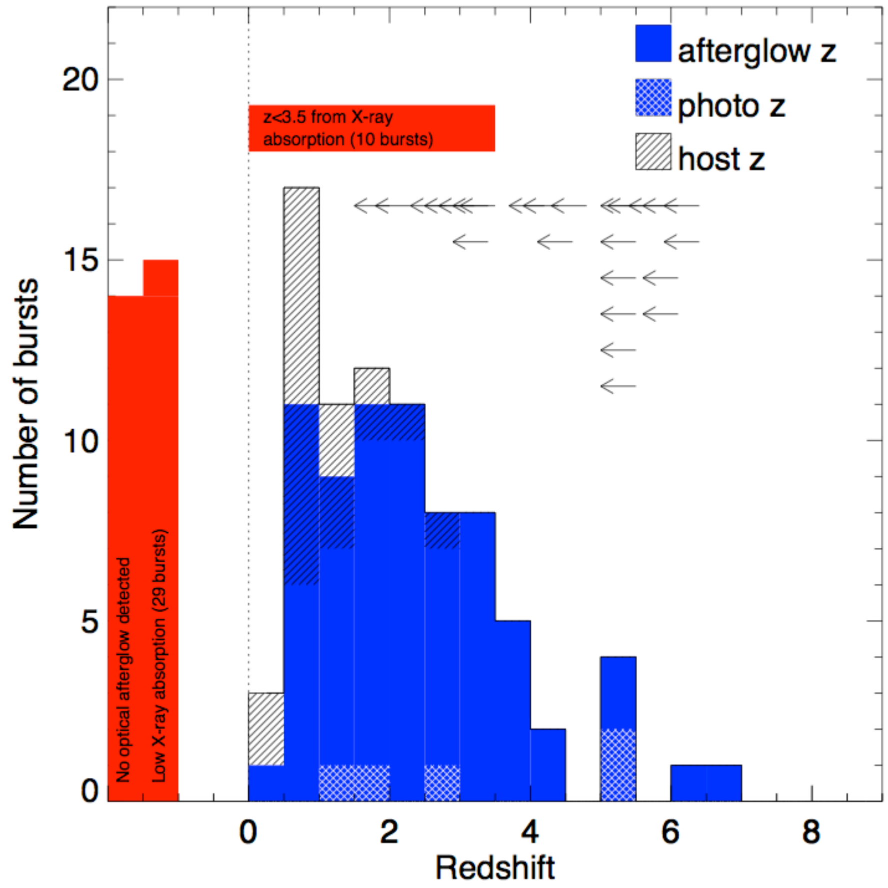
Sample definition:

1. $T_{90} > 2$ sec
2. XRT localized within 12 hr.
3. Galactic $A_V < 0.5$.
4. $-70^o <$ declination $< +70^o$
5. $\theta_{Sun} > 55^o$.

From March 2005 - June 2009:

- 185 bursts
- ~150 optical afterglows detected
- 100 redshifts determined

http://astro.ku.dk/~pallja/GRBsample.html



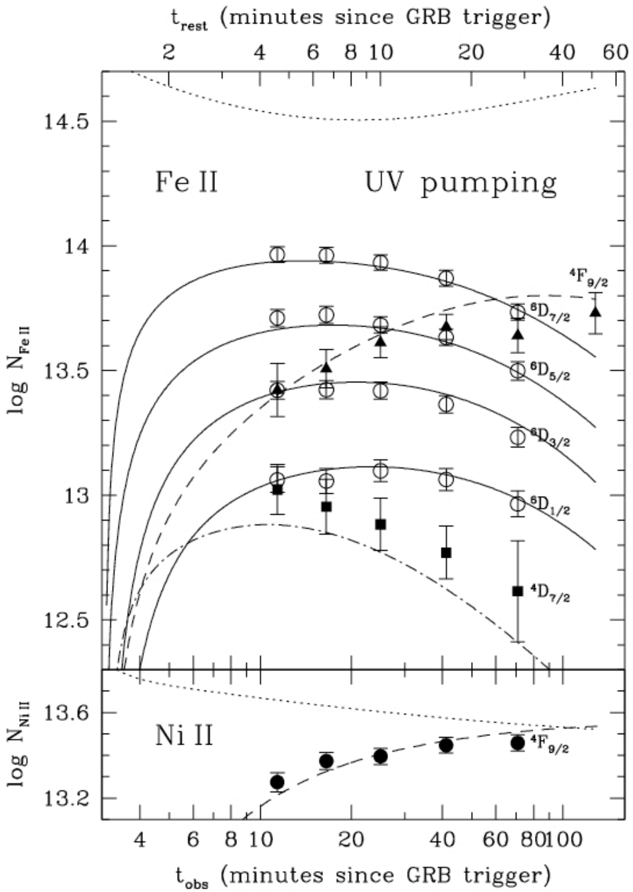
Redhsift Distribution for the Swift Sample

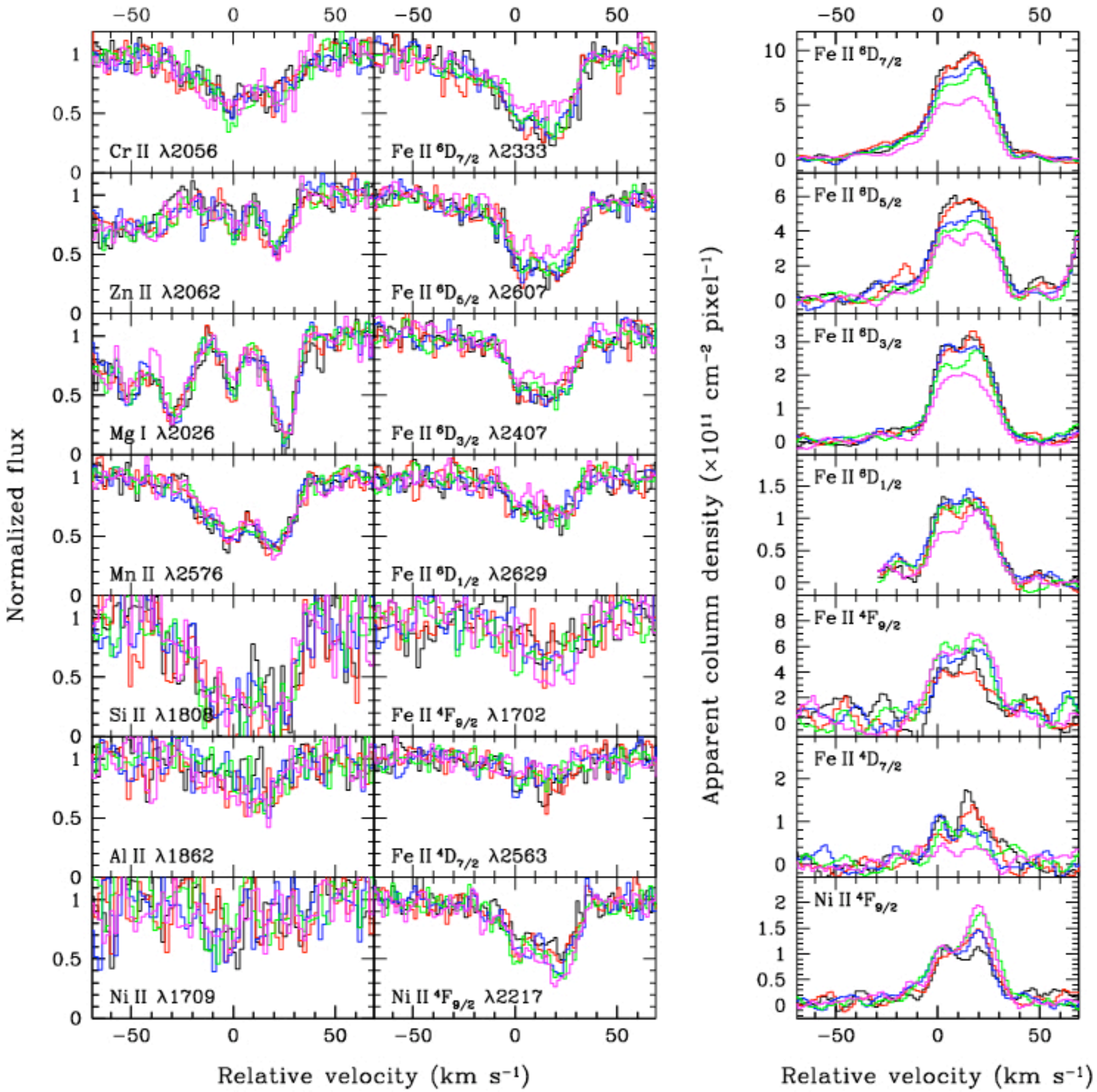
Absorption Studies using GRBs

- Optical/UV
- IR
- X-ray

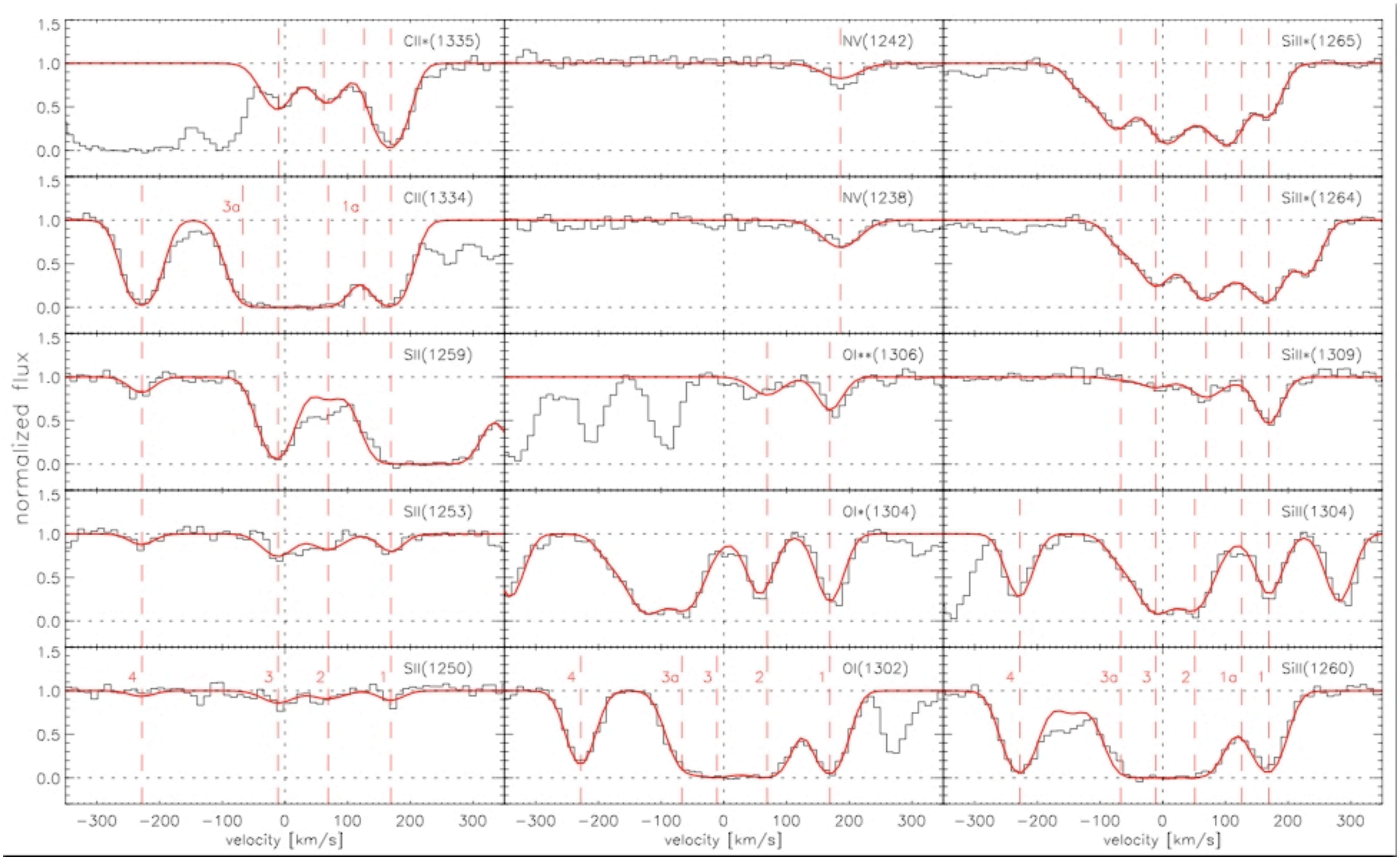
Results from high resolution spectroscopy

Line variability from rapid UVES spectroscopy

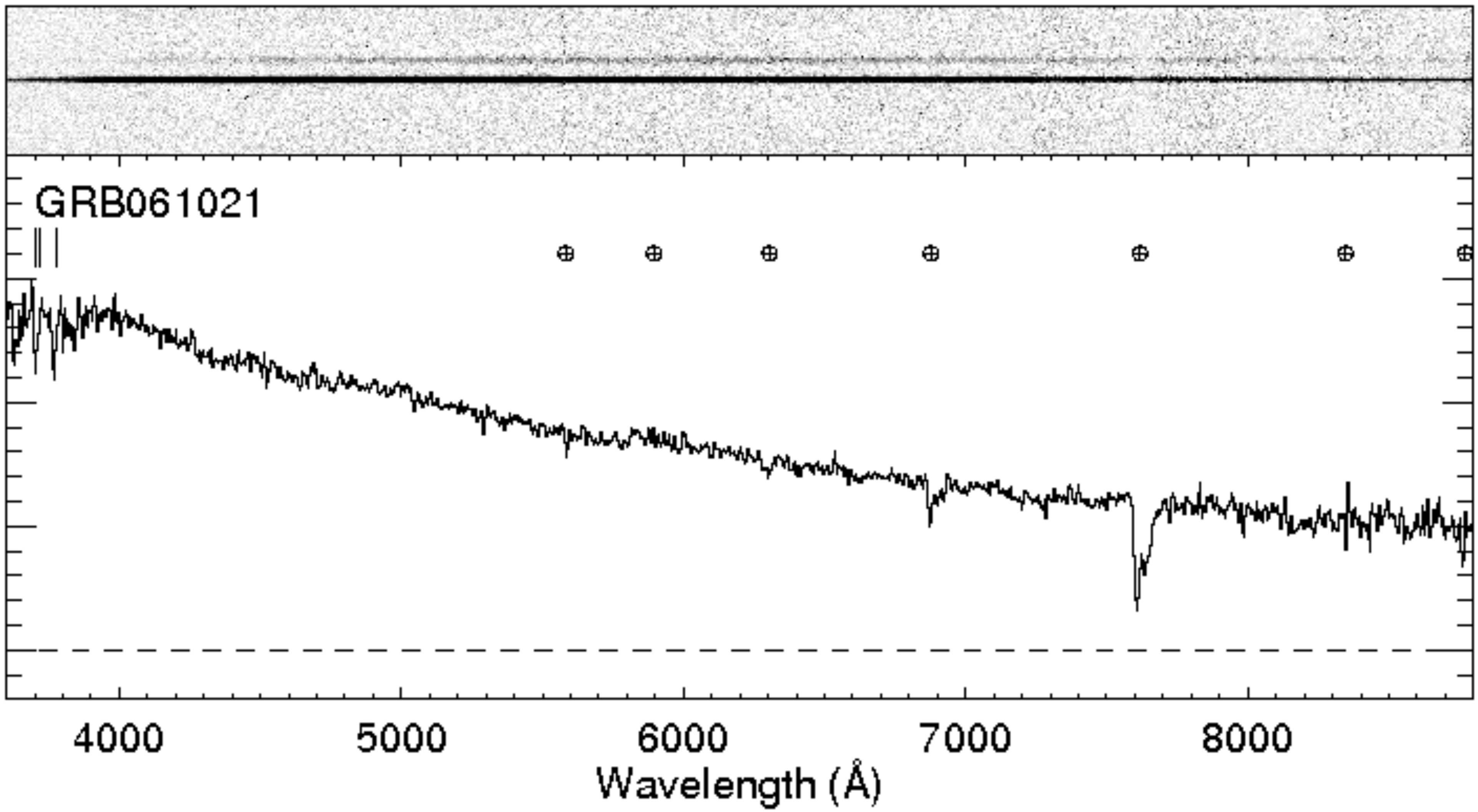




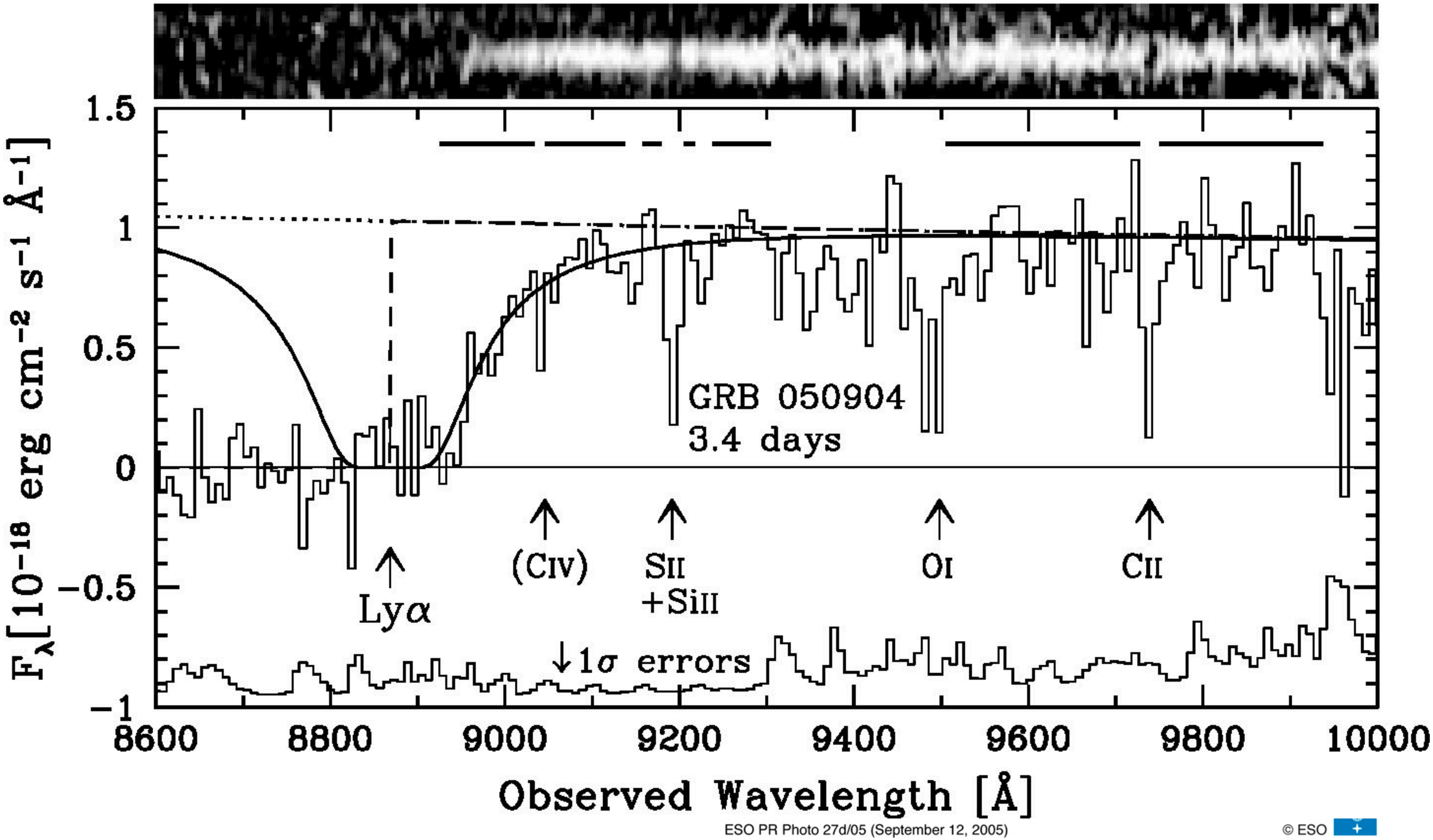
Low vs. medium resolution



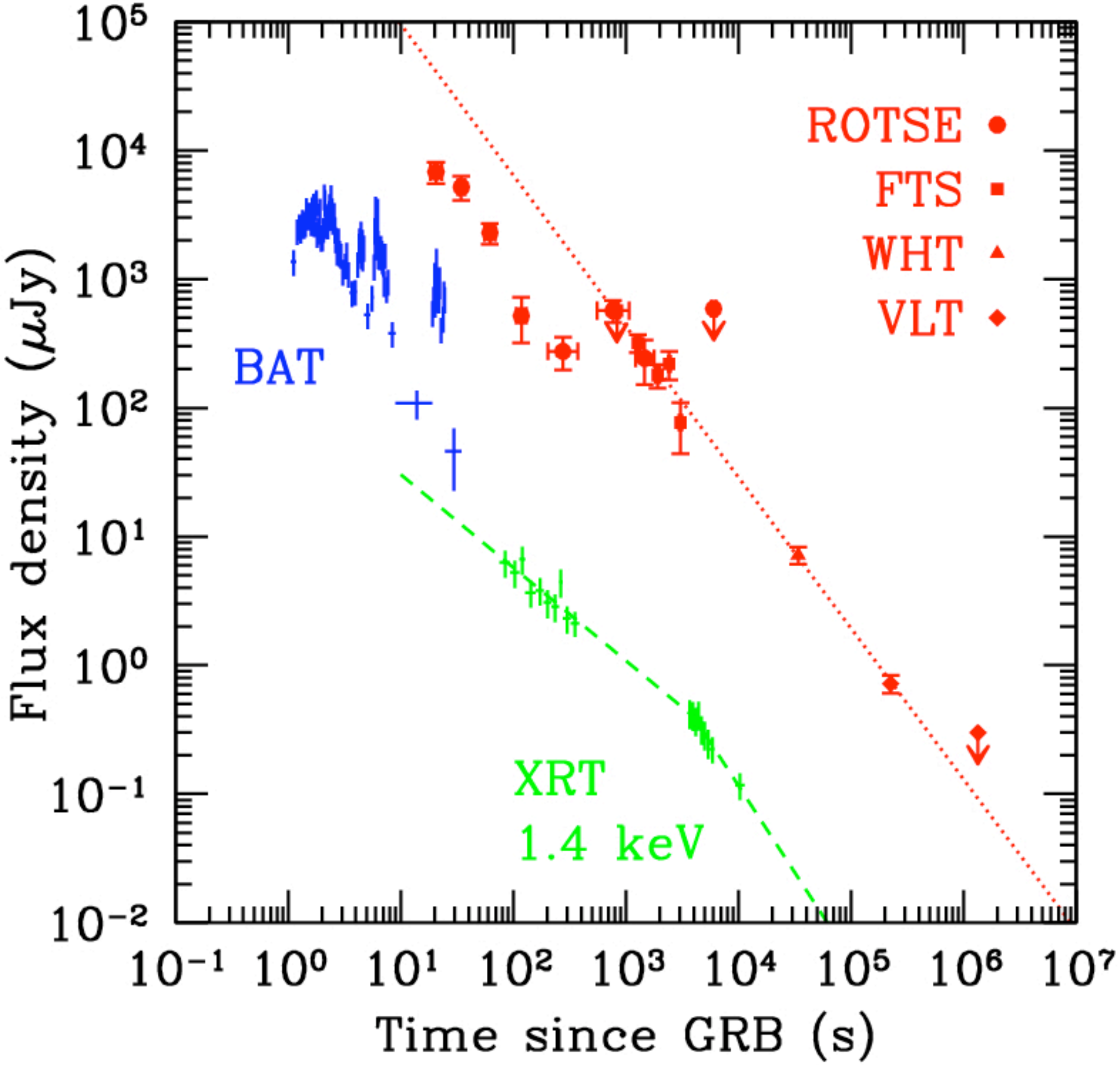
Examples: Low redshift, z=0.34, VLT



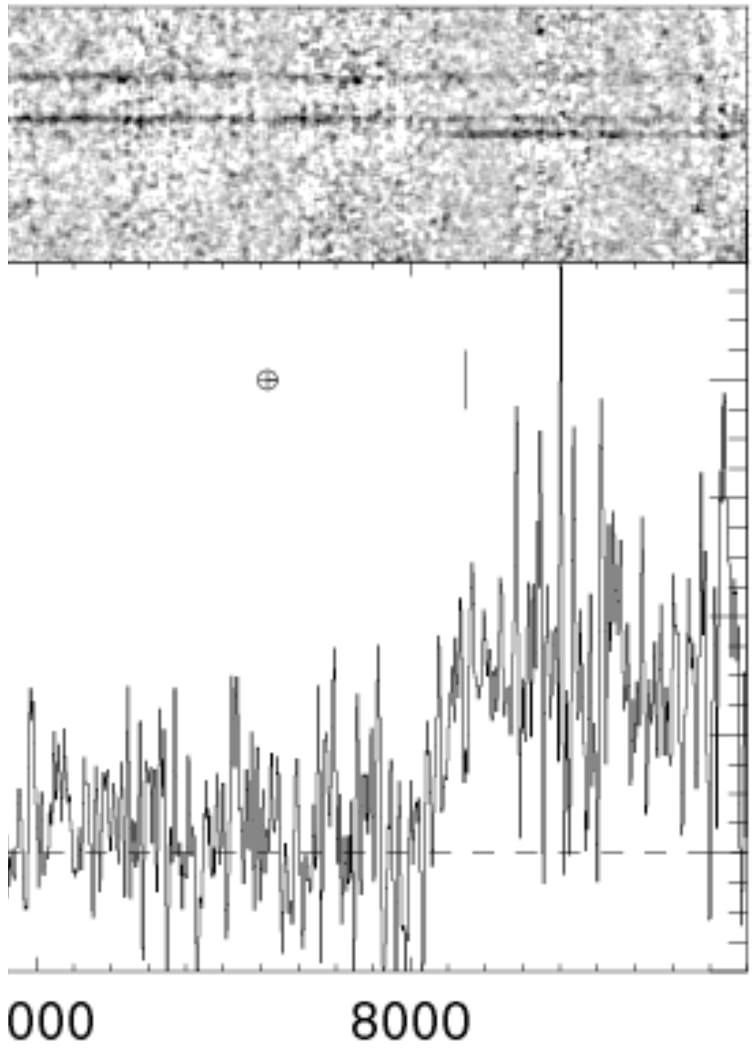
Most distant: z=6.3, SUBARU



z=5.47, VLT

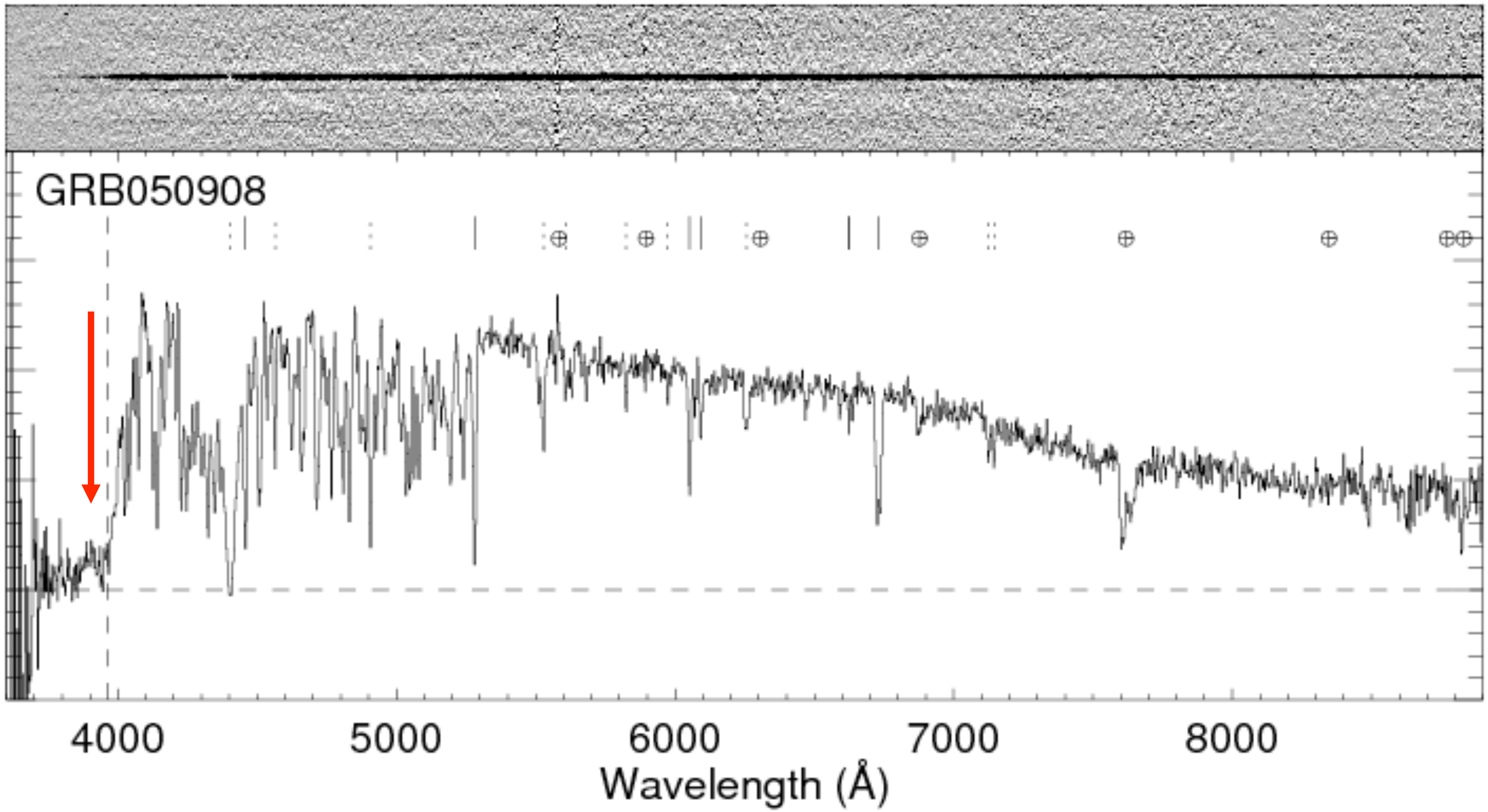


ROTSE
FTS
WHT
VLT
BAT
XRT
1.4 keV
Flux density (μJy)
Time since GRB (s)



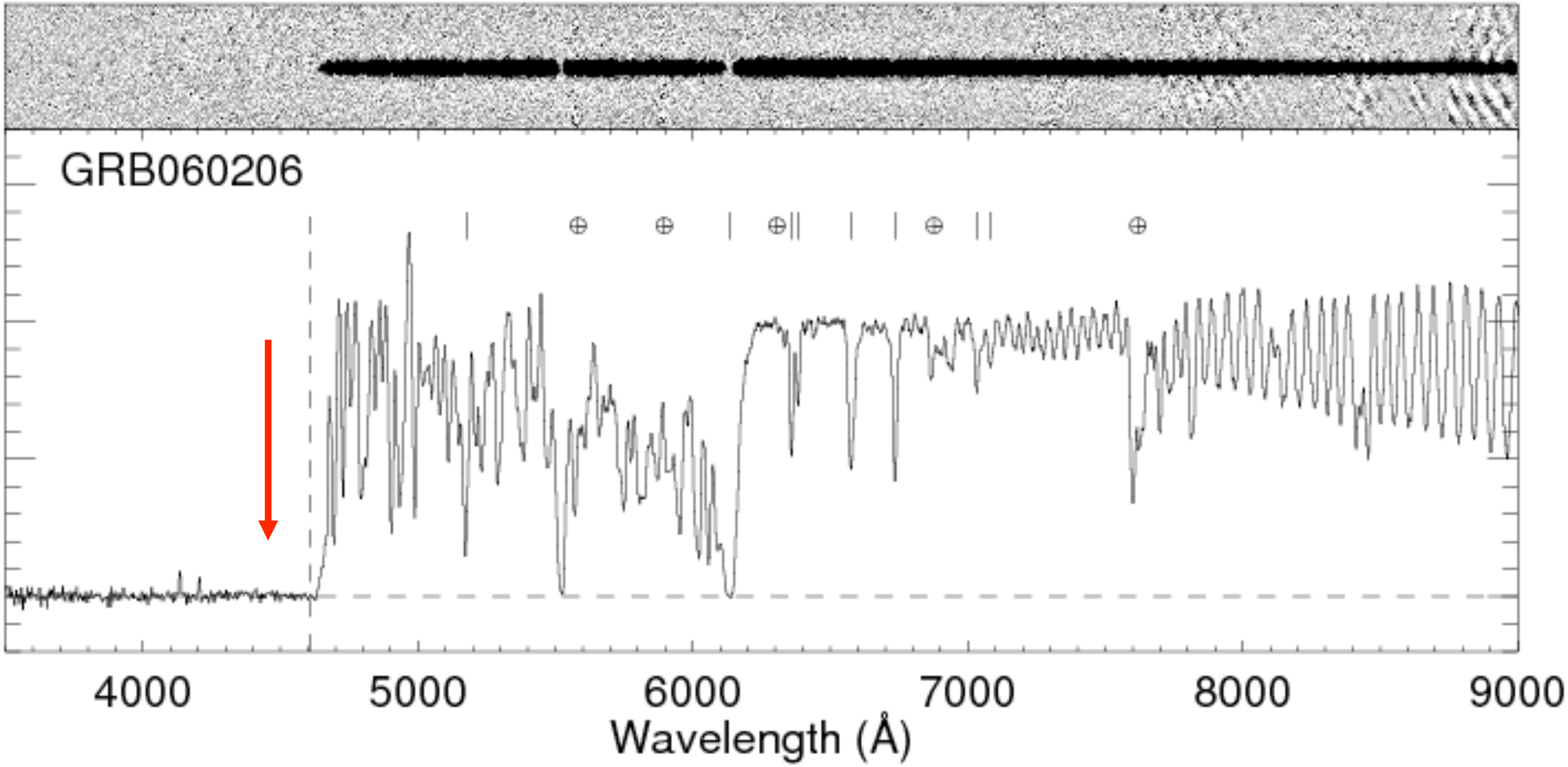
000
8000

z=3.345, VLT/MISTICI, logNHI=17.5

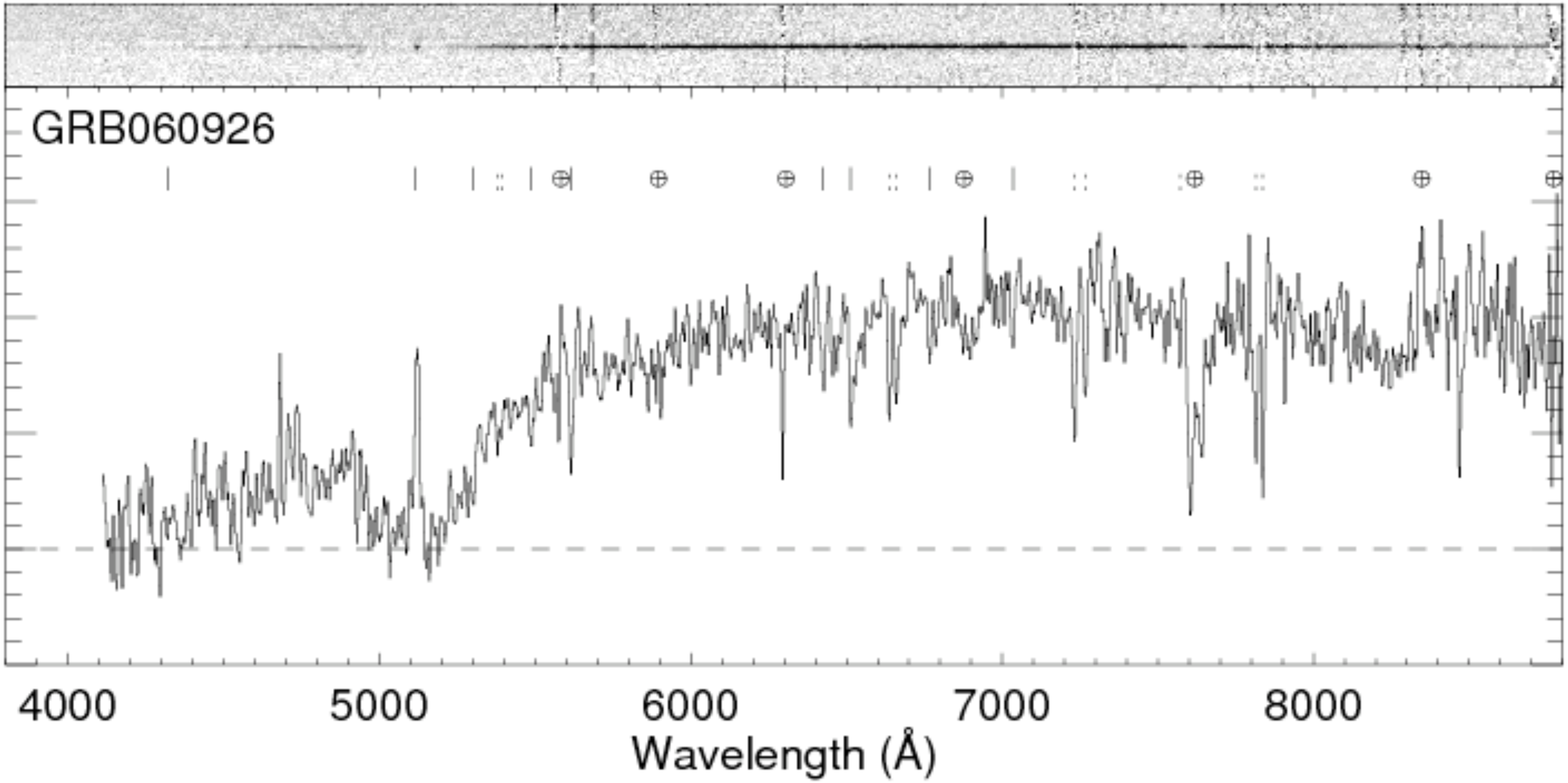


z=4.05, NOT, logNHI=20.84

No escape...

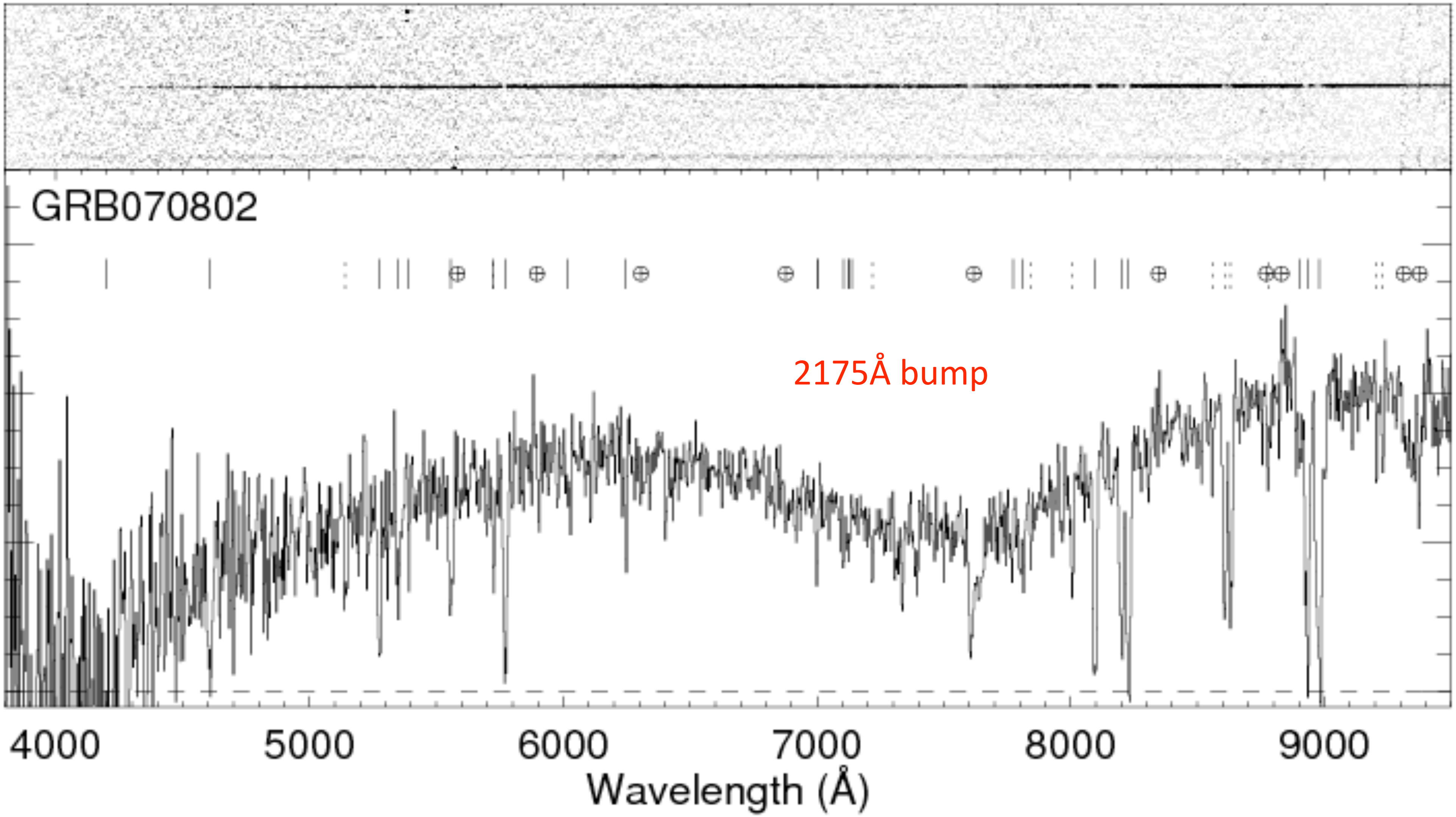


z=3.21, VLT/MISTICI, logNHI=22.7

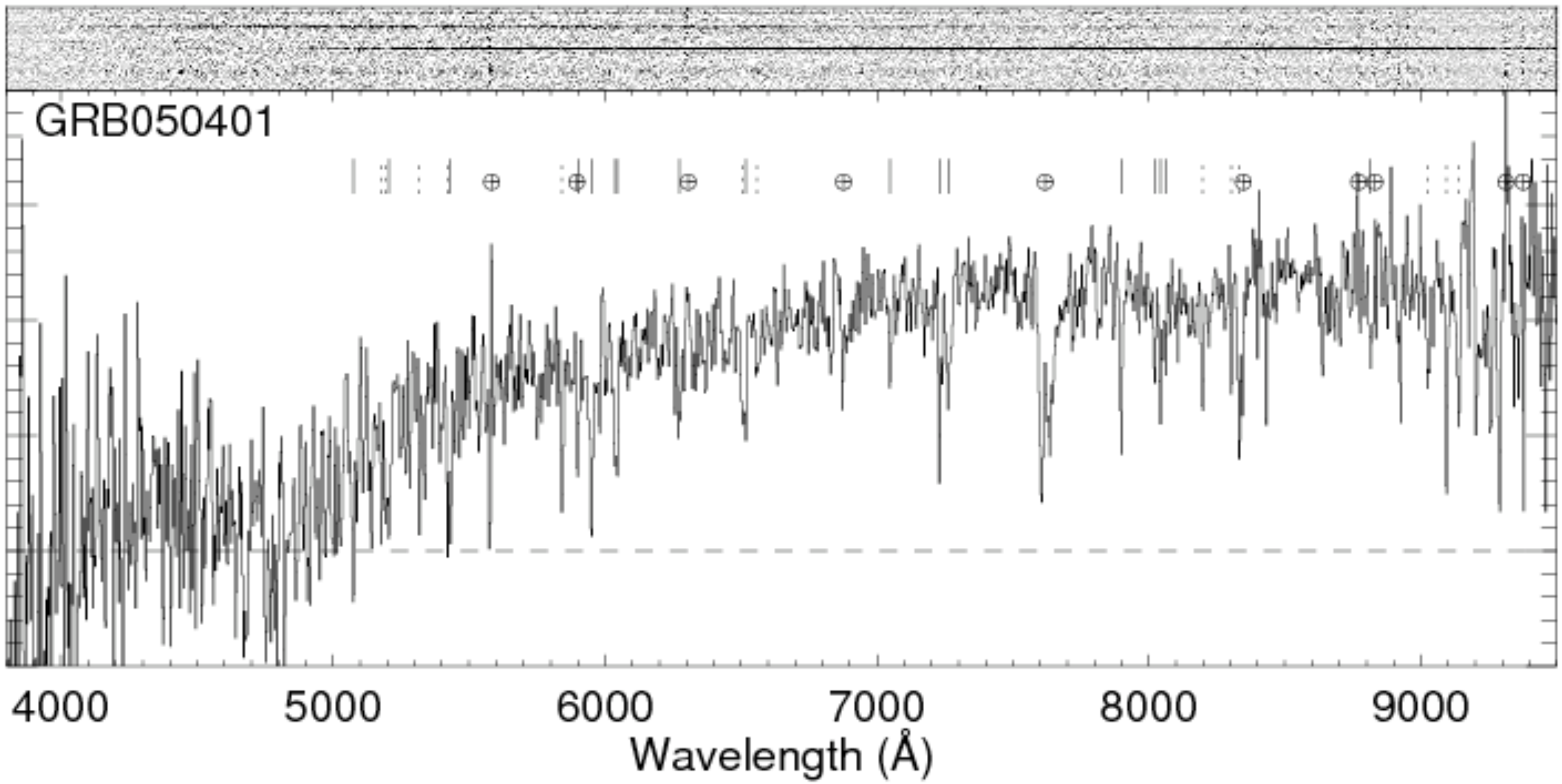


z=2.45, VLT, 2175Å bump

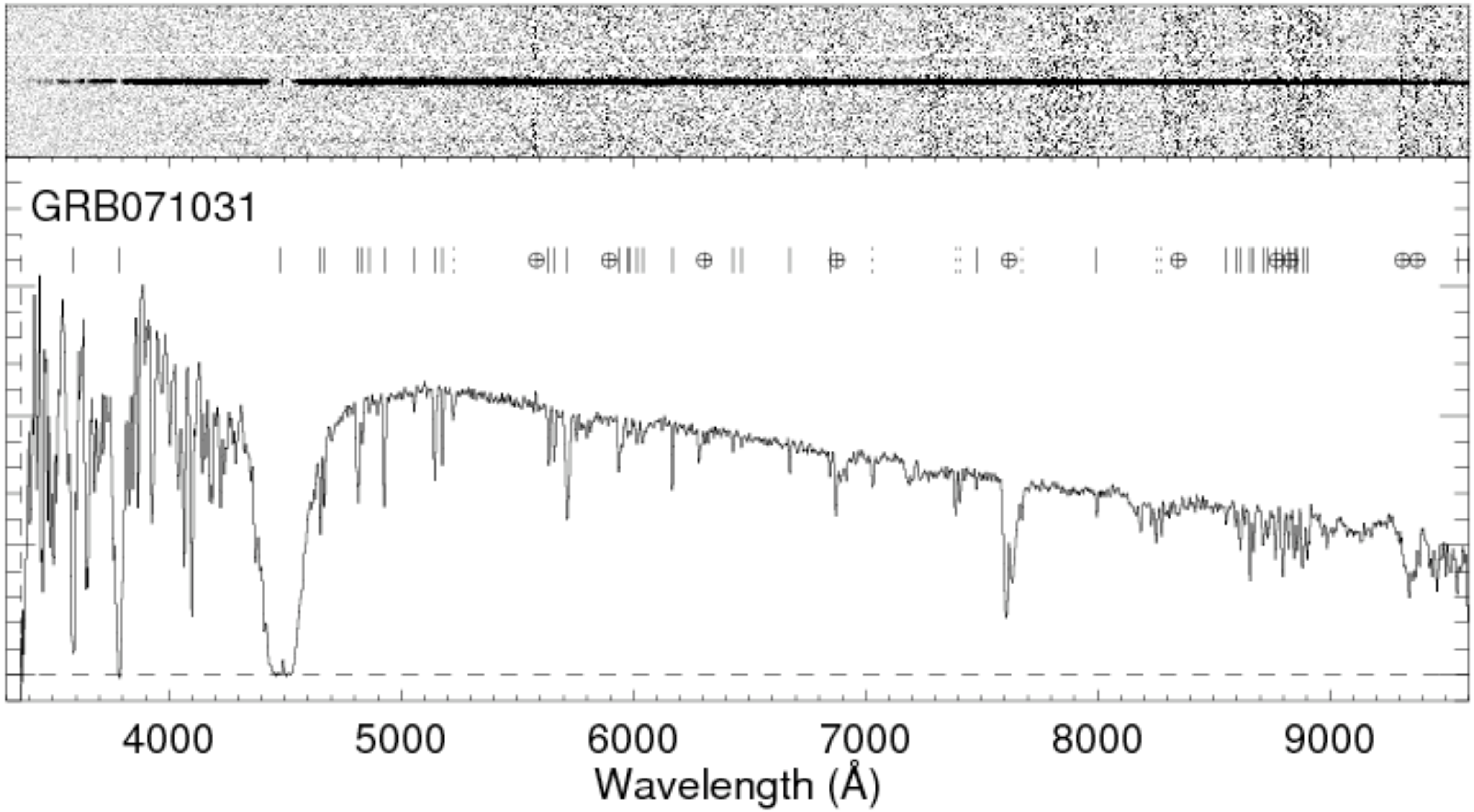
Important for understanding dust in galaxies.



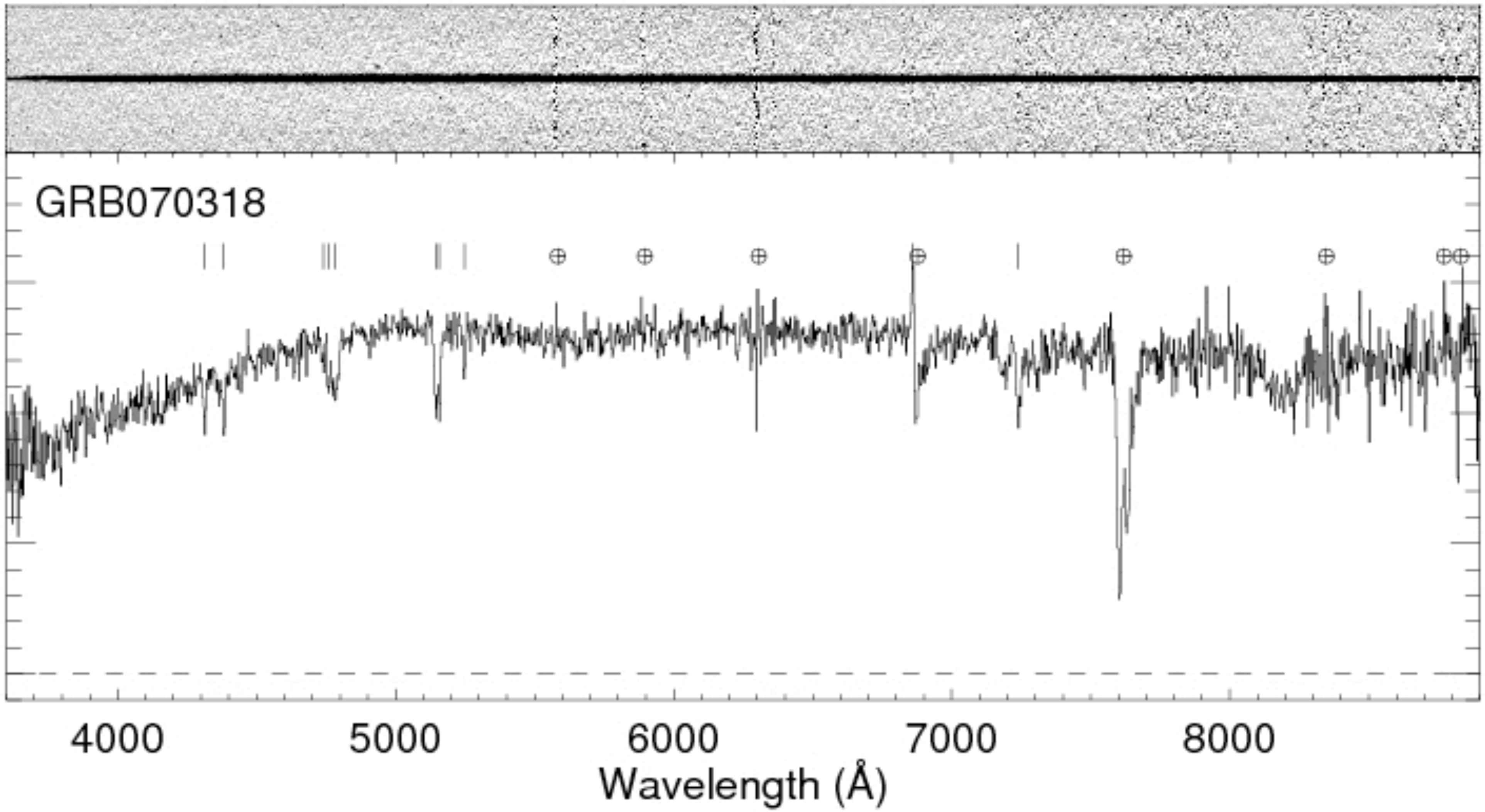
z=2.89, VLT, reddening, but no 2175Å bump



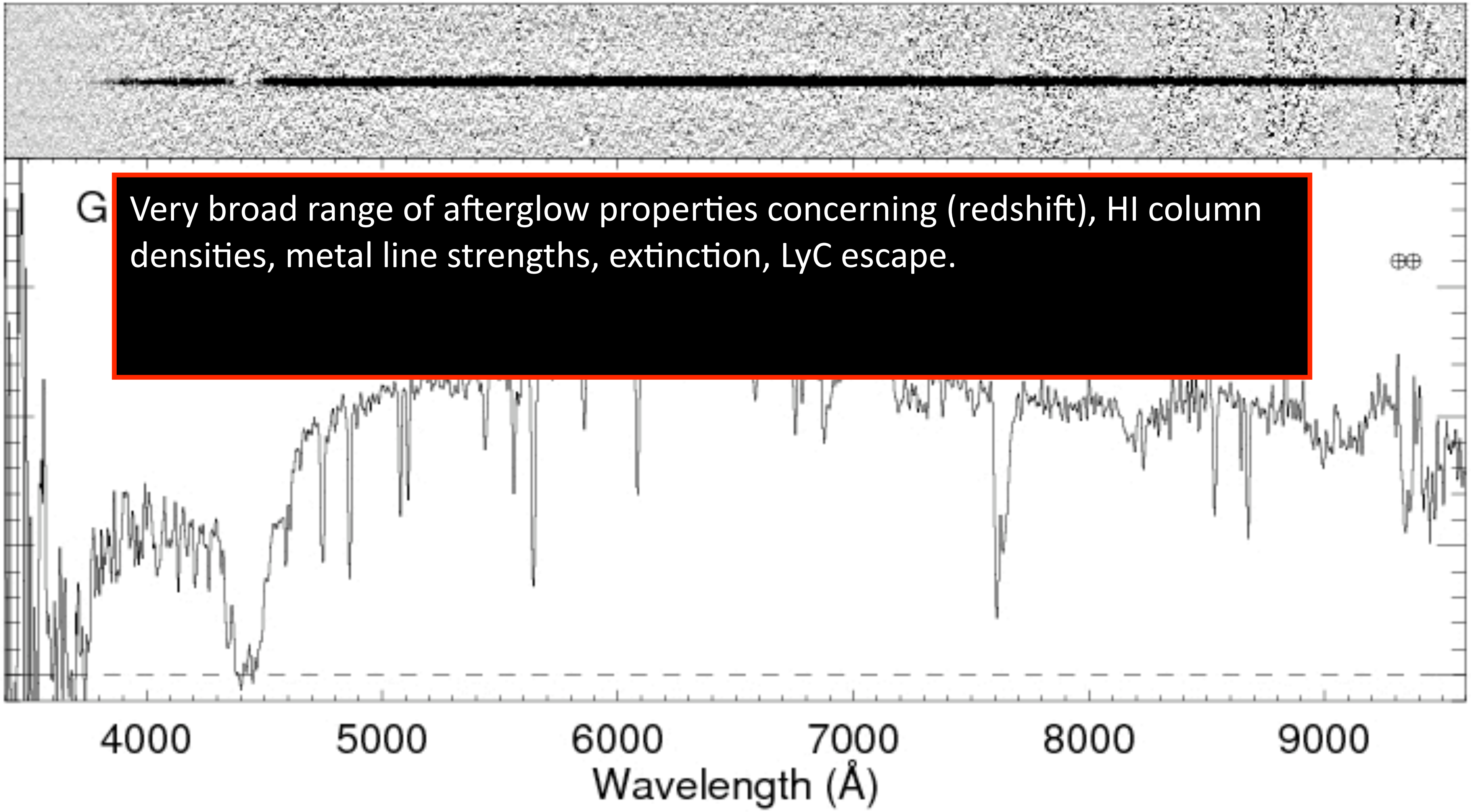
z=2.69, RRM, no reddening



z=0.84, break in spectrum. Nature under investigation...

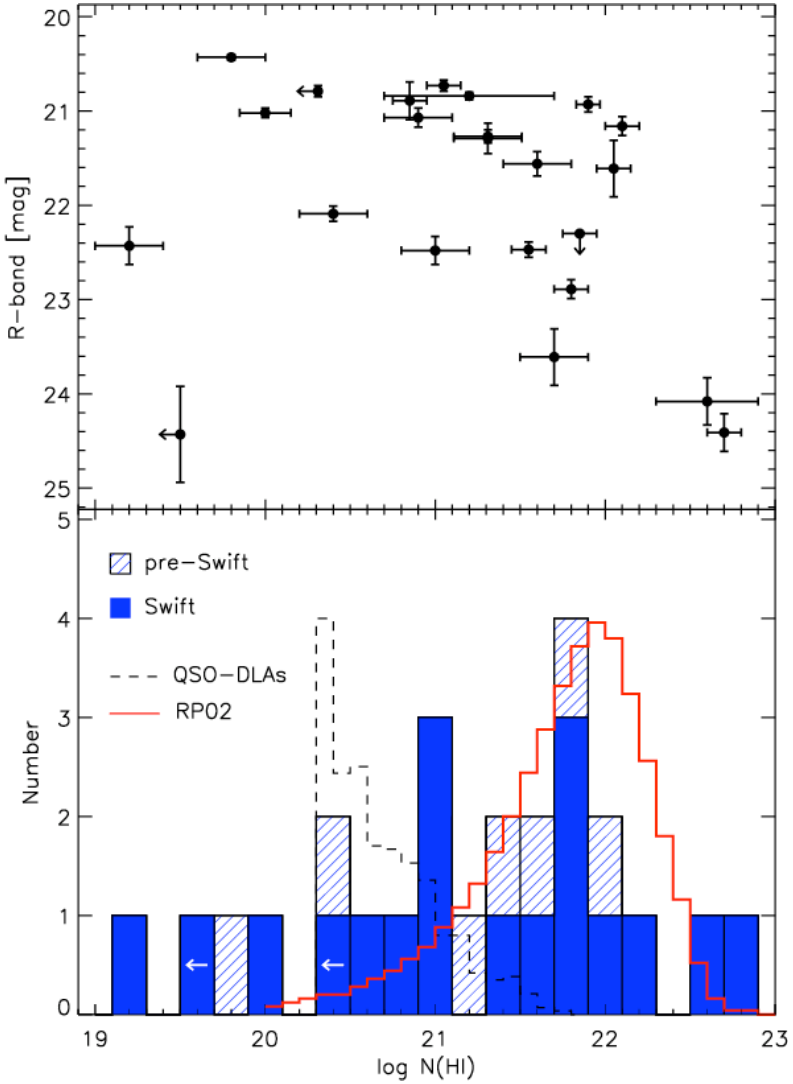


z=2.64, RRM. Also evidence for deviation from power-law spectrum

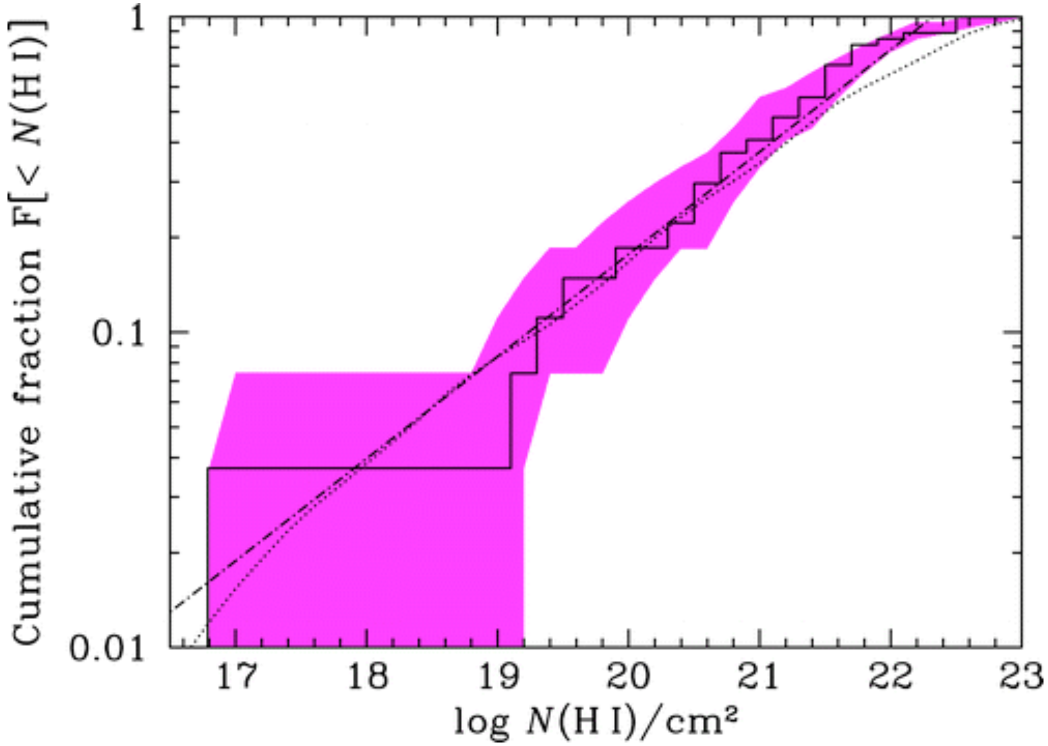


Very broad range of afterglow properties concerning (redshift), HI column densities, metal line strengths, extinction, LyC escape.

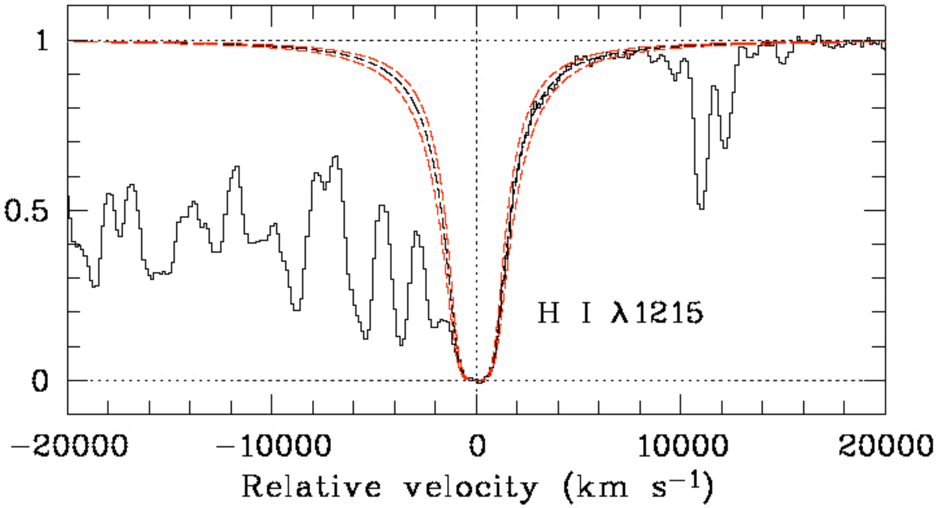
HI column density distribution

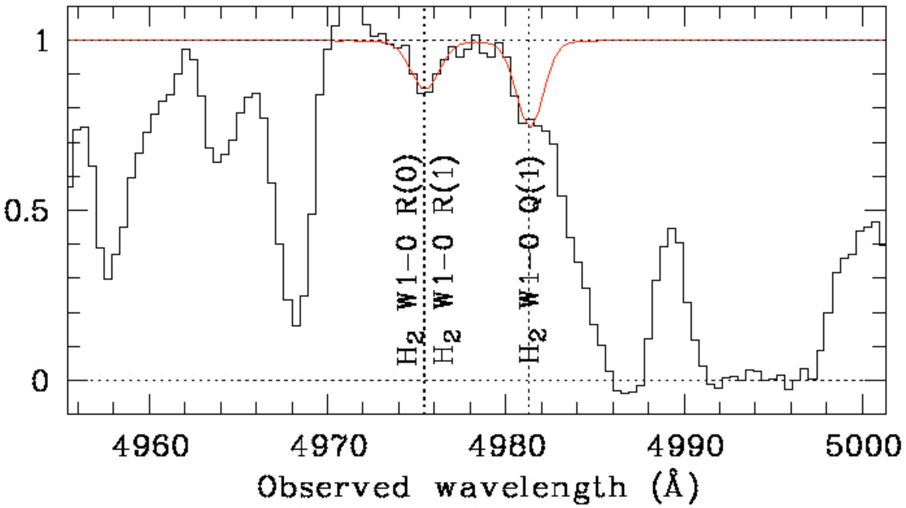


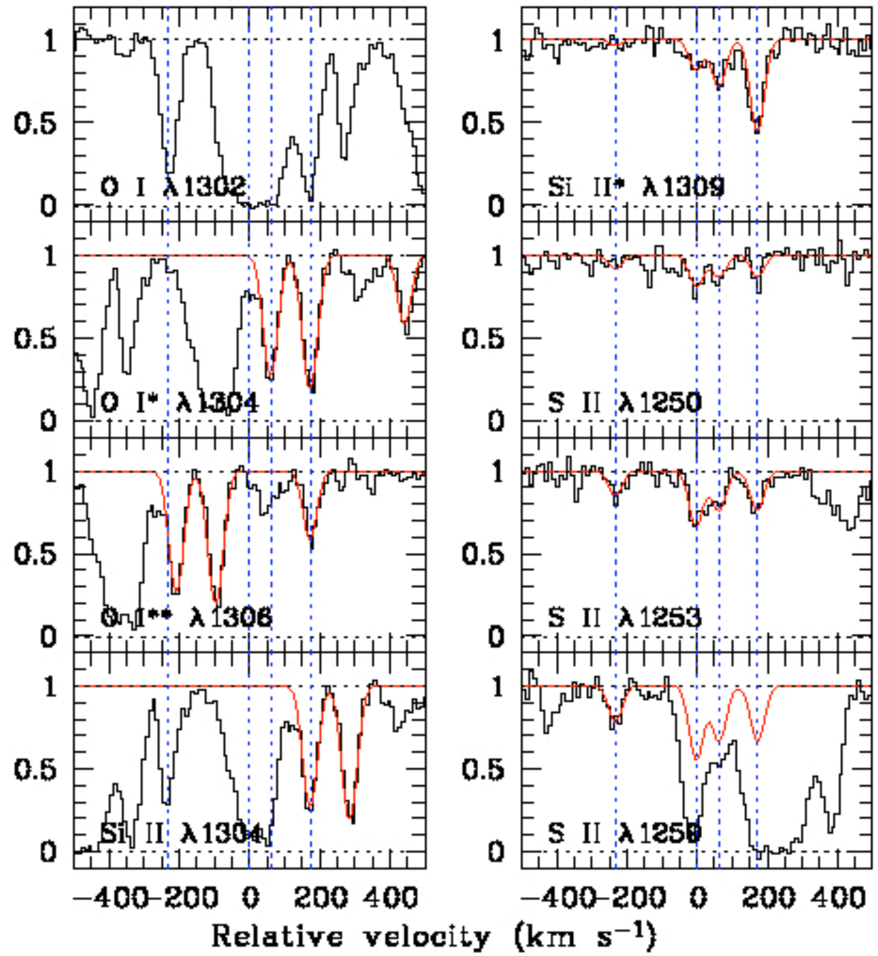
bias



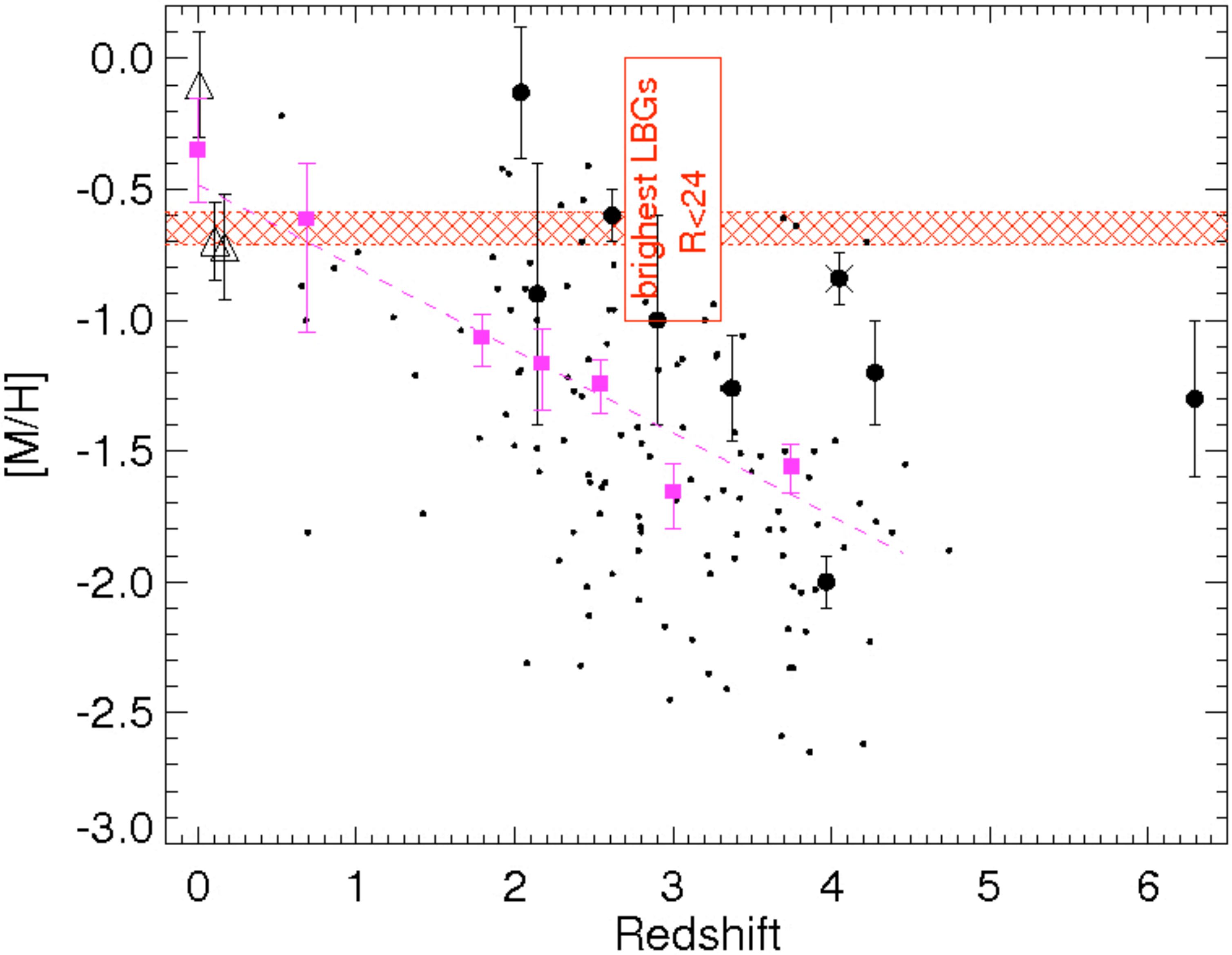
GRB metallicities (metal = element ∉ [H,He])

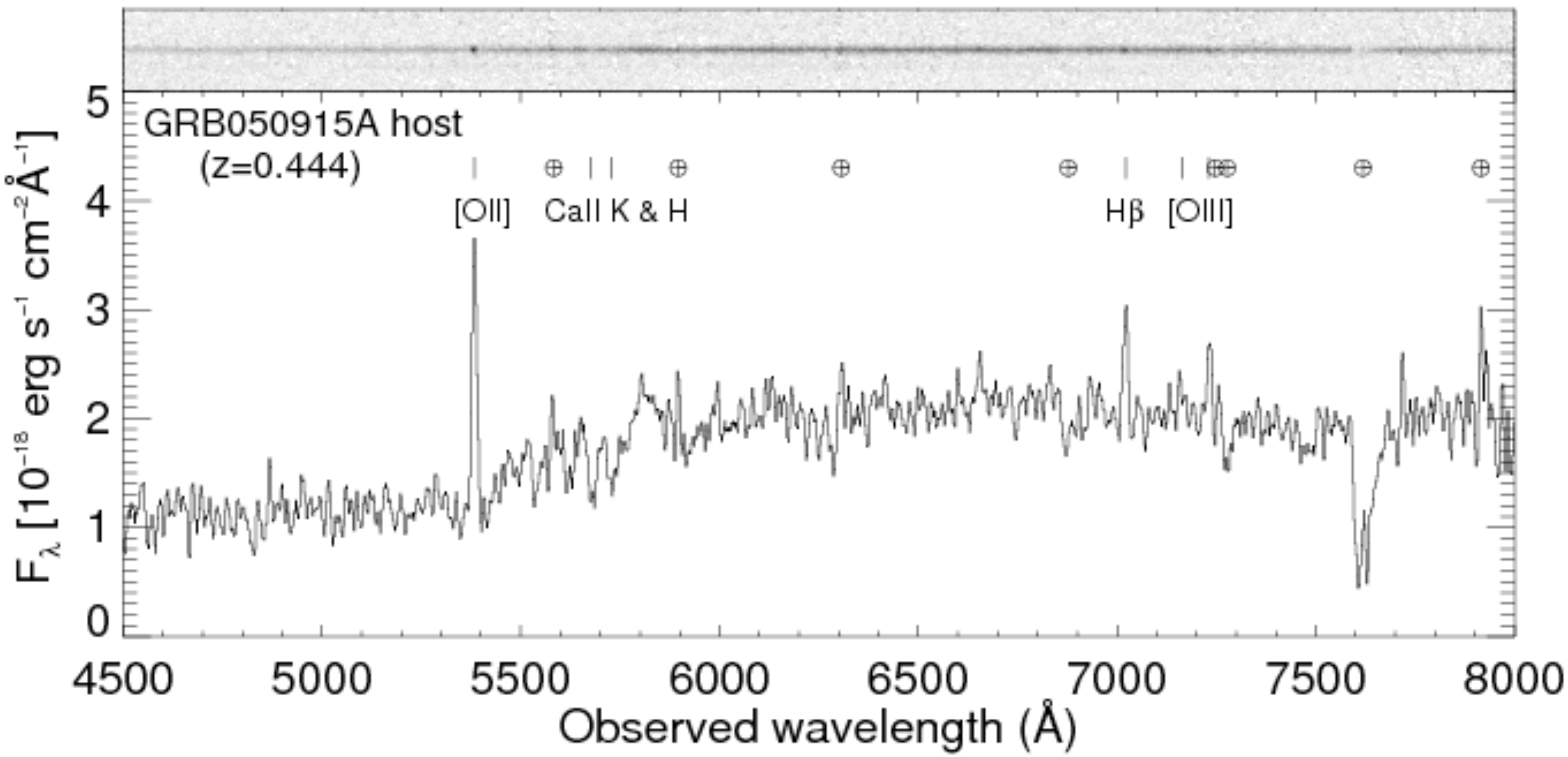






GRB metallicities

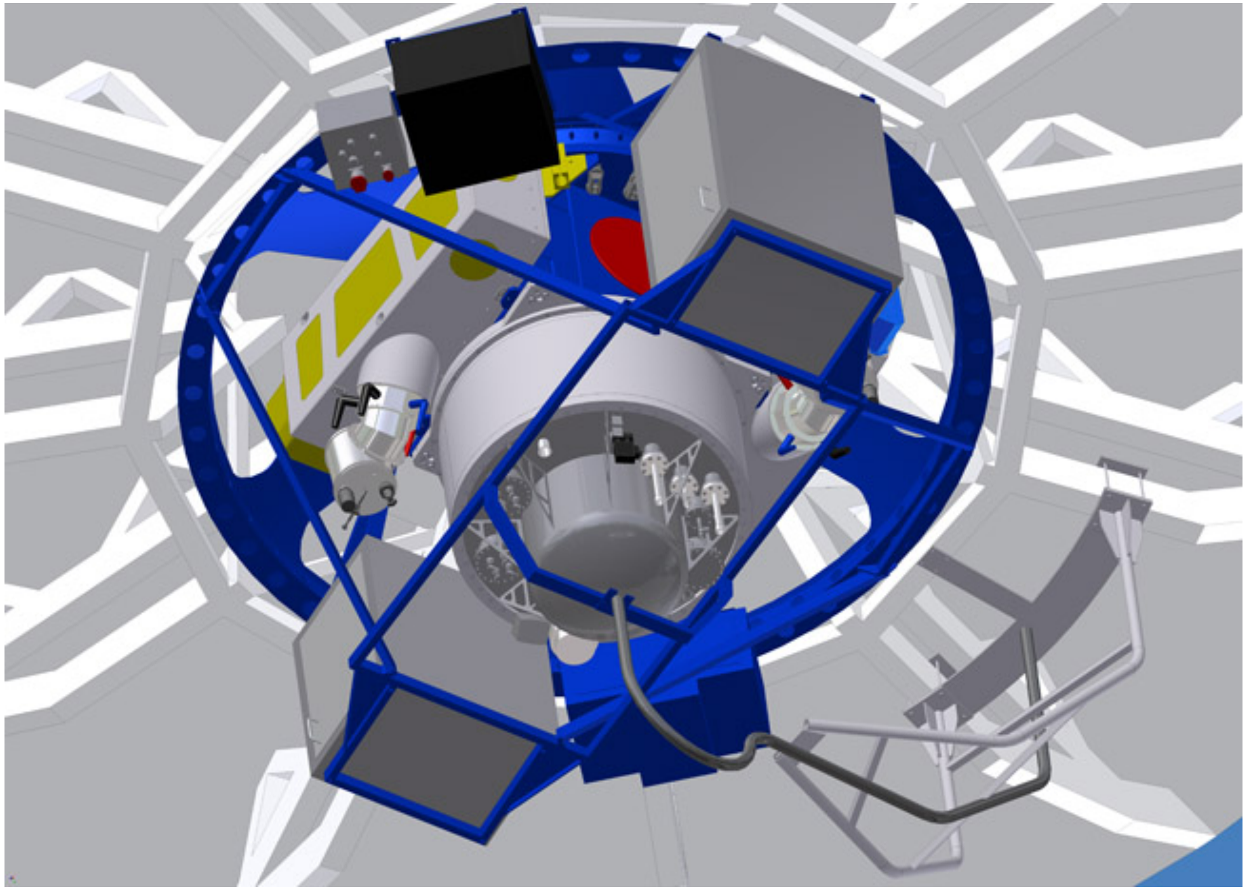



GRB050915A host
(z=0.444)
[OII]
CaII K & H
Hβ
[OIII]
F_λ [10^-18 erg s^-1 cm^-2 Å^-1]
0
1
2
3
4
5
4500
5000
5500
6000
6500
7000
7500
8000
Observed wavelength (Å)

GRB afterglow spectroscopy

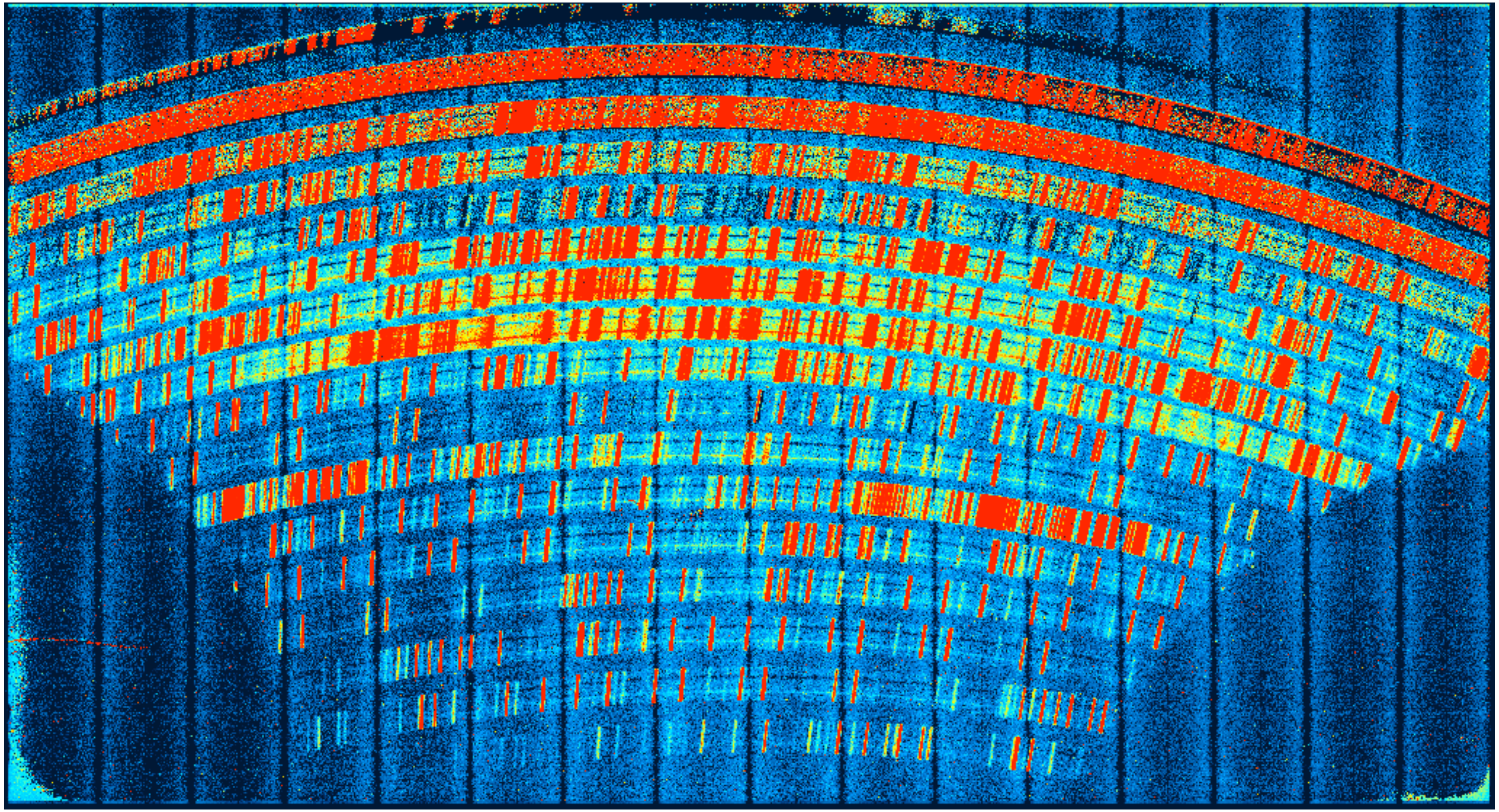
New spectrograph partly build in Copenhagen will improve the situation: X-shooter

First light 09/2008



http://www.eso.org/instruments/xshooter/

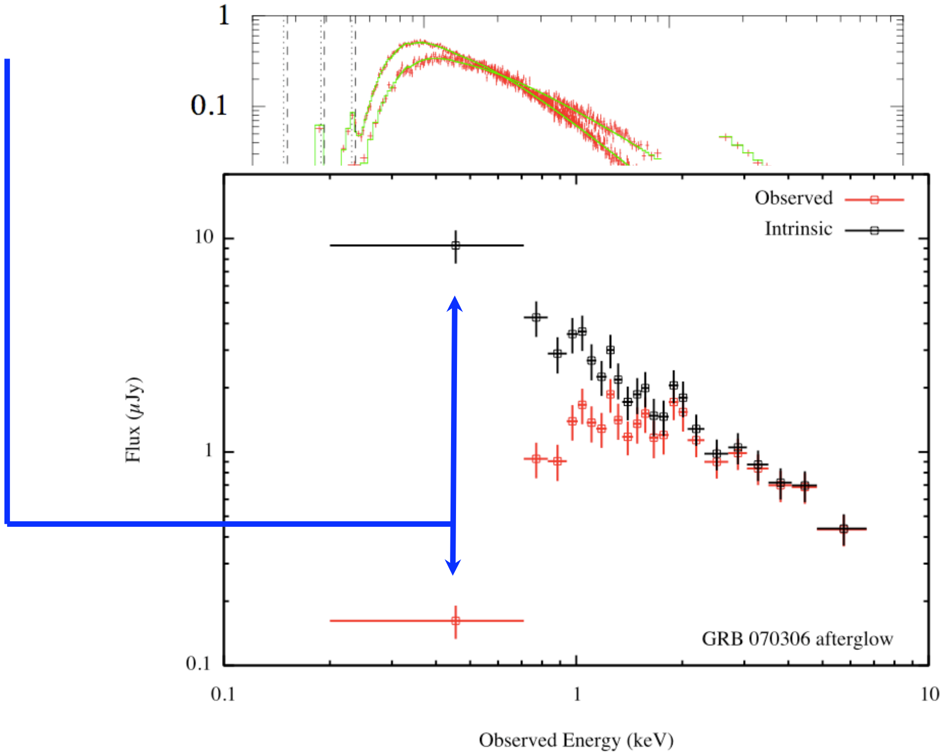
IR spectroscopy

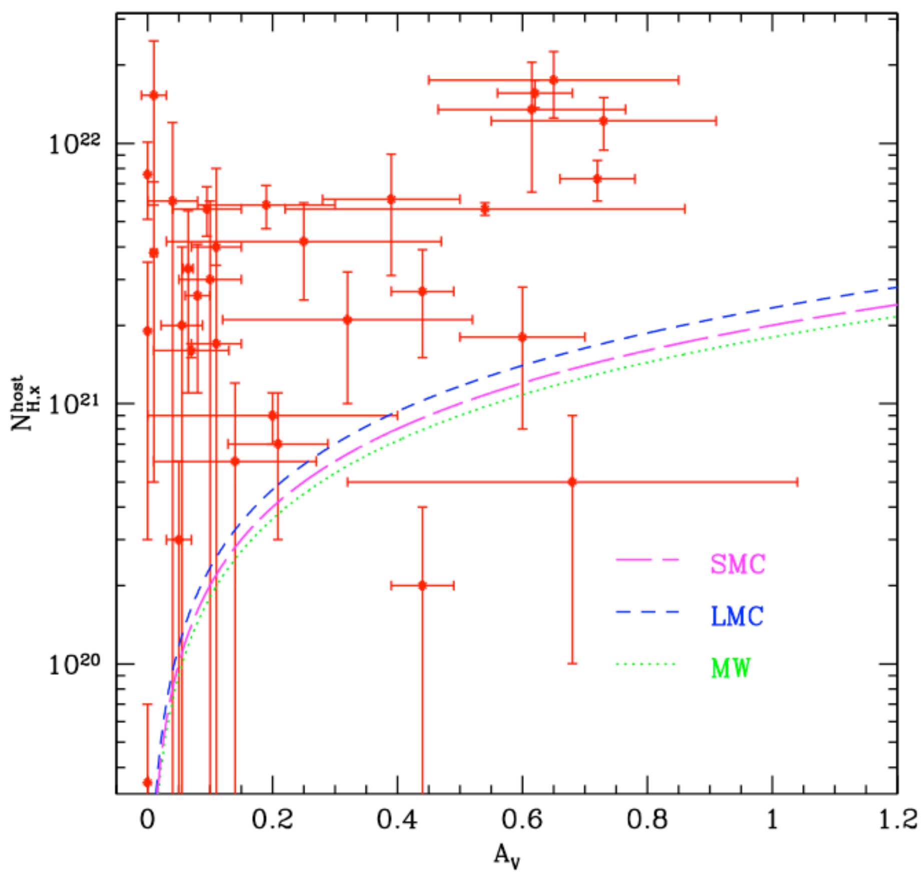


X-ray spectroscopy

- X-rays measure the total metal column density (K-shell absorptions)

- High-resolution X-ray spectroscopy not possible—afterglows too faint and/or response too slow



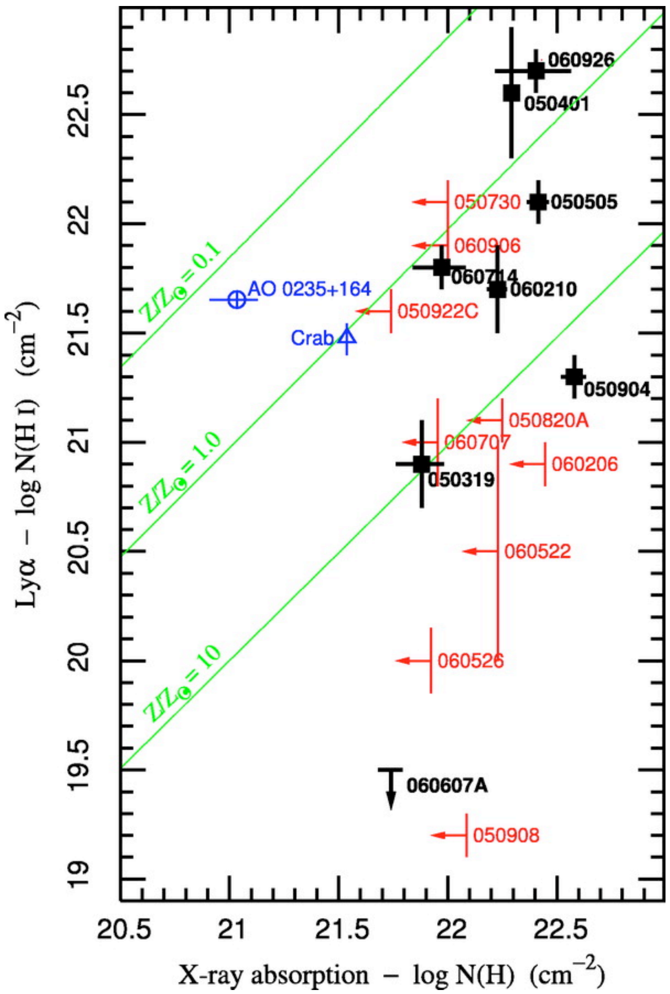


Where are the metals?

X-ray metal column densities much higher than typical dust reddening

Metals not in the gas

- No correlation between the X-ray column density and the neutral gas Ly-alpha column density



Summary of todays lecture

GRBs are good tracers of massive stars (bright, unhindered by dust).

- Swift makes it possible to build a larger and more complete sample of (long)-GRBs.

- In the current Swift sample there is a very broad range of (redshifts), HI column densities, metal line strengths, extinction, LyC escape.

- GRBs will allow us to go beyond z=7 and hence probe the end of the 'dark ages'.

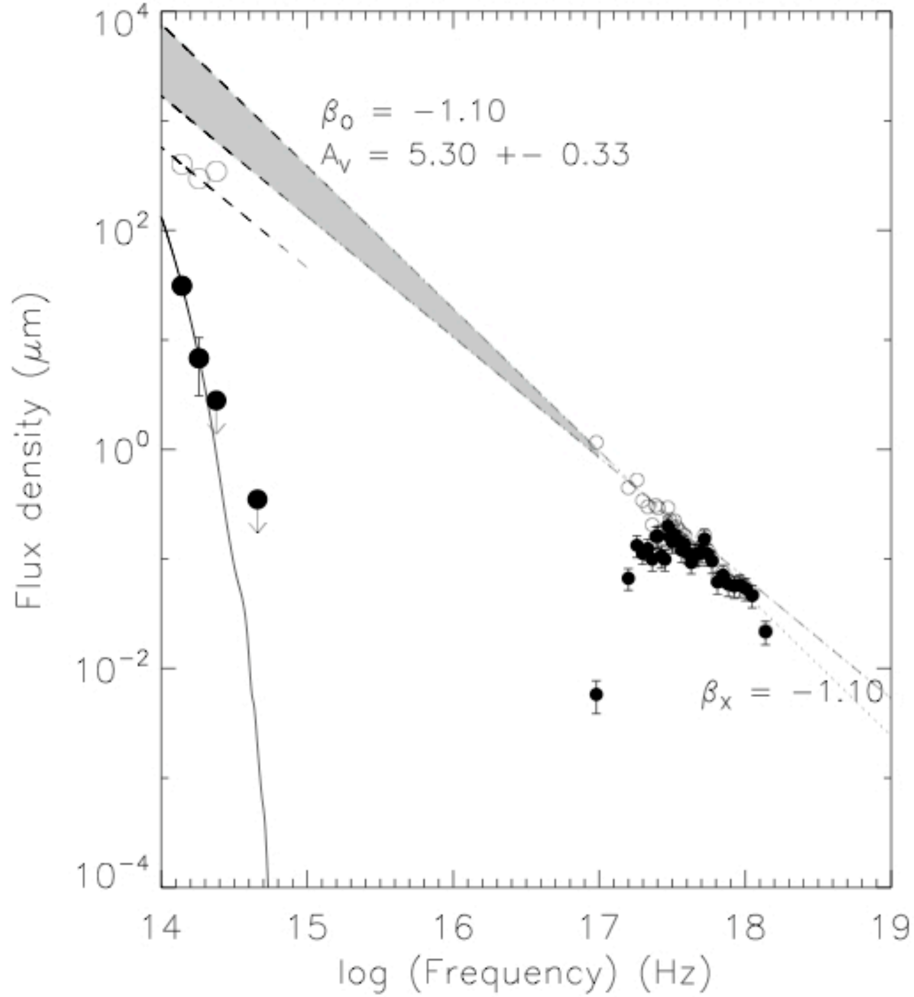
Thanks for your attention!

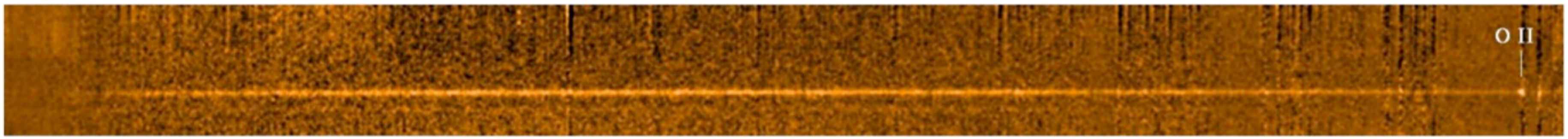
Studies of Dust with GRBs

DUST IS INTERESTING

…HONESTLY

z=1.50, VLT, strong reddening

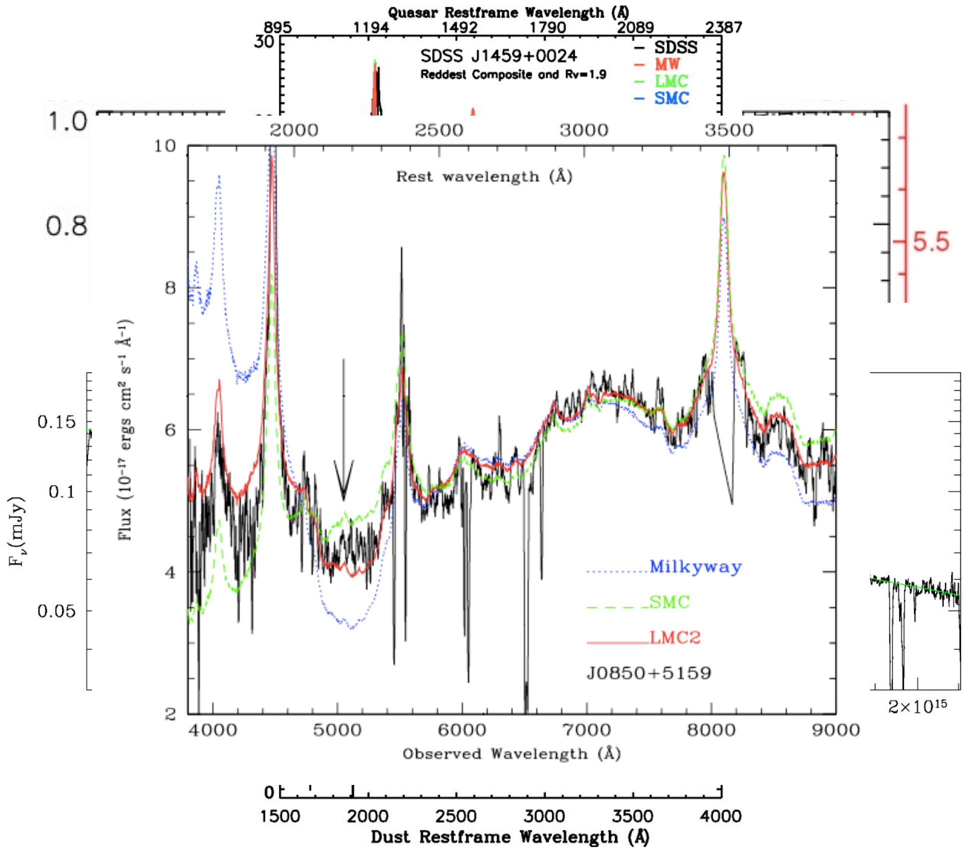




Jaunsen et al. 2008

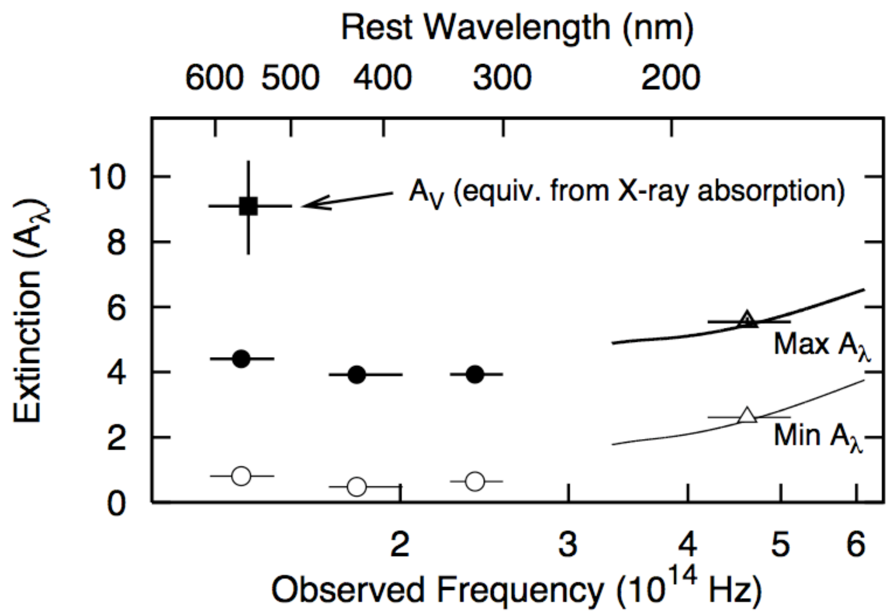
Why are they useful for dust?

- Luminous
- Huge range of redshifts (<z>=2.5)
- Power-law spectra
- Occur in the hearts of star-forming galaxies



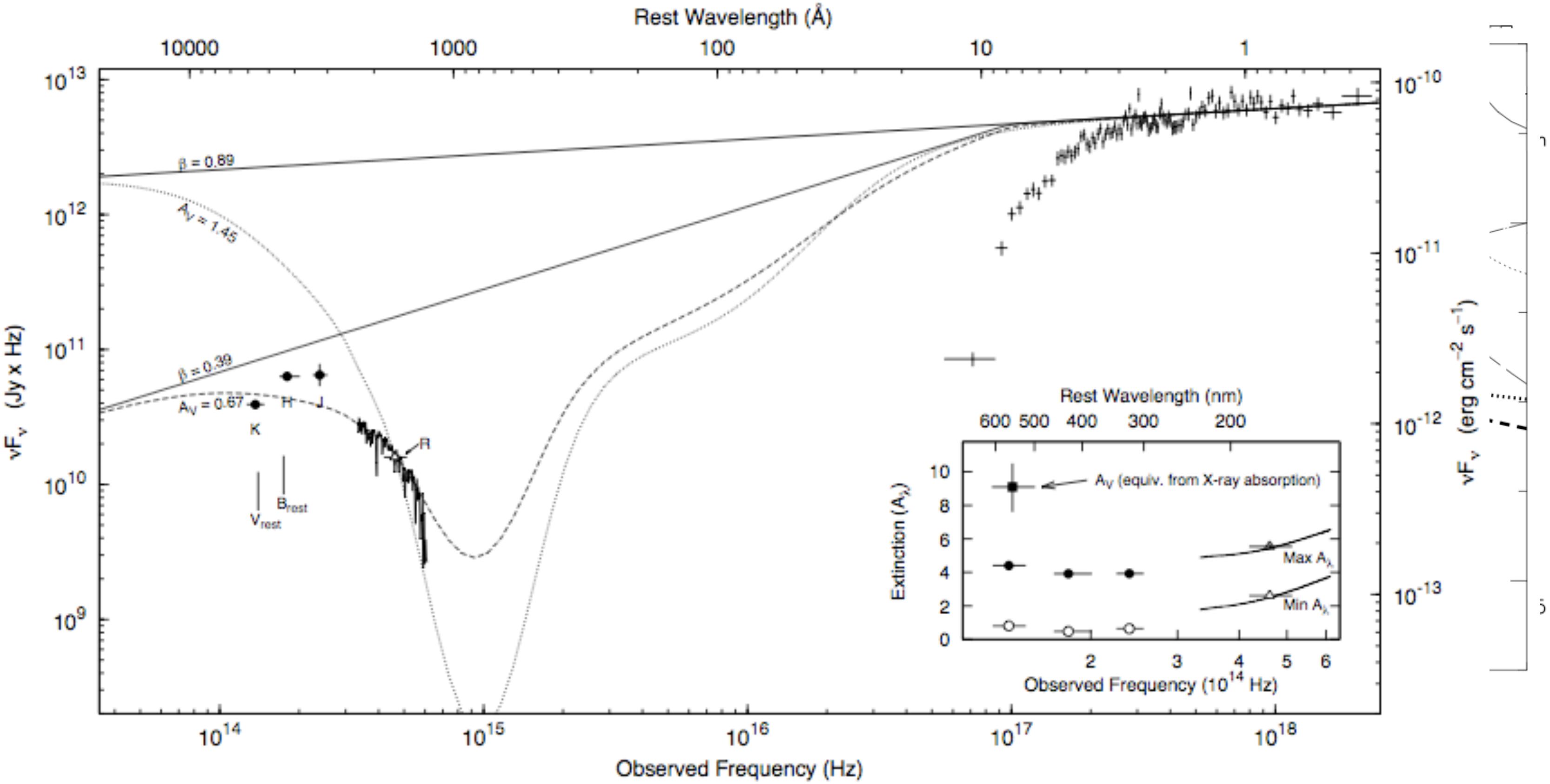
What’s been done so far

- Reddening (fits with standard laws)
- All GRB hosts have “SMC-type” extinction curves
- Dust depletion (‘grey’ dust?)
- First attempts at absolute extinction curves



Dark Cosmology Centre

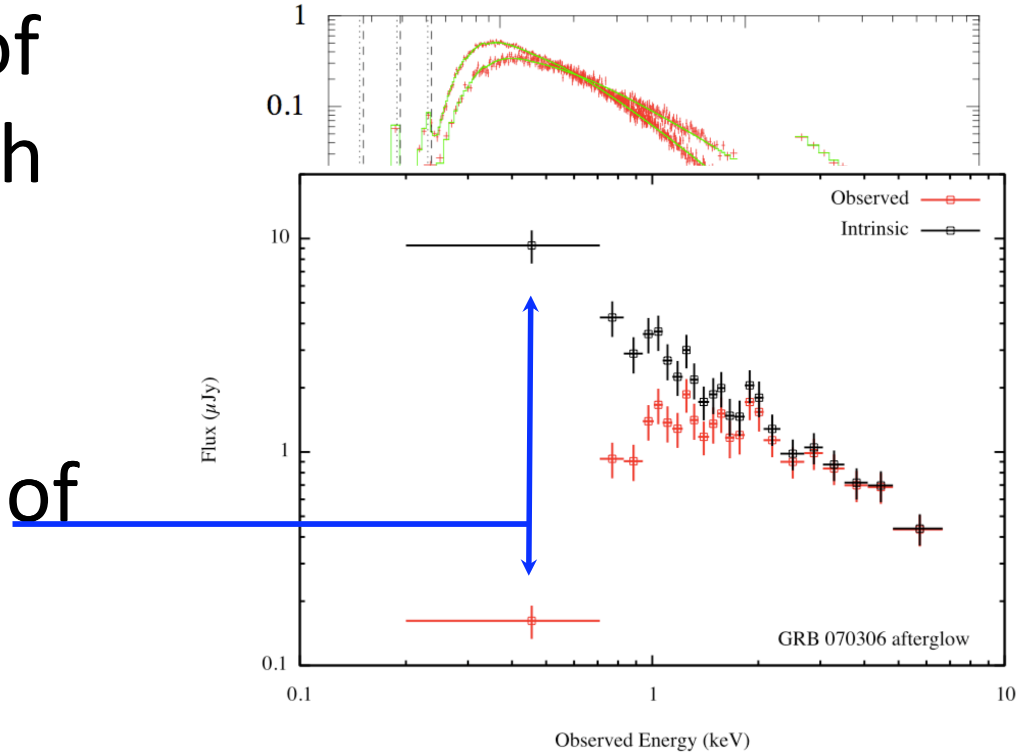
What is the main challenge now?



Dark Cosmology Centre

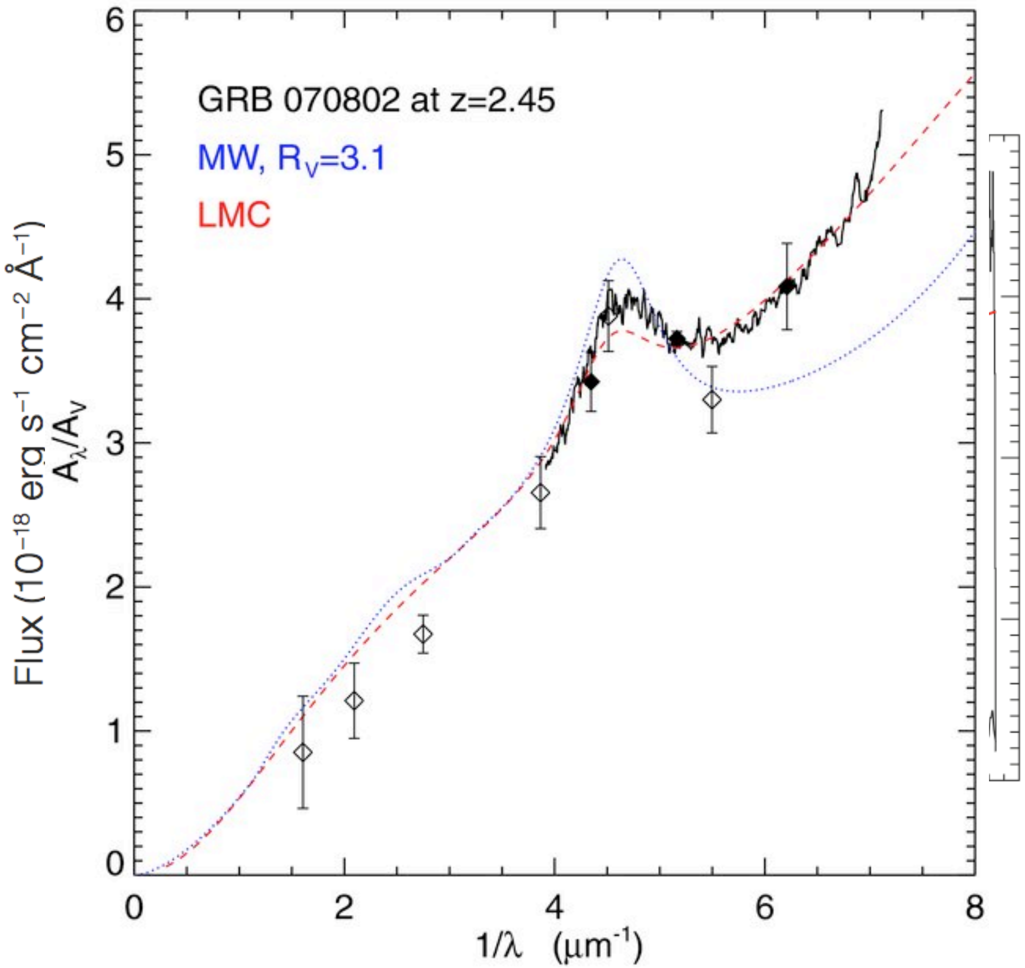
Added bonuses

- Optical spectroscopy of the region (high resolution in some cases)
- X-ray measure of total metal column



First 2175Å feature in a GRB host (070802)

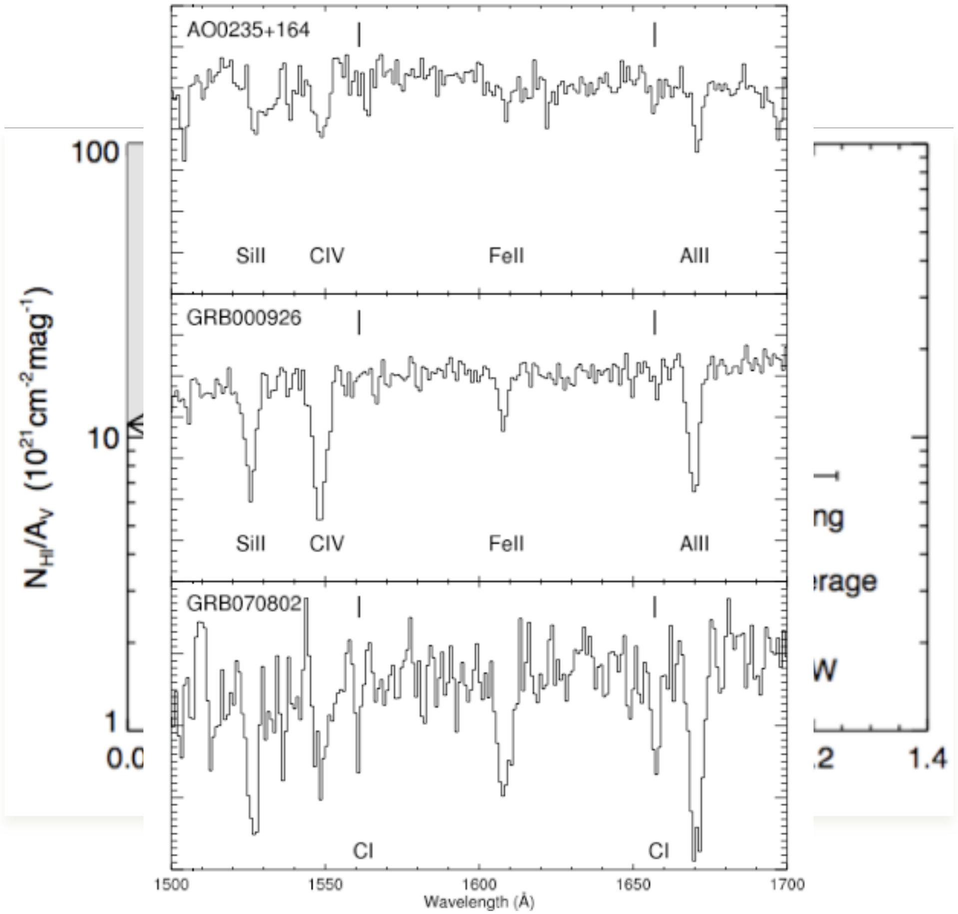
- Most GRB hosts show no bump
- Young stellar populations
- Little carbonaceous dust?
- Extremely tasty



Dark Cosmology Centre

Evolved systems?

- Speculate that we see 2175Å feature in evolved systems
- => Softer intrinsic radiation field, and shielding
- => More dust, more carbon
- Strong CI and bump appear together?



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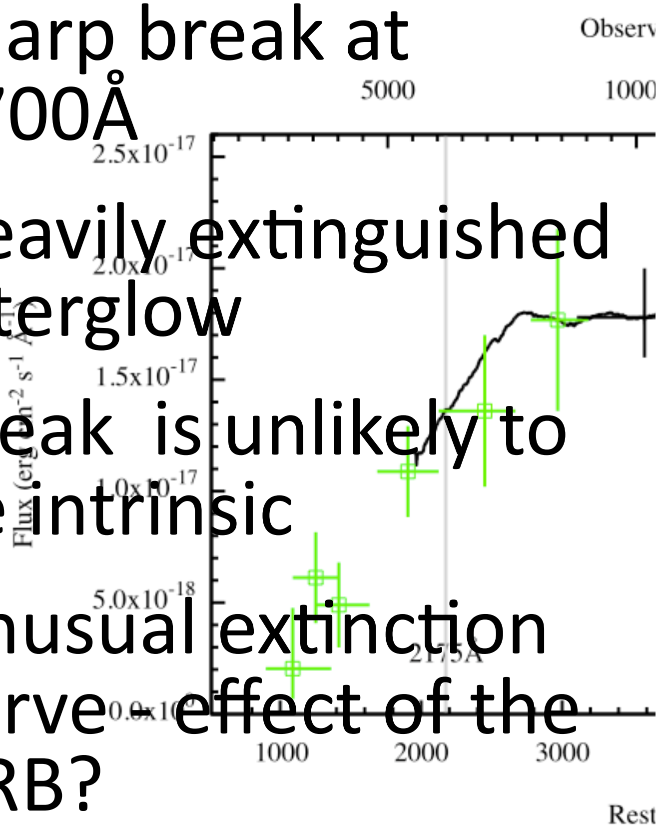
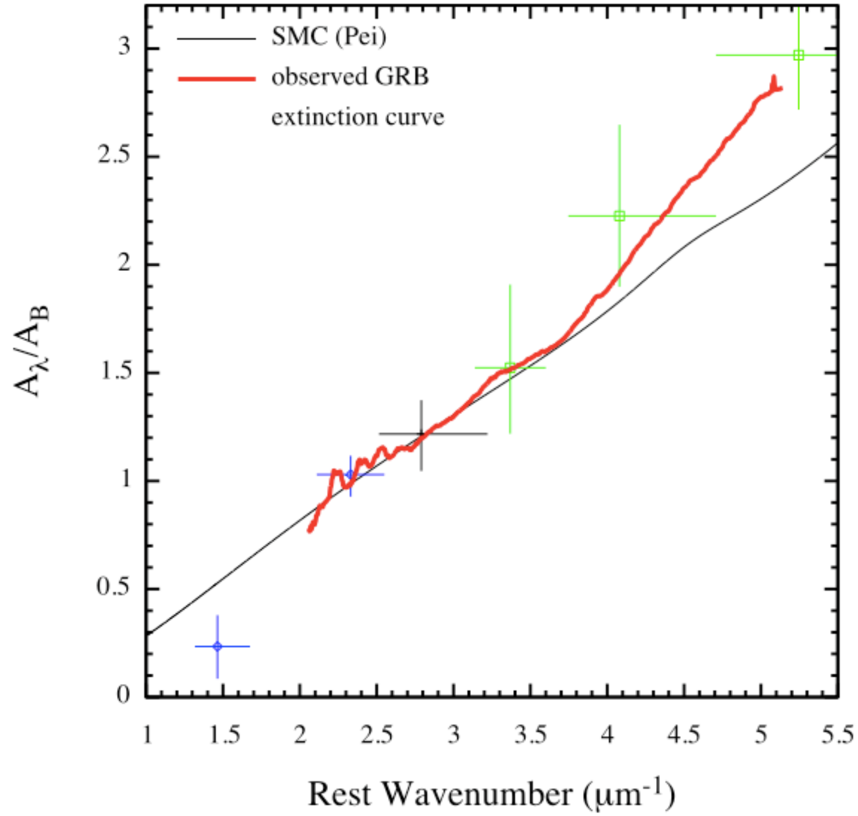
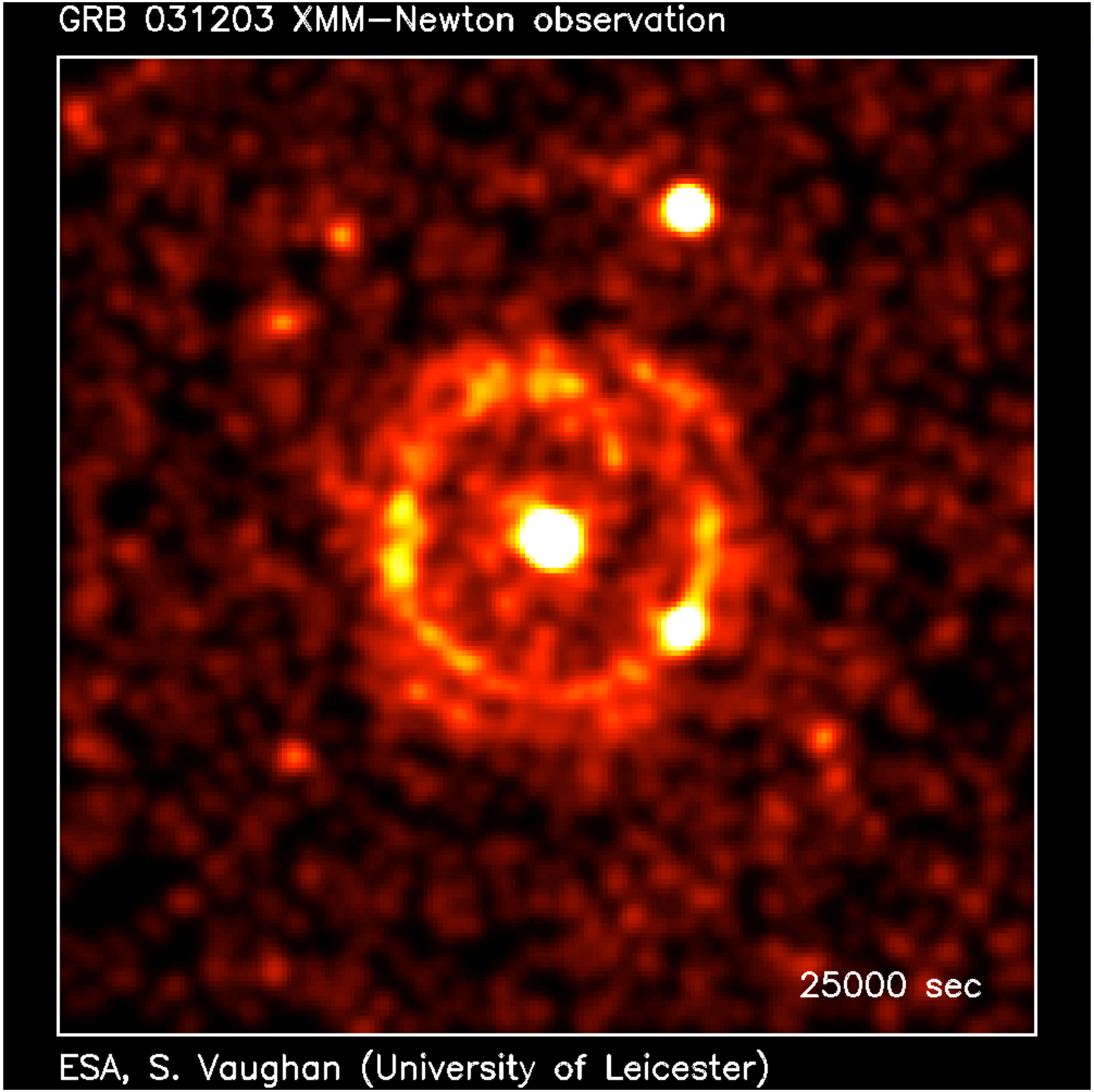
Does the GRB affect the dust we are probing?

- Sharp break at 2700Å
- Heavily extinguished afterglow
- Break is unlikely to be intrinsic
- Unusual extinction curve - effect of the GRB?






GRB 031203 XMM–Newton observation
25000 sec
ESA, S. Vaughan (University of Leicester)

Notable GRBs

- 050904, 080913, 090423
- Naked Eye GRB / Clarke Burst
- GRB980425/SN1998bw, GRB030329/SN2003dh, GRB031203/SN2003lw, GRB060218/SN2006aj
- 670702
- 070802/ Molecular Hydrogen GRB