GAMMA-RAY BURSTS
As Tools for Extragalactic Astrophysics and Cosmology

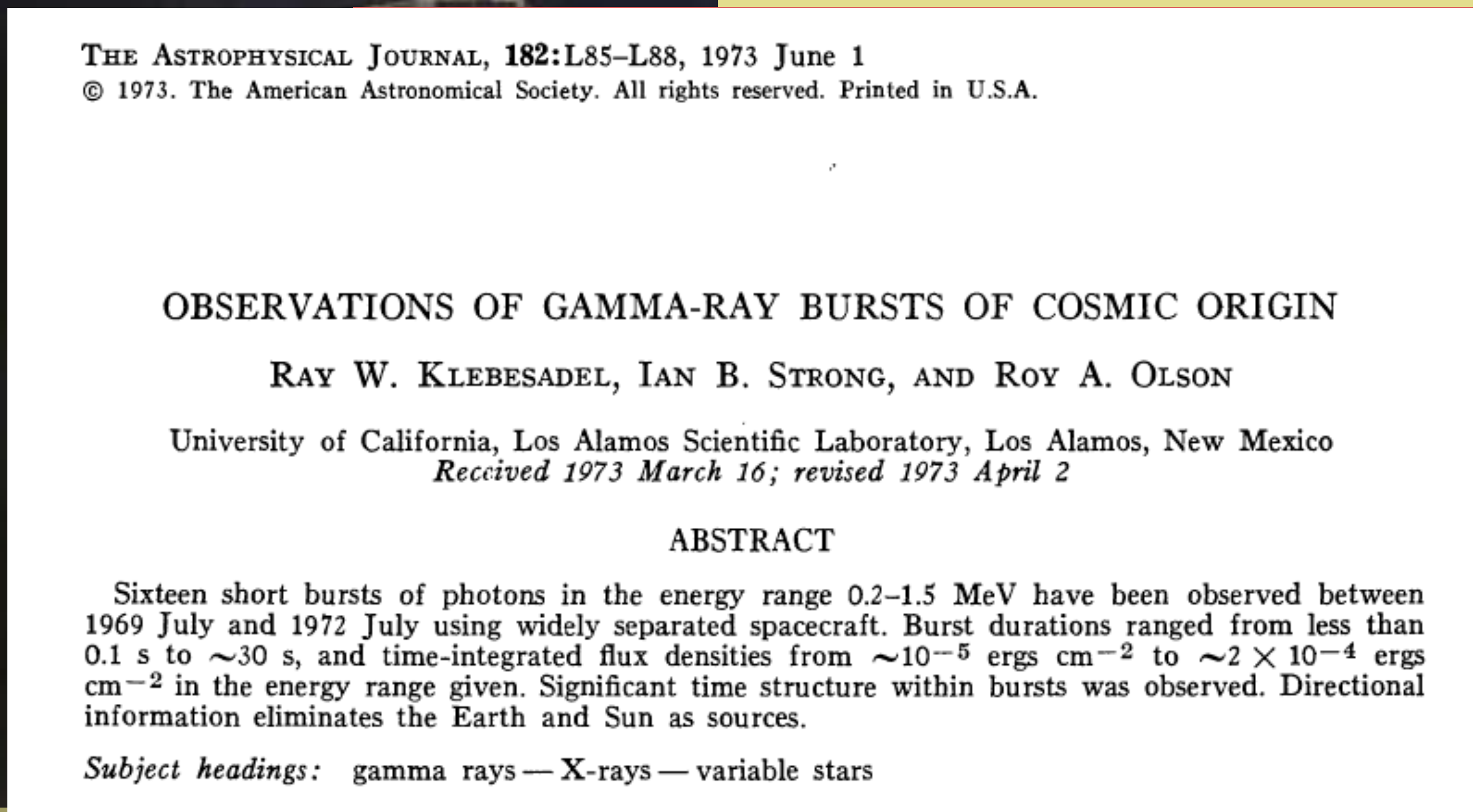
Rosalba Perna

(University of Colorado@Boulder)

How it all started…..

mid 1960s: VELA satellite..

“something” is detected



THE ASTROPHYSICAL JOURNAL, **182**:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

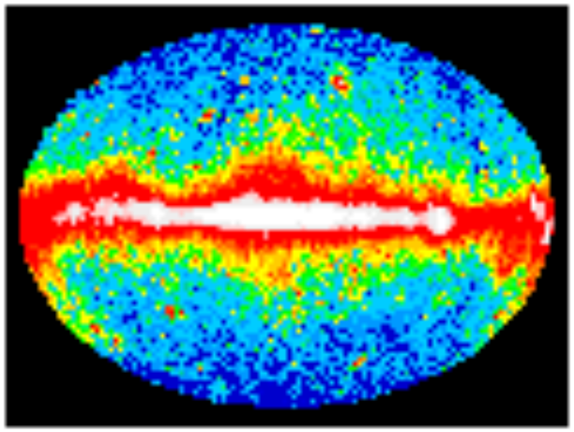
ABSTRACT

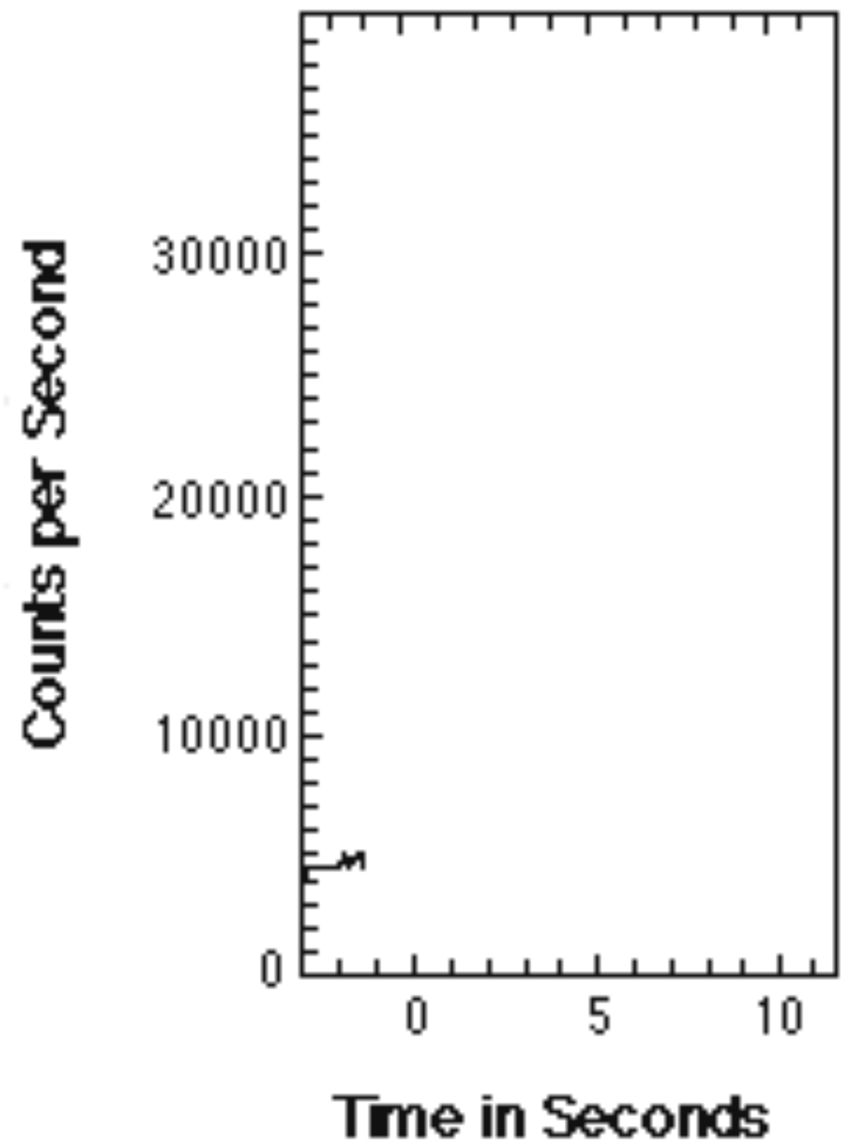
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to $\sim$30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

… looking for signs of nuclear tests…

TYPICAL GAMMA-RAY BURST

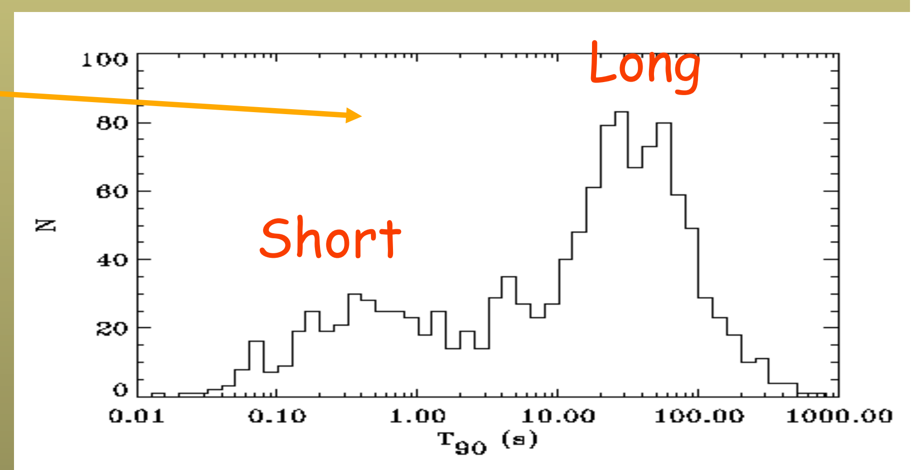




Most GRB data gathered by BATSE in the 1990s

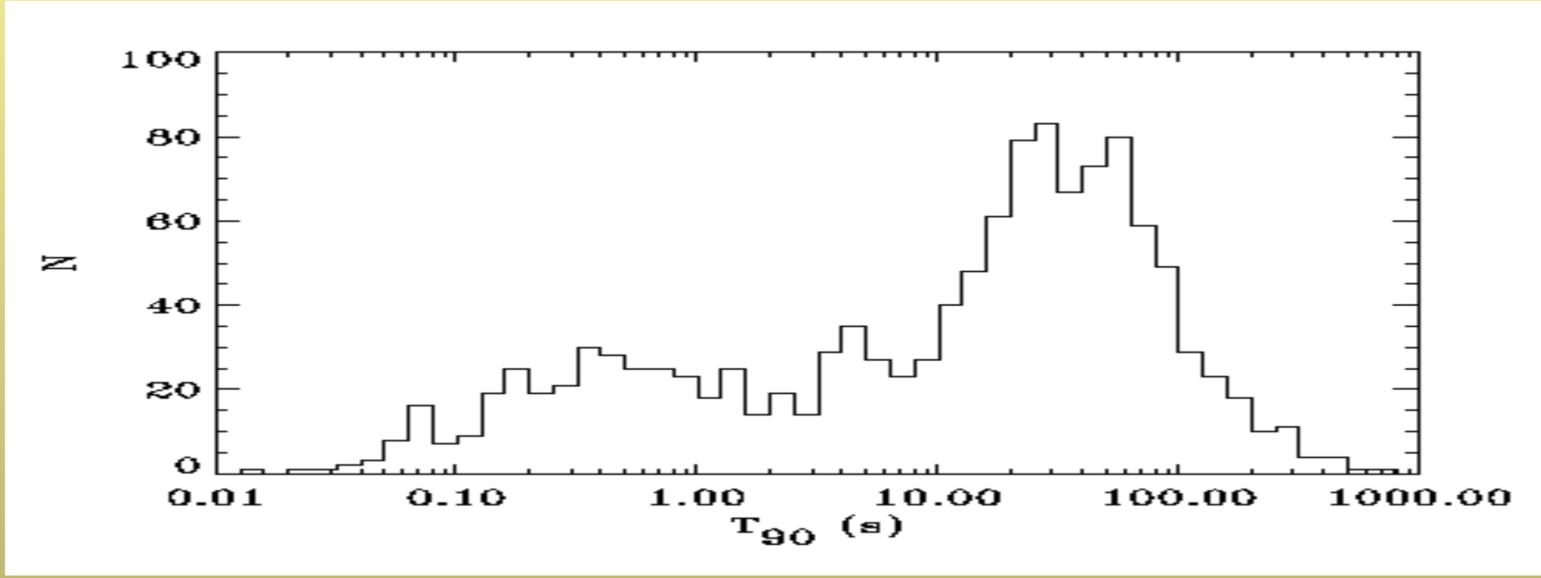
Main properties of GRBs:

- Rates: about 1 per day
- Durations: from tens of milliseconds to several hundreds of seconds, with *bimodal* distribution



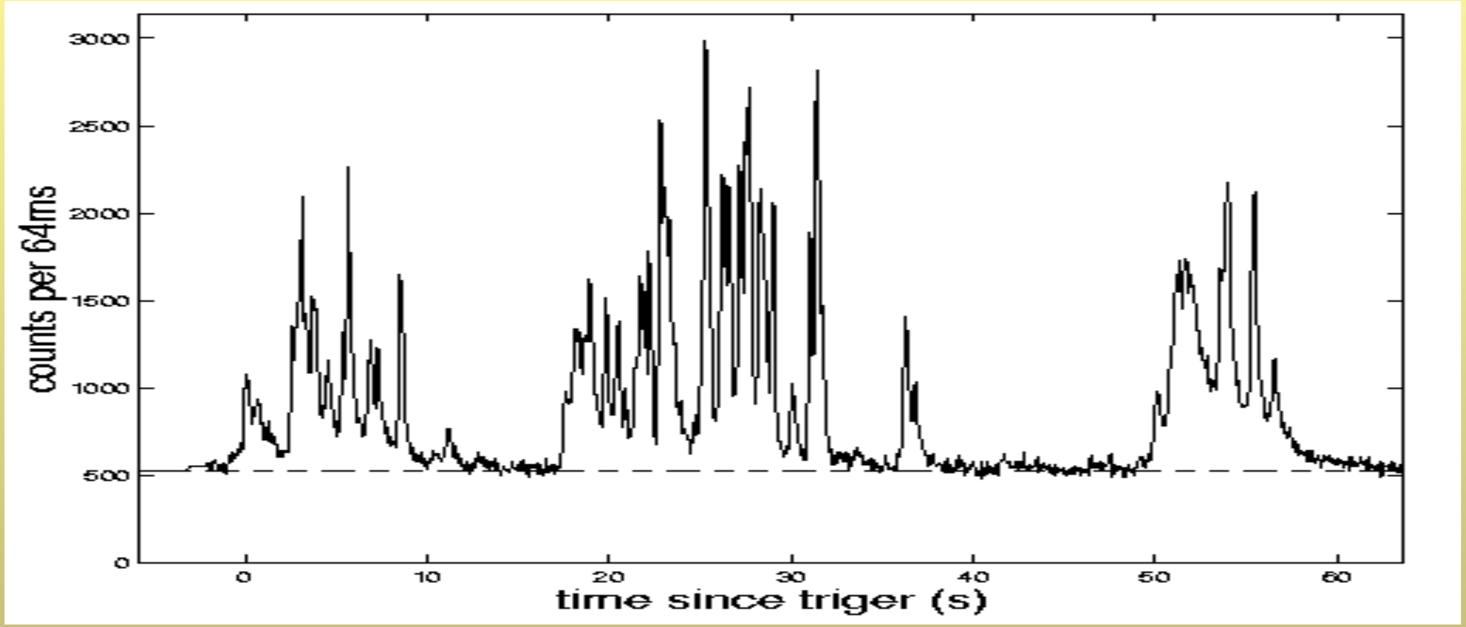
- Highly variable
- Non-thermal spectra with peak energy ~ 500 keV

Some basic facts

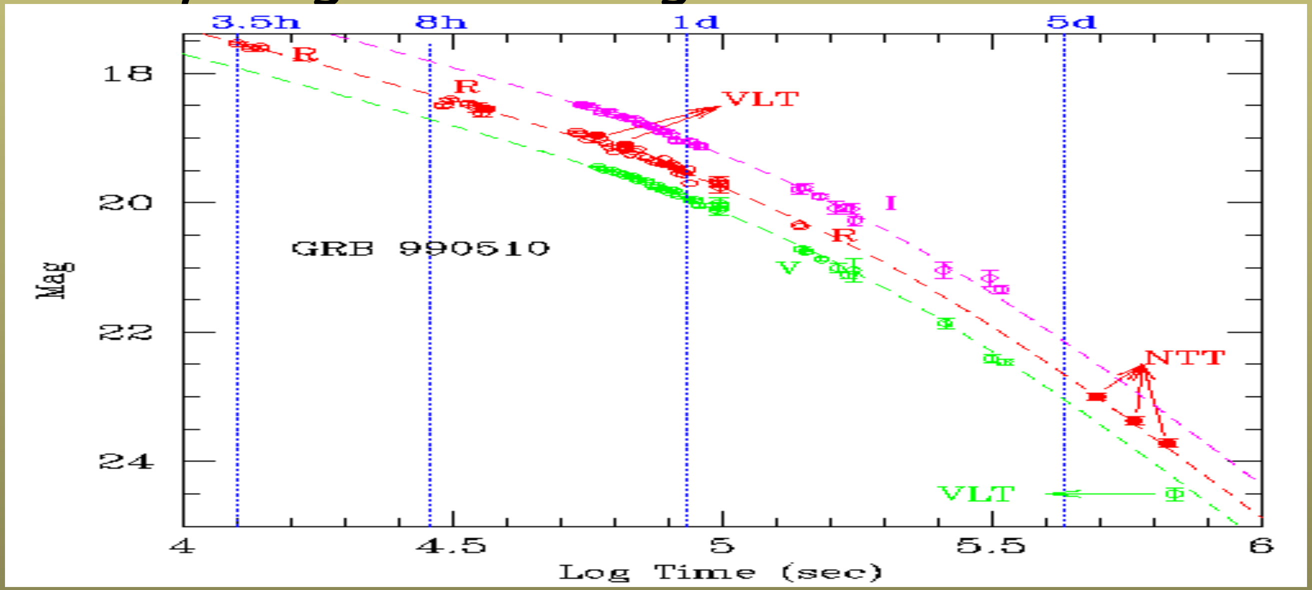


- GRBs are cosmological (*both* long and short)
- Isotropic energies $E \sim 10^{50} - 10^{54}$ ergs
- High Lorentz factors $\gamma \geq 100$

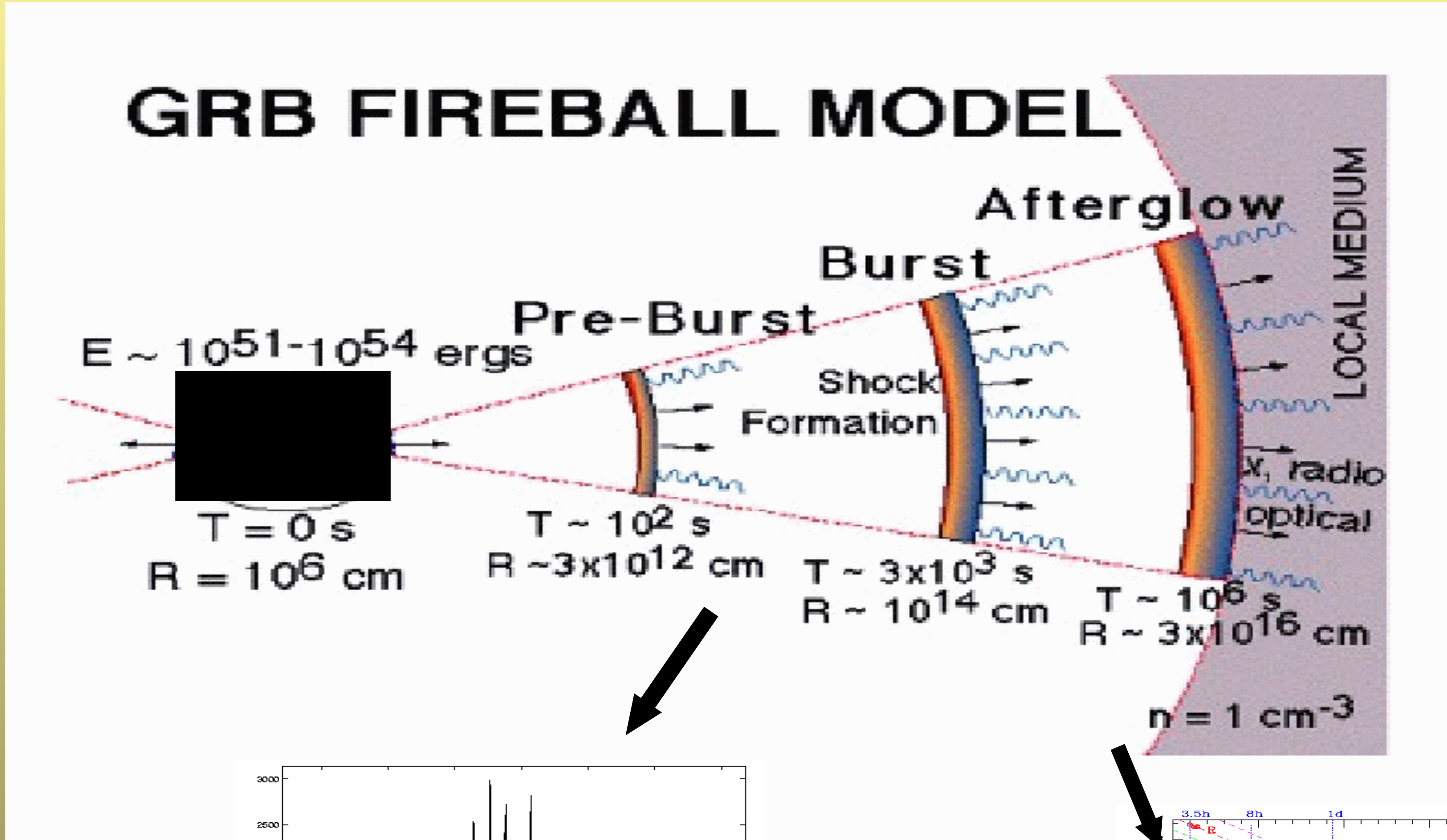
The highly variable gamma-ray "prompt" emission….

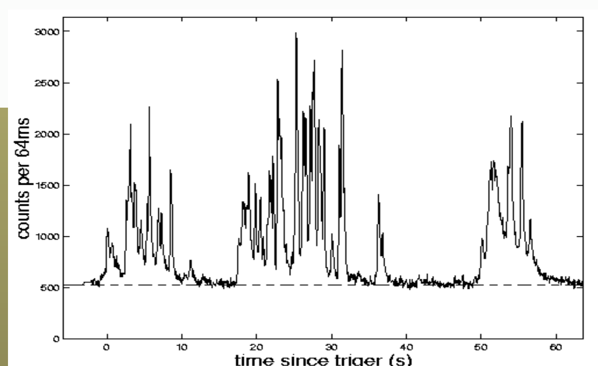


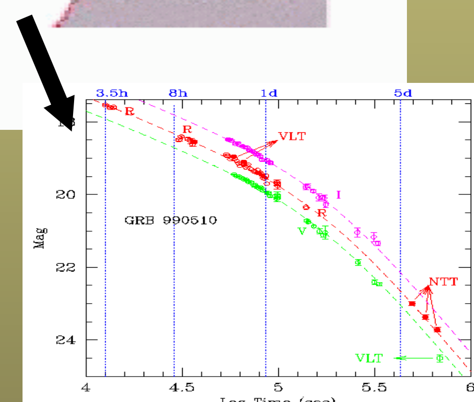
… is followed by longer wavelength radiation called "afterglow"



"STANDARD" MODEL

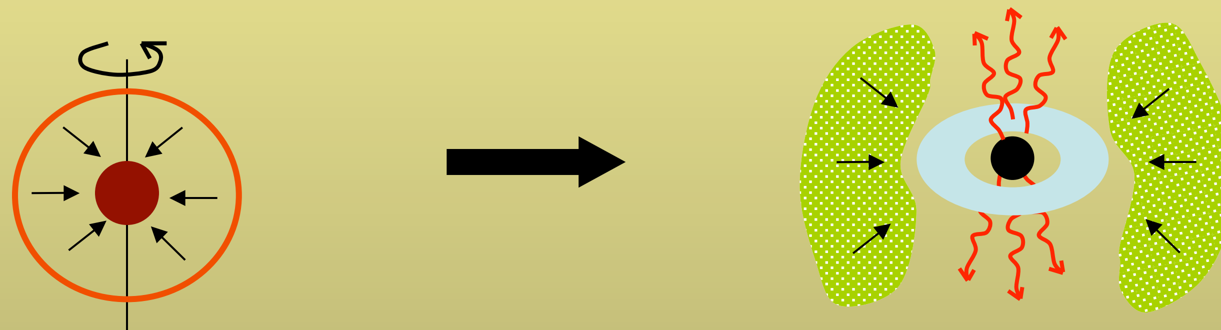




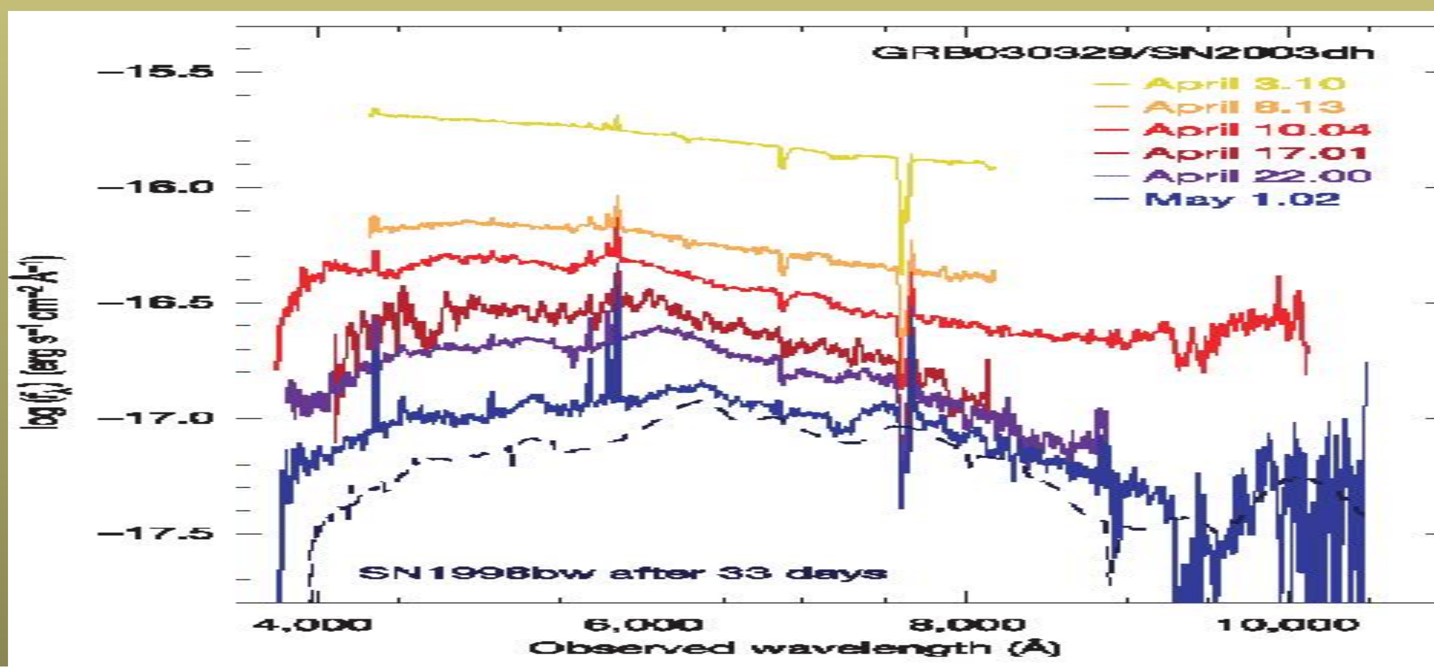


Progenitor models

Long GRBs



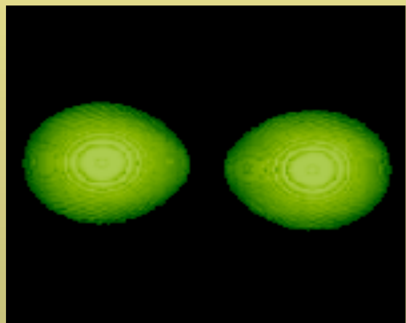
"Proof"

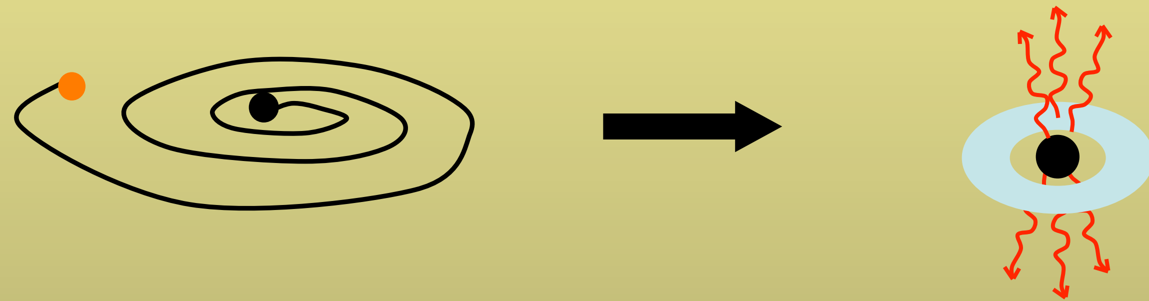


[Stanek et al. 2003]

(likely) Progenitor models

Short GRBs



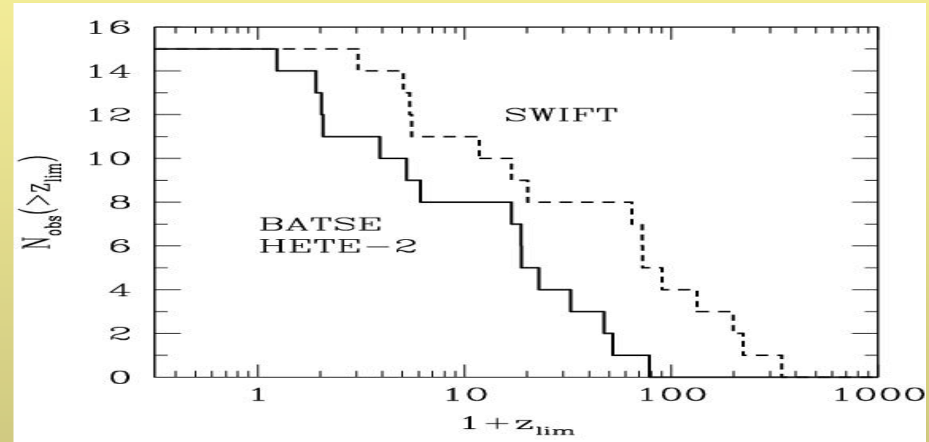


Corroborative pieces of evidence:

- No SN ever found associated with a short GRB
- energies a factor of 10 or more lower than for long GRBs
- generally associated with early type galaxies, with low star-formation, unlike long GRBs, associated with regions of high star formation.
- average redshift lower than for long GRBs

Swift era (2005 on) ideal for cosmology studies

[image credit: NASA]



[Lamb & Reichart 2000]

- X-ray, UV , optical telescopes on board
- Pointing in X-ray and optical within several tens of seconds: much brighter sources
- Sensitive to short bursts as well

Cosmological studies with GRBs

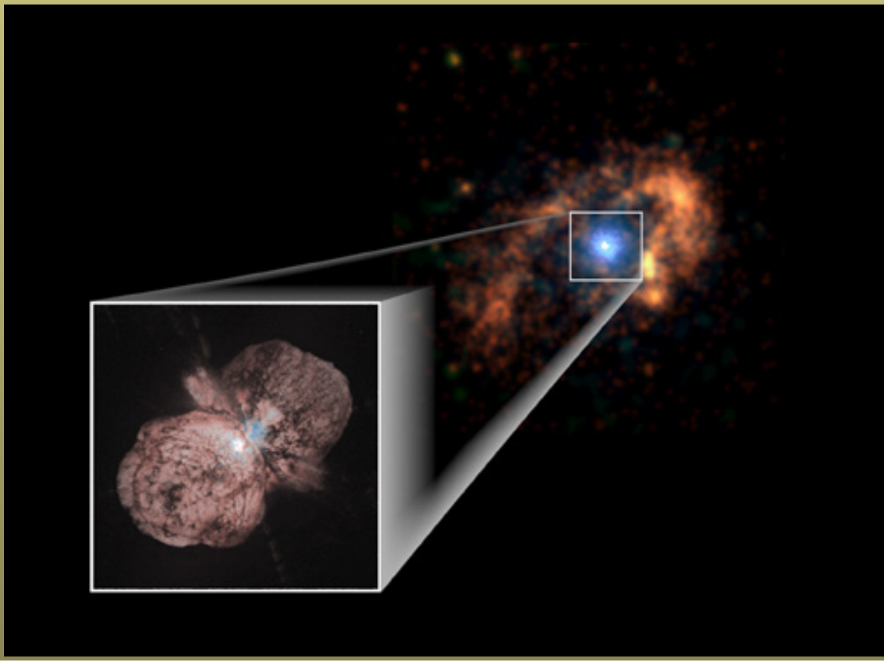
- Probe ISM structure (i.e. clumping) in high redshift galaxies
- Probe extinction curves in high-redshift galaxies
- Test cosmological models of structure formation
- Use long GRBs to probe the close environment and wind structure of massive stars at different redshifts
- Use short GRBs to constrain the cosmological evolution of compact-object binaries

GRBs as probes of the medium in their host galaxies

- GRBs brighter than QSOs : $L_{QSO} \sim 10^{46}$ erg/s; $L_{GRB} \sim 10^{49}$ erg/s
- GRBs likely to exist to higher redshifts than QSOs:

  $z_{QSO} <\sim 6$ $z_{GRB} <\sim 20$ (April 2009: a GRB was detected at z=8.2!!)

- GRBs can probe the inner, denser regions of galaxies that are not easily accessible to QSO absorption studies (whose los more likely intersects the outskirts of galaxies)

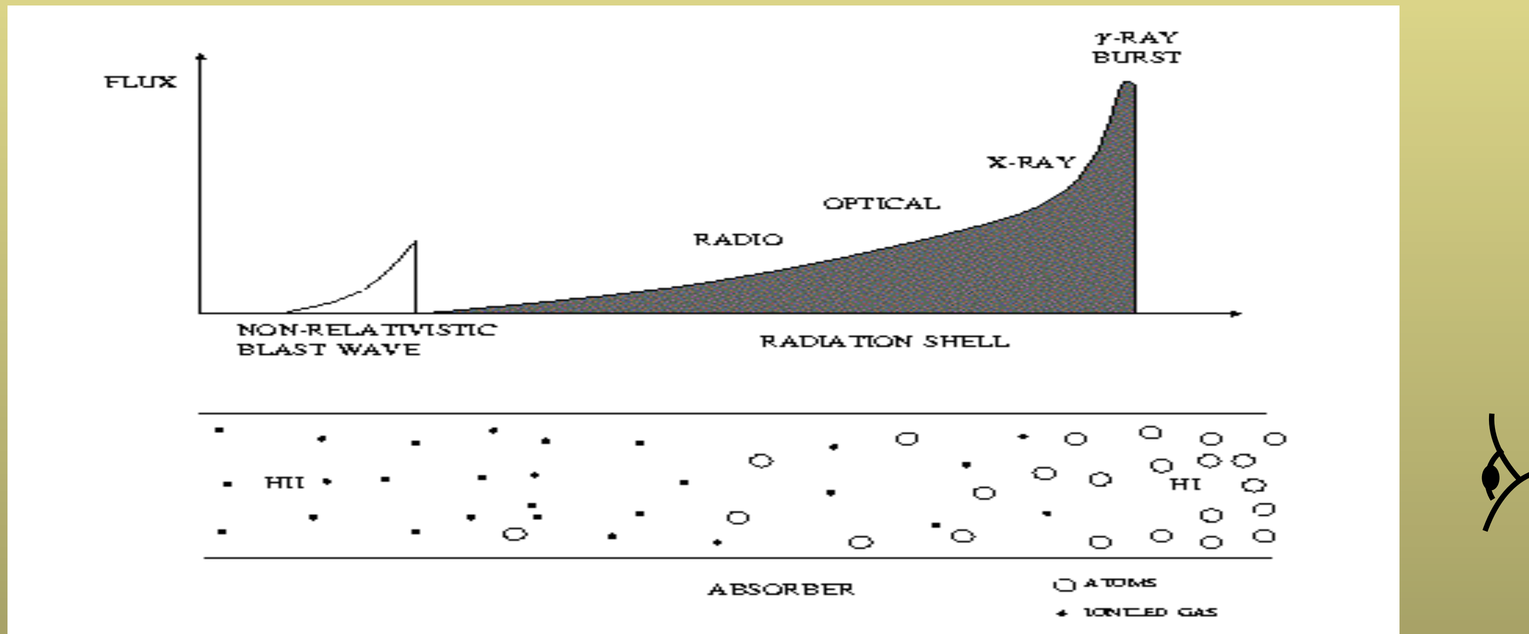


→ Have a more complete picture of the properties of high redshift galaxies

Difference between GRBs and QSOs as “lighthouses”

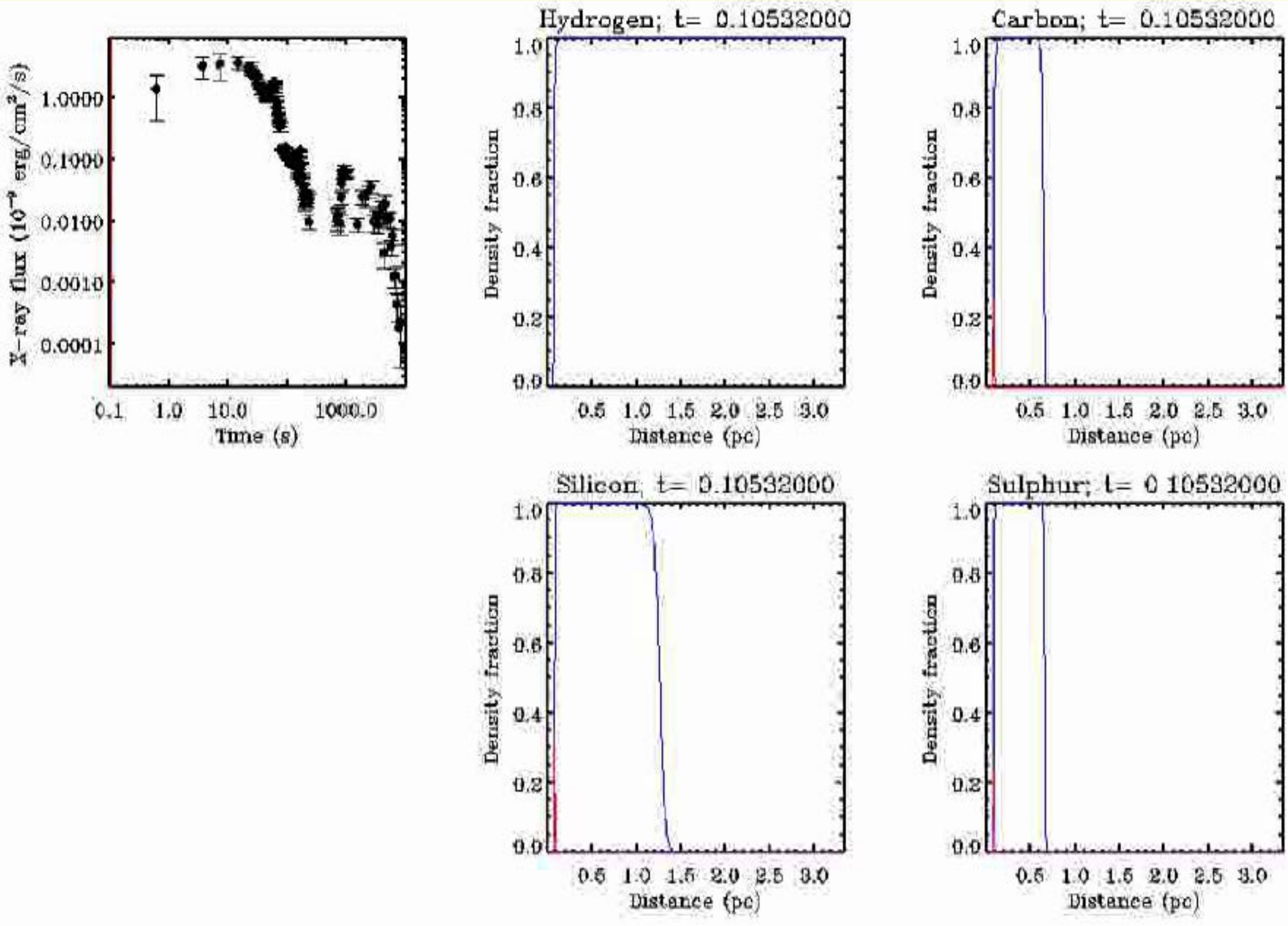
GRBs output large amount of radiation in *very short time*

→ *Close-by medium* photoionized by X-ray/UV photons accompanying GRB - *generally observable* time-scale



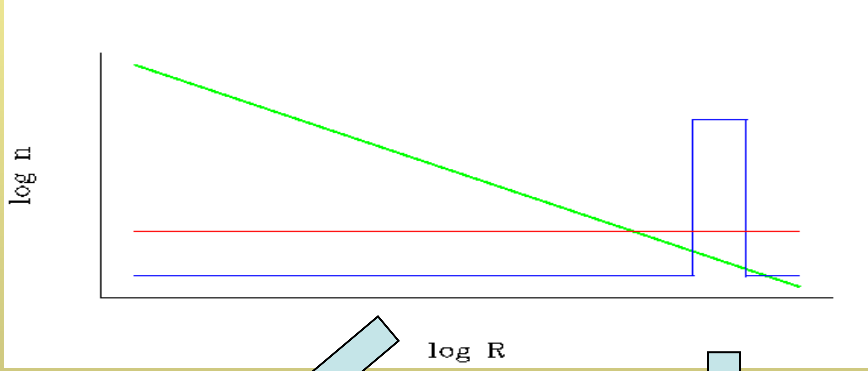
→ Time-dependent absorption lines in trasmission spectra

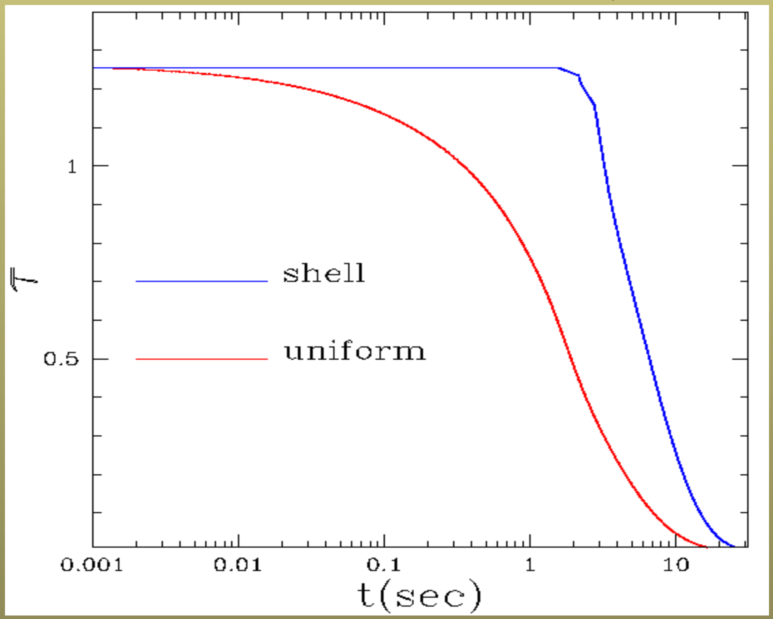
[Perna & Loeb 1998]

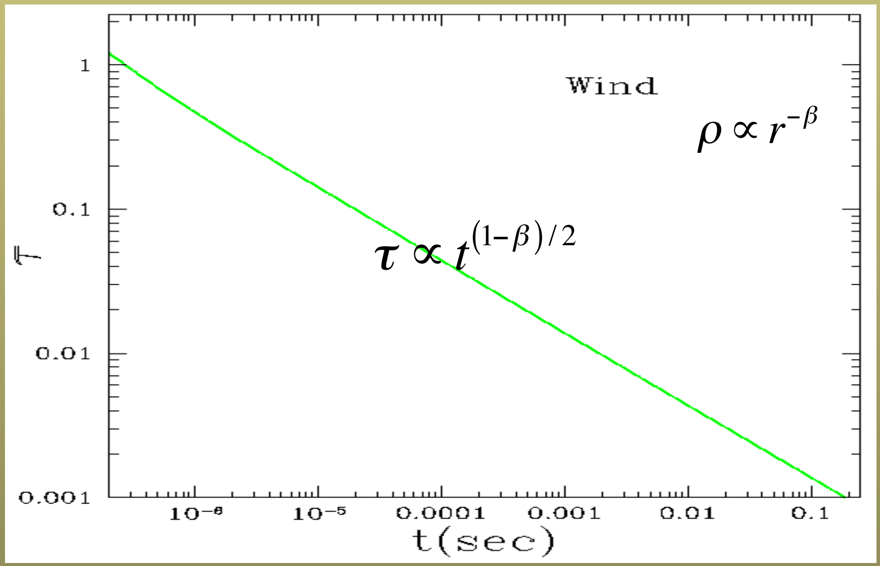


[movie courtesy of D. Lazzati]

Time variability in the opacity tracks density profile in the close environment of the burst







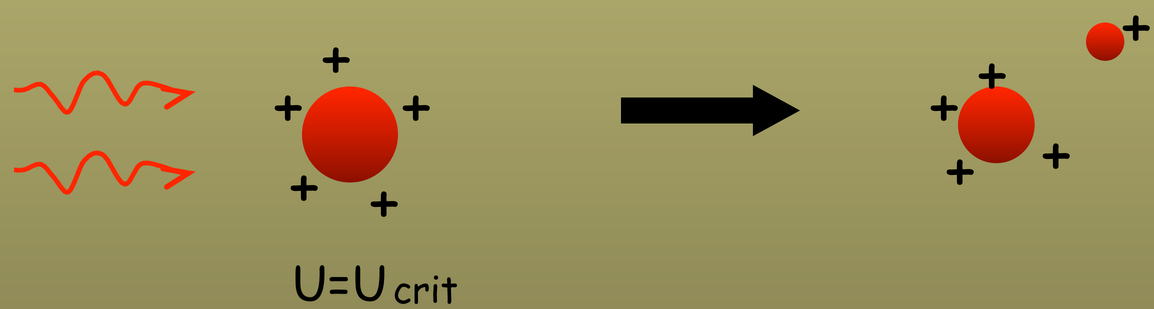
[Lazzati, Perna & Ghisellini 2002]

Not only gas, but also dust grains are affected by an intense radiation field

UV heating/sublimation

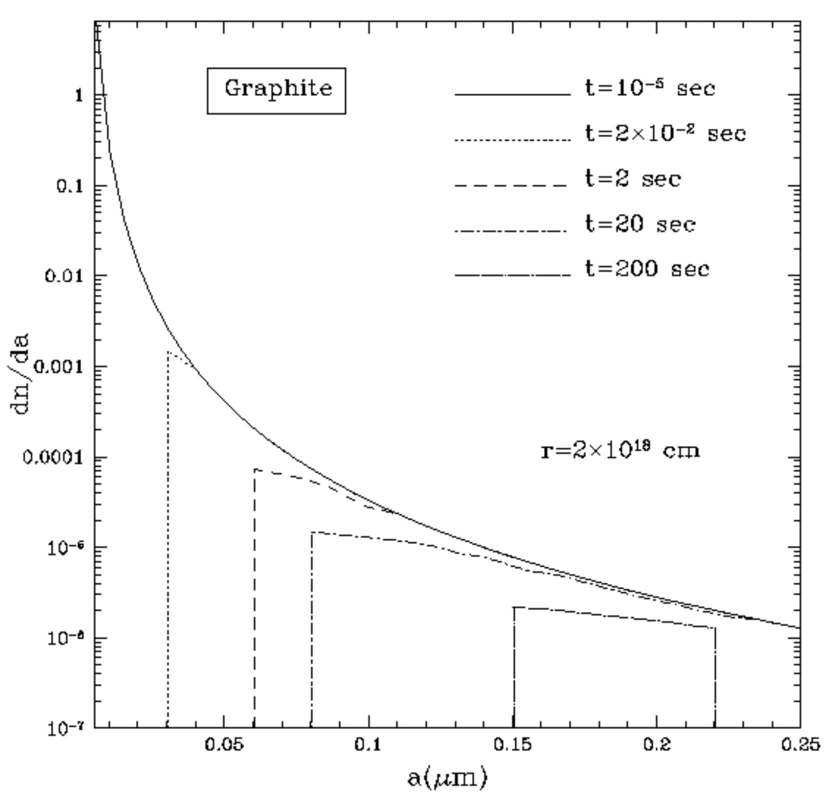
X-ray heating/sublimation

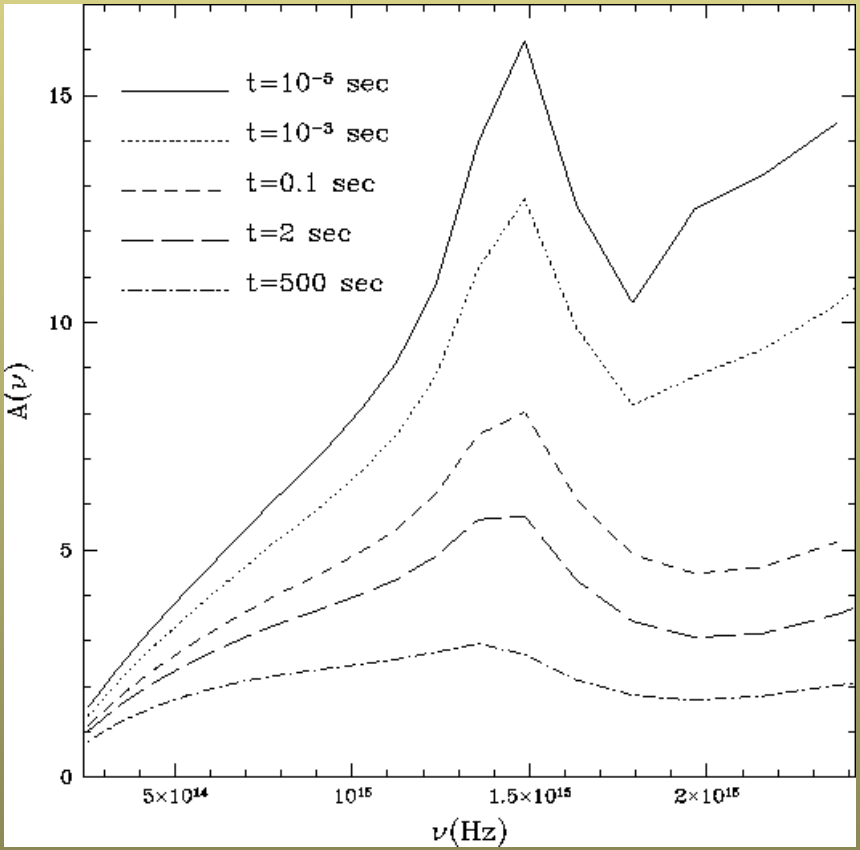
Ion field emission



Dust grain distribution in GRB environment modified by X-ray/UV radiation field

- The radiation field from the GRB selectively destroys the smallest grains





→ Greyer dust distribution

[Perna & Lazzati 2002; Perna, Lazzati & Fiore 2003]

How do we use (long) GRBs to probe their environment?

- For the close environment (winds produced by massive stars) time variability in the X-ray through optical opacity provides a diagnostic.

- For the farther away environment (host galaxy ISM) same use as for QSOs, with the plus benefit of being brighter, and having a smooth powerlaw spectrum extending all the way from the X-rays to the radio

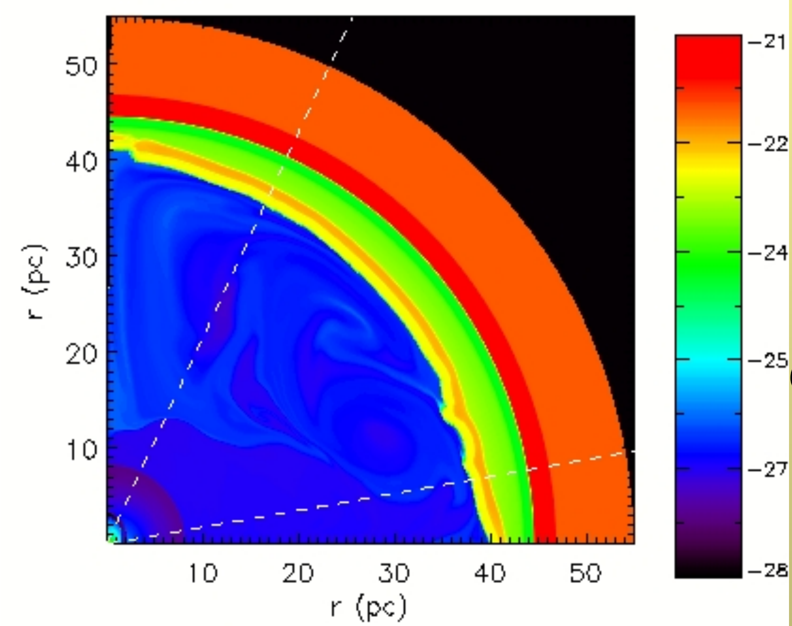
Probing the properties of the massive stars progenitors of long GRBs

- Theoretical predictions: rapidly rotating, low-metallicity stars.

<u>How to test?</u>

- Explode GRB inside environment created by the progenitors star, and compute the observable trasmission spectra [Robinson, Perna et al. 2010]

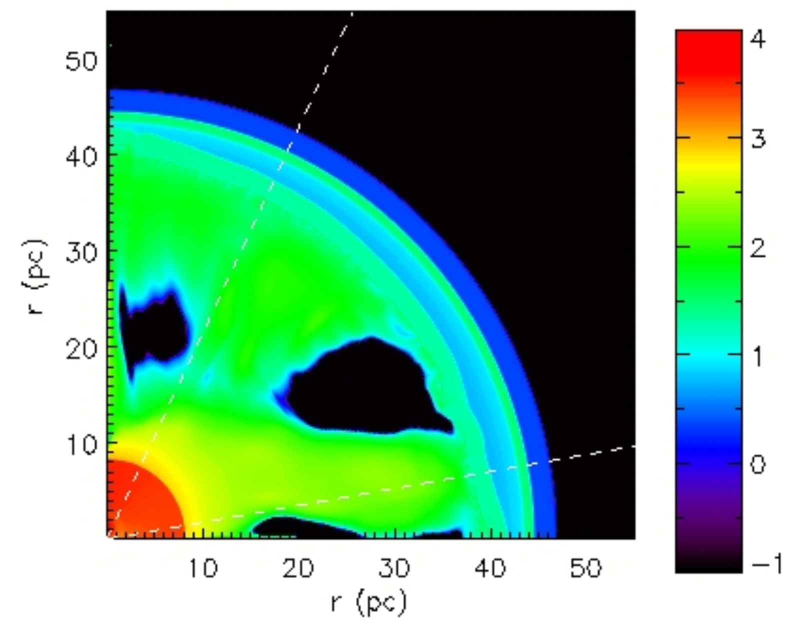
Models of GRB progenitors stars



density

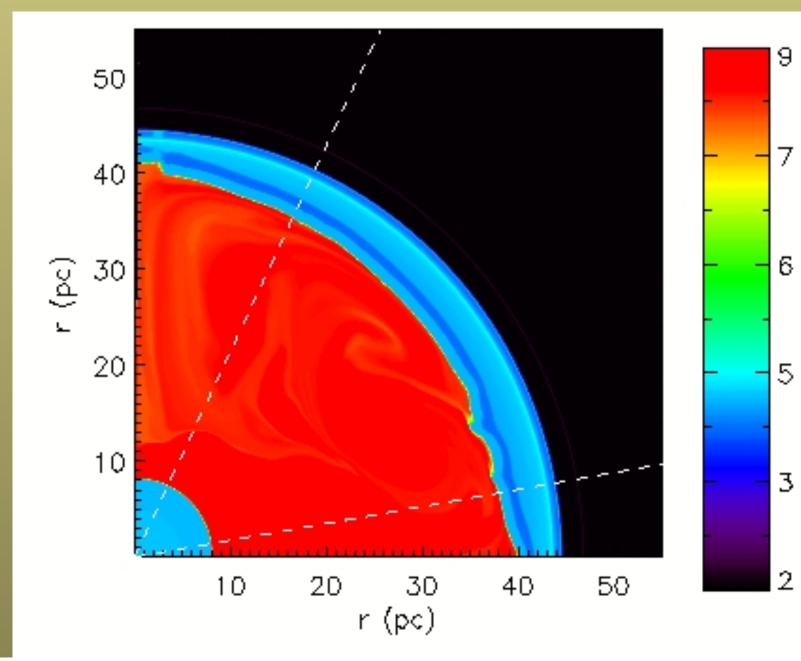
Structure of the CSM created by the progenitor star just prior to its explosion

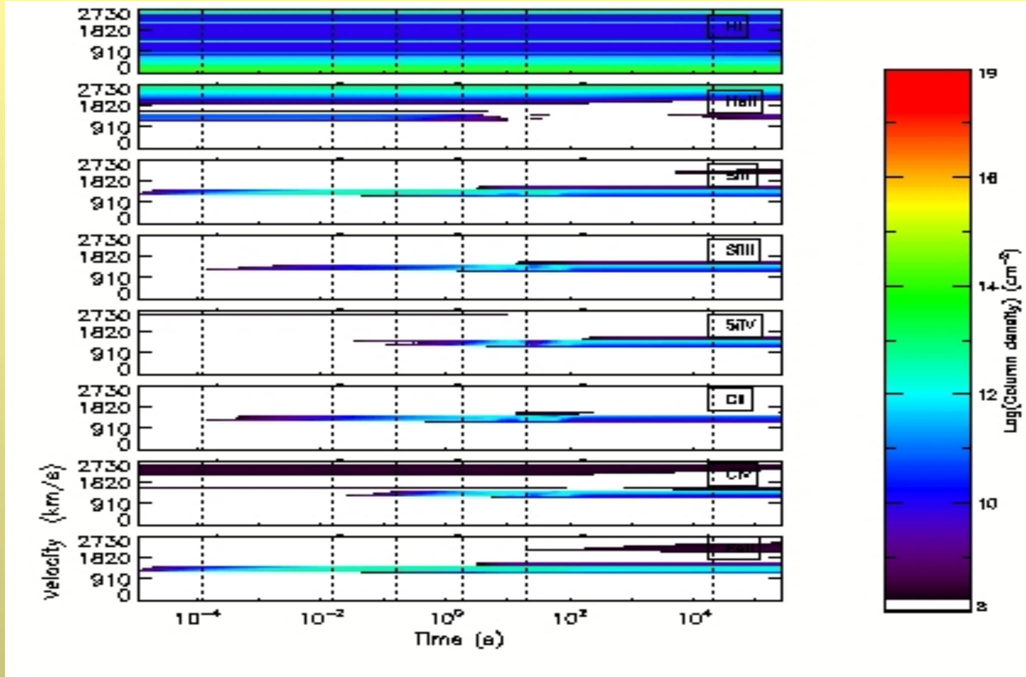
[van Marle et al. 2008]



velocity

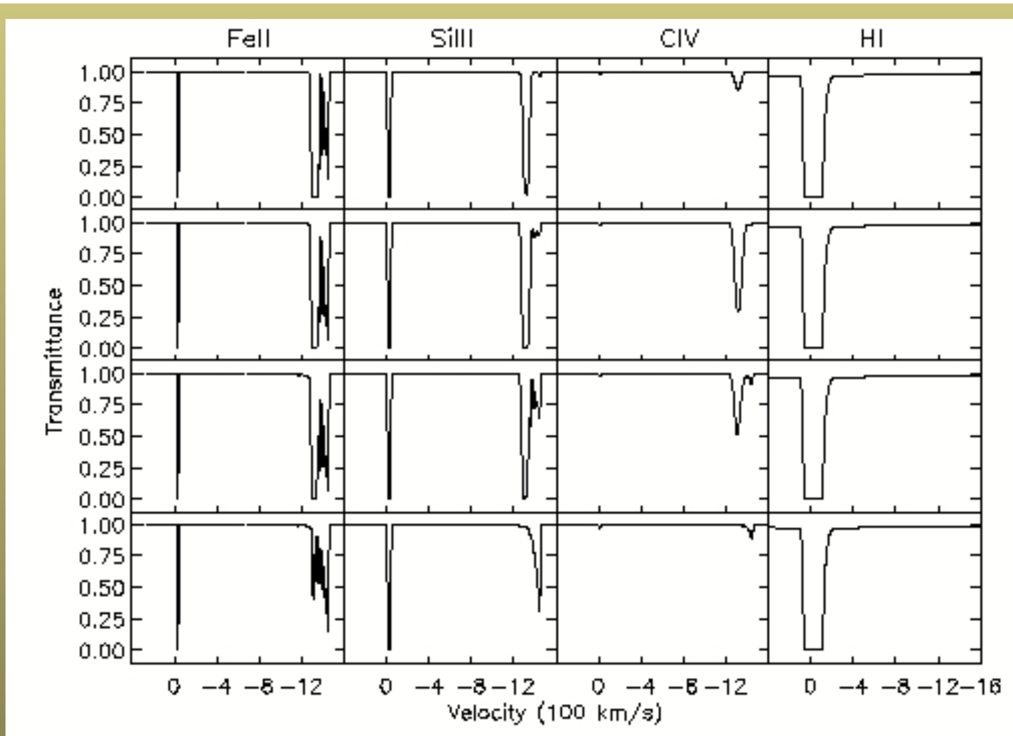
temperature





Time-dependent evolution of the column densities of various ions

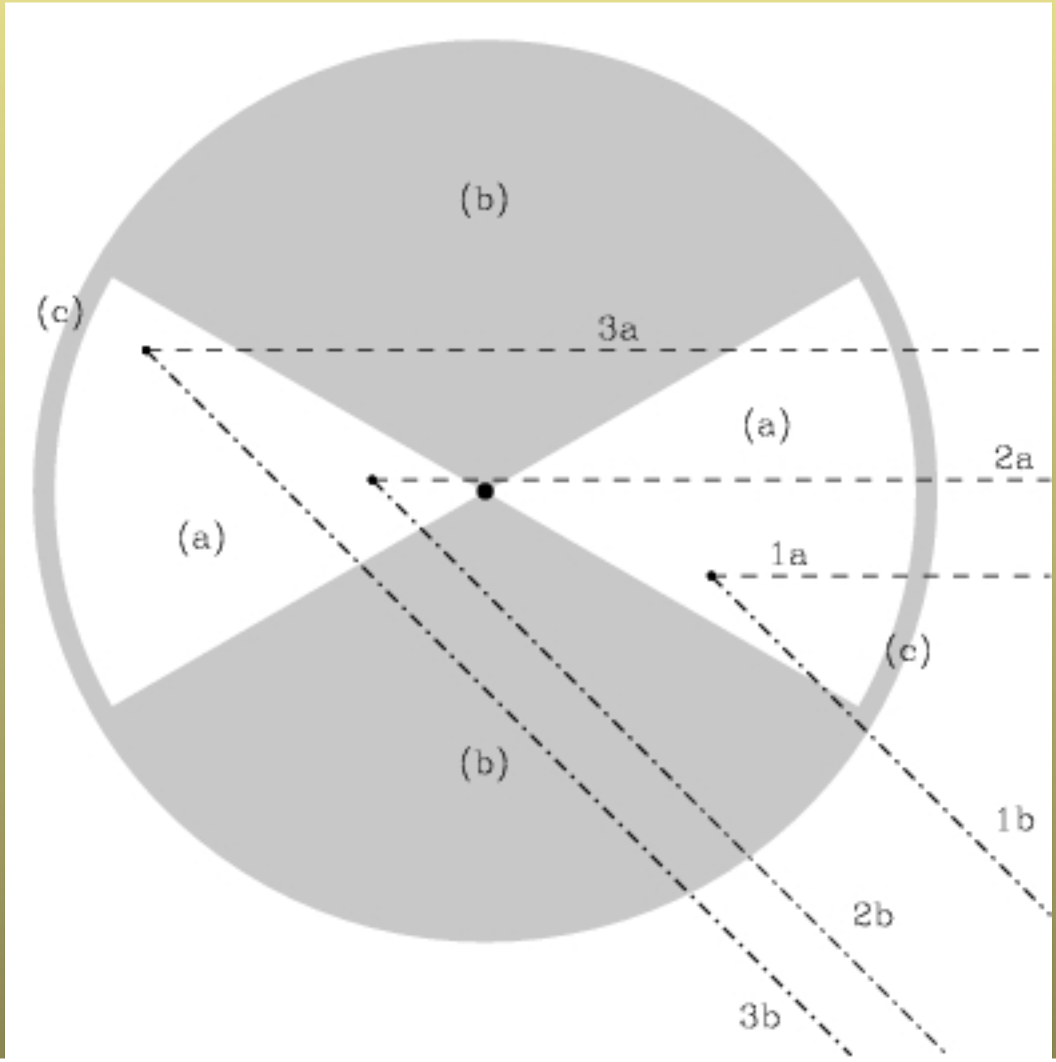
High-speed lines present only *if wind is dusty*



Time-dependent transmission spectra of the afterglow (t=0.2,2,20,20000 sec)

[Robinson, Perna et al. 2010]

More information on 3D dust geometry and size of GRB jets from DUST ECHOES

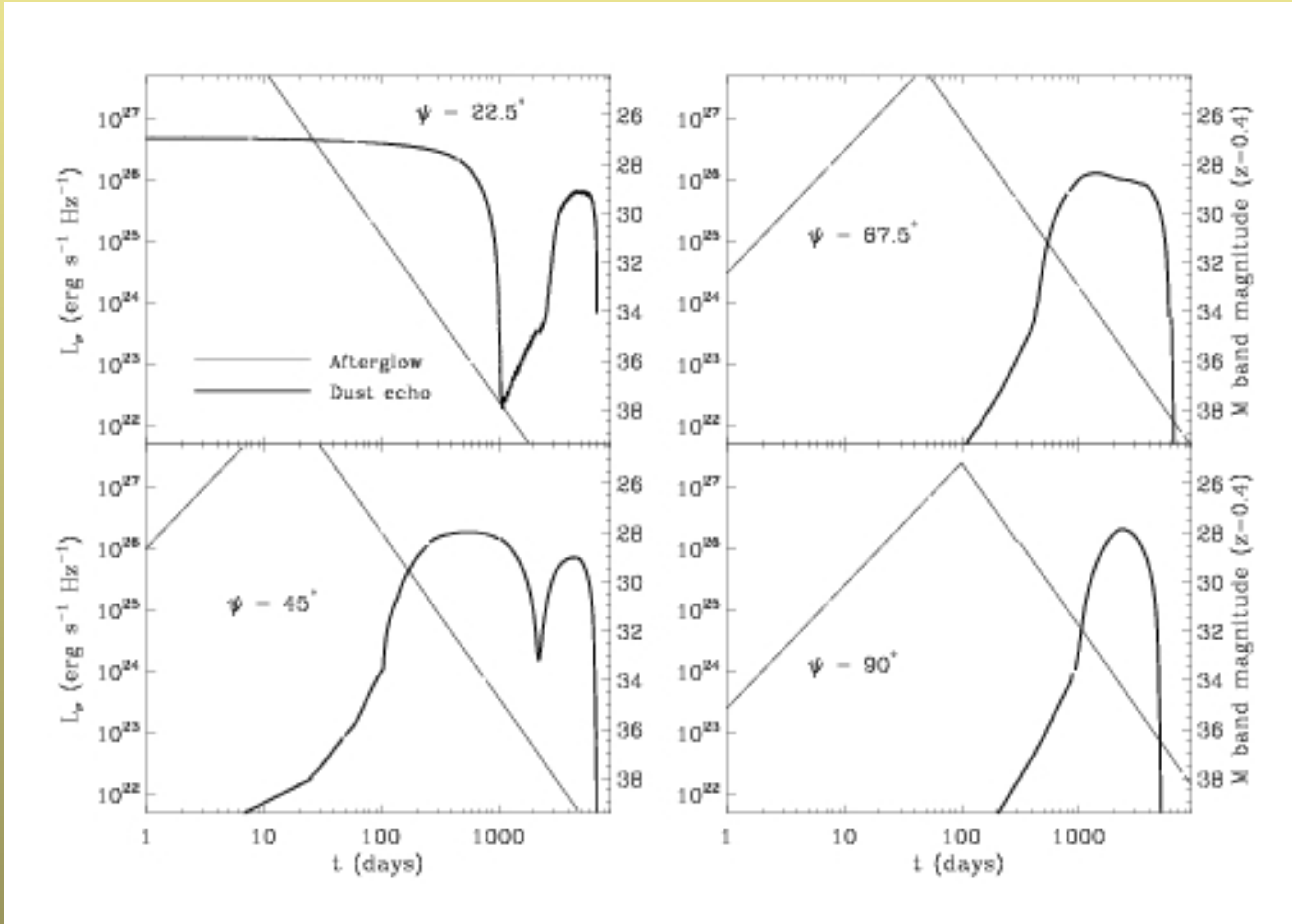


Cloud illuminated by beamed GRB -- Grains scatter and absorb/re-emit

(a): sublimated dust
(b): unmodified dust
(c): heated dust

Size of various regions dependent on both time and grain size

Time-dependent dust echo from a compact dusty cloud surrounding the progenitor star



Jet size =45 deg

Different viewing angles explored

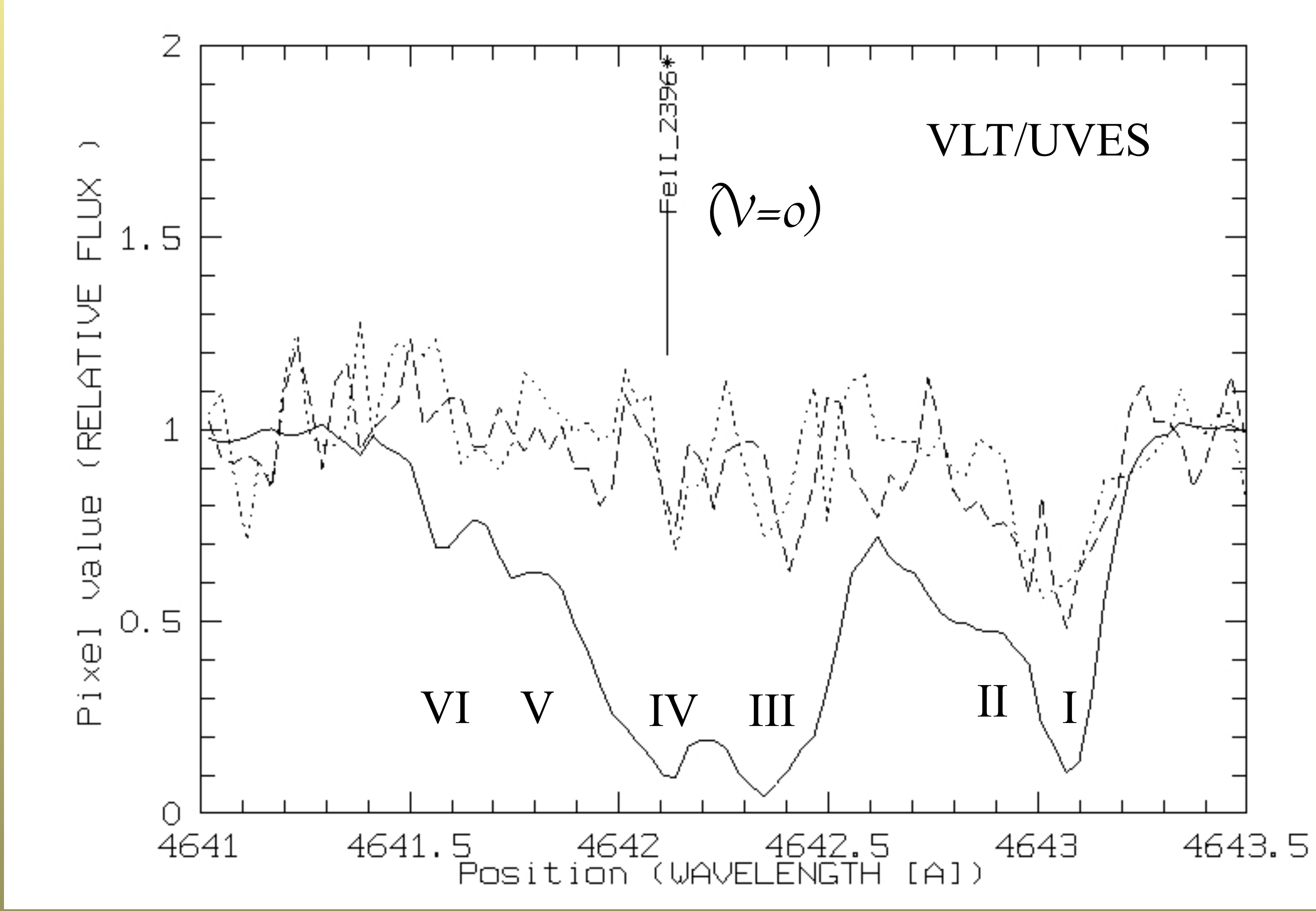
[Heng, Perna & Lazzati 2007]

Far away environments: no appreciable photoionization/dust-destruction by the burst radiation

Probe host galaxy conditions:

- ISM clumping
- Extinction curves

The case of "The Naked Eye" GRB080319B



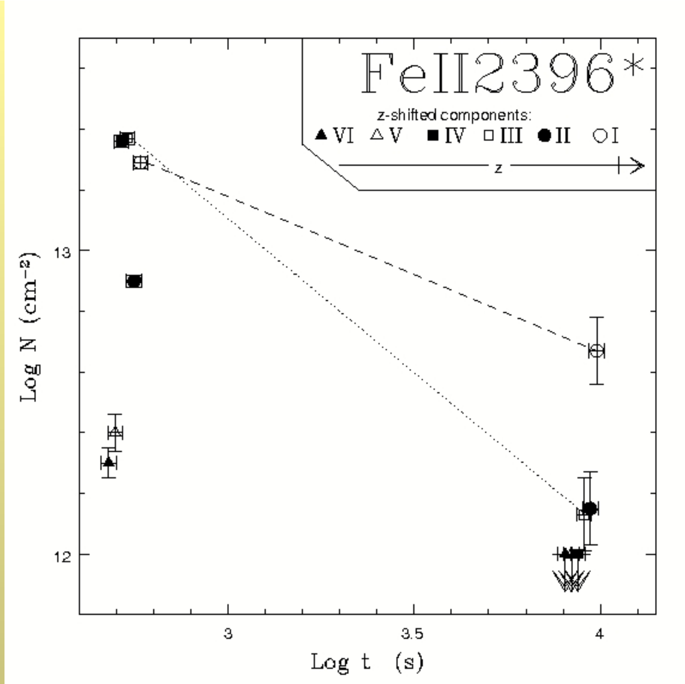
(Z=0.937)

[D'Elia, Fiore, Perna et al. 2009]

Solid: 8:30m
Dashed: 1.9hr
Dotted: 2.9hr

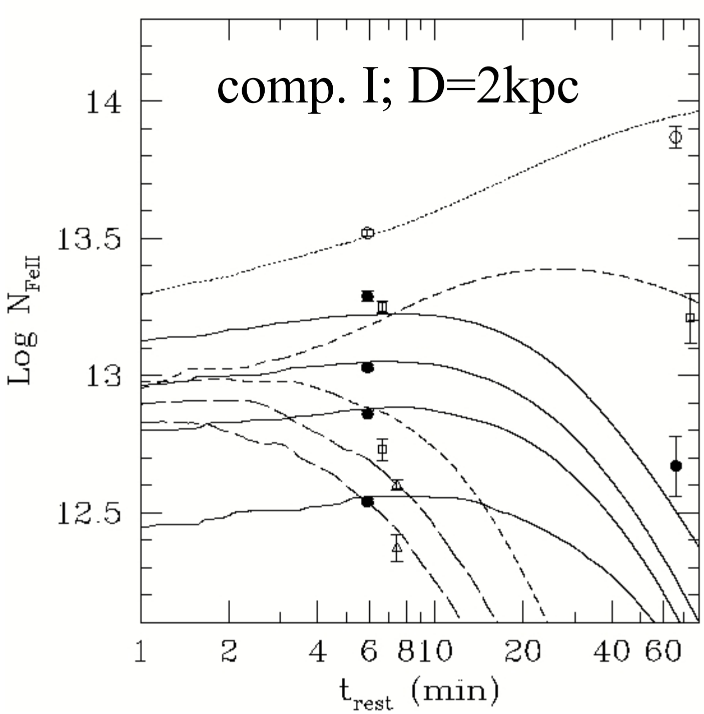
6 separate components identified, spanning ~ 100 km/s

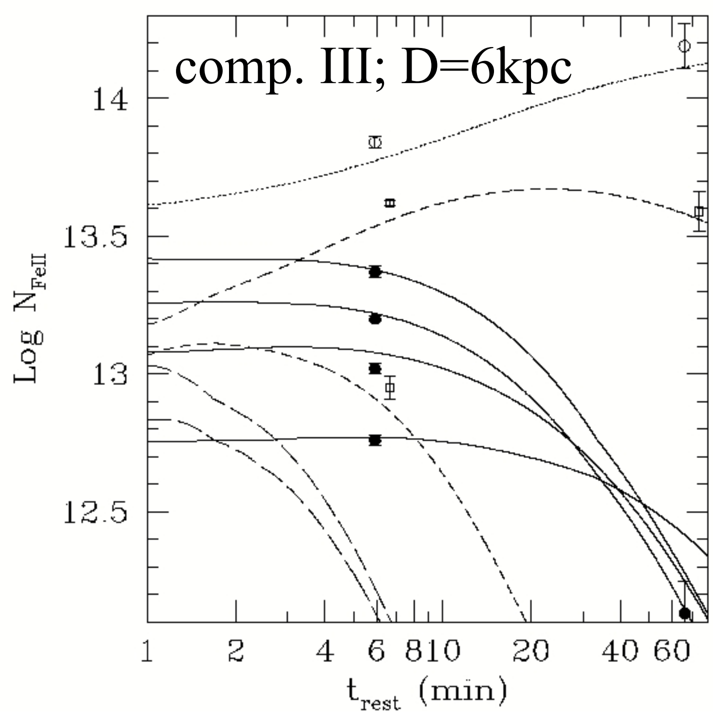
No signs of photoionization, *but* excitation of fine lines by UV pumping



Time-dependent line modeling of 2 of the variable components allowed to locate one component at D=2kpc and another at D=6kpc

→ ***Large scale clumps!***





Open circles: ground level

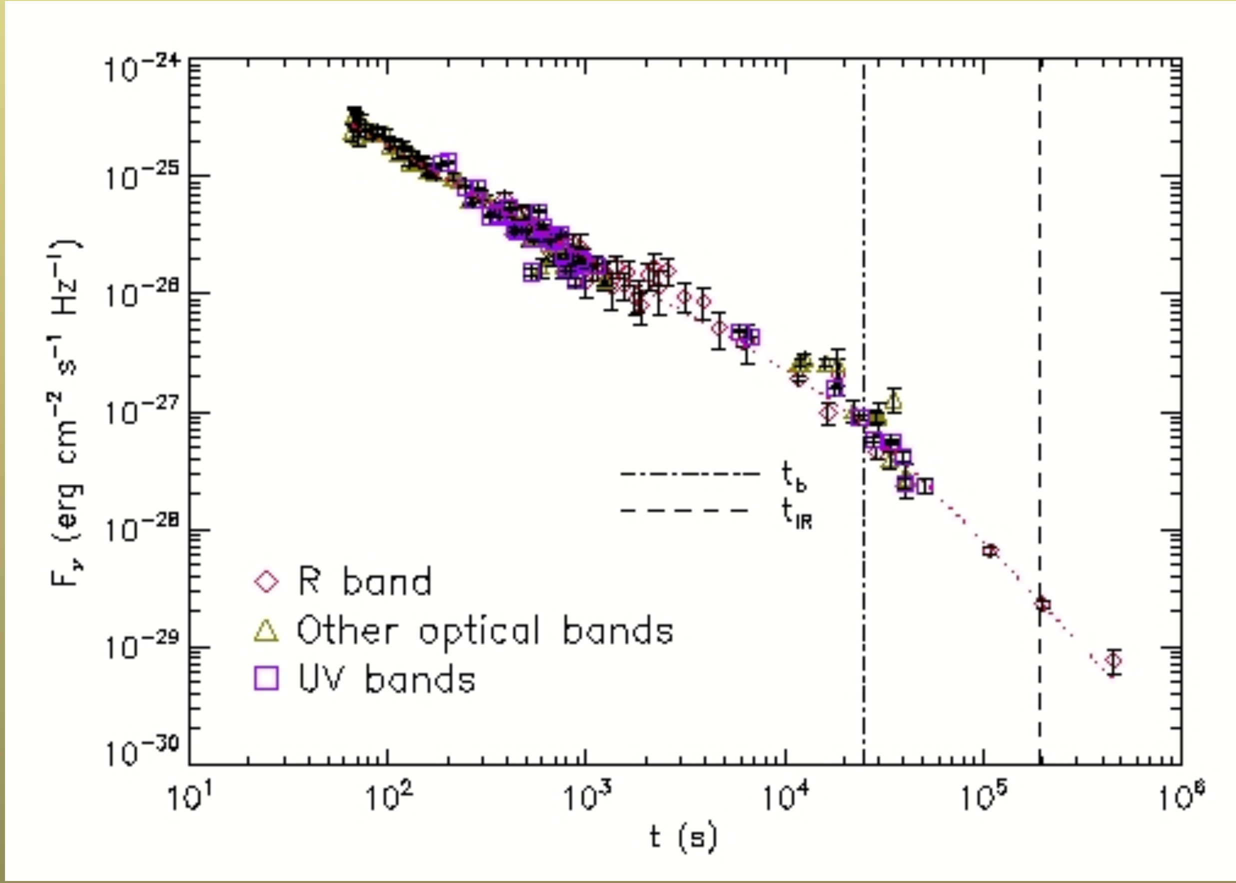
Solid circles: ground level fine transitions

Squares: 1st excited level fine transitions

Triangles: 2nd excited level fine transitions

Constraints on the EXTINCTION CURVE of GRB host galaxies: the case of GRB050525A

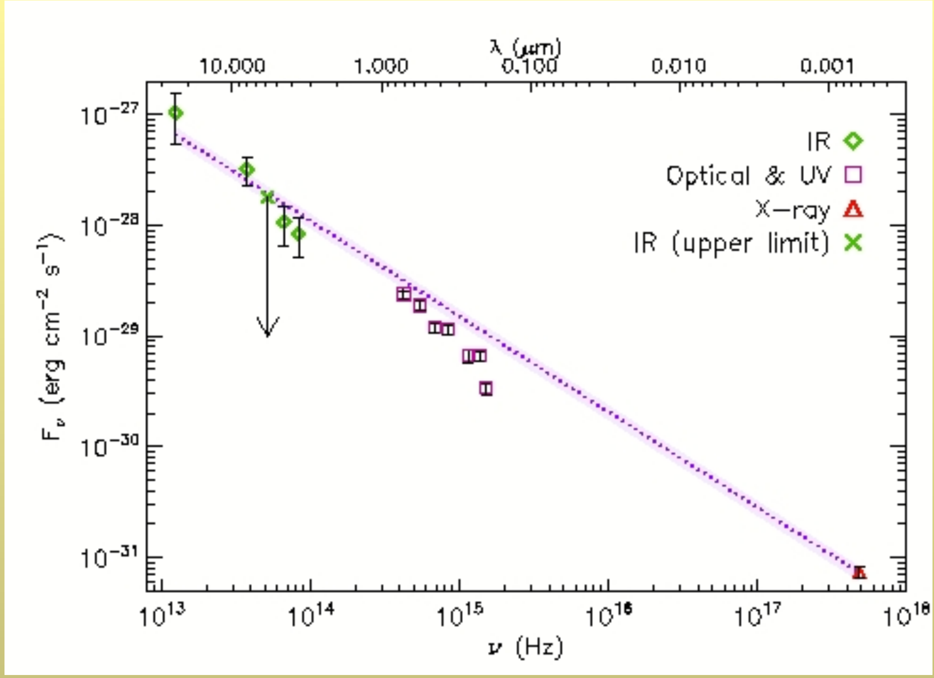
Observed in X-rays, UV, optical, IR (z=0.606)

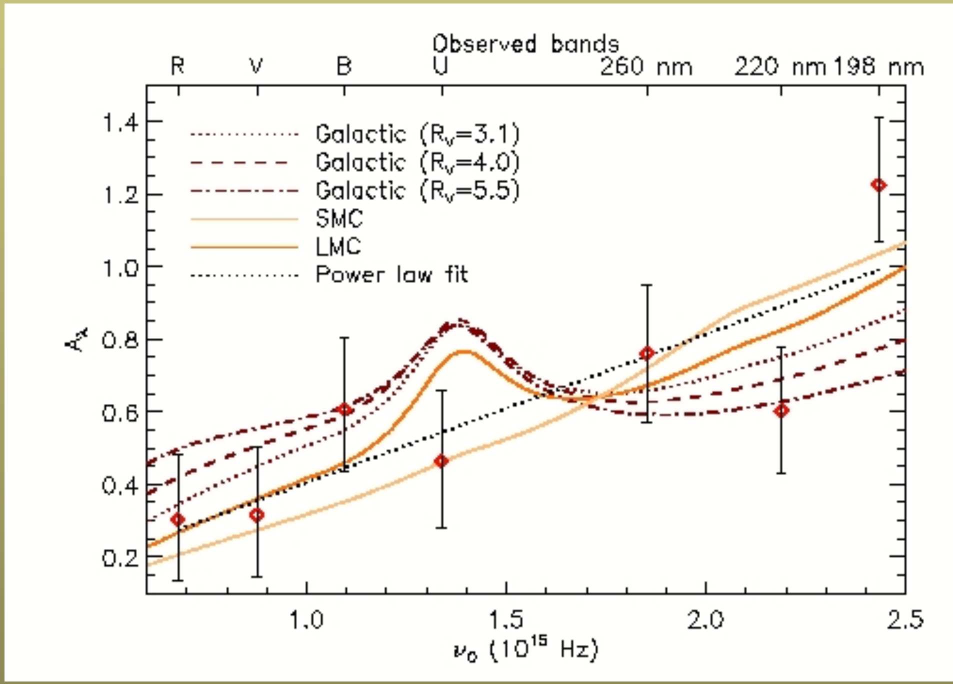


[Heng, Lazzati, Perna et al. 2008]

X-ray through IR data allow to calibrate spectral slope of the powerlaw of the afterglow

[Heng, Lazzati, Perna et al. 2008]





Fit results:

LMC: $\chi^2 = 0.9$

SMC: $\chi^2 = 1.1$

MW(R=3.1): $\chi^2 = 1.4$

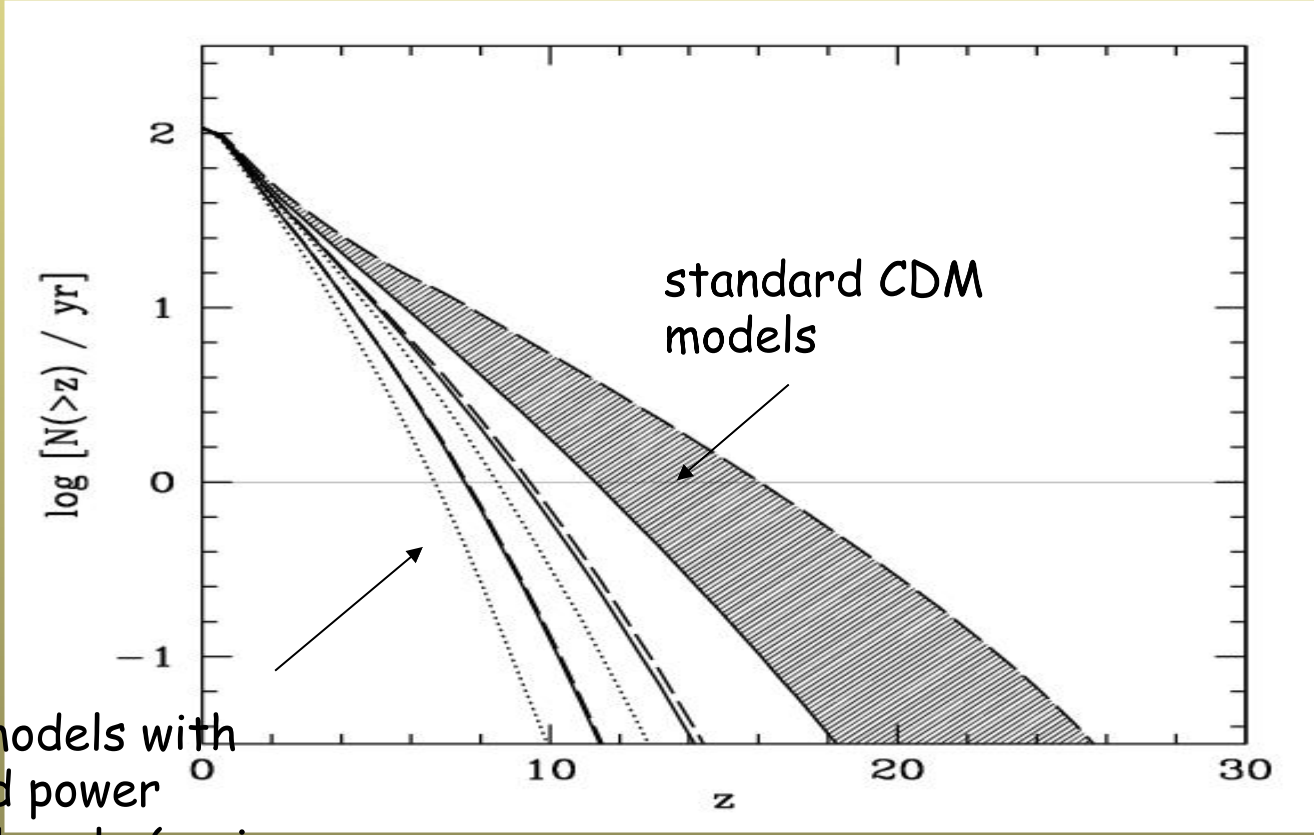
MW(R=4.0): $\chi^2 = 1.9$

MW(R=5.5): $\chi^2 = 2.5$

LMC/SMC extinction curves favoured

Detection of high-z GRBs has potential for cosmology: test power spectrum of density fluctuations at small scales

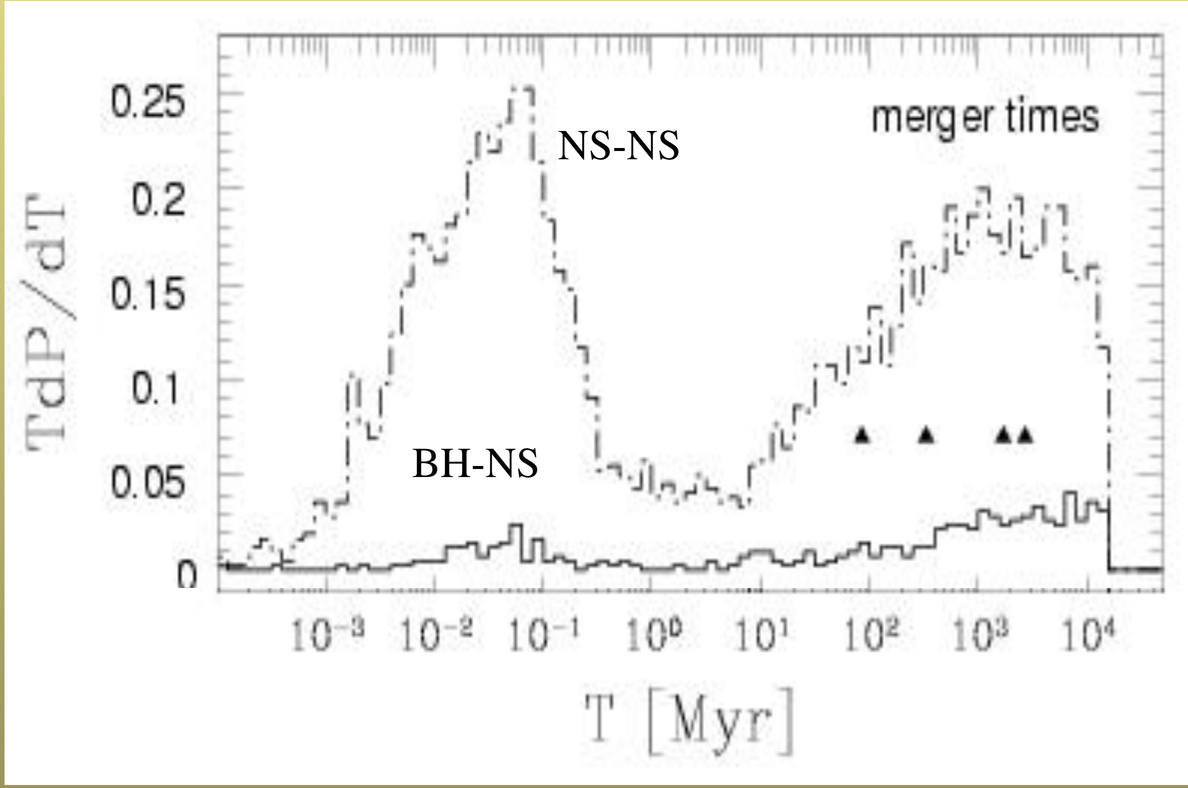
Long GRBs → trace massive stars → trace small scale structure



WDM models with reduced power at small scale (various curves for different particle masses)

[Mesinger, Perna & Haiman 2005]

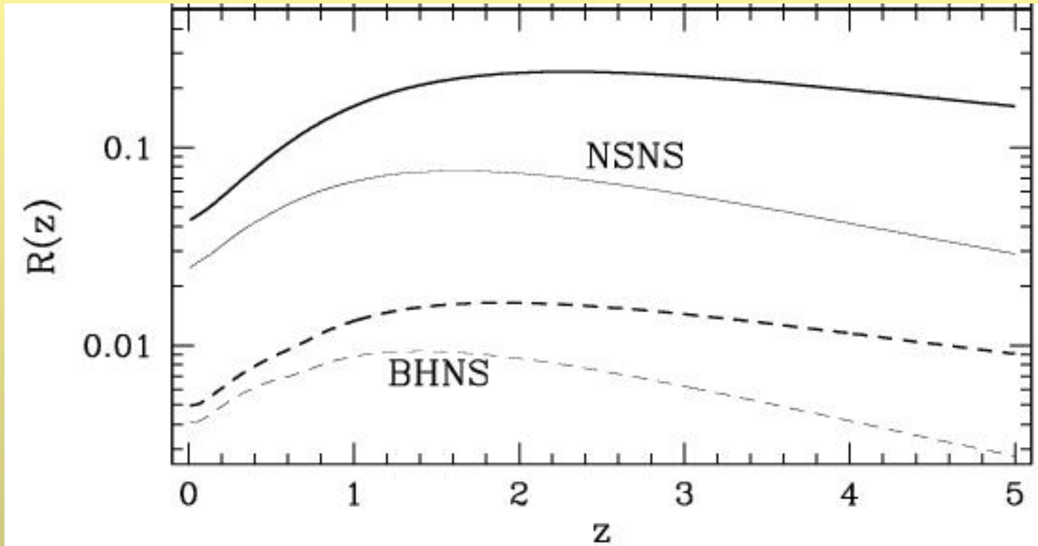
Use Short GRBs to constrain evolutionary binary models



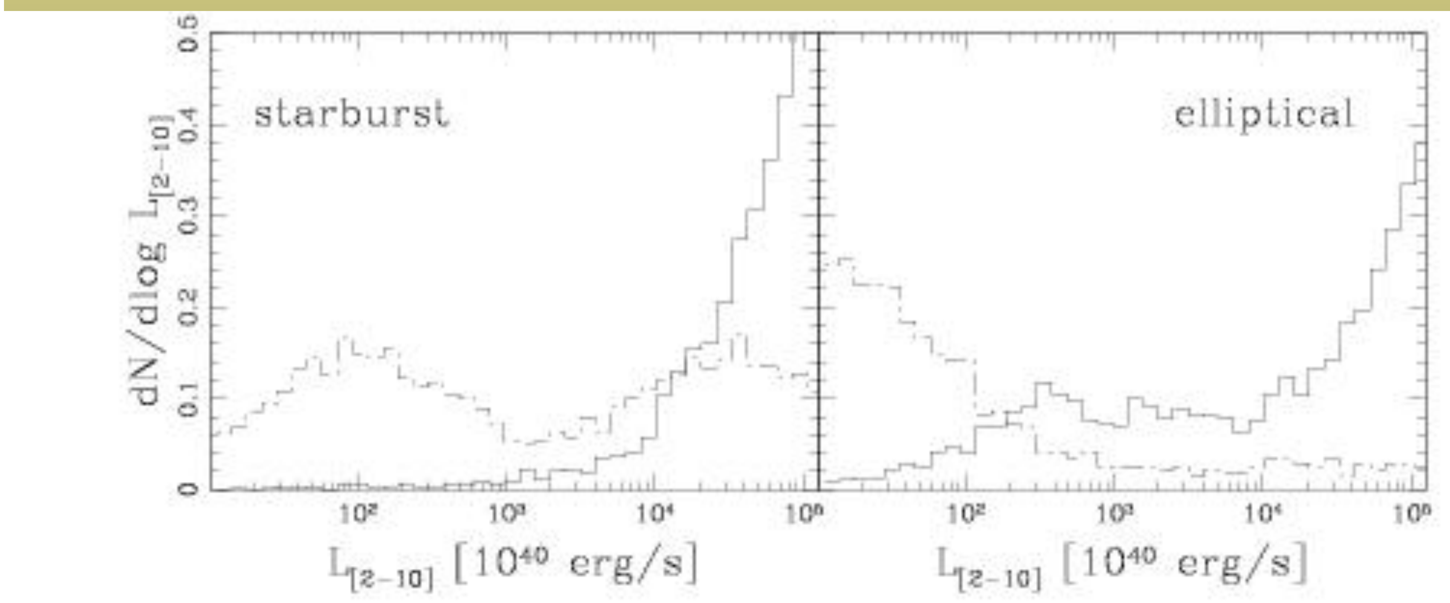
Merger times can considerably vary depending on the types of binary progenitors and on the evolutionary path that they follow

Triangles: Galactic NS-NS systems

[Belczynski, Perna et al. 2006]



Statistical studies of the distribution of short GRBs with redshift, and their relative fraction in various galaxy types, can constrain the binary evolutionary model giving rise to GRBs.



[Belczynski, Perna et al. 2006]

Summary

GRBs constitute a powerful tool for astrophysical / cosmological studies

- Time variability in opacity of selected absorption lines allows to constrain properties of massive stars progenitors of long GRBs
- Time variability in IR emission allows to constrain 3d dust structure surrounding massive star
- Presence and variability of fine structure lines can constrain the clumping structure of the absorbing medium in the GRB host
- Multiwavelength observations of GRB afterglow can allow to reconstruct extinction curve of GRB host galaxy
- Probe the era of the transition of the Universe from the dark ages to the first light and test cosmological models of structure formation
- Use properties of short GRBs to learn about binary evolution