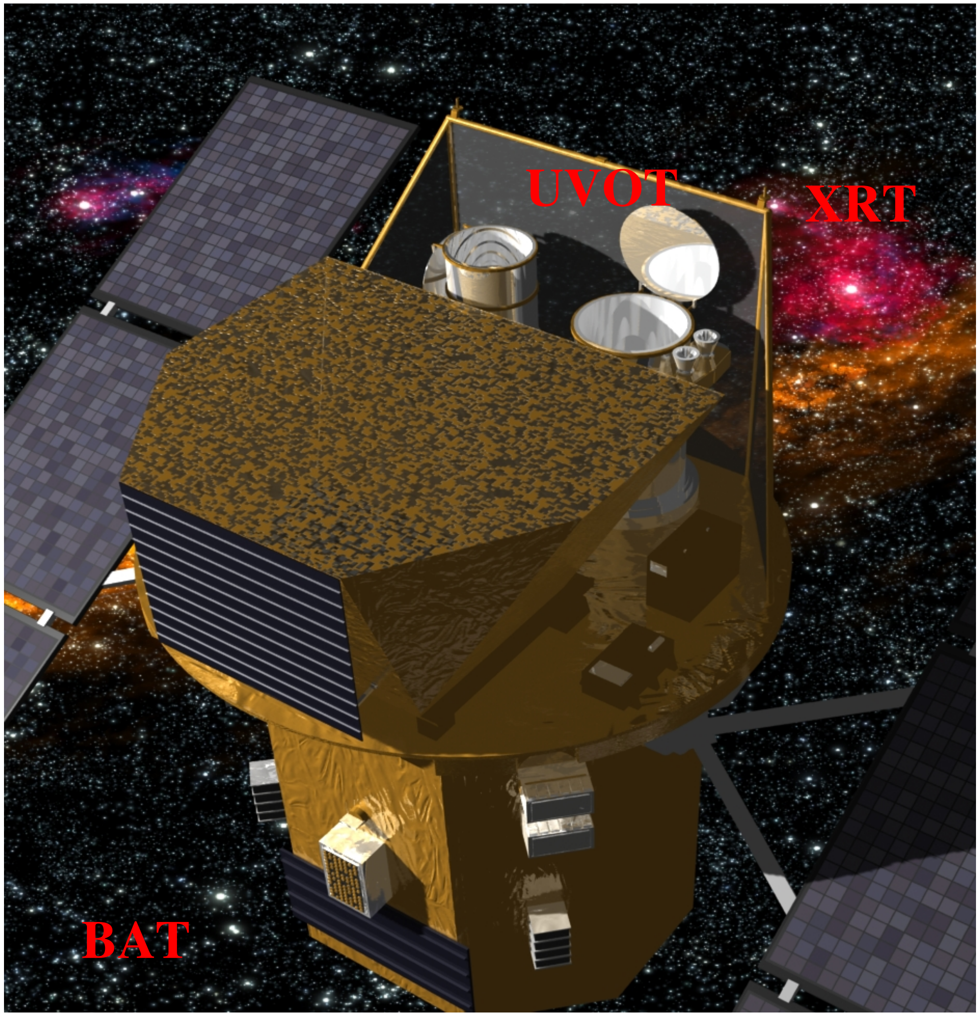
Particle Acceleration

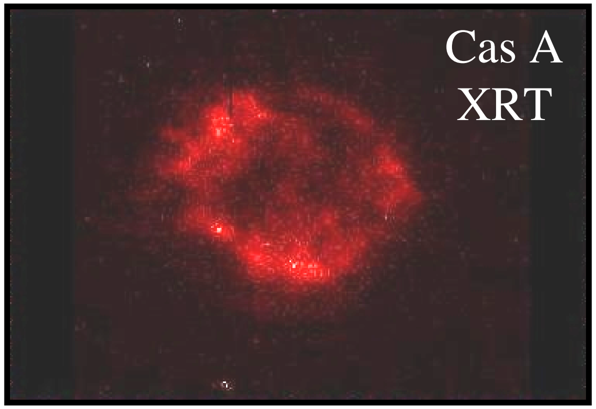
- The continuum radiation from GRBs is due to highly relativistic particles
- just like in SNR collisionless shocks are thought to be the main agents for accelerating ions as well as electrons to high energies (e.g., Blandford and Eichler 1987, Achterberg et al. 2001).
- Particles reflected from the shock and from scattering centers behind it in the turbulent compressed region and experience multiple scattering and acceleration by First-order Fermi acceleration when coming back across the shock into the turbulent upstream region.
- Second-order or stochastic Fermi acceleration in the broadband turbulence downstream of collisionless shocks will also contribute to acceleration.
- With each reflection at the shock the particles gyrate parallel to the moving electric field, picking up energy and surfing along the shock surface.

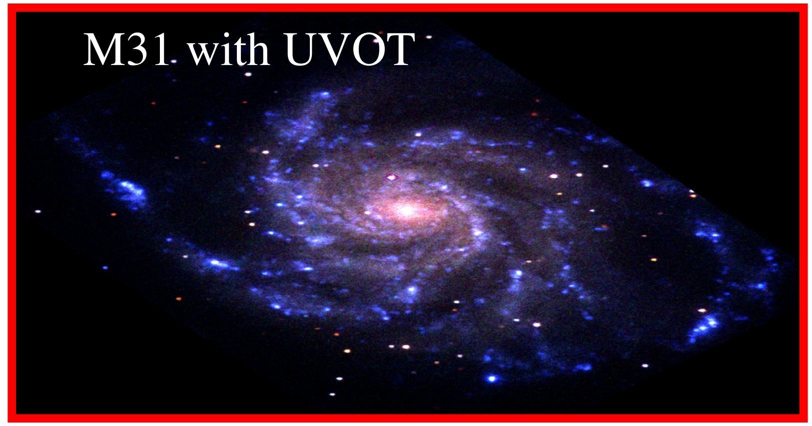
Swift γ-ray Burst Chaser



Swift was designed to find and study GRBs
BAT- GRB finder and localizer
UVOT, XRT: UV/optical and x-ray telescopes

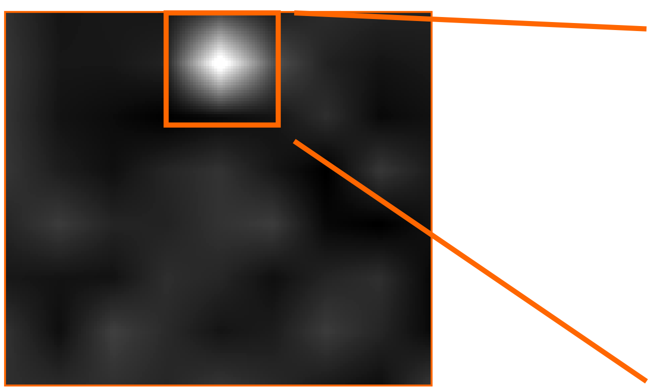
Swift Data- Multi-Wavelength





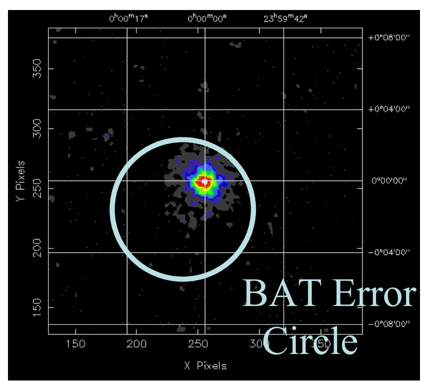
GRB Imaging

BAT Burst Image



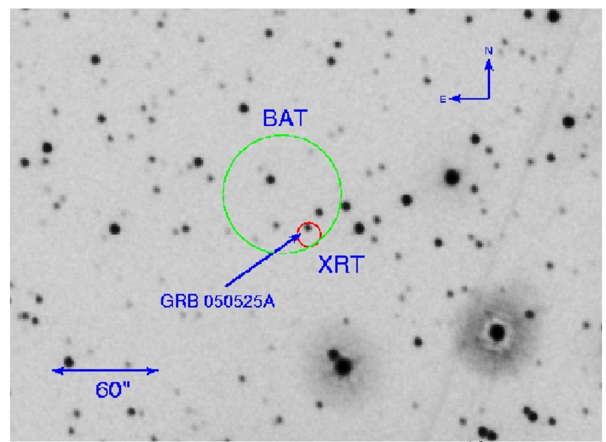
T<10 sec

XRT Image



T<90 sec

UVOT Image

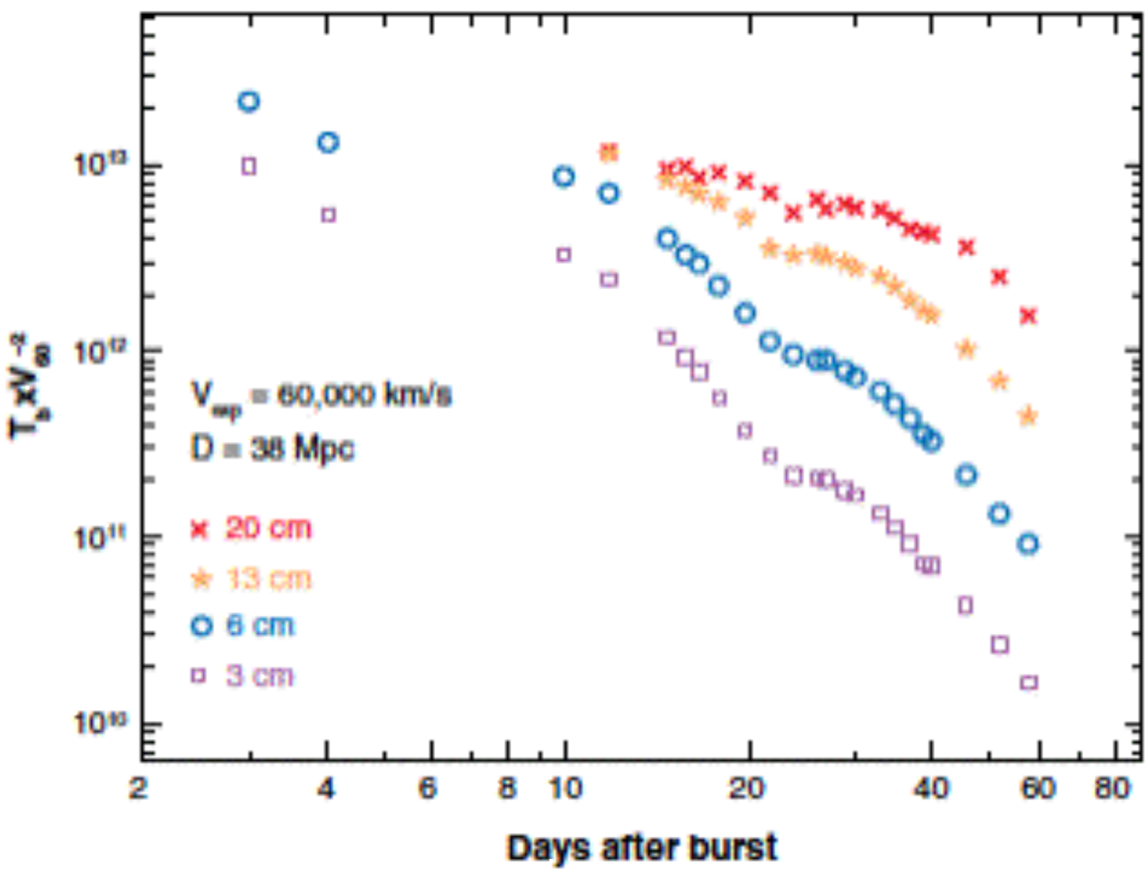


T<2 min

Evidence for relativistic beaming- ak ajets

- Brightness temperature is> 10^{12}K (Compton catastrophe)

γ-rays seen up to 7GeV; to avoid e+ – e– pair production (and the accompanying thermal spectrum), the GRB jet must be moving toward the observer with ultra-relativistic speeds (the "compactness" problem; Cavallo & Rees 1978)



The evolution of the brightness temperature of radio SN 1998bw, the most luminous radio SN ever recorded. The brightness temperature is computed under the assumption that the radio photosphere expanded with the same velocity inferred from optical spectroscopy (~0.2c). In order for the true brightness temperature to be less than the "Compton Catastrophe" value ($T_{CC} \approx 10^{12}$ K), relativistic motion in the first week after GRB 980425 is required. From Kulkarni et al. (1998b).

- If you keep scattering the same electrons, if the system is dense enough, the system runs away: e.g. the amplification of scattered radiation energy density, or a"Compton Cooling Catastrophe".
- This occurs if $L_{IC} >> L_{synch}$
- Remember that $L_{IC}/L_{synch}=U_{photon}/U_{magnetic\ field}$
- (U is energy density)
- in order to avoid having infinite energy in the Compton scattered electrons, there has to be alimit on the brightness temperature
- This is aself-regulating process–if the brightness temperature goes too high, an infinite energy demand is set up, knocking it back down.

Pair Production and alimit on the Relativistic Factor

Lithwick And Sari 2001

a photon with energy E' can annihilate asecond photon with energy greater than $(m_e c^2)^2/E'$ yielding an electron-positron pair,(m_e is the electron mass).

When the energy of the second photon is ~ $(m_e c^2)^2/E'$ then the cross section for this process is approximately the Thomson cross section,σ_T The cross section falls as apower law of the annihilating photon energy (Klein-Nishina)

Averaging over the observed photon distribution the average cross section is ~$0.06\sigma_T$

If the emitting material is moving toward the observer with a Lorentz factor γ, the photons are blueshifted by γ. Thus, aphoton with detected energy $E=\gamma E'$ can only annihilate photons whose detected energies are greater than $(\gamma m_e c^2)^2/E$. Since most of the photons are at low energies, the photon with the highest energy will be most susceptible to annihilation by other photons.

alower limit on the Lorentz factor can be obtained by requiring that the photon with energy E_{max} will have optical depth smaller than unity.

- When mass accretes onto aBH or NS under these conditions, the densities and temperatures are so large that photons are completely trapped and neutrinos, are the main source of cooling
- The Eddington limit is then modified to be (using the cross section for neutrino pair production)

$L_{Edd}=8x10^{53}(E_\nu/50MeV)^{-2}(M/M_\odot)erg /s$

E_ν -the mean energy of the emitted neutrinos (since cross section is energy dependent)

The effective black body temperature is

- $T_{Edd} = (L_{Edd}/4\pi r^2{}_g\sigma_{SB})^{-1/4} =45\ (M/M_\odot)^{-1/4}(E_\nu/50MeV)^{-1/2}$ MeV

$\tau_T\sim 10^{16}$ so photons are incapable of escaping and constitute part of the fluid.

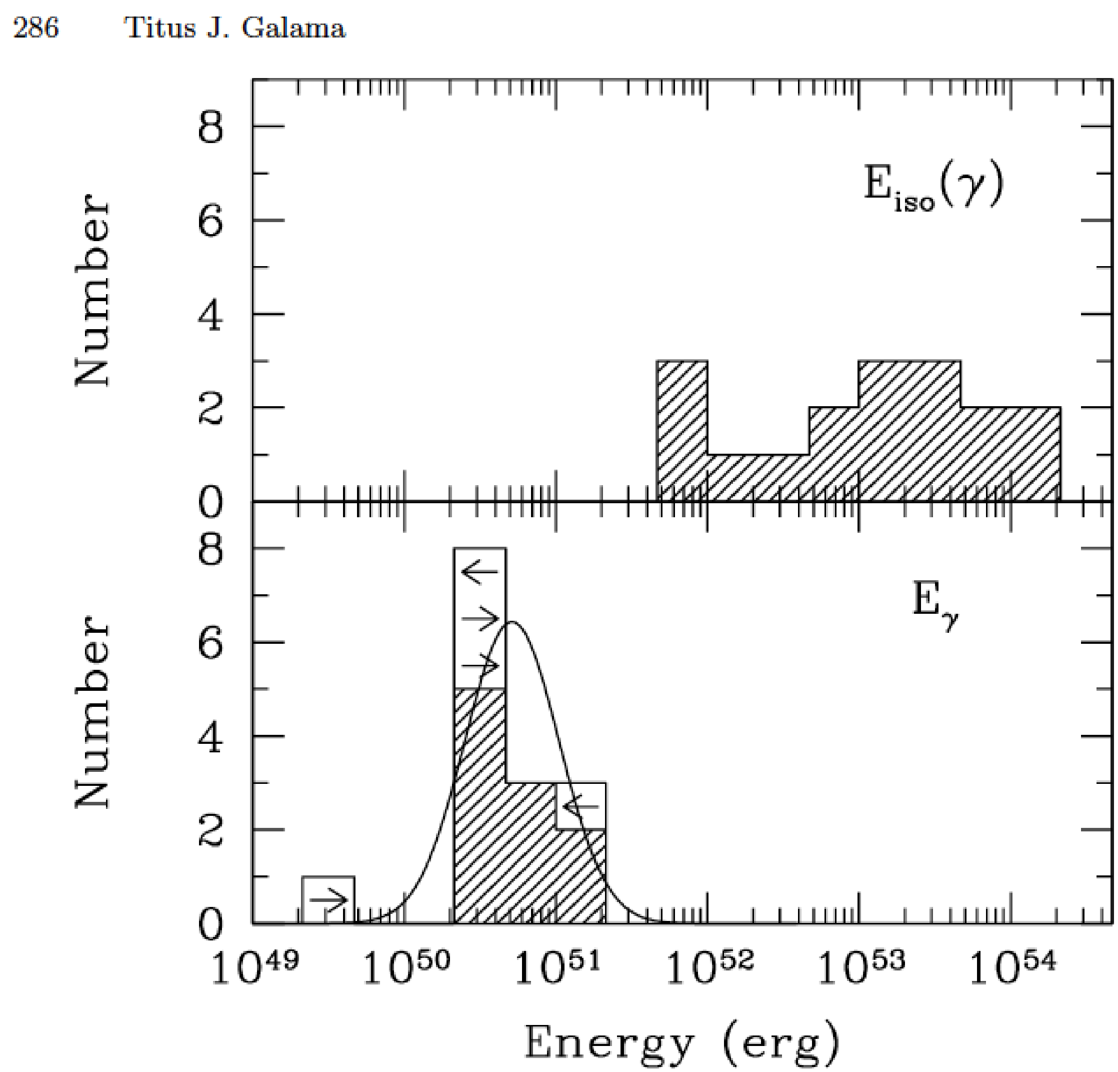
Optical Depth

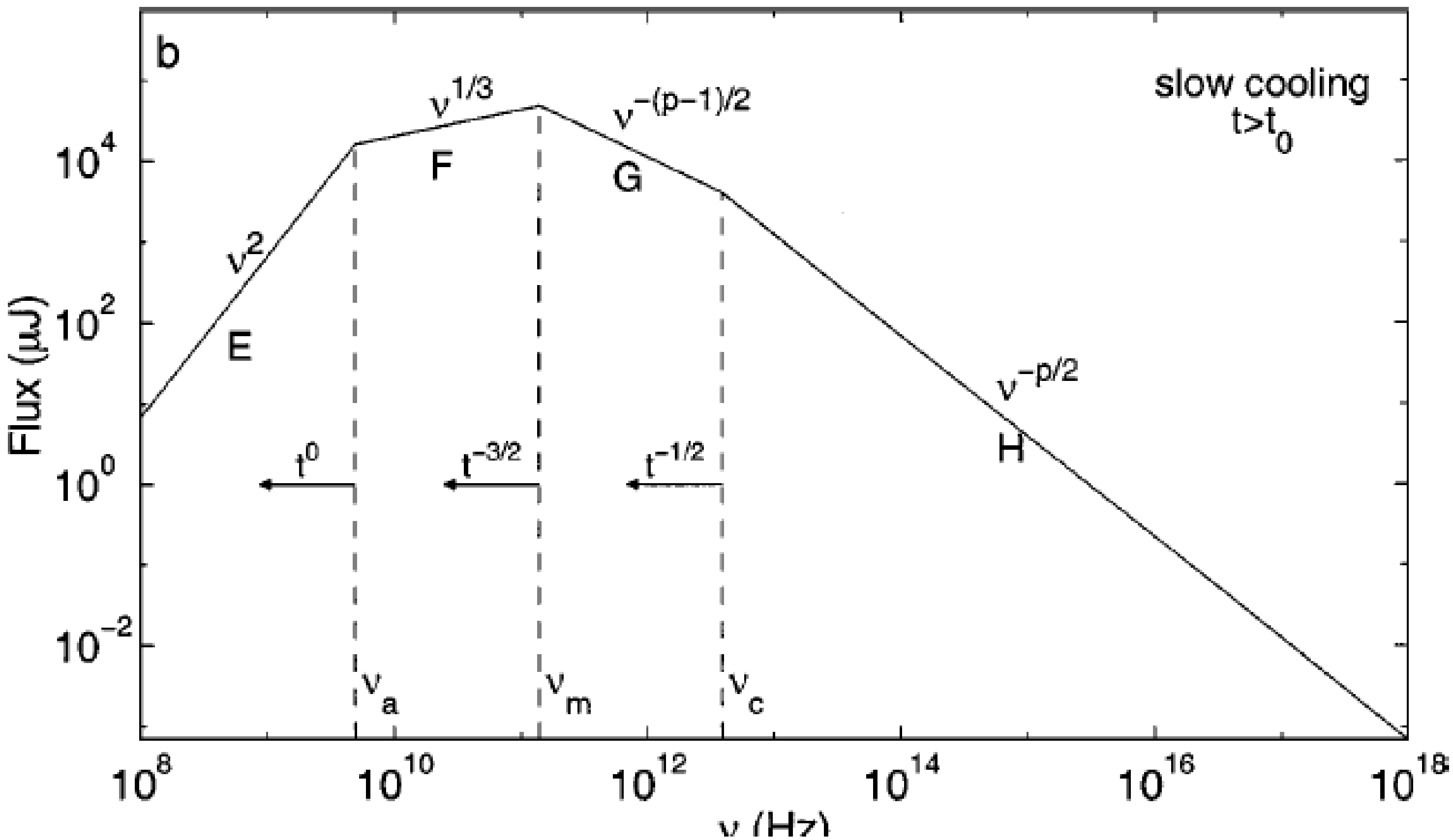
$\gamma^2 c\delta T \sim R$ (δT is the elapsed time) ; if N is the number of photons then the optical depth to pair creation is

$\tau_p = 0.06 N\sigma_T/4\pi R^2 \sim 0.06 N\sigma_T/4\pi(\gamma^2 c\delta T)^2$

Luminosity 'Corrected' for Beaming

- Absolute luminosity and variance reduced
- Number of bursts in universe increased by 1/beaming factor
- E_{iso} is the observed luminosity, E_{γ} is the luminosity corrected for beaming.





- The predicted time dependence and shape of the emitted synchrotron spectrum from a fireball model- synchrotron emission from a slowing down relativistic shell that collides with an external medium. (Sari et al 1998)
- Notice the different time dependences and spectral slopes

- Radio to x-ray spectrum of GRB afterglow 12 days after the burst
- Fireball looks like agood description of data.

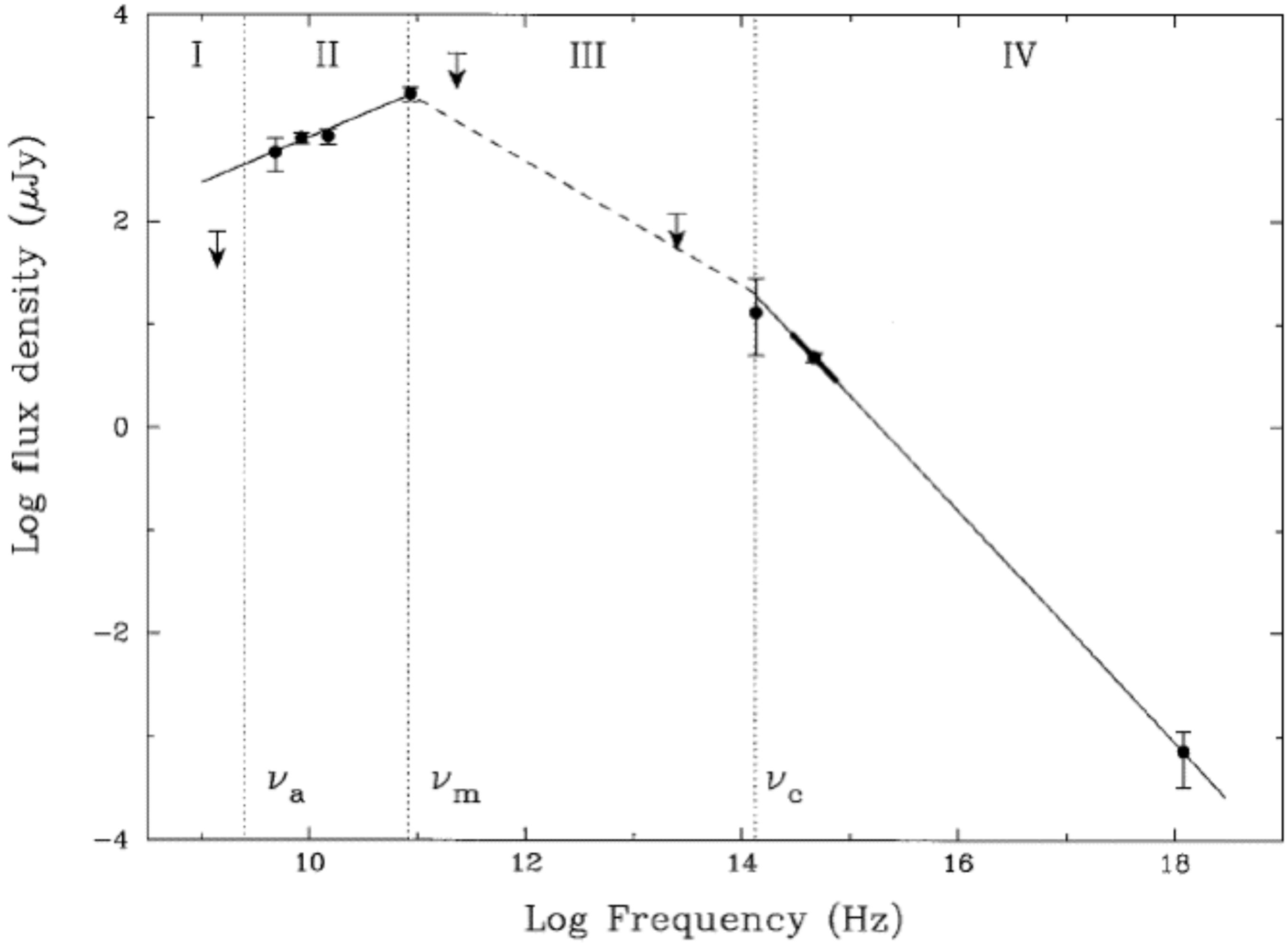
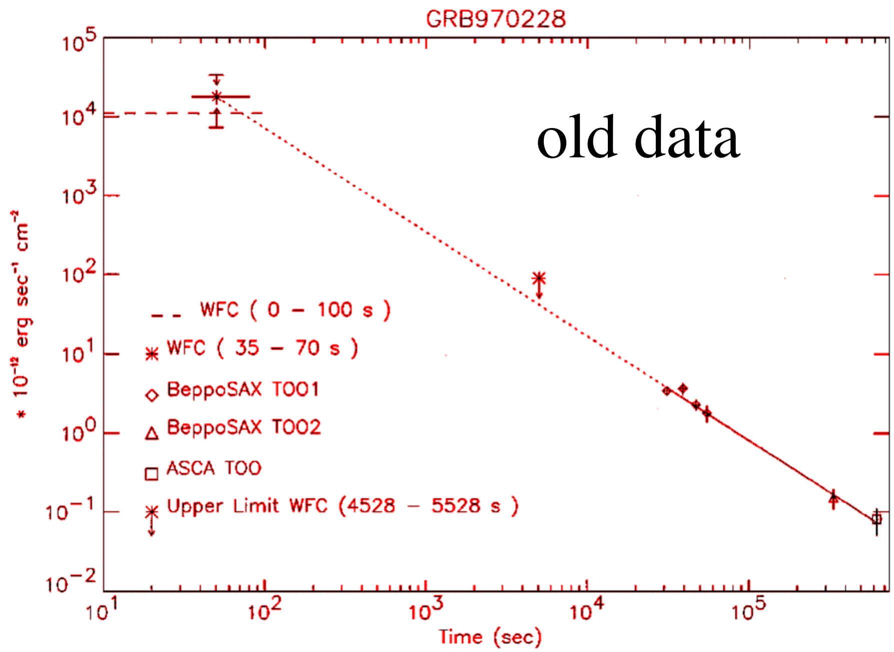


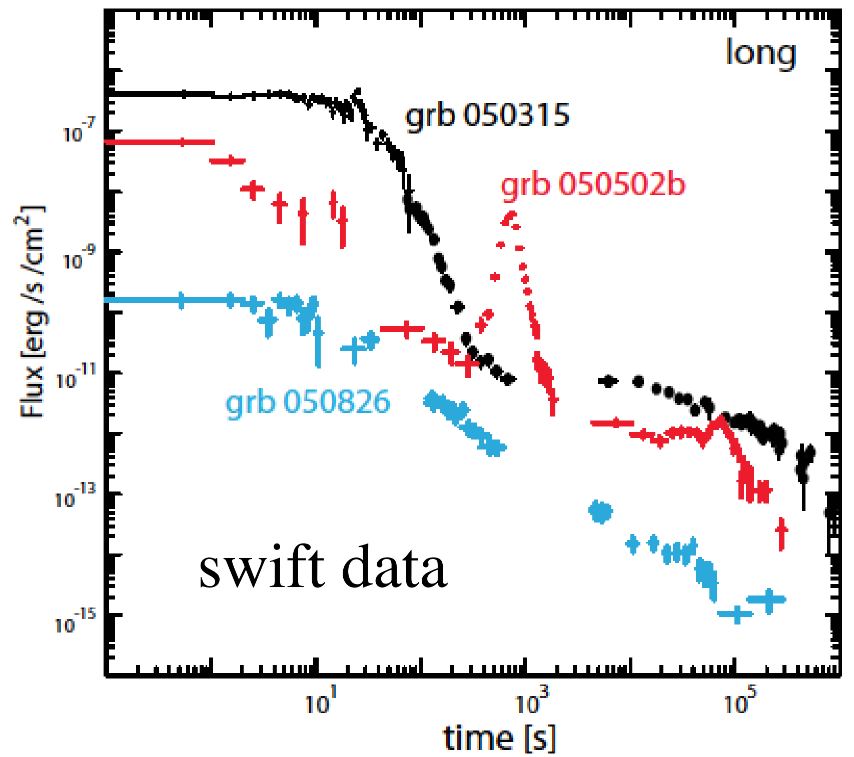
Figure 12 The radio to X-ray spectrum of the afterglow of GRB 970508, 12.1 days after trigger, showing all the characteristics of synchrotron emission (Galama et al 1998d).

aFull Solution (Zheng et al 2011)

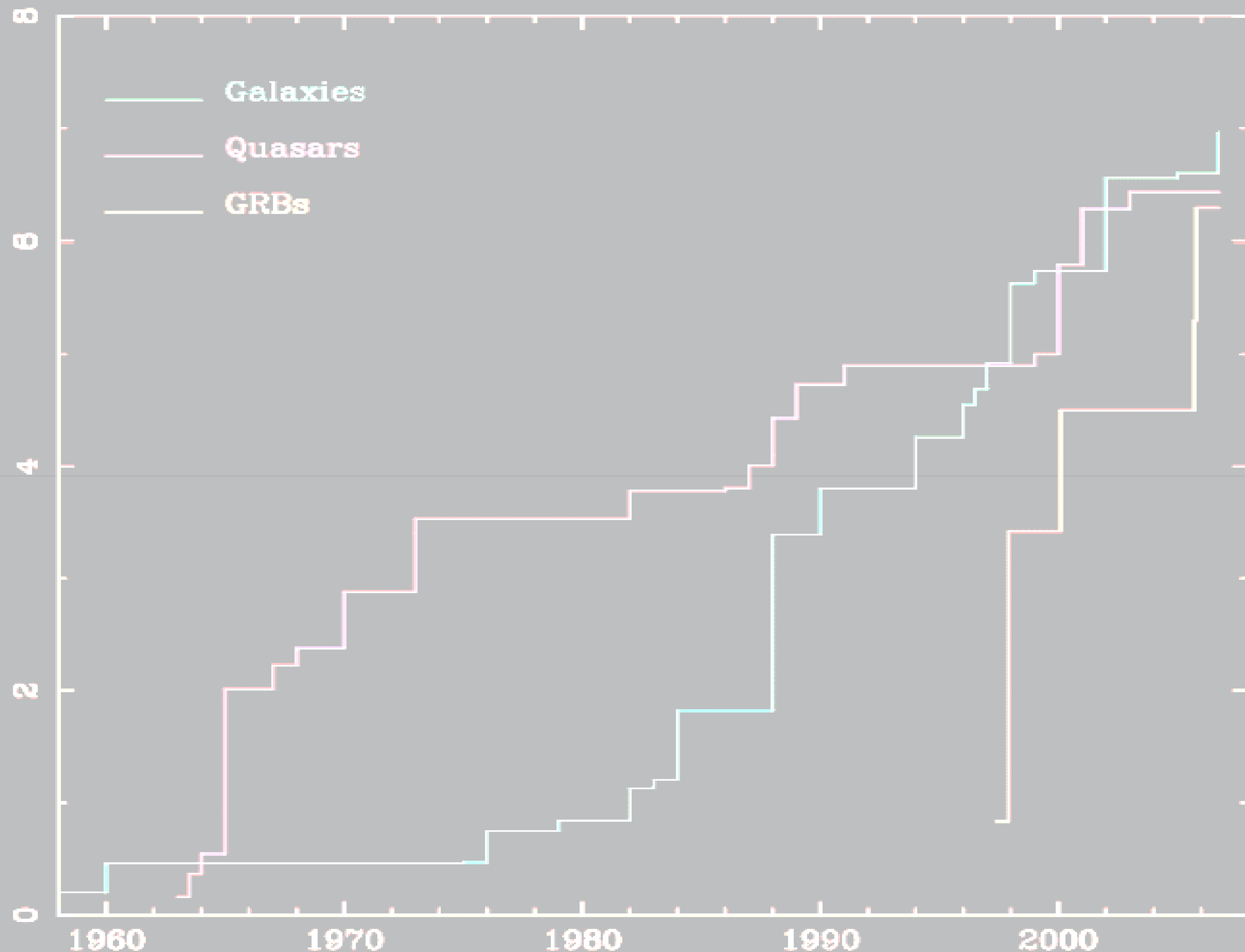
- Generally, the prompt emission can be modeled as originating from internal shocks or the photosphere of the fireball eject aor magnetic dissipation from a magnetically dominated jet,
- the afterglow emission originates from external shocks that may include both forward shock and reverse shock components (Meszaros & Rees 1997, 1999; Sari & Piran 1999).
- For some GRBs many of the physical parameters can be determined if the full optical and X-ray afterglow lightcurves can be interpreted within the standard reverse shock (RS) + forward shock (FS) model.
  - appling the standard fireball model
    - the radiation mechanism is synchrotron,
    - the radius of prompt emission, R_{GRB}~3 x 10^{13} cm
    - initial Lorentz factor of the outflow (Γ_0~ 250)
    - that the eject aare mildly magnetized
    - collimation angle ~3-4°
    - the total energy budget ~7x10^{50} ergs.

- Until Swift data became available the fireball model seemed to fit both the spectral and temporal data
  - this was due to undersampled data
- Things are now known to be more complex and there is no accepted theory which explains the burst light curves in detail - seems to require that the engine remain active for hours or lots of structure in the shocks





Spectroscopically Secure High Redshift Record



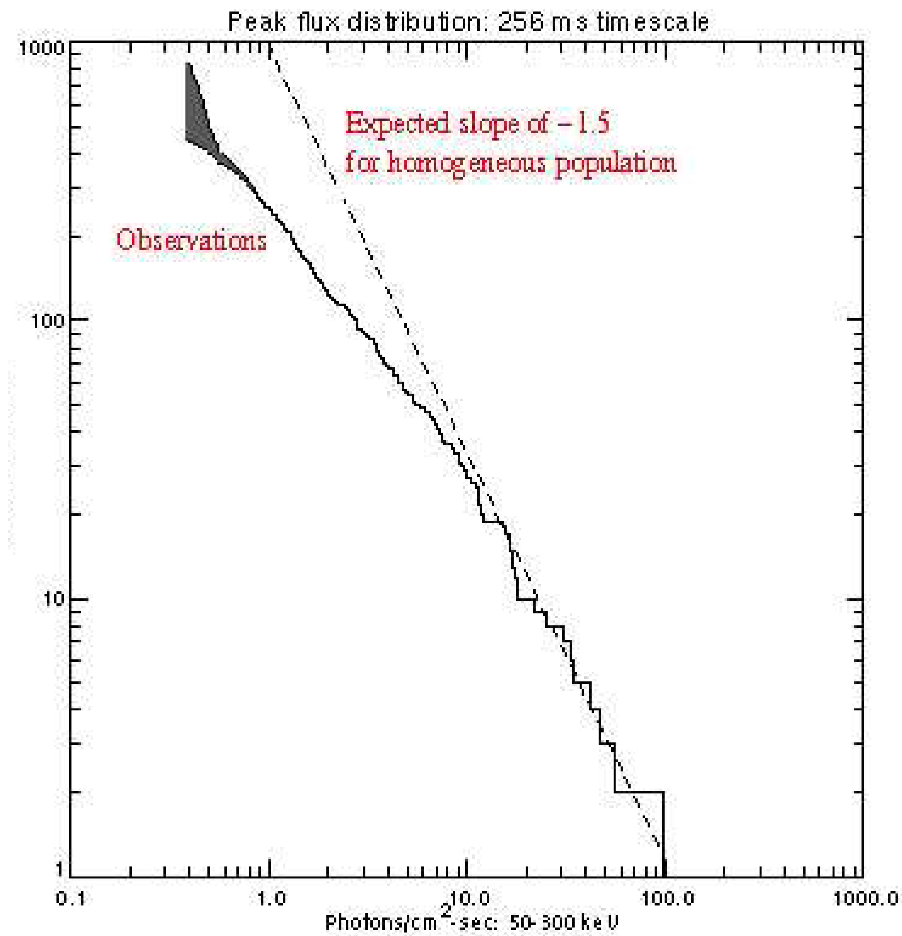
redshift z

Year

LOG N-LOG S- Numbers of sources with aflux >S

- At high fluences slope is consistent with Eucledian
- At lower fluences deviation is seen (flatter)
  - generic reason is have reached the end of the distribution or the volume element is no longer Eucledian
  - For a narrow distribution in intrinsic luminosity sources distributed randomly in Eucledian space have a slope of 1.5 in log N-log S

flux

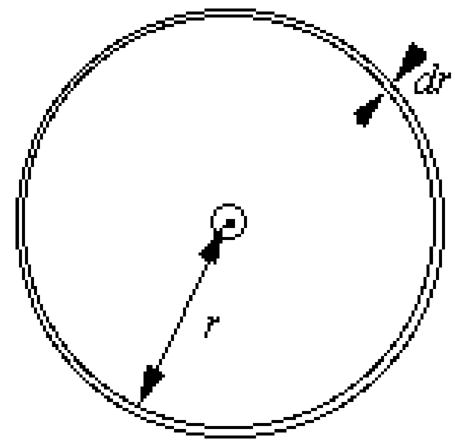


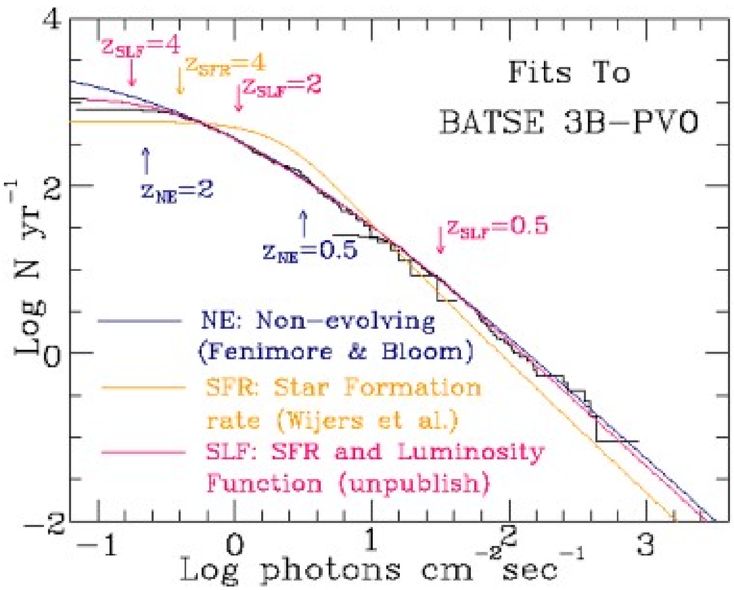
flux

LOG N-LOG S

- Consider ahomogeneous distribution of sources of luminosity L and space density n
- derivation: $f=L/4\pi r^2$; $df/dr=r^{-3}$
- $n(f)df=n\,4\pi r^2dr= n\,4\pi r^2dr$
- $n(f)= n\,4\pi r^2dr/df\sim f^{-5/2}$
- Number of sources brighter than $f = \int n(f)df = f^{-3/2}$

- GR Volume element is different; assumes n is not a function of r

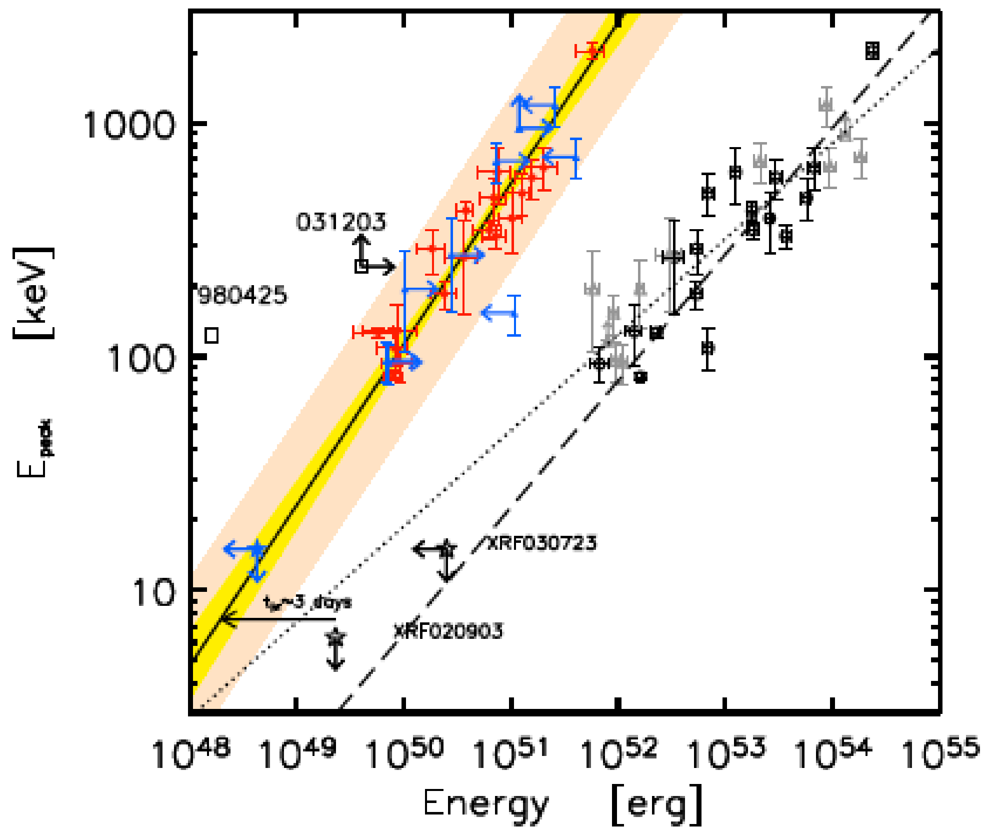




GRBs as standardizable candles

- The extremely large luminosity of Gamma Ray Bursts (GRBs) makes them detectable out to very large redshifts z < 20 which make them, potentially, exquisite tools for observational cosmology.
- (i) the study the epoch of re-ionization; (ii) the characterization of the properties of the cosmic intervening medium; (iii) the study of the cosmic star formation history back to unprecedented epochs; (iv) the description of the geometry of the Universe and (v) the investigation of the nature of Dark Energy (DE) (Ghirland aet al 2005)
- **However this requires that GRBs be standardizable candles**

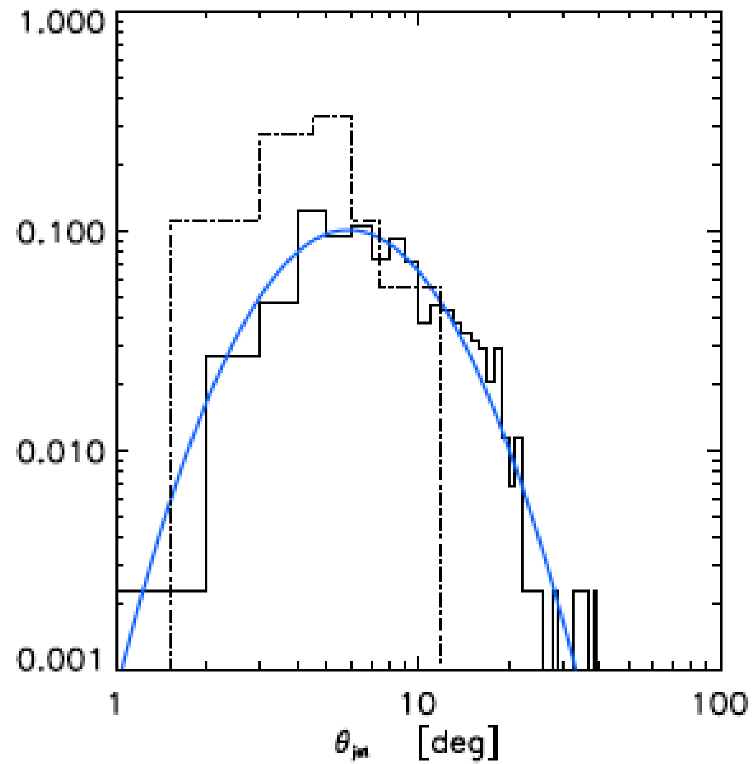
Correlation of Epeak and energy in GRBs (with and without beaming correction)- Amati relation

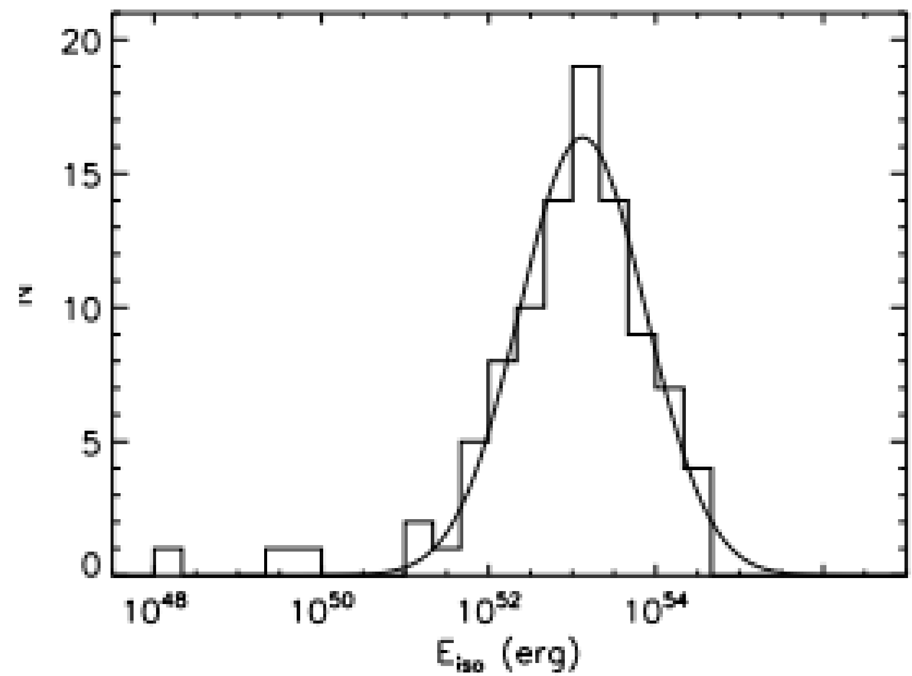


black- observed luminosity
color- corrected for beaming

Implied Jet Opening Angle Distribution

- Rather narrow implied beaming angle distribution- but this is a selection effect
- small number of objects at small angles, at large angles flux is severly reduced

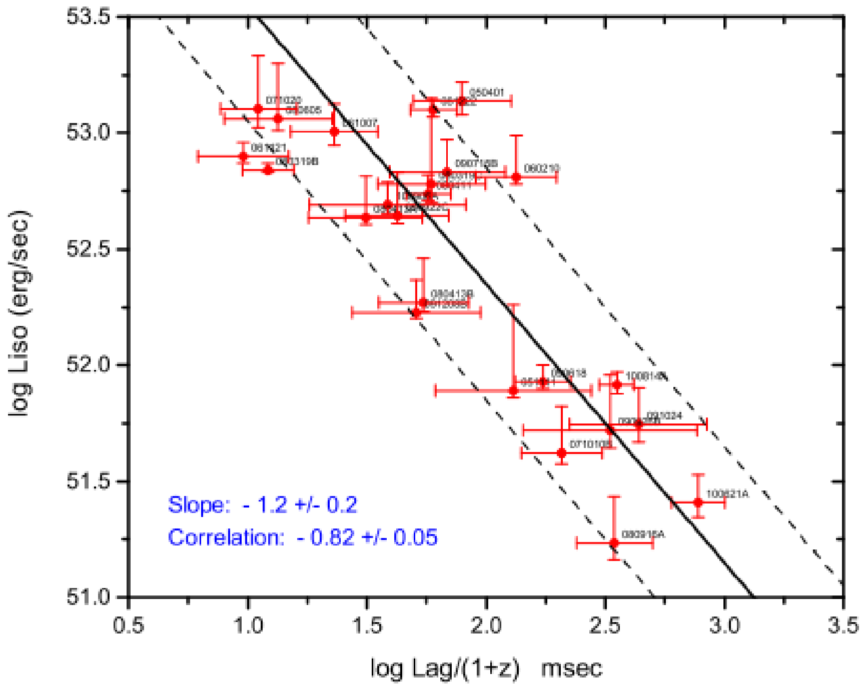




Observed distribution of burst luminosities (Amati 2009)

Empirical Relations

- Relation between L_{iso} and lag in peak between 2 energies



Ukwatt aet al 2012

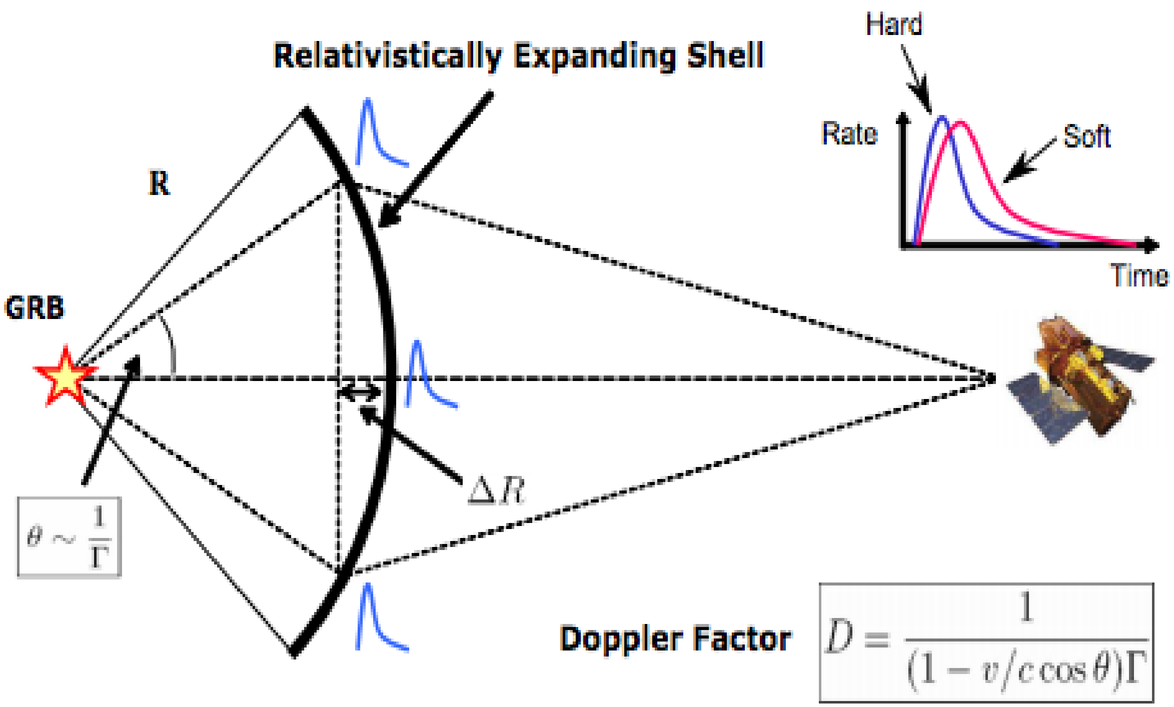
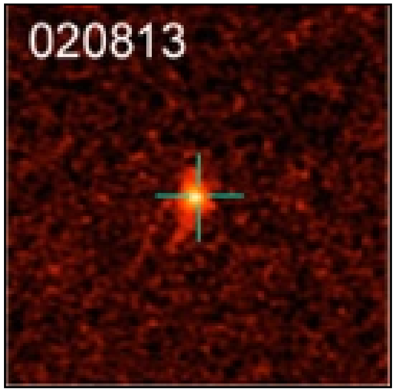


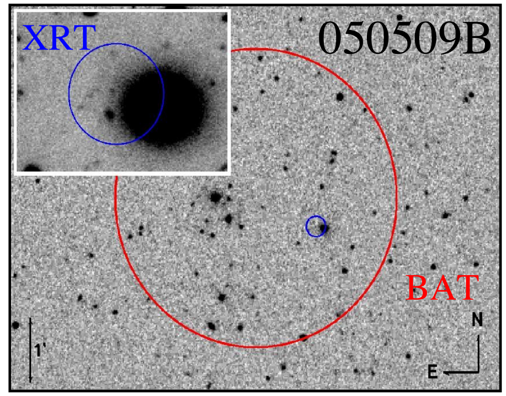
Figure 6. Spectral lags could arise due to the curvature effect of the shocked shell. At the source, the relativistically expanding shell emits identical pulses from all latitudes. However, when the photons reach the detector, on-axis photons get boosted to higher energy (hard). Meanwhile off-axis photons get relatively smaller boost and travel longer to reach the detector. Thus these photons are softer and arrive later than the on-axis photons.

Long GRBs | Short GRBs

SF
irregulars

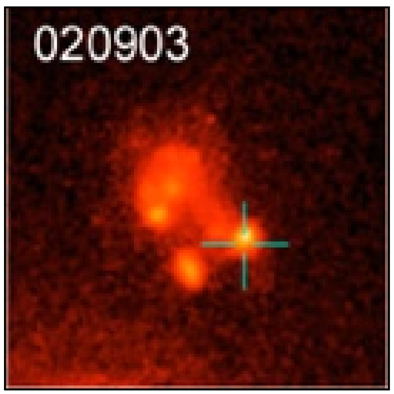
Fruchter
et al.

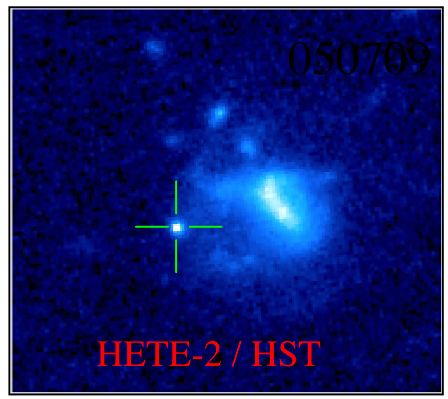




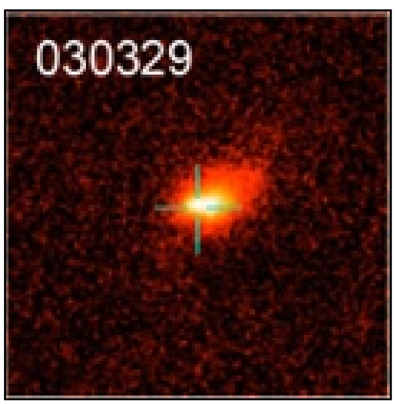
cD elliptical

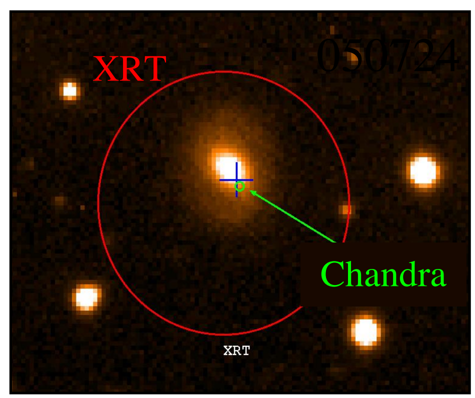
SFR < 0.2 M_O yr^{-1}
z = 0.225





SF galaxy
with offset
z = 0.161



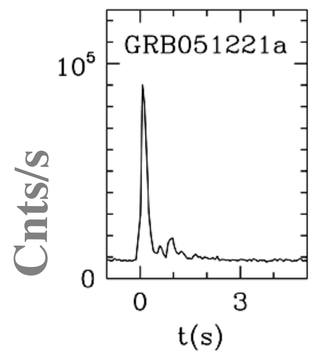


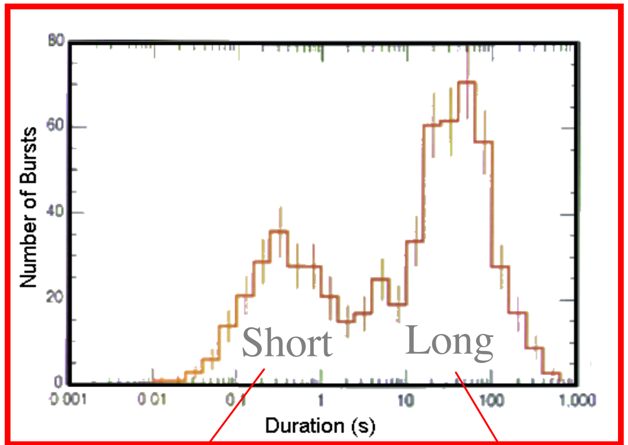
elliptical

SFR < 0.02 M_O yr^{-1}
z = 0.258

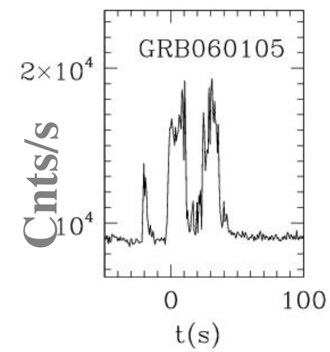
Short vs Long GRBs

Short GRB

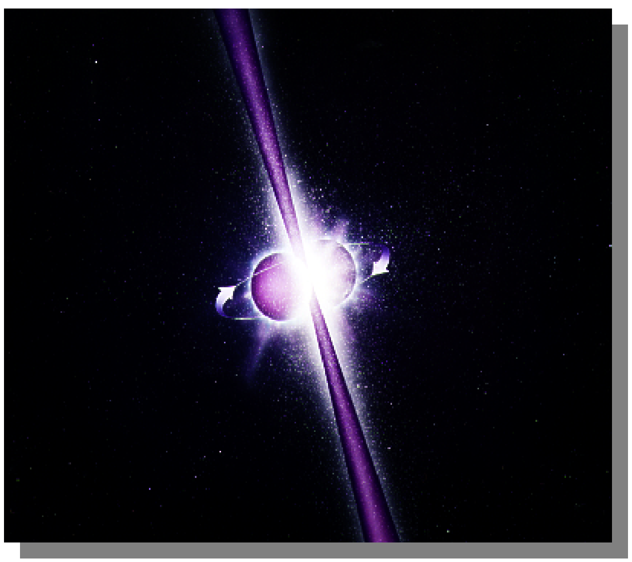


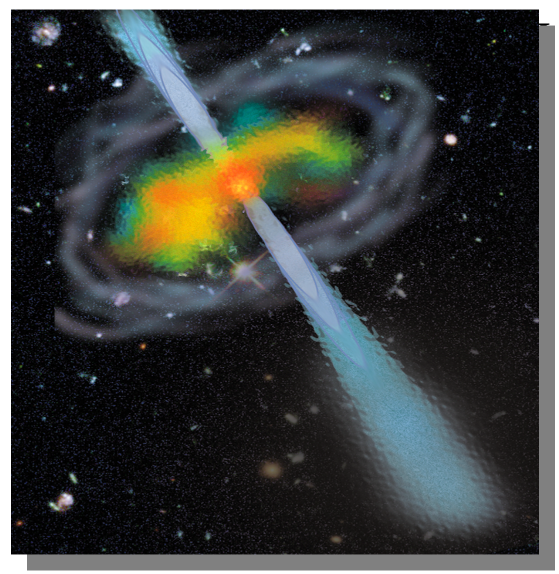


Long GRB



Short GRBs in non-SF elliptical galaxies



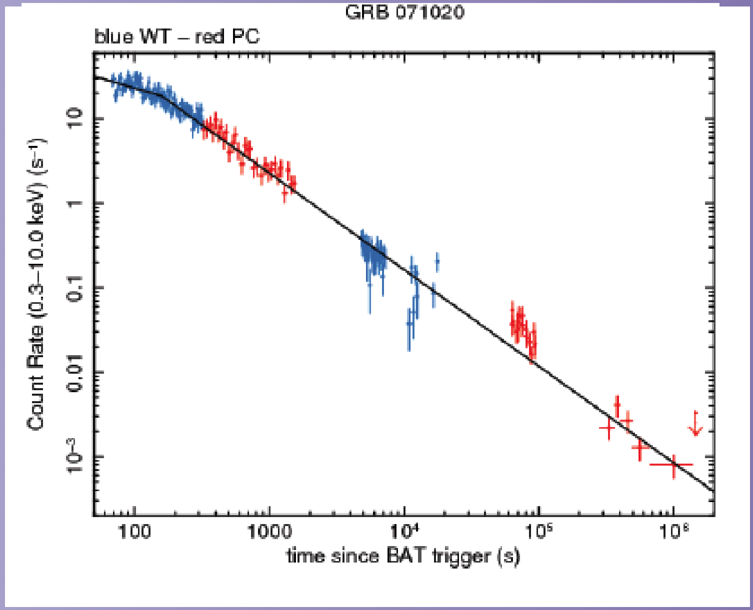


Long GRBs in SF galaxies

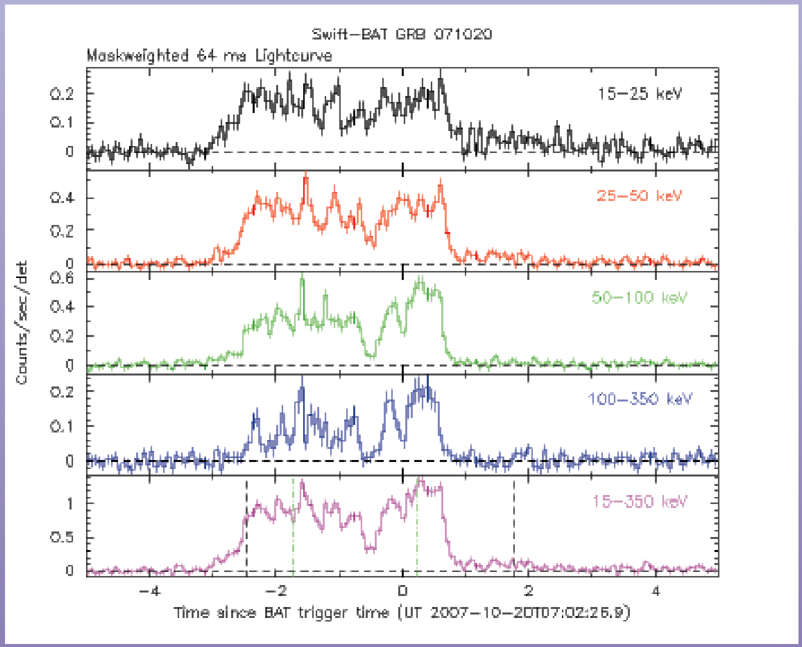
Swift GRB Data

GRB 071020

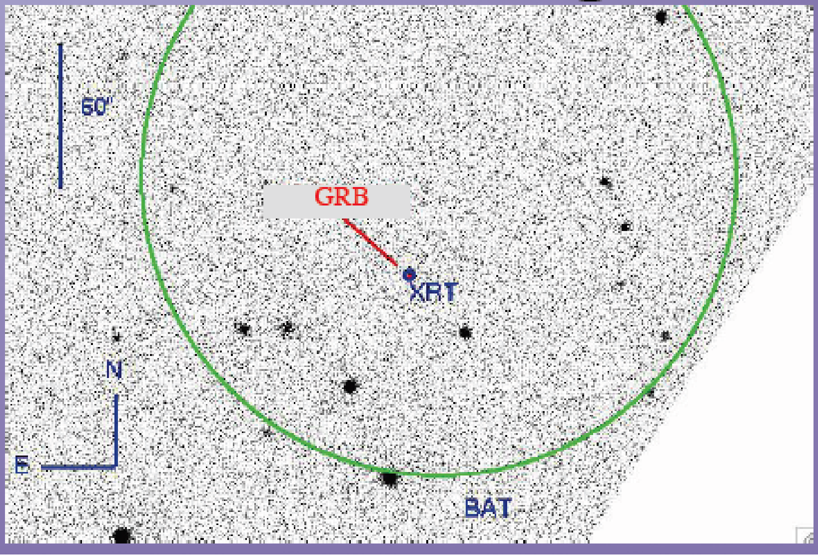
XRT lightcurve



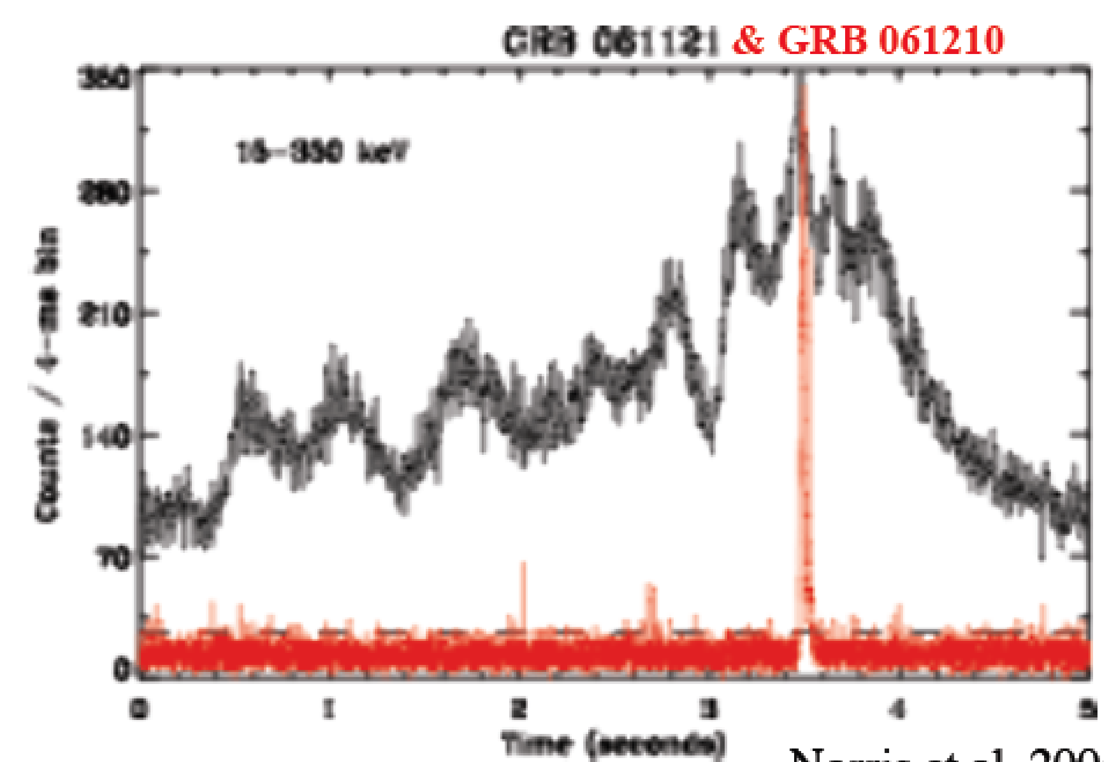
BAT lightcurve



UVOT image



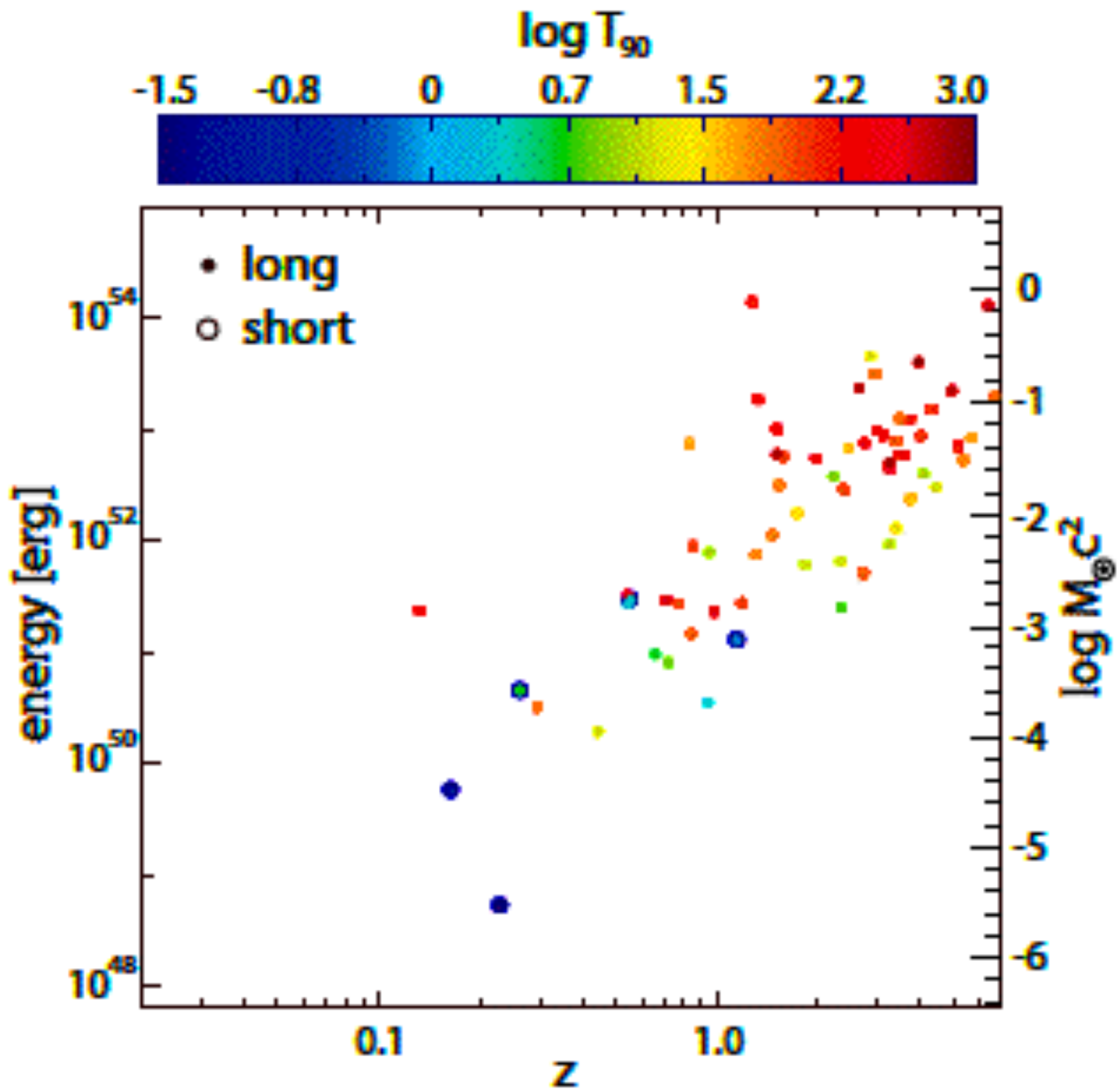
Comparing Short and Long GRBs



Norris et al. 2006

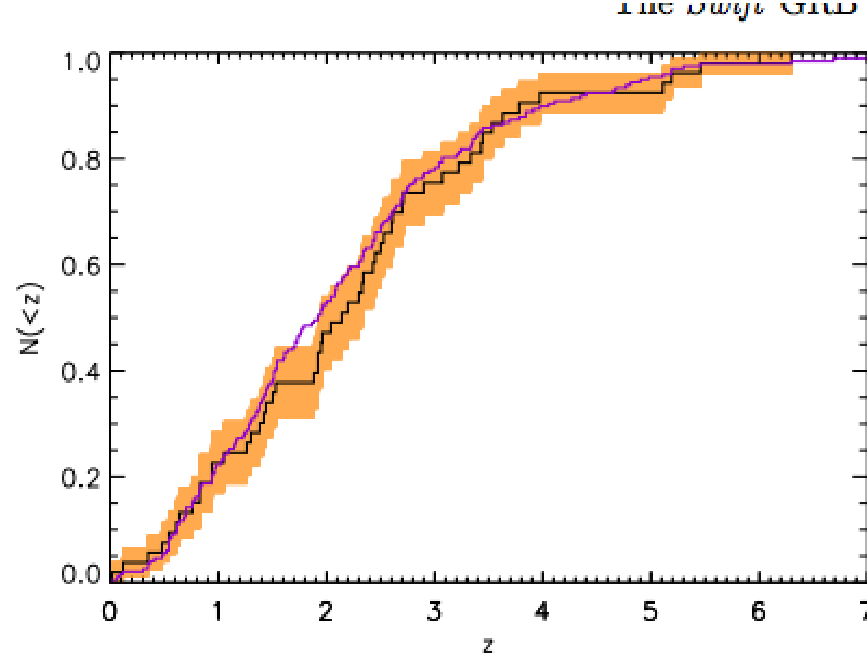
GRB 061121 = brightest long GRB
GRB 061210 = brightest short GRB

- Averaged over the burst long bursts are more luminous that short bursts

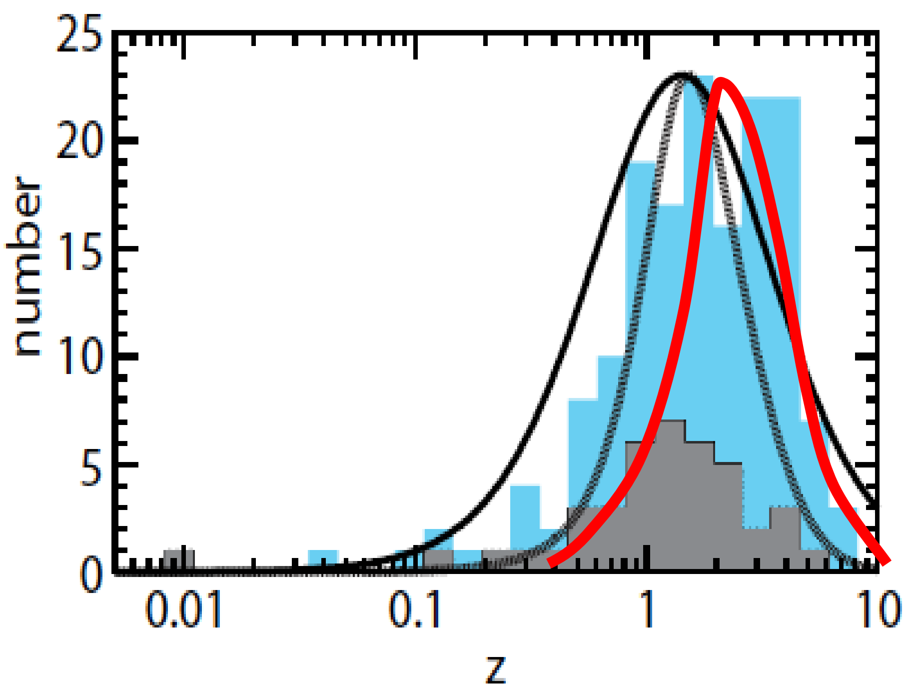


blue=observed, red= corrected for redshift

- Redshift distribution- redline is assuming GRBs trace star formation, black hole is constant co-moving density

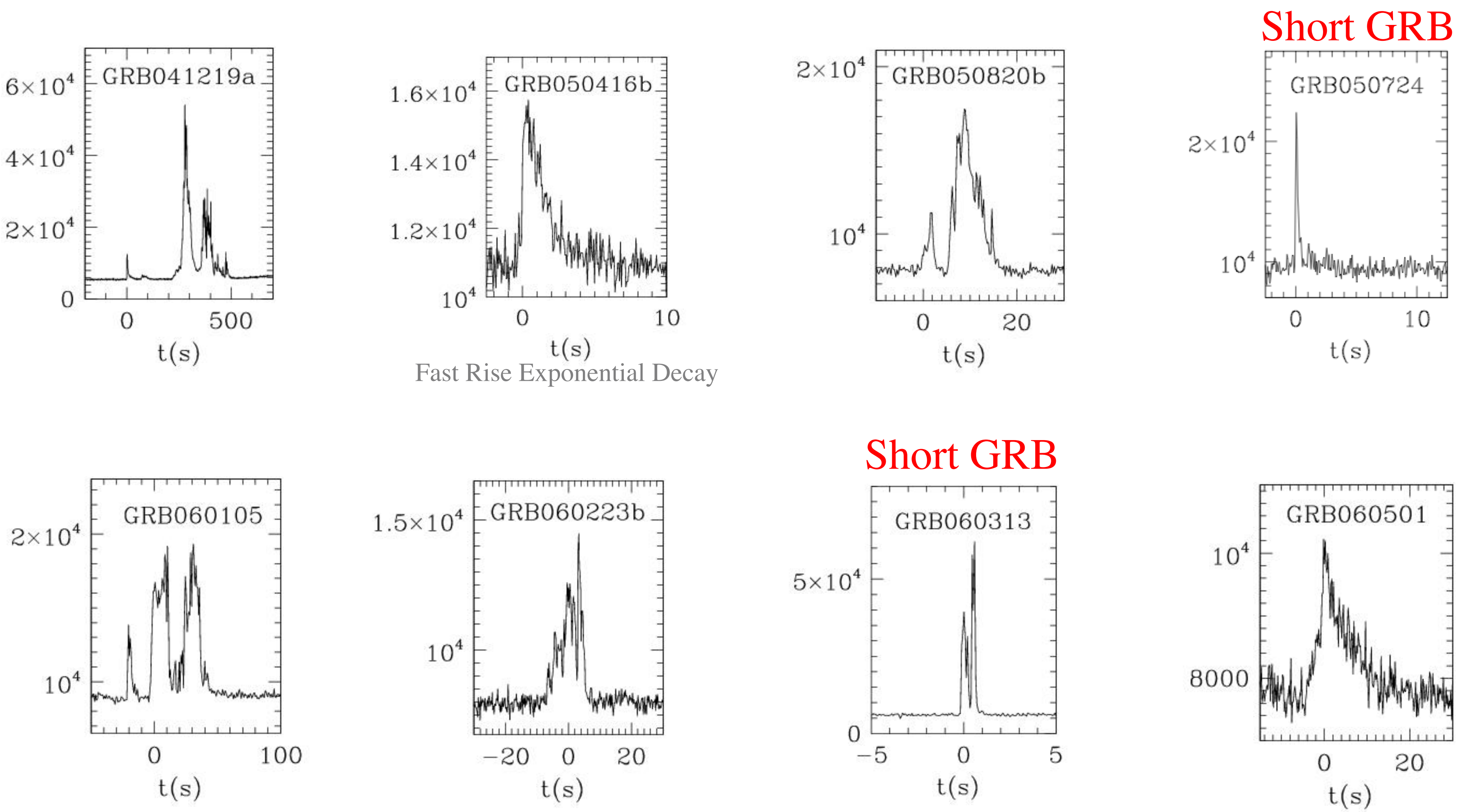


Jakobsson et al 2012

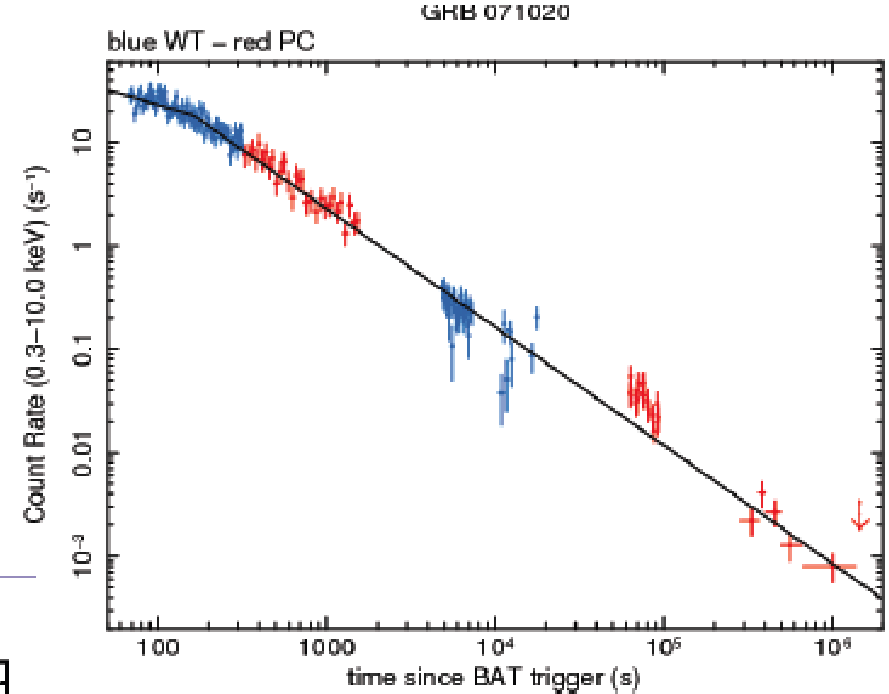


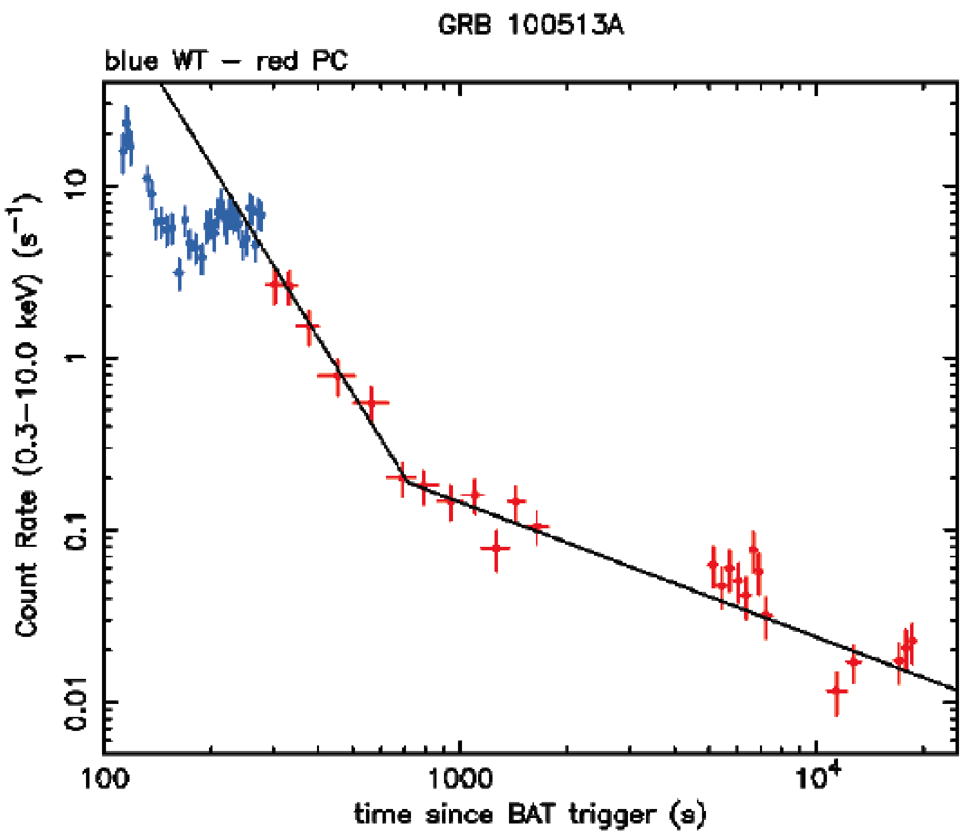
Montage of Burst Light Curves

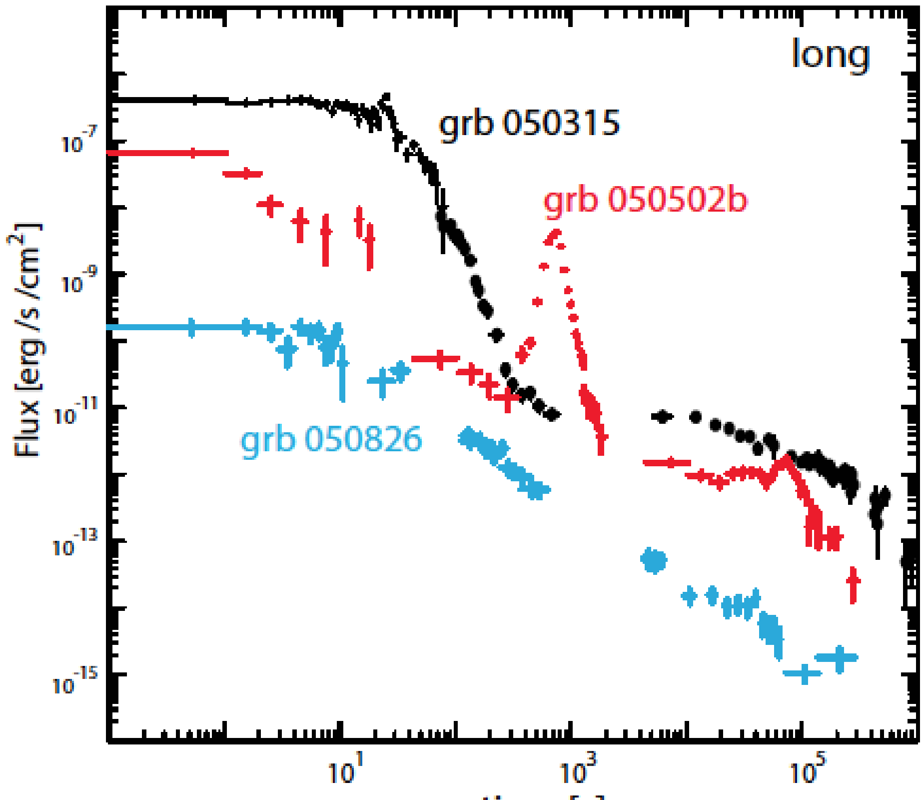
~100 GRBs per year
82% with x-ray detections
50% with optical detection

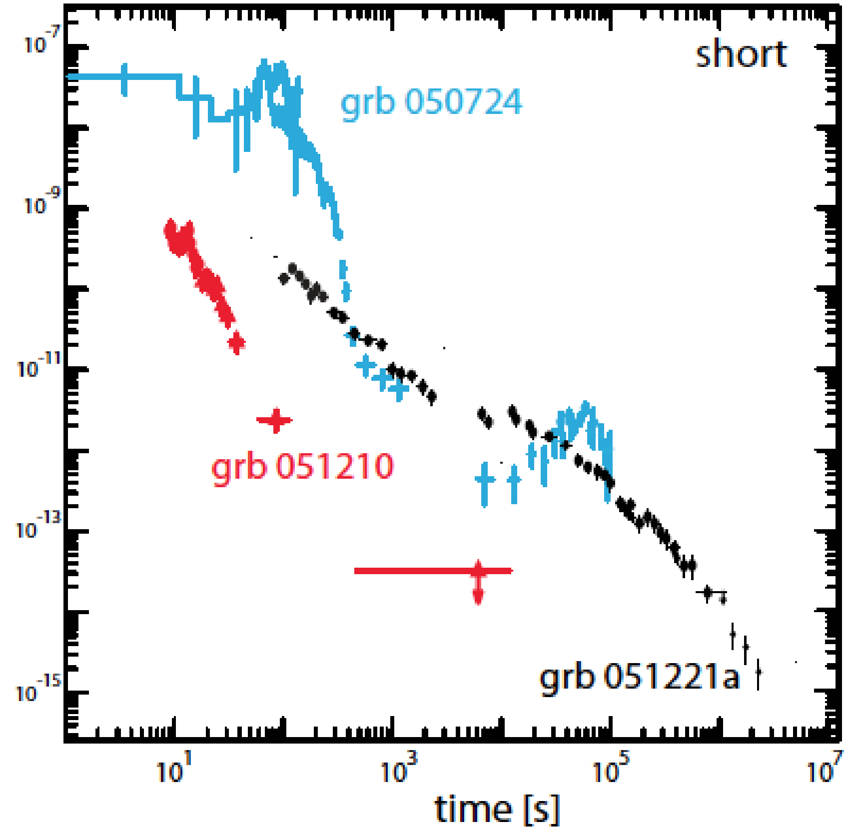


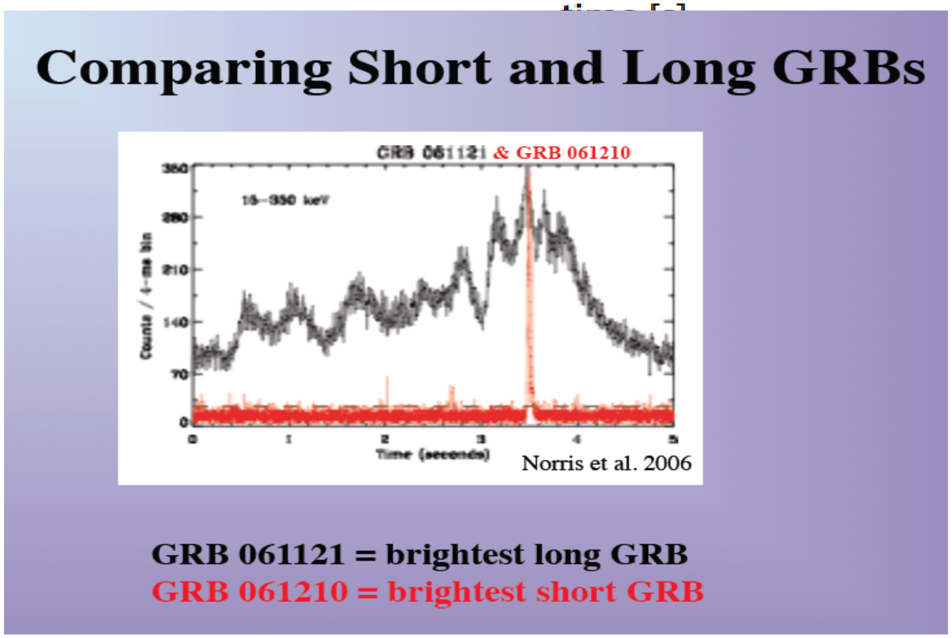
- Flux often declines as a power law in time- but not always



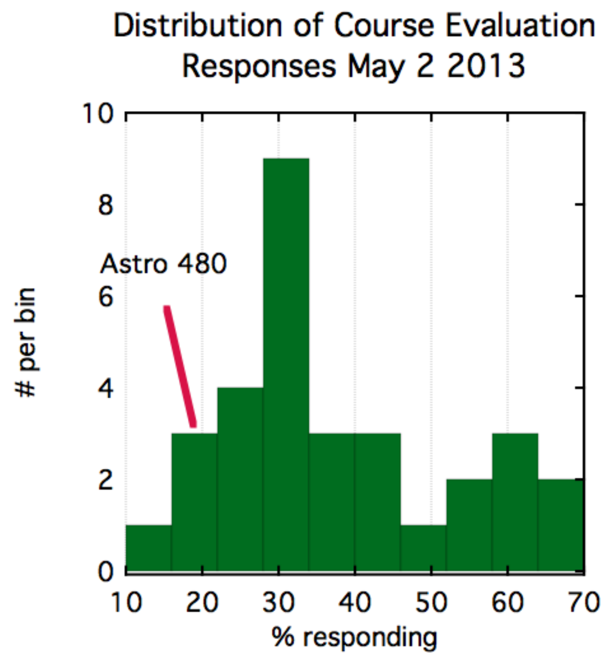



long
grb 050315
grb 050502b
grb 050826
Flux [erg /s /cm^2]
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^1
10^3
10^5


short
grb 050724
grb 051210
grb 051221a
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^1
10^3
10^5
10^7
time [s]

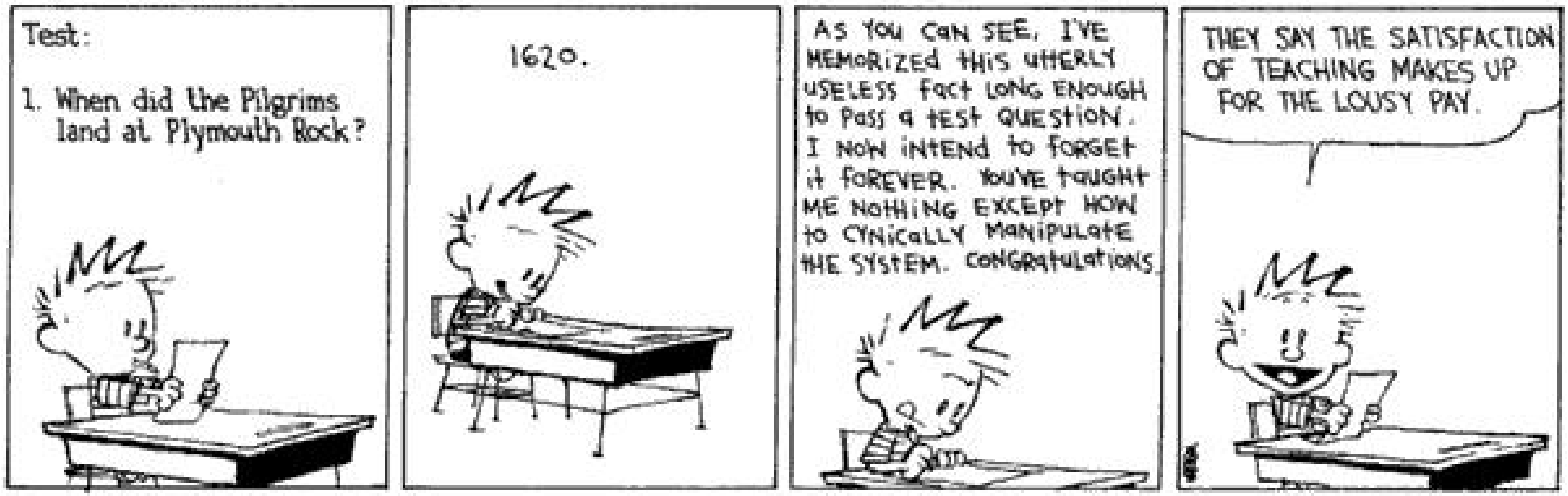

Comparing Short and Long GRBs
GRB 061121 & GRB 061210
15–350 keV
Time (seconds)
Norris et al. 2006
GRB 061121 = brightest long GRB
GRB 061210 = brightest short GRB

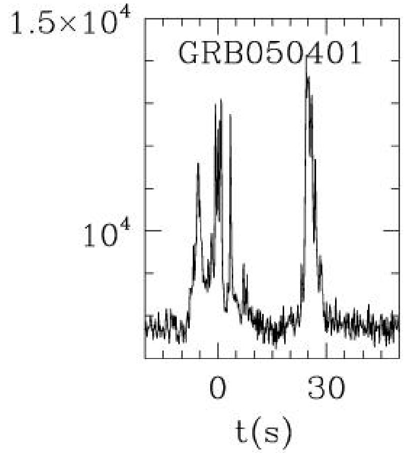
- the CourseEvalUM website (www.CourseEvalUM.umd.edu) is open till May 10. The evaluations are confidential
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc?-or dull, boring, stodgy, unprepared?
- Please do this - What did we do that you liked-disliked? How can I improve? **Only 3 students have filled it in so far !!!**



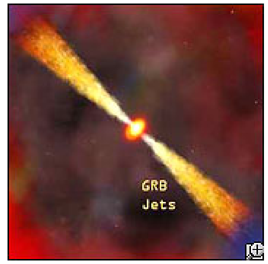
Fill in your course evaluation!

- www.CourseEvalUM.umd.edu
- Your responses are strictly anonymous. I only see the statistics
- If 70% of people signed up respond, evaluations are made public. As of this morning we are at 20%.
- If you complete evaluations for all your courses, you'll be able to access the results

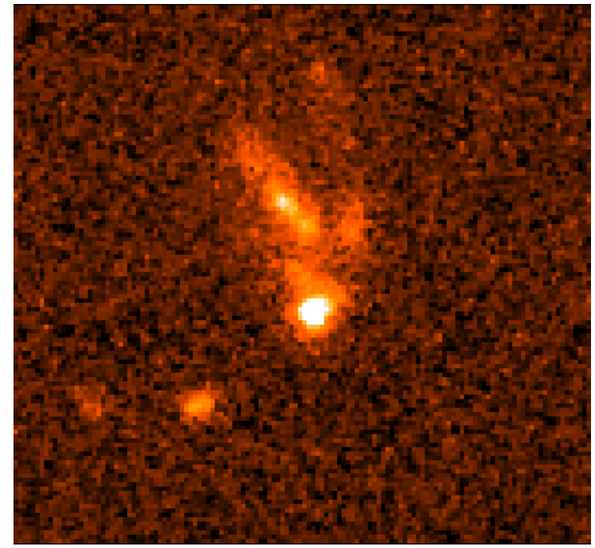




Long GRBs

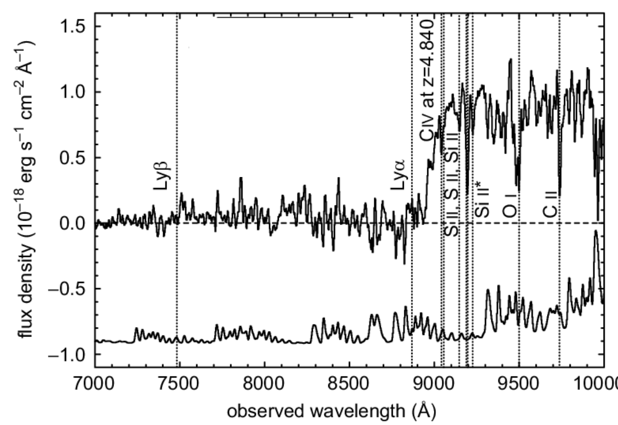


GRB 990123 - HST



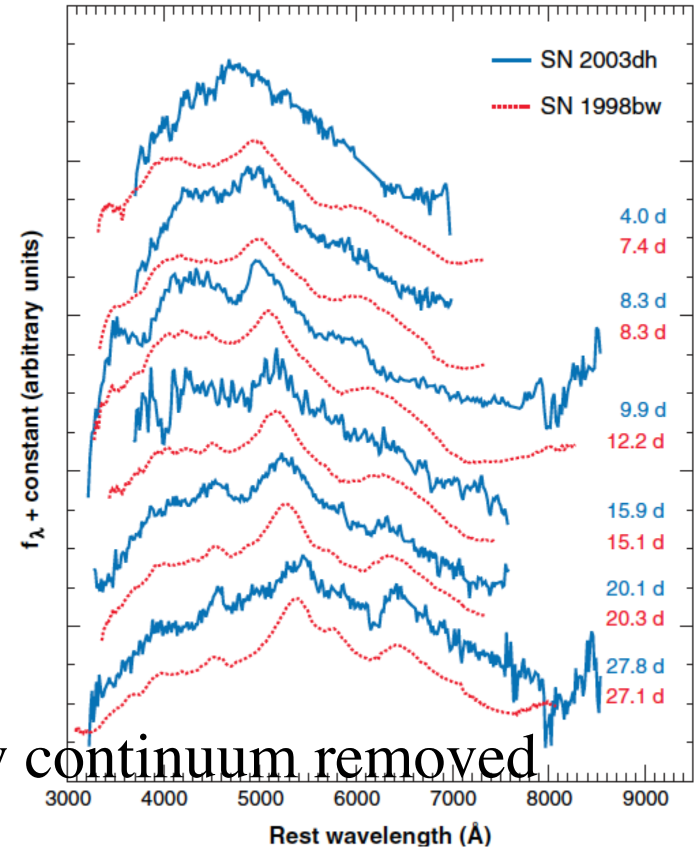
Energy:	~10^{51} ergs in γ-rays (~5° beams)
	≤ 10^{51} ergs in afterglow
	~10^{52} ergs in outflow
Distance:	<z>=2.3 (*Swift* average - long GRBs)
	11 Gyr light travel time
Jet Outflow:	highly relativistic (Γ > 100)
Variability:	msec time structure in prompt burst
Power source:	gravitational infall on new-born BHs

GRB 050904 z = 6.29 - Subaru

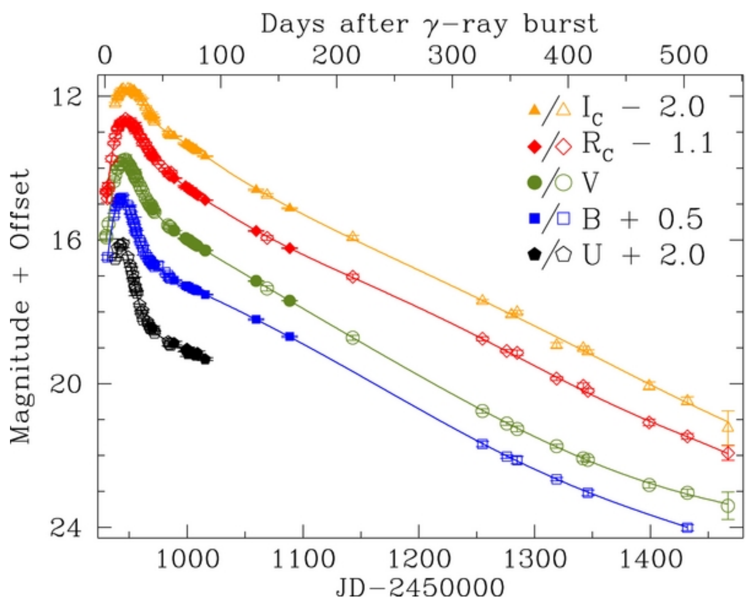


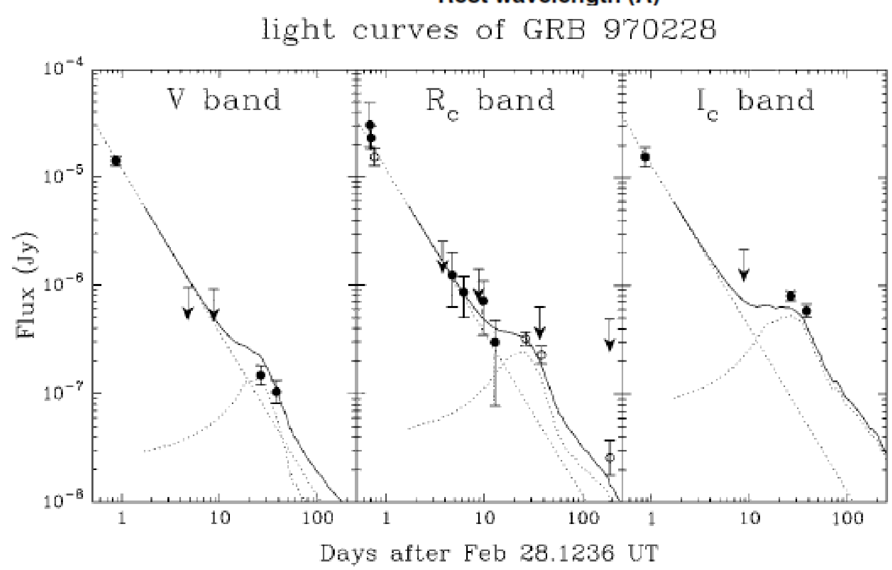
Long Burst Nature of Progenitor

- It is believed that the progenitor is amassive star based on the association of some (<10%) bursts with a peculiar type of SN (SNIbc, characterized by an absence of hydrogen, helium and silicon absorption lines (ARA&a44: 507 S.E. Woosley and J.S. Bloom)
- most z<1 hosts are dwarf galaxies with intense star formation, and the GRB locations track the brightest star formation regions in the hosts



Power law continuum removed



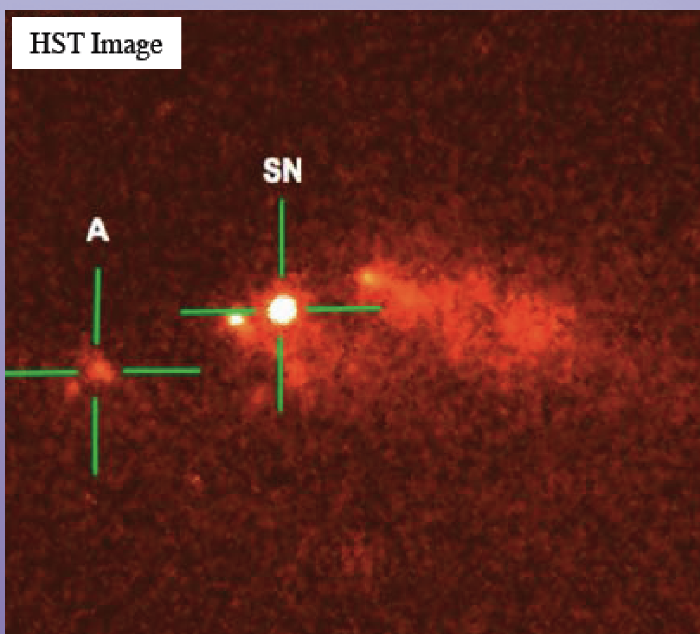


Nature of Supernov aAssociated with Long GRBs

GRB 100316D / SN 2010bh

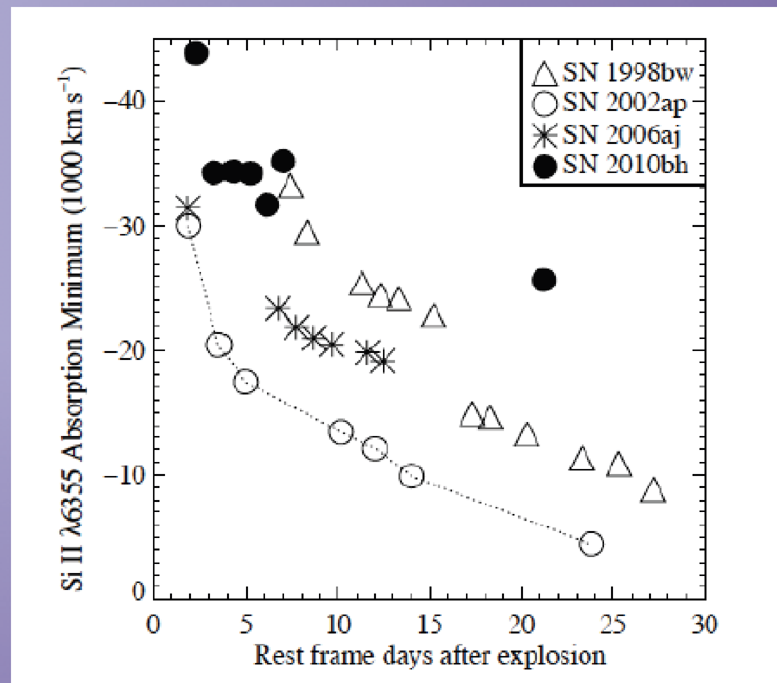
GRB duration > 12 minutes

$z = 0.059$



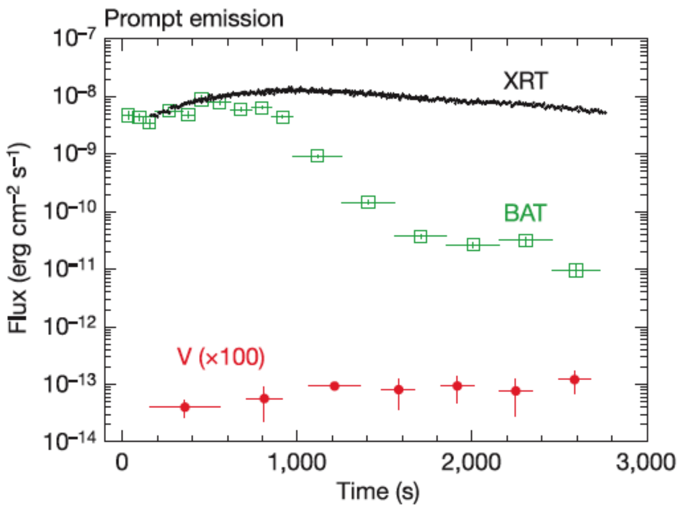
Starling et al. 2010

Highest velocity SN Ibc



Chornock et al. 2010

GRB 060218: GRB + Supernova



Super-long GRB ~35 minutes

BAT, XRT, UVOT during GRB

z = 0.033 d = 145 Mpc

SN 2006aj SN Ib/c hypernova

E_{iso} = few x 10^{49} erg - **underluminous**

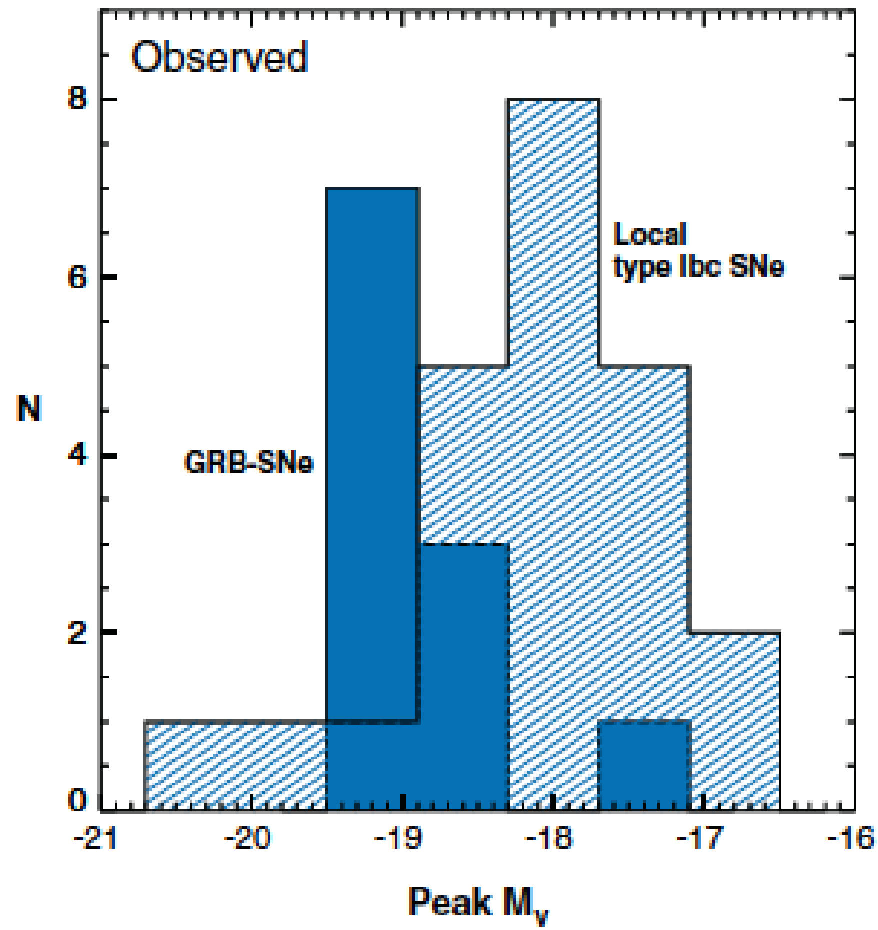
GRB and SN Rates

Event Type	Rates (1/Gpc^3-yr)
SN II	200,000
SN Ib/c	20,000
GRBs	100
Short GRBs (10° beaming)	~300

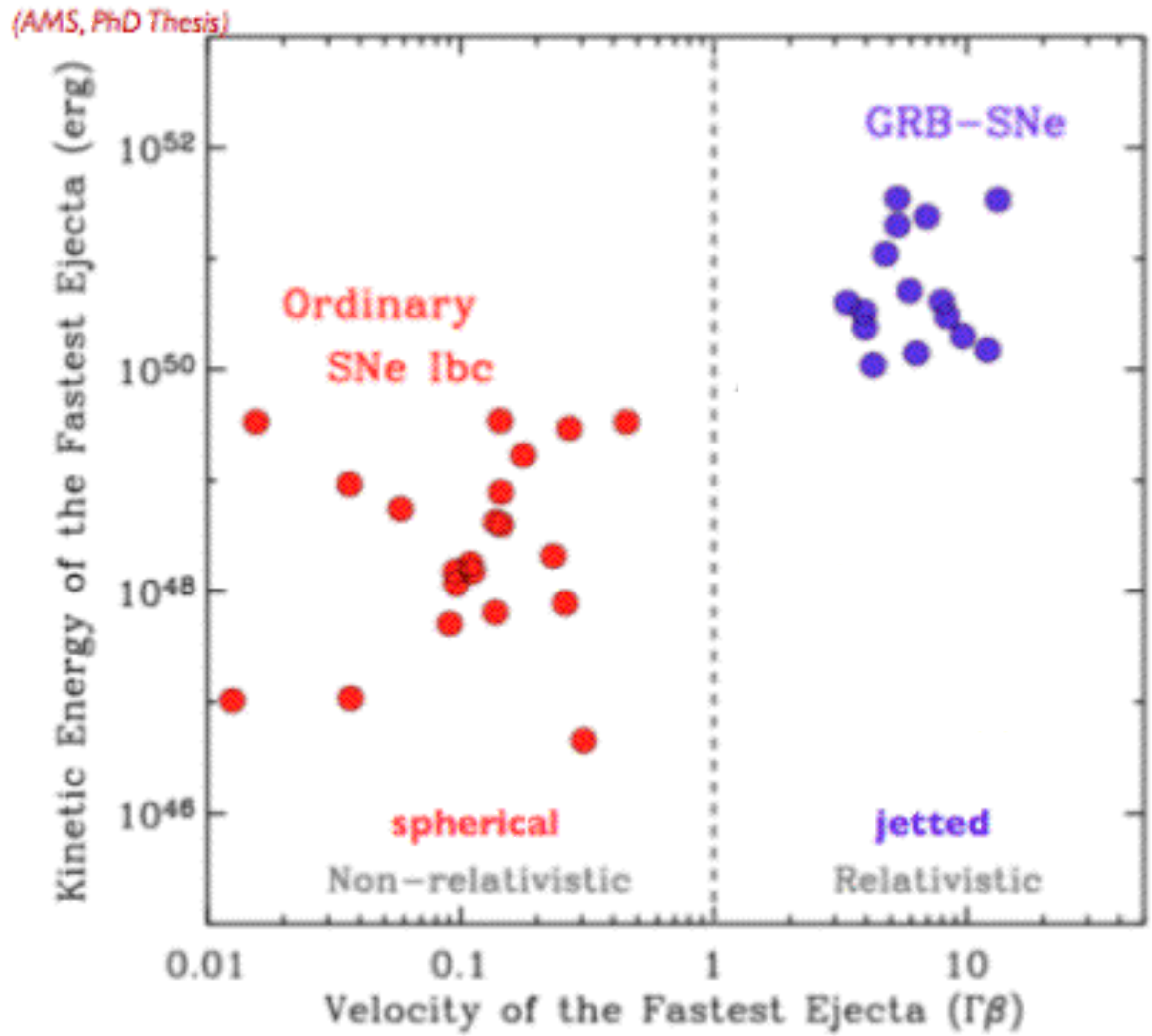
Campan aet al., Mazzali et al., Pian et al., Soderberg et al.

Nature of Progenitor

- ~0.2% of all SN produce GRBs (corrected for beaming)
- However only 5% of all SN are of type SNIbc
- Strong selection effects against detecting high z SN associated with GRBs
- Data are not inconsistent with most (all?) long GRBS being associated with SN- collapse of massive star (formation of aBH)
- problem: there are 'dark' bursts with no optical afterglow- seems to be due to dust in the host

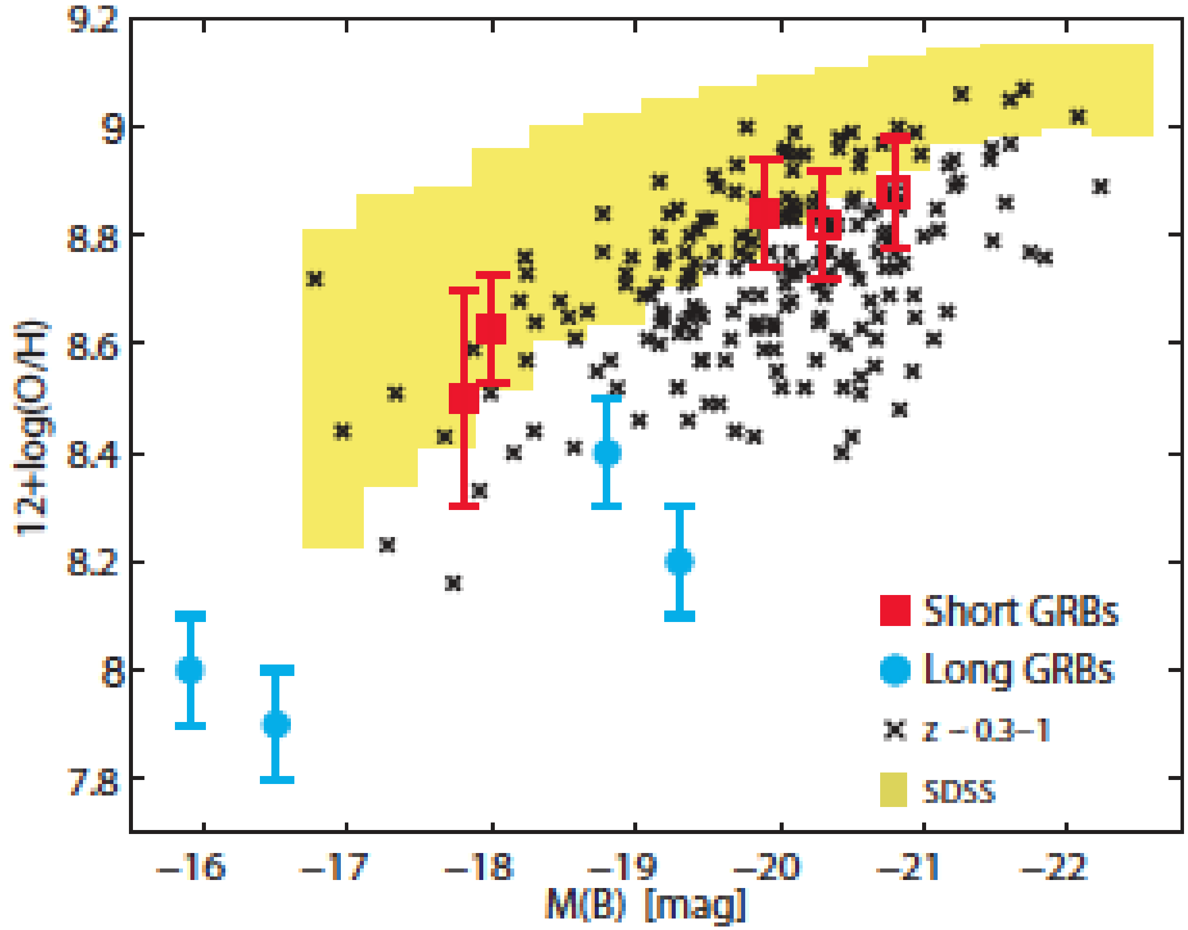


- Apparent energies much higher than 'normal' supernovae



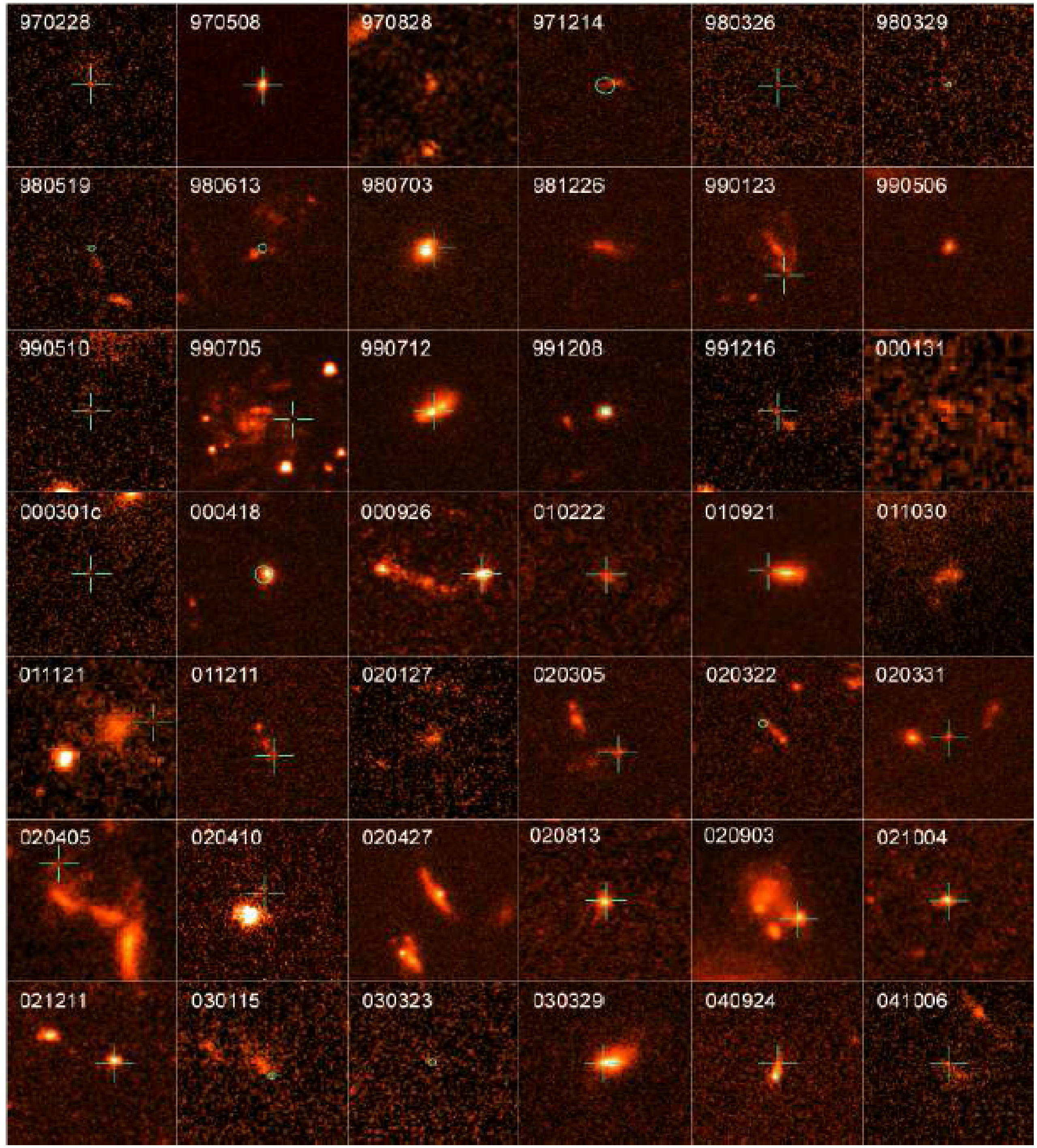
Where GRBS occur- clues to their origin

- Long GRBs occur preferentially in low mass and low metallicity galaxies at z<1
- Tend to occur in regions of high star formation rate (see next page)- consistent with origin in high mass stars

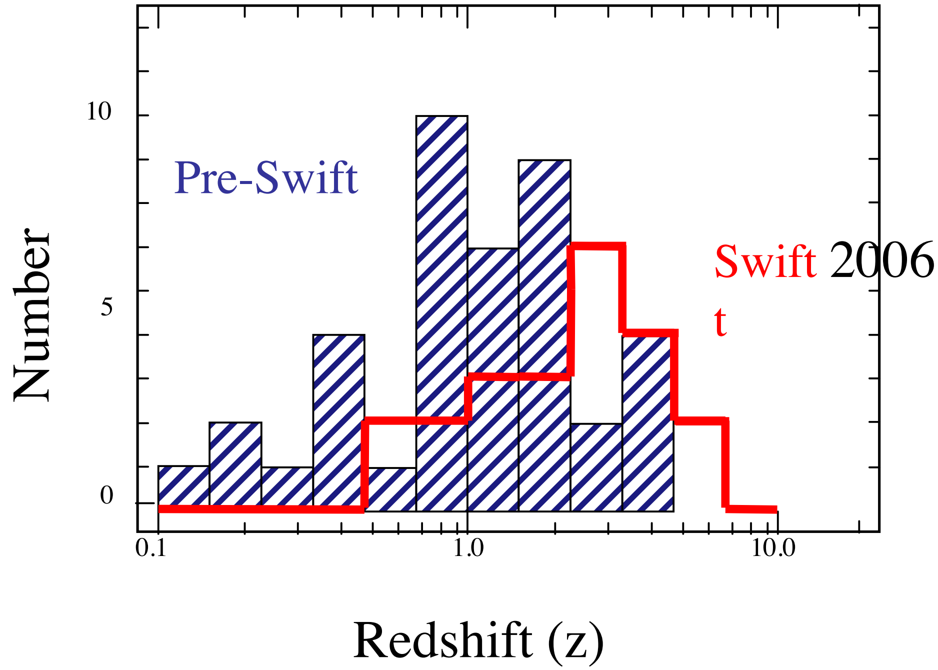


yellow band is distribution of luminosity and metallicity of 'random' galaxies at low z from SDSS

- HST images of GRB host galaxies (Fruchter et al 2006)- cross is position of GRB- tends to occur in bright spot in host galaxy.

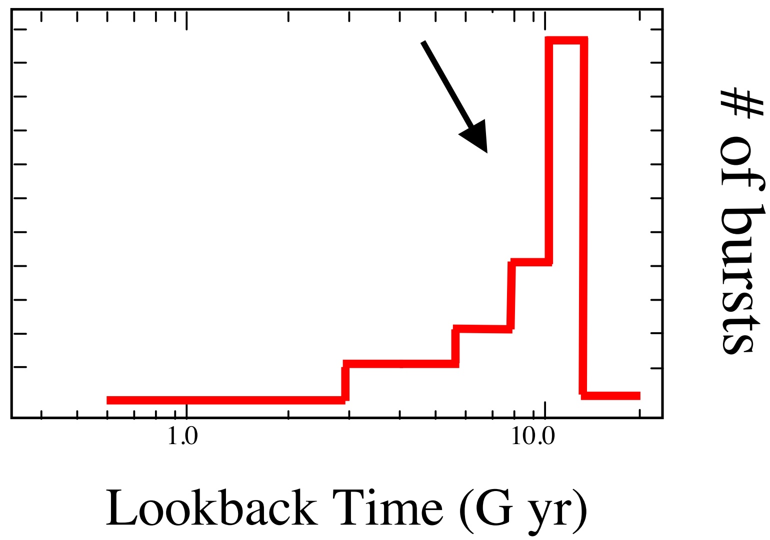


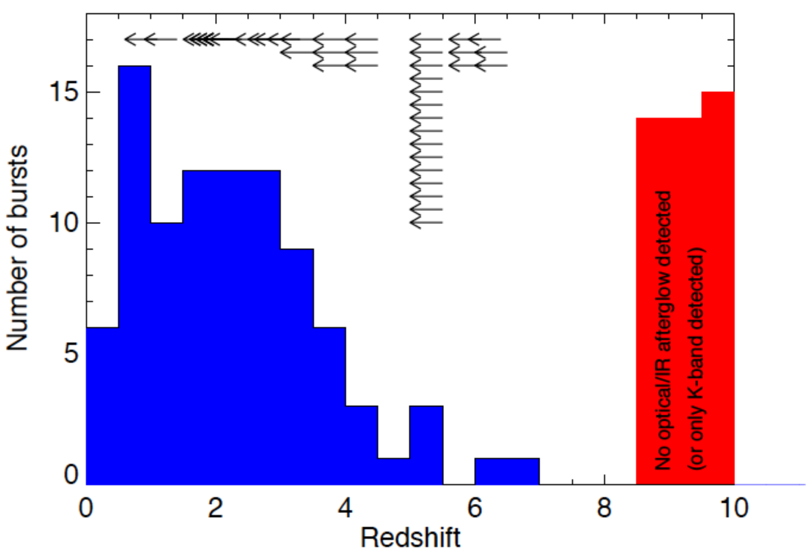
Redshift and Time Distributions



Average Redshift
- Pre-Swift: z = 1.2
- Swift: z = 2.7

Er aof GRBs



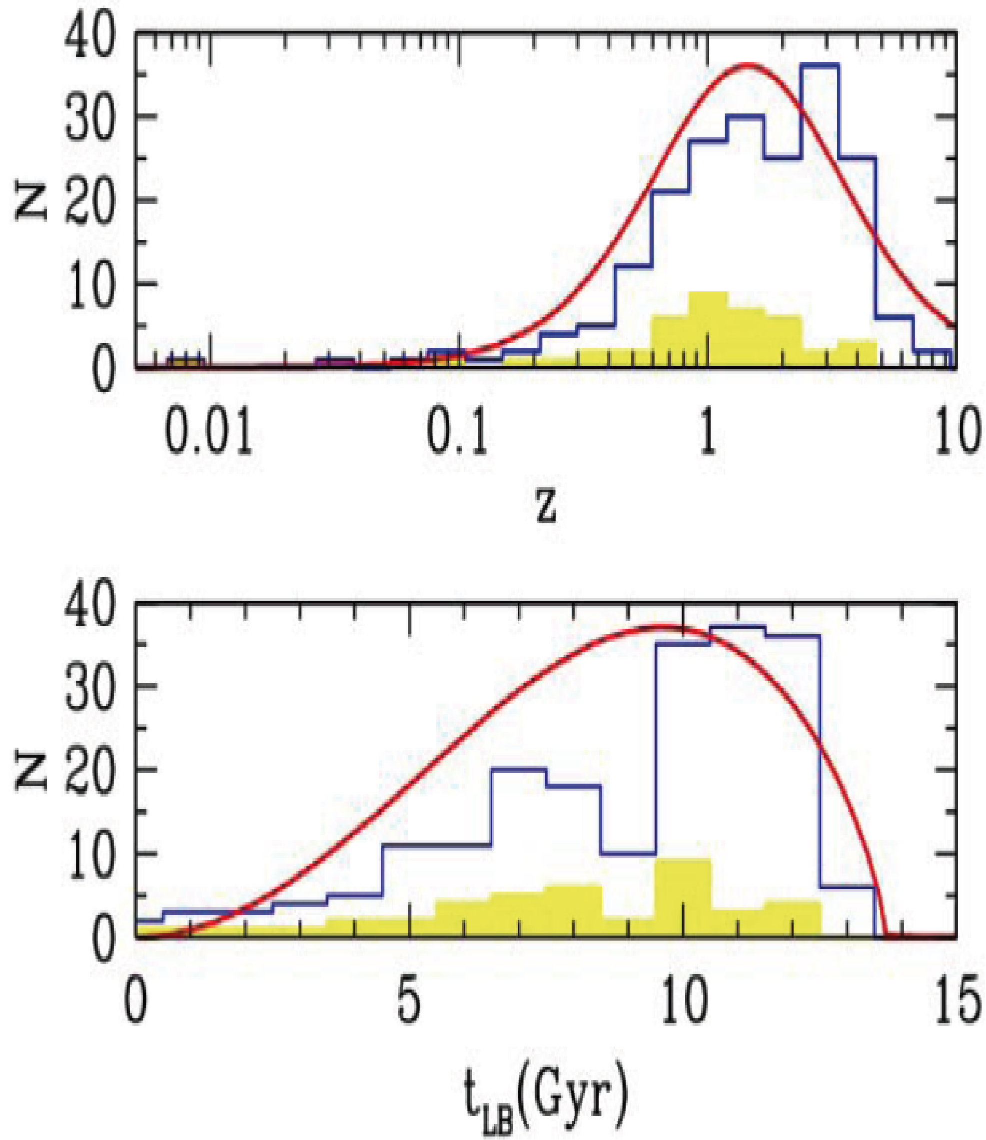


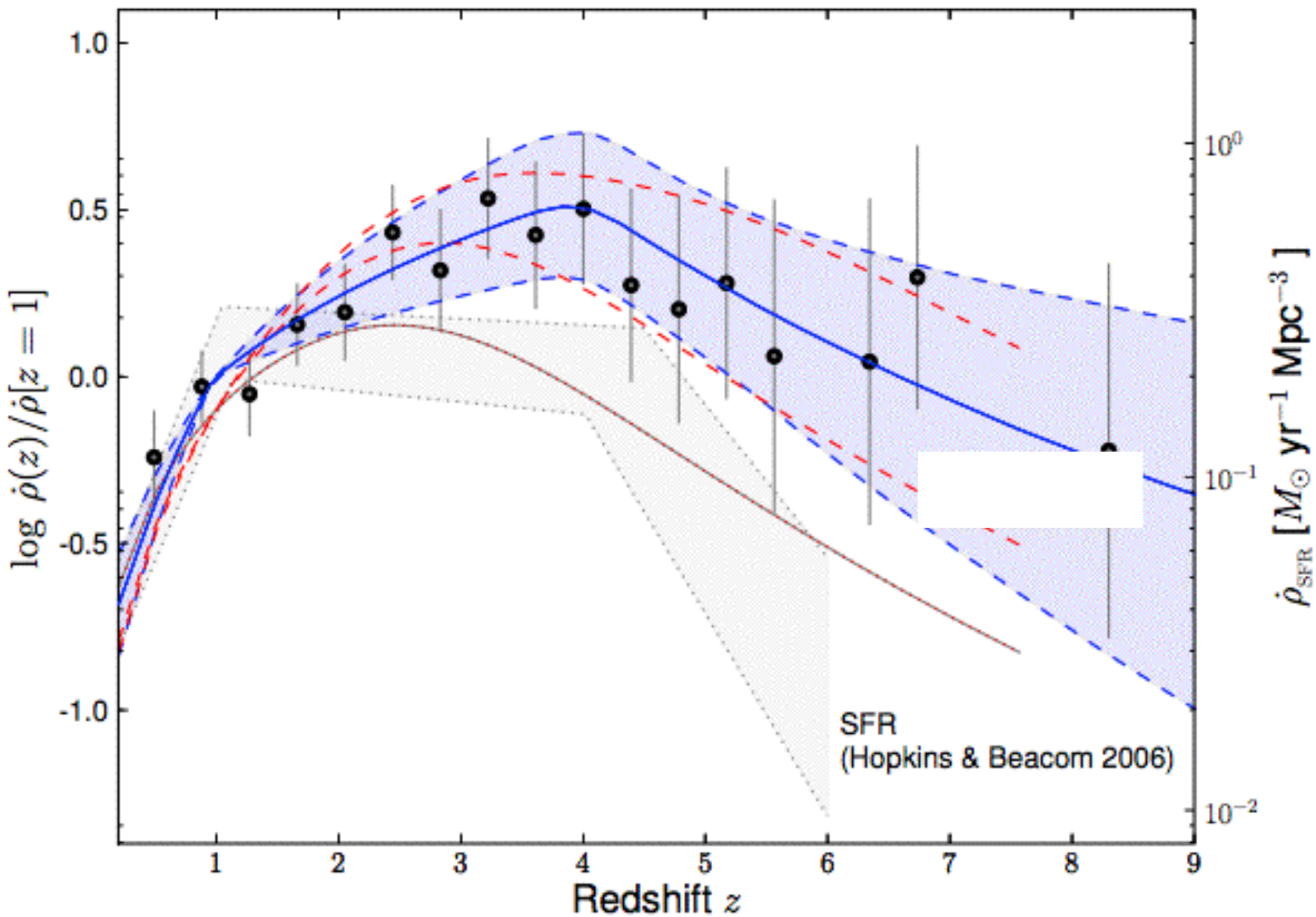
Gehrels & Norris 2006
Fynbo, Malesani,Jakobsson 2013

γ-ray Burst Rate Per Unit Time/Redshift

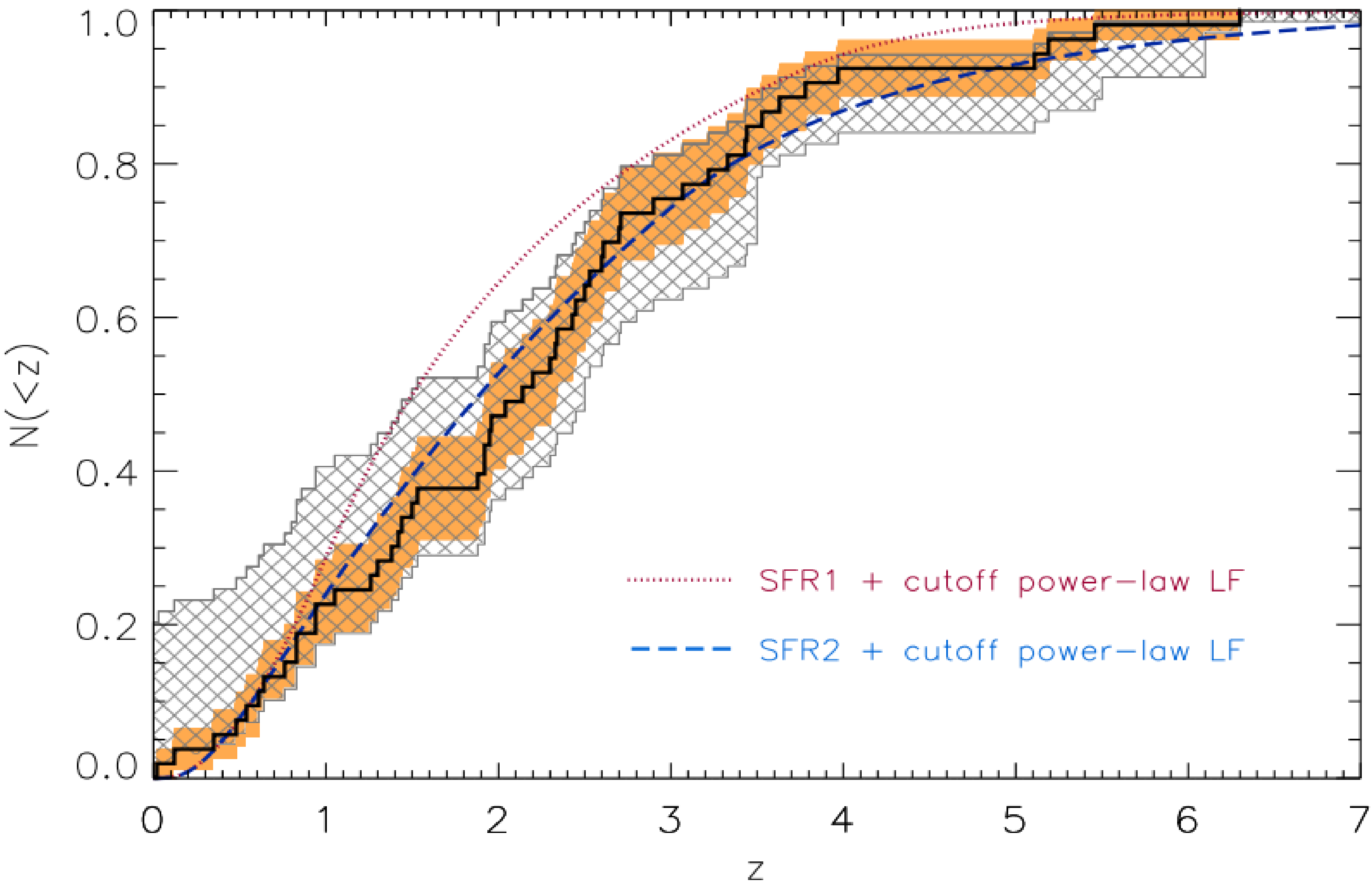
- Red line is a constant rate per co-moving volume- more bursts per unit volume at higher redshifts.
- Maybe related to the increase in star formation rate at higher redshifts-GRBs as a tracer of cosmic star formation rate.

yellow- short bursts
blue - long bursts





- Co-moving rate density of GRBs normalized to z=1
- compared to the star formation rate (Butler 2010)



- Do GRBs trace star formation in the universe?? Jakobsson et al 2012-Data imply that GRBs follow a cosmic SFR history that is significantly enhanced at high redshift compared to estimates from optical surveys.

- GRBs populate all types of star-forming galaxies including the most massive, luminous systems at z > 2
- But at redshifts z < 1.5 the overall GRB population has very few massive galaxies compared to an optical purely SFR selected galaxy sample

Fynbo, Malesani, Jakobsson 2013; Perley et al 2013

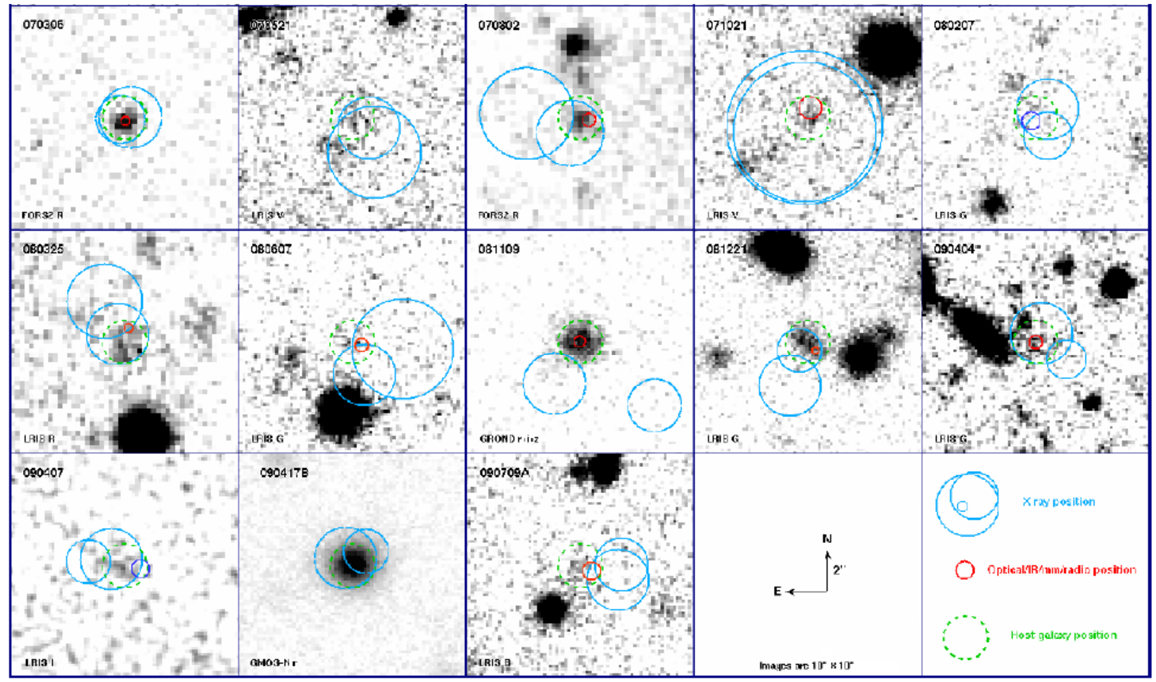
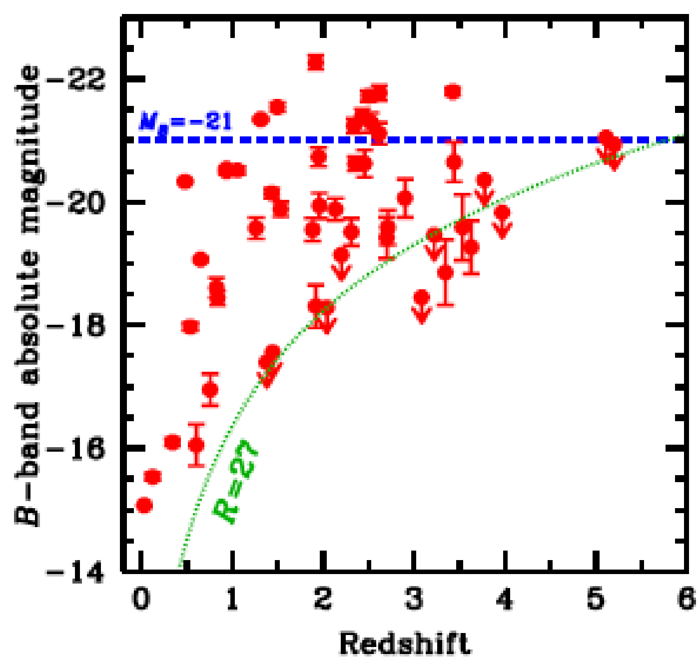


FIG. 4.— Optical mosaic, showing a 10″×10″ cutout of an image chosen from our optical imaging of each source (generally, the filter



fiducial luminosity of amassive galaxy

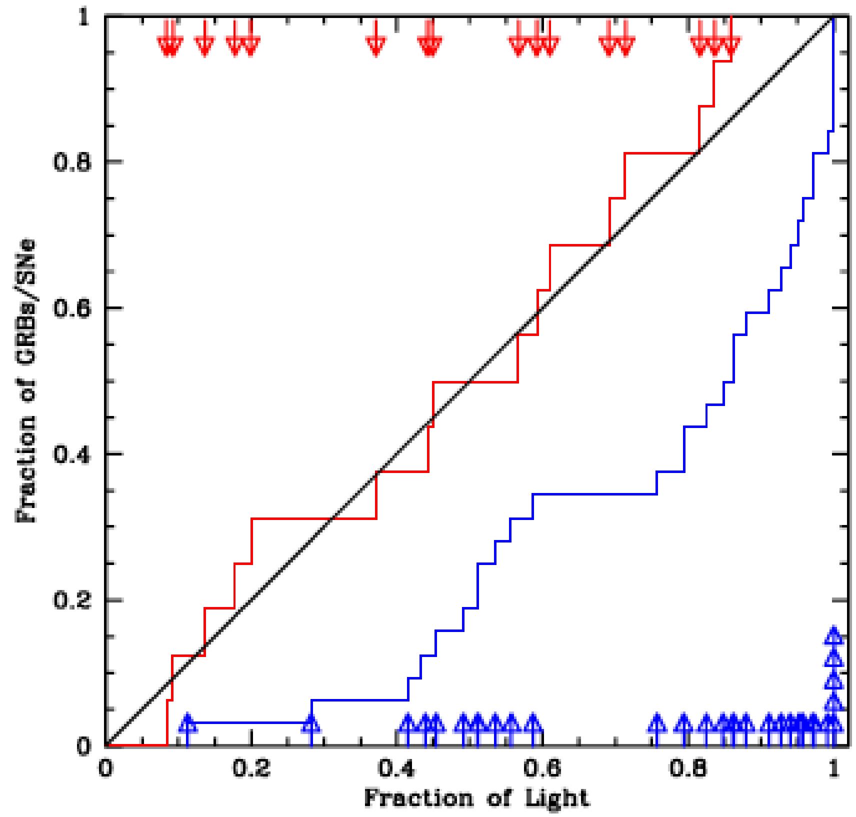
Comparison of Location of GRBs vs SN

- SN trace the light distribution in galaxies, GRBs are more concentrated

long γ-ray bursts are

- more concentrated on the very brightest regions of their host galaxies than core-collapse supernovae.
- the host galaxies of the long

γ-ray bursts are significantly fainter and more irregular than the hosts of the core-collapse supernovae and more metal poor



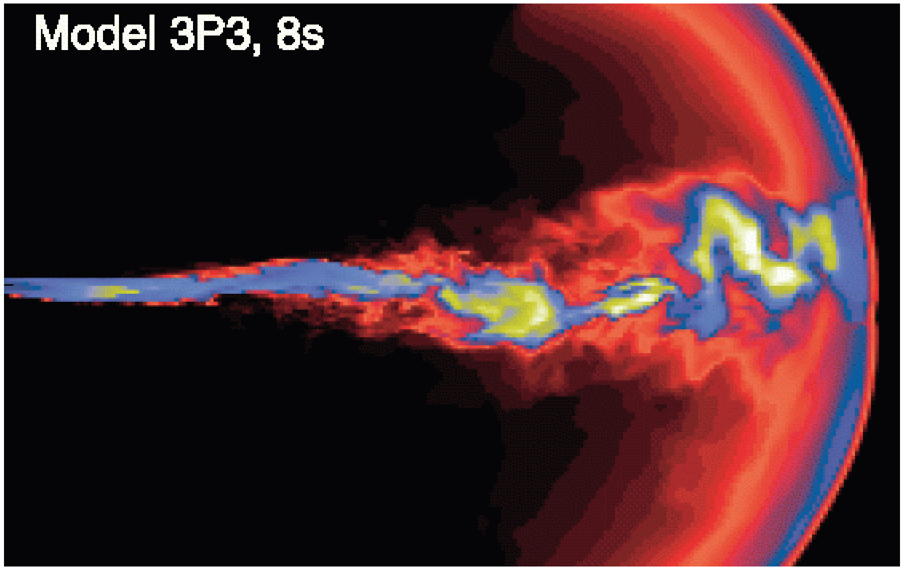
Long Bursts

- amassive (> 40 M_{sun}) star reaching the end of its life,
  - the explosion is even more extreme, with an energy output ~ 100 times greater than 'standard' type II. - a 'hypernovae'
  - . The GRB itself is likely to be formed when a narrow jet of highly relativistic plasma erupts from the collapsing star; the jet is most likely a by-product of the rotation of the star.(Zhang, Woosley & Heger, 2004, ApJ 608, 365)

SN rate is ~6/sec (all sky);
GRB is ~0.02/sec- 1/300 of SN produce aGRB

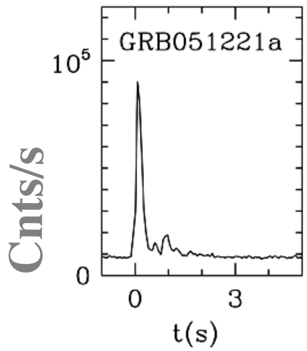
theory says need :

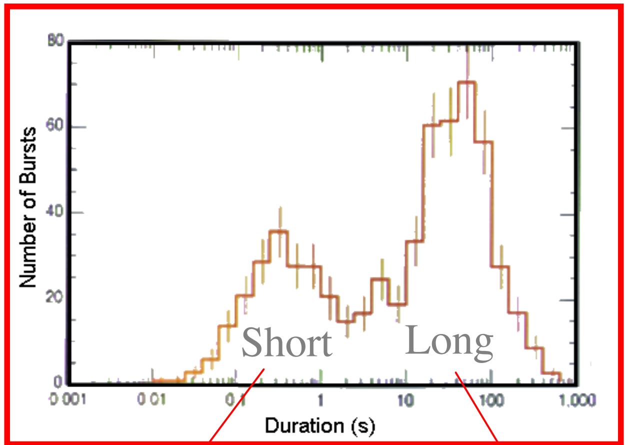
high mass,
high rotation rate ,
low metallicity,
high rate mass-loss



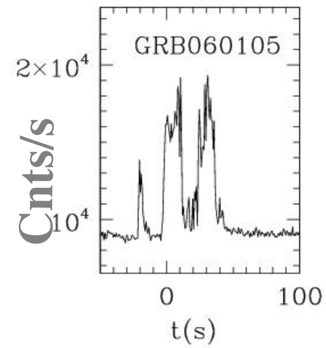
Short vs Long GRBs

Short GRB

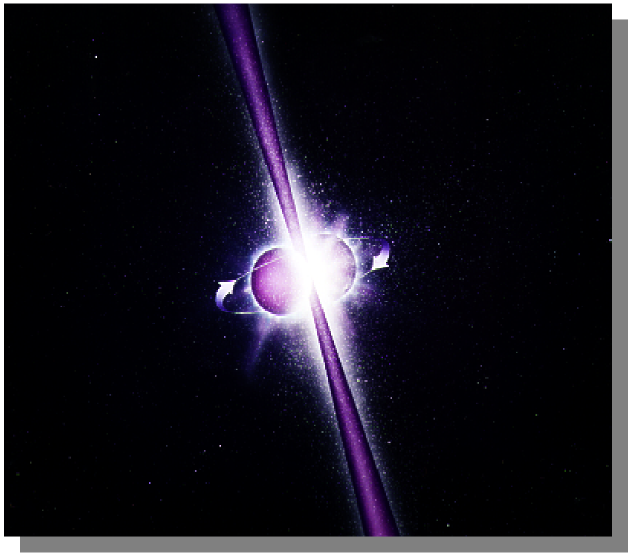


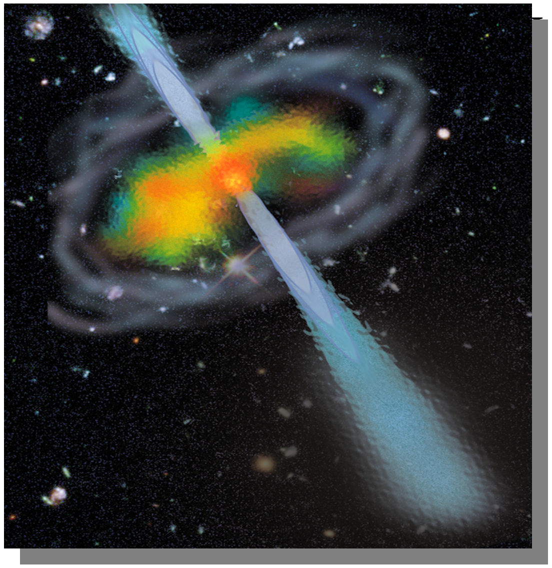


Long GRB



Short GRBs in non-SF elliptical galaxies

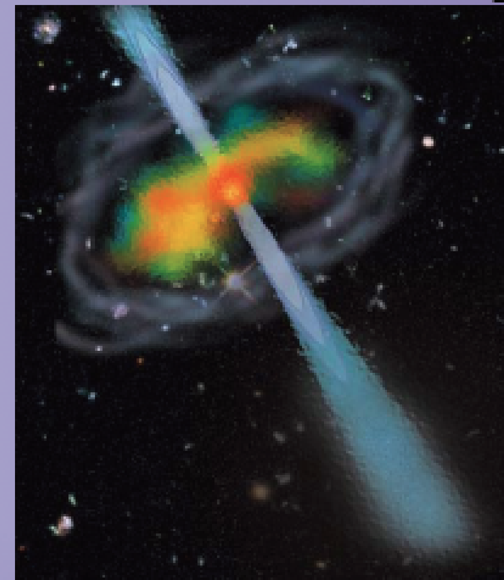




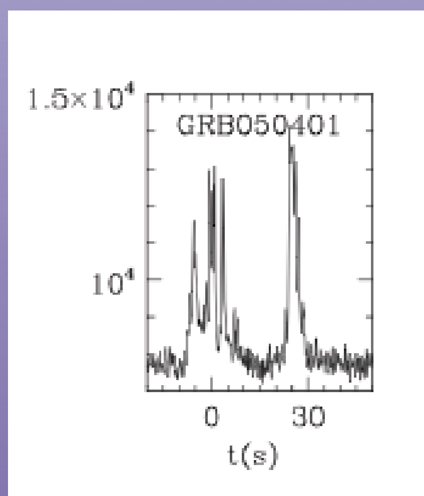
Long GRBs in SF galaxies

Short Bursts
Neutron Star Merger

Long Bursts
Collapsar - Massive Star Explosion



short time
structure
$\Rightarrow$ small size



Black Hole Energetics

$$\textbf{Energy} = \frac{GMm}{r}$$

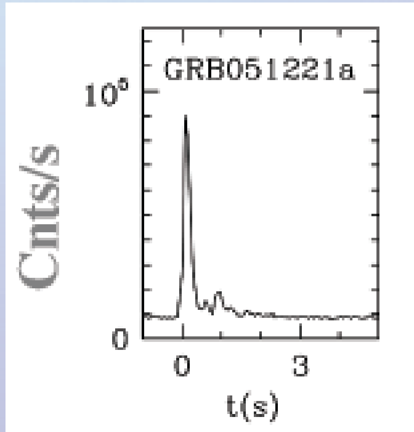
$$\approx mc^2 \qquad \text{for } r = R_{BH} = \frac{2\,GM}{c^2}$$

$$= 3\text{x}10^{54} \text{ ergs for } m=3M_{\odot}$$

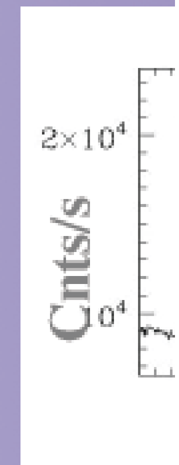
Gehrels

Short vs Long GRBs

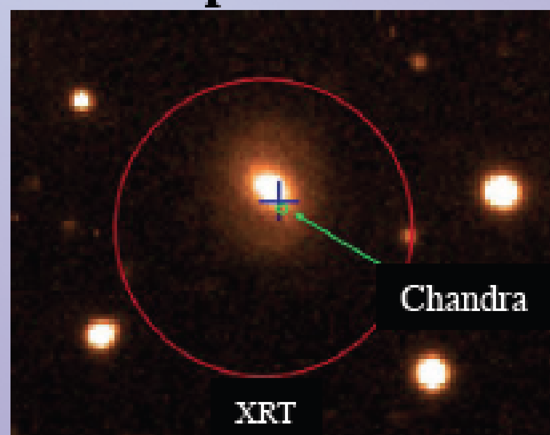
Short GRB



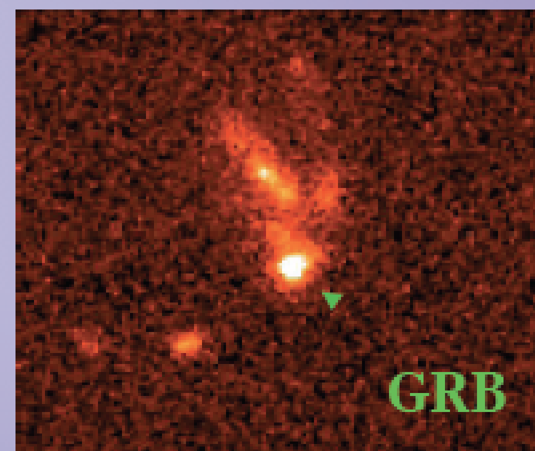
Lo



GRB 050724 - *Swift*
elliptical host

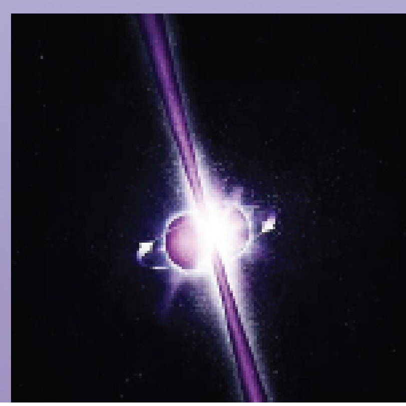


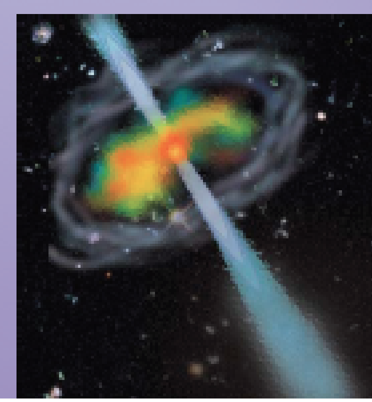
GRB 990123 - *SAX*
SF dwarf host



In non-SF
and SF galaxies

No SNe detected





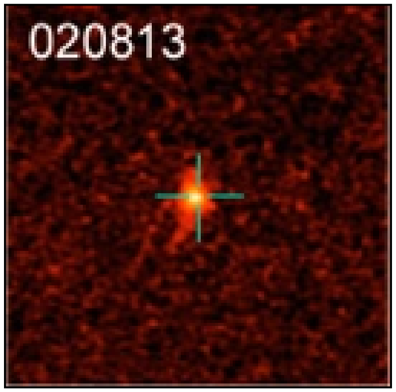
I
ga

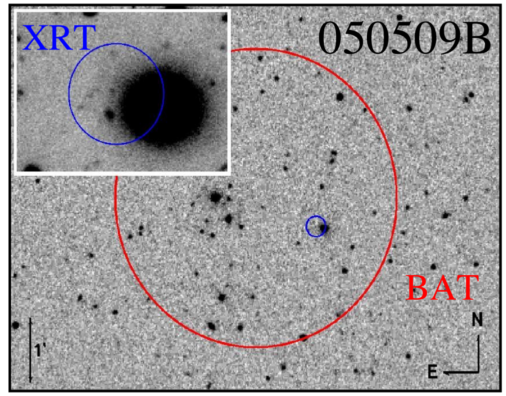
Accom
S

Long GRBs   Short GRBs

SF
irregulars

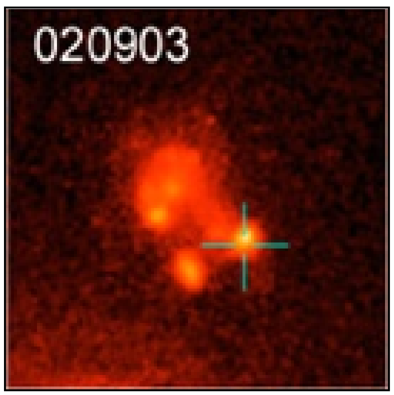
Fruchter
et al.

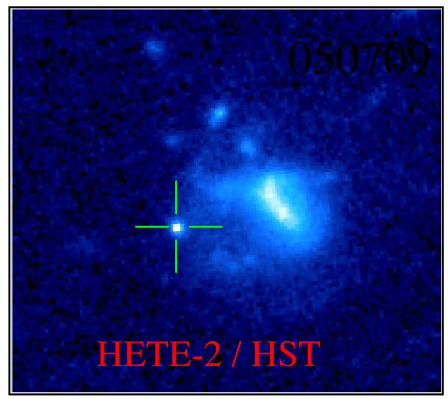




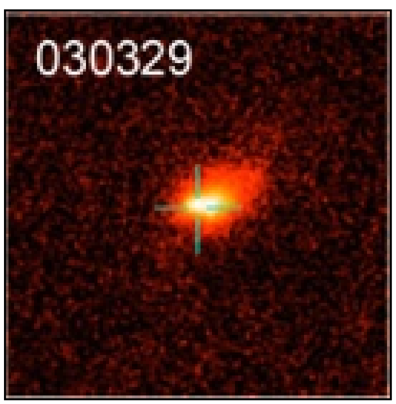
cD elliptical

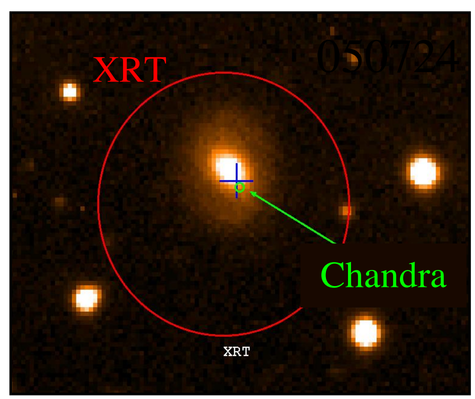
SFR < 0.2 M_O yr^{-1}
z = 0.225





SF galaxy
with offset
z = 0.161





elliptical

SFR < 0.02 M_O yr^{-1}
z = 0.258

Nature of Progenitor of Short GRBs

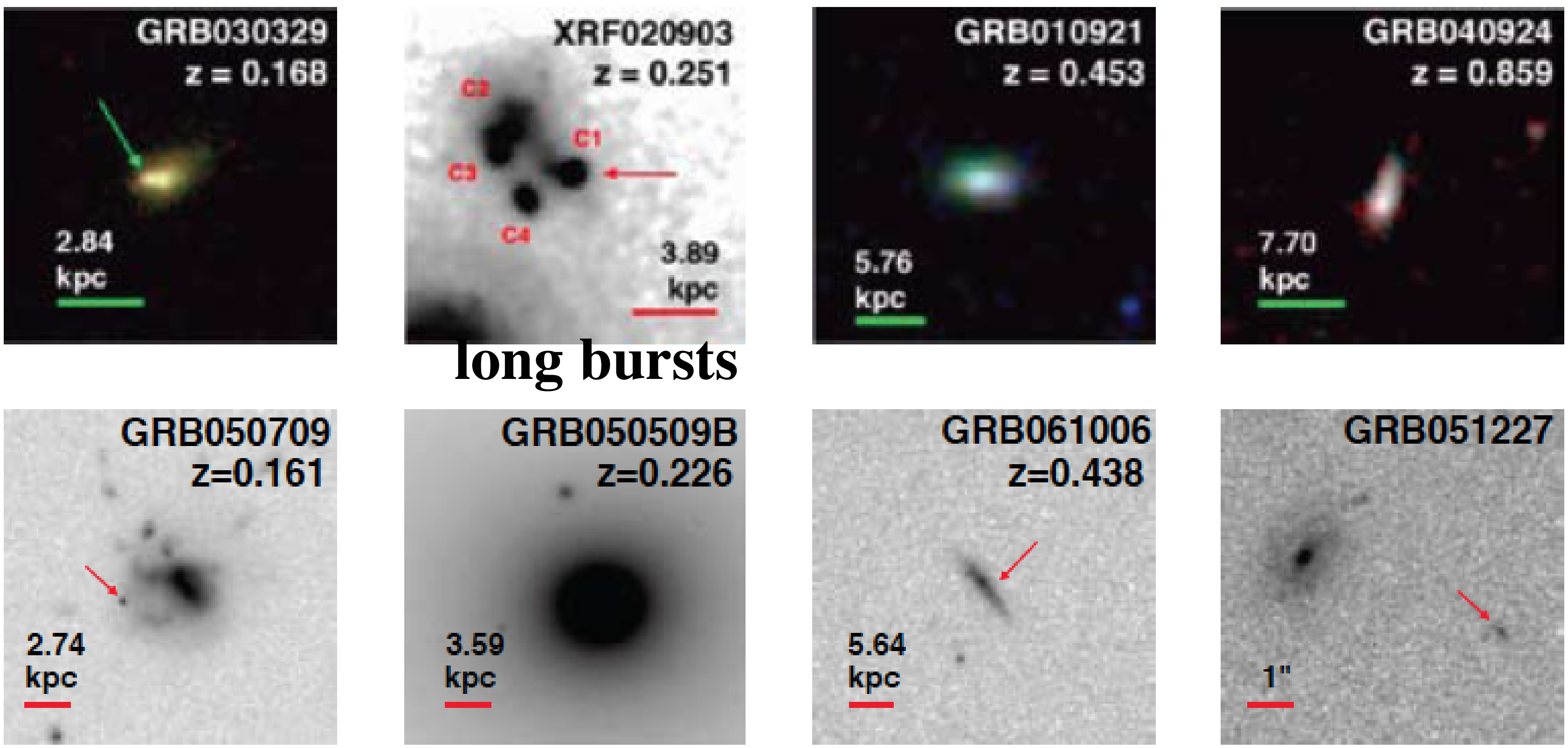
Short bursts not associated with supernovae to deep limits (Hjorth et al. 2005a, Fox et al. 2005)

Redshift distributions of the two populations are different

Nature of host galaxies is different, burst location often in non-star forming region

both star-forming and early-type galaxies has led to analogies with type Ia supernovae

May have much high volume density than long bursts



short bursts

Short GRBs Compared to Long GRB

52 short GRBs detected by Swift

Lower Redshifts

$< z > \; = \; 0.4$ short

$< z > \; = \; 2.3$ long

Weaker Afterglows

$< F_X > = 7x10^{-10}$ erg cm^{-2} s^{-1} short

$< F_X > = 3x10^{-9}$ erg cm^{-2} s^{-1} long

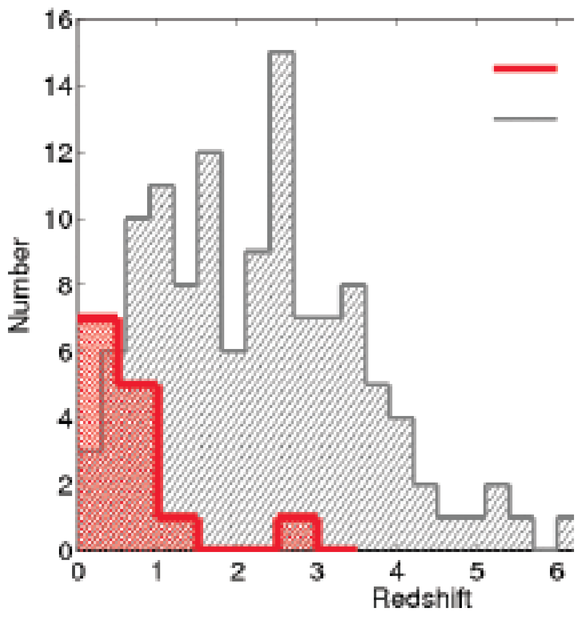
Less Jet Collimation ?

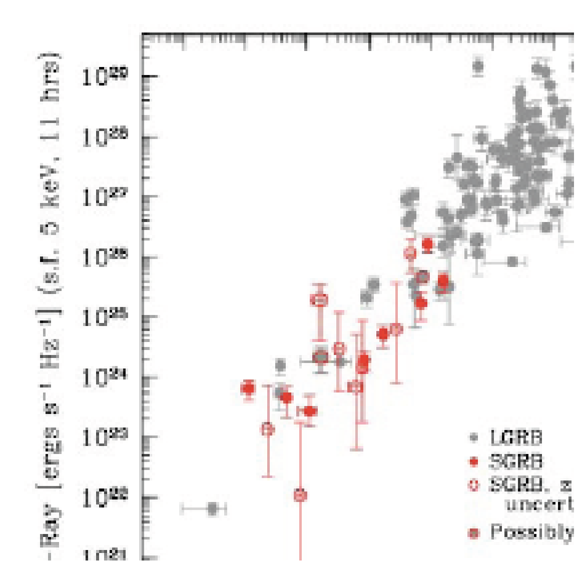
~ 15° (wide spread) short

~ 5° (wide spread) long

Less Total Energy

~ 10^{49} ergs short





Short Bursts- Progenitor

- One of the ideas is that short bursts are the result of the merger of 2 neutron stars (B. Paczynski 1991)
- Right now theoretical, but no observational support
- Based on their observed properties
- SGRBs are cosmological in origin (z > 0:1)
- have a beaming-corrected energy scale of ~10^{49}–10^{50} erg
- lack associated supernovae
- occur in a mix of star-forming and elliptical galaxies
- have a broad spatial distribution around their

hosts, with some events offset by tens of kpc

and are located in low-density parsec-scale environments

The confluence of these characteristics provides support to the popular model of compact object (CO) mergers (Stone et al 2013)

- Kicks imparted to NS at birth can produce space velocities of 100's of km/sec- merger can occur far from birth site
- Gravitational waves remove orbital angular momentum and energy from a NS-NS or black hole--neutron star (BH-NS) binary
- driving it to inspiral and merge.
- In the merger, the NS may tidally disrupt and form a hot accretion disk with the collimated magnetic fields necessary to launch jets, providing the central engine for a short gamma-ray burst (GRB).
- Not clear what fraction of mergers produce short GRBs

Short GRBs Compared to Long GRB

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$< z > \; = \; 2.3$ long

Weaker Afterglows

$< F_X > = 7 \times 10^{-10}$ erg cm^{-2} s^{-1} short

$< F_X > = 3 \times 10^{-9}$ erg cm^{-2} s^{-1} long

Less Jet Collimation ?

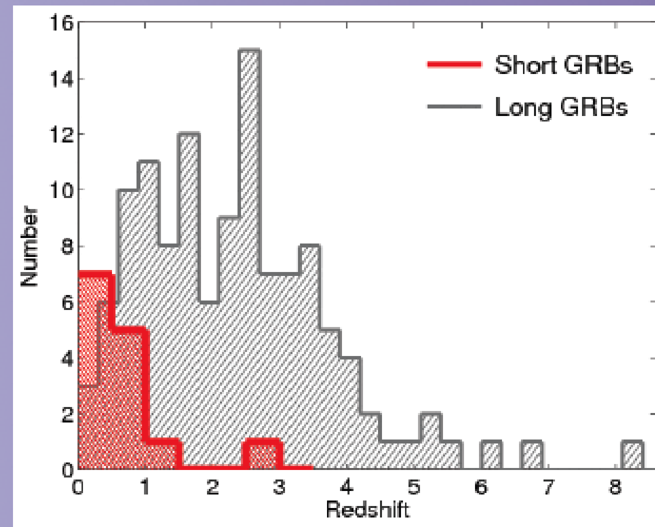
$\sim 15^\circ$ (wide spread) short

$\sim 5^\circ$ (wide spread) long

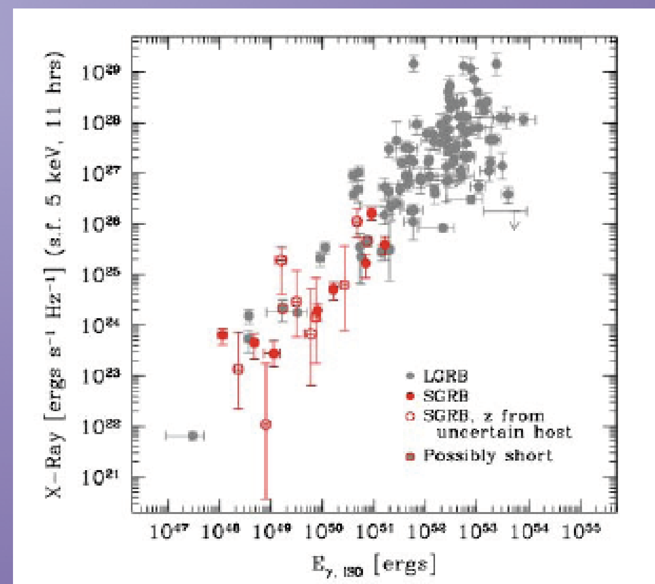
Less Total Energy

$\sim 10^{49}$ ergs short

$\sim 10^{51}$ ergs long



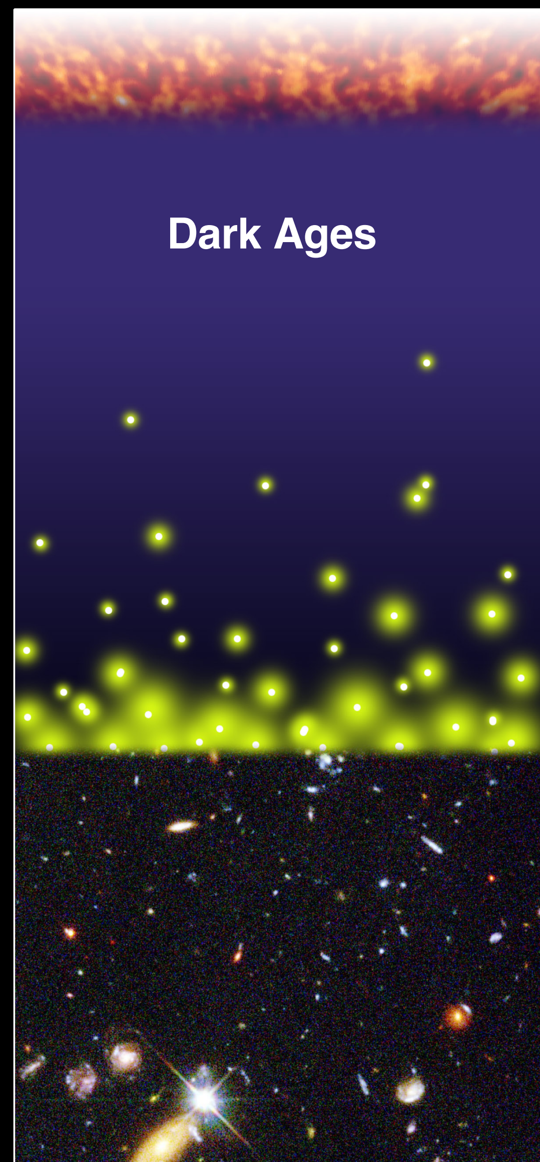
Berger 2009



Nysewander, Fruchter & Pe'er 2009

History of the Universe

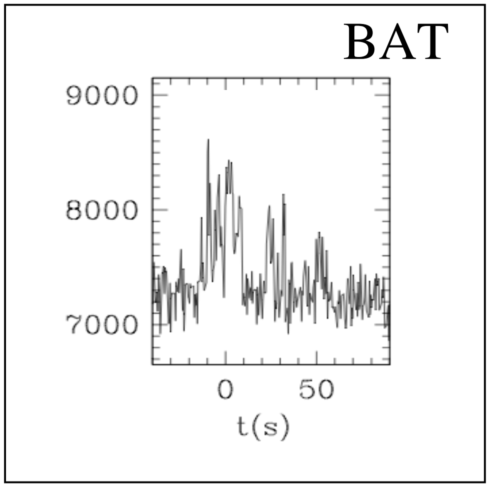
Redshift	Time	
1000 -		Big Bang - Hot ionized gas
100 -	17 Myr	The Universe becomes neutral and opaque
10 -	480 Myr	Stars and galaxies form Reionization starts
8.2 (GRB 090423)		Cosmic Renaissance Dark Ages end
5 -	1.2 Gyr	Reionization complete
		Galaxies evolve
0.5 -	8.7 Gyr	Solar System forms
0 -	13.7 Gyr	



er, Caltech

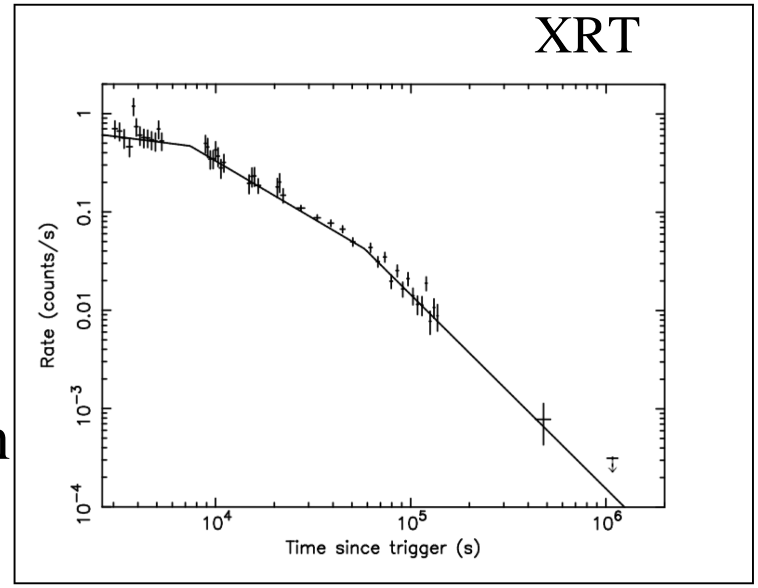
Djorgovski et al.

GRB 050505

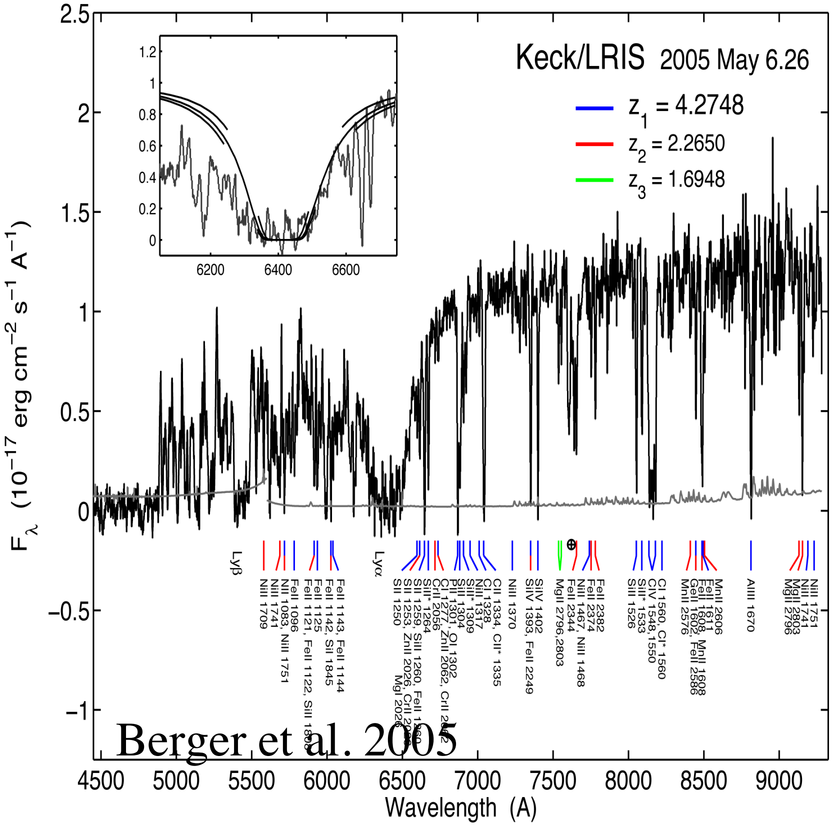


z = 4.27
Duration = 60 s

Bright afterglows allows high resolution optical spectroscopy

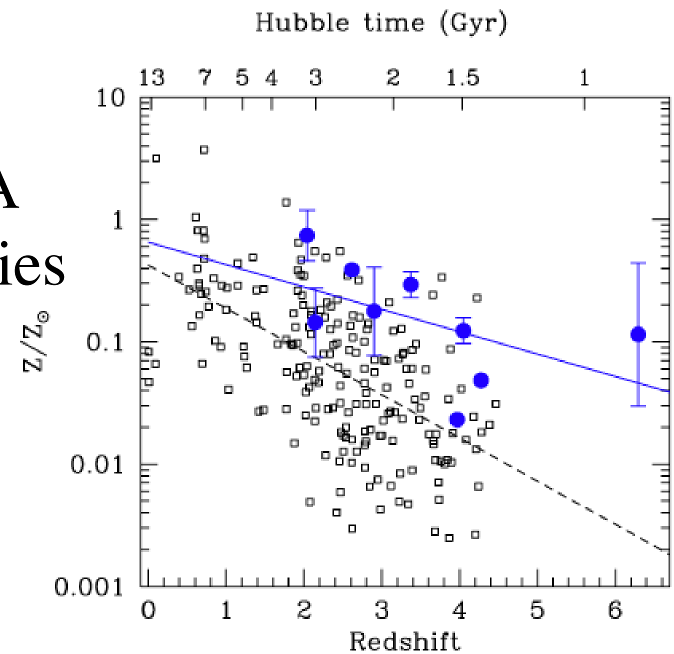


Hurkett et al. 2005



Berger et al. 2005

DLA studies



Savaglio 2006

GRB Effect on Host Galaxy

- GRB sightlines probe the tiny regions with high surface density that are associated with star-forming regions in high z galaxies (Prochask a2011)
- As the afterglow fades, the UV excitation rate decreases and the majority of excited levels depopulate. Detailed analysis(the closer is the gas to the GRB, the higher are the column densities of the excited levels) indicates the gas lies at 100pc to 2 kpc. (Vreeswijk et al. 2007, D'Eli aet al. 2009a),
- The values are 0.3-6kpc away for this absorption - e.g. the GRB effects gas this far away!
- Press Release 'Gamma-ray burst 'hit Earth in 8th Century- http://www.bbc.co.uk/news/science-environment-21082617
- some old cedar trees in Japan had an unusual level of carbon-14.
- In Antarctica, there was a spike in levels of of beryllium - beryllium-10 (an - in the ice.
- Both anomalies occurred in 774-775AD- consistent with GRB 1-4kpc away (Hambaryan and Neuhauser et al 2012 MNRAS)

Abstract of Hambaryhan and Neuhauser 2012

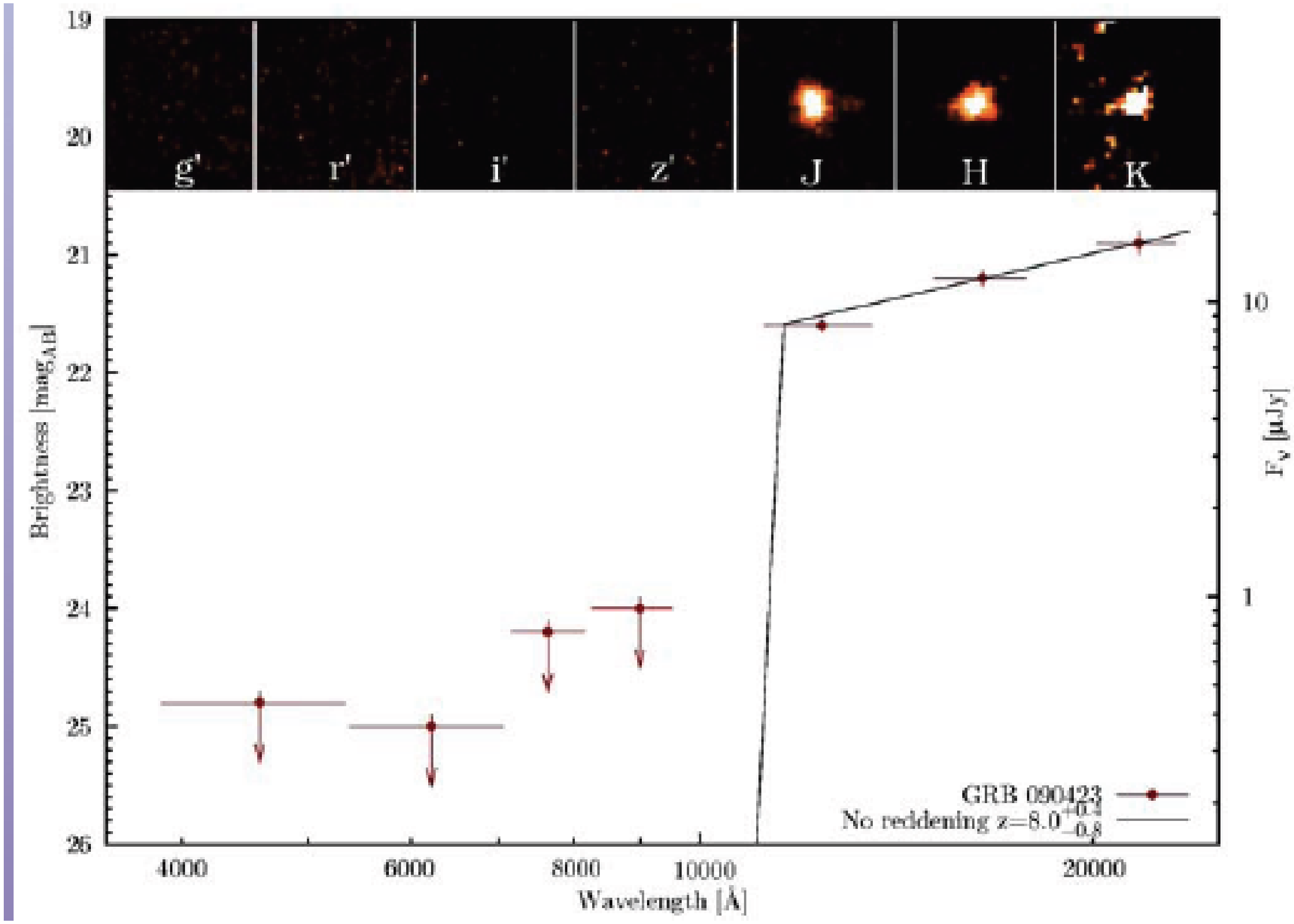
In the last 3000 yrs, one significant and rapid increase in the concentration of ^{14}C in tree rings was observed ; it corresponds to a γ-ray energy input of 7×10^{24} erg at Earth within one year AD 774/5 . A normal supernova and or solar or stellar flare are unlikely as cause , so that the source remained unknown . Here, we show that a short gamma-ray burst (GRB) in our Galaxy is consistent with all observables : such an event is sufficiently short and provides the necessary energy in the relevant spectral range of γ- rays. Its spectral hardness is consistent with the differential production rates of ^{14}C and ^{10}Be as observed. The absence of reports about a historic sighting of a supernova in AD 774/5 or a present-day supernova remnant is also consistent with a short GRB . We estimate the distance towards this short GRB to be <4kpc, sufficiently far away, so that no extinction event on Earth was triggered . This is the first evidence for a short GRB in our Galaxy .

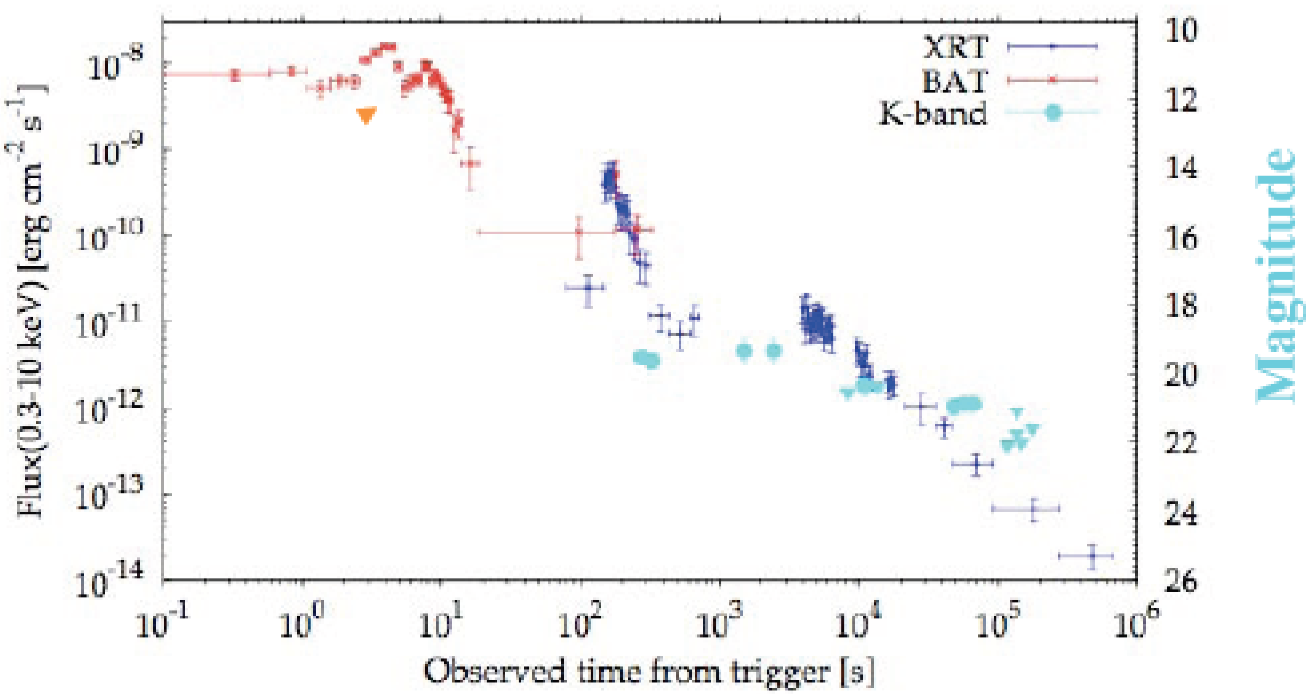
The ^{14}C was detected in ice cores in Antarctica

Photometric Redshift

- Opacity at short λ due to Intergalactic medium, host galaxy or intervening galaxy- need to go into near IR to get spectroscopic redshift

z~8.2 from Lyman limit





GRB 090423
z = 8.2

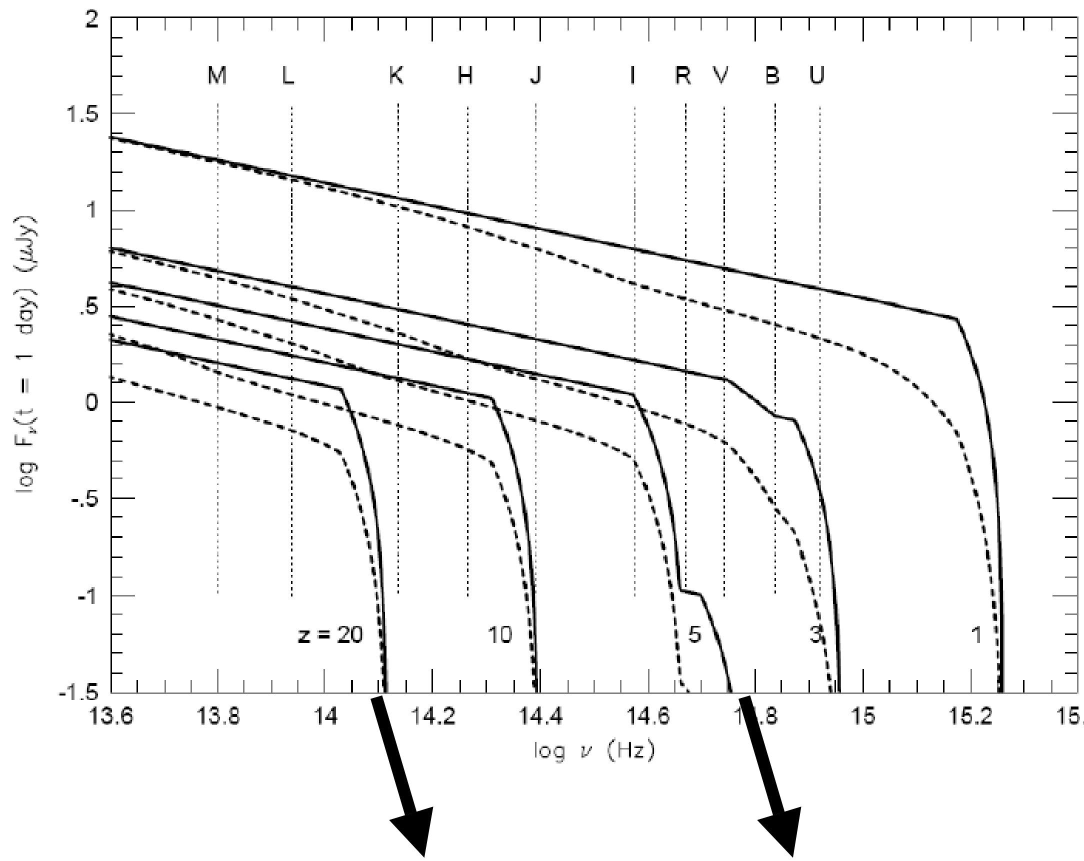
K ~ 32 for Milkyway @ z = 8

Salvaterra et al. 2009

Detecting GRBs at Very High Redshift

- Factors decreasing spectral energy flux:
  - 1. Distance away
  - 2. Redshift
- Factor increasing spectral energy flux:

  Time dilation
  - Space between GRB and observer decreases and amount of energy release over an hour is received in less time
- Effects ~cancel- little or no decrease in flux with redshift



cutoff due to Lyman limit at different redshifts

Use of GRBs for Cosmology

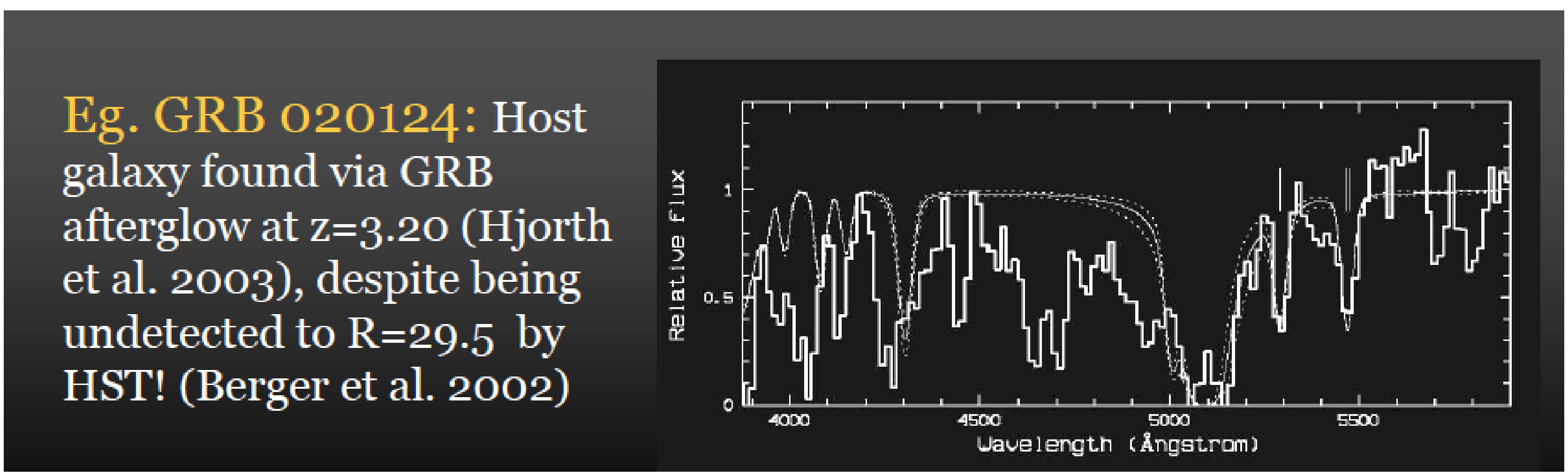
- Identify and study high redshift galaxies. Including many which are too faint to study directly.
- Backlight for absorption line studies.

  Power law continuum.

  Probes directly into parent galaxy ISM, including the locality of the progenitor itself.

When afterglow disappears, host (or other absorption systems) can be studied directly

Tanvir 2009



Delayed HE Emission - GRB 0905

Short GRB

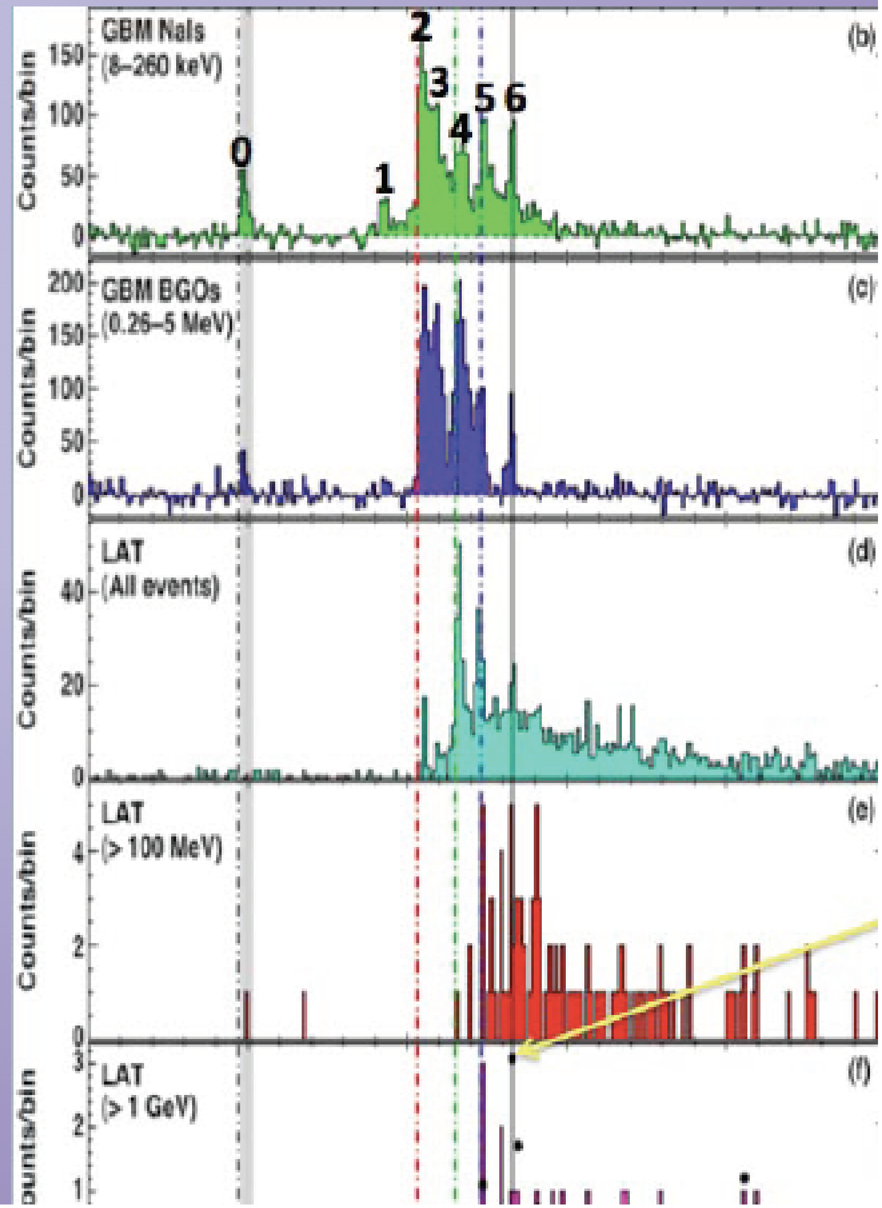
$z = 0.903$ 7.3 Gyr light travel

Extended emission

Lag in MeV/GeV onset

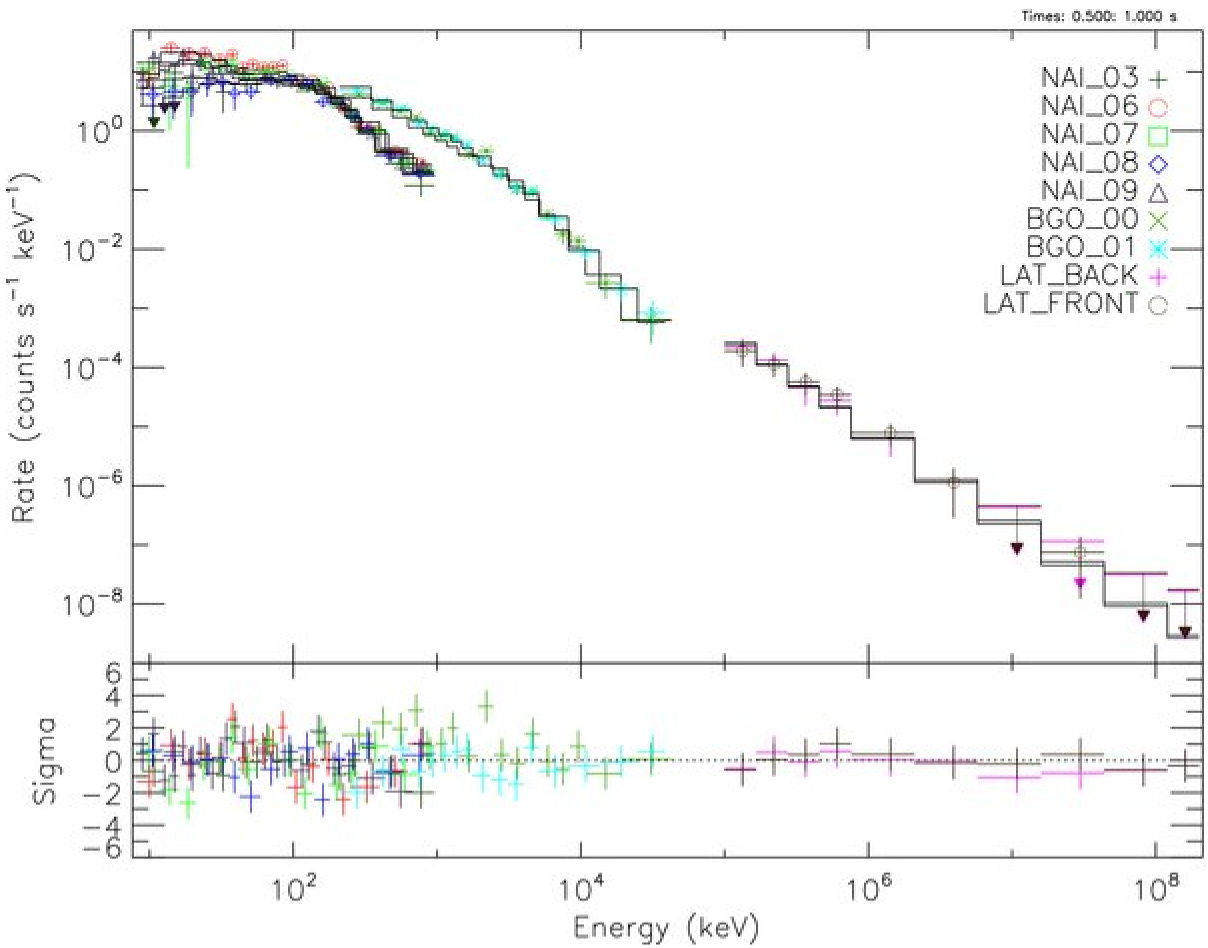
Lorentz factor (jet) > 1000
(γγ absorption argument)

Lorentz invariance violation
limits - no observed dispersion
$\Delta c/c < 10^{-16}$
Quantum Gravity mass scale
above Planck mass



GRB090510

- Detected to 100GeV by FERMI
- Simple broken power law model fits over a factor of 10^7 in energy
- The onset of the high-energy spectral component appears to be delayed by ~0.1 s
- Presence of very high E photons argues for very high beaming factor $\Gamma > 10^3$



Present status

- Open questions in GRB physics as of 2011, include classification, progenitor, central engine, ejecta composition, energy dissipation and particle acceleration mechanism, radiation mechanism, long term engine activity, external shock afterglow physics, origin of high energy emission, and cosmological setting (arXiv:1104.0932 Zhang)

Gamma-ray bursts (GRBs)

- Gamma-ray bursts (GRBs) are bright flashes of radiation with spectral energy distributions peaking in the γ-ray band.
- They have durations measured in seconds and appear to be capable of producing directed flows of relativistic matter with kinetic luminosities exceeding 10^{53} erg s^{-1}, making them the most luminous events known.
- All evidence points to agravitational power source associated with the cataclysmic formation of arelativistic star or to aprecursor stage whose inevitable end point is astellar mass black hole.

Implications for GW Detections

Assuming:

- 250 short GRBs/yr (BATSE)
- 1/2 short GRBs are within z=0.5
- γ-rays collimated to 10˚ beam
- all short GRBs due to NS-NS mergers

⇒ NS-NS merger rate is >300 $Gpc^{-3}\ yr^{-1}$

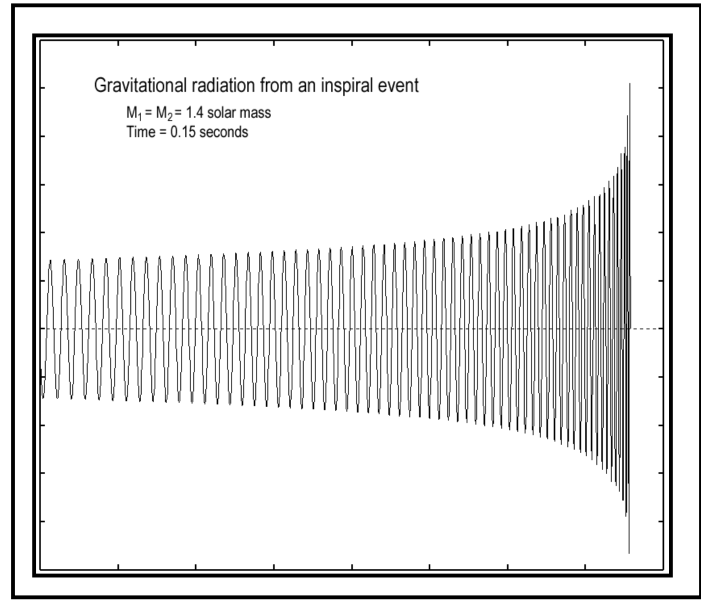
[Concsistent with NS-NS population synthesis modeling O'Shaughnessy, Kalogera, & Belczynski (2005)]

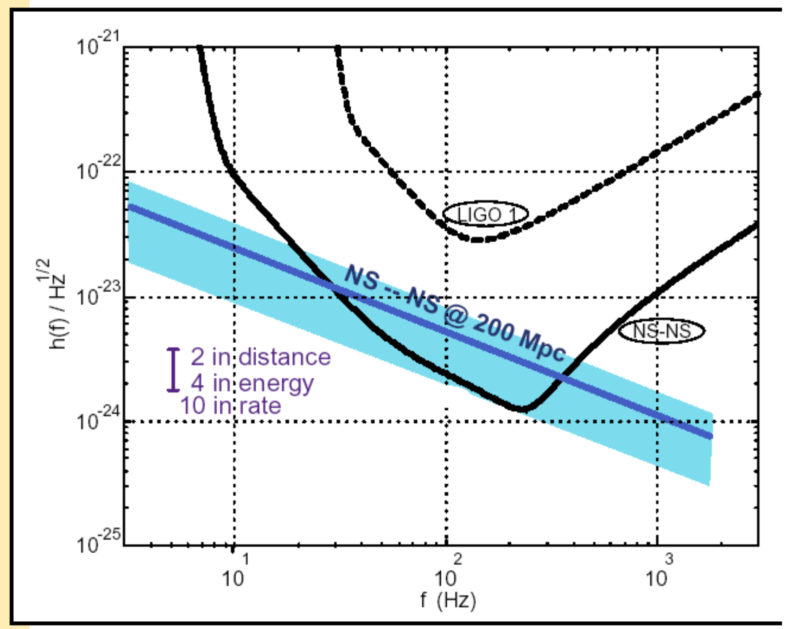
For aLIGO NS-NS merger sensitivity distance of 170 Mpc:

aLIGO detection rate is >6 yr^{-1}

The GW spectrum contains information on the coalescence dynamics, formation process of disk, equation of state for neutron stars, total masses, and mass ratio

Swift will be in orbit until > 2020

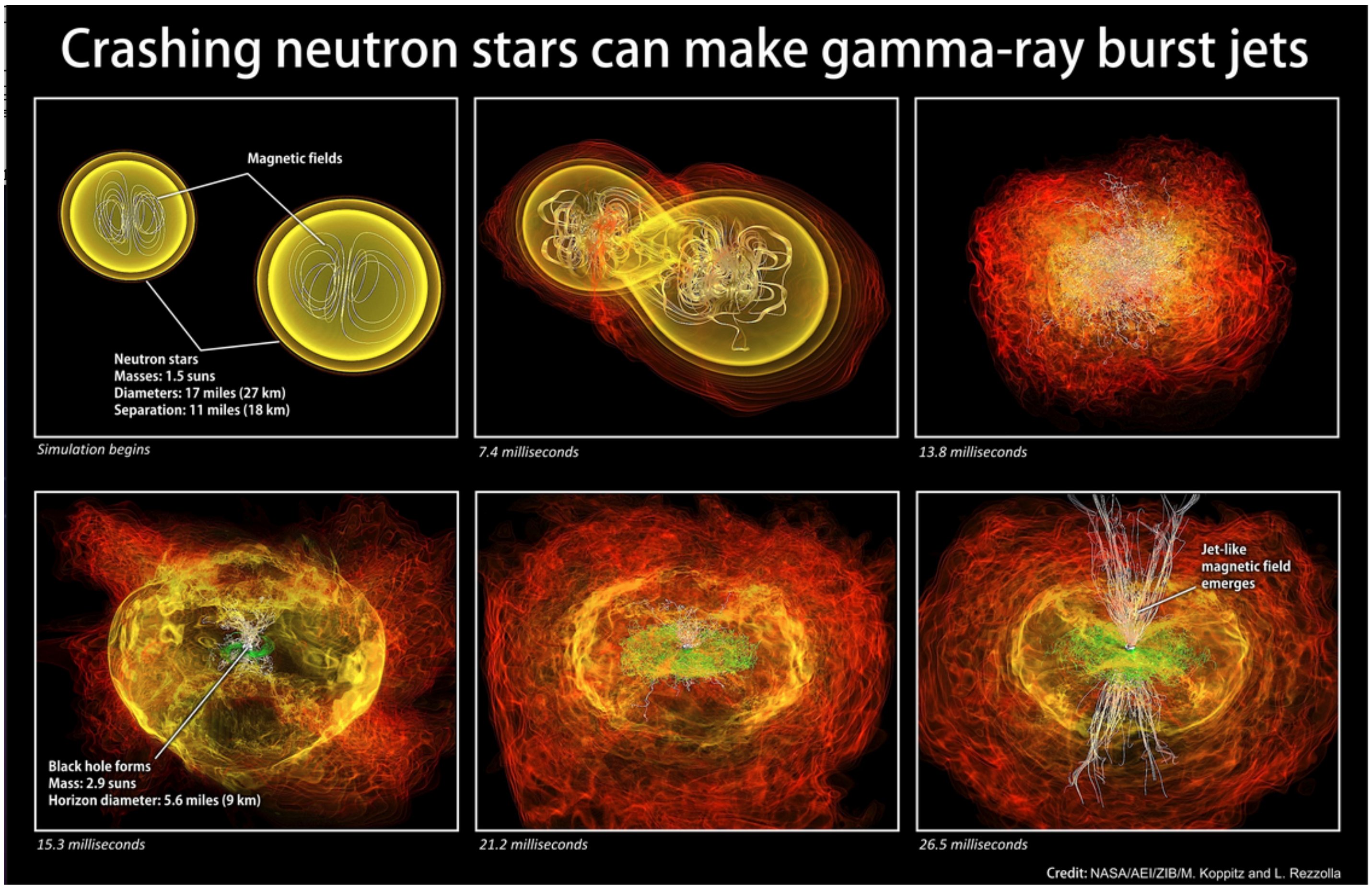




(K. Thorne)

Numerical Simulation of NS-NS Merger

- a merging binary magnetized neutron stars results in a rapidly spinning black hole surrounded by a hot and highly magnetized torus
- an initially turbulent magnetic field of ~ 10^{12} G is amplifed and produces an ordered poloidal field of ~ 10^{15} G along the black-hole spin-axis, within a half-opening angle of ~ 30 deg, which may naturally launch a relativistic jet.
- http://numrel.aei.mpg.de/images/relativistic-binary-neutron-star-inspirals



- The EM energy release is broadly compatible with observations, BUT
  - the simulations lack a proper treatment of the energy losses via photons and neutrinos, which can provide a fundamental contribution to the energy input necessary to launch the fireball and cool the torus
  - This additional energy input, whose self consistent inclusion in general relativity remains extremely challenging, may help to launch an ultrarelativistic outflow very early after the BH forms and complet the picture of the central engine of a SGRB