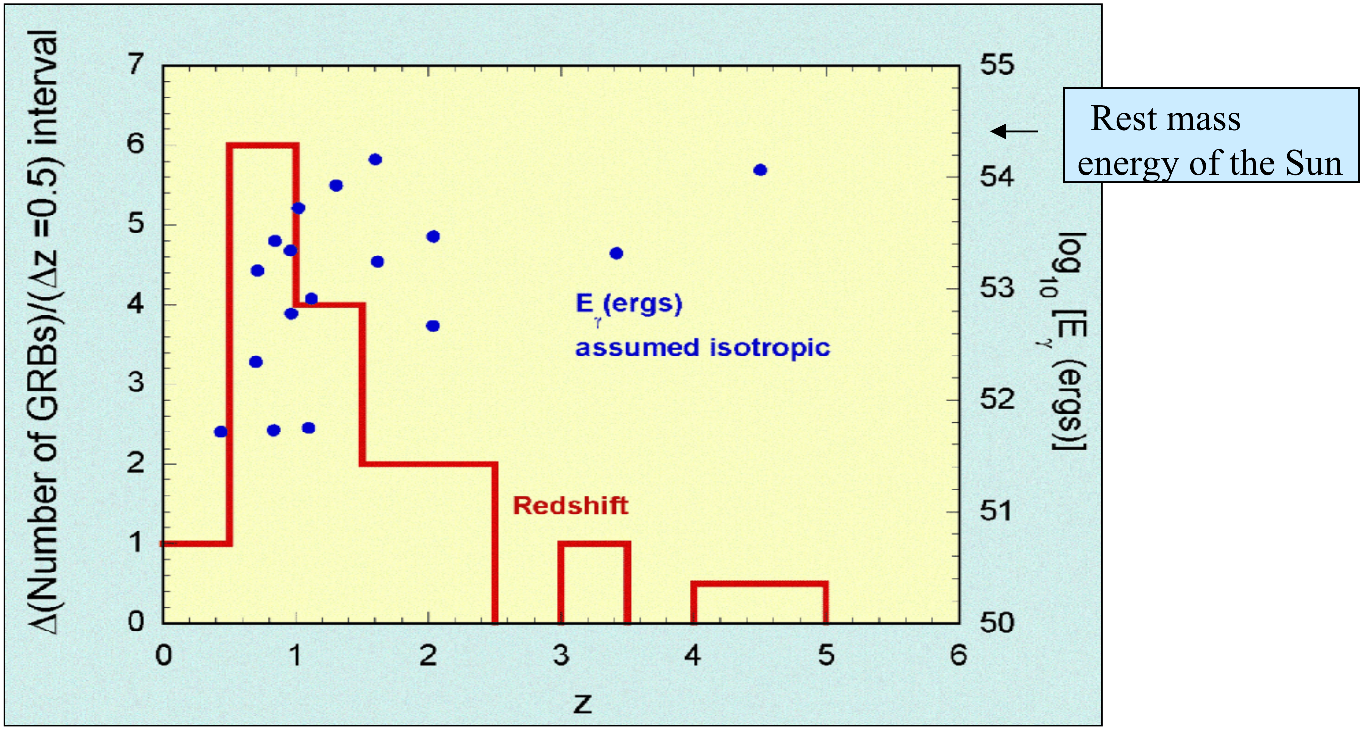
Gamma-Ray Bursts

- Burst energies, relativistic fireball, beaming
- Swift
- Long GRBs, SN, collapsars
- Short GRBs and mergers
- Low luminosity GRBs and soft gamma repeaters

Redshift and Apparent Energy Distribution



L_γ (ergs s^{-1}) = $4\pi\, d_L^{\,2}\, \nu F_\nu$ (ergs $cm^{-2}\, s^{-1}$) (definition)

E_γ (ergs) = $\Delta t_{obs}\, L_\gamma \,/\, (1+z) = 4\pi\, d_L^{\,2} (\nu F_\nu)\, \Delta t_{obs} / (1+z)$

Compactness Problem

- Take $E \sim 10^{53}$ erg and $\Delta t \sim 10$ ms $\rightarrow$ $R < c\Delta t$
- For thermal radiation the energy density is $u = 4\sigma T^4/c$, find $T^4 > E/4\sigma c^2 \Delta t^3$
- Thus, $T > 2\times 10^{10}$ K and $kT >$ 2 MeV

  This is high enough to produce e+e- pairs.
- Optical depth $\sim \sigma_T n R \gg 1$ so spectrum should be blackbody.
- But, observed spectrum is power-law meaning the source is optically thin.

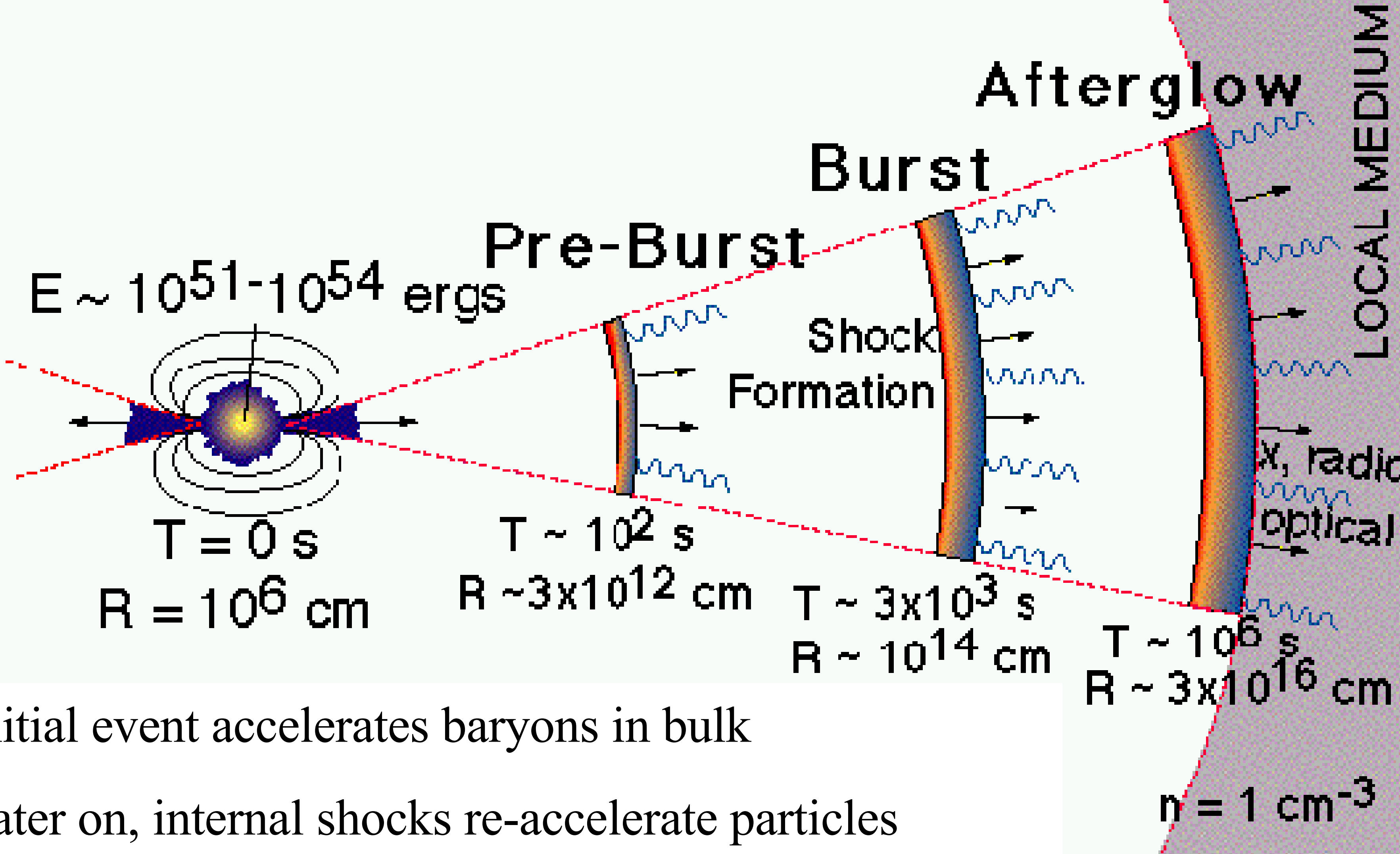
Relativistic outflow

- Matter flowing outwards with velocity v
- Lorentz factor of bulk motion is Γ, $\Gamma^2 = 1/(1-v^2/c^2)$
- Observed photon energy is a factor Γ higher than the photon energy in the rest frame
- For spectrum with an energy index Γ this reduces the number of photon pairs above the electron-positron threshold by $\Gamma^{-2\alpha}$
- Size of the emitting area can be larger.

$$\Delta t = \Delta\tau - (v/c)\Delta\tau \quad \rightarrow \quad R = 2\Gamma^2 c \Delta t$$

- Need $\Gamma > 100$ to solve the problem

GRB FIREBALL MODEL

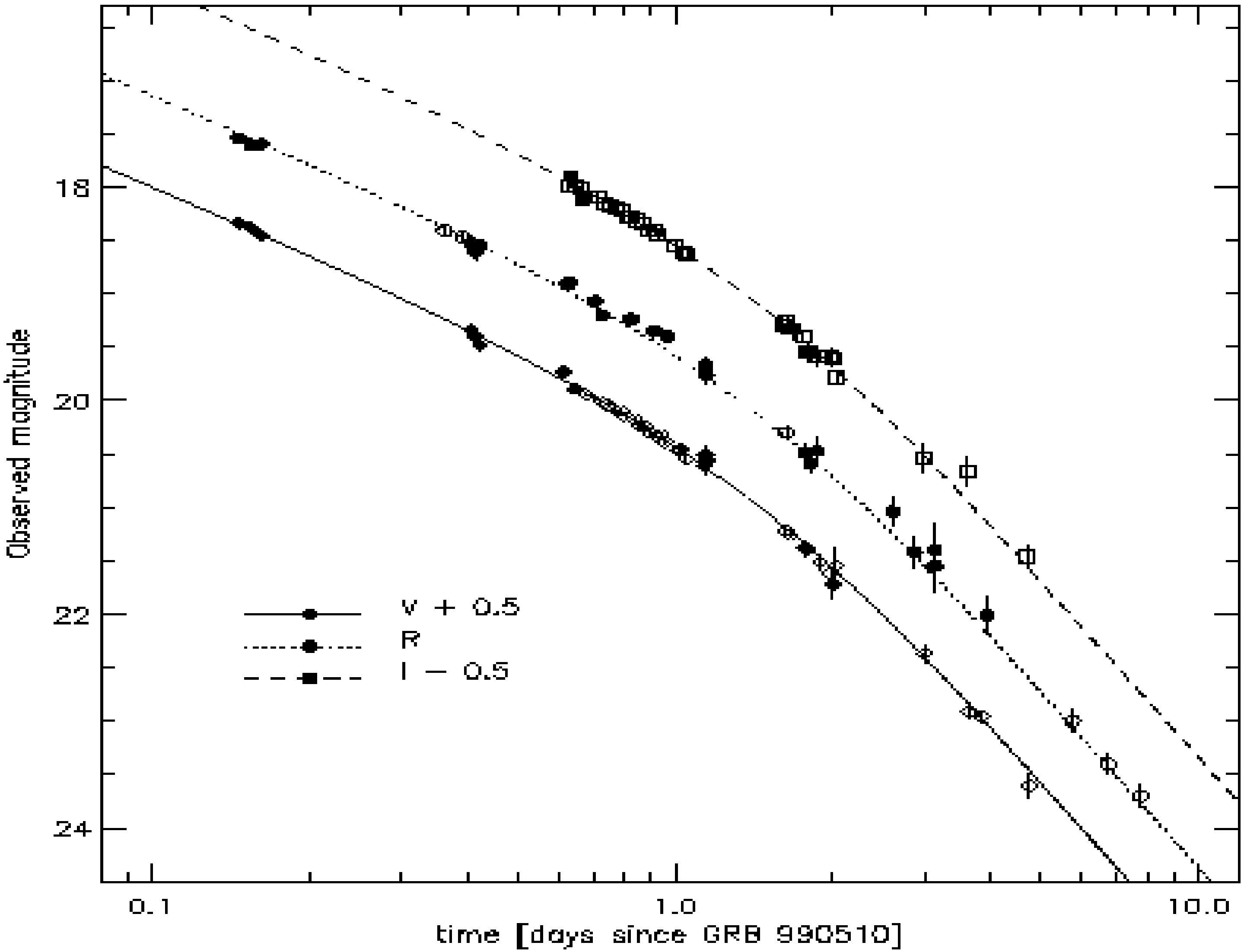


Initial event accelerates baryons in bulk

Later on, internal shocks re-accelerate particles produce GRB

Even later, external shocks produce afterglow

Monochromatic Break in Light Curve



Beaming

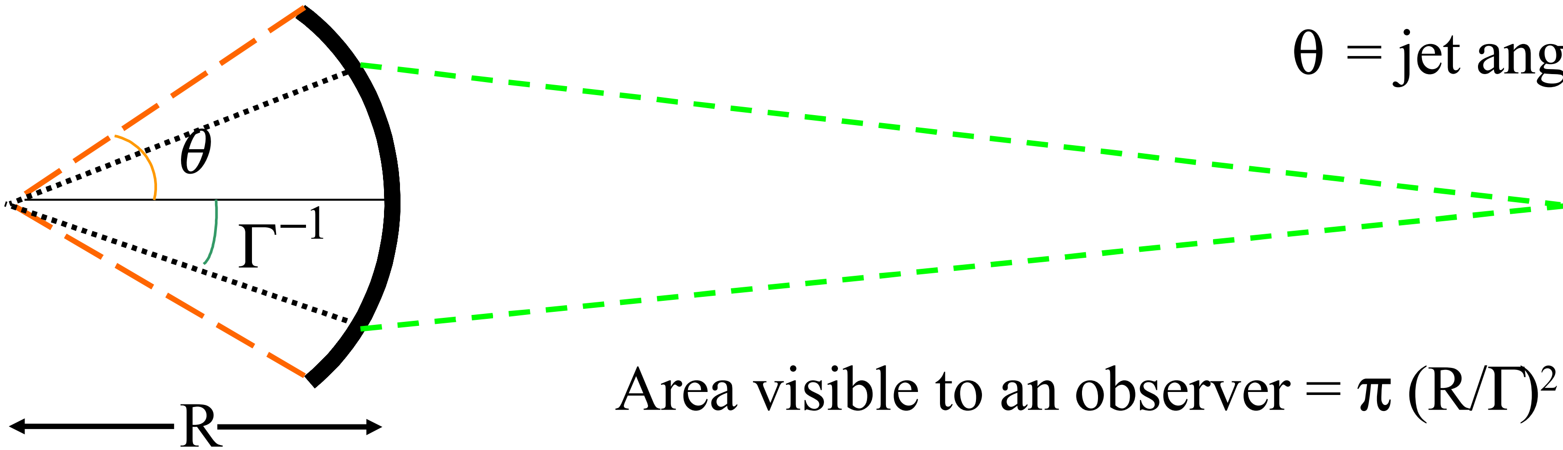
Assume that GRB is an explosion expanding out at relativistic velocities.

Because of relativistic motion, radiation is beamed with an opening angle ~ $1/\Gamma$

Therefore, observer can see only a limited piece of an expanding shell

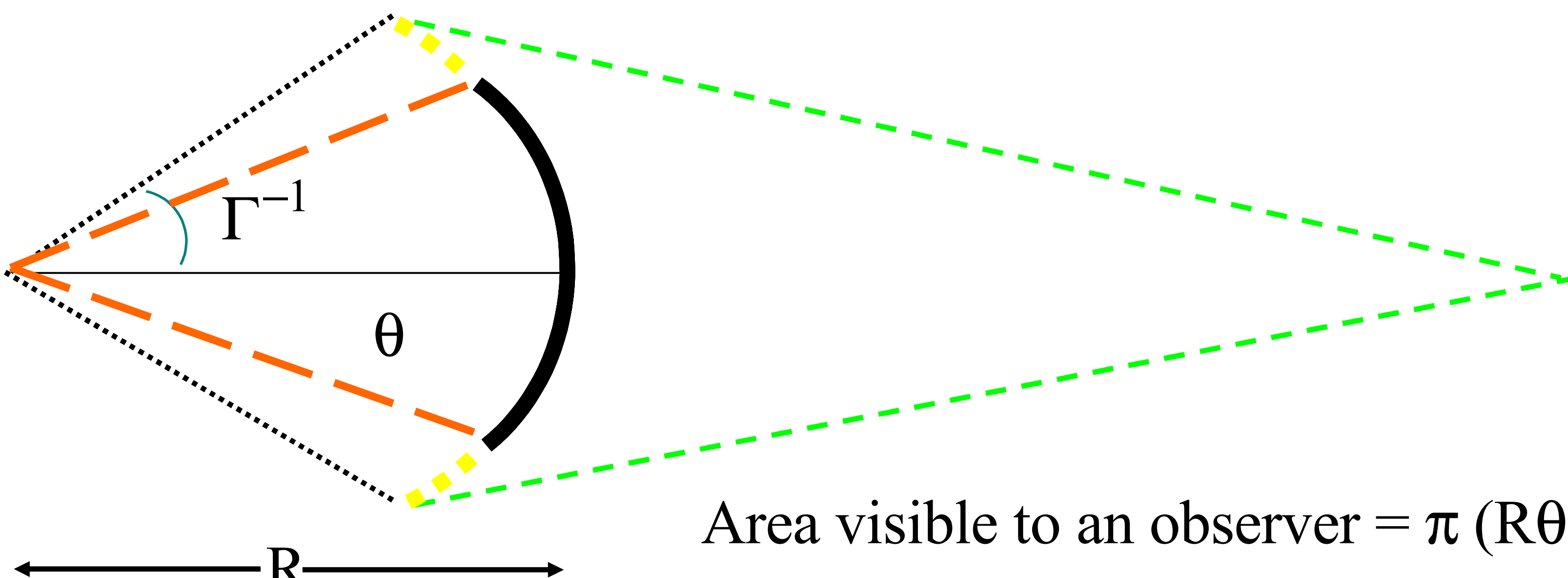
At Early time: $\Gamma^{-1} \leq \theta$

θ = jet angle



Area visible to an observer = $\pi\,(R/\Gamma)^2$

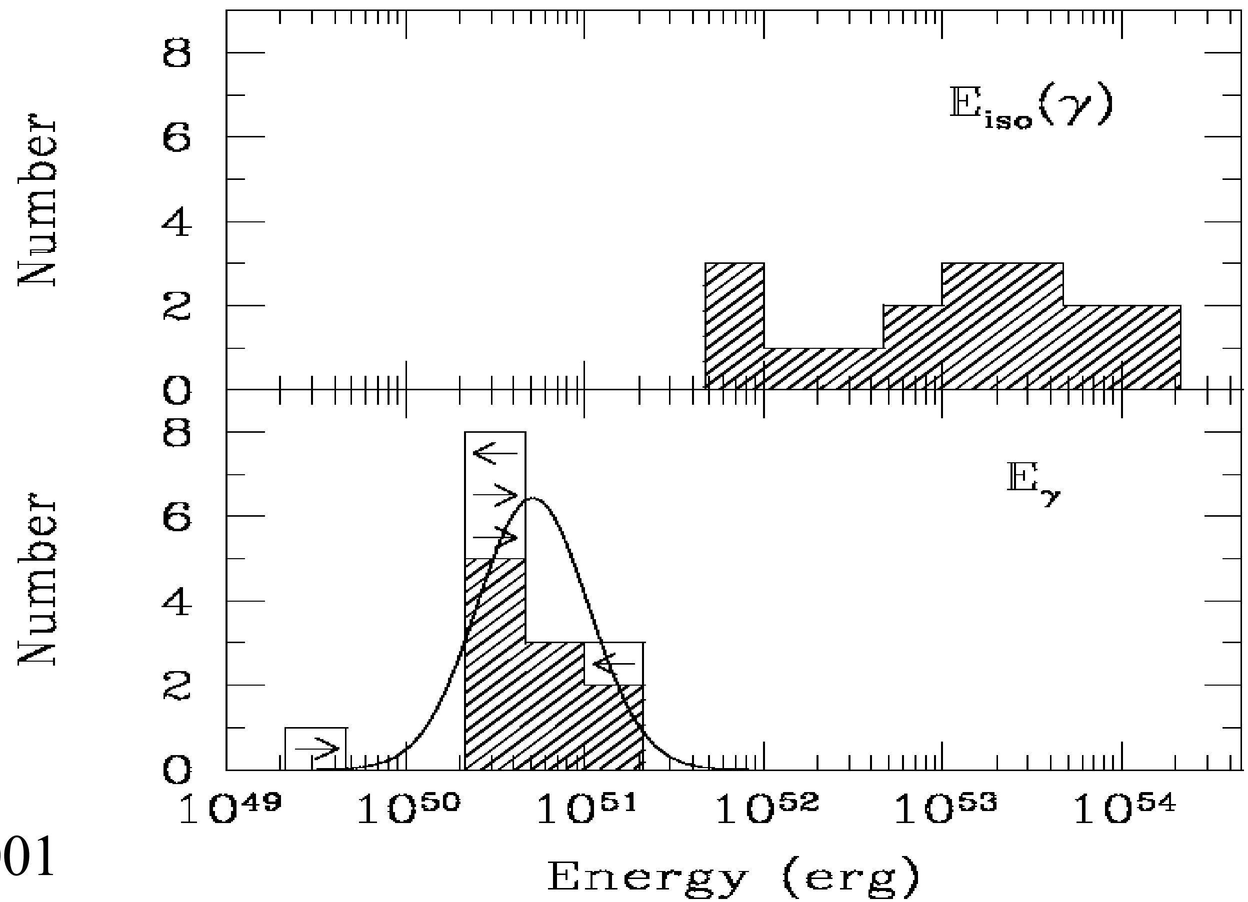
As expansion slows: $\Gamma^{-1} \geq \theta$



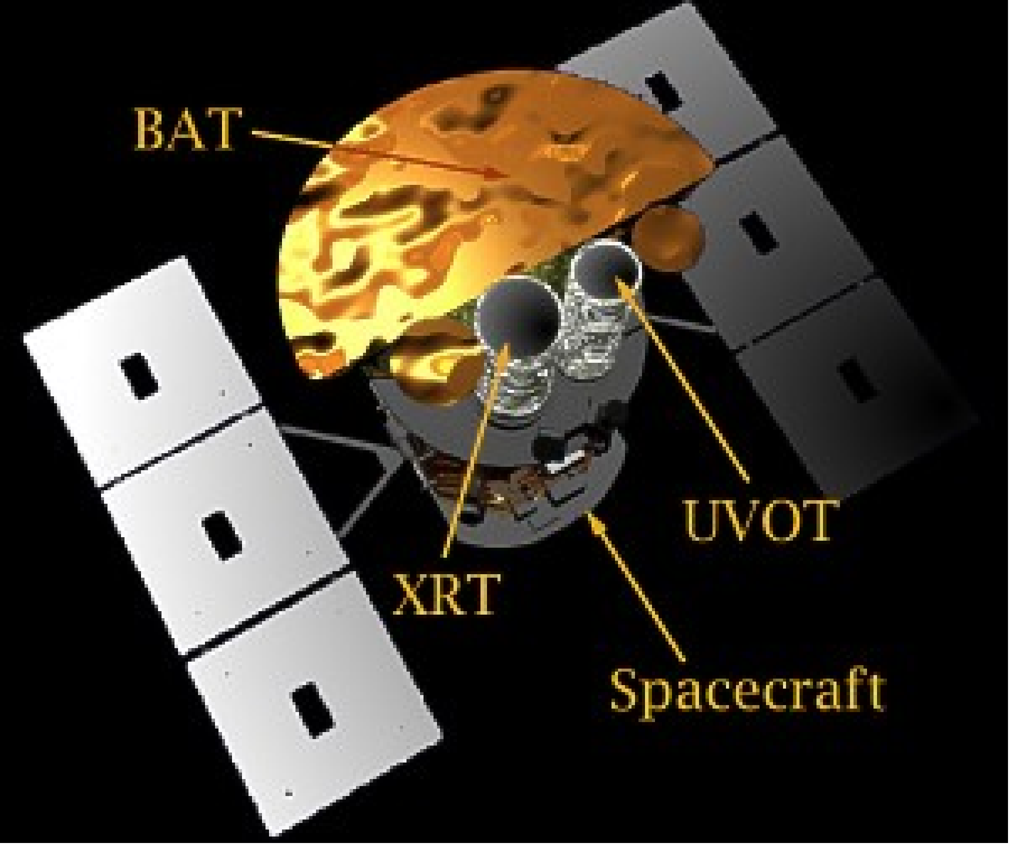
Area visible to an observer = $\pi\,(R\theta)^2$

Jet Breaks

- Beaming fraction is determined by jet opening angle = $1 - \cos\theta \approx \theta^2/2$
- Energy required is reduced by a factor $\theta^2/2$



Frail et al. 2001



Swift

BAT – CZT detector with 5200 cm^2 area sensitive in 15-150 keV band.

Coded aperture imaging of 1.4 steradian field with 4 arcmin resolution suing 32768 pixels.

After detecting a burst, Swift autonomously repoints bringing the burst into view of the XRT and UVOT, often within 90 seconds.

XRT – focusing X-ray telescope in 0.5-6 keV band, 2.5 arcsecond source location accuracy.

UVOT – focusing UV/optical telescope.

Swift Results

- Launched in 2004, detects about 100 bursts/year
- Increased red shift range

  GRB 090423 with *z* = 8.2, Swift <z> = 2.7 versus pre-Swift <z> = 1.2

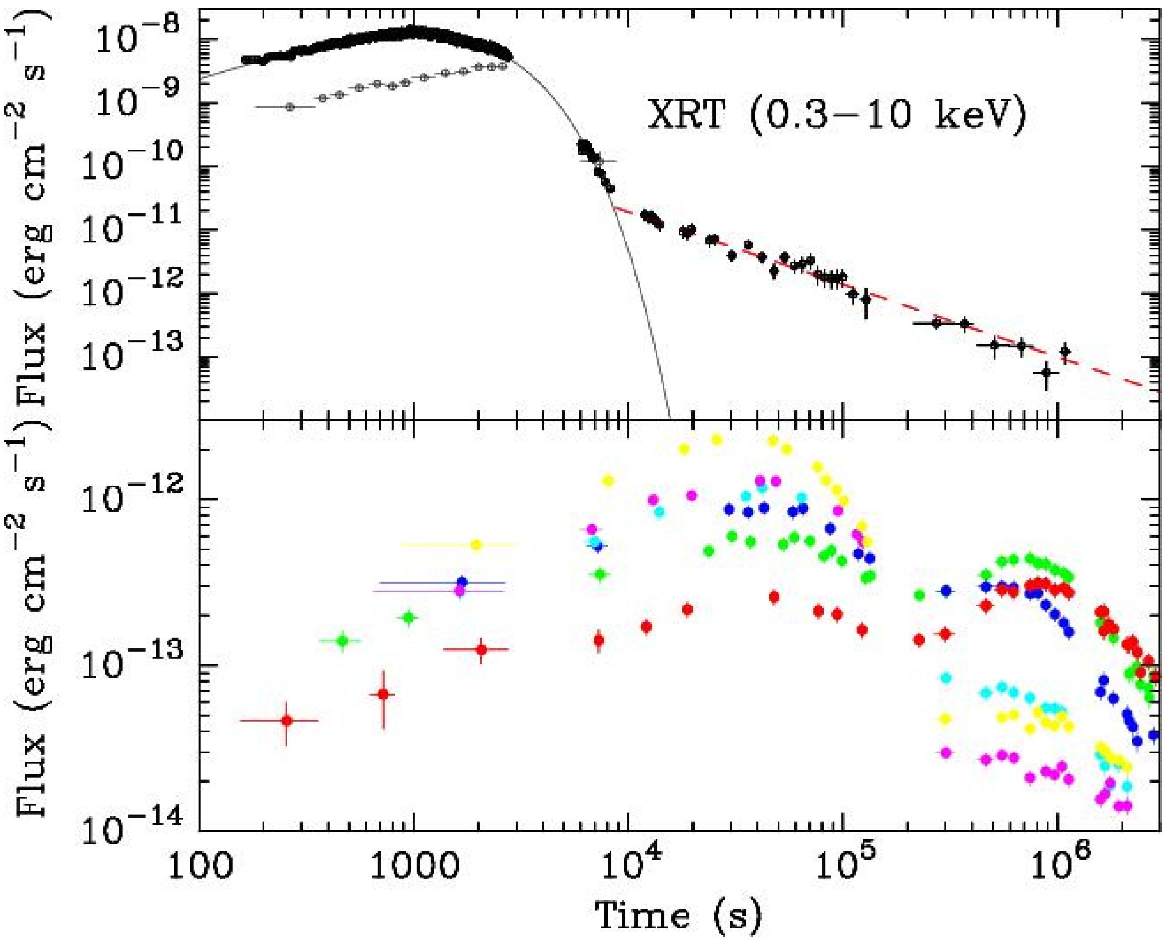
- Huge sample of afterglow X-ray/optical light curves with excellent coverage

  Afterglow light curves far more complex than anticipated.

  Jet breaks in only 20% of GRBs (coverage for 40% incomplete)

- More data on long GRB/SN connection
- Afterglow of short GRB
- Low luminosity GRBs

GRB 060218 = SN 2006aj



- Clear type SN Ic

Compared to usual GRB-SN:

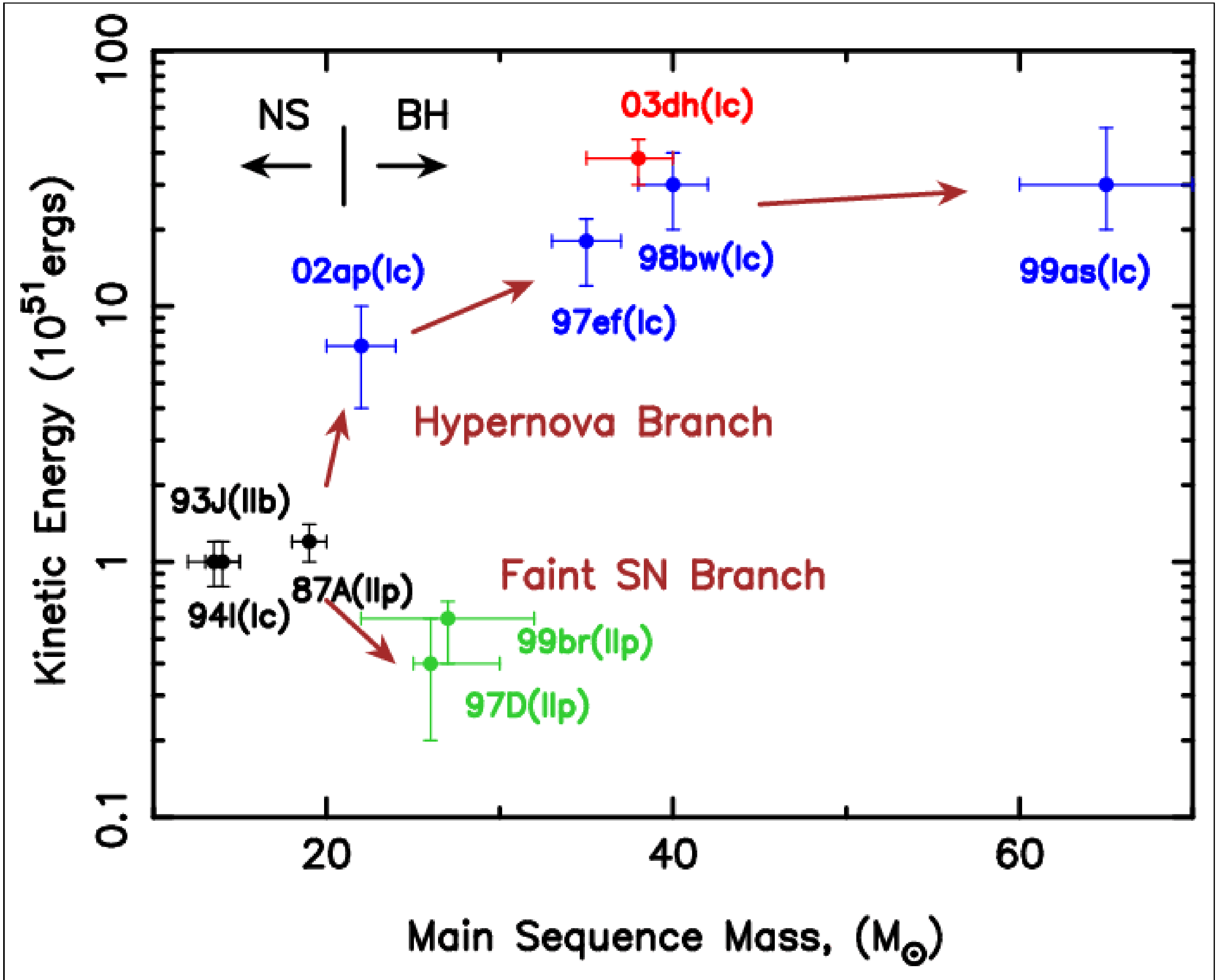
- SN was 100x less powerful
- More frequent events
- Less ejected mass
- Thought to have NS at core

More on GRB/SN connection

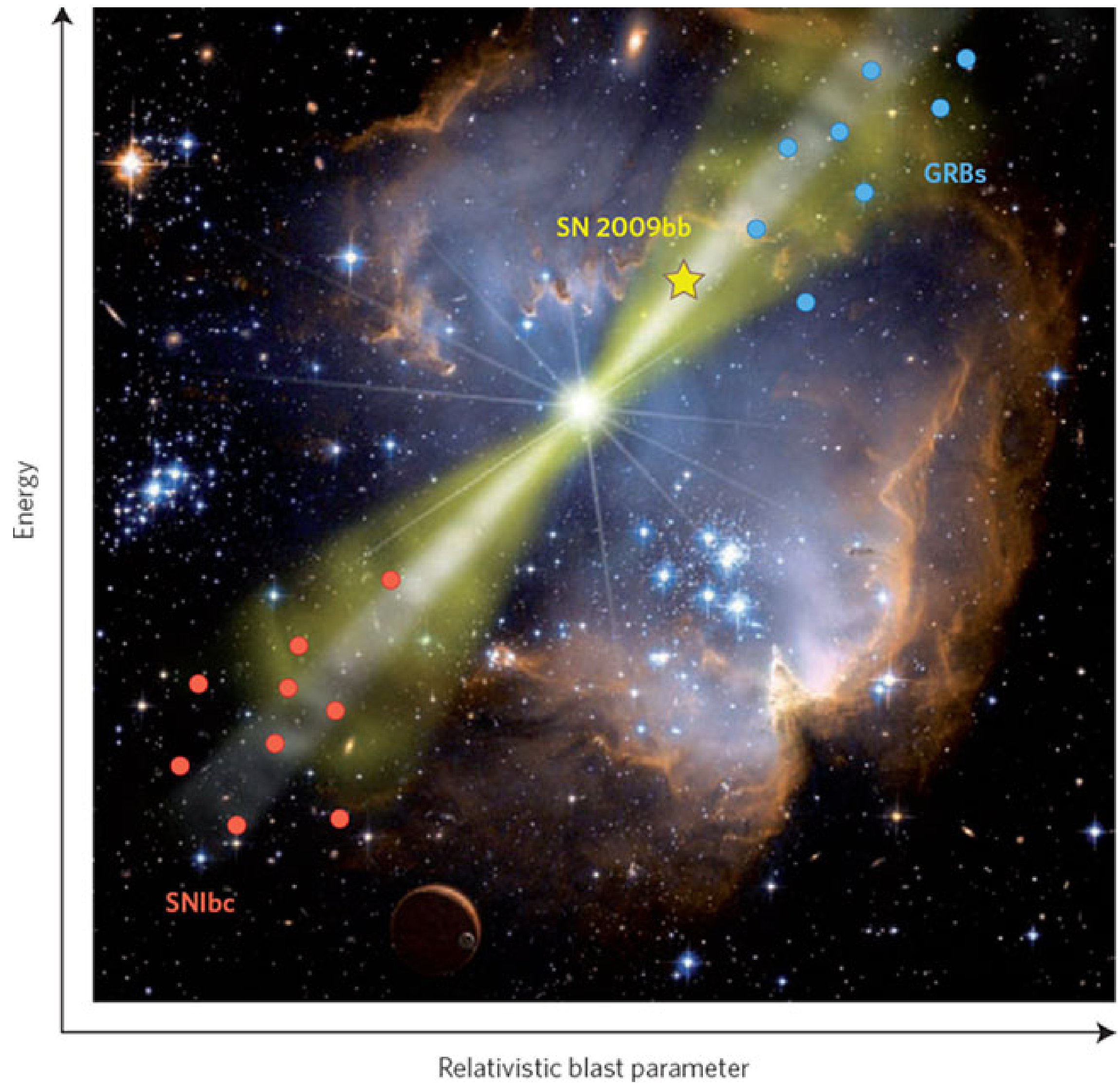
- Type of SN associated with GRBs established as SN Ic – core collapse SN with absence of H, He, Si absorption lines
- SNR-SNe also show high speed ($v \sim 0.1c$) outflows

- Do all SN Ic make GRBs?
- At late times, fire ball should produce unbeamed radio emission. Radio survey of SN Ic shows that not every (or even most) SN Ic harbors a GRB
  - Most SN Ic have no relativistic ouflows
  - Some have mildly relativistic outflows (SN 2009bb), but no gamma-rays
  - Some have highly relativistic outflows

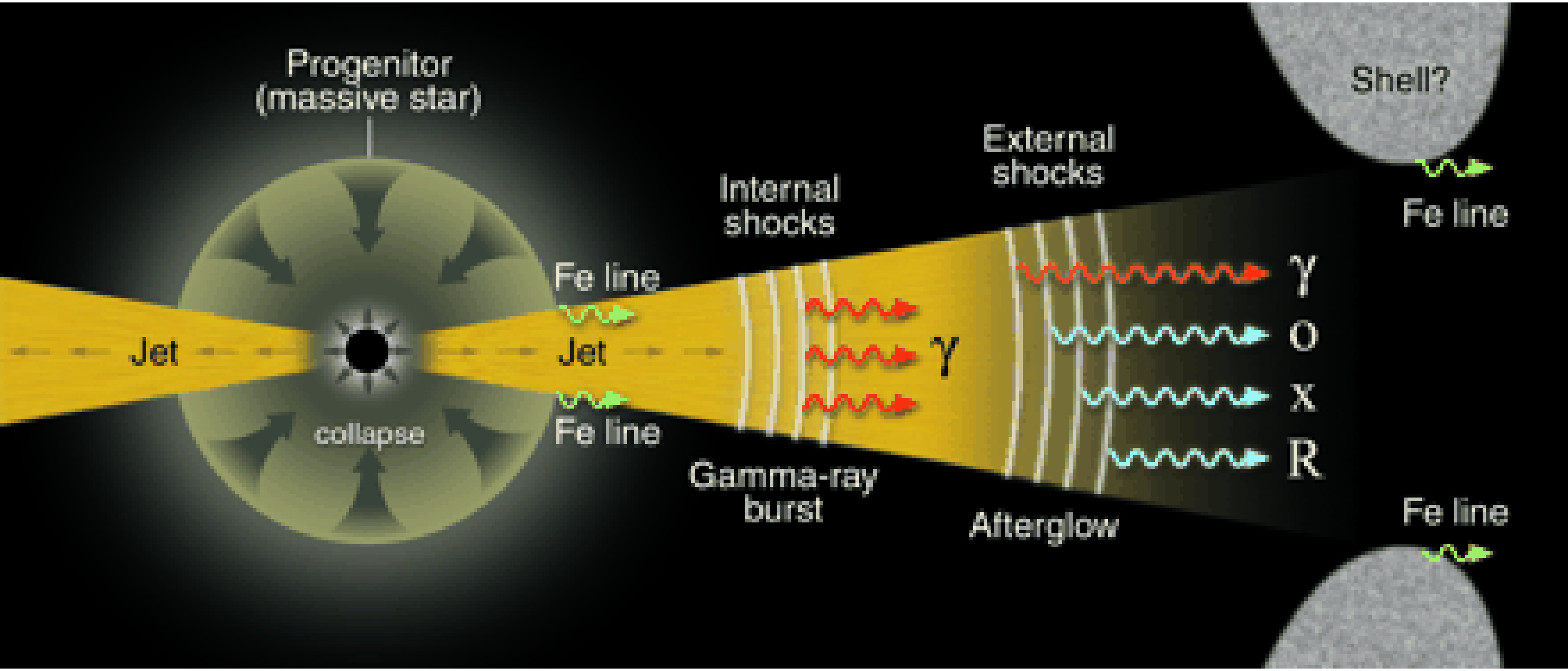
Supernovae/GRB connection



Supernovae/GRB connection

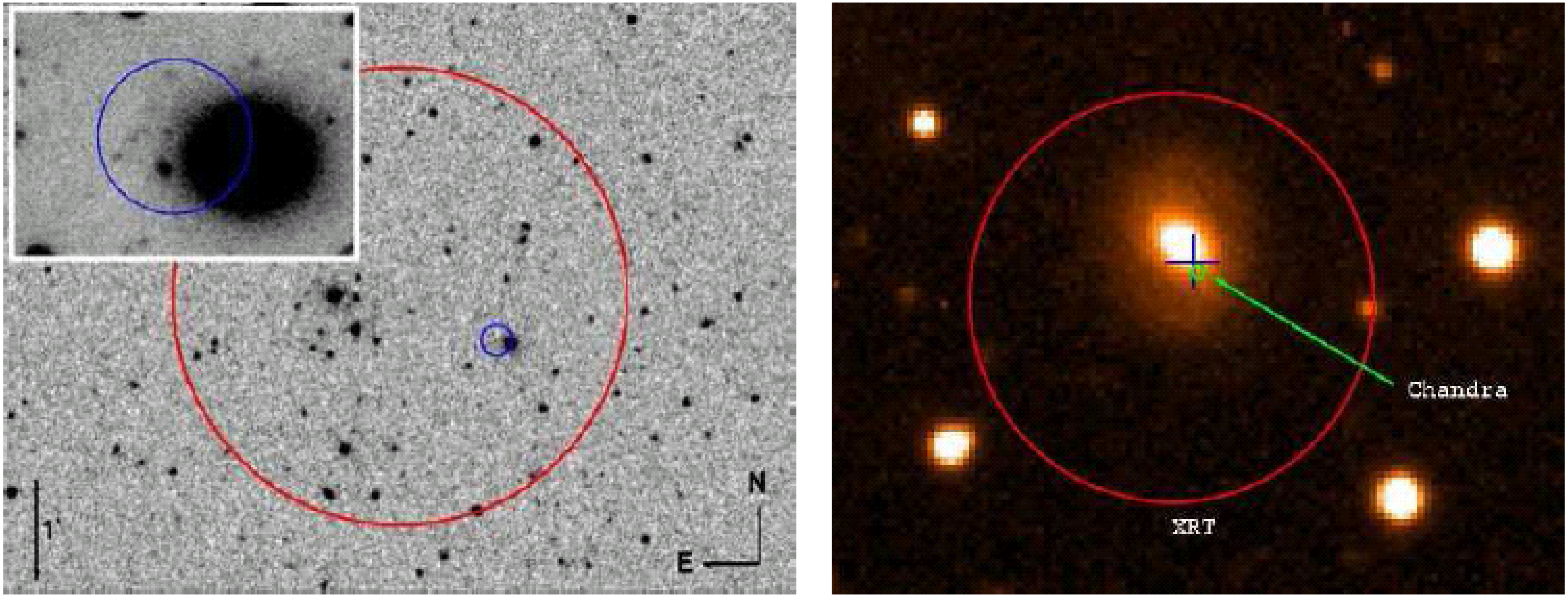


Massive Star Collapse



Massive star collapses, forming NS or BH
Matter briefly forms accretion disk around compact object
Accretion disk produces collimated relativistic outflow along spin axis
Beamed outflow makes GRB, supernova explosion accompanies

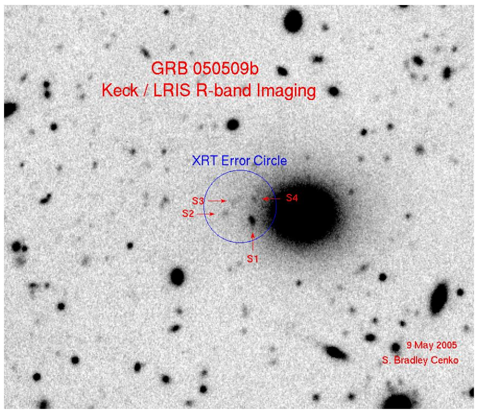
Short GRBs



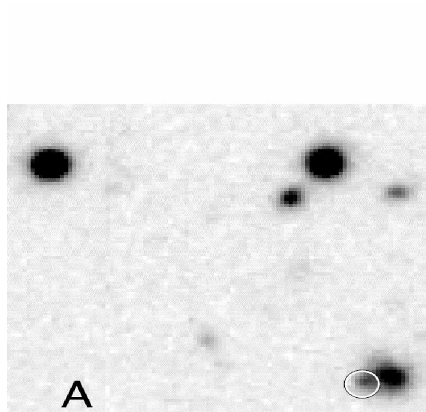
Short GRBs associated with elliptical galaxies. *left:* GRB 050509B; z=0.226 (Gehrels et al. 2005; Bloom et al. 2006a), the red and blue circles are BAT and XRT error boxes, respectively; *Right:* GRB 050724; z=0.257 (Barthelmy et al. 2005b; Berger et al. 2005a)

Host Galaxies of Short GRBs

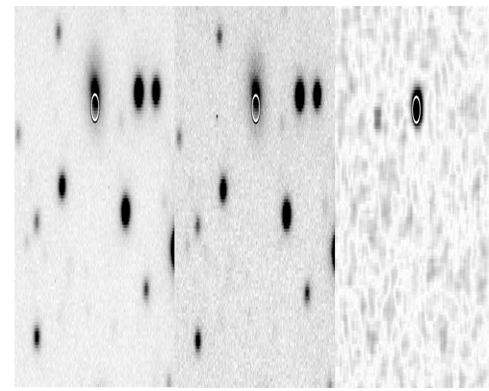
GRB050509



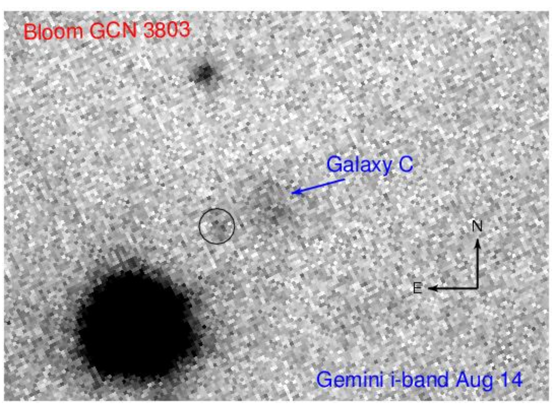
GRB050709



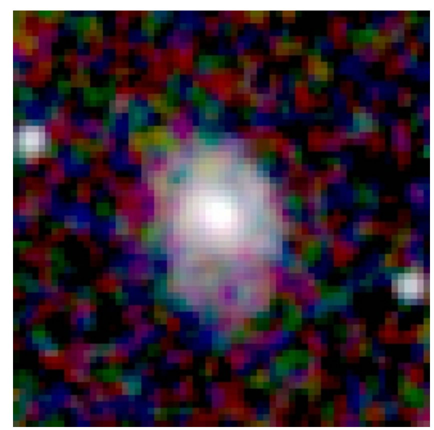
GRB050724



GRB050813



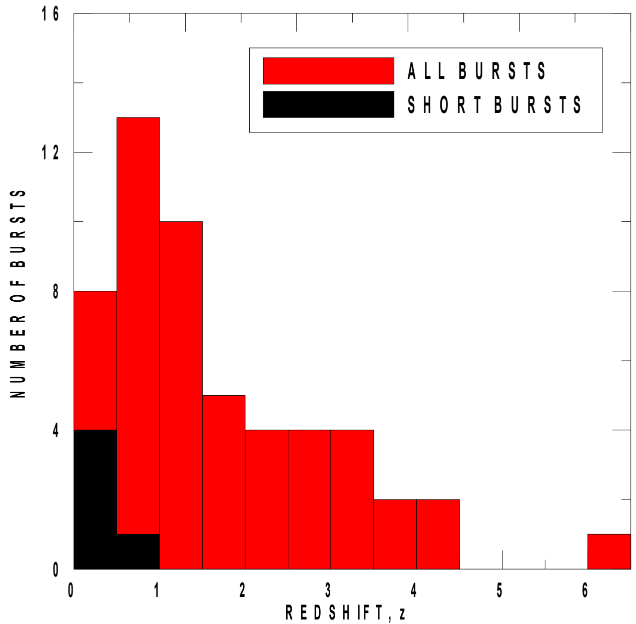
GRB050906



Properties of Short GRBs

GRB	X-RAY?	OPTICAL?	RADIO?	REDSHIFT	GALAXY	ENERGY erg
050509	YES	NO	NO	0.225?	ELLIPTICAL?	1.1×10^{48}?
050709	YES	YES	NO	0.1606	EARLY	2.8×10^{49}
050724	YES	YES	YES	0.257	ELLIPTICAL	9.9×10^{49}
050813	YES	NO	NO	0.722?	?	1.7×10^{50}?
050906	NO	NO	NO	0.03?	BLUE, SPIRAL	1.2×10^{47}?

- Found in both elliptical and star forming galaxies
- No evidence for supernova emissions
- Offset from host galaxy



Properties of Short GRBs

GRB	Mission	T_{90}(s)	z	Host galaxy	Location	Refs
050509B	Swift	0.04 ± 0.004	0.226	elliptical	outskirts?	[1, 2]
050709	HETE	0.07 ± 0.01	0.1606	irregular	outskirts	[3–5]
050724	Swift	3.0 ± 1.0	0.257	elliptical	outskirts	[6–9]
050813	Swift	0.6 ± 0.1	–	–	–	[10]
050911*	Swift	~ 16	0.1646?	galaxy cluster?	–	[11, 12]
051210	Swift	1.4 ± 0.2	–	–	–	[13]
051221A	Swift	1.4 ± 0.2	0.5465	star forming galaxy	slightly off-center	[14, 15]
051227*	Swift	8.0 ± 0.2	–	–	–	[16, 17]
060121	HETE	4.25 ± 0.56	1.7? or 4.6?	early-type?	outskirts?	[18–20]
060313	Swift	0.7 ± 0.1	–	–	–	[21]
060502B	Swift	0.09 ± 0.02	0.287?	early-type?	outskirts?	[22, 23]
060505	Swift	4.0 ± 1.0	0.089?	star-forming galaxy	–	[24–26]
060614*	Swift	102 ± 5	0.125	star-forming galaxy	off-center	[27, 28]
060801	Swift	~ 0.50	1.1304??	–	–	[29, 30]
061006	Swift	~ 0.42	–	–	–	[31, 30]

Short hard GRBs are different class than Long-duration GRBs on the basis of:

Host galaxies

Energies

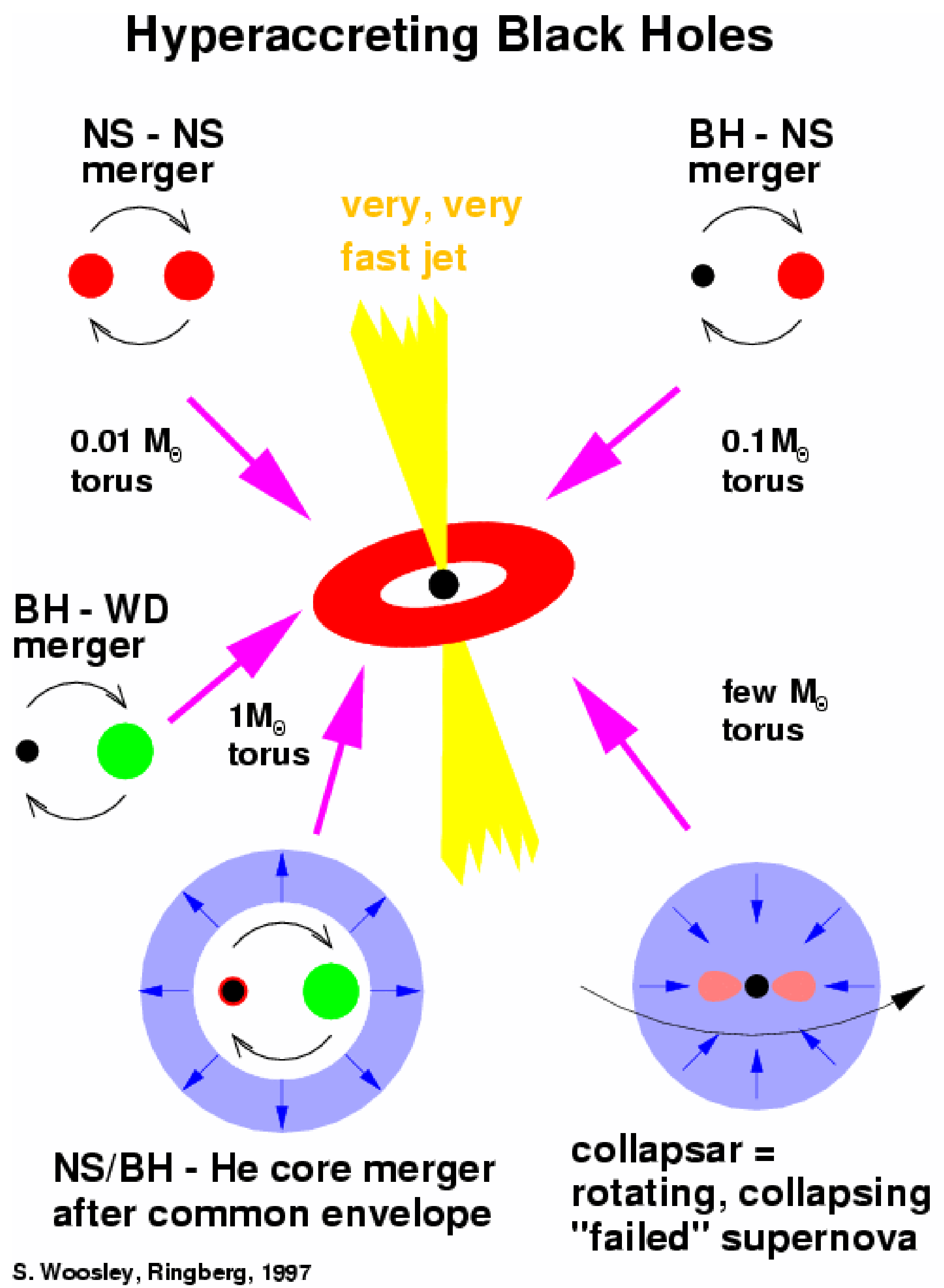
Redshift distribution

Lag-luminosity relation

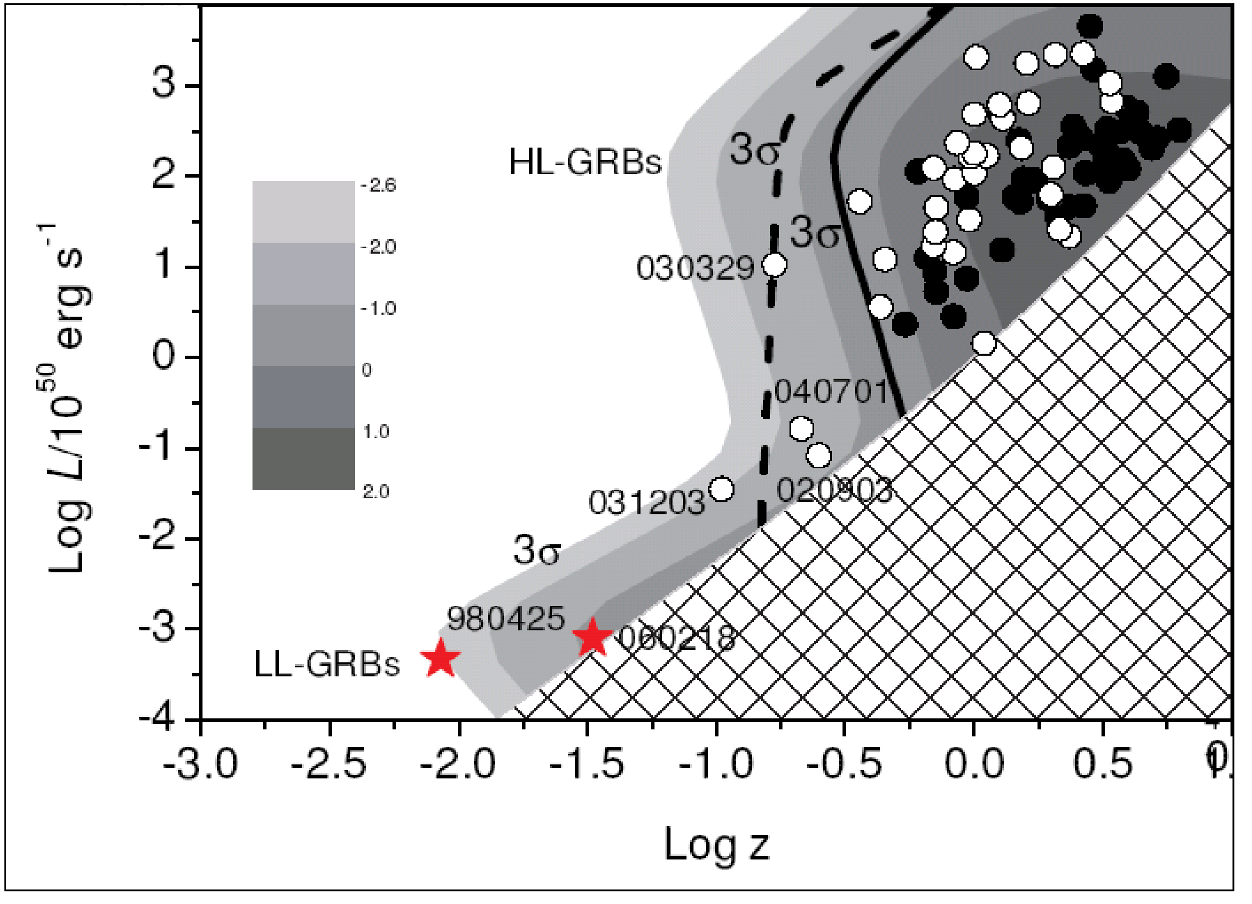
Mergers

Binaries must evolve before merger and binaries have non-zero speeds due to kicks in compact object formation.

Thus, GRBs can occur in outskirts of or even far from host galaxy.



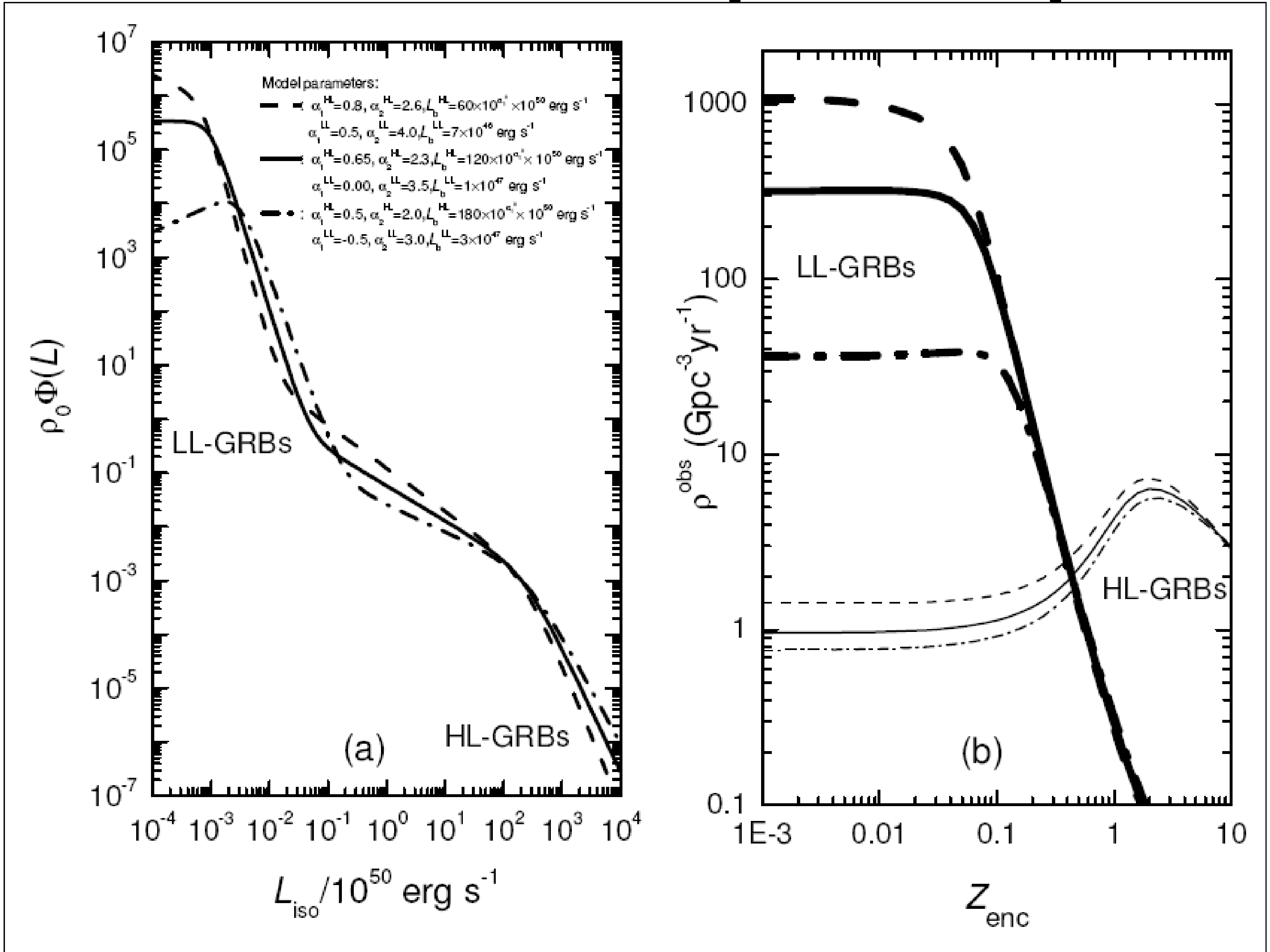
Low Luminosity GRBs



GRB 980425: z = 0.0085
GRB 060218: z = 0.0331

Zhang (2007)

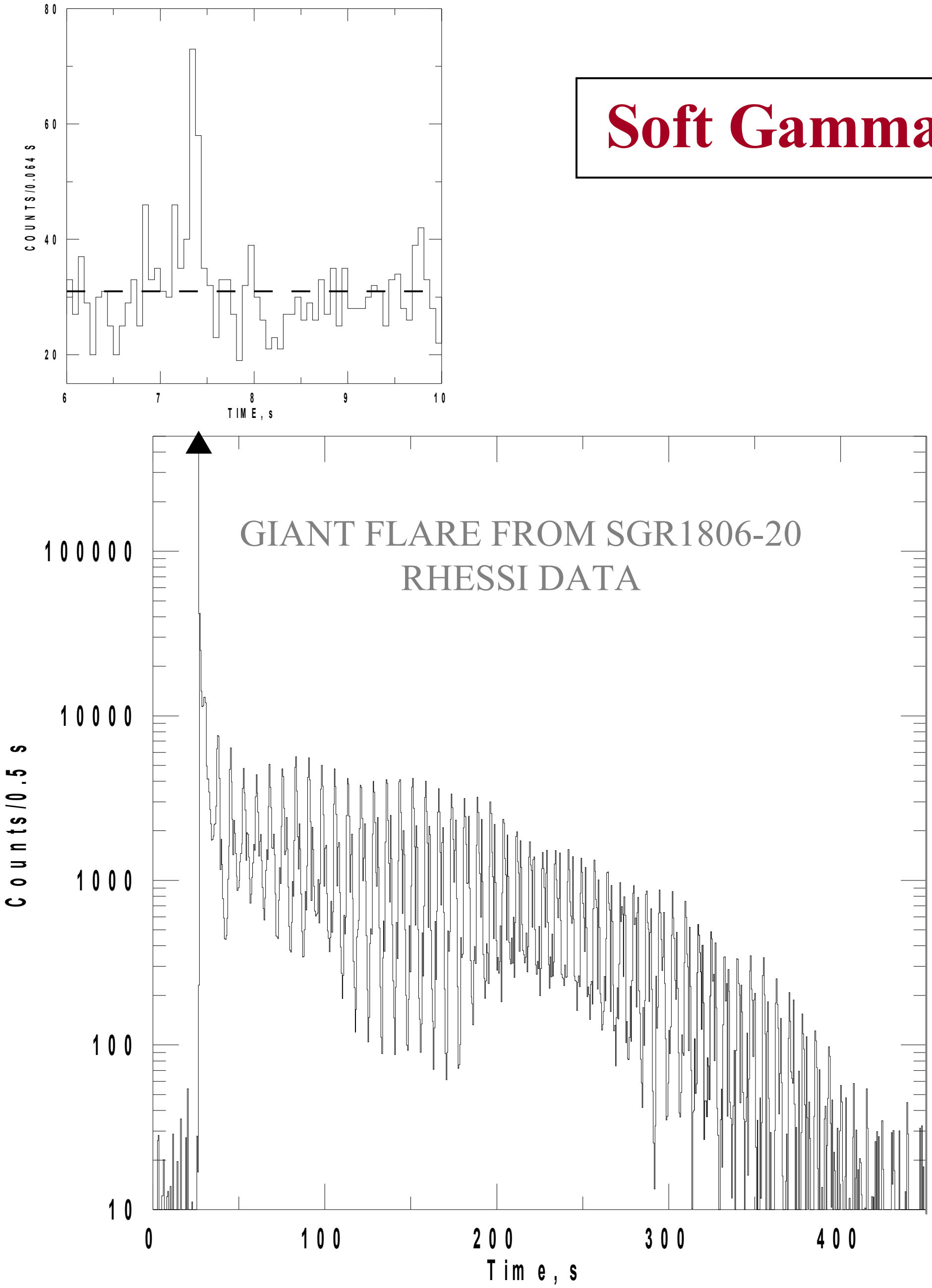
LLGRBs as a Separate Population



Event rate density: long GRBs ~ 1/Gpc^3-yr versus LLGRBs: ~ 800/Gpc^3-yr

Redshift and luminosity distribution suggest a separate population

Soft Gamma Repeaters



Extraordinary SGR event of Dec. 27, 2004

Begin with ~0.2 s long, hard spectrum spikes with E~10^{46}-10^{47} erg

The spike is followed by a pulsating tail with ~1/1000th of the energy

Viewed from a large distance, only the initial spike would be visible

It would resemble a short GRB

It could be detected out to 100 Mpc

GRB050906 at z=0.03 could be a magnetar flare