Gamma-Ray Bursts:
I. Observations and Overview*

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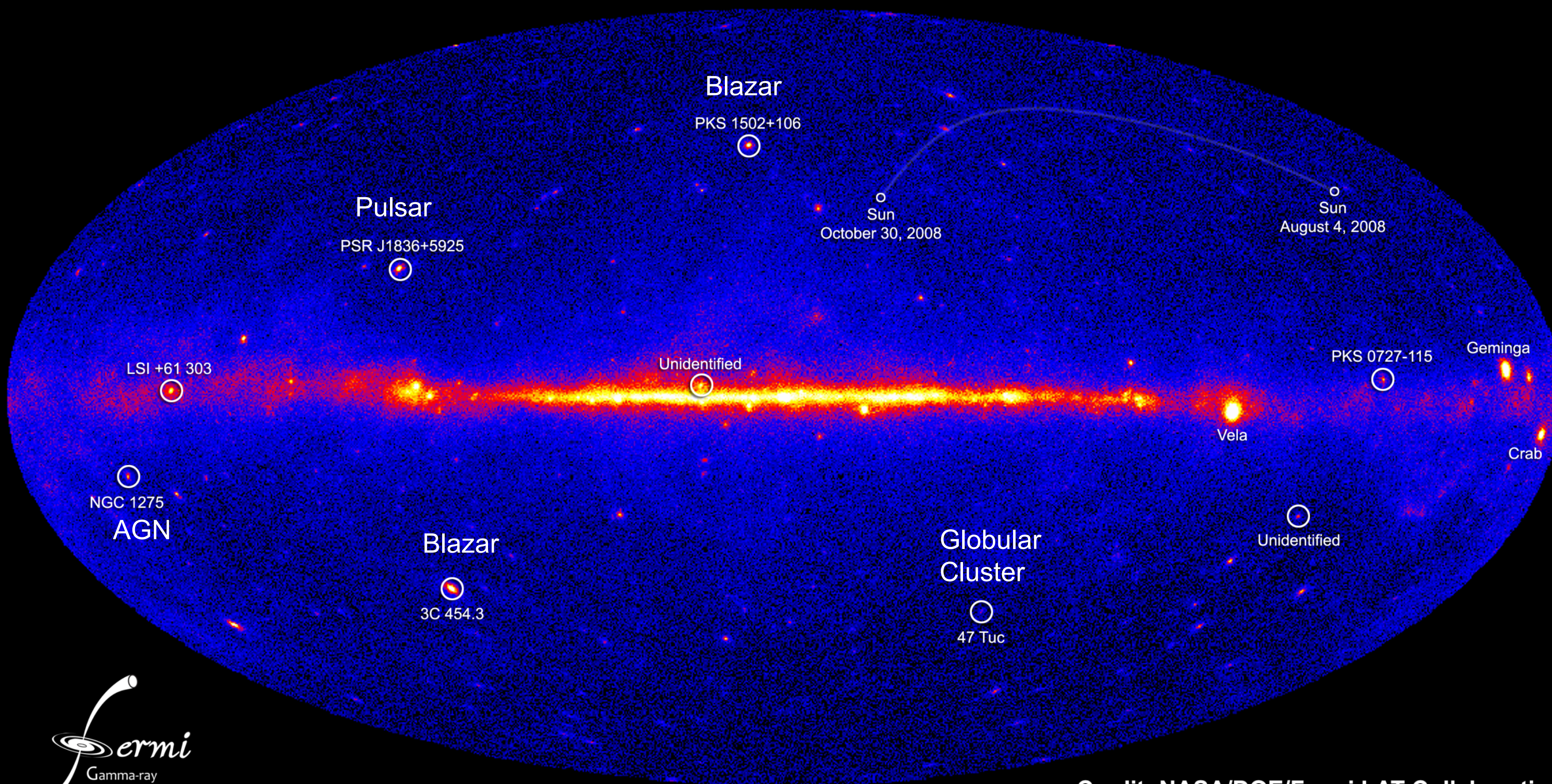
*select slides borrowed from Chuck Dermer, Jim Lattimer, Stan Woosley

NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



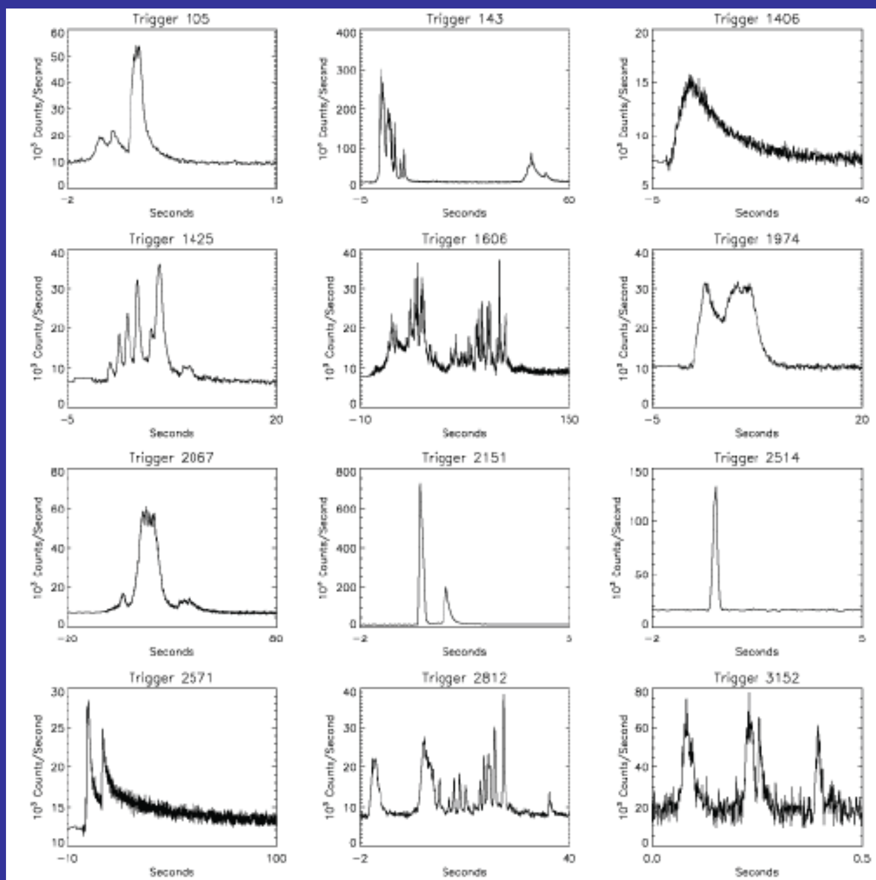
Fermi
Gamma-ray
Space Telescope

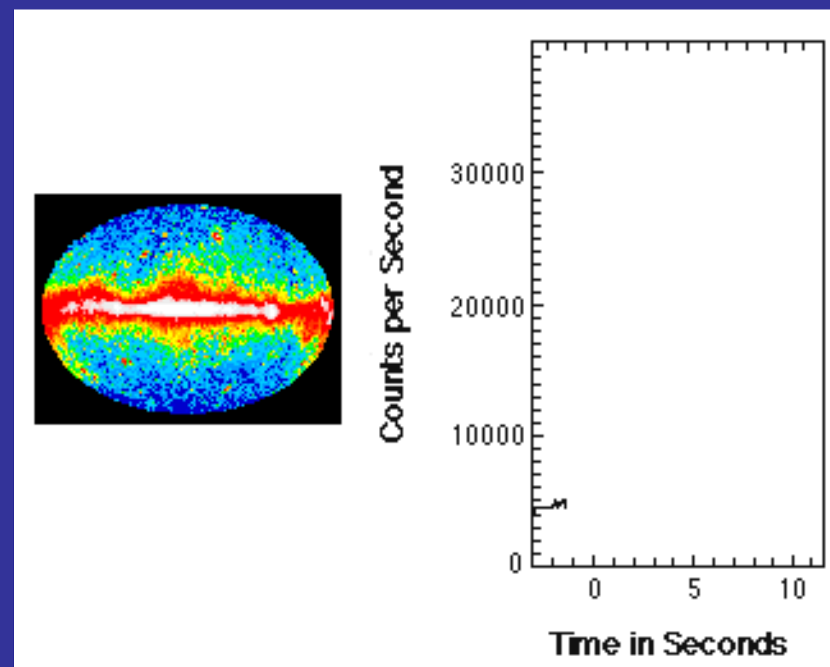
Credit: NASA/DOE/Fermi LAT Collaboration

Gamma-Ray Bursts (GRBs)

- Variable `bursts' of gamma-rays lasting milliseconds to minutes.
- Discovered by the VELA satellites in 1967 when monitoring nuclear test ban treaty (declassified 1972)
- GRBs occur about once per day across the whole sky.

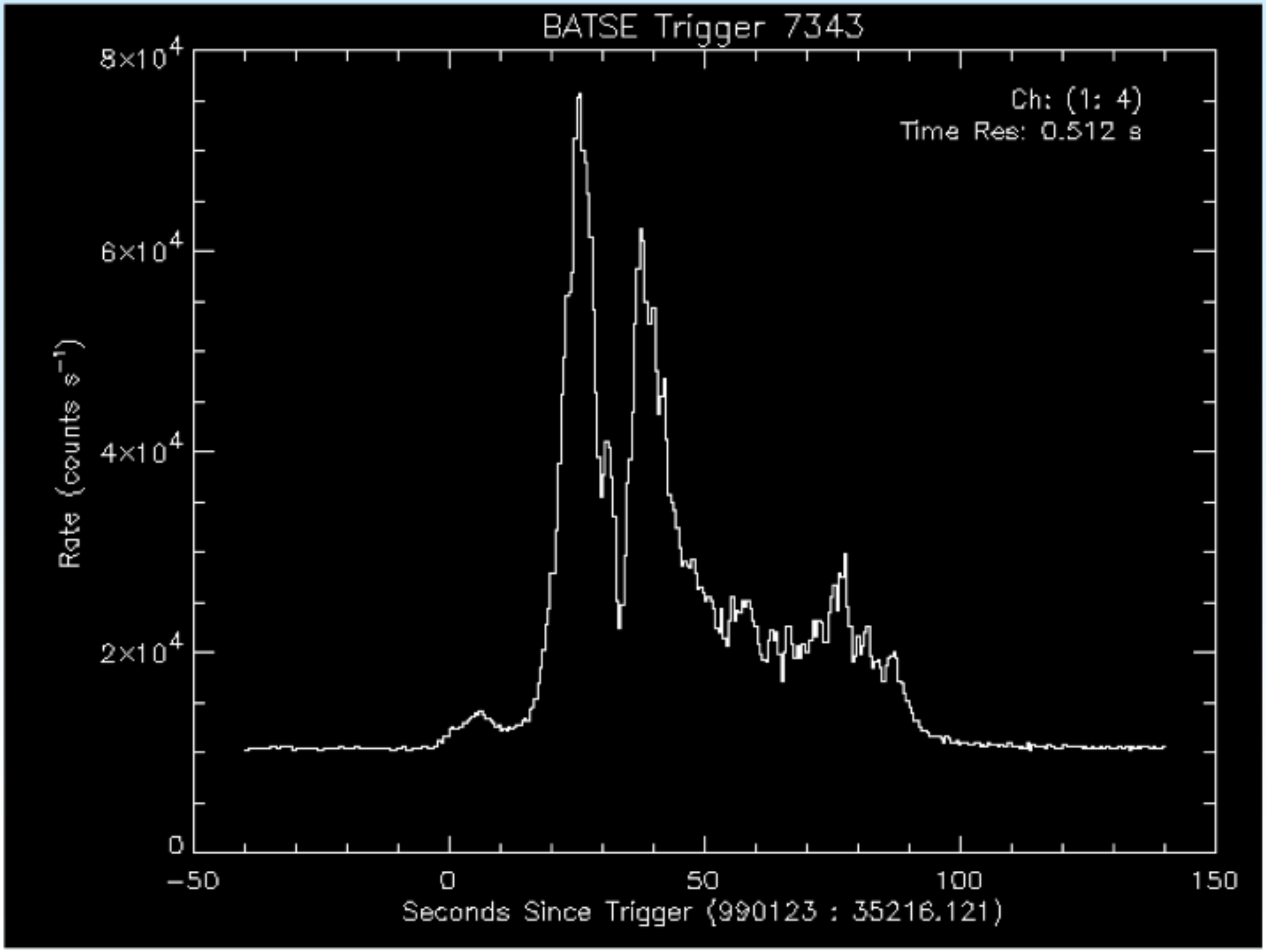
counts per second



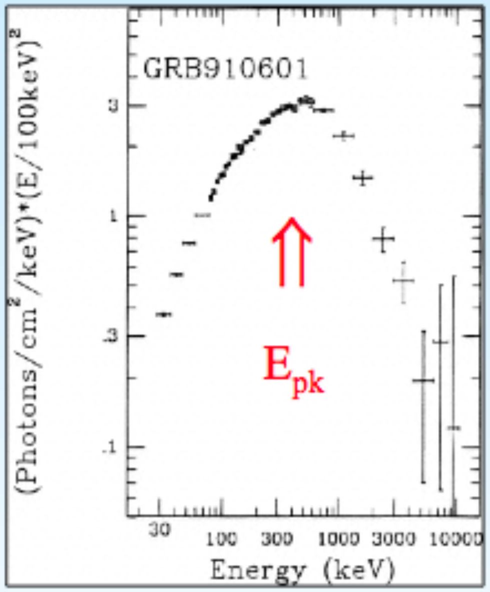


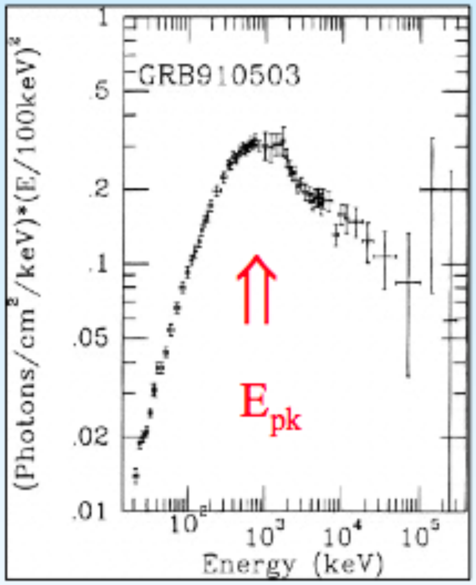
“When you’ve seen one GRB…. you’ve see one GRB”

Light Curve: GRB 990123

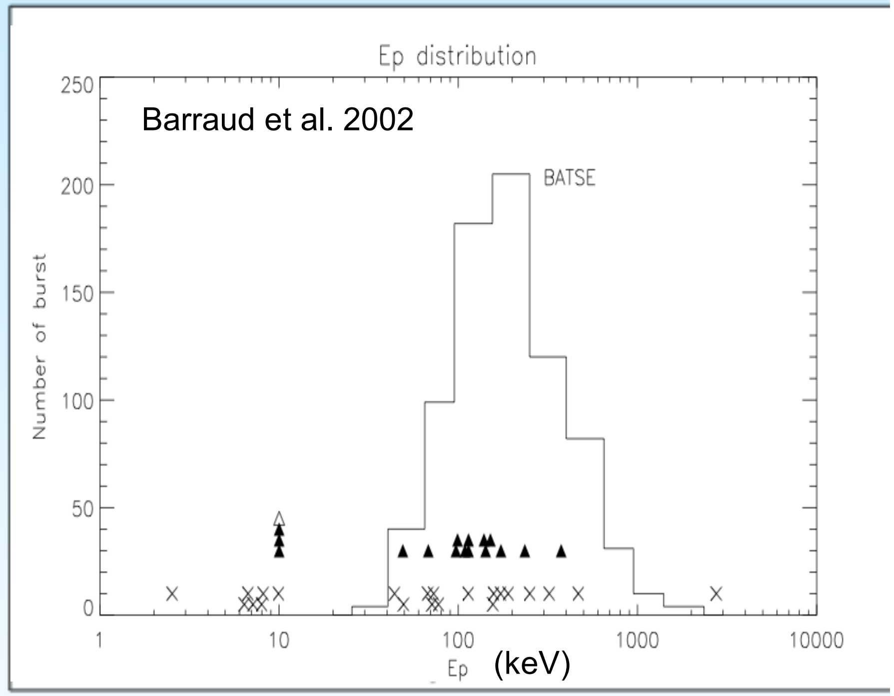


Spectral Properties of GRBs





Schaefer et al. (1998)



Peak Energy Distribution

Band Function: Smoothly Broken Power-Law

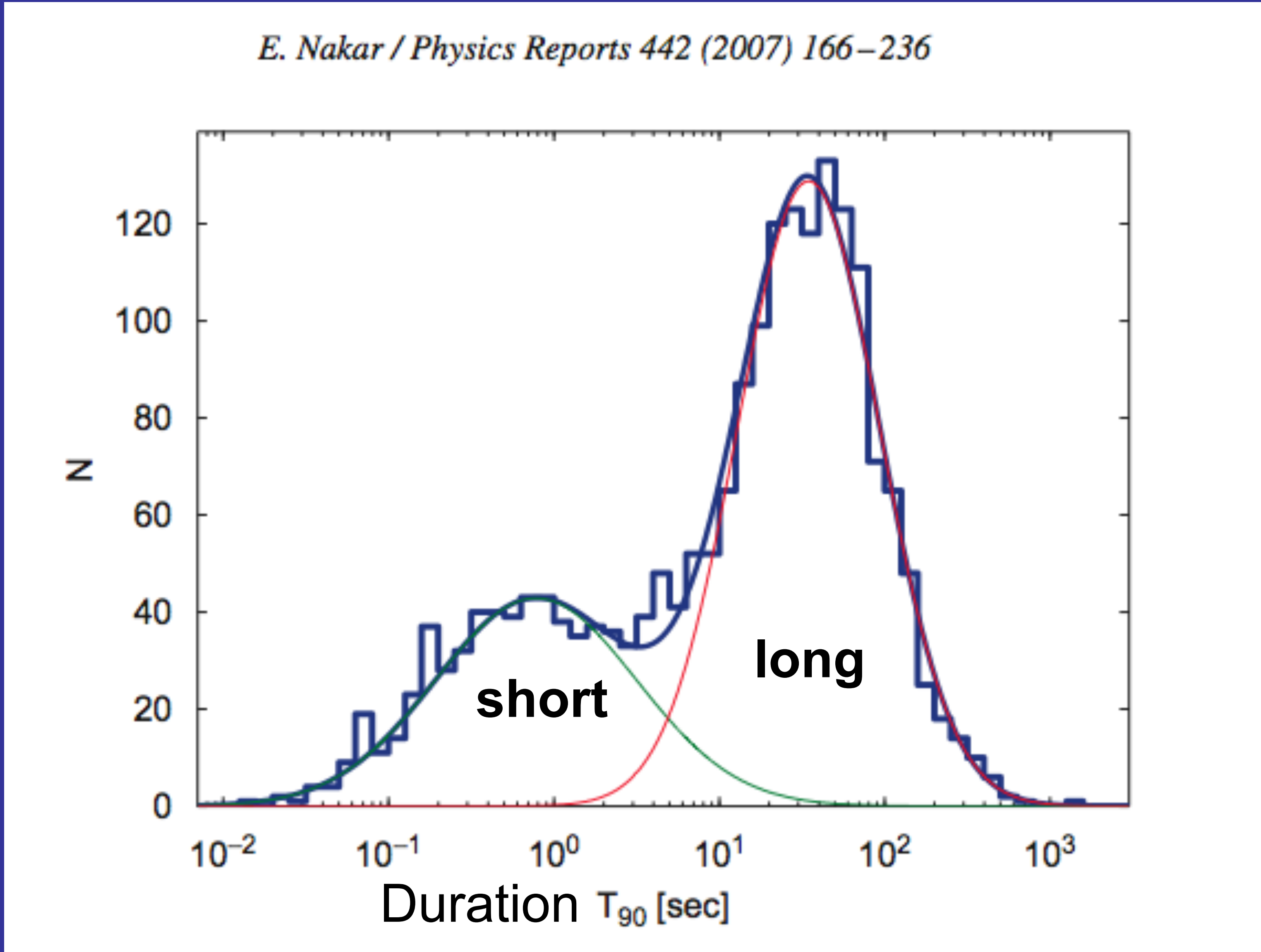
$$\phi(\varepsilon;t) = k_B \varepsilon^{\alpha} \exp[(\beta-\alpha)\varepsilon/\varepsilon_{br}], \varepsilon \le \varepsilon_{br}$$

$$\phi(\varepsilon;t) = k_B \varepsilon^{\beta} \varepsilon_{br}{}^{\alpha-\beta} \exp(\beta-\alpha), \varepsilon > \varepsilon_{br}$$

$$\varepsilon_{pk} = \left(\frac{2+\alpha}{\alpha-\beta}\right)\varepsilon_{br}$$

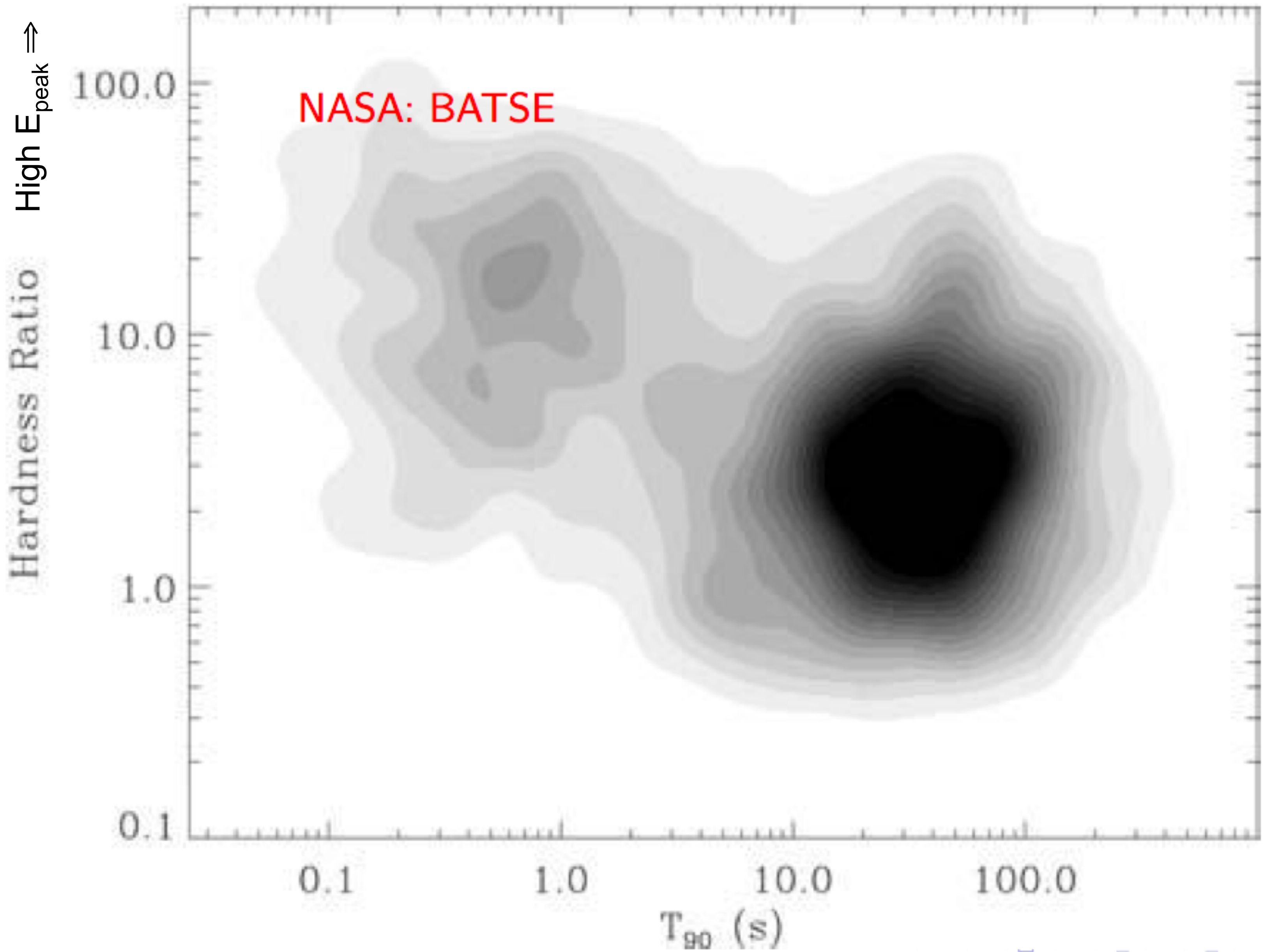
Band et al. (1993)

Gamma-Ray Burst Durations



BATSE Bursts (from Nakar 2007)

Bimodality of Gamma Ray Bursts



The Dark Ages (1972-1991)

- Gamma-rays are difficult to focus. The precise location of a GRB on the sky is difficult to pin down accurately.
- 'Consensus' opinion in the 1970s & 80s: GRBs come from within our Galaxy.

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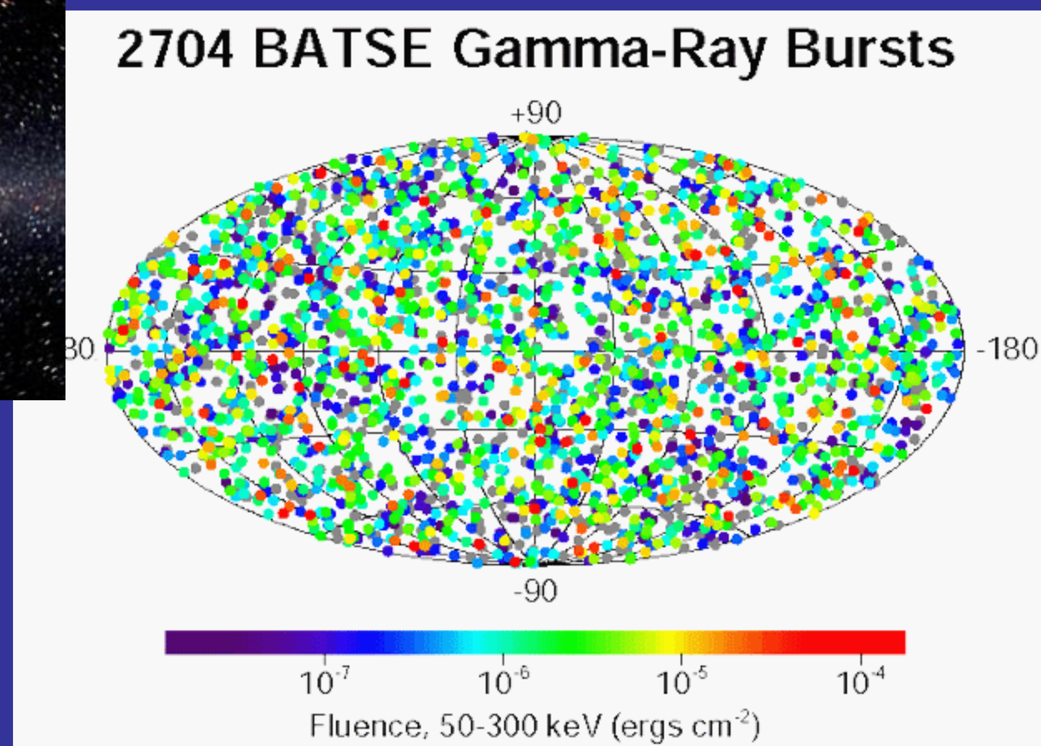
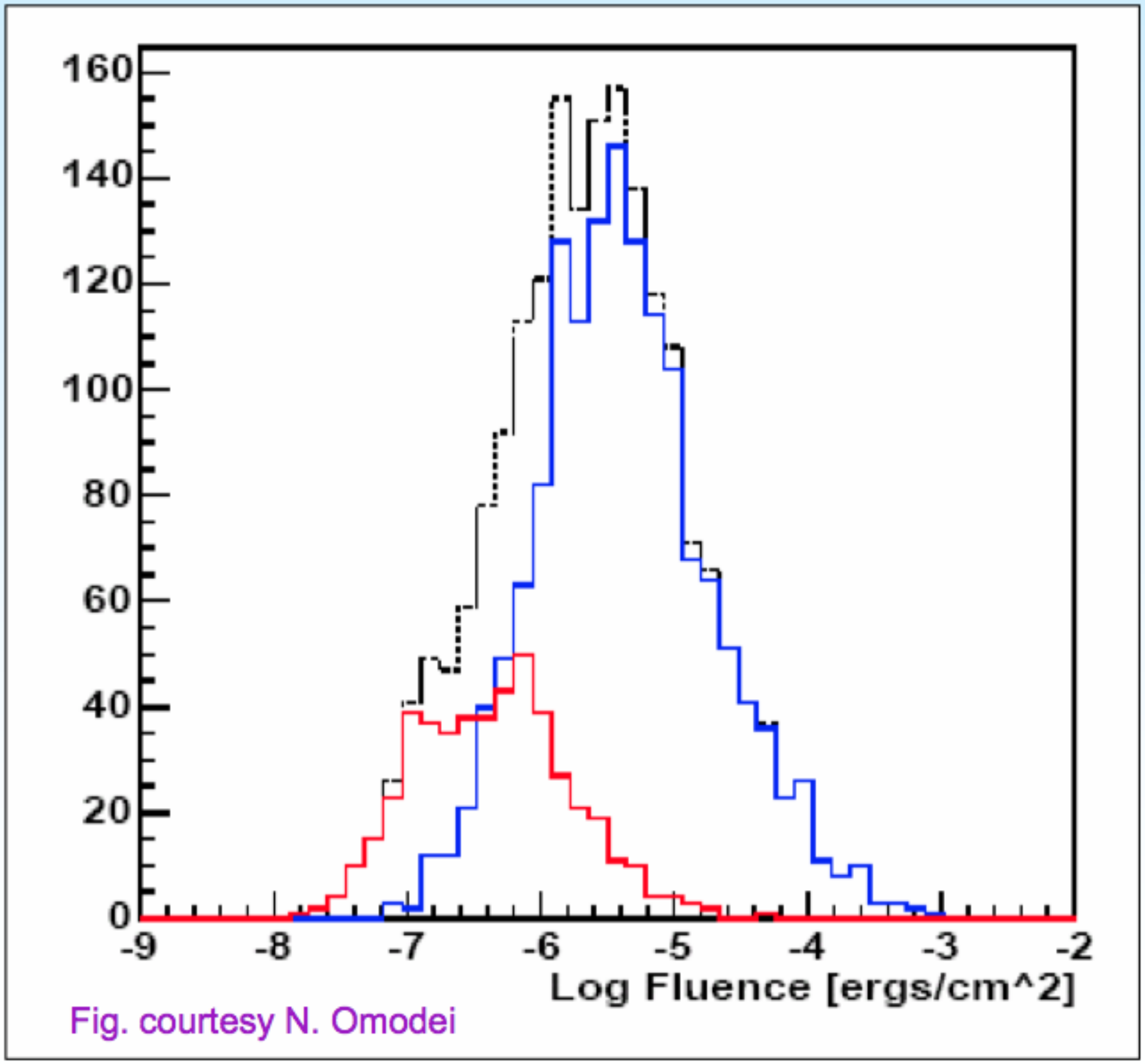
Paczynski, Rees, and Lamb



Fluence Distribution of GRBs

Fluence distribution of 2135 BATSE GRBs



BATSE detected ~ 1 GRB per day

Viewed ~40% of full sky

~550 GRBs/yr above peak flux threshold of 0.3×10^{-7} ph (50 – 300 keV)/cm^2-s

GRBs at fluence levels > 3×10^{-4} ergs/cm^2 (2-5 GRBs per year at this level)

Fluence distribution of 477 short and 1496 long BATSE GRBs

Distances to Gamma Ray Bursts

A source emitting energy E at distance d would give an integrated flux (fluence) S

$$S = \frac{E}{4\pi d^2}.$$

If $d = 100$ AU (comets), $E \sim 10^{27}$ erg
$d = 1$ kpc (neutron star), $E \sim 10^{40}$ erg
$d = 1$ Gpc (galaxies), $E \sim 10^{52}$ erg.
All sources with $S > S_{min}$ are detected out to a maximum distance

$$d_{max} = \sqrt{\frac{E}{4\pi S_{min}}}.$$

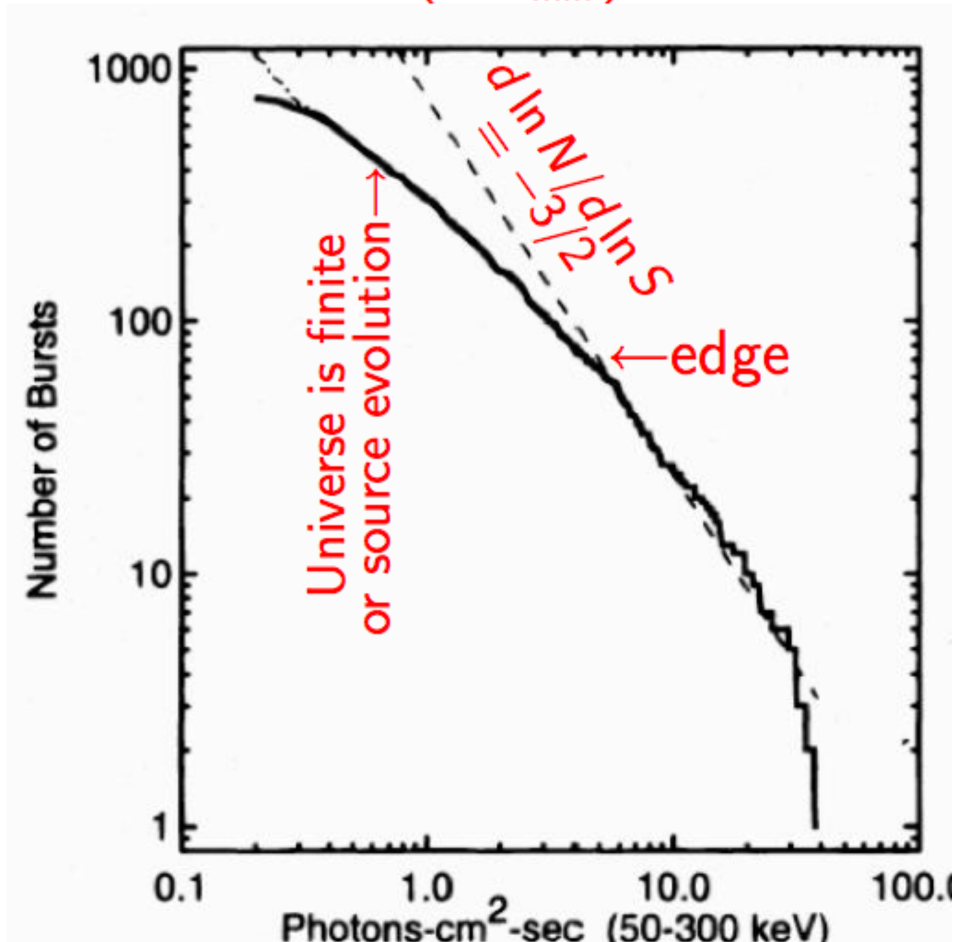
The volume with sources having $S > S_{min}$ is

$$V = \frac{4\pi}{3} d_{max}^3.$$

Distribution is isotropic, the 'edge' is cosmological, not galactic.

If n is the source number density, the number in volume V is

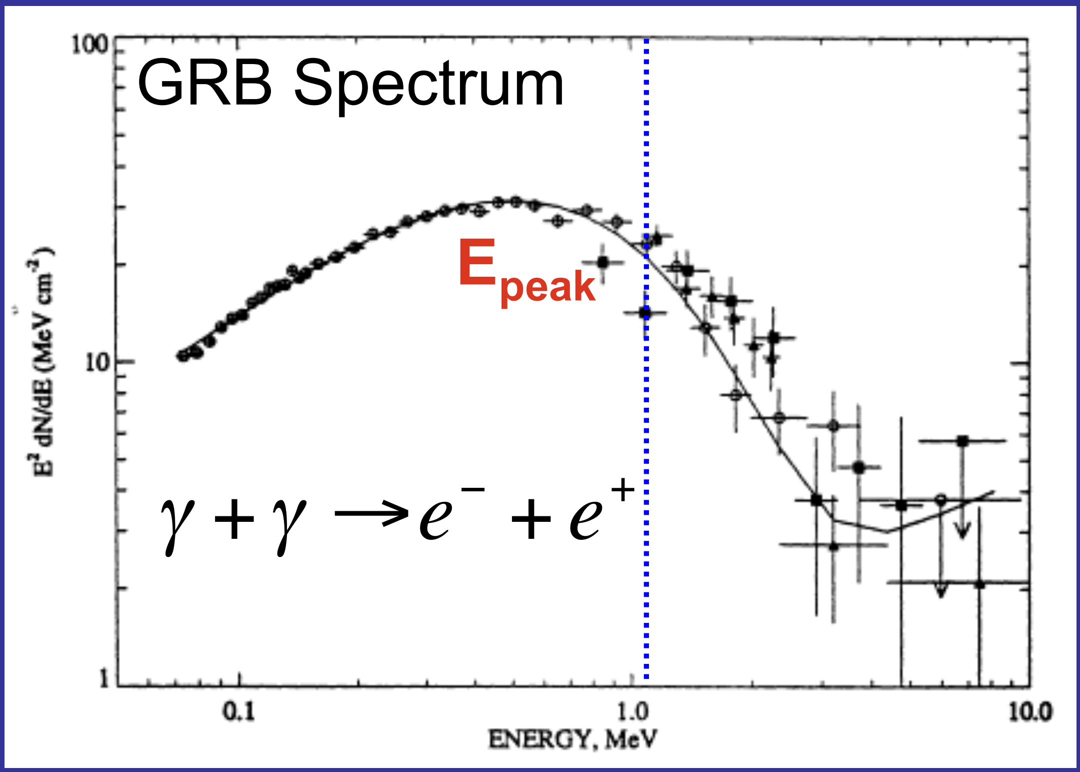
$$N = nV = \frac{4\pi}{3} n \left(\frac{E}{4\pi S_{min}} \right)^{3/2} \propto S_{min}^{-3/2}.$$

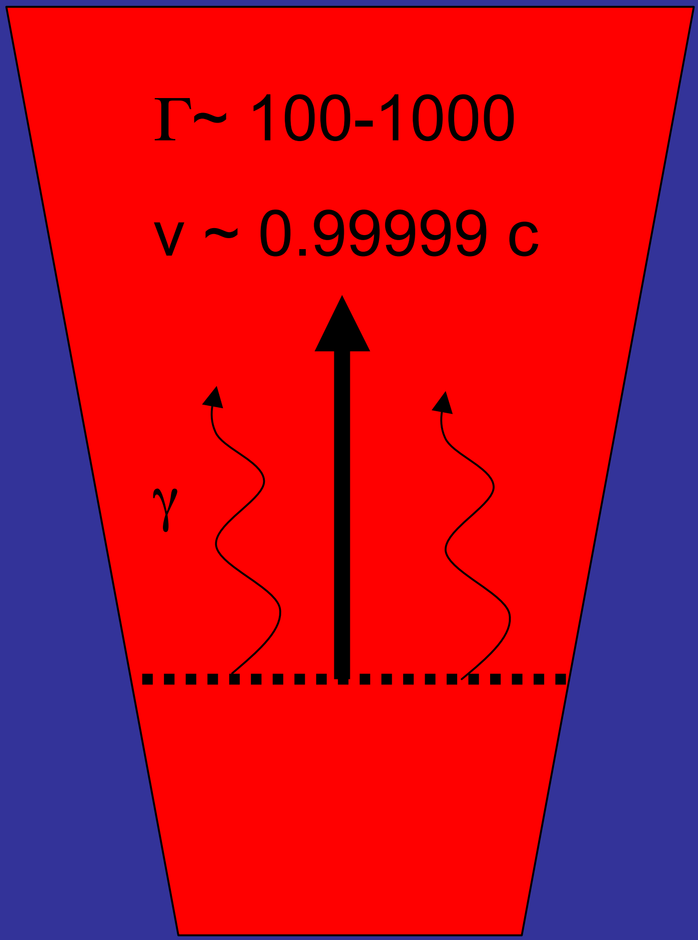


GRBs as Ultra-Relativistic Explosions

Large (cosmological) distances ⇒
huge energies $E_\gamma \sim 10^{51}$-10^{54} ergs ~ 10^{-3} - $1 M_\odot c^2$

fast variability δt_{var} ~ 10 ms ⇒
compact source $R_{max} \sim c/\delta t_{var} \sim 10^7$ cm





Why GRBs must originate from relativistic outflows

Zhang & Meszaros (2004)

For a typical GRB gamma-ray fluence $F \sim 10^{-6}$ erg cm^{-2} and distance $D \sim 3$ Gpc, the total isotropic gamma-ray energy released is typically $E = 4\pi D^2 F \sim 10^{51}$ ergs. Naively (without relativistic motion), the scale of the emission area is $c\delta t = 3 \times 10^8$ cm $(\delta t/10\text{ms})$. Assuming that a fraction f_p of photons is above the two-photon pair production ($\gamma\gamma \to e^+e^-$) threshold [$\epsilon_1\epsilon_2(1 - \cos\theta_{12}) \geq 2(m_e c^2)^2$, where m_e is the electron mass, ϵ_1 and ϵ_2 are the energies of two photons, and θ_{12} is the angle between the momenta of the two photons], and using an approximate pair production cross section of the order of the Thomson cross section $\sigma_T = 6.25 \times 10^{-25}$ cm^2, the pair-production optical depth is huge, i.e. $\tau_{\gamma\gamma} = f_p \sigma_T F D^2/(c\delta t)^2 m_e c^2 \sim 10^{15} f_p (F/10^{-6} \text{ erg cm}^{-2})(D/3 \text{ Gpc})^2 (\delta t/10 \text{ ms})^{-2}$. Thus, the gamma-rays should have been attenuated in the source before traveling through the universe and reaching the earth. The only way to get rid of this apparent paradox is by invoking relativistic bulk motion, i.e., the GRB emitting region as a whole moves towards us observer with a high Lorentz factor.

radius of 1st photon: $R_1 = ct$

1st photon leaves at t=0

radius of 2nd photon: $R_2 = c(t - \Delta t) + \beta c \Delta t$

2nd photon leaves Δt later..

…over which time the gamma-emitting shell has moved this distance

$$\Delta t_{\text{obs}} \sim (R_1 - R_2)/c \sim (1-\beta)\Delta t \underset{\beta \sim 1}{\sim} 2\Delta t/\Gamma^2$$

Table 3

CITED IN TEXT | ASCII | TYPESET IMAGE |

Limits on Selected Bursts

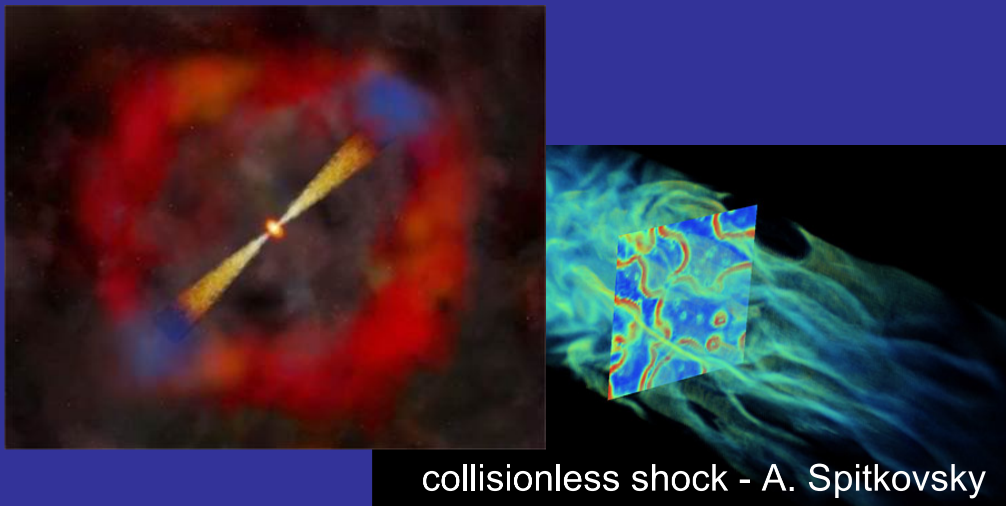
GRB	f_1	α	$\epsilon_{max}/m_e c^2$	z	$\hat{\tau}$	Limit A	Limit B	Reference
Bursts with Very High Energy Photons								
910503...	8.71	2.2	333	1	3.0×10^{12}	**340**	300	1
910601...	0.5	2.8	9.8	1	1.8×10^{11}	72	**110**	2
910814...	13.5	2.8	117	1	4.7×10^{12}	**200**	190	3
930131...	1.95	2.0	1957	1	7.0×10^{11}	**420**	270	4
940217...	0.36	2.5	6614	1	1.2×10^{11}	**340**	120	5
950425...	1.62	1.93	235	1	6.0×10^{11}	**300**	280	6
990123...	1.1	2.71	37	1.6	1.2×10^{12}	150	**180**	7
Bursts with Redshifts								
971214...	0.35	2	1	3.42	2.6×10^{12}	192	**410**	8
	0.1	3	1	3.42	7.5×10^{11}	64	**160**	8
980703...	0.08	2	1	0.966	2.7×10^{10}	69	**140**	8
	0.02	3	1	0.966	8.0×10^{9}	24	**56**	8
990510...	0.1	2	1	1.62	1.2×10^{11}	98	**200**	8
	0.03	3	1	1.62	3.7×10^{10}	34	**79**	8
Unusual Bursts								
980425...	0.04	2	1	0.0085	1.0×10^{4}	4.6	**6.4**	8
	0.01	3	1	0.0085	2.9×10^{3}	2.8	**3.8**	8

Minimum Lorentz factors for the burst to be optically thin to pair production and to avoid scattering by pairs.

Lithwick & Sari, ApJ, 555, 540, (2001)

$$\Gamma \geq 200$$

The Afterglow Revolution (~1997)



collisionless shock - A. Spitkovsky

- If GRBs originate from far away, they must be very energetic explosions.
- Space is filled with tenuous gas. When the explosion runs into the gas, the resulting shock will accelerate electrons. This powers synchrotron emission from radio to X-rays.

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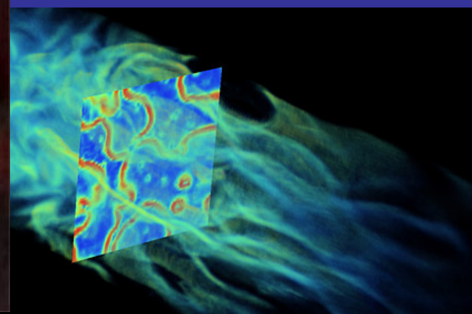

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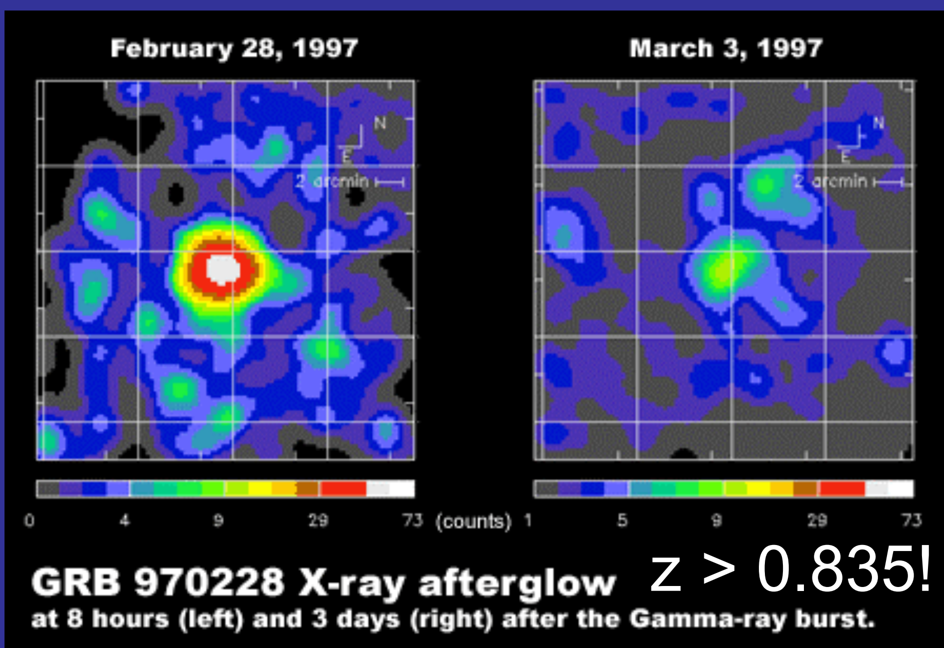
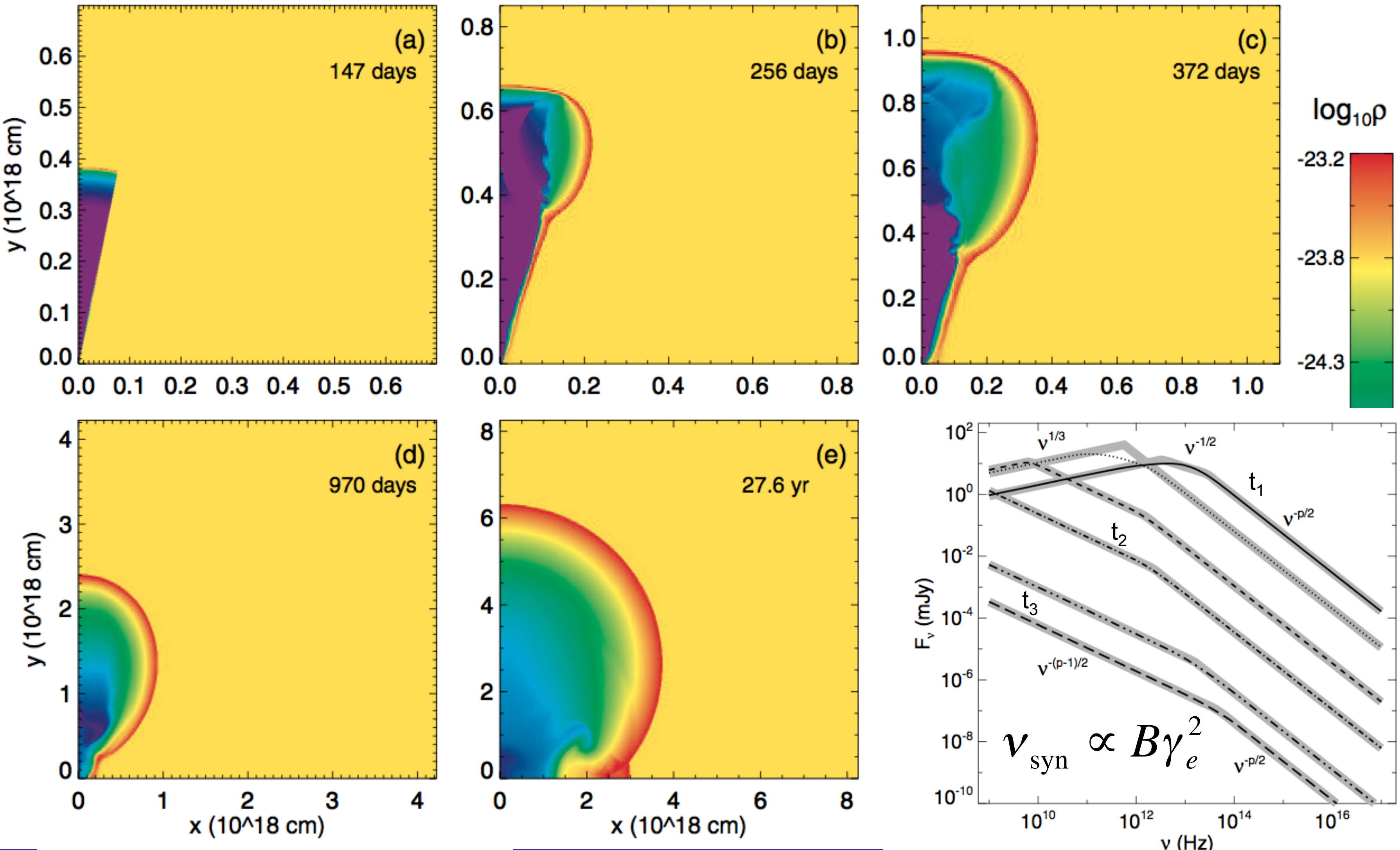


Deceleration of a Relativistic Jet



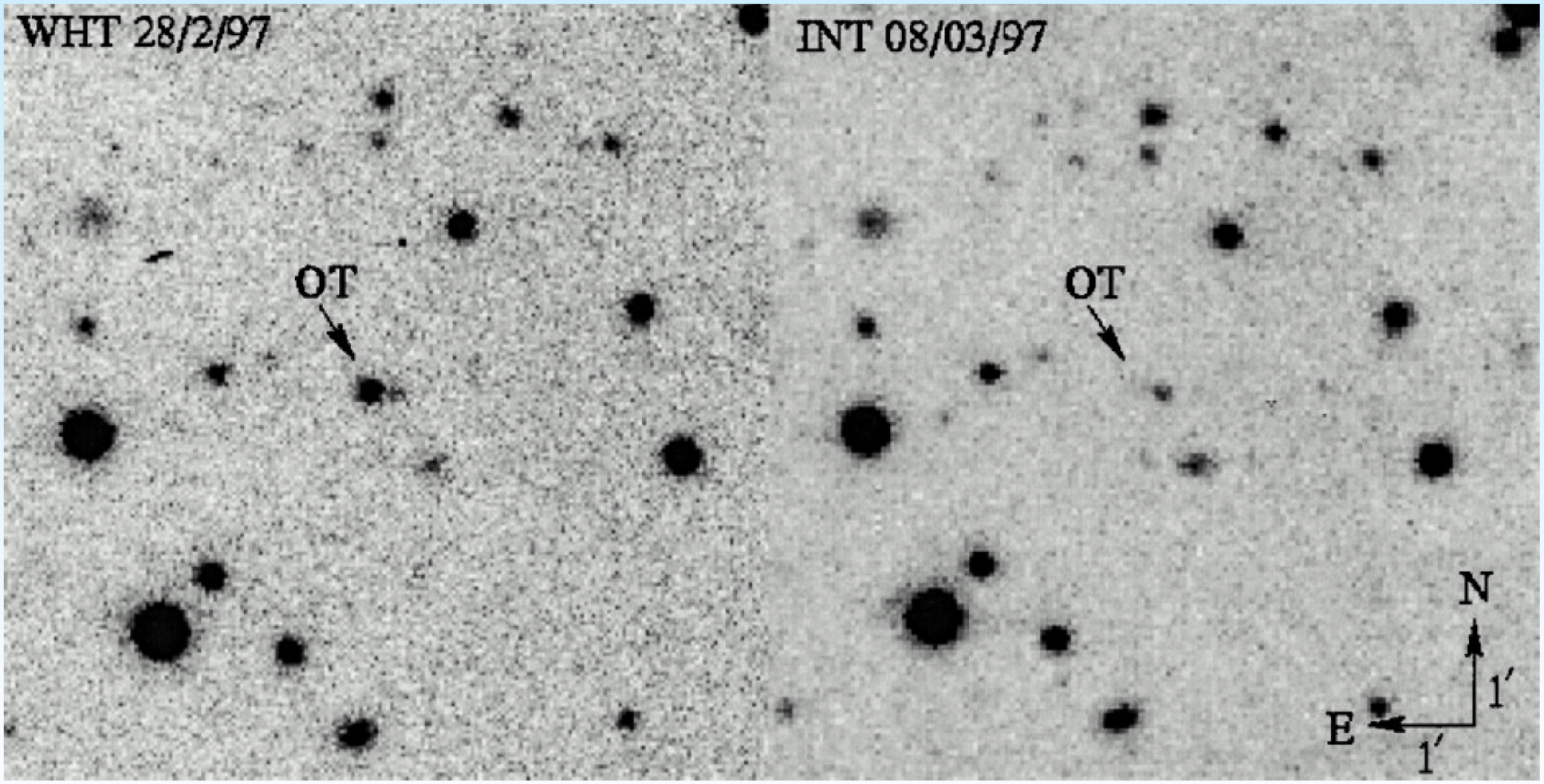
Zhang & MacFadyen 2009

$$E = \rho\Gamma^2 r^3 = \mathrm{const}$$

$$t \sim r/2c\Gamma^2 \Rightarrow$$

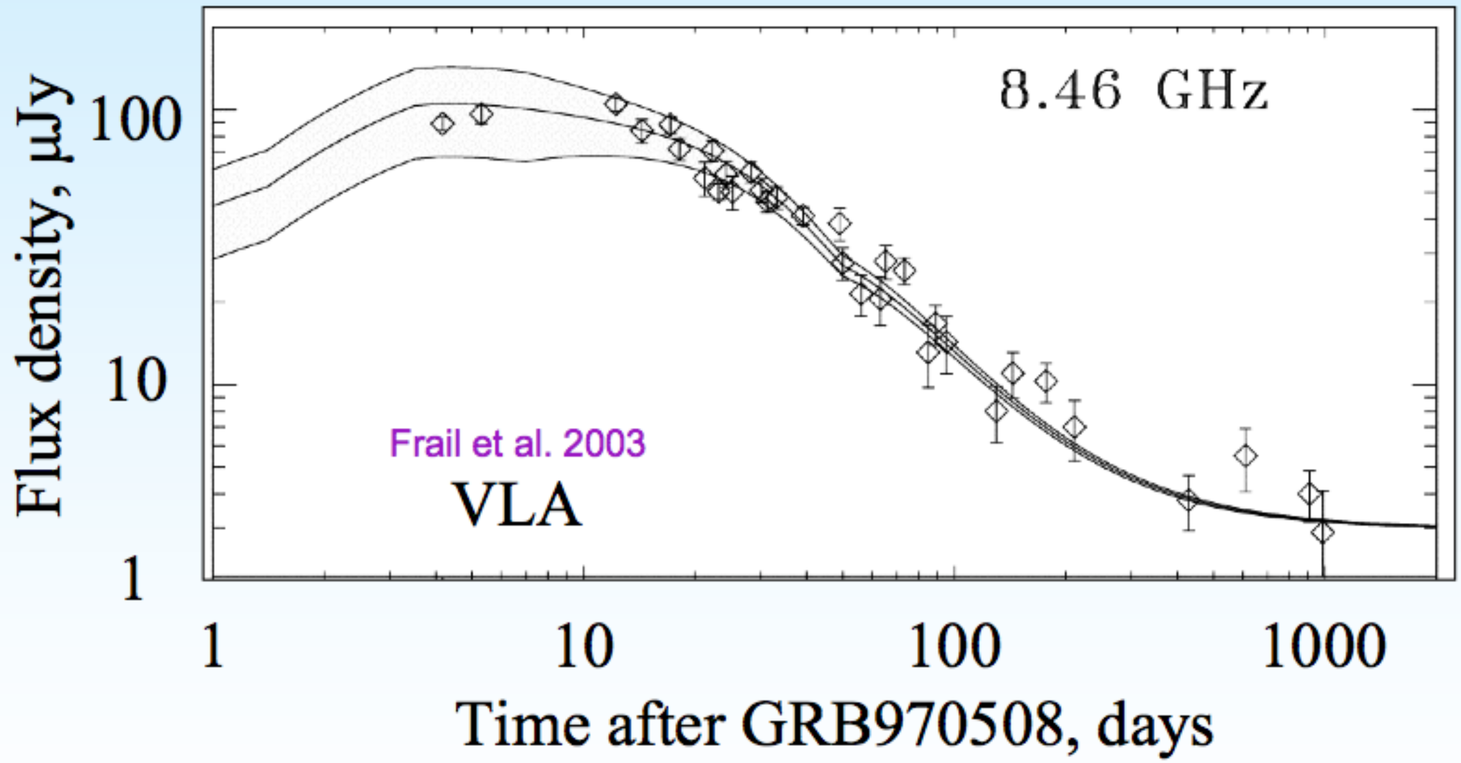
$$\Gamma \propto r^{-3/2} \propto t^{-3/8},\ r \propto t^{1/4}$$

Optical transient discovery image

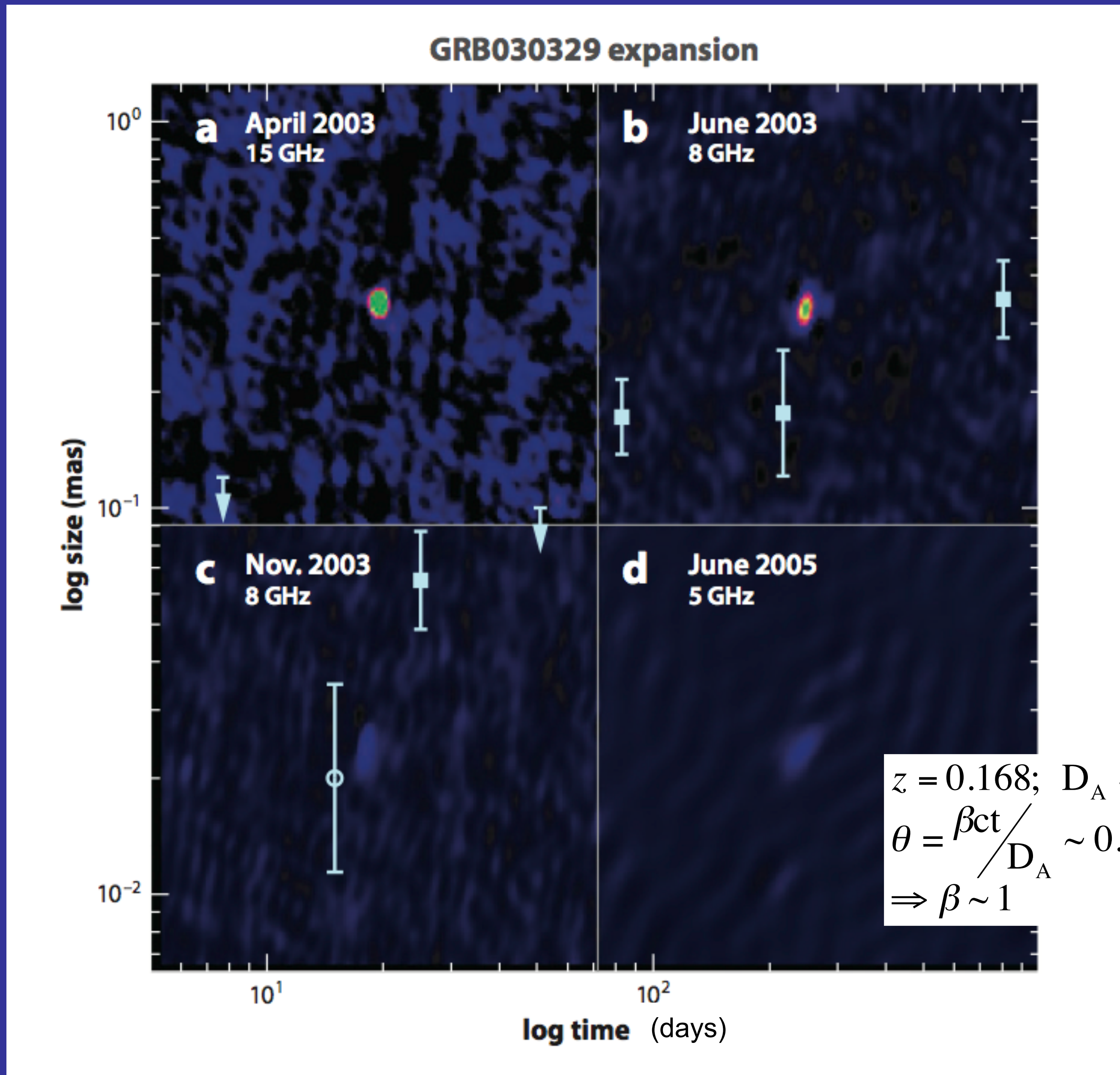


van Paradijs et al. (1997)

Radio Afterglow of GRB 970508 – 3 years on



Resolving the Radio Afterglow => Relativistic Motion



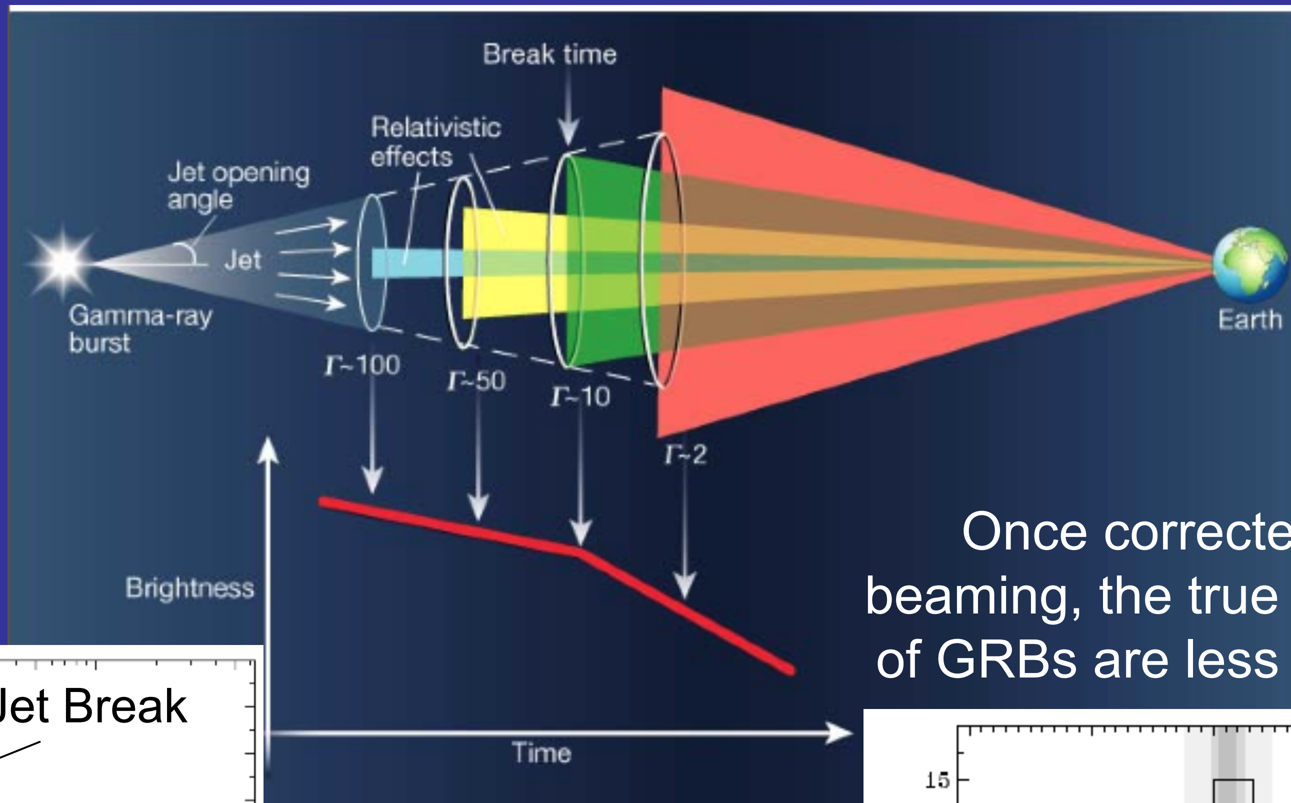
$z = 0.168$; $D_A \sim 600$ Mpc

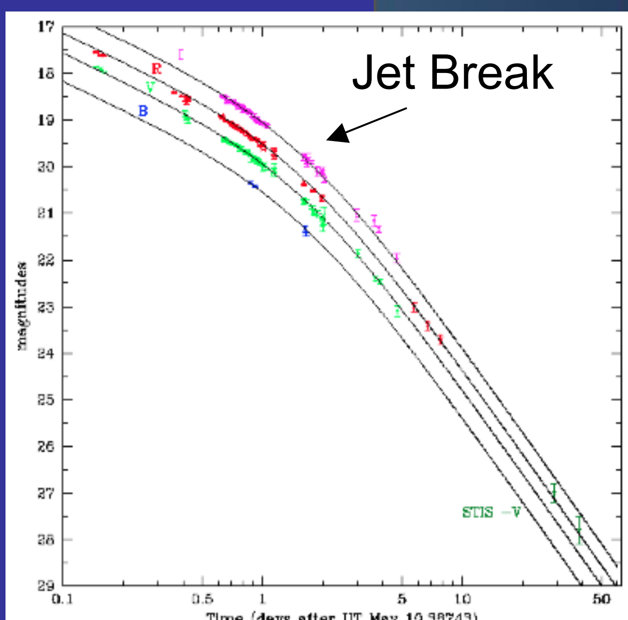
$$\theta = \beta c t / D_A \sim 0.2\ \beta \left(t / 100\ \mathrm{d} \right) \mathrm{mas}$$

$\Rightarrow \beta \sim 1$

Gehrels, Ramirez-Ruiz, & Fox 2009; data from Pihlstrom et al. 2008

GRBs as *Jetted* Relativistic Explosions



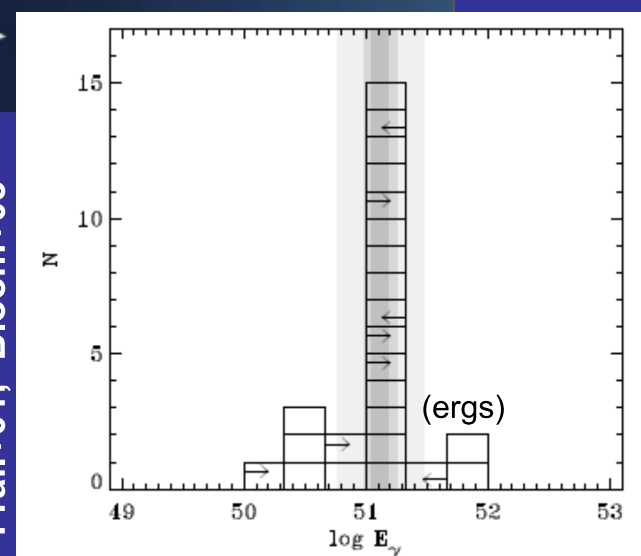


Once corrected for beaming, the true energies of GRBs are less extreme

jet opening angle

Θ_{jet} ~ 5-10^{o}

Frail+01; Bloom+03

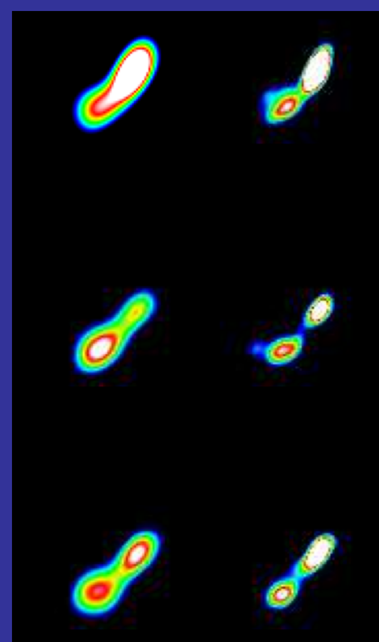


Implications for the "Central Engine"

- Rapid variability dt ~ 10 ms ⇒ R < c dt ~ 10^3 km
- Relativistic velocities v ~ c
- Huge energy release ~10^{50}-10^{52} ergs ~ 10^{-4} -10^{-2} $M_{\odot}c^2$

⇒ Catastrophic birth or destruction of stellar mass compact objects (neutron stars or black holes)

NS Circinus X-1

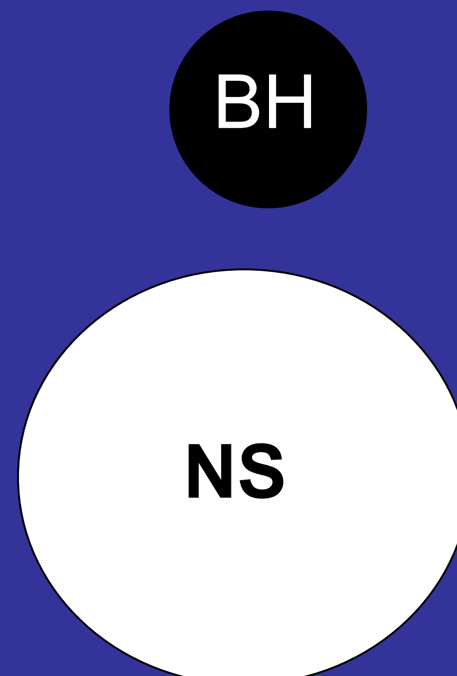


~day 1

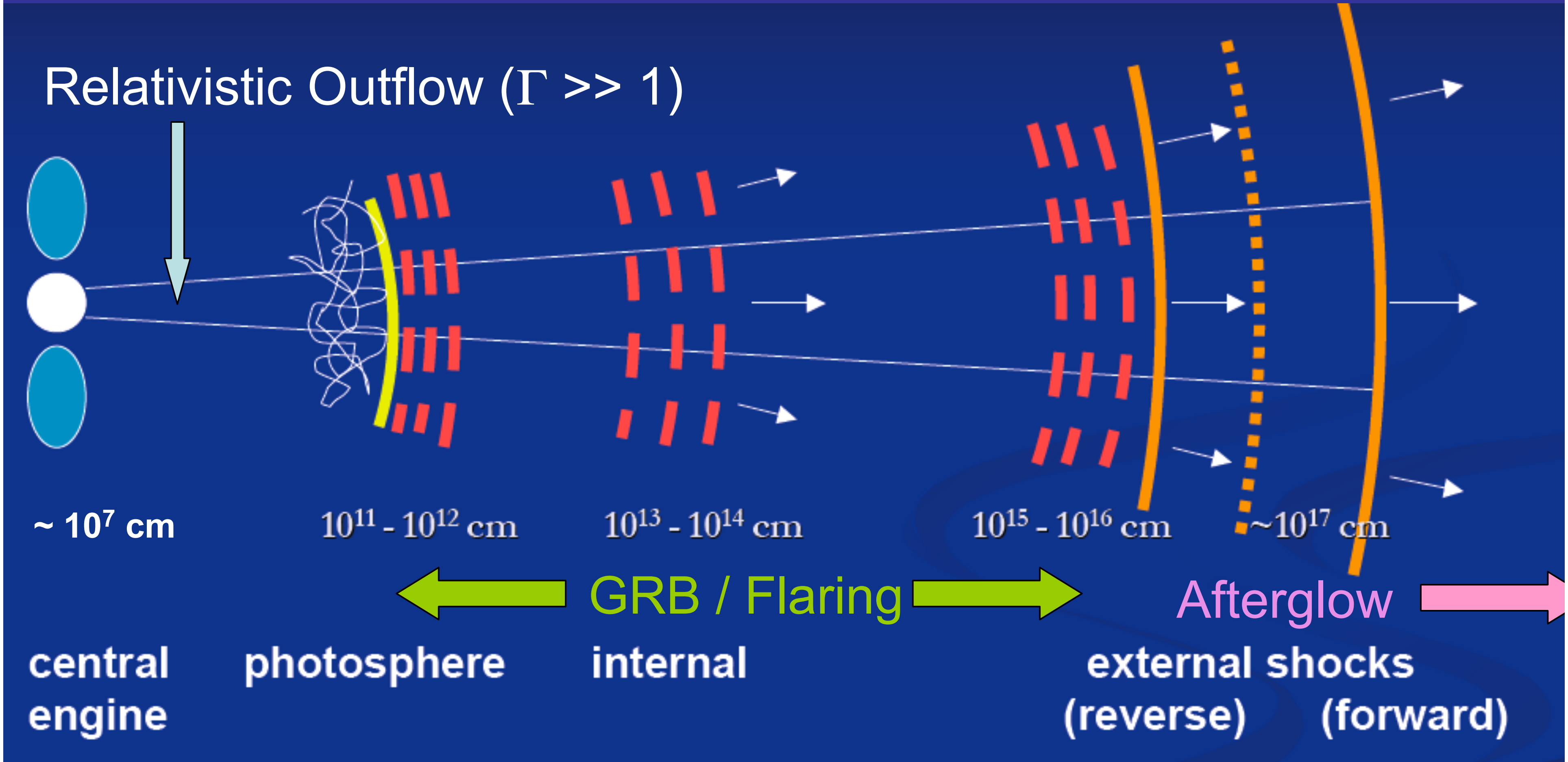
~day 3

~day 5

Fender et al. 2004



GRB Emission: Still Elusive!

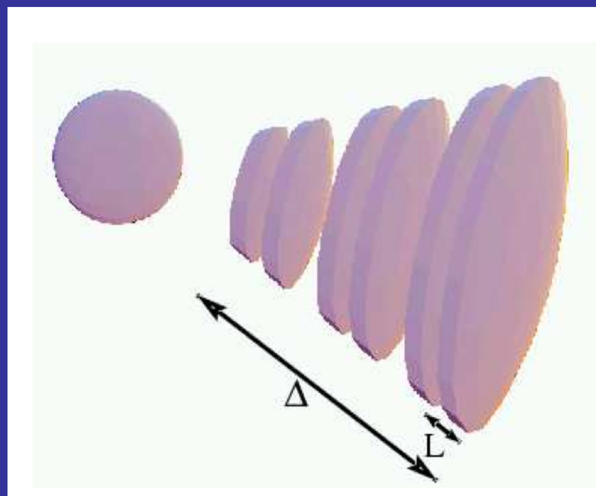


1. **What** is jet's composition? (kinetic or magnetic?)
2. **Where** is dissipation occurring? (photosphere? deceleration radius?)
3. **How** is radiation generated? (synchrotron, inverse-compton, hadronic?)

Prompt Emission Models

Internal Shocks (Synchrotron)

Piran 2004



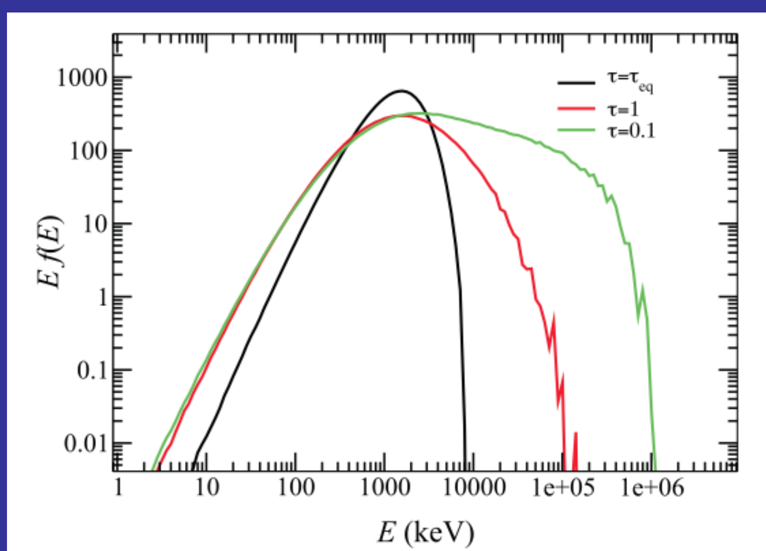
- jet variability ⇒ internal collisions ⇒ shocks ⇒ particle acceleration + B field amplification ⇒ synchrotron

pros: shocks inevitable in variable flows

cons: low radiative efficiency, requires fine tuning of shock parameters

"Photospheric" Dissipation (IC Scattering)

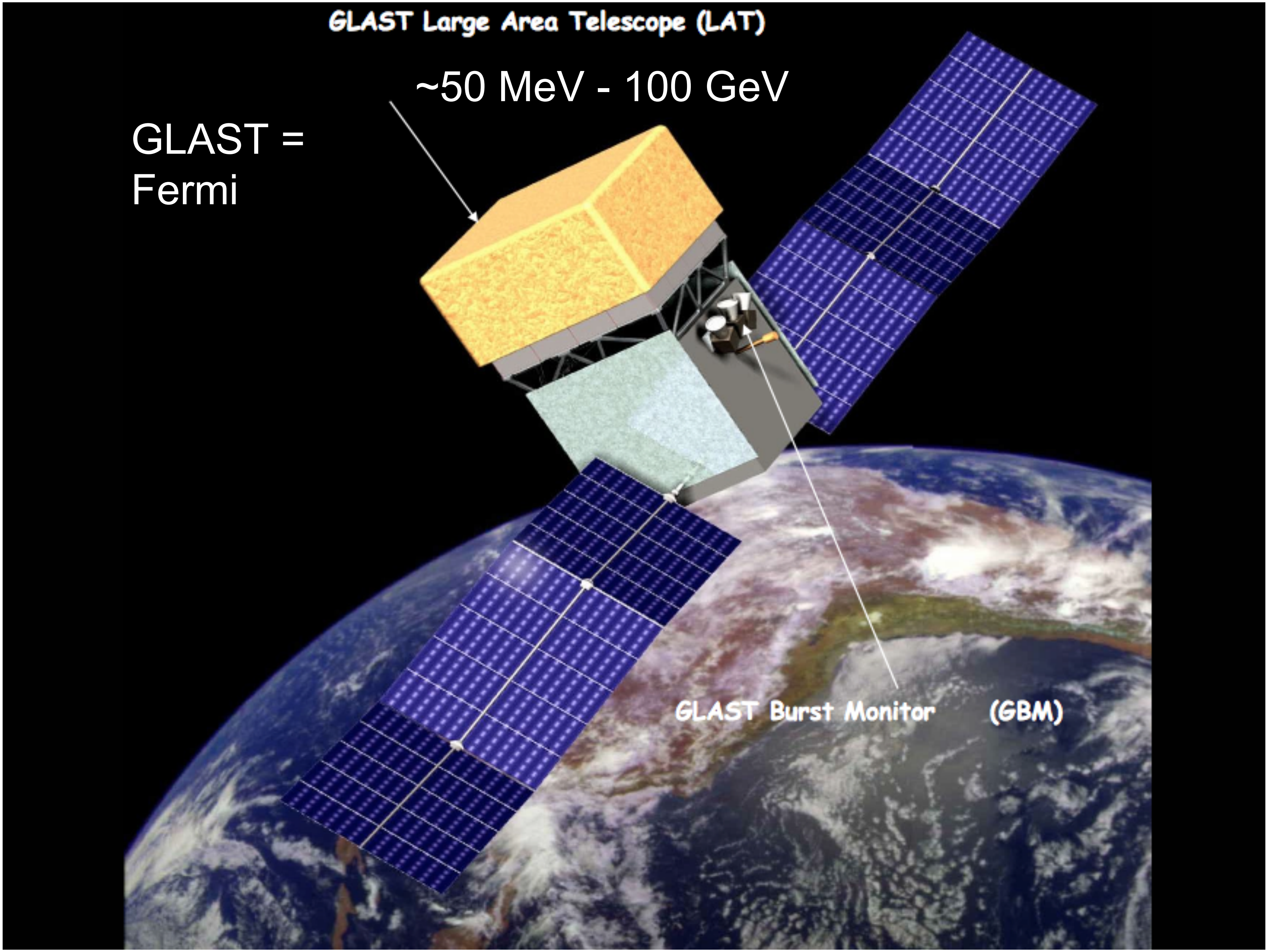
Giannios 2011



- GRB emission = thermal spectrum Comptonized (producing high energy power-law tail) by hot electrons near photosphere.

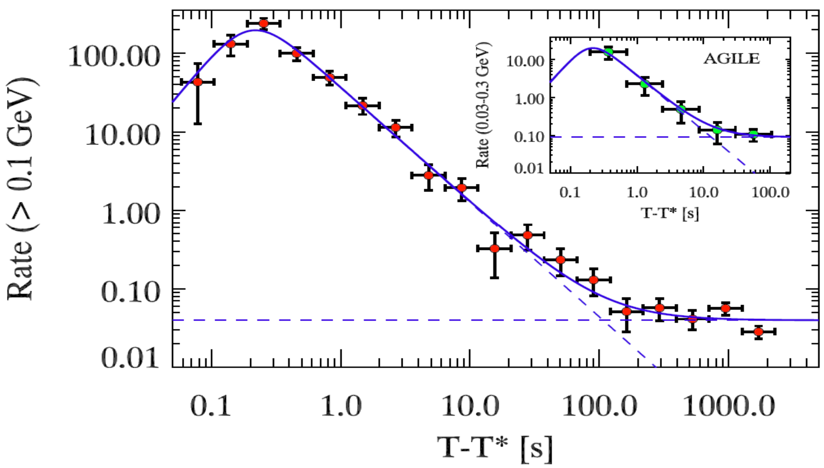
pros: ~MeV spectral peak set by photosphere temperature (robust)

cons: source of electron heating uncertain (shocks, collisions, reconnection)

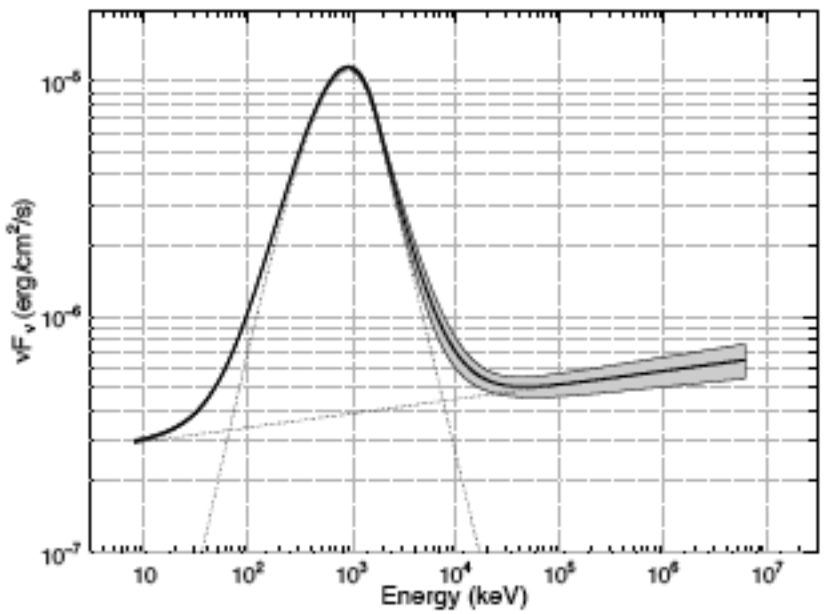

GLAST Large Area Telescope (LAT)
~50 MeV - 100 GeV
GLAST =
Fermi
GLAST Burst Monitor (GBM)

- **Extreme** Bursts (e.g. 080916C: E_{iso} = 8.8 x 10^{54} ergs)
- Distinct GeV Component
  - Delayed wrt MeV photons
  - Slow Decay (~ $t^{-1.5}$)
  - Origin: Prompt? Afterglow? (e.g. Kumar & Barniol Duran 09; Ghirlanda+09)

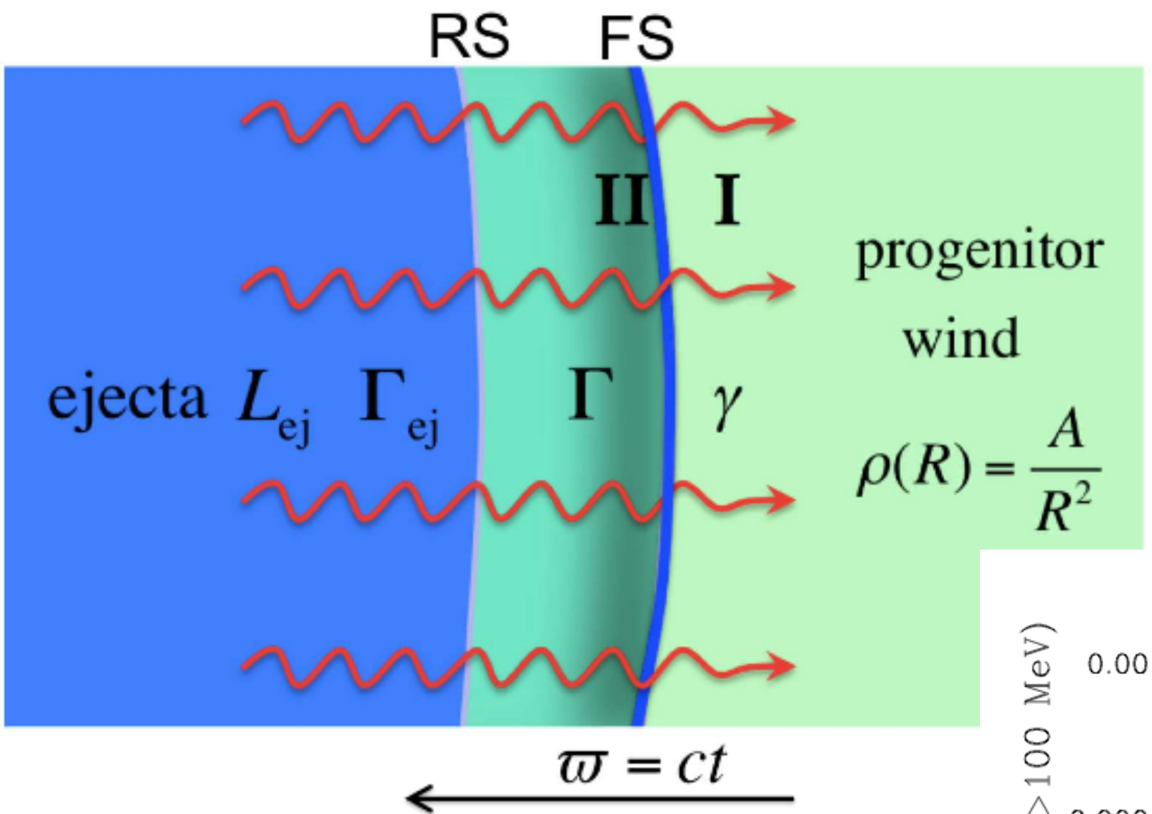
090510



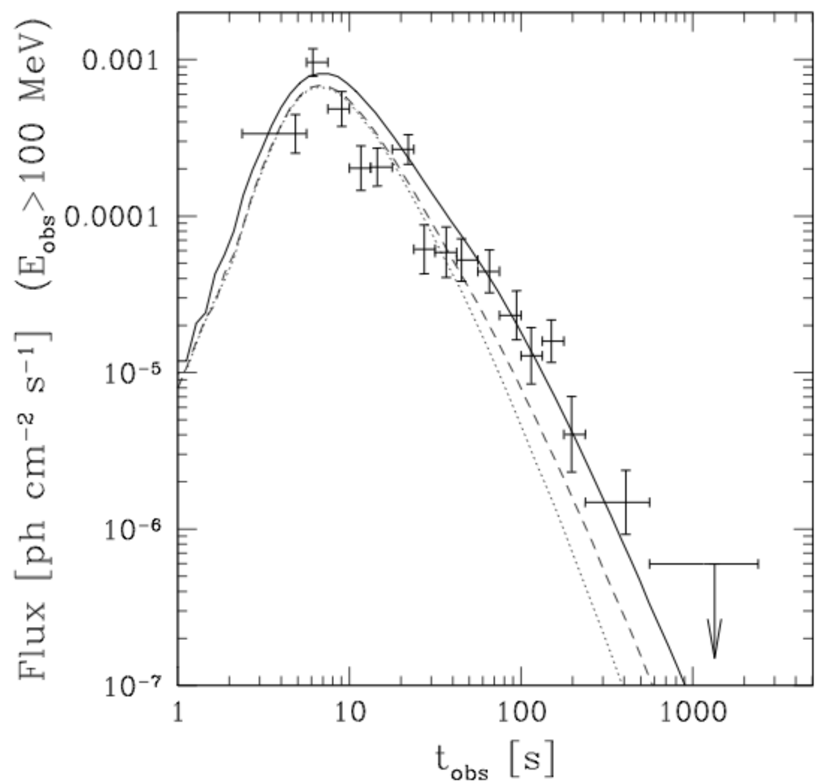
Ghirlanda et al. 2009



090902B (Fermi Collaboration 09)



Beloborodov et al. 2011



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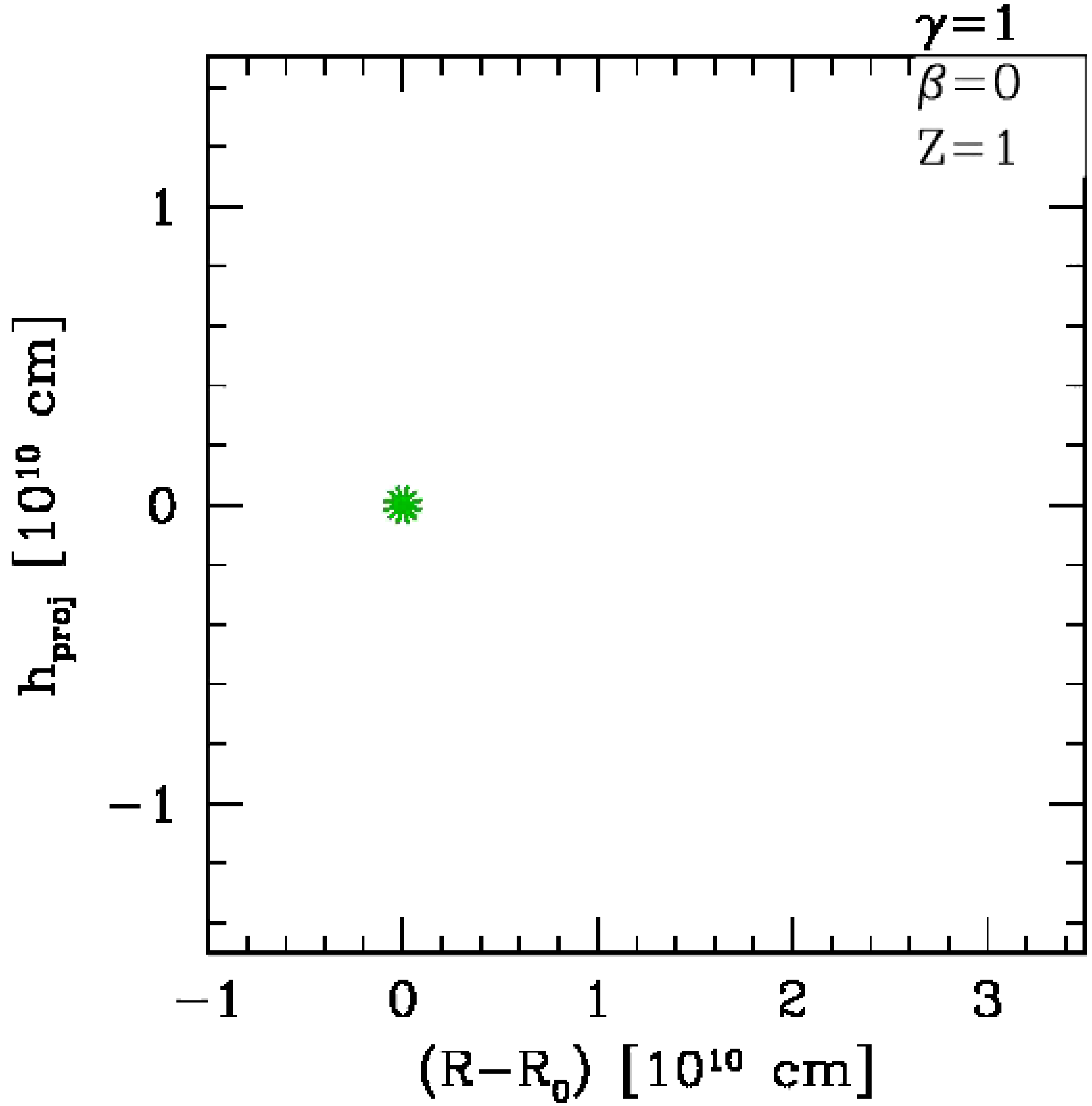
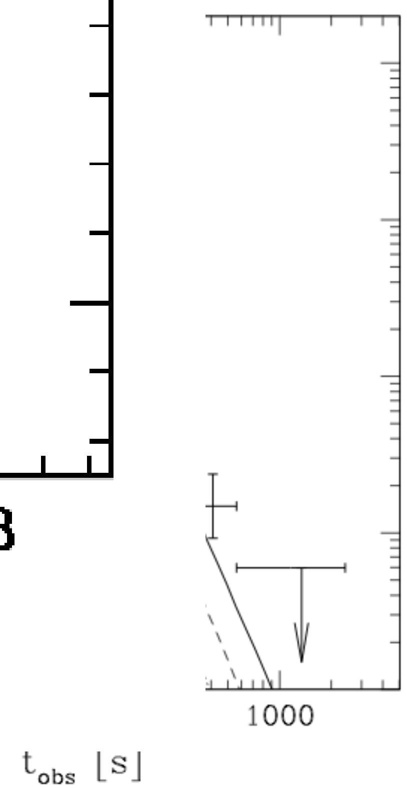
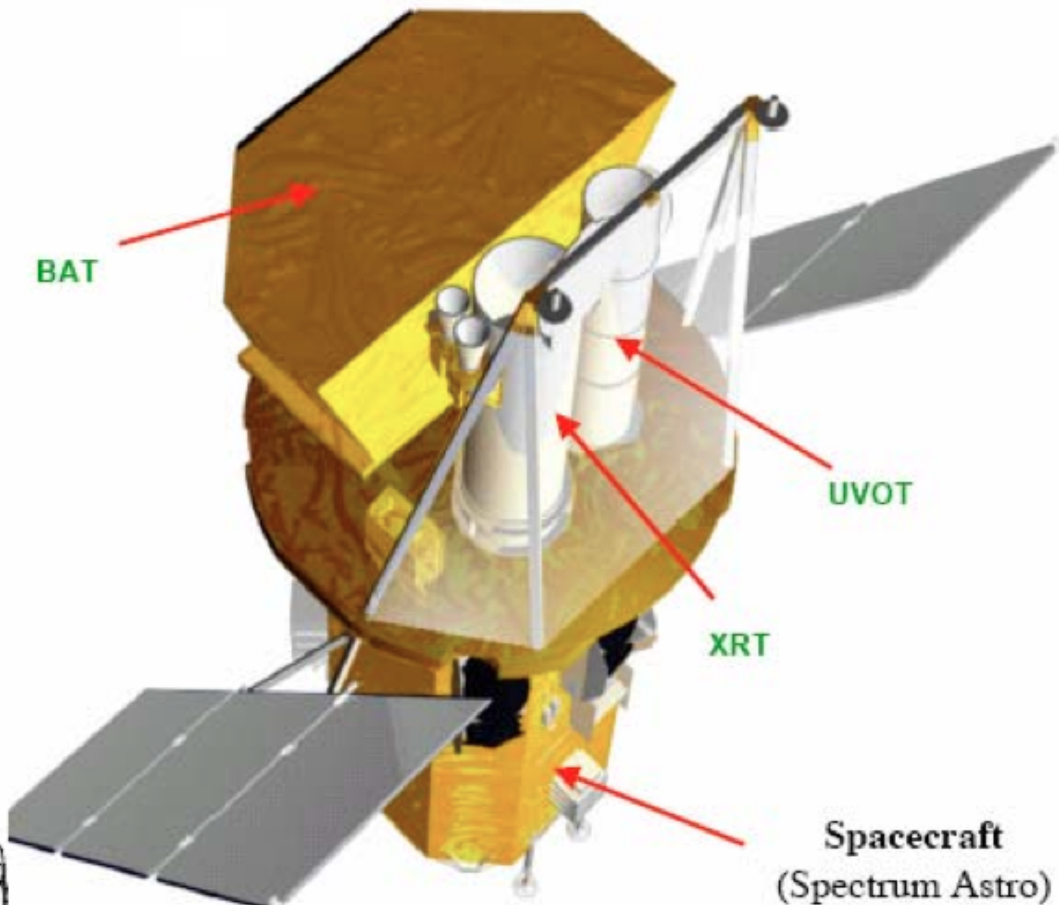




Swift Explorer

Swift Observatory



Launched November 20, 2004

Orbit
600 km x 21° inclination

Data Downlinks
TDRSS rapid (2 kbps)
ASI Malindi gnd station

Operations
Ops Center @ Penn State
Science Center @ GSFC

BAT
New CdZnTe detector
~100 GRBs/yr

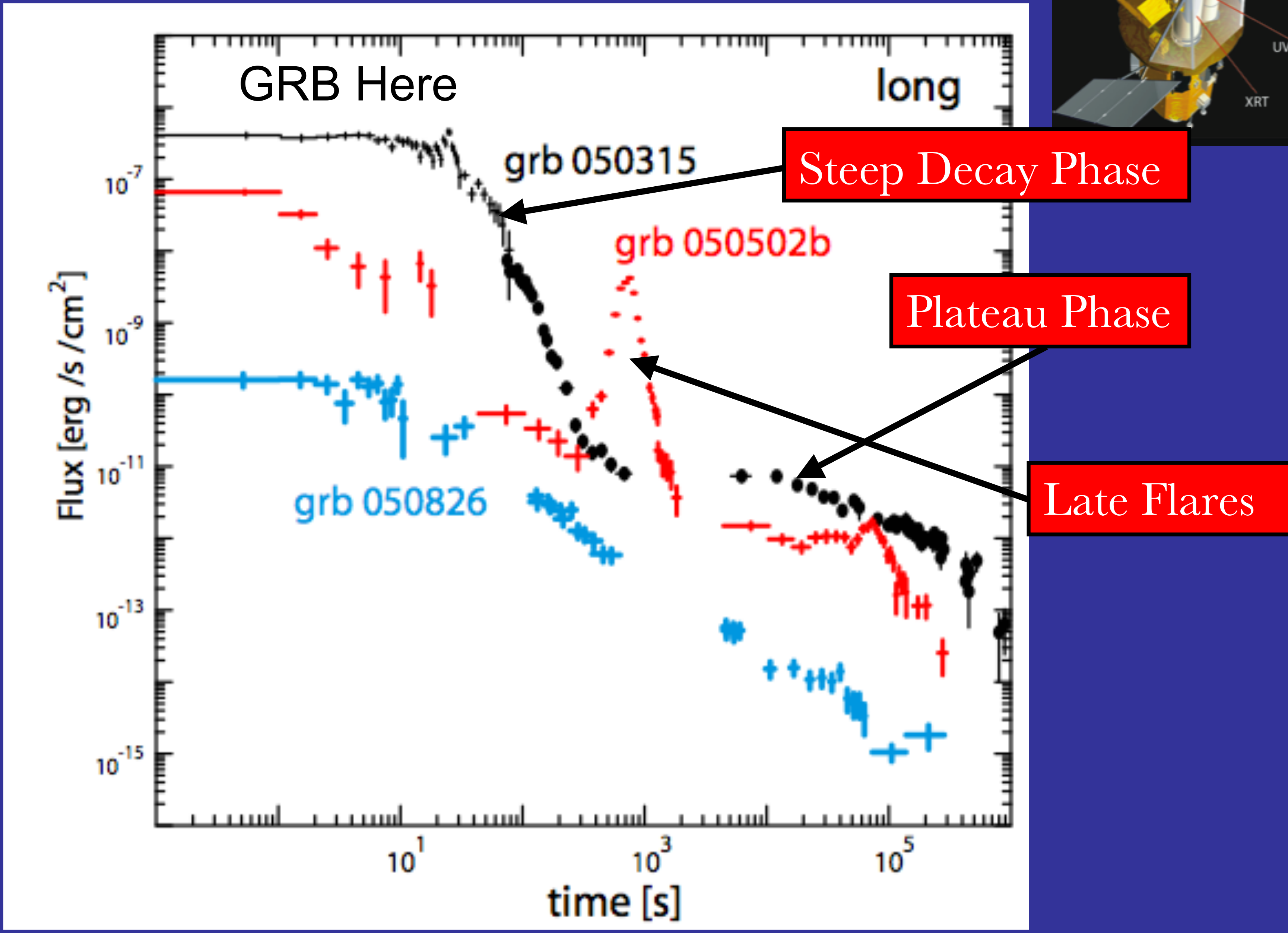
XRT
Arcsec GRB positions
CCD spectroscopy

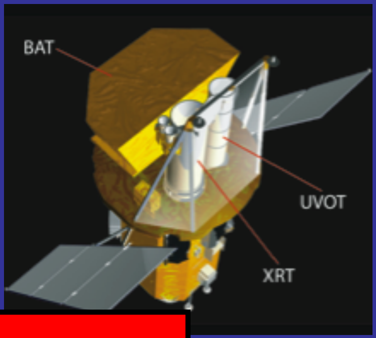
UVOT
Sub-arcsec positions
Grism spectroscopy

Spacecraft
Autonomous slews 20-75s

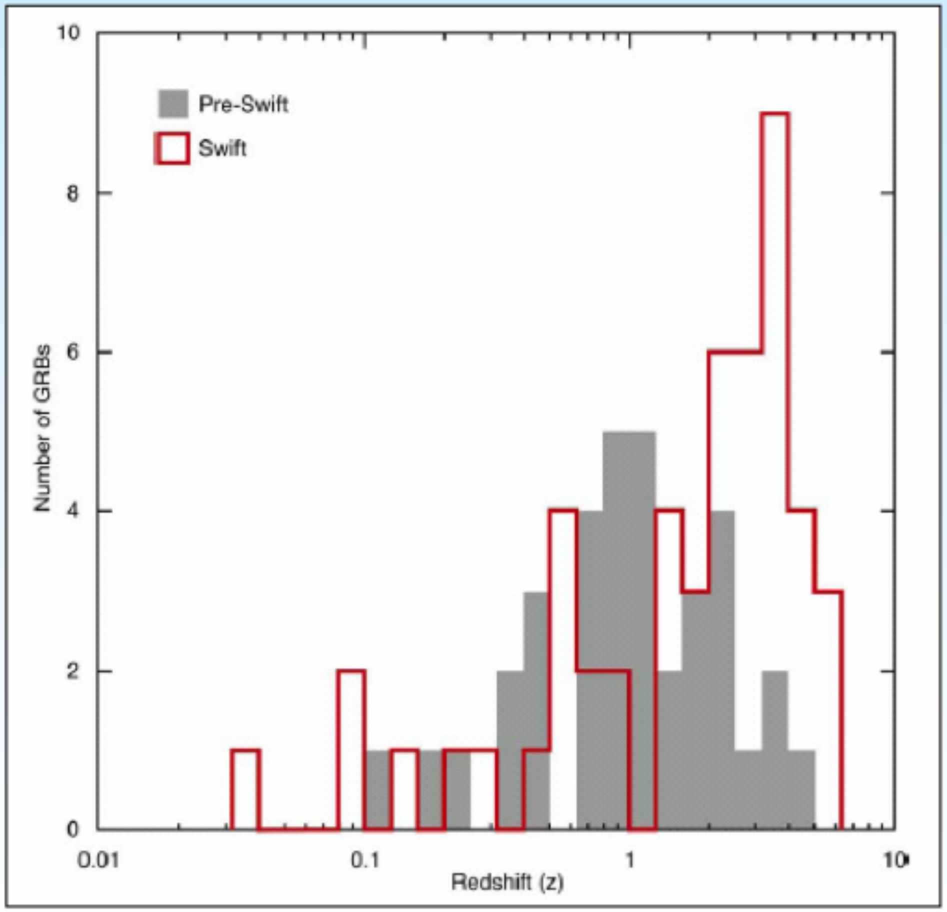
X-Ray Afterglows in the Swift Era

Gehrels, Ramirez-Ruiz & Fox 2009





Redshift Distribution of Swift Long-Duration GRBs



Mean redshift $\langle z \rangle \sim 2$ vs. $\langle z \rangle \sim 1$ for pre-Swift GRBs

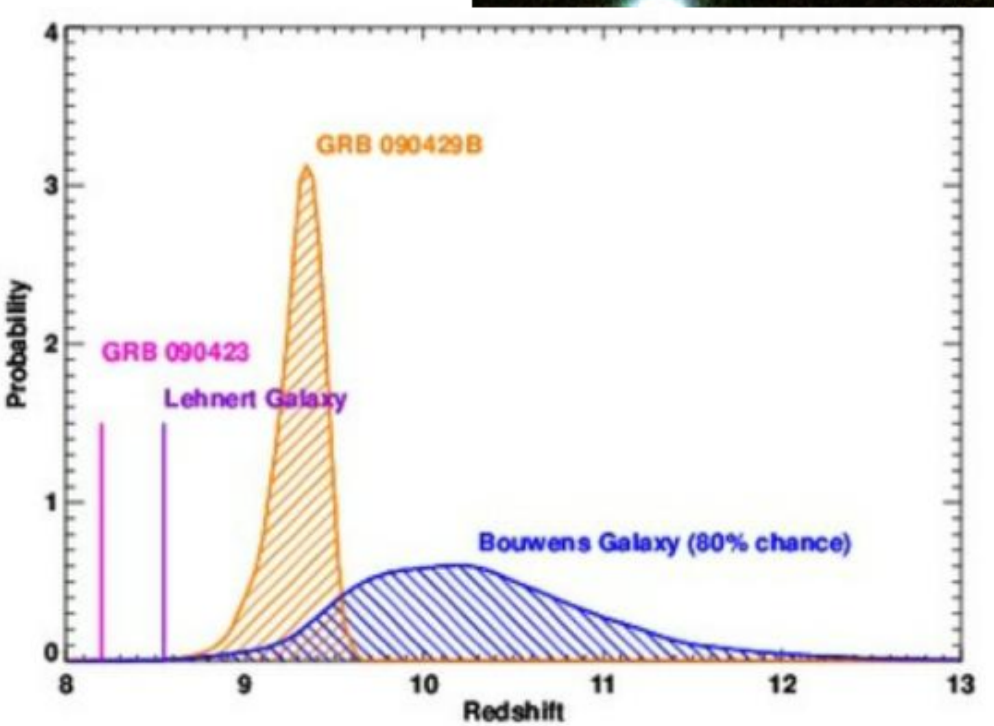
Most Distant GRBs

$z = 8.26$

$t = 630$ Myr

$z = 10$

$t = 480$ Myr



GRBs As Probes of Chemical Evolution

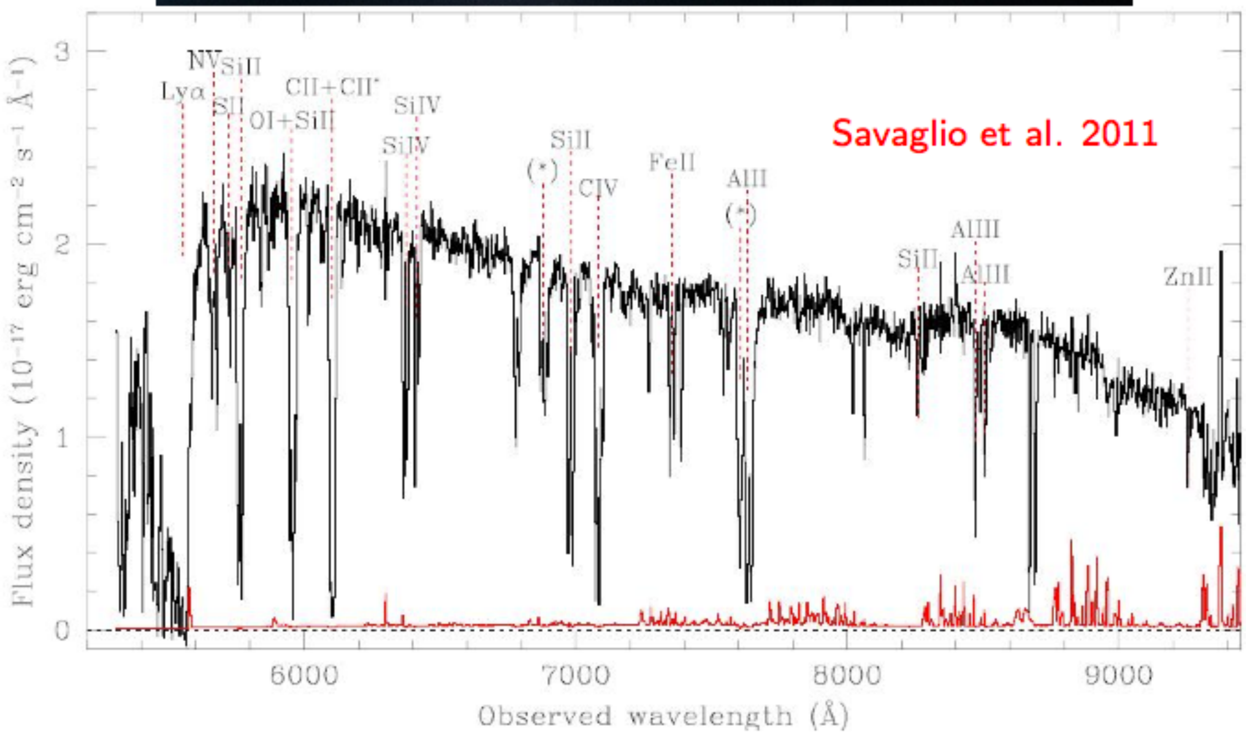
GRB light is absorbed by intervening galaxies.

Two systems, $z = 3.5673$ and $z = 3.5774$, probably merging galaxies, are illuminated.

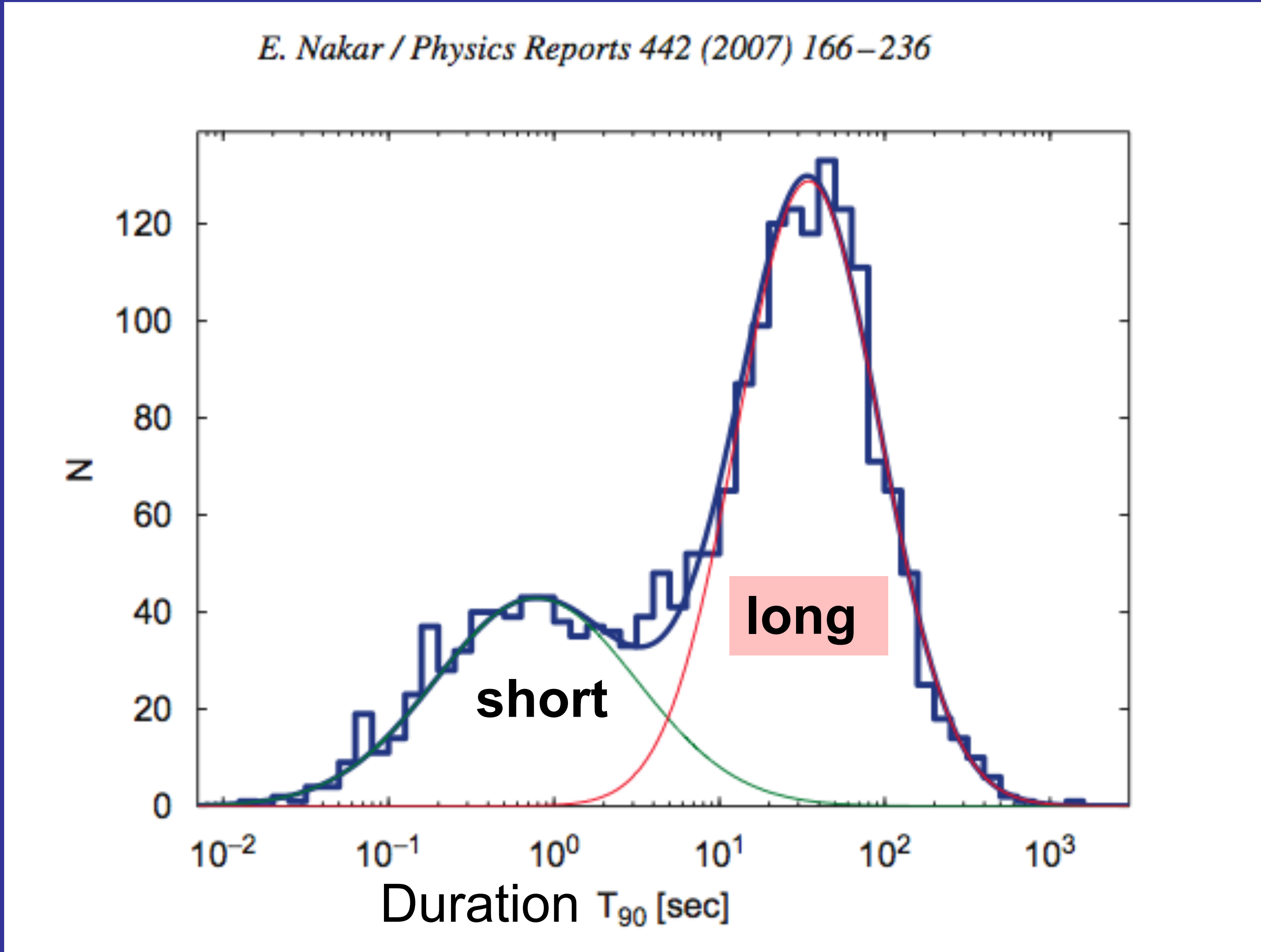
GRB could have a progenitor formed in star formation triggered by merger.

[Zn/H] $= 0.29$ and [S/H] $= 0.67$ are highest metallicies recorded for $z > 3$ objects.

Shows star formation and metallicities heightened by interaction of galaxies.

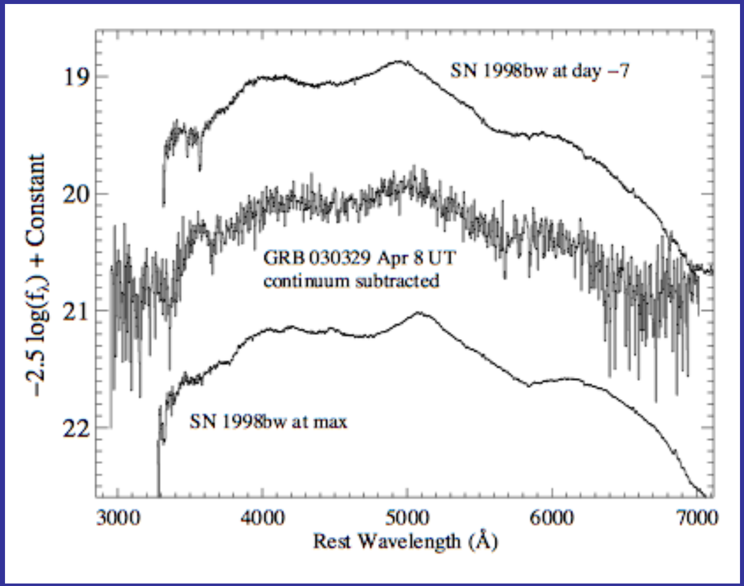


Gamma-Ray Burst Durations

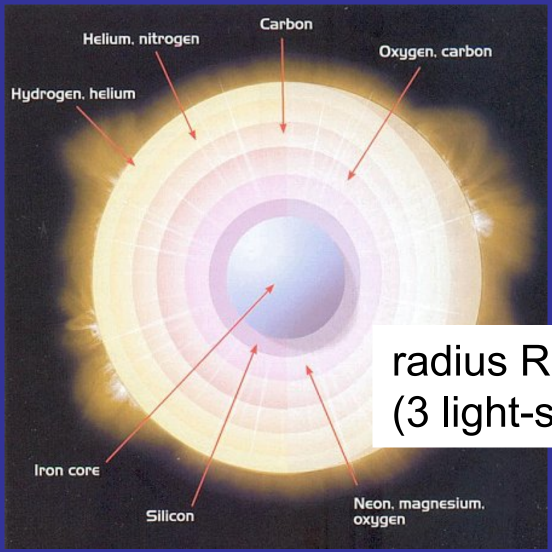


BATSE Bursts (from Nakar 2007)

GRB 030329 and the Supernova Connection



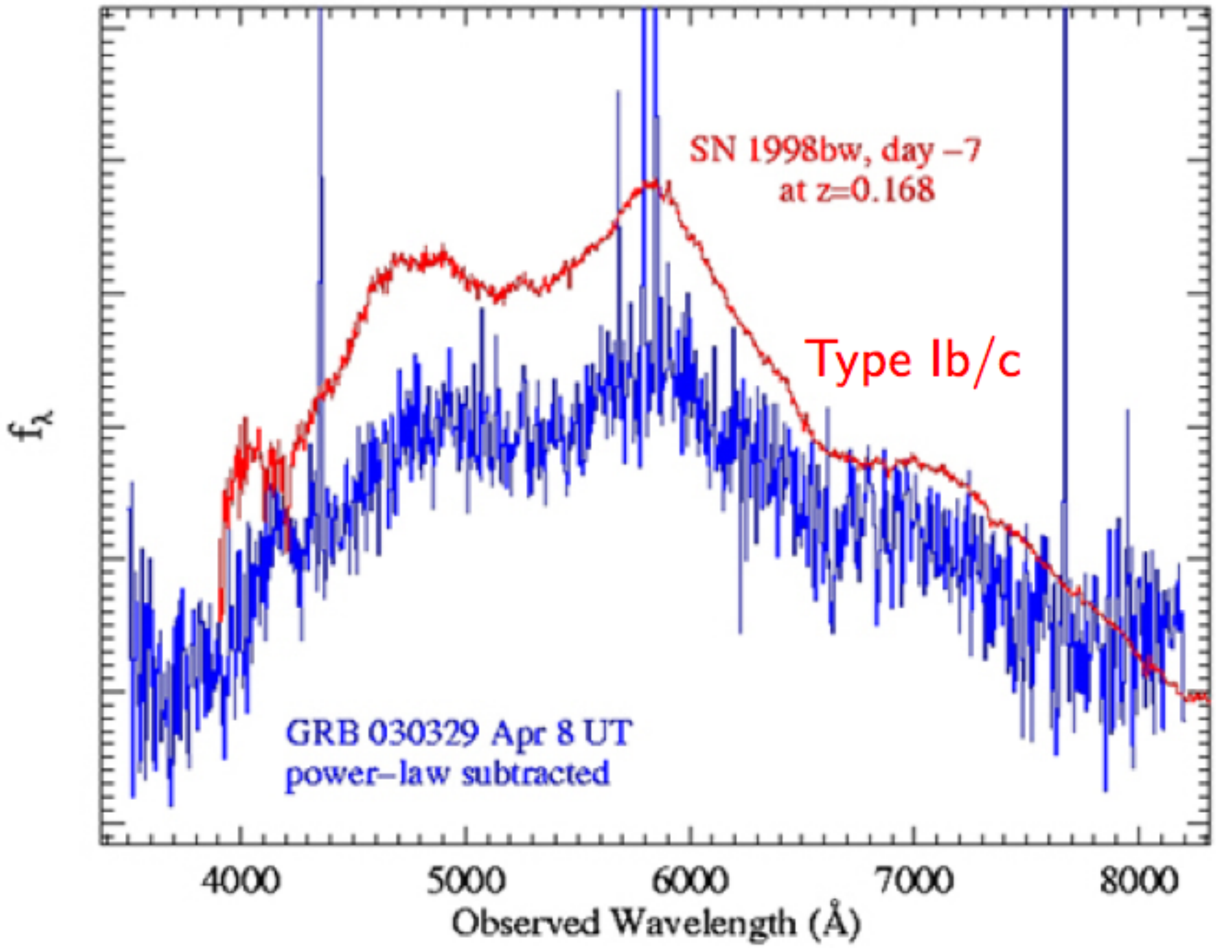
Exploding "Wolf-Rayet" Star



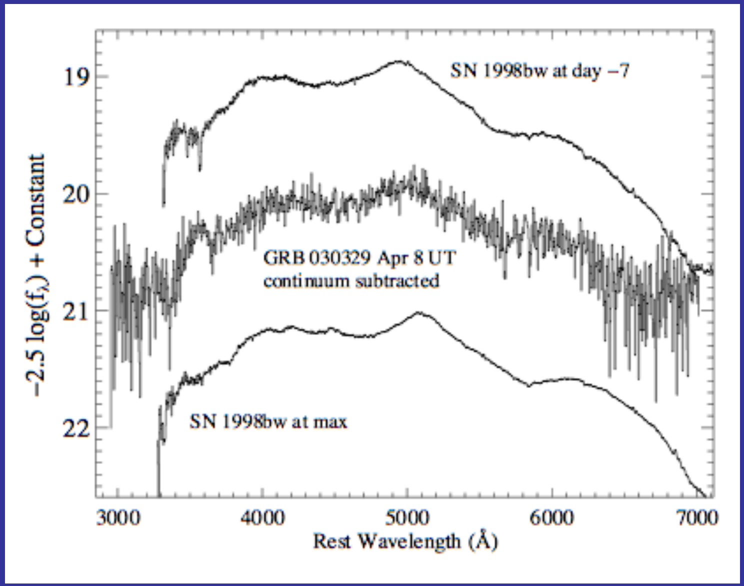
radius R~10^{11} cm (3 light-seconds).

GRBs and Supernovae

Della Valle et al. 2003

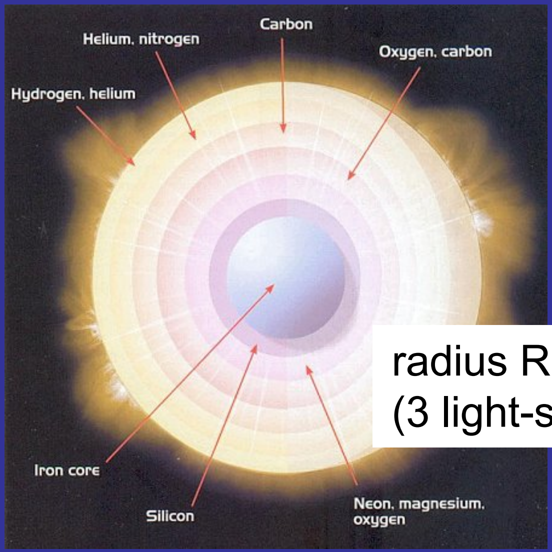


GRB 030329 and the Supernova Connection

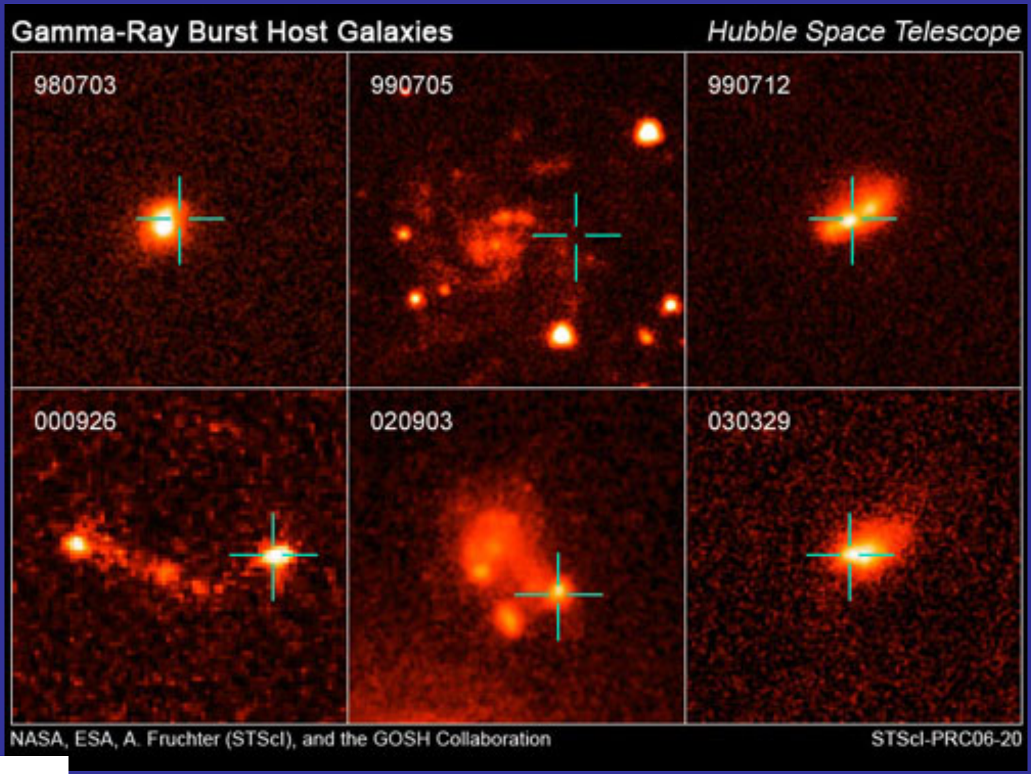


⇒ Long GRBs come from the deaths of massive Stars

Exploding "Wolf-Rayet" Star



radius $R \sim 10^{11}$ cm (3 light-seconds).



Gamma-Ray Burst Galaxies
(courtesy A. Fruchter)

GRB/Supernovae Rates and Energetics

	GRBs	SUPERNOVAE
UNIVERSE-WIDE RATE	**100 - >1000/day**	**100000/day (all types)** **1000-10000/day (Ic)**
RATE PER GALAXY	**1/10^5 years**	**1/50-100 years**
ENERGY	**10^{51-52} erg**	**10^{51-52} erg**