GRBs with the Fermi LAT and GBM

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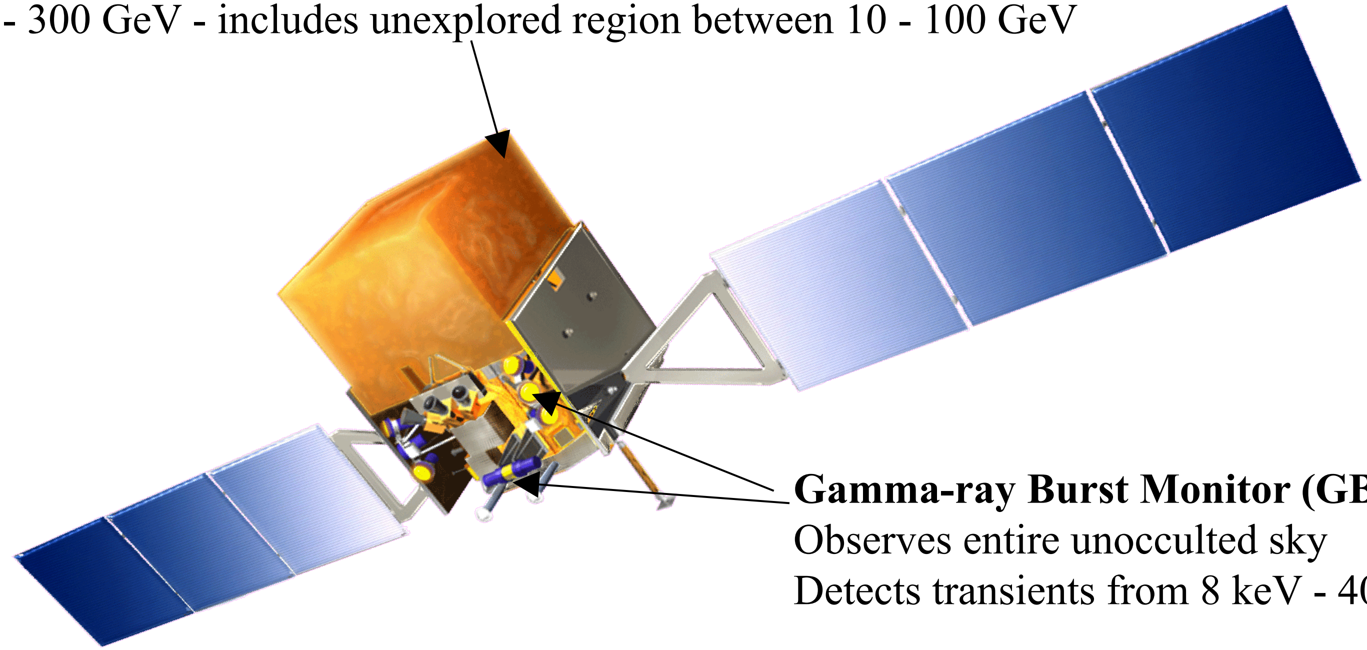
On behalf of the **Fermi Collaboration**

Outline

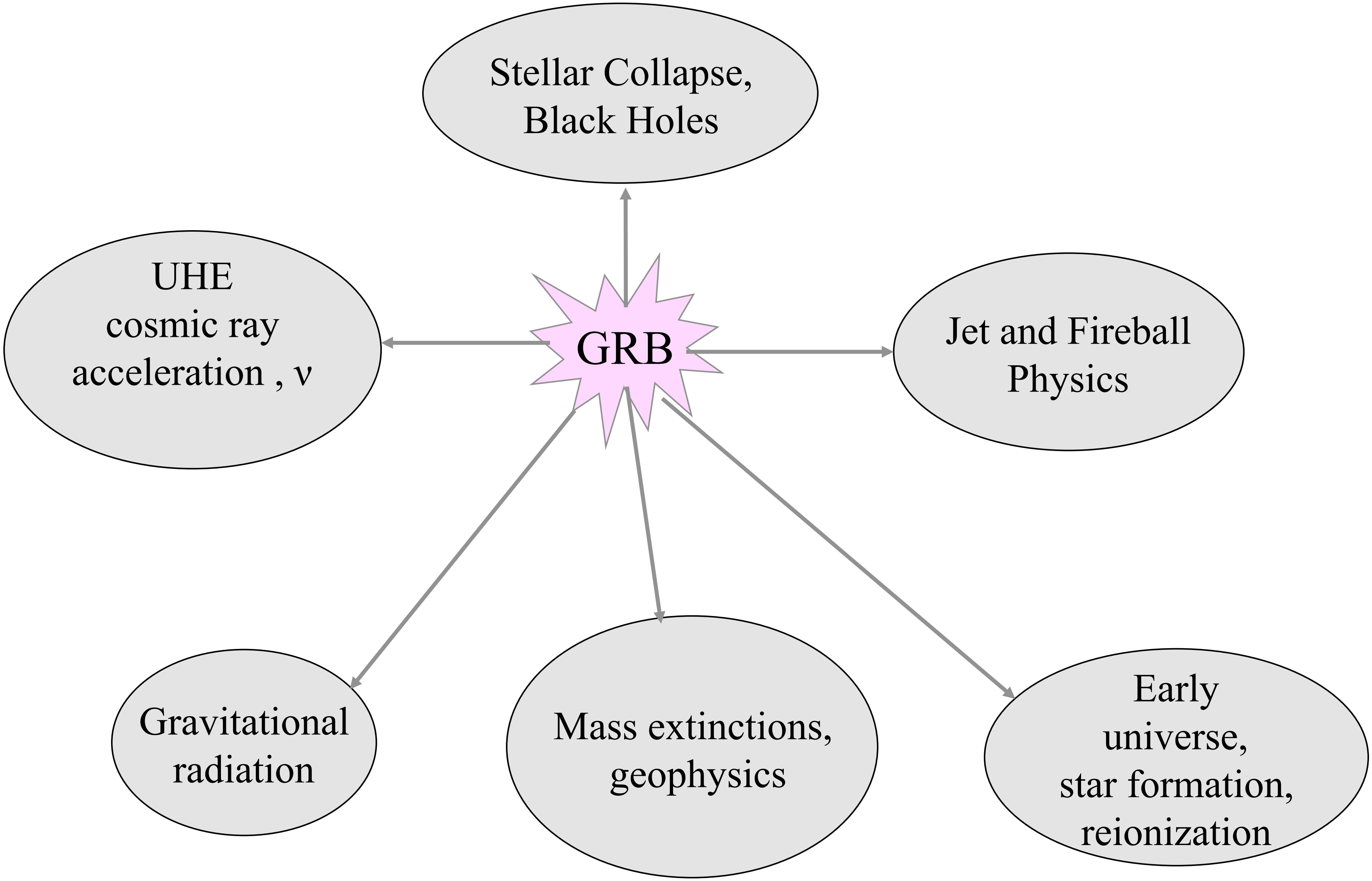
1. **Different Types of GRBs**
2. **Properties of LAT GRBs**
3. **Leptonic Modeling**
4. **Hadronic Modeling**

The Fermi Observatory



Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV

Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV



GRB

Stellar Collapse,
Black Holes

UHE
cosmic ray
acceleration , ν

Jet and Fireball
Physics

Gravitational
radiation

Mass extinctions,
geophysics

Early
universe,
star formation,
reionization

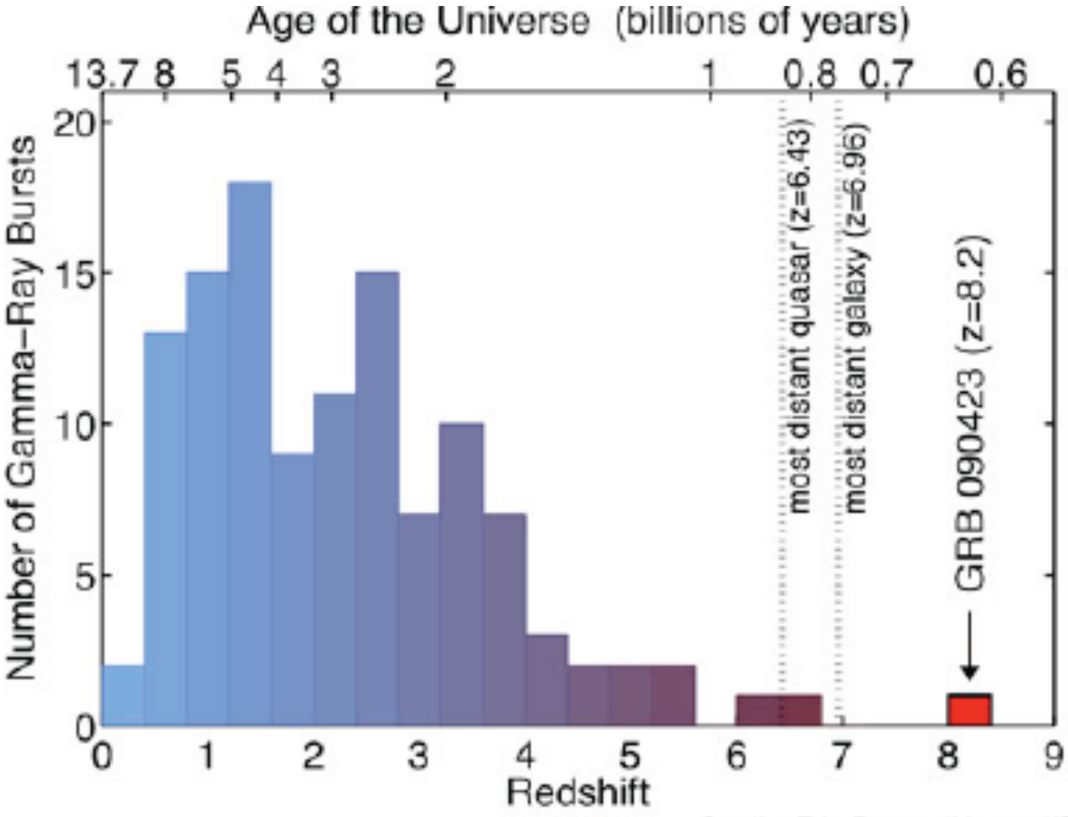
Photometric Redshift of z ~ 9.4 for GRB 090429B

(Cucchiara et al. 2011)

GRB 090423, z = 8.2

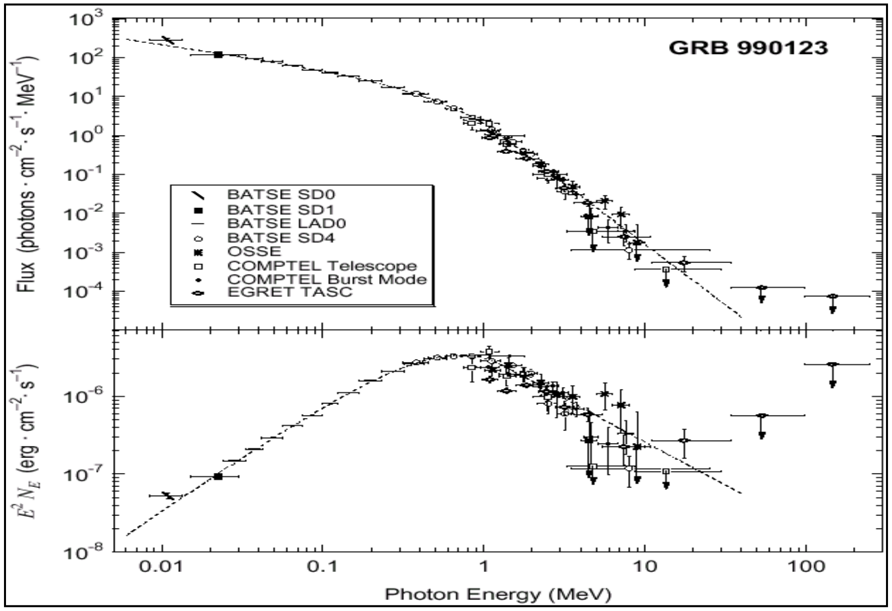
“GRB” 110328A

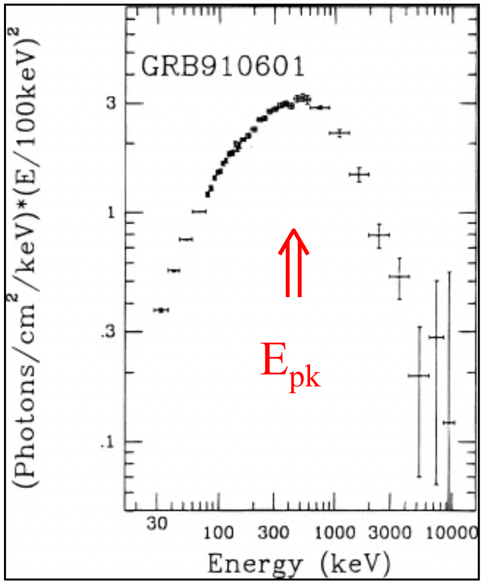
Tidal disruption of
a star by a massive
(~10^7 M_o) black hole

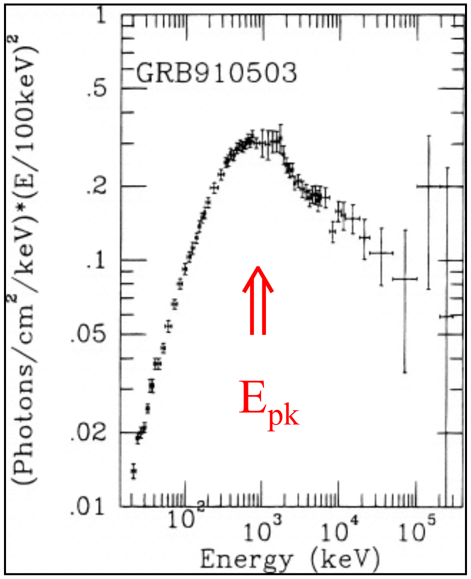


Credit: Edo Berger (Harvard/CfA)

Spectral Properties of GRBs







Schaefer et al. (1998)

Band Function: Smoothly Broken Power-Law

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right),$$

$$(\alpha - \beta)E_0 \geq E$$

$$= A\left[\frac{(\alpha - \beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta - \alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta},$$

$$(\alpha - \beta)E_0 \leq E$$

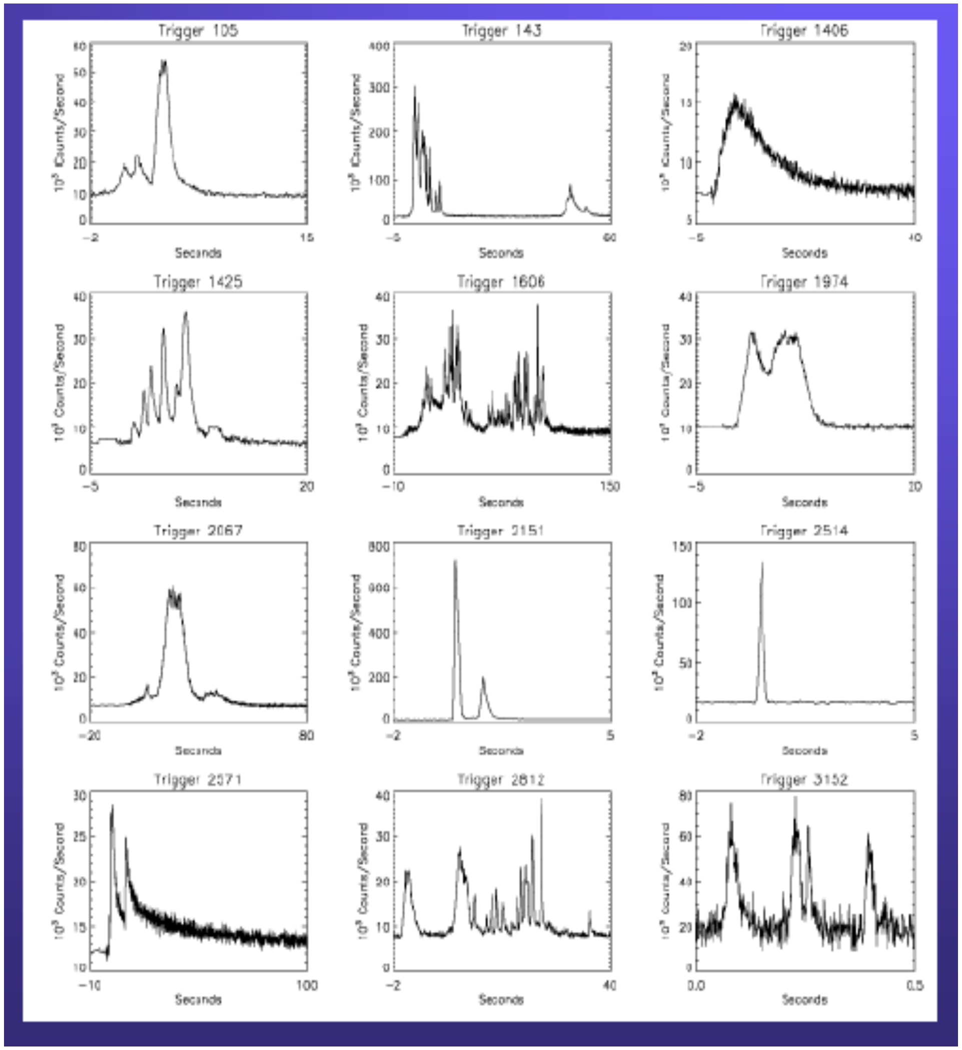
Prior to Fermi, all γ-ray spectra of GRBs (except for GRB 970417) consistent with Band function

Test LINE OF DEATH

Band et al. (1993)

1. Classes of Gamma Ray Bursts

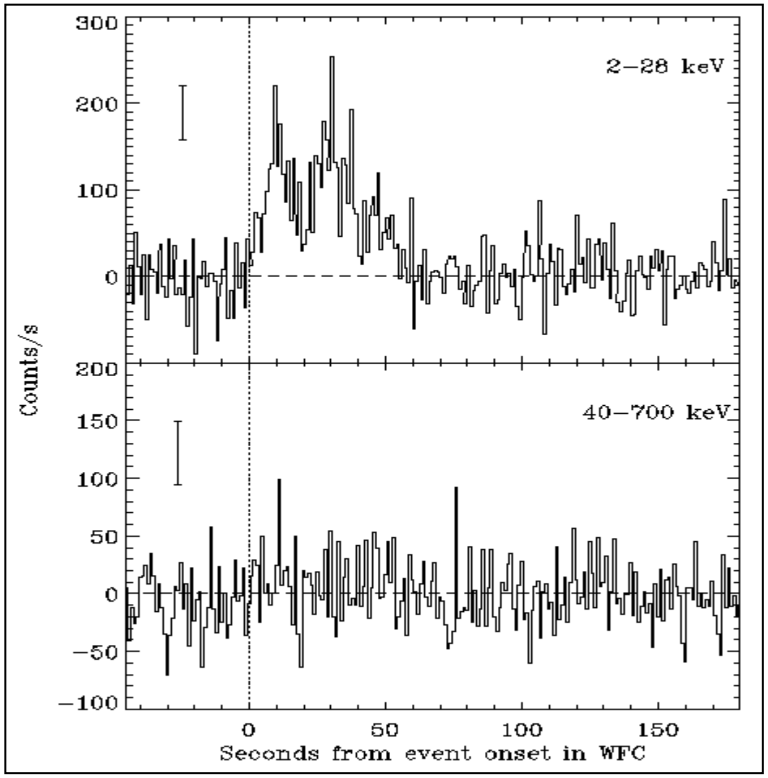
1. **Long duration GRBs**
2. **Short hard GRBs**
3. **Low luminosity GRBs**
4. Soft Gamma Repeaters

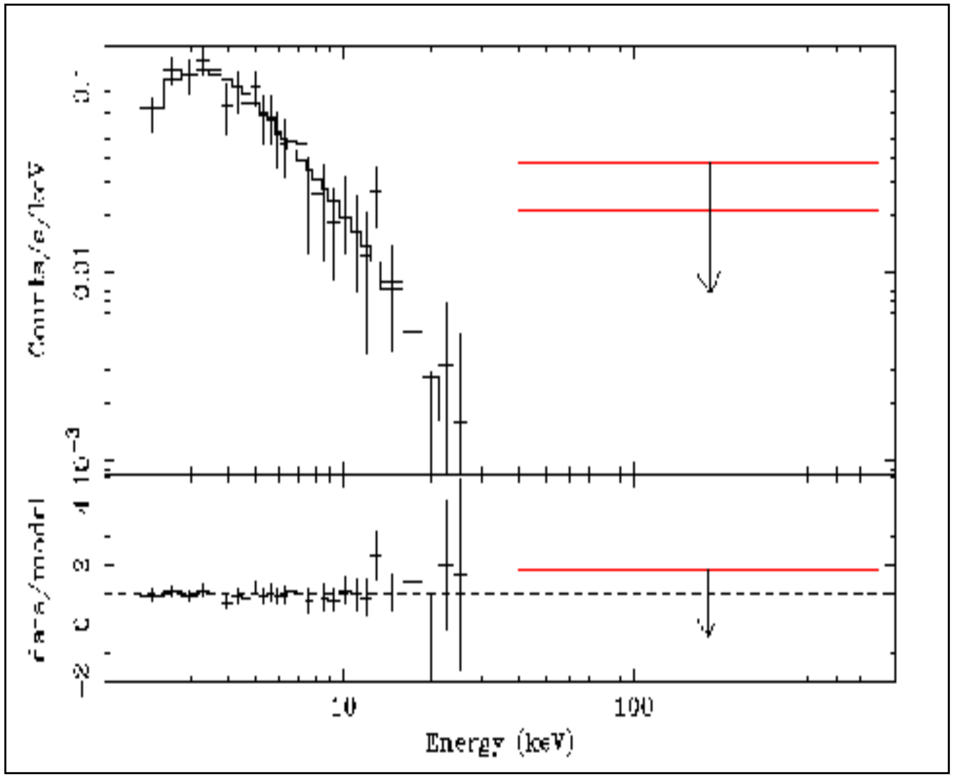


(Classical) Long Duration GRBs

- Light curves: durations ranging from ~1 s to hundreds of s
- Reddened supernova emission in late time optical afterglow spectra indicates SN-GRB connection (SN Ib/c)
- Long GRBs in low-metallicity star-forming hosts (dwarf spirals)

X-ray Rich GRBs and X-Ray Flashes



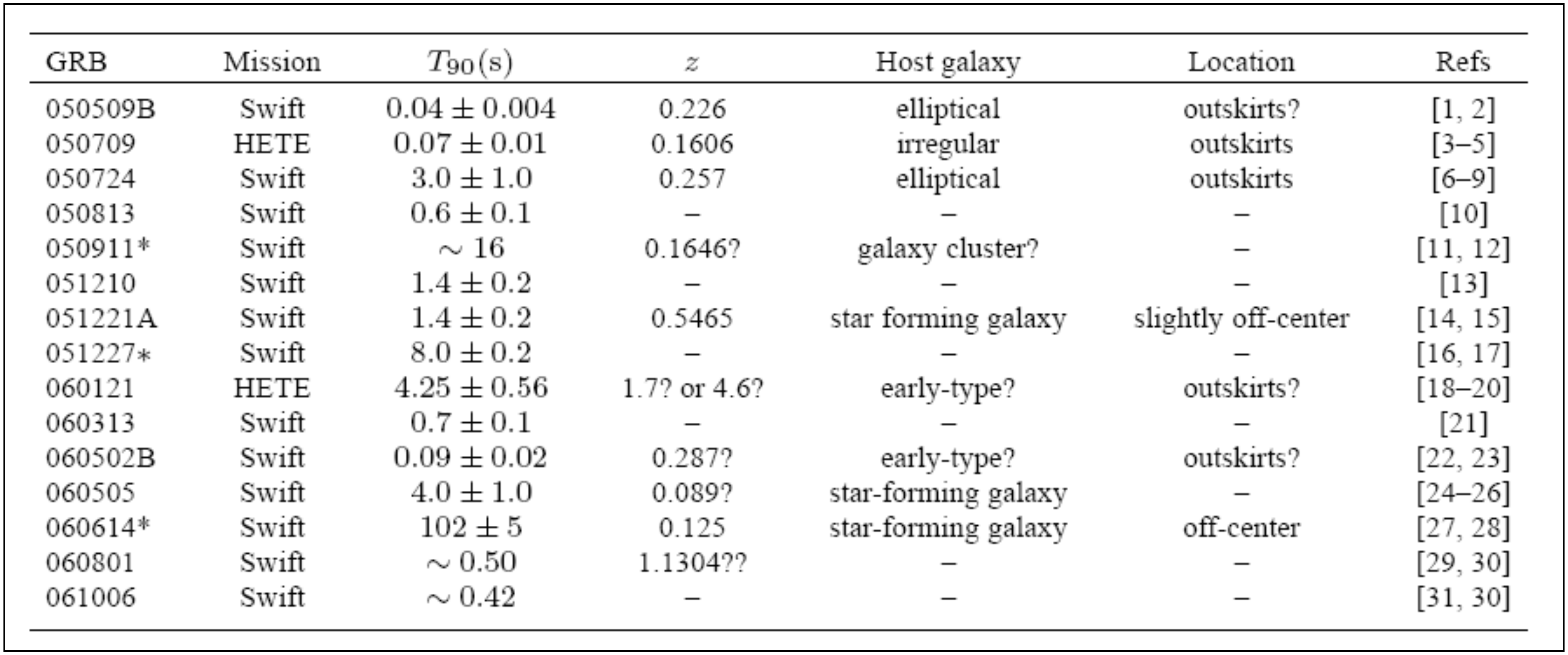


Amati et al. (2004)

- X-Ray Flashes (XRF) discovered with Beppo-SAX and HETE-II
- Defined by ratio of X-ray (e.g., 2 – 30 keV) to γ-ray (e.g., 30 – 400 keV) fluence ratio
- Definition corresponds to low E_{pk} values

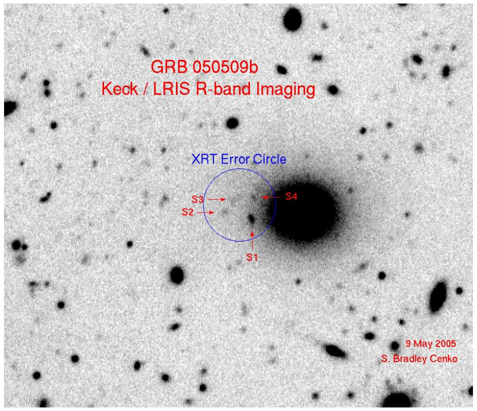
Dirty fireballs?

Short-hard 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]

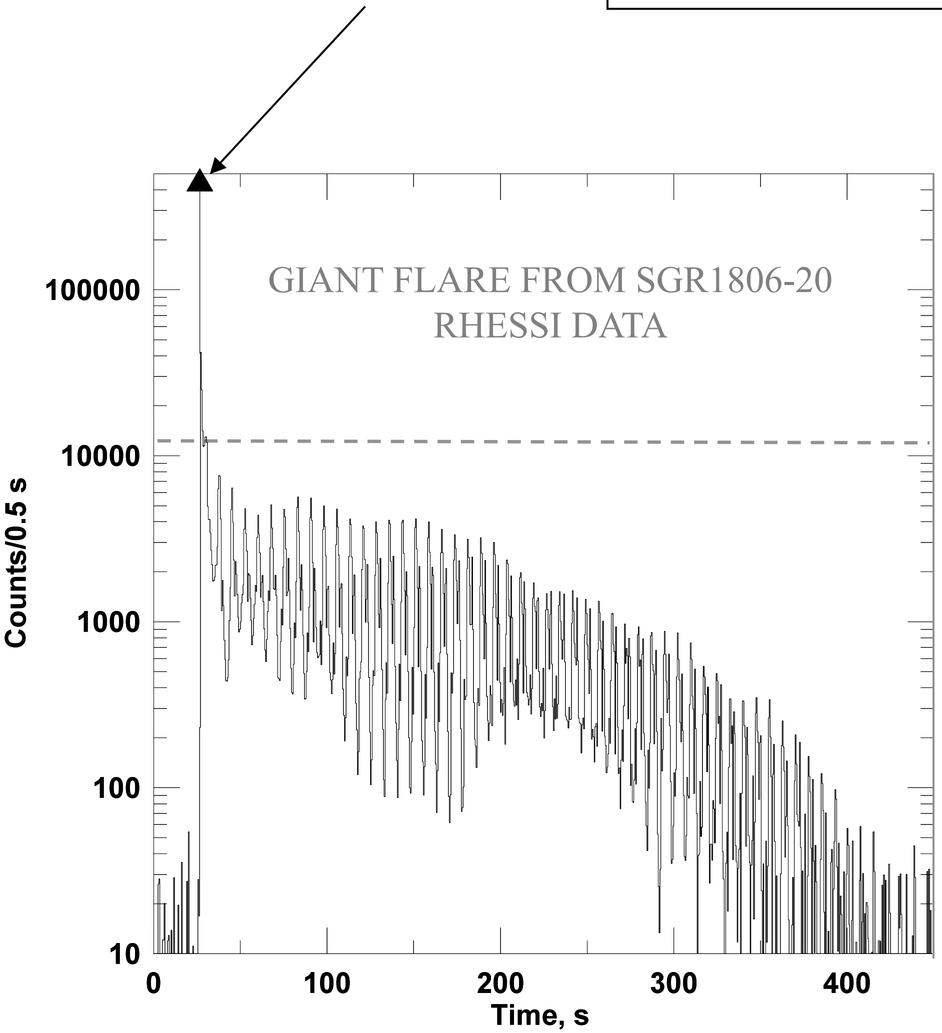
- Found in both elliptical and star forming galaxies
- No evidence for supernova emissions
- Offset from host galaxy



Short GRBs differ from Long GRBs:

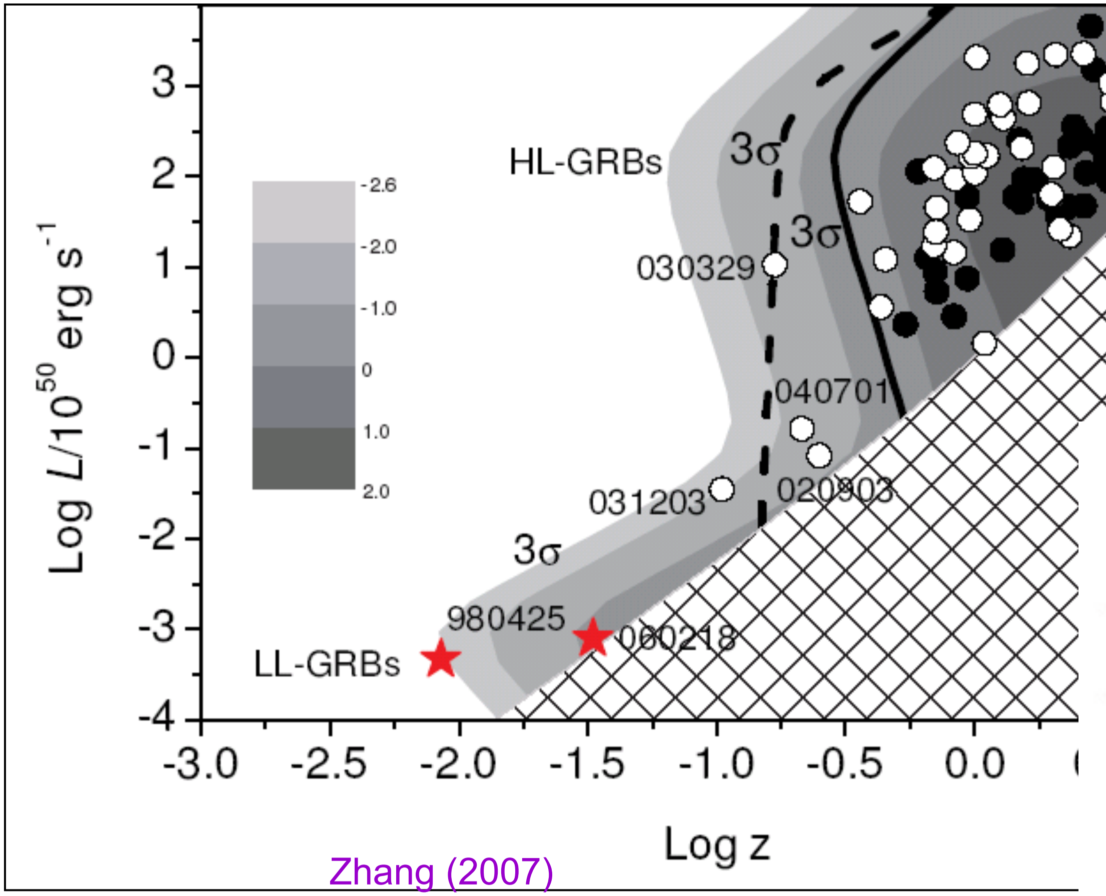
- **Host galaxies**
- **Energies**
- **Redshift distribution**
- **Lag-luminosity relation**

Soft Gamma Repeaters

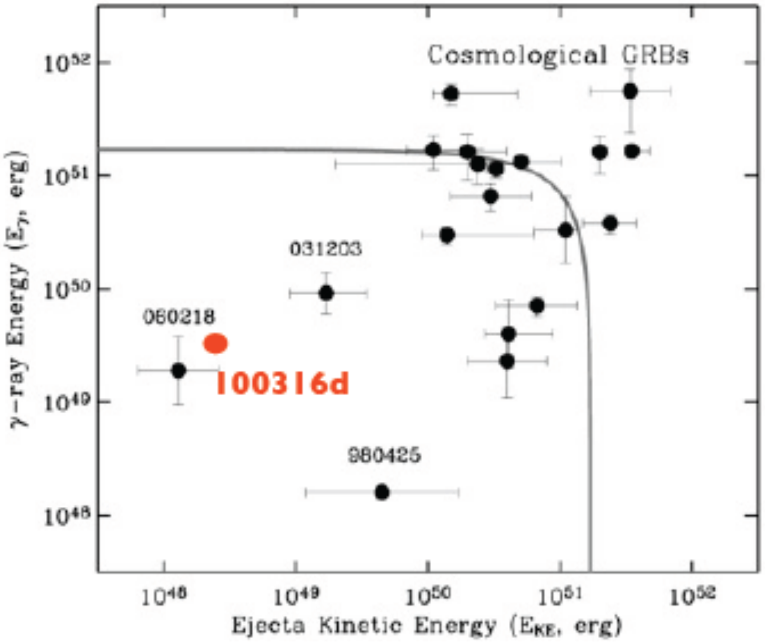


1. Extraordinary SGR event of Dec. 27, 2004
2. Begin with ~0.2 s long, hard spectrum spikes with E~10^{46}-10^{47} erg
3. The spike is followed by a pulsating tail with ~1/1000th of the energy
4. Viewed from a large distance, only the initial spike would be visible
5. It would resemble a short GRB
6. It could be detected out to 100 Mpc
7. GRB050906 at z=0.03 could be a magnetar flare

Low Luminosity GRBs



Zhang (2007)



Soderberg et al. (2010)

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

Long vs. Short Classes of GRBs

1. Long duration GRBs ↔ Collapsar (incl. XRR, XRF)
2. Short hard GRBs ↔ Mergers of compact objects

HYPERNOVAE

- A “typical” long-duration GRB lasts 20 s in γ-rays from keV to MeV energies
- It takes place in star-forming (spiral or dwarf irregular) galaxies, but not in ellipticals
- It takes place in a galaxy at $z \sim 1$
- About $10^{51} – 10^{55}$ ergs of (apparent isotropic) energy are emitted and (apparent isotropic) powers of $\sim 10^{50} – 10^{53}$ ergs/s
- It is followed by long-lived X-ray, optical, and radio afterglow emission
- Variability times as short as ms (more typically 1 sec)
- Collapse of a >30 $M_\odot$ star
- ISM density allows shock formation

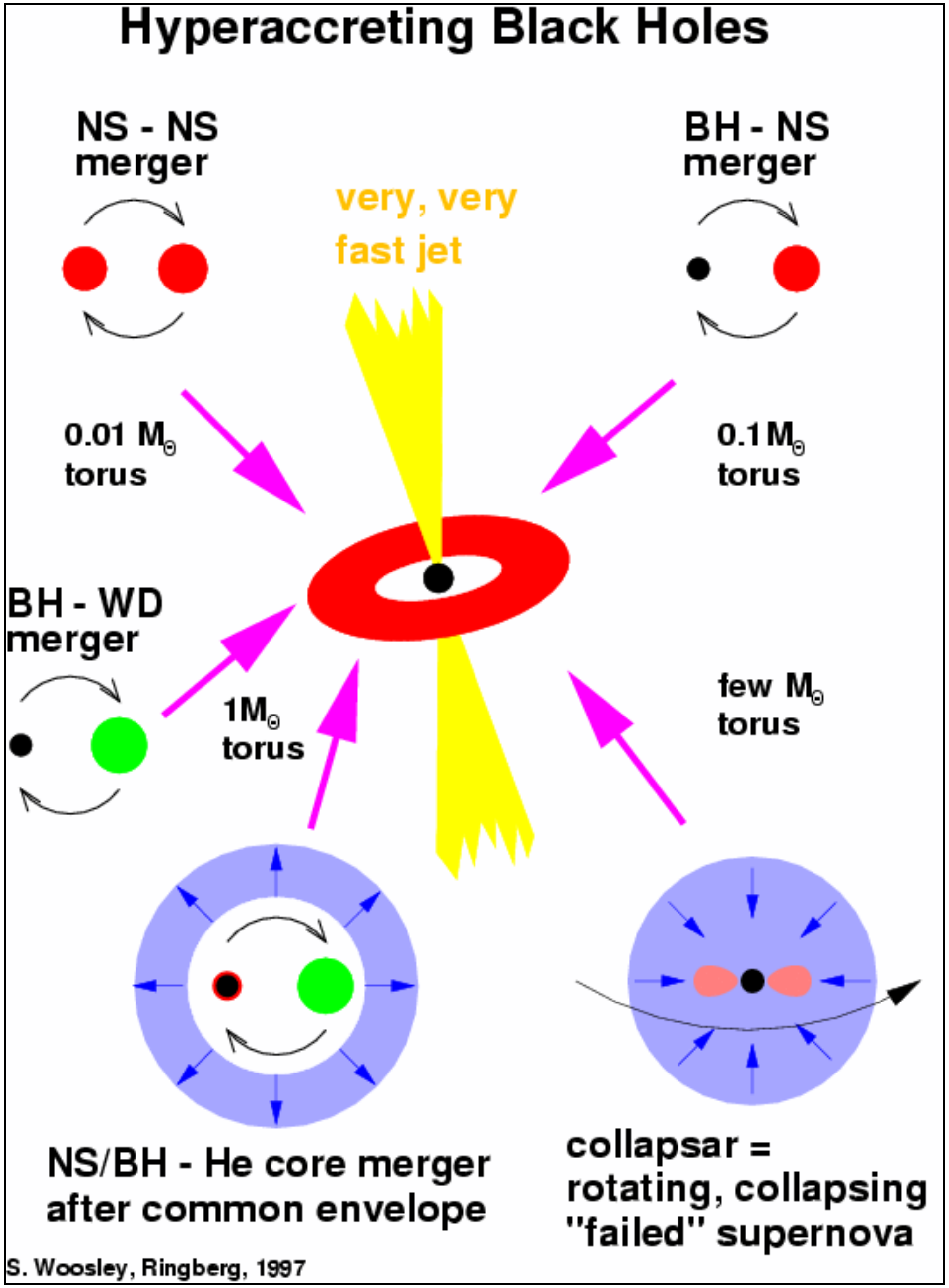
MERGING NEUTRON STARS

- A binary neutron star system may be born with a high kick velocity, > 200 km/s
- The system loses orbital energy by gravitational radiation
- Merger takes place in $10^8 – 10^9$ y. By then, the system may be outside the galaxy where it was born
- The tenuous medium might not allow strong shock formation, and therefore the production of intense afterglows
- The host galaxy might not be forming stars at a high rate any more

Principal GRB Models

Black-hole GRB models: Collapsars vs. Compact object mergers

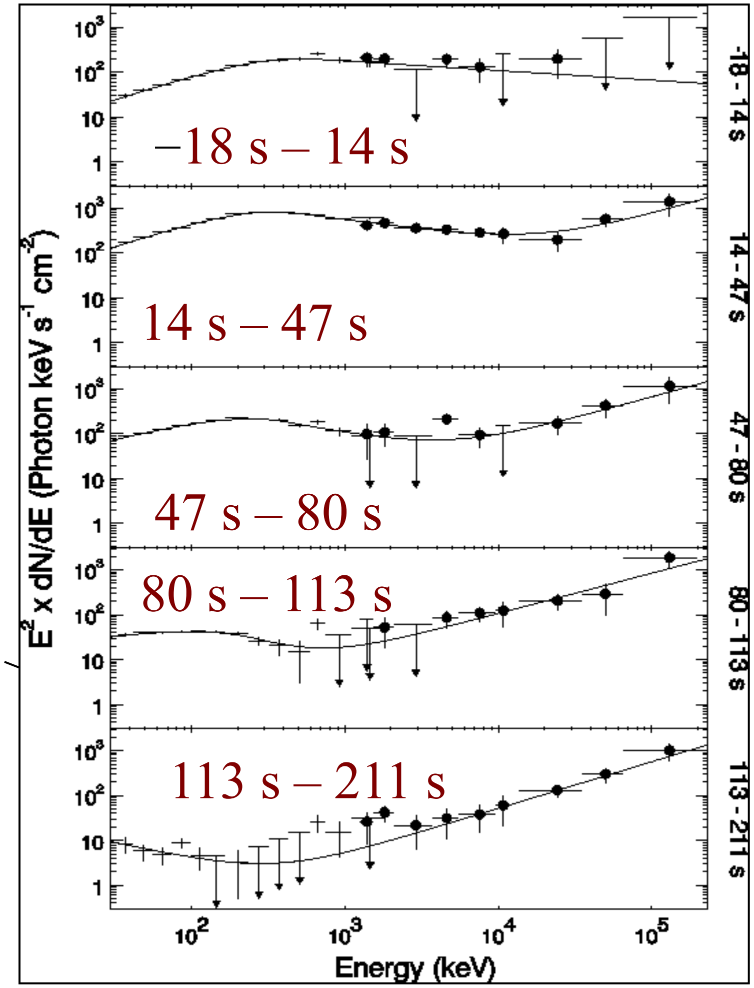
- ☐ Collapse of a rotating massive star (binary or single star)
- ☐ Neutron star/black hole merger with a helium core: “He-star Merger”
- ☐ Neutron Star – Neutron Star Mergers (Hulse-Taylor Pulsar System)
- ☐ Black Hole – Neutron Star Mergers
- ☐ Black Hole – White Dwarf Mergers



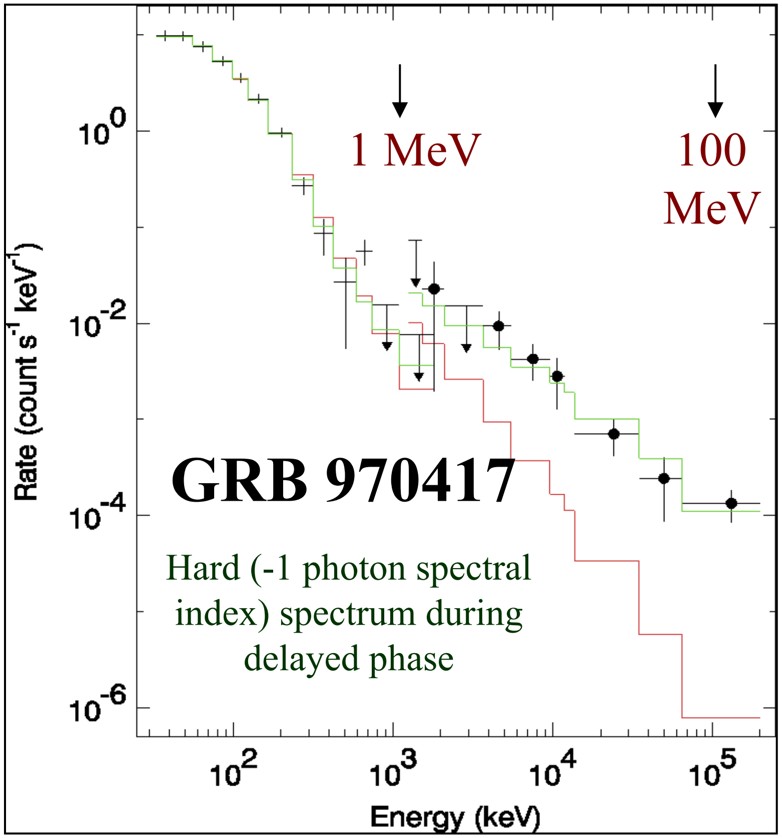
S. Woosley, Ringberg, 1997

Anomalous High-Energy Emission Components in GRBs

Evidence for Second Component from BATSE/TASC Analysis



(González et al. 2003)

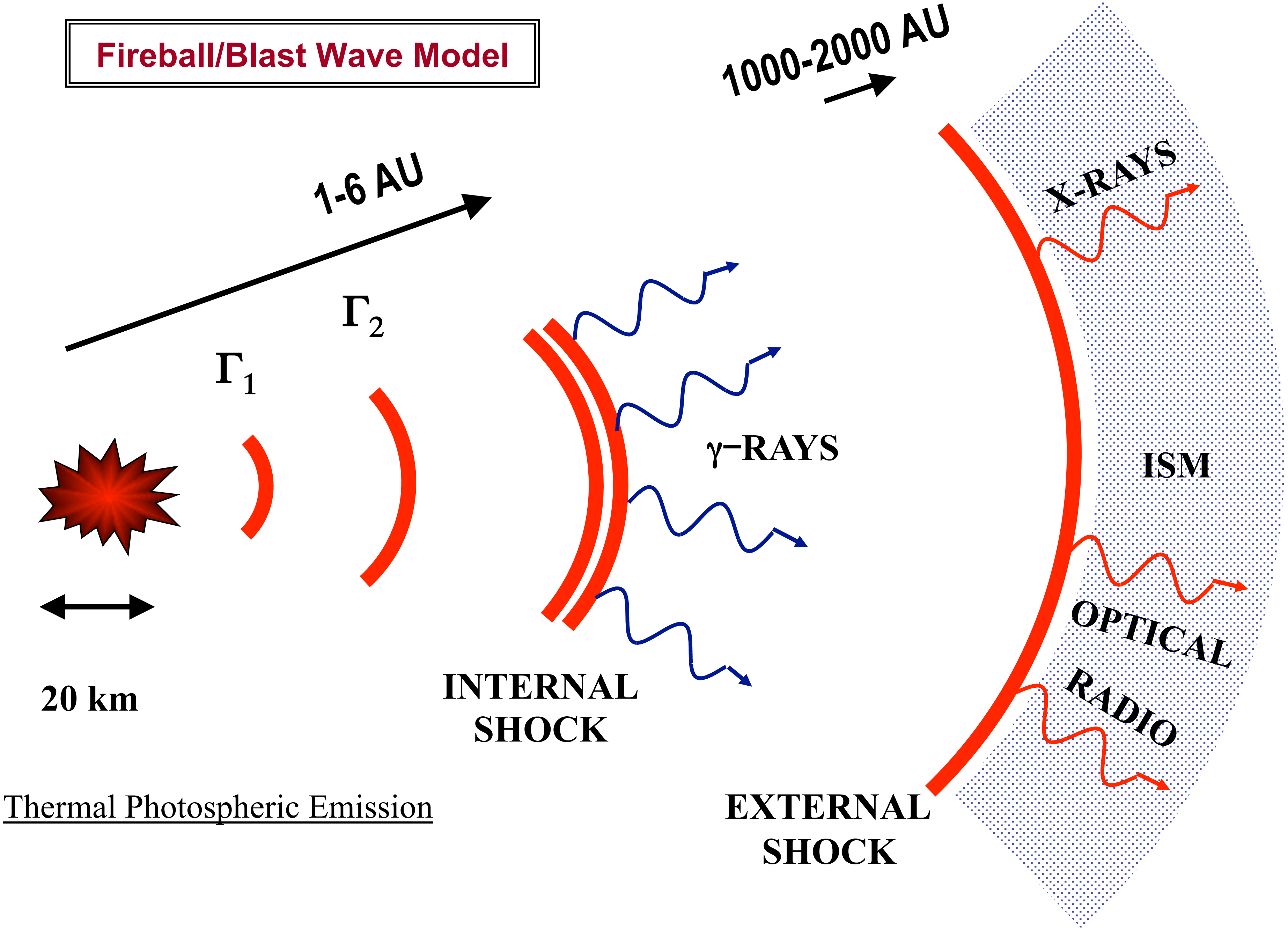


GRB 970417

Hard (-1 photon spectral index) spectrum during delayed phase

Fluence, including hard γ-ray component, is > 6.5 10^{-4} ergs cm^{-2}
(Two other GRBs display anomalous components)
Hard to explain with standard leptonic GRB models

Fireball/Blast Wave Model



1000-2000 AU

1-6 AU

Γ_2

Γ_1

X-RAYS

γ–RAYS

ISM

OPTICAL

RADIO

20 km

INTERNAL
SHOCK

EXTERNAL
SHOCK

Thermal Photospheric Emission

Blast Wave and Afterglow Theory

Initial Explosion Energy: E_0

Swept-up mass: $M_{sw} = 4\pi m_p n_0 x^3/3$

Baryonic mass mixed into explosion: M_0

Density of surrounding medium = n_0

$$\Gamma_0^2 M_{sw}c^2 = E_0 \equiv M_0 c^2 \Rightarrow$$

Deceleration radius

$$x_d = \left(\frac{3E_0}{4\pi m_p c^2 n_0 \Gamma_0^{\,2}}\right)^{1/3} = 2.6\times 10^{16}\left(\frac{E_{52}}{n_0\Gamma_{300}^2}\right)^{1/3}\ cm$$

$$\Gamma_{300} \equiv \Gamma_0/300$$

Rees and Mészáros (1992)
Mészáros and Rees (1993)

Deceleration time

$$t_d = (1+z)\frac{x_d}{\beta_0\Gamma_0^2 c} \cong 10(1+z)\left(\frac{E_{52}}{n_0\Gamma_{300}^8}\right)^{1/3} s$$

Blast Wave Evolution

$$\Gamma[M_0 + \Gamma m_{su}(x)] = \Gamma[M_0 + k\Gamma x^3] = const$$

$$\Rightarrow \Gamma \propto x^{-3/2}$$

Afterglow Theory

- ☐ Injection of power-law electrons downstream of forward shock

$$\dot{N}(\gamma_e) = N_e \gamma_e^{-p}, \gamma_{\min} < \gamma_e < \gamma_2 \ (comoving\ \gamma_e)$$

$$N_e(x) = 4\pi\, n_* x^3/3$$

- ☐ Magnetic field parametrized in terms of equipartition field

$$B^2/8\pi \cong 4\varepsilon_B m_p c^2 n_* (\Gamma^2 - \Gamma) \Rightarrow B \propto \Gamma$$

- ☐ Minimum electron γ (Joint normalization swept-up power and number)

$$\gamma_{\min} \cong \varepsilon_e \left(\frac{p-2}{p-1}\right)\left(\frac{m_p}{m_e}\right)\Gamma\ ;\ \dot{E}'_e = \varepsilon_e (dE'/dt')$$

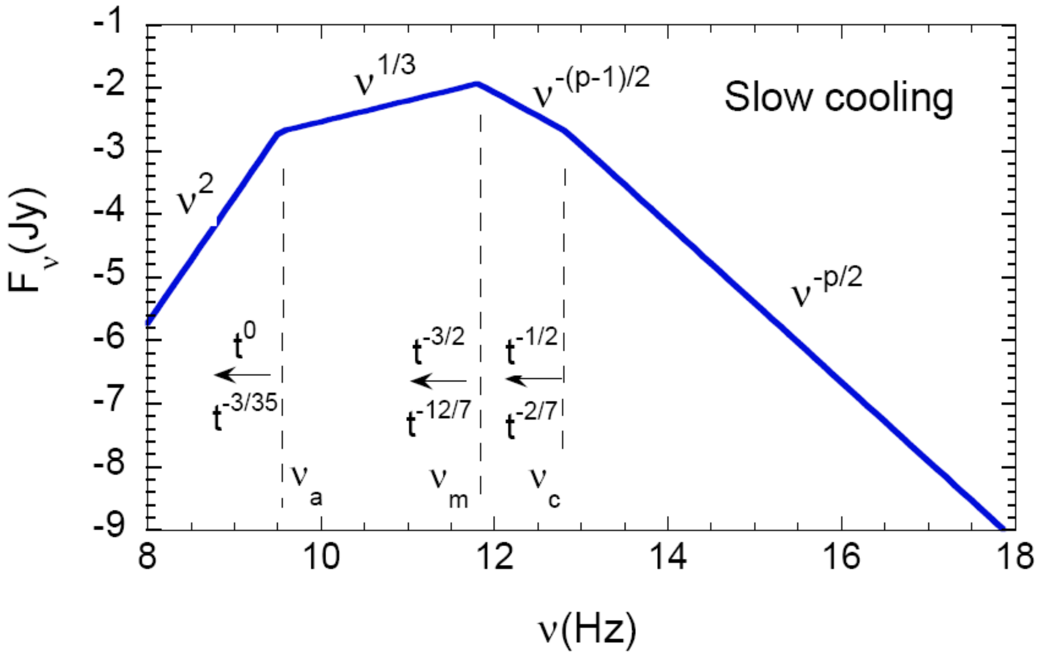
- ☐ Maximum electron γ: balancing losses and acceleration rate

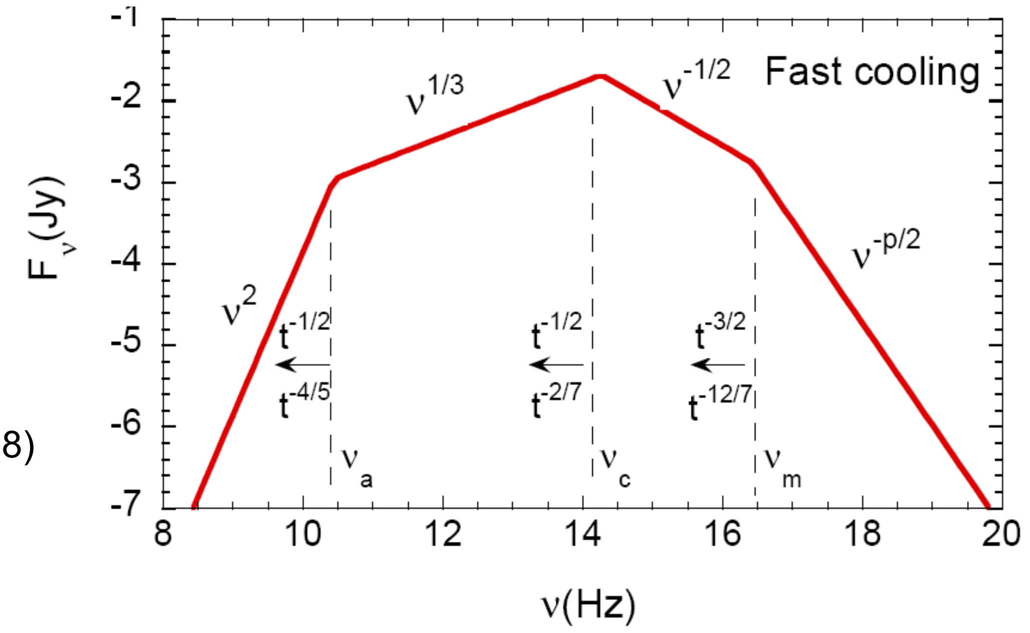
$$\gamma_2 \cong 4\times 10^7/\sqrt{B(G)}$$

- ☐ Cooling electron γ: balance synchrotron loss time with adiabatic expansion (comoving) time

$$t'_{adi} \cong x/\Gamma c \cong \Gamma t \cong t'_c \cong \left(\frac{4}{3} c\sigma_T \frac{u_B}{m_e c^2}\gamma_c\right)^{-1} \Rightarrow \gamma_c \cong \frac{3m_e}{16\varepsilon_B n_* m_p c \sigma_T \Gamma^3 t}$$

Synchrotron Afterglow Spectrum

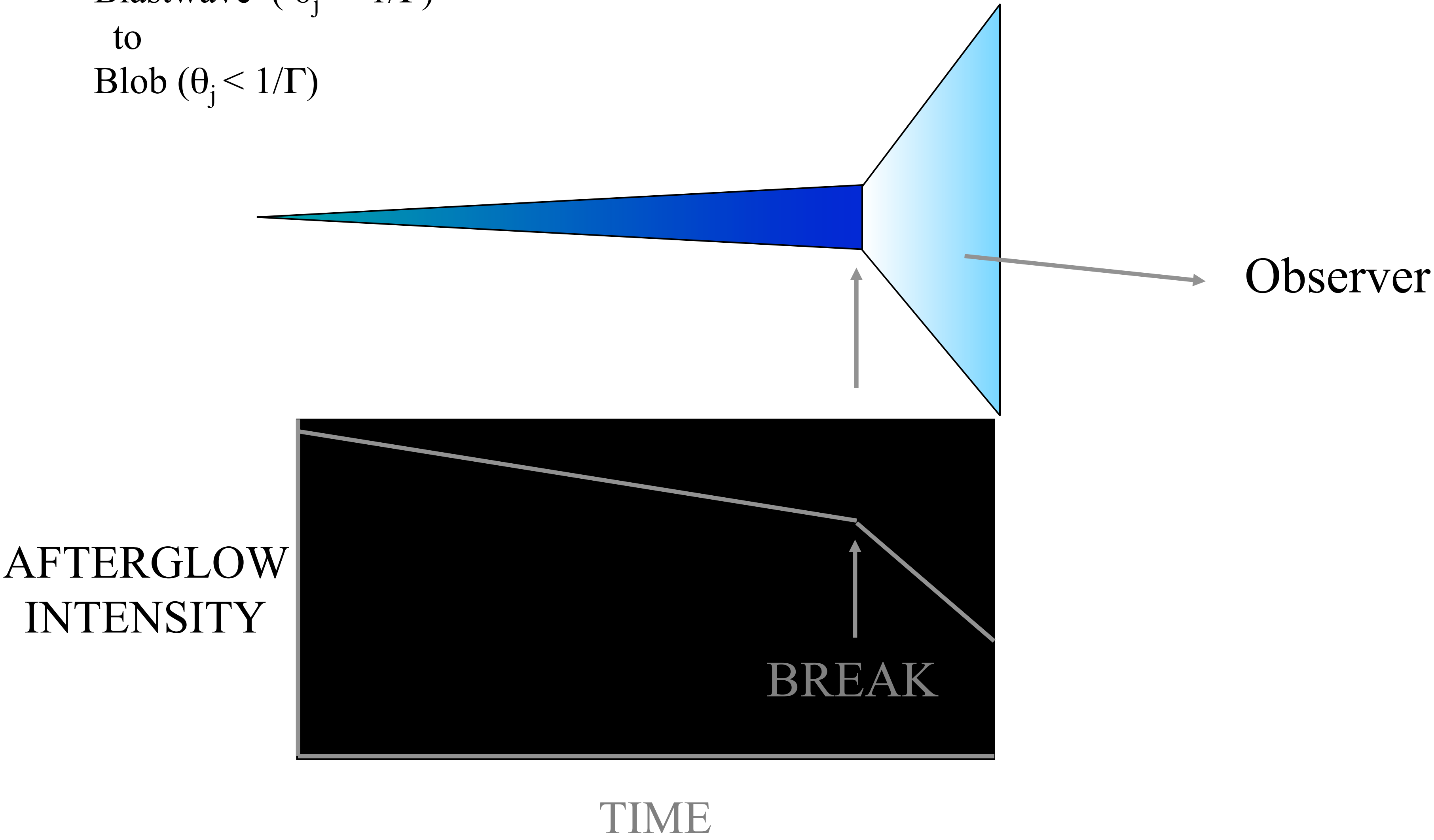




(Sari, Piran, and Narayan 1998)

Optical Afterglow gives Information about Beaming

Blastwave ($\theta_j >> 1/\Gamma$)
to
Blob ($\theta_j < 1/\Gamma$)



2. Properties of LAT GRBs

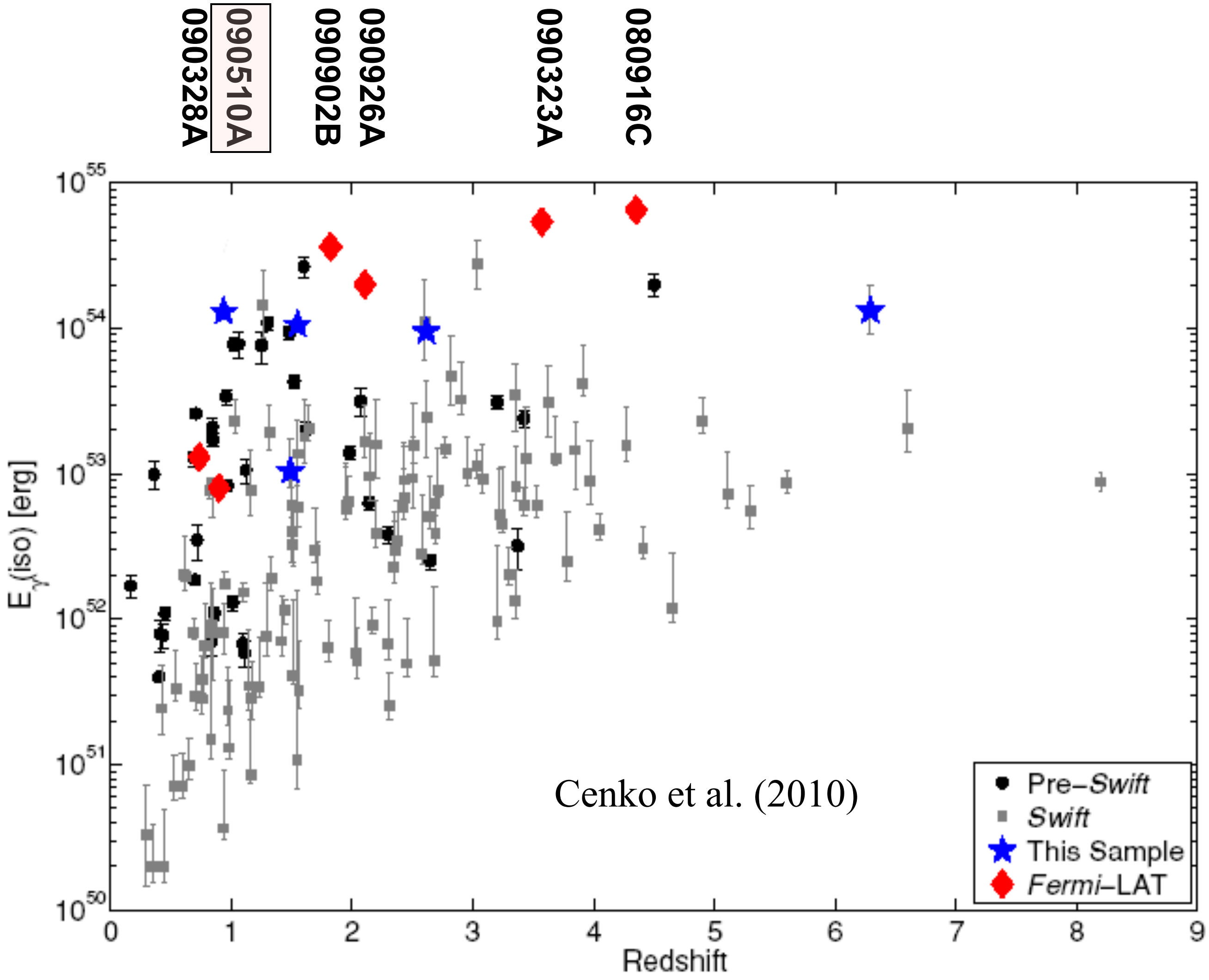
Apparent Isotropic Energies of Swift and Fermi LAT GRBs

LAT GRBs (red) have large apparent isotropic energy releases

Bright Swift bursts (blue) (in terms of apparent isotropic energy release) used to determine absolute energy release from beaming breaks

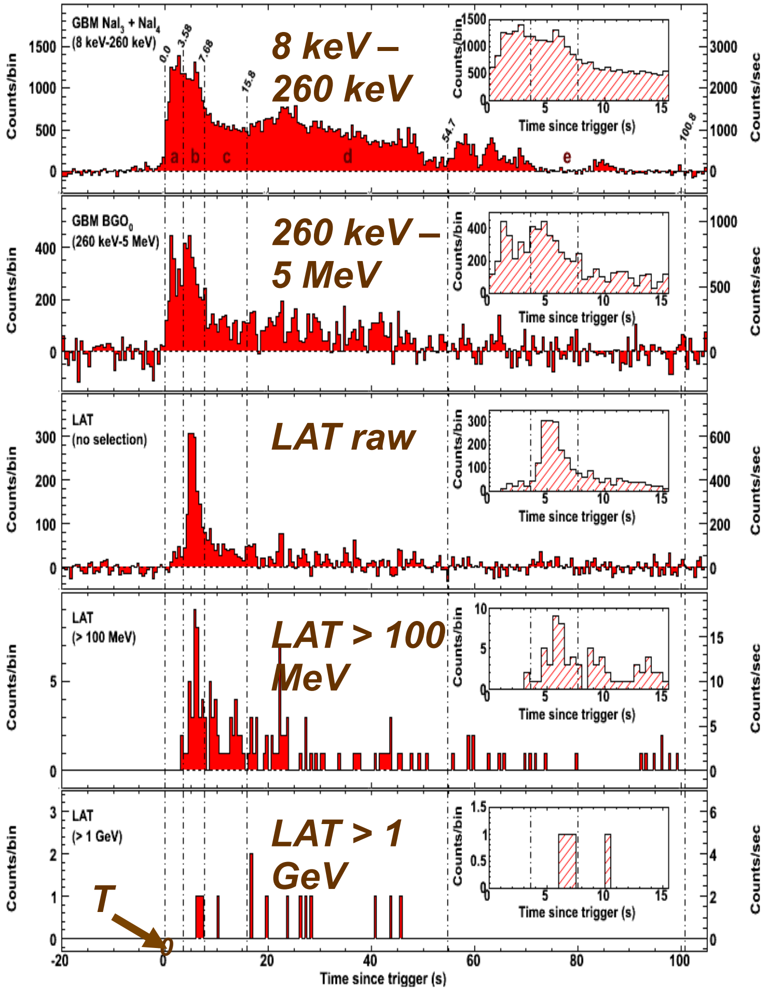
Compare: 1 $M_o c^2 \cong 2\times10^{54}$ erg

Do Fermi LAT GRBs have preferentially smaller jet opening angles?

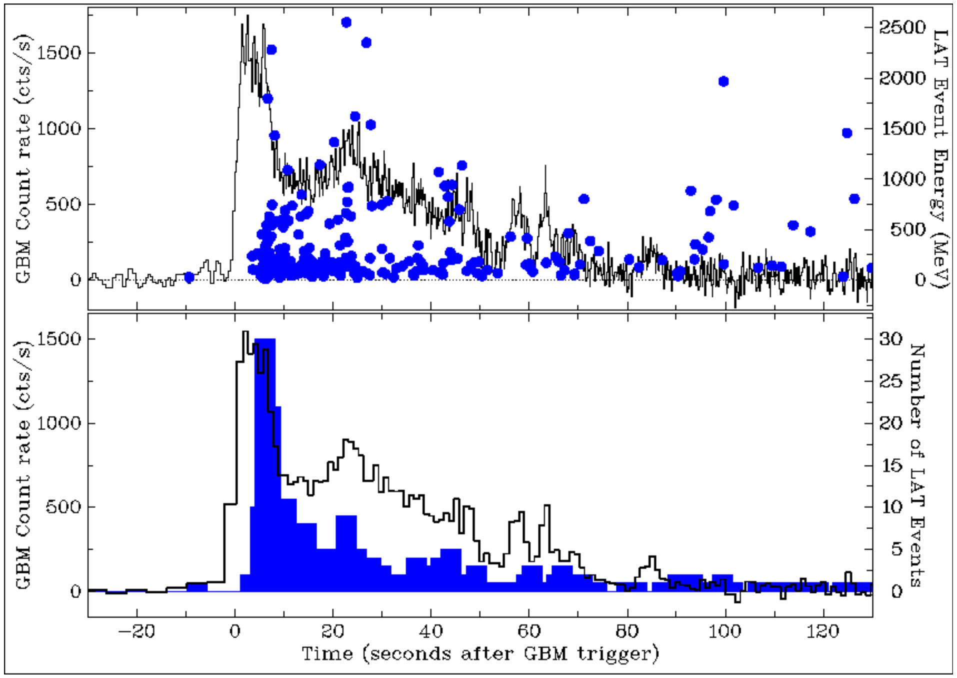


Ackermann et al. 2011

Light Curves of GRB 080916C



Abdo, A. A., et al. 2009, Science, 323, 1688

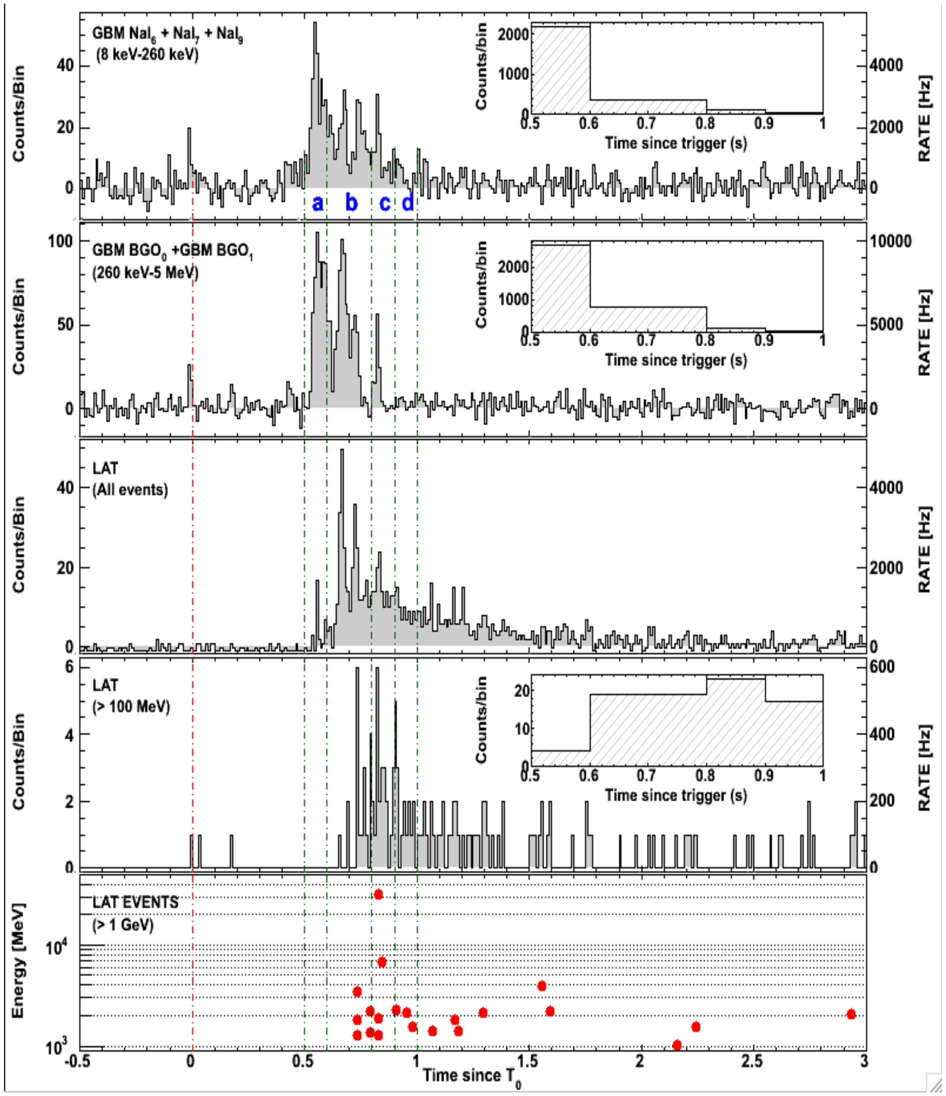


Two notable features:

1. Delayed onset of high-energy emission
2. Extended ("long-lived") high-energy γ rays

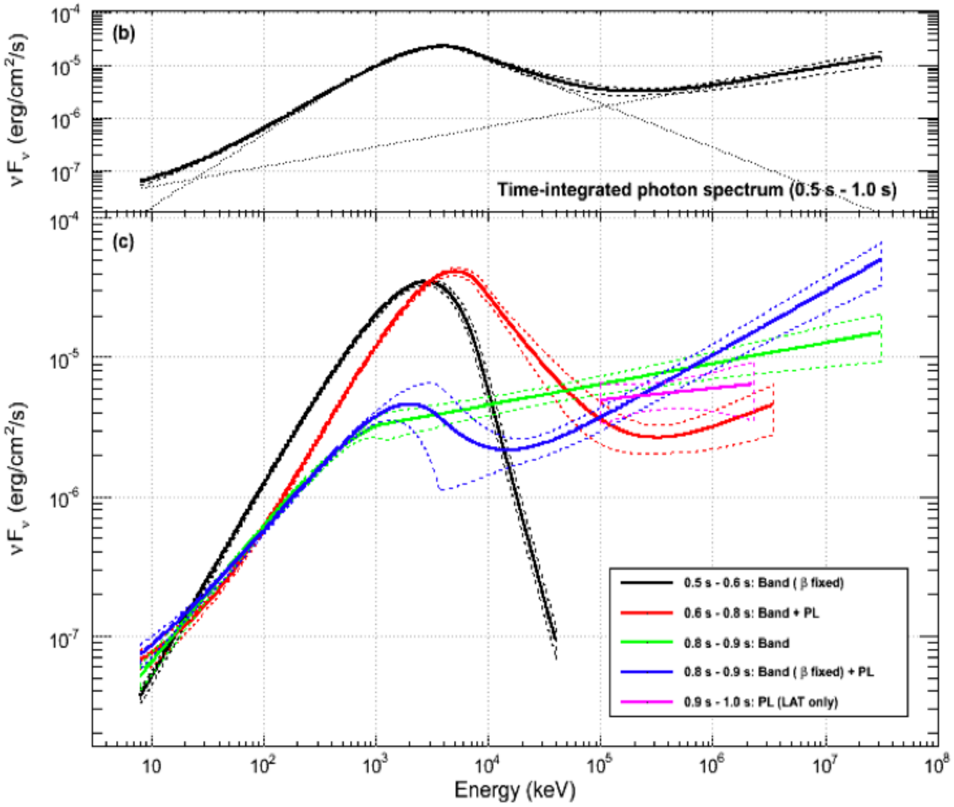
Spectra consistent with Band functions

GRB 090510: A Short Hard GRB with an extra component

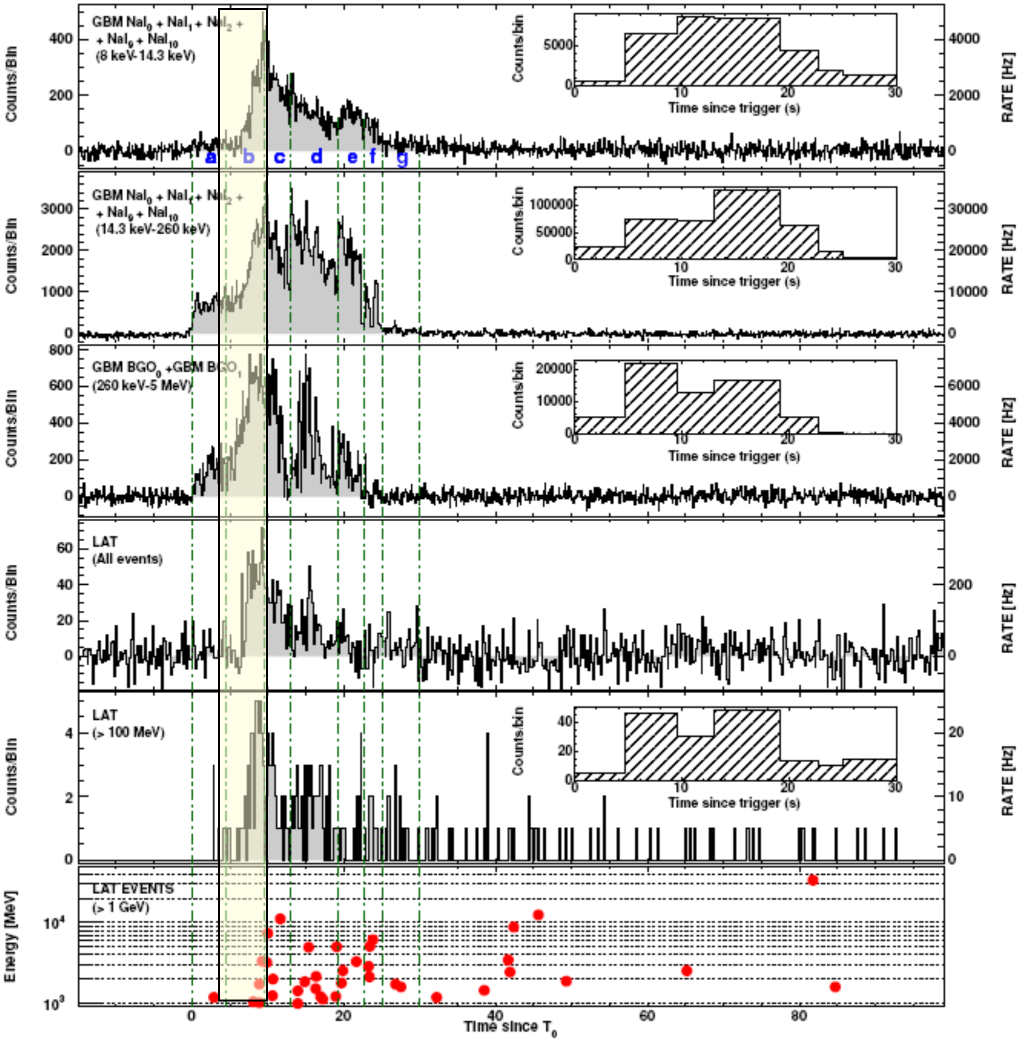


GRB090510. First bright short GRB
Clear detection of an extra component, inconsistent with the Band function.

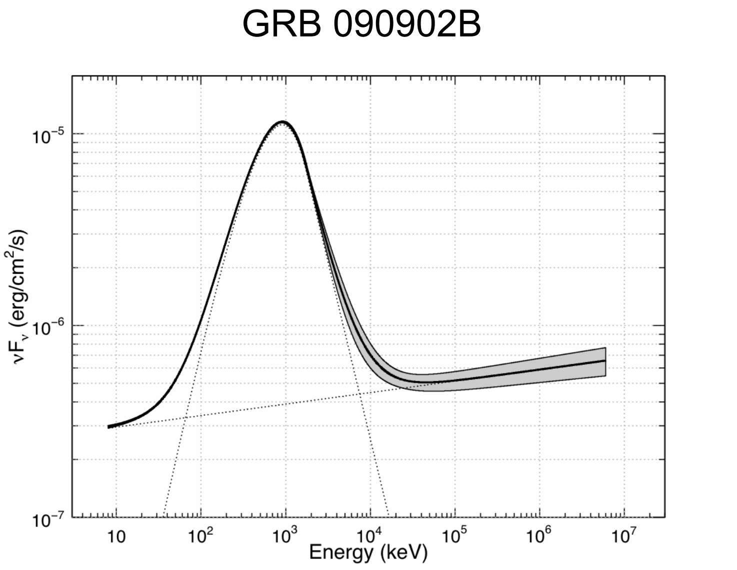
Ackermann et al. 2010



GRB 090902B: A Hard Component in a Long GRB



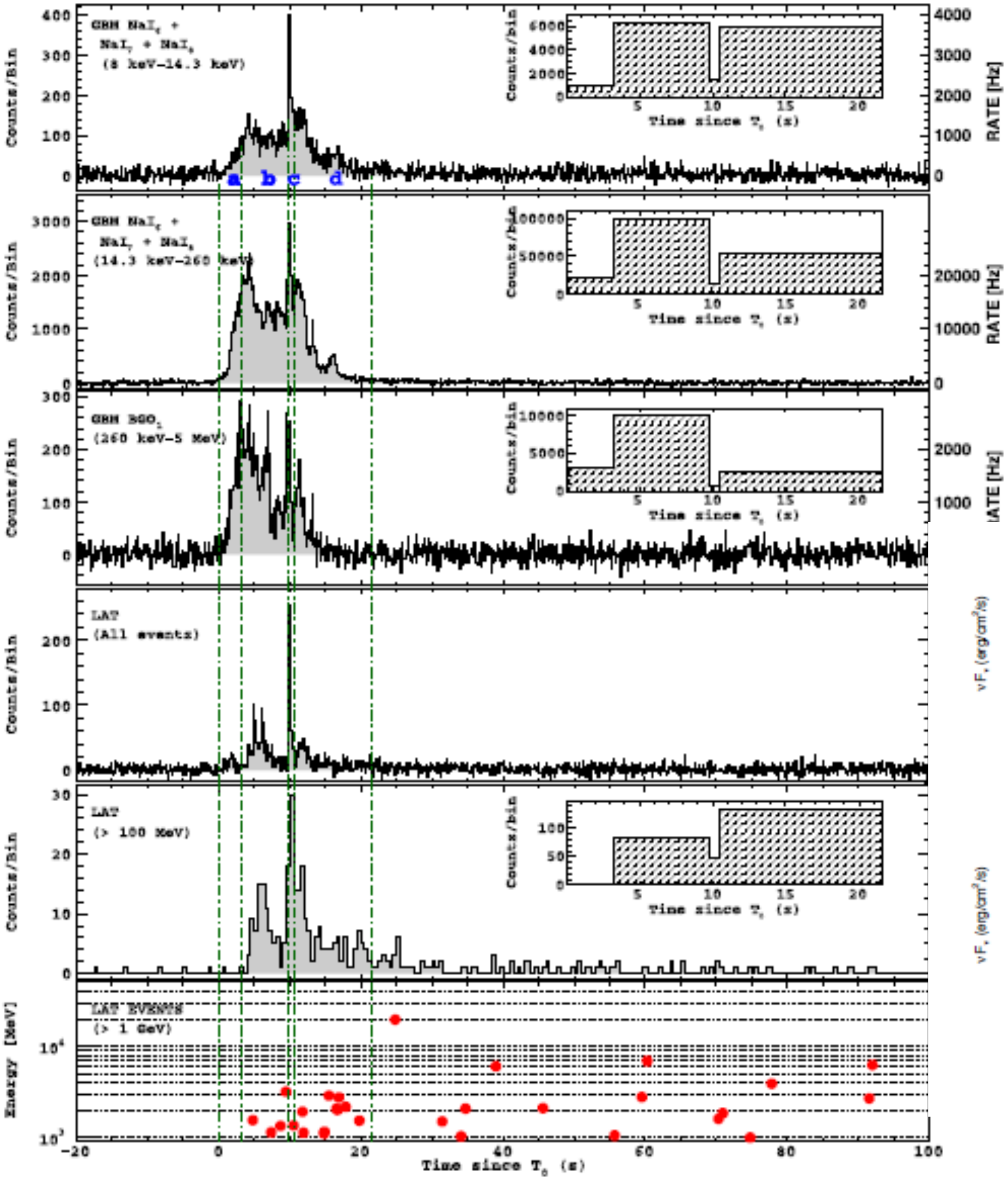
Abdo et al. 2009

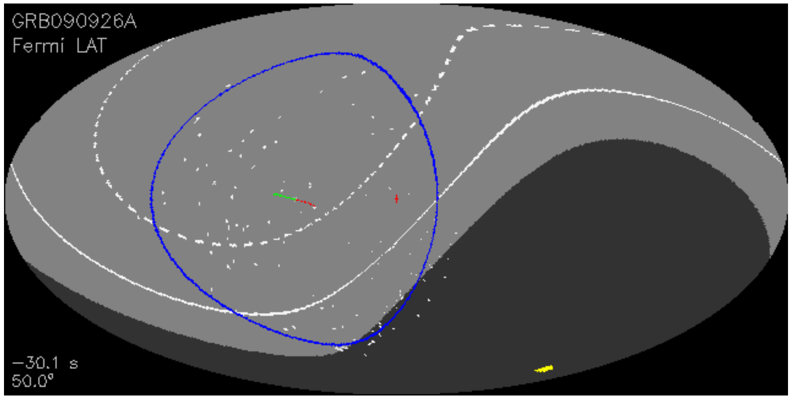


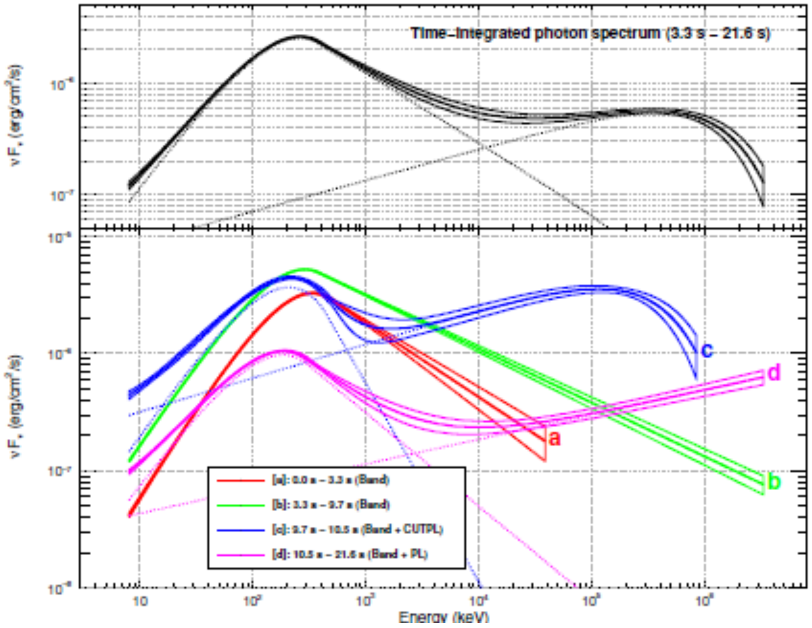
Best fit spectrum to interval b (T_0+4.6 s to T_0 + 9.6 s) is a band function (smoothly broken power-law) + power-law component.

Note narrowness of the MeV component

GRB 090926A







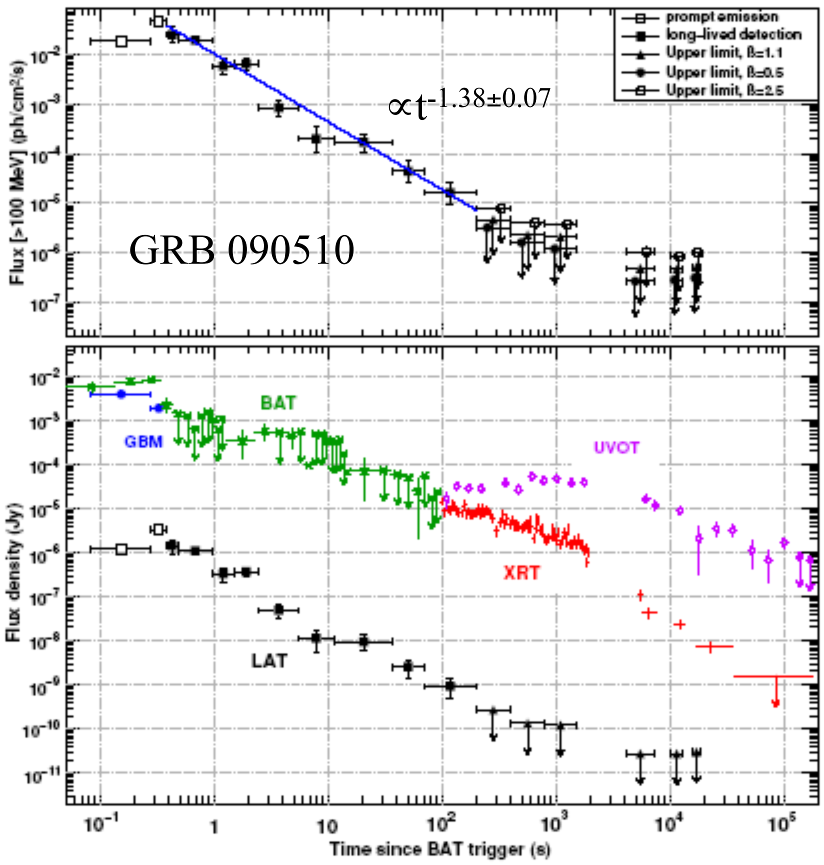
Ackermann et al. 2011

GRB 090926A

Ackermann et al. 2011

- ❑ **High-energy events up to ~ 20 GeV**
- ❑ **Extra hard component in integrated spectrum; spectral break at ≈1.4 GeV**
- ❑ **Extra component dominates the emission in the high (>1 MeV) energy range at the time of narrow pulse simultaneously observed by LAT and GBM**
- ❑ **The ~3.3 s delay of the LAT emission onset can be explained as the overall flux increase and the spectral hardening of the Band component, since the clear emergence of the extra component occurs only at a later time**
- ❑ **The rapid temporal variability of the extra component and the correlation of the Band and extra components put strong constraints on the external shock scenario: the external medium needs to be highly clumpy, and the emission mechanisms of the two components should be related**
- ❑ **Bulk Lorentz factor of the emitting shell in range of Γ ~ 200–700**
- ❑ **Suggests that the Γ are widely distributed over a range of values.**

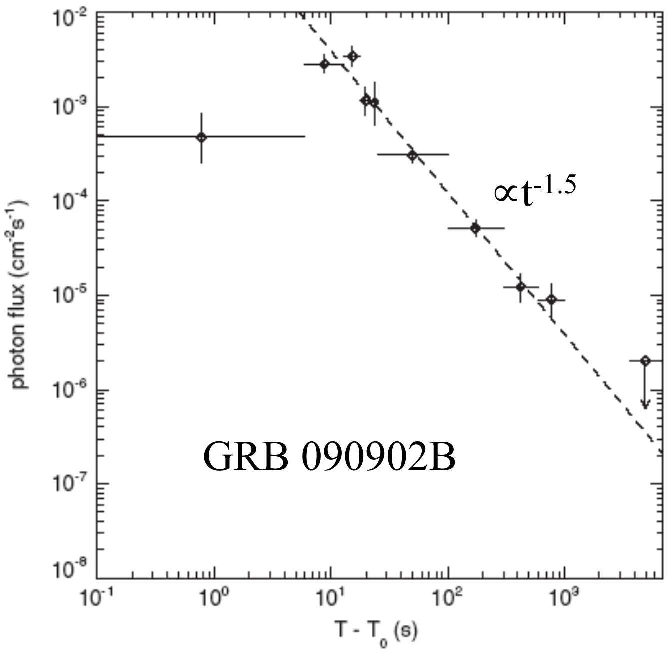
Long-lived Emission with power-law temporal decays



$\propto t^{-1.38\pm0.07}$

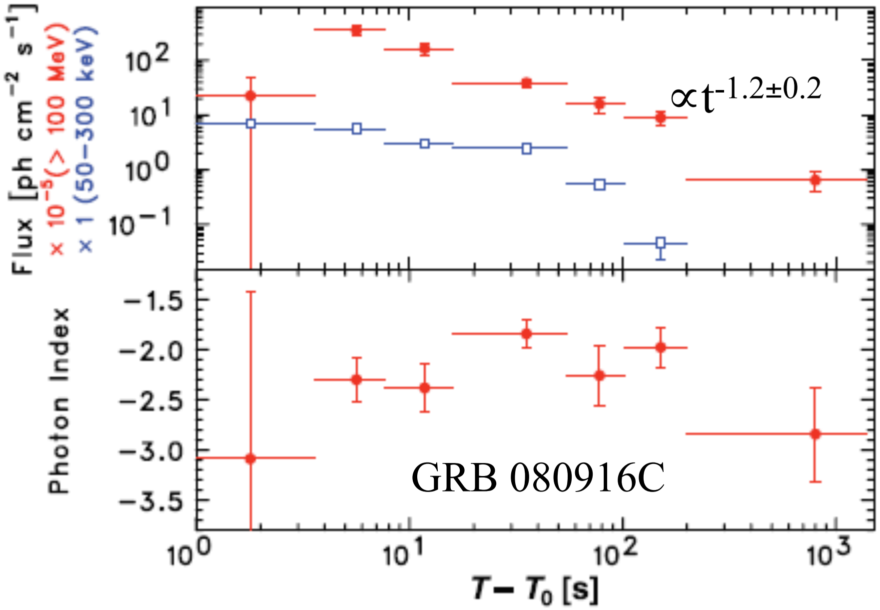
GRB 090510

De Pasquale, M., et al. 2010, ApJ, 709, L146



$\propto t^{-1.5}$

GRB 090902B



$\propto t^{-1.2\pm0.2}$

GRB 080916C

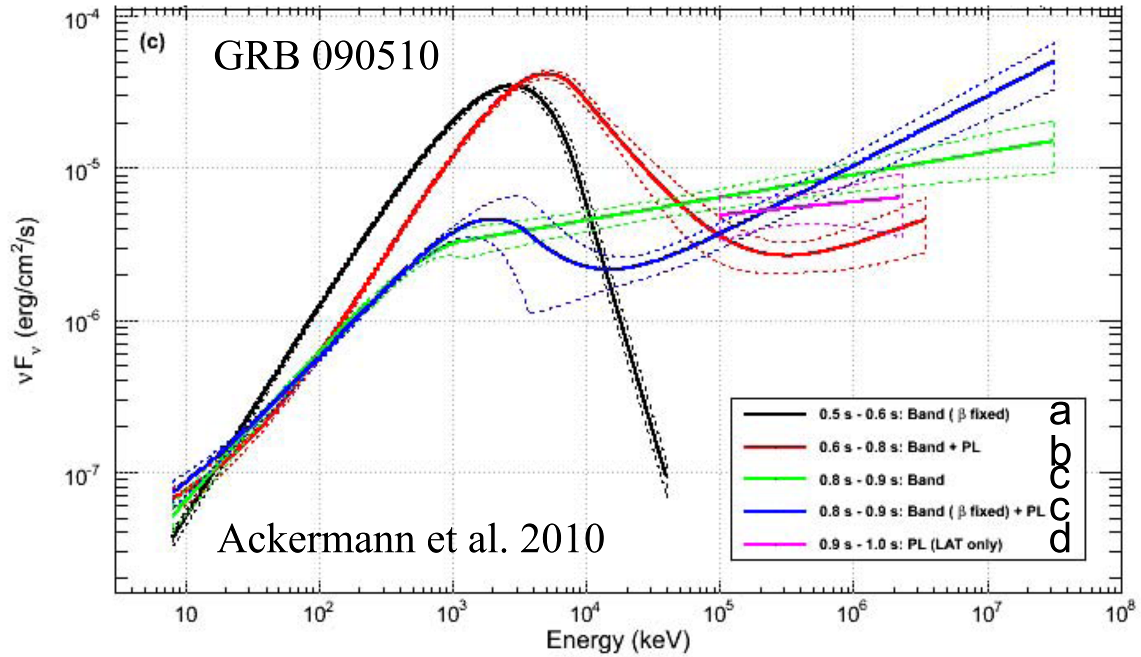
Minimum Bulk Lorentz Factor: Simple Estimate

$$\Gamma_{\min} \cong \left[\frac{\sigma_{\rm T} d_L^2 (1+z)^2 f_{\hat{\epsilon}} \epsilon_1}{4 t_v m_e c^4}\right]^{1/6} \quad , \quad \hat{\epsilon} = \frac{2\Gamma^2}{(1+z)^2 \epsilon_1}$$

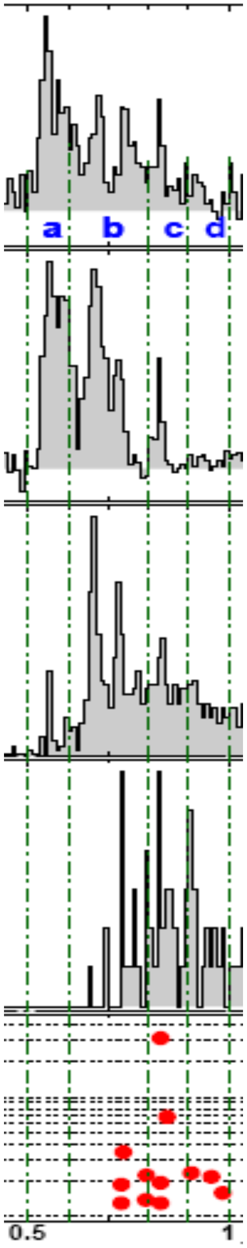
$f_\varepsilon = \nu F_\nu$ spectrum at energy $m_e c^2 \varepsilon$

$z = 0.903 \pm 0.003$, $d_L = 1.80 \times 10^{28}$ cm, $t_v = 0.01\ t_{-2}$ s

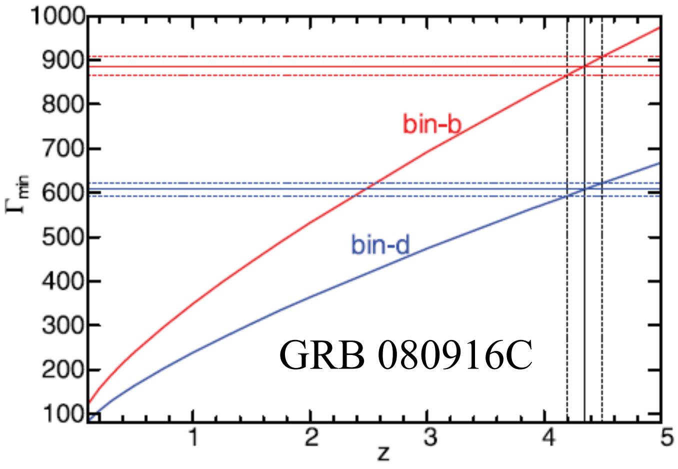
Time bin b: 3.4 GeV	Time bin c: 30.5 GeV
$\Gamma_{\min}$ = 950 (total)	$\Gamma_{\min}$ = 1370 (total)
720 (PL)	1060 (PL)



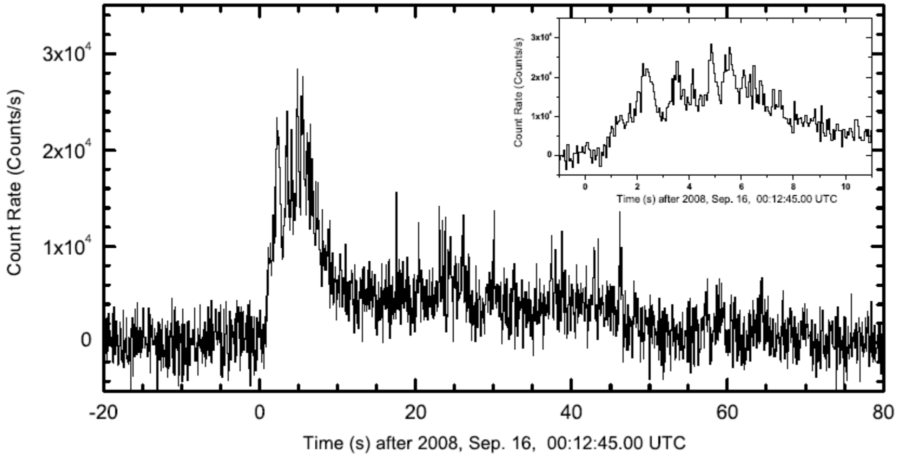
Ackermann et al. 2010



Γ_{min} for Fermi LAT GRBs



Greiner et al., A&A (2009)



$$\tau_{\gamma\gamma}(\epsilon'_1) = \int_{r'_1}^{r'_2} dr' \int_{-1}^{1} d\mu'(1-\mu') \int_{2/\epsilon'_1(1-\mu')}^{\infty} d\epsilon' \; \sigma_{\gamma\gamma}[\epsilon'\epsilon'_1(1-\mu')]\, n_{ph}(\epsilon',\mu';r')$$

INTEGRAL-SPI at 50 ms resolution; Variability as short as 100 ms

Table 3. Γ_{min} values for the shortest time scale pulses from GRB 090510

$T - T_0$ (s)	Spectrum	t_v (ms)	E_{max} (GeV)	Γ_{min}[a]
0.6–0.8	Band + PL	14 ± 2	3.4	951 ± 38
0.6–0.8	PL[b]	14 ± 2	3.4	703 ± 34
0.8–0.9	Band[c]	12 ± 2	30.5	1324 ± 50
0.8–0.9	Band + PL	12 ± 2	30.5	1218 ± 61
0.8–0.9	PL[b]	12 ± 2	30.5	1083 ± 88

⇒ Γ_{min} ≈ **900, GRB 080916C**
1000, GRB 090902B
1200, GRB 090510

Γ_{min}: Issues

1. t_v: FWHM of shortest pulse measured in any detector during the chosen time interval
2. Cospatial assumption: test by correlated variability between LAT and GBM emission components
3. Assumed geometry and temporal evolution
   - Photon escape probability
   - Radiation process
   - Shell vs. blob
4. Random fluctuation from a relativistic shell with $\Gamma < \Gamma_{\text{min}}$

Exponential escape:

$$\Gamma/\Gamma_{\rm min} = 0.96,\ 0.88,\ \text{and}\ 0.80$$

Slab/spherical escape:

$$\Gamma/\Gamma_{\rm min} = 0.89,\ 0.69,\ \text{and}\ 0.49$$

at 1,2, 3σ significance, respectively

2nd and 3rd highest energy photons can be more constraining

Properties of Fermi LAT GRBs: summary

1. Large apparent isotropic energy releases ($\Rightarrow$ small jet angles)
2. Delayed onset of GeV emission
3. Hard power-law component in addition to Band component
4. Extended GeV radiation decaying as a power-law in time
5. Large values of Γ_{min}

How to explain phenomenology in context of

1. Leptonic Model?
    - photospheric (Ryde, Pe'er, et al.)
    - synchrotron-SSC
    - external shock
2. Hadronic Model?
    - proton/ion synchrotron
    - photohadronic

Interpretation of Delayed Onset of >100 MeV Emission

- ☐ Random collisions between plasma shells
  - ➔ Separate emission regions from forward/reverse shock systems
  - ➔ Second pair of colliding shells produce, by chance, a harder spectrum
  - ➔ Expect no time delays for >100 MeV in some GRBs, yet to be detected
- ☐ Opacity effects
  - ➔ Expansion of compact cloud, becoming optically thin to >100 MeV photons
  - ➔ Expect spectral softening break evolve to higher energy in time; not observed
- ☐ Up-scattered cocoon emission *Toma, Wu, Meszaros (2009)*
  - ➔ Synchrotron-self-Compton for < MeV
  - ➔ External Compton of cocoon photons, arriving late from high-latitude, to >100 MeV
- ☐ Photospheric emission upscattered by internal shock electrons
  - ➔ photospheric emission for < MeV *Toma, Wu, Meszaros (2010)*
  - ➔ internal shock electrons Compton scatter photosphere photons
  - ➔ time delays occur in limited parameter regime

3. Leptonic Models

Synchrotron/SSC model for GRB 090510

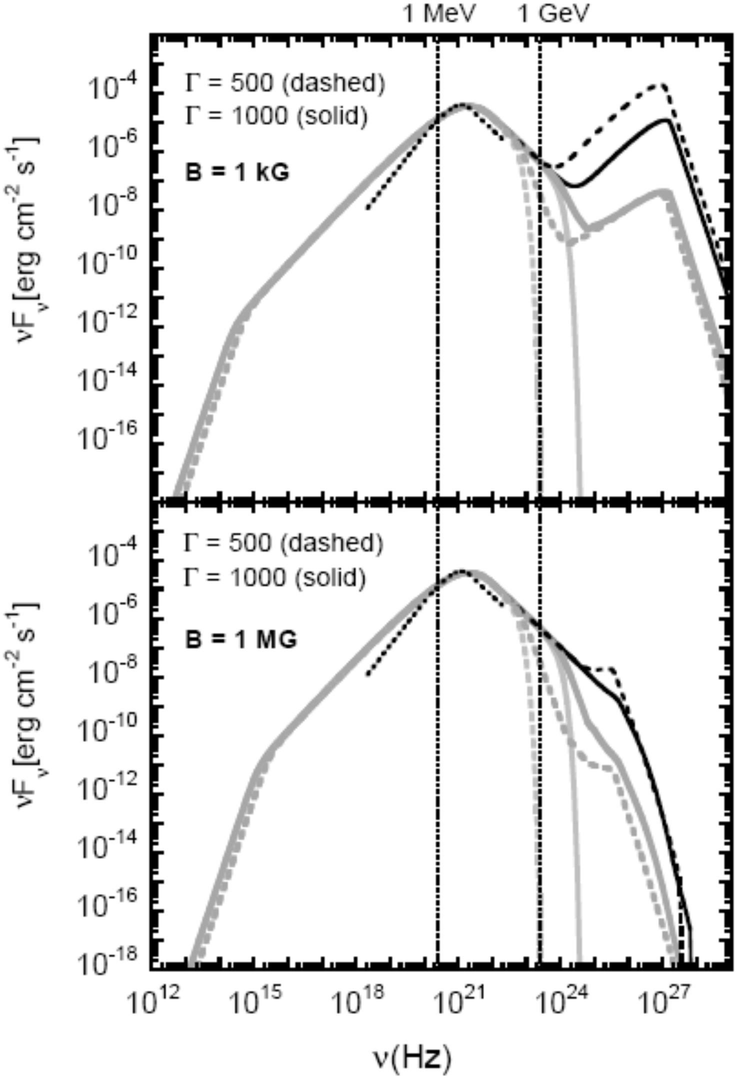
Given synchrotron spectrum and t_v (defining size scale of emission region), SSC component depends only on Γ and B′

Cascade to make hard component

Model for time interval b: B′ = 1 kG (near equipartition), B′ = 1 MG, Γ = 500, 1000

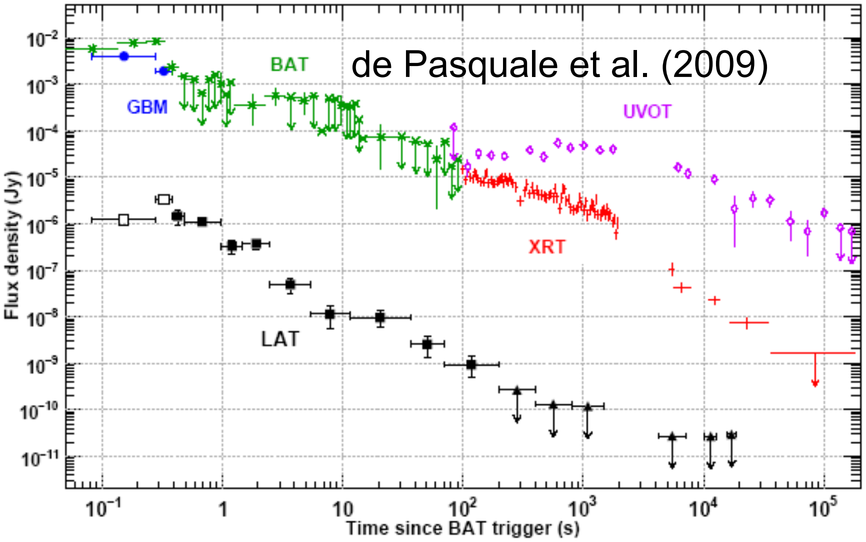
Problems:

1. Line-of-death
2. Time to make synchrotron cascade
3. If large B, then need to invoke separate origin for hard component



Afterglow Synchrotron Model

LAT radiation due to nonthermal synchrotron emission from decelerating blast wave (Kumar and Barniol Duran 2009, Ghirlanda et al. 2009, Ghisellini et al. …)



de Pasquale et al. (2009)

Identifying peak of LAT flux (≈0.2 s after main GBM emission) with $t_{dec} \Rightarrow \Gamma_0\ n^{-1/8}$

For uniform external medium, $\nu > \nu_c, \nu_m$

Adiabatic blast wave:

$$\nu F_\nu \propto t^{(2-3p)/4} \nu^{(2-p)/2} \propto t^{-1}\ (p=2)$$

Radiative blast wave:

$$\nu F_\nu \propto t^{2(1-3p)/7} \nu^{(2-p)/2} \propto t^{-10/7}\ (p=2)$$

Problems:

1. Closure relation
2. Highest energy photon
3. Variability (?)

Radiative External Shock Model

(Ghisellini et al, 0910.2459)

- GeV light curves *roughly* $F_E \sim E^{-1.5}$ for most LAT obs.
- Spectrum *roughly* $F_E \sim E^{-1}$, not strongly evolving
- Argue it is external shock, with $L \sim t^{-10/7}$ as expected

for `radiative' f'balls $\Gamma \sim r^{-3} \sim t^{-3/7}$

- To make 'radiative', need `enrich' ISM with e±
- Argue pair-dominated fireball obtained from backscattering of E>0.5 MeV photons by ext. medium, → cascade
- External shock (afterglow) delay: explain GeV from

MeV delay (MeV prompt is something else (?))

- Problem: $r \gtrsim 10^{15}$ cm needed, where $n_{\pm} \lesssim n_p$ (e.g. '01, ApJ, 554,660)

(from P. Meszaros, Kyoto 2010)

Adiabatic Unmagnized External Shock

(Kumar and Barniol-Duran 2009, 2010)

- Consider late (>4 s) afterglow at >100 MeV
- $E>E_c$, E_m (sync.) ⇒spectrum indep. of Γ, n
- $F_E \sim t^{-1.2} \pm 0.2$ ⇒ as adiabatic ext. shock
- At t< 4s argue KN negligible ($Y \lesssim 1$)
- Derive ε_B, n from argument that ES at t<50 s should not dominate spectrum at <500 keV (which is unspecified ‘prompt’ emiss.)
- →εs params. from >0.1 GeV predict XR, O ✓
- →B′ ~ 0.1G →B_{ext}~10-70 μG shock comp.✓

PROBLEMS:

- Densities rather low
- In SNR shocks have indications for B >> Bcompr.
- Adiabaticity relies on low n (param. fit assumptions)

(P. Meszaros, Kyoto 2010)

4. Hadronic Models

Synchrotron Radiation from UHE Protons

Instantaneous energy flux Φ (erg cm^{-2} s^{-1}); variability time t_v, redshift z

$$u'_\gamma \approx \frac{4\pi d_L^2 \Phi}{\Gamma^2 4\pi R^2 c} \approx \frac{(1+z)^2 d_L^2 \Phi}{\Gamma^6 c^3 t_v^2}$$

Implies a jet magnetic field

$$B'(kG) \approx 2\frac{\sqrt{\varepsilon_B \Phi_{-5} / \varepsilon_e}}{\Gamma_3^3 t_v(s)} \leq 6\sqrt{\varepsilon_B / \varepsilon_e}\left(\frac{t_v}{0.1\, s}\right)^{-1/2}$$

ε_e is baryon loading-parameter (particle vs. leptonic γ-ray energy density)

ε_B gives relative energy content in magnetic field vs. total

$\Gamma > \Gamma_{min} \equiv 10^3\Gamma_3$ from $\gamma\gamma$ opacity arguments

$$\Gamma_{\min} \approx \left(\frac{\sigma_T d_L^2 (1+z)^2 \Phi \varepsilon_1}{6 t_v m_e c^4 \ln(\varepsilon_u / \varepsilon_\ell)}\right)^{1/6}$$

Fermi Acceleration and Synchrotron Radiation of Protons in GRB Blast Waves

Razzaque, Dermer, Finke, Open Astronomy Journal (2010)

Protons gain energy on timescales exceeding Larmor timescale, implying acceleration rate; ϕ is acceleration efficiency

$$\dot{\gamma}'_{acc,p} = \frac{eB'}{\phi m_p c}$$

Saturation Lorentz factor:

$$\gamma'_{sat,p} = \phi^{-1/2}\frac{m_p}{m_e}\left(\frac{B_{cr}}{B'}\right)^{1/2}\sqrt{\frac{9}{4\alpha_f}} \approx \frac{2\times 10^8}{(\phi/10)^{1/2}B_5'^{1/2}}$$

Proton saturation frequency:

$$\varepsilon_{sat,p} = \frac{\Gamma}{1+z}\varepsilon'_{sat,p} = \frac{\Gamma}{1+z}\phi^{-1}\frac{m_p}{m_e}\frac{27}{8\alpha_f} \approx \frac{1.6\times 10^7\Gamma_3}{(\phi/10)}$$

Observer measures a time for protons to reach

$$t_{sat} = \frac{1+z}{\Gamma}\phi^{1/2}\frac{m_p^2 c}{m_e}\left(\frac{6\pi}{e\sigma_T B'^3}\right)^{1/2} \approx \frac{0.01\sqrt{\phi/10}}{\Gamma_3 B_5'^{3/2}}\, s$$

$\gamma\gamma$ processes induce second generation electron synchrotron spectrum at

$$\varepsilon_{sat,e} \approx \frac{3}{2}\frac{\Gamma}{1+z}\frac{B'}{B_{cr}}\phi^{-2}\left(\frac{m_p}{m_e}\frac{27}{16\alpha_f}\right)^2 \approx \frac{10^3\Gamma_3 B_5'}{(\phi/10)^2}$$

Time for proton synchrotron radiation to reach $\varepsilon_{sat,e}$:

$$t_{cl} = t_{sat}\sqrt{\phi\frac{B_{cr}}{B'}\frac{m_e}{m_p}\frac{64\alpha_f}{81}} = \frac{4}{3}\frac{1+z}{\Gamma}\phi\frac{m_p c B_{cr}}{eB'^2}\sqrt{\frac{m_p}{m_e}} \approx 1.4\frac{(\phi/10)}{\Gamma_3 B_5'^2}\, s$$

Proton Synchrotron Model for GeV Radiation in GRBs

Accumulation and cooling of protons makes delayed proton synchrotron γ radiation

γγ processes induce second-generation electron synchrotron spectrum

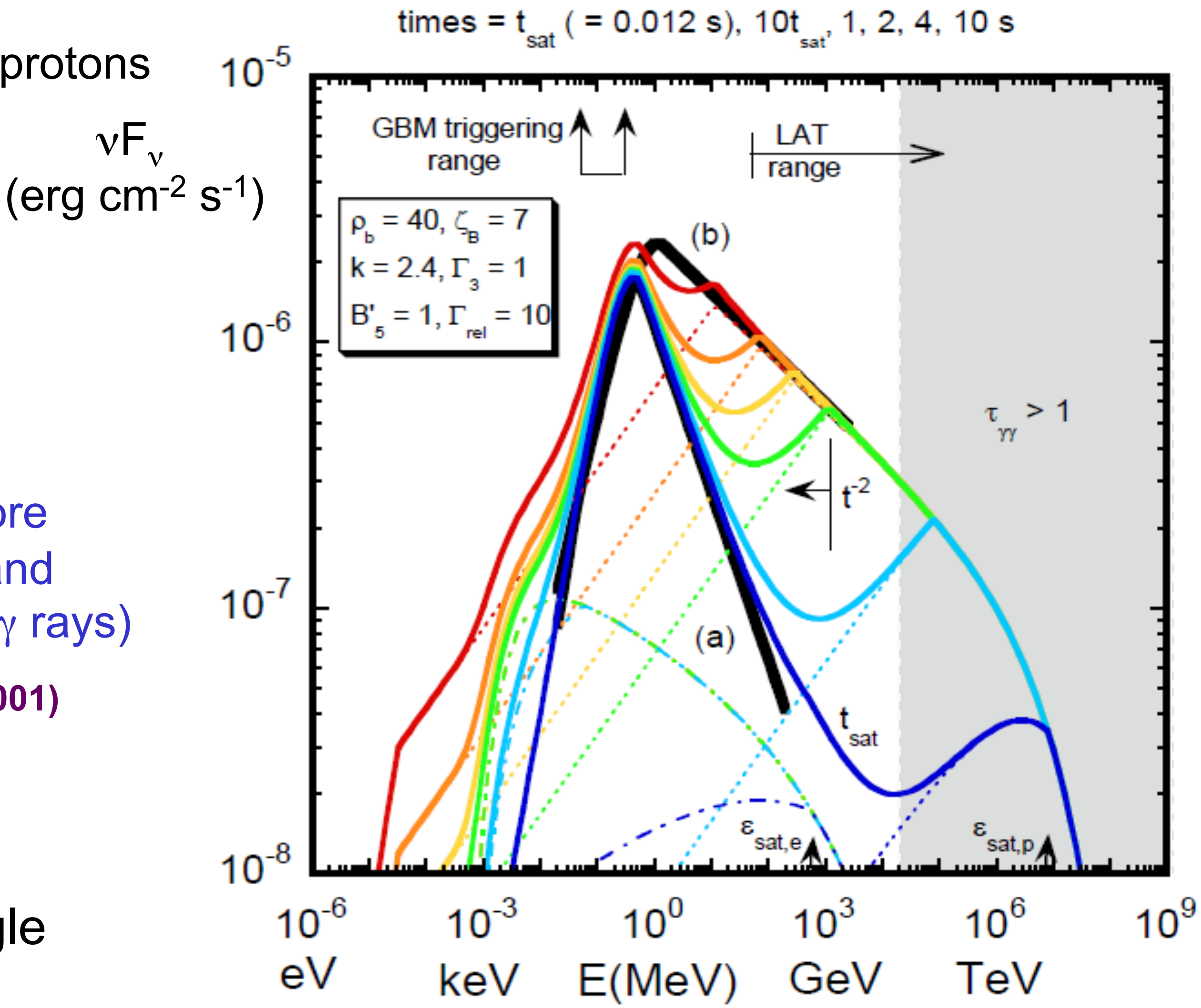
Energetics difficulties

(requires ~100 – 1000 more energy in magnetic field and protons than observed in γ rays)

see also Zhang & Mészáros (2001)
Wang, Li, Dai, Mészáros (2009)

Only plausible for

1. small jet opening angle
2. $\Gamma \sim< \Gamma_{min}$



Efficiency of Hadronic (Proton Synchrotron Photopion and Photopion) Models

Proton-synchrotron energy requirements

$$\mathcal{E} \approx 1.3 \times 10^{54} (\Gamma/1000)^{16/3} (t_{\rm onset}/0.1\ {\rm s})^{5/3} ({\rm E}_\gamma/100\ {\rm MeV})^{-2/3} (\theta_{\rm j}/1\ {\rm deg})^2\ {\rm erg}$$

(Wang et al. 2009;
Razzaque et al. 2009)

Photopion efficiency *(see my Saas-Fee lecture)*

$$\eta_{p\gamma}(E_p^{pk}) \cong \frac{K_{p\gamma}\sigma_{p\gamma} d_L^2 f_{\varepsilon_{pk}}}{m_e c^4 \Gamma^4 t_v \varepsilon_{pk}}$$

$$E_p^{pk} \cong \frac{400 m_p c^2 \Gamma^2}{(1+z)\varepsilon_{pk}} \approx \frac{2\times 10^{17}\Gamma^2}{\varepsilon_{pk}} eV$$

$$\eta_{p\gamma}(E_p^{pk}) \cong 0.03 \frac{f_{-5}}{\Gamma_3^4 (t_v/0.01 s)\varepsilon_{pk}}$$

$$\eta_{p\gamma}(E_p) = \eta_{p\gamma}(E_p^{pk})\left(\frac{E_p}{E_p^{pk}}\right)^{1-b}$$

Large Γ-factors unfavorable for ~PeV neutrino production

Problem:

Large amounts of energy required

~100x amount of energy radiated at MeV energies

$$2^{16/3} \cong 40$$

$$3^{16/3} \cong 350$$

Photohadronic GRB Modeling

Energy injected in protons normalized to GRB MeV fluence

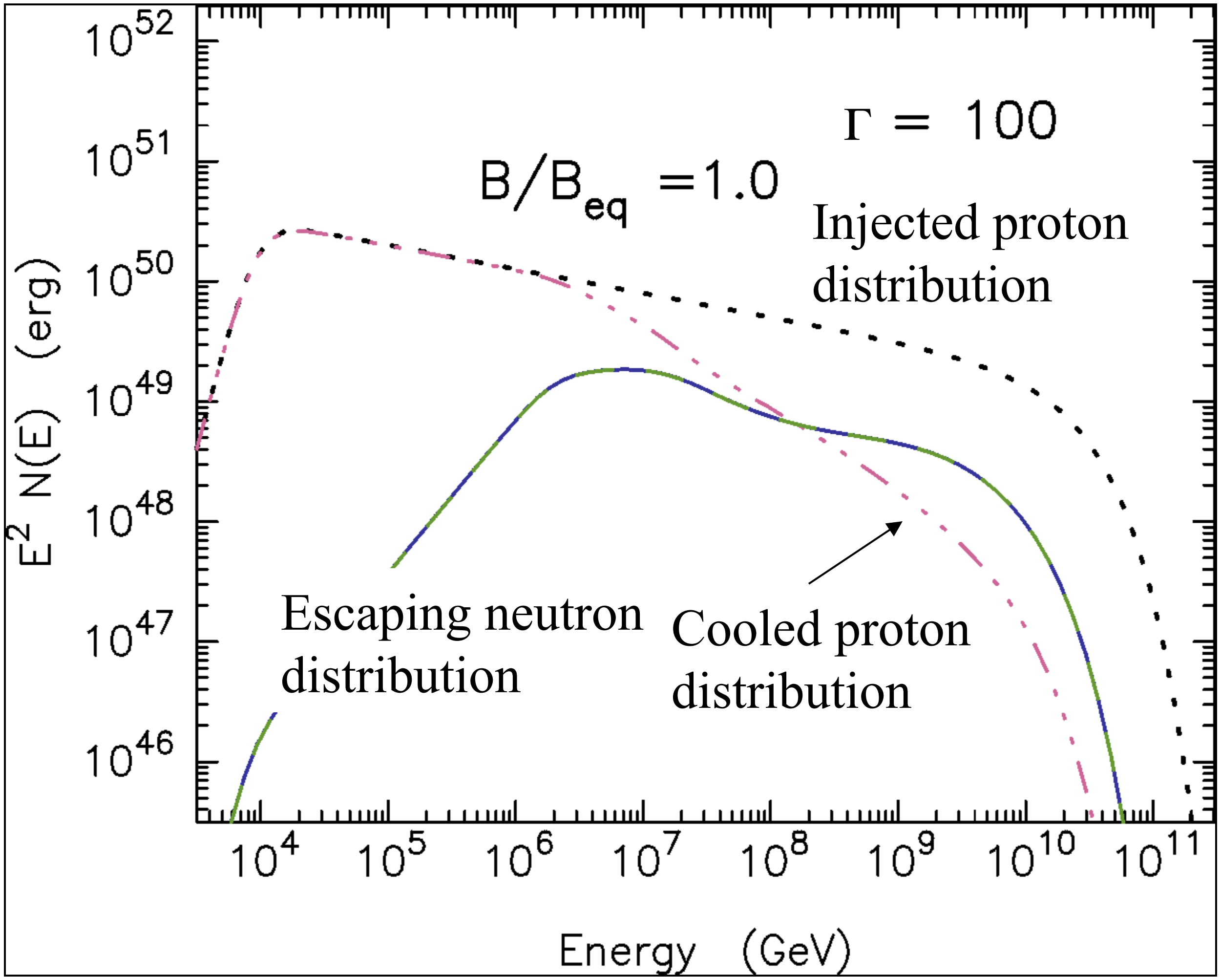
$\Phi = 3\times10^{-5}$ erg cm^{-2}

in 50 one-second pulses

UHE neutral beam:

- **neutrons**
- **γ rays**
- **neutrinos**

Baryon Loading Factor $f_b = 20$



Photohadronic Cascade Radiation Fluxes

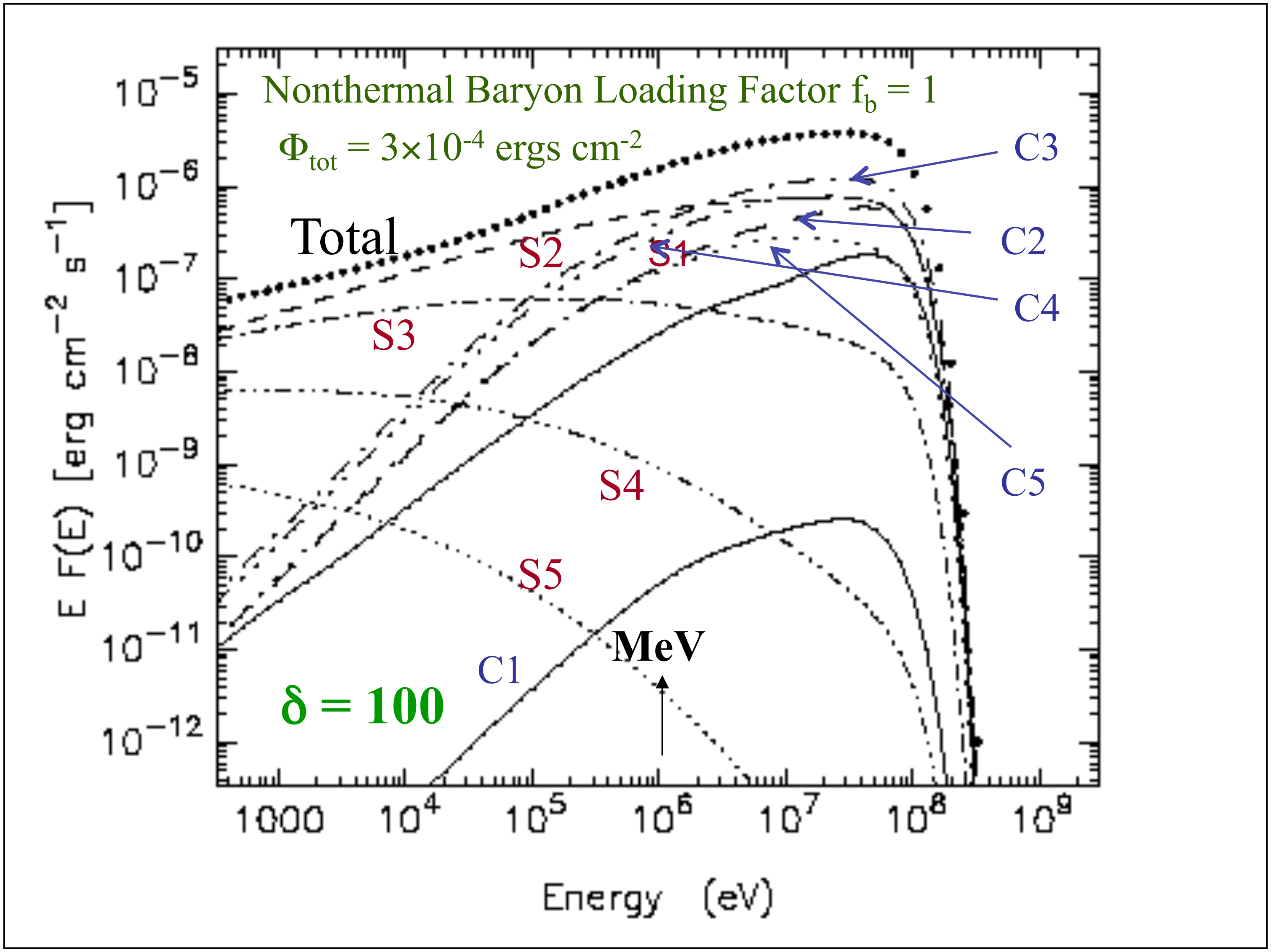
Photomeson Cascade

$$p\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}$$

$e^{\pm}$ emits synchrotron (S1) and Compton (C1) photons

$\gamma\gamma' \rightarrow e^{\pm}$ emits synchrotron (S2) and Compton (C2) photons, etc.

Photon index between −1.5 and −2

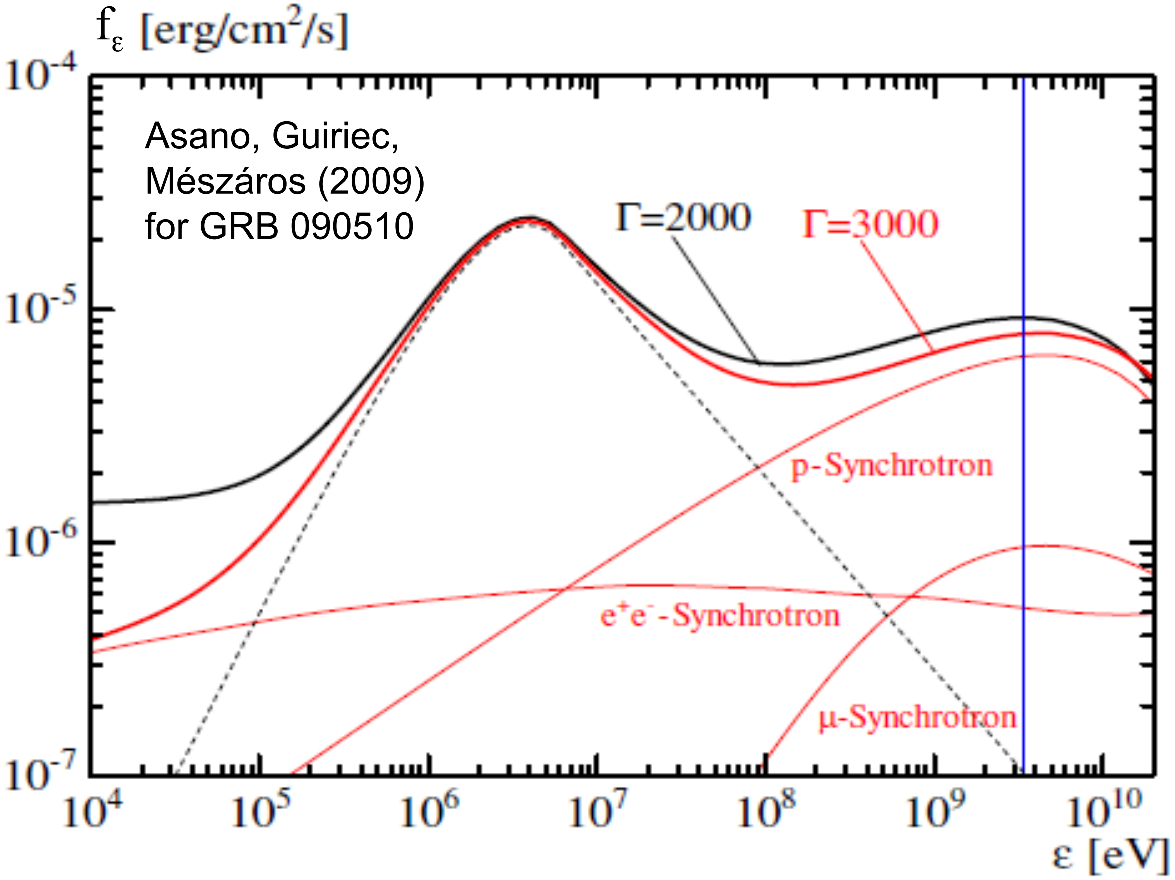


Photohadronic Model for GeV Radiation in GRBs

Hard γ-ray emission component from hadronic-induced electromagnetic cascade radiation inside GRB blast wave

Second component from outflowing high-energy neutral beam of neutrons, γ-rays, and neutrinos

Also requires large energies



$$p\gamma \to \pi^{\pm} \to e^{\pm}\ (+n, p, \nu) \to \pi^0 \to 2\gamma \to e^{\pm}$$

Neutrinos from GRBs in the Collapsar Model

For a fluence of 3×10^{-4} erg cm^{-2} (~2 GRBs per year)

N_ν predicted for IceCube:

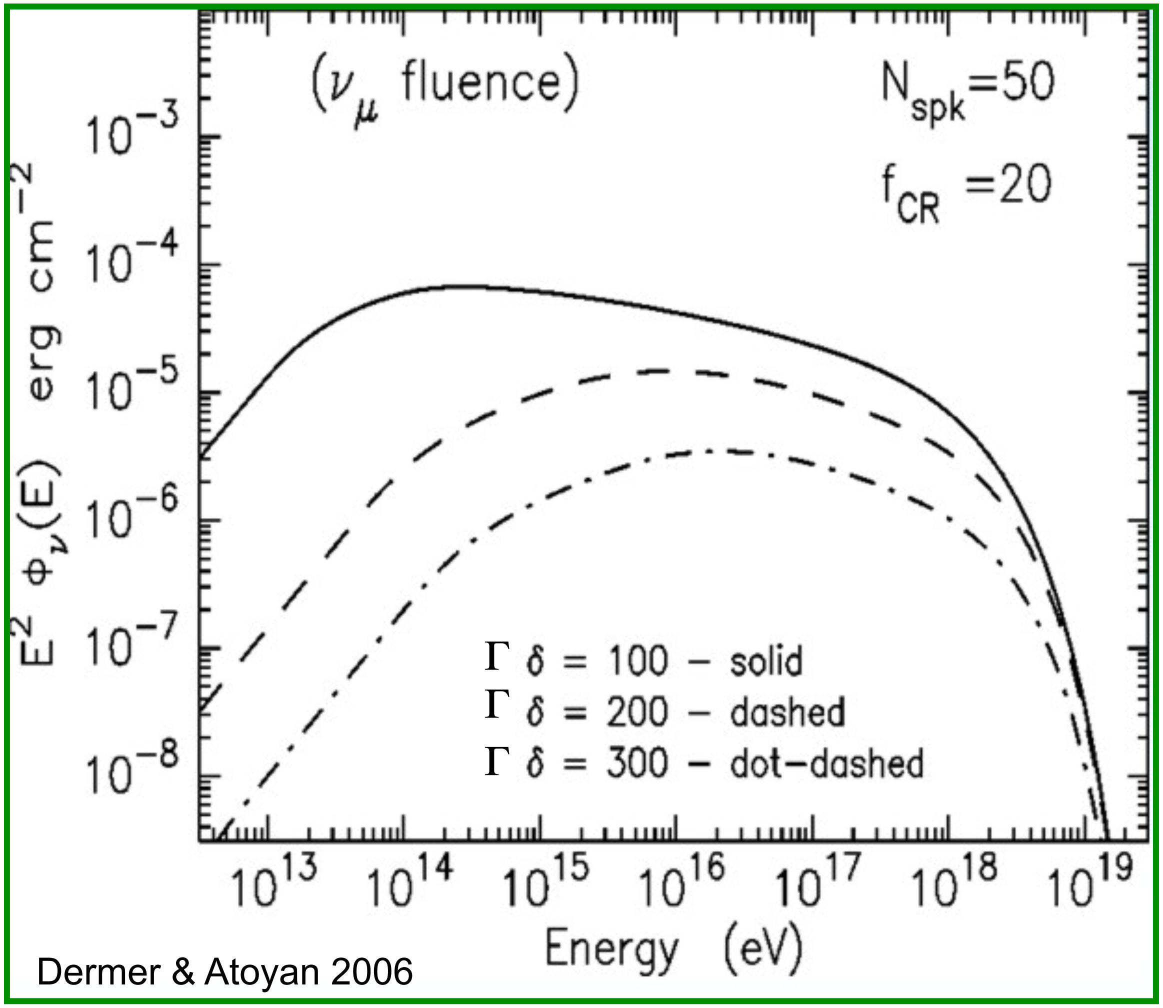
$N_\nu \approx$ 1.3, 0.1, 0.016 for Γ = 100, 200, 300

(f_b = 20 for Γ = 100, limited by requirement that cascade γ-ray fluence less than MeV fluence)

Large values of Γ imply small neutrino production

Look for neutrinos from GRBs with attenuated γ-ray emission

Baryon Loading Factor f_b = 20



Dermer & Atoyan 2006

Latest Fermi Results on GRBs

- ❑ Use prompt emission to determine jet opening angle

(Goldstein et al. 2011)

$$\theta = \cos^{-1}\left(1 - \frac{E_{peak}^{1/\eta}}{S_\gamma\, G_L}\right)$$

- ❑ Stacking analysis to constrain LAT afterglow emission

(Chiang & Racusin 2011)

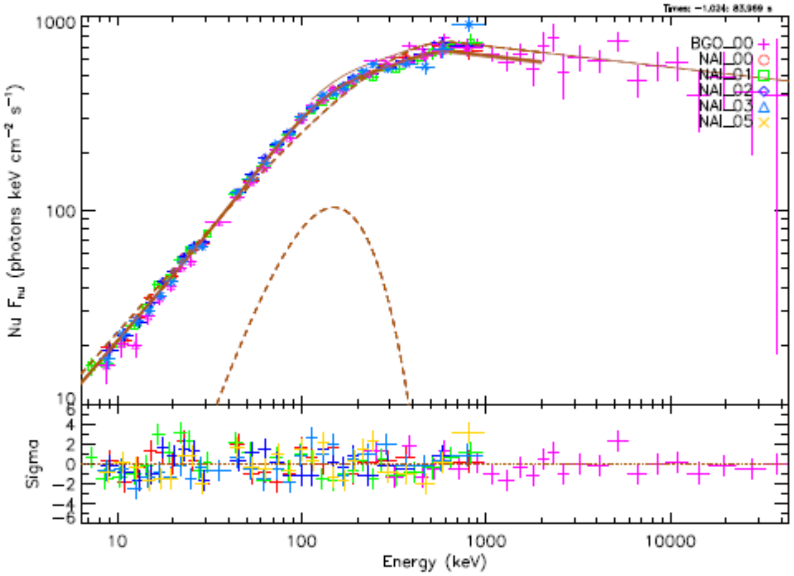
- ❑ Time-resolved spectral analysis of bright Fermi GRBs

(Zhang et al. 2011)

- ❑ Spectral modeling of GRB 102704B

(Guiriec et al. 2011)

(requires addition of a photospheric component)



Summary

- Examples of both long soft and short hard GRBs with intense GeV radiation
- Occurrence of delayed onset can be explained in both leptonic (external shock) and hadronic (time required to accelerate and accumulate protons)
- Energy requirements much greater for hadronic models, depending sensitively on Γ
- Neutrinos are the “smoking gun” hadronic emission signature from photopion processes; not yet seen
- Addition of photospheric component improves fit in some GRBs, and solves the line of death problem