GRB Theory

3 June 2014

Fermi Summer Science School

Lewes, Delaware

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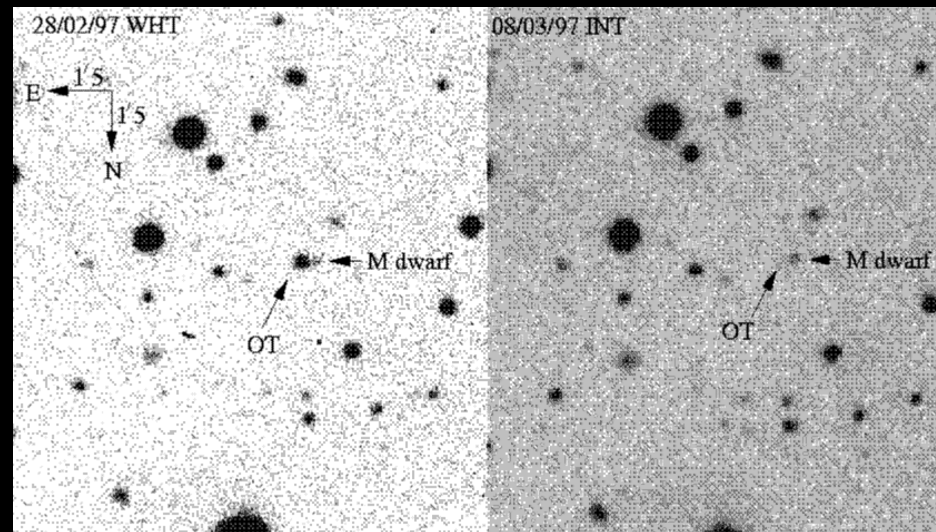
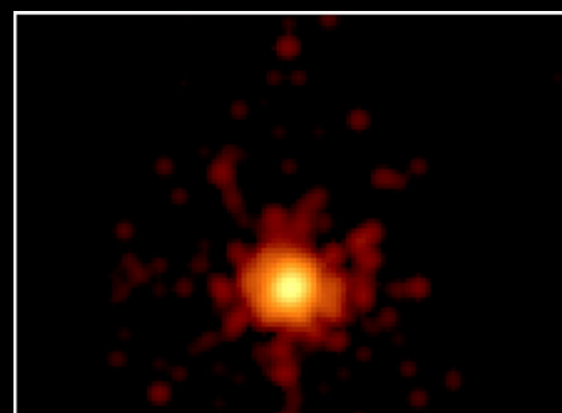
Outline

““A few observations and much reasoning lead to error;
many observations and a little reasoning to truth." A. Carrel

0. Introduction/GRB Topics
I. Long vs. Short: Progenitors
II. GRB Radiation Theory
    $\gamma\gamma$ opacity $\Rightarrow \Gamma$
    A. Photosphere/Engine
    B. Colliding Shells
    C. External Shock/Afterglow
III. GRB 130427A
IV. Advanced Topics
    A. Hadronic Models
    B. LIV tests

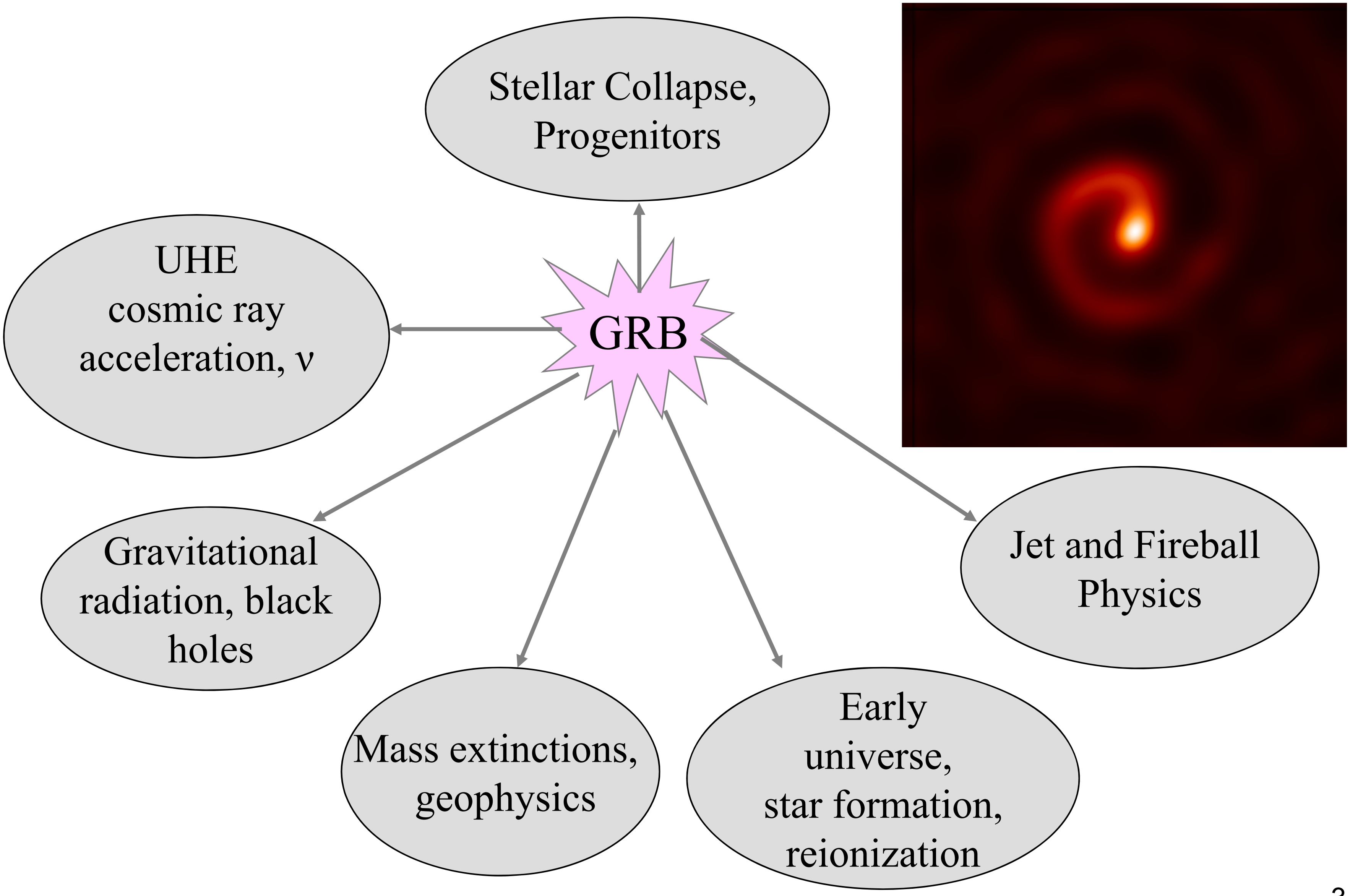
What does it all mean?





GRB 130427A (0.1-second exposure) as viewed by Swift's X-Ray Telescope

GRB Theory Topics



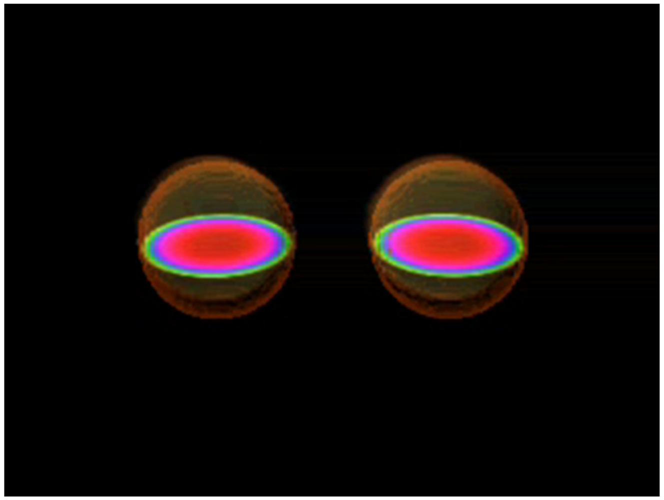
Long Soft GRBs vs. Short Hard GRBs

HYPERNOVAE/COLLAPSAR

- "Typical" long-duration GRB lasts 3 –100 s in γ-rays from keV to MeV energies <z> > 1
- Emits about $10^{51} – 10^{55}$ ergs of (apparent isotropic) energy and radiates (apparent isotropic) powers of ~ $10^{50} – 10^{53}$ ergs/s
- Variability times typically 0.1 sec or less
- Followed by long-lived X-ray, optical, radio, and GeV γ-ray afterglow emission
- Takes place in star-forming (spiral or dwarf irregular) galaxies at z ~ 1, but not in elliptical galaxies
- Collapse of a >30 $M_{\odot}$ star
- ISM allows shock formation

MERGING NEUTRON STARS

- MeV emission lasts less than ~ 3 s; <z> < 1; apparent energies smaller
- 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 host galaxy might not be forming stars at a high rate any more
- The tenuous medium might not allow strong shock formation, and therefore the production of intense afterglows



Progenitor GRB Models

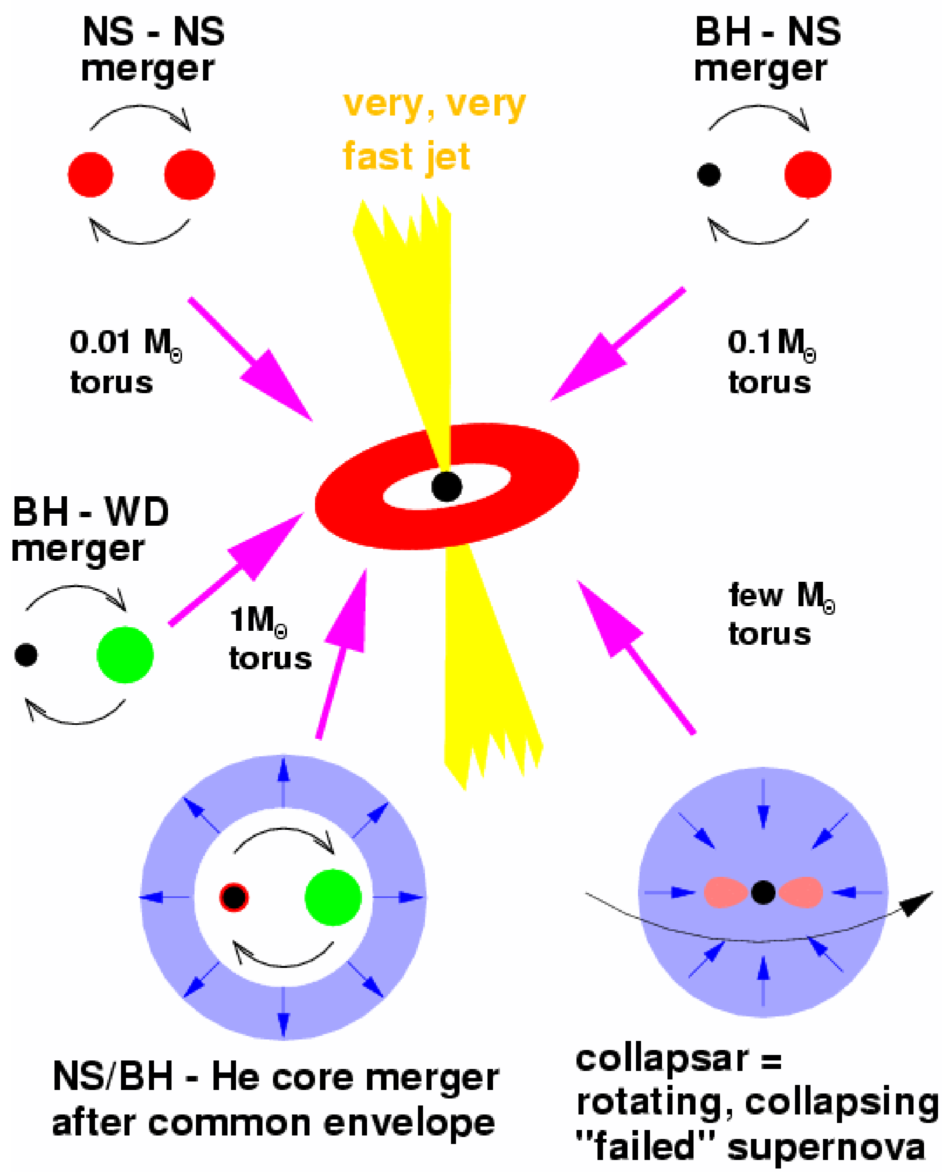
GRB models with hyper-accreting black holes:

Collapsars

- Collapse of a rotating massive star (binary or single star)
- Neutron star/black hole merger with a helium core: “He-star Merger”

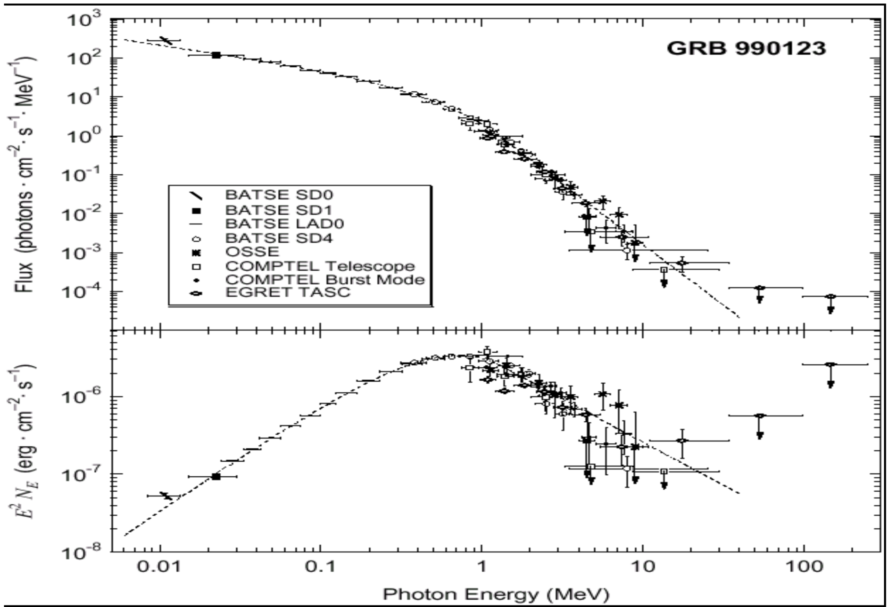
Compact object mergers

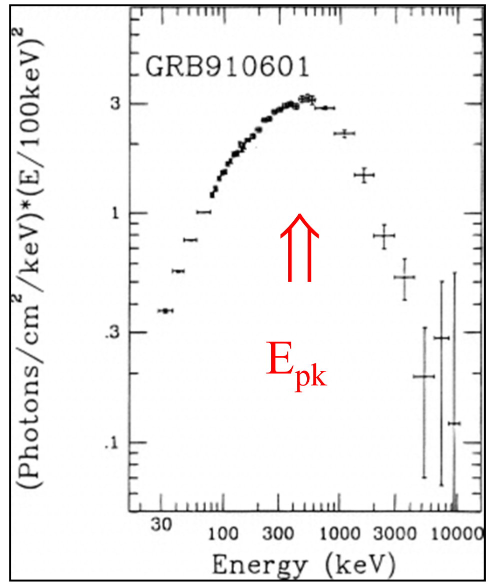
- Neutron Star – Neutron Star Mergers (Hulse-Taylor Pulsar System)
- Black Hole – Neutron Star Mergers
- Black Hole – White Dwarf Mergers

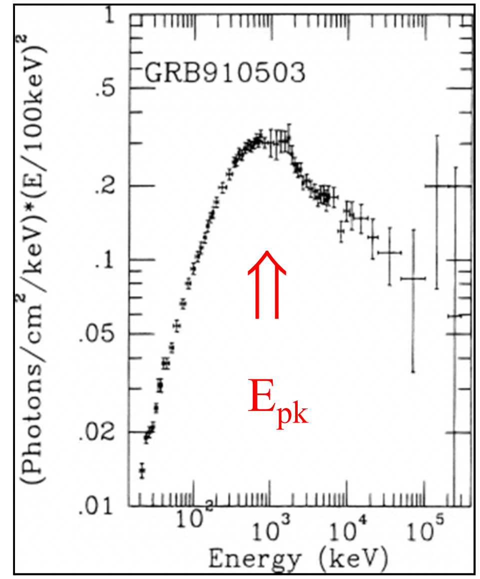


S. Woosley, Ringberg, 1997

Spectral Properties of GRBs







Schaefer et al. (1998)

Band Function: Smoothly Broken Power-Law

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

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

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

SYNCHROTRON LINE OF DEATH

Band et al. (1993)

Relativistic Bulk Motion in GRBs

What is Γ, and why is it important?

After redshift ***z,*** Γ is the most important property to make the extreme behavior of GRBs comprehensible

$$4\pi d_L^2\,\Phi_\gamma = L_\gamma \approx \Gamma^2 L'_\gamma \approx 4\pi c R^2 \Gamma^2 u'; \varepsilon \approx \Gamma \varepsilon'$$

$$R \approx \Gamma^2 c t_{\rm var} \Rightarrow L_\gamma (erg/s) \sim c^3 \Gamma^6 t_{\rm var}^2 u'$$

$$u'_\gamma \propto \frac{L_\gamma}{t_{\rm var}^2 \Gamma^6} \Rightarrow \tau_{\gamma\gamma} \approx n'_\gamma \sigma_{\gamma\gamma} R' \propto \frac{u'_\gamma \sigma_T R'}{\varepsilon'} \propto \frac{L_\gamma \Gamma \varepsilon'_1}{t_{\rm var} \Gamma^6} \propto \frac{L_\gamma \varepsilon_1}{t_{\rm var} \Gamma^6}$$

Using threshold condition $\varepsilon' \varepsilon'_1 > 2 \quad or \quad \varepsilon\, \varepsilon_1 > 2\Gamma^2$

$$\therefore \Gamma > \Gamma_{\min} \propto (L_\gamma \varepsilon_1 / t_{\rm var})^{1/6}$$

To be optically thin to $\gamma\gamma$ absorption, Γ **>100 in GRBs**

Minimum Bulk Lorentz Factor: Simple Estimate

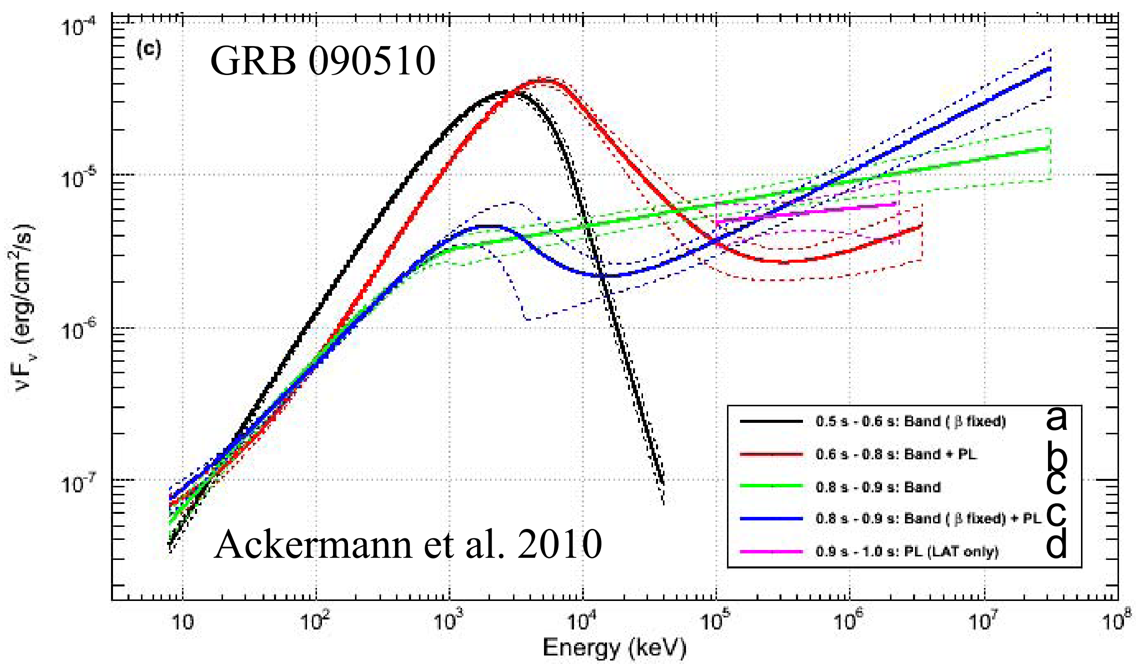
$$\Gamma_{\min} \cong \left[\frac{\sigma_T d_L^2 (1+z)^2 f_{\hat{\epsilon}} \epsilon_1}{4 t_v m_e c^4}\right]^{1/6} \quad , \quad \hat{\epsilon} = \frac{2\Gamma^2}{(1+z)^2 \epsilon_1}$$

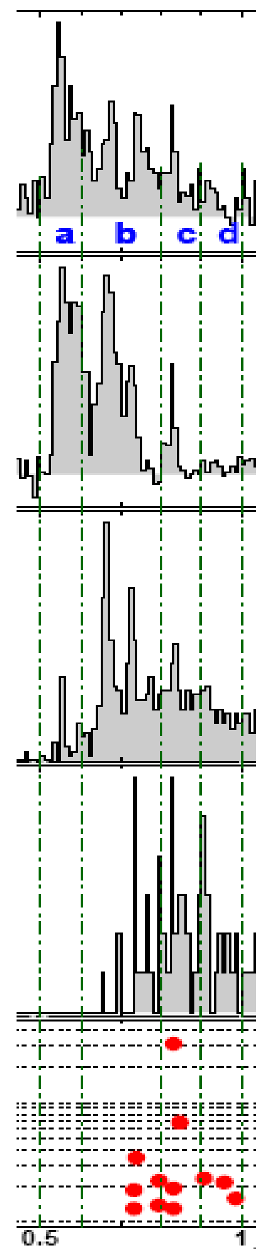
$f_\varepsilon = \nu F_\nu$ spectrum at energy $m_e c^2 \varepsilon$

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

Time bin b: 3.4 GeV
Γ_{min} = 950 (total)
720 (PL)

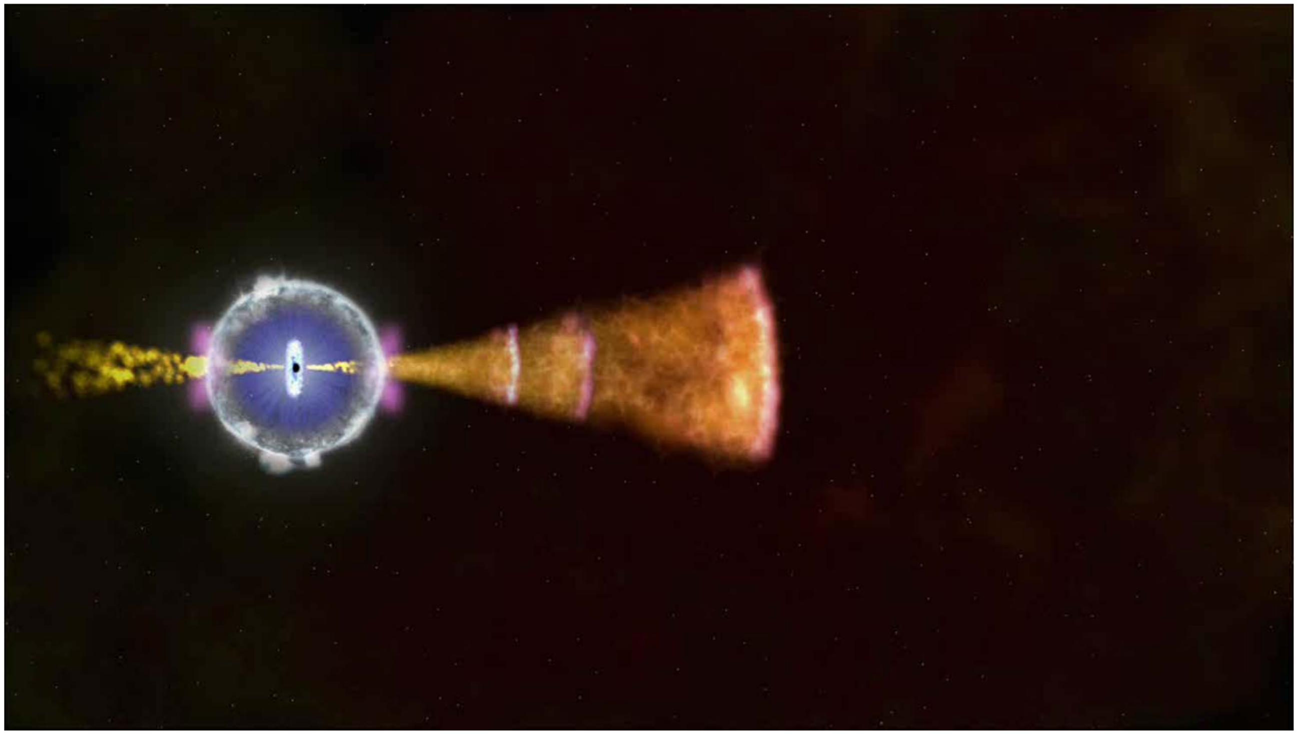
Time bin c: 30.5 GeV
Γ_{min} = 1370 (total)
1060 (PL)





GRB Radiation Theory

Cartoon of the Black Hole/GRB System



- Engine Emissions/Photosphere
- Relativistic Outflows making Colliding Shells/Internal Shocks
- External Shock/Blast wave

Blackbody/photospheric component in GRBs

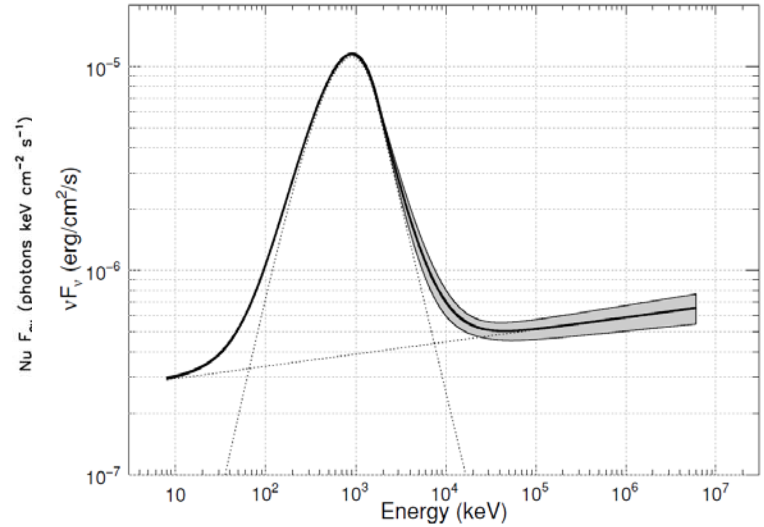
- Addition of blackbody component can improve spectral fits
- Possible solution to “Line of Death”
- Parameters of blackbody give nozzle radius (typically less than 10^{10} cm), and Lorentz factor Γ; Pe’er et al. 2007, Ryde et al. 2011

$$L_\gamma' = 4\pi R_{ph}^2 \sigma_{SB} T'^4$$

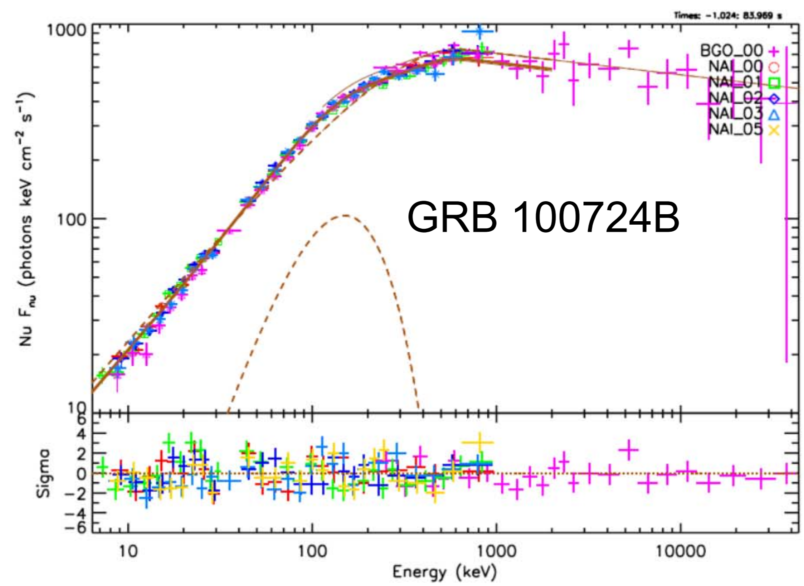
$$T' \approx T_{obs}/\Gamma,\ L_\gamma = \Gamma^2 L_\gamma'$$

$$\Rightarrow \Gamma \propto \frac{R_{ph} T^2}{L_\gamma^{1/2}}$$

- Essentially all prompt emission is photospheric {Beloborodov et al.)

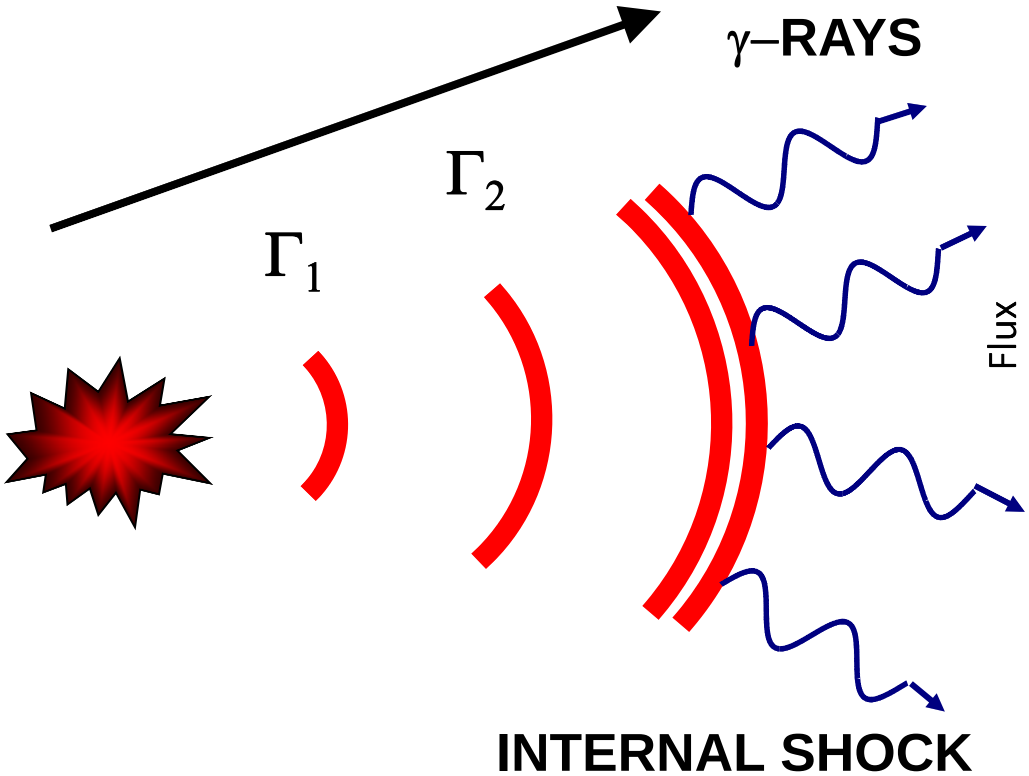


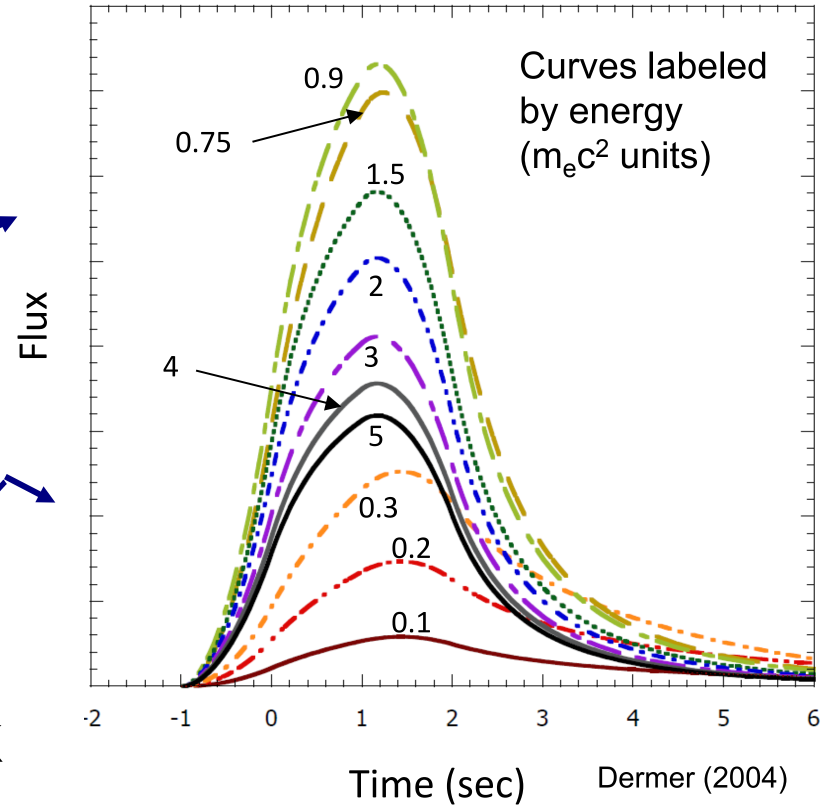
GRB 090902B; Abdo et al. 2009, ApJ, 706, L138



Guiriec et al. 2011

Kinematic Pulse Modeling of Colliding Shells

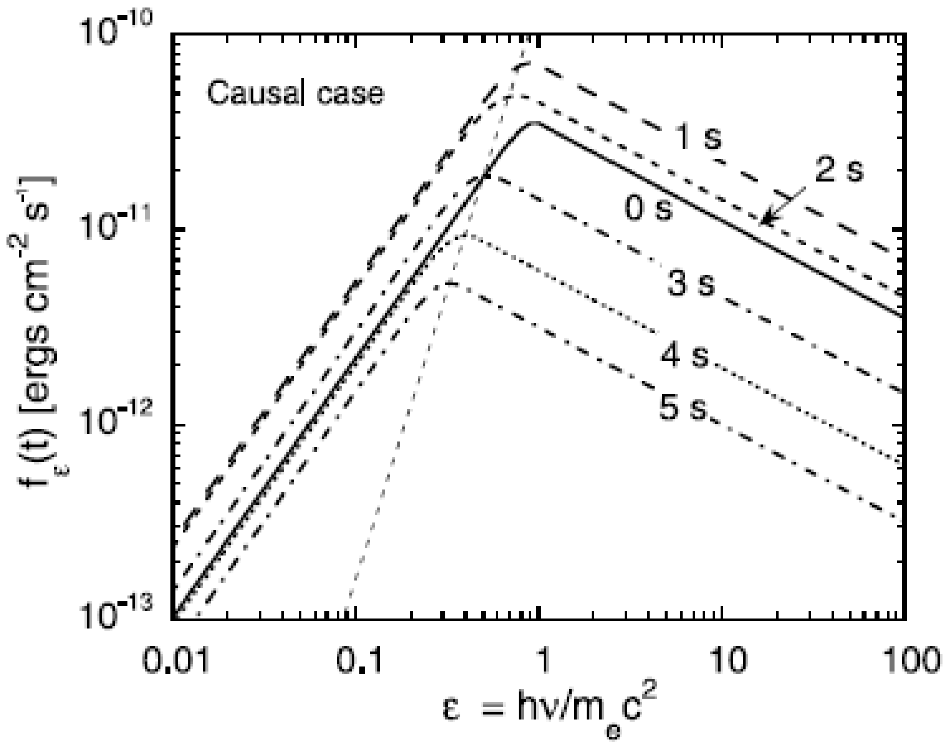




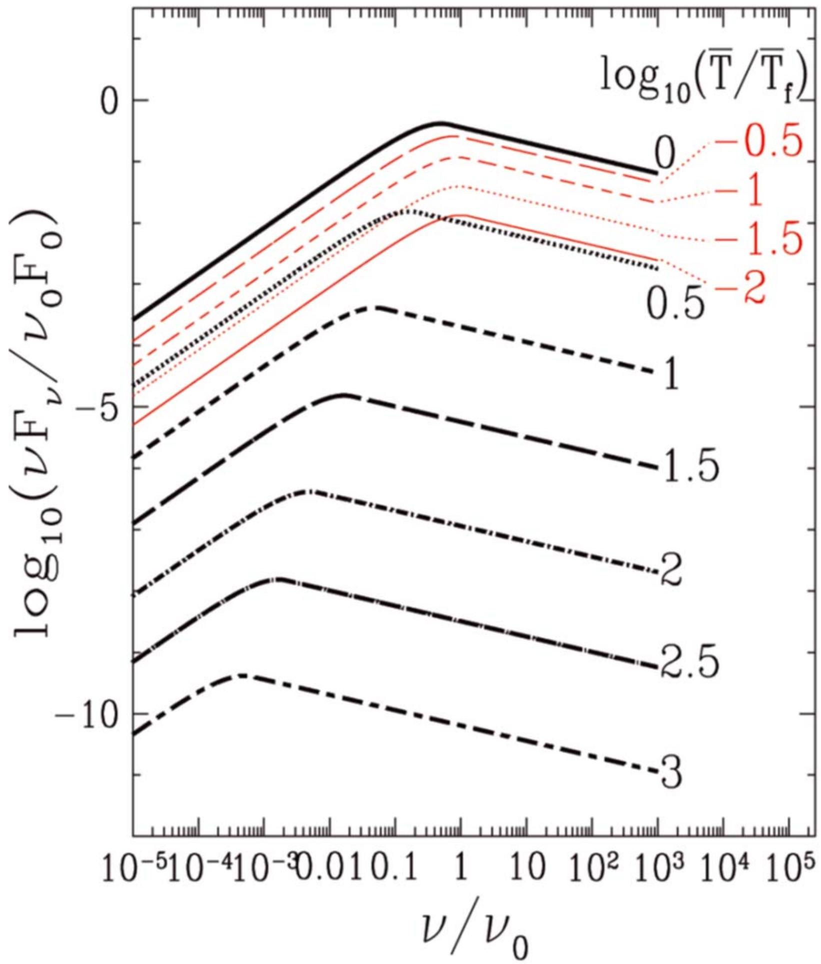
Model predicts $E_{peak} \propto 1/time$

$L(E_{peak}) \propto E_{peak}^3$

Evolving SEDs from High-Latitude Emission

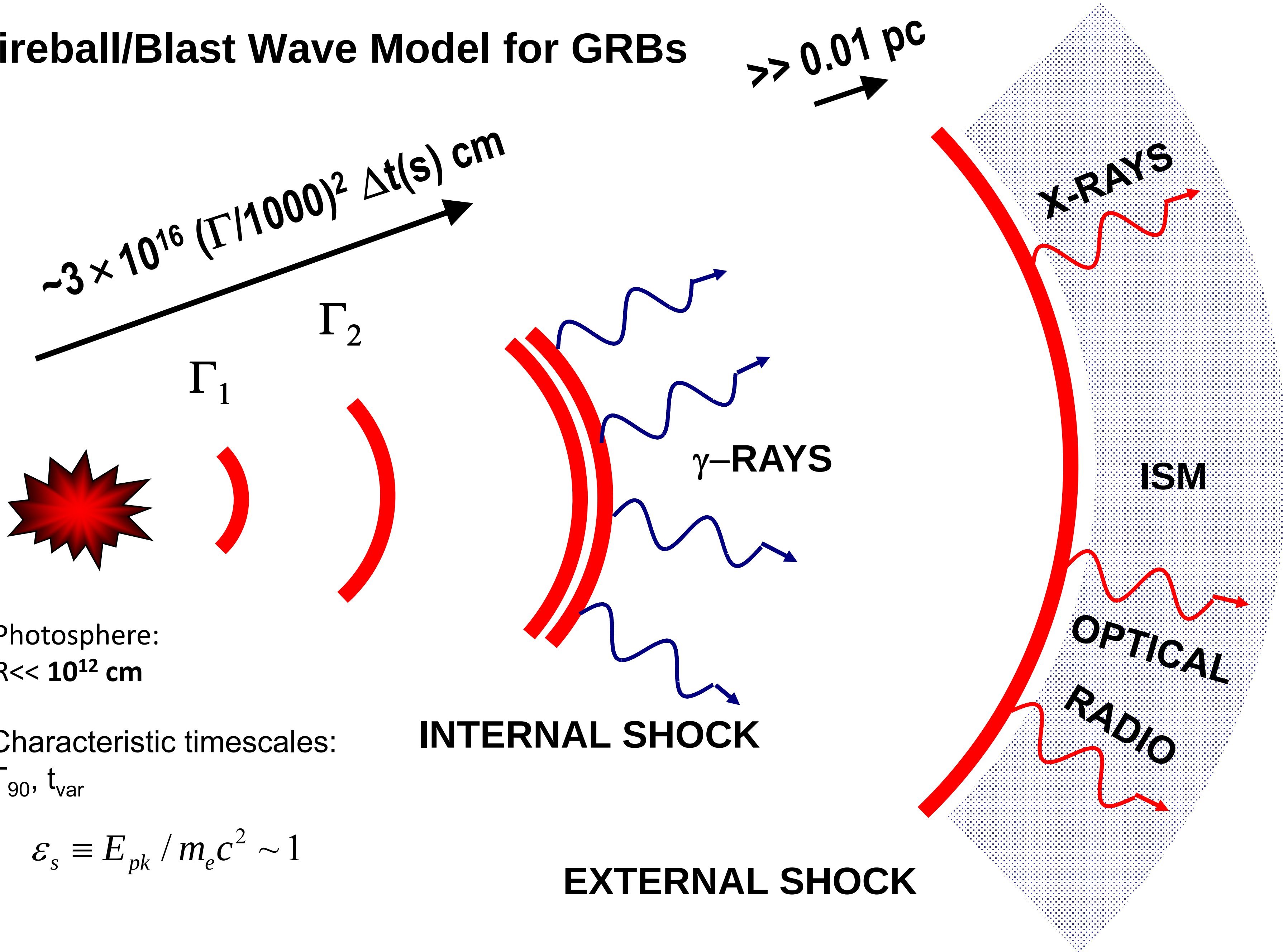


Dermer, Curvature Effects in Gamma-Ray Burst Colliding Shells, ApJ, 2004



Genet and Granot, Realistic analytic model for the prompt and high-latitude emission in GRBs, MNRAS, 2009

Fireball/Blast Wave Model for GRBs



Photosphere:
R<< **10^{12} cm**

Characteristic timescales:
T_{90}, t_{var}

$$\varepsilon_s \equiv E_{pk} / m_e c^2 \sim 1$$

Blast Wave and Afterglow Theory

Initial Explosion Energy: E_0; Baryonic mass mixed into explosion: $M_0 = E_0/\Gamma_0 c^2$

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

Density of surrounding medium = n_0 $\qquad \Gamma_0^2 M_{sw} c^2 = E_0 \equiv M_0 c^2 \Rightarrow$

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

Sari, Piran, and Narayan (1998)

- 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)

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

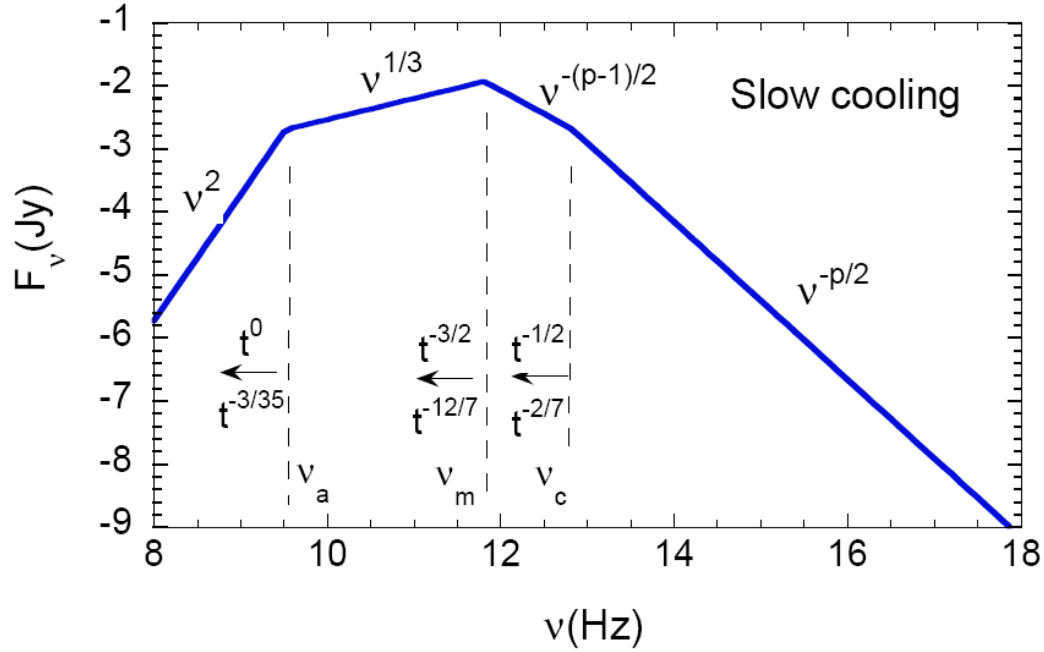
- Maximum electron γ: balancing losses and acceleration rate

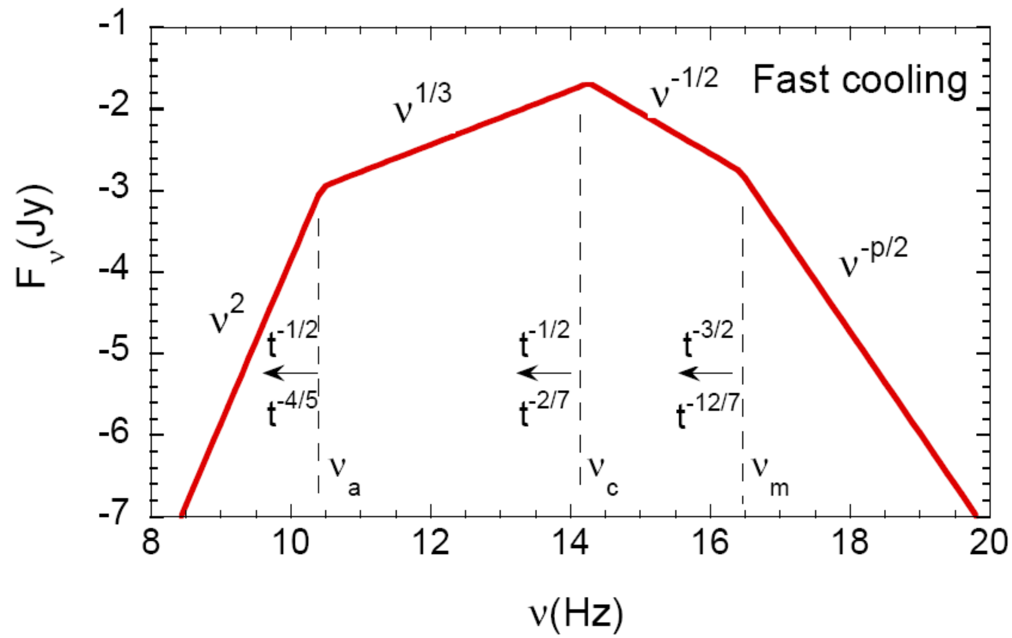
$$\gamma_2 \cong 4 \times 10^7 / \sqrt{B(G)}$$

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

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

Synchrotron Afterglow Spectrum





Sari, Piran, and Narayan 1998

Synchrotron and SSC Features in GRB Light Curves

Associated synchrotron self-Compton (SSC) component
(Dermer, Chiang, Mitman 2000)

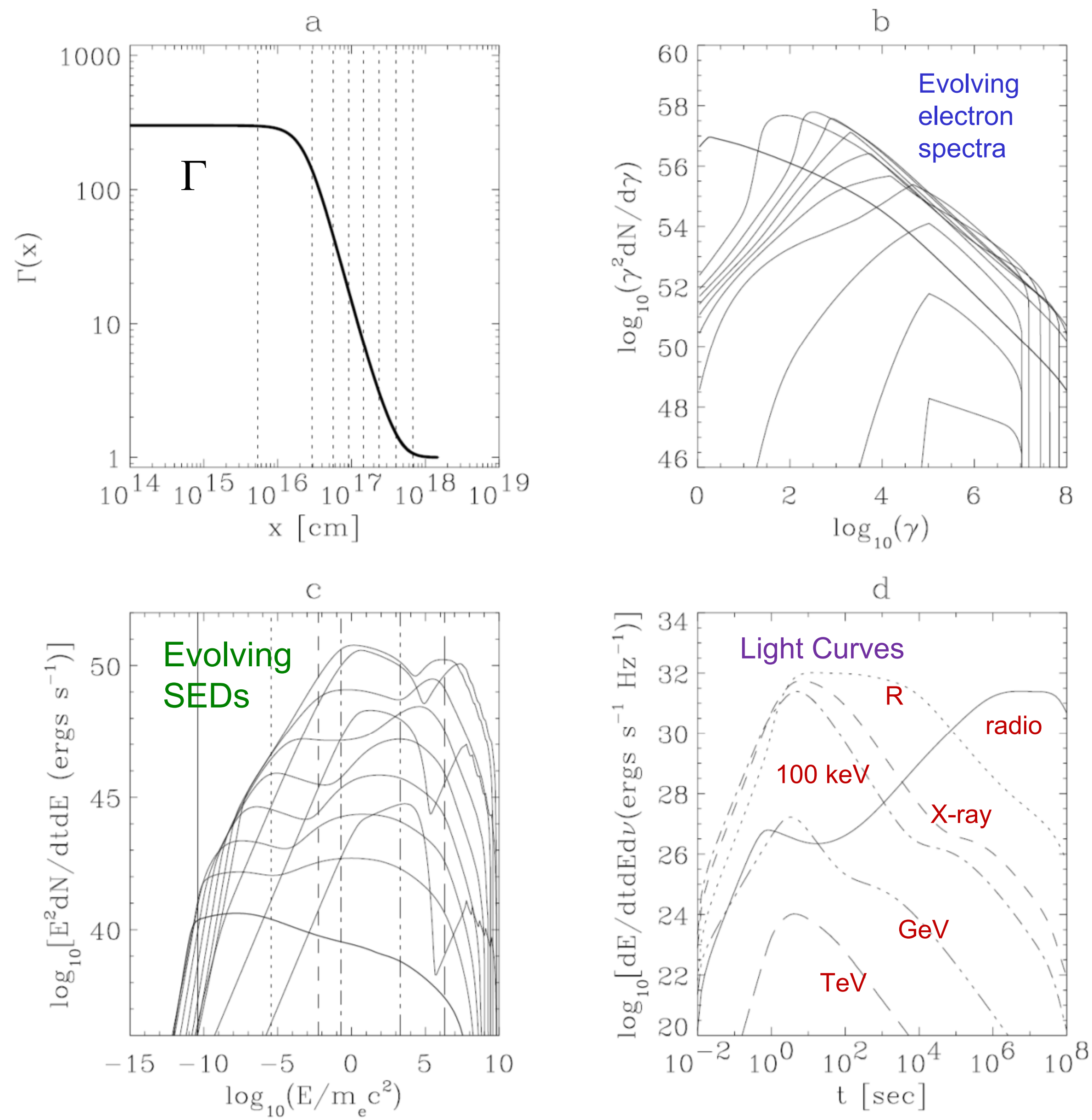
Calculations assume strong forward shock

8.6 GHz radio (solid)
optical R band (dotted)
keV X-ray (dashed)
100 keV (dash-dotted)
GeV (dalsh-triple-dotted)
TeV (long-dashed)

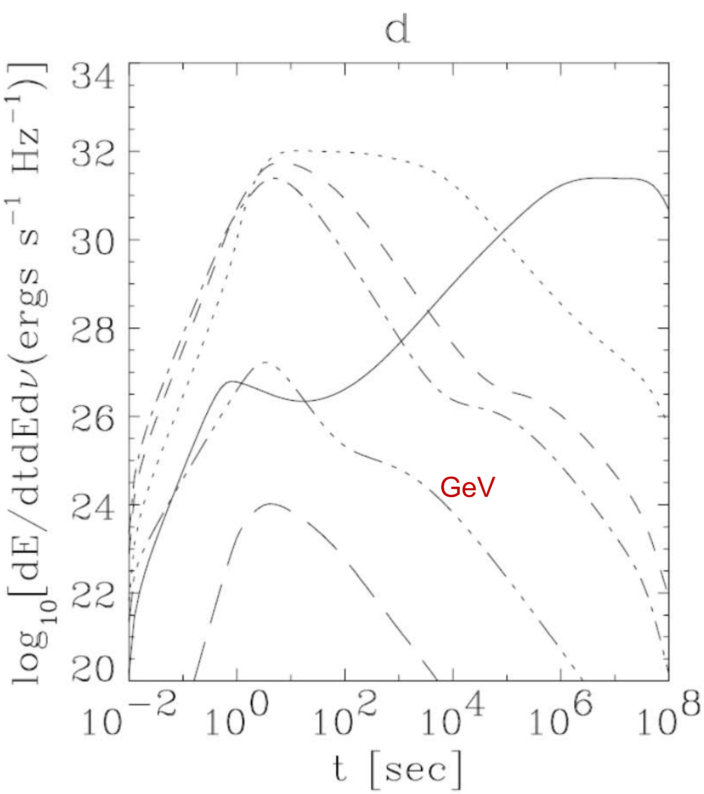
Other Compton origins?

Coccoon photons
(Toma, Wu, Meszaros 2009)

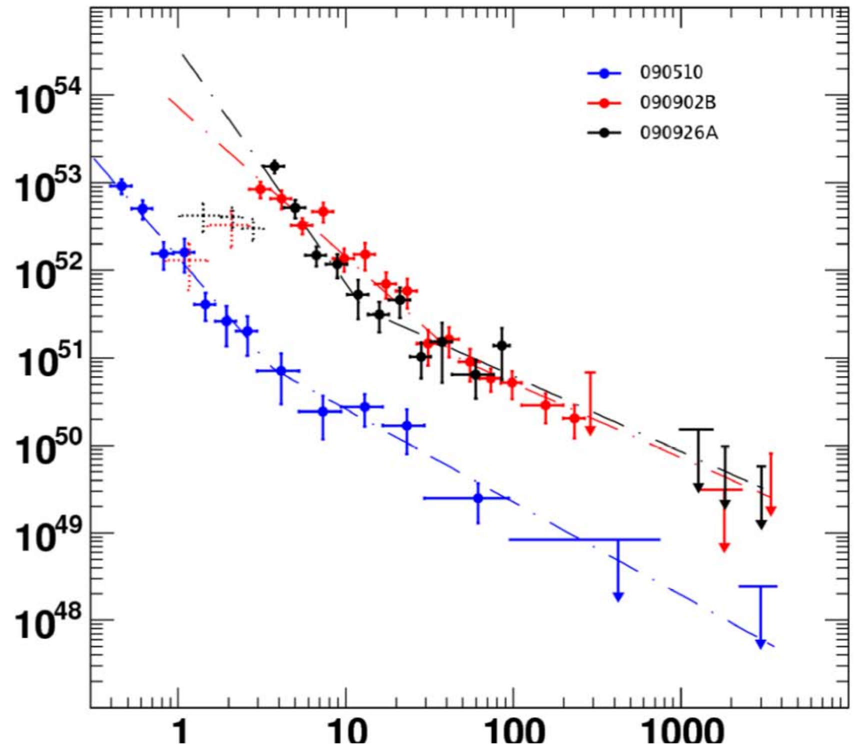
Target photons from central engine Compton-scattered by external shock electrons
(Fan et al. 2013)



Light curves vs. external shock predictions



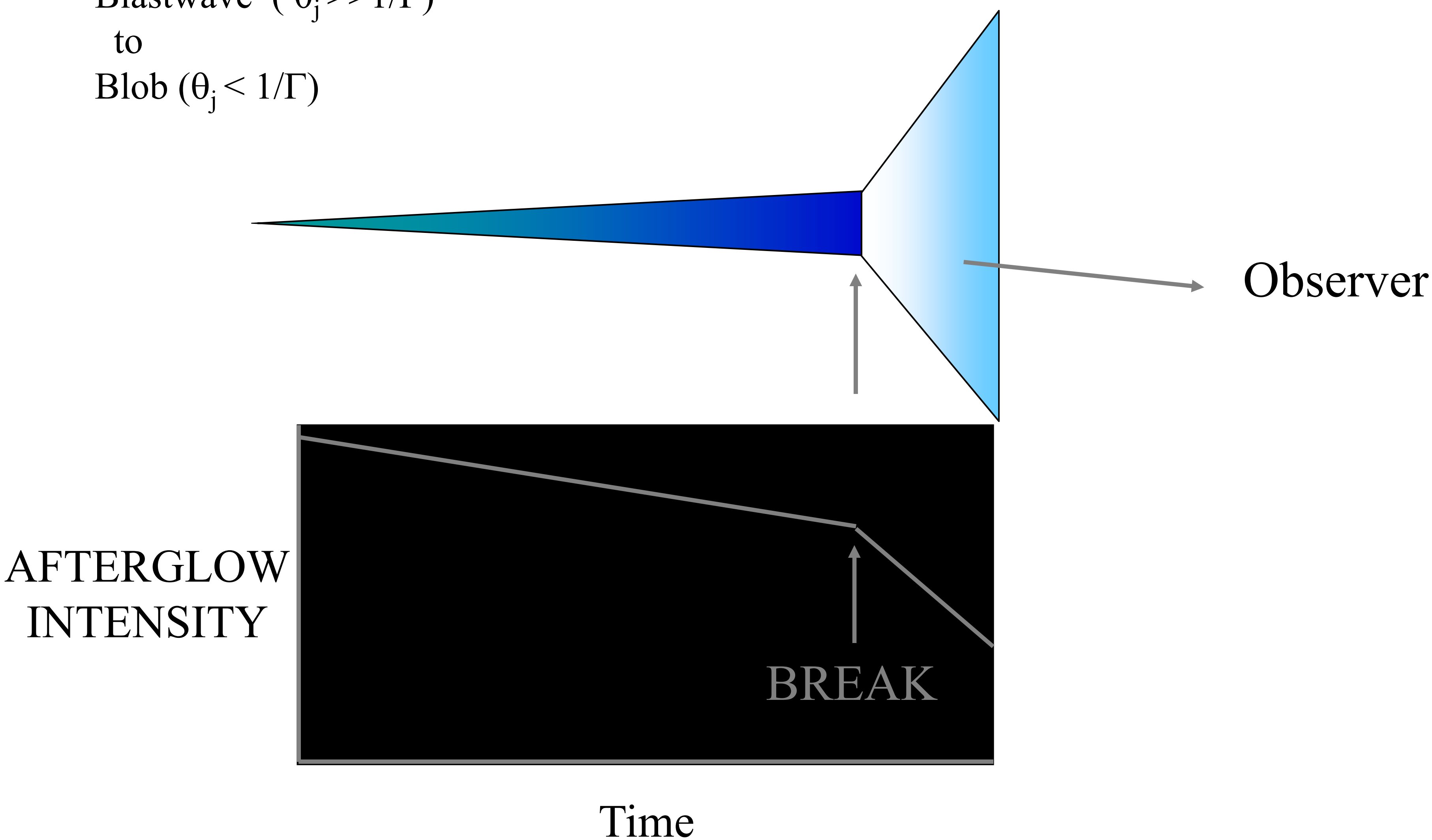
Distinctive feature of SSC: structure in the GeV light curves around 100 s



LAT GRB catalog, Ackermann et al. 2013 (arXiv:1303.2908)

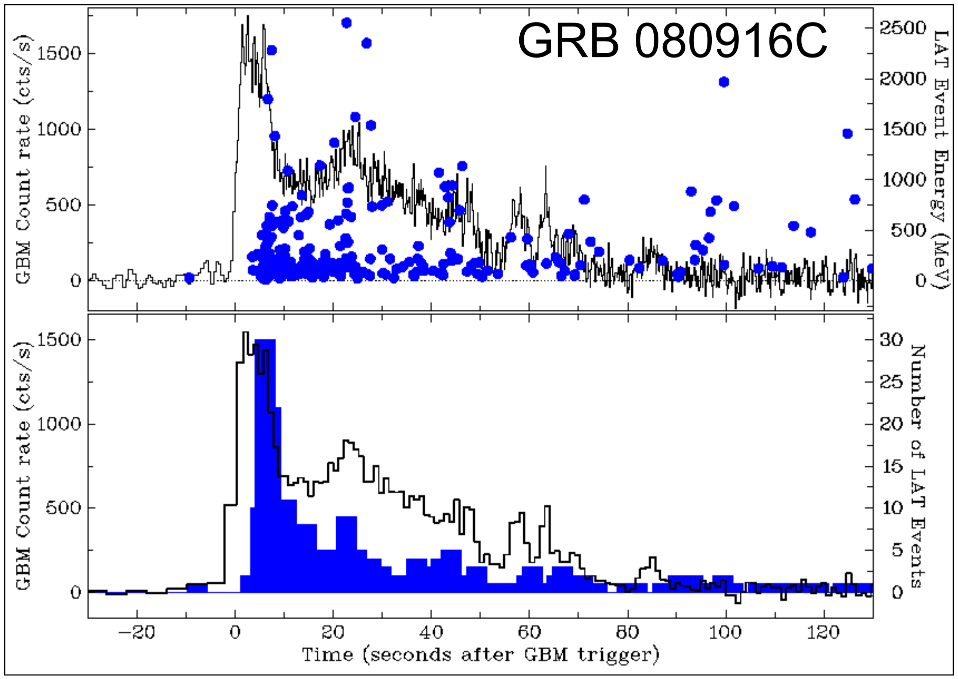
Optical Afterglow gives Information about Beaming

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



Afterglow Synchrotron Model

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



LAT radiation due to nonthermal synchrotron emission from decelerating blast wave

(Kumar and Barniol Duran 2009, Ghirlanda et al. 2009, Ghisellini et al. …)

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:

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

Afterglow onset method (optical or γ-ray)

$$t_{pk} \approx t_{dec} \approx \frac{r_d}{2\Gamma_0^2 c} \Rightarrow \Gamma_0 \approx \left(\frac{3E_\gamma}{32\pi\, n_0 m_p c^5 \eta t_{pk}^3} \right)^{1/8}$$

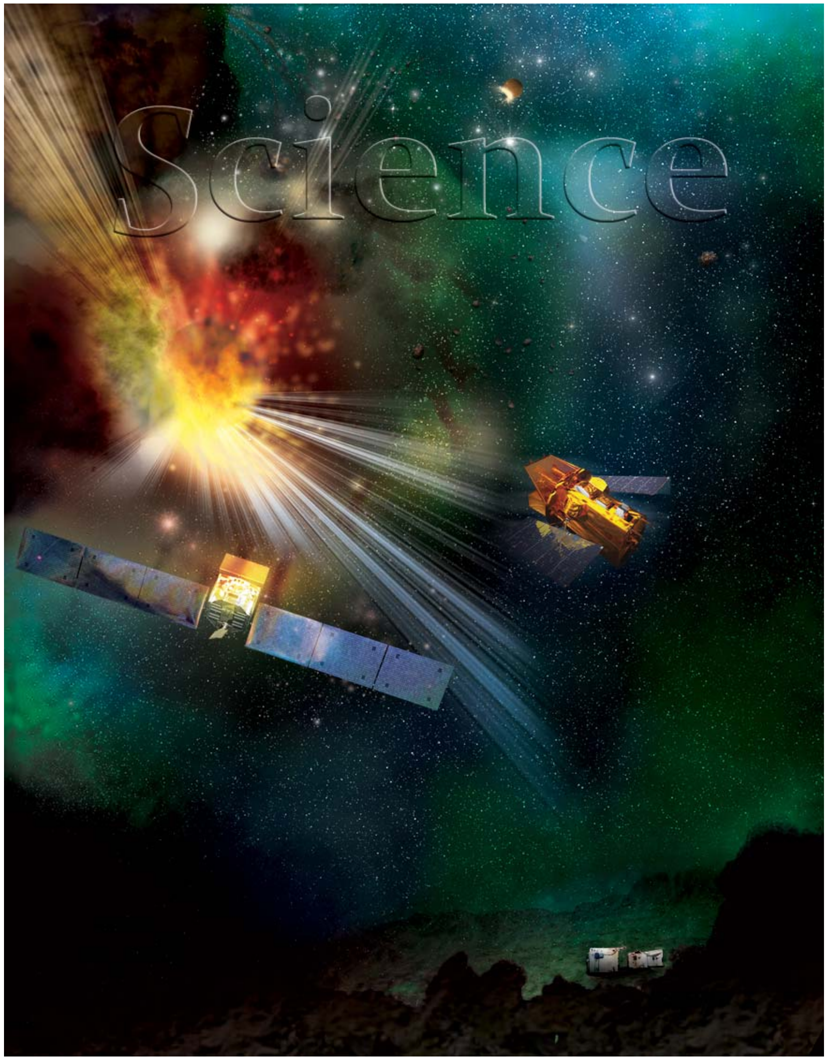
$$\Gamma_0 \approx 540 \left(\frac{E_{55}}{n_0 (t_{pk}/10\,s)^3} \right)^{1/8}$$

Record-Breaking GRB 130427A

A watershed event!

- Summary of observations
  - Among nearest 5% of GRBs
  - Energy released in γ rays ≈10^{54} erg
  - Second brightest optical flash
  - Radio, optical, infrared, X-ray, GeV, TeV, ν...
- γ-ray records broken:
  - Highest γ-ray fluence (≈5×10^{-3} erg cm^{-2})
  - γ-ray photon w/ the highest observed energy (95 GeV)
  - Longest-lasting GeV emission (19 hours)

$$Fluence = \int \Phi(t)dt \quad (erg/cm^2)$$

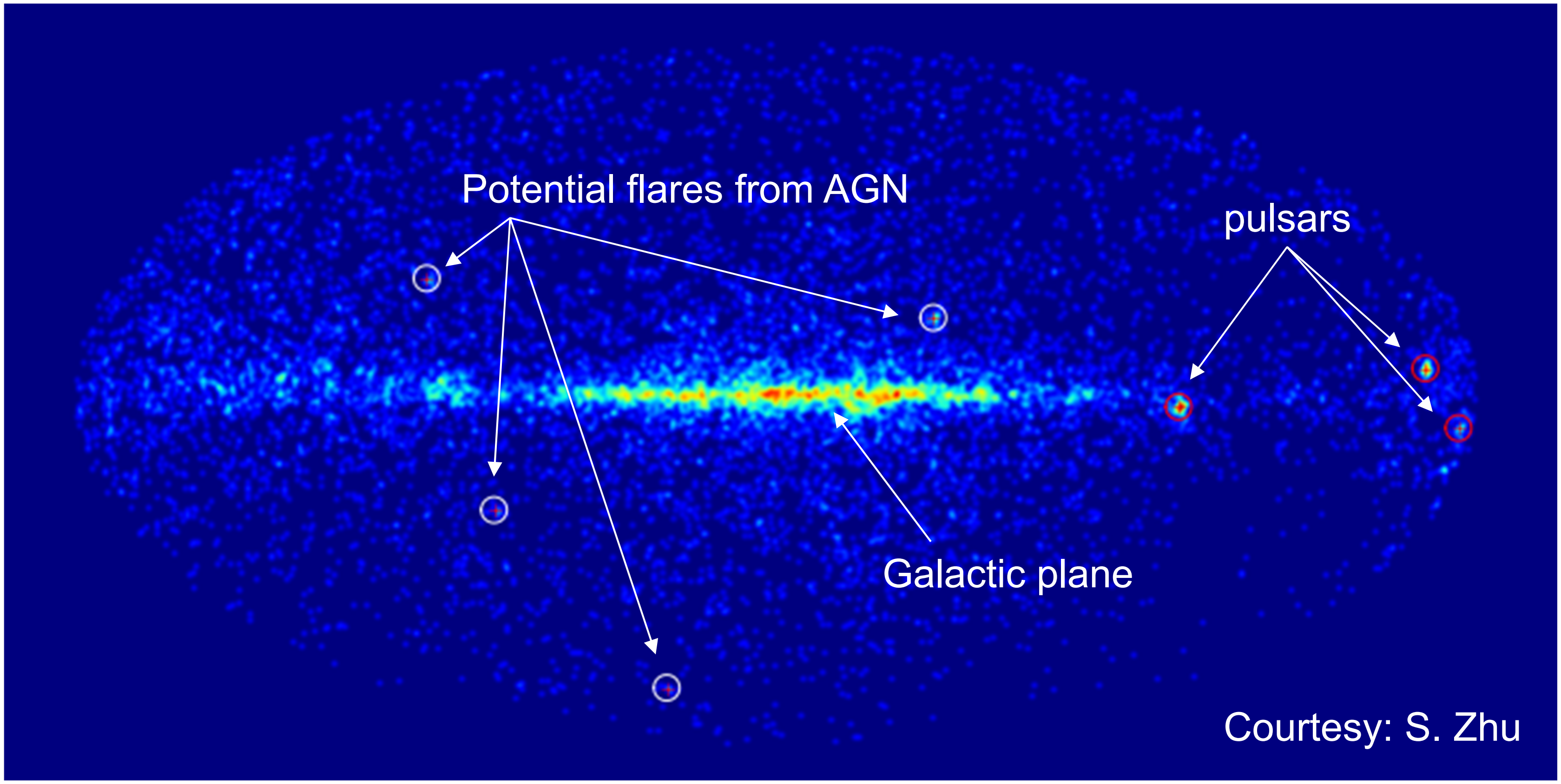


Science Magazine (3 Jan 2014)

How Bright was GRB 130427A?

Plot from automated software that searches for transients on 6-hour timescale

Shown here: The 6-hour map before GRB 130427A occurred



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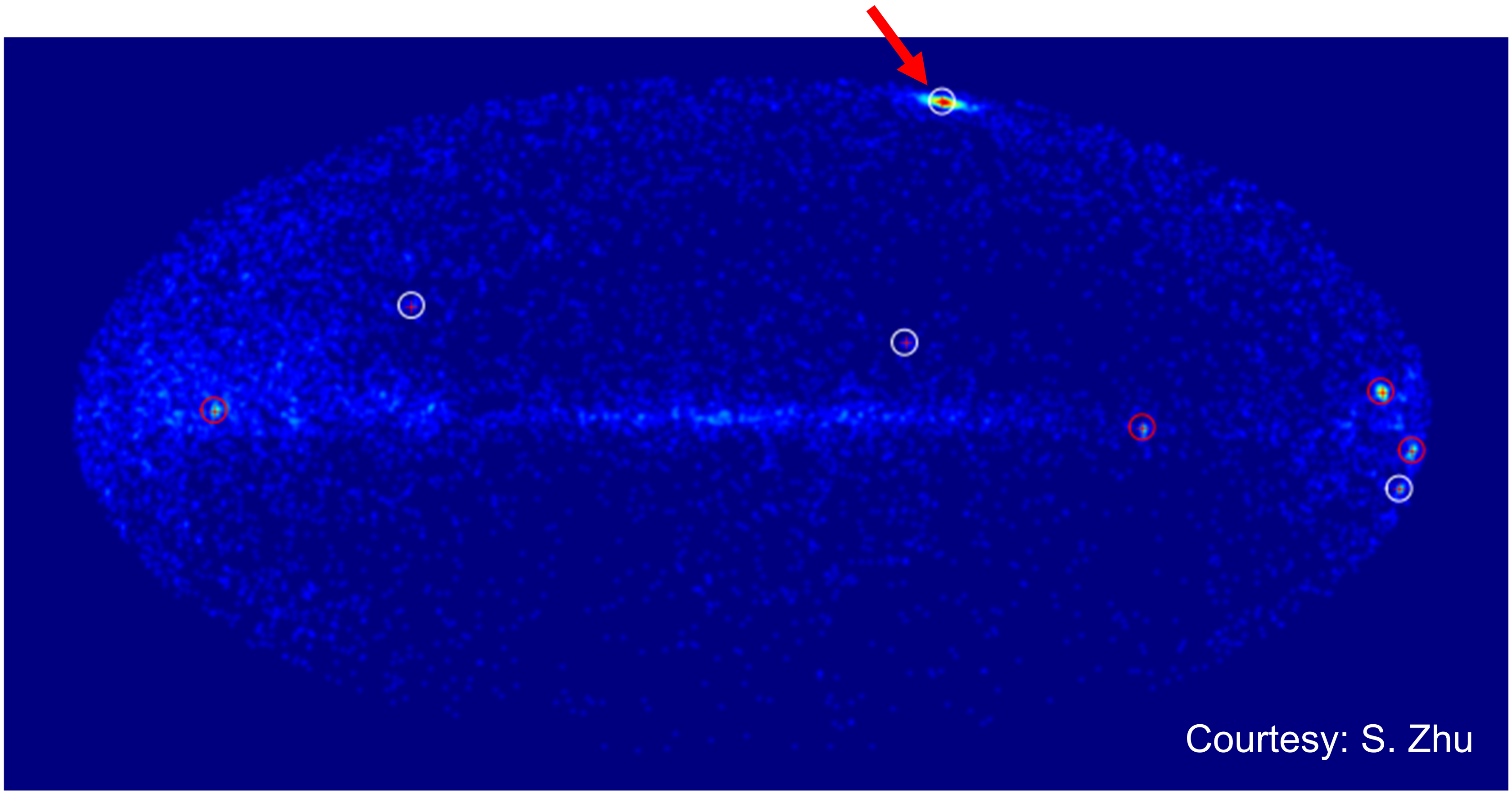


GRB 130427A: The Most Fluent GRB Ever

"insanely bright" – Judy Racusin, Apr 27, 2013

Le & Dermer 2009

Table 2
EGRET GRB Spark-Chamber Detections

Burst Date	θ[a]	N_{sc}[b]	$N_{>100}$[c]	E_{max}(GeV)	Φ_{BATSE}[d] 10^{-4} erg/cm^2	EGRET GRB γ-Rays Φ_{EGRET}[e]	$\rho(\%)$[f]
910503	24	9[g]	2	10	2.92 (±0.01)	1.28	0.43
910601	12	8	3	0.31	1.5 (±0.01)	1.13	0.75
930131	28	18	12	1.2	0.66 (±0.11)	26.6	40.3
940217	10	28	10	18	6.6 (±0.03)	13.0	1.97
940301	6	7	5	0.16	1.12 (±0.01)	1.14	1.02

10^{-6} erg/cm^2

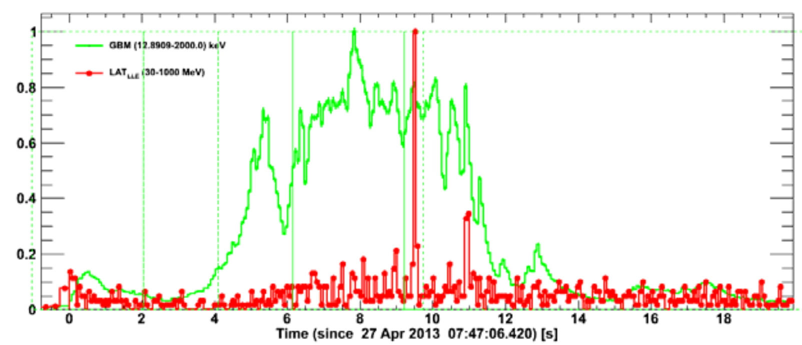
- Most fluent GRBs
  BATSE GRB 990123; >20 keV
  Fluence = 5.1×10^{-4} erg cm^{-2} (Briggs et al. 1999)
- Two major GRBs in the 1980s:
  GRB840304: Fluence = 2.8×10^{-3} erg/cm^2
  (http://heasarc.gsfc.nasa.gov/docs/cgro/batse/grb_cats/pvo.html)
  GRB 830801 fluence ~2×10^{-3} erg/cm^2

  First ionospheric disturbance (Fishman & Inan 1988)
- Was it an soft gamma repeater (SGR)?
  SGR 1806-20/GRB041227
  (27 December 2004): fluence ~1 erg/cm^2

$z = 0.34$, $d_L = 1783$ Mpc

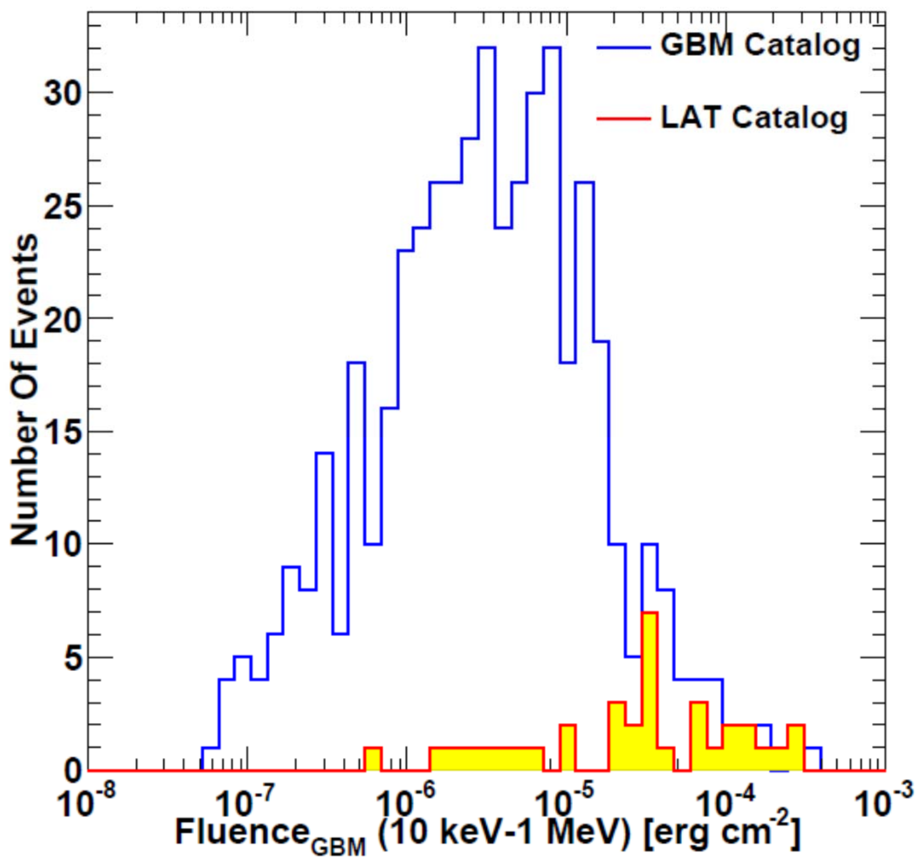
GBM 10 keV - 20 MeV fluence (0 -- 400 s):
4.2×10^{-3} erg/cm^2
LAT > 100 MeV fluence (0 – 100 ks):
$7(\pm1) \times 10^{-4}$ erg/cm^2
10 keV -- 100 GeV fluence: 4.9×10^{-3} erg/cm^2

$E_{iso} = 1.40\times10^{54}$ erg
$L_{iso} \approx 7.8 \times 10^{52}$ erg/s ($0 < t < 18.4$ s)
$L_{iso,pk} \approx 2.8 \times 10^{53}$ erg/s (1 keV–10MeV)
(1 every ~60 yr; Salvaterra 2012)



Pulse pileup/deadtime in GBM
NaI between ~5 and 12 s

GRB 130427A: Large Fluence, so what?



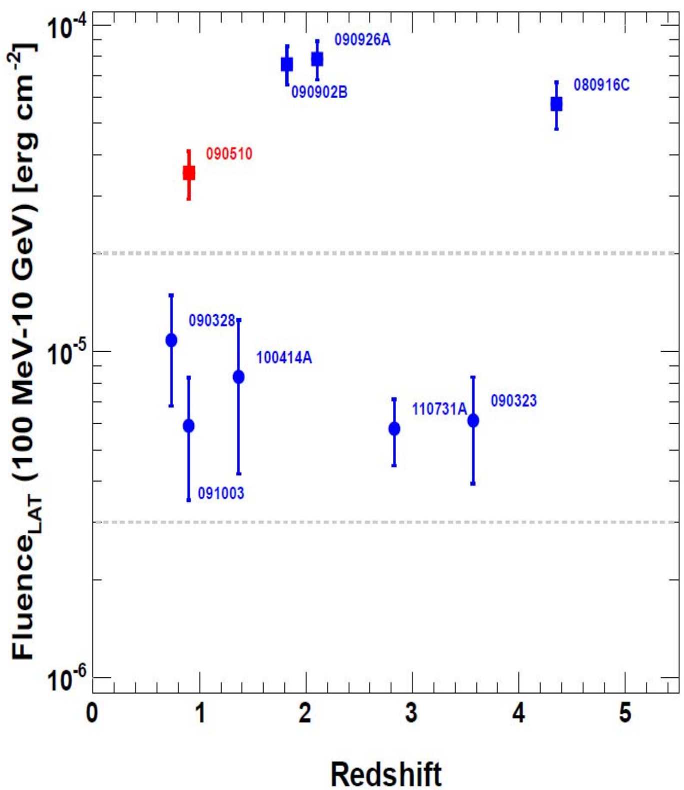
Fermi LAT GRB catalog (Ackermann et al. 2013)

Total > 20 keV GRB fluence per year:
7.9 x10^{-3} erg/cm^2 vs. 4.2 x 10^{-3} erg/cm^2
for GRB 130427A

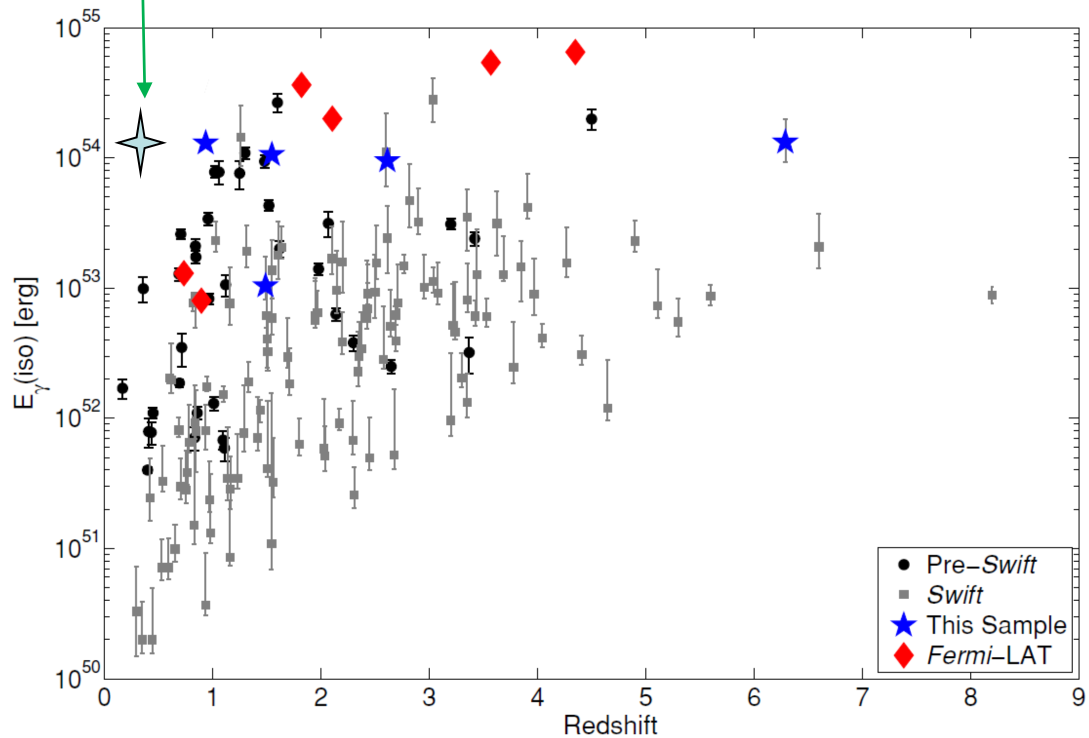
- With redshift, gives luminosity distribution or distribution of E_{iso} $\Rightarrow$ emissivity (energy/volume/time)
- Fluence distribution provides normalization of injection scenarios
- EBL studies $\tau_{\gamma\gamma}(E_\gamma,z)\sim 1$ when $E_\gamma\sim 100$ GeV/z (better constraints from higher redshift GRBs)
- UHECR origin scenarios: underlying assumption is that UHECR emissivity $\propto$ γ-ray emissivity (GBM or LAT)
  UHECR + soft photon → $\pi^{0,\pm}$ → 2γ, $e^\pm$, ν
- Neutrino production: scales with cascade fluence; need >~10^{-3} erg/cm^2 for neutrino detection with IceCube
- Exquisite statistics; observed with multiple detectors

GRB 130427A: A Nearby Ordinary Monster

GRB 130427A

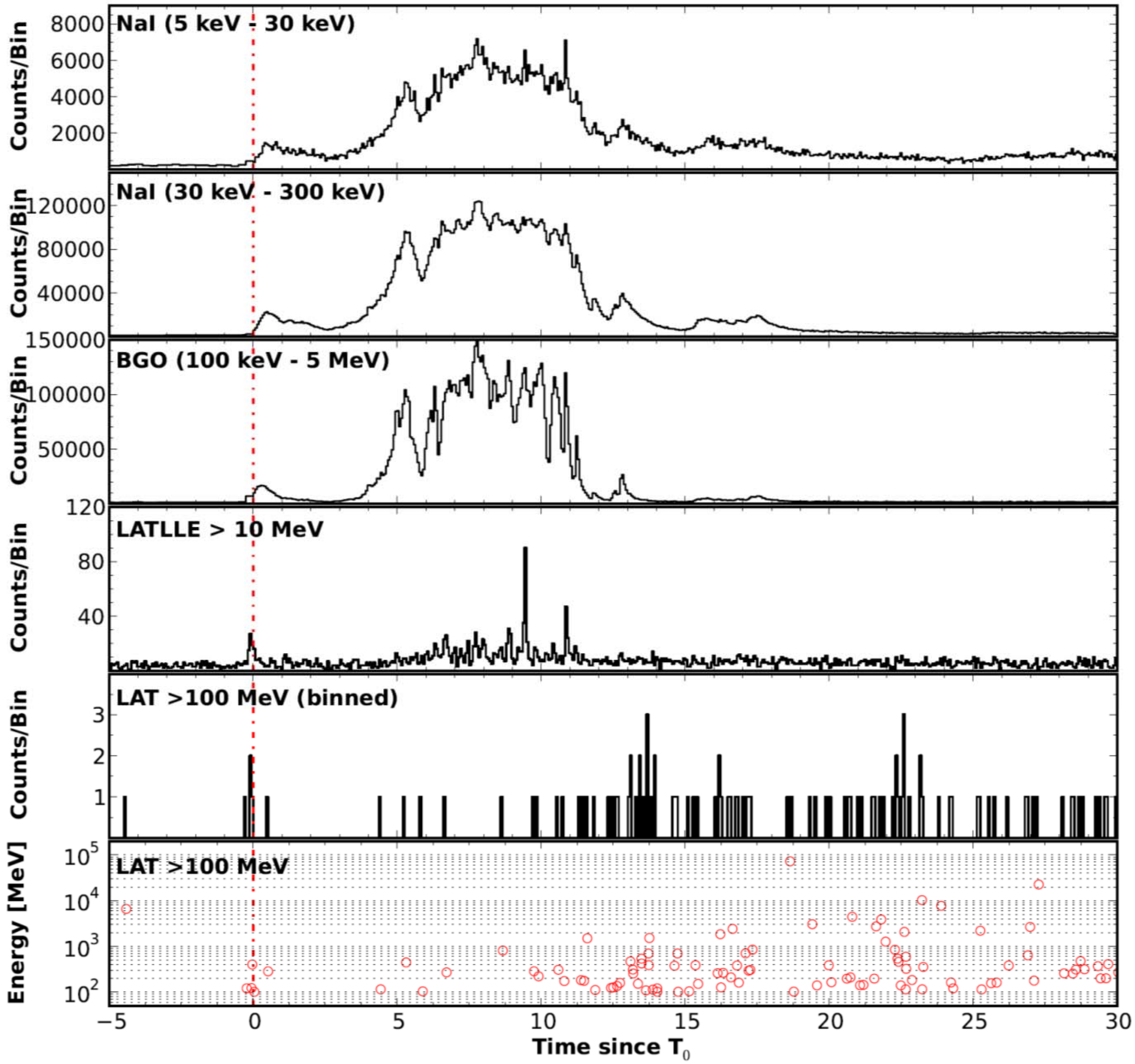


Ackermann et al. 2013



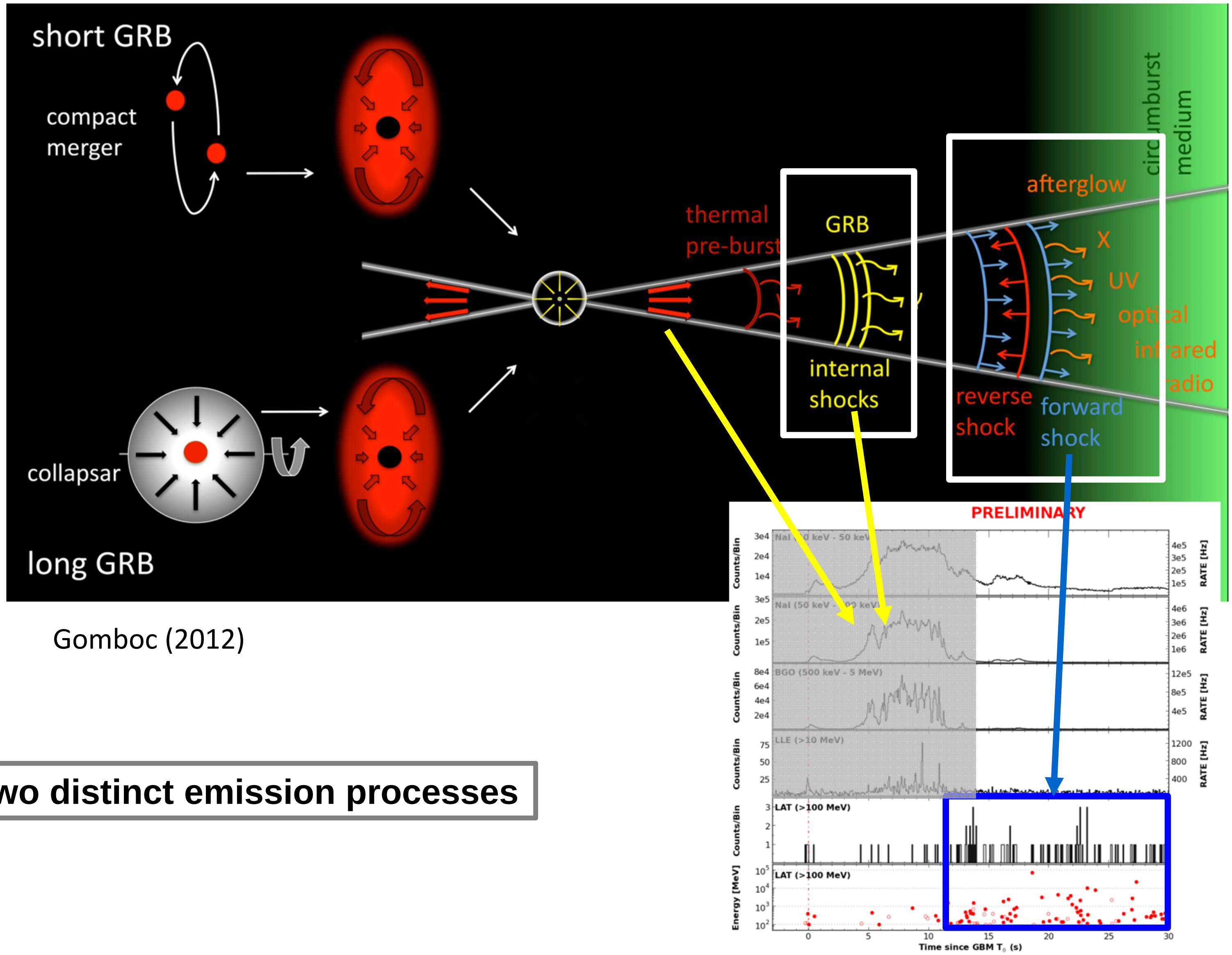
Cenko et al. 2010

GRB 130427A γ-ray Light Curves



- ❑ Engine vs. afterglow
- ❑ shock emission
- ❑ Delayed onset of LAT emission
- ❑ Highest energy photons late, not early
- ❑ No GeV photons until >10 s
- ❑ Isolated GBM triggering pulse

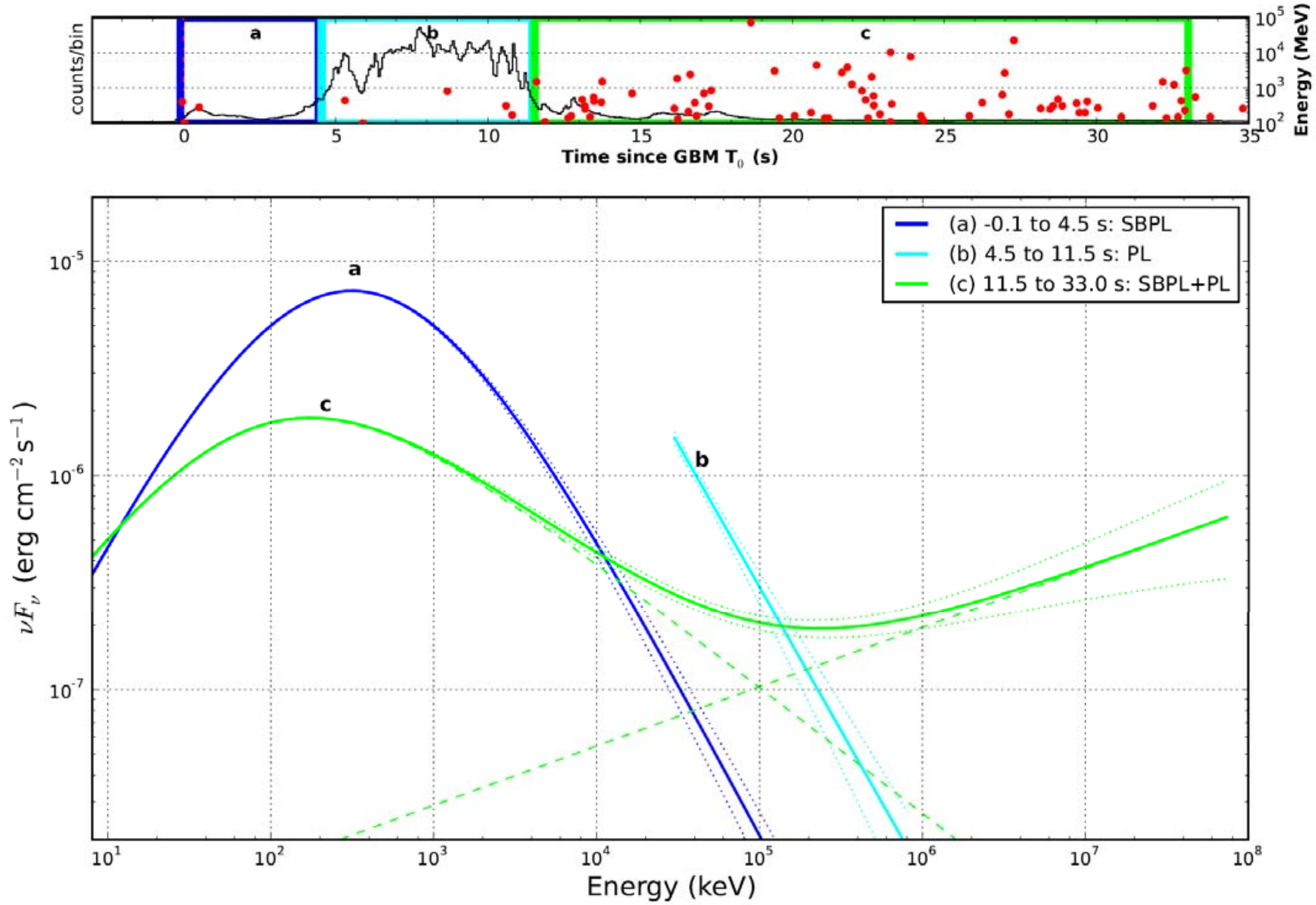
GRB Fireball/Blastwave Model and GRB 130427A



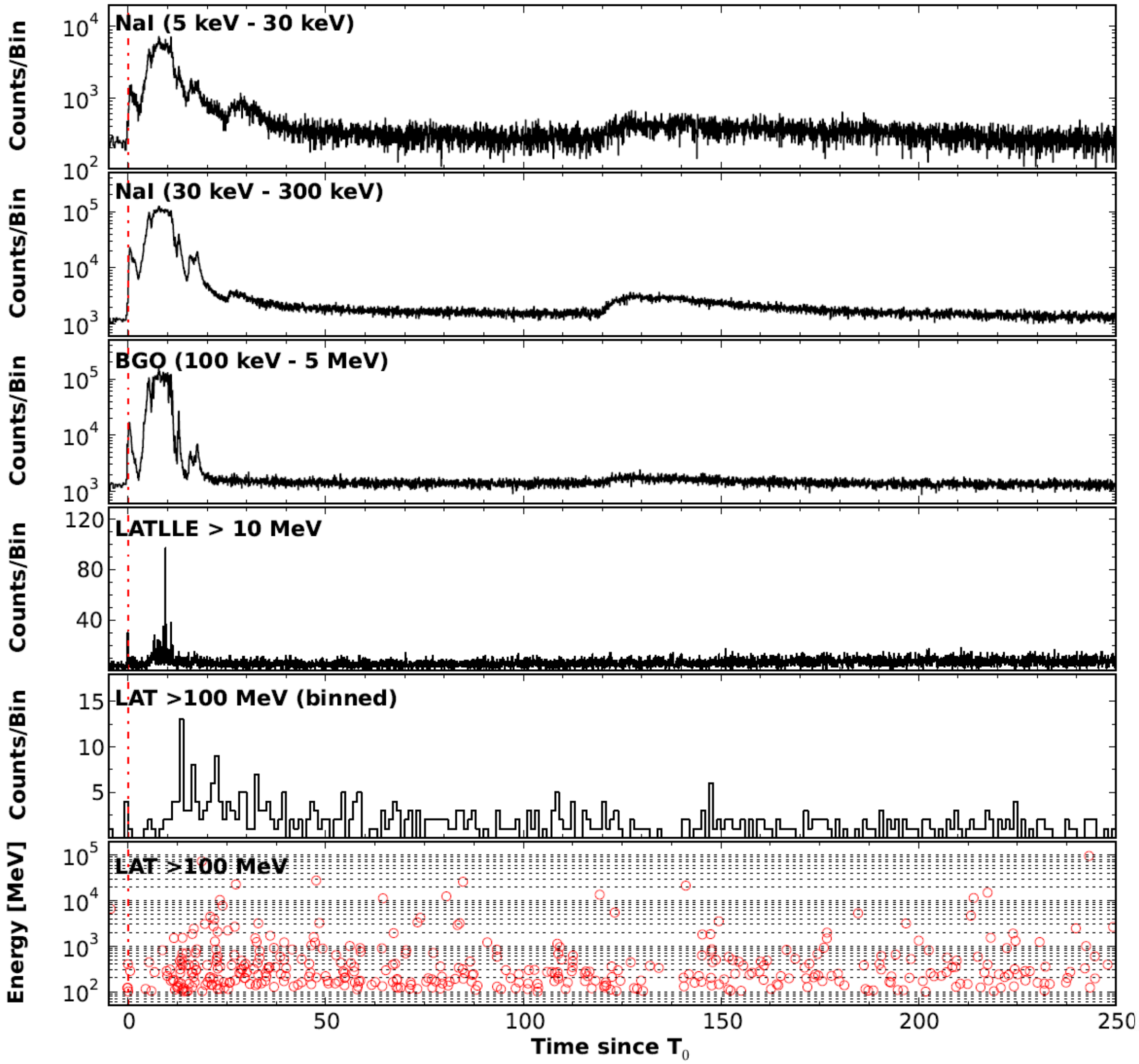
Gomboc (2012)

Two distinct emission processes

Emergence of Delayed Hard Component in GRB 130427A



GRB 130427A γ-ray Light Curves

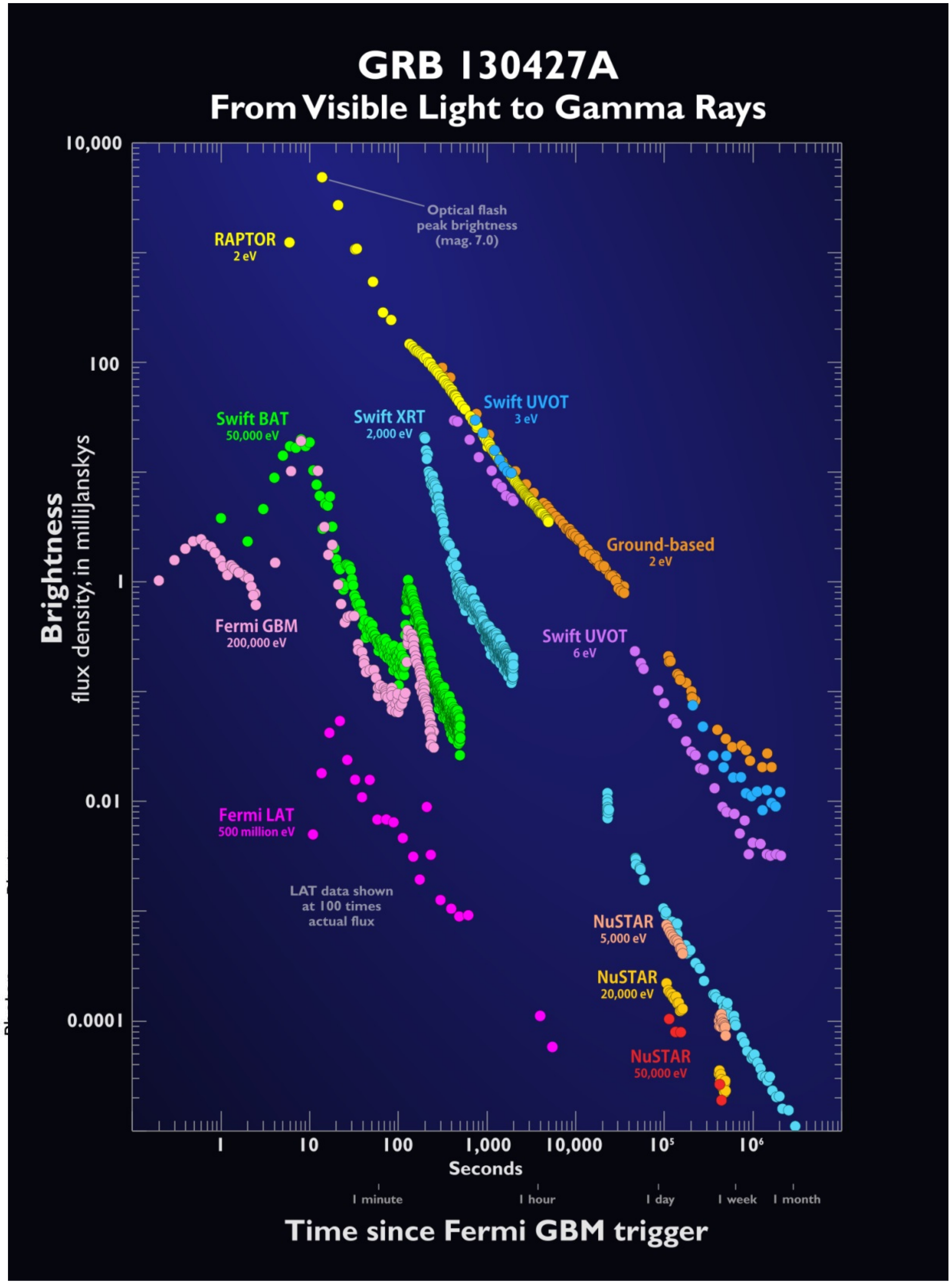


- Second episode commencing at ~125 s
- Delayed onset of LAT emission for second episode
- High energy photons at late times

E	$E_{\rm rf}$	$T - T_0$
95	128	243.55
73	97	19.06
47	63	256.70
41	55	611.01
39	52	3410.26
32	43	34366.58
28	37	48.01
26	35	85.16
21	21	141.53
15	20	217.89

Light Curves of GRB 130427A

- Fermi LAT energy flux light curve well-described by single power-law with temporal decay index = -1.17±0.06
- Fermi LAT (500 MeV), RAPTOR optical (2 eV), Swift XRT (2 keV) light curves track early afterglow
- Swift BAT (50 keV) and Fermi GBM (200 keV) track prompt emission
- Reactivation of central engine at ~150 s



Pulse Analysis of GRB 130427A Triggering pulse

Data:
green: GBM NaI (10 – 300 keV)
blue: GBM BGO (0.3 – 50 MeV)
red: LAT LLE (> 20 MeV)
(normalized to peak intensities)
red dots: LAT > 100 MeV

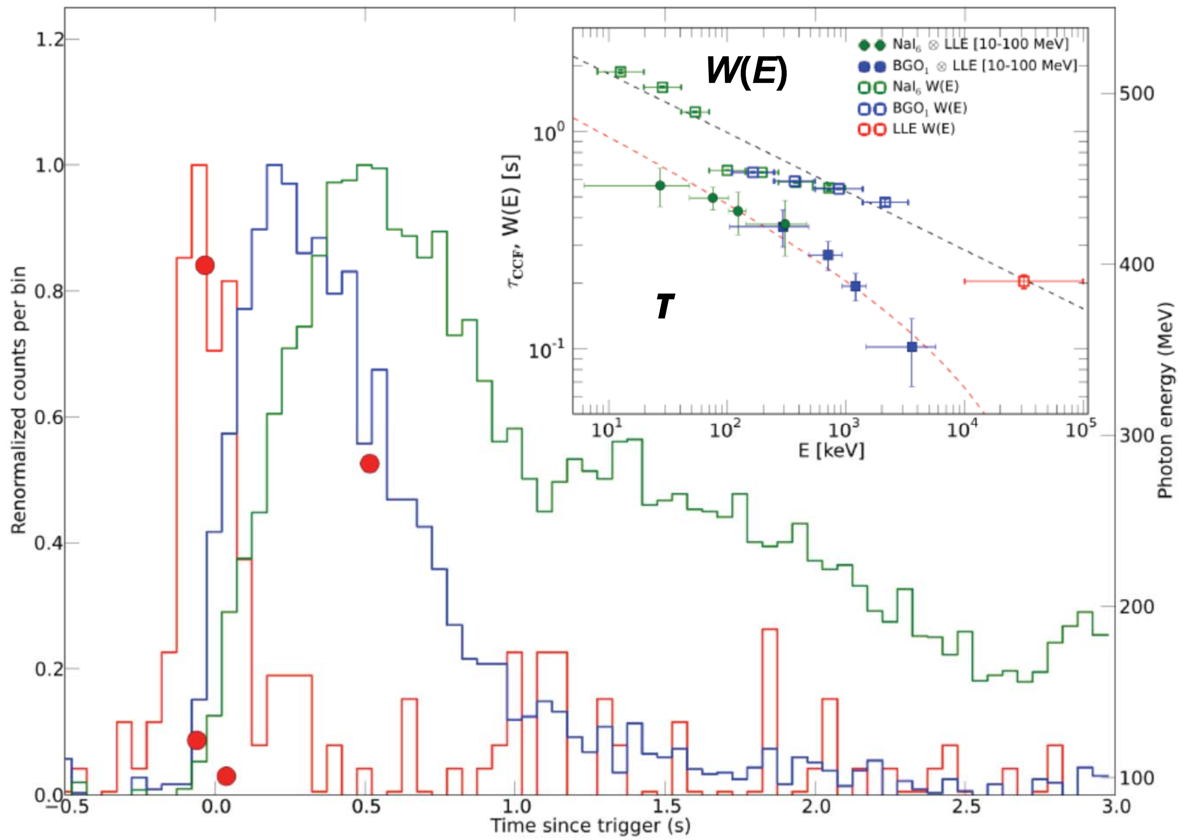
Inset:
Lag analysis of triggering pulse of GRB 130427A

Time lag τ as determined by the CCF analysis between 10--100 MeV LLE lightcurve and selected energy bands of NaI and BGO lightcurves

$$\tau(E_1, E_2) = t_{rise}\,(E_1^{\alpha} - E_2^{\alpha})$$

Fitted pulse widths as a function of energy

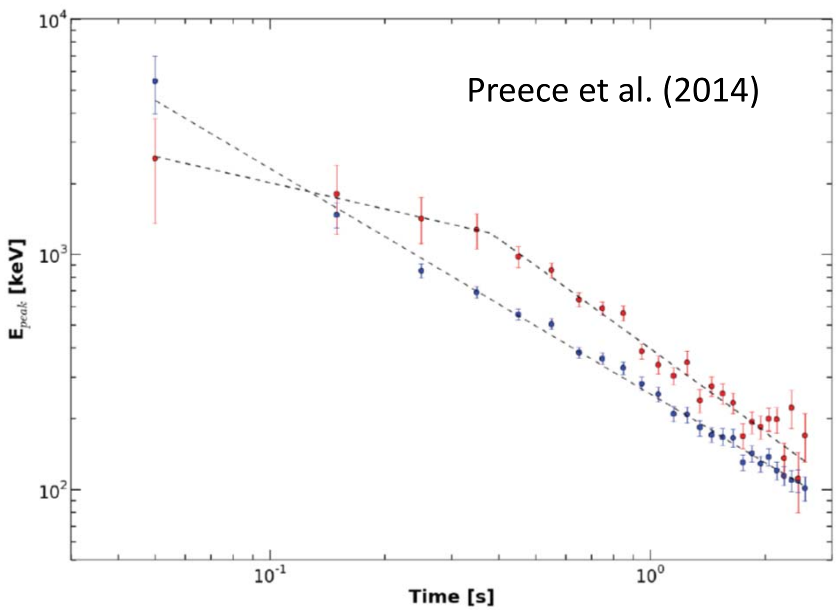
$$W(E) \propto E^{\alpha}, \quad \alpha = -0.27 \pm 0.03$$

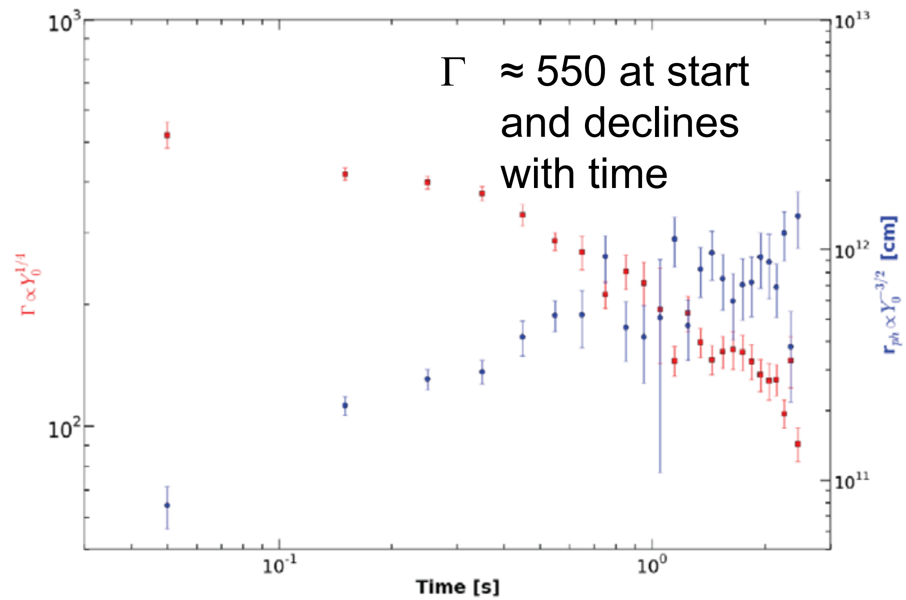


Preece et al. (2014)

⇒ **Most detailed data set yet to model GRB pulse physics**

$E_{peak} \propto$ 1/time in decay phase

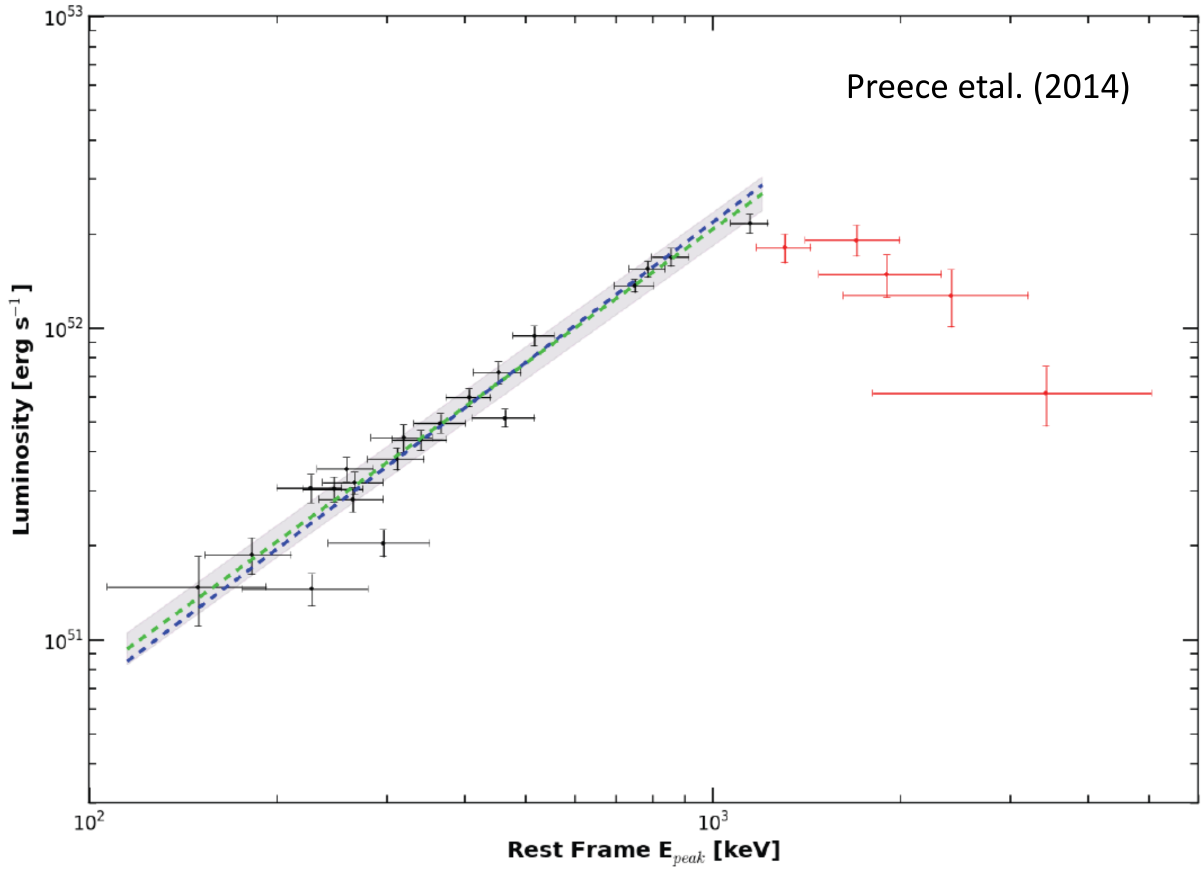




Fitted Band function E_{peak} (blue) and synchrotron peak energies (red) vs. time beginning 0.1 s before the trigger. Band function E_{peak} with decay index α = –0.96 ± 0.02. Broken power-law fit to the red points (early time decay index α = –0.4 ± 0.2, break at 0.38 ± 0.08 s, late time index α = f –1.17 ± 0.05)

Curvature model predicts $E_{peak} \propto$ 1/time

$L \propto E_{pk}^{3/2}$ in decay phase



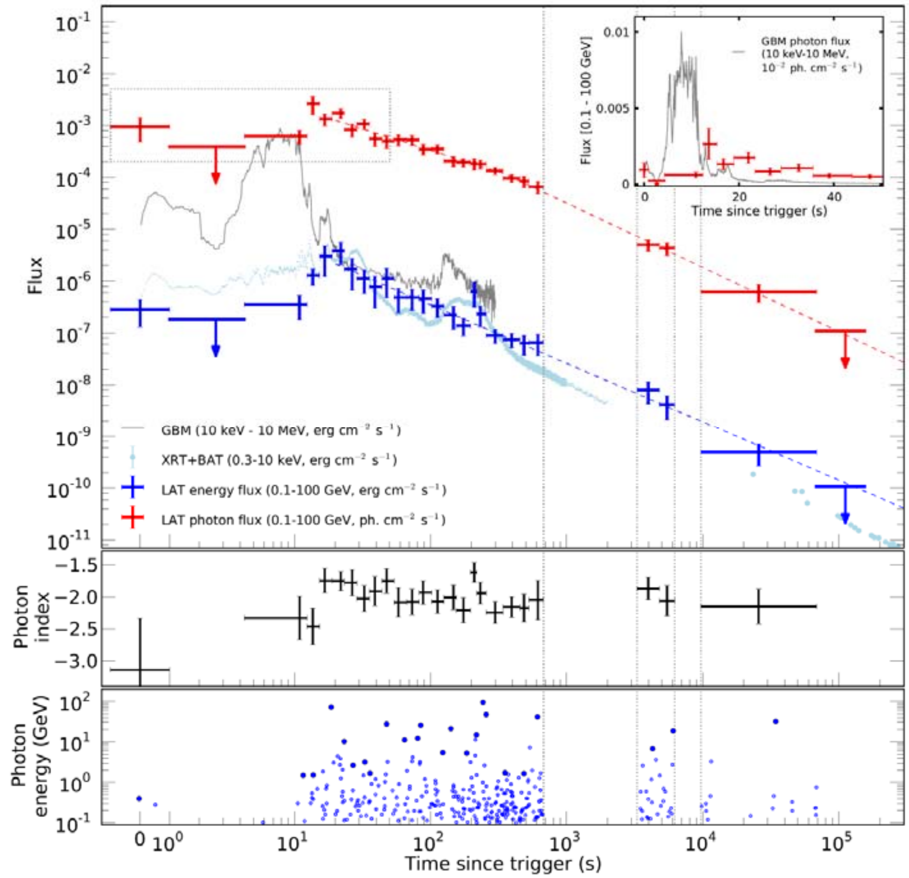
Curvature model predicts $E_{peak} \propto 1/\text{time}$ (as shown by data)

and $L(E_{peak}) \propto E_{peak}^{3}$ (Not $L(E_{peak}) \propto E_{peak}^{3/2}$)

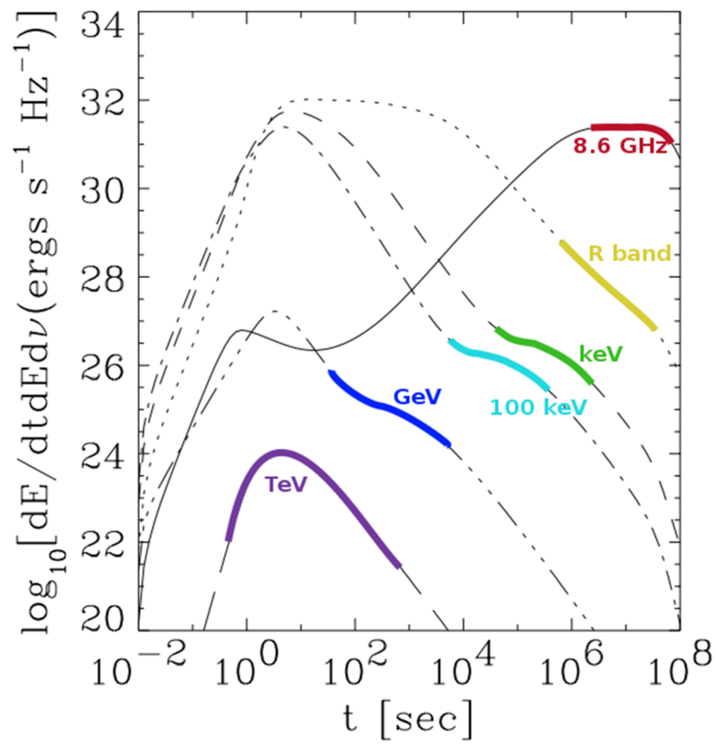
Favors photospheric model?

Gamma-ray Burst Light Curve Calculations vs. Fermi LAT Data

Smooth power-law decay of LAT emission suggests all synchrotron radiation



Ackermann et al. (2014, Science)



Dermer et al. (2000);
Code of Chiang & Dermer (1999)

No evidence for emergence of synchrotron self-Compton component

Maximum Electron Synchrotron Photon Energy

Electron synchrotron energy-loss rate: $-\frac{dE_e}{dt}|_{syn} = \frac{4}{3} c\sigma_T \left(\frac{B^2}{8\pi}\right)\gamma^2$

$$E_e = m_e c^2 \gamma \quad \Rightarrow \quad -\frac{d\gamma}{dt}|_{syn} = \frac{4}{3} c\sigma_T \left(\frac{B^2}{8\pi m_e c^2}\right)\gamma^2 \qquad t_{syn} = \left|\frac{\dot{\gamma}_{syn}}{\gamma}\right|^{-1} = \frac{6\pi m_e c}{\sigma_T B^2 \gamma}$$

In Fermi acceleration scenarios, acceleration timescale > Larmor timescale:

$$\therefore t_{acc} = \phi t_L = \phi \frac{E}{QBc} \rightarrow \phi \frac{m_e c \gamma}{eB} \;, \phi \geq 1 \qquad t_{syn} = t_{acc} \Rightarrow \gamma^2 = \frac{6\pi e}{\phi \sigma_T B}$$

Mean synchrotron photon energy radiated by an electron with Lorentz factor γ in a magnetic field of strength B:

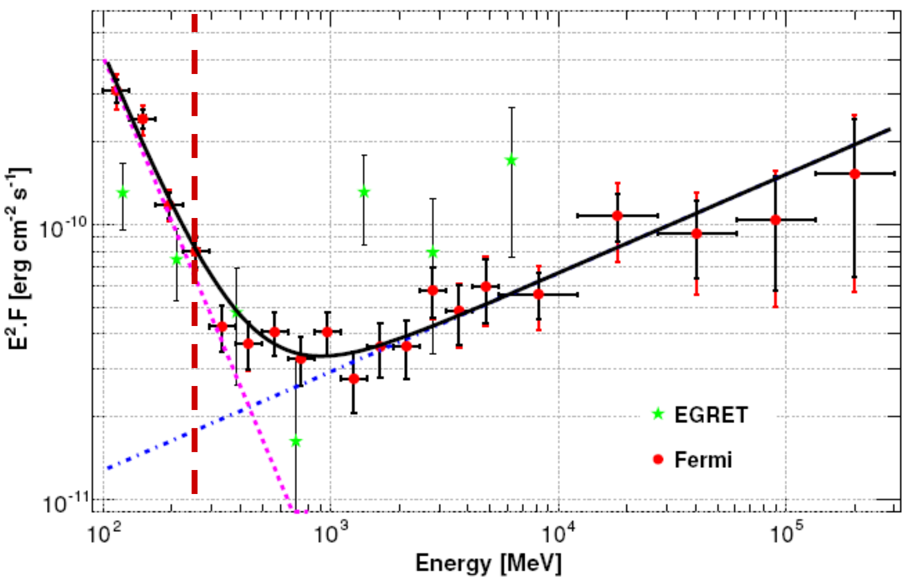
$$\varepsilon_{syn} = \frac{3}{2}\frac{B}{B_{cr}}\gamma^2 = \frac{9\pi e}{\phi \sigma_T B_{cr}} \;, B_{cr} = \frac{m_e^2 c^3}{e\hbar}$$

$$\varepsilon_{syn} \cong \phi^{-1} \frac{3^3}{2^3} \alpha_f^{-1} \leq \frac{27}{8\alpha_f} \cong 460; \alpha_f = \frac{e^2}{\hbar c}$$

(de Jager & Harding 1992)

$$or\ E_{syn,\max} \cong 100 \times \Gamma\ MeV$$

230 MeV

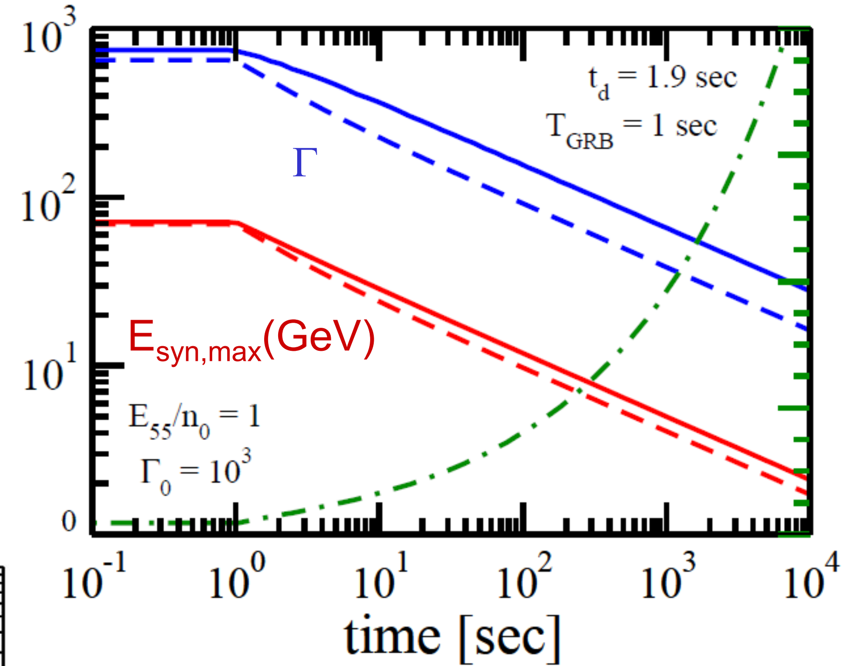


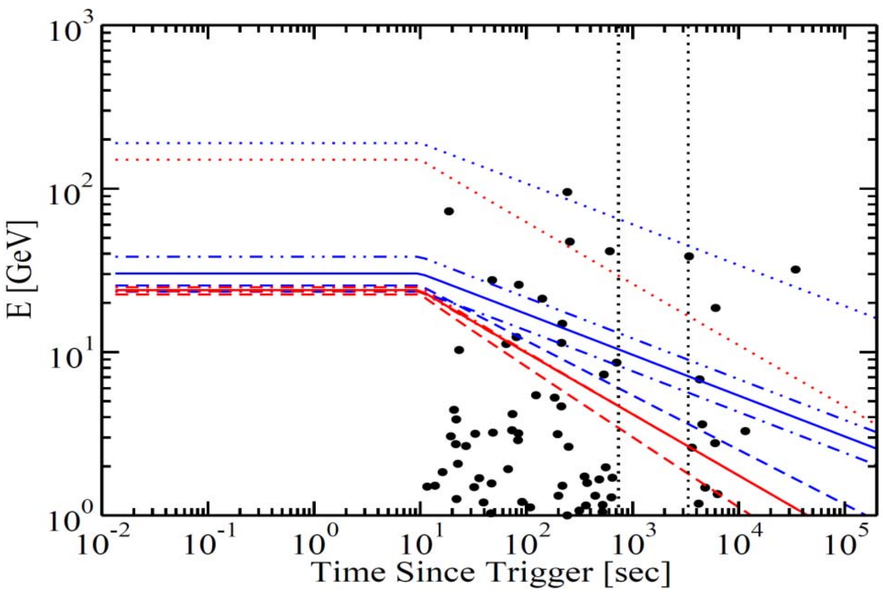
Maximum Synchrotron Energies in Decelerating Blast Wave

$$\therefore E_{syn,\max} \approx 10\, GeV \times (\Gamma / 100) / (1+z)$$

Describe evolution of Γ by self-similar solution (Blandford & McKee 1976)

Account for off-axis emission emitted earlier when blast wave was more highly relativistic (Piran & Nakar 2010)





External shock model predictions for highest synchrotron photon energy as a function of time, overlaid on a plot of energy vs. time of highest energy LAT photons

⇒ Highest energy LAT photons cannot be synchrotron

Advanced GRB Theory: Photohadronic GRB Modeling

Energy injected in protons normalized to GRB MeV fluence

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

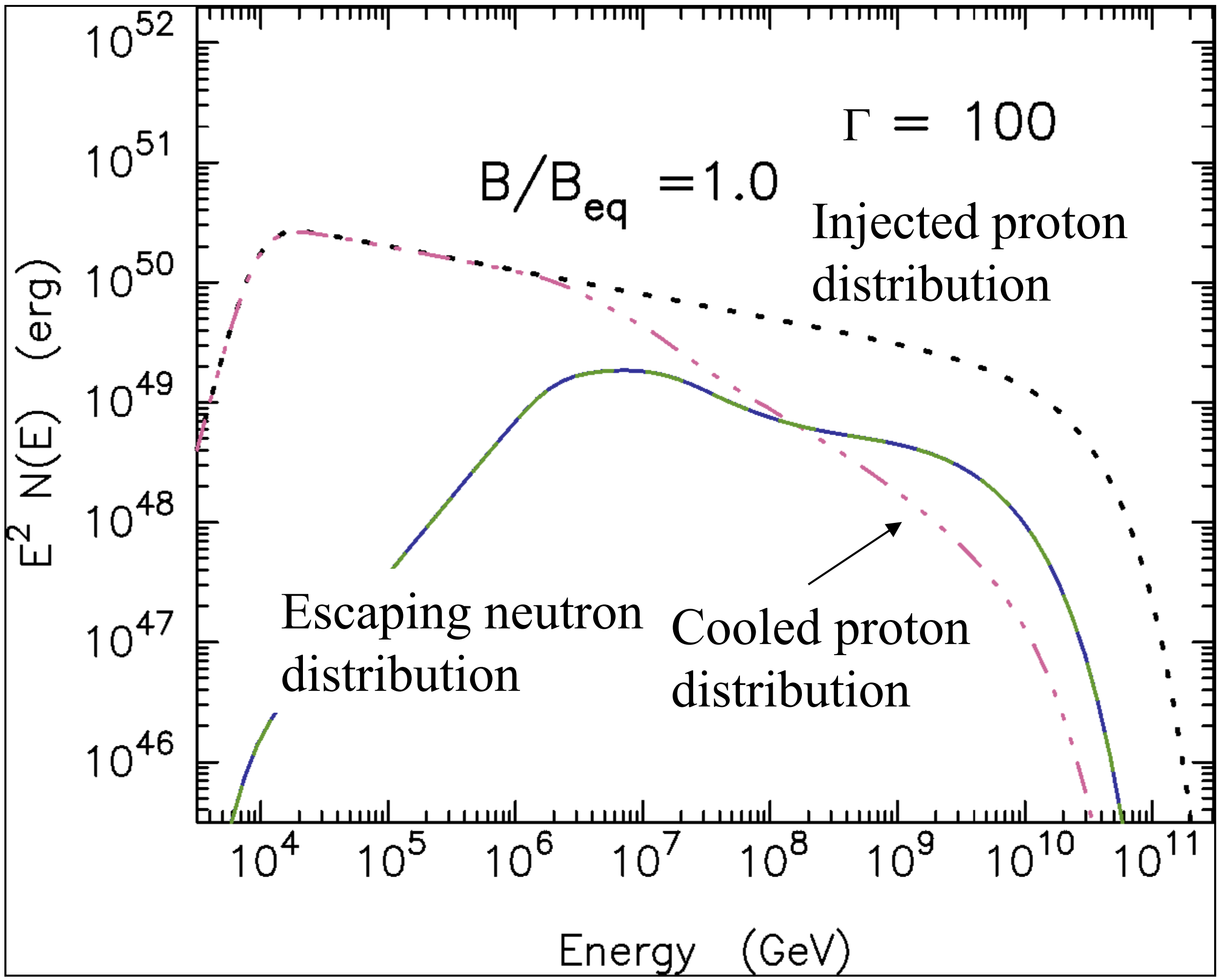
in 50 one-second pulses

UHE neutral beam:

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

UHECR/GRB connection
Waxman 1995,1997, …

Baryon Loading Factor f_b = 20



Photohadronic Cascade Radiation Fluxes

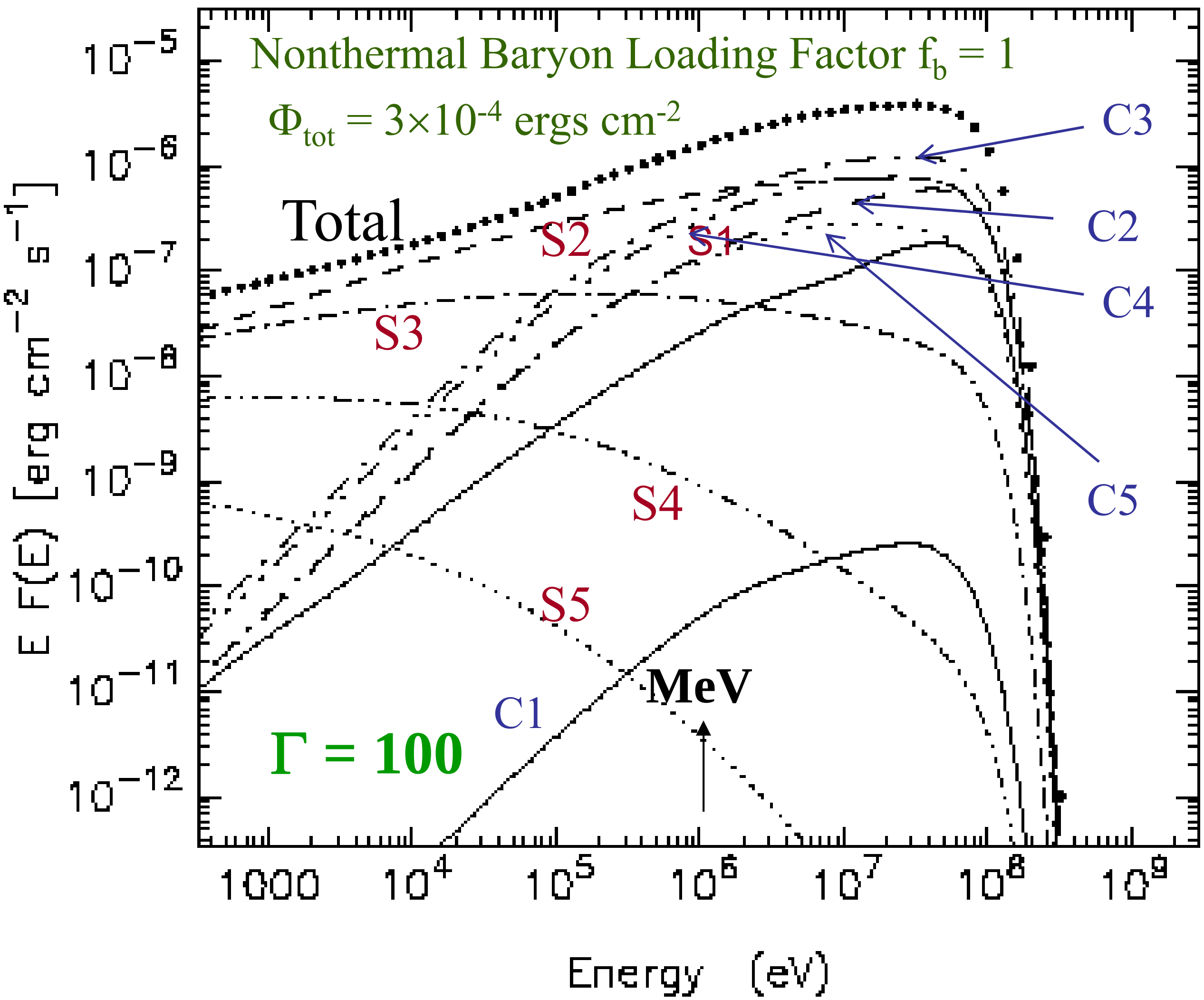
Photomeson Cascade

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

$e^{\pm}$ 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



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:

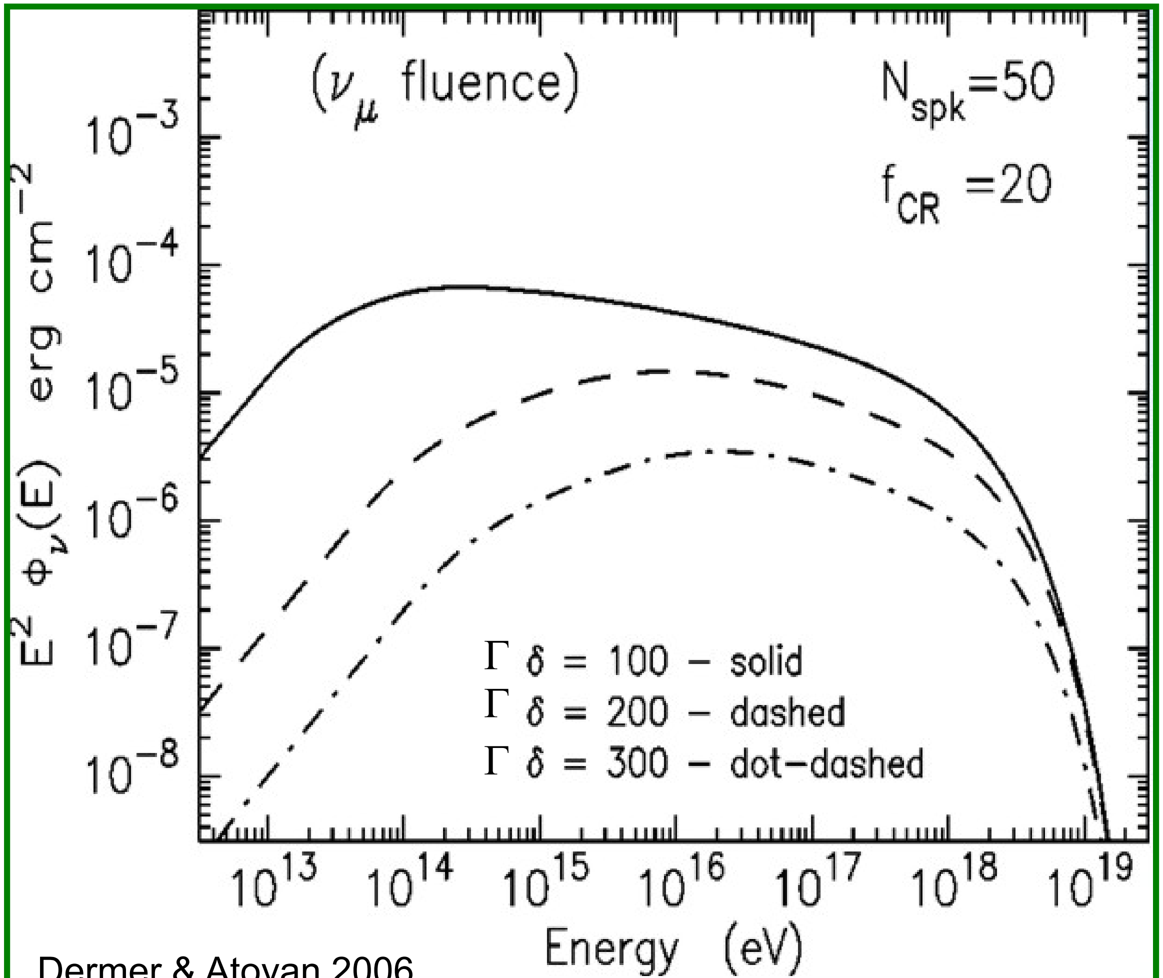
$N_\nu \approx$ 1.3, 0.1, 0.016 for Γ = 100, 200, 300

(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

Tests of Lorentz Invariance Violation

- Planck mass $m_{Pl} = \sqrt{\frac{\hbar c}{G}} = 1.2 \times 10^{19}\ GeV \approx M_{QG}\ (?)$

- Some quantum gravity models allow Lorentz symmetry violation

  (e.g., Amelino-Camelia et al.1998, Ellis et al. 2003)

  – Speed of light becomes energy dependent
  – Time dispersion between low and high-energy photons from same source

Leading term in classical photon dispersion relation

$$|1 - \frac{v_{ph}}{c}| \approx (\frac{E_{ph}}{M_{QG,n}})^n \Rightarrow \Delta t = \pm(\frac{\Delta E}{M_{QG,1} c^2})\frac{D}{c} \quad \text{(linear)}$$

Does quantum nature of space-time cause variation of speed of light with energy?

Constraints on LIV from GRB 080916C

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

- The highest-energy, 13.22 GeV, photon arrives 16.54 sec. after the GRB trigger
- High degree, 4.3σ, of association with the GRB (or not from the background)
- High redshift, z=4.35, allows large LV induced time dispersion between the 13.22 GeV and MeV photons
- 13.22 GeV photon cannot be emitted before the GRB trigger ➔ $\Delta t = 16.54$ s

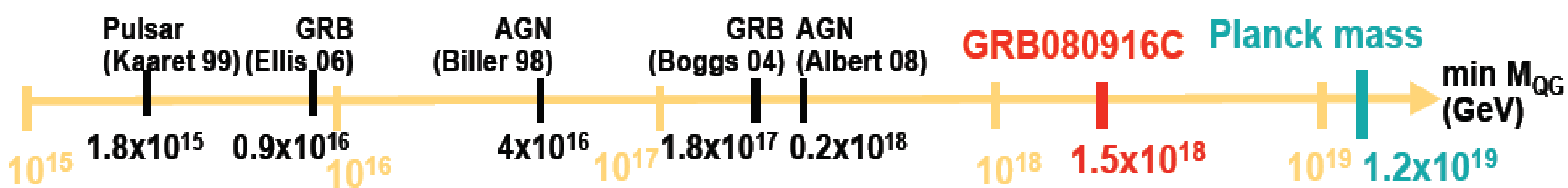
Conservative lower limits on the QG mass — Abdo et al., Science, 2008

Linear, n=1

$$M_{\mathrm{QG},1} > (1.55 \pm 0.04) \times 10^{18} \left(\frac{E_h}{13.22\ \mathrm{GeV}}\right) \left(\frac{t}{16.54\ \mathrm{s}}\right)^{-1} \mathrm{GeV}/c^2\ ,$$

Quadratic, n=2

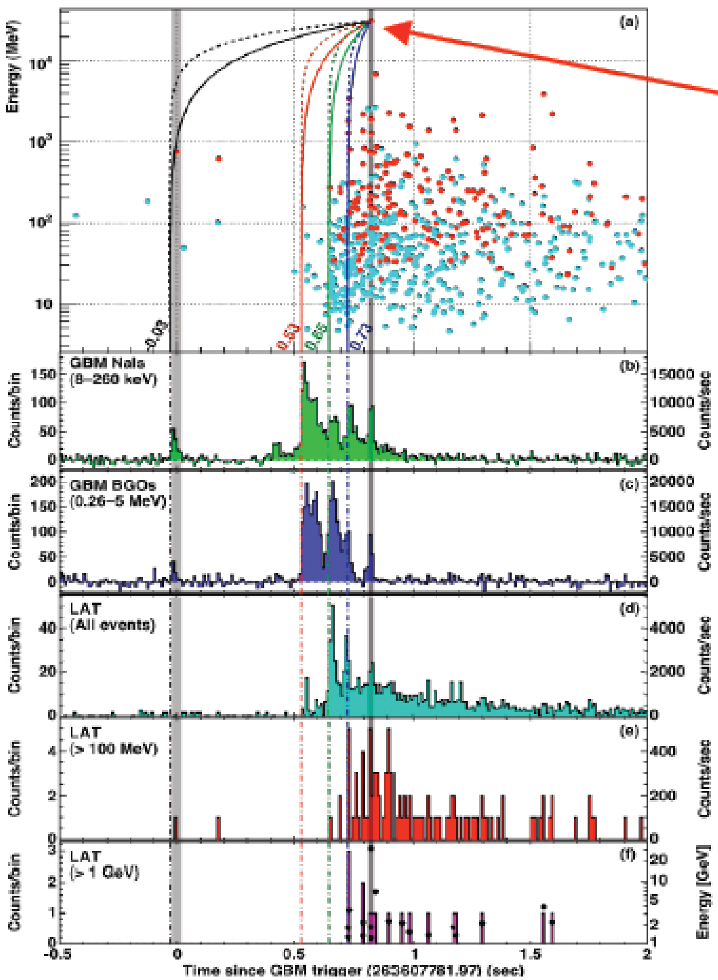
$$M_{\mathrm{QG},2} > (9.66 \pm 0.24) \times 10^{9} \left(\frac{E_h}{13.22\ \mathrm{GeV}}\right) \left(\frac{t}{16.54\ \mathrm{s}}\right)^{-1/2} \mathrm{GeV}/c^2$$



Constraints on Quantum Gravity Time Delay

Abdo et al. 2009, Nature, 462, 331

GRB 090510



- Short hard GRB with many "spikes"
- High redshift, z = 0.903 +/- 0.003
- 31 GeV photon (27.97, 36.32 GeV 1s CL) 0.829 s after the GRB trigger
- Constraint on QG mass depends on Δt

The most conservative constraint comes from Δt < 0.859 s, time from precursor

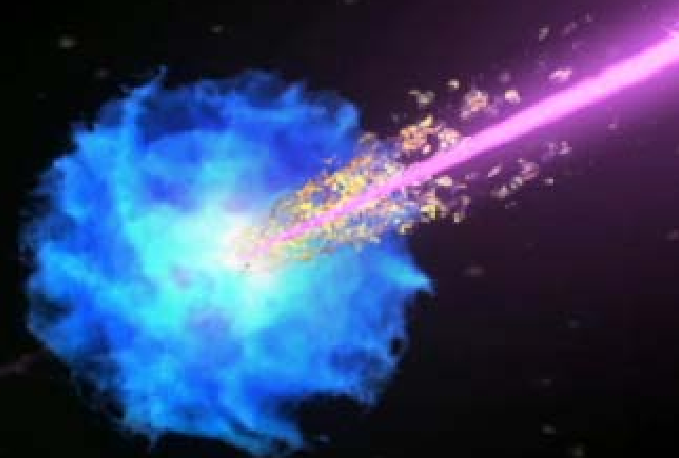
$$M_{QG,1} > 1.19\ M_{Pl}$$

Table 1 | Limits on Lorentz invariance violation

	Limit on $\lvert\Delta t/\Delta E\rvert$ or $\lvert\Delta t\rvert$	Limit on $M_{QG,1}/M_{Planck}$	Valid for s_n
Limit a:	$\lvert\Delta t/\Delta E\rvert < 30$ ms GeV^{-1}	>1.22	± 1
Limit b:	$\lvert\Delta t\rvert < 859$ ms	>1.19	1

Summary

- Measuring the bulk Lorentz factor Γ
  - $\gamma\gamma$ opacity
  - Photospheric method
  - Afterglow onset method



- GRB 130427A
  - Once (?) in a lifetime event
  - Observed in prompt phase at optical, X-ray, MeV and GeV gamma-ray energies; excellent afterglow data
  - Best data set yet for testing models

- Challenges
  - How can high-energy radiation be synchrotron emission?
  - Why does the pulse radiation not follow predicted behaviors?
  - Is our understanding of GRBs lacking?

What does it all mean?

How Γ is determined

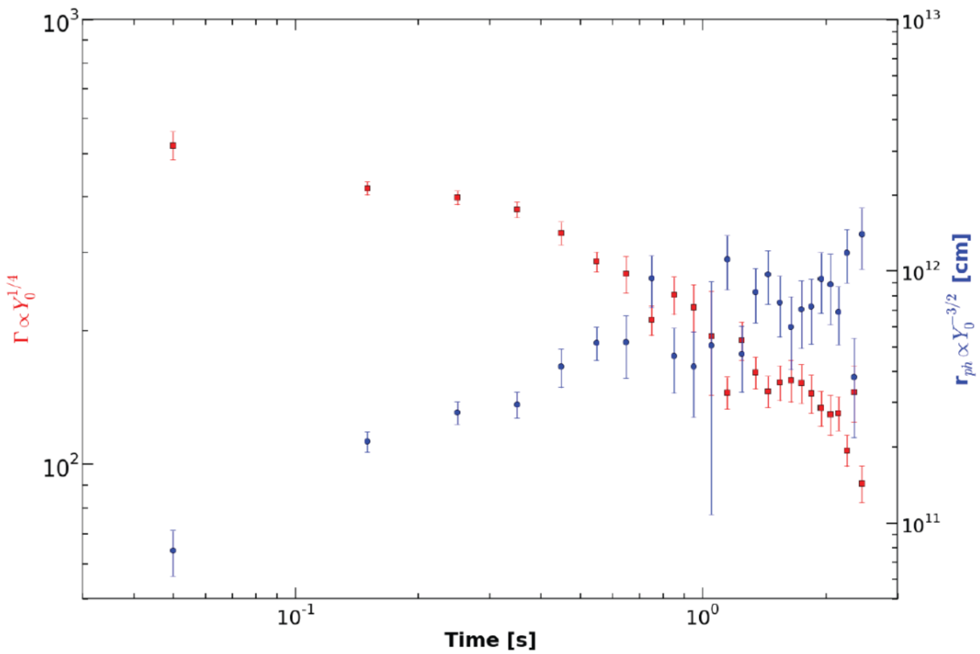
1. **γγ opacity method**

Minimum bulk Lorentz factor:

$$\Gamma_{\min} \cong \left[\frac{\sigma_T (1+z)^2 d_L^2 f_{\hat{\varepsilon}} \varepsilon_1}{2 m_e c^4 t_{\rm var}} \right]^{1/6} , \quad \hat{\varepsilon} \cong \frac{2\Gamma^2}{(1+z)^2 \varepsilon_1}$$

$\Gamma_{\min} \approx 500$ for 73 GeV photon detected 19.06 s after t_0; $t_{\rm var} = 40 \pm 1$ ms

2. **Photospheric method**



Γ ≈ 550 at start and declines with time

How Γ is determined, pt. 2

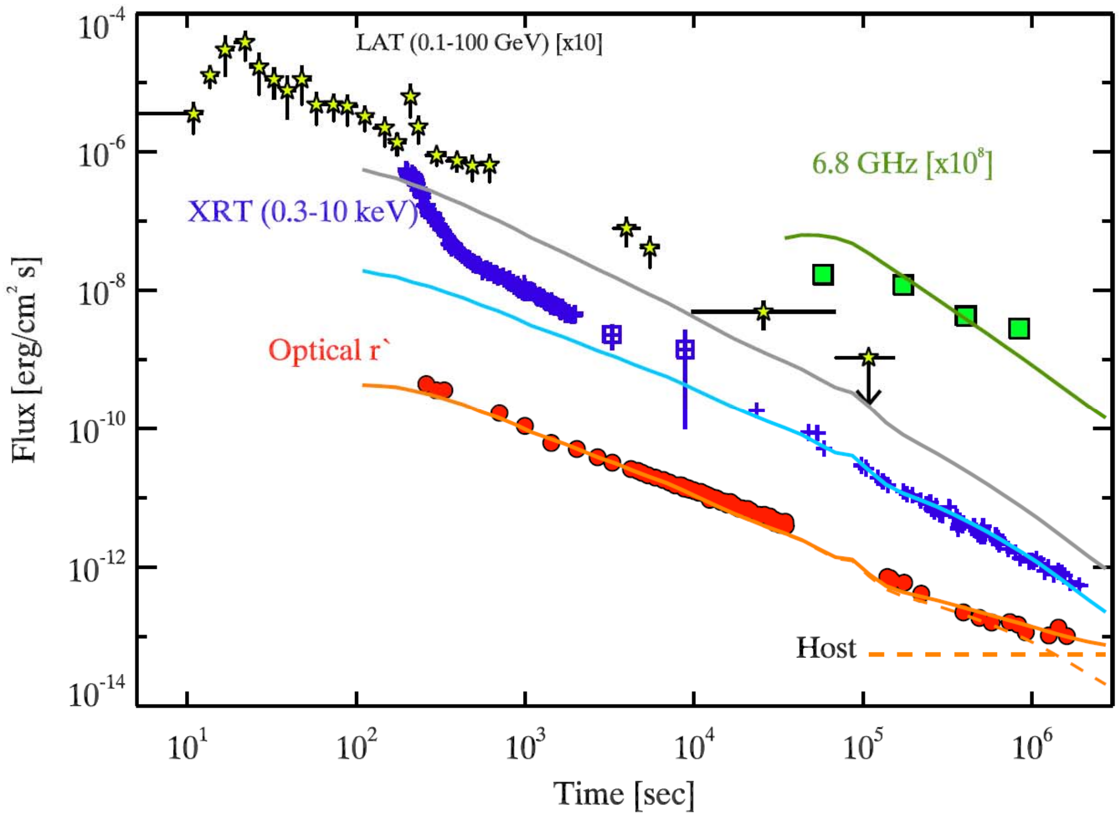
3. Afterglow onset method (optical or γ-ray)

(Lü et al. 2012; Ghirlanda et al. 2012)

$$t_{pk} \approx t_d \approx \frac{r_d}{2\Gamma_0^2 c}$$

$$\Rightarrow \Gamma_0 \approx \left(\frac{3E_\gamma}{32\pi\, n_0 m_p c^5 \eta t_{pk}^3} \right)^{1/8}$$

$$\Gamma_0 \approx 540 \left(\frac{E_{55}}{n_0 (t_{pk}/10\,s)^3} \right)^{1/8}$$

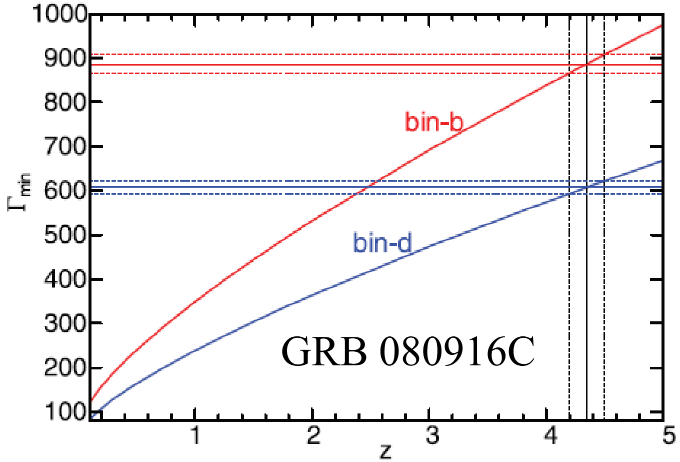


LAT data show $t_{pk} \approx 10 - 20$ s

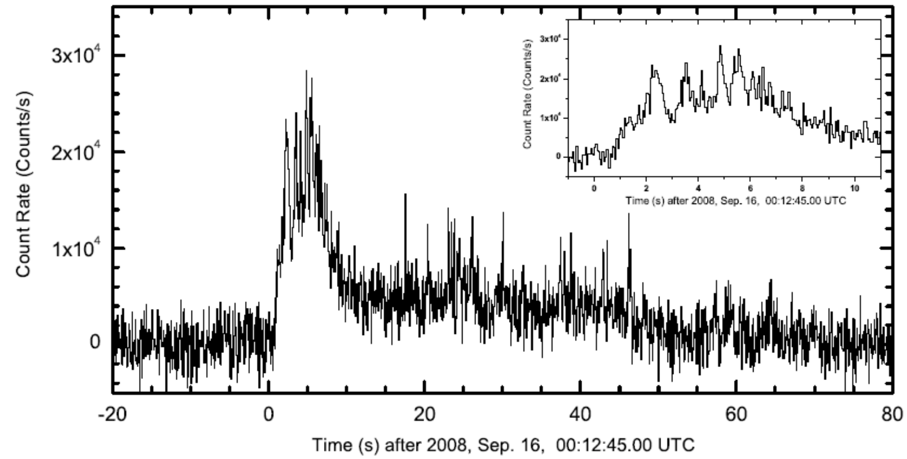
Generalize to include engine timescale; wind vs. uniform medium

Methods converge on $\Gamma \approx 500 - 100$

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

$\Rightarrow \Gamma_{min} \approx$ **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 $\Gamma < \Gamma_{min}$

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