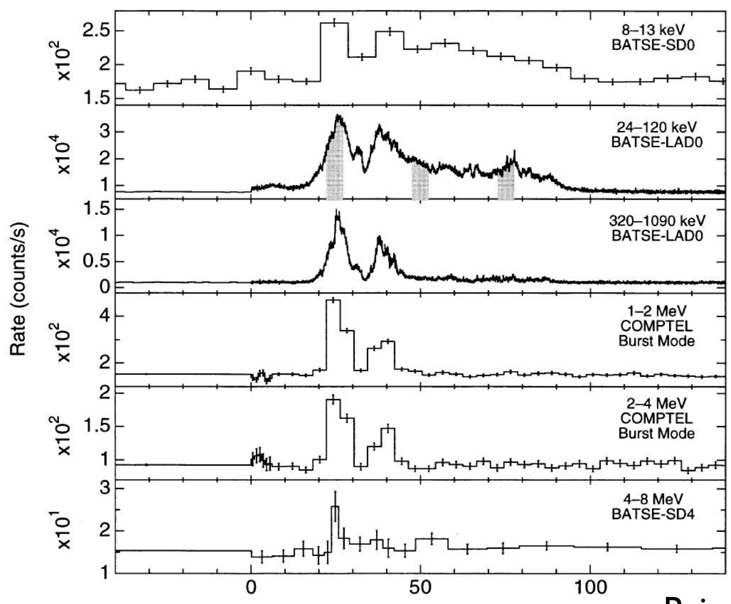
High Energy Emission from Gamma-Ray Bursts

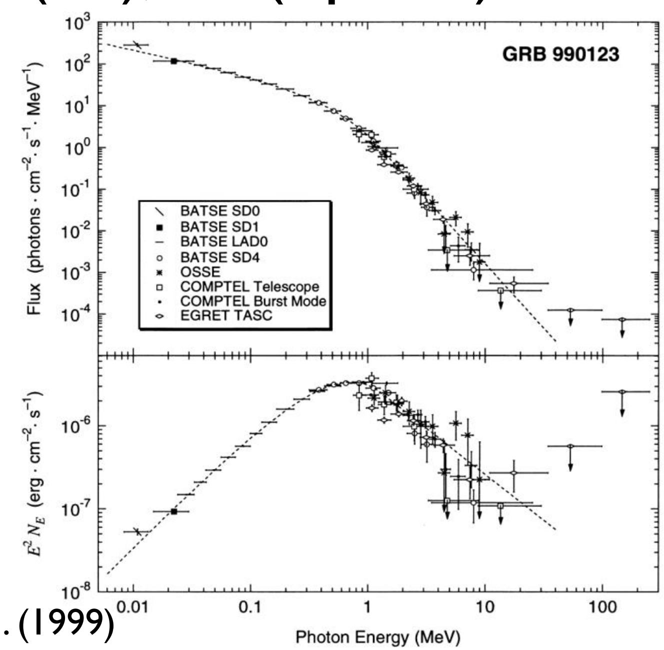
Bo Zhang
Purple Mountain Observatory

首届LHAASO合作组会议 2016-8-30

Fast Facts of GRBs

- Intense gamma-ray flash in the sky
- Temporal behaviors:
  - Duration: ~30s for long (>2s) and ~0.3s for short (<2s)
  - Light curve: complicated with variabilities and mutiple pulse
- Spectral features: non-thermal (PL); eV (optical) to keV to

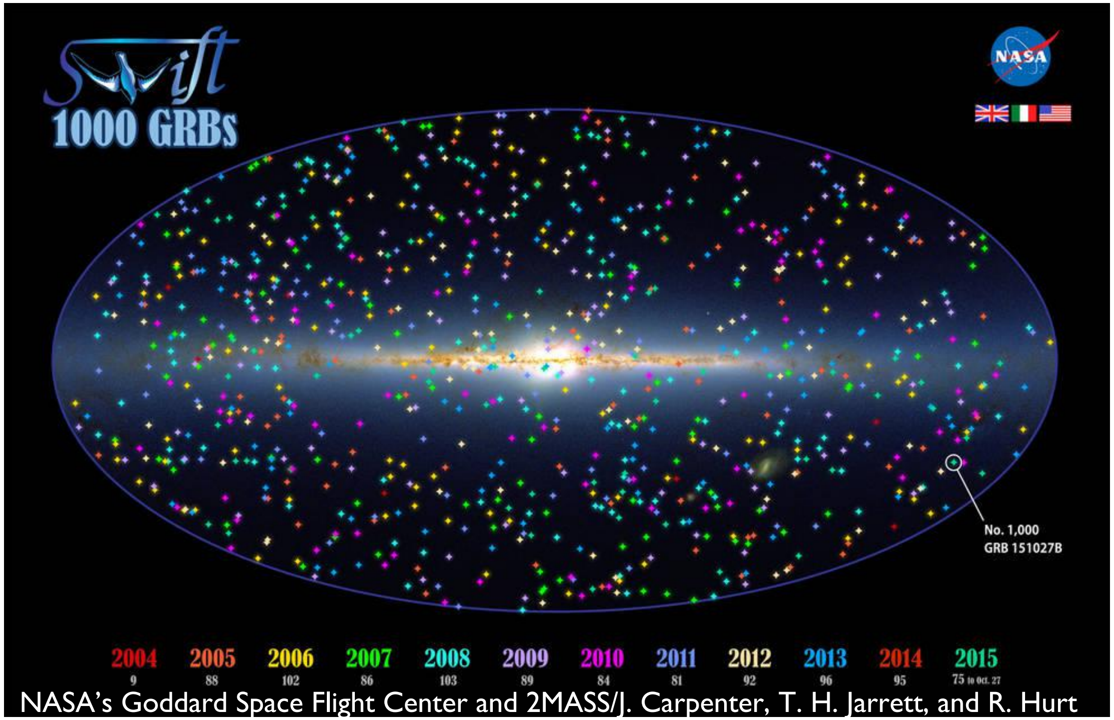




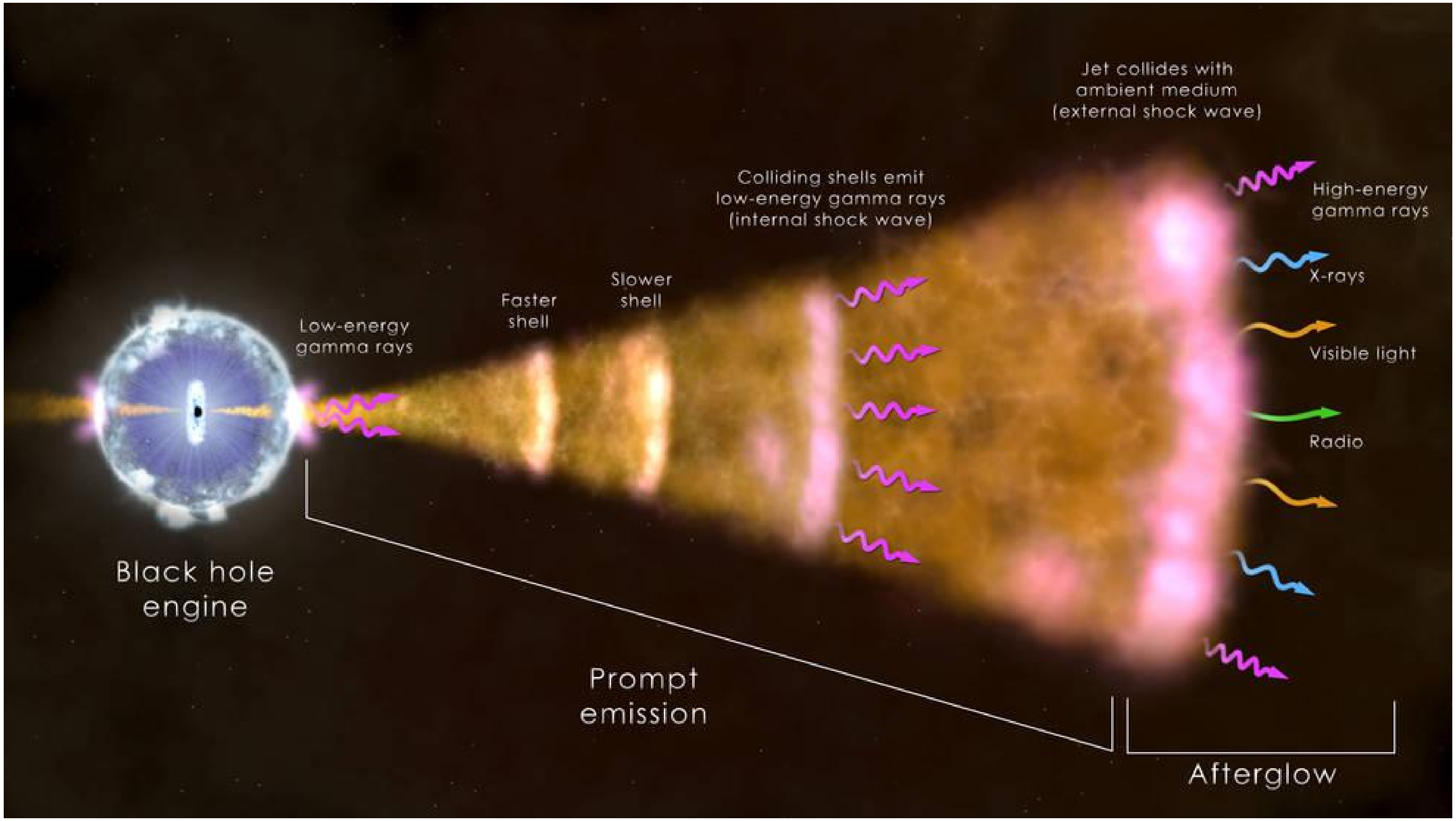
Briggs et al. (1999)

Fast Facts of GRBs

- Formation: death of massive stars or compact star merger
- Burst rate: 1-2 for BATSE; similar for Fermi/GBM; lower for Swift/BAT
- Distributions: isotropic; typical redshift: z~3



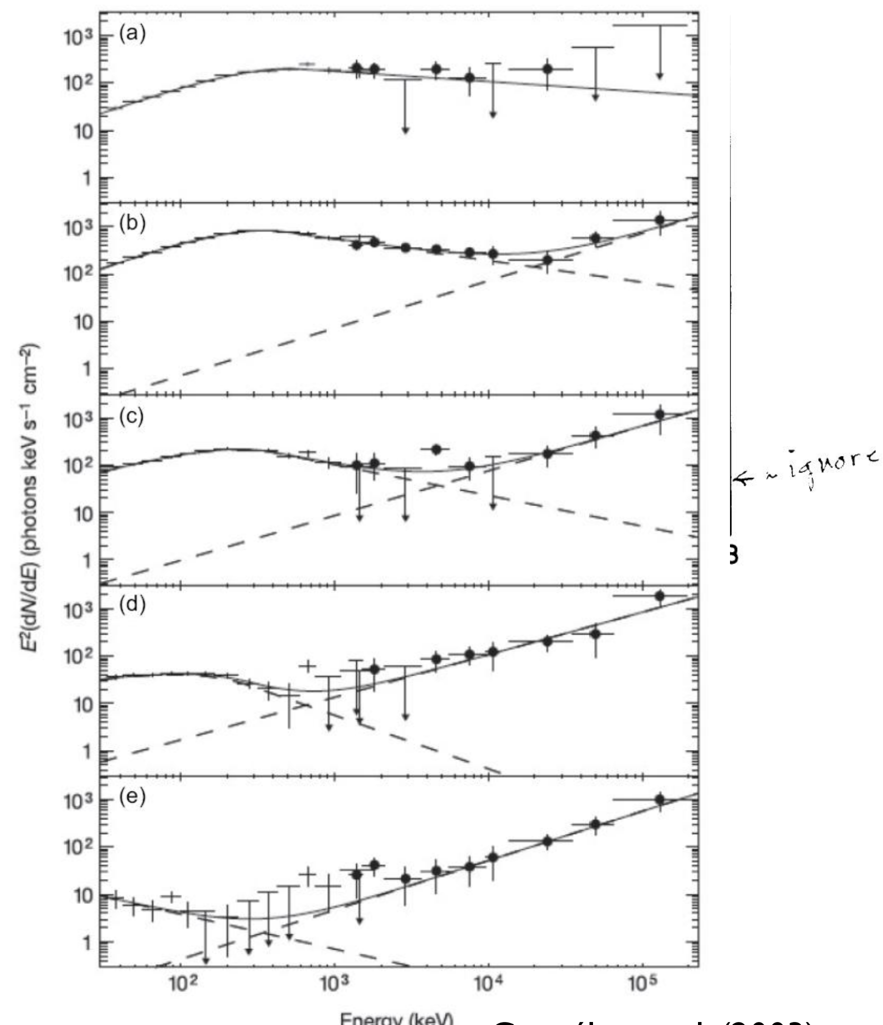
Fast Facts of GRBs



NASA's Goddard Space Flight Center

High Energy Emission of GRBs: Pre-Fermi Era

- 1985: no spectral break above 25 MeV
- GRB 940217: high energy emission 90 min after trigger
- GRB 941017: HE with different temporal; 18 GeV photon detected
- GRB 970417A: possible detection by Milagro?
- GRB 080514B: AGILE detection



González et al. (2003)

High Energy Emission of GRBs: the Fermi Era

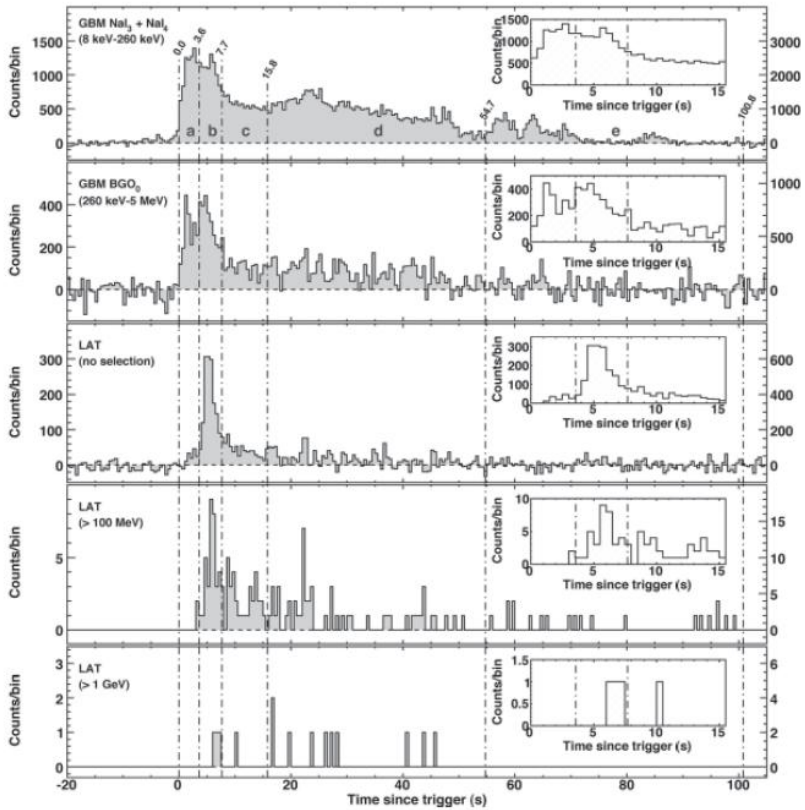
- 2008.6.11-present
- Low-Earth orbit (~550 km)
- Full sky coverage every 3 hr
- Detection rate: ~250 GRBs with GBM; 10 GRBs/yr with LAT

NASA/MSFC/D. Higginbotham

- Detector Area: 100 m^2
- Energy range
  - LAT: 20 MeV to >300 GeV
  - GBM: 8 keV to 40 MeV
- Field of View:
  - LAT: >2 sr
  - GBM: all unocculted sky (>8 sr)

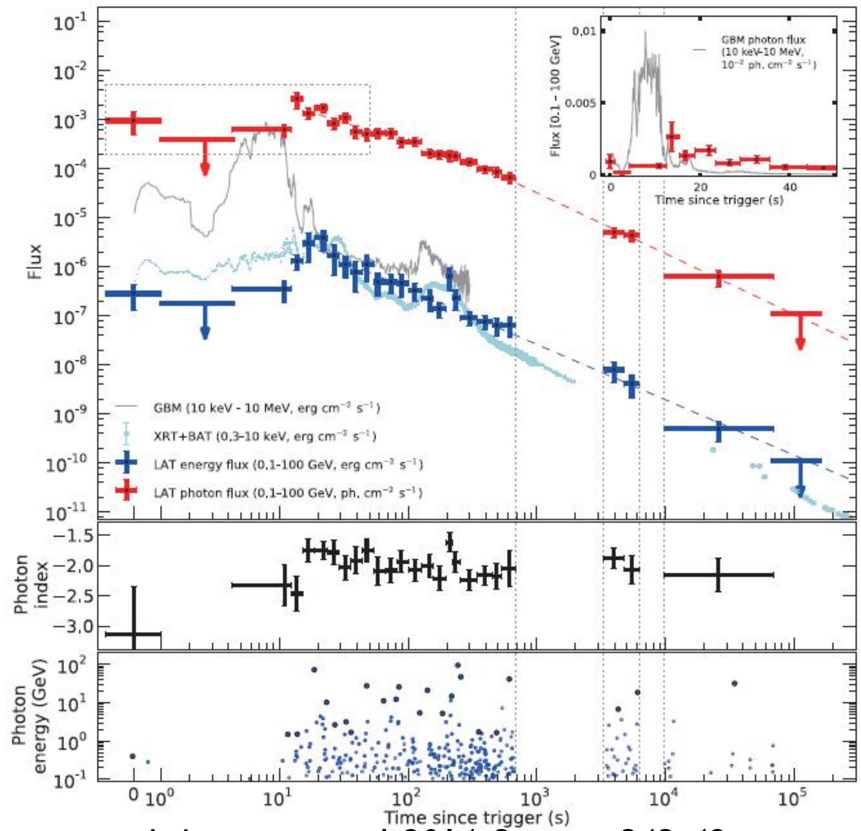
GRB High Energy Properties: Temporal

- Delayed onset: first LAT peak coincides with later GBM peak; first low energy peaks missing



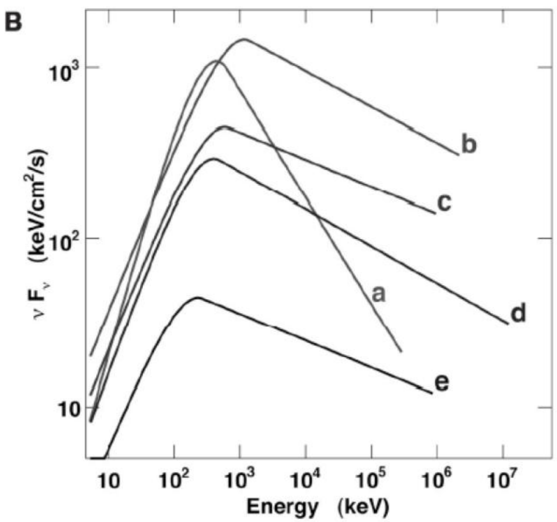
Abdo et al. 2009, Science, 323, 1688

- Long lasting HE emission: >1000 s; afterglow origin; PL decay



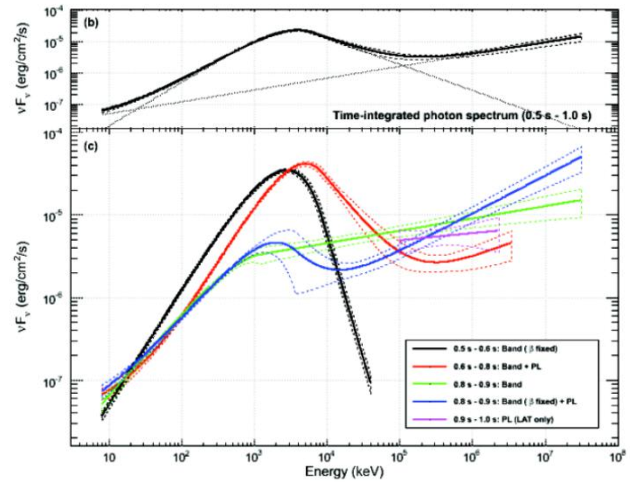
Ackermann et al. 2014, Science, 343, 42

GRB High Energy Properties: Spectral



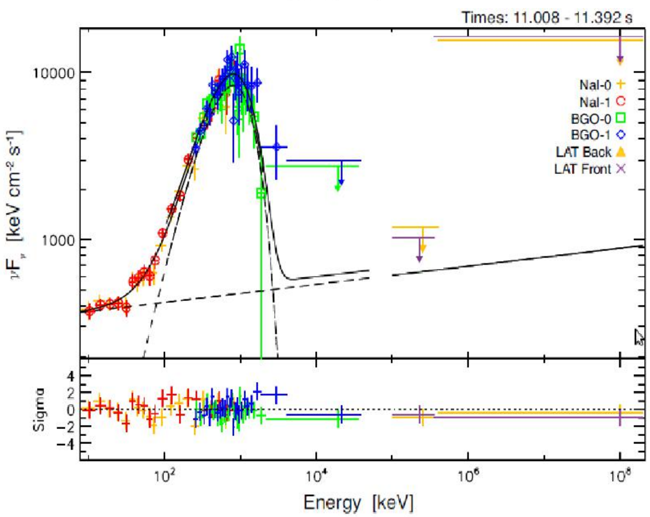
Band only

Abdo et al. 2009, Science, 323, 1688



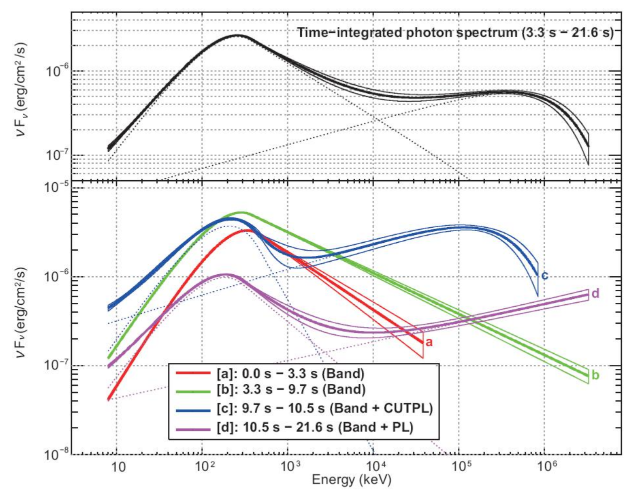
Band + PL

Abdo et al. 2009, Nature, 462, 331



black body + PL

Ryde et al. 2010, ApJ, 709, L172



Band + cutoff PL

Ackermann et al. 2011. ApJ, 2011, 729, 114

GRB High Energy Properties: Spectral

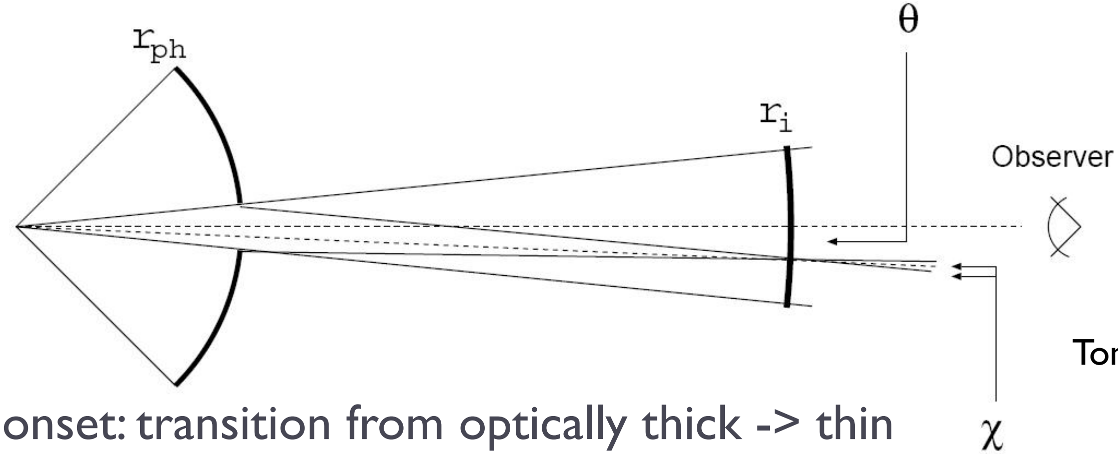
- Additional component may dominate both high and low energies
- PL component usually not present during the all burst duration
- Soft-to-hard evolution in LAT band
- Hard/soft flux: 10% for long GRB; ~100% for short GRB

Origins of GRB HE Emission: Prompt

- Inverse Compton scattering: not feasible due to asynchronous HE and LE emission
- Leptonic models:
  - Up-scattered cocoon emission/photosphere emission
  - IC scattering of residual collision-driven internal shocks
  - Electron-positron pair loading
  - Late expansion of relativistic internal shock to $\Gamma \sim 1000$-1000000 in low baryon loading fireballs
  - ……
- Hadronic modes:
  - Synchrotron radiation of protons
  - Cascade processes driven by photon-pion reactions

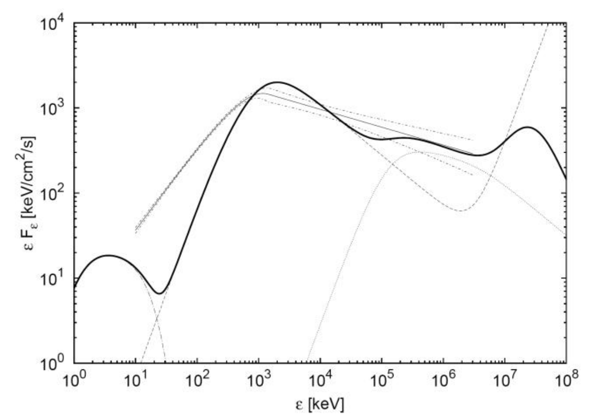
Origins of GRB HE Emission: Prompt

- Up-scattered cocoon emission: Toma et al. (2009)
  - Origin of cocoon: dissipation of jet propagation inside progenitor star



Toma et al. (2009)

  - Delayed onset: transition from optically thick -> thin
  - 2 components
    - ~1 MeV SSC from shock accelerated e⁻
    - ~100 MeV IC scattering by accelerated e⁻
  - Optical flash predicted
  - Not suitable for short GRBs/extra PL
  - Fine tuning needed

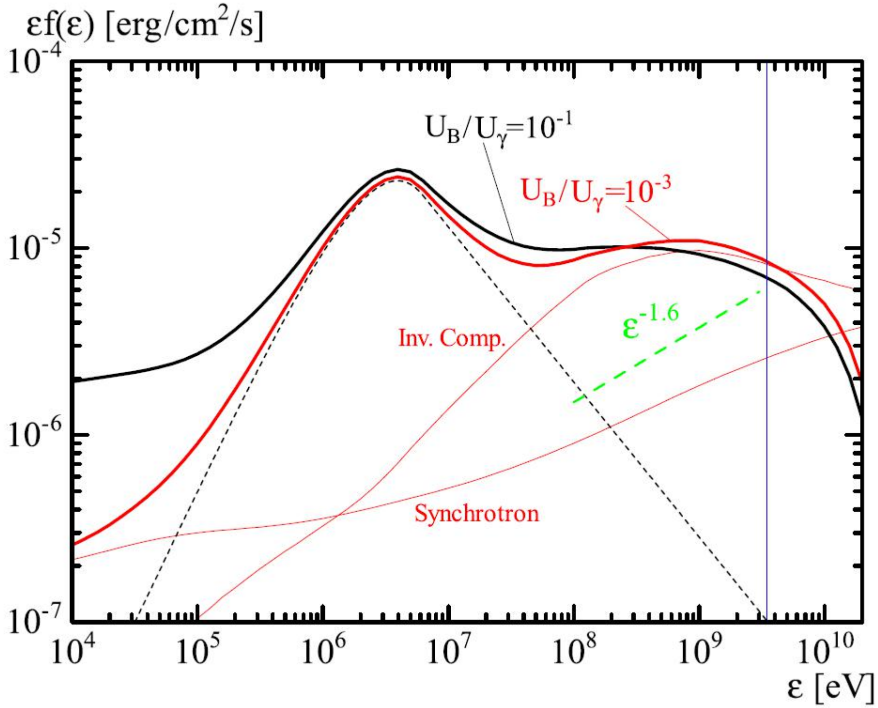


Origins of GRB HE Emission: Prompt

- Up-scattered photosphere emission: similar to Up-scattered cocoon model; Fine tuning needed (Toma et al. 2011)
- Residual collision: PL spectrum expected beyond the previously thought cutoff; not suitable for long-lasting HE emissions (Li 2010)
- Electron-positron pair loading: Beloborodov et al. (2014)
  - Scattering of GRB prompt photons by wind-type circumburst medium
  - Origin of pairs: collision between IC scattered photons with other prompt photons
  - Bright > 100 GeV photons and prompt optical flash at GeV peak predicted
- Late expansion of relativistic baryon component: Ioka (2010)
  - High energy cutoff: synchrotron cooling break/maximum synchrotron cutoff
  - Yonetoku relation can be explained; steep/shallow decay can be explained
  - Anticorrelation between ~ TeV neutrinos and the extra variable GeV γ-rays

Origins of GRB HE Emission: Prompt

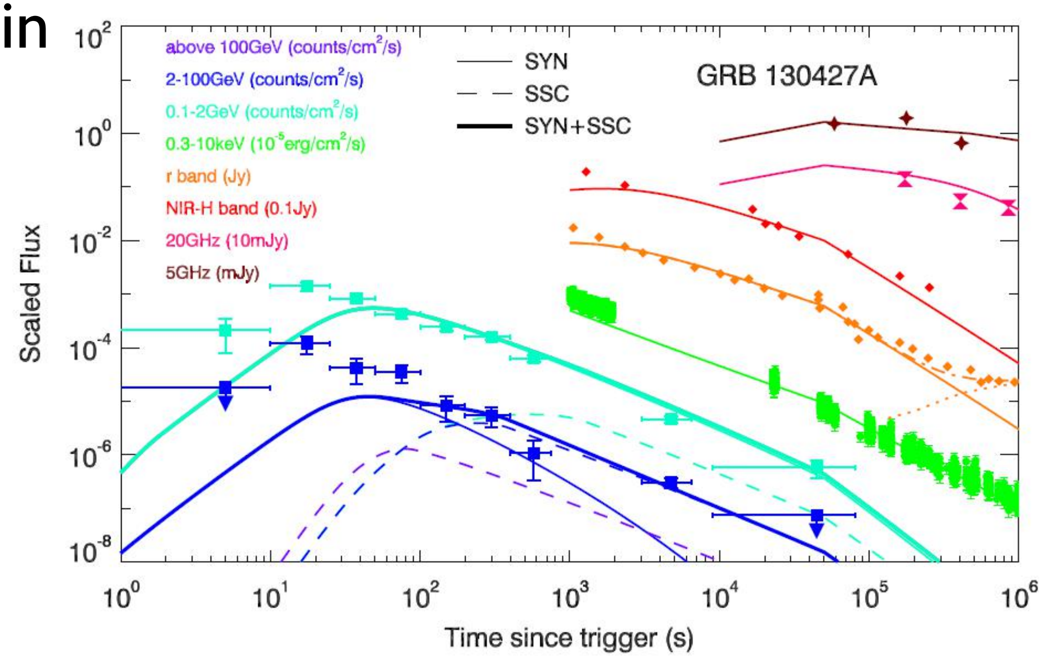
- Hadronic models:
  - Delay due to longer timescale of hadron acceleration
  - Higher peak for hadron process
  - High isotropic-equivalent proton energies >10^{55} erg/s required



Asano et al. (2009)

Origins of GRB HE Emission: Afterglow

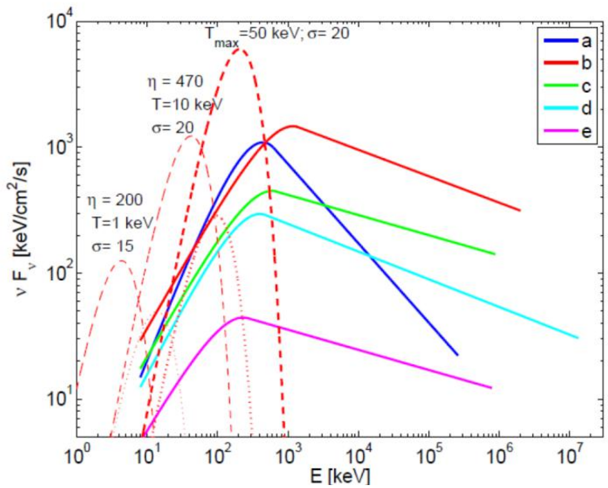
- Synchrotron radiation:
  - PL decay/delay onset explained
  - Hard to produce > 10 GeV photons
  - Hard to produce temporal structure
- Forward shock SSC in Afterglow



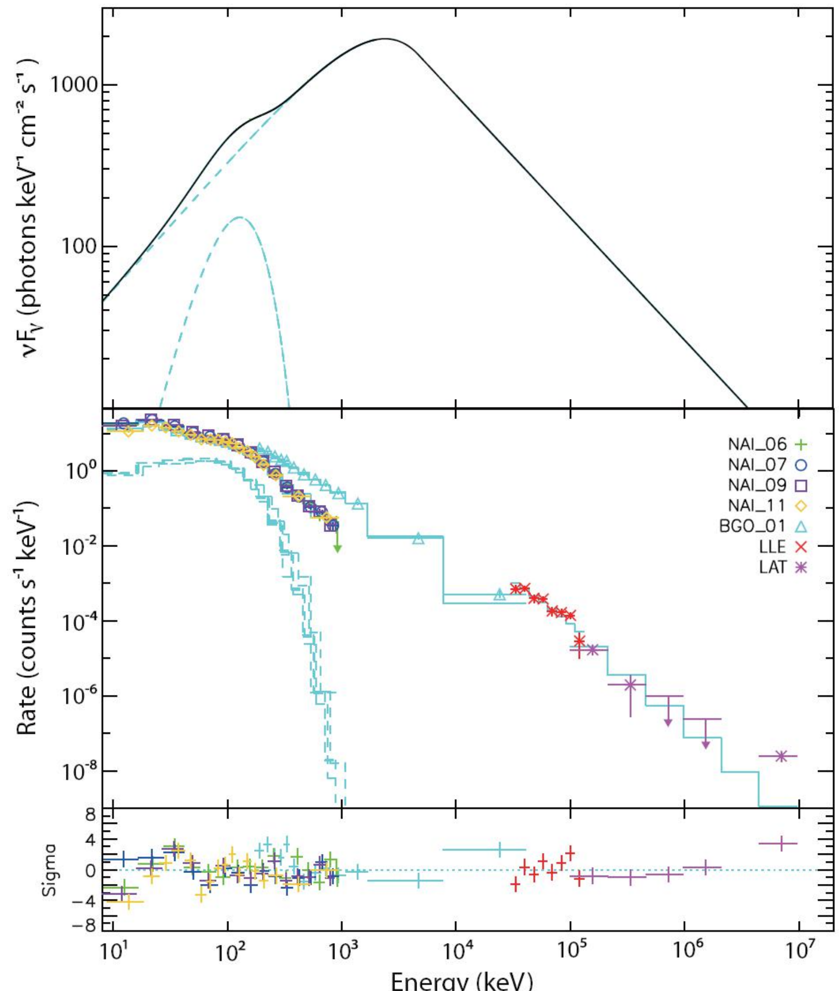
Liu et al. (2013)

Applications of GRB HE Emission: Photosphere Emission

- GRB photosphere: the surface with ~1 optical depth
- Photospheric emission: blackbody
- High magnetization -> low photospheric emission
- Magnetization parameter > 20 for GRB 080916C
- BB components for GRBs 090902B/110721A



Zhang & Pe'er (2009)



Axelsson et al. (2012)

Applications of GRB HE Emission: Bulk Lorentz Factor of Ejecta

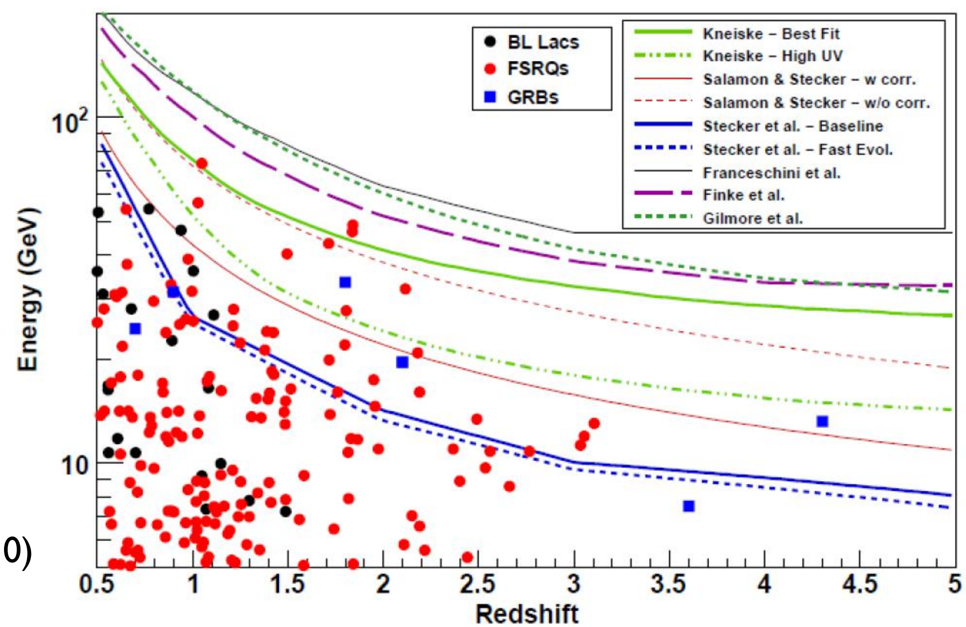
- Compactness problem: large amount of energy + stellar explosion: γ-γ pair production
- Solution: relativistic motion
- For simple jets:

$$\Gamma_{\min}(E_{\max}) = \left[\frac{4\,d_L^2\,A}{c^2\,t_v}\,\frac{m_e^2\,c^4}{(1+z)^2\,E_{\max}}\,g\,\sigma_T\right]^{\frac{1}{2-2\beta}}\left[\frac{(\alpha-\beta)\,E_{\rm pk}}{(2+\alpha)\,100\,{\rm keV}}\right]^{\frac{\alpha-\beta}{2-2\beta}}\exp\left(\frac{\beta-\alpha}{2-2\beta}\right)\left[\frac{2\,m_e^2\,c^4}{E_{\max}\,(1+z)^2\,100\,{\rm keV}}\right]^{\frac{\beta}{2-2\beta}}$$

- Typical LAT burst: Γ>300-400; highest: Γ~1200 for GRB 090510; smaller for time-dependent thin-shell model or multi-zone model

Applications of GRB HE Emission: Constraining Extragalactic Background

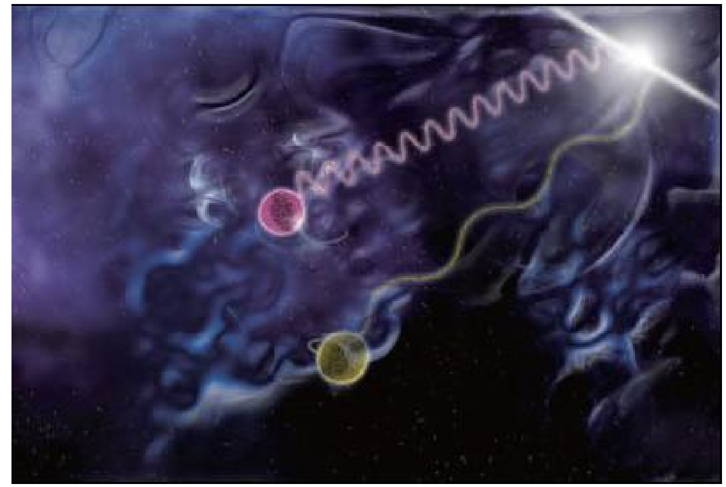
- EBL arises from star formations and related dust emissions
- γ-γ pair production for HE photons with $E\varepsilon\,(1+z)^2 x > 2\,(m_e c^2)^2$
- EBL should be optically thin for GRB photons with highest energies
- Stecker et al. excluded using Fermi data



Abdo et al. (2010)

Applications of GRB HE Emission: Constraining Lorentz Invariance Violation

- Lorentz Invariance Violation: foamy space-time structure under Planck energy scale
- Predicted by some quantum gravitational theories
- Foamy space-time -> light dispersion, HE photons arrive later



NASA/Sonoma State University/Aurore Simonnet

$$\left|v_{\rm ph}/c - 1\right| \approx \left(E_{\rm ph}/M_{QG,n}c^2\right)^n$$

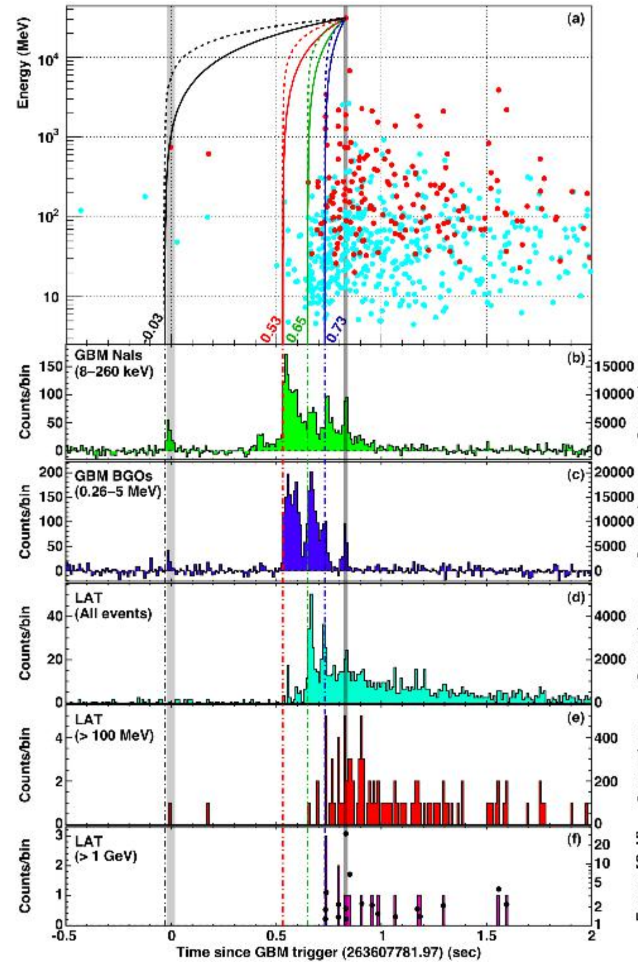
$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{\rm QG,n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'$$

Applications of GRB HE Emission: Constraining Lorentz Invariance Violation

- GRBs as LIV testbed: cosmological distance; high energy; rapid variations in light curves
- Assumption: time delay between HE & LE photons due to LIV
- Constraint from GRB 090510:

$$M_{QG,1} > 1.2 M_{Planck}$$

$t_{\rm start}$ (ms)	limit on $\vert\Delta t\vert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$	limit on $M_{\rm QG,2}$ in 10^{10} GeV/c^2
−30	< 859	start of any observed emission	0.1	1	> 1.19	> 2.99
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42	> 5.06
630	< 199	start of > 100 MeV emission	100	1	> 5.12	> 6.20
730	< 99	start of > 1 GeV emission	1000	1	> 10.0	> 8.79
—	< 10	association with < 1 MeV spike	0.1	±1	> 102	> 27.7
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	−1	> 1.33	> 0.54
$\vert\Delta t/\Delta E\vert < 30$ ms/GeV		lag analysis of all LAT events	—	±1	> 1.22	—



Abdo et al. 2009, Nature, 462, 331

The Role of LHAASO in GRB Research

- WCDA: Water Cherenkov Detector Array with detection area of 10^4 m^2 (at ~100 GeV), ~ 10000 LAT!
- Suppose:
  - GRB spectrum $\mathrm{d}N\left(E\right)/\mathrm{d}N \propto E^{-\beta}$, β~2.3
  - ~10 GeV photon detected by LAT
- $10^5 \times 10 \times 100^{1-\beta} \sim 6 \times 10^3$> 100 GeV photons detected by WCDA!
- > 100 GeV light curves can be produced for bright HE GRBs!

What Can We Do with HE Data…

- Diagnosing GRB HE theories: the shape of >100 GeV spetral -> confirm/reject model predictions
- Calculate key parameters: bulk Lorentz factor, magnetization parameter…
- Classify GRBs with HE behaviors?
- Better constraint of EBL
- Better (1-2 orders of magnitude) constraint of LIV

Thanks!