Fermi-LAT Collaboration Meeting at CERN, 27-31 March 2017

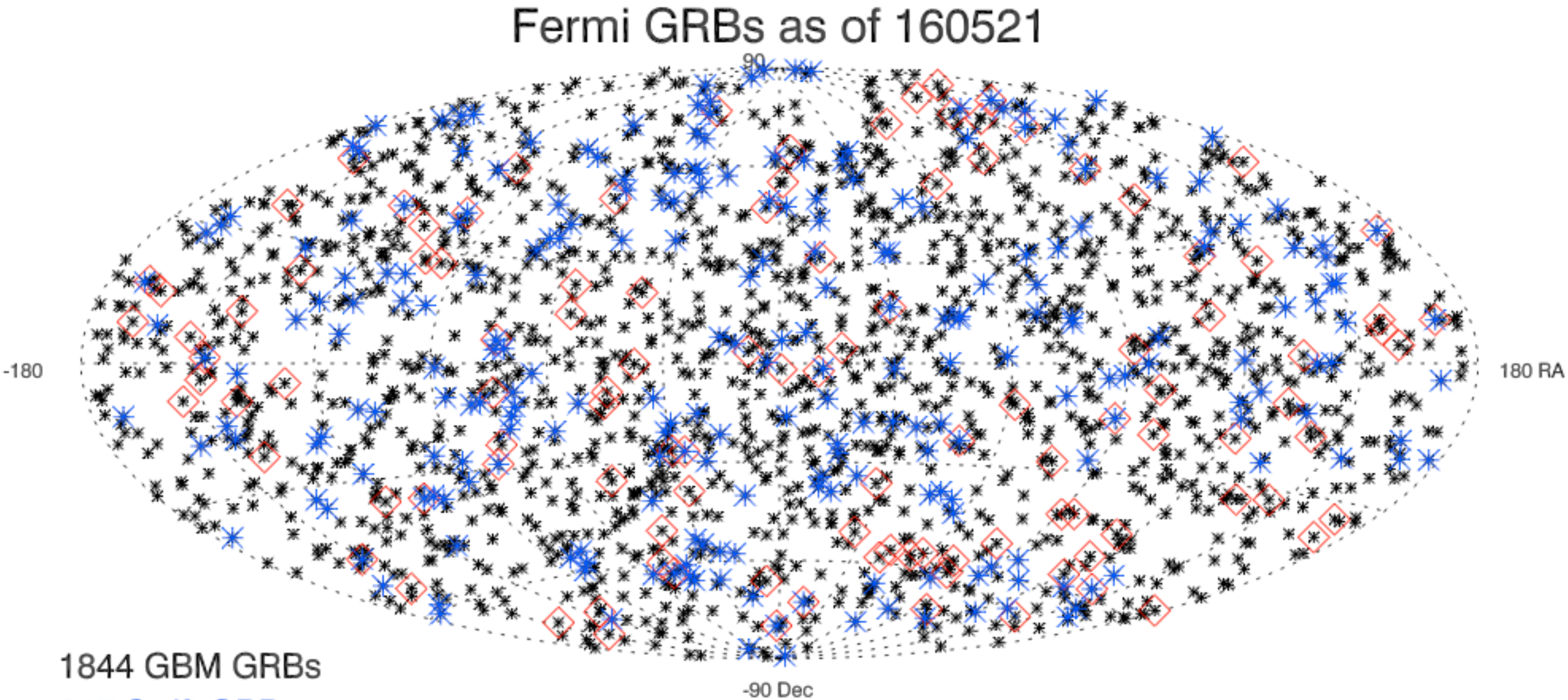
FERMI-LAT GRB OBSERVATIONS: WHAT HAVE WE LEARNED?

Soeb Razzaque
University of Johannesburg
South Africa

UNIVERSITY OF JOHANNESBURG

GRB population emitting high-energy (HE, ≥100 MeV) γ rays

LAT GRB rate



1844 GBM GRBs
247 Swift GRBs
111 LAT GRBs

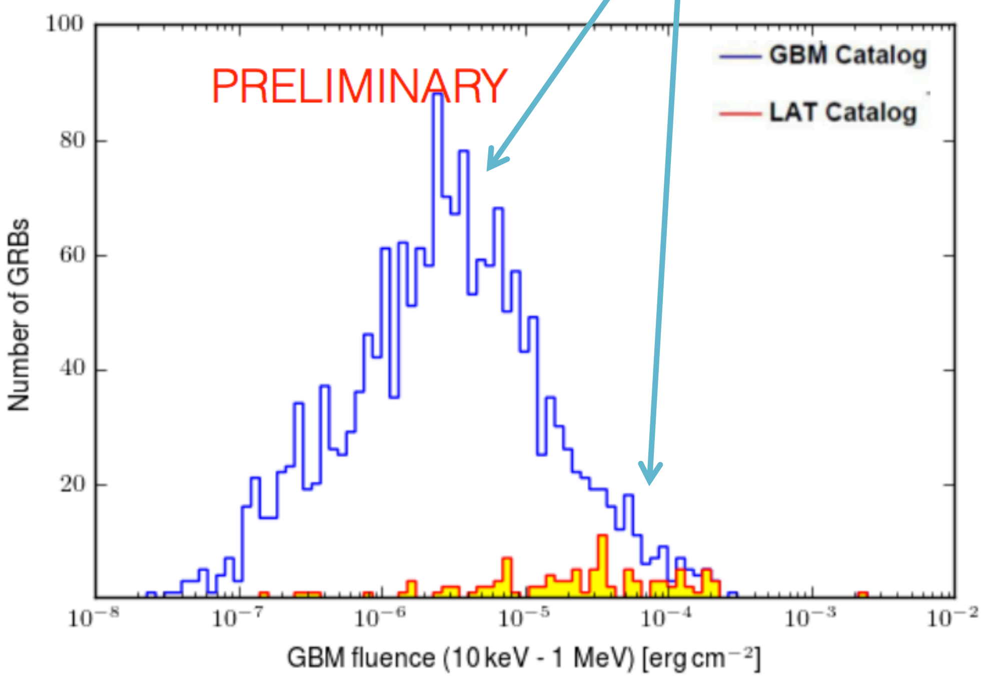
≈ 240/year GBM GRBs (8 keV – 40 MeV)

≈ 15/year LAT GRBs (>100 MeV)

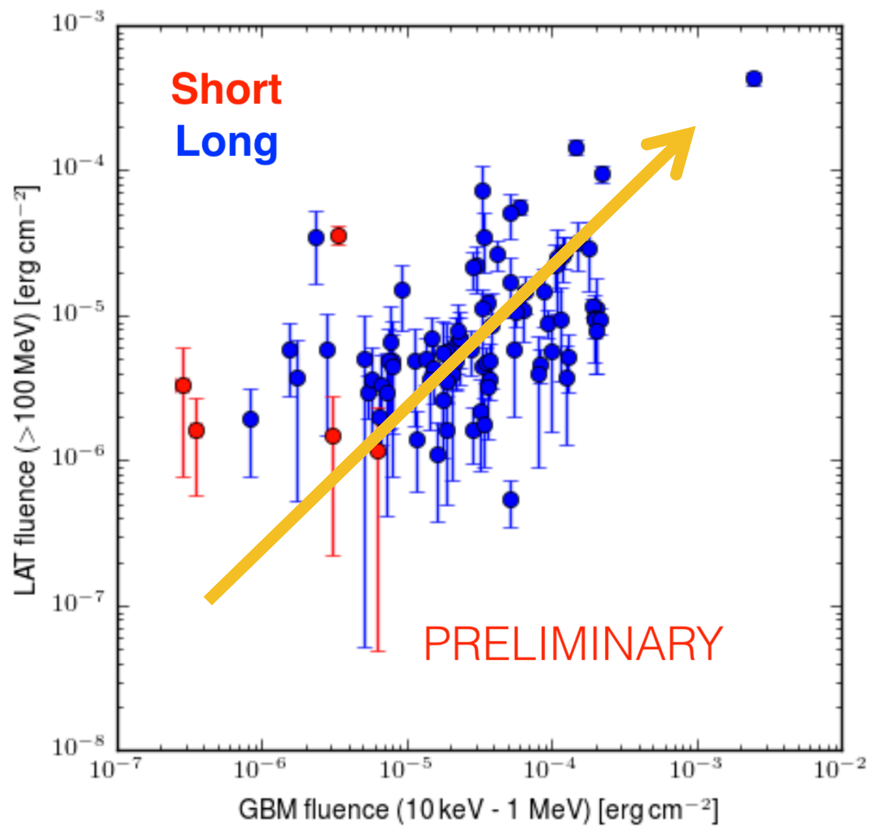
LAT GRB fluence

>100 MeV fluence is ~10% of 10 keV – 1 MeV fluence

LAT GRBs have higher than average GBM GRB fluence



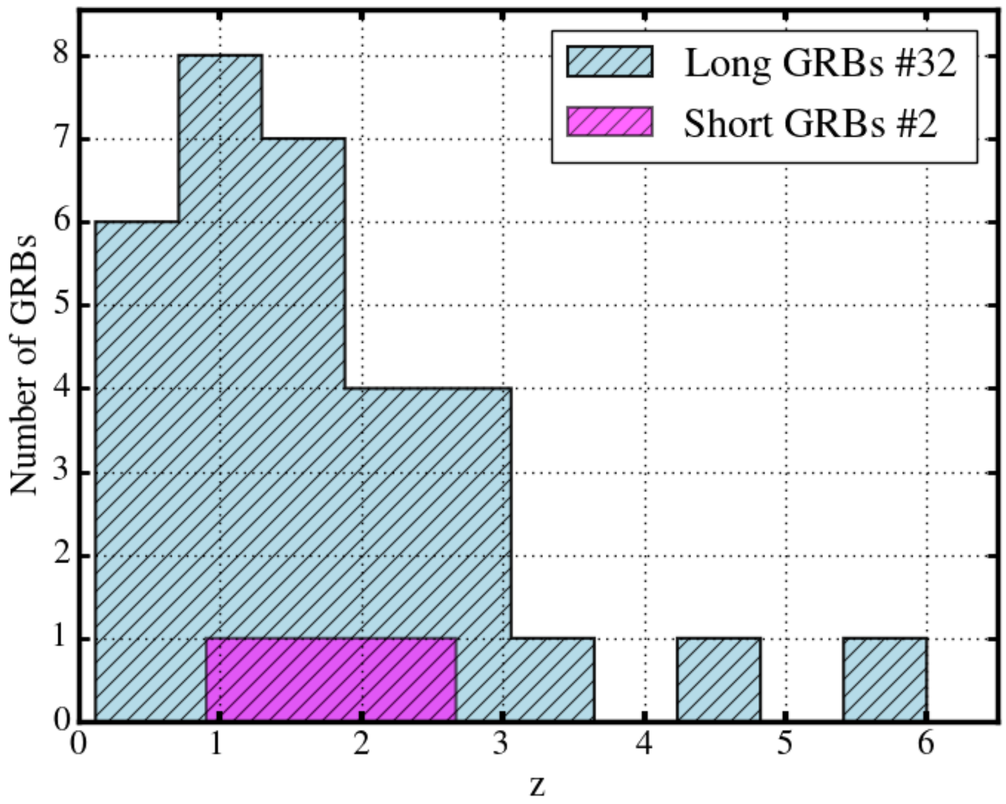
LAT & GBM fluences are correlated



x-axis is GBM 10 keV – 1 MeV fluence

LAT GRB redshift

Large fluence of LAT GRBs is not a distance effect

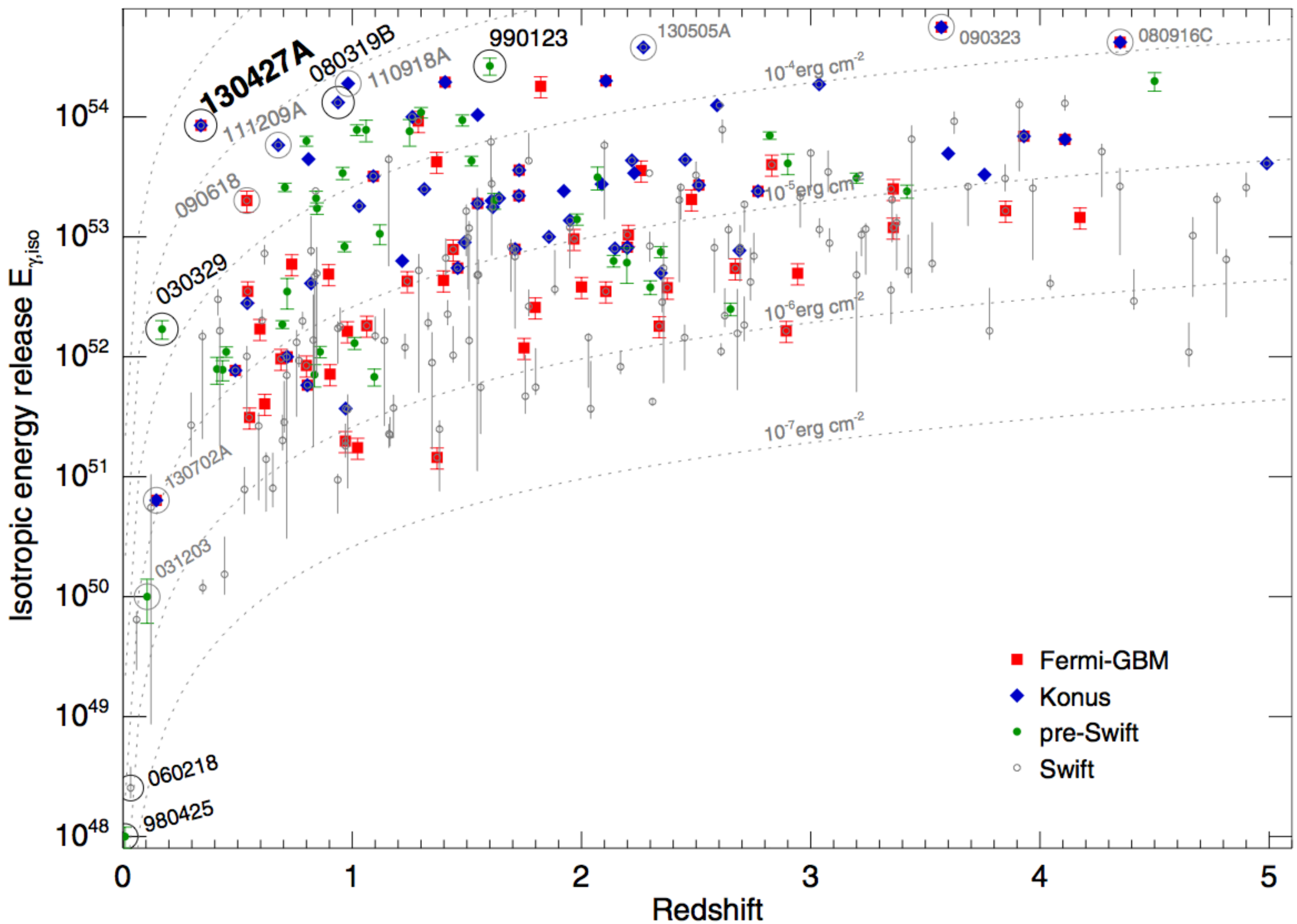


- No particular trend in redshift distribution other than average GRB redshift ~ 1-2
- LAT GRBs are not the closest ones
- Huge energy release

LAT GRB energetic

Up to ≈ 10^{55} erg in isotropic γ rays

LAT is sampling some of the most energetic GRBs



Perley et al. 2014

GRB central engine

Can newly-born magnetars power LAT GRBs?

Rotational energy of a maximally spinning neutron star

$$E_{\rm rot} \sim 3 \times 10^{52} \left(\frac{P}{1\ {\rm ms}}\right)^{-2} \left(\frac{R}{10\ {\rm km}}\right)^{2}\ {\rm ergs}$$

Vacuum/force-free electromagnetic spin-down power of a NS with surface (equatorial) dipole magnetic field (*Spitkovsky 2006)*

$$\dot{E}_{\rm FF} \approx \frac{4\pi^4 B_{\rm dip}^2 R^6}{P^4 c^3} \sim 10^{49} \left(\frac{B_{\rm dip}}{10^{15}\ {\rm G}}\right)^{2} \left(\frac{P}{1\ {\rm ms}}\right)^{-4} \left(\frac{R}{10\ {\rm km}}\right)^{6}\ {\rm ergs/s}$$

Jet beaming factor ~200 (~6 degree opening angle)

Maximum isotropic γ-ray power from magnetar engine ~ 10^{49} – 10^{51} ergs/s

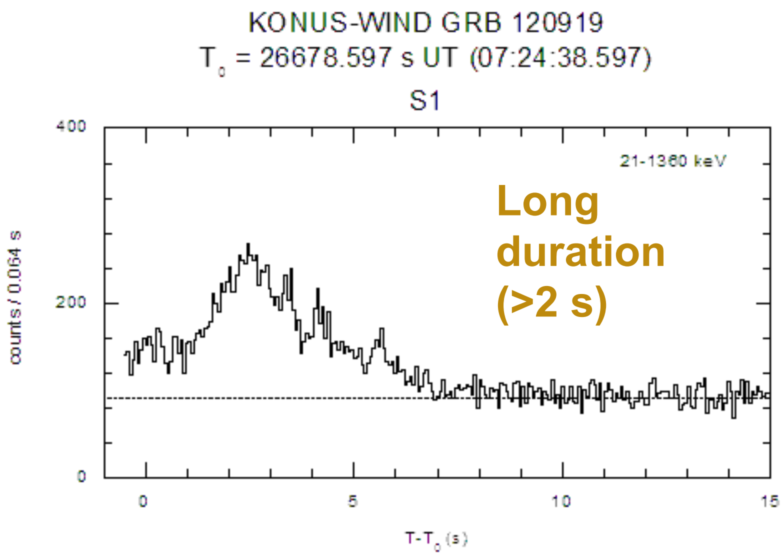
Peak luminosity (ergs/s) of some LAT GRBs:

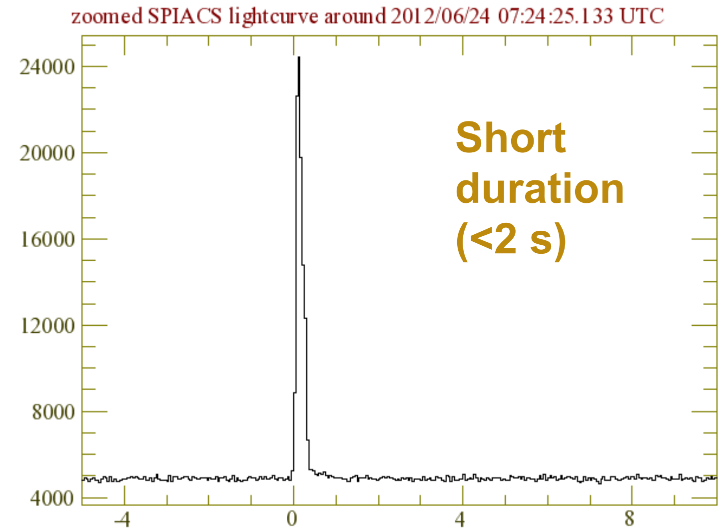
6×10^{53} (080916C), 4×10^{53} (090510, 160625B), etc.

A magnetar engine does not work!

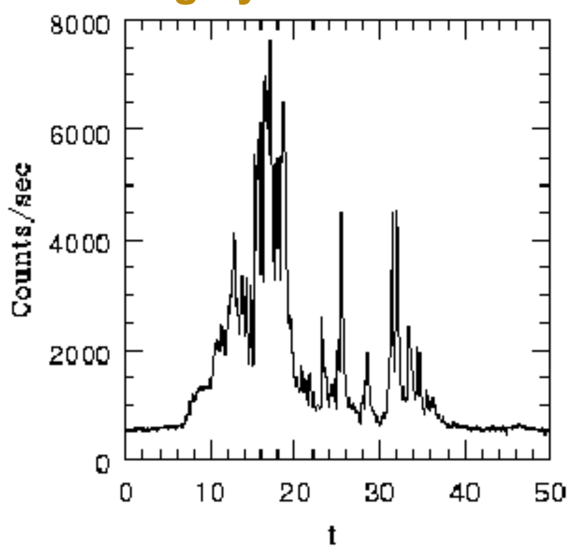
GRB prompt - afterglow emission and theoretical framework

Three features of prompt γ ray emission

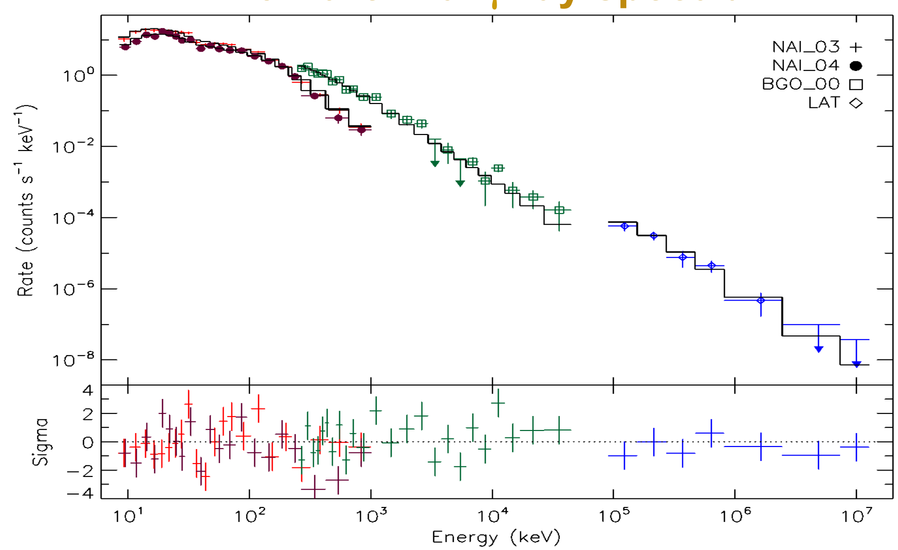




Highly variable flux



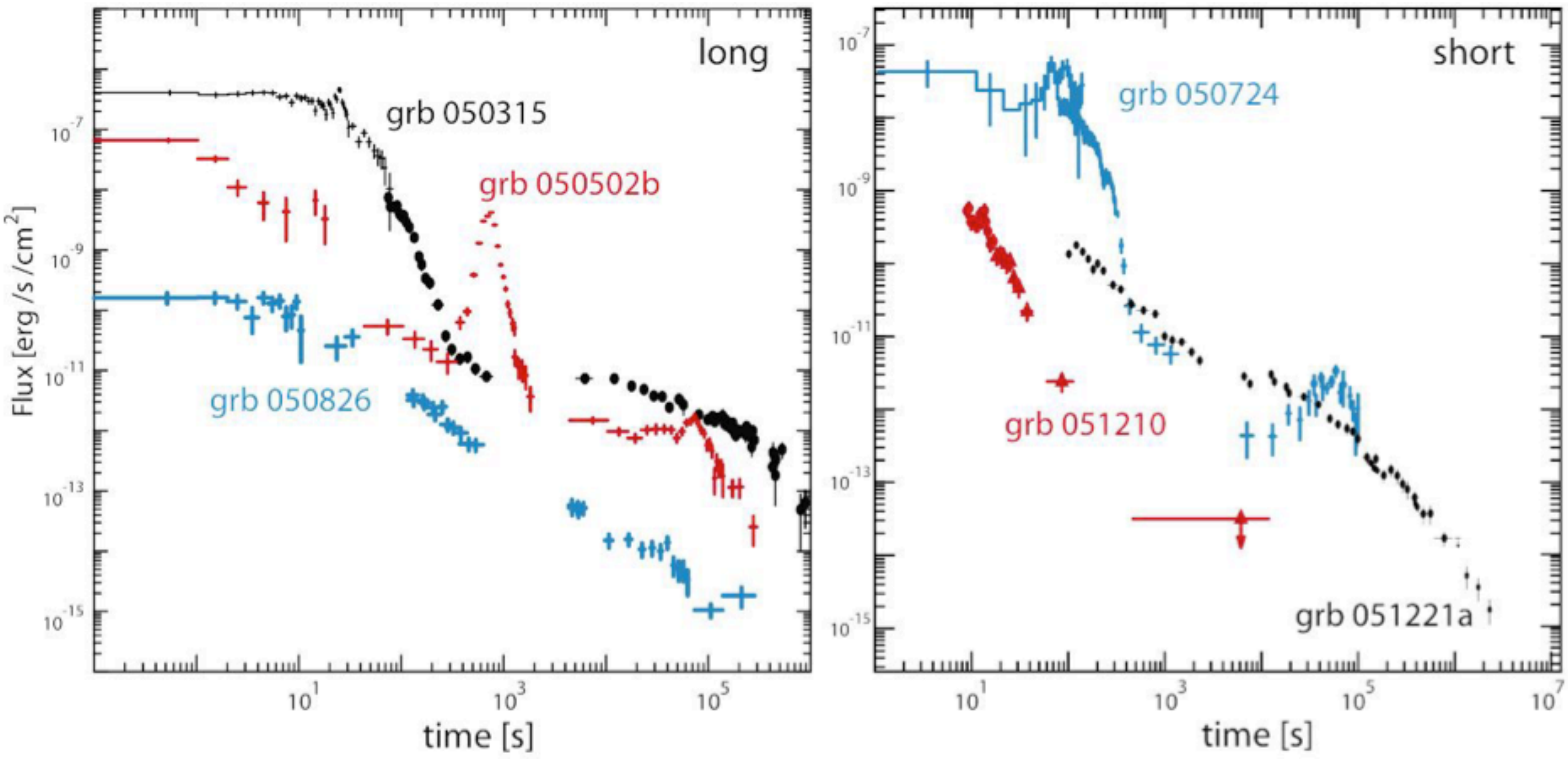
Non-thermal γ-ray spectrum



Long-term evolution: GRB afterglow

Prompt γ-ray emission is followed by longer wavelength emissions, lasting for much longer time scale

X-ray light curves from Swift of long and short GRBs



Prompt and afterglow are not often distinct

Gehrels et al. 2009

GRB fireball shock model

Synchrotron radiation by shock-accelerated electrons for prompt and afterglow emission

Rees, Meszaros, Paczynski, Narayan, Piran, …

Collisions between ejecta material

Decelerating ejecta material

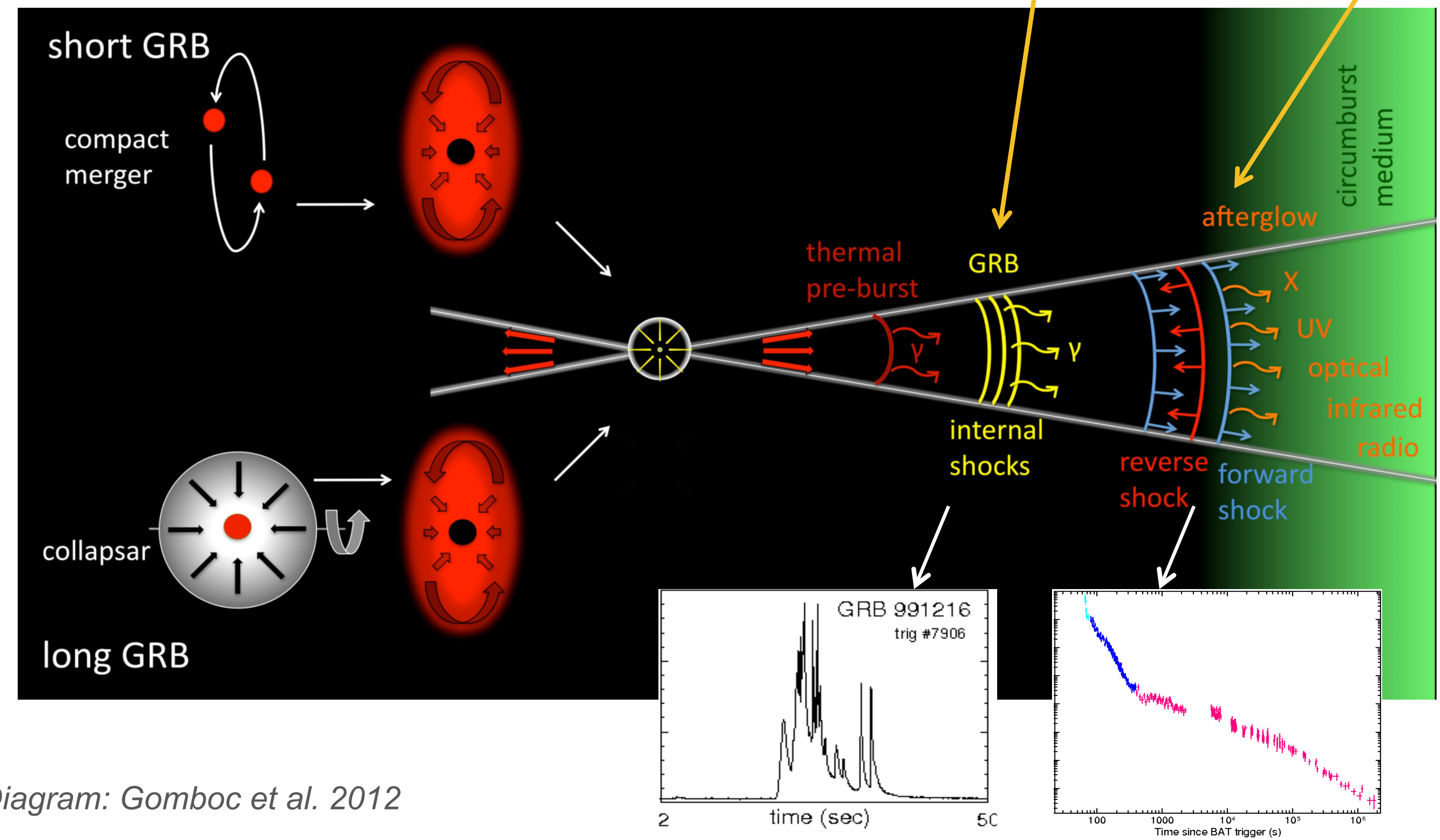
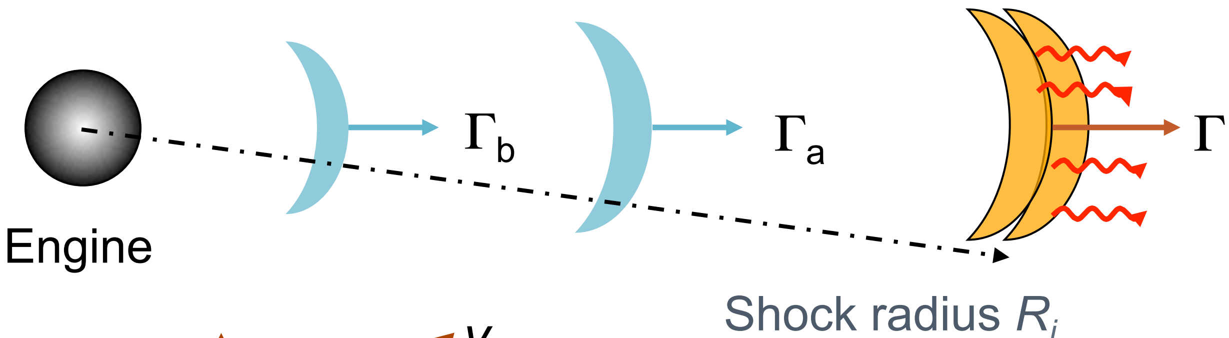


Diagram: Gomboc et al. 2012

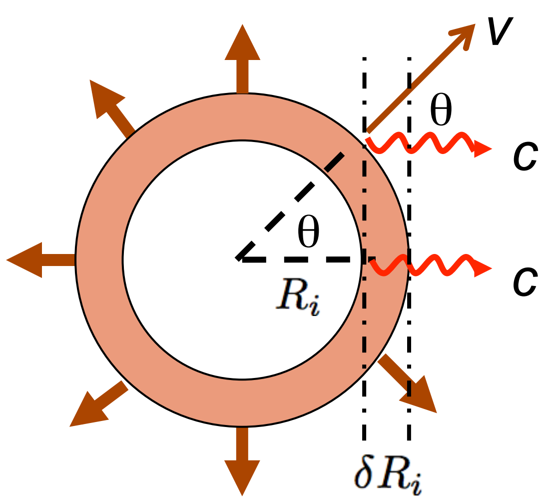
Variability of prompt γ ray emission

Simplest form … Discrete outflow or "shells" with variable speeds or Γ

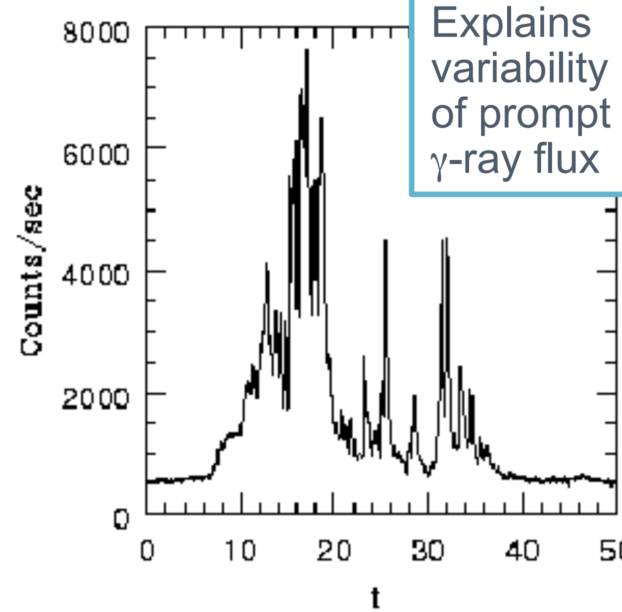
plasma "shells" colliding "shells"



Radiation by electrons that are accelerated in the shocks



Shells can be treated as spherical when $\theta_{jet} > 1/\Gamma$



Explains variability of prompt γ-ray flux

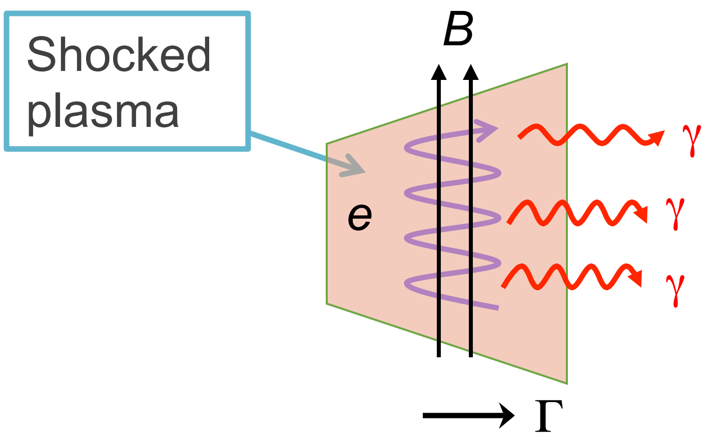
Flux variability time $\delta t = \frac{\delta R_i}{c} = \frac{1}{c}(R_i - R_i \cos\theta)$

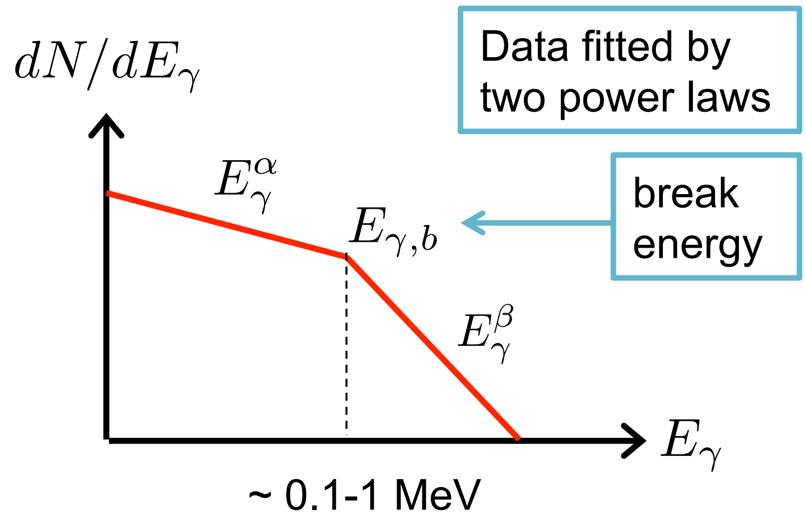
Internal shock radius $R_i \simeq 2\Gamma_i^2 c\delta t \approx 10^{12}\text{–}10^{14}$ cm

Synchrotron model of prompt γ ray spectra

Most popular model for MeV γ

Synchrotron radiation by a population of shock-accelerated electrons





Typical values from data: α ~ -1 and β ~ -2

Fermi shock-accelerated electron spectrum

$$\frac{dN}{dE_e} \propto E_e^{-q}$$

Synchrotron radiation spectrum

$$\frac{dN}{dE_\gamma} \propto E_\gamma^{-(q+2)/2} \propto E_\gamma^{-2} \ ; \ q = 2$$

γ spectrum below $E_{\gamma,b}$ from synchrotron theory

$$\frac{dN}{dE_\gamma} \propto E_\gamma^{-2/3} \propto E_\gamma^{-3/2}$$

Some tension with data giving α < -2/3

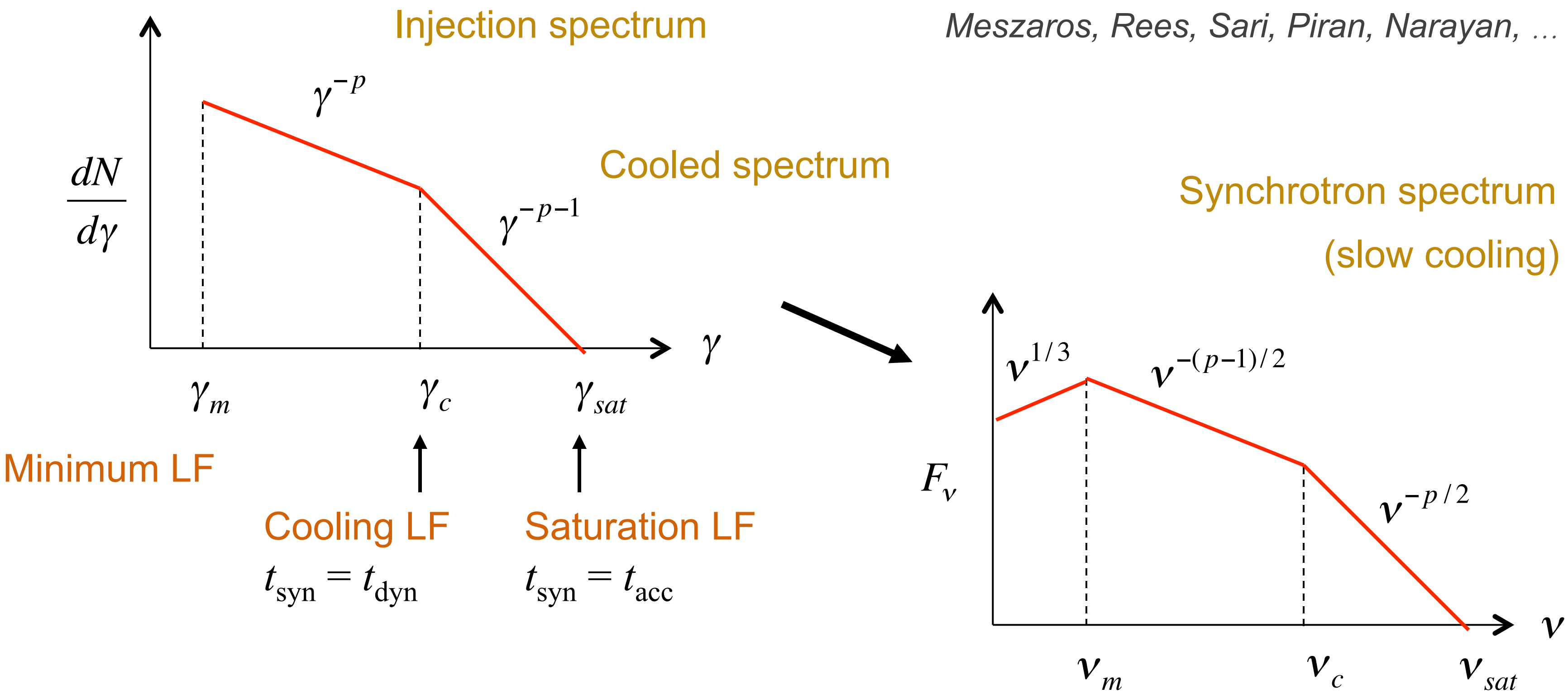
Preferred by theory

Synchrotron model for broadband afterglow

GRB ejecta drive a blast-wave evolving with time *Blandford & McKee 1976*

Synchrotron radiation by shocked electrons

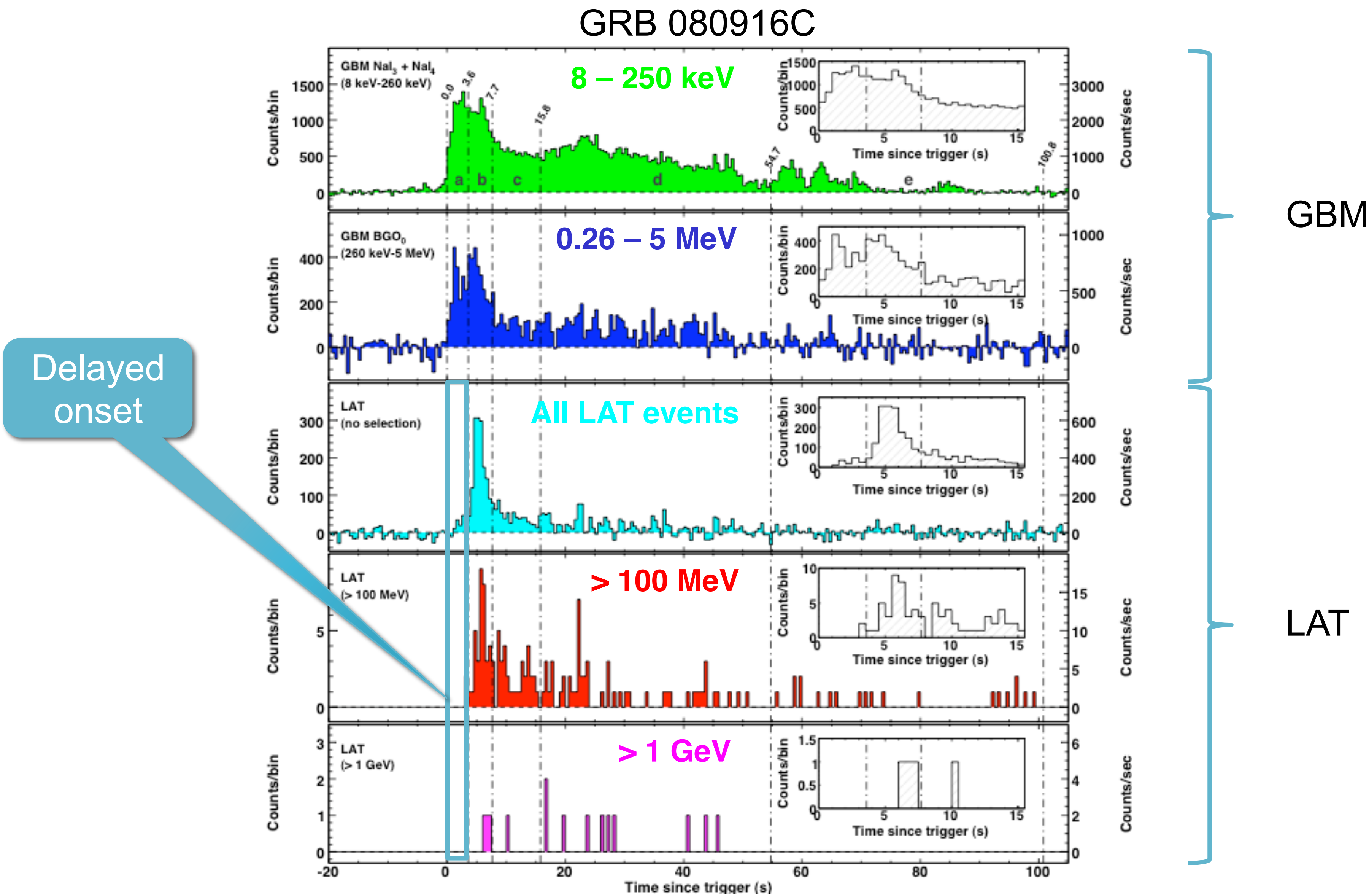
Meszaros, Rees, Sari, Piran, Narayan, …



- Fast (slow) cooling γ_m > (<) γ_c or ν_m > (<) ν_c
- All break frequencies evolve with time as the *B* field and Γ do

Characteristics of HE emission detected by Fermi-LAT

Delayed onset of HE emission

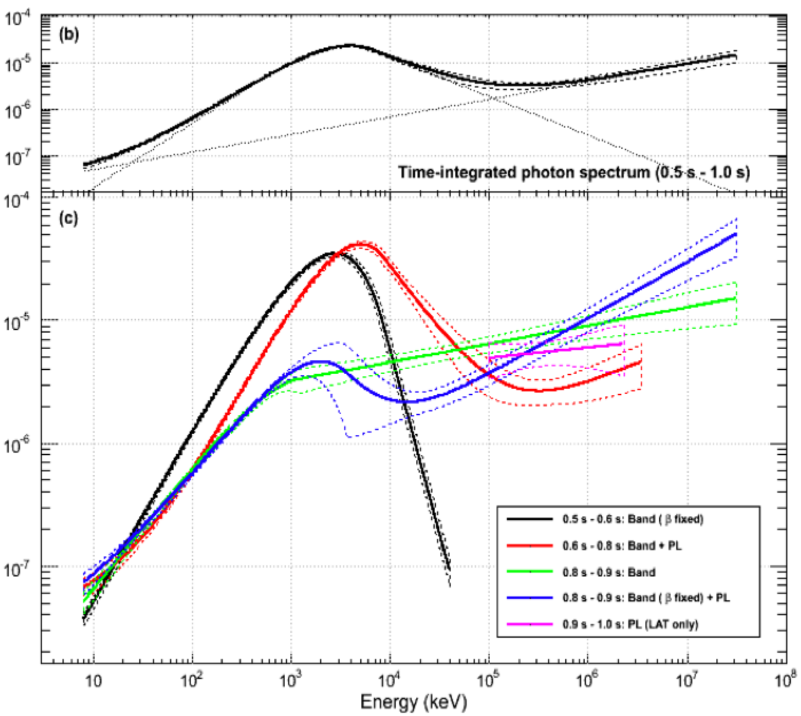


Spectral variation

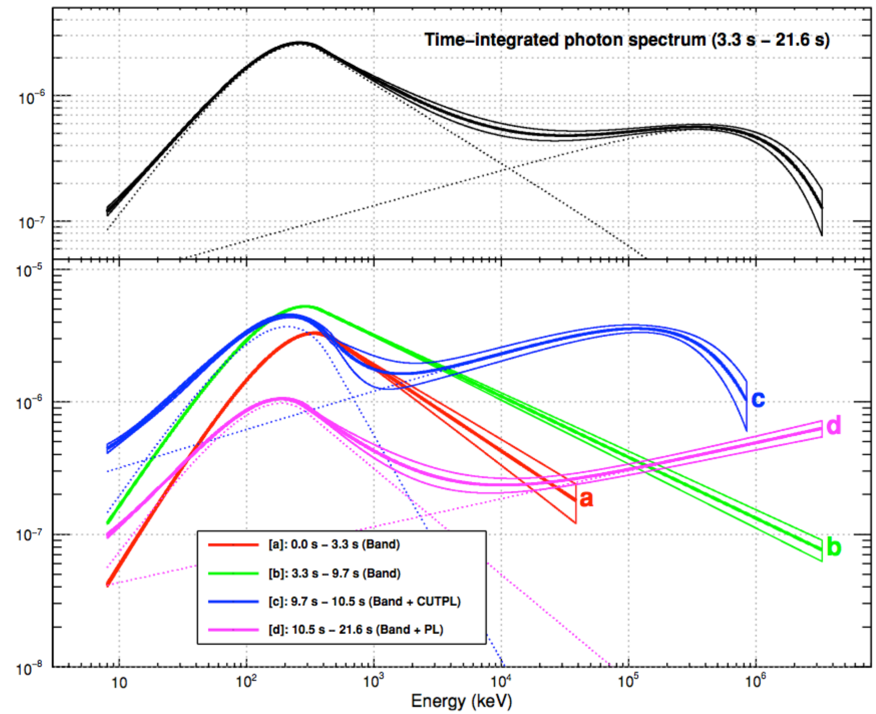
Energy spectra at early time – prompt phase

Additional component is present in both long and short bursts, dominates at GeV energies

GRB 090510 (short)



GRB 090926A (long)

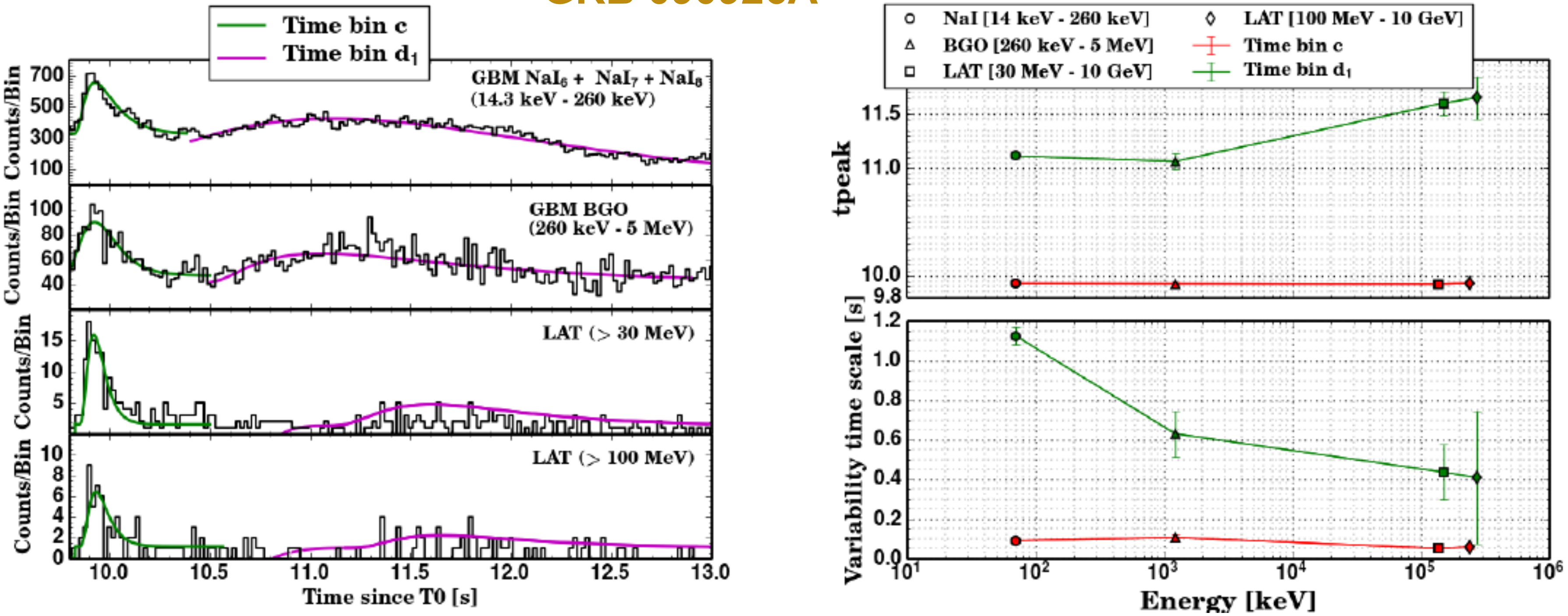


top panels: time-integrated spectra, *bottom panels:* time-resolved spectra

Early time variability in HE emission

Evidence of fluctuating LAT emission in a few GRBs during prompt phase

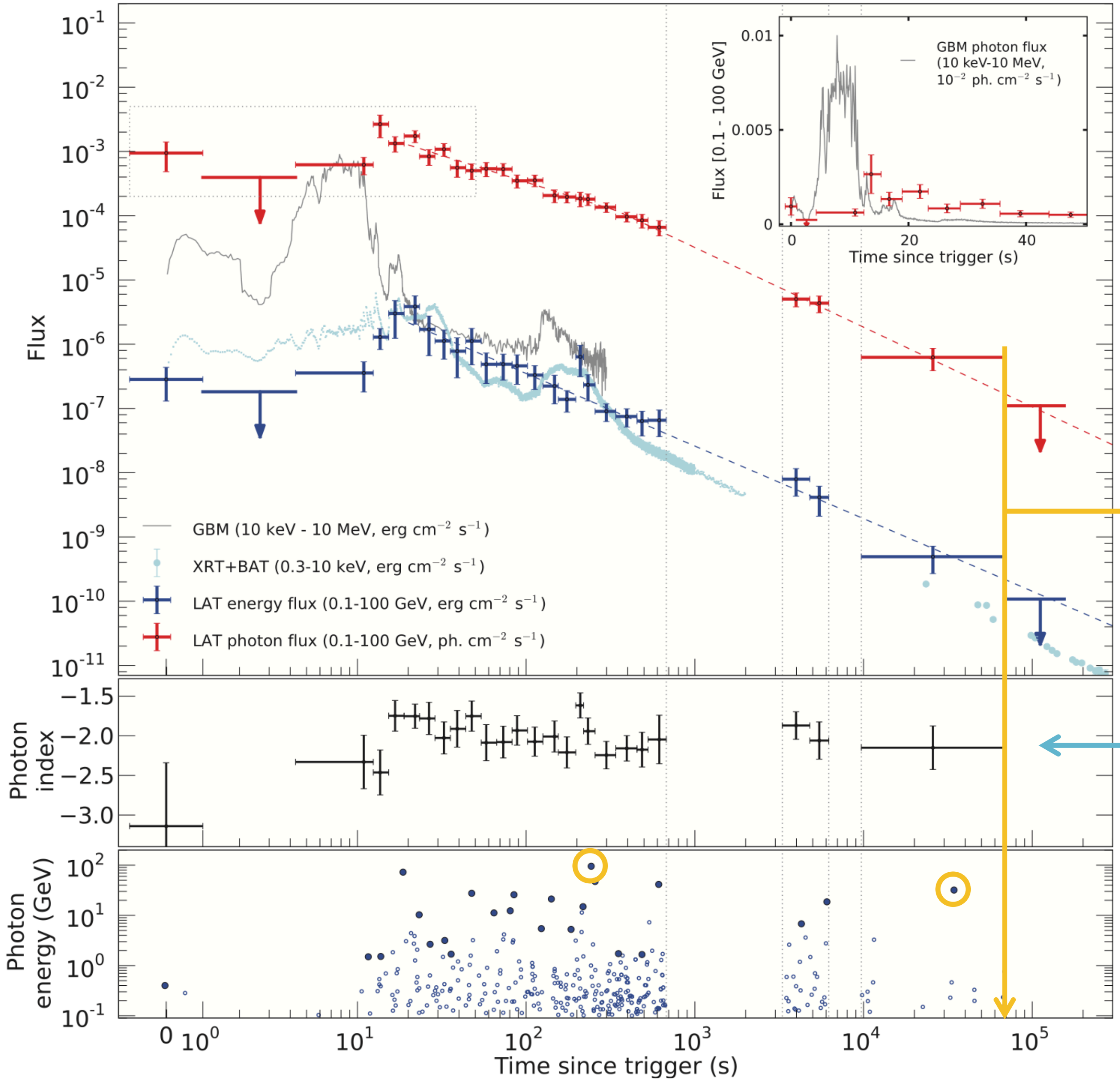
GRB 090926A



Light curves fitted with rising+falling functions of time
variability time is half width at half maximum

Yassine et al. 2017

Temporally extended HE emission



GRB 130427A

Longest-lasting GRB at >100 MeV

20 hours!

power-law HE spectrum

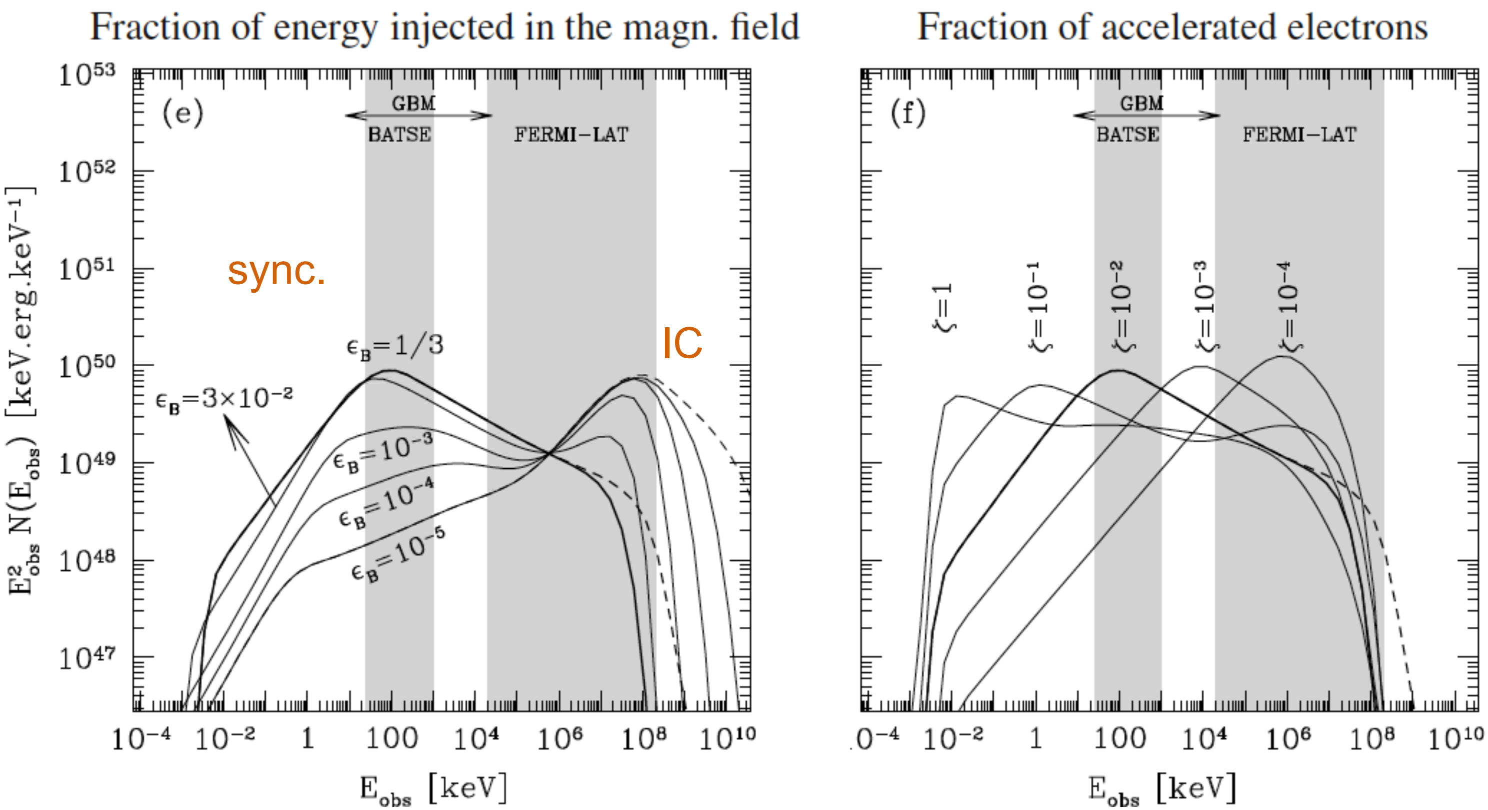
95 GeV γ at 244 s

32 GeV γ at 34.3 ks

Delayed onset and additional HE emission component
Prompt models

Inverse Compton for HE emission

- Low magnetization of the jet allows dominant IC emission
- If only a small fraction of the electrons is given the shock energy, they emit at HE

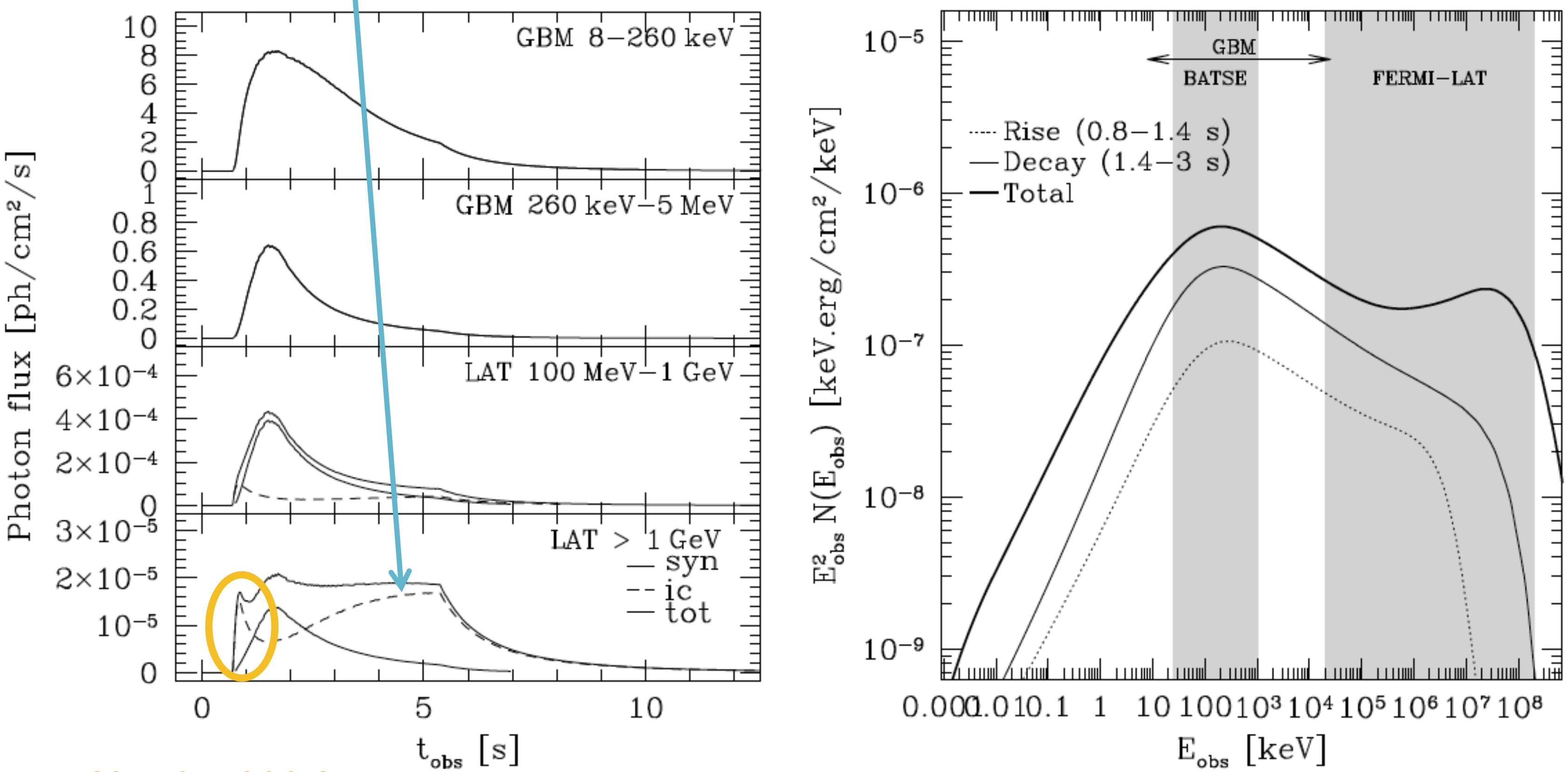


Bosnjak, Daigne & Dubus 2009

Inverse Compton for HE emission

- IC emission at >1 GeV energies may appear delayed by a pulse width

$\epsilon_B = 5 \times 10^{-3}$, $\epsilon_e = 1/3$, $\zeta = 2 \times 10^{-3}$ and $p = 2.5$



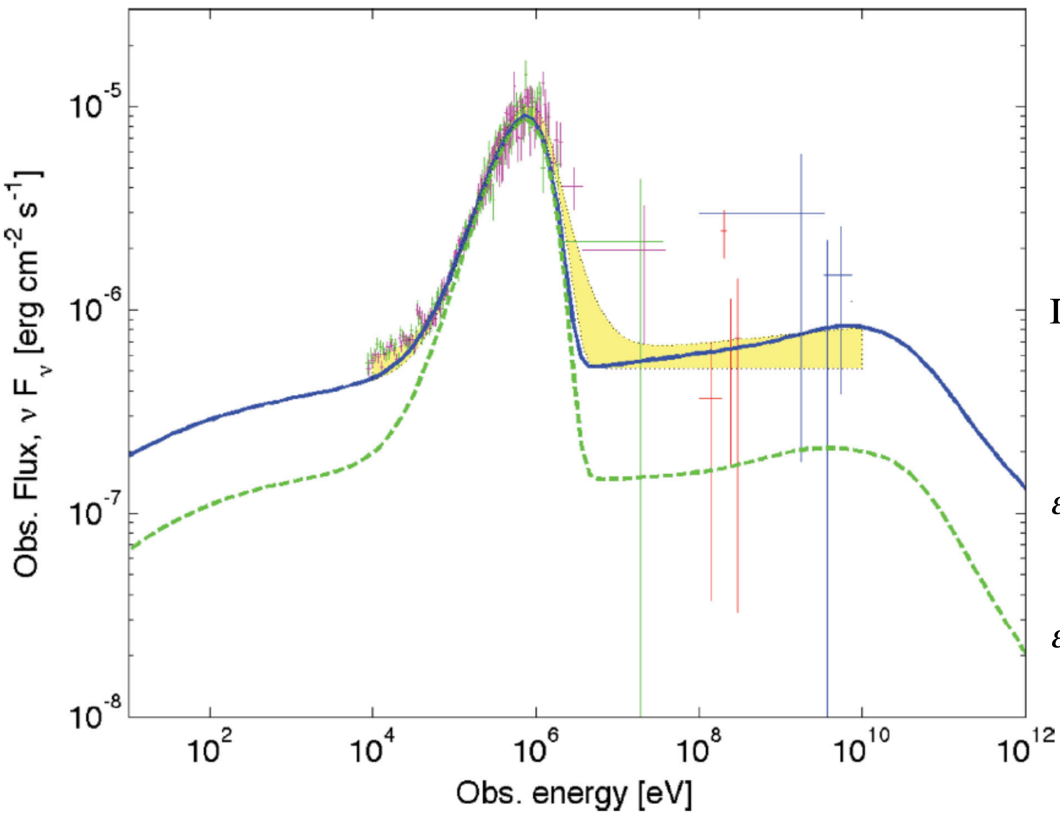
Need to hide!

Bosnjak, Daigne & Dubus 2009

Photospheric + IC for HE emission

- Multicomponent blackbody - proxy for thermal emission from jet photosphere
- IC of thermal photons in the photosphere – HE emission

GRB 090902B



$\Gamma = 910$

$\varepsilon_e = 0.5$

$\varepsilon_e = 0.17$

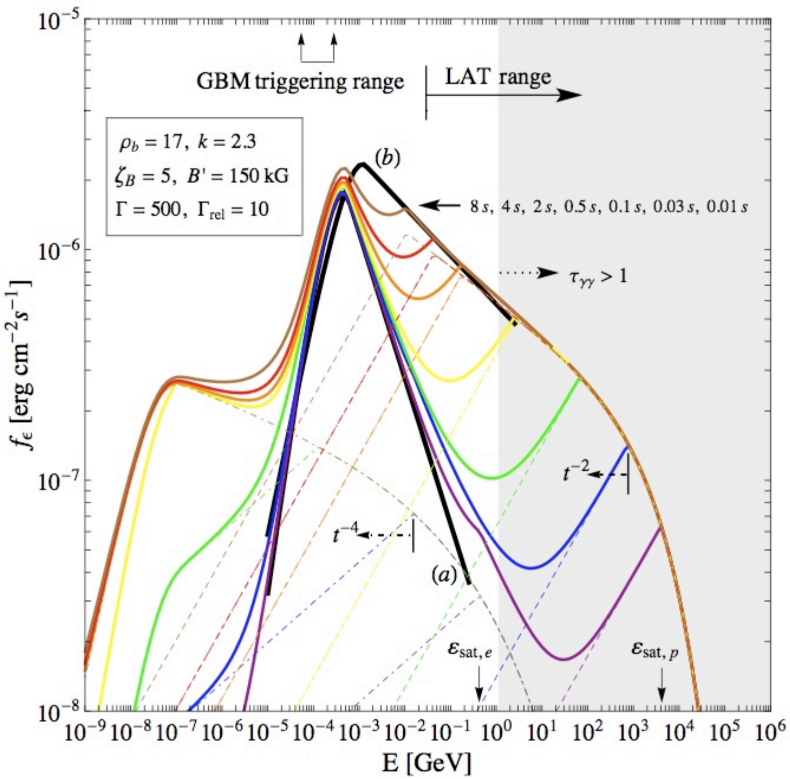
Pe'er et al. 2011

No delay for HE emission is expected!

Hadronic model for HE emission

Proton-synchrotron and $\gamma\gamma \rightarrow e^+e^-$ cascade synchrotron radiation

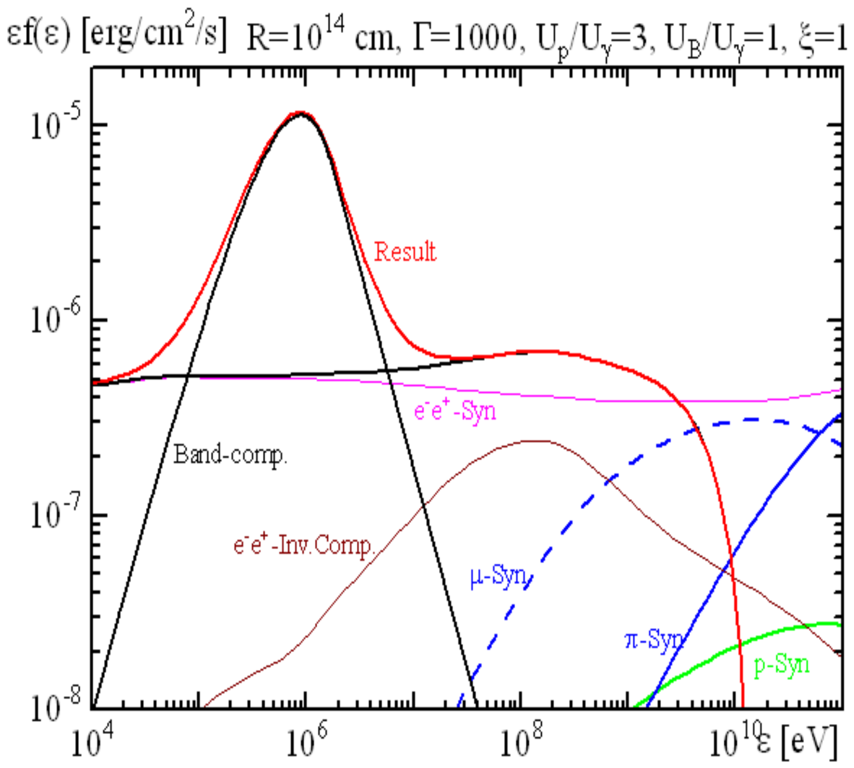
GRB 080916C



Razzaque, Dermer & Finke 2009

Photohadronic cascade and secondary synchrotron, $\pi^0 \rightarrow \gamma\gamma$

GRB 090902B

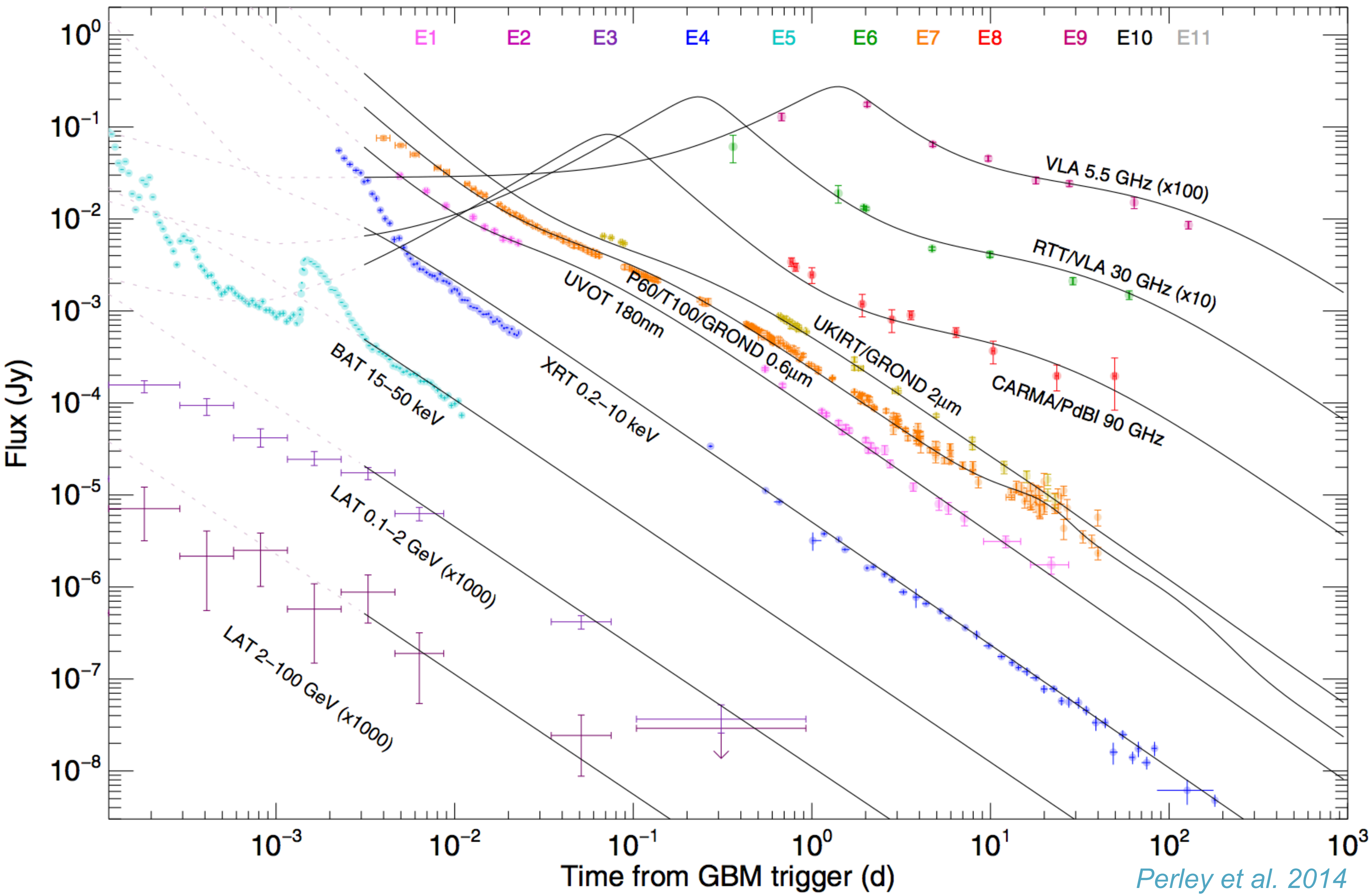


Asano, Meszaros & Guiriec 2009

Total energy needs to be ~100 times or larger than observed in γ

Delayed onset, additional component and extended HE emission
Afterglow models

Broad-band afterglow of GRB 130427A



Perley et al. 2014

Afterglow model for HE emission

A highly relativistic jet can produce very early afterglow: ~ few seconds

$$t_{\rm dec} \sim 2\,(1+z)\left(\frac{E_{\rm kin,iso}}{10^{55}\ {\rm ergs}}\right)^{1/3}\left(\frac{n_{\rm ISM}}{1\ {\rm cm}^{-3}}\right)^{-1/3}\left(\frac{\Gamma}{1000}\right)^{-8/3}\ {\rm s}$$

Synchrotron radiation from the very early afterglow

→ origin of >100 MeV emission in LAT (*Kumar & Barniol-Duran 2009*)

- Explains time delay with keV-MeV emission and longevity of LAT emission
- Additional spectra component detected at early time

- Baryon-loading/entropy:

$$\eta = \frac{L_{\rm k,iso}}{4\pi R^2 c n m_p}$$

Ratio of energy to mass outflow rates

- Critical radiation entropy:

$$\eta_{\rm rad} = \left(\frac{L_{\rm k,iso}\sigma_T}{4\pi R_0 m_p c^3}\right)^{1/4} \approx 1800\left(\frac{L_{55}}{R_7}\right)^{1/4}$$

Coupling between material and radiation

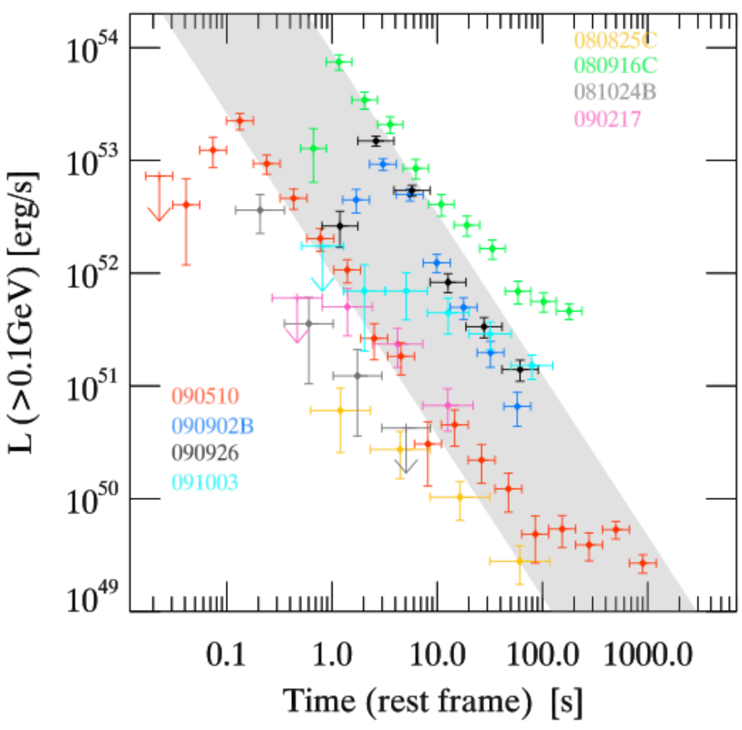
Coasting baryonic fireball Lorentz factor $\Gamma \leq \eta_{\rm rad}$

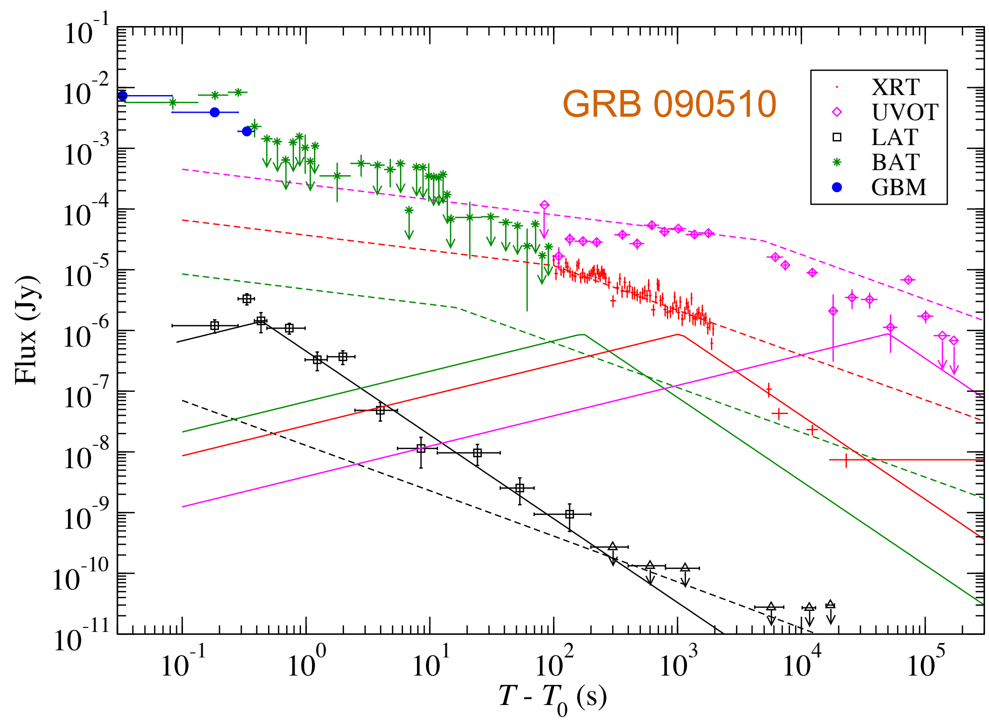
Leptonic e^+e^- fireball or magnetic fireball can have even higher Γ

Afterglow model for HE emission

Evolution of LAT emission compared with electron-synchrotron radiation from a **radiative** fireball

Fit to multiwavelength (optical-GeV) data with **e- and p-synchrotron radiation** from an adiabatic fireball





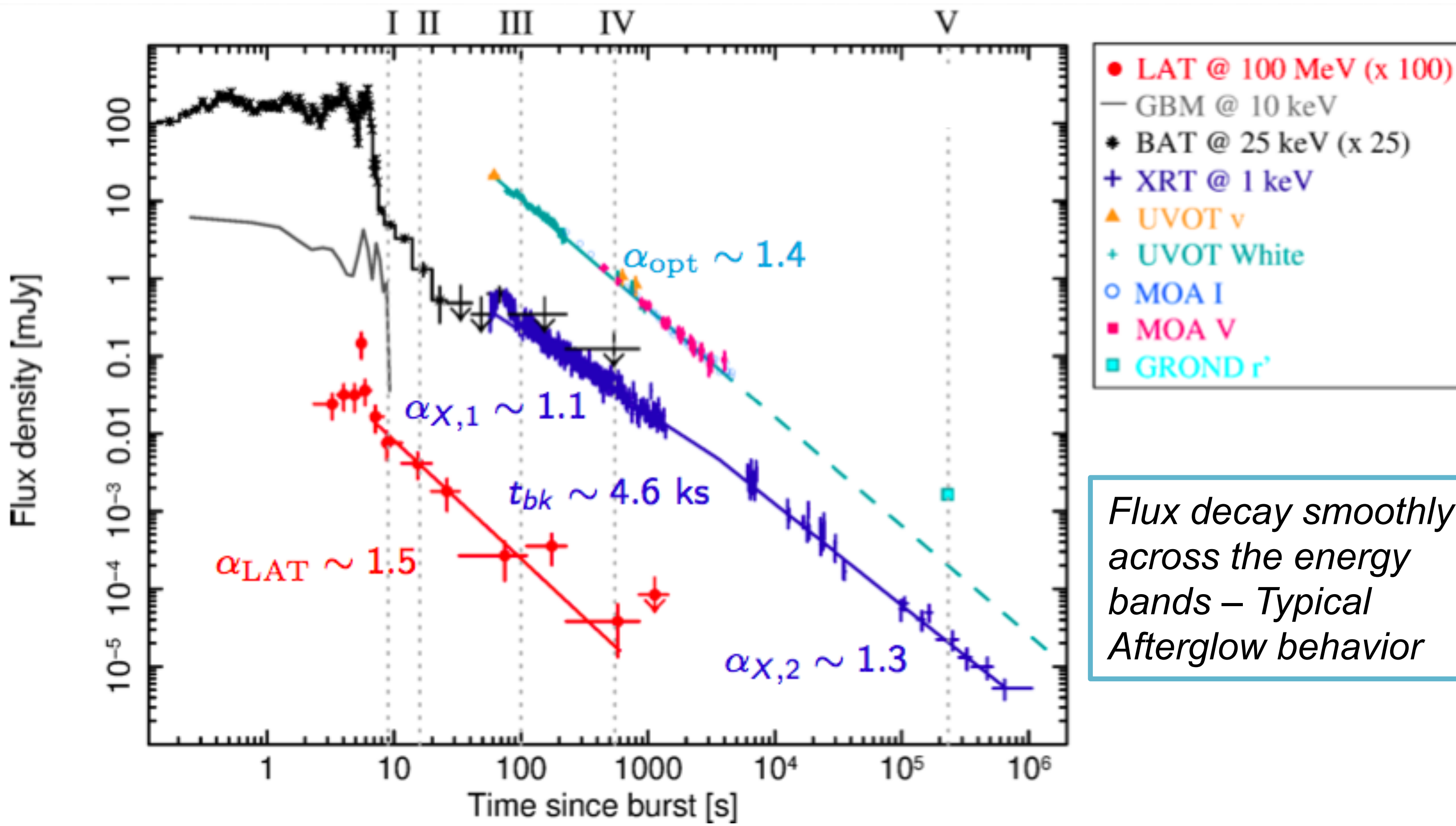
Ghisellini et al. 2010

Razzaque 2010

Afterglow of GRB 110731A

First long GRB with multi-wavelength coverage from trigger to afterglow

All light curves peak at ~T0+5.5 s → Evidence for afterglow onset



Flux decay smoothly across the energy bands – Typical Afterglow behavior

GRB 110731A broadband SED

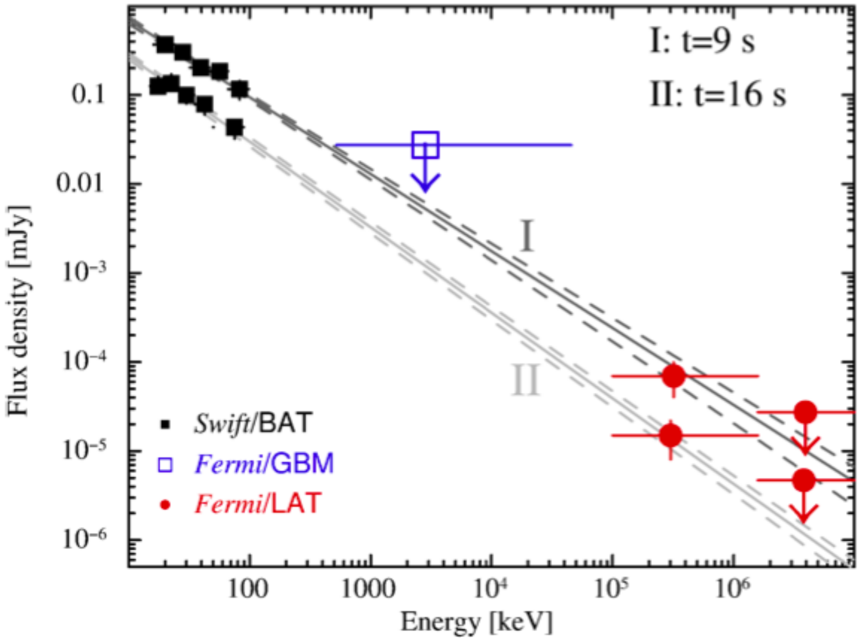
- Temporally extended HE emission is afterglow
- Very early afterglow onset time < T_0+8 s

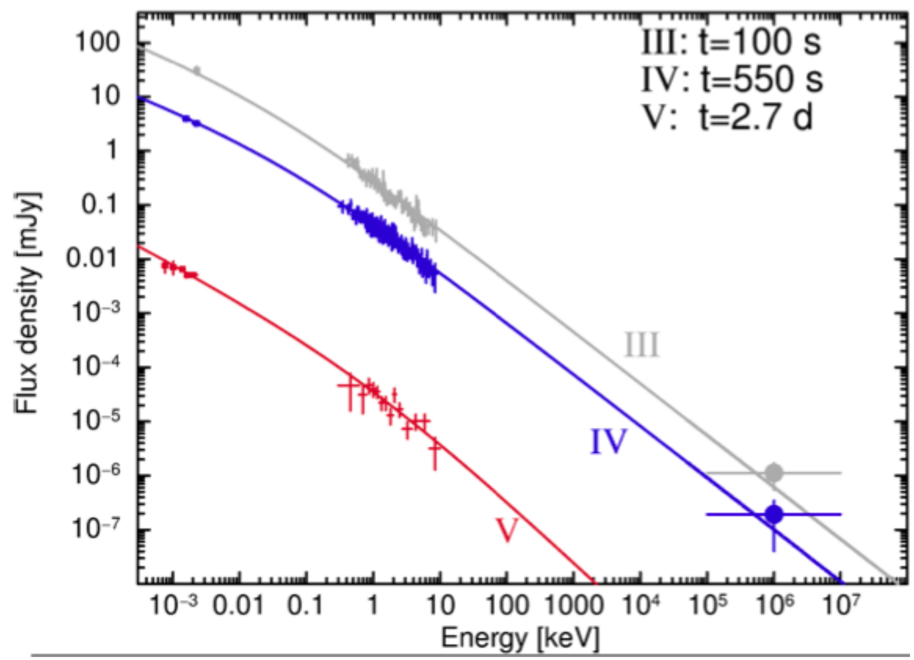
Detailed modeling of lightcurves and broadband spectra

Fast-cooling

slow-cooling

Ackermann et al. 2012

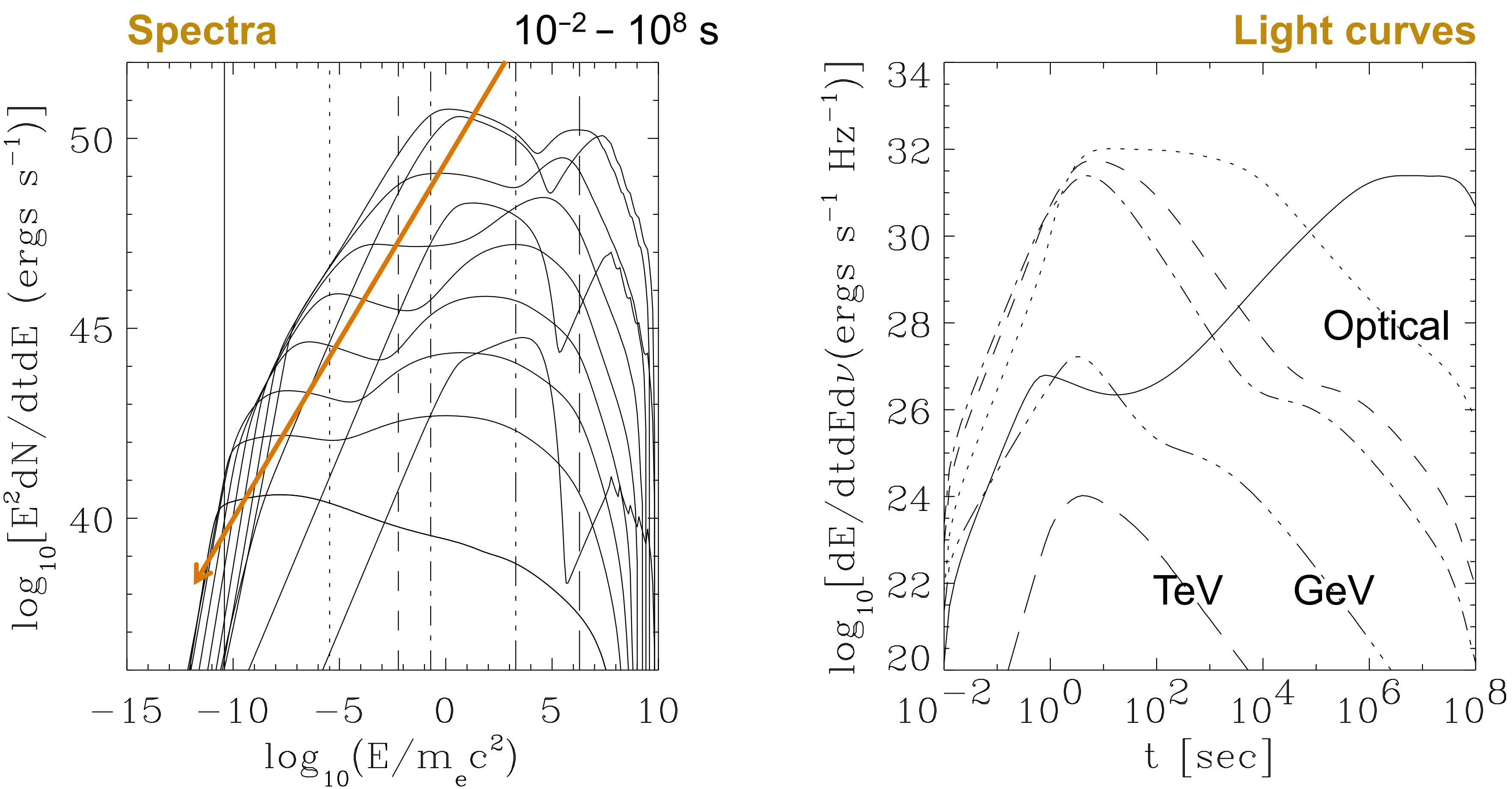




Synchrotron emission from an adiabatic blast-wave in wind

SSC emission in afterglow

Expected for blast-wave with very weak magnetic field → Not detected yet



$\epsilon_e = 0.5 \ \epsilon_B = 10^{-4}$

Dermer, Chiang & Mitman 2000

Conclusions

- Fermi-LAT GRBs are high in γ ray fluence
    - LAT fluence appears to be correlated with the GBM fluence
        - Favors an afterglow interpretation of HE emission
- Fermi-LAT GRBs are among the most energetic bursts
    - High luminosity of many of those cannot be explained with magnetar model
    - A black hole engine is favored
- New and interesting features in high energy (≥100 MeV) emission
    - Delayed onset, additional spectral components, extended emission
- Models of high-energy emission
    - Prompt phase: inverse-Compton, proton-synchrotron, photo-hadronic
        - Cannot explain extended emission, smooth feature
    - Afterglow phase: synchrotron radiation
        - Currently favored