Leptonic-Hadronic Modeling of Extended High-Energy Emission from Fermi LAT GRBs

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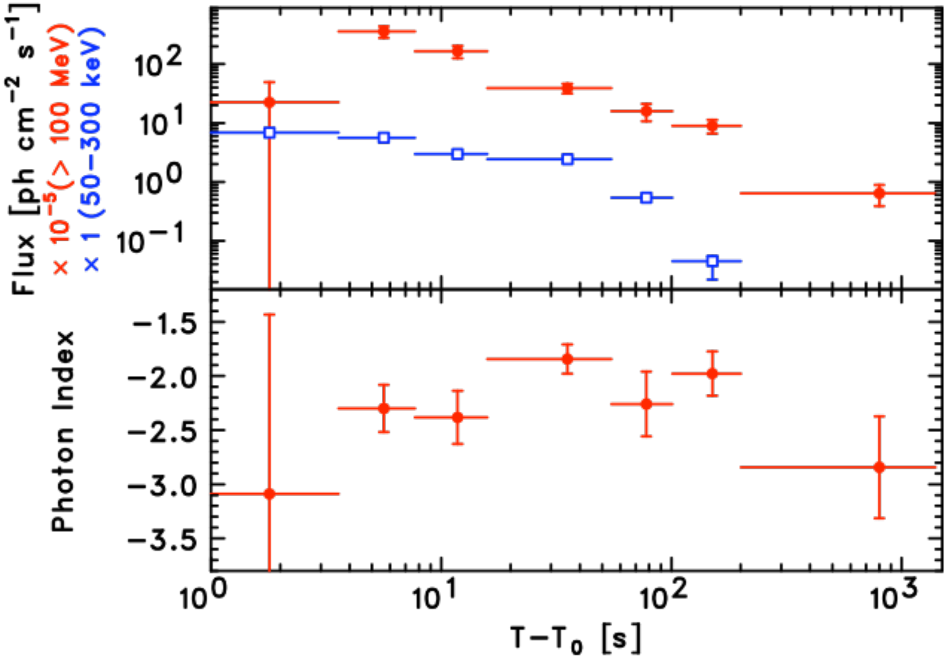
Gamma Ray Bursts Conference, Nov 1-4, Annapolis, MD

Extended HE Emission from LAT GRBs

Bright LAT GRBs show significant high energy emission extending after the low energy emission disappear below detection threshold



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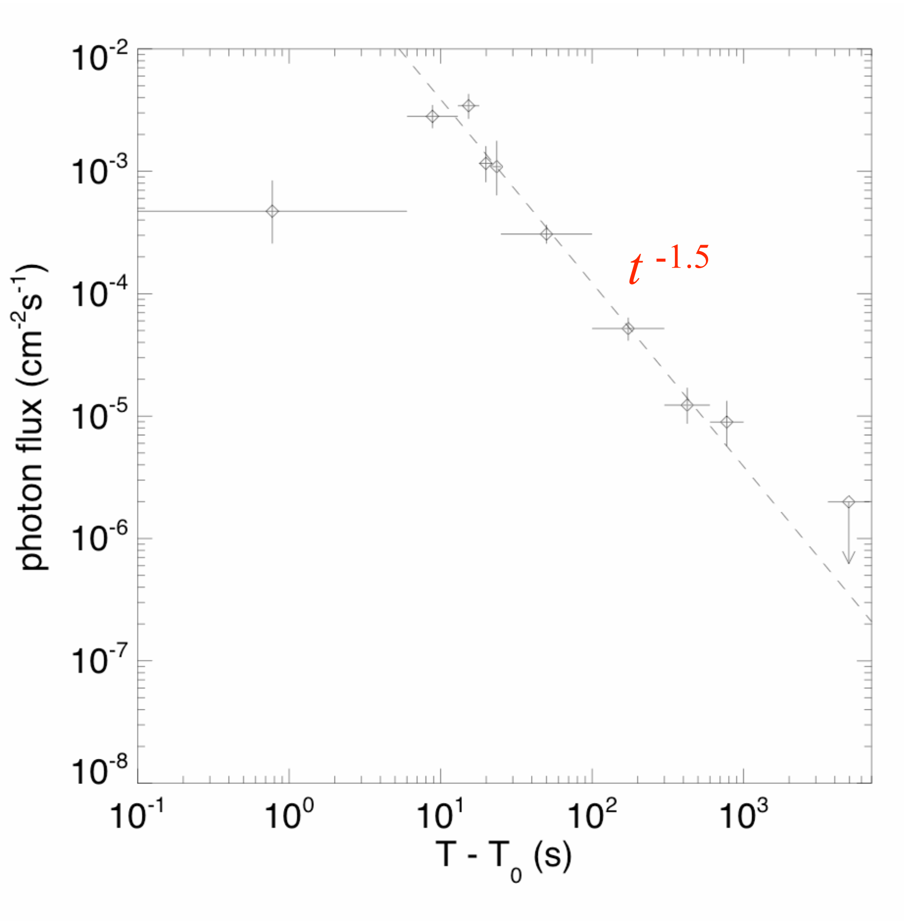
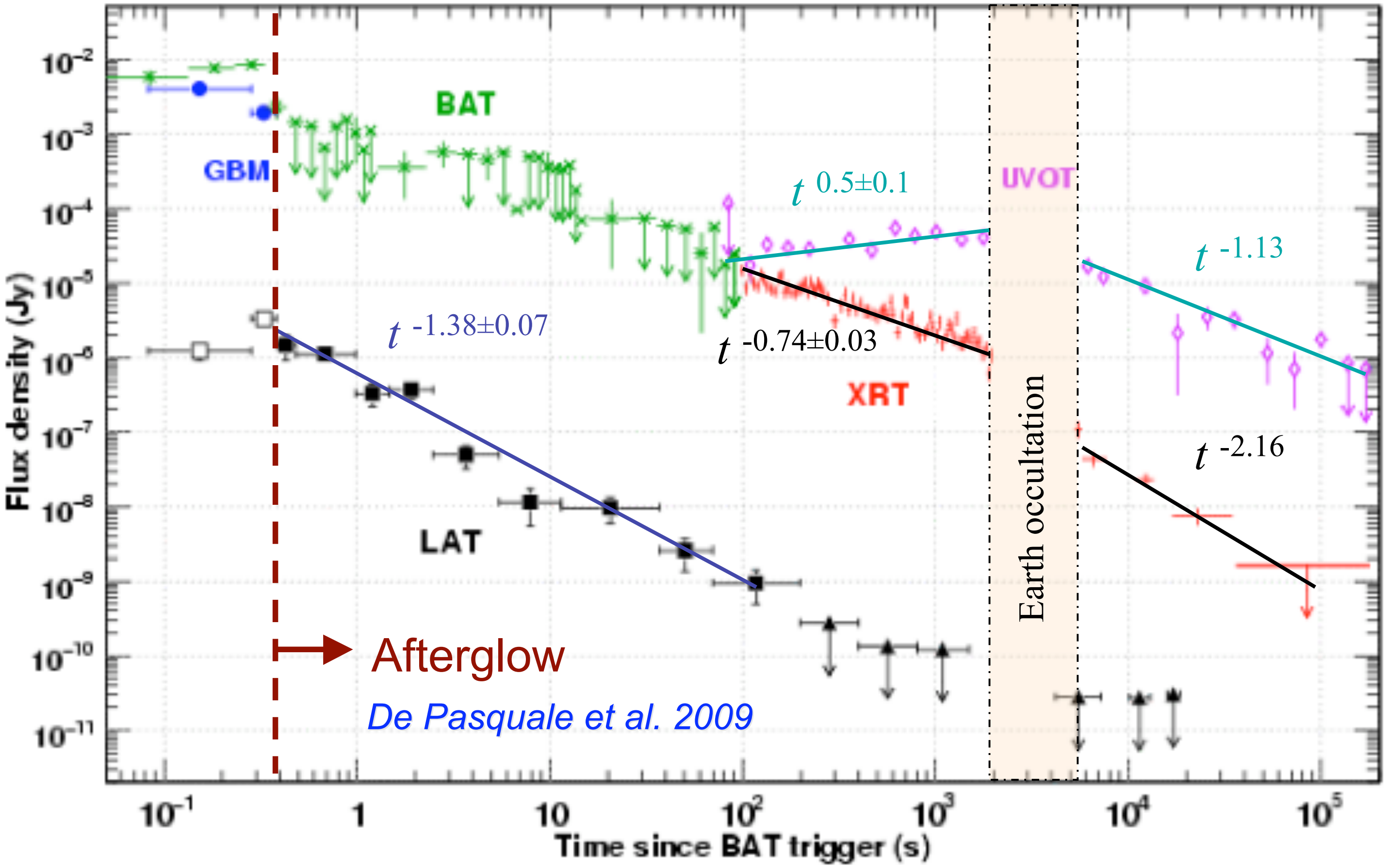


090902B

Extended Emission from GRB 090510

Multi-wavelength light curves in γ ray, x ray and UV

Smooth power-law evolution of the fluxes are compatible with afterglow model



De Pasquale et al. 2009

GRB Afterglow - Blast Wave Evolution

Adiabatic blast wave decelerating in uniform density medium

Blandford-McKee 1976

- Relationship between t, Γ and R : $R = 2\Gamma^2 act(1+z)^{-1}$

$a = 1$ for coasting
$a = 4$ after decel.

- Deceleration time: $t_{dec} \approx 1.9(1+z)(E_{55}/\mathrm{n})^{1/3}\Gamma_3^{-8/3}$ s

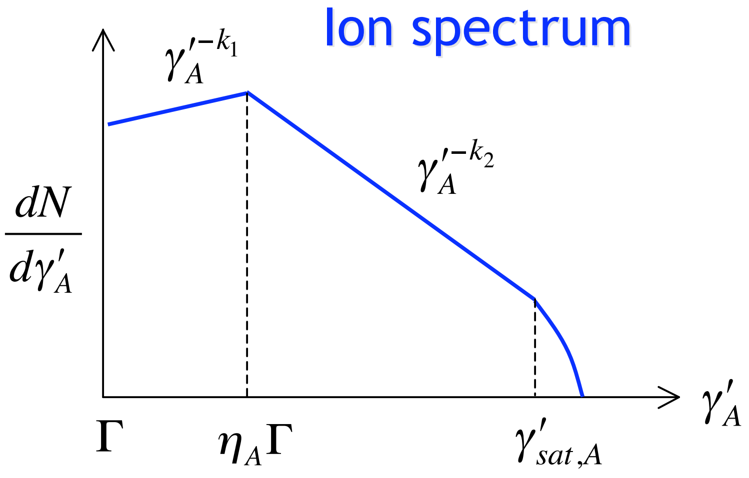
Total KE in blast wave = swept-up material

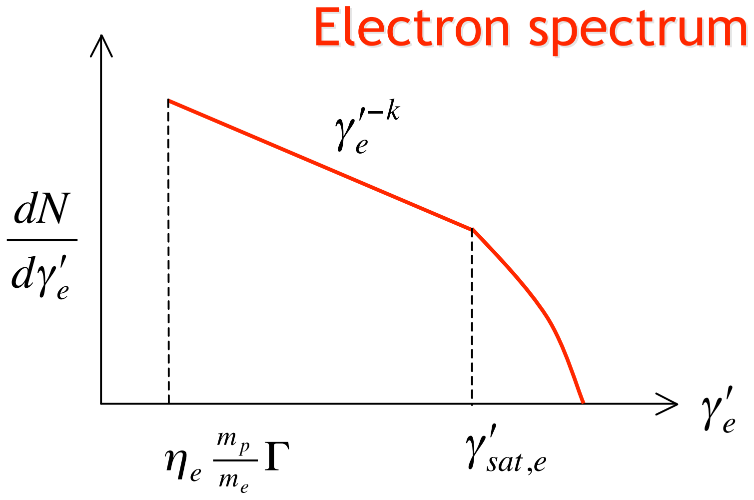
- Bulk Lorentz factor: $\Gamma \approx 763(1+z)^{3/8}(E_{55}/\mathrm{n})^{1/8} t_s^{-3/8}$
- Blast wave radius: $R \approx 1.4 \times 10^{17}(1+z)^{-1/4}(E_{55}/\mathrm{n})^{1/4} t_s^{1/4}$ cm
- Energy injection rate in the forward shock: $e_{shock} = 4\pi n m_p c^2 \Gamma^2$
- Magnetic field in the FS: $B' \approx 300(1+z)^{3/8} \varepsilon_B^{1/2} (E_{55}\mathrm{n}^3)^{1/8} t_s^{-3/8}$ G

Leptonic-Hadronic Synchrotron Model

Both electrons and ions are accelerated in the Forward shock

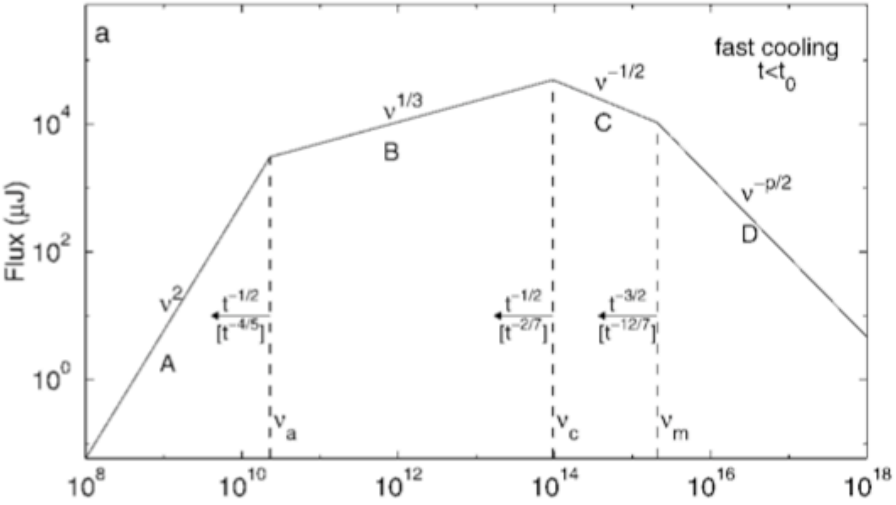
- Total isotropic-equivalent jet energy : $E_{\mathrm{k,iso}} > E_{\gamma,\mathrm{iso}} \cong 10^{53}$ erg
- Constant density surrounding medium : $n_{\mathrm{ISM}} \cong 1\ \mathrm{cm}^{-3}$
- Jet deceleration time scale : $t_{\mathrm{dec}} \leq 1$ s and $\Gamma_0 \geq 1000$


Ion spectrum

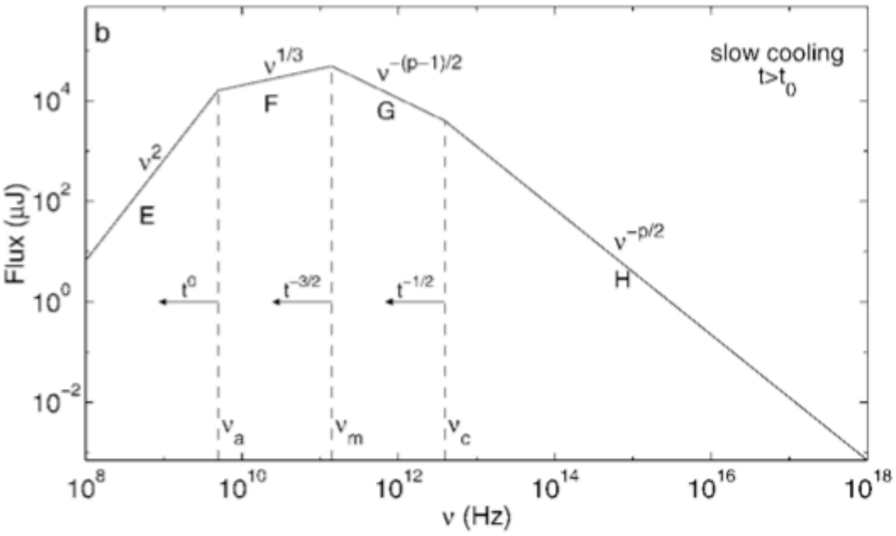

Electron spectrum

- Crucial parameters: ε_B; η_A, η_e, k and k_2 are fitted from data
- Fraction of jet energy: ε_A and ε_e are calculated from required spectra

GRB Afterglow - Synchrotron Spectra



Sari, Piran & Narayan 1998



Fast cooling : $\nu_m > \nu_c$

$F_\nu \propto \nu^{-\beta} t^{-\alpha}$ closure relations

$$\nu_c < \nu < \nu_m : F_\nu \propto \nu^{-1/2} t^{-1/4}$$

$$\nu > \nu_m > \nu_c : F_\nu \propto \nu^{-p/2} t^{-(3/4)(p-2/3)}$$

p-particle spectral index : $\frac{dN}{dE} \propto E^{-p}$

Slow cooling : $\nu_c > \nu_m$

$F_\nu \propto \nu^{-\beta} t^{-\alpha}$ closure relations

$$\nu_m < \nu < \nu_c : F_\nu \propto \nu^{-(p-1)/2} t^{-(3/4)(p-1)}$$

$$\nu > \nu_c > \nu_m : F_\nu \propto \nu^{-p/2} t^{-(3/4)(p-2/3)}$$

Modeling GRB 090510 Data

Use closure relations $F_\nu \propto \nu^{-\beta} t^{-\alpha}$ to determine β and k or k_2

Note: e-synchrotron model alone cannot satisfy the closure relations

- ☐ XRT light curve: $t^{-0.74\pm0.03}$ in between $\sim$100 s and 1.4 ks
  - ☐ Model with e-synchrotron in the fast-cooling and for $\nu_{\rm XRT} > \nu_{\rm m,e} > \nu_{\rm c,e}$
  - ☐ $k = (4/3)\alpha_{\rm XRT} + 2/3 = 1.65 \pm 0.04$; $\beta_{\rm XRT} = k/2 = 0.83 \pm 0.02$
- ☐ LAT light curve: $t^{-1.38\pm0.07}$ in between $\sim$0.3 s and 100 s
  - ☐ Model with p-synchrotron in the slow-cooling and for $\nu_{\rm m,p} < \nu_{\rm LAT} < \nu_{\rm c,p}$
  - ☐ $k_2 = (4/3)\alpha_\gamma + 1 = 2.84 \pm 0.09$; $\beta_\gamma = (k_2 - 1)/2 = 0.92 \pm 0.05$
  - ☐ β_γ needs to be compatible with measured LAT photon index (and it is)
- ☐ Parameters such as $n_{\rm ISM}$ and Γ_0 are mainly constrained by $t_{\rm dec} \le 0.3$ s
- ☐ Parameters such as $E_{\rm k,iso}$, ϵ_B , η_e , η_p are set to produce required fluxes
- ☐ Parameters ϵ_e , ϵ_p are calculated from other parameters and constrained <1
- ☐ UVOT light curve is constrained by XRT (e-synchrotron)
- ☐ BAT light curve can not be fitted ➔ continued central engine activity

Leptonic-Hadronic Synchrotron Spectra

Protons and electrons

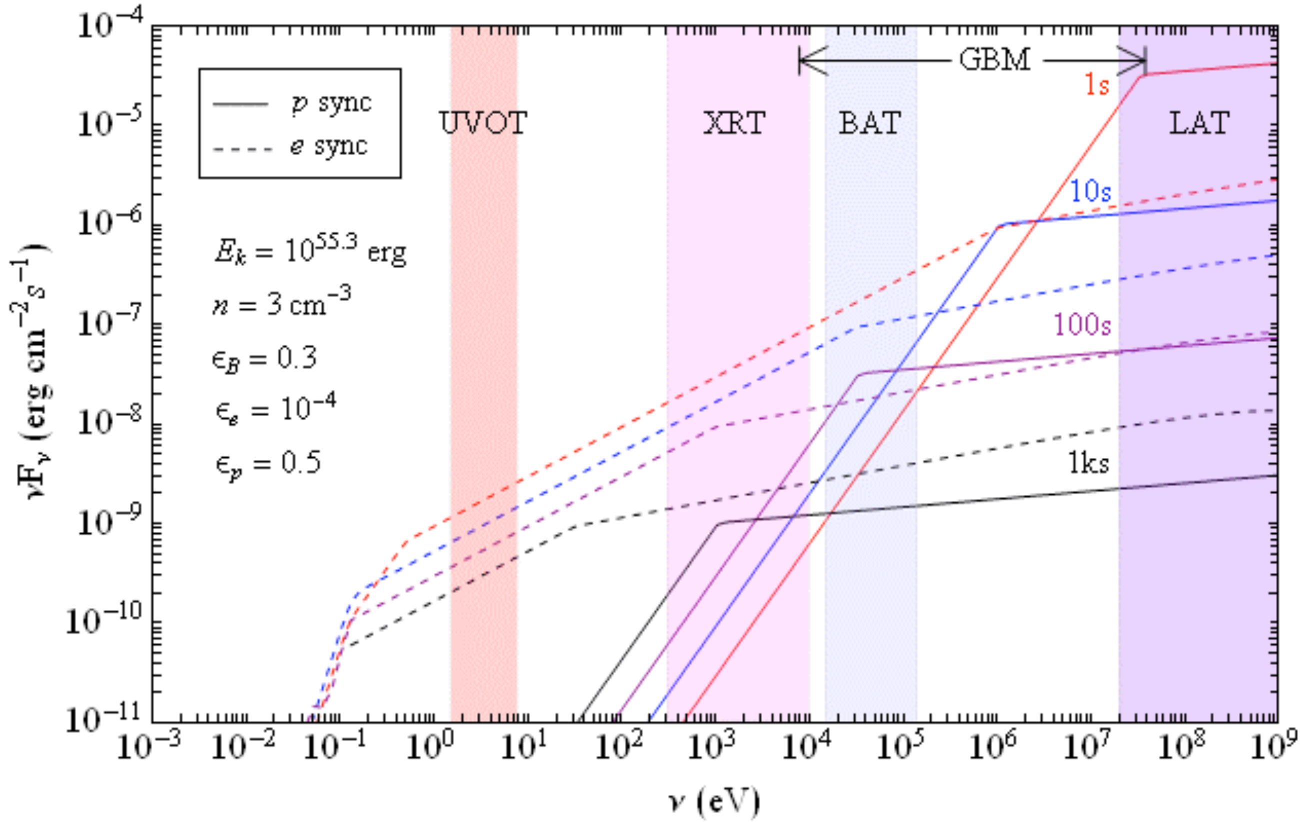
- ➔ p is always slow-cooling
- ➔ e shifts from fast- to slow- cooling in 2×10^6 s

p - synchrotron ($k_2 = 2.84$)

$$\nu F_\nu \propto \begin{cases} \nu^{4/3} & ; \nu < \nu_{m,p} \\ \nu^{0.08} & ; \nu \geq \nu_{m,p} \end{cases}$$

e - synchrotron ($k = 1.65$)

$$\nu F_\nu \propto \begin{cases} \nu^{4/3} & ; \nu < \nu_{c,e} \\ \nu^{1/2} & ; \nu_{m,e} > \nu \geq \nu_{c,e} \\ \nu^{0.18} & ; \nu \geq \nu_{m,e} \end{cases}$$



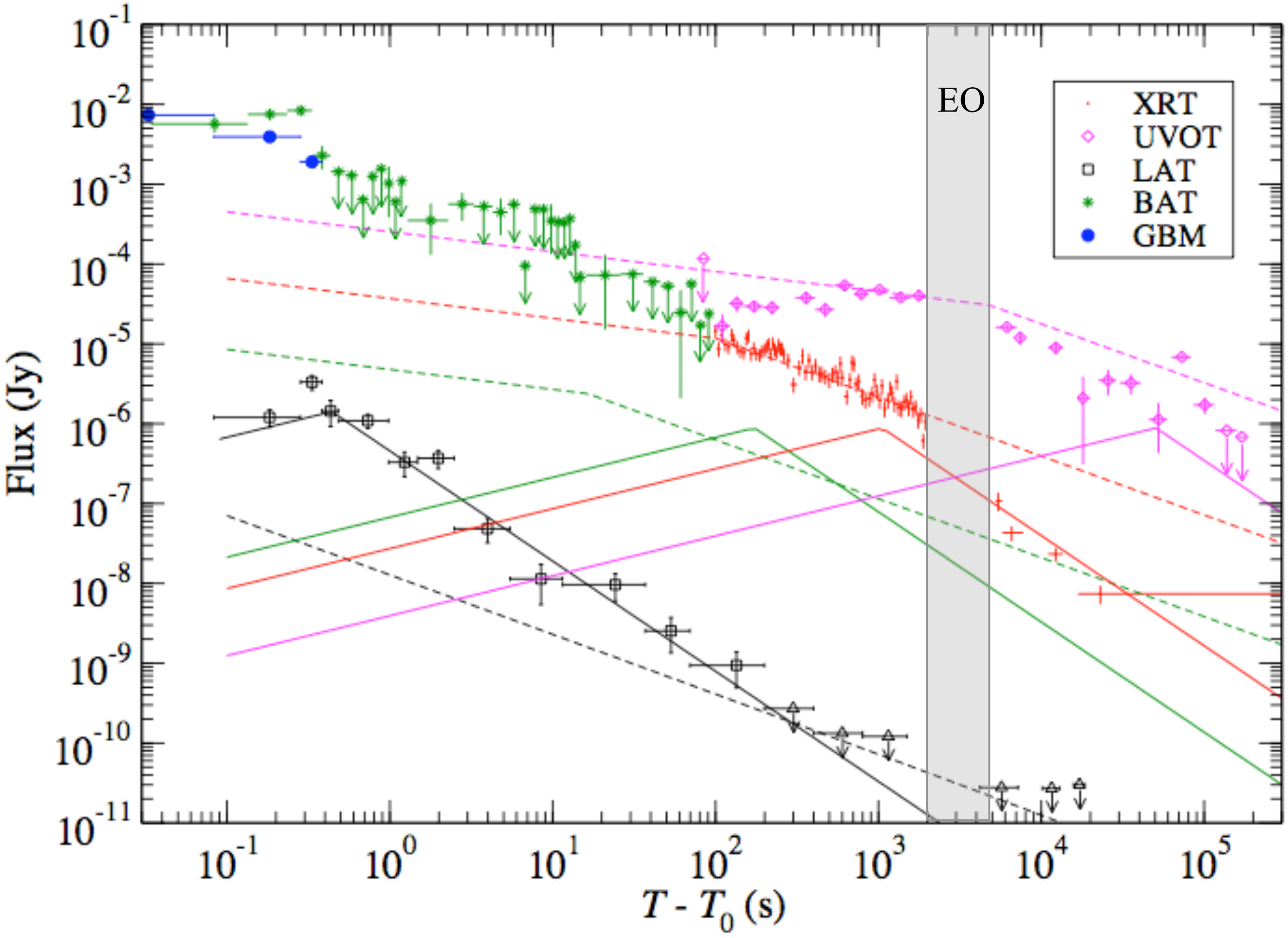
LAT emission is dominated by p-synchrotron with photon spectrum $\propto \nu^{-1.92}$

Compatible with data

Light Curves from Afterglow Modeling

Multiwavelength light curves from combined leptonic-hadronic modelling

Solid lines: *p*-synchrotron, Dashed lines: *e*-synchrotron



$E_{k,iso} = 2\times10^{55}$ erg
$n = 3$ cm^{-3}
$\Gamma_0 = 2400$
$\varepsilon_B = 0.3$
$\varepsilon_p = 0.5$
$\varepsilon_e = 10^{-4}$

$\eta_e = 20(m_e/m_p)$
$\eta_p = 5000$
$k = 1.65\pm0.04$
$k_2 = 2.84\pm0.09$

Absolute GRB Energy

Ratio of gamma-ray to kinetic energy
Too low efficiency?
→
$E_{\gamma,\mathrm{iso}} \sim 10^{53}$ erg
$E_{\gamma,\mathrm{iso}} / E_{\mathrm{k,iso}} \sim 0.01$

Not in supernova remnants!

Collimation-corrected energy from jet-break time

$$t_{jet} \approx 10^5 (1+z)\,(E_{55}/\mathrm{n})^{1/3}\,\theta_{-1}^{8/3}\ \mathrm{s}$$

Sari, Piran & Halpern 1999

Jet-break time during the Earth Occultation: $1.4\ \mathrm{ks} < t_{jet} < 5.1\ \mathrm{ks}$

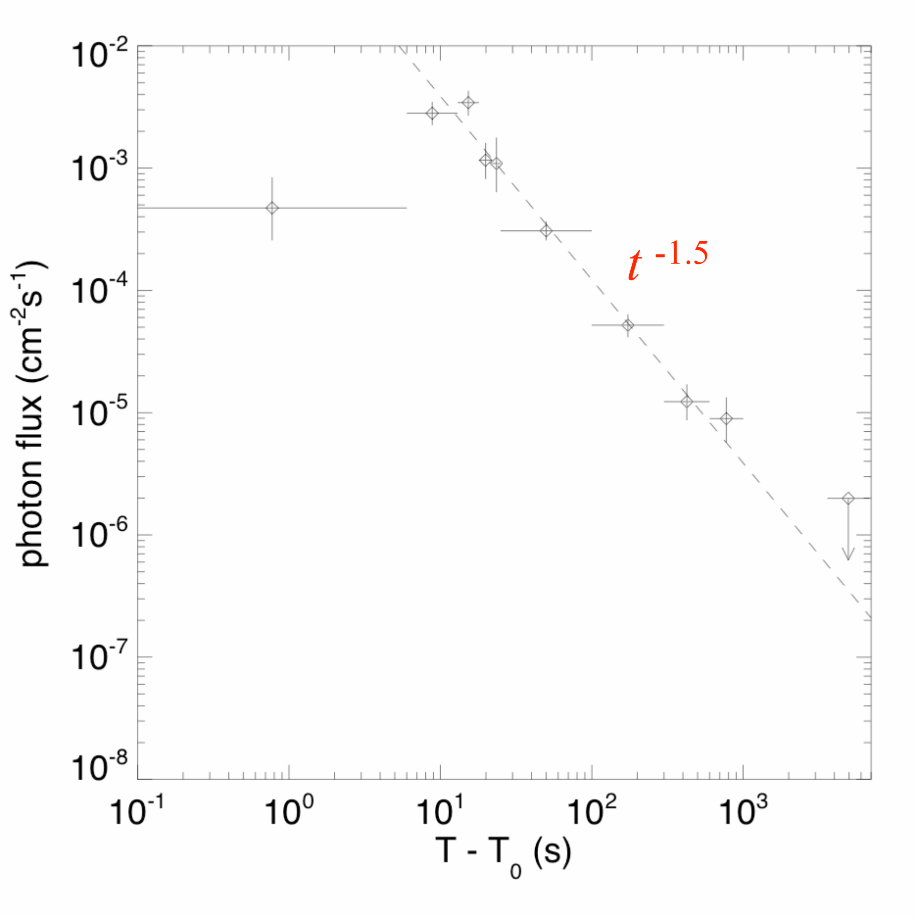
→ Jet opening angle: 1 degree $< \theta_{jet} <$ 1.5 degree

→ Absolute jet energy: $(3\text{-}7)\times 10^{51}$ erg

Is there an absolute maximum? 10^{53} erg → $\theta_{jet} \sim 6$ degree *Dale Frail*

LAT Light Curve of GRB 090902B

$z = 1.82$



Deceleration time

$$t_{dec} \approx 1.9(1+z)\,(E_{55}/\mathrm{n})^{1/3}\,\Gamma_3^{-8/3}\ \mathrm{s}$$

Fitting parameters

$$E_{\mathrm{k,iso}} = 2\times10^{56}\ \mathrm{erg}\ ;\ n = 20\ \mathrm{cm}^{-3}$$
$$\Gamma_0 = 900\ ;\ \varepsilon_B = 0.3\ ;\ \varepsilon_p \sim 0.5$$
$$\eta_p \sim 2\times10^4\ ;\ k_2 \sim 3$$

$$\boxed{\begin{array}{l} E_{\gamma,\mathrm{iso}} \sim 4\times10^{54}\ \mathrm{erg} \\ E_{\gamma,\mathrm{iso}}/E_{\mathrm{k,iso}} \sim 0.02 \end{array}}$$

Total energy constraint

$$E_{\mathrm{k}} \le 10^{53}\ \mathrm{erg}$$
$$\theta_{\mathrm{jet}} \le 2\ \mathrm{degree}$$

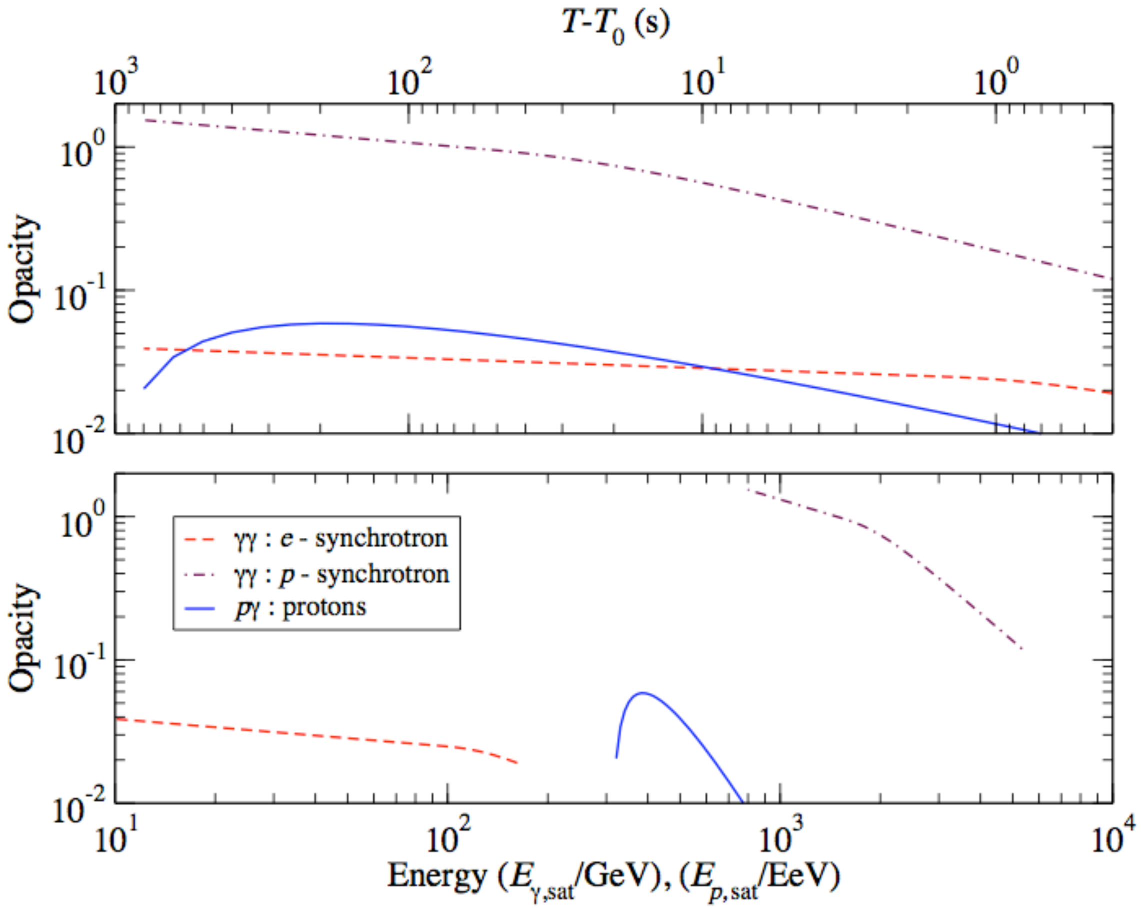
Within 1-10 deg.

Other Processes in the Blast Wave

Opacities for γγ pair production and photopion production for maximum energy particles

- ➔ synchrotron photons are targets for γγ and *p*γ
- ➔ maximum *e*-sync. photon ~100 GeV
- ➔ maximum *p*-sync. photon >1 TeV
- ➔ γγ pair production can only be marginally important

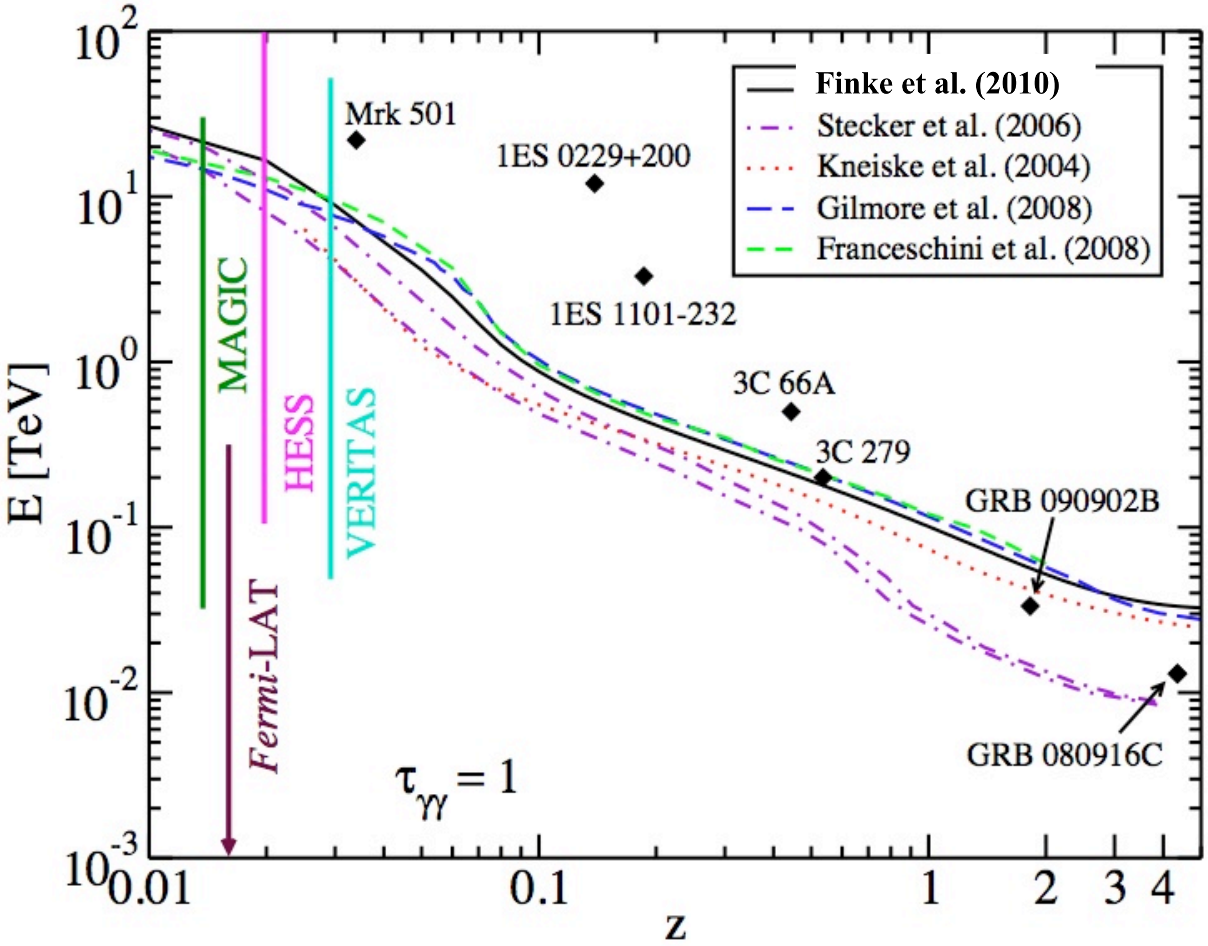
Ground-based detectors can probe *p*-synch model



Detectability of >100 GeV Gamma Rays

Extragalactic Background Light (EBL) limits distance of the source

GRBs up to $z \sim 0.5$ can be detected at ≤ 200 GeV



Finke, Razzaque and Dermer 2010

See
Joel Primack's
talk

Conclusions

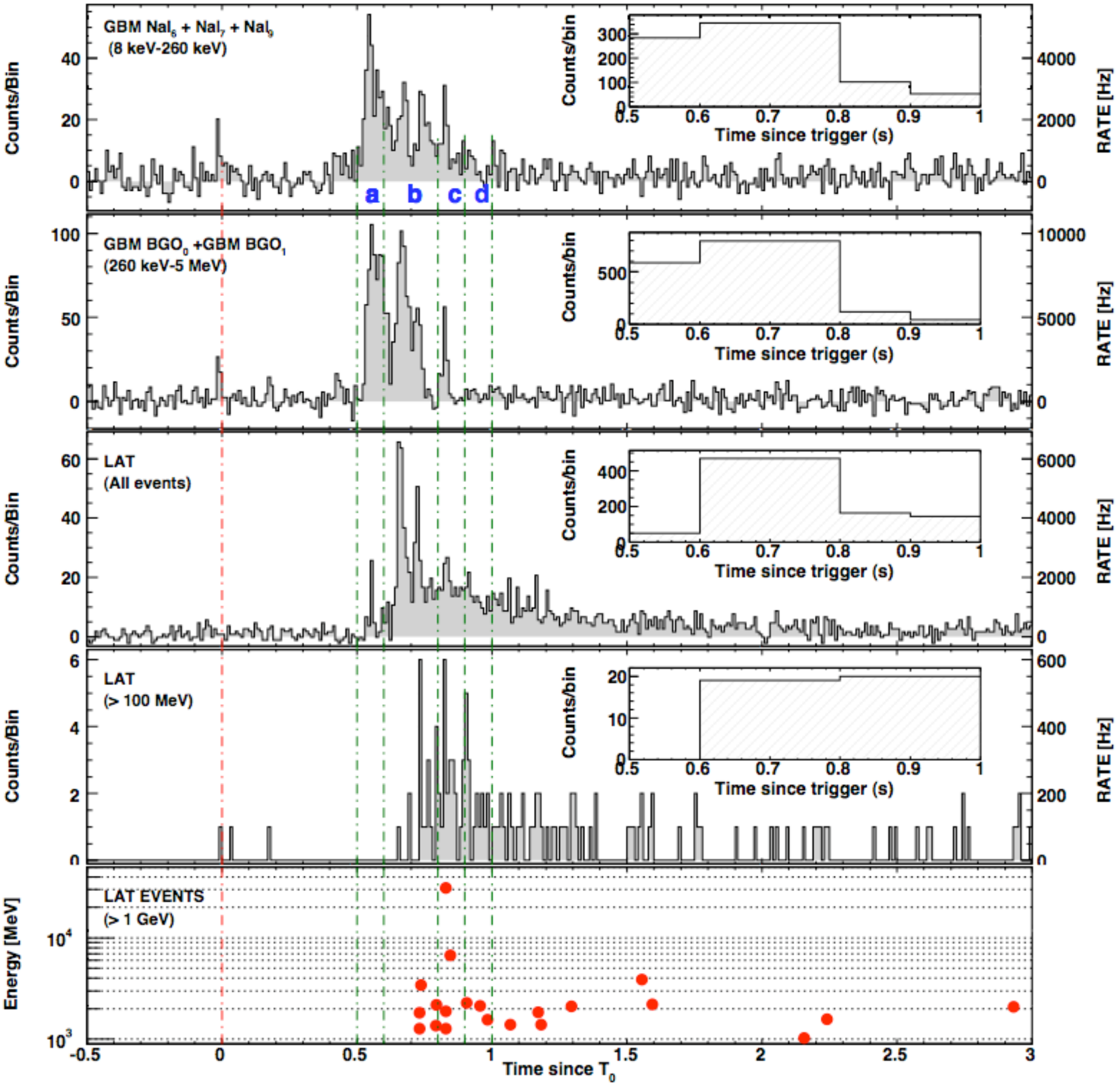
- ❑ Detection of GRB 090510 is an extraordinary event
  - ❑ Multiwavelength contemporaneous data for the first time from *Fermi* GBM and LAT, *Swift* BAT, XRT and UVOT
  - ❑ Most energetic short GRB: 10^{53} erg compared to typical 10^{49}-10^{51} erg
- ❑ Emission is complex, involving multiple components
  - ❑ Simple afterglow model with electron-synchrotron radiation fails to reproduce multi-wavelength light curves
  - ❑ Delay in high-energy, >100 MeV, emission with different temporal decay than in other wavelength suggest a different origin
- ❑ I have presented a leptonic-hadronic afterglow model
  - ❑ p-synchrotron radiation explains high-energy emission
  - ❑ e-synchrotron radiation explains XRT and UVOT (part) light curves

Multi-wavelength data from more GRBs and detection by ground-based detectors will either provide evidence or constrain *p*-synchrotron radiation model

Detection of GRB 090510

- Fermi GBM and LAT observations
  - Trigger on 2009 May 10 at 00:22:59 UT
  - Fluence of the burst : ($T_0+0.5$ - $T_0+1.0$) s
    - 5×10^{-5} erg cm^{-2} (10 keV - 30 GeV) ; 4×10^{-7} erg cm^{-2} (15 keV - 150 GeV)
- Swift BAT observations
  - Trigger on 2009 May 10 at 00:23:00 UT
  - (RA, DEC) = (333.55°, -26.58°)
  - Duration : $T_{90} = 0.3 \pm 1$ s
  - Fluence of the burst : (T_0+0 - $T_0+0.4$) s
    - 4×10^{-7} erg cm^{-2} (15 keV - 150 GeV)
- Spectroscopic redshift (3.5 days) from VLT/FORS2
  - 0.903 ± 0.003
  - 10^{53} erg isotropic-equivalent gamma-ray energy release!
  - Most luminous short GRB detected to-date!!

GBM and LAT Light Curves

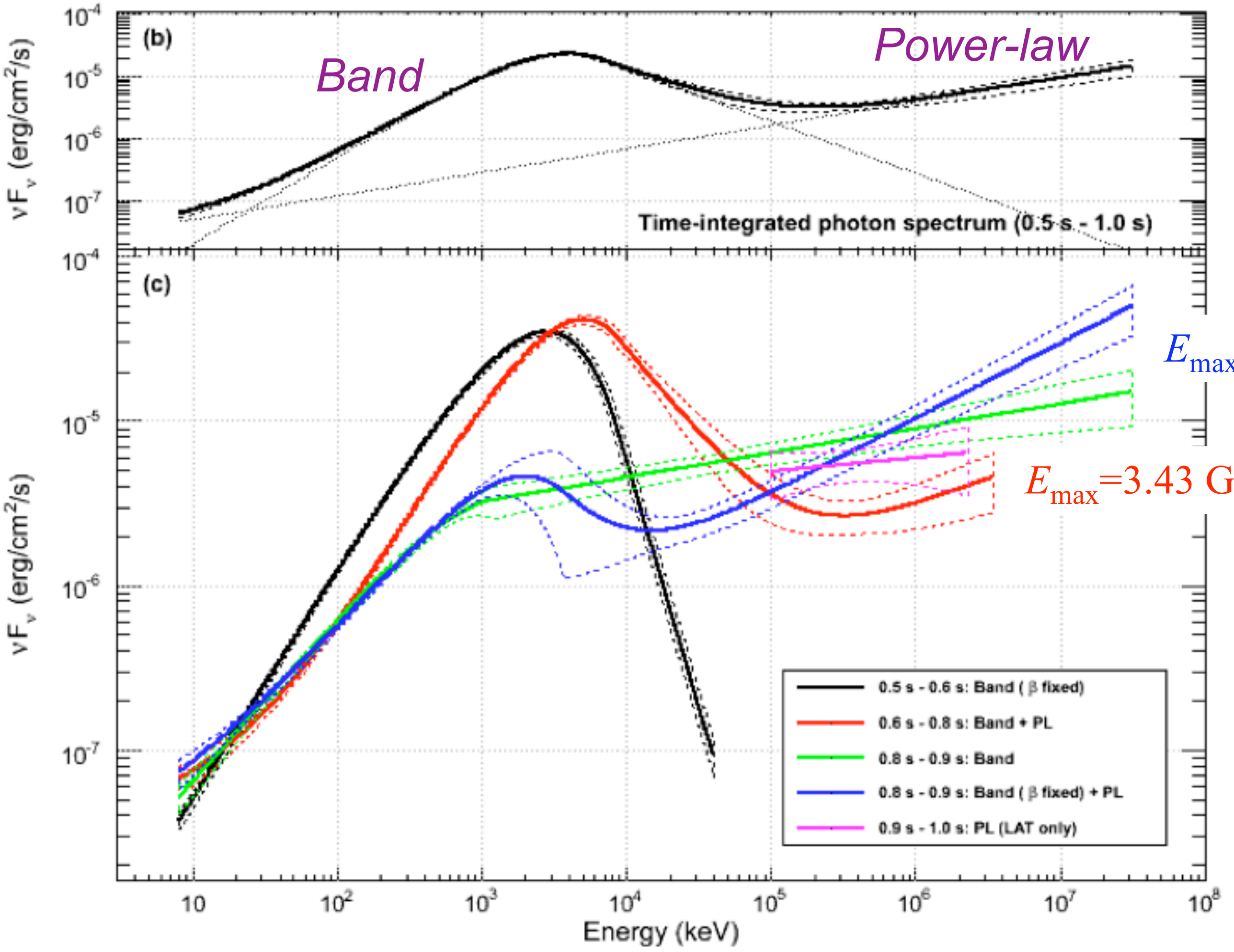


Photon arrival info.

- ➔ GBM triggered on a weak precursor
- ➔ Main GBM emission starts at ~T_0+0.5 sec
- ➔ >100 MeV emission starts at ~T_0+0.65 s
- ➔ >1 GeV emission starts at ~T_0+0.7 s
- ❑ 31 GeV photon at ~T_0+0.83 s
- ➔ Highest from a SGRB
- ❑ Extended HE emission

Spectroscopy of GRB 090510

PL component in addition to phenomenological Band Spectrum



Band

Power-law

$E_{\max}$=30.5 GeV

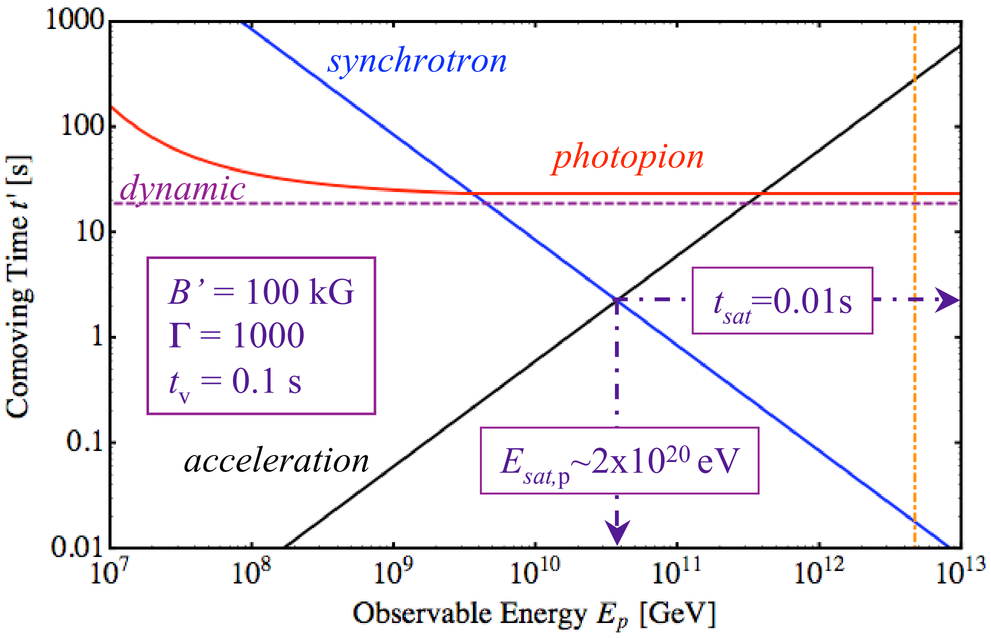
$E_{\max}$=3.43 GeV

UHECR Signature in GRB Emission

UHECR acceleration in magnetic field and interactions may provide γ ray signature from GRBs, specially in *Fermi* LAT

- *Synchrotron radiation and associated e^+e^- cascade radiation*
- *Photohadronic interactions with observed keV - MeV γ rays and cascade emission*

GRB 080916C

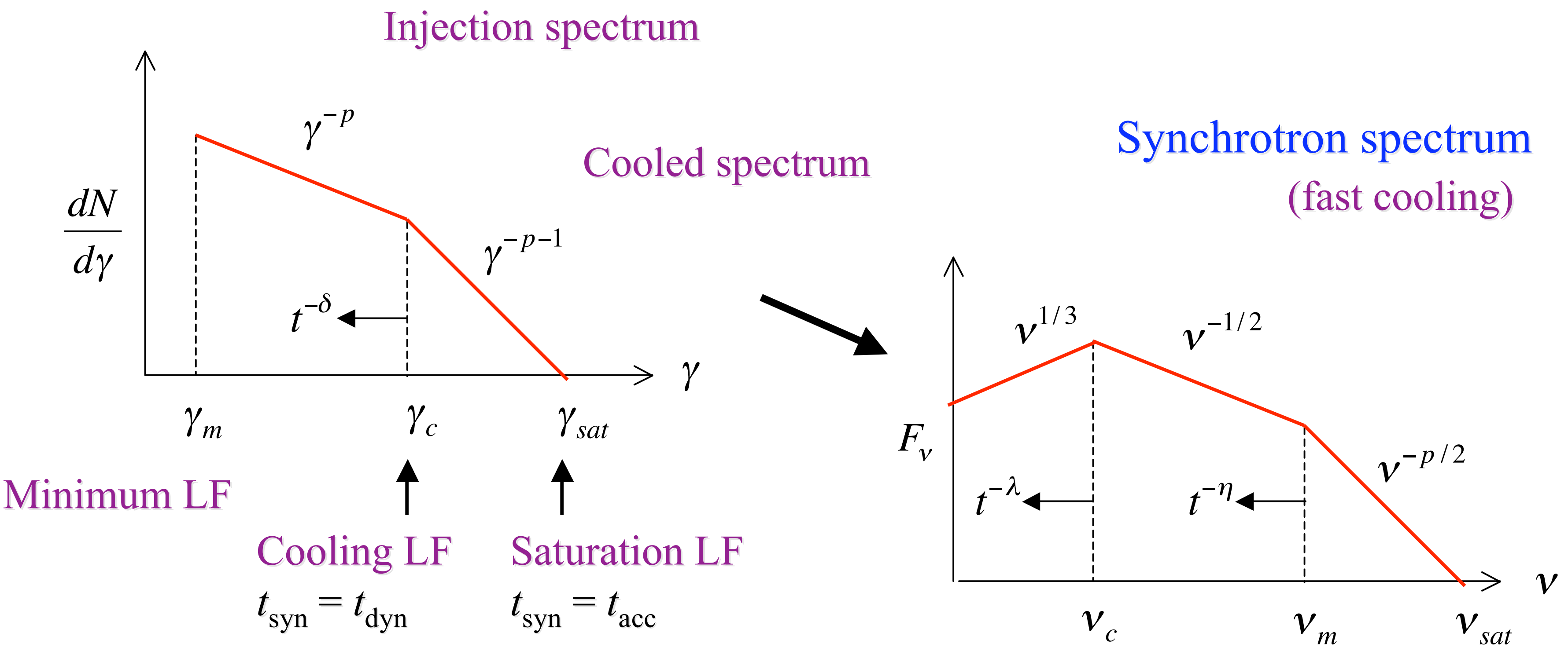


- Very high jet bulk Lorentz factor reduces photohadronic cooling
  - *Could work in other bright GBM bursts*
  - *A γγ cutoff in HE spectrum would be an indication*
- Synchrotron cooling is dominant in high *B* field

Razzaque, Dermer, Finke & Atoyan, arXiv:0811.1160

Synchrotron Radiation from GRB Jets

- Particle acceleration in the forward shock *B* field
- Cooling is dominated by synchrotron radiation in the same *B* field



Injection spectrum

Cooled spectrum

Synchrotron spectrum
(fast cooling)

Minimum LF

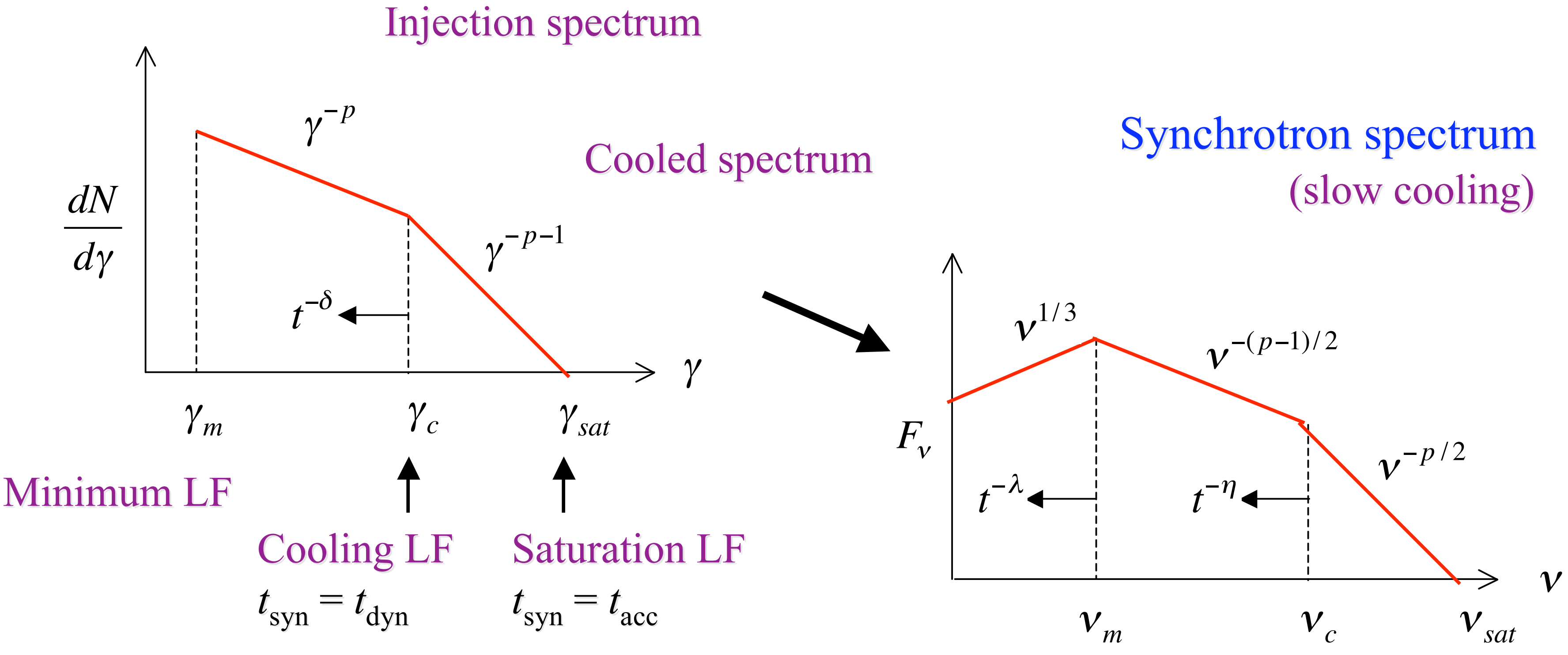
Cooling LF
$t_{\text{syn}} = t_{\text{dyn}}$

Saturation LF
$t_{\text{syn}} = t_{\text{acc}}$

- Fast cooling $\gamma_m > \gamma_c$ or $\nu_m > \nu_c$
- All break frequencies evolve with time as the *B* field (and Γ) does

Synchrotron Radiation from GRB Jets

- ☐ Particle acceleration in the forward shock *B* field
- ☐ Cooling is dominated by synchrotron radiation in the same *B* field



Injection spectrum

Cooled spectrum

Synchrotron spectrum
(slow cooling)

Minimum LF

Cooling LF
$t_{\text{syn}} = t_{\text{dyn}}$

Saturation LF
$t_{\text{syn}} = t_{\text{acc}}$

- ☐ Fast cooling $\gamma_m > \gamma_c$ or $\nu_m > \nu_c$; Slow cooling $\gamma_m < \gamma_c$ or $\nu_m < \nu_c$
- ☐ All break frequencies evolve with time as the *B* field (and Γ) does