Prompt GRB Emission: High-Energy Spectra & Polarization

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Workshop on Gamma-Ray Bursts: Prompt to Afterglow

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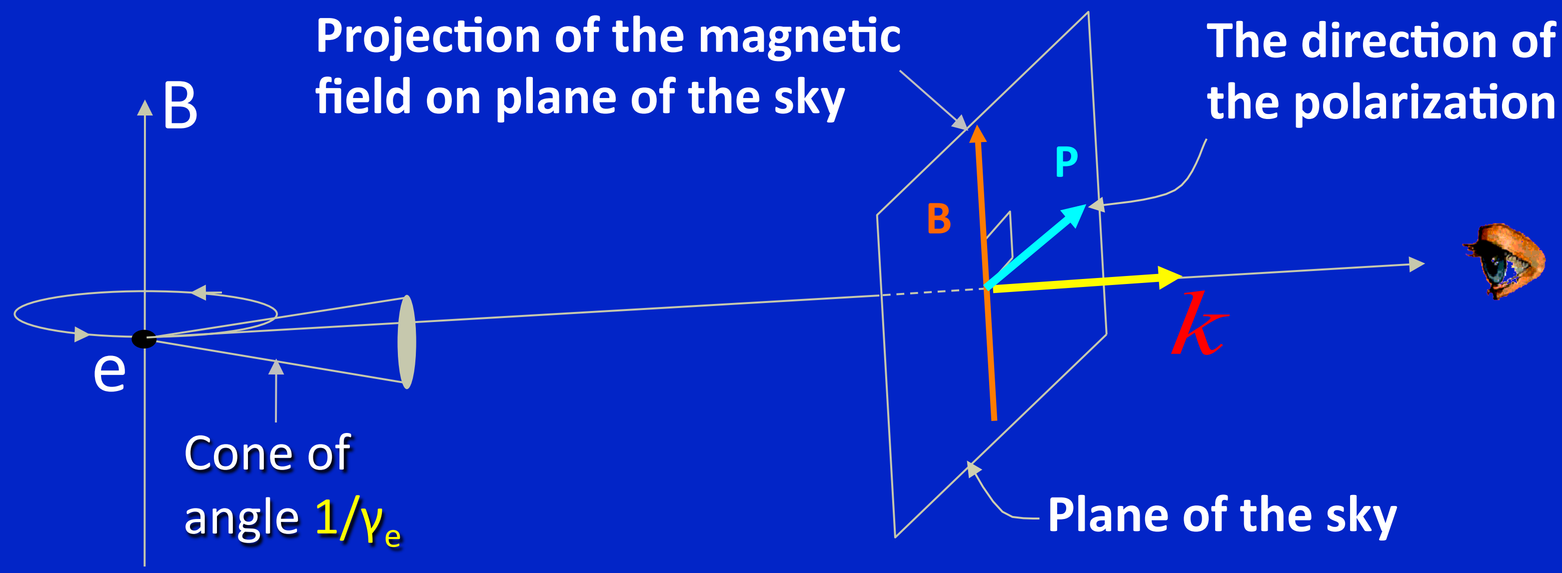
Outline of the Talk:

- Polarization in GRBs:
  - Motivation, synchrotron emission, B-field structure
  - Relativistic beaming, jet + viewing angle effects
  - Alternative models: photospheric, Compton drag
  - Model comparison: different pulses vs. whole GRB
- Fermi: new perspectives on prompt GRB spectra
- High-energy & photospheric spectral components
- Constraints on Γ: the compactness problem
- Time-dependent intrinsic $\gamma\gamma \rightarrow e^+e^-$ opacity model

Why is GRB Polarization Interesting

- It teaches us about the **magnetic field structure** in the GRB ejecta & provides clues as to whether most of energy is in **Poynting flux** or **kinetic energy**:
  - $E_{EM} \gg E_{kin} \Rightarrow$ ordered magnetic field is expected
  - $E_{kin} \gtrsim E_{EM} \Rightarrow$ ordered & random fields are possible
- Provides a strong test for the **jet structure** in GRBs, both in the prompt GRB & in the afterglow
- Constrains the **prompt GRB emission mechanism**
- Probes magnetic field structure behind afterglow shock
- Helps pin down cause of time variability in afterglows

Polarization of Synchrotron Emission

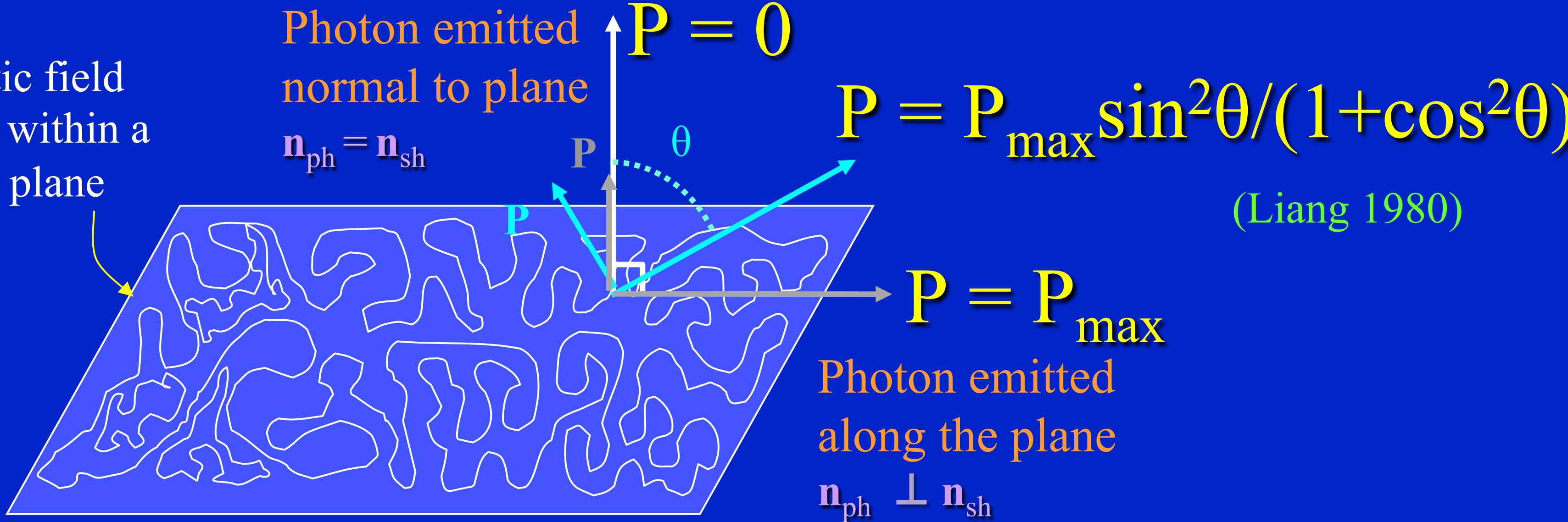


- **linear polarization** perpendicular to the projection of **B** on the plane of the sky
- The maximal polarization is for the local emission from an ordered **B**-field: $P_{max} = (\alpha+1)/(\alpha+5/3)$ where $F_\nu \propto \nu^{-\alpha}$, $-1/3 \le \alpha \lesssim 1.5 \Rightarrow 50\% \le P_{max} \lesssim 80\%$ (Rybicki & Lightman 1979; Granot 2003)

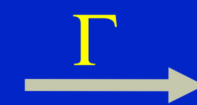
Shock Produced Magnetic Field:

- A magnetic field that is produced at a relativistic collisionless shock, due to the two-stream instability, is expected to be **tangled within the plane of the shock** (Medvedev & Loeb 1999)

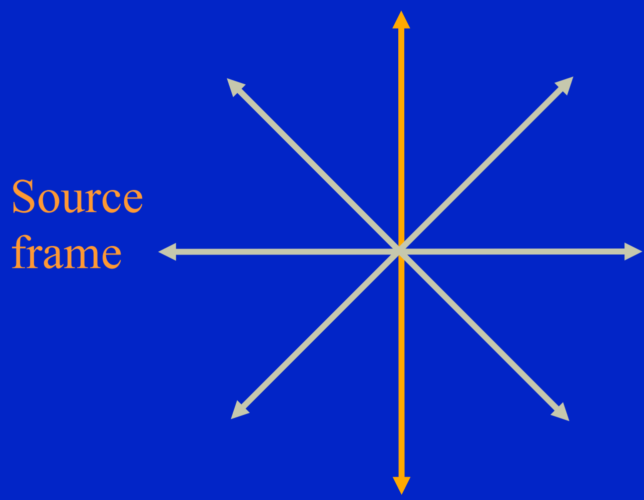
Magnetic field tangled within a (shock) plane

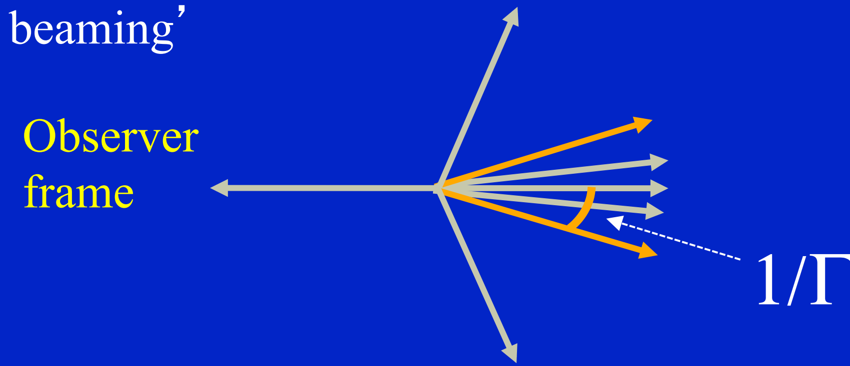


Relativistic source:

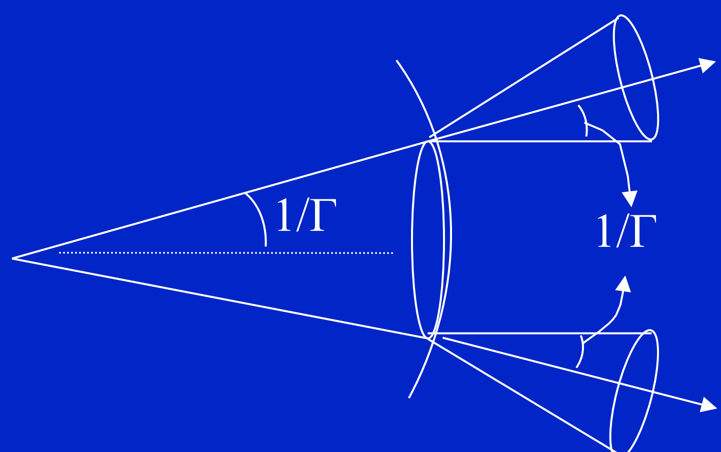


Aberration of light or
'relativistic beaming'

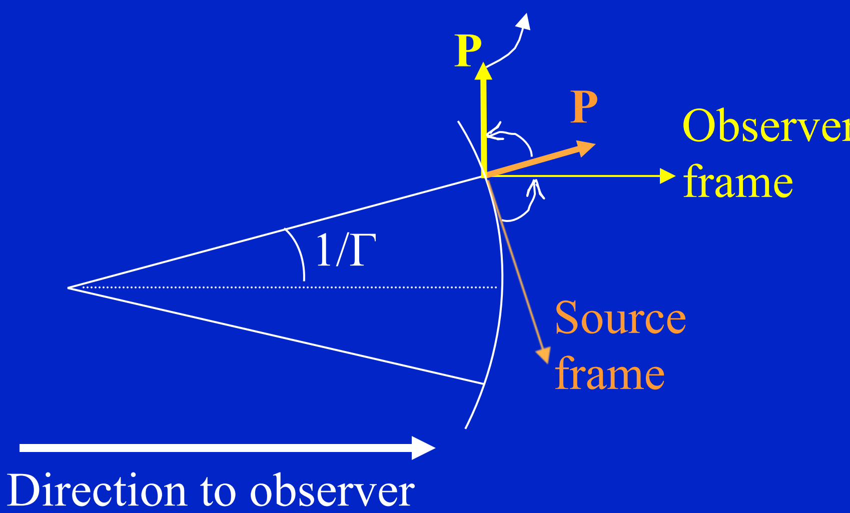




The observer sees mostly emission from within an angle of $1/\Gamma$ around the l.o.s.

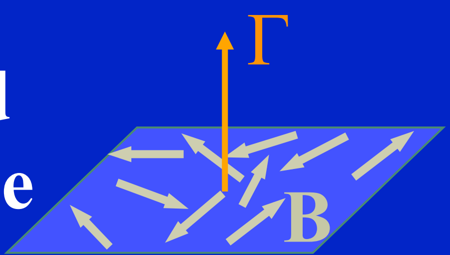


Direction of
Polarization

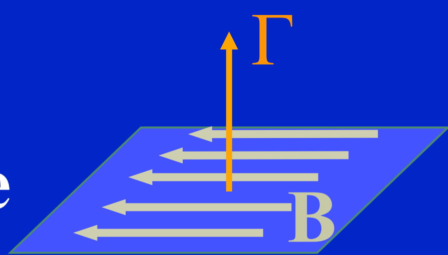


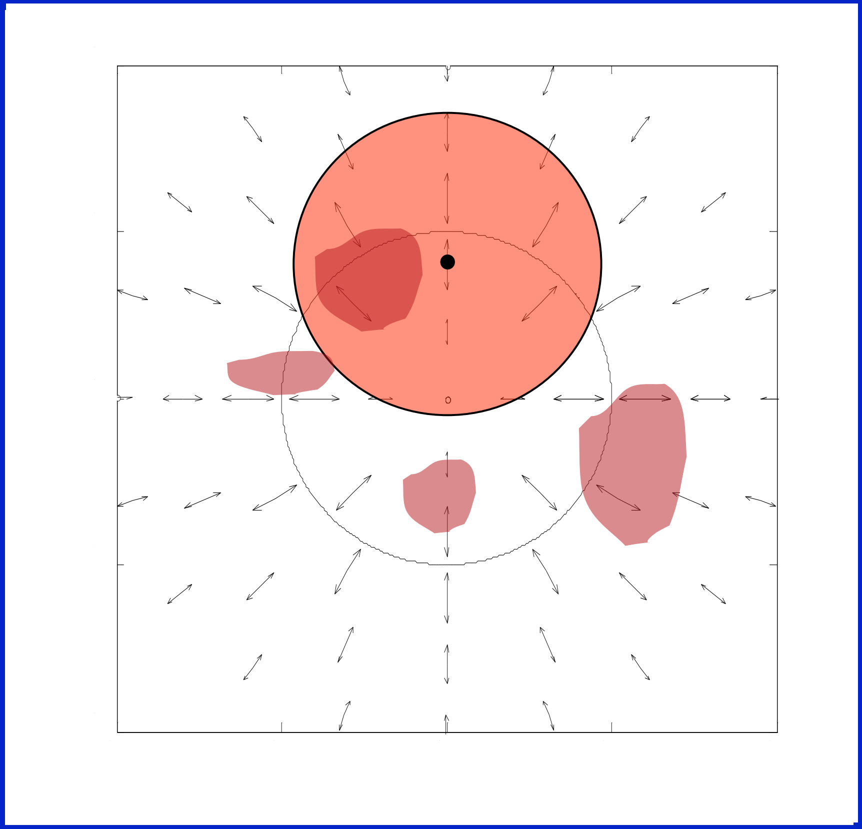
Polarization in the observer frame

Random field in shock plane

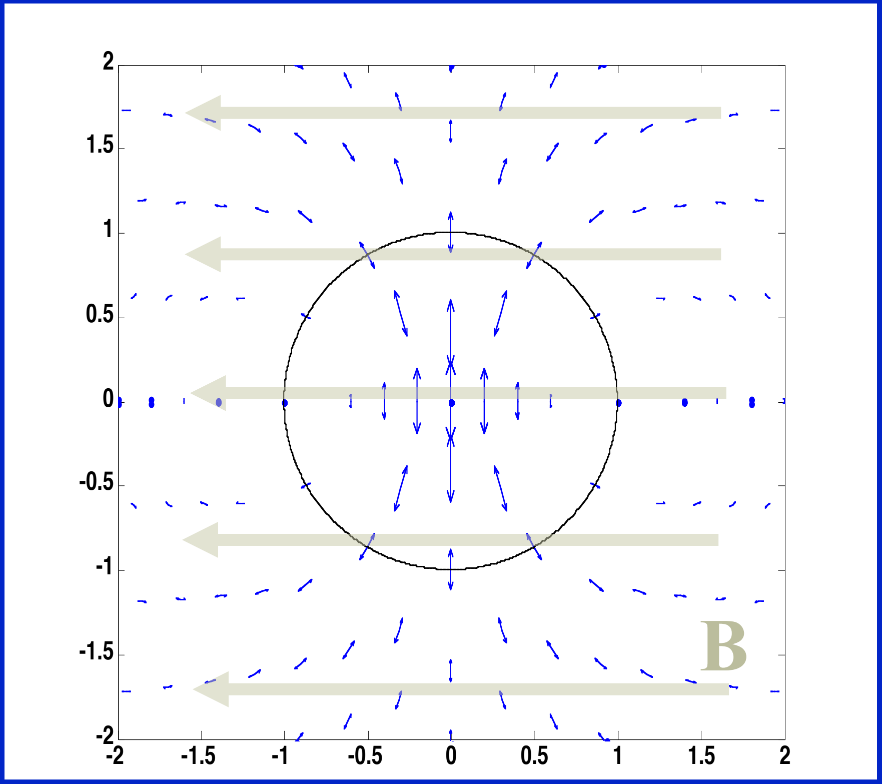


Ordered field in shock plane





Sari 99; Ghisellni & Lazzati 99



Granot & Königl 03

$P \sim P_{max}$

Polarization of Prompt γ-ray emission:

Observations: very hard to measure in γ-ray or hard X-rays

- GRB021206 P=80±20% RHESSI (Coburn & Boggs 2003)
  Soon refuted (Rutledge & Fox 2003; Wigger et al. 2004)
- GRB930131, 960924 P>35,50% CGRO/BATSE (Willis+05)
- GRB041219a 98±33%, 98±33%, 43±25% Integral/SPI,IBIS (Kalemci et al. 2007; McGlynn et al. 2007; Götz et al. 2009)
- GRB061122 P>60% (1σ), 33% (90%) Integral/IBIS (Götz+13)
- GRB140206a P>48% (1σ), 28% (90%) Integral/IBIS (Götz+14)
- GRB100826a 27±11% , 110301a 70±22%, 110721a 80±22% Ikaros/GAP (Yonetoku et al. 2011, 2012)
- **Astrosat/CZTI ???**

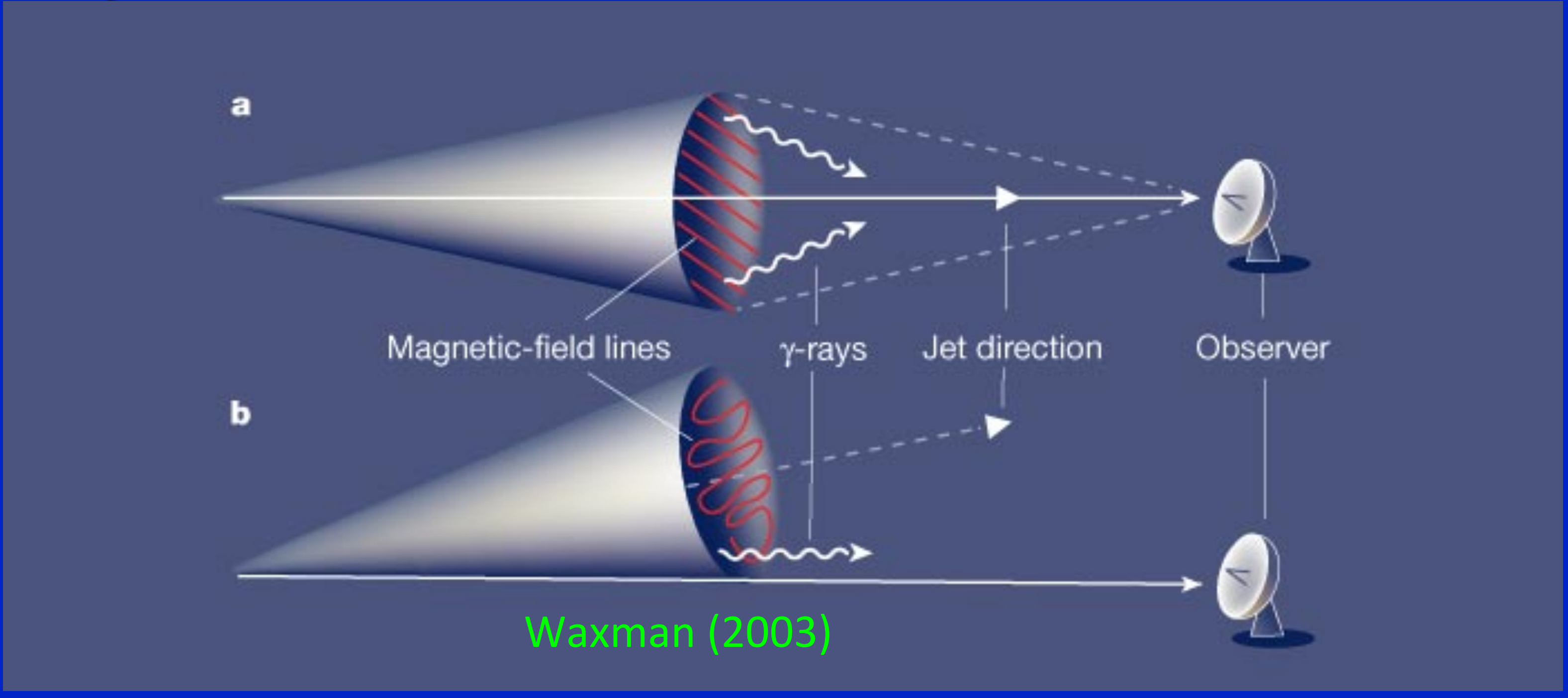
Polarization of Prompt γ-ray emission:

Theory: first consider synchrotron emission

- Shock produced B-field + $\theta_{obs} \lesssim \theta_j - 1/\Gamma \Rightarrow P \approx 0$
- $P \sim P_{max}$ can be achieved in the following ways:

  (1) **ordered magnetic field** in the ejecta,

  (2) **special geometry**: $|\theta_{obs} - \theta_j| \lesssim 1/\Gamma \;\Rightarrow$ favors narrow jets: $\theta_j \lesssim 1/\Gamma$ (works with a shock produced B-field)



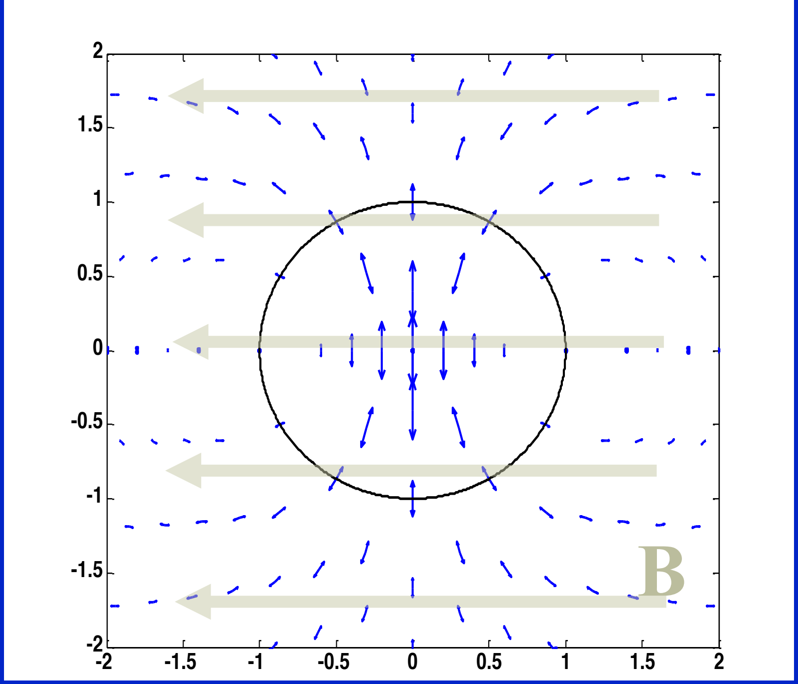
Waxman (2003)

Ordered Magnetic Field in the Ejecta:

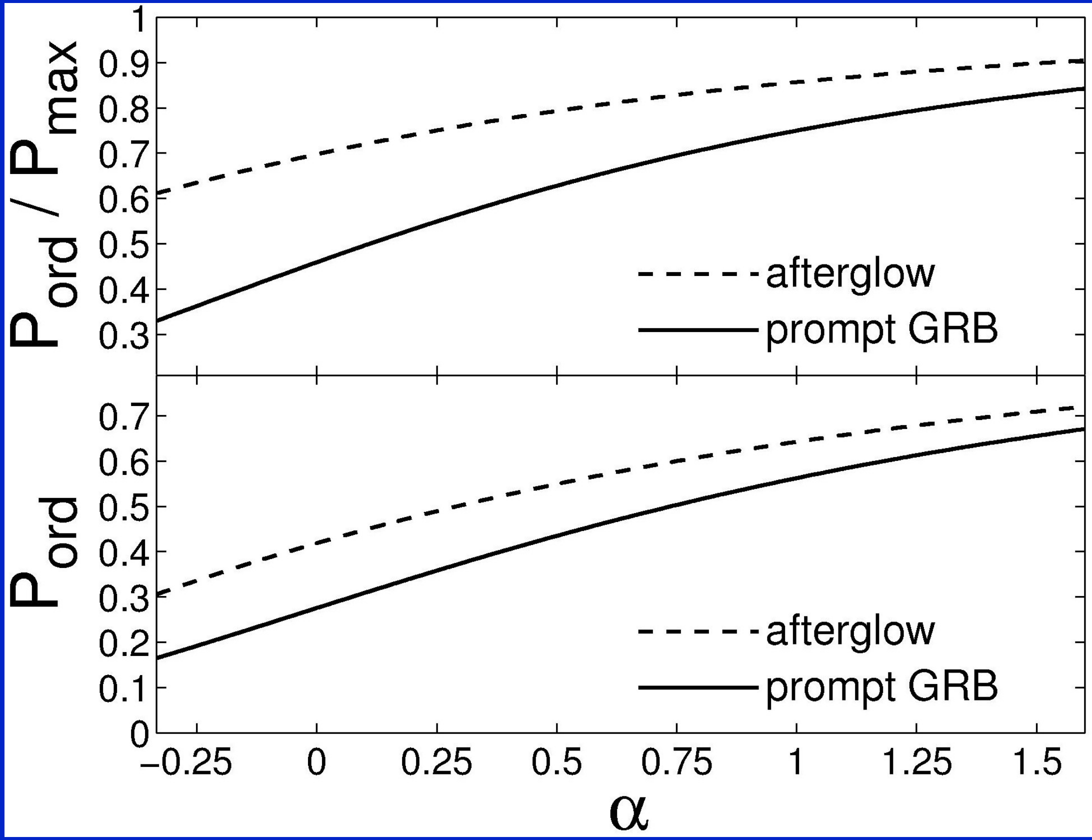
Total emission from jet

Afterglow:
instantaneous emission

Prompt GRB:
time integrated emission



Granot & Königl 03



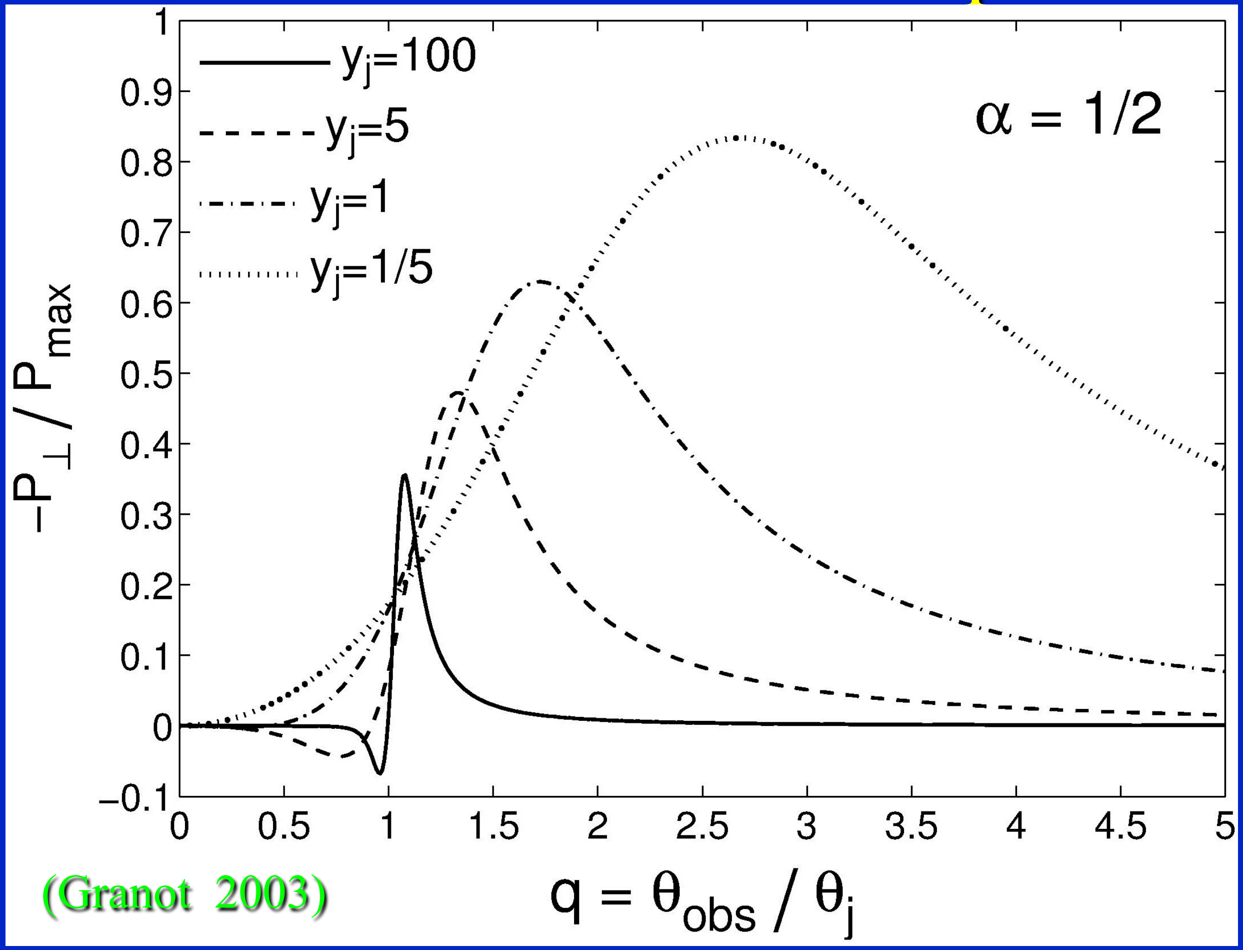
(Granot 2003)

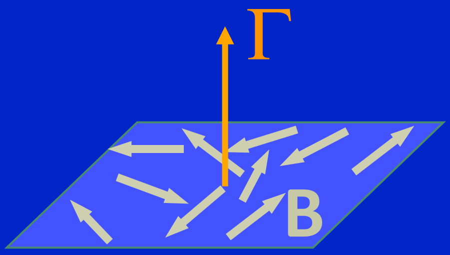
- $F_\nu \propto \nu^{-\alpha}$, P increases with α
- P from an ordered B-field is slightly larger in afterglow

Narrow Jet + shock produced B-field

- High polarization + reasonable flux $\Rightarrow \theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma$
- A reasonable probability for such $\theta_{obs} \Rightarrow \Gamma\theta_j \lesssim$ a few
- Since $\Gamma \gtrsim 100$ & $\theta_j \gtrsim 0.05$, $\Gamma\theta_j \gtrsim 5$ and is typically larger
- However GRB 021206 was very bright, suggesting a very narrow jet: $f = 1.6\times10^{-4}$ erg which for $z\sim1$ implies $E_{iso}\sim10^{54}$ erg & $\theta_j \sim (10^{51}\mathrm{erg}/E_{iso})^{1/2} \sim 0.03$ (Frail et al. 01)
- $\Rightarrow \Gamma\theta_j \sim 3(\Gamma/100) \Rightarrow \Gamma\theta_j \lesssim$ a few is possible (Waxman 03)
- The **jet** must have **sharp edges**: $\Delta\theta_j \lesssim 1/4\Gamma$ (Nakar et al. 03)
- a ‘structured jet’ produces low polarization (several %)
- Most GRBs are viewed from $\theta_{obs} < \theta_j$ and are expected to have a very low polarization in this scenario

Random B-field in sock plane





$y_j = (\Gamma\theta_j)^2$

$F_\nu \propto \nu^{-\alpha}$

- $\Delta\Gamma \sim \Gamma$ between different shell collisions (different pulses in GRB light curve) reduces P by a factor ~ 2

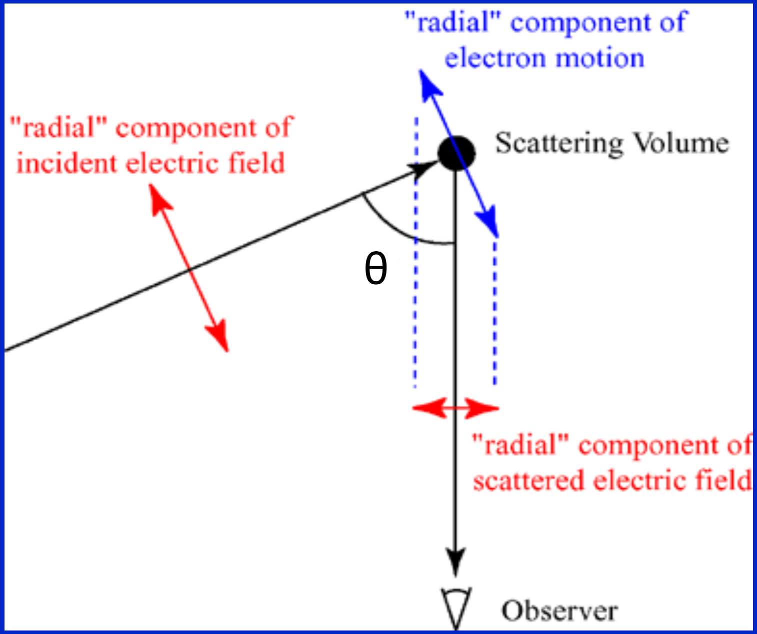
	Ordered Field	Narrow Jet
$P \sim 80\%$	X	X
$P \sim 50\%$	✓	X
$P \sim 25\%$	with $B_{rnd} \lesssim B_{ord}$	✓
$P \lesssim 10\%$	with $B_{rnd} > B_{ord}$	with $B_{rnd} \gtrsim B_{ord}$
statistics	High P in all GRBs	low P in most GRBs
Optical flash	High P - similar to the prompt GRB	Similar to prompt GRB (low P in most GRBs)
Potential problems	Some B_{rnd} required for Fermi acceleration	$\Gamma\theta_j \lesssim$ a few, $\Delta\Gamma \sim \Gamma$, B_{rnd} (afterglow obs.)

Alternative to Synchrotron: Compton Drag

(Bulk Inverse Compton Scattering of External photons)

(Lazzati et al. 2003; Dar & De Rujula 2003, Eichler & Levinson 2003)

- Requires special geometry/viewing angle, $\theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma$
- Polarization properties similar to synchrotron + B_{rnd} with an advantage: **local polarization** $P = (1-\cos^2\theta)/(1+\cos^2\theta)$ can reach up to 100% while $P_{max} \sim 70\%$ for synchrotron
- Shares drawbacks of shock produced field + narrow jet
- It has additional problems, unrelated to polarization:
  - Explaining prompt GRB spectrum
  - Supplying external photons for all the ejected shells
  - High photon density $\Rightarrow$ small radii $\Rightarrow$ high $\tau_{\gamma\gamma}$



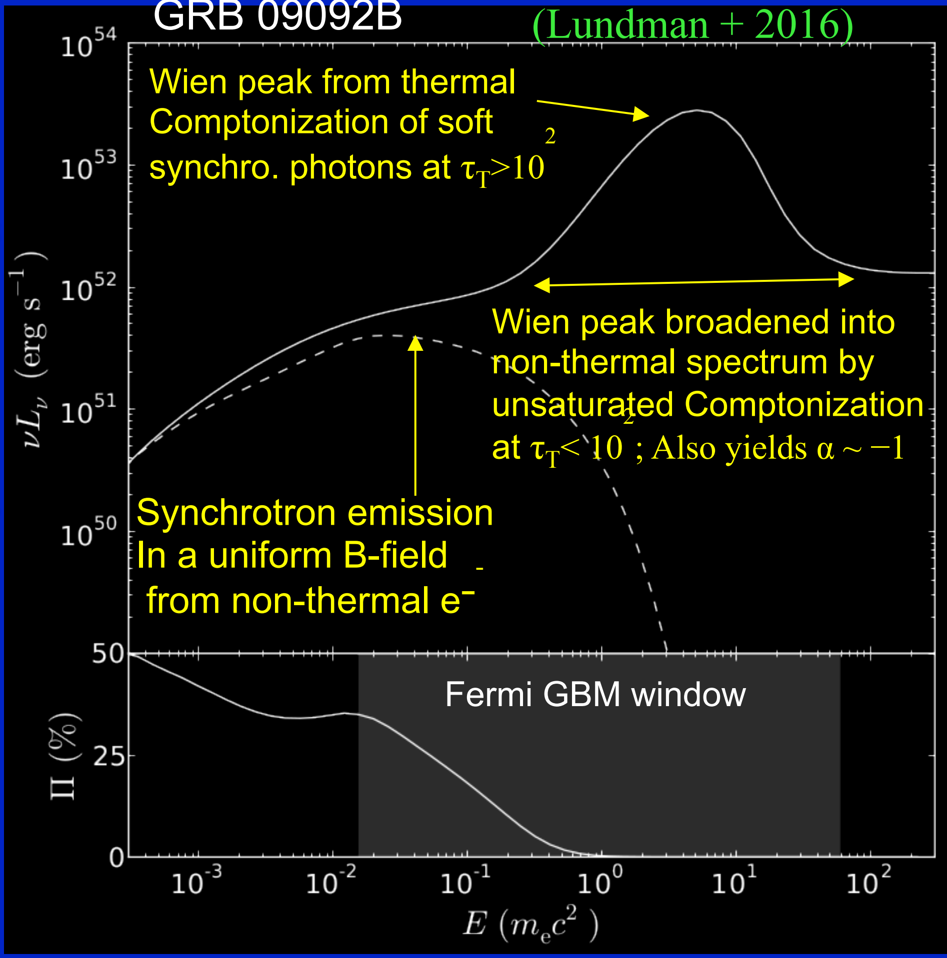
Alternative to Synchrotron: **Photospheric Emission**

(Comptonized radiation advected from optically thick to thin region of the jet)

(Beloborodov 2011; Thompson & Gill 2014; Lundman + 2014; Vurm & Beloborodov 2016; Lundman + 2016)

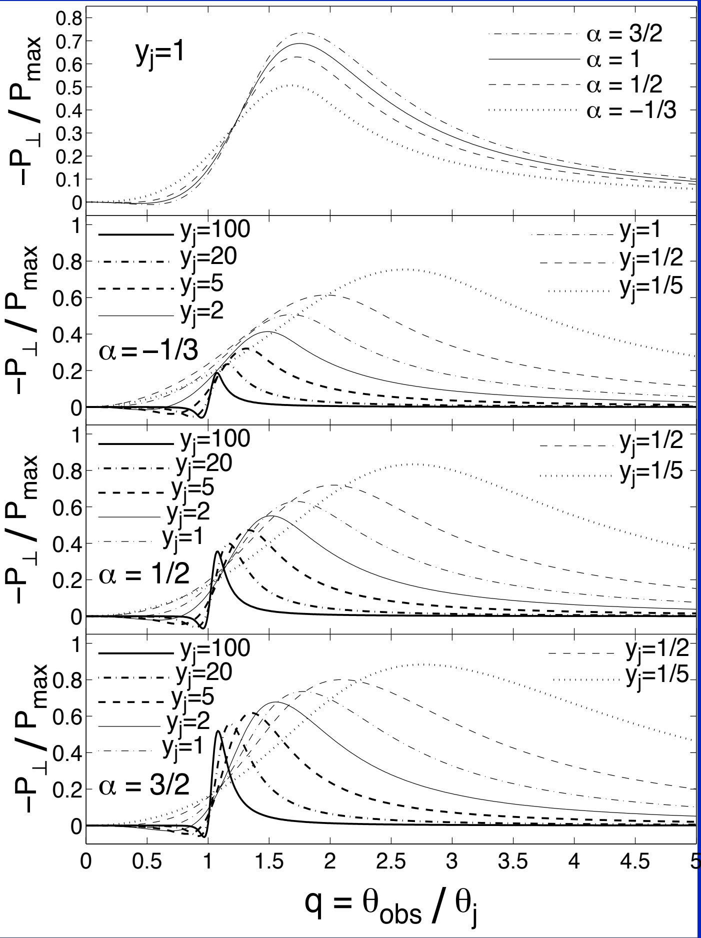
- Need to integrate radiation transfer equations for the Stokes parameters $I(r,\mu)$ & $Q(r,\mu)$ from $\tau_T \gg 1$ to $\tau_T \ll 1$.
- $P=0$ seed photons become anisotropic at $\tau_T \lesssim 10 \Longrightarrow P \approx 0.45P_{\text{Compton-drag}}$
- This requires symmetry breaking e.g.
  - special viewing angle: $|\theta_{obs} - \theta_j| \lesssim 1/\Gamma$
  - θ-dependent bulk-Γ and/or luminosity (in structured jets $P \leq 40\%$)

- Synchrotron + B_{ord} (spherical flow): Unscattered syn. photons emitted at $\tau_T{\sim}1$ dominate at $E \ll E_{pk} \Rightarrow P \sim P_{syn,max}$



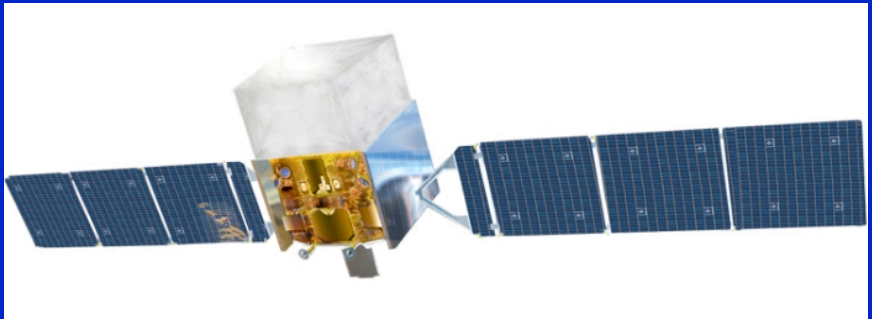
Different Pulses in the same GRB:

- Harder to measure (requires very bright GRB), more rewarding
- $\theta_j = \text{const}^*$, Γ varies $\Rightarrow$ $q = \theta_{obs}/\theta_j = \text{const}^*$, $y_j = (\Gamma\theta_j)^2$ varies
- Synchrotron + B_{ord}: $\theta_p = \text{const}$, $P \sim P_{max} \sim 50\%$ also when integrating over all the GRB pulses
- Models requiring special viewing angle (Synchrotron+B_{rnd}, Compton drag, photospheric emission) $\theta_j < \theta_{obs} \lesssim \theta_j + 1/\Gamma$:
  - For a **sharp-edged jet** the special condition on θ_{obs} occurs only in some pulses $\Rightarrow$ P varies between pulses (θ_p may flip by 90°) $\Rightarrow$ smaller integrated P over all the GRB
  - For a **smooth-edged jet**, e.g. Gaussian or core+power-law wings, P is low for any θ_{obs} even in a single pulse (unless $\Gamma\theta_{j/c} < 1$)

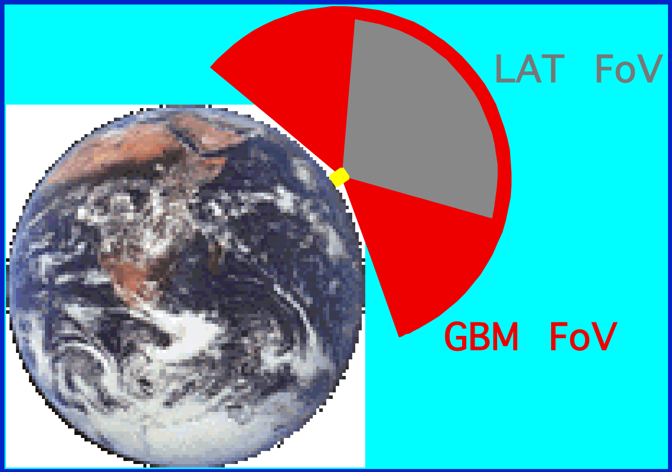


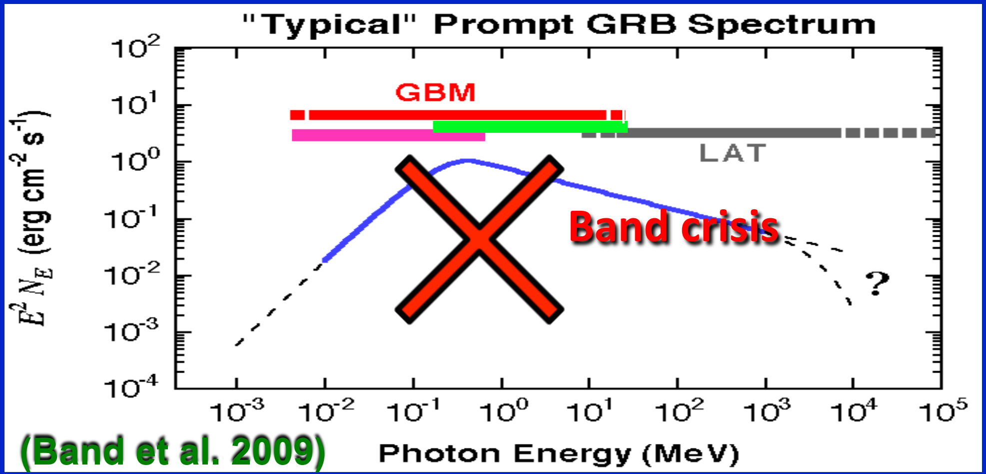
Fermi Gamma-ray Space Telescope

(launched on June 11, 2008)



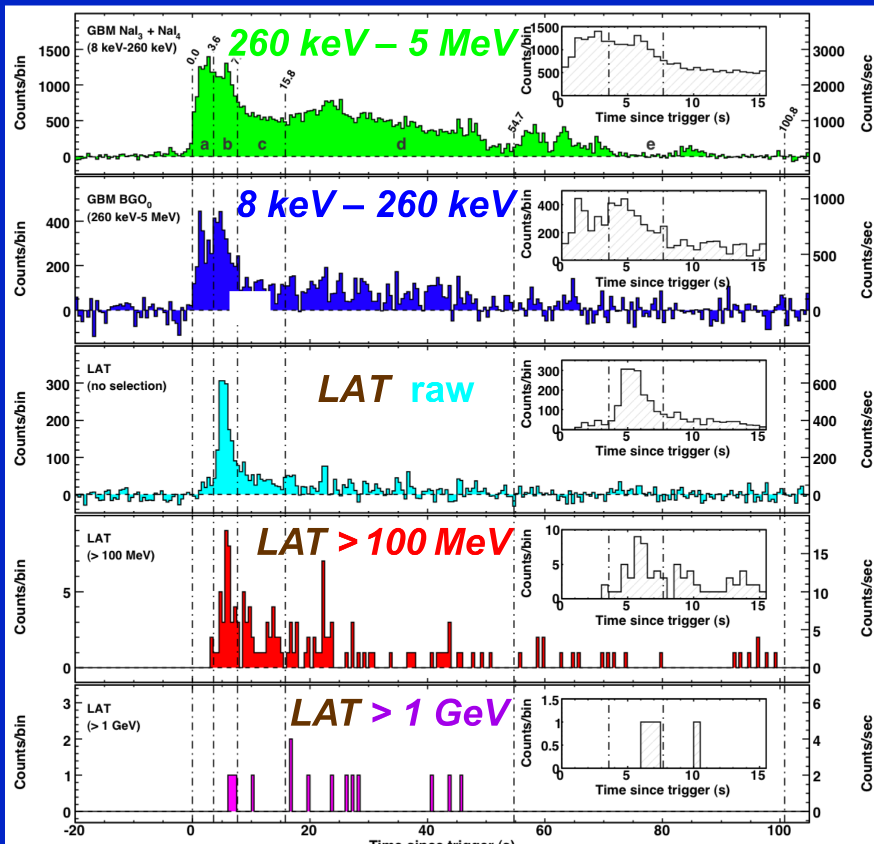
- Fermi GRB Monitor (GBM): 8 keV – 40 MeV (12×NaI 8 – 10^3 keV, 2×BGO 0.15 – 40 MeV), full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime





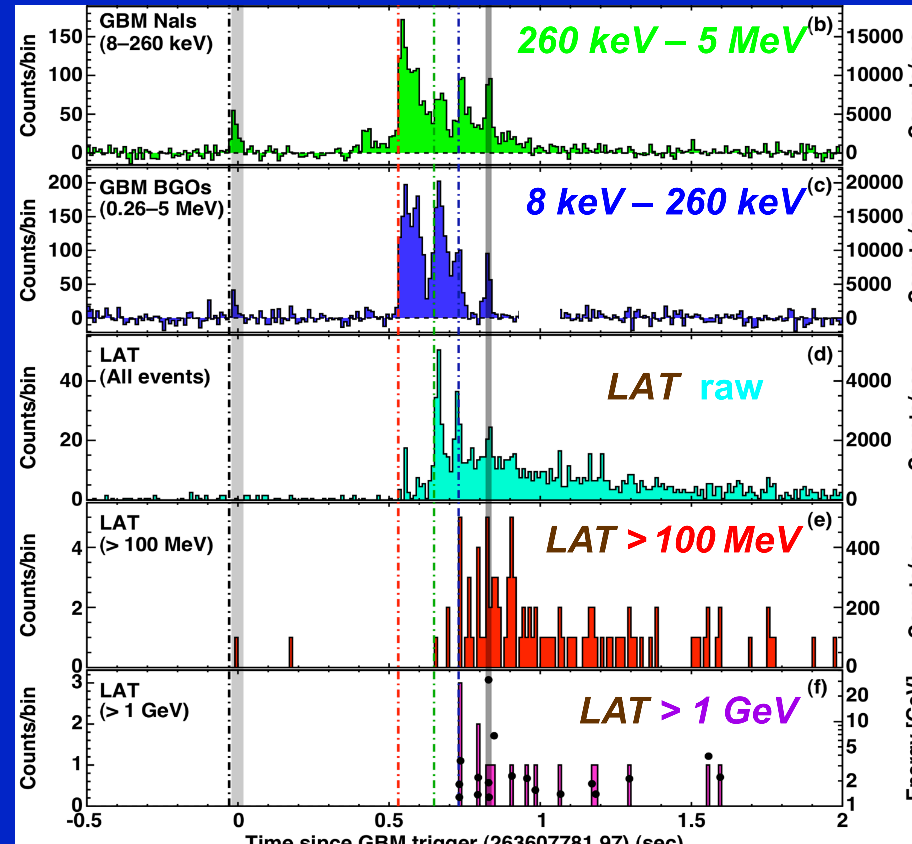
Delayed onset of High-Energy Emission

GRB080916C



(Abdo et al. 2009, Science, 323, 1688)

GRB090510

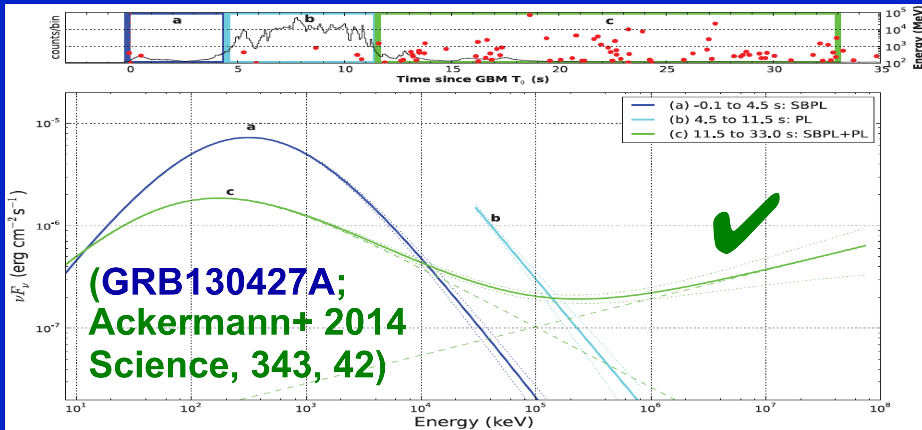


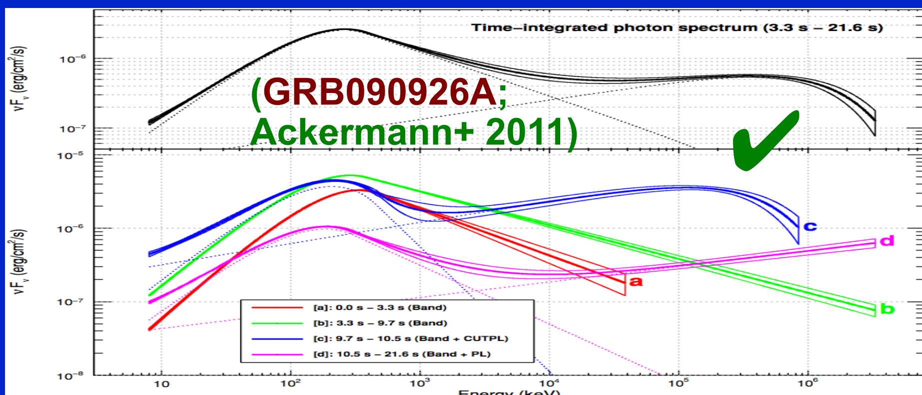
(Abdo et al. 2009, Nature, 462, 331)

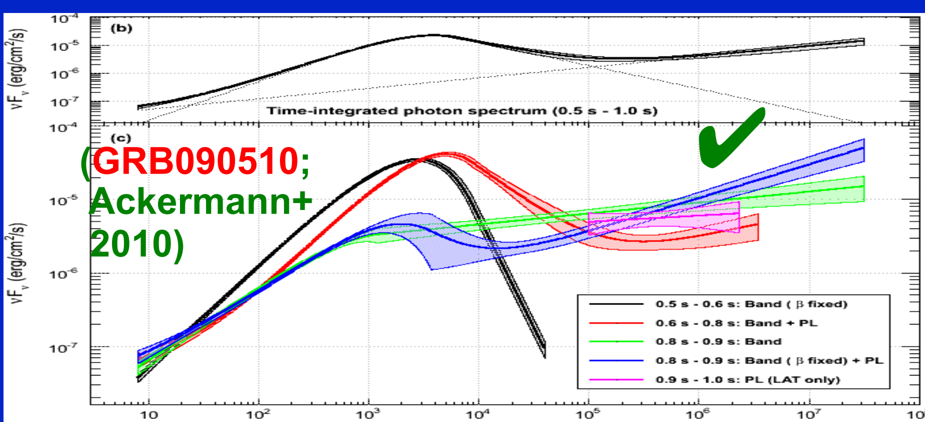
- The 1st LAT peak coincides with the 2nd GBM peak
- Delay in HE onset: ~ 4-5 s

- The first few GBM peaks are missing in LAT but later peaks coincide; the delay is 0.1-0.2 s

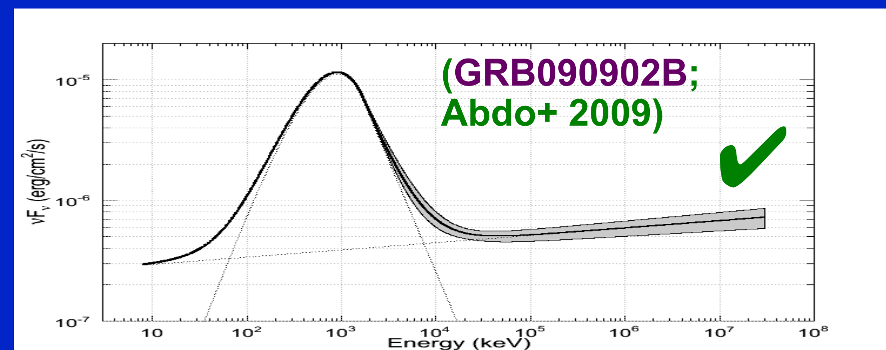
Distinct High-Energy Spectral Component

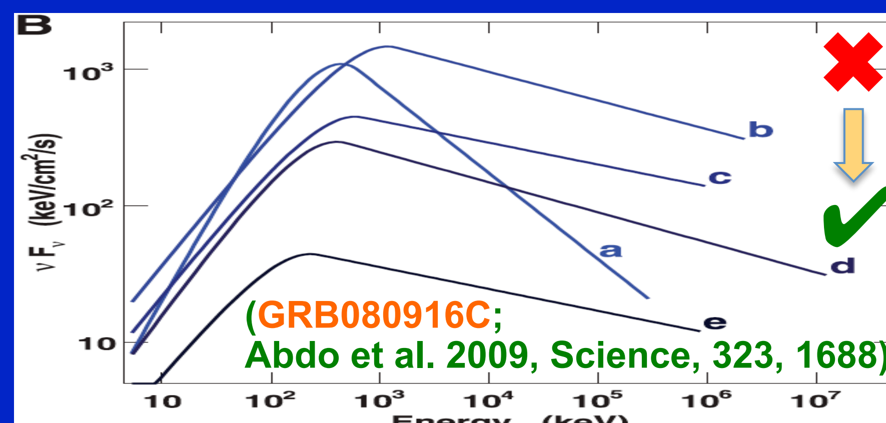






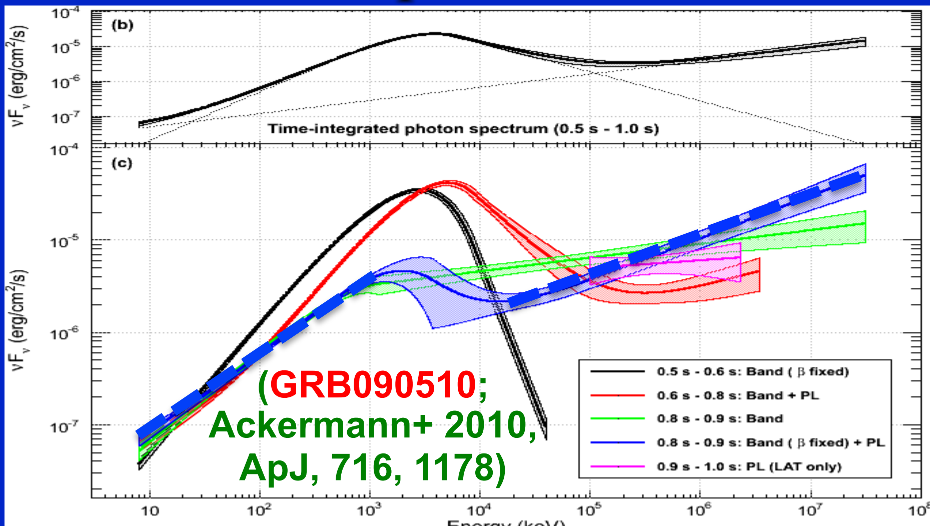
- Clearly (>5σ) exists in several LAT GRBs, but very common in the brightest LAT GRBs
- Suggests that it is common but good photon statistics is needed for clear evidence

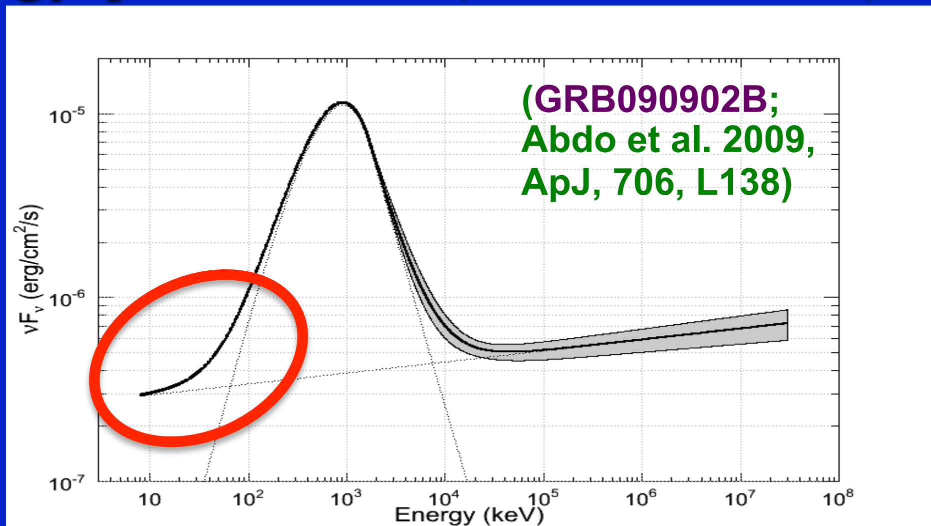




Late onset/HE spectral component: Possible Origin

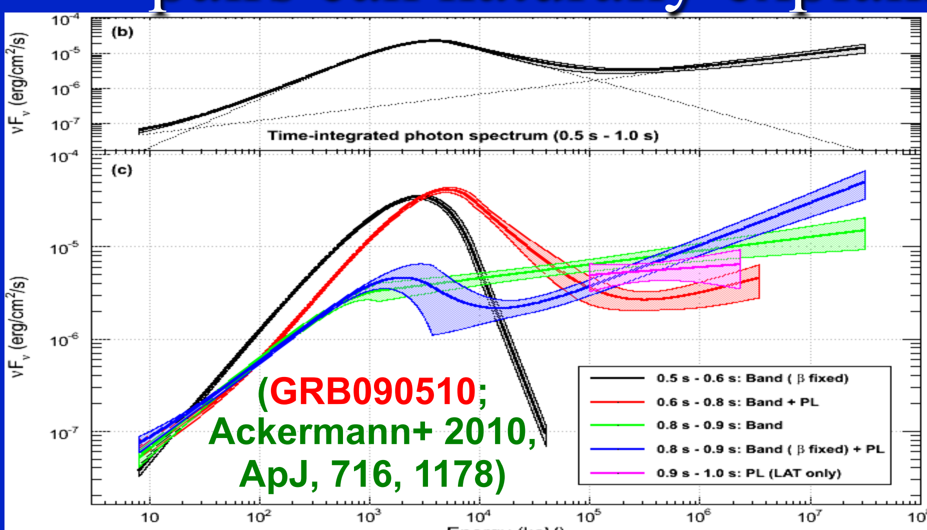
- **Leptonic**: inverse-Compton (or synchrotron self-Compton)?
  - Hard to produce a delayed onset longer than spike widths (the seed photon field builds-up on the dynamical time)
  - A gradual increase in the HE photon index **β** (determined by the electron energy dist.) is not naturally expected
  - Hard to account for the different photon index values of the HE component & the Band spectrum at low energies
  - Hard to produce a low-energy power-law (GRB090902B)

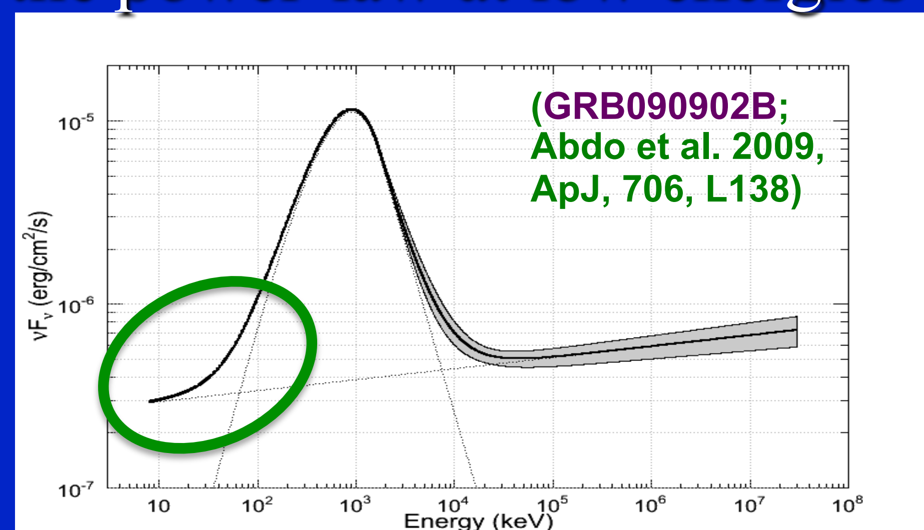




Late onset/HE spectral component: Possible Origin

- **Hadronic**: (pair cascades, proton synchrotron) ?
  - Late onset: time to accelerate protons+develop cascades?
  - Does not naturally account the gradual increase in **β**
  - Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset)
  - GRB090510: large energy needed: $E_{total}/E_{\gamma,iso} \sim 10^2 - 10^3$
  - GRB090902B: synchrotron emission from secondary $e^{\pm}$ pairs can naturally explain the power-law at low energies

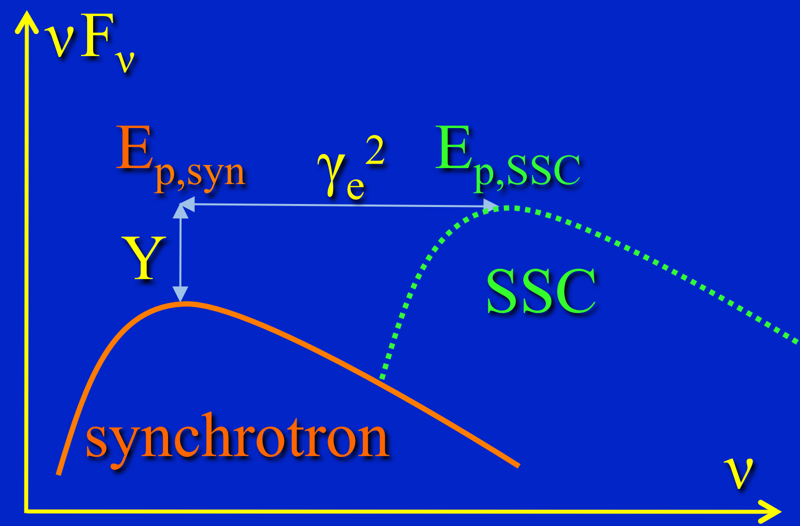




GRB: High Energy Emission Processes

- **Leptonic**: Inverse-Compton or Synchrotron-Self Compton:

  $E_{p,SSC}/E_{p,syn} \sim \gamma_e^2$, $L_{SSC}/L_{syn} = Y$, $Y(1+Y) \sim \varepsilon_{rad}\varepsilon_e/\varepsilon_B$



- **Hadronic** processes: photopair production ($p+\gamma \rightarrow p+e^+e^-$), proton synchrotron, pion production via $p-\gamma$ (photopion) interaction or p-p collisions

GRB: High Energy Emission Processes

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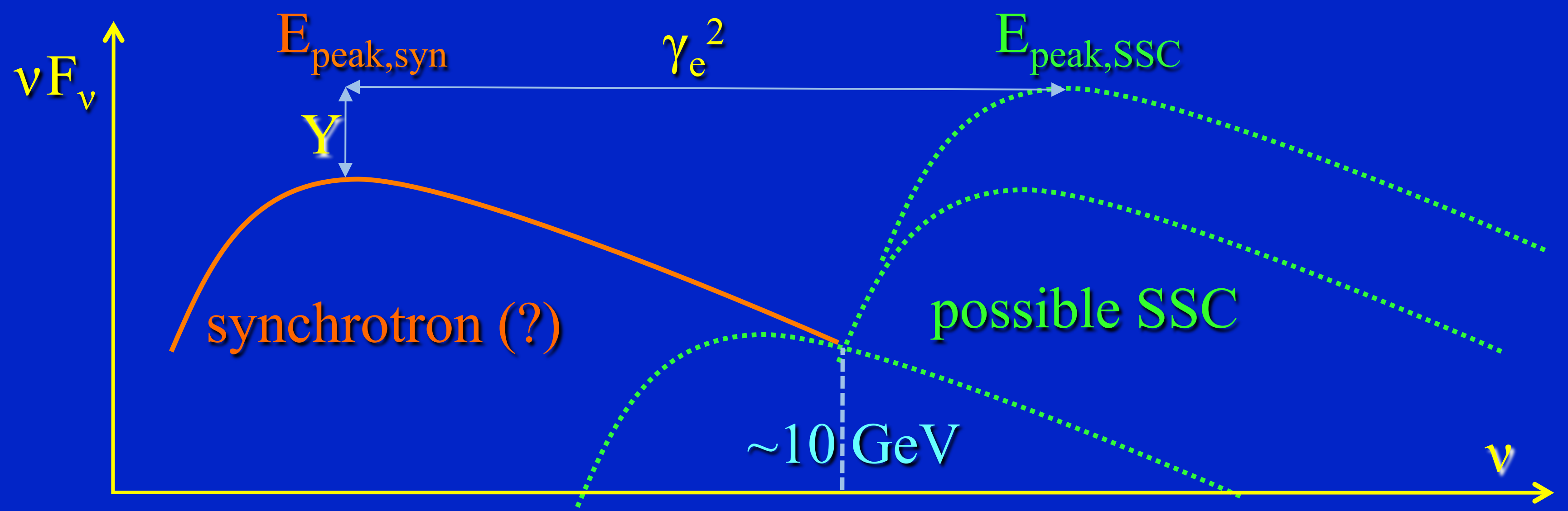
  $E_{p,SSC}/E_{p,syn} \sim \gamma_e^2$, $L_{SSC}/L_{syn} = Y$, $Y(1+Y) \sim \varepsilon_{rad}\varepsilon_e/\varepsilon_B$
- **GRBs 090510, 090926A:** Y varies, and sometimes $Y > 1$
- **GRB080916C**: single dominant emission mechanism $\Rightarrow$ if synchrotron, SSC is expected, and can avoid detection if $E_{peak,SSC} \gg 10$ GeV ($\gamma_e \gg 100$), or if $Y \approx \varepsilon_e/\varepsilon_B \lesssim 0.1$



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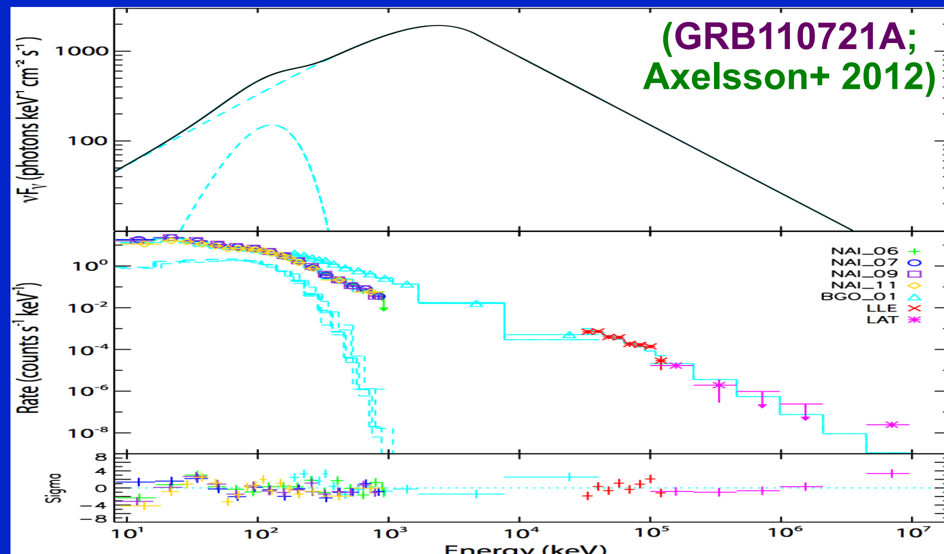
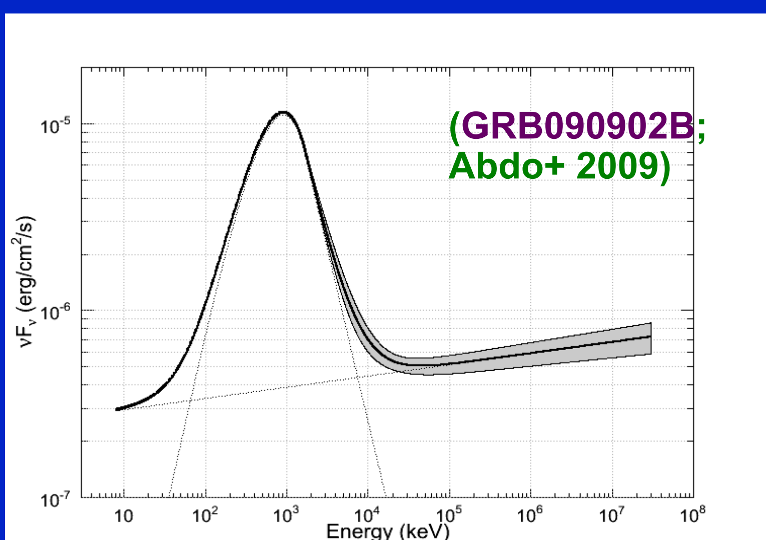
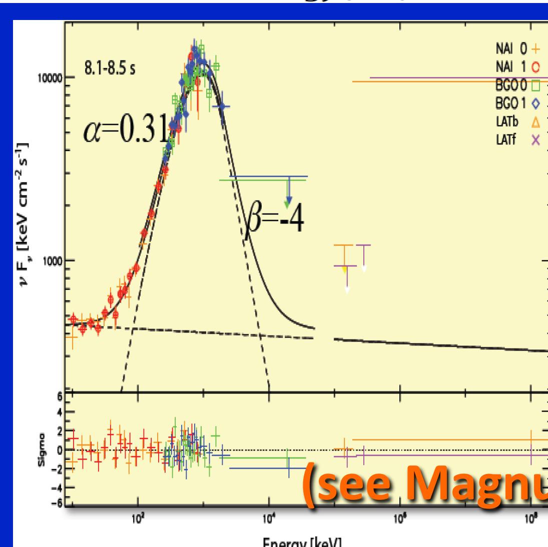
  $E_{peak,SSC} \gg 10$ GeV ($\gamma_e \gg 100$), or if $Y \approx \varepsilon_e/\varepsilon_B \lesssim 0.1$
- **Parameter space study** (Benyamini & Piran 2013):
  $0.1 < \boldsymbol{\varepsilon_e/\varepsilon_B} < 10^4$ ($0.1 \lesssim \mathbf{Y} \lesssim 100$), $300 \lesssim \boldsymbol{\Gamma} \lesssim 3000$,
  $3\times10^3 \lesssim \boldsymbol{\gamma_e} \lesssim 10^5$, 10^{15} cm $\lesssim \mathbf{R} \lesssim 10^{17}$ cm
  ($E_{peak,SSC} \sim E_{KN} \sim \Gamma\gamma_e m_e c^2 \sim 1.6(1+z)^{-1}\Gamma_{2.5}\gamma_{e,4}$ TeV $\Rightarrow$ CTA?)

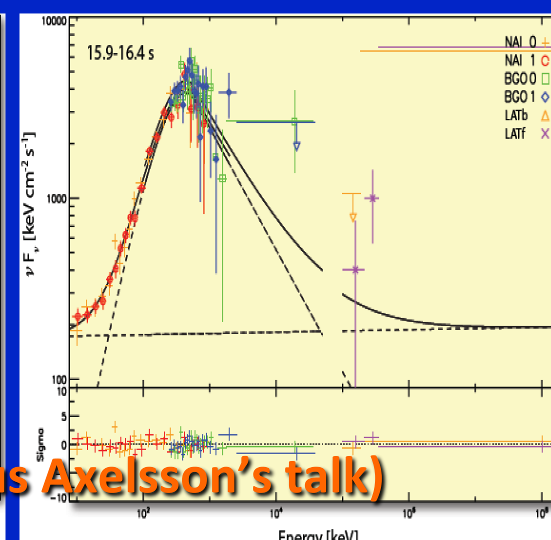
Thermal components in prompt spectrum?

- Usually **sub-dominant** ⇒ degeneracy with the assumed (usually phenomenological Band) dominant component





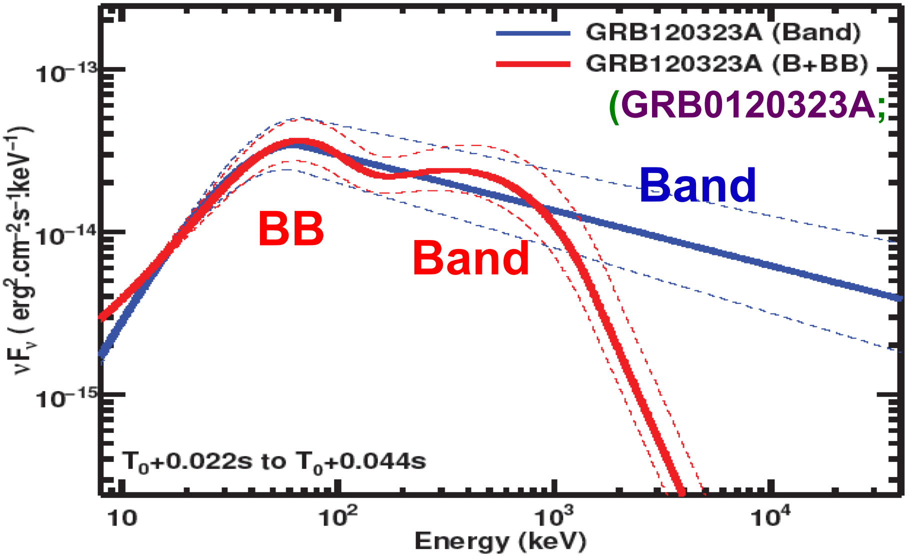




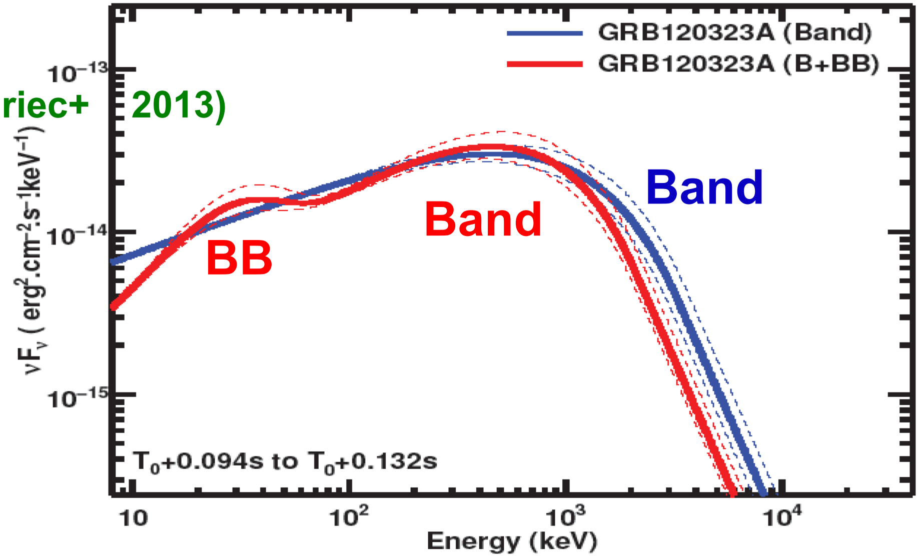
(see Magnus Axelsson's talk)

Thermal components in prompt spectrum?

- Usually **sub-dominant** ⇒ degeneracy with the assumed (usually phenomenological Band) dominant component
- Photospheric emission is not a perfect black body (BB)
  - Even for a local BB emission + a spherical flow, Doppler factor & R_{ph} variations with the angle to the line of sight smear/widen spectrum
  - Temperature variations (with time/location) smear/widen spectrum
  - Non-thermal e^-/e^+ from dissipation near R_{ph} ⇒ power-law wings
- Many options (continuum of physically motivated spectra) + many degrees of freedom ⇒ non-uniqueness (many viable options)



(GRB0120323A; Guiriec+ 2013)



Photospheric components

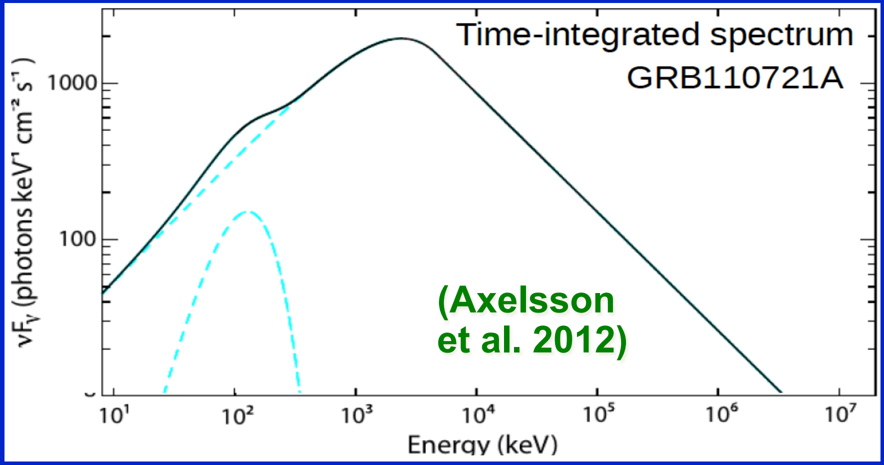
- Suggested in some cases by low energy data ($kT \lesssim 0.1$ MeV)
- Usually sub-dominant energetically (+not unique interpretation)
- In the **Fireball Model**: a remnant of the thermal acceleration

$$E_{ph}/E = T_{ph}/T_0 = 0.05 E_{52}^{-2/3} R_{0,6}^{2/3} t_1^{2/3} \Gamma_{2.5}^{8/3}$$ (Nakar et al. 2005)

$$kT_0 = 3(1+z)^{-1} E_{52}^{1/4} R_{0,6}^{-1/2} t_1^{-1/4} \text{ MeV}$$ $t = T_{GRB}/(1+z)$

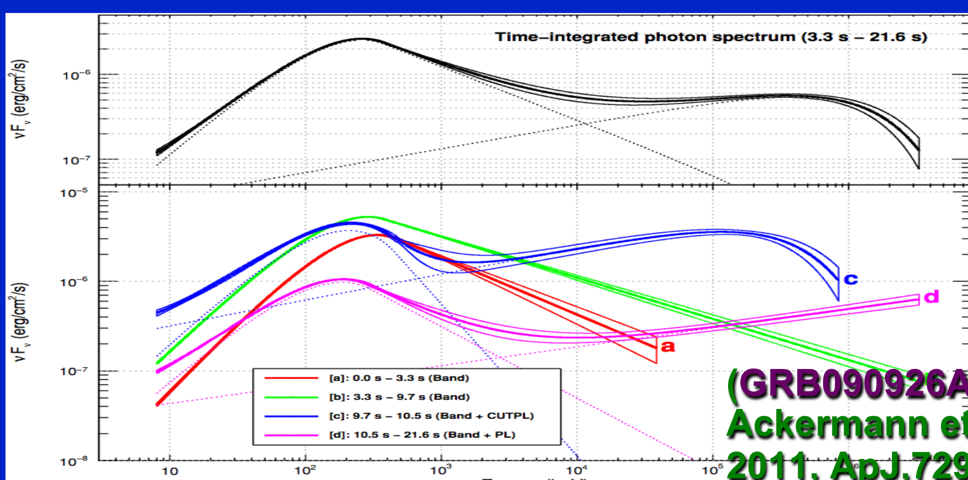
$$kT_{\mathbf{ph}} = 300(1+z)^{-1} \mathbf{E_{th,51}} E_{52}^{1/4} R_{0,6}^{-1/2} t_1^{-1/4} \text{ keV}$$

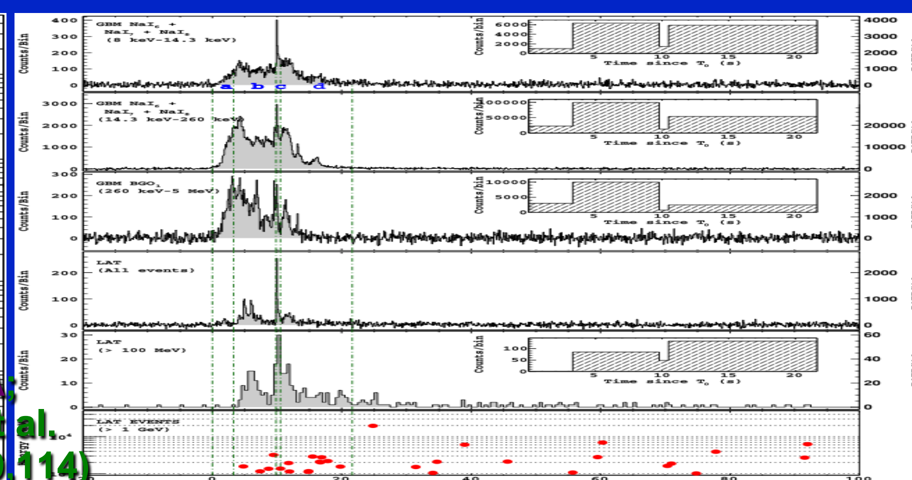
- For **magnetic** acceleration:
  - Dissipation below the photosphere can give such a spectral component
  - can arise from gradual reconnection or multiple passages of weak shocks



Constraints on Γ for Fermi LAT GRBs

- Γ_{min}: no high-energy cutoff due to intrinsic pair production
  $\Rightarrow$ lower limit on the Lorentz factor of the emitting region
- **Fermi**: more robust limits – don't assume photons $>E_{obs,max}$
- $\tau_{\gamma\gamma} \propto \Gamma^{2\beta}/R \Rightarrow \Gamma_{min}$ requires assuming $R(\Gamma)$ (e.g. $R \sim \Gamma^2 c\Delta t$)
- For bright LAT GRBs (long/short): $\mathbf{\Gamma \gtrsim 10^3}$ for simple model (steady-state, uniform, isotropic) but $\mathbf{\Gamma \gtrsim 10^{2.5}}$ for more realistic time-dependent self-consistent thin shell model (**JG et al. 2008**)
- **GRB 090926A**: high-energy cutoff – if due to intrinsic pair production then $\mathbf{\Gamma \sim 300 - 700}$





(GRB090926A; Ackermann et al. 2011, ApJ,729,114)

Γ_{min}: The Compactness Problem:

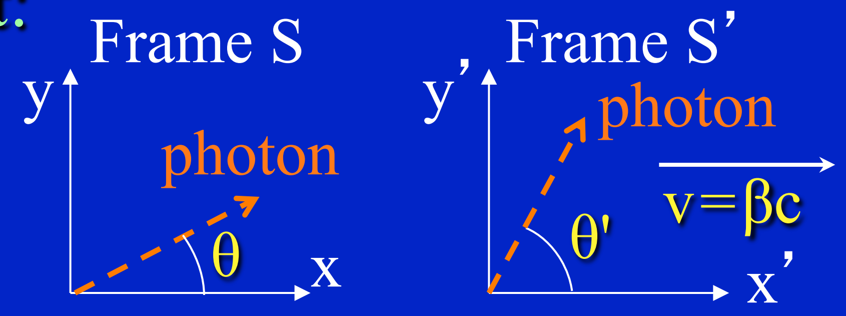
(Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;…)

- The large γ-ray flux implies huge luminosities for cosmological GRBs, $L_{iso} \sim 10^{50} - 10^{53}$ erg/s
- For sources at rest: short variability time $\Delta t \Rightarrow$ small source $R < c\Delta t$ & $\varepsilon = E_{ph}/m_e c^2 \sim 1 \Rightarrow$ large fraction of γ's can pair produce ($\gamma\gamma \rightarrow e^+e^-$)
- $\tau_{\gamma\gamma}(\varepsilon) \sim \sigma_T n_{ph}(1/\varepsilon)R$, $n_{ph}(1/\varepsilon) \sim L_{1/\varepsilon}/4\pi R^2 m_e c^3 \Rightarrow$ $\tau_{\gamma\gamma}(\varepsilon) \sim \sigma_T L_{1/\varepsilon}/4\pi m_e c^3 R \gtrsim 10^{14} L_{1/\varepsilon,51}(\Delta t / 1\text{ ms})^{-1}$
- Such a huge $\tau_{\gamma\gamma}$ would produce a thermal spectrum $\Rightarrow$ inconsistent with the observed high energy tail

Solution: Relativistic Motion $\Gamma \gg 1$

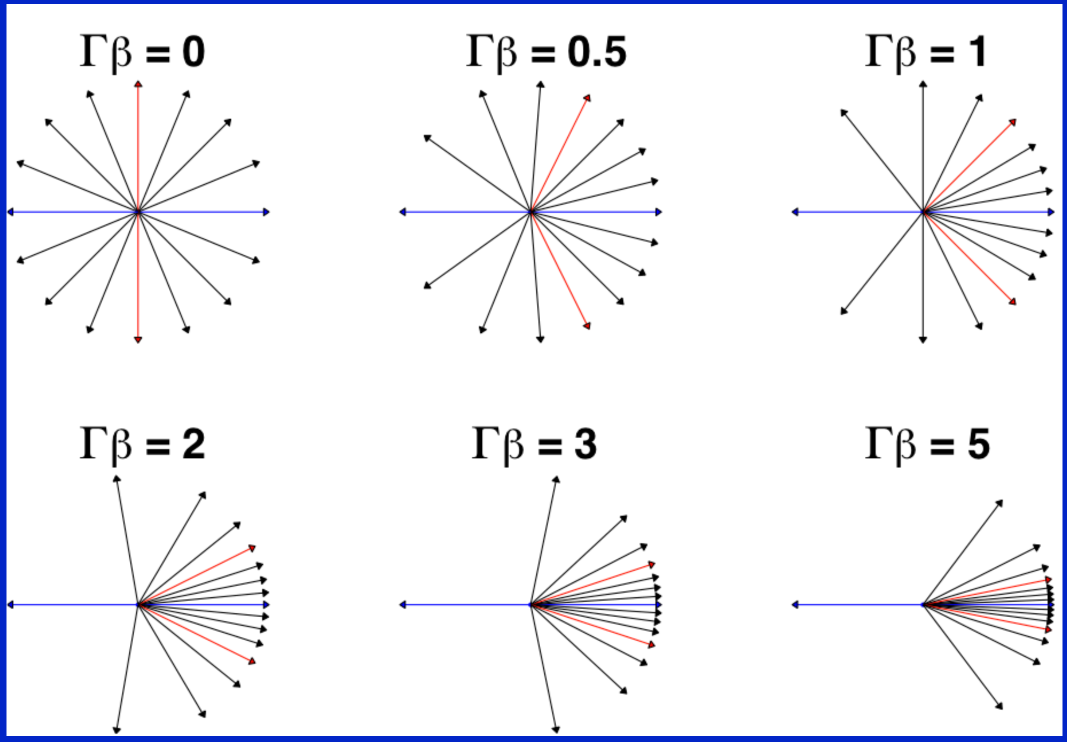
- The effects of special relativity help us out here:
- The (relativistic) **Doppler effect**:

  $E_{ph}/E'_{ph} = 1/\Gamma(1-\beta\cos\theta) \sim \Gamma$



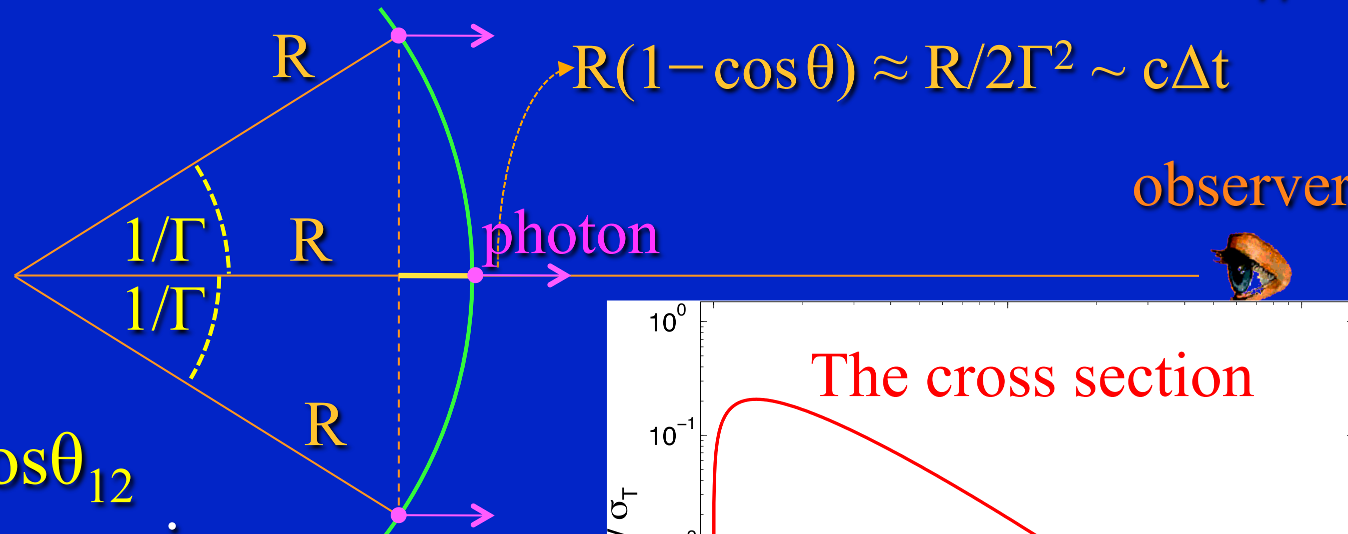
- Aberration of light or **relativistic beaming**:
  - For $\theta' = 90°$, $\cos\theta = \beta$ ($\theta \approx 1/\Gamma$ for $\Gamma \gg 1$)

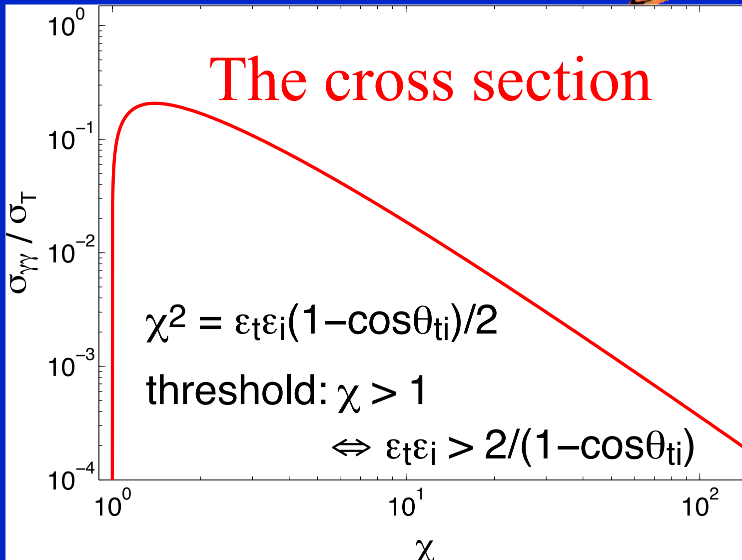
The direction of photons in the lab frame for a point source emitting isotropically in its own rest frame and moving to the right at different proper speeds $\Gamma\beta$:



Solution: Relativistic Motion $\Gamma \gg 1$

- Emission region can be larger: $R \lesssim \Gamma^2 c\Delta t$ (factor Γ^{-2} in $\tau_{\gamma\gamma}$)





- Factor of $1-\cos\theta_{12}$ ($\sim\Gamma^{-2}$) in $\tau_{\gamma\gamma}$ expression
- $\gamma\gamma \to e^+e^-$ threshold: $\varepsilon_1\varepsilon_2 \gtrsim \Gamma^2$ (factor $\Gamma^{2(1+\beta)}$, where $L_\varepsilon \propto \varepsilon^{1+\beta}$)
- Total reduction in $\tau_{\gamma\gamma}$: $\Gamma^{2(\beta-1)}$

  $\Rightarrow$ since $-\beta \sim$ 2-3, $\tau_{\gamma\gamma} < 1$ typically implies $\Gamma > \Gamma_{min} \sim 100$

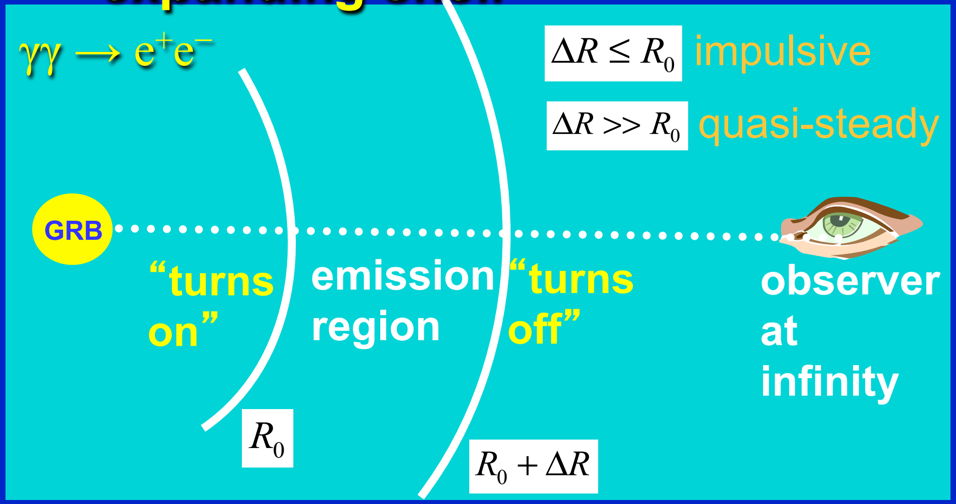
$$\tau_{\gamma\gamma}(\varepsilon_t) = \int ds \int d\varepsilon_i \int d\Omega_i\, \sigma_{\gamma\gamma}[\chi(\varepsilon_t,\varepsilon_i,\theta_{ti})](1-\cos\theta_{ti})\frac{dn_i}{d\Omega_i d\varepsilon_i}$$

Time Dependence of Intrinsic $\gamma\gamma \rightarrow e^+e^-$ Opacity

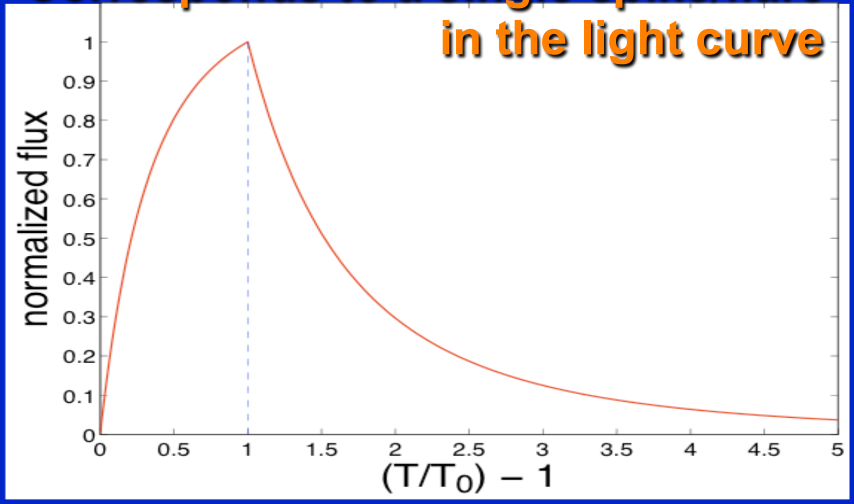
Semi-Analytic Model (JG, Cohen-Tanugi & do Couto e Silva 08)

- Ultra-relativistic ($\Gamma \gg 1$) spherical thin ($\Delta \ll R/\Gamma^2$) shell emits over a finite range of radii $R_0 \leq R \leq R_0+\Delta R$
- Emission: uniform over the shell & isotropic in its local (co-moving) rest frame; $L'_{\nu'} \propto (\nu')^{1-\alpha} R^b$, $\Gamma^2 \propto R^{-m}$
- F_ν calculated by integral over **equal arrival time surface**
- The photon field is fully calculated at **all space & time**
- $\tau_{\gamma\gamma}$ calculated by **integral along trajectory** of each photon

expanding shell

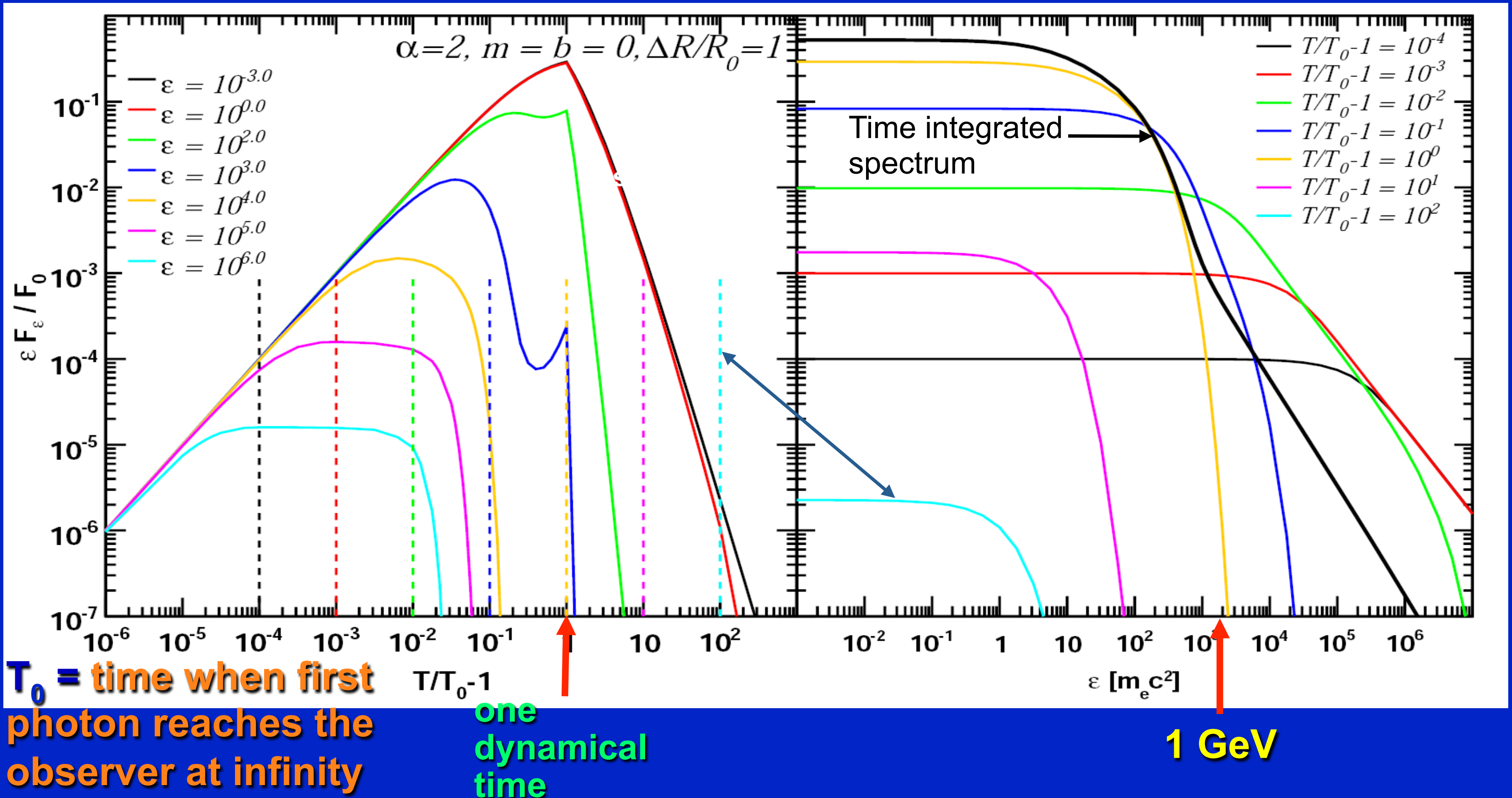


Corresponds to a single spike/flare in the light curve



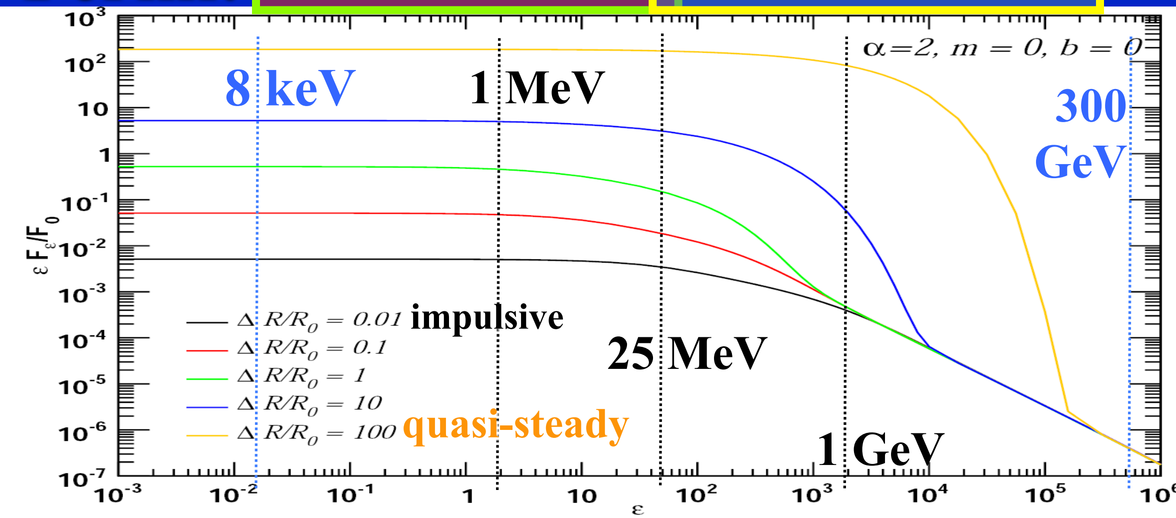
Results: Light Curves & Instantaneous Spectra

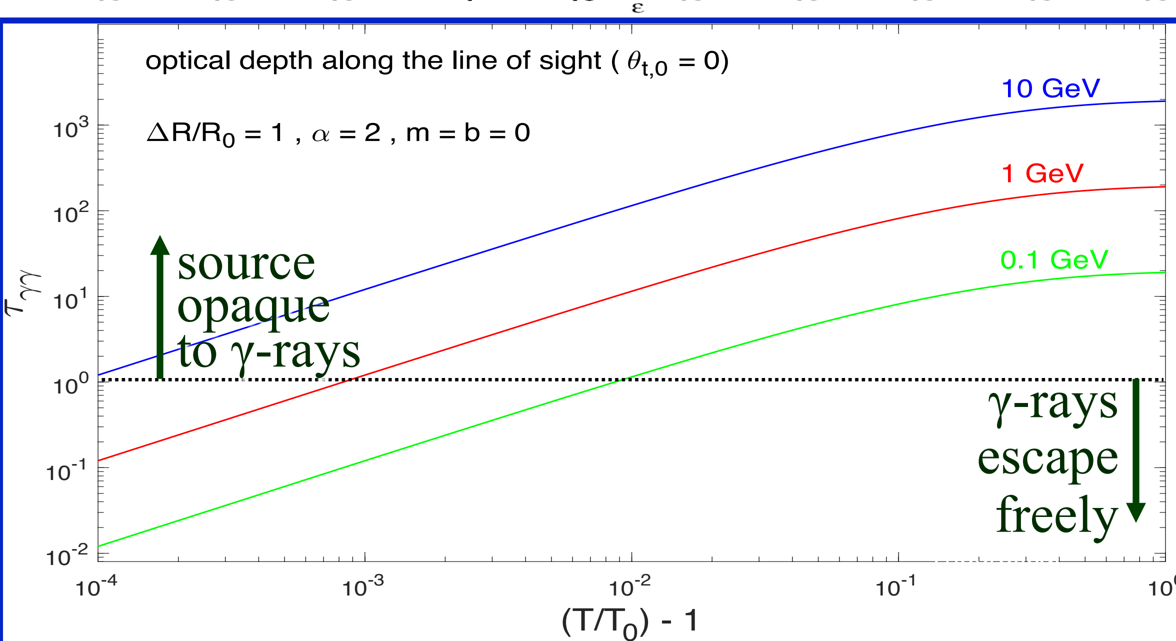
- There is no initial photon field - opacity gradually builds-up: $\varepsilon > \varepsilon_1$(steady state) photons can escape early on while $\varepsilon_1(t) > \varepsilon$
- $\Rightarrow$ a distinct temporal & spectral signature



Time Integrated Spectrum: power-law high energy tail

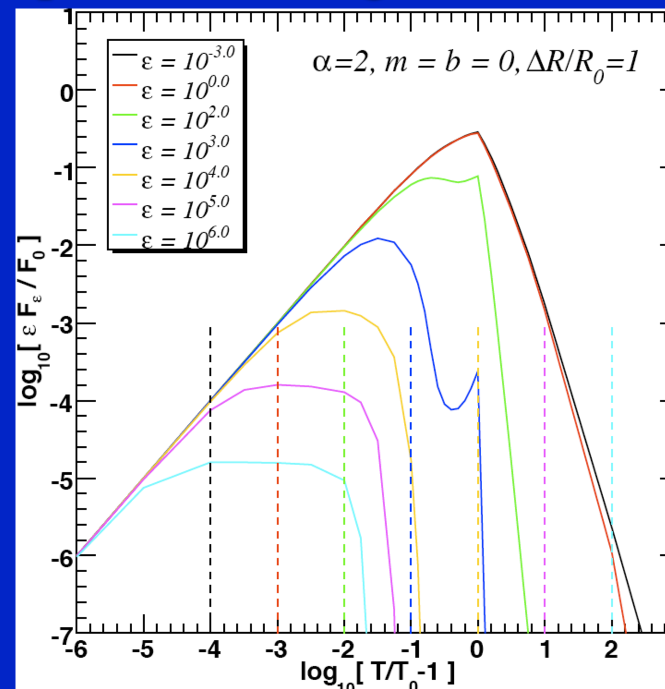
Fermi: GBM LAT





Unique signature:

High-energy γ-rays above break in time integrated spectrum escape mainly near the onset of a flare/ spike in the light curve



The opacity builds-up & saturates on a dynamical time scale

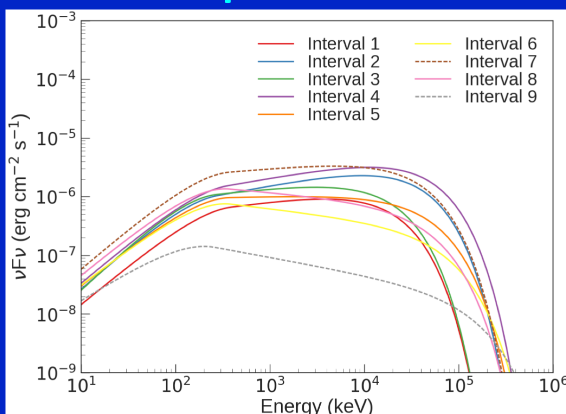
Spectral Cutoffs at ~100 MeV

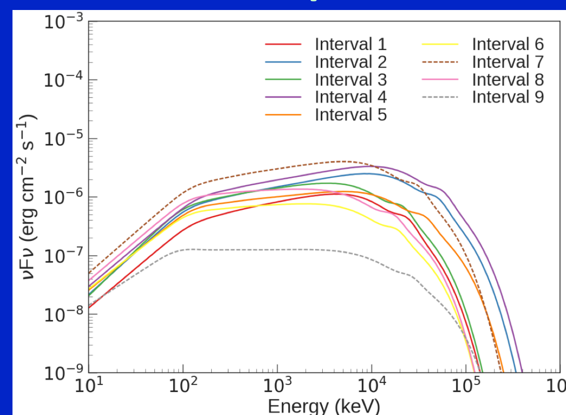
(Vianello, Gill, Granot, Omodei, Cohen-Tanugi & Longo 2017)

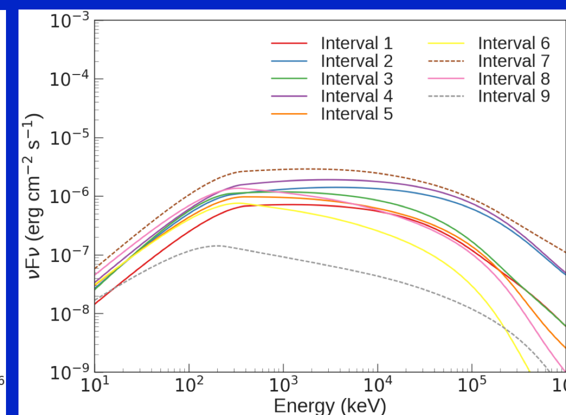
- Time-resolved spectra of 2 GRBs with cutoffs $E_c \lesssim 100\,\mathrm{MeV}$
- Best fit phenomenological model + 2 theoretical models fits
- Gill & Thompson 2014: photospheric (high-σ breakout from star)

Band + exponential cutoff | **Gill & Thompson 2014** | **Granot et al. 2008**

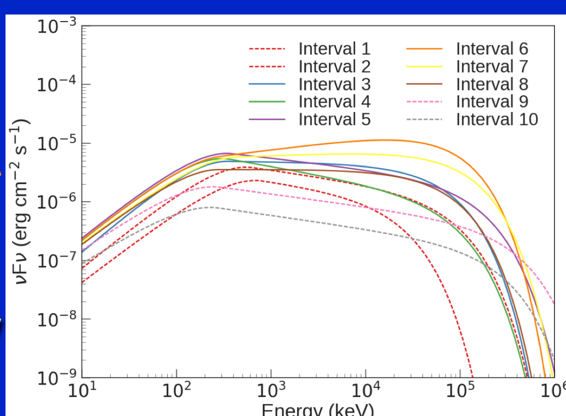
GRB 100724B
$E_c \sim$ 20 – 60 MeV

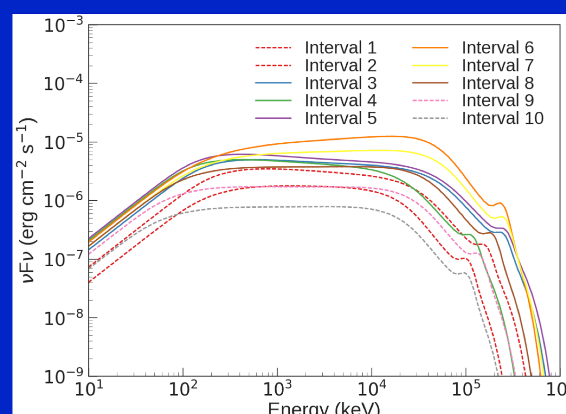


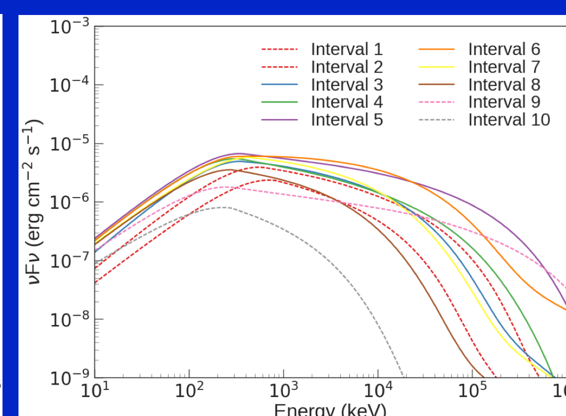




GRB 160509A
z = 1.17
$E_c \sim$ 80 - 150 MeV





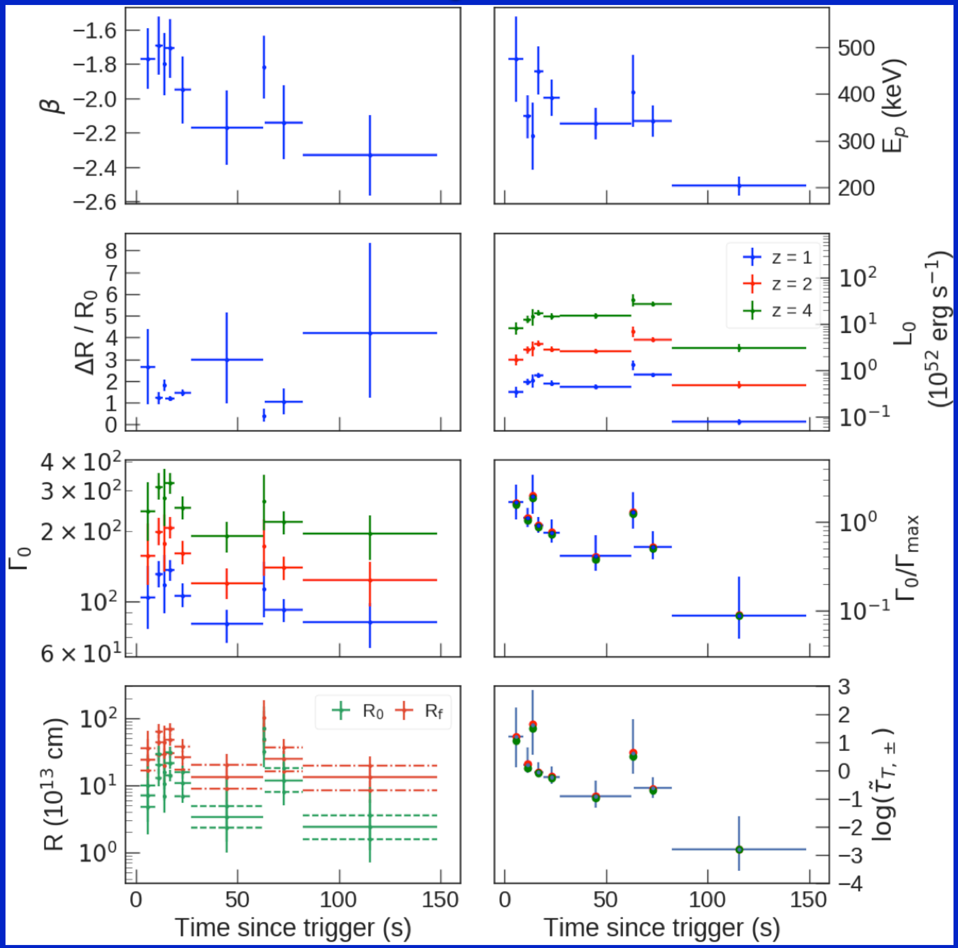


Spectral Cutoffs at ~100 MeV

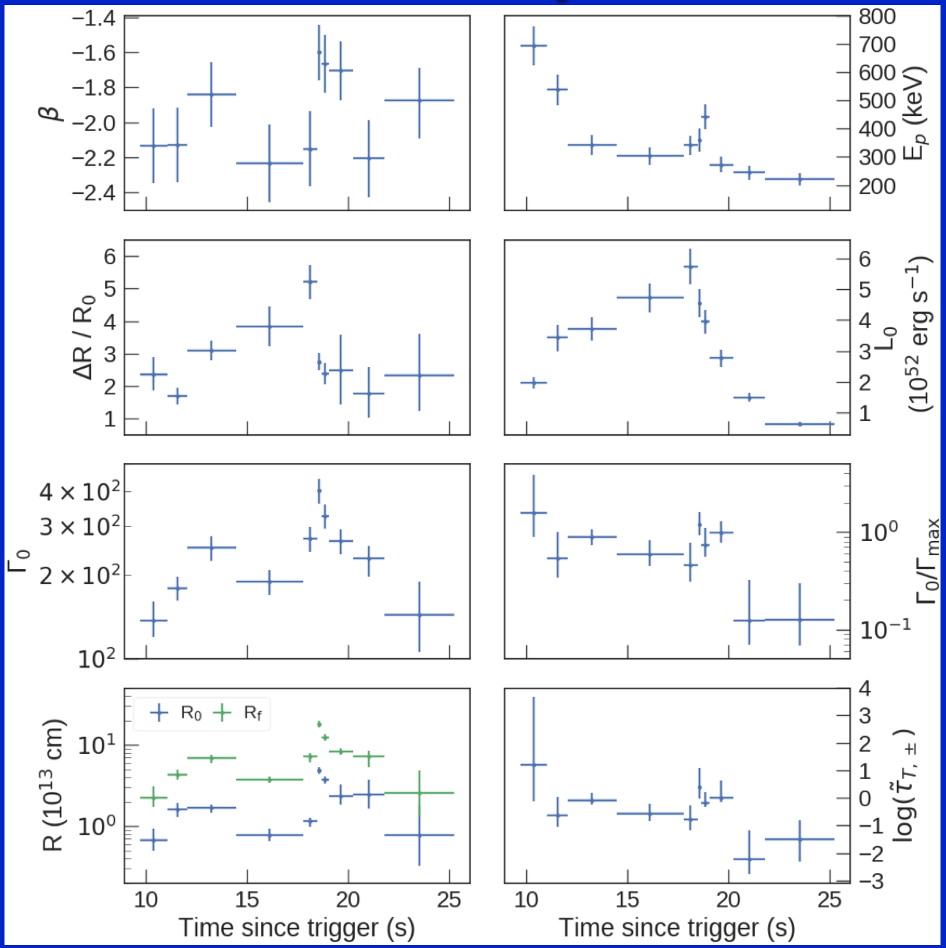
(Vianello, Gill, Granot, Omodei, Cohen-Tanugi & Longo 2017)

- Granot et al. 2008: model parameters inferred from the fits:
- $\varepsilon'(\Gamma_{max}) = 1 \Rightarrow$ model is self-consistent for $\Gamma_0 < \Gamma_{max}$ ($\tau_{T\pm} < 1$)

GRB100724B $E_c \sim$ 20 – 60 MeV



GRB160509A z = 1.17 $E_c \sim$ 80 - 150 MeV



Thank You