# GRB Prompt Emission Mechanism: Implications of Fermi Observations


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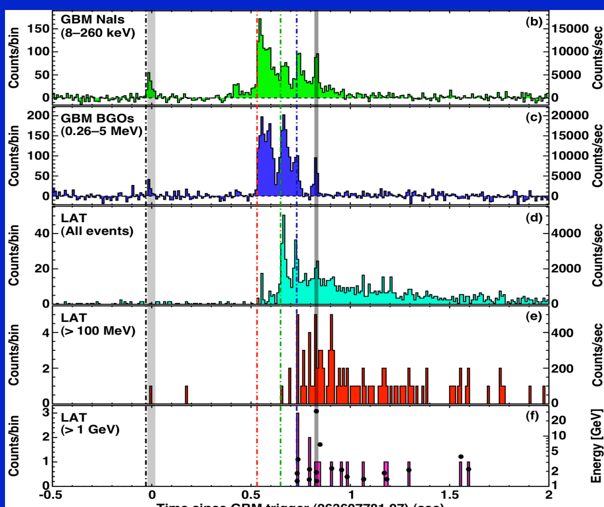
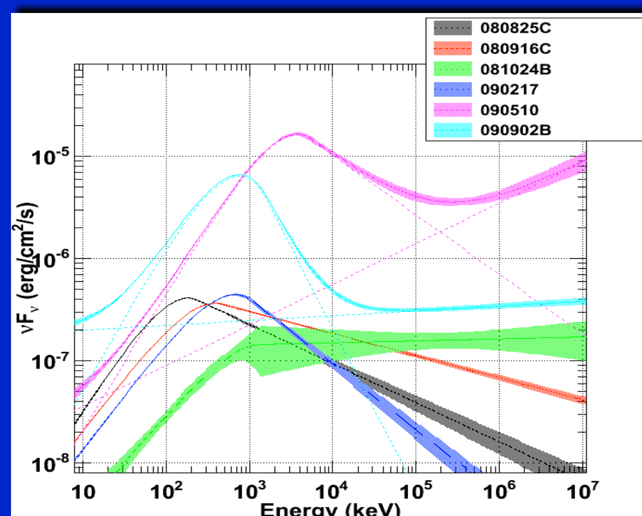
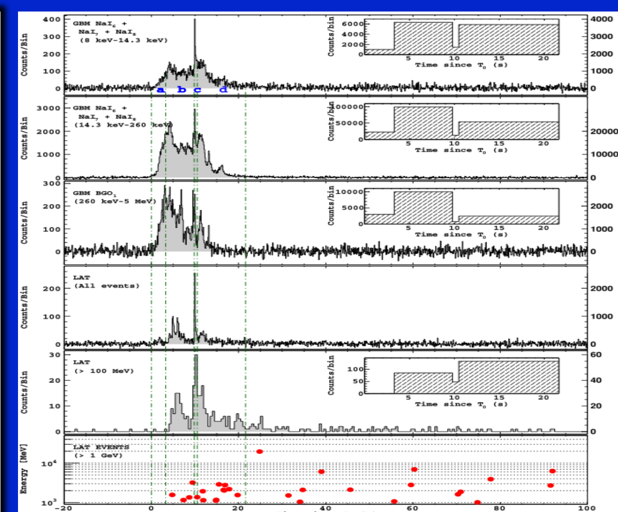


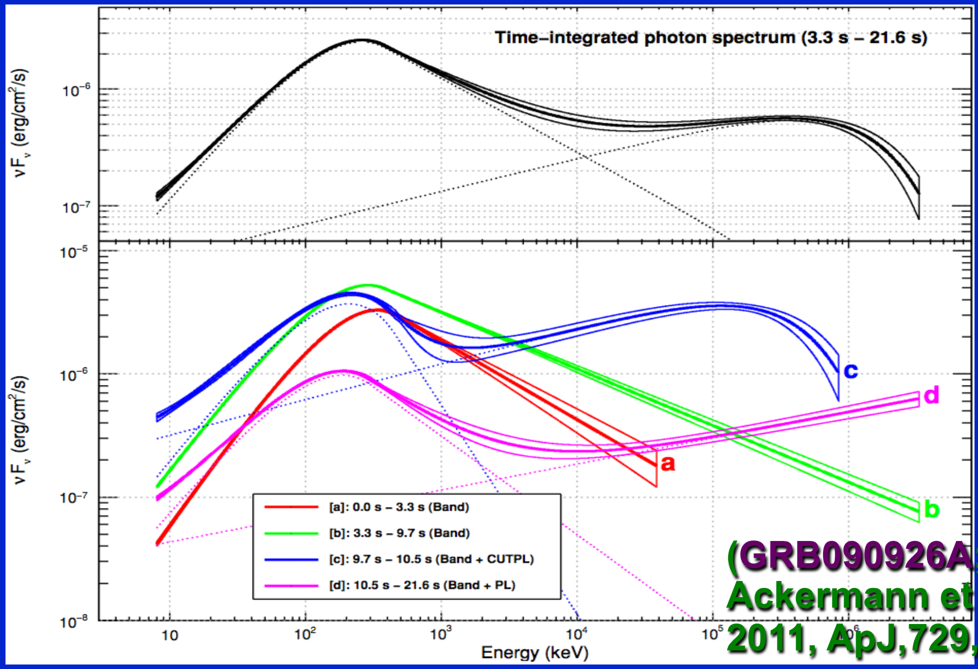



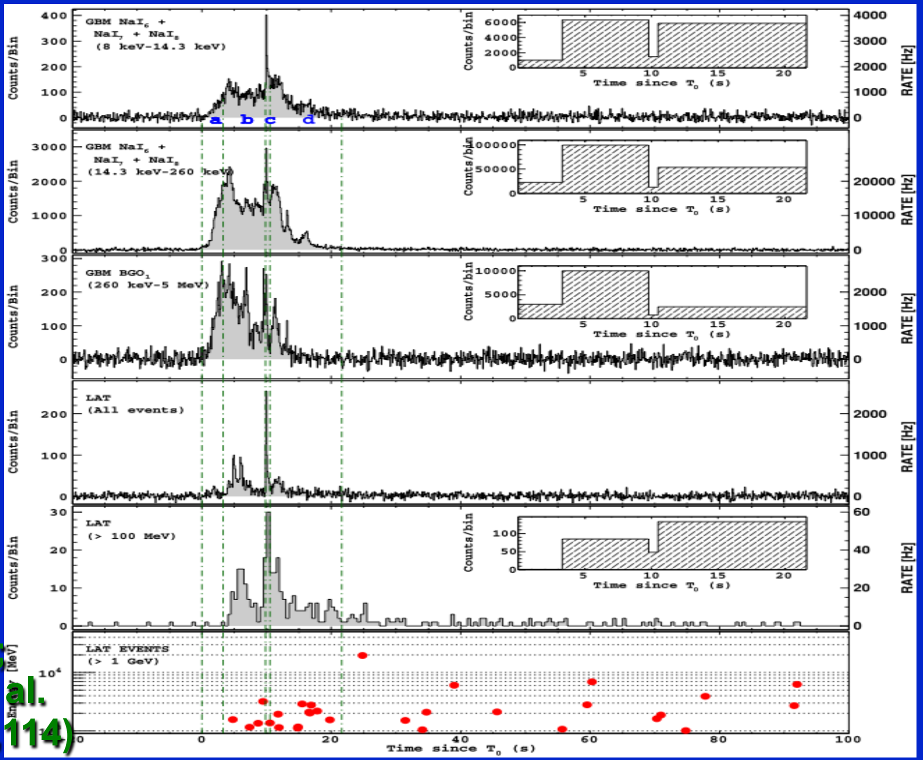



## 13th Meeting of the High Energy Astrophysics Division of the AAS, Monterey, California, April 10, 2013

# Constraints on Γ for Fermi LAT GRBs

- $\Gamma_{min}$: no high-energy cutoff due to intrinsic pair production
  $\Rightarrow$ lower limit on the Lorentz factor of the emitting region
- For bright LAT GRBs (long/short): $\Gamma \gtrsim 10^3$ for simple model (steady-state, uniform, isotropic) but $\Gamma \gtrsim 10^{2.5}$ 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 $\Gamma \sim 200 - 700$



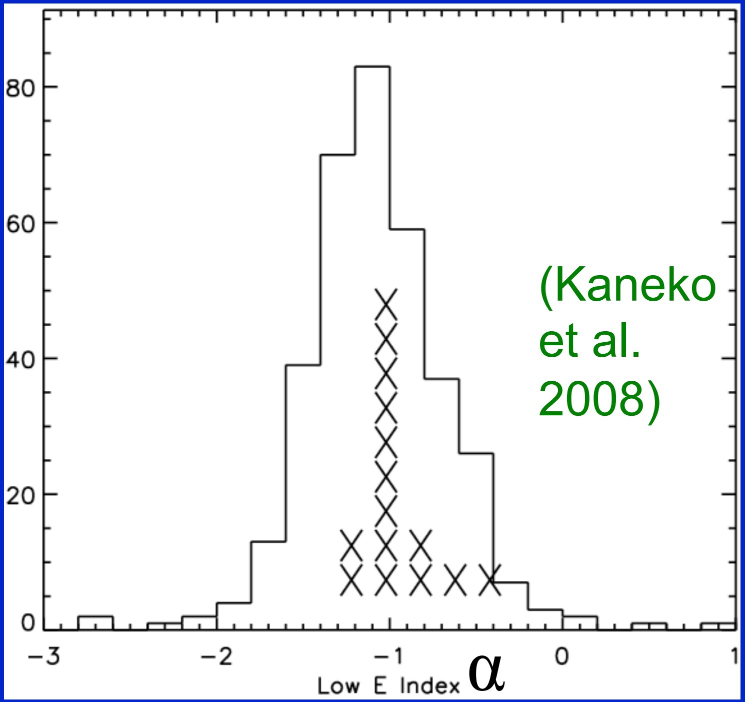

(GRB090926A; Ackermann et al. 2011, ApJ,729,114)

# Outflow Acceleration & Dissipation:

- **Fireball**: thermal acceleration (by radiation pressure)
  - Fast ($\Gamma \propto R$), robust, allows efficient internal dissipation
  - Baryon kinetic energy eventually dominates
  - Requires a small baryon loading ($\sim 10^{-5}\ M_{\odot}$)
  - Naturally produces internal shocks (dissipate $\lesssim 10\%$ of energy)
  - n-p collisions in a neutron rich outflow
- **Magnetic** acceleration: Poynting flux dominated jets
  - Can naturally produce a small baryon loading
  - Steady, axisymmetric, ideal-MHD: slow, not robust or efficient
  - Gradual dissipation (of alternating fields or instability induced) can enhance the acceleration & contribute to the radiation
  - Strong time dependence: enhances acceleration & dissipation
  - Fast **reconnection** can accelerate particles, produce relativistic turbulence, spikes in lightcurve & high radiative efficiencies

# Candidate Prompt Emission Processes

- **Leptonic:** ($dN/dE \propto E^{-\alpha}$ below $E_{peak}$)
  - Inverse-Compton or Synchrotron-Self Compton (HE?)
  - Synchrotron (optically thin: $\alpha \le -2/3$ ; fast cooling: $\alpha \le -3/2$)
  - Jitter (similar to synchrotron but from tangled B-field; $\alpha \le 0$)
  - Photospheric (not always BB; $\alpha \sim 1$ ; also from high-$\sigma$)



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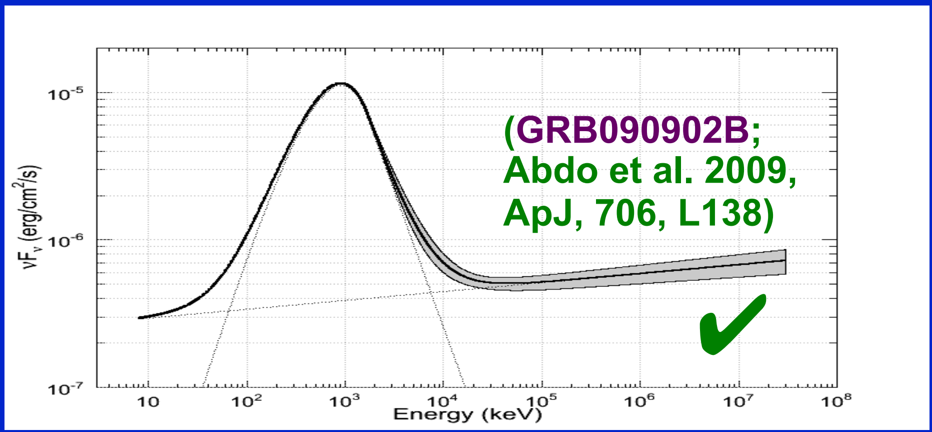
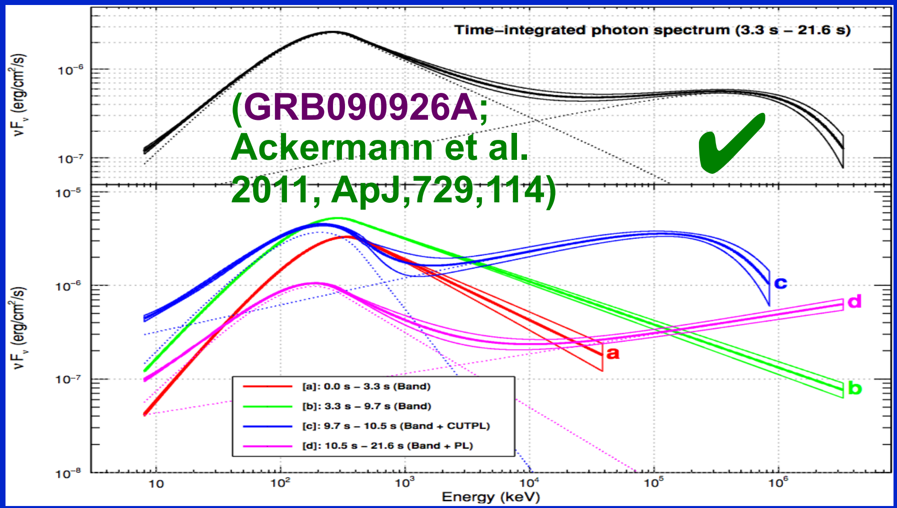
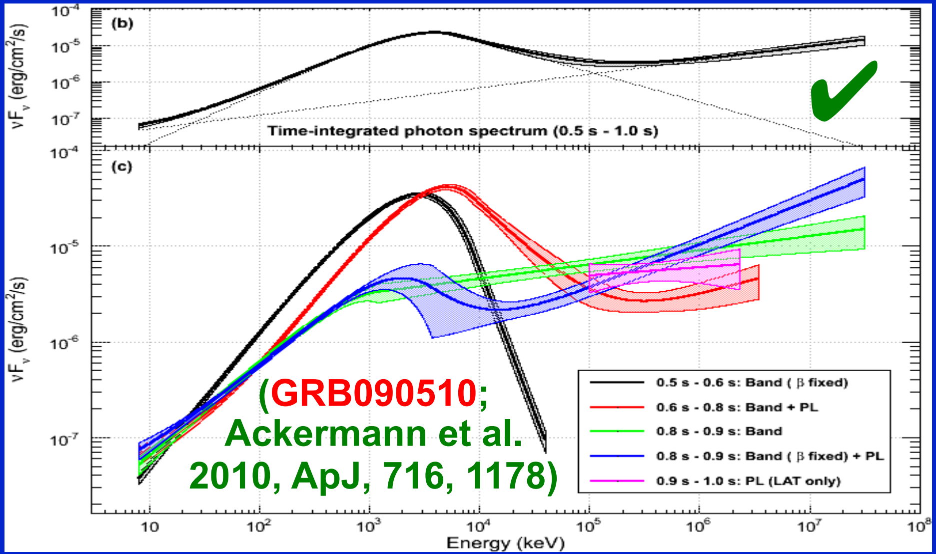
- **Hadronic** processes: photopair production ($p+\gamma \rightarrow p+e^+e^-$), proton synchrotron, pion production via $p\!-\!\gamma$ (photopion) interaction or p-p collisions
  - The neutral pions decay into high energy photons $\pi^0 \rightarrow \gamma\gamma$ that can pair produce with lower energy photons $\gamma\gamma \rightarrow e^+e^-$ producing a pair cascade

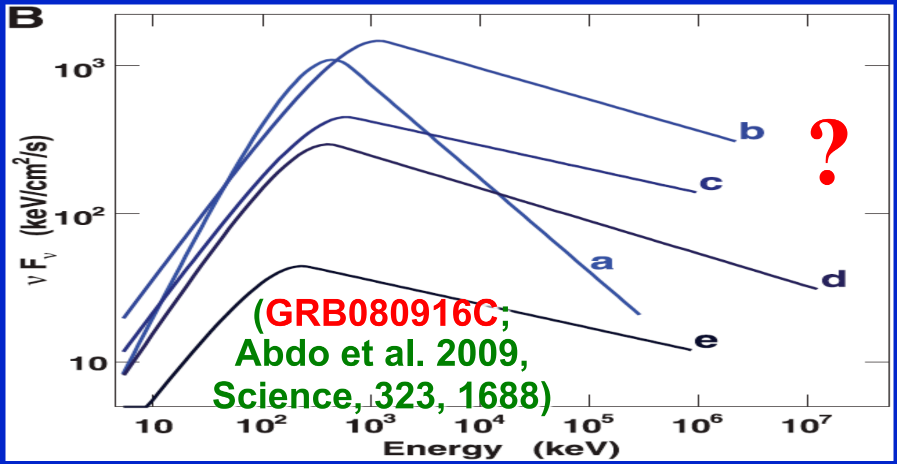
# Distinct High-Energy Spectral Component

- Appears in 3 or 4 out of the brightest 4 LAT GRBs
- It is likely very common but clearly detected only if bright



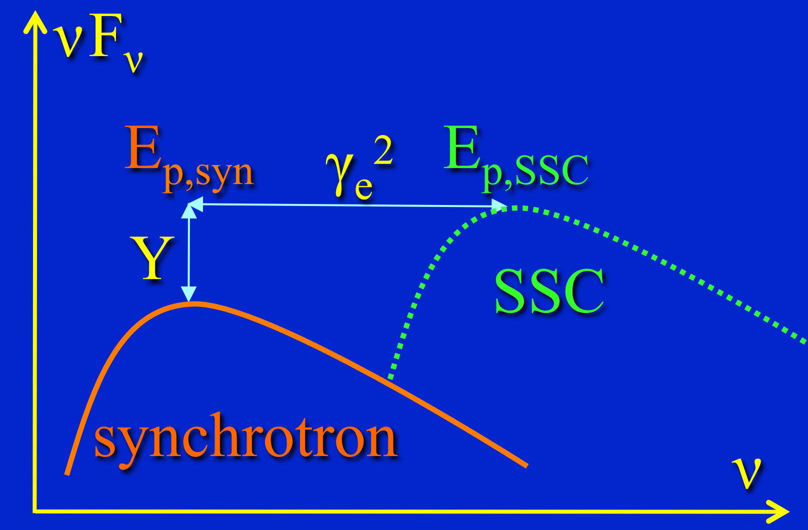



# GRB: High Energy Emission Processes

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

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

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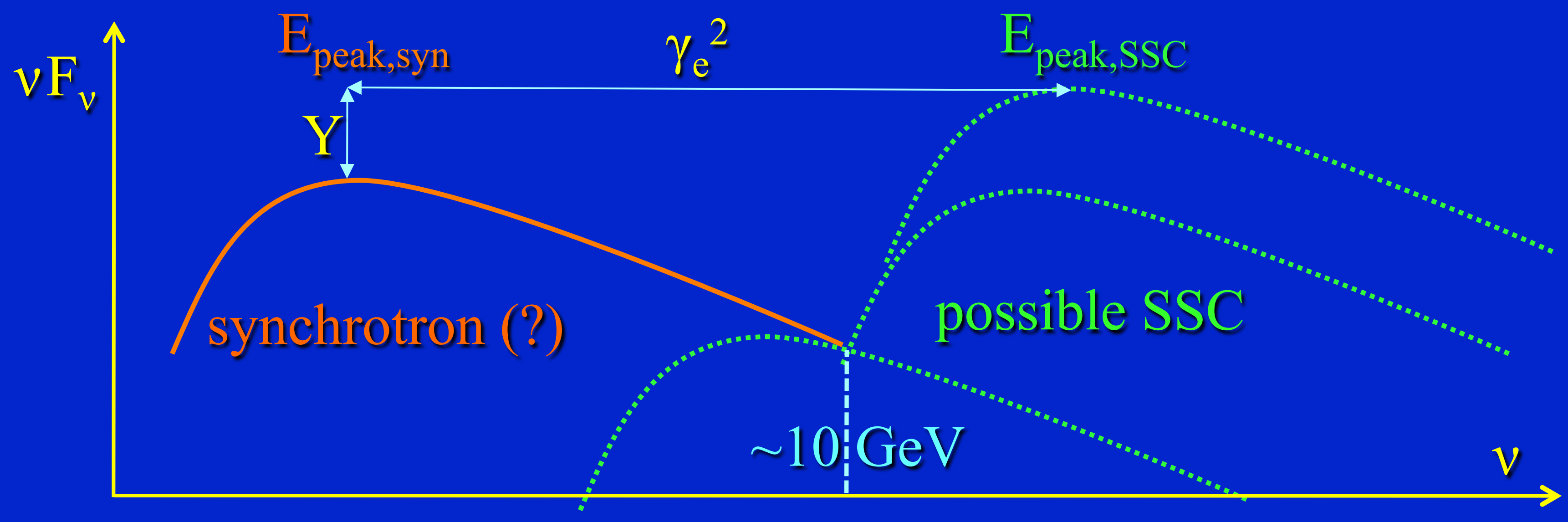
- **GRBs 090510, 090926A:** $Y$ varies, and sometimes $Y > 1$
- **GRB080916C**: single dominant emission mechanism ⇒ if synchrotron, SSC is expected, and can avoid detection if $E_{peak,SSC} \gg 10$ GeV ($\gamma_e \gg 100$), or if $Y \approx \varepsilon_e/\varepsilon_B \lesssim 0.1$



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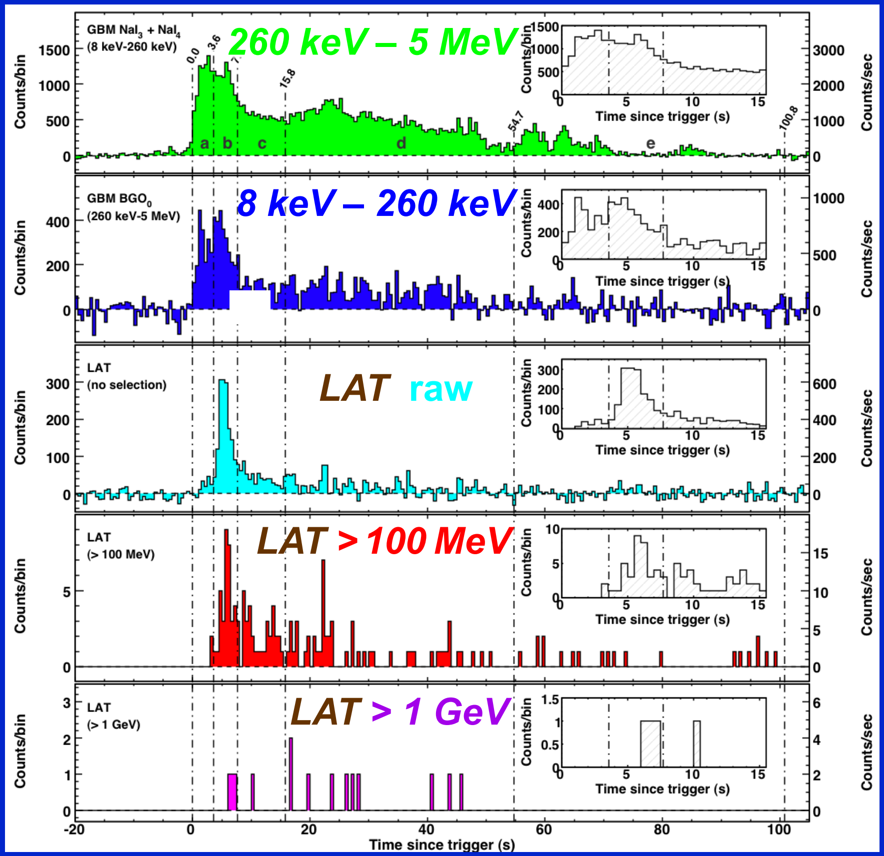
- **Parameter space study** (Benyamini & Piran 2013):
  $0.1 < \boldsymbol{\varepsilon_e/\varepsilon_B} < 10^4$ $(0.1 \lesssim \mathbf{Y} \lesssim 100)$, $300 \lesssim \boldsymbol{\Gamma} \lesssim 3000$,
  $3\times10^3 \lesssim \boldsymbol{\gamma_e} \lesssim 10^5$, $10^{15}$ cm $\lesssim \mathbf{R} \lesssim 10^{17}$ 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 ⇒ CTA?)

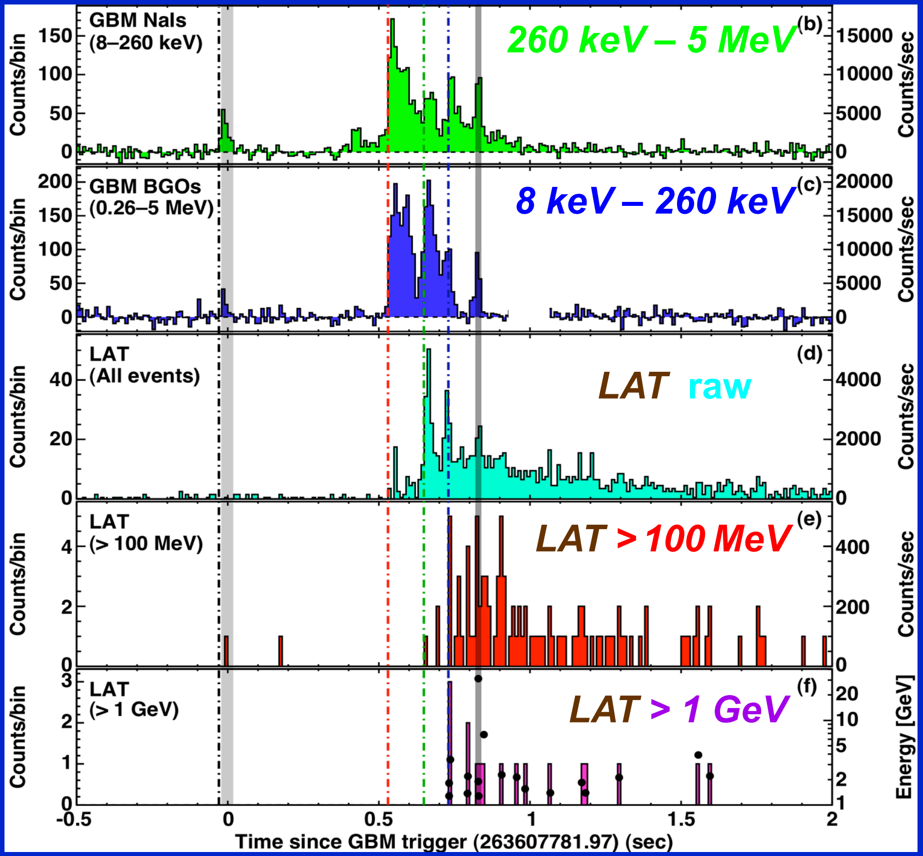
# Delayed Onset of High-Energy Emission

GRB080916C




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

GRB090510



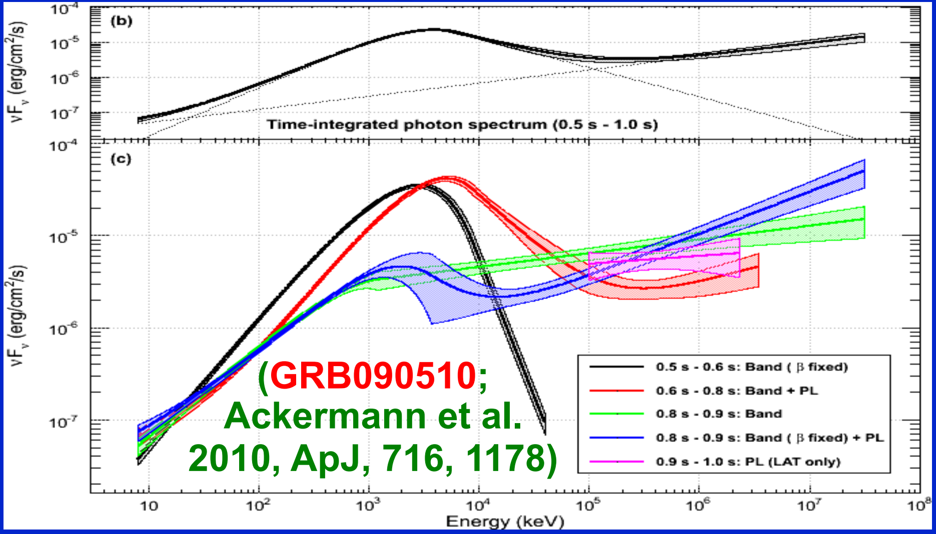

(Abdo et al. 2009, Nature, 462, 331)

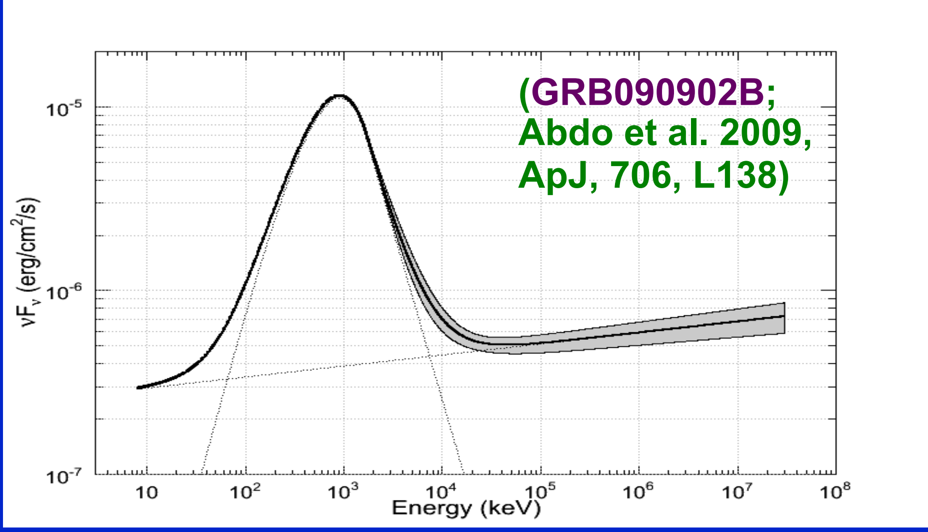
- The 1st LAT peak coincides with the 2nd GBM peak
- Delay in HE onset: ~ 4-5 s

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

# Late onset/HE spectral component: Possible Origin

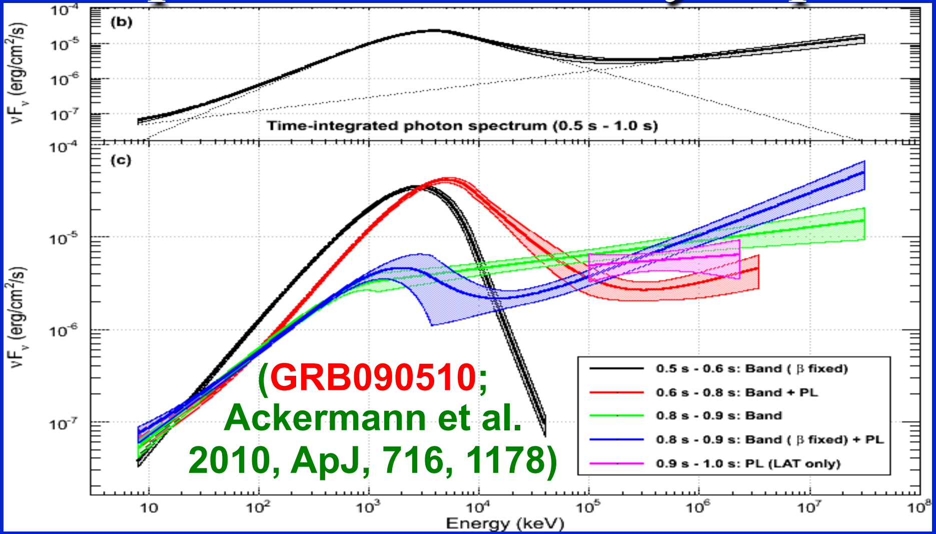
- **Leptonic**: inverse-Compton (or synchrotron self-Compton)?
  - Hard to produce a delayed onset longer than spike widths (the seed photon field builds-up on the dynamical time)
  - A gradual increase in the HE photon index **β** (determined by the electron energy dist.) is not naturally expected
  - 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)

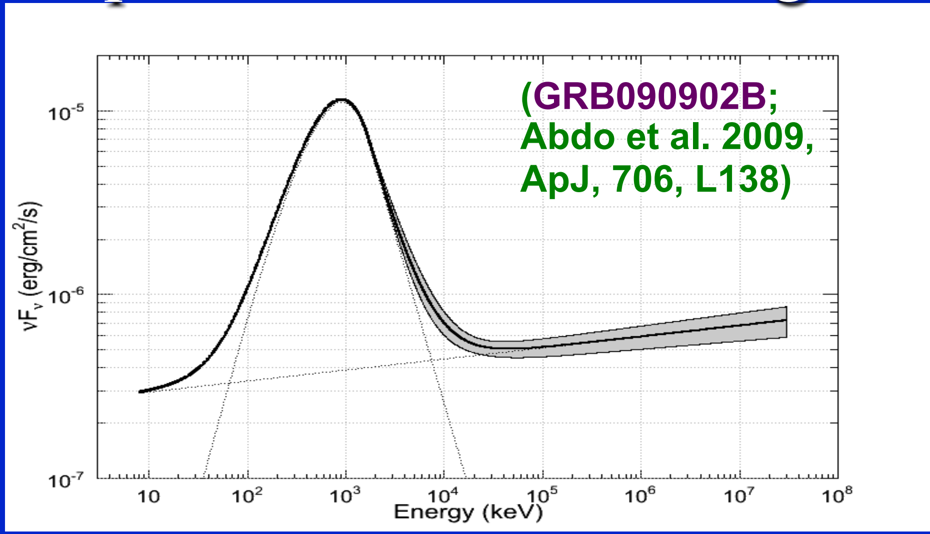


# Late onset/HE spectral component: Possible Origin

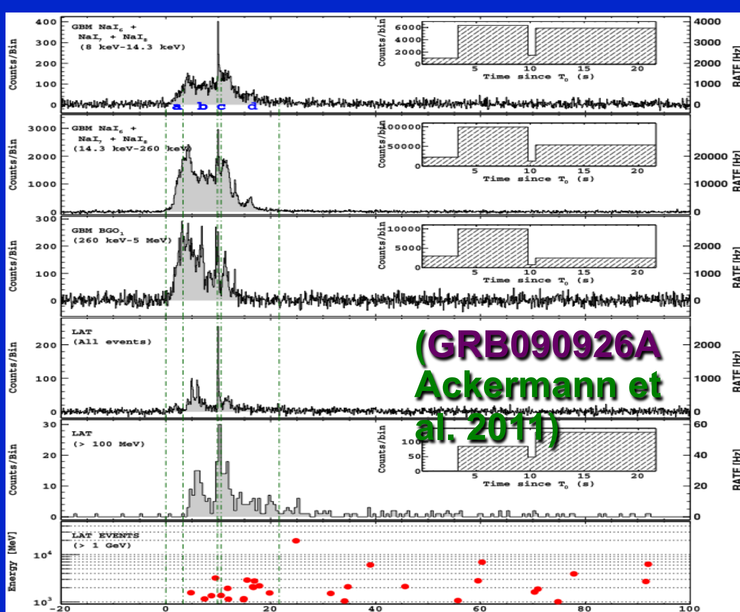
- **Hadronic**: (pair cascades, proton synchrotron) ?
  - Late onset: time to accelerate protons+develop cascades?
  - Does not naturally account the gradual increase in **β**
  - Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset)
  - GRB090510: 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

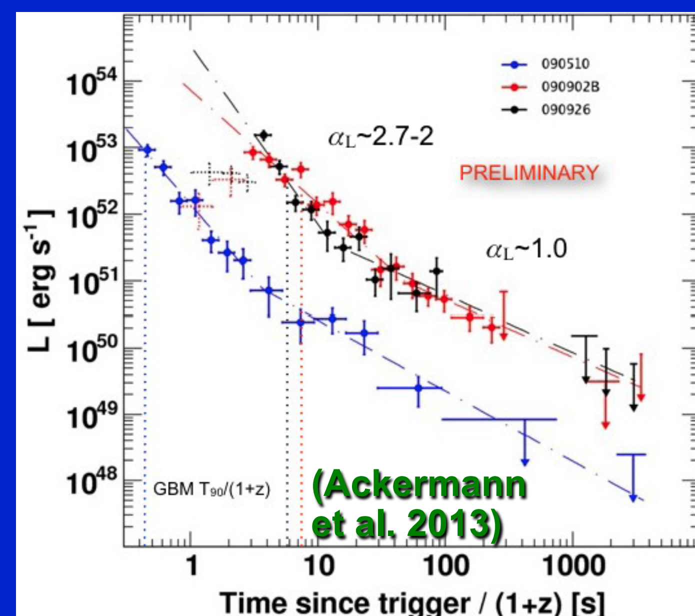


# Location of the HE Emission Region

- Sharp spikes in the prompt phase ⇒ not from external shock
- Sharp prompt spikes **coincident** at all energies ⇒ common prompt emission region, likely different emission mechanism
- **Long lived** emission is likely **afterglow** (synchrotron from the forward external shock): fits both spectrally & temporally
- ⇒ transition from prompt to afterglow is expected (& seen?):



# Photospheric components

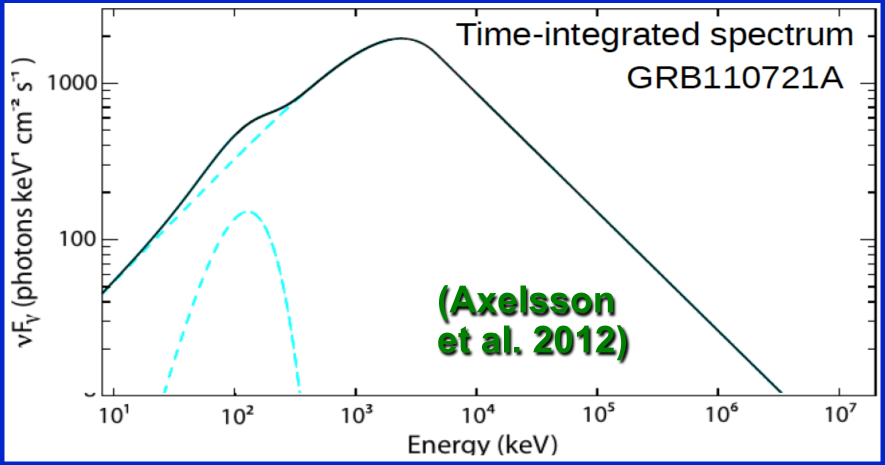
- Suggested in some cases by low energy data ($kT \lesssim 0.1$ MeV)
- Usually sub-dominant energetically (+not unique interpretation)
- In the **Fireball Model**: a remnant of the thermal acceleration

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

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

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

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



# Conclusions:

- **$\Gamma \gtrsim 10^{2.5}$** (from lack of HE cutoff due to intrinsic $\gamma\gamma$ opacity)
- Acceleration → dissipation → radiation (all related)
- Origin of ~GeV emission: first prompt dissipation from the outflow & later external shock synchrotron (afterglow)
- Prompt emission mechanism: unclear (likely 2-3 mechanisms: synchrotron, SSC, photospheric, comptonized, hadronic,…)
- Future observations may help (CTA, Ice Cube,…)