GeV Emission from GRBs: New Perspectives from *Fermi*

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On behalf of the Fermi LAT & GBM collaborations

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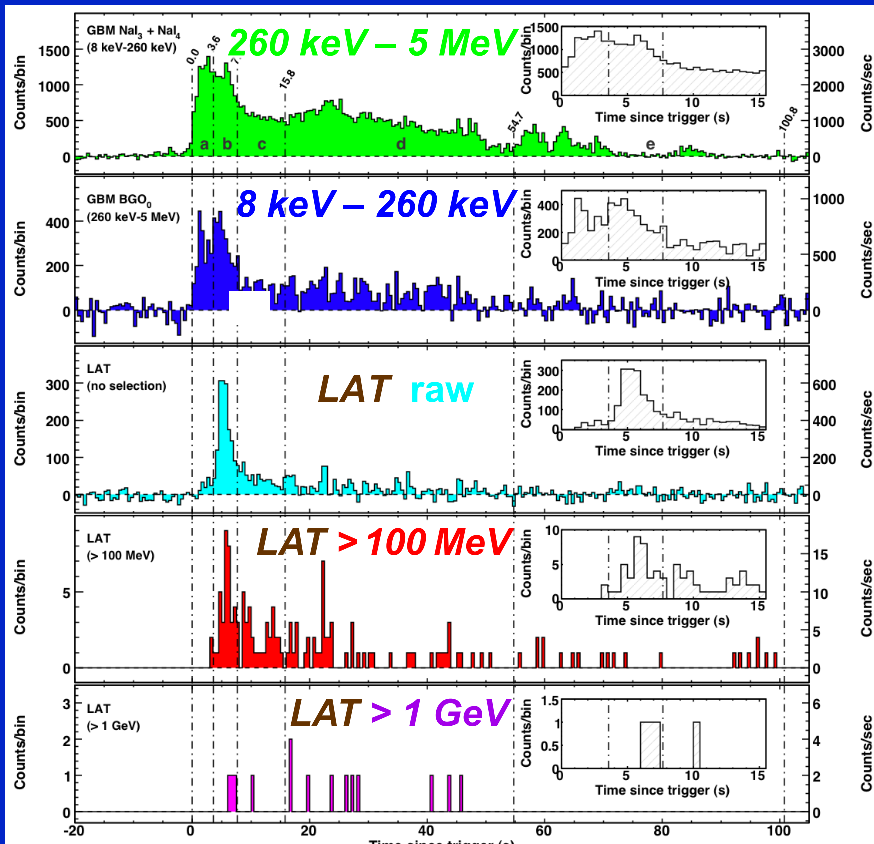
Outline of the Talk:

- GRB prompt emission: GBM + LAT @ high-energy
  - Delayed HE onset, HE spectral component, BB component?
  - ⇒ emission region: **Γ**, **R**
  - short vs. long GRBs @ HE
  - Long-lived HE emission
- High-energy afterglow & GRB 130427A:
  - Implications for relativistic collisionless shock physics
- non-GRB physics: EBL, Lorentz invariance violation

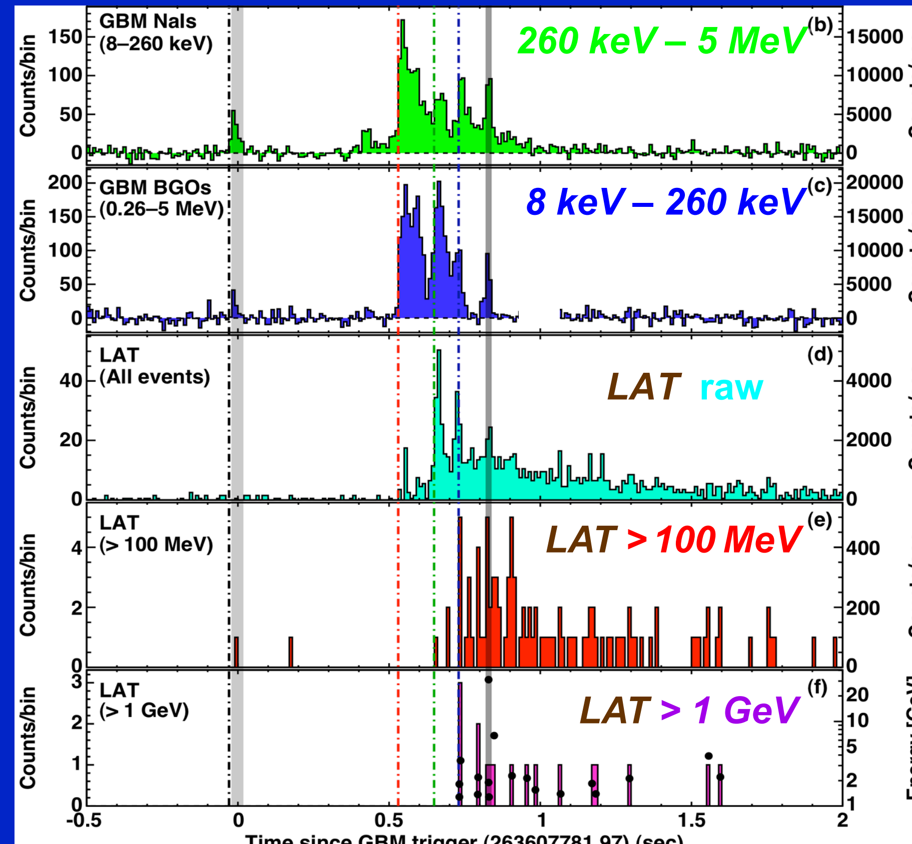
Delayed onset of High-Energy Emission

GRB080916C



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

GRB090510

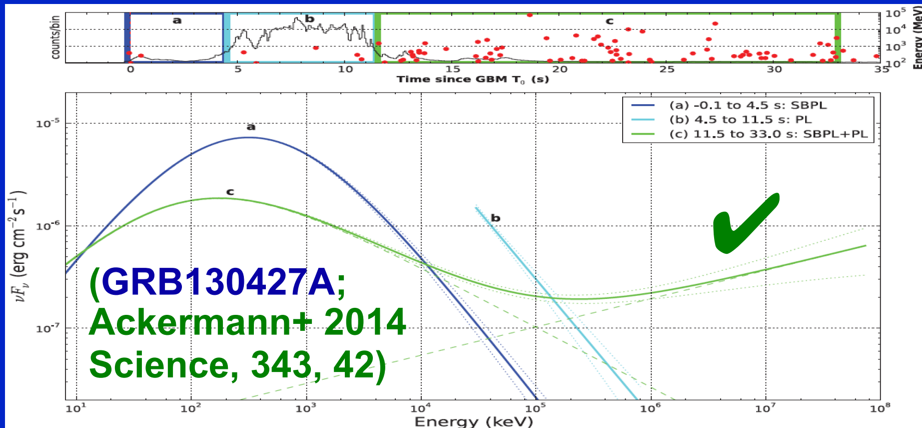


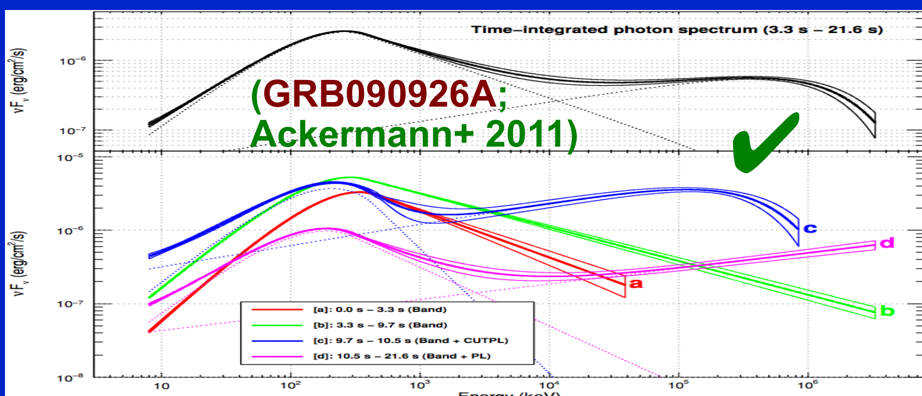
(Abdo et al. 2009, Nature, 462, 331)

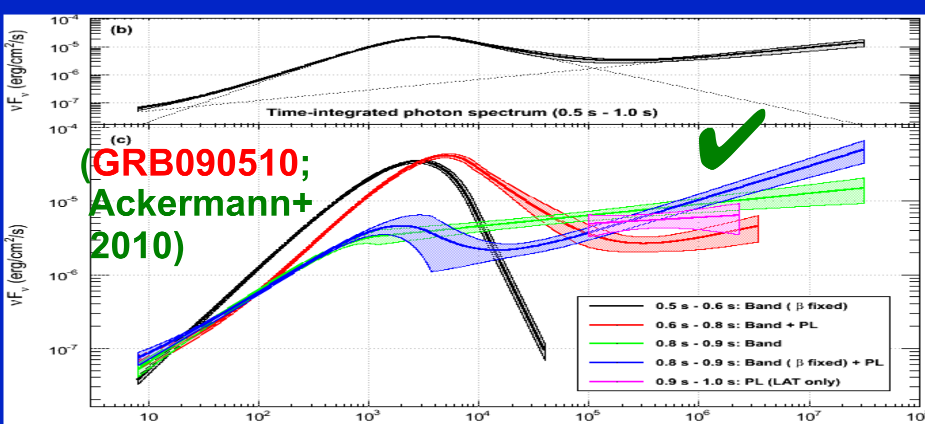
- The 1st LAT peak coincides with the 2nd GBM peak
- Delay in HE onset: ~ 4-5 s
- The first few GBM peaks are missing in LAT but later peaks coincide; the delay is 0.1-0.2 s

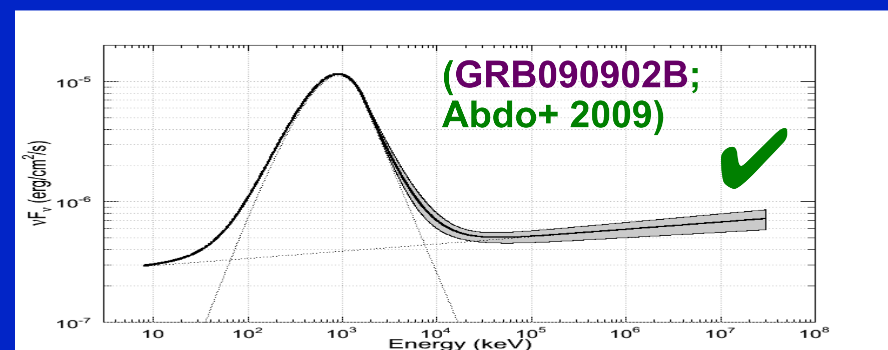
Distinct High-Energy Spectral Component

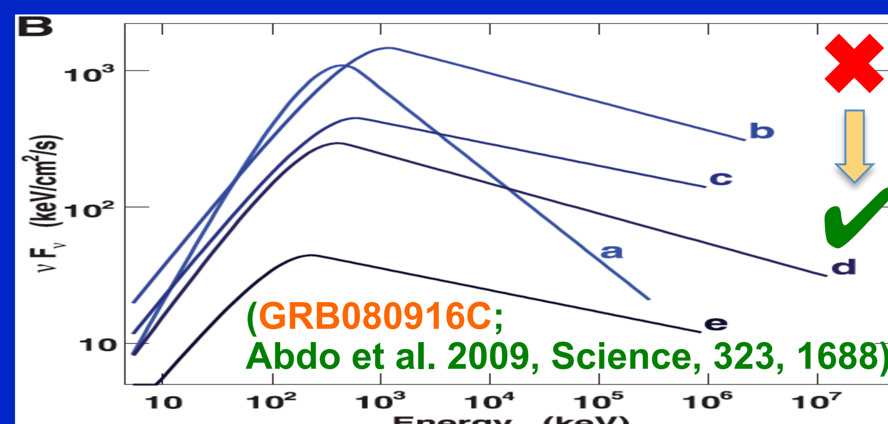
- Clearly (>5σ) exists in several LAT GRBs, but very common in the brightest LAT GRBs
- Suggests that it is common but good photon statistics is needed for clear evidence





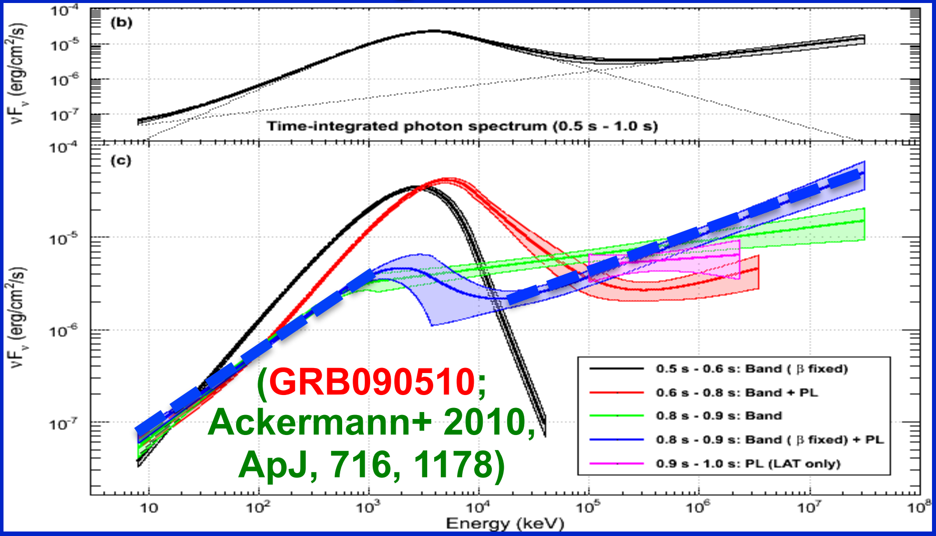


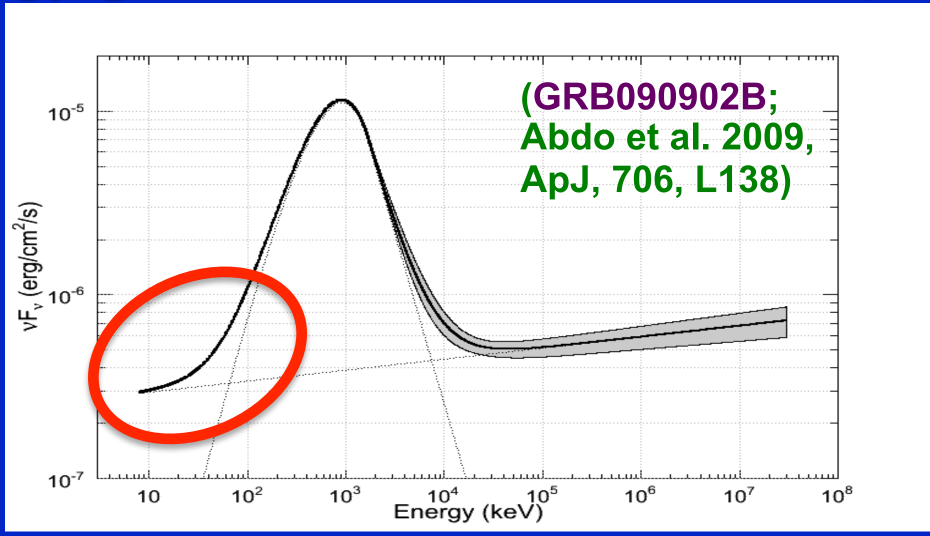




Late onset/HE spectral component: Possible Origin

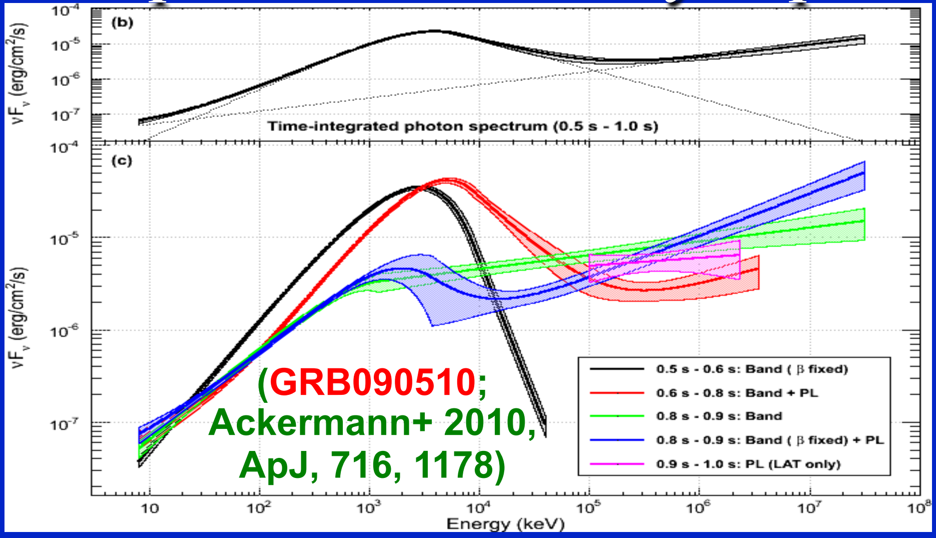
- **Leptonic**: inverse-Compton (or synchrotron self-Compton)?
  - Hard to produce a delayed onset longer than spike widths (the seed photon field builds-up on the dynamical time)
  - A gradual increase in the HE photon index **β** (determined by the electron energy dist.) is not naturally expected
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

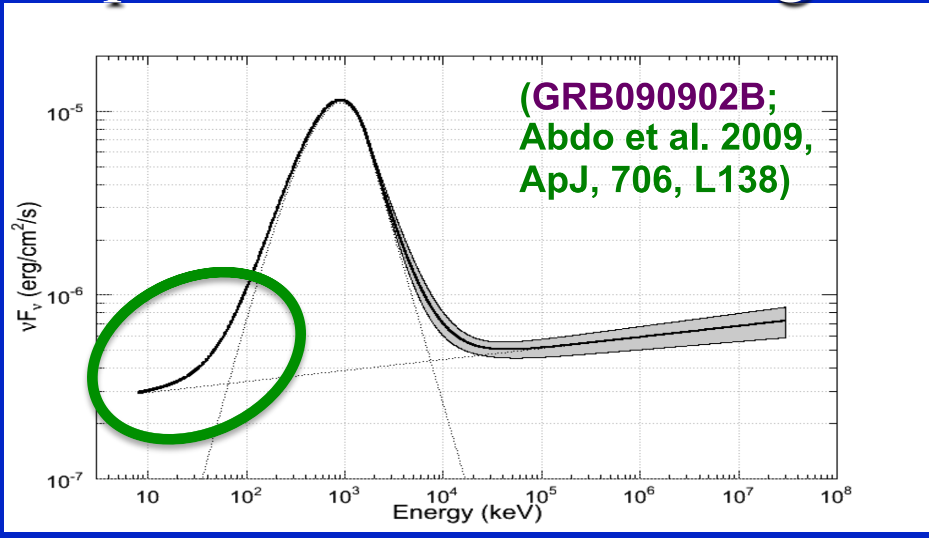




Late onset/HE spectral component: Possible Origin

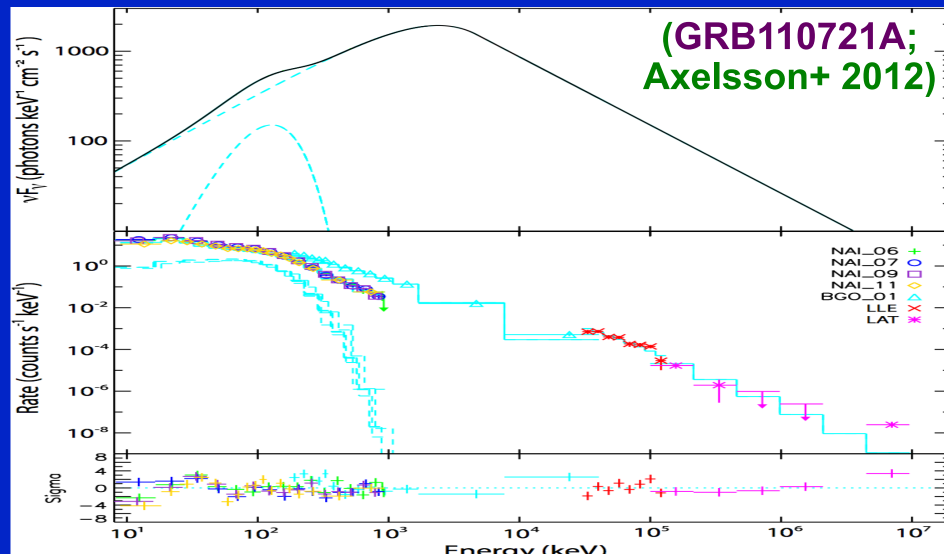
- **Hadronic**: (pair cascades, proton synchrotron) ?
  - Late onset: time to accelerate protons+develop cascades?
  - Does not naturally account the gradual increase in **β**
  - Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset)
  - GRB090510: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

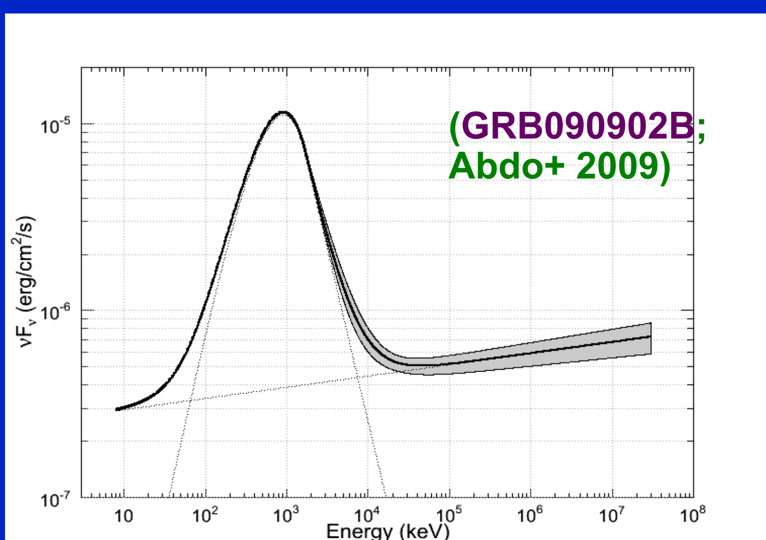


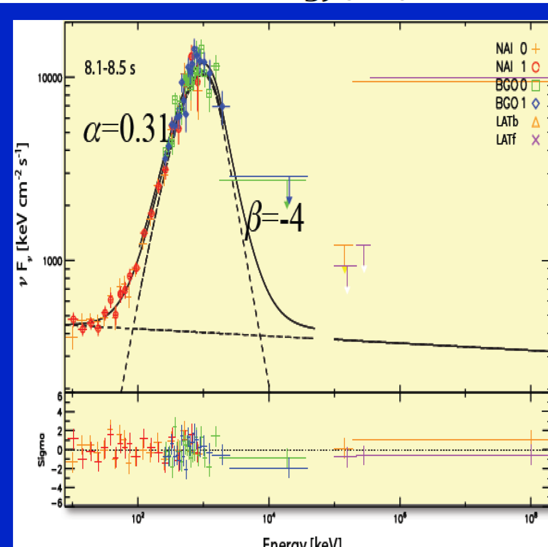


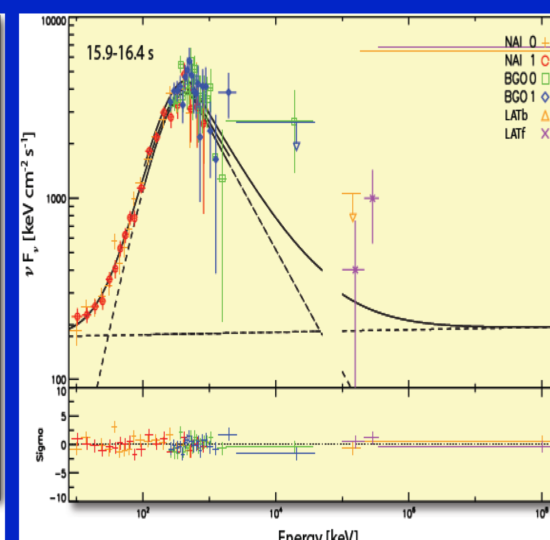
Thermal components in prompt spectrum?

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



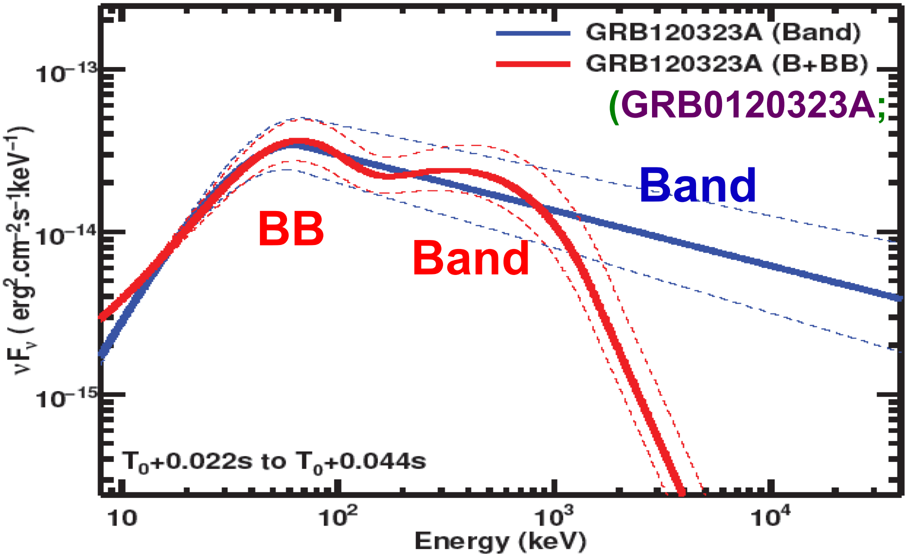






Thermal components in prompt spectrum?

- 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)



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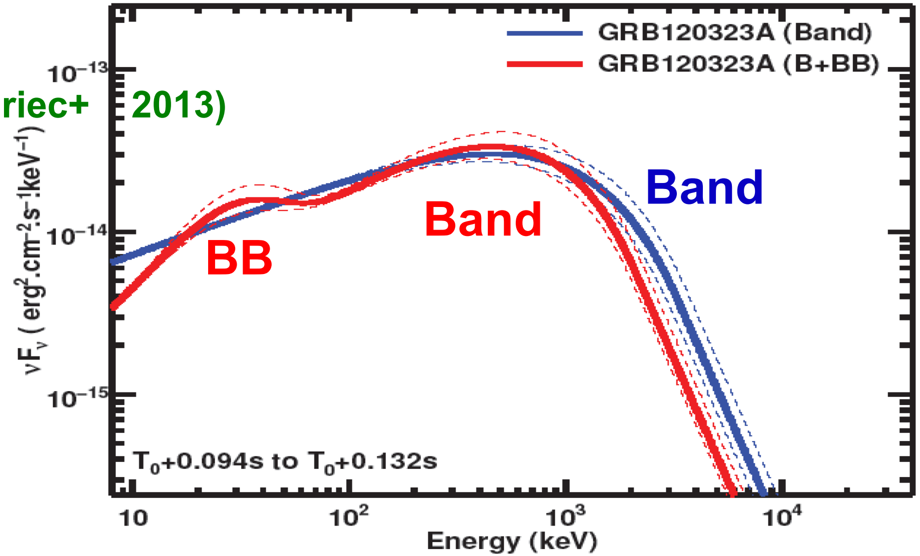


Photospheric components

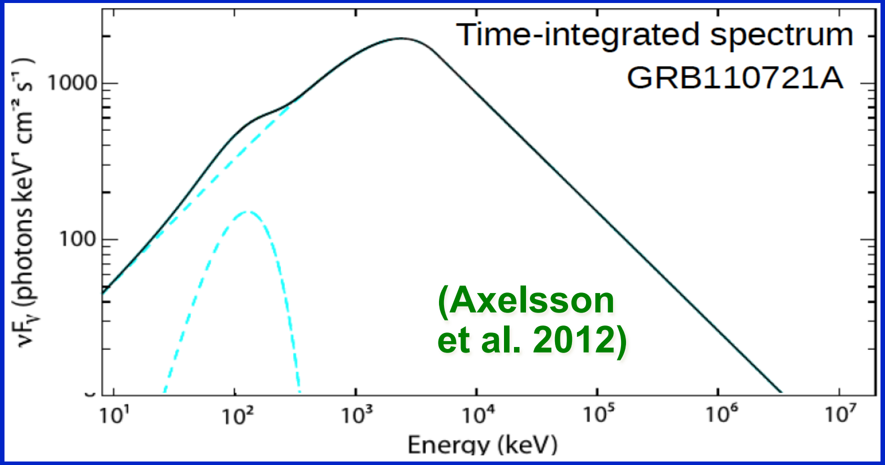
- Suggested in some cases by low energy data ($kT \lesssim 0.1$ MeV)
- Usually sub-dominant energetically (+non-unique interpretation)
- In the **Fireball Model**: a remnant of the thermal acceleration

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

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

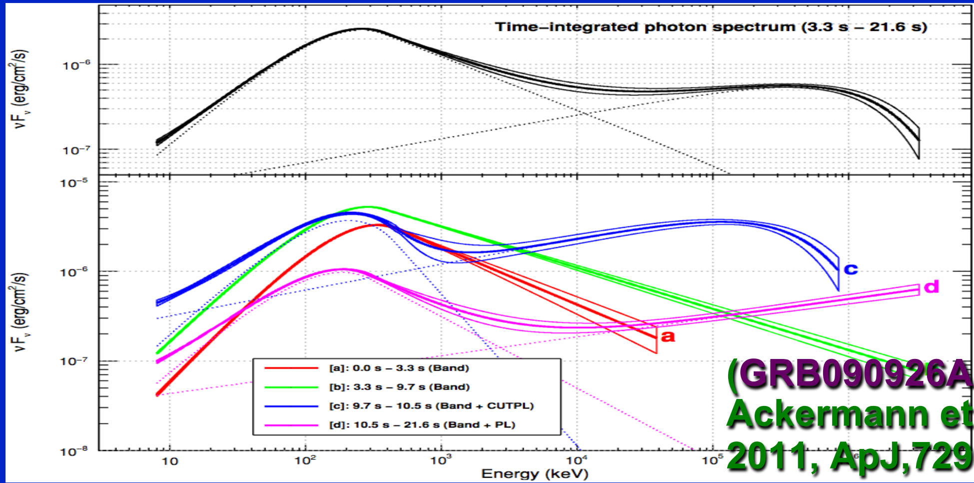
$$kT_{\mathbf{ph}} = 300(1+z)^{-1} \mathbf{E_{th,51}} E_{52}^{1/4} R_{0,6}^{-1/2} t_1^{-1/4} \text{ keV}$$

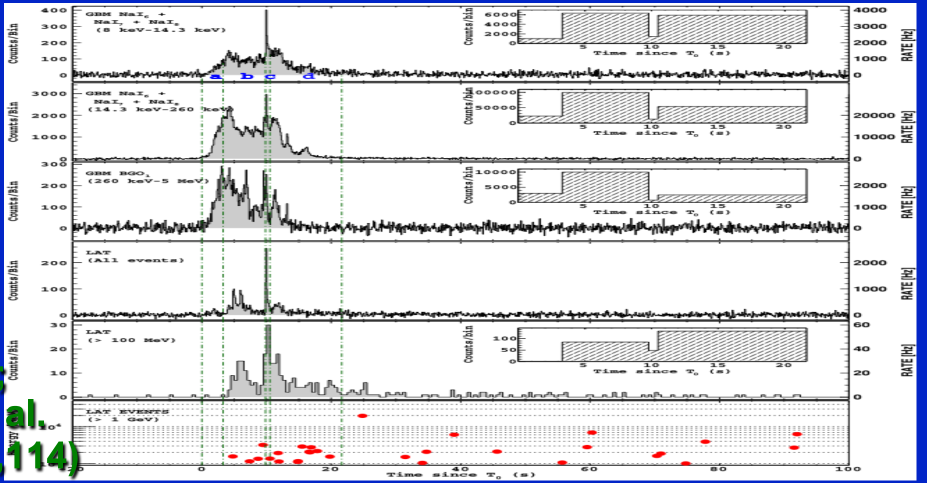
- For **magnetic** acceleration:
  - Dissipation below the photosphere can give such a spectral component
  - can arise from gradual reconnection or multiple passages of weak shocks



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 $\mathbf{\Gamma \gtrsim 500}$ 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 $\mathbf{\Gamma \sim 300 - 700}$

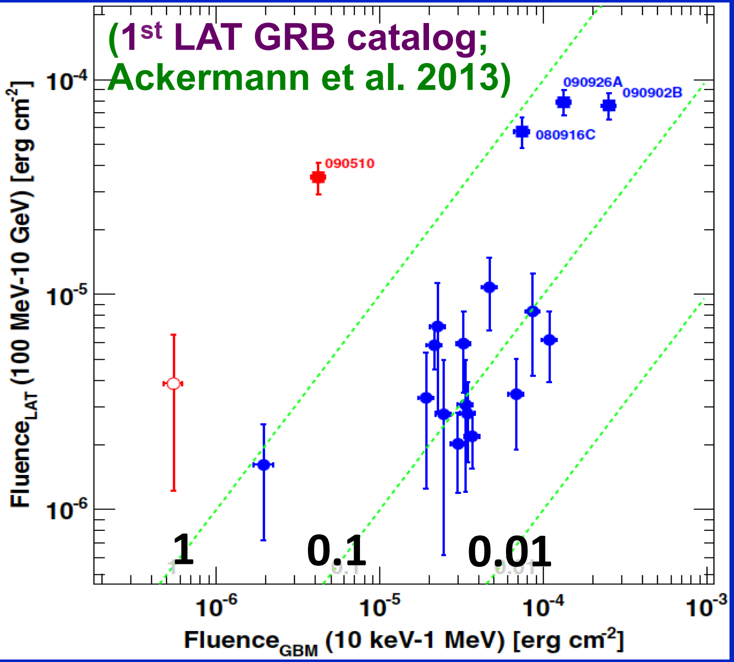


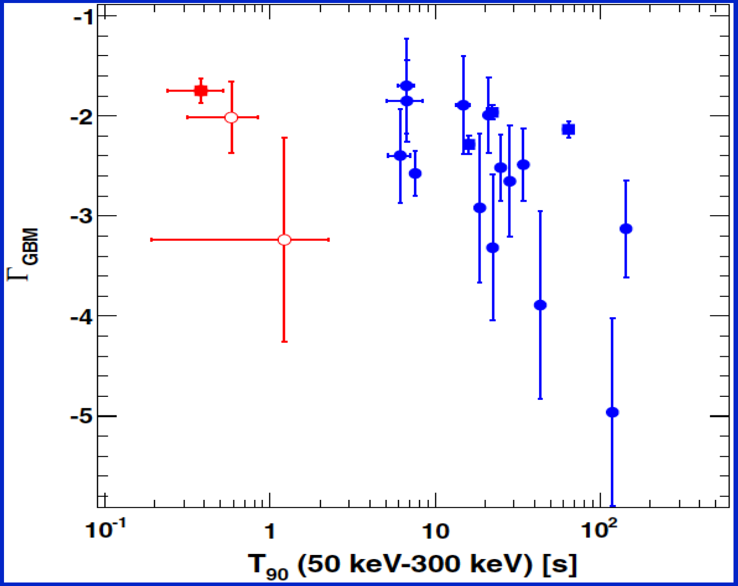


(GRB090926A; Ackermann et al. 2011, ApJ,729,114)

Long vs. Short GRBs @ High-Energies:

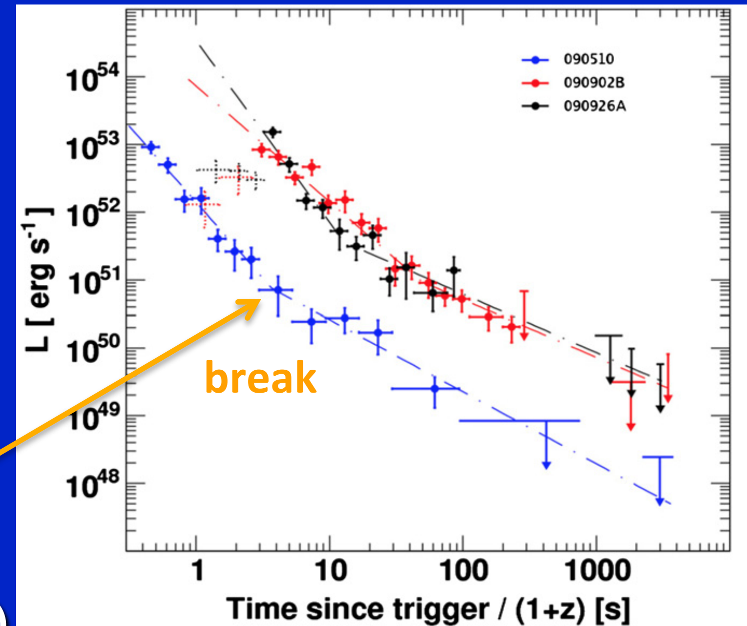
- **Trend:** larger LAT/GBM fluence ratio in short (rel. to long) GRBs
- Short GRBs are harder (higher β & E_{peak} in time integrated spectrum)
- Both show delayed onsets, but the delay scales with the GRB duration
- Both show HE hard PL component
- Both show long-lived HE emission
- Both include very bright LAT GRBs
- Both have very constraining Γ_{mim}
- Both have some redshifts but long GRBs are usually easier to follow up

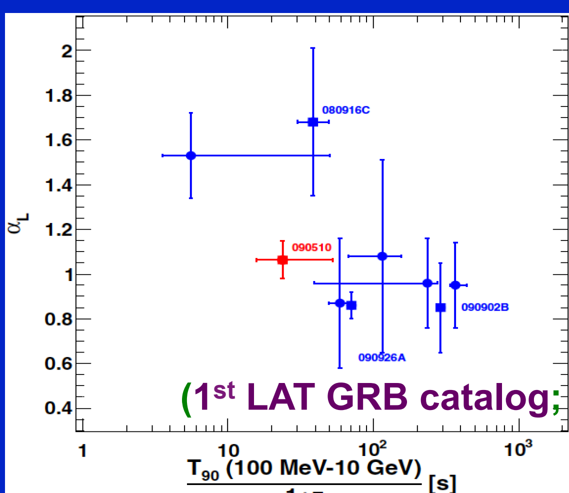


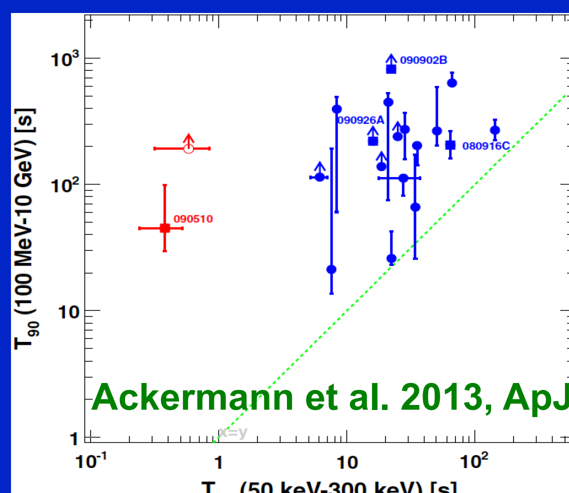


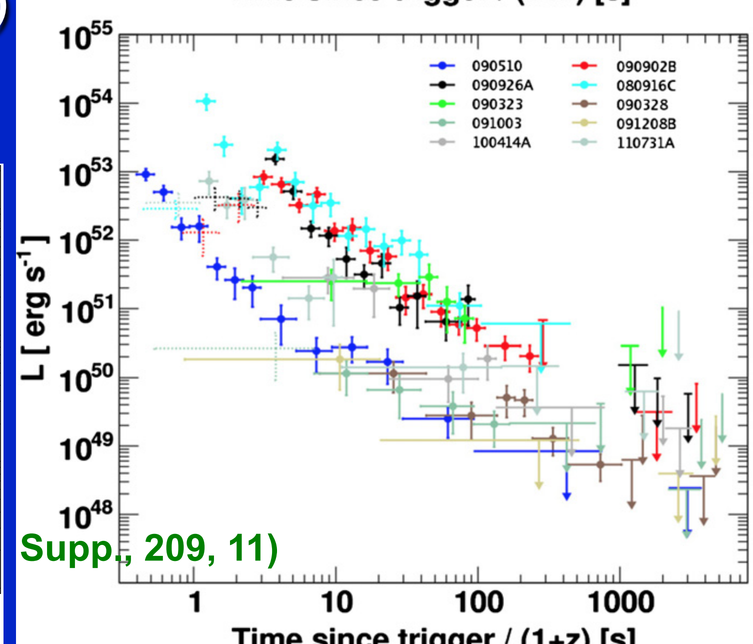
Long-Lived High-Energy emission

- Seen in many/most LAT GRBs: a power-law in time/energy $\propto t^{-\alpha_L} E^{\beta}$ with $\beta \approx -2$ and $\alpha_L \sim 1 - 1.5$
- Consistent with afterglow @ $t \gg T_{90}$ (at $t \lesssim T_{90}$ sharp spikes $\Rightarrow$ not afterglow)
- Prompt to afterglow transition?
- Some emission from X-ray flares (?)
- Hadronic, pair echo, SSC,… ???





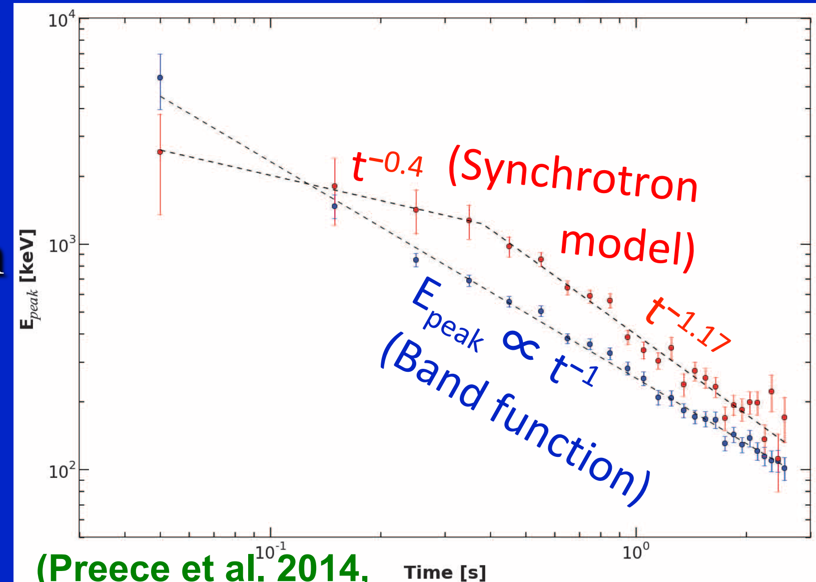




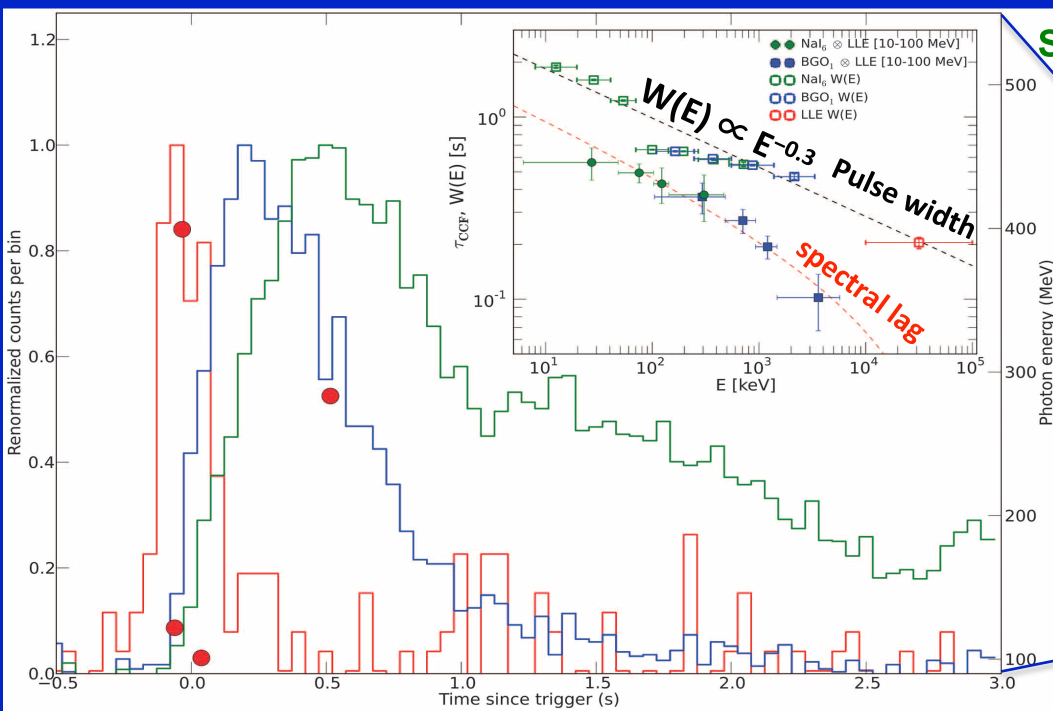
(1st LAT GRB catalog; Ackermann et al. 2013, ApJ Supp., 209, 11)

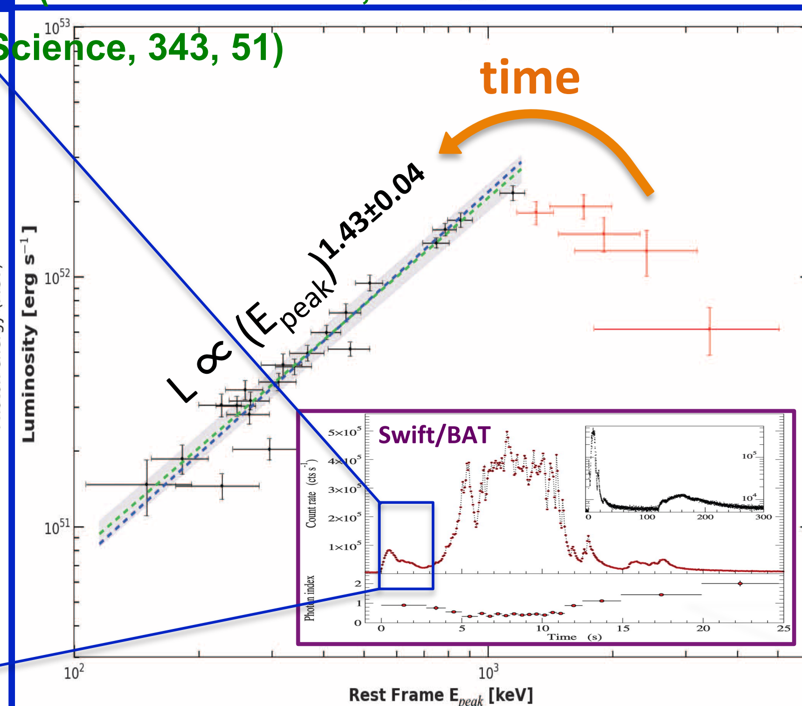
GBM observations of GRB130427A 1st pulse

- Detailed time-resolved study of a pulse
- $E_{peak} \propto t^{-1}$, pulse width $W(E) \propto E^{-0.3}$ consistent with internal shock synchrotron
- $L \propto (E_{peak})^{1.4}$ inconsistent with shock curvature effect (high-latitude; $L \propto E_p^{\,3}$)
- No current model explains all details



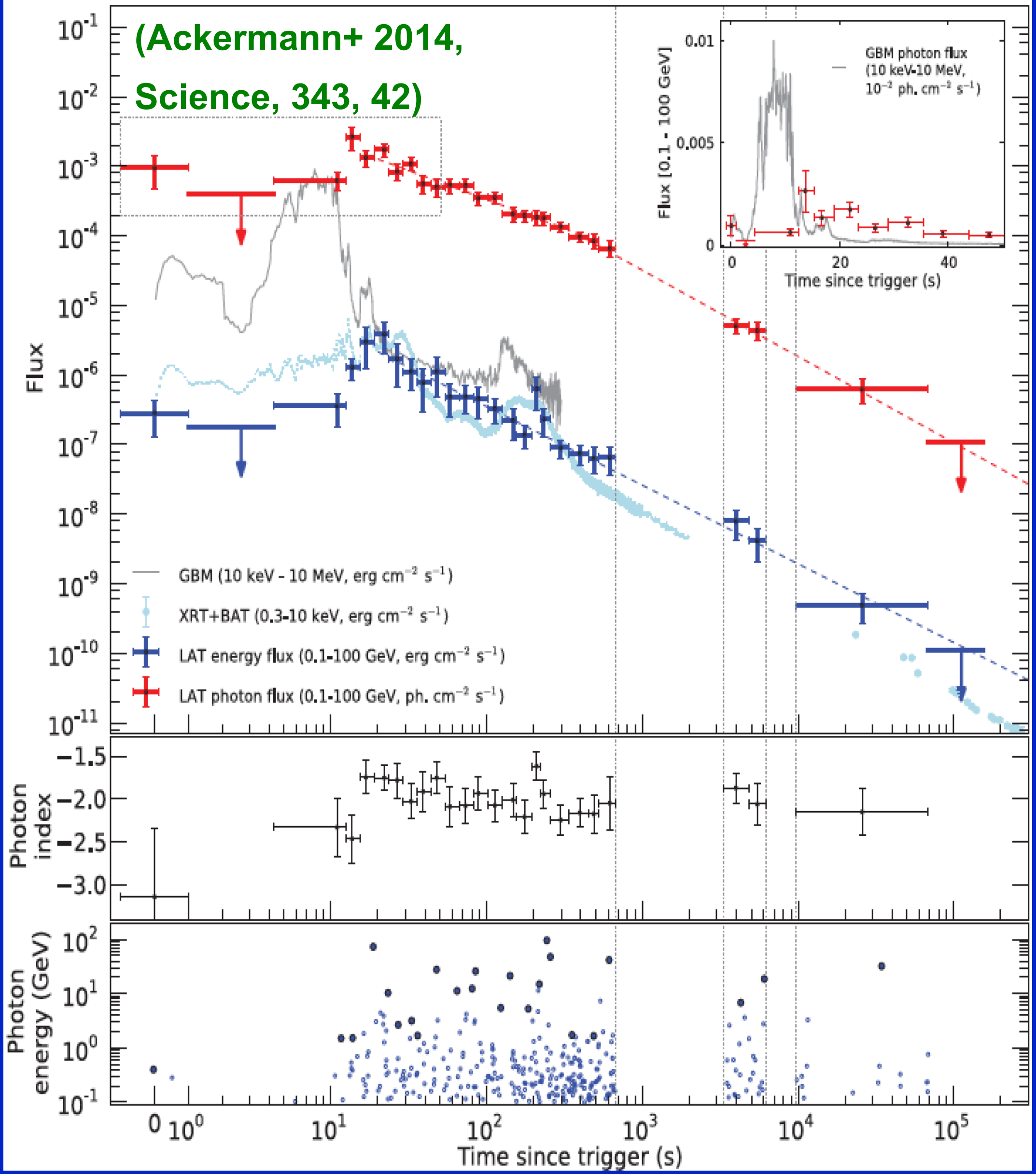
(Preece et al. 2014, Science, 343, 51)





High-Energy Afterglow: GRB130427A

- LAT detected emission up to ~ 20 hr after GRB
- >10 GeV γ's observed up to hours after GRB
- May arise at least partly from the prompt γ-ray emission up to few 10^2 s
- At later times there is no prompt emission, only a simple power-law decay: afterglow



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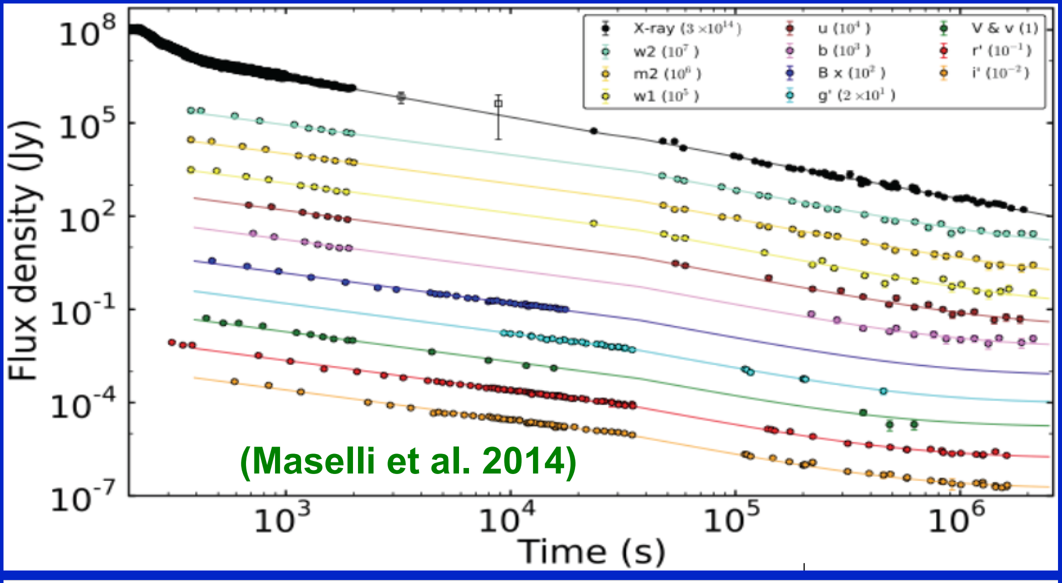
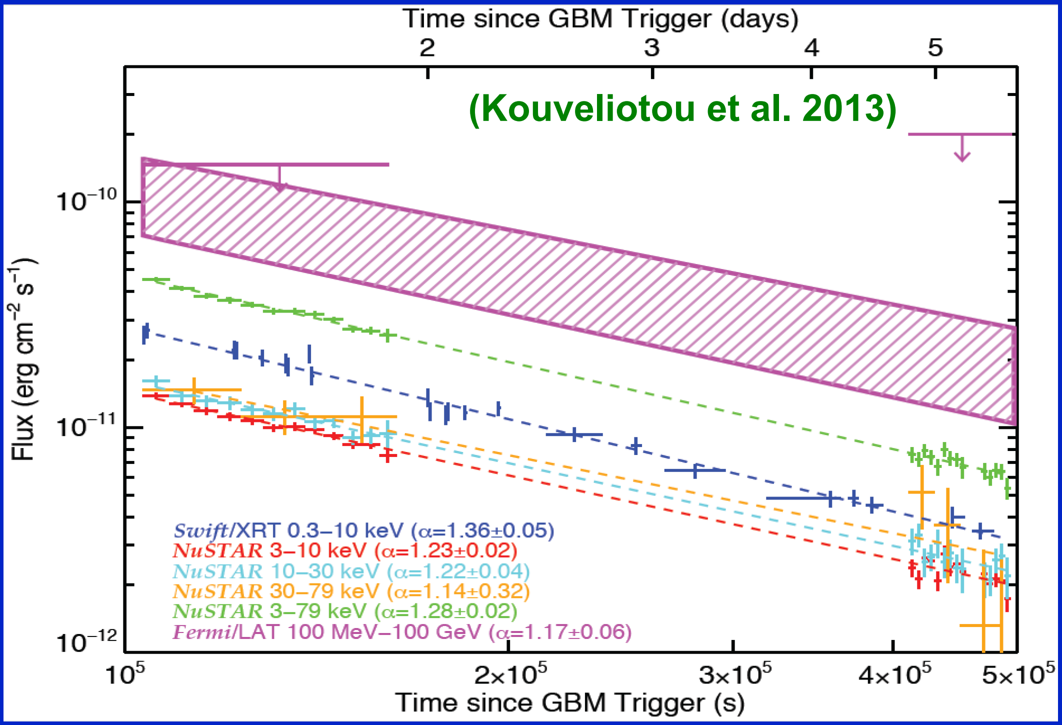
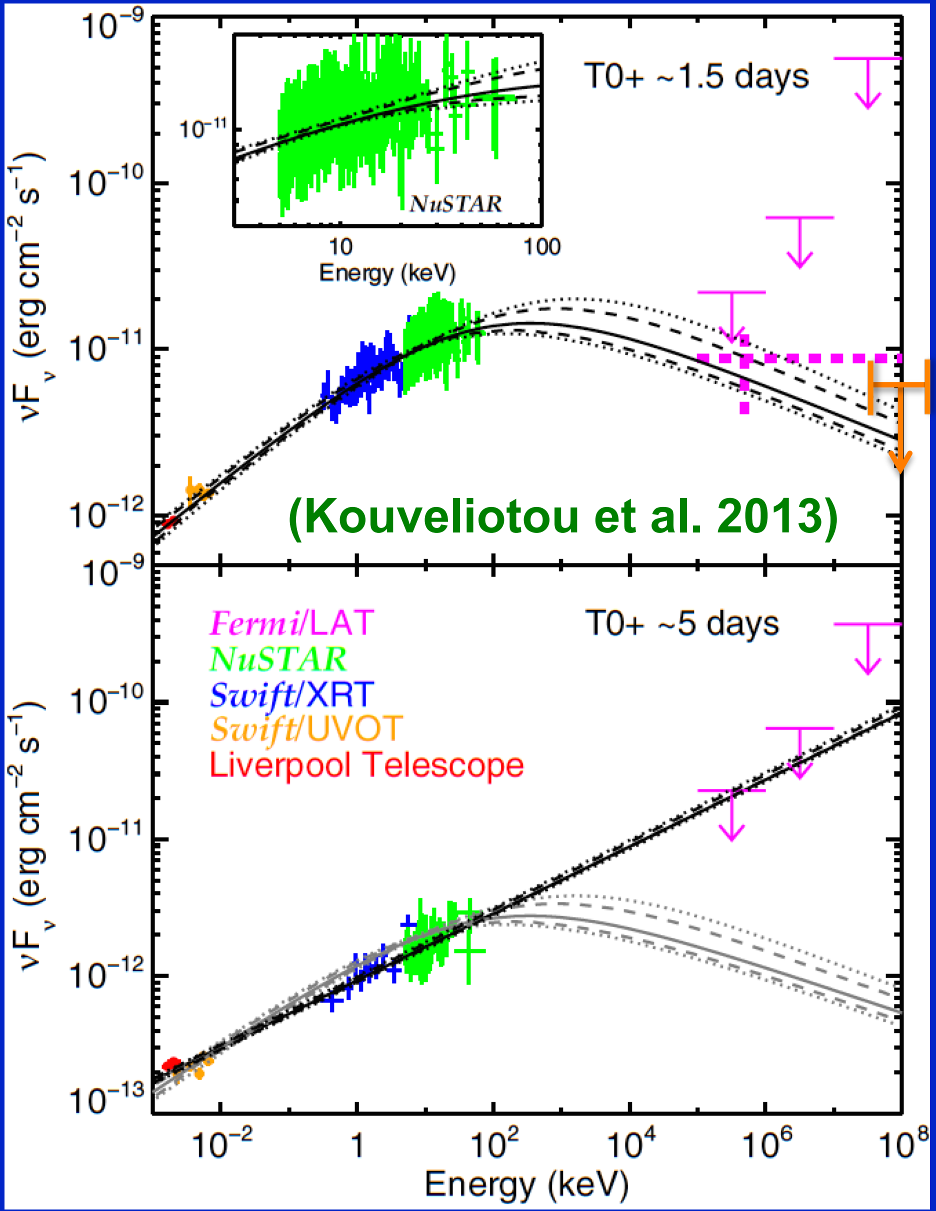
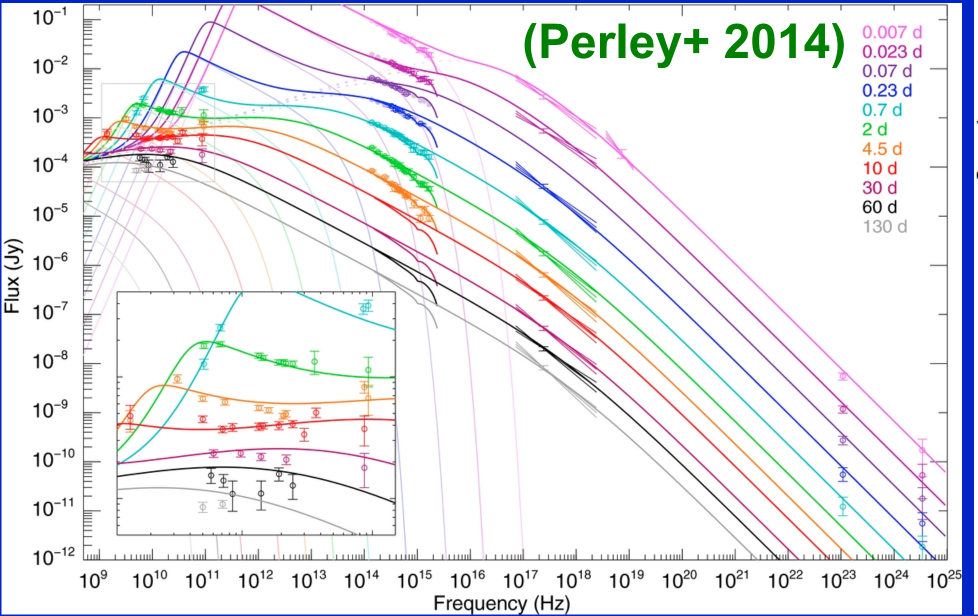




High-Energy Afterglow: GRB130427A

- **NuSTAR**: 1st late-time GRB afterglow detection at 3-79 keV
- A single-component synchrotron spectrum nicely fits all energies
- No need or much room for SSC
- Also supported by VERITAS observations (Aliu et al. 2014)



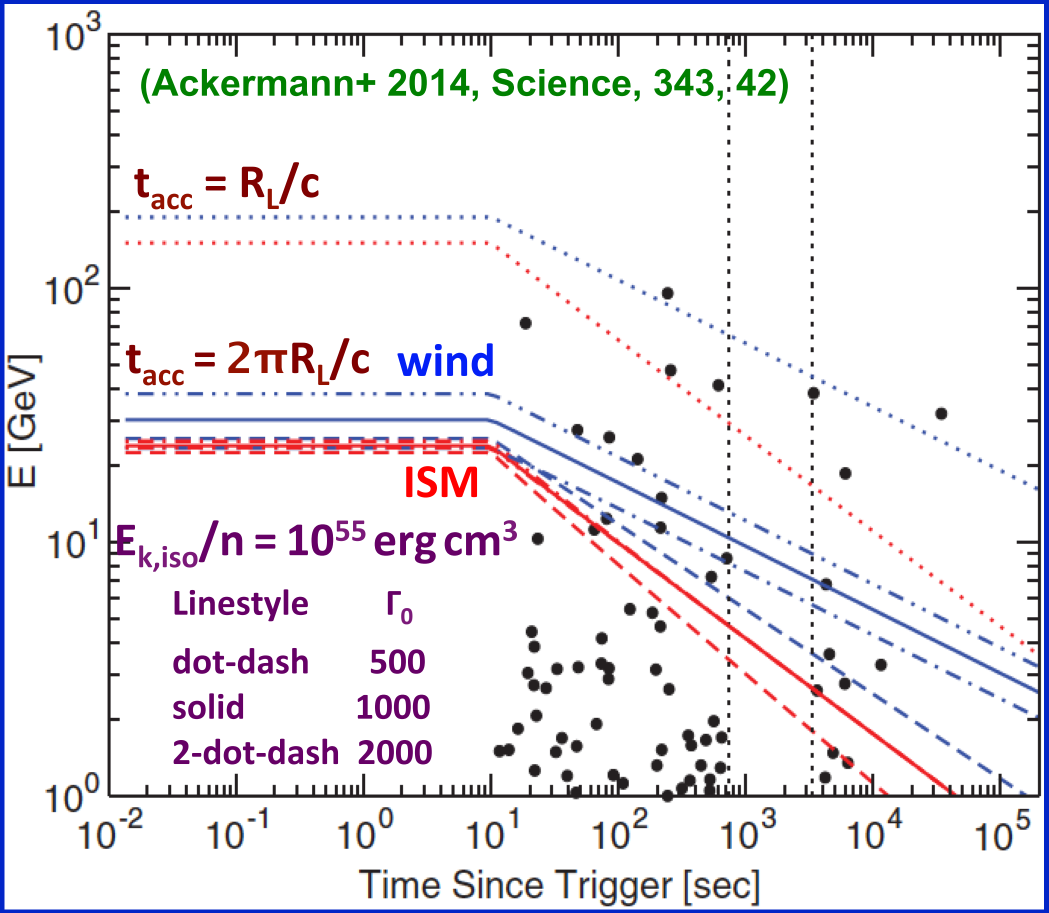


High-Energy Afterglow: GRB130427A

- **LAT HE photons violate:**

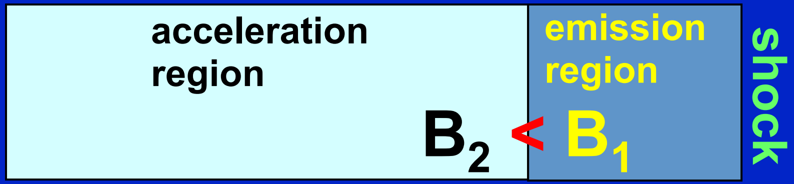
$$E_{\rm syn,max} \sim \frac{\Gamma}{(1+z)}\frac{m_e c^2}{\alpha} \approx 5\left(\frac{\Gamma}{100}\right)\ \mathrm{GeV}$$

- Based on a one-zone model balancing electron energy gains and losses: $t_{acc} \sim t_{syn}$
- $t_{acc} \sim 1/\omega_L = R_L/c$ (extremely fast) or $P_L = 2\pi/\omega_L$ (still very fast but a bit more realistic)
- An "easy way out" would be if SSC emission dominated at highest LAT energies (Fan+ 2013; Liu+ 2013), but it doesn't work



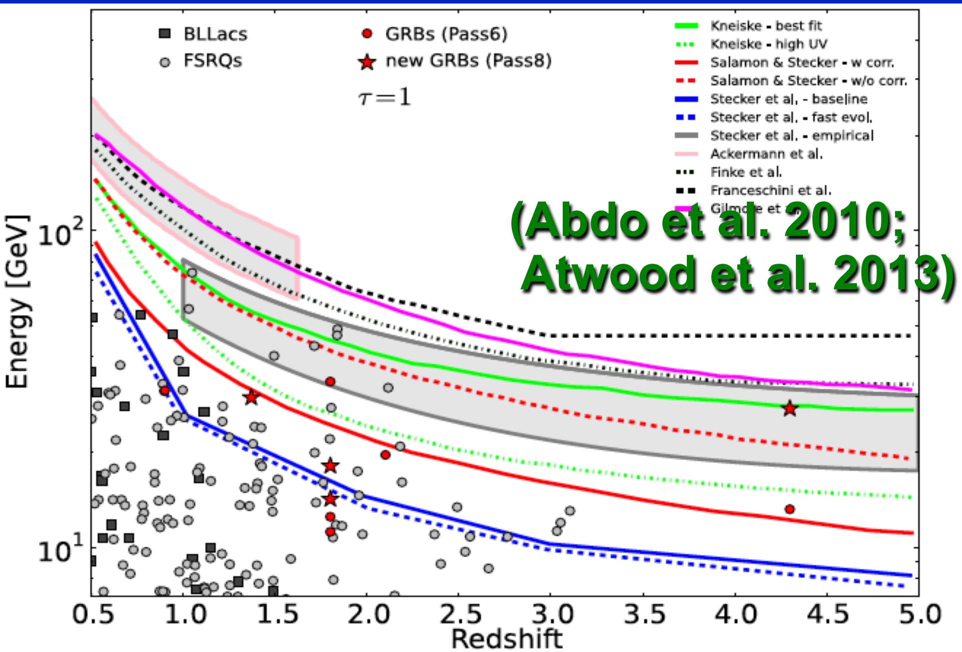
- $\Rightarrow E_{\rm syn,max}$ appears to be truly violated $\Rightarrow \geq 1$ assumption must break
- Non-uniform magnetic field?

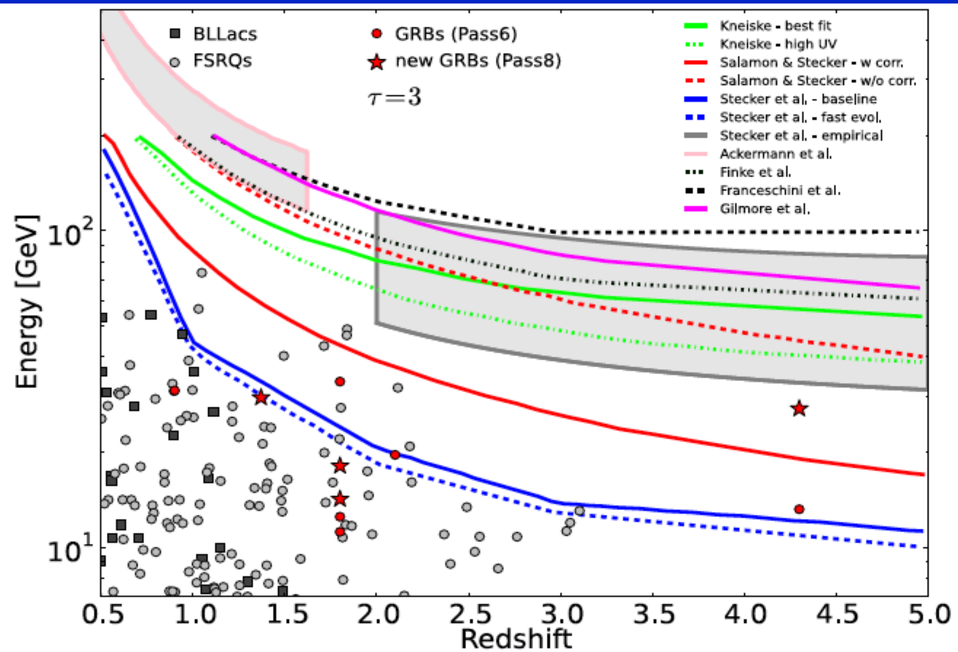
$E_{\rm syn,max}$ grows by a factor of B_1/B_2



Constraining the opacity of the Universe

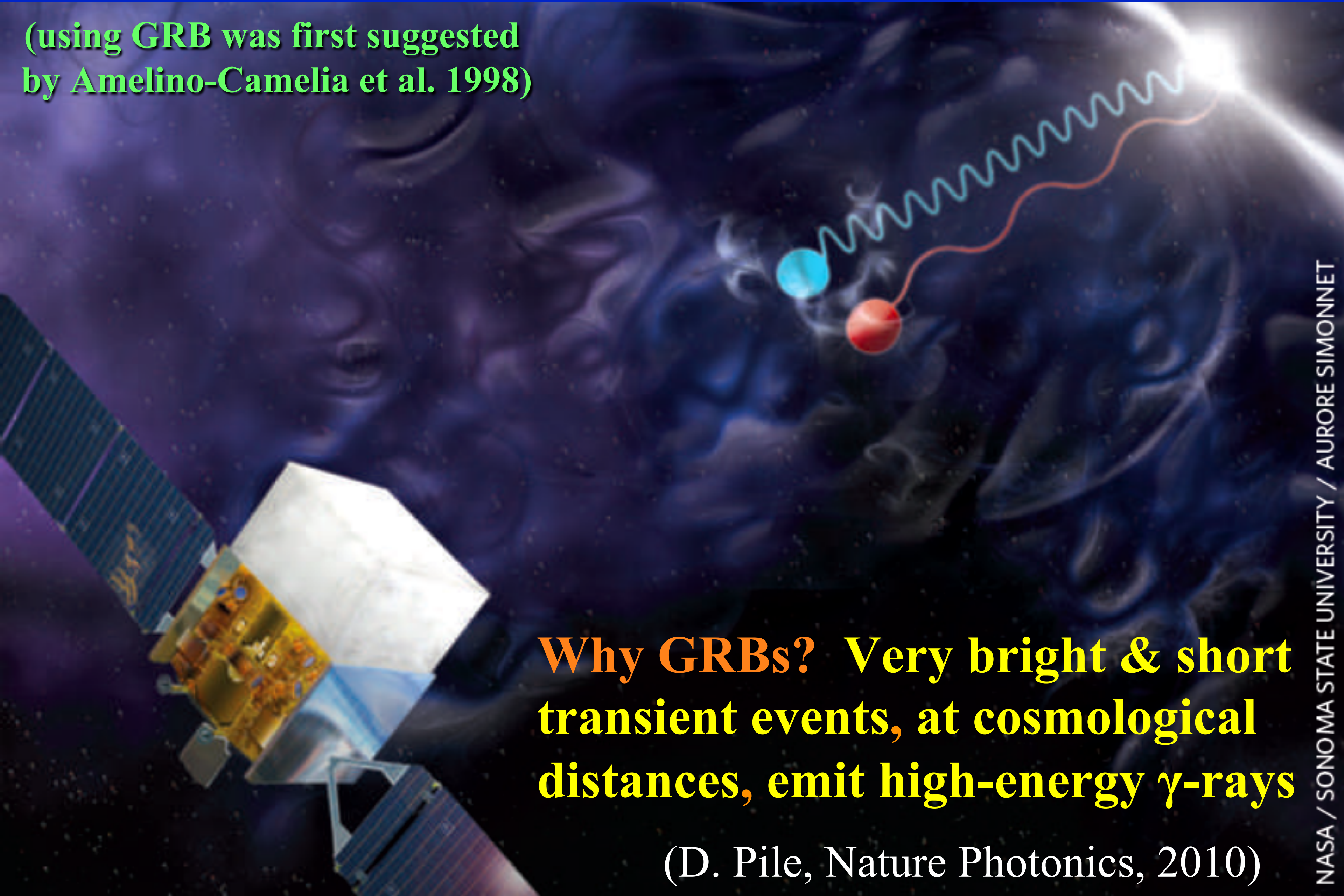
- γ-rays from distant sources can pair produce ($\gamma\gamma \rightarrow e^+e^-$) on the way to us with the extragalactic background light (EBL)
- This can test the transparency of the Universe and constrain EBL models (or the massive star formation rate at $z \gtrsim 1$)
- GRBs are already competitive with AGN, & probe higher z
- EBL possibly detected (using blazars: LAT+IACTs; Dominguez+ 2013)





Testing for Lorentz Invariance Violation

(using GRB was first suggested by Amelino-Camelia et al. 1998)



Why GRBs? Very bright & short transient events, at cosmological distances, emit high-energy γ-rays

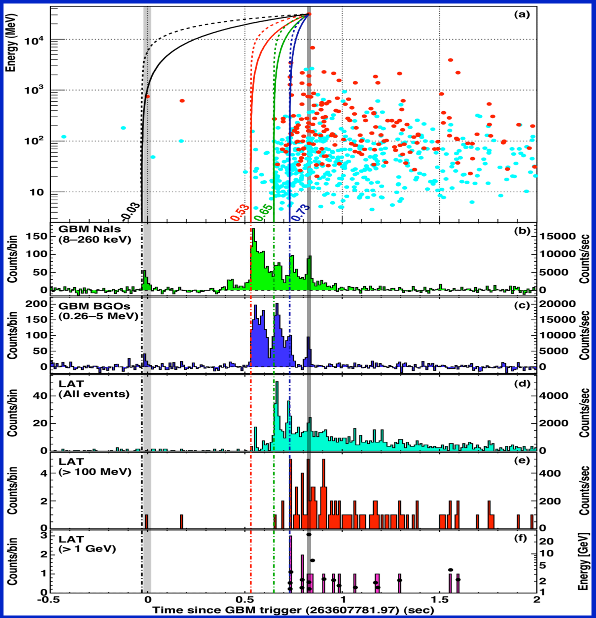
(D. Pile, Nature Photonics, 2010)

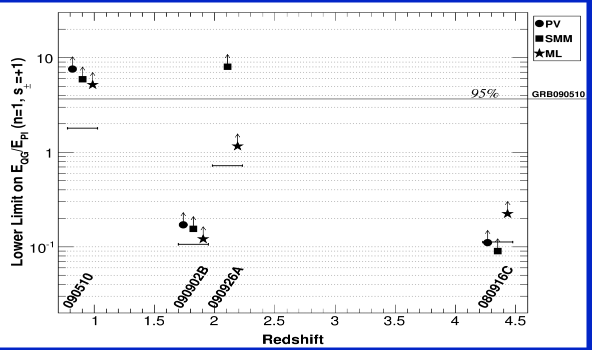
Testing for Lorentz Invariance Violation

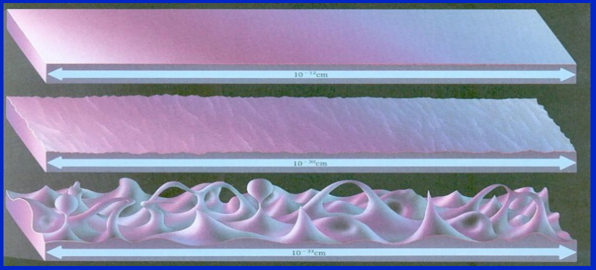
- GRB 090510 is much better than the rest (short, hard, very fine time structure)
- Abdo+ 2009, Nature, 462, 331: 1st direct time-of-flight limit beyond Plank scale on linear ($n = 1$) energy dispersion:

$$v_{\rm ph}/c \approx 1 \pm \tfrac{1}{2}(1+n)\left(E_{\rm ph}/E_{\rm QG,n}\right)^n \qquad E_{\rm QG,1} > 1.2 E_{\rm Planck}$$

  (robust, conservative, 2 independent methods)
- Vasileiou+ 2013: 3 different methods, 4 GRBs (090510 is still the best by far), the limits improved by factors of a few
- Vasileiou+ 2015, Nature Phys., 11, 344: stochastic LIV – motivation: space-time foam (1st Planck-scale limit of its kind)







Thank You