High-Energy Emission from GRBs: Theoretical Perspectives

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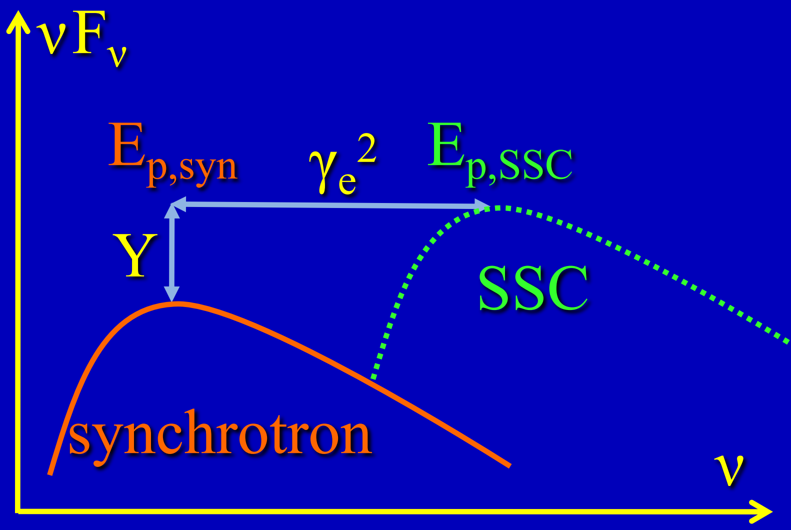
Outline of the Talk:

- High-Energy (HE) emission mechanisms
- GRB prompt HE emission – observations vs. theory:
  - Delayed HE onset, HE spectral component
  - ⇒ emission region: **Γ**, **R**
  - Long-lived HE emission
- High-energy afterglow & GRB 130427A:
  - Implications for relativistic collisionless shock physics
- non-GRB physics: EBL, Lorentz invariance violation

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–γ (photopion) interaction or p-p collisions **(inefficient, especially in afterglow)**

- Photospheric quasi-thermal emission @ $\lesssim 0.1$ MeV (not HE)

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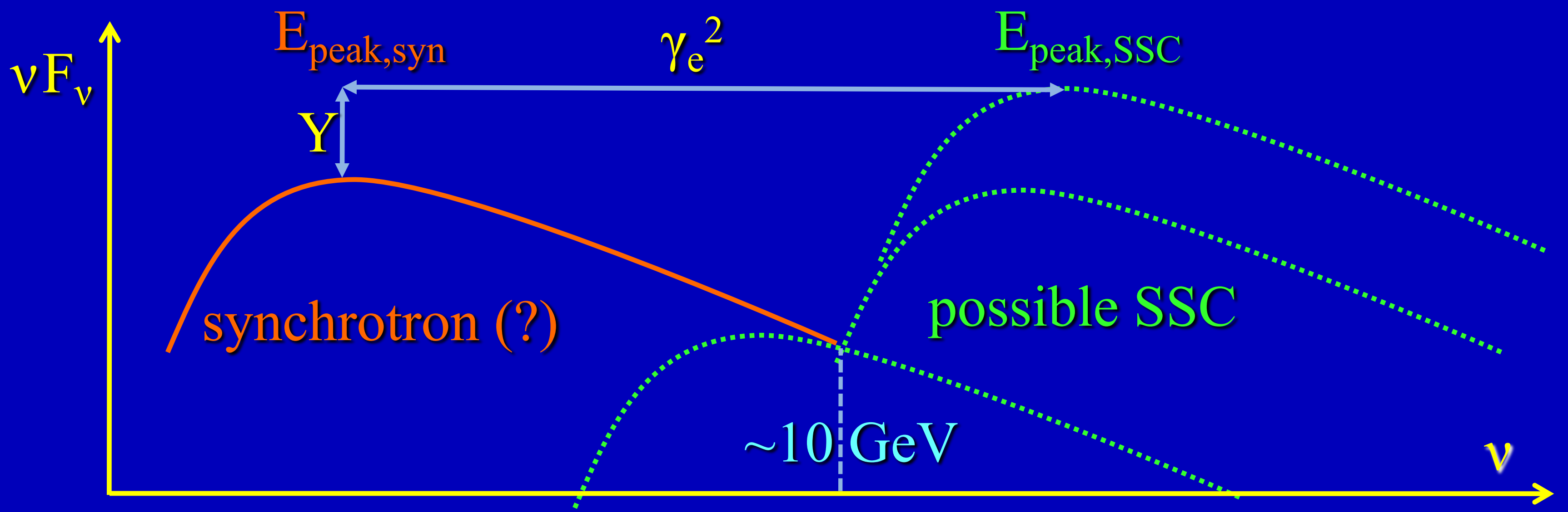
- **GRBs 090510, 090926A:** Y varies, and sometimes $Y > 1$
- **GRB080916C**: single dominant emission mechanism ⇒ if synchrotron, SSC is expected, and can avoid detection if $E_{peak,SSC} \gg 10$ GeV ($\gamma_e \gg 100$), **or** if $Y \approx \varepsilon_e/\varepsilon_B \lesssim 0.1$



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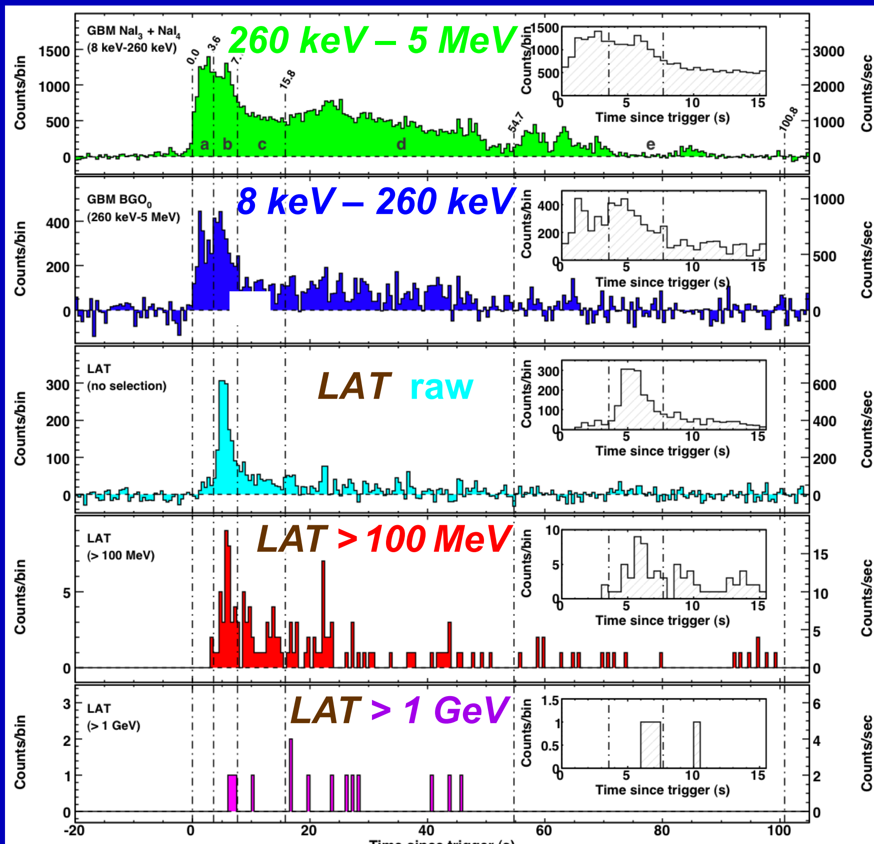
- **Parameter space study** (Beniamini & Piran 2013):
  $0.1 < \boldsymbol{\varepsilon_e/\varepsilon_B} < 10^4$ ($0.1 \lesssim \mathbf{Y} \lesssim 100$), $300 \lesssim \boldsymbol{\Gamma} \lesssim 3000$,
  $3 \times 10^3 \lesssim \gamma_e \lesssim 10^5$, 10^{15} cm $\lesssim \mathbf{R} \lesssim 10^{17}$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

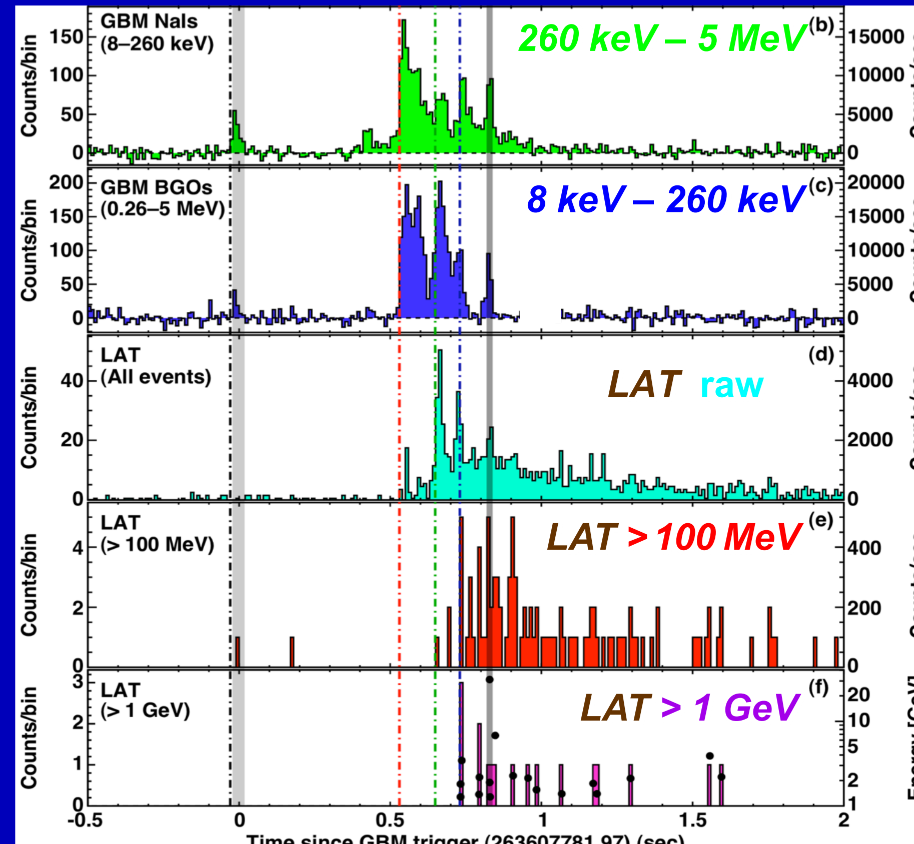
Delayed onset of High-Energy Emission

GRB080916C



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

GRB090510

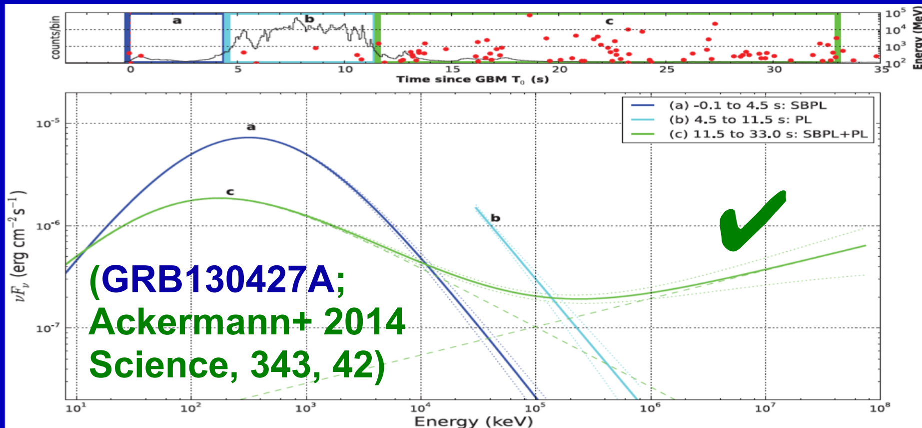


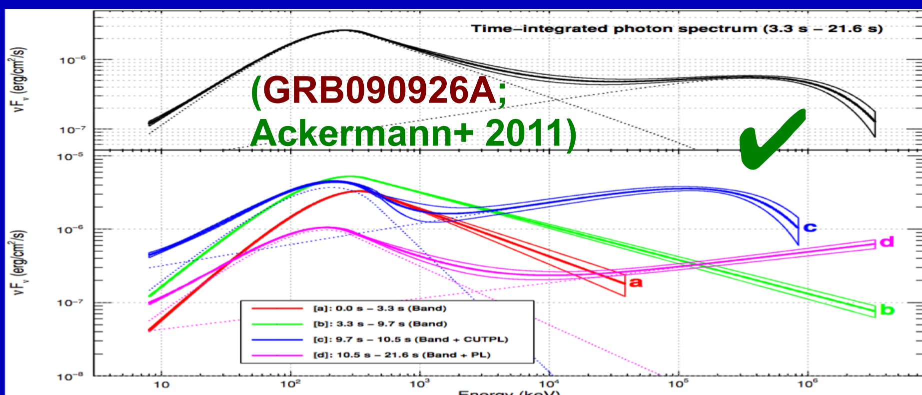
(Abdo et al. 2009, Nature, 462, 331)

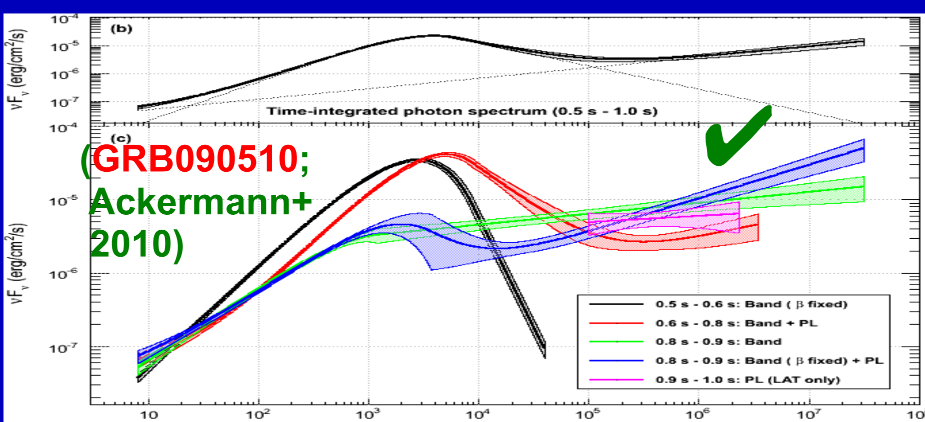
- The 1st LAT peak coincides with the 2nd GBM peak
- Delay in HE onset: ~ 4-5 s

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

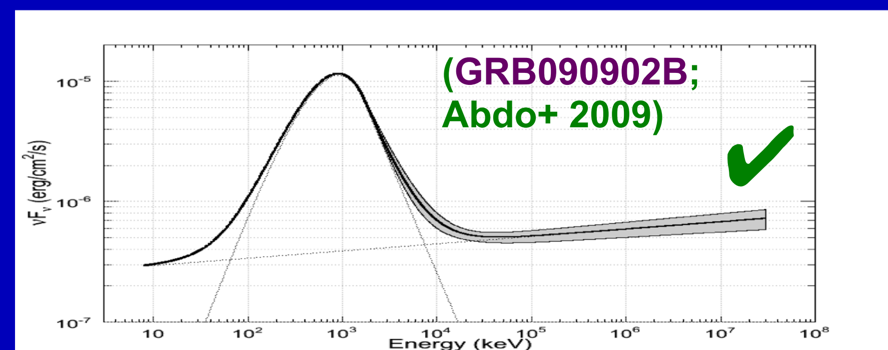
Distinct High-Energy Spectral Component

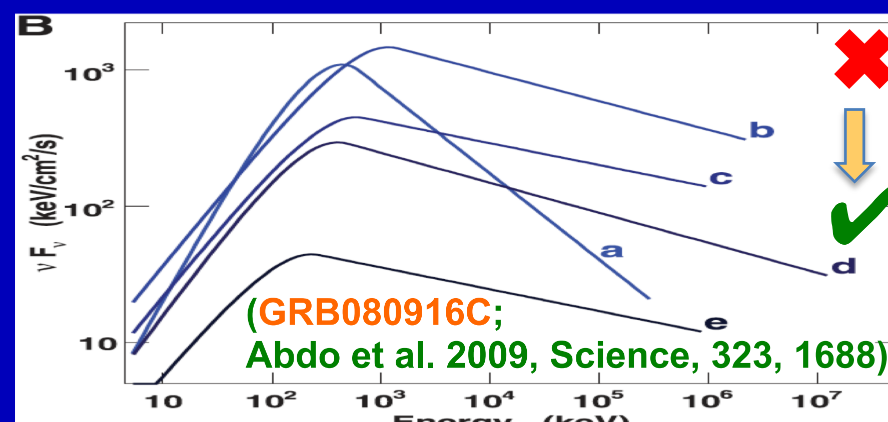






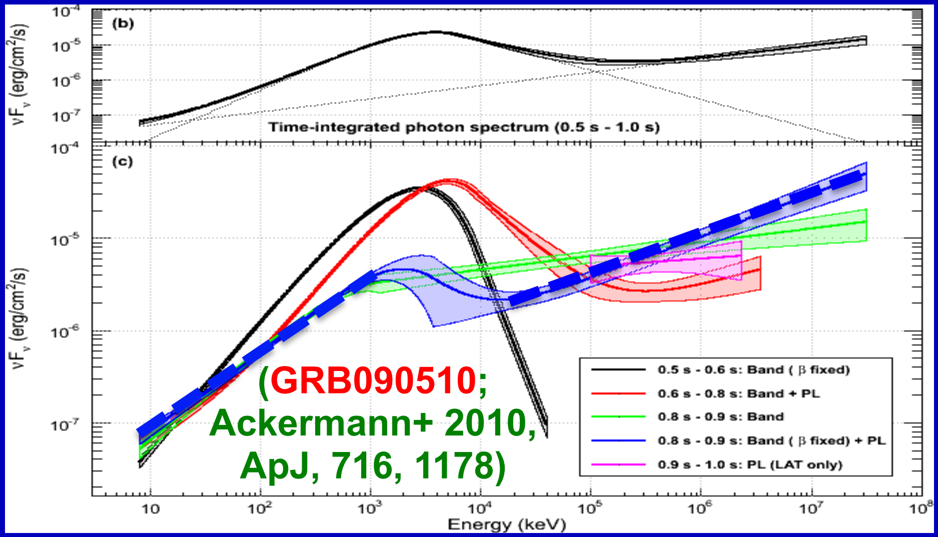
- Clearly (>5σ) exists in several LAT GRBs, but very common in the brightest LAT GRBs
- Suggests that it is common but good photon statistics is needed for clear evidence

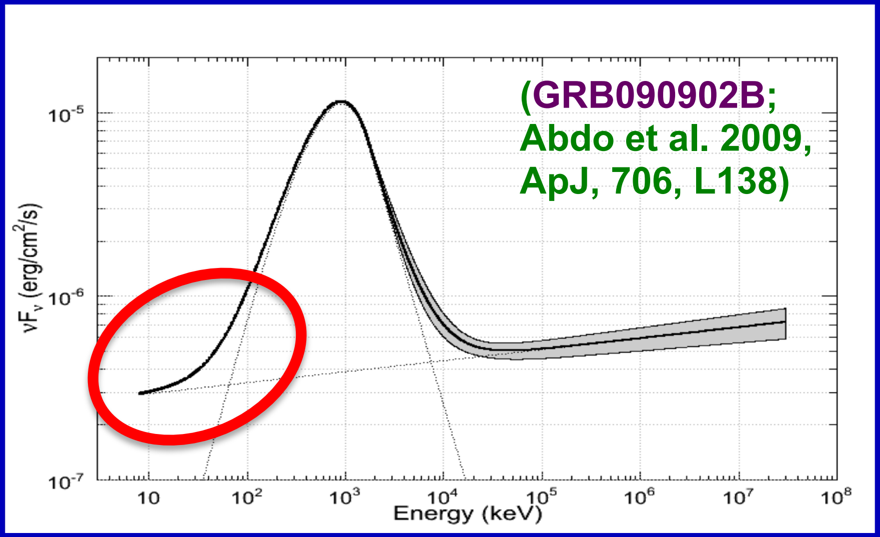




Late onset/HE spectral component: Possible Origin

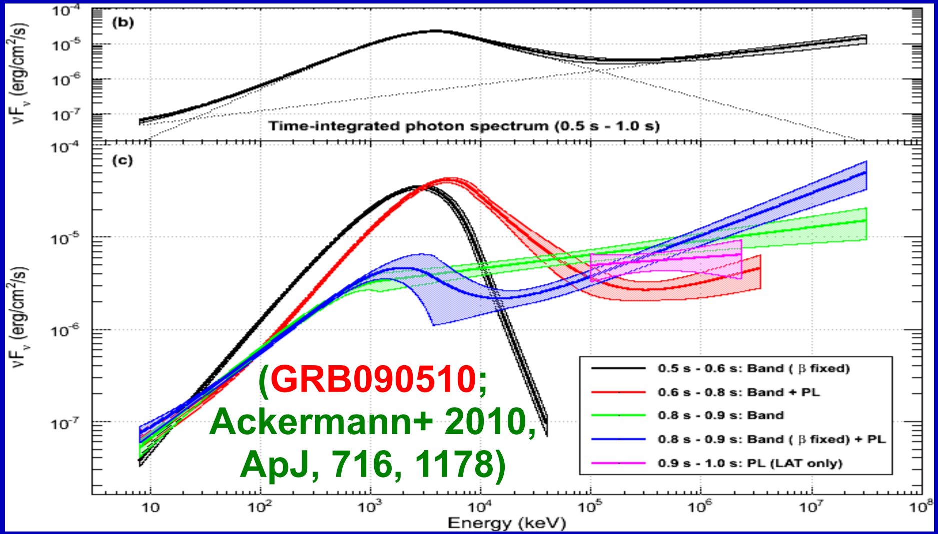
- **Leptonic**: inverse-Compton (or synchrotron self-Compton)?
  - A gradual increase in the HE photon index **β** (determined by the electron energy dist.) is not naturally expected
  - Hard to account for the different photon index values of the HE component & the Band spectrum at low energies
  - Hard to produce a low-energy power-law (GRB090902B)

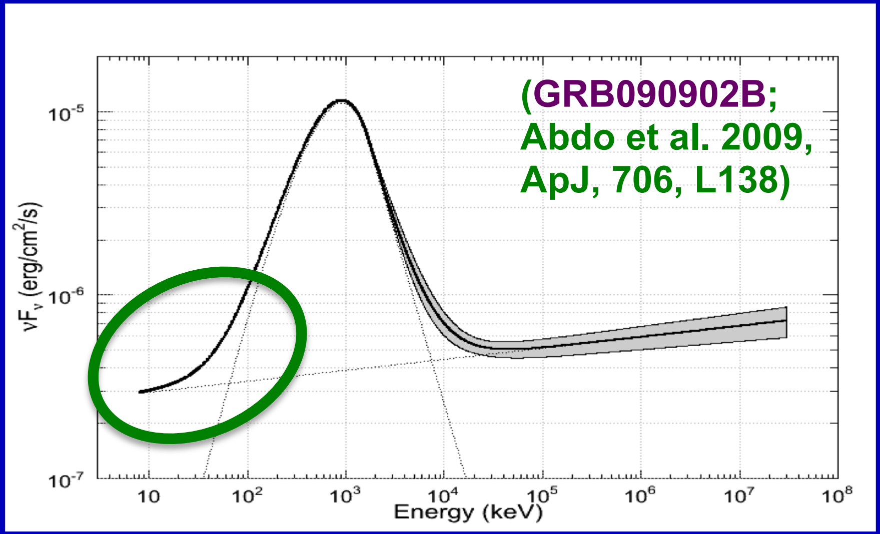




Late onset/HE spectral component: Possible Origin

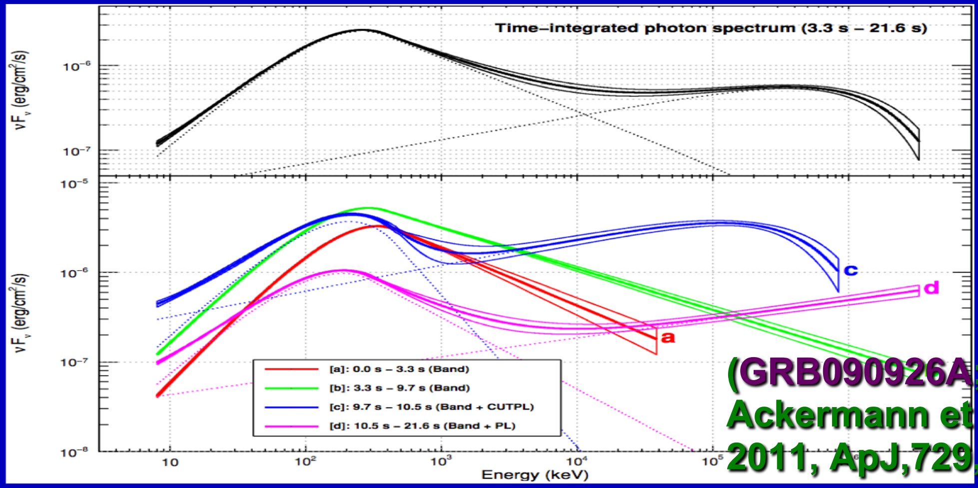
- **Hadronic**: (pair cascades, proton synchrotron) ?
  - Does not naturally account the gradual increase in β
  - GRB090510: large energy needed: $E_{total}/E_{\gamma,iso} \sim 10^2 - 10^3$
  - GRB090902B: synchrotron emission from secondary $e^{\pm}$ pairs can naturally explain the power-law at low energies

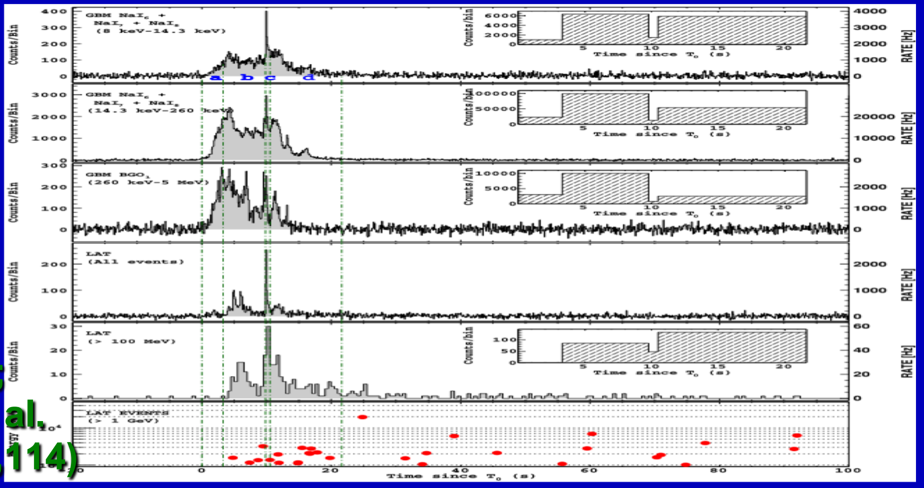




Constraints on Γ for Fermi LAT GRBs

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

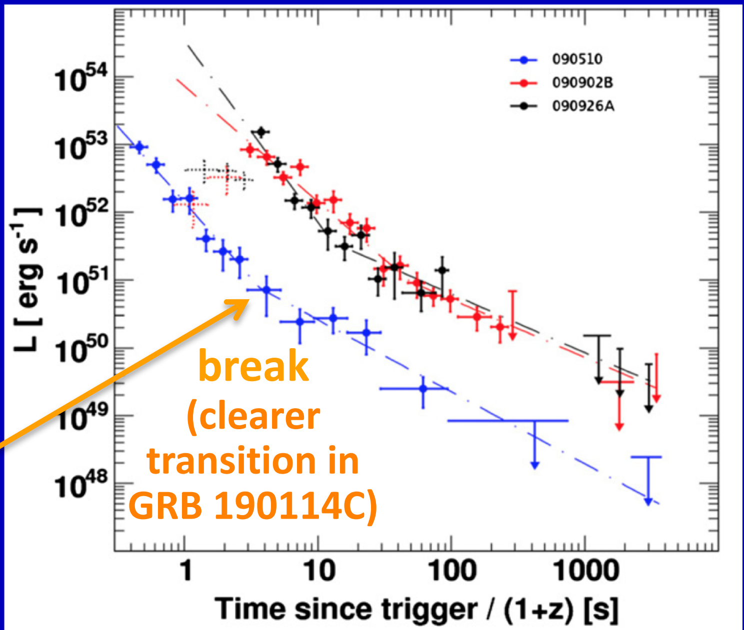


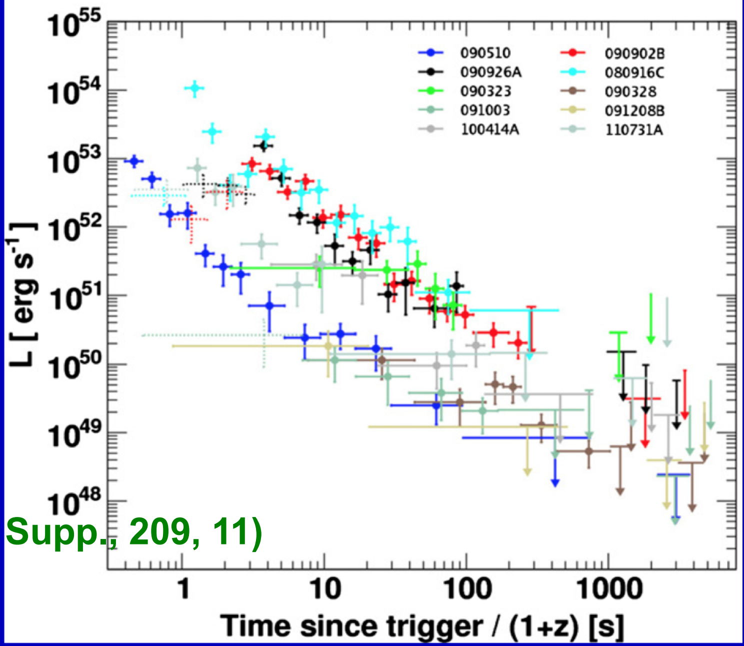


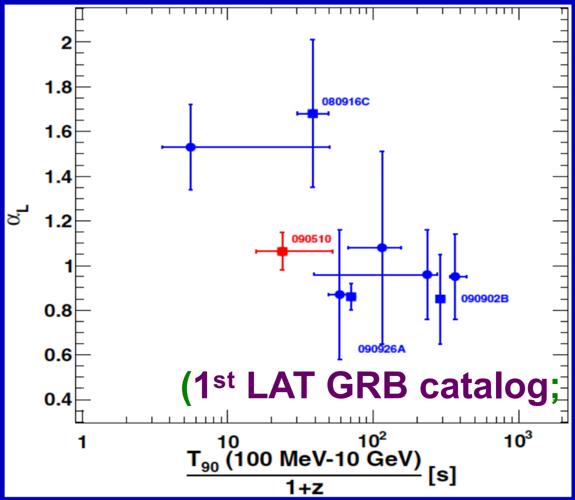
(GRB090926A; Ackermann et al. 2011, ApJ,729,114)

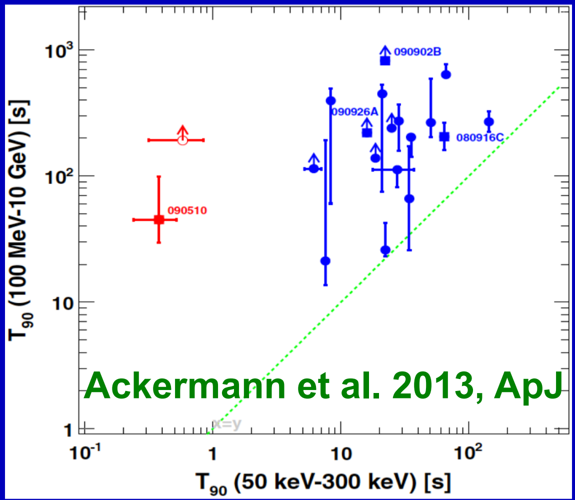
Long-Lived High-Energy emission

- 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 $t \leq T_{90}$ sharp spikes $\Rightarrow$ not afterglow)
- Prompt to **afterglow** transition?
- X-ray flares @ HE? (GRB100728A?)
- Hadronic, pair echo, SSC,… ???





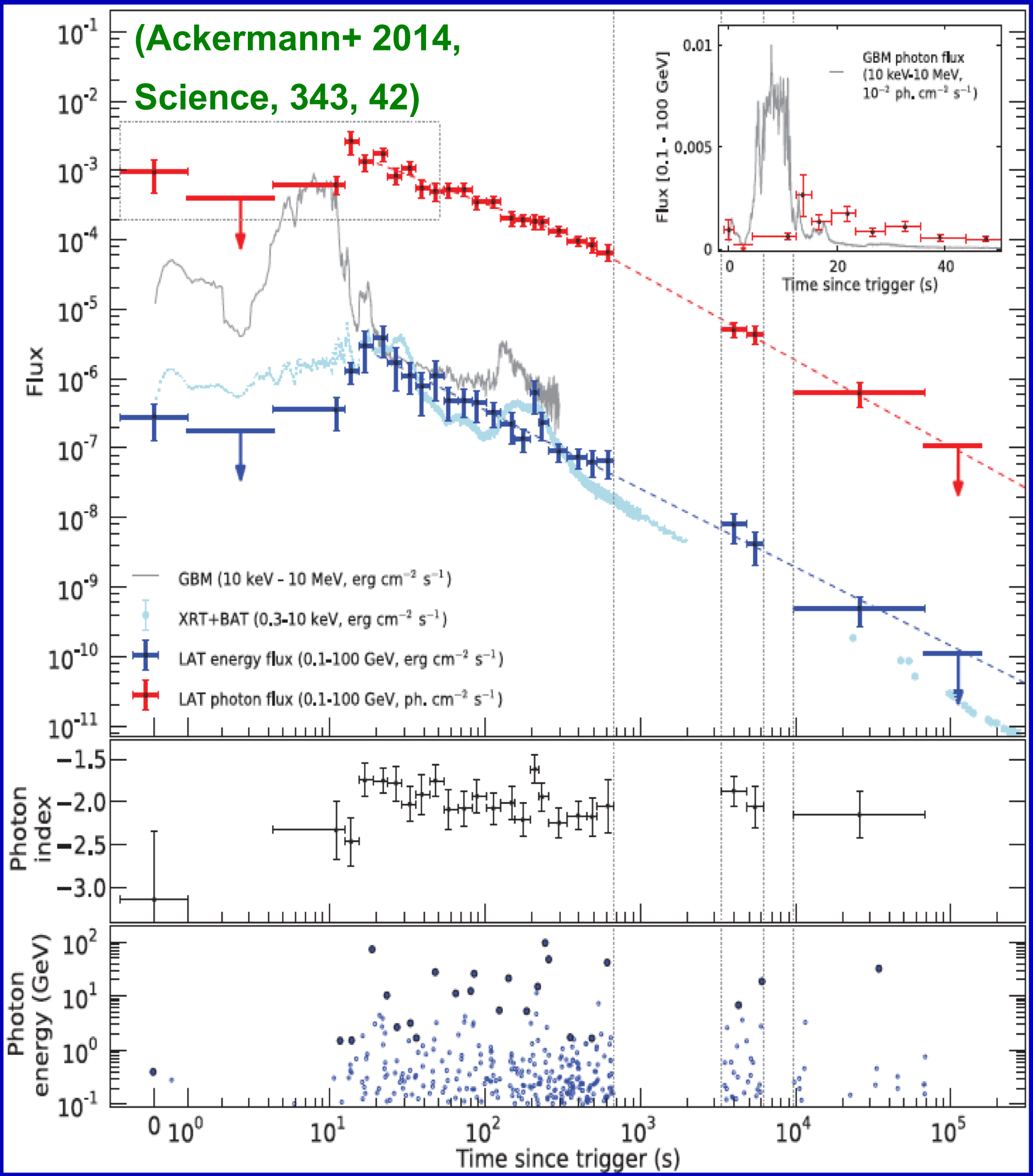




(1st LAT GRB catalog; Ackermann et al. 2013, ApJ Supp., 209, 11)

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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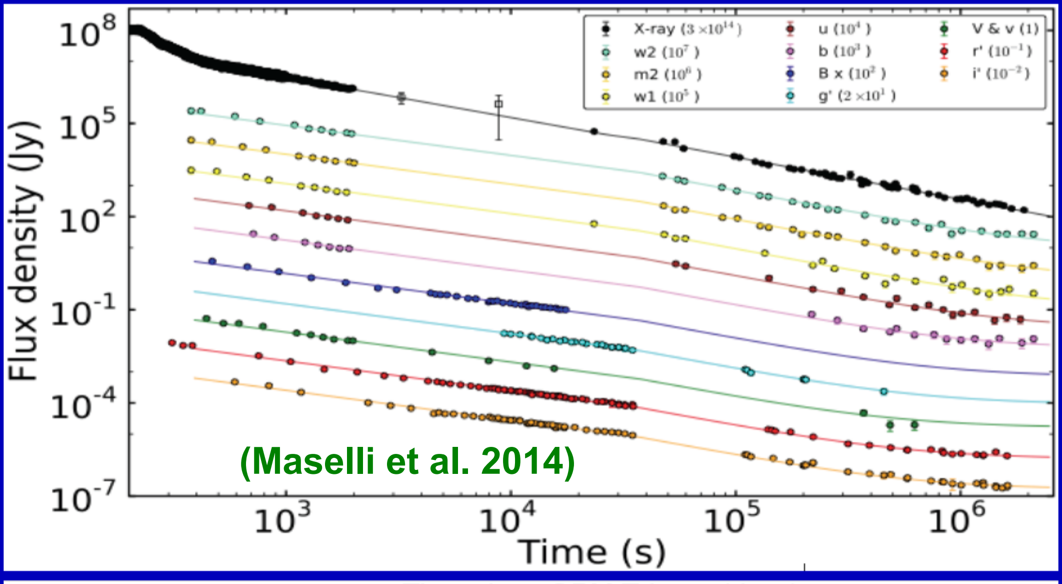
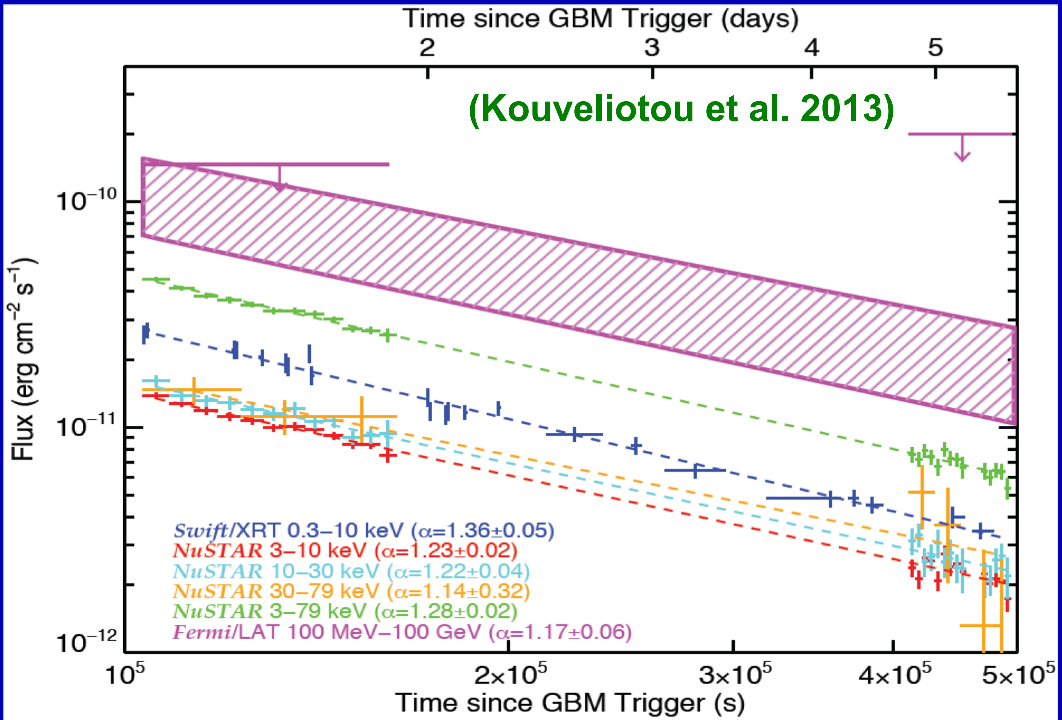
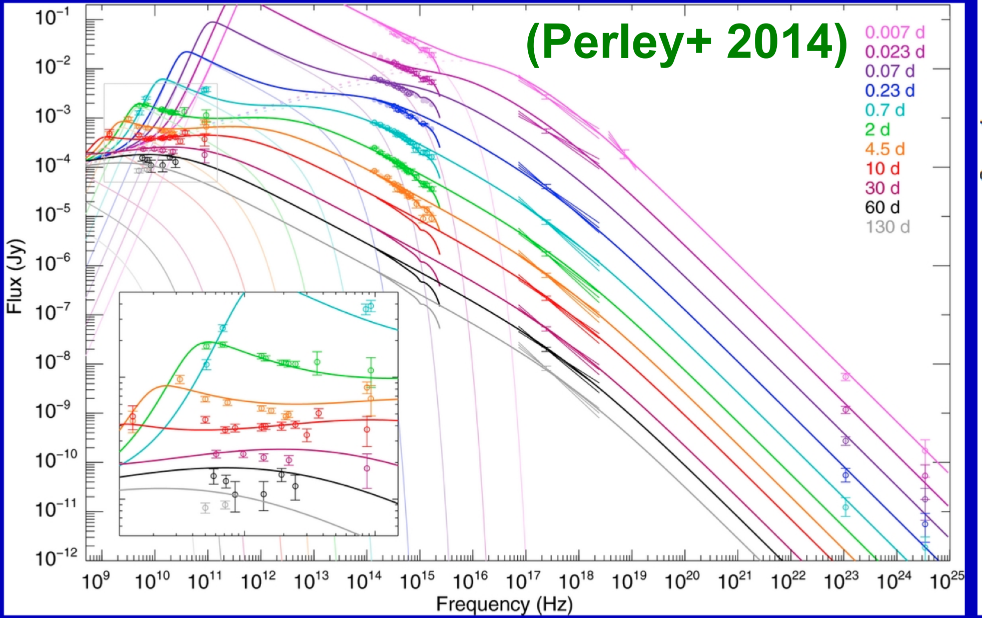
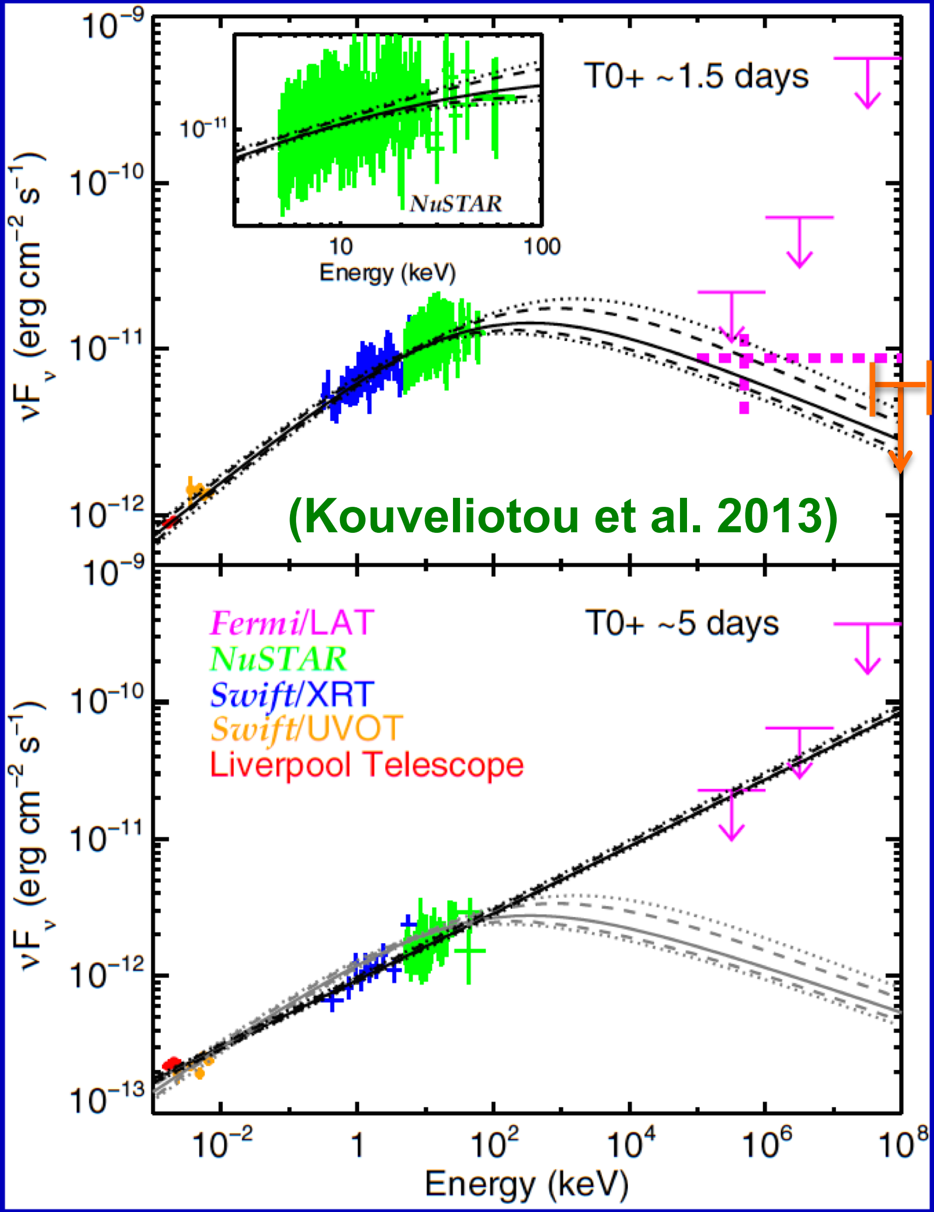




High-Energy Afterglow: GRB130427A

- **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)

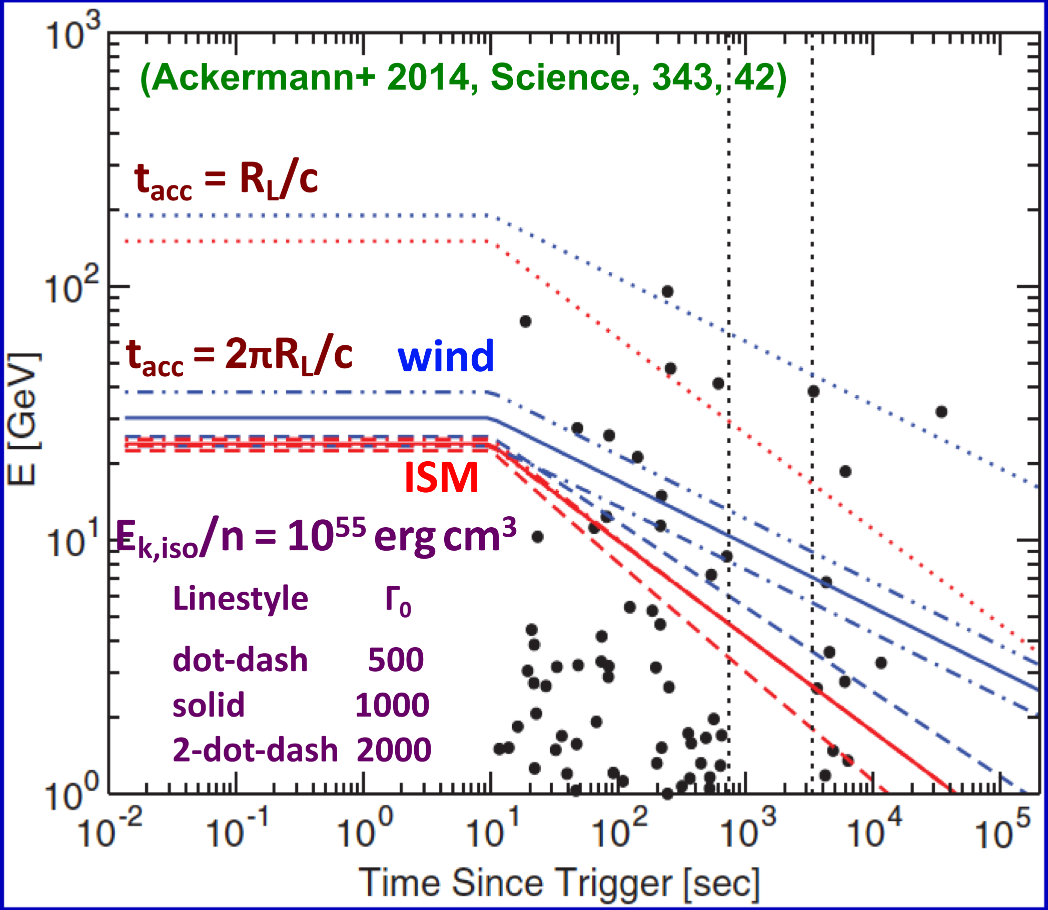




High-Energy Afterglow: GRB130427A

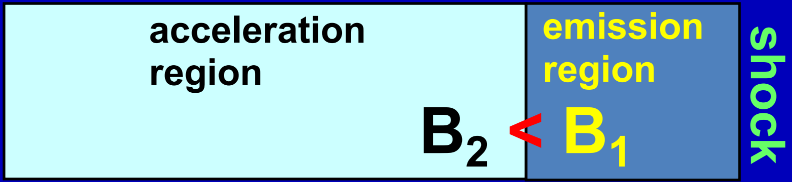
- **LAT HE photons violate:**

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



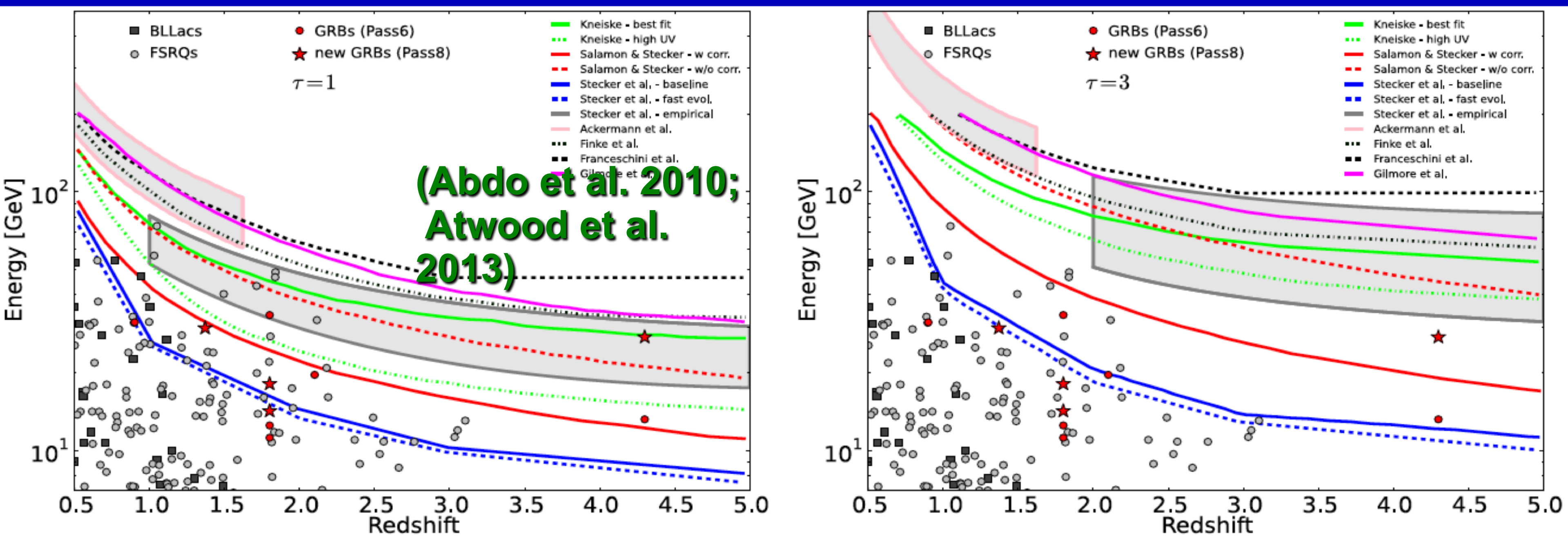
- Based on a one-zone model balancing electron energy gains and losses: $t_{acc} \sim t_{syn}$
- $t_{acc} \sim 1/\omega_L = R_L/c$ (extremely fast) or $P_L = 2\pi/\omega_L$ (still very fast but a bit more realistic)
- An "easy way out" would be if SSC emission dominated at highest LAT energies (Fan+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

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



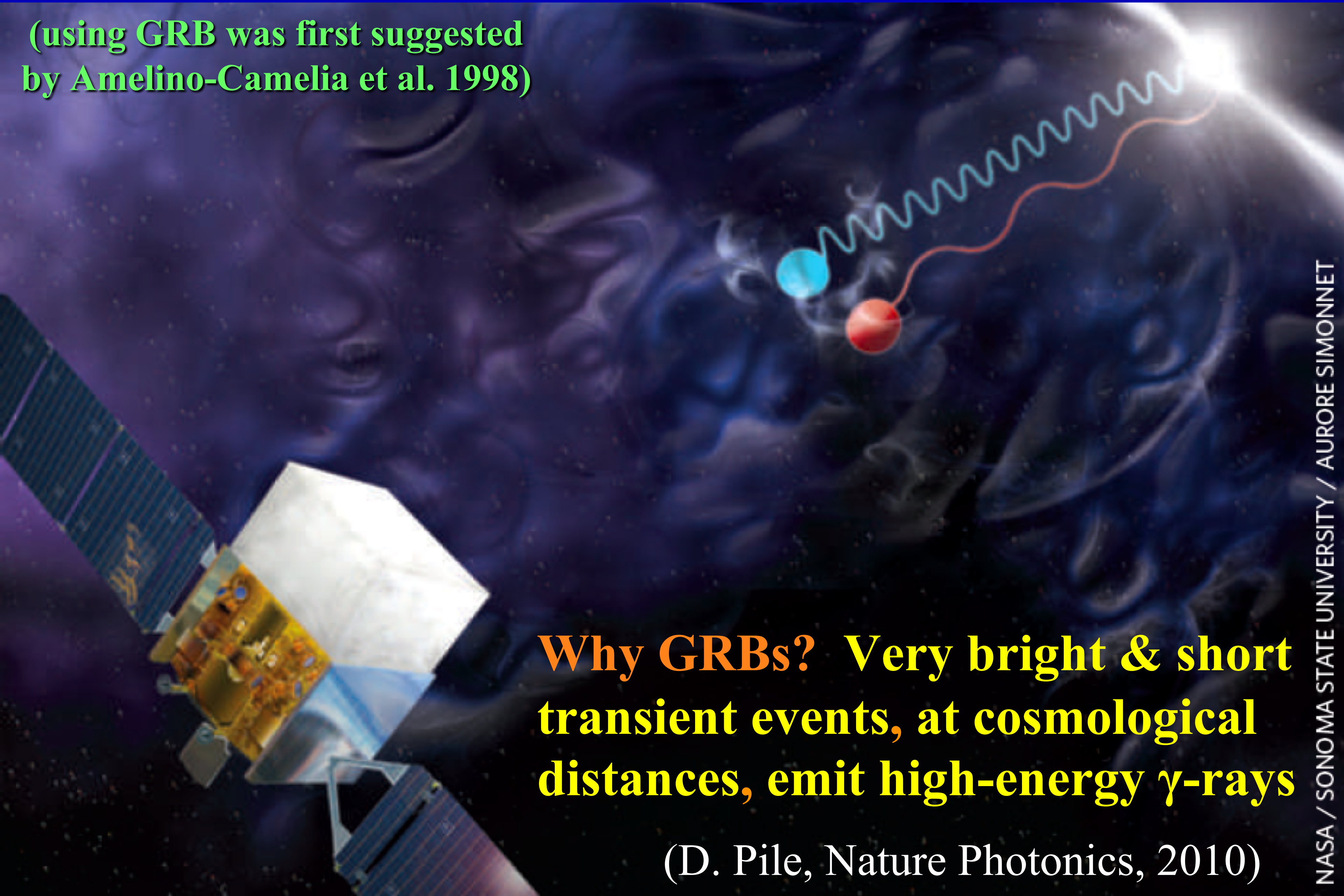
Constraining the opacity of the Universe

- 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 likely detected (with blazars: LAT+IACTs; Dominguez+13; Acciari+19)



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)

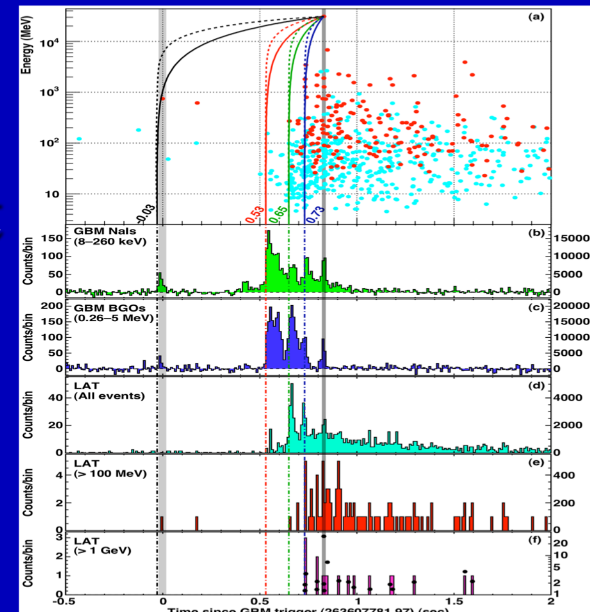
Testing for Lorentz Invariance Violation

- 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:

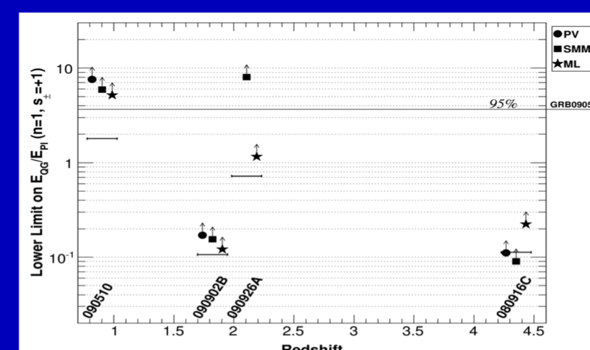
$$v_{\rm ph} / c \approx 1 \pm \tfrac{1}{2}(1+n)\left(E_{\rm ph} / E_{\rm QG,n}\right)^{n}$$

$$E_{\rm QG,1} > 1.2 E_{\rm Planck}$$

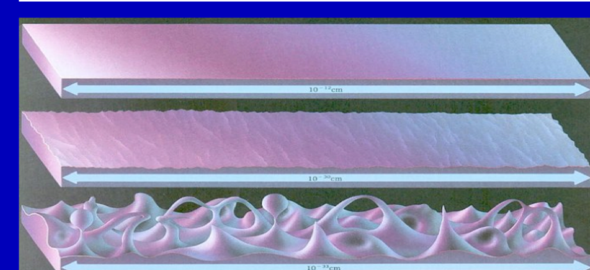
(robust, conservative, 2 independent methods)



- 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