Physics of Short Gamma-Ray Bursts Explored by CTA and DECIGO/B-DECIGO

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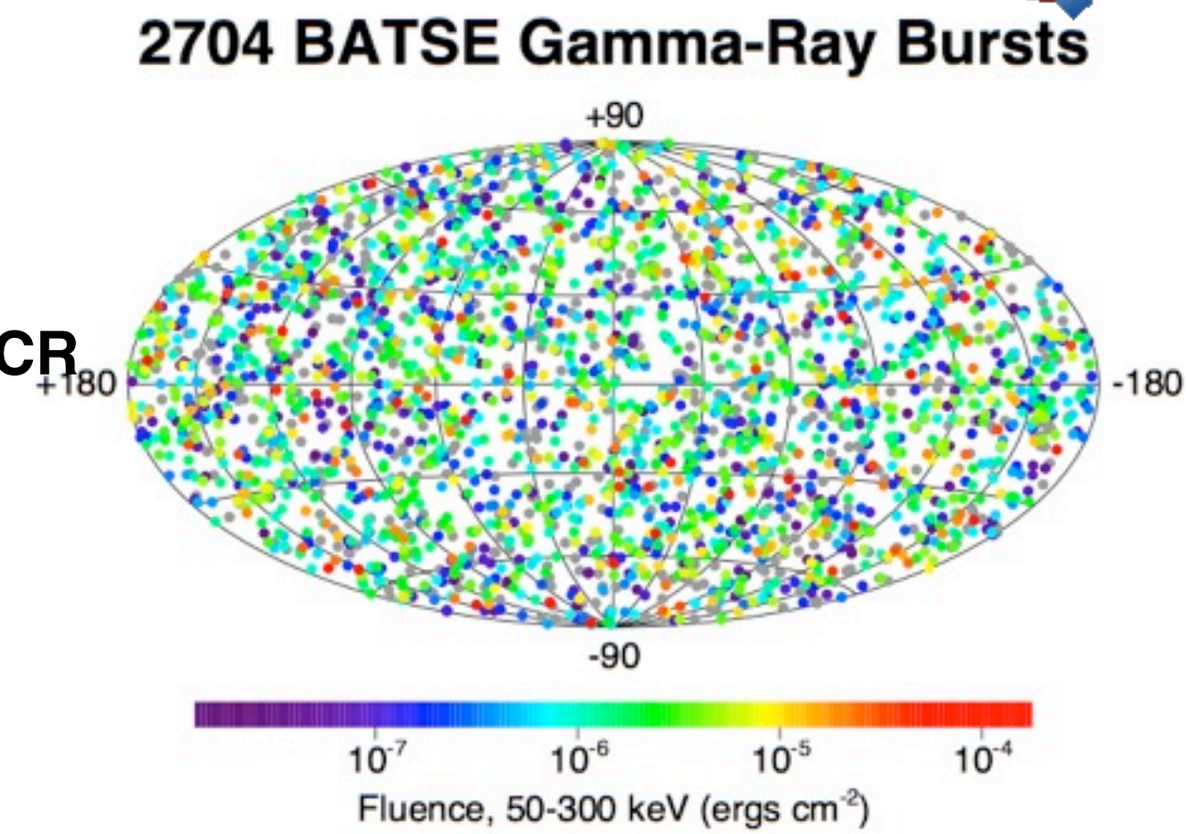
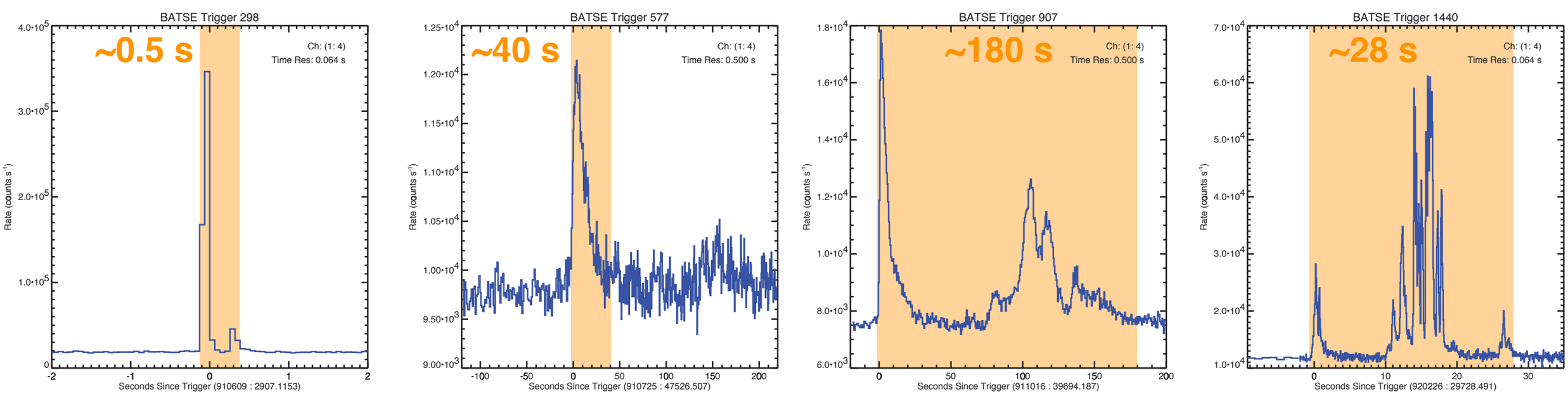
Gamma-Ray Bursts Overview (1)

- Discovered in 1967
- Cosmological origin
  - Large apparent energy release: 10^{52}~10^{54}
  - Energetics consistent with origin of UHECR
- Peak in ~MeV gamma rays
  - Band function:
    smoothly joined two power law
  - Synchrotron radiation of
    ultra-relativistic electrons in jet?





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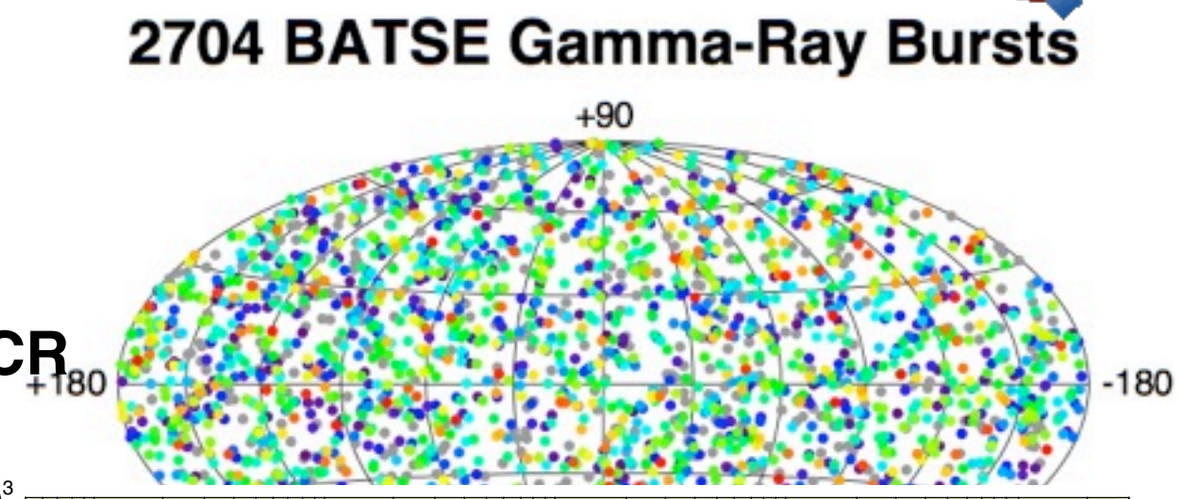
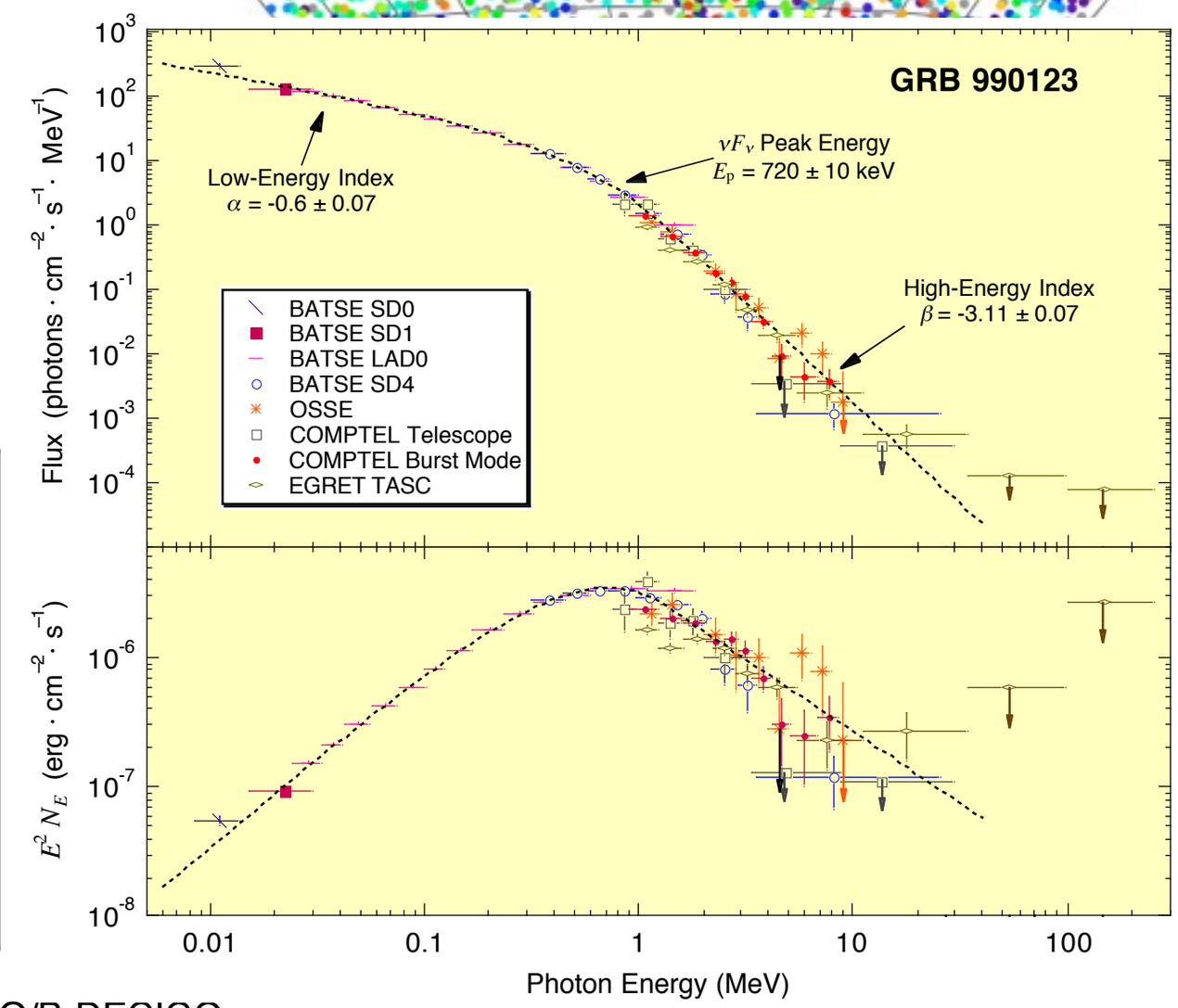
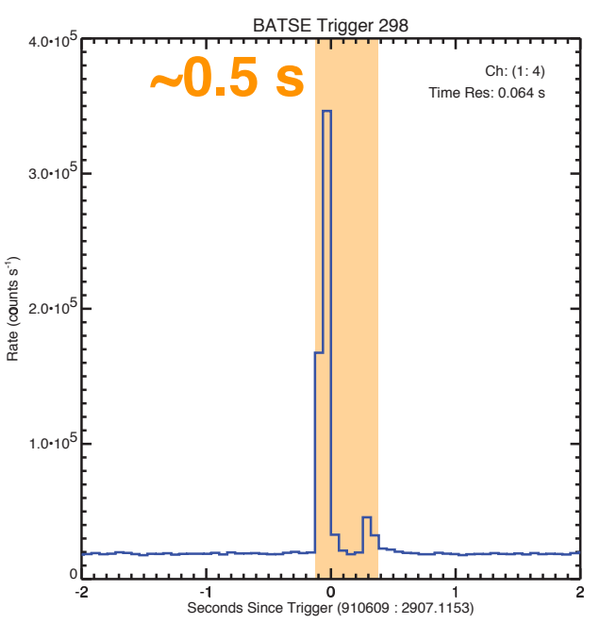
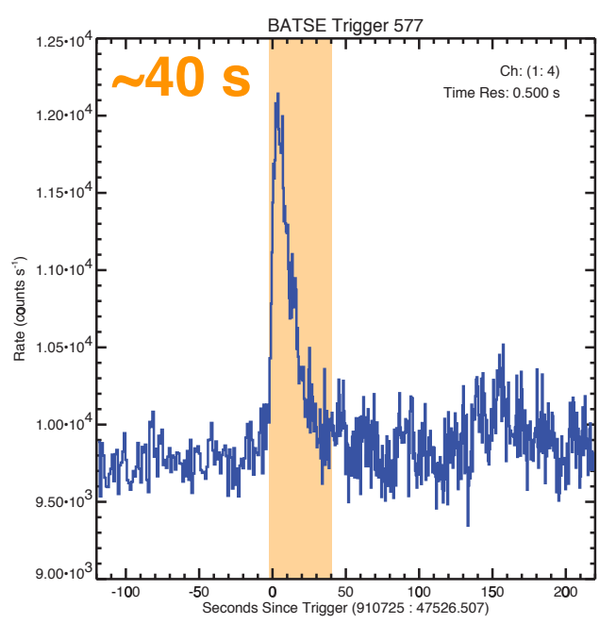


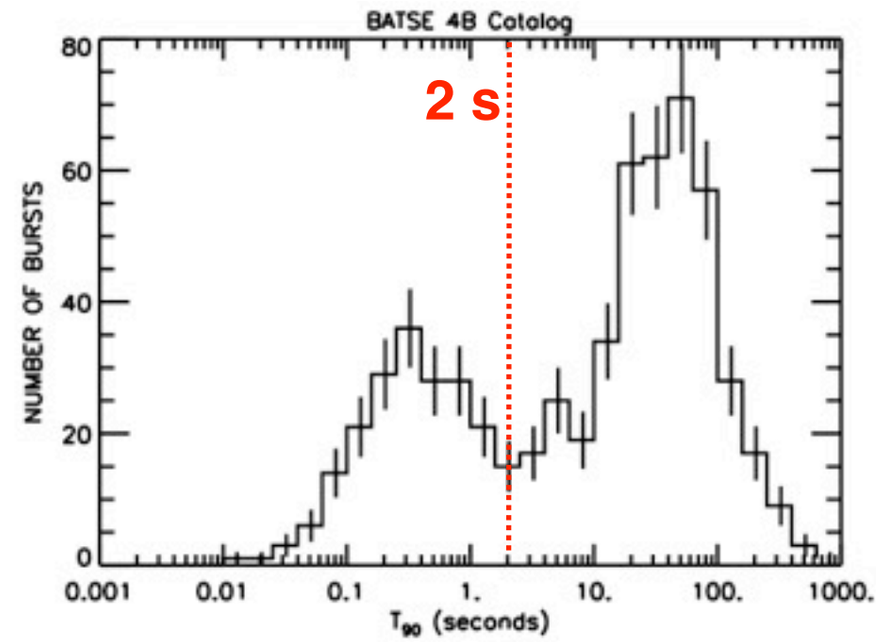


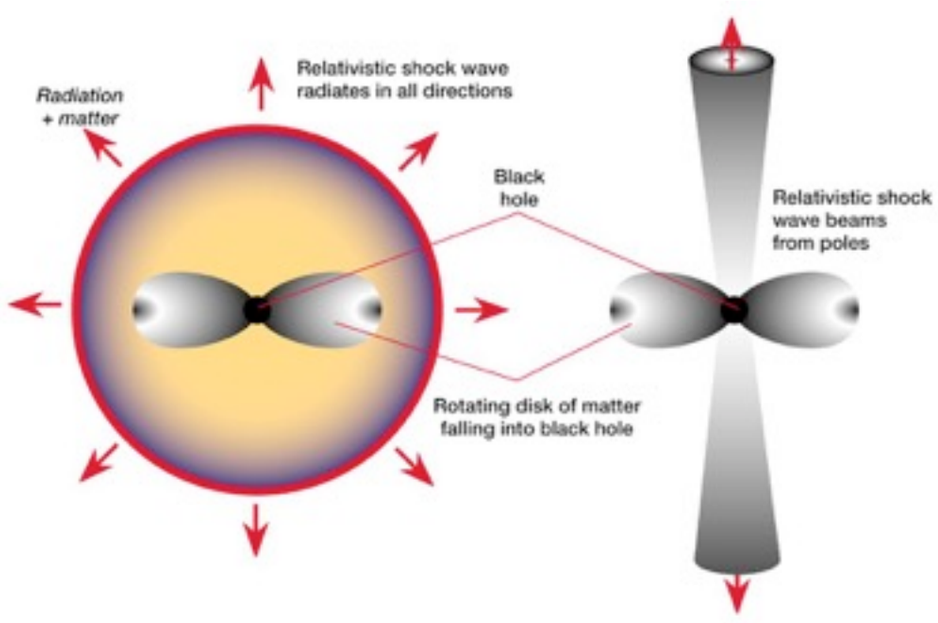


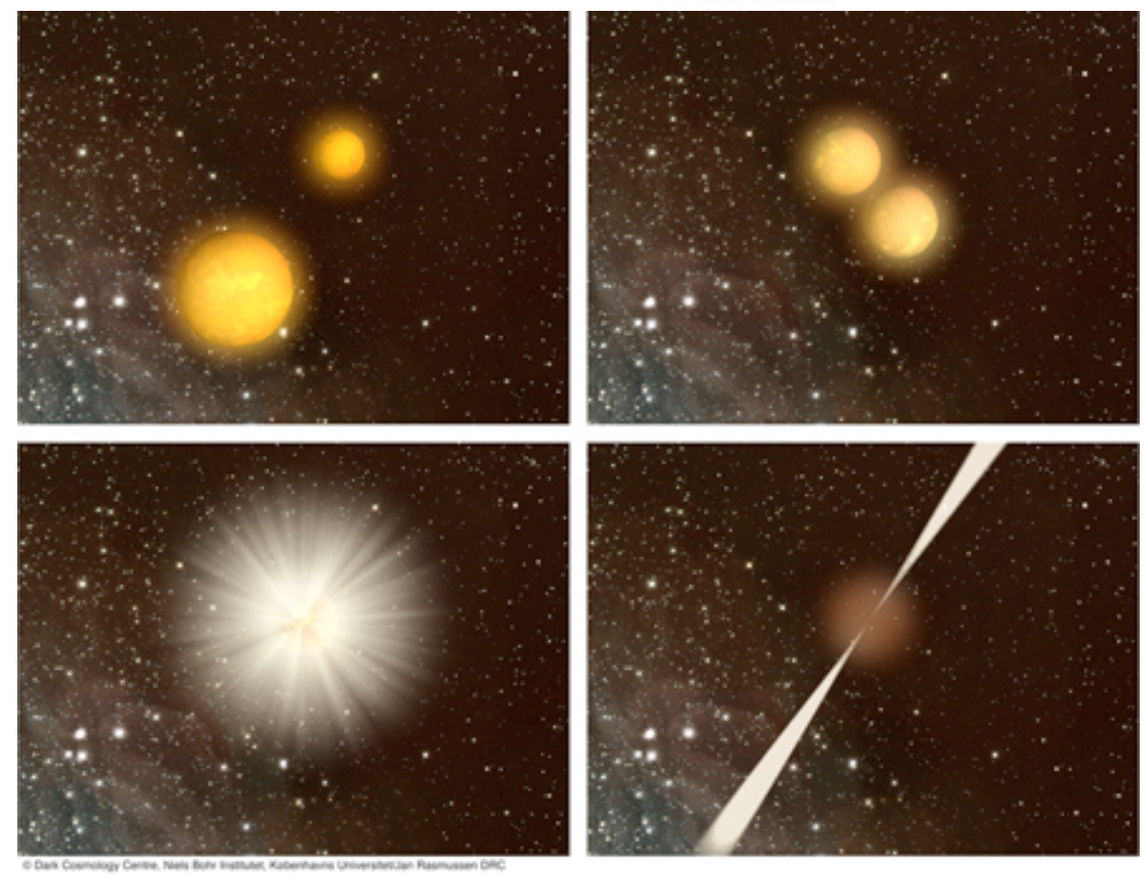


Gamma-Ray Bursts Overview (2)

- **Bimodal Duration Distribution**
  - **Short (< 2s) GRB: progenitor unknown**
    - **Merger of compact objects (NS or BH)**
  - **Long (> 2s) GRB:**
    - **Association with supernovae**
      - ☒ **Core-collapse supernovae**
- **Gamma-ray emission mechanism not well understood**







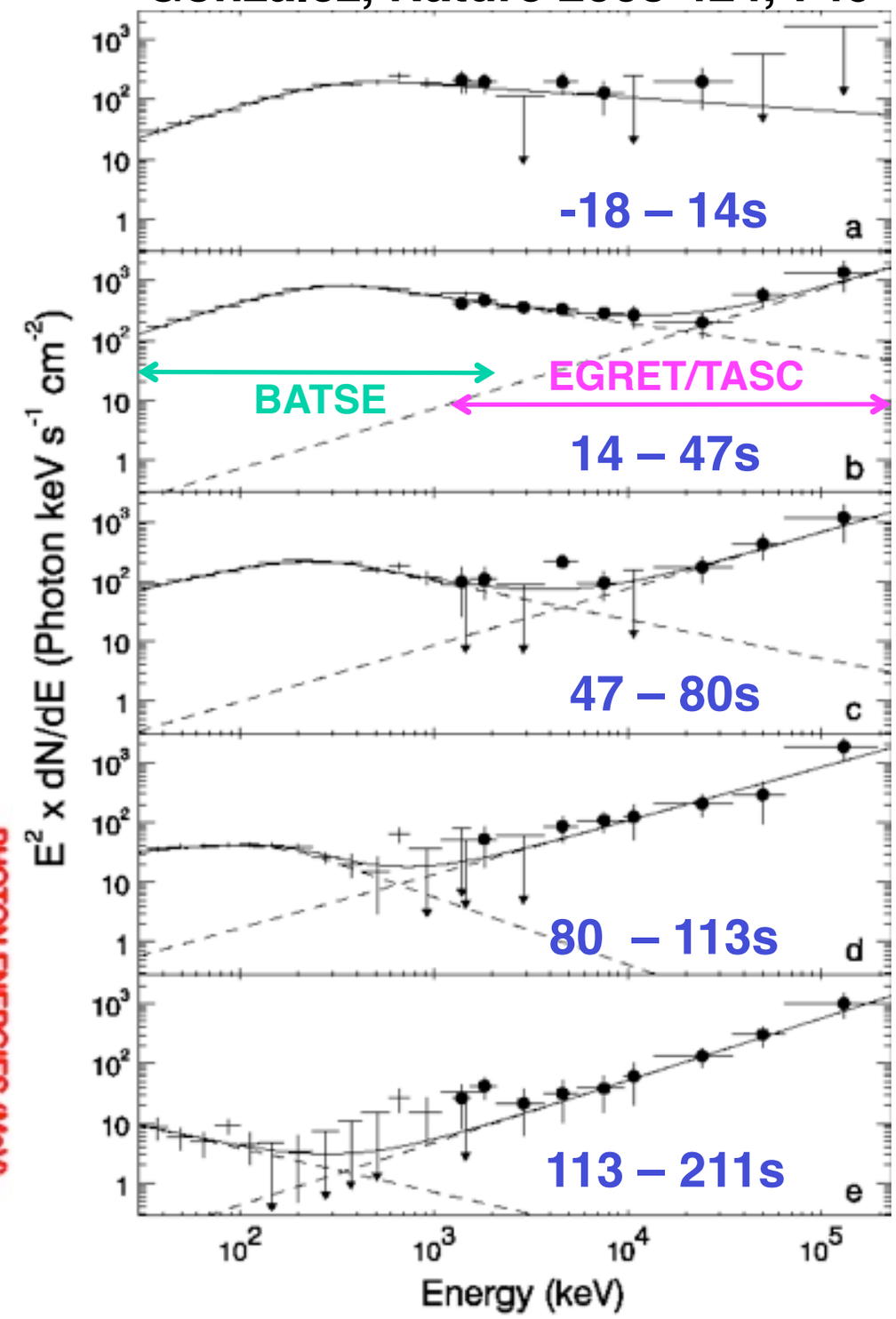
The Neutron Stars Merging Scenario

ESO PR Photo 32c/05 (October 6, 2005)

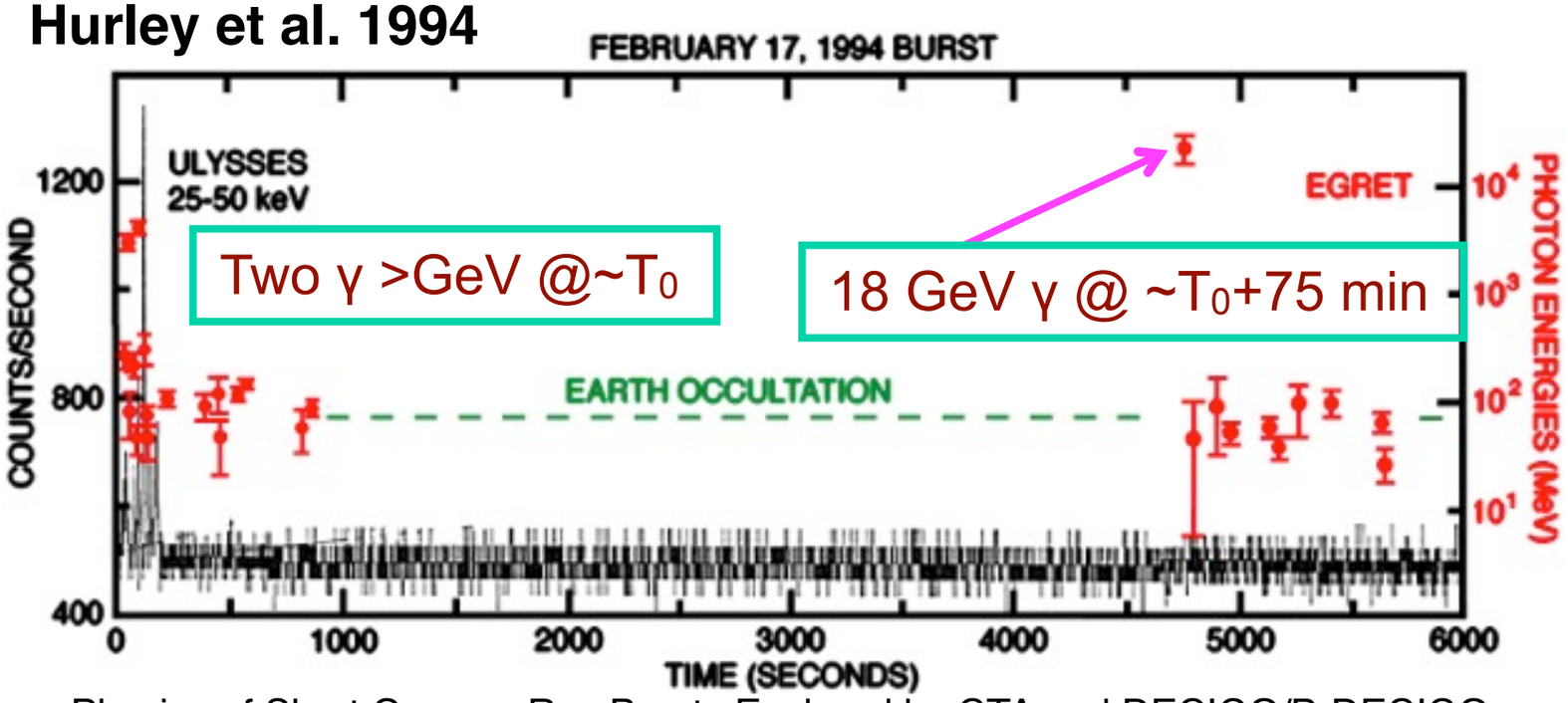
High-Energy Emissions from GRBs

- **EGRET observations of delayed HE gamma-ray emissions**
  - **It is not straightforward to explain by conventional electron synchrotron models**
  - **Proton acceleration? Origin of UHECR?**

Gonzalez, Nature 2003 424, 749

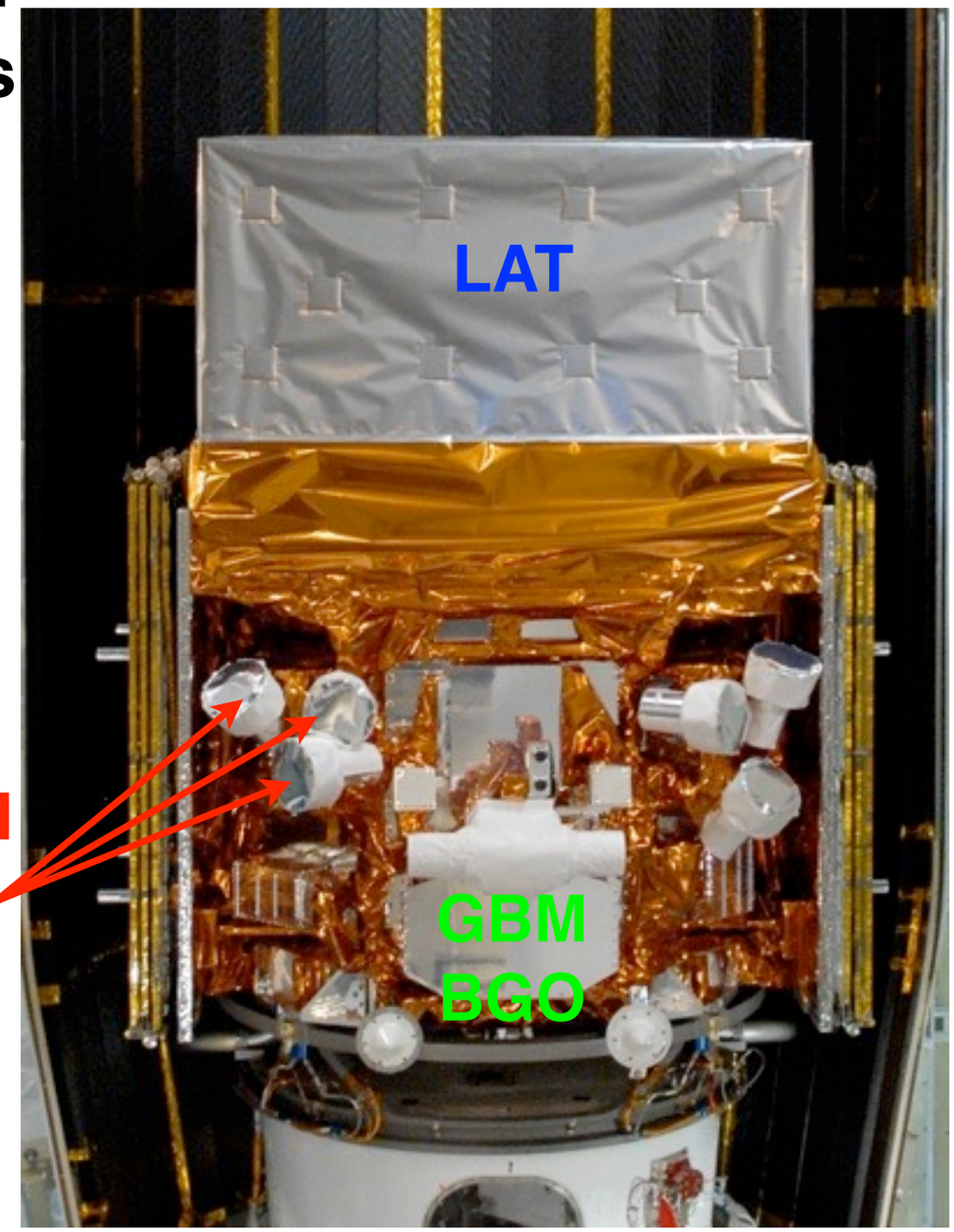


Hurley et al. 1994



GRB Observations by Fermi

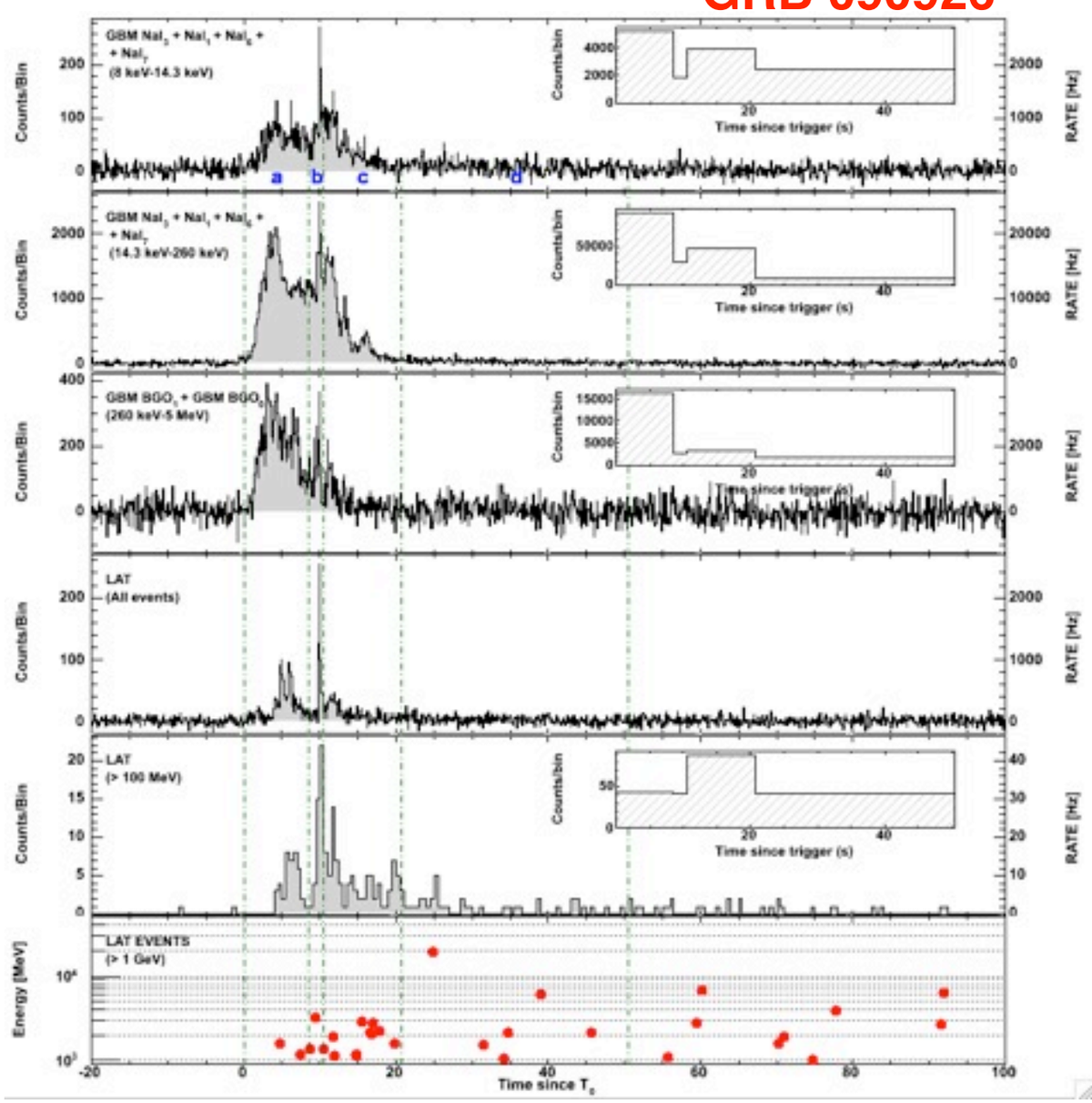
- Improved performance of Fermi LAT (Large Area Telescope)
  - Larger FOV (>2.4 sr): more GRB samples
  - Larger effective area: better statistics
  - Less dead time: detailed lightcurve, time-resolved analysis
  - Wider energy coverage: up to > 300 GeV
- Fermi Gamma-ray Burst Monitor
  - Views entire unocculted sky
  - NaI: 8 keV - 1 MeV
  - BGO: 150 keV - 30 MeV
- Fermi GBM-LAT covers >7 decades of energy band (8 keV to > 300 GeV)



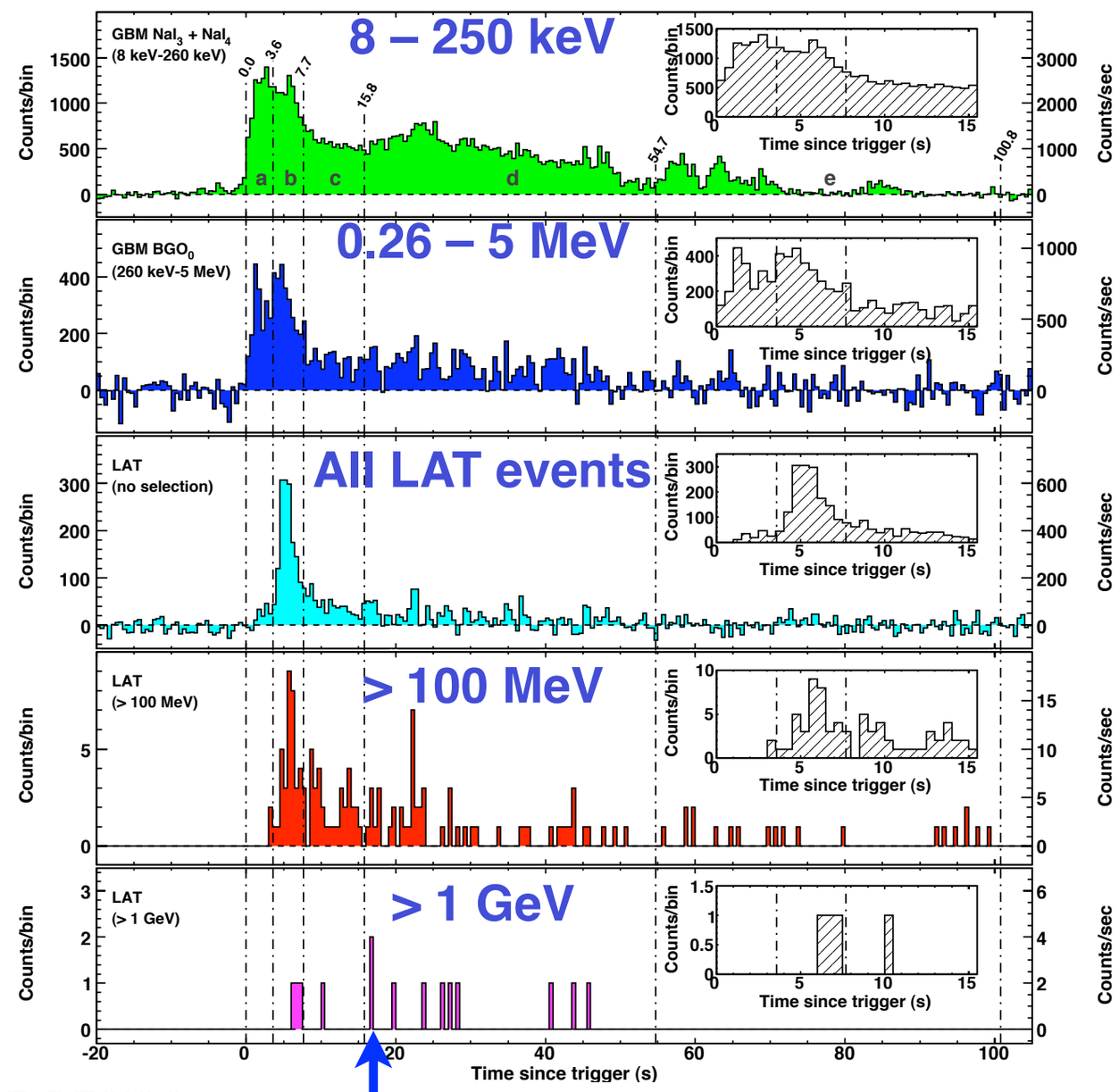
Delayed HE Gamma-ray Emission

- Opacity due to $\gamma\gamma \rightarrow e^+e^-$ in the first peak
- Late arrival of highest energy gamma rays

GRB 090926



GRB 080916C



13.2 GeV photon

Science 323 1688A (2009)

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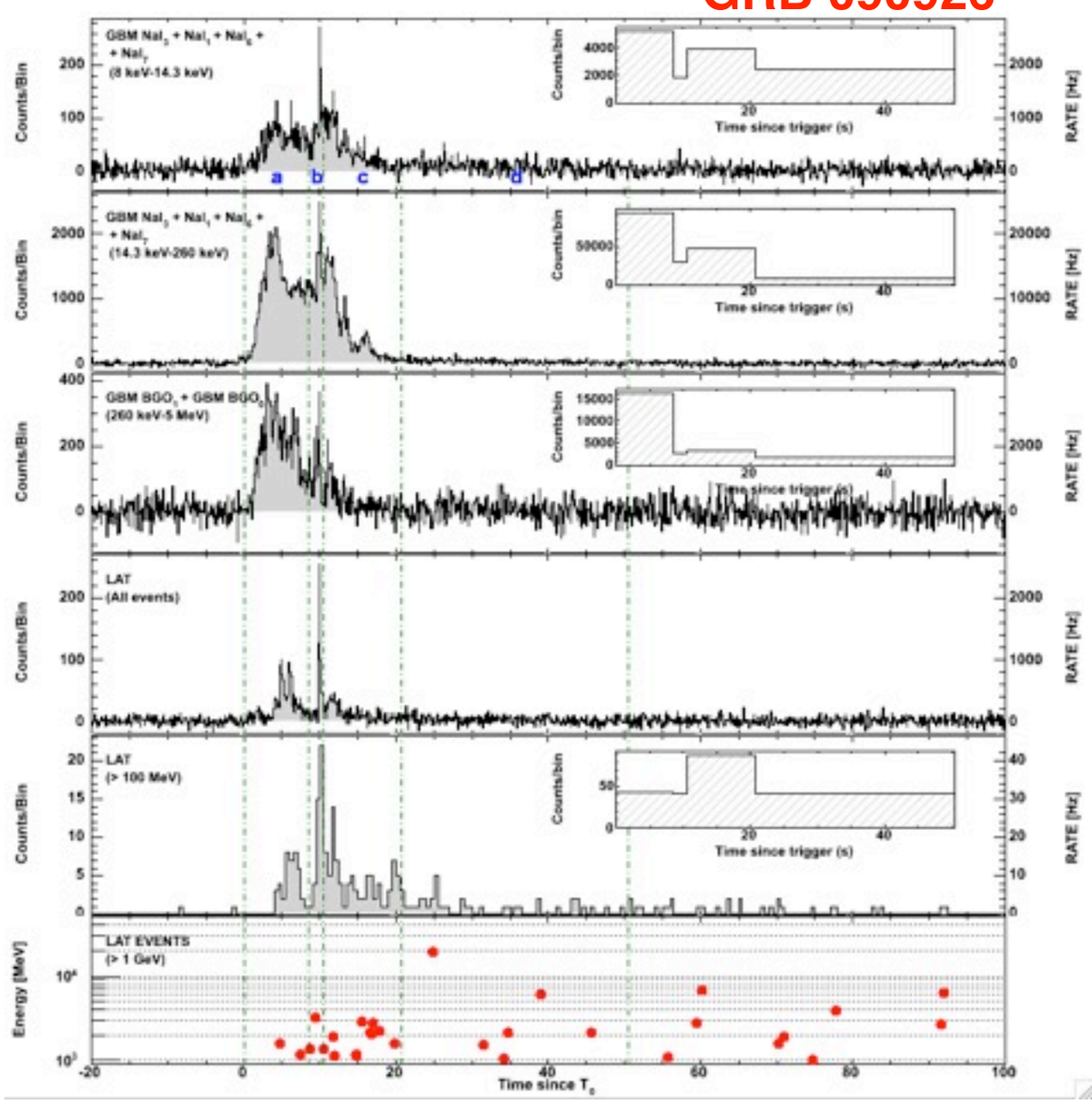

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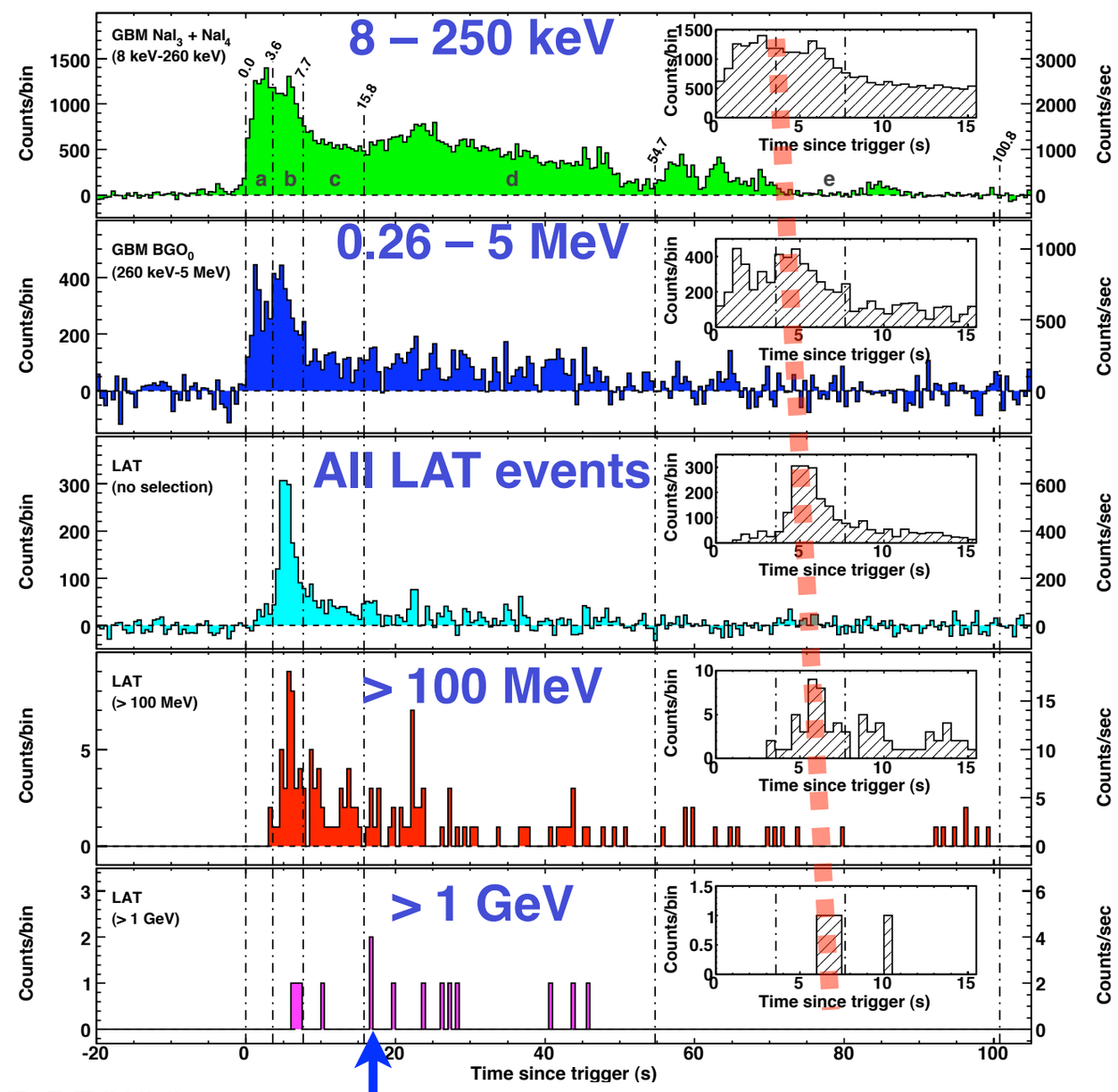

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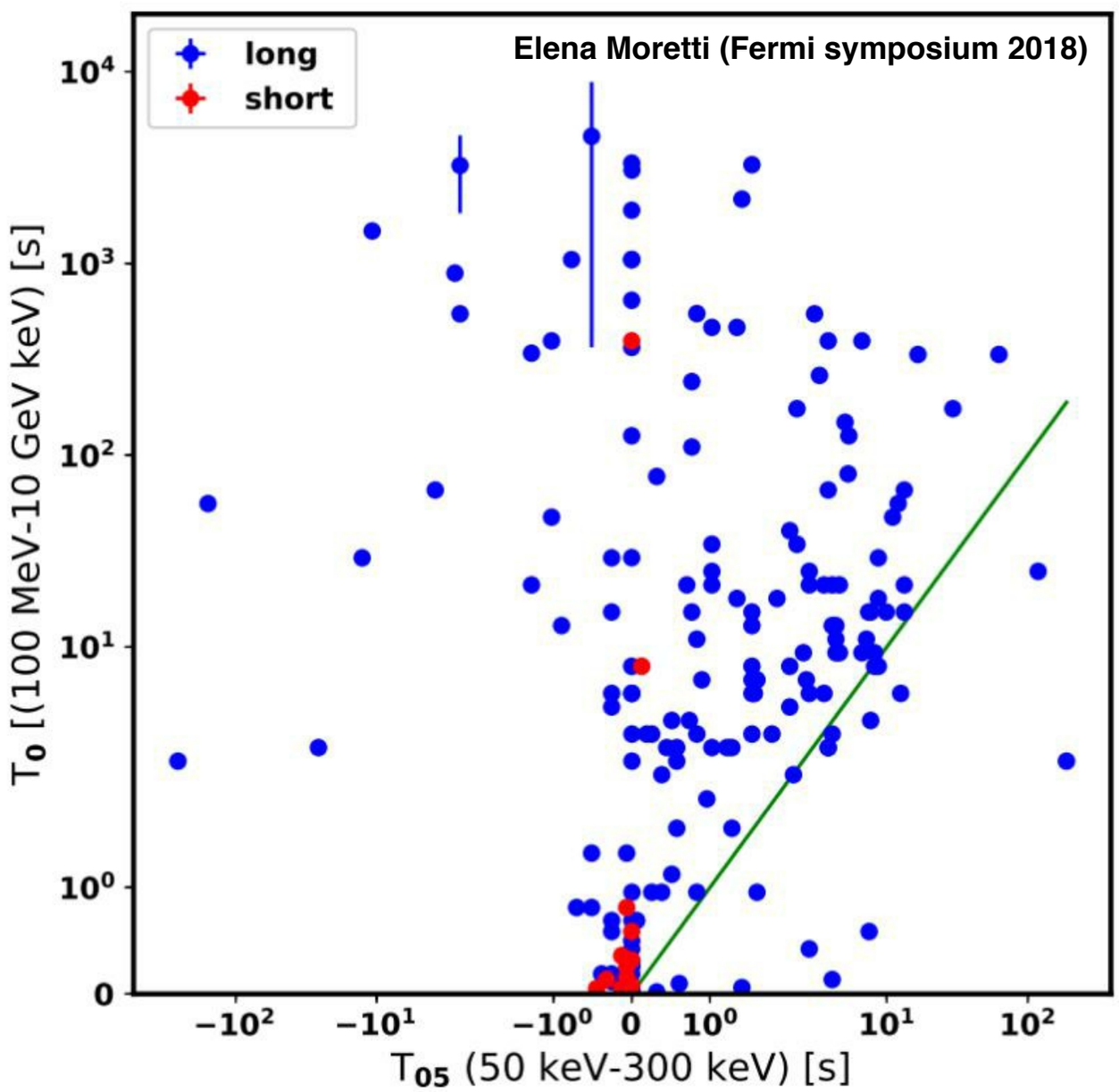

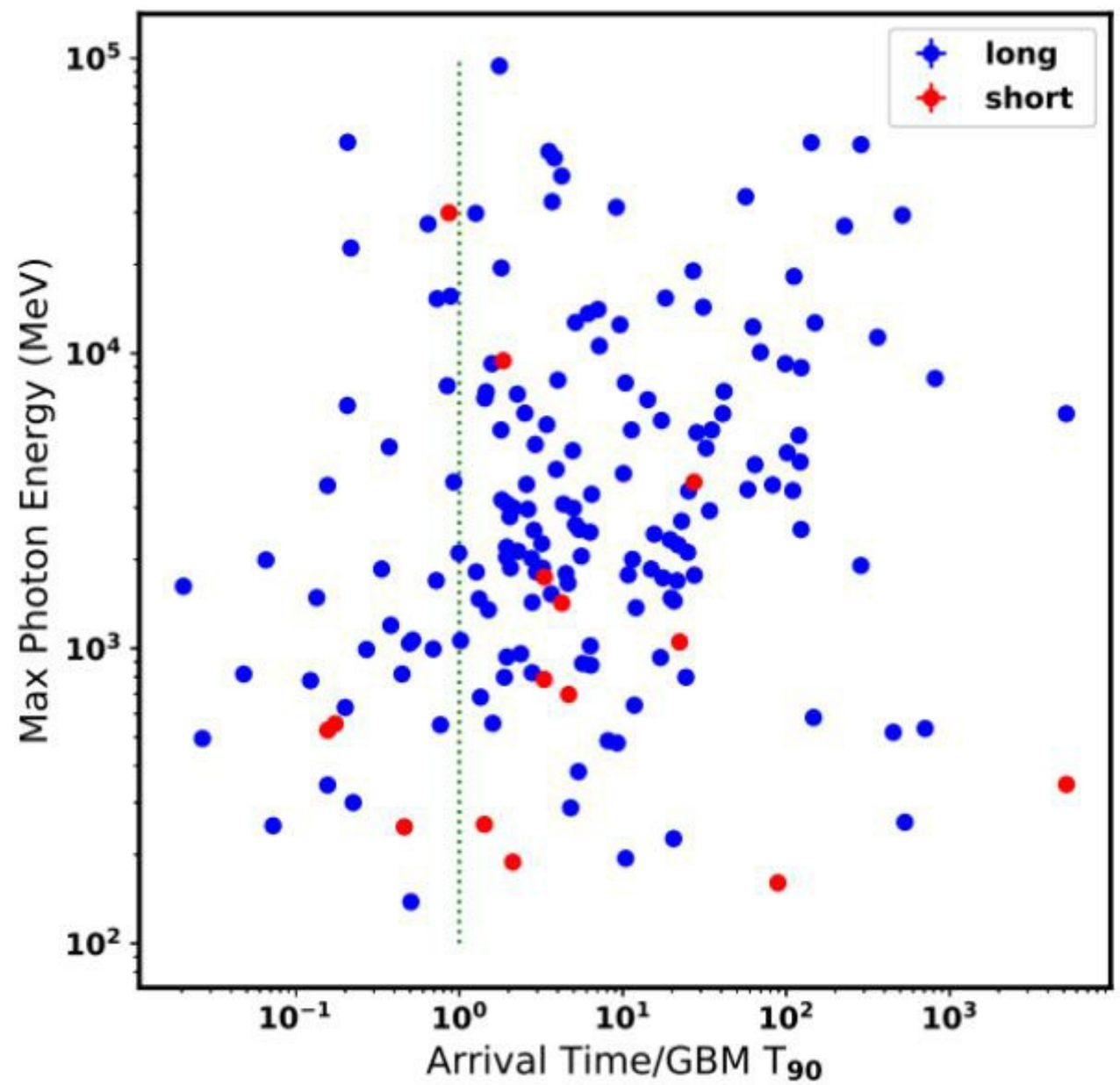

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GRB Long-Lived HE Emission

- HE (>100 MeV) emission shows different temporal behavior
  - Temporal break in LE emission while no break in HE emission

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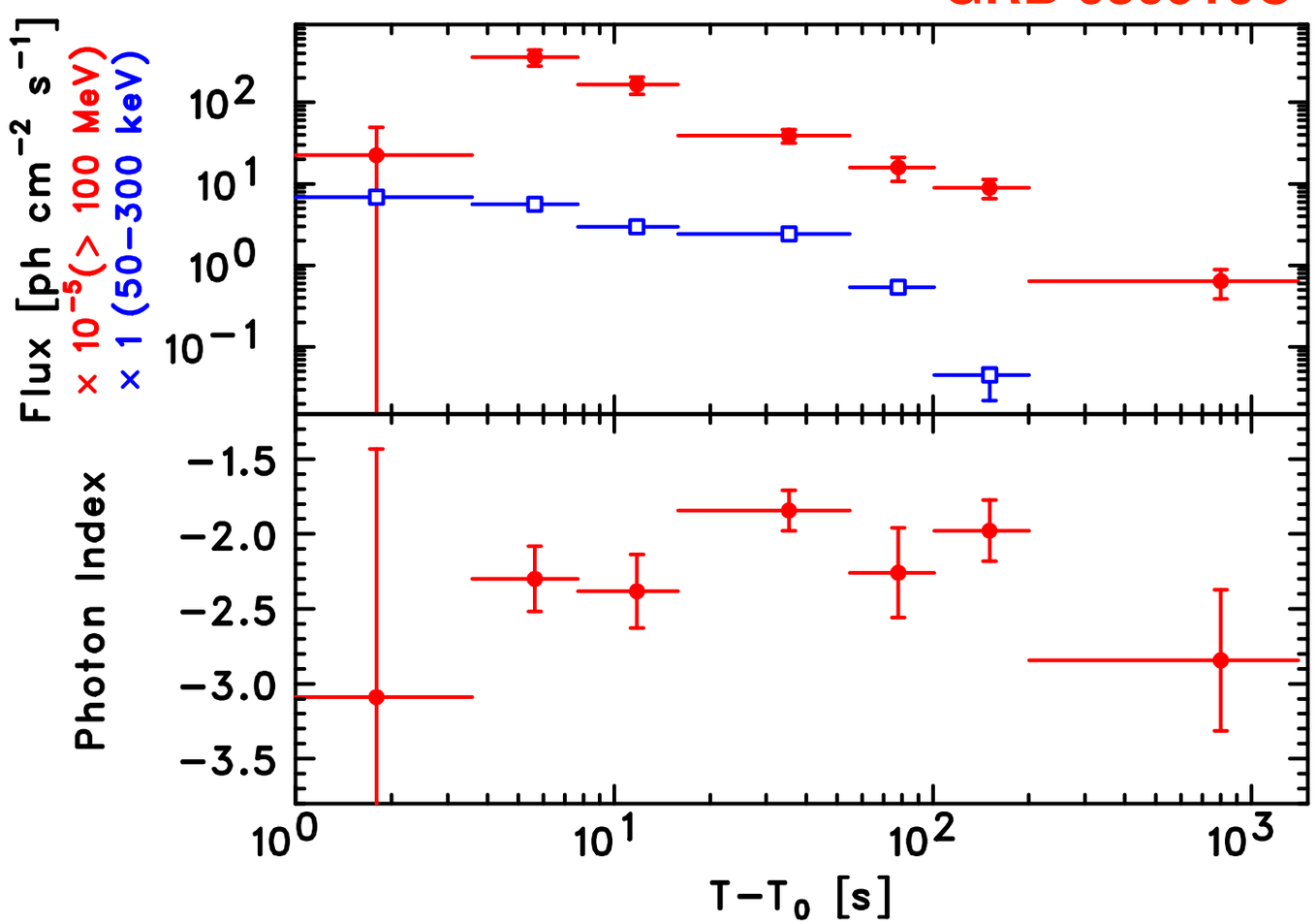
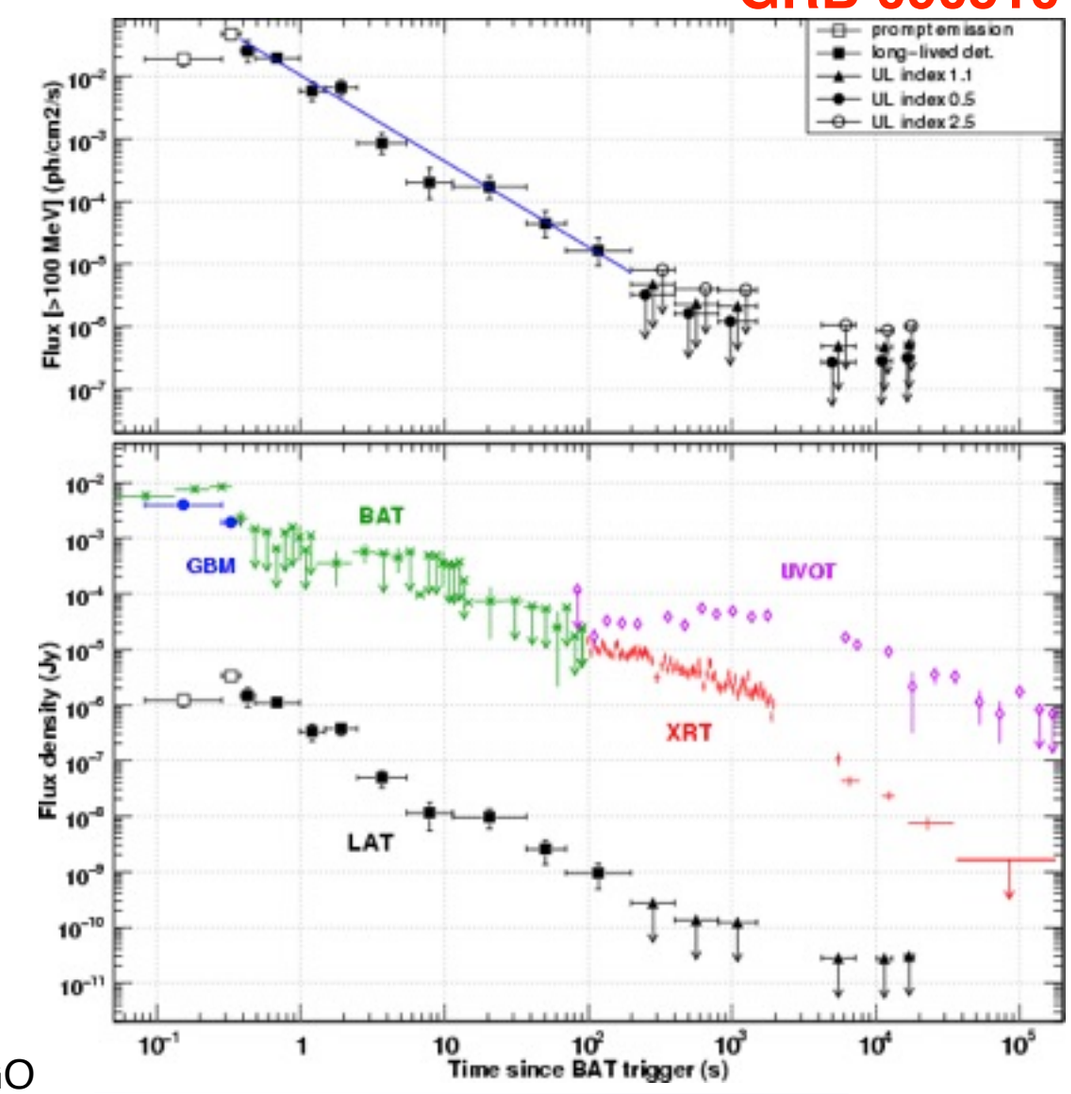


GRB 090510



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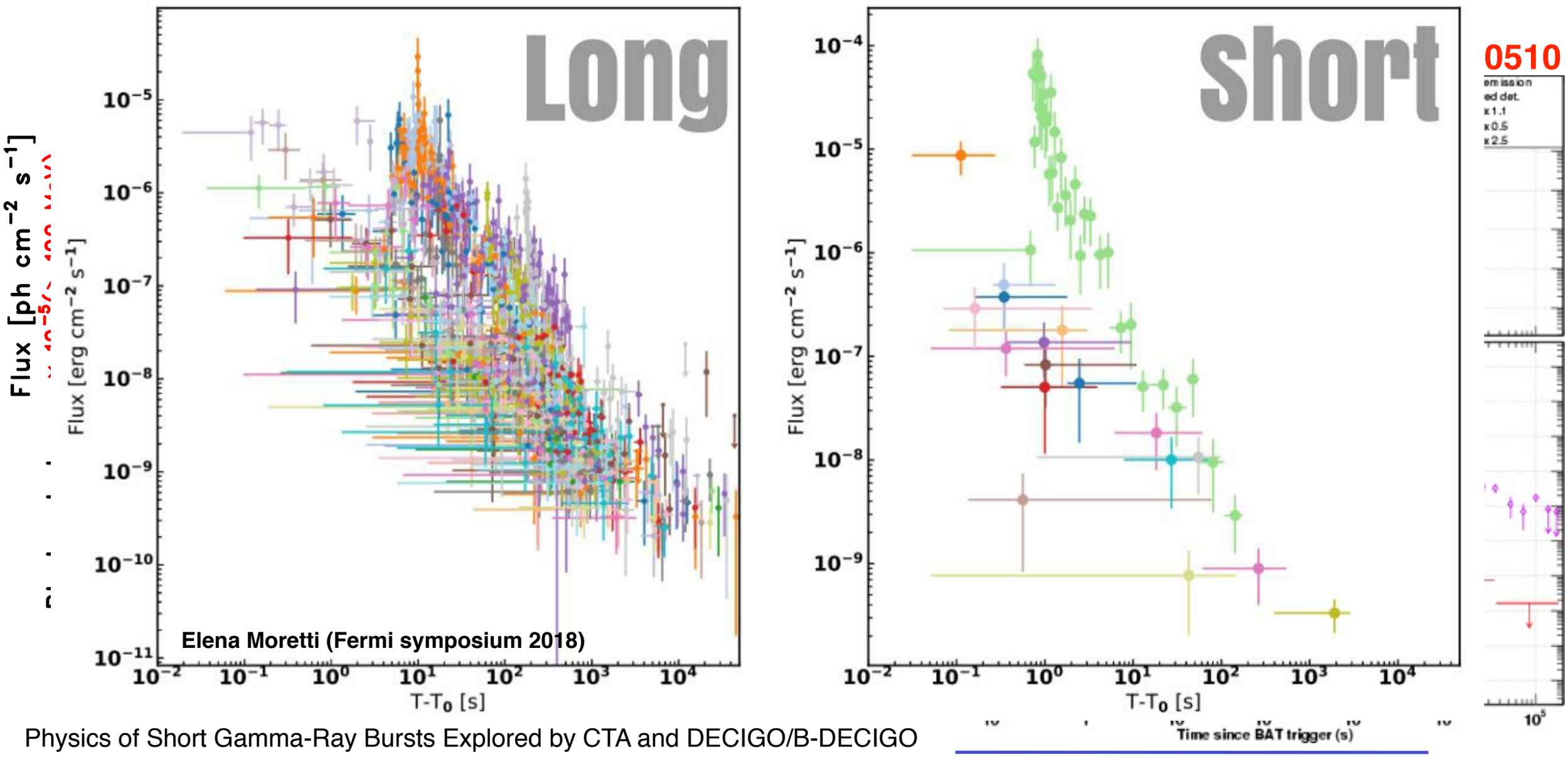
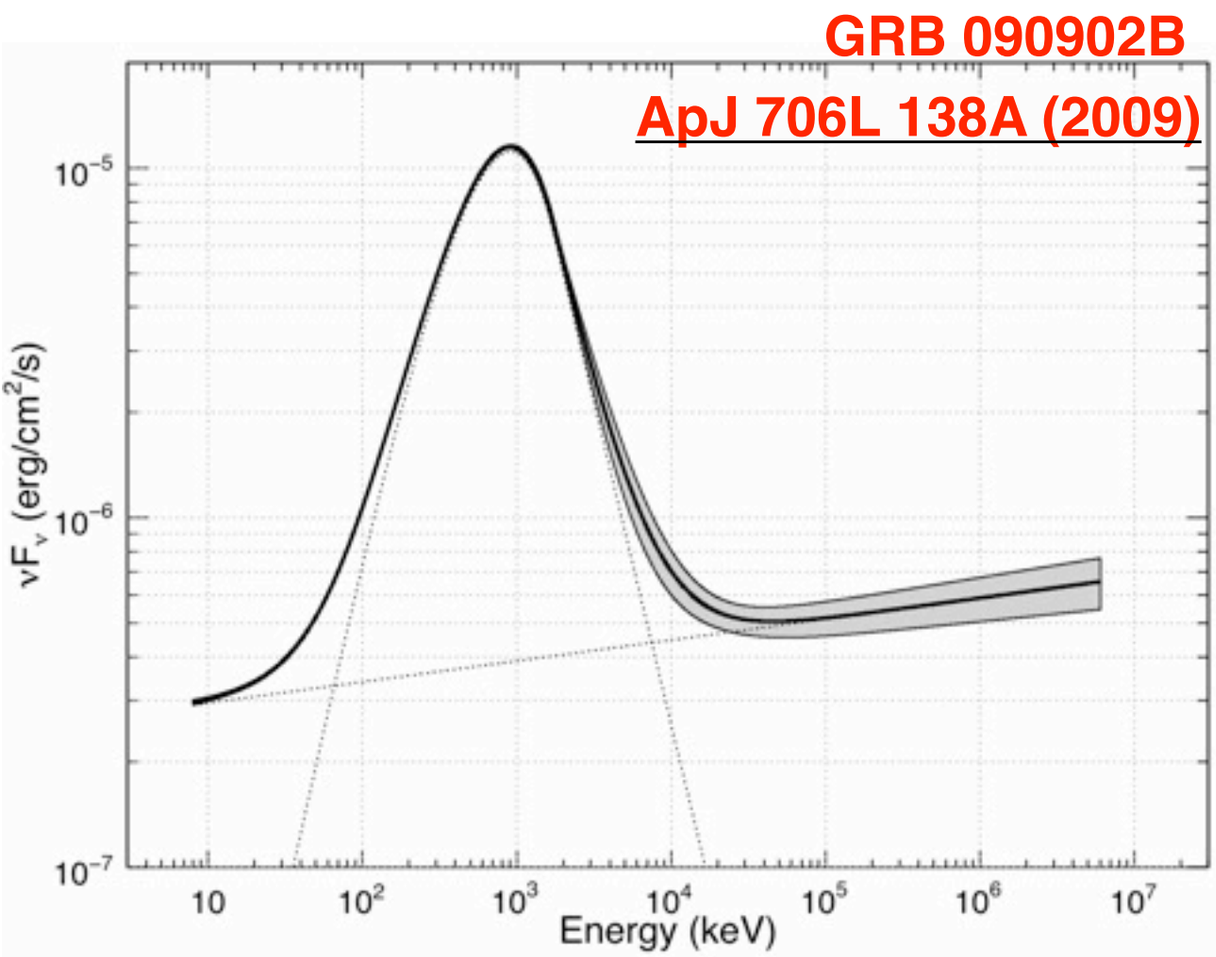
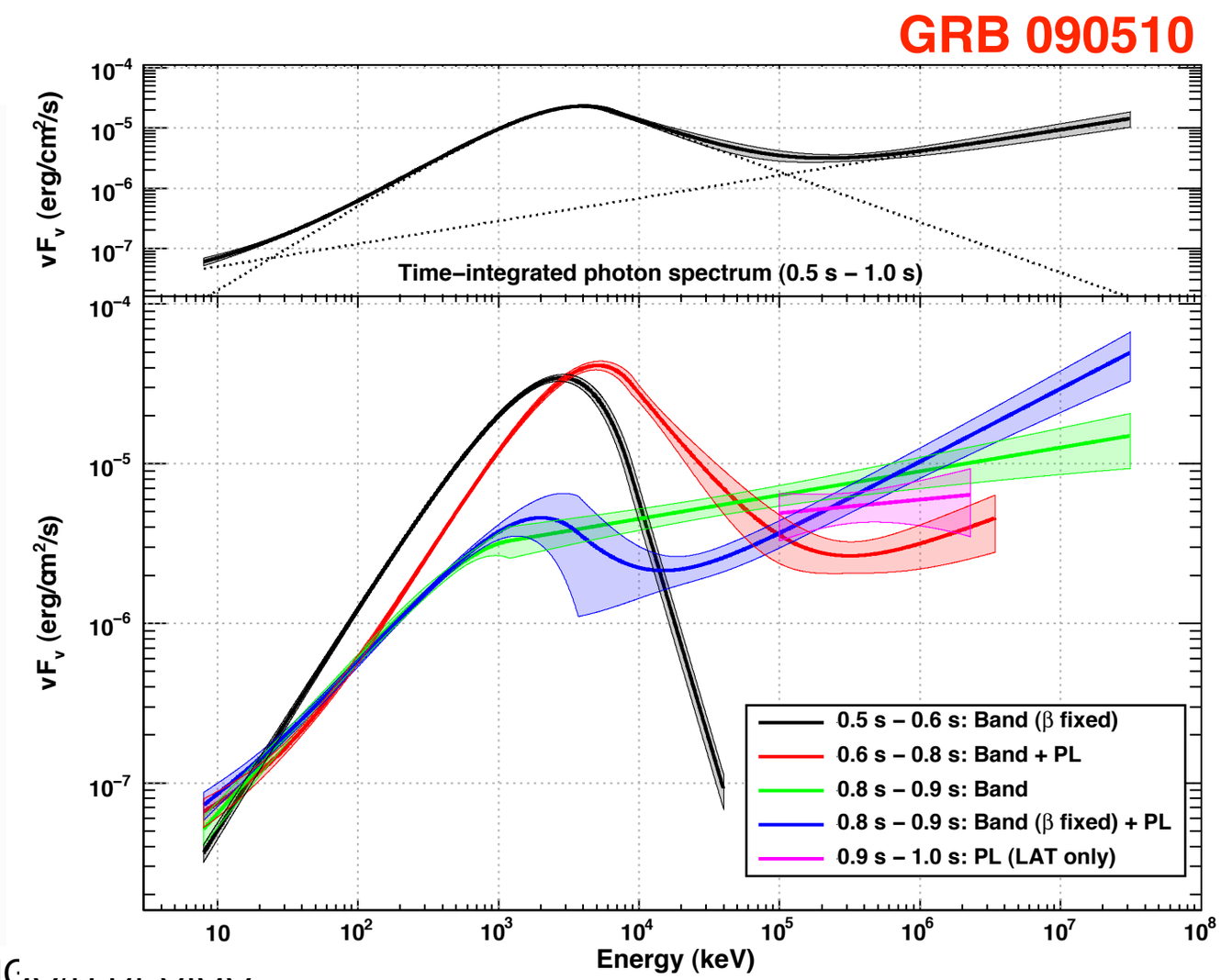


Extra Component

- Extra spectral component inconsistent with Band function
  - Both in low- and high-energy regions
- Lack of information for short GRBs





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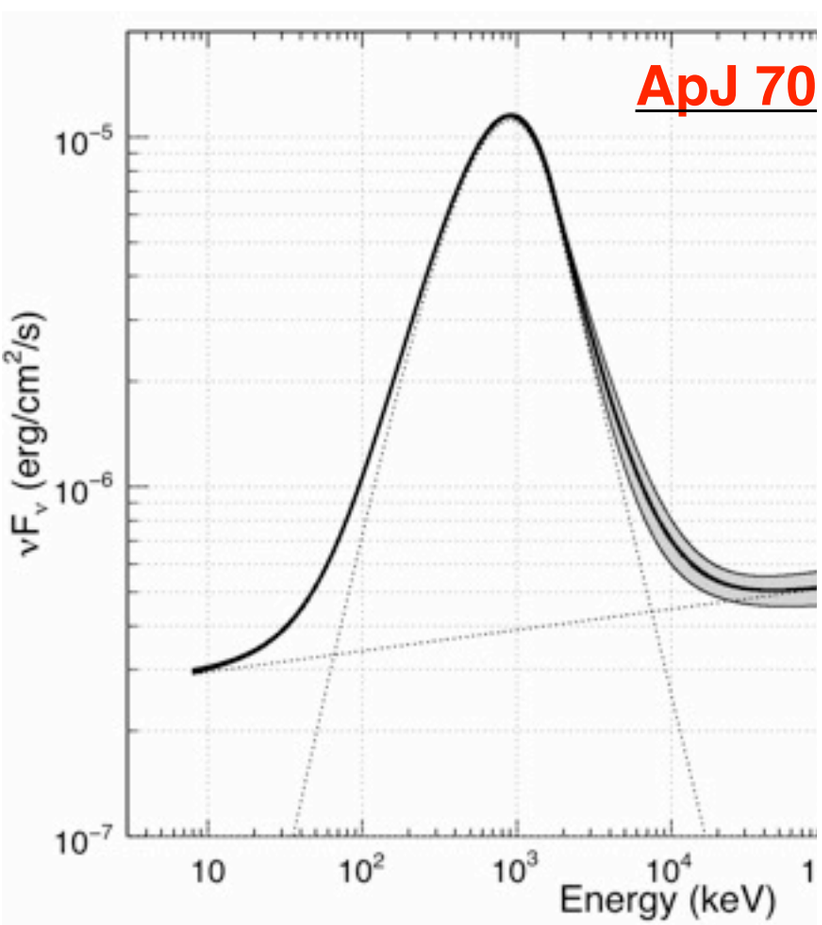
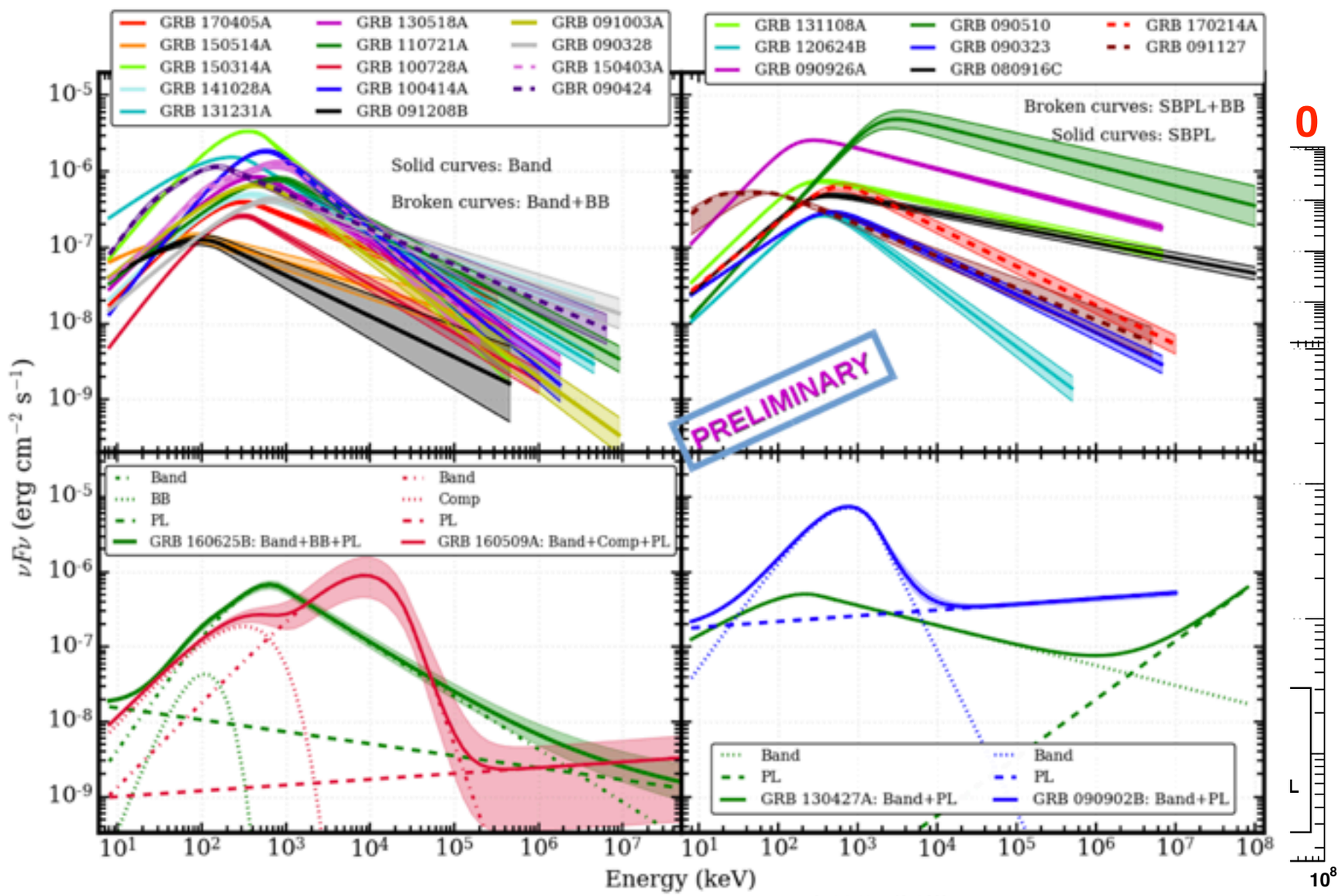
Soeb Razzaque (Fermi symposium 2018)

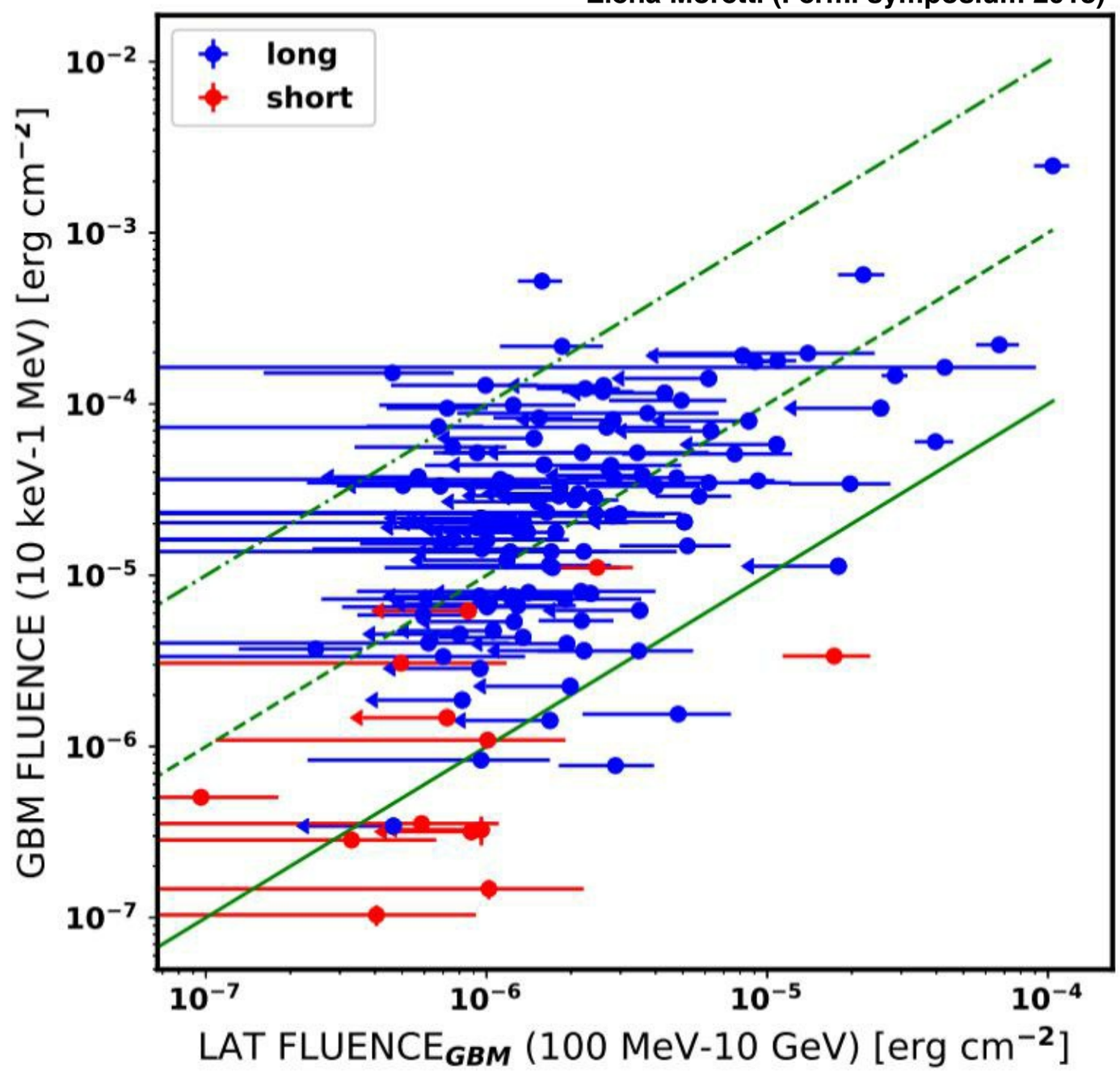




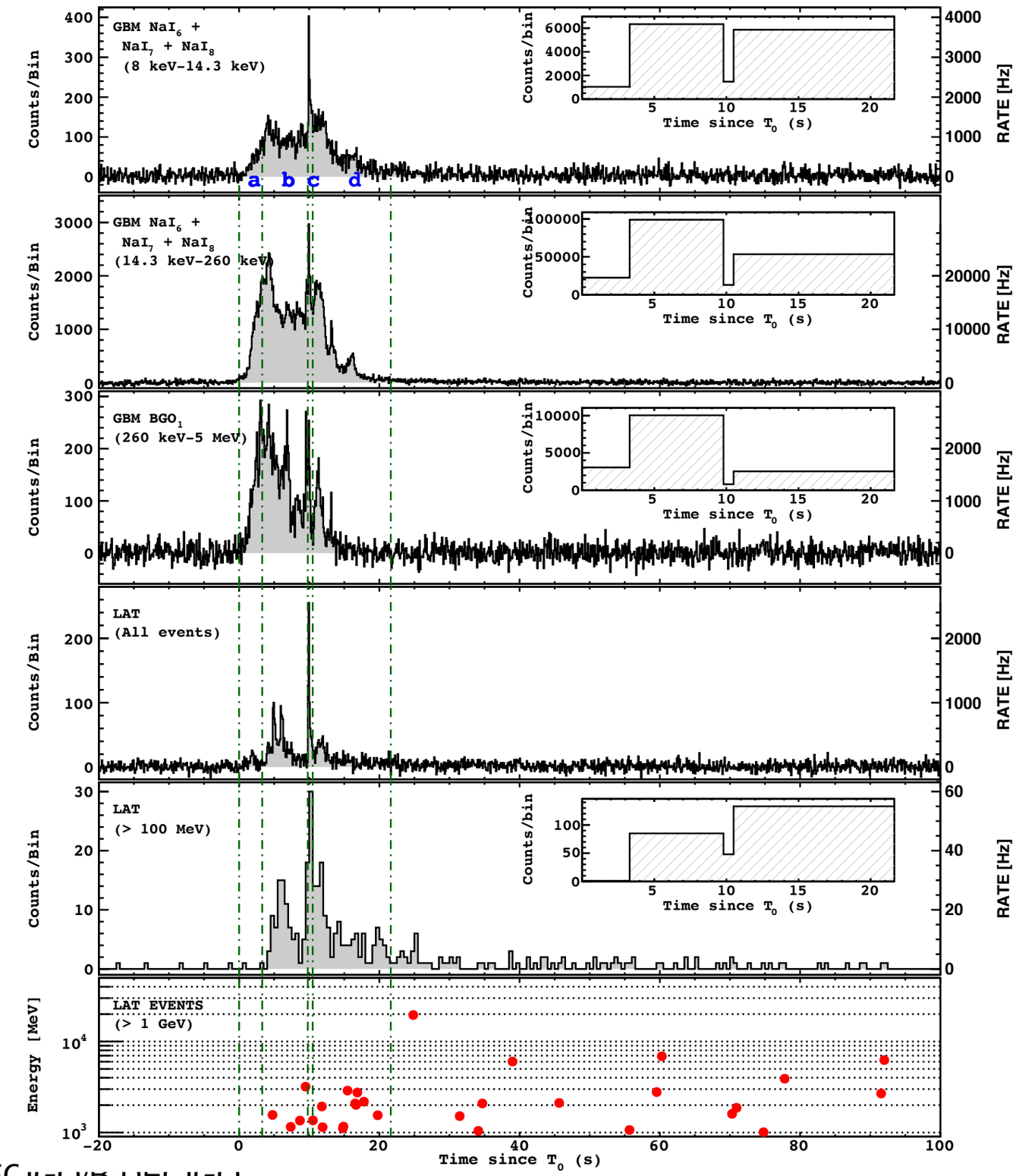
LAT and GBM Emissions

- **LAT and GBM emissions are not strongly correlated**
  - **Indicates different origins**

Elena Moretti (Fermi symposium 2018)

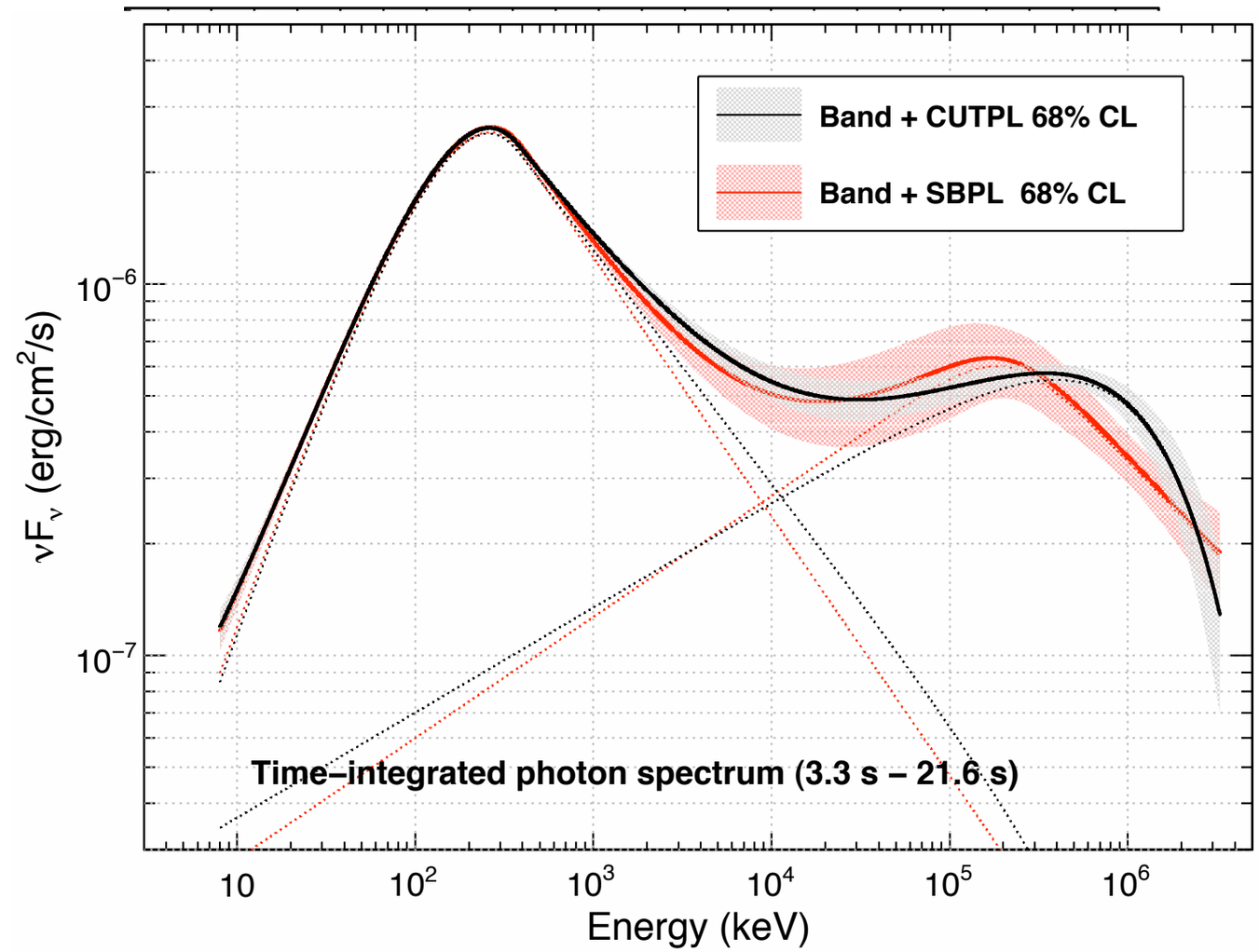


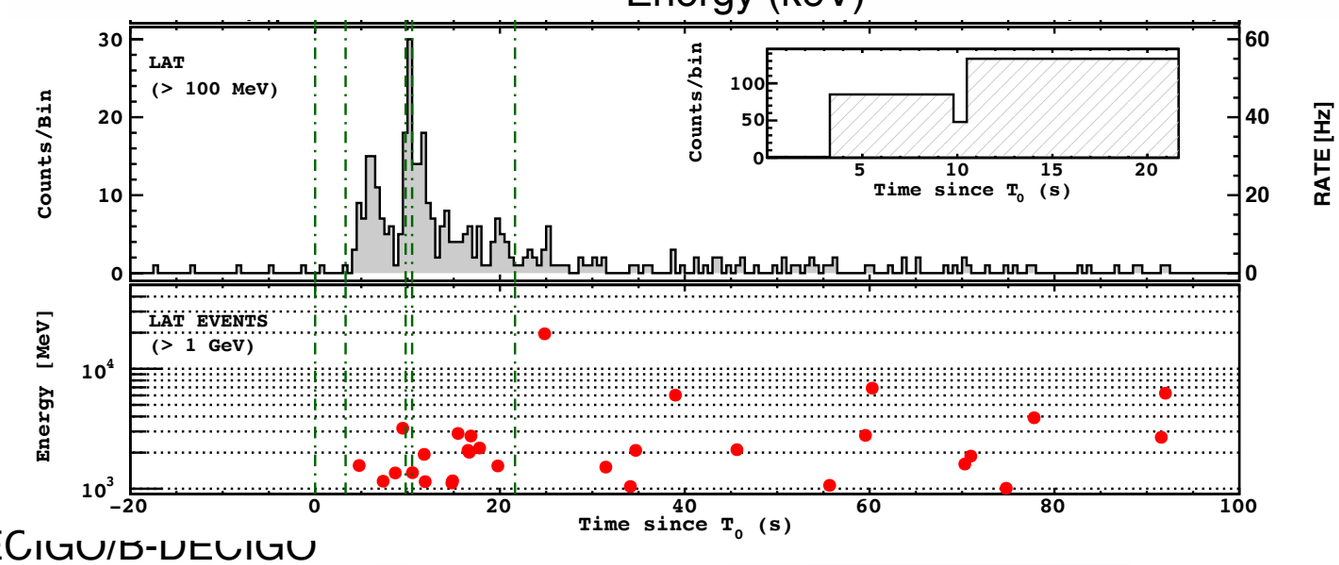
Spectral cutoff - GRB 090926A



Spectral cutoff - GRB 090926A

- Narrow spikes correlated in all energy band
- Significant spectral break
  - Shape is not constrained
  - if cutoff due to γ-γ absorp.
    - 1st direct measurement of bulk Lorentz factor (Γ~200-700)





Lorentz Invariance Violation (LIV)

- **Some QG models predict a violation of Lorentz Invariance at HE:**

$$c^2 p_\gamma^2 = E_\gamma^2\left[1+\sum_{k=1}^{\infty} s_k\left(\frac{E_\gamma}{M_{QG,k}c^2}\right)^k\right] \rightarrow v_\gamma^2 = \frac{\partial E_\gamma}{\partial p_\gamma} \approx c\left[1 - s_n \frac{1+n}{2}\left(\frac{E_\gamma}{M_{QG,k}c^2}\right)^n\right]$$

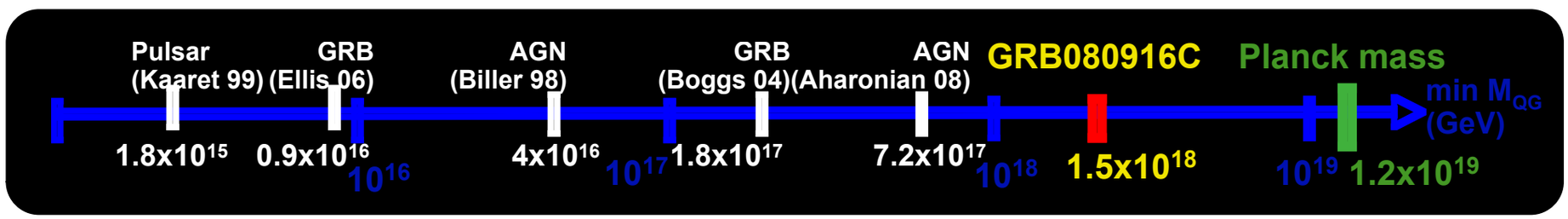
QG mass: energy scale where QG effect are expected to be significant

- **Time delay between 2 photons of energies E_h and E_l emitted simultaneously:**

$$\Delta t = \frac{(1+n)}{2H_0}\frac{(E_h^n - E_l^n)}{(M_{\mathrm{QG},n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\,dz'$$

geometrical distance assuming ΛCDM

- **GRB is a excellent light source due to long distance (high z) and short duration**
  - **Constraint using GRB 080916C: 13.2 GeV photon detected 16.5 sec after trigger**

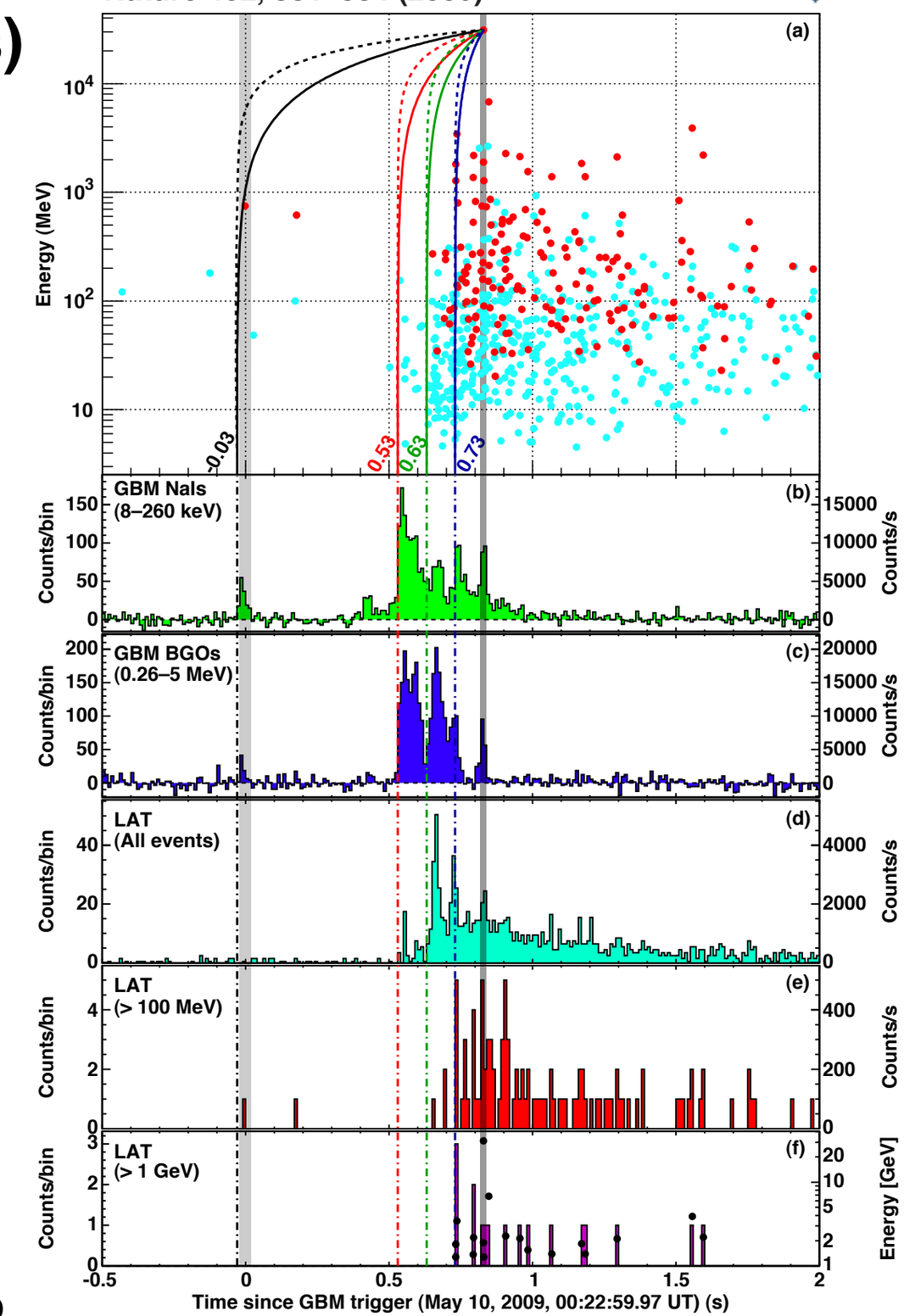


LIV Test with GRB 090510

- 30 GeV photon from $z = 0.9$ (7.3B years)
- Quantum Gravity models predicting linear LIV are strongly disfavored

choice for t_{start}	limit on Δt (ms)	lower limit on $M_{QG,1}/M_{planck}$
start of any observed emission	< 859	> 1.19
start of main < 1 MeV emission	< 299	> 3.42
start of > 100 MeV emission	< 199	> 5.12
start of > 1 GeV emission	< 99	> 10.0
association with < 1 MeV spike	< 10	102

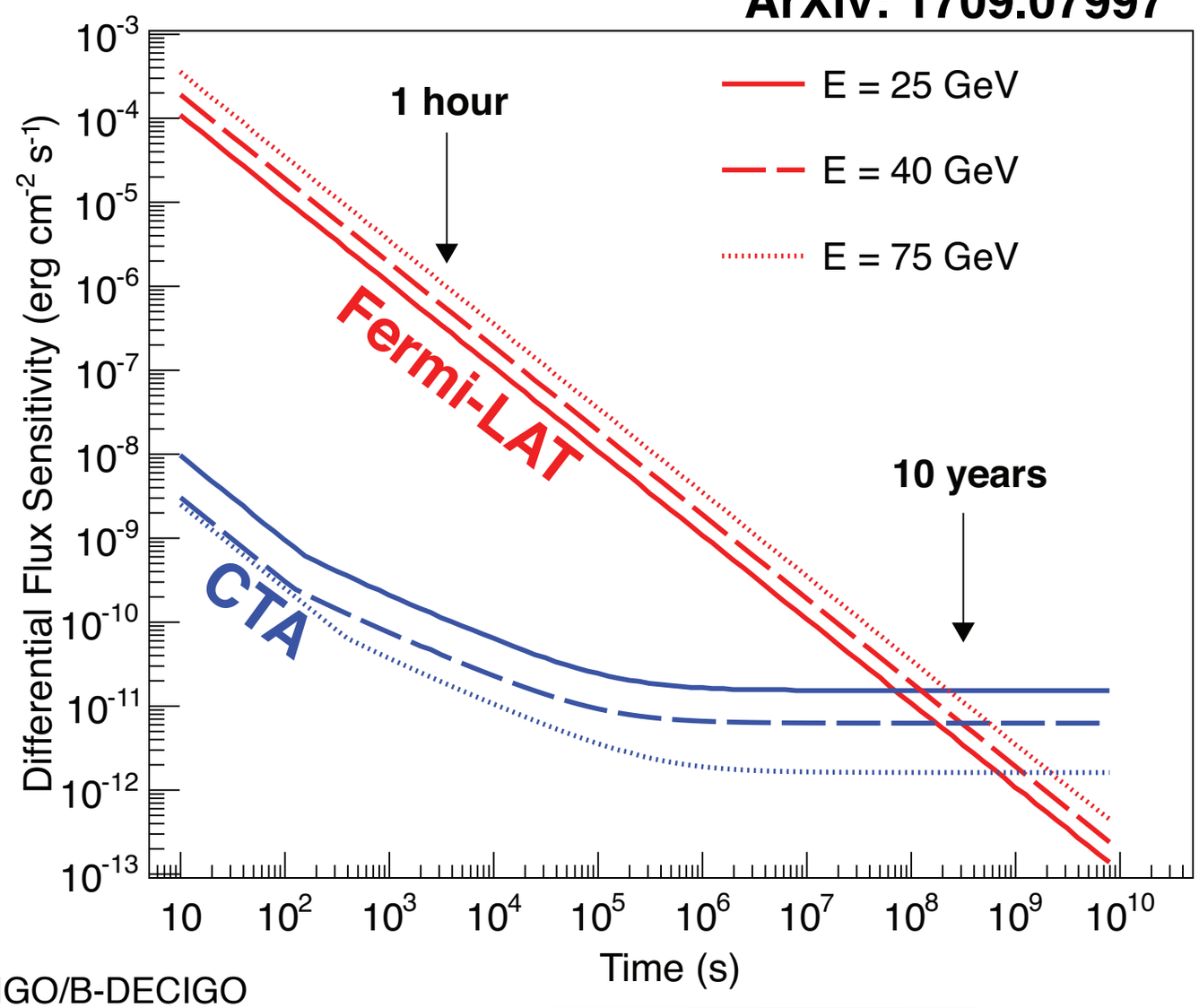
Nature 462, 331–334 (2009)



CTA Performance on Short Transients

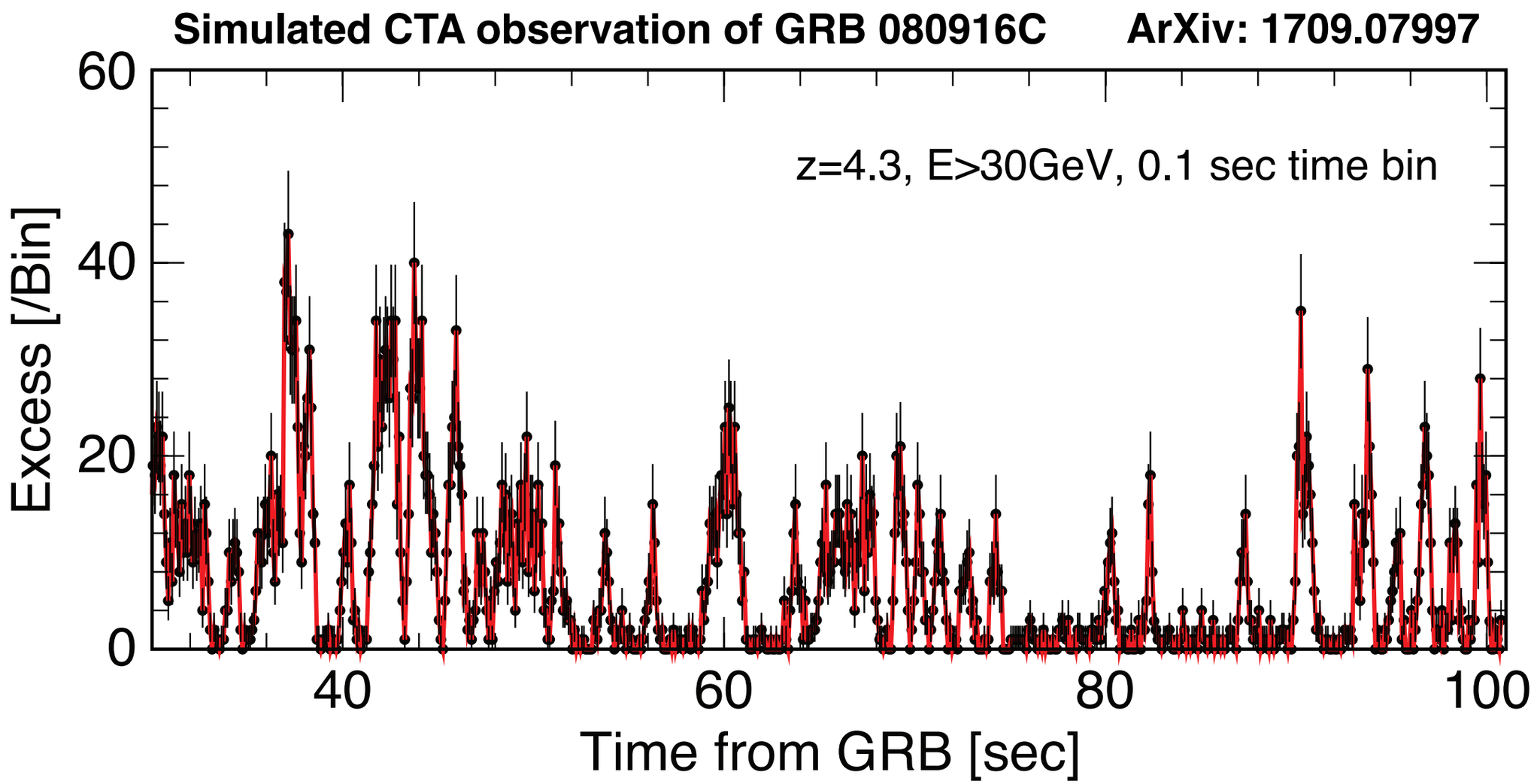
- CTA is ~10^4 times more sensitive than Fermi-LAT for short transients (< 100 s)
- However, CTA has very small field of view (~4°) and low duty cycle (~10%)
- CTA needs to know when and where GRBs will occur

ArXiv: 1709.07997



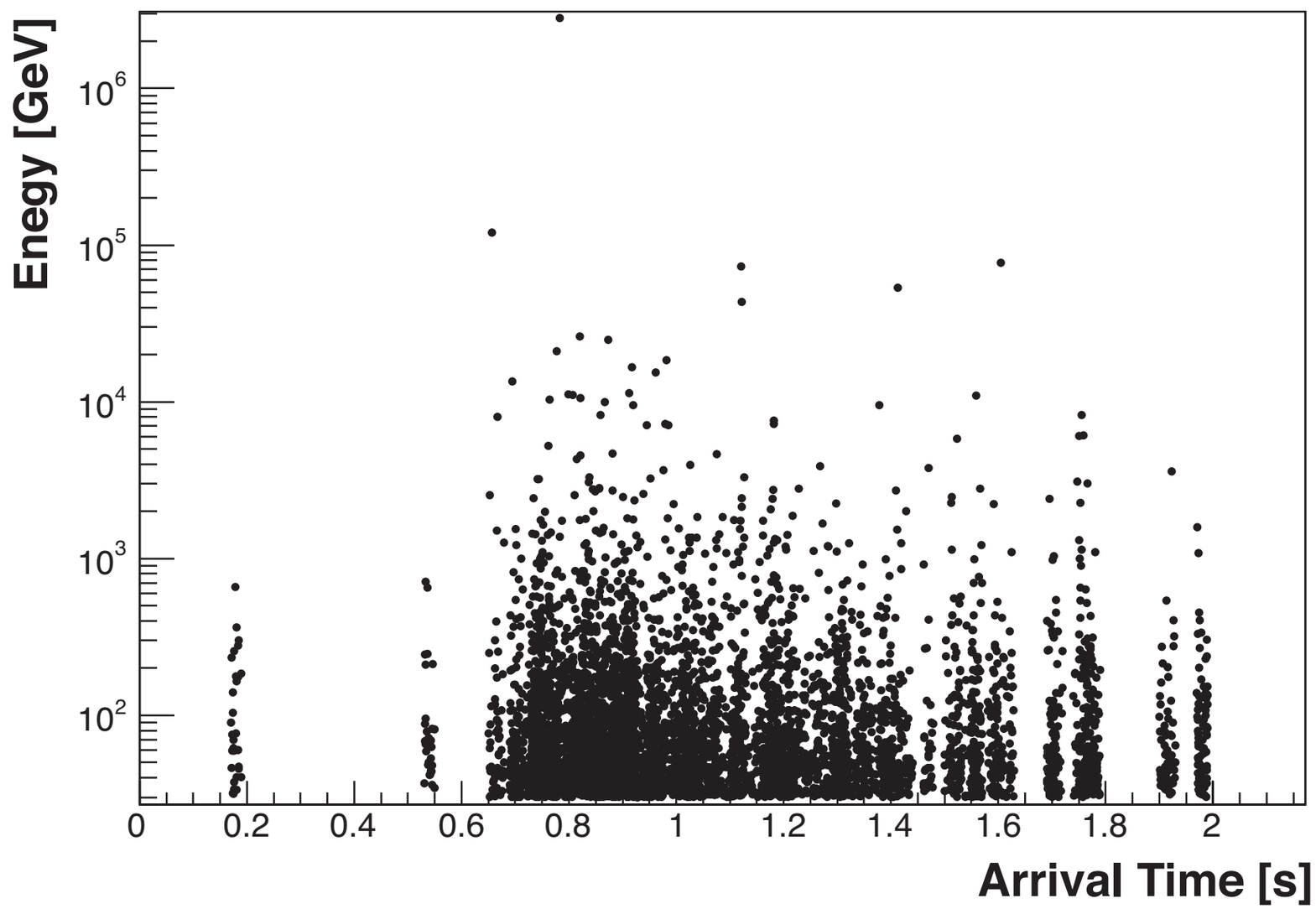
GRB Time Profile expected for CTA

- **CTA can detect ~30 times more photons above 30 GeV than Fermi-LAT above 100 MeV (assuming E^{-2} spectrum)**



GRB Energy-Time Relation by CTA

- If a event like GRB 090510 occurs 10 Mpc away from us
  - CTA can study detailed time profile of very high energy emissions
  - CTA can detect Lorentz Invariance Violation



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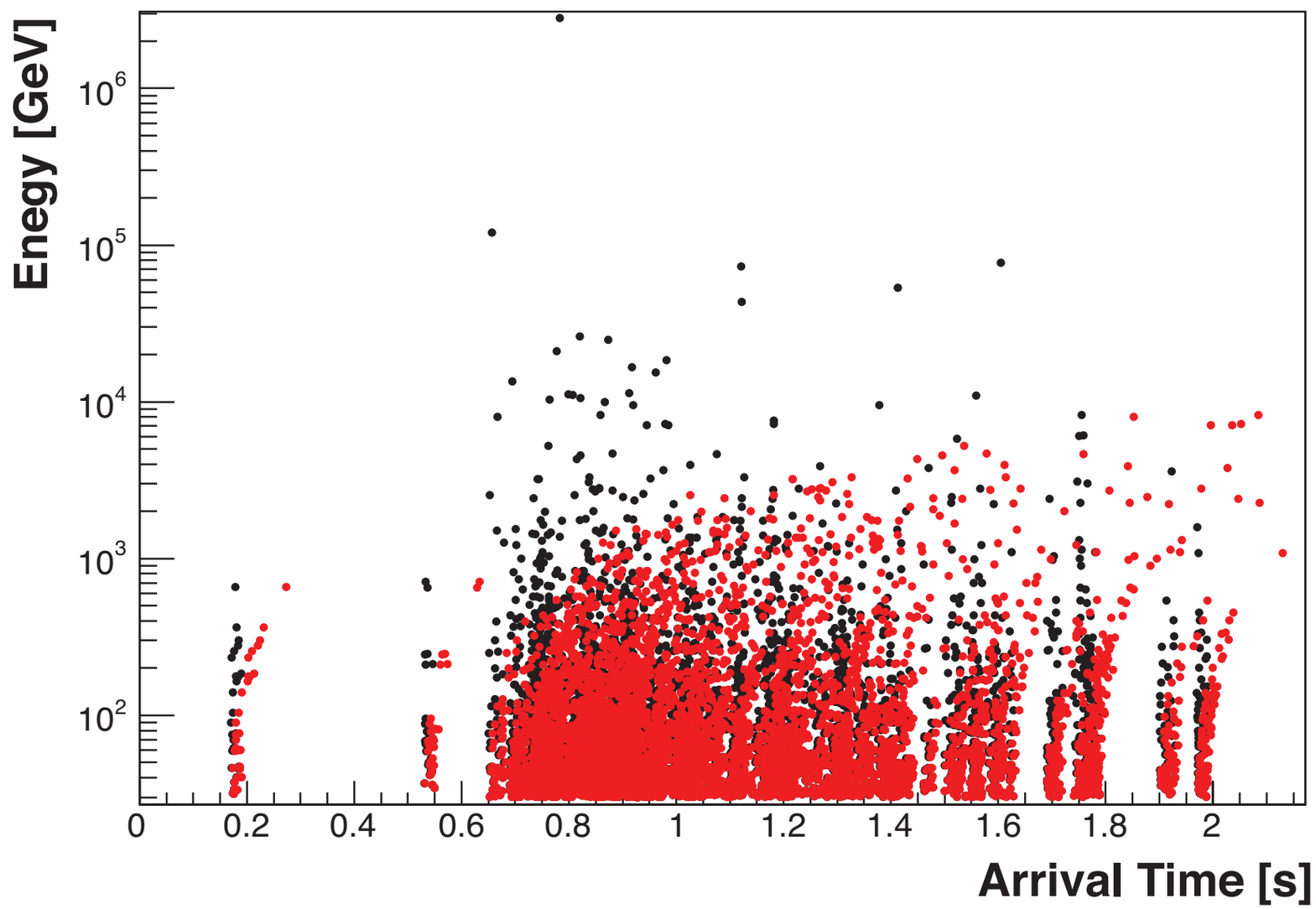


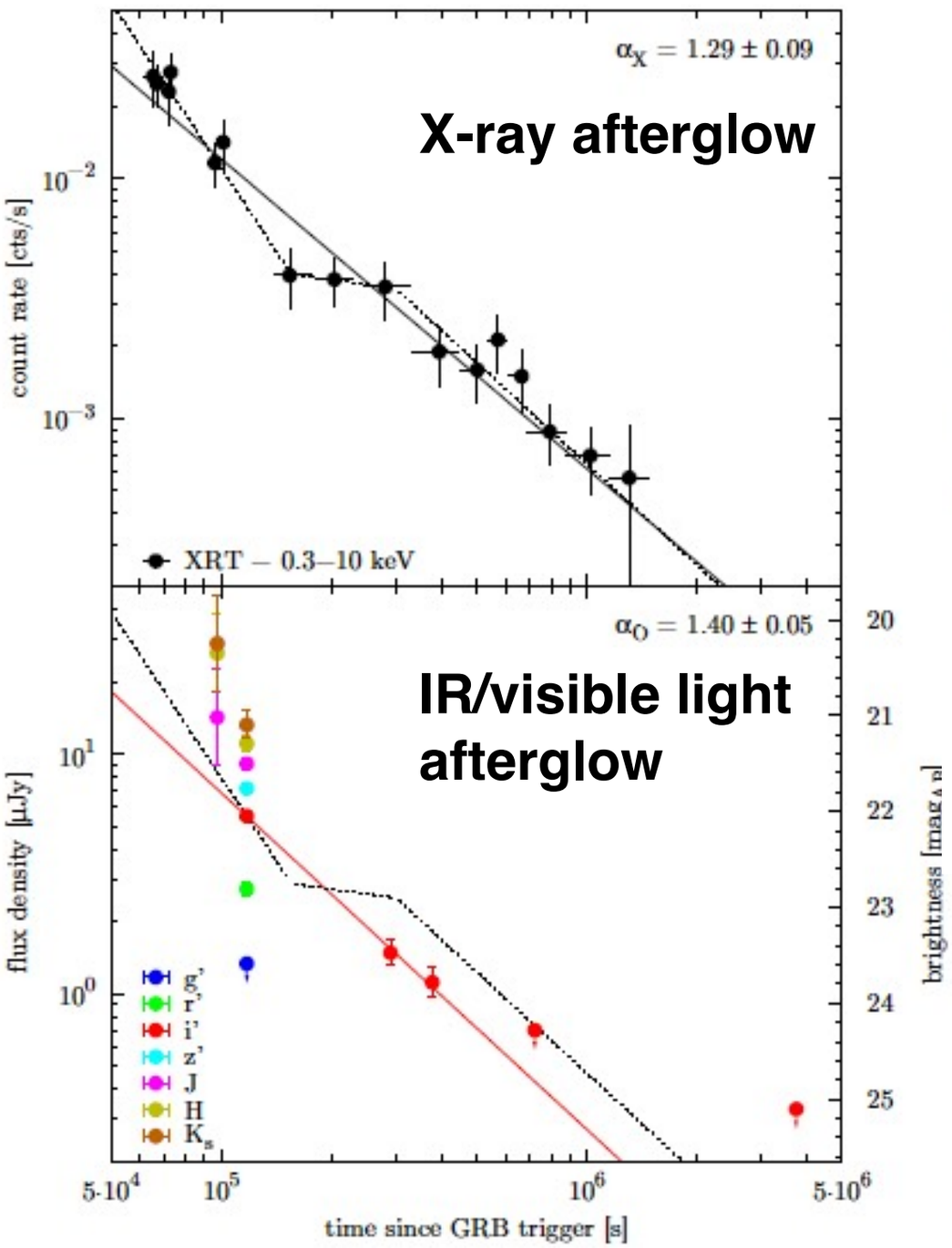
Summary

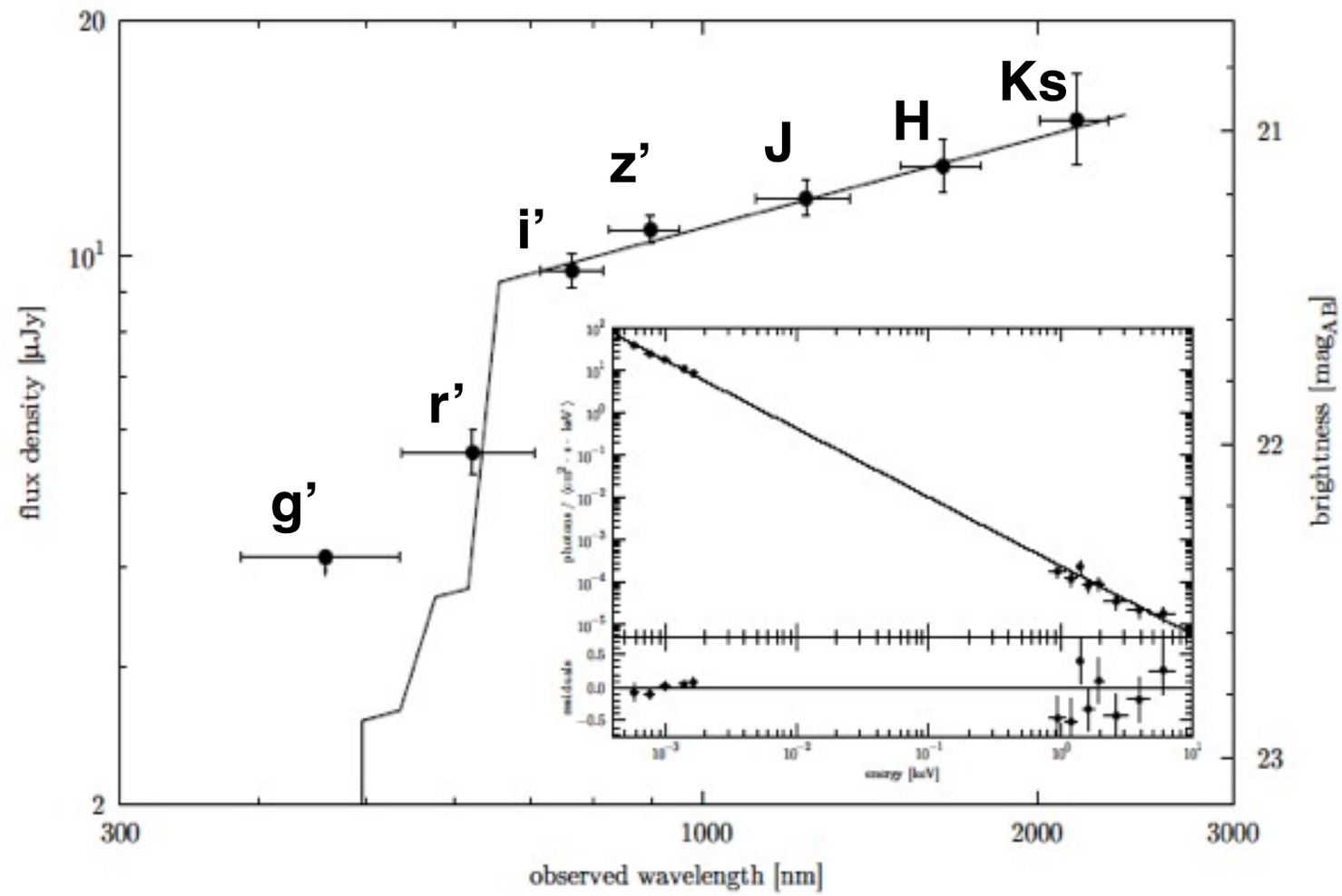
- Fermi LAT revealed nature of high energy emission from long GRBs
- Fermi LAT observed only handful of short GRBs
- CTA has much larger collection area than Fermi LAT and will be able to study GRB emissions in detail
- If DECIGO/B-DECIGO can predict the time and location of short GRBs, CTA can observe them from the beginning at 10% probability (moonless night in La Palma or Chile)
  - CTA can place very strong constraints on violation of Lorenz invariance

backup slides

GRB Afterglow

(Greiner et al. 2009)

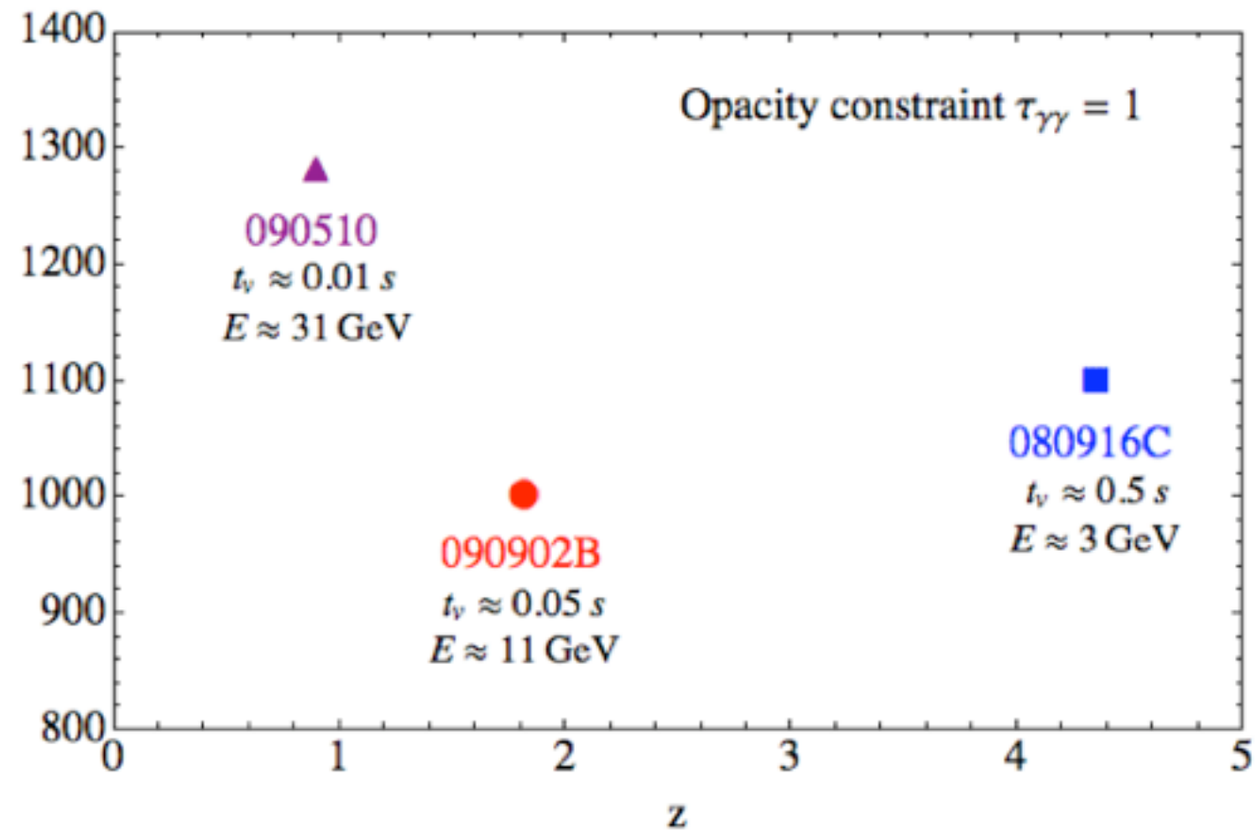




z = 4.35 ± 0.15

Constraints on Bulk Lorentz Factor

- Large luminosity and short variability time imply large optical depth due to $\gamma\gamma \rightarrow e^+e^-$
  - Small emission region: $R \sim c\Delta t$
  - $\tau_{\gamma\gamma}(E) \sim (11/180)\sigma_T N_{>1/E}/4\pi R^2$
    - $\tau_{\gamma\gamma}$(1 GeV) ~ 7×10^{11} for fluence=10^6 erg/cm^2, z=1, Δt=1 s
- Relativistic motion ($\Gamma \gg 1$) can reduce optical depth
  - Lager emission region: $R \sim \Gamma^2 c\Delta t$
  - Reduced # of target photons: $N_{>1/E} \propto \Gamma^{2\beta+2}$ (note: $\beta \sim -2.2$)
    - Blue shift of energy threshold: $E_{th} \propto \Gamma$
    - Blue shift of spectrum: $N(E) = (\Gamma E)^{\beta+1}$
  - Overall reduction of optical depth: $\Gamma^{2\beta-2} \sim \Gamma^{-6.4}$



- Possible selection bias due to large E_{ISO}
- Assume common emission region for all gamma rays