The Search for High-Energy Extended Emission by Fermi-LAT from Swift-localized Bursts

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Motivation and Proposed Study

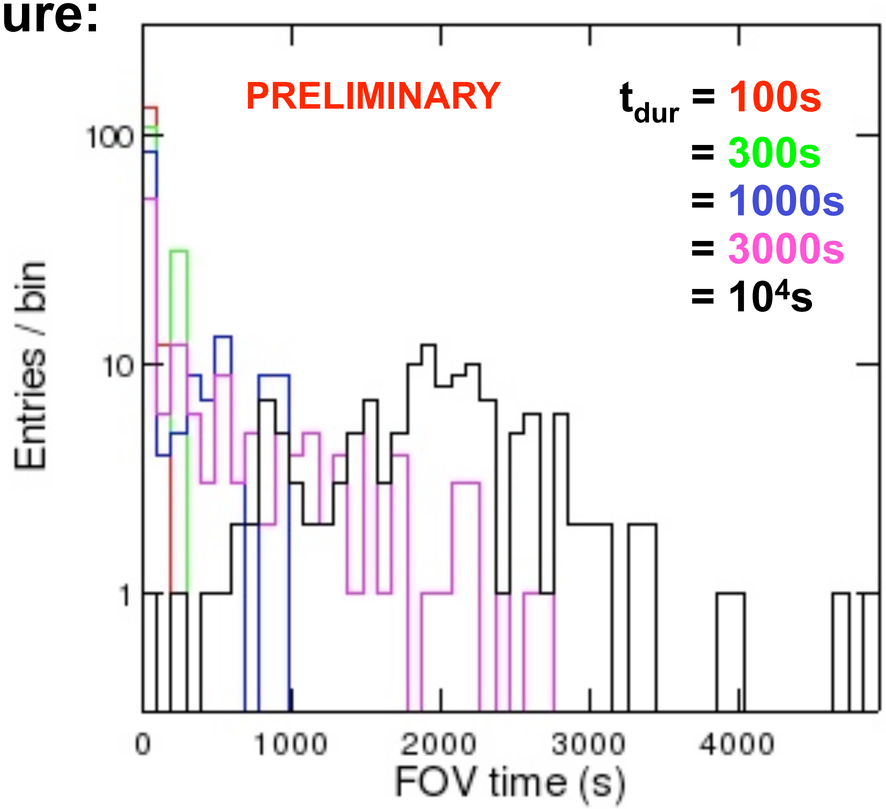
- Extended emission is a recurring feature in LAT GRBs.
- The accurate Swift locations enable reliable unbinned likelihood analyses of LAT data.
- 145 GRBs with Swift XRT data from 11 Aug 2008-23 Oct 2010.
- Search for prompt emission in LAT is hampered by small overlap of sky coverage during prompt phase.
- In survey mode, LAT has reasonable coverage of Swift bursts on extended emission time scales, i.e., up to 8.4 ks post-trigger.

- For upper limit cases ($T_s < 25$), “stacking” can provide a deeper average flux measurement.
- We will handle LAT detections separately (See E. Troja’s talk, Session 5).

Fermi Gamma-ray Space Telescope

LAT Integration Window

- Extended emission in LAT decays as $t^{-\gamma}$ where $\gamma \approx 1.3\text{-}2.2$ (V. Vasileiou's talk, Session 2).
- To optimize S/N for dim afterglows, we want an integration window with $t_{stop}/t_{start} \sim$ few. For LAT observations of weak sources, this means the shortest window with non-trivial exposure:



For UL studies and stacking analysis we will use 10^4s (~2 orbits)

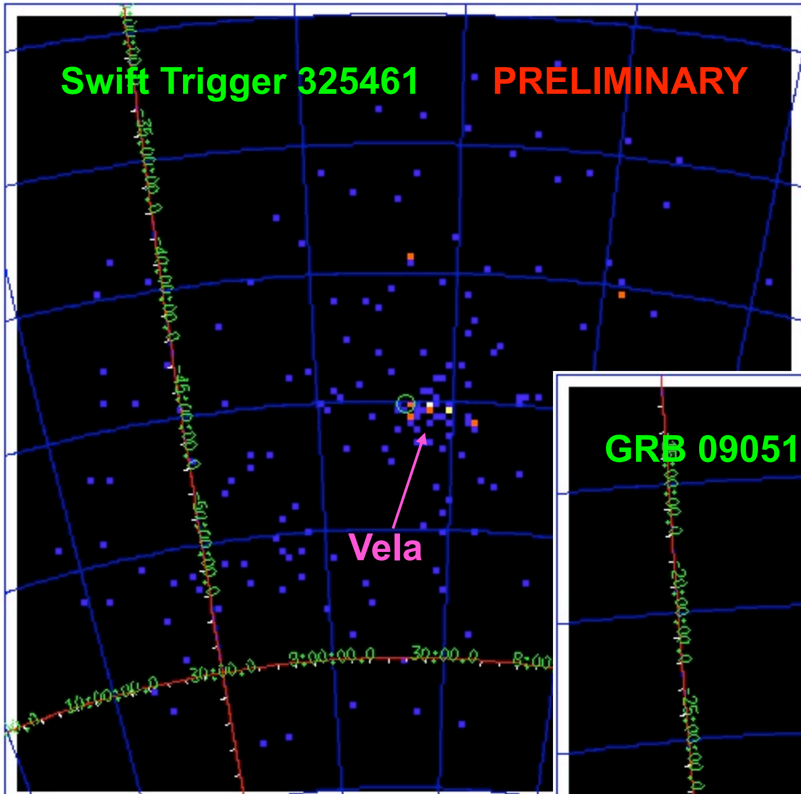
Stacking Procedure

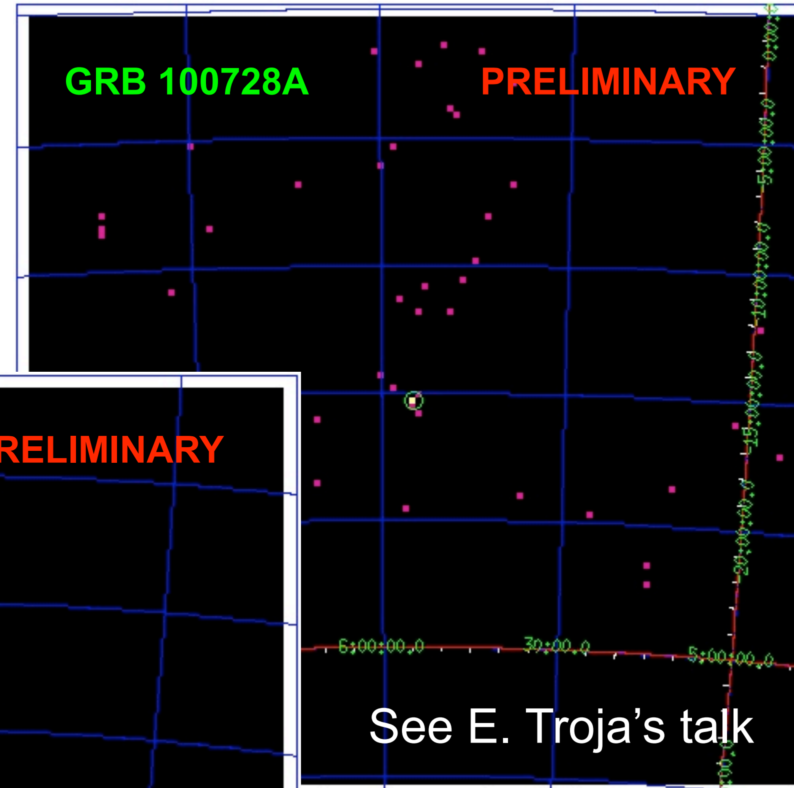
- **Standard unbinned analysis for each source:**
  - Point source at Swift location + Gal. Diffuse + EG Diffuse
  - Extract data in 15° ROI over desired time interval, starting at Swift trigger
  - P6_V3_DIFFUSE, 0.1-300 GeV
  - Model GRB spectrum with power-law and fixed photon index of 2.1.
  - Scan in GRB spectrum normalization (i.e., flux), deriving likelihood profile and 95% CL UL for each burst.
- **To stack, simply add the profiles together and compute T_s:**

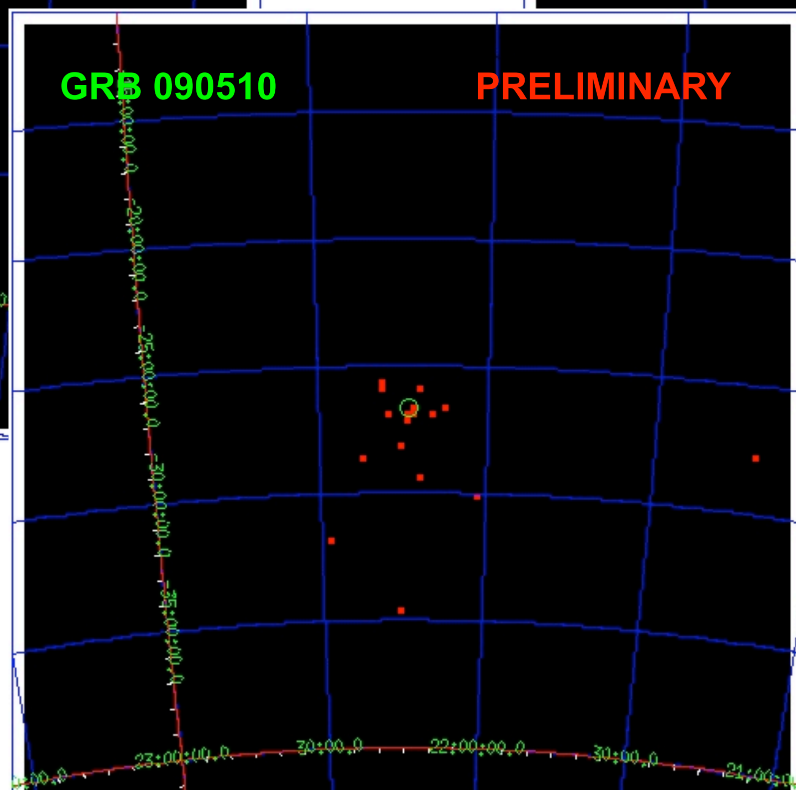
$$T_s(f) = 2(\log \mathcal{L}(f = 0) - \log \mathcal{L}(f))$$

The peak of the T_s profile gives the stacked maximum likelihood estimate of the population average flux.

Three Extended Emission Detections

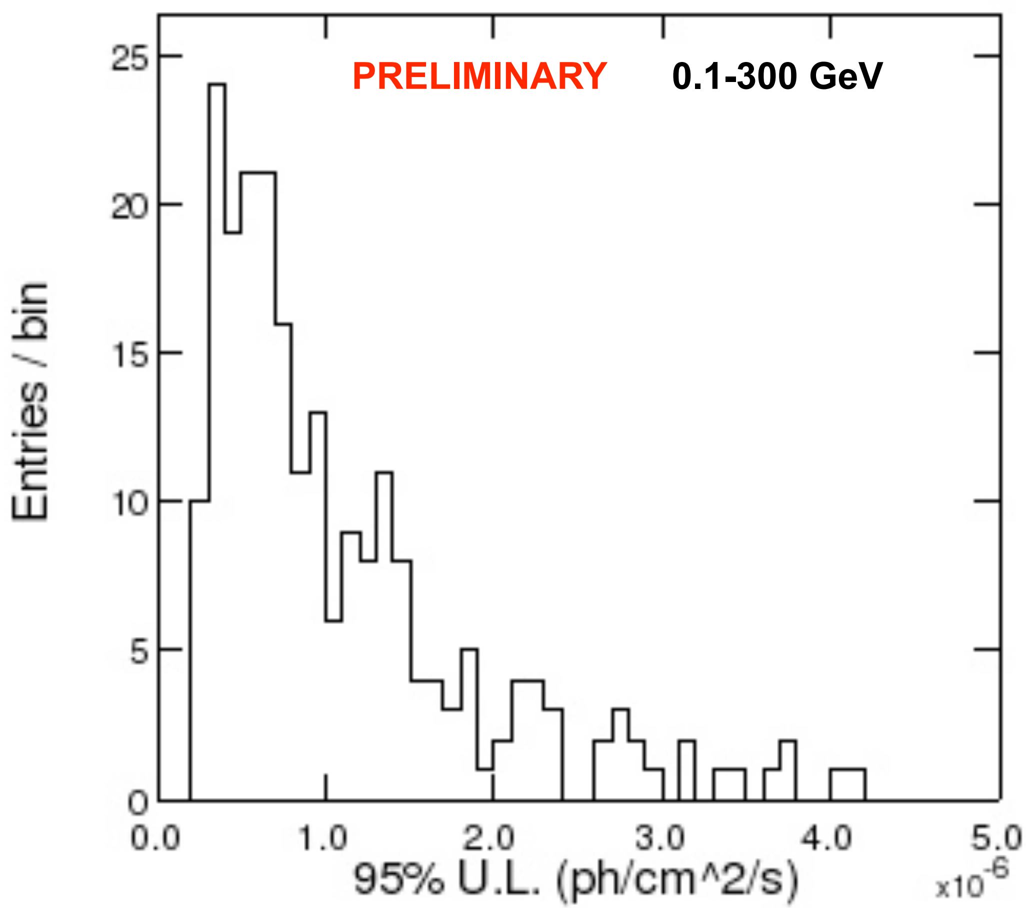






Individual Flux Upper Limits

- LAT 95% CL flux upper limits for $t_{dur}=10^4$s post-trigger for Swift GRBs since 11 Aug 2010



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Stacking Results

- Full energy range (0.1-300 GeV):

  $F_{0.1\text{-}300} = (5.0 \pm 1.7) \times 10^{-8}$ ph cm^{-2}s^{-1}, $T_s = 21.8$

- ½ subsets of the data have expected behavior: T_s grows linearly with sample size.
- High band (1-300GeV):

  $F_{1\text{-}300} = (4 \pm 2) \times 10^{-9}$ ph cm^{-2}s^{-1}

  $T_s = 12.6$

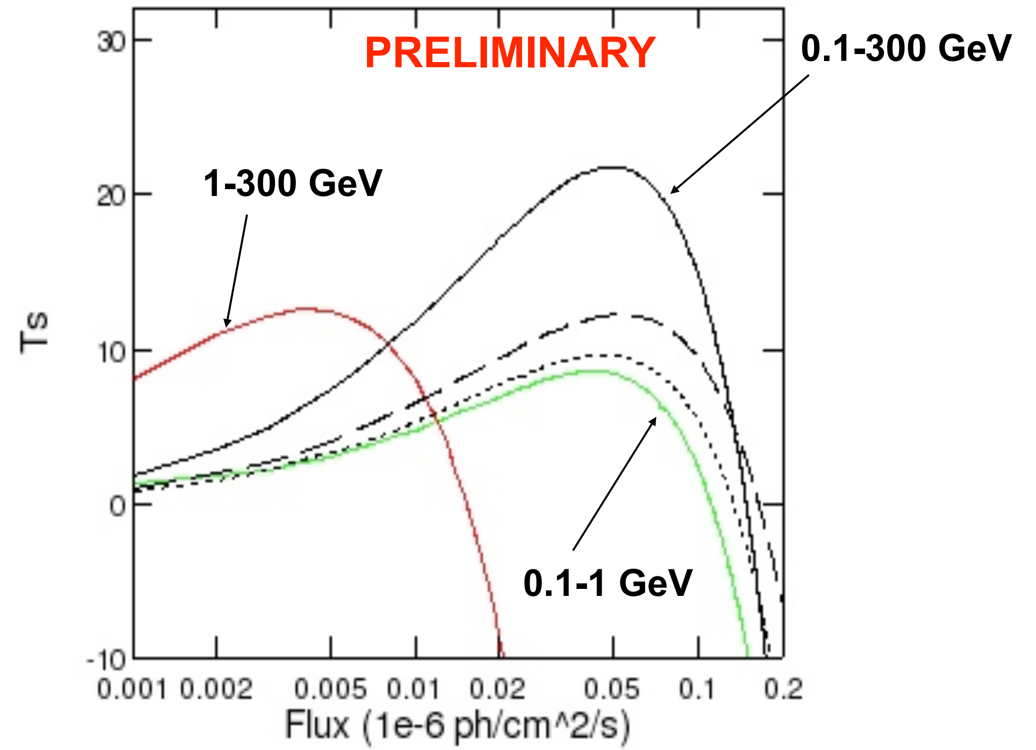
- Low band (0.1-1 GeV):

  $F_{0.1\text{-}1} = (4 \pm 2) \times 10^{-8}$ ph cm^{-2}s^{-1}

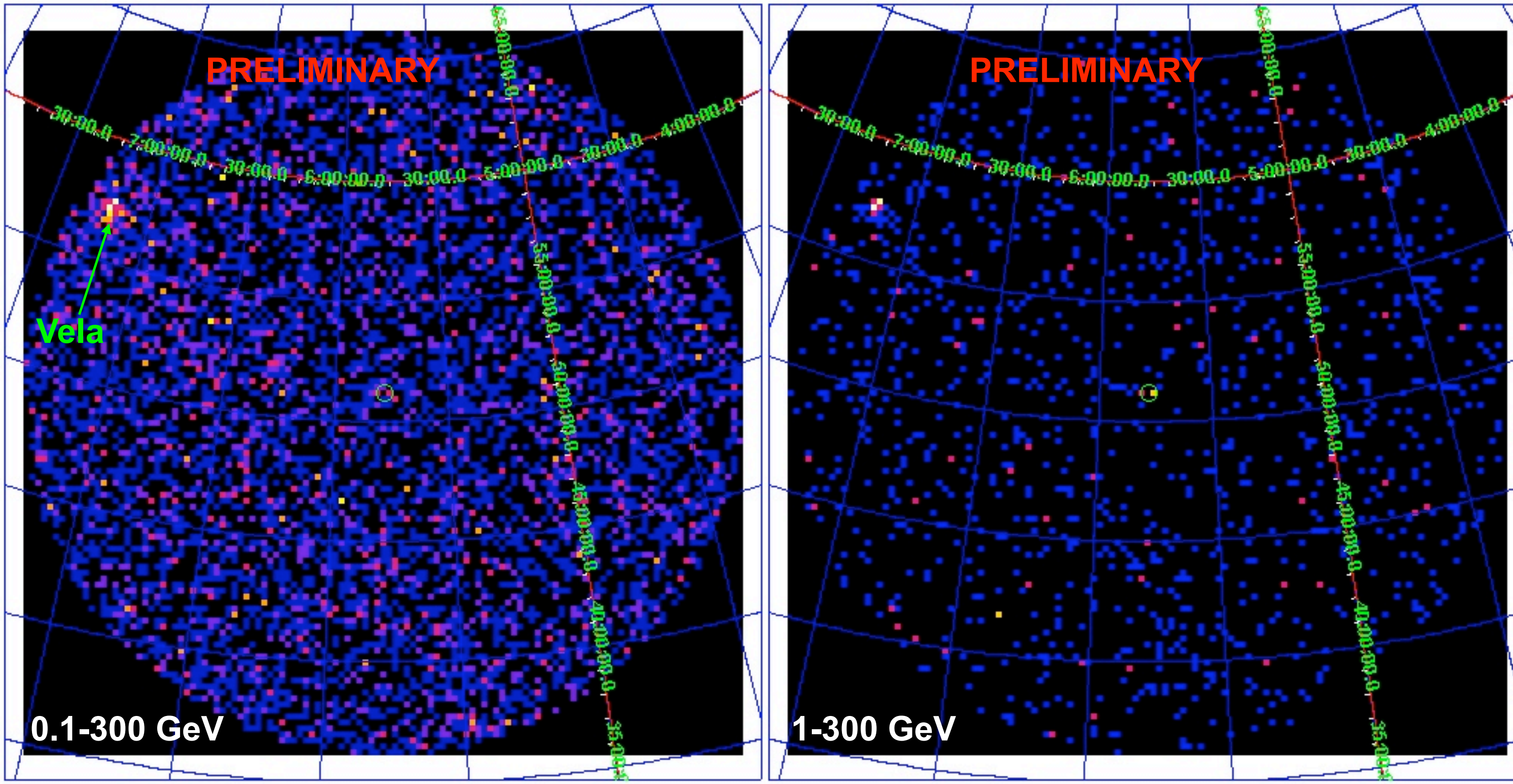
  $T_s = 8.6$

⇒ Photon index = 2.07 (consistent with assumed index)

Stacked T_s profiles



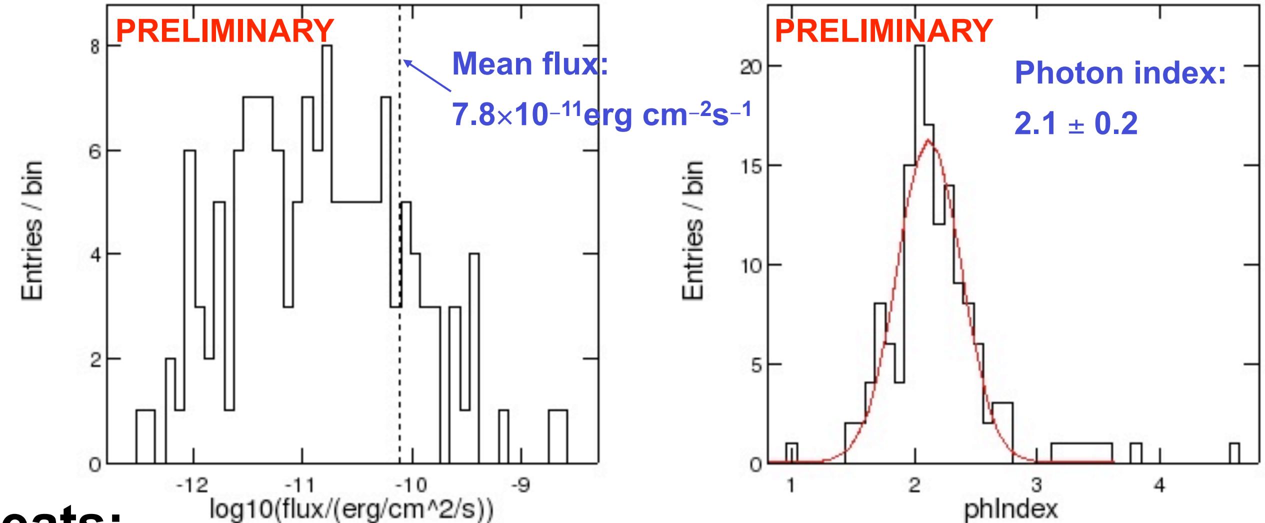
Stacked Counts Maps



GRB location set at the center of the map for each of the 145 ROIs.

Swift-XRT Observations

- We have derived the Swift XRT fluxes (0.3-10keV) and photon indexes for the first 10^4s post-trigger:

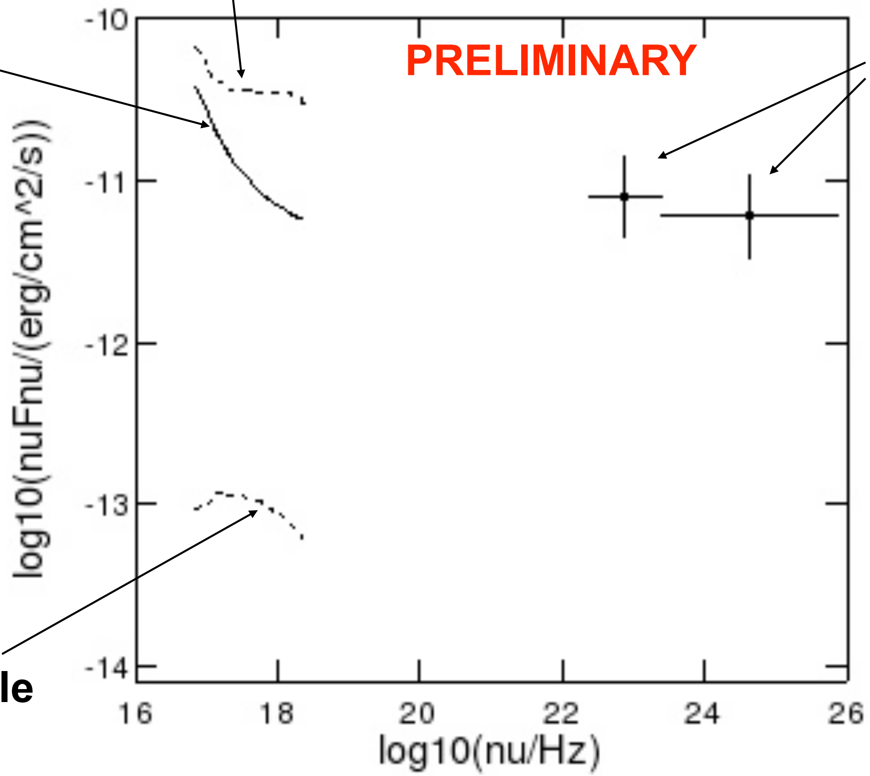


- Caveats:
  - Flaring episodes were excluded from fits.
  - Photon indices were derived from data later in the light curves. Known strong spectral evolution may complicate interpretation with LAT results.

Average Swift-XRT/Fermi-LAT SED

95% quantile

sample average νF_ν



5% quantile

νF_ν from Fermi-LAT stacked fluxes

$\alpha_{x\gamma} \sim 1$

$\Rightarrow$ evidence for an SSC component?

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Conclusions

- Stacking analysis of LAT data can provide much deeper limit than for individual analyses: $O(N_{srcs})$ more sensitive for photon-limited data.

- Marginal signal (T_s=22) seen in LAT stacking of 145 Swift GRB locations.

- Preliminary analysis of the X-ray to γ-ray SED suggests $\alpha_{x\gamma} \sim 1$ and possible indication of an SSC component.

Backup Slides

Optimization of the Observing Window

- Extended emission from LAT bursts decay as $t^{-\gamma}$, $\gamma \approx 1.3 - 2.2$
  $\Rightarrow$ Too short a window and data will lack statistics; too long and data will be background-dominated.

- Optimize signal-to-noise ξ in Poisson case:

$$\xi = \int_{t_{\rm min}}^{t_{\rm max}} S(t)\,dt \Big/ \left[\int_{t_{\rm min}}^{t_{\rm max}} (S(t) + B(t))\,dt\right]^{1/2} \quad (1)$$

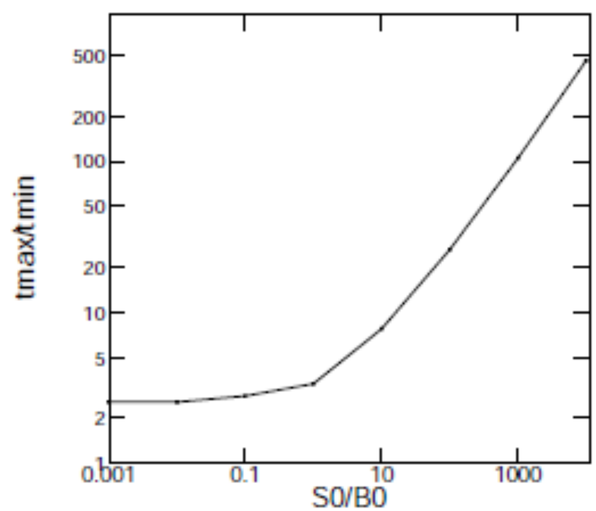
Here $S(t)$ and $B(t)$ are the signal and background count rates as a function of time, and $t_{\rm min}$ and $t_{\rm max}$ are the start and stop times of the LAT integrations.
We wish to optimize ξ with respect to $t_{\rm max}$: $\partial\xi/\partial t_{\rm max} = 0$ yields

$$\frac{B(t_{\rm max})}{S(t_{\rm max})} = 1 + 2\frac{\displaystyle\int_{t_{\rm min}}^{t_{\rm max}} B(t)\,dt}{\displaystyle\int_{t_{\rm min}}^{t_{\rm max}} S(t)\,dt} \quad (2)$$

For $S(t) = S_0(t/t_{\rm min})^{-\gamma}$ and $B(t) = B_0 =$ constant (the latter corresponding roughly to constant effective area), we obtain

$$\left(\frac{t_{\rm max}}{t_{\rm min}}\right)^{\gamma} = \frac{S_0}{B_0} + 2\frac{(t_{\rm max} - t_{\rm min})(1-\gamma)}{(t_{\rm max}/t_{\rm min})^{1-\gamma} - 1} \quad (3)$$

Setting $\gamma = 1.5$, we find for $S_0/B_0 \gg 1$, $t_{\rm max}/t_{\rm min} \sim (S_0/B_0)^{1/\gamma} \sim (S_0/B_0)^{2/3}$, while for $S_0/B_0 \ll 1$, $t_{\rm max}/t_{\rm min} \to 2.53$.



For weak signals (our case), the optimal interval is given by $t_{\rm max}/t_{\rm min} \approx 2.5$.