~~Looking for~~ *Finding* Needles in Haystacks

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Using the Swift/XRT and the Fermi/GBM to uncover GRB γ-rays in the Fermi/LAT detector

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GRBs and High Energy γ–rays

- Max Eγ > 20 GeV (but limited by $\gamma\gamma \rightarrow e^+e^-$)
- Both short and long bursts emit >100 MeV photons
- Prediction prior to launch: ~200 LAT GRB detections/year
- Fermi/GBM detections: ~250/year
- Fermi/LAT detections: ~9/year
- LAT fluence ~ GBM fluence
- GBM localization ~ 10°
- LAT localization ~ 1°
- Swift XRT localization ~ 1″

Challenge: With better & faster localizations, more bursts could be optically detected and better characterized.

“Haystack I” (XRT): arXiv:1010.1436v2 [astro-ph.HE], ApJ 725 (2010)

“Haystack II” (GBM): arXiv:1010.1588v2 [astro-ph.HE], ApJLett (2011)

Using XRT localizations to find LAT GRB γ-rays

Matched filter technique: w ~ p(signal) / p(background)

$$w(E,\theta,t,c) = w_E \cdot w_\theta \cdot w_t \cdot w_c$$

$$w_E = \frac{1}{4\pi\sigma^2(E)}\left(\frac{E}{E_{th}}\right)^{\Gamma_{back}-\Gamma_{GRB}}$$

$$w_\theta = 2e^{-\frac{\theta^2}{2\sigma^2(E)}}$$

$$w_c = \left(\frac{r_{GRB}(i)}{r_{GRB}(3)}\right) / \left(\frac{r_{back}(i)}{r_{back}(3)}\right); \quad 1 \le i \le 3$$

$$w_t = \begin{cases} c \cdot \left(\frac{t}{t_b}\right)^{\alpha_0} & 0 \le t \le t_b \\ c \cdot \left(\frac{t}{t_b}\right)^{-\alpha} & t_b < t \le t_c \end{cases}$$

$$\zeta = \frac{3\left(w_0 \cdot w_1 \cdot w_2\right)^{1/3}}{w_0 + w_1 + w_2}$$

Modified matched filter weight for each GRB event: $\zeta \, \Sigma w_i$

Data Selection:

DATA_QUAL = 1

IN_SAA = 0

100 MeV < E_γ < 300 GeV

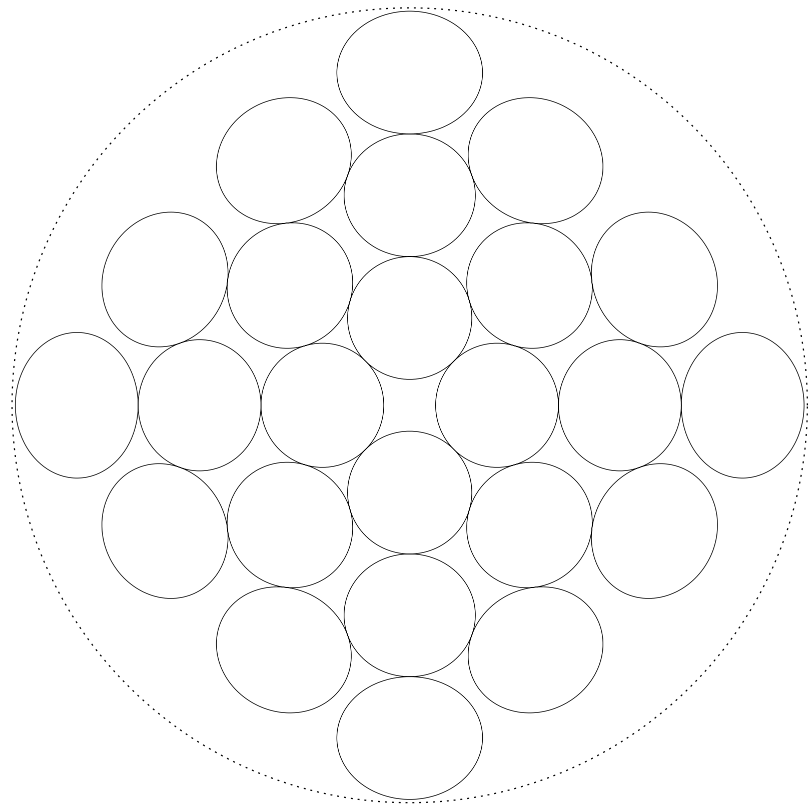
gb_{GRB} > 10°

Θ_{zenith} < 105°

$\Theta_{GRB\text{-}bore}$ < 66°

θ_γ < 10.5° relative to XRT localization

0 < t < 47.5 s relative to GRB trigger



Circular 10.5° tiling of the LAT FoV for defining random fields. Dotted circle at 68° to boresight.

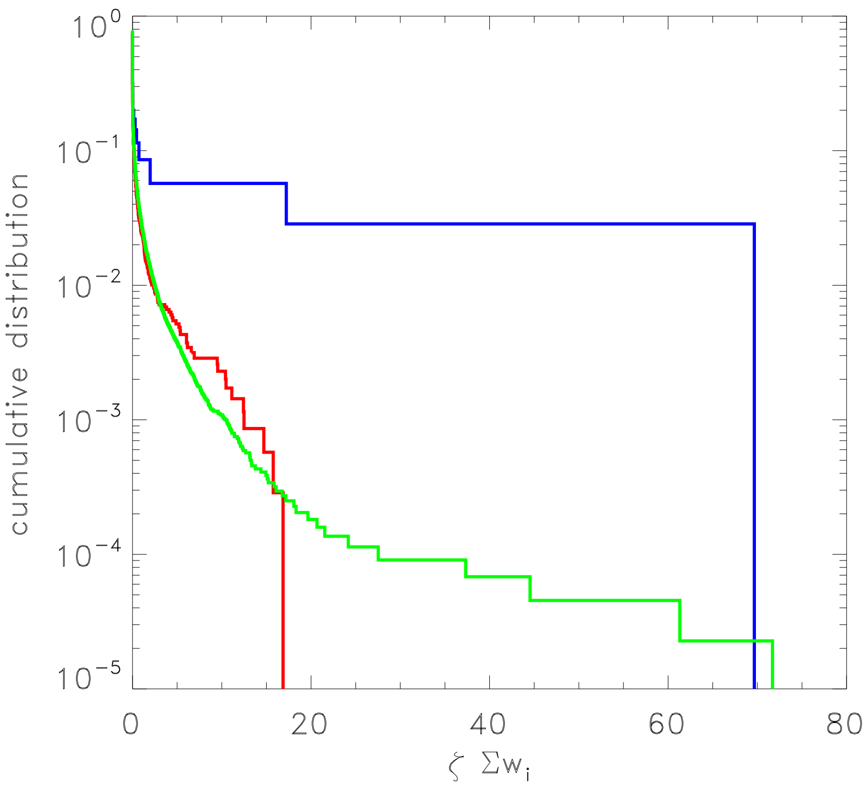
41 fields selected:

6 with previous LAT GRB detections

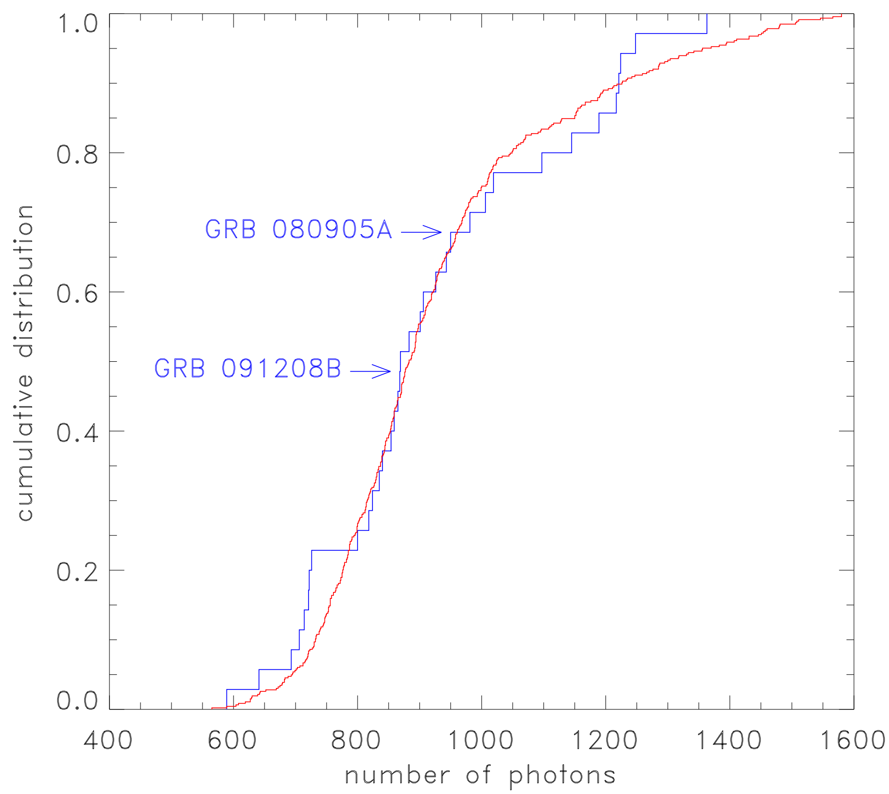
35 with no prior evidence for LAT GRBs

LAT photon event class counts for XRT-localized fields

GRB	α	δ	n_1 (transient)	n_2 (source)	n_3 (diffuse)	$\zeta \; \Sigma w_i$
Previously reported GRBs with LAT-detected photons						
080916C	119.847	-56.638	26	31	85	7910.5
090323	197.709	17.054	2	0	2	10.6
090328A	90.665	-41.883	4	2	1	0.6
090510	333.553	-26.583	26	48	112	31389.8
090902B	264.939	27.325	54	49	93	8530.5
091003	251.520	36.625	8	2	7	1107.3
New candidate GRBs with LAT-detected photons						
080905A	287.674	-18.880	2	1	3	69.7
091209B	29.392	16.890	2	1	3	17.2
Average photon counts for random fields						
			3.86	0.34	0.40	

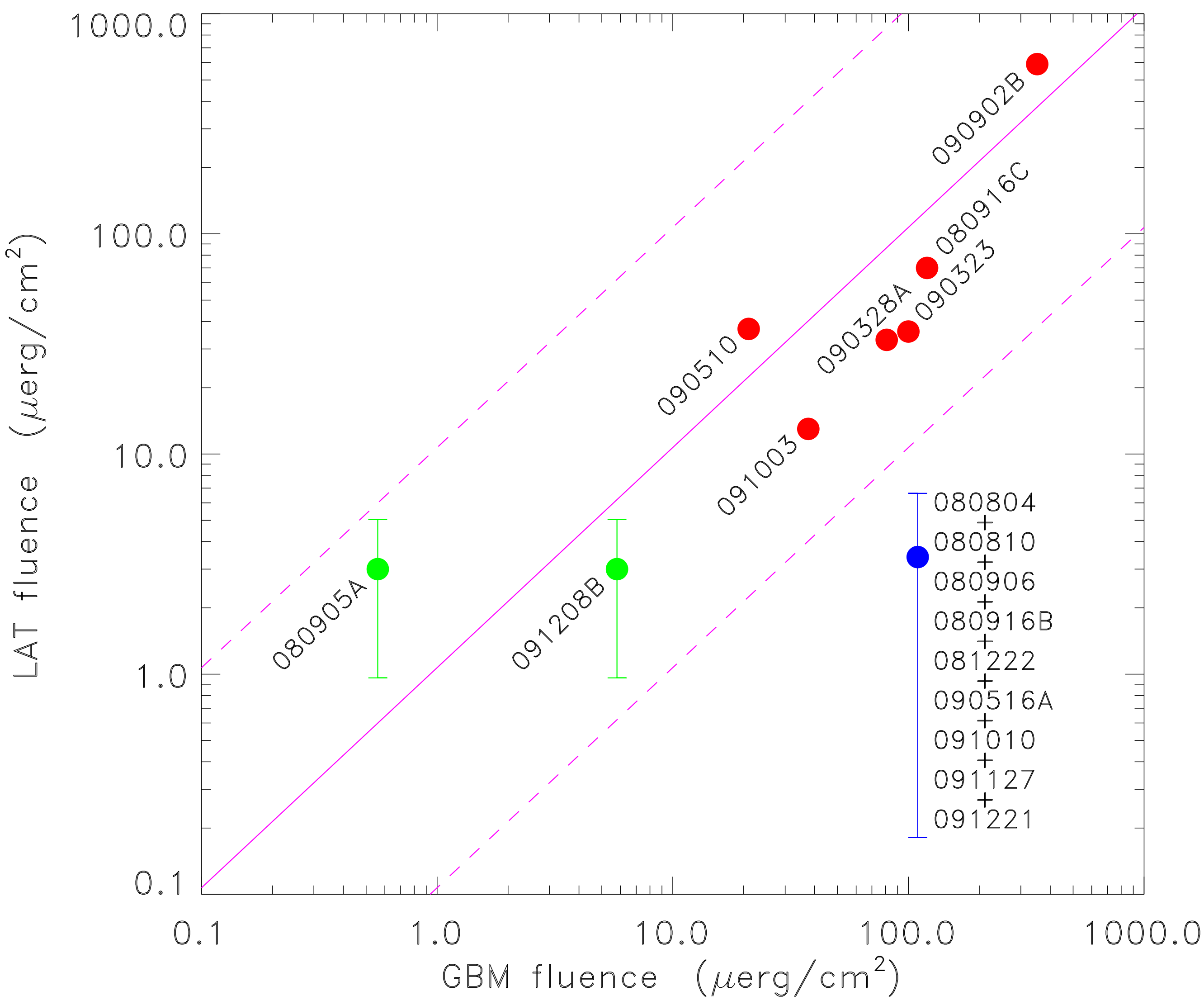


Cumulative distributions of modified matched filter weights, blue line represents 35 XRT-localized fields, red and green are for random fields.



Cumulative distributions of LAT photon number, blue line represents 35 XRT-localized fields

Independent confirmation: "diffuse" class photon rate for 35 XRT fields is >2σ higher than rate for random background fields.



LAT vs GBM fluences for XRT-localized GRBs. The two green points have been identified by our analysis.

☠ ☠ ☠ → **LAT fluences may not be statistically robust!** ← ☠ ☠ ☠

Using GBM localizations to find LAT GRB γ-rays

GRB photon cluster finder:

a) **Compute pair score,** $Q_{ij} = w_i \cdot w_j \cdot \Delta_{ij}$,

where w_i **traces E, t and event class correlations**

and Δ_{ij} **traces pair angular correlation**

b) **Rank photon triplet weights,** $R_{ijk} = (w_i \cdot w_j \cdot w_k \cdot \Delta_{ij} \cdot \Delta_{jk} \cdot \Delta_{ik})^{1/3}$

c) **Select triplet with largest** $\zeta \ \Sigma w_i$ **as best GRB candidate**

Data Selection: Same as before EXCEPT:

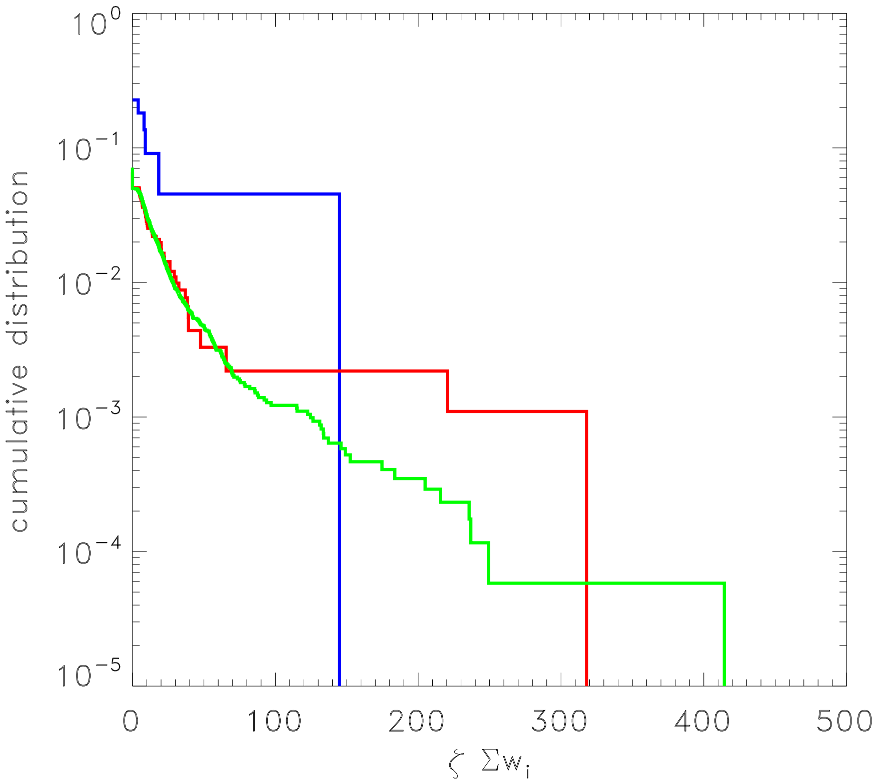
No gb_{GRB} cut

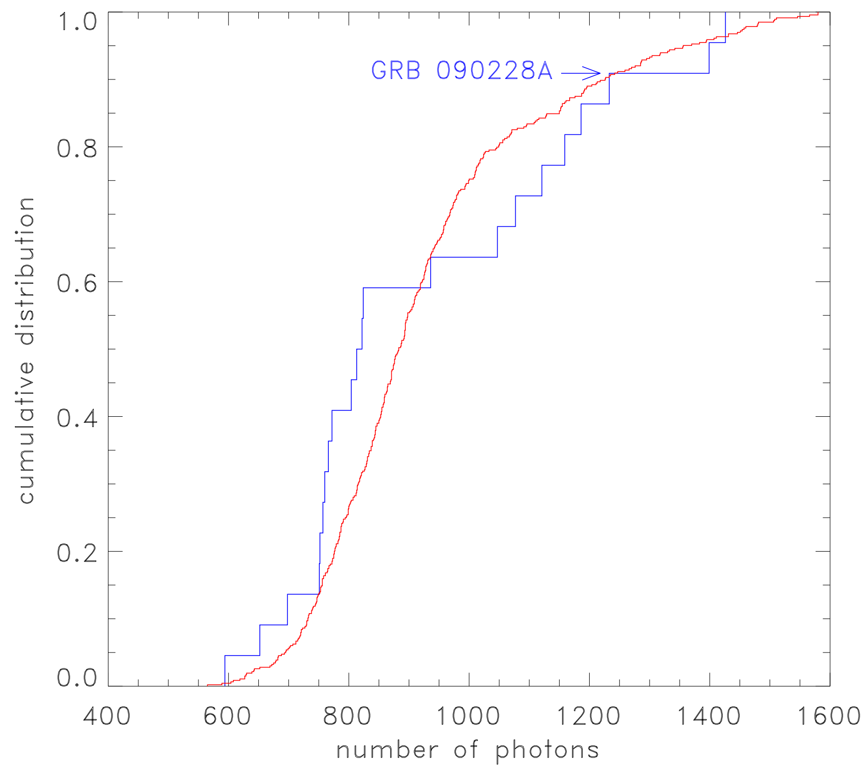
$\Theta_{GBM\text{-}bore} < 52°$

θ_{γ} < 16.0° relative to GBM localization

GBM fluence > 5.0 μerg/cm^2

22 fields selected with no prior evidence for LAT GRBs

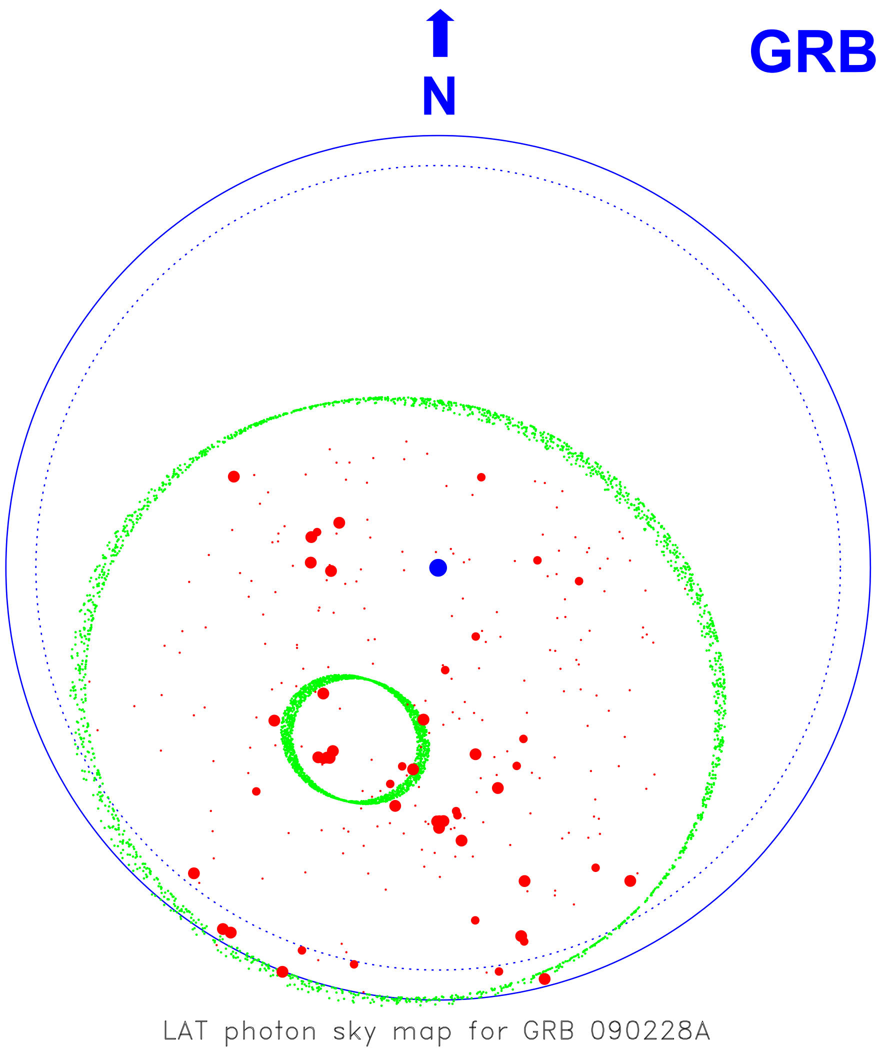




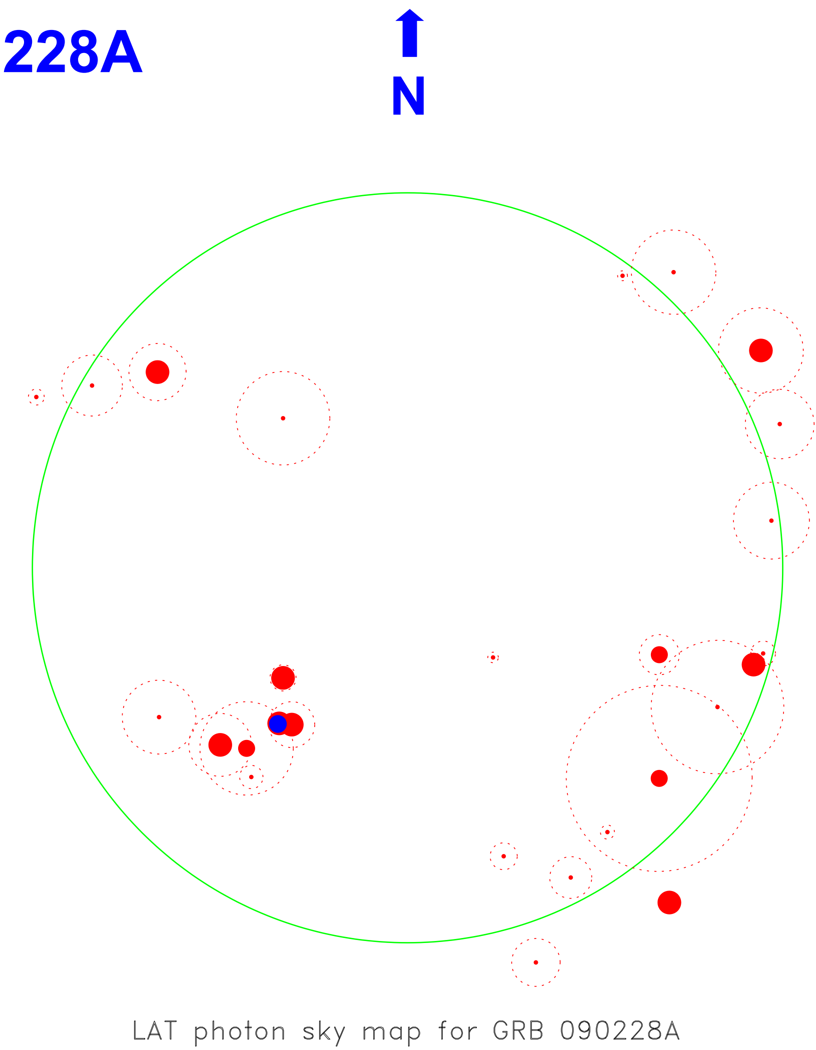
Cumulative distributions of modified matched filter weights, blue line represents 22 GBM-localized fields, red and green are for random fields.

Cumulative distributions of LAT photon number, blue line represents 22 GBM-localized fields

GRB 090228A



solid blue circle is Earth limb, outer green circle is LAT FoV

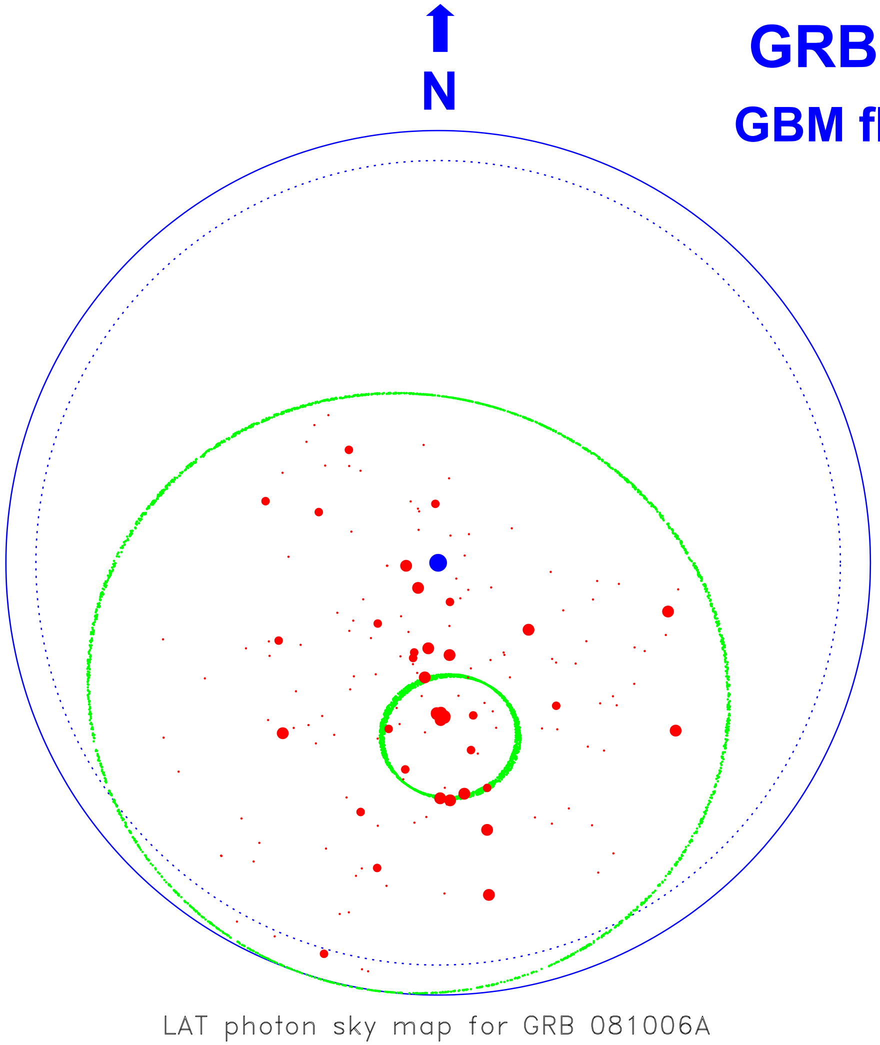


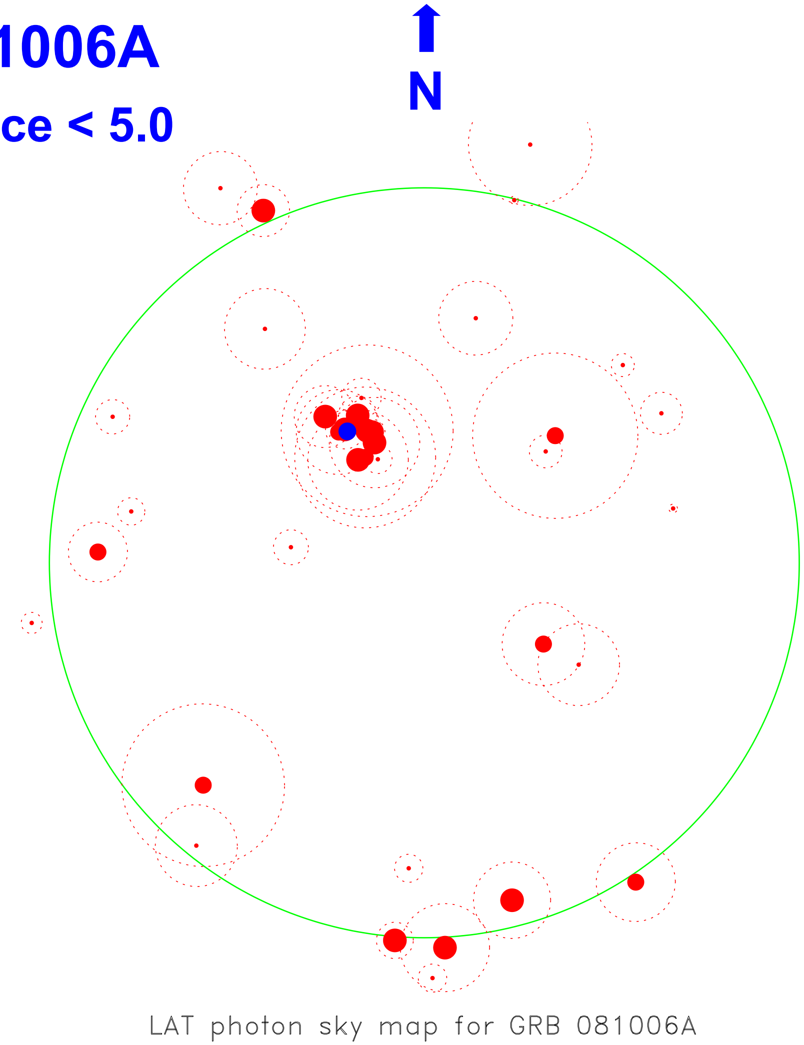
green circle is 16° locus from GBM estimated direction

Our localization is 8.7° from GBM (von Kienlin et al.) and 0.5° from IPN (Guirec et al.)

GRB 081006A

GBM fluence < 5.0





solid blue circle is Earth limb, outer green circle is LAT FoV

green circle is 16° locus from GBM estimated direction

Conclusions:

1. High energy, low fluence GRBs can be identified using matched filter techniques.
2. The number of additional detectable LAT GRBs is somewhere between 25% and 50% of the current rate.
3. The real-time identification of such events is probably possible within the constraints of the Fermi flight software. Since the Fermi mission is not likely to be emulated soon, this enhancement deserves some immediate consideration from the GRB community.
4. The number of low fluence events is surprisingly small relative to the majority of the GRBs identified by the LAT to date. This dearth is extremely difficult to understand.

Estimating LAT GRB fluences - an unusual statistical problem

Estimating the population mean from a sample mean:

$$\langle \bar{x}_s \rangle = \bar{x} \quad ; \qquad \sigma^2_{\bar{x}_s} = \frac{\sigma_x^2}{n}$$

However, for LAT GRB fluence estimates:

$$\frac{dn}{dE} = \left(\frac{E}{E_{th}} \right)^{-\Gamma} \frac{c}{E_{th}} \quad ; \qquad 2 < \Gamma < 3$$

$$\bar{E} = \frac{\Gamma - 1}{\Gamma - 2} E_{th} \quad ; \qquad \sigma_E^2 \to \infty$$

Conclusion: Fluence can not be robustly computed by summing photon energies. Instead, find median energy and multiply by number of detected photons. Even for finite *E_{max}*, these considerations apply as long as $n_\gamma < (E_{\max}/E_{\min})^{\Gamma-1} \approx 500$.