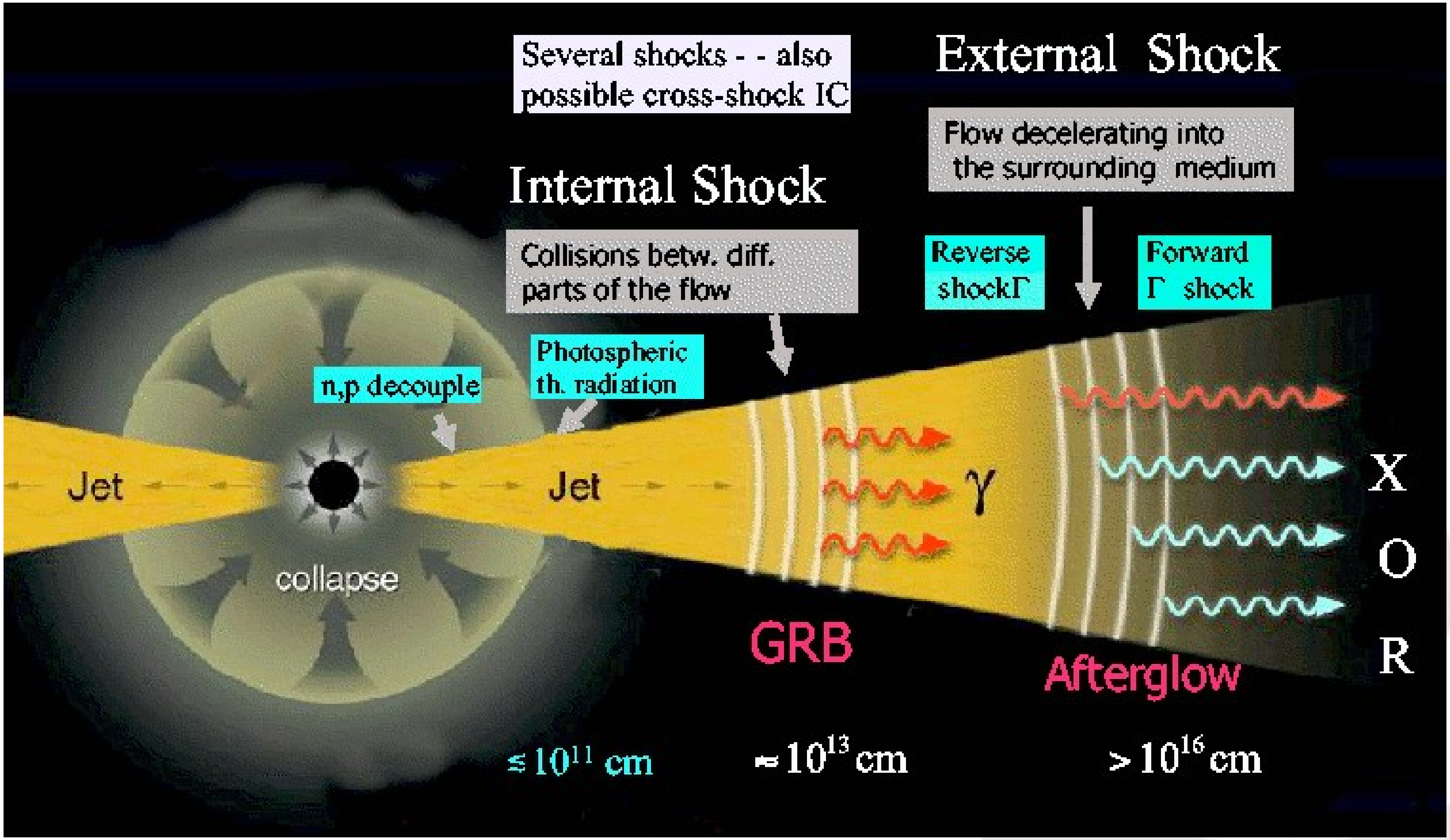
Les sursauts gamma avec *Fermi*

- **Motivations scientifiques**
- **Résultats marquants**
- **Contributions du LUPM**

Le modèle de la boule de feu

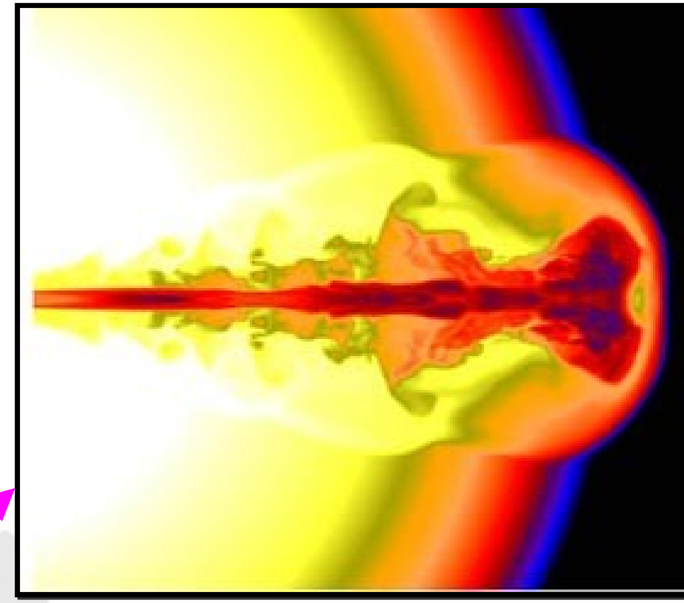
- Jet accéléré jusqu'à $\Gamma>100$, opaque (émission photosphérique attendue à R~10^{11-12} cm)
- Chocs internes entre surdensités dans les éjectas à R~10^{14-15} cm (émission prompte)
- Jet freiné par le milieu interstellaire et chocs externes à R~10^{16-17} cm (émission rémanente)

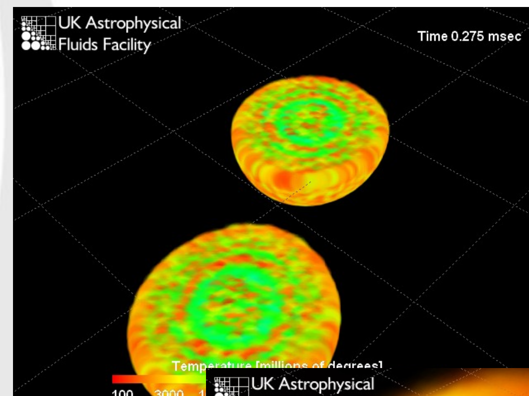


Fermi Gamma-ray Space Telescope

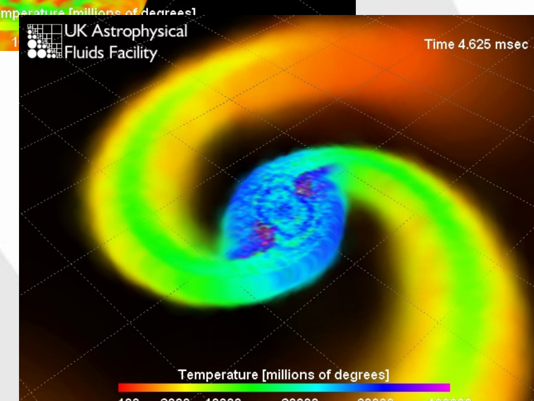
Progéniteurs ?

- **Sursauts longs (> 2s typiquement)**
  - Ingrédients : étoiles Wolf-Rayet >10 $M_\odot$ de rayon ~ $R_\odot$, en rotation rapide
  - Effondrement et formation d'une supernova et d'un trou noir de ~2-3 $M_\odot$ entouré d'un disque d'accrétion (maintenu pendant qq 10 s)
  - Energie émise suivant l'axe de rotation
  - Sortie du jet de l'enveloppe stellaire en qq 10 s
  - Facteurs de Lorentz Γ ~ 10-100
  - Angle d'ouverture du jet θ_{jet} ~ 5°
  - Régions de formation stellaire





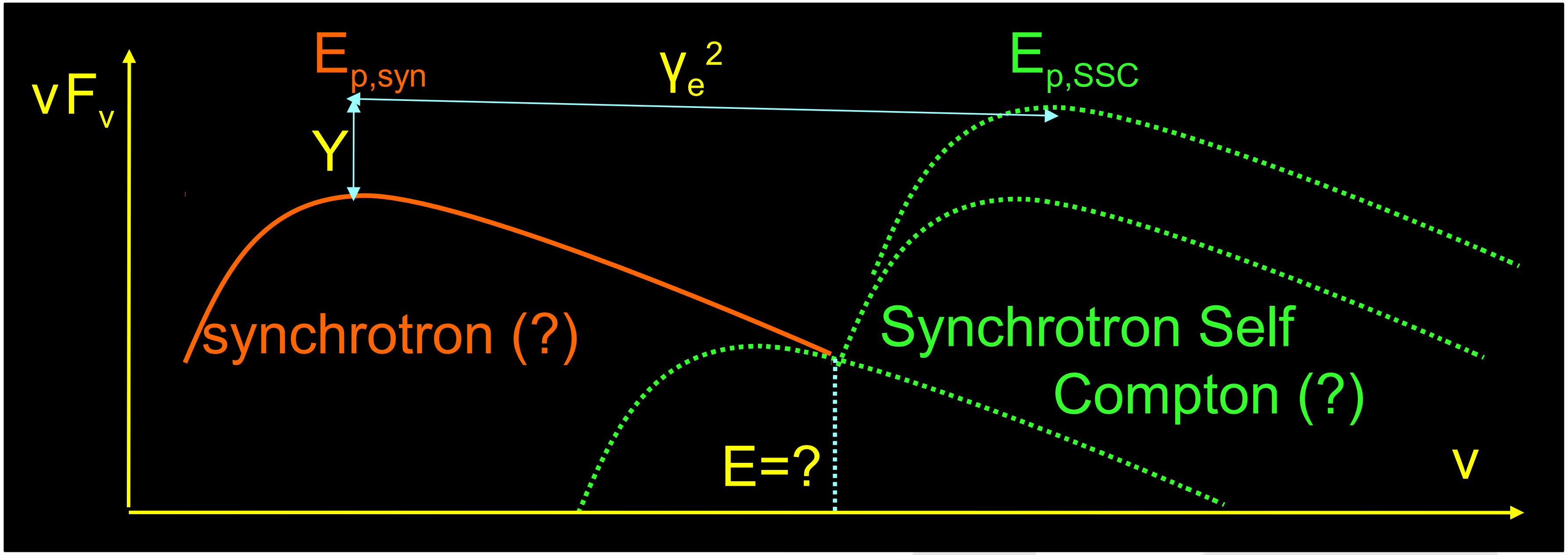
- **Sursauts courts (< 2s)**
  - ~15% des sursauts détectés
  - Associés à des galaxies elliptiques (population d'étoiles vieilles)
  - Fusion d'objets compacts (NS-NS ou NS-BH)
  - Echelle de temps de la fusion de l'ordre de la ms
  - Ejection dans une région de plus faible densité (faible émission rémanente)



Mécanismes d'émission à haute énergie

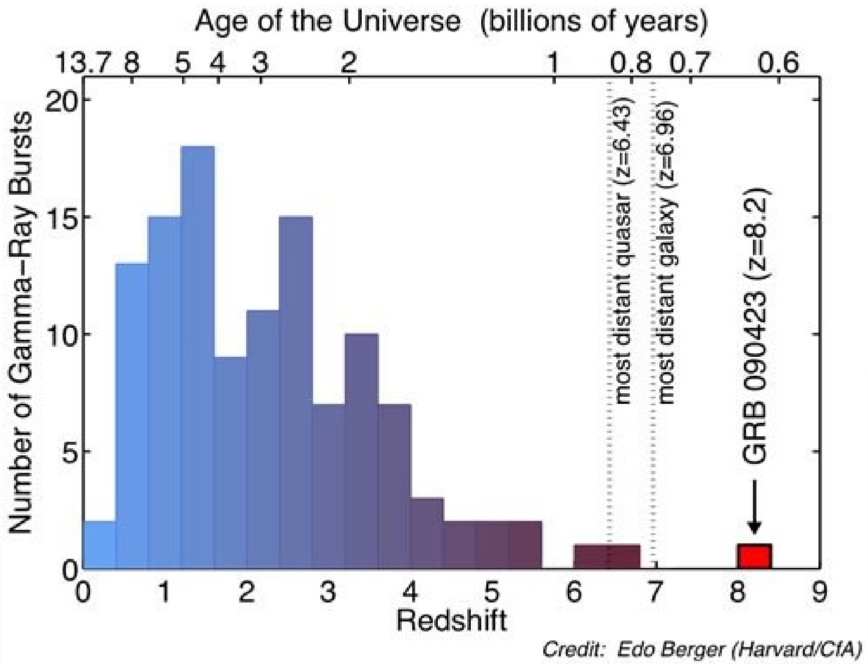
- **Effet Compton inverse ou Synchrotron Self Compton (SSC)**

  $E_{p,SSC} / E_{p,syn} \sim \gamma_e^2$, $L_{SSC} / L_{syn} = Y$, $Y(1+Y) \sim \varepsilon_{rad}\varepsilon_e / \varepsilon_B$



- **Processus hadroniques (accélération de RCUHE ?!) :**
  photopair production ($p + \gamma \rightarrow p + e^+ e^-$), émission synchrotron des protons, production de pions via $p - \gamma$ (photopion), interactions ou collisions p-p
  - **Les pions neutres se désintègrent en 2 photons de haute énergie $\pi^0 \rightarrow \gamma\gamma$ qui peuvent cascader en paires avec des photons de plus basse énergie $\gamma\gamma \rightarrow e^+ e^-$**
  - ***Fermi* aide à déterminer les mécanismes dominant à basse et haute énergies**

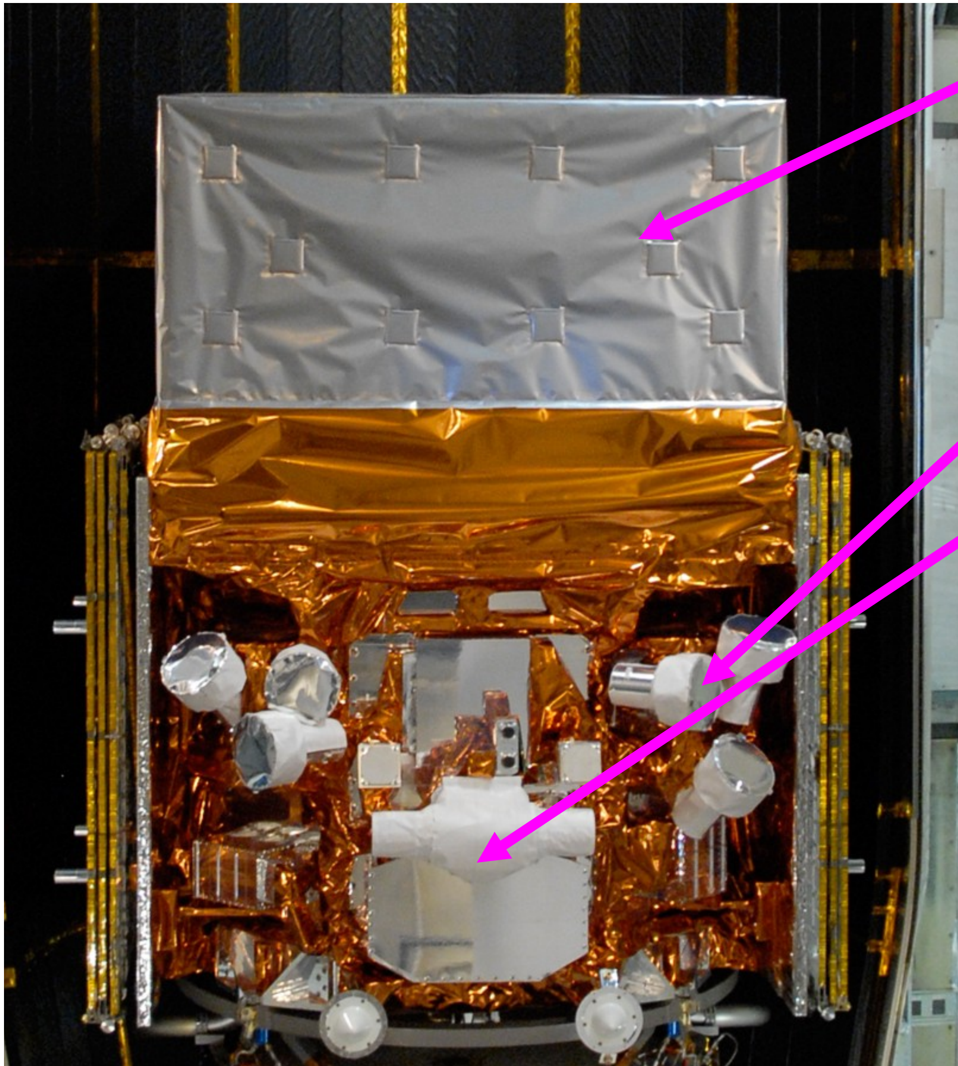
Pourquoi un mouvement relativiste ?



- Les sursauts gamma (Gamma-Ray Bursts) sont des objets distants et très énergétiques ($E_{\gamma,iso} \sim 10^{52}$ -10^{54} erg) → sources compactes accrétantes

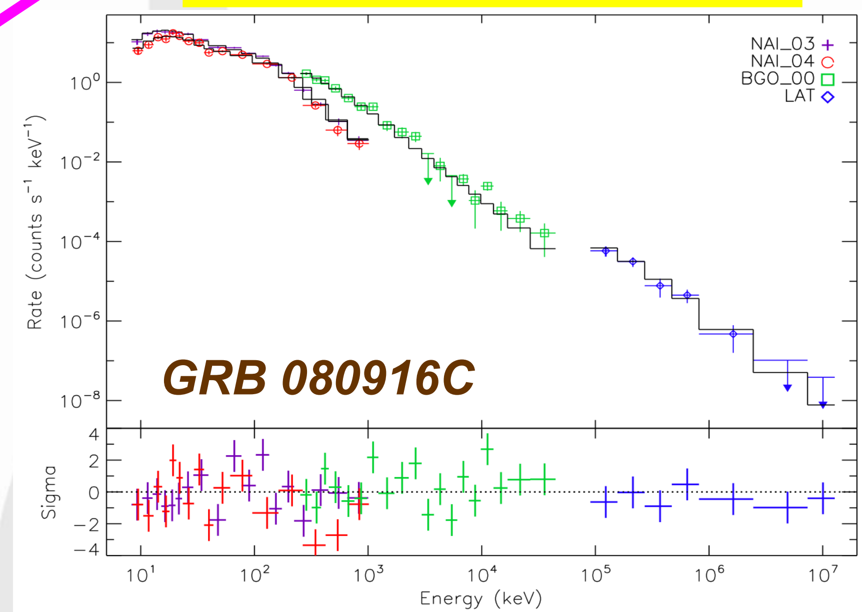
- Le problème de compacité
  - Très grande luminosité $L_{iso} \sim 10^{50}$-10^{53} erg/s
  - Pour une source au repos, la variabilité rapide Δt implique une source de dimension R < cΔt suffisamment petite pour que les photons d'énergie $\varepsilon = E_{ph} / m_e c^2 \sim 1$ s'annihilent en paires ($\gamma\gamma \rightarrow e^+e^-$) :
    - la densité de photons cibles $n_{ph}(1/\varepsilon) \sim L_{1/\varepsilon}/(4\pi R^2 m_e c^3)$ conduit à l'opacité suivante : $\tau_{\gamma\gamma}(\varepsilon) \sim \sigma_T n_{ph}(1/\varepsilon) R = \sigma_T L_{1/\varepsilon} /(4\pi m_e c^3 R) > 10^{14}\, L_{1/\varepsilon,51} (\Delta t / 1\ \mathrm{ms})^{-1}$
    - une telle opacité devrait créer un spectre thermique, incompatible avec les observations à haute énergie
  - Pour une source en mouvement relativiste, $\tau_{\gamma\gamma}$ est réduit d'un facteur $\Gamma^{2(1-\beta)}$
    - -β (indice spectral HE)~ 2-3 et $\tau_{\gamma\gamma} < 1 \Rightarrow \Gamma > \Gamma_{min} \sim 100$ (↑ avec 1/Δt, E_{max}, z et flux)

Les instruments à bord de Fermi



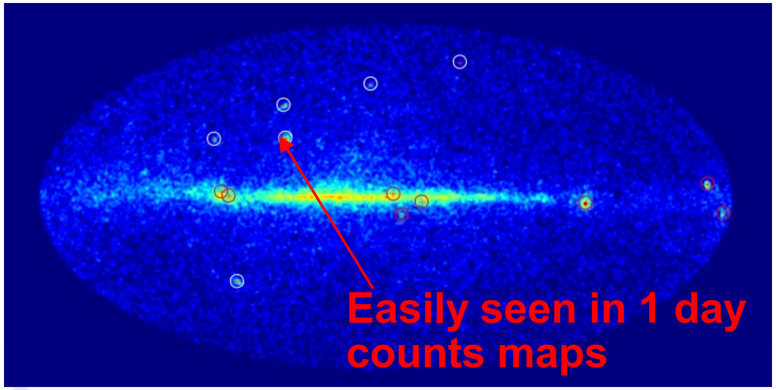
- **Large Area Telescope (LAT)**
  - **20% du ciel à tout instant**
  - **20 MeV à >300 GeV**
  - **Triggers GRB à bord et au sol**
  - **Localisation, spectroscopie**
- **Gamma-ray Burst Monitor (GBM)**
  - **Tout le ciel non occulté à tout instant**
  - **12 détecteurs au NaI (8 keV à 1 MeV)**
    - **Trigger GRB à bord, localisation à bord et au sol, spectroscopie**
  - **2 détecteurs au BGO (150 keV à 40 MeV)**
    - **Spectroscopie**

Abdo et al. 2009, Science 323, 1688



Spectre de Band de 10 keV à 10 GeV !

Séquence d'observation (GRB 090902B)

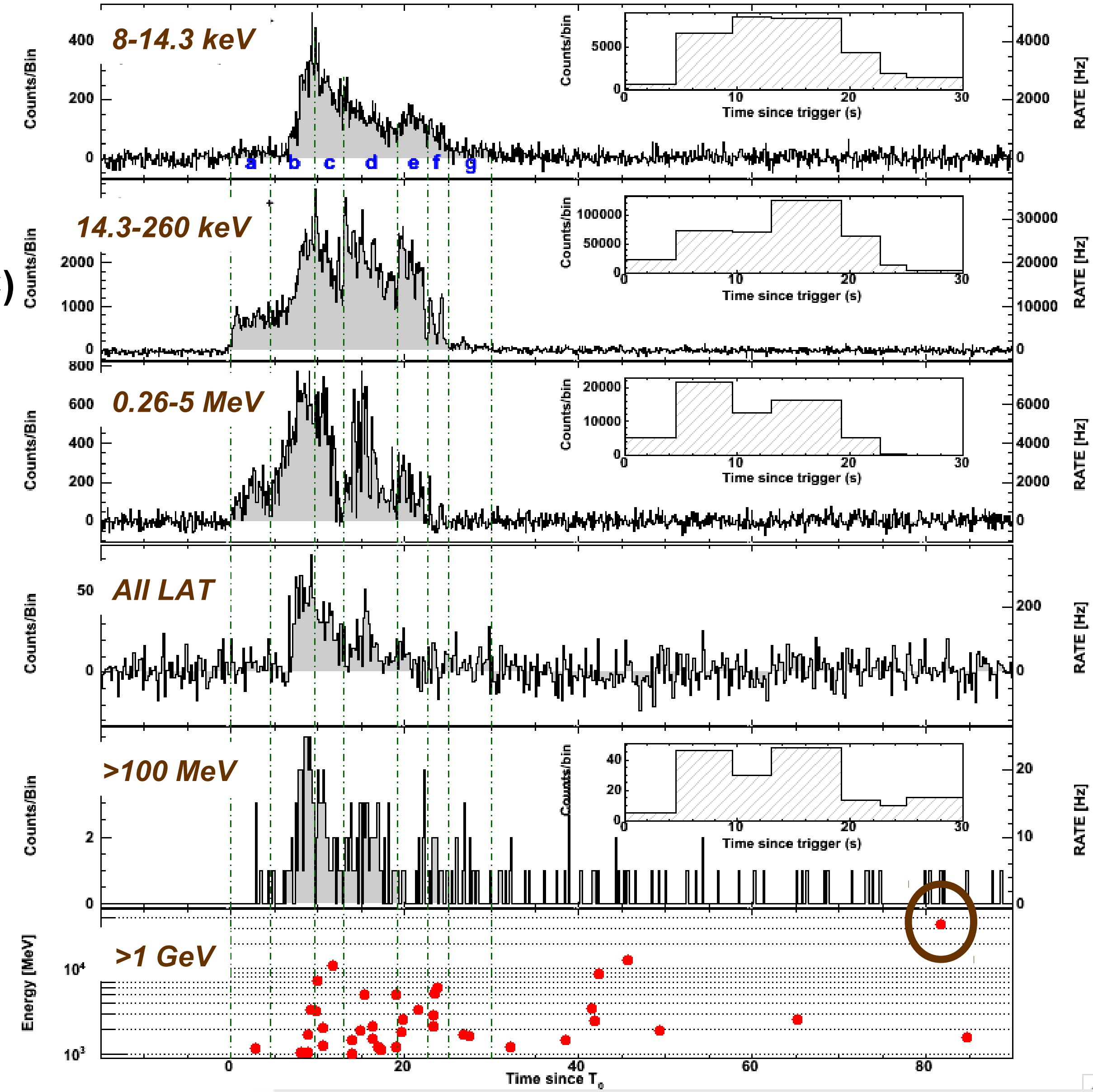


- 11:05:15 UT = T0 – GBM GCN alert – ARR initiated
  - 15:05 UT – GBM human-in-the-loop localization
- LAT data monitoring and processing
  - 14:44 UT – GRB is seen in the telemetry
  - 18:24 UT – data ingest
  - 19:54 UT – GRB is seen in datamon plots
- 20:59:48 UT – FT1 file available [T0 + 10 hr]
  - ASP results ~20 min later, human-in-the-loop localization
  - Swift ToO request issued at ~21:30 UT, begins at 23:36 UT [T0 + 12.5 hr]
- 21:19:03 UT – 1st GBM circular (GCN 9866)
- 22:48:18 UT – 1st LAT circular (GCN 9867)
  - (RA,Dec=265.00, 27.33) with a 90% containment radius of 0.06 deg (statistical; 68% containment radius: 0.04 deg, systematic error <0.1 deg)
- 03:00:57 UT – Swift/XRT afterglow candidate (GCN 9868) [T0 + 16hr]
  - Estimated uncertainty of 4.2 arcseconds radius (90% confidence)
  - XRT position 3.2 arcmin from LAT position, inside error radius
- 04:57:44 UT – Swift/UVOT observations, no afterglow confirmation (GCN 9869)
- 04:57:44 UT – enhanced Swift/XRT position (GCN 9871)
- 07:36:42 UT – *Fermi* LAT and GBM refined analysis (GCN 9872)
- 08:23:17 UT – Gemini-N absorption redshift (GCN 9873) z=1.822 (GMOS spectro) [T0 + 21.3 hr]
- 09:14:50 UT – GROND localization 3.3 arcmin from LAT position

GRB 090902B multi-detector light curve

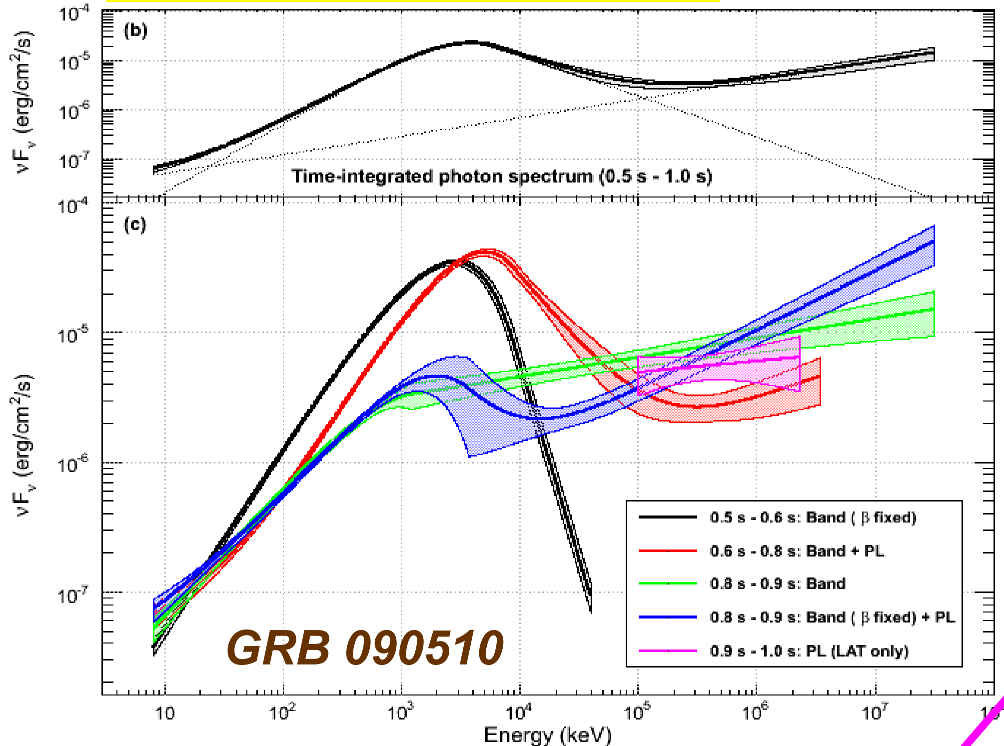
- T90 = 21.9 s, 50-300 keV
- Fluence = 4.4×10^{-4} erg cm^{-2} (10 keV – 10 GeV)
- **Eiso = 3.6×10^{54} erg** (~9×10^{54} erg for GRB 080916C)
- **Delayed onset of >100 MeV emission (~7 s)** (~5 s for GRB 080916C), also observed in short GRBs
- **LAT extended emission**, well beyond GBM prompt phase
- **Highest energy photon measured from a burst: 33.4 GeV at T0 + 82 s (very constraining for EBL models)**
- Correlated variability in various bands

Abdo et al. 2009, ApJL 706, 138

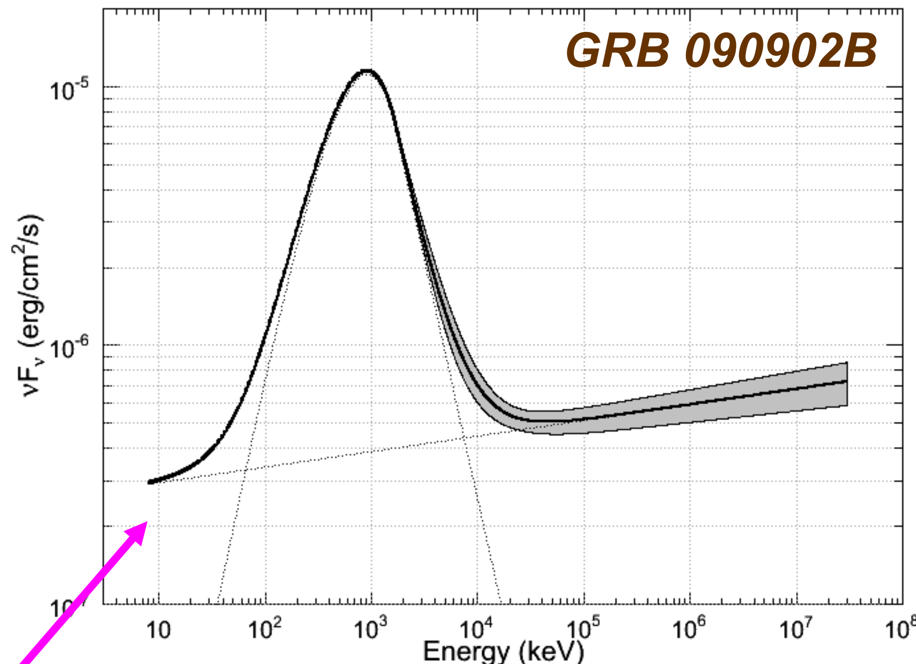


Extra PL component in short and long GRBs

Ackermann et al. 2010, ApJ 716, 1178



Abdo et al. 2009, ApJL 706, 138



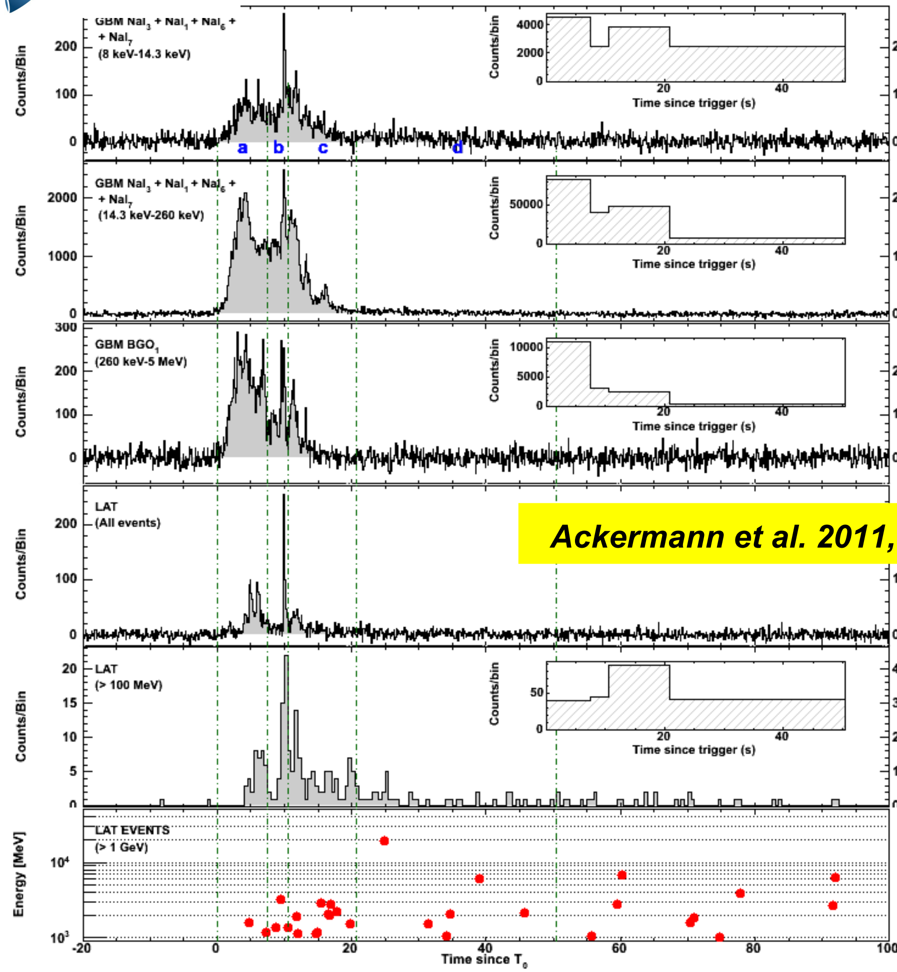
Band function + Power-Law Fit Parameters for the Time-Resolved Spectral Fits

Interval	Time Range (s)	E_{peak} (kev)	α	β	Γ	CSTAT/DOF	ΔCSTAT
…	0.0–30.0	726 (±8)	−0.61 (±0.01)	$-3.8\,(^{+0.2}_{-0.3})$	$-1.93(^{+0.01}_{-0.01})$	2562/963	2005
a	0.0–4.6	526 (±12)	−0.09 (±0.04)	$-3.7\,(^{+0.3}_{-0.6})$	$-1.87(^{+0.04}_{-0.05})$	901/963	43
b	4.6–9.6	$908\,(^{+15}_{-14})$	0.07 (±0.03)	$-3.9\,(^{+0.2}_{-0.3})$	−1.94 (±0.02)	1250/963	3165
c	9.6–13.0	821 (±16)	−0.26 (±0.03)	$-5.0(^{+0.8}_{-\infty})$	−1.98 (±0.02)	1310/963	2109
d	13.0–19.2	529 (±9)	−0.65 (±−0.02)	$-3.2\,(^{+0.1}_{-0.2})$	−1.86 (± 0.02)	1418/963	199
e	19.2–22.7	317 (±8)	−0.78 (±−0.02)	−2.4 (±0.1)	…	1117/965	…
f	22.7–25.0	$236\,(^{+25}_{-33})$	$-1.30\,(^{+0.04}_{-0.03})$	−2.2 (±0.1)	…	1077/965	…
e+f	19.2–25.0	327 (±8)	−0.91 (±0.02)	−2.6 (±0.1)	−1.59 (±0.20)	1219/963	16
g	25.0–30.0	…	…	…	$-1.93\,(^{+0.25}_{-0.26})$	1209/967	…

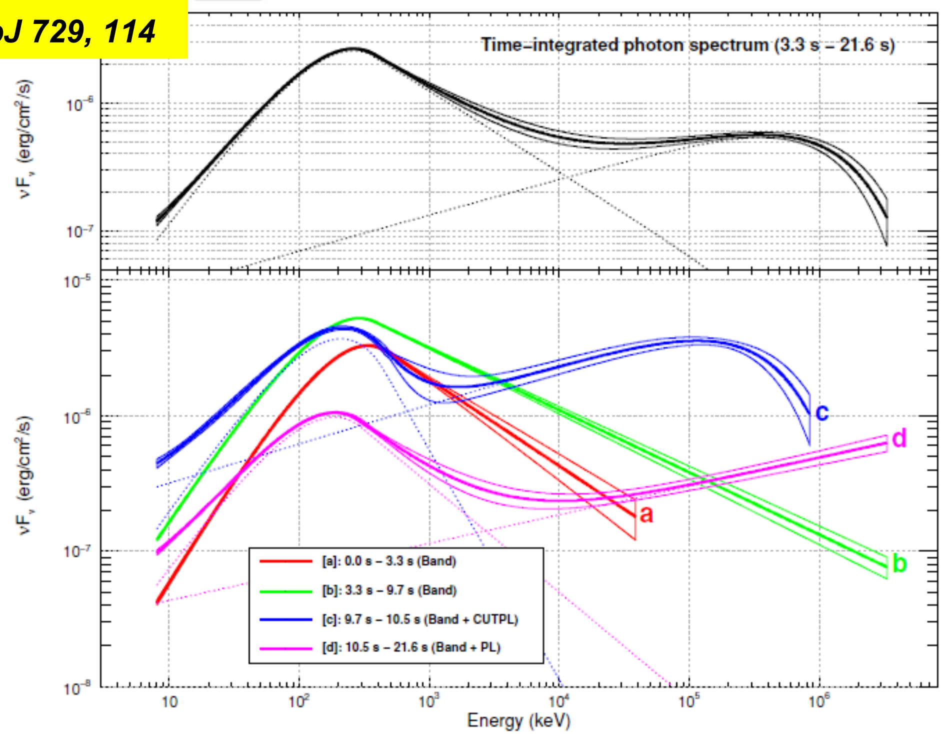
- **Soft-hard-soft evolution in E_{peak}**
- **Extra-PL can emerge right after the onset of the Band emission in the LAT**
- **GRB 090902B, time interval**
  - **Extension of the extra PL down to <50 keV energies!**

GRB 090926A bulk Lorentz factor

- Fluence = 2.1×10^{-4} erg cm^{-2} (10 keV – 10 GeV) Eiso = 2.2×10^{54} erg
- The extra PL dominates >10 MeV
- ~6 σ spectral break at ~1.4 GeV (shape not constrained)
- First direct measurement of the bulk Lorentz factor: Γ ~200 – 700 (model dependent) if cutoff due to gamma-gamma absorption
  - 3 other LAT bright GRBs: Γ_{min}~1000



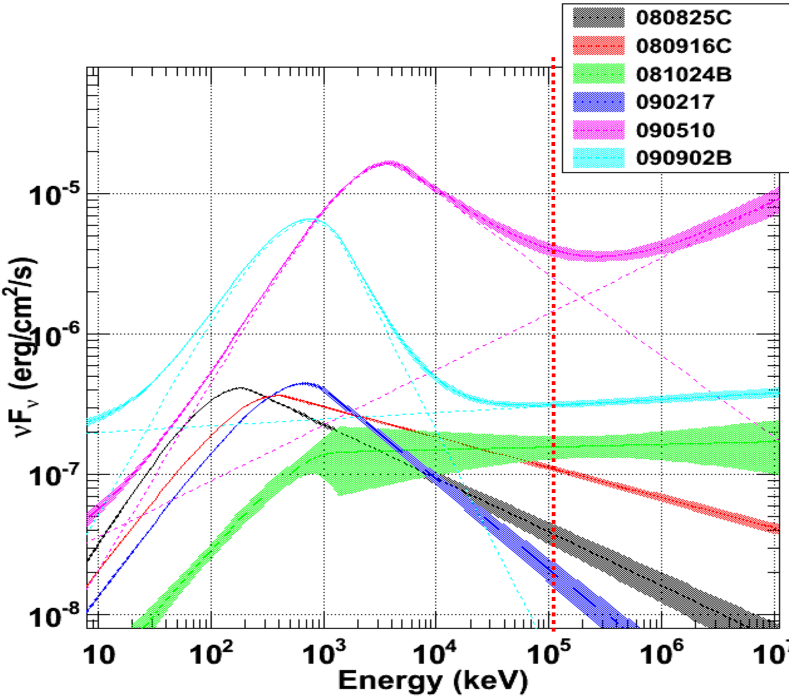
Ackermann et al. 2011, ApJ 729, 114

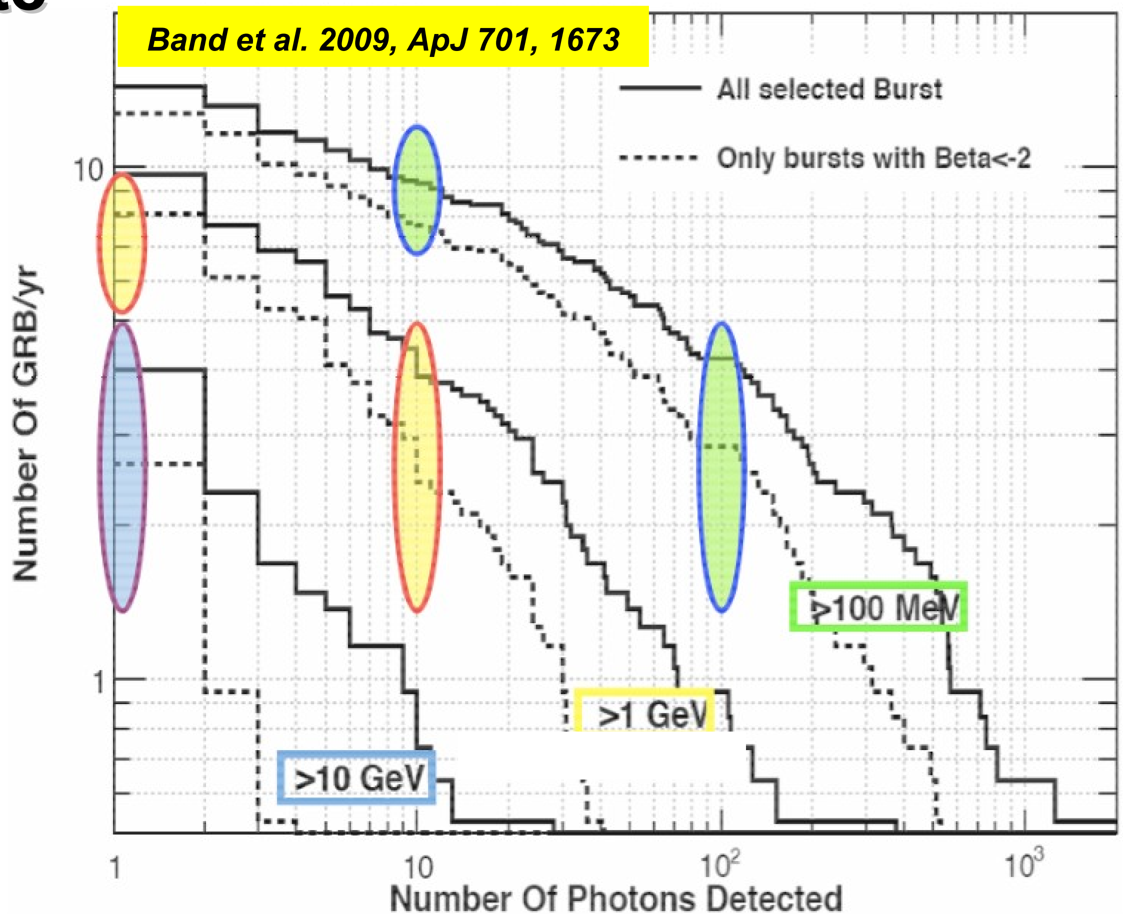


- Delay in HE onset: ~3 s
- Many sub-structures
- Very narrow spike of ~0.1 s at ~10 s from ~10 keV to >100 MeV

Fermi Gamma-ray Space Telescope

LAT burst rate





- ~10 LAT GRBs/yr with >10 photons above 100 MeV (GBM detects ~250 GRBs/yr, 50% outside the LAT FoV)
- ~20%-30% less LAT detections (to be confirmed with more statistics) than pre-launch estimates based on Band spectrum fits to bright BATSE GRBs
  - On average, GRBs don't have much excess (HE extra component), and rather some deficit (cutoff) in the LAT energy range (and ~5-20 times less energy in the LAT for long GRBs than for short GRBs)

Constraints on Lorentz Invariance Violation

- Some QG models violate Lorentz invariance: $v_{ph}(E_{ph}) \neq c$

$$c^2 p_{ph}^2 = E_{ph}^2 \left[1 + \frac{E_{ph}}{M_{QG,1} c^2} + \left(\frac{E_{ph}}{M_{QG,2} c^2} \right)^2 + \ldots \right] \quad , \quad v_{ph} = \frac{\partial E_{ph}}{\partial p_{ph}} c \left[1 - \frac{1+n}{2} \left(\frac{E_{ph}}{M_{QG,n} c^2} \right)^n \right]$$

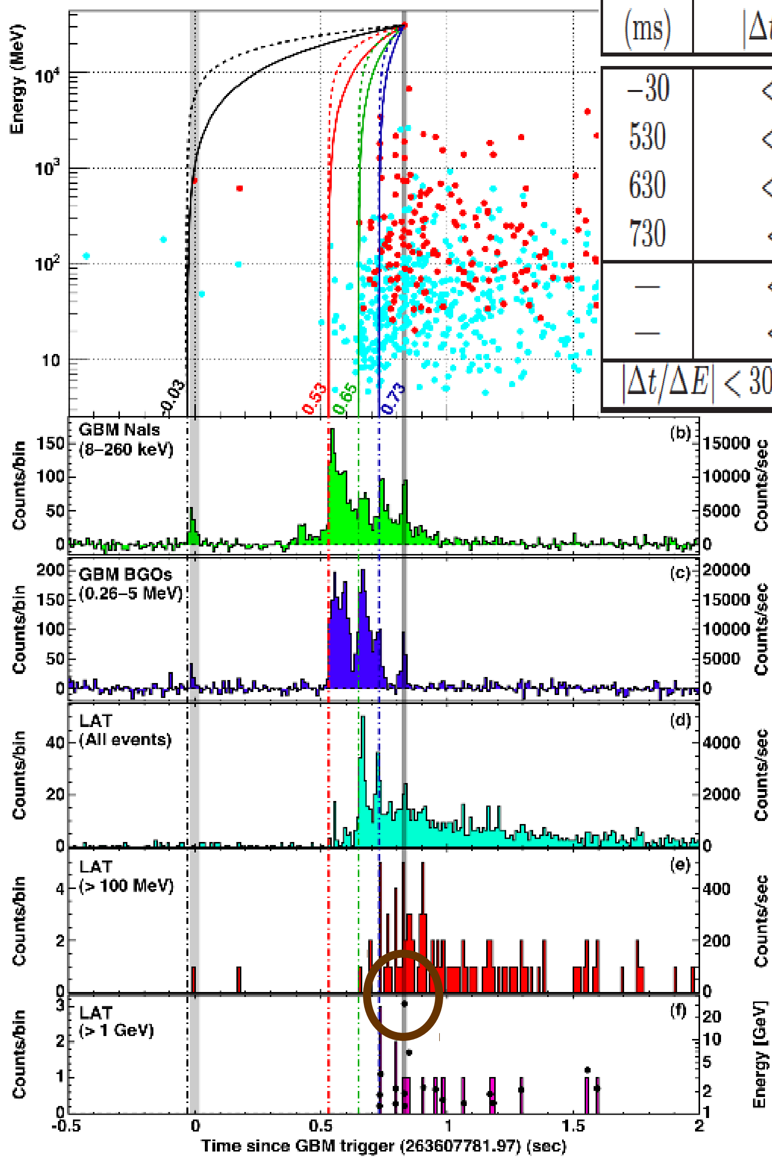
- Since $E_{ph}/c^2 \ll M_{QG,k}$, the lowest order non-zero term, of order n = min{k | $s_k \neq 0$}, dominates (n=1/2 for linear/quadratic LIV – the LAT is essentially sensitive to n=1)
- A high-energy photon Eh would arrive after (in the sub-luminal case: $v_{ph} < c$, $s_n = 1$), or possibly before (in the super-luminal case, $v_{ph} > c$, $s_n = -1$) a low-energy photon El emitted together

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

- GRB 080916C:
  - Highest energy, ≅ 13.2 GeV photon, detected 16.5 sec after GBM trigger
  - Conservative lower limit for n=1, assuming that the high-energy photon was emitted after the GRB trigger: $M_{QG,1} > (1.50 \pm 0.20) \times 10^{18}$ GeV/c^2 ~ 0.1 M_{Planck}

Constraints on Lorentz Invariance Violation

t_{start} (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of t_{start} or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{QG,1}/M_{Planck}$	limit on $M_{QG,2}$ in 10^{10} GeV/c^2
-30	< 859	start of any observed emission	0.1	1	> 1.19	> 2.99
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42	> 5.06
630	< 199	start of > 100 MeV emission	100	1	> 5.12	> 6.20
730	< 99	start of > 1 GeV emission	1000	1	> 10.0	> 8.79
—	< 10	association with < 1 MeV spike	0.1	± 1	> 102	> 27.7
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	-1	> 1.33	> 0.54
$\lvert\Delta t/\Delta E\rvert < 30$ ms/GeV		lag analysis of all LAT events	—	± 1	> 1.22	—

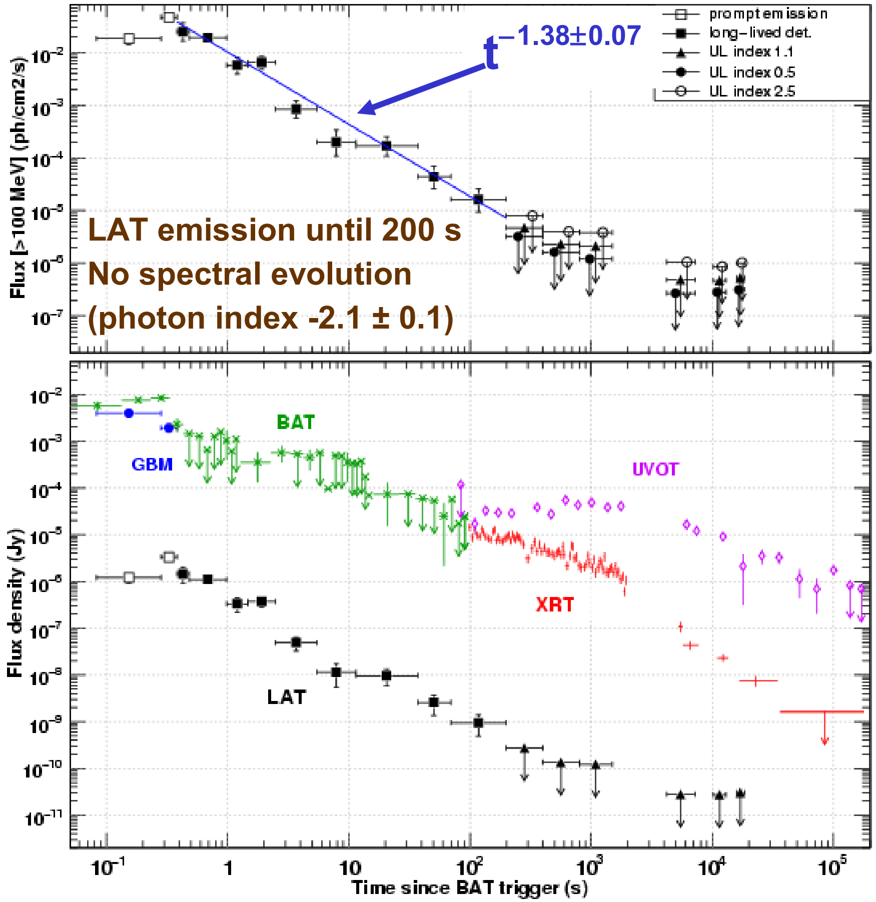


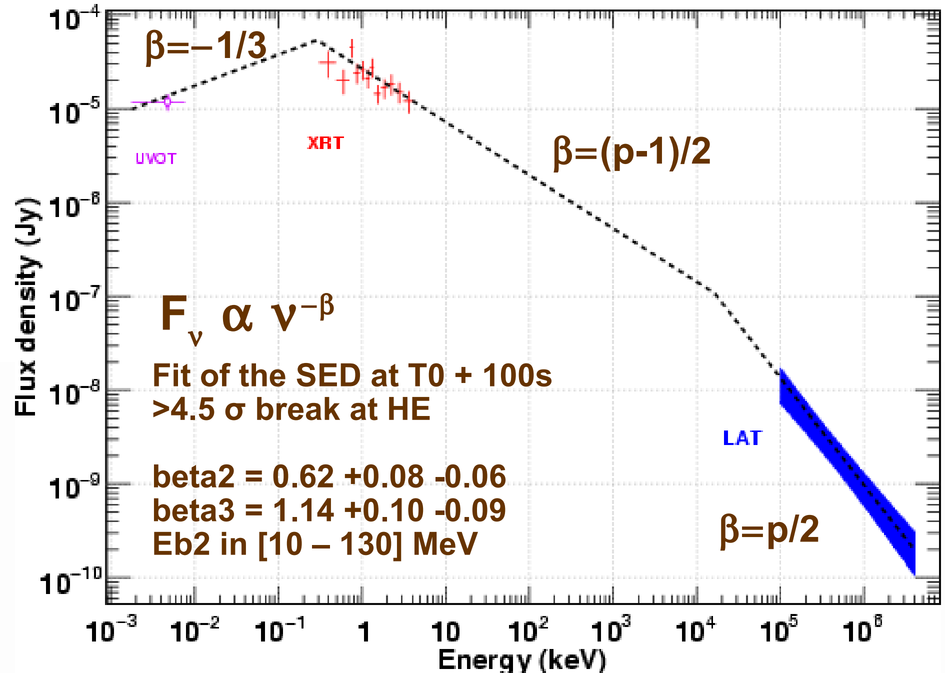
Abdo et al. 2009, Nature 462, 331

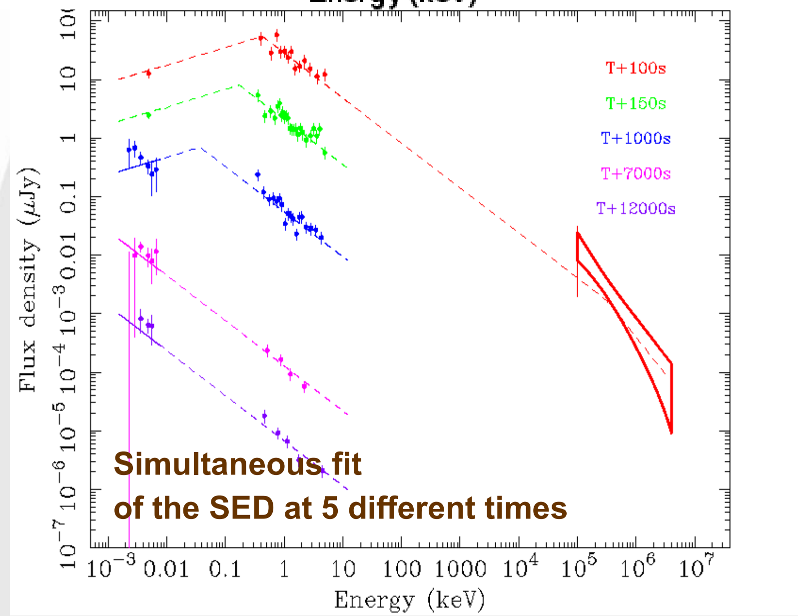
- **GRB 090510:**
  - **a-e based on 31 GeV photon**
  - **a-d assume that tem >= tstart (emission onset time)**
  - **e,f: association with a specific low-energy spike**
  - **g: sharpness of HE spikes**
  - **All of our lower limits $M_{QG,1}$ > M_{Planck}**
  - **Our results disfavor QG models with linear LIV**

Swift and *Fermi* view of GRB 090510

De Pasquale et al. 2010, ApJL 709, 146







- **Forward shock model can reproduce the spectrum from the optical up to GeV energies! (non thermal synchrotron emission from the decelerating blast wave)**
- **Extensions needed to arrange the temporal properties**

GRB-related activities at LUPM

- **Before launch**
  - **1 PhD thesis [SG], 1 CNRS postdoc [NK]**
  - **Joint GBM/LAT analyses**
    - **Application of Science Tools to all simulated data sets (Data and Service Challenges), validation of analysis methods [NK, VP, FP]**
    - **First developments of a s/w platform (gtgrb) for interactive or scripted analysis by Burst Advocates (BA) [JCT, VP, FP] – most GRB analyses (automated or not) make now use of it**
  - **Operations Simulations: contribution to BA shifts and end-to-end tests of alert / analysis chain**

- **Since launch (June 2008)**
  - **1 PhD thesis [VP], 1 CNRS postdoc [VV]**
  - **Fermi GRB Science Working Group Coordination: FP from 08/2008 to 03/2010 (first Fermi GRB communication, on GRB 080916C, at the GRB Conference in HSV, Oct 2008), VV since 03/2011**
  - **BA shifts and joint GBM/LAT/Swift analyses [VP, VV, FP]**
  - **Software developments**
    - **New spectral analysis technique using the LAT Low-Energy events (fill the gap between GBM/BGO and LAT) [VP, FP] – LLE data release end of 2011!**
    - **Background Estimator (BKGE) [VV] – background estimates for temporal / spectral analyses**
    - **New functionalities in gtgrb [VV, FP] – BKGE, localization, LAT durations (BKGE, LLE)**
  - **Future projects (after completing on-going publications): GRB variability characterization in the LAT, comprehensive LIV paper including all LAT bright GRBs**

- **Organisation de 2 ateliers GRBs (financement PPF AMT et GdR PCHE) en 2008 (LUPM) et 2010 (CESR)**

GRB-related publications at LUPM

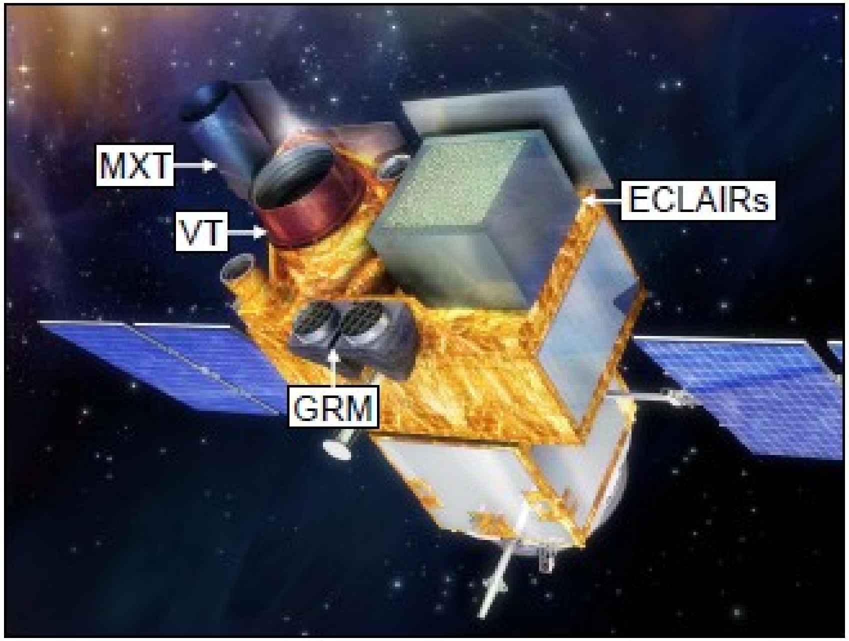
- Contribution to many papers (and conferences...)
  - including Band et al. 2009, "Prospects for GRB Science with the Fermi Large Area Telescope", ApJ 701, 1673 (2009) [NK, VP, FP]

- Among Contact Authors for:
  - "A limit on the variation of the speed of light arising from quantum gravity effects", Nature 462, 331 (2009) [VP]
  - "Swift and Fermi Observations of the Early Afterglow of the Short Gamma-Ray Burst 090510", ApJL 709, 146 (2010) [VP]
  - "Fermi observations of high-energy gamma-ray emission from GRB 090217", ApJL 717, 127 (2010) [FP]
  - "Detection of high-energy gamma-ray emission during the X-ray Flaring Activity of GRB 100728A", ApJL accepted [VV]

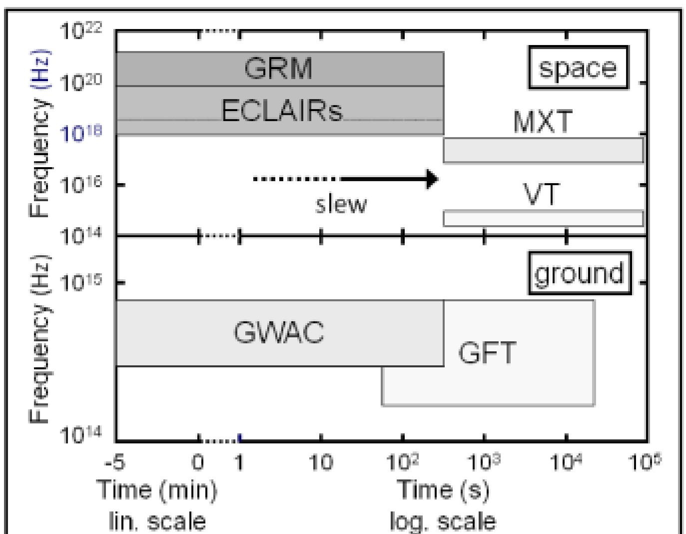
- Among Lead Authors for (in-prep papers):
  - "Discovery of temporally extended high-energy gamma-ray emission from GRB090323 and GRB090328" [FP] – afterglow detection with the LAT up to 8.4 ks, benefits from ARRs
  - "Clues to the origin of X-ray flares with Swift and Fermi" [VV]
  - "First LAT GRB Catalog" [FP, VV] – temporal / spectral properties of >30 LAT bursts (3 years)
  - "LLE Validation Paper" [VP, FP]
  - "Swift observations of GRB091127" [VV]

- "The Fermi view of gamma-ray bursts", special issue of Comptes Rendus Physique (Académie des Sciences) "GRB studies in the SVOM era", April 2011 [FP]

Interests for the future



GRB phenomenon	• Diversity and unity of GRBs
GRB physics	• Acceleration and nature of the relativistic jet • Radiation processes • The early afterglow and the reverse shock
GRB progenitors	• The GRB-supernova connection • Short GRB progenitors
Cosmology	• Cosmological lighthouses (absorption systems) • Host galaxies • Tracing star formation • Re-ionization of the universe • Cosmological parameters
Fundamental physics	• Origin of high-energy cosmic rays • Probing Lorentz invariance • Short GRBs and gravitational waves



- **SVOM (end of 2017?)**
  - **ECLAIRs, 2 sr coded-mask, 4-250 keV – ~80 alerts / yr with fast localization (~12' in <1min to ground)**
  - **GRM, 2 sr non-imaging spectro-photometer, 30-5000 keV**
  - **Narrow FoV telescopes (VT visible, MXT 0.3-6 keV) – GRB afterglows**
  - **GWAC, array of cameras to monitor ECLAIRs FoV in the visible**
  - **GFTs, two robotic telescopes, NIR and visible – GRB afterglows**
  - **Non-GRB Science Program (~80%) includes: AGNs and surveys, solar system / Earth space environment, galactic stars (e.g. active stars), SNe detections, ISM and diffuse matter / emission, high-energy phenomena (SGRs, AXPs, accreting X-ray binaries)**
- **New "MeV" gamma-ray telescopes: Cf Matthieu**