Observation de sursauts gamma avec le satellite *Fermi*

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Séminaire IPHC (Strasbourg, 8 février 2013)

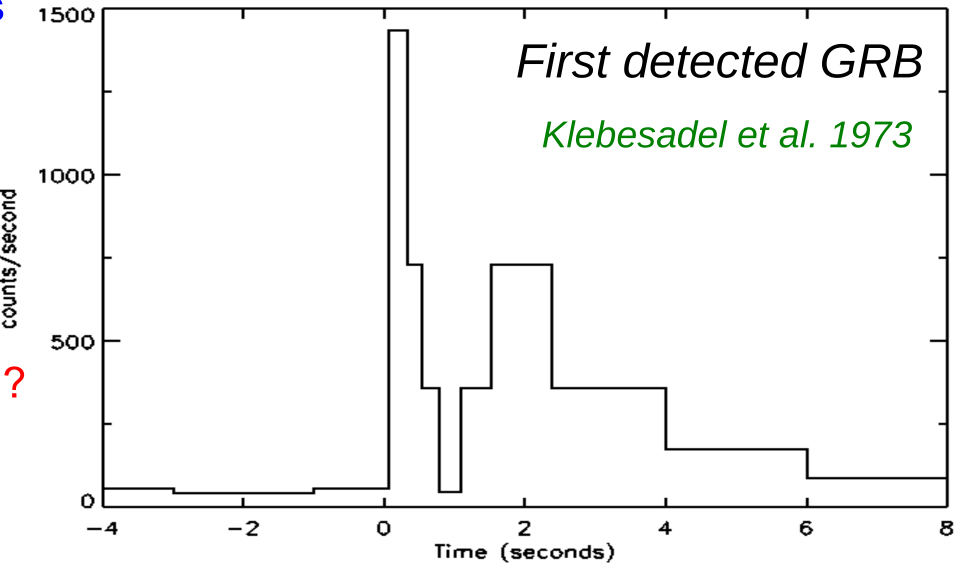
Plan de l'exposé

- Bref historique des observations de GRBs (Gamma-Ray Bursts)
- La mission *Fermi* et ses instruments
- Etude des GRBs à l'ère de *Fermi*

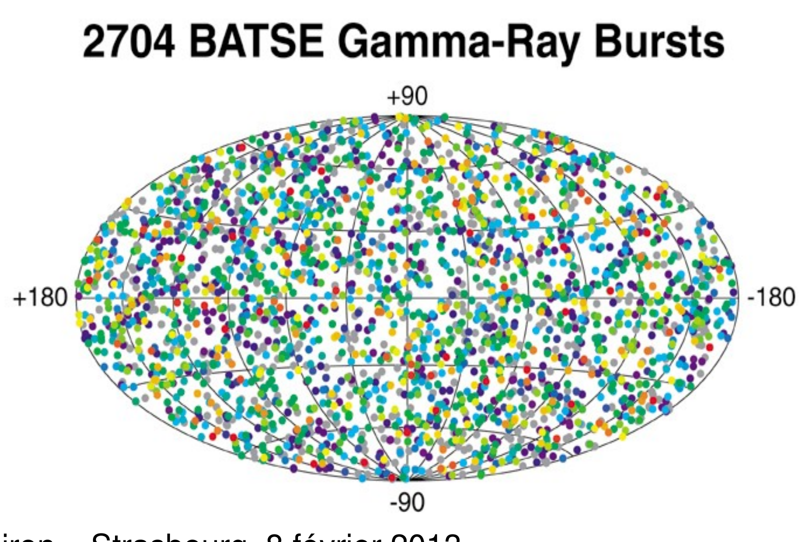
Un peu d'histoire...

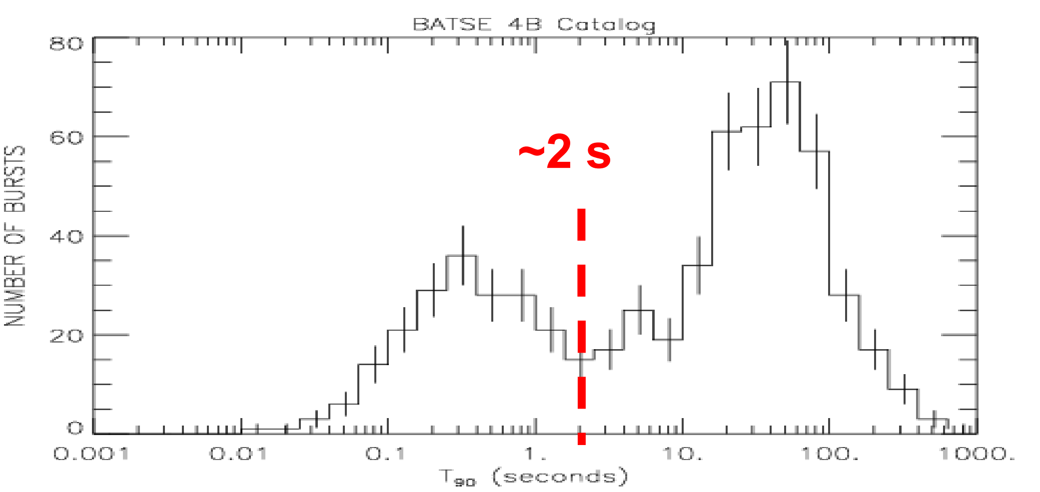
Rappels historiques (1/4)

- 1967 : découverte accidentelle des sursauts (émission prompte) par les satellites militaires Vela (annonce en 1973)
  - Beaucoup de théories dans les premières années
  - Origine Galactique (étoiles à neutrons) ?



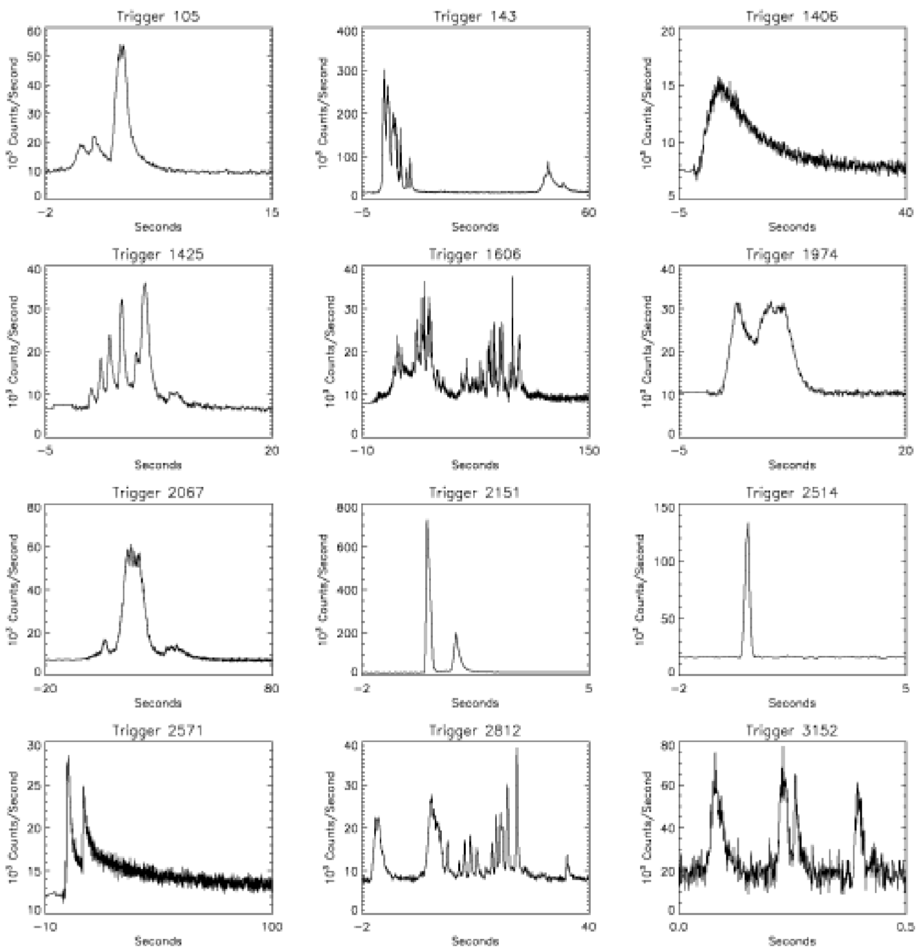
- 1991 - 2000 : observatoire Compton (CGRO)
  - BATSE (~30 keV – 2 MeV, ciel non occulté)
    - Un sursaut par jour
    - Isotropie dans le ciel : origine cosmologique ?
    - Sursauts courts (<2 s) ou longs (plus mous)
  - EGRET (~30 MeV – 30 GeV, FoV ~ 0.6 sr)

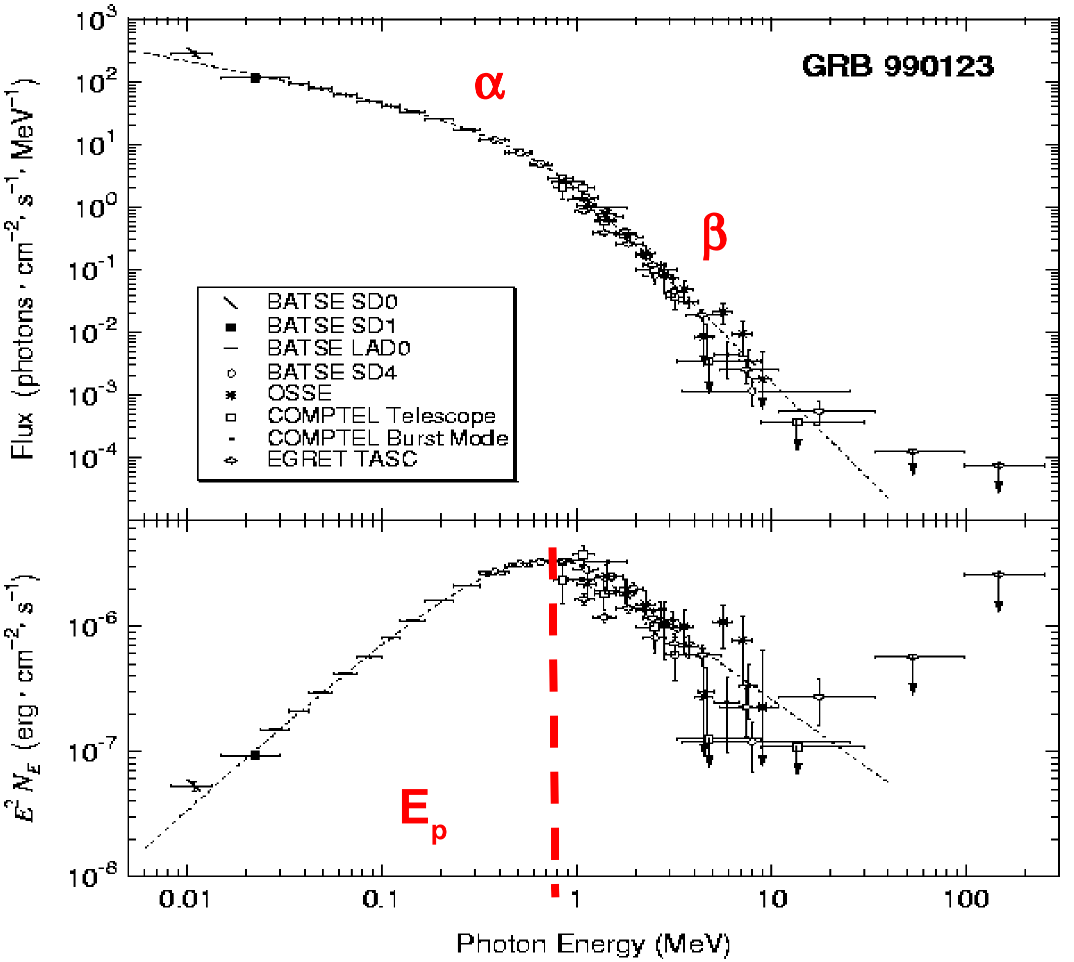




Rappels historiques (2/4)

- Une grande variété de courbes de lumière
- En général, spectre de Band non thermique (2 lois de puissance)
  - Indices spectraux $\alpha \sim -1.0$, $\beta \sim -2.5$, énergie au pic $E_p \sim$ quelques 100 keV

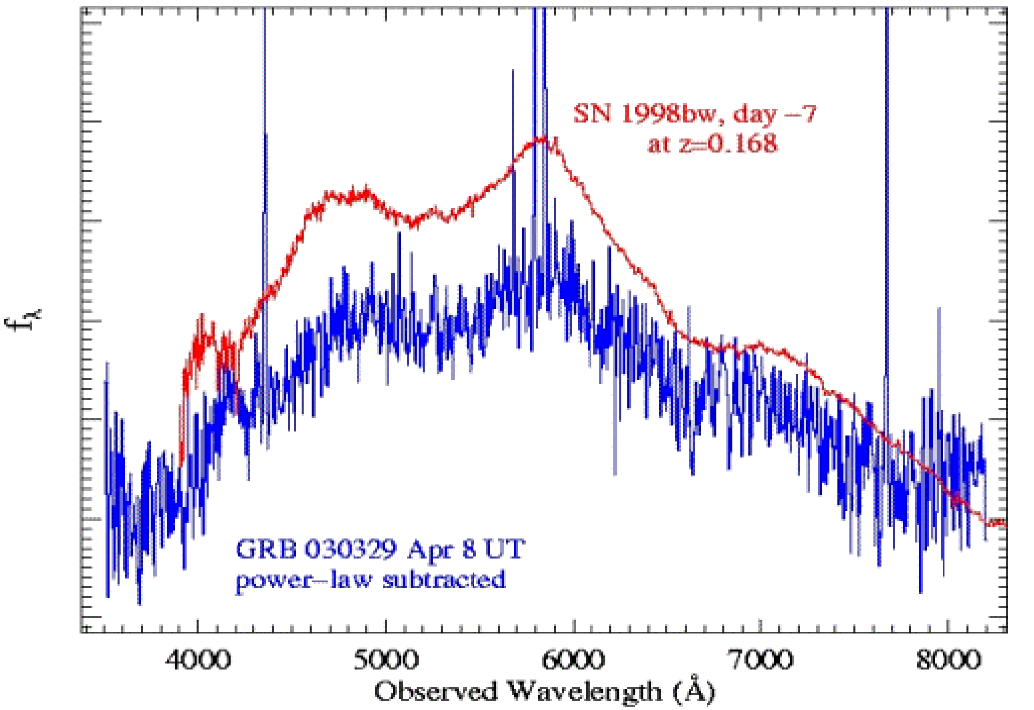




Rappels historiques (3/4)

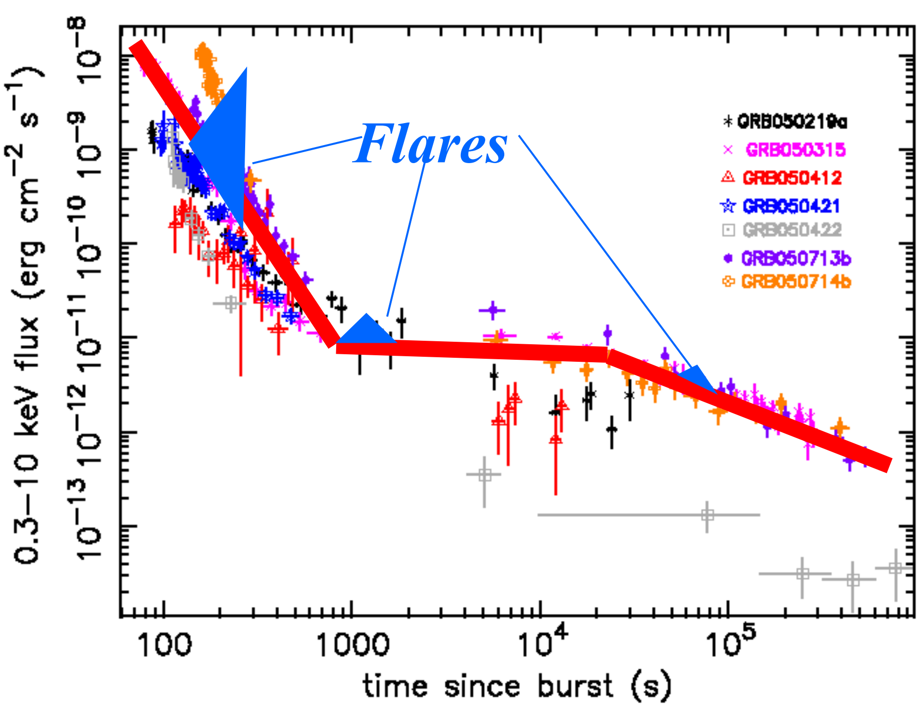
- 1996 - 2002 : Beppo-SAX et suivi au sol des sursauts longs
  - Découverte d'une émission rémanente (afterglow) en X, optique, radio
    - Premières mesures de distances (GRB 970228 à z~0.7 et GRB 971214 à z~3.4)
    - Les GRBs sont des objets distants et très énergétiques : $E_{\gamma,iso} \sim 10^{52}$ - 10^{54} erg ($M_{sun}c^2 \sim 2\ 10^{54}$ erg)
      → sources compactes accrétantes et émission collimatée
  - Premières contraintes sur le jet ($E_\gamma \sim 10^{51}$ erg), taux d'occurence, densité du milieu extérieur, connexion avec les supernovae (association de GRB 980425 avec SN1998bw), progéniteurs supposés des sursauts longs

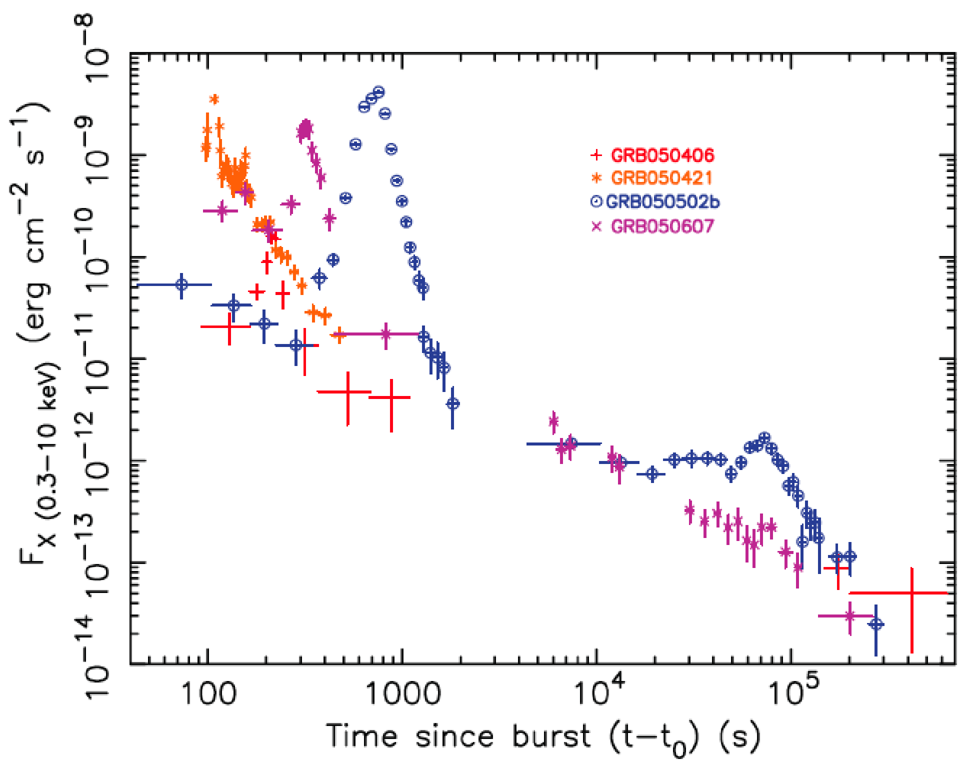
- 2003 - 2006 : HETE-2
  - Confirmation de la connexion sursauts longs / supernovae (GRB 030329)



Rappels historiques (4/4)

- 2004 - ? : Swift
  - Tous les instruments réunis à bord pour étudier la connexion entre phases prompte et rémanente et pour la mesure de grands z
    - BAT (Burst Alert Telescope) : moniteur gamma (15 – 150 keV) grand champ (2 sr) pour la détection (localisation à quelques arcmin)
    - XRT : caméra CCD petit champ (~20') pour la localisation précise (~5") et l'observation de l'afterglow en rayons X (0.2-10 keV) ; repointage en ~1-2 min
    - UVOT : télescope UV/optique pour la photométrie et la spectroscopie (<1")
  - Découverte de propriétés étonnantes de l'émission rémanente (plateau faiblement décroissant, X-ray flares dans ~50% des cas), notamment des sursauts courts
    - distances, galaxies hôtes, taux d'occurence, information sur le progéniteur

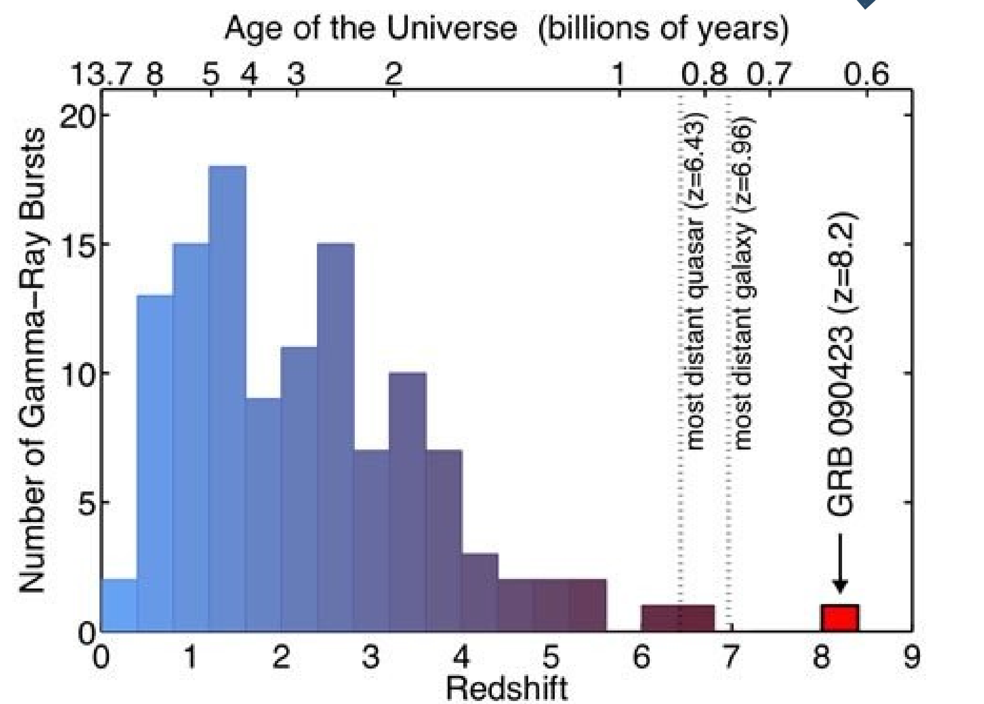




Pourquoi un mouvement relativiste ?

- Des sources très énergétiques car à distance cosmologique...
  - GRB 090423 à z=8.2 : univers âgé de 630 Myr
  - GRB 090429B à z=9.4 : univers âgé de 520 Myr

  … et très variables

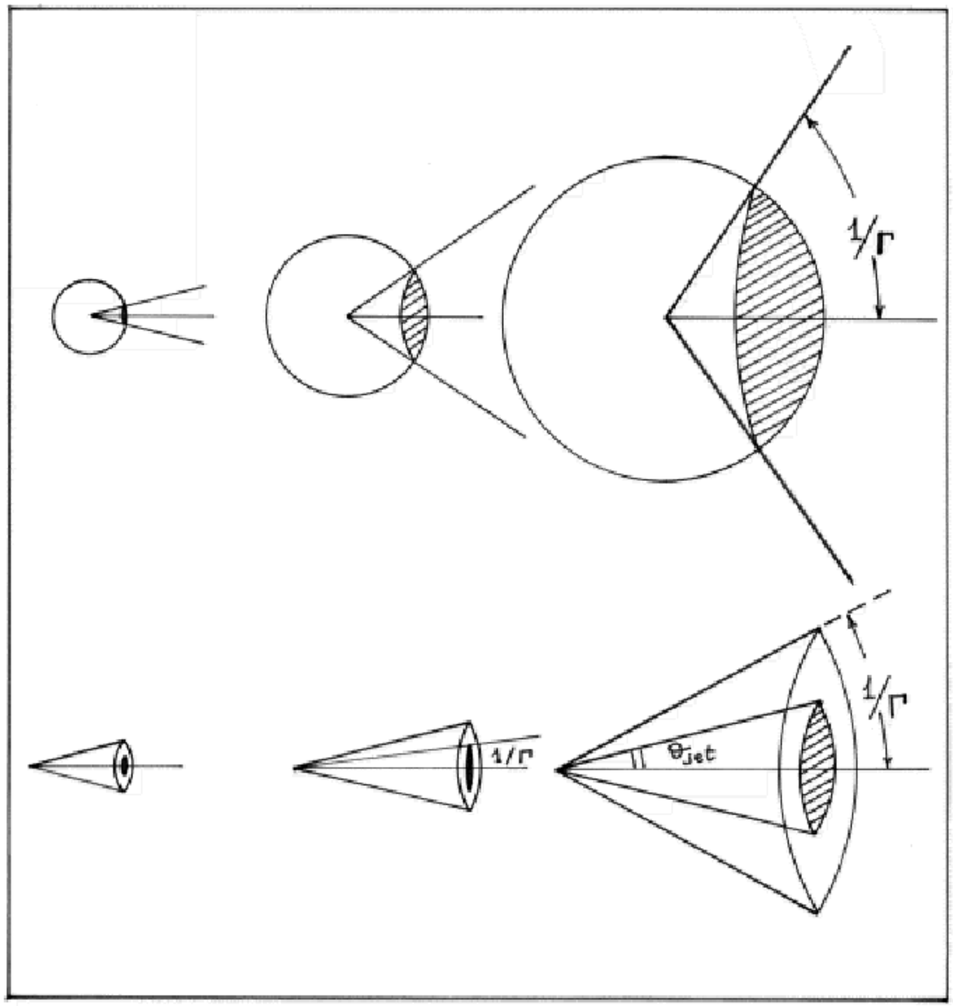


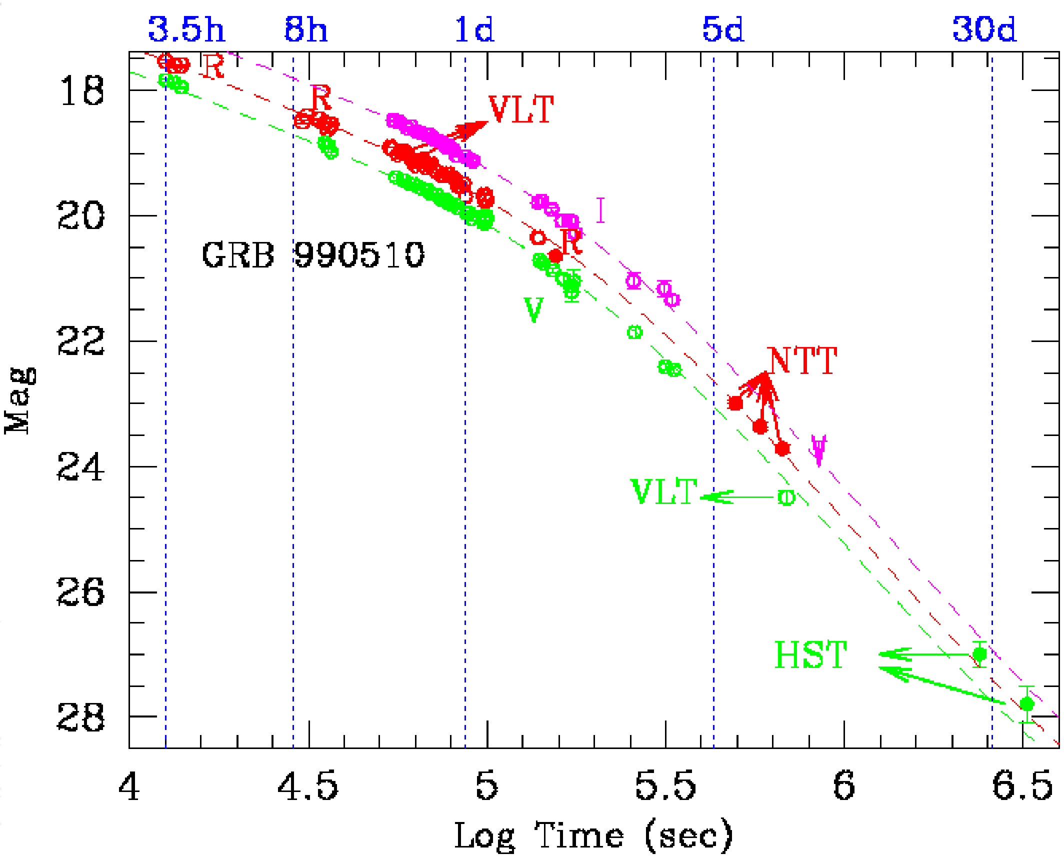
Credit: Edo Berger (Harvard/CfA)

- 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 : $\tau_{\gamma\gamma}(\varepsilon) \sim \sigma_T n_{ph}(1/\varepsilon) R = \sigma_T L_{1/\varepsilon}/(4\pi m_e c^3 R) > 10^{14} L_{1/\varepsilon,51} (\Delta t / 1\text{ ms})^{-1}$
    - → 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)

Pourquoi un jet ?

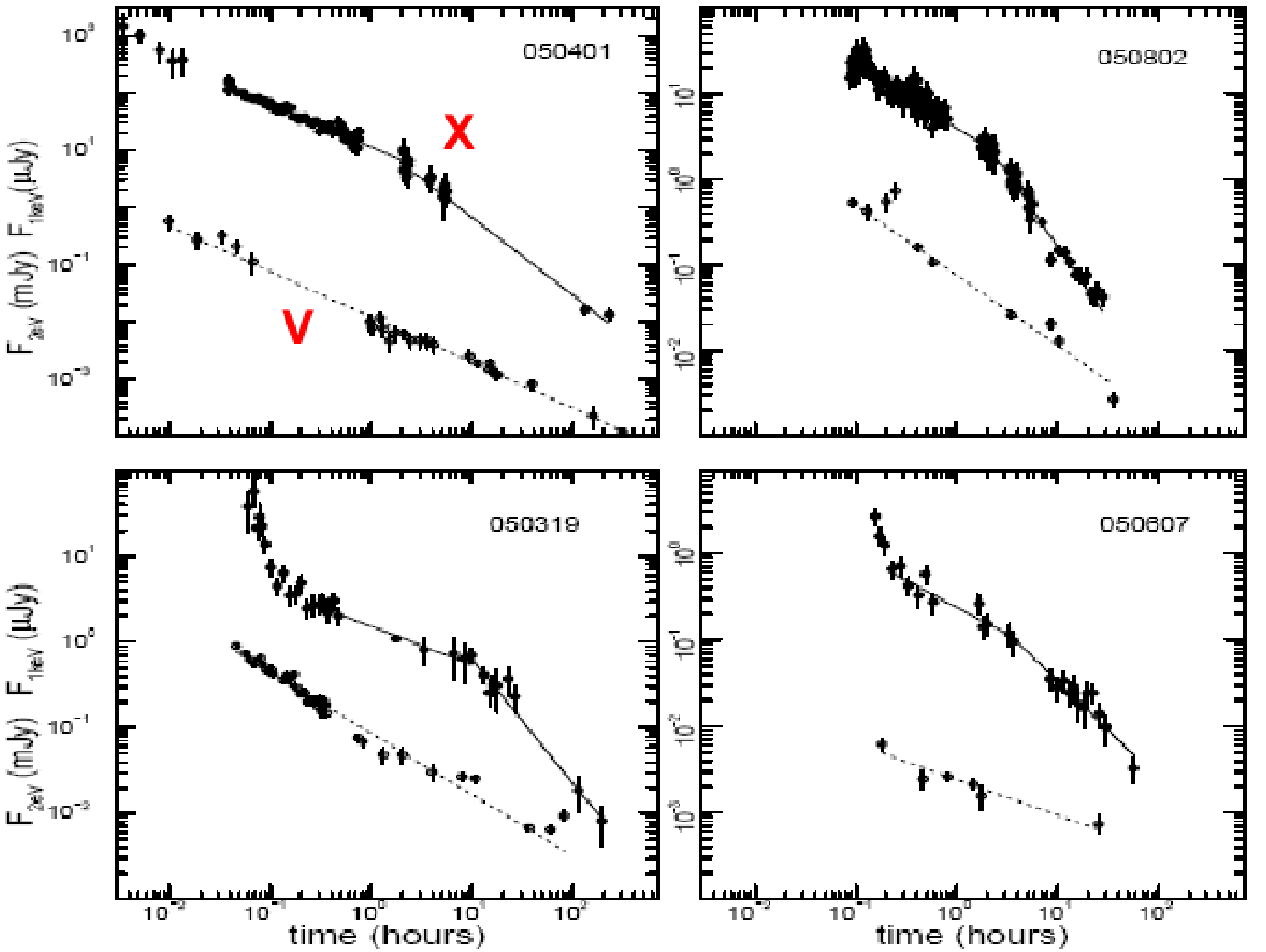
- Les courbes de lumière présentent des cassures chromatiques dans le visible
  - Pour un mouvement relativiste, l'angle d'ouverture de la région émittrice ($\sim 1/\Gamma$) augmente et sature à θ_{jet} contrairement au cas sphérique





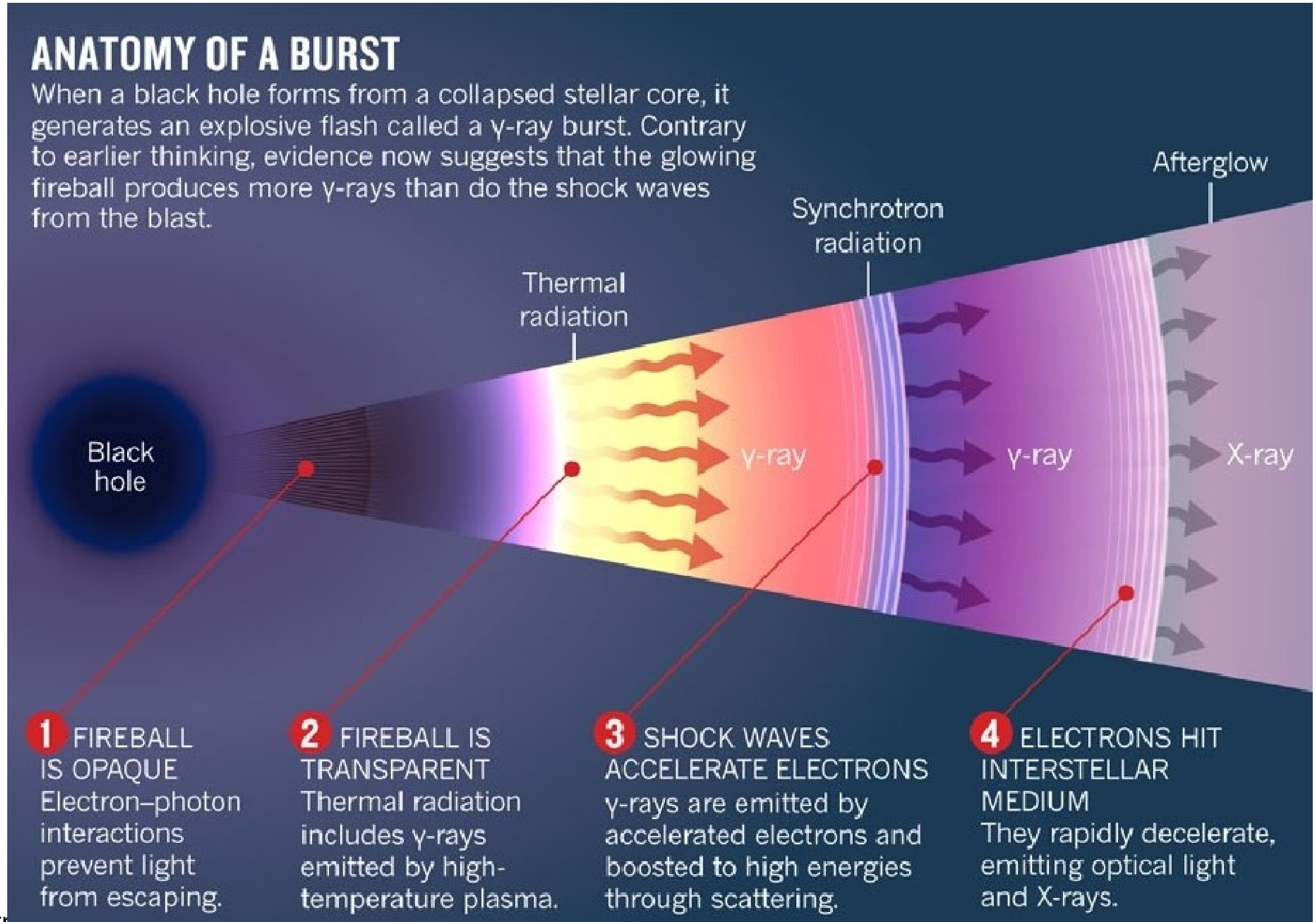
Cassures chromatiques

- Courbes de lumière en rayons X (Swift) vs. dans le visible
  - Les cassures achromatiques sont rares
  - Modèles plus élaborés requis (microphysique variable dans le choc avant, effet du choc en retour)



"Boule de feu" et chocs internes / externes

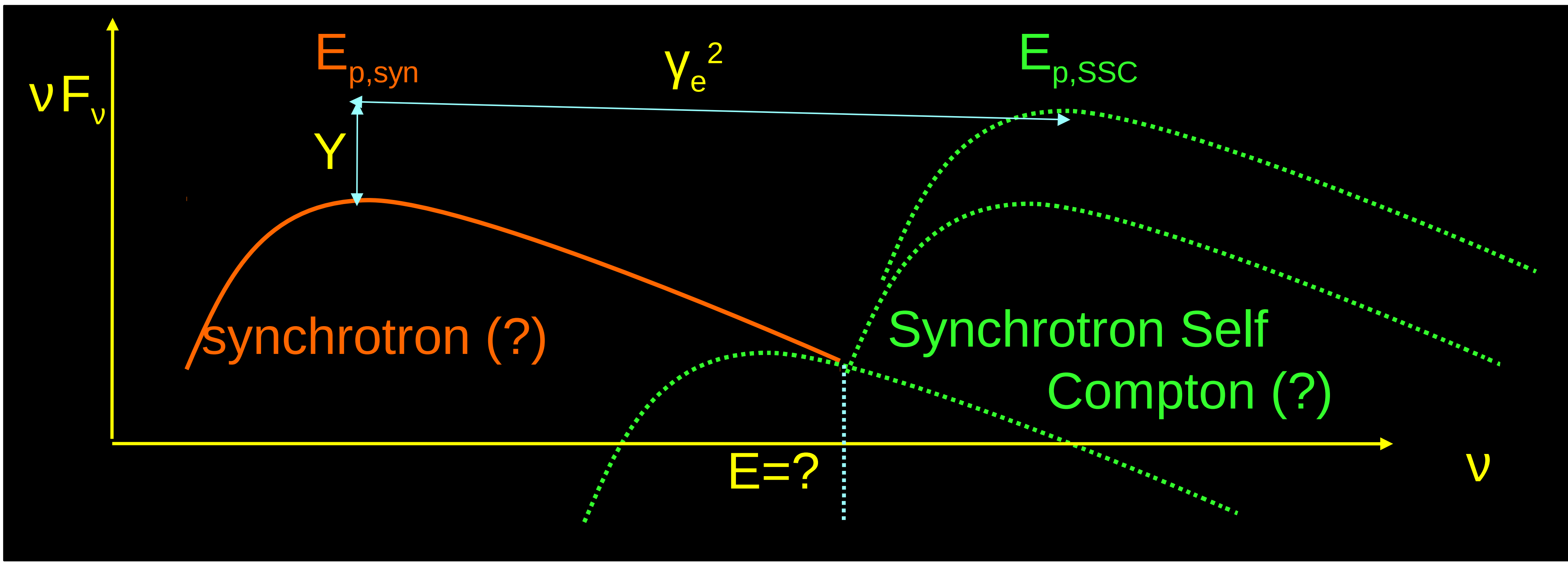
- Jet accéléré jusqu'à $\Gamma > 100$, opaque (émission photosphérique attendue à $R \sim 10^{11\text{-}12}$ cm)
- Chocs internes entre surdensités dans les éjectas à $R \sim 10^{14\text{-}15}$ cm (émission prompte)
- Jet freiné par le milieu interstellaire et chocs externes à $R \sim 10^{16\text{-}17}$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



Mécanismes d'émission à haute énergie

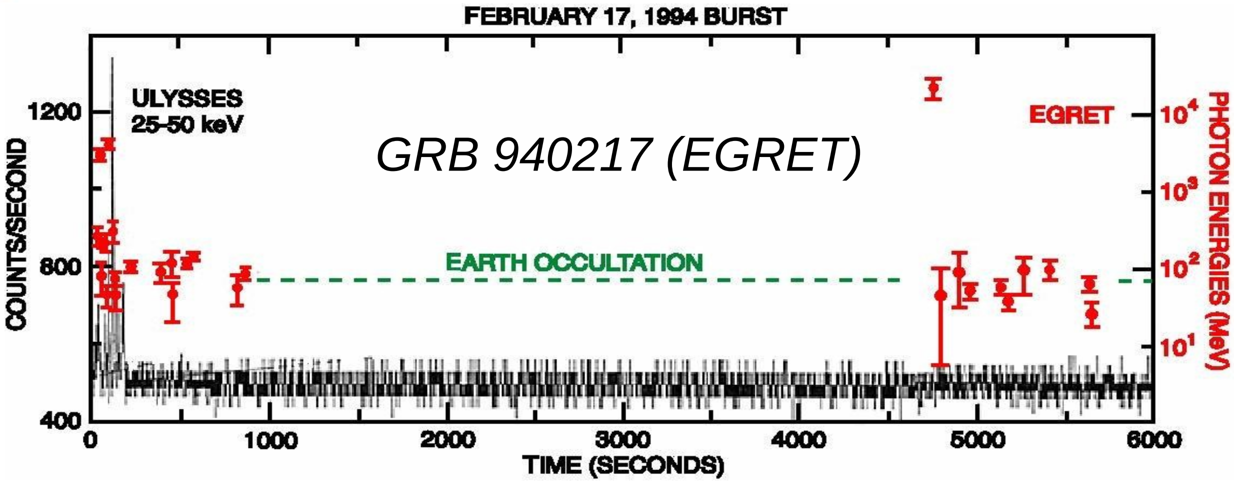
- Effet Compton inverse ou Synchrotron Self Compton (SSC)

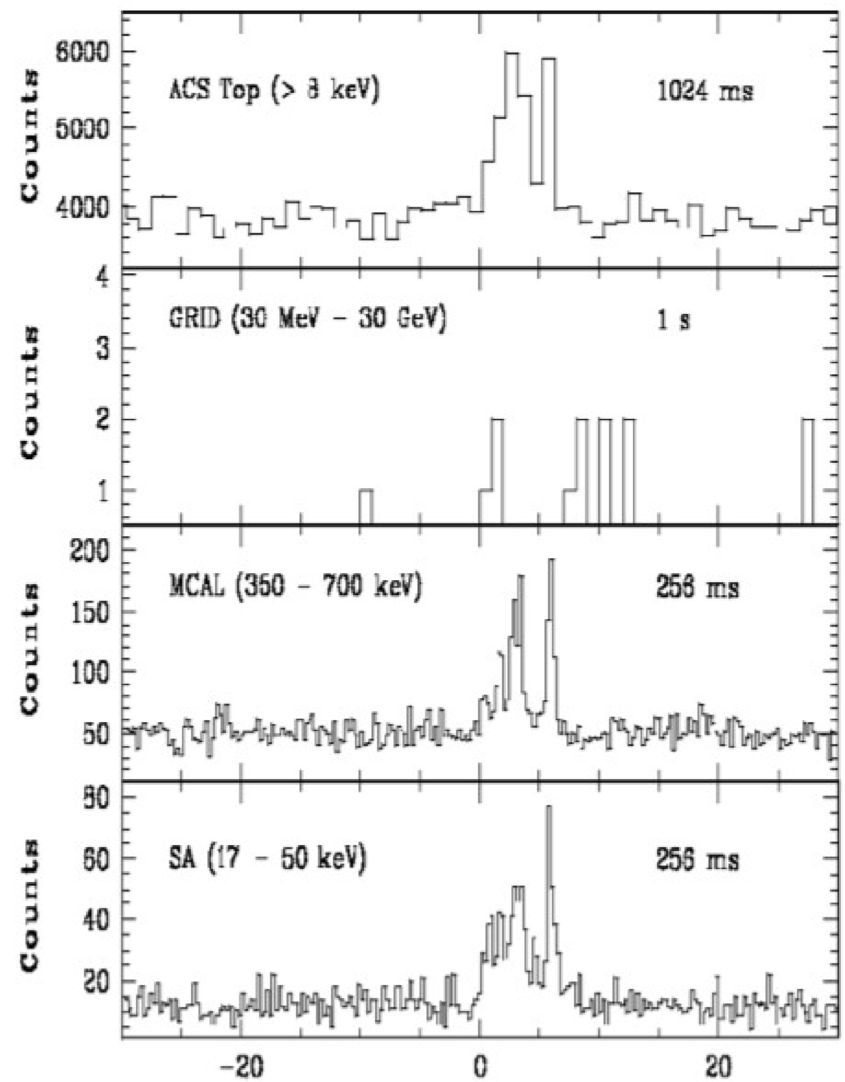
  $E_{p,SSC} / E_{p,syn} \sim \gamma_e^2$, $L_{SSC} / L_{syn} = Y$, $Y(1+Y) \sim \varepsilon_{rad}\varepsilon_e / \varepsilon_B$



- Processus hadroniques (voire accélération de rayons cosmiques d'ultra-haute énergie?) : 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

Les sursauts à haute énergie avant *Fermi* (1/2)

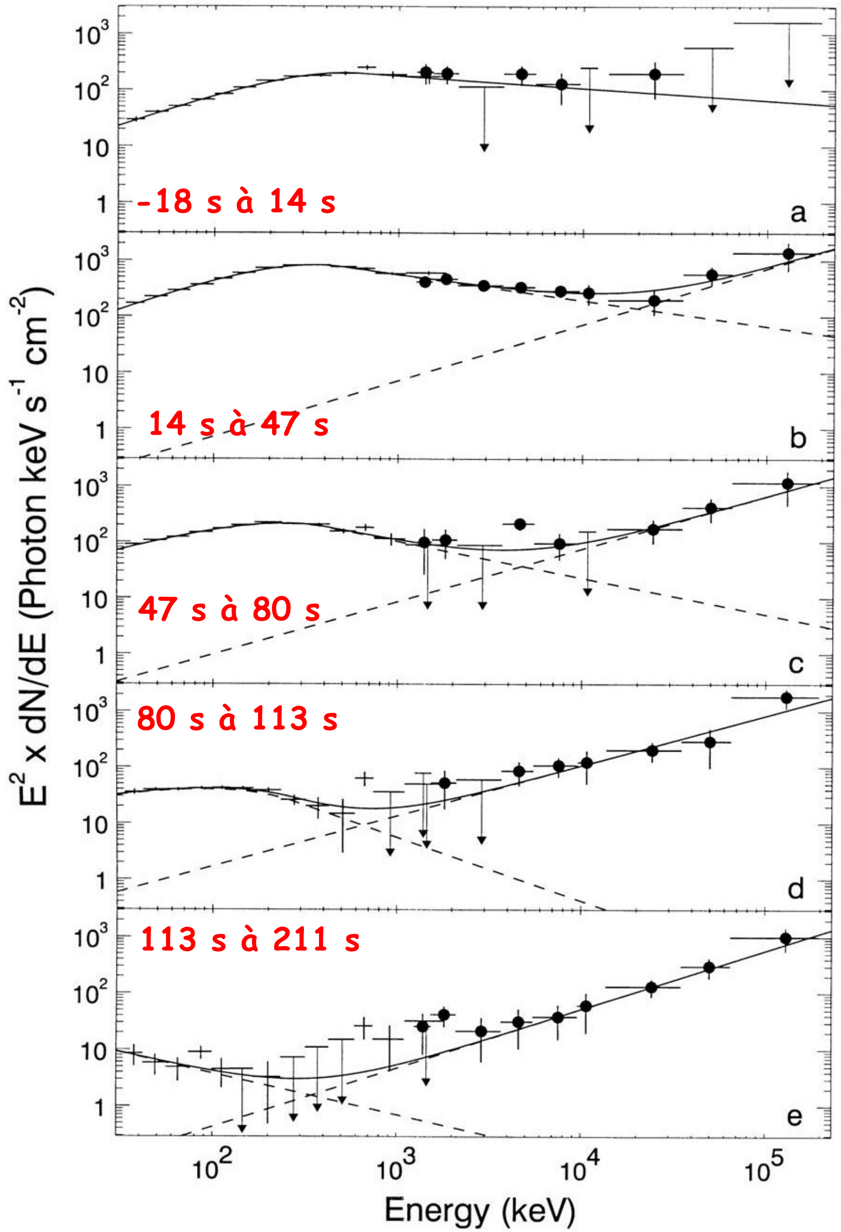




- Très peu d'observations >100 MeV (EGRET, AGILE)
- GRB 940217
  - Emission prompte simultanée >100 MeV, pas de coupure spectrale
  - Emission retardée de photons >GeV jusqu'à 90 min après le trigger (BATSE) ; origine peu claire :
    - Emission SSC rémanente ?
    - Processus hadroniques ?
    - Activité tardive ?
    - Interaction avec le fond diffus IR ?
- GRB 080514B
  - Observation par AGILE de quelques photons >100 MeV avec une durée un peu plus grande qu'à basse énergie

Les sursauts à haute énergie avant *Fermi* (2/2)

GRB 941017 (EGRET)



- GRB 941017
  - Composante spectrale additionnelle distincte du ~MeV jusqu'à 200 MeV
  - Evolution temporelle différente : stable, dure (~200 s) plus longtemps que la composante <MeV
  - Contient ~3 fois plus d'énergie
  - Incompatible avec modèle SSC simple
  - Production de rayons cosmiques d'ultra-haute énergie et cascades hadroniques ?
  - Plus probable : émission Compton inverse du système de chocs en avant / en retour

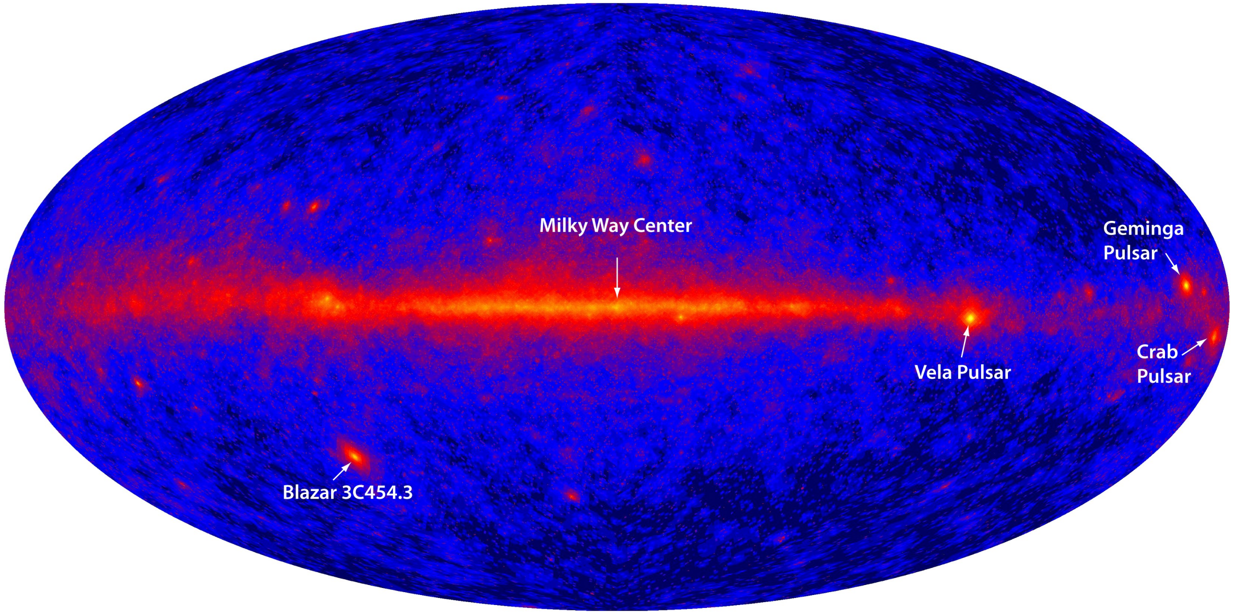
- Questions ouvertes
  - A quelle énergie s'arrête la composante additionnelle ?
  - Y a-t-il une coupure spectrale ?
  - Chocs internes ou externes ?
  - Quelle est la part des hadrons ?
  - Evolution spectrale fine ?
  - Est-ce une propriété commune aux sursauts ?

La mission *Fermi* et ses instruments

The observatory (prior to fairing installation)

Launch and first light

- Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT
- Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination
- Launch & Early Operations (2 months up to 11 August 2008)
- First light on 4 days of engineering data



Enrico Fermi

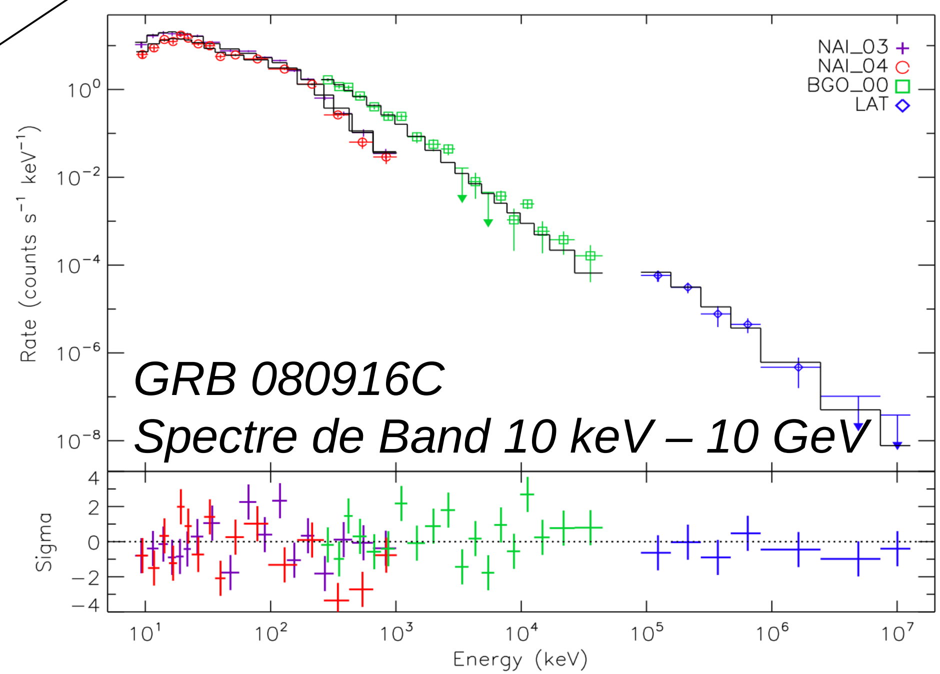
GLAST renamed *Fermi* by NASA on August 26, 2008

http://fermi.gsfc.nasa.gov/

"Enrico Fermi (1901-1954) was an Italian physicist who immigrated to the United States. He was the first to suggest a viable mechanism for astrophysical particle acceleration. This work is the foundation for our understanding of many types of sources to be studied by NASA's Fermi Gamma-ray Space Telescope, formerly known as GLAST."

Les instruments à bord de *Fermi*

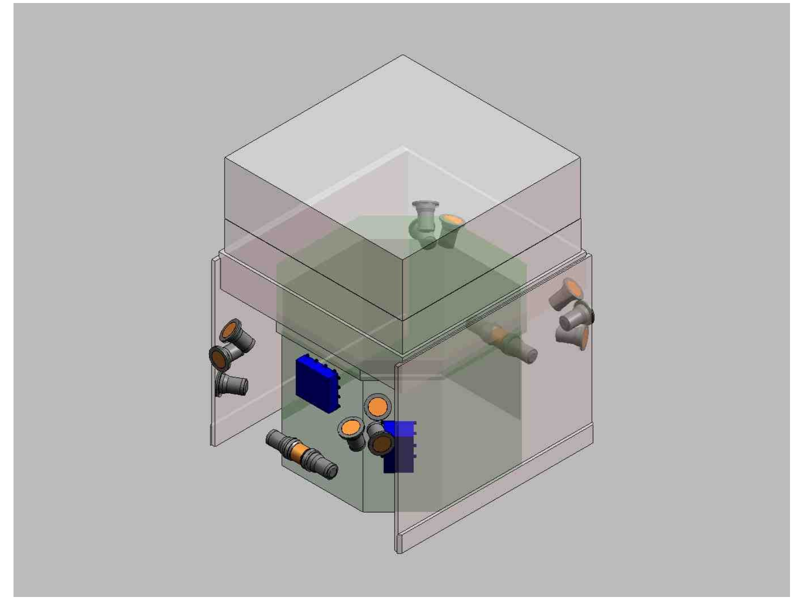
- Large Area Telescope (LAT)
  - 20% du ciel à tout instant (100% couvert toutes les 3h)
  - 20 MeV à >300 GeV
  - Triggers GRB à bord et au sol
  - Localisation, spectroscopie
- Gamma-ray Burst Monitor (GBM)
  - Tout le ciel non occulté à tout instant
  - 12 détecteurs au NaI (8 keV à 1 MeV)
    - Trigger 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

GBM Collaboration

PI: William Paciesas
Co-PI: Jochen Greiner



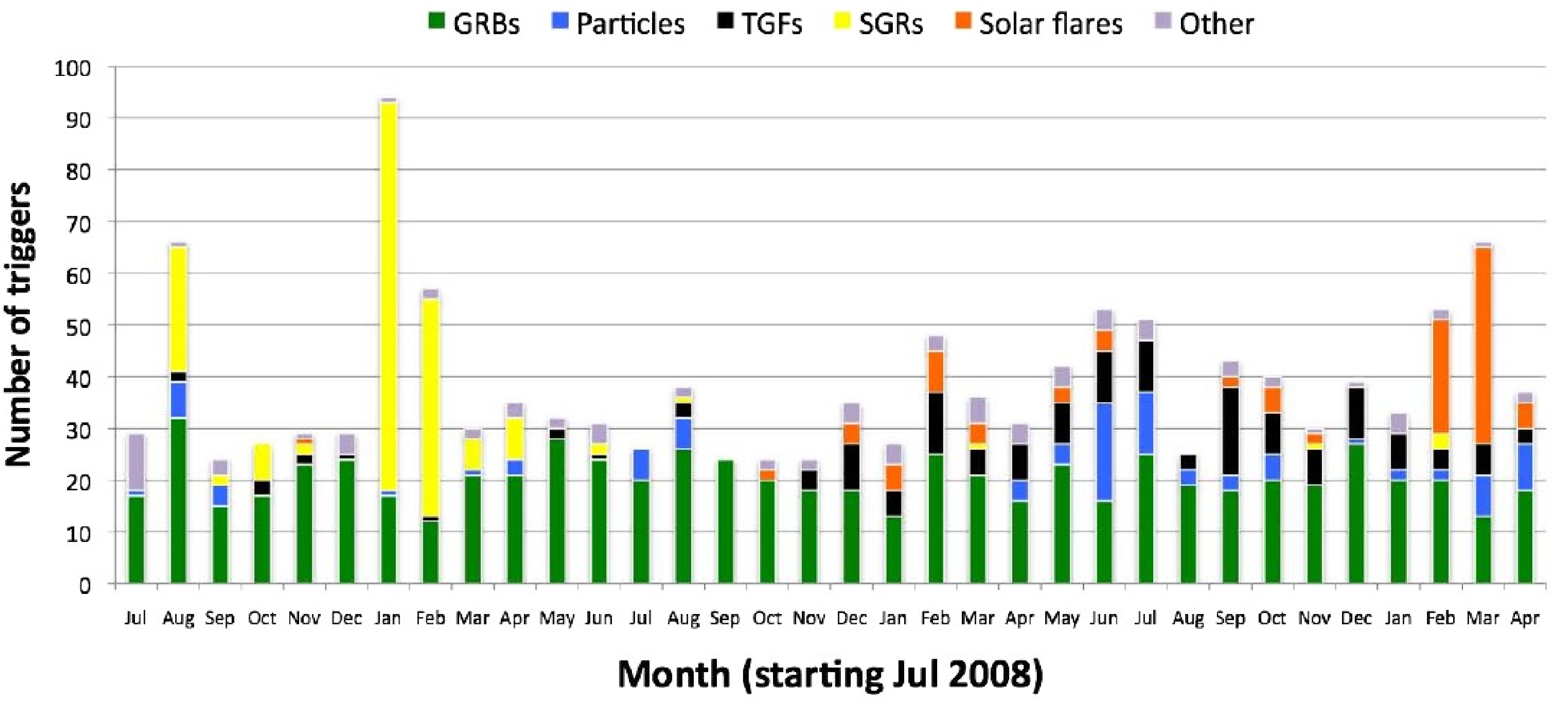
National Space Science & Technology Center

University of Alabama in Huntsville

NASA Marshall Space Flight Center

Max-Planck-Institut für extraterrestrische Physik

GBM monthly triggers



LAT Collaboration

- France
  - CNRS/IN2P3 (LLR, CENBG, LUPM)
  - CEA/Saclay (Irfu)
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

PI: Peter Michelson
(Stanford)

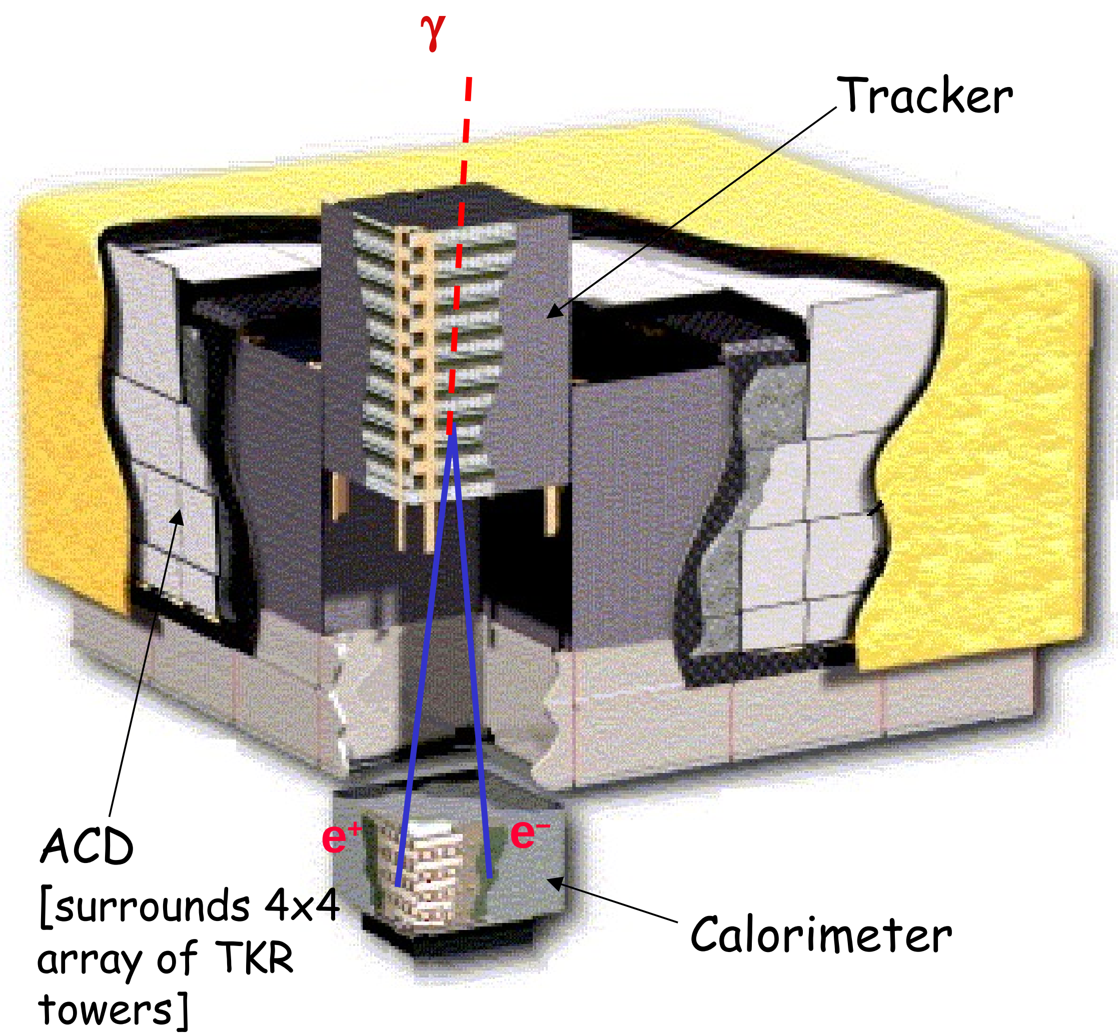
~390 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Managed at SLAC.

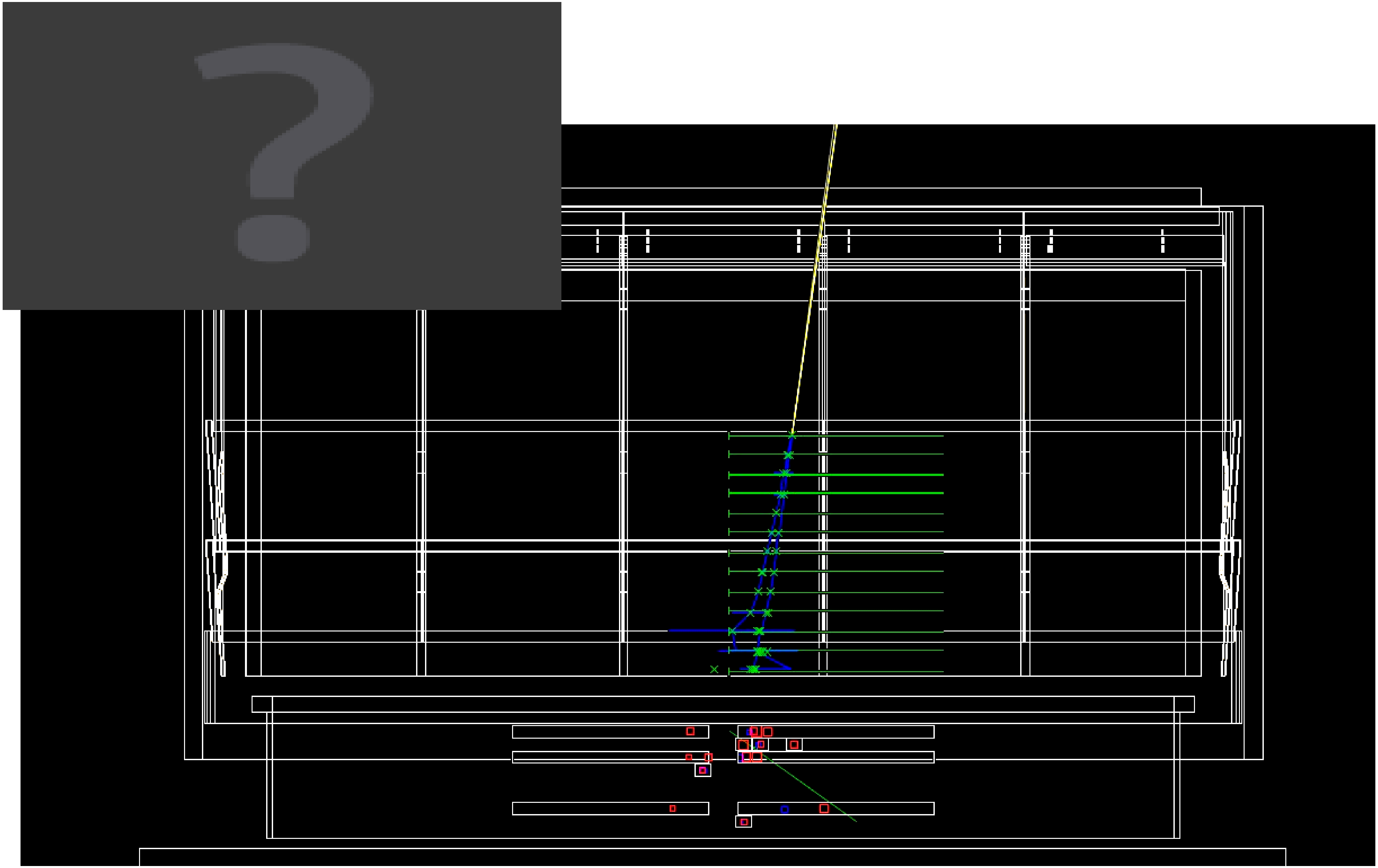
The Large Area Telescope

- Precision Si-strip Tracker
  - 18 XY tracking planes
  - Single-sided silicon strip detectors (228 μm pitch), 880,000 channels
  - Tungsten foil converters (1.5 X_0)
  - Measures the photon direction; gamma ID
- Hodoscopic CsI Calorimeter
  - Array of 1536 CsI(Tl) crystals in 8 layers
  - 3072 spectroscopy chans (8.5 X_0)
  - Hodoscopic array supports bkg rejection and shower leakage correction
  - Measures the photon energy; images the shower
- Segmented Anticoincidence Detector
  - 89 plastic scintillator tiles
  - Rejects background of charged cosmic rays
  - segmentation minimizes self-veto effects at high energy
- Electronics System
  - Includes flexible, robust hardware trigger and software filters



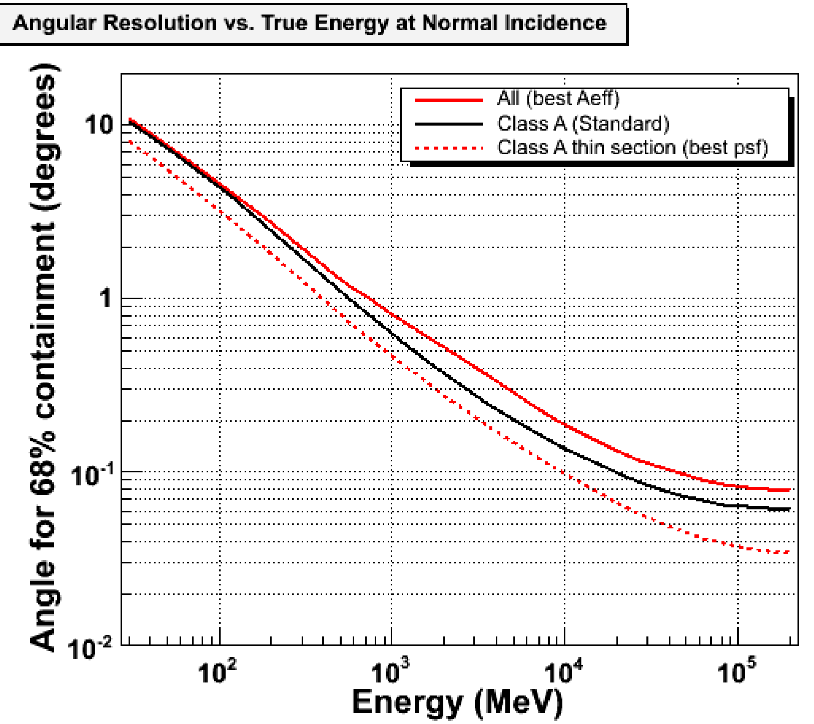
Sub-systems work together to identify and measure the flux of cosmic gamma rays with energy between 20 MeV and 300 GeV

LAT gamma-ray candidate event



Performances du LAT

	LAT	EGRET
Energy range	20 MeV to >300 GeV	20 MeV – 30 GeV
Energy resolution (on axis, 100 MeV – 10 GeV)	<15%	10%
Peak effective area	~ 8000 cm²	1500 cm²
Angular resolution (single photon, 10 GeV)	0.15°	0.54°
Field of view	~2.4 sr (@ 1 GeV)	0.4 sr
Deadtime per event	27 us	100 ms



- Capacités améliorées pour l'observation des sursauts
  - Mode d'observation efficace (ciel non occulté)
  - Grand champ de vue
  - Faible temps mort (variabilité sondée jusqu'à la µs)
    - Possibilité d'étudier les sursauts courts
  - Grande surface de collection
  - Bonne résolution angulaire
  - Couverture en énergie plus grande

Beaucoup de GRB

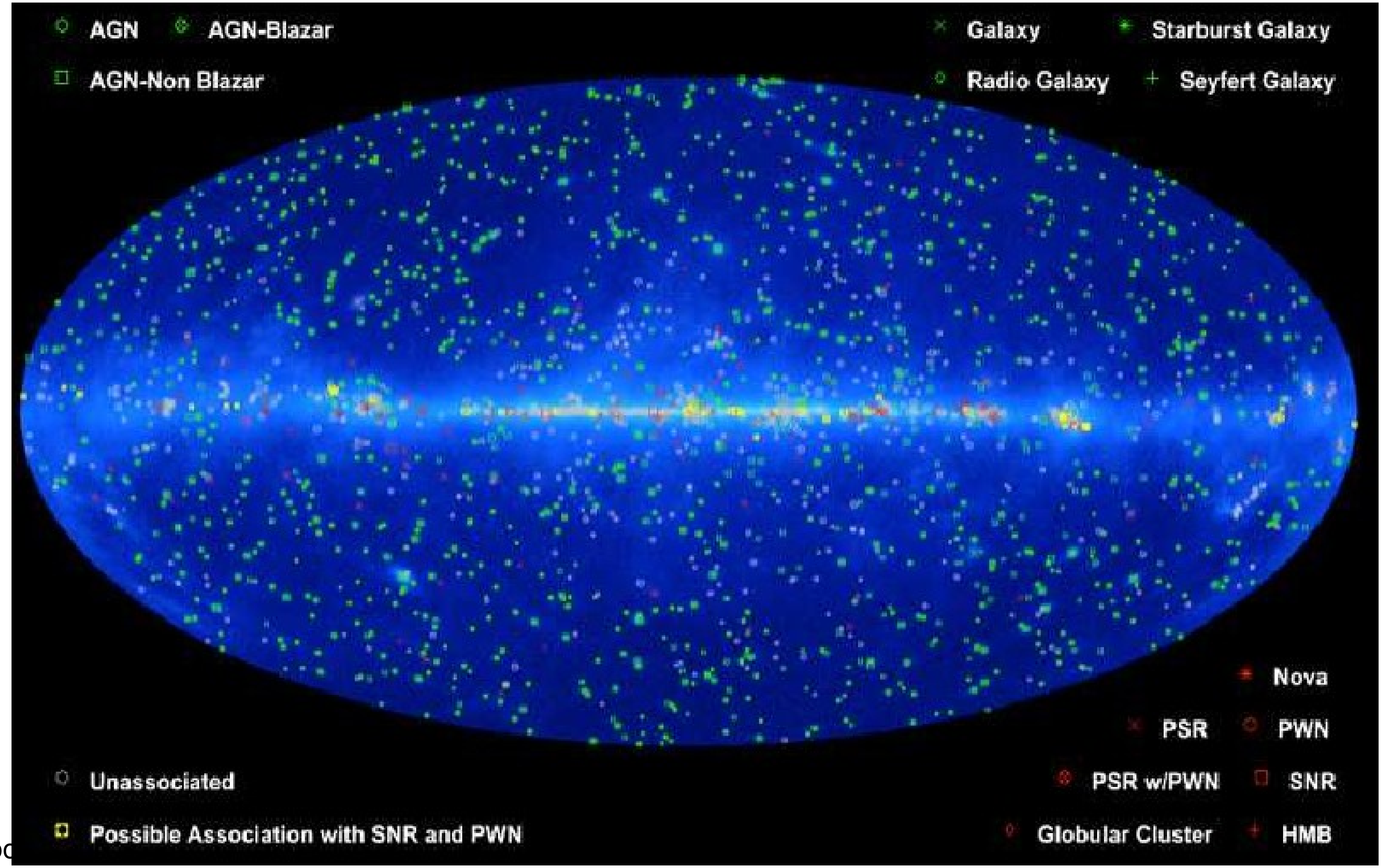
Plus de photons pour chaque GRB

Bonne localisation des GRB

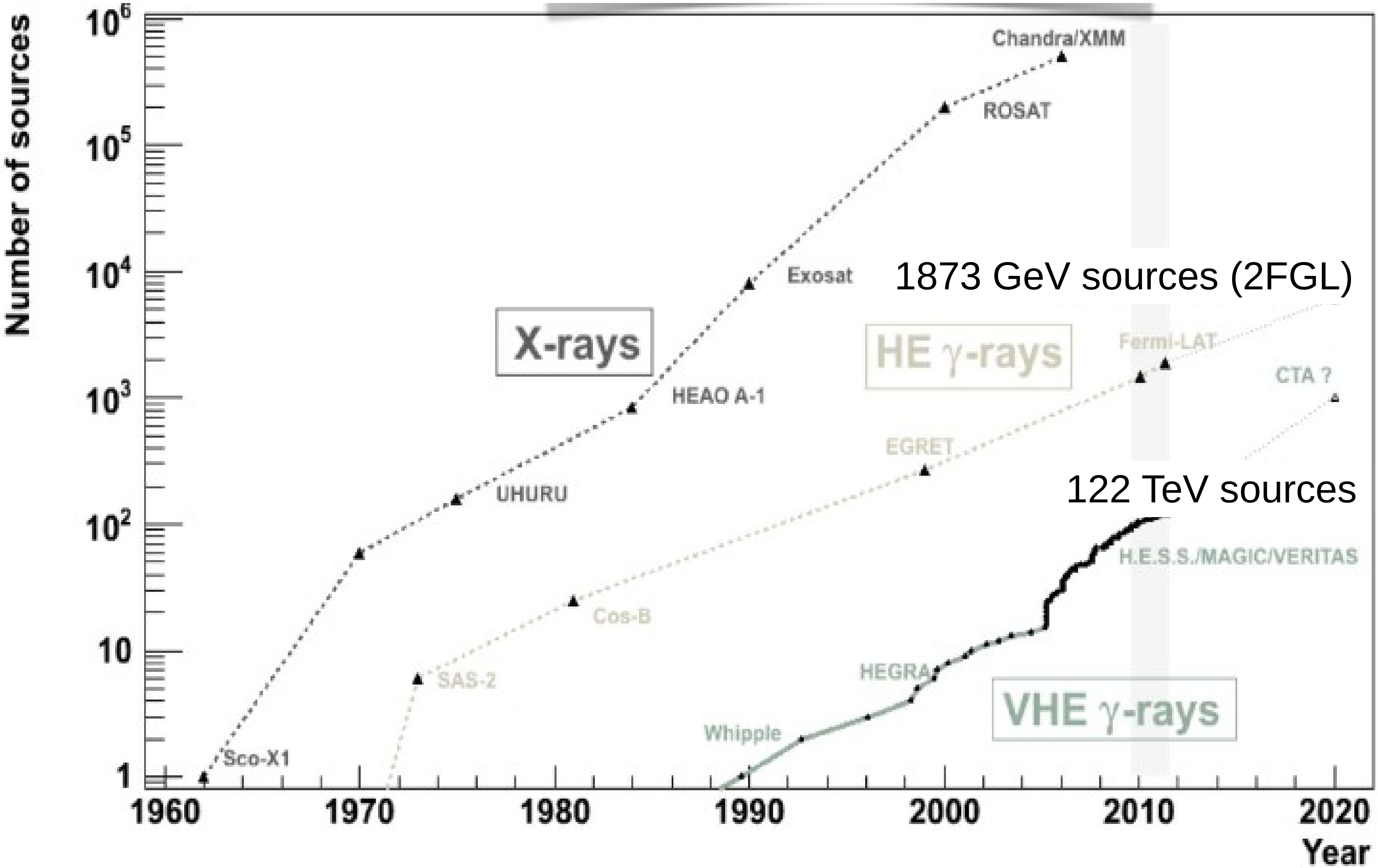
Fermi : record mondial de citations en 2012 pour le catalogue 2FGL !

Lundi, 14 Janvier 2013

And the winner is… le deuxième catalogue Fermi-LAT de sources cosmiques de rayons gamma, baptisé 2FGL[1] ! Cette publication a suscité le plus grand nombre de citations parmi tous les articles astronomiques publiés dans le monde en 2012. Les catalogues successifs 0FGL, 1FGL et 2FGL, qui recensent à eux trois les sources gamma du ciel découvertes par le télescope spatial Fermi depuis 2008, ont ainsi été cités près de 1 000 fois[2]. Une belle récompense pour les chercheurs français (CEA/CNRS) de la collaboration Fermi-LAT qui ont coordonné la création de ces catalogues.



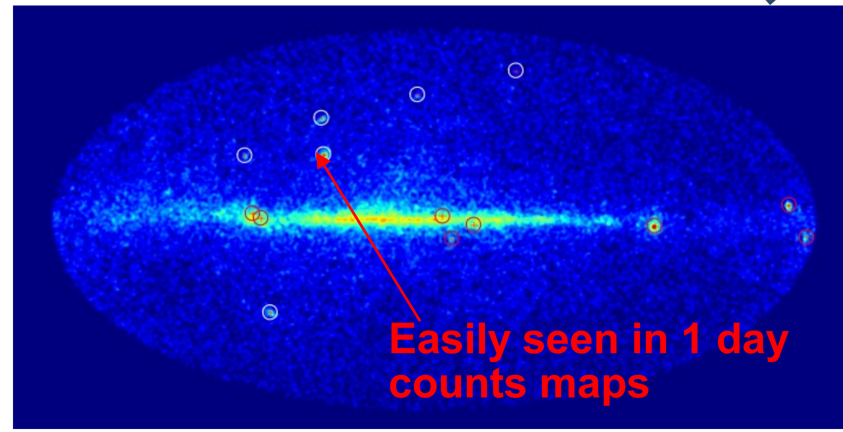
L'astronomie gamma en plein essor



Les sursauts gamma vus par *Fermi*

Exemple de GRB 090902B

Séquence d'observation



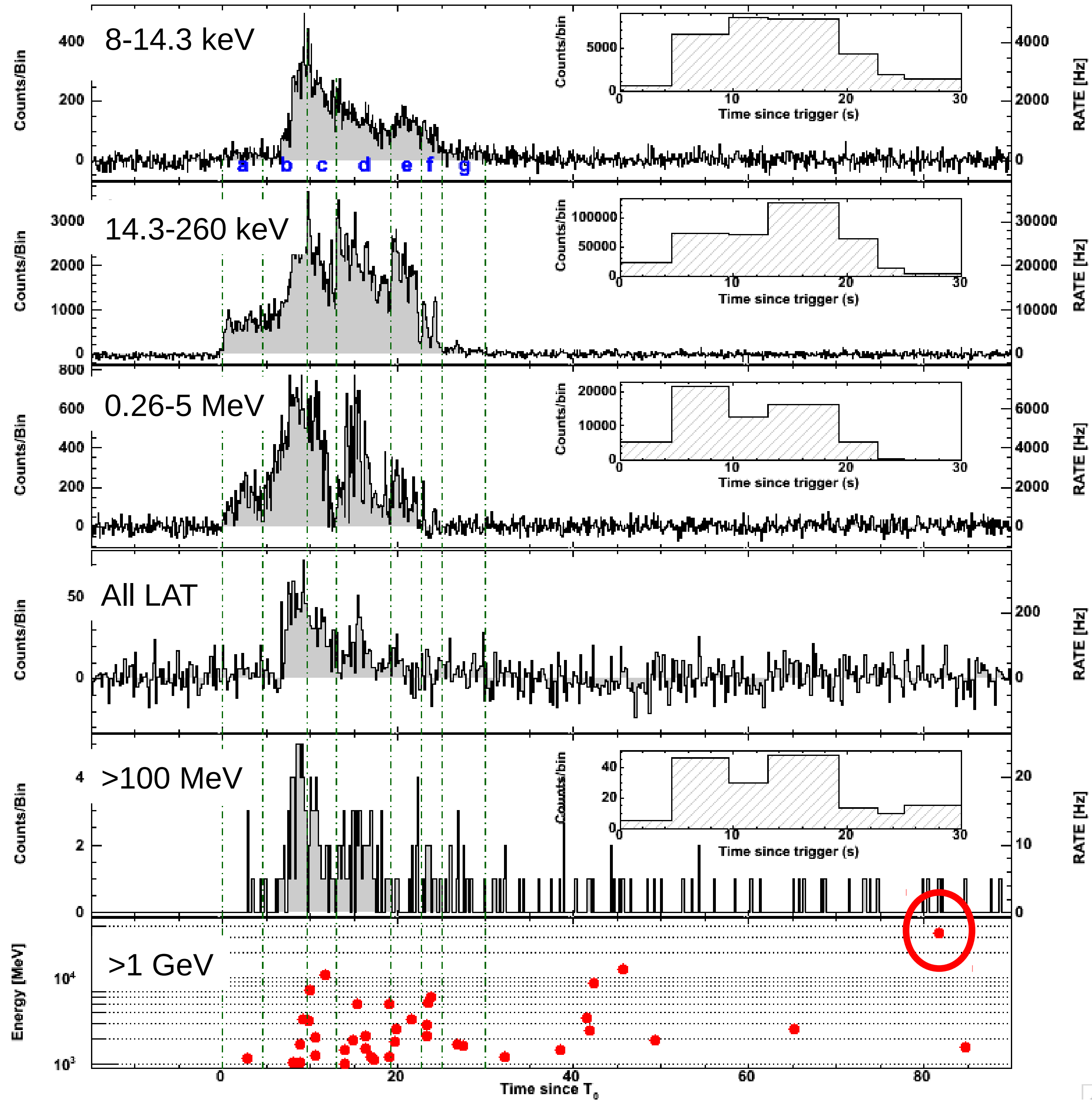
- 11:05:15 UT = T_0 – GBM GCN alert – ARR initiated
  - 15:05 UT – GBM human-in-the-loop localization
- LAT data monitoring and processing
  - 14:44 UT – GRB is seen in the telemetry
  - 18:24 UT – data ingest
  - 19:54 UT – GRB is seen in datamon plots
- 20:59:48 UT – FT1 file available [T_0 + 10 hr]
  - ASP results ~20 min later, human-in-the-loop localization
  - Swift ToO request issued at ~21:30 UT, begins at 23:36 UT [T_0 + 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) [T_0 + 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) [T_0 + 21.3 hr]
- 09:14:50 UT – GROND localization 3.3 arcmin from LAT position

GRB 090902B multi-detector light curve

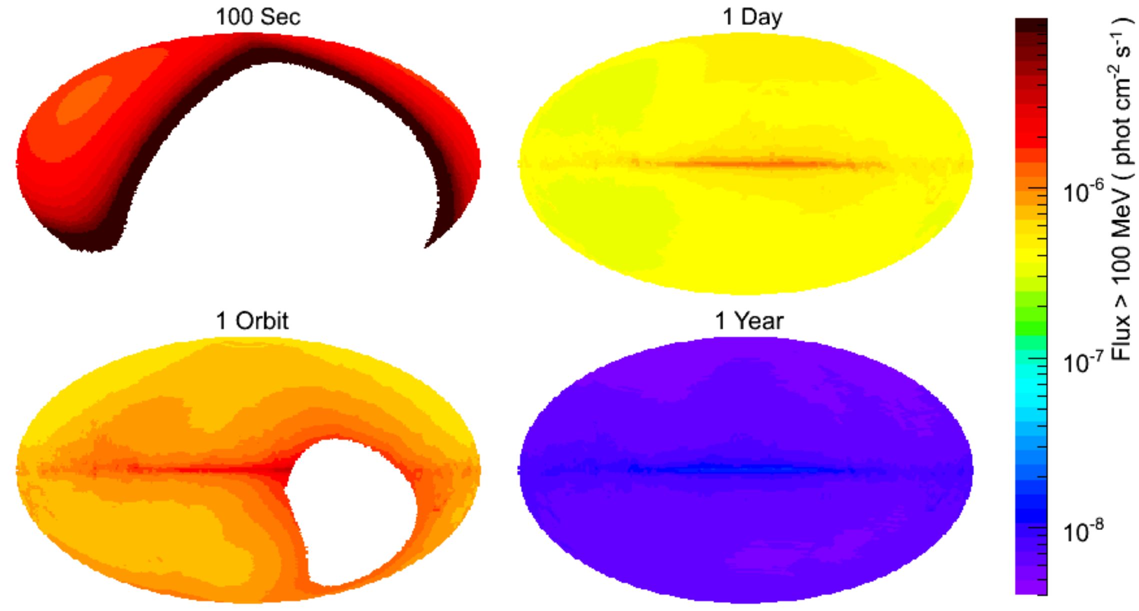
- T_{90} = 21.9 s, 50-300 keV
- Fluence = 4.4×10^{-4} erg cm^{-2} (10 keV – 10 GeV)
- E_{iso} = 3.6×10^{54} erg (9×10^{54} erg for GRB 080916C)
- Delayed onset of >100 MeV emission (~9 s) (~4.5 s for GRB 080916C)
- LAT extended emission, well beyond GBM prompt phase
- Highest energy photon measured from a burst: 33.4 GeV at T_0 + 82 s
- Study correlated variability in various bands

Abdo et al. 2009, ApJL 706, 138



“Autonomous Repoint Recommendation”

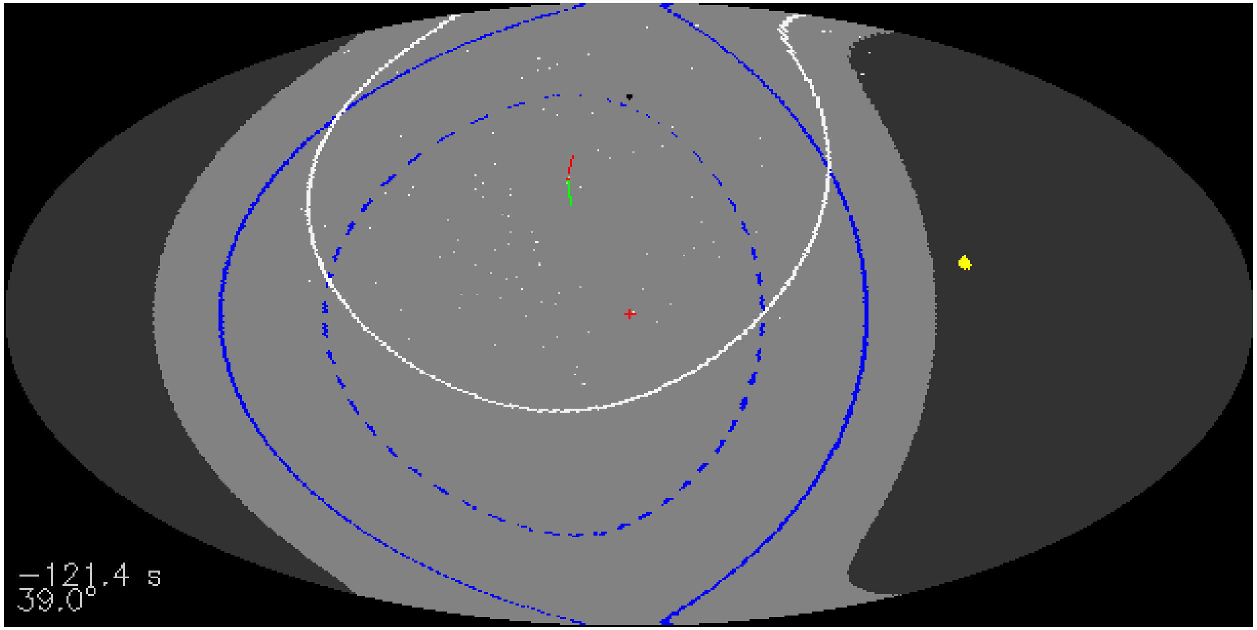
- Mode principal = cartographie du ciel
  - Ciel complet
    toutes les 2 orbites (3 h)
  - Exposition uniforme :
    chaque zone du ciel est vue
    durant ~30 min toutes les 2 orbites

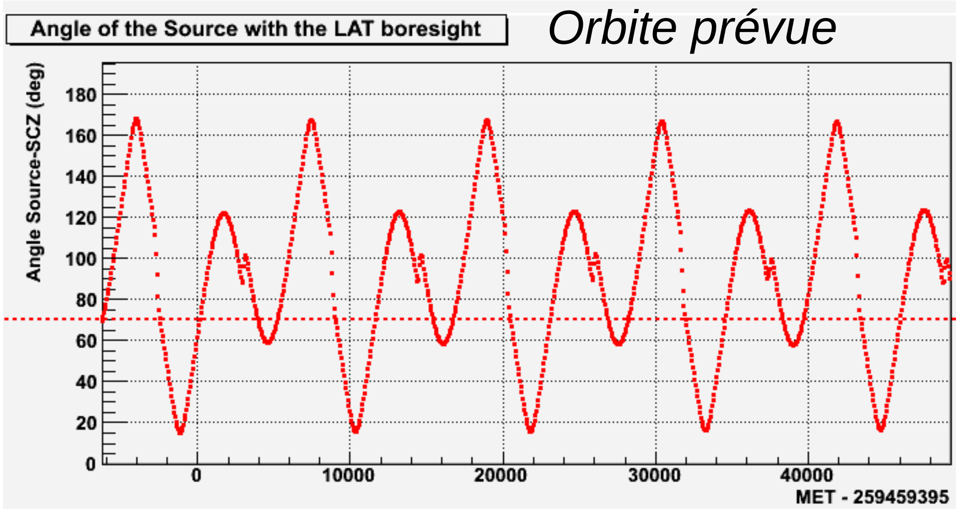


- Le satellite peut repointer (“Autonomous Repoint Recommendation” - ARR) pour la recherche d'émission rémanente de sursauts brillants avec le LAT
  - Depuis le 8 octobre 2008 à 14:11:08
  - ARR déclenchée soit par le trigger GRB du LAT à bord, soit par un trigger GBM intense (le GBM transmet au LAT, qui transmet au satellite)
  - Sursaut dans le champ de vue du LAT ou en dehors (seuils différents)
  - Cible suivie durant 5h (nominalement, 2.5h depuis 2011) tant qu'elle est au-dessus de l'horizon à plus de 20º (“Earth avoidance angle”), sinon orbite à 50º de l'horizon jusqu'à ce que la cible soit de nouveau visible
  - Conséquence (faible) sur la prise de données en mode cartographique

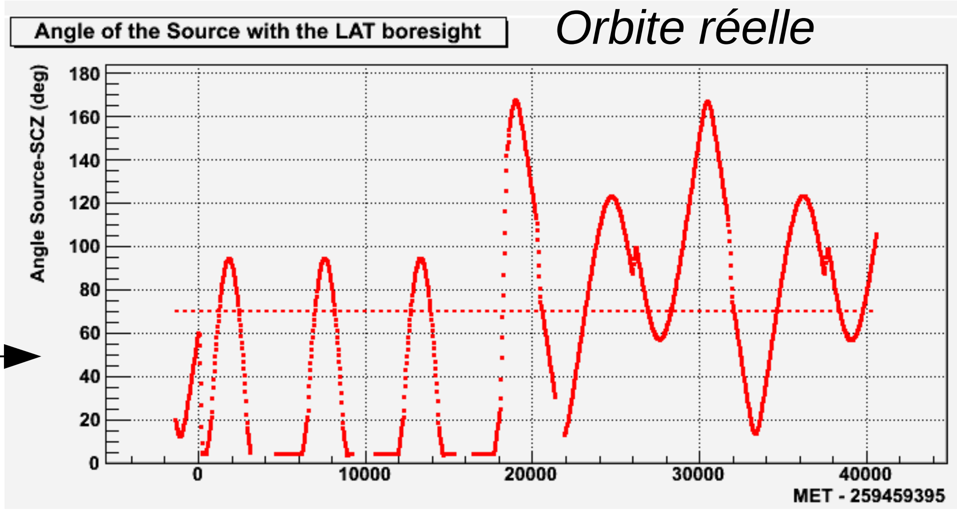
GRB 090902B et ARR

- Pointé du LAT (coordonnées célestes) de ~ -120 s à ~2000 s
  - Croix rouge = GRB 090902B
  - Point jaune = soleil
  - Région sombre = occultée par la Terre (θ_z>113°)
  - Cercle blanc = champ de vue du LAT (±66°)
  - Cercles bleus = 20° / 50° au-dessus de l'horizon
  - Points blancs : evts





ARR →

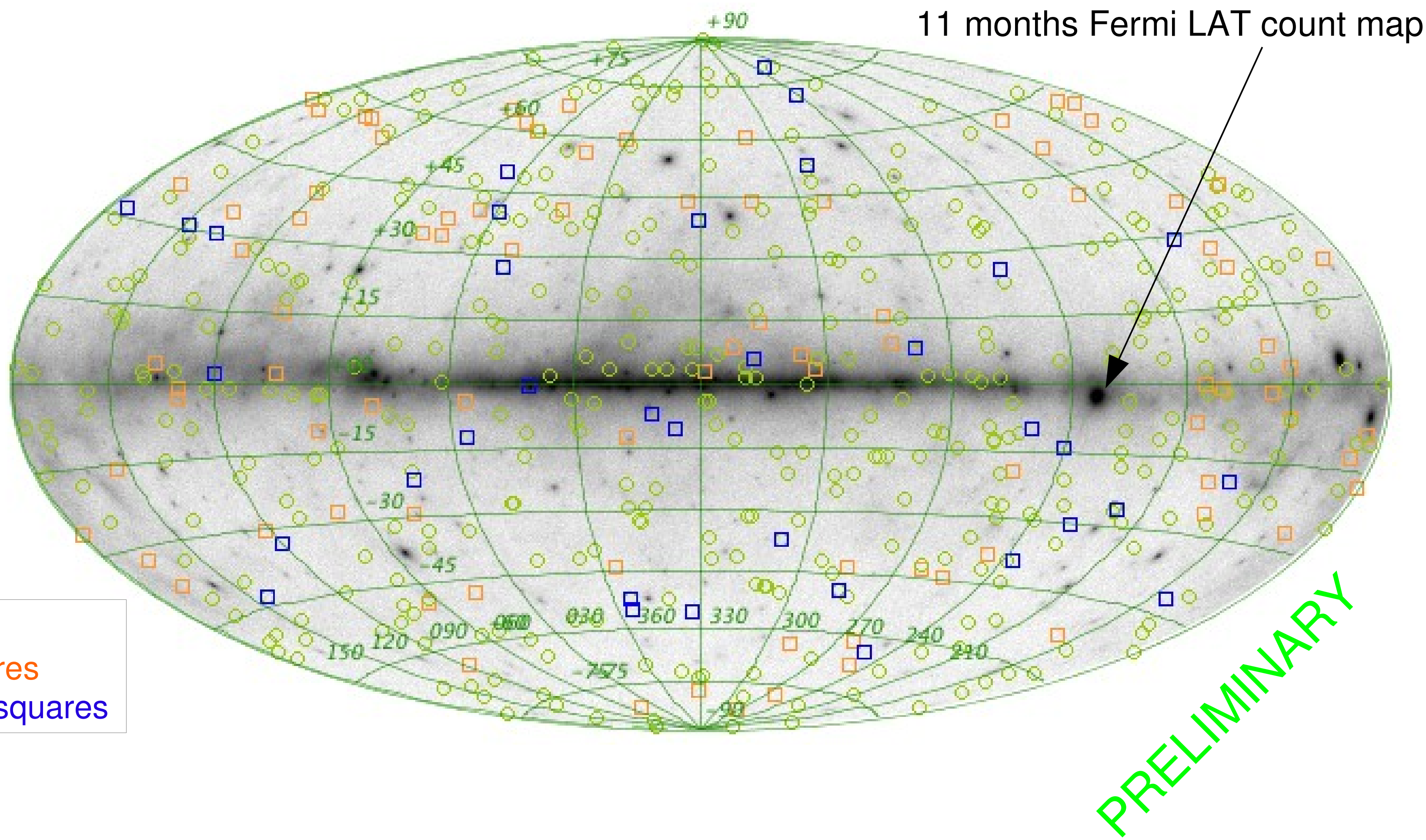


Les sursauts gamma vus par *Fermi*

Prompt emission

Fermi GRB detection statistics

GBM 2-year catalog
LAT 3-year catalog



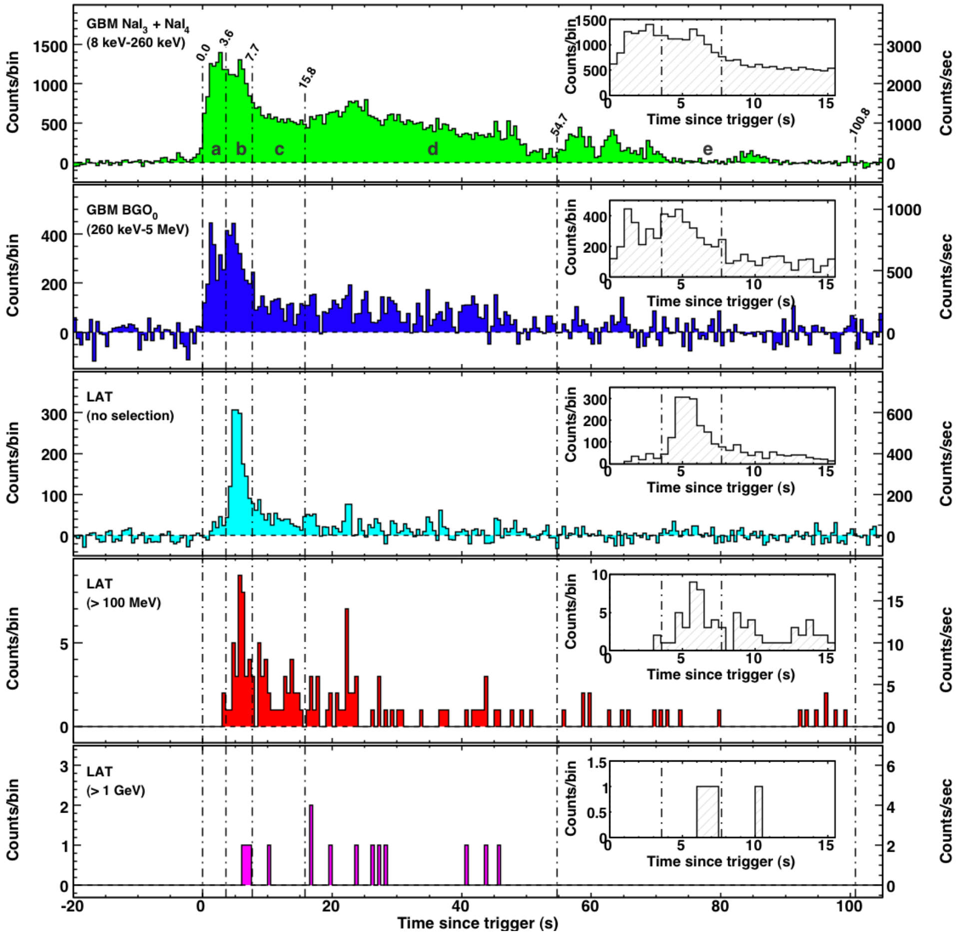
GBM LGRB: green circles
GBM SGRB: orange squares
LAT detections (35): blue squares

- The GBM detects ~250 GRBs / year, ~half in the LAT FoV
- The LAT detected 35 GRBs in 3 years (30 long, 5 short), including 7 “LLE-only” GRBs
  - 10 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C)

Delayed onset of >100 MeV emission (1/2)

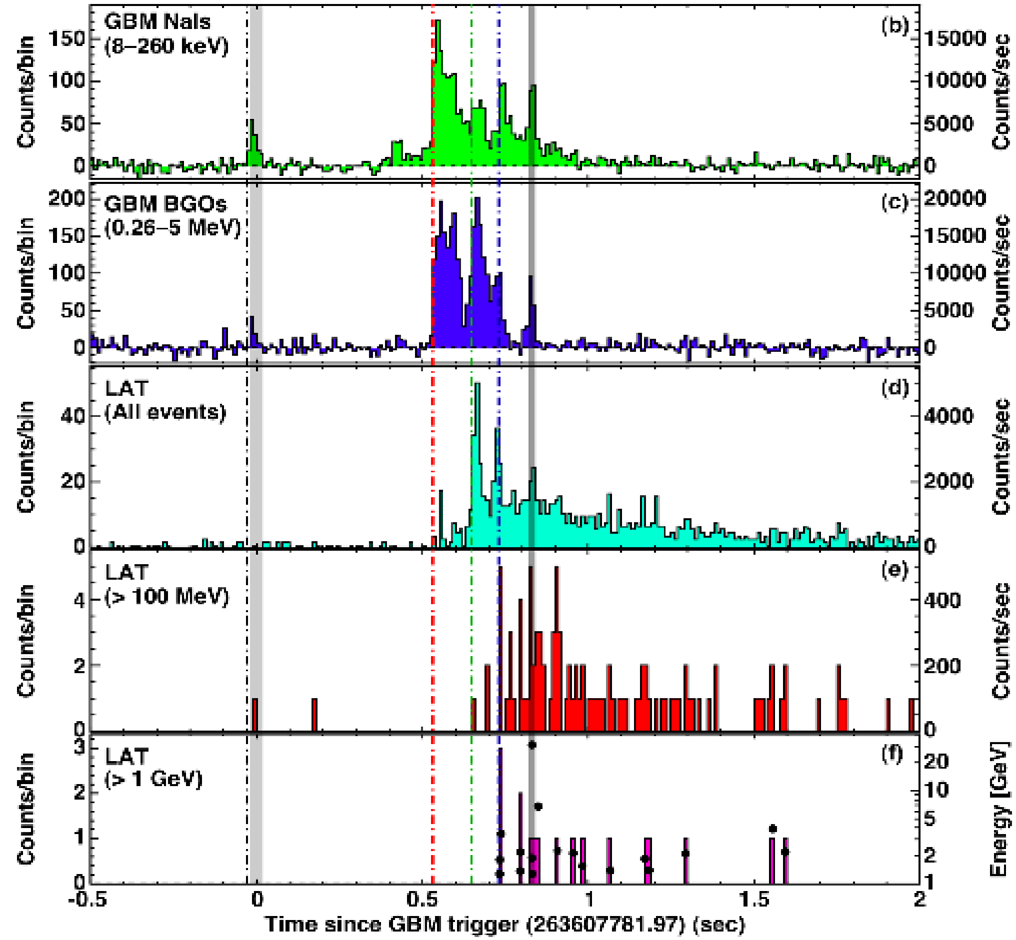
GRB 080916C

Abdo et al. 2009, Science 323, 1688



GRB 090510

Abdo et al. 2009, Nature 462, 331

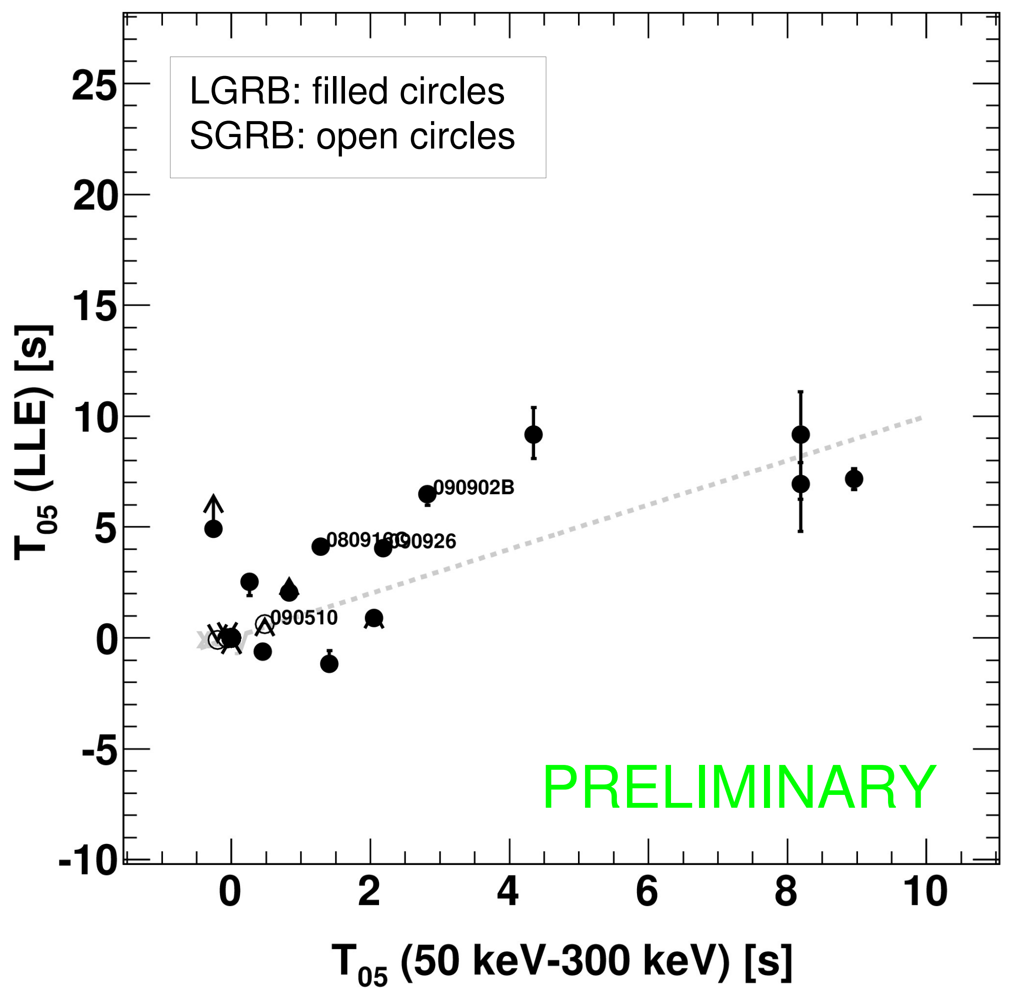


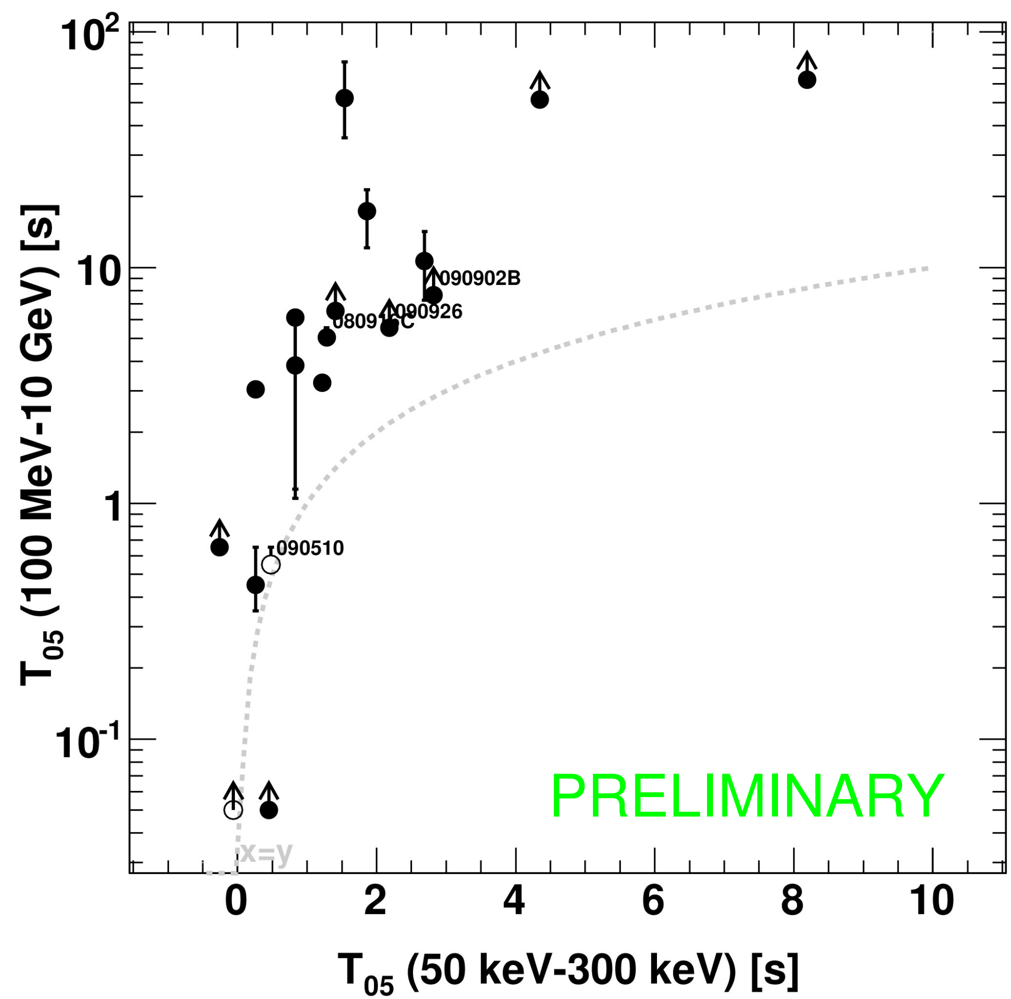
- The first LAT peak coincides with the 2nd GBM peak
- Delay in HE onset: ~4-5 s

- The first few GBM peaks are missing in the LAT but later peaks coincide
- Delay in HE onset: ~0.1-0.2 s

Delayed onset of >100 MeV emission (2/2)

- GBM T_{05} vs. LLE T_{05}: onset of LLE emission is compatible with GBM
- GBM T_{05} vs. LAT T_{05}: LAT >100 MeV emission is systematically delayed

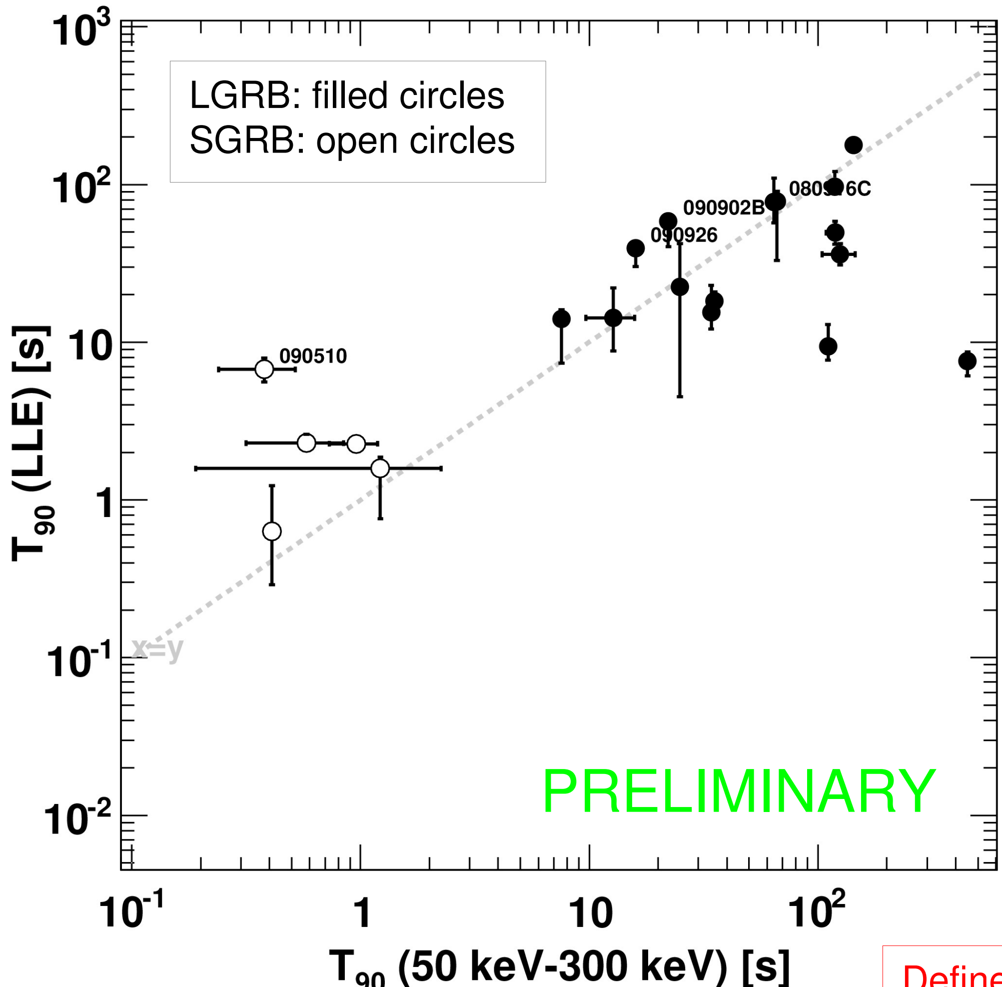


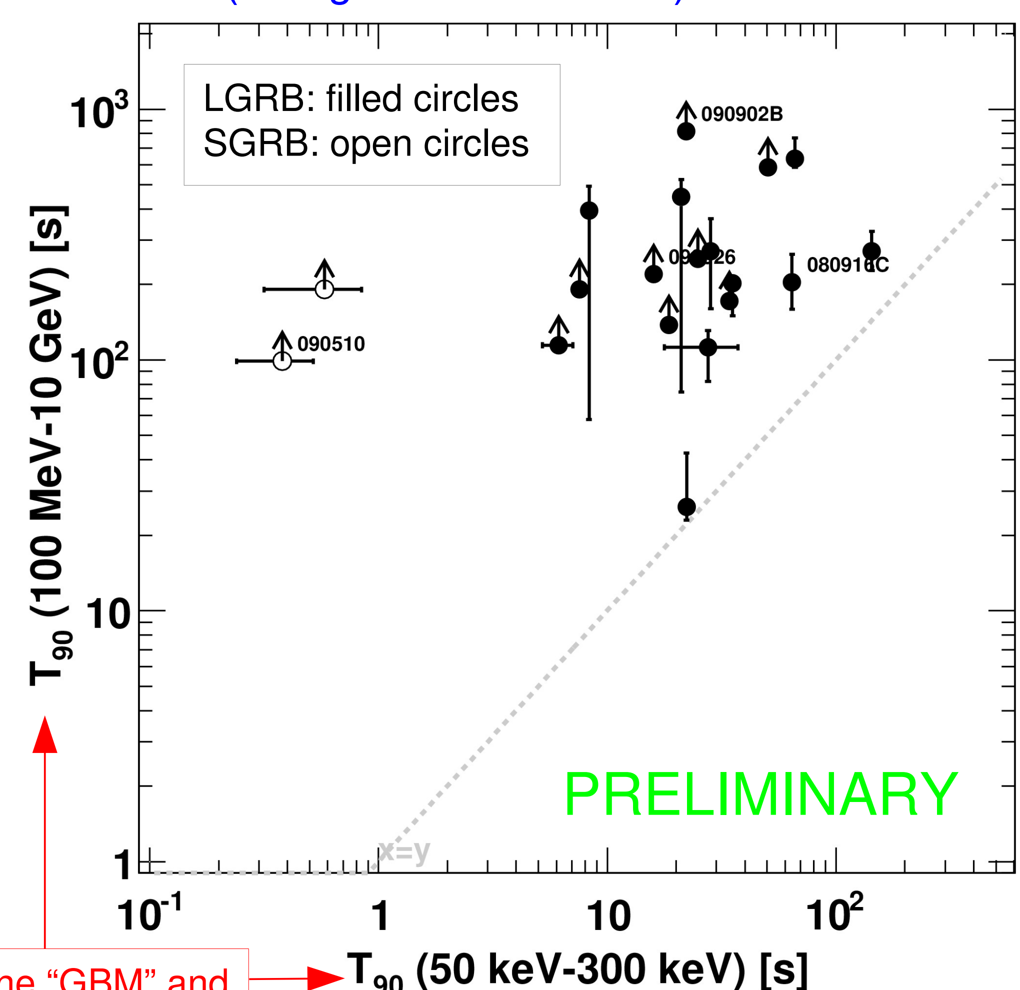


LAT >100 MeV emission is temporally extended

- GBM T_{90} vs. LLE T_{90}: duration of LLE emission is compatible with GBM

- GBM T_{90} vs. LAT T_{90}: LAT >100 MeV emission lasts systematically longer
  - Different component or better sensitivity of the LAT detector than the GBM detector (background dominated)?

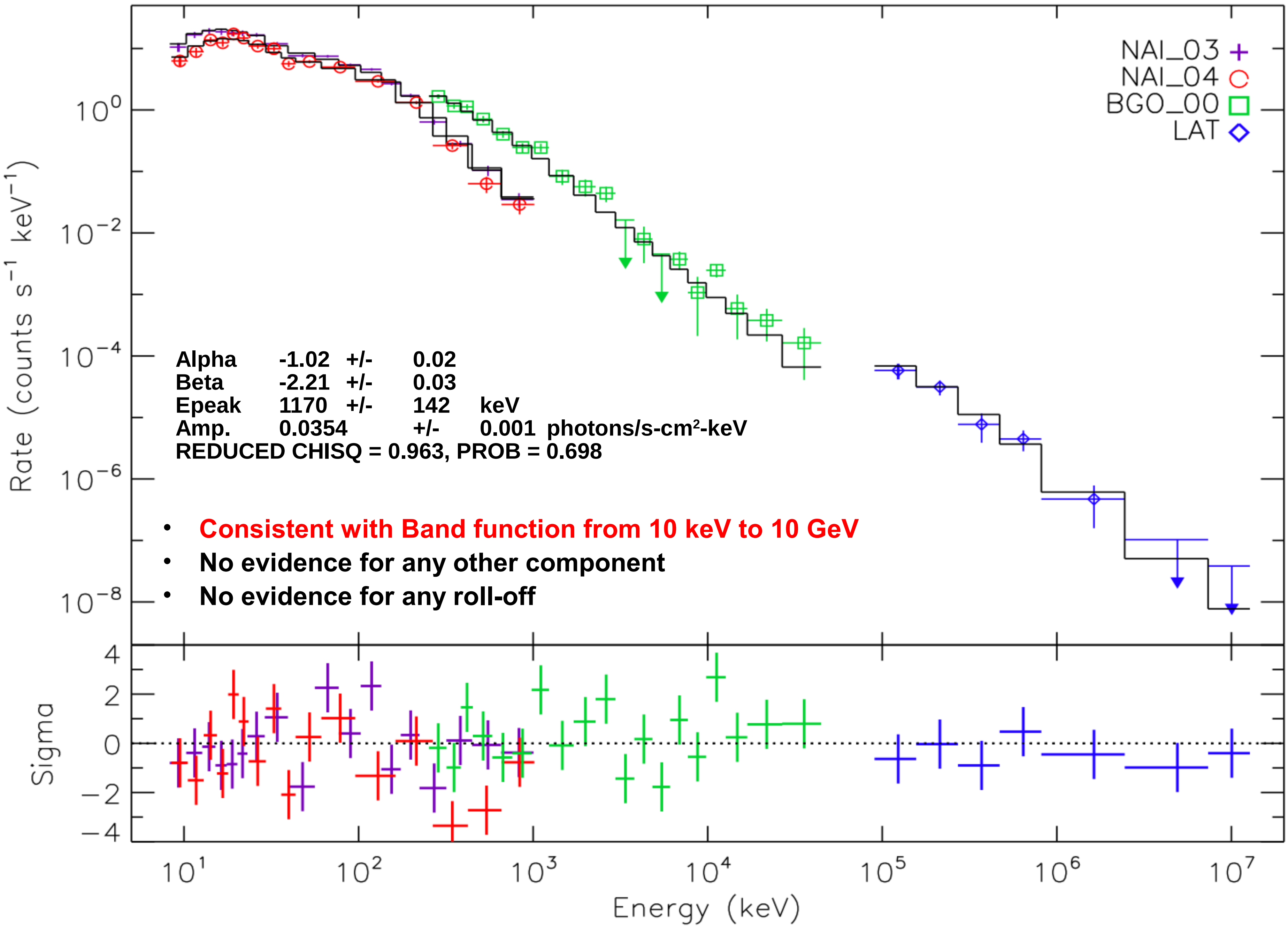




Define the “GBM” and “LAT” time windows

GRB 080916C: spectroscopy of main LAT peak

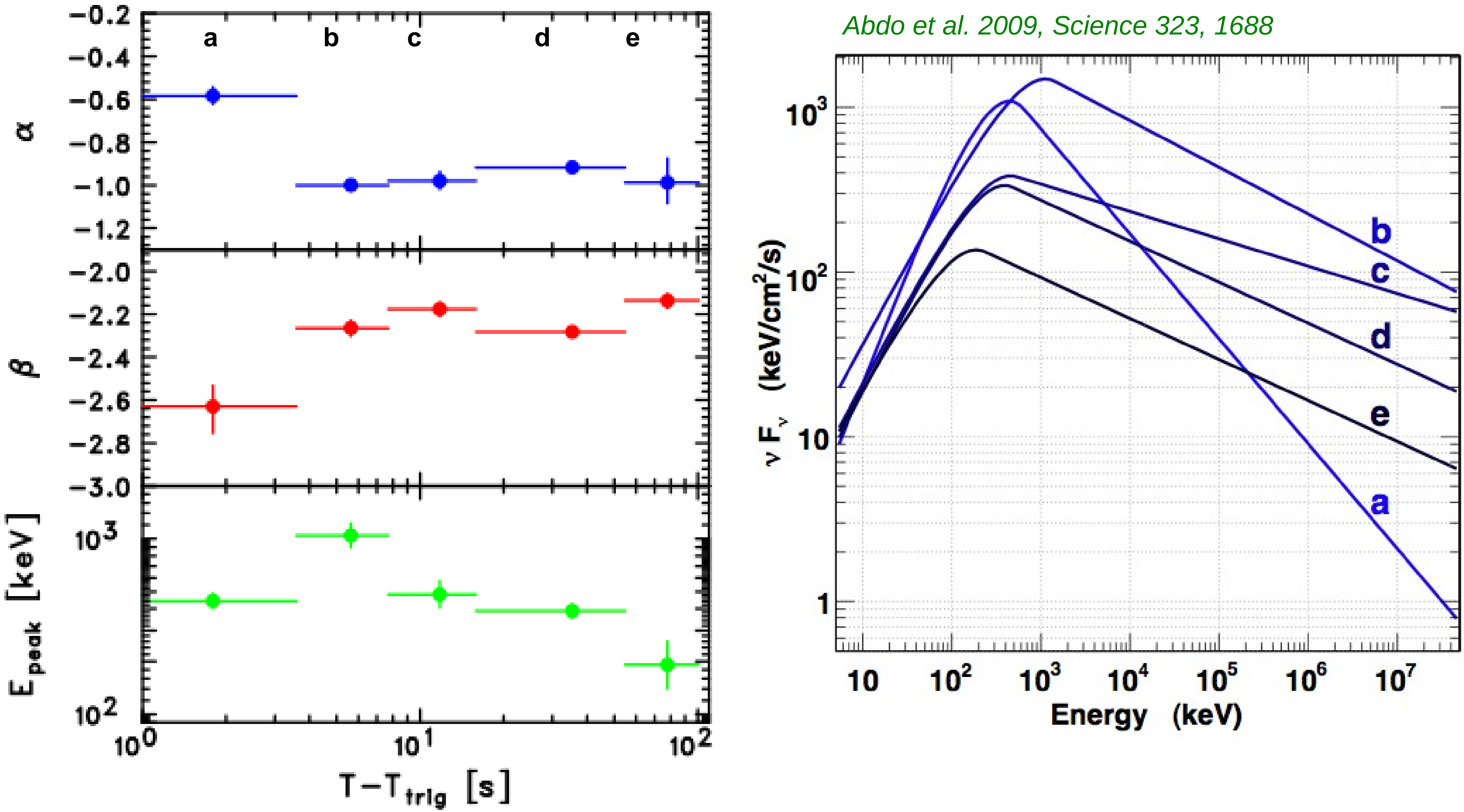
Abdo et al. 2009, Science 323, 1688



Spectral evolution of GRB 080916C

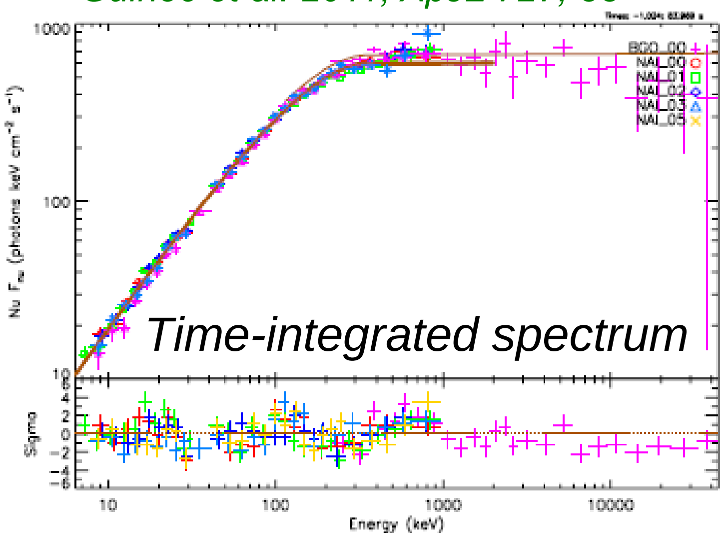
Soft-to-hard, then hard-to-soft evolution of E_{peak}

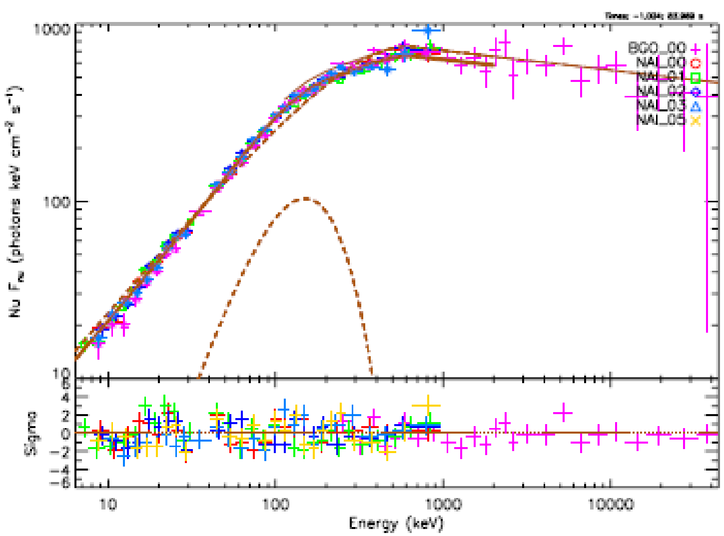
Abdo et al. 2009, Science 323, 1688



GRB 100724B thermal component

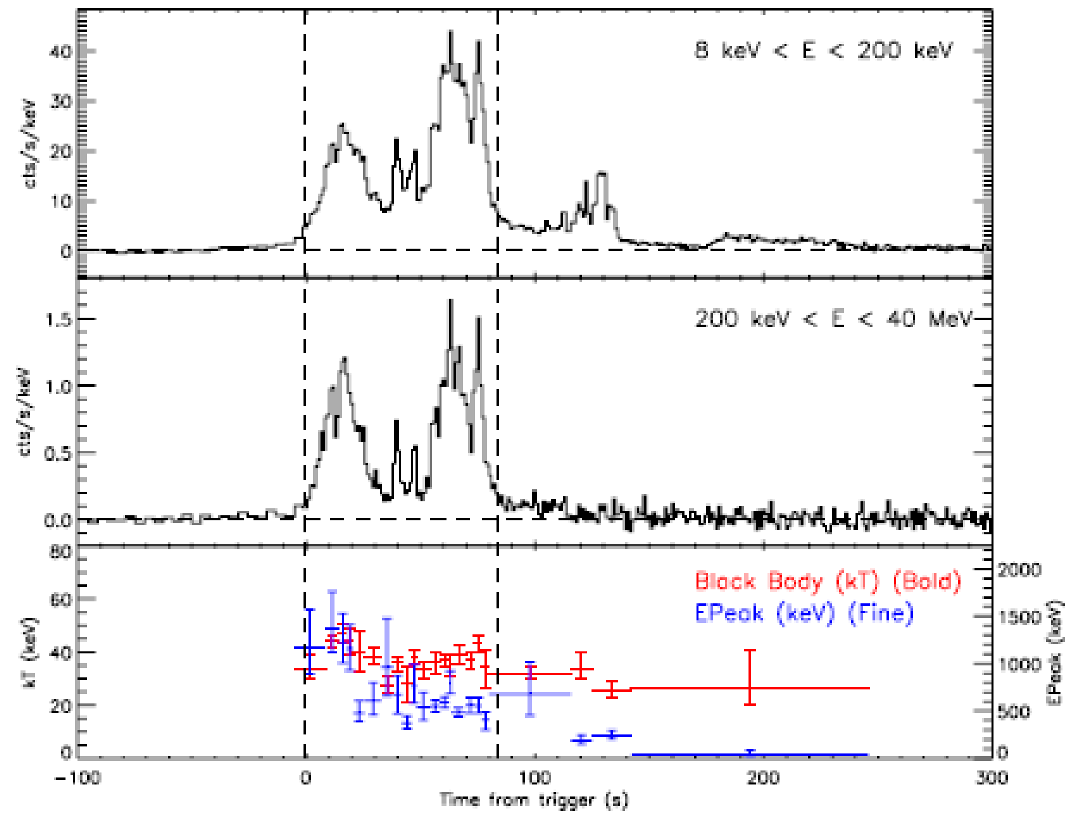
Guiriec et al. 2011, ApJL 727, 33





Parameters	E_{peak}	α	β	kT
Band	352	−0.67	−1.99	
	±6	±0.01	±0.01	
Band+BB	615	−0.90	−2.11	38.14
	±29	±0.02	±0.02	±0.87

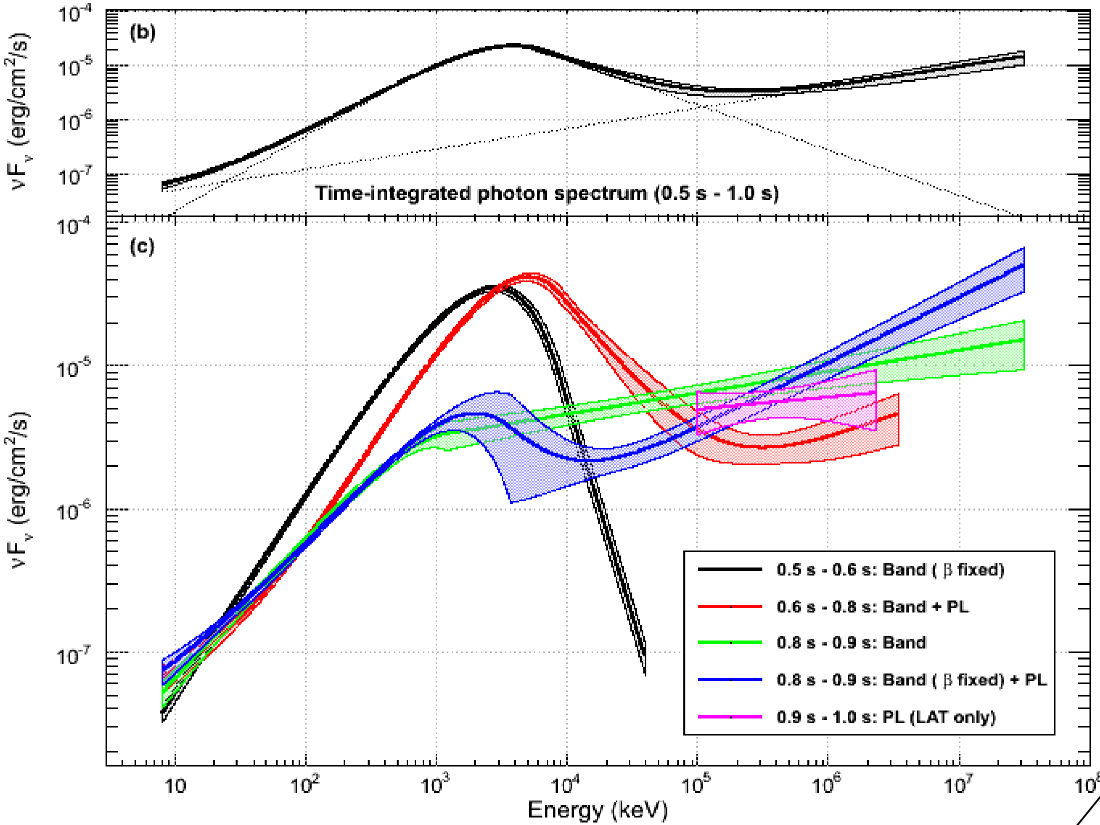
- Band+BB improves significantly the fit w.r.t. Band only (ΔC_{STAT}=95)
- First clear simultaneous detection of thermal and non-thermal components
- Larger E_{peak}, steeper spectral slopes (alpha compatible with synchrotron emission – line of death problem)
- E_{peak} (from ~90 keV to ~1100 keV) tracks the global soft-hard-soft evolution while BB temperature is ~constant



Extra PL component in short and long GRBs

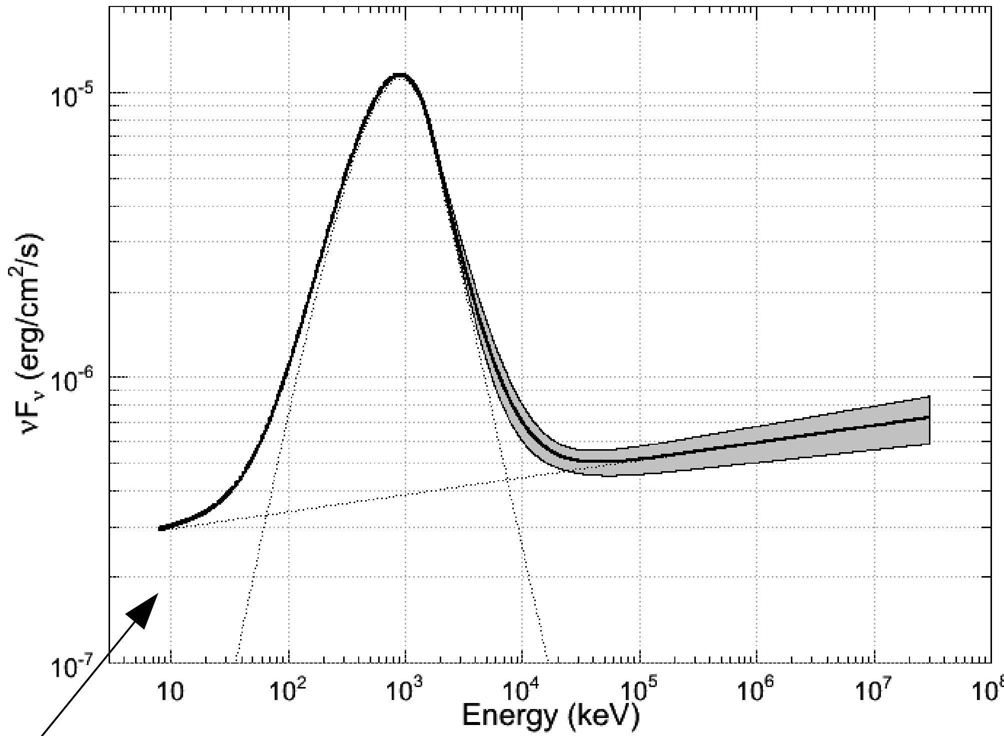
GRB 090510

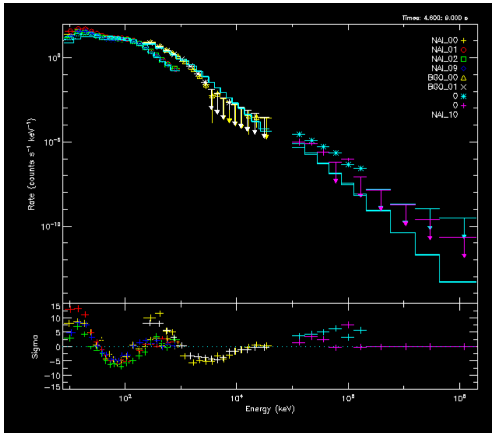
Ackermann et al. 2010, ApJ 716, 1178

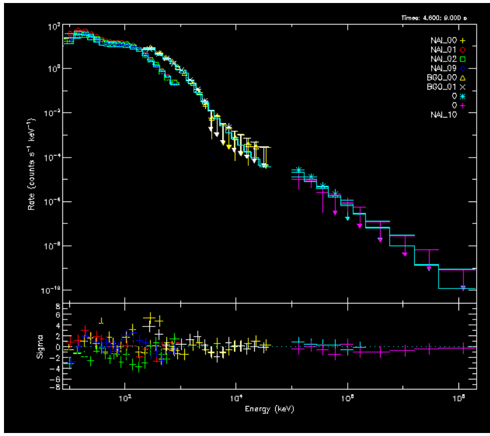


GRB 090902B

Abdo et al. 2009, ApJL 706, 138



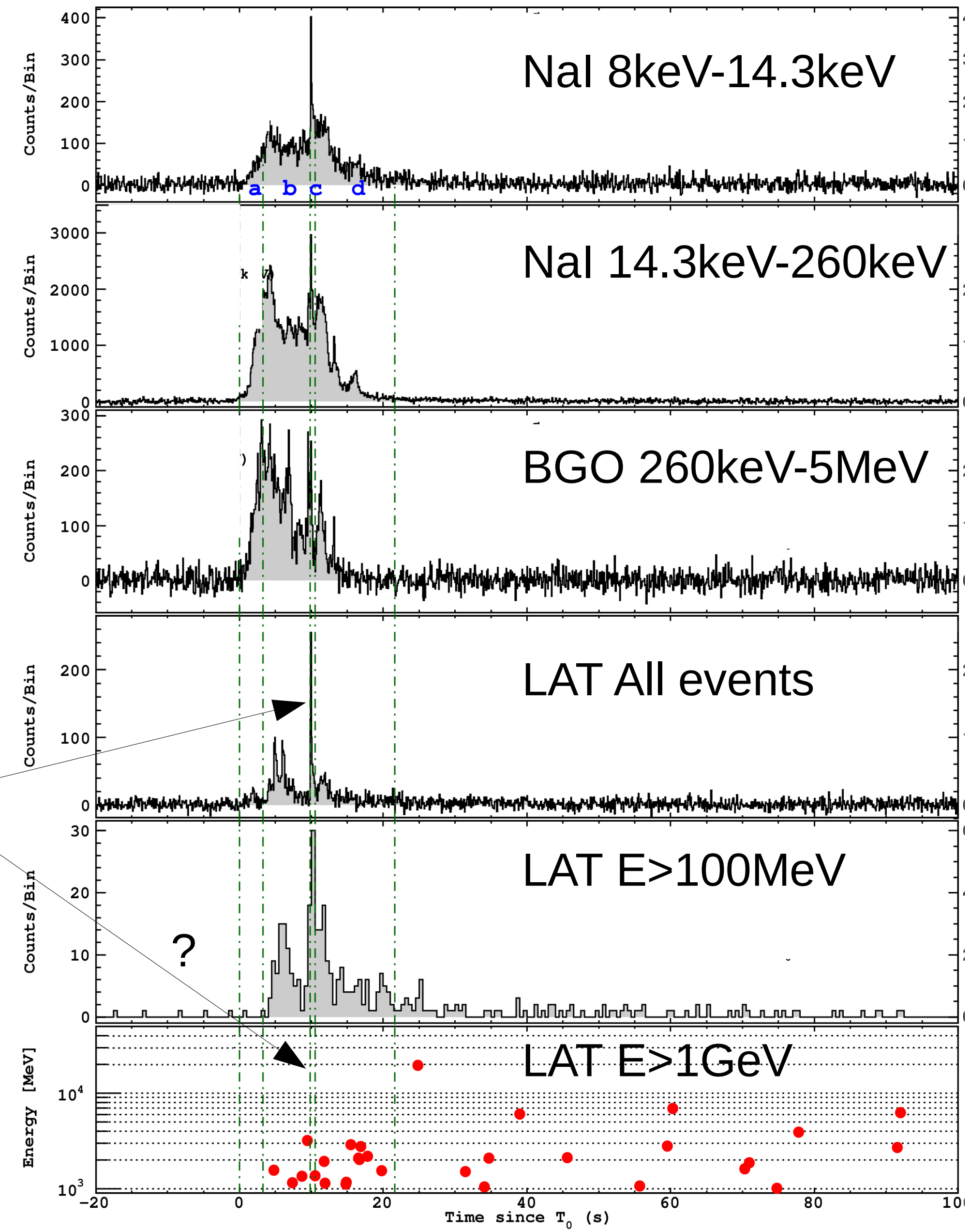




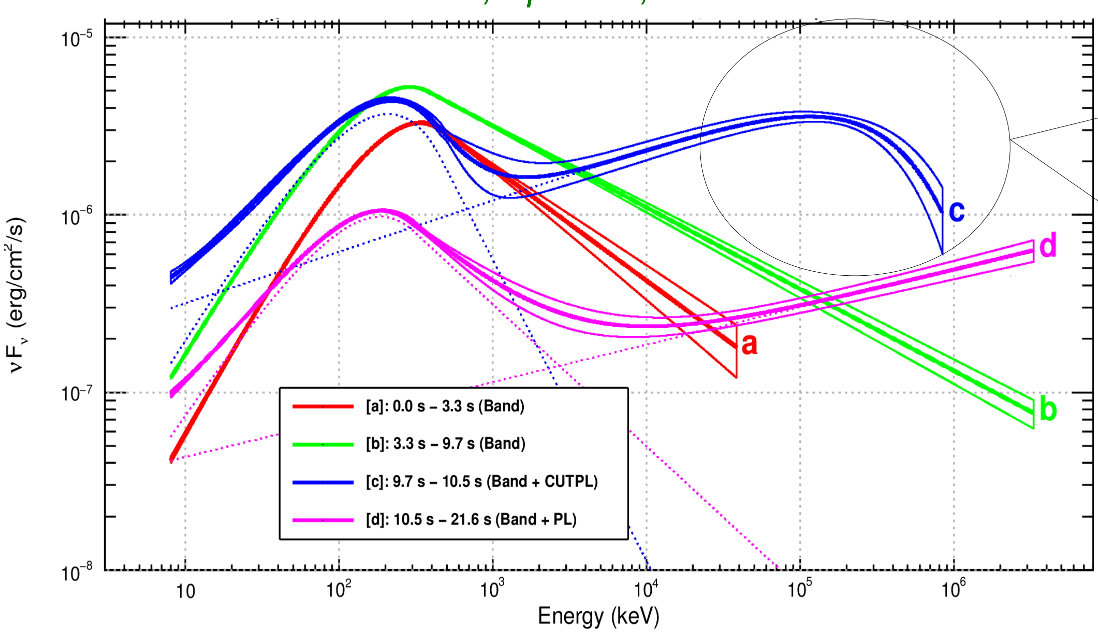
- GRB 090902B, interval b (T_0 + 4.6 s to 9.6 s):
  - ΔC_{STAT}=3165 (≥ 1000 for GBM only)
  - First time a low-energy extension of the PL component has been seen
  - Weak evidence (3 σ) for a spectral cutoff at ~1 GeV

GRB 090926A: the first observed cutoff PL

- Extra power-law
  - Starts delayed and persists at longer times (5ks)
  - First time ever a cutoff on the extra PL observed.
    - Significant at bin c – sharp spike
    - Marginally significant at bin d
    - Permits direct measurement of Γ~200–700
- Sharp spike at bin c
  - It peaks at all energy ranges synchronized (<50ms) and with similar widths → PL and Band related (co-located or otherwise causally correlated)?



Ackermann et al. 2011, ApJ 729, 114



Models for HE delayed onset and PL component

- Leptonic models (inverse-Compton or SSC)
  - Hard to produce a delayed onset longer than spike widths
  - Hard to produce a low-energy (<50 keV) power-law excess (as in GRBs 090510, 090902B)
  - Hard to account for the Band α and the HE component spectral index
  - Photospheric emission models could help to explain these properties
- Hadronic models (pair cascades, proton synchrotron)
  - GRBs as possible sources of Ultra-High Energy Cosmic Rays
  - HE onset time = time to accelerate protons & develop cascades?
  - Synchrotron emission from secondary e± pairs produced via photo-hadron interactions can naturally explain the power-law at low energies
  - Proton synchrotron radiation requires large B-fields
  - Both scenarios require substantially more energy (1-3 orders of magnitude) than observed (much less stringent constraint with lower values of Γ)
  - Hard to produce correlated variability at low- and high-energies (e.g., spike of GRB 090926A)
- Early afterglow model: e^+e^- synchrotron from forward shock (FS) as the jet propagates in the external medium
  - HE onset time = time required for FS to sweep up enough material and brighten (difficult for 090902B)
  - Hard to explain rapid HE variability observed in some bursts (e.g., GRBs 090902B, 090926A)
  - Requires large Γ (larger than that of GRB 090926A) or a dense circumburst medium
  - Synchrotron can not explain correlated light curves (e.g., spike of GRB 090926A)
  - IC of Band photons by HE electrons at the FS? → possible & can explain correlated light curves

Constraints on the bulk Lorentz factor (1/2)

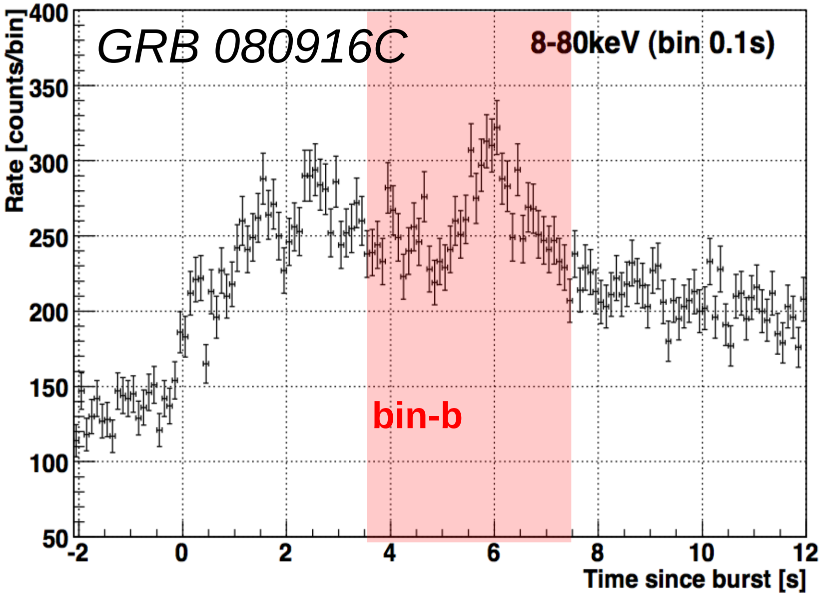
- Evaluation of the jet opacity to gamma rays
  - The target photon field needs to be evaluated during the short variability time scales of the high-energy emission
  - For a Band spectrum of the target photon field

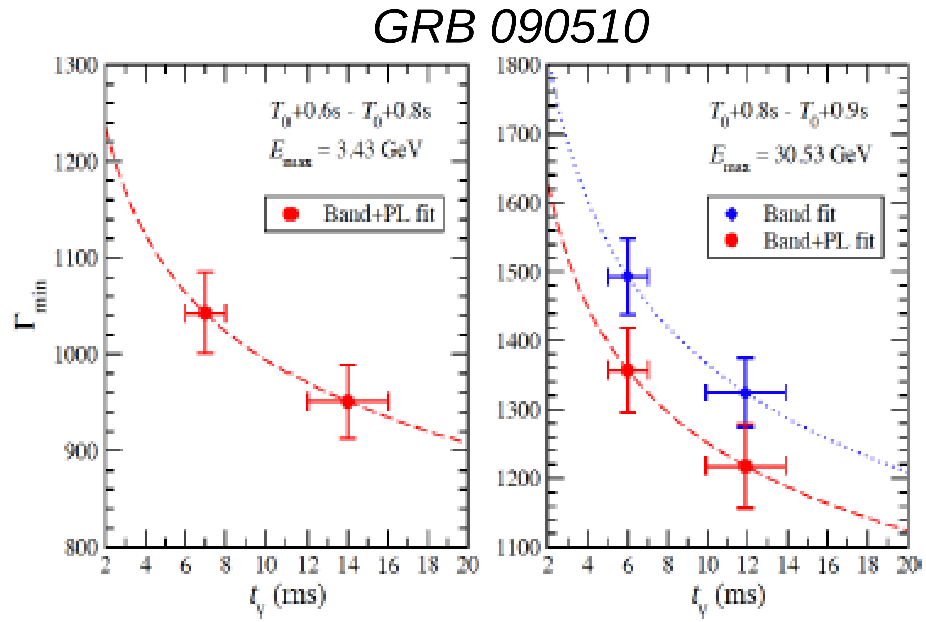
$$\Gamma_{\min}(E_{\max}) = \left[\frac{4\, d_L^2\, A}{c^2\, t_v}\, \frac{m_e^2\, c^4}{(1+z)^2\, E_{\max}}\, g\, \sigma_T\right]^{\frac{1}{2-2\beta}} \left[\frac{(\alpha-\beta)\, E_{\rm pk}}{(2+\alpha)\, 100\,{\rm keV}}\right]^{\frac{\alpha-\beta}{2-2\beta}} \exp\left(\frac{\beta-\alpha}{2-2\beta}\right) \left[\frac{2\, m_e^2\, c^4}{E_{\max}\,(1+z)^2\, 100\,{\rm keV}}\right]^{\frac{\beta}{2-2\beta}}$$

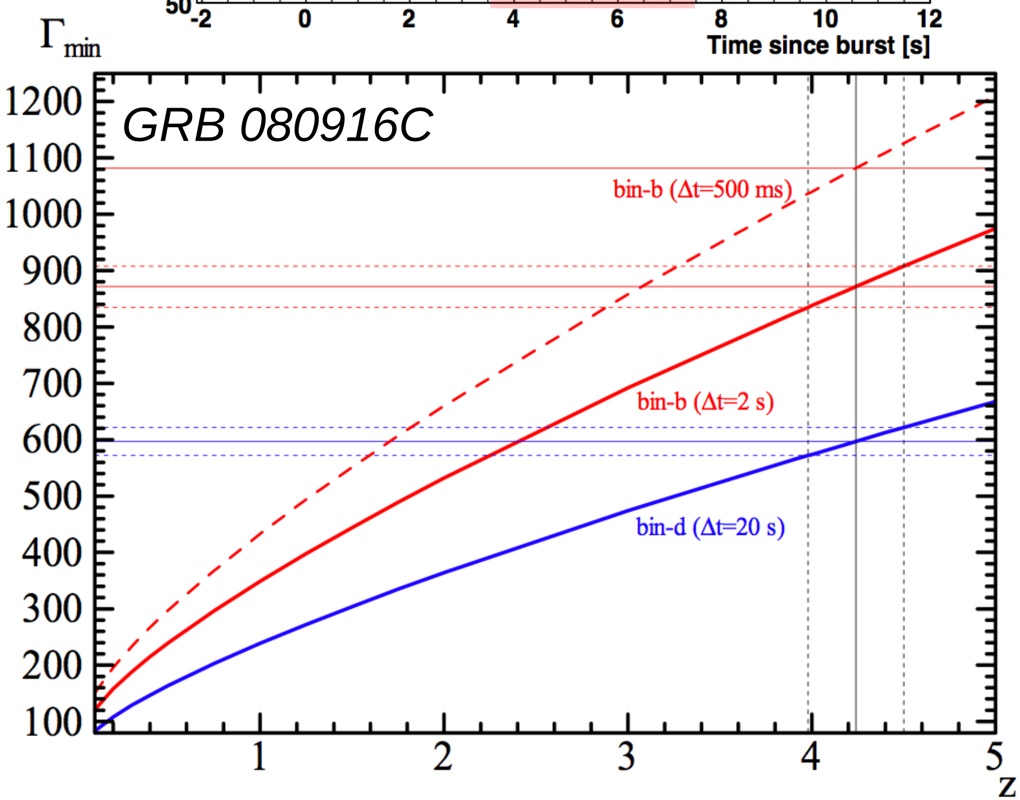
- More robust estimates than before
  - Does not assume that the spectrum extends beyond the highest energy detected photon
  - E.g. GRB 090902B: E_{max}=11.16 GeV, t_v=53 ms (from BGO)

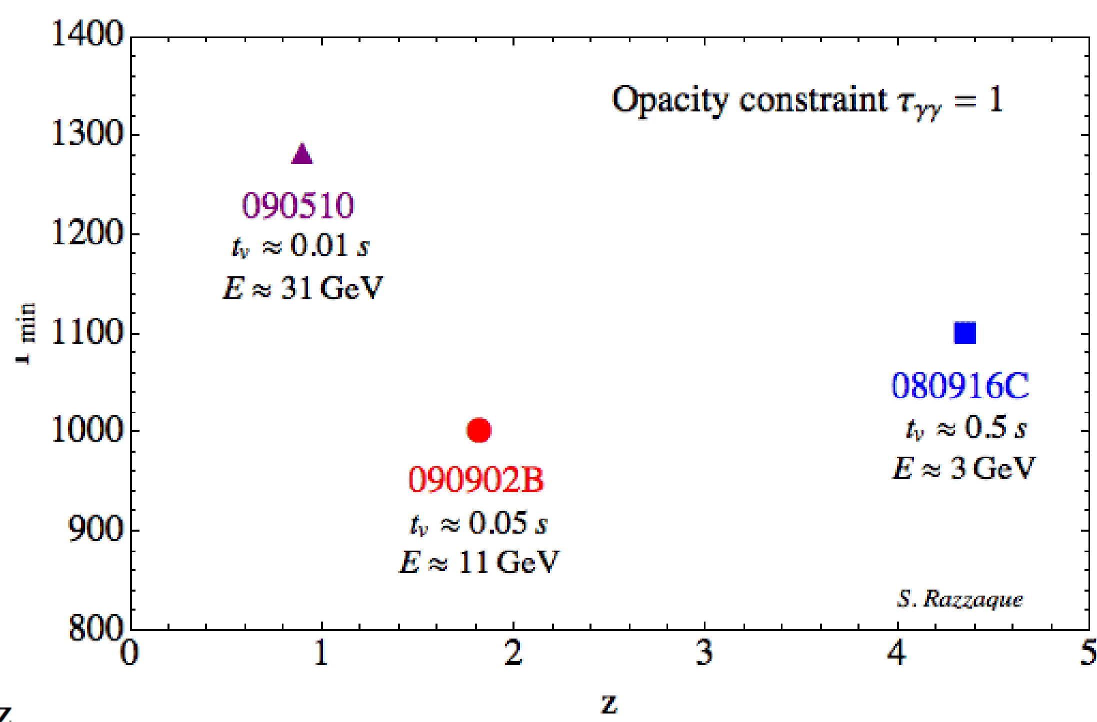
- This computation assumes a uniform, isotropic and time-independent target photon field
  - More realistic models (e.g. Granot 2008, Hascoet & Daigne 2011) give significantly (~3 times) lower values

Constraints on the bulk Lorentz factor (2/2)



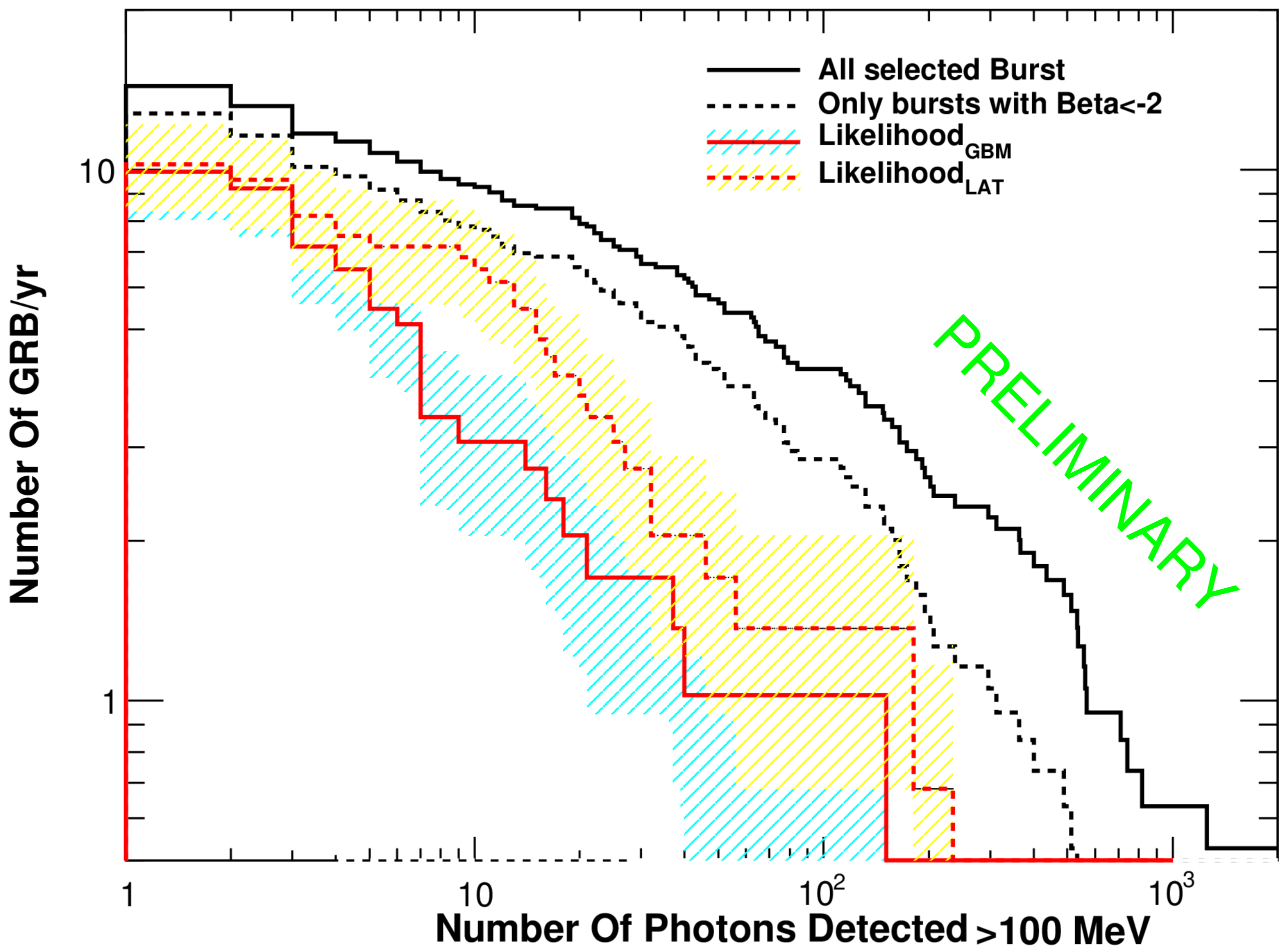






LAT GRB rate

- Pre-launch estimates (Band et al. 2009):
  - 9.3 GRBs expected / year with >10 photons above 100 MeV
- Compared with number of "predicted" photons from likelihood fit (in "GBM" and "LAT" time windows)
  - 6.3 GRBs observed / year with >10 photons above 100 MeV

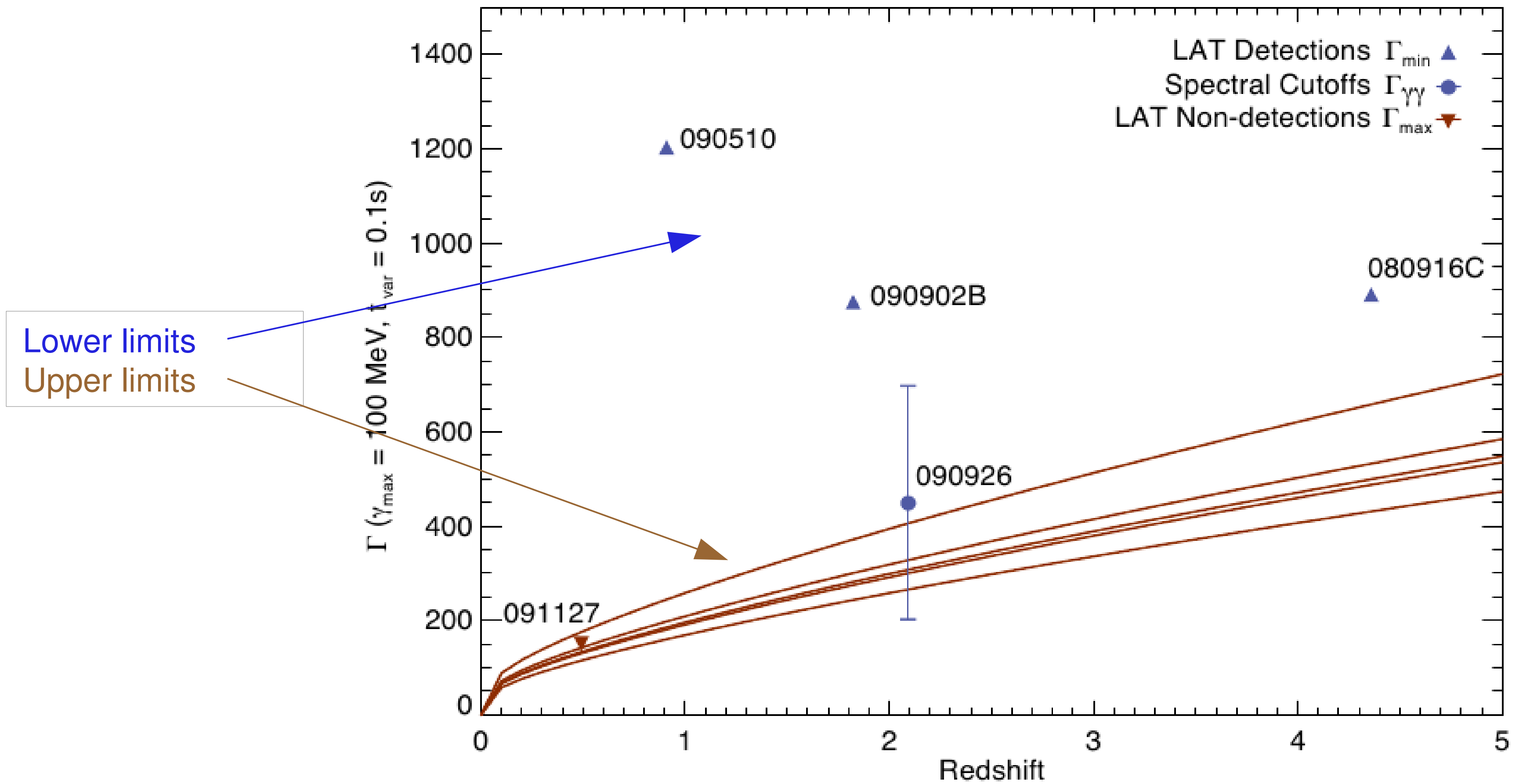


- Suggests that the LAT detects fewer GRBs than anticipated
  - Both analyses have their own systematic uncertainties
  - Extrapolating from BATSE energy range to the LAT energy range is uncertain (large lever arm, errors on beta)
  - Past estimates used simple detection threshold and negligible background
- Extra components must be rare
- Is the high-energy emission suppressed?

New limits on GRB bulk Lorentz factors

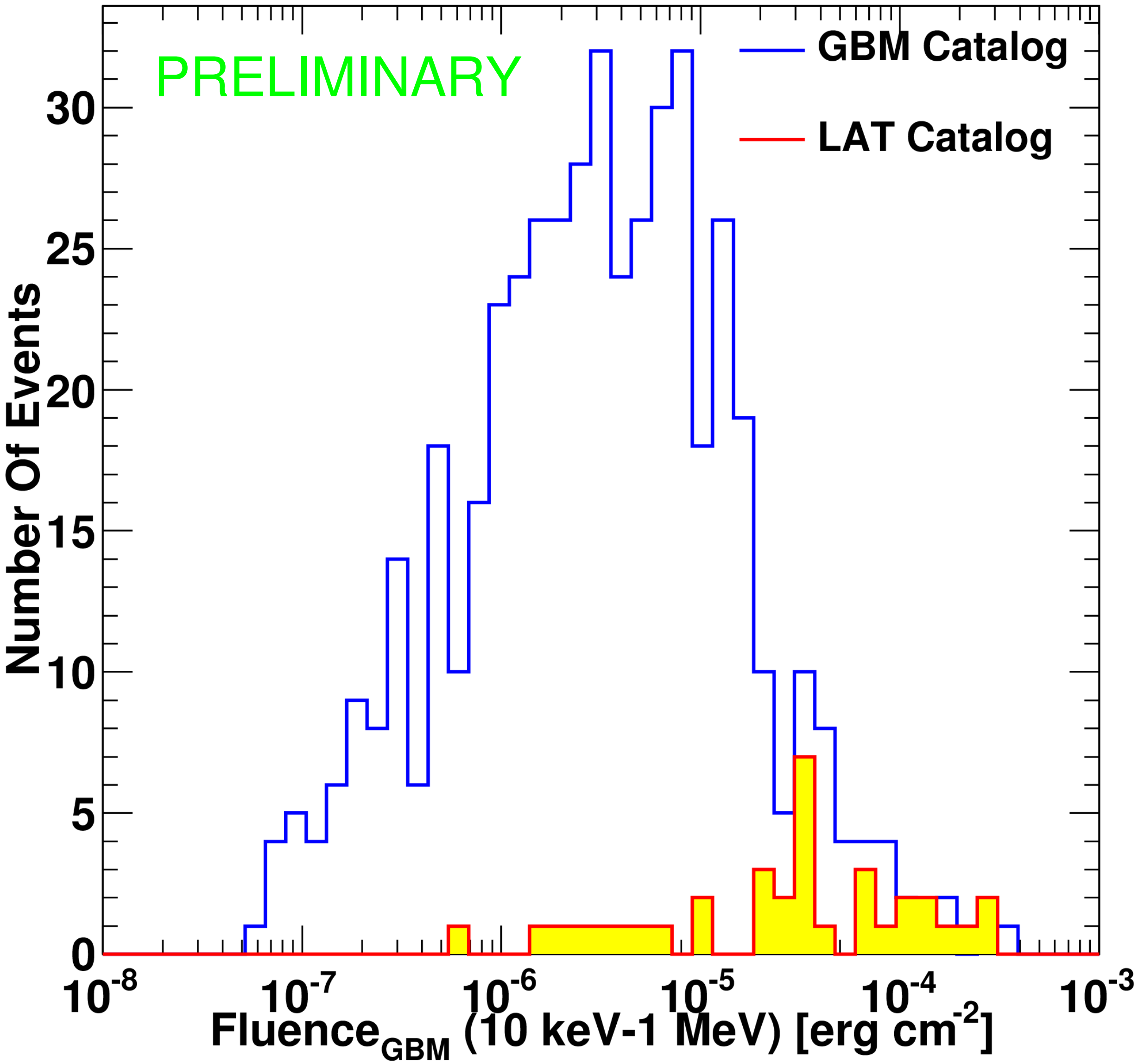
- 6 GBM very bright bursts not detected by the LAT show some form spectral softening at tens of MeV
- Assume that this is due to internal opacity effects and set upper limits on the bulk Lorentz factors
  - We only know the redshift for 091127 so we set $\Gamma_{max}(z)$ for the rest
  - Γ_{max}~150-650 assuming 100 ms variability and 1<z<5

Ackermann et al. 2012, ApJ 754, 121



- Target photon field for γγ absorption assumed uniform, isotropic and time-independent (but error bar for GRB 090926A accounts for different models)
  - Granot 2008, Hascoet & Daigne 2011 give significantly (~3 times) lower values

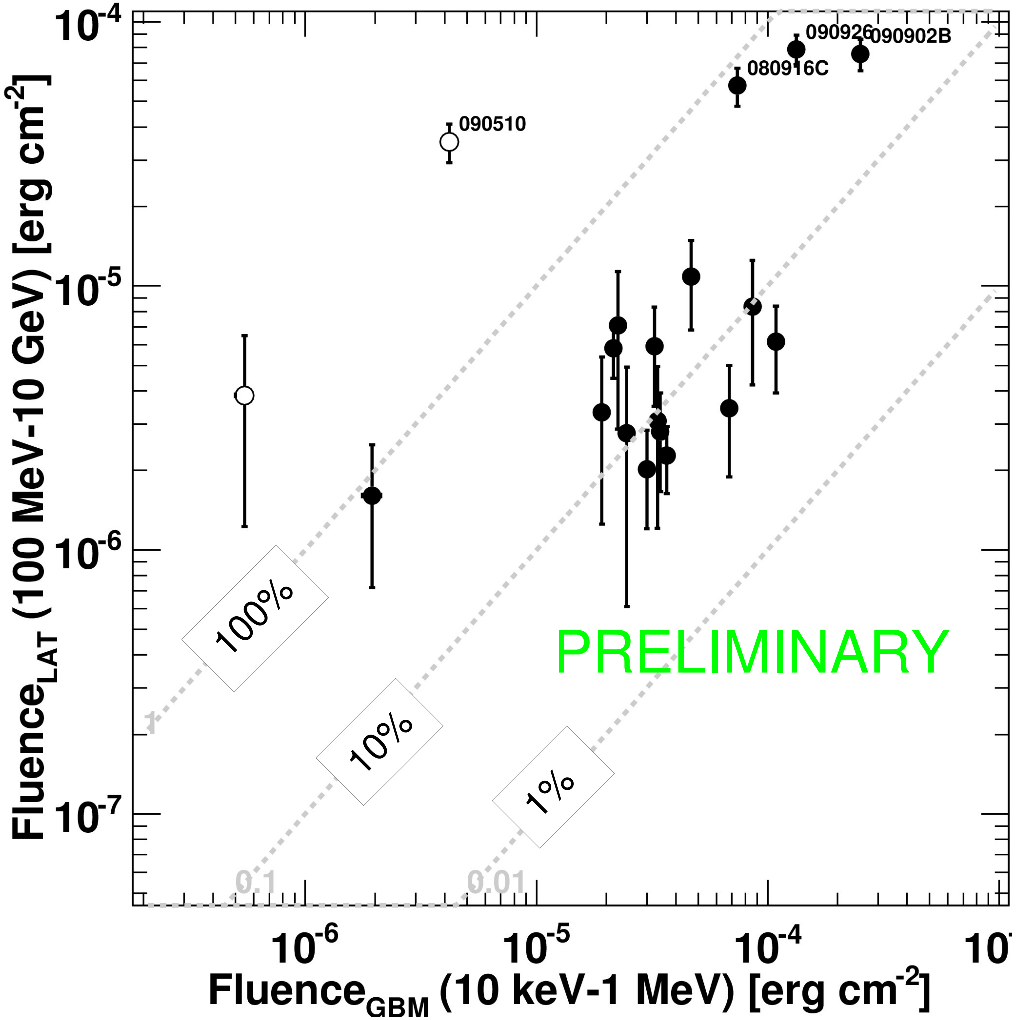
GBM fluence of LAT GRBs

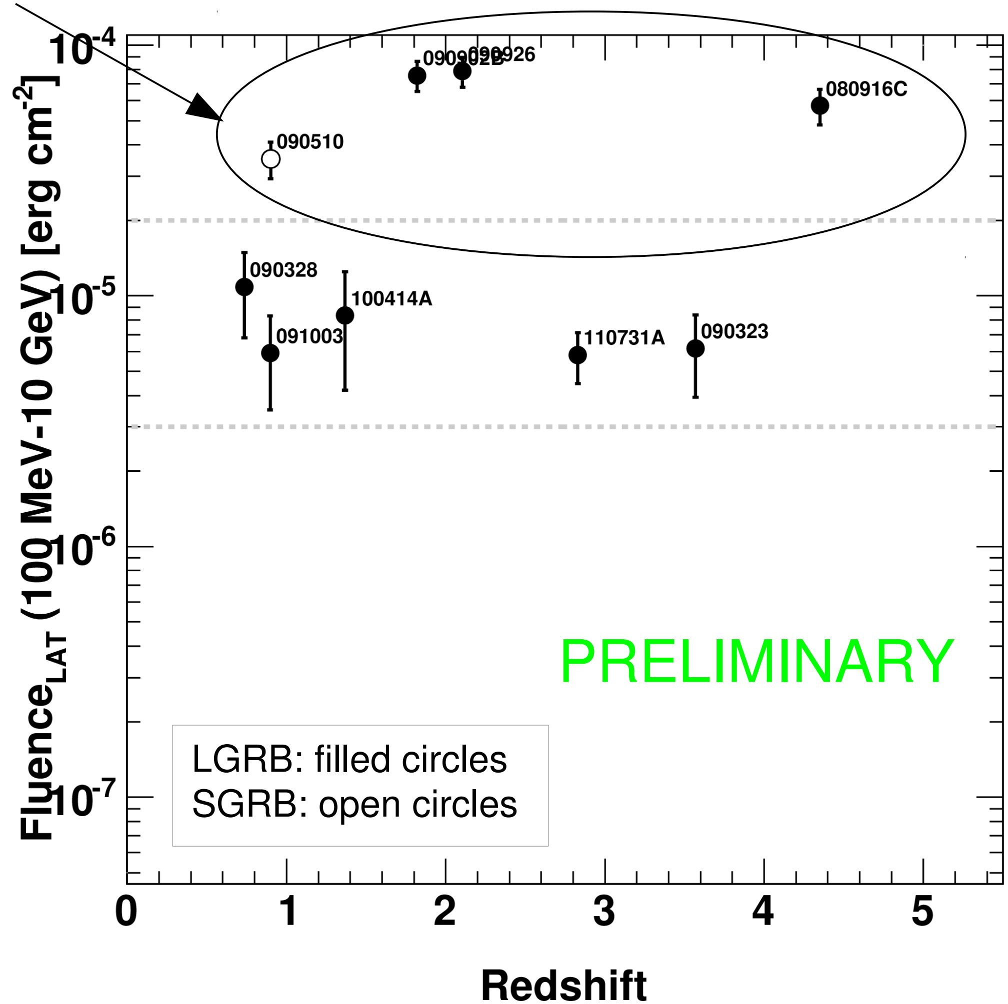


- Fluence in GBM energy range and "GBM" time window
  - LAT GRBs vs. entire sample in GBM spectral catalog (Goldstein et al. 2012)
- Not surprisingly, LAT GRBs are among the brightest GBM GRBs
  - Selection effects (ARRs) should be investigated though

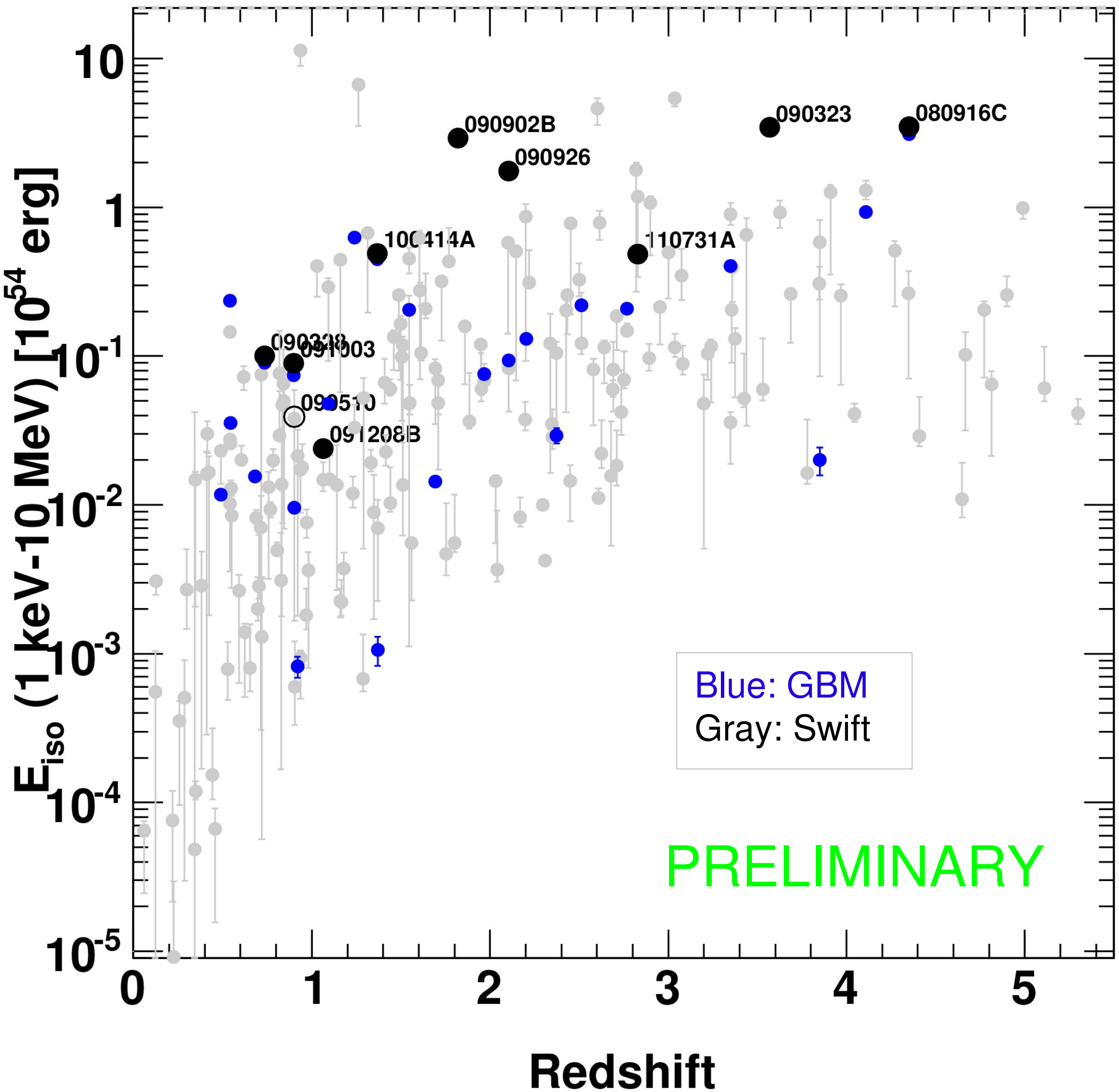
GBM vs. LAT fluences

- GBM and LAT fluences computed in “GBM” and “LAT” time windows, respectively
  - Long GRBs: LAT fluence ~10% of GBM fluence
  - Short GRBs: LAT fluence > GBM fluence
- A hyper-energetic class of long bursts? GRBs 080916C, 090902B, 090926A are exceptionally bright
  - They do not appear bright because they are systematically closer to us





Energetics



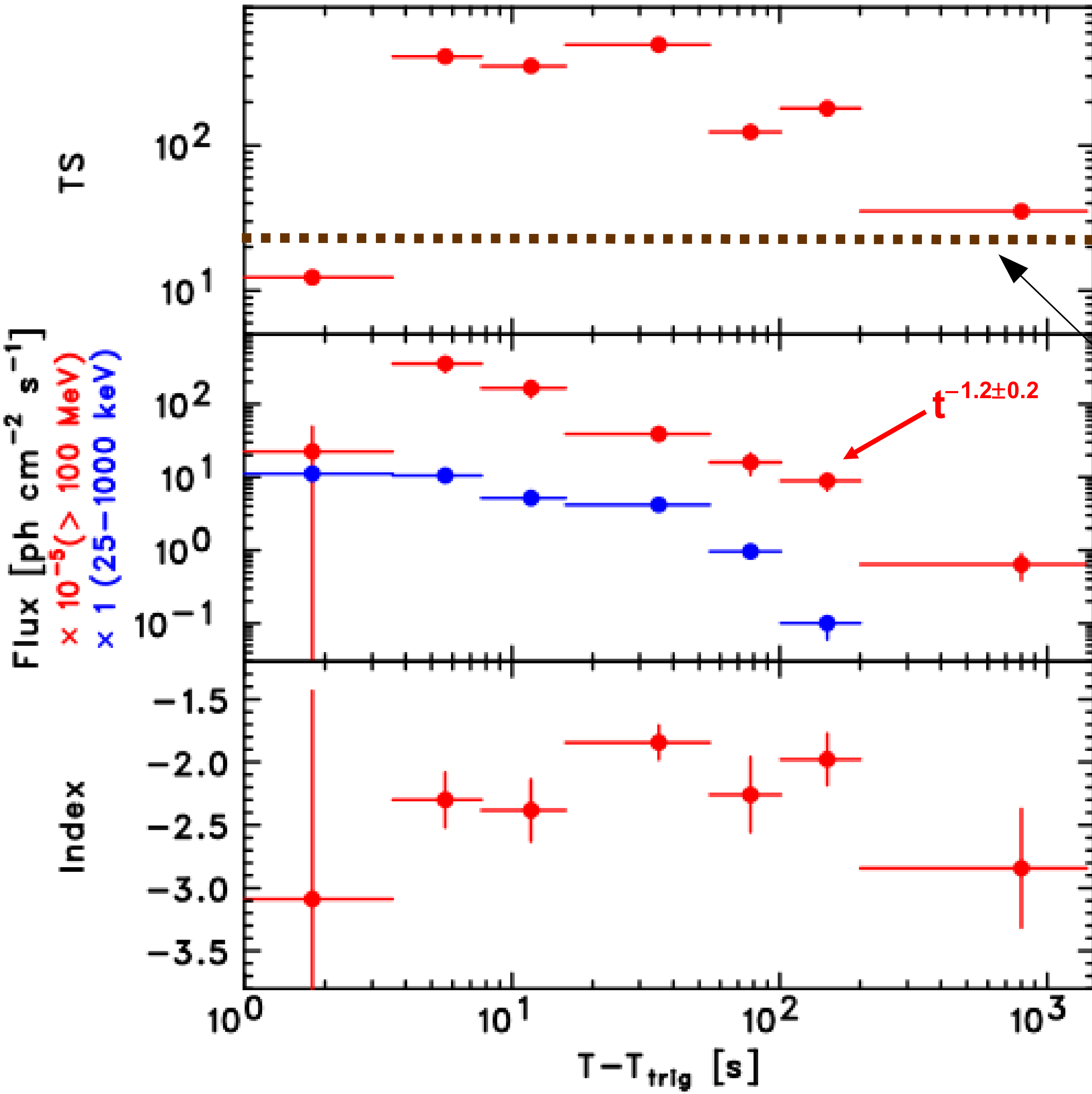
- 10 GRBs with known redshift
- E_{iso} (1 keV - 10 MeV) in "GBM" time window vs. redshift
  - LAT GRBs vs. GBM (Goldstein et al. 2012) and Swift (Butler et al. 2007) samples
- LAT GRBs are among the most energetic bursts, both intrinsically and observationally
- GRB 090510 is also one of the most energetic short bursts
- No particular trend in redshift (small sample)

Les sursauts gamma vus par *Fermi*

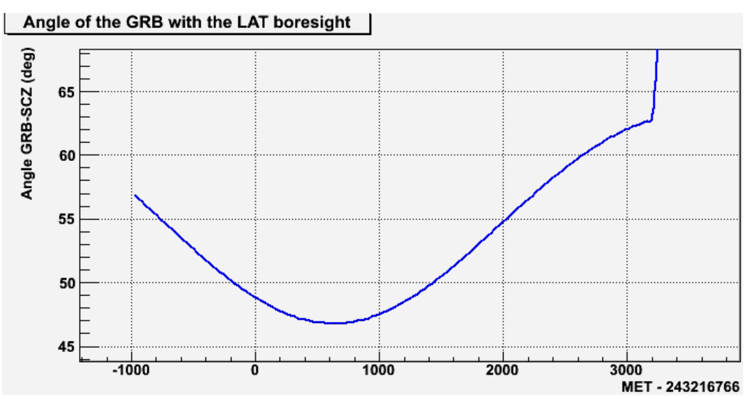
Long lasting GeV emission

GRB 080916C

Abdo et al. 2009, Science 323, 1688



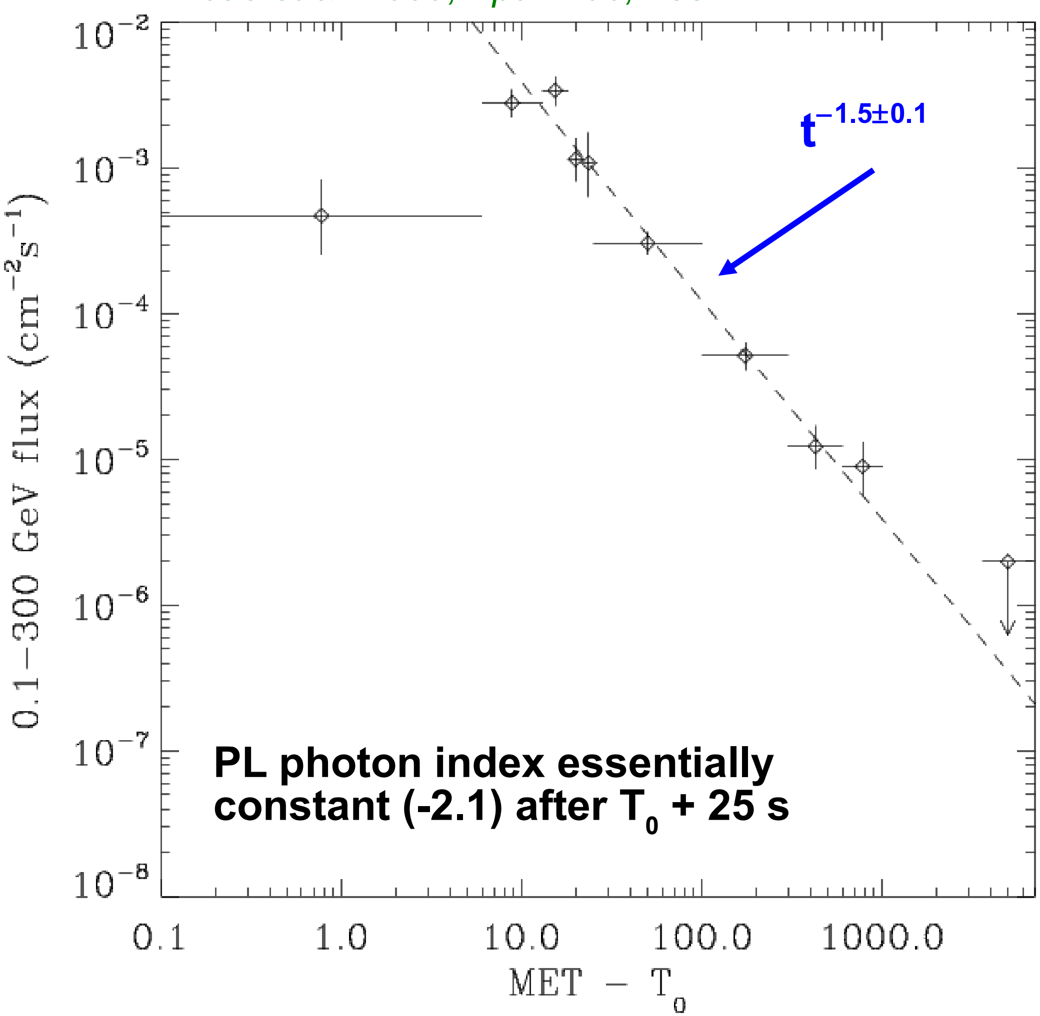
- **GBM emission drop-off ~55 seconds after T_0**
- **Significant LAT emission from T_0+3.6 s to T_0+1400 s**
  - **Tighter event selection cuts, optimized for weak sources**
  - **Test Statistics>25 with position fixed at GROND location: TS > 25 (square of significance)**
  - **Still significant (5.9σ) between T_0+200 s and T_0+1400 s, and consistent with the trend from the prompt emission**



GRBs 090902B and 090926A

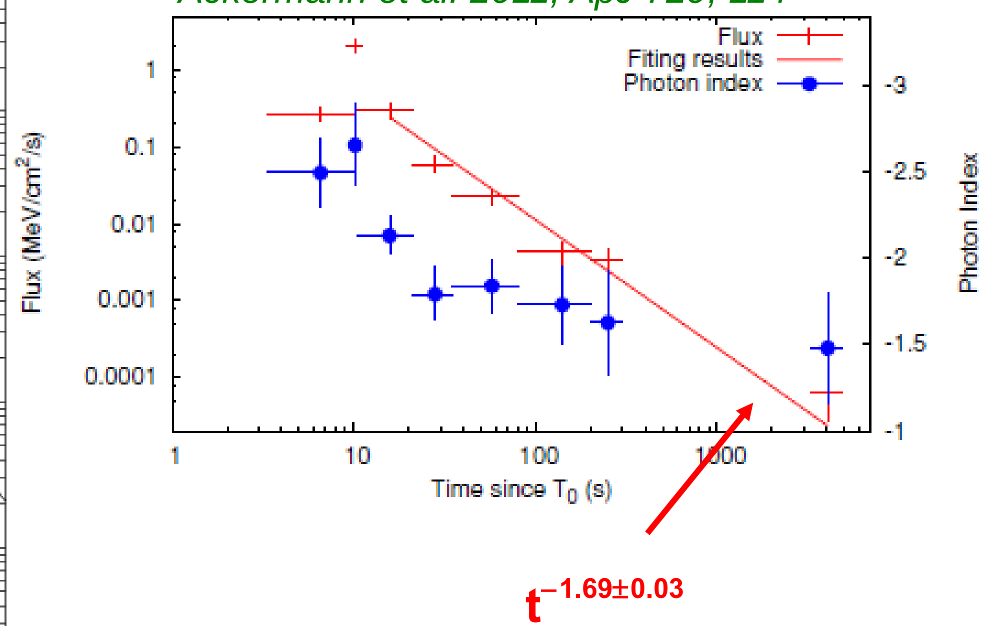
GRB 090902B

Abdo et al. 2009, ApJL 706, 138



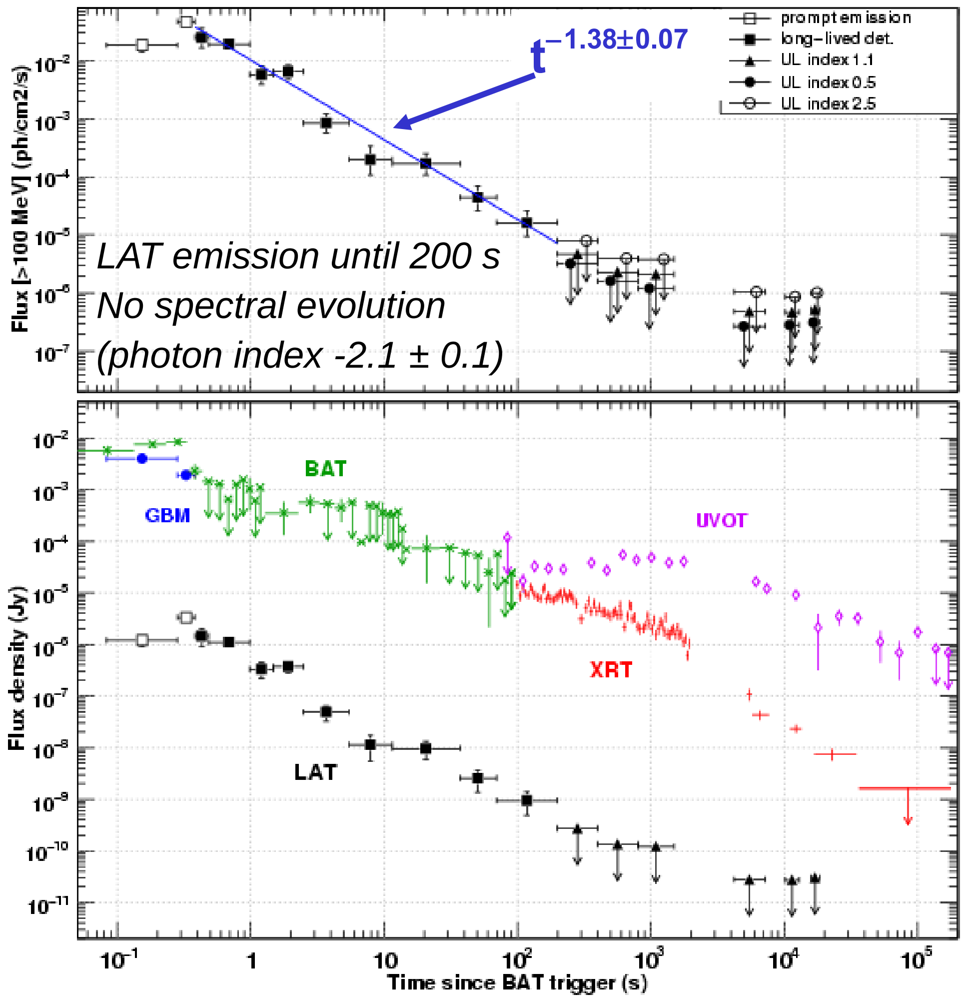
GRB 090926A

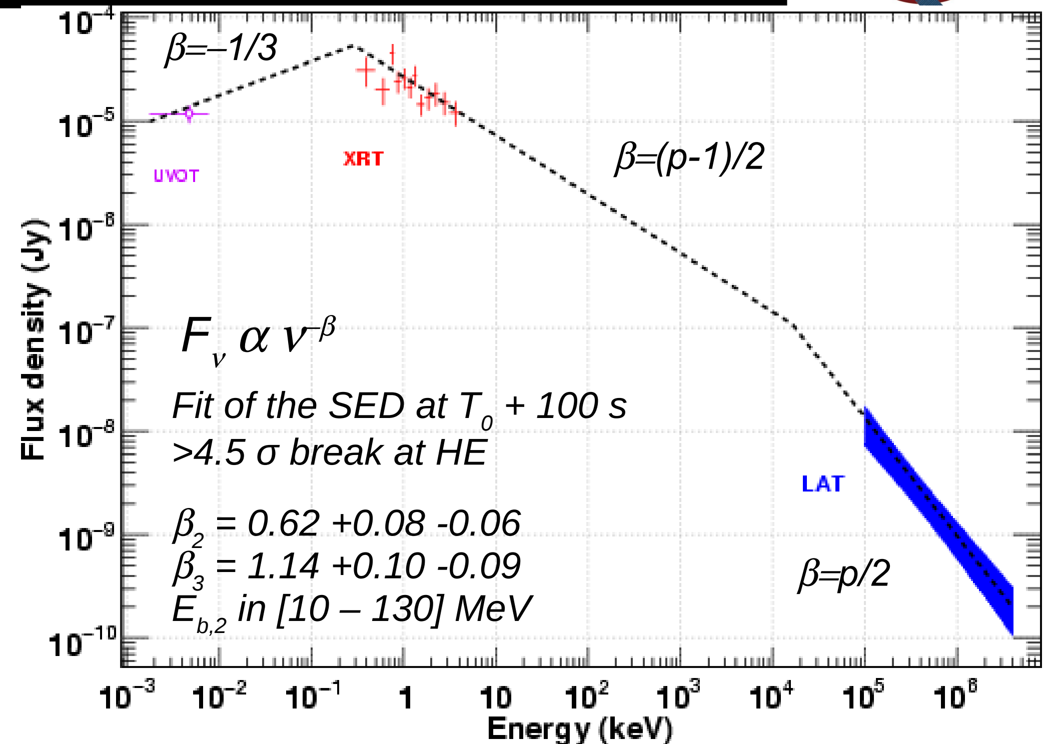
Ackermann et al. 2011, ApJ 729, 114

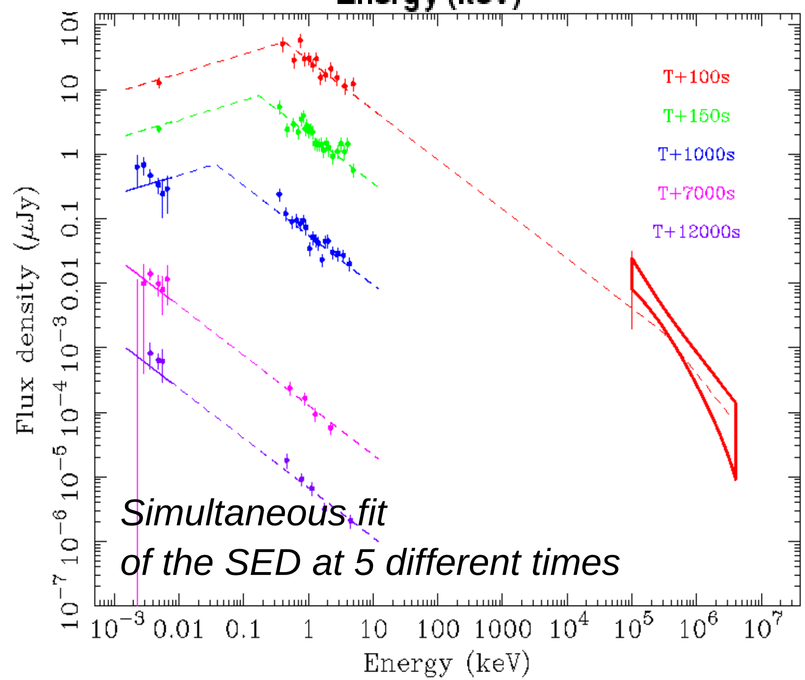


Swift and *Fermi* view of GRB 090510

De Pasquale et al. 2010, ApJL 709, 146



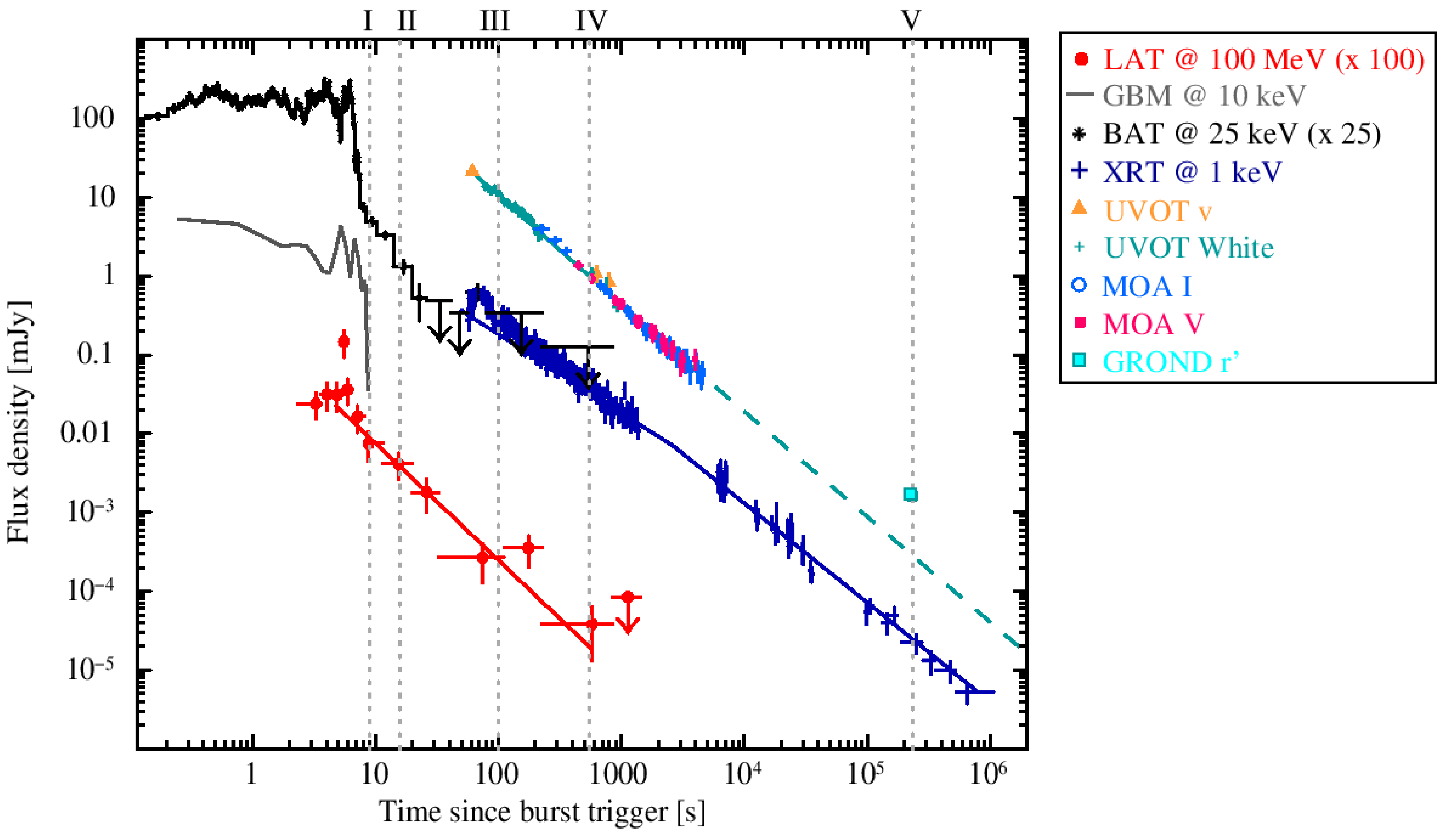




- Forward shock model can reproduce the spectrum from the optical up to GeV energies! (non thermal synchrotron emission from the decelerating blast wave)
- Extensions needed to arrange the temporal properties

Swift and *Fermi* view of GRB 110731A

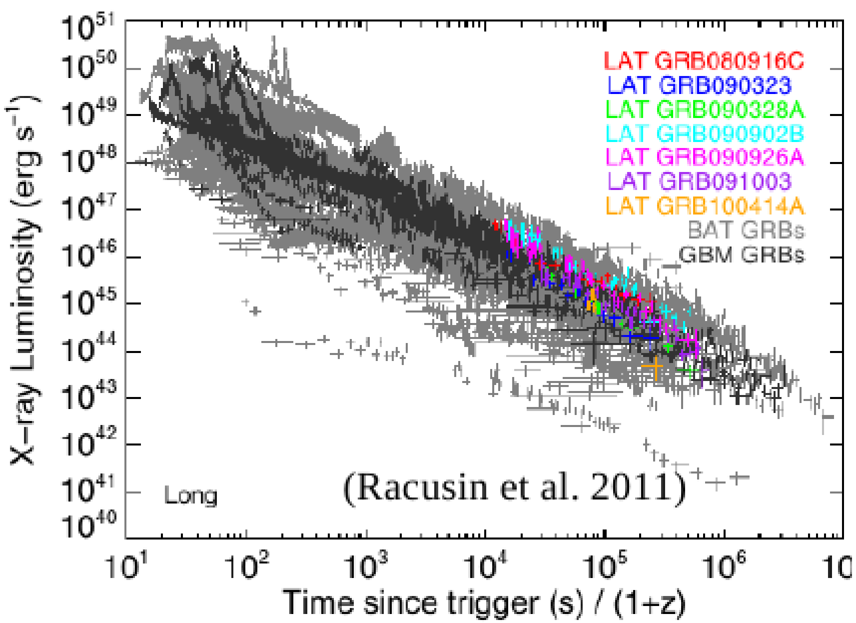
Ackermann et al. 2013, ApJ 763, 71

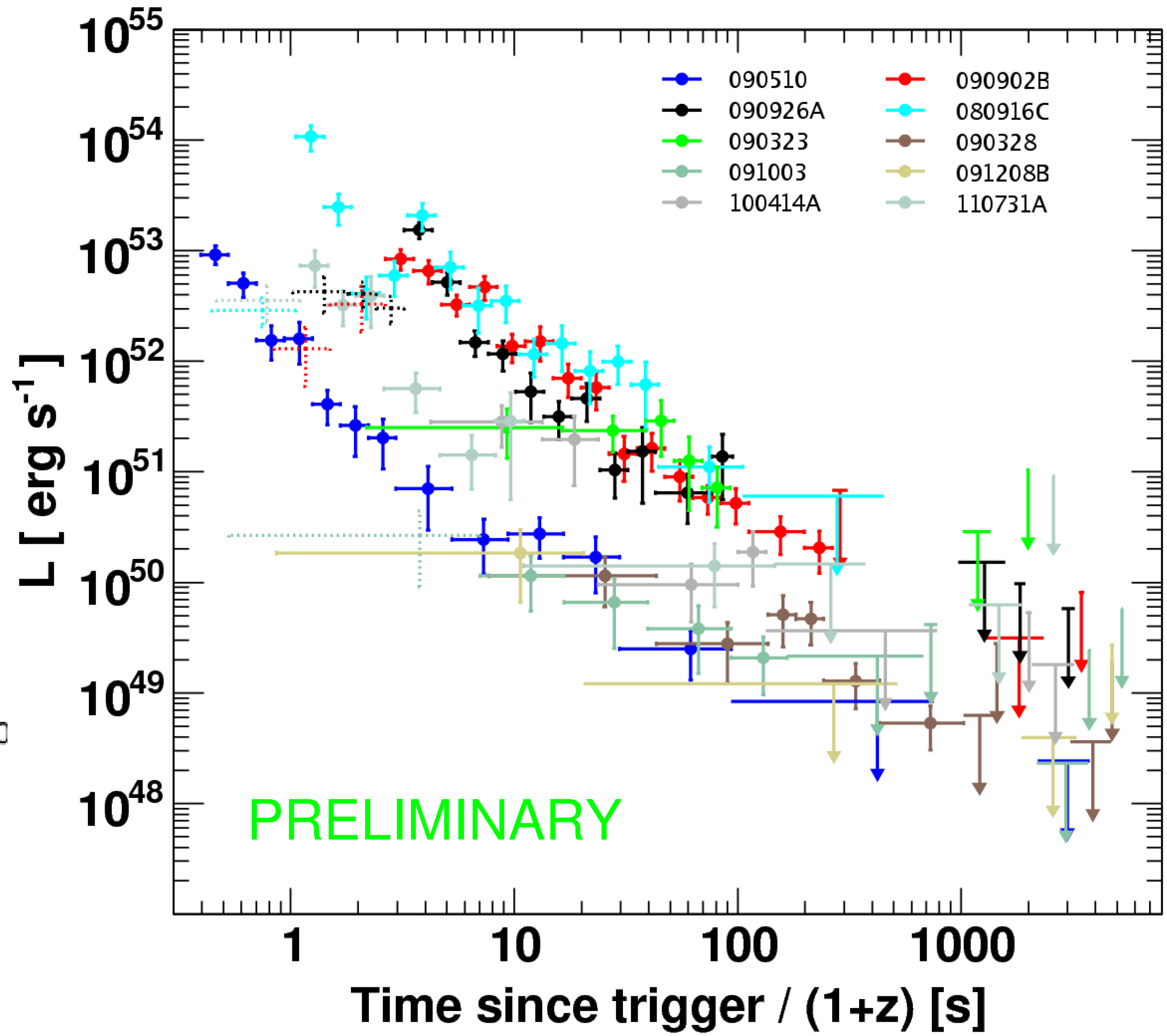


Afterglows of LAT GRBs are bright

- Photon spectral index is constant and typically averages around $\Gamma_{EXT} \sim -2$
- Rest-frame luminosity (100 MeV – 10 GeV) in the afterglow phase: $L(E,t) \sim t^{-\alpha}E^{-\beta}$

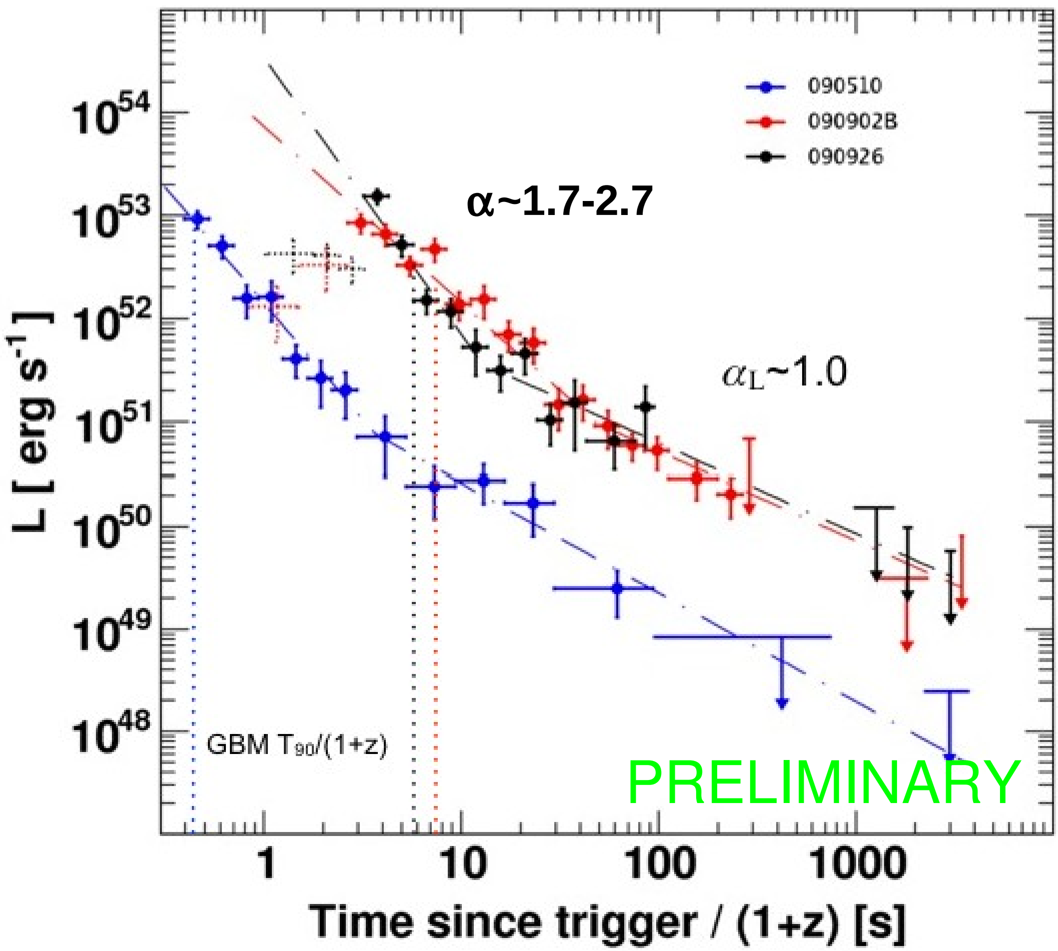
  $\beta = -\Gamma_{EXT} - 1 = 1$, $\alpha = 1$ for an adiabatic fireball in a constant density environment (10/7 if radiative)

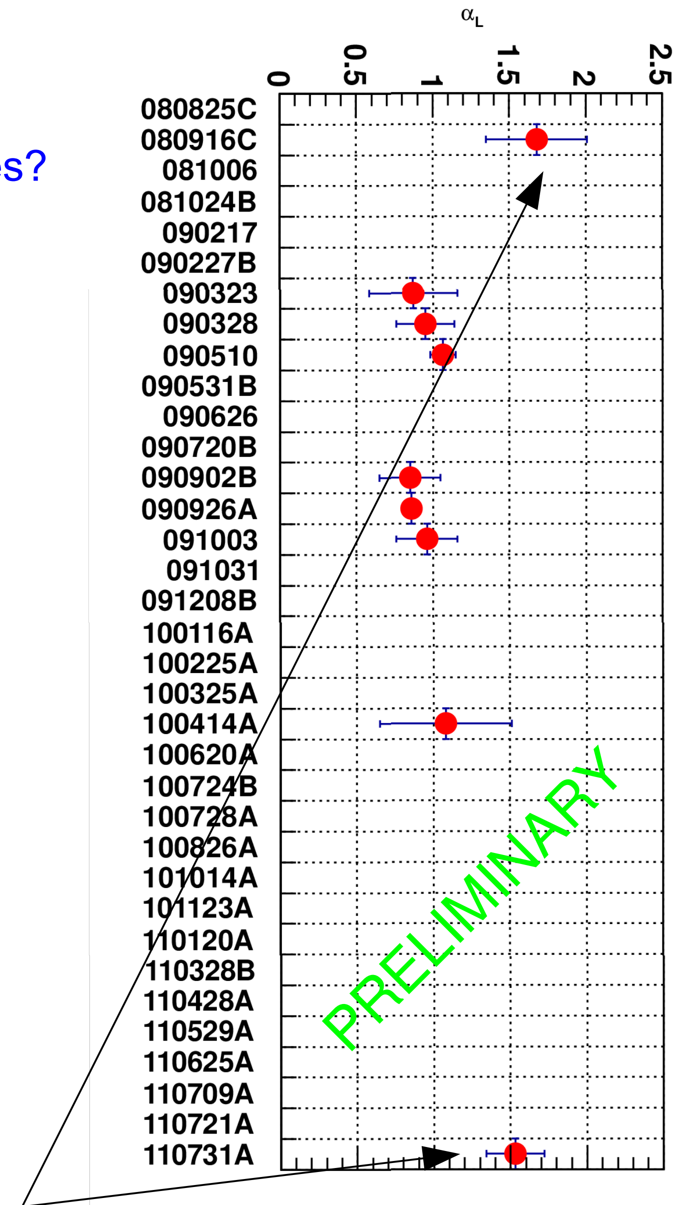




Decay of the high-energy flux

- Light curves fitted with a simple or a broken power law (BPL)
- BPL significant in 3 cases (chance probability < 10^{-3})
  - Transition between prompt- and afterglow-dominated phases?
- α_L ~ 1 at late times → adiabatic fireball



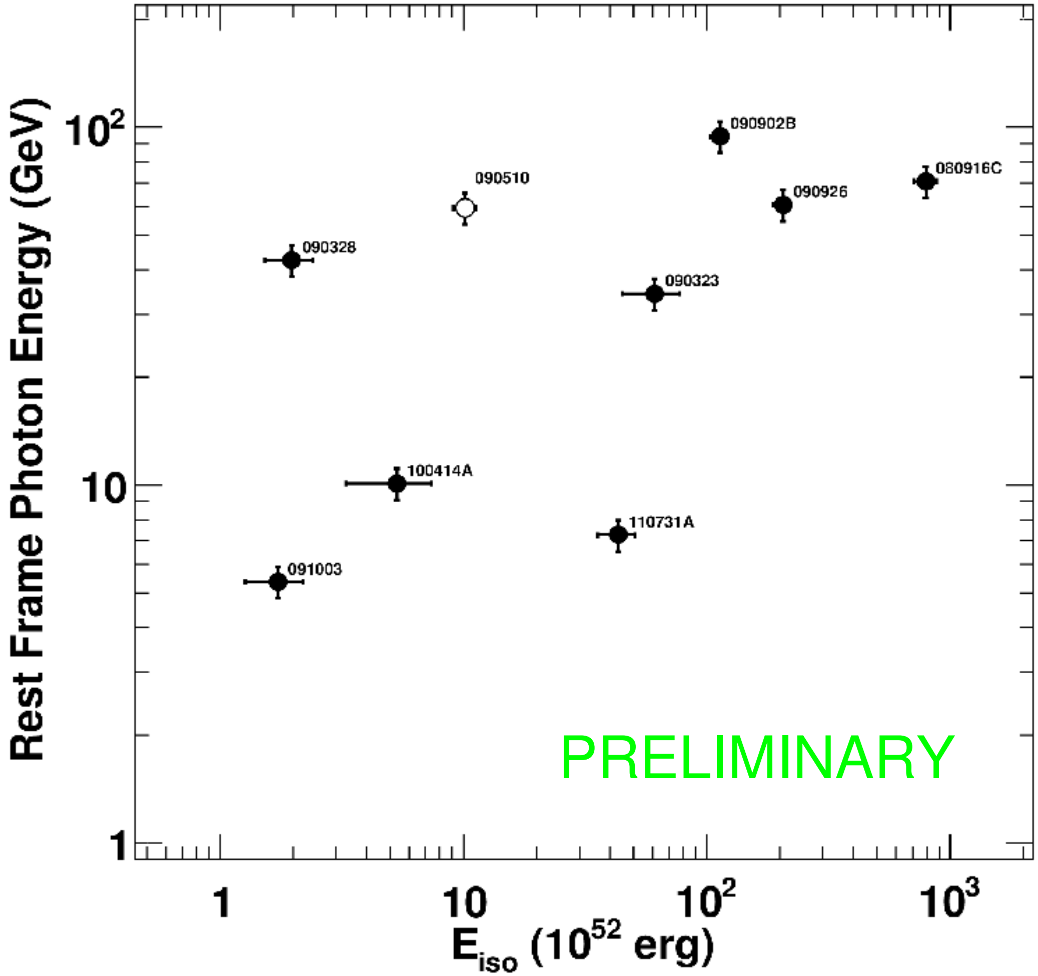


- 2 outliers: break not detected?

Les sursauts gamma vus par *Fermi*

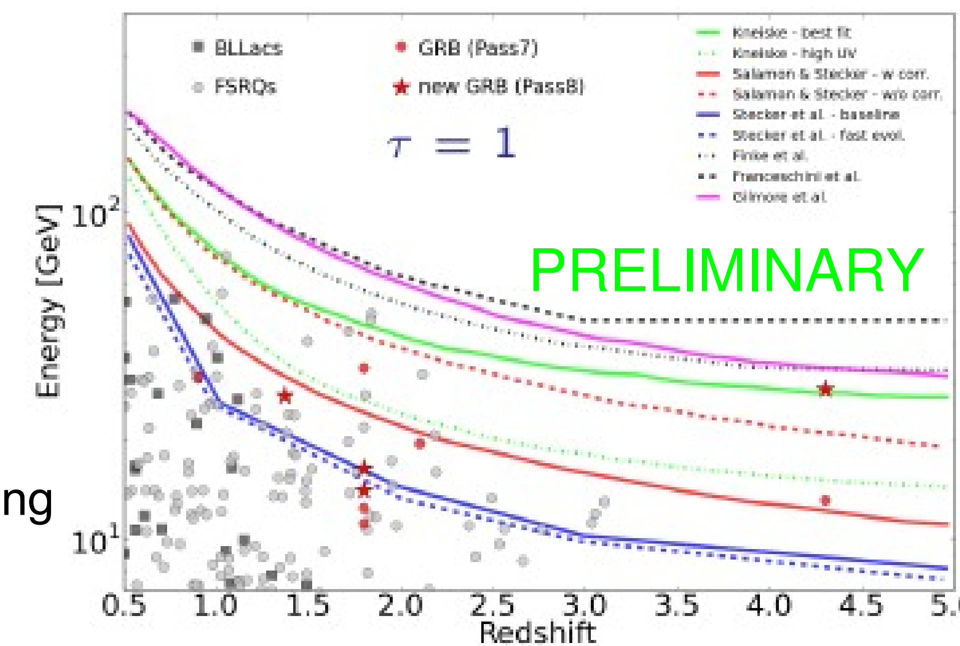
Sonder l'Univers et la nature de l'espace-temps

Highest-energy detected photons



- Several tens-of-GeV photons in the rest frame
  - Constraints on jet Lorentz factor
  - Constraints on LIV (Vasileiou's talk)
  - Constraints on EBL

- Encouraging for VHE observatories (HAWC, CTA)



- Even better with "Pass8" : 4 new photons, among which a 28 GeV photon from GRB 080916C (147 GeV rest frame)

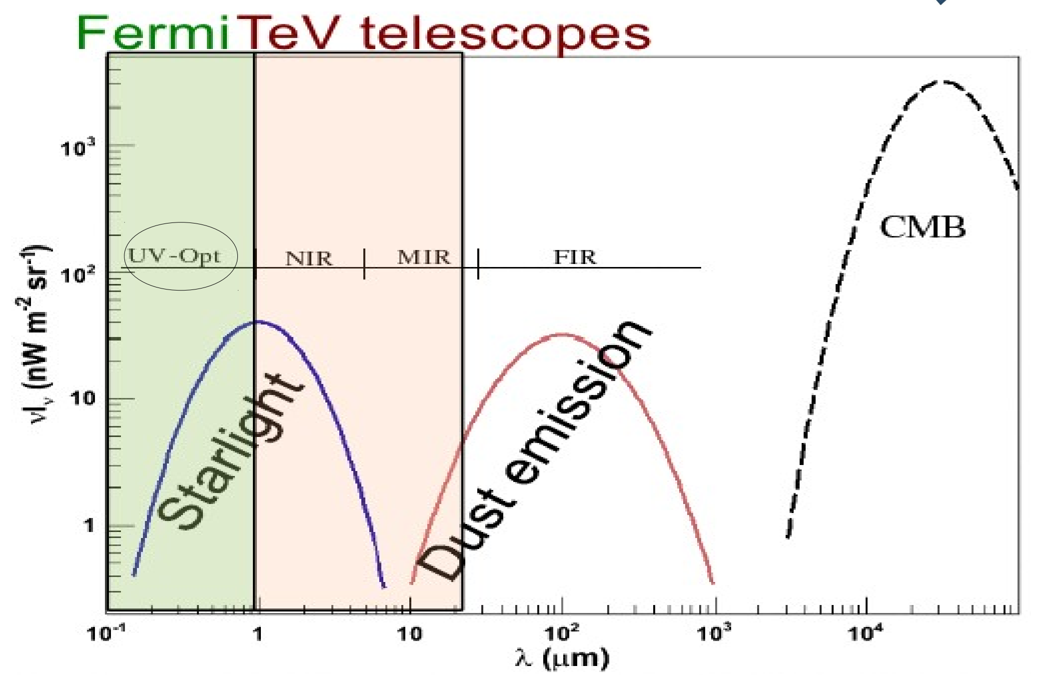
The extragalactic background light (EBL)

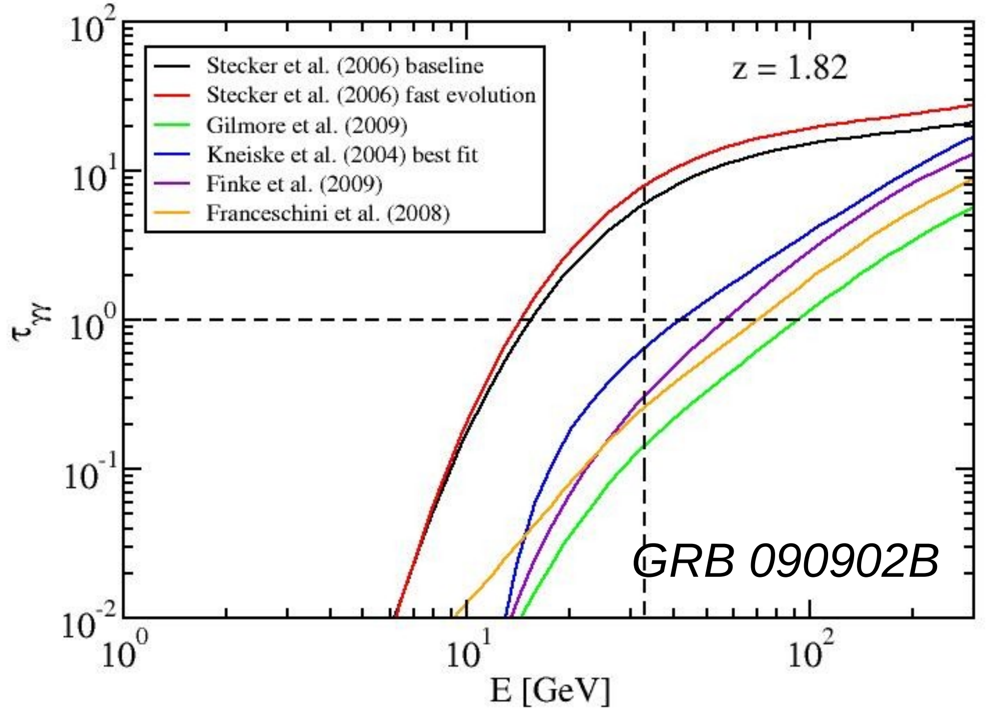
- Accumulation of all energy releases in the form of electromagnetic radiation
- Includes everything but CMB and the local foreground emissions (Milky Way, Solar System, etc.)

- Opacity effect: E>GeV gamma-rays from extragalactic sources interact with it through $\gamma\gamma \rightarrow e^- e^+$

- Why is it important?
  - Contains information about the evolution of matter in the universe: SFR, dust extinction, light absorption and re-emission by dust, etc.
  - Its knowledge is necessary to infer the actual spectra of extragalactic gamma-ray sources.

- Observations of spectra that show no signs of absorption and that extend to >10 GeV energies from extragalactic sources can set upper limits on the opacity of the universe or equivalently on the density of the EBL





GRB observations and the EBL

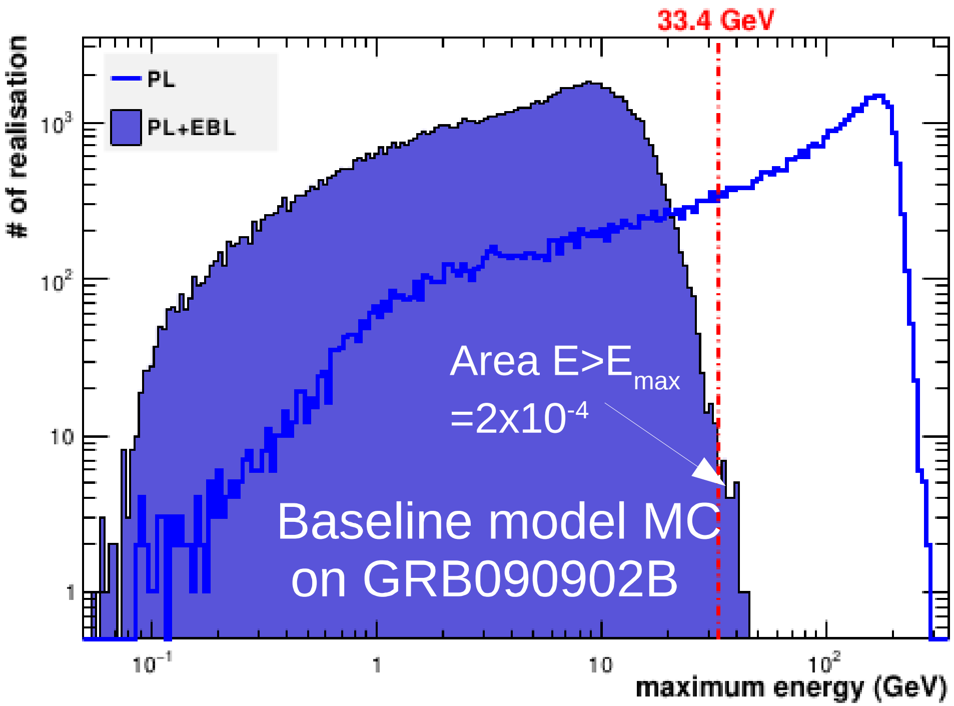
1. Assume intrinsic spectrum extends "as is" (with no extra curvature, breaks, etc.) from unabsorbed-by-the-EBL energies (say under ~10 GeV) to higher energies
2. Calculate probability of this assumed intrinsic spectral model giving a detected photon of energy $E \geq E_{max}$ (for our actual observation of the source).

Application to the Stecker et al. Baseline model. The Fast Evolution model predicts an even higher opacity

Source	z	E_{max} (GeV)	$\tau(z, E_{max})$ (St06, baseline)	Number of photons above 15 GeV	HEP method applied to Stecker 06 P_{HEP}	$P_{rejection}$	HEP Rejection Significance
GRB 090902B	1.82	33.4	7.7	1	2.0×10^{-4}	2.0×10^{-4}	3.7 σ
GRB 080916C	4.24	13.2	5.0	1	6.5×10^{-4}	6.5×10^{-4}	3.4 σ

Abdo et al. 2010, ApJ 723, 1082

- Stecker et al. ('06) Baseline and Fast Evolution models predict too much opacity
  → probability for $E \geq E_{max}$ applied on our GRB090902B and 080916C observations too low
- These results are part of a more comprehensive paper that uses multiple methods on multiple source types (blazars and GRBs)
- Overall results significantly (>11σ) reject these two EBL models



Constraints on Lorentz Invariance Violation (1/3)

- There is a fundamental scale (the Planck scale $\lambda_{Pl} \approx 10^{-35}$ m) at which quantum gravity (QG) effects are expected to strongly affect the nature of space-time

- Lorentz symmetry implies a scale-free space-time (all scales are equivalent) → QG effects may cause violations of Lorentz Invariance (LIV)
  → speed of light in vacuum may acquire a dependence on its energy → $\upsilon_\gamma(E_\gamma) \neq c$

- The Lorentz-Invariance violating terms are typically expanded using a series of powers of the photon energy E_γ over the *Quantum Gravity mass* M_{QG}:

$$c^2 p_\gamma^2 = E_\gamma^2 \left[1 + \sum_{n=1}^{\infty} s_n \left(\frac{E_\gamma}{M_{QG,n} c^2} \right)^n \right]$$

  where $s_n = \{-1, 0, +1\}$ is a model-dependent factor

- The Quantum-Gravity Mass M_{QG}
  - Sets the energy (mass) scale at which QG effects become important.
  - Is expected to be of the order of the Planck Mass and most likely smaller than it

$$M_{QG} \lesssim M_{Planck} \equiv \sqrt{\hbar c/G} \simeq 1.22 \times 10^{19} GeV/c^2$$

Constraints on Lorentz Invariance Violation (2/3)

- Since $E_\gamma \ll M_{QG,n}c^2$, the sum is dominated by the lowest-order term (n) with $s_n \neq 0$, usually n=1 or 2 ("linear" and "quadratic" LIV respectively):

$$u_\gamma = \frac{\partial E_\gamma}{\vartheta p_\gamma} \simeq c\left[1 - s_n \frac{1+n}{2}\left(\frac{E_\gamma}{M_{QG,n}c^2}\right)^n\right]$$

where s_n=+1 or -1 for subluminal and superluminal speeds respectively.

- There are many models that allow such LIV violations, and some others that actually require them (e.g. stringy-foam model J. Ellis et al. 2008)

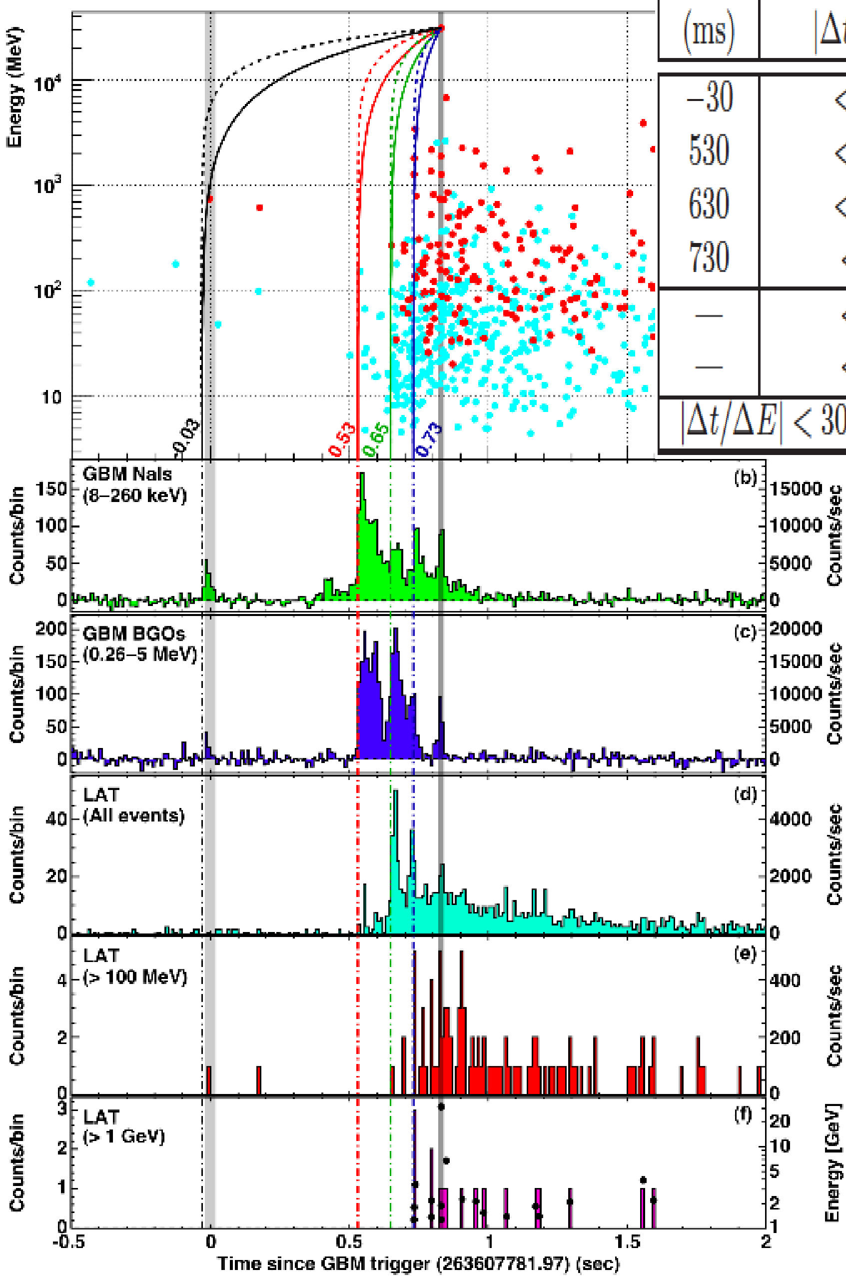
- If the speed of light depends on its energy, then two photons with energies $E_h > E_l$ emitted together will arrive at different times. For s_n=+1 (speed retardation):

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

- We want to constraint LIV → Set lower limits on $M_{QG,n}$
- We accomplish that by setting upper limits on the time delay Δt between photons of different energies.

Constraints on Lorentz Invariance Violation (3/3)

Abdo et al. 2009, Nature 462, 331



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	—

- 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

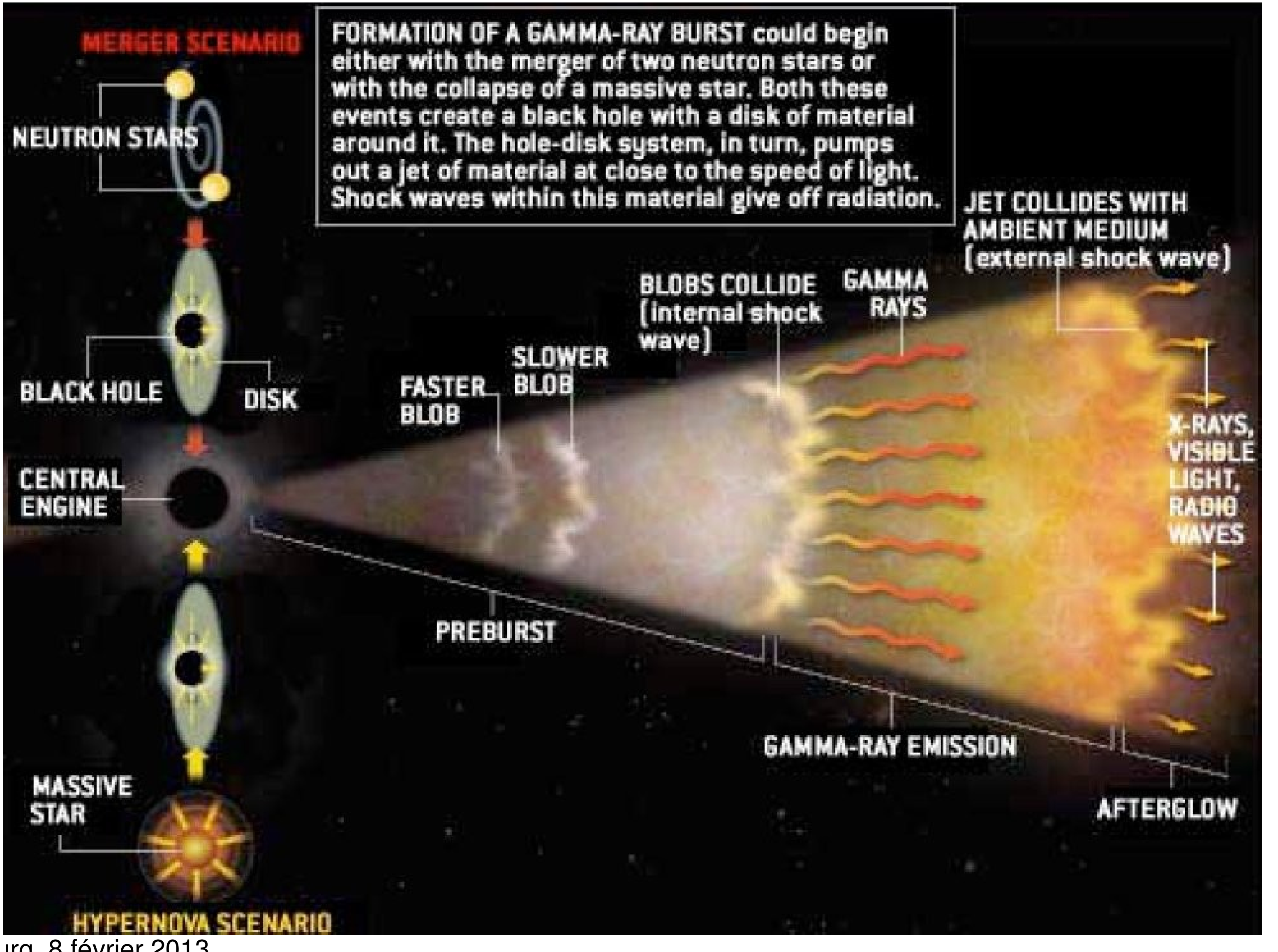
Summary

- The *Fermi* GBM and LAT have jointly detected the keV-MeV-GeV emission from a large sample of GRBs
  - 35 LAT GRBs in the first 3 years of operations
- Population studies indicate (or confirm) interesting patterns and emergent groups
  - Short and long GRBs seem to have similar HE properties, but short GRBs may be harder
    - Delayed onset of LAT >100 MeV emission with respect to GBM emission
    - Temporally extended LAT >100 MeV emission beyond the burst duration in GBM
    - LAT GRBs are among the brightest sub-population of GBM GRBs, and have bright afterglows
    - LAT GRBs are the most energetic ones (only ~10%-20% of their energy is radiated in the LAT range)
  - Evidence of a class of hyper-energetic GRBs (4 bursts)
  - Fewer GRBs are detected by the LAT than would be expected by extrapolating BATSE/GBM spectra
    - The 3 brightest LAT GRBs show a distinct HE spectral component (PL) and have a high $\Gamma_{min} \sim 1000$
    - Extra components must be rare: softening or high-energy cutoffs in other GRB spectra $\rightarrow \Gamma_{max}$
- Prompt emission
  - Leptonic or hadronic emission at high energies? Band model crisis: not enough to describe the spectra of the best-observed *Fermi* GRBs. Multi-zone / component models needed?
  - Highest energy photons constrain EBL models && provide best lower limits on LIV (n=1 disfavored)
- Long-lived GeV emission
  - Power-law temporal decay extending up to a few ks (~5 ks for GRB 090926A)
  - How the extended emission relates to the hard PL component seen in the prompt emission spectra?
  - Most likely comes from external shock (FS), e.g., GRBs 090510, 110731A

Backup

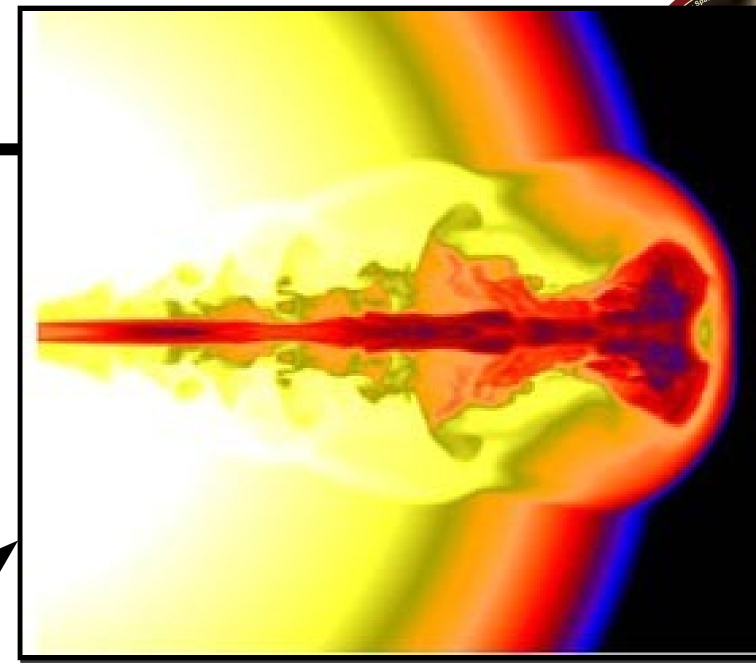
"Boule de feu" et chocs internes / externes

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

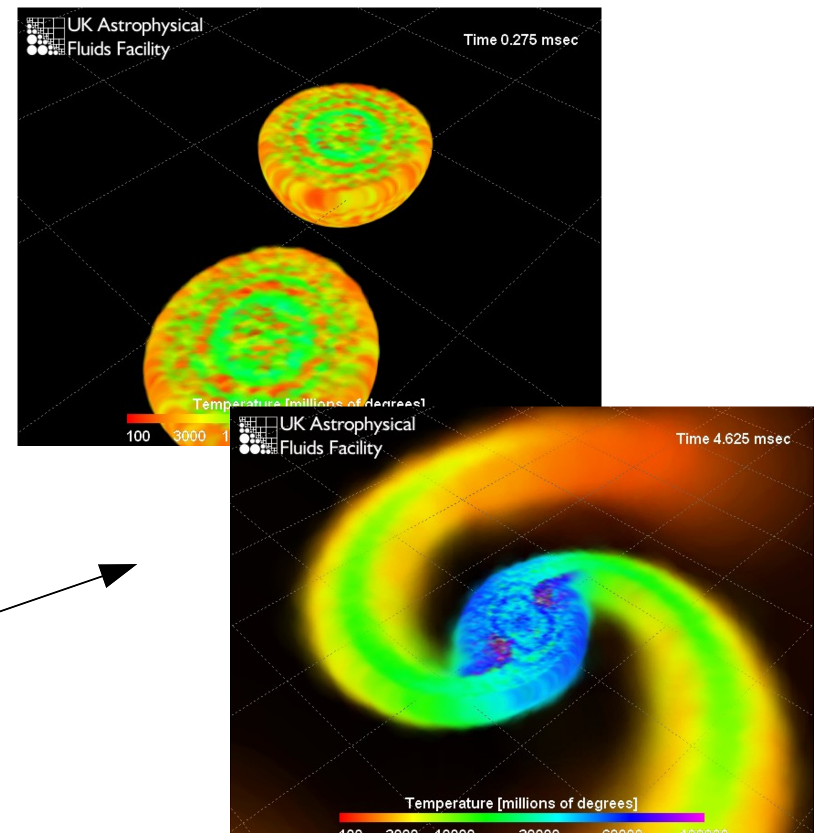


Progéniteurs ?

- 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

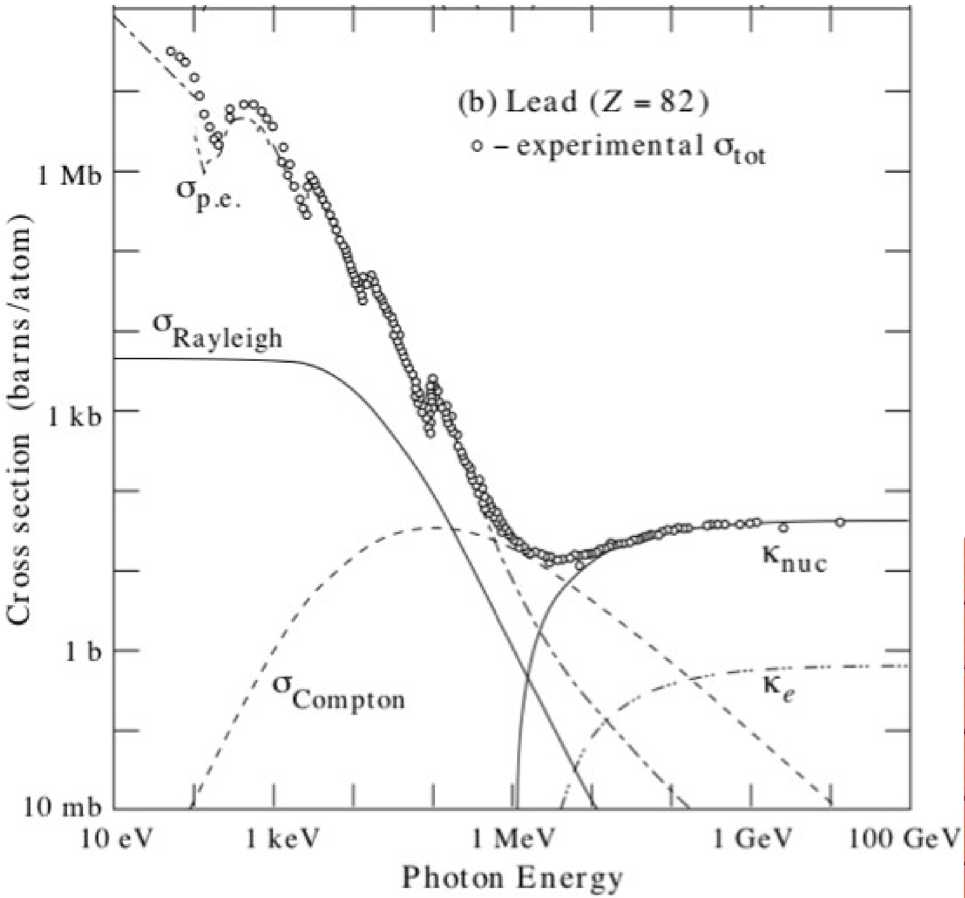


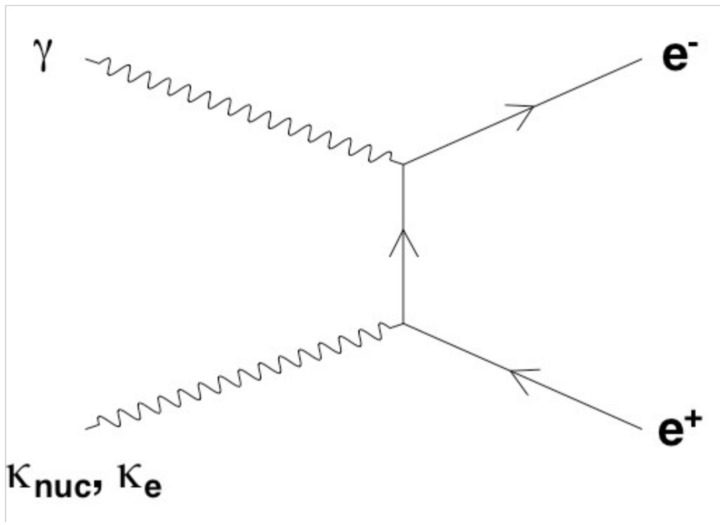
- Sursauts courts (< 2s)
  - ~15% des sursauts détectés
  - Associés à des galaxies elliptiques (population d'étoiles vieilles)
  - Fusion d'objets compacts (NS-NS ou NS-BH), émission attendue d'ondes gravitationnelles
  - Echelle de temps de la fusion de l'ordre de la ms
  - Ejection dans une région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

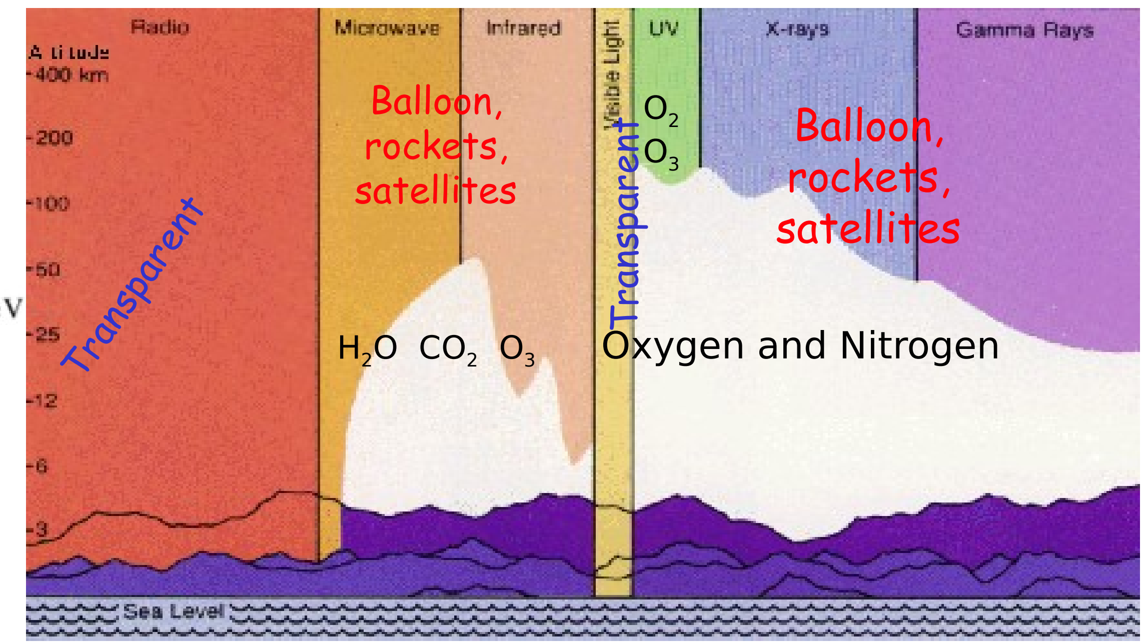


Gamma-ray astronomy in space

Pair conversion is the dominating interaction process for gamma rays (>10 MeV)

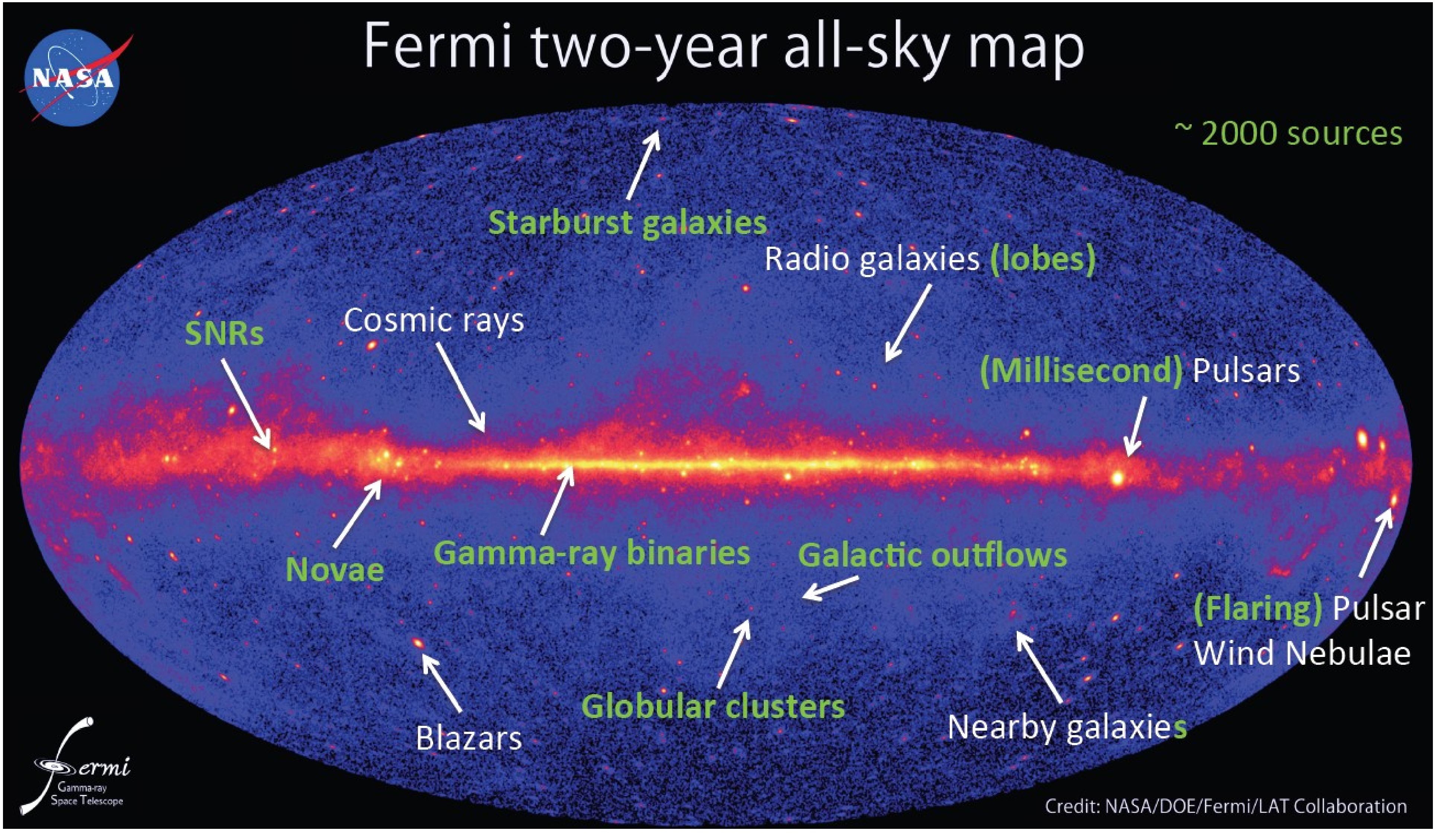






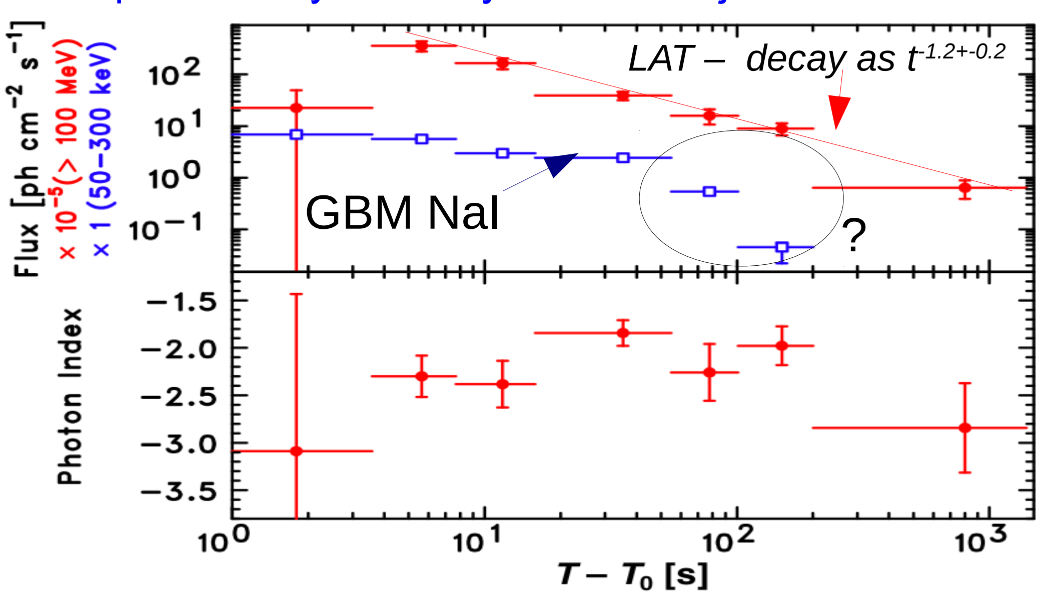
The atmosphere is opaque to gamma-rays:
(Non-VHE) gamma-ray astronomy is a domain of **balloons**, **rockets**, **satellites**!

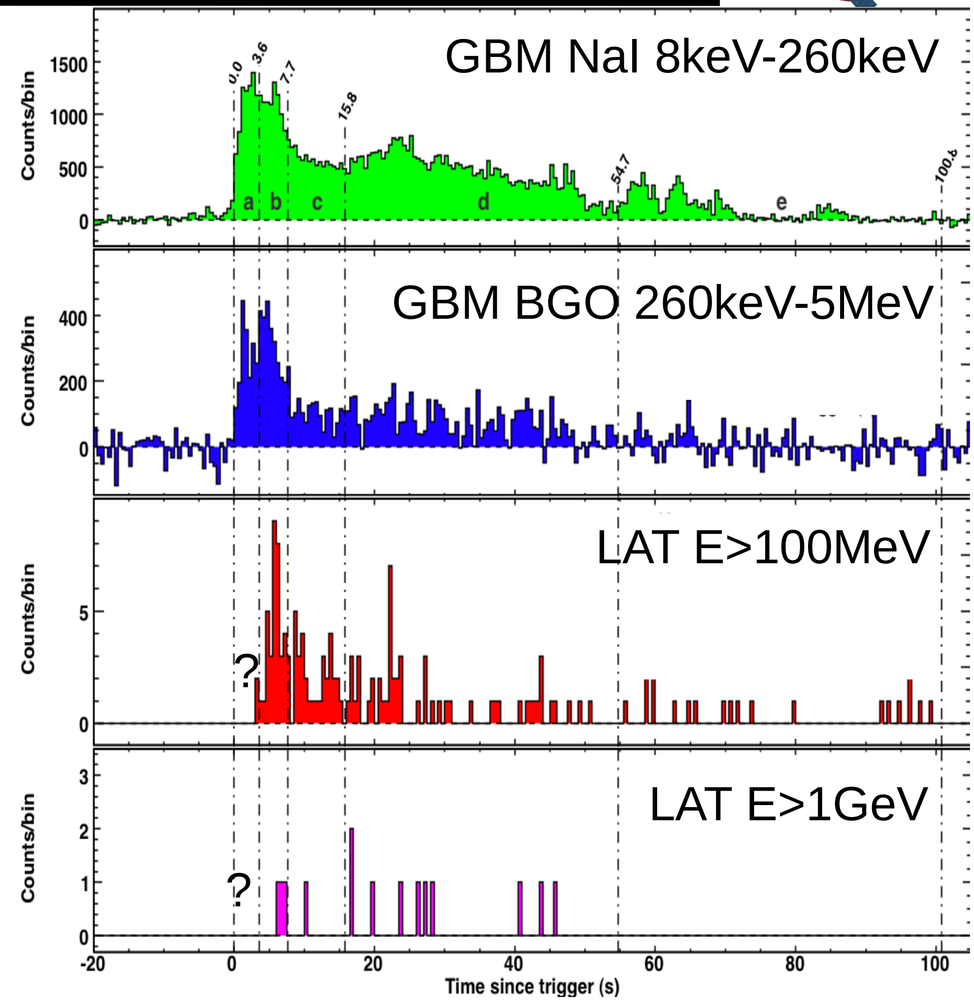
Fermi 2-year allsky map

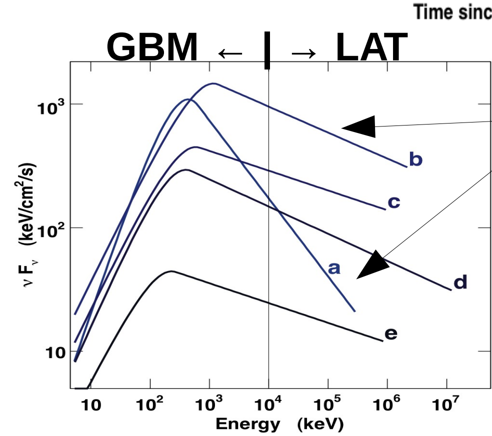


GRB 080916C: our first bright GRB

- LAT emission starts delayed and persists longer (up to 1.4ks) with respect to GBM emission
- Highest-energy photon detected: 13GeV at 16.5s
  - ~70GeV in the GRB frame (z=4.35)
  - Constrains dependence of c on E_γ
- Minimum bulk Lorentz Factor (γγ opacity arguments):
  - Γ_{min}=887+-21 and 608+-15 for bins b and d
- Minimum emission radius:
  - $R_{min} \approx \Gamma_{min}^2 c\Delta t/(1+z) = 9\times10^{55}$ cm for bin b
- Brightest E_{iso} ever measured:
  - 4.3×10^{54}erg (20keV–2MeV) and 9×10^{55} (10keV-10GeV)
  - implies a very narrowly-collimated jet







Delayed emission appears as a spectral hardening

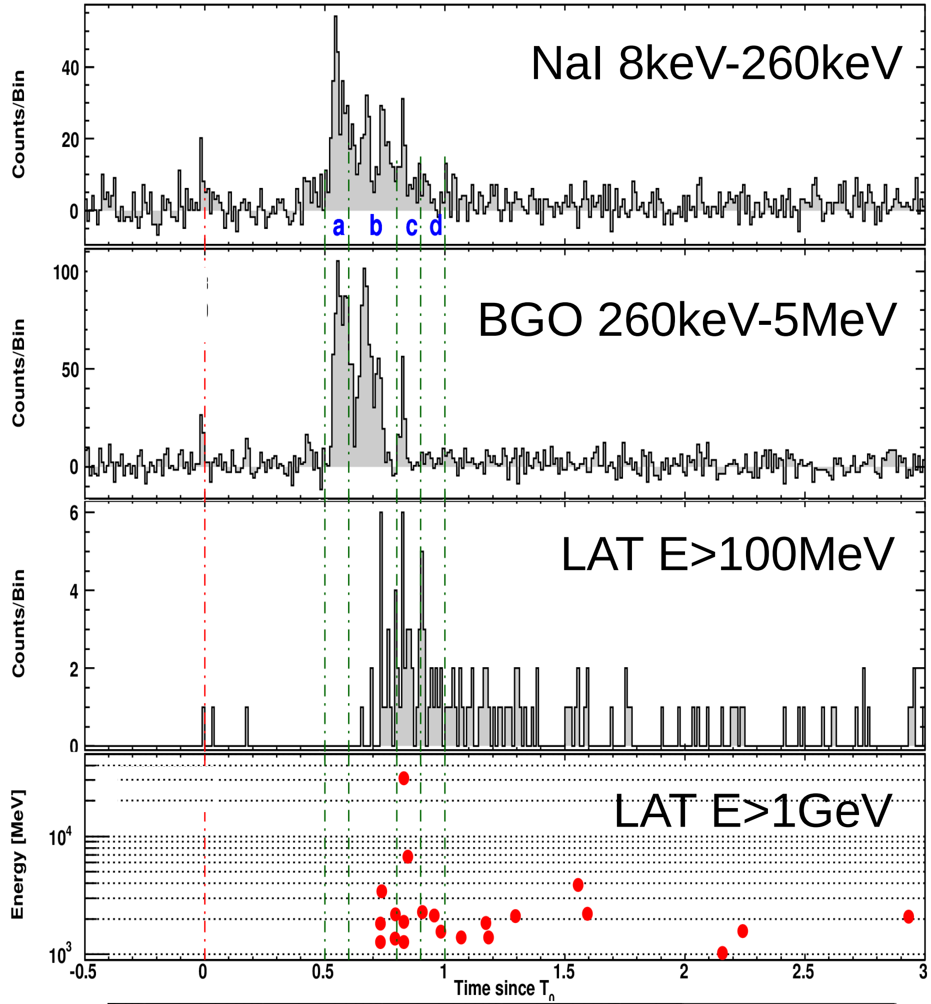
Abdo et al. 2009, Science 323, 1688

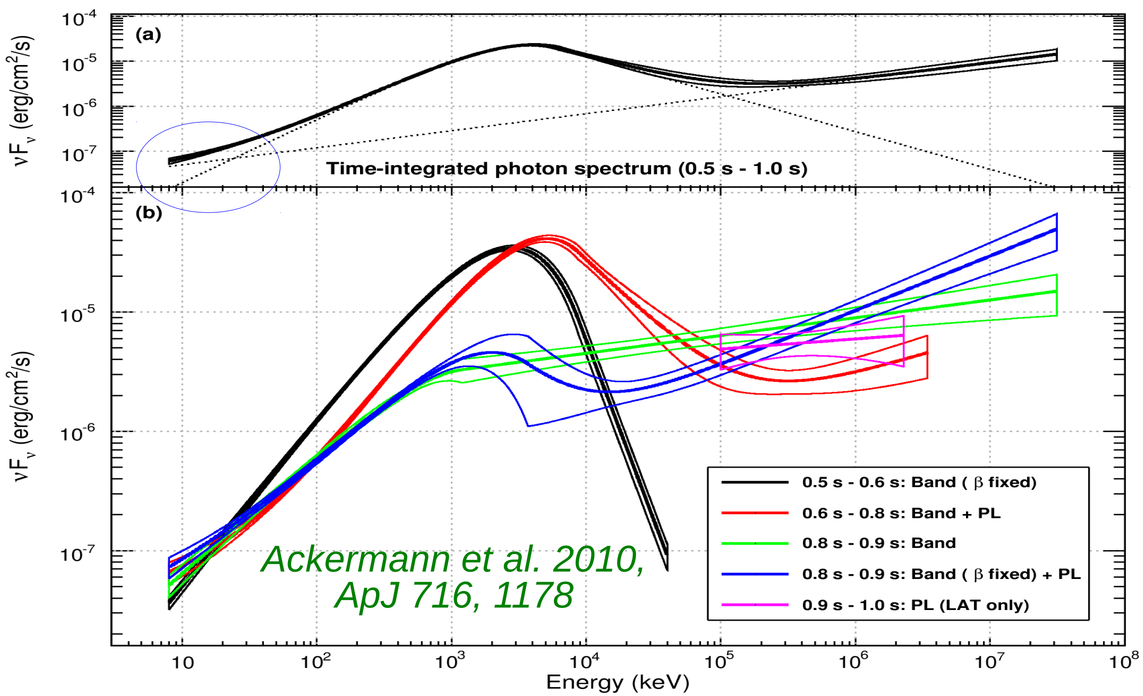
F.

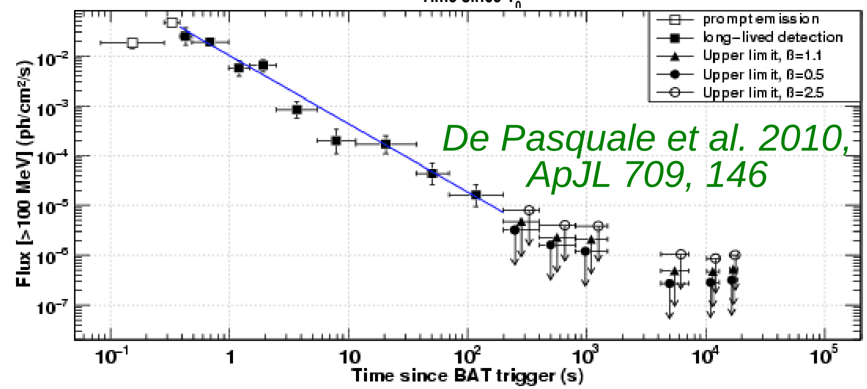
GRB 090510: our bright short GRB

- Additional power-law component
  - First time detected in a Short GRB
  - Starts delayed in the prompt and persists up to ~200s
  - Dominates at E>100MeV and E<20keV

- Highest E_{peak}=~4MeV ever for a time-integrated spectrum
- Highest-E photon detected ~31GeV at 0.83s post-trigger
  - Sets Γ_{min}=1200 – 1000 interval c
  - Sets strongest constraints on dependence of c on E_γ



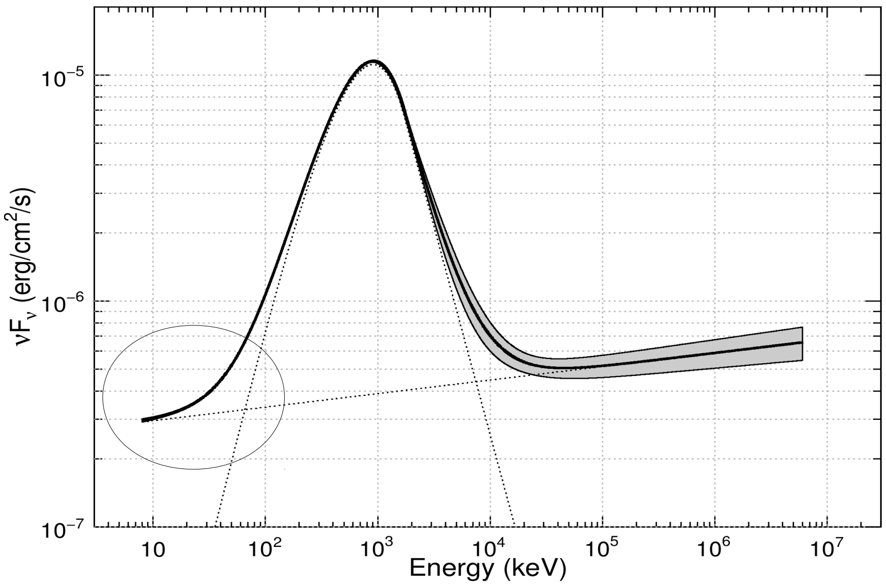


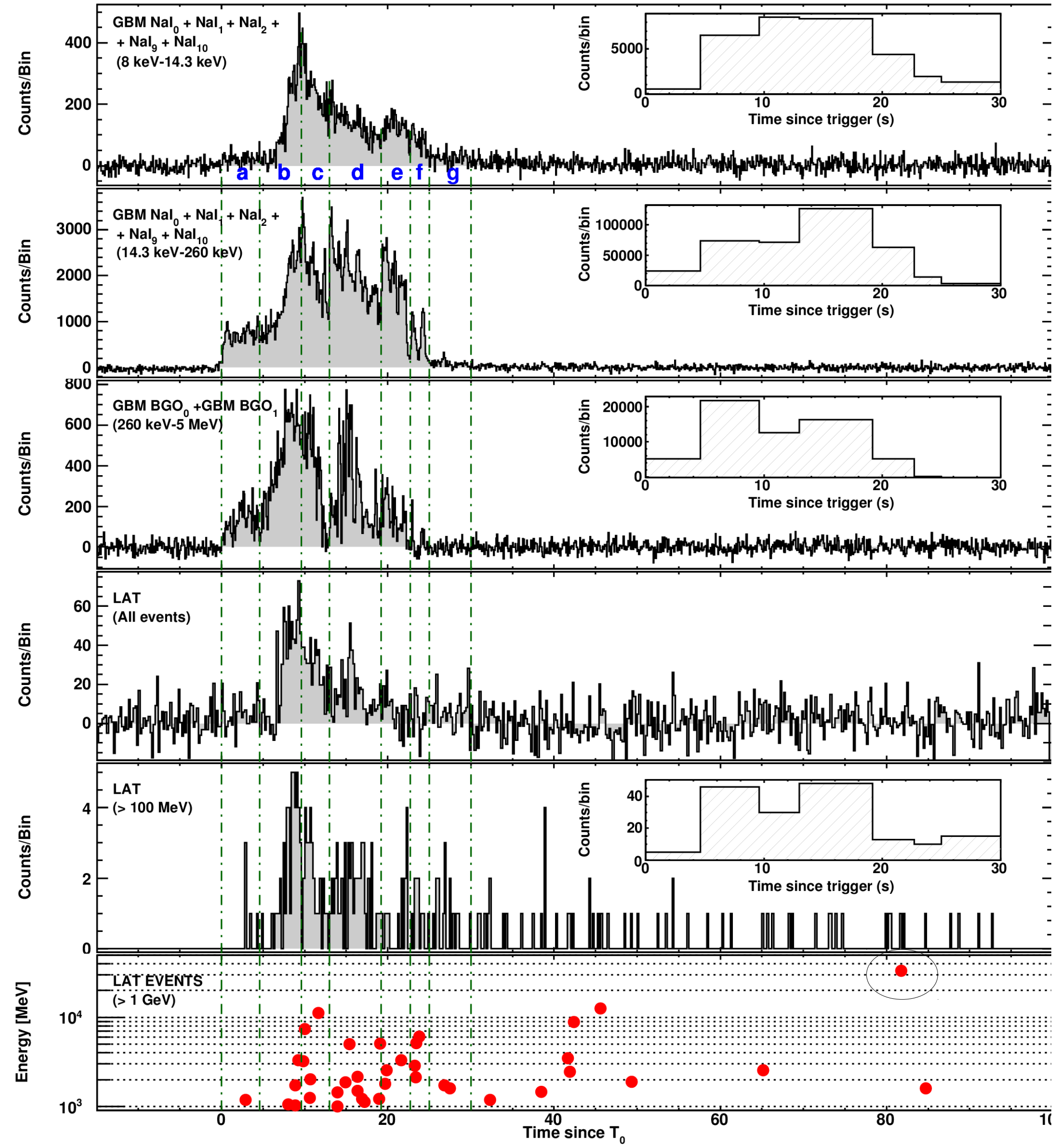


GRB 090902B: highest energy ever detected

- Highest-energy photon detected ever from a GRB:
  - 33.4 GeV at 82s from z=1.822
  - 94 GeV in the GRB frame!
- Also this is the second GRB after 090510 (a short GRB) in which the PL extended at lower energies.

Abdo et al. 2009, ApJL 706, 138



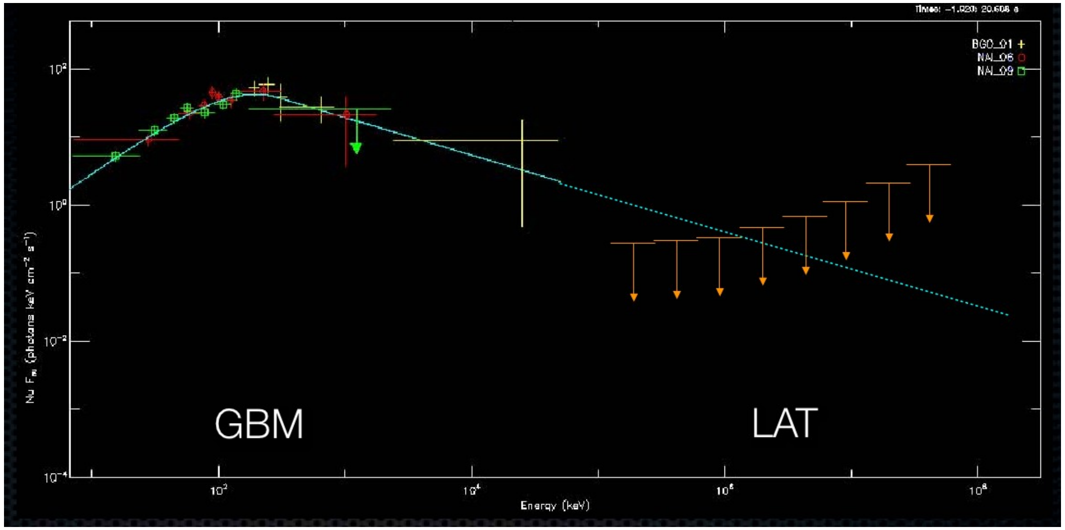


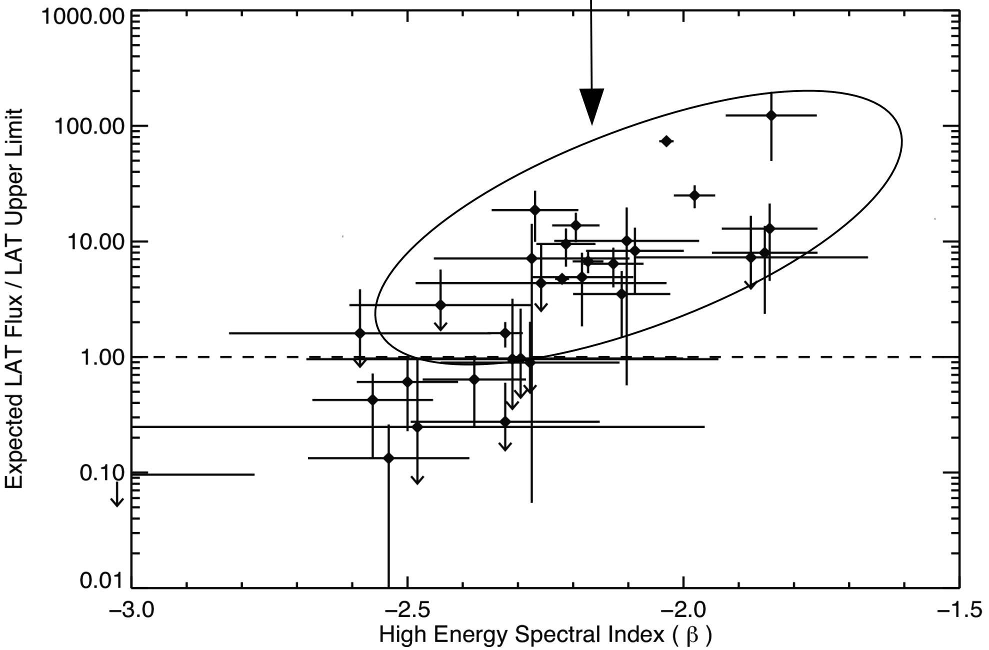
Explaining the absence of LAT detections (1/3)

- ~Half of GBM GRBs happen in the LAT FoV, however only ~10% are detected >100MeV
  - We investigated why we did not detect the rest 90%

- 1st step: estimated fraction of GRBs that should have been detected
  - Sample: 30 GBM GRBs with >70cts/s in the BGO and Δβ<0.5
  - Upper limits on LAT flux (0.1-10 GeV) over GBM duration were compared with predictions from extrapolation of the GBM spectral fit
  - 50% (15) have predicted flux>LAT UL (i.e. should have been detected by the LAT)

Ackermann et al. 2012, ApJ 754, 121

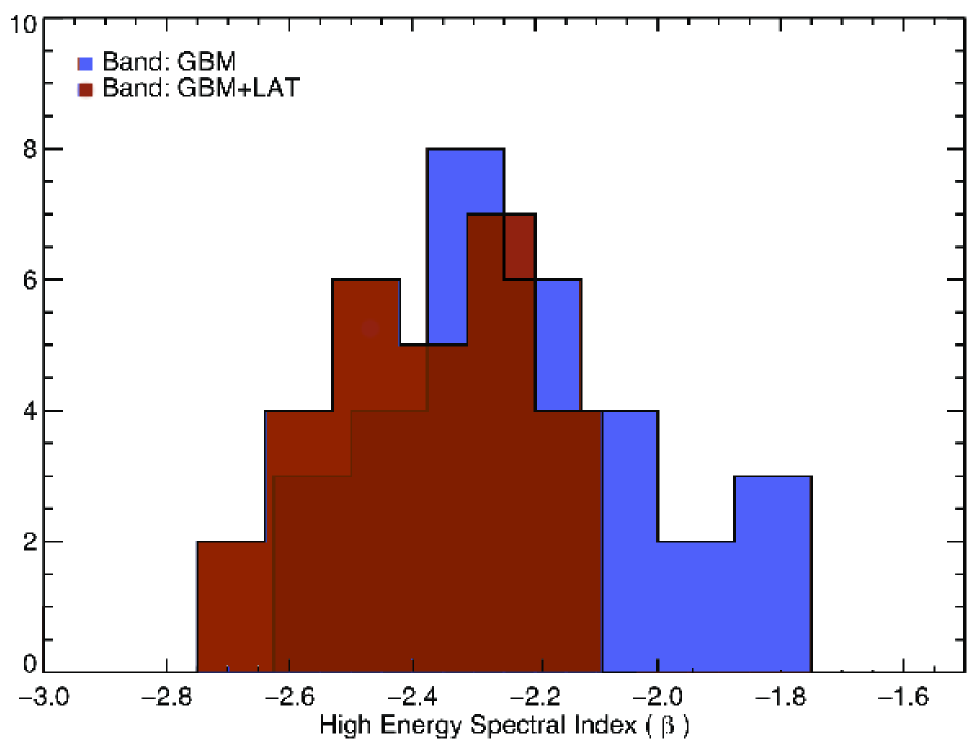


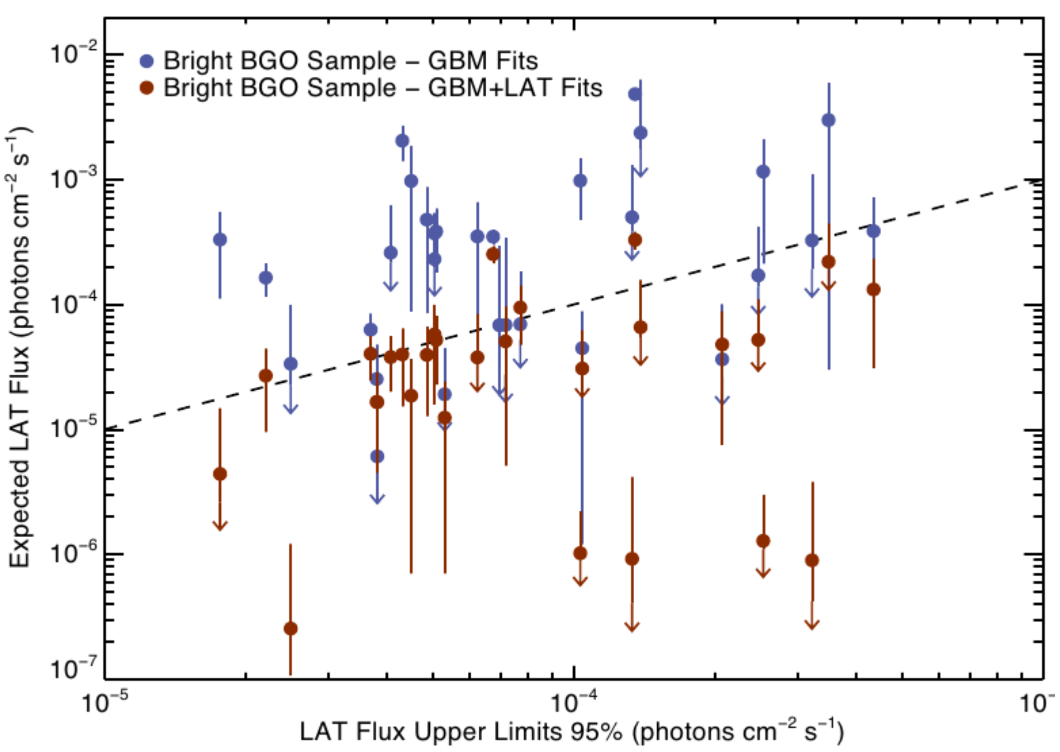


Explaining the absence of LAT detections (2/3)

- 2nd step: GBM+LAT joint spectral fits
  → β becomes considerably softer
- Fraction of detectable but not detected GRBs down to ~23%

Ackermann et al. 2012, ApJ 754, 121





Explaining the absence of LAT detections (3/3)

- 3rd step: repeat joint fits with modified spectral model, adding a spectral softening in the model between BGO and LAT energy ranges
- Fit improved for 6 GRBs (20%) – some form of spectral softening at tens of MeV is required
  - The 6 GRBs have the smallest Δβ
  - Rest 80% of the GRBs consistent with a softer β