Gamma-Ray Bursts in the Fermi Era :

A Large Step Forward in the Understanding of the Prompt Emission

by

Sylvain Guiriec

NASA Marshall Space Flight Center

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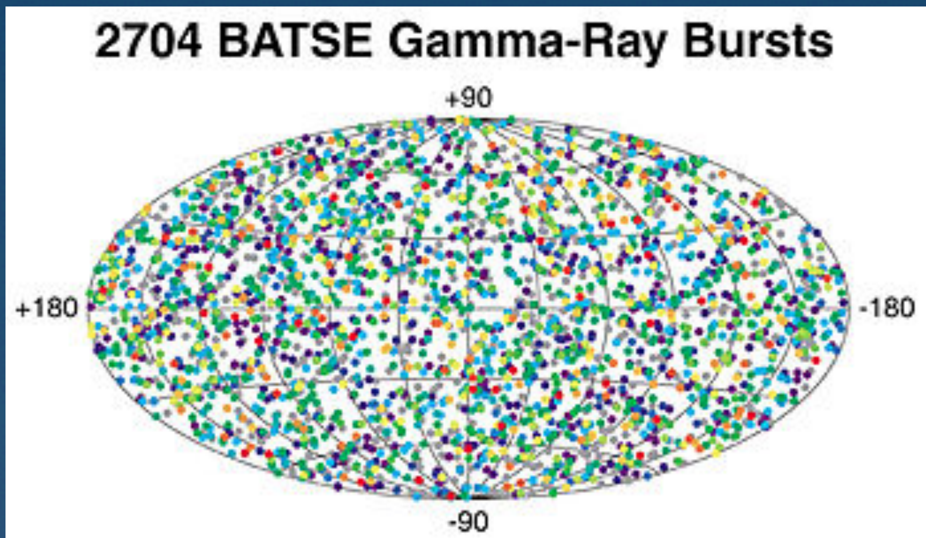
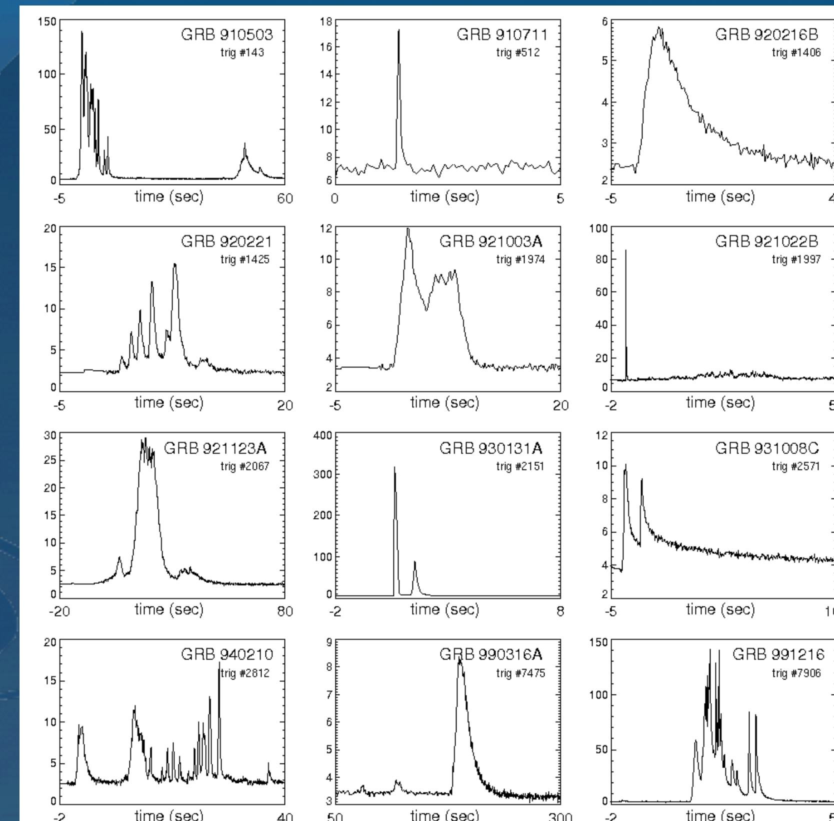
Outline

- GRBs and the Fireball model
- GRB science bridges astrophysics, cosmology and fundamental physics
- The Fermi Gamma-ray Space Telescope
- The Fermi Era : breakthroughs in our understanding of GRBs
- The future of GRB science : France, a future world leader ?

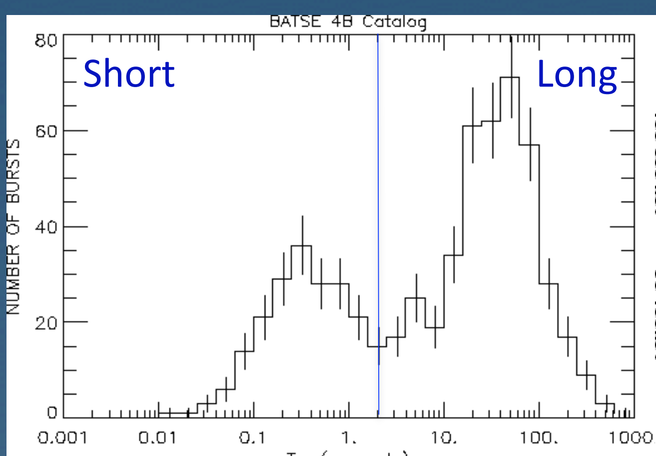
GRBs - Overview

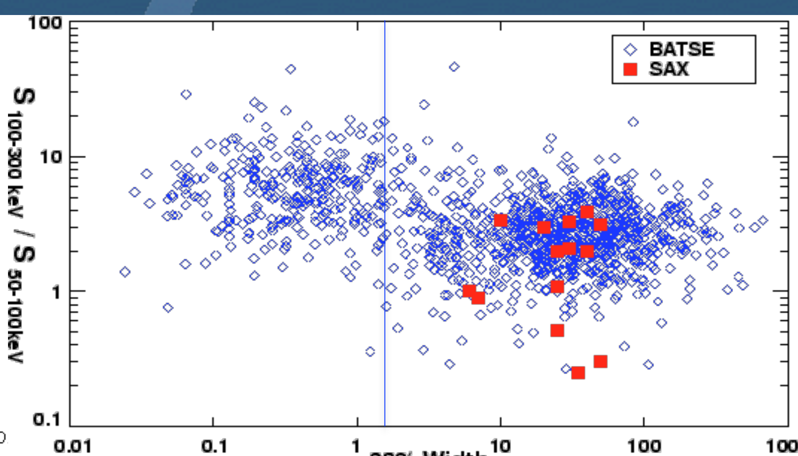
- **Brightest sources in the Universe : several $M_\odot$ in few s emitted in γ-rays (keV-MeV->GeV)**
  → Fermi energy range
- **Cosmological distance**



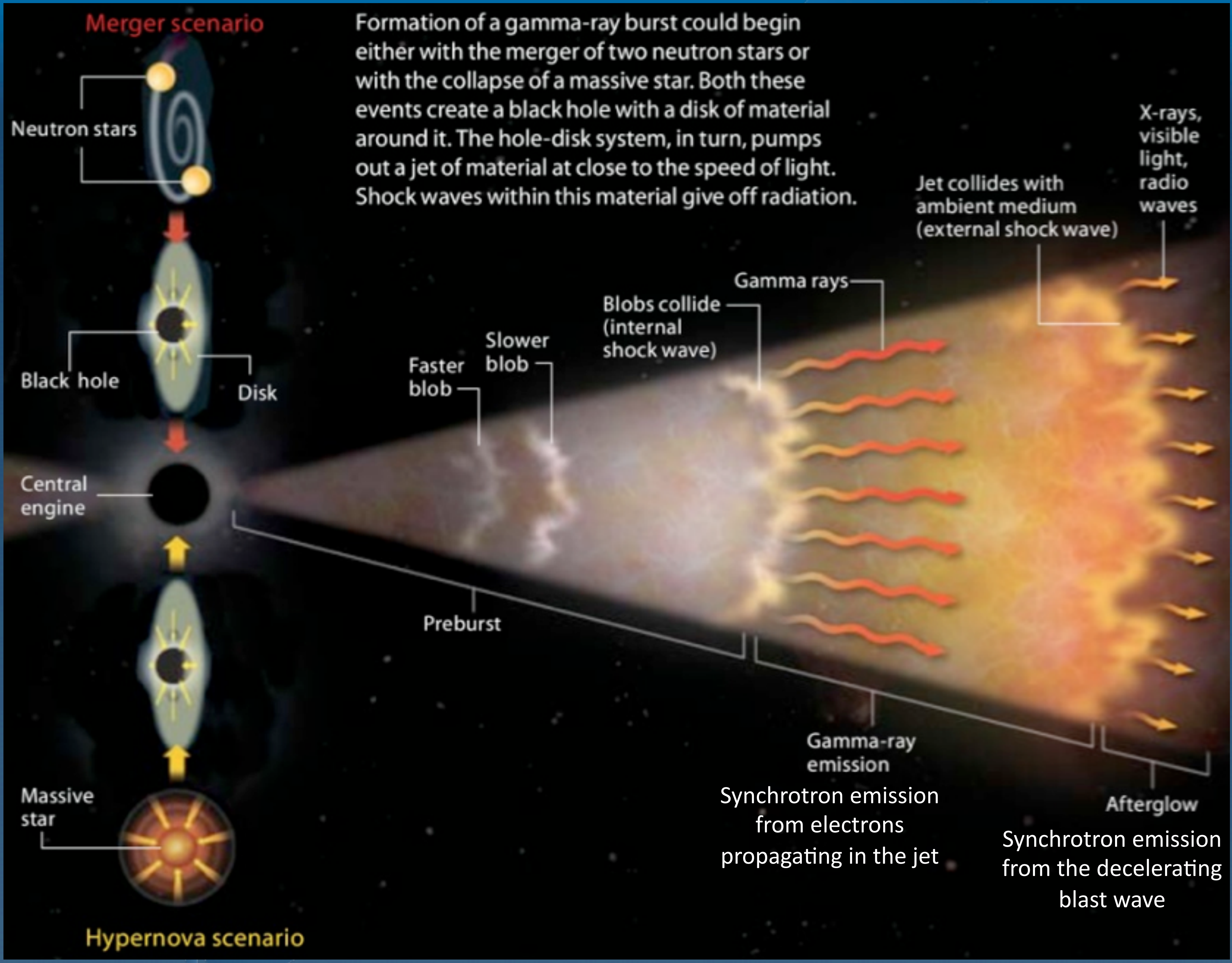


- **Short duration transient sources which do not repeat**





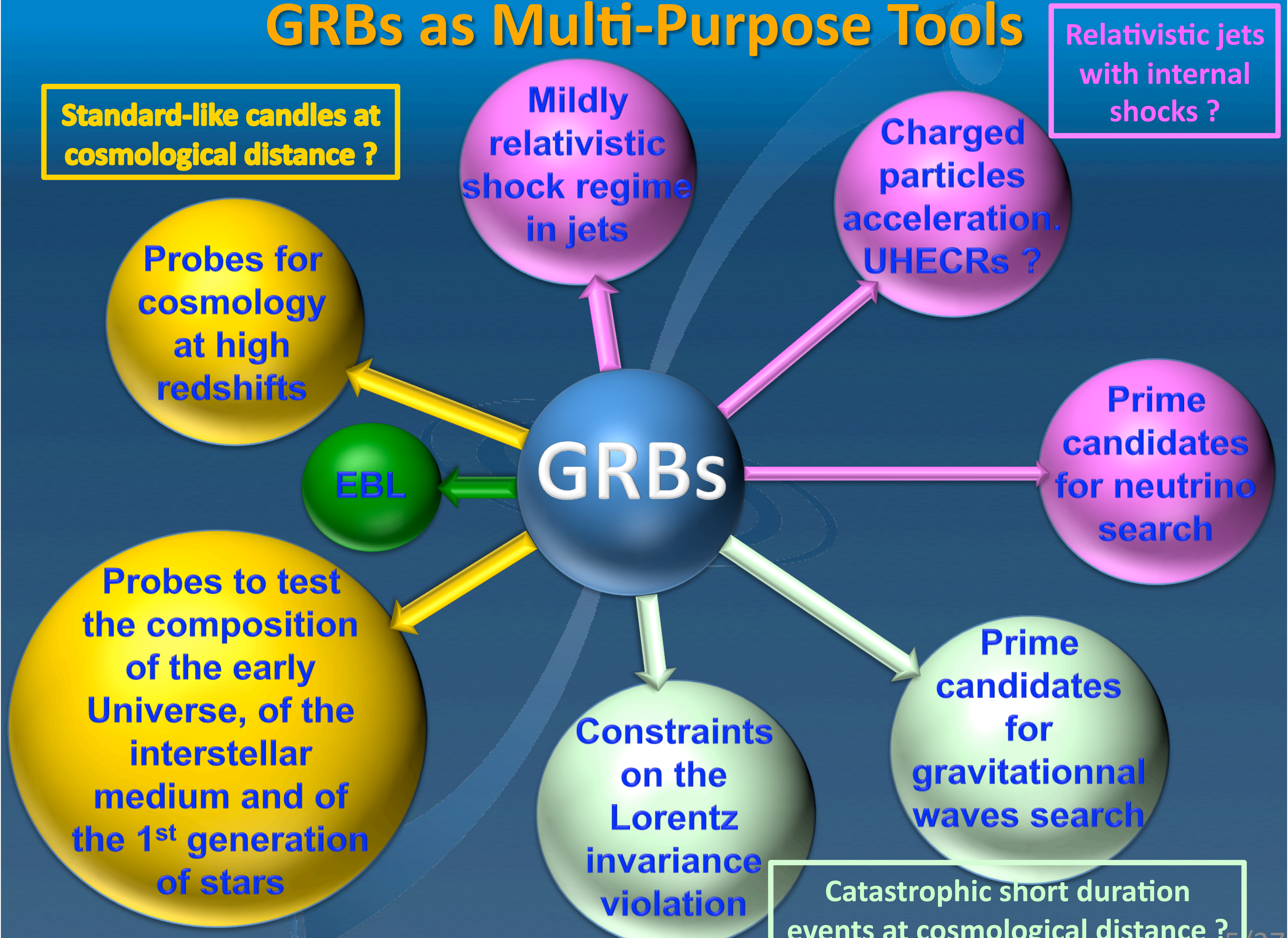
The Fireball Model



Synchrotron emission from electrons propagating in the jet

Synchrotron emission from the decelerating blast wave

GRBs as Multi-Purpose Tools



GRBs as Multi-Purpose Tools

Standard-like candles at cosmological distance ?

Relativistic jets with internal shocks ?

Mildly relativistic shock regime in jets

Charged particles acceleration. UHECRs ?

Probes for cosmology at high redshifts

EE

Only Possible with a Good Understanding of the GRB phenomenon !!!

- Formation of the central engine
- Nature of the central engine
- Composition of the jet and energy reservoirs
- Magnetic field

Prime candidates for neutrino search

Probes to test the composition of the early Universe, of the interstellar medium and of the 1st generation of stars

Constraints on the Lorentz invariance violation

Prime candidates for gravitationnal waves search

Catastrophic short duration events at cosmological distance ?

GRBs as Multi-Purpose Tools

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Only Possible with a Good
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- Composition of the jet an
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To answer these questions, I focused on the spectroscopy of the prompt emission with Fermi

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Probes to test the composition of the early Universe, of the interstellar medium and of the 1st generation of stars

Constraints on the Lorentz invariance violation

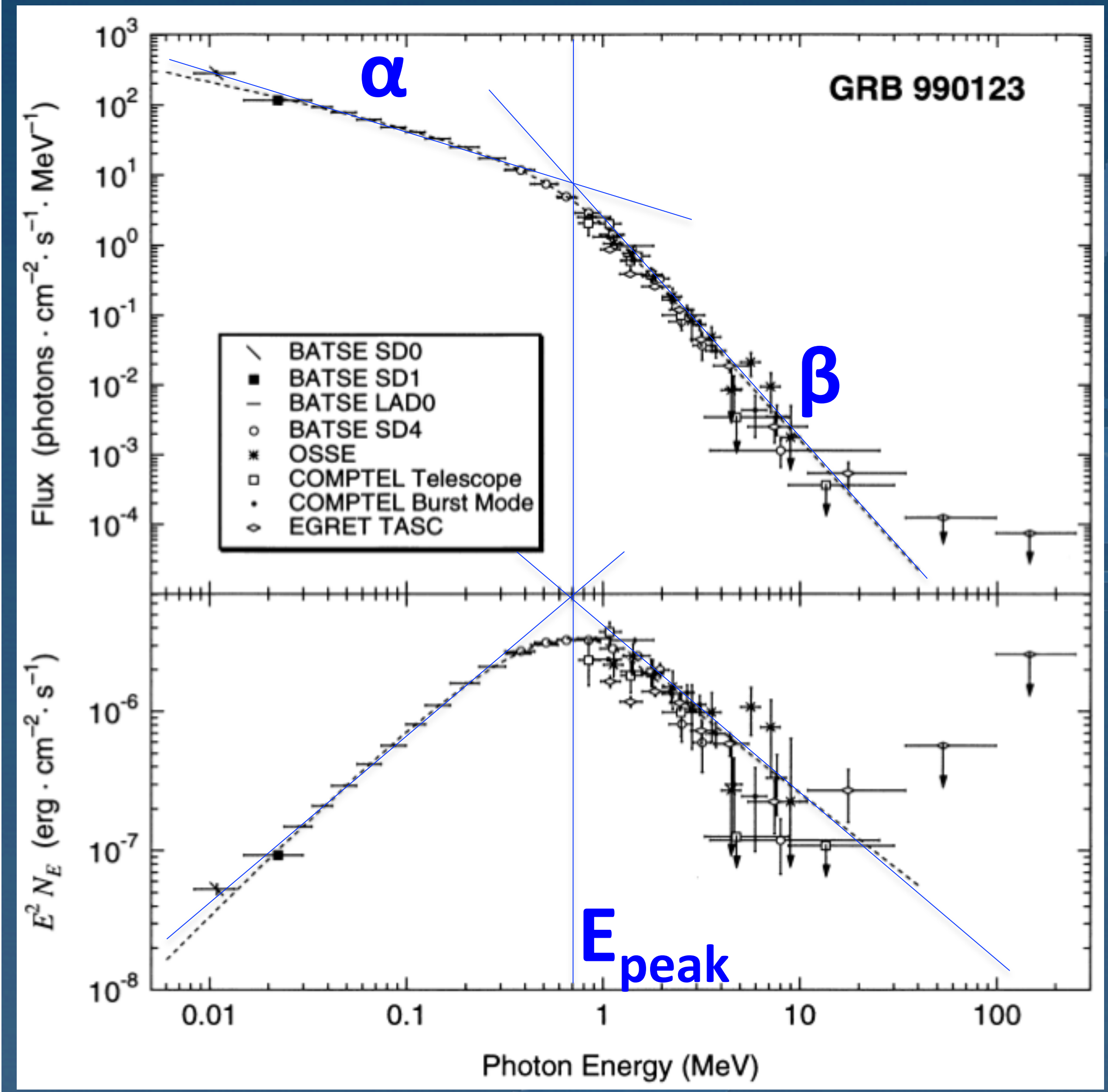
Prime candidates for gravitationnal waves search

Catastrophic short duration events at cosmological distance ?

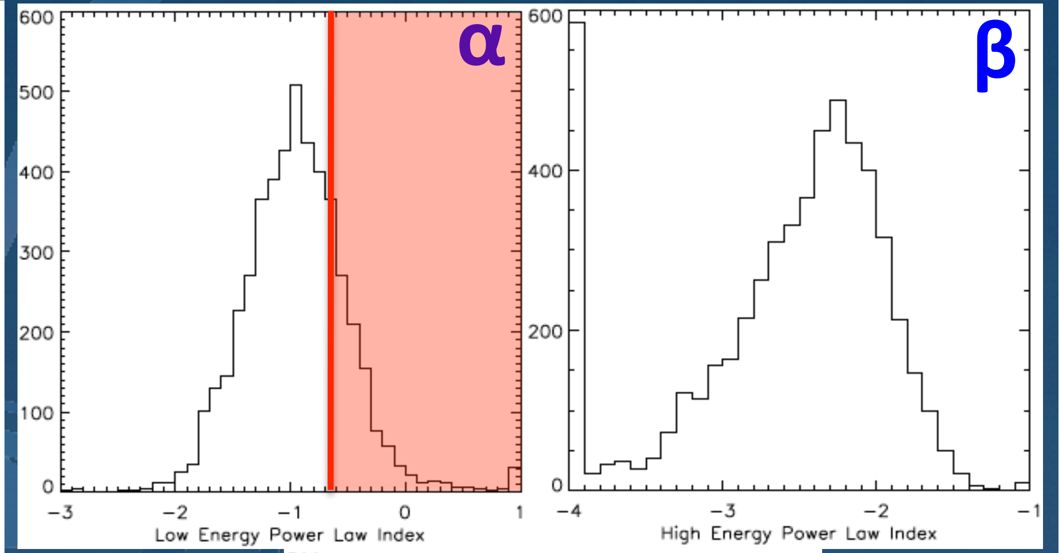
GRBs – Spectroscopy with CGRO/BATSE

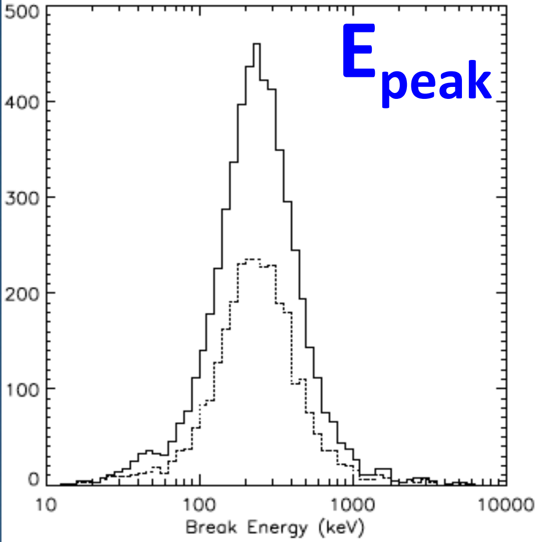
GRB spectra : The Band function (smoothly broken PL)

(Briggs et al. 1999, ApJ, 524, 82-91)



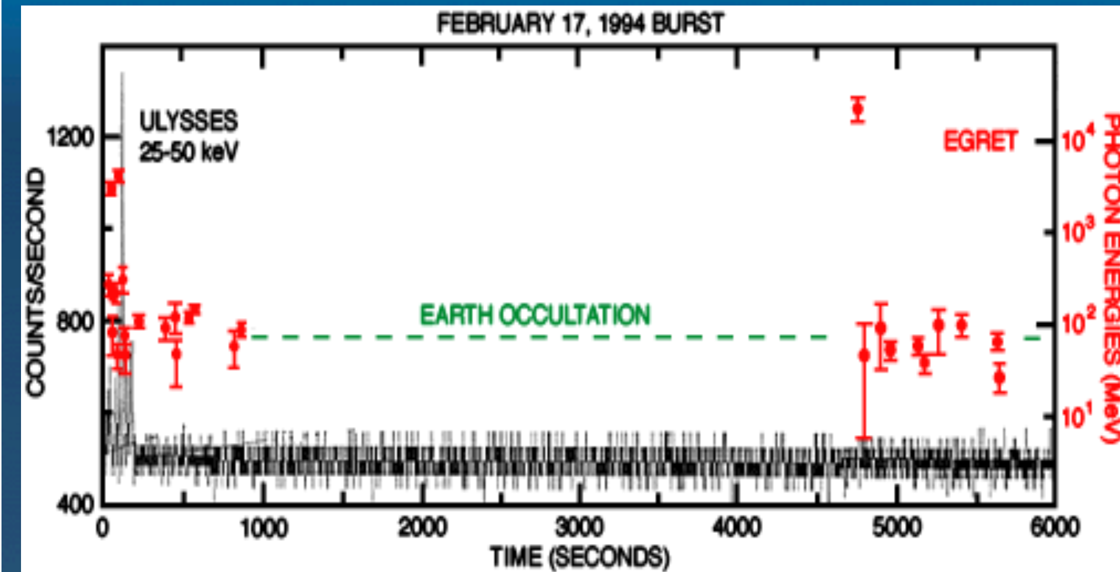
(Preece et al. 2000, ApJS, 126, 19-36)





Most likely synchrotron emission from electrons propagating in the jet and accelerated through internal shocks but α often inconsistent with synch models.

GRB – CGRO/EGRET

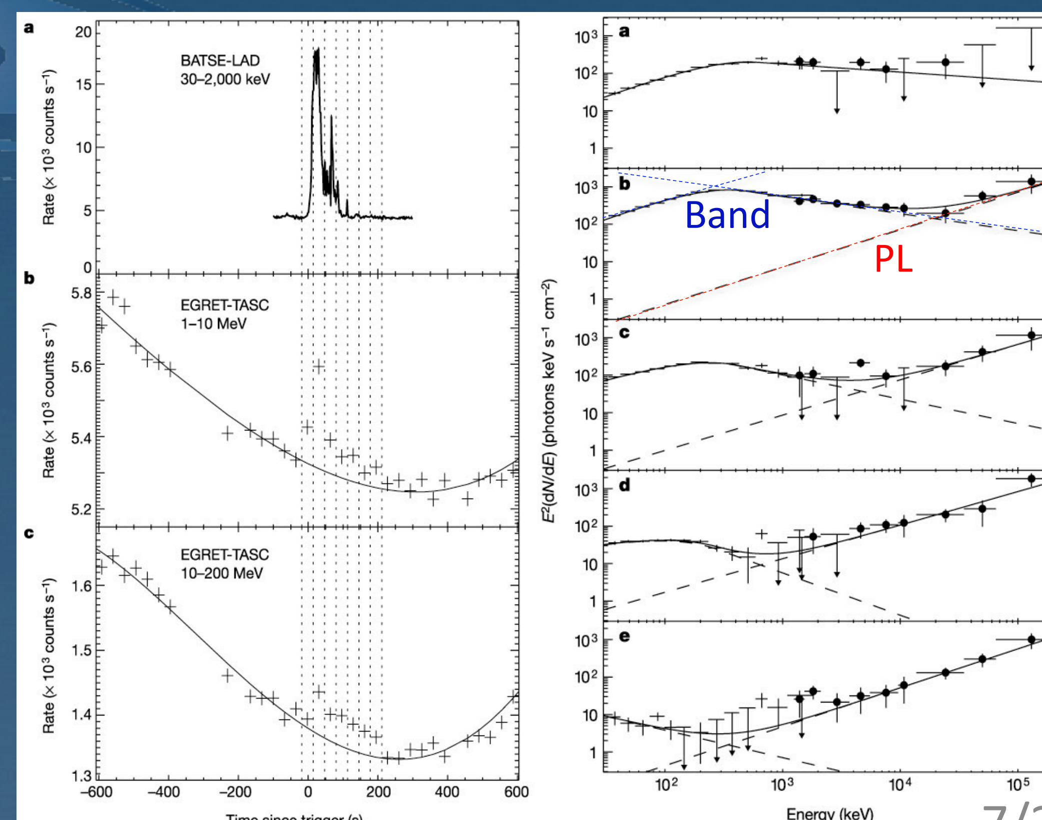


GRB 940217
(Gonzalez et al. 2003, Nature 424, 749)

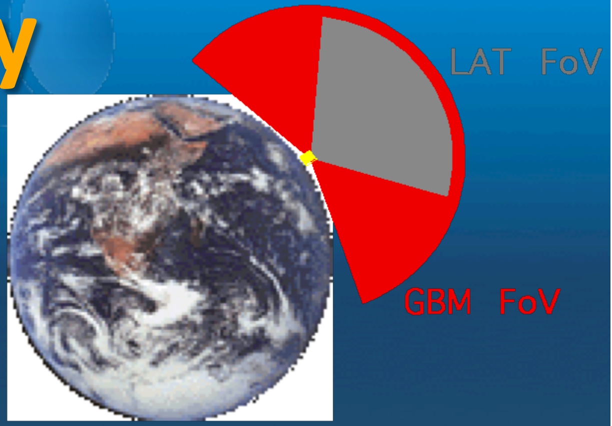
Late very high energy emission (13 GeV photon at T_0+1.5h)

GRB 941017
(Gonzalez et al. 2003, Nature 424, 749)

Additional high energy PL not compatible with synchrotron models



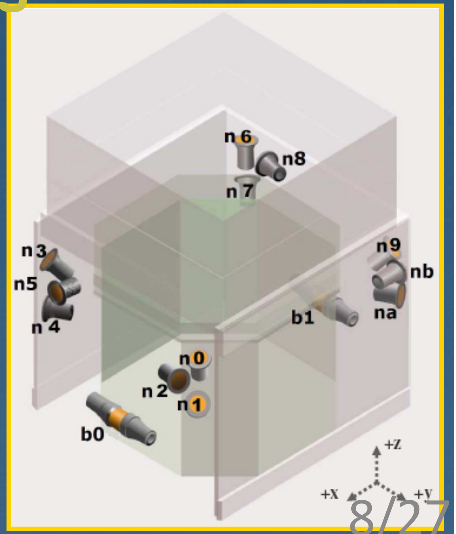
The Fermi Observatory



- **Spacecraft :**

  Low-Earth Circular Orbit (altitude 550 km) with 28.5° inclination

- **Large Area Telescope (LAT) :**
  - Energy range : 20 MeV to >300 GeV
  - Large field of view : ~2.4 sr at 1 GeV
  - Full sky coverage every 3 hours
  - Localization, spectroscopy and GRB trigger capabilities (on board and ground)
- **Gamma-ray Burst Monitor (GBM):**
  - Full unocculted sky coverage : >9.5 sr
  - On board triggers
  - 8 keV to 40 MeV
  - 12 NaI (8 keV to 1 MeV)
    - Localization (on board & ground)
    - Spectroscopy
  - 2 BGO (200 keV to 40 MeV)
    - Spectroscopy



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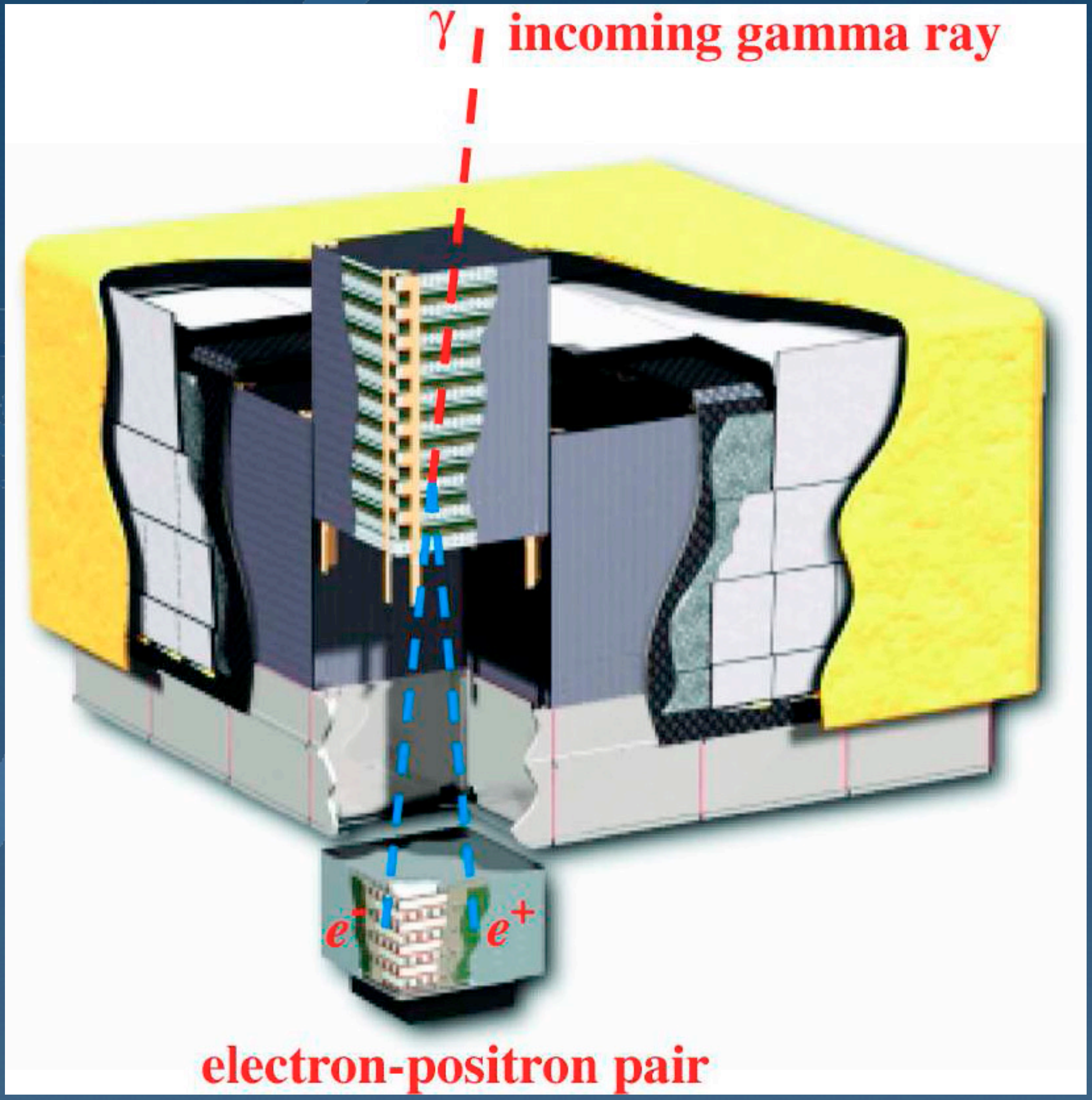
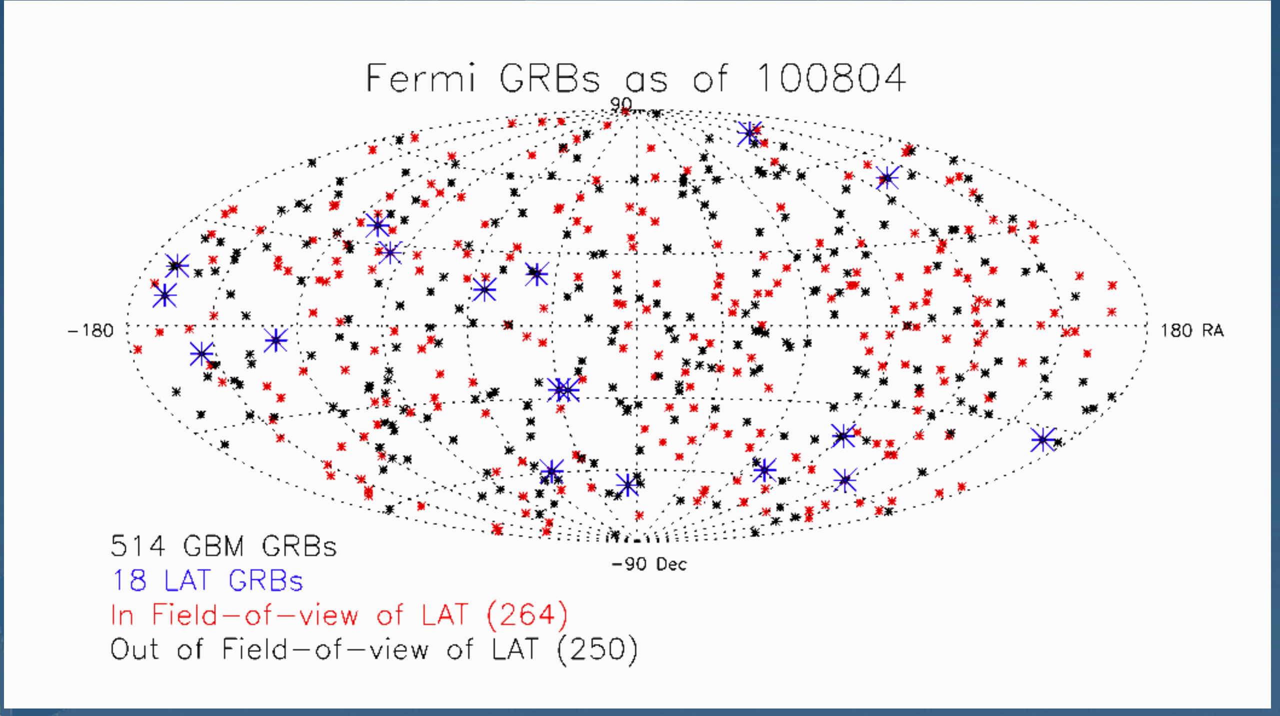


Fermi Results :

Toward a Better Understanding of the Prompt Emission

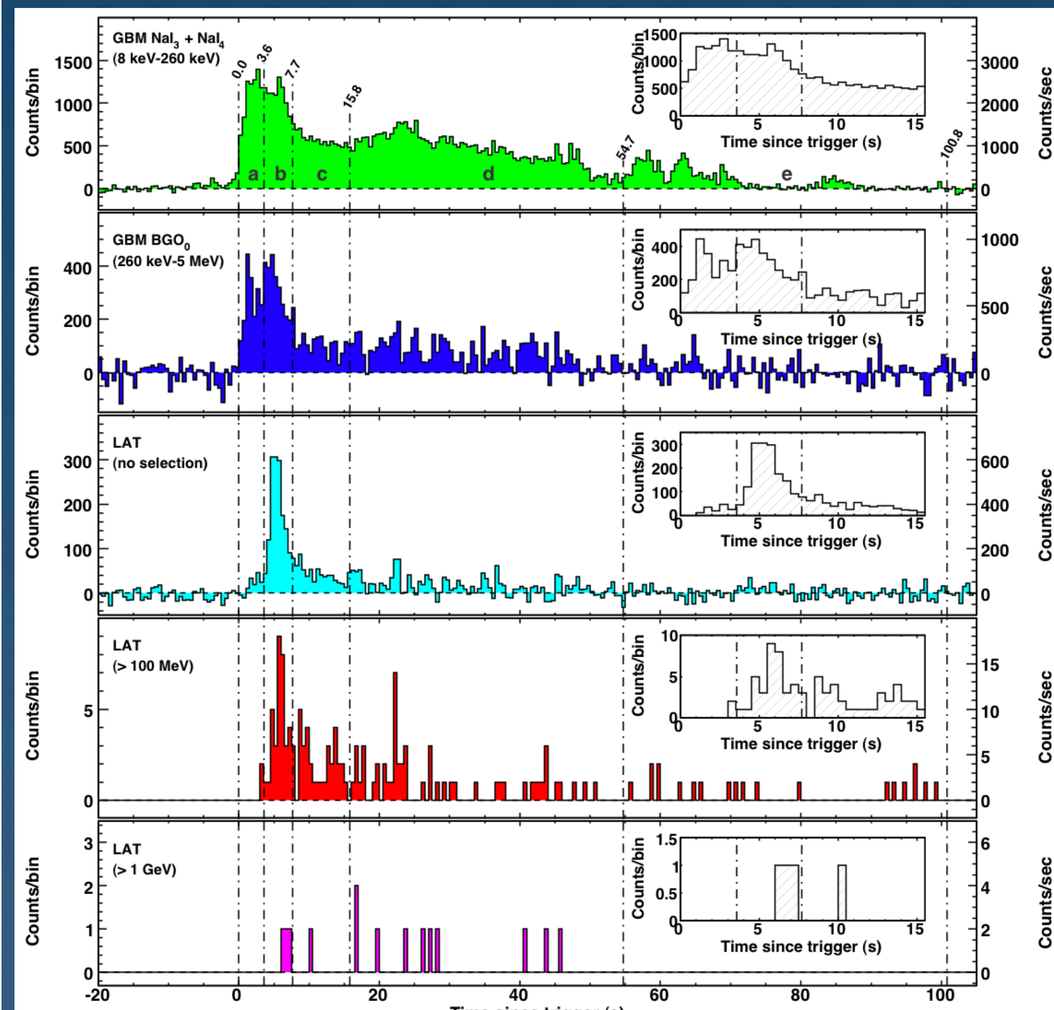
- Delayed high energy emission onset (>100 MeV)
- Long lived GeV emission
- Spectral evolution
- Multi-spectral components analysis

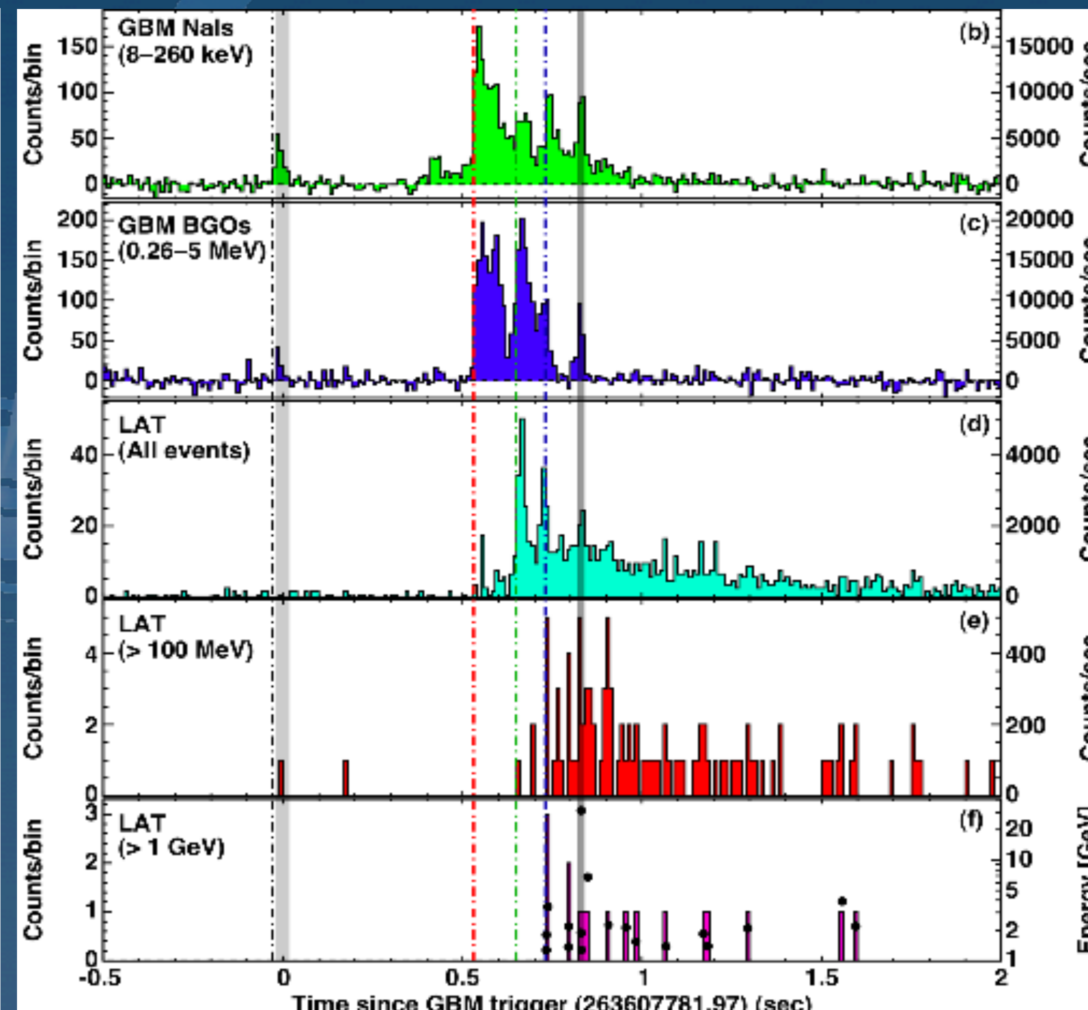


Delay High-Energy Emission onset (>100 MeV)

Case of the long GRB 080916C
(Abdo et al. 2009, Science 323, 1688)

Case of the short GRB 090510
(Abdo et al. 2009, Nature 462, 331)



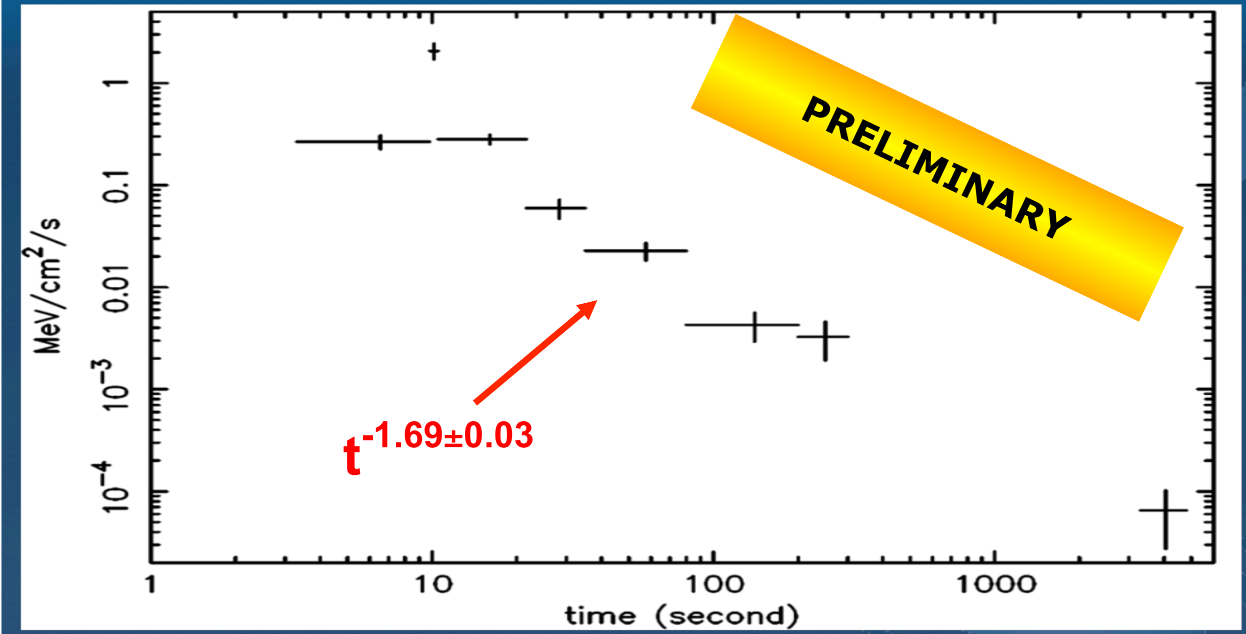


- **The first LAT peak coincides with the second GBM peak**
- **Delay in HE onset: ~4-5 s**

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

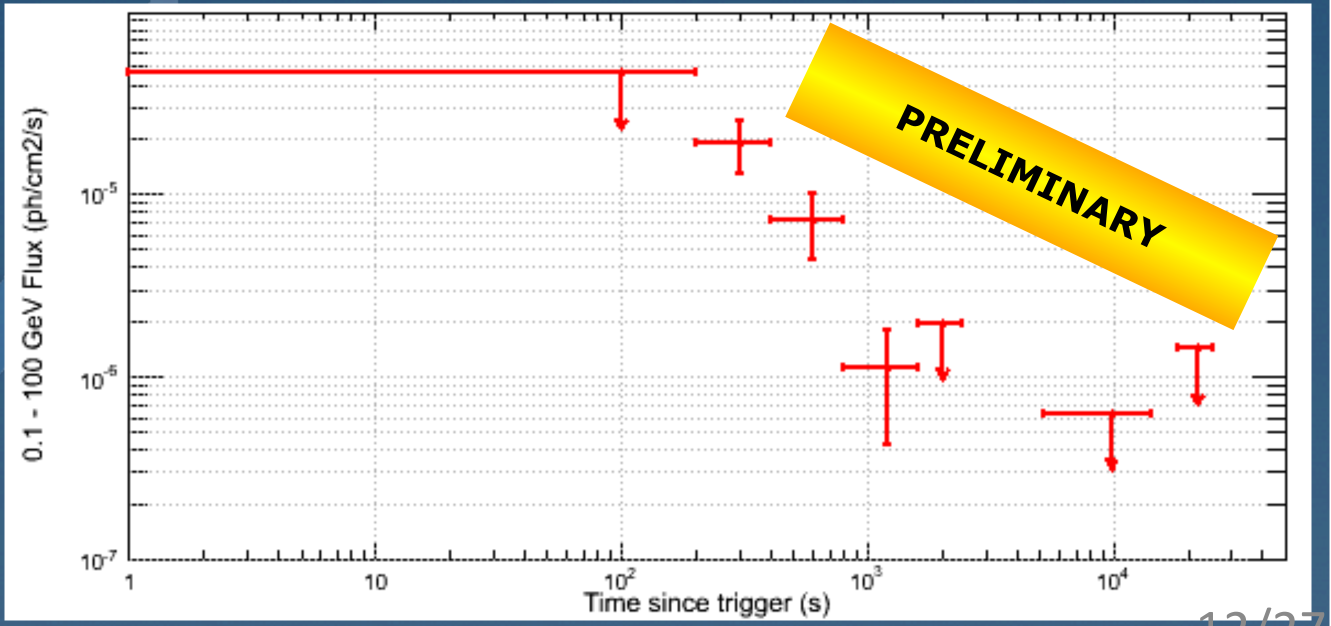
Long Lived GeV Emission

Case of GRB 090926A



→ 5σ Detection up to 4800s

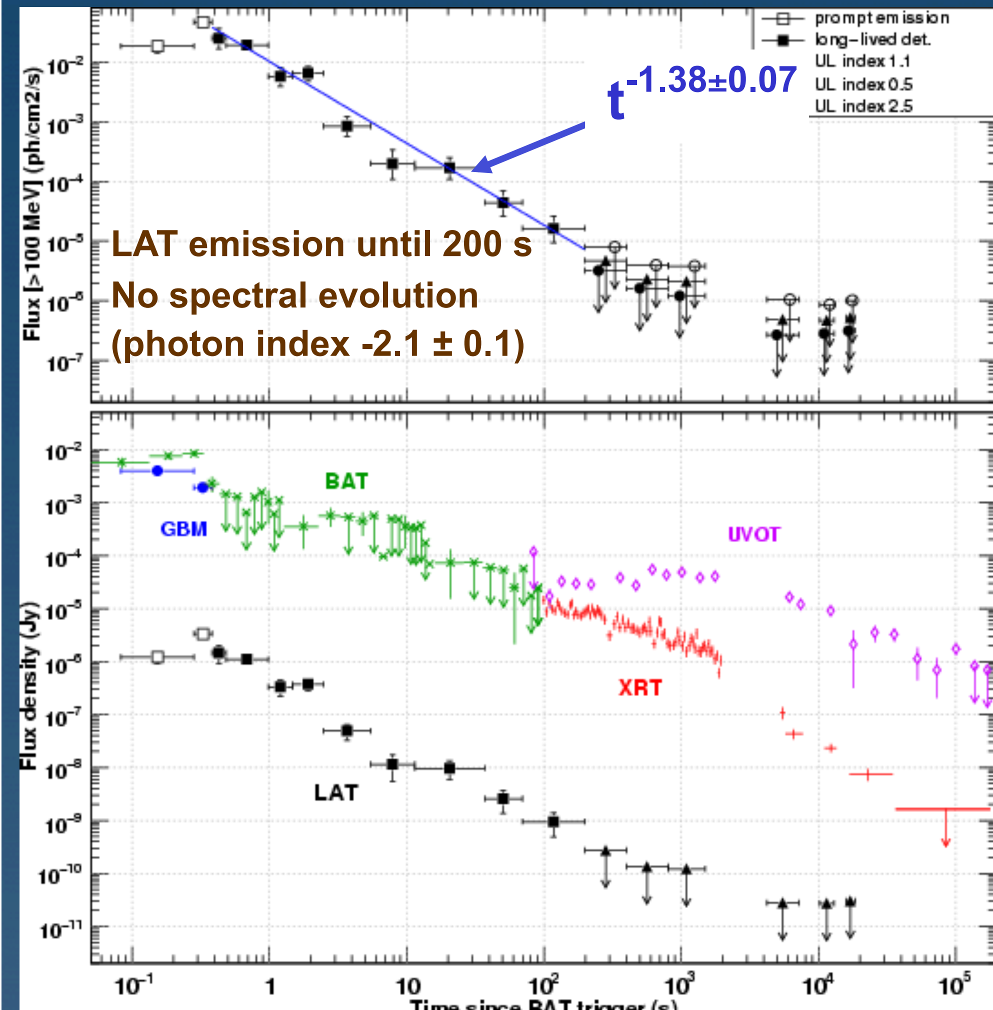
Case of GRB 090328

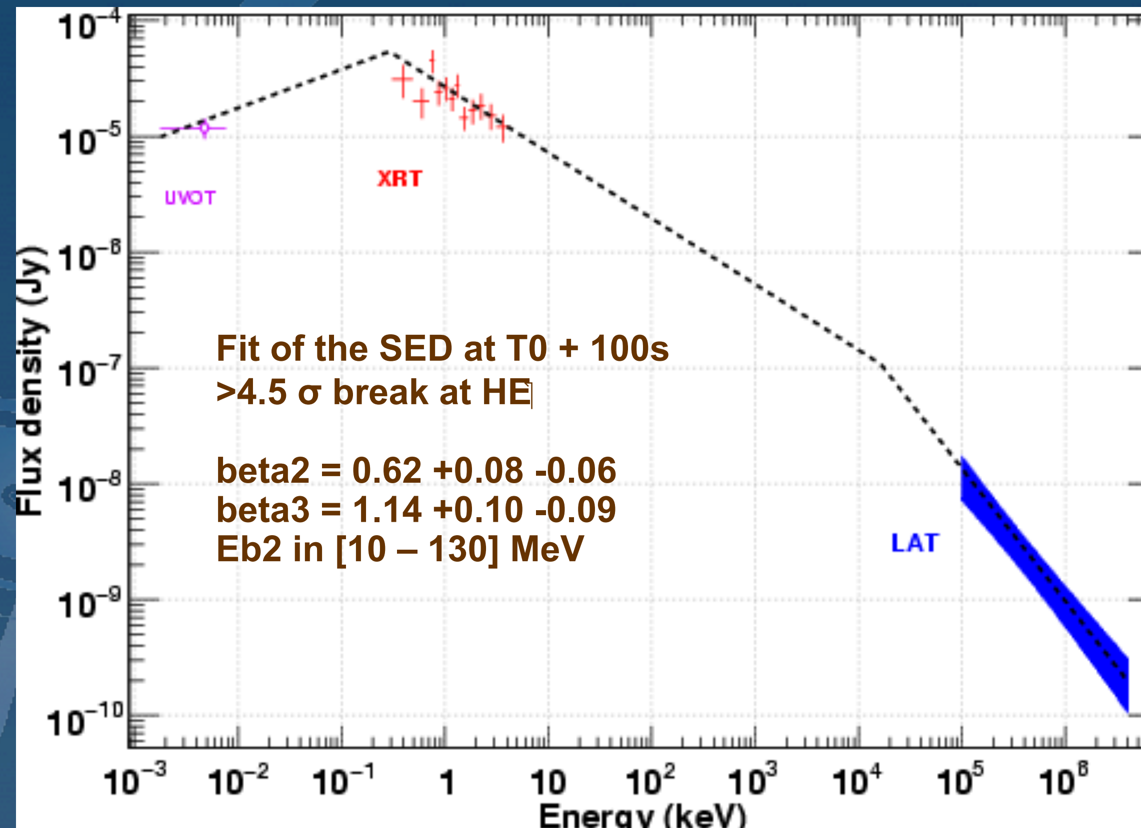


5σ Detection up to 1600s ←

Long Lived GeV Emission

Case of GRB 090510 (De Pasquale et al 2010, ApJL 709, 146)

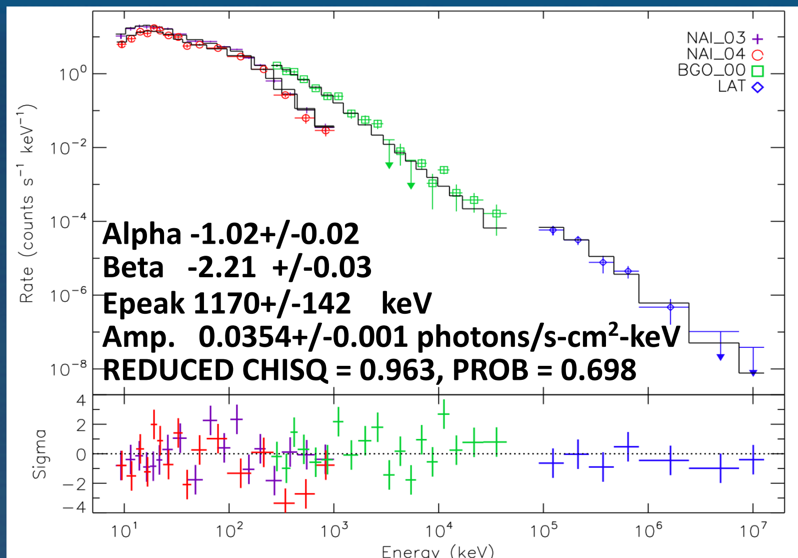


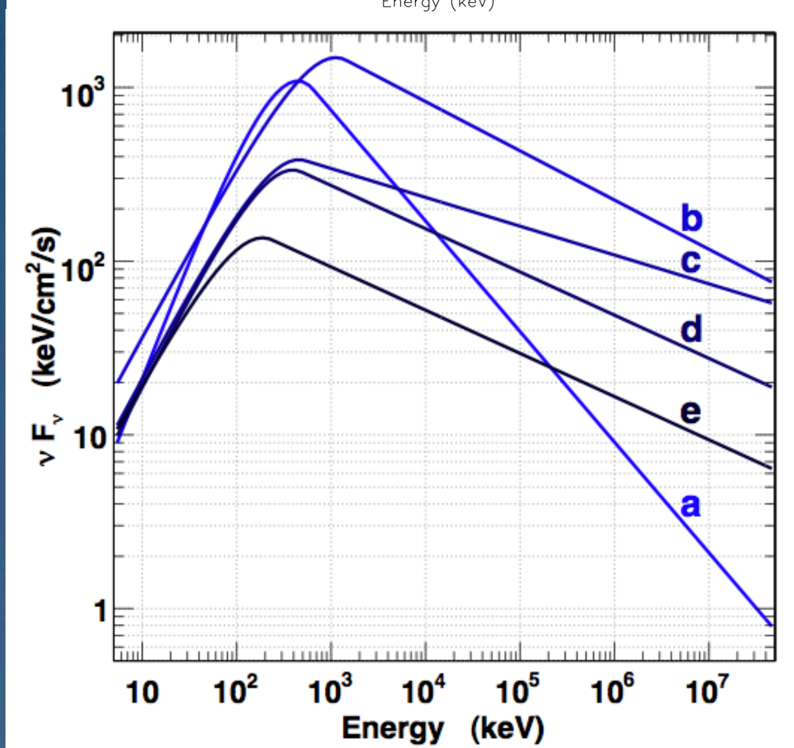


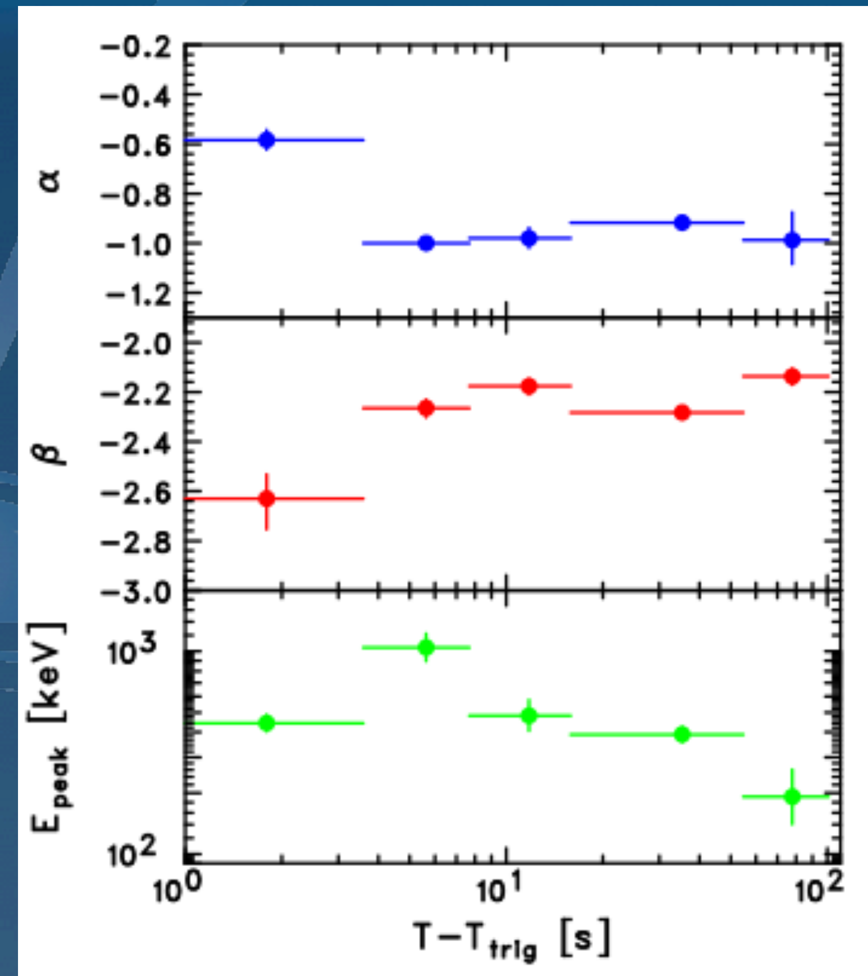
Forward shock model can reproduce the spectrum from the optical up to GeV energies! (non thermal synchrotron emission from the decelerating blast wave)

Spectral Evolution

Case of GRB 080916C (Abdo et al. 2009, Science 323, 1688)



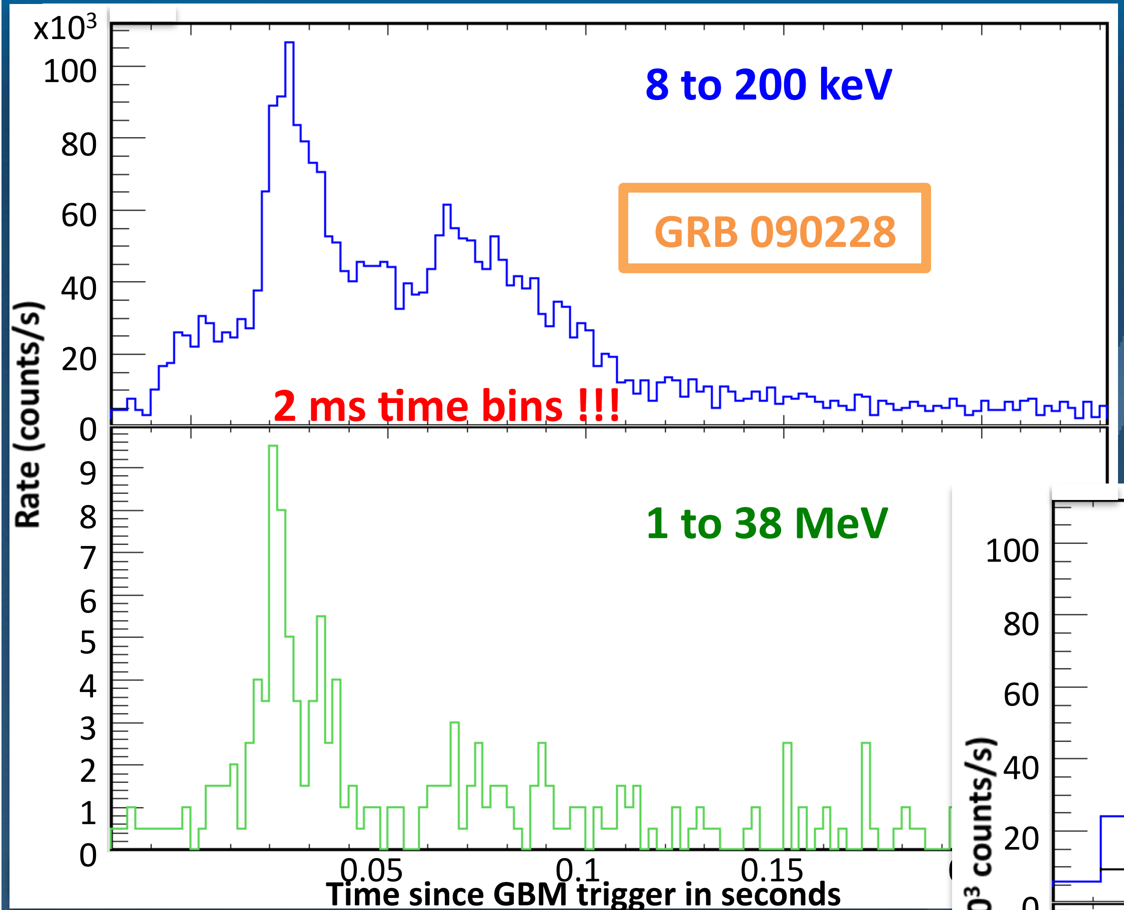


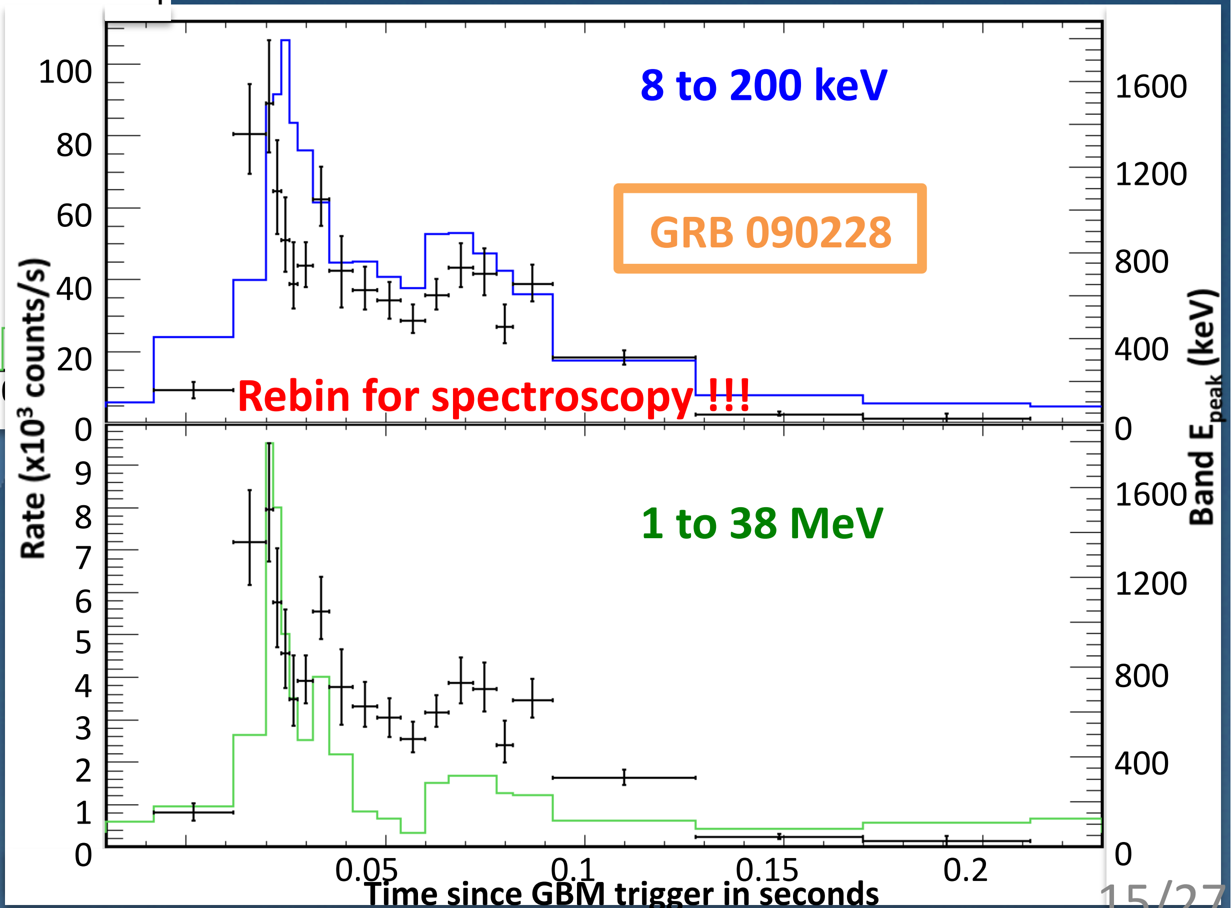


- Consistent with a single Band function from 10 keV to 10 GeV.
- Global soft-hard-soft evolution.

Fine-Time Resolved Spectroscopy of Short GRBs

Case of GRB 090228 (Guiriec et al. 2010, ApJ 725, 225)

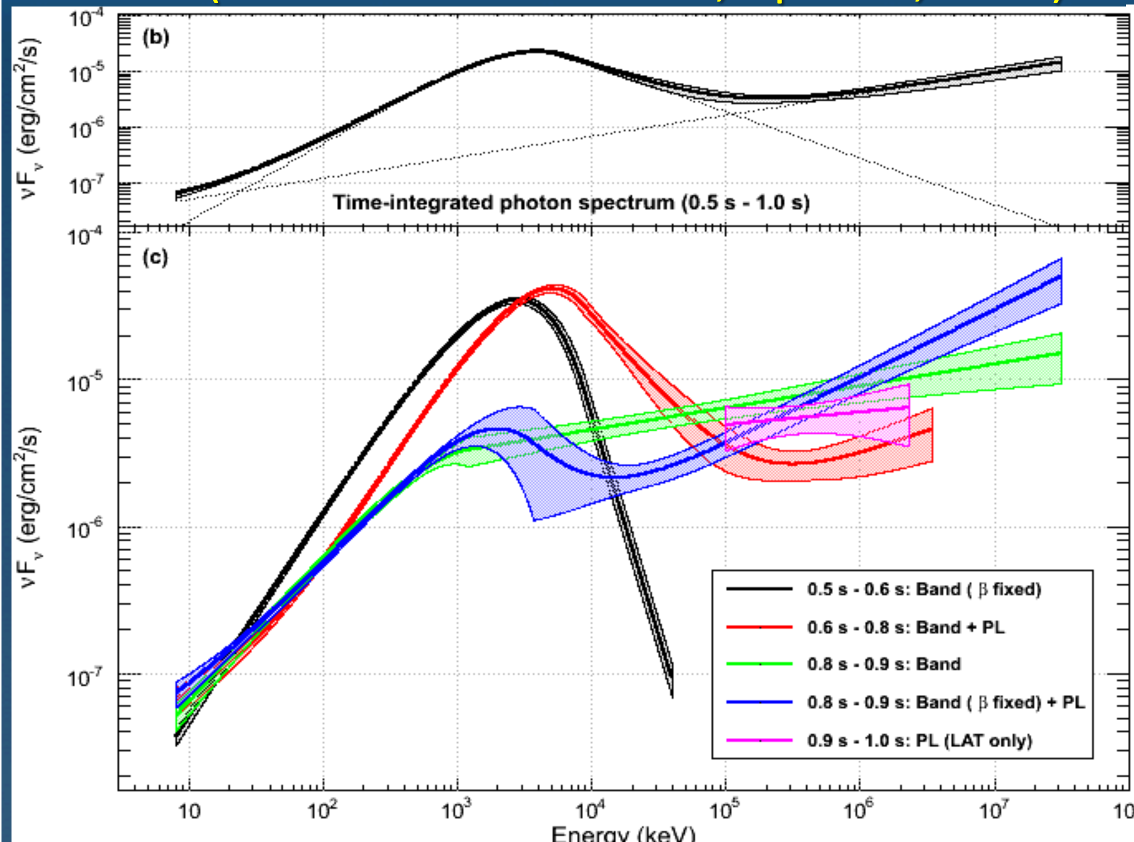




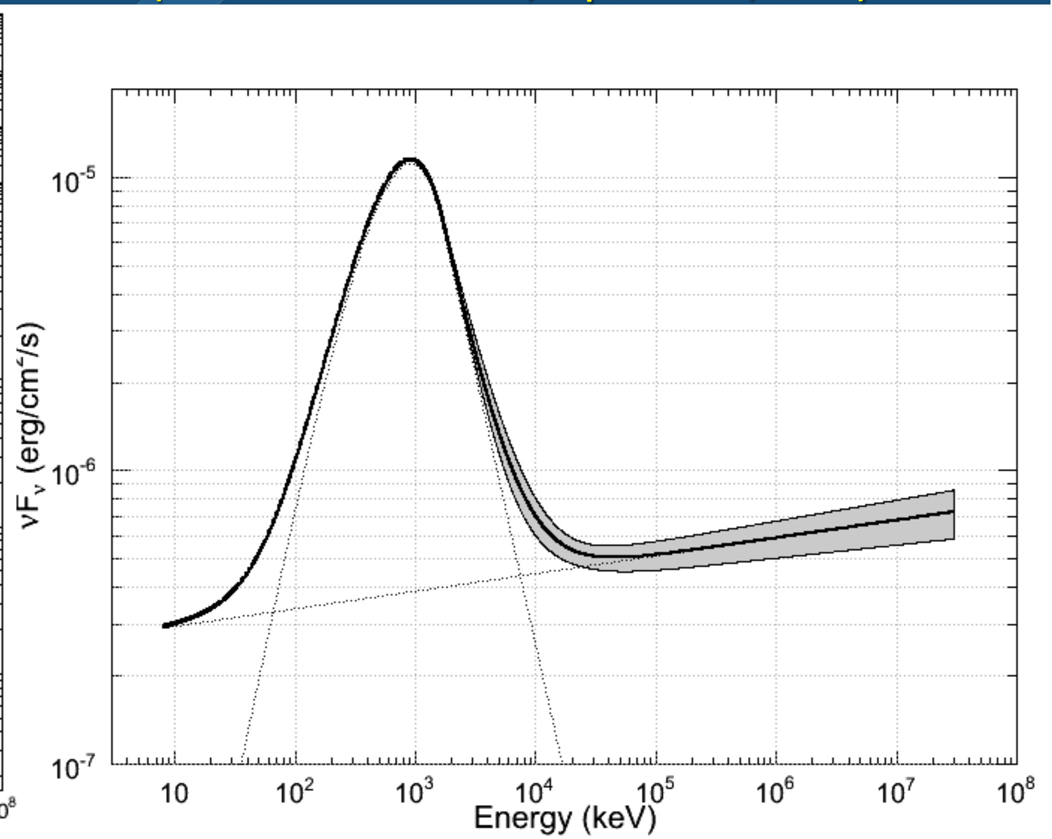
- Light curves of short GRBs similar to the light curves of long GRBs but contracted in time and stretched toward the highest energies.
- Band E_{peak} tracks the LC structures.
- Soft-hard-soft evolution.

Additional Spectral Component

Case of the short GRB 090510
(Ackermann et al. 2010, ApJ 716, 1178)



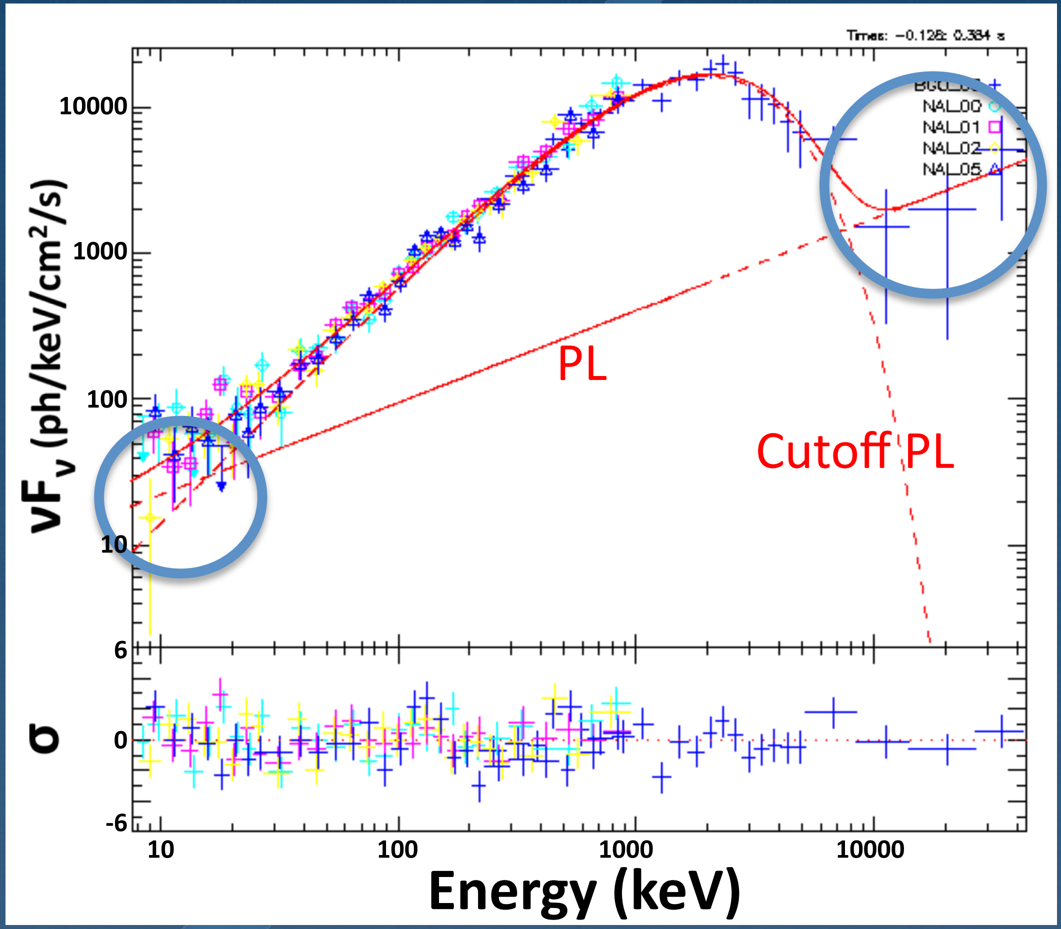
Case of the long GRB 090902B
(Abdo et al. 2009, ApJL 706, 138)



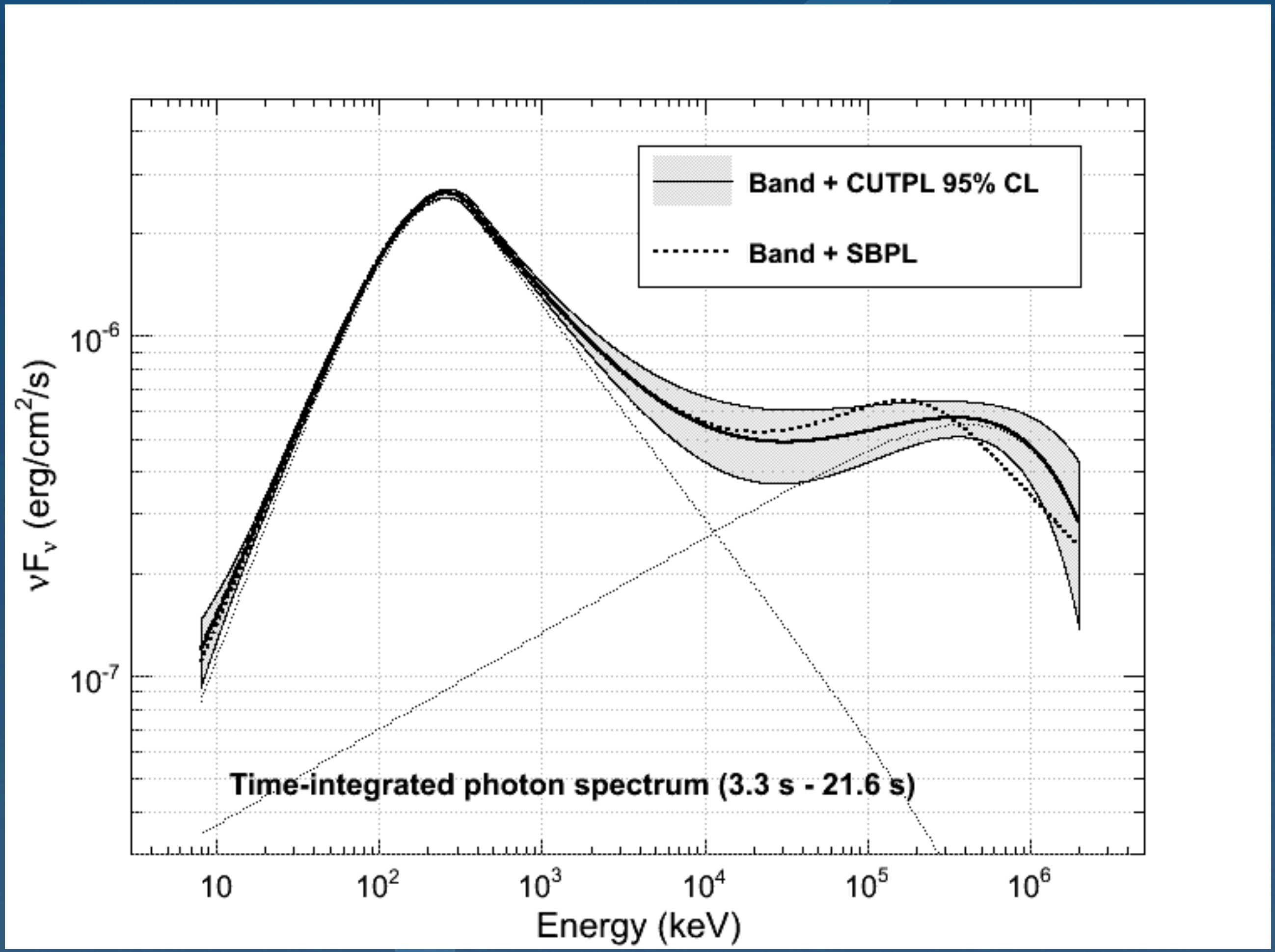
- Spectral deviation from the standard Band function adequately fit with an additional power law in long and short GRBs.
- The Extra-PL is usually not present during the all burst duration.
- Usually, the extra-PL over-powers the Band function at low (< ~tens of keV) and high (> ~tens of MeV) energy.
- Possible PL break in a time resolved spectrum of GRB 090902B.

Additional Spectral Component in GBM Data Only

Case of GRB 090227B (Guiriec et al. 2010, ApJ 725, 225)



High-Energy spctral cuttoff in the extra-PL component of GRB 090926A



(Ackermann et al. 2011, ApJ 725, 225)

- The extra-PL overpower the standard Band function above ~10 MeV.
- Existence of a 6σ spectral cutoff at ~1.4 GeV in the extra-PL.
- Break shape not constraint.

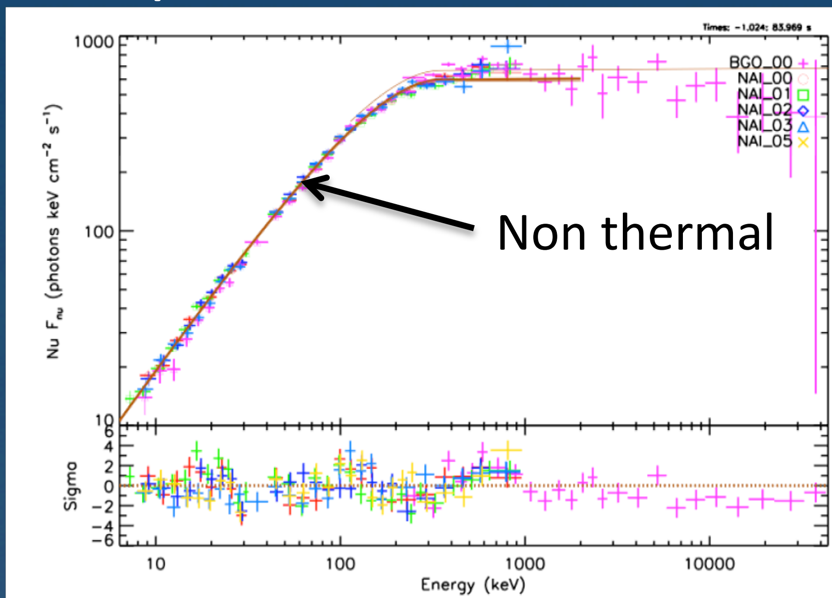
Interpretation of the HE Delayed Onset and of the Extra Power-law Spectral Component

- **Leptonic models (inverse-Compton or SSC)**
  - \+ Can explain the high energy PL excess
  - \- Hard to produce a delayed onset longer than spike width
  - \- Hard to produce a low-energy (<50 keV) power-law excess
- **Hadronic models (pair cascades, proton synchrotron) – Asano 2009, Razzaque 2009**
  - \+ Late onset: time to accelerate protons & develop cascades?
  - \- Hard to produce correlated variability at low- and high-energies (e.g. spikes of GRB 090926A)?
  - \- Proton synchrotron radiation requires large B-fields
  - \+ Synchrotron emission from secondary $e^{\pm}$ pairs produced via photo-hadron interactions can naturally explain the power-law at low energies
- **Early Afterglow (e+e- synchrotron from external shock) – Kumar 2009, Ghirlanda 2010**
  - \+ Can account for the delayed onset of the PL
  - \- Short variability time scales in LAT data argues against external shock

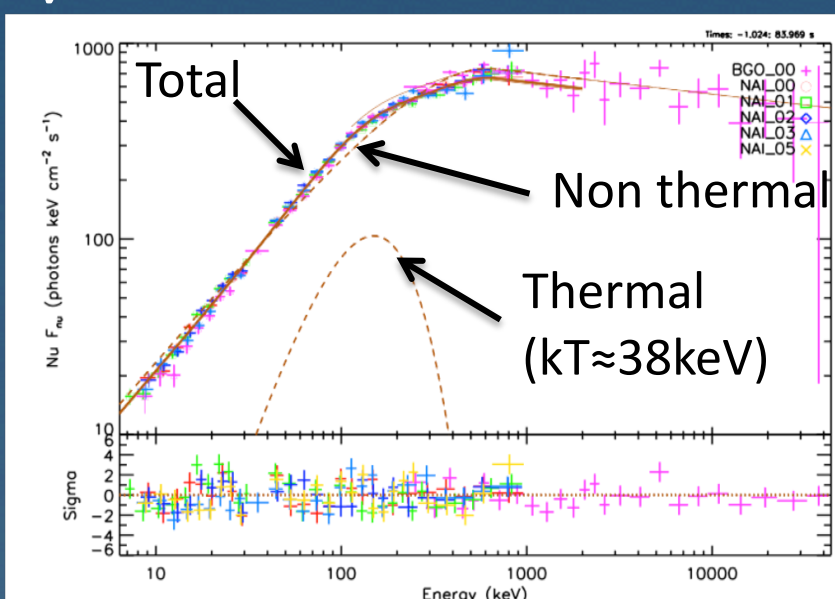
1st Clear Identification of a Physical Component (black body) in a Prompt Emission Spectrum (GRB 100724B)

(Guiriec et al. 2011, ApJL 727, L33)

νF_ν Spectrum – non-thermal



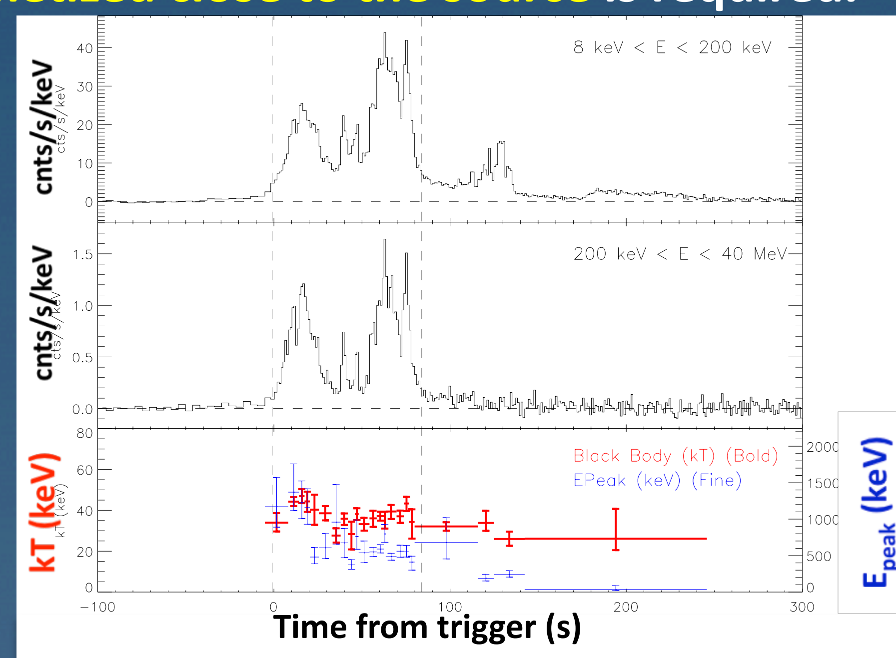
νF_ν Spectrum – non-thermal + thermal



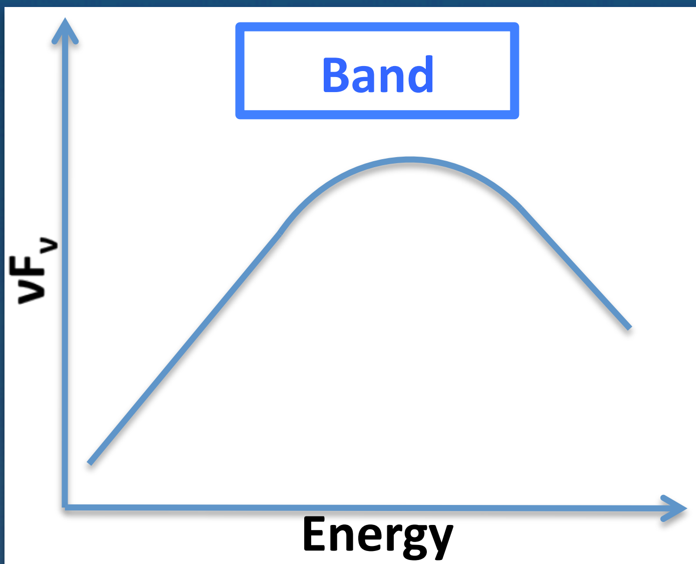
- **Standard fireball model** predicts **thermal** and **non-thermal** emission during the prompt emission. => **Thermal** emission **never** clearly **detected**.

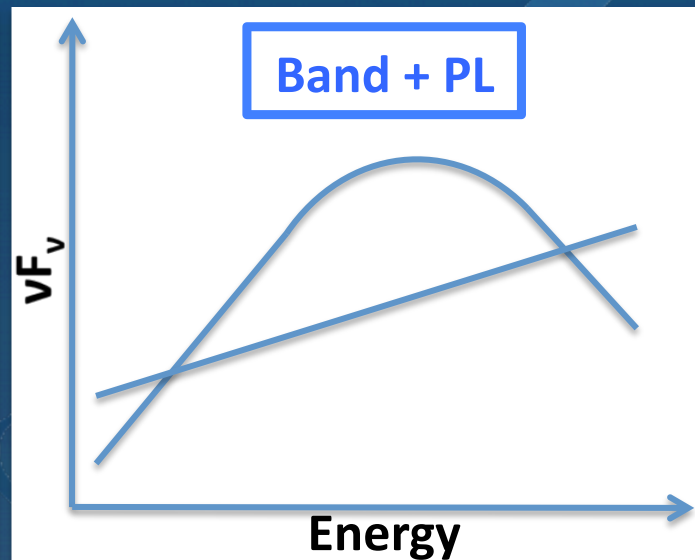
- **For the first time**, simultaneous identification of the **thermal** and non-thermal components in the spectrum of GRBs observed with GBM.

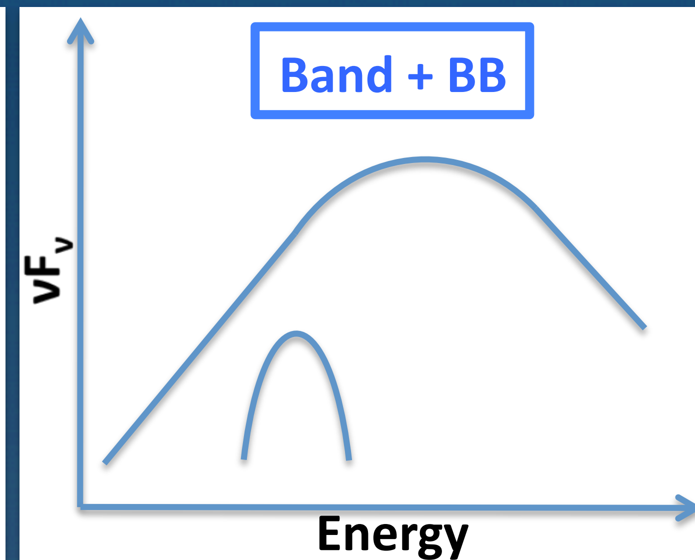
A pure **internal energy** reservoir is not sufficient to explain the observations and an **outflow highly magnetized close to the source** is required.

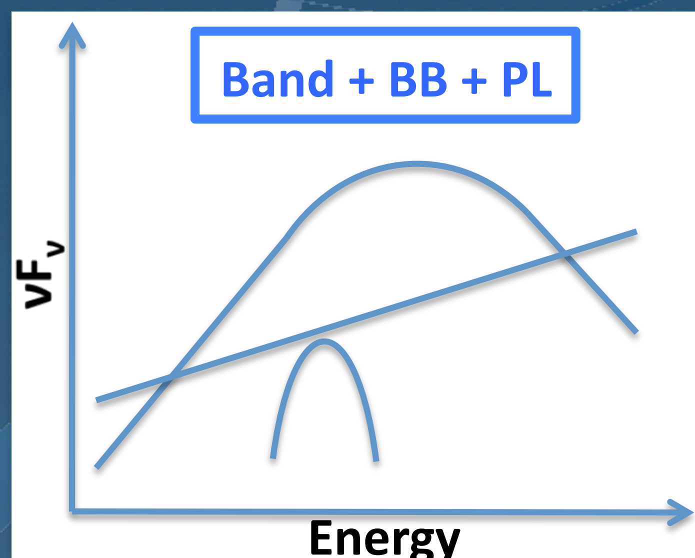


Spectral Shapes









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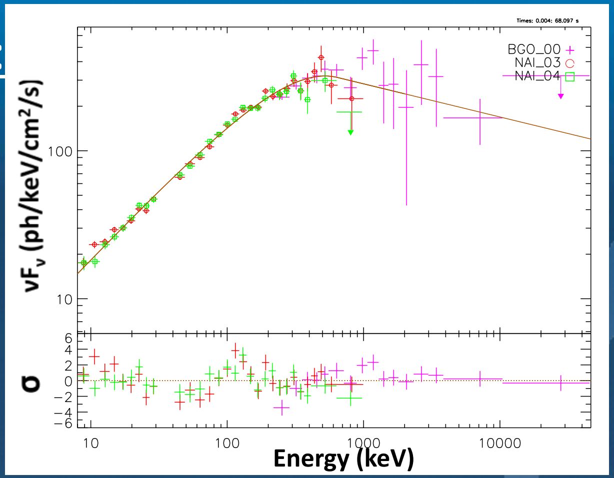
A New View of Fermi GRBs : Multi-Spectral Components

Most famous Fermi GRBs :

GRB 080916C

(Abdo et al. 2009, Science 323, 1688)



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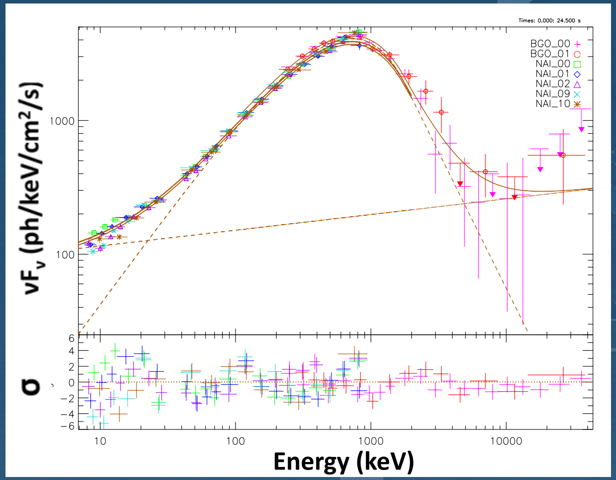
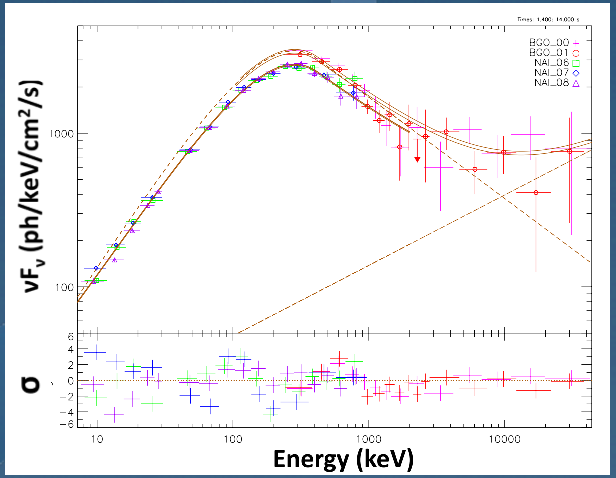


GRB 090926A

(Ackermann et al. 2011, ApJ 725, 225)



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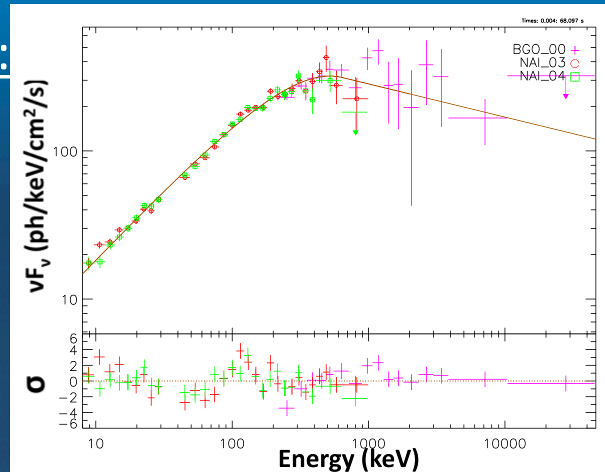

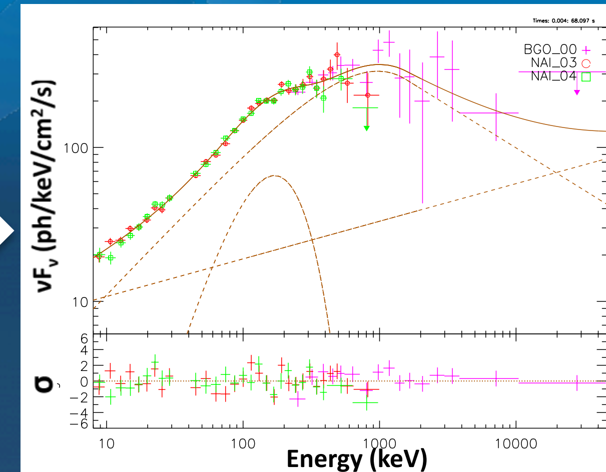

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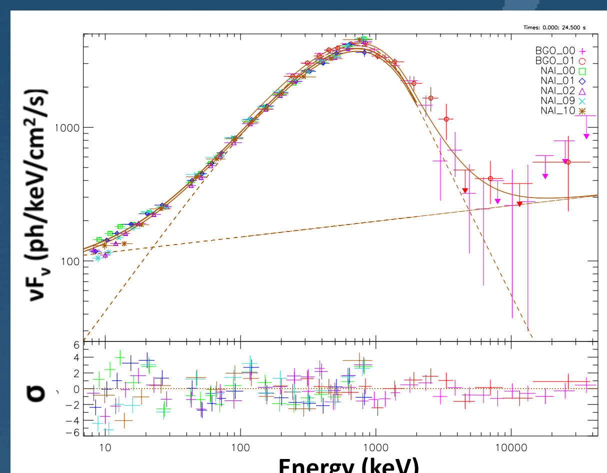

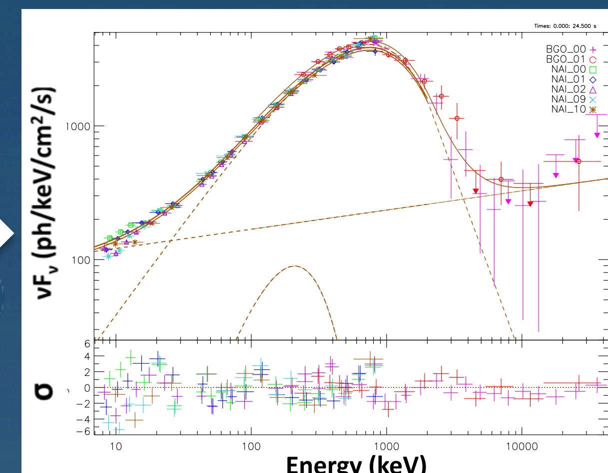

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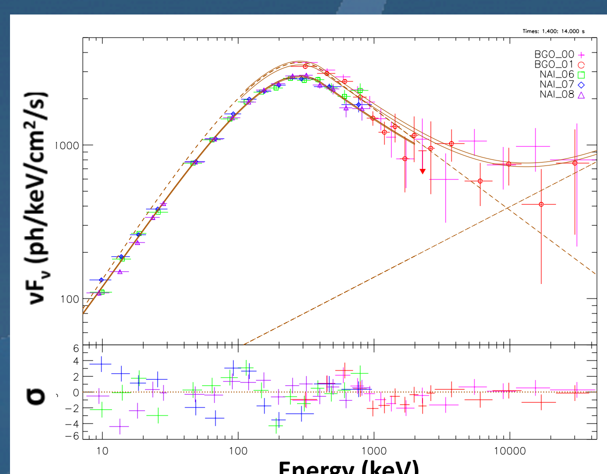

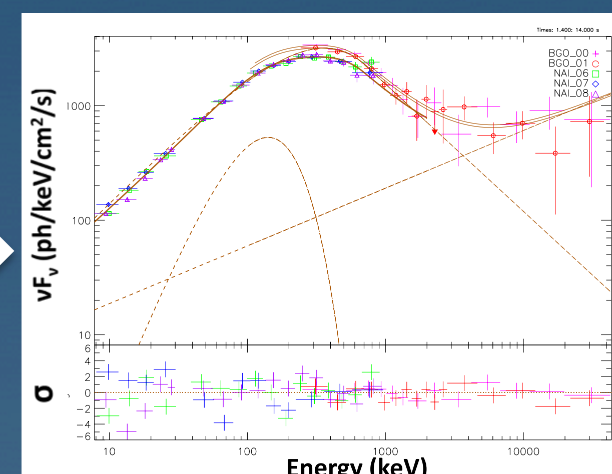

Guiriec et al. in preparation

A New View of Fermi GRBs : Multi-Spectral Components

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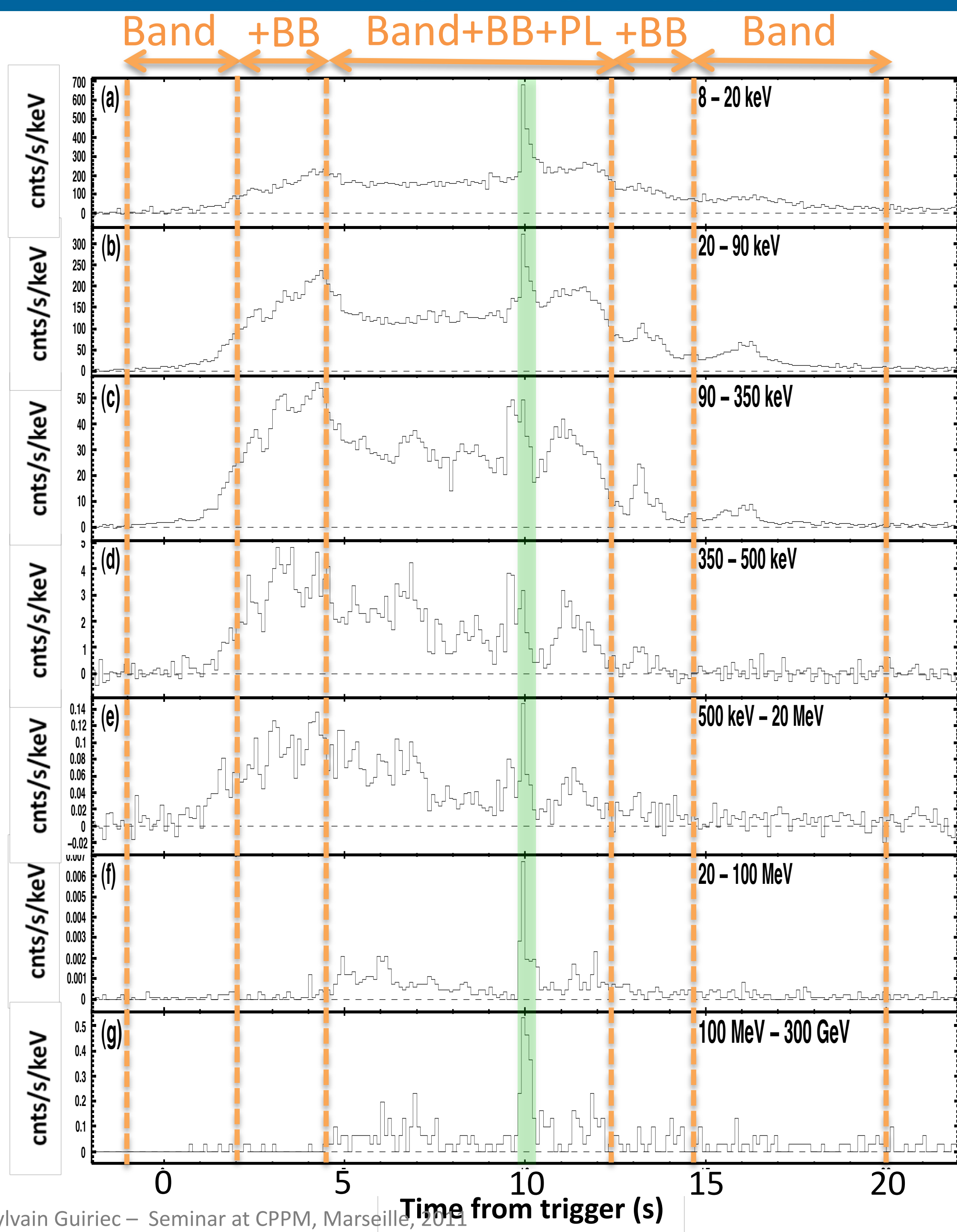

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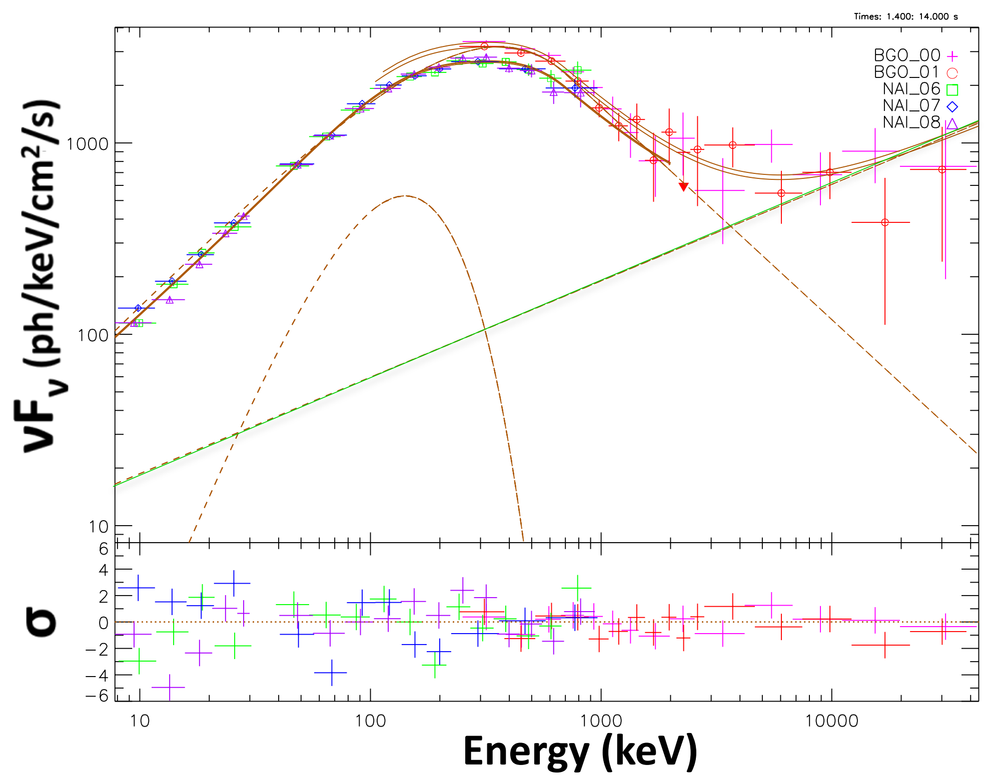

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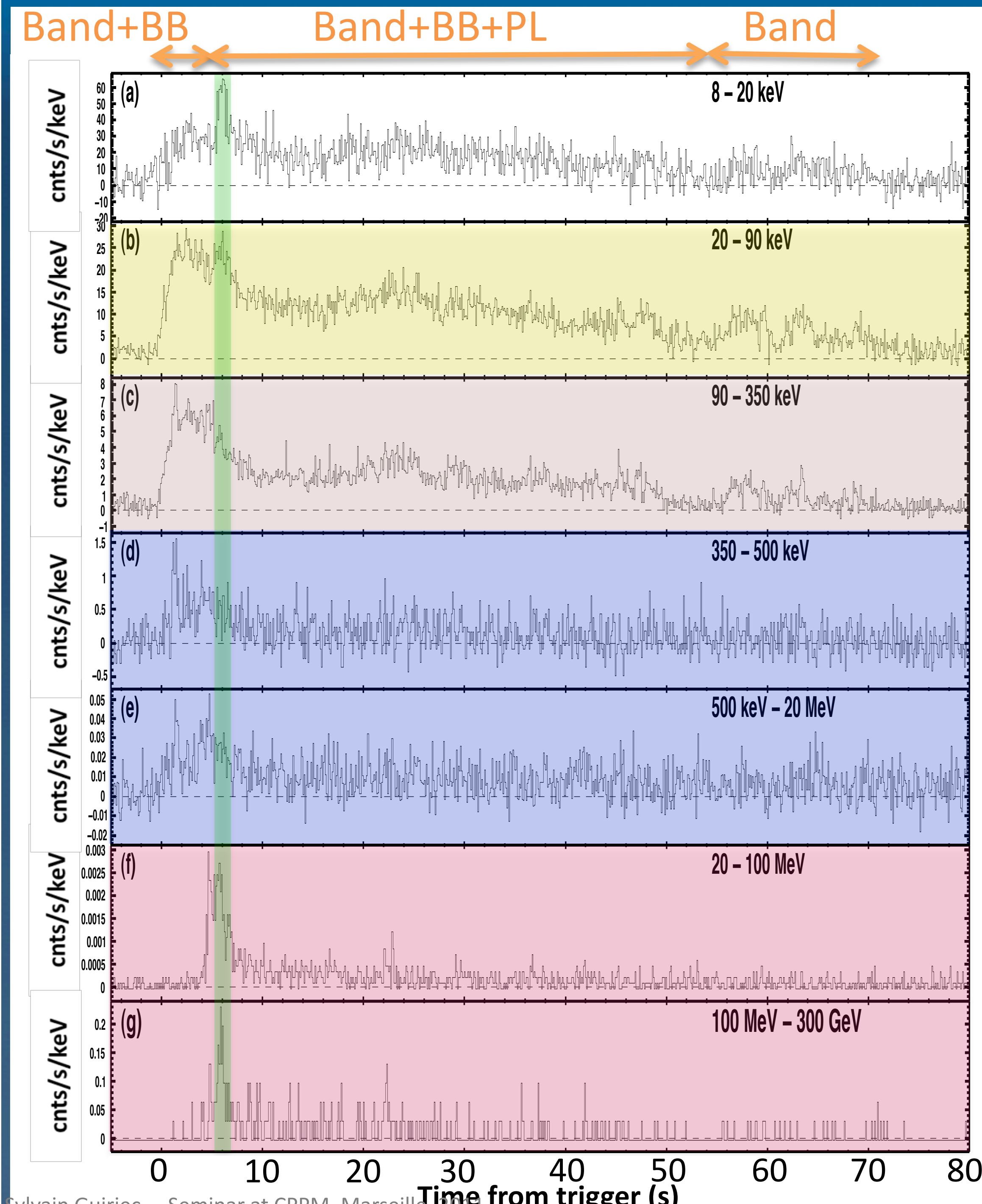

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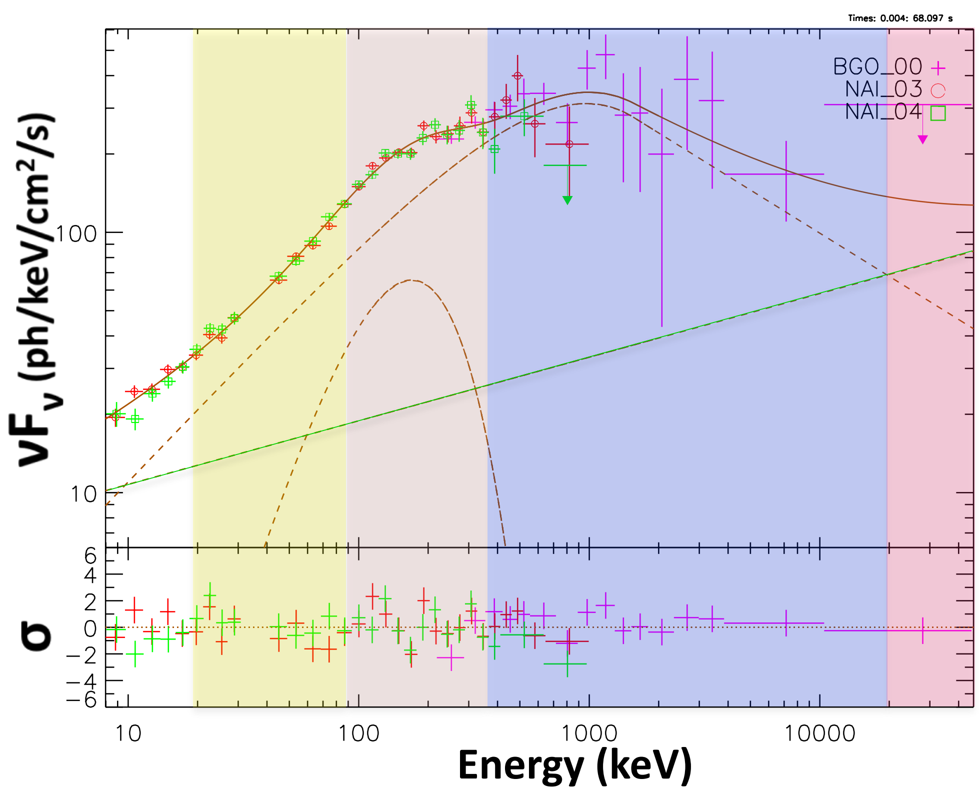
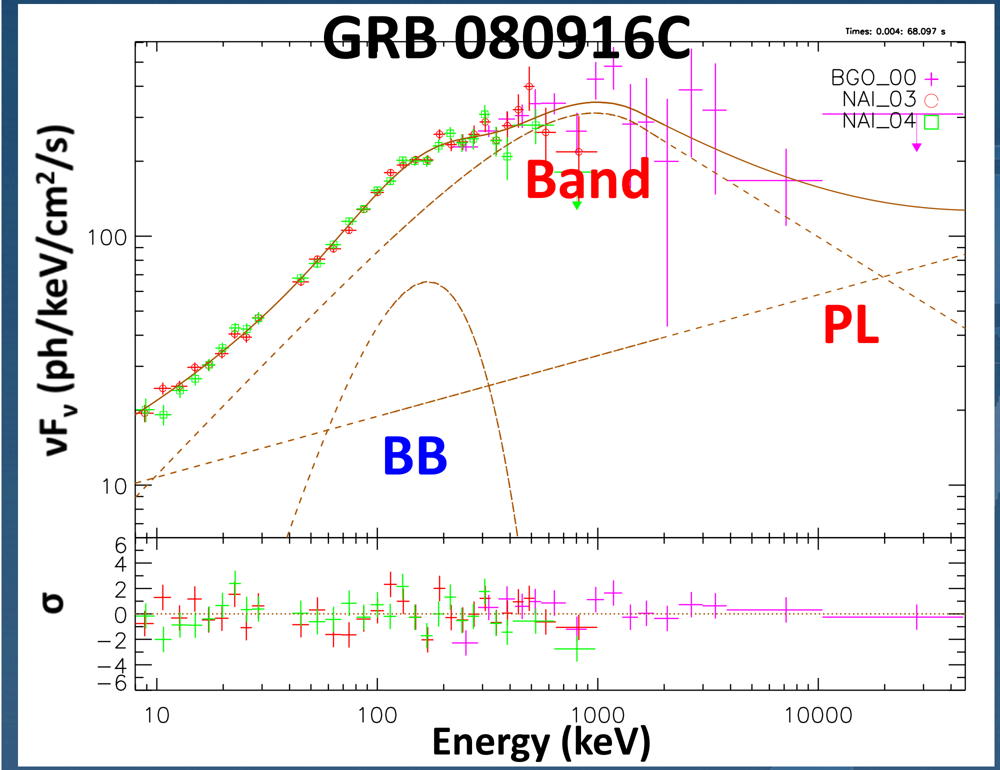


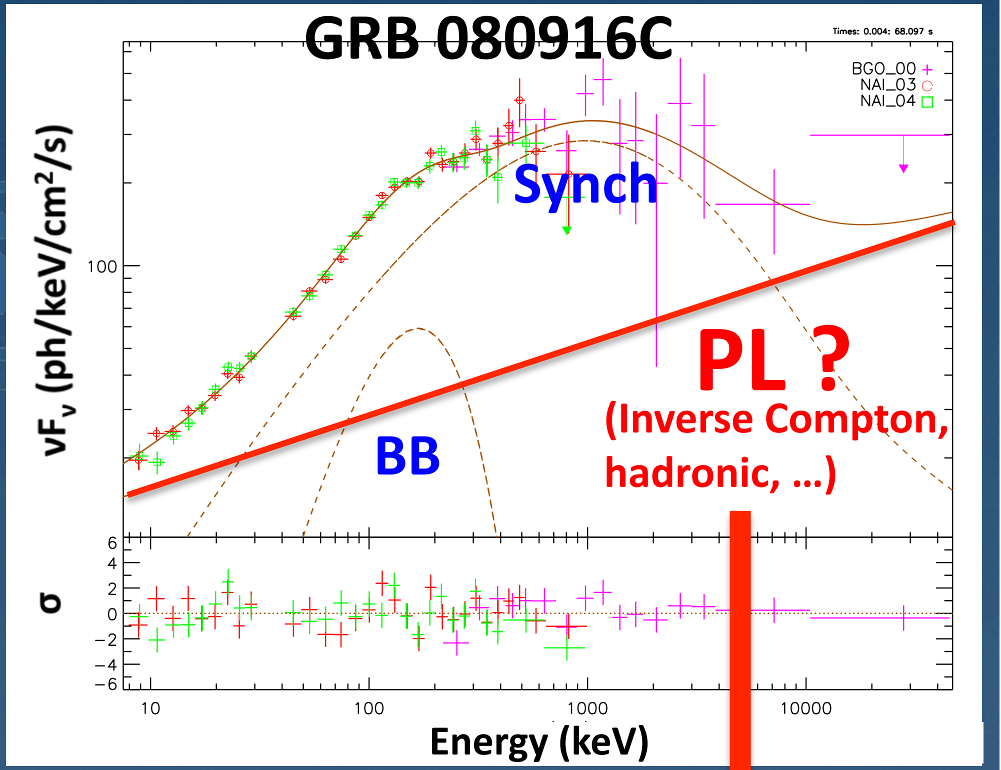
Towards Fits with Only Physical Components

Burgess et al. (submitted to ApJL) implemented a detailed electron synchrotron emission description as fit model available in the software package RmFit

Band + BB + PL



Synch model + BB + PL

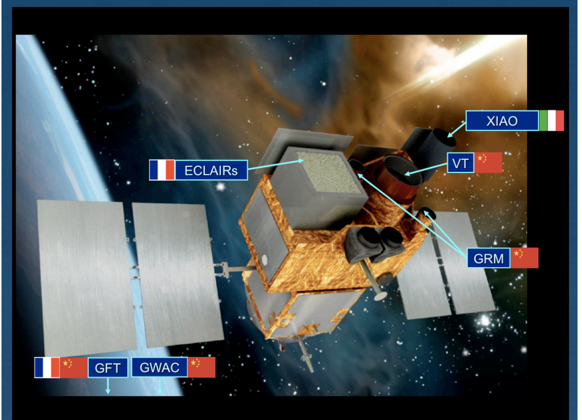


The synchrotron model requires the use of the BB component to get a good fit !!!

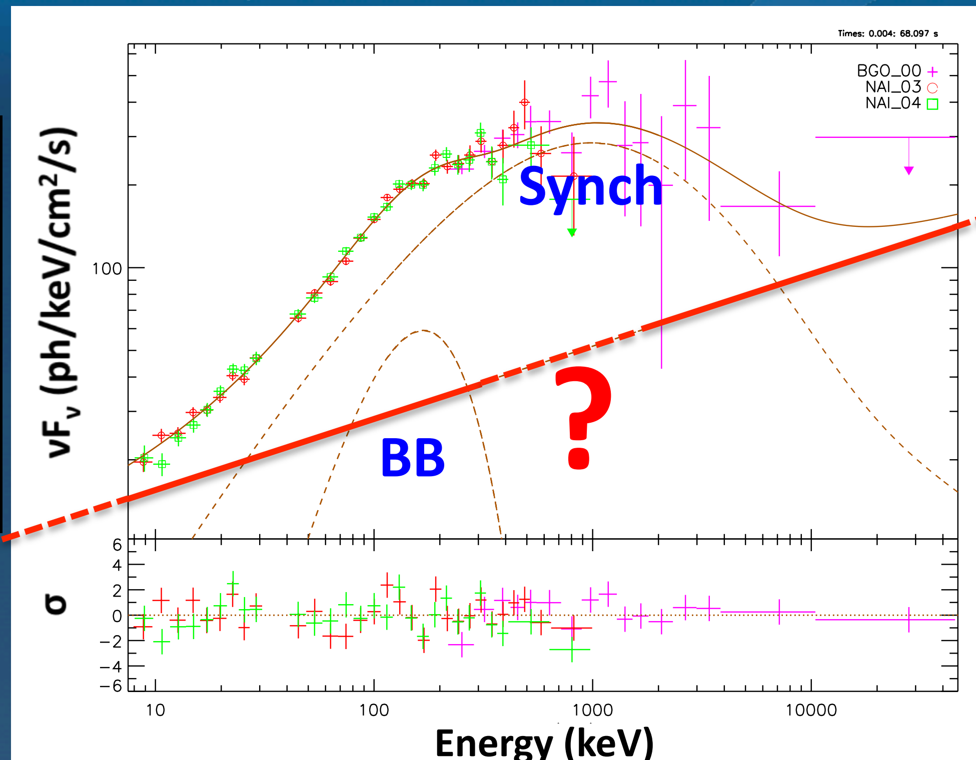
Guiriec et al. in preparation

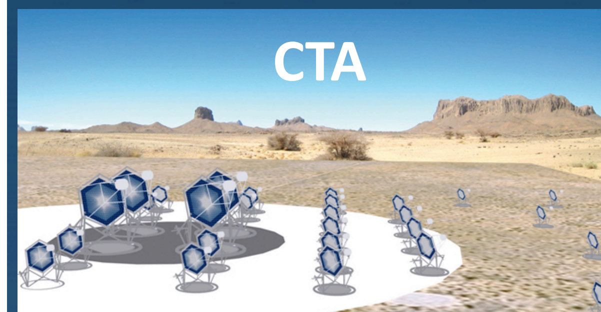
France, a Possible Future Leader ?

SVOM

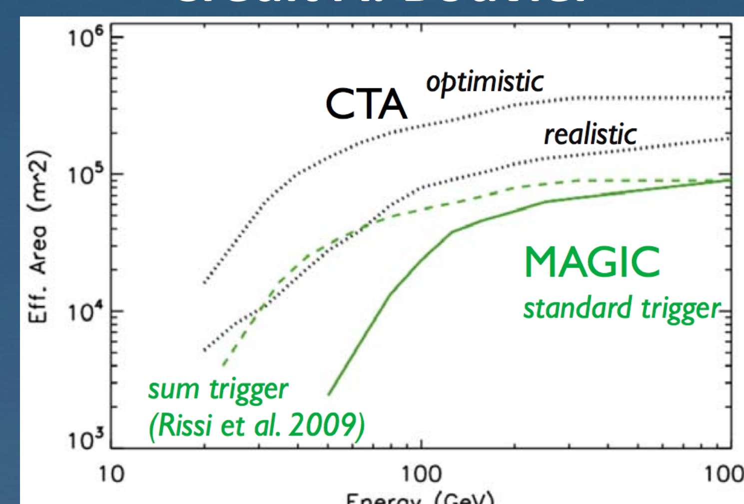


Synch model + BB + PL



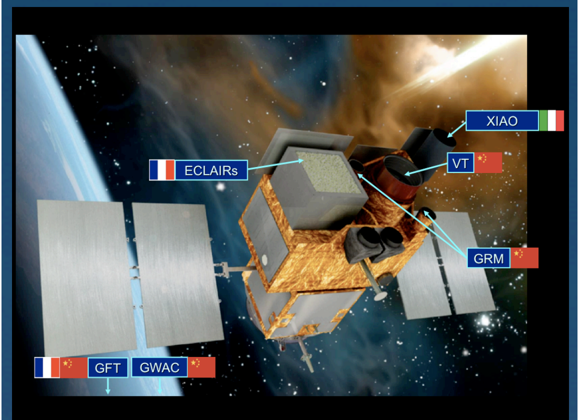


Credit A. Bouvier

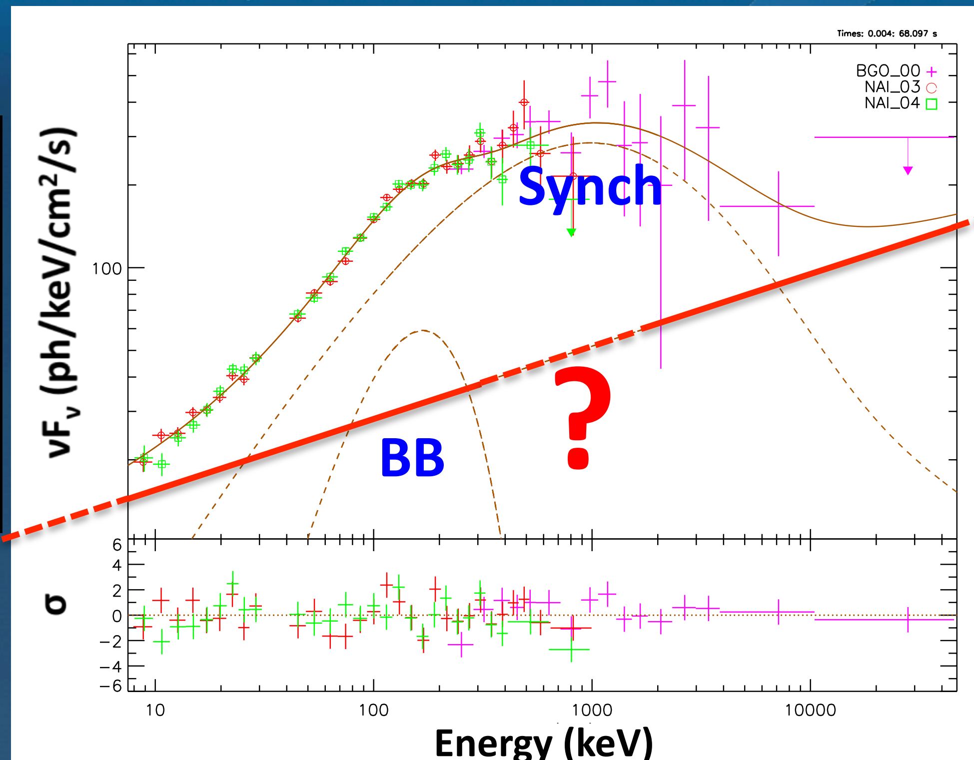


France, a Possible Future Leader ?

SVOM



Synch model + BB + PL



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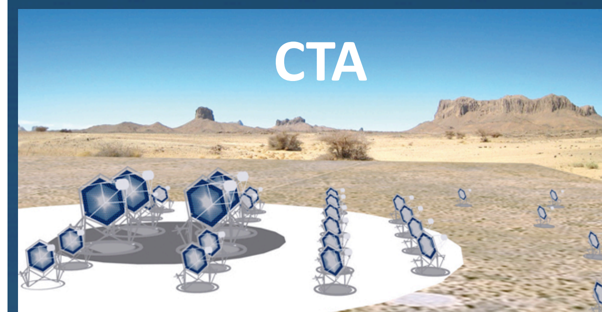
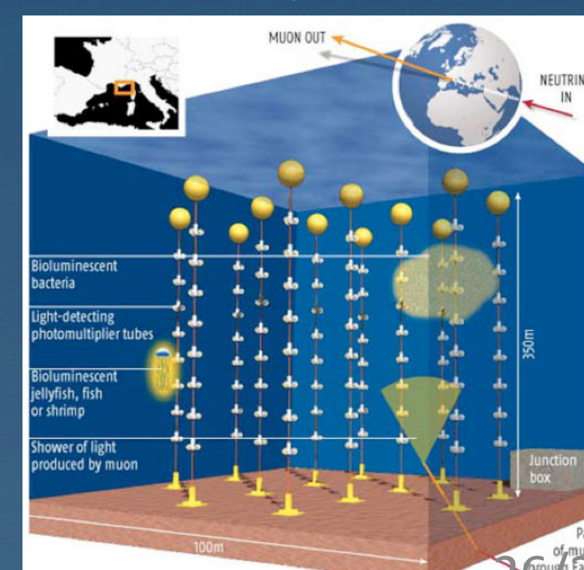


If hadrons

Neutrinos ? (Antares/KM3)



France, a Possible Future Leader ?

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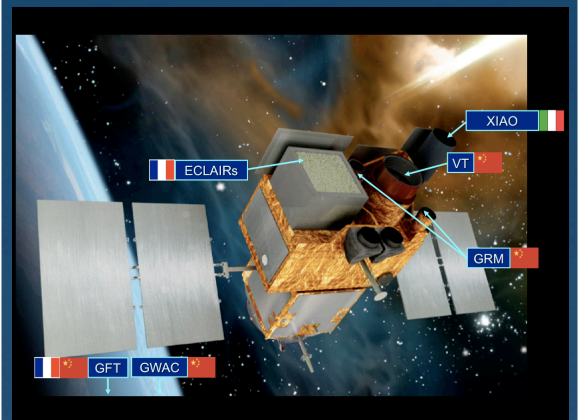

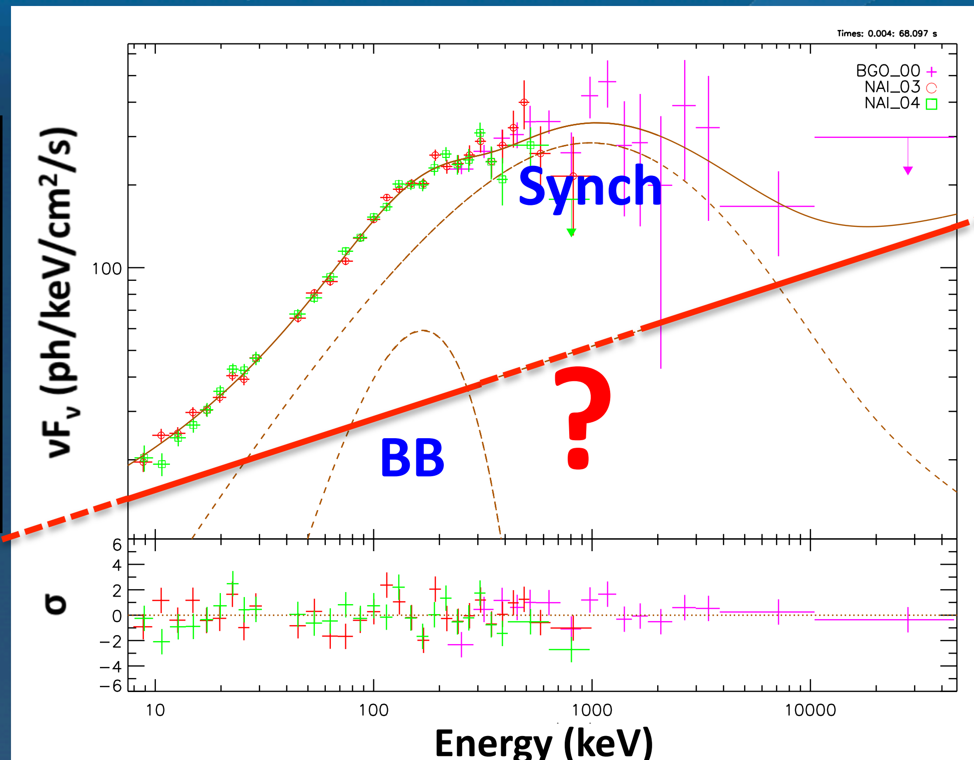

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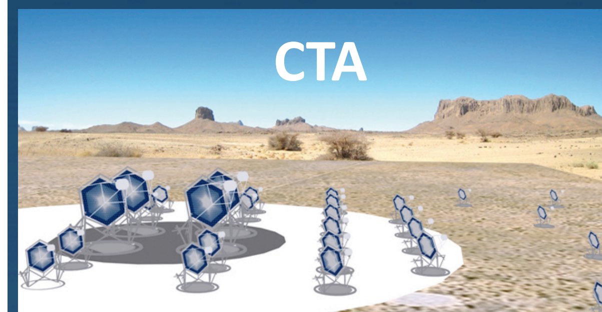
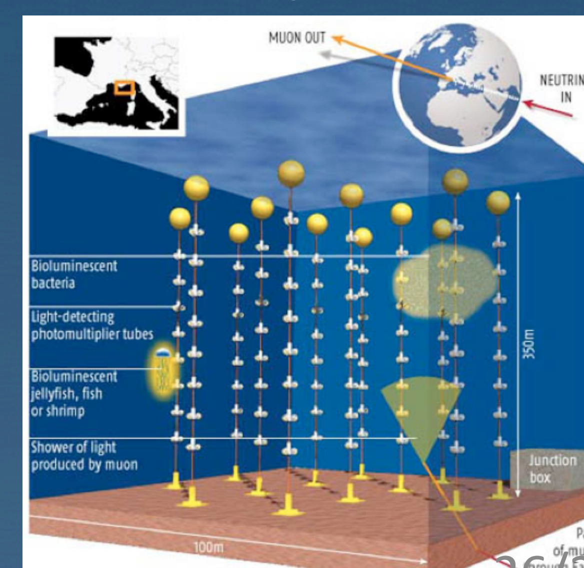


If hadrons

Neutrinos ? (Antares/KM3)

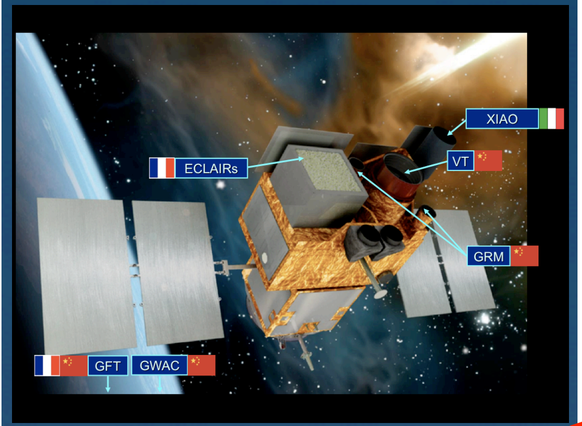
If new born stellar mass black hole (z~1)

Gravitational waves (Virgo)

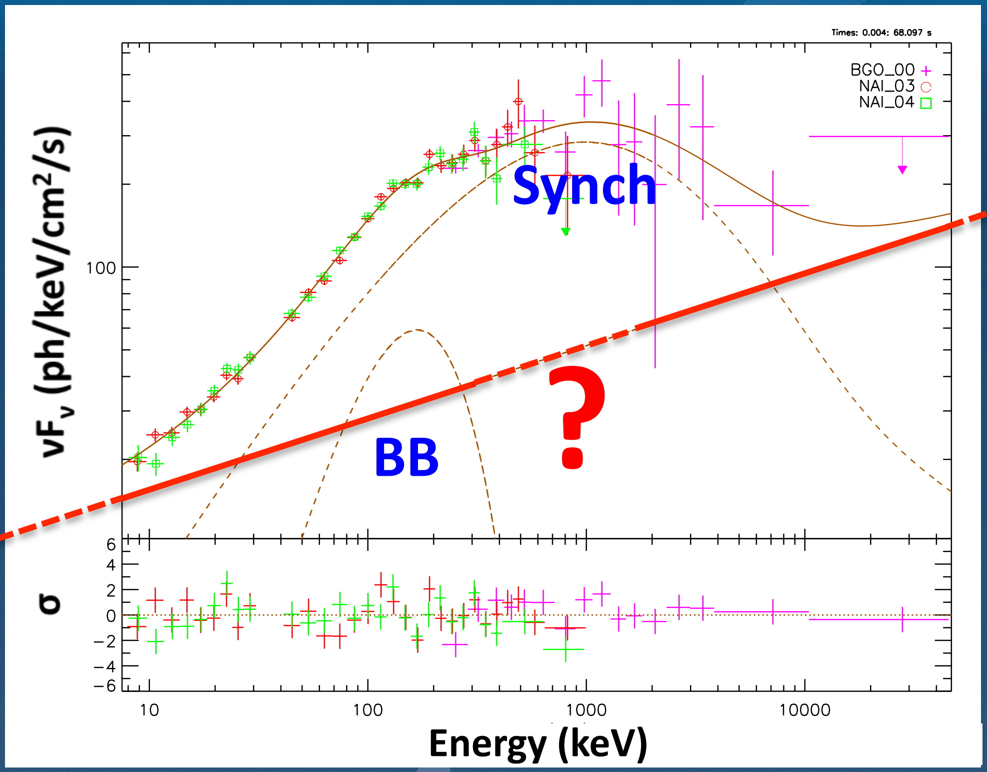


France, a Possible Future Leader ?

SVOM



Synch model + BB + PL



If new born stellar mass black hole (z~1)

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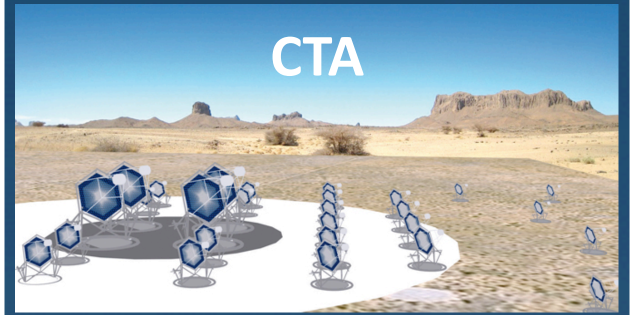
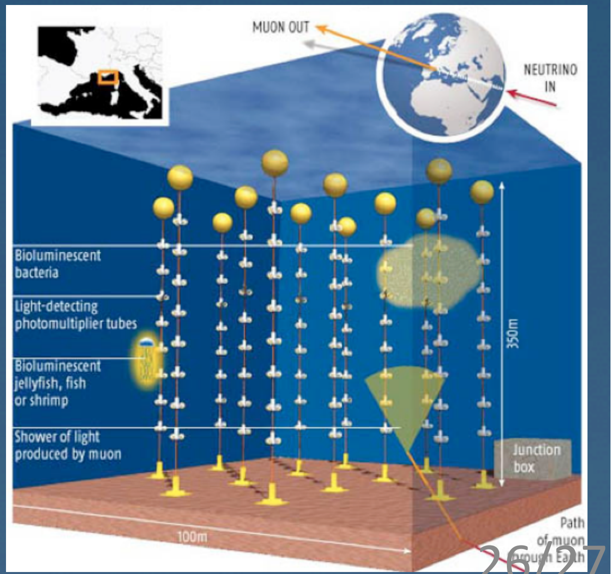


If hadrons

Neutrinos ? (Antares/KM3)



SVOM could remain the only GRB "sky monitor" after GBM

Crucial for neutrino and gravitational wave experiments, and CTA

Conclusion

- GRB observations are challenging because they require a very fast repointing of various space and ground based instruments simultaneously.
- A better understanding of GRBs is required prior to use them for cosmology, fundamental physics, among others, …
- With Fermi, we made major forward steps in the understanding of the prompt emission.

Empirical spectra models → Nearly pure physical models : Synch e^- + BB + PL (IC, hadron synch …)

↓

CTA and SVOM (with France) will be the best instruments to identify definitely the PL and to fully constrain various spectral parameters

- SVOM (Chino-French) will be probably the only GRB "sky monitor" after GBM

→ Major asset for neutrino and gravitational waves experiments as well as for CTA