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OAR

Gamma-ray Burst Theory in the Fermi Era

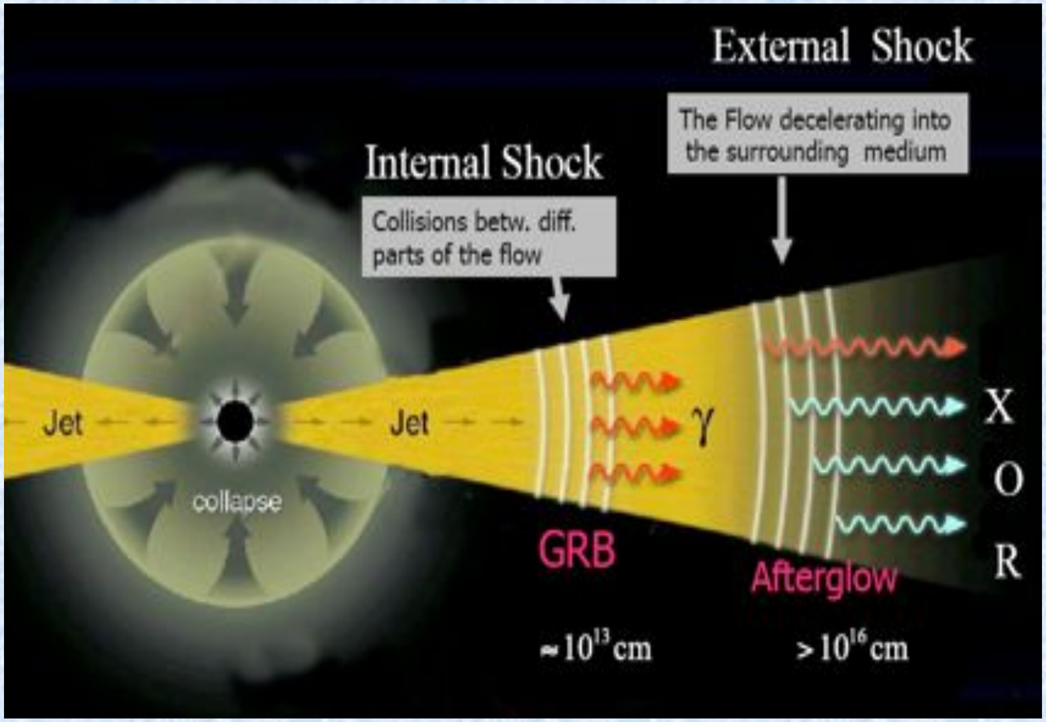
Dafne Guetta

Outline of the Talk:

- What are GRBs
- What do we learn on GRBs from the Fermi data
- Synergies with other measurements
- Specific areas that need more effort
- Future prospects

GRB Theoretical Framework:

- **Progenitors**:
  - Long: massive stars
  - Short: binary merger?
- **Acceleration**: fireball or magnetic?
- **Prompt γ-rays**: internal shocks? magnetic plasma?



- **Deceleration**: the outflow decelerates as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

What do we think to know about GRBs?

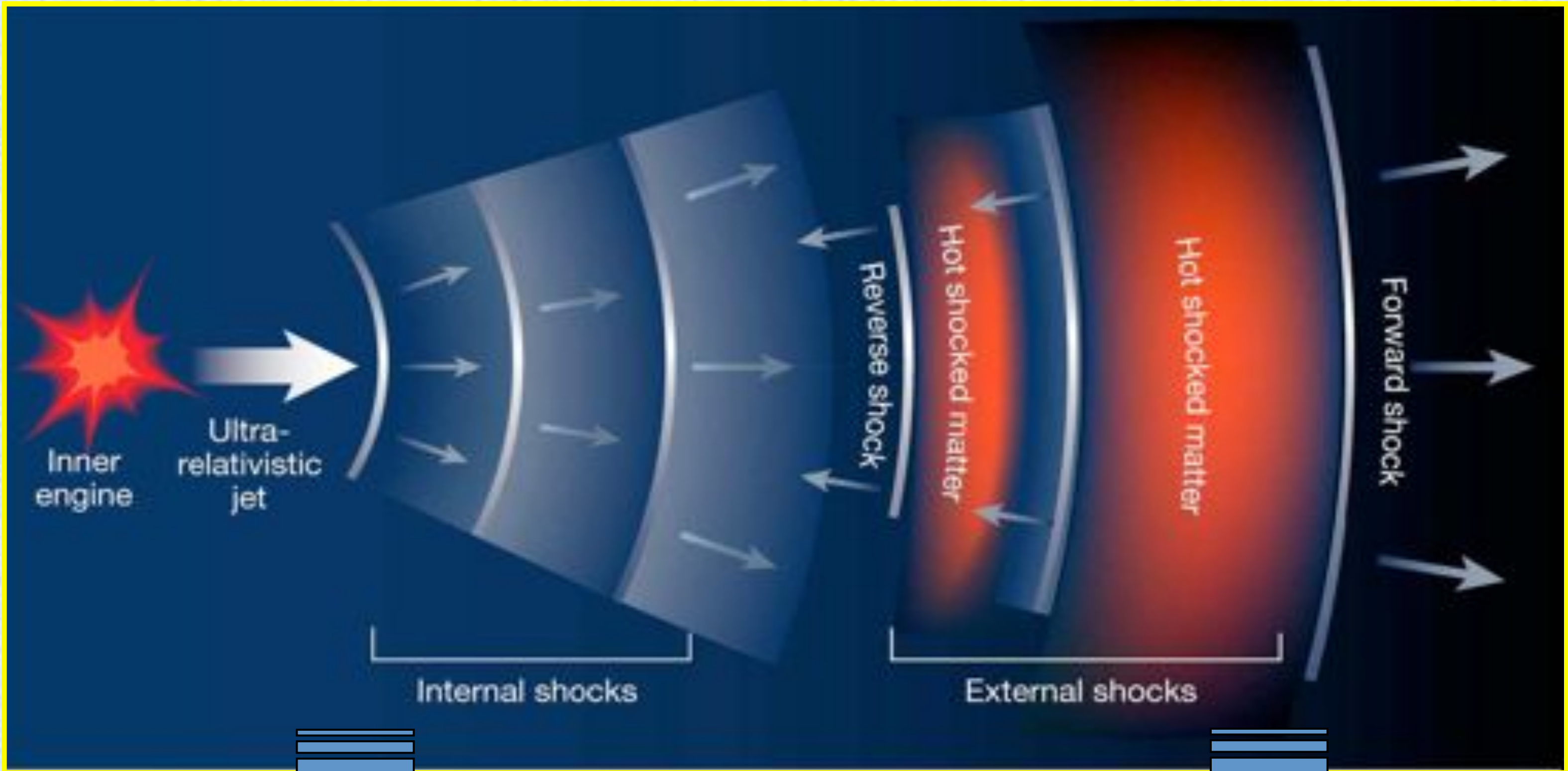
- Cosmological distance:Typical observed z>1
- Relativistic expansion: high Γ~ 100 required by observation
- Energy released is up to few times the rest mass of Sun (if isotropic) in a few seconds => narrow beam
- Two populations of GRBs: short (T_{90}<2 s) and long
- Spectrum non-thermal
- Central Engine
  - Collapse of massive, rotating star? (long GRBs)
  - Coalescence of binary neutron stars? (short GRBs)
- Final Product is Black Hole (probably)

Open questions before Fermi

- Nature of the progenitor?
- The dynamics of GRB jet why Γ so high, fireball?
- What is the dissipation mechanism that lead to the emission of γ-rays? Internal shocks? ☺
- Jet composition, there are hadron in the jet? ☺
- Radiative processes and physical explanation to the broad band spectrum observed *(Guiriec talk)* ☺

☺ = Fermi results may help us in understanding

High Energy emission in GRBs: predictions



- SSC in internal shocks, 1 MeV-10 GeV (Guetta & Granot 2003, Meszaros et al., Galli & Guetta 2007)
- p-γ interaction, MeV – TeV (Gupta & Zhang 2007)

- SSC in RS, keV-GeV (Granot & Guetta 2003 Kobayashi et al. 2007)
- SSC in FS, MeV-TeV (Galli & Piro 2007)
- p-γ interaction in FS, GeV – TeV (Boettcher & Dermer 2003) p-sync. (Razzaque 2010)

Theoretical models for high-energy emission - before Fermi -

MATTER DOMINATED	
LEPTONIC	**HADRONIC**
IS – Synchrotron	IS – Proton Synchrotron
IS – SSC	IS – π^0 decay
ES forward shock –synchrotron	ES – Proton Synchrotron
ES forward shock –SSC	ES –Proton SSC
ES reverse shock –synchrotron	Synchrotron and IC from secondary e^+e^-
ES reverse shock –SSC	
Inverse Compton on external photons	
X-ray Flares –SSC	

Theoretical models for high-energy emission - Fermi era-

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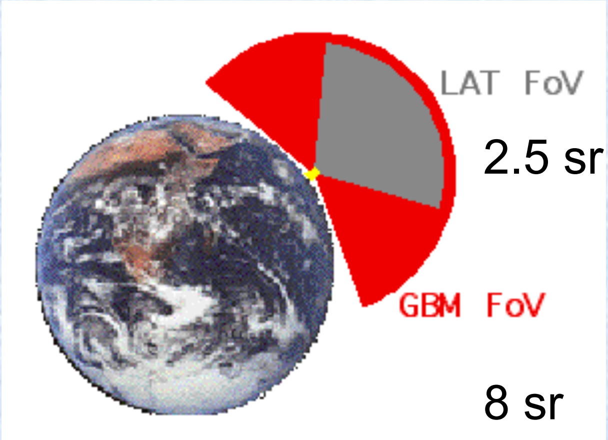
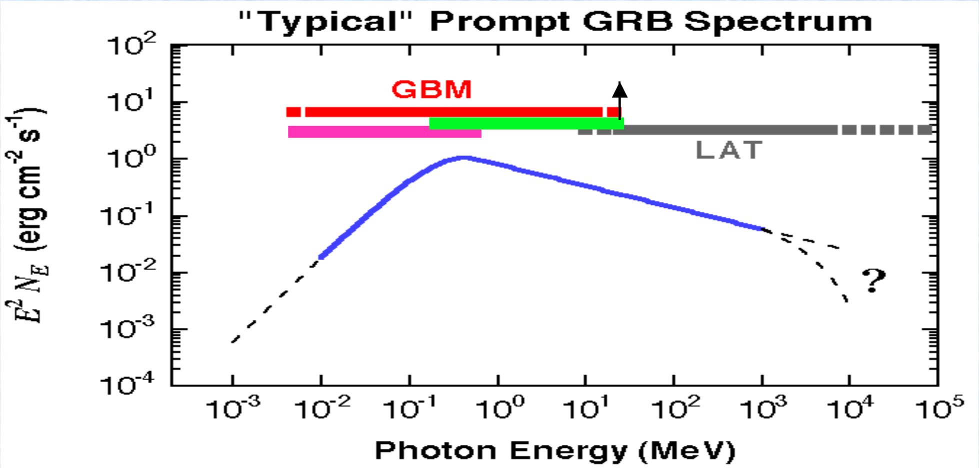
ES forward shock –synchrotron	ES – Proton Synchrotron
ES forward shock –SSC	ES – Proton SSC
ES reverse shock –synchrotron	Synchrotron and IC from secondary e^+e^-
ES reverse shock –SSC	Strong constraints from IceCube data
Inverse Compton on external photons	But we try our best…….
X-ray Flares –SSC	

Fermi and GBM

- Fermi GRB Monitor (GBM): 8 keV – 40 MeV full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV

  FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime





Fermi key results

- GBM, Swift, BATSE samples consistent (Guetta et al. 2011)
- The GBM detects ~250 GRBs / year, ~half in the LAT FoV
- The LAT detected 35 GRBs in 3 years (30 long, 5 short) **Why so few?**
- Most high energy emission fitted with one component some GRBs show an extra-component (long GRB090902B, short GRB090510) . **Origin of extra component?**
- LAT photons arrive with a delay respect to GBM photons. **Origin of this delay?**
- Longer lived high energy emission: **How can we explain this?**
- Photons detected up to 30 GeV. **Implication on Γ~1000!**
- First detections of short GRBs at HE
- 9 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C). **Not only low z detected.**

Why so few?: The Large Area Telescope (LAT) and EGRET performances

	LAT	EGRET
Energy range	20 MeV to >300 GeV	20 MeV – 30 GeV
Angular resolution (single photon, 10 GeV)	<10%	10%
Peak effective area	9000 cm^2	1500 cm^2
Energy resolution (on axis, 100 MeV – 10 GeV)	0.15°	0.54°
Field of view	>2.2 sr	0.4 sr
Deadtime per event	27 us	100 ms

20 EGRET over 3000 BATSE > 20 MeV

35 LAT over 1000 GBM > 100 MeV

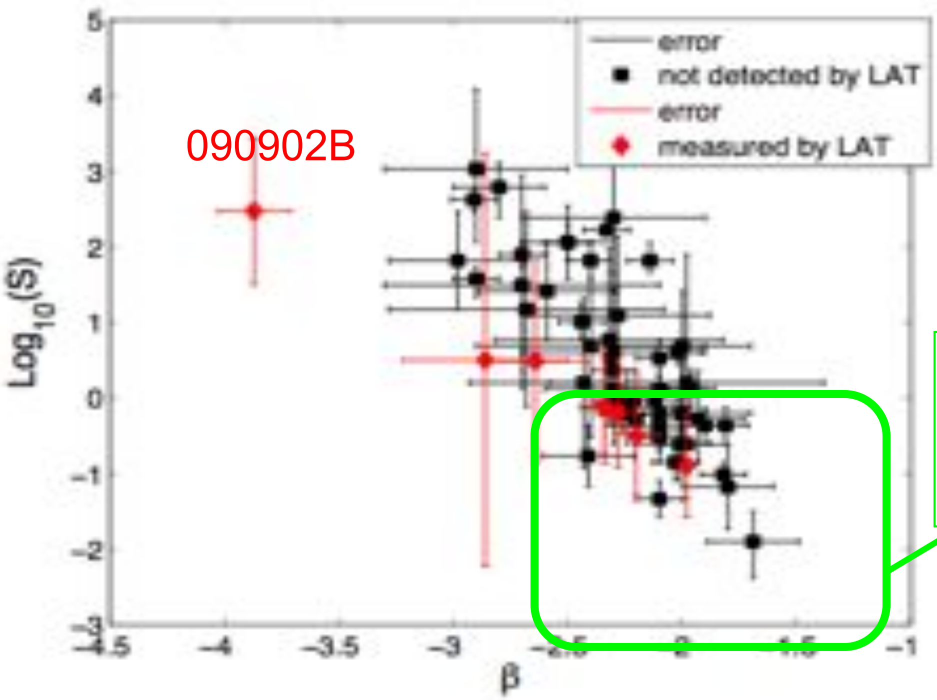
PAUCITY EXPECTED:
EGRET vs BATSE ~ LAT vs GBM
statistics: reflects a paucity of detection of high energy tails!
PAUCITY IS REAL!!!

They are bright bursts and with hard Spectra both EGRET and LAT

Why less than 10% of GRBs detected by LAT?

(Guetta, Pian &Waxman 2010)

For ~ 80 GRBs fitted by Band law, using the LAT trigger algorithm, we define s= [minimum flux for LAT detection at 100 MeV]/ [flux(100 MeV)]



Found assuming extended sync. emission

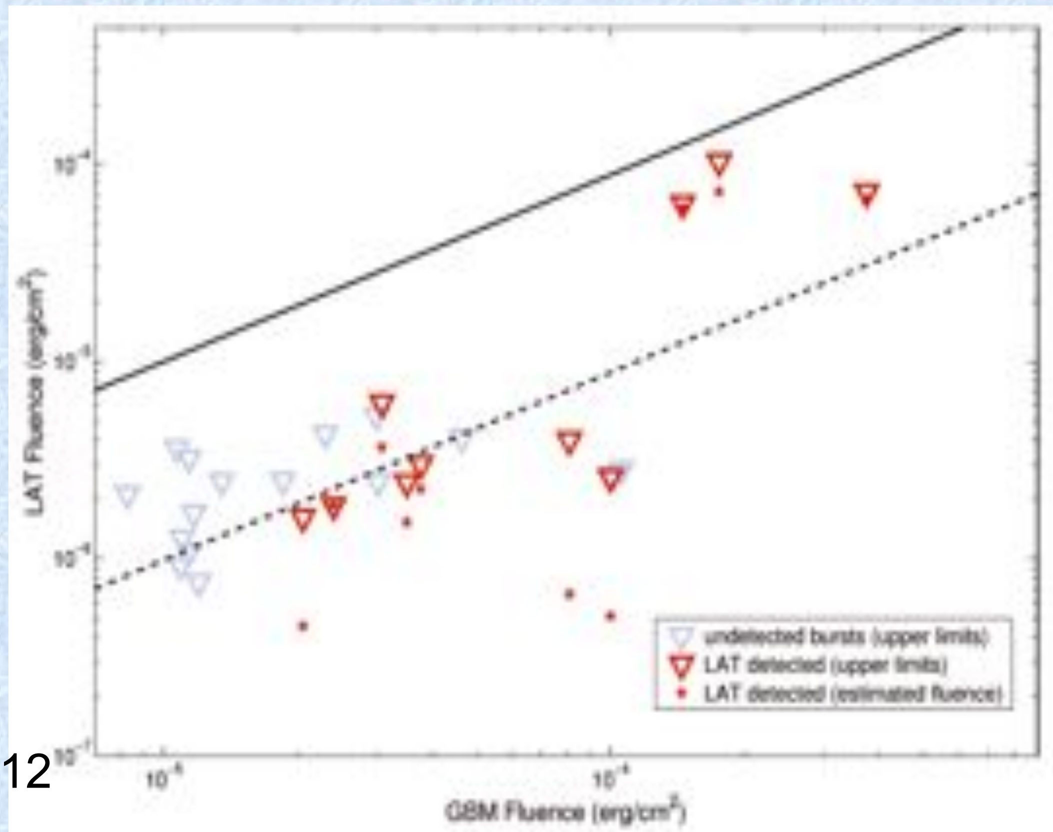
090902B: too soft to be extended synchrotron emission extra component needed!!!

LAT detectable: ~10 GRBs in the range of LAT detectability if extended synch. emission assumed not detected: **WHY??**

The emission at high energy is SUPPRESSED :
1) Electron energy distribution does not follow a power law over a wide energy range
2) Pair production at 100 MeV ⇒ upper limit on $\Gamma \leq 300$

LAT Upper limits and opacity

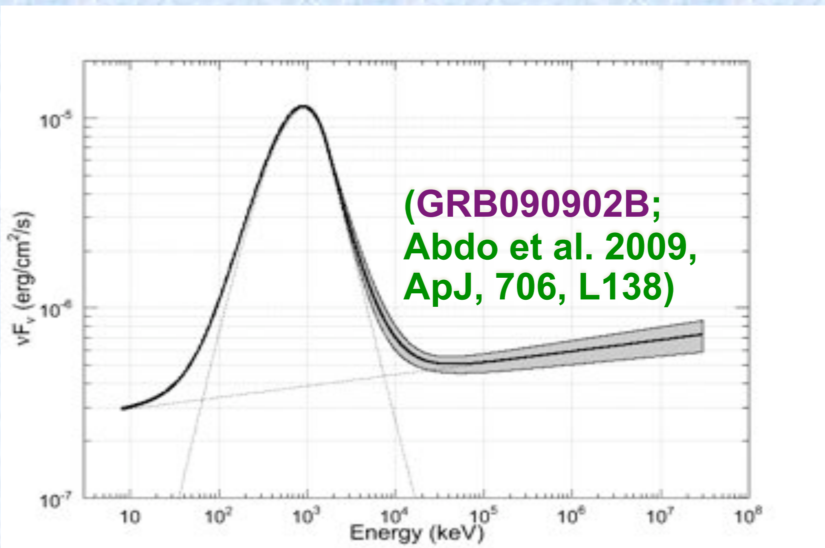
- Pre-launch: about 10 bright per year(>10 ph >100MeV)
- About ½ detected => **spectral break or cut off at 10-100 MeV**
- **Models where the prompt ~1 MeV emission is produced by IC scattering of optical photons** (Stern & Poutanen 2004) **excluded!**



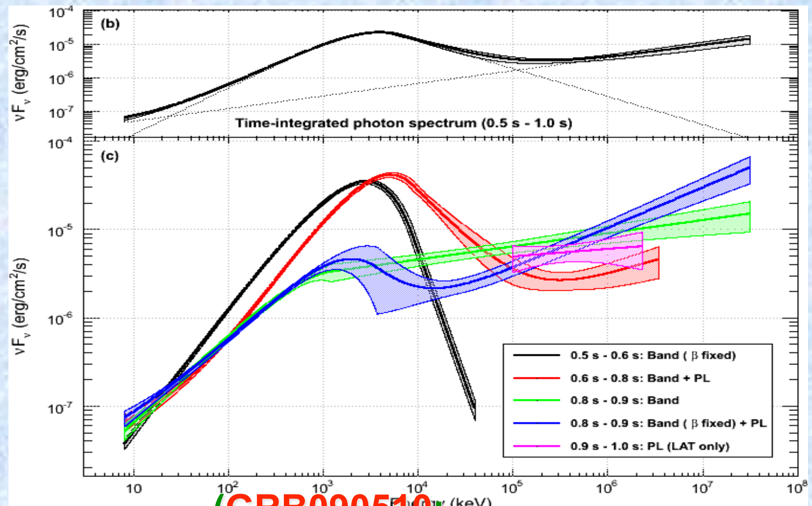
Beniamini et al 2011,
Guetta+ 2011 Fermi+ 2012

Origin of the extra component

Distinct high energy spectral component: Clearly (>5σ) appears only in 3 LAT GRBs, but these are the brightest in LAT so far. Suggests it may be common but good photon statistics is needed for clear evidence



(GRB090902B; Abdo et al. 2009, ApJ, 706, L138)



(GRB090510; arXiv:0908.1832)

HE emission from GRBs

Most GRB spectra may be explained: synchrotron radiation from relativistic electrons accelerated in the shock, which radiate in the strong magnetic field: **Single component**

Extra component of the prompt emission ?

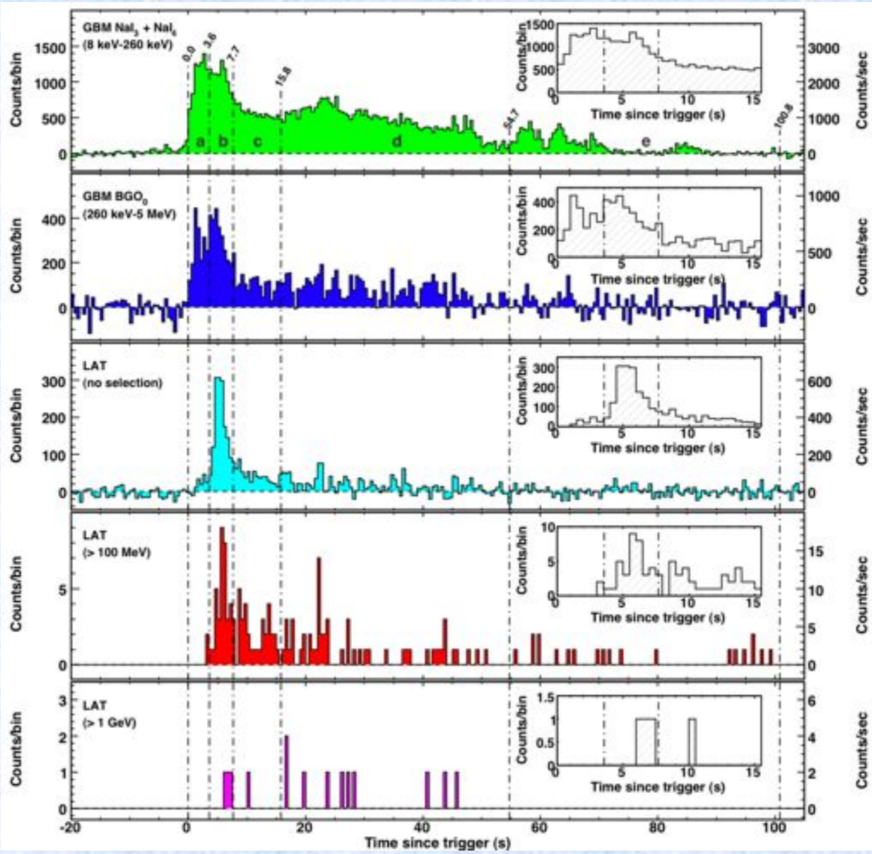
Synchrotron self Compton: upscattering of synchrotron photons by relativstic electrons or Hadronic origin p-$\gamma \Rightarrow \pi^0$, π^+

EGRET: GRB941017 shows the sign of extra component

The neutrino detector IceCube put a STRONG constraint on the hadronic origin of the HE emission. IceCube-Fermi Synergy

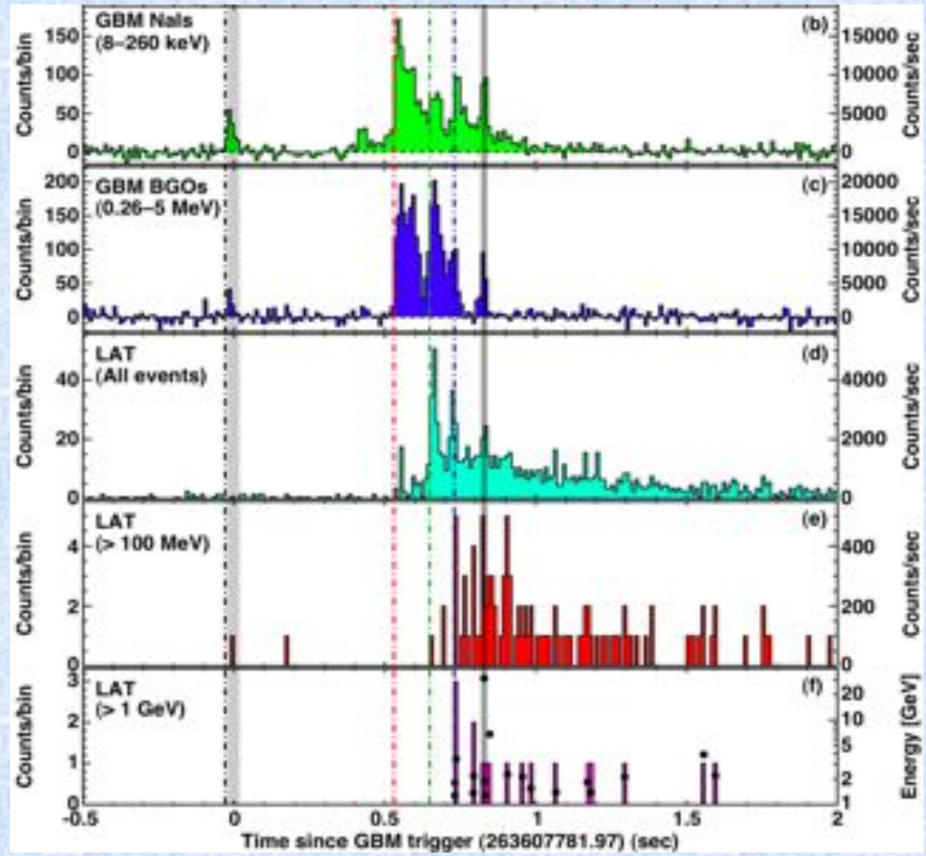
Origin of the delay: Explain the delayed onset of HE emission seen in several GRBs

GRB080916C



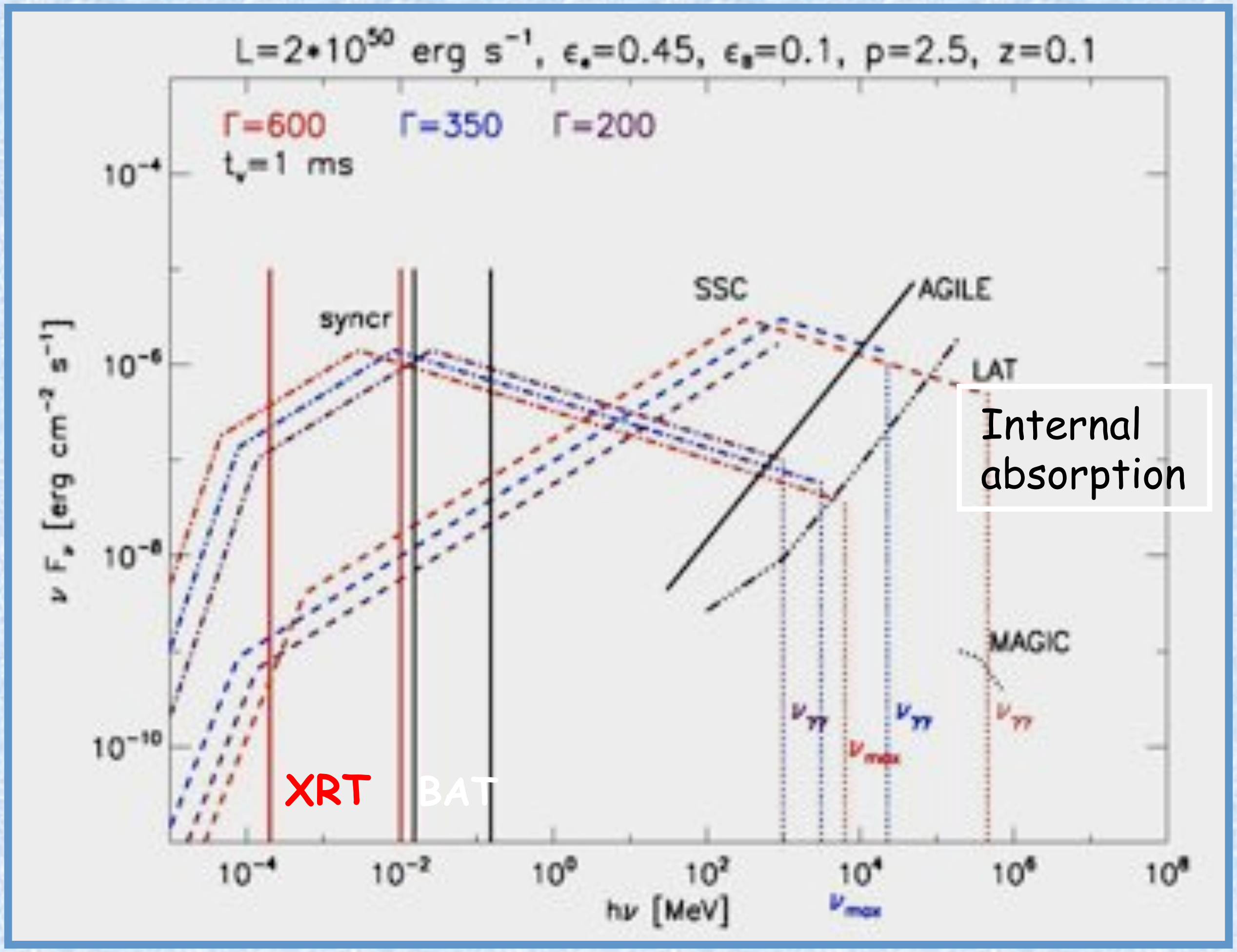
Delay in HE onset: ~ 4-5 s

GRB090510



Delay in HE onset: ~ 0.1-0.2 s

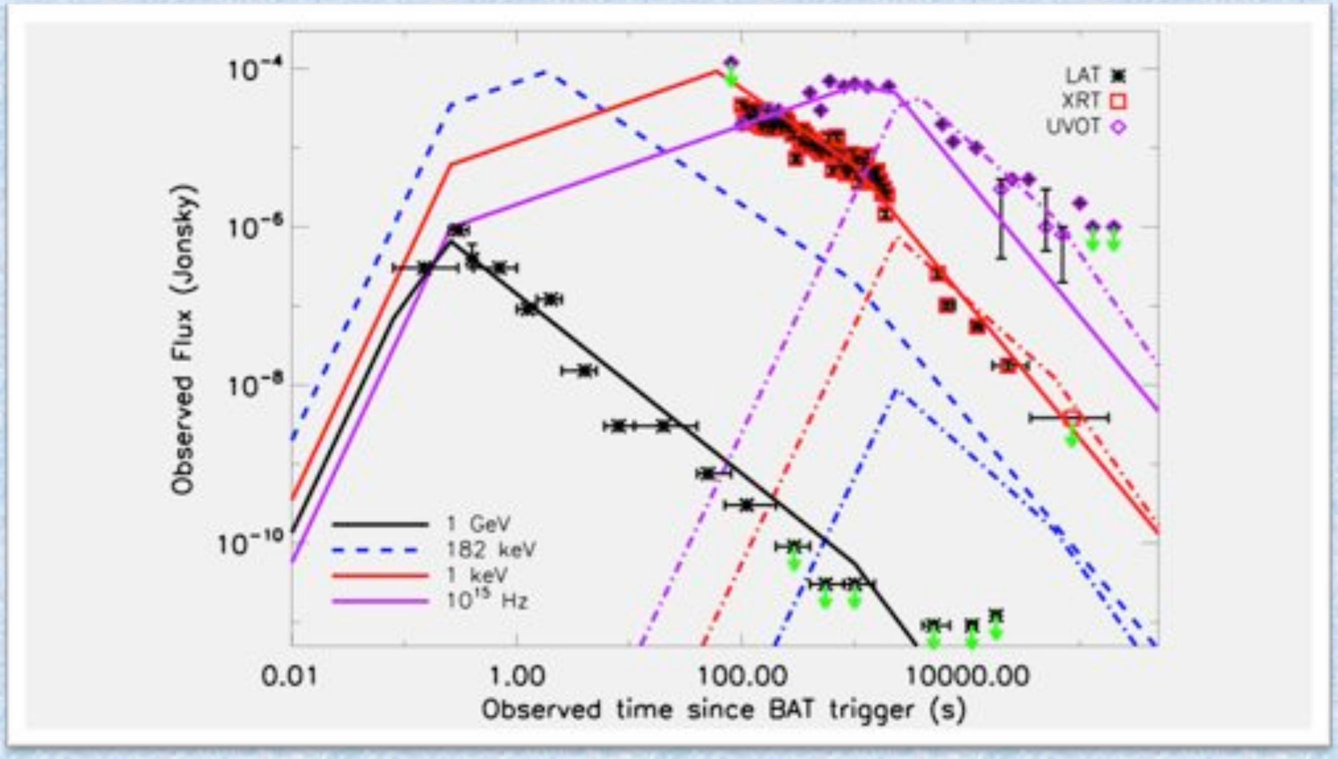
Predictions for the prompt phase: IS



Galli&Guetta(2007)

- GeV-Tev emission suppressed by internal absorption, depending on Gamma **Hard to explain a delay with IS.** Extended sync. Emission consistent GRB080916C

GRB 090510 from Fermi (and AGILE) within the ES model



(Corsi, Guetta, Piro ApJ 2009; see also Kumar & Duran, 2009, De Pasquale et al 09, Ghrilanda et at 09).

$$t_{\rm dec} \sim \left(\frac{3E_{\rm k,iso}}{32\pi n m_{\rm p} c^5 \Gamma_0^8}\right)^{1/3} \Rightarrow \quad \Gamma > 1000$$

$\Gamma \gtrsim 1000$ from $\gtrsim$10 GeV photons detected in GRB 080916C, GRB090510, GRB090902B

Temporally extended emission: HE afterglow?

- **Most LAT detected GRBs show significant HE emission lasting after the low-energy emission becomes (almost) undetectable** (originally detected by EGRET; Hurley et al. 94)
- **Possible origins:**
  - **Afterglow SSC emission (though no spectral hardening, time gap, or synchrotron/SSC valley in the spectrum are observed)**
  - **Afterglow synchrotron: likely at $t \gg T_{GRB}$; but: variability**
  - **Hadronic origin? Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset) Constraints from IceCube!!**

IS? Constraints on Quantum Gravity Models

- Some Quantum Gravity models allows Lorentz symmetry violation (LV) (e.g., *Amelino-Camelia et al. 2001, Ellis et al. 2003; 2008*)
  - ➔ Speed of light becomes energy dependent $V_{ph}(E_{ph}) \neq c$
  - ➔ Time dispersion between low and high energy photons coming from the same source

Parametrized through a Taylor expansion of the LV terms In the dispersion relation

Photon dispersion relation

$$E^2 - k^2\left[1 + \xi_1 \frac{E}{M_{QG}} + \xi_2 \frac{E^2}{M_{QG}^2} + \dots\right]$$

QG mass scale

Photon propagation speed given by Photon group velocity

$$c_{LV}(E) \simeq c\left[1 - \xi_1 \frac{E}{M_{QG}} - \xi_2 \frac{E^2}{M_{QG}^2}\right]$$

$\xi_1, \xi_2 \simeq \pm 1$ expansion coefficients

$M_{QG} \sim M_{Pl} = 1.2\text{x}10^{19}$ GeV

Time dispersion over cosmological distance

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

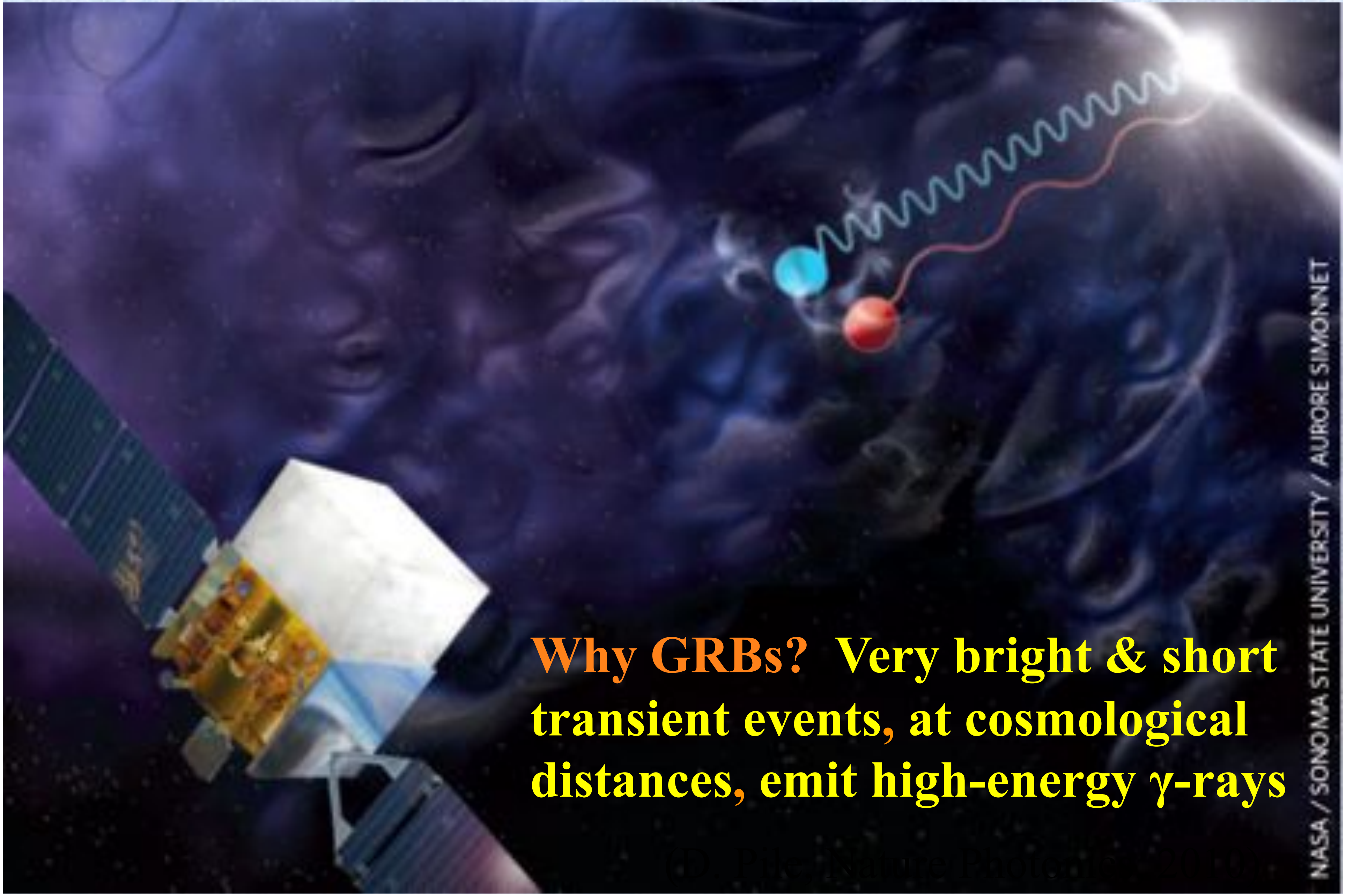
Light Travel Time (LTT) effect

The most natural scale for LV is the Plank scale where quantum effects on the structure of space time are expected to be strong

$l_{Planck} = (hG/c^3)^{1/2} \approx 1.62\times10^{-33}$ cm or $E_{Planck} \cong M_{Planck}c^2 \cong 1.22\times10^{19}$ GeV

Constraining QG Using GRBs

(first suggested by Amelino-Camelia et al. 1998)



Why GRBs? Very bright & short transient events, at cosmological distances, emit high-energy γ-rays

Why GRBs?

- A small variation in photon speed, when accumulated over cosmological light-travel time, may be revealed by observing characteristic features in the GRB lightcurves at high energy
- The known distance of the source and the detection of E>GeV photons few seconds after the GRBs from its onset allow us to constrain the possible variation of speed of light with photon energy (photon dispersion).

Limits on LIV from Fermi GRBs

GRB	duration or class	# of events > 0.1 GeV	# of events > 1 GeV		Lower Limit on $M_{QG,1}/M_{Planck}$	Valid for S_n =	Highest photon Energy	redshift
080916C	long	145	14		0.11	+1	~ 13 GeV	~ 4.35
090510	short	> 150	> 20		1.2	+1	~ 31 GeV	0.903
090902B	long	> 200	> 30		0.068	+1	~ 33 GeV	1.822
090926	long	> 150	> 50		0.066	+1	~ 20 GeV	2.1062

- Method : assuming a high-energy photon was emitted sometime during the lower energy emission. The emission time is bigger than the onset time of the relevant low-energy emission episode

Drawbacks of these approaches

- Limits may be intrinsically fuzzy: not possible to know the exact time of emission of a single or few photons.

- It is difficult to assess the statistical meaning of each limit, to which confidence interval is referred to.

- Work in progress: Fiore, Guetta, Amelino Camelia suggest a method that resolve these drawbacks. Consider large sample of GRBs observed by LAT with different z to put constraint on LTT as QG effect depend on z: the effect is stronger for farther GRBs.

- This method uses full GRB energy distribution: GRB spectrum and its temporal variations

Method description: Representative Model

- Assume a Gaussian shape for the GRB intrinsic light curve. Describe sufficiently well the core of the main peaks of LAT GRBs.

- Intrinsic GRB spectrum 100 MeV -100 GeV single power law model

$$F(E') = cE'^{-\Gamma}$$

- Time resolved spectrum at observed time t:

$$F(t,E) = cE'^{-\Gamma} \exp\left[-\frac{\left(t' - t'_0 - \frac{E' D}{cE_{QG}}\right)^2}{2\sigma^2}\right]$$

GRB frame

$$E' = E(1+z) \qquad t' = t/(1+z)$$

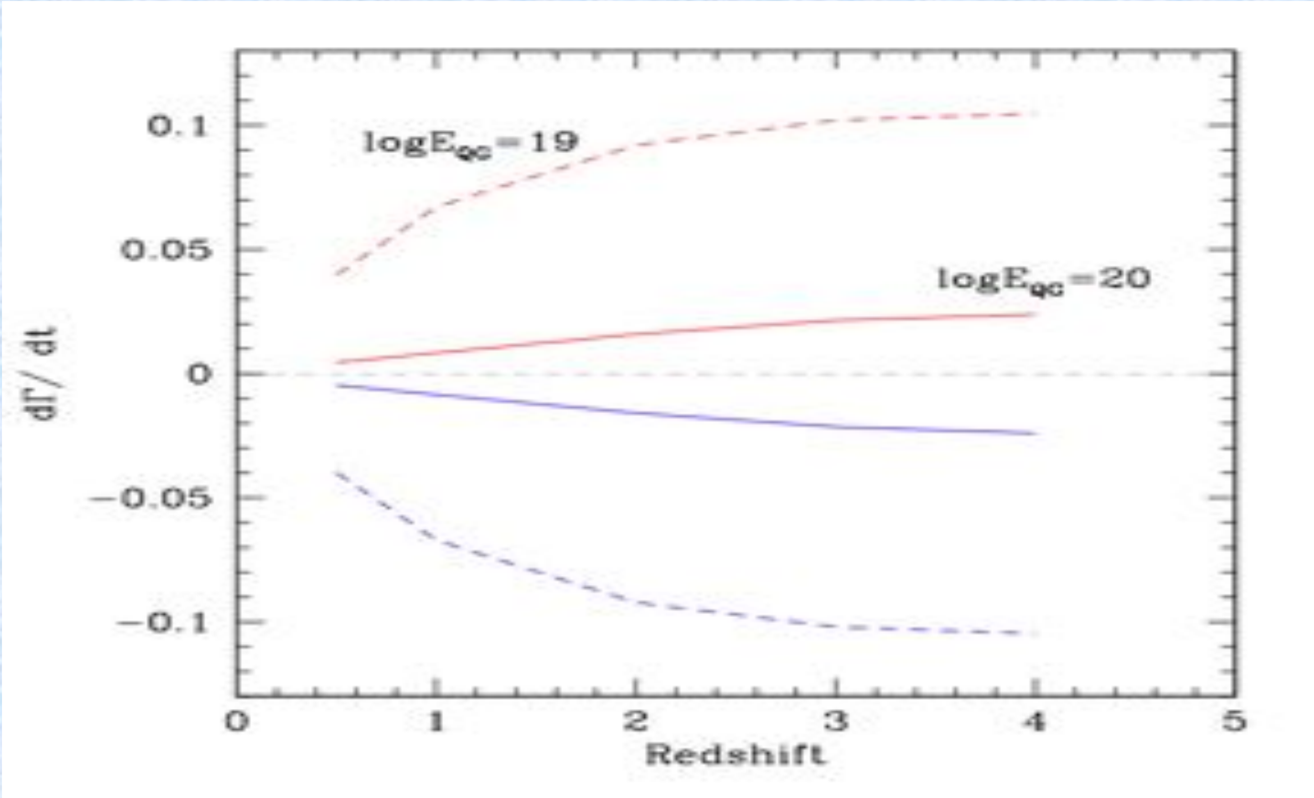
The observed photon index Γ between energies E'_1 and E'_2.

$$d\Gamma / dt \propto -\frac{(E'_2 - E'_1)\ D}{2cE_{QG}\sigma^2}$$

The shape of the observed spectrum is complex and it will change with time as a function of z

The rate of variation of the observed photon index scale with the inverse of E_{QG} and inverse of the square of the GRB duration (for a gaussian shape T90=4.2(1+z)σ)

Model predictions (Fiore,Guetta+ in prep.)



This figure show $d\Gamma/dt$ as a function of the redshift for two values of E_{QG}

Red: superluminal, blu: subluminal. This analysis suggests that QG effects can be

❖measured or constrained comparing the observed spectral variation of GeV GRBs to the predicted ones. **We find that the rate of change of spectral index with time can vary from 0.02 to 0.1 from z=0.2 to z=3.**

The intrinsic spectral variation are UNCORRELATED with distance unlike the QG effects

Possibility to disentangle the QG effects and put constraints on QG

Swift-Fermi synergy: X-ray flares and their GeV-TeV counterparts

- **Open Issue**: do X-ray flares require a long duration and/or re-activation of the central engine activity? Swift observations alone can be explained by a variety of models.
- Goal: constrain the mechanism underlying the X-ray flare emission
- Method: broad-band analysis from optical to GeV energies: correlate the temporal and spectral behavior as observed by **Swift and Fermi**

The X-ray Flares sample

- 140 Swift GRBs (2008 Aug - 2010 Aug) with rapid repointing (updating to 2011)
- 48 (35%) show bright X-ray flares at early times (<1000 s)
    - » only one short GRB
- 12 with good LAT observations: $\theta_{LAT}< 65°$ and $\theta_z<95°$
- Only 4 bursts with known redshift, <z>~2.1

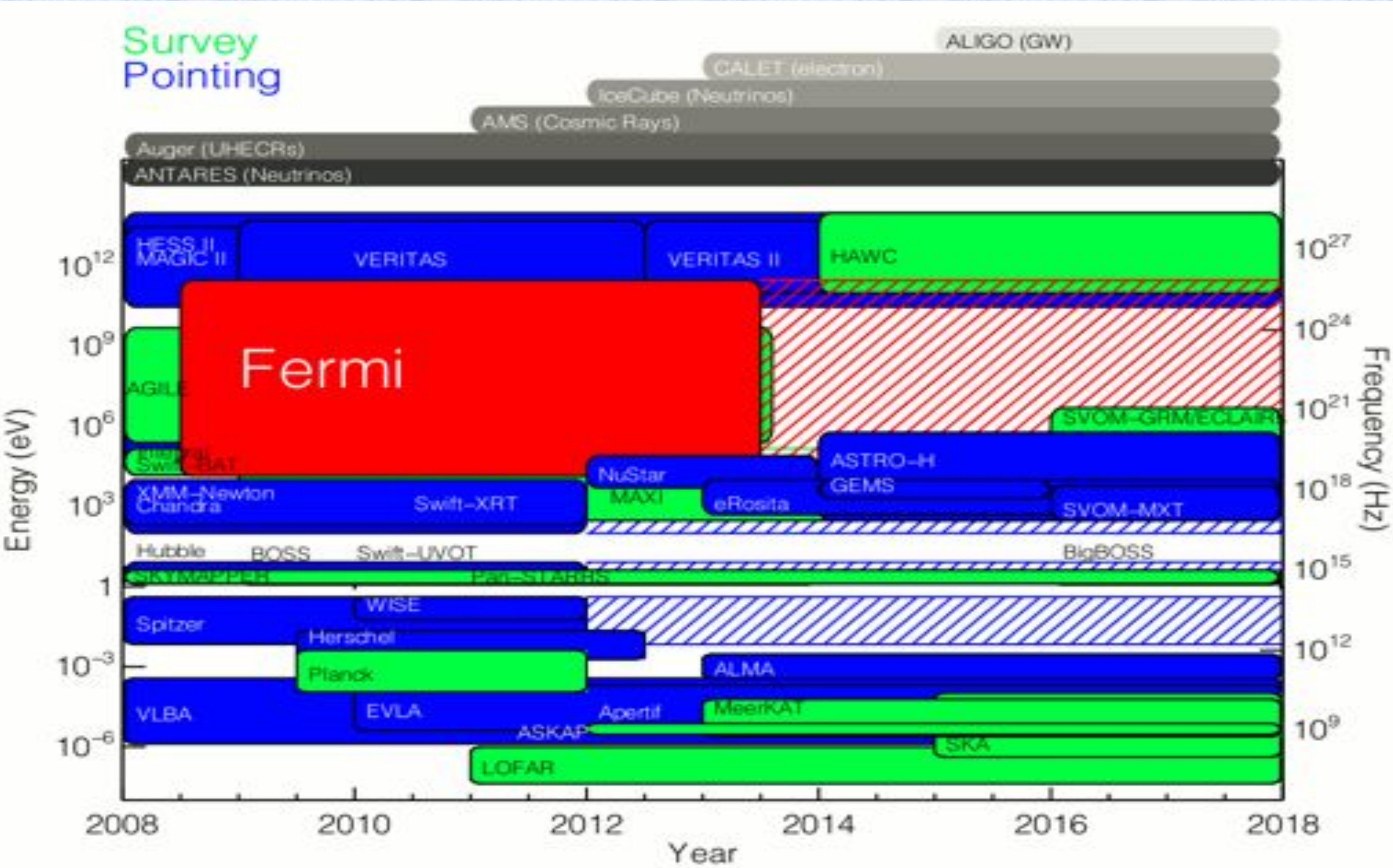
Final sample:

- 29 X-ray flares with simultaneous Swift/Fermi observation

first detection of HE emission in GRB 100728A

(Piro+ work in progress)

Synergies with other Observatories and Missions



From McEnergy

Synergies with other Observatories and Missions

- **Icecube** starts collecting data. Fermi can detect the electromagnetic counterpart of a neutrino signal from GRB: **Smoking gun for the presence of hadrons in the jet. Icecube data can already constrain the hadronic nature of the GeV emission.**

- ALIGO will either detect gravitational waves in coincidence with GBM detections of short GRBs, or neutron star-black hole and neutron star- neutron star mergers may be ruled out as the progenitors of these events (Blandford talk)

Controversial Conclusions

- **Few GRBs detected by LAT**:Prompt phase characterized by paucity of GeV photons => break or opacity (consistent with IS) **Γ<300**
- **Bright Delayed emission in few bright GRBs**: high Lorentz factor, but counterexamples. Consistent with Synch. ES or IS with QG effects. **Γ>1000**
- Lack of IC component: magnetic dominated flow?
- GeV counterparts to X-ray flares: substantial contribution to delayed emission. Consistent with Inverse Compton from Internal Shock
- **Delay: IS +LIV or ES?**
- **Hadronic component? Icecube constraints**

Specific areas that need more effort

- **QG effects**: bigger sample of LAT GRBs with enough counts in $0.2<z<2$ more sensitivity and FoV
- **Radiative processes:** Increase sensitivity synergy with Swift
- **Hadron in the jet:** Synergy with neutrino telescopes IceCube and KM3
- **SGRBs as NS mergers**: Synergy with GW detectors
- **GeV-TeV emission:**synergy with future TeV detectors

Effort: Need more sensitivity and larger FoV

Future prospects

- **Spectral properties**: More LAT GRBs will help to understand the GRB spectral properties and to understand the LAT GRB rate.
- **QG effects**: bigger sample of LAT GRBs with enough counts in $0.2<z<2$ and redshift stronger limits and statistically well defined on E_{QG}
- **Synergy with ν and GW detectors:** The detection of electromagnetic counterparts from GW and ν events is the only way to identify the GW and ν source, and also enhances the confidence level of these GW and ν detections.
- **Synergy with Swift and CTA**: The X-ray flares project help to understand the role of the IC emission