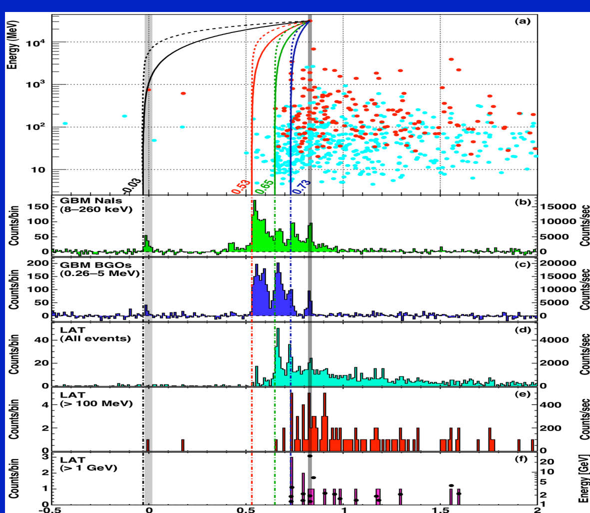
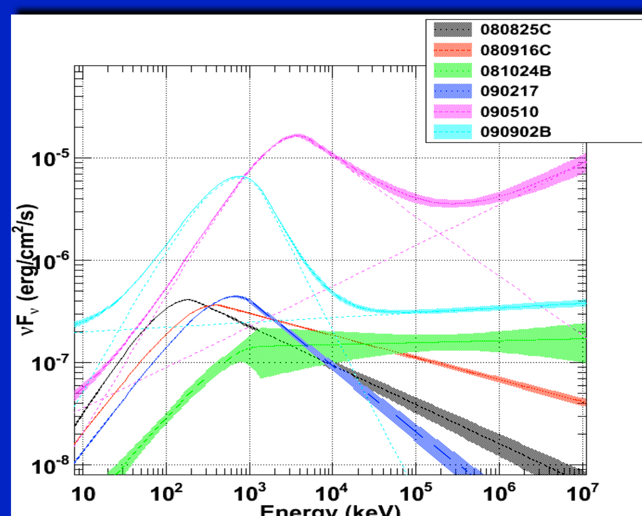
Gamma-Ray Bursts in the Fermi Era

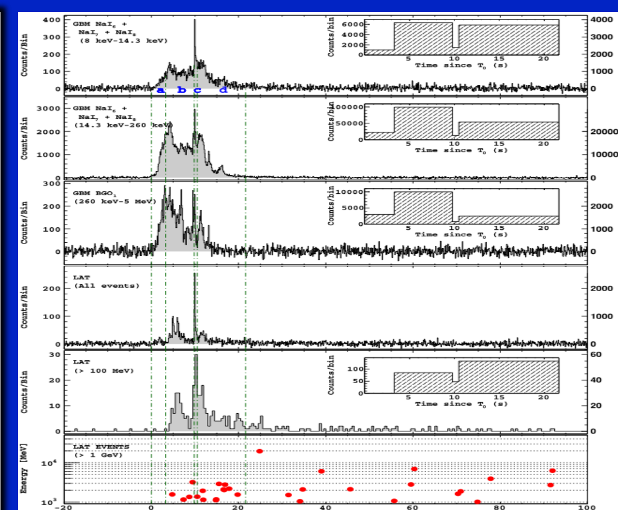
Jonathan Granot

Open University of Israel

On behalf of the Fermi LAT & GBM collaborations







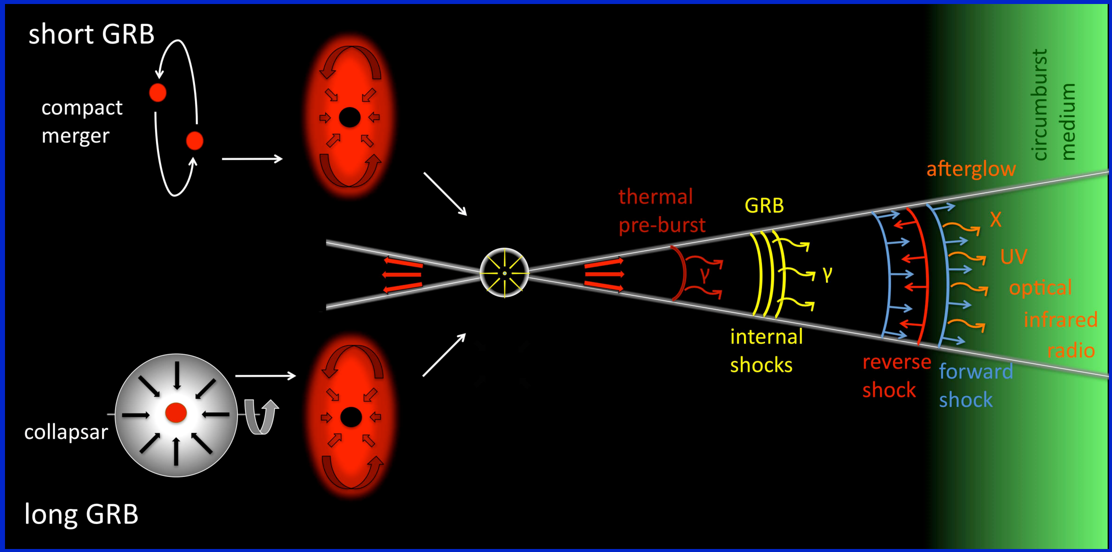
Fifth International Fermi Symposium, Nagoya, Japan, Oct. 23, 2014

Outline of the Talk:

- GRB theoretical framework; how ***Fermi*** fits in
- GRB prompt emission: GBM + LAT @ high-energy
  - Delayed HE onset, HE spectral component, BB component?
  - ⇒ emission region: **Γ**, **R**, geometry? emission mechanism?
  - LAT GRB detection rate, short vs. long GRBs @ HE
  - Long-lived HE emission
- High-energy afterglow & GRB 130427A:
  - Implications for relativistic collisionless shock physics
- non-GRB physics: EBL, Lorentz invariance violation
- Synergies with other instruments & **Conclusions**

GRB Theoretical Framework:

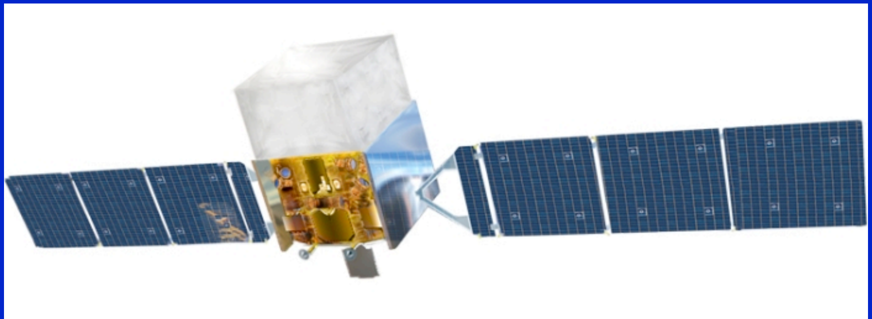
- **Progenitors**:
  - Long: massive stars
  - Short: binary merger?
- **Jet Acceleration**: fireball or magnetic?



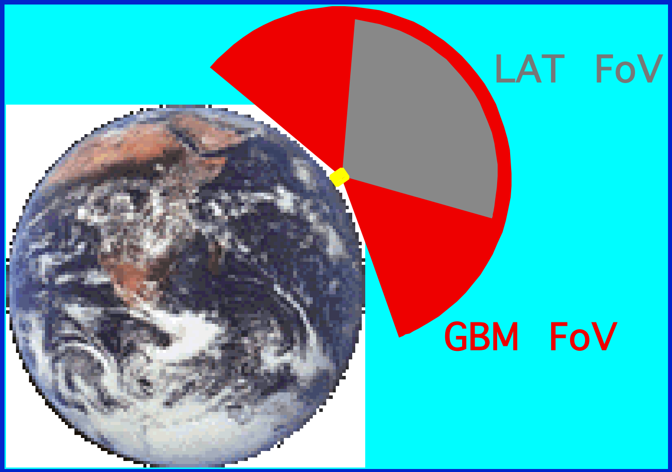
- **γ-rays**: internal shocks? emission mechanism?
- **Deceleration**: the outflow decelerates (by a **reverse** shock for $\sigma \lesssim 1$) as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

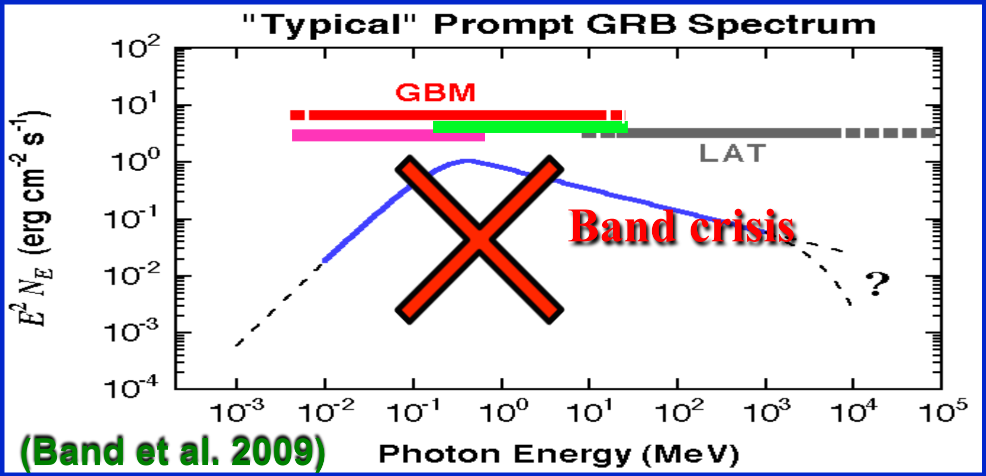
Fermi Gamma-ray Space Telescope

(launched on June 11, 2008)



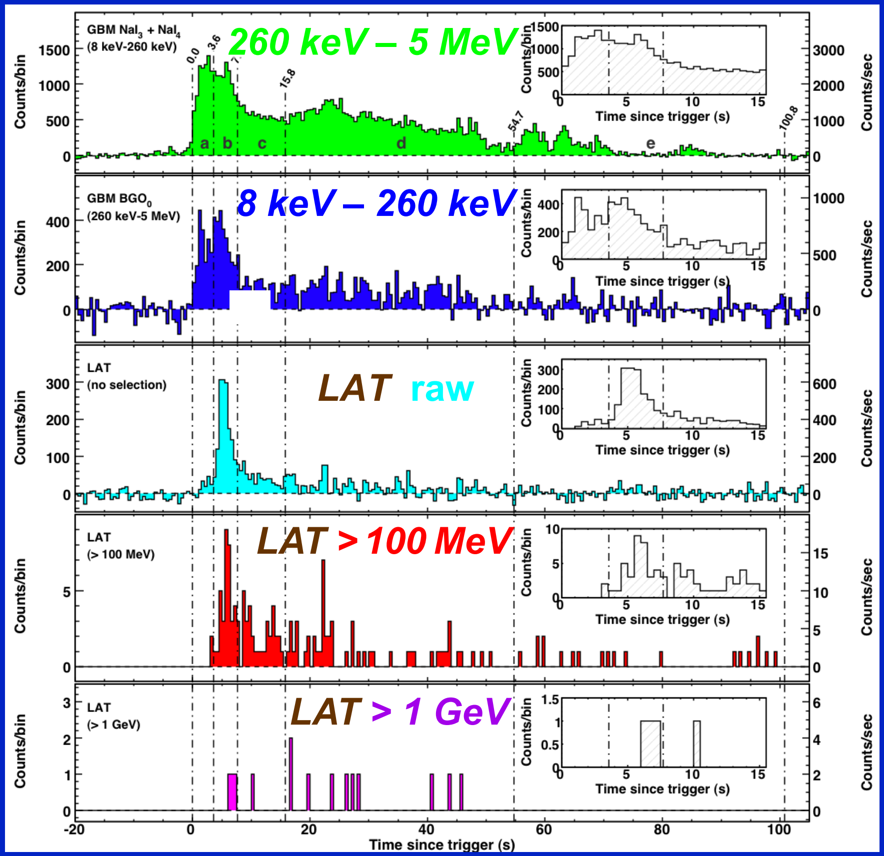
- Fermi GRB Monitor (GBM): 8 keV – 40 MeV (12×NaI 8 – 10^3 keV, 2×BGO 0.15 – 40 MeV), full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime





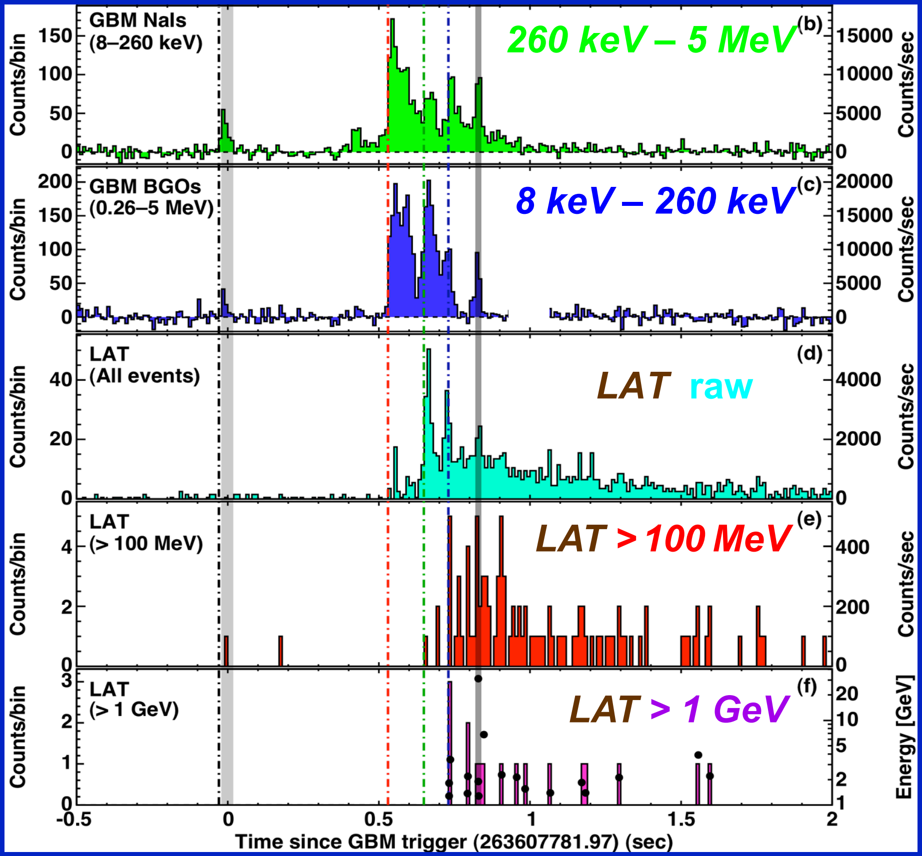
Delayed onset of High-Energy Emission

GRB080916C



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

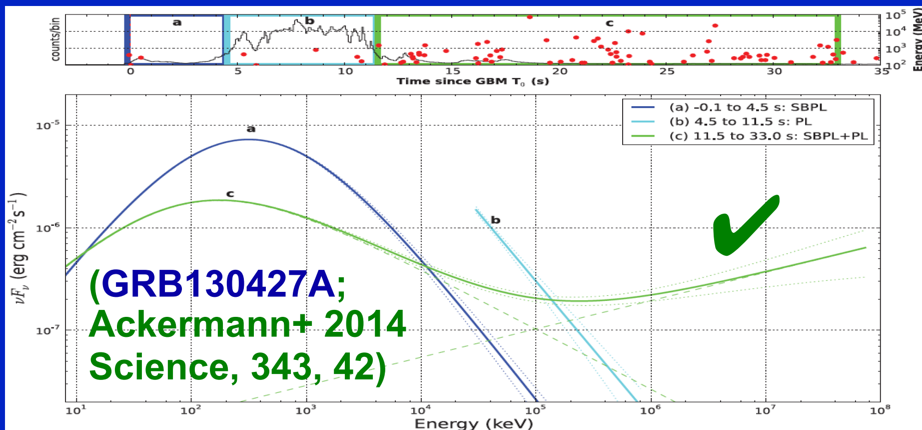
GRB090510



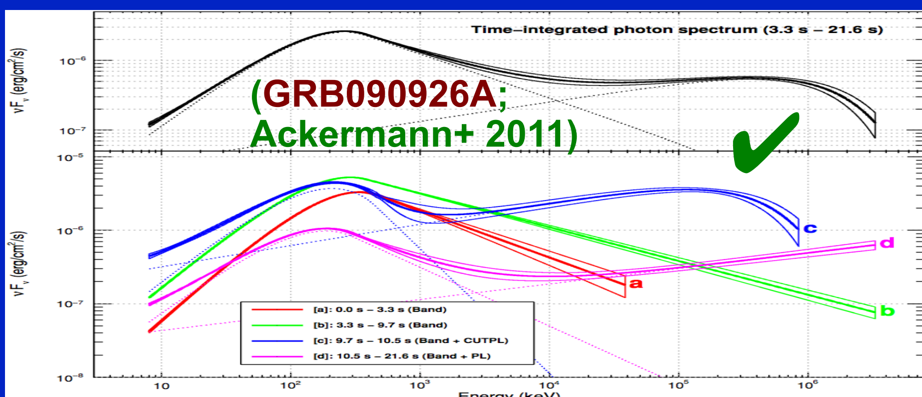
(Abdo et al. 2009, Nature, 462, 331)

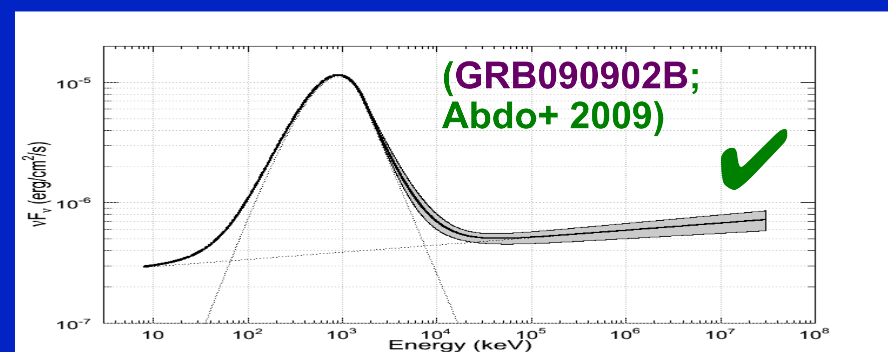
- The 1st LAT peak coincides with the 2nd GBM peak
- Delay in HE onset: ~ 4-5 s
- The first few GBM peaks are missing in LAT but later peaks coincide; the delay is 0.1-0.2 s

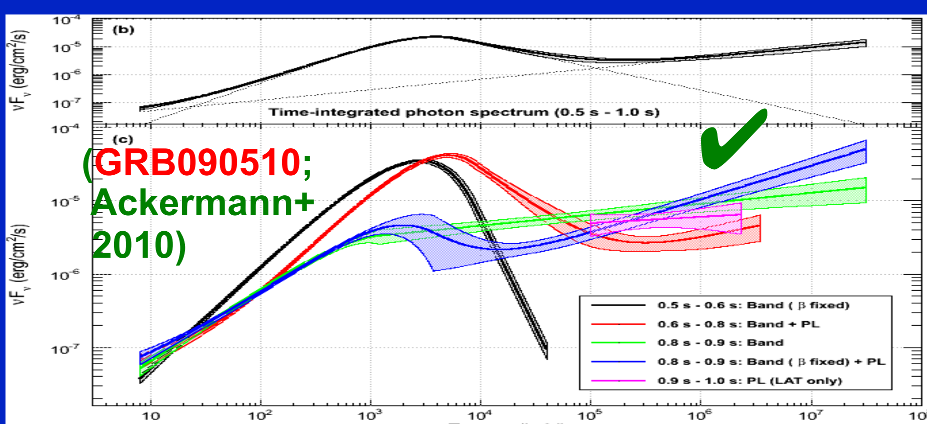
Distinct High-Energy Spectral Component

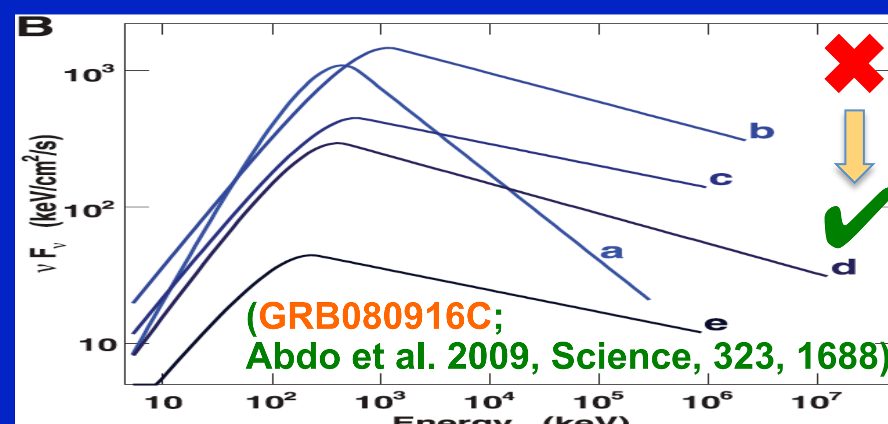


- Clearly (>5σ) exists in several LAT GRBs, but very common in the brightest LAT GRBs
- Suggests that it is common but good photon statistics is needed for clear evidence



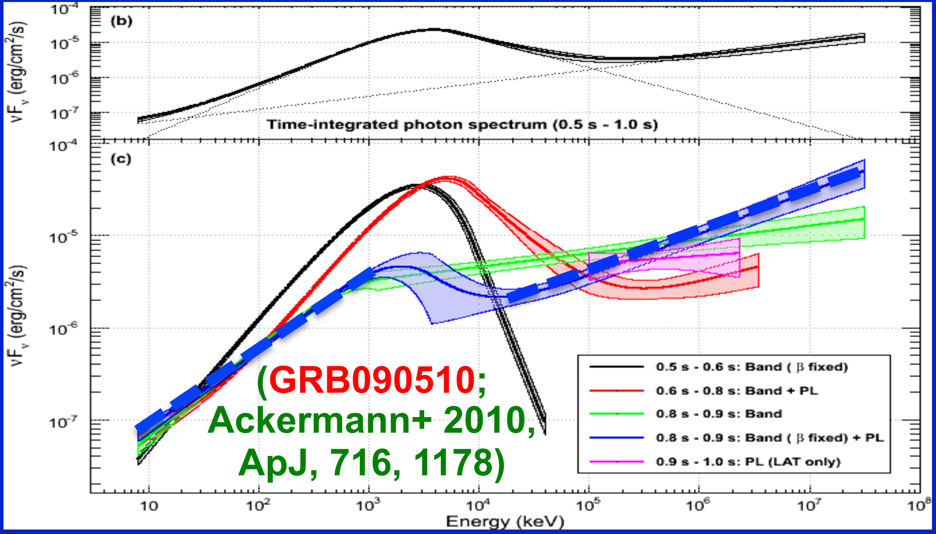


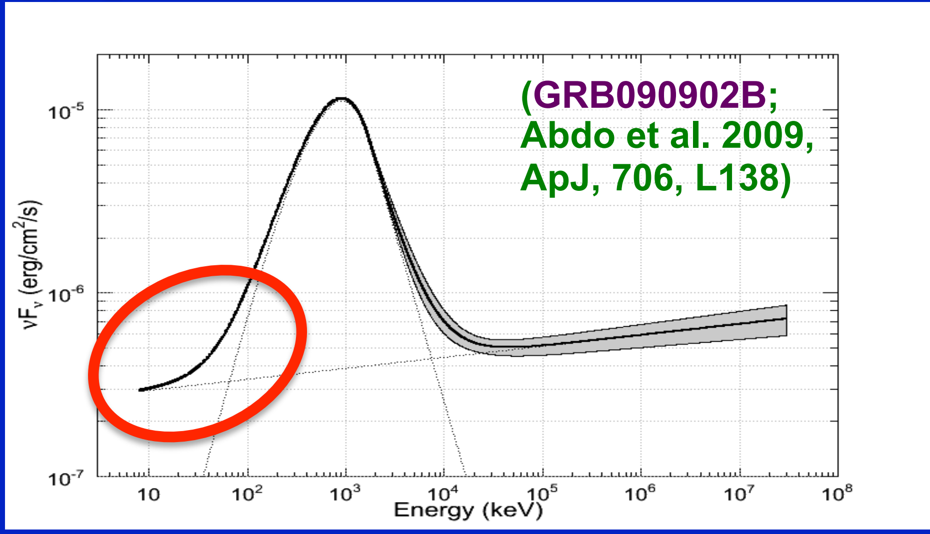




Late onset/HE spectral component: Possible Origin

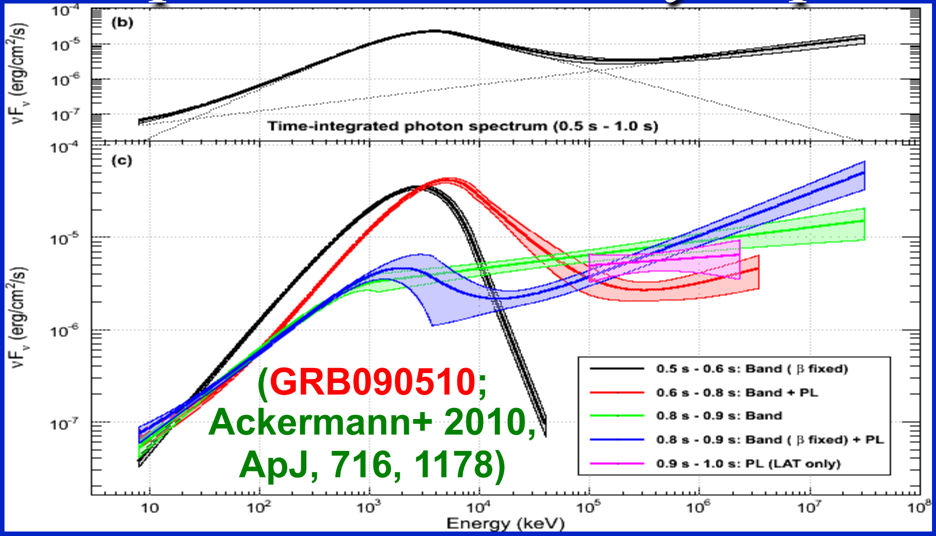
- **Leptonic**: inverse-Compton (or synchrotron self-Compton)?
  - Hard to produce a delayed onset longer than spike widths (the seed photon field builds-up on the dynamical time)
  - A gradual increase in the HE photon index **β** (determined by the electron energy dist.) is not naturally expected
  - Hard to account for the different photon index values of the HE component & the Band spectrum at low energies
  - Hard to produce a low-energy power-law (GRB090902B)

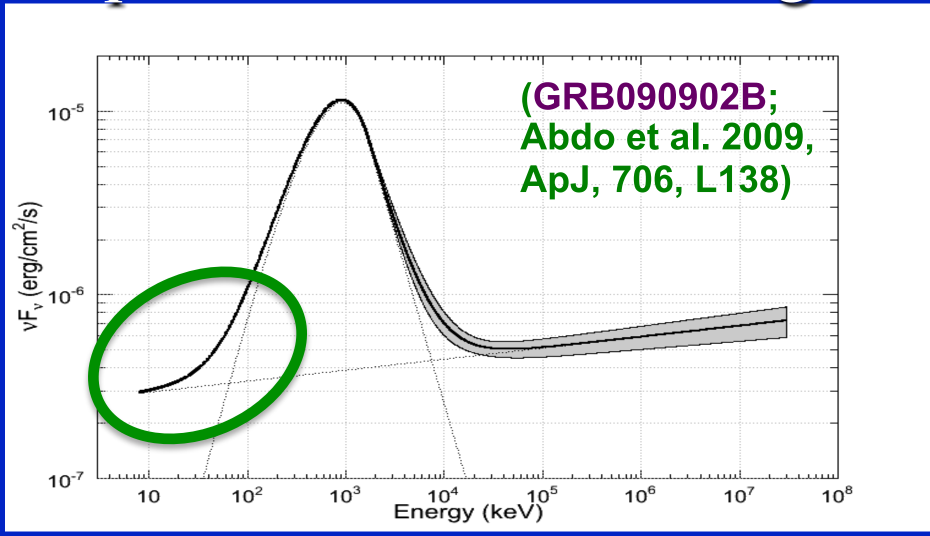




Late onset/HE spectral component: Possible Origin

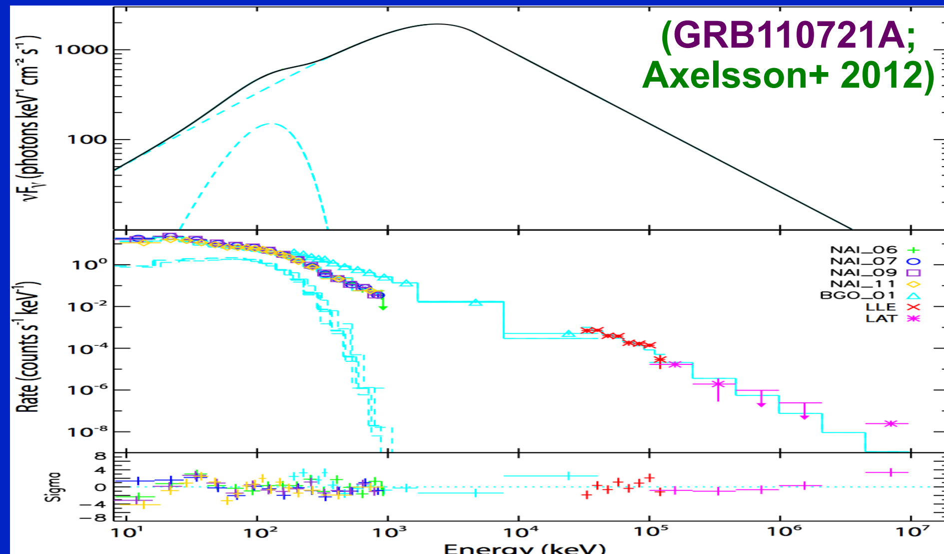
- **Hadronic**: (pair cascades, proton synchrotron) ?
  - Late onset: time to accelerate protons+develop cascades?
  - Does not naturally account the gradual increase in **β**
  - Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset)
  - GRB090510: large energy needed: $E_{total}/E_{\gamma,iso} \sim 10^2 - 10^3$
  - GRB090902B: synchrotron emission from secondary $e^{\pm}$ pairs can naturally explain the power-law at low energies

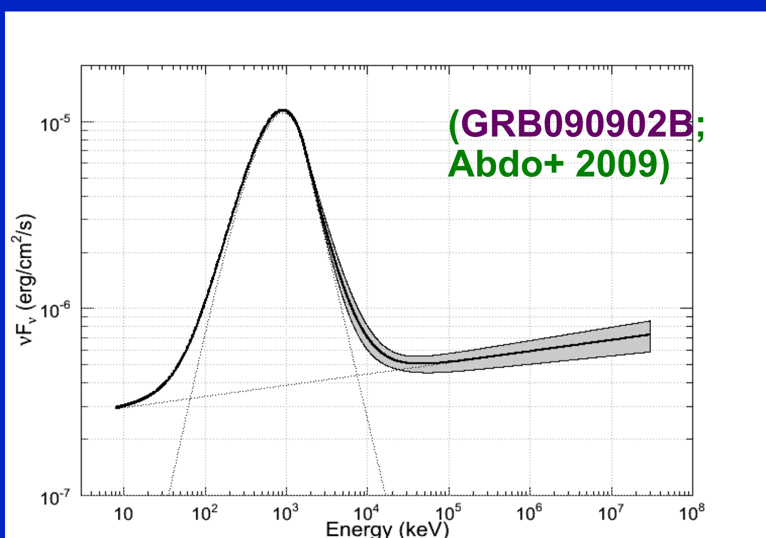


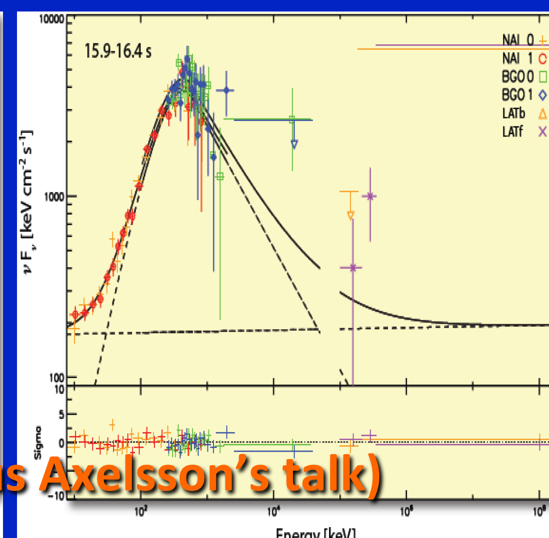


Thermal components in prompt spectrum?

- Usually **sub-dominant** ⇒ degeneracy with the assumed (usually phenomenological Band) dominant component







(see Magnus Axelsson's talk)

Thermal components in prompt spectrum?

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- Photospheric emission is not a perfect black body (BB)
  - Even for a local BB emission + a spherical flow, Doppler factor & R_{ph} variations with the angle to the line of sight smear/widen spectrum
  - Temperature variations (with time/location) smear/widen spectrum
  - Non-thermal e^-/e^+ from dissipation near R_{ph} $\Rightarrow$ power-law wings
- Many options (continuum of physically motivated spectra) + many degrees of freedom $\Rightarrow$ non-uniqueness (many viable options)

  (see poster 9.03 by M. Burgess+)

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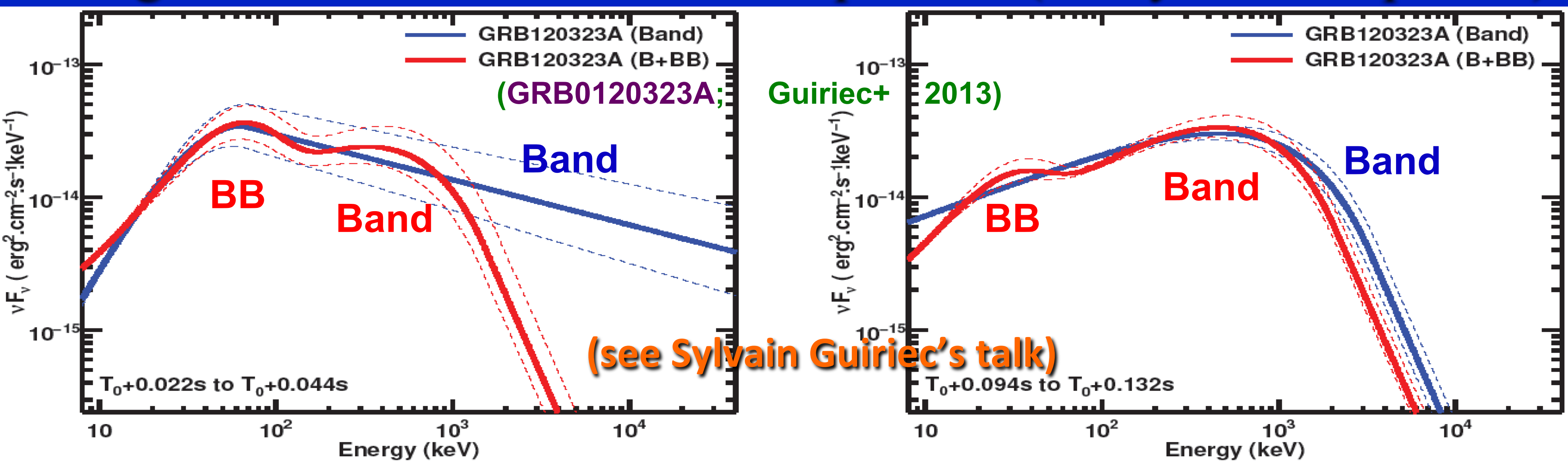
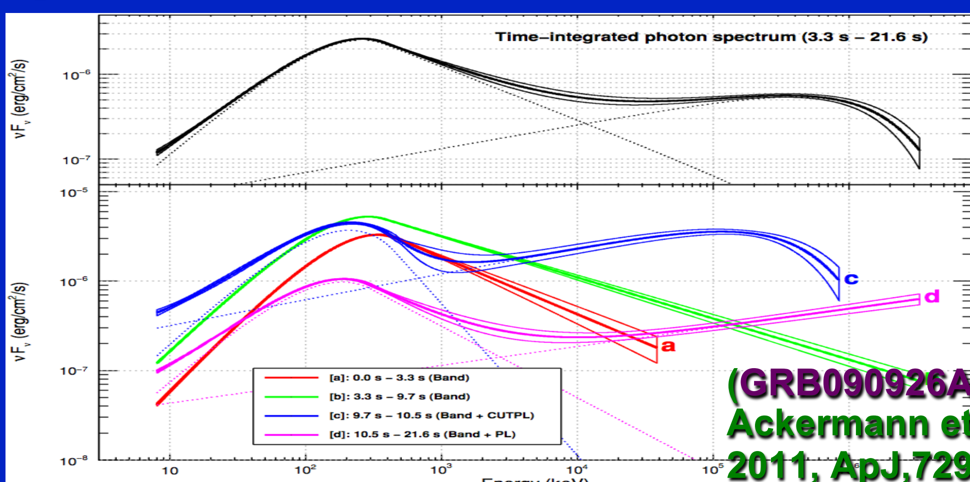
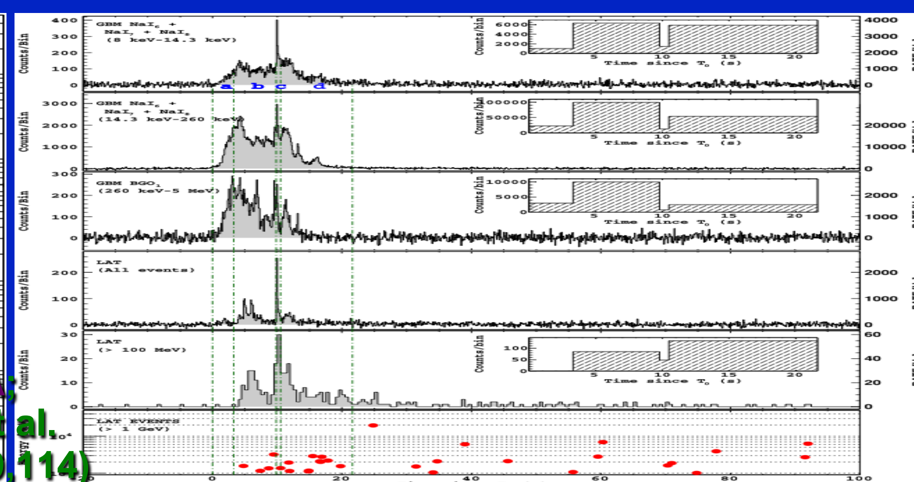


Constraints on Γ for Fermi LAT GRBs

- Γ_{min}: no high-energy cutoff due to intrinsic pair production
  ⇒ lower limit on the Lorentz factor of the emitting region
- **Fermi**: more robust limits – don't assume photons $>E_{obs,max}$
- $\tau_{\gamma\gamma} \propto \Gamma^{2\beta}/R \Rightarrow \Gamma_{min}$ requires assuming $R(\Gamma)$ (e.g. $R \sim \Gamma^2 c\Delta t$)
- For bright LAT GRBs (long/short): $\boldsymbol{\Gamma \gtrsim 10^3}$ for simple model (steady-state, uniform, isotropic) but $\boldsymbol{\Gamma \gtrsim 10^{2.5}}$ for more realistic time-dependent self-consistent thin shell model (**JG et al. 2008**)
- **GRB 090926A**: high-energy cutoff – if due to intrinsic pair production then $\boldsymbol{\Gamma \sim 200 - 700}$

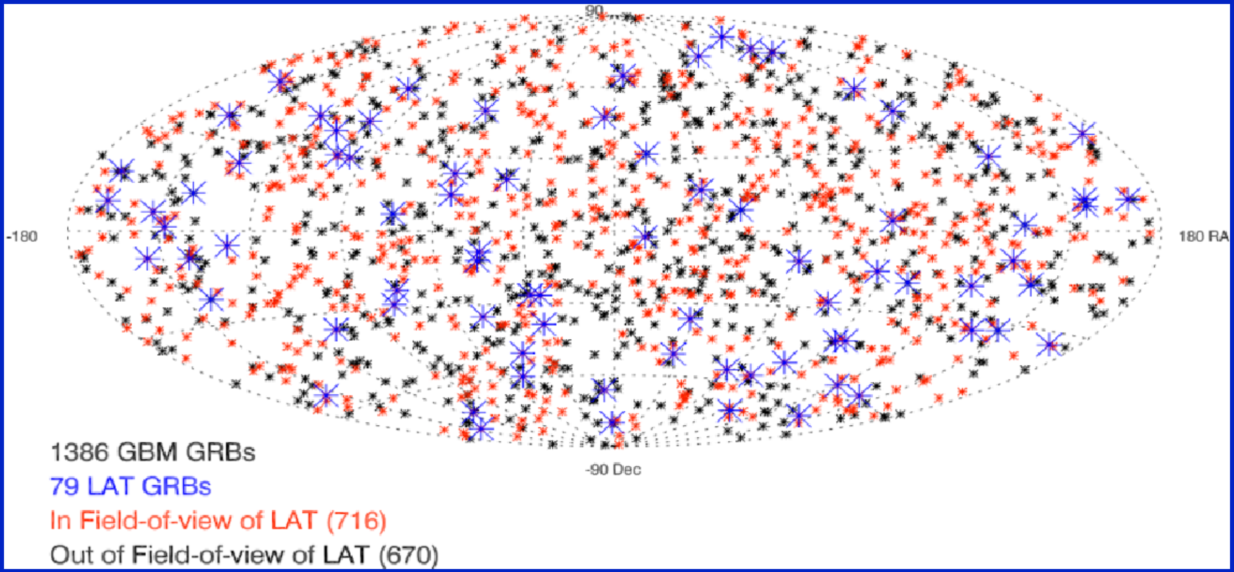


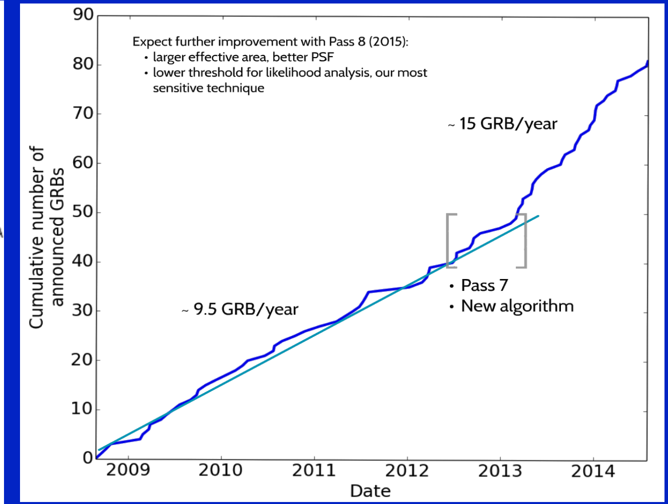


(GRB090926A; Ackermann et al. 2011, ApJ,729,114)

GBM/LAT GRB detection rate

- **GBM** detects ~240 GRB/yr, ~45 (~19%) of them are short
- **LAT:** ~9.5 → 15 GRB/yr (~6% of GBM); ~7/79 ~ 9% short

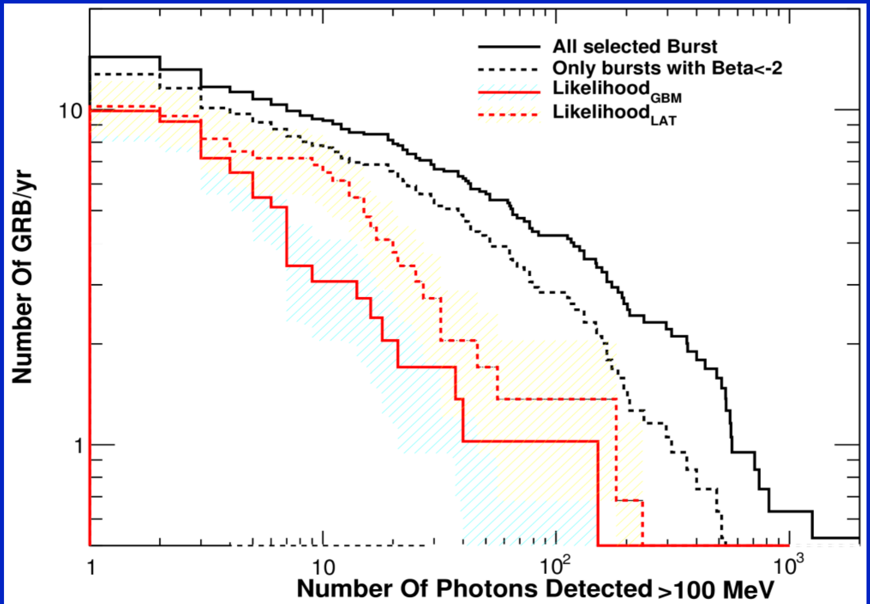




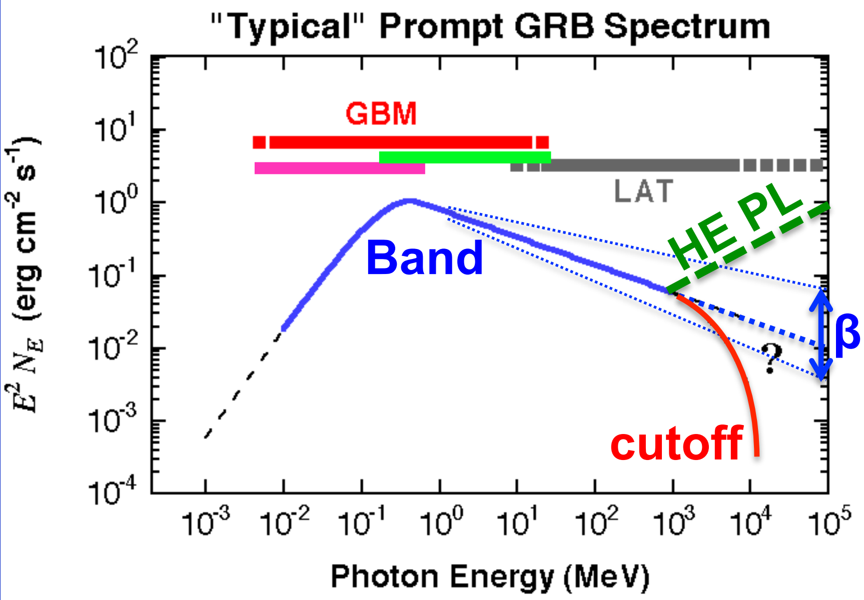
New detection algorithm (see Giacomo Vianello's talk)

GBM/LAT GRB detection rate

- **LAT** pre-launch prediction (based on Band extrapolation) 9.3 GRB/yr with ≥10 photons ≥ 0.1 GeV vs. 6.3/yr detected
- Likelihood detection (TS > 28): 12/yr expected, 9.5/yr detected

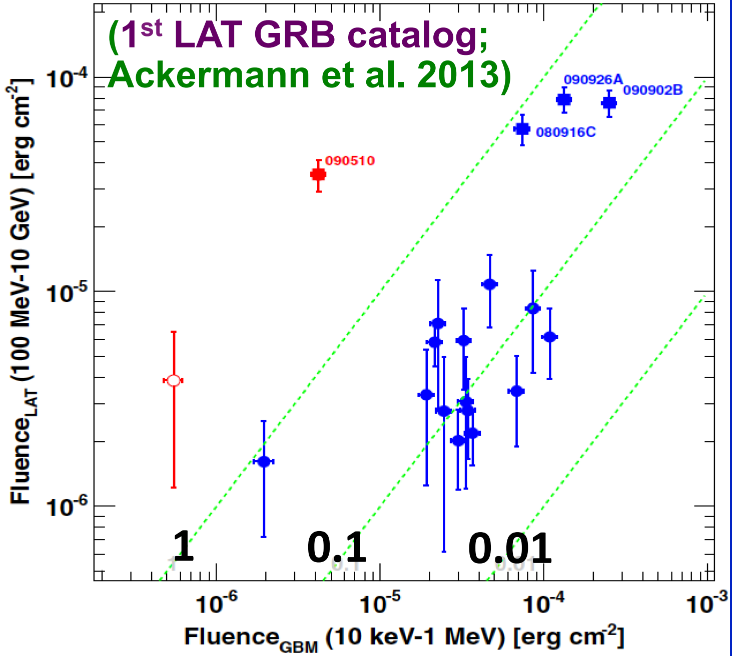


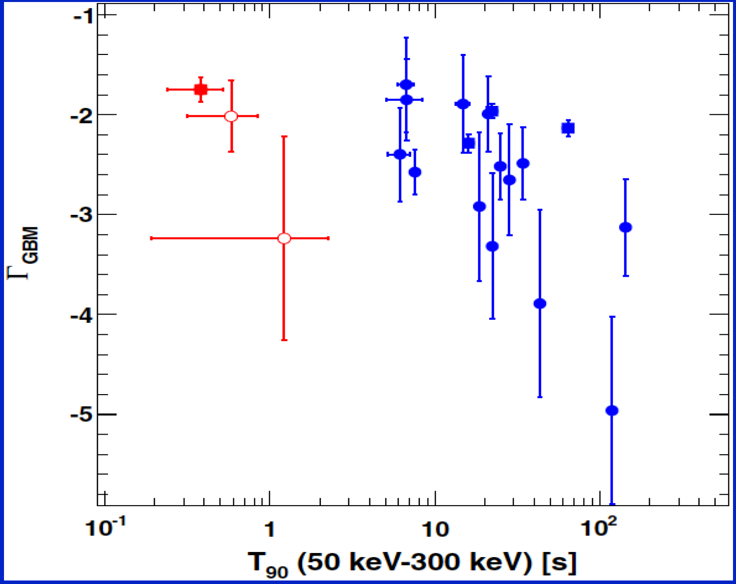
- Overestimates of β + cutoffs at 10's MeV just win over HE PL
- Perhaps Band fails completely
- On average, the high-energy emission is energetically sub-dominant compared to ≲ MeV



Long vs. Short GRBs @ High-Energies:

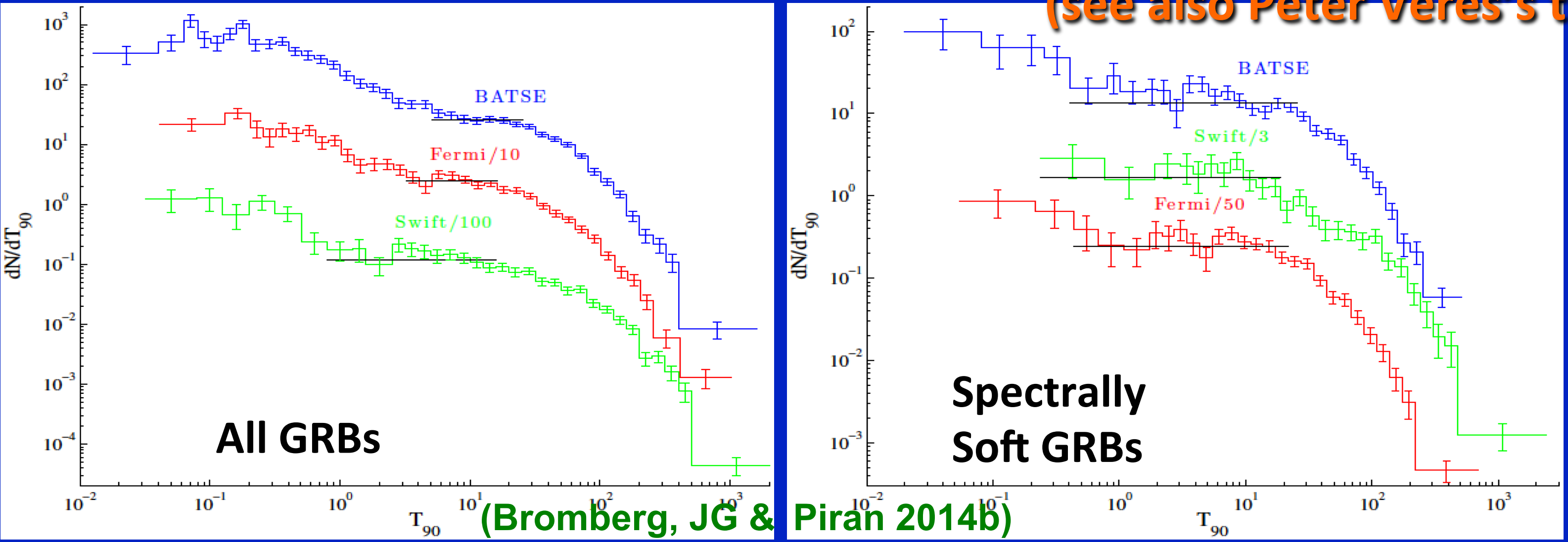
- **Trend:** larger LAT/GBM fluence ratio in short (rel. to long) GRBs
- Short GRBs are harder (higher β & E_{peak} in time integrated spectrum)
- Both show delayed onsets, but the delay scales with the GRB duration
- Both show HE hard PL component
- Both show long-lived HE emission
- Both include very bright LAT GRBs
- Both have very constraining Γ_{mim}
- Both have some redshifts but long GRBs are usually easier to follow up



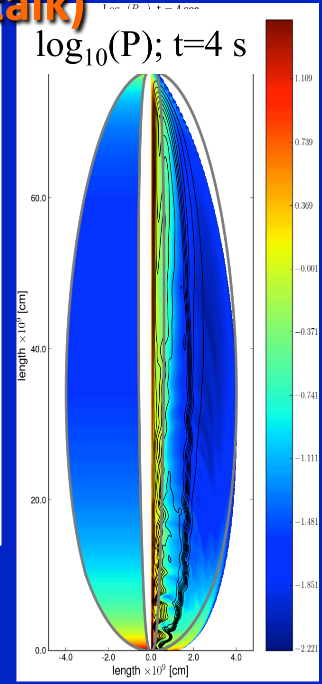


GBM GRB Durations: Jet Composition

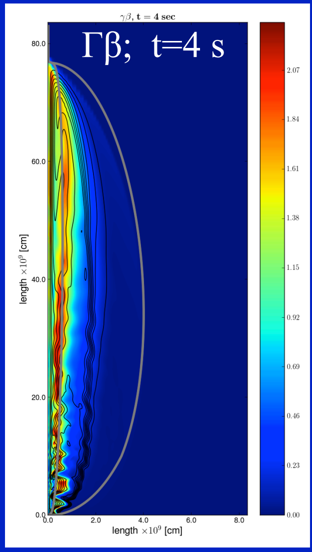
(see also Peter Veres's talk)



(Bromberg, JG & Piran 2014b)



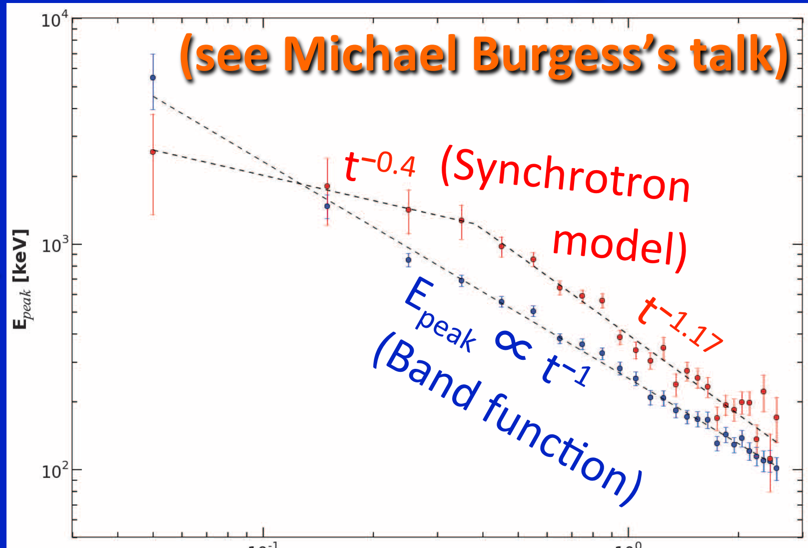
(Bromberg+ 2014a)



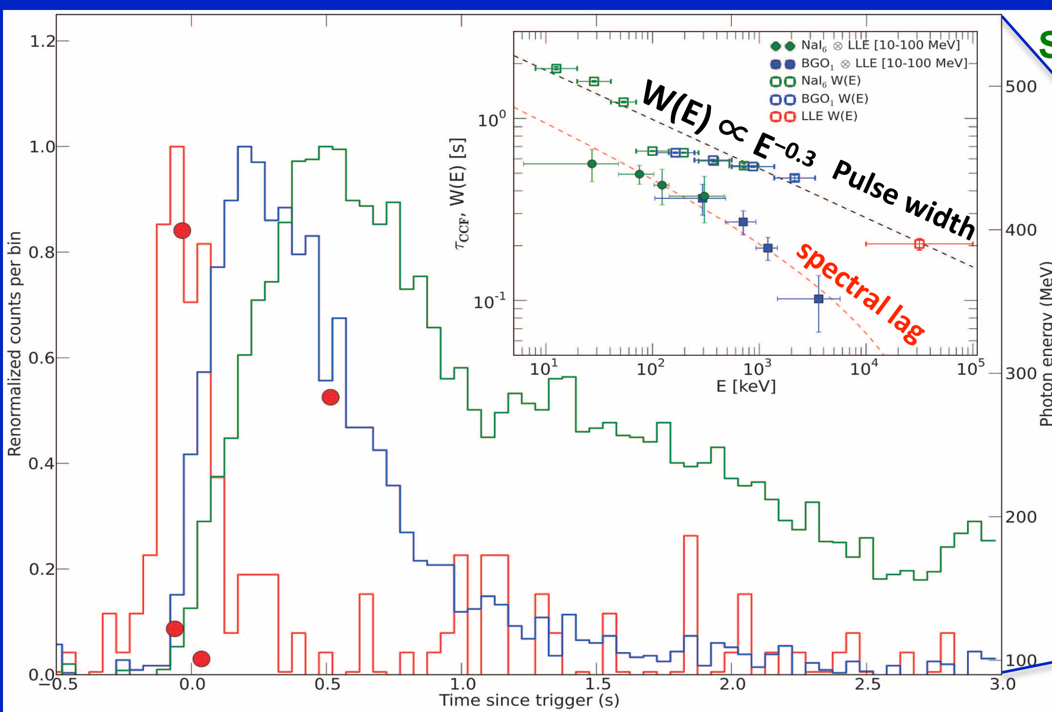
- Plateau observed in the dN_{GRB}/dT_{90} distribution, naturally occurs in the collapsar model: jet break out time from star
- Clearer for soft GRBs + there in all major GRB missions
- $\Rightarrow t_{breakout} \sim 10$ s consistent with a hydrodynamic jet but not with a highly magnetized jet ($t_{breakout}(\sigma \gg 1) \sim 1$ s)
- The jet in hydrodynamic around $t_{breakout} \sim 10$ s
- The initial magnetization σ_0 can increase over jet's lifetime (natural in newly born ms-magnetar or rapidly accreting BH)

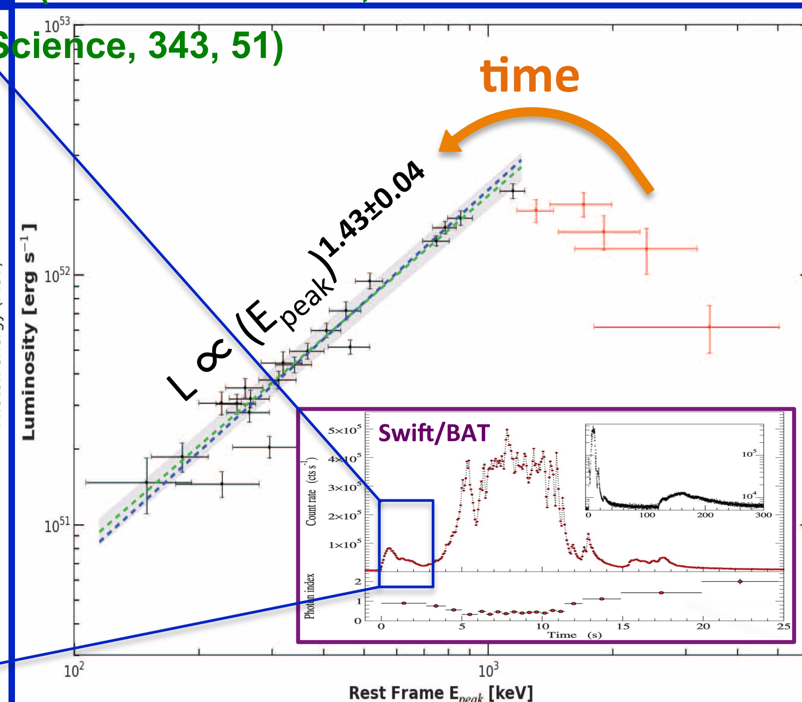
GBM observations of GRB130427A 1st pulse

- Detailed time-resolved study of a pulse
- $E_{peak} \propto t^{-1}$, pulse width $W(E) \propto E^{-0.3}$ consistent with internal shock synchrotron
- $L \propto (E_{peak})^{1.4}$ inconsistent with shock curvature effect (high-latitude; $L \propto E_p^3$)
- No current model explains all details



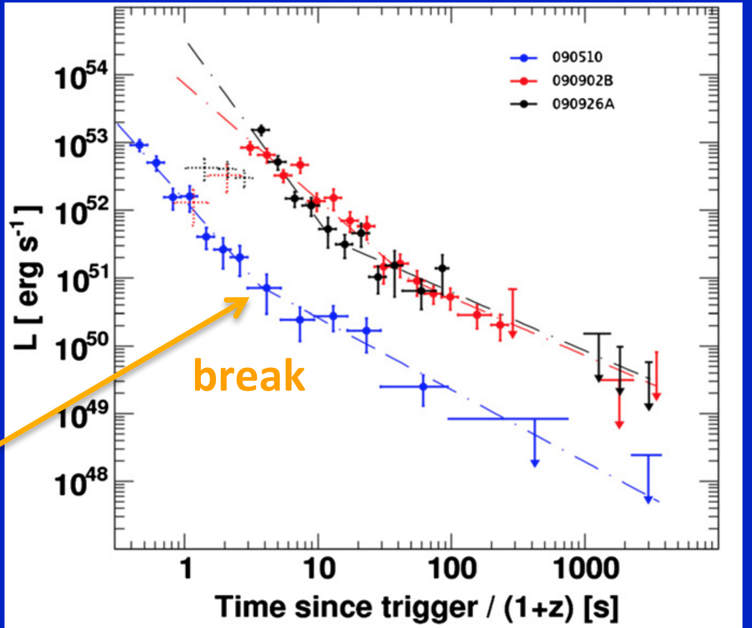
(Preece et al. 2014, Science, 343, 51)

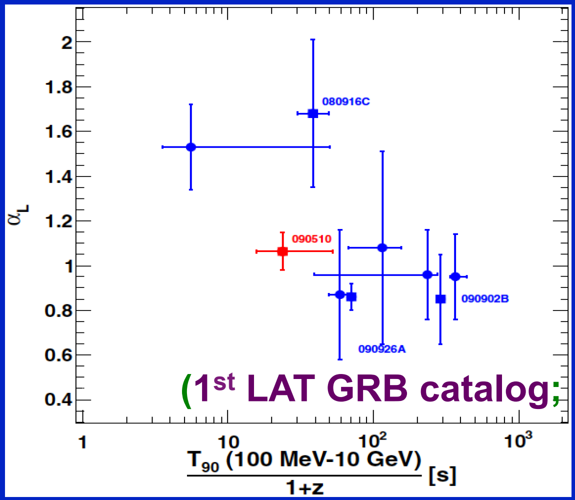


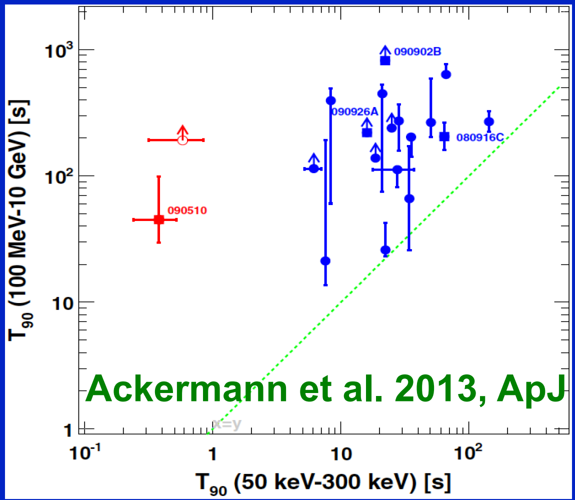


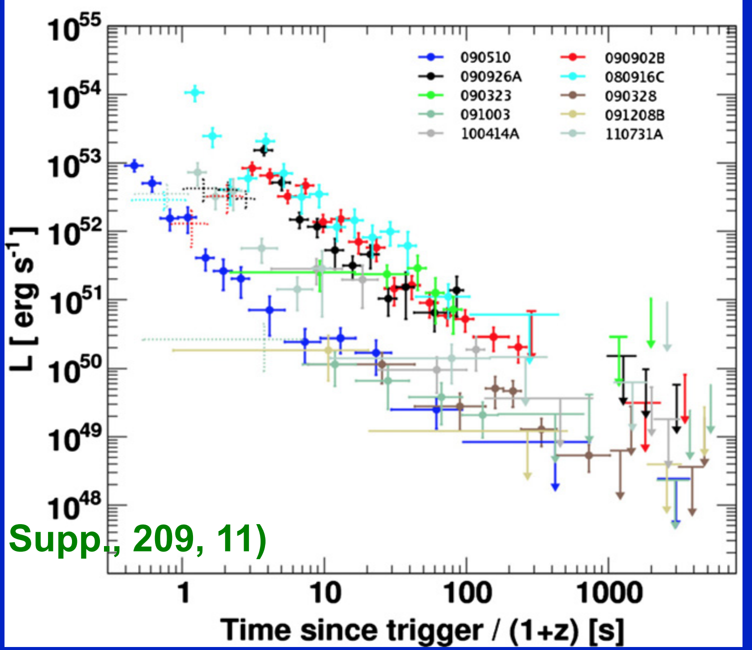
Long-Lived High-Energy emission

- Seen in many/most LAT GRBs: a power-law in time/energy $\propto t^{-\alpha_L}E^{\beta}$ with $\beta \approx -2$ and $\alpha_L \sim 1-1.5$
- Consistent with afterglow @ $t \gg T_{90}$ (at $t \lesssim T_{90}$ sharp spikes $\Rightarrow$ not afterglow)
- Prompt to afterglow transition?
- Some emission from X-ray flares (?)
- Hadronic, pair echo, SSC,… ???







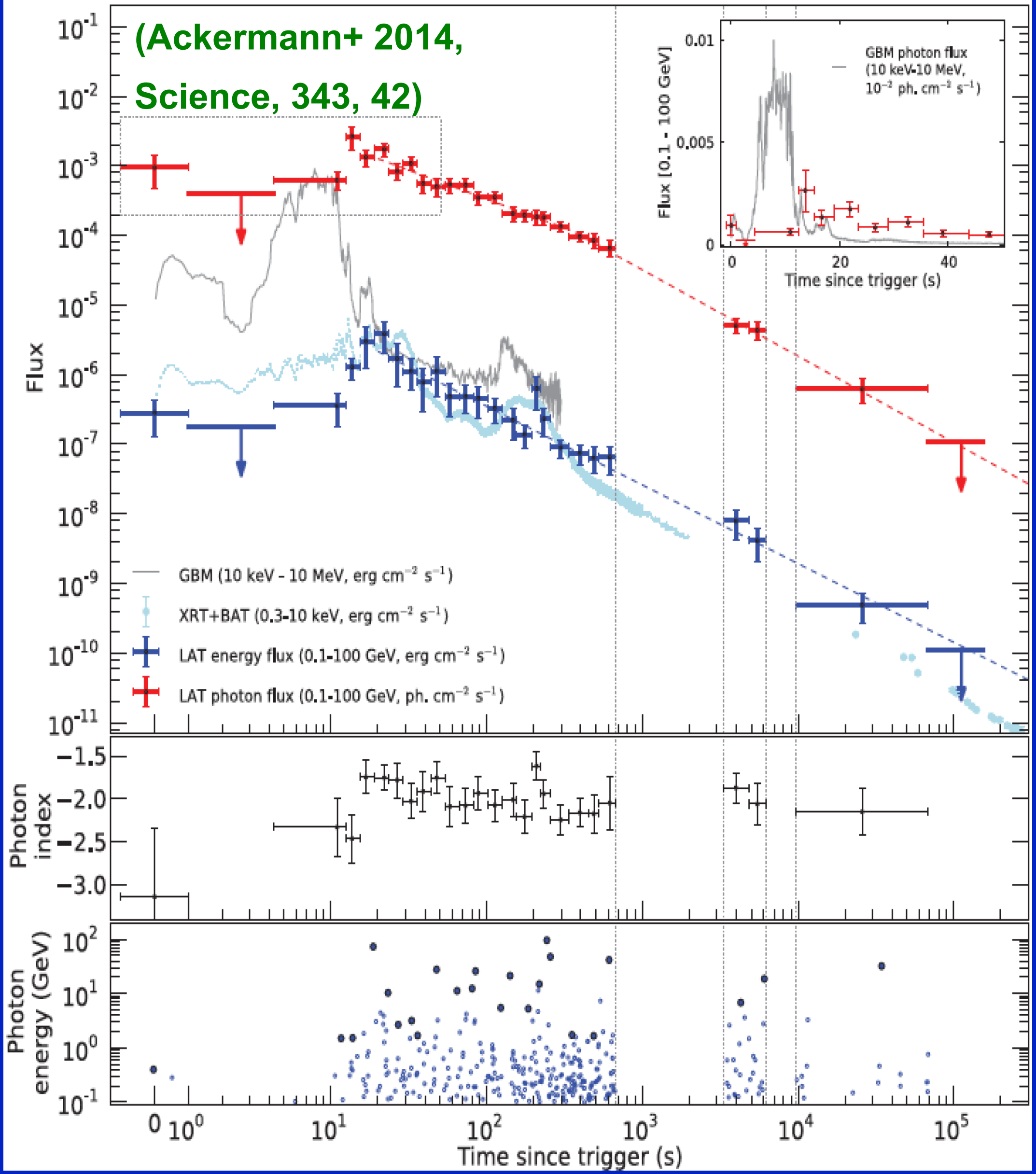


(1st LAT GRB catalog; Ackermann et al. 2013, ApJ Supp., 209, 11)

High-Energy Afterglow: GRB130427A

(see Judy Racusin's talk)

- LAT detected emission up to ~ 20 hr after GRB
- >10 GeV γ's observed up to hours after GRB
- May arise at least partly from the prompt γ-ray emission up to few 10^2 s
- At later times there is no prompt emission, only a simple power-law decay: afterglow



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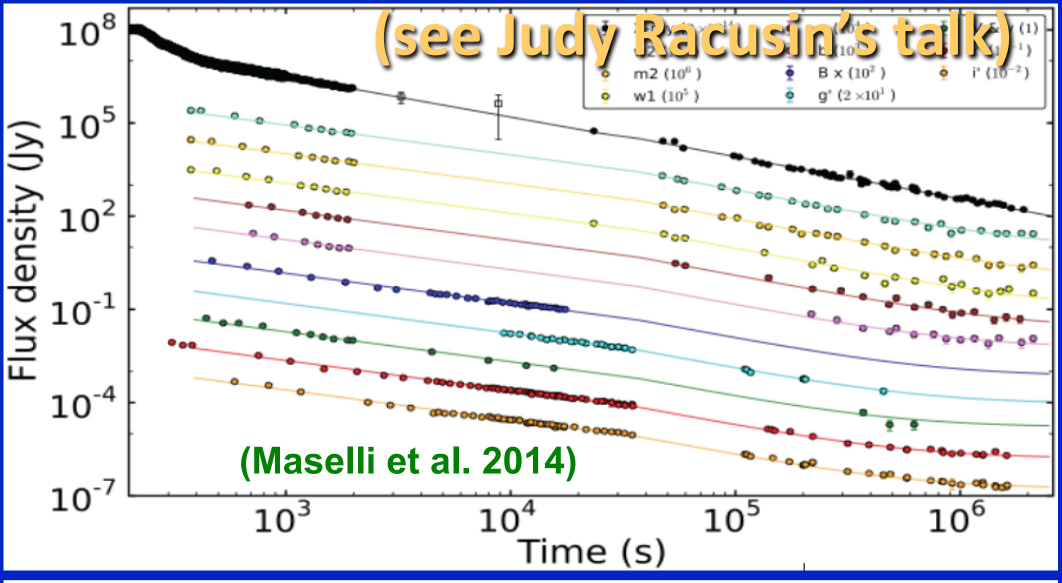
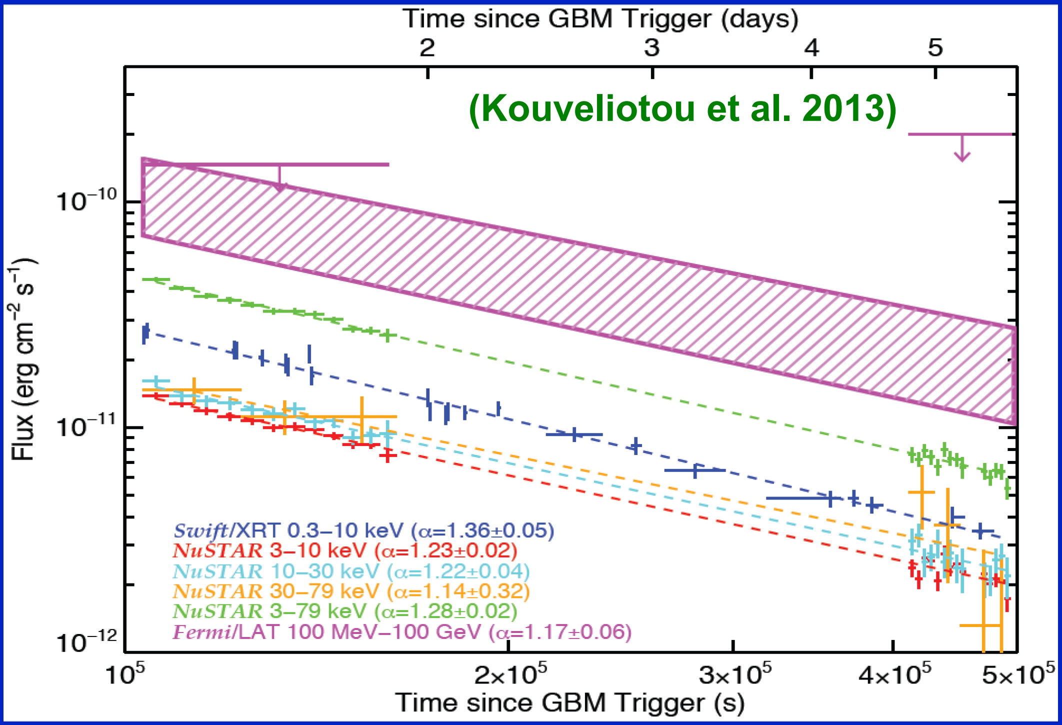


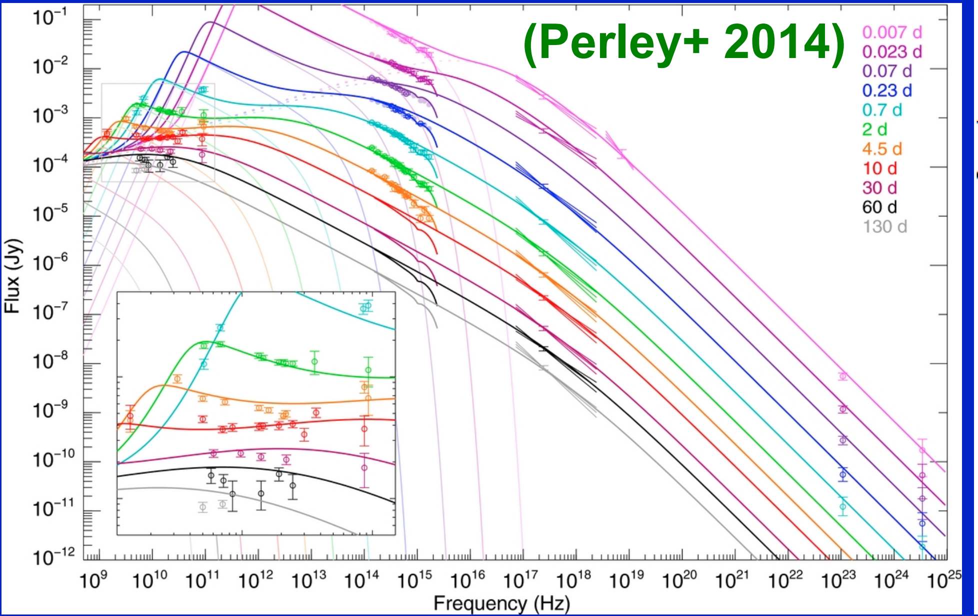


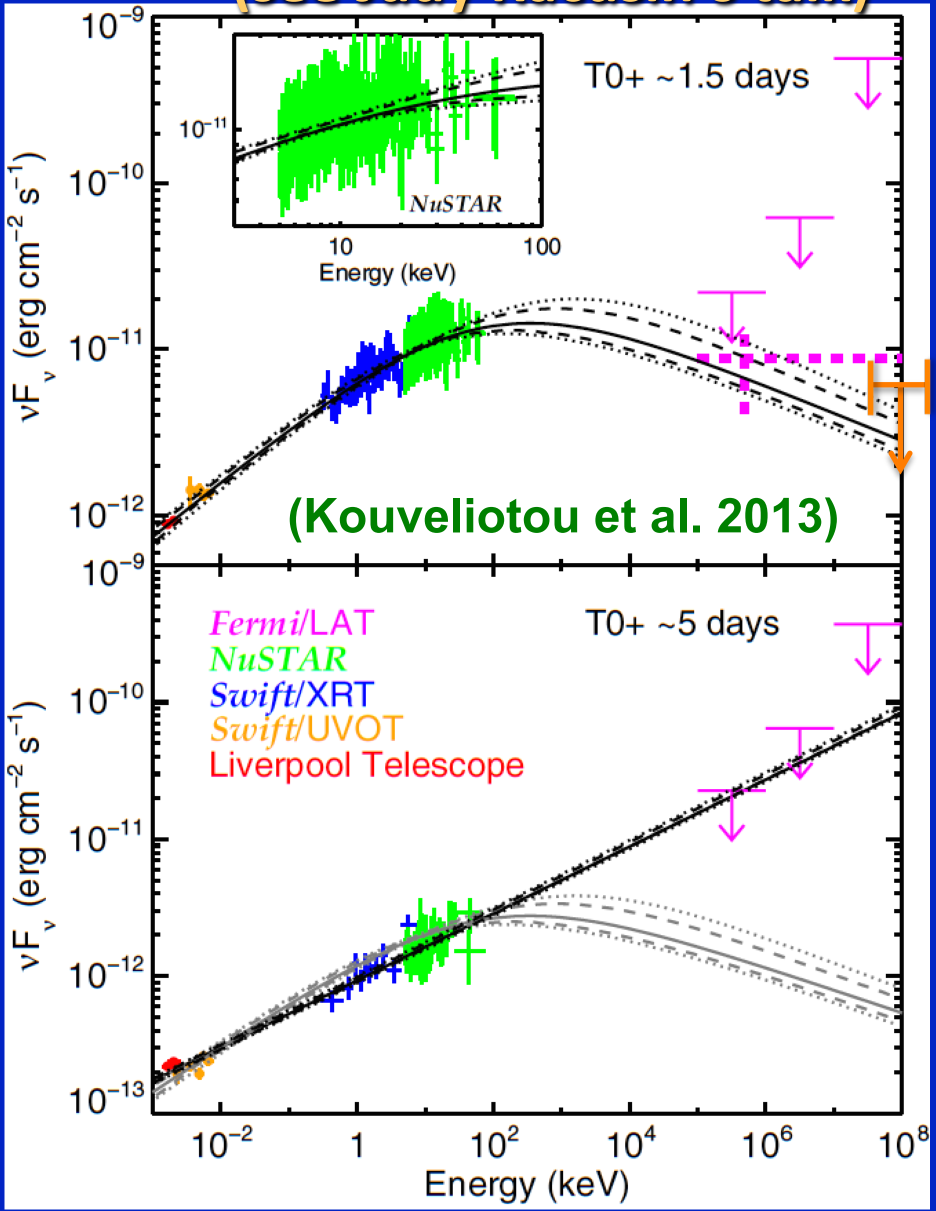
High-Energy Afterglow: GRB130427A

(see Judy Racusin's talk)

- **NuSTAR**: 1st late-time GRB afterglow detection at 3-79 keV
- A single-component synchrotron spectrum nicely fits all energies
- No need or much room for SSC
- Also supported by VERITAS obs.

(see poster 9.08 by Jeremy Perkins+)





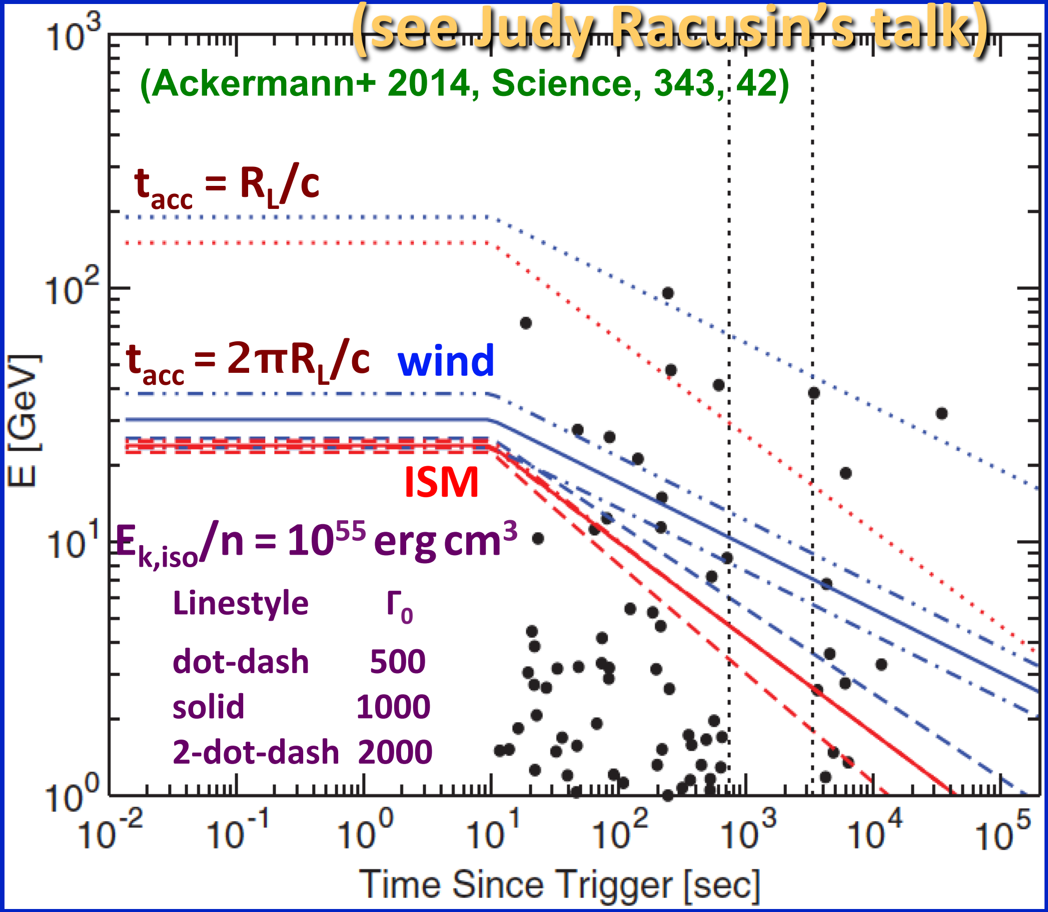
High-Energy Afterglow: GRB130427A

(see Judy Racusin's talk)

- **LAT HE photons violate:**

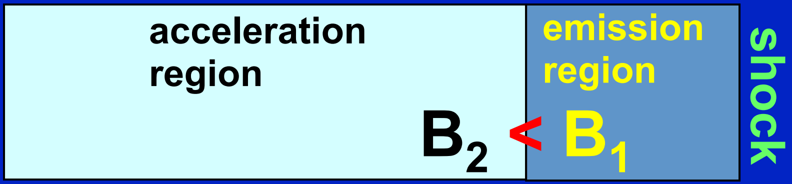
$$E_{\rm syn,max} \sim \frac{\Gamma}{(1+z)}\frac{m_e c^2}{\alpha} \approx 5\left(\frac{\Gamma}{100}\right)\,\mathrm{GeV}$$

- Based on a one-zone model balancing electron energy gains and losses: $t_{acc} \sim t_{syn}$
- $t_{acc} \sim 1/\omega_L = R_L/c$ (extremely fast) or $P_L = 2\pi/\omega_L$ (still very fast but a bit more realistic)
- An "easy way out" would be if SSC emission dominated at highest LAT energies (Fan+ 2013; Liu+ 2013), but it doesn't work (see, however, Xiang-Yu Wang's talk)



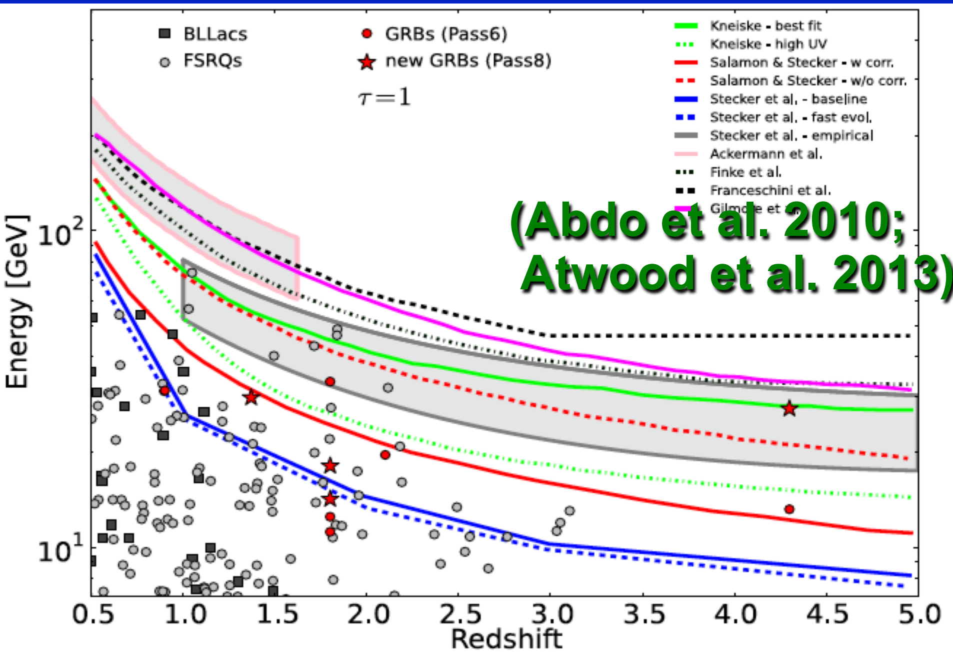
- $\Rightarrow E_{\rm syn,max}$ appears to be truly violated $\Rightarrow \geq 1$ assumption must break
- Non-uniform magnetic field?

$E_{\rm syn,max}$ grows by a factor of B_1/B_2

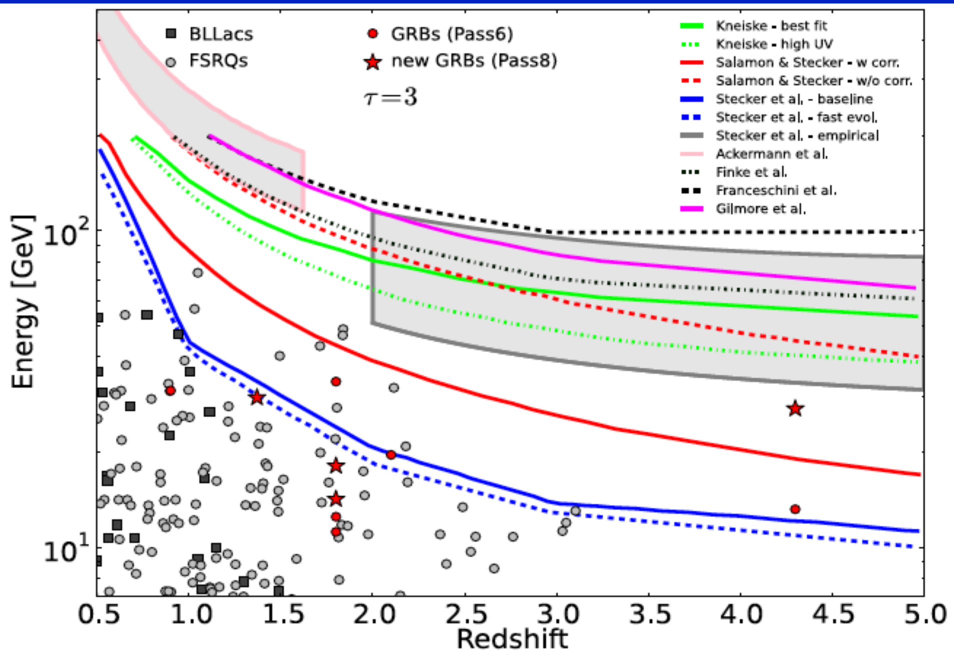


Constraining the opacity of the Universe

- γ-rays from distant sources can pair produce ($\gamma\gamma \rightarrow e^+e^-$) on the way to us with the extragalactic background light (EBL)
- This can test the transparency of the Universe and constrain EBL models (or the massive star formation rate at $z \gtrsim 1$)
- GRBs are already competitive with AGN, & probe higher z
- EBL possibly detected (using blazars: LAT+IACTs; Dominguez+ 2013)

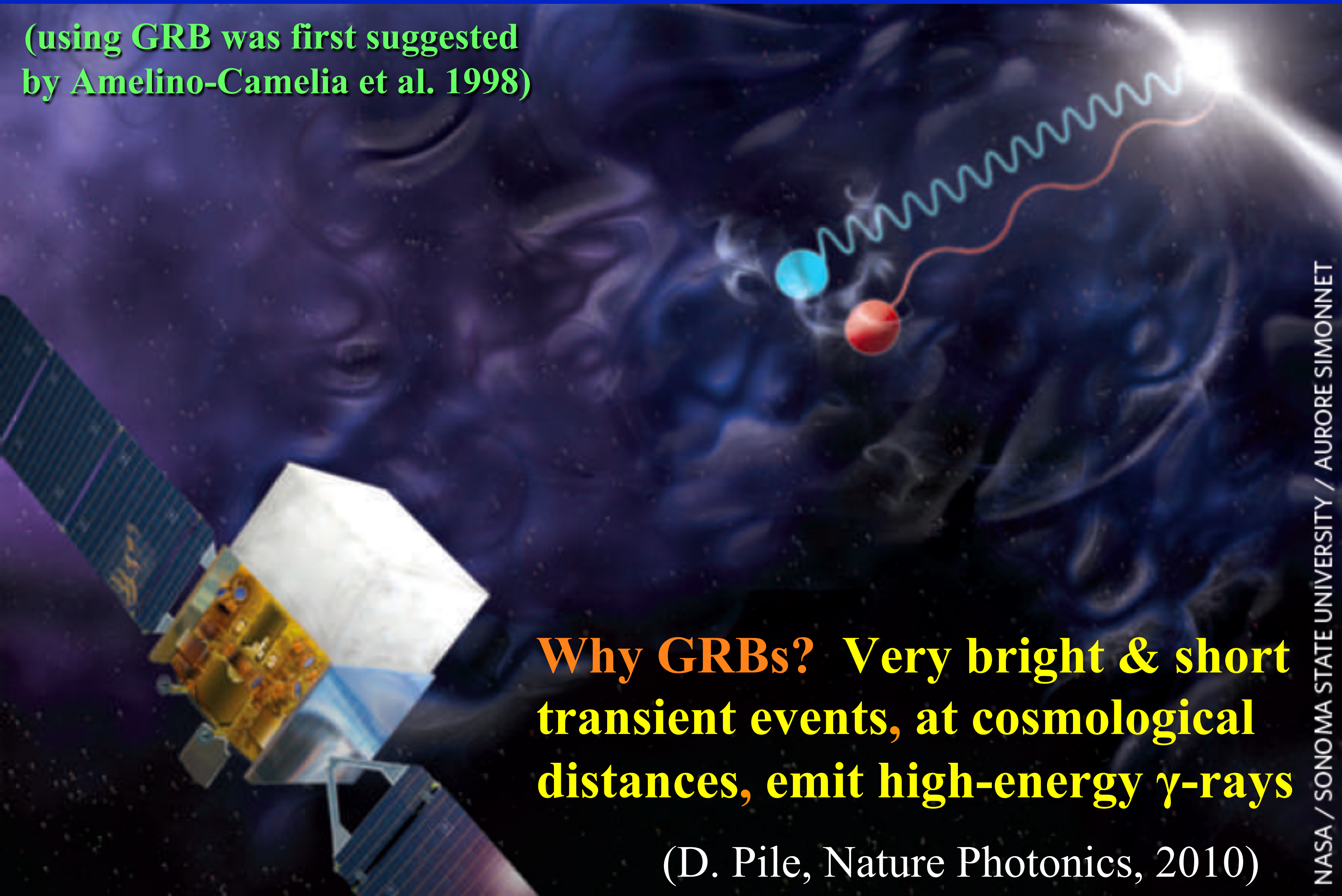


(Abdo et al. 2010; Atwood et al. 2013)



Testing for Lorentz Invariance Violation

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



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

(D. Pile, Nature Photonics, 2010)

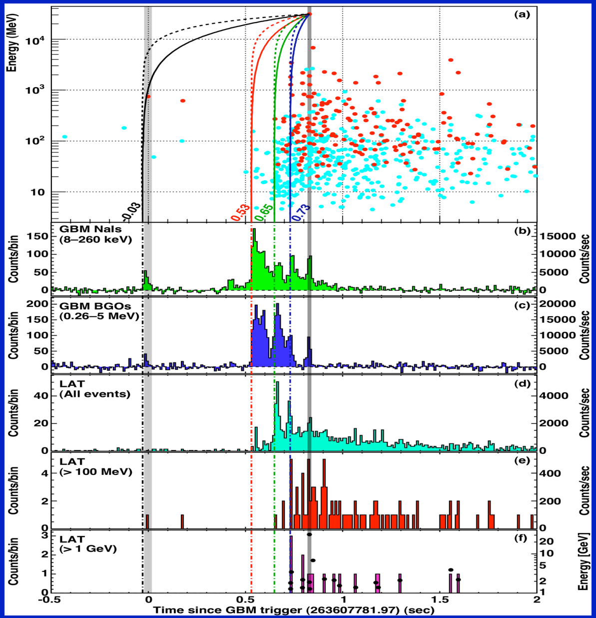
Testing for Lorentz Invariance Violation

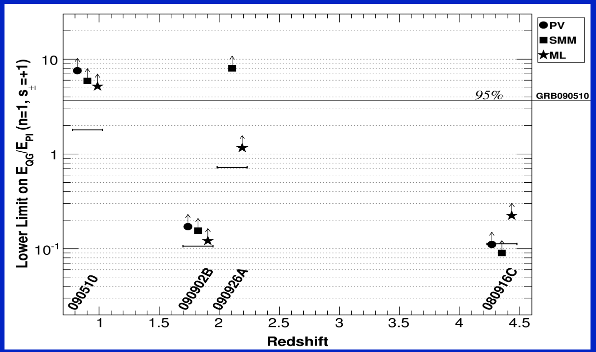
- GRB 090510 is much better than the rest (short, hard, very fine time structure)
- Abdo+ 2009, Nature, 462, 331: 1st direct time-of-flight limit beyond Plank scale on linear ($n = 1$) energy dispersion:

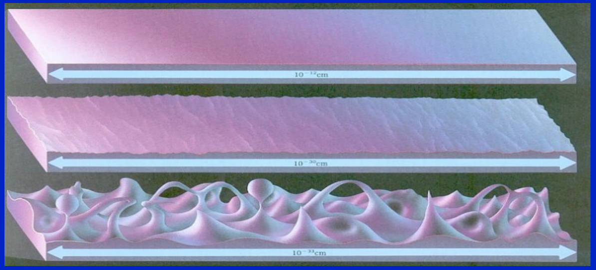
$$v_{\rm ph}/c \approx 1 \pm \tfrac{1}{2}(1+n)\left(E_{\rm ph}/E_{\rm QG,n}\right)^n \qquad E_{\rm QG,1} > 1.2 E_{\rm Planck}$$

(robust, conservative, 2 independent methods)

- Vasileiou+ 2013: 3 different methods, 4 GRBs (090510 is still the best by far), the limits improved by factors of a few
- Vasileiou+ 2014 (submitted): stochastic LIV – motivated by space-time foam (1st Planck-scale limit of its kind)







Synergies with other instruments & Conclusions

- Current: Swift, optical/radio telescopes, NuSTAR, Suzaku, TeV (HAWC, IACTs), …
- Multi-messenger: neutrinos (Ice Cube), UHECRs, gravitational waves
- Future: CTA, SVOM, LSST, ZTF, SKA, aLIGO/VIRGO, Astro-H, X/γ-ray polarimetry, ISS-lobster, …
- ***Fermi*** has greatly contributed to GRB science
- We got some answers, but more new questions
- ***Fermi*** GRBs also contributed to non-GRB science
- There is still a lot to look forward to…