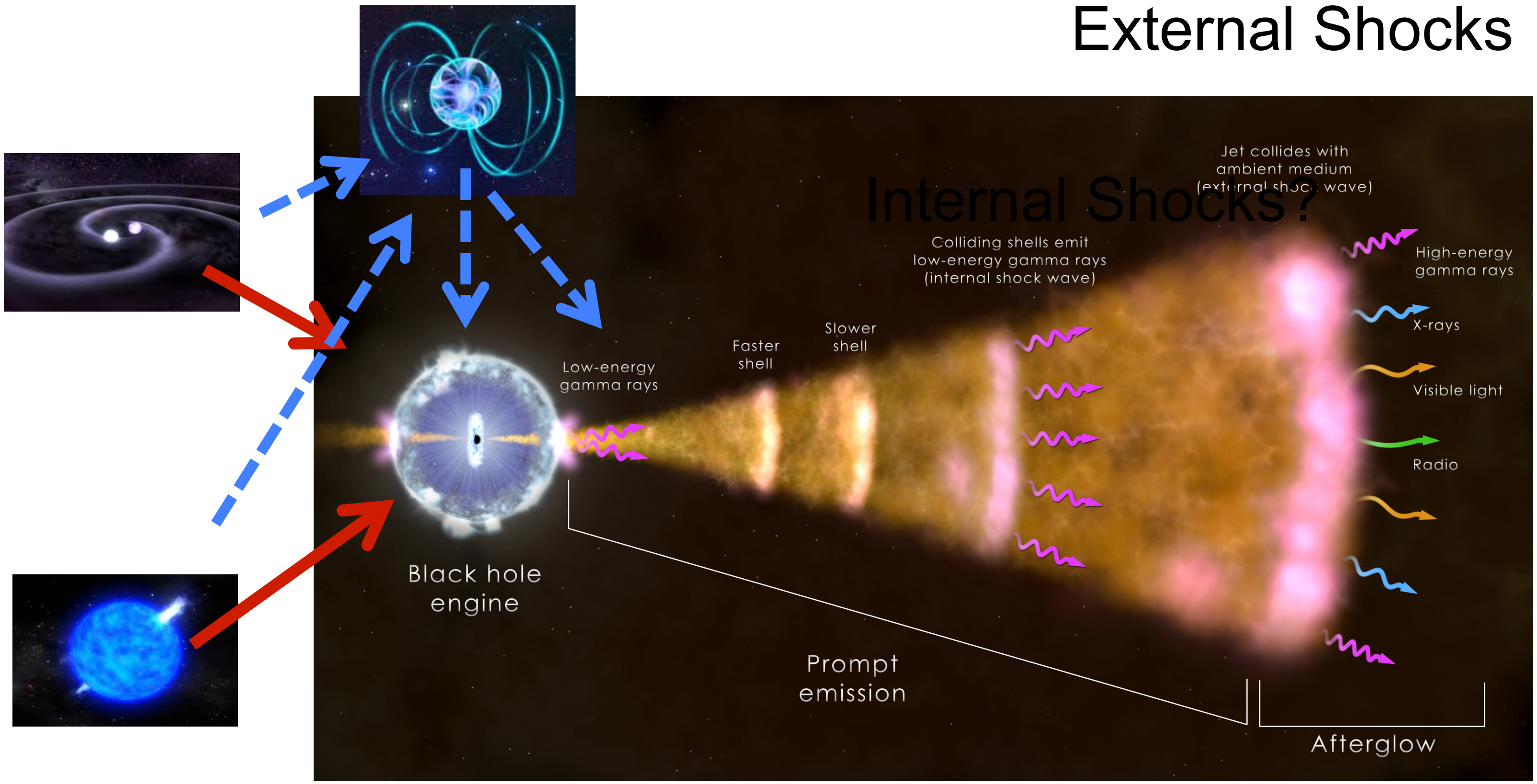
Fermi Observations of Gamma-ray Bursts

Judy Racusin (NASA/GSFC)
on behalf of the Fermi
GBM & LAT Collaborations

GRB Formation

Newly Formed Magnetar?

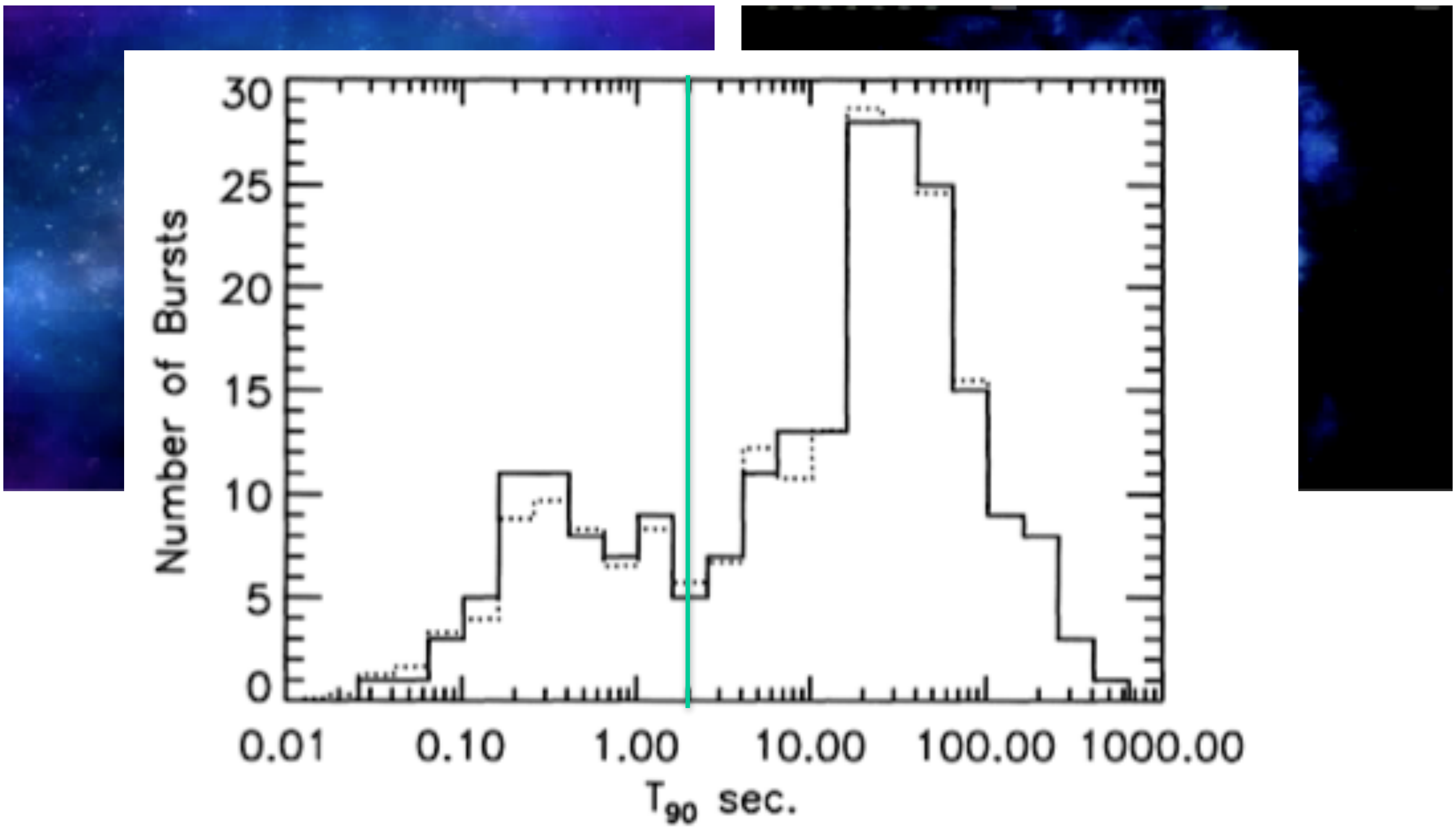
External Shocks



GRB Progenitors

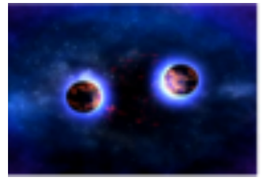
Binary Neutron Star Merger

Collapse of Massive Star

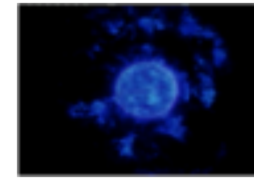


GRB Categories

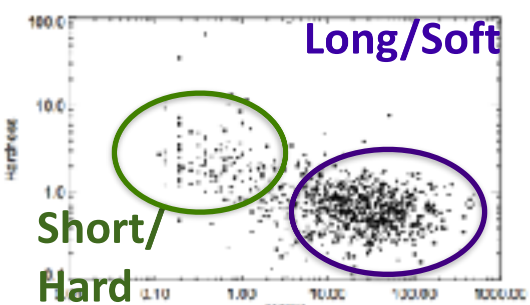
Short Hard GRBs

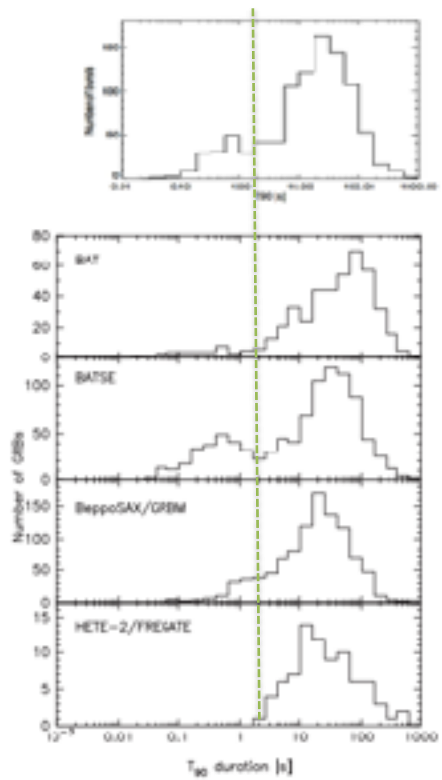


Long Soft GRBs



- Harder Spectra
- $T_{90} < 2$ s
- Associated with old stellar populations on outskirts of old galaxies
- Consistent with picture of Neutron star – Neutron star merger or Neutron star – blackhole merger



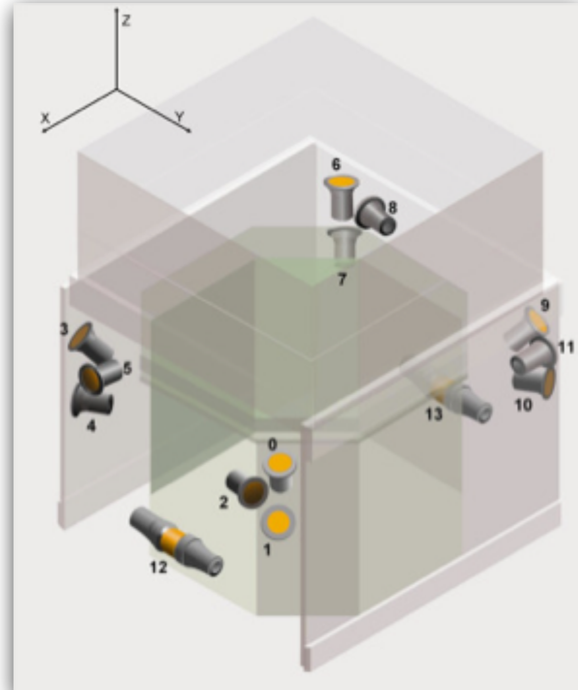


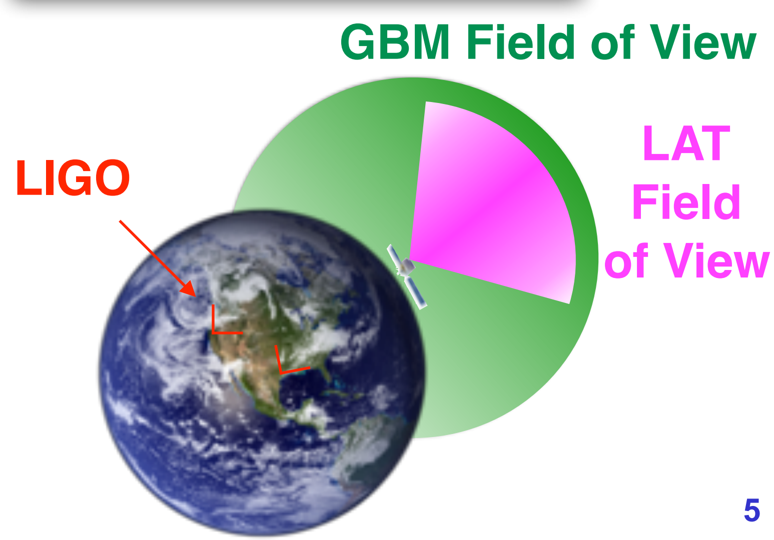
von Kienlin et al. 2014

- Softer Spectra
- T90 > 2 s
- Associated with young stellar populations in star forming regions
- Consistent with picture of massive star collapsing into blackhole
- Associated supernovae

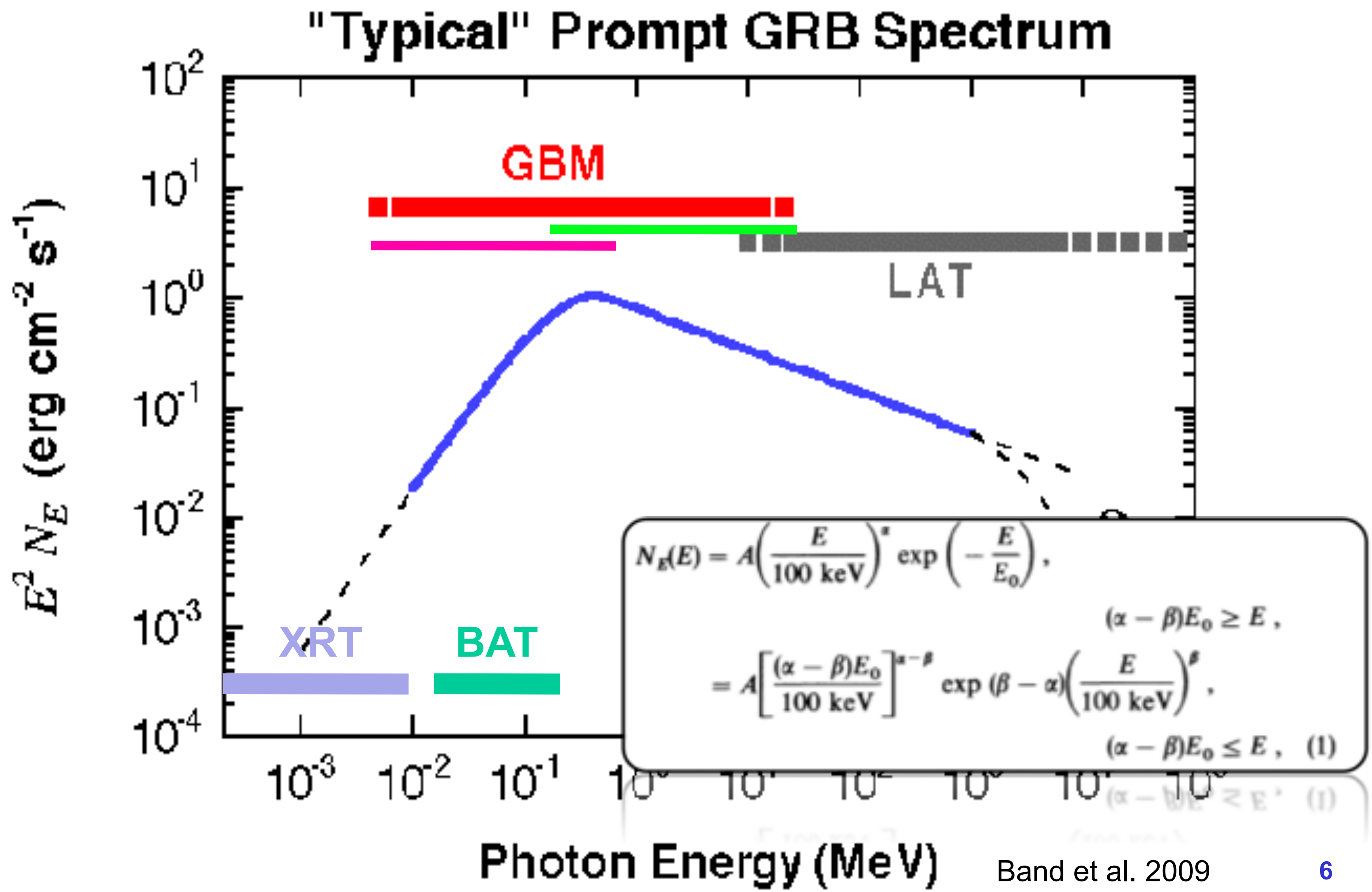
Gamma-ray Burst Monitor (GBM)

- GBM detectors
  - 12 NaI (8 keV - 1 MeV)
  - 2 BGO (150 keV - 30 MeV)
  - Provides all sky coverage (not blocked by Earth)
- Triggers on GRBs, Solar Flares, Terrestrial Gamma-ray Flashes, Soft Gamma-ray Repeaters, other bright galactic transients
  - Time-tagged event data around all triggers
- Continuous time-tagged event data (since 2011), binned continuous data since launch
- GBM also initiates autonomous repoint requests (ARRs) for bright, high fluence bursts, initiating a pointed/Earth limb tracing observation with LAT for 2.5 hours, increasing LAT exposure





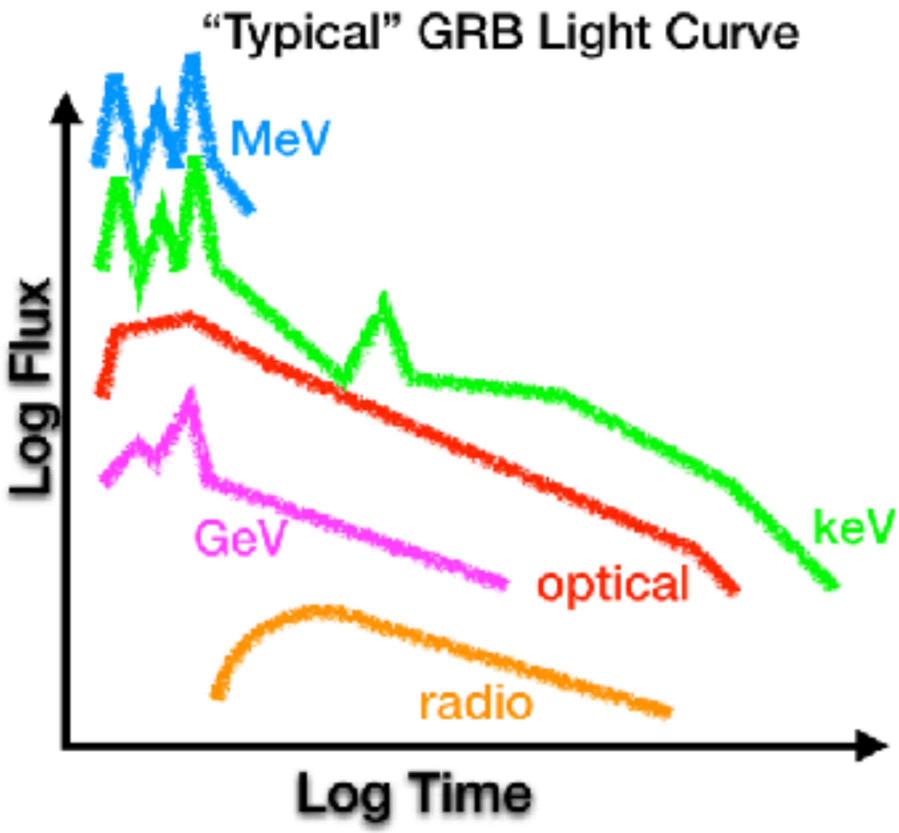
How does Fermi add to our understanding of GRBs?

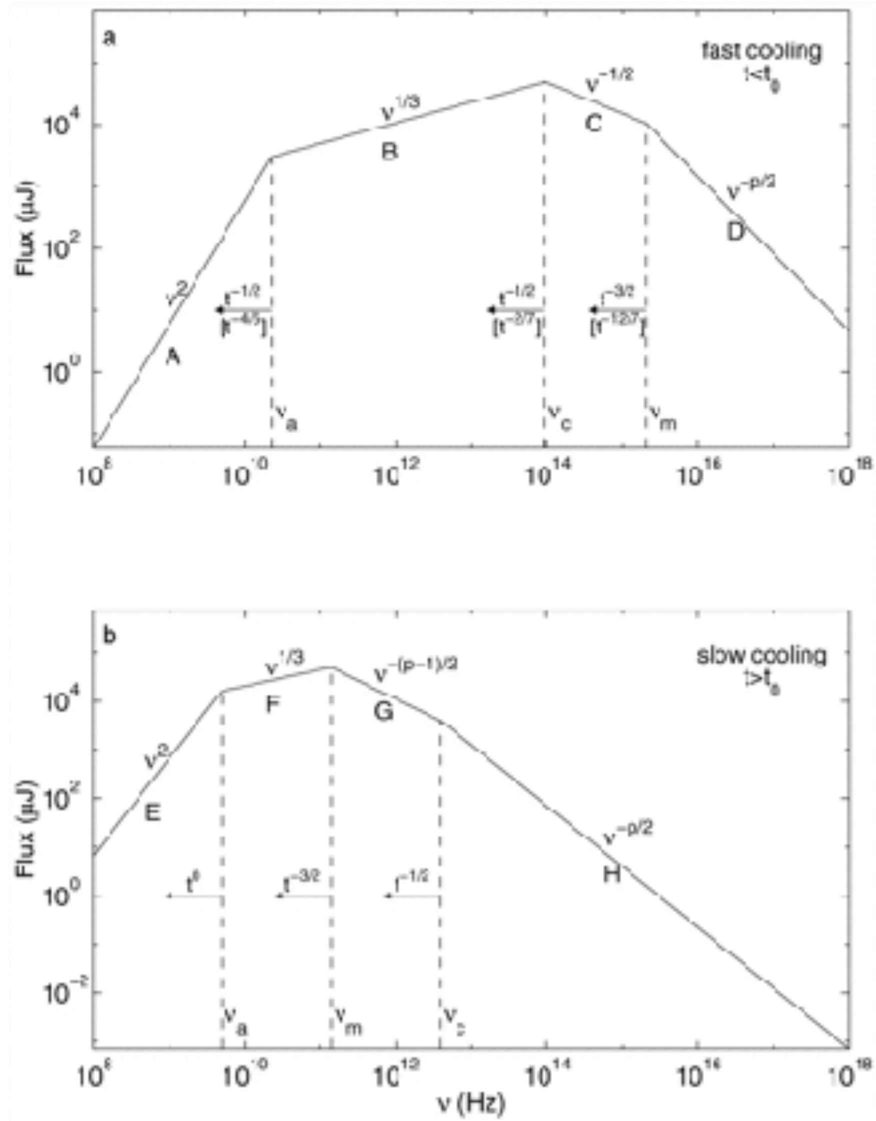


$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \qquad (\alpha-\beta)E_0 \geq E\,,$$
$$= A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, \qquad (\alpha-\beta)E_0 \leq E\,, \quad (1)$$

Band et al. 2009

Broadband Observations of GRBs



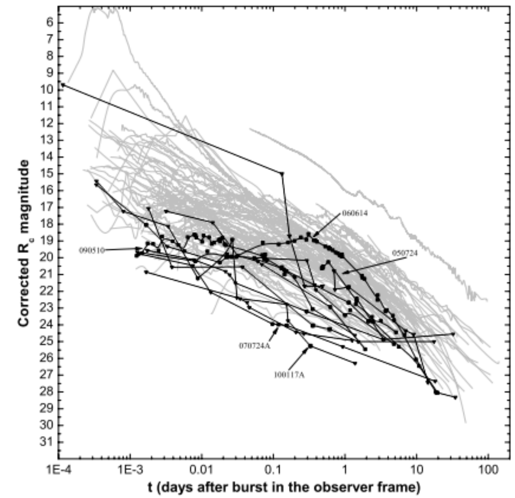


Sari 1998

Afterglows

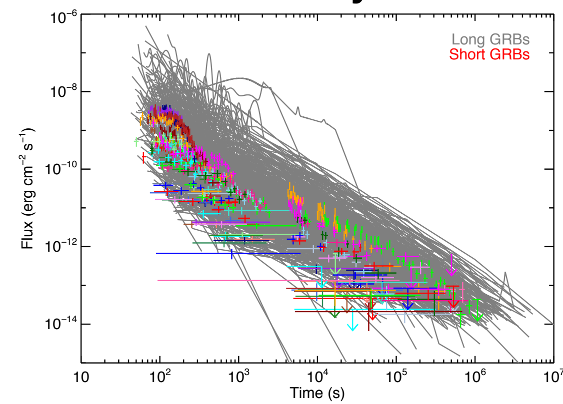
- External shock interacting with surrounding environment
- Depends on:
  - density and profile of gas/dust
  - electron spectrum
  - magnetic field
  - energy input
  - bulk Lorentz factor
  - jet structure
  - viewing angle

Optical



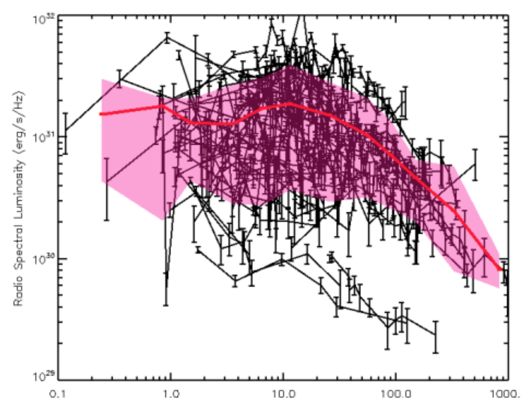
Kann et al. 2011

X-ray



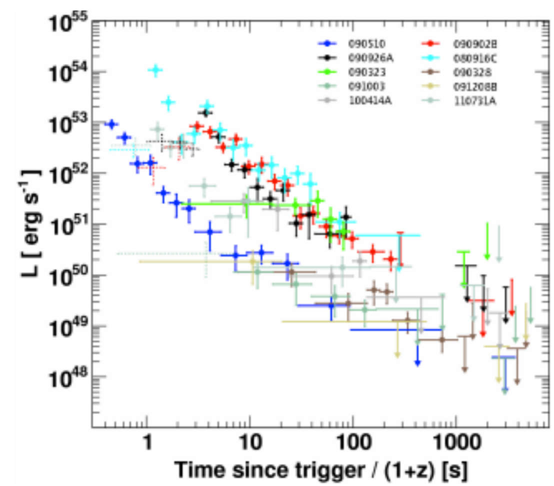
Racusin et al. 2009

Radio



Chandra et al. 2011

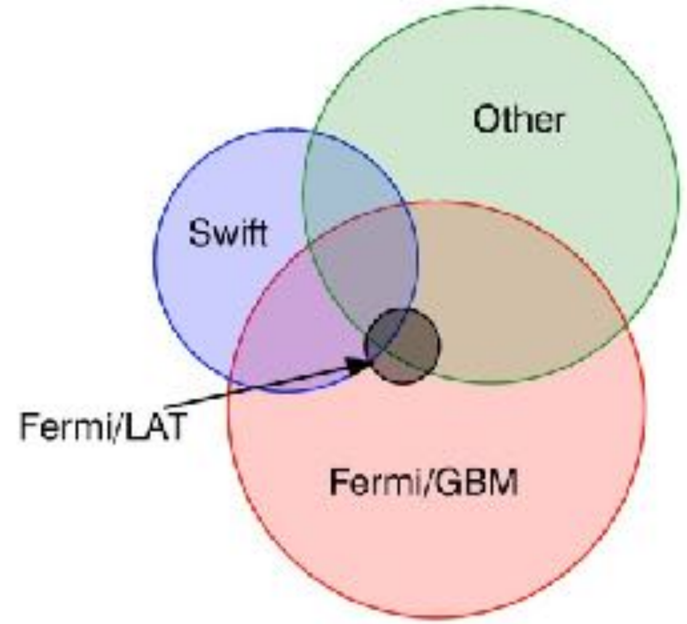
GeV γ-ray



Ackermann et al. 2013

Fermi GRB Observations

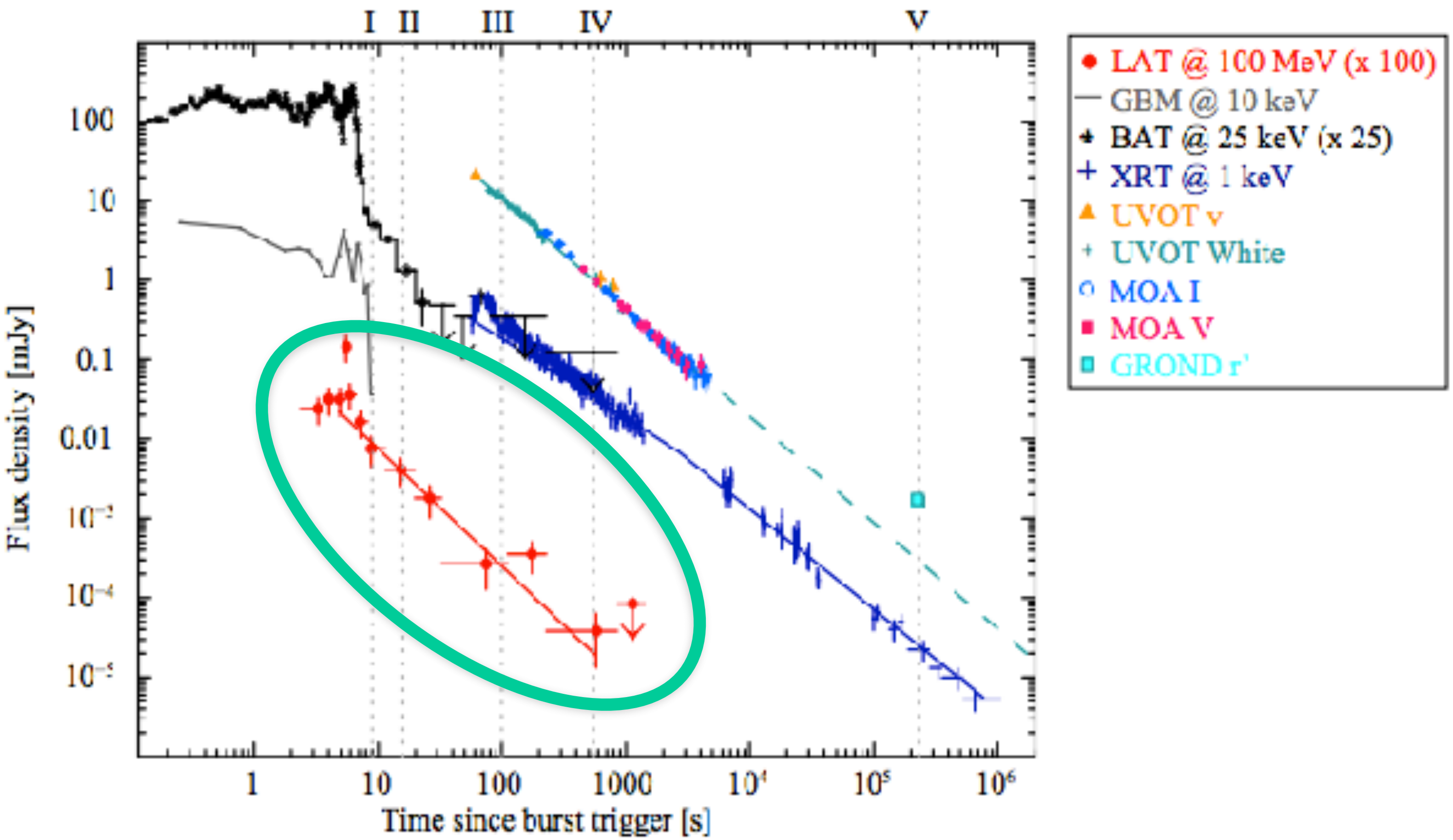
- Including bursts from Aug 2008-May 2018
  - ~1000 Swift GRBs
  - ~2300 Fermi-GBM GRBs
  - ~150 Fermi-LAT GRBs
  - ~1000 Other (AGILE, Suzaku, Konus, INTEGRAL, etc.)
- Limitations
  - ~300 Swift GRBs with no high energy (>150 keV) observations
  - ~1200 poorly localized GRBs without afterglow observations
- Best Observed Subset
  - Those with both high and low energy coverage
- Future
  - Wide-field Optical/X-ray instruments may change this (e.g. ZTF, ISS-TAO)



Credit: A. Goldstein

How does LAT add to our understanding of GRBs?

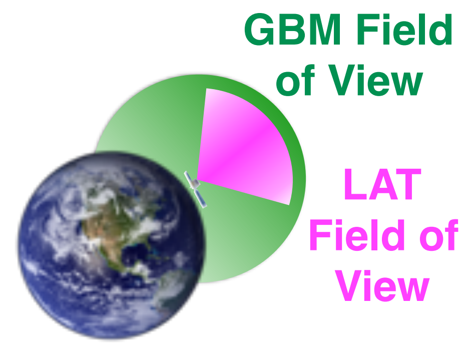
GRB 110731A



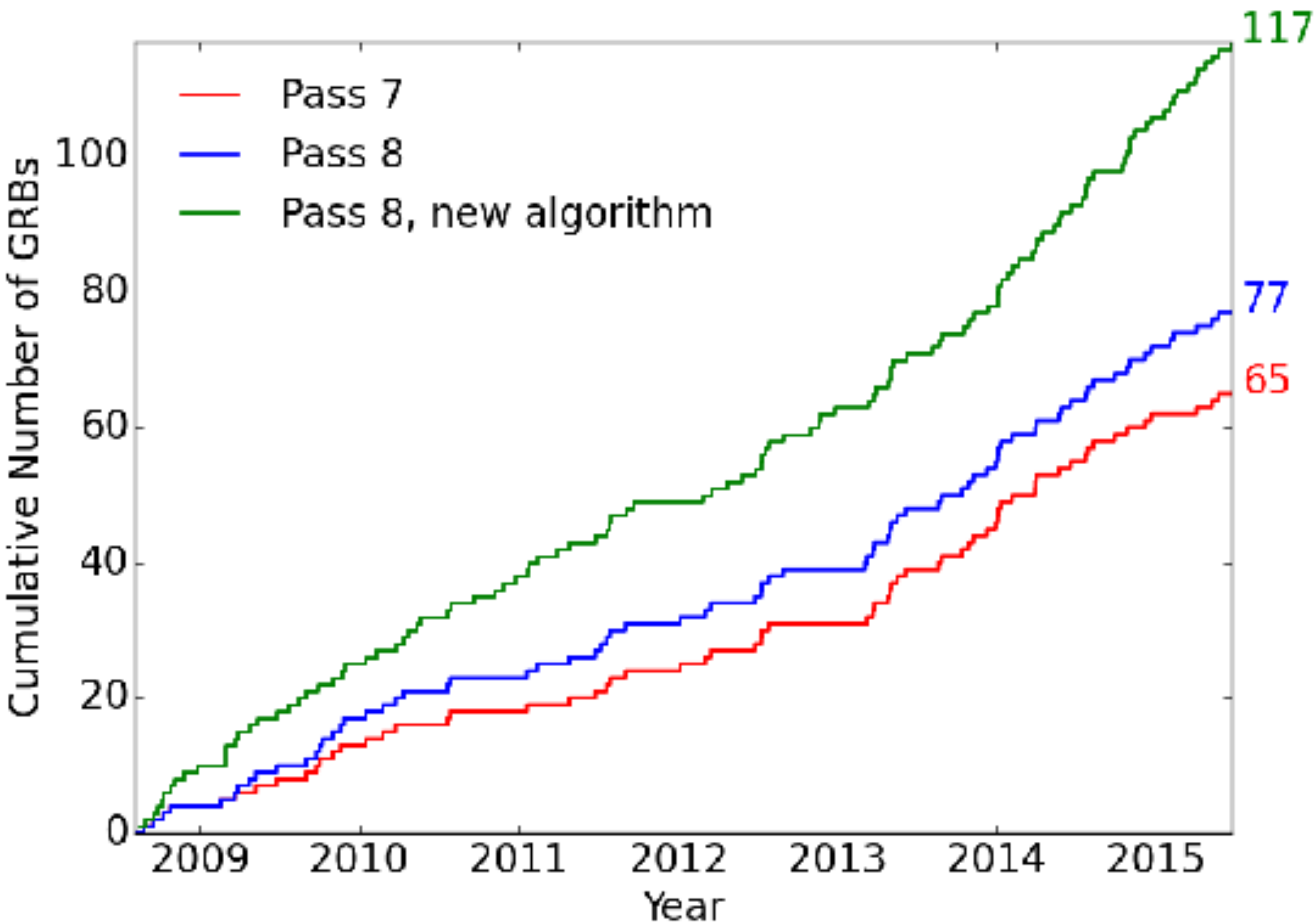
Ackermann et al 2012

GBM Triggers

- **Onboard localization (5-10 deg radius)**
  - **Followed by automatic ground localization (3-5 deg radius)**
  - **Human in the loop position (taking into account subjective decisions like interval and energy range)**
- **If high peak flux, or high fluence criteria are met -> ARR**
  - **triggers Autonomous Repoint Request (ARR)**
  - **LAT centers GRB in FoV for 2.5 hours (except when occulted)**
  - **Better effective area by bring burst into central area of detector**
  - **Improves temporal coverage for light curve to compare to broadband measurements**
  - **Background in GBM & LLE can be problematic due to slew**
  - **Occur with rate of ~1-2/month**
  - **Currently disabled due to solar panel issue**



LAT GRB Detections



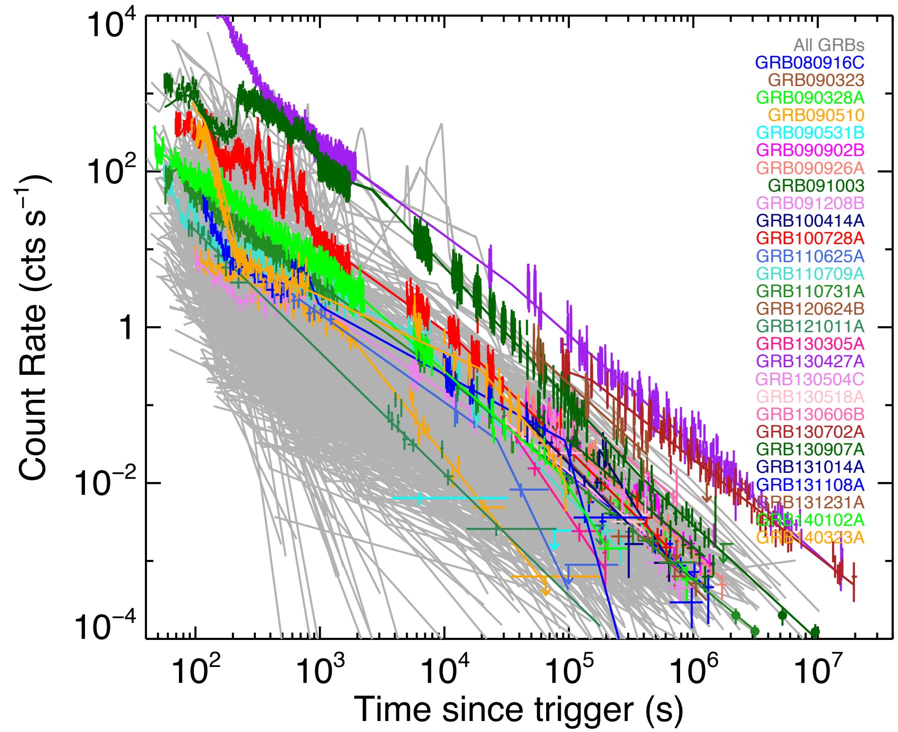
Fermi GRB Observations

- LAT observations begin
  - Rare onboard triggers (GRBs 090510, 131108A, 160509A, 160625A, 160821A) of GRBs with bright short spikes
    - provides prompt ~0.5 deg localizations - good enough to initiate follow-up
    - refined localizations from ground analysis later
  - Most detections found via ground analysis
    - processed in ~6-12 hours
    - automated scripts + humans (Burst Advocates)
  - LAT position disseminated to world (errors ~0.1-1 deg radius, 90%)
- Swift Follow-up (ideally)
  - Tiled or single (or 4 or 7) pointing observations with XRT/UVOT
  - Arcsec position sent to world via GCN (gamma-ray coordinates network)
  - Ground-based telescopes find afterglow, get spectrum and redshift

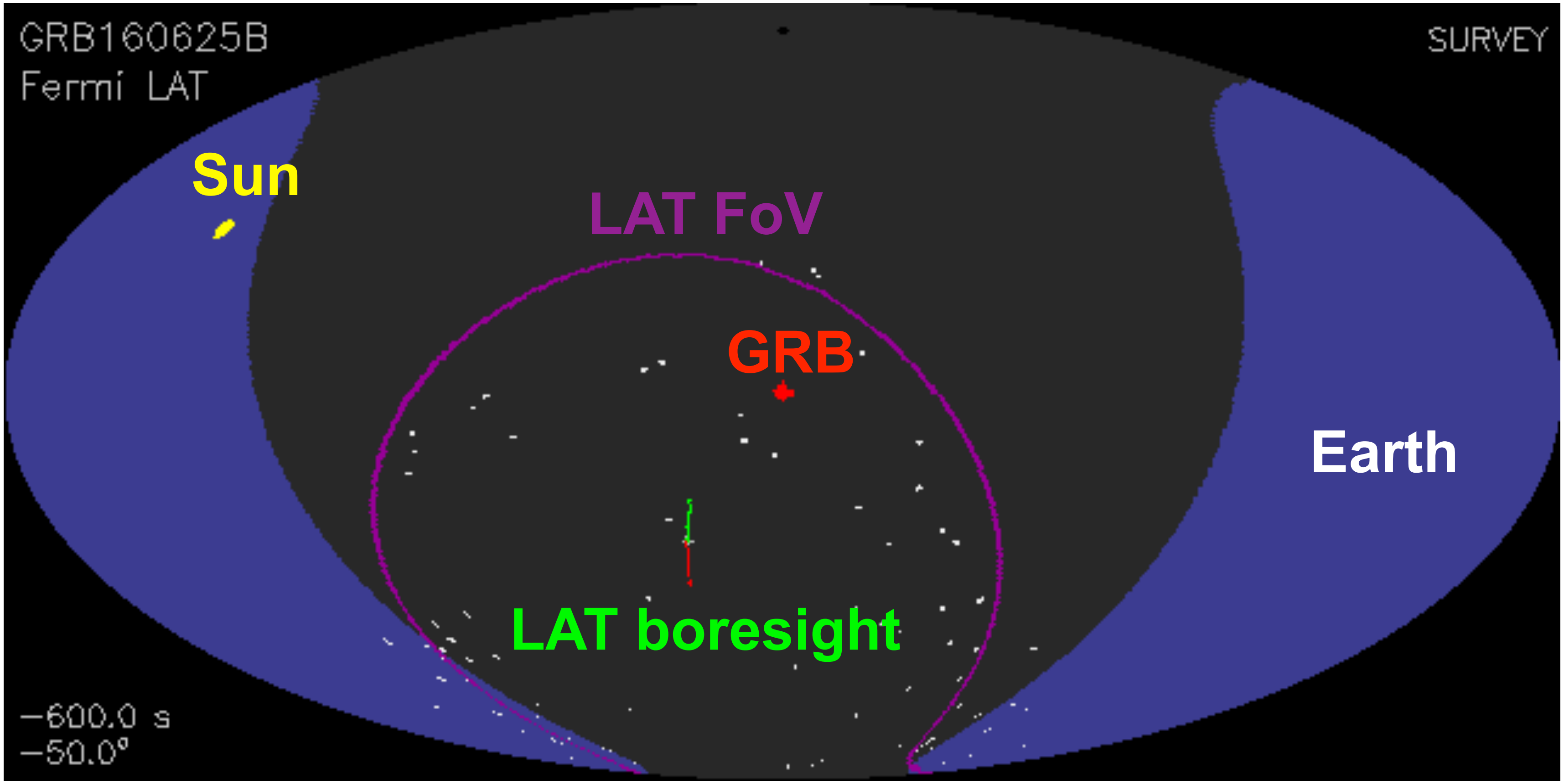
Swift-XRT Observations of LAT GRBs: Follow-up Successes

- **148 LAT detections (new catalog in prep)**
- **26 BAT/GBM/LAT co-detections**
- **60 detected by XRT**
- **67 followed-up by XRT**
  - **23 tiled**
    - **9 w/ 7 tile pattern (3 det)**
    - **11 w/ 4 tile pattern (2 det)**
    - **3 w/ other patterns (mainly older bursts) (0 det)**
  - **44 single pointing (29 detected)**

Swift-XRT GRB Afterglows

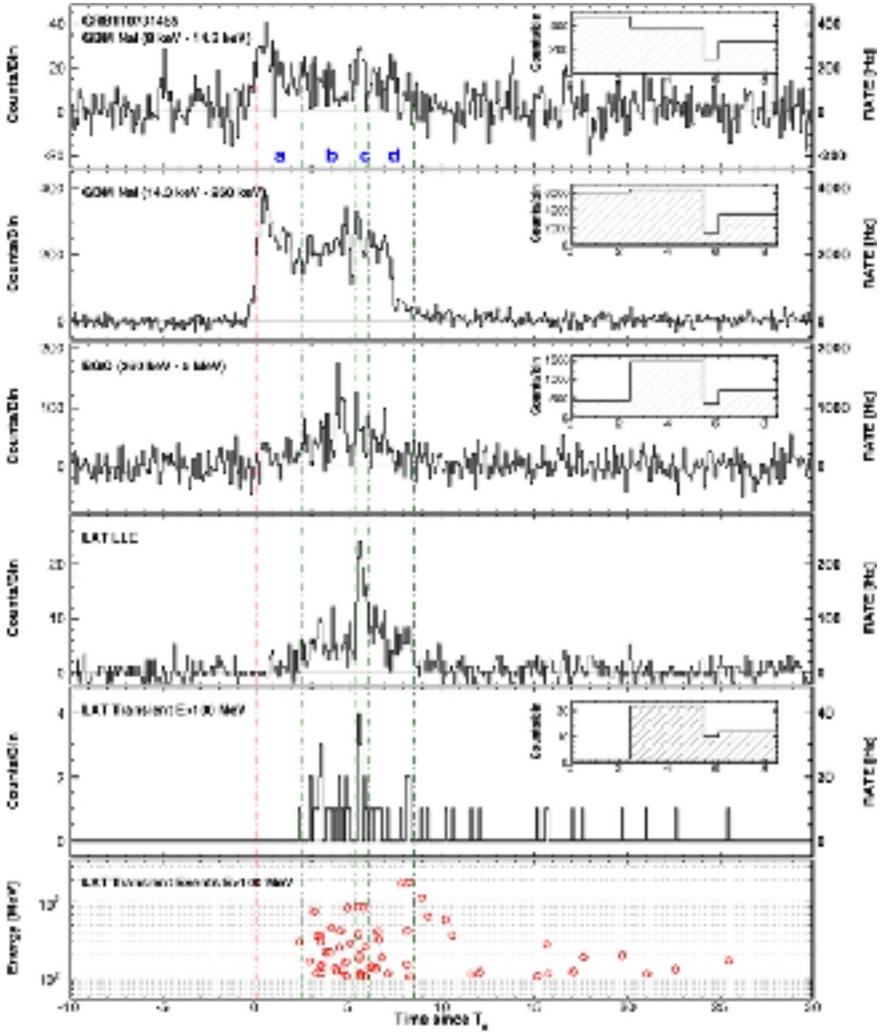


Autonomous Repoint Towards a GRB

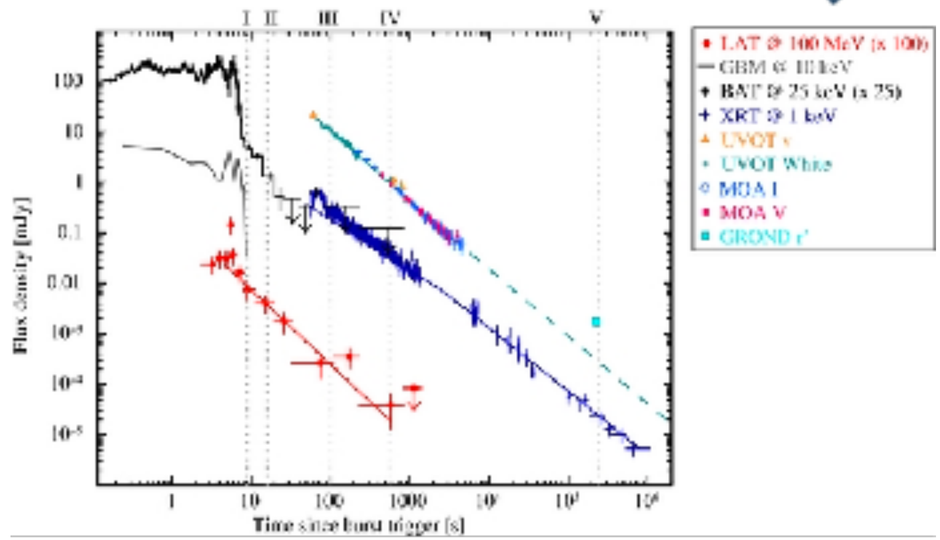


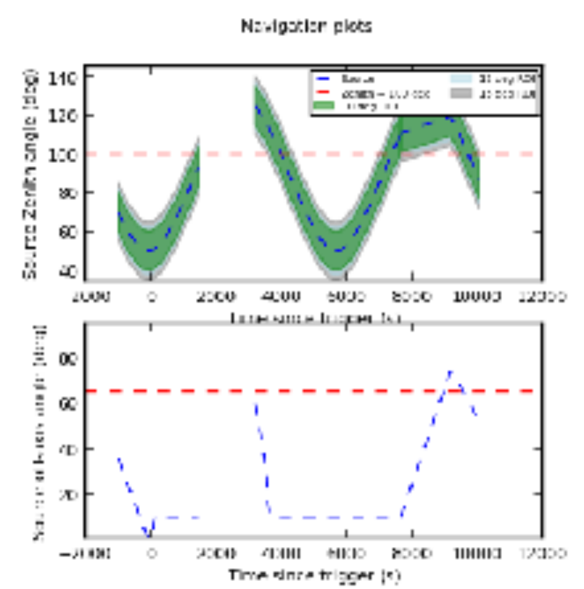
Fermi Observations of a GRB

GRB 110731A



Ackermann et al. 2012

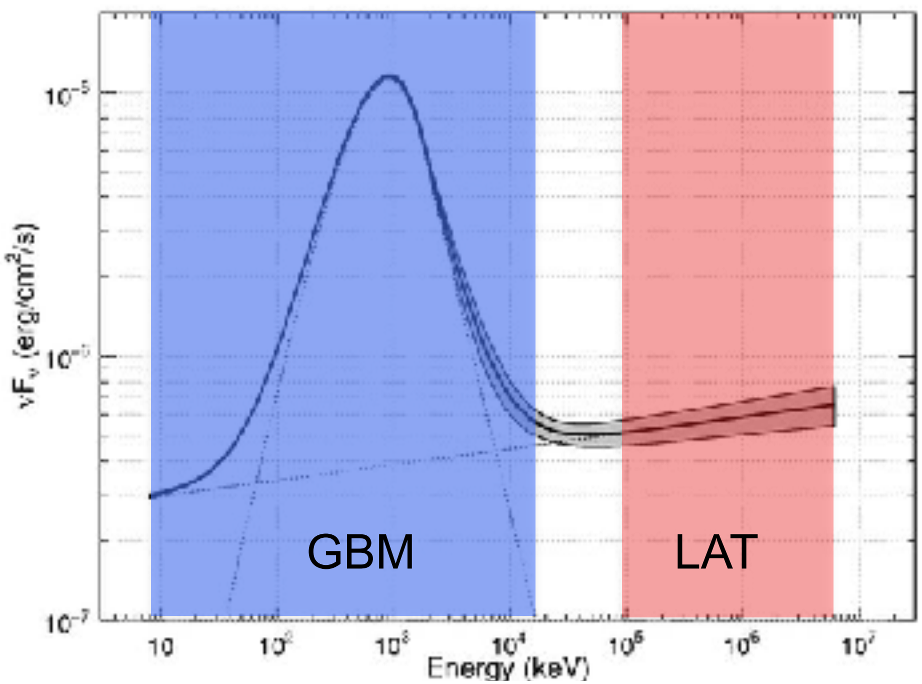




Common New Features in Bright Fermi GRBs

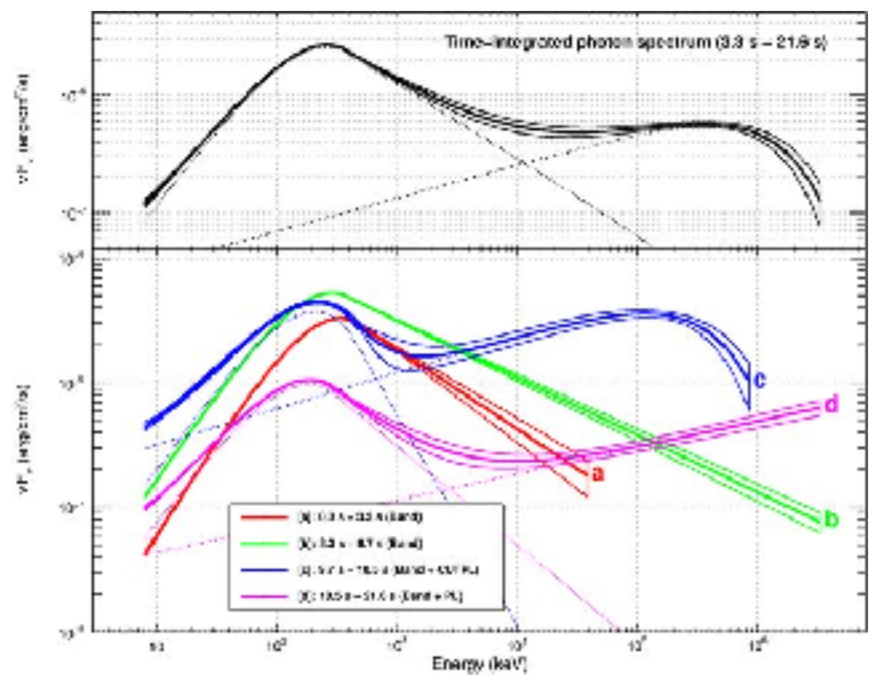
- **GRB spectra deviate from Band functions**
  - **Low energy deviation**
  - **Additional power law at high energies**
  - **High energy cut-offs is some cases**

GRB 090902B



Abdo et al. 2009, ApJ, 706L, 138A

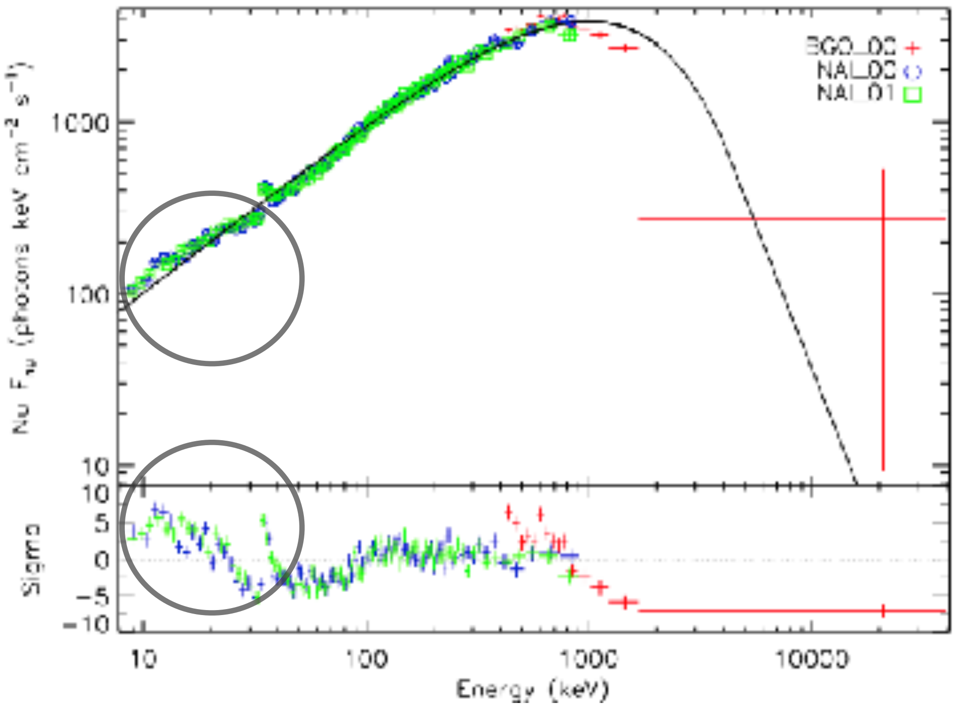
GRB 090926A



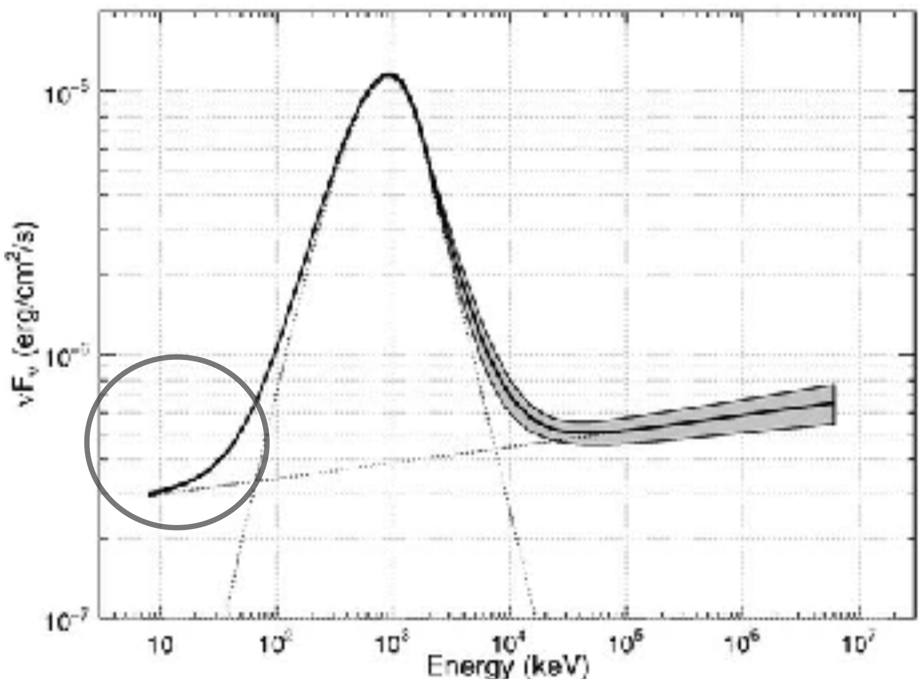
Ackermann et al. 2011, ApJ, 729, 114
Yasine et al. 2017

Low-Energy Excess

GRB 090902B



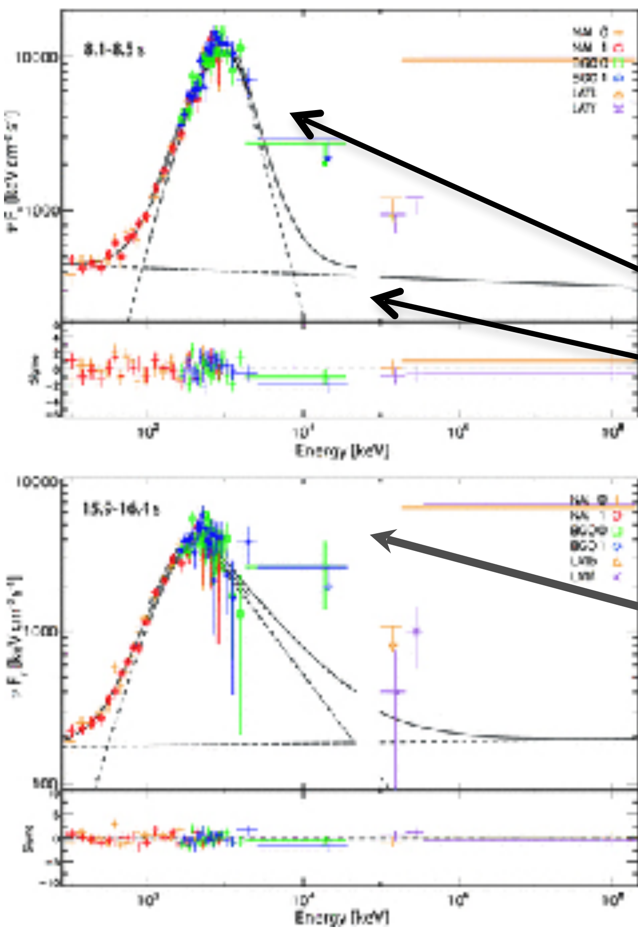
Tierney et al. 2013



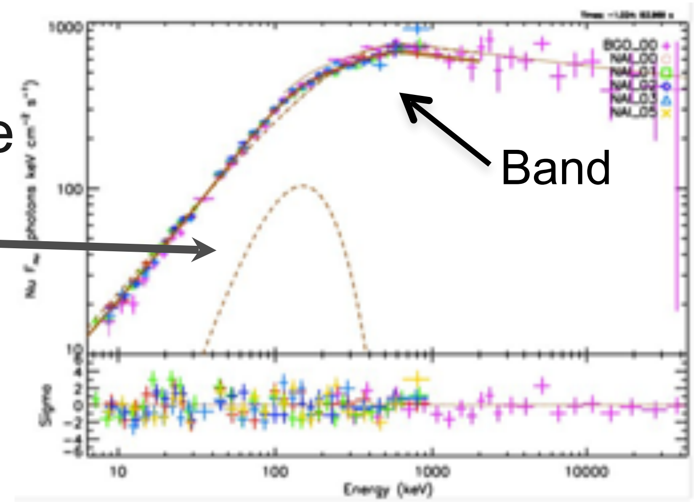
Abdo et al. 2009, ApJL 706, 138

Thermal Emission - Photospheric?

GRB 090902B



GRB 100724B



Sub-dominate Blackbody

Band

Dominate Blackbody + power law

Guiriec et al. 2011, ApJL 727, L33

Broadening not consistent with Band function

Ryde et al. 2011, MNRAS 415, 3693

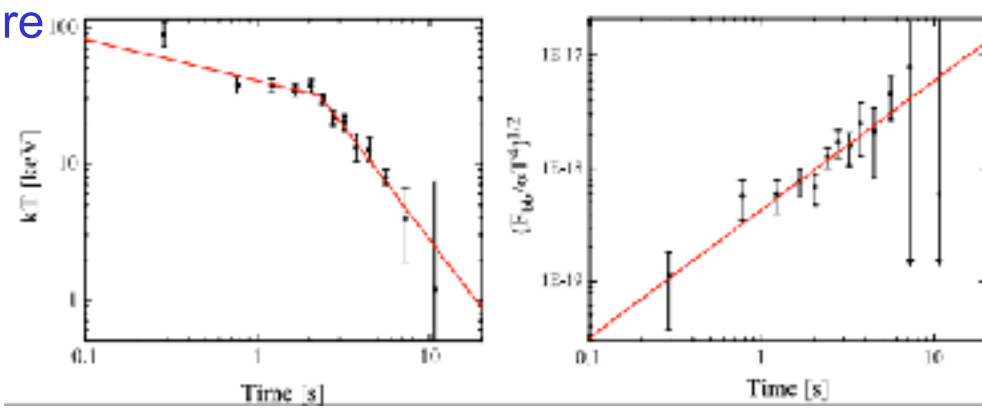
Photospheric Emission

- Blackbody emission from turbulent relativistic outflow
- Deviations from Band function
- Thermal photosphere does not have to emit as a perfect blackbody – smeared by multiple temperatures, evolution, different emission regions
- However, GRB 090902B is best fit by a dominant blackbody component + power law
- Low energy excess in many other bursts fit by a sub-dominant blackbody

GRB 110721A

Evolving blackbody temperature

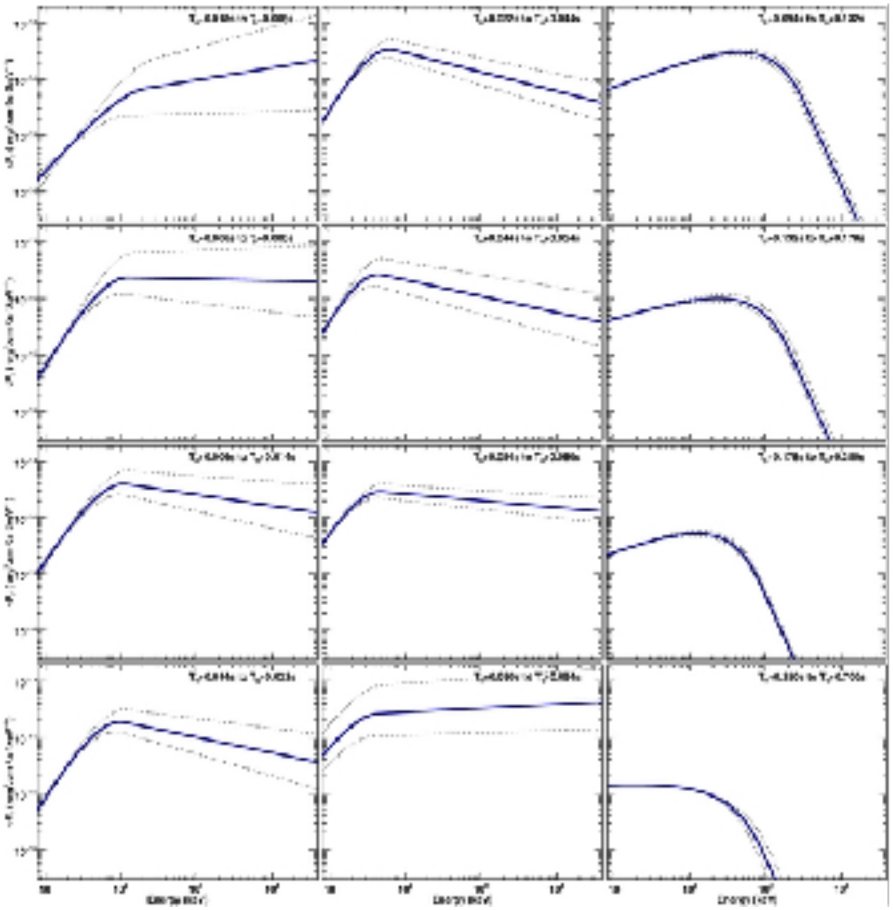
Evolving blackbody normalization



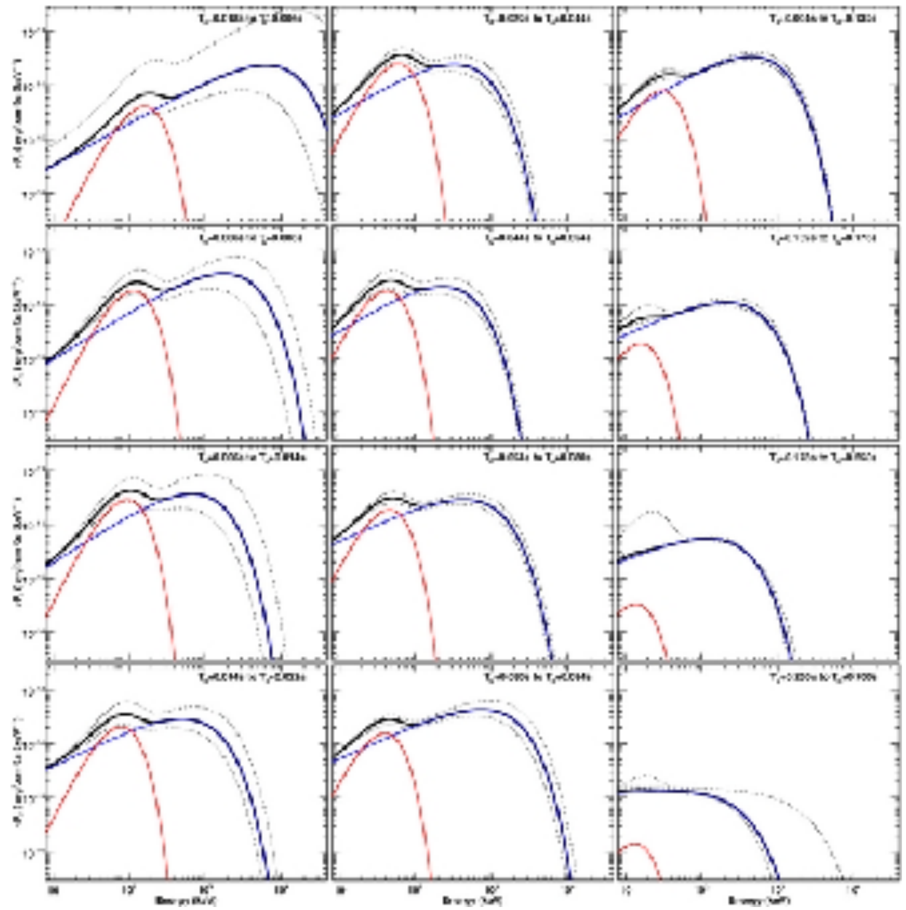
Axelsson et al. 2012

Photospheric Emission

Band only fits



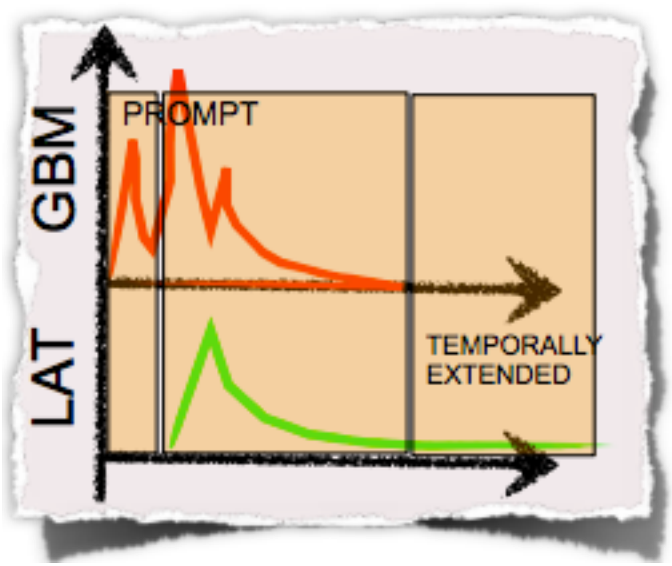
Band+BB fits



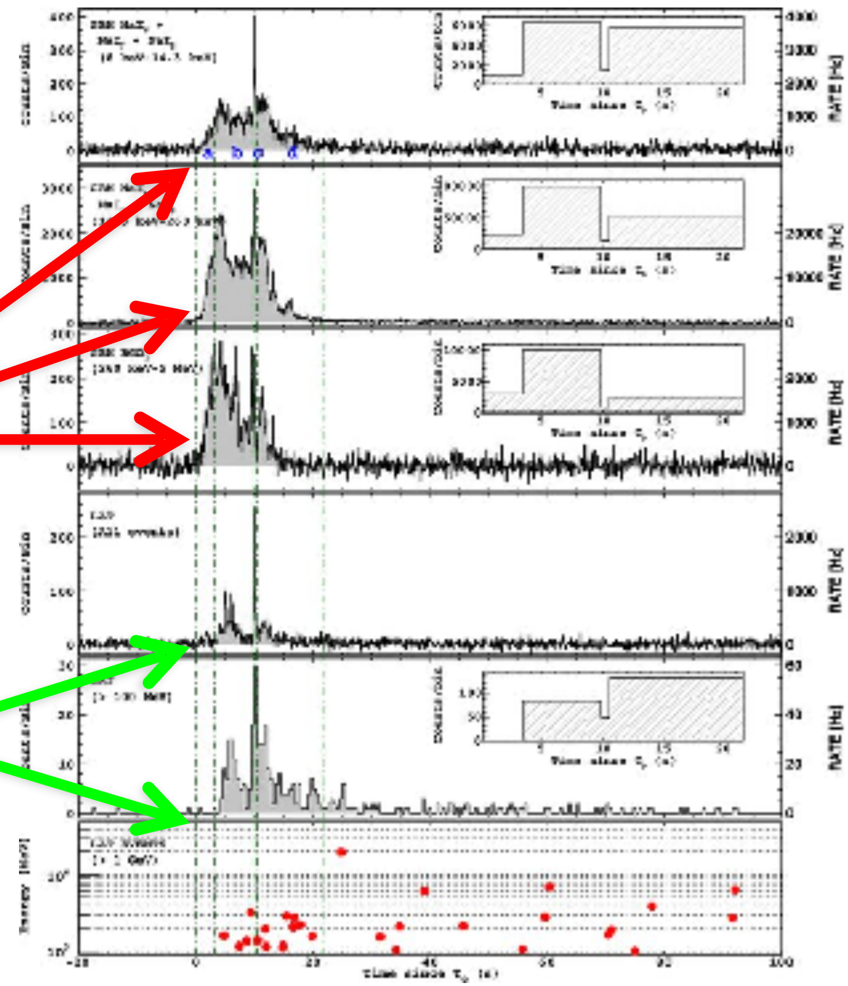
Guiriec et al. 2013, 2015, 2016

Common New Features in Fermi GRBs

- **LAT High-energy emission sometimes starts later the GBM low-energy emission**



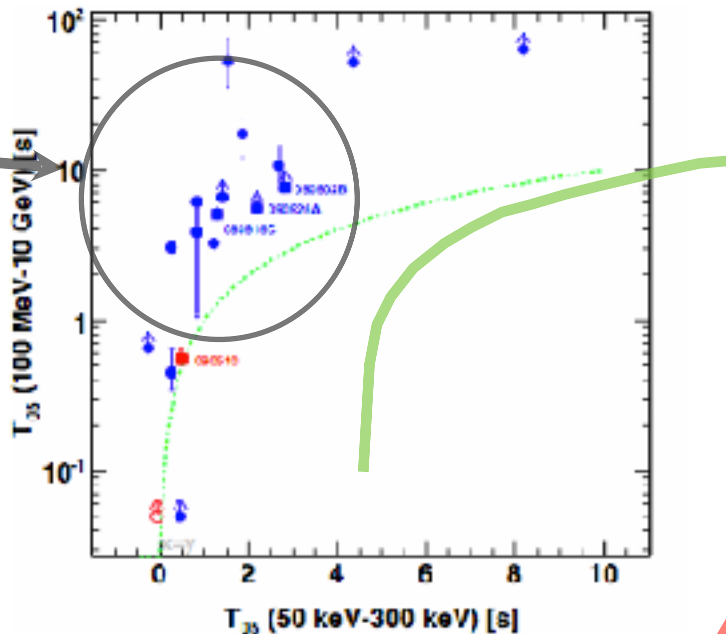
Credit: Nicola Omodei



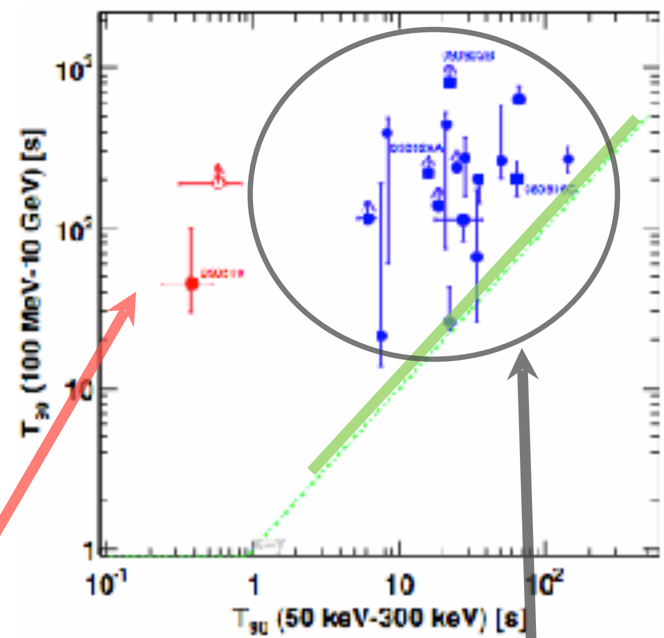
Ackermann et al. 2011, ApJ, 729, 114

Delayed High-Energy Emission

High-energy emission in the LAT is delayed from the emission in the GBM



Ackermann et al., 2013

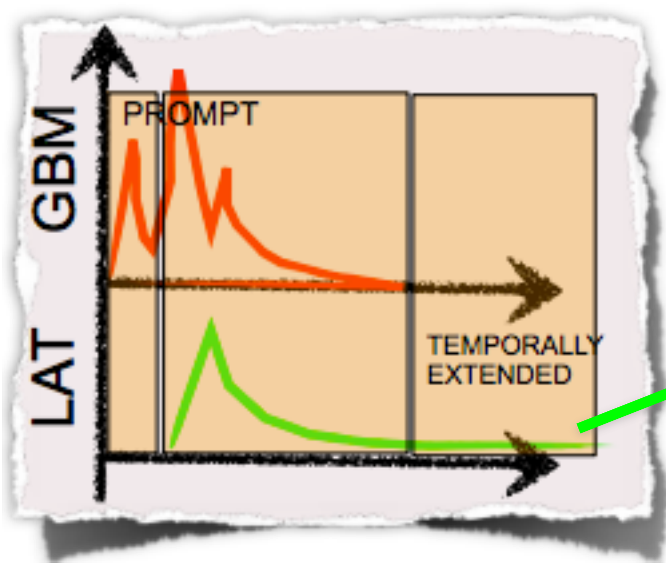


High-energy emission in the LAT also extends beyond the duration of the emission in the GBM

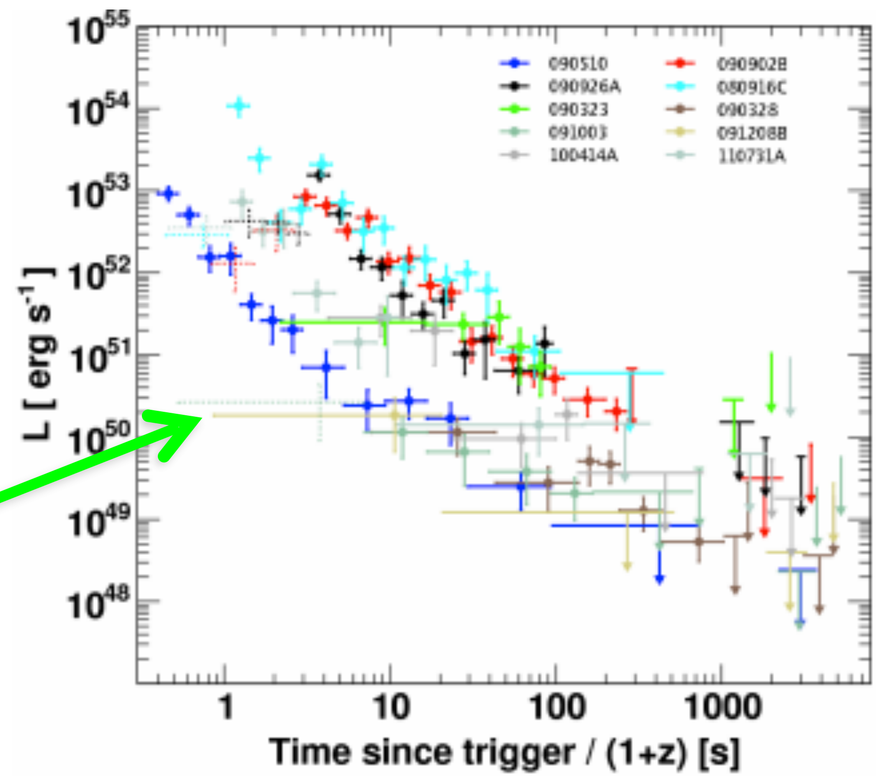
Short and Long GRBs show same extended emission behavior

Common New Features in Fermi GRBs

- **LAT High-energy emission sometimes lasts significantly longer then the GBM low-energy emission**



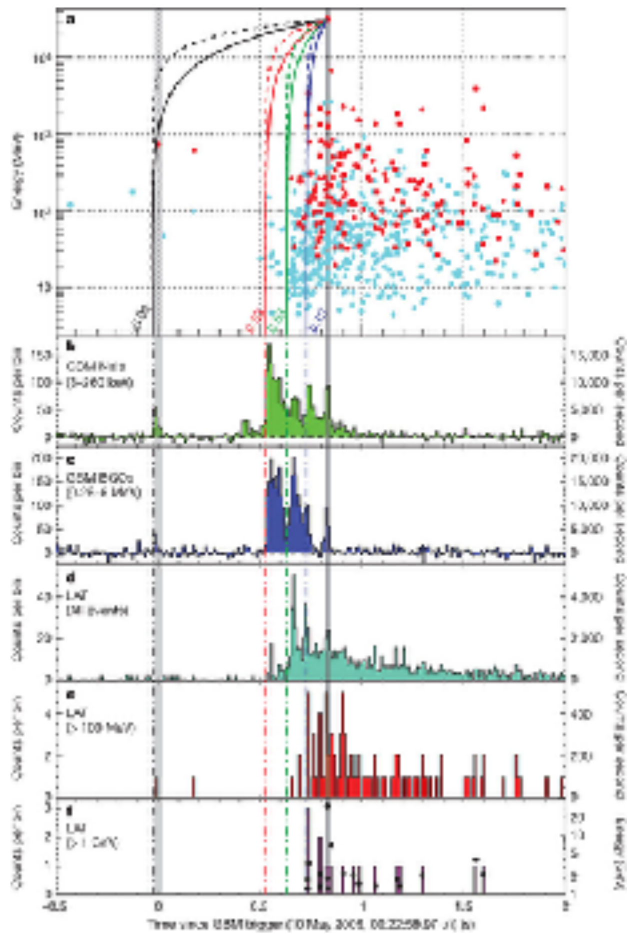
Credit: Nicola Omodei



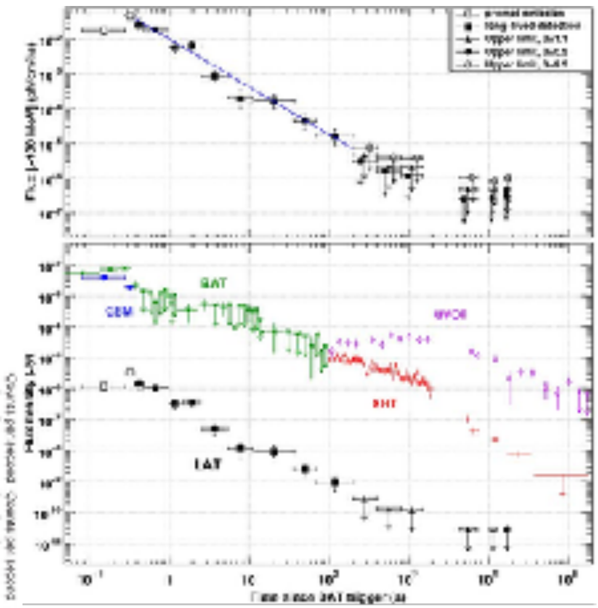
Ackermann et al. 2013, ApJS

GRB 090510
The Most Energetic Short GRB

- **Bright Short GRB z=0.903**
- **Co-detected by *Swift* & *Fermi***
- **First evidence of short GRB GeV afterglow**
- **LAT onboard trigger**
- **Lorentz Invariance Violation limits**
  - **measures consistency of speed of light**
  - **broad range of photon energies observed within short interval**
  - **eliminates some quantum gravity models**
  - **see Vasileiou et al. 2013**



Abdo et al. 2010

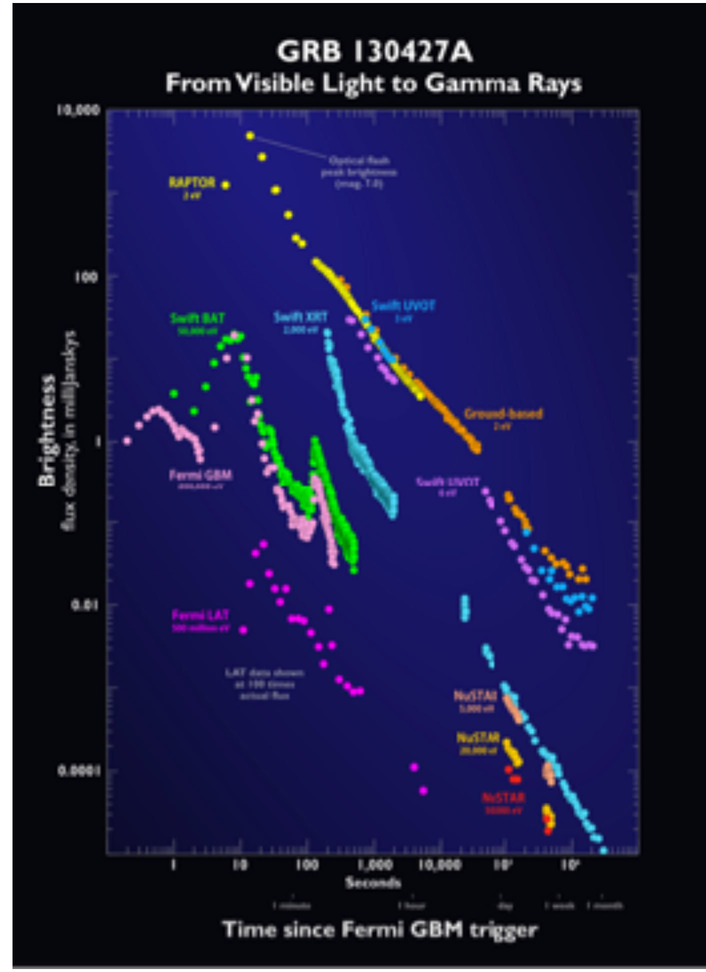


de Pasquale et al. 2010

Origin of Extended Emission

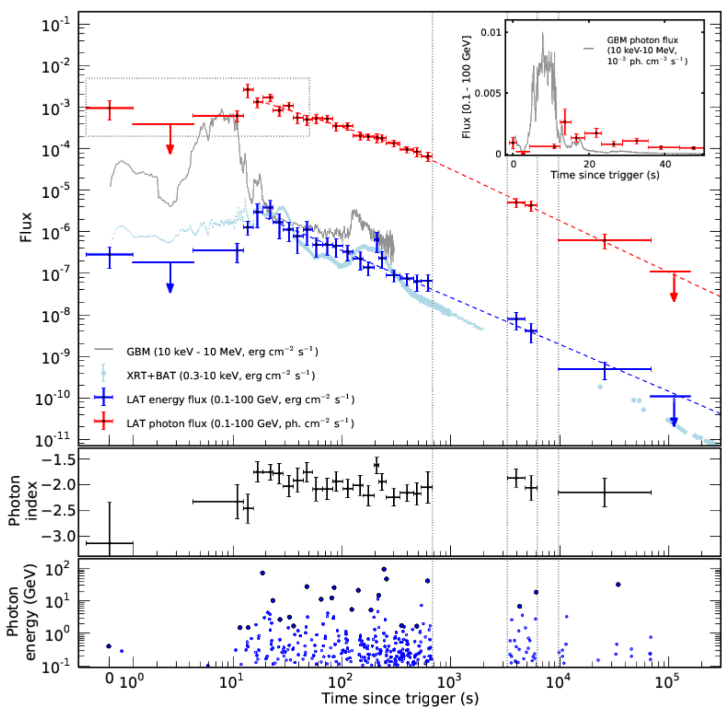
GRB 130427A

- Highest fluence GRB ever detected
- LAT emission lasted 20 hours
- Coincident trigger with Swift
- Bright (7.4 mag) optical flash
- Relative low redshift of 0.34
- Late-time afterglow emission consistent with single synchrotron spectrum
- Highest energy photon with 95 GeV at T0+244 s
- "Nearby Ordinary Monster"
- Really bright, but just normal burst like at cosmological distances, only nearby
- Lots of detailed observations, tons of papers

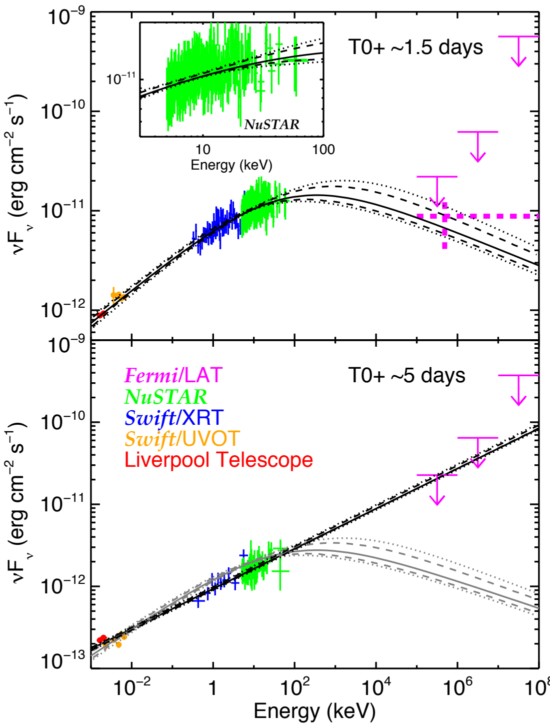


GRB 130427A Challenges
Synchrotron Shock Physics?

- **Single component from radio to GeV strongly suggests Synchrotron origin, and no secondary SCC or IC component**
- **High energy photons violate maximum Synchrotron energy**

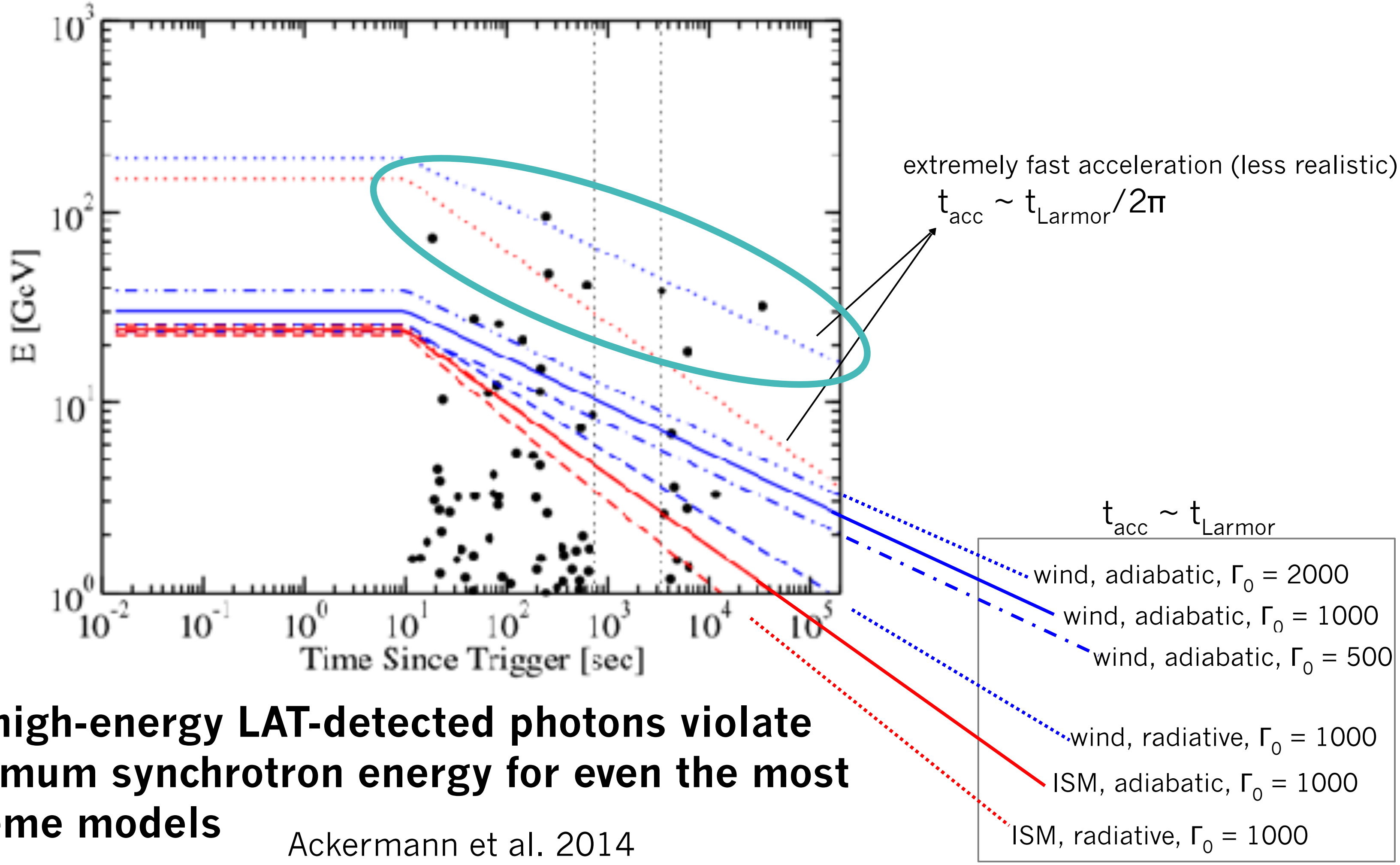


Ackermann et al. 2014



Kouveliotou et al. 2013

GRB 130427A Challenges Synchrotron Shock Physics?

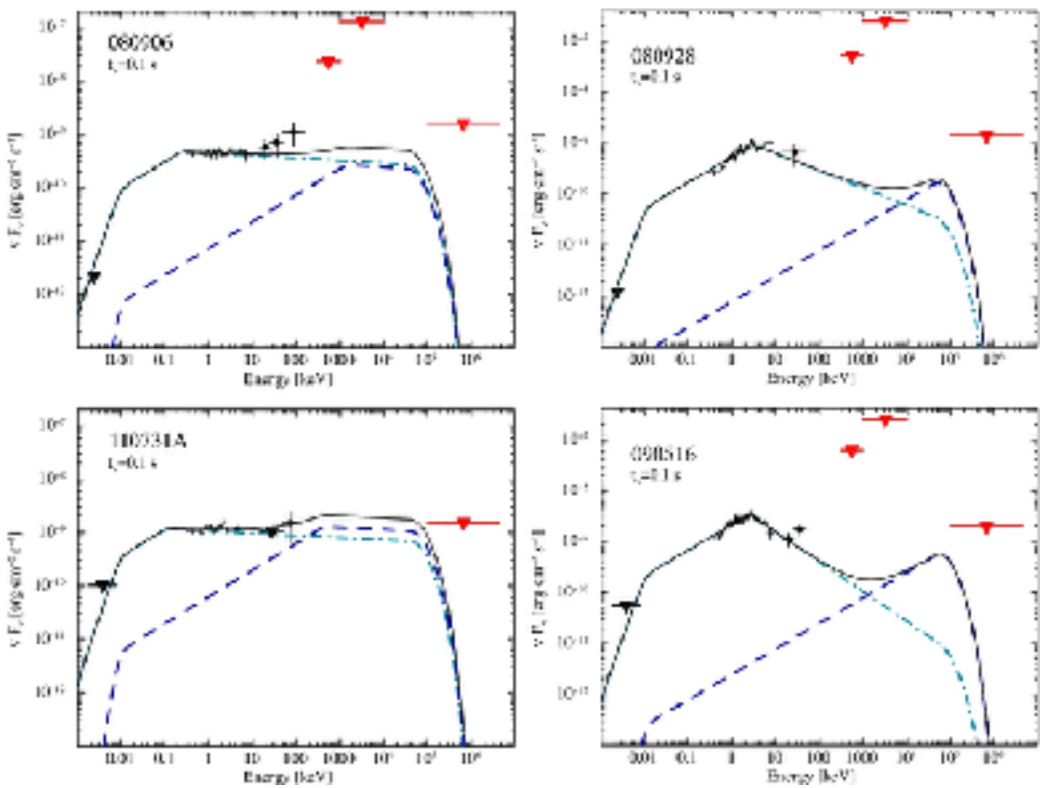


The high-energy LAT-detected photons violate maximum synchrotron energy for even the most extreme models

Ackermann et al. 2014

X-ray Flares and GeV Emission

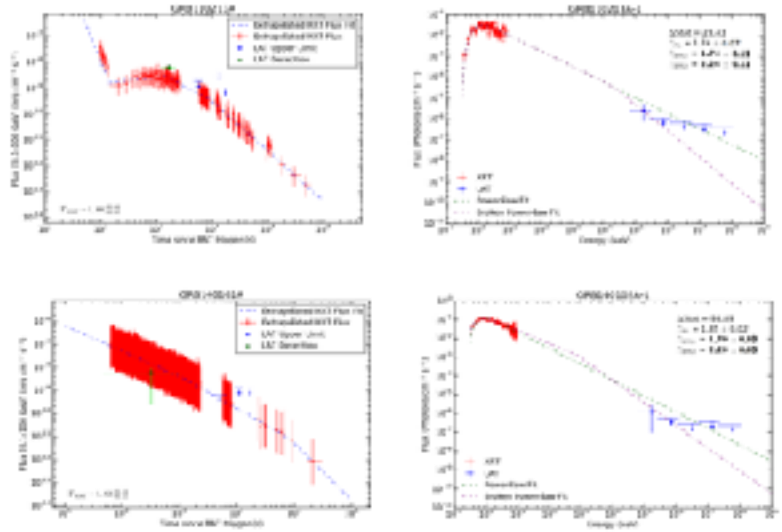
- No optical/gamma-ray flares during X-ray flares
- Disfavors inverse Compton origin of flares
- Favors late internal shock origin (Γ > 50 outflow at $R \sim 10^{13}$-10^{14} cm)
- Troja et al. 2015

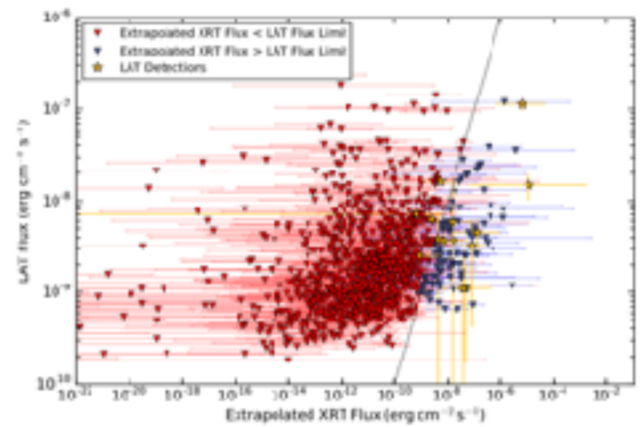


Troja et al. 2015

Origin of GeV Afterglows

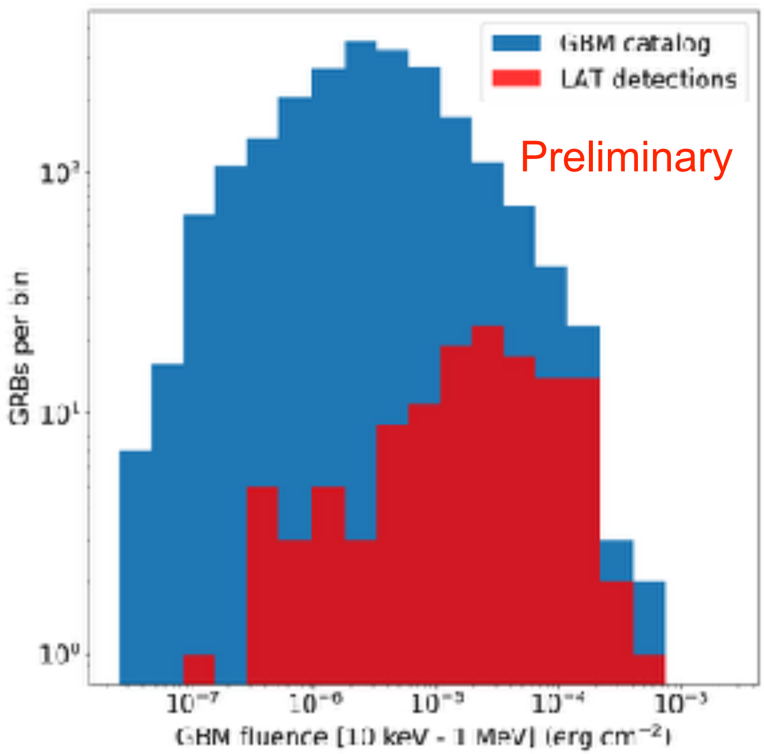
- Extrapolating XRT spectra/ lightcurves into GeV band to compare with LAT
- Fit either power laws or broken power laws (with delta of 0.5 for cooling break)
- No evidence of additional spectral component - no dominant SSC component in 100 MeV - 10 GeV range
- Lack of movement of cooling break hints that LAT GRBs may be preferentially in low-density wind-like environments
- Ajello et al. 2018 (submitted, contact authors Kocevski & Racusin)

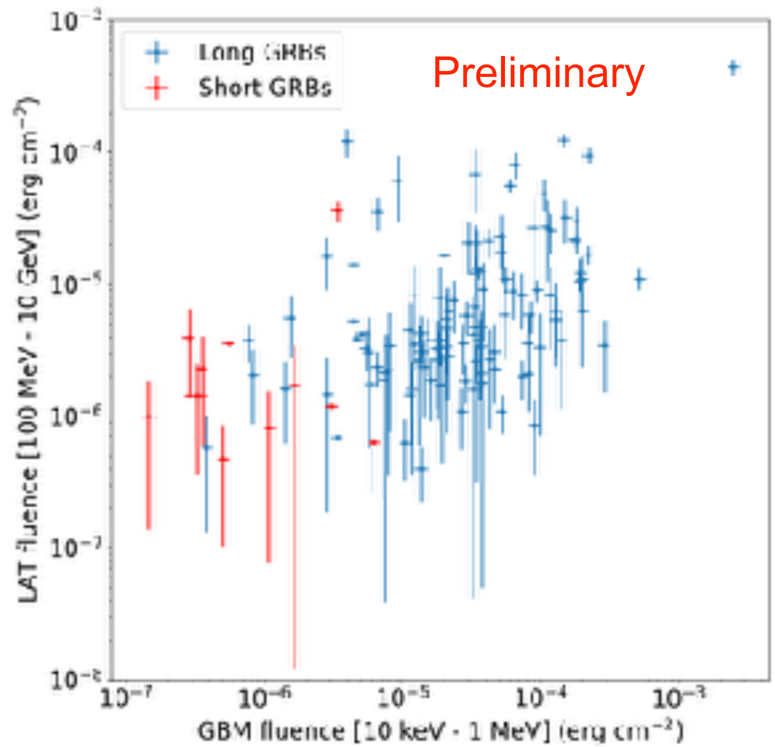




2nd LAT GRB Catalog (in-preparation)

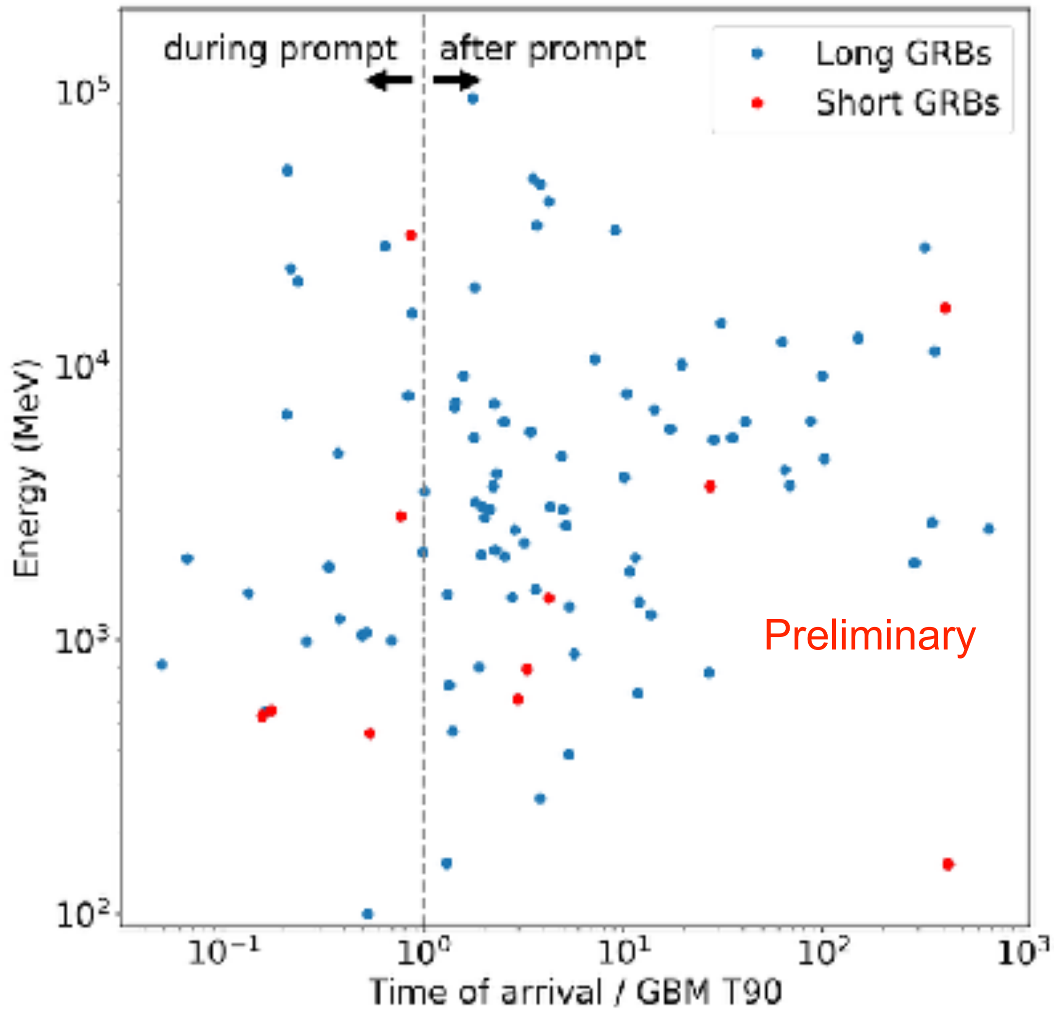
- ~150 GRBs in catalog
- Sample defined and validated
- Characterization and analysis ongoing





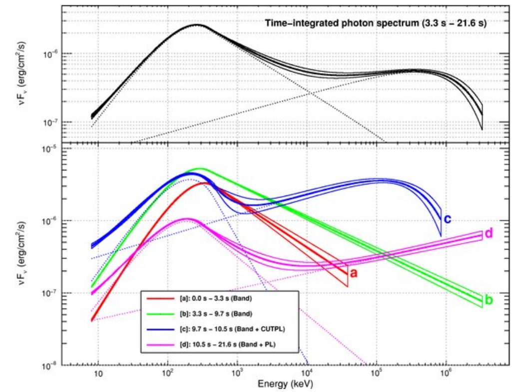
2nd LAT GRB Catalog (in-preparation)

- **Most high-energy photons come from the afterglow, not prompt emission**

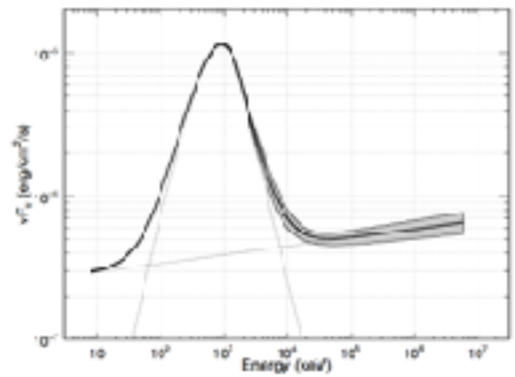


Origin of GeV emission

- **Leptonic: inverse-Compton (or synchrotron self-Compton)?**
  - **Hard to produce a delayed onset longer than spike width**
  - **Hard to account for the different photon indices of the HE component & the Band spectrum at low energies**
  - **Hard to produce a low-energy power-law**
- **Hadronic: (pair cascades, proton synchrotron)?**
  - **Late onset: time to accelerate protons+develop cascades?**
  - **Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset)**
  - **Synchrotron emission from secondary e^+/e^- pairs can naturally explain the power-law at low energies**



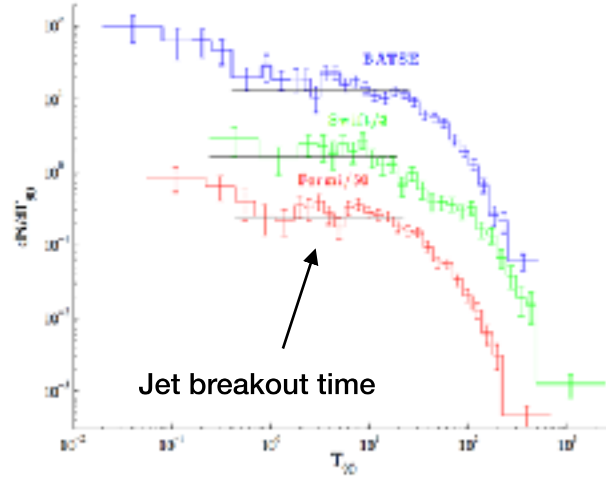
Ackermann et al. 2011



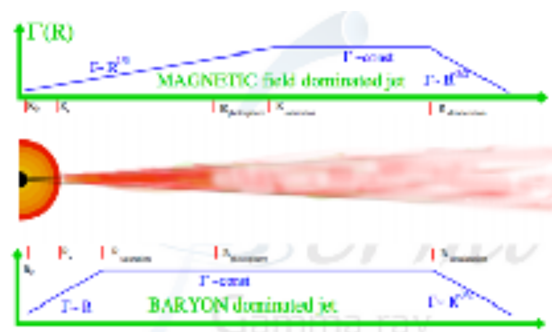
Abdo et al. 2009

Magnetic vs Baryon Dominated Jets

- **Baryon dominated**
  - Gravitational energy (from explosion) converted to thermal pressure driving acceleration to relativistic velocities
  - Some thermal photons released at photosphere
  - Rest converted to kinetic energy driving internal shocks
- **Magnetic dominated**
  - Magnetic energy from blastwave converted to particle and radiation energy
  - Requires magnetic field remain high as it expands which is hard to make stable
- **Reality is probably some combination**
- **Polarization measurements would help**



Bromberg et al. 2014



Veres, Zhang, Meszaros 2013, credit: Peter Veres

Recent review: Zhang 2014

Other Topics in Fermi GRB Studies

- Cutoffs in prompt spectra
- Bulk Lorentz factors inferred from highest energy photons
- High-energy photons from GRBs with known redshifts helps constrain the Extragalactic Background Light (EBL)
- Gravitational Wave Counterparts (see talk Monday)