Fermi Observations of Gamma-ray Bursts and Gravitational Wave Counterparts

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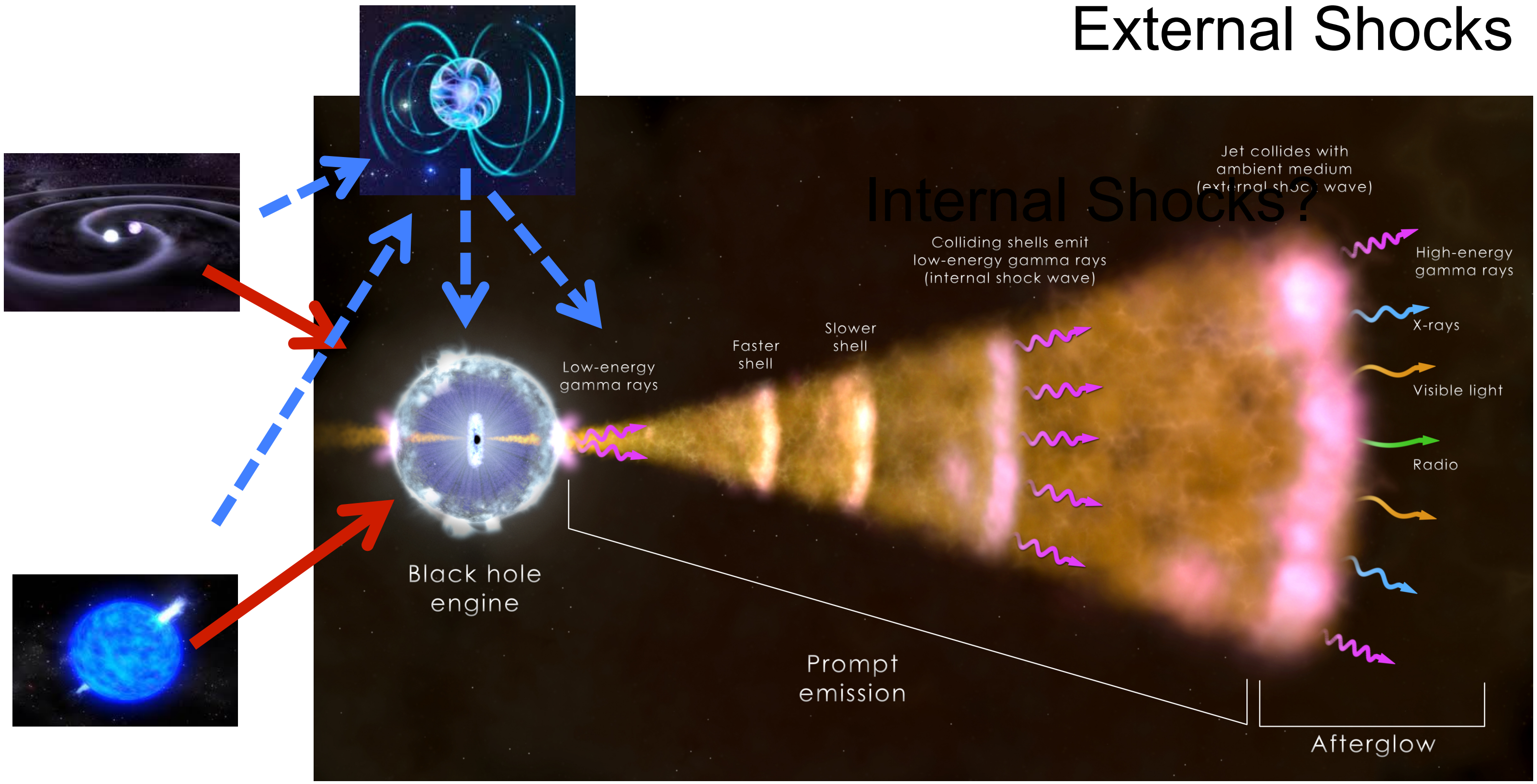
on behalf of the Fermi Large Area Telescope Collaboration

GRB Formation

Newly Formed Magnetar?

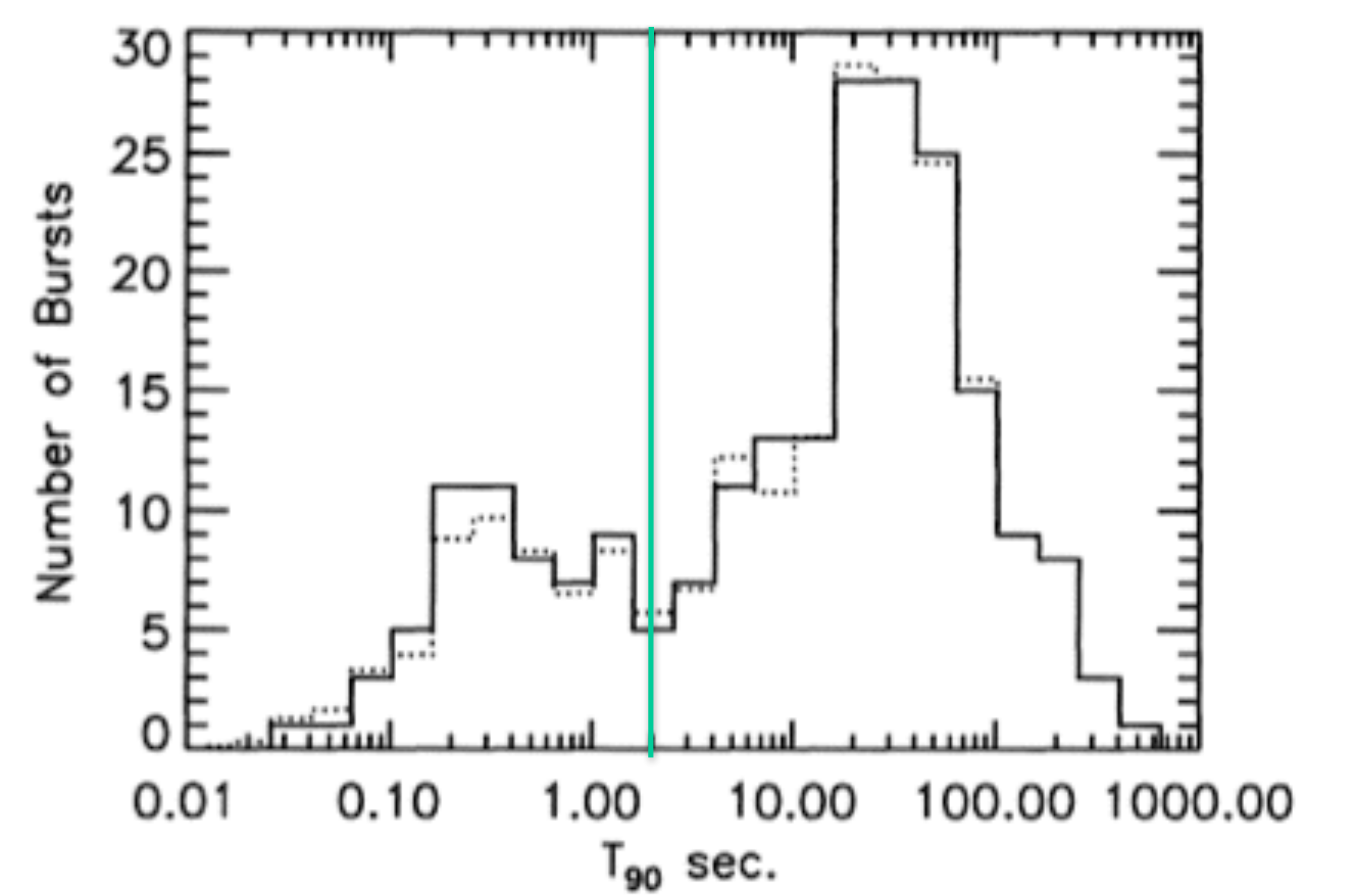
External Shocks



GRB Progenitors

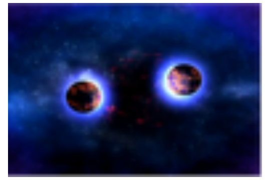
Binary Neutron Star Merger

Collapse of Massive Star

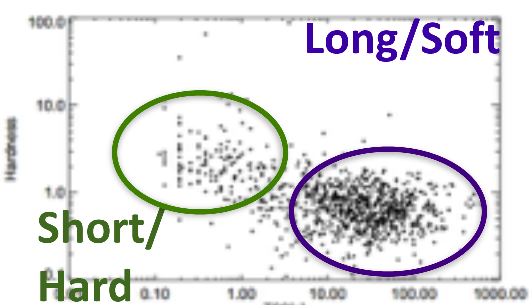


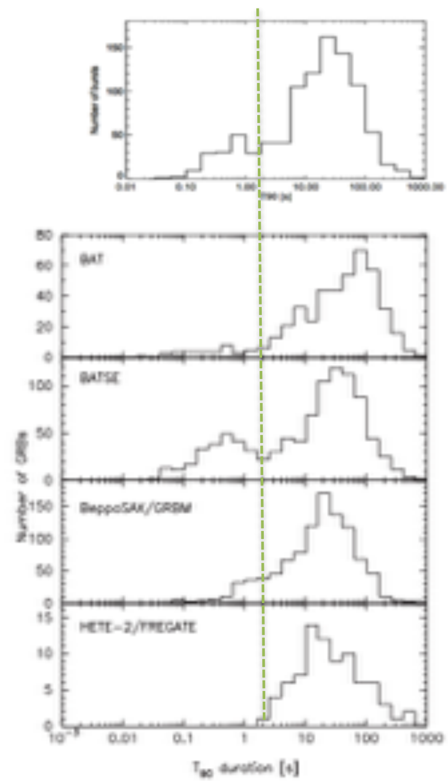
GRB Categories

Short Hard GRBs



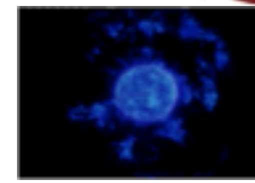
- Harder Spectra
- $T_{90} < 2$ s
- Associated with old stellar populations on outskirts of old galaxies
- Consistent with picture of Neutron star – Neutron star merger or Neutron star – blackhole merger





von Kienlin et al. 2014

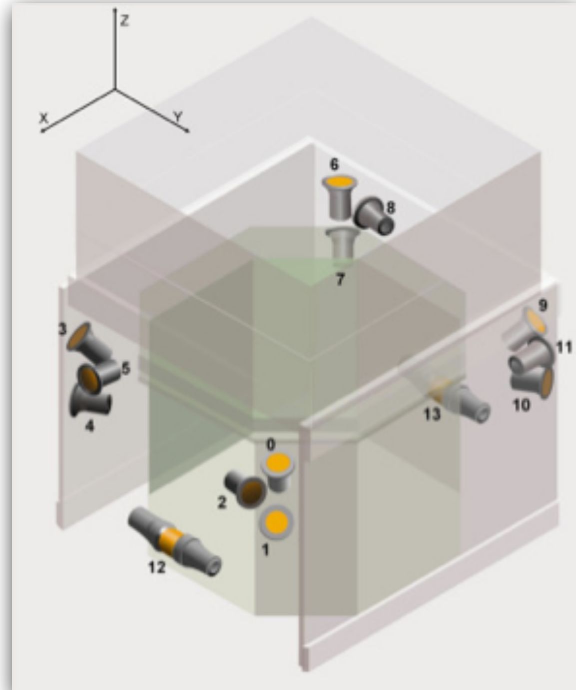
Long Soft GRBs

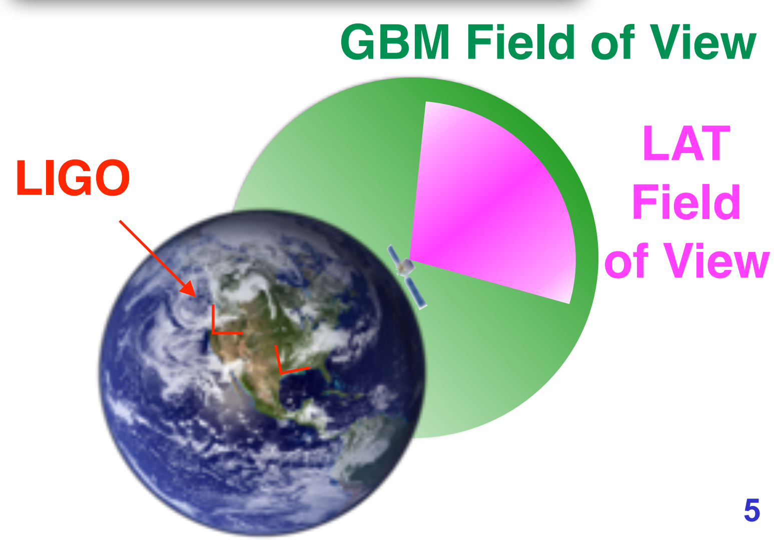


- Softer Spectra
- T90 > 2 s
- Associated with young stellar populations in star forming regions
- Consistent with picture of massive star collapsing into blackhole
- Associated supernovae

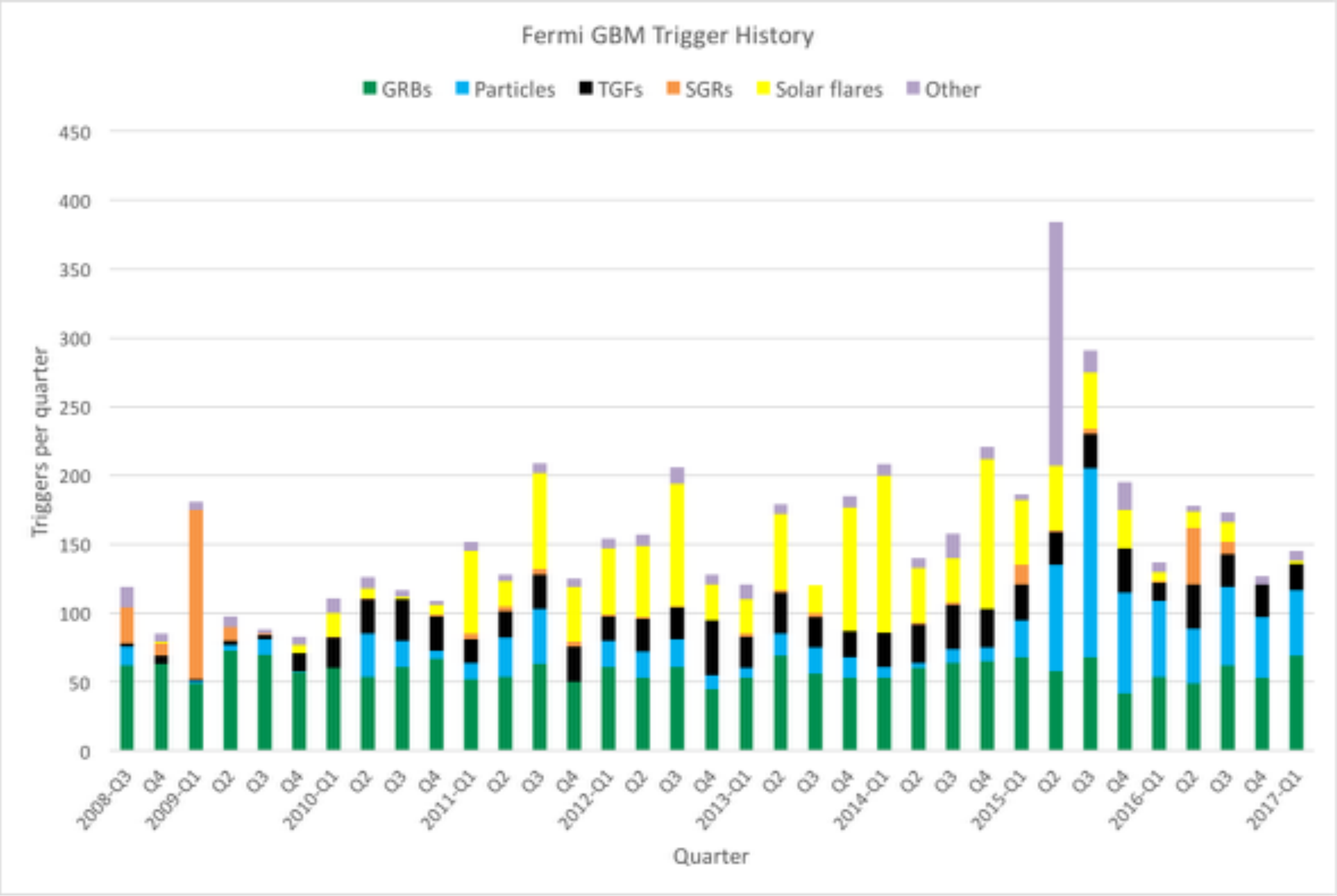
Gamma-ray Burst Monitor (GBM)

- 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

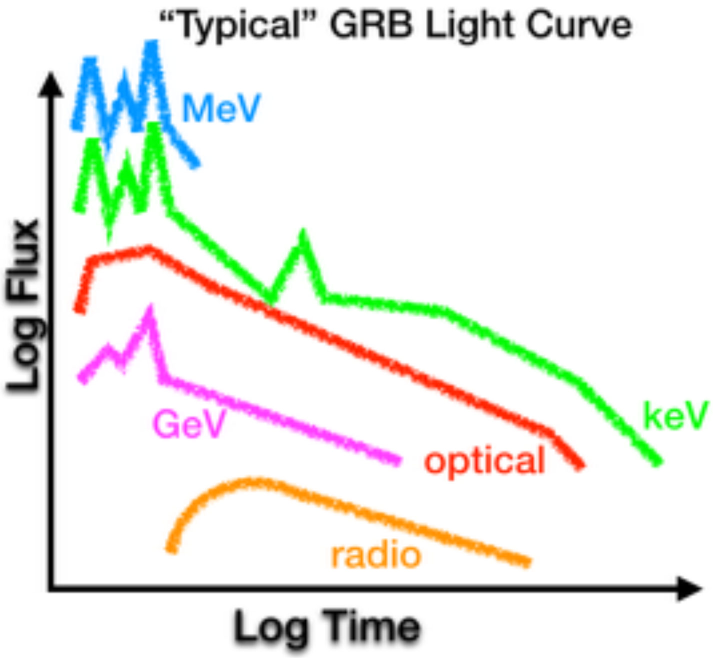


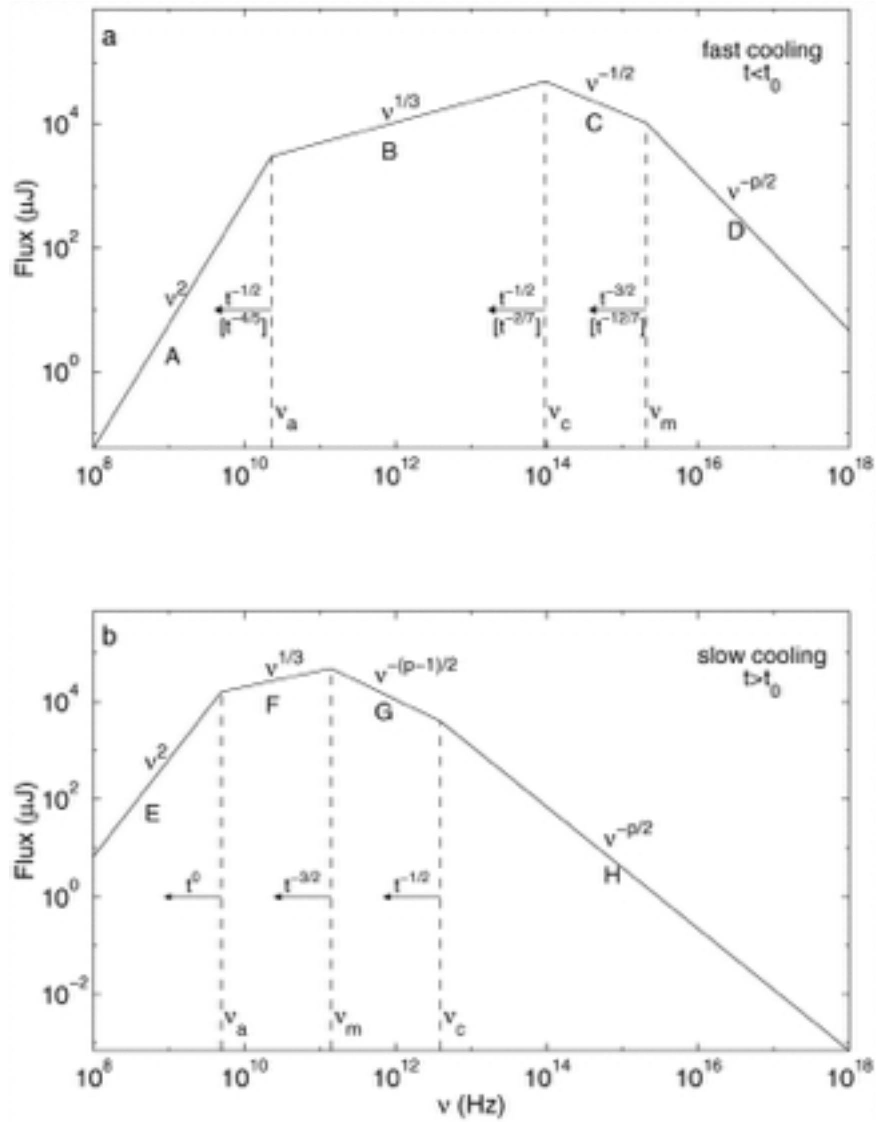


GBM Triggers



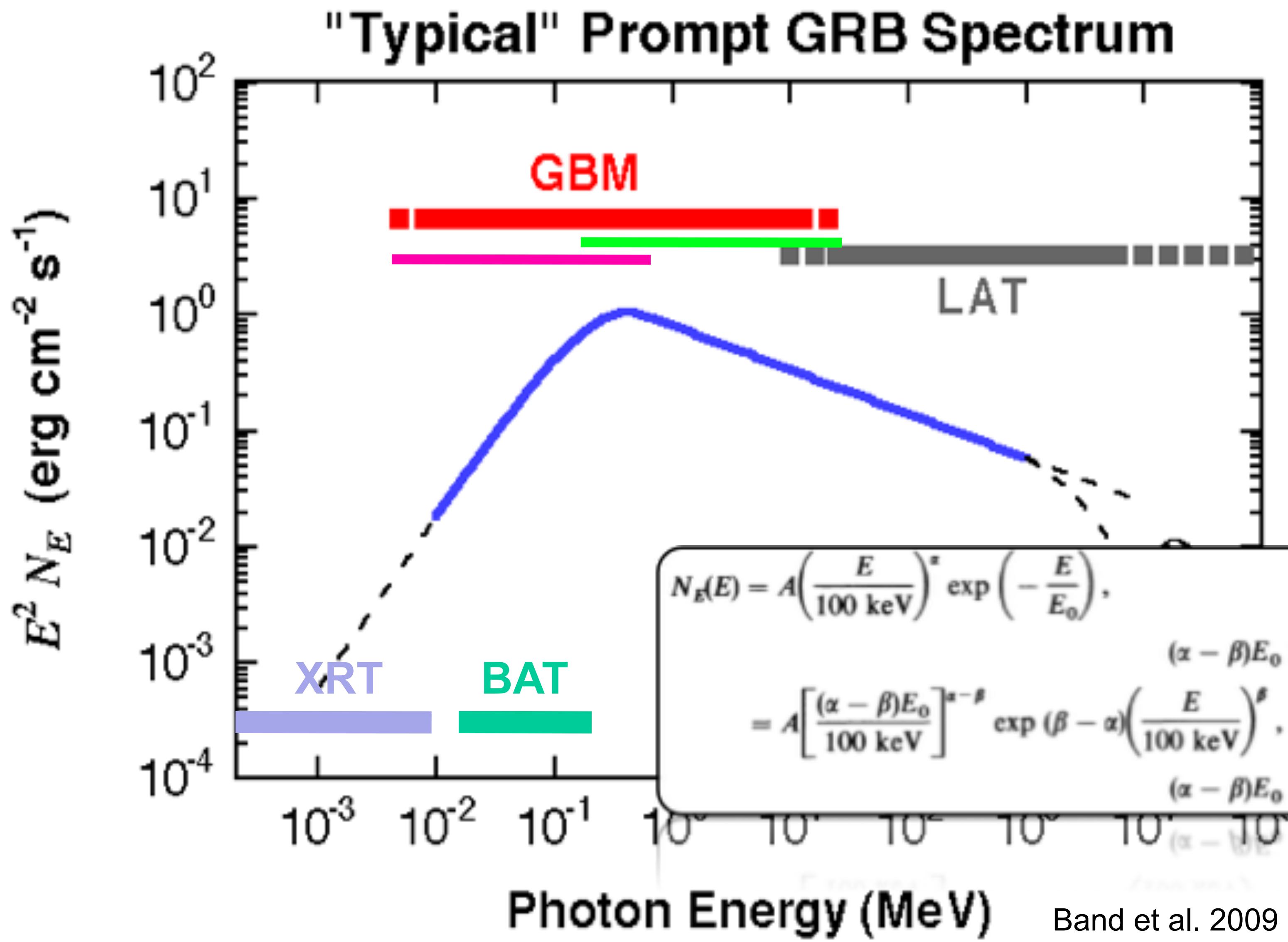
Broadband Observations of GRBs





Sari 1998

How does Fermi add to our understanding of GRBs?



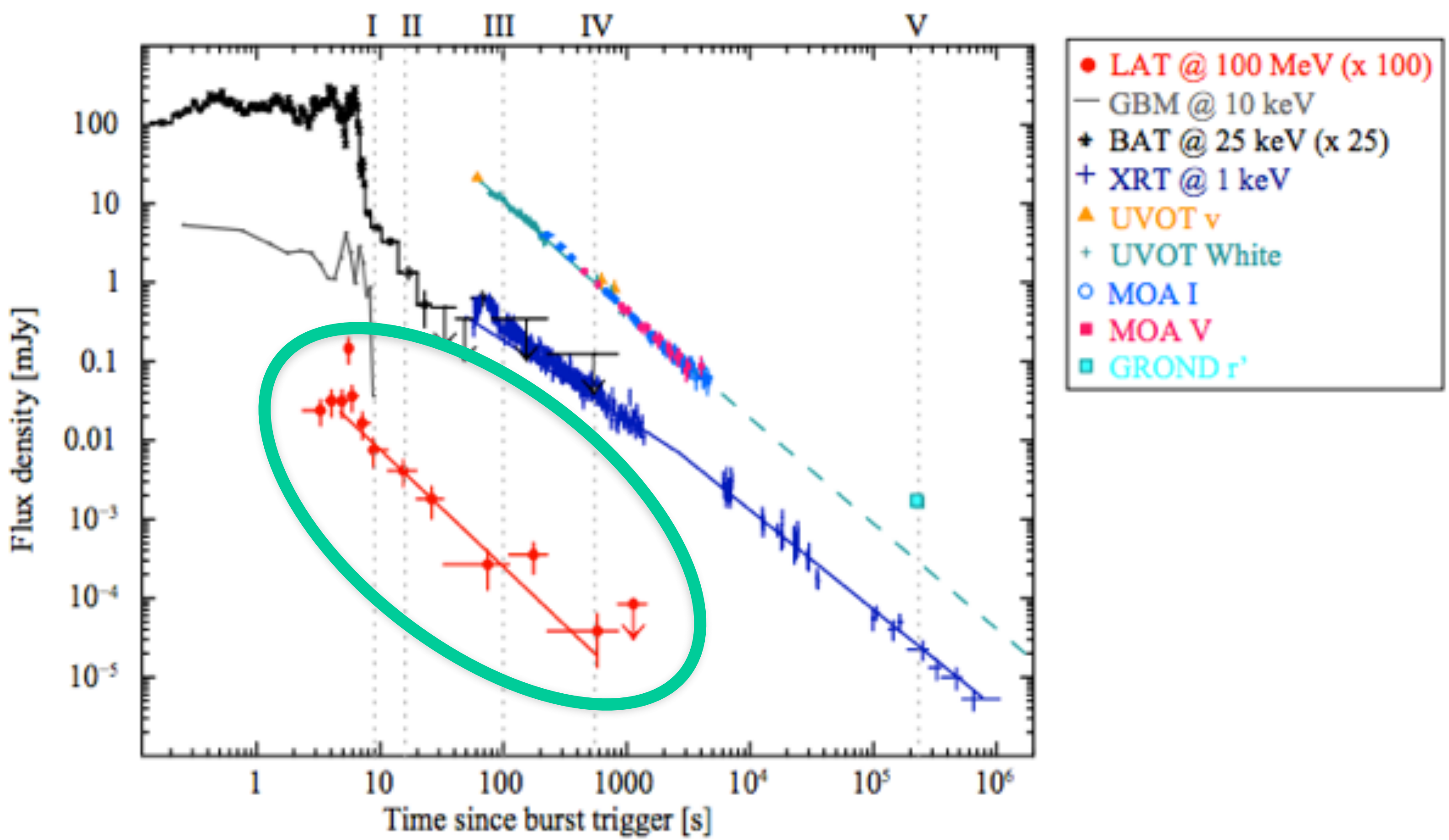
$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \quad (\alpha-\beta)E_0 \geq E,$$

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

Band et al. 2009

How does LAT add to our understanding of GRBs?

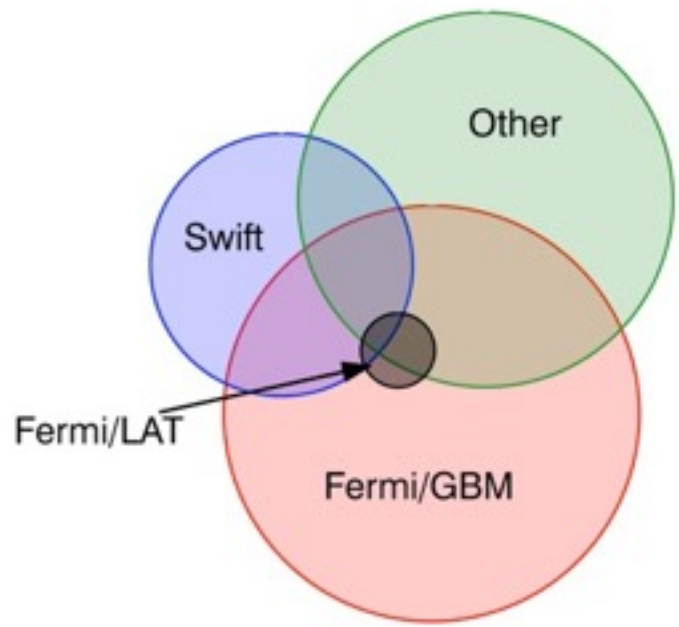
GRB 110731A



Ackermann et al 2012

Fermi GRB Observations

- **Including bursts from Aug 2008-May 2017**
  - **~900 Swift GRBs**
  - **~2100 Fermi-GBM GRBs**
  - **~134 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**

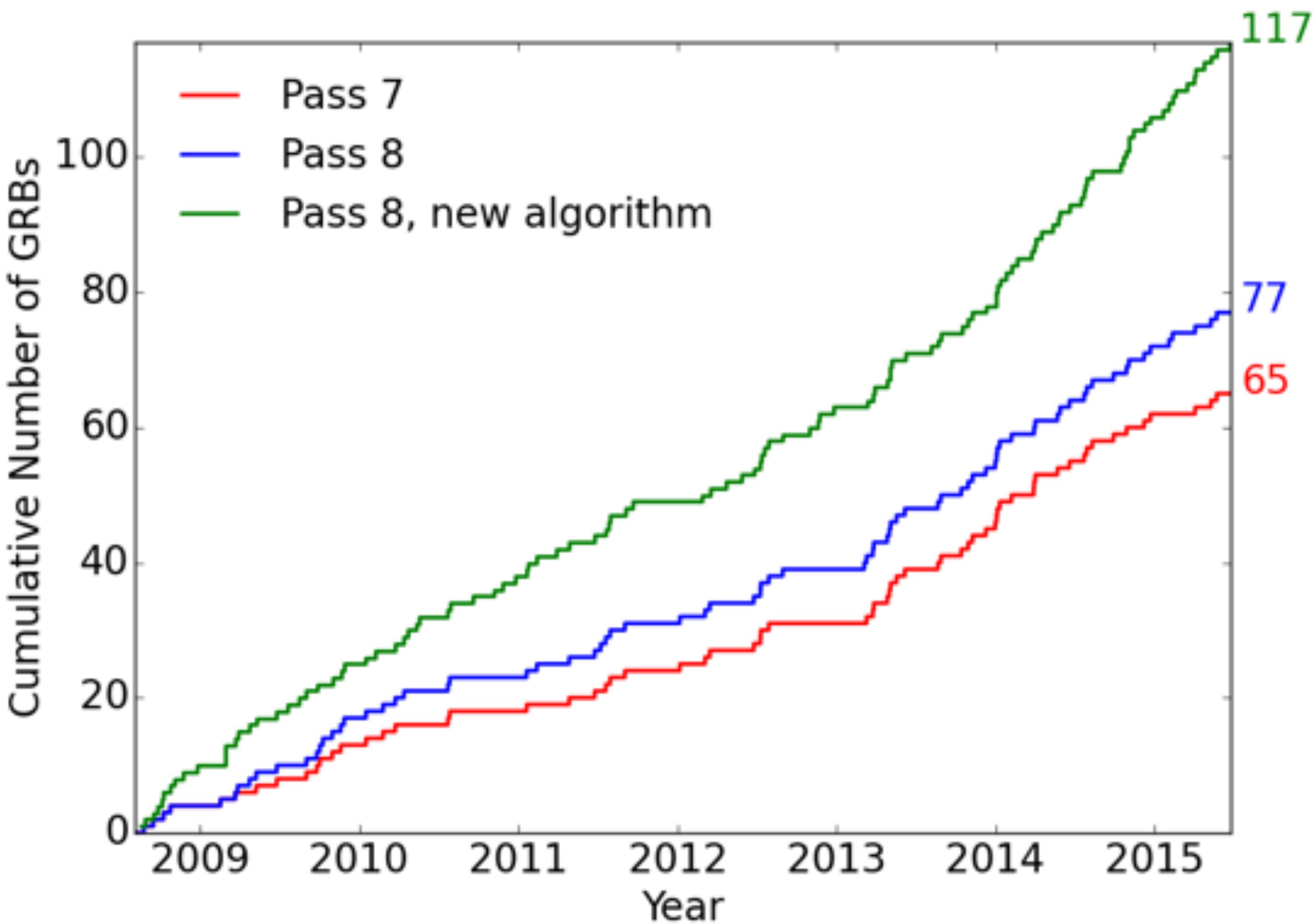


Credit: A. Goldstein

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

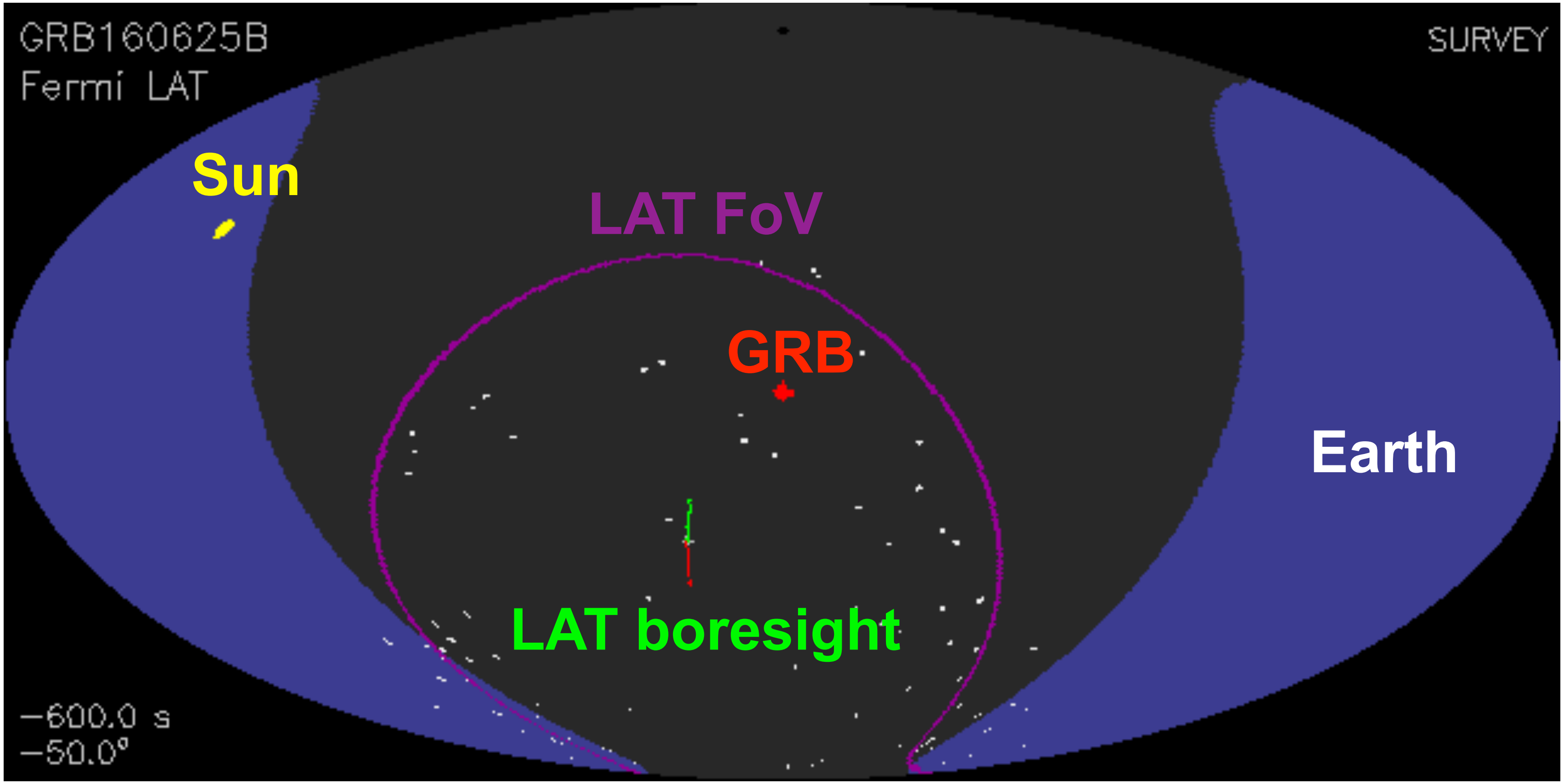
LAT GRB Detections



Fermi GRB Observations

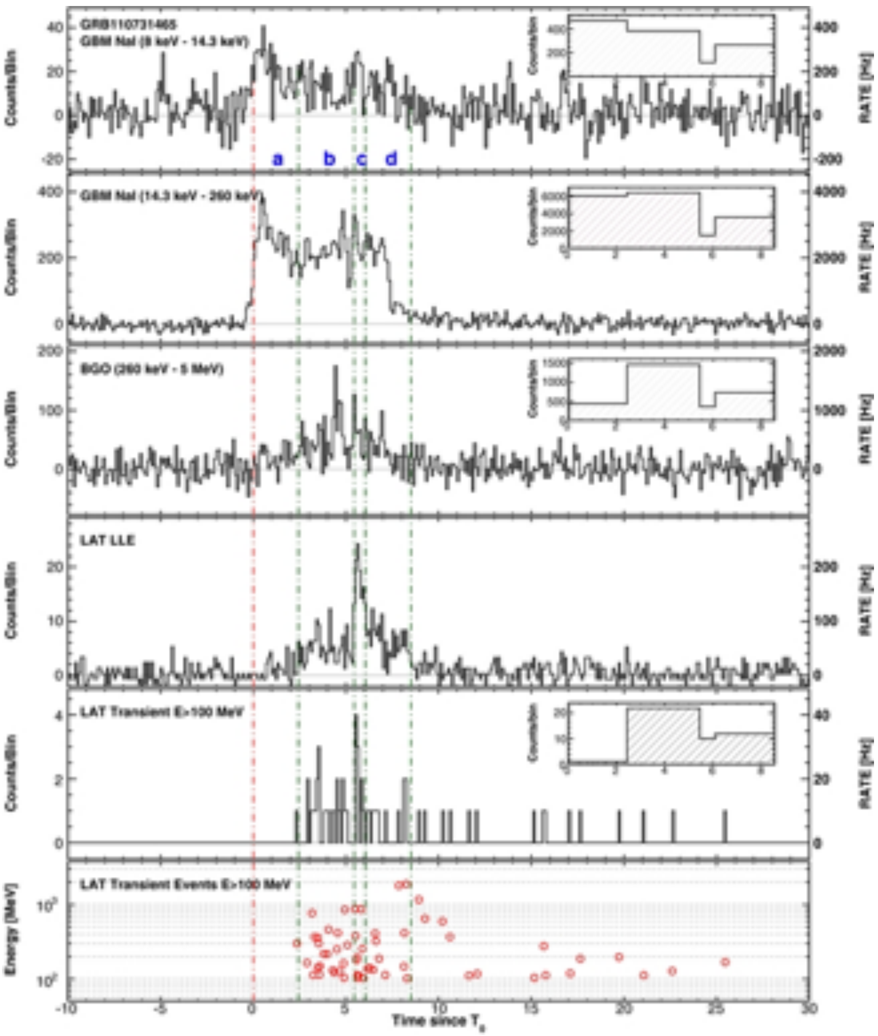
- **LAT observations begin**
  - Rare onboard triggers (GRBs 090510, 131108A, 160509A, 160625A, 160821A) of GRBs with bright short spikes
    - provides prompt ~0.5 deg localizations - good enough to initiate follow-up
    - refined localizations from ground analysis later
  - Most detections found via 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

Autonomous Repoint Towards a GRB

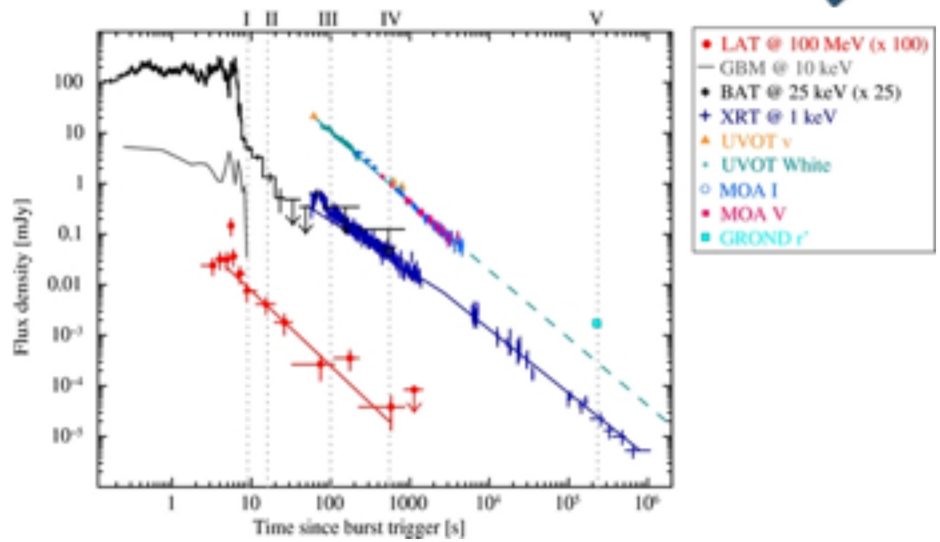


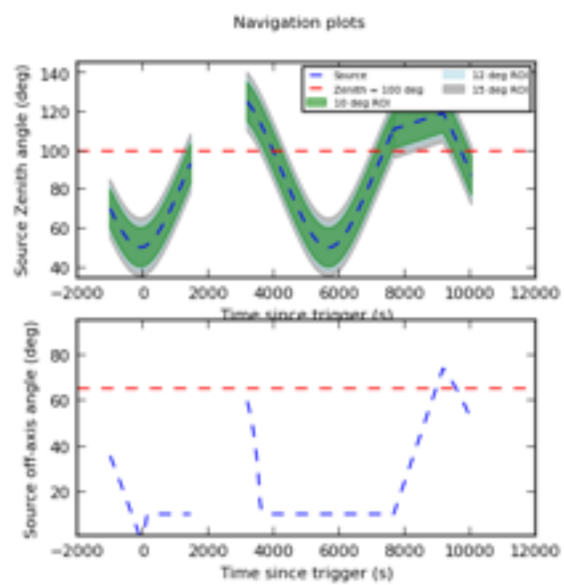
Fermi Observations of a GRB

GRB 110731A



Ackermann et al. 2012

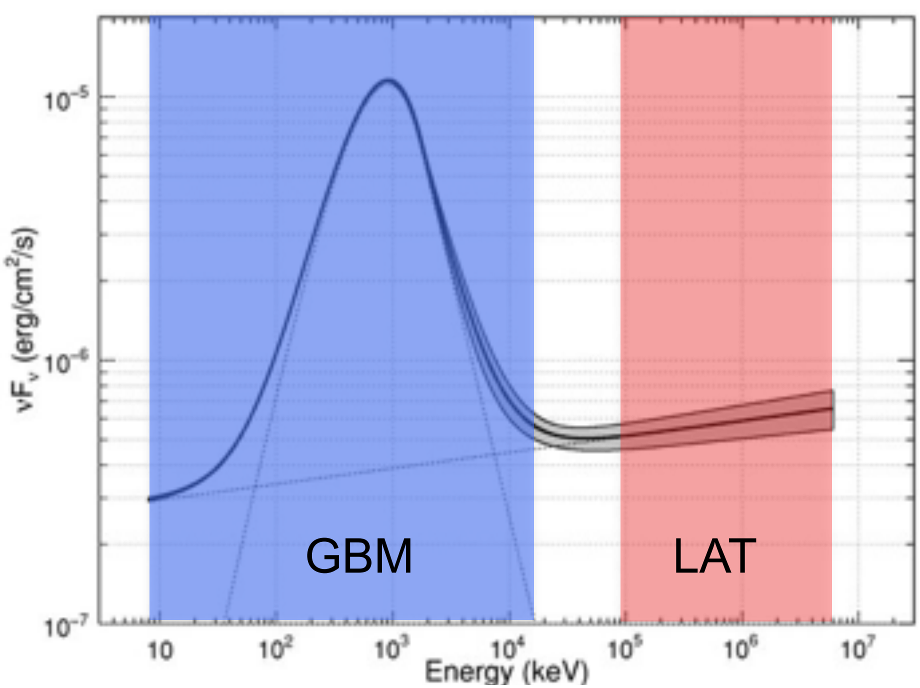




Common New Features in Bright Fermi GRBs

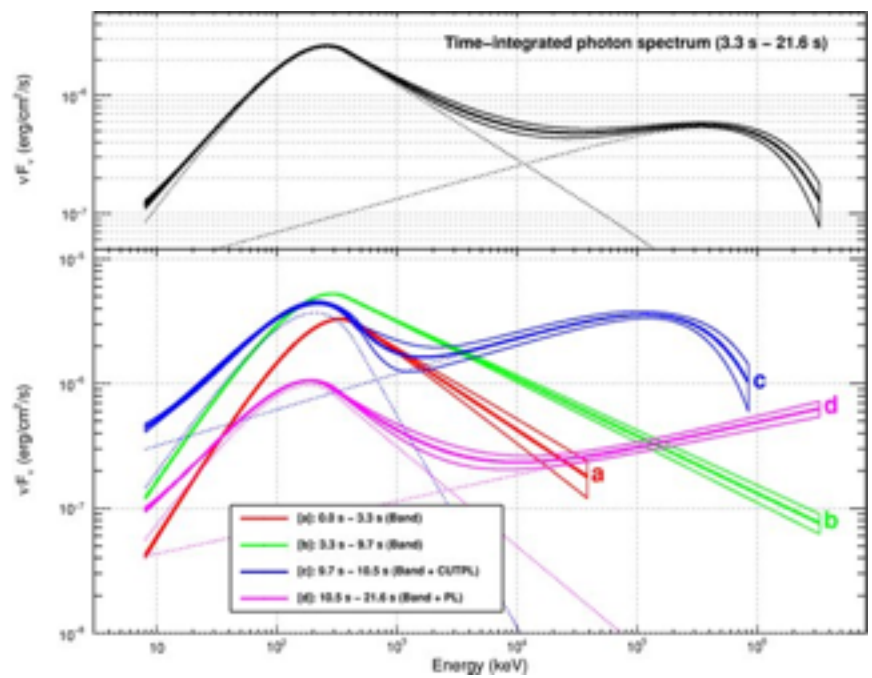
- **GRB spectra deviate from Band functions**
  - **Low energy deviation**
  - **Additional power law at high energies**
  - **High energy cut-offs is some cases**

GRB 090902B



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

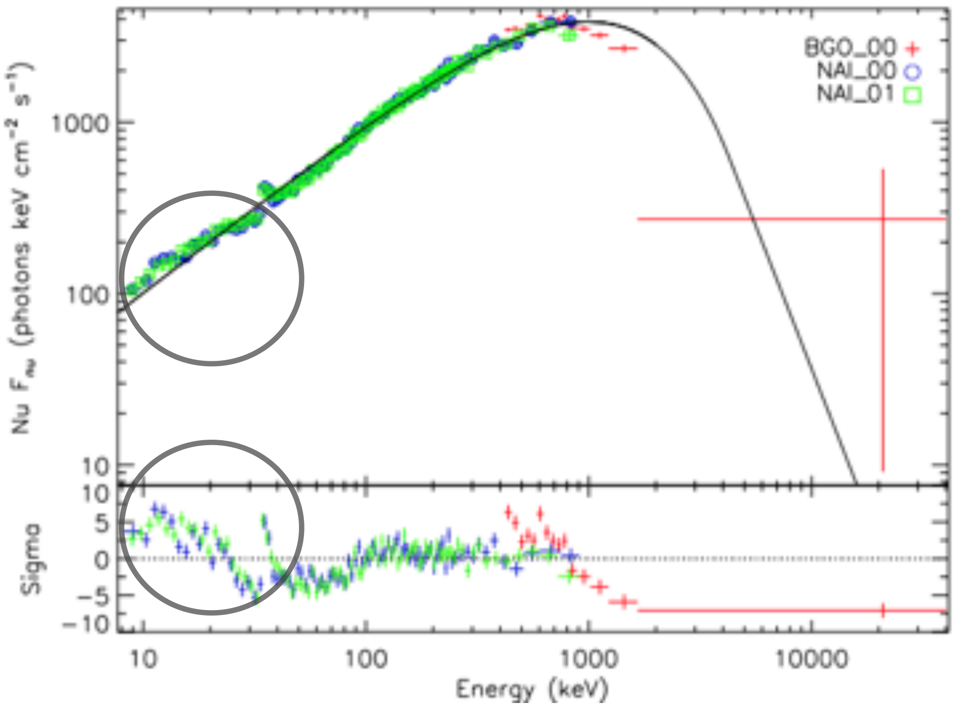
GRB 090926A



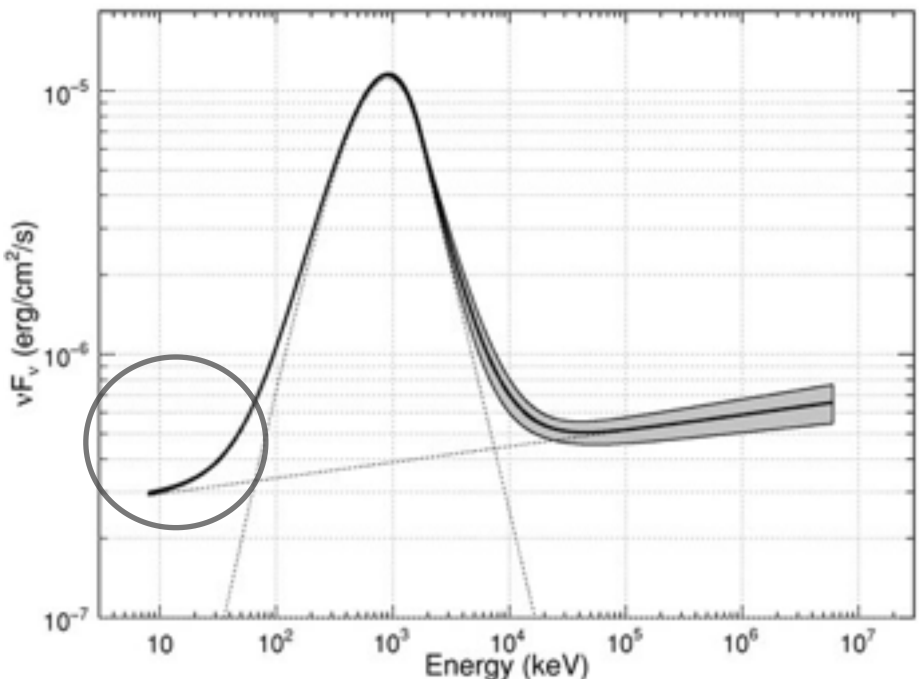
Ackermann et al. 2011, ApJ, 729, 114
Yasine et al. 2017

Low-Energy Excess

GRB 090902B



Tierney et al. 2013

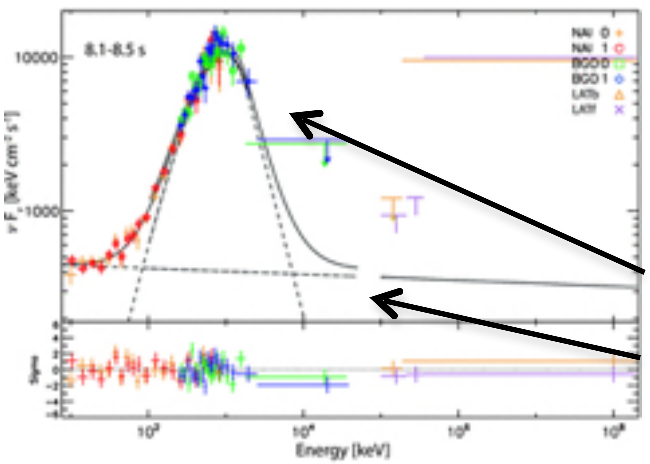


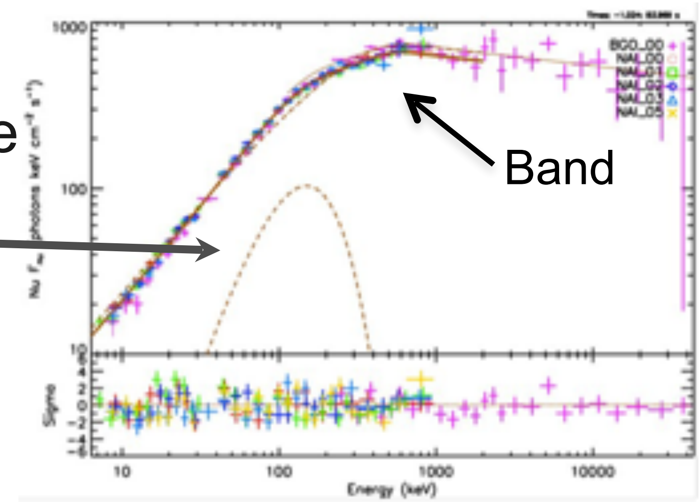
Abdo et al. 2009, ApJL 706, 138

Thermal Emission - Photospheric?

GRB 100724B

GRB 090902B



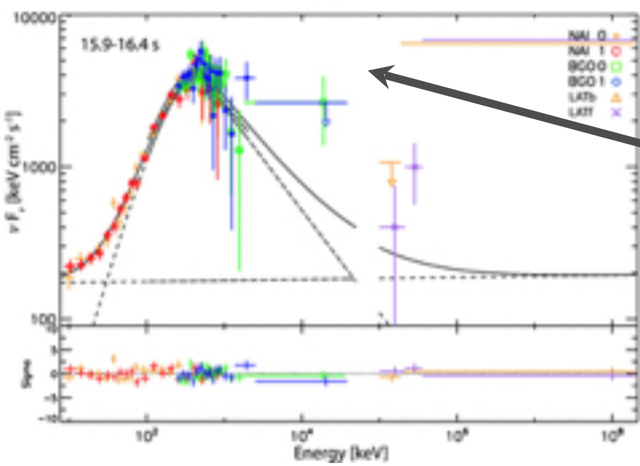


Sub-dominate Blackbody

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

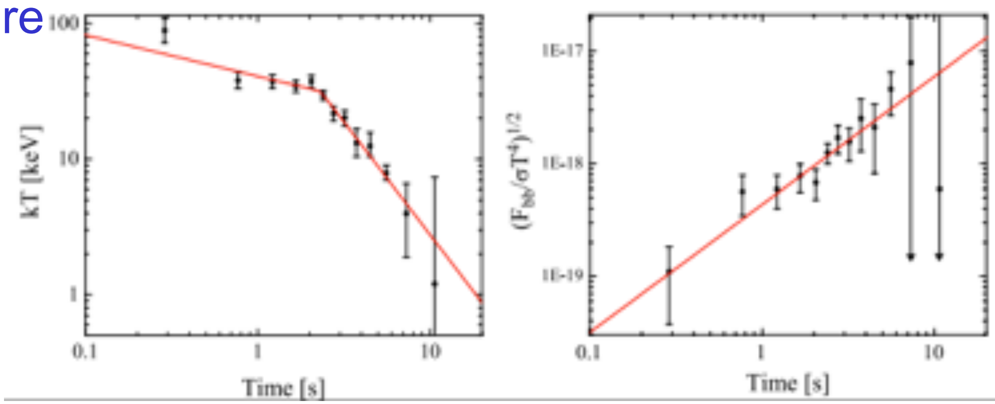
Photospheric Emission

- 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

Evolving blackbody temperature

GRB 110721A

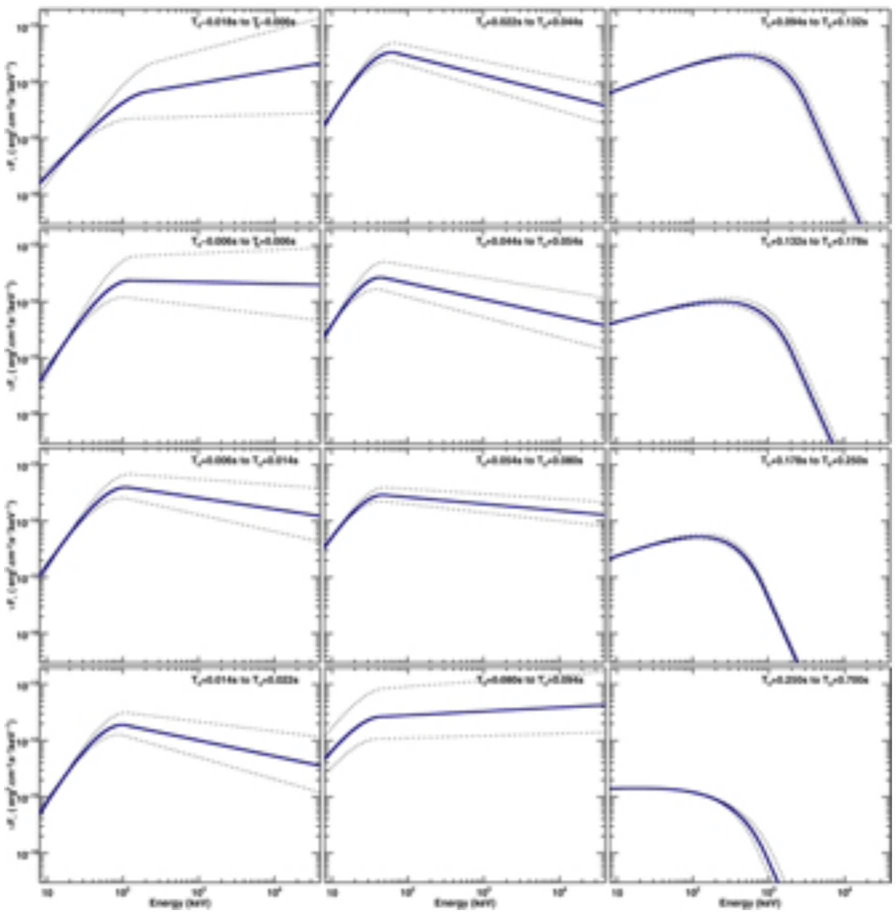
Evolving blackbody normalization



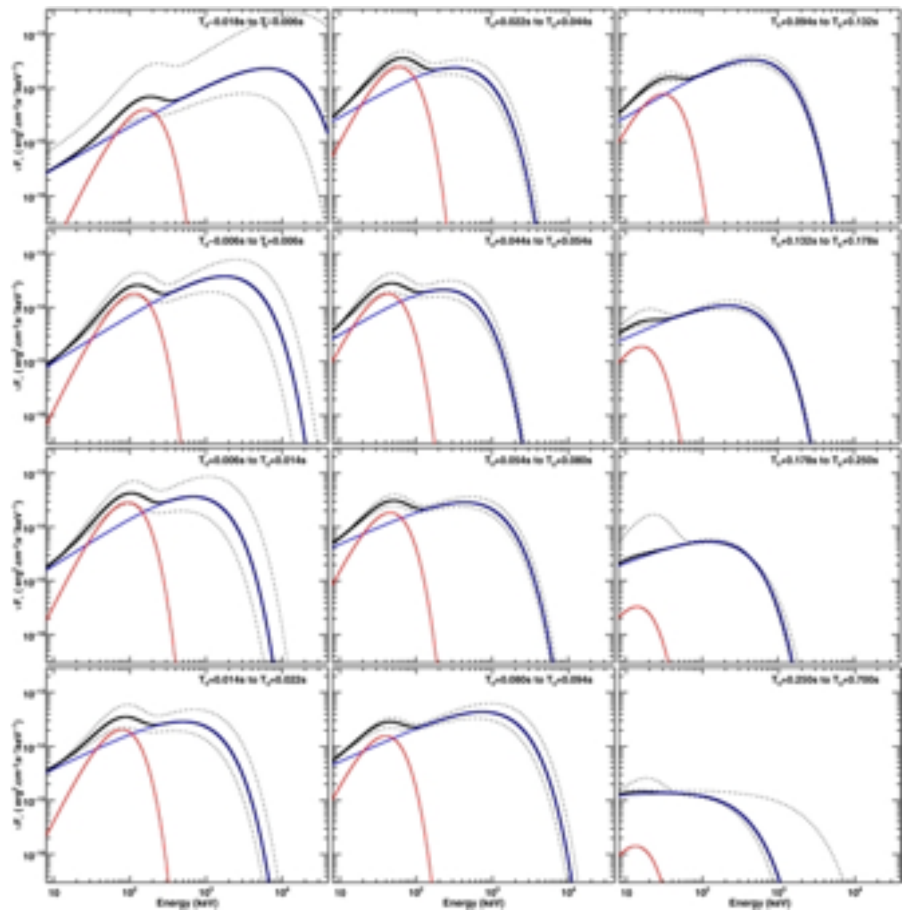
Axelsson et al. 2012

Photospheric Emission

Band only fits



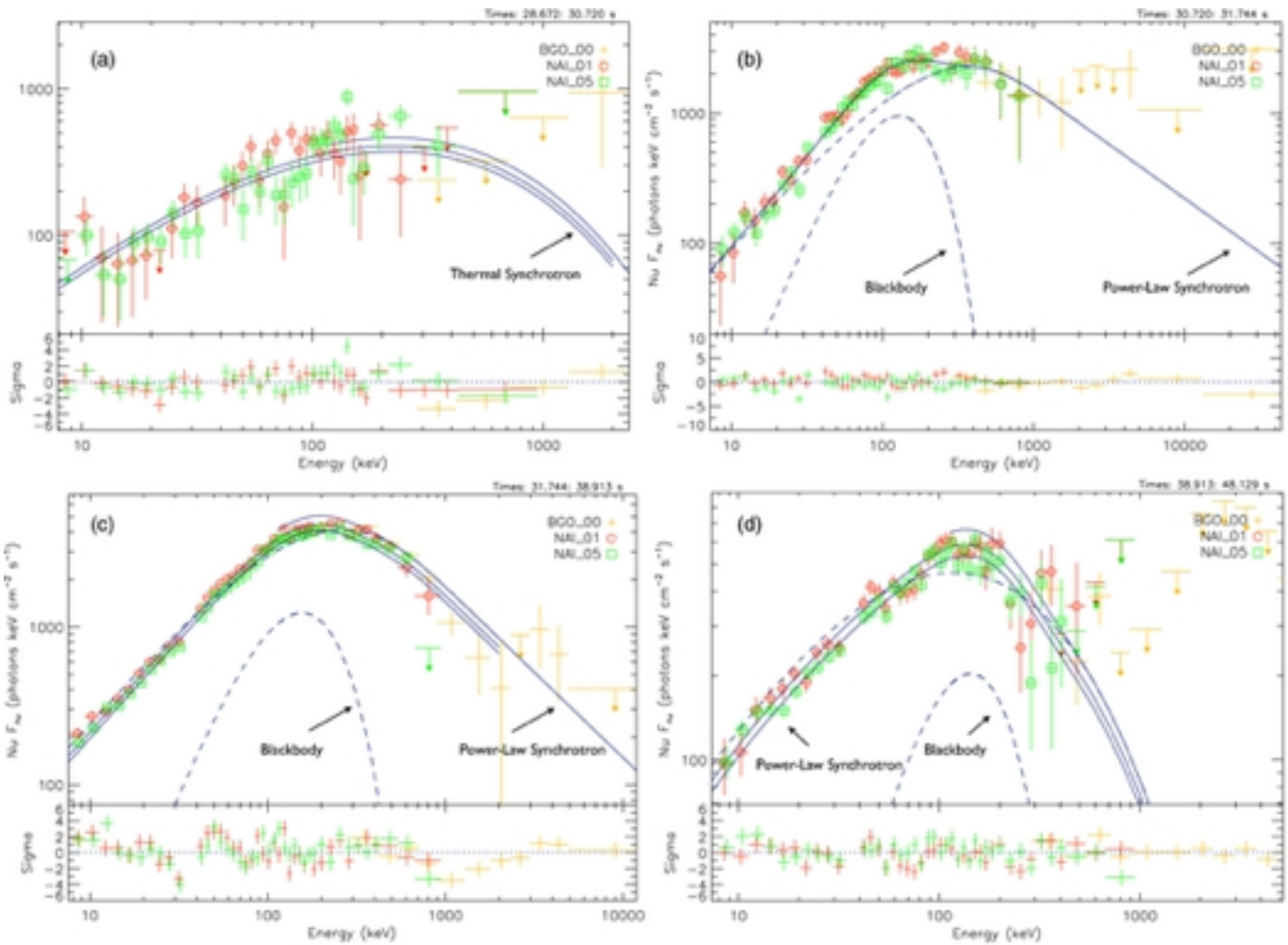
Band+BB fits



Guiriec et al. 2013, 2015, 2016

Synchrotron + Blackbody

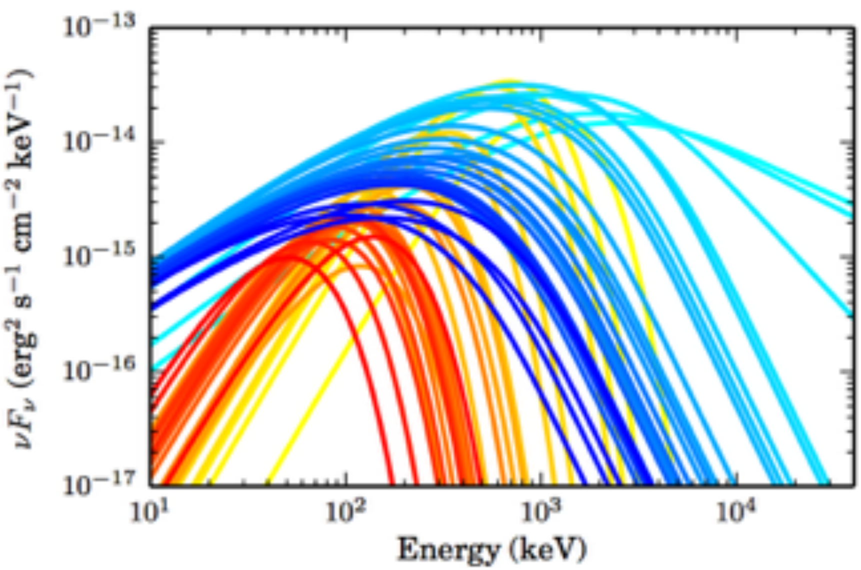
GRB 090820A

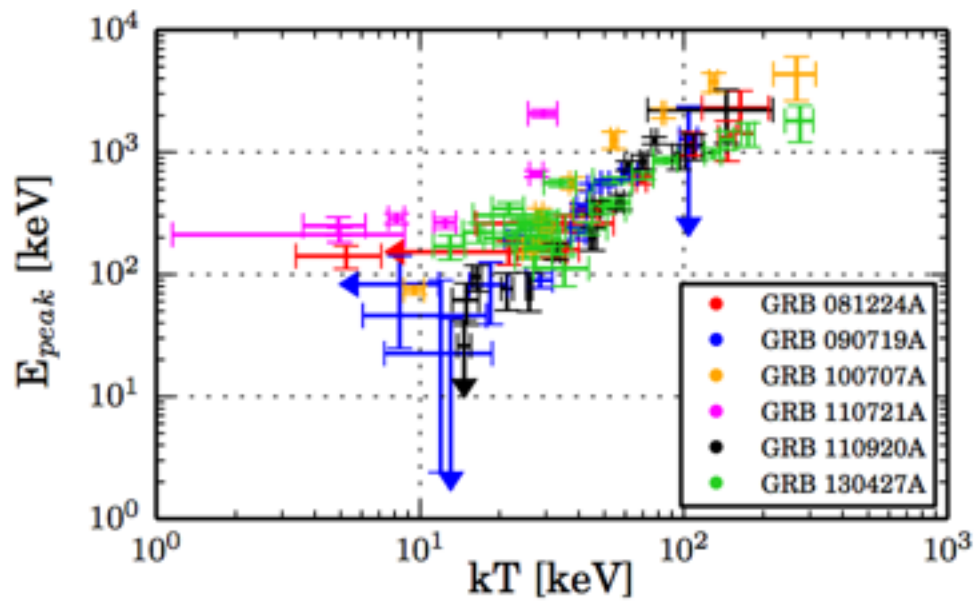


Burgess et al. 2011, ApJ 741, 24

Synchrotron + Blackbody

- **Synchrotron fits to the prompt emission work well with addition of blackbody in some cases**
  - Find correlation between kT and Epeak

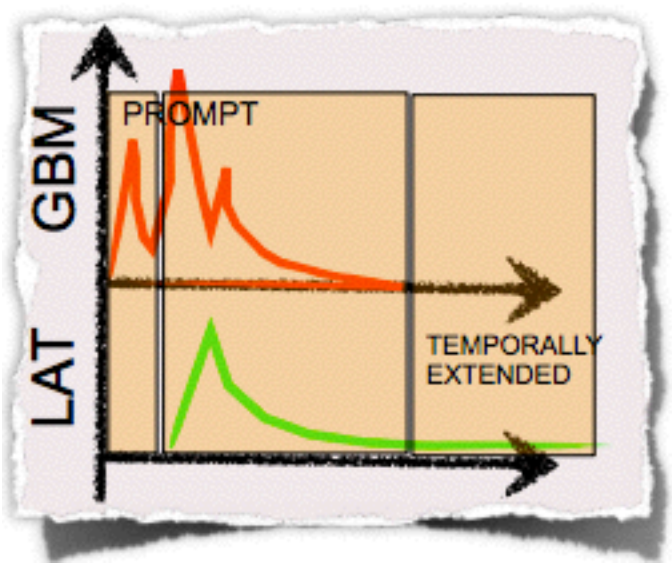




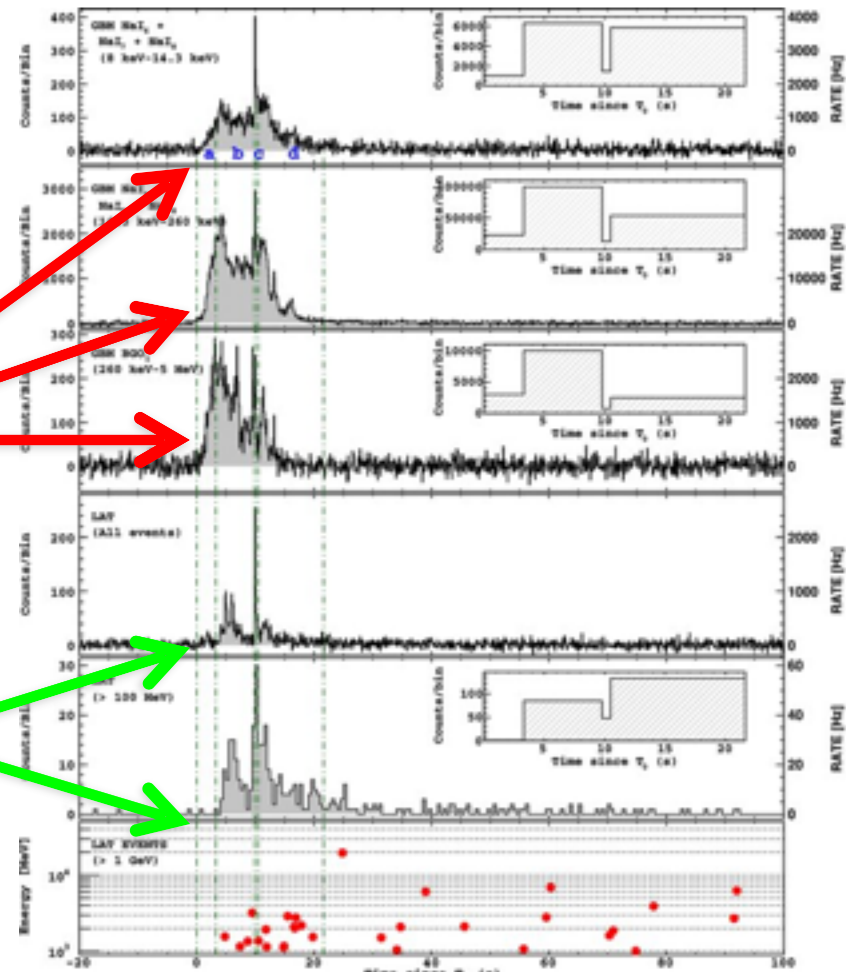
Burgess et al. 2014

Common New Features in Fermi GRBs

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



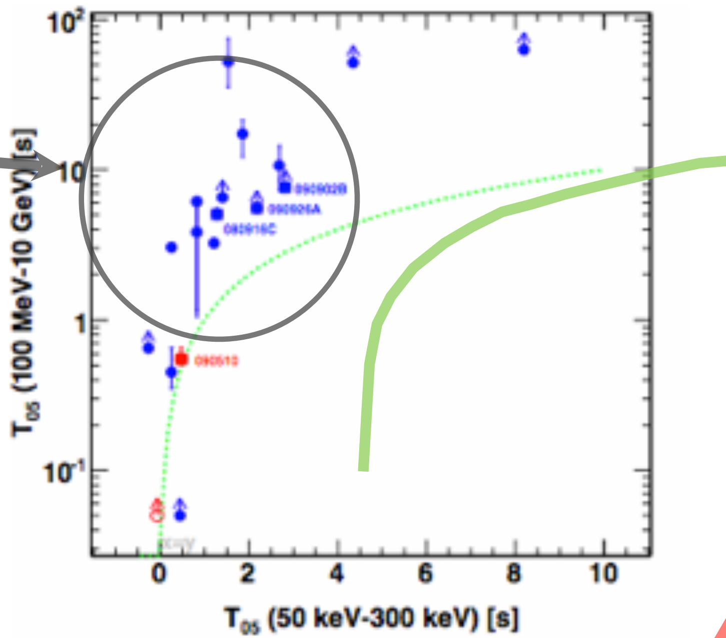
Credit: Nicola Omodei

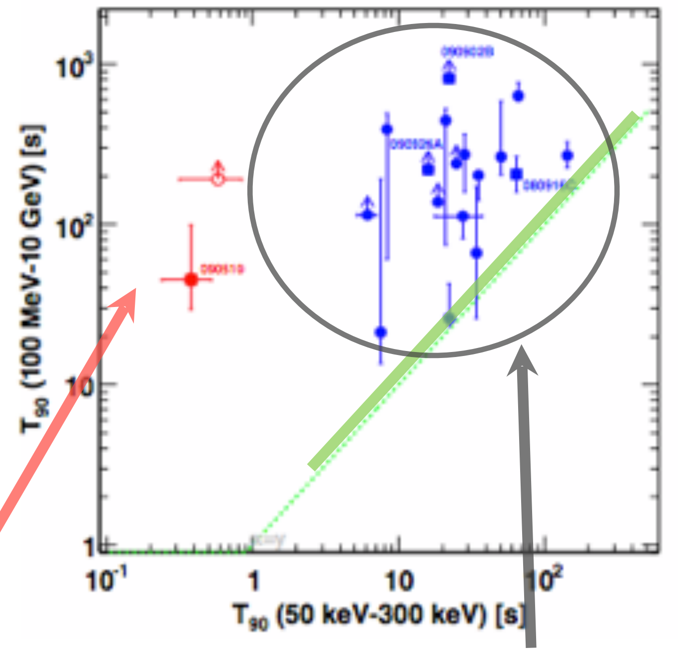


Ackermann et al. 2011, ApJ, 729, 114

Delayed High-Energy Emission

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





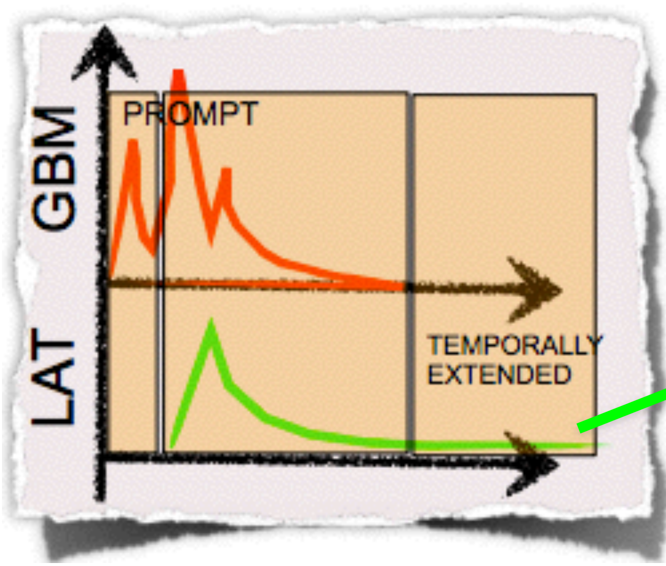
LAT Team et al., 2013, arXiv: 1303.2908

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

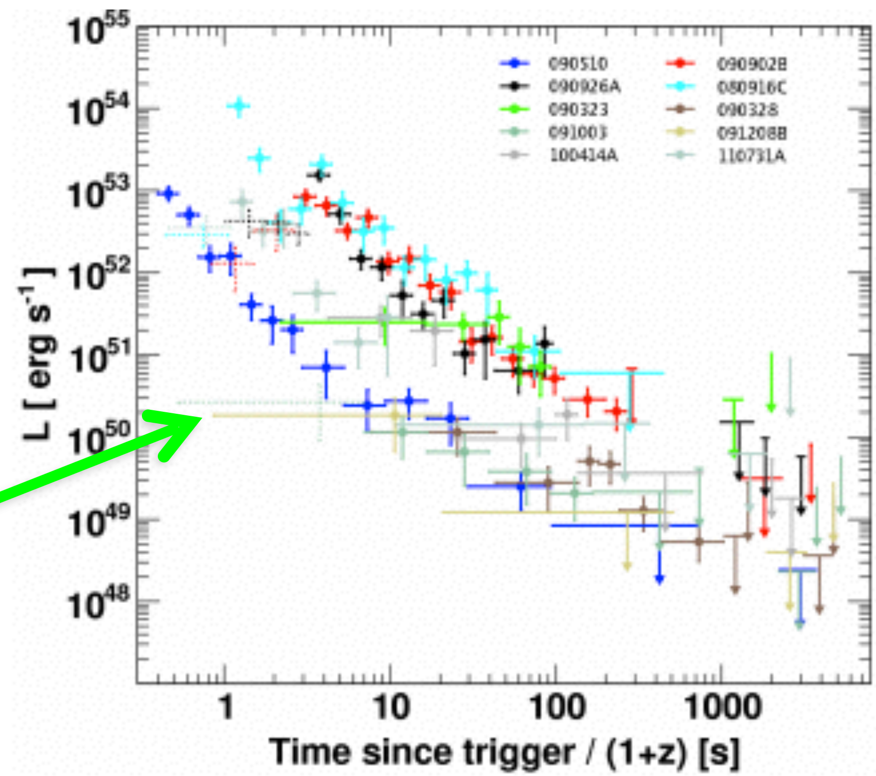
Short and Long GRBs show same extended emission behavior

Common New Features in Fermi GRBs

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



Credit: Nicola Omodei

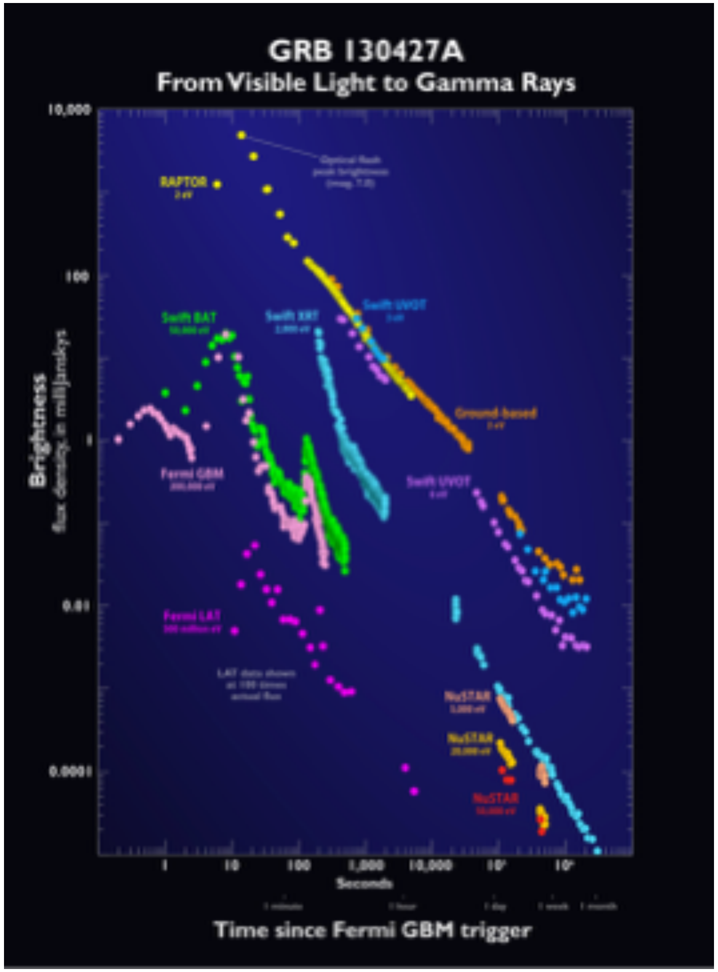


Ackermann et al. 2013, ApJS

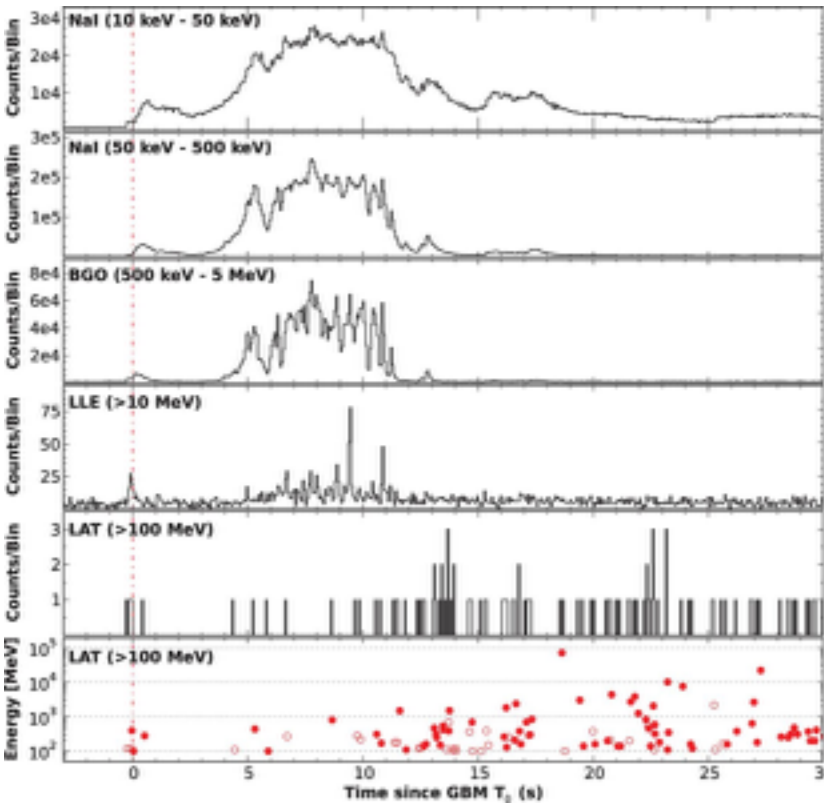
Origin of Extended Emission

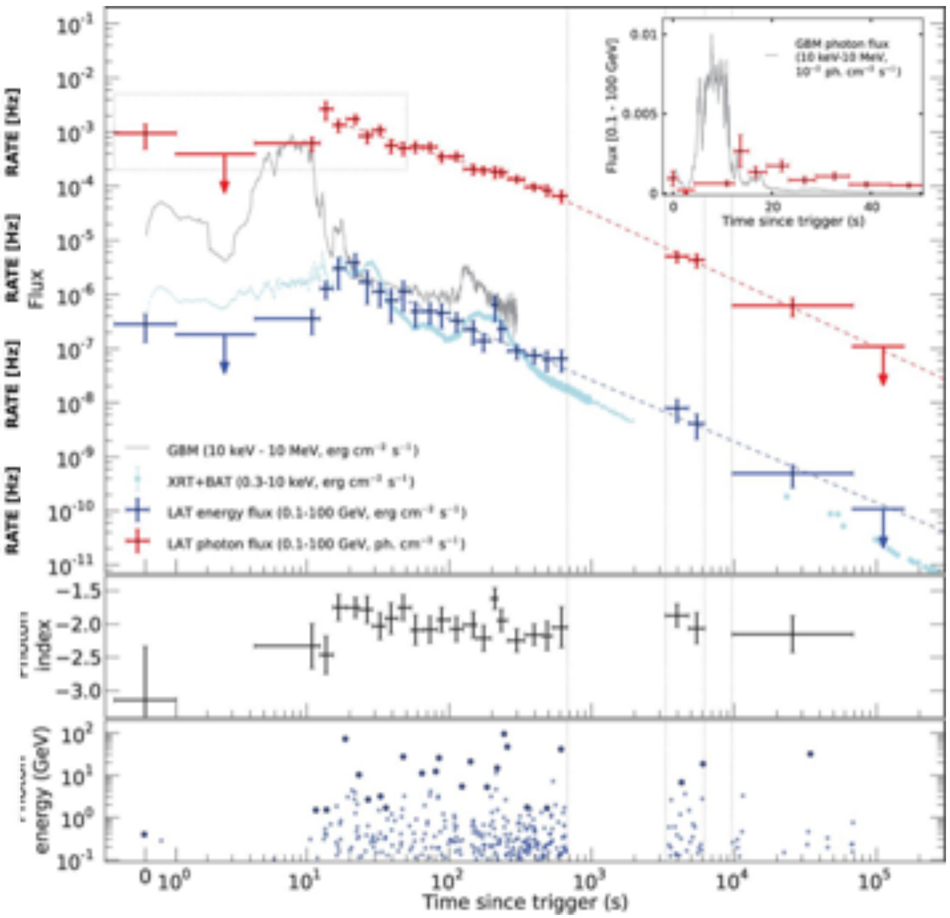
GRB 130427A

- 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



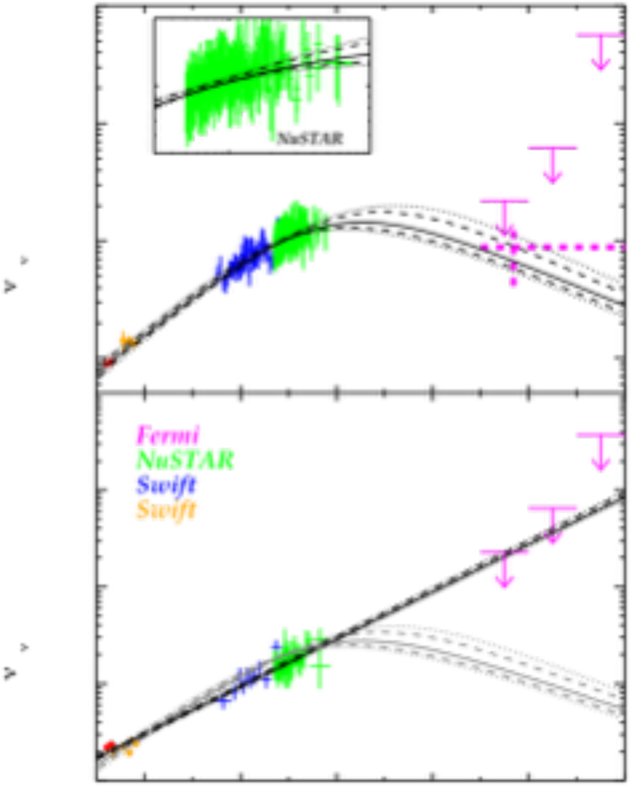
GRB 130427A

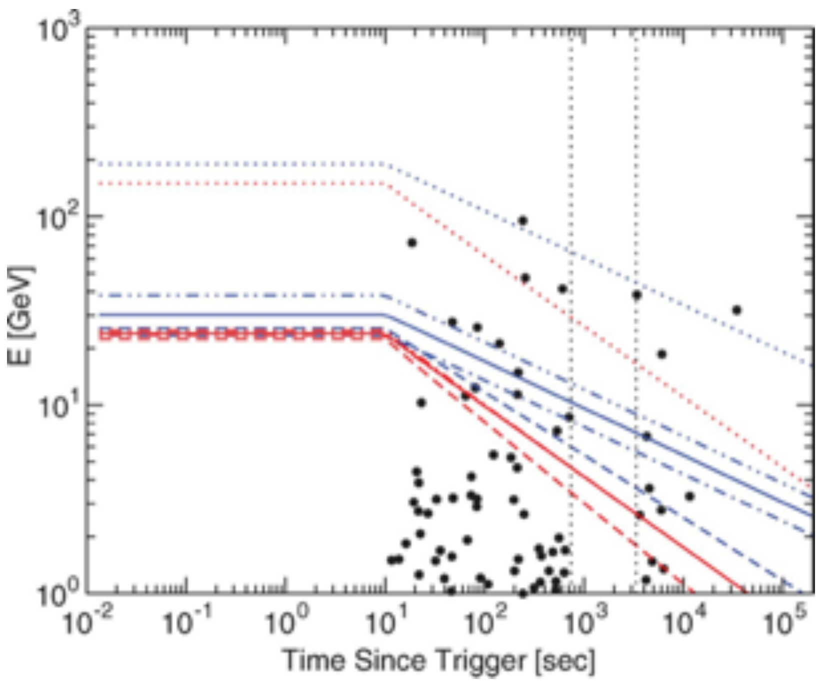




Ackermann et al. 2013, Science

GRB 130427A



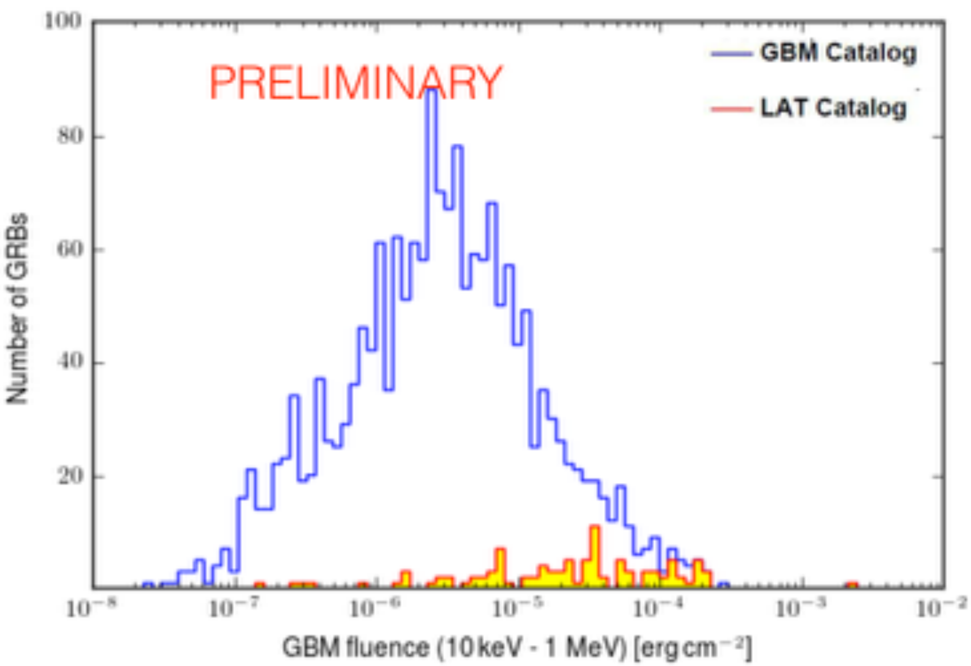


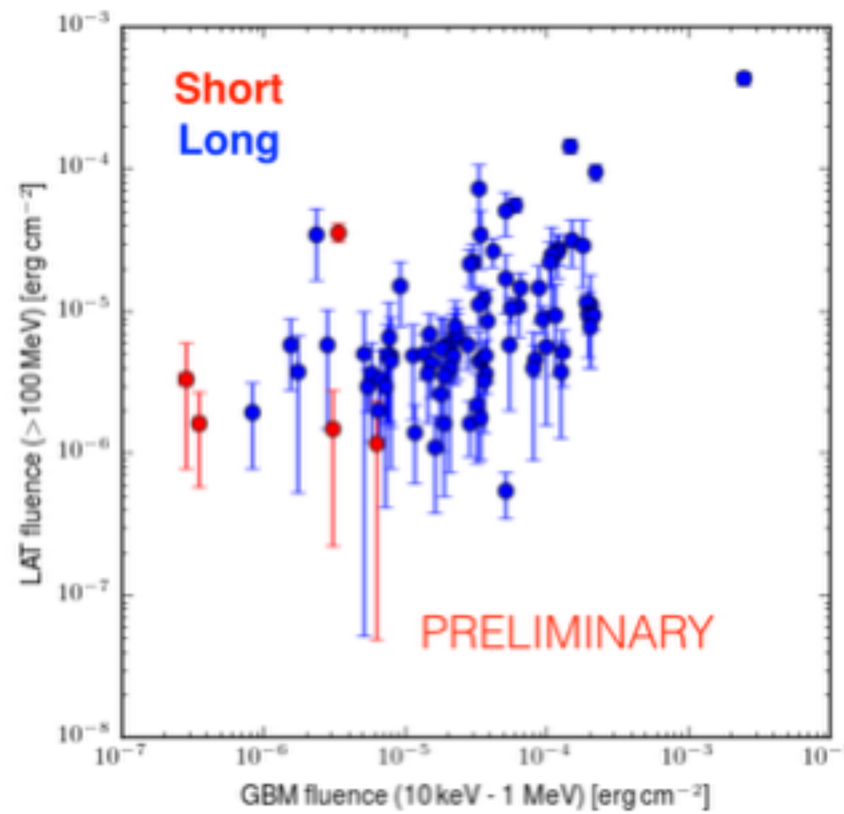
Ackermann et al. 2013, Science

Kouveliotou et al. 2013

2nd LAT GRB Catalog (in-preparation)

- **>130 GRBs in catalog**
- **Sample defined and validated**
- **Characterization and analysis ongoing**



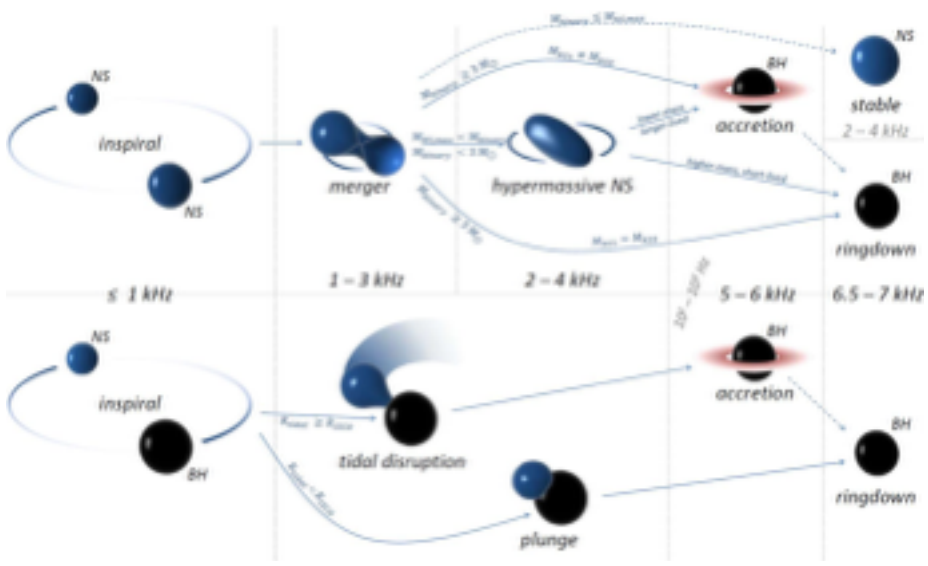


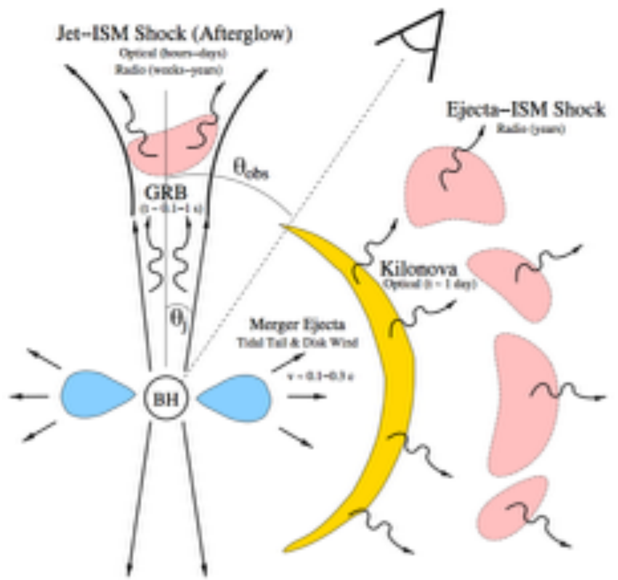
Other Topics in Fermi GRB Studies

- Cutoffs in prompt spectra
- Bulk Lorentz factor limits inferred from highest energy photons
- Short GRBs and constraints on Lorentz Invariance Violation
- High-energy photons from GRBs with known redshifts helps constrain the Extragalactic Background Light (EBL)
- Prompt spectral modeling insights into GRB jet composition (baryonic or magnetic)
- Broadband afterglow modeling and GRB progenitor environments
- LAT GRB energetics
- Gravitational Wave Counterparts

Short GRBs as Gravitational Wave Counterparts

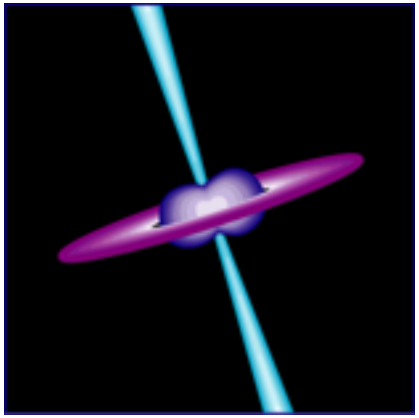
- NS-NS & NS-BH mergers should produce a GRB
  - detected if jet is pointed towards Earth (on axis)
- merging compact objects produce GWs
  - we know this from LIGO BH events
- If short GRBs are within LIGO detection range and pointed towards Earth, we should see gamma rays & GWs concurrently
- Short GRBs are rare, and LIGO NS-NS range at design sensitivity is expected to be 200 Mpc (sky and orientation averaged)
  - can increase for NS-NS with short GRBs





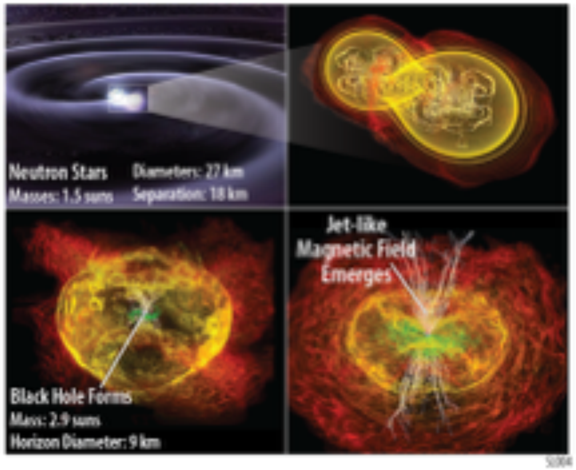
Short GRB/GW Rates

- short GRB rates come from gamma-ray observations (inherently accounts for beaming)
  - ~10±5 Gpc^{-3} yr^{-1} (Guetta and Piran 2006; Nakar et al. 2006; Guetta & Stella 2009, Coward et al. 2012, Wanderman & Piran 2015, Ghirlanda et al. 2016)
- 200 Mpc NS-NS merger horizon distance (400 Mpc - NS+10 $M_\odot$ BH)
  - (GW volume)*(Rate/vol) -> 0.34 ± 0.17 sGRBs yr^{-1}
- Enhanced GW amplitude along jet axis - horizon x 1.5
  - -> 1.13 ± 0.57 sGRBs yr^{-1}
- Coincident prompt signal pushes GW threshold lower - horizon x 1.5 (Cutler and Thorne 2002)
  - NS-NS rate: 3.8 ±1.7 sGRBs yr^{-1} (all sky)
  - NS-BH rate: 30 ±15 sGRBs yr^{-1} (all sky)
- Scale total rate by fraction of sky covered by instrument field of view



How to optimize GRB/GW coincident observations?

- Need wide field of view instrument
  - detections = sky fraction in FoV * rate
- Need accurate absolute timing (to confirm coincidence)
- Need localization capability
  - spatial coincidence (though timing still useful)
- Need rapid trigger and location dissemination
- Need broad energy coverage with good sensitivity
- Need high rate of GRB detection

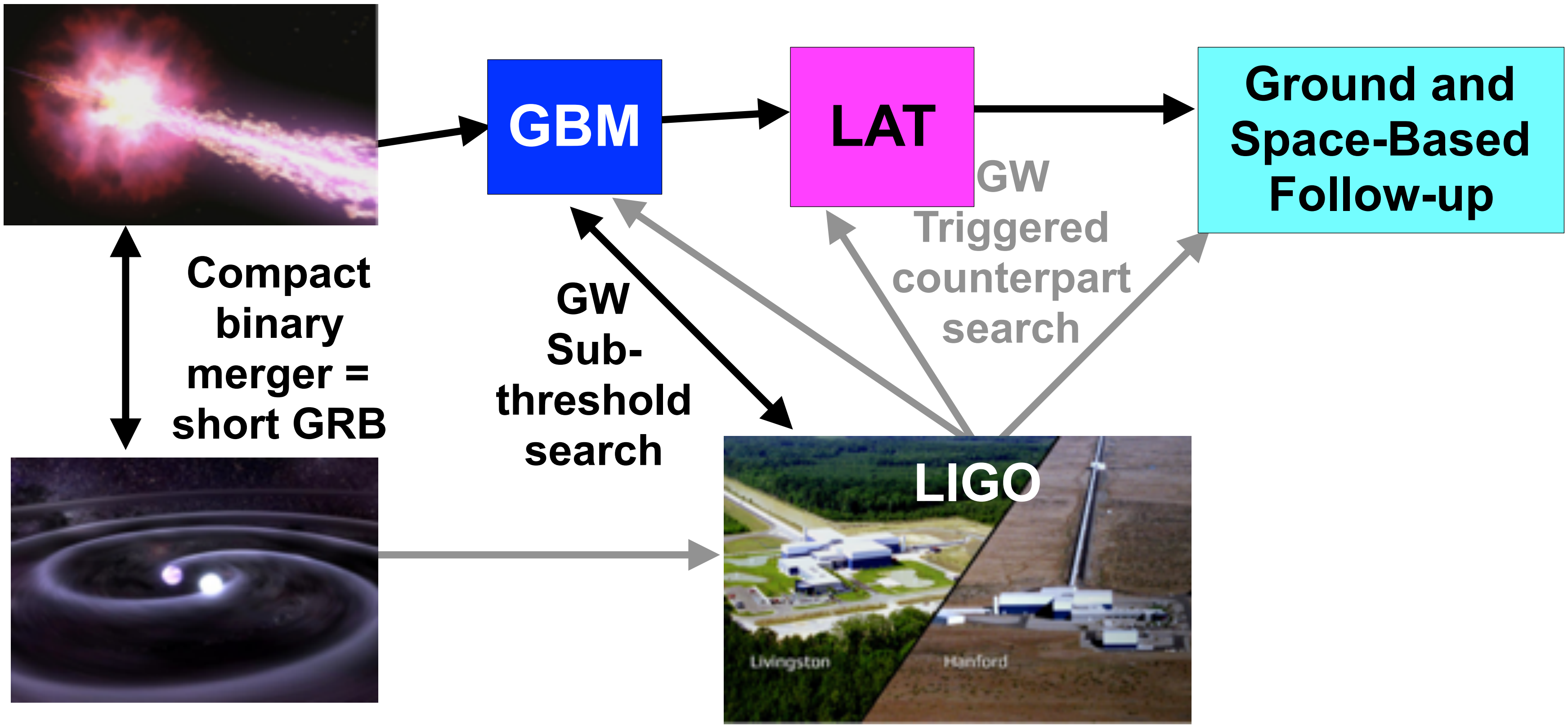


- Fermi
  - GBM is the most prolific detector of short GRBs
  - LAT detects afterglow emission from brightest/hardest short GRBs
  - LAT is the only instrument capable of searching for GRB afterglows <u>all-sky</u> in reasonable timeframe (~hours), without changing observing strategy

GBM-LIGO Studies

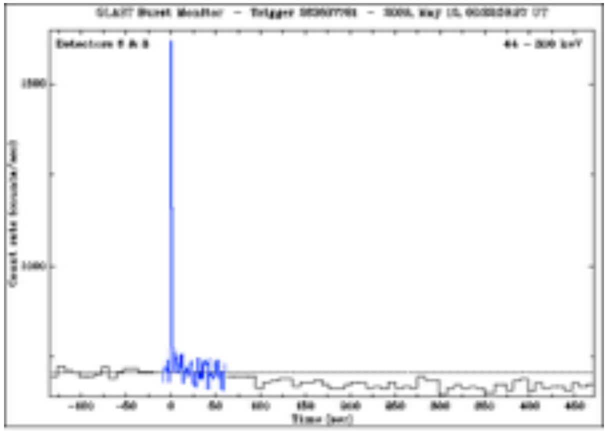
- Most probable LIGO counterparts are short GRBs associated with binary neutron star mergers or neutron star - black hole mergers
- All O1 LIGO detections have been BH-BH mergers
- GBM is the most prolific detector of GRBs, especially short GRBs
  - detects ~40 onboard triggered short GRBs per year
  - new sub-threshold pipelines detect ~40-80 untriggered short GRBs per year
- More short GRBs ➡ more probable LIGO-counterpart detection
- Current LIGO horizon is 70 Mpc (1.4+1.4 $M_\odot$), 300 Mpc (10+10 $M_\odot$) and 700 Mpc (30+30 $M_\odot$) mergers - See more at: http://www.ligo.org/news/index.php
- LIGO O2 will continue to August 2017
- LIGO/Virgo O3 will start in ~Fall 2018

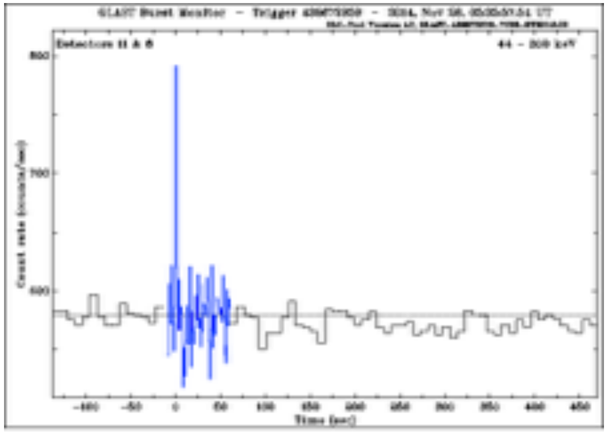
Paths to GW Counterpart Searches with Fermi



GBM Short GRB Searches - Onboard Triggers

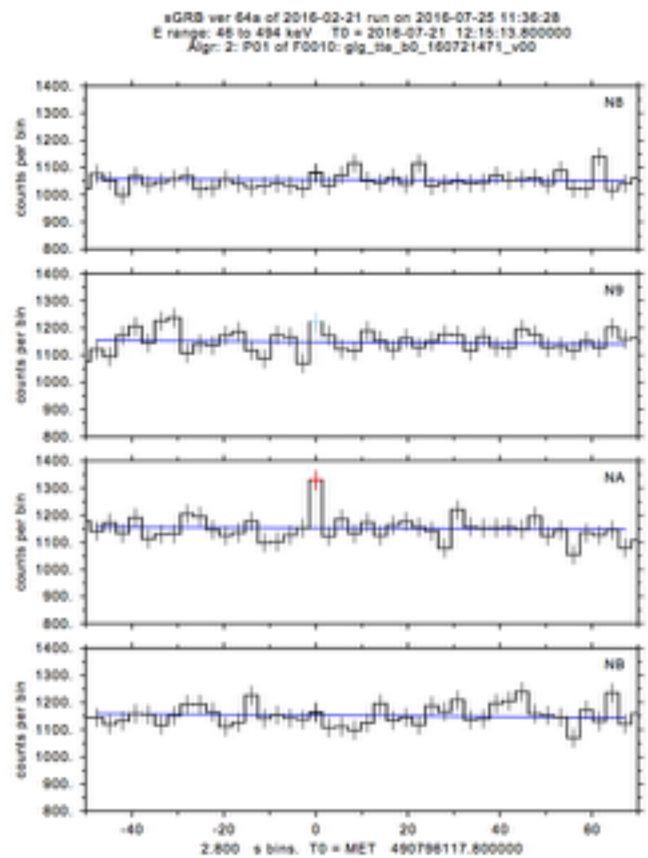
- **Onboard triggers**
  - standard triggers on bright GRBs
  - requires 2+ detectors to trigger
  - hard trigger time/energy scales
    - 16 ms to 4.096 s
    - 50– 300 keV, >100 keV, >300 keV
  - soft trigger time/energy scales
    - 16 to 128 ms
    - 25–50 keV
  - ~40 short GRBs per year
  - limited primarily by the onboard processing power
  - the search algorithm and background estimation can be improved upon by ground-based analysis





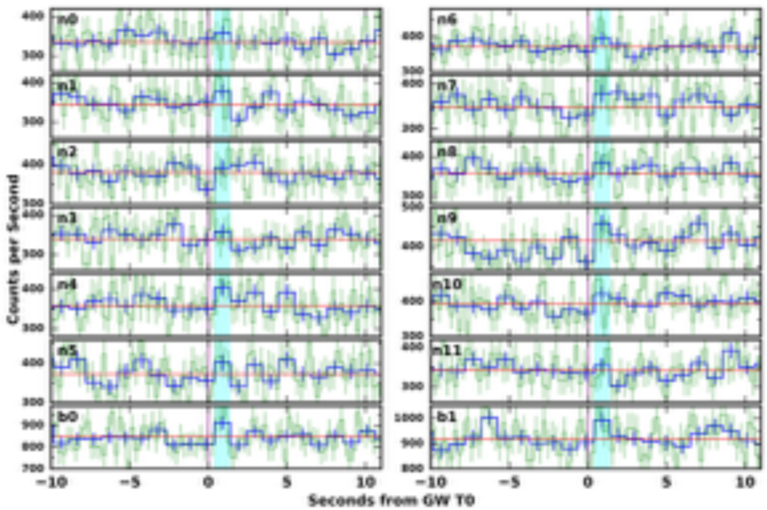
GBM Short GRB Searches - Untargeted Search

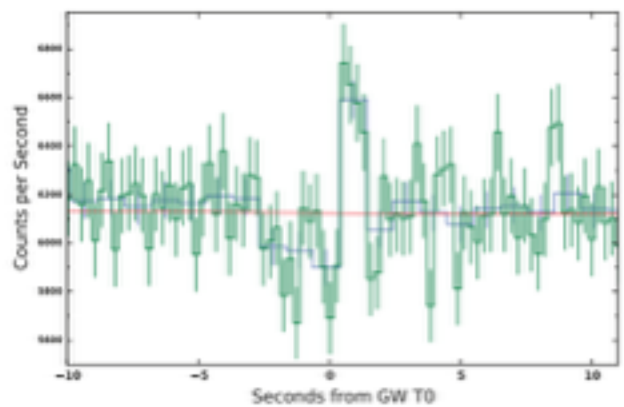
- **Untargeted Search**
  - **Briggs et al., in-prep**
  - **real-time ground-based analysis**
  - **blind search of continuous time tagged event data**
  - **takes advantage of increased processing power on the ground to search a wider parameters space than flight software**
  - **searches for excess signal in at least two legal detectors**
  - **improved background fitting**
  - **adds ~40-80 short GRB candidates per year, some confirmed with other instruments (Swift, INTEGRAL SPI-ACS, etc.)**
  - **https://gammaray.msfc.nasa.gov/gbm/science/sgrb_search.html**



GBM Short GRB Searches - Targeted Search

- **Targeted Search (Blackburn et al. 2015, Connaughton et al. 2016, Goldstein et al. 2016 arXiv:1612.02395)**
  - ground-based search using LIGO trigger and (optionally) localization as a prior ➡ sub-threshold signals
  - searches a wider parameter space than the blind search (hence not in real-time)
  - add all 14 GBM detectors
  - searches on 0.1–2.8 s timescales in four energy bands spanning ~30–1000 keV
  - better SAA veto (background triggers), 3 spectral templates (Band function: soft, normal, hard)
  - found GW150914-GBM

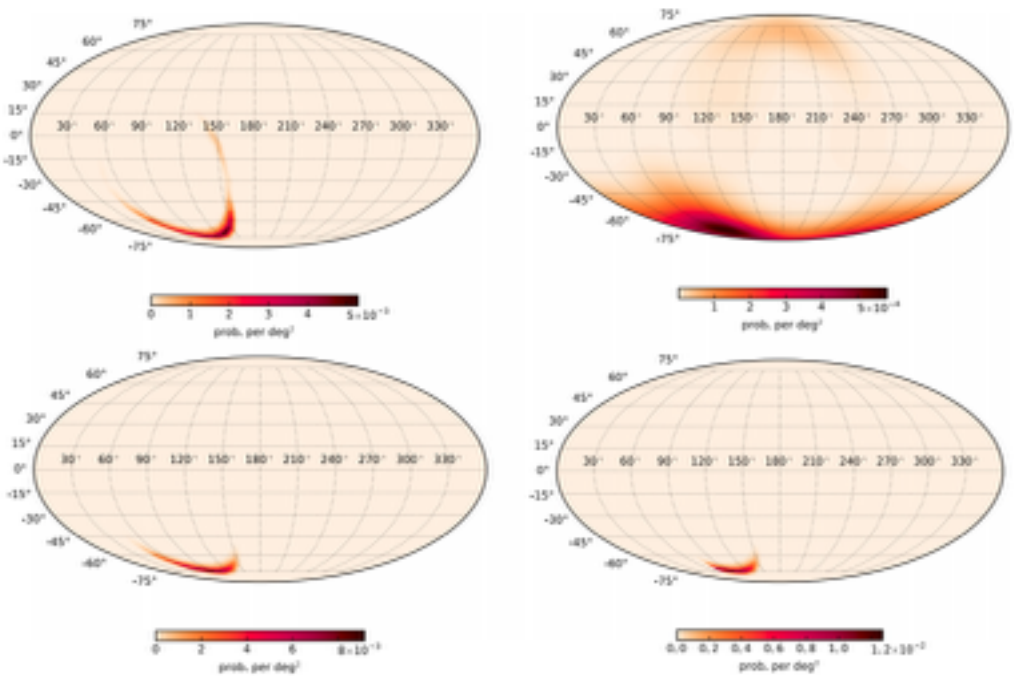


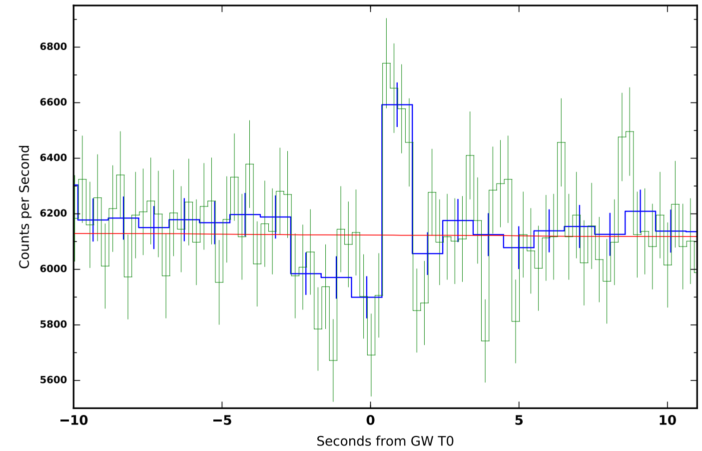


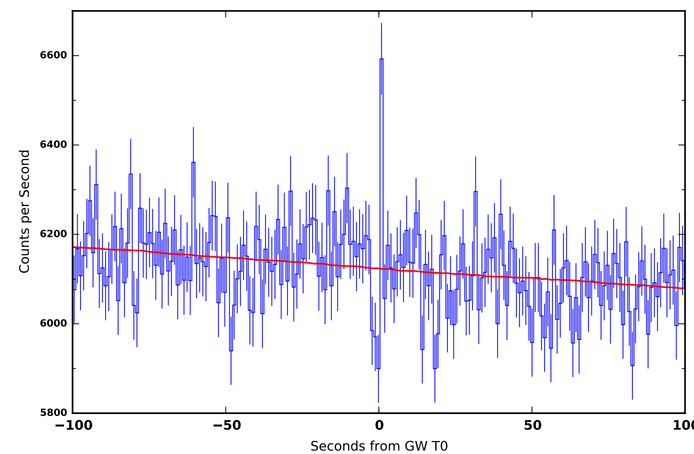
Connaughton et al. (2016)

GW150914-GBM

- **Weak signal seen ~0.4 s after the GW trigger, ~1 s duration**
- **Did not trigger GBM onboard**
- **Targeted search: energy and detector coherent signal over all 14 detectors (Blackburn+ 2015)**
- **Raw summed light curve SNR ~6, >50 keV**
- **Large localization due to poor viewing geometry**





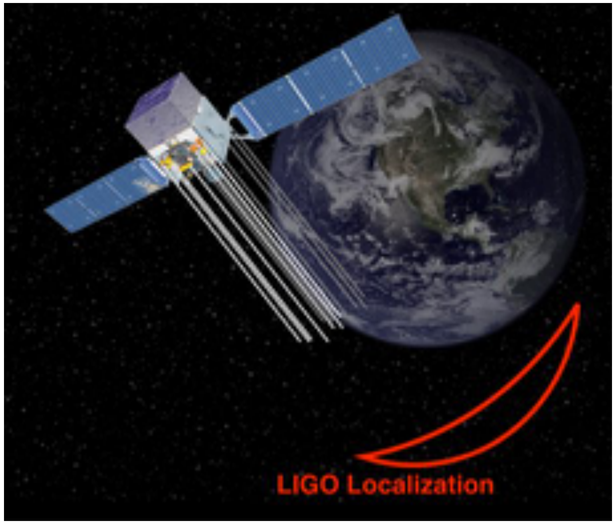


Connaughton et al. (2016)

GW150914-GBM

- No EM signal expected from BH-BH merger, resulting in much debate and theoretical speculation in the community
  - Rapidly rotating massive star causes dumbbell shaped core that collapses to BHs, merging together quickly with material around for GRB (Loeb et al. 2016)
  - Common envelope phase of merging close binaries (Woosley et al. 2016)
  - Extant BH-BH system that possesses a residual neutral disk at large radii suppressing the magneto-rotational instability (Perna et al. 2016)
  - Role of Winds (Murase et al. 2016)

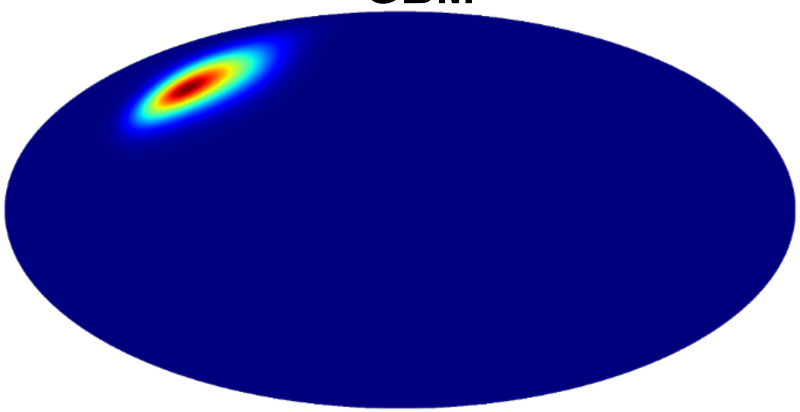
- Greiner et al. 2016 claimed the signal was consistent with background
  - Only used 1 NaI and 1 BGO detector
  - Signal is only significant when adding all 14 detectors (poor geometry to GBM)
- Connaughton et al. rebuttal paper in the works



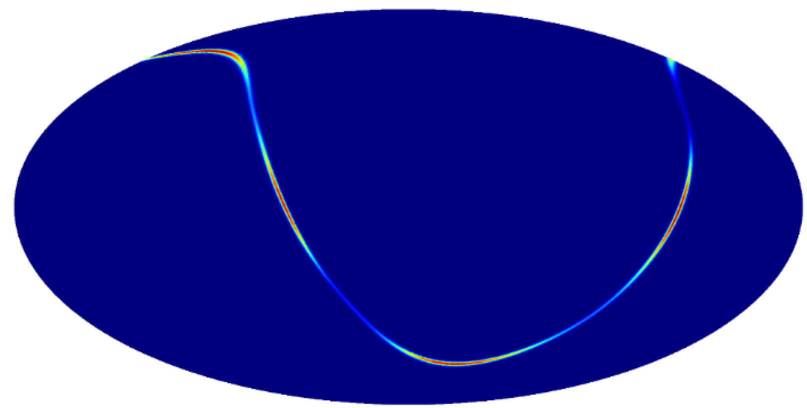
Joint LIGO-GBM Localizations

- **The combination of GBM+LIGO can significantly decrease the area in which to search for GW counterparts**

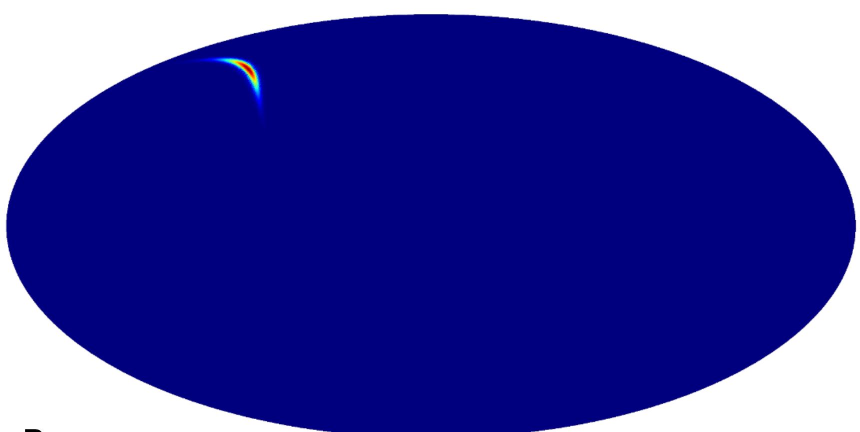
GBM



LIGO



GBM+LIGO



- **GBM ~ 10-100 deg^2**
- **LIGO ~ 100's deg^2**
- **GBM+LIGO ~ 10's deg^2**

Courtesy of Eric Burns

LAT as a GW Counterpart Detector

- LAT detects ~20 GRBs per year (1-2 short GRBs)
  - typically seeded by GBM & Swift GRB detections
  - LAT GRBs tend to be most energetic GRBs with bright afterglows
- LAT sees both prompt emission and afterglow emission
  - longest afterglow detected (GRB 130427A) lasted ~20 hours (Ackermann et al. 2014)
- LAT sees the entire sky every 3 hours
- LAT is the only instrument capable of searching for GRB afterglows <u>all-sky</u> in reasonable timeframe (~hours), without changing observing strategy
- A LAT counterpart would provide:
  - Localizations to aid broadband follow-up
  - High-energy measurement/constrains on prompt and/or afterglow spectra, emission mechanisms
  - constraint or measurement of bulk Lorentz Factor
  - constrain Lorentz Invariance Violation

Fermi Transient Searches

Pipeline
Method
Timescale
Distribution
Status

LAT Transient Factor (LTF)
Likelihood Around GBM/BAT triggers
seconds to orbits
LAT Team - Results in GCNs
Triggered Operating + *Blind Search Coming Soon*

***Fermi* All-sky Variability Analysis (FAVA)**
Counts Map Aperture Photometry
3 day (coming soon), 1 week
ATels
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/

Pipelines

GBM Targeted Searches (GW, neutrino)
ground search around external triggers
ms - s
GCNs

LAT Burst Advocate Tool
Likelihood Around GBM/BAT triggers
100 s, 1000 s
LAT Team - Results in GCNs
Operating

LAT Automated Science Processing (ASP) + Flare Advocates
Likelihood
6 & 24 hour
ATels, GCN notices (on AGN)
Operating

LAT Catalogs
Likelihood, associations
3 month (0FGL), 1 year (1FGL), 2 years (2FGL), 4 years (3FGL)
http://fermi.gsfc.nasa.gov/ssc/data/access/
4FGL in progress

GBM Untargeted Search
ground search
ms - s
GCN Notices
http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices
Operating

Timescale

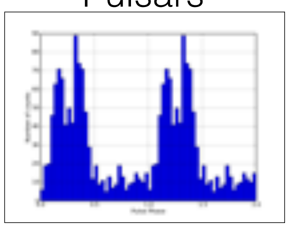
µs ***ms*** ***s*** ***minutes*** ***hours*** ***days*** ***months*** ***years***

Photon Timing

All Sky Cadence

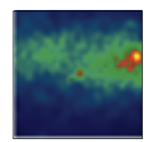
Transients

Pulsars



Solar Flares

Novae



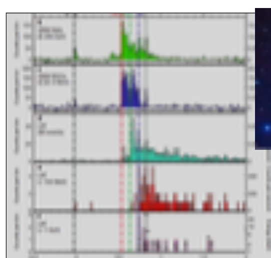
γ-ray Binaries

Blazar Flares

Crab Flares

Magnetar Flares

GRBs



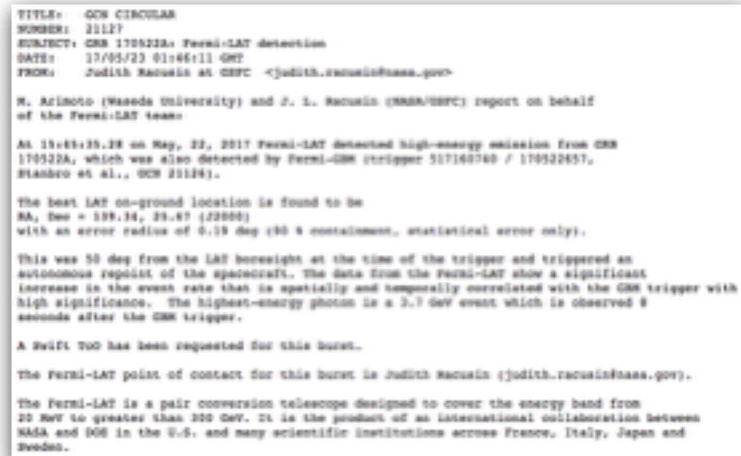
Terrestrial γ-ray Flashes

Not to scale

LAT Transient Factory (LTF) & Burst Advocate (BA) Tools

- Internal team pipelines that are seeded by GBM/Swift/INTEGRAL/etc.
- Search timescales from a few seconds to 10 ks
- Alerts LAT burst advocates of detections
- Used in preparation of GCN Circulars
- LTF Blind Search in the works

- Public products
  - GCN Circulars
  - GRB table: https://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/lat_grbs/table.php
- LTF developed by Giacomo Vianello & Nicola Omodei (Stanford)
- BA Tool developed by Dan Kocevski (NASA/MSFC)


TITLE: GCN CIRCULAR
NUMBER: 21127
SUBJECT: GRB 170522A: Fermi-LAT detection
DATE: 17/05/23 01:46:11 GMT
FROM: Judith Racusin at GSFC <judith.racusin@nasa.gov>

M. Arimoto (Waseda University) and J. L. Racusin (NASA/GSFC) report on behalf of the Fermi-LAT team:

At 15:45:35.28 on May, 22, 2017 Fermi-LAT detected high-energy emission from GRB 170522A, which was also detected by Fermi-GBM (trigger 517160740 / 170522657, Stanbro et al., GCN 21124).

The best LAT on-ground location is found to be RA, Dec = 139.34, 25.67 (J2000) with an error radius of 0.19 deg (90 % containment, statistical error only).

This was 50 deg from the LAT boresight at the time of the trigger and triggered an autonomous repoint of the spacecraft. The data from the Fermi-LAT show a significant increase in the event rate that is spatially and temporally correlated with the GBM trigger with high significance. The highest-energy photon is a 3.7 GeV event which is observed 8 seconds after the GBM trigger.

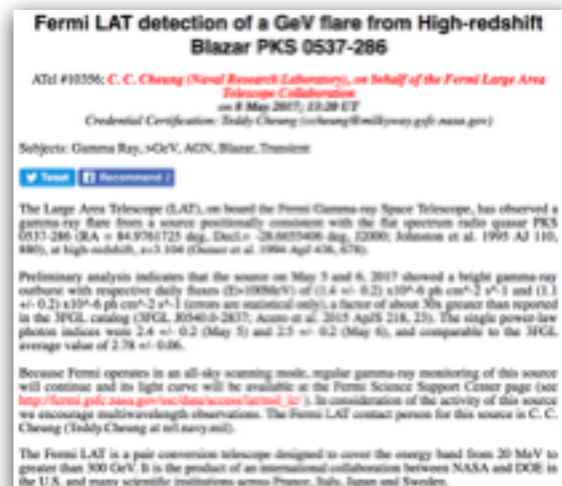
A Swift ToO has been requested for this burst.

The Fermi-LAT point of contact for this burst is Judith Racusin (judith.racusin@nasa.gov).

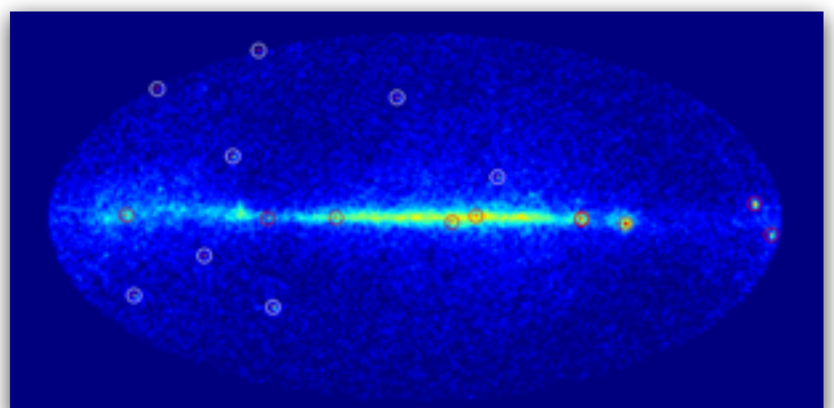
The Fermi-LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

LAT Automated Science Pipeline (ASP)

- Search for flares in known sources (blazars, Galactic transients)
- Blind search transient sources on 6 hour & 24 hour timescales
- Used by the Flare Advocates to put out GCNs & ATels & to trigger follow-up observations with Swift, radio, optical
- Reports weekly on flaring sources: http://fermisky.blogspot.com/
- Nice description:
  Ciprini et al. 2011, arXiv:1111.6803
- Developed by Jim Chiang, maintained by the flare advocates

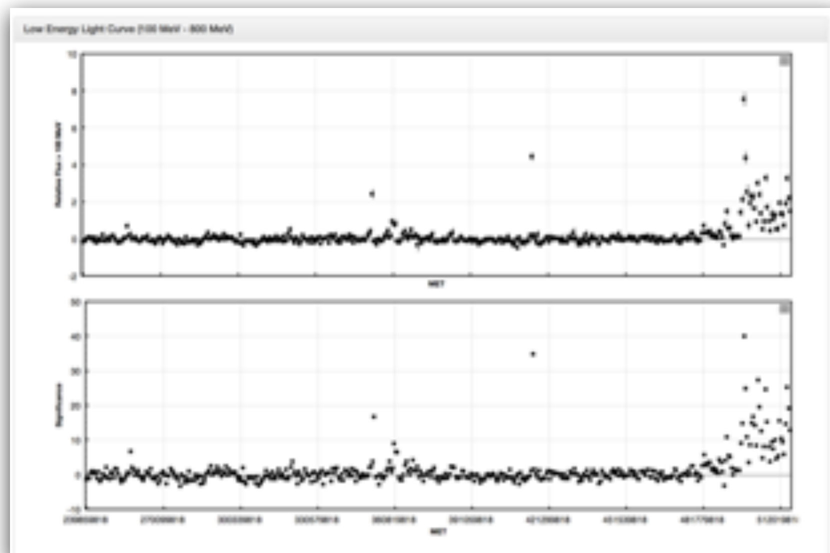


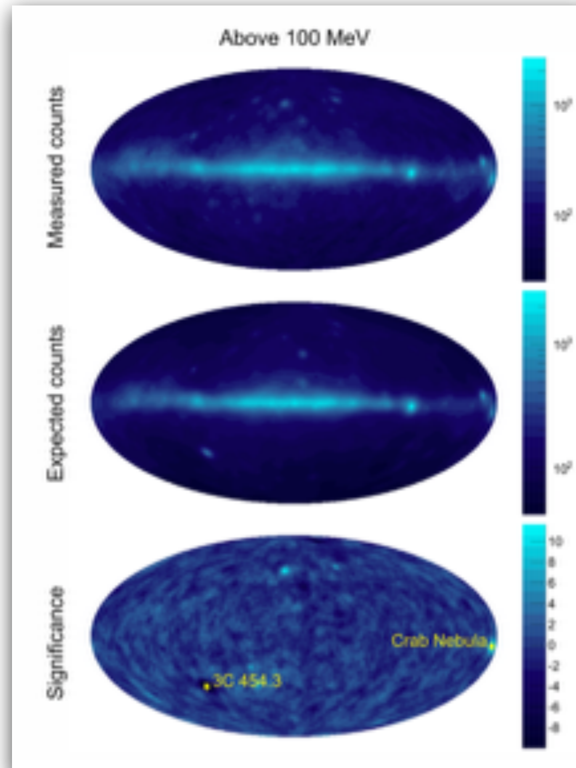
Fermi LAT detection of a GeV flare from High-redshift Blazar PKS 0537-286



Fermi All-Sky Variability Analysis (FAVA)

- **Photometric technique for searching for flaring and variable sources relative to their average flux history**
- **Splits sky into thousands of pixels, and measures weekly time history of every pixel**
- **Pixels that flare above a 3σ significance threshold are followed-up by a standard likelihood analysis**
- **FAVA products public: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/index.php**
- **FAVA developed and operated by: Rolf Buehler, Dan Kocevski, Matteo Giommi, and Marco Ajello**

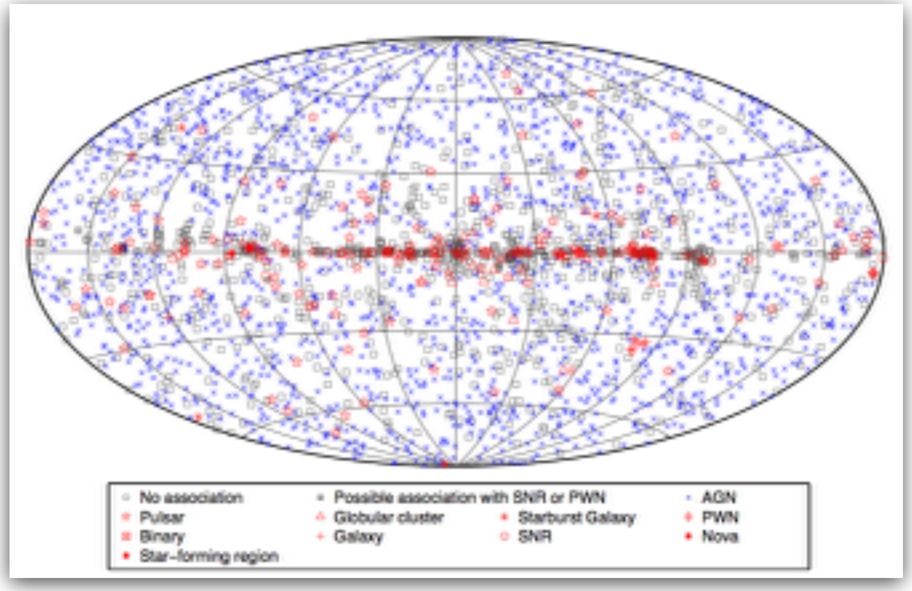




Ackermann et al. 2013

LAT Catalogs

- General Catalogs - 0FGL, 1FGL, 2FGL, 3FGL
- High-Energy Catalogs - 1FHL, 2FHL
- Flaring Source Catalogs - 1FAV, 2FAV
- https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/
- Provides source descriptions for steady sources, or sources flaring enough to be significant in catalog interval
- Relevant for comparisons to sources detected during transient searches



http://www.asdc.asi.it/fermi3fgl/

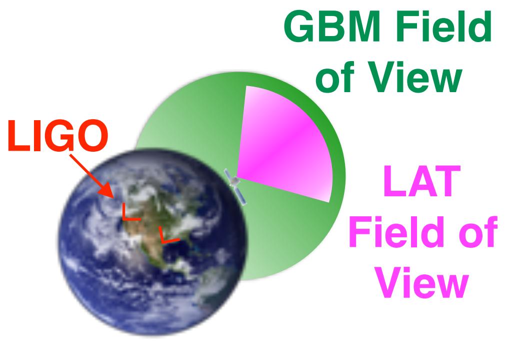
Custom LAT GW Counterpart Searches

- Large GW localization regions present unique challenges
  - GW Seed provides time, but large sky region
  - LAT has a large field of view, but exposure varies throughout 2 orbit rocking profile
- GeV band has low rate of transients on short timescales
- GBM provides all-sky coverage (not occulted by Earth), which could provide seed
- LAT team (Giacomo Vianello, Nicola Omodei, Dan Kocevski) have developed pipelines to split LIGO 90% localization contours into pixels (sized ~LAT PSF at 1 GeV) and performed likelihood analyses on each pixel searching for excesses
- Depends on time intervals chosen - requires balance between sky coverage and exposure at each point

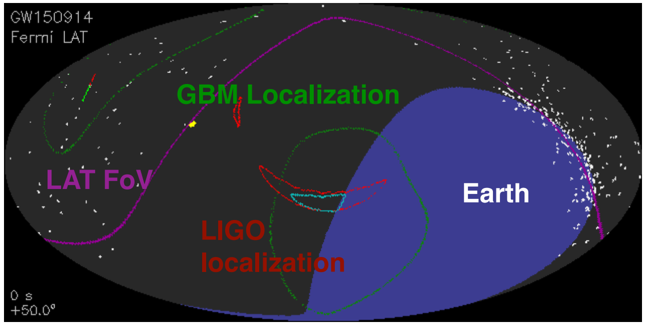
Fermi Observations of GW Detections and Candidates

- **Fermi Observations of LIGO detections and candidates**

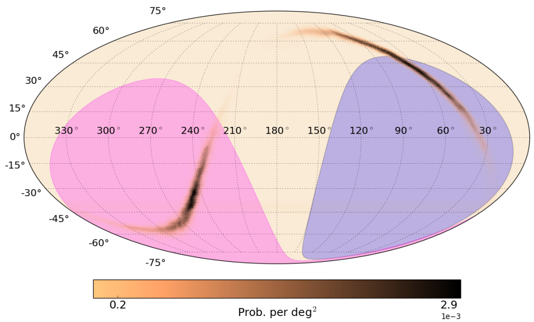
	GW150914	LVT151012	GW151226
GBM coverage of LIGO region at trigger time	75%	68%	83%
GBM observed entire LIGO region within	25 min	8 min	34 min
LAT coverage of LIGO region at trigger time	0%	47%	32%
LAT observed entire LIGO region within	70 min	113 min	140 min



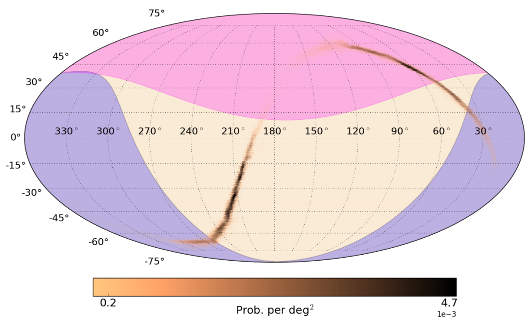
GW150914



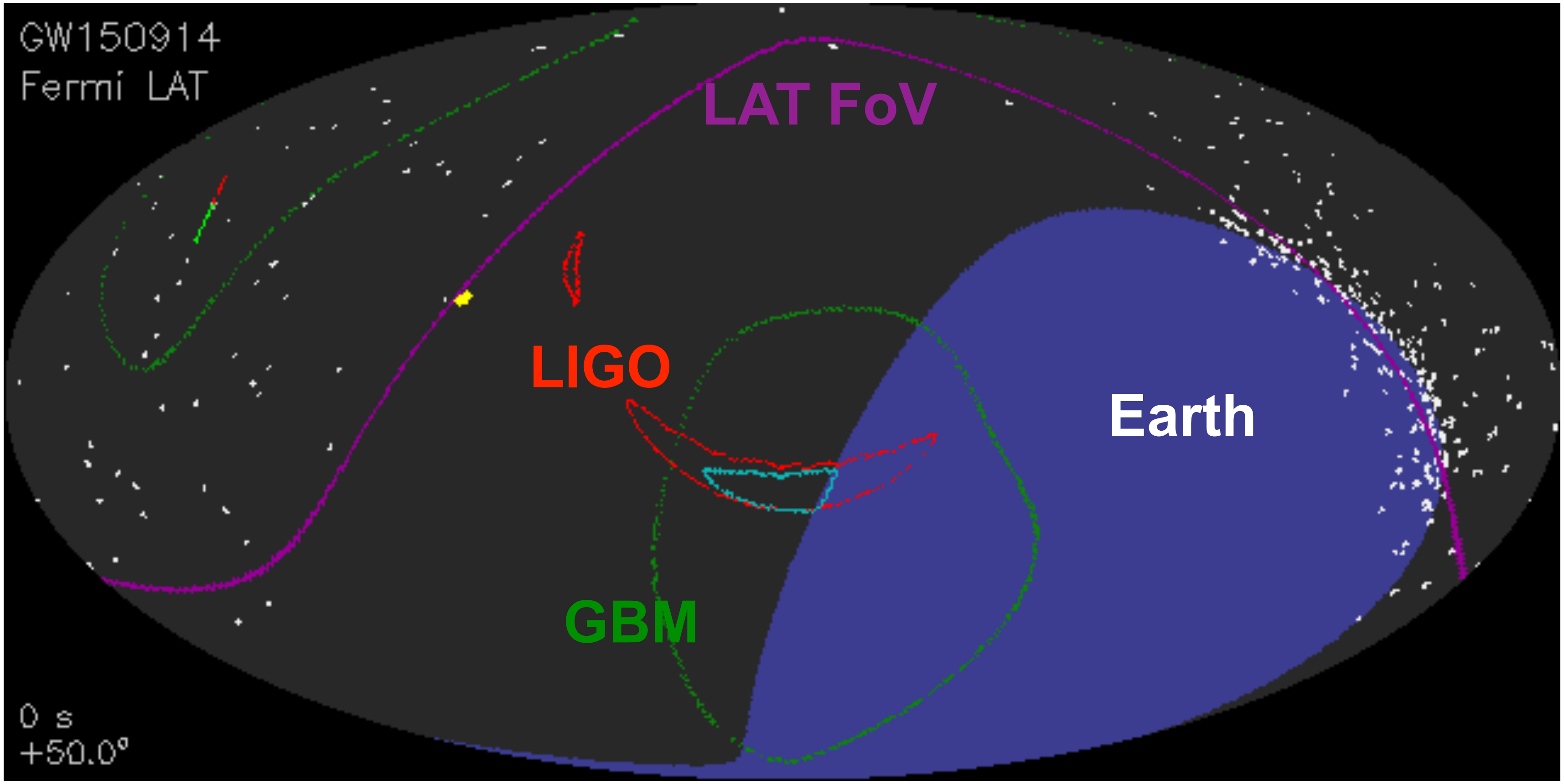
LVT151012



GW151226

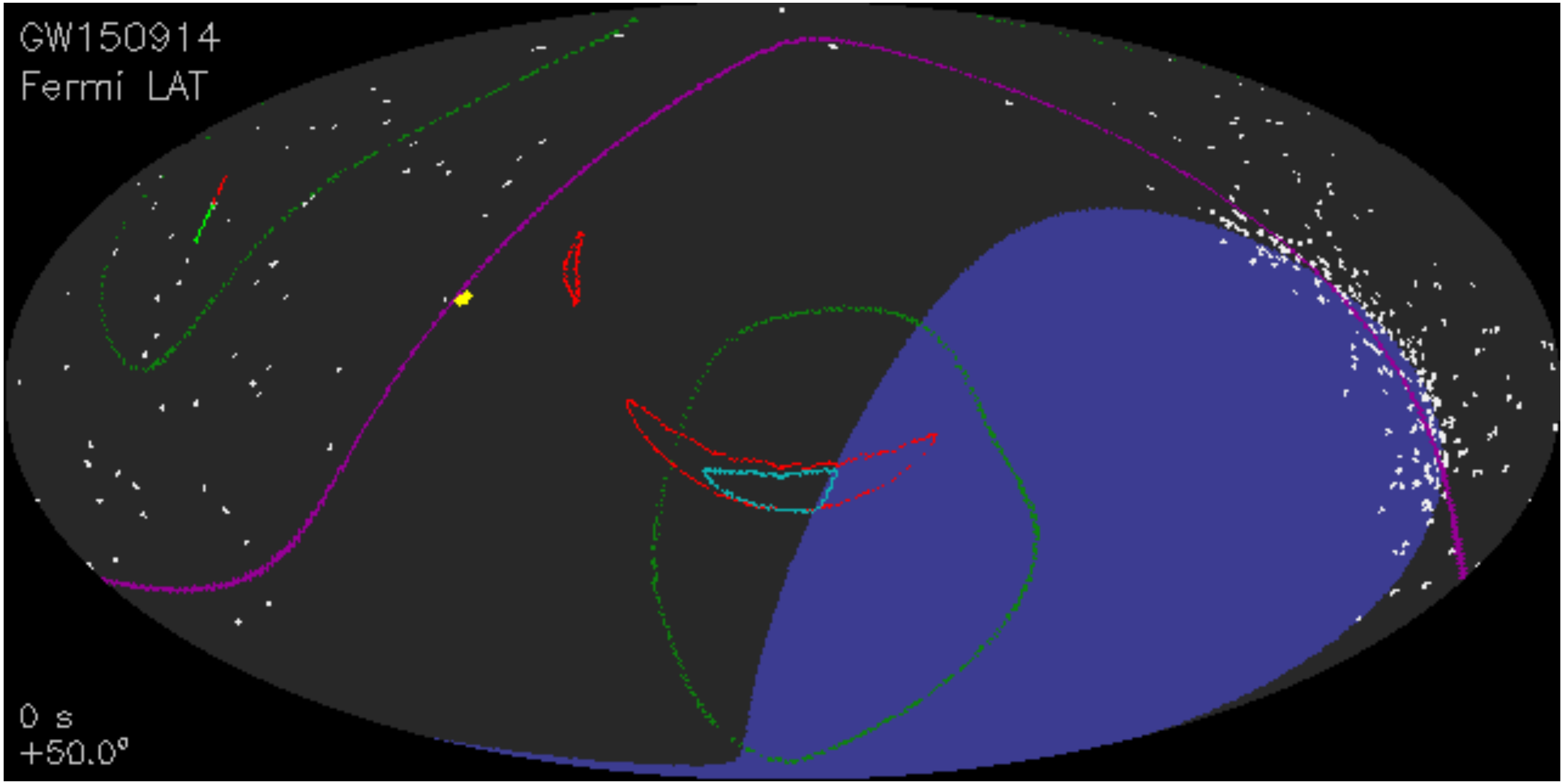


Fermi Coverage of GW150914



Credit: Seth Digel

Fermi Coverage of GW150914

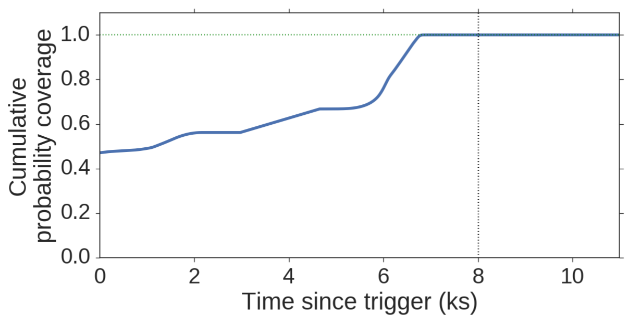


Credit: Seth Digel

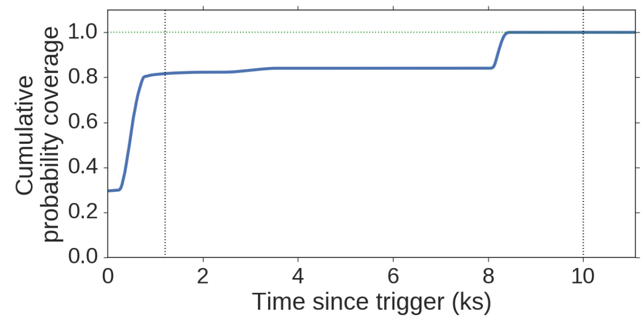
Fixed Time Window

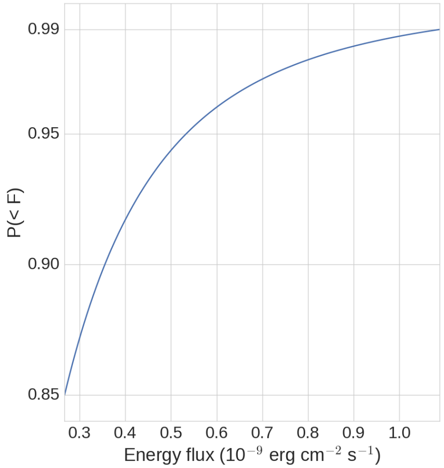
- **Fixed interval (± 10 s, 0-10 ks), time it took for LAT to observe 90% of LIGO localization region**
- **Likelihood analysis performed on each sky pixel over that region**
- **Flux upper bounds measured for each pixel**
- **Useful to place single global upper bound in some interval**

LVT151012

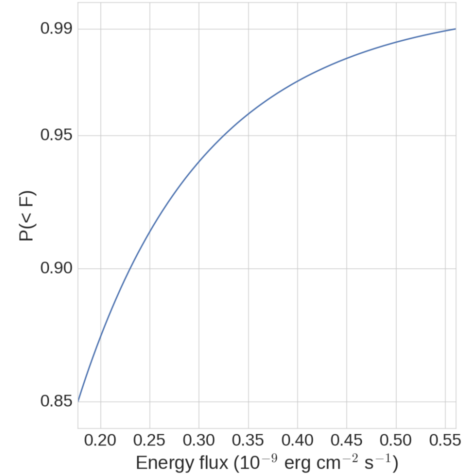


GW151226





Flux upper bound corresponding to credibility level

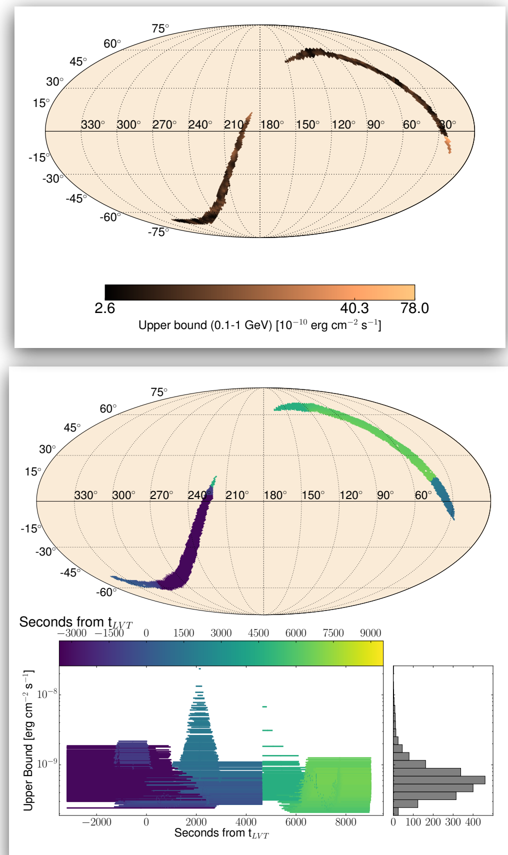


Racusin et al 2017, Vianello et al. 2017

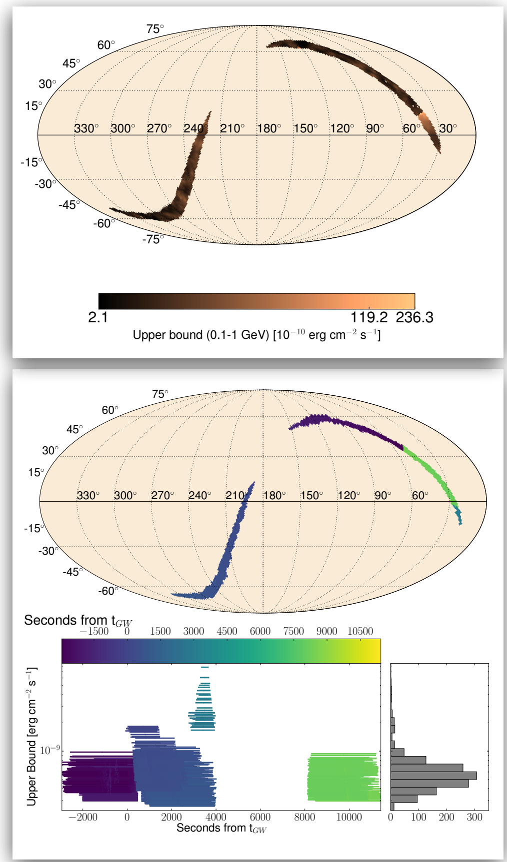
Adaptive Time Windows

- **Time interval set by period in which each pixel in GW localization passed through LAT FoV during some interval (e.g. first two orbits)**
- **Useful to evaluate LAT upper bound at specific location (e.g. like that of an external counterpart)**

LVT151012



GW151226



Racusin et al 2017,
Vianello et al. 2017

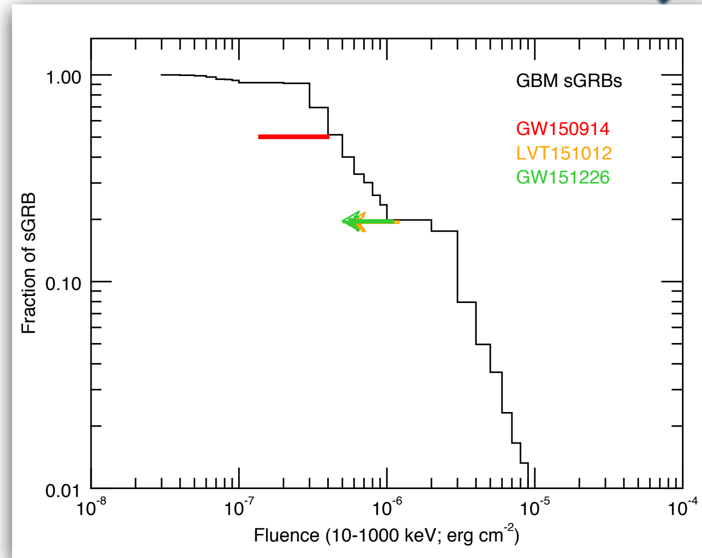
Results

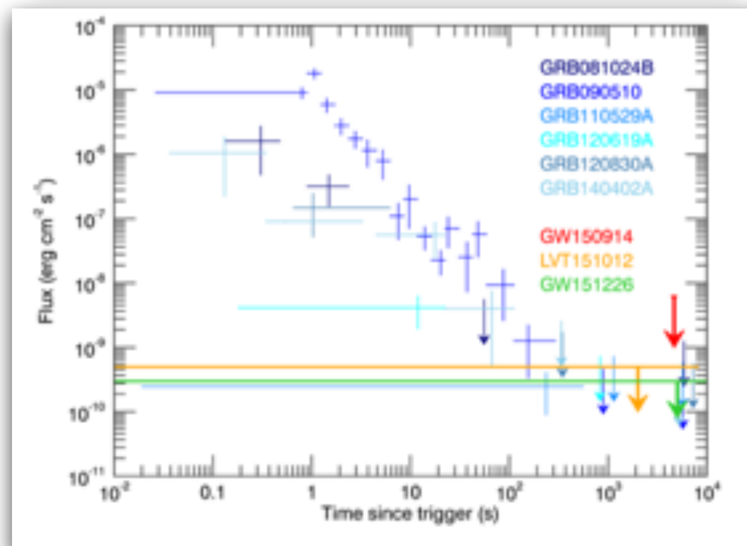
- GW150914-GBM only candidate counterpart found by GBM, no counterpart seen for LVT151012 & GW151226
- No candidate counterparts found by LAT for GW150914, LVT151012, or GW151226 using any of the techniques described
- Lack of GBM counterpart for other events does not contradict GW150914-GBM
  - LIGO localization regions not fully covered at time of trigger for LVT151012 & GW151226
  - to-date GW150914 still has the highest mass and lowest distance, which might correspond to luminosity
  - GBM background rates higher at the times of LVT151012 & GW151226 that GW150914-GBM

- See also LIGO/Virgo paper to be released at 11 am EDT today (June 1)
  - Look for Fermi paper on arXiv soon

LIGO/Virgo O2 and beyond

- ***Fermi*-LAT continues to observe the whole sky every 3 hours, automatically observing GW localizations in normal survey mode operations**
- ***Fermi* is ready to search for counterparts to compact mergers that include a neutron star, or any other kind of gamma-ray transient associated with GW events**
- **Nearby short GRBs would be easily detectable by LAT (if jet pointed towards Earth)**
- **Looking forward to more GW detections!**



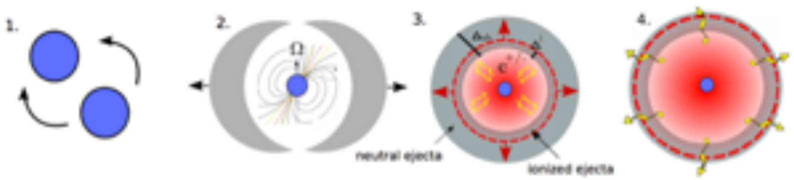


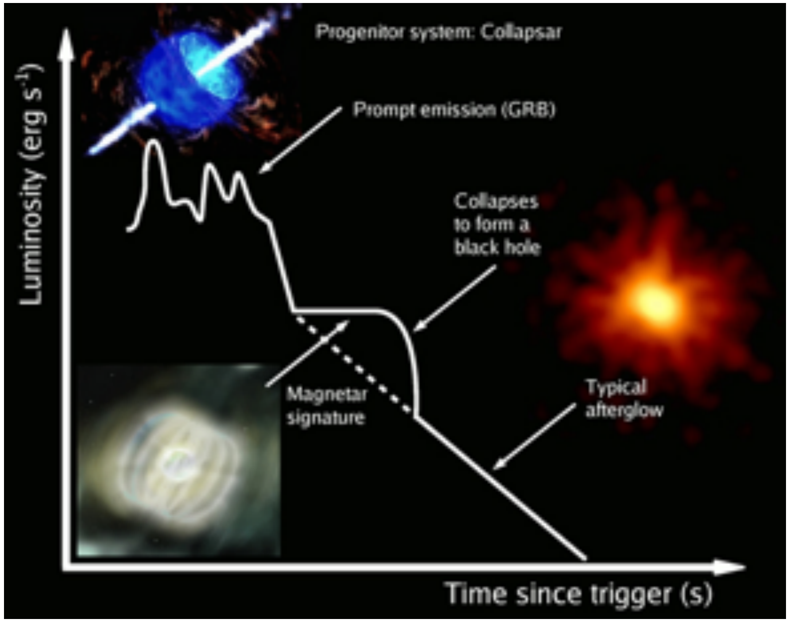
Racusin et al. (2017), Vianello et al. (2017)

Backup

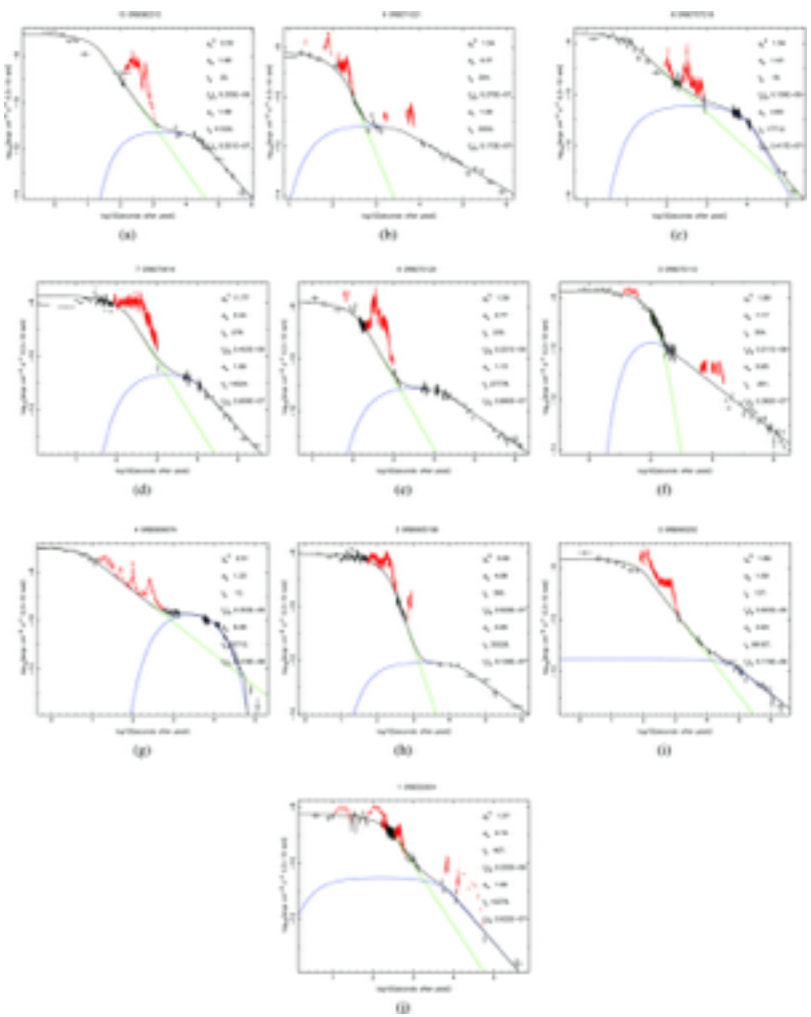
Evidence for Short-Lived Magnetars

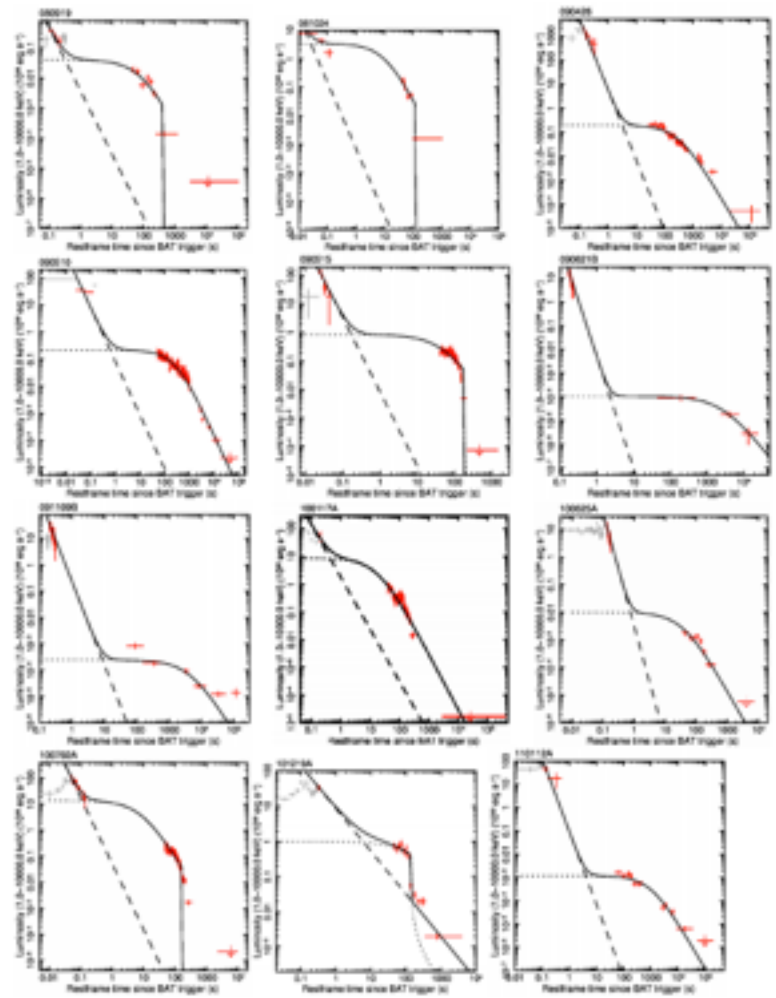
- Massive star collapses to a newly formed millisecond magnetar with enough rotational energy to prevent gravitational collapse
- Energy released as gravitational waves and EM radiation as magnetar spins down
- Magnetic field strength & rotation period could modulate jet production
- Can explain observational features
  - internal plateaus in X-ray afterglows
  - durations
  - energetics
  - lorentz factors
  - jet collimation





Long and Short GRB Magnetar Candidates





Lyons et al. 2009

Rowlingson et al. 2013