Fermi: an Ideal Partner for Gravitational Waves Observatories

Sara Buson

L. Blackburn, M. Briggs, E. Burns, J. Camp, T. Dal Canton, N. Christensen, V. Connaughton, A. Goldstein, M. Hui, P. Jenke, T. Littenberg, P. Shawhan, L. Singer, J. Veitch, C. Wilson-Hodge, B. Zhang

G. Vianello, N. Omodei, J. McEnery, J. Racusin, on behalf of the LAT Collaboration

GW:

IN THEORY

first kick to the field in 1916 (Einstein, Schwarzschild)

IN PRACTICE

Interesting, but challenging:

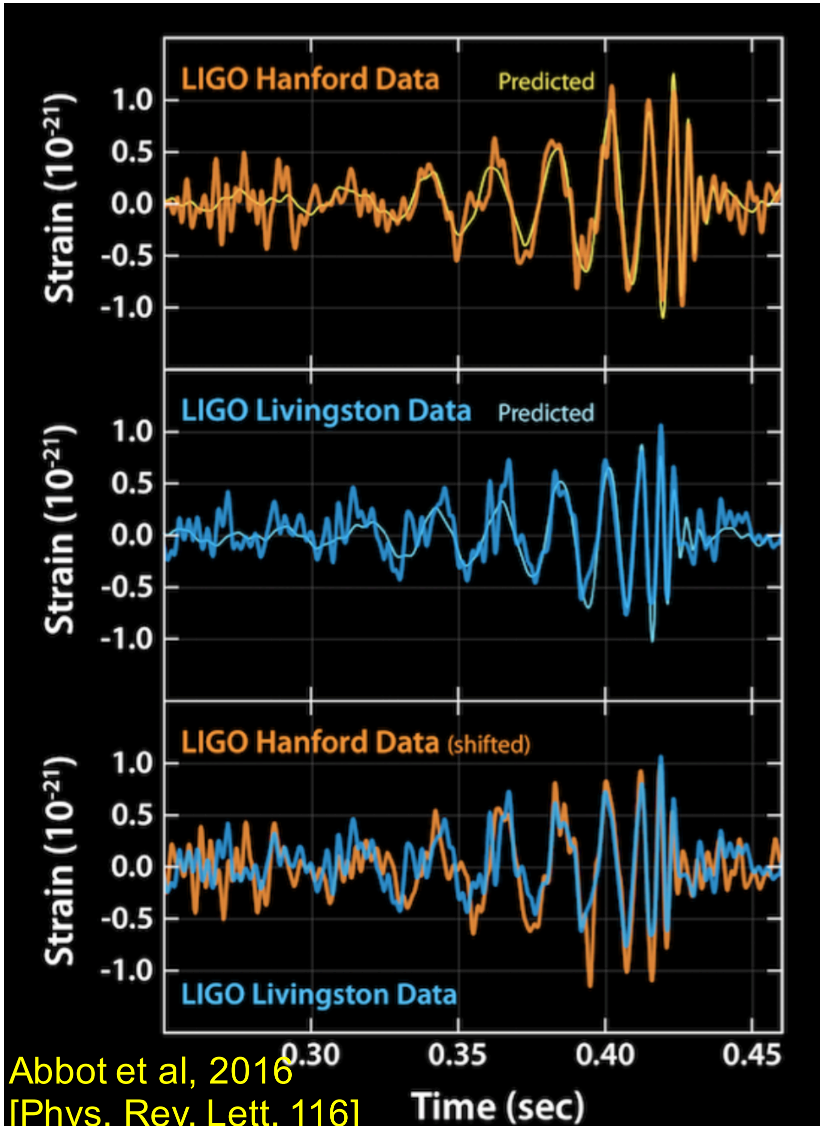
MANY YEARS OF OBSERVATIONS

.. IMPROVING LIMITS

… FINALLY, ON 2015-09-14

FIRST DETECTION!

GW150914

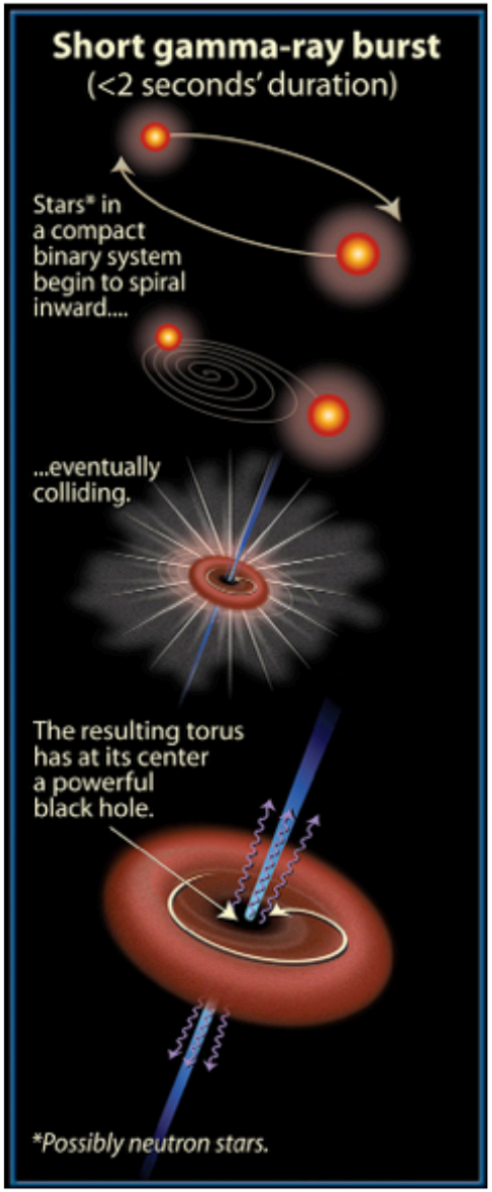


Abbot et al, 2016
[Phys. Rev. Lett. 116]

- Binary black-hole system
  - 9/14/2015 09:50:45 UTC
- 3 days before official start of 1st science run!
- 30-250 Hz sweep through LIGO band with peak h ~ 10^{-21}
- LIGO Hanford+Livingston, 7ms between sites
- Perfect match to GR waveform
- localized to an area of approximately 600 deg^2 (90% credible region)

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

SGRB / CBC association



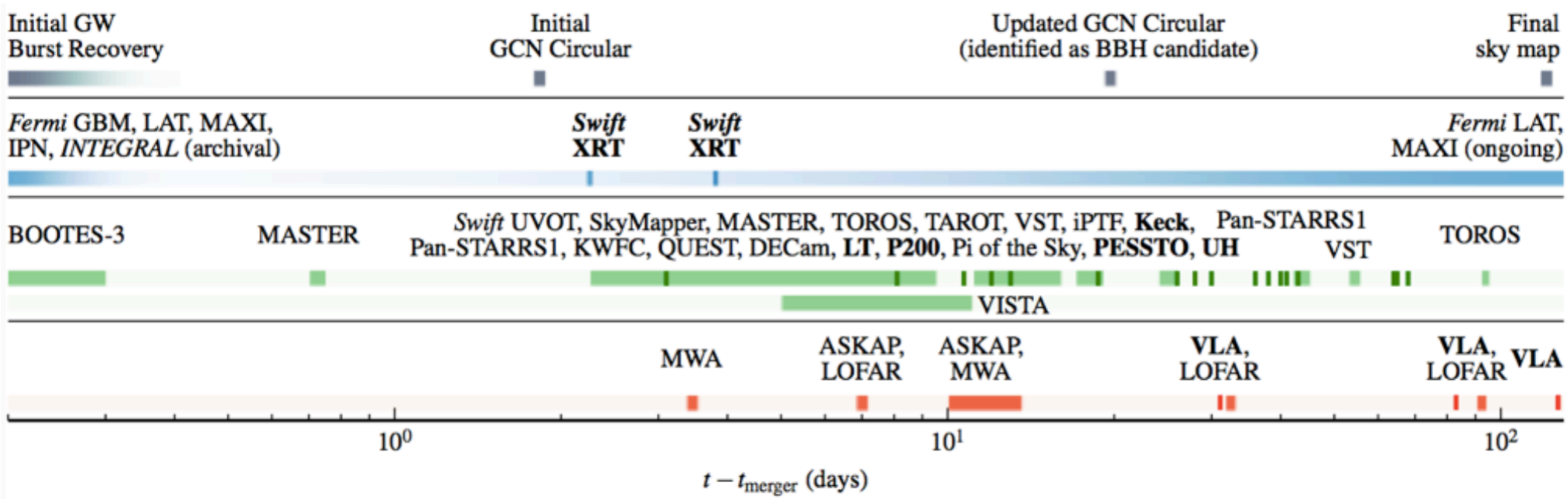
NASA and A. Feild (STScI)

- NS-NS merger is a leading candidate for SGRB progenitor
  - Expect coincident SGRB+GW observation for nearby events

Synergy between GW and EM observation:

- GW
  - inspiral signature confirms compact binary coalescence (CBC)
  - progenitor model
  - information about binary system parameters
  - precise merger time
  - standard candle → luminosity distance
- EM
  - detection confidence
  - EM energetics
  - x-ray or optical afterglow gives precise location
  - breaks degeneracies in binary parameter estimation
  - host galaxy / redshift
  - local environment

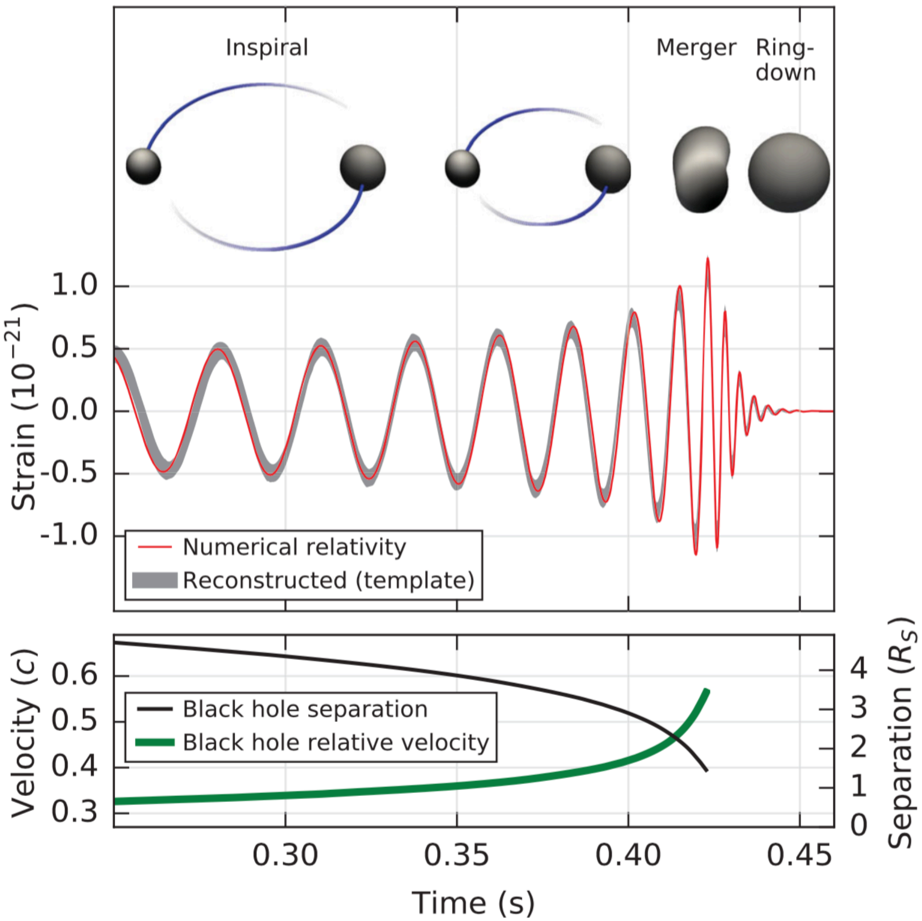
GW150914 broadband EM follow-up



- Real-time un-modeled search triggered within 3m of event
- Alert sent within 2d (due to O1 not having started yet)
- 63 EM groups prepared to observed during O1, 25 follow-ups in EM via private GCN

Abbot et al, 2016 [arXiv:1602.08492]

First GW detection /// *Fermi* EM Follow up



Abbott+ 2016

***Fermi* GBM** Observations of LIGO Gravitational Wave event GW150914

arXiv:1602.03920

ABSTRACT

With an instantaneous view of 70% of the sky, the *Fermi* Gamma-ray Burst Monitor (GBM) is an excellent partner in the search for electromagnetic counterparts to gravitational wave (GW) events. GBM observations at the time of the Laser Interferometer Gravitational-wave Observatory (LIGO) event GW150914 reveal the presence of a weak transient source above 50 keV, 0.4 s after the GW event was detected, with a false alarm probability of 0.0022. This weak transient lasting 1 s does not appear connected with other previously known astrophysical, solar, terrestrial, or magnetospheric activity. Its localization is ill-constrained but consistent with the direction of GW150914. The duration and spectrum of the transient event suggest it is a weak short Gamma-Ray Burst arriving at a large angle to the direction in which *Fermi* was pointing, where the GBM

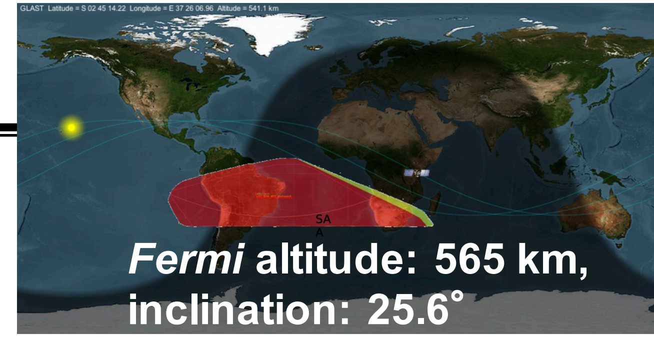
***Fermi* LAT** Observations of the LIGO Event GW150914

arXiv:1602.04488

ABSTRACT

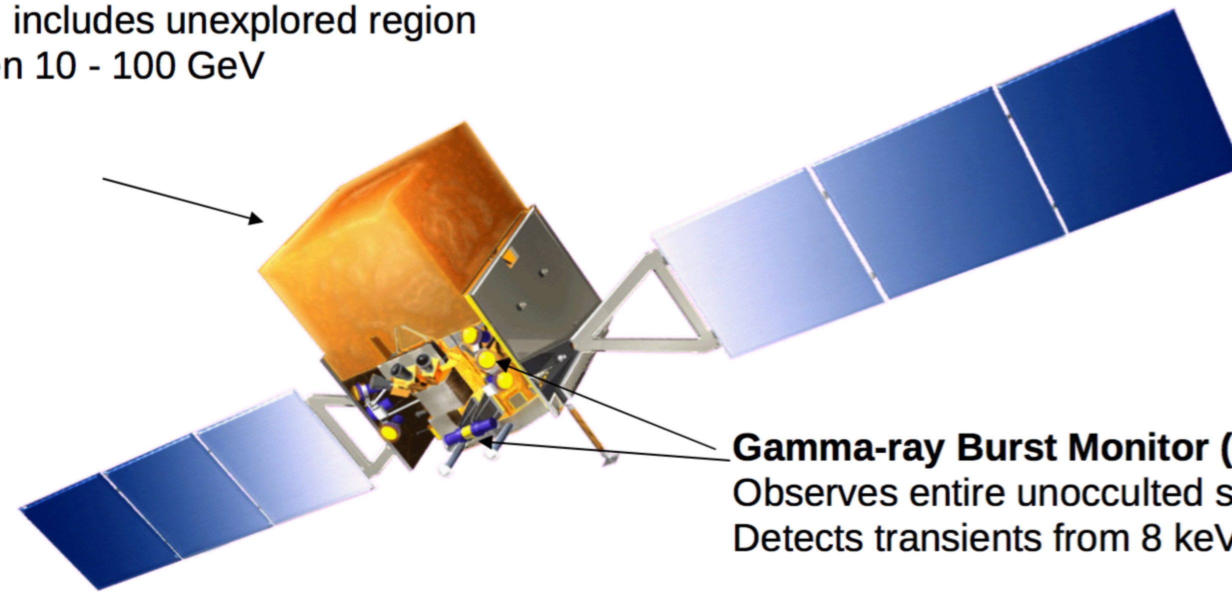
The *Fermi* Large Area Telescope (LAT) has an instantaneous field of view covering $\sim 1/5$ of the sky and completes a survey of the entire sky in high-energy gamma rays every 3 hours. It enables searches for transient phenomena over timescales from milliseconds to years. Among these phenomena could be electromagnetic counterparts to gravitational wave sources. In this paper, we present a detailed study of the LAT observations relevant to Laser Interferometer Gravitational-wave Observatory (LIGO) event GW150914 (Abbott et al. 2016), which is the first direct detection of gravitational waves and has been interpreted as due to the coalescence of two stellar-mass black holes.The localization region for GW150914 was outside the LAT field of view at the time of the gravitational-wave signal. However, as part of routine survey observations, the LAT observed the entire LIGO localization region within ~ 70 minutes of the trigger, and thus enabled a comprehensive search for a γ-ray counterpart to GW150914. The study of the LAT data presented here did not find any potential counterparts to GW150914, but it did provide limits on the presence of a transient counterpart above 100 MeV on timescales of hours to days over the entire GW150914 localization region.

The *Fermi* Observatory



Fermi monitors the sky 8 keV → 300 GeV, timescales from μs to years, responds autonomously to bright triggers

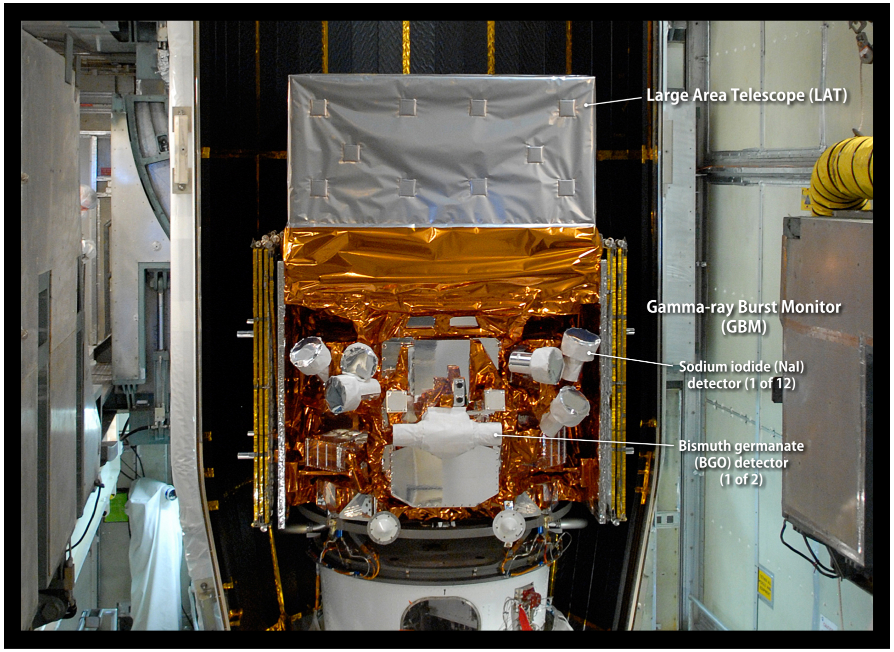
Large Area Telescope (LAT)
Observes 20% of the sky at any instant, includes unexplored region between 10 - 100 GeV



Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

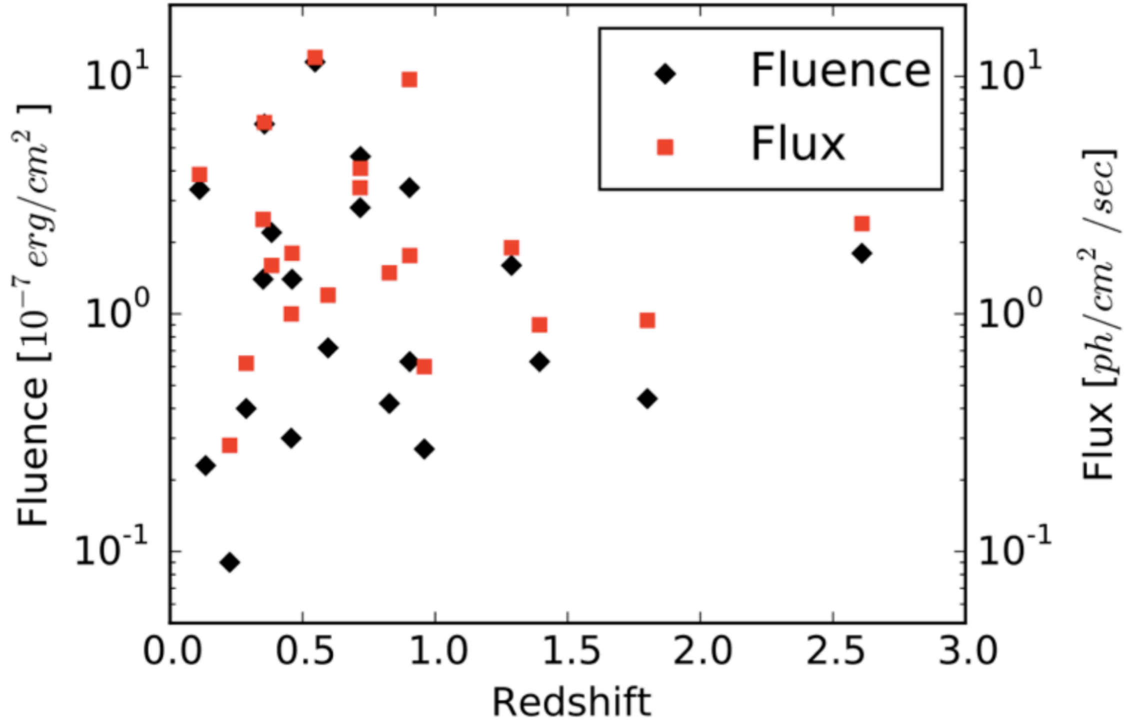
Gamma-ray Burst Monitor (GBM)

- Most prolific detector of GRBs currently operating with capability to localize and characterize
  - ~240 triggered GRBs per year (200 long, 40 short)
- Wide energy response (8 keV - 40 MeV) with 12 NaI and 2 BGO scintillation detectors
- All-sky exposure (except what is blocked the Earth) ~70%



GBM fluence vs red-shift
close ≠ bright

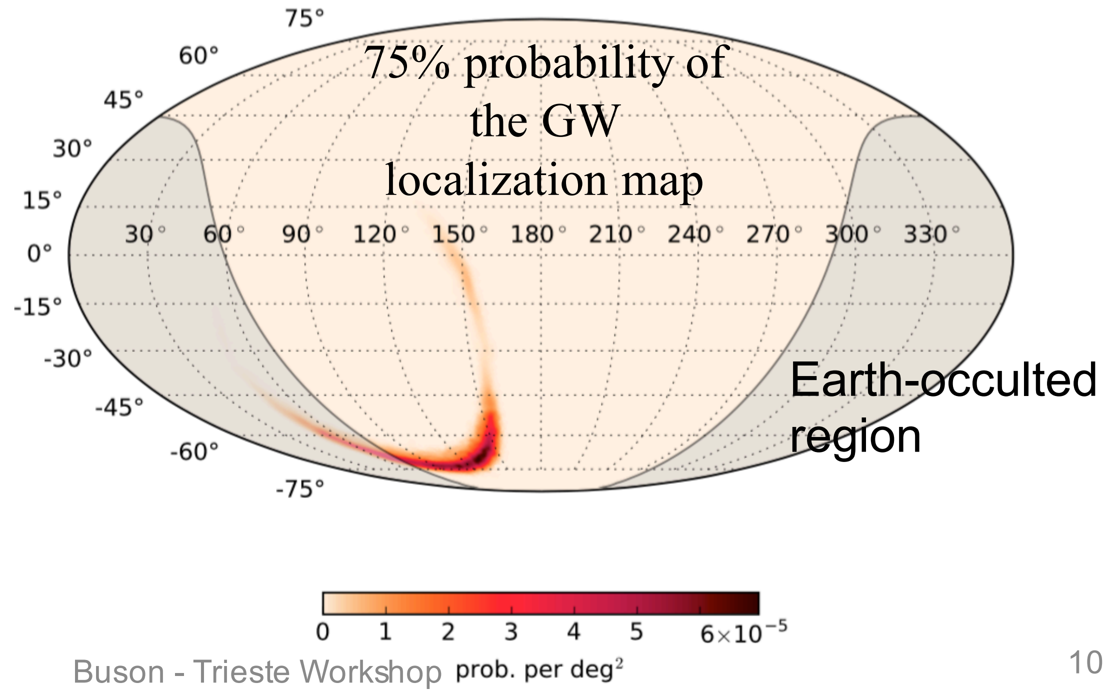
- Brightness of weak short GRBs does not appear to be redshift dependent
- finding more weak short GRBs (intrinsic or observational) benefits GW counterpart search
- Increasing the number of short GRBs



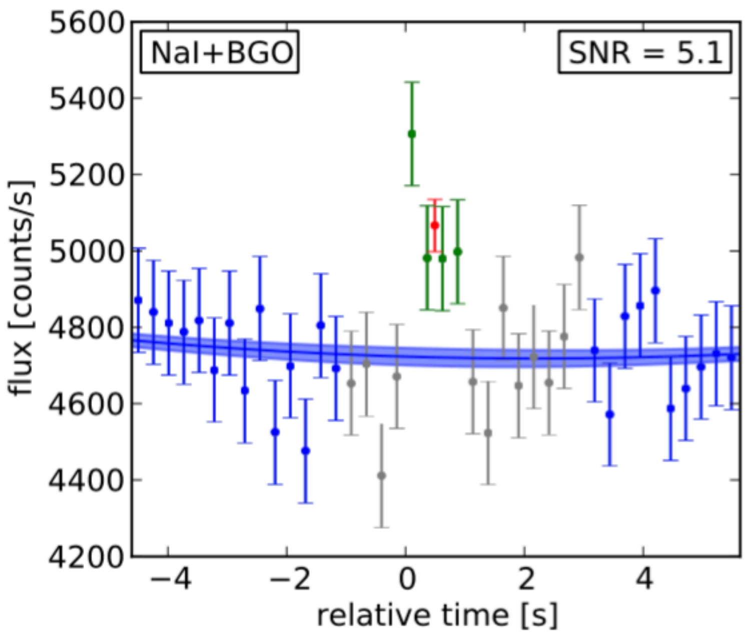
- untriggered blind search pipeline: http://gammaray.nsstc.nasa.gov/ gbm/science/sgrb_search.html
- joint LIGO-GBM coherent search pipeline (Blackburn et al. 2015)

Fermi Counterpart Candidate GW150914-GBM

- At the time of the GW detection Fermi was operating in survey mode. GBM instantaneous sky coverage of ~ 70% (the rest is Earth blocked)
- Continuously recording data from ~2hrs before and 7hrs after the GW event
- Entire region was visible to Fermi GBM 25 minutes after the GW event was detected



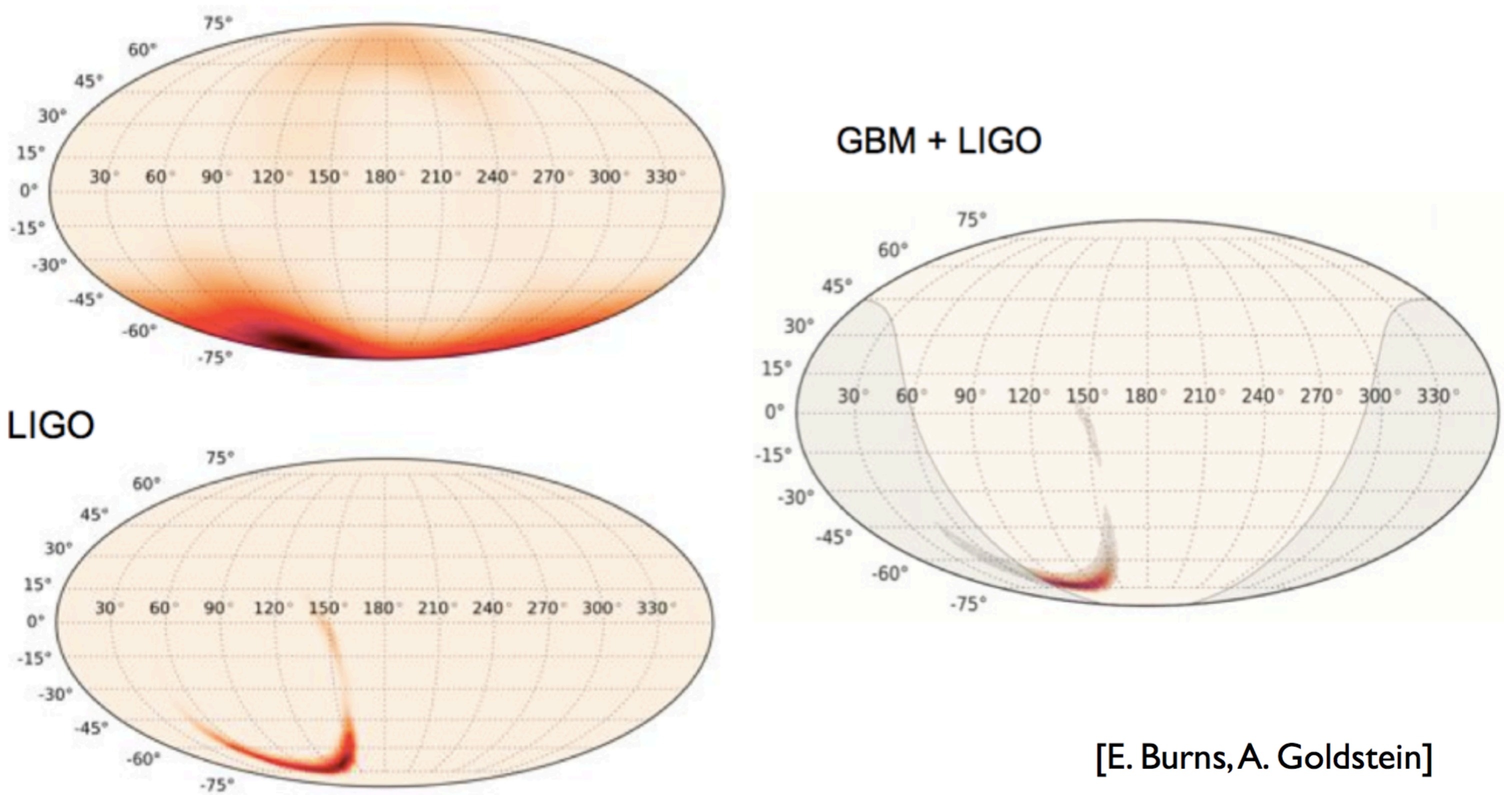
Fermi Counterpart Candidate GW150914-GBM



- Untriggered sub-threshold signal is consistent with a low-fluence short GRB coming from behind *Fermi*
- 0.4 s after LIGO trigger
- poorly localized, but consistent with LIGO localization

- **Search within ±30s GW event** (if GRBs are related to compact binary mergers we expect the impulsive gamma-ray emission to be close in time to the GW; precursors to sGRBs have been observed)
- **One plausible candidate: GW150914-GBM**
- **Sub-threshold signal**
- **Localization close to the Earth's limb**
- **False alarm probability: 0.0022**

Localization

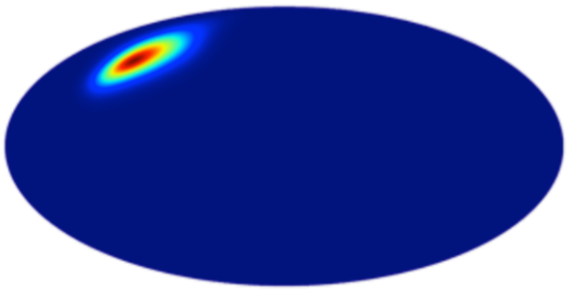


[E. Burns, A. Goldstein]

- localization difficult due to hard spectrum, poor detector geometry, and poor statistics
- Typical localization done in 50-300 keV, expanded to 100-1000 keV to collect more photons
- GBM counterpart detections can significantly constrain LIGO sky region

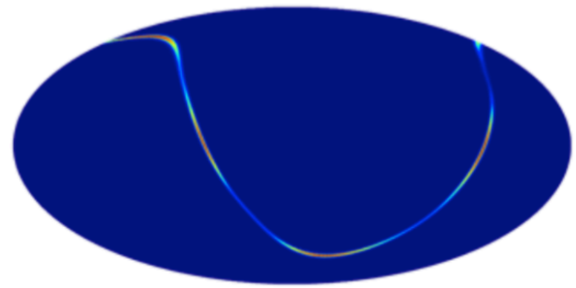
Benefits of Coincident GBM-LIGO Localizations

Typical GBM GRB localization region
for weak GRB



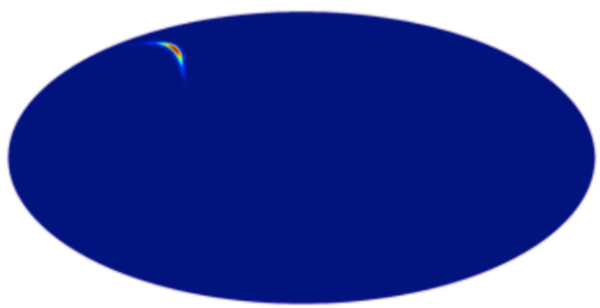
+

Typical LIGO localization region from
http://www.ligo.org/scientists/first2years/:
changes in 2016 with addition of Virgo



18 +/- 5 nearby galaxies (N. Gehrels et al. 2015, arXiv:1508.03608)

=



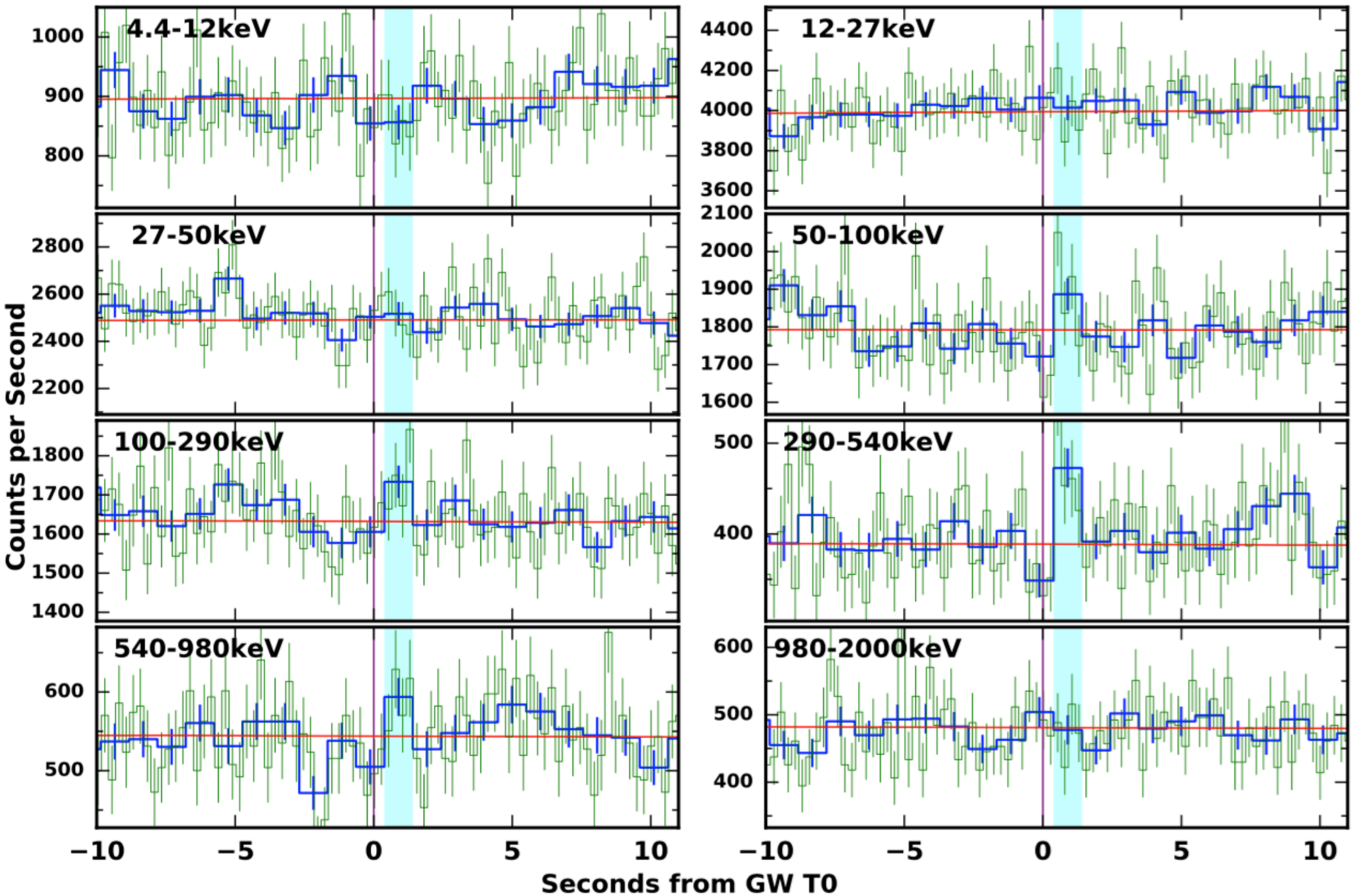
Typical reduction of 80% in sky region:

4 nearby galaxies: easier to follow up
with XRT or optical telescopes.

Credit: Valerie Connaughton & Eric Burns

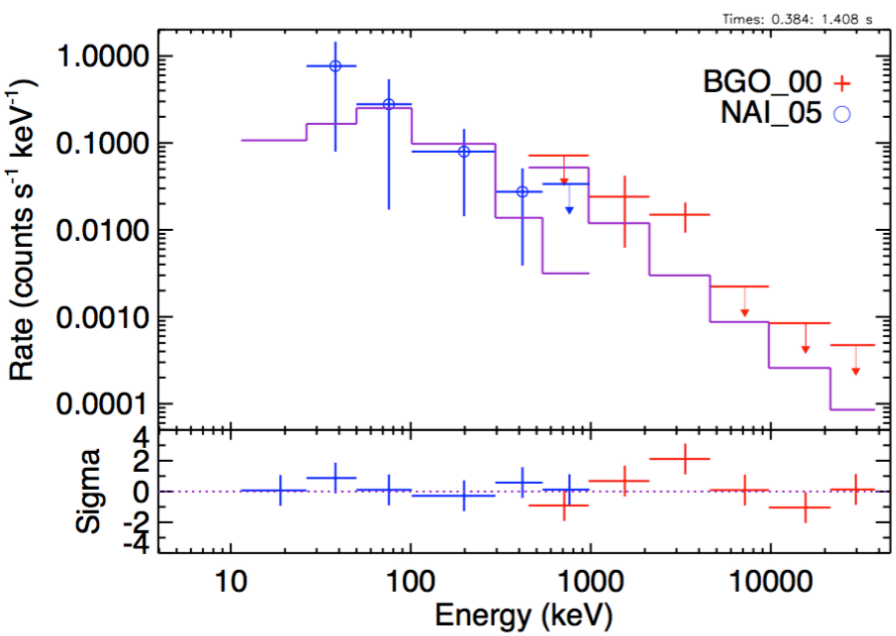
Count Rates Summed over NaI Detectors in 8 Energy Channels

rise and fall of signal across NaI energy range similar to typical sGRB



GW150914-GBM spectrum

Power-law fit to the GBM data



- The model is a reasonable fit to the count spectrum even at low energies
- The fit parameter values are typical for short GRBs
- Power law index of about -1.4
- A fluence of 2.4 x 10^{-7} erg cm^{-2} is nearly average for short GRBs (with 40% of short GRBs detected by GBM weaker than this)

- If GW150914-GBM is part of the short GRB population, then its fluence is not atypical but its unfortunate arrival direction yields only a weak signal in GBM

Comparison to known background

	Duration	Localization	Energy Spectrum	Lightcurve Shape	*Fermi* Orbit Position	Possible?
Lightning	No	No			No	No
Galactic Sources		No	No			No
Solar Activity		No	No	No		No
Magnetospheric				No	No	Unlikely
Something New	?	?	?	?	?	?
Short GRB	Yes	Yes	Yes	Yes		Yes

Does not match known sources of transient noise seen in GBM
Consistent with expected signature of short GRB, although weak (low statistics) and unfavorable geometry

Gamma-ray Counterpart to BBH: Theoretical Speculation and Discussion

- **One or both are black holes are charged** - Bing Zhang (arXiv: 1602.04542)
- **Collapse of massive star into two black holes** - Abraham Loeb (arXiv:1602.04735)
- **Difficulty explaining signal from a single massive star** – S. E.Woosley (arXiv: 1603.00511)
- **Predicted radio and optical afterglow observations if signal is real** – Ryo Yamazaki, et al. (arXiv:1602.05050)
- **Both have magnetic fields leading to magnetic reconnection** – F. Fraschetti (arXiv: 1603.01950)
- **Short-lived naked singularity** – Daniele Malafarina, Pankaj S. Joshi (arXiv: 1603.02848)
- **Fossil accretion disk re-activated during merger** – Rosalba Perna, Davide Lazzati, Bruno Giacomazzo (arXiv: 1602.05140)
- **Require strong astrophysical magnetic field for gamma-ray counterpart** – Maxim Lyutikov (arXiv: 1602.07352)

GW150914-GBM Characteristics

The data for GW150914-GBM imply a weak but significant hard X-ray source with a spectrum that extends into the MeV range and a location that is **consistent with** an arrival direction along the southern lobe of the sky map for **the GW event GW150914**.

At a distance of ~410 Mpc implied by the GW observations, one obtains a source luminosity between 1 keV and 10 MeV of 1.8×10^{49} erg s^{-1}

Lyutikov 2016:

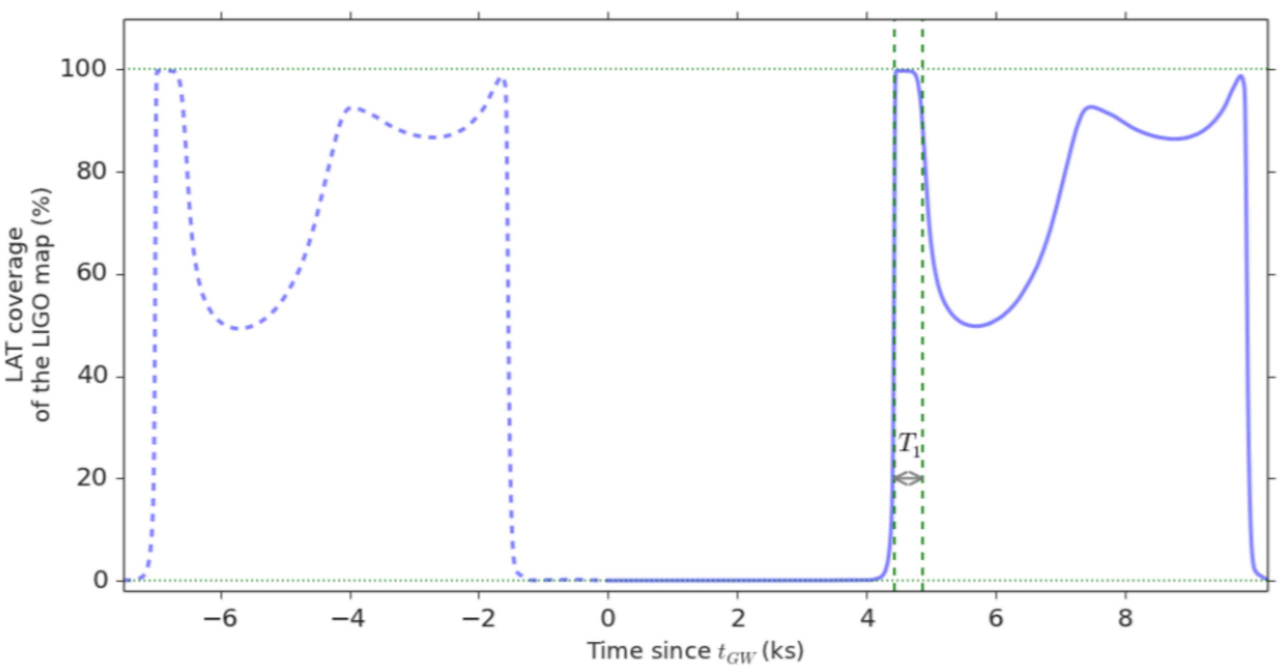
The physical constraints required by the association of the Fermi GBM signal contemporaneous with GW150914 - radiative power of 10^{49} erg s^{-1}, and corresponding magnetic fields on the black hole of the order of 10^{12} Gauss - are astrophysically highly implausible.
(e.g. would require bulk Lorentz factor $\Gamma \approx 100$)

INTEGRAL Upper Limit

- **Looking for a signal in INTEGRAL-ACS** at the time of GW150914-GBM: **no excess above background is found**
- The INTEGRAL-ACS team reported a fluence limit of 1.3×10^{-7} erg cm^{-2} in the 100 keV – 100 MeV energy range based on a null detection over a 1s period (Ferrigno et al. 2015).
  - This is lower than the value 3.8×10^{-6} erg cm^{-2} obtained by propagating the fluence of GW150914-GBM into the INTEGRAL range using the power-law function fit to the GBM data
  - However, more realistic a power-law fit with a break, which gives: $2.0/6.2 \times 10^{-7}$ erg cm^{-2}
  - Additionally, a search of the INTEGRAL-ACS data revealed a detection rate of only 55% of GBM-detected weak short GRBs (Briggs et al., in preparation)
- **Ongoing work to investigate population of missing GBM weak short-GRBs in Integral, and joint spectral fitting of any plausible GW150914 counterpart**

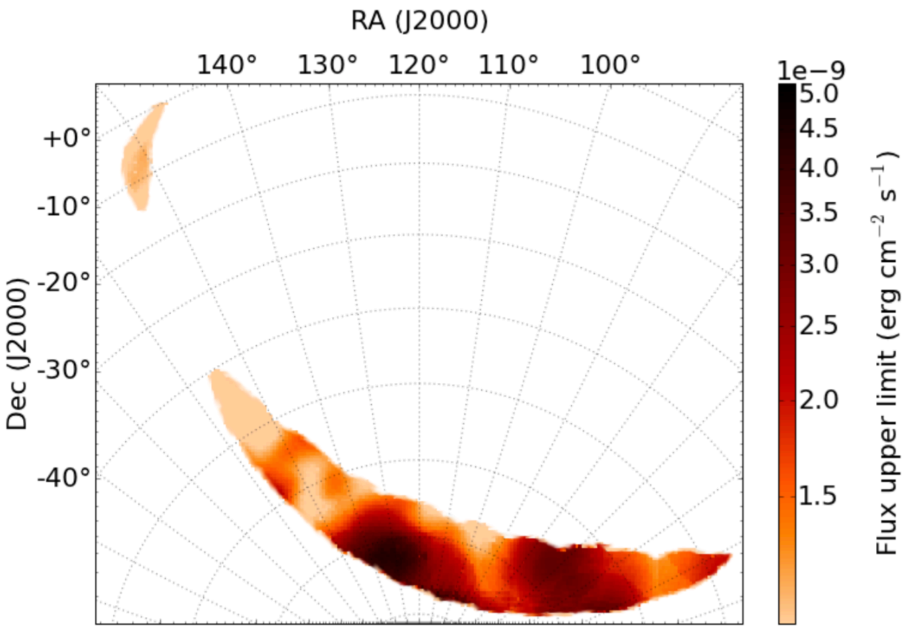
Fermi-LAT coverage of LIGO localization map

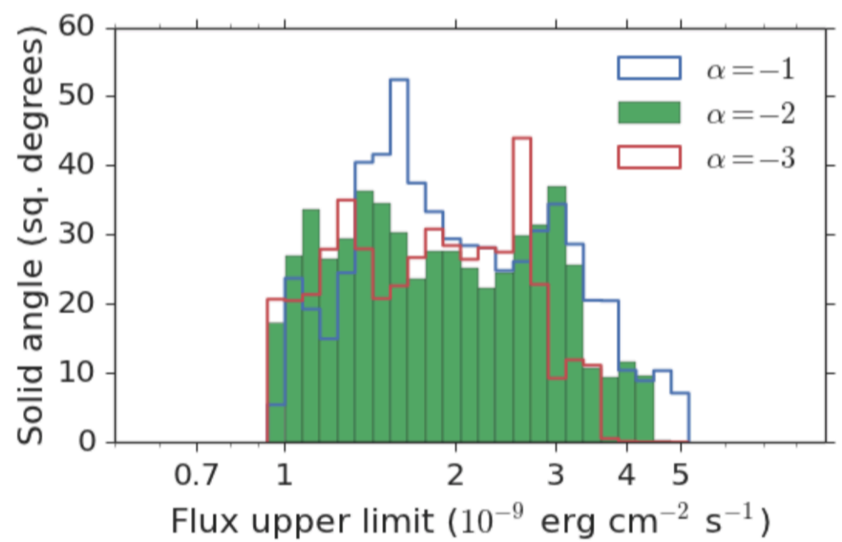
The LIGO localization arc for GW event GW150914 became observable by the *Fermi* LAT ~4000 s after the GW event
Entire LIGO localization region observed within ~70 minutes of the trigger
A search for high-energy emission over time-scales comparable to the search in hard X rays has been performed



LAT Flux UL -- *Short-baseline search*

- **Unbinned likelihood analysis: No significant excess found**
- **95% CL Flux upper limits during the interval *T*1 (4442–4867s from t_0) (100MeV-1GeV) calculated for each pixel in the MAP**
  - **Source assumed to be a power law with alpha=2 (but only weak dependence**





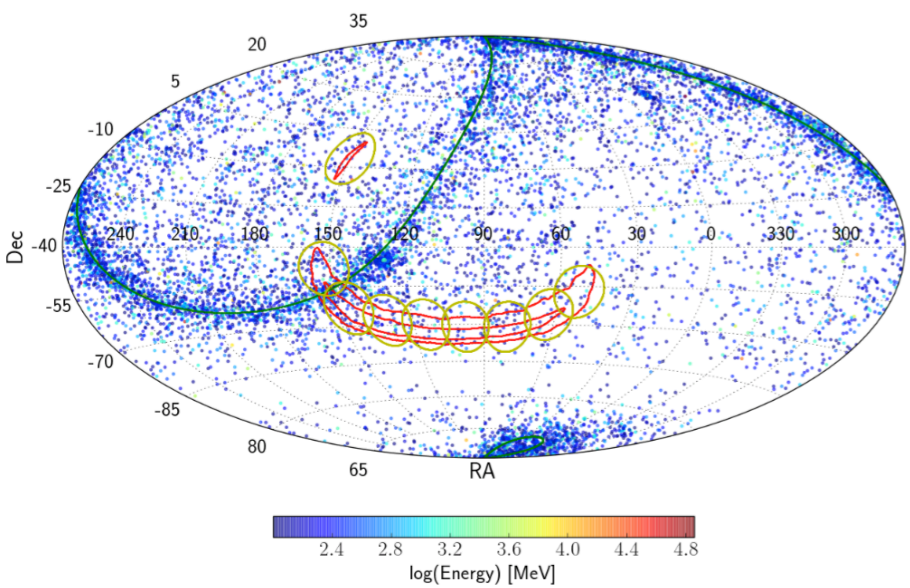
LAT Flux UL -- *Long-baseline search*

Cover the LIGO contour with 9 partially overlapping ROIs, for each ROI we do 2 different analysis:

– Search for long transients (+/-10 ks and +/- 1 days since t_0)

– Search for short transient (orbit-by-orbit) in +/- 1 months since t_0)

No signal was significantly detected in any of these time windows.



EM Counterparts to BBH Mergers

- The GW150914 waveform is consistent with the expectation from the merger of **two stellar-mass BHs** (Abbott et al. 2016).
  - Expected progenitors of sGRBs are double NS binaries or NS-BH systems, → **a classical sGRB counter part to GW150914 is not expected**.
  - Predictions for EM counterparts to stellar-mass BH mergers few in number:
    - Most of the numerical simulation work has focused on supermassive BH mergers, where circumbinary disk formation is expected with ample gas supply available to power the EM counterpart
    - Stellar-mass BH mergers requires a substantial quantity of nearby gas to form the disk-jet system
    - **Stellar mass BH-BH systems are "clean" systems**, where little accretion is expected: **NO EM counterpart expected!**
    - ***GW150914-GBM poses an interesting dilemma for theoretical models***
    - ***Unfortunately, the GBM candidate cannot be corroborated with LAT***

- **More opportunities to search for EM counterparts to gravitational waves in future runs**
  - ***Fermi will be central in the quest***

Fermi Transient Searches

Fermi Gamma-ray Space Telescope

Pipelines Timescale

Pipeline
Method
Timescale
Distribution
Status

LAT Transient Factory (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/

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

GBM Untriggered 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

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

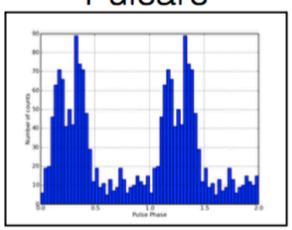
μs ***ms*** ***s*** ***minutes*** ***hours*** ***days*** ***months*** ***years***

Transients Timescale

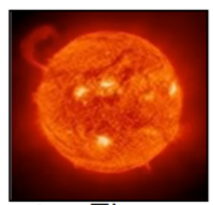
Photon Timing

All Sky Cadence

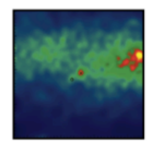
Pulsars



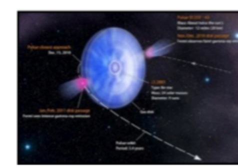
Solar Flares



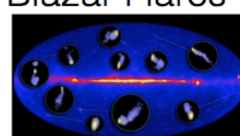
Novae



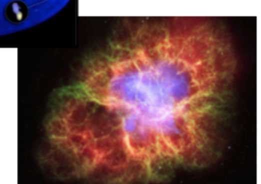
γ-ray Binaries



Blazar Flares

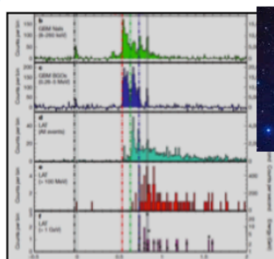


Crab Flares



Terrestrial γ-ray Flashes

GRBs



Magnetar Flares

Not to scale

Back up

Gamma-ray Burst Monitor (GBM)

- **12 NaI detectors**, 1.27 cm thick by 12.7 cm diameter, directly coupled to a 12.7 cm diameter photomultiplier tube (PMT)
- Spectral coverage from about **8 keV to 1 MeV**
- Arranged in 4 banks of 3 detectors so that the larger number of detectors, each viewing a smaller field-of-view, reduces systematic errors for burst locations and allow an improved triggering algorithm

- **2 BGO detectors,** 12.7 cm in diameter, 12.7 cm thick, and is viewed by 2 PMTs for improved resolution and redundancy
- Spectral coverage from ~ **150 keV to 40 MeV**
- Overlap with lower energy range of the LAT

Trigger: two detectors are required to be above a threshold specified in standard deviations **above background in the 50-300 keV energy range on a 1.024 second time-scale**