Fermi-LAT Observation of GW events

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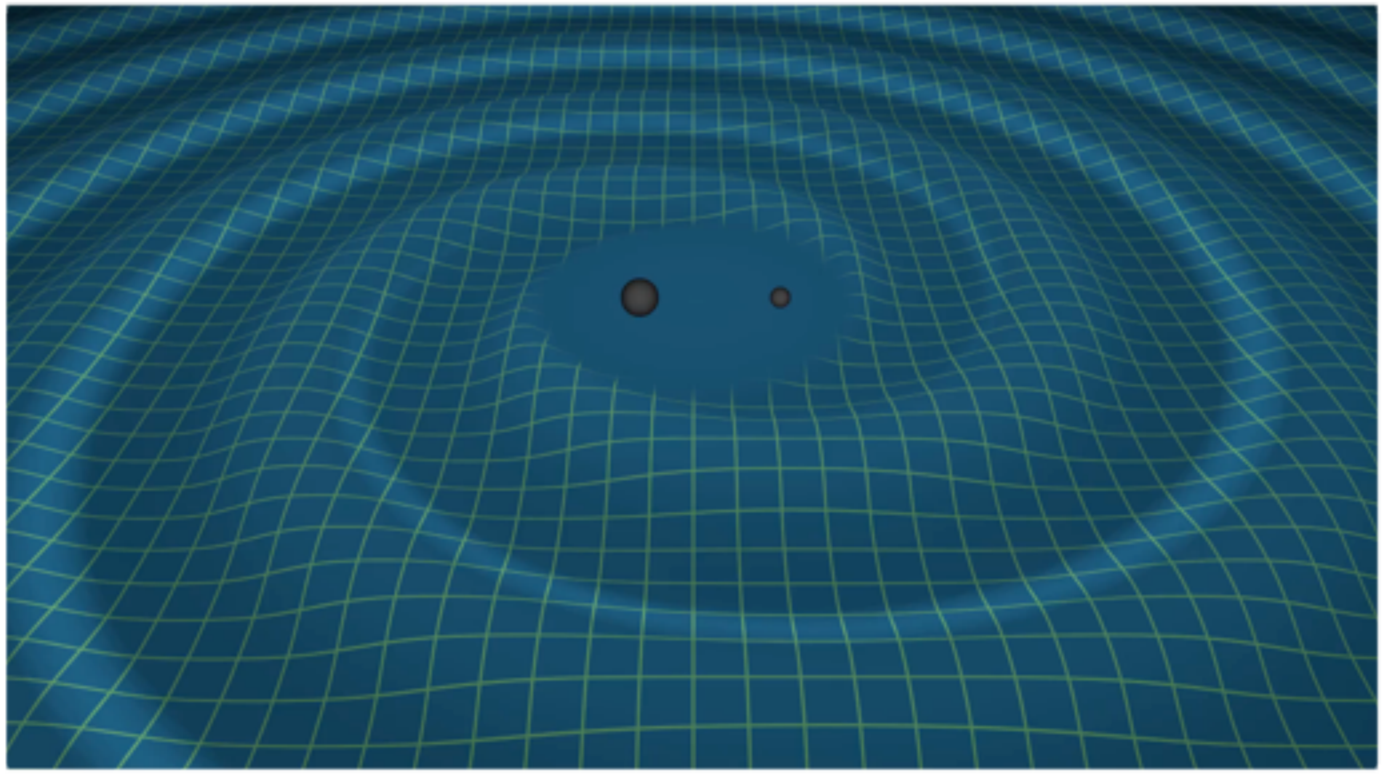
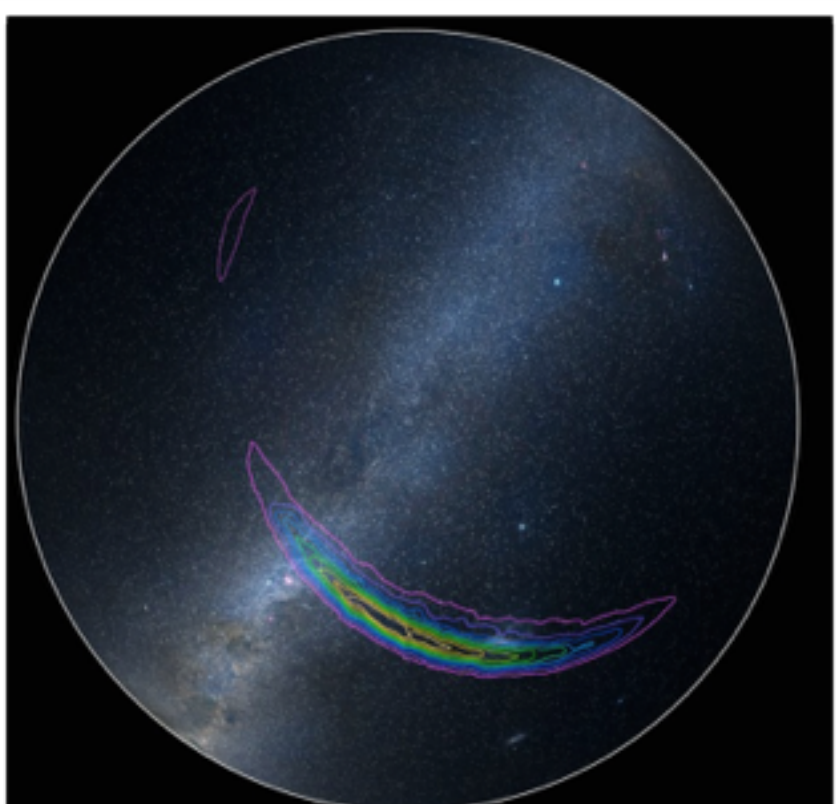
for the Fermi LAT collaboration

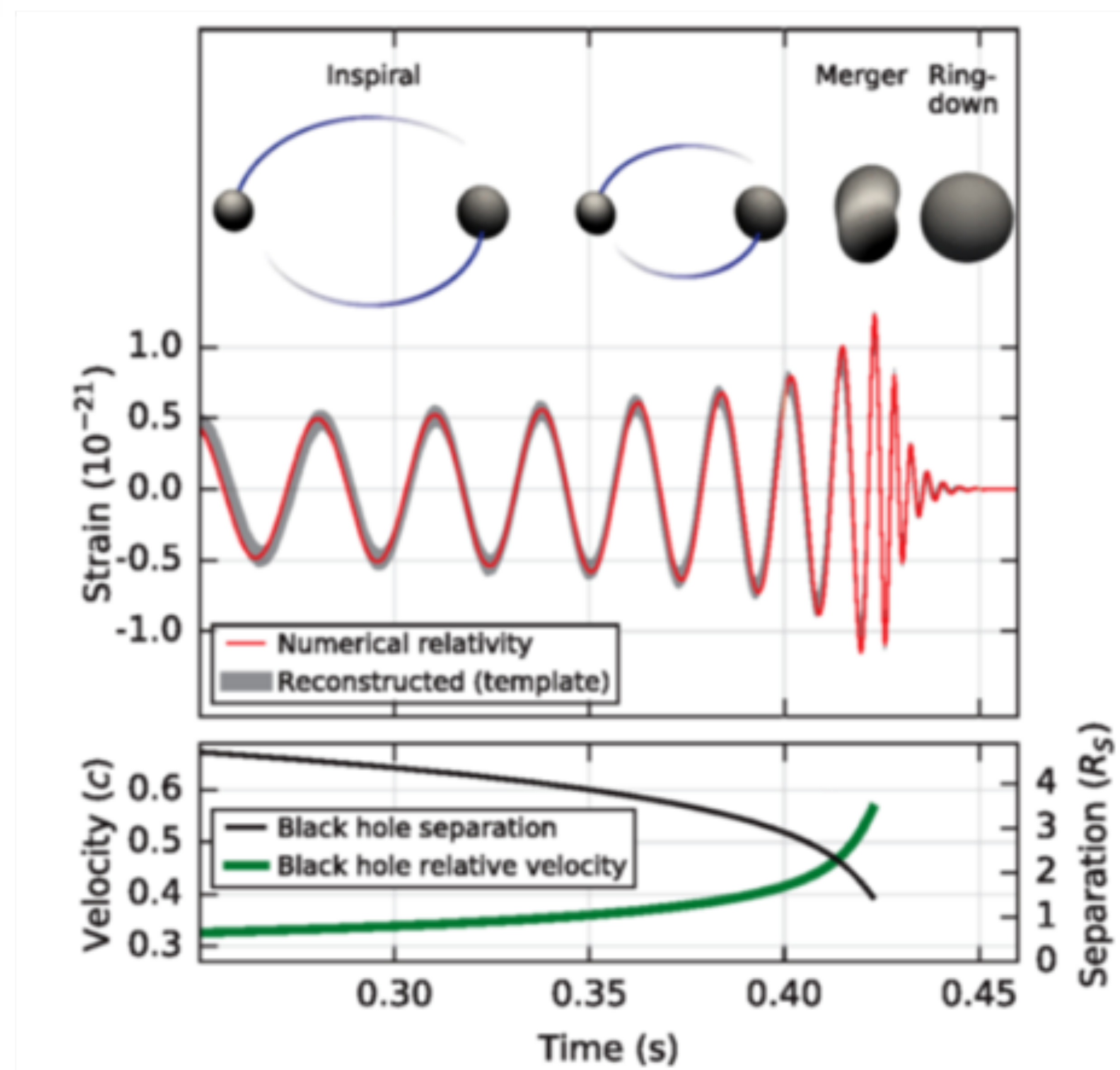
KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS AND COSMOLOGY

The Discovery



February 11, 2016, the LIGO Scientific Collaboration and Virgo Collaboration teams announced that they had made the first observation of gravitational waves, originating from a pair of merging black holes using the Advanced LIGO detectors.





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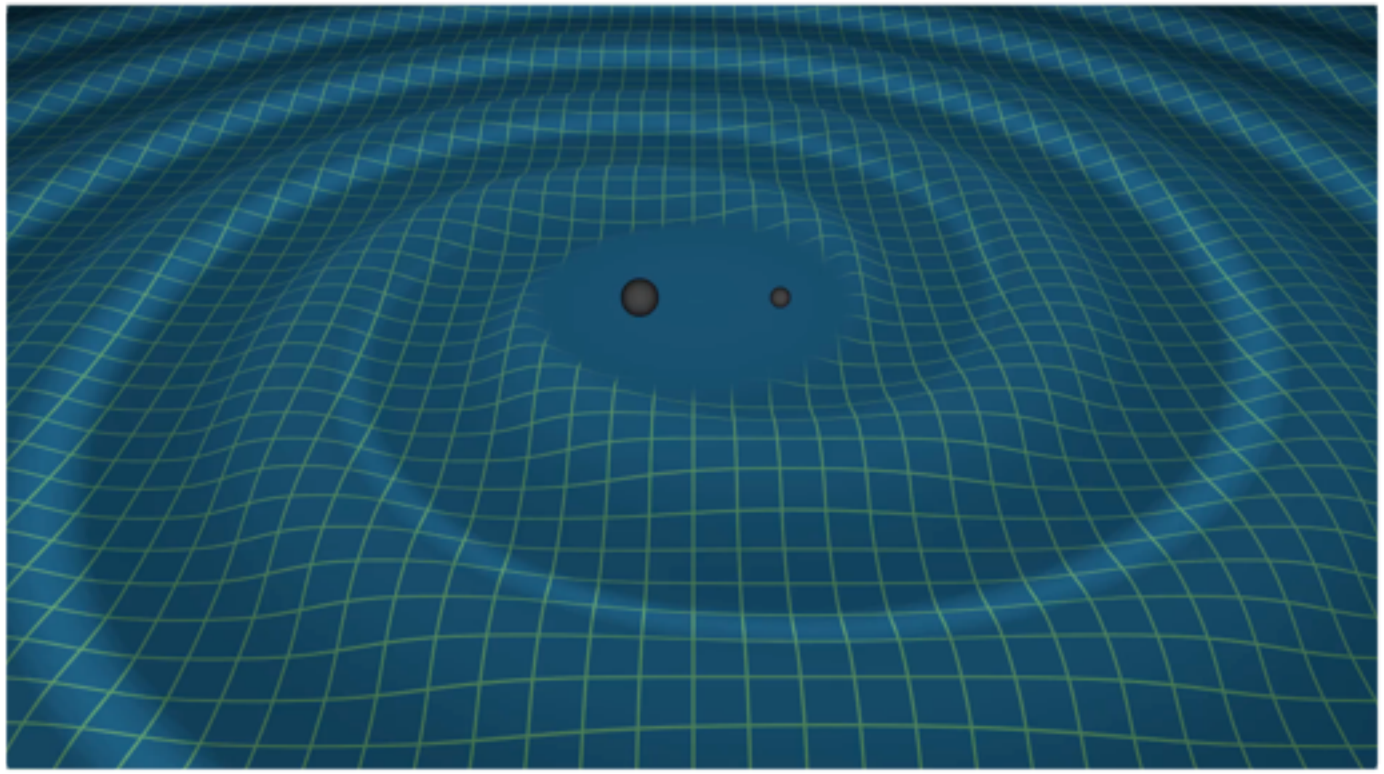

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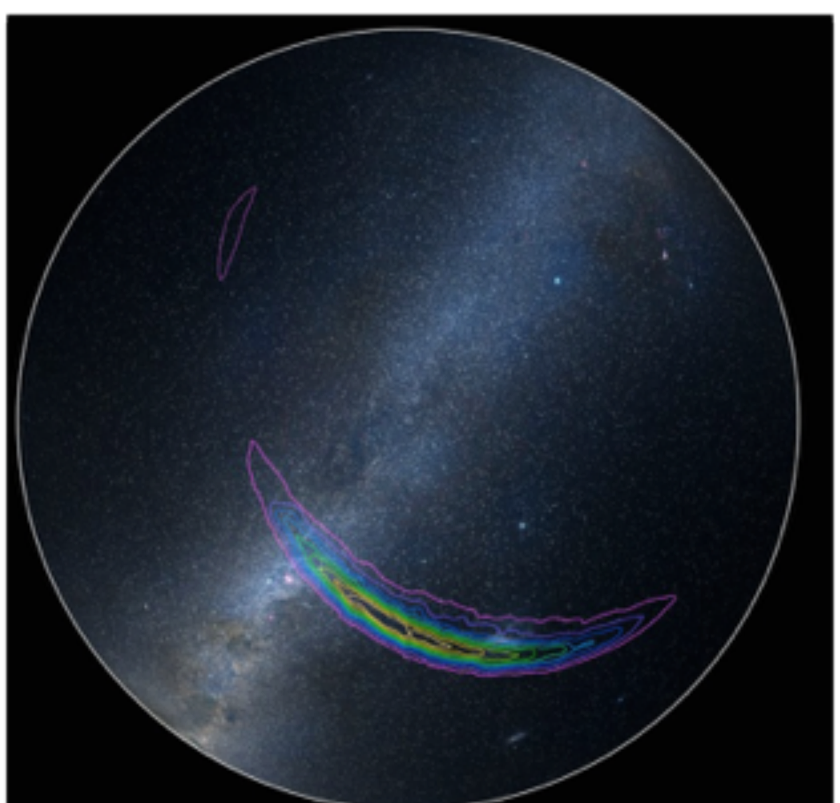
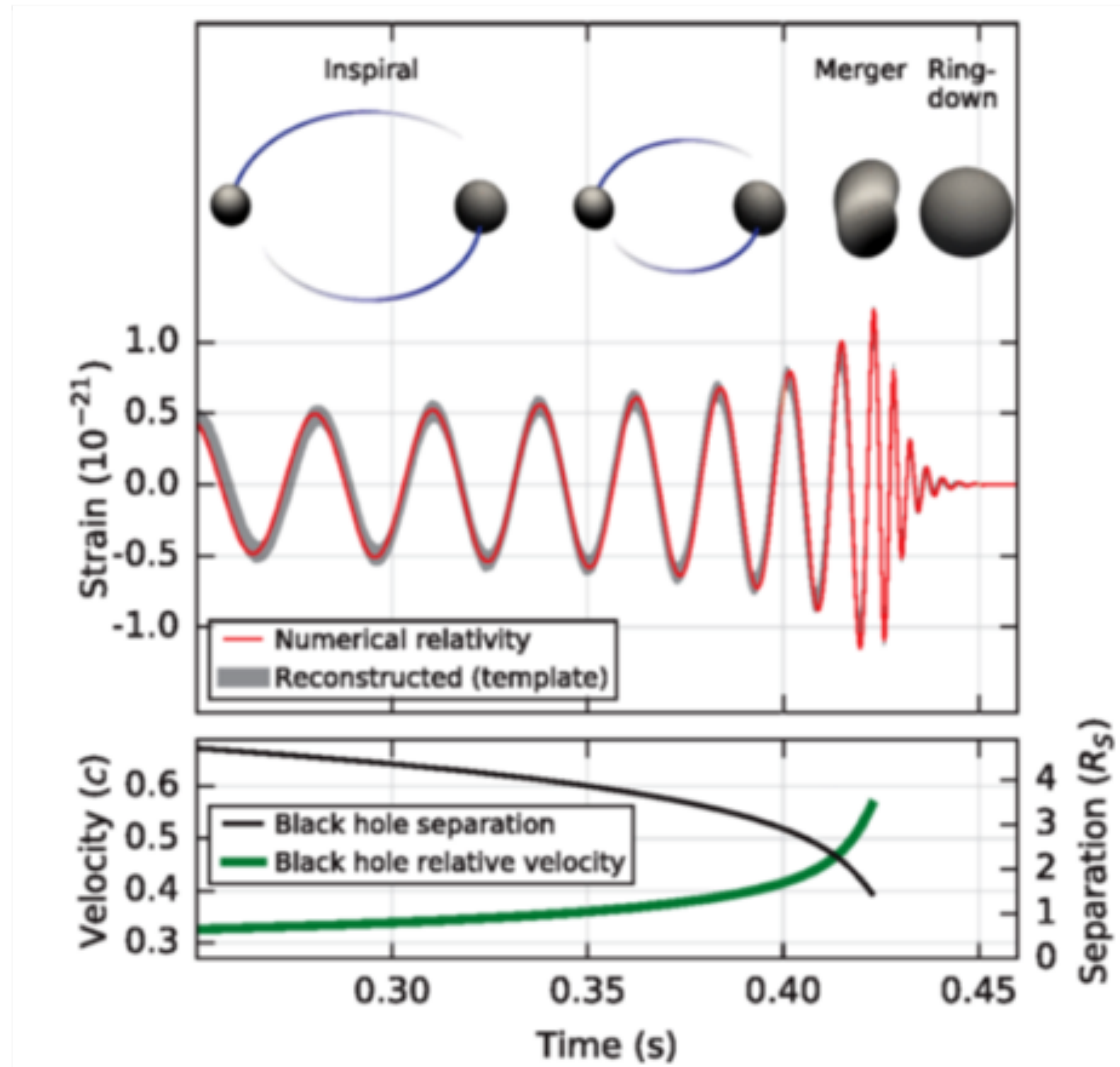
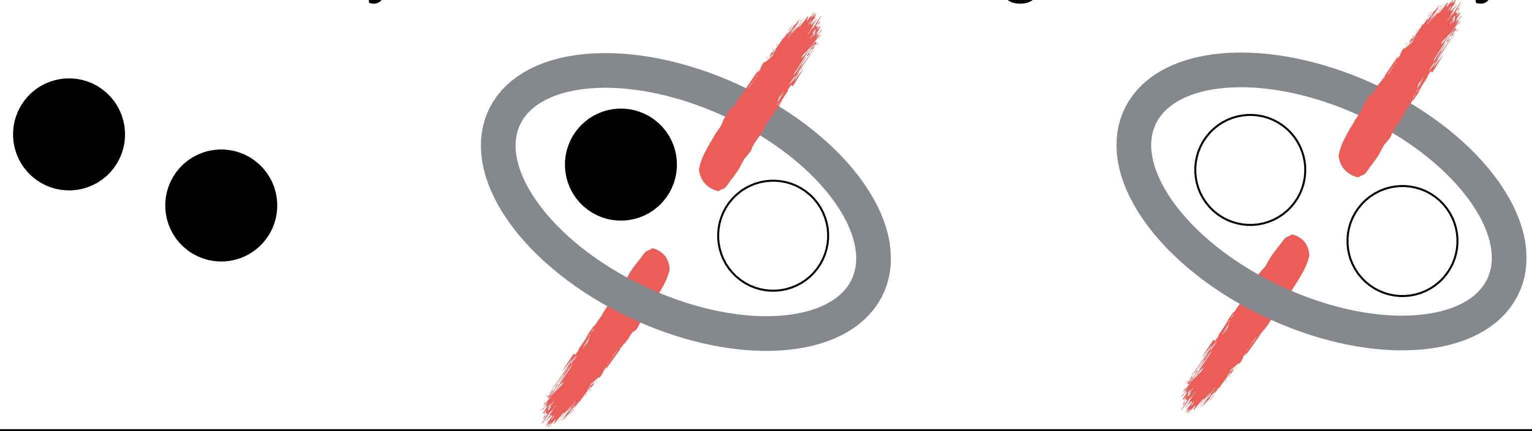




GW and EM signal

GW astronomy vs multi messenger astronomy

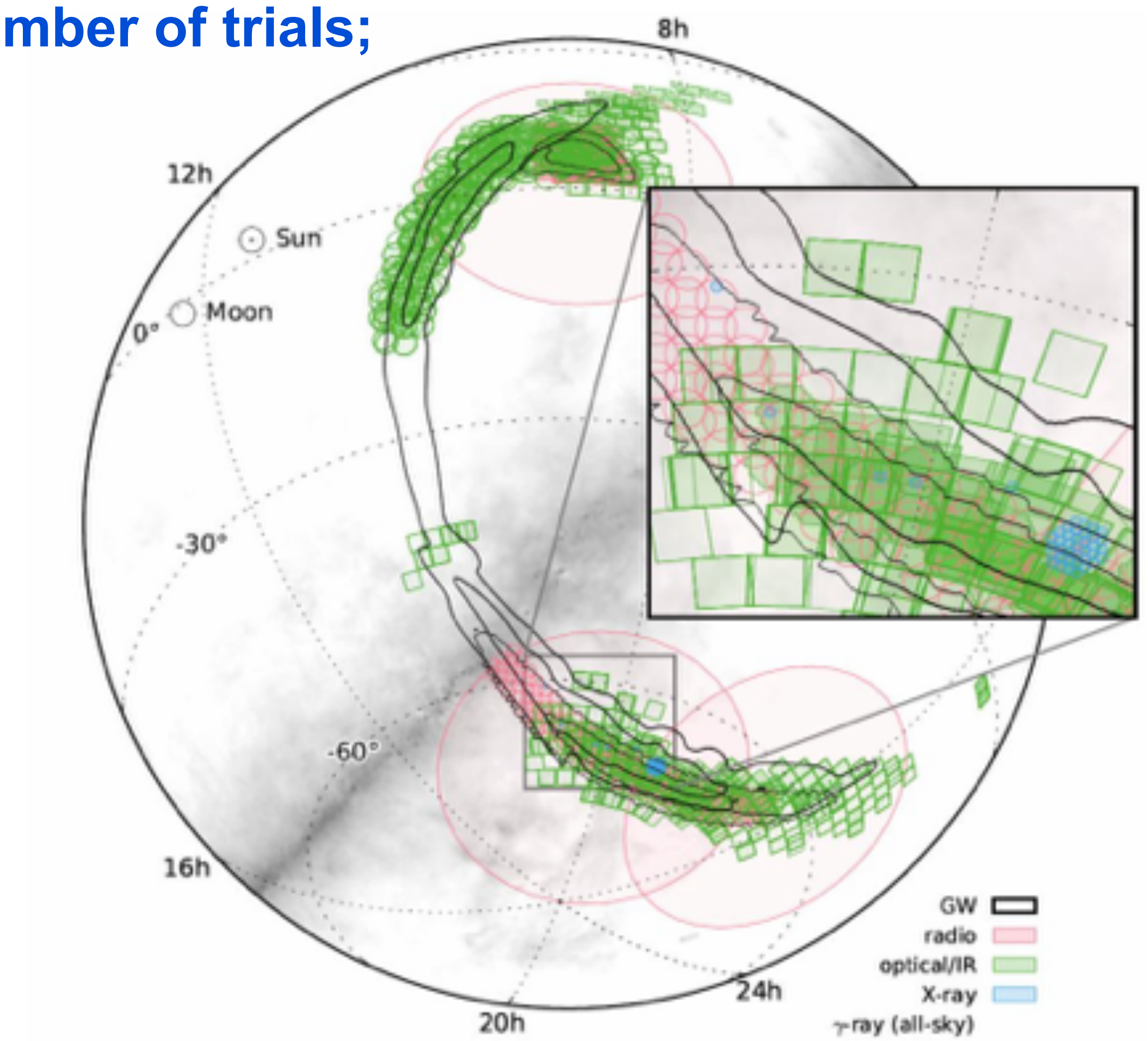


Binary System Type	BH-BH	NS-BH	NS-NS
GW signal ?	Yes!	Predicted	Predicted
GW Detection Rate (from data)	~1/month	UL from O1: (<3600 Gpc^{-3} yr^{-1})	UL from O1: (<12600 Gpc^{-3} yr^{-1})
EM signal	Not expected if system is isolated	Predicted (sGRB)	Predicted (sGRB)

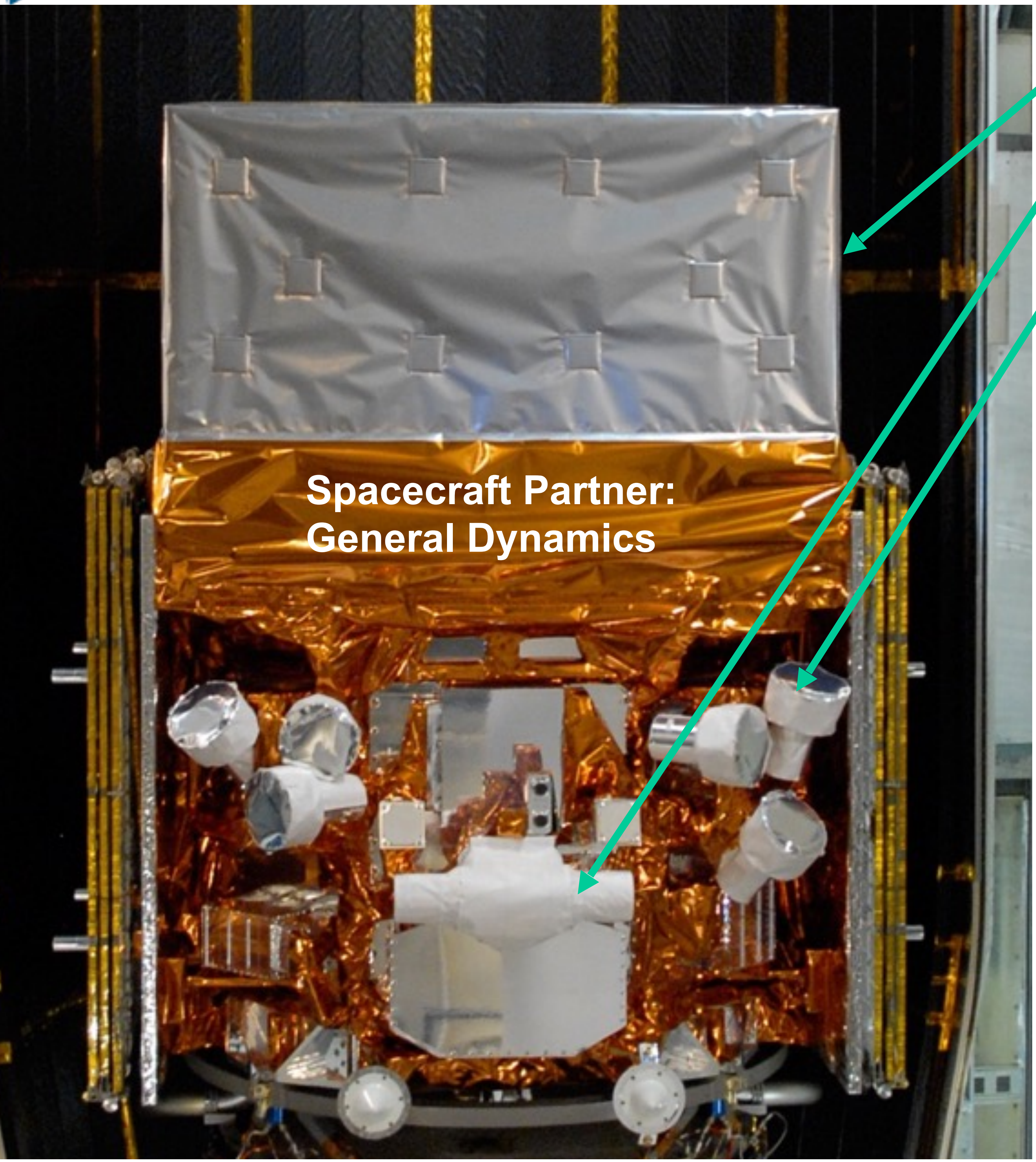
Upper limits on the rates of binary neutron star and neutron-star--black-hole mergers from Advanced LIGO's first observing run (arXiv:1607.07456)

Follow up strategies

- **Search for GW signal for each "GRB-like" signal detected in EM counterpart**
  - The EM localization can be used as a prior for GW searches;
  - Most of the GRB events are outside the VIRGO/LIGO volume;
  - Several trials involved in the search;
- **Search for EM counterpart of GW signal**
  - Large localization implies large number of trials;
  - The precise trigger time information reduce the number of trials;
  - Large field of view instruments are optimal;



The Fermi Gamma-Ray Space Telescope



Large AreaTelescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

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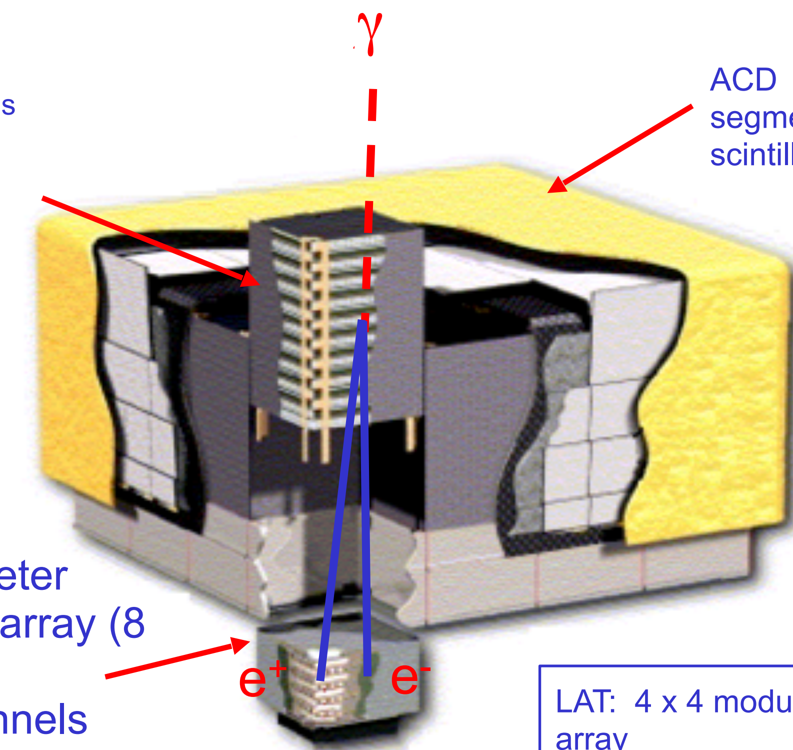

Si Tracker
pitch = 228 μm
8.8 10^5 channels
18 planes

ACD
segmented
scintillator tiles

CsI Calorimeter
hodoscopic array (8 layers)
6.1 10^3 channels

LAT: 4 x 4 modular array
3000 kg, 650 W
20 MeV – 300 GeV

International collaboration

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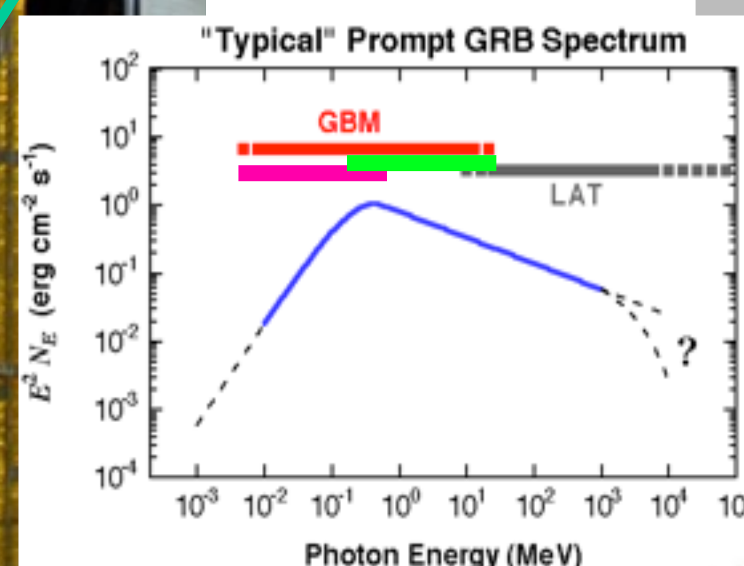
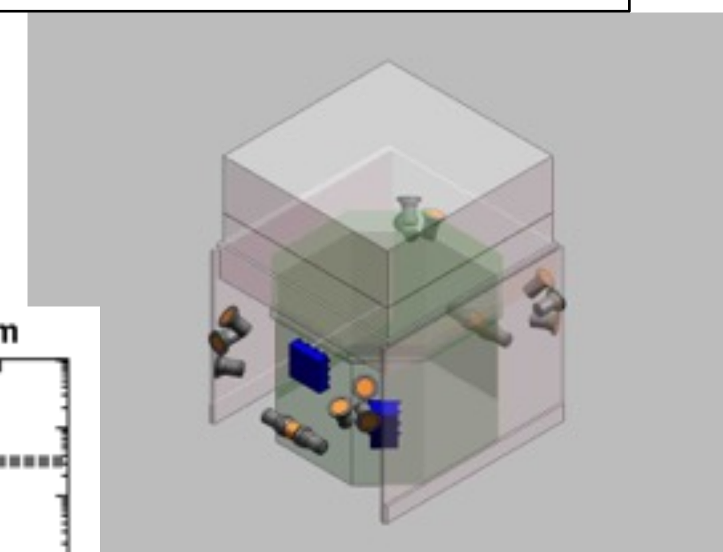
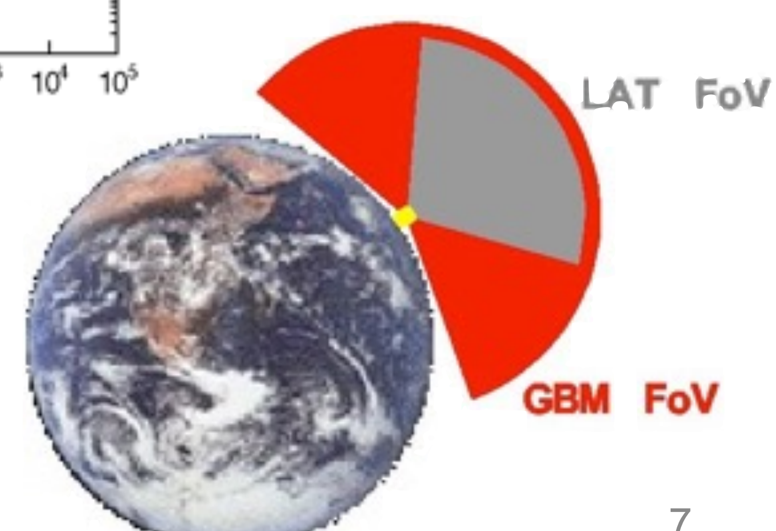






The Fermi Gamma-Ray Space Telescope

Large AreaTelescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

GBM:

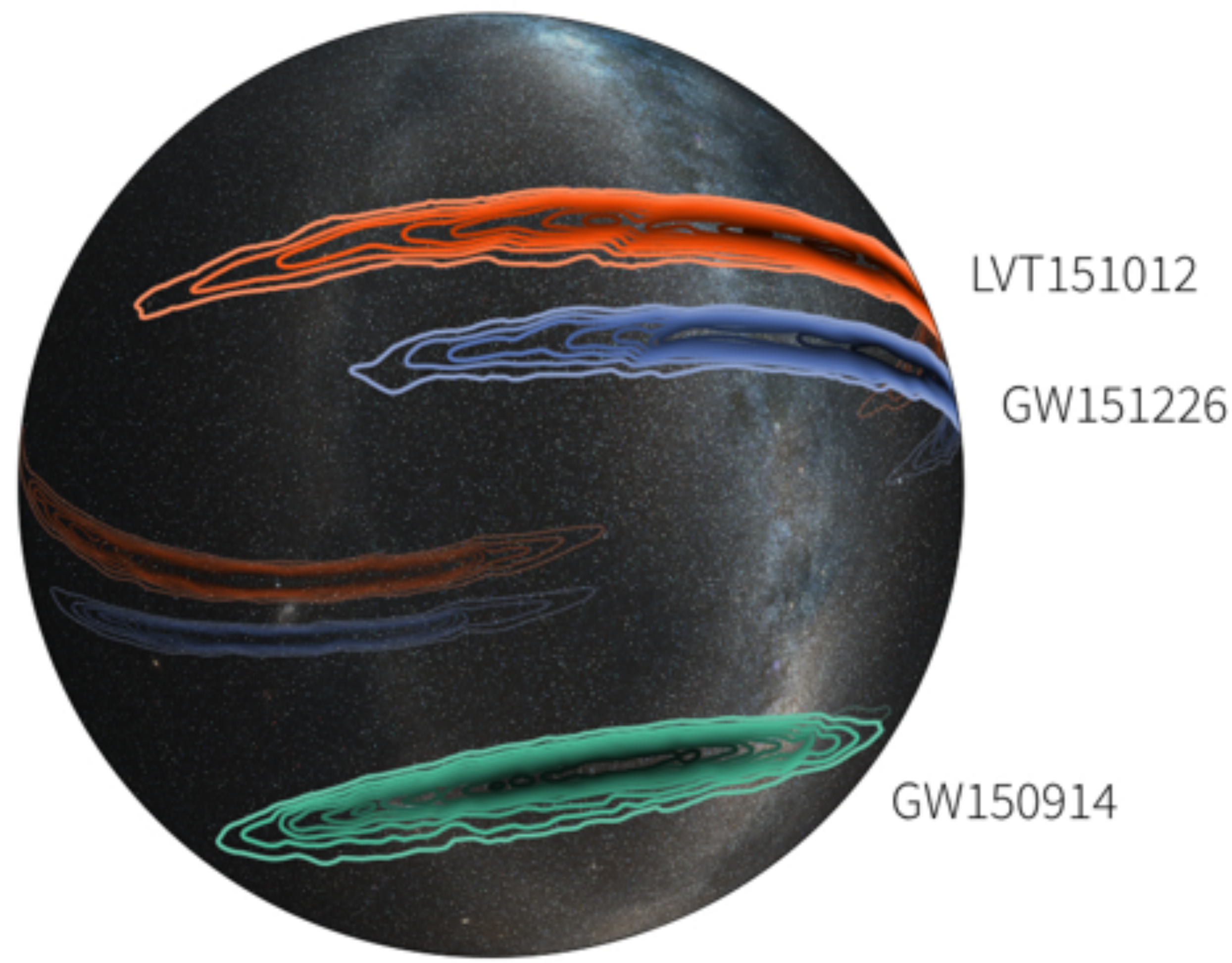
- Most prolific detector of sGRB (~40/yr)
- Detect only the prompt emission

LAT:

- Fewer sGRB (~2/yr)
- Can detect the high-energy afterglow

Following up LIGO events

- 3 GW events announced by the LIGO/VIRGO Collaboration
  - GW150914, LVT151012, GW151226, all associated to BH-BH mergers
- BH-BH mergers are not expected to produce EM radiation. Keeping that in mind, and acknowledging that surprises and serendipitous discoveries are not new in astrophysics, we searched our data performing different analysis:
  - Automated Searches
  - Specific searches in the LIGO contours



Fermi Transient Searches

Fermi Gamma-ray Space Telescope

Pipelines

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

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

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

Timescale

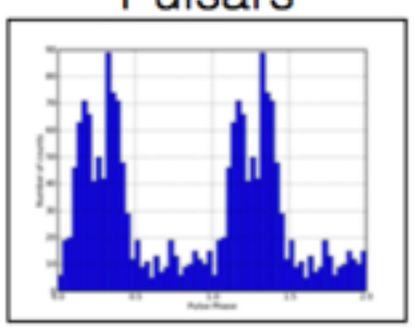
μs ***ms*** ***s*** ***minutes*** ***hours*** ***days*** ***months*** ***years***

Transients

Photon Timing

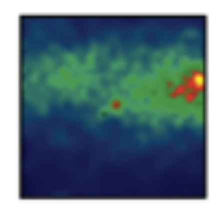
All Sky Cadence

Pulsars

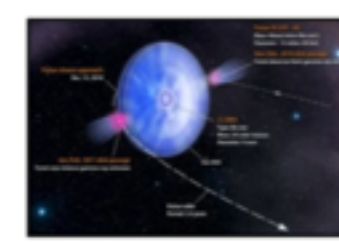


Solar Flares

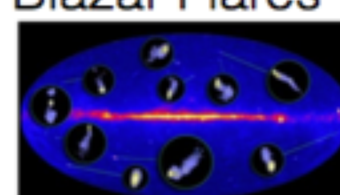
Novae



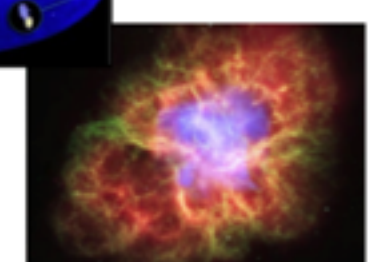
γ-ray Binaries



Blazar Flares

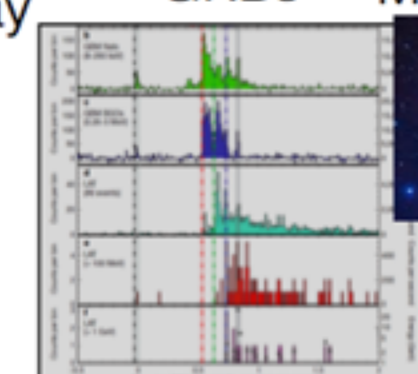


Crab Flares



Terrestrial γ-ray Flashes

GRBs



Magnetar Flares

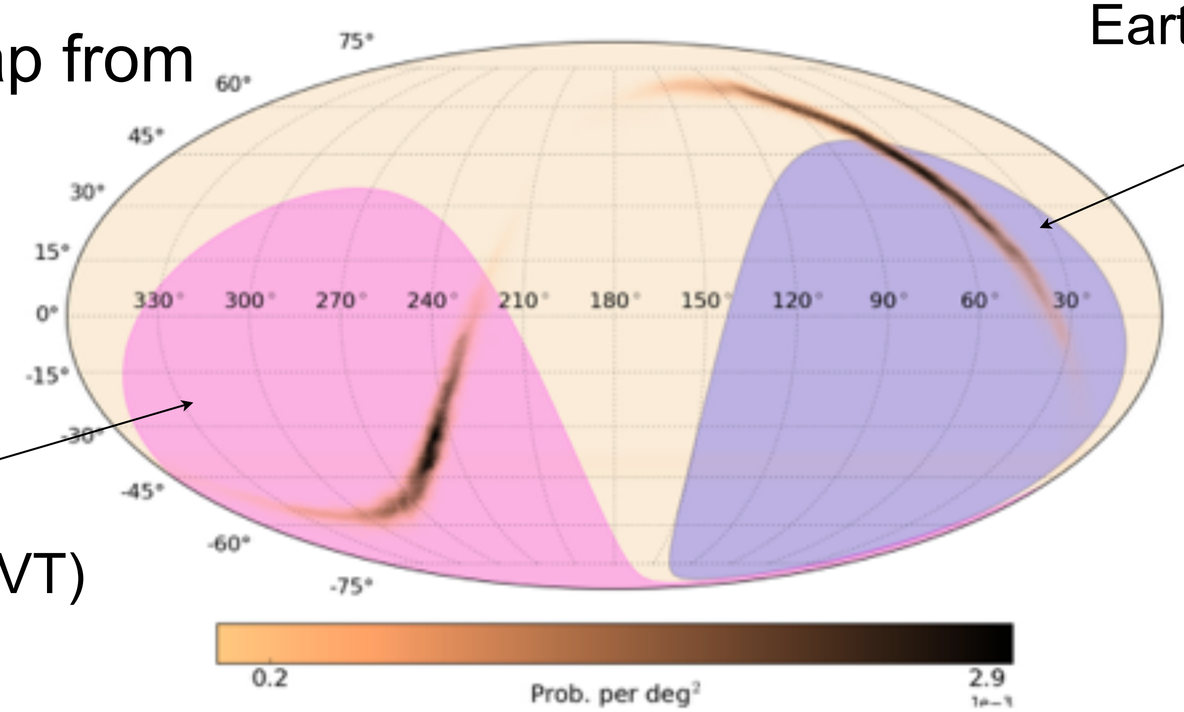
Not to scale

From LVC probability maps to LAT analysis

- **We developed a novel technique (Vianello, et al.) to search for EM counterpart in LAT data starting from LIGO probability maps**
  - **LVC releases probability maps (in HELPix).**
  - **We downscale the maps to match the Fermi LAT PSF (~4 degrees at 100 MeV)**
  - **We center a ROI in each pixel (p>0.9), and we run standard likelihood analysis (Unbinned)**
  - **We adopt several timescales to be sensitive to transients of different duration**

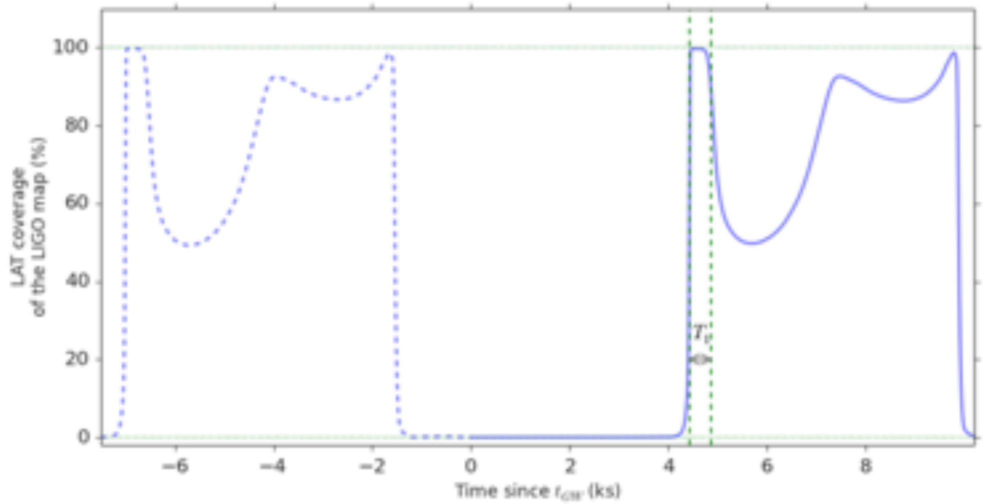
Probability map from LVT151012.

Earth (at the time of the LVT)

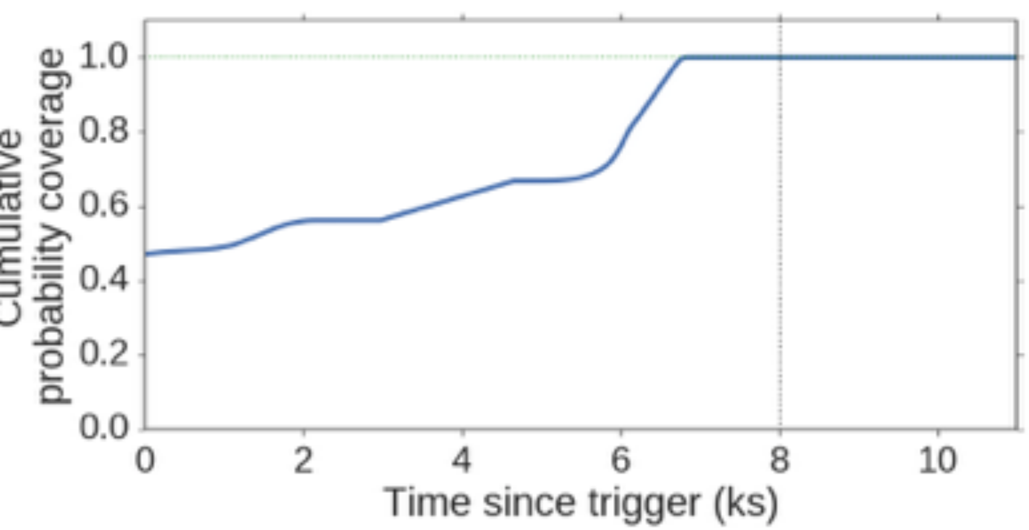


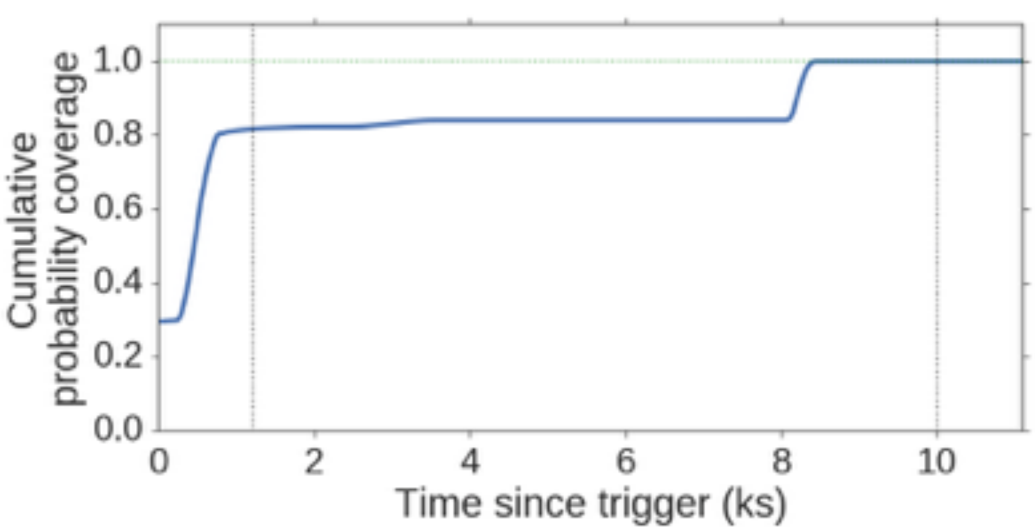
LAT FoV (at the time of the LVT)

Coverage



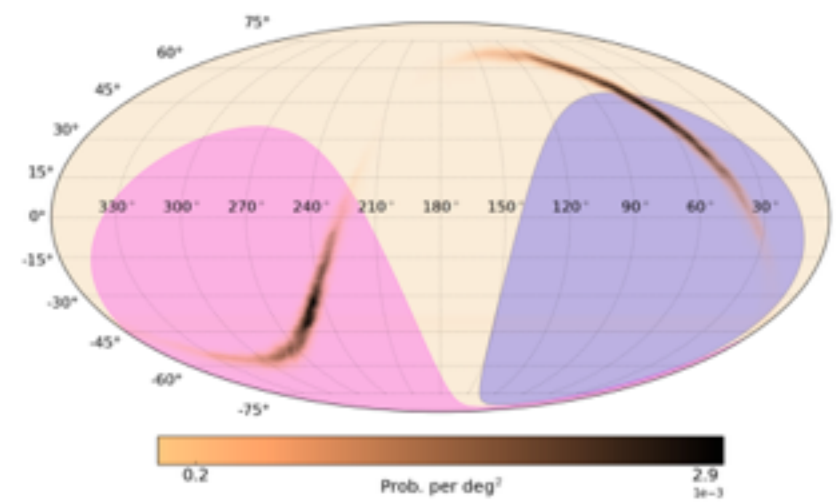
For **GW150914** the coverage was very bad, in fact we start observing the region of the GW event only 4ks after the trigger.

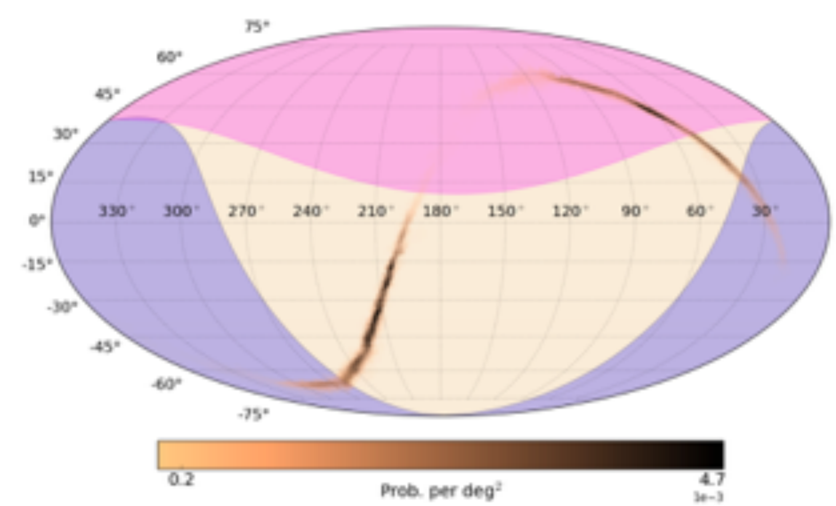




For **LVT151012** and **GW151226**, the coverage was much better: **50%** and **30%** of the GW region was covered **at the time of the trigger.**

In 8ks and 10ks after the GW trigger the entire probability map is covered





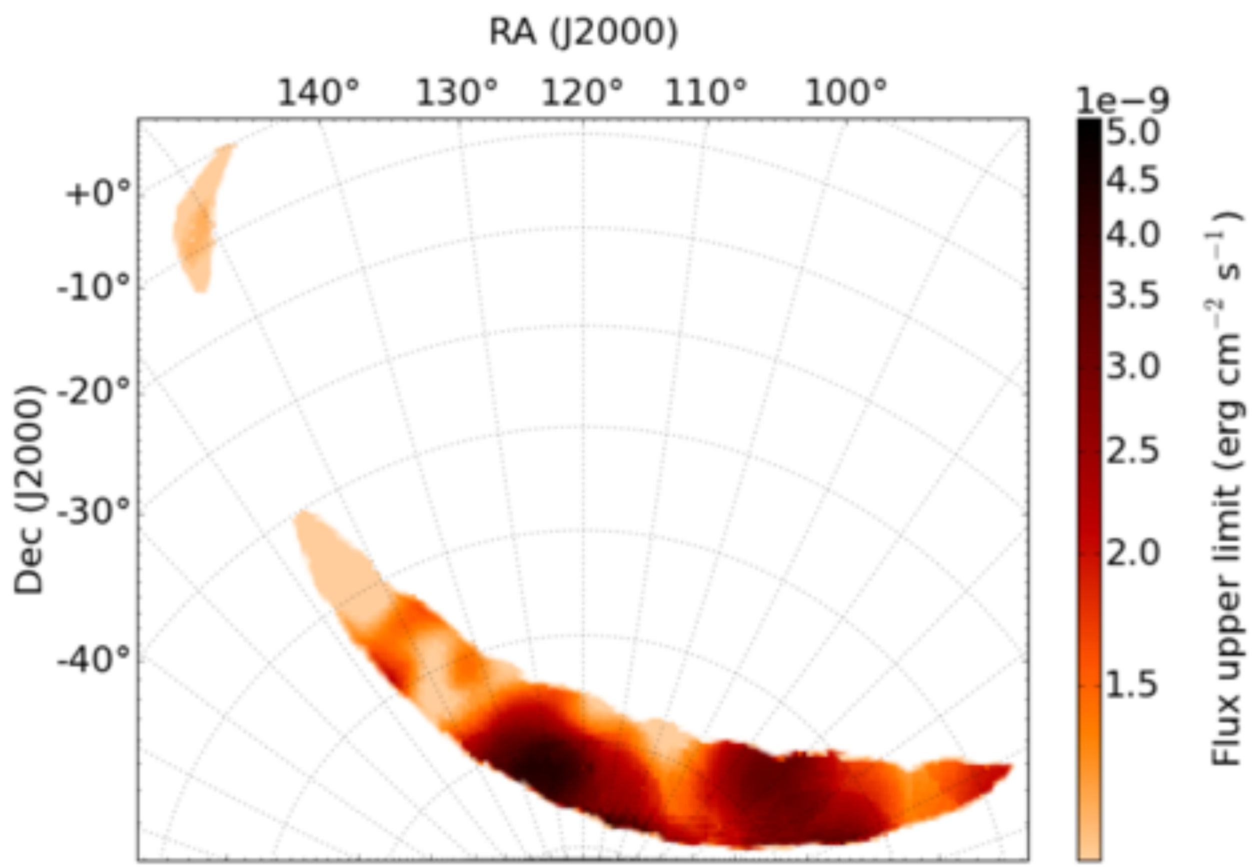
Different time windows for the LAT Analysis

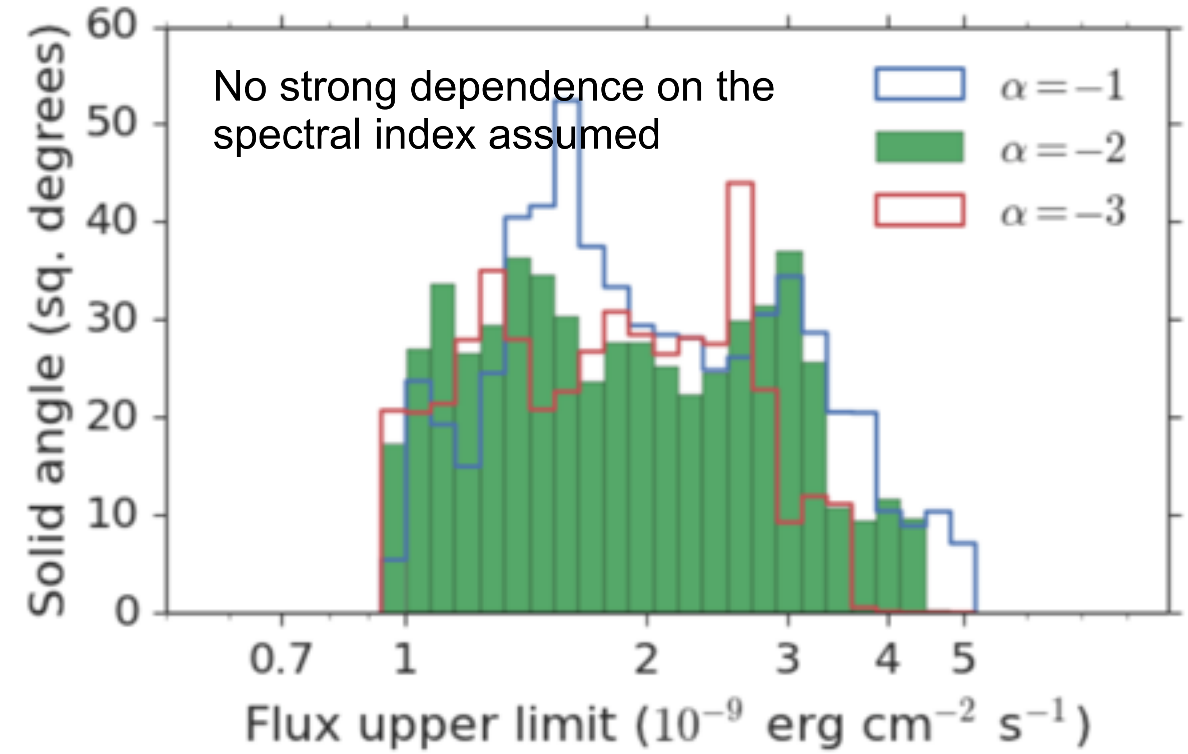
	GW150914	LVT151012	GW151226
Optimized, Fixed, Short	4.4-4.5 ks	±10 s	±10 s
Optimized, Fixed, Long	10 ks	8 ks	1.2 ks - 10 ks
Optimized, Adaptive	Adaptive (±10 days)	Adaptive (±10 days)	Adaptive (±10 days)
Automatic	6 h, 1day, 1 week	6 h, 1day, 1 week	6 h, 1day, 1 week

No significant excess was detected in any of our searches
(therefore, we compute a series of flux upper limits)

Results - GW150914 - fixed time window

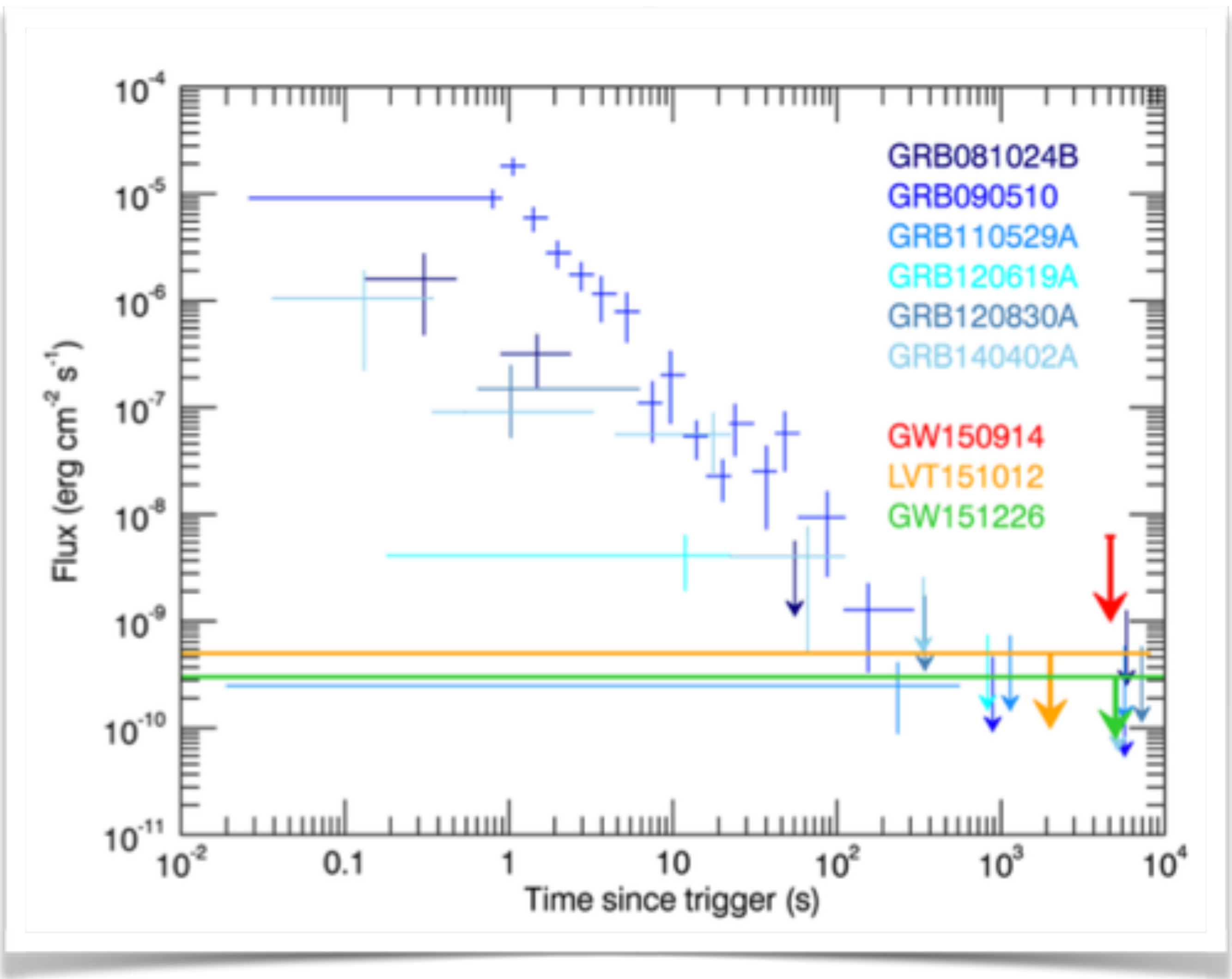
- For **GW150914** we calculate UL map for the fixed time window search (from T0+4400, T0+4500).





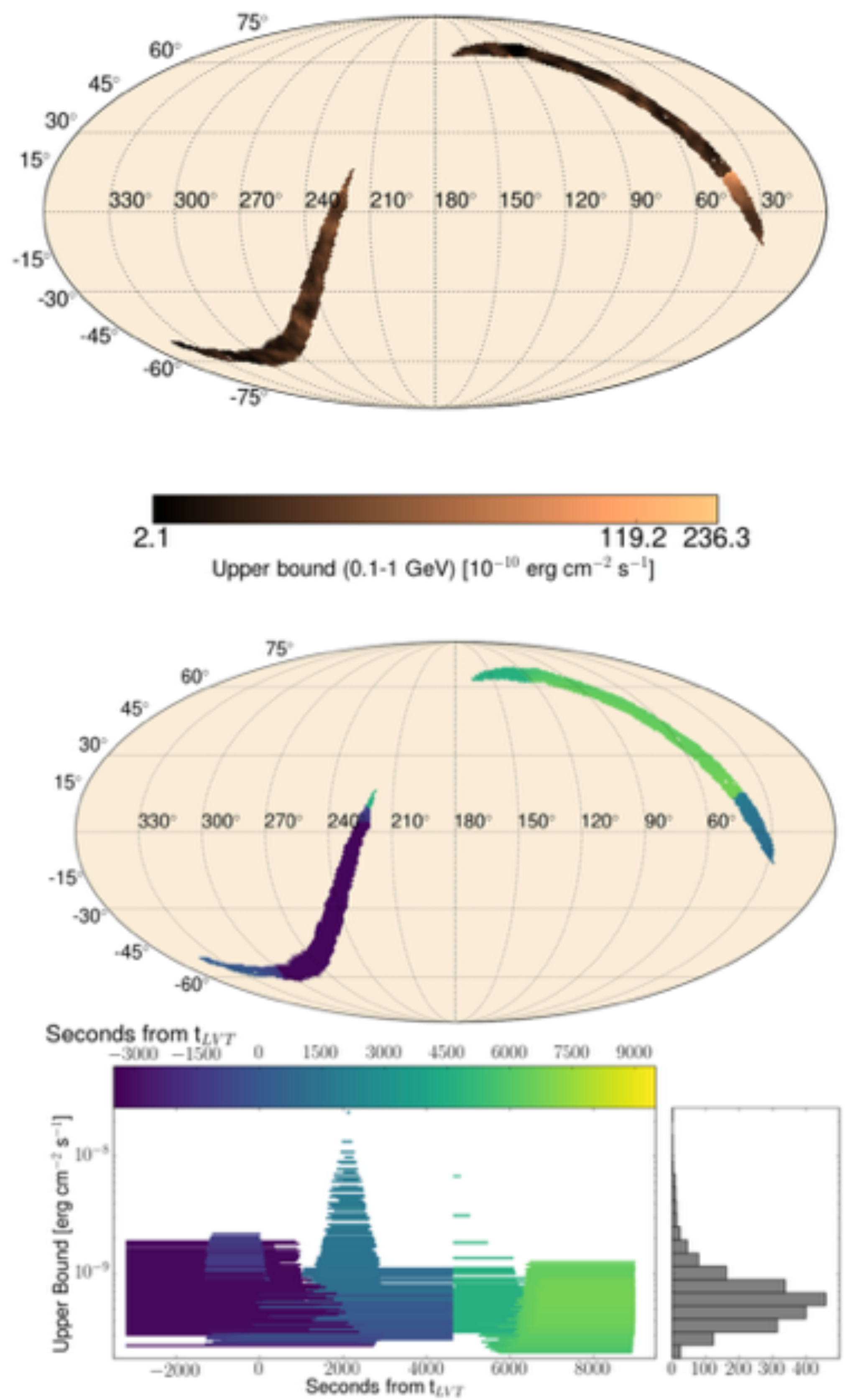
Calculating a global upper bound

- We developed a fully bayesian method to calculate a “global” UL, using the probability map as prior (and using Markov-Chain Monte Carlo to marginalize the posterior probability)
  These UL can be used to constrain models <u>if the location of the GW event is unknown</u>



- **If GW events have similar behaviors of sGRB detected by the LAT, they would have been detected within tens to hundreds of seconds;**
- **But: the proximity of these events makes them very rare;**
- **Also beaming is important;**

LVT151012 - GW151226 - Adaptive intervals



- We compute Flux LAT upper limit maps.
- These upper limits depend on the location of the pixel in the sky, which also determines the interval of time we used in our analysis.
  - The colors of the horizontal lines in the last panel matches the colors of the pixels in the second panel.
- These UL can be used to constrain models <u>if the location of the GW event is known</u> (for example from its detection by some other facility)

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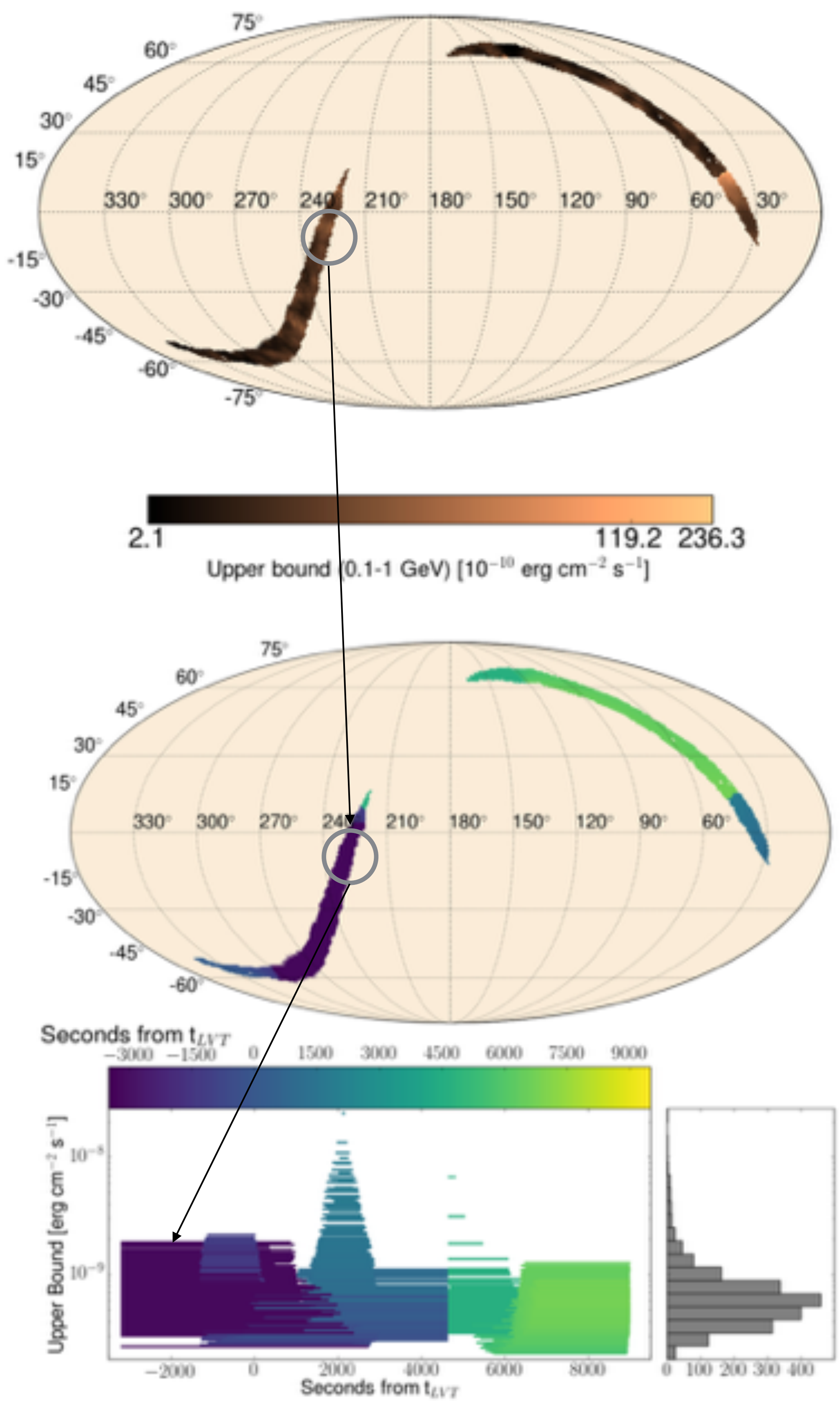

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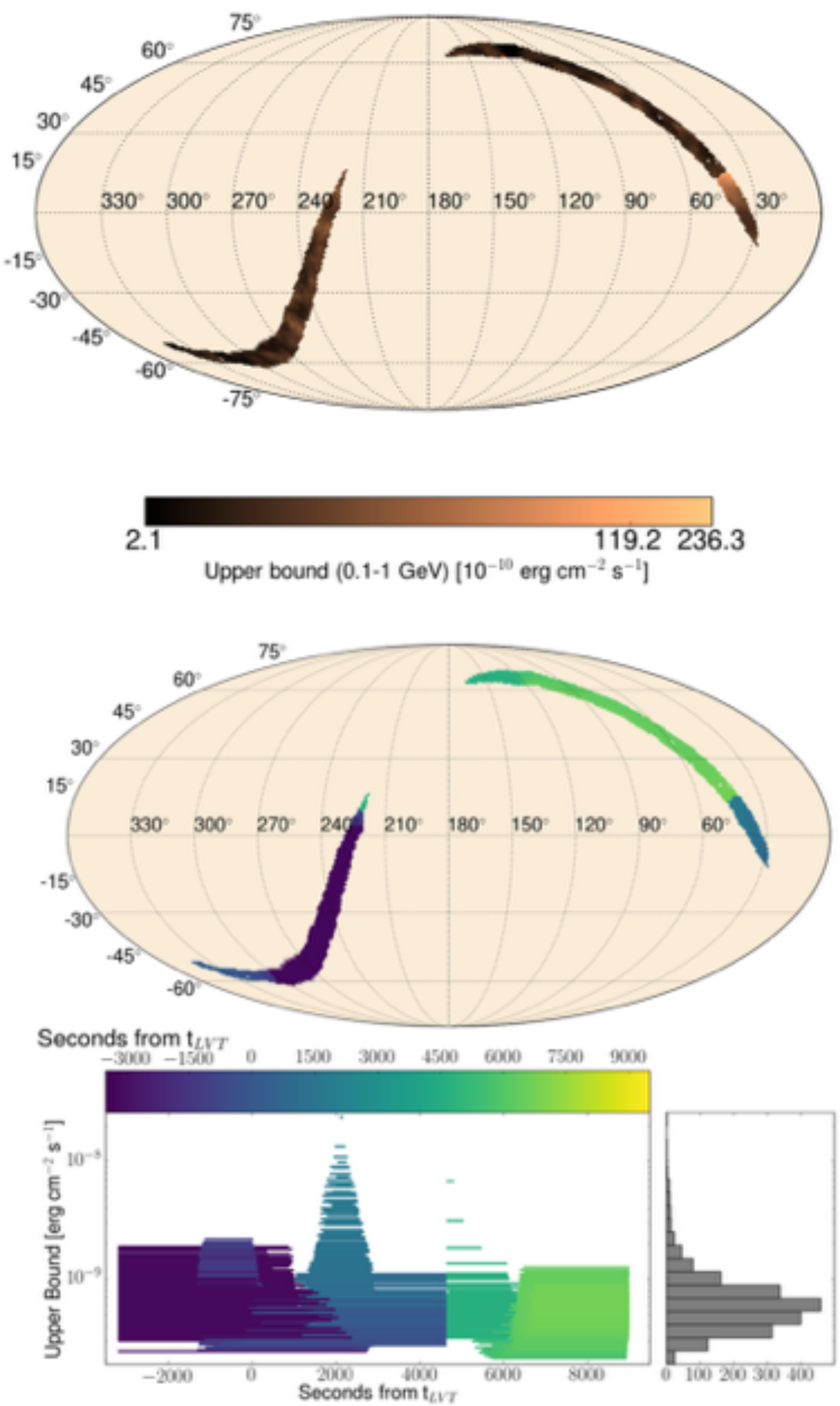

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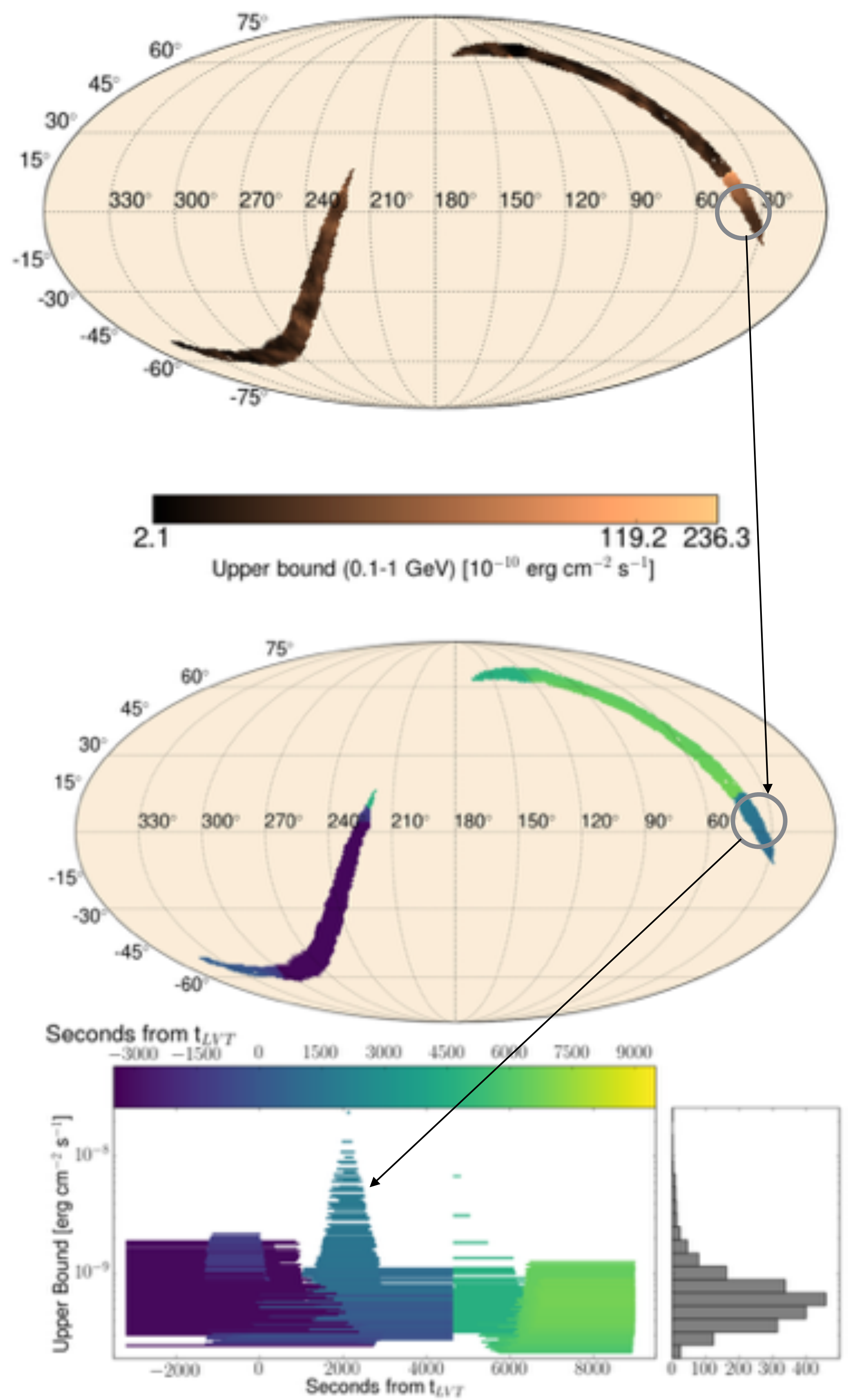

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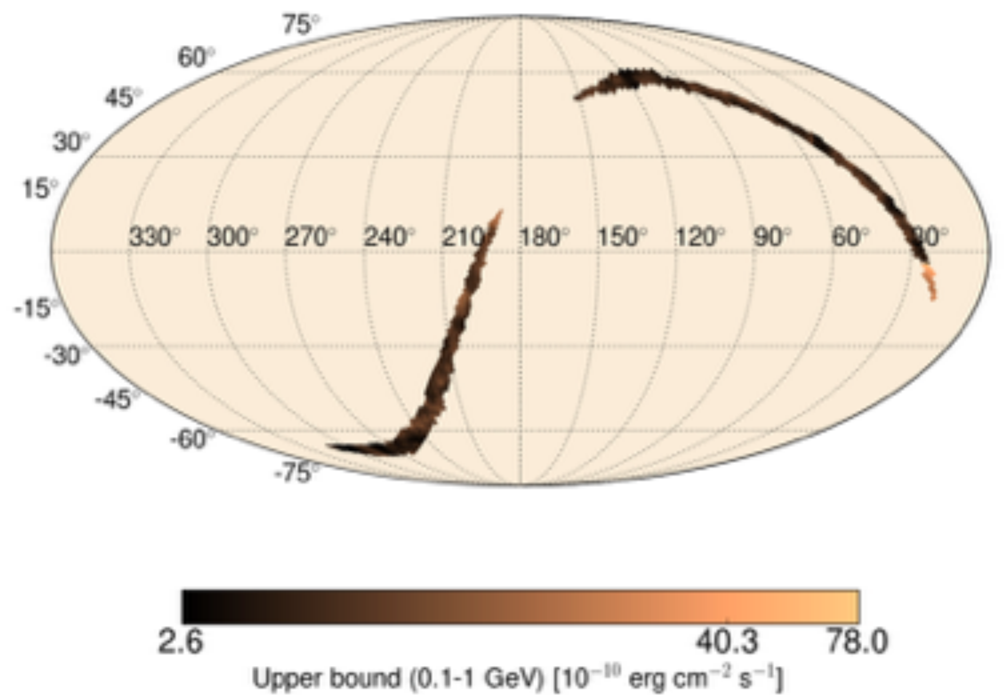

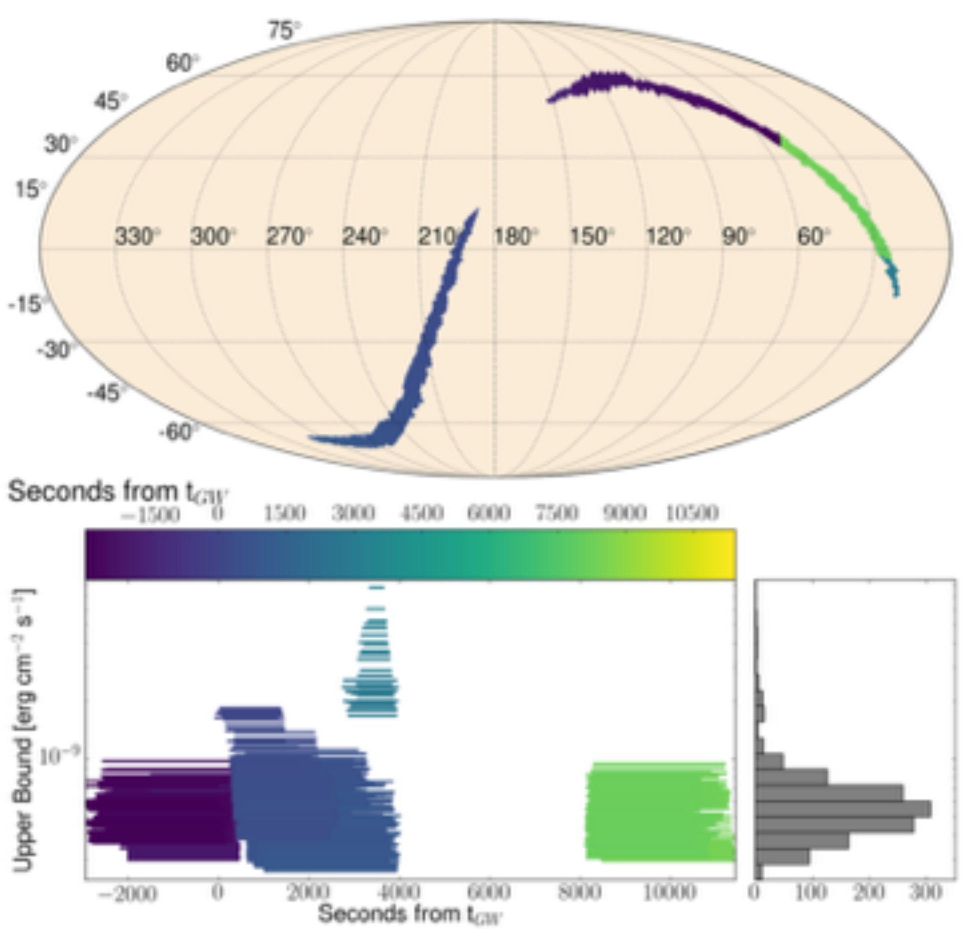

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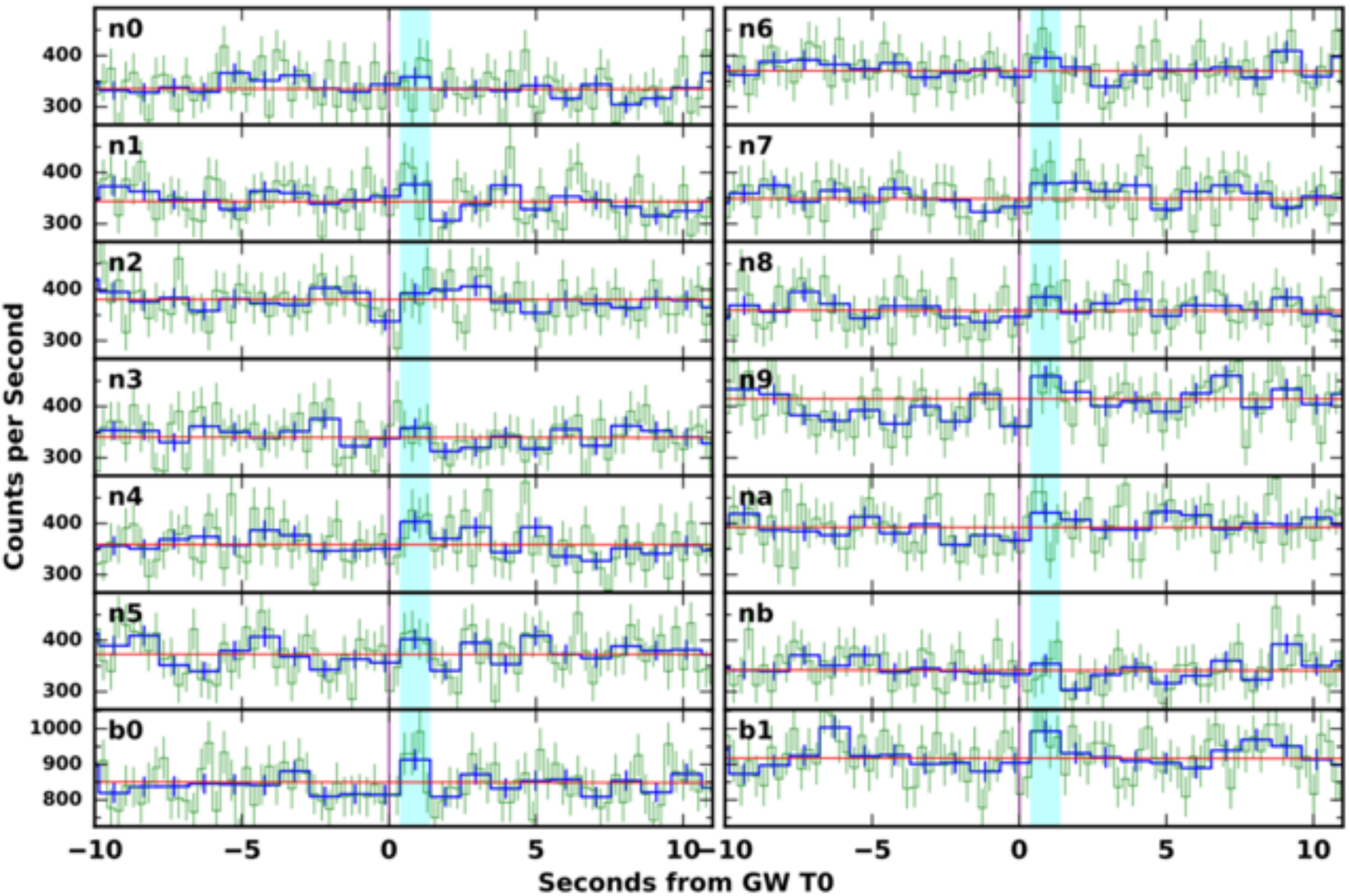
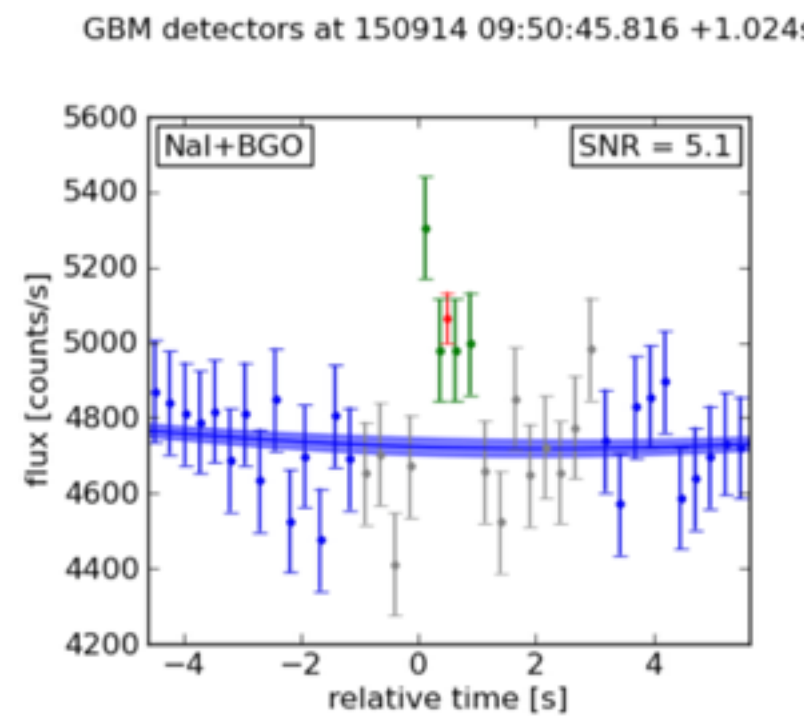
  - **–The colors of the horizontal lines in the last panel matches the colors of the pixels in the second panel.**
- **These UL can be used to constrain models <u>if the location of the GW event is known</u> (for example from its detection by some other facility)**

Results - GW150914 - GBM





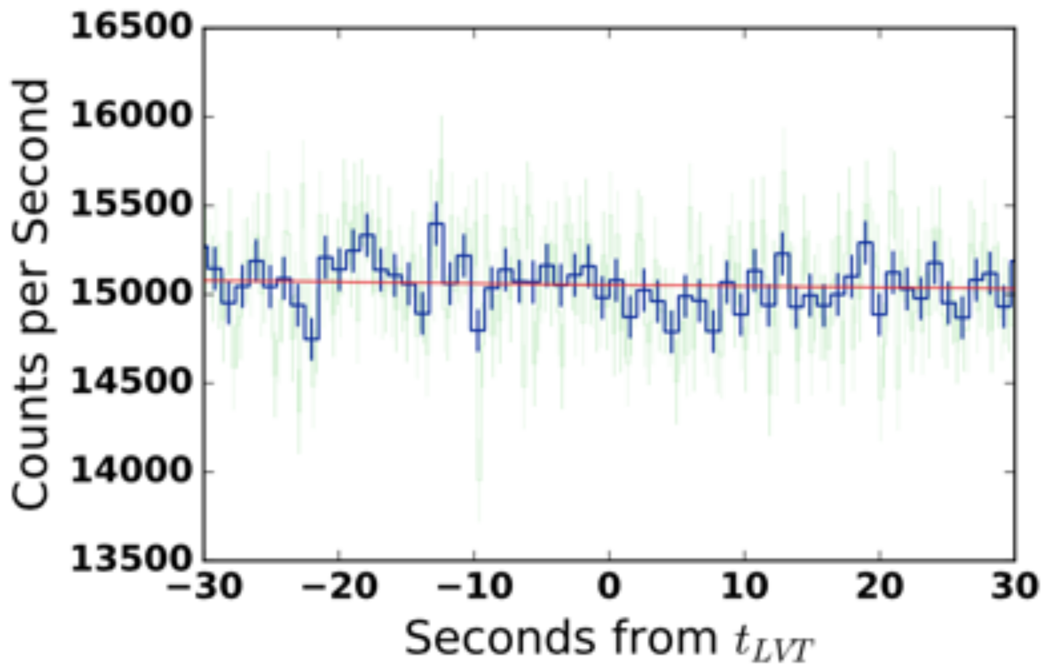
Model-dependent count rates with maximized SNR for a modeled source. Green points are significant emission, red is the 1.024s average, and blue points were used in the background fit.

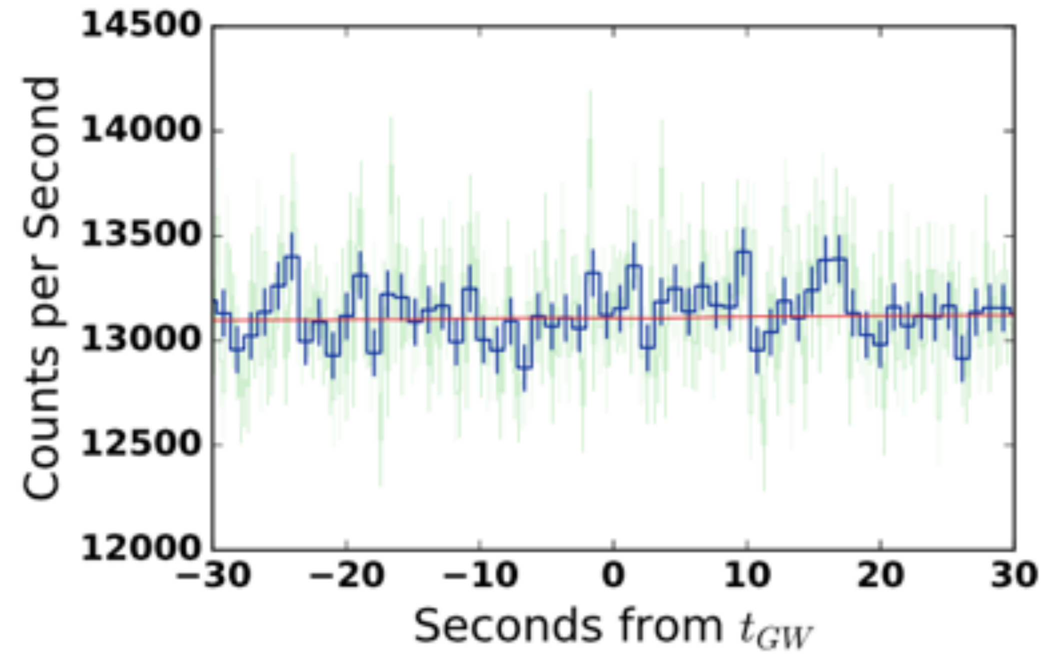
Flux GBM (10 keV - 1 MeV) = 2.4x10^{-7} erg/cm^{2} (2.7x10^{-6} Msol)

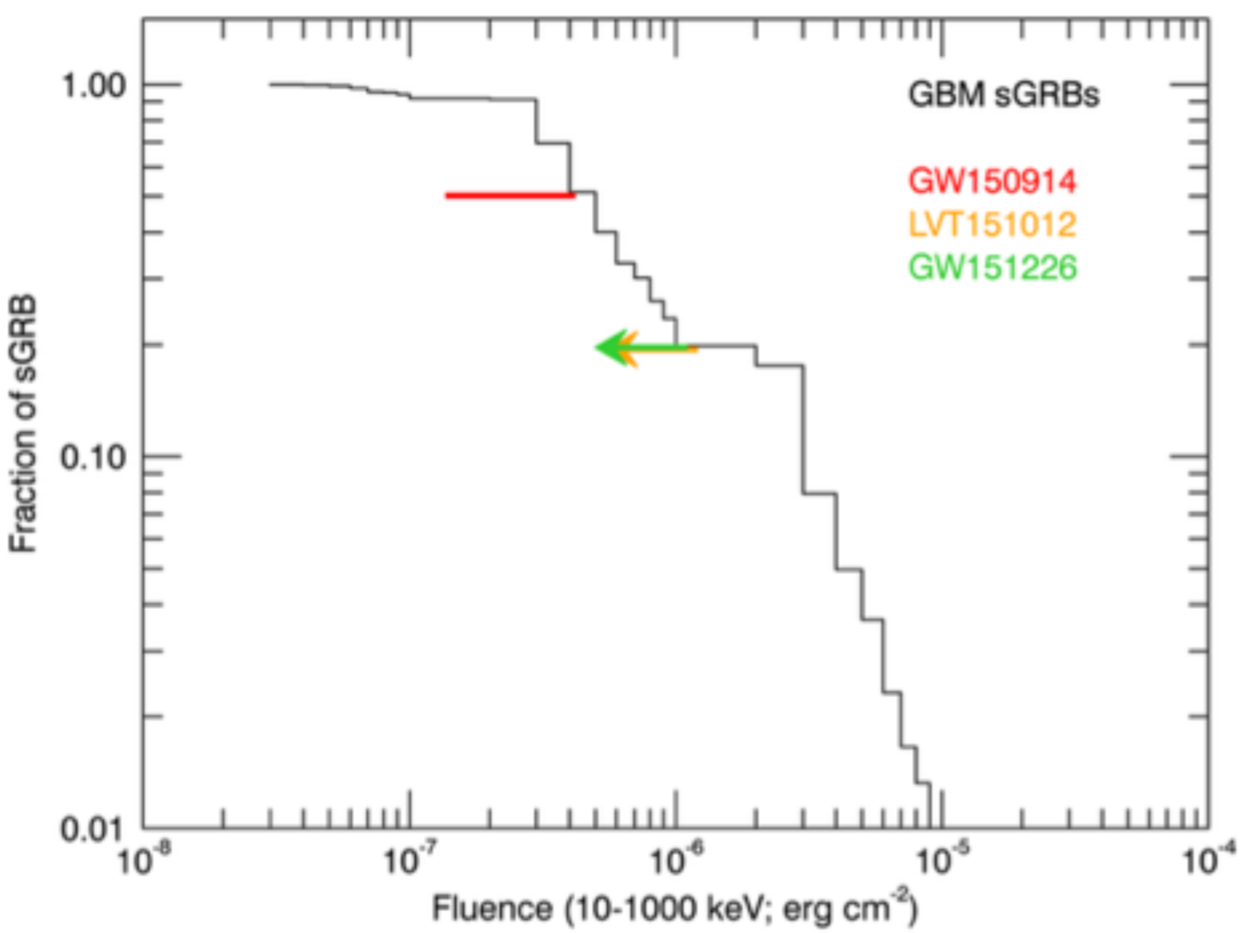
in tension with Integral ACS Upper Limit (100 keV - 100 MeV) = 1.3x10^{-7} erg/cm^{2} (1.5x10^{-6} Msol)

See Savchenko et al. 2016, Greiner et al. 2016.

GBM - LVT151012 & GW151226







- **GBM: 150914: if real, would be quite weak (given the proximity, it is likely sub-luminous GRB);**
- **80% of the GRB fluxes are compatible with the flux upper bound derived by the GBM analysis;**

Putting in the context...

- What about the GW150914-GBM?
  - After the LIGO discovery and the claim of a weak signal in the GBM: Numerous merger models with EM emission components proposed;
  - EM counterpart: extraction of energy and angular momentum of the merging BHs via the Blandford-Znajek mechanism (Blandford & Znajek 1977).
    - Hard to make EM radiation if the system is isolated (BBH acts as a "blender")
    - BBH system needs a disk, a common envelope (see Woosley, 2016 or Janiuk et al. 2016, Perna et al. 2016, Murase 2016) or a single star progenitor forming a BBH merger (Loeb et al 2016)
    - Lyutikov 2016, Murase et al. 2016: not really working with stellar-mass BH with GW150914-GBM luminosity
- What does the non detection of LVT151012 and GW151226 tell about GW150914-GBM?
  - If we assume that all BBH mergers produce sGRB-like signals, the GBM might reasonably not detect them for four reasons:
    - Outside the field of view (only 68% and 83% of the LIGO localization map was in the GBM field of view)
    - Higher background rate (3% and 18% higher). LVT151012 is also 3 time further.
    - Collimation of the EM-jet (only 15% - 30% toward the Earth)
    - Fainter objects (if EM luminosity scales with the progenitor mass, for example.)

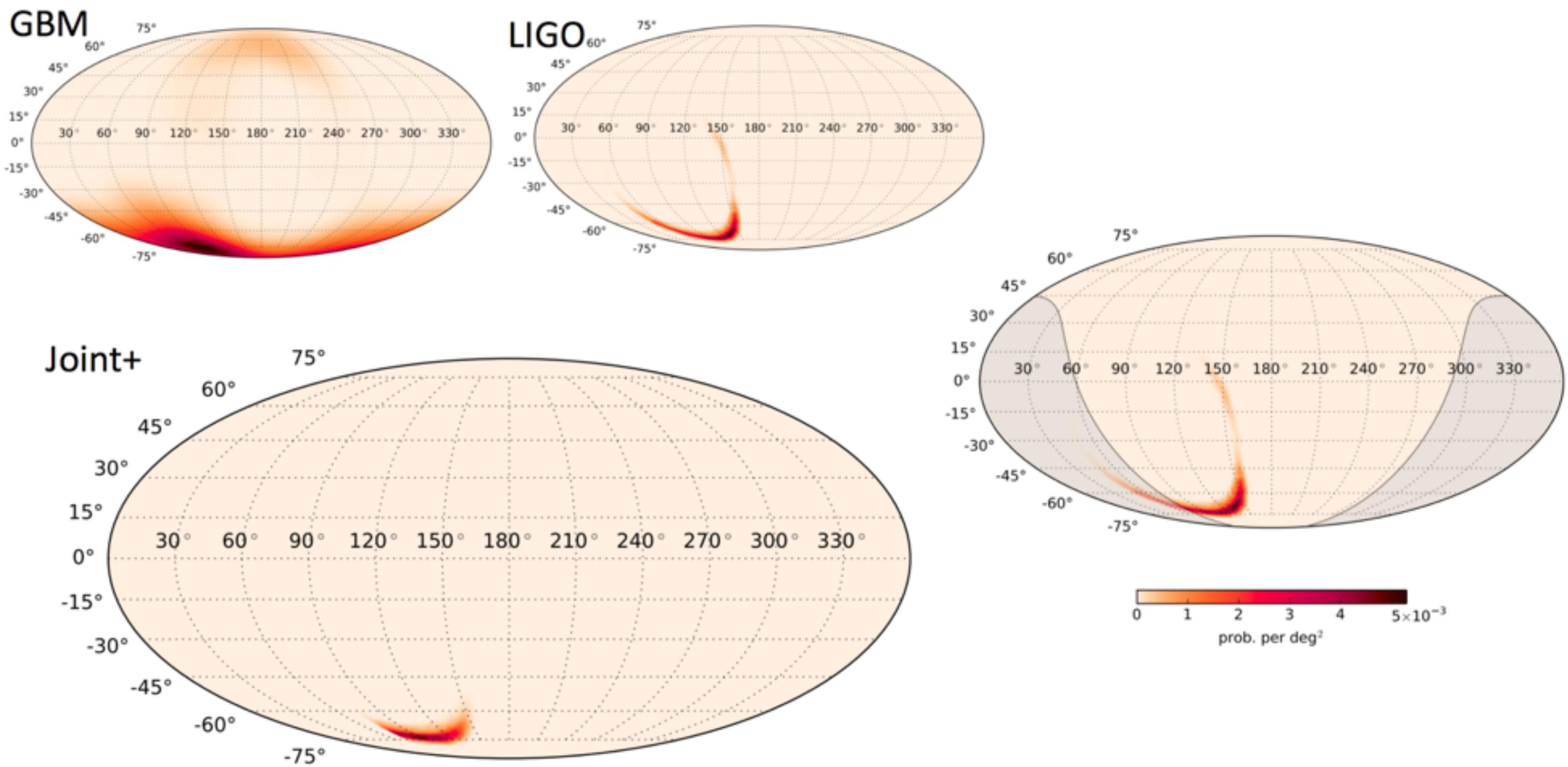
More events are needed:
GW astronomy -> Multi-messenger astronomy

Conclusions

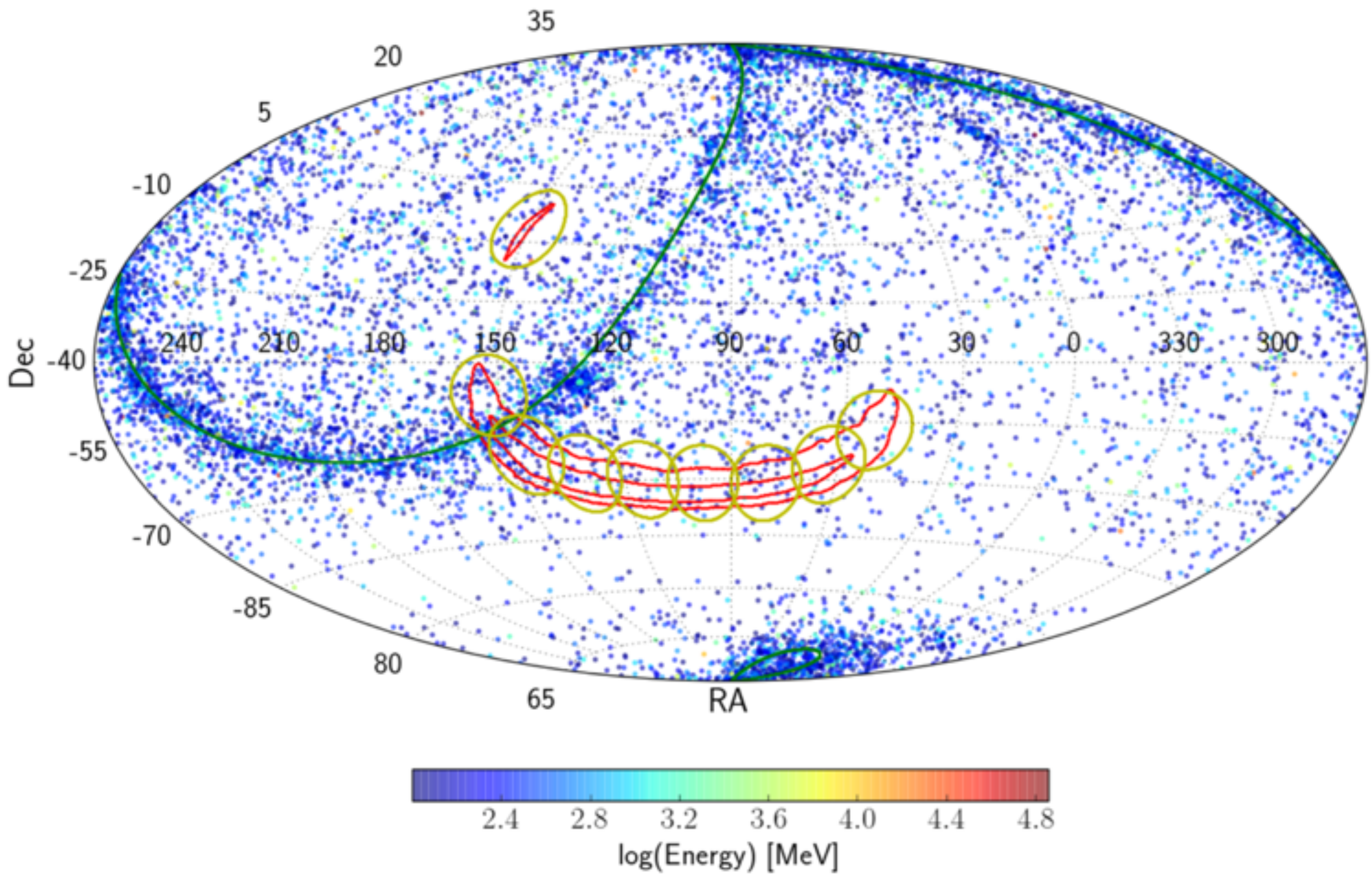
- We have set up a series of tools to monitor and followup with Fermi-LAT GW events triggered by LIGO/VIRGO
- Successfully applied to Observing Run “O1”:
  - Fermi-LAT Observations of the LIGO Event GW150914 (Ackermann et al. 2016, astro-ph:1602.04488);
  - Searching the Gamma-ray Sky for Counterparts to Gravitational Wave Sources: Fermi GBM and LAT Observations of LVT151012 and GW151226 (Racusin et al. 2016, astro-ph:1606.04901);
  - Paper describing the details of the methodology (Vianello, Omodei & Chiang arXiv:1607.01793);
- No LAT counterpart detected so far: flux upper limits derived to be used to constrain models;
- Only a larger statistic will help to understand the EM nature of these objects;
- Looking forward for NS-NS/NS-BH events;
- Excitement for the new LIGO Observing Run “O2” and looking forward for VIRGO!!

Back up

How to help followup campaign



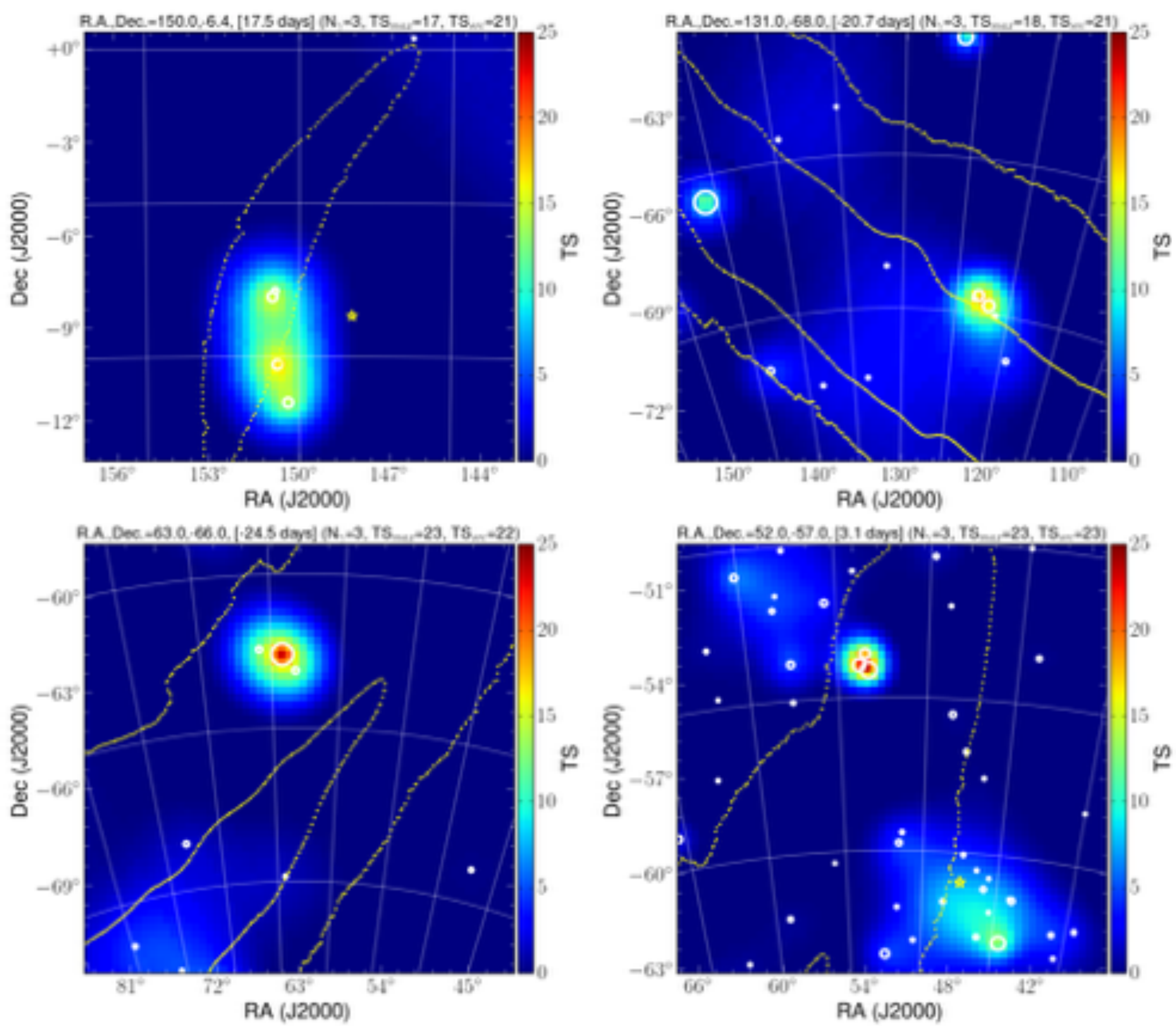
Adaptive interval over long time widow

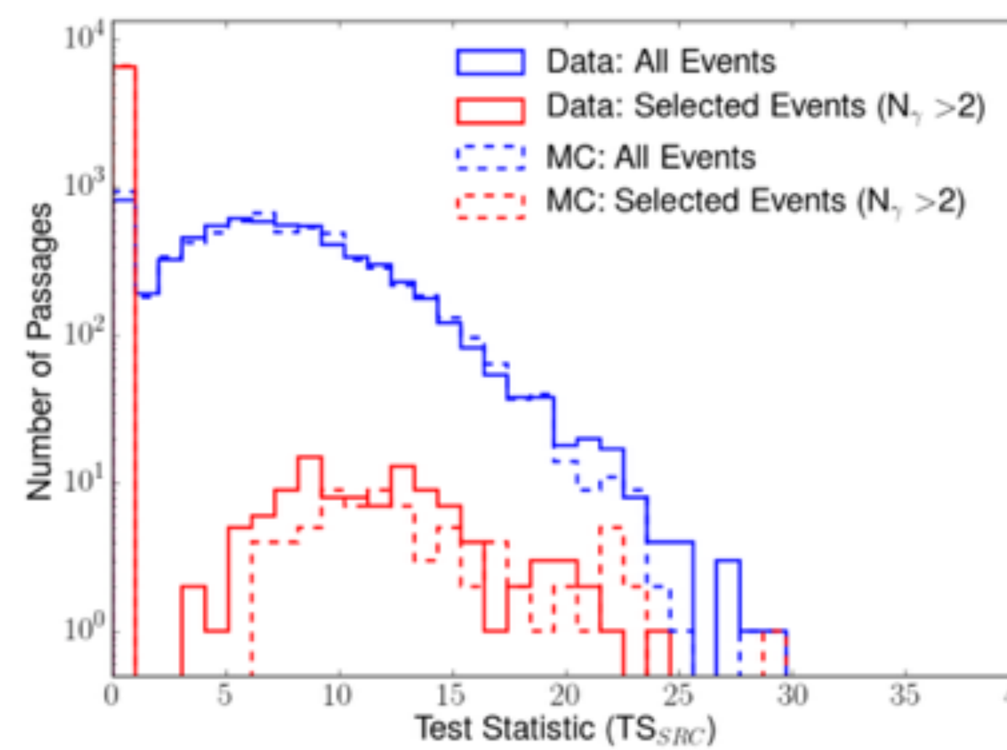


- **For 150914 we calculate TS maps in 9 partially overlapping regions orbit-by-orbit (adaptive interval) over ling period of time (+/- 30 days)**
  - **Large number of trials!**

Comparison with MC simulations

- **Due to the large number of trials, high values of TS can be obtained by random coincidence of LAT events**
  - **Monte Carlo simulation are essential to study the significance of these excess**
  - **Our study shows that the distribution of TS obtained from MC data matches perfectly the observed once: no statistically significant excess**





Left: most significant excesses found on searches over +/- 30 days.
Top: Data-MC comparison

Some problems…

$L_{EM} \approx V^2/\mathcal{R}$ V: potential, R: Impedance

$L_{EM} \approx \Phi^2\Omega^2/c$ For spinning objects $\Phi_{BH} \approx B_{BH}R_{BH}^2$ $\Omega_{BH} \approx a\frac{c}{R_{BH}}$

Magnetic field Angular Speed

Observed by GBM

$L_{EM} \sim 10^{49}$ erg s^{-1}

$$B_{BH} \approx \frac{c^{3/2}\sqrt{L_{EM}}}{aGM} = 3 \times 10^{12}\mathrm{G}$$

- **The magnetic field is extremely high , and would imply a too high accretion rate (Lyutikov, 2016)**

2 recently published LAT papers

Fermi-LAT Observations of the LIGO Event GW150914

M. Ackermann[1], M. Ajello[2], A. Albert[3], B. Anderson[4,5], M. Arimoto[6], W. B. Atwood[7], M. Axelsson[8,9], L. Baldini[10,3], J. Ballet[11], G. Barbiellini[12,13], M. G. Baring[14], D. Bastieri[15,16], J. Becerra Gonzalez[17,18], R. Bellazzini[19], E. Bissaldi[20], R. D. Blandford[3], E. D. Bloom[3], R. Bonino[21,22], E. Bottacini[3], T. J. Brandt[17], J. Bregeon[23], R. J. Britto[24], P. Bruel[25], R. Buehler[1], T. H. Burnett[26], S. Buson[17,27,28,29], G. A. Caliandro[3,30], R. A. Cameron[3], R. Caputo[7], M. Caragiulo[31,20], P. A. Caraveo[32], J. M. Casandjian[11], E. Cavazzuti[33], E. Charles[3], A. Chekhtman[34], J. Chiang[3], G. Chiaro[16], S. Ciprini[33,35], J. Cohen-Tanugi[23], L. R. Cominsky[36], B. Condon[37], F. Costanza[20], A. Cuoco[21,22], S. Cutini[33,38,35], F. D'Ammando[39,40], F. de Palma[20,41], R. Desiante[42,21], S. W. Digel[3], N. Di Lalla[19], M. Di Mauro[3], L. Di Venere[31,20], A. Domínguez[2], P. S. Drell[3], R. Dubois[3], D. Dumora[37], C. Favuzzi[31,20], S. J. Fegan[25], E. C. Ferrara[17], A. Franckowiak[3], Y. Fukazawa[43], S. Funk[44], P. Fusco[31,20], F. Gargano[20], D. Gasparrini[33,35], N. Gehrels[17], N. Giglietto[31,20], M. Giomi[1], P. Giommi[33], F. Giordano[31,20], M. Giroletti[39], T. Glanzman[3], G. Godfrey[3], G. A. Gomez-Vargas[45,46], J. Granot[47], D. Green[18,17], I. A. Grenier[11], M.-H. Grondin[37], J. E. Grove[48], L. Guillemot[49,50], S. Guiriec[17,51], D. Hadasch[52], A. K. Harding[17], E. Hays[17], J.W. Hewitt[53], A. B. Hill[54,3], D. Horan[25], T. Jogler[3], G. Jóhannesson[55], T. Kamae[56], S. Kensei[43], D. Kocevski[17], M. Kuss[19], G. La Mura[16,52], S. Larsson[8,5], L. Latronico[21], M. Lemoine-Goumard[37], J. Li[57], L. Li[8,5], F. Longo[12,13], F. Loparco[31,20], M. N. Lovellette[48], P. Lubrano[35], G. M. Madejski[3], J. Magill[18], S. Maldera[21], A. Manfreda[19], M. Marelli[32], M. Mayer[1], M. N. Mazziotta[20], J. E. McEnery[17,18,58], M. Meyer[4,5], P. F. Michelson[3], N. Mirabal[17,51], T. Mizuno[59], A. A. Moiseev[28,18], M. E. Monzani[3], E. Moretti[60], A. Morselli[46], I. V. Moskalenko[3], S. Murgia[61], M. Negro[21,22], E. Nuss[23], T. Ohsugi[59], N. Omodei[3,62], M. Orienti[39], E. Orlando[3], J. F. Ormes[63], D. Paneque[60,3], J. S. Perkins[17], M. Pesce-Rollins[19,3], F. Piron[23], G. Pivato[19], T. A. Porter[3], J. L. Racusin[17,64], S. Rainò[31,20], R. Rando[15,16], S. Razzaque[24], A. Reimer[52,3], O. Reimer[52,3], T. Reposeur[37], S. Ritz[7], L. S. Rochester[3], R. W. Romani[3], P. M. Saz Parkinson[7,65], C. Sgrò[19], D. Simone[20], E. J. Siskind[66], D. A. Smith[37], F. Spada[19], G. Spandre[19], P. Spinelli[31,20], D. J. Suson[67], H. Tajima[68,3], J. G. Thayer[3], J. B. Thayer[3], D. J. Thompson[17], L. Tibaldo[69], D. F. Torres[57,70], E. Troja[17,18], Y. Uchiyama[71], T. M. Venters[17], G. Vianello[3,72], K. S. Wood[48], M. Wood[3], G. Zaharijas[73,74], S. Zhu[18], S. Zimmer[4,5]

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Searching the Gamma-ray Sky for Counterparts to Gravitational Wave Sources: *Fermi* GBM and LAT Observations of LVT151012 and GW151226

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Fermi LAT Collaboration:

M. Ackermann[15], A. Albert[16], W. B. Atwood[17], M. Axelsson[18,19], L. Baldini[20,21], J. Ballet[22], G. Barbiellini[23,24], M. G. Baring[25], D. Bastieri[26,27], R. Bellazzini[28], E. Bissaldi[29], R. D. Blandford[21], E. D. Bloom[21], R. Bonino[30,31], J. Bregeon[32], P. Bruel[33], S. Buson[+,1], G. A. Caliandro[21,34], R. A. Cameron[21], R. Caputo[17], M. Caragiulo[35,29], P. A. Caraveo[36], E. Cavazzuti[37], E. Charles[21], J. Chiang[21], S. Ciprini[37,38], F. Costanza[29], A. Cuoco[39,30], S. Cutini[37,38], F. D'Ammando[40,41], F. de Palma[29,42], R. Desiante[43,30], S. W. Digel[21], N. Di Lalla[28], M. Di Mauro[21], L. Di Venere[35,29], P. S. Drell[21], C. Favuzzi[35,29], E. C. Ferrara[1], W. B. Focke[21], Y. Fukazawa[44], S. Funk[45], P. Fusco[35,29], F. Gargano[29], D. Gasparrini[37,38], N. Giglietto[35,29], R. Gill[46], M. Giroletti[40], T. Glanzman[21], J. Granot[46], D. Green[1,47], J. E. Grove[48], L. Guillemot[49,50], S. Guiriec[1], A. K. Harding[1], T. Jogler[51], G. Jóhannesson[52], T. Kamae[53], S. Kensei[44], D. Kocevski[1], M. Kuss[28], S. Larsson[18,54], L. Latronico[30], J. Li[55], F. Longo[23,24], F. Loparco[35,29], P. Lubrano[38], J. D. Magill[47], S. Maldera[30], D. Malyshev[45], J. E. McEnery[1,47], P. F. Michelson[21], T. Mizuno[56], A. Morselli[57], I. V. Moskalenko[21], M. Negro[30,31], E. Nuss[32], N. Omodei[21*], M. Orienti[40], E. Orlando[21], J. F. Ormes[59], D. Paneque[60,21], J. S. Perkins[1], M. Pesce-Rollins[28,21], F. Piron[32], G. Pivato[28], T. A. Porter[21], G. Principe[45], S. Rainò[35,29], R. Rando[26,27], M. Razzano[28,61], S. Razzaque[62], A. Reimer[63,21], O. Reimer[63,21], P. M. Saz Parkinson[17,64,65], J. D. Scargle[66], C. Sgrò[28], D. Simone[29], E. J. Siskind[67], D. A. Smith[68], F. Spada[28], P. Spinelli[35,29], D. J. Suson[69], H. Tajima[70,21], J. B. Thayer[21], D. F. Torres[55,71], E. Troja[1,47], Y. Uchiyama[72], G. Vianello[21*], K. S. Wood[48], M. Wood[21]

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