Follow-up of Gravitational Wave Events with the Fermi-LAT.
Current Status and Prospects for the Future

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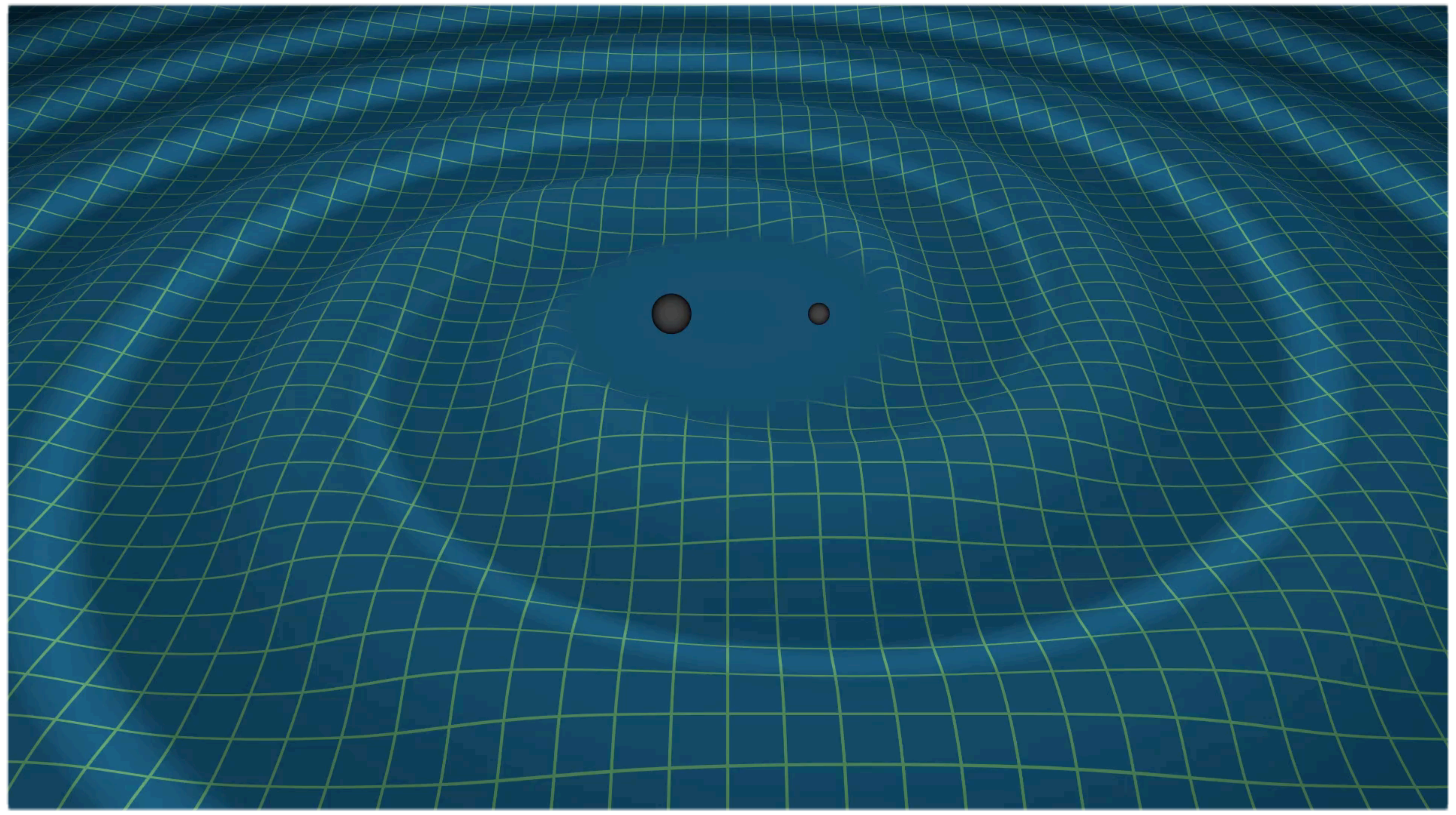
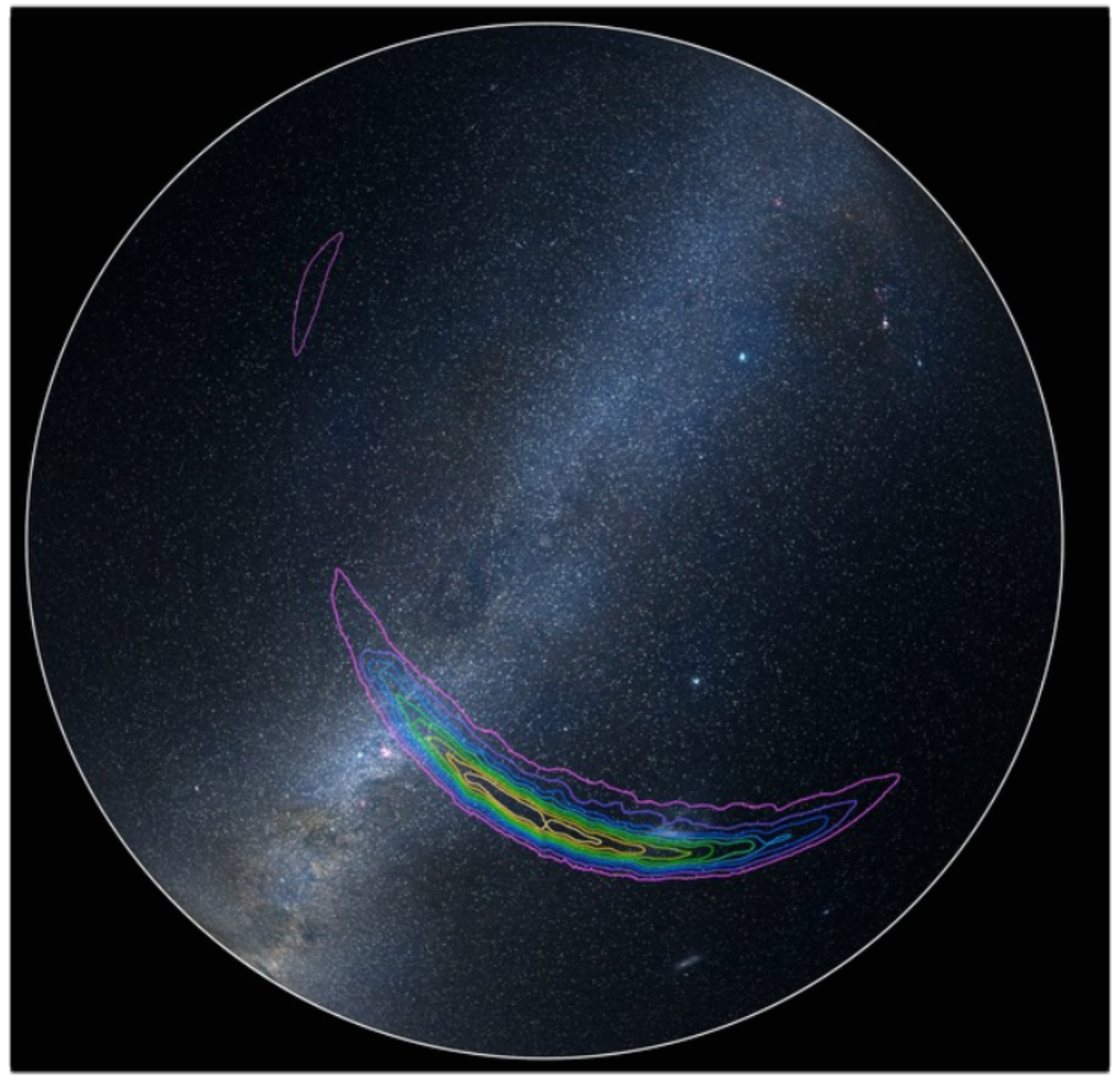
for the Fermi/LAT collaboration

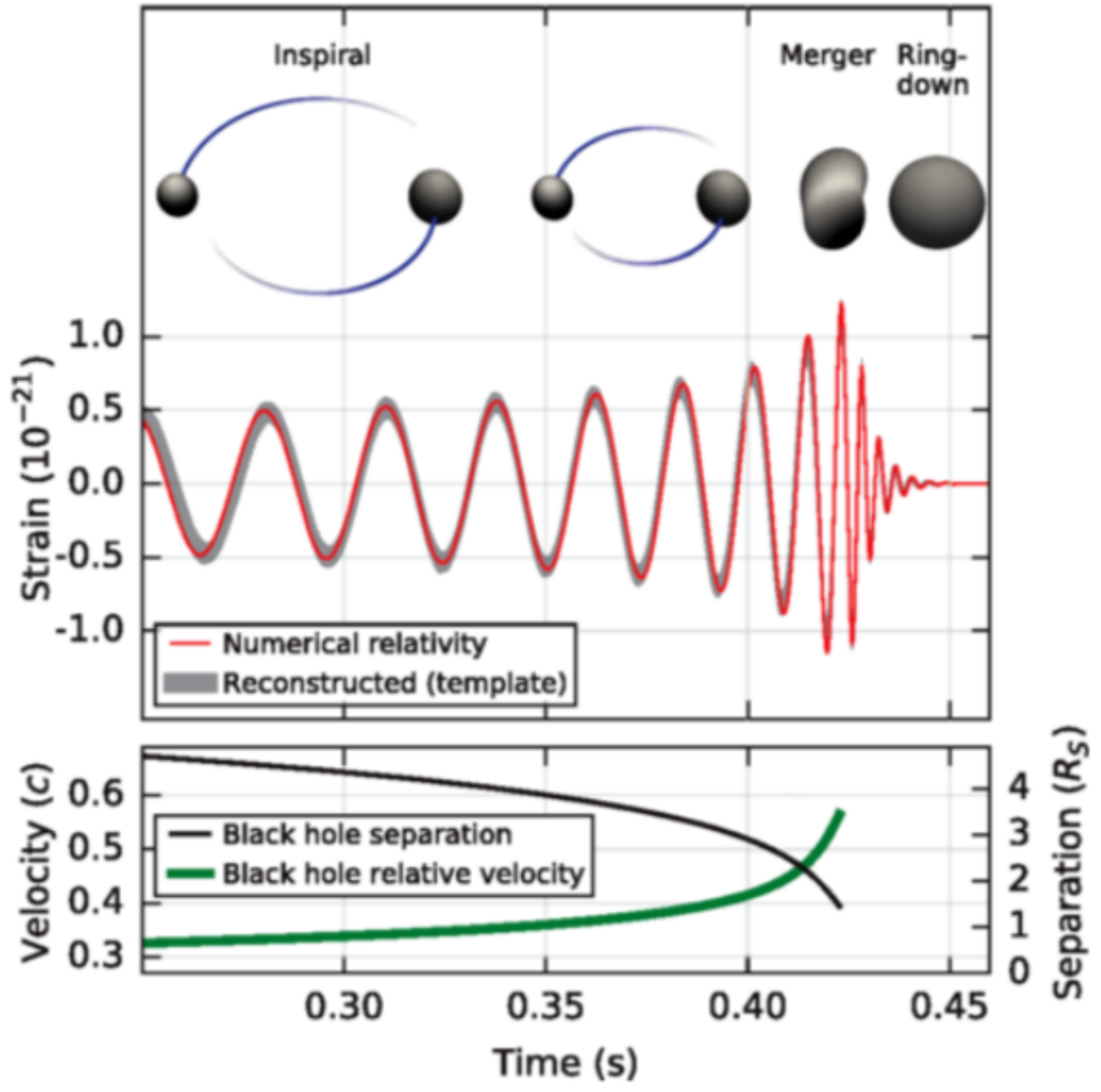
7th International Fermi Symposium

The Discovery



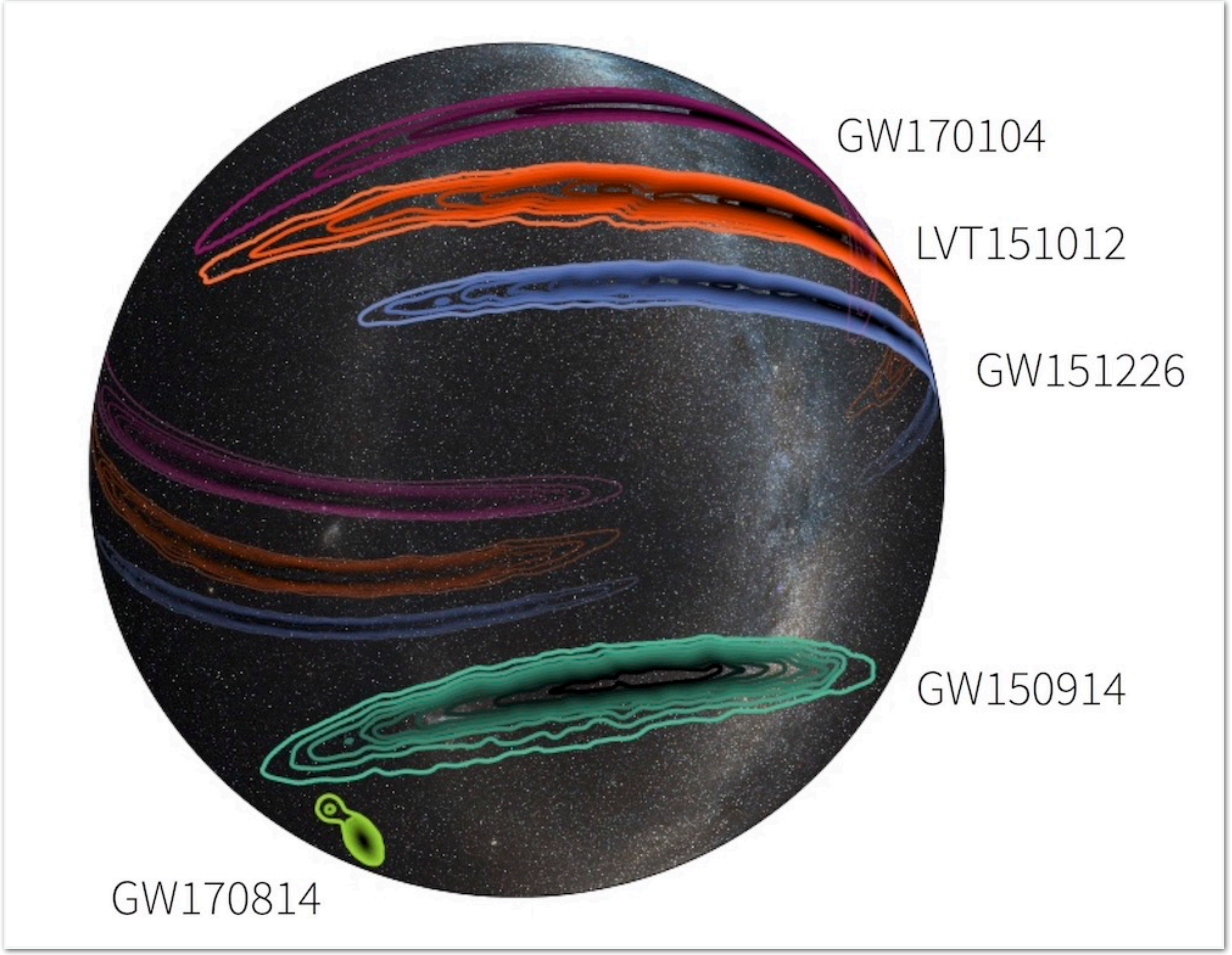


September 14, 2015, the LIGO Scientific Collaboration and Virgo Collaboration made the first observation of gravitational waves, originating from a pair of merging black holes using the Advanced LIGO detectors.



Following up LIGO events

- 6 GW events announced by the LIGO/VIRGO Collaboration:
  - 5 BH- BH: GW150914, LVT151012, GW151226,GW170104, GW170814;
  - 1 NS-NS: GW170817;
- BH-BH mergers are not expected to produce EM radiation.
- NS-NS: predicted (and confirmed) to have EM radiation.
- General strategy for Fermi-LAT searches at high-energy:
  - Automated full sky searches of transients;
  - Specific searches in the LIGO contours;
  - Specific followups of detected counterparts;
  - All done automatically in pipelines to quick alert the community;



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

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

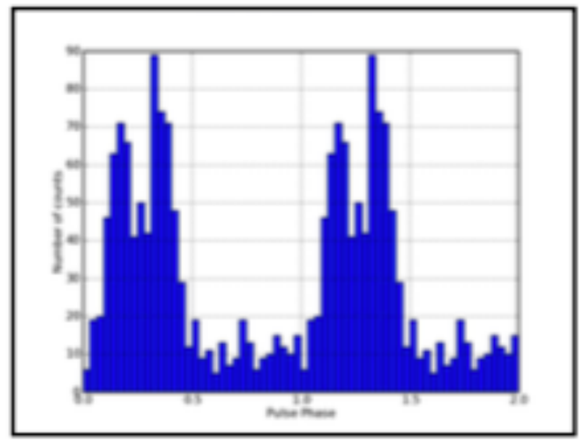
LAT Automated Science Processing (ASP) + Flare Advocates
Likelihood
6 & 24 hour
ATels, GCN notices (on AGN)
Operating

Transients Timescale

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

Photon Timing

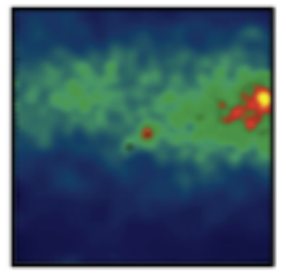
Pulsars



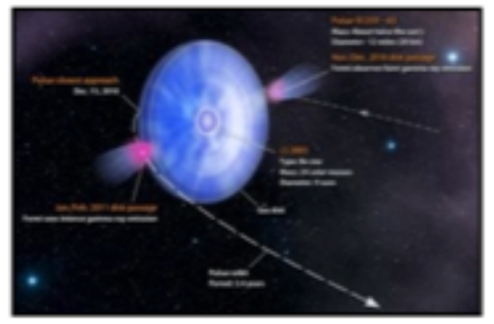
Solar Flares

All Sky Cadence

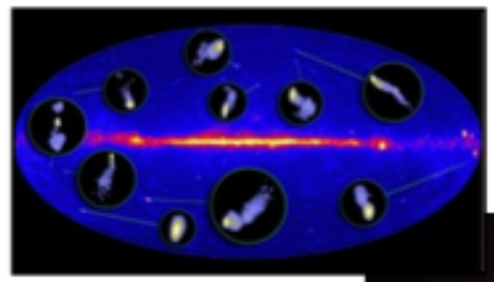
Novae



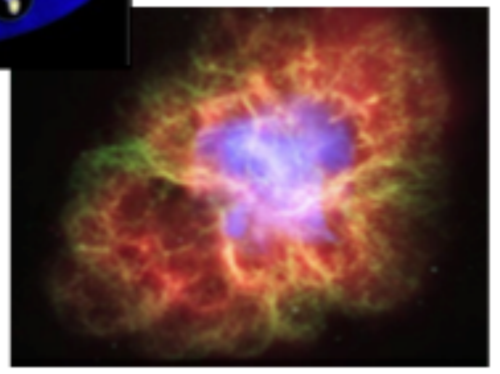
γ-ray Binaries



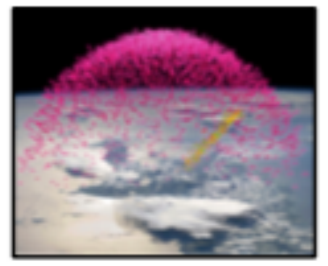
Blazar Flares



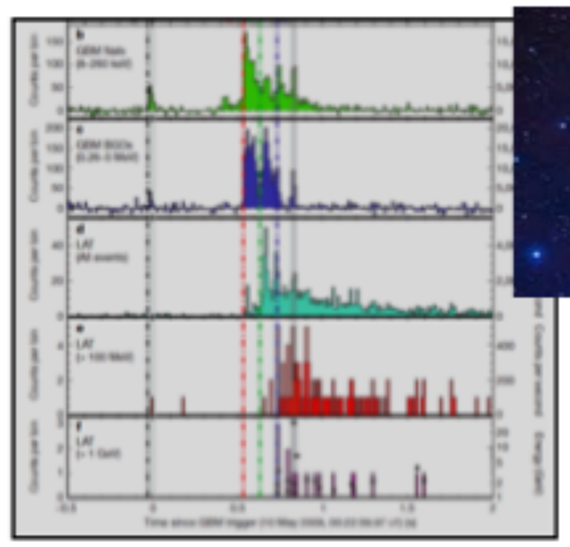
Crab Flares



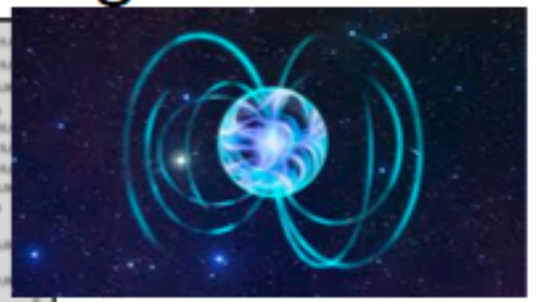
Terrestrial γ-ray Flashes



GRBs



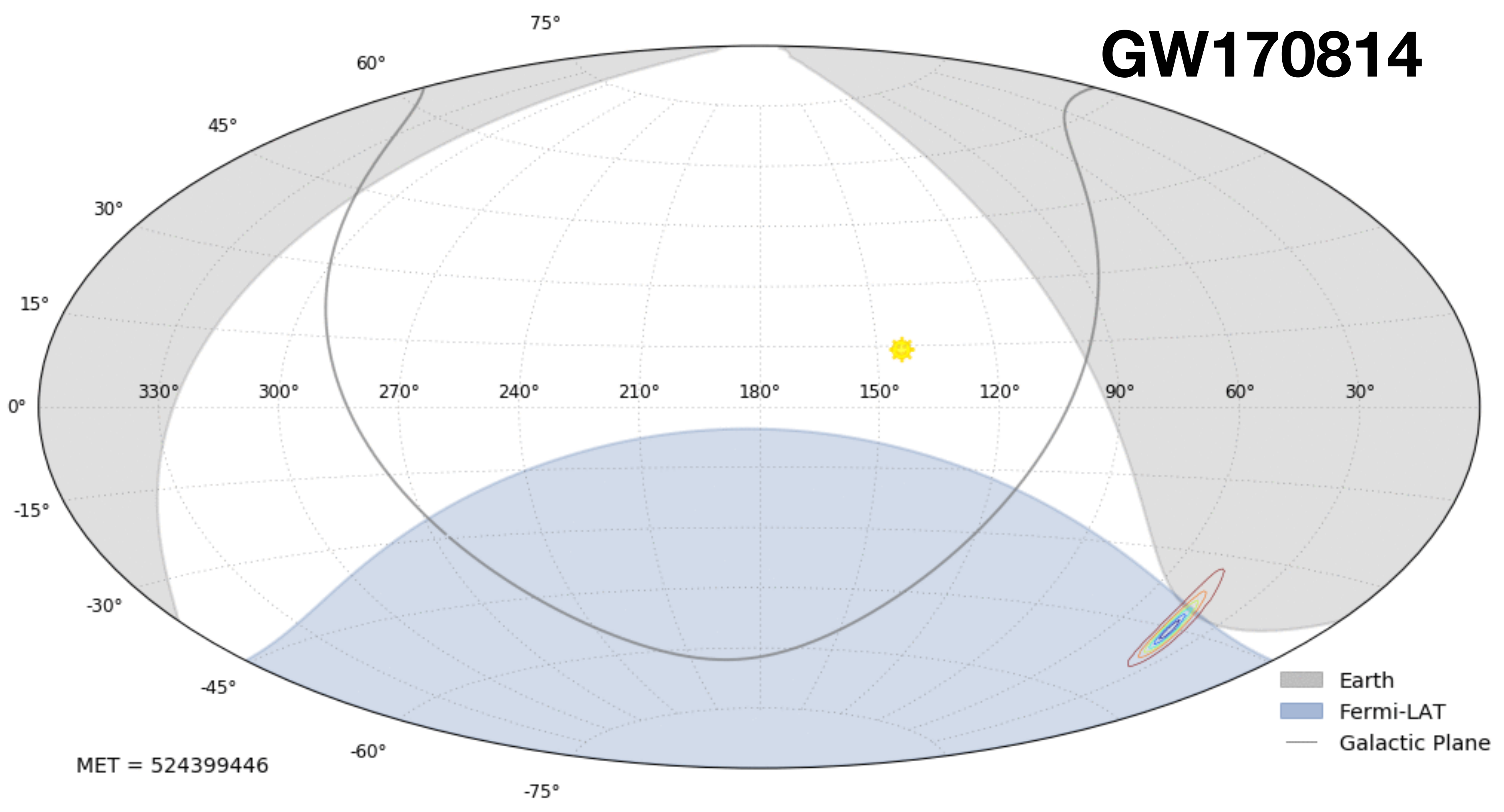
Magnetar Flares

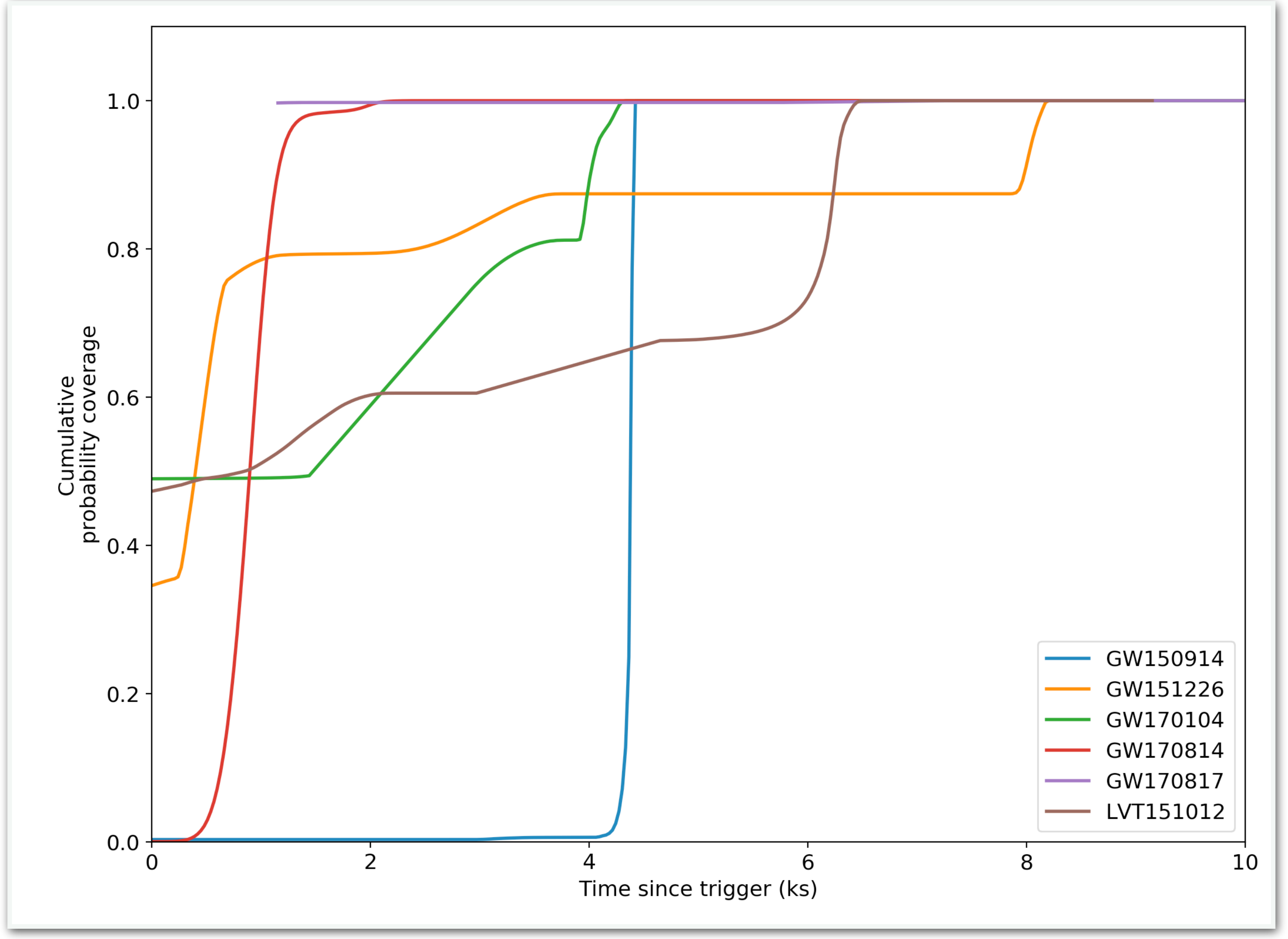


Not to scale

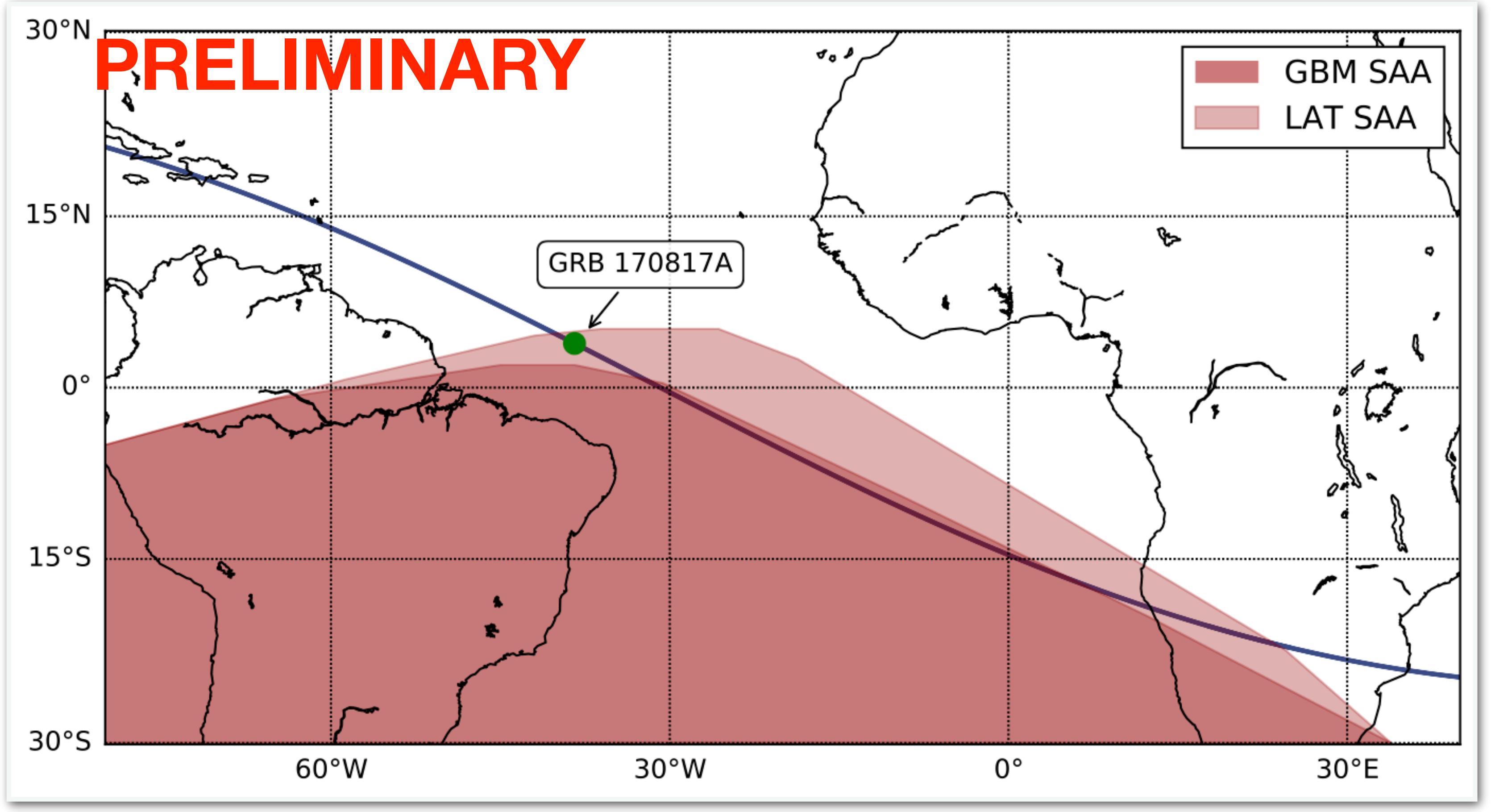
From LVC probability maps to LAT analysis

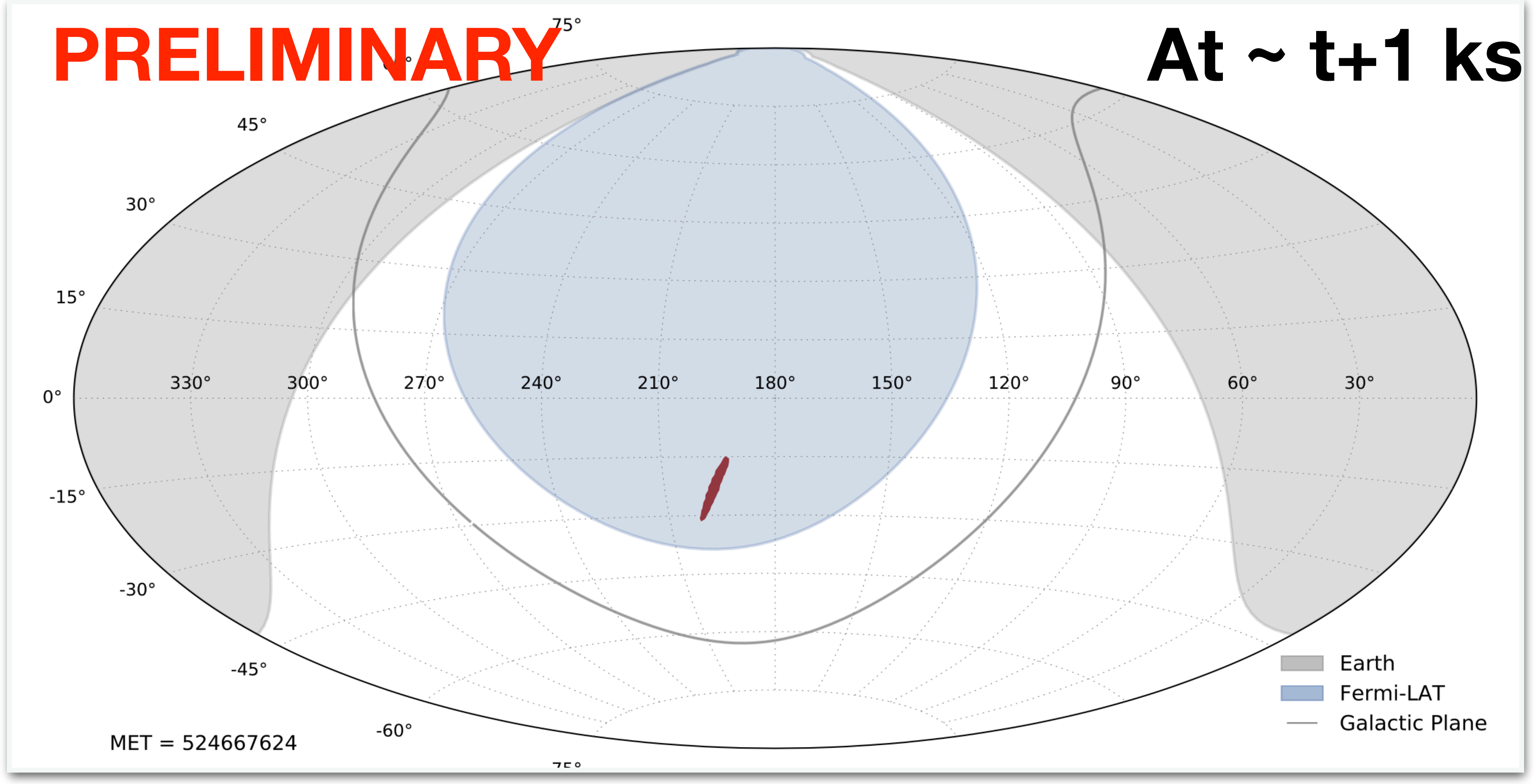
- We developed a novel technique to search for EM counterpart in LAT data starting from LIGO probability maps:
  - LVC probability maps (in HEALPix) downscaled to match the Fermi LAT PSF (~4 degrees at 100 MeV);
  - We center a ROI in each pixel (p>0.9), and we run standard likelihood analysis (Unbinned);
- Cumulative coverage of the map as a function of time:
  - In some cases we started with ~40-50% of the credibility region in the field of view at the time of the trigger;
  - In all cases we reached 100% of the coverage within 8 ks;
  - Different pixels of the map enter and exit at different time:
    - We set up two different analysis: fixed time window and adaptive time window
    - see: Ackermann et al. 2016 (GW150915), Racusin et al. 2017 (GW151226, LVT151012), Goldstein at al. 2017 (GW170114), Vianello et al. 2017 (Methods)





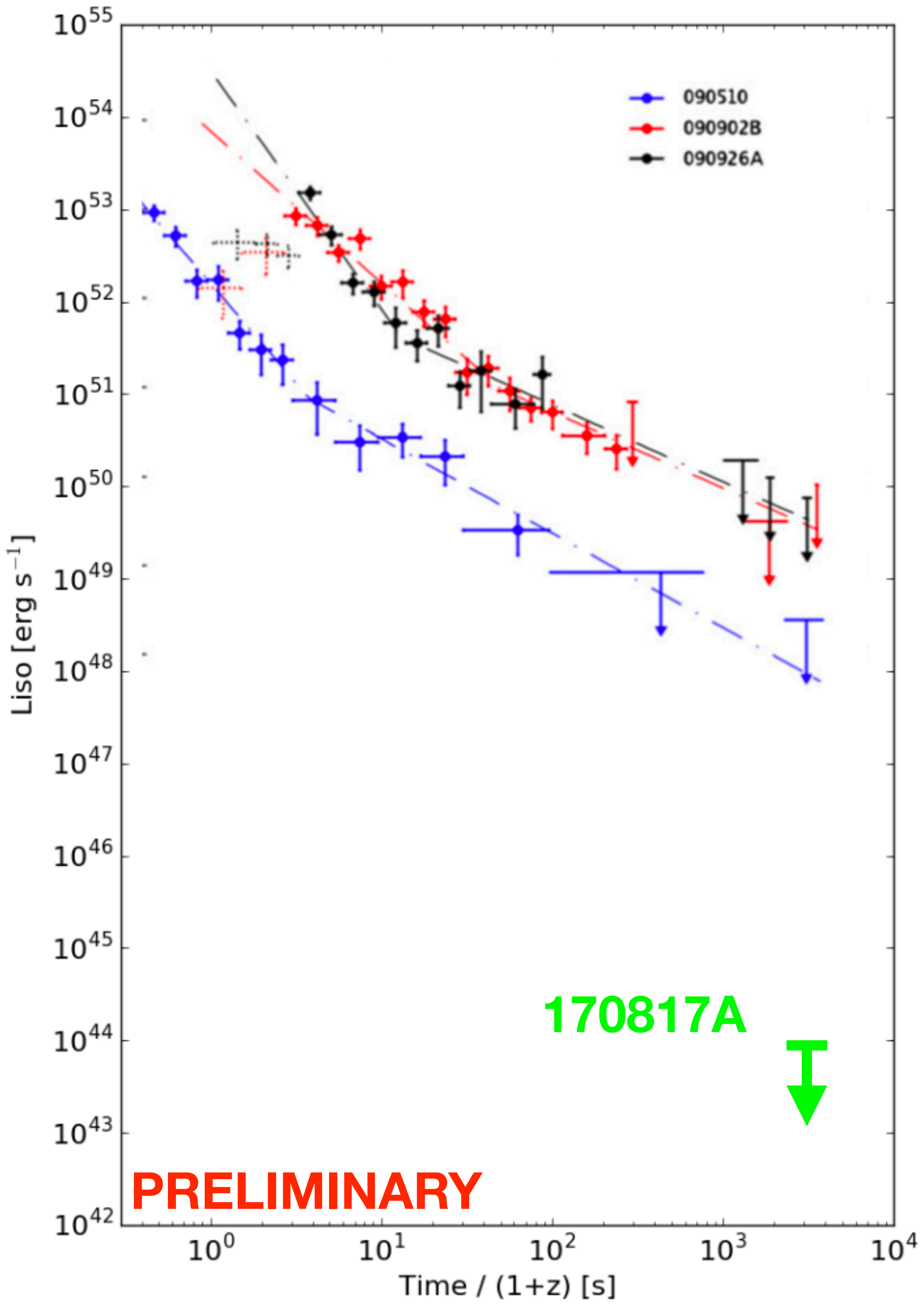
GW170817/GRB170817A, an unlucky event



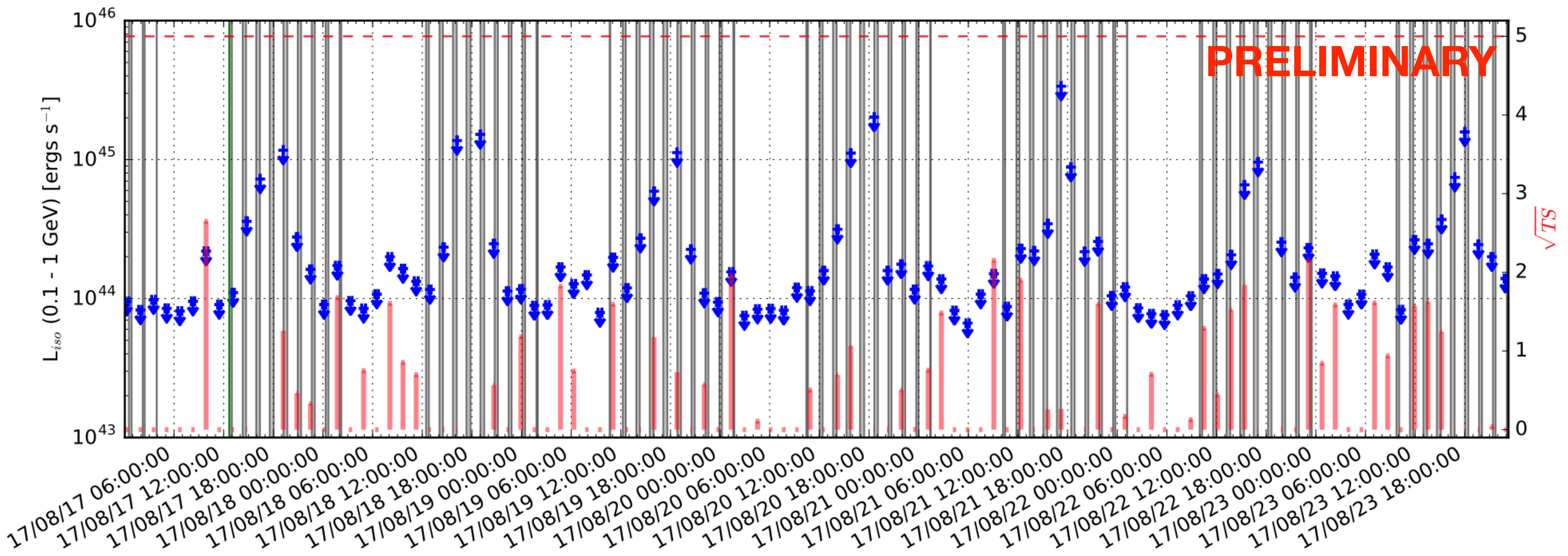


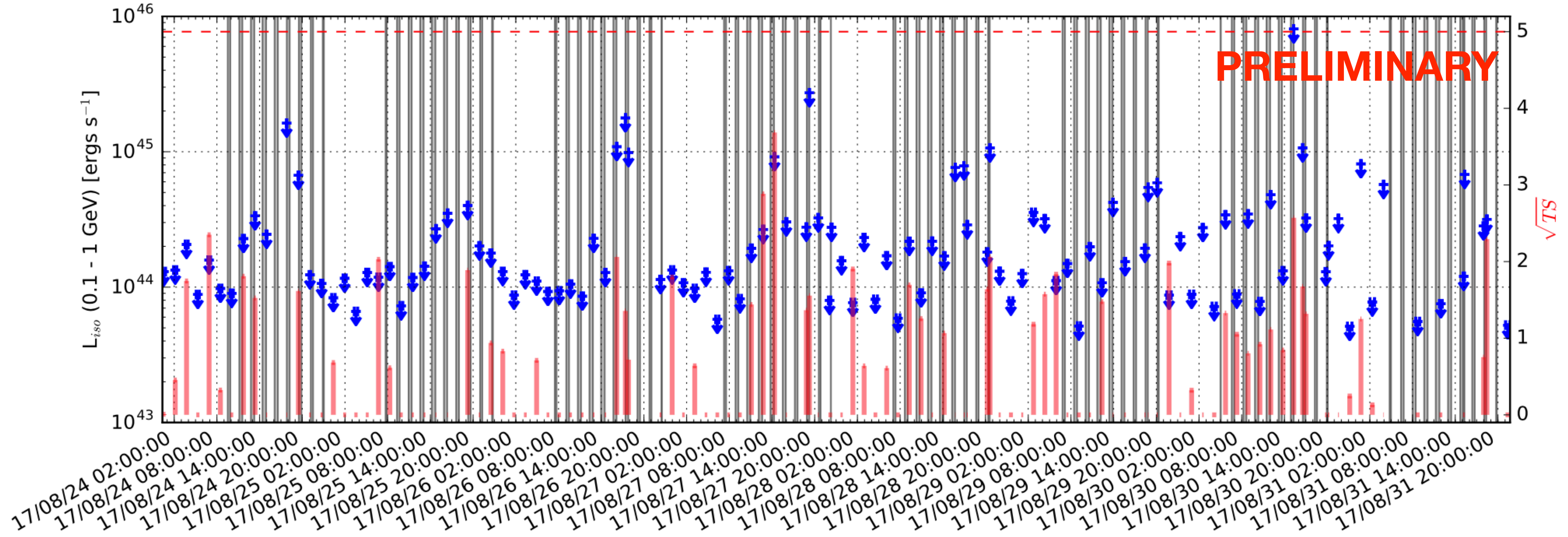
- The LAT and the GBM do not collect data when in the SAA
  - For different instument requirements, the SAA definition for the LAT is slightly larger (14%) than the GBM one;
  - At the time of the GW event (and GBM trigger), the LAT was in the SAA;
  - We observe the entire region between t_{GW}+1153 – t_{GW}+2017;
  - Upper bound (0.1–1 GeV):
    - F < 4.5×10^{-10} erg cm^{-2} s^{-1}
  - At the distant of GW170817:
    - L_{iso} < 9.3×10^{43} erg s^{-1}

★ Very strong constrain on the luminosity of GRB170817A at high energy



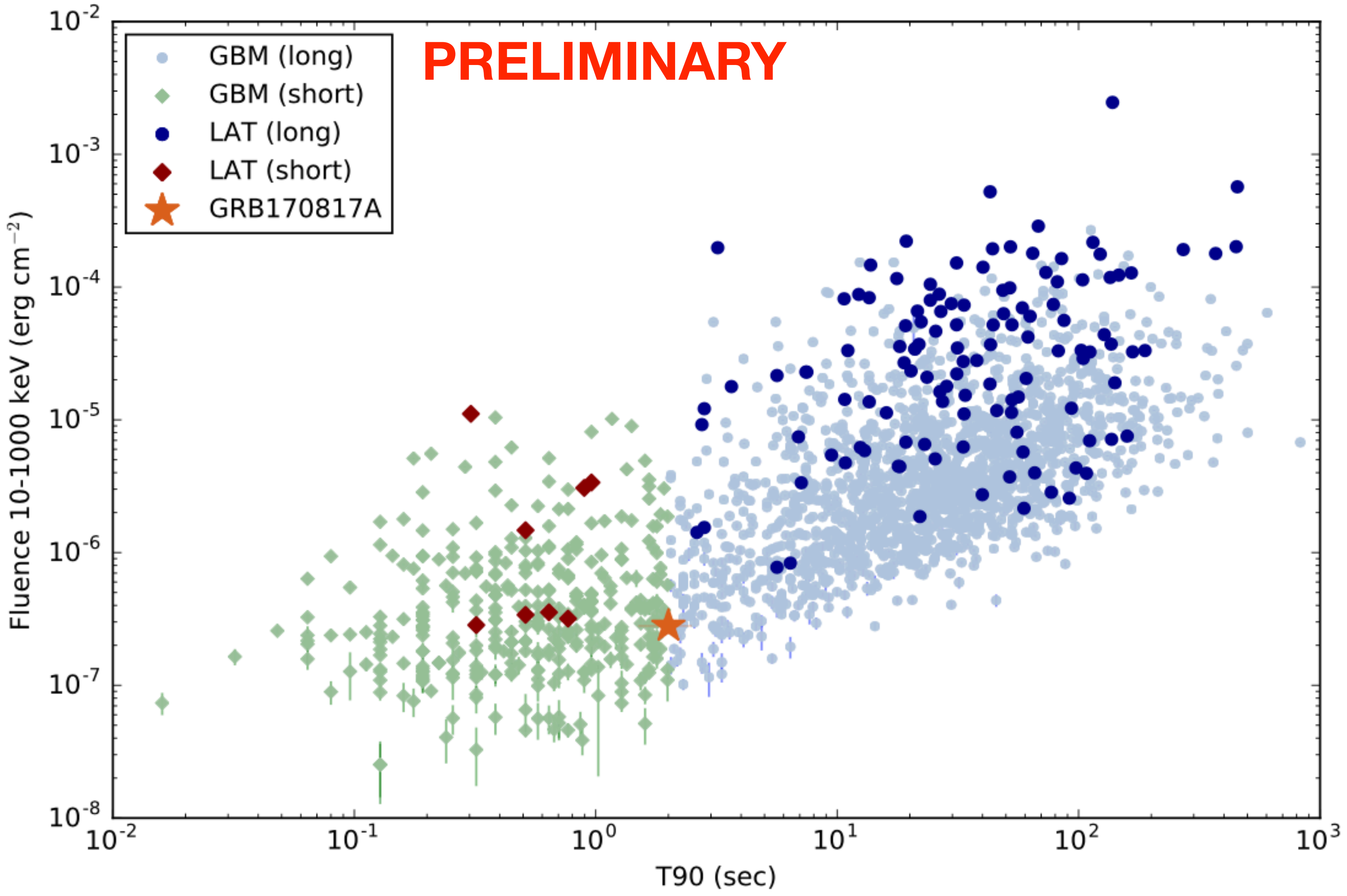
GW170817/GRB170817A, long time monitoring

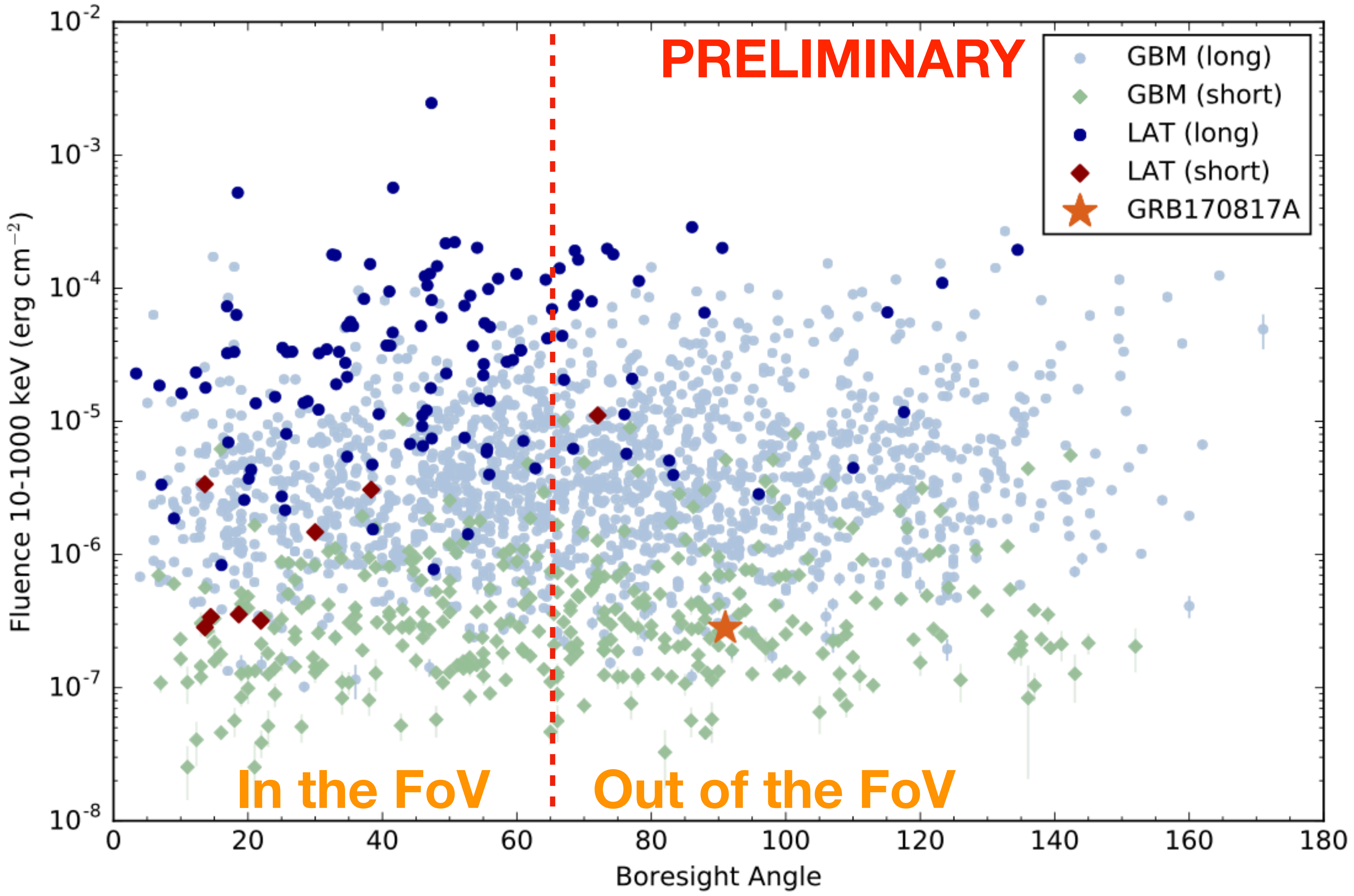




- **Given the continuous evolution of the transient, we are keeping the source monitored;**
- **No significant excess at later time:**
  - **F< 9.7×10^{-11} to 3.7×10^{-8} erg cm^{-2} s^{-1}**
  - **L< 2.1×10^{43} to 8.1×10^{45} erg s^{-1}**
- **On the life time of the mission (9 years):**
  - **F< 1.32×10^{-12} erg cm^{-2} s^{-1}**
  - **L< 2.9×10^{41} erg s^{-1}**

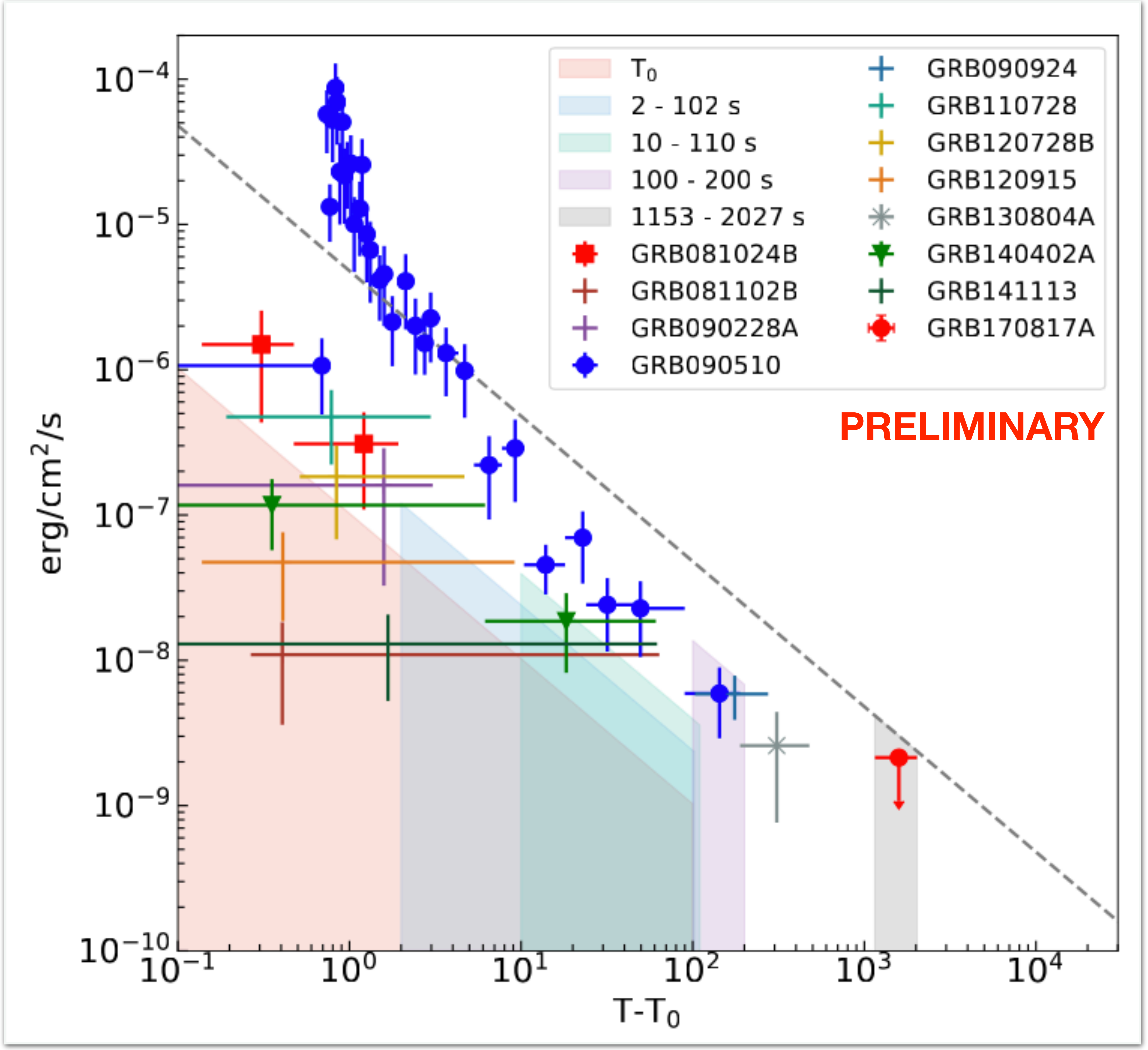
GW170817/GRB170817A, and other GBM GRBs





- **GBM flux (10 keV – 1 MeV): in the middle of the GBM SGRB population:**
  - **other 4 SGRBs of similar fluence have been detected by the LAT at high-energy (>100 MeV);**
- **Detectability of SGRBs depends on the off-axis angle:**
  - **LAT can repoint within few hundreds of seconds;**

Fermi LAT sensitivity to SGRBs



- LAT detected GRBs exhibit a long lasting high-energy emission (lasting ~200 seconds for SGRBs);
- We estimate the average flux a SGRB would need to be detected by the LAT (50% of the time with TS≥25)
  - In a 100 s exposure starting at T_0, T_0+2s, +10, +100 (typical for LAT detected SGRBs)
  - Between T_0+1153 and T_0+2027 (as GRB170817A);
- LAT detected SGRB consistent with our significance estimation;
- Even the brightest SGRB detected by the LAT (090510) would have not been detected if the observation had started at ~1000 seconds;
- We need to start observing a burst within ~100s to really have a chance of seeing it;
- Rate estimation:
  - LAT sees 23% of the all sky SGRBs within 100 s (either a detection or upper bound)
  - LAT detects 5% of all GBM-detected SGRB
  - Assuming 1 (2) GW+SGRB events per year : 5% (10%) probability to detect it in the LAT
  - Modifying the observing profile (re-pointing every SGRB within 100 seconds): 7% (13%)

Conclusions

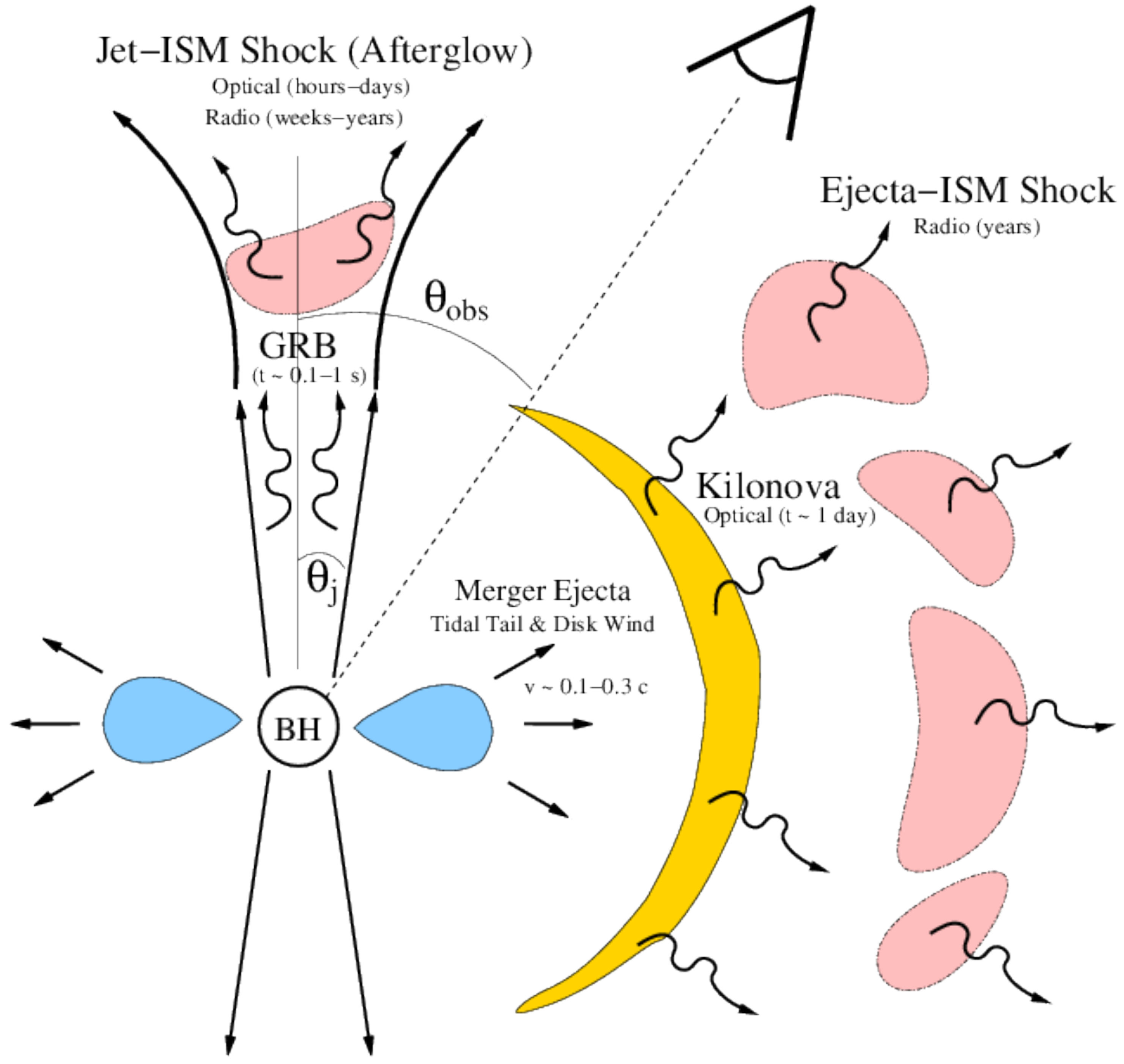
- **The discovery of GW170817/GRB 170817A strongly supports the conjectured association of SGRBs with merging neutron stars;**
- **LAT was in the SAA at the time of the GW/GBM trigger: Upper bound at t0+1000s**
  - **Very constraining, due to its proximity**
  - **Continuous monitor at late times**
- **Prospects for the future:**
  - **LAT probability to detect a GW event at high-energy: ~ 5%–10%.**
  - **With the improvement in LIGO-Virgo sensitivity: larger detection rate;**
- **From what we know from GBM and LAT: there is every reason to believe that gamma-ray observations will play a crucial rule in the developments of the exciting field of multi messenger astronomy.**

Fermi-LAT observation of the LIGO/Virgo event GW170817 => (arXiv:1710.05450)

Backup Slides

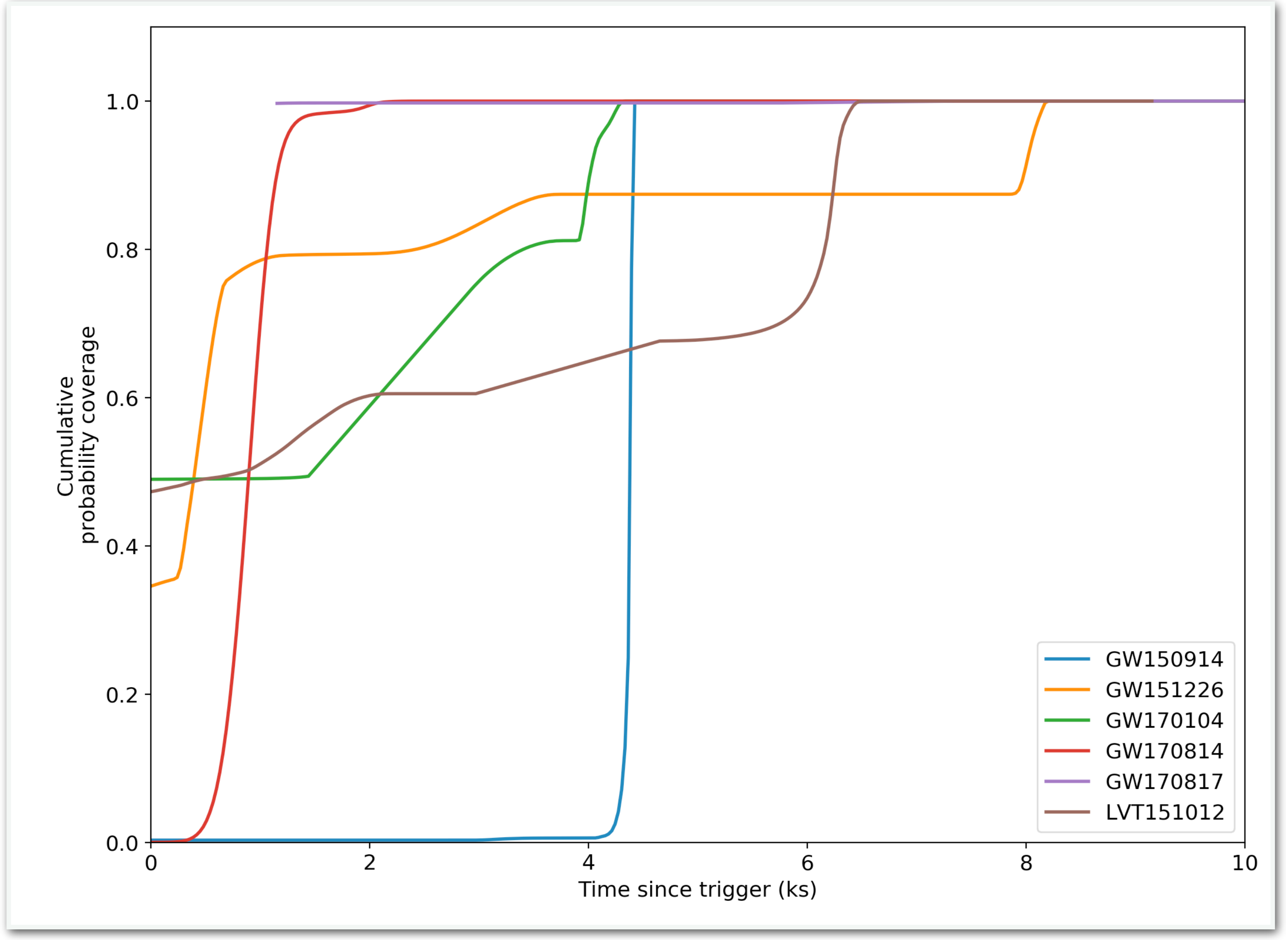
Short GRB associated with GW events

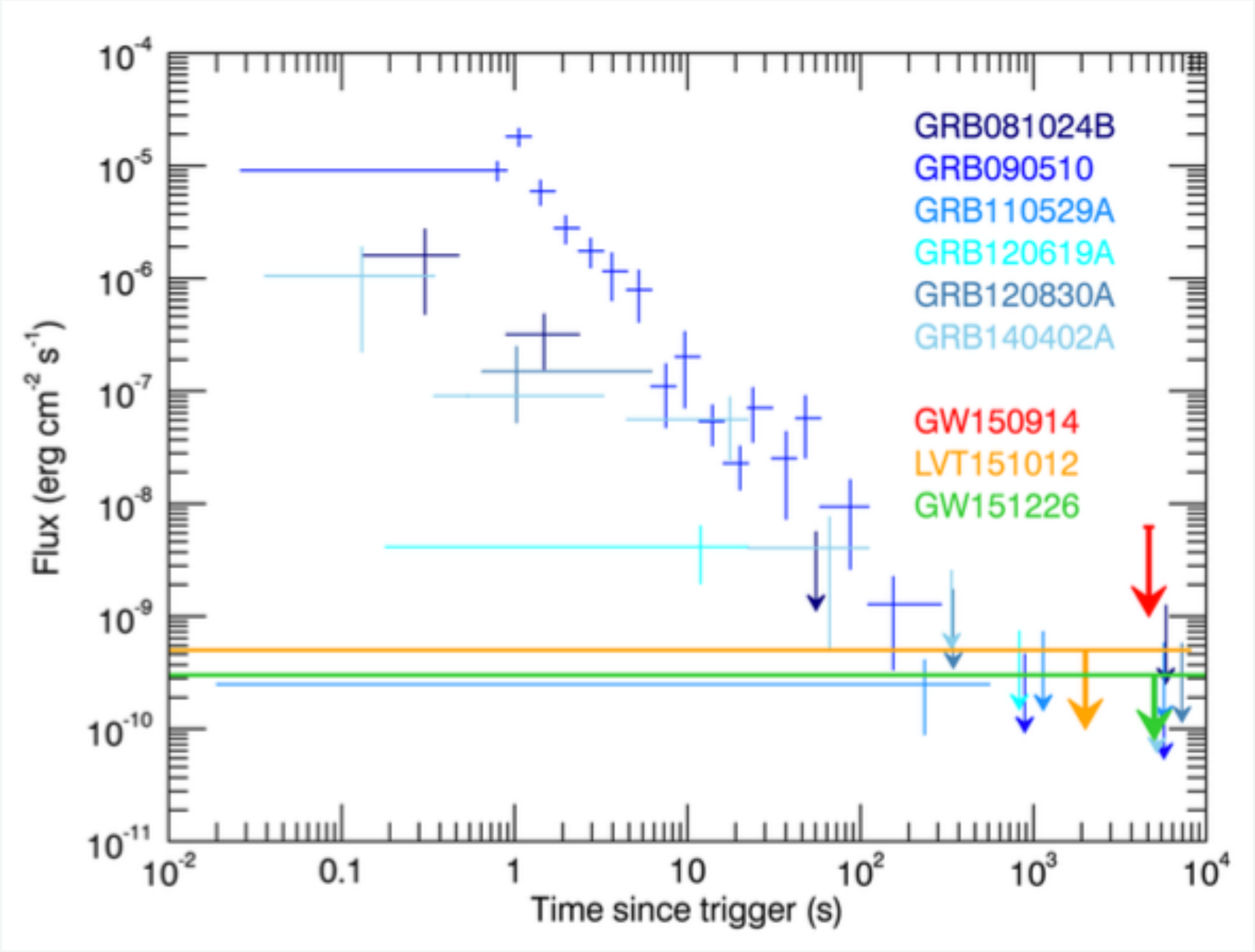
- **sGRB phenomenology in a nutshell:**
  - Progenitors: NS-NS, NS-BH -> BH
  - On-axis sGRB:
    - More rare (needs to point toward us);
    - "Standard" afterglow due to the Jet-ISM interaction
    - Observed at high-energy by the LAT (8 sGRB detected by the LAT so far);
    - temporally extended emission detected up to ~100 seconds after the trigger;
  - Off-axis:
    - No prompt emission (or weak?) in <MeV (due to the beaming);
    - Isotropic optical bump ("kilonova");
    - Late "orphan" X-ray afterglow (when the beaming decreases);
    - At high-energy: little is know…



Metzger & Berger.

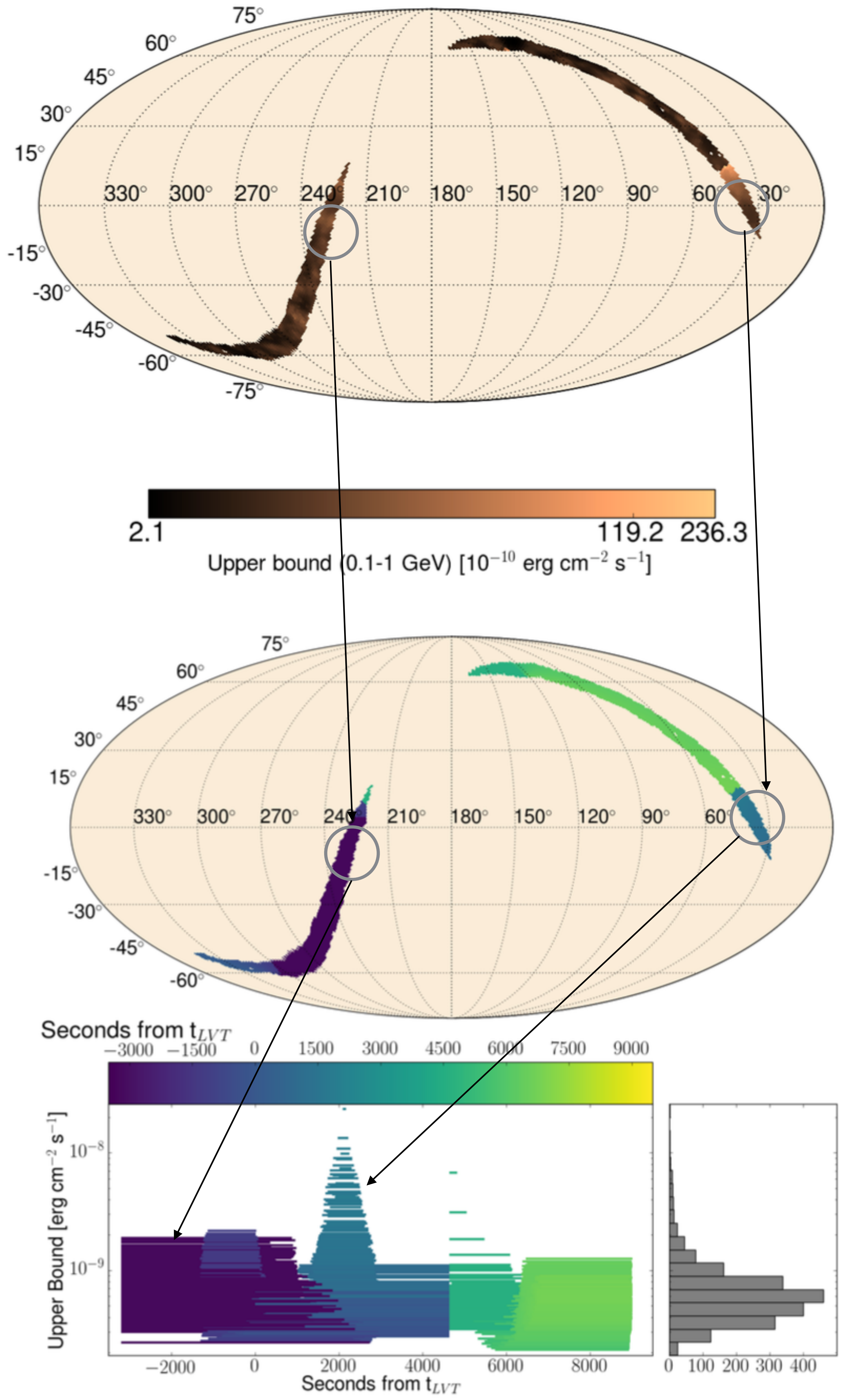
Fixed Time Windows - Adaptive intervals





- **Duration estimated from the full coverage of the event:**
  - **Typically ~10 ks;**
- **Standard unbinned likelihood analysis:**
  - **In each pixel, Test Statistics (TS) evaluates the significant of an excess with respect the background (galactic + isotropic emission + known point source from 3FGL);**
  - **Significance map for every LIGO/Virgo alert;**
  - **When no detection (TS<25): map of upper bounds;**
- **Bayesian upper bounds:**
  - **We developed a fully bayesian method to calculate a "global" upper bound, using the probability map as prior (and using Markov-Chain Monte Carlo to marginalize the posterior probability);**
  - **These UB can be used to constrain models if the location of the GW event is unknown.**

Fixed Time Windows - Adaptive intervals



- Adaptive time window:
  - –Entry-exit for each pixel in the sky;
  - –During the trigger or the orbit right after;
  - –Scan an interval of days (before and after the trigger);
- Standard unbinned likelihood analysis:
  - –TS (significance) maps;
  - –Maps of upper bounds;

- These upper bounds 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 match the colors of the pixels in the second panel;
  - –They can be used to constrain models if the location of the GW event is known (for example from its detection by some other facility);