Fermi-GBM highlights in the Era of Gravitational-Wave Astronomy

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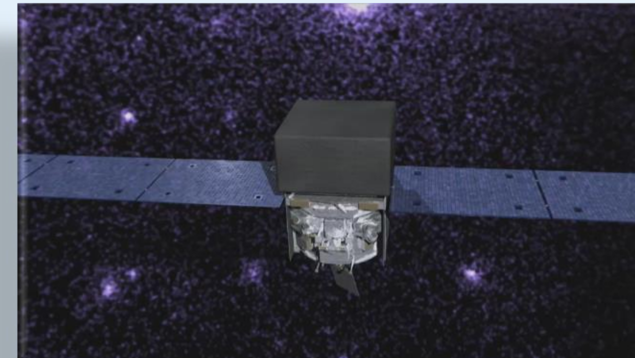
*on behalf of the **Fermi-GBM Team**

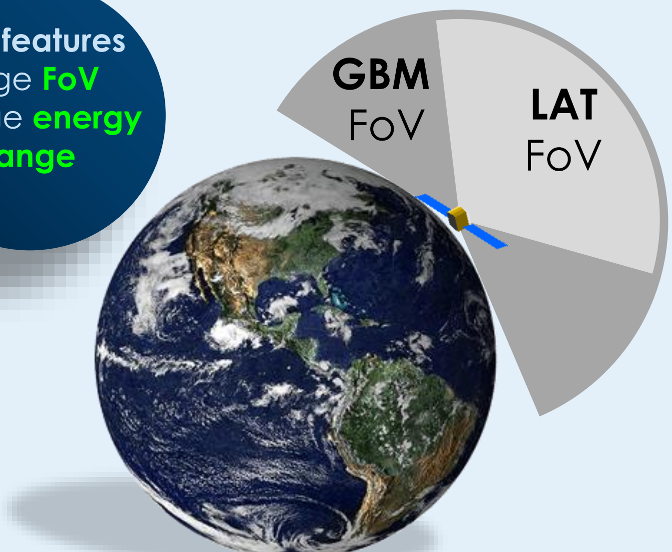
The Fermi Gamma-Ray Burst Monitor

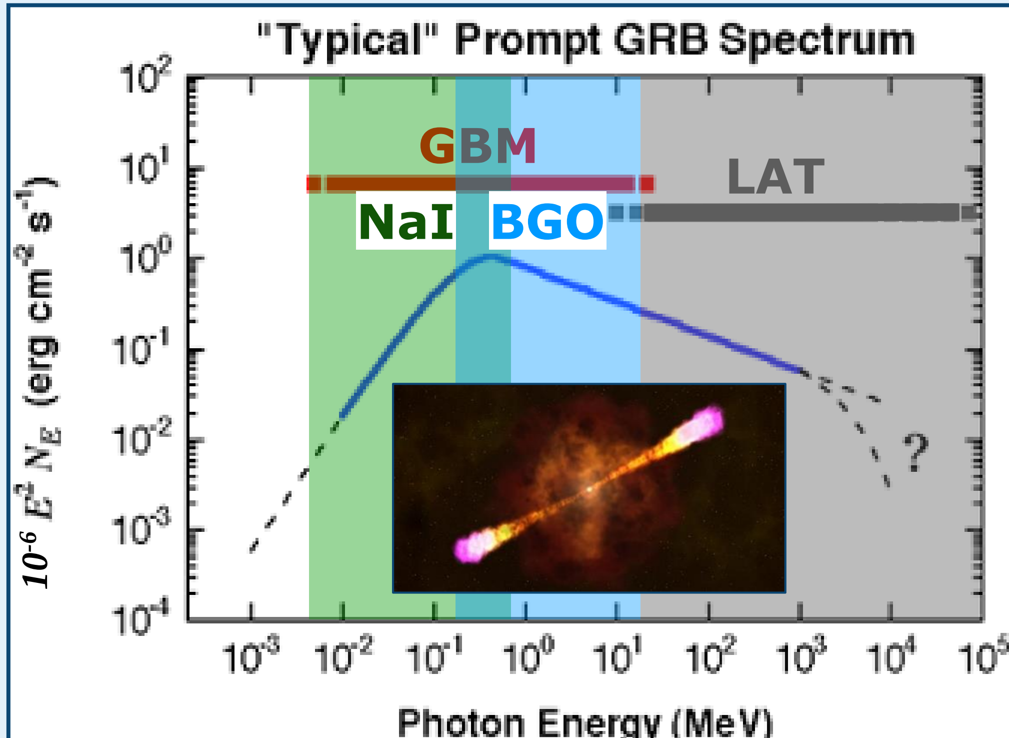
Designed to study Gamma-Ray Bursts (GRBs)

- GBM primary **objectives**:
  1. **Extend** the energy range downward from the Fermi-LAT one (100 MeV – 300 GeV)
  2. Compute burst **locations** onboard to allow re-orienting the spacecraft



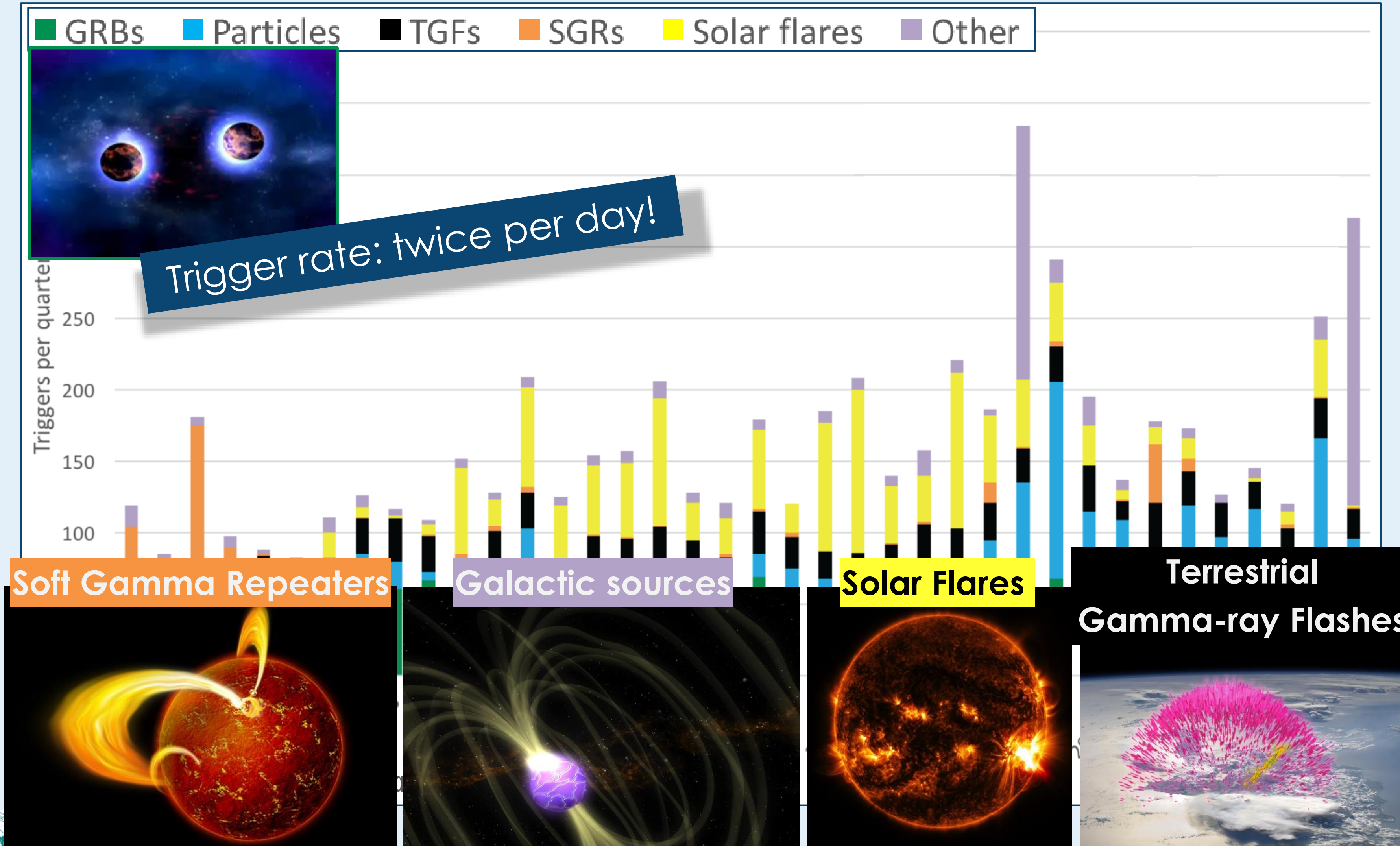
Key features
huge **FoV**
& huge **energy range**



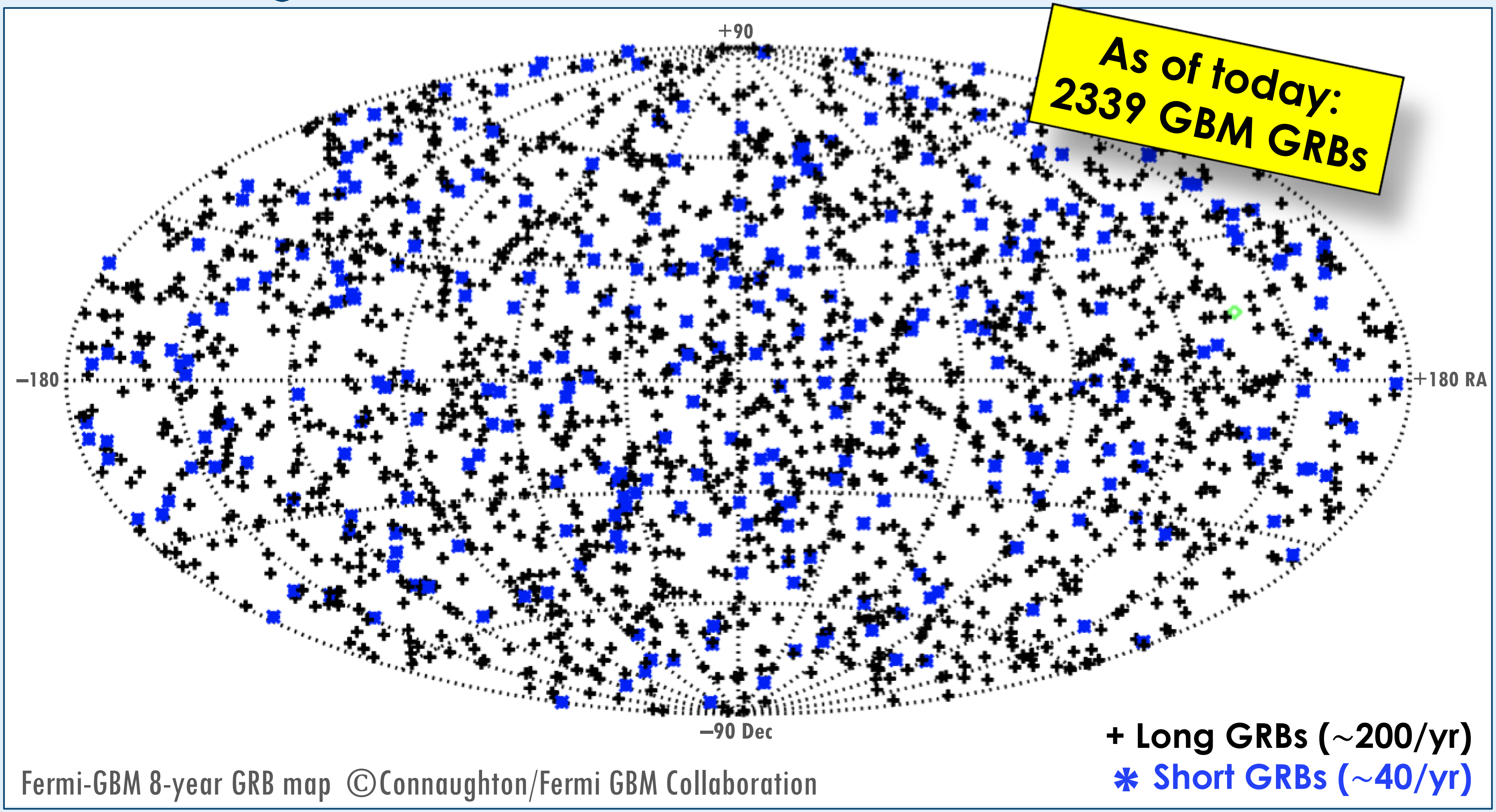


Fermi-GBM triggers

Quarterly trigger statistics over **9.5 years** of the mission



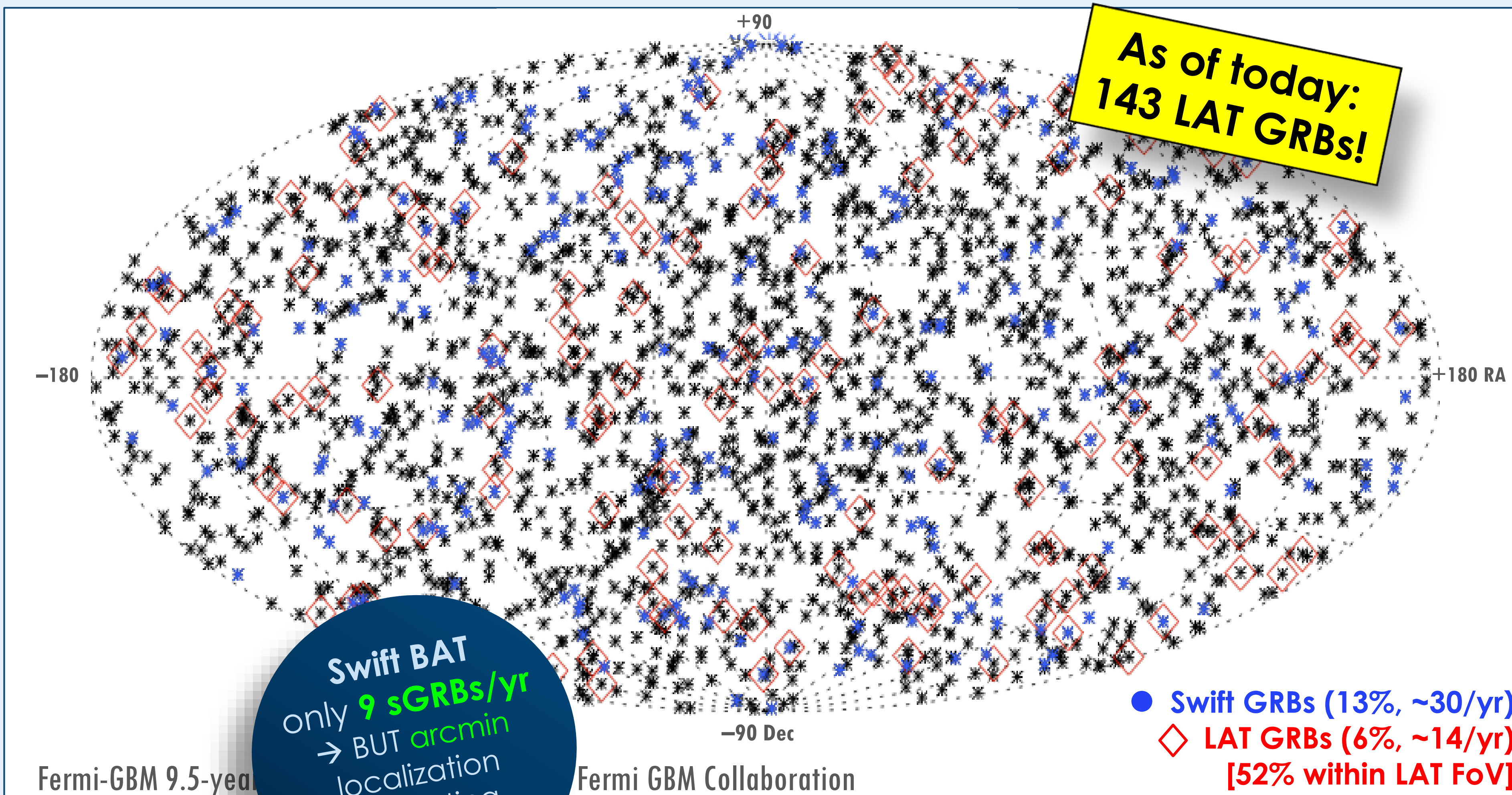
Fermi GBM skymaps



The **GBM GRB online catalog** is updated **within 1 hour**:

➔ http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html

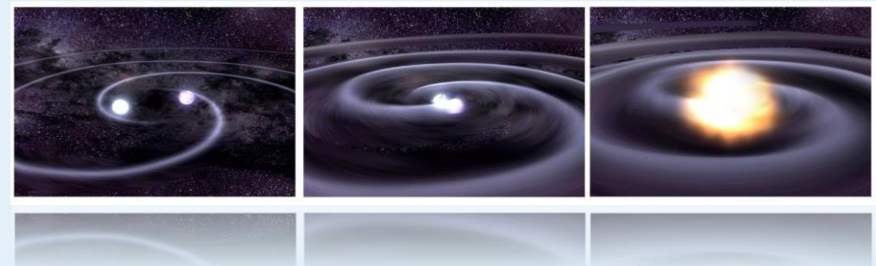
Fermi GBM skymaps



As of today: 143 LAT GRBs!

Swift BAT
only **9 sGRBs/yr**
→ BUT arcmin localization facilitating follow-ups

Fermi GBM – LIGO/Virgo Partnership



- **Special MoU**: Small team of members from both collaborations that have worked together for years
  - Recognition that GBM is the **most prolific sGRB detector**, providing energy discrimination and localization capabilities
  - LVC has access to **sub-threshold GBM triggers**
    - **Untargeted blind search** for weak GBM sGRBs
  - GBM has access to **sub-threshold GW triggers**
    - Developement and constant refinement of a GBM sub-threshold **targeted search**

→ The **joint sub-threshold work** may eventually be able to push GW detection horizon further by associating weak signals in both detectors

→**All-O1 analysis of sub-threshold GW triggers** is currently under review by the LVC
→**All-O2 sub-threshold analysis is just now beginning**, obviously very important now!

Fermi GBM untargeted searches

- **Since 2013**: Development of **automated search algorithms** for **untriggered** transient sources **(POC: M.S.Briggs)**
  - Magnetar burst (~200), TGFs (> 1000), other Galactic sources (>100), Short GRBs (sGRBs)

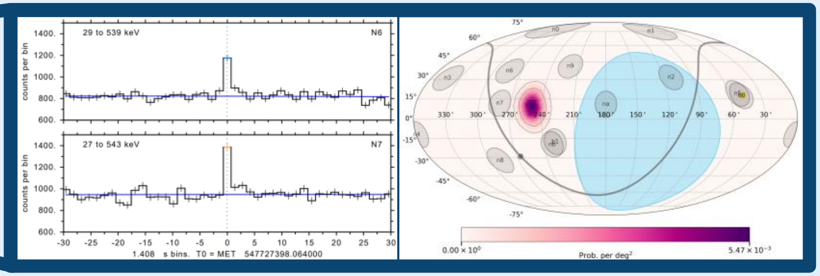
- CTTE data search over **4 energy ranges and 10 timescales** (0.064 – 2.8 s)
- Uses **all 12 NaI detectors** and flags candidates that meet a pre-defined count rate threshold in **“legal” detector pairs** in 50-300 keV
- Improved spline background can also find some **long GRBs**
- Standard GBM **localization** technique (uncertainties 10–40 deg, (68%))
- **Fast, efficient**, runs over a complete hour of data as it is downlinked

Additional **~100 GRBs/yr** (verification)

- **Since 2017**: **automated GCNs** can trigger **follow-up** observations
  https://gcn.gsfc.nasa.gov/fermi_gbm_subthreshold_archive.html

Fermi-GBM Subthreshold Triggers

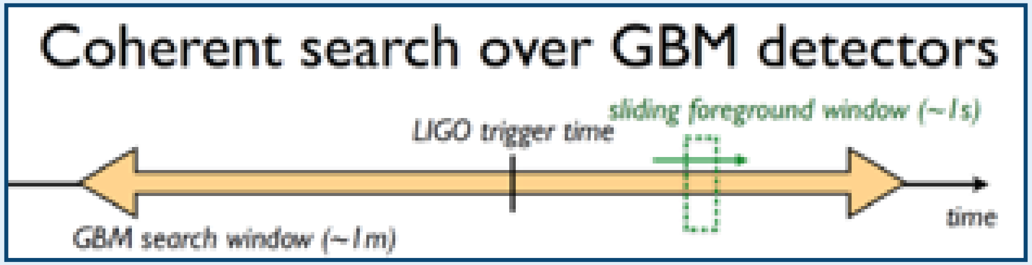
TRIGGER			OBSERVATION								
TrigNum	Date	Time UT	RA (J2000) [deg]	Dec (J2000) [deg]	Error [deg]	Dur [sec]	Spec	Type	Rel	URLs	Comments
548485652	18/05/20	05:07:27.02	269.880	-60.430	17.92	1.407	1	0	2	HEALPIX MAP LC	Fermi-GBM Subthreshold. This Notice was ground-generated -- not flight-generated.
548482684	18/05/20	04:17:59.94	297.580	-0.700	15.38	0.192	1	0	2	HEALPIX MAP LC	Fermi-GBM [illegible]hold. This Notice was ground-generated -- not flight-generated.
548385290	18/05/19	01:14:45.61	266.500	+45.550	11.24	1.407	1	0	8	HEALPIX MAP LC	Fermi-GBM Subthreshold. This Notice was ground-ge[illegible] not flight-generated.
548326303	18/05/18	08:51:38.92	155.080	-33.870	17.89	1.024	1	0	2	HEALPIX MAP LC	Fermi-GBM Subthreshold. This Notice was ground-generated -- not flight-generated.



Online sGRB catalog 2013–2017
http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

Fermi GBM ~~Un~~targeted searches

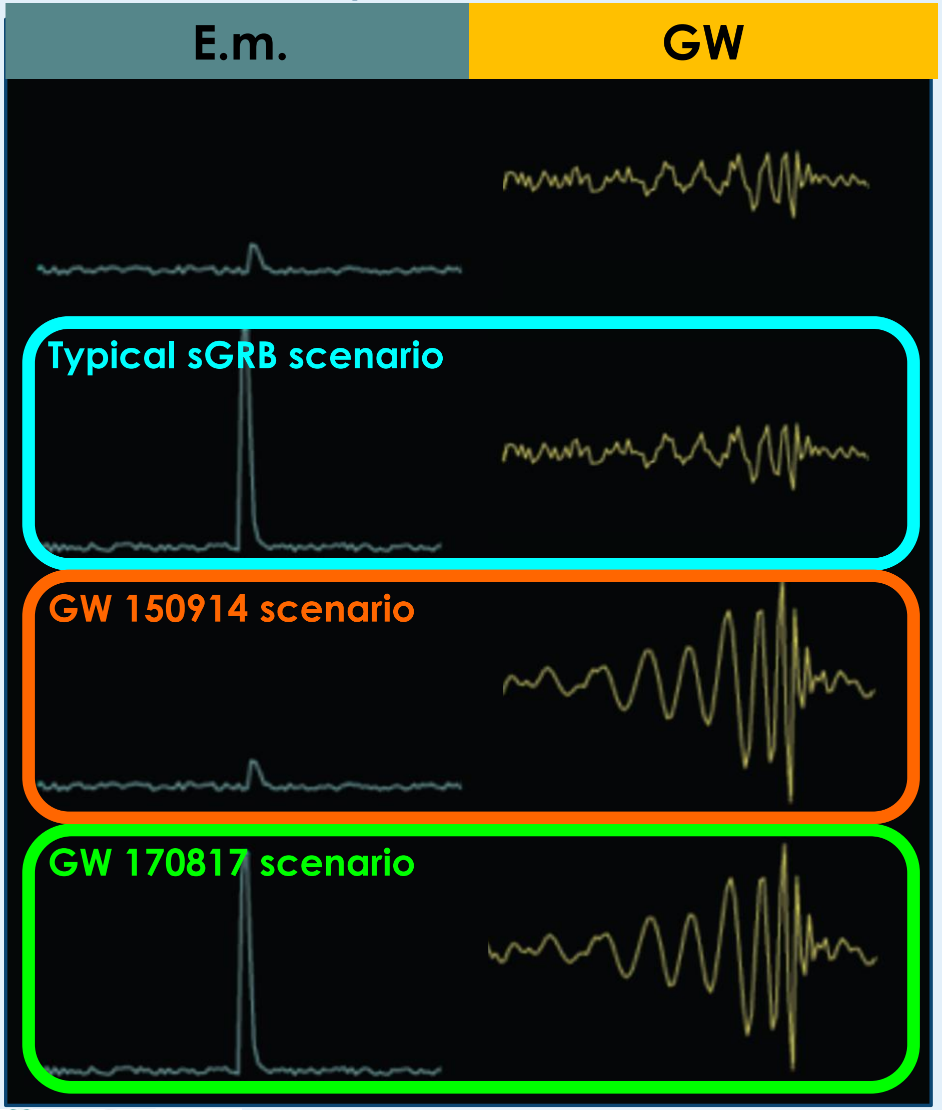
- Targeted search in **CTTE data** (Blackburn+2015, Goldstein+2016)
  - Search for **coherent signals in all detectors**
    - Seeded with a time of interest and optionally a sky map (prior)
      - Assume spectral templates
      - Convolve assumed spectrum with detector responses, calculated over the entire sky
      - Expected signal in count rate compared to observed count rate
  - Very powerful but expensive



→ Intended to be follow-up search for multi-messenger events

→ Many Improvements during O1 and O2: Various bug fixes, better background estimation, more realistic hard spectral template

Joint GBM/LVC subthreshold search

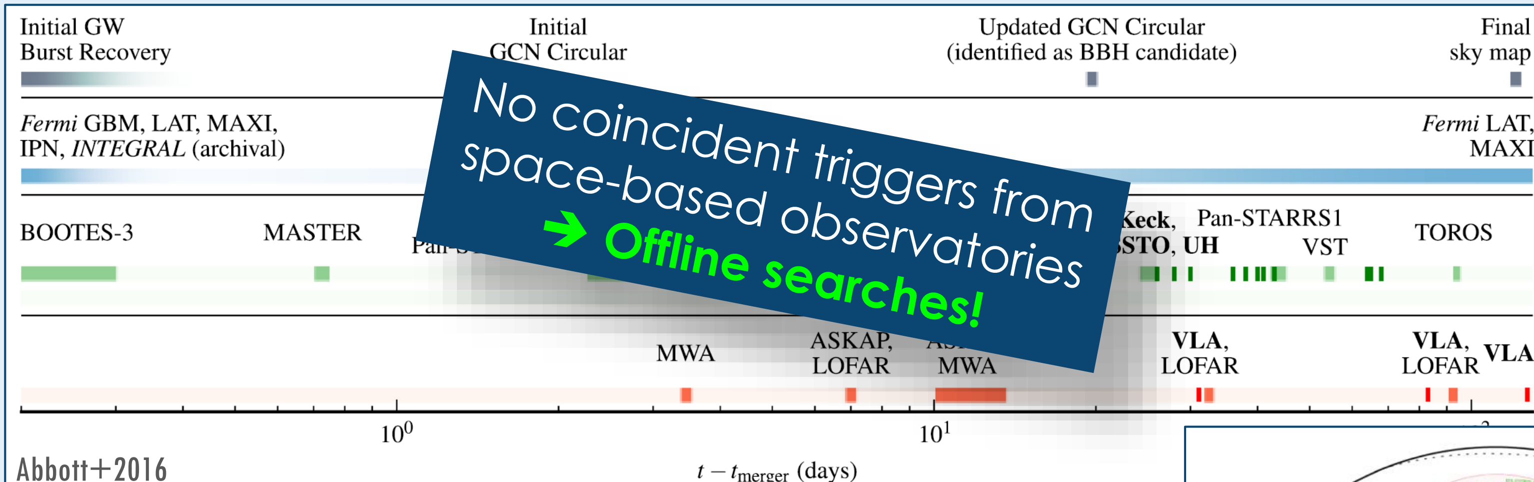


- In all cases, the presence of a signal in GBM or LV, can **raise the significance** of the signal being real in the other instrument

- A confident gamma-ray signal allowing a fainter gravitational wave signal, would push the LV detection distance limit further, in turn **increasing the event rate** by a factor of distance cubed

The follow-up of LIGO GW 150914

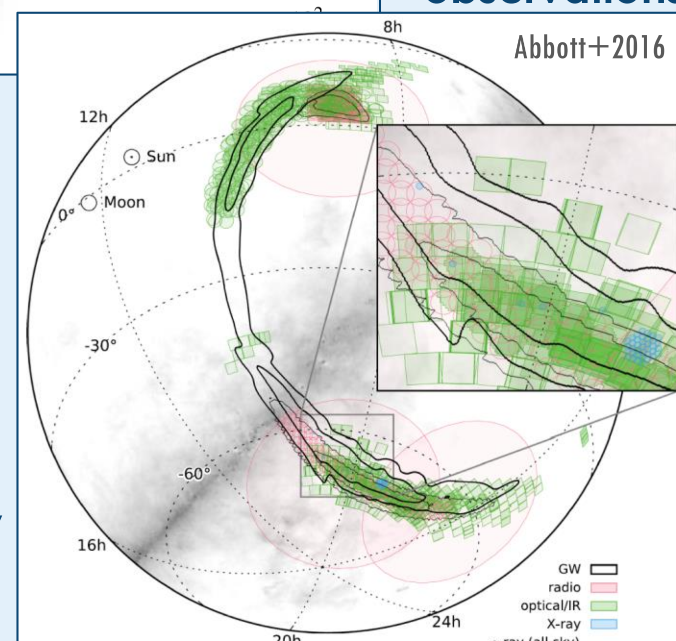
Follow-up observations reported by **25 teams** via private GCN circulars



No coincident triggers from space-based observatories
➔ Offline searches!

Timeline of observations

Skymap of observations



- Event nature: Binary black hole merger
  - Little expectation of a detectable electromagnetic (EM) signature
- But: **Milestone** achieved!
  - **First broadband campaign** to search for a counterpart of a LIGO source
  - Broad capabilities of the transient astronomy community and observing strategies

The transient "GW150914-GBM"

- **Targeted search** around **GW150914**:
  - **Best candidate**: Hard transient @t_{GW}+0.4 s, 1s long **"GW150914-GBM"**

→ **Association significance: 2.9 σ**

FAR = 27 hard events in 218821.1 s of GBM live time, factor of 3 for spectra searched, 90% confidence

$$P = 2 \times (4.79 \times 10{-}4\ \text{Hz}) \times 0.4\ \text{s} \times (1 + \ln(30\ \text{s} / 0.256\ \text{s})) = 0.0022$$

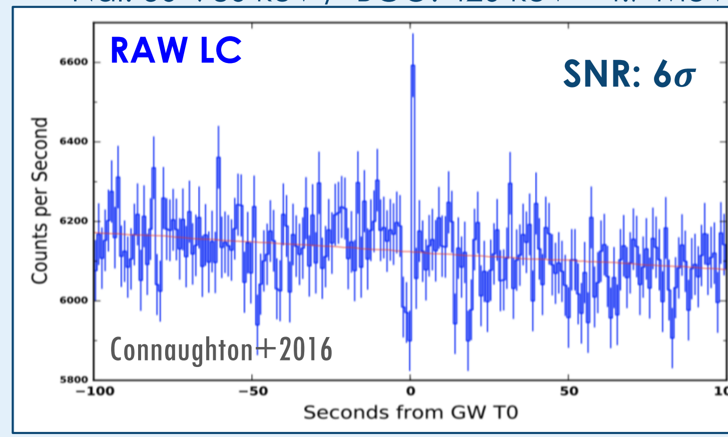
Factor of 2 to account for offset in time in either direction

Offset between GW T0 and GBM event start

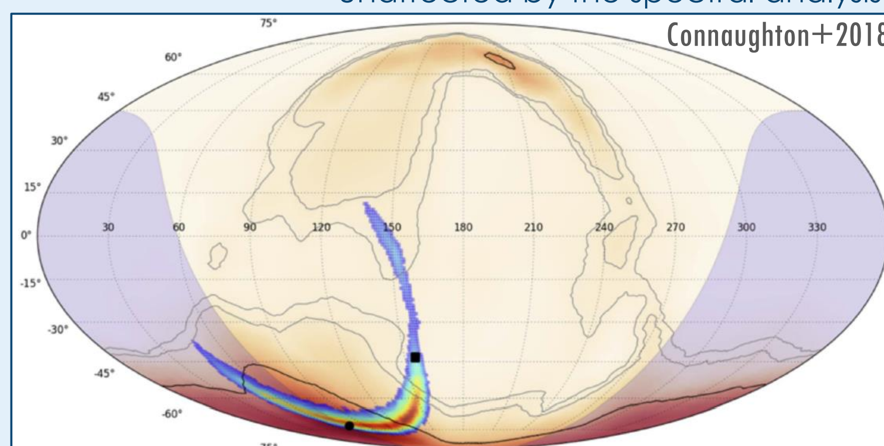
Effective trials factor for non-independent, variable time bins (30s is maximum offset set by the search window, 0.256 is the minimum set by native CTIME data)

- **Localization**: source direction **underneath the spacecraft (θ=163°)**
- **Energy spectrum** peaking in BGO energy range. Best fit simple PL with index –1.4 (**average for sGRBs**), fluence 2.4 x 10^{-7} erg cm-2 (**weaker than average for sGRBs**)

Raw count rates:
Sum of all GBM detectors: 12 x NaI + 2 x BGO
NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV



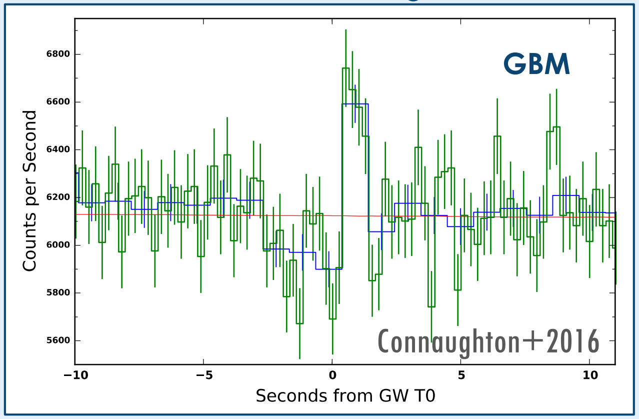
Recent verification that original spectral analysis not biased. FAR and FAP unaffected by the spectral analysis!



GBM Observations of GW Events

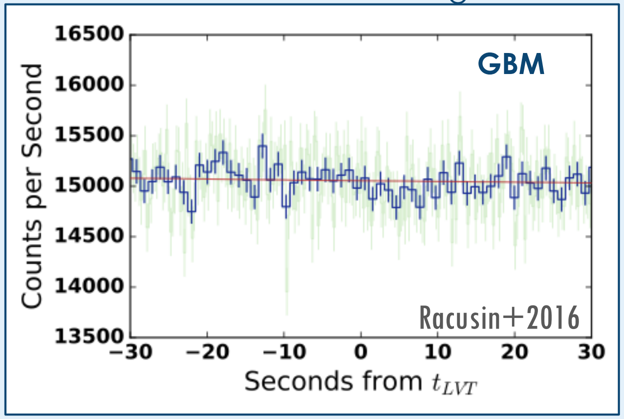
GW 150914

BH+BH Merger, 36 & 29 $M_\odot$, 410 Mpc



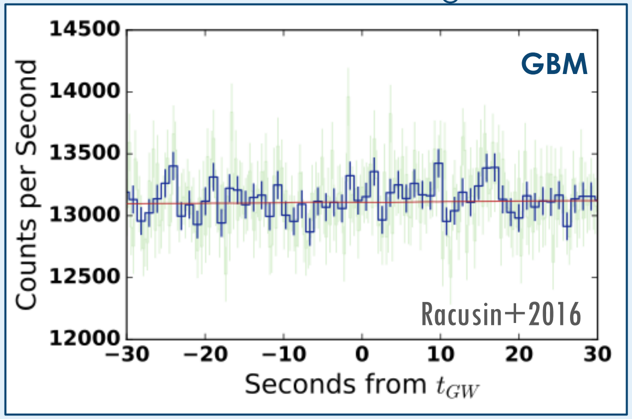
LVT 151012

Candidate BH+BH, 23 & 13 $M_\odot$, 1100 Mpc



GW 151226

BH+BH Merger, 14 & 7.5 $M_\odot$, 440 Mpc

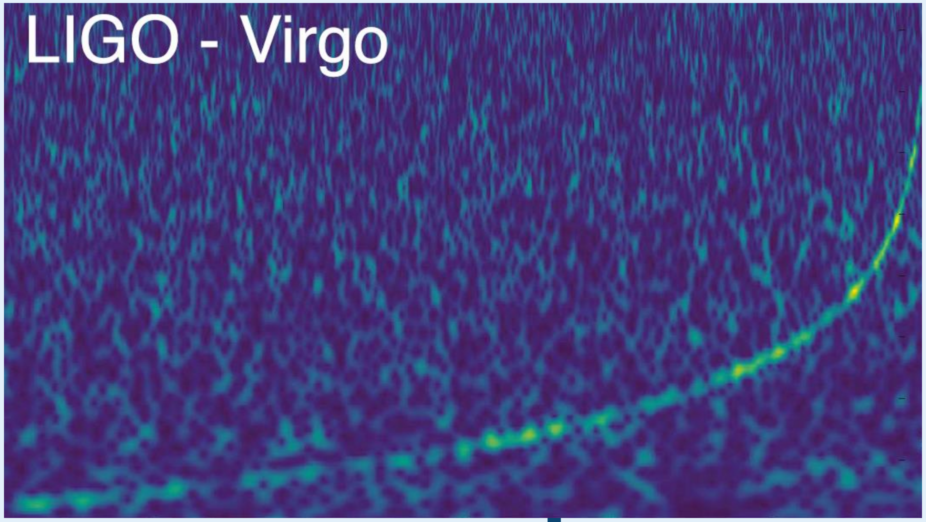


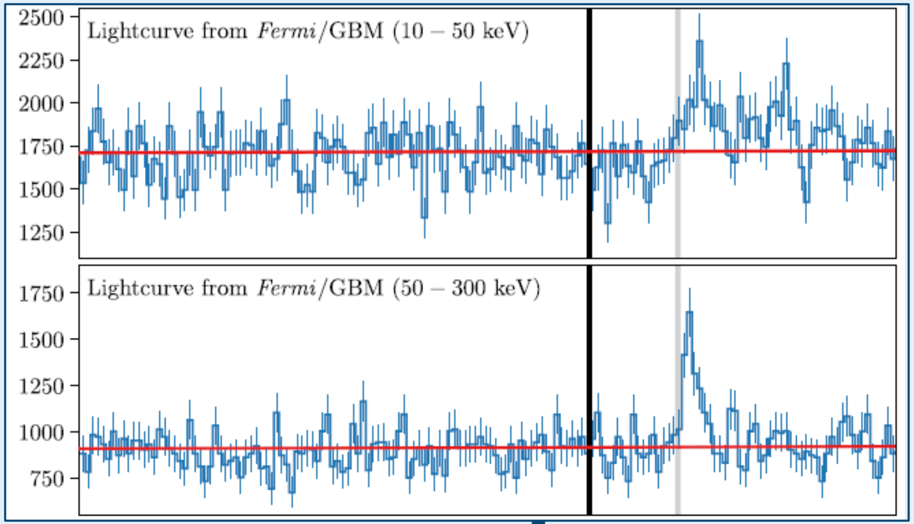
- GW150914-GBM, a 2.9σ event consistent with a **short GRB**
  - Not predicted by theoretical models
- **No gamma-ray detections** for LVT151012 or GW151226 – not constraining
  - 32% and 17% of LIGO localization region blocked by Earth for GBM
  - Backgrounds were 18% and 3% higher in GBM
  - Distance for LVT151012 was 3x larger
  - If gamma-ray emission is in a jet, only 15-30% would be pointed toward Earth

➔ **Need more events** before we can say more!


2017
BREAKTHROUGH *of the* YEAR

August 17, 2018: Timeline





T_{GW}

T_{GW} +1.7 s

August 17, 2018: Timeline

https://gcn.gsfc.nasa.gov/other/524666471.fermi

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/FERMI NOTICE
NOTICE_DATE:      Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE:      Fermi-GBM Alert
RECORD_NUM:       1
TRIGGER_NUM:      524666471
GRB_DATE:         17982 TJD;    229 DOY;    17/08/17
GRB_TIME:         45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF:   4.8 [sigma]
TRIGGER_DUR:      0.256 [sec]
E_RANGE:          3-4 [chan]   47-291 [keV]
ALGORITHM:        8
DETECTORS:        0,1,1, 0,0,1, 0,0,0, 0,0,0, 0,0,
LC_URL:           http://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/
COMMENTS:         Fermi-GBM Trigger Alert.
COMMENTS:         This trigger occurred at longitude,latitude = 321.53,3.90 [deg].
COMMENTS:         The LC_URL file will not be created until ~15 min after the trigger.
```

The FIRST notice

GBM Trigger
moc@sledgehammer.nsstc.nasa.gov

Subject:BAA: New Trigger (524666471)
Trigger 524666471 (trigcat name:170817529) received at 2017.08.17 12:41:24 UT.
7:41 AM

First GBM On-board Localization and classification

+16 s

+27 s

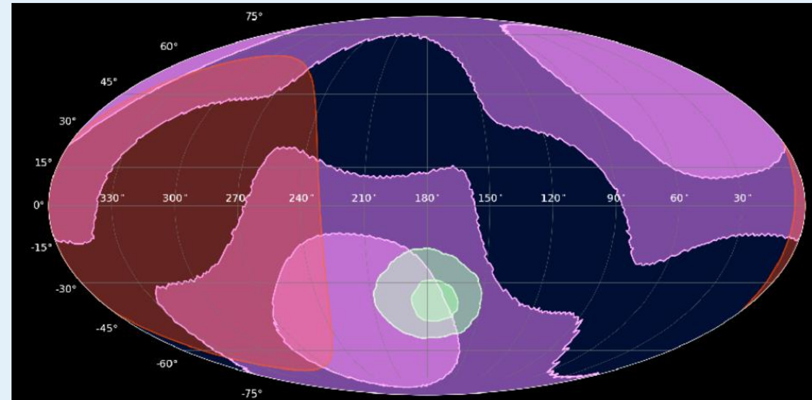
August 17, 2018: Timeline

WAKE UP

Subject:[gbm+ligo] WAKE UP
Date: Thu, 17 Aug 2017 13:23:13 +0000
From: Littenberg, Tyson B. (MSFC-ST12) <[redacted]>
To:GBM+LIGO <[redacted]>

ivo://nasa.gsfc.gcn/Fermi#GBM_Gnd_Pos_2017-08-17T12:41:06.47_524666471_57-431

this morning's GBM trigger has a friend....



GBM Automated On-ground Localization

+40 s

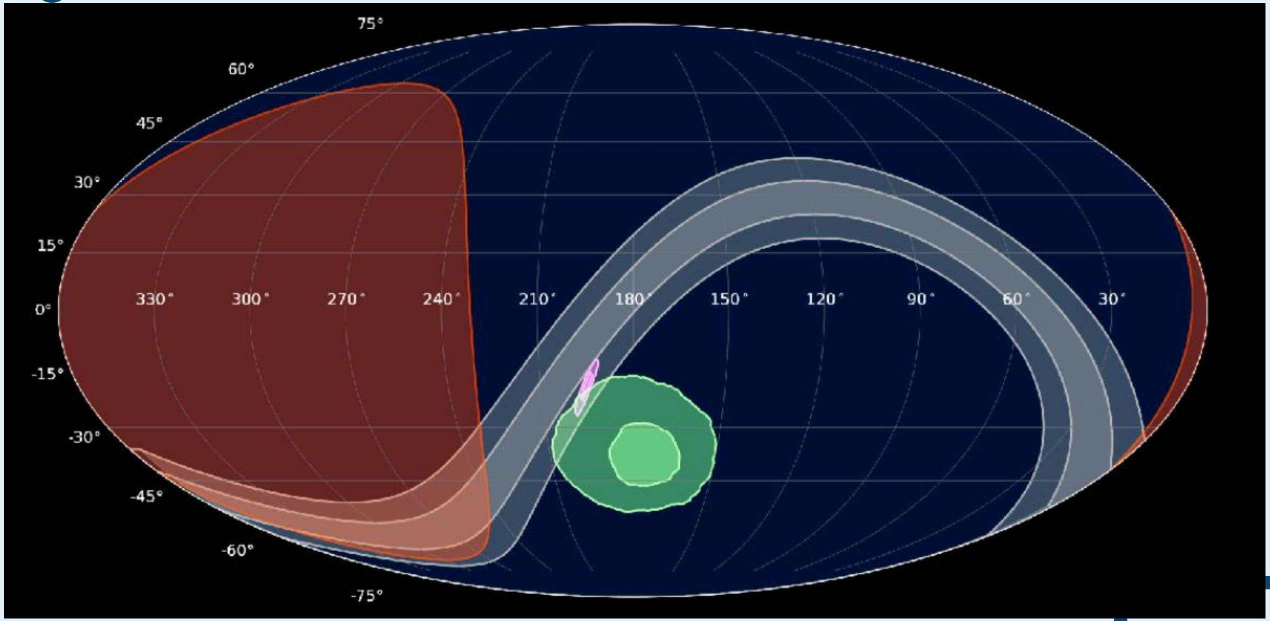
LIGO report on GW trigger coincident with GBM

+40 min

GBM-BA «human in the loop» localization

+47 min

August 17, 2018: Timeline



IPN report on timing annulus between GBM and SPI-ACS

GBM report on localization and short duration GRB

INTEGRAL SPI-ACS report of a coincident weak GRB

Preplanned LV-EM telecon

Mistaken report on IceCube neutrino candidates

First LIGO/Virgo skymap using all 3 detectors

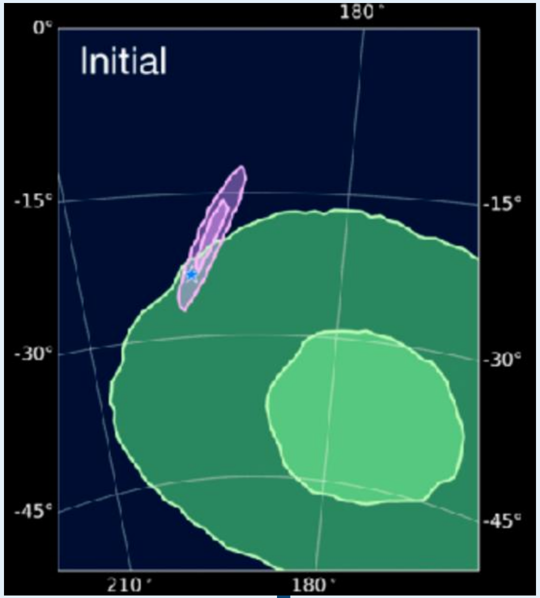
+67 min **+77 min** **+84 min** **+5 hr** **+6 hr**

August 17, 2018: Timeline

```
TITLE:   GCN CIRCULAR
NUMBER:  21520
SUBJECT: GRB 170817A: Fermi GBM detection
DATE:    17/08/17 20:00:07 GMT
FROM:    Andreas von Kienlin at MPE  <azk@mpe.mpg.de>

A. von Kienlin (MPE), C. Meegan (UAH) and A. Goldstein (USRA)
report on behalf of the Fermi GBM Team:

"At 12:41:06.47 UT on 17 August 2017, the Fermi Gamma-Ray Burst Monitor
triggered and located GRB 170817A (trigger 524666471 / 170817529).
```



+6 hr — List of 15 host galaxies in LIGO/Virgo map volume

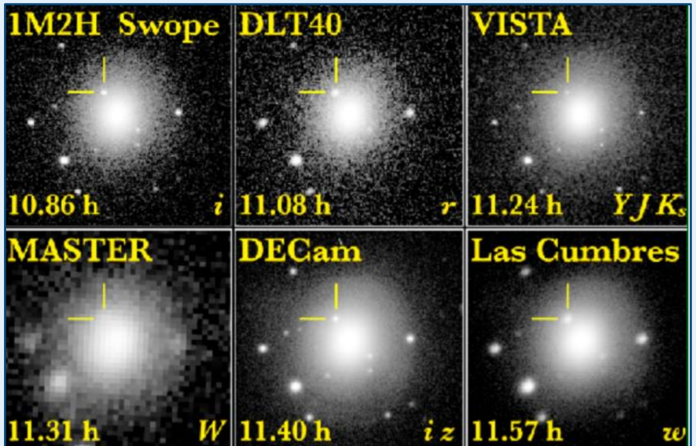
+7 hr — GBM science data data arrives. GCN Circular published giving GRB official name **GRB 170817A**

+11 hr — Updated LIGO/Virgo skymap

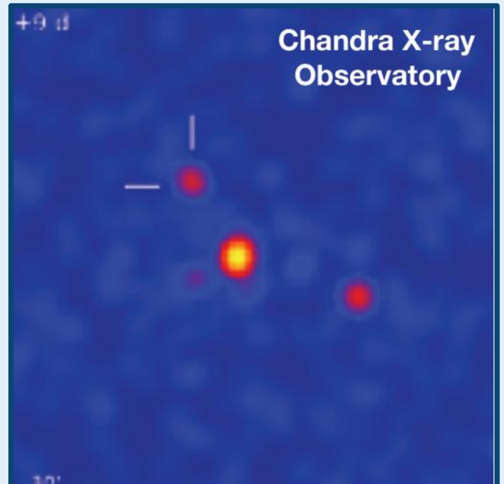
+12 hr — GBM report of energetics & Initial False Alarm Rate

August 17, 2018: Timeline

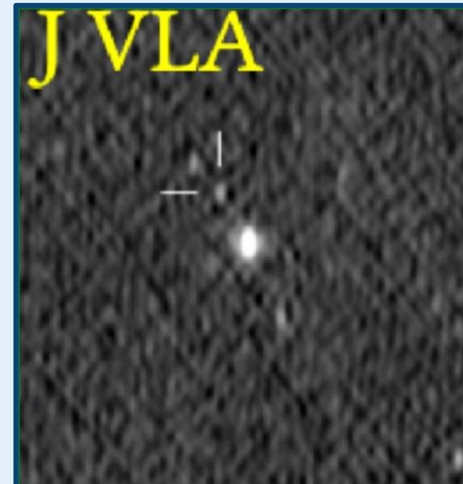
The electromagnetic follow-up



Report of optical Transient by three independent telescopes



X-ray counterpart reported by Chandra



Radio counterpart reported by VLA

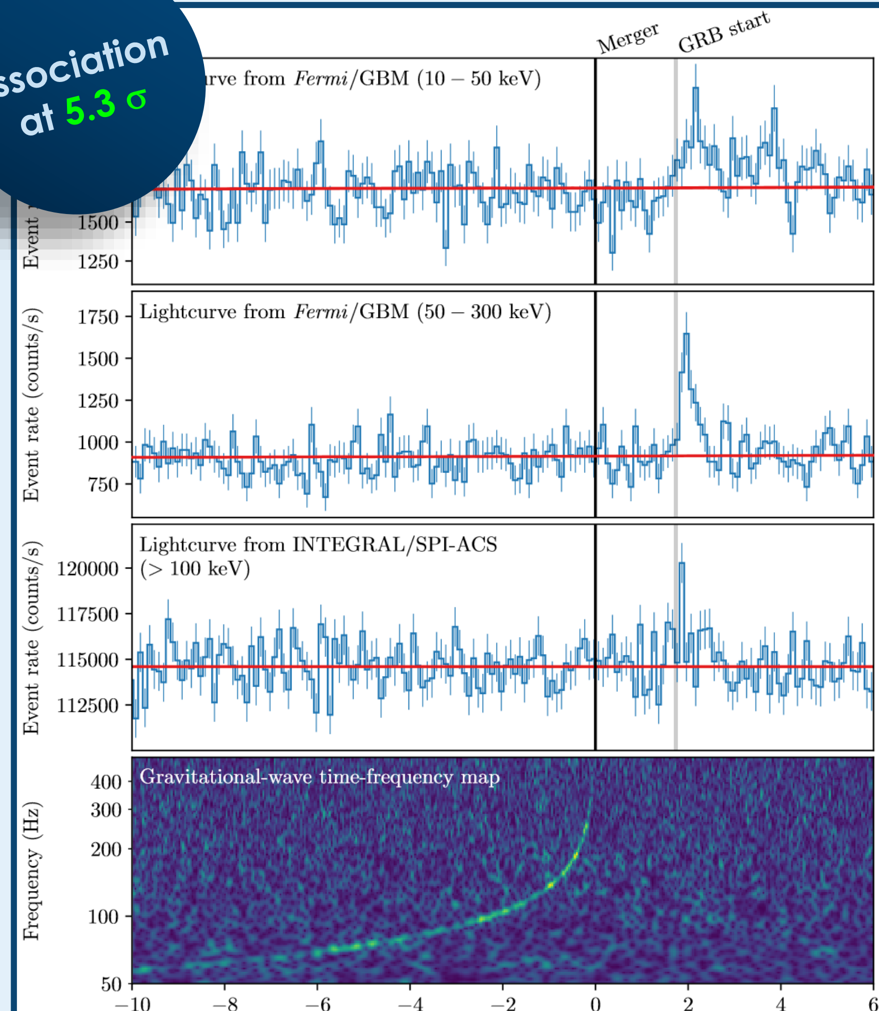
+12-13 hr **+13 day** **+18.5 day**

Theory confirmed!

- The **onset** of gamma-ray emission from a binary neutron star merger progenitor is predicted to be within **a few seconds after** the merger
  - Central engine is **expected** to form within a few seconds
  - Jet propagation delays are at most of the order of the sGRB duration [Finn+1999; Abadie+2012 and references therein]

Measured time delay between GW and light:
Δt = 1.74 +/- 0.05 s

Association at 5.3 σ



Abbott+2017 ApJ 848, 13

The Speed of Gravity

- The time delay can help constrain the **speed difference**:

$$\Delta v = v_{GW} - v_{EM}$$

  - Fractional speed difference: $\frac{\Delta v}{v_{EM}} \approx \frac{v_{EM}\Delta t}{D}$

- **Conservative estimate**, assuming:
  1. **Distance** $D = 26\ MpC$ (lower bound GW 90% credible interval)
  2. GWs and gamma-rays emitted **at same time** ($\Delta t = 1.74$ s) OR gamma-rays emitted 10 s **before** GWs ($\Delta t = 10$ s)

  ➔ **Gravitational waves travel at c** to within one part in one quadrillion

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{EM}} \leq 7 \times 10^{-16}$$

  - Rules out some alternative general relativity theories

The Equivalence Principle

Equivalence Principle: Gravitational mass = inertial mass

- Test using the **Shapiro delay**
  - Propagation time of massless particles traveling in curved spacetime (through gravitational fields) will be slightly increased compared to flat spacetime

$$\delta t_s = -\frac{1+\gamma}{c^3}\int_{r_e}^{r_0} U(r(i))dl$$

    - δt_s = Shapiro delay using the same time bounds (simple form)
    - r_o = observation positon, r_e = emission position
    - $U(r)$ = gravitational potential (here the Milky Way's)
    - l = wave path
    - γ = **deviation** from Einstein-Maxwell theory (in which $\gamma_{EM} = \gamma_{GW} = 1$)
- We find that

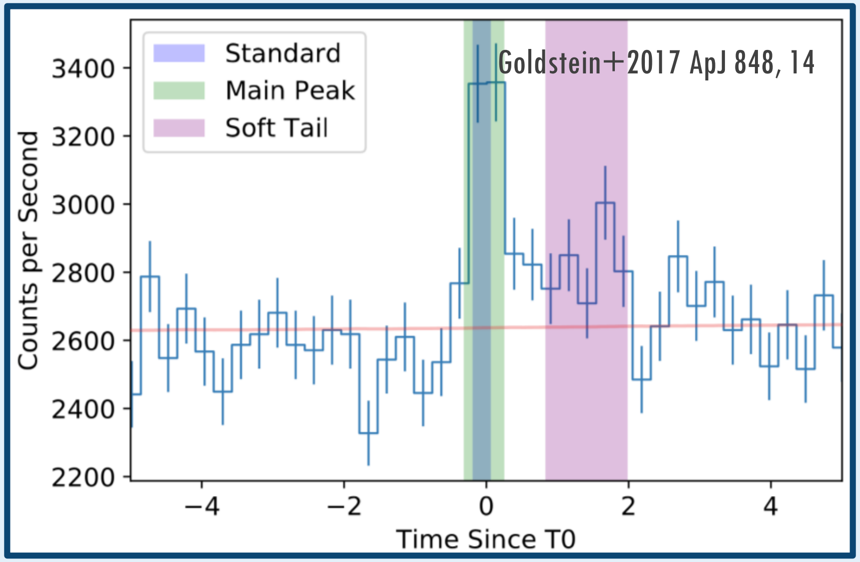
$$-1.2 \times 10^{-6} \leq \gamma_{GW} - \gamma_{EM} \leq 2.6 \times 10^{-7}$$

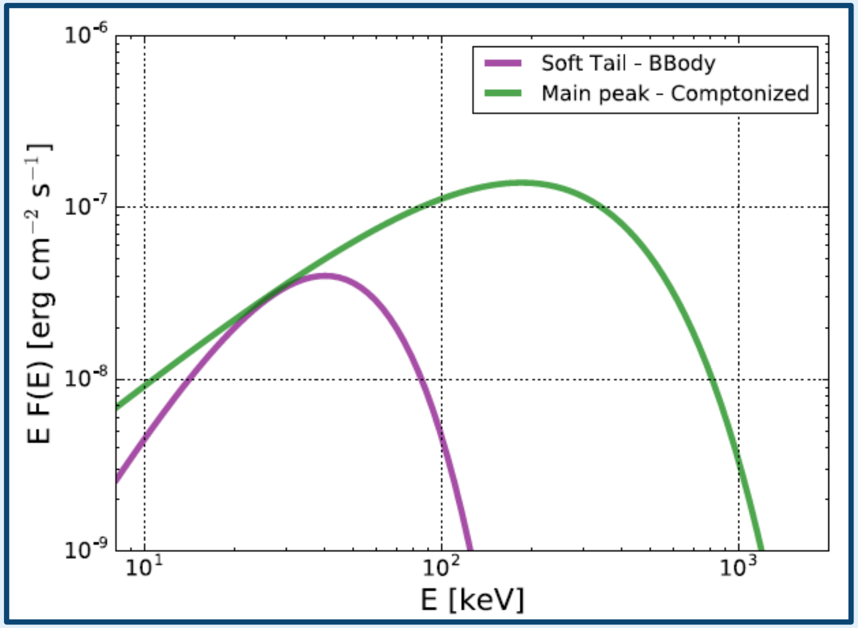
➔ This is 1-2 orders of magnitude less than the best absolute bound on γ_{EM} based Shapiro delay of radio waves

Fermi GBM analysis of GRB 170817A

GBM spectral analysis results:
two components!

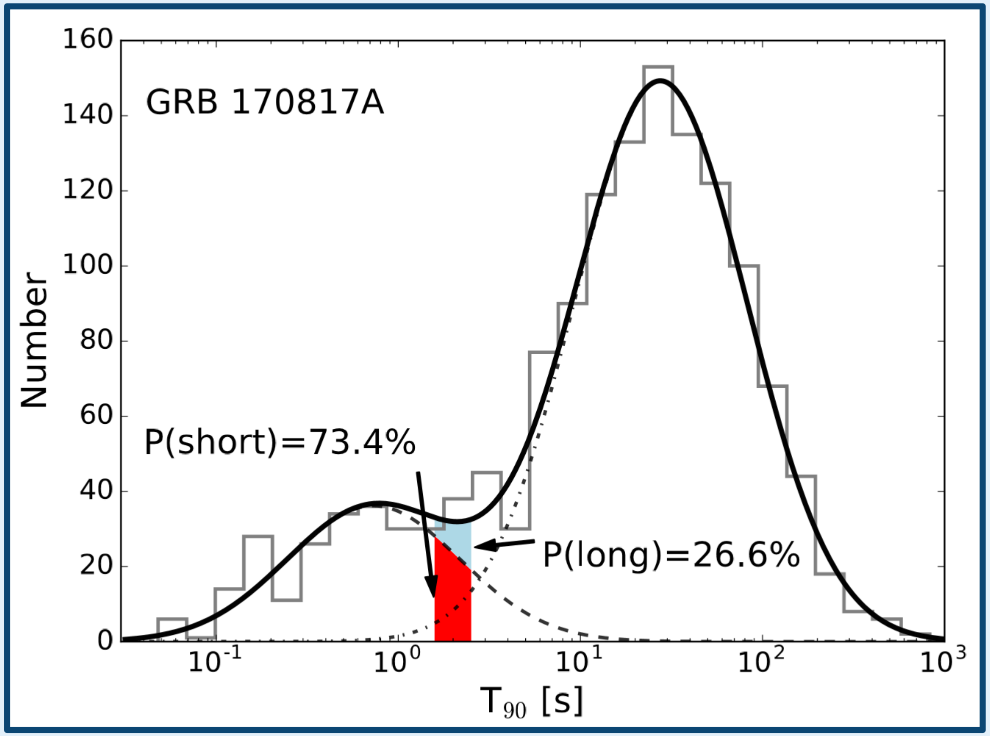
- **Main peak** (~0.5 s single pulse, no substructure)
  - Comptonized model
    - Epeak ~220 keV
- **Soft tail** (~1 s, distinct component?)
  - Blackbody model
    - kT ~10 keV
    - photospheric emission from a cocoon [Lazzati+2017]

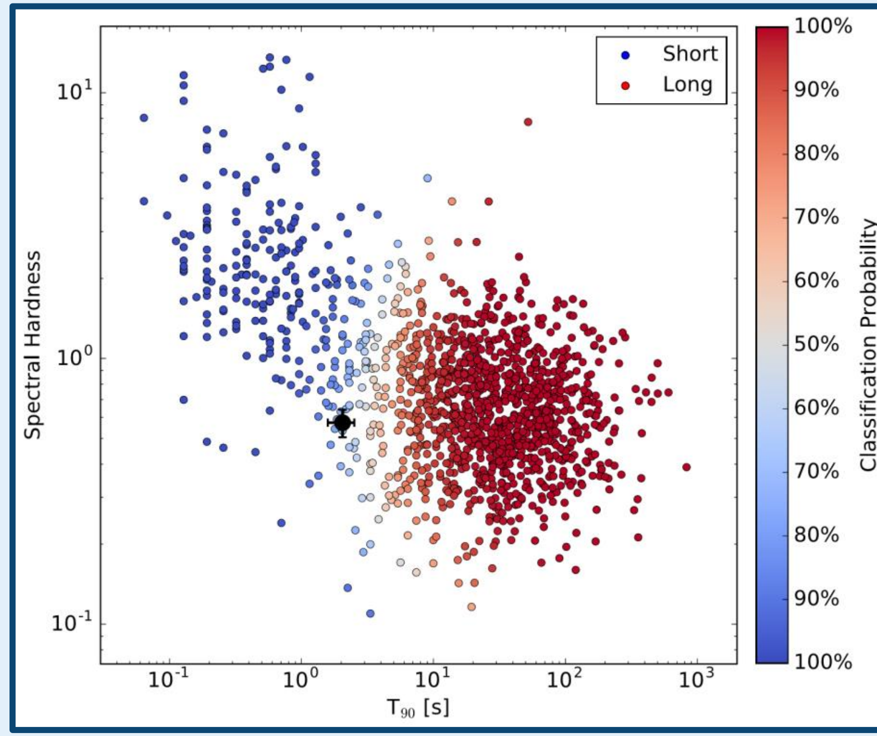




Fermi GBM analysis of GRB 170817A

Goldstein+2017 ApJ 848, 14

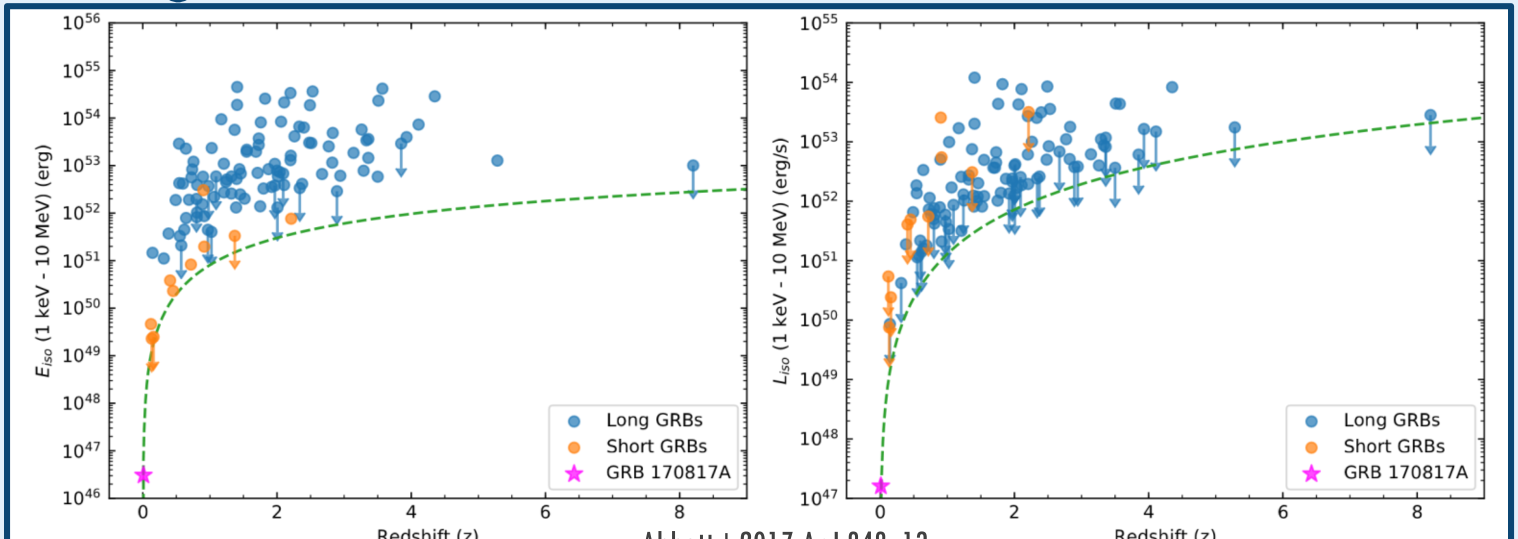




GBM temporal analysis results

- GRB 170817A is 3 times more like to be a **short GRB** than a long GRB, although it is **spectrally softer** than many sGRBs
  - Excluding the soft tail makes this classification far more certain

Fermi GBM analysis of GRB 170817A



Abbott+2017 ApJ 848, 13

GBM energetics results

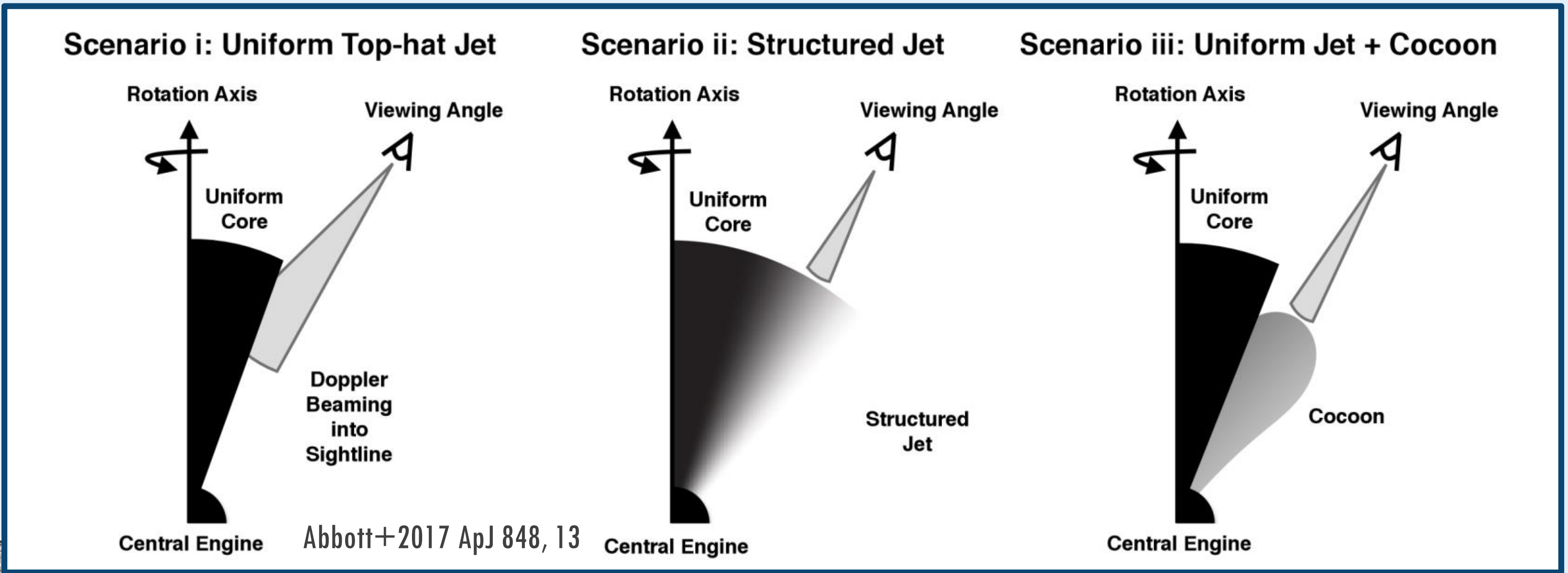
- Estimated peak luminosity and isotropic-equivalent energy is **~2-3 orders of magnitude lower** than previous observations
- Why the large gap? Malmquist bias
  - We see bright things far away that look weak, bright things nearby that look bright, and weak things nearby that look weak
    → **We can't see weak things far away…**

Fermi GBM analysis of GRB 170817A

- Some **interpretation**:
  - Observations: ordinary GRB
  - Distance information: very dim GRB
  - GRB viewed off-axis
  - Intrinsically dim GRB on-axis
  - Soft pulse: cocoon emission

→ sGRB are associated with mergers of compact objects!

Late-time observations of GW/GRB 170817 at other wavelengths are **crucial** for full understanding!

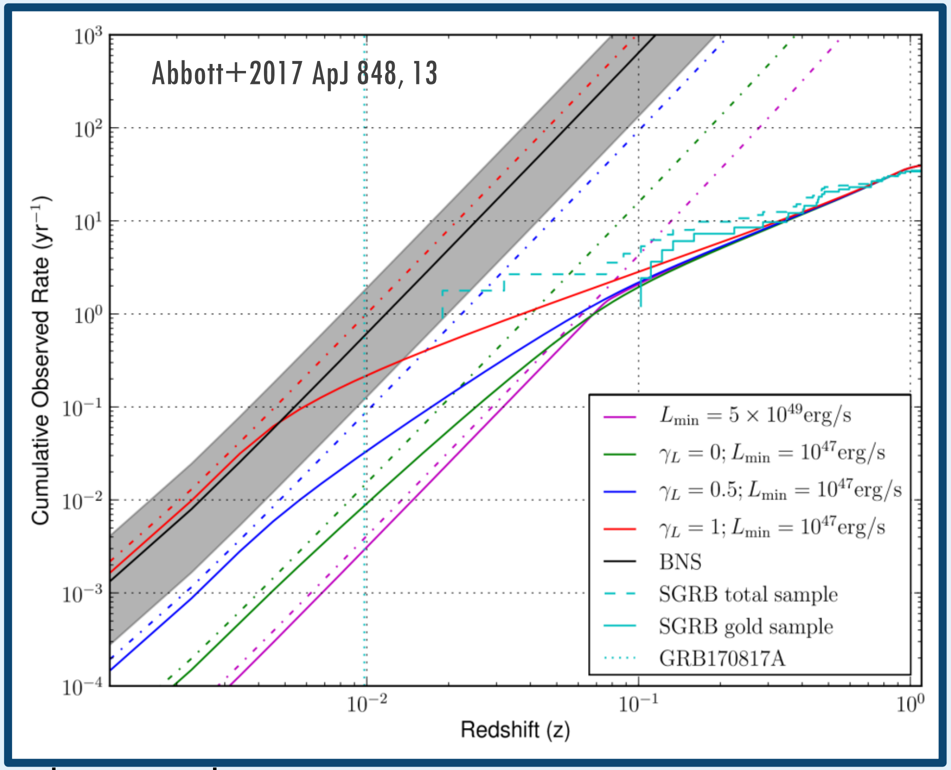


Abbott+2017 ApJ 848, 13

Joint Detection Rates with GBM and LIGO/Virgo

SGRBs at <40 Mpc are rare!

- Expectations for O3 (2018-2019):
  - **1 – 50 BNS/yr** *uncertainty on detector sensitivities during that run*
    - ➔ 0.1 – 1.4 **joint** BNS-sGRB/yr
- At design sensitivity:
  - 6 – 120 BNS/yr
    - ➔ 0.3 – 1.7 **joint** BNS-sGRB/yr

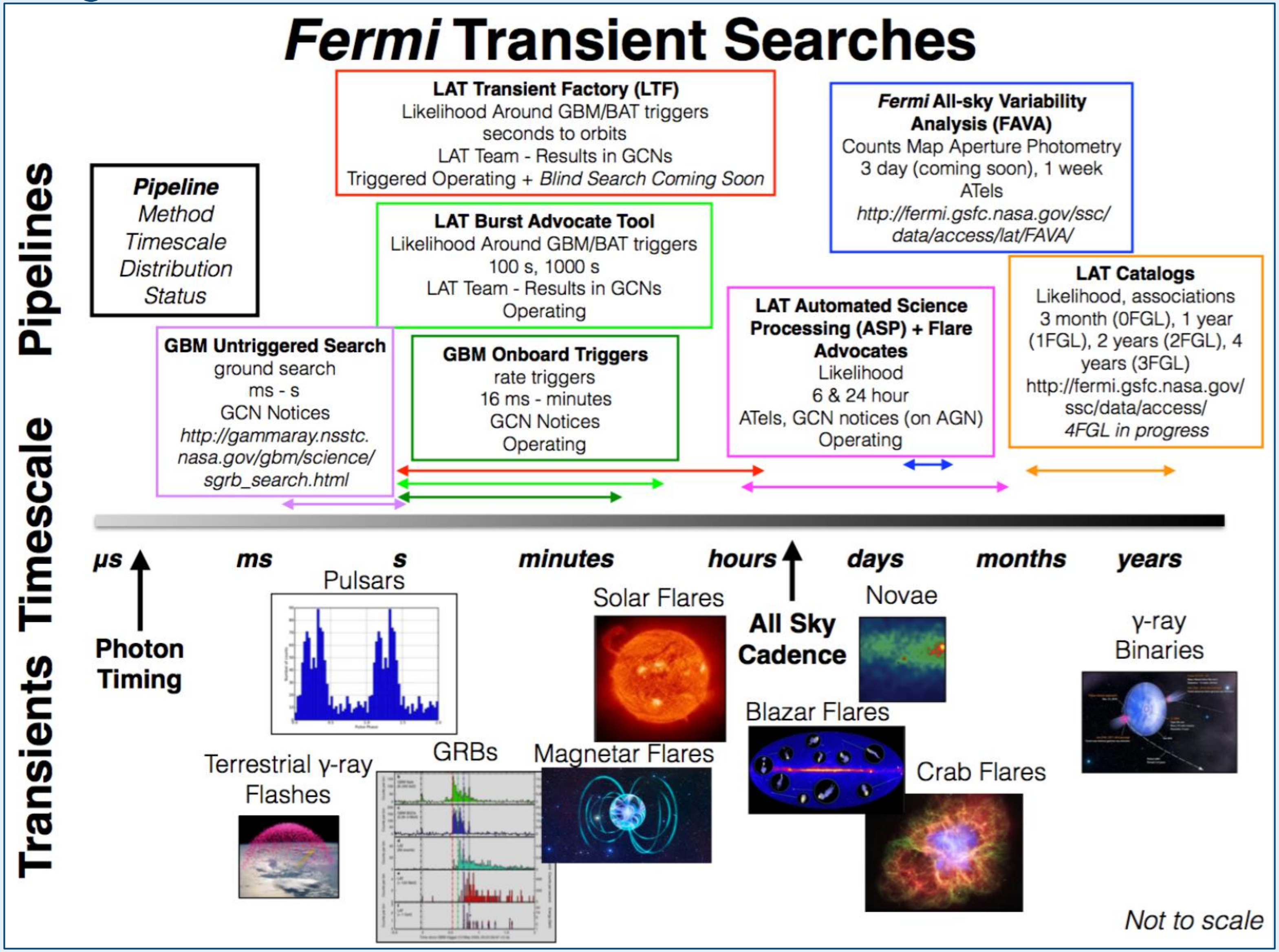


Predicted detection rates per year as a function of redshift. The 4 curves are normalized by imposing 40 triggered SGRB/yr

GBM preparation for O3:

- Overall optimization of the targeted search
  - Best timescales and bin phases to use
  - Implementing a thermal template for the target search
  - Recalculation of the FAR distribution

Fermi GW follow-up

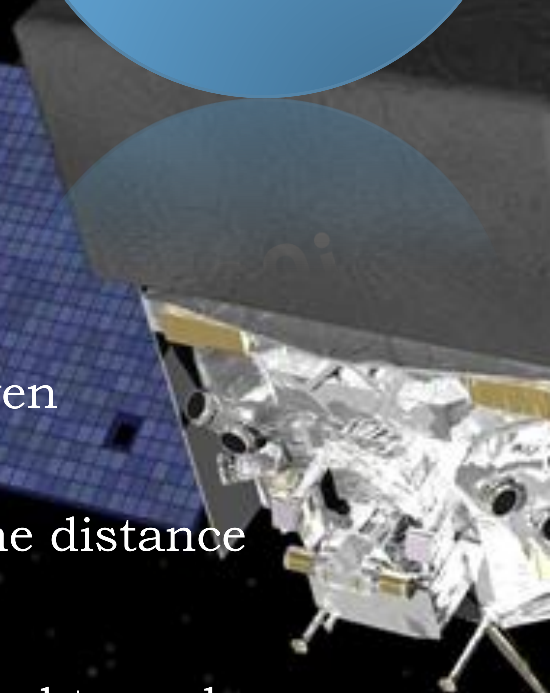


Conclusions

Thank you!

Detectors like **GBM** are efficient detectors of counterparts

- No pointed observations required
- Observing large fraction (~67%) of the sky
- Continuously observing (~15% downtime)
- In normal operations mode, these detectors produce GW counterparts for free!



Sub-threshold offline searches of data can uncover even weaker events that didn't trigger GBM

- Could have detected GRB 170817A at about twice the distance

GBM and the high-energy community are looking forward to make many more key discoveries in the coming years!

→ Design and build more detectors like this!