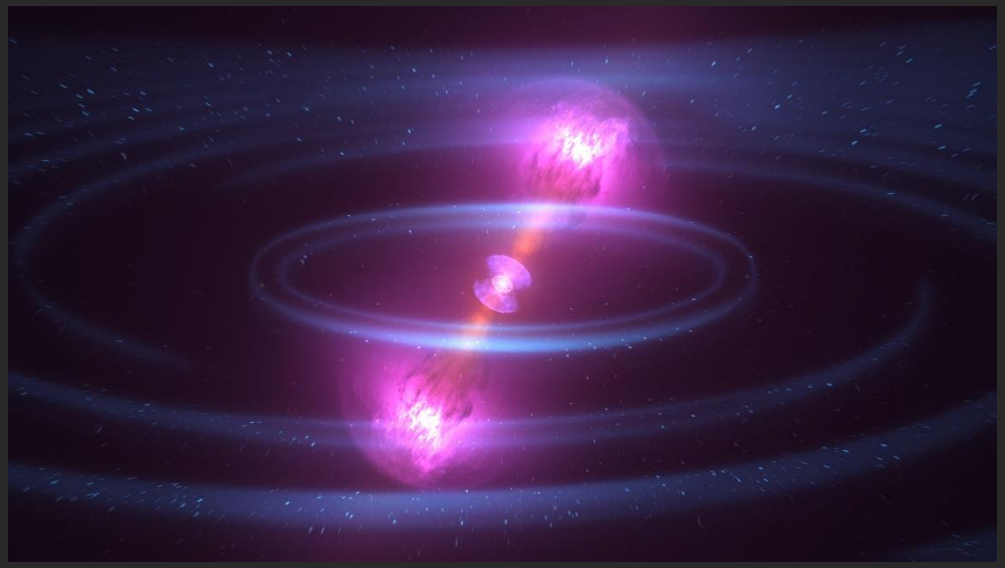
Fermi/GBM's key role at the dawn of the era of multi-messenger astronomy

GW170817 ⟷ GRB 170817 A

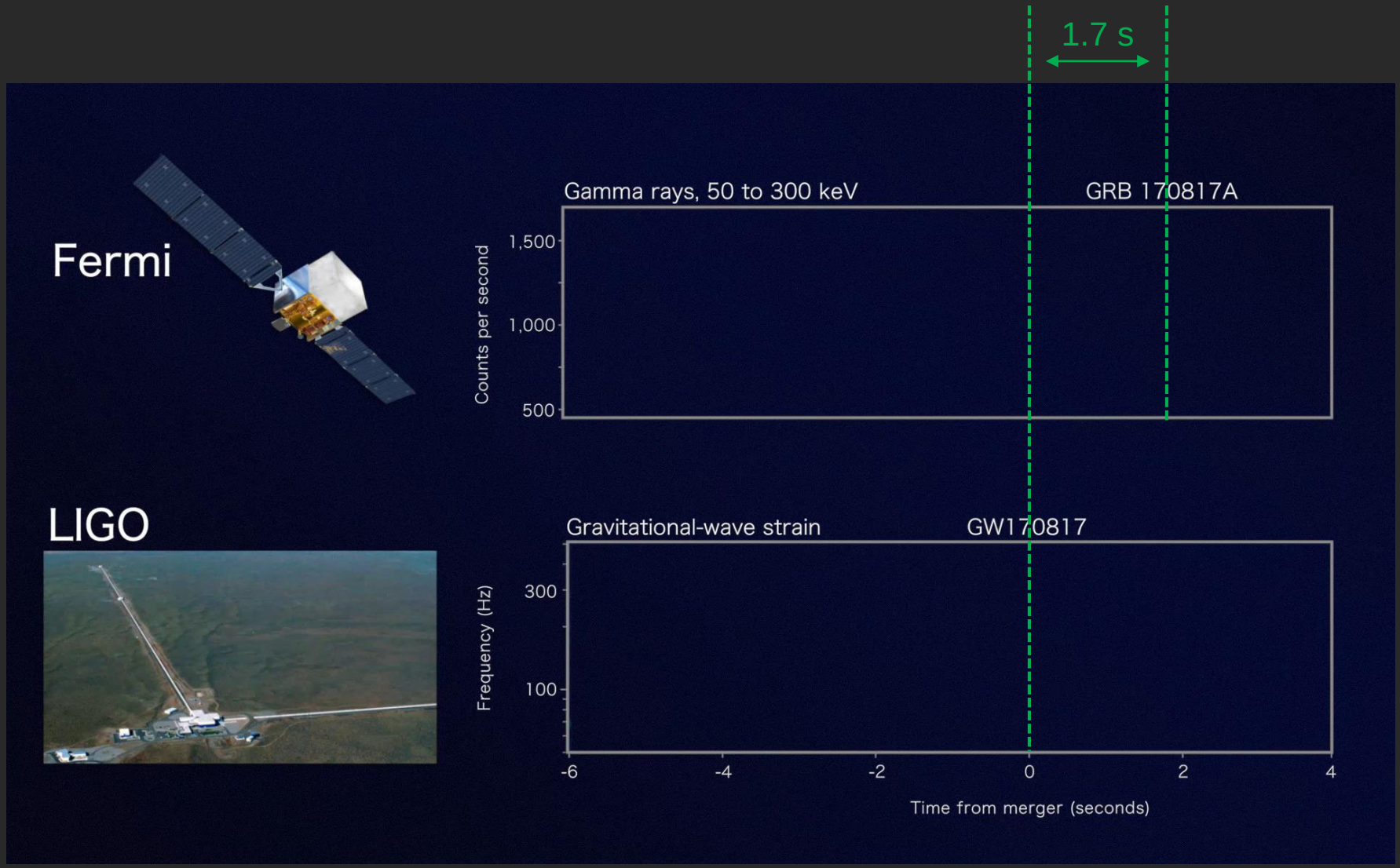
Andreas von Kienlin

Max-Planck-Institut für extraterrestrische Physik (MPE), Garching

on behalf of the *Fermi* GBM Science Team



GW170817 / GRB 170817A



The Fermi Mission

Large Area Telescope (LAT)

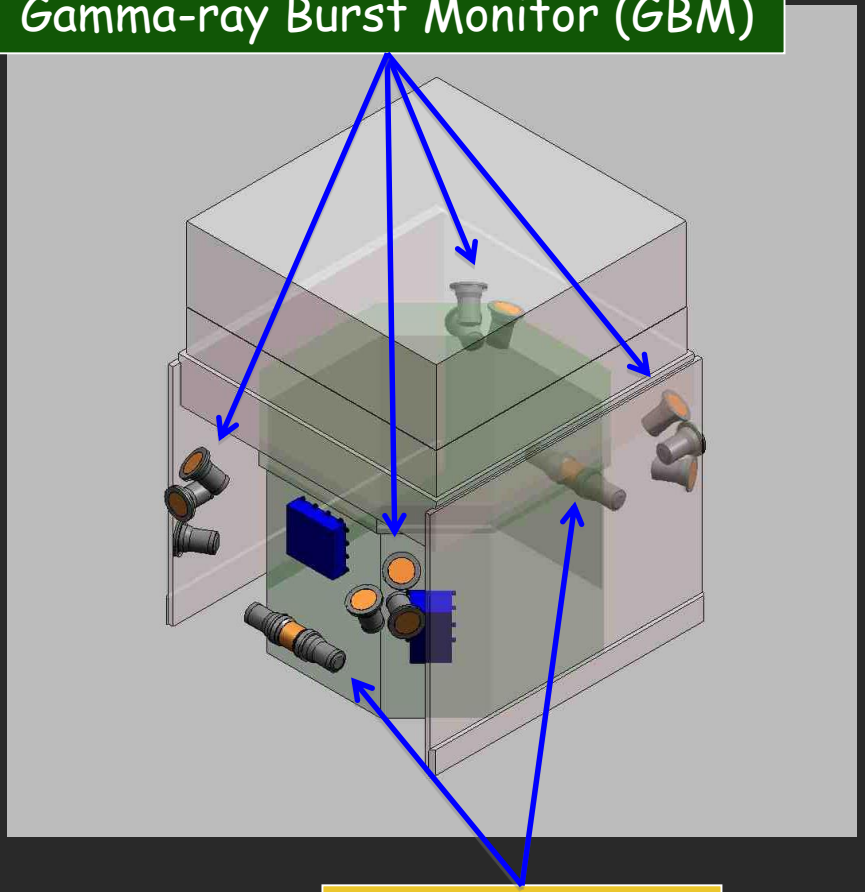
Gamma-Ray Burst Monitor (GBM)

Launched June 11 , 2008

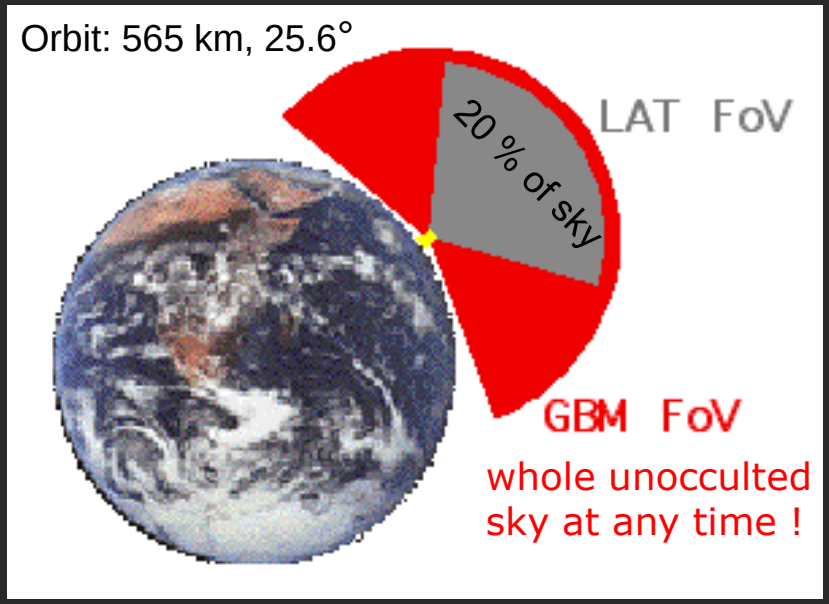
The *Fermi* Observatory

Large Area Telescope (LAT)

Gamma-ray Burst Monitor (GBM)

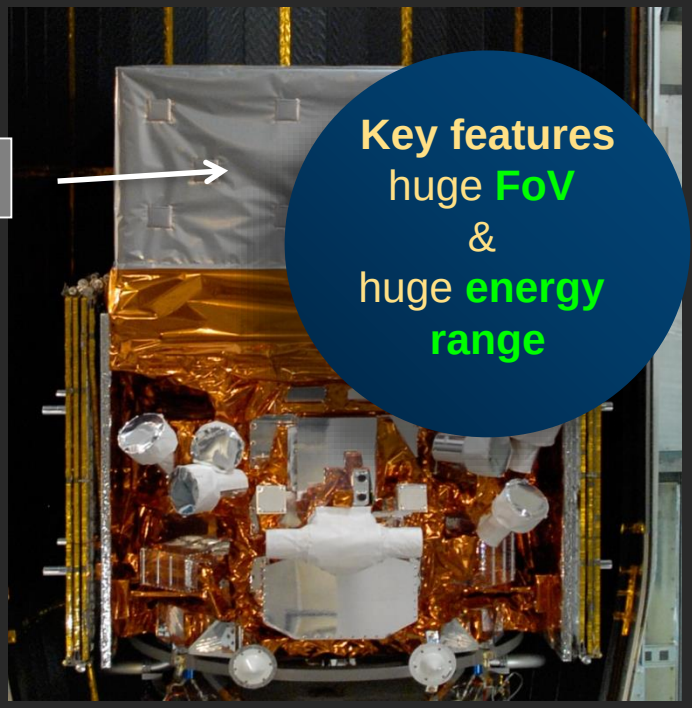


GBM detectors

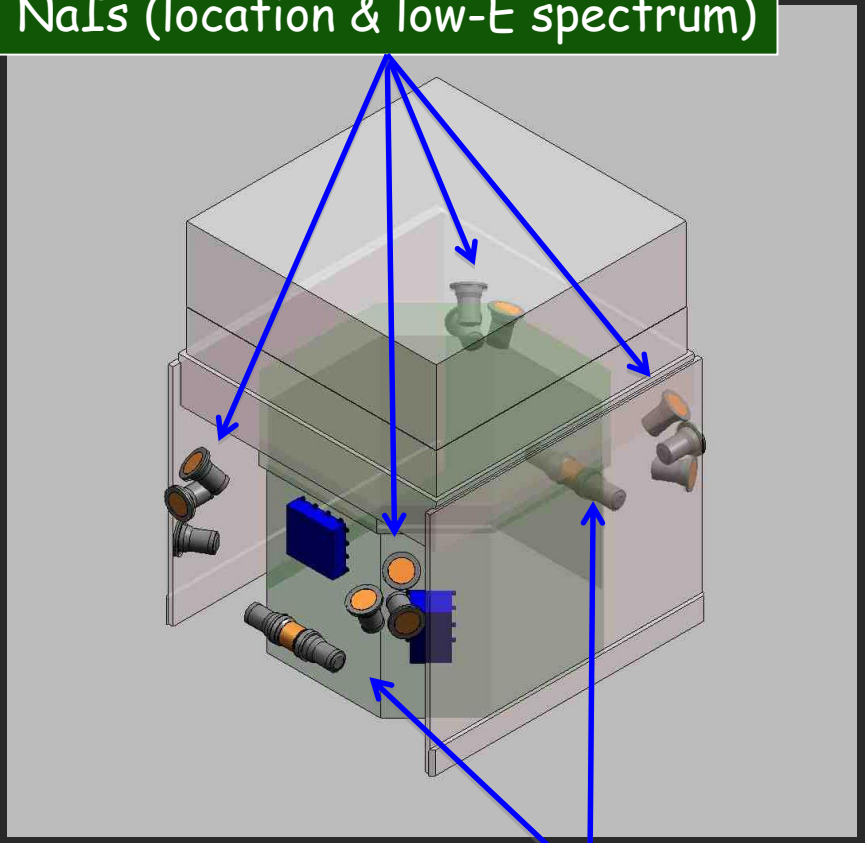


The *Fermi* Observatory

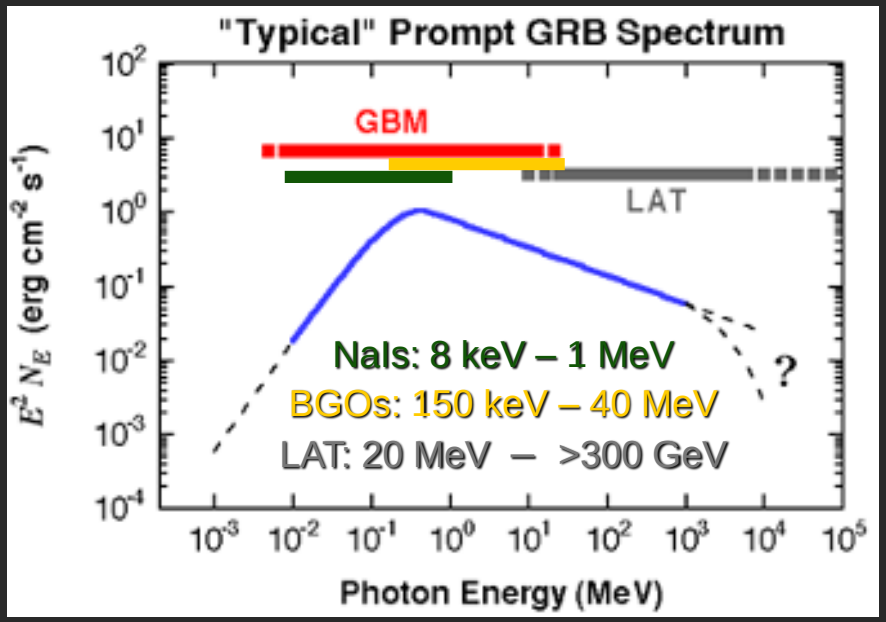
LAT (high-E spectrum)



NaIs (location & low-E spectrum)

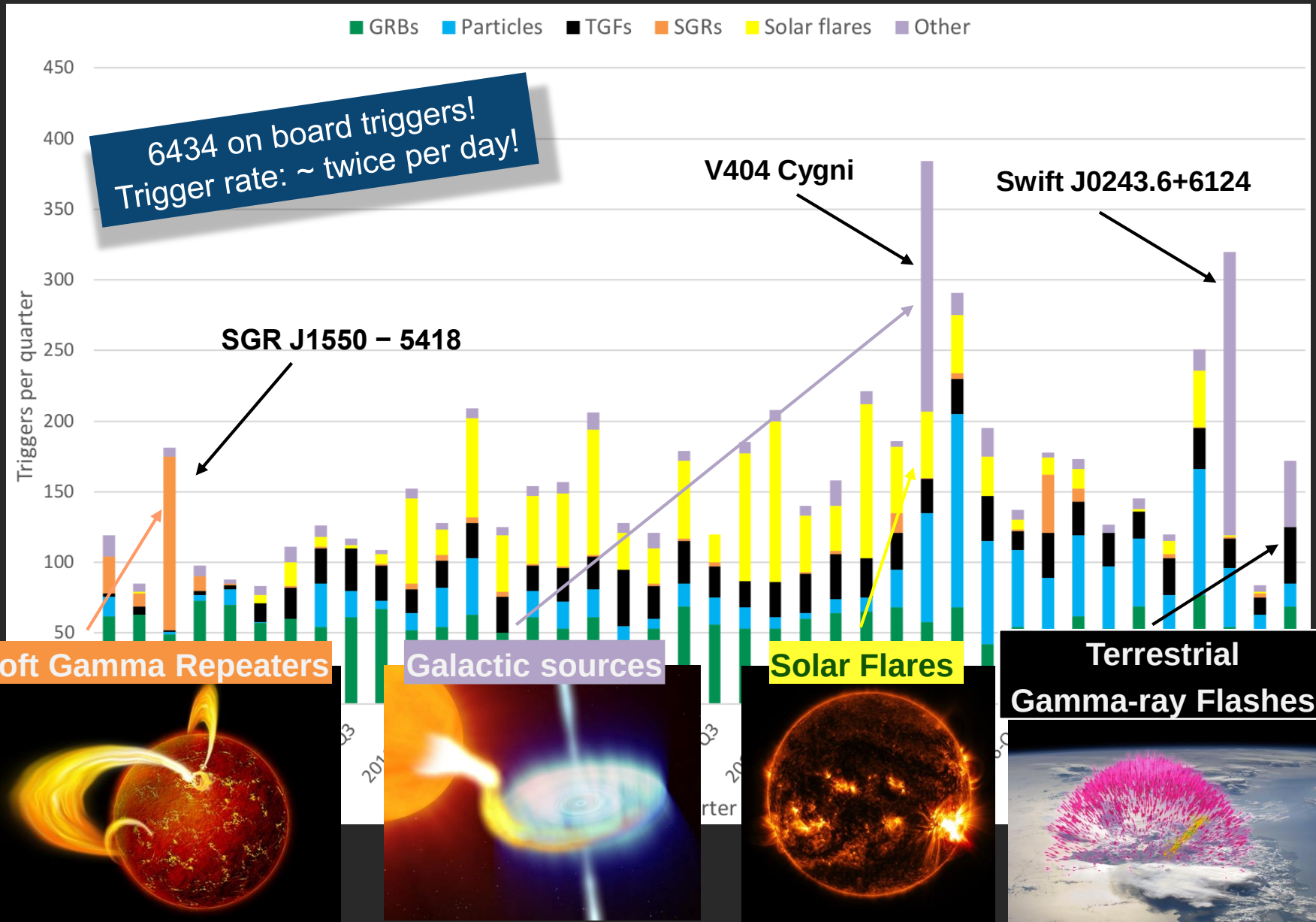


BGOs (mid-E spectrum)

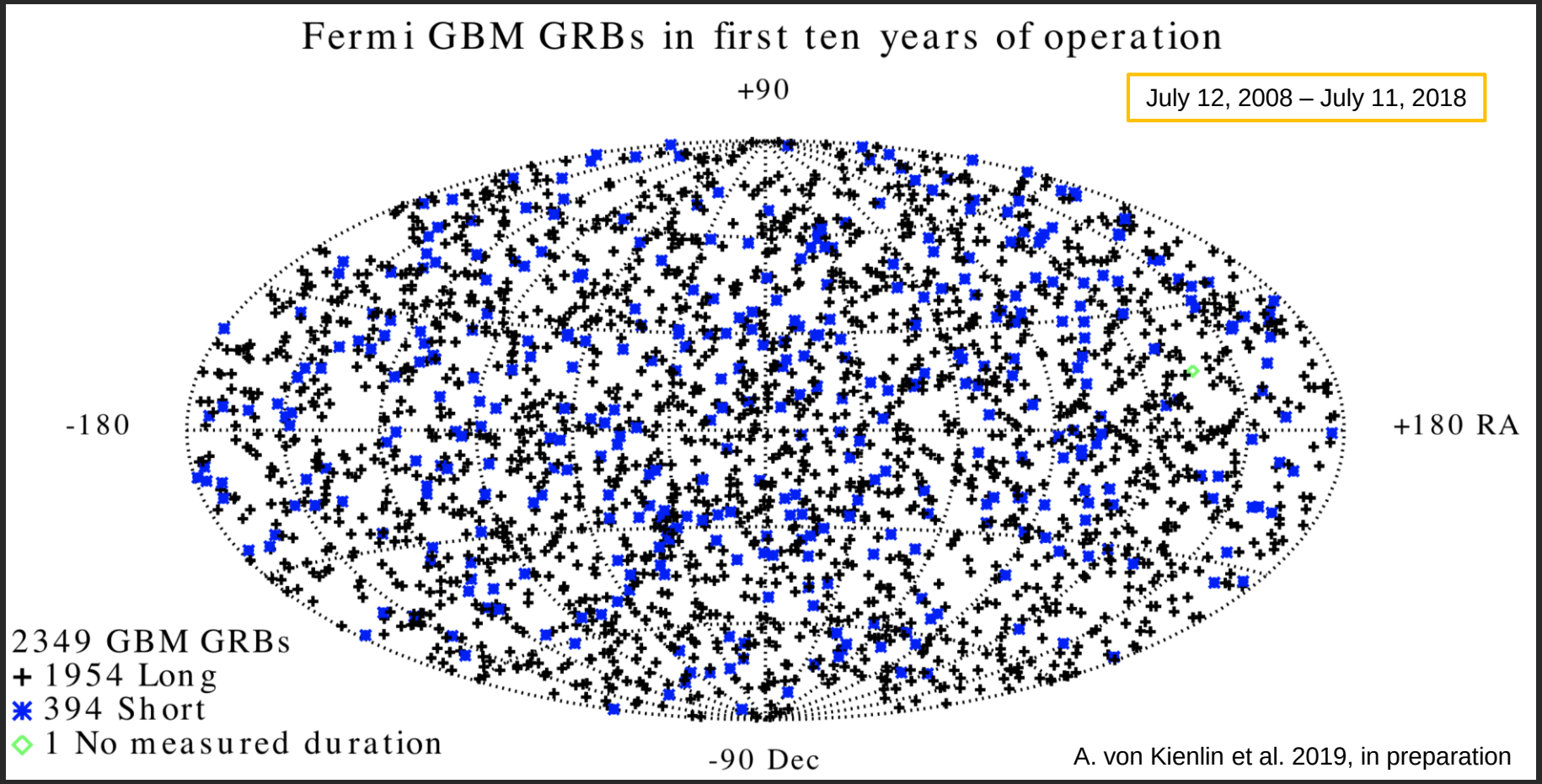


What does GBM see ?

Quarterly trigger statistics over 10 years of the mission

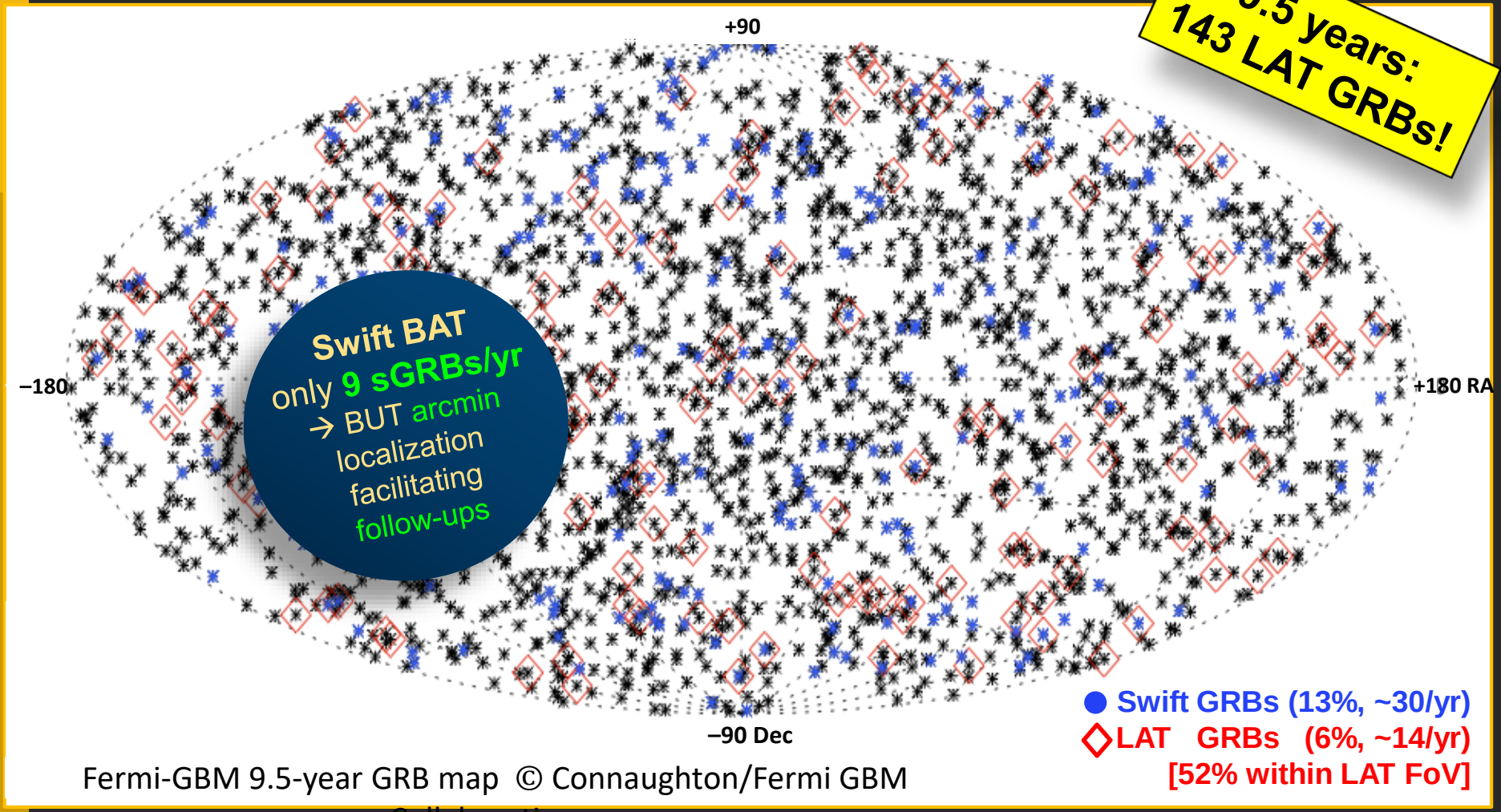


Fermi GBM skymaps



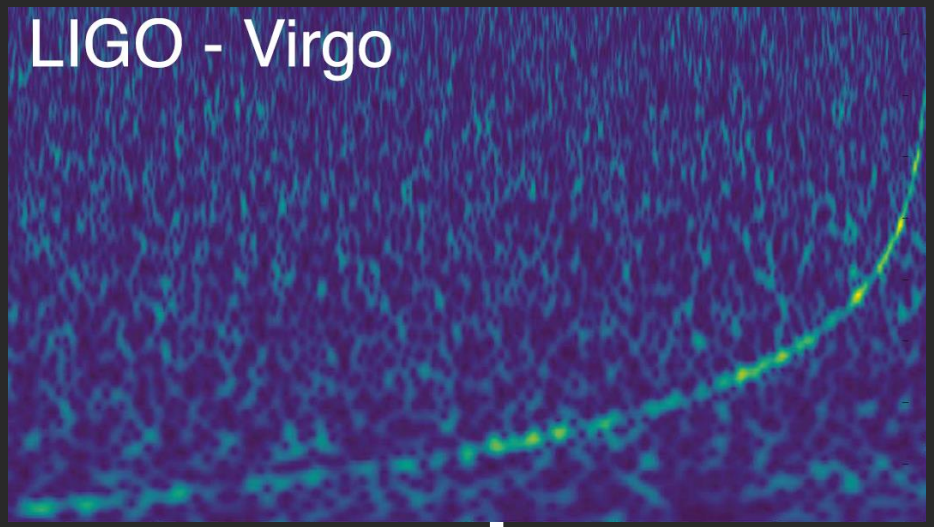
The **GBM GRB online catalog** is updated **within 1 hour**:
➔ http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html

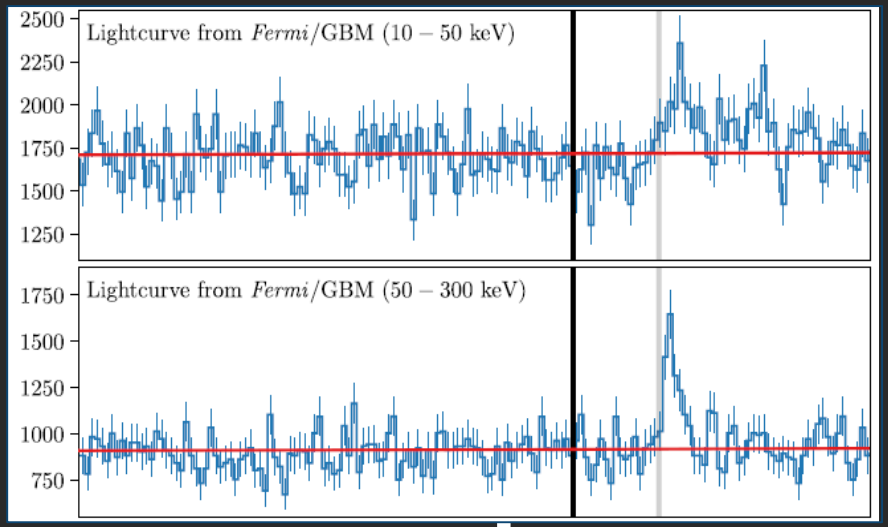
Fermi GBM skymaps



Fermi-GBM 9.5-year GRB map © Connaughton/Fermi GBM Collaboration

August 17, 2017: Timeline

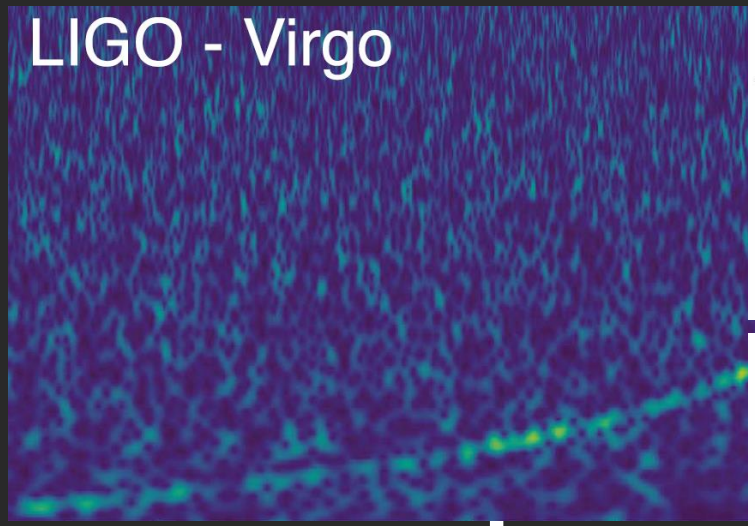


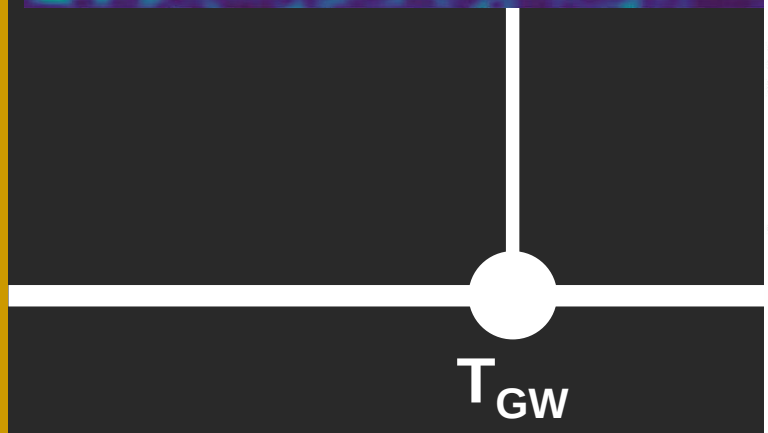


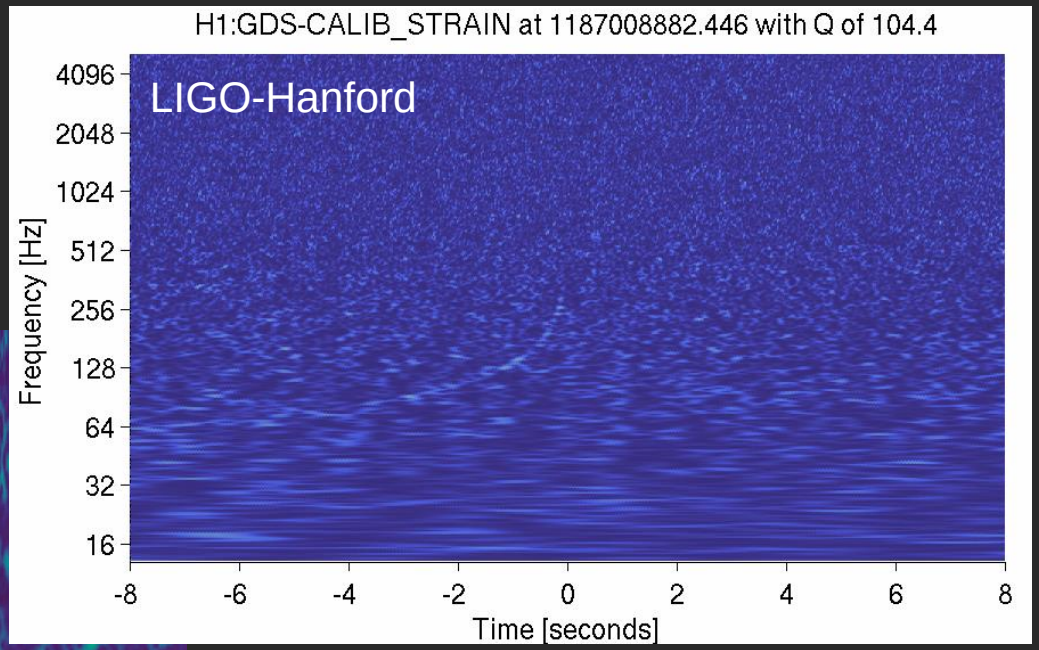
T_{GW}

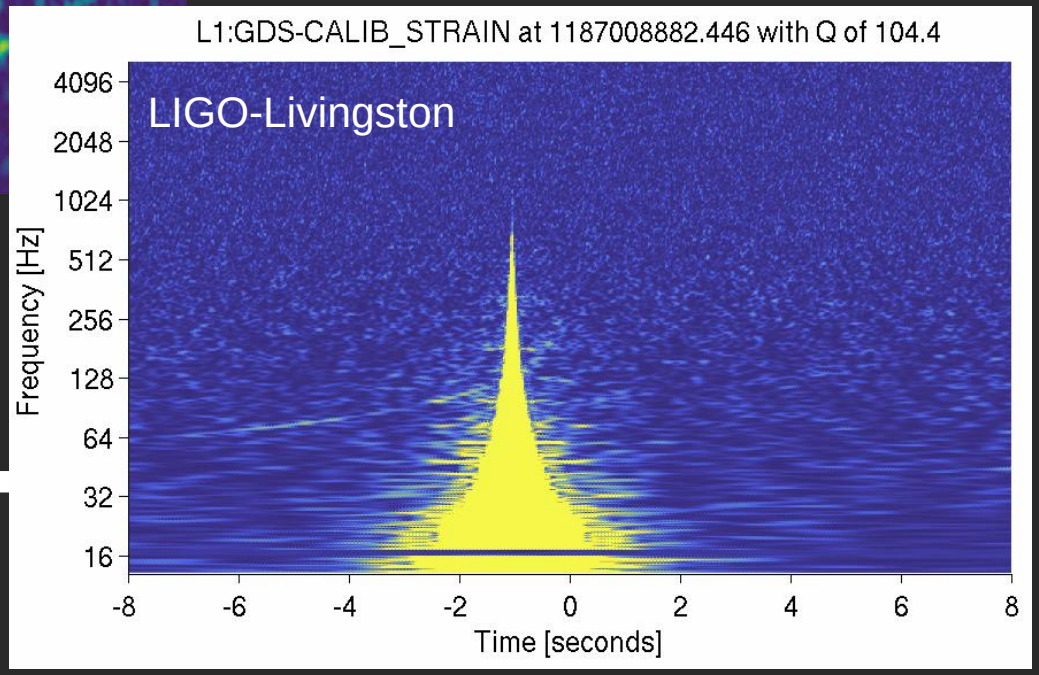
T_{GW} +1.7 s

LIGO had good signal in both detectors, BUT:
→ Single-detector trigger









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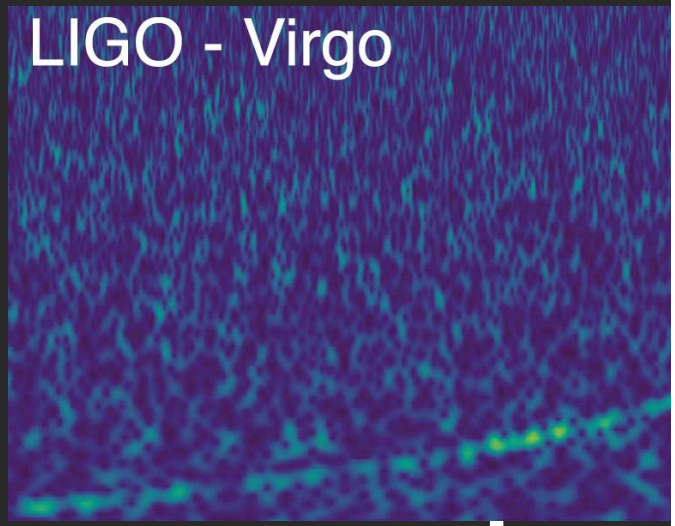
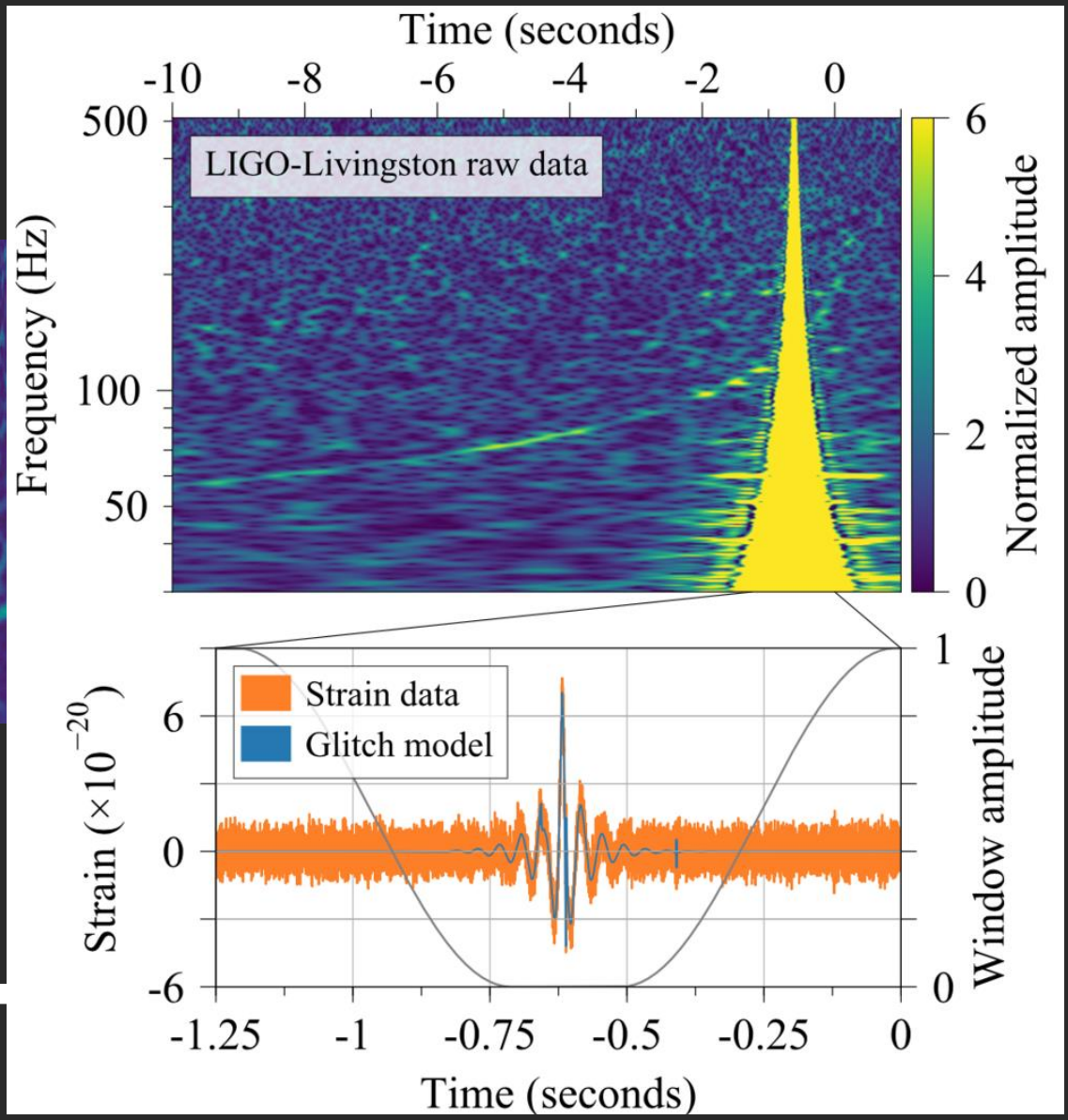
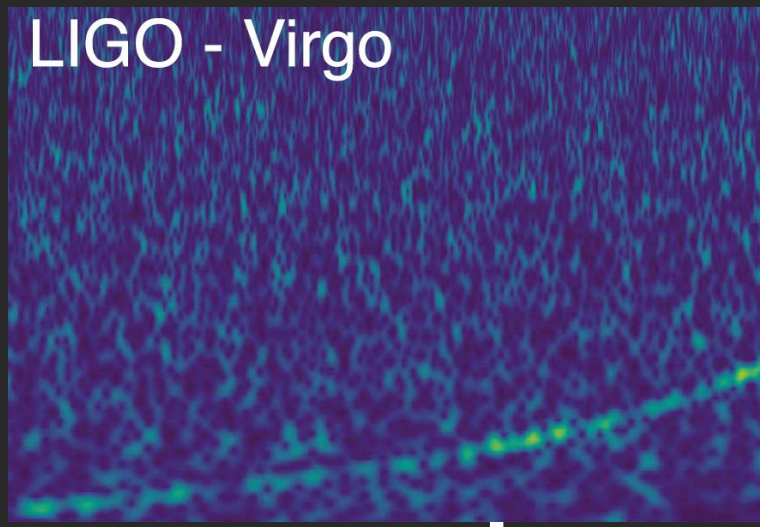
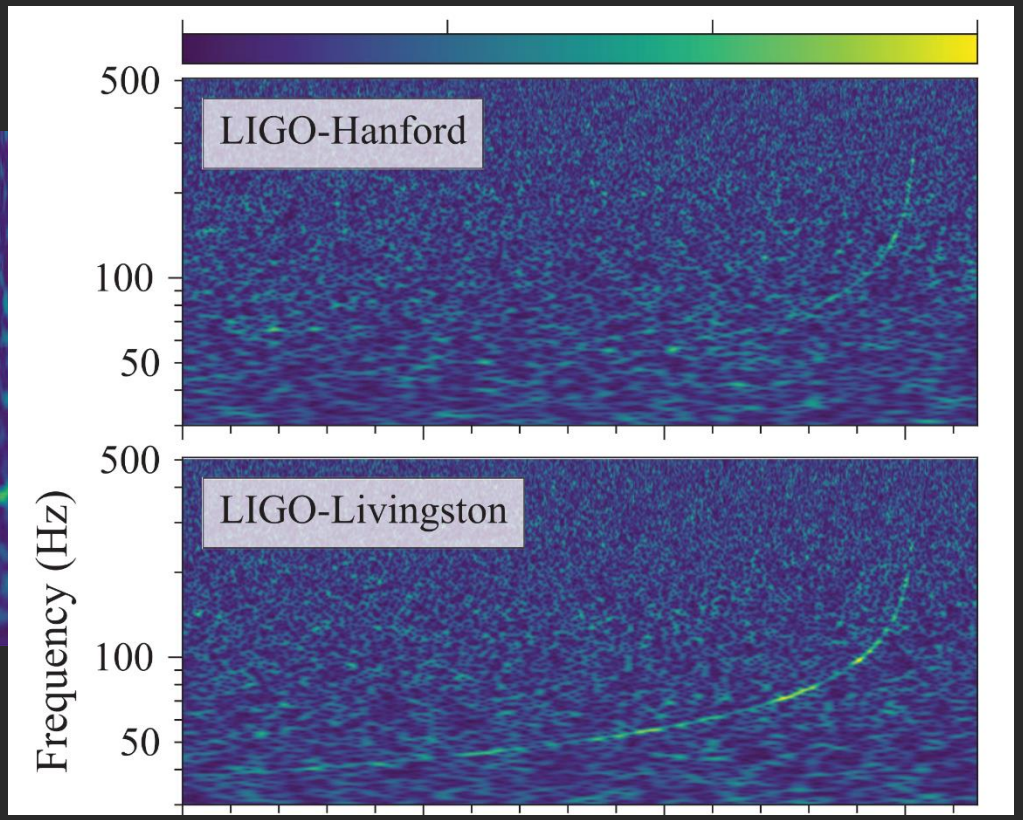




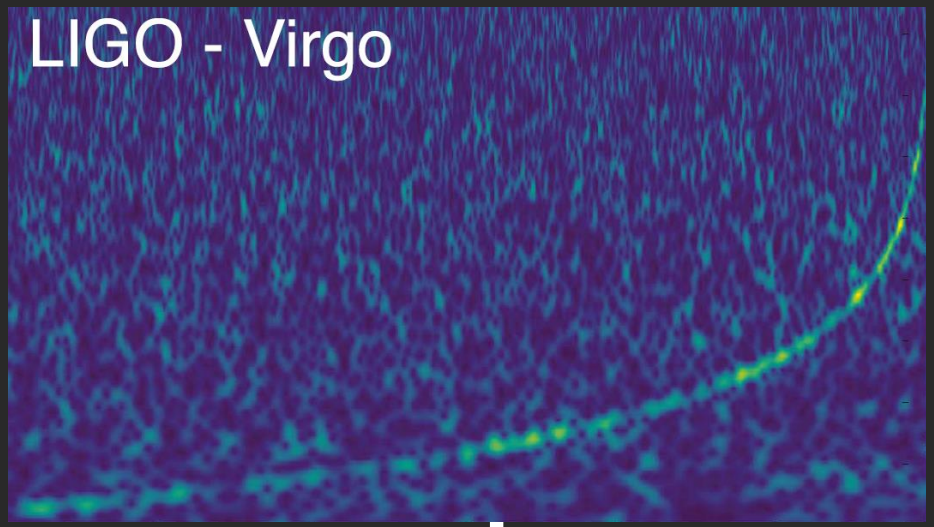
August 17, 2017: Timeline

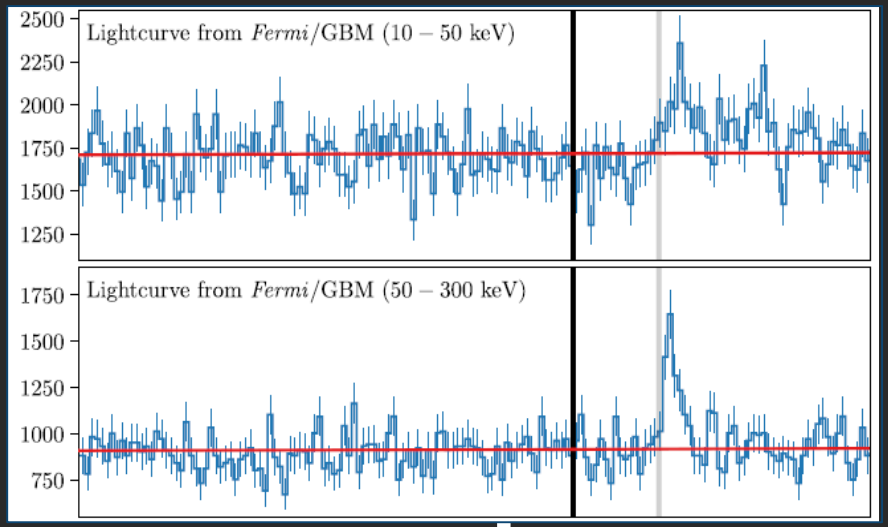




T_{GW}

August 17, 2017: Timeline





T_{GW}

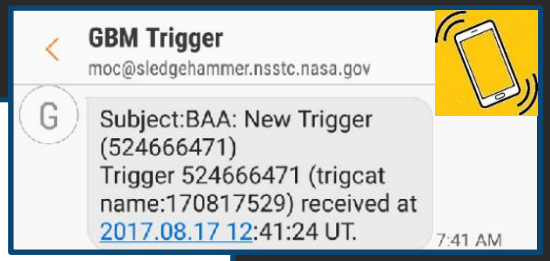
T_{GW} +1.7 s

GBM Trigger

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

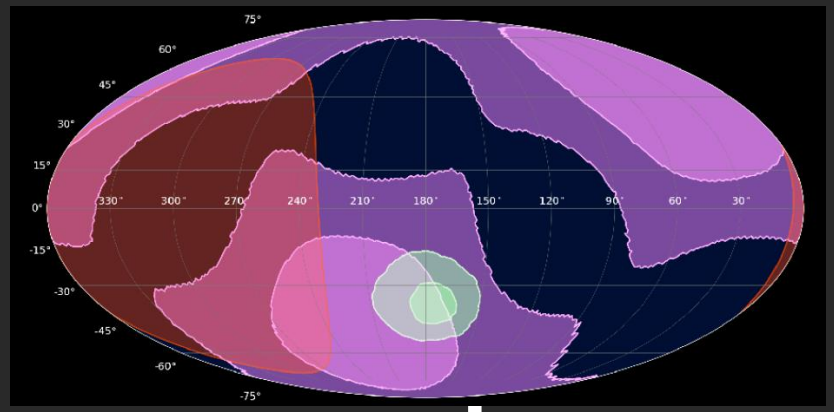


First GBM On-board localization and classification

+16 s

+27 s

GBM Localization



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

LIGO report on GW trigger coincident with GBM

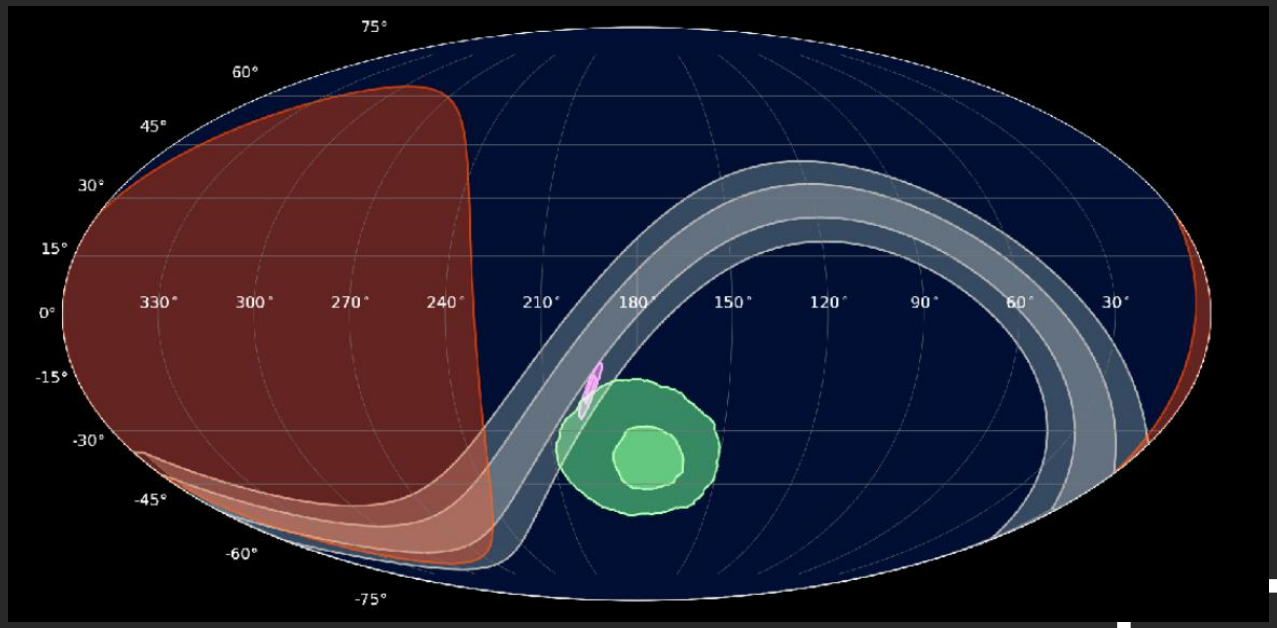
GBM-BA « human in the loop » localization

+40 s

+40 min

+47 min

More Reporting/Updates



GBM report on localization and short duration GRB

INTEGRAL SPI-ACS report on coincident weak GRB

Preplanned LV-EM telecon

Mistaken report On Ice-Cube candidates

First LIGO/Virgo skymap using all 3 detectors

IPN report on timing annulus between GBM and SPI-ACS

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

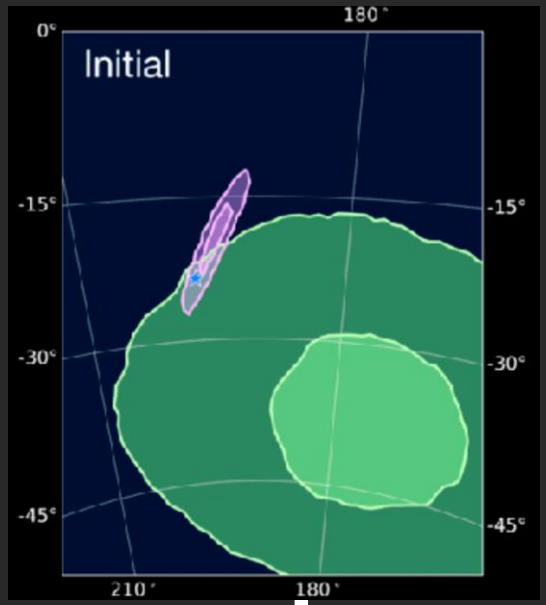
Continued Reporting

FIRST public GCN

```
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).
```



List of 15 host galaxies in LIGO/Virgo map volume

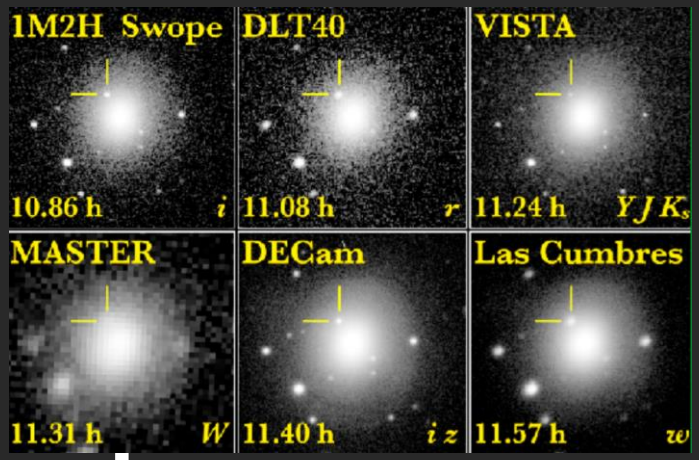
GBM science data arrives. GCN circular published Giving GRB official name **GRB 170817 A**

Updated LIGO/Virgo skymap

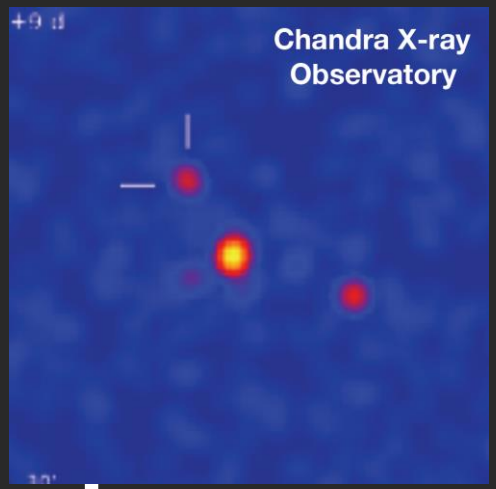
GBM report of energetics & Initial False Alarm Rate

+6 hr **+7 hr** **+11 hr** **+12 hr**

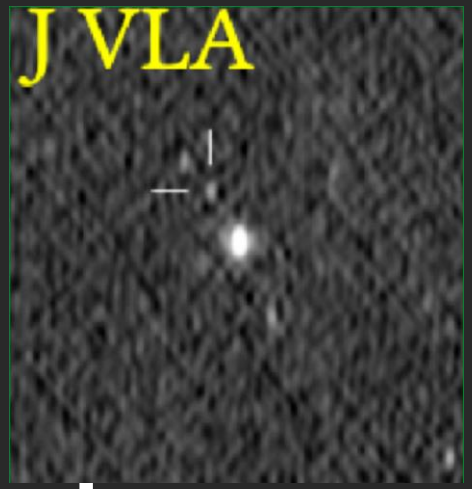
Electromagnetic Follow-up



Report of optical Transient by three independent telescopes



X-ray counterpart reported by Chandra

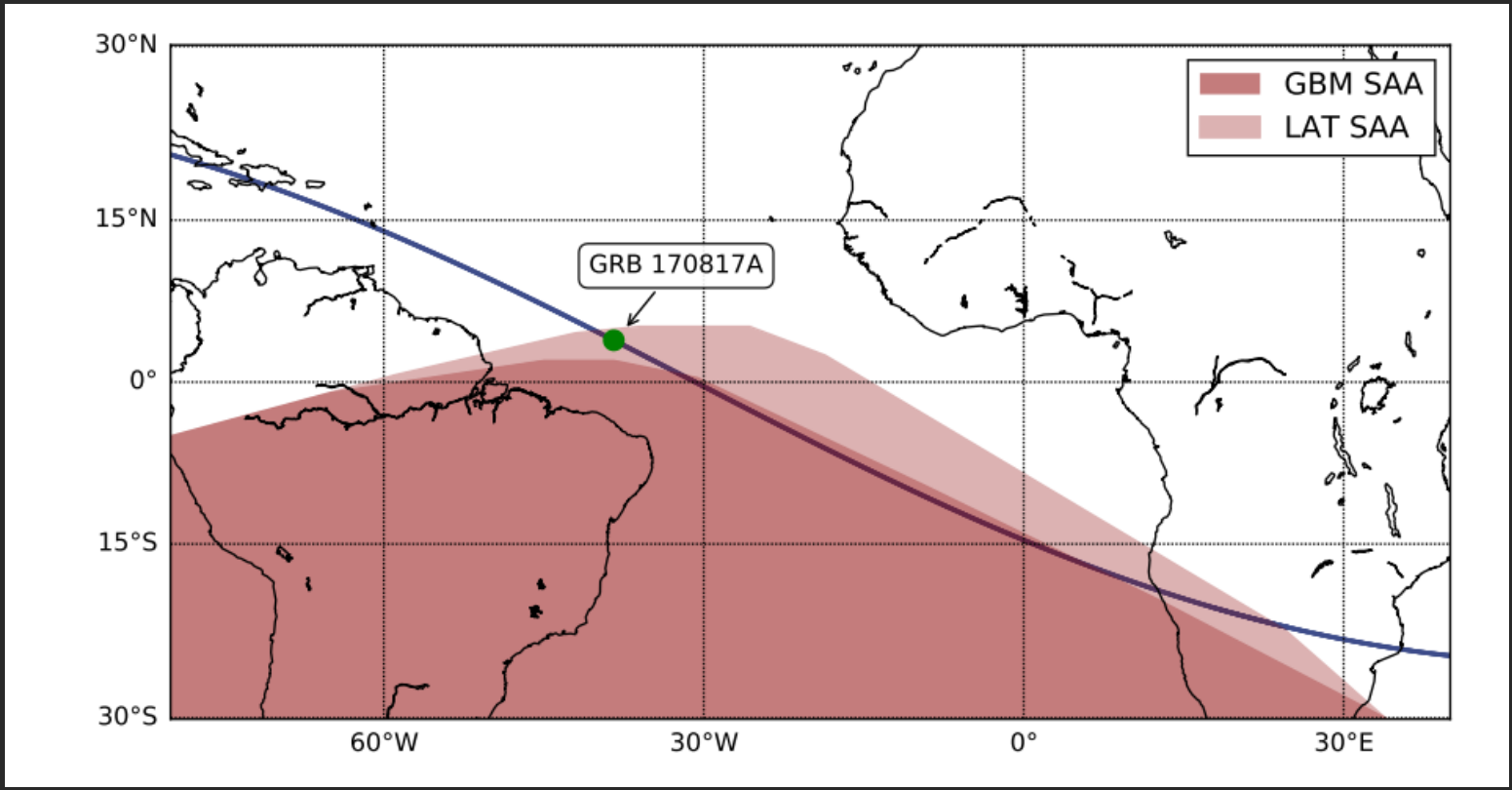


Radio counterpart reported by VLA

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

Fermi's orbital path

- SAA high levels of charged particles
  - GBM: data stream ended 2 minutes post-trigger
  - Slightly different shape for LAT ⇨ switched off

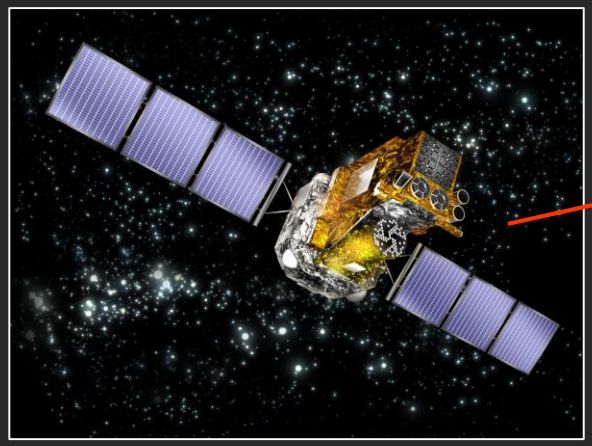


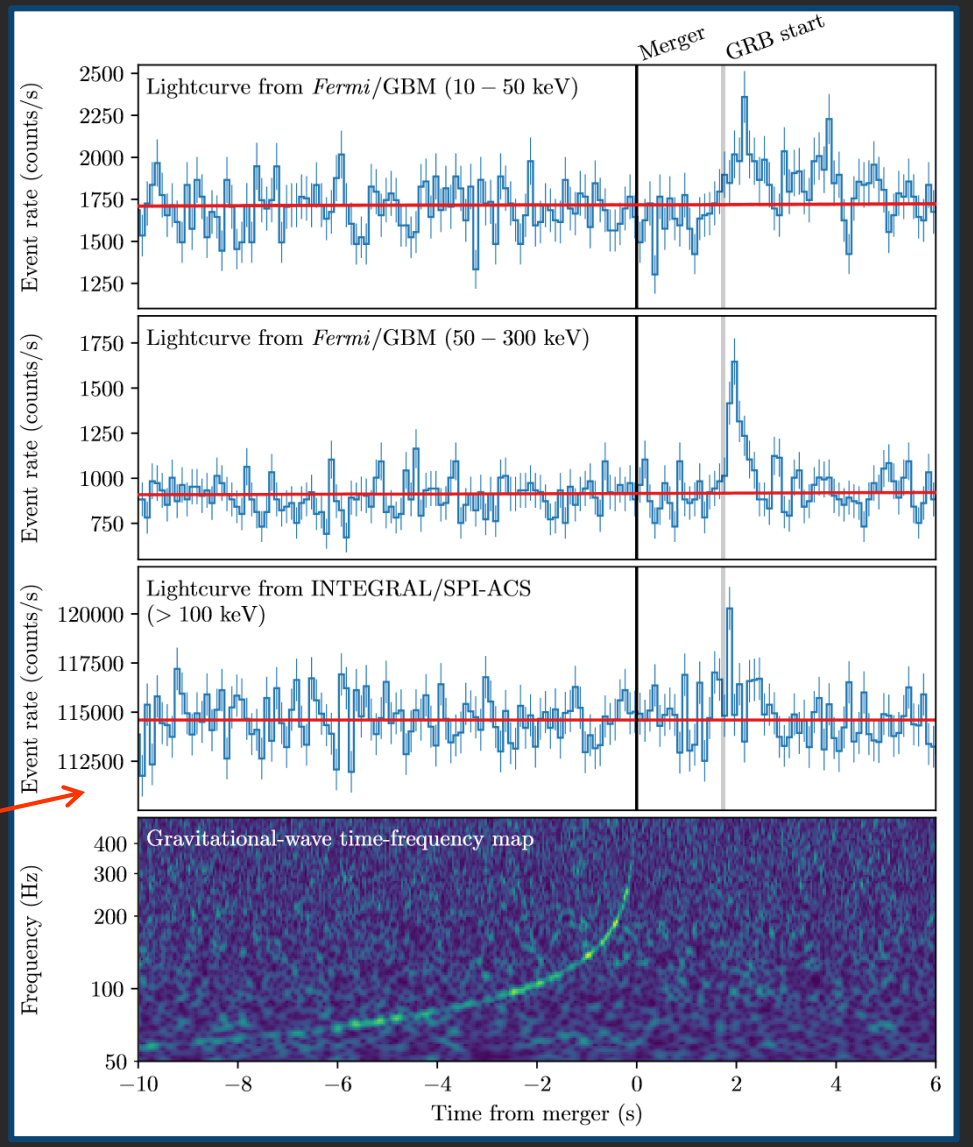
GW170817 / GRB 170817A

MPE ⇨ SPI-ACS

- 91 BGO crystals: 512 kg
- viewed by 181 PMTs

ESA *Integral* : 2002 –





BNS – short GRB Association

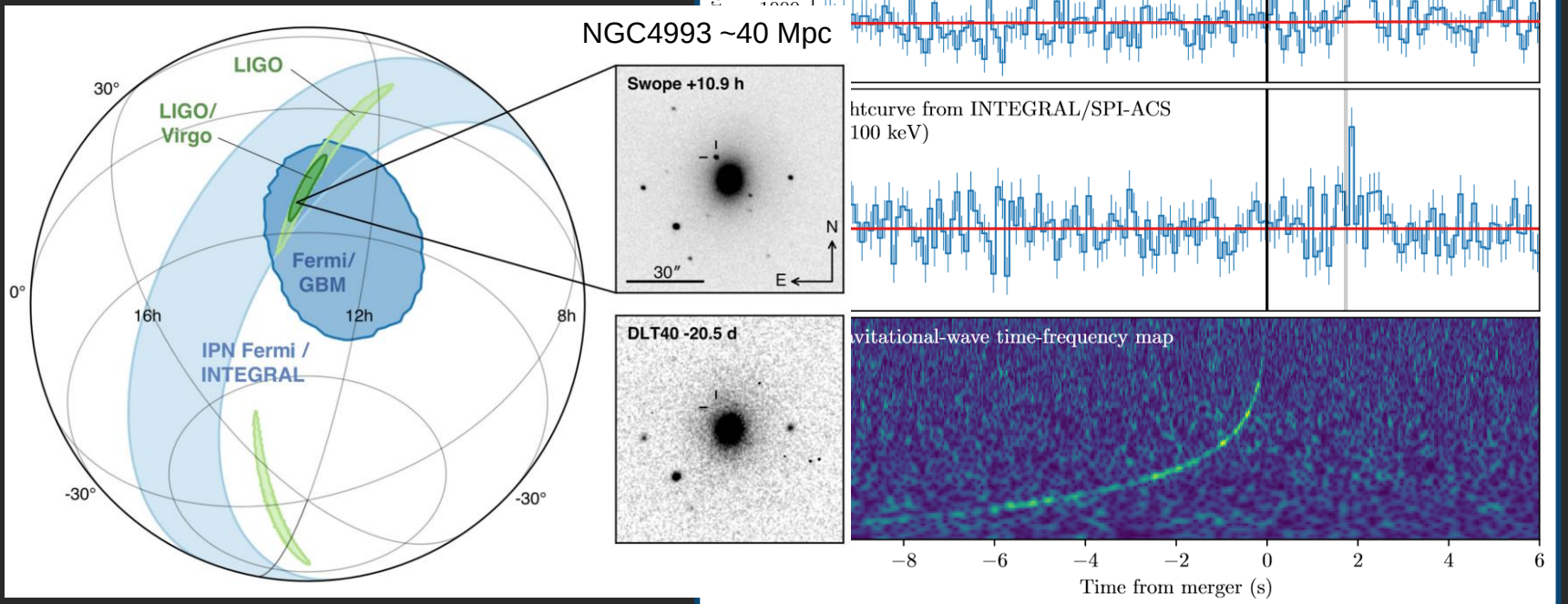
CONFIRMED !

Association at 5.3 σ

- Temporal association

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

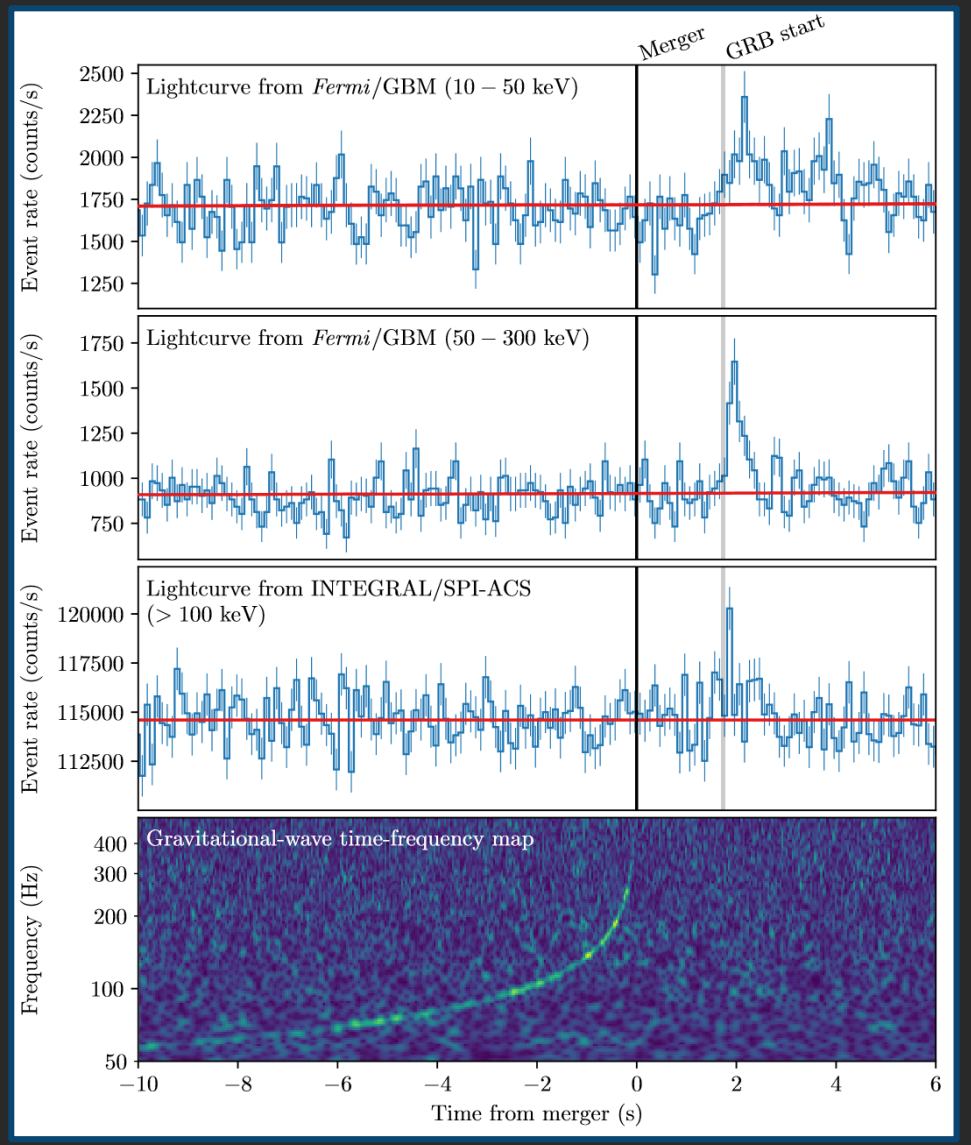
- Spatial association



BNS – short GRB Association

Measured time delay between GW and light: $\Delta t = 1.74 +/- 0.05$ s

- T
  e
  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]



The Speed of Gravity

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

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

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

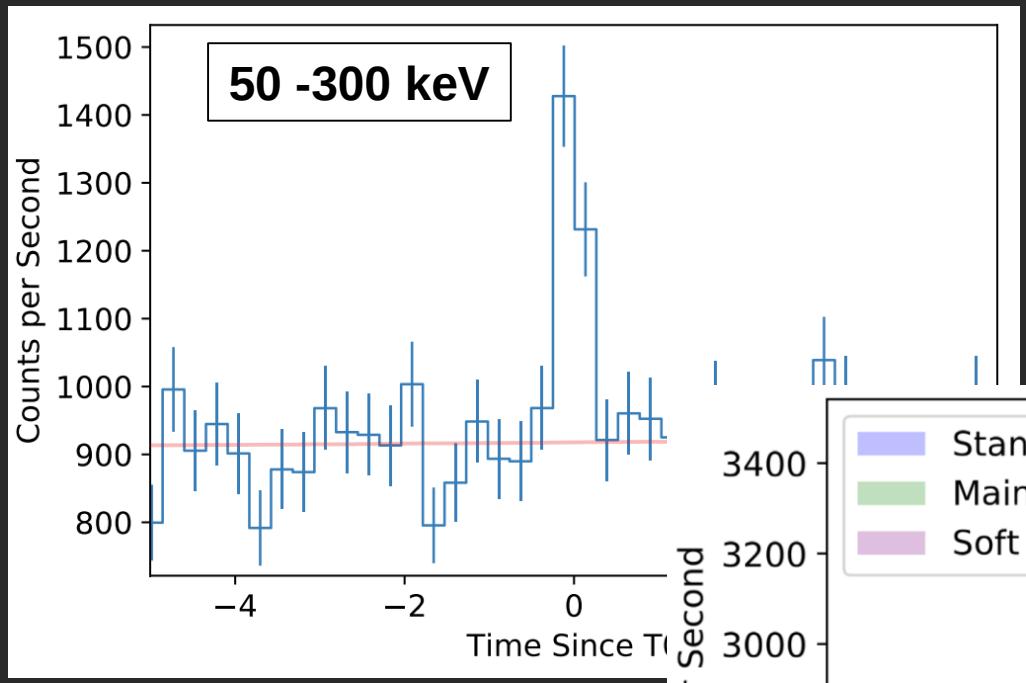
- Conservative estimate, assuming:
  1. Distance $D = 26\ MpC$ (lower bound GW 90% credible interval)
  2. GWs and gamma-rays emitted **at same time** ($\Delta t = 1.74\ s$) OR gamma-rays emitted 10 s **after** GWs ($\Delta t = 10\ s$)

  ⇨ 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

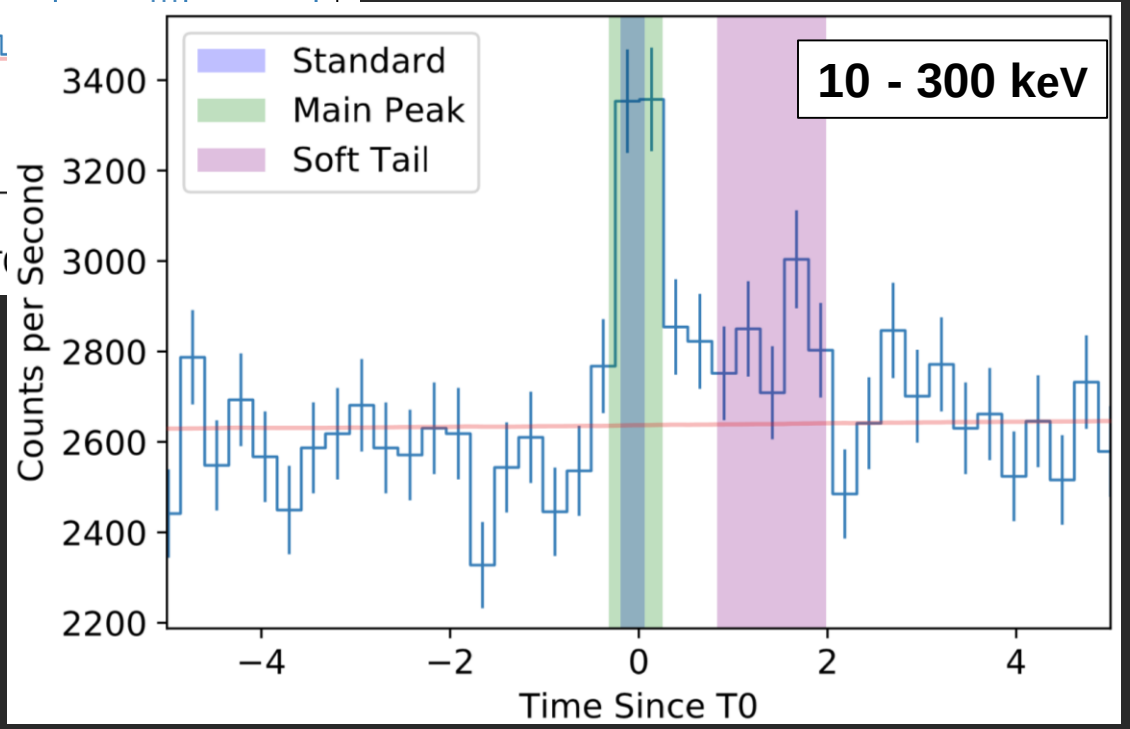
Fermi GBM analysis of GRB 170817A



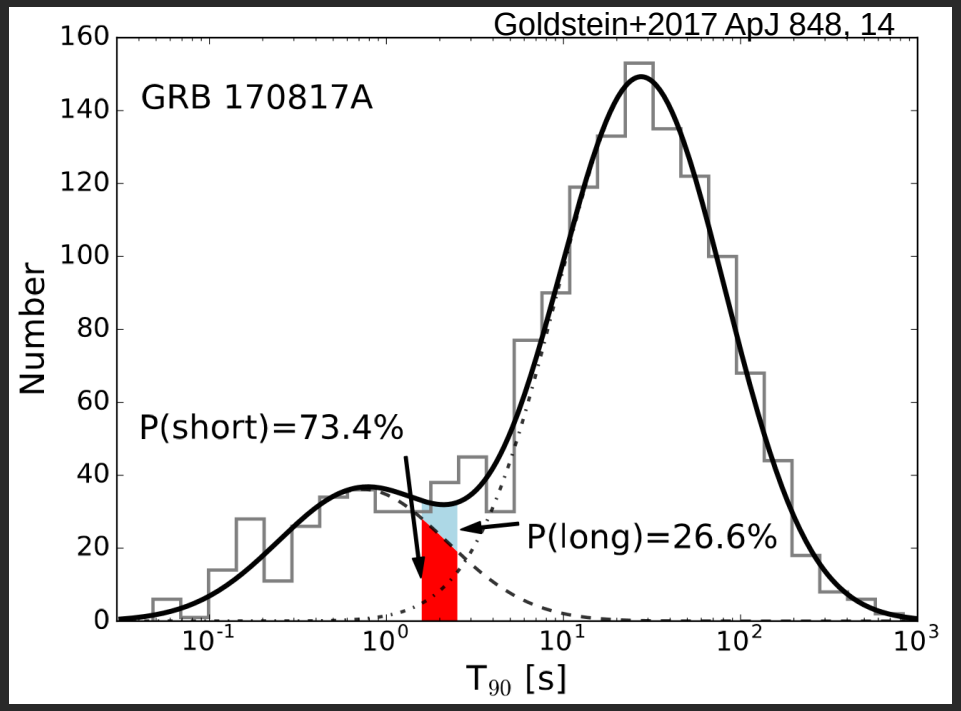
A tail

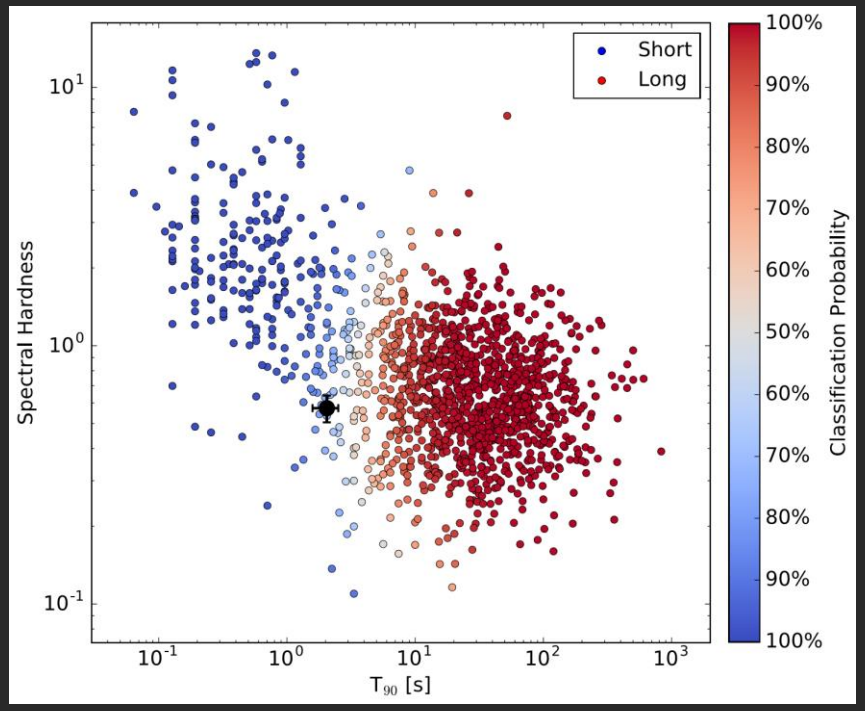
is it real? – or background?

- **Localization ✓**
- **Bayesian Block Anal. (→1.12 s)**



Fermi GBM analysis of GRB 170817A



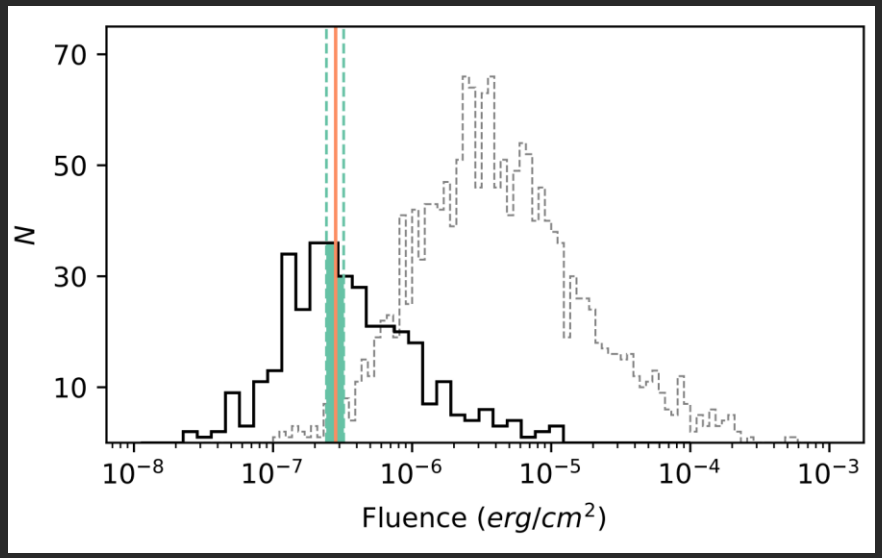


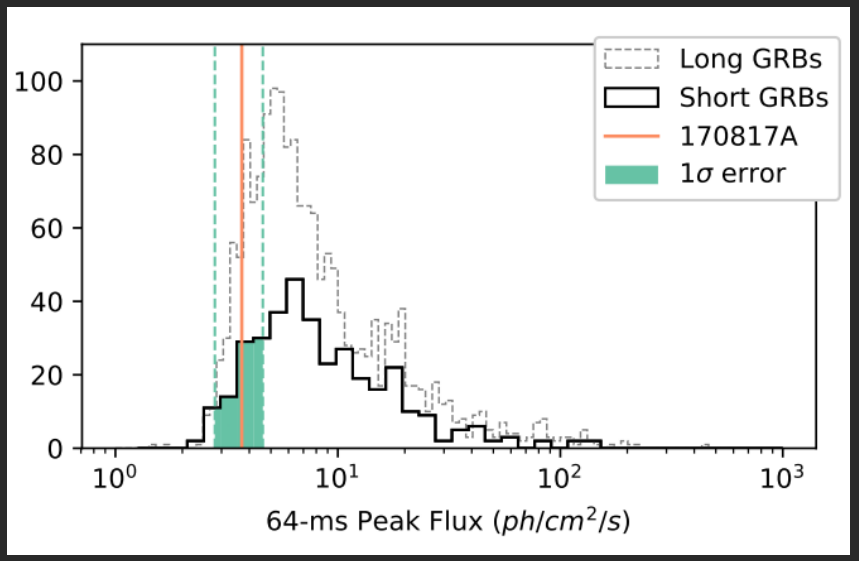
- Two classes of GRBs: short (mergers) and long (collapsars)
- These two classes are also spectrally different: short-hard and long-soft

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

Comparison with Catalogs





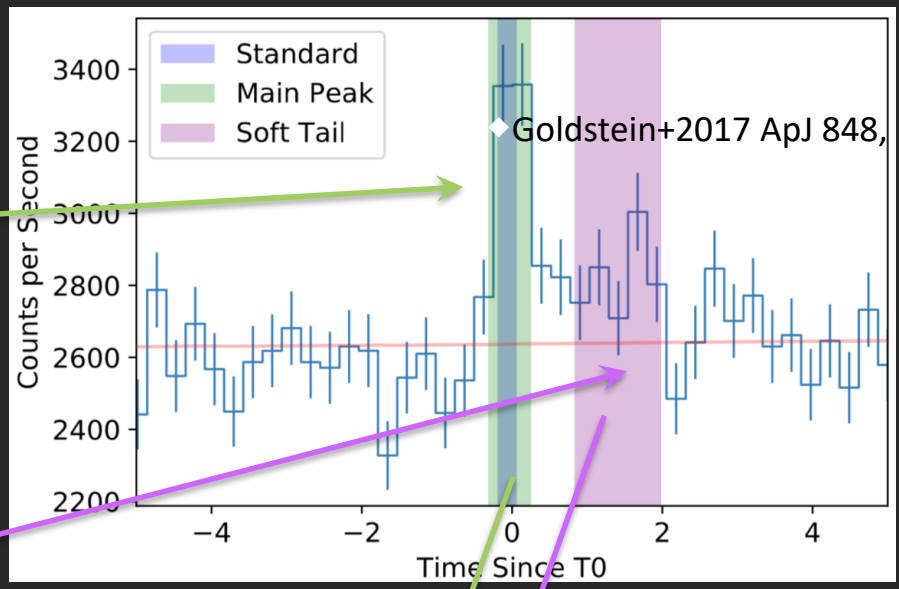
Standard GBM Catalog analysis

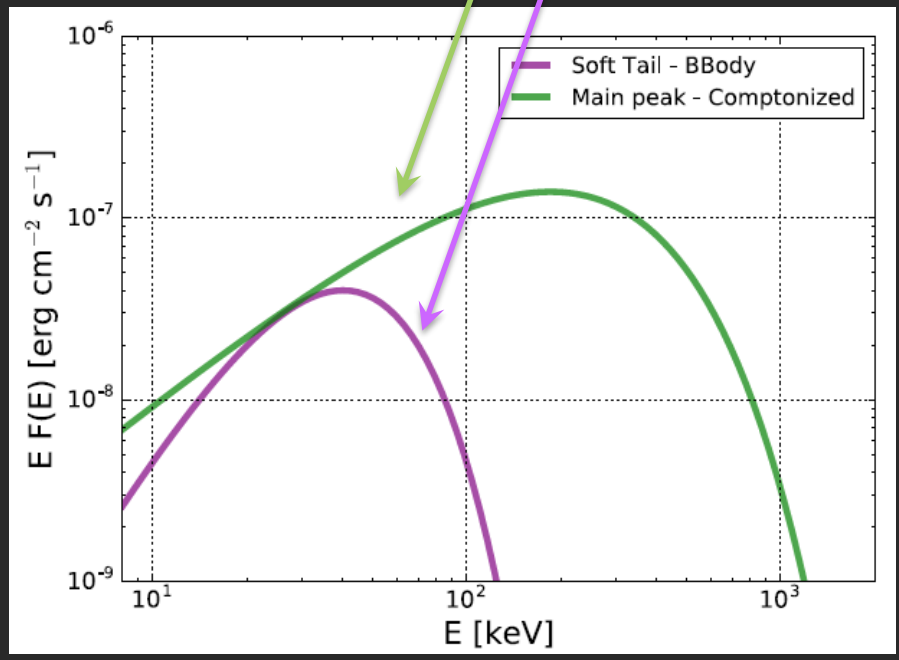
- Average short GRB by fluence
- Lower third in 64 ms peak flux

Fermi GBM analysis of GRB 170817A

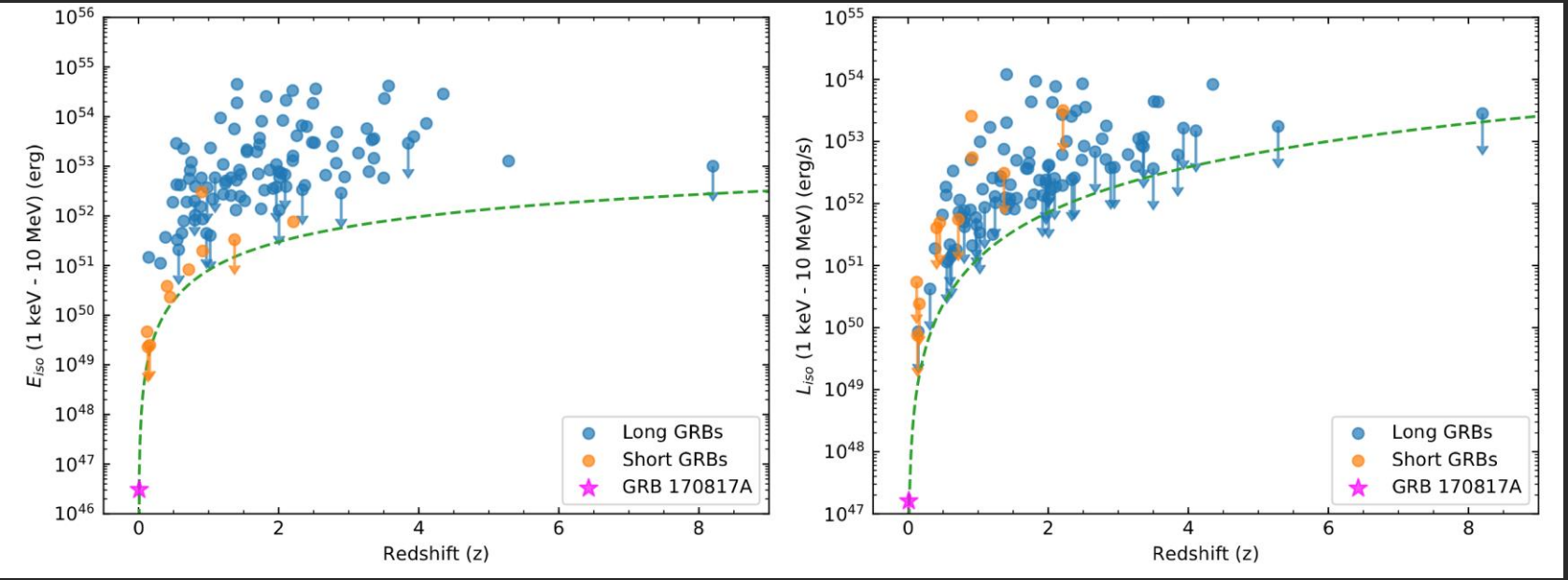
GBM spectral analysis results:
→ two components!

- 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
- GRB 150101B
  - One of the closest short GRBs
    - z = 0.134
  - A second nearby event with a short hard spike and a soft tail
    - Burns et al. 2018 ApJ, L34





Fermi GBM analysis of GRB 170817A



Abbott+2017 ApJ 848, 13

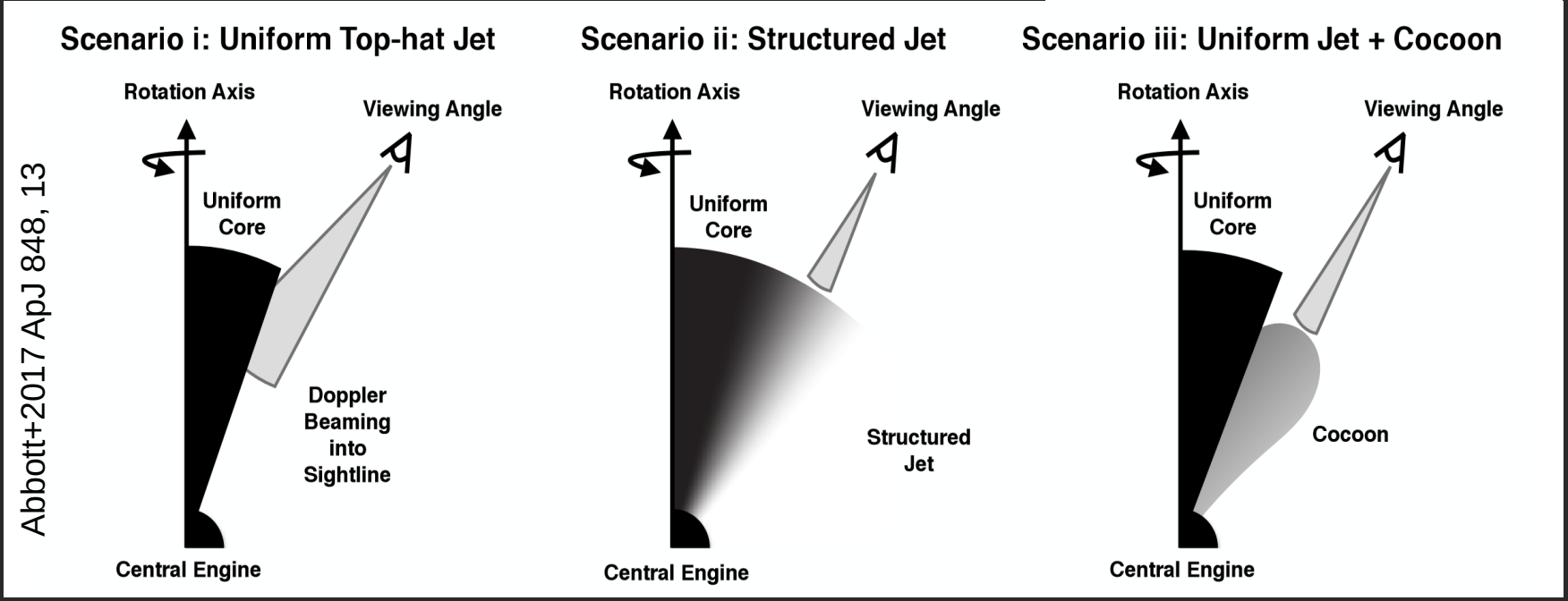
GBM energetics results

- 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

- **Observations:** ordinary GRB
- **Distance information:** very dim GRB
- GRB **Observing Scenarios**:
  - GW data restricts viewing angle < 56 deg off-axis
  - Assuming the association with NGC 4993, viewing angle < 36 deg off-axis
  - Afterglow observations of GRB 170817A, 200-300 days post-merger show a turnover in the temporal decay from X-ray to radio that appears to favor the structured jet scenario over the cocoon scenario (Alexander et al. 2018)

Scenario iv: Intrinsically Dim



Conclusions

Detectors like GBM are efficient detectors of counterparts to GWs

- 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

Other candidate: GRB150101B

- The search of the full GBM sGRB population is the subject of an ongoing study

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

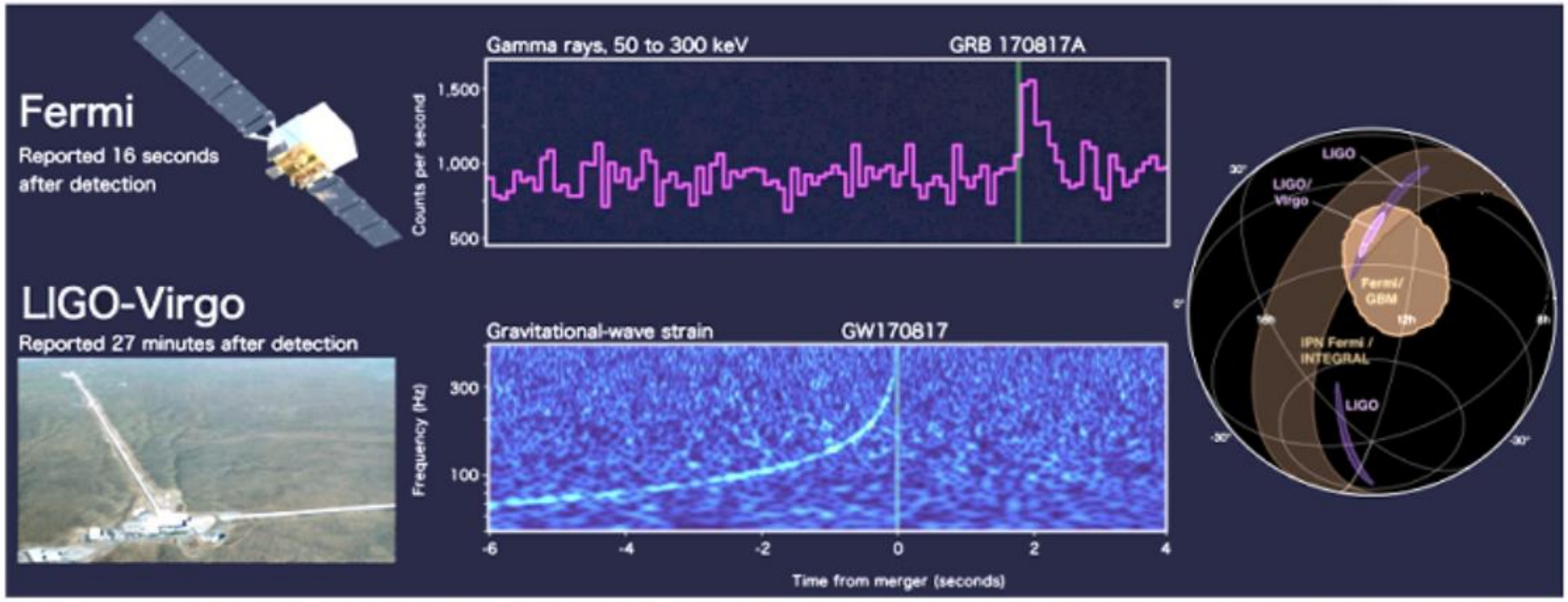
→ **Design and build more detectors like this!**

Fermi's Gamma-Ray Burst Monitor wins 2018 Rossi Prize

AAS **High Energy Astrophysics Division**

Bruno Rossi prize

The Rossi Prize is awarded annually in honor of Bruno Rossi ``for a significant contribution to High Energy Astrophysics with particular emphasis on recent, original work.''



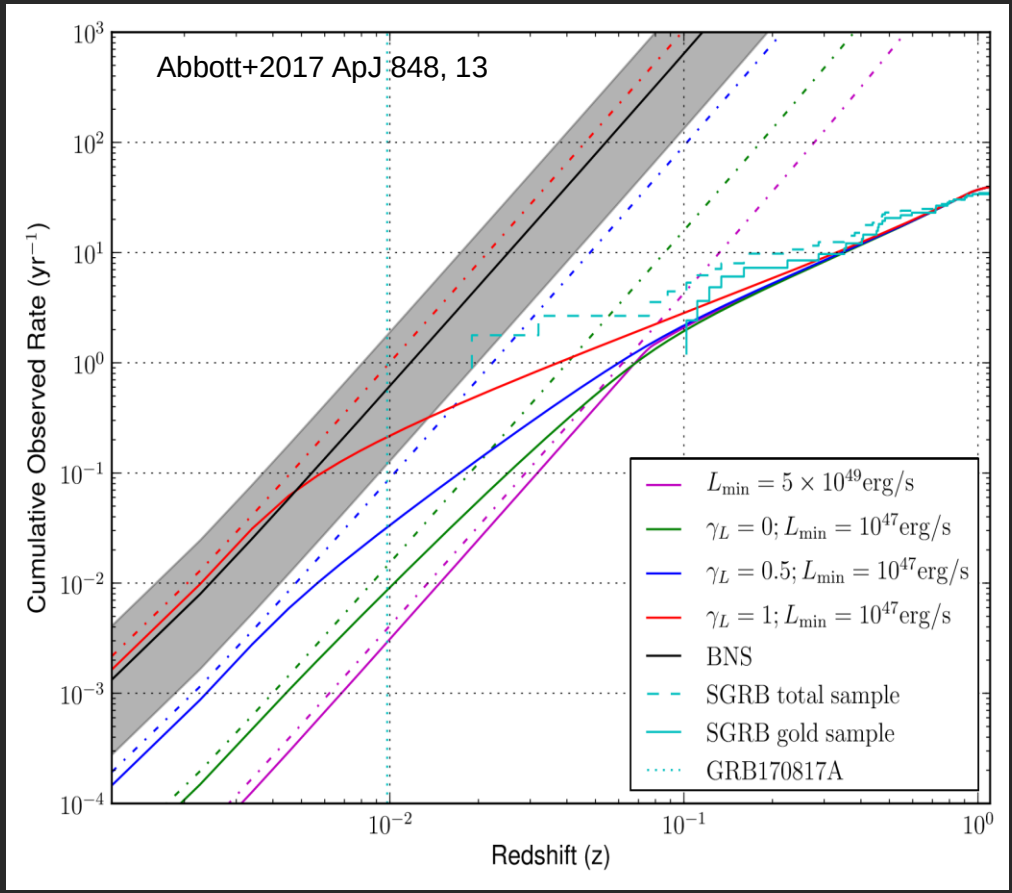
Joint Detection Rates: GBM and LIGO/Virgo

sGRBs at <40 Mpc are rare!

- Expectations for O3 (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

GBM preparation for O3:

- Overall optimization of the targeted and untargeted search search



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

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)

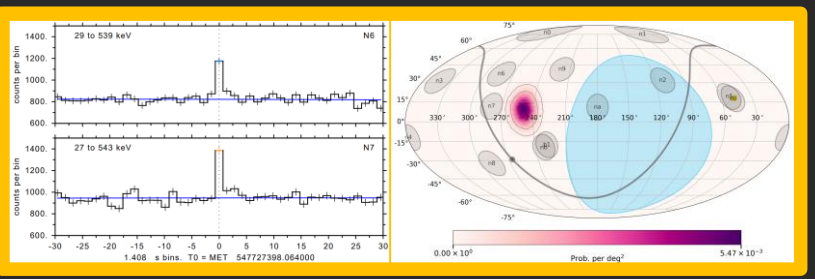
- CTTE data search over **4 energy ranges and 10 timescales** (0.064 – 2.8 s)
- Uses **all 12 NaI detectors** and flags candidates that meet a pre-defined count rate threshold in **"legal" detector pairs** in 50-300 keV
- Improved spline background can also find some **long GRBs**
- Standard GBM **localization** 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
548482684	18/05/20	04:17:59.94	297.580	-0.700	15.38	0.192	1	0	2	HEALPIX MAP LC	Fermi-GBM Subthreshold. This Notice was ground-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-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



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

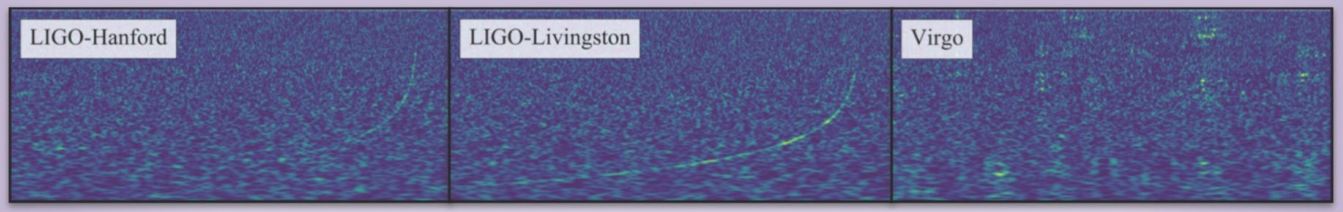
Fermi GBM ~~un~~targeted searches

- 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

GW 170817 LIGO Factsheet



observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≤ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}