

# Multi-messenger studies with the Fermi Satellite

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

**INFN**  
Istituto Nazionale di Fisica Nucleare

**NOW 2018**  
Neutrino Oscillation Workshop

Home History Science People Venue Registration and Fee

Rosa Marina (Ostuni, Italy)  
September 9 - 16, 2018  
(Participation by invitation only)

Particle Physics in the Cosmos  
Multimessenger Astrophysics  
Neutrino Oscillations  
Oscillation Parameters  
Oscillation Parameters in the Future  
Compass Rose

# The Fermi Mission



## Large Area Telescope (LAT)

- 20 MeV to more than 300 GeV
- observes 20% of the sky at any instant
- entire sky every 3 hrs absolute timing to  $\sim 300$  ns

International and interagency  
collaboration between NASA and DOE  
in the US and agencies in France,  
Germany, Italy, Japan and Sweden

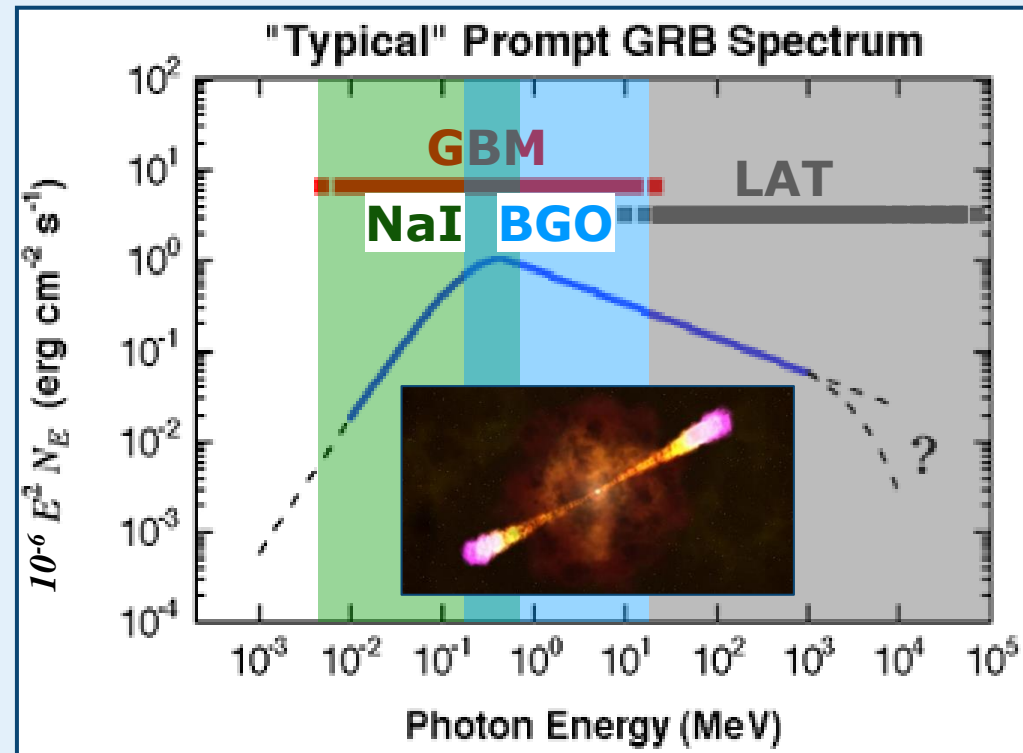
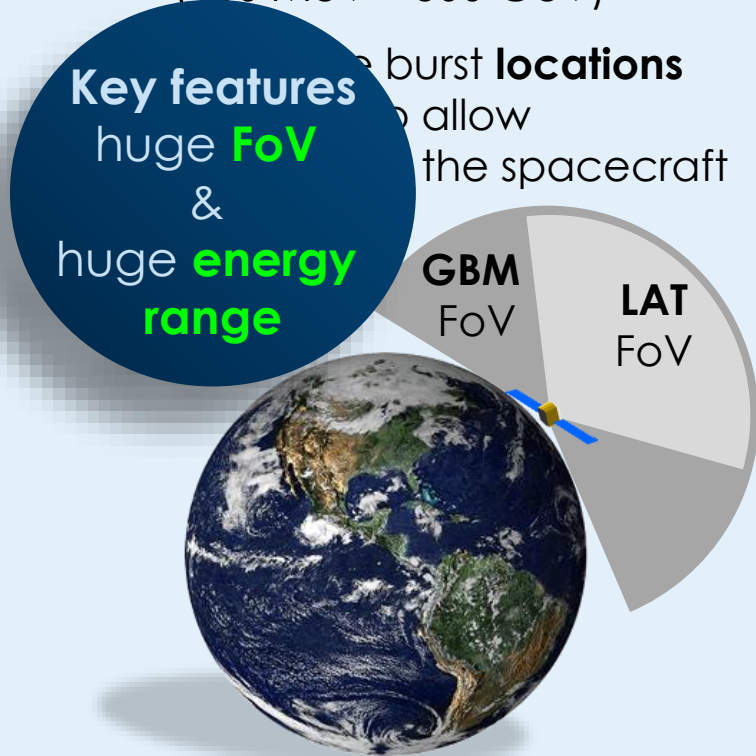
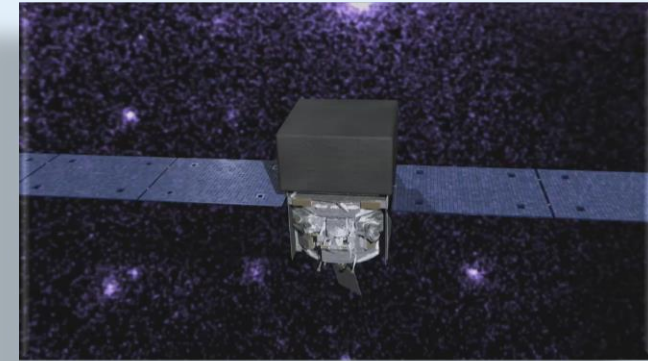
## Gamma-ray Burst Monitor (GBM)

- 8 keV to 40 MeV
- observes entire unocculted sky
- absolute timing  $\sim 2$   $\mu$ s

# The Fermi Gamma-Ray Burst Monitor

## Designed to study Gamma-Ray Bursts (GRBs)

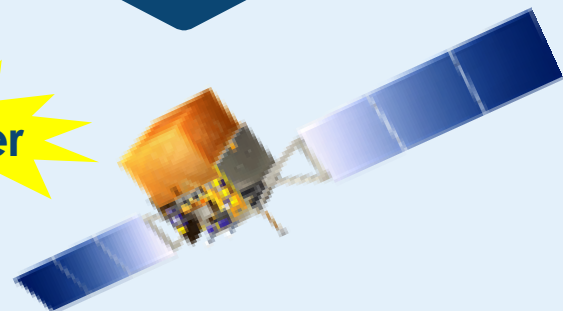
- GBM primary **objectives**:
  - Extend** the energy range downward from the Fermi-LAT one (100 MeV – 300 GeV)



# Fermi-GBM: 1) Triggering Operations



trigger



A total of **120 different triggers** can be specified, each with a distinct threshold

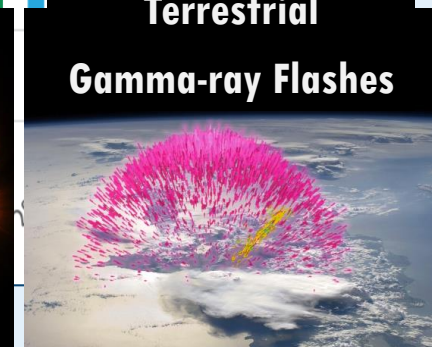
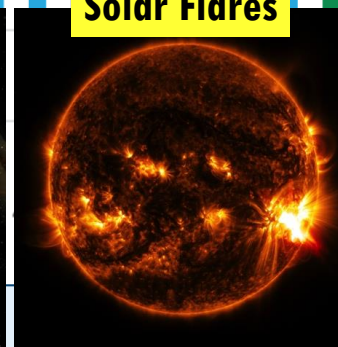
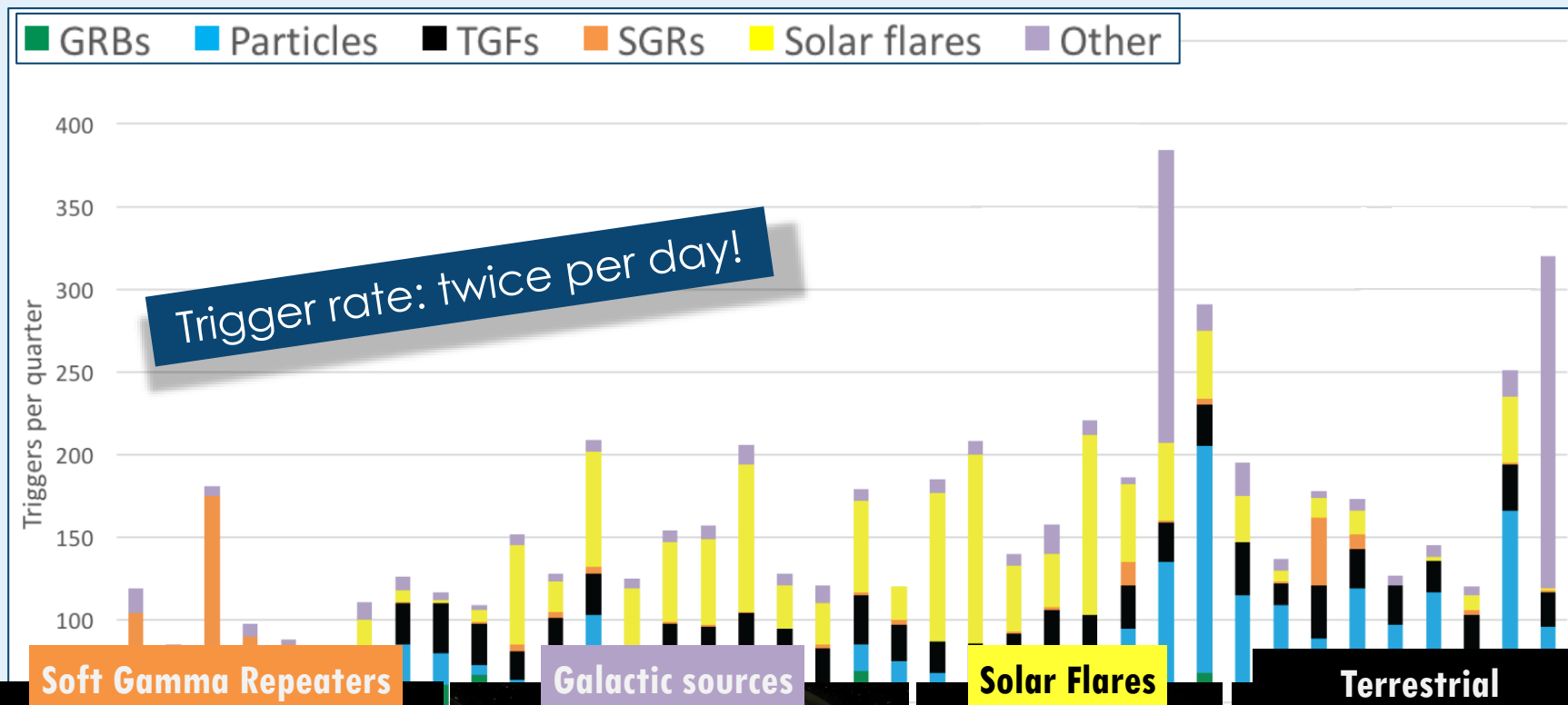
- GBM triggers when **2 or more detectors** exceed a preset but adjustable threshold specified in units of the standard deviation of the **background rate**.
  - Background rate: average rate accumulated over the previous 17 s, excluding the most recent 4 s
- Four **energy** ranges
  - 25 – 50 keV
  - 50 – 300 keV
  - 100 – 300 keV
  - >300 keV
- Ten **timescales**
  - from 16 ms to 8.192 s in steps of a factor of 2



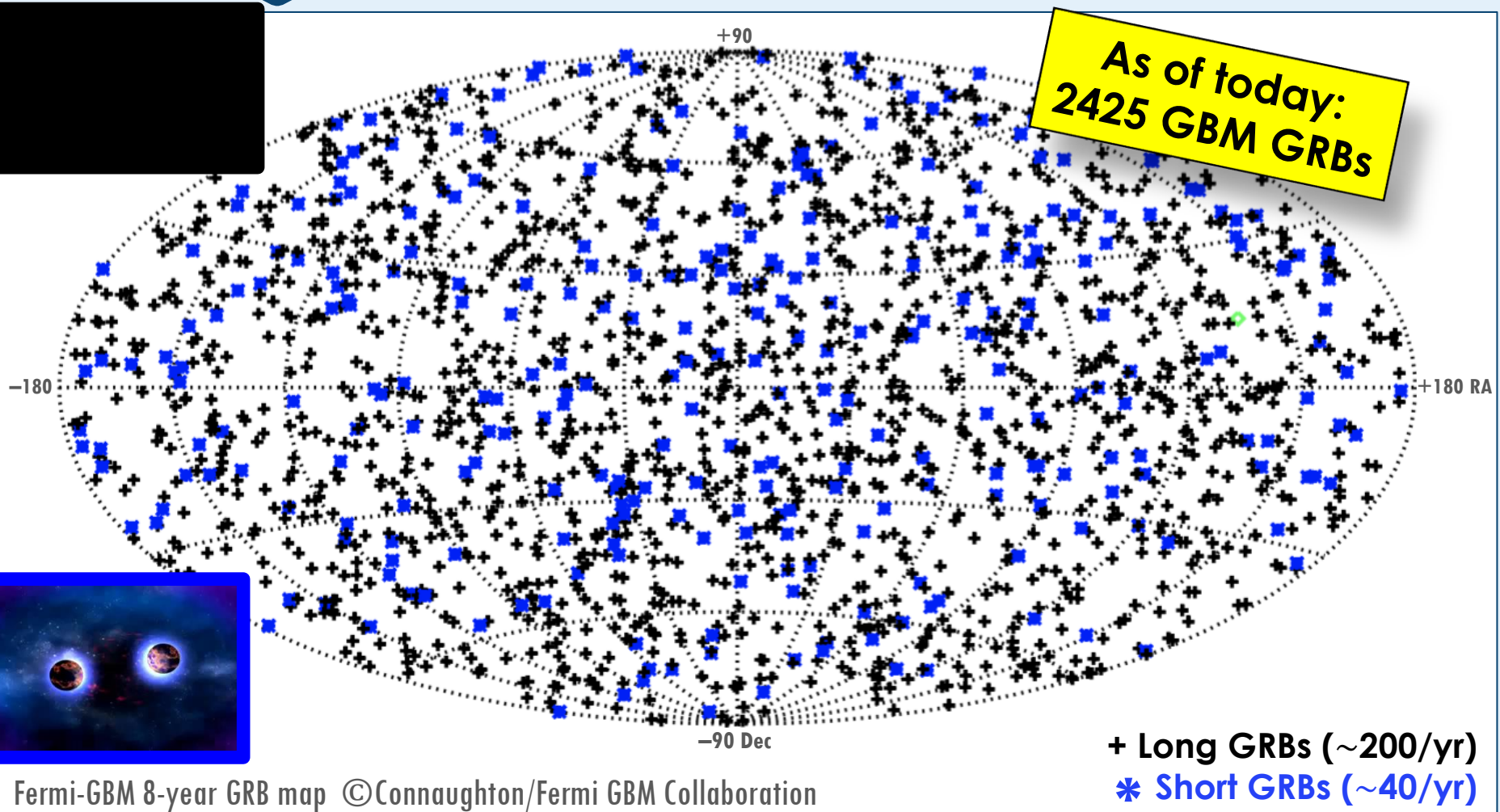
28 trigger  
algorithms  
currently enabled

# Fermi-GBM: 2) Trigger Statistics

Quarterly trigger statistics over 9.5 years of the mission

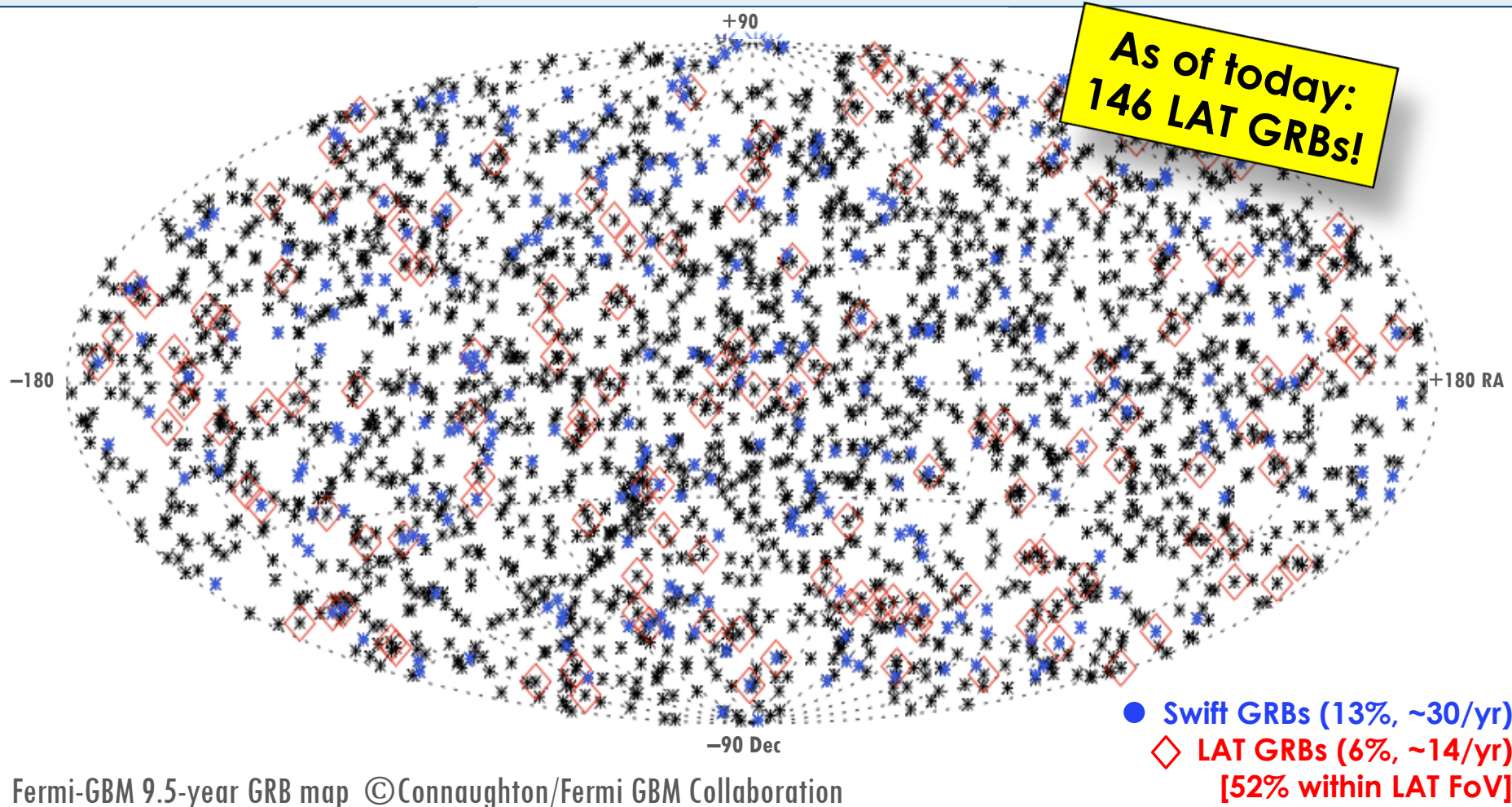


# Fermi-GBM: 3) Skymaps



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

# Fermi-GBM: 3) Skymaps



Swift BAT: **only 9 sGRBs/yr** (arcmin localization!)

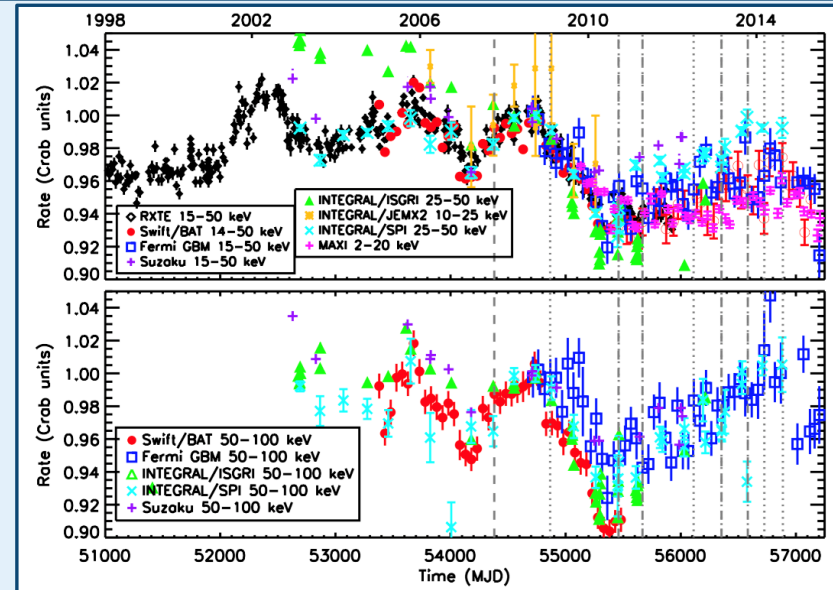
Fermi-LAT: **only 2-3 sGRBs/yr** (~0.1÷0.5 deg localitazion)

Facilitating  
follow-up!

# Fermi-GBM: 4) Untriggered Sources

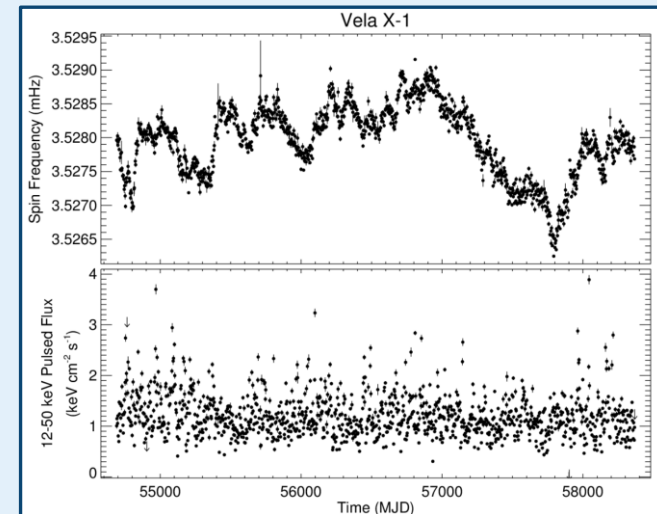
## 1. Earth Occultation Monitoring

- Measure of the **change in the count rate** observed in the GBM detectors when the source **enters** or **exits** Earth occultation
- Counts in each energy channel converted to **fluxes** using an assumed spectrum for each source
  - **~250 sources are monitored** (X-ray binaries, AGNs, etc., for a full list see [https://gammaray.nsstc.nasa.gov/gbm/science/earth\\_occ.html](https://gammaray.nsstc.nasa.gov/gbm/science/earth_occ.html))



## 2. Accreting Pulsars Monitoring

- Using **epoch folded searches**
  - **36 sources detected** (8 **persistent**, 28 **transient pulsars**, for a full list see <http://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html>)



Vela X-1 Full History

# Fermi-GBM: 5) Untargeted Searches

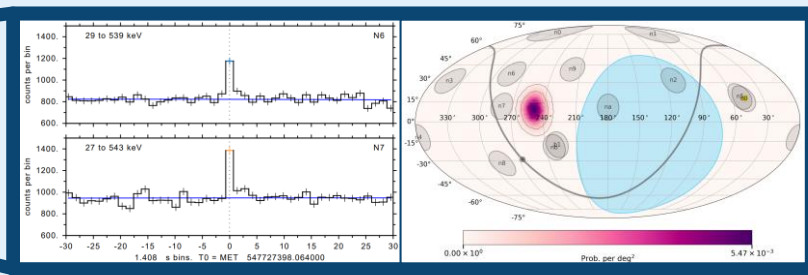
- Since 2013: Development of **automated search algorithms** for **untriggered** transient sources (POC: M.S.Briggs)
  - Magnetar burst (~200), TGFs (> 1000), other Galactic sources (>100), Short GRBs (sGRBs)

- 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](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
<a href="#">548485652</a>	18/05/20	05:07:27.02	269.880	-60.430	17.92	1.407	1	0	2	<a href="#">HEALPIX MAP LC</a>	Fermi-GBM Subthreshold. This Notice was ground-generated -- not flight-generated.
<a href="#">548482684</a>	18/05/20	04:17:59.94	297.580	-0.700	15.38	0.192	1	0	2	<a href="#">HEALPIX MAP LC</a>	Fermi-GBM Subthreshold. This Notice was ground-generated -- not flight-generated.
<a href="#">548385290</a>	18/05/19	01:14:45.61	266.500	+45.550	11.24	1.407	1	0	8	<a href="#">HEALPIX MAP LC</a>	Fermi-GBM Subthreshold. This Notice was ground-generated -- not flight-generated.
<a href="#">548326303</a>	18/05/18	08:51:38.92	155.080	-33.870	17.89	1.024	1	0	2	<a href="#">HEALPIX MAP LC</a>	Fermi-GBM Subthreshold. This Notice was ground-generated -- not flight-generated.

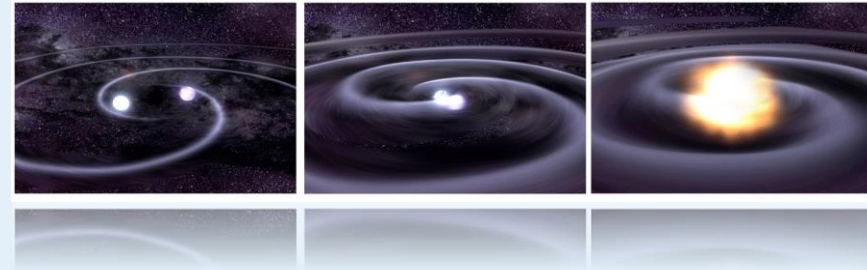


Online sGRB catalog 2013–2017

[http://gammaray.nsstc.nasa.gov/gbm/science/sgrb\\_search.html](http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html)

# Fermi-GBM: 6) LIGO/Virgo Partnership

- **Special MoU:** Small team of members from both collaborations that have worked together for years

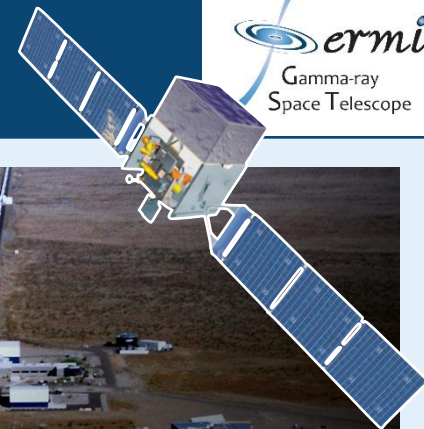


- Recognition that GBM is the **most prolific sGRB detector**, providing energy discrimination and localization capabilities
- LVC has access to **sub-threshold GBM triggers**
  - **Untargeted blind search** for weak GBM sGRBs
- GBM has access to **sub-threshold GW triggers**
  - Development and constant refinement of a GBM sub-threshold **targeted search**

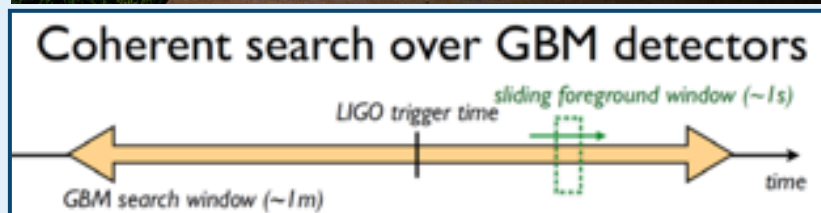
→ The **joint sub-threshold work** may eventually be able to push GW detection horizon further by associating weak signals in both detectors

→ **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: 7) Targeted searches



- Search for **coherent signals in all detectors** given an input time and optional skymap (Blackburn+2015, Goldstein+2016)
  - Sliding timescales** from 0.064 s to 8 s with a factor of 4 phase shift
  - 3 source spectral templates using Band function: soft, normal, and hard
  - Many **improvements during O1 and O2**: Various bug fixes, better **background** estimation, more realistic hard spectral **template**

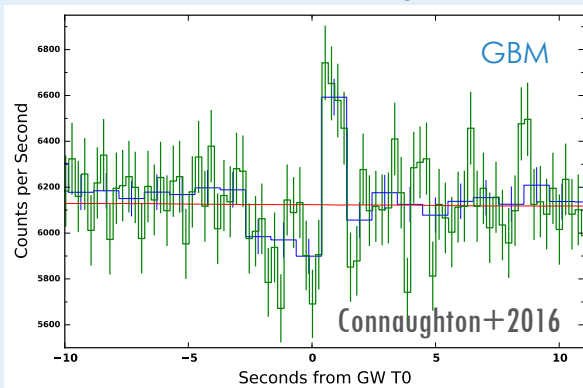


Ideal Scenario	Bright GBM	Bright LIGO	GBM	LIGO
GW150914 Scenario	Sub-threshold GBM	Bright LIGO		
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO		
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO		

# Fermi-GBM: 8) Observations of GW Events

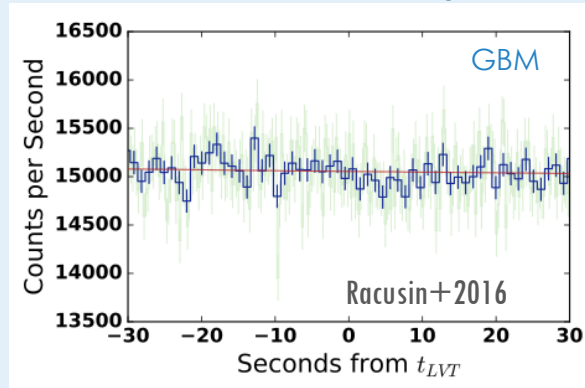
## GW 150914

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



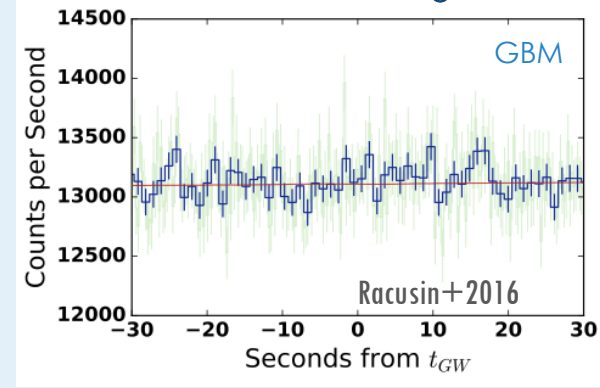
## LVT 151012

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



## GW 151226

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



- **GW150914-GBM, a  $2.9 \sigma$  event** consistent with a **short GRB**
  - Not predicted by theoretical models, poorly localized but consistent
- **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!

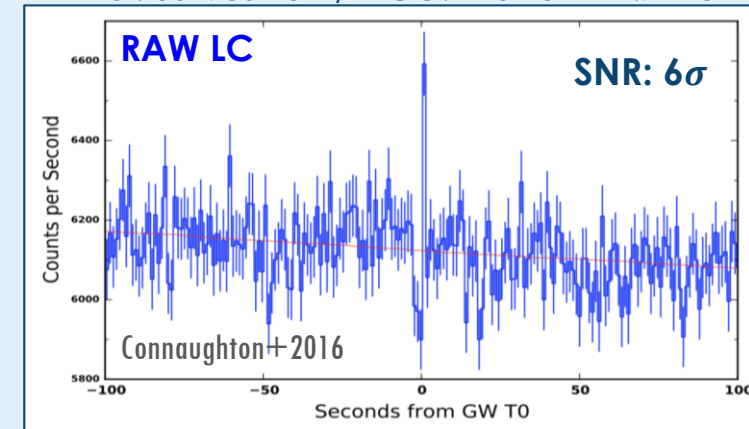
# Fermi-GBM: 8) Observations of GW Events

## The transient “GW150914-GBM”

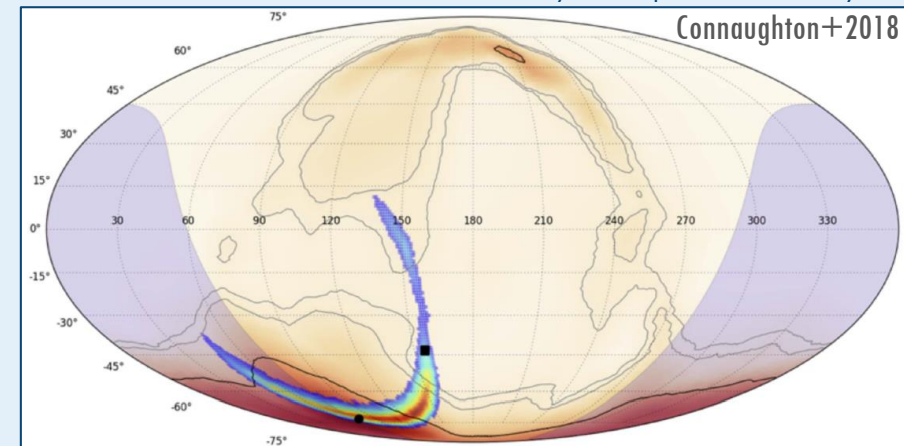
- Discovered through a targeted search around **GW150914**:
  - **Hard** transient @  $t_{\text{GW}} + 0.4$  s, 1 s long
  - ➔ **Association significance:  $2.9 \sigma$**
- **Localization**: source direction **underneath the spacecraft ( $\theta = 163^\circ$ )**
- **Energy spectrum** peaking in BGO energy range
  - Best fit simple PL index  $-1.4$  (**average for sGRBs**)
  - Fluence  $2.4 \times 10^{-7}$  erg  $\text{cm}^{-2}$  (**weaker than average for sGRBs**)
- **Not detected** by other gamma-ray instruments

### Raw count rates:

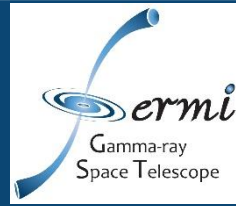
Sum of all GBM detectors: 12 x NaI + 2 x BGO  
NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV



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



# Fermi-GBM: 9) GRB 170817A and GW170817



Fermi



Gamma rays, 50 to 300 keV

GRB 170817A

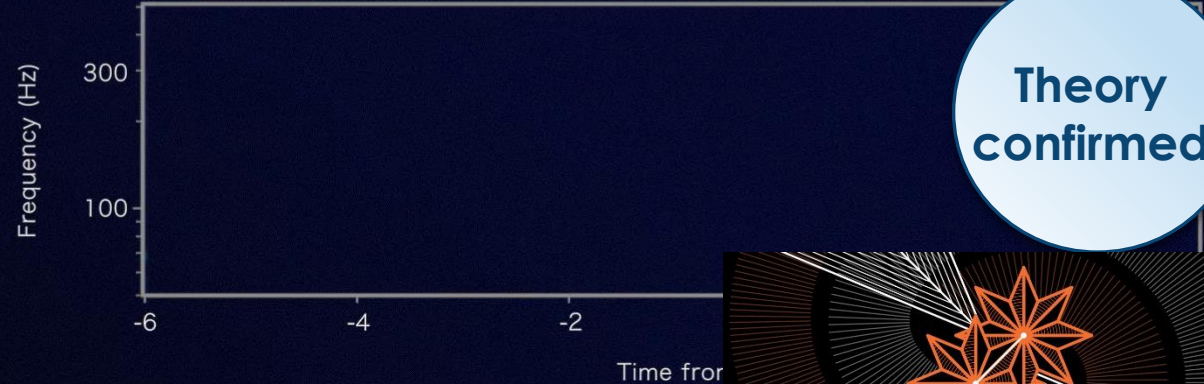


LIGO



Gravitational-wave strain

GW170817



Theory confirmed!



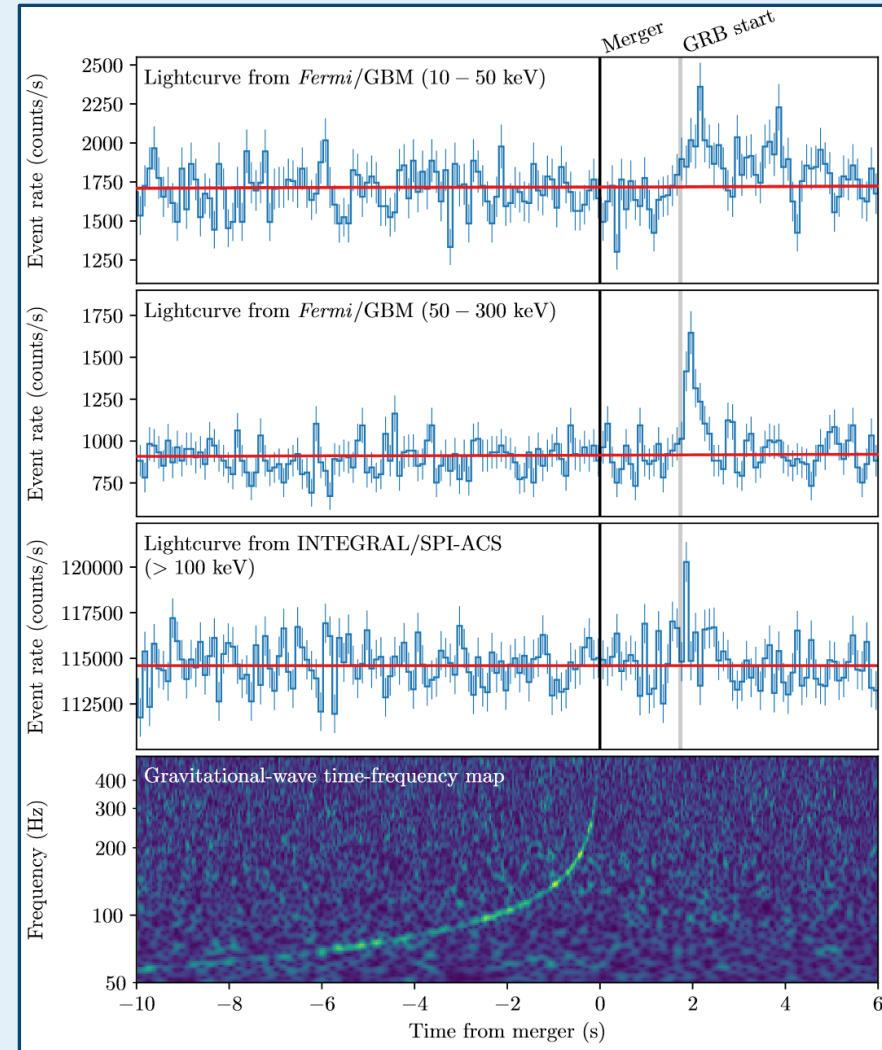
Credit: LIGO; Virgo; Fermi; NASA/DOE; NSF; EGO; ESA



# Fermi-GBM: 9) GRB 170817A and GW170817

- GRB170817A also detected by the Anti-Coincidence Shield for the Spectrometer for **Integral (SPI-ACS)**
  - Conclusive evidence for the **Binary Neutron Star – short GRB connection**
  - **GW–GRB association significance:  $5.3 \sigma$**
- Delayed onset** of gamma-ray emission from a BNS 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

Measured time delay  
between GW and light:  
 $\Delta t = 1.74 \pm 0.05 \text{ s}$

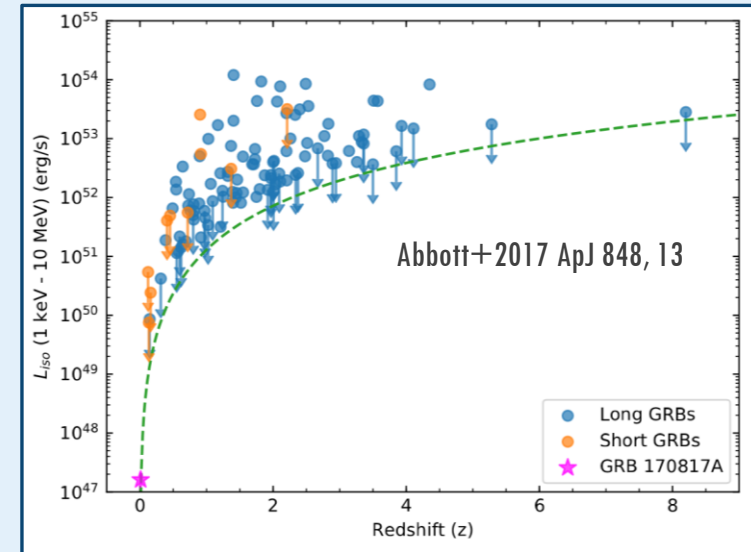


Abbott+2017 ApJ 848, 13

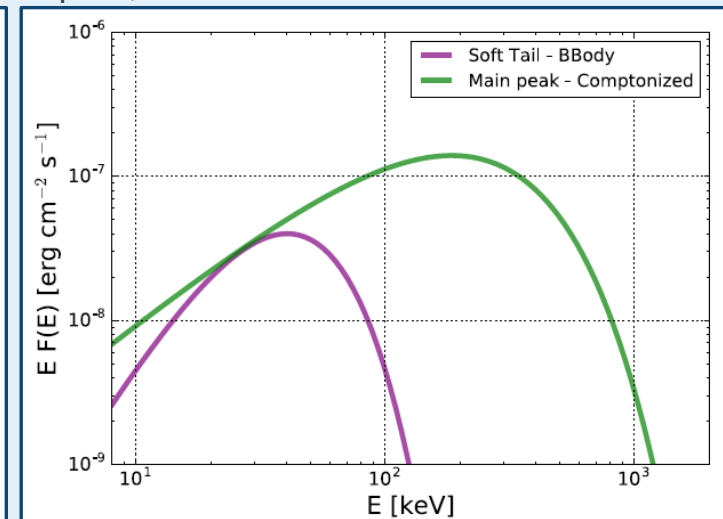
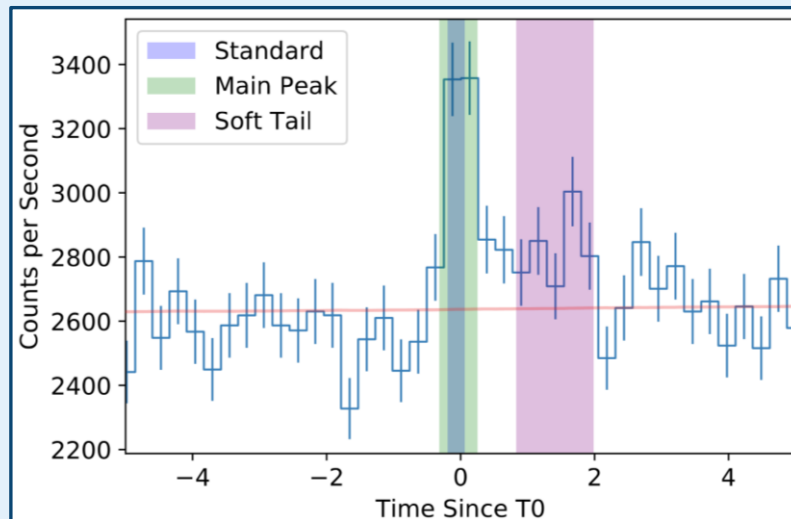
# Fermi-GBM: 9) GRB 170817A and GW170817

## Standard GBM spectral analysis

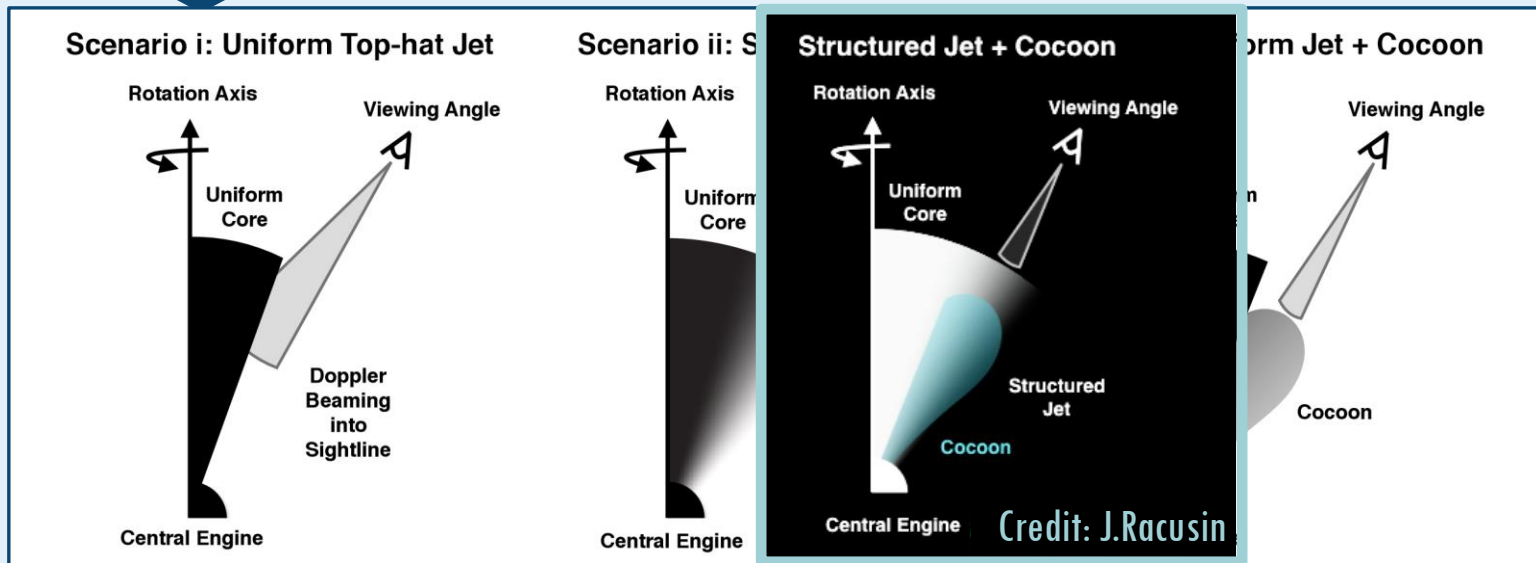
- **Main peak:** typical non-thermal spectrum (peak at  $\sim 200$  keV)
  - **Soft tail:** 10 keV blackbody
- Estimated peak luminosity and isotropic-equivalent energy is  **$\sim 2$ -3 orders of magnitude lower** than previous observations



Goldstein+2017 ApJ 848, 14



# Fermi-GBM: 9) GRB 170817A and GW170817



Abbott+2017 ApJ 848, 13

## Emerging scenario ii/iii: Structured jet + cocoon

- Unlikely to be observing on-axis (down the center of the jet)
- Could be a structured jet with “wings” of shocked material (e.g. Lazzati+ 2018)
- Could be a shock breakout from a “choked” trans-relativistic jet (e.g. Gottlieb+ 2018)

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

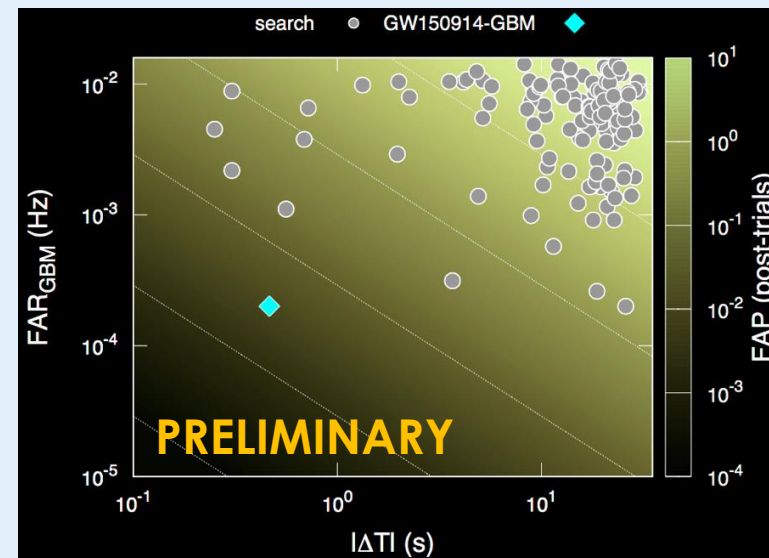
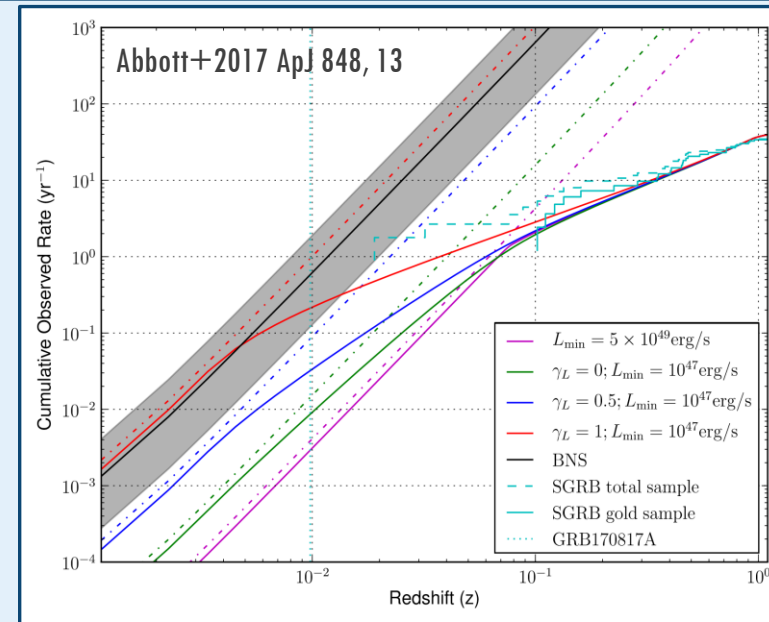
# Fermi-GBM: 9) Future prospects

## Short GRBs at <40 Mpc are rare! Expectations for O3:

- 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 BNS-sGRB/yr

## Current GBM preparation for O3:

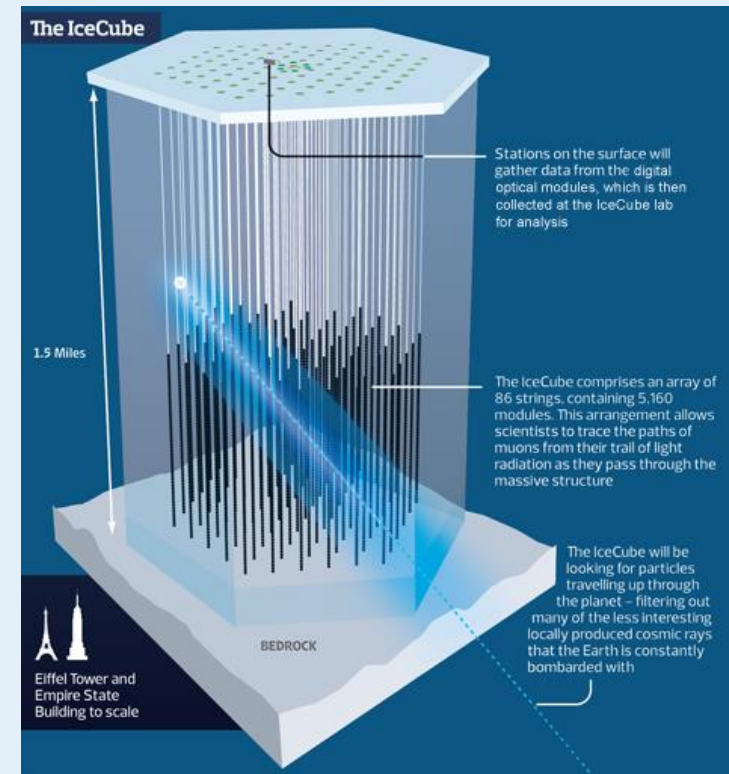
- All-O1 Offline Follow-up Analysis
- Optimization of the targeted search
  - GBM-LVC Joint Result (Littenberg+2018 in prep)



# Fermi-GBM: 10) Follow-up of IceCube neutrino events

- Utilizes **all search methods**:
  - On-board **triggers**
  - **Untargeted** search within the hour
  - **Targeted** search using event time
  - **Earth occultation** technique

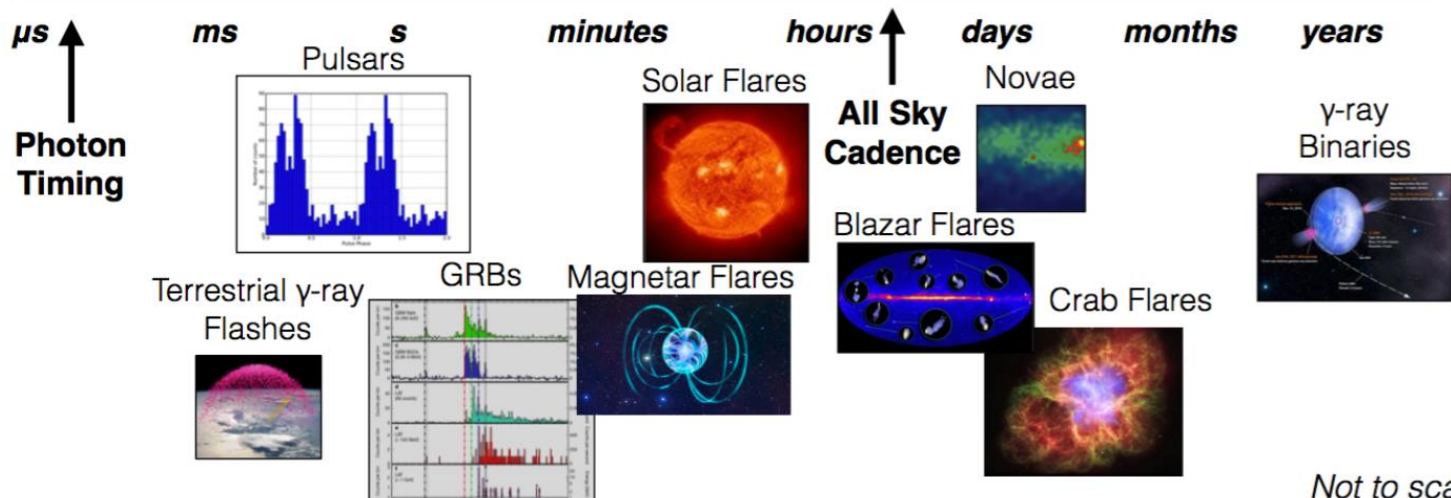
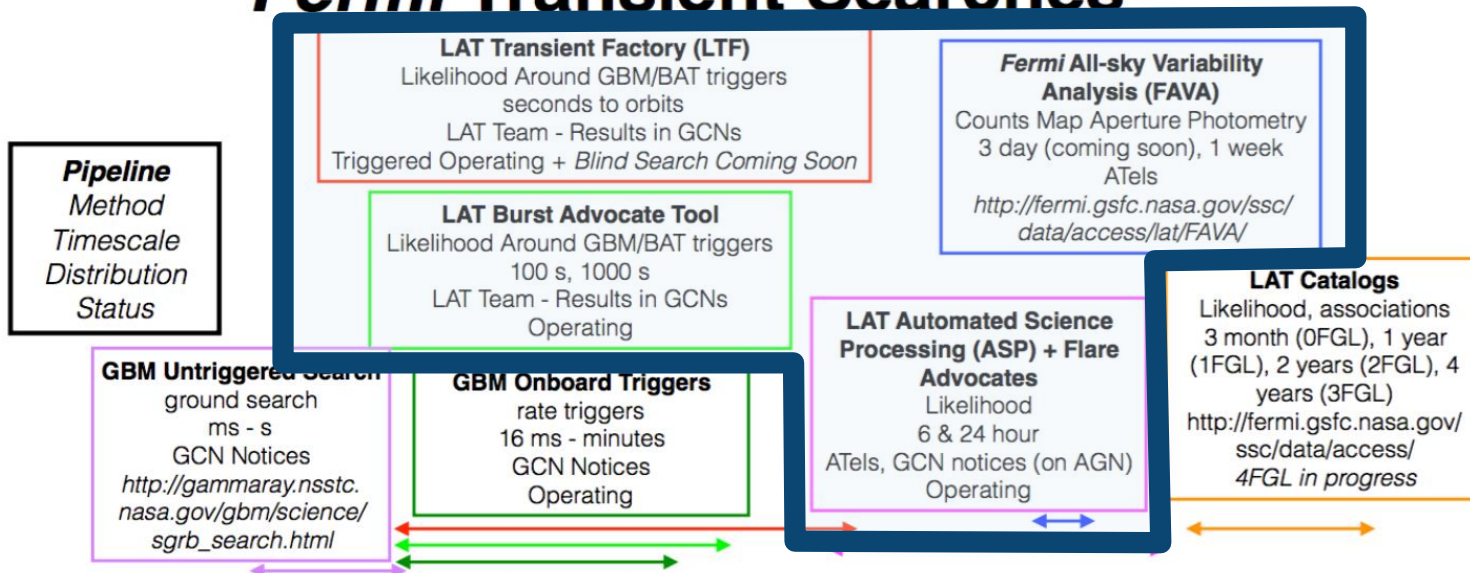
- Good follow-up observation for **IceCube-161103**, upper limit published in **GCN #20127**



- Other follow-up with limited GBM coverage:
  - **IceCube-170321A** (GCN 20932)
- Also can use these techniques to search for counterparts to **Fast Radio Bursts**

## Fermi Transient Searches

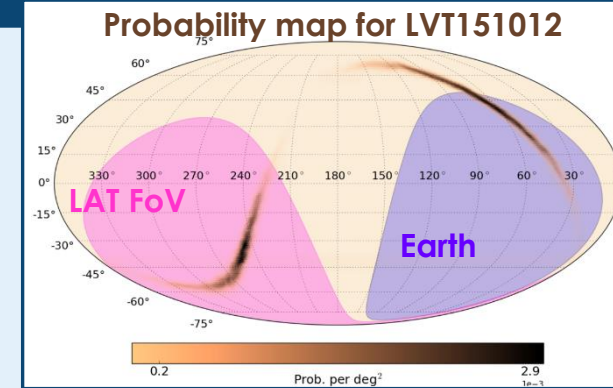
**Pipelines**  
**Timescale**



# Fermi-LAT: 1) GW follow-up

## ■ Fermi-LAT Automated Searches:

- ASP, LAT BA, LAT Transient Factory, and FAVA
- Long baseline search
  - ASP: integration time of 6 hours, 1 day
  - FAVA: integration time of 1 week



## ■ Recent development of **specific searches in the LIGO contours**

- See Ackermann et al. 2016 (GW150915), Racusin et al. 2017 (GW151226, LVT151012), Goldstein et al. 2017 (GW170114), Vianello et al. 2017 (Methods)

### 1. **GW150914:** very bad coverage, search in the time interval from $T_0+4400-4500$ s

- **Fixed** window of 10ks
- **“Adaptive”** time window (entry-exit for each pixel in the interval of 10 days (before and after the trigger).

### 2. **LVT151012 & GW151226:** Much better sky coverage

- Fixed (short) time windows of  $T_0-10$ s,  $T_0+10$ s
- Fixed (long) time windows (8ks for GW151012 and 1.2 ks and 10ks for GW151226)
- “Adaptive” time windows, as defined above

No significant excess detected → **Upper Limits calculations**

# Fermi-LAT: 2) The unlucky case of GW170817

## Sky coverage: LAT was off, due to SAA

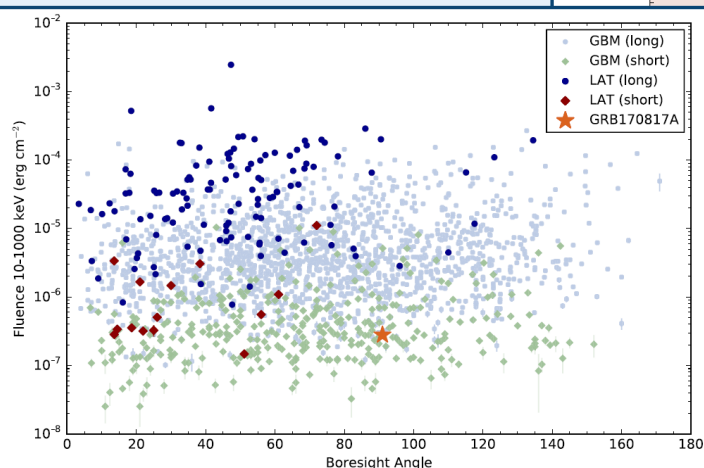
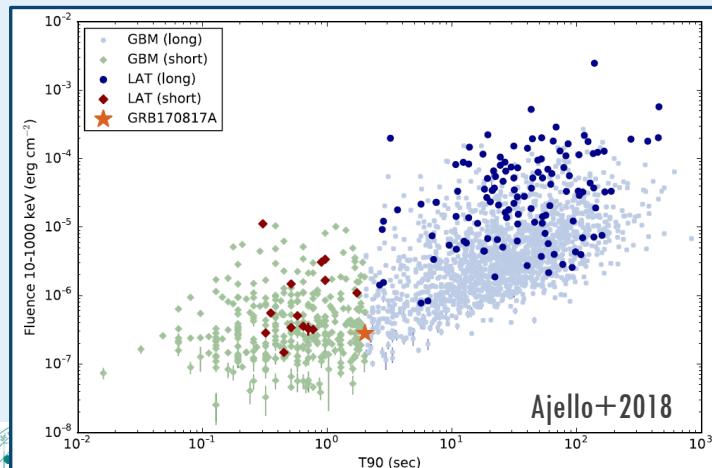
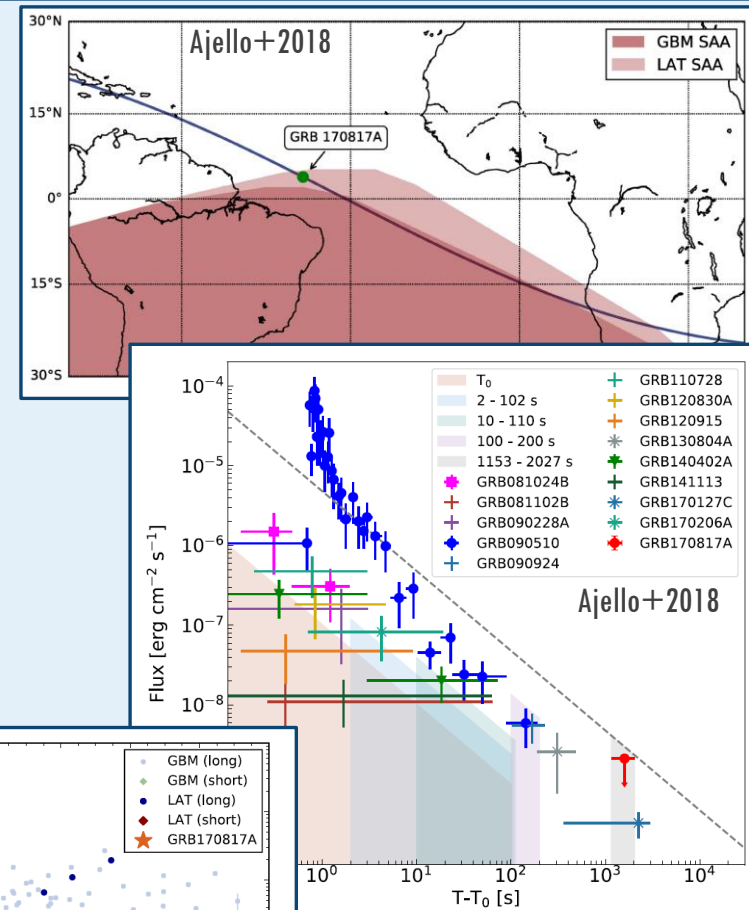
- LAT SAA slightly larger than GBM (14%)
- LAT observations of the entire region  $t_{\text{GW}} + [1153 - 2017]$ . Flux upper bound (0.1–1 GeV)

$$F < 4.5 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$$

- Five orders of magnitude less luminous than GRB090510 (only LAT sGRB with redshift)

➔ BUT: LAT has detected **14 sGRBs** with durations shorter than GRB 170817A, eight with comparably low fluence!

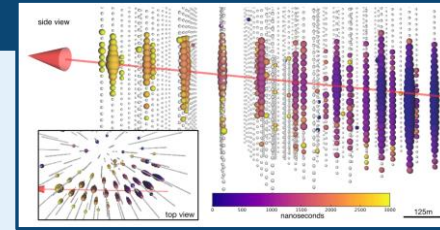
- LAT can detect fainter sGRBs **the earlier the observation starts!**



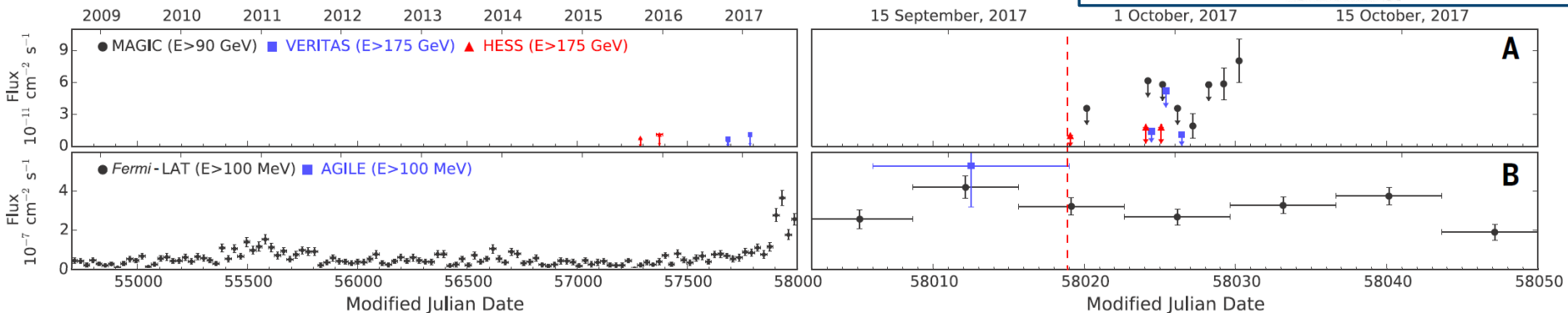
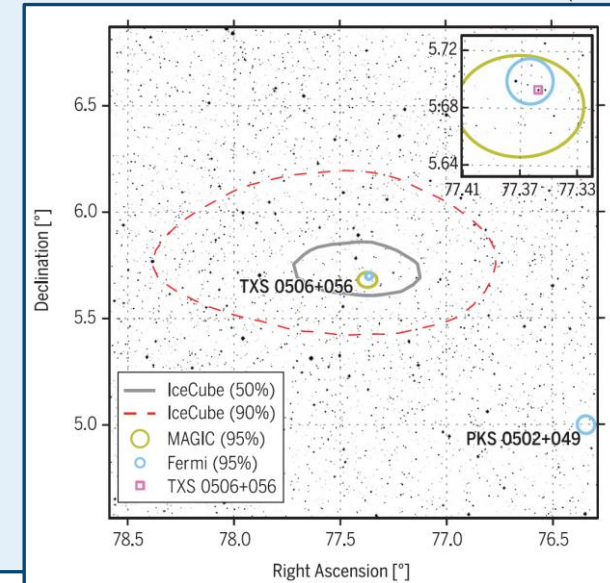
# Fermi-LAT: 3) Observation of IC170922A

## The IceCube-170922A neutrino

- Arrived in a period of **flaring activity** (high-emission state) in high-energy gamma-rays of the very luminous blazar TXS 0506+056 detected by **Fermi-LAT** and **MAGIC**
  - Most probable neutrino energy: 290 TeV (>183 TeV)
  - Signalness (probability of astrophysical origin) reported to be 56.5 %
- **Correlation** of the neutrino with the flare of TXS 0506+056 is statistically significant at the **3 sigma** level



The IceCube Collaboration et al., Science 361, eaat1378 (2018)



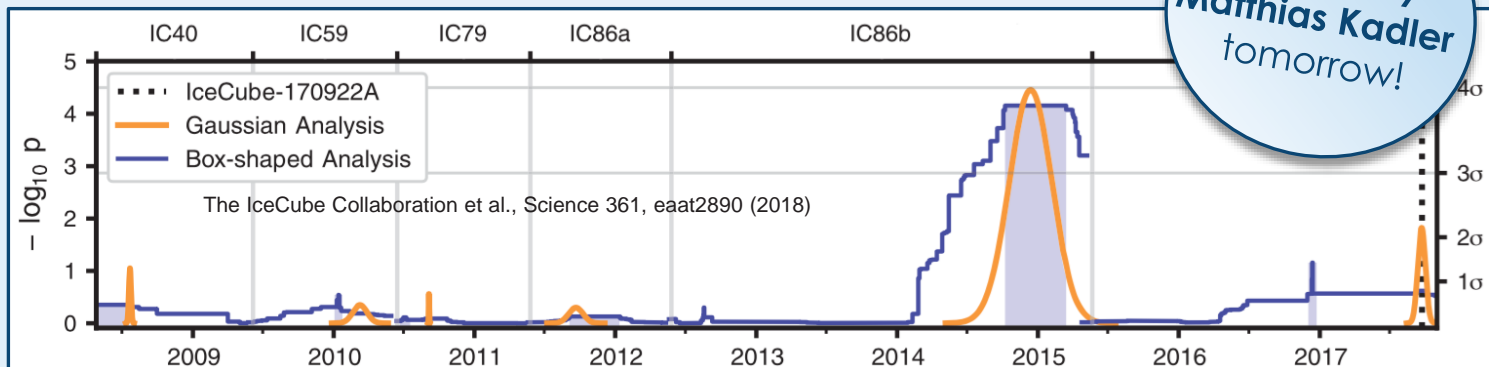
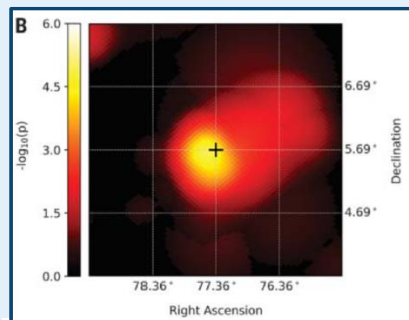
# Fermi-LAT: 3) Observation of IC170922A

## The 3-months neutrino “flare” in 2014/2015

- IceCube **archival search** finds a compelling evidence for a **3.5 sigma excess** ( $13 \pm 5$  events) positionally consistent with the same blazar
- **No Fermi-LAT flare observed** in coincidence with this excess
  - Gamma-ray lightcurve consistent with a **quiescent state**, with an average flux lower than in 3FGL. No significant evidence of hardening
  - Neutrino luminosity is 5 times larger than the gamma-ray luminosity.
- **Open questions:**
  - Which models can explain the MW data?
  - How does the IC170922A fit together with the 2014/15 neutrino excess without coincident EM activity?

➔ **Further observations needed!**

See talk by  
Matthias Kadler  
tomorrow!



# Conclusions

With the combined studies of gamma-ray transients / variable sources / gravitational wave events / neutrino events we are definitely entering the **Multi-Messenger astronomy Era**

**Fermi-GBM** and **Fermi-LAT** celebrated their 10th anniversary in space, and have proven to be FUNDAMENTAL instruments in unveiling the high-energy sky

- **GBM** is an **efficient** detector of counterparts to GWs
  - No pointed observations required, **continuously** observing **large fraction** (~67%) of the sky (~15% downtime)

The GBM and LAT Teams are looking forward to make many more key discoveries in the coming years!

Thank  
You!