Time Domain Astronomy with the Fermi Gamma-ray Burst Monitor in the Multimessenger Era

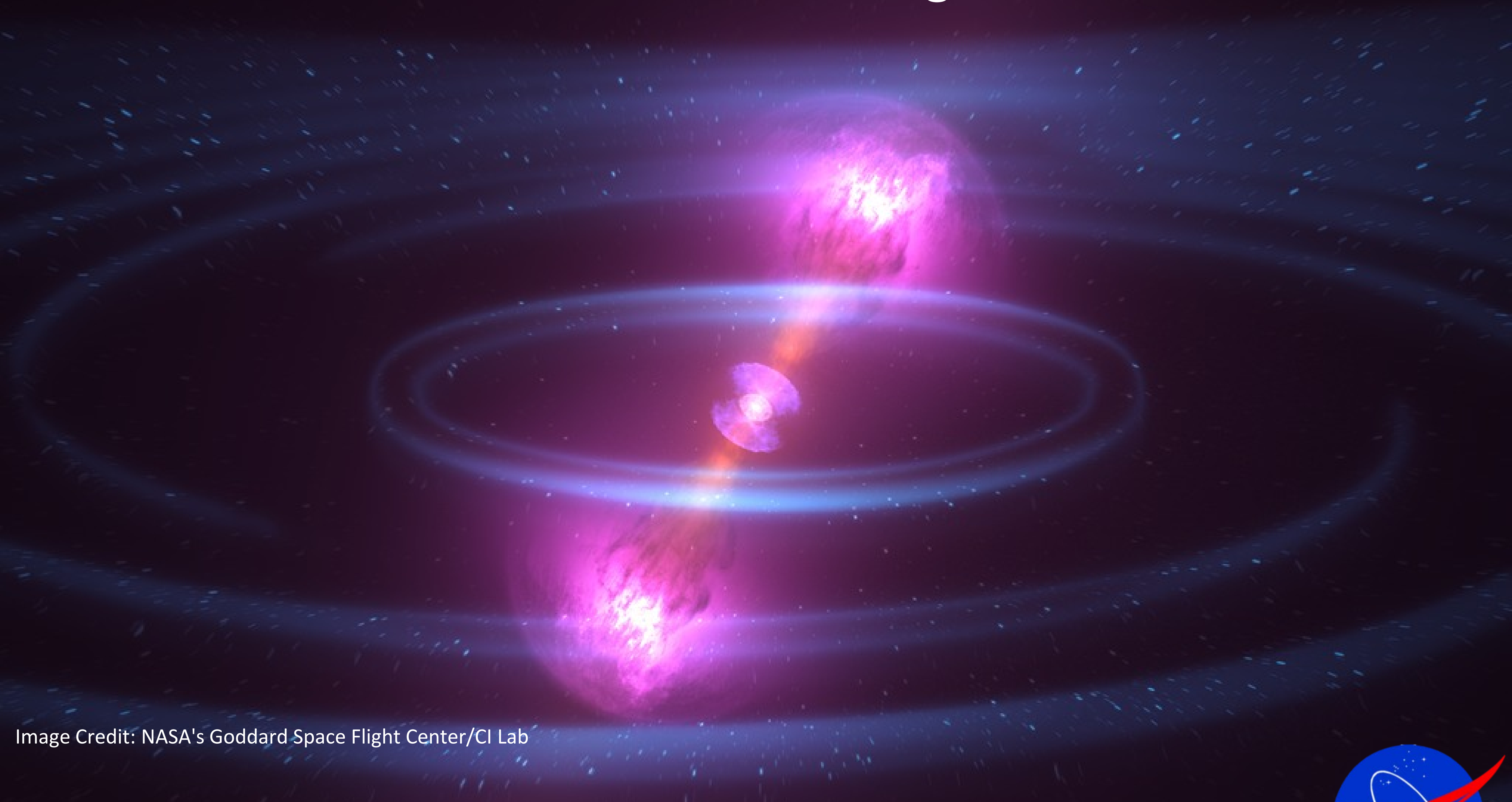


Image Credit: NASA's Goddard Space Flight Center/CI Lab

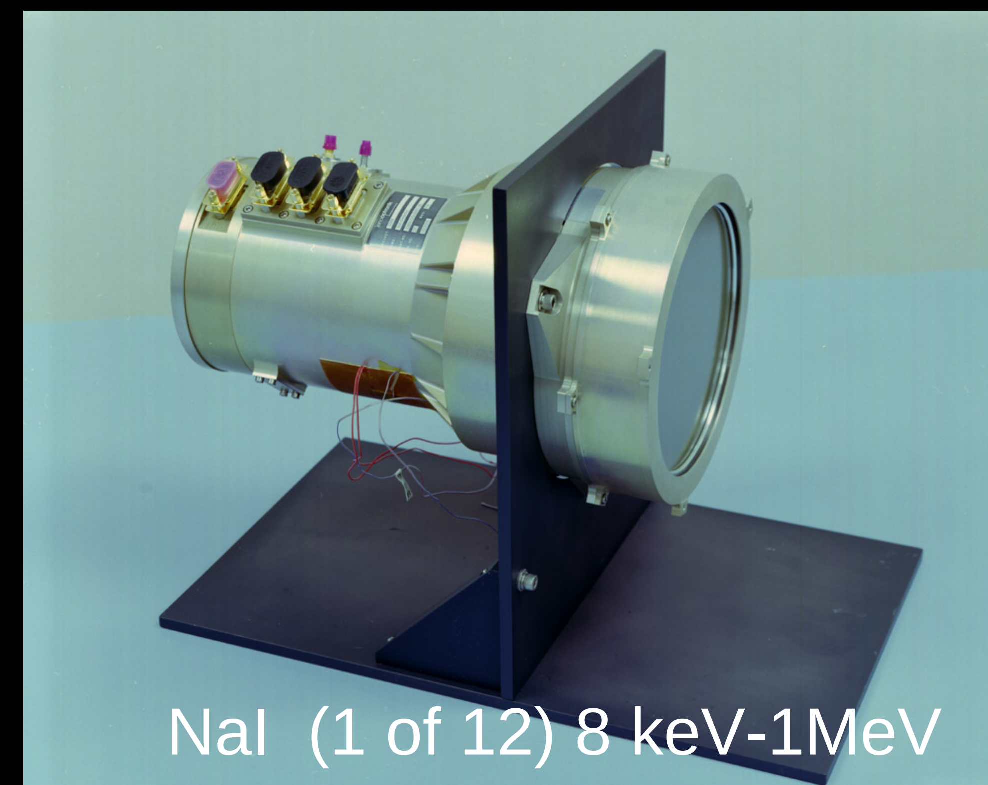
Colleen A. Wilson-Hodge (NASA/MSFC)

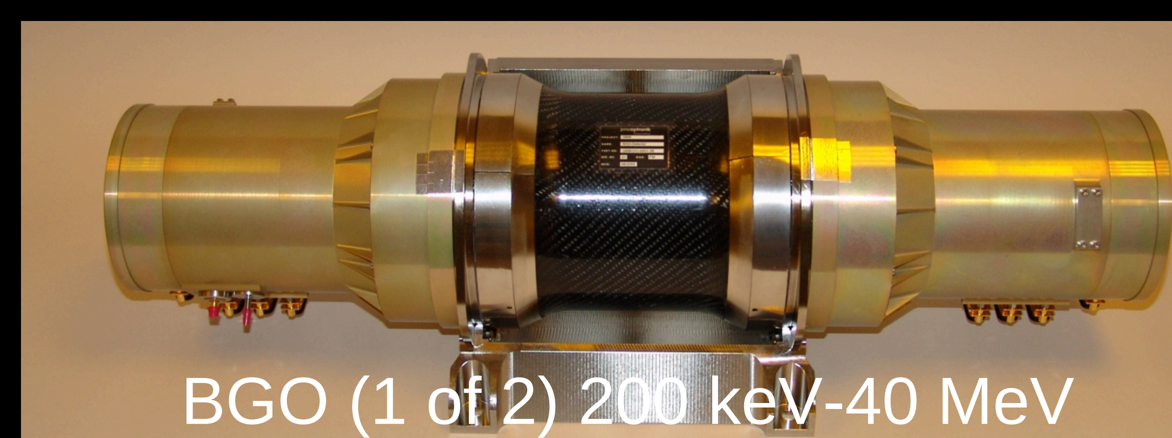
Outline

- Introduction
  - Fermi Gamma-ray Burst Monitor (GBM)
  - Gamma-ray Bursts (GRBs)
- GRB 170817A – GBM's most famous GRB
  - Gamma-ray Observations
  - Timeline of multimessenger observations
  - Implications for GRB models
  - Similar events observed with GBM
- Highlights from non-GRB transient sources observed with Fermi GBM
  - Crab Nebula
  - Swift J0243.6+6124

The Fermi Gamma ray Space Telescope

Gamma ray Burst Monitor (GBM)

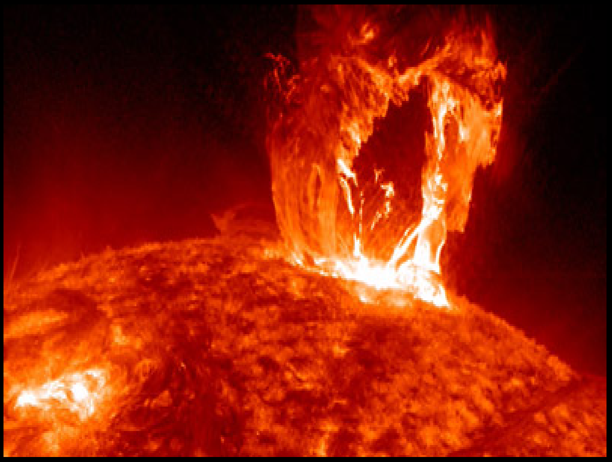


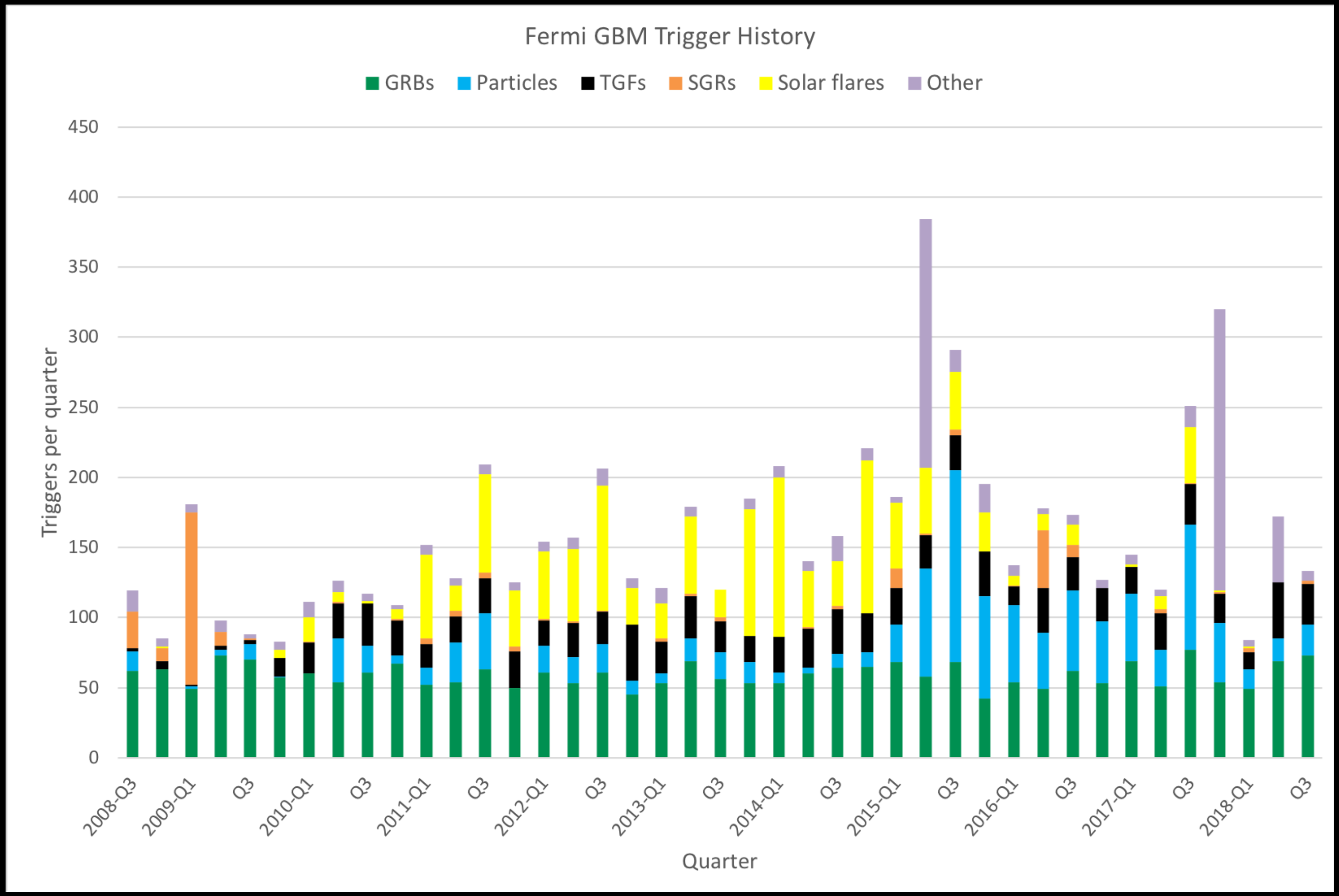


6222 Fermi GBM triggers

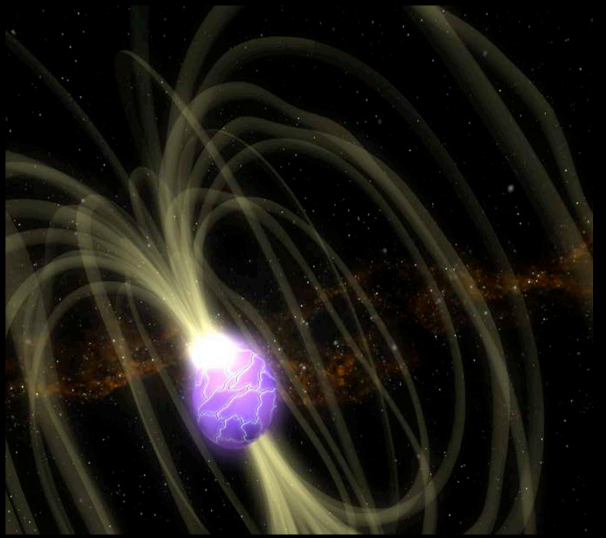
2238 GRBs

1176 Solar Flares





275 Magnetars



875 TGFs

- 668 Others:
- 189 from Swift J0243.6+6124 and 169 from V404 Cyg;
- 1041 particles

What is a gamma-ray burst?

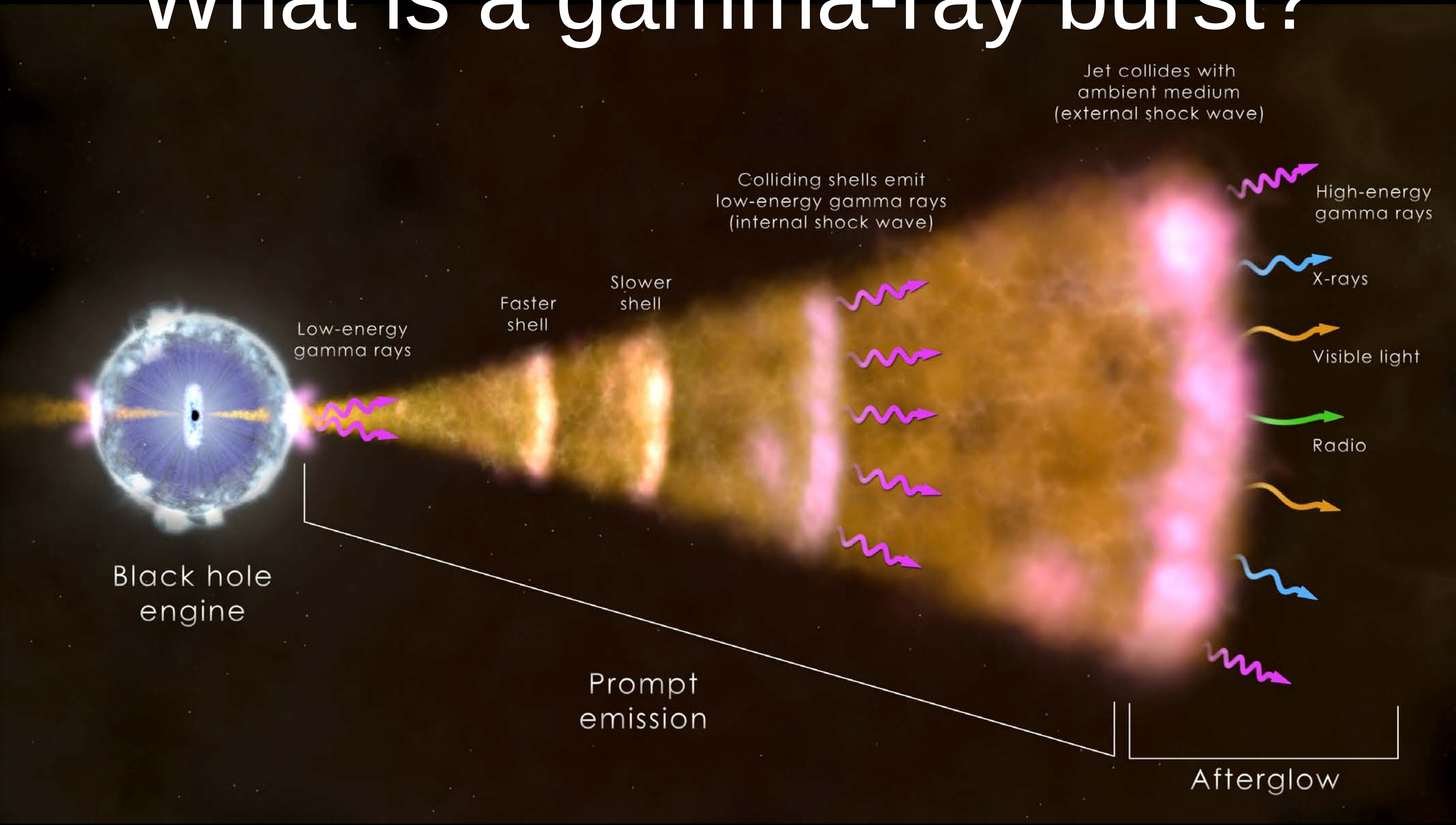
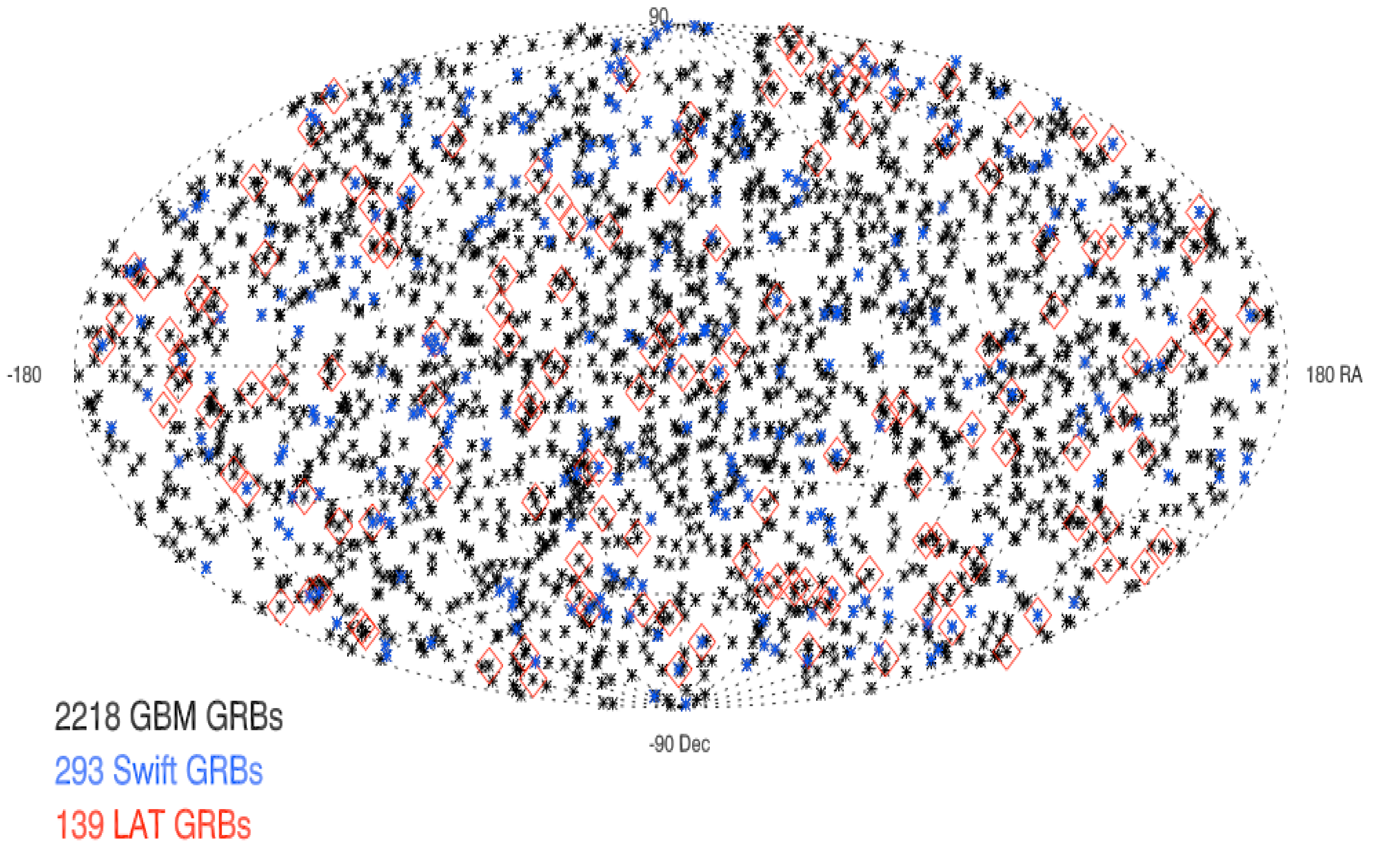


Image credit: NASA/GSFC

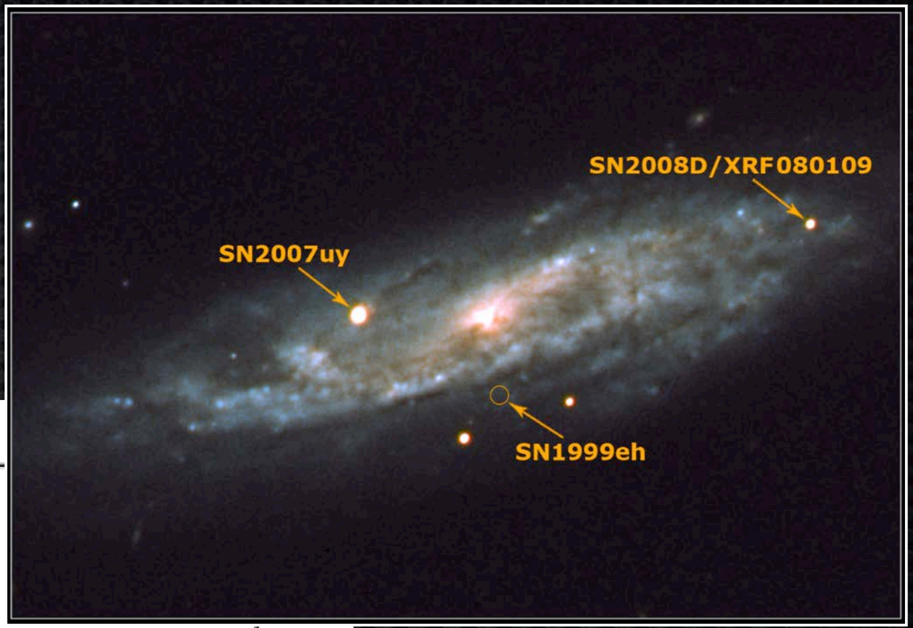
GBM Triggered GRBs

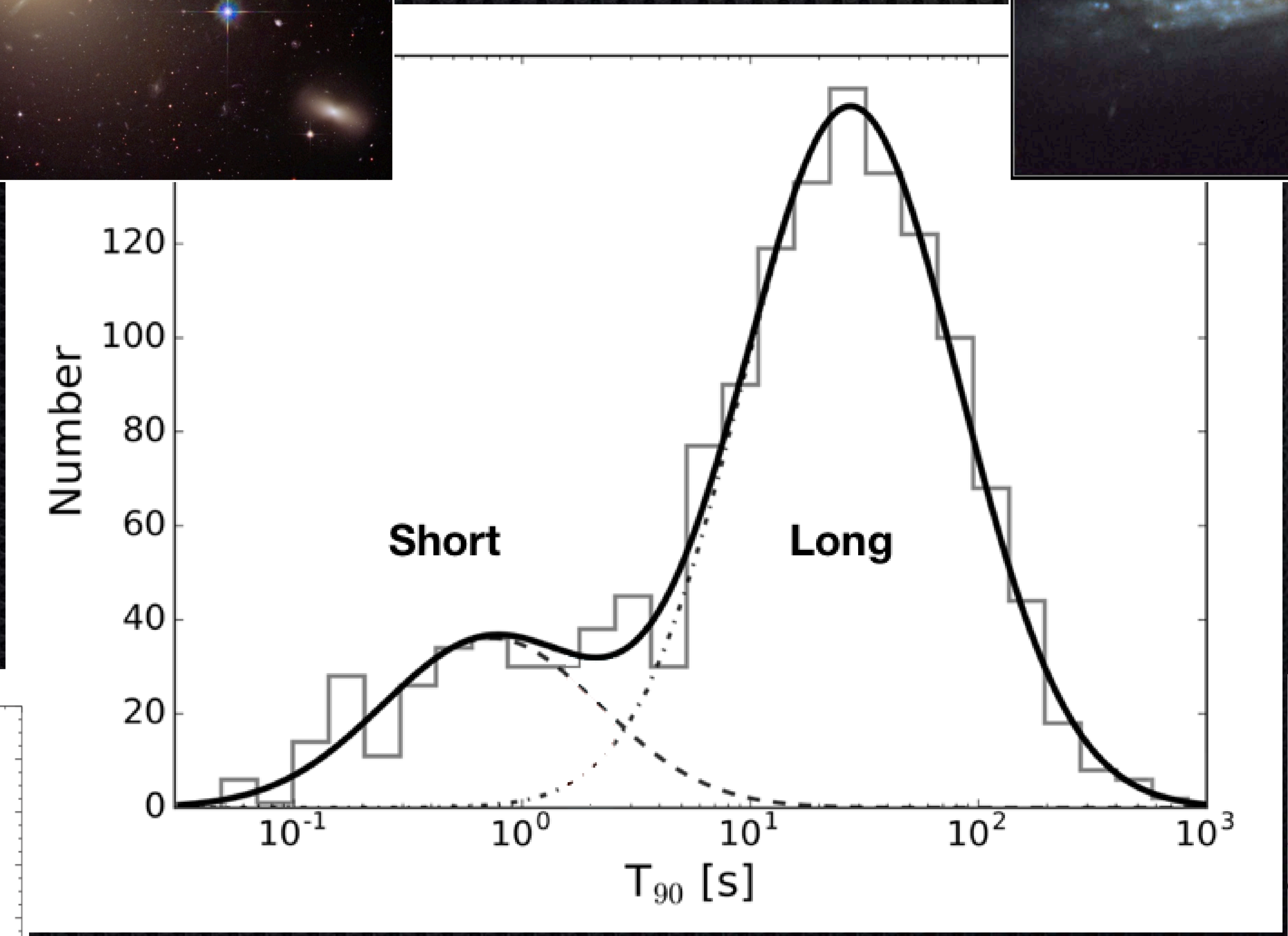


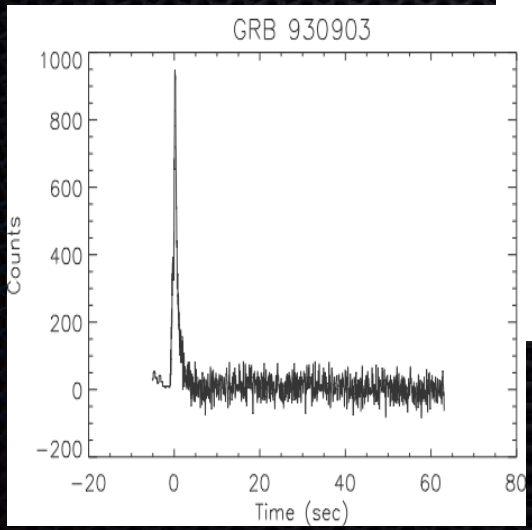
Types of GRBs

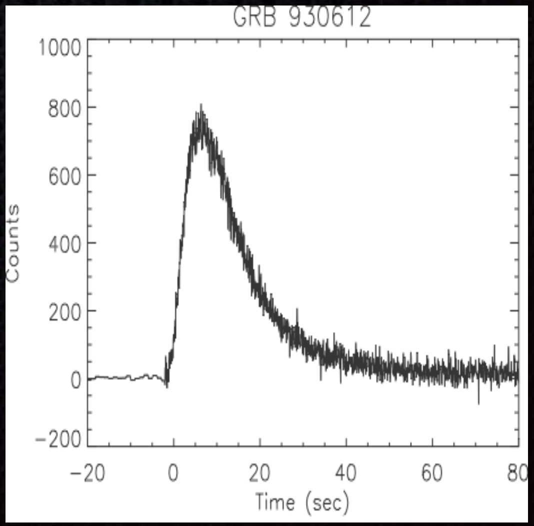
Early-type galaxies

Late-type galaxies









GBM Partnership With LIGO/Virgo

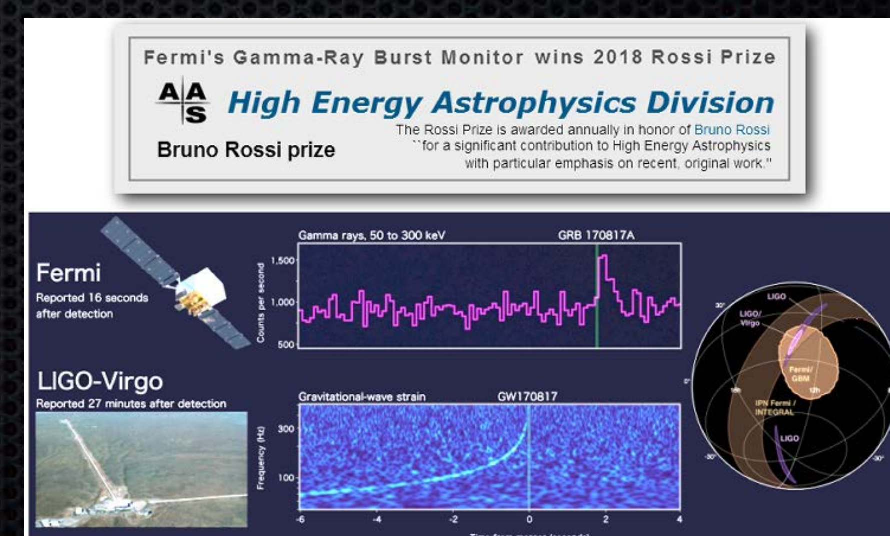
- GBM-LIGO MoU allows for a unique data sharing agreement
- GBM provides sub-threshold GRBs in low-latency for GW follow-up
- LIGO provide “sub-threshold” GW candidates below EM Follow-up threshold
  - In low-latency for autonomous targeted (seeded) GRB follow-up
- GBM detections would provide increased confidence in weak GW detections, effectively increasing the volume of the Universe accessible to LIGO/Virgo

The morning of August 17, 2017

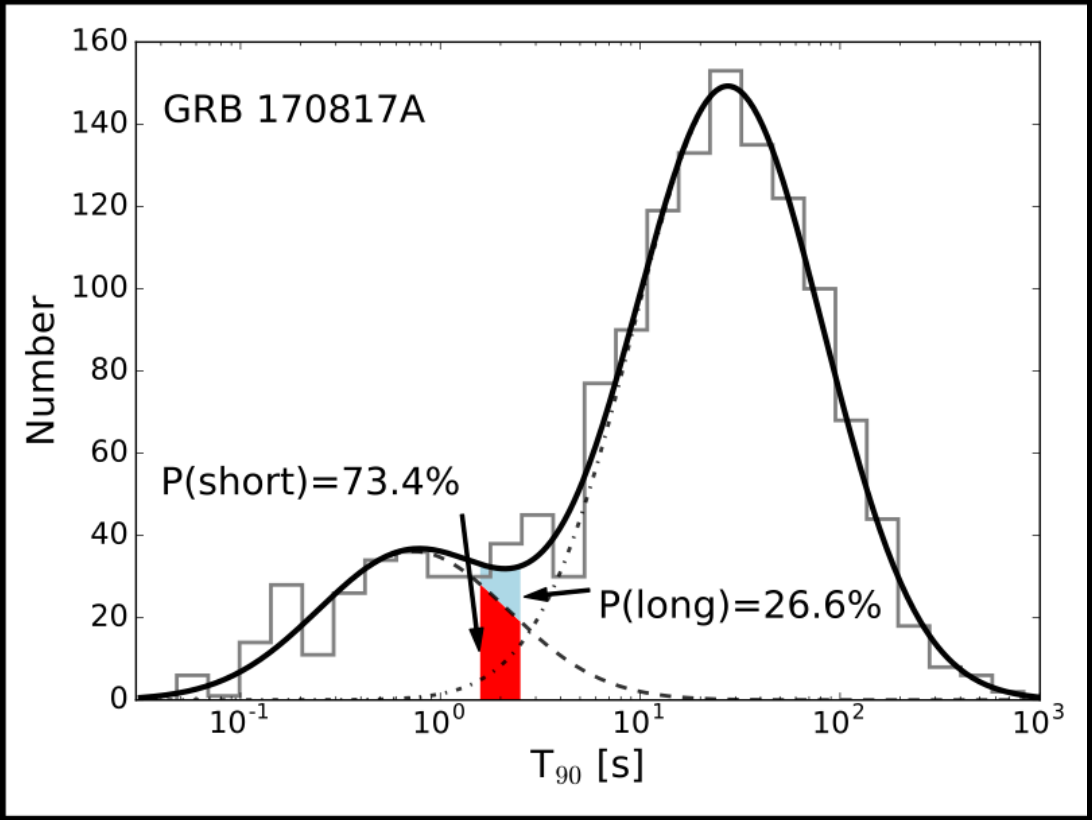
Video and image Credit: NASA GSFC, Caltech/MIT/LIGO Lab and E

GRB 170817A

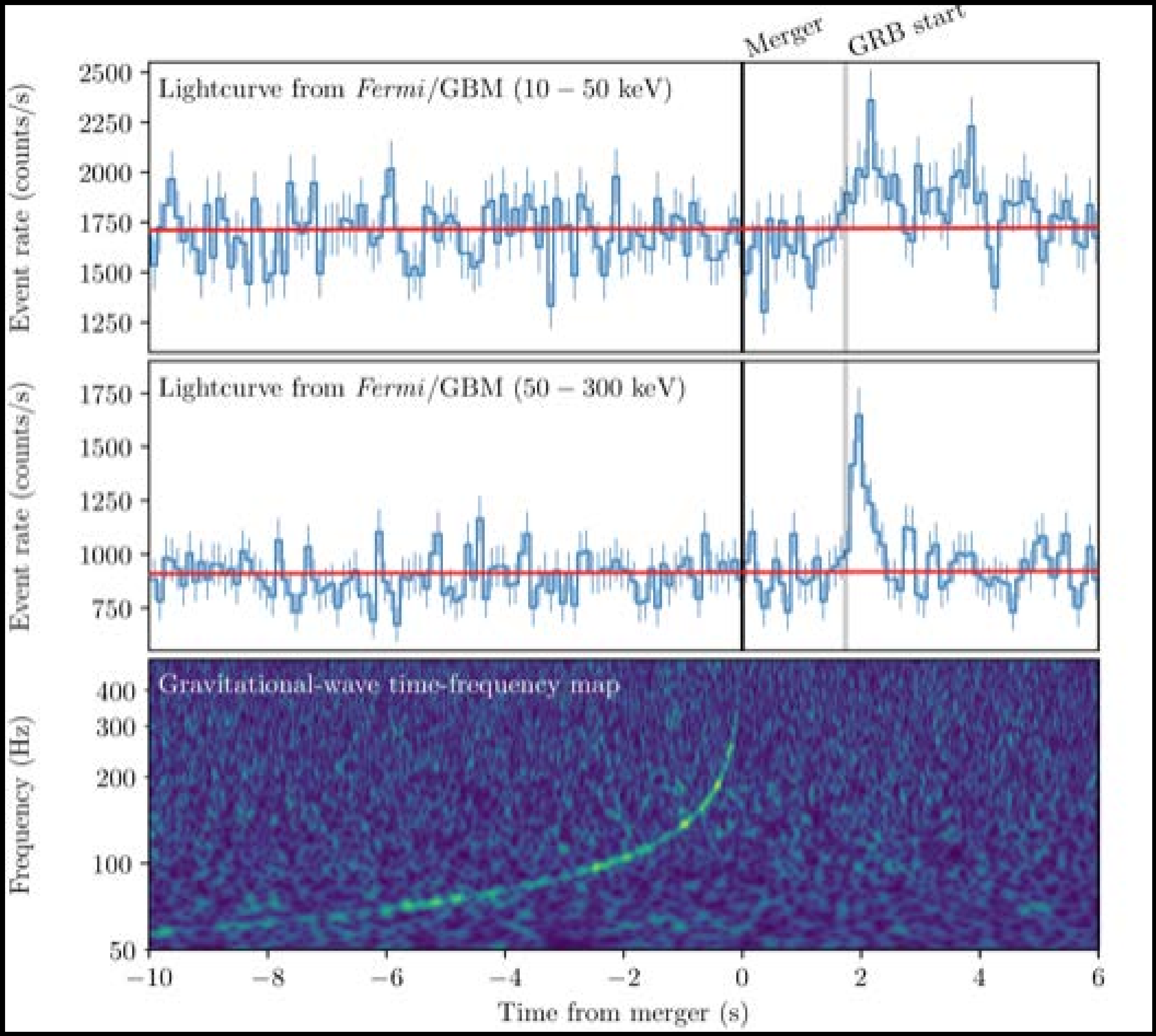
- >80 papers coordinated for release
  - >3500 Authors, >900 Institutions
- GBM Team paper (Goldstein et al. 2017)
  - Summarized GBM observations
- Joint GBM/LIGO paper (Abbot et al. 2017)
  - Focused on joint EM-GW science
  - GRB theory, Speed of gravity, NES
- The detection was named the 2017 breakthrough of the year by Science
- Colleen Wilson-Hodge and the GBM team received the AAS 2018 Rossi price for the work
- Interesting questions remain about this event!



A weak short GRB with a low-energy tail

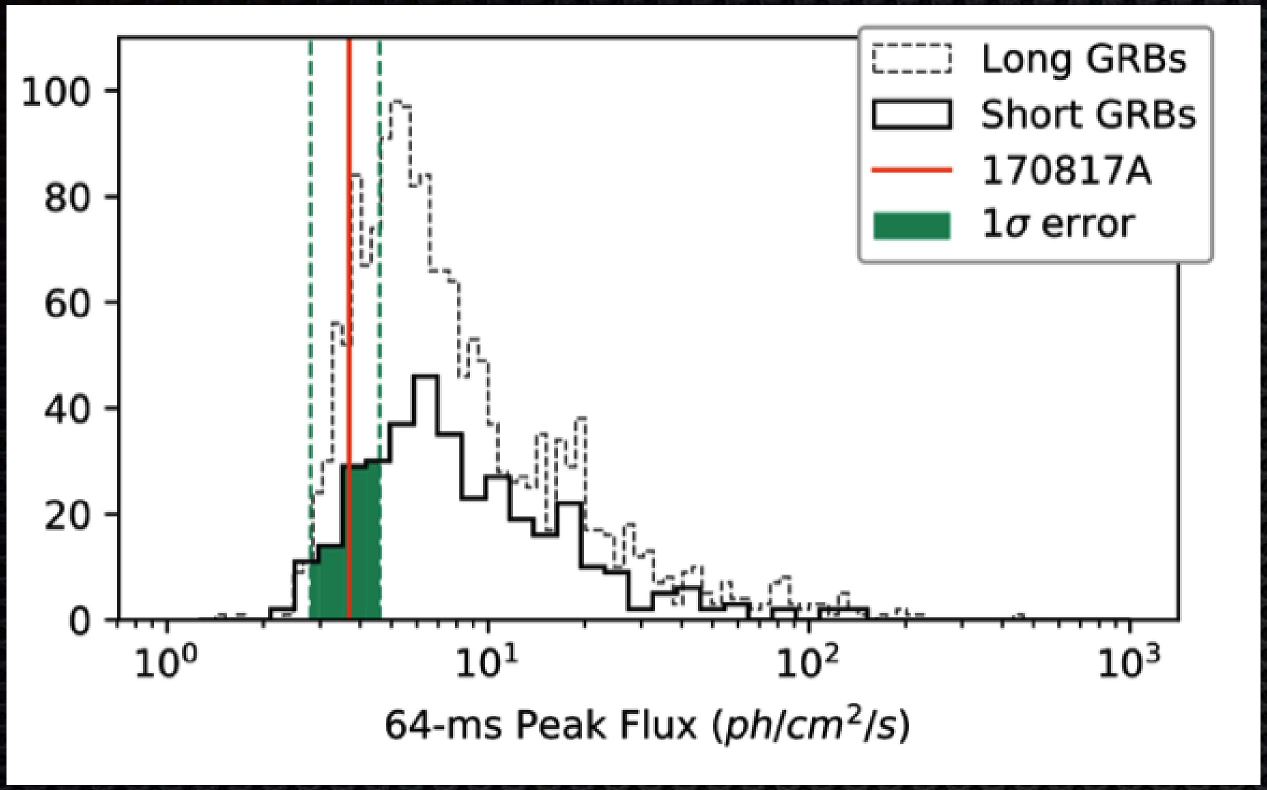


- GRB 170817A is a short GRB—predicted to originate from mergers
- It appears to have the traditional “spike” but also a weak lower-energy tail
- It appears intrinsically less luminous than any other GRB with measured distance

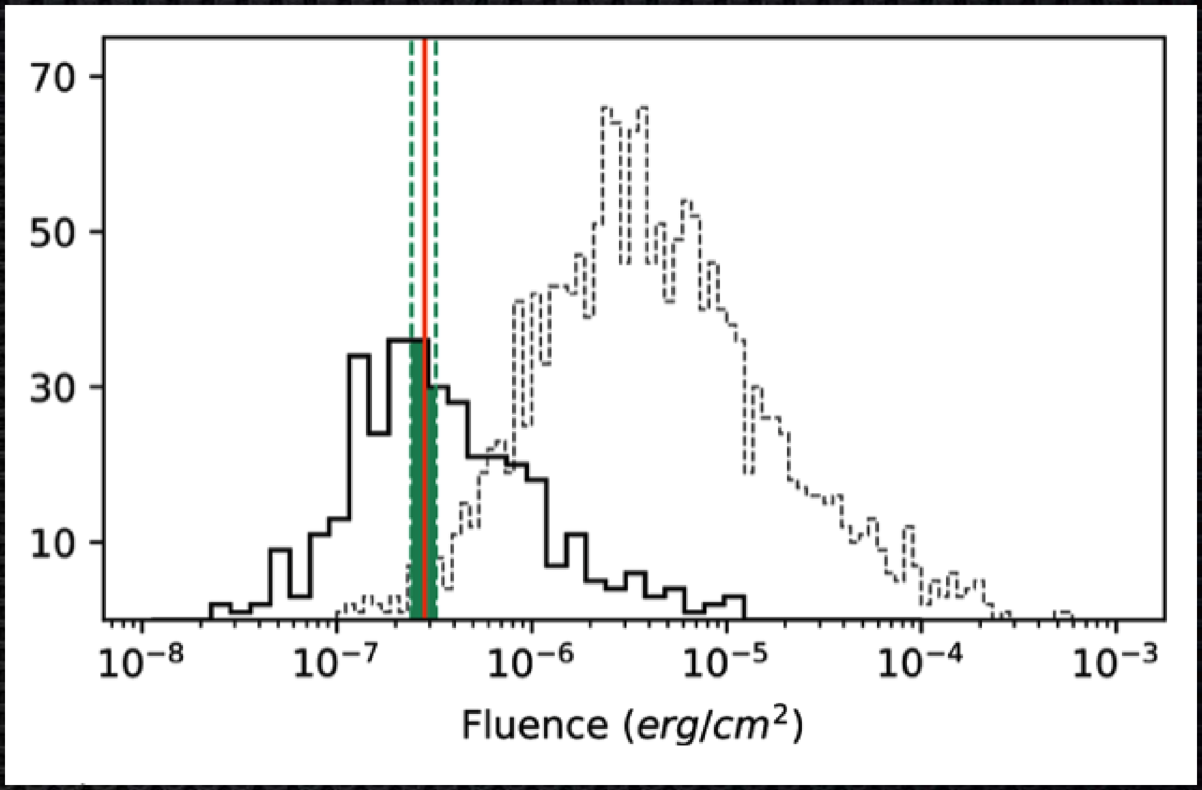


Goldstein et al. 2017, ApJ, 848, L14; Abbot et al. 2017, ApJ, 848, L13

Spectral Properties



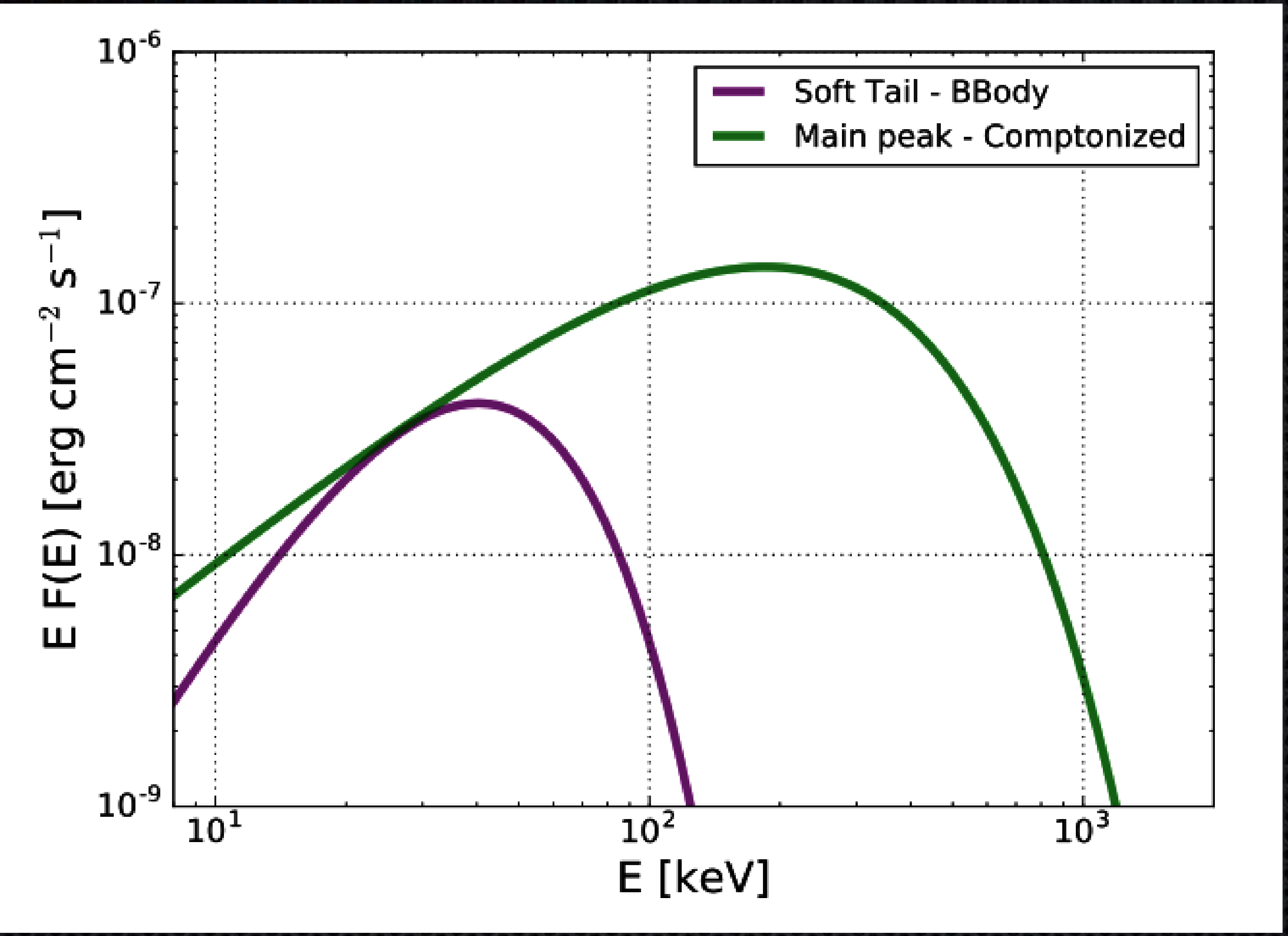
Goldstein et al. 2017

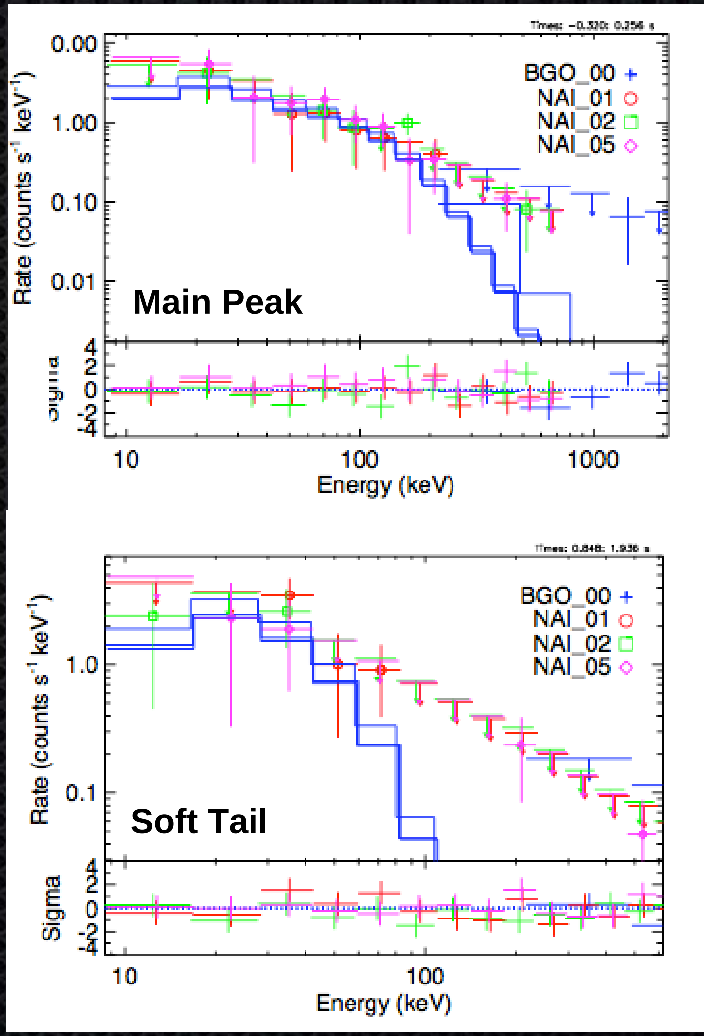


Goldstein et al. 2017

- Using the standard GBM catalog analysis, GRB 170817 does not look particularly unique
- Average fluence for a short GRB compared to the catalog distribution
- Relatively weak in peak flux
  - In the lower third in the 64ms peak flux distribution
- It appears as a typical SGRB in the observer frame

Spectral Properties

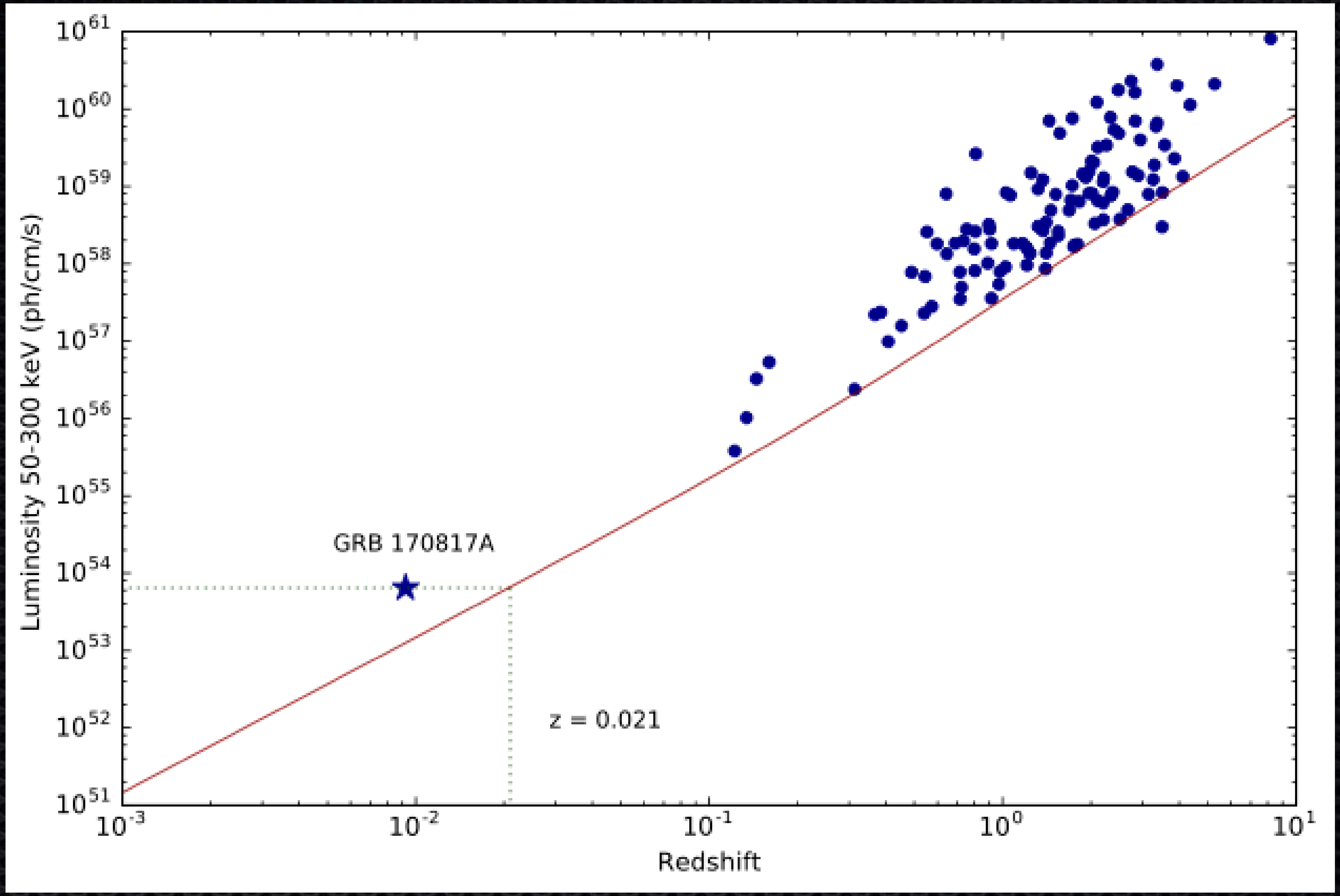




Goldstein et al. 2017

- The main hard peak is best fit with a Comptonized model with E_{pk} = 185 ± 62 keV
- The soft tail is best fit by a black body with kT = 10.3 ± 1.5 keV
- Spectra with photospheric components have been seen (e.g. Ryde, Guiriec, etc), but not in this order

Source Frame Energetics



- GRB 170817 was extremely under luminous compared to other GRBs
  - It was the closest and least luminous GRB ever detected
- Estimated isotropic-equivalent energy is ~2-3 orders of magnitude lower than previous observations
- This observations combined with the late-time emission hints at the viewing geometry

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//////////////////////////////////////////////////////////////////////
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/quicklook/g
lg_lc_medres34_bn170817529.gif
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.
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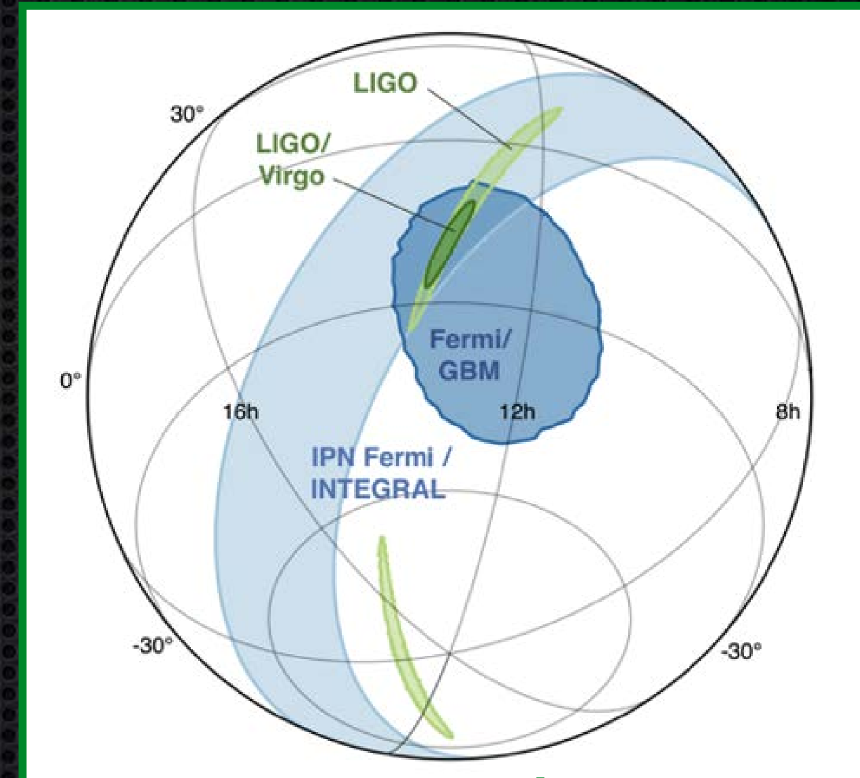


GBM Alert

First On-board GBM Localization

LIGO Report of coincident GW/GRB

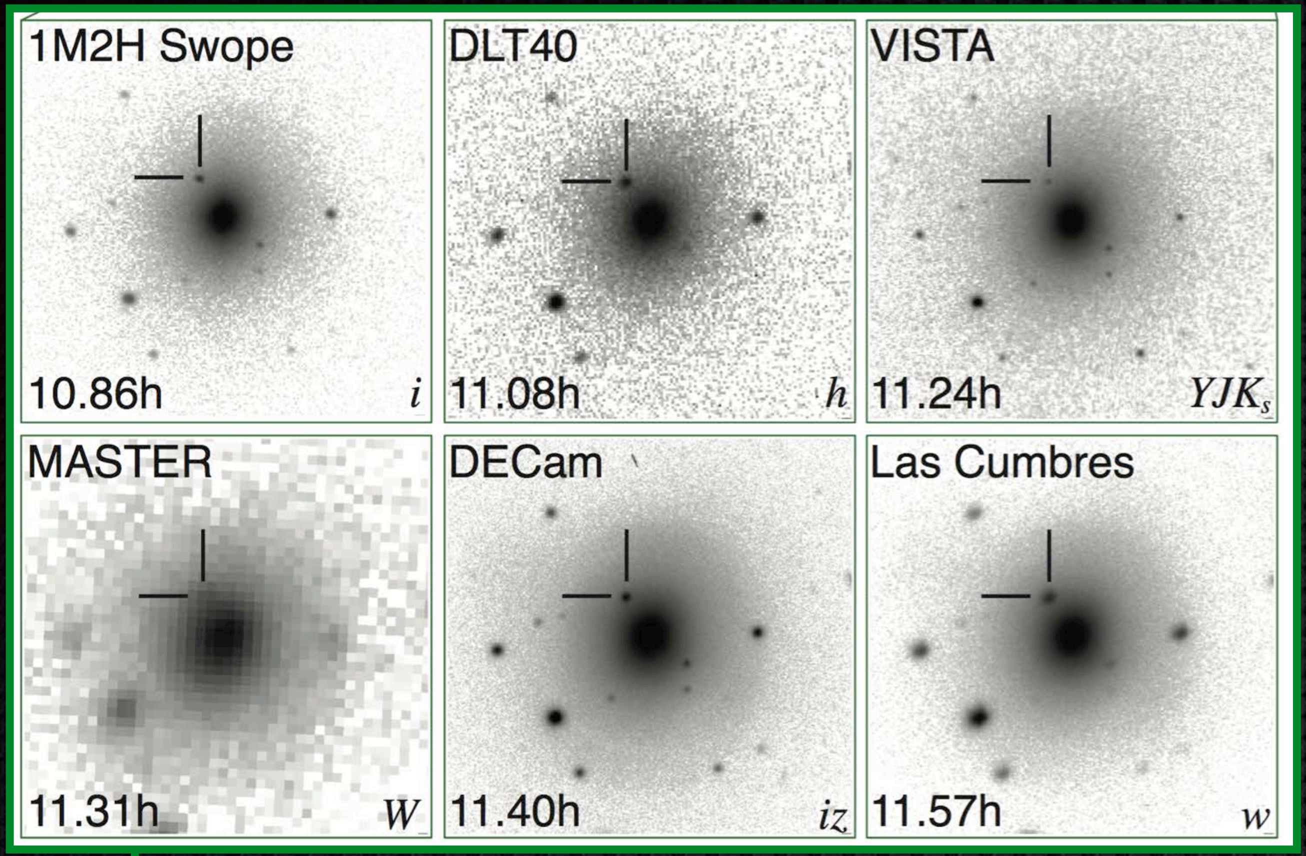
Joint LIGO/Virgo sky map

+16 s

+27 s

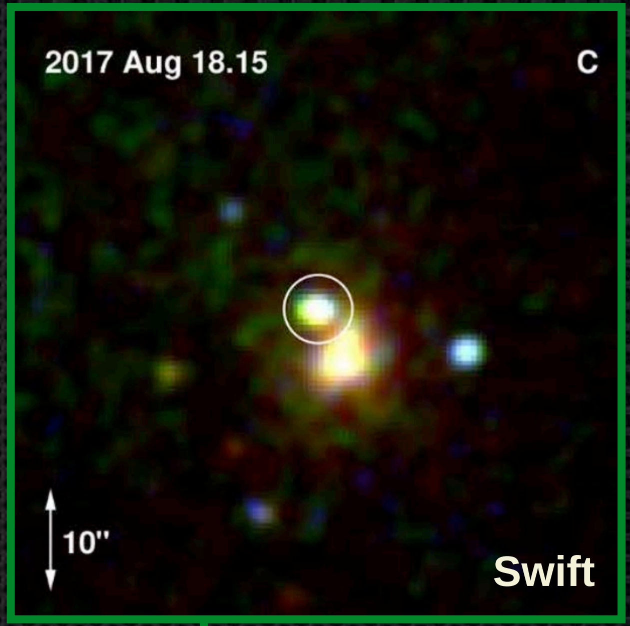
+45 min

+5 hour



Reports of a blue optical transient near an elliptical S0 type galaxy NGC 4993 at ~40 Mpc (Abbot et al. 2017).

Discovery credit goes to Coulter et al. (2017) who observed the region with the 1m Swope telescope at Las Campaas Observatory



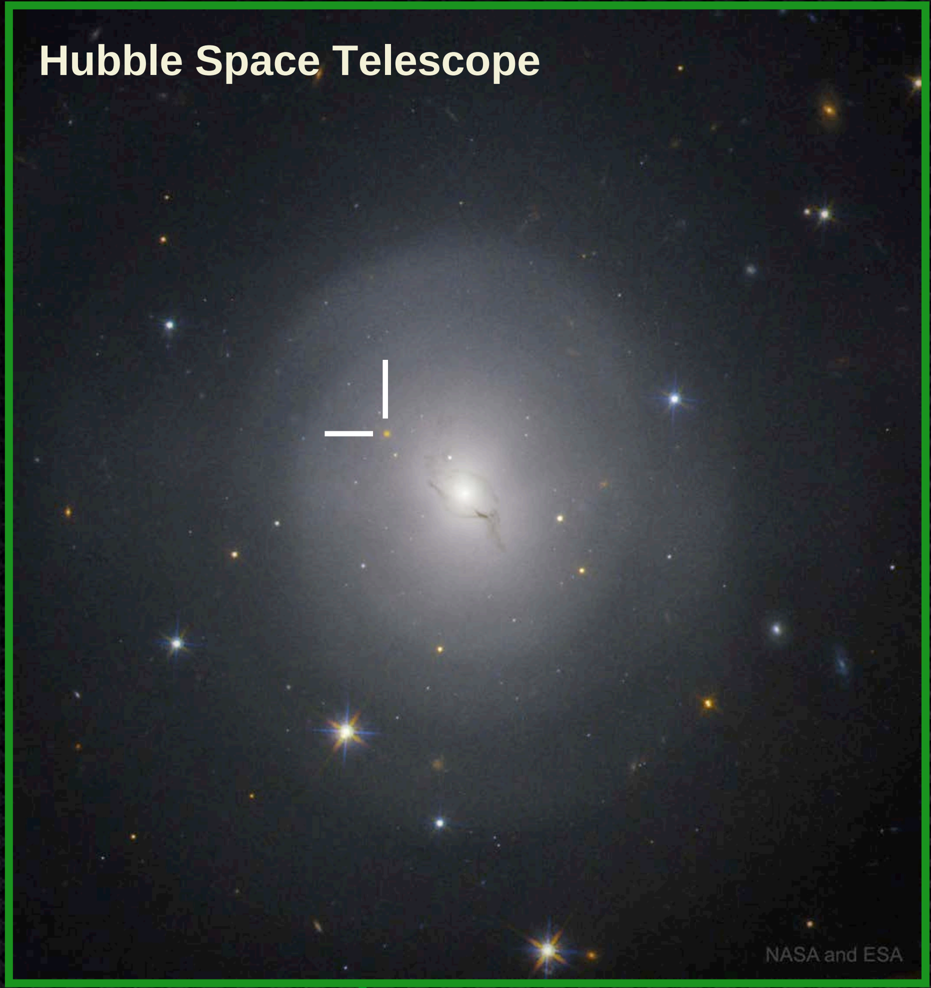
Swift observations reveal bright, but quickly fading, UV source with no evidence of X-ray emission (Evans et al. 2017)

NuStar observations show no X-ray emission (Evans et al. 2017)

+12 hours

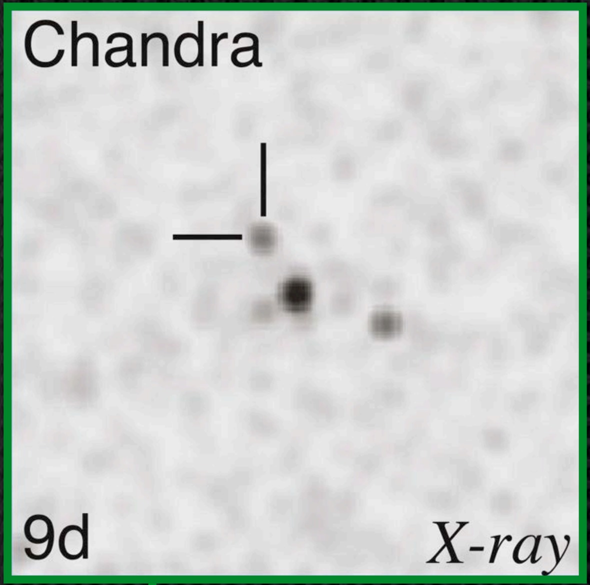
+13 hours

+14 hours

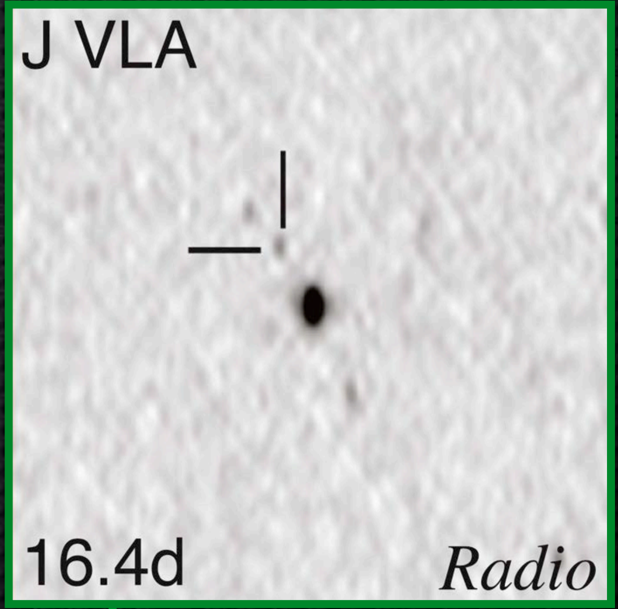


Chandra observations show no X-ray emission (Fong et al. 2017)

Hubble observations reveal a reddening source (Adams et al. 2017)



Chandra observations reveal first evidence of delayed X-ray emission (Troja et al. 2017)



Radio counterpart reported by VLA (Mooley et al. 2017)

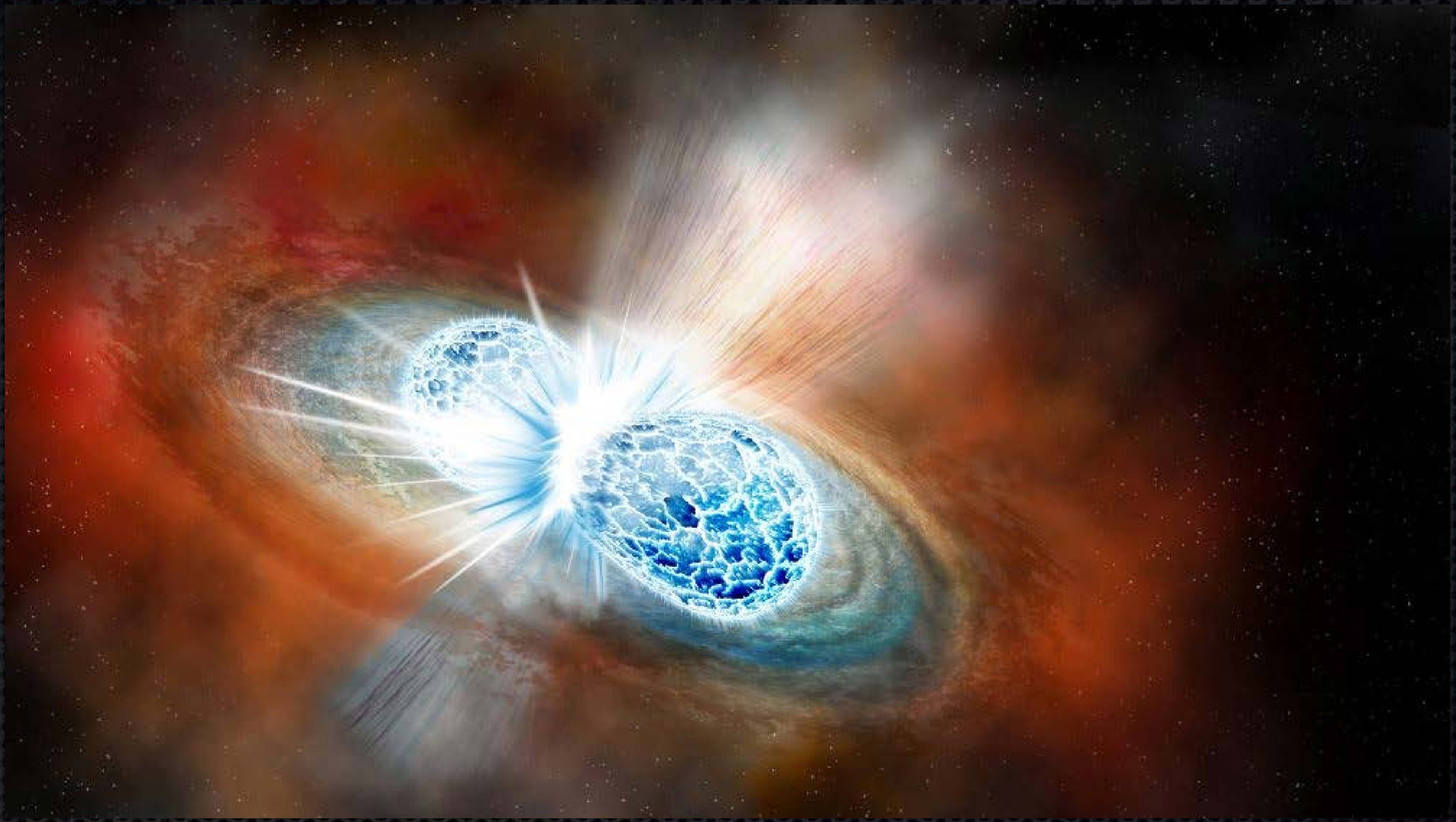
+2 days

+5 days

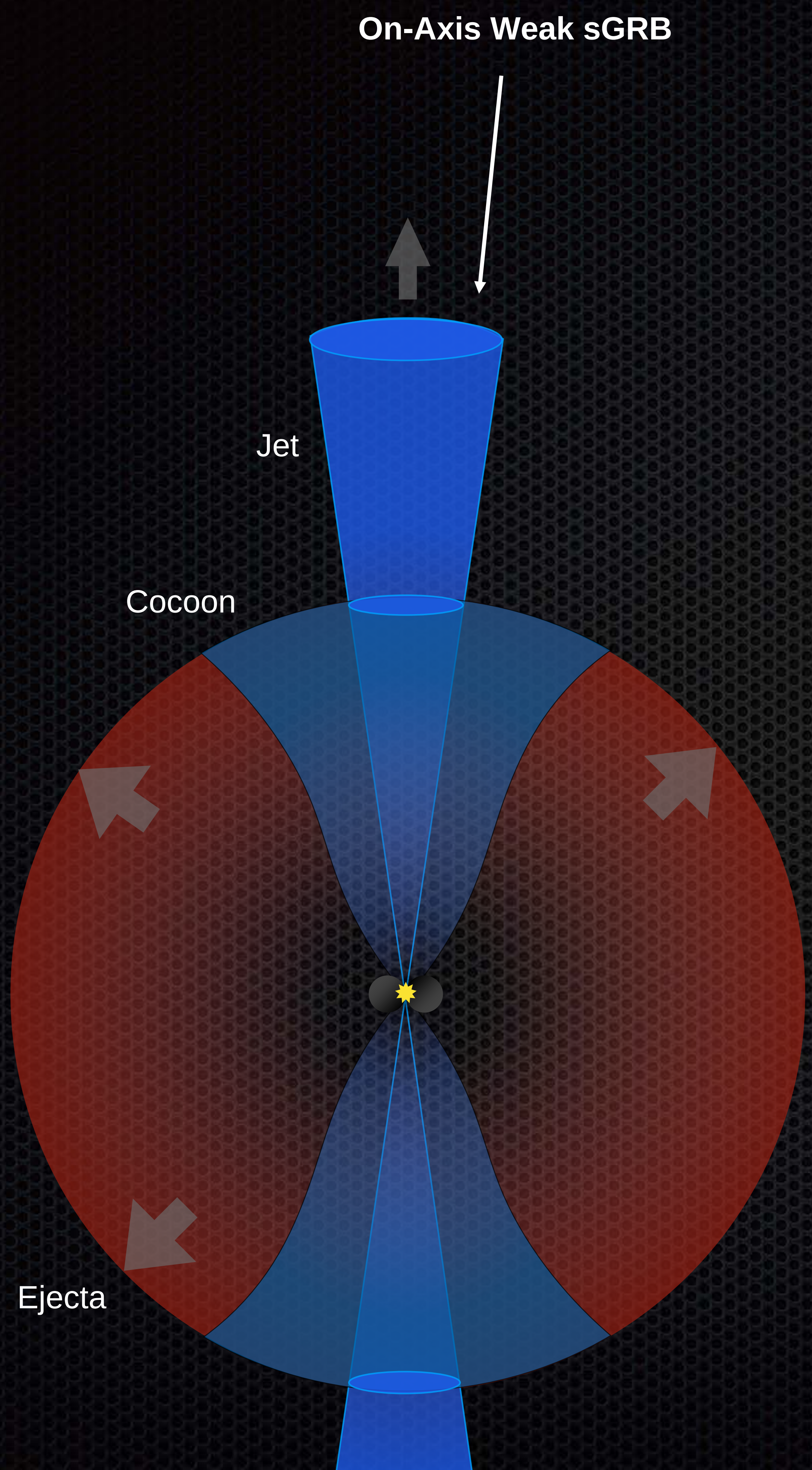
+9 days

+16.4 days

Kilonova

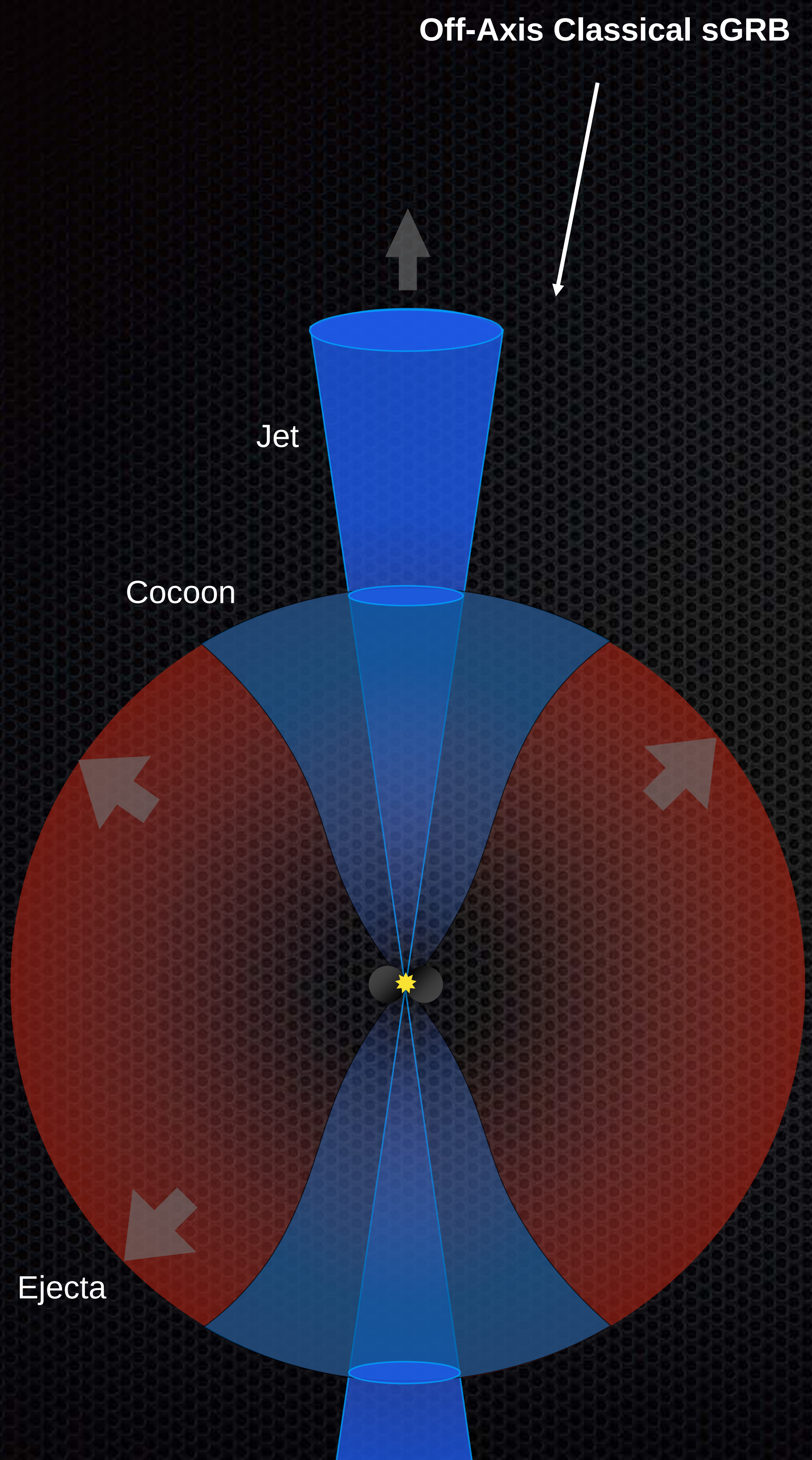


- The production of heavy elements through rapid neutron capture (r-process) and their eventual decay
- Red kilonova is expected from lanthanide-rich dynamical ejected via processes such as tidal forces
- Blue kilonova could be due a lanthanide-poor wind driven outflow or cooling of shock-heated ejecta
- What does this tell us about the gamma-ray emission? There are multiple plausible explanations



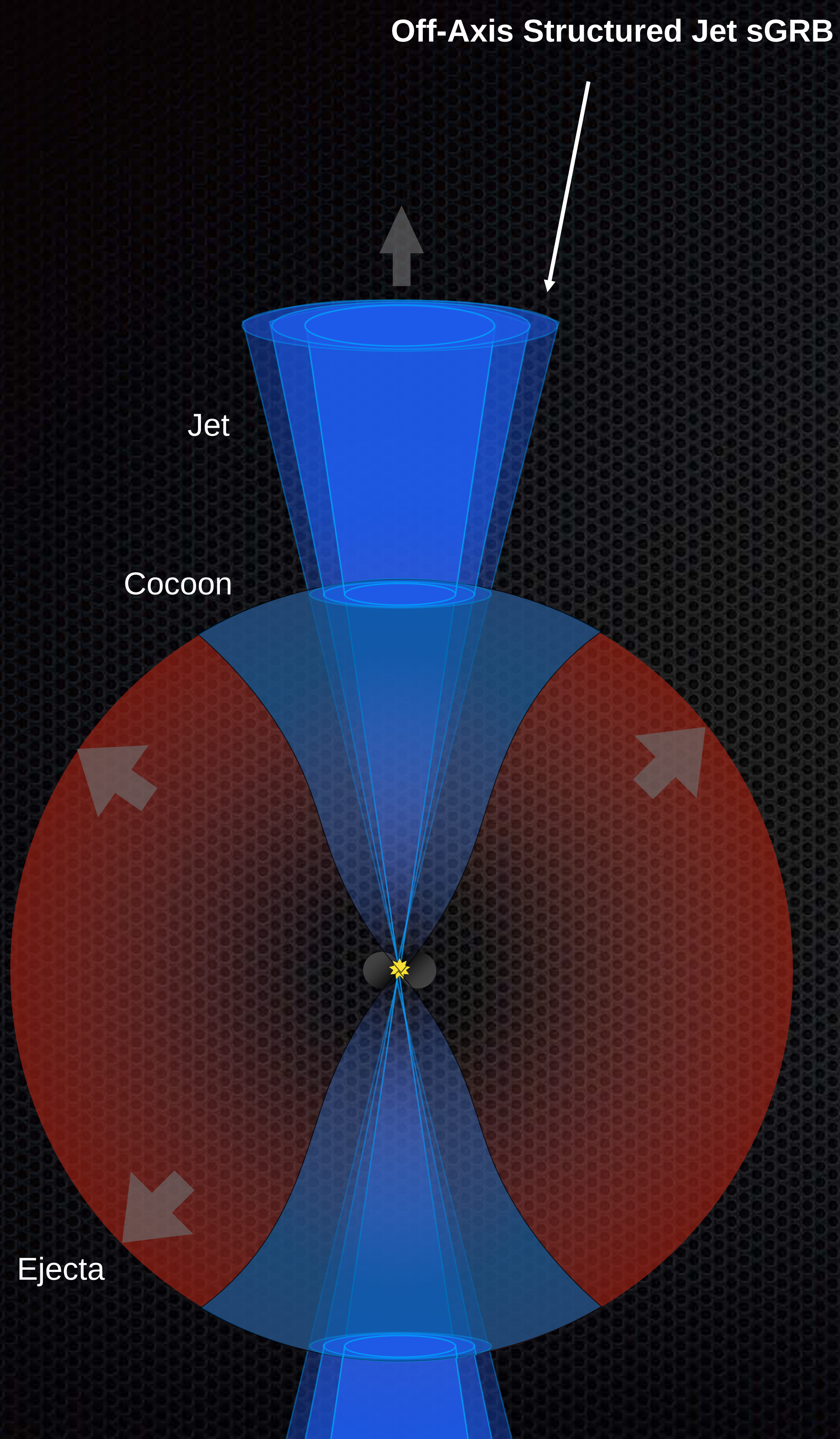
On-Axis Weak sGRB

- We simply observed a top hat jet on the low end of the GRB luminosity function
- Pros:
  - Logical starting point
  - GW-EM delay is on the order of T90
- Cons:
  - Cannot explain the late-time X-ray and radio observations
  - Not clear how to produce delayed thermal emission
  - Would require very low ejecta mass to allow the low-energy jet to successfully breakout
- GW: $\theta_v \sim 29^o +15^o/-10^o$ (LIGO - arXiv:1805.11579v1)
  - Average sGRB is $\theta_{jet} \sim 16^o$ (Fong et al. 2015)



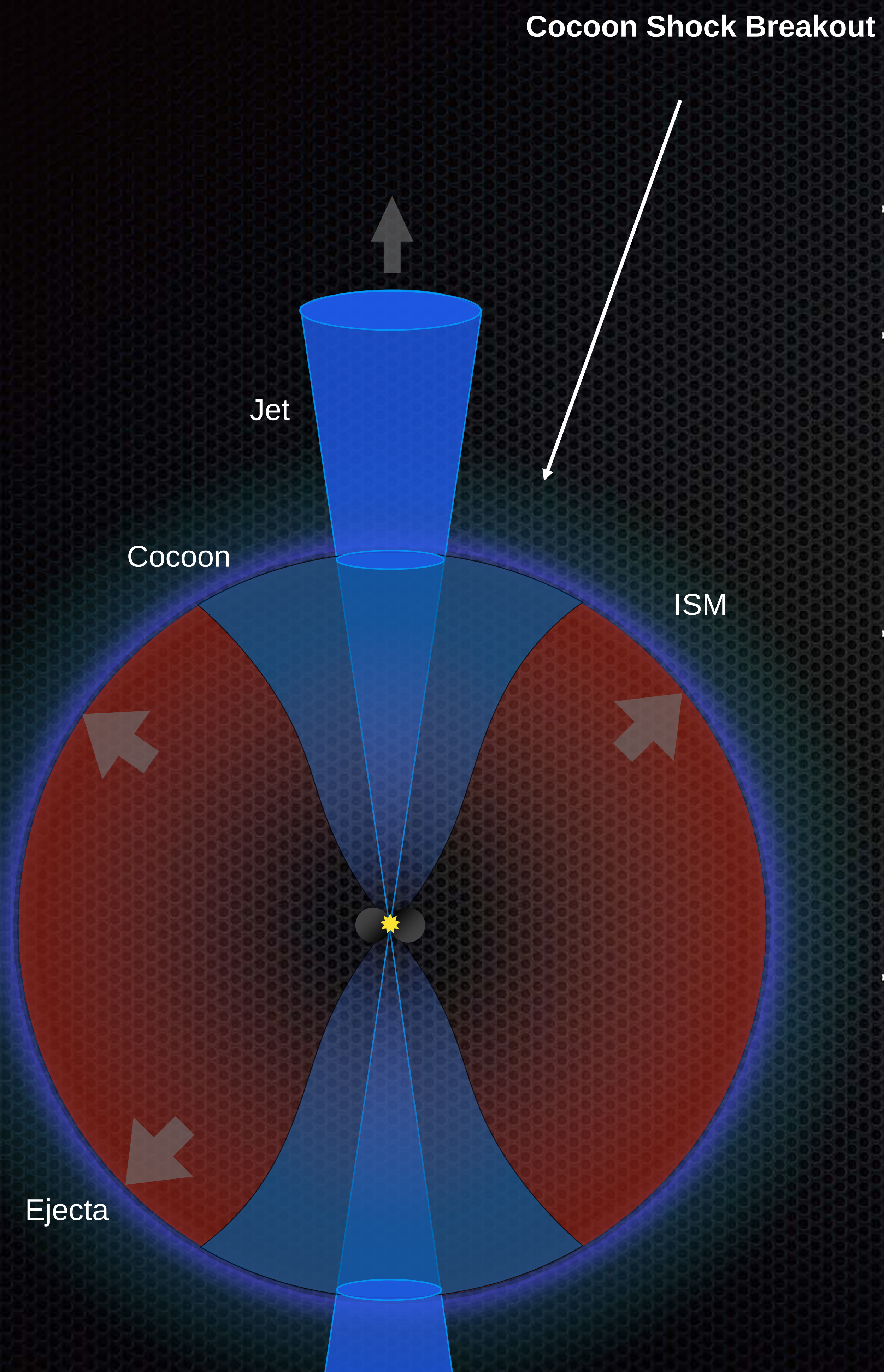
Off-Axis Classical sGRB

- We observed outside the jet of a classical sGRB
- Pros:
  - Can naturally explain the lower energetics
  - Thermal emission could be from the GRB photosphere or the cocoon
- Cons:
  - Observed Epk & Eiso drop very quickly outside θ_{jet}
    - θ_{v} would need to be just outside the jet edge
  - The on-axis Epk would be on the high end of the observed GBM catalog distribution
  - Expect bright afterglow in X-ray after ~1 day



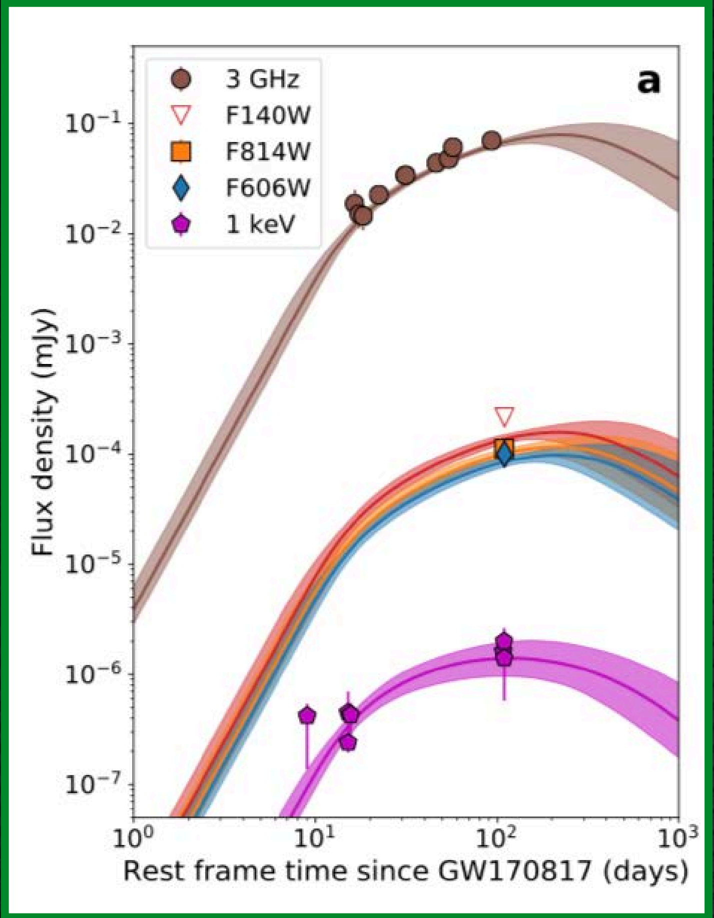
Off-Axis Structured Jet sGRB

- We observed the less energetic region of a structure jet where the Lorentz factor decreases with θv
- Pros:
  - Could produce arbitrary Epk and Eiso values
  - GW-EM delay is on the order of T90
  - Thermal emission could be from the GRB photosphere or the cocoon
- Cons:
  - Not entirely clear how such wings are generated or what their Lorentz profiles look like
  - On-axis Eiso would still need to be relatively low
- Predictions
  - Afterglow should peak and fade as the jet decelerates and we see the more energetic core region of the jet
  - VLBI imaging would reveal proper motion of the jet

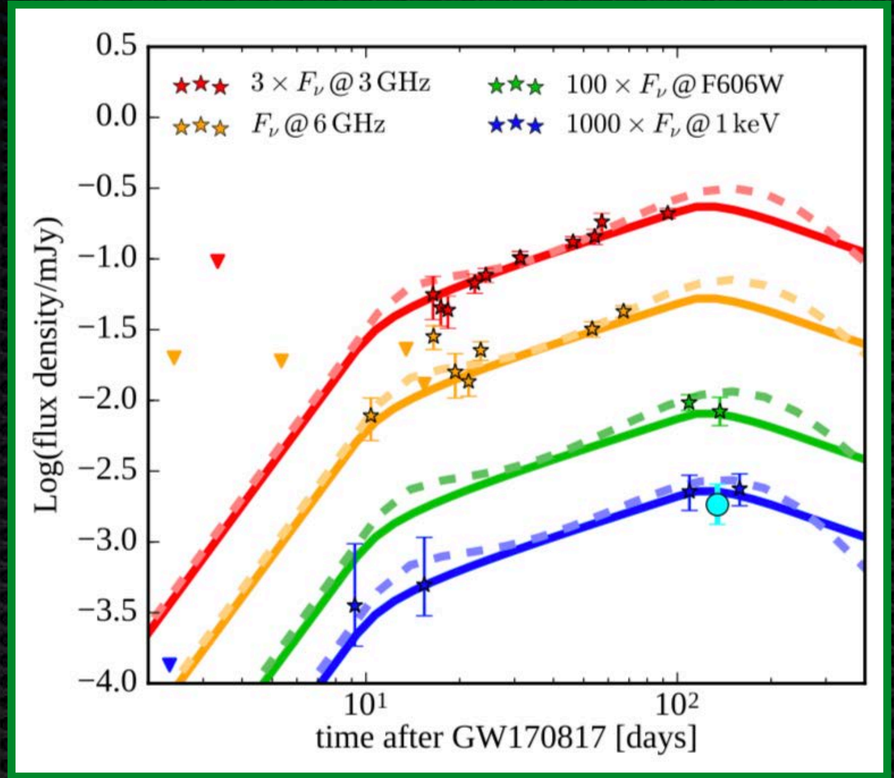


Cocoon Shock Breakout

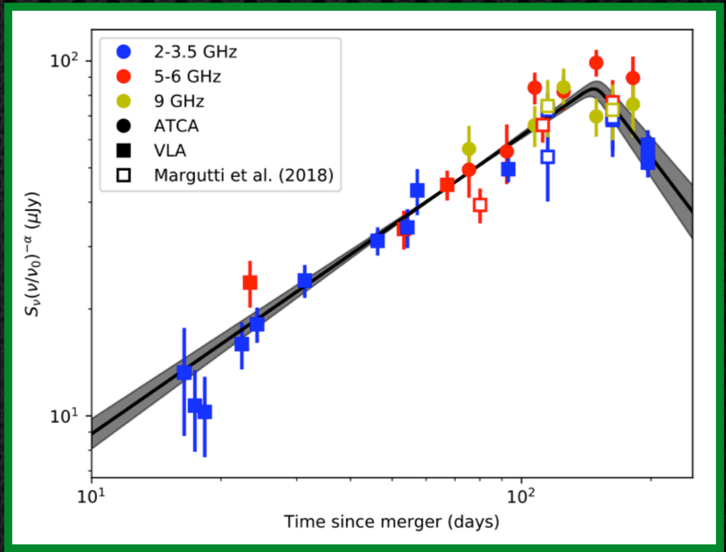
- Hard emission from mildly-relativistic shock breakout and thermal emission from cocoon
- Pros:
  - Can naturally explain the lower energetics
  - Could naturally explain both hard and thermal components
- Cons:
  - Cannot explain very high Epk values
  - Difficult to explain fast variability
  - Should overproduce look alike sGRBs
- Predictions:
  - Late time x-ray and radio should rise for months to years as the cocoon interacts with the ISM
  - Quasi-spherical outflow should not produce any proper motion in VLBI imaging



HST and *Chandra* observations continue to show rising afterglow flux (Lyman et al. 2018, Ruan et al. 2018, Troja et al. 2018)



Hints of a plateau in x-rays (D'Avanzo et al. 2018) and radio (Resmi et al. 2018)

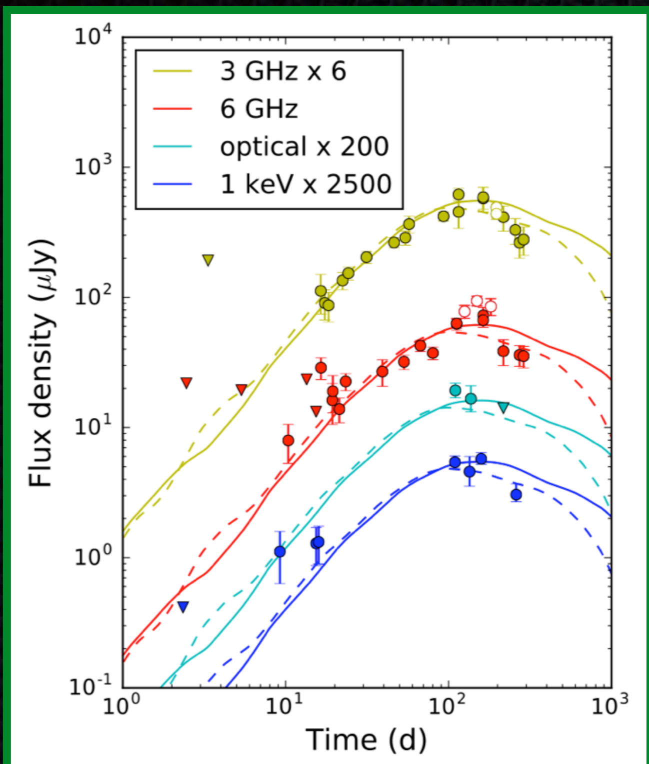


Evidence for a turn over in radio (Dobie et al. 2018)

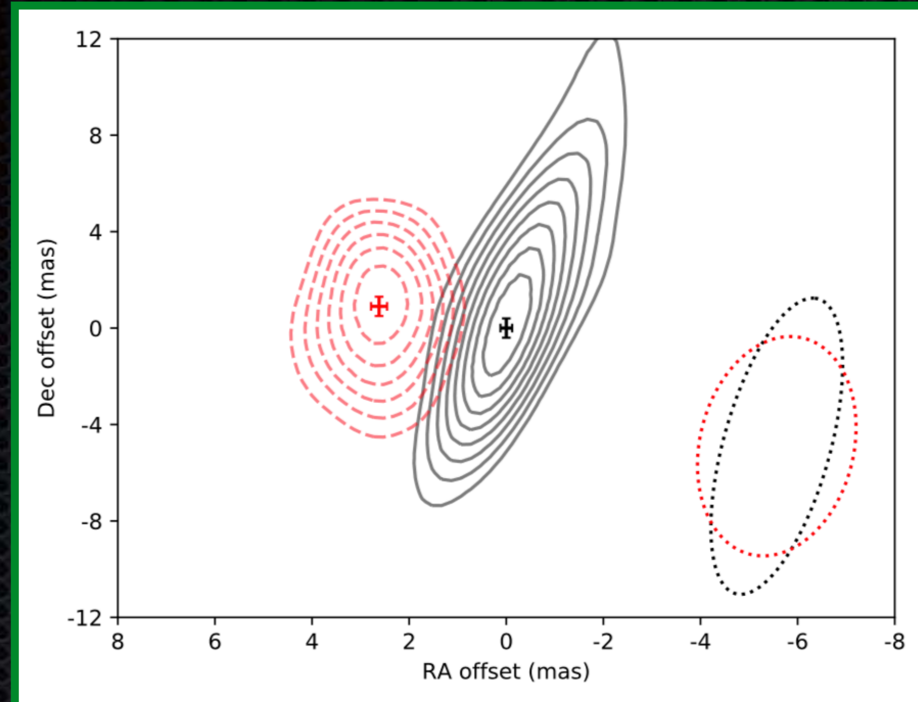
+100 days

+135 days

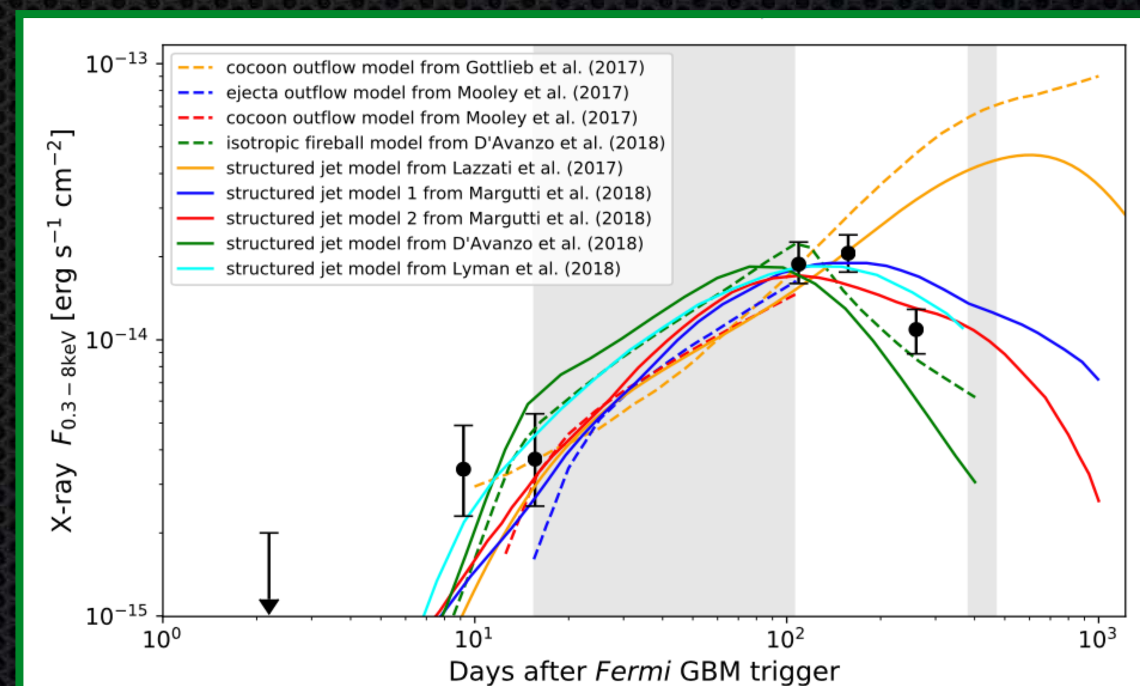
+150 days



Further evidence for a turn over (Alexander et al. 2018)



Superluminal motion of the unresolved radio source and undeniable evidence of a off-axis jet (Mooley et al. 2018)



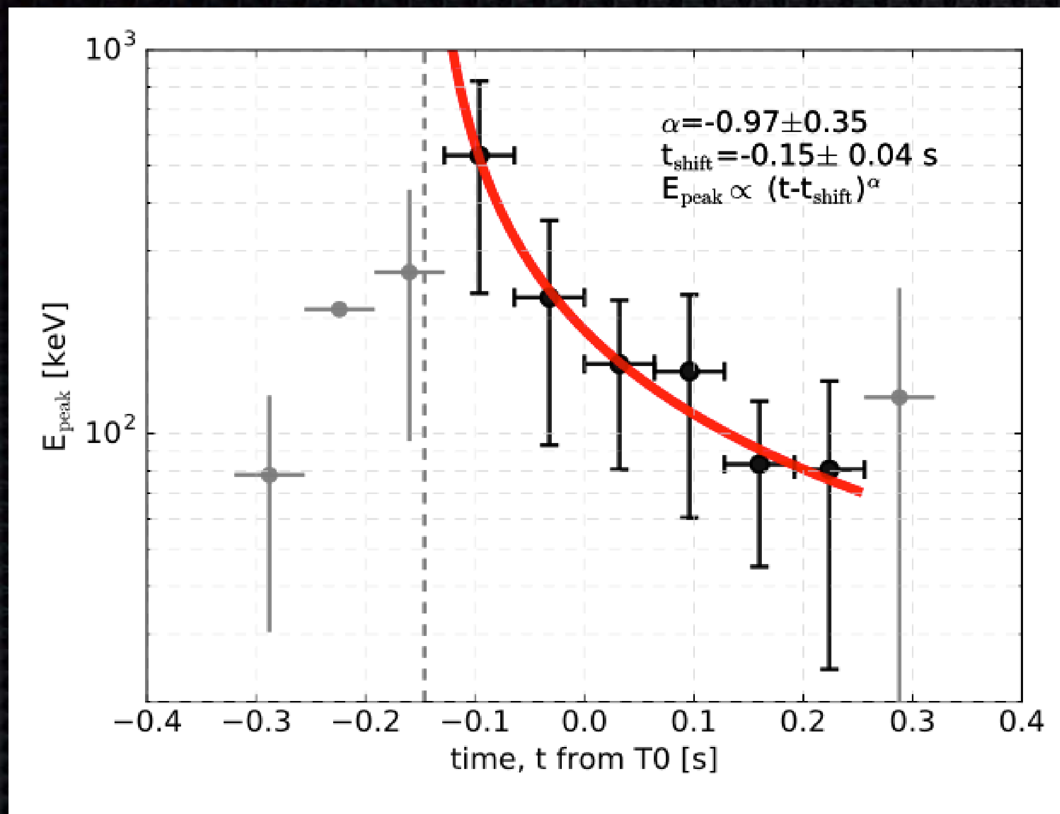
Cocoon is ruled out at late times, but it could still explain prompt and early afterglow (Nynka et al. 2018, Mooley et al. 2018)

+220 Days

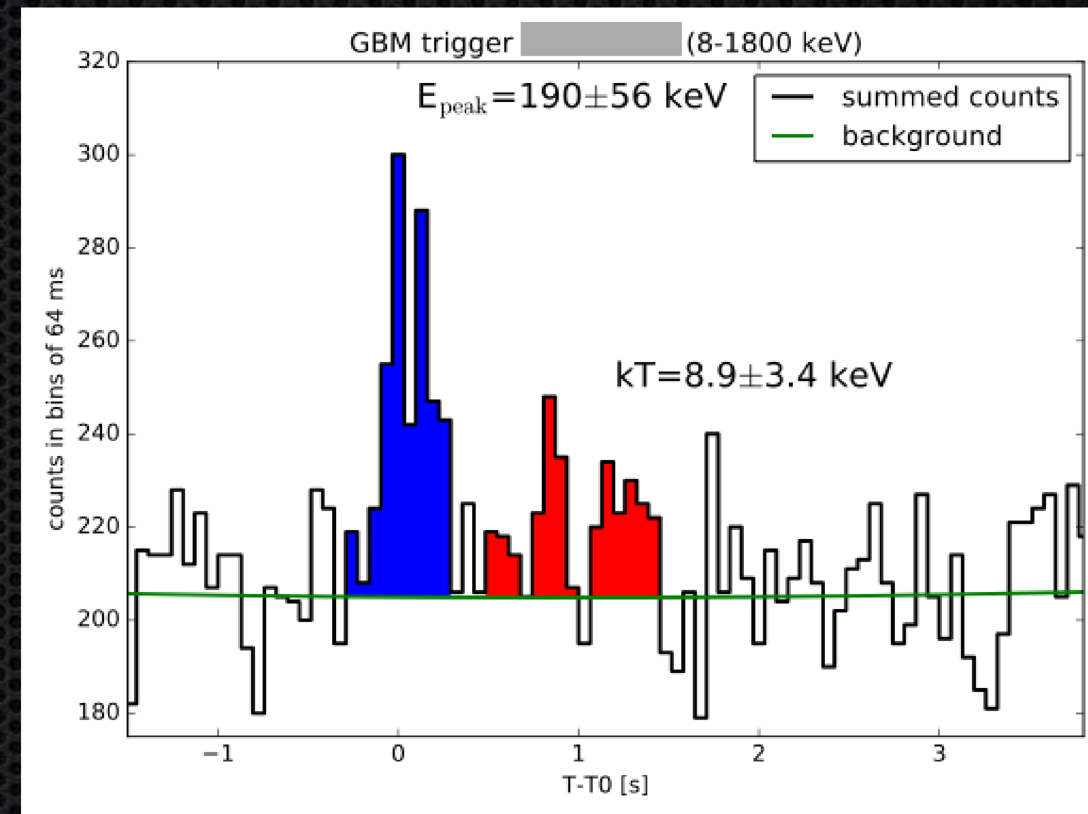
+230 days

+260 days

Challenging Gamma-ray Observations



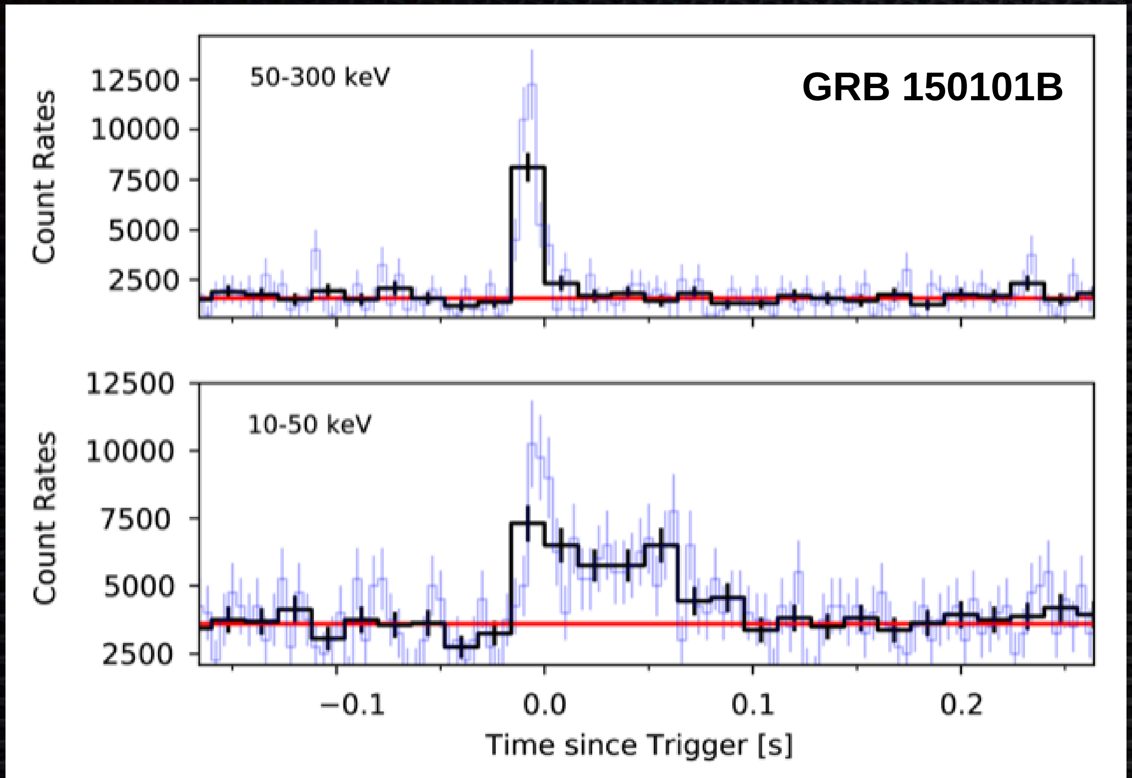
Veres et al. 2018



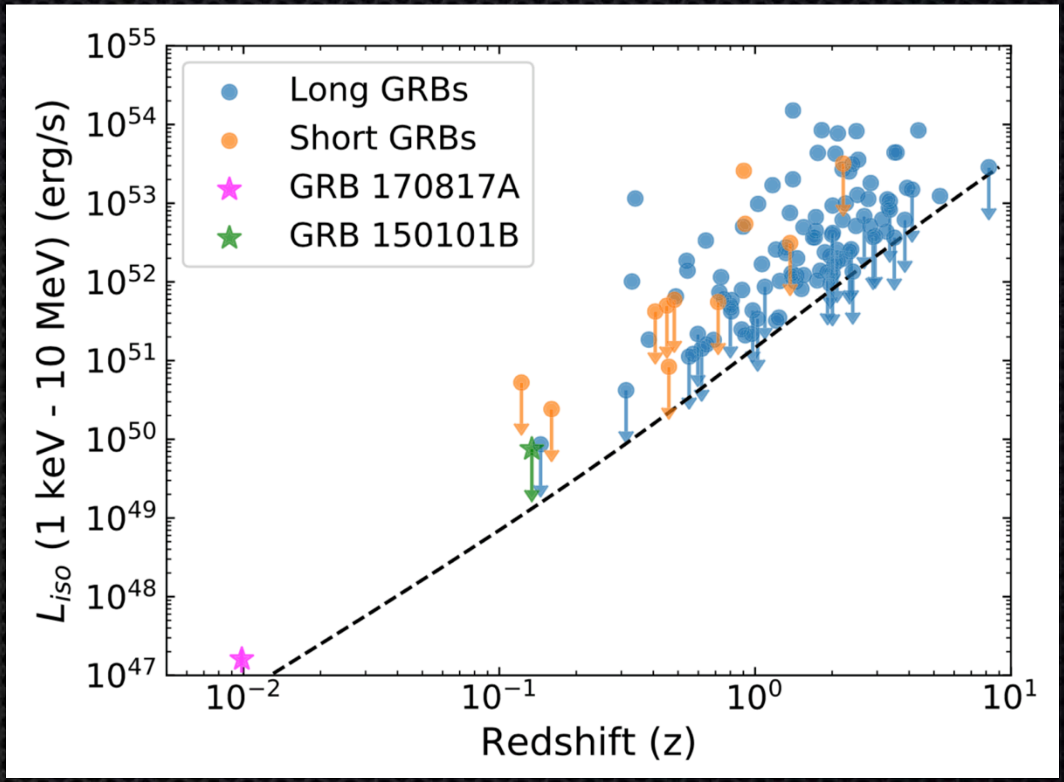
Von Kienlin in prep.

- A time resolved spectral analysis has shown evidence for very high Epk values
- High Epk values become challenging for the cocoon shock breakout model to explain
- We have found bursts that resemble GRB 170817 in BATSE, GBM, and Swift data
- Very preliminary, but evidence for sub-structure in some of these cases

GRB 150101B



Burns et al 2018

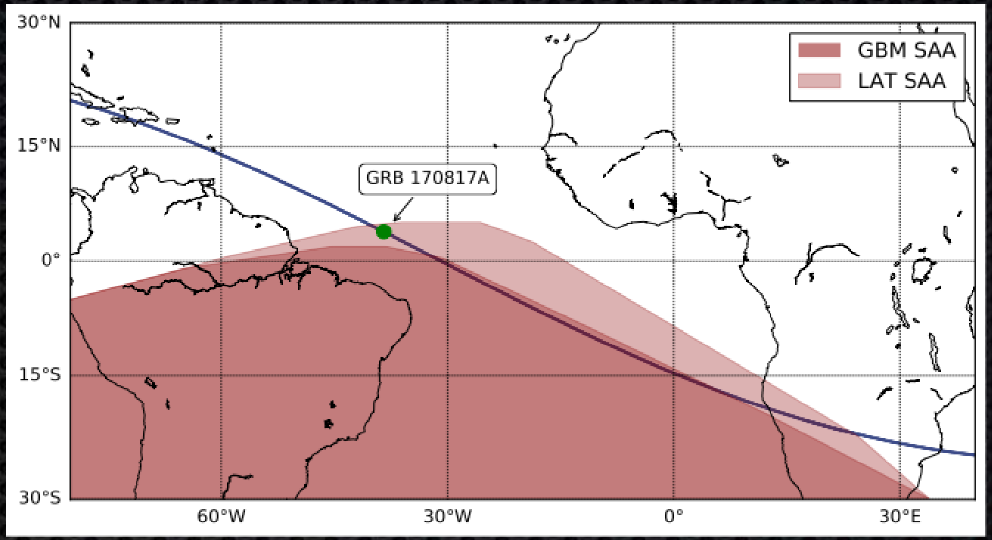


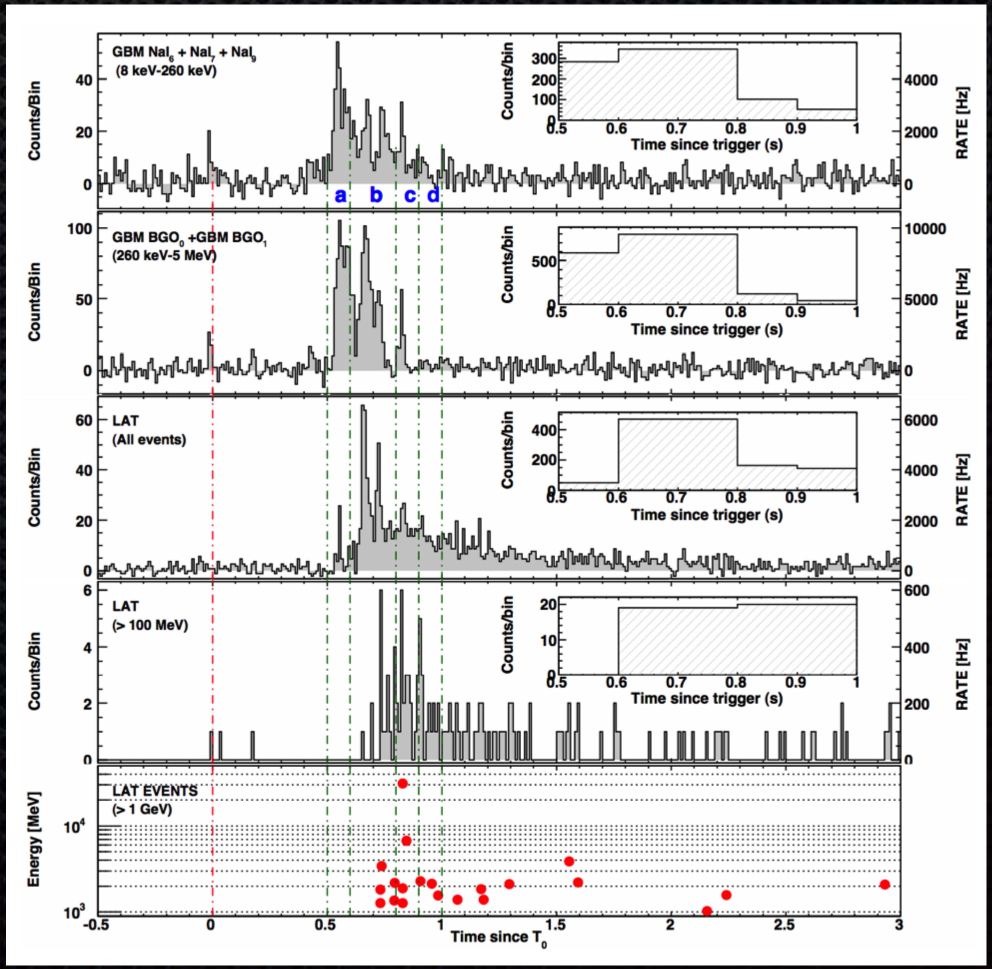
Burns et al 2018

- Eric Burns led a paper on the study on the third closest SGRB with known redshift - GRB 150101B
- Very hard initial pulse with Epk =1280±590 keV followed by a soft thermal tail with kt~10 keV
- Unlike GRB 170817, 150101B was not under luminous and can be modeled as an on-axis burst
- Suggests that the soft tail is common, but generally undetectable in more distant events
- Thermal tail can be explained as GRB photosphere, but degeneracy with the cocoon model still exists

Things to look for in O3

- Several high-energy observations should be able to help discriminate between jet and shock breakout emission
- Observation of MeV/GeV emission from such an event would be impossible to explain from a cocoon alone
  - Would require inverse Compton scattering of the cocoon emission by relativistic particles which would impart a distinct spectral shape
  - We have never seen evidence for IC emission in GRBs
- Observation of high time variability in GBM data would also effectively rule out shock breakout and/or cocoon emission
- Ratio of BNS mergers with/without a gamma-rays will allow us to estimate the average beaming angle of SGRB jets and the isotropy of any cocoon like emission
- Observation of gamma-ray signal with a long tail and no red kilonova would be a evidence for a long lived HMNS
- Ultimately we need more observations of joint NS-NS mergers to definitely address these open questions





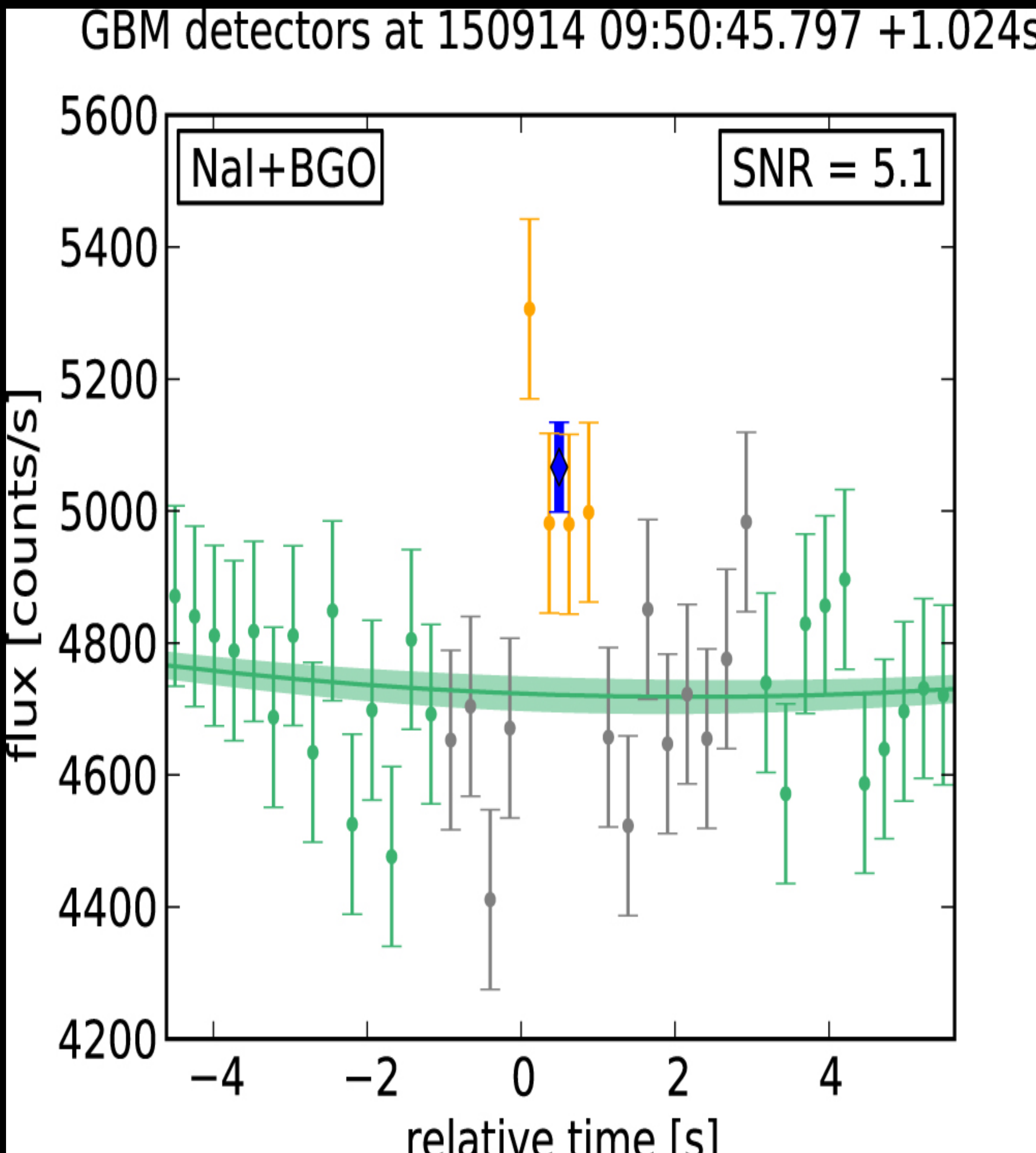
GRB 090510

Ackermann et al. 2010

Science from GW170817 and GRB 170817A

- Directly measured the speed of gravity
  - It is the same as the speed of light within one part in one quadrillion
- Probed the neutron star equation of state: the densest matter in the universe
- Investigated the emission physics of relativistic jets and the engine that produces the short GRB
- Estimated the rate of events like these throughout the universe

Counterpart to a Black hole merger?



Connaughton et al. 2016

GW150914

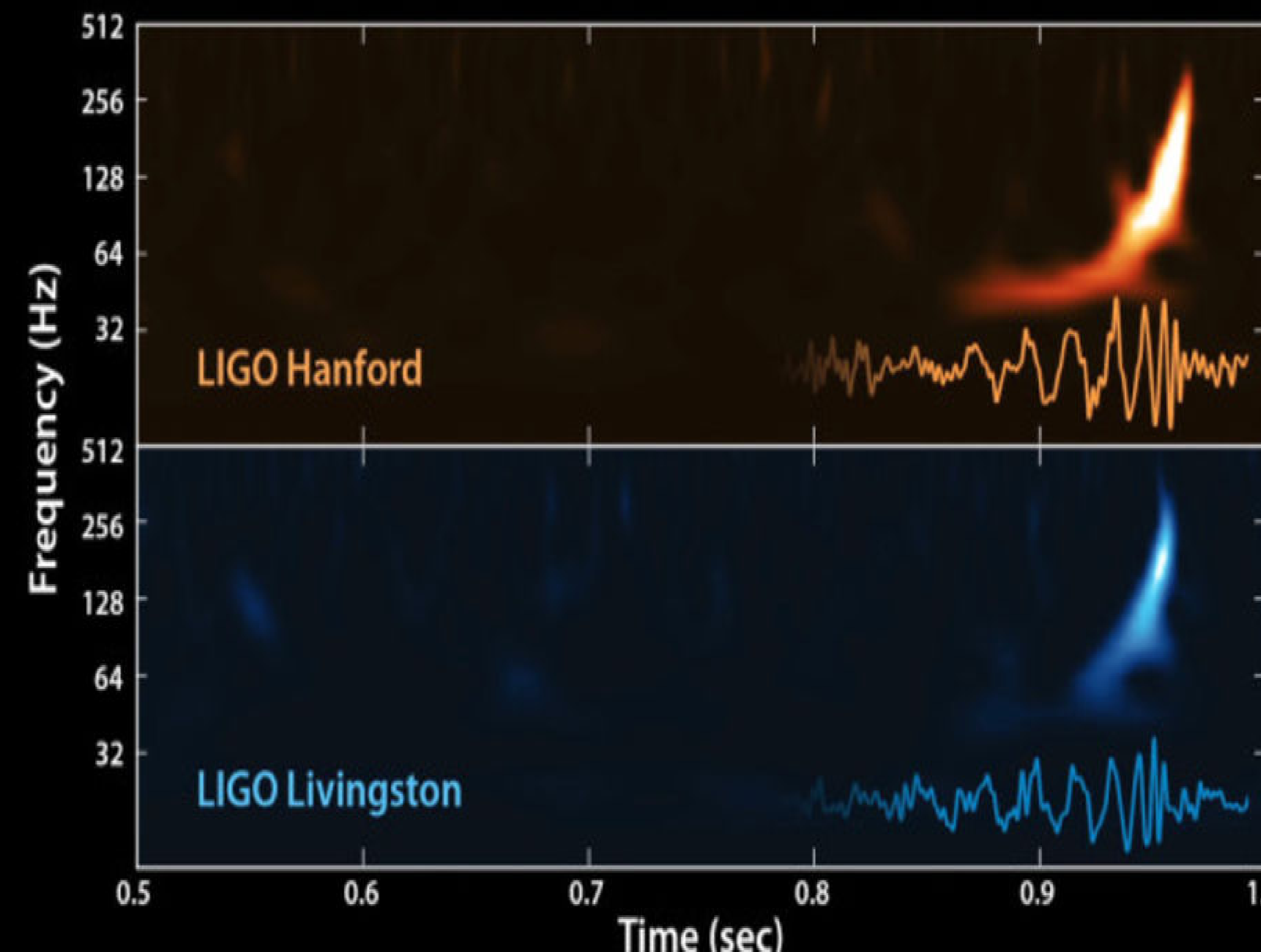
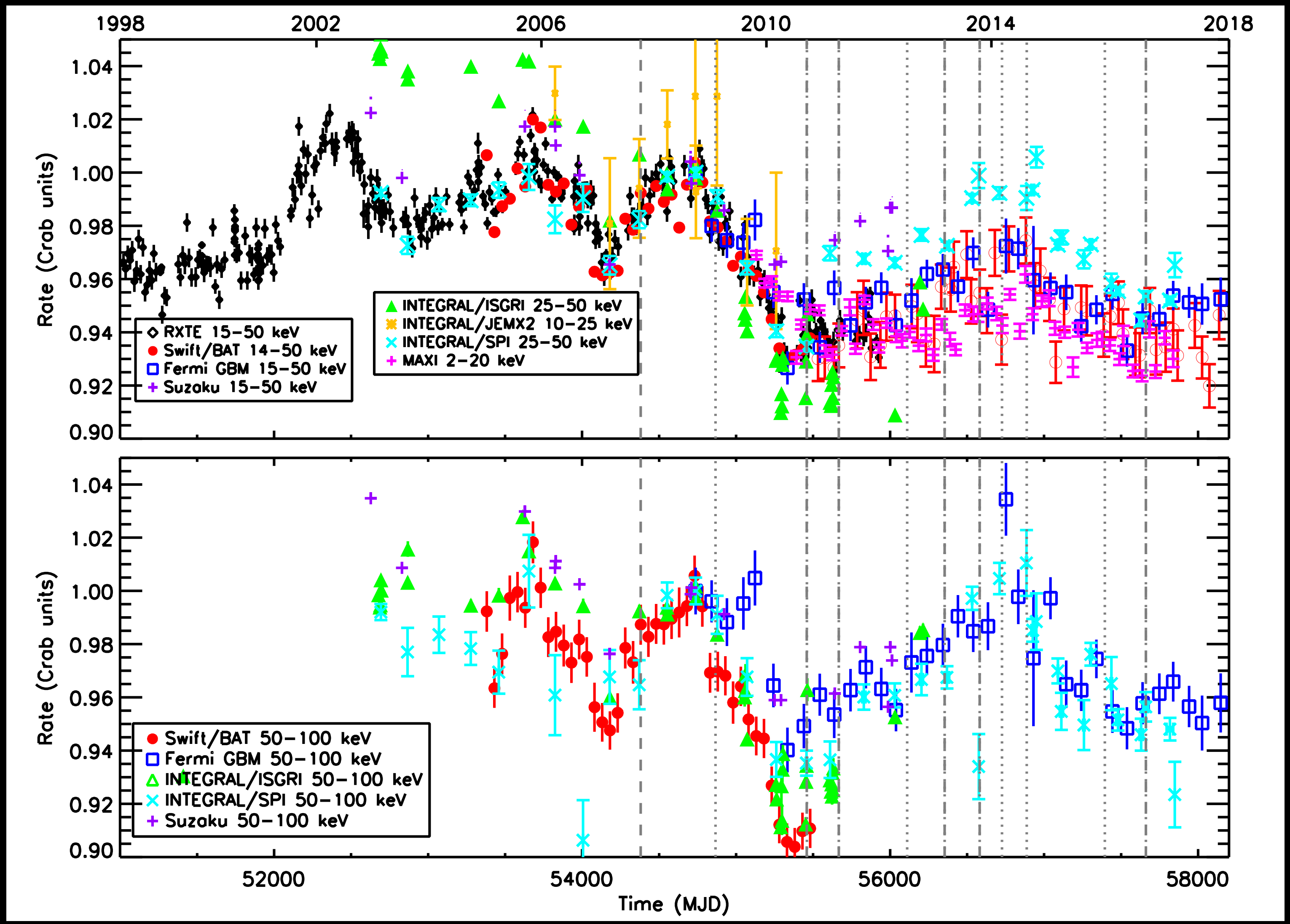


Image Credit: LIGO

A Few Highlights from Other Transient and Variable Sources Observed with Fermi GBM

GBM Discovery of Crab Nebula Variations



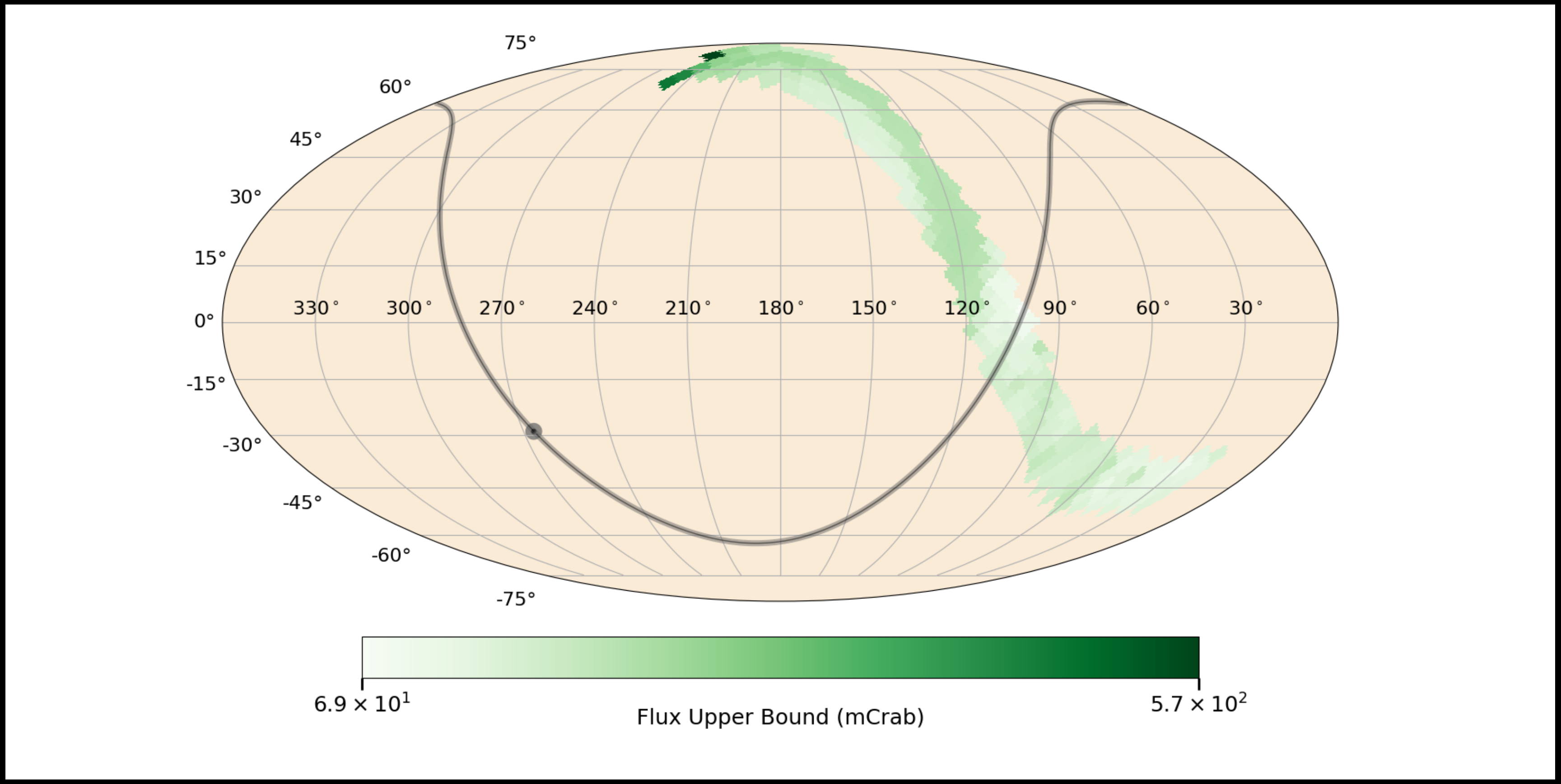
- GBM Earth Occultation measurements – monitor 229 Galactic & extragalactic sources
- With GBM, we discovered that the hard X-ray flux from the Crab decreased by 7% from 2008-2010 and increased by 7% from 2010-2014
- This is very significant because the Crab was thought to be so constant, it was our “meterstick” for X-ray brightness!

Monitoring the sky using the Earth Occultation Technique

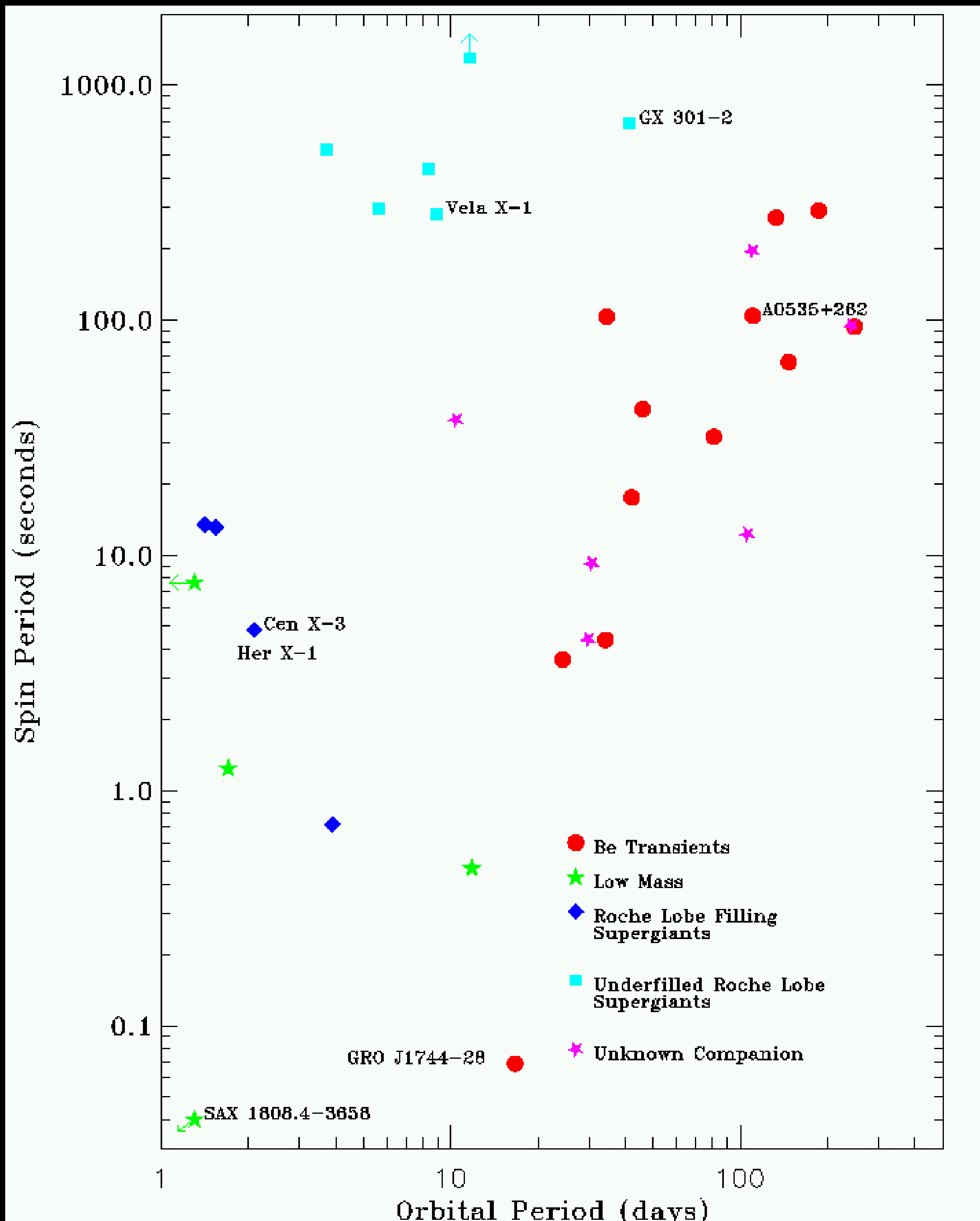
https://gammaray.nsstc.nasa.gov/gbm/science/earth_occ.html

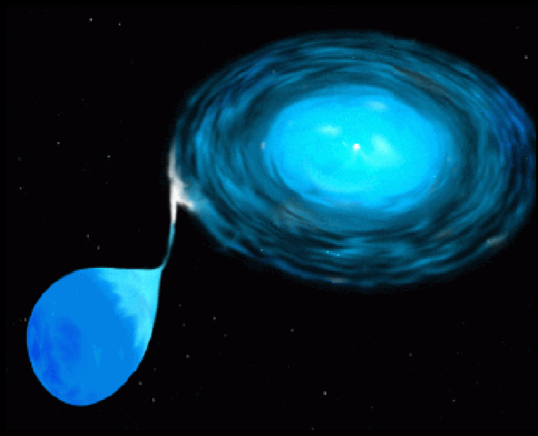
- 200+ sources are monitored from X-ray binaries to Active Galactic Nuclei.
  - 102 detections, 9 at >100 keV.
- Earth occultation technique can be used to search for longer lasting emission from GW candidates

GW 170104 upper limits map (+/- 1 day)

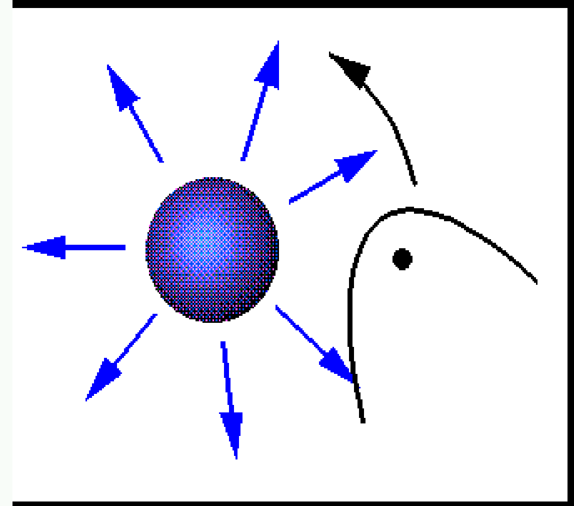


Accreting X-ray Pulsars

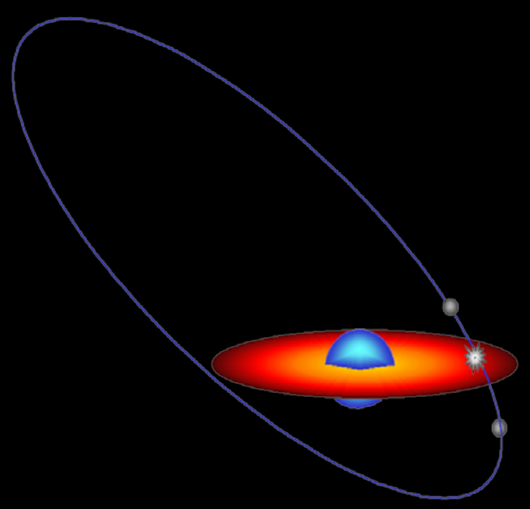




Roche lobe overflow

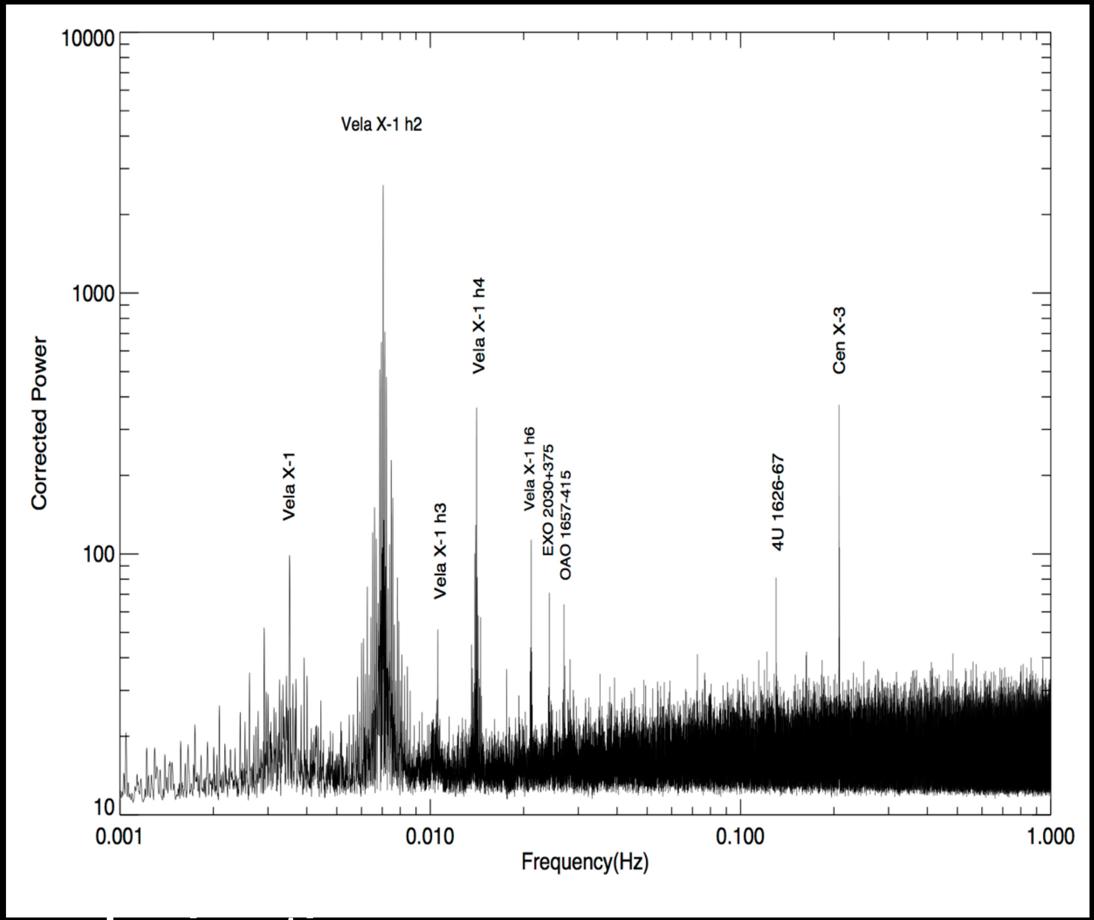


Wind accretion



Be star’s circumstellar disk

GBM Pulsar Searches



Daily Blind Search

- 24 source directions equally spaced on the galactic plane + LMC and SMC.
- Each direction - FFT based search from 1 mHz to 2 Hz.

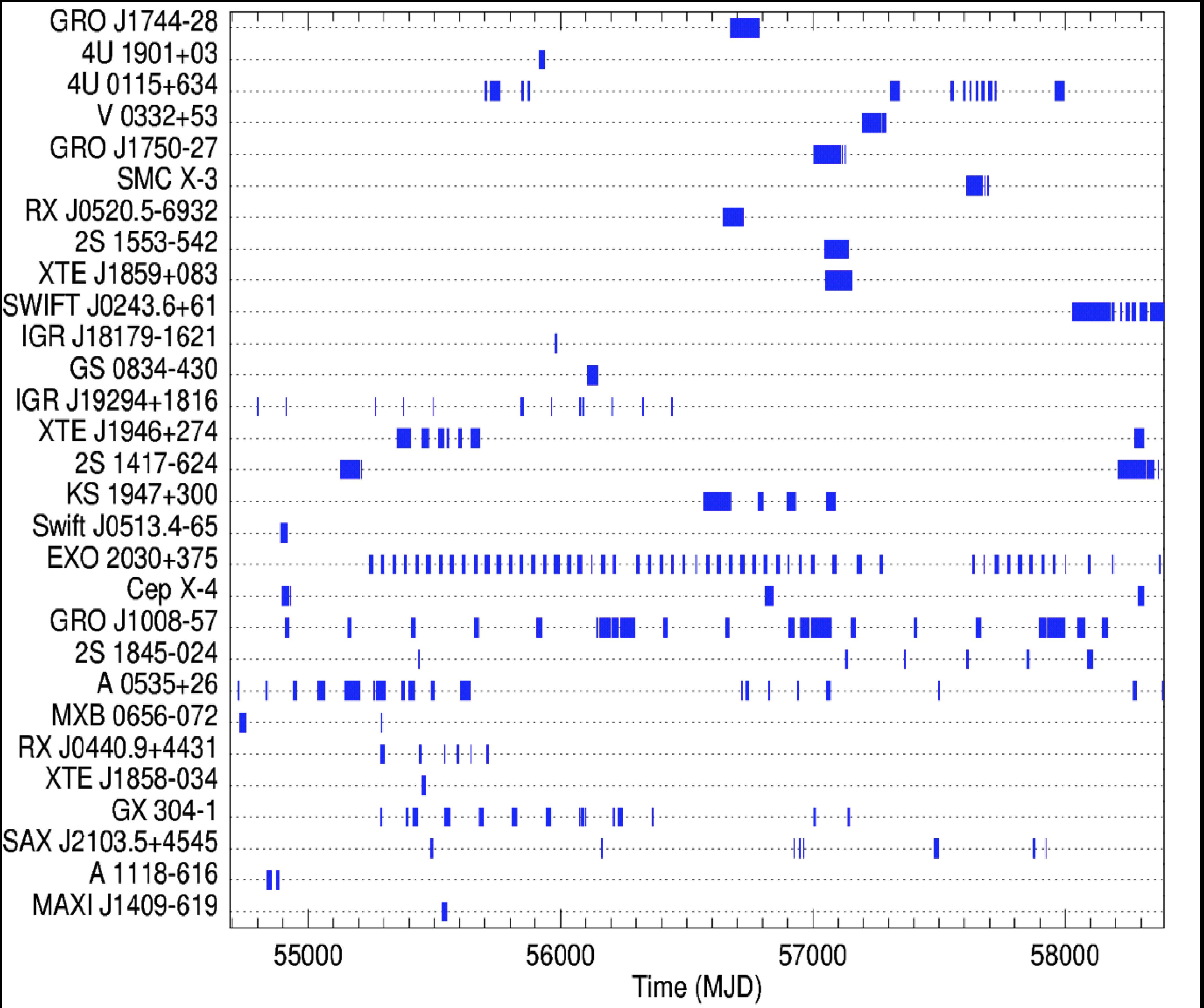
Source Specific Searches.

- Small ranges of frequency and frequency derivative
- Phase shifting and summing pulse profiles from short intervals of data
- Barycentered and possibly orbitally corrected times.
- Typical exposure times are ~40 ks/day.

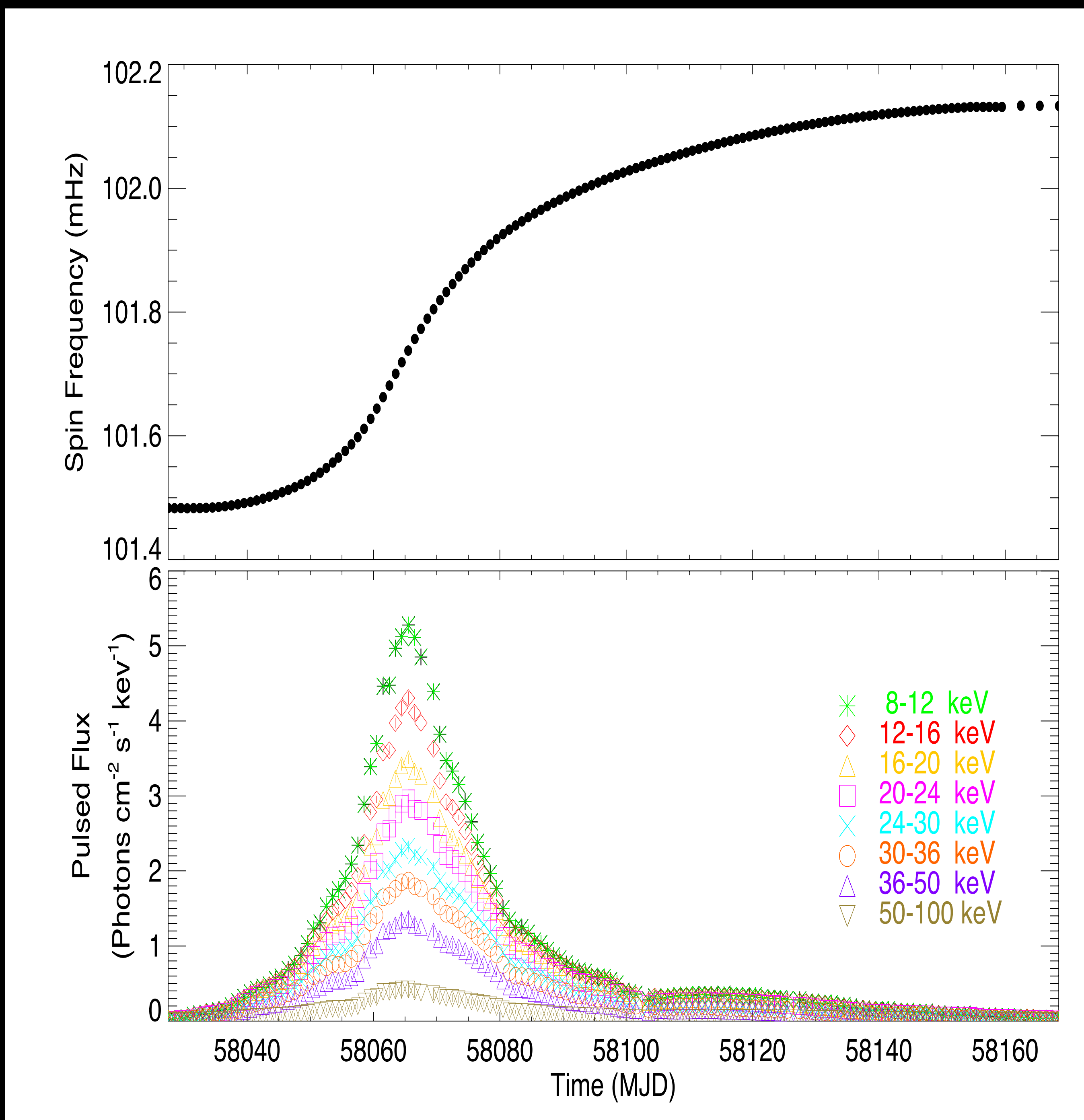
- Detections – Total of 40 systems monitored
  - 8 of 8 persistent sources
  - 29 of 32 transients

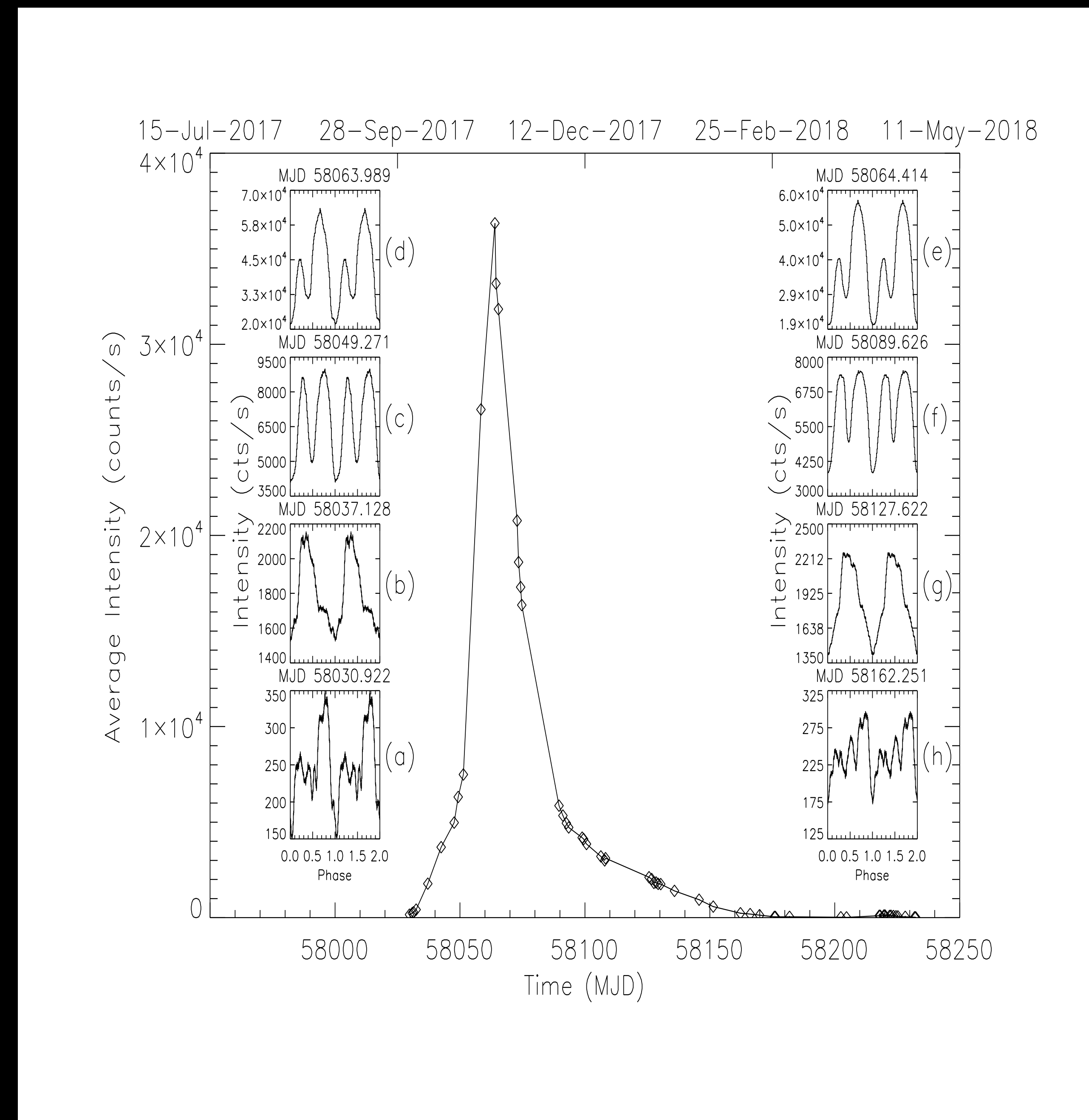
Transient Pulsar Zoo of Outburst Behavior

http://gammaray.nsstc.nasa.gov/gbm/science/pulsars



Swift J0243.6+6124: The First Galactic Ultraluminous X-ray Pulsar





Wilson-Hodge et al. 2018

Swift J0243.6+6124: Comparisons with ULX pulsars in other galaxies

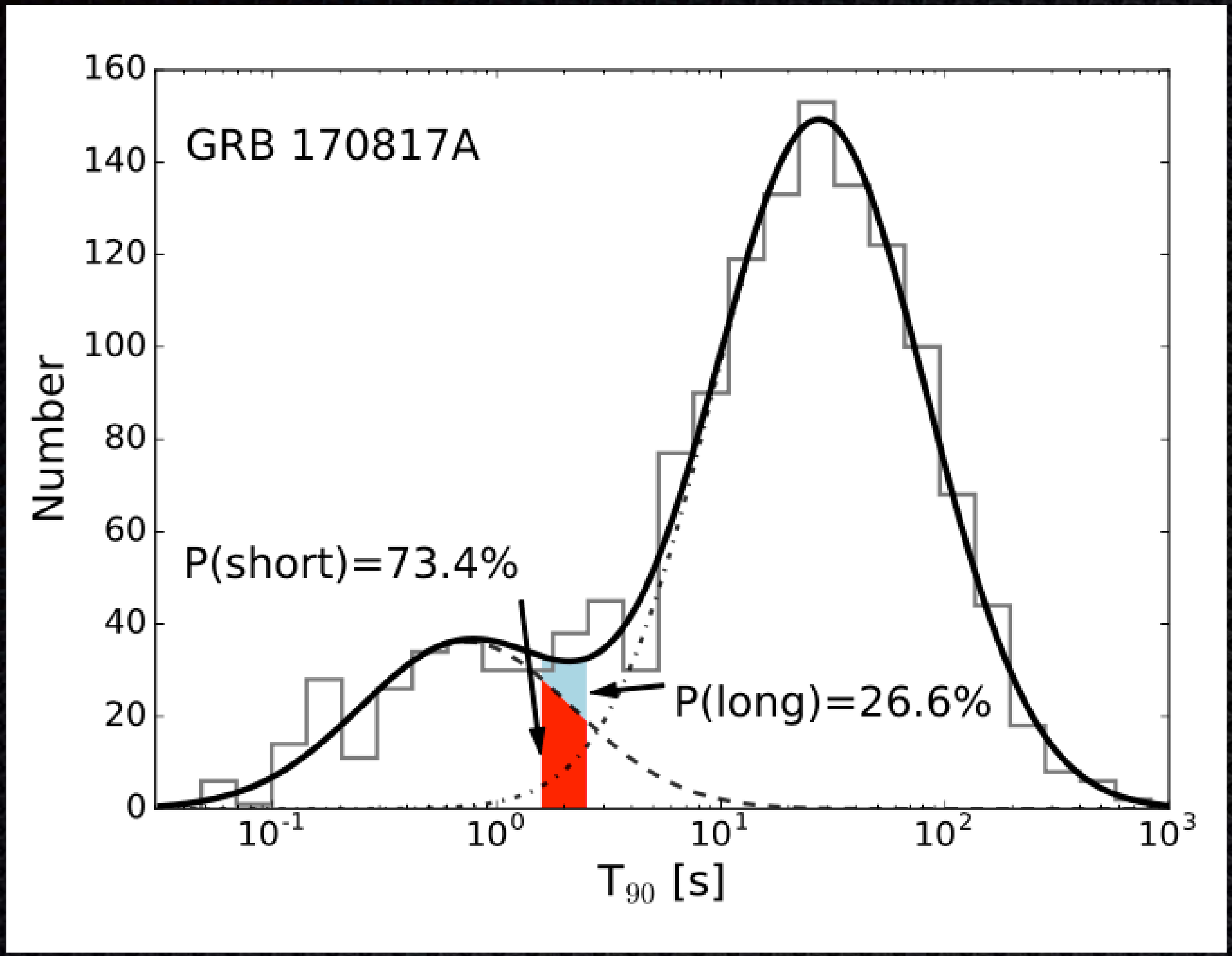
- Properties like known ULX pulsars (Kaaret et al. 2017)
  - Peak luminosity ~2 x 10^{39} erg s^{-1} (d=7 kpc; 0.1-10 keV) (>10^{39} ergs s^{-1})
  - normal outbursts peaking around 10^{37} erg s^{-1} (0.1-10 keV)
  - Spin period ~9.8 s (0.43-32 s)
  - Peak spin-up rate (2.23+/-0.02)x10^{-10} Hz/s (>10-^{10} Hz/s)
  - RMS Pulsed fraction increasing with energy and with intensity
    - 8%-33% (0.2-1 keV)
    - 22%-95% (8-12 keV)
  - Evidence for strong magnetic field of ~10^{13} G
- Properties unlike known ULX pulsars
  - Pulse profile definitely not sinusoidal.
  - Source was not known before it was detected as a pulsar in outburst.
  - Evidence for jets in radio (van den Eijnden et al. 2018)

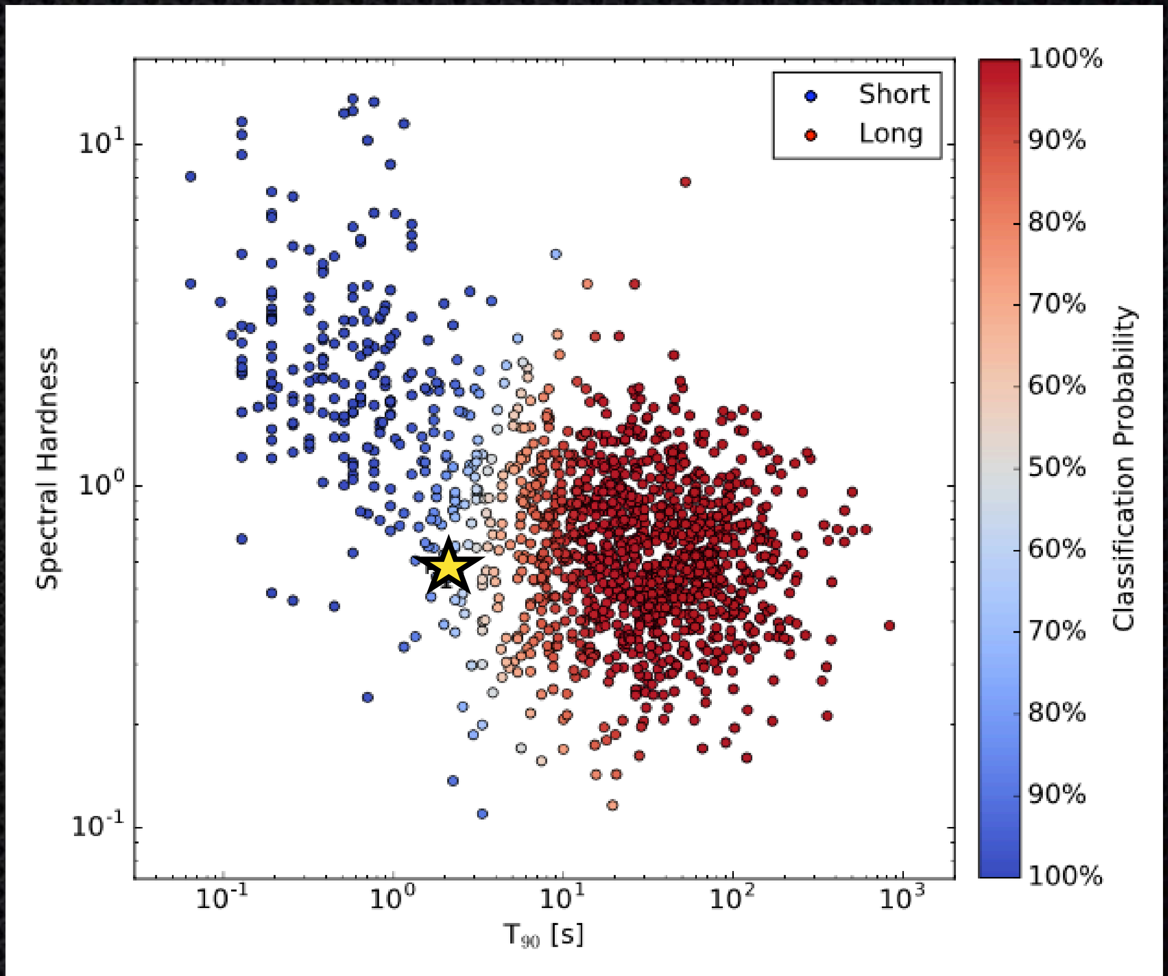
Summary

- Fermi GBM is the most prolific detector of short gamma-ray bursts
- GRB 170817A/GW170817
  - Short gamma-ray bursts are unambigously associated with merging neutron stars
  - The speed of light and the speed of gravity are equal to 1 part in 1 quadrillion
  - This burst was likely caused by either a structured jet, a cocoon shock breakout, or a combination of the two models
  - We have found other similar events in the GBM data
  - Many open questions remain. We need more observations!
  - We expect ~1 new coincident GW/GRB in O3. Subthreshold searches increase our chances of coincident detections
- Fermi GBM observes many other transient sources
  - Variations in the “constant” Crab Nebula were discovered with GBM in 2010.
  - In 2017, Fermi GBM observed an outburst from the first Galactic Ultraluminous X-ray pulsar, which continues to be active
  - Fermi GBM monitors more than 40 pulsars with epoch-folding techniques and more than 200 X-ray sources using Earth Occultation
  - Fermi GBM triggers on magnetar flares, solar flares, terrestrial gamma-flashes, and X-ray binaries in addition to gamma-ray bursts

Backup

Duration/Hardness

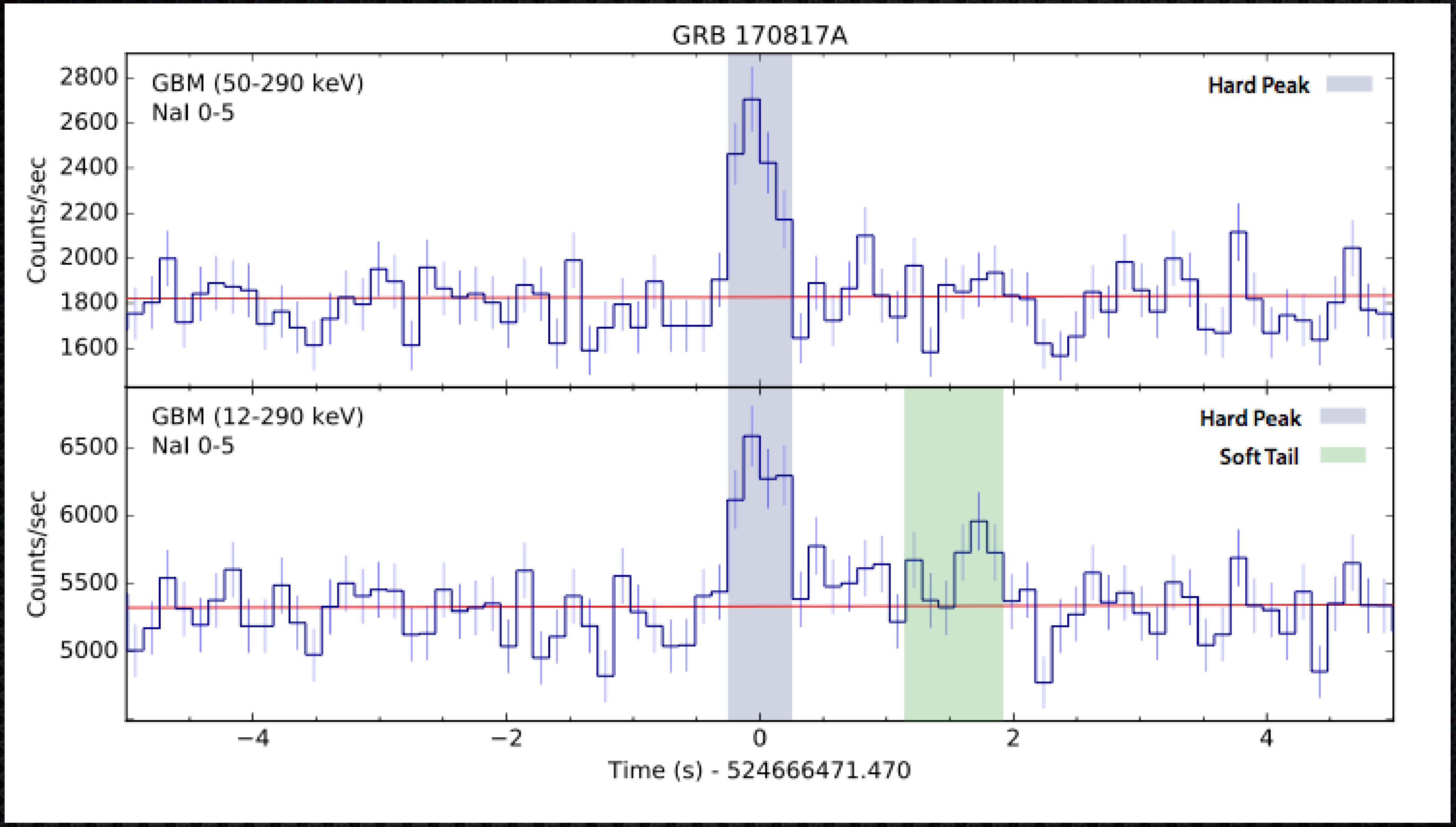




Goldstein et al. 2017

- A standard catalog analysis using 50-300 keV photons yields a T_{90} = 2.0 ± 0.5
- Combining both the duration and hardness information, we get P_{short} = 73.4%
- Hardness ratio between the 50-300 keV and 10-30 keV photons yields a relatively soft burst

Hard Pulse and Soft Thermal Tail

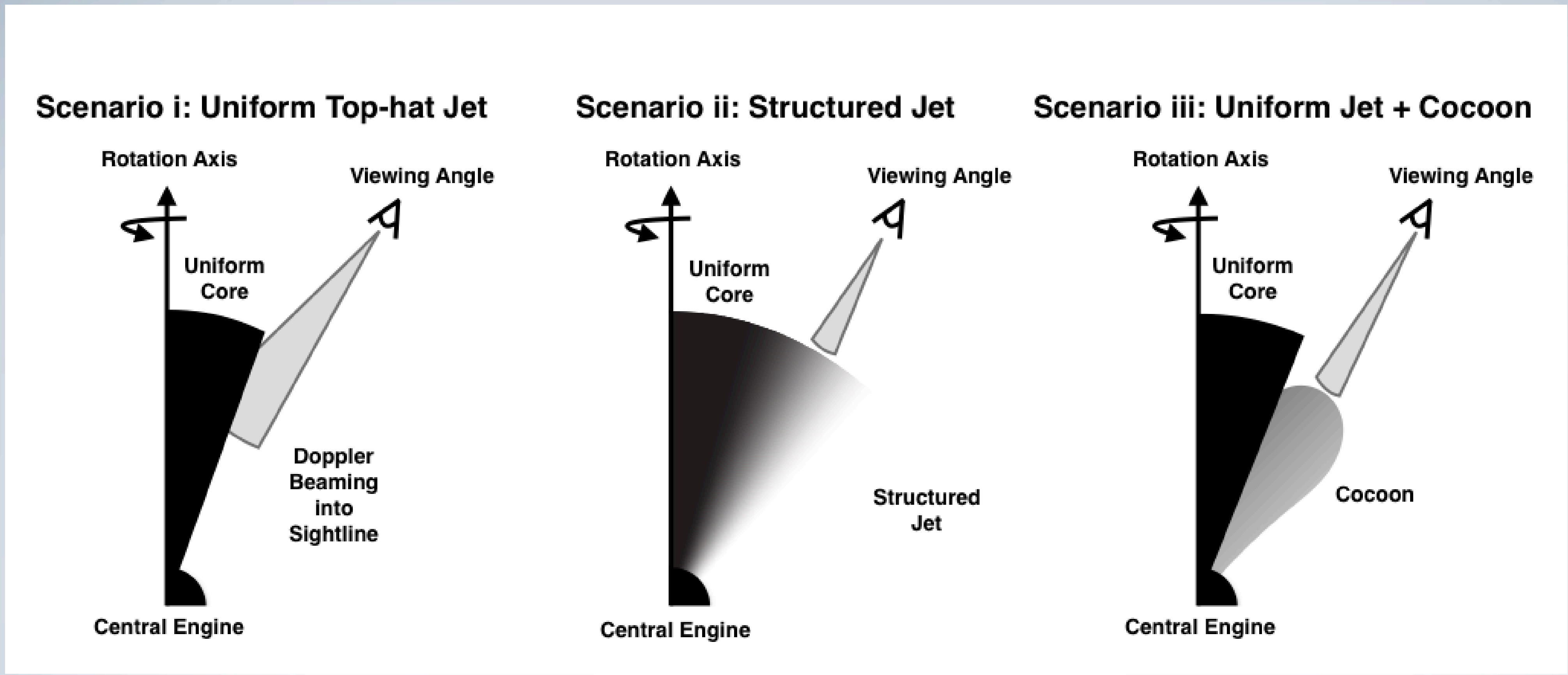


- Burst appears as a single component in the 50-300 keV energy range
- Two components emerge when including photons in the 10-50 keV energy range
- Initial hard pulse with a delayed and much softer tail

Conclusions

- GRB 170817 may have been the best observed transient in the history of astronomy
- Despite this, many questions regarding its nature still remain
- The GBM observations show GRB 170817 to be a normal sGRB in observer frame
- Source frame energetics and non-standard analysis reveal unique peculiarities
- The exact origin of the observed gamma-ray emission is still in question
- An off-axis structured jet or shock breakout from an energetic cocoon could work
- Recent GBM observations reveal prompt gamma-ray emission that is in tension with the cocoon model
- Late time x-ray and radio observations support an off-axis structured jet as well
- Need to find more sGRB counterparts to GW detections to answer these questions!
- Lots of exciting work to be done in O3!

GRB Observing Scenarios



- **Simplest model is just a uniform density jet with sharp edges**
- **Possible that we are looking off the center of the jet, which does not have a uniform density**
- **For the low-energy emission after the initial GRB spike, there may be a “cocoon” of surrounding material that is pulled along by the interior jet**