HMXBs in Gamma-rays and EM Counterparts of GW events: A Fermi Perspective

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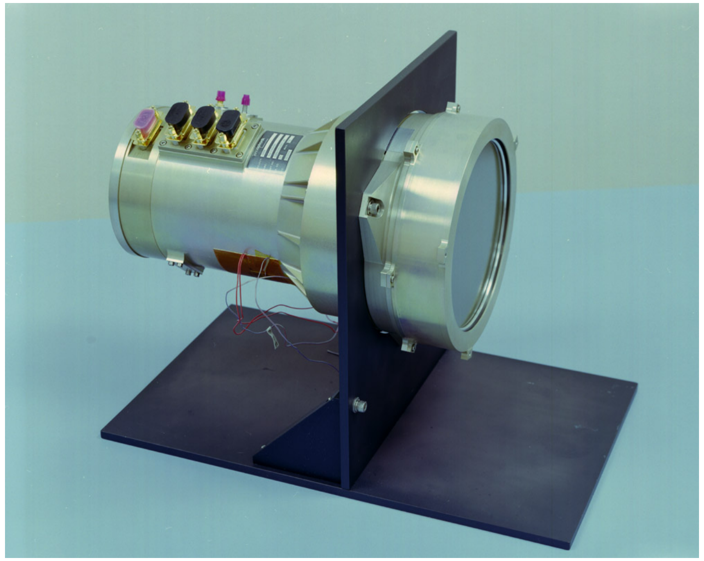
Outline

- HMXBs in gamma-rays with Fermi LAT
- HMXBs in hard X-rays with Fermi GBM
- Electromagnetic counterparts to gravitational wave events
  - GW170817
  - GRB 150101B
  - GW150914
  - Future work
- Summary

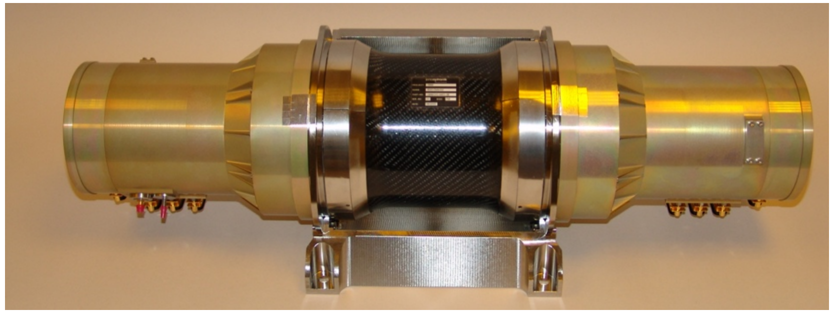
The Fermi Gamma ray Space Telescope

Fermi Gamma ray Burst Monitor (GBM)

NaI Detector
8 keV-1 MeV



BGO Detector
200 keV-40 MeV



Gamma-ray Binaries

- Dozens known compared with hundreds of X-ray binaries
- Basic characteristics
  - Emission > 1 MeV dominates its spectral energy distribution
  - Variable gamma-ray emission, sometimes modulated at orbital period
  - Five types of binaries are seen in gamma-rays
    - HM companion + young ms pulsar (6+1)
      - Only type where gamma-rays dominate emission
    - Microquasars (2)
    - Novae (5)
    - Colliding wind binaries (1)
    - LM companion + recycled ms pulsar
      - 100s known, handful variable in gamma-rays

G. Dubus / C. R. Physique 16 (2015) 661–673

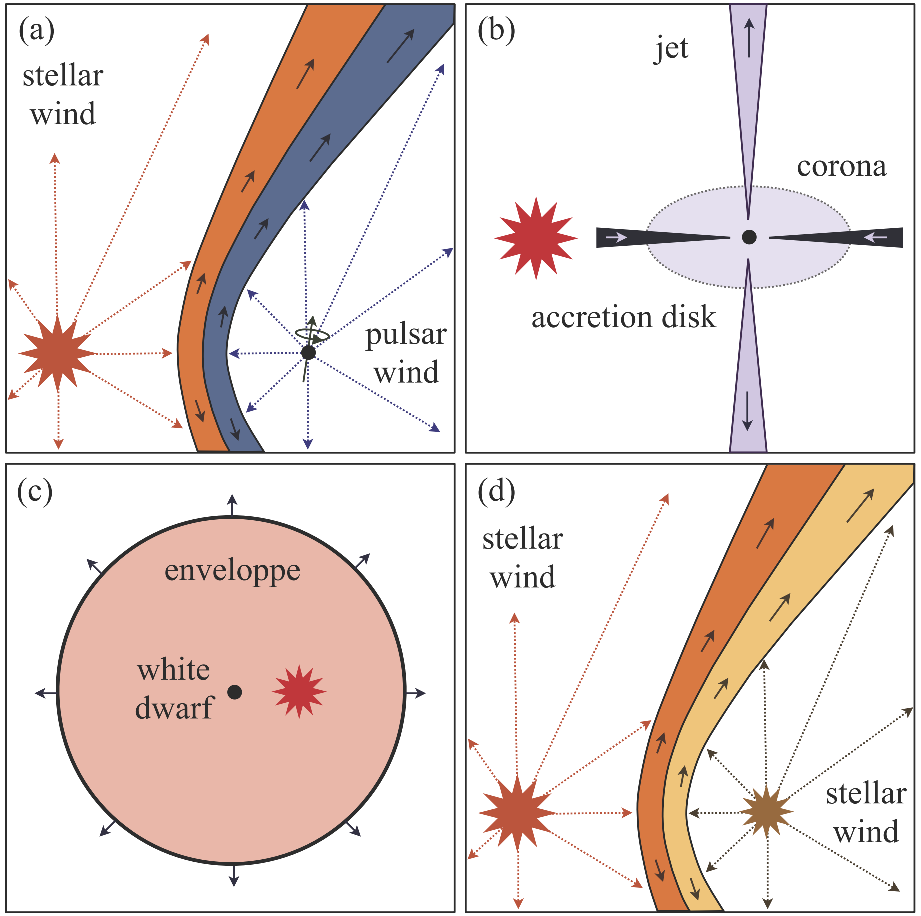


Fig. 1. (Color online.) Sketch of the types of gamma-ray emitting binaries. (a) A high-mass gamma-ray binary, with a rotation-powered pulsar. The filled in region represents the shocked pulsar wind and the shocked stellar wind (panel adapted from [41]). (b) A microquasar, with its accretion disk + corona, and the relativistic jet. (c) A nova, with the expanding ejecta and envelope around the white dwarf. (d) A colliding wind binary, with two stellar winds interacting. The sketches are not to scale.

High Mass Gamma-ray Binaries with Young Pulsars

Name	Pulsar	Companion	P_{orb}	HE	VHE	notes
PSR J2032+4127	140 ms	Be	~50 yr	✔	✔	Pulsations discovered with Fermi LAT
PSR B1259-63	47.7 ms	Be	1236.7 d	✔	✔	
HESS J0632+057	?	Be	315 d		✔	
LS I +61 303	?	Be	26.5 d	✔	✔	
1FGL J1018.6-5856	?	O	16.6 d	✔	✔	
LMC P3	?	O	10.3 d	✔		
LS 5039	?	O	3.9 d	✔	✔	

Adapted from Table 1 in Dubus 2015.

- Only two new gamma-ray binaries discovered with Fermi LAT
- Dubus et al. 2017 predict 101^{+89}_{-52} gamma-ray binaries in Milky Way → up to 10 new ones expected with initial CTA
- Short lived phase of binary evolution – lasting a few 10^5 years
- Likely progenitors to accreting Be/X-ray binaries and Supergiant X-ray Transients

B1259 System Geometry

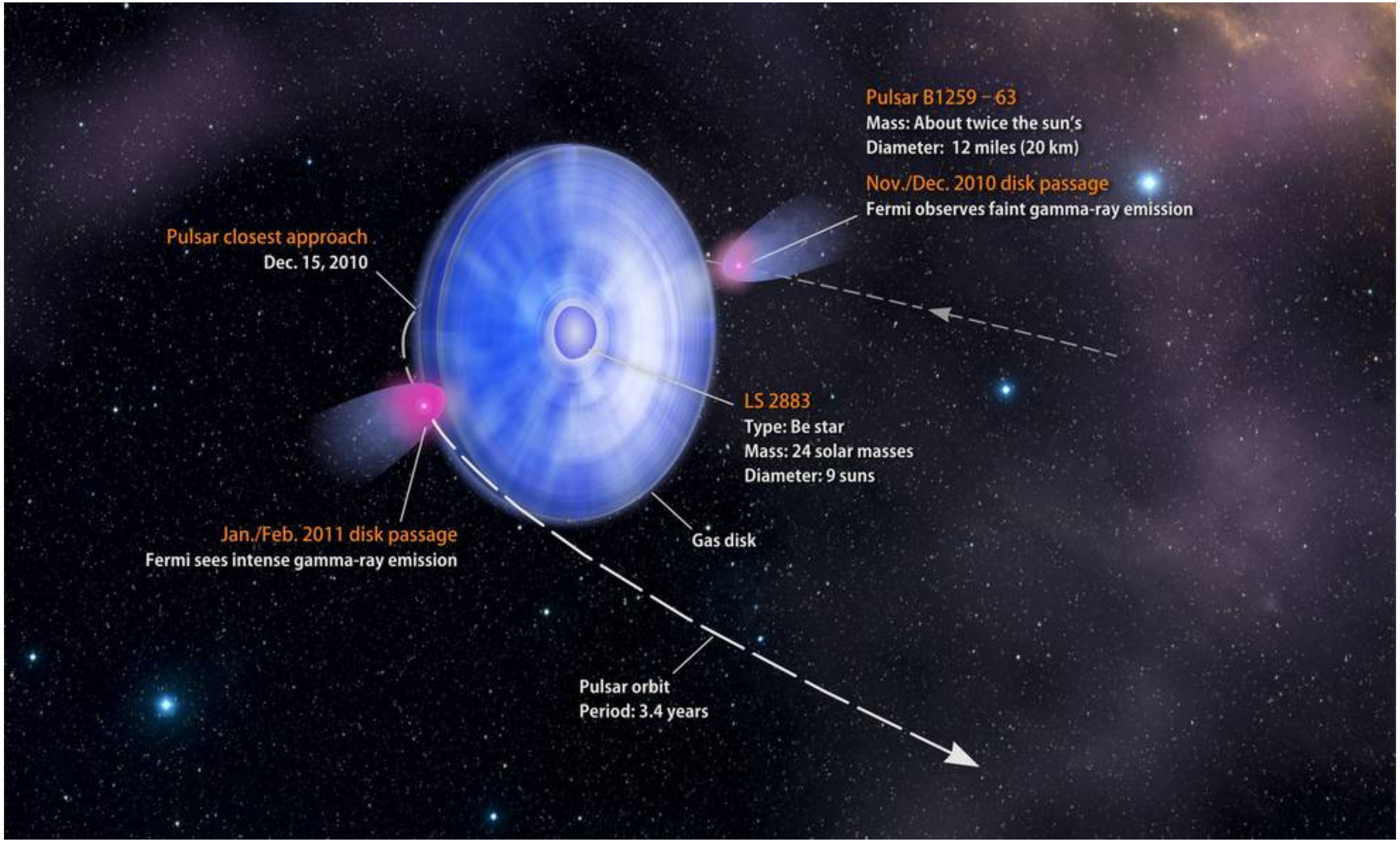
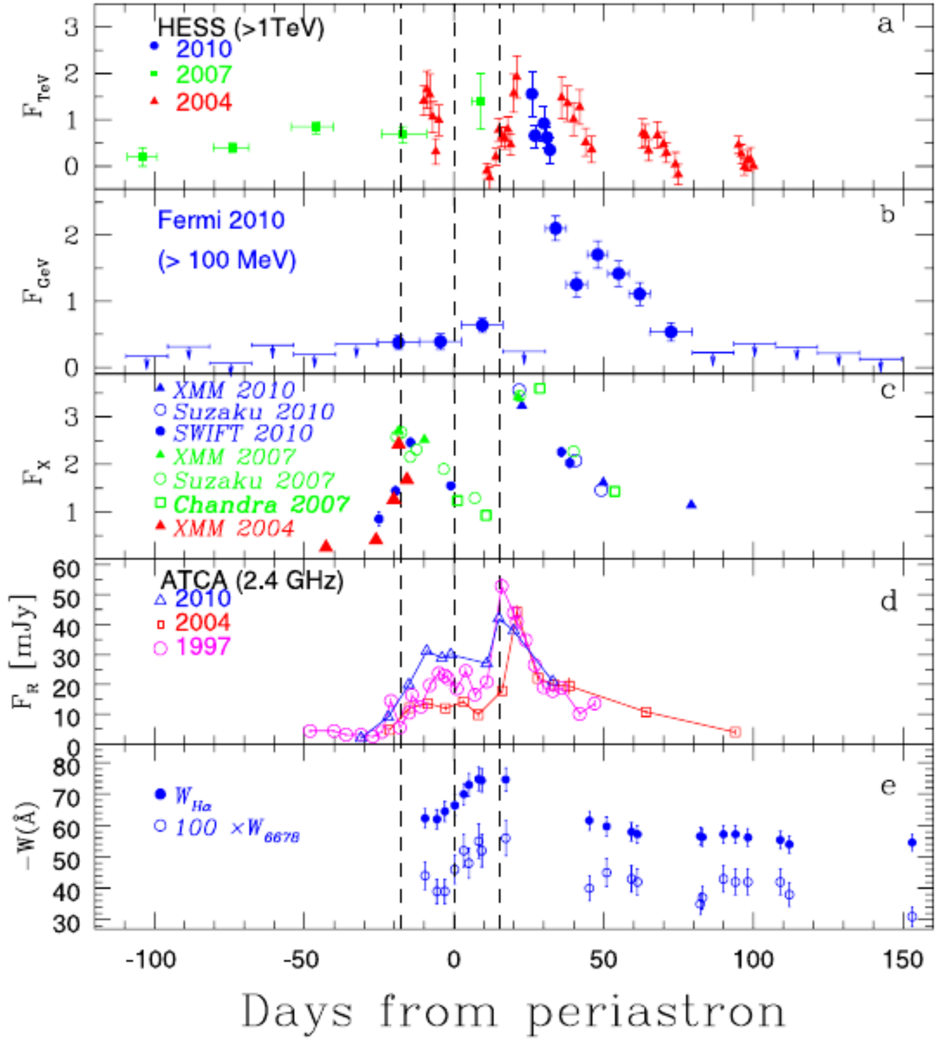


Fig. Credit: NASA

B1259 in the Era of *Fermi*

- First periastron passage *Fermi* observed was late 2010.
- Detections near periastron. Low-significance.
- Unexpected flare ~30 days after periastron.
- Unmatched at other wavelengths.
- Benefit of a survey instrument.
- Hints of curvature, not confirmed
- 2014 and 2017 periastron passages were different, with fastest variability in 2017.

Chernyakova et al. (2014)



LMC P3

- Discovered with 5 years of Fermi LAT data
- Up to 10x more luminous than Galactic sources implies P_{spin} <39 ms
- Massive O5III companion
- Suggests all of gamma-ray binaries in MW have been found

Corbet et al. 2016

CORBET ET AL.

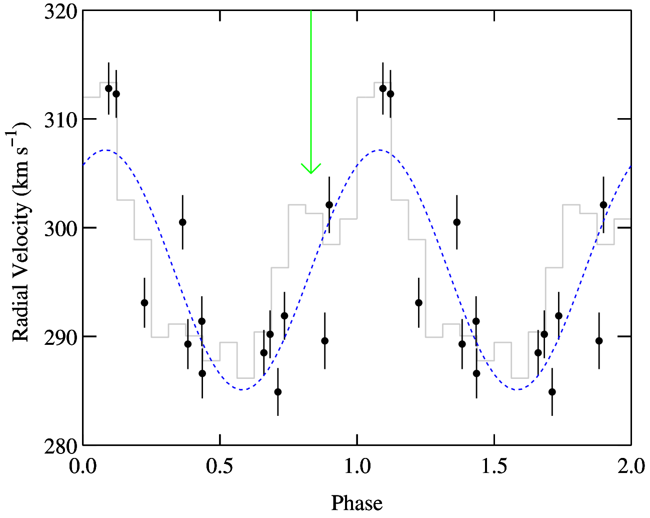


Figure 5. Radial velocity measurements of the optical counterpart of CXOU J053600.0–673507, that was obtained with SOAR (plotted as filled circles with error bars) folded on the 10.3 day orbital period. The arrow indicates the time of superior conjunction, determined from a fit to the radial velocity measurements (MJD 57408.61 ± 0.28). The gray histogram shows the gamma-ray flux measured with the LAT.

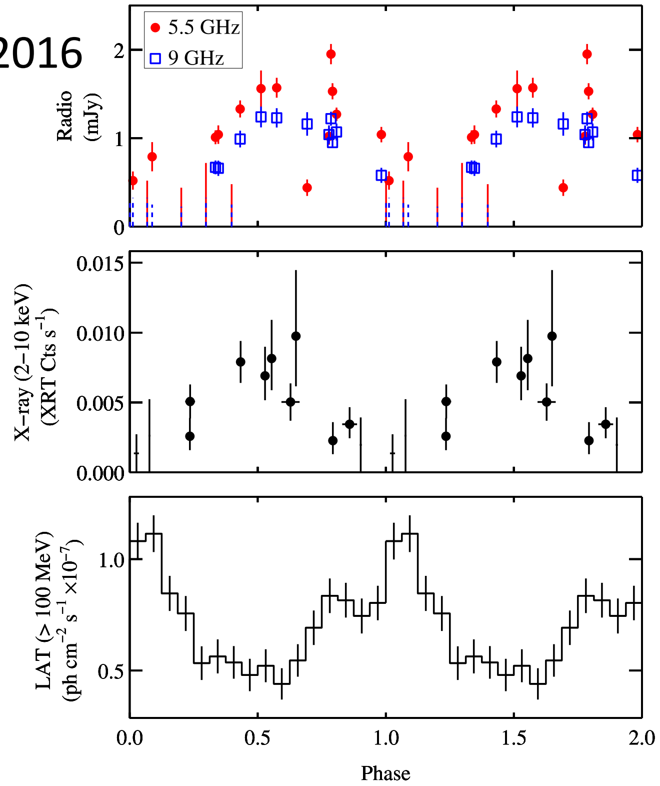
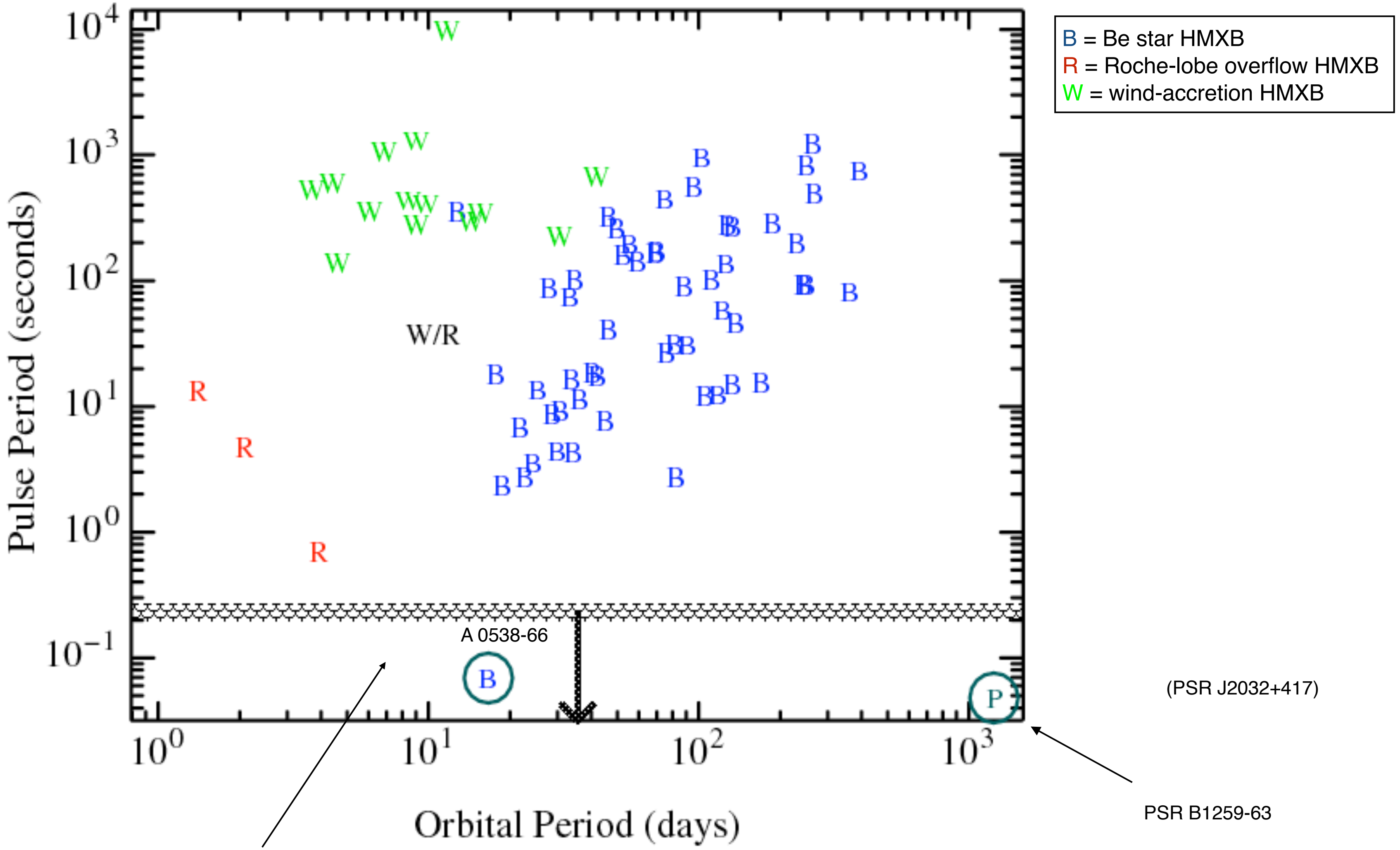


Figure 3. Radio (top), X-ray (middle), and gamma-ray (bottom) fluxes from LMC P3/CXOU J053600.0–673507, folded on the 10.3 day period. Phase zero is the time of maximum flux for sinusoidal modulation of the gamma-ray flux and corresponds to MJD 57,410.25. For the radio flux densities, the lines extending down to zero indicate 4σ upper limits. For the X-ray, the three lines extending down to zero show 3σ upper limits.

Are HMXBs Born as Gamma-ray Binaries?

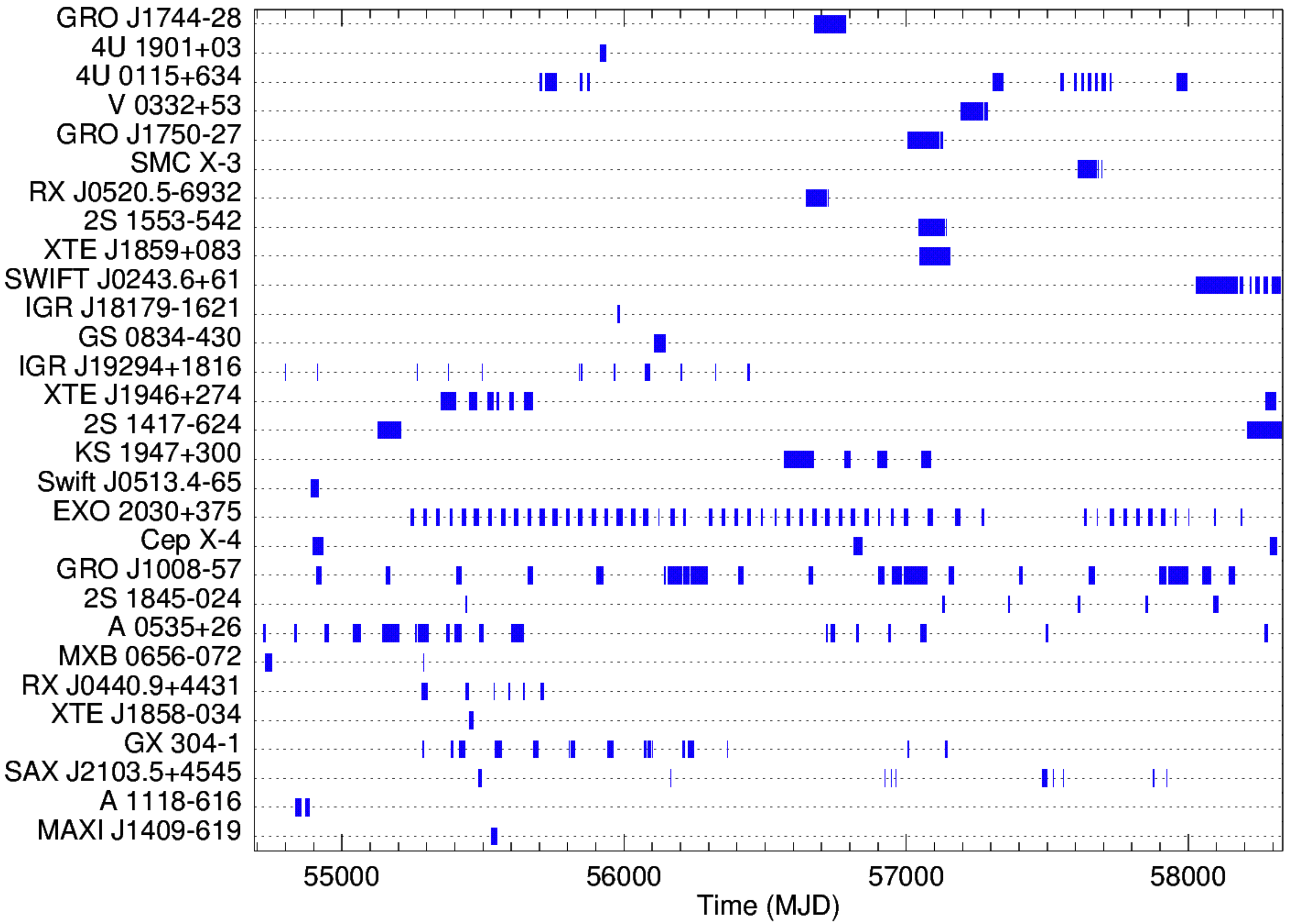


HMXBs containing neutron stars may begin as gamma-ray binaries with rapidly rotating neutron stars before spinning down.

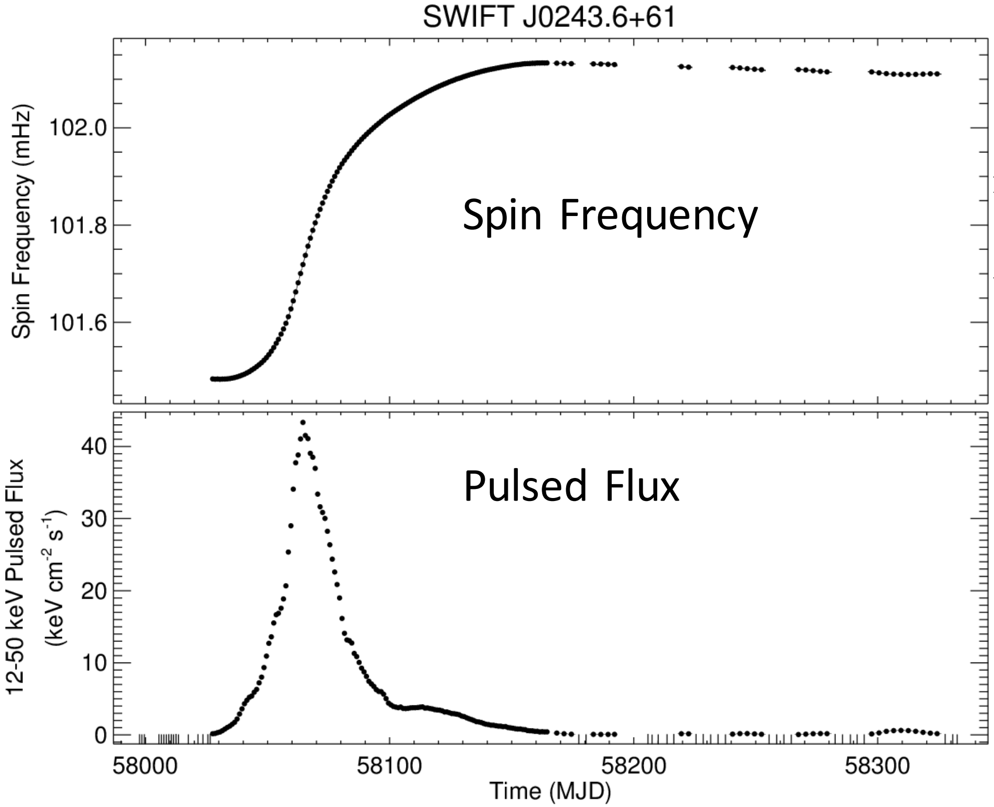
Corbet et al. 2017

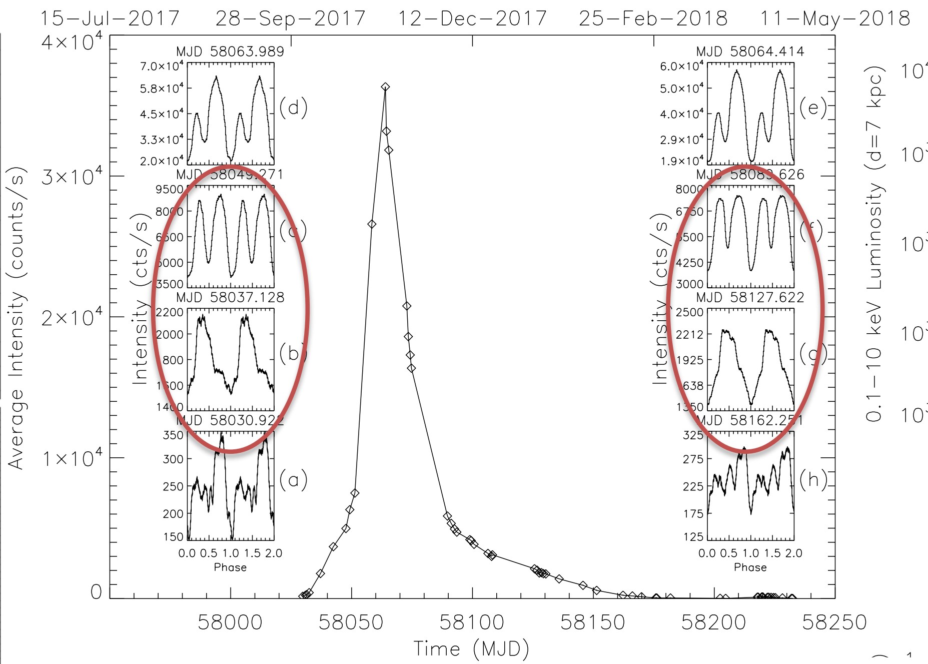
HXMB Pulsars with Fermi GBM
https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html

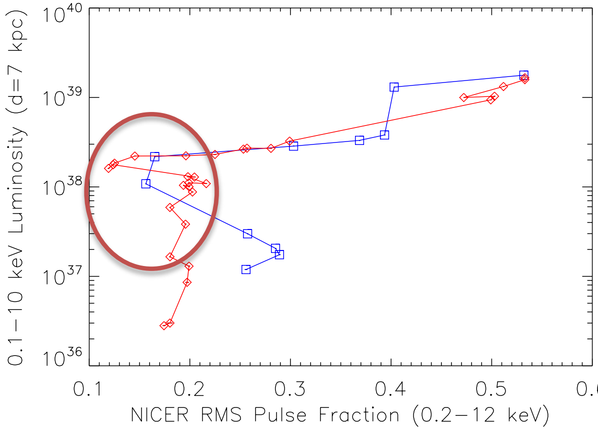
- Daily Blind Search
  - 24 source directions on galactic plane + SMC and LMC
- Source specific searches
  - Narrow spin-frequency range
  - Typical exposures are ~40 ks/day
- Detections
  - Total of 40 systems monitored
  - 8 of 8 persistent sources
  - 29 of 32 transients



Swift J0243.6+6124: First Galactic ULX Pulsar



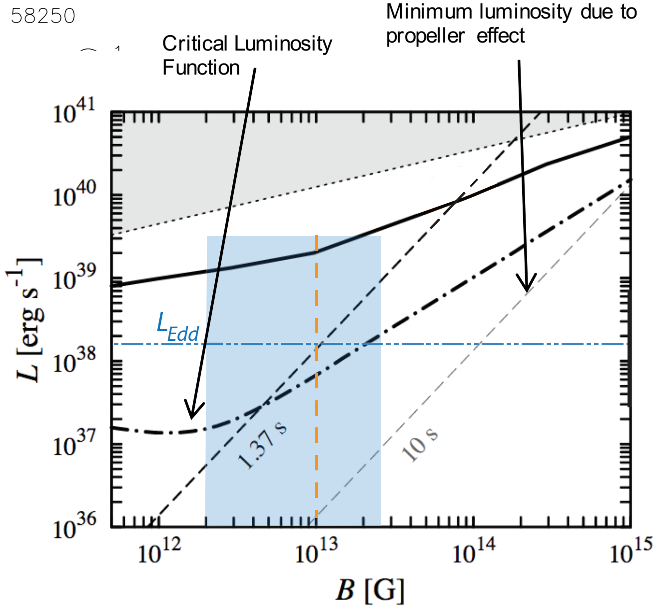




Orbital Parameters	
Orbital Period	27.656100 days
Period Deriv.	0.0000E+00 days/day
$T_{\pi/2}$	2458116.13686 (JED)
axsin(i)	116.860 light-sec
Long. of periastron	-73.93 deg
Eccentricity	0.0964

- P_{spin} 9.86 s
- Be star companion
- d = 5.7-8.4 kpc
- L_{peak} =2 x 10^{39} erg/s (0.1-10 keV)

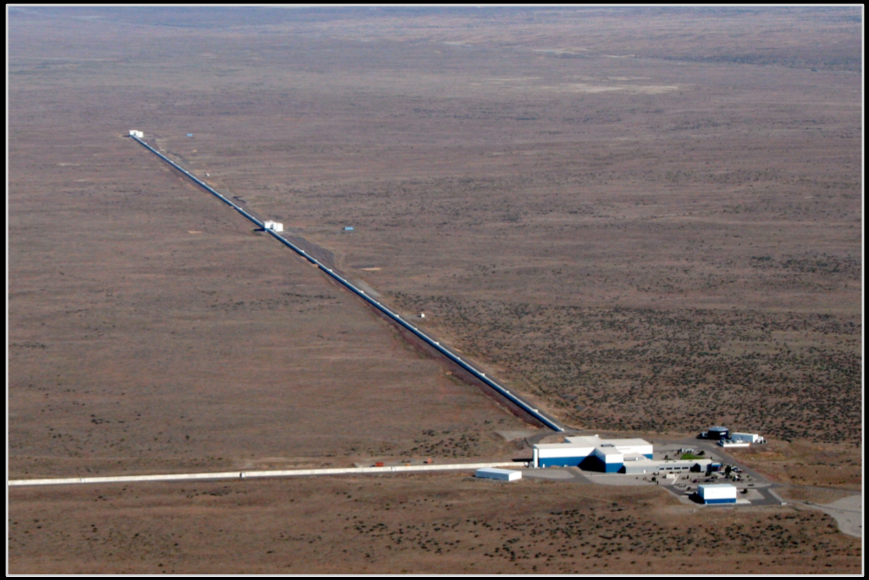
Wilson-Hodge et al 2018



LIGO and Virgo Gravitational Wave Observatories

LIGO
Livingston
Louisiana

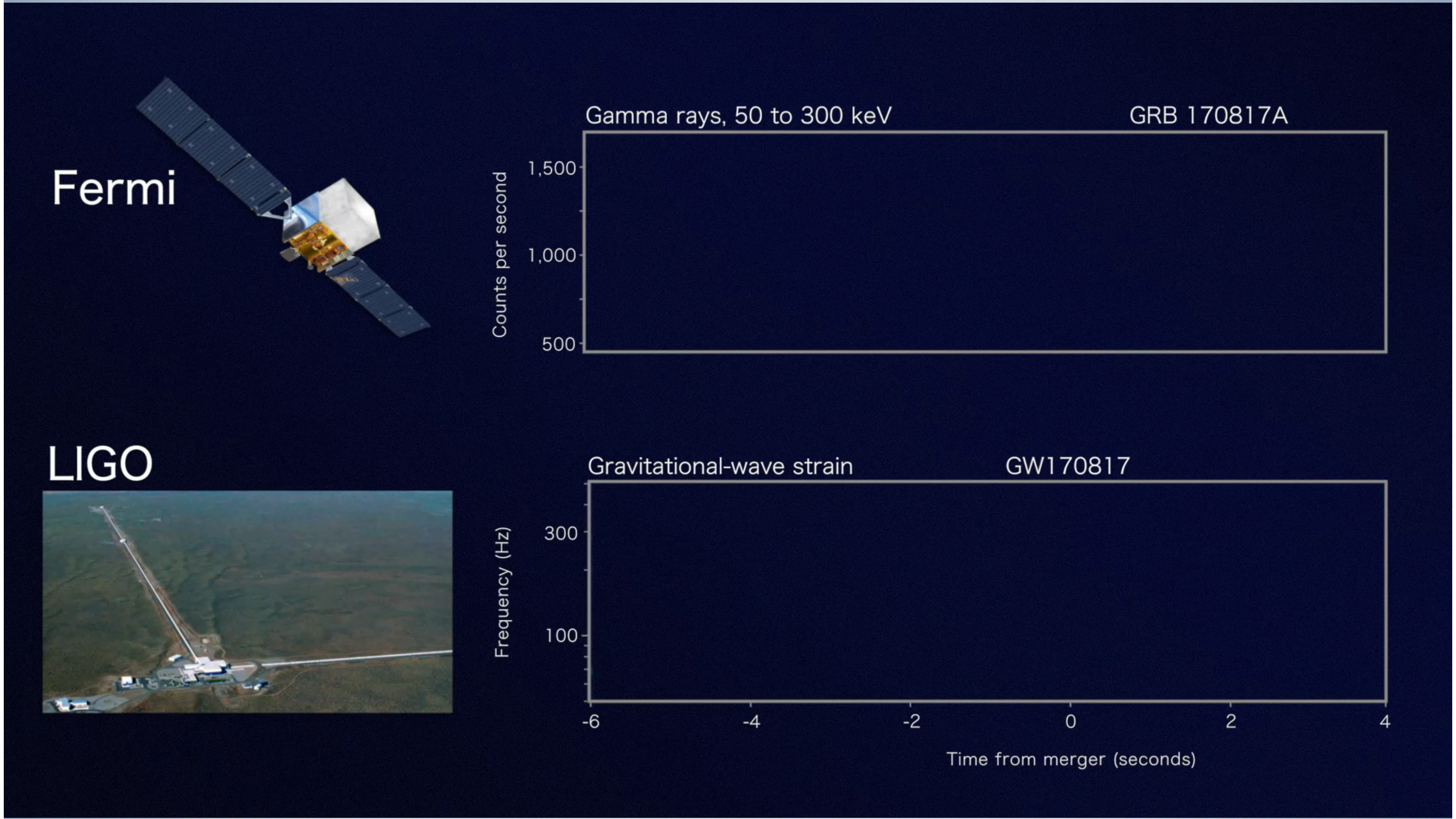
LIGO
Hanford
Washington



Virgo
Pisa
Italy

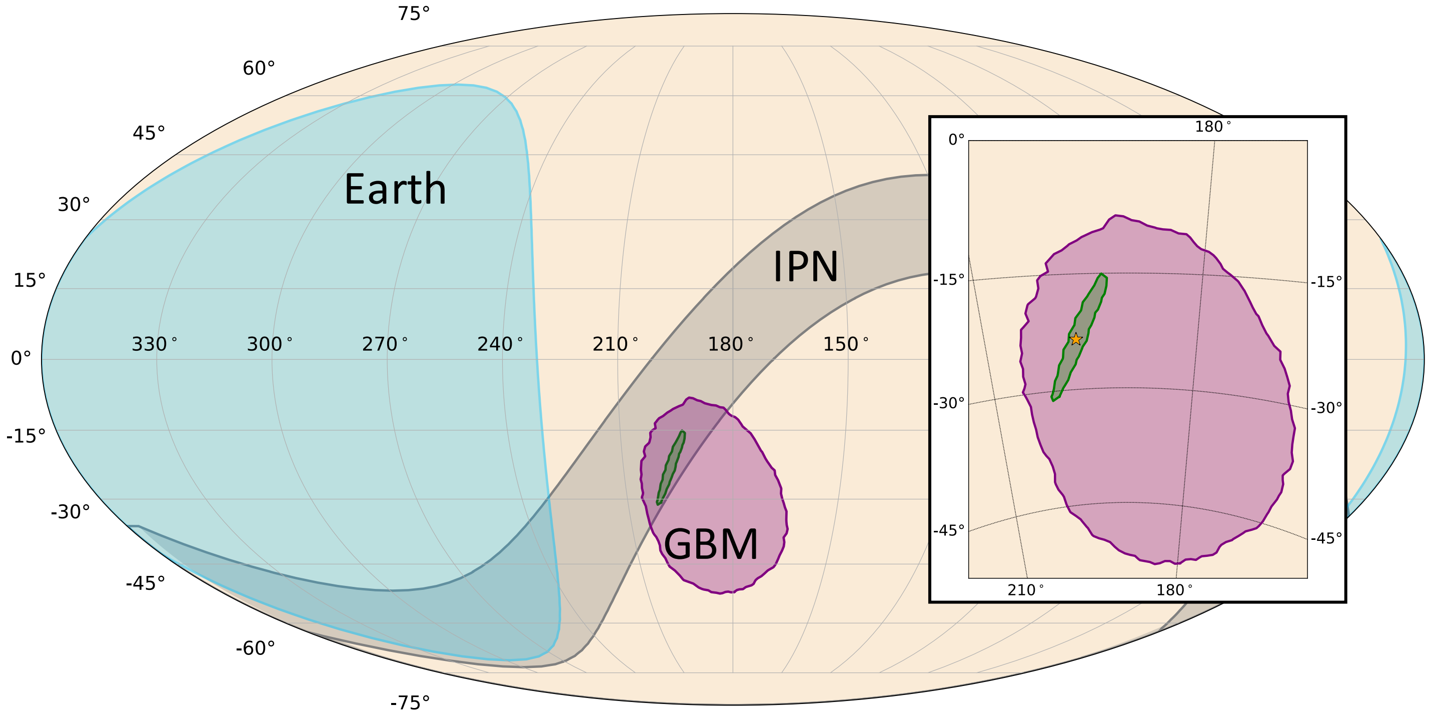
Image credits: Caltech/MIT/LIGO

The morning of August 17, 2017



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

Locating the events on the sky



Abbot et al. 2017, ApJ, 848, L13

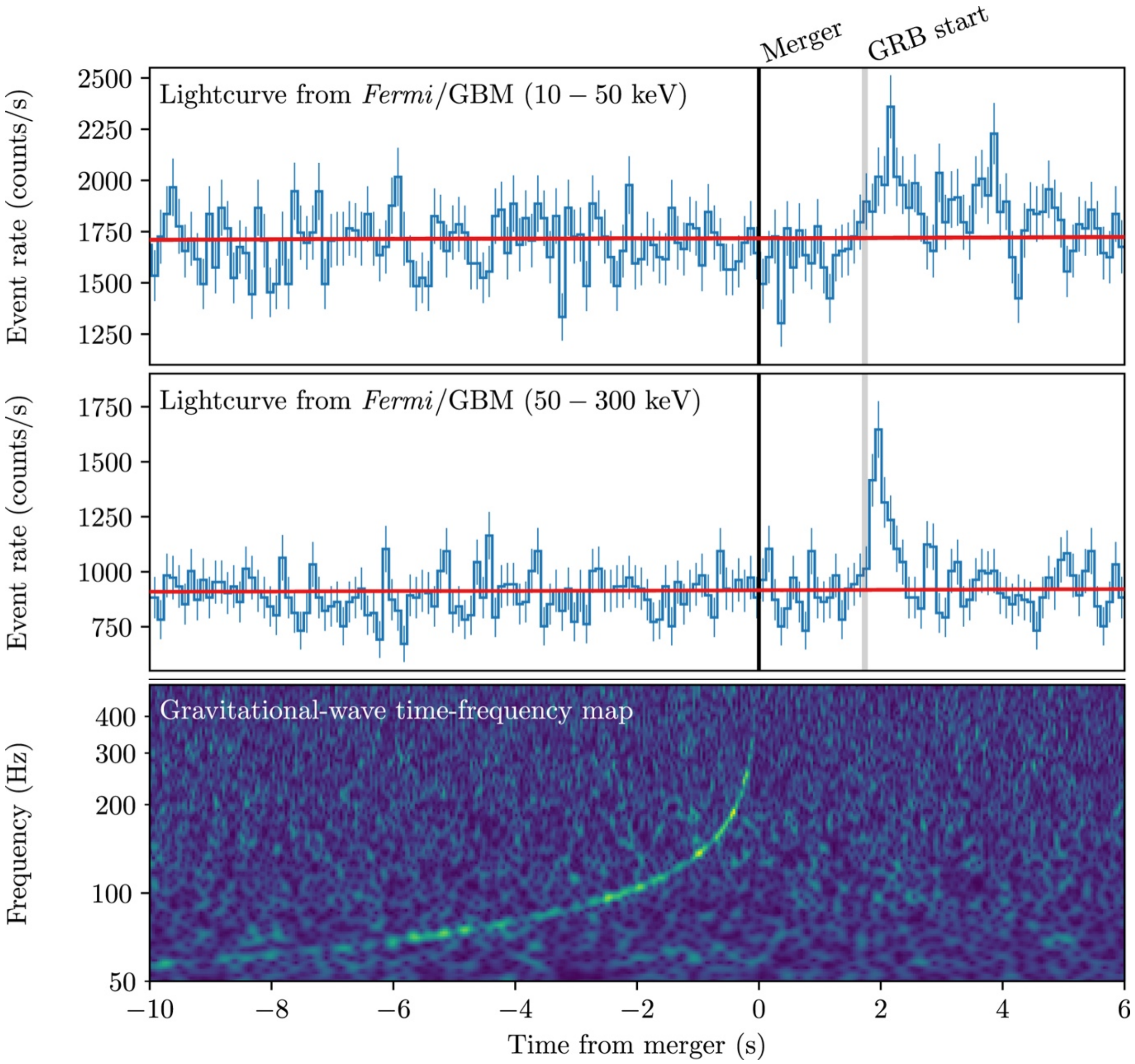
Probability of chance coincidence: 1 in 20,000,000

GRB 170817A: A short burst with a weak low-energy tail

Low energy tail

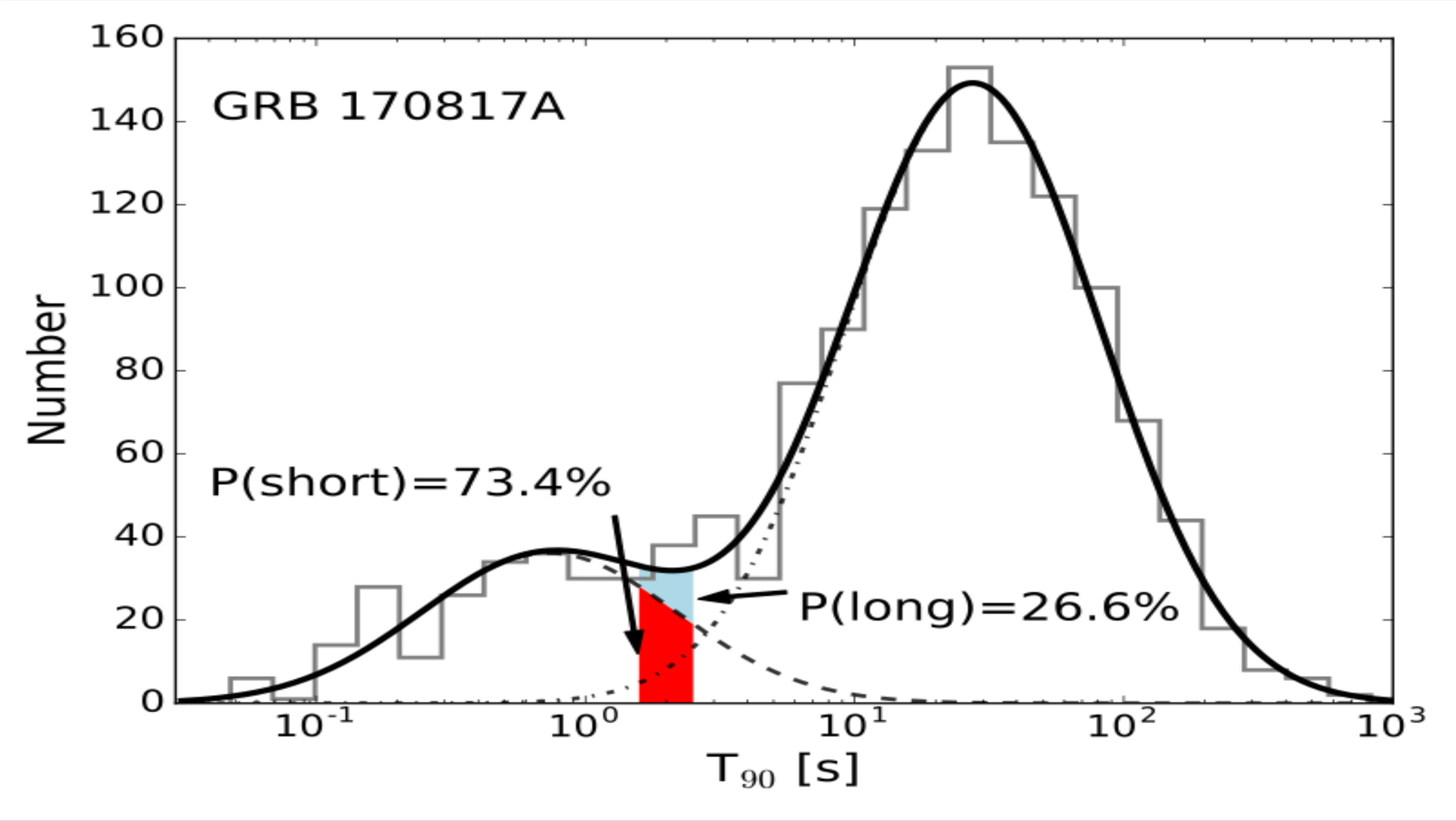
Typical spike

Gravitational Wave signal



Abbot et al. 2017, ApJ, 848, L13

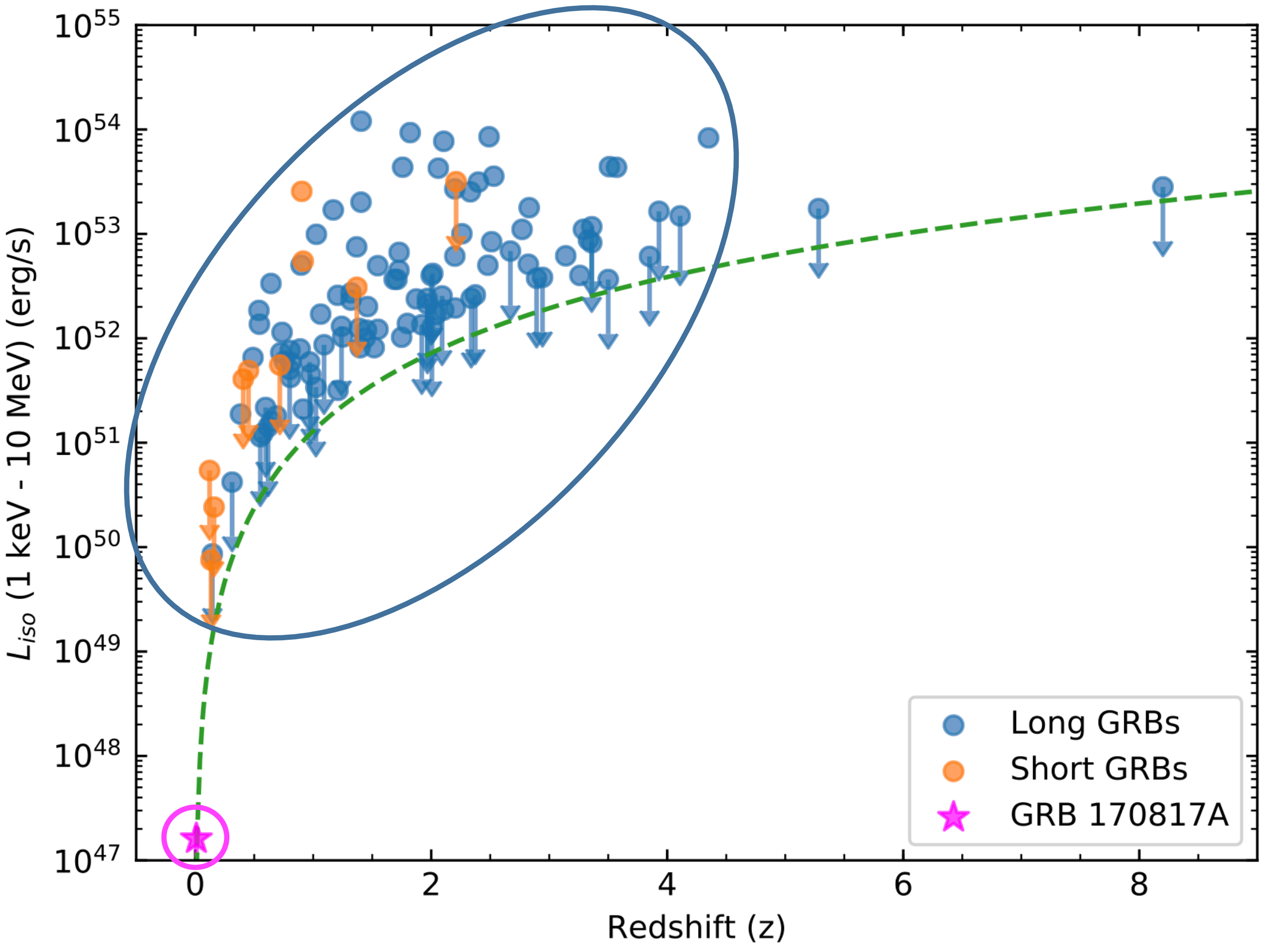
GRB 170817A: a short GRB



GRB 170817A is a short GRB—predicted to originate from mergers

Goldstein et al. 2017, ApJ, 848, L14

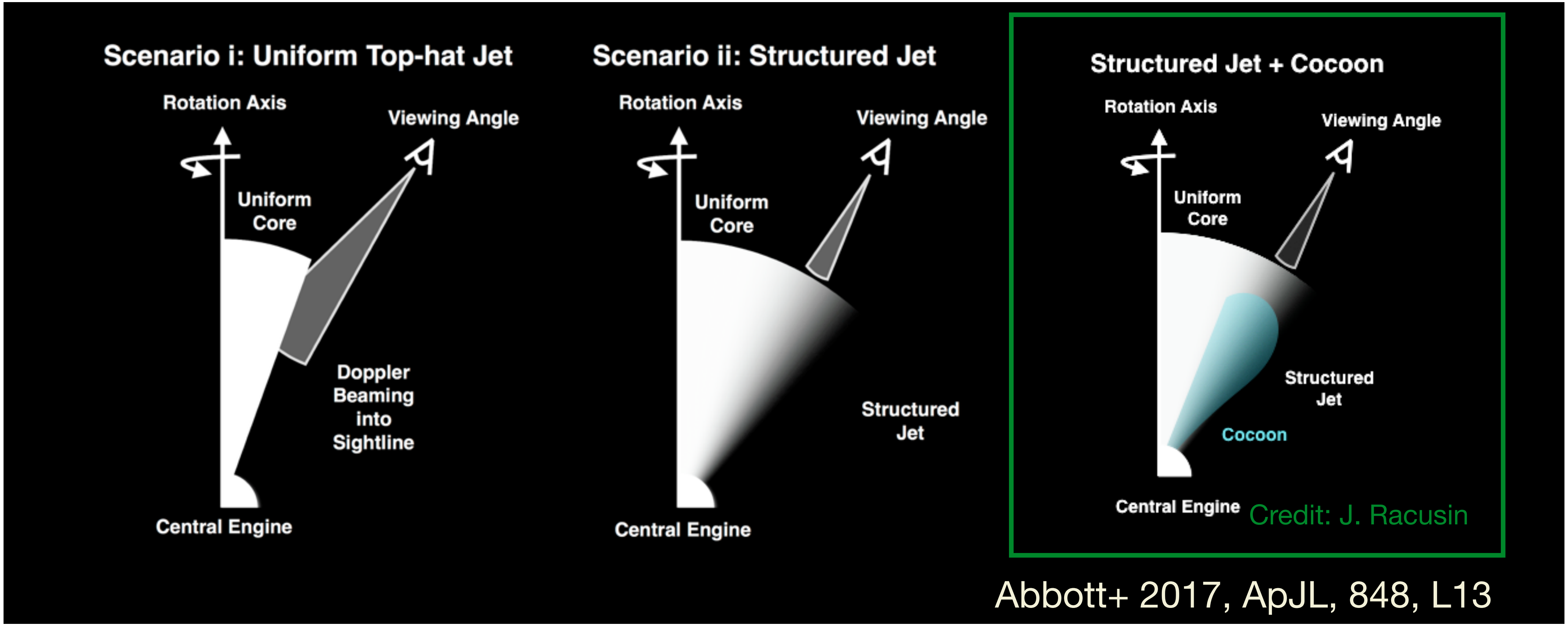
GRB 170817A: Faintest GRB with known distance



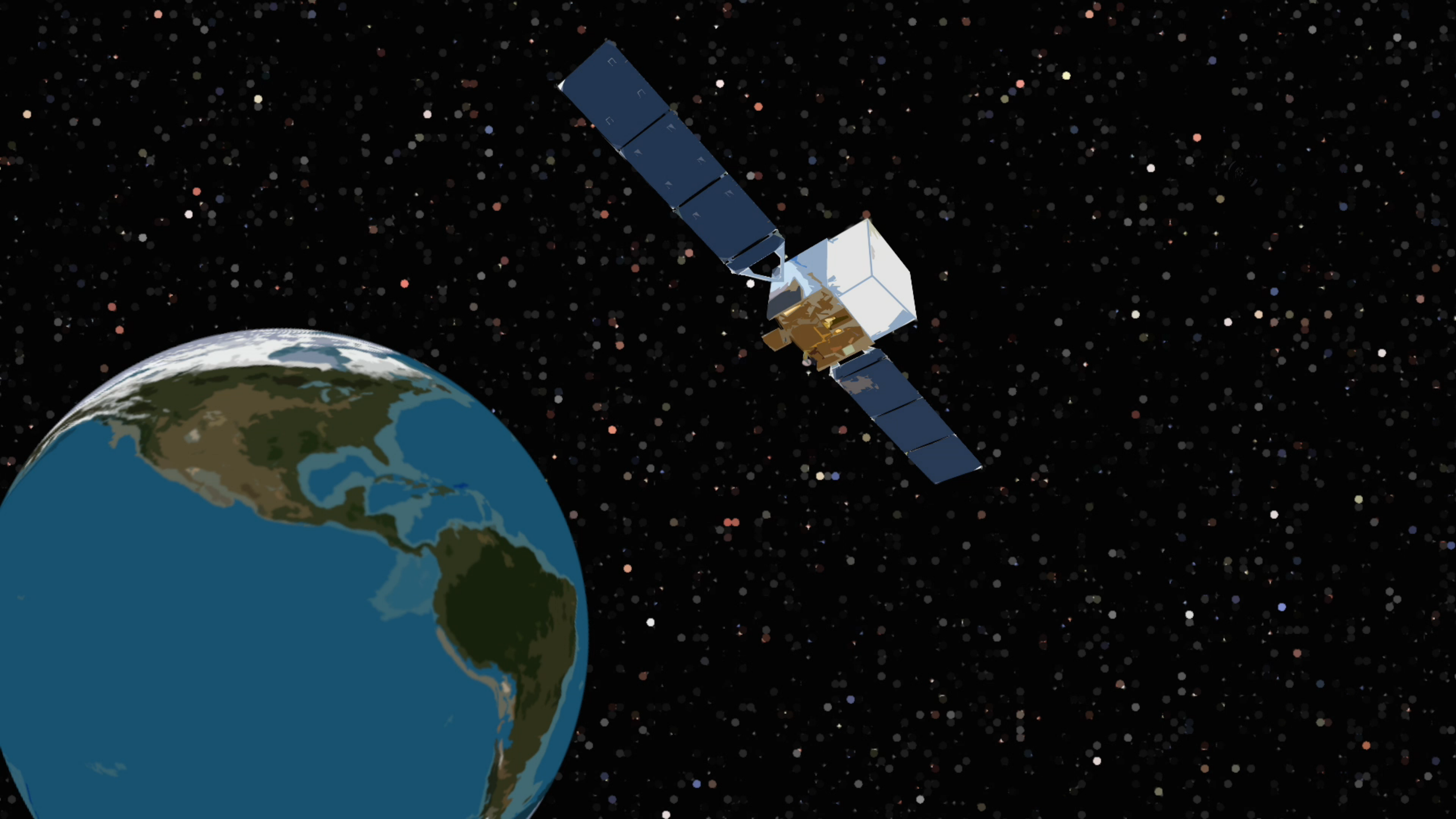
Nearby: Only 130 million light years away!

Abbot et al. 2017, ApJ, 848, L13

GRB Observing Scenarios



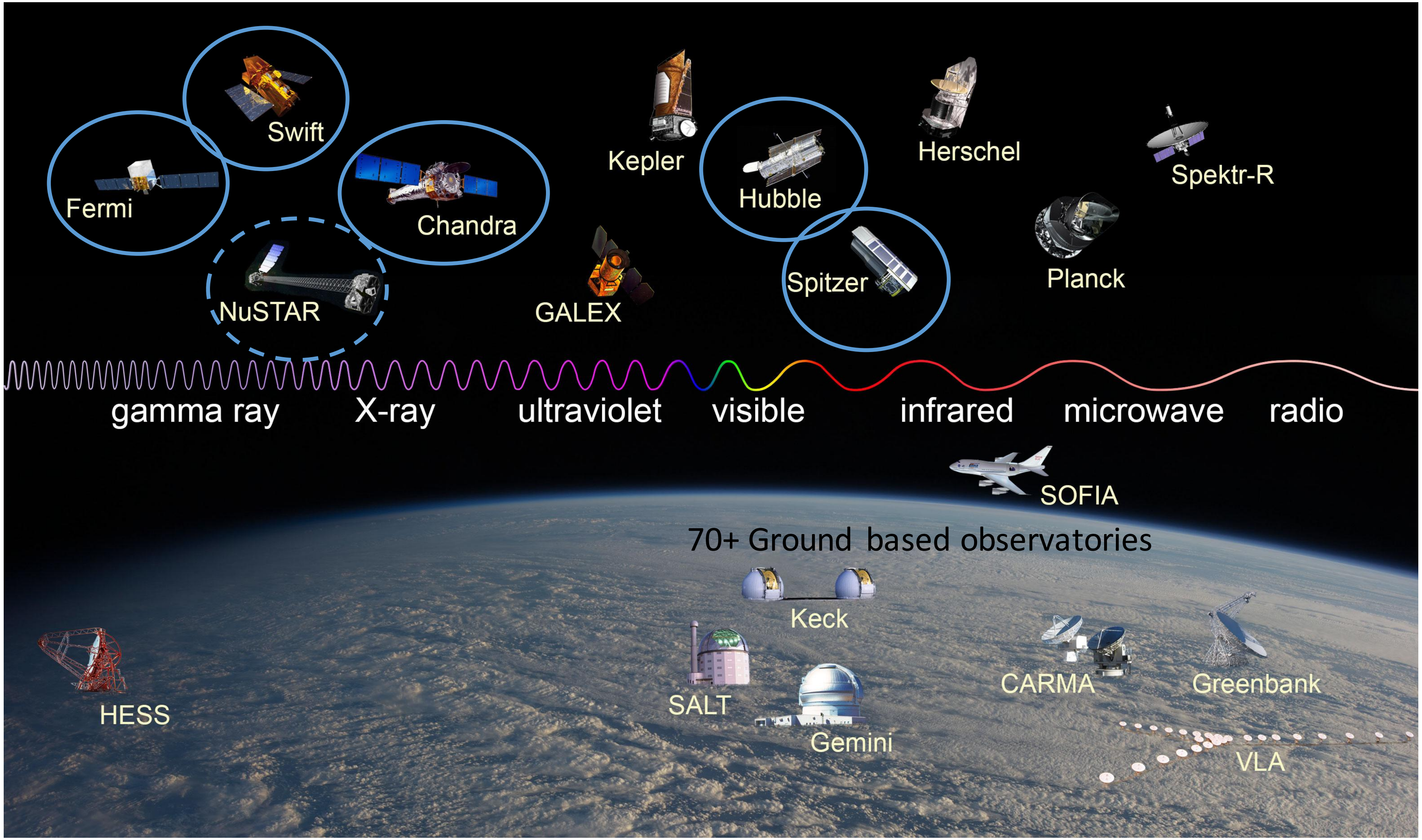
- Viewing Angle <36 deg off-axis (20+/-5 Mooley et al. ArXiv:1806.09693)
- Unlikely to be observed down the center of the jet (on-axis)
- Could be a structured jet with "wings" of shocked material (e.g. Lazzati et al. 2018
- Could be a shock breakout from a "chocked" trans-relativistic jet (e.g. Gottleib et al 2018)



Science from GW170817 and GRB 170817A

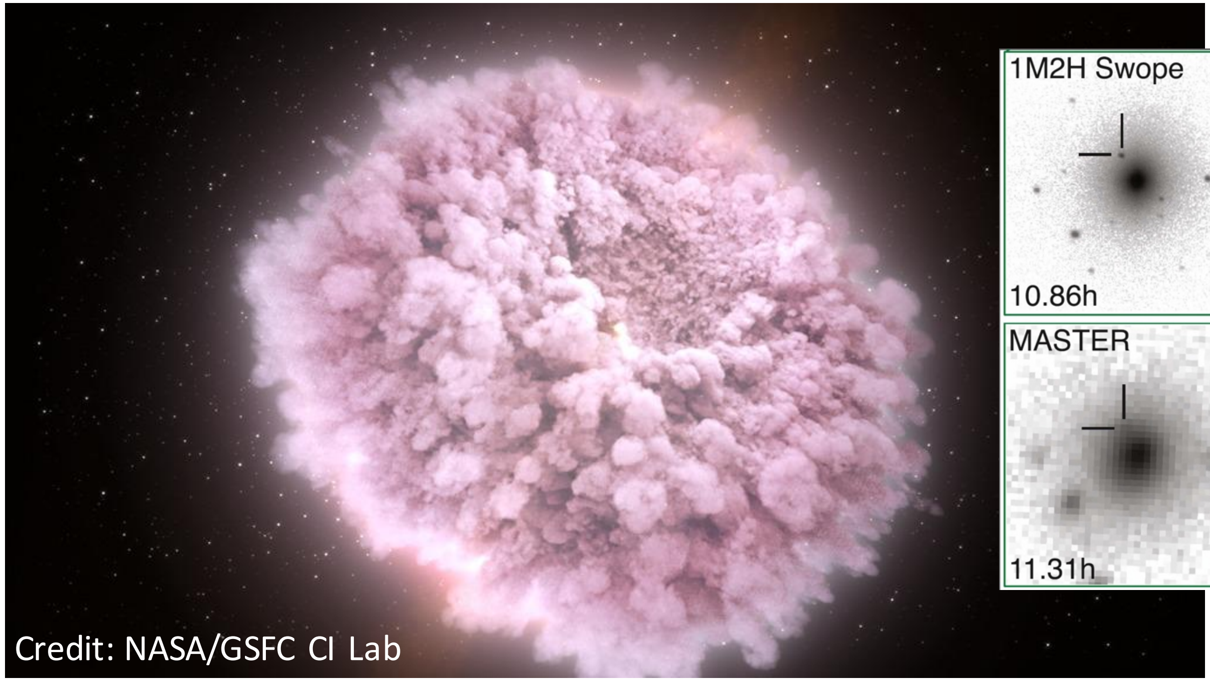
- Directly measure the speed of gravity
  - It is the same as the speed of light within one part in one quadrillion!
- Probe the neutron star equation of state: the densest matter in the universe!
- Understand the emission physics of relativistic jets and the engine that produces the short GRB
- Estimate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

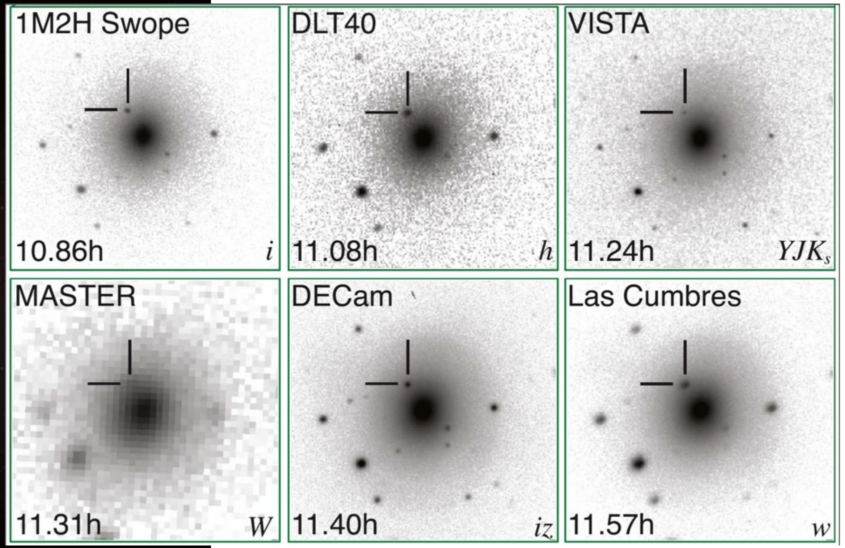
NASA Missions Observing GW170817/GRB 170817A



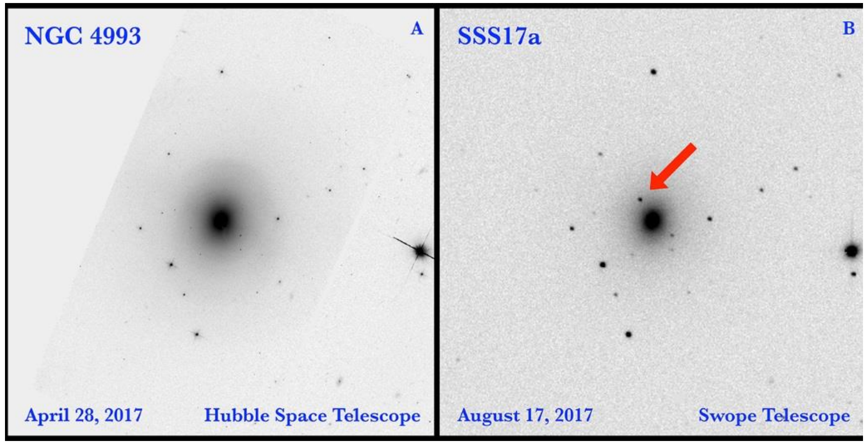
Credit: Observatory images from NASA, ESA (Herschel and Planck), Lavochkin Association (Specktr-R), HESS Collaboration (HESS), Salt Foundation (SALT), Rick Peterson/WMKO (Keck), Gemini Observatory/AURA (Gemini), CARMA team (CARMA), and NRAO/AUI (Greenbank and VLA); background image from NASA

Discovery of a Kilonova 12 hours later

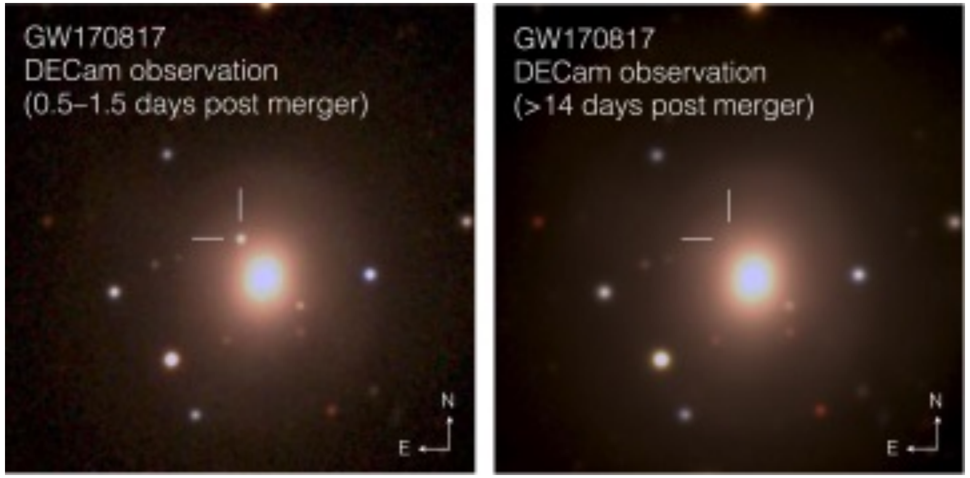




Abbot et al 2017, ApJL, 848, L12

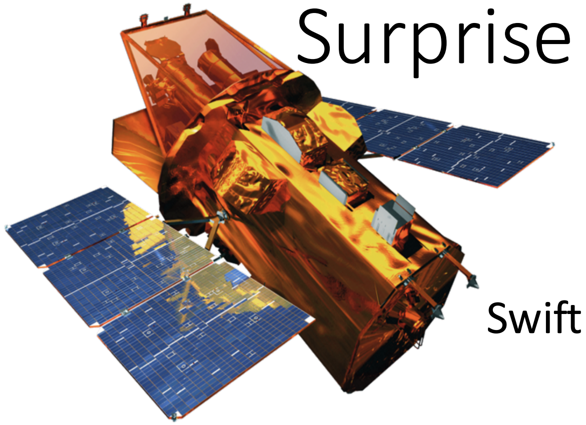


Coulter et al. 2017, 10.1126/scienceaap9811

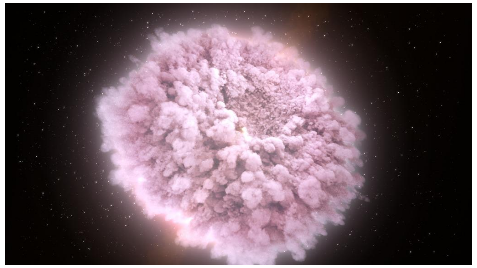


Soares-Santos et al. 2017, ApJ, 848, L16

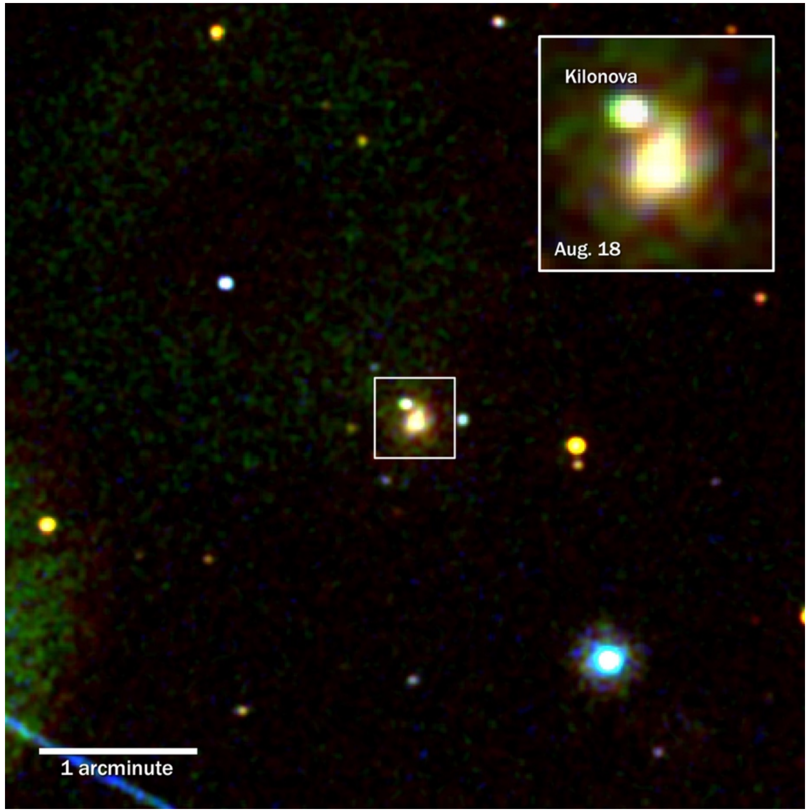
Surprise! – a bright UV source with Swift



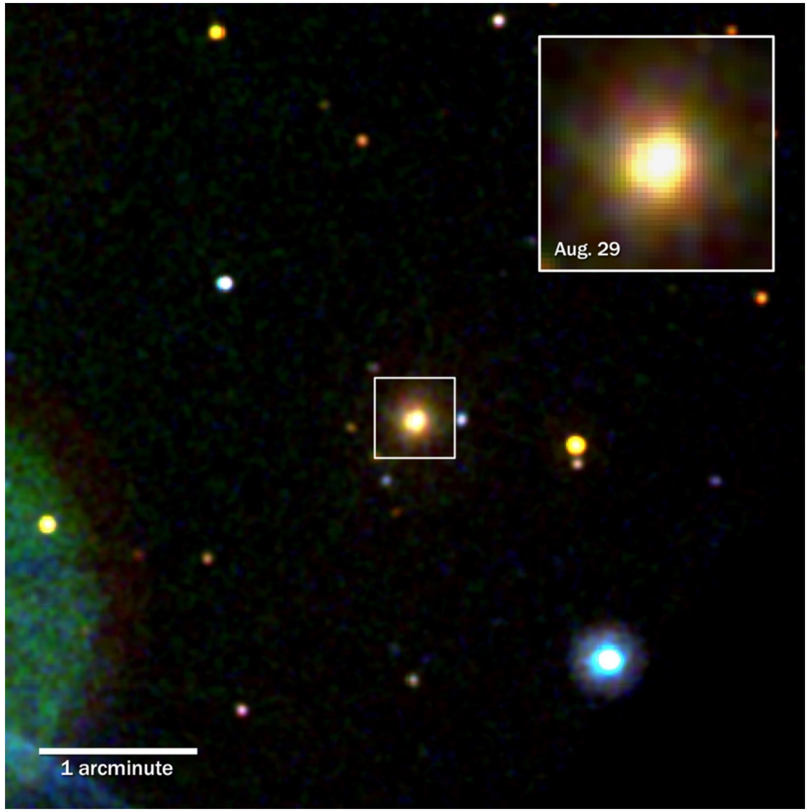
Swift



Aug 18

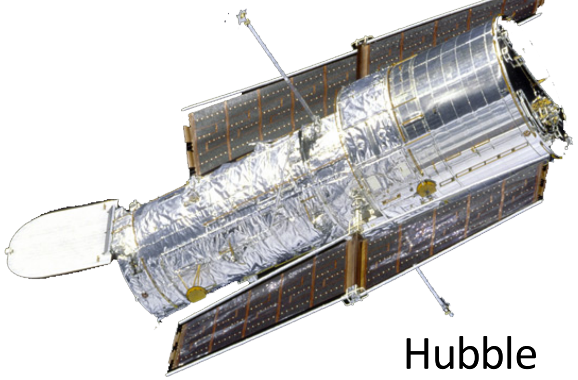


Aug 29

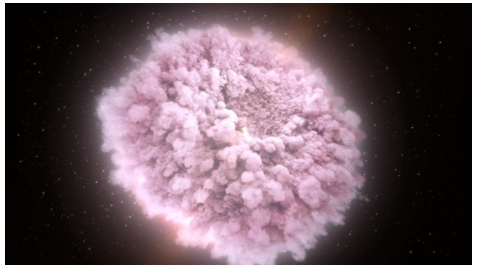


Credit: NASA/Swift

Fading Kilonova in Optical/IR



Hubble



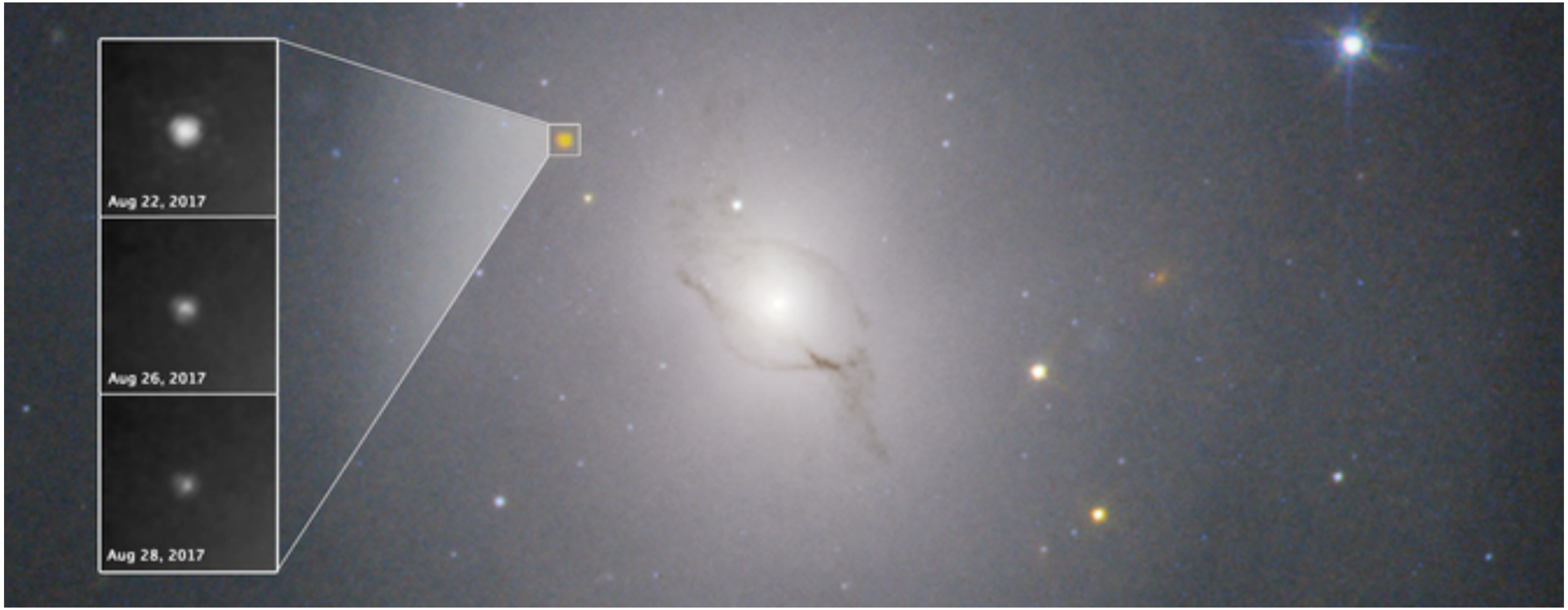
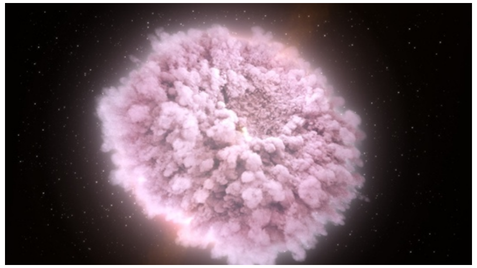


Image Credit: NASA and ESA, Acknowledgment: A. Levan (U. Warwick), N. Tanvir (U. Leicester), A. Fruchter and O. Fox (STScI)

IR Observations – Sep 29, 2017

Spitzer



Composite image

Filtered Image

Host galaxy subtracted

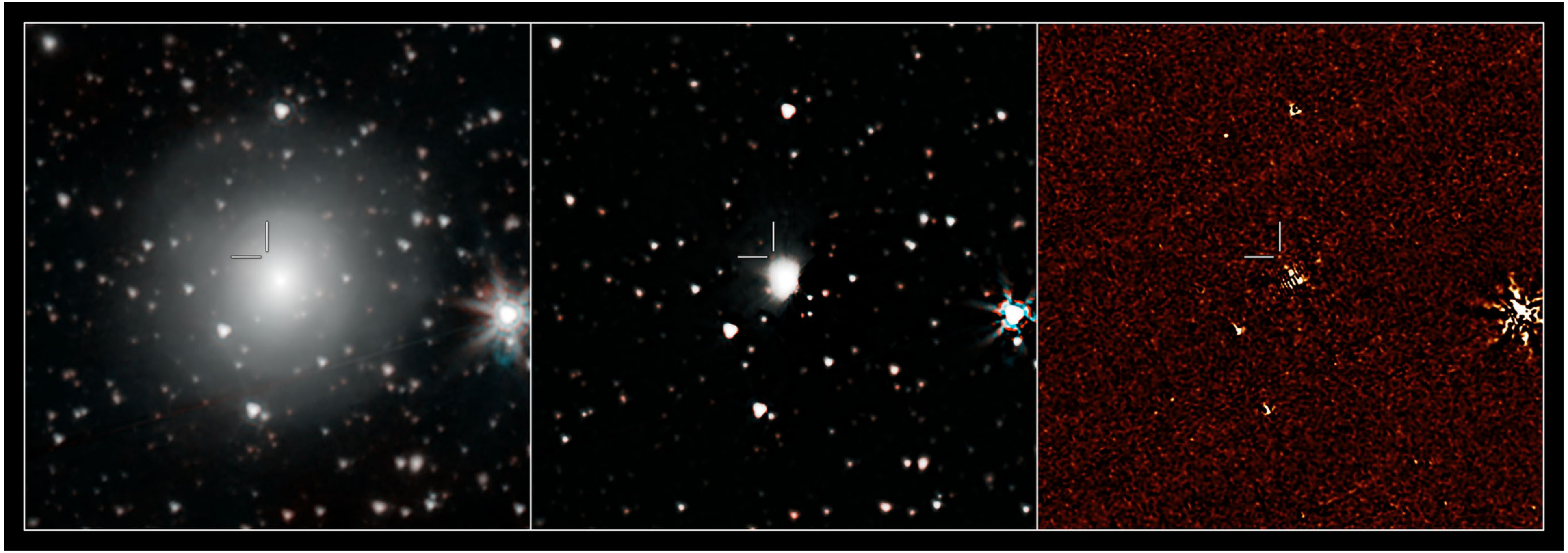
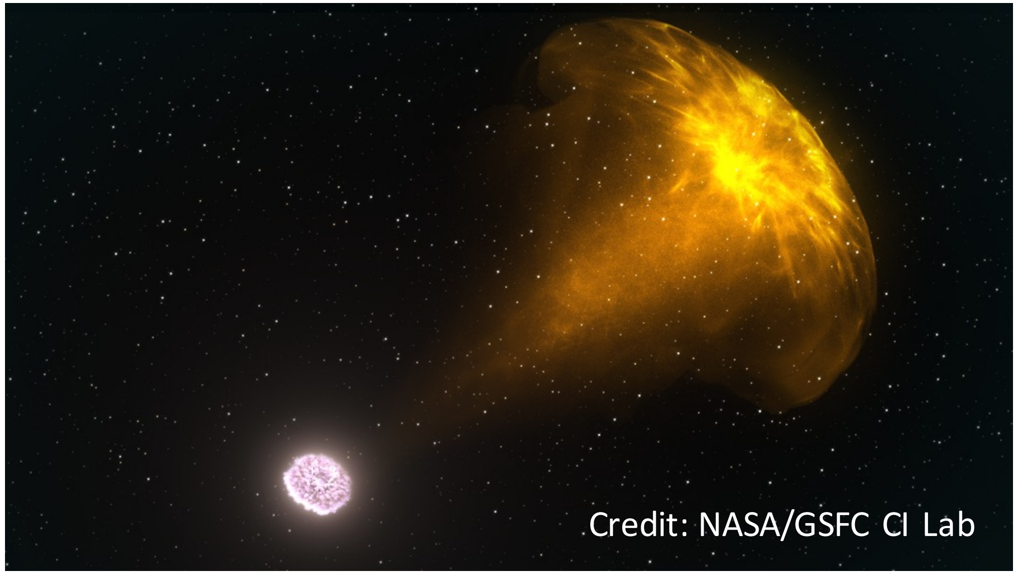
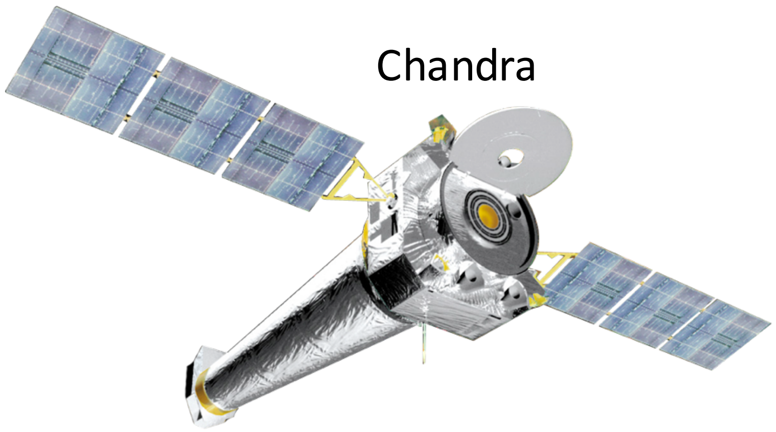


Image Credit: NASA/JPL-Caltech

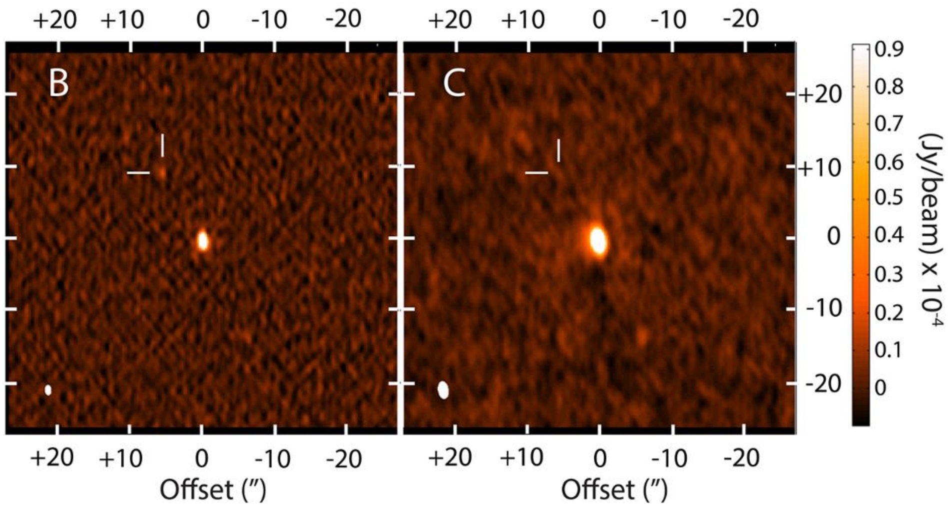
X-ray and Radio Observations





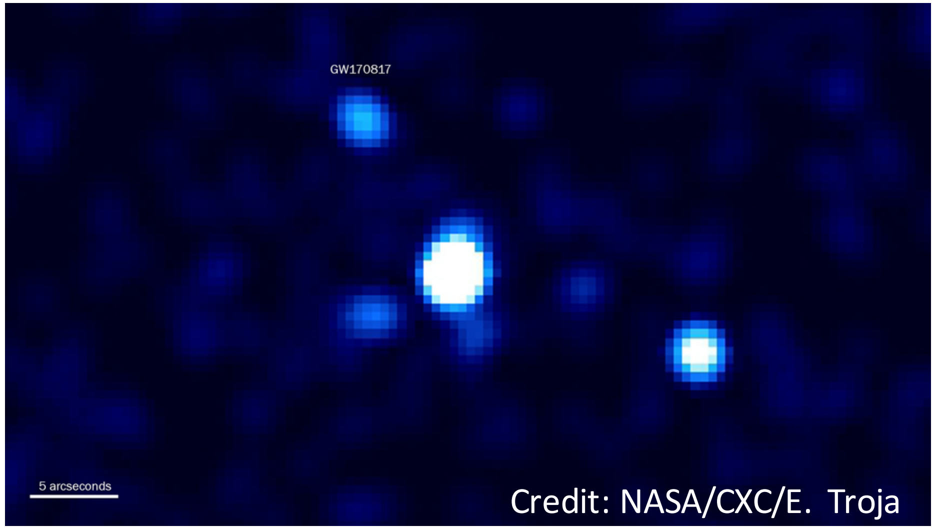
Credit: NASA/GSFC CI Lab

Radio VLA (B) Sep 9 (C) Aug 22-Sep1



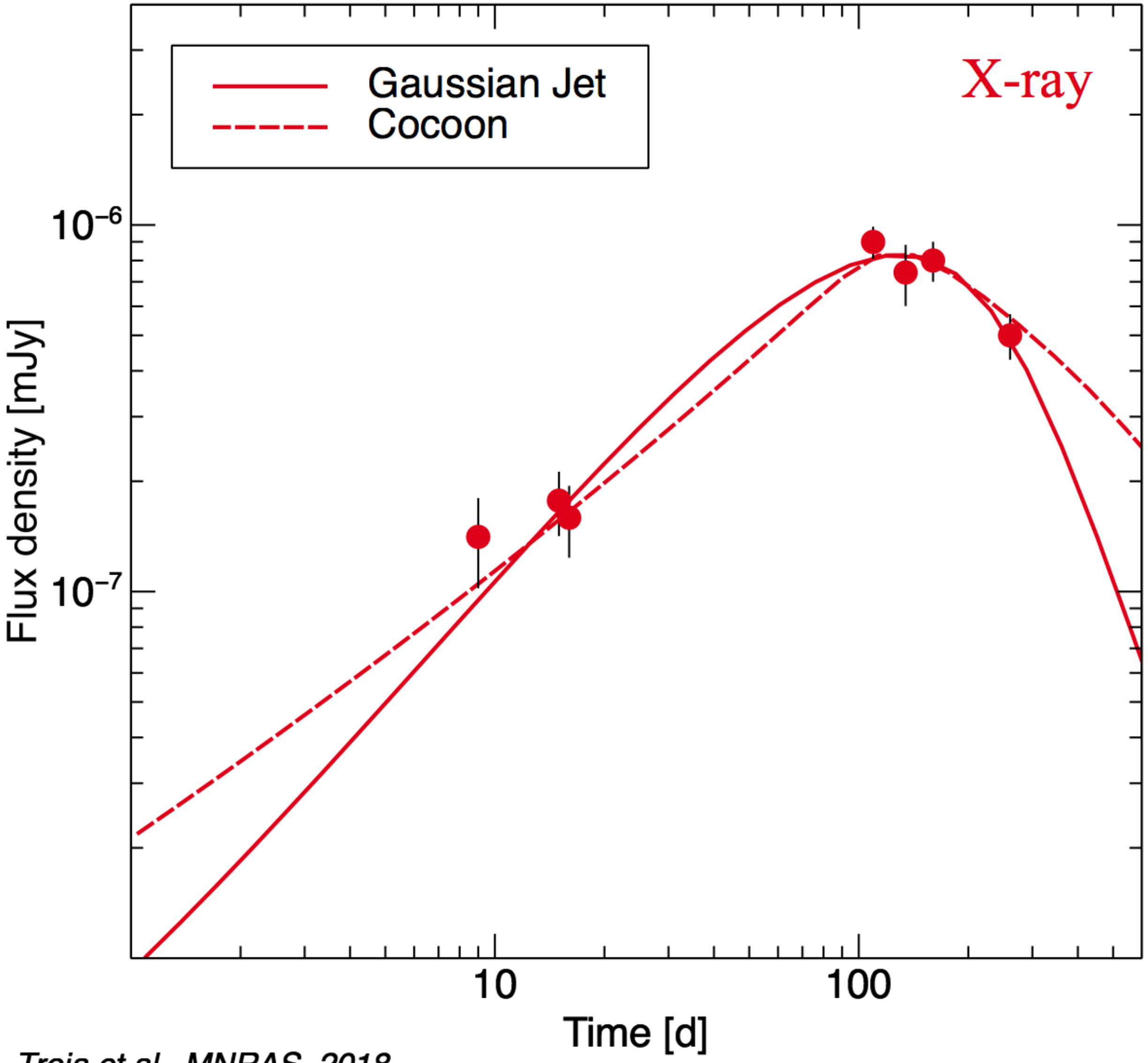
Hallinan et al., Science 10.1126/science.aap9855 (2017)

X-ray Aug 26, 2017



X-ray afterglow is finally starting to fade!

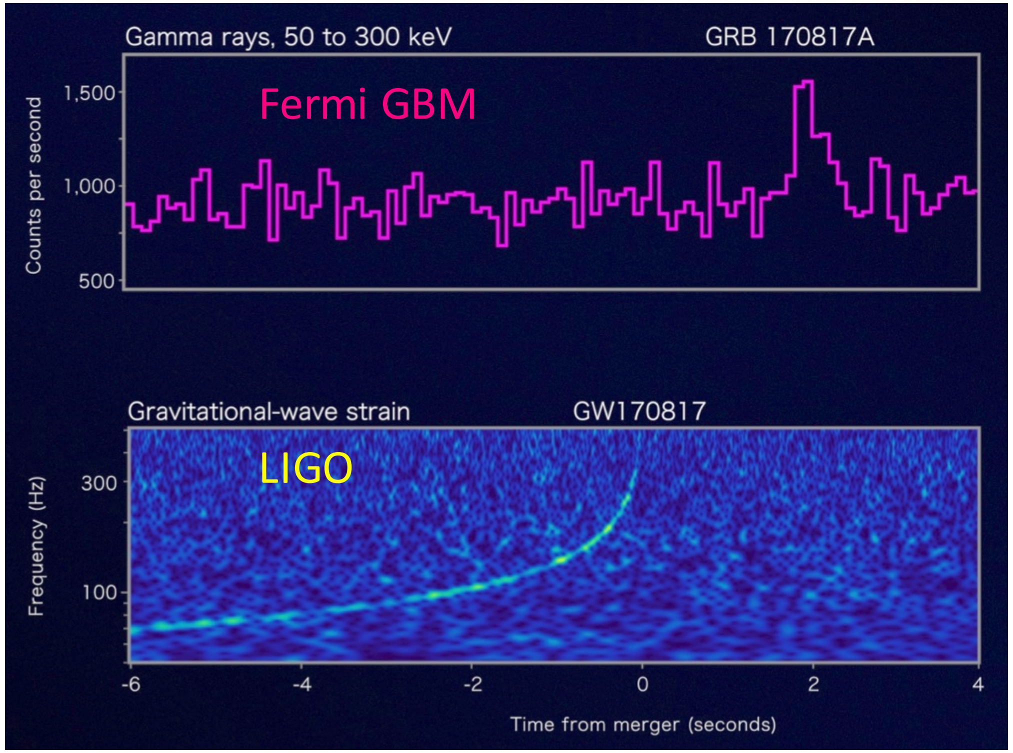
X-ray observations with Chandra in early May, 2018, show that the X-ray afterglow is finally fading.



Troja et al., MNRAS, 2018

What have we learned?

- Predicted
  - Short duration gamma ray bursts are caused by merging neutron stars
  - The speed of gravity = the speed of light
  - The aftermath of the merger produces many of the heavy elements, including gold and platinum

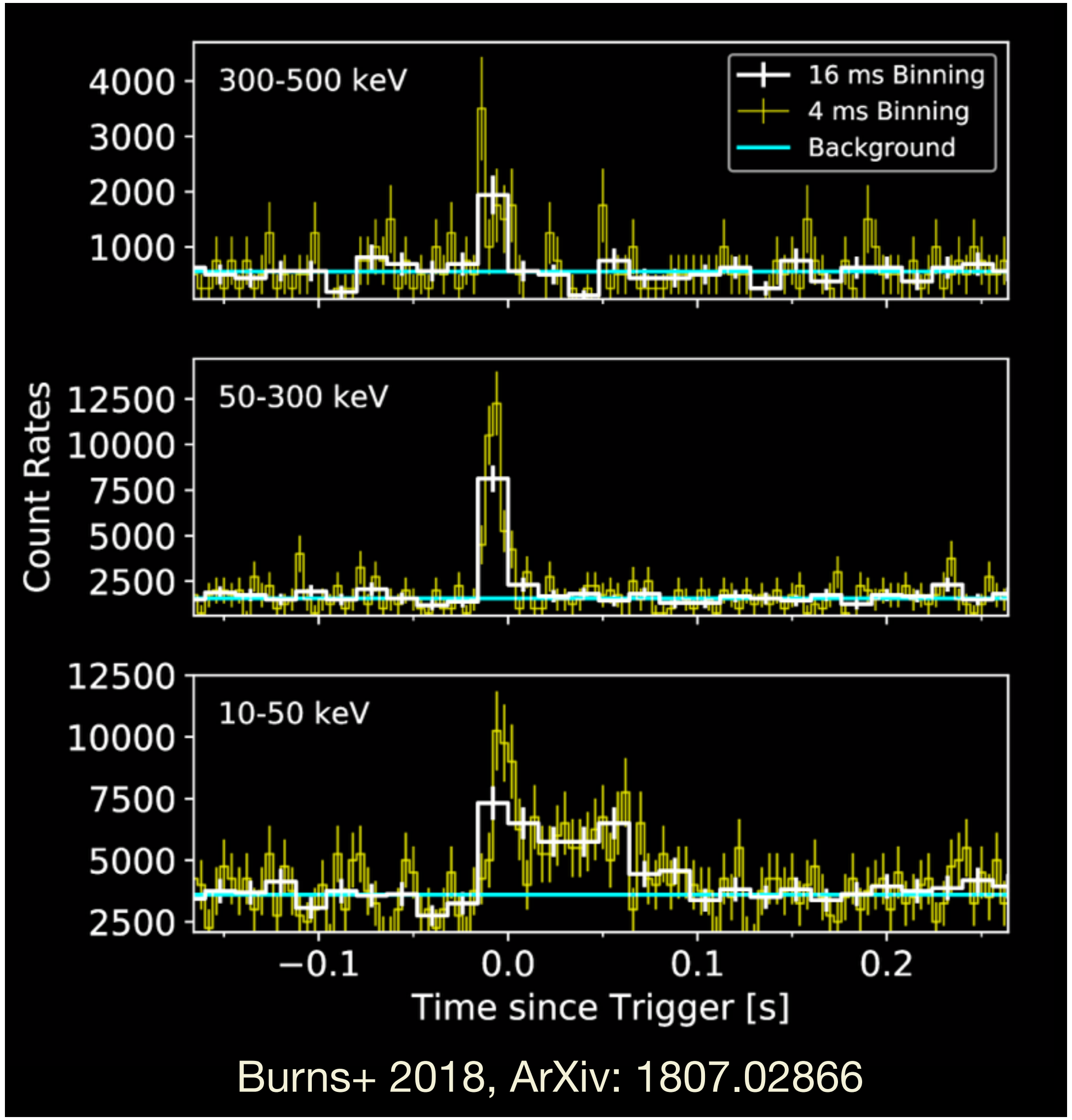


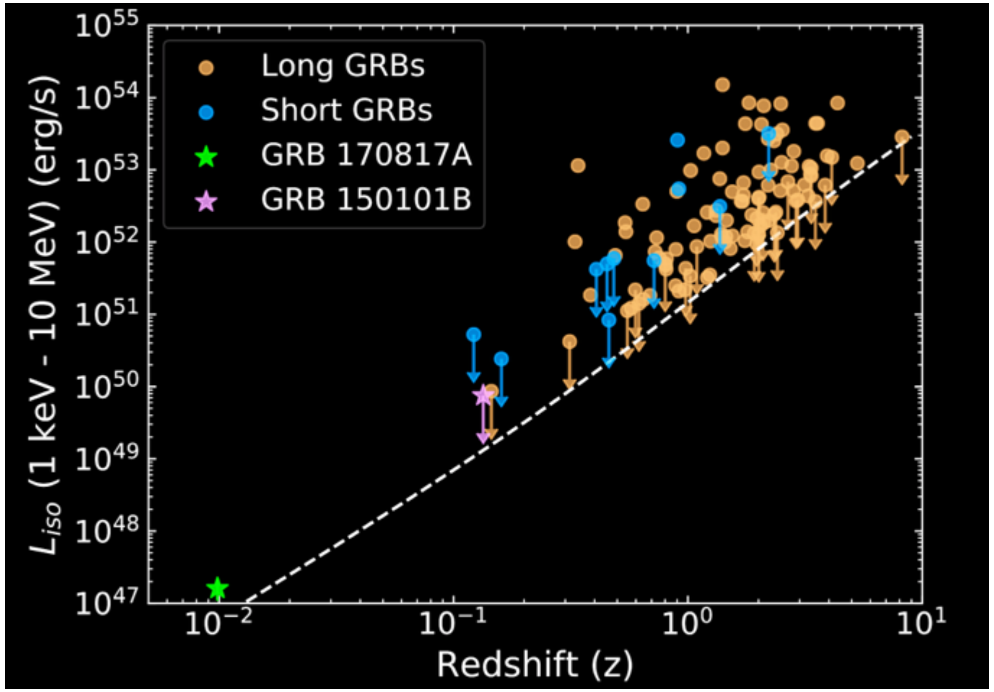
- Observed
  - Gravitational waves from merging neutron stars followed by a short gamma-ray burst 1.7 s later
  - Light and gravitational waves traveling 130 million light years and arriving 1.7s apart means the speed of gravity = the speed of light (to 1 part in 1 quadrillion)
  - Hours after the merger, a kilonova was observed in optical/IR, consistent with the production of heavy elements
  - >1 week later, X-ray and radio emission were detected, and continued to get brighter until ~260 days after the merger.

The Unexpected

- Detecting merging neutron stars so soon, before LIGO/Virgo reached full sensitivity.
- Detecting a gamma-ray burst along with the first detection of gravitational waves from merging neutron stars
- GRB 170817A was dim despite being the closest on record.
- The X-ray afterglow rose in brightness instead of fading quickly.
- A bright ultra-violet counterpart was detected 12 hours after the merger, not previously predicted by kilonova models.

GRB 150101B: A Nearby Signature?

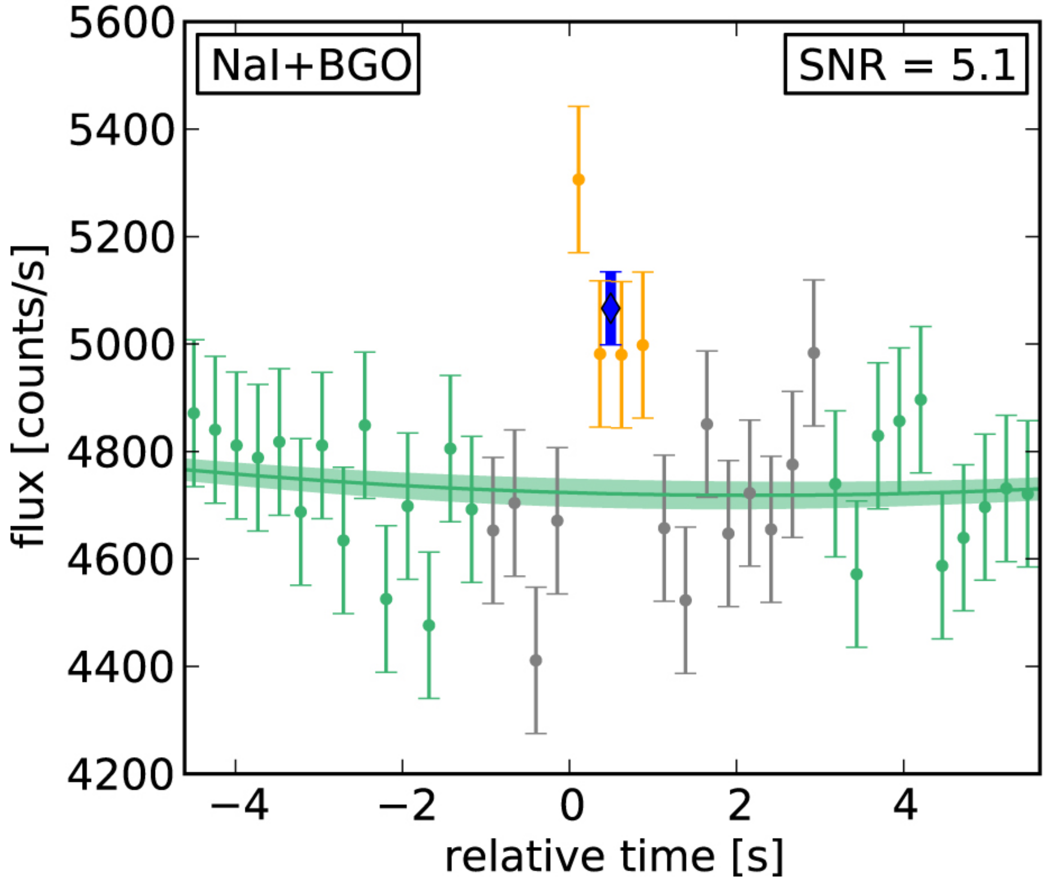




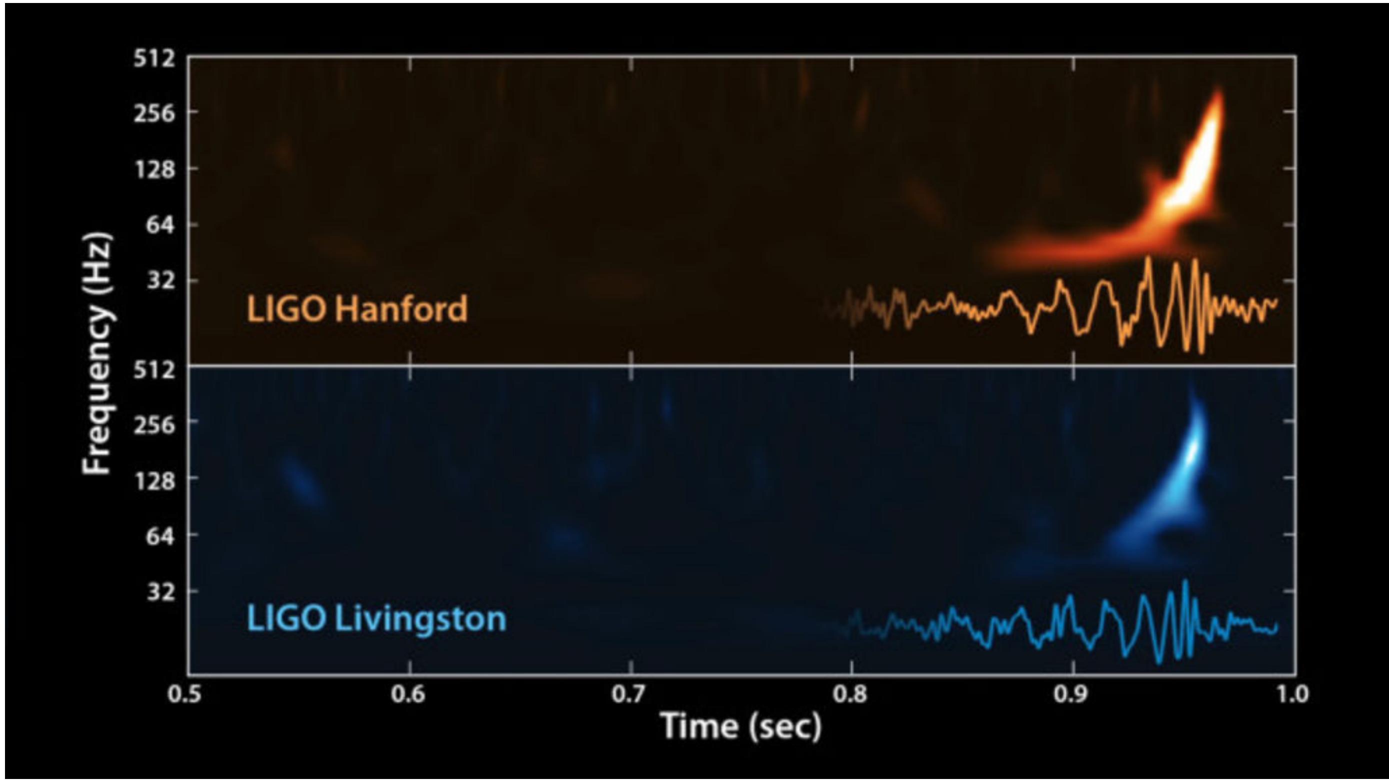
- Similar soft (blackbody?) tail
- Much shorter than 170817A, ratio of timescales of peak to tail similar
- Third closest known short GRB, not underluminous
- More on-axis version of GRB 170817A?
- But – this signature is not seen in the 2nd and 4th closest SGRBs

Counterpart to a Black hole merger?

GBM detectors at 150914 09:50:45.797 +1.024s



GW150914



Summary

- Gamma-ray binaries
  - Defined as having dominant emission >1 MeV
  - Handful – appear to be young pulsar + Be or O-type star
  - Short lived stage in evolution – possibly shorter than predicted
- HMXBs
  - Much more numerous, longer lived stage
  - Likely evolve from Gamma-ray Binaries
  - Most have Be companions and are transients
- EM counterparts to GW Mergers
  - Short Gamma-ray Bursts
  - Possible softer extended tail, only visible for nearby?
  - Fermi GBM is most prolific detector of Short GRBs, both on-board triggered and through subthreshold searches.
  - Looking forward to O3!

https://fermi.gsfc.nasa.gov/fermi10/