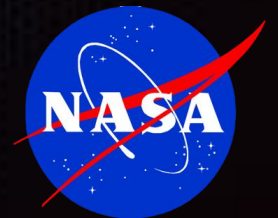




The First Electromagnetic Counterpart to a Gravitational-Wave Signal

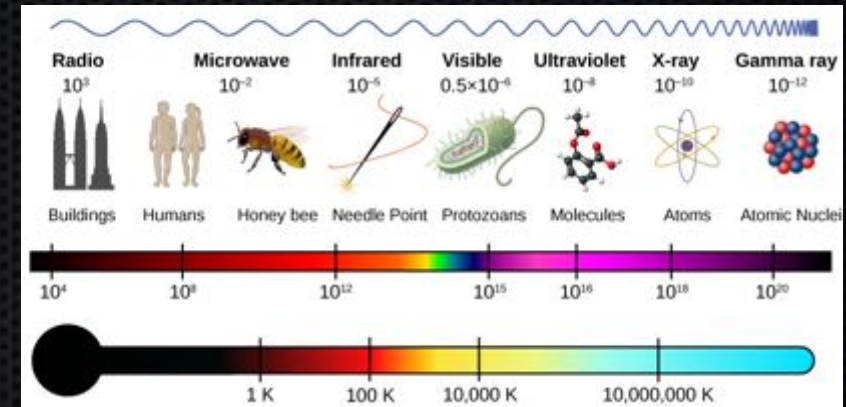
Daniel Kocevski

Marshall Space Flight Center

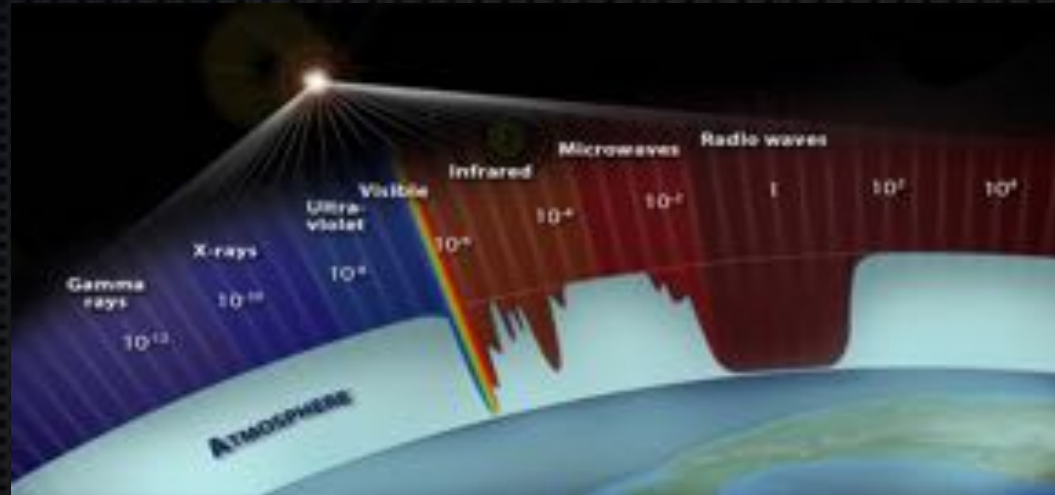
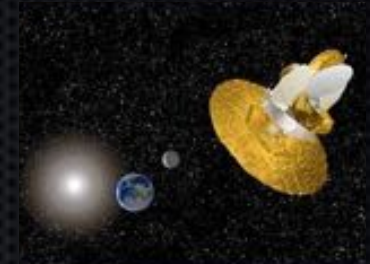
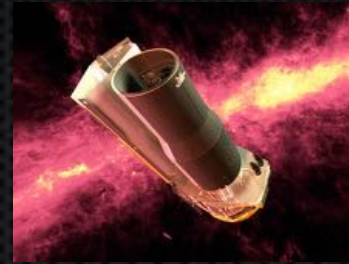
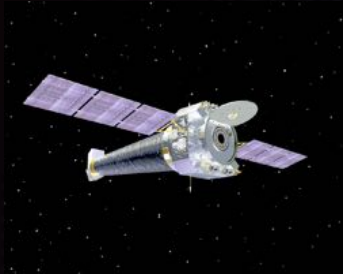


What Can We Learn From γ -rays?

- ✦ The highest energy form of light
 - ✦ >100 times the energy of a dentist's x-rays
- ✦ Gamma-rays are produced by the most energetic sources in the Universe
 - ✦ Black holes, neutron stars, and relativistic shocks
- ✦ Gamma-rays are not easily attenuated by intervening dust and gas
- ✦ Possible connection to exotic physics
 - ✦ Dark matter annihilation?
- ✦ Probe the most energetic particle acceleration mechanisms in the Universe



Astronomy Across The Electromagnetic Spectrum



X-ray and gamma-ray astronomy (direct detection) must be done from space!

The Fermi Gamma-ray Space Telescope

- ✦ Launched in June 11th, 2008
- ✦ Low earth orbit: 340 miles, 92 min period
- ✦ Fermi Gamma-ray Burst Monitor (GBM)
 - ✦ Scintillation detectors
 - ✦ 12 NaI: 8 keV - 1 MeV
 - ✦ 2 BGO: 200 keV - 40 MeV
 - ✦ View the entire unobstructed sky
- ✦ Fermi Large Area Telescope (LAT)
 - ✦ Pair conversion telescope
 - ✦ Energy coverage: 100 MeV to >300 GeV

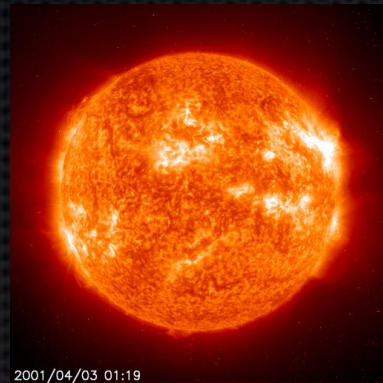


Transient Gamma-ray Sources

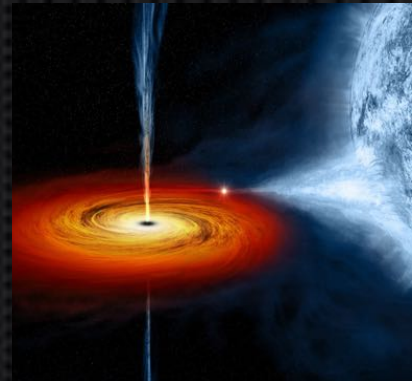
Terrestrial
 γ -ray Flashes



Solar
Flares



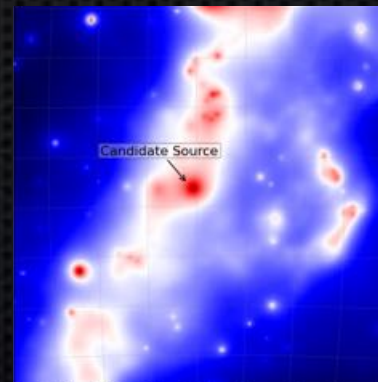
High-Mass
X-ray Binaries



AGN
Flares

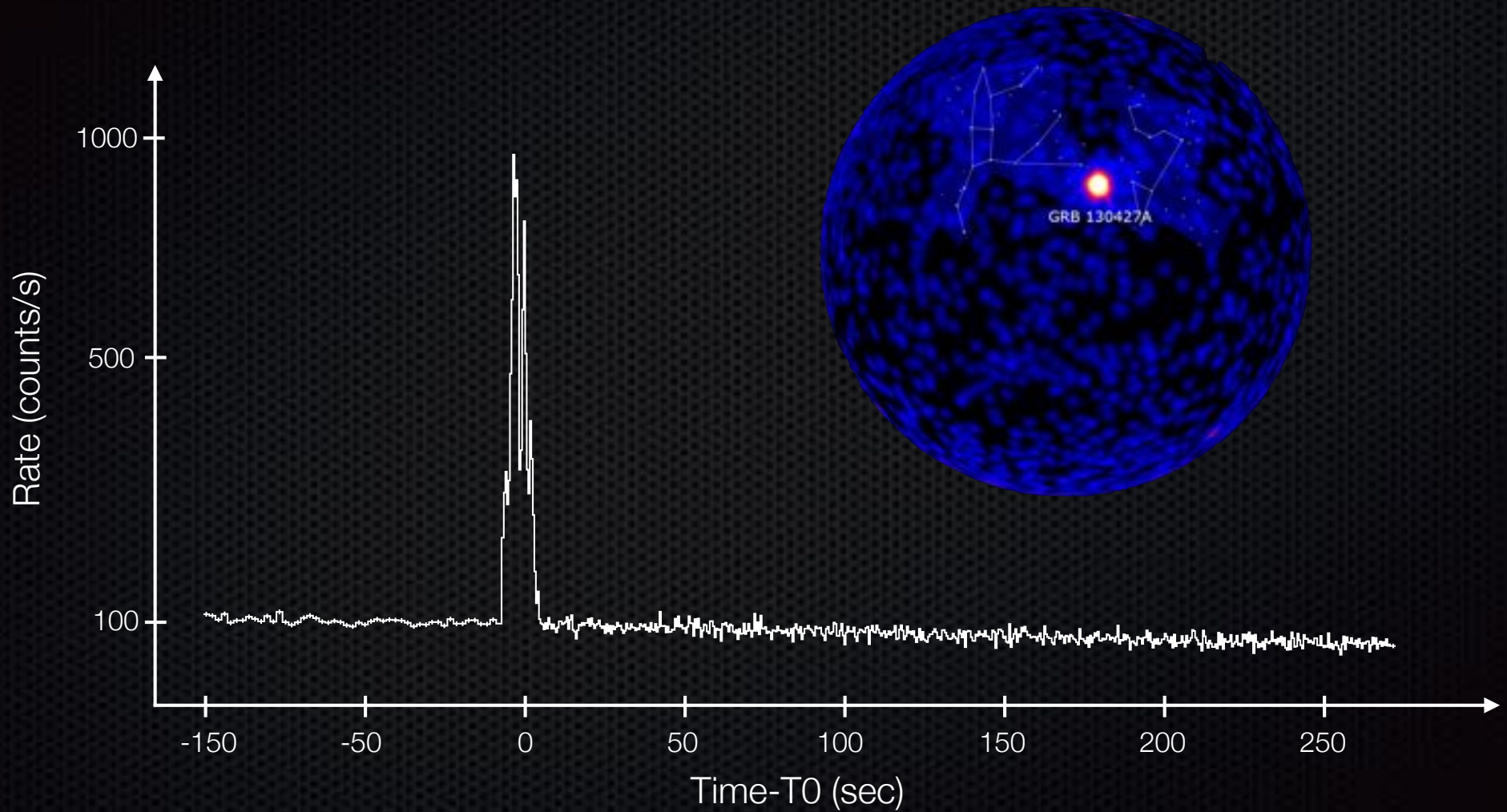


γ -ray
Bursts

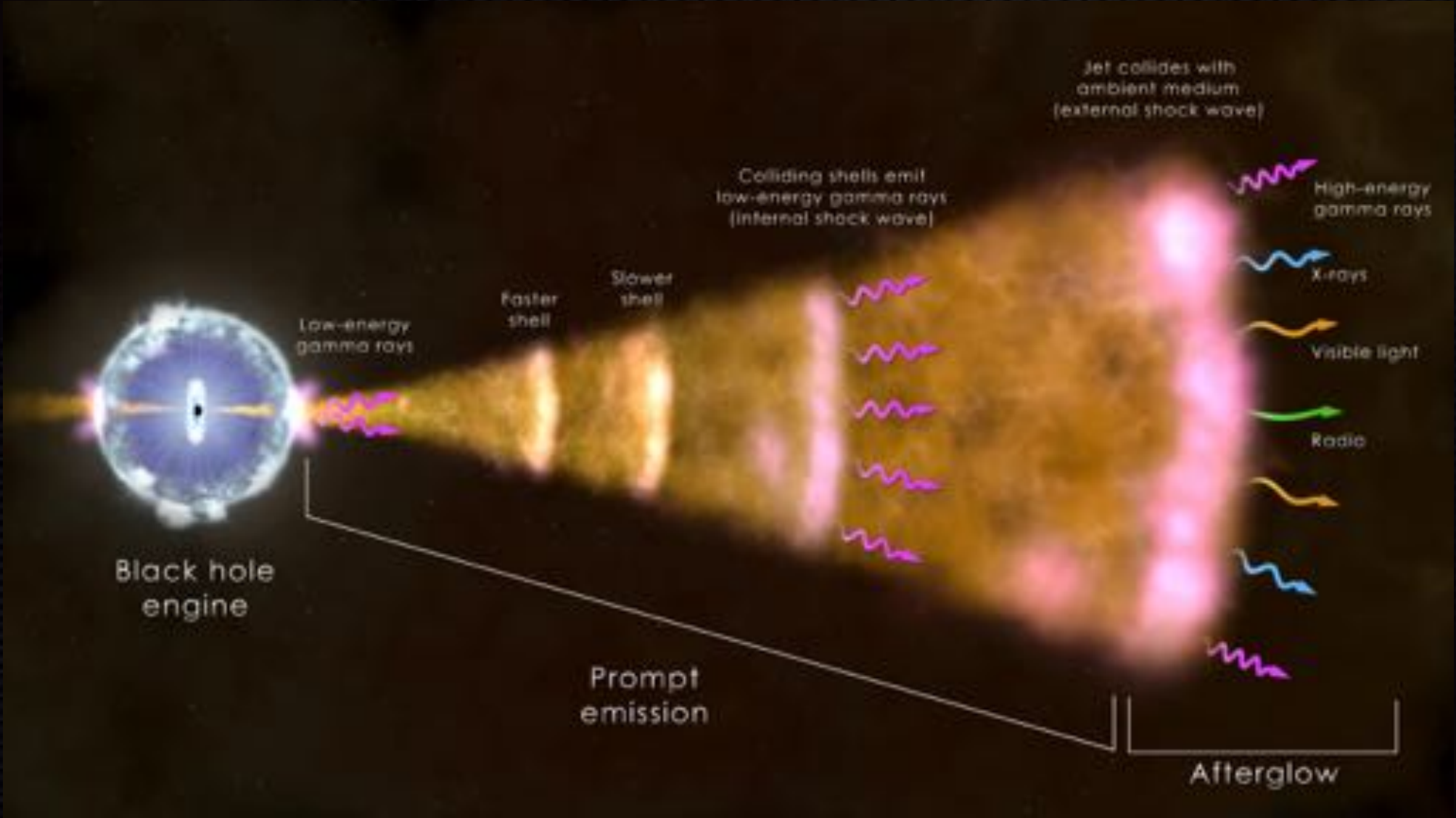


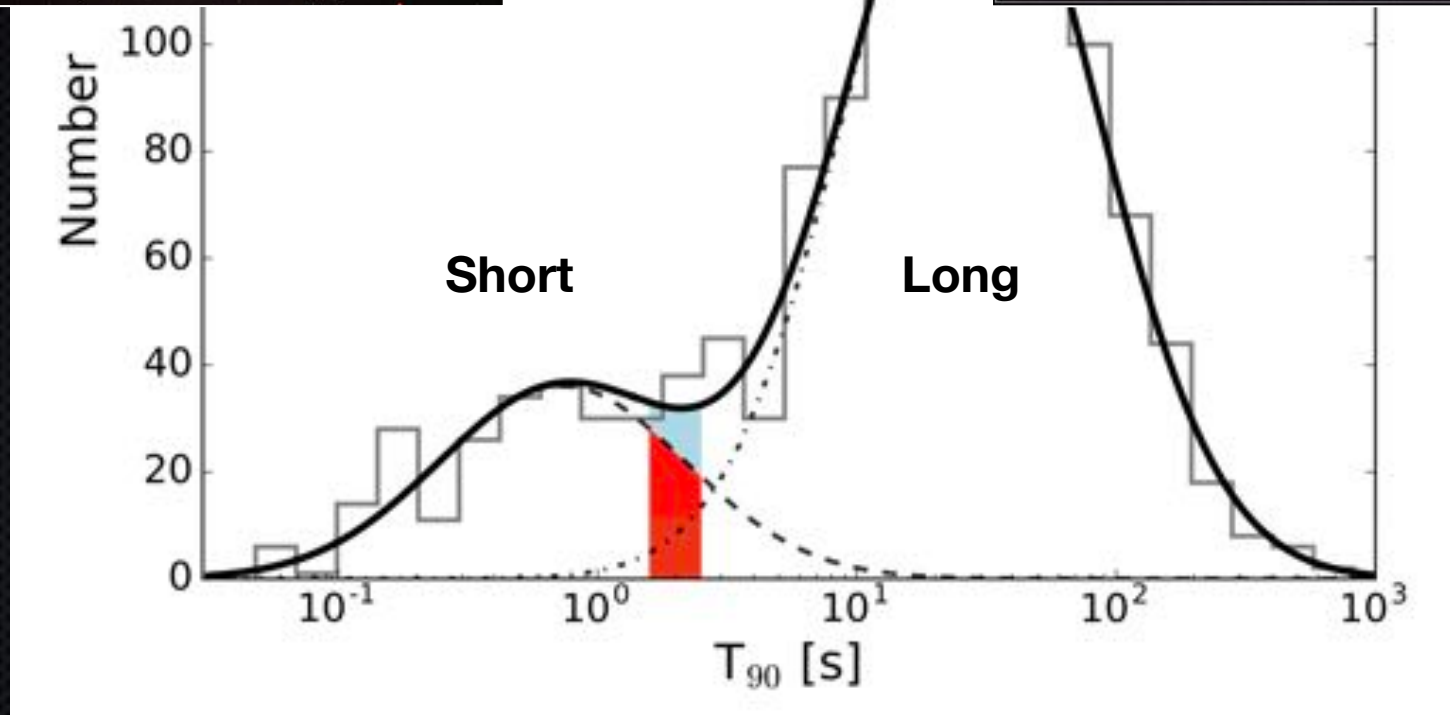
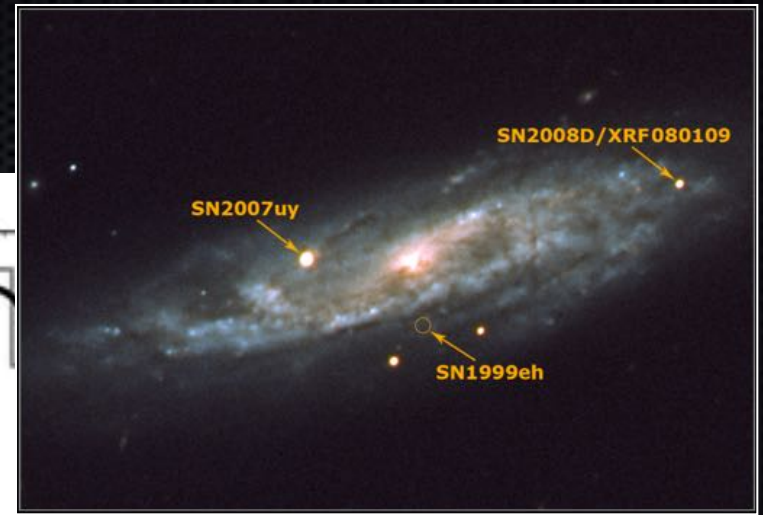
Unknown
Sources

Gamma-ray Bursts







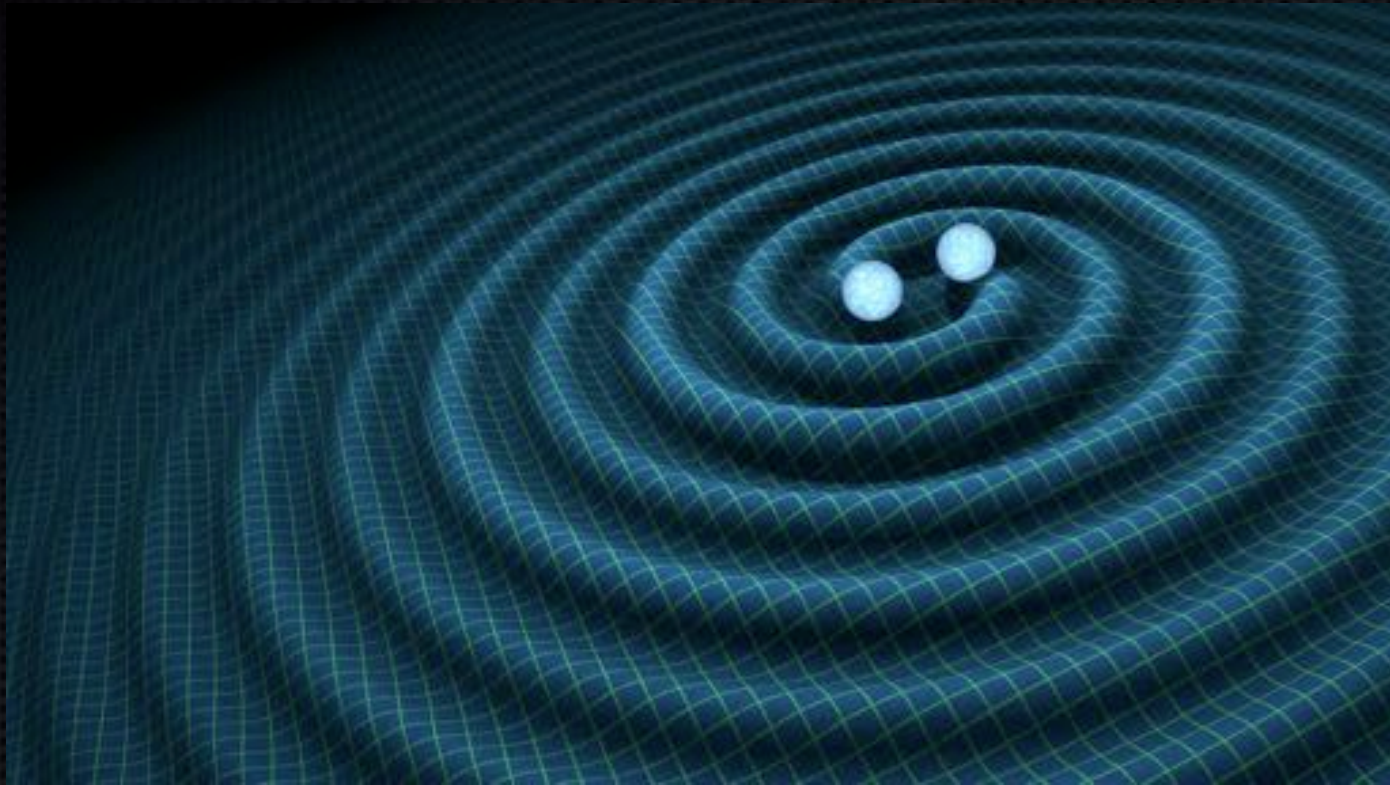


Neutron Star Collisions



- Left over core of massive stars that were not heavy enough to form a black hole
- Radius of 10 km, but the mass of twice the Sun!
- Rapidly rotating with estimate surface temperatures of 600,000 K
- Long suspected to be the origin of short GRBs, but only circumstantial evidence exists

Gravitational Waves from SGRBs



- Short gamma-ray bursts are thought to be due to the inspiral of two compact objects
- The merger of two compact objects is expected to emit gravitational waves
- Predicted by Einstein as a consequence of this theory of General Relativity

Gravitational Wave Detection

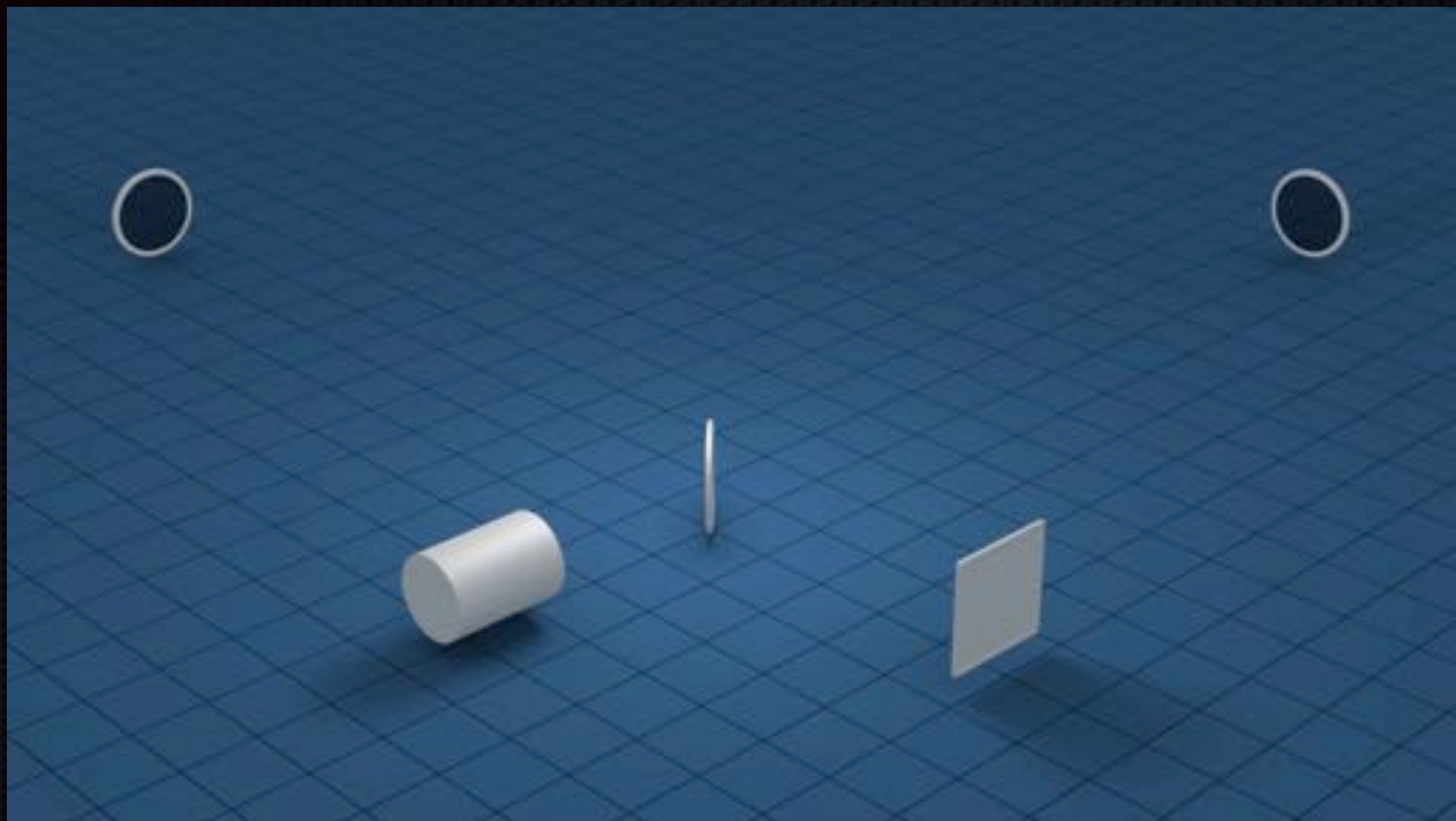
- The Laser Interferometer Gravitational-Wave Observatory (LIGO)
- Advanced LIGO became fully operational in 2015
- Laser interferometers designed to detect spatial-strain due to in-spiral of compact objects
- Passage of a gravitational wave lengthens one arm and shortens the other
- Two sites: Hanford, WA and Livingston, LO
 - Separated by a light travel time of 10 ms
- LIGO can detect spatial-strain of 10^{-19} meters
- 10,000 times smaller than the radius of a proton!



LIGO - Livingston, Louisiana

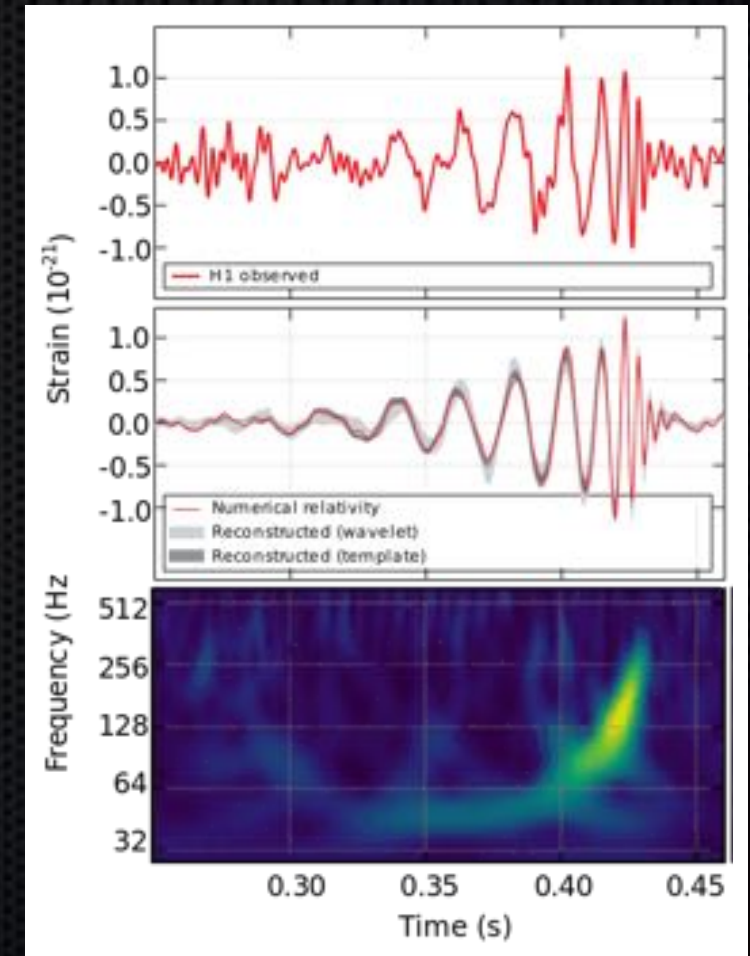


LIGO - Hanford, Washington



LIGO Detection of GW150914

- Detected on September 14, 2015
- Observed by both Hanford and Livingston
- Entire signal lasted only 0.2 sec!
- Merger parameters are encoded in the waveform
 - Component masses of $36 M_{\odot}$ and $29 M_{\odot}$
 - Distance of $z \sim 0.1$ or 1.5 billion light years
 - Orbital frequency of 75 Hz and only 350 km apart
- Merger of 2 black holes is the only possible explanation
- Peak luminosity $\sim 3.6 \times 10^{56}$ erg/s ($200 M_{\odot}c^2$)

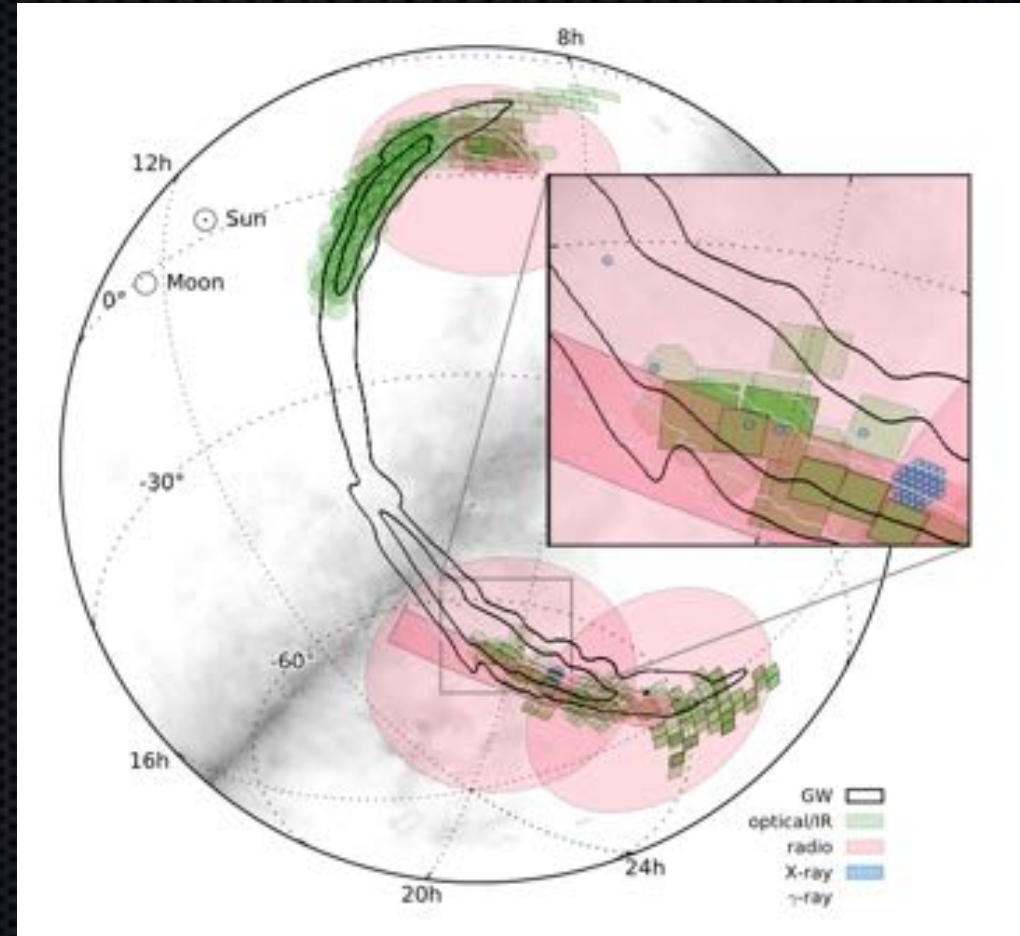
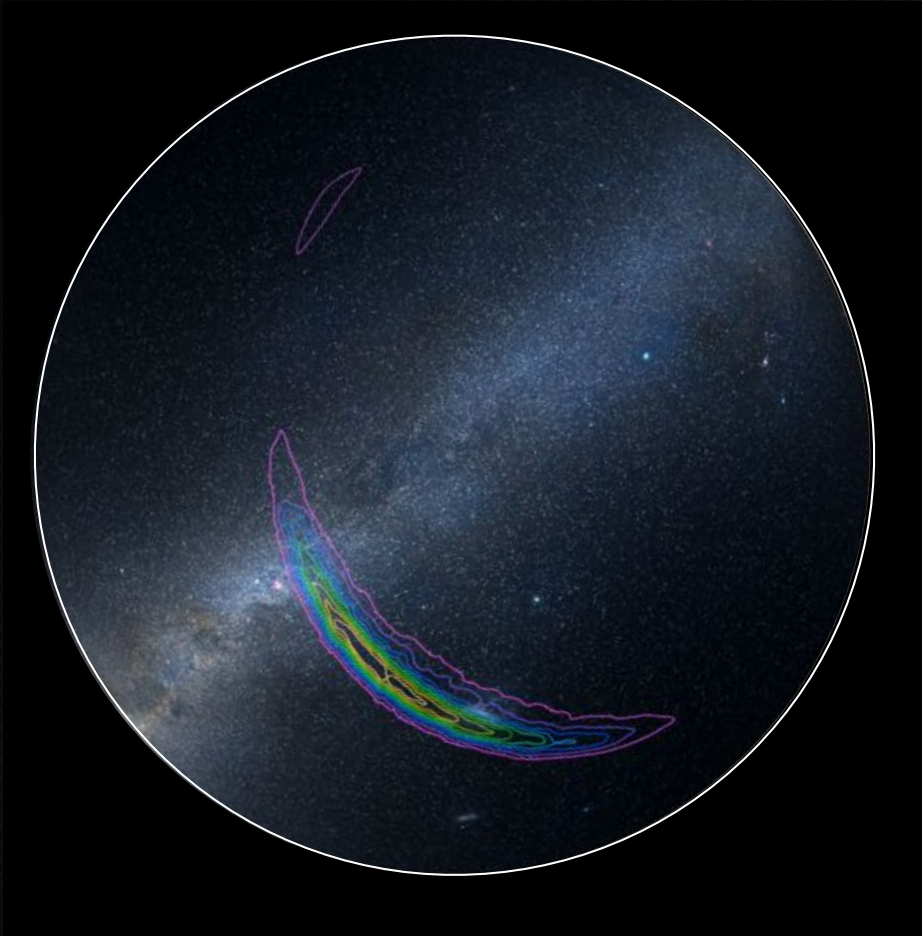


Abbot et al. 2016

- 50 times the entire energy output of all the stars in the visible Universe!



Electromagnetic counterpart

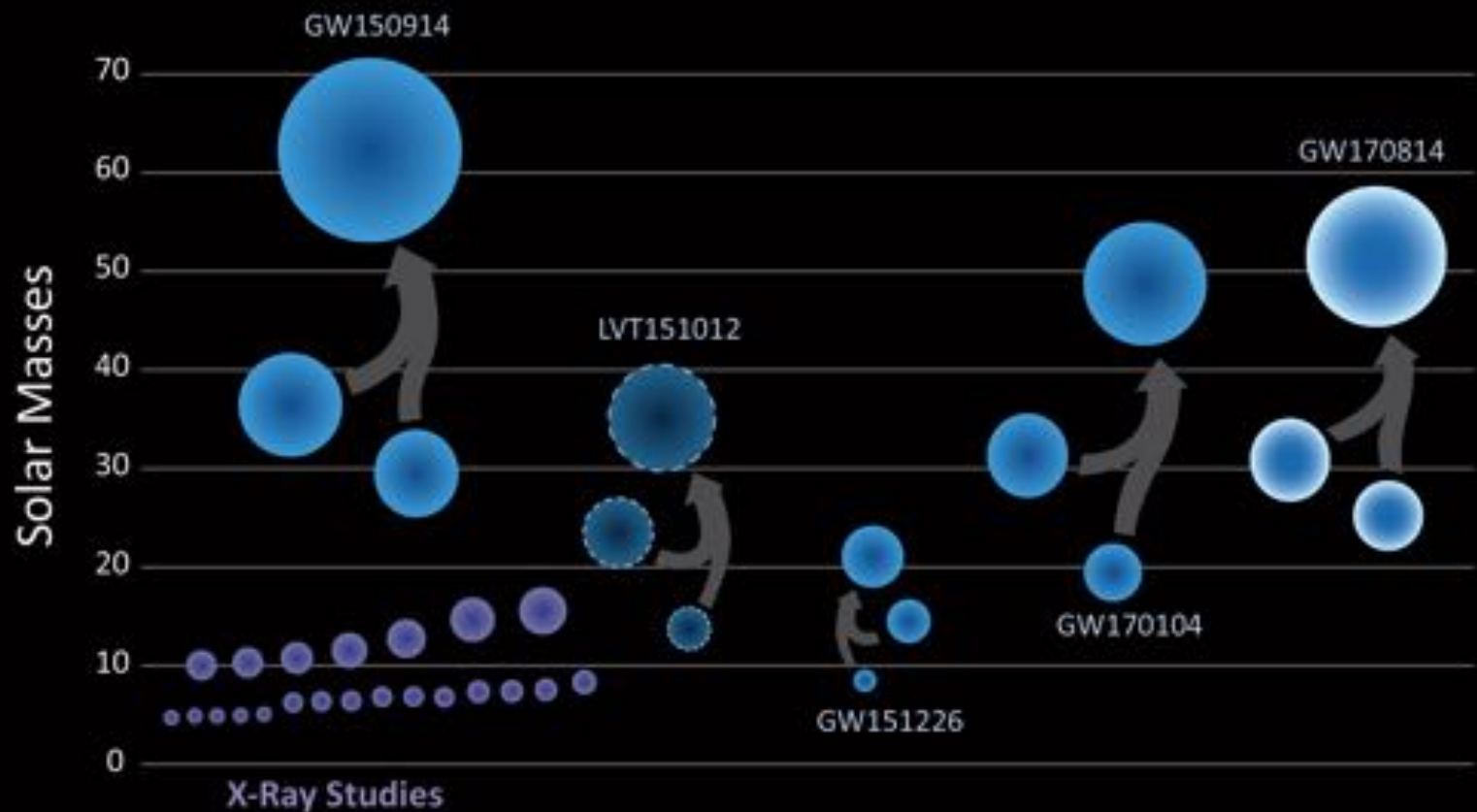


- Localized by relative arrival time at Hanford and Livingston to $\sim 600 \text{ deg}^2$
- Over 62 teams responded to the counterpart search, including the Fermi team
- EM counterparts provide astrophysical context, but not expected from black hole mergers

LIGO Detections

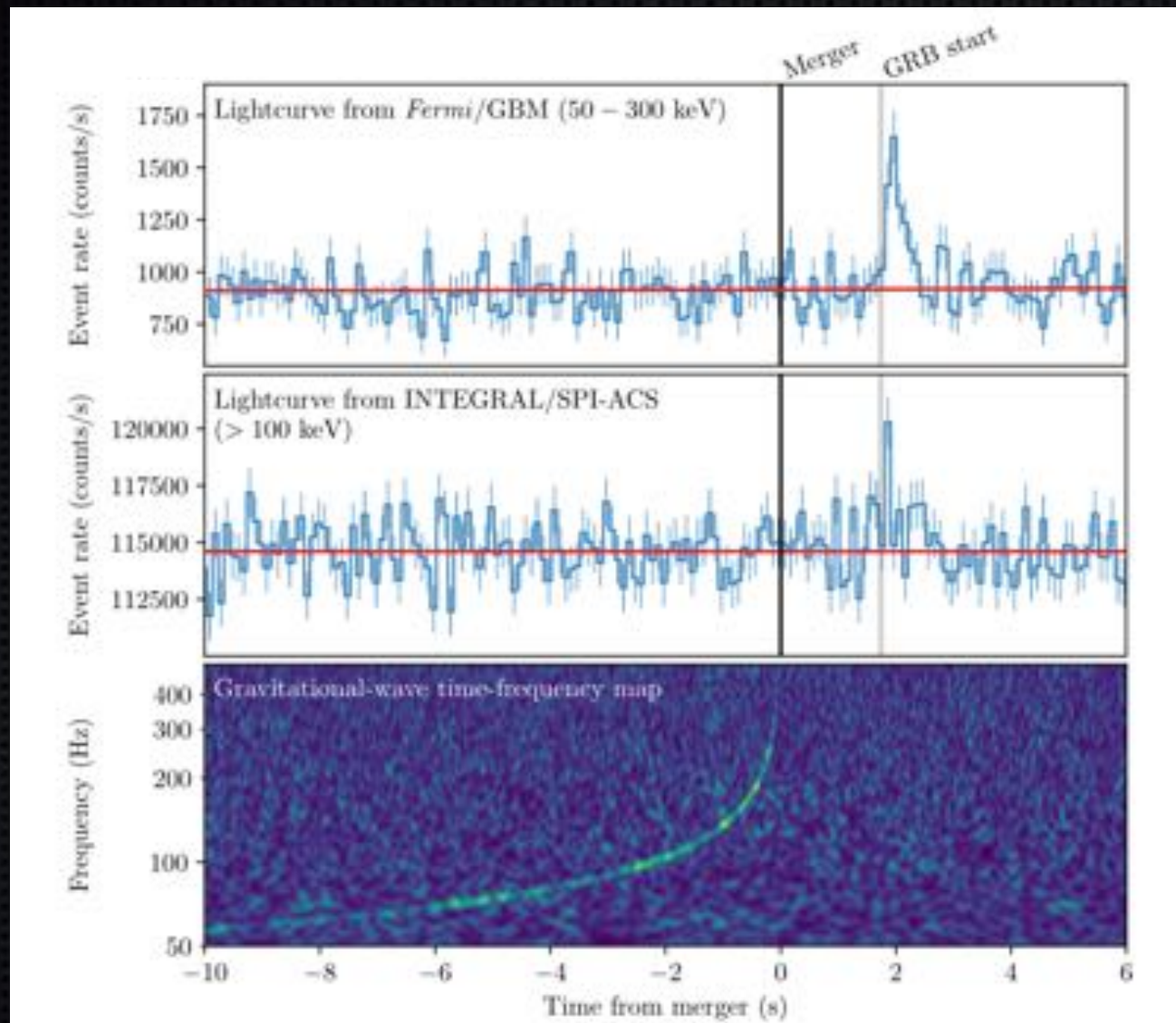


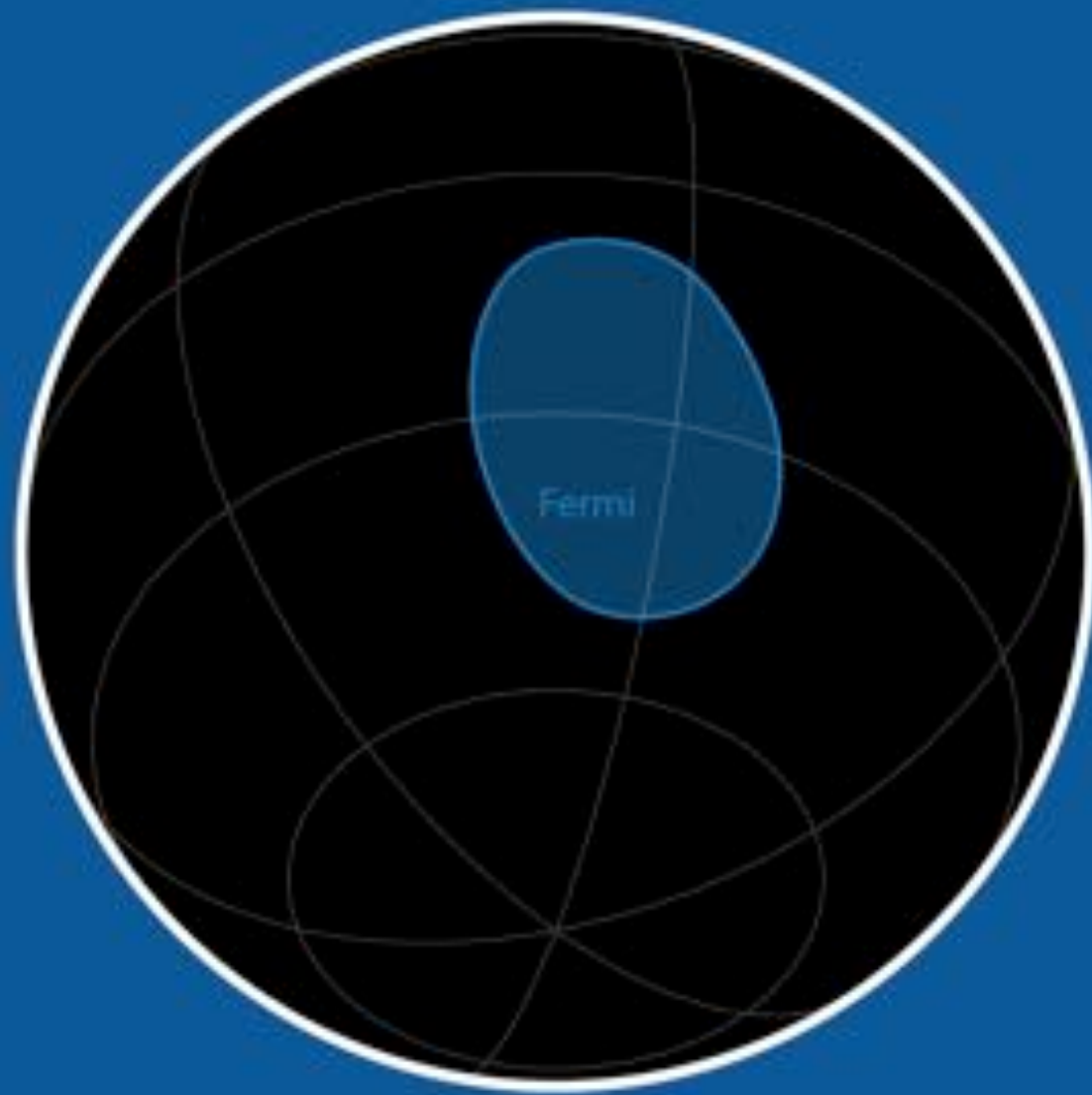
Black Holes of Known Mass

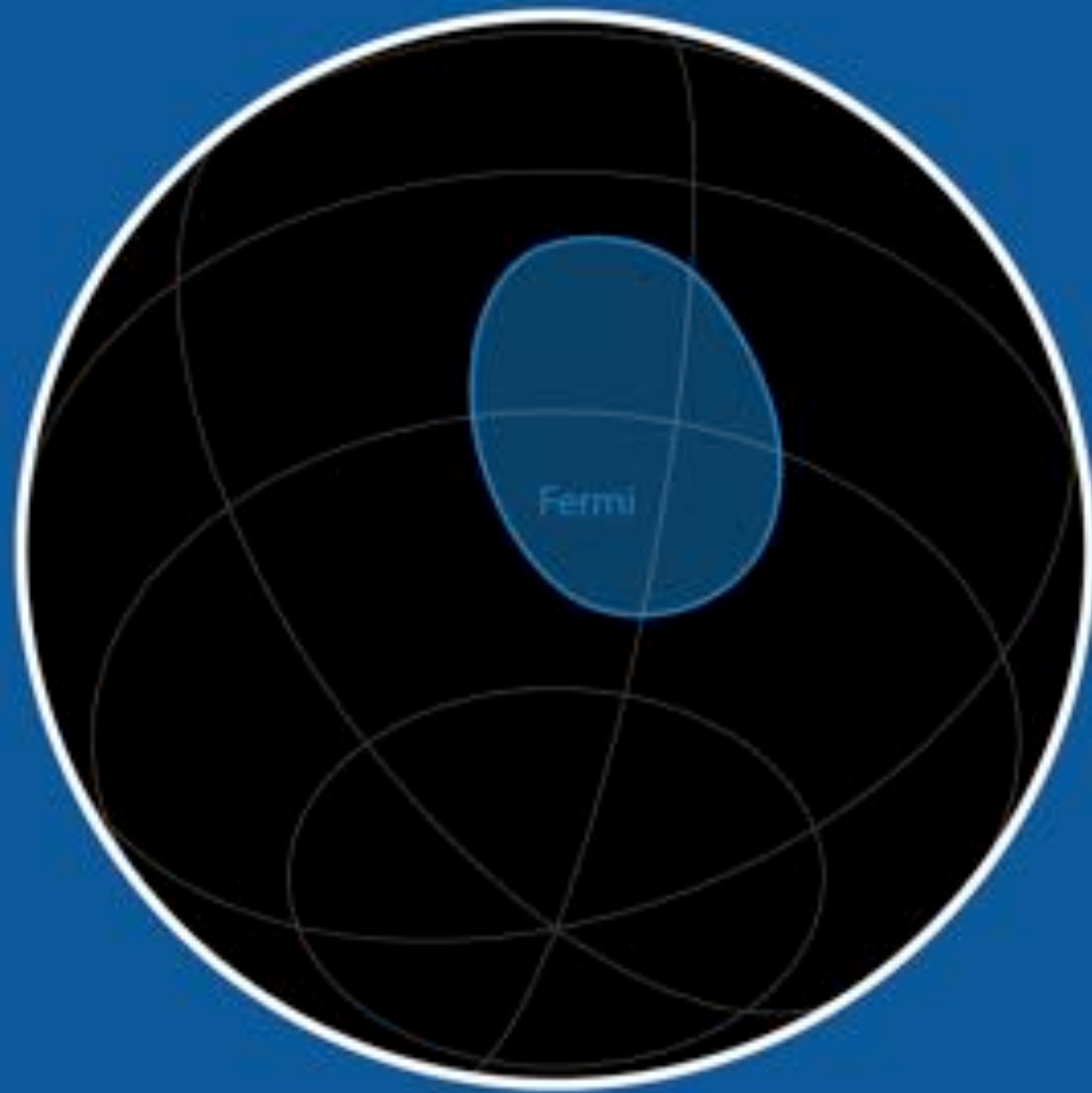


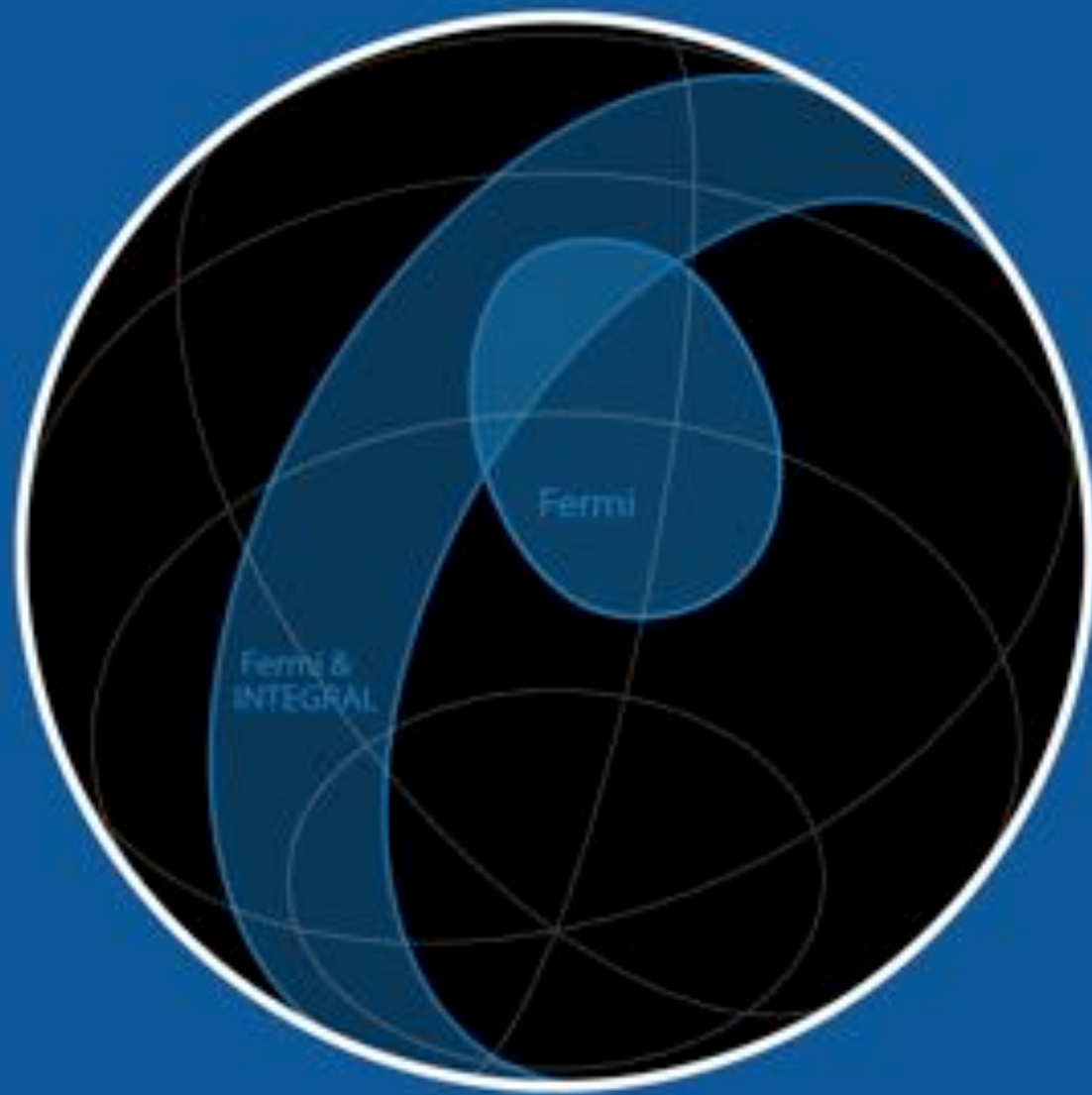
LIGO/VIRGO

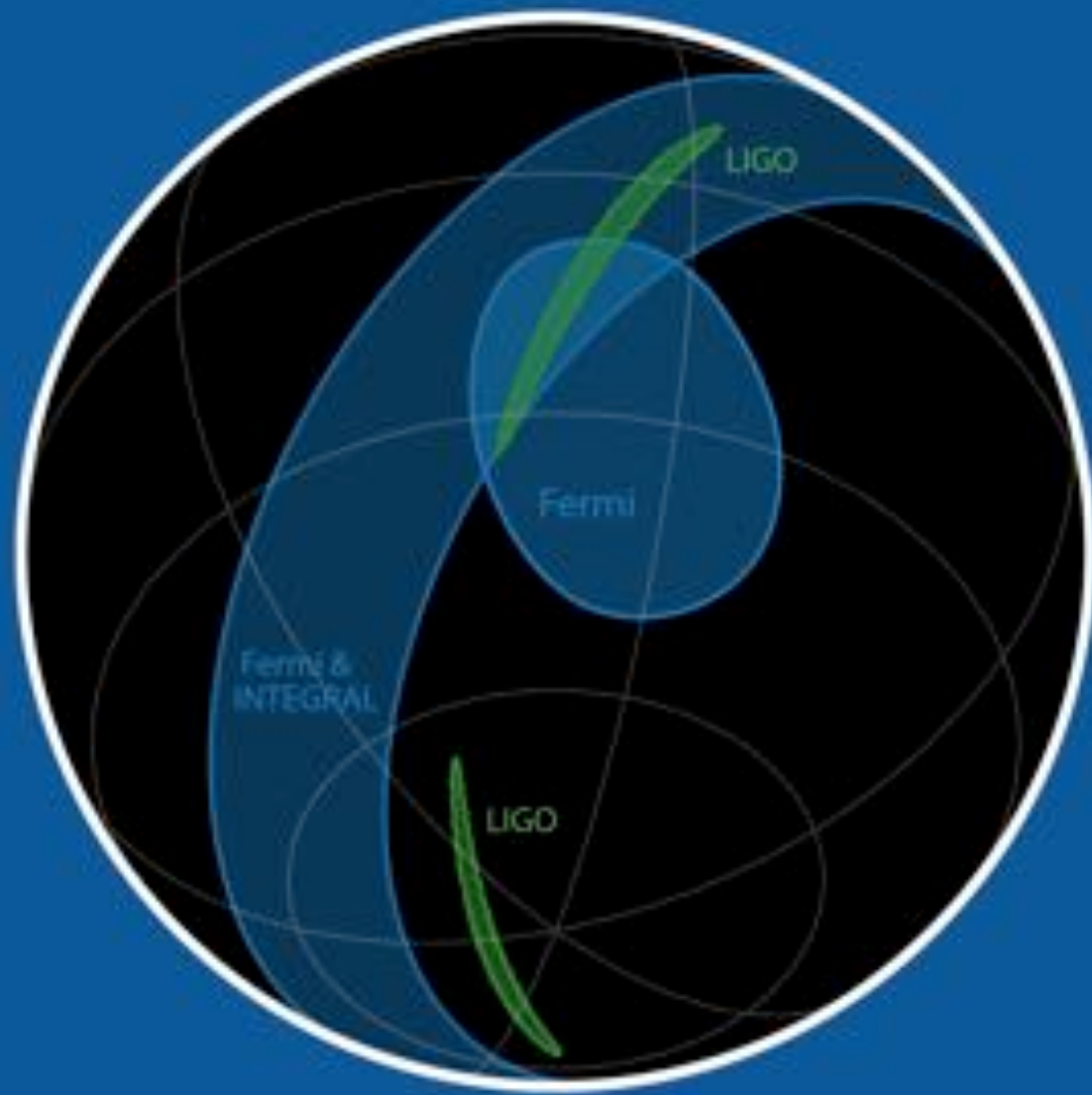
GW180718 - First Joint GW/GRB

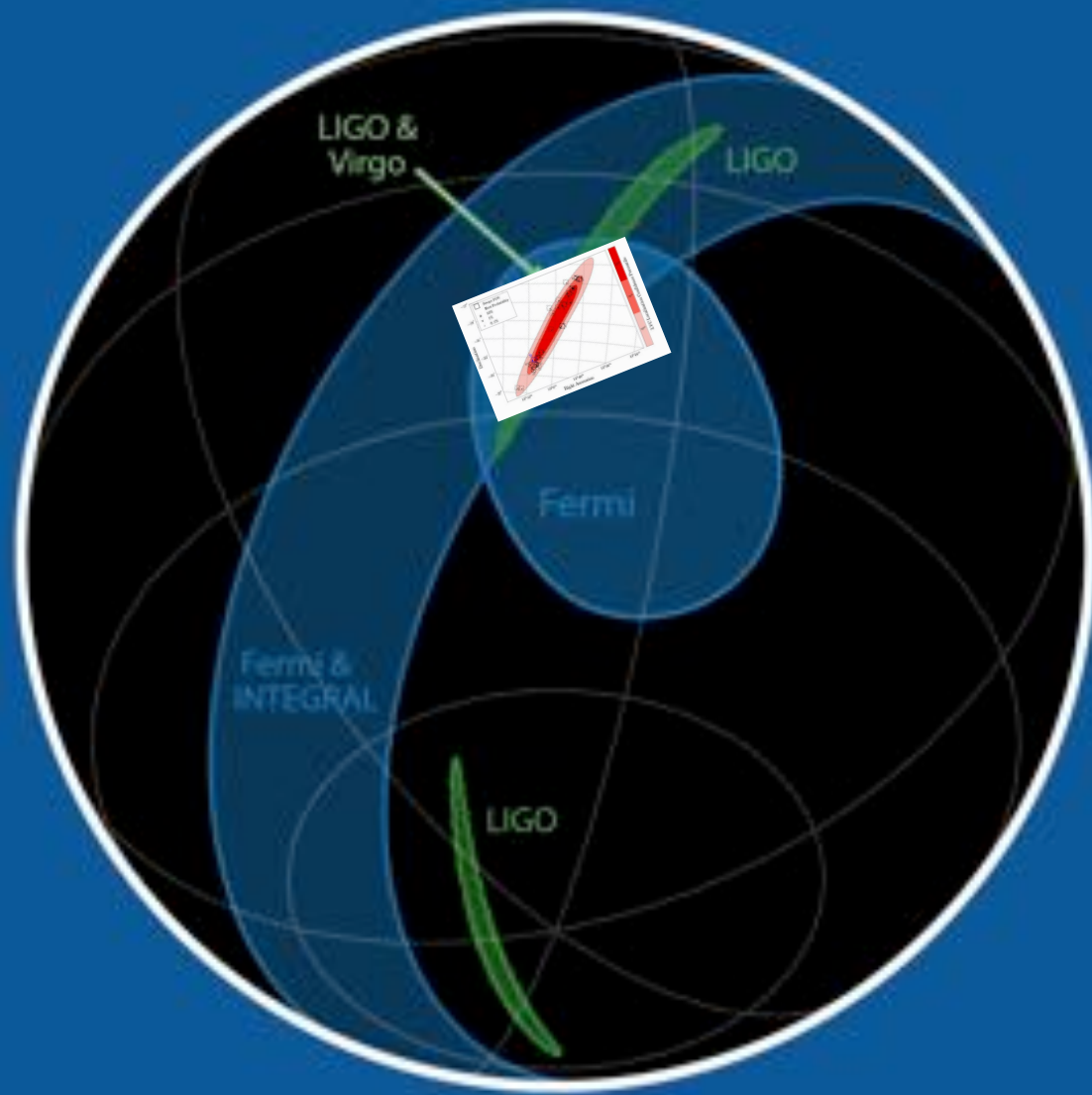






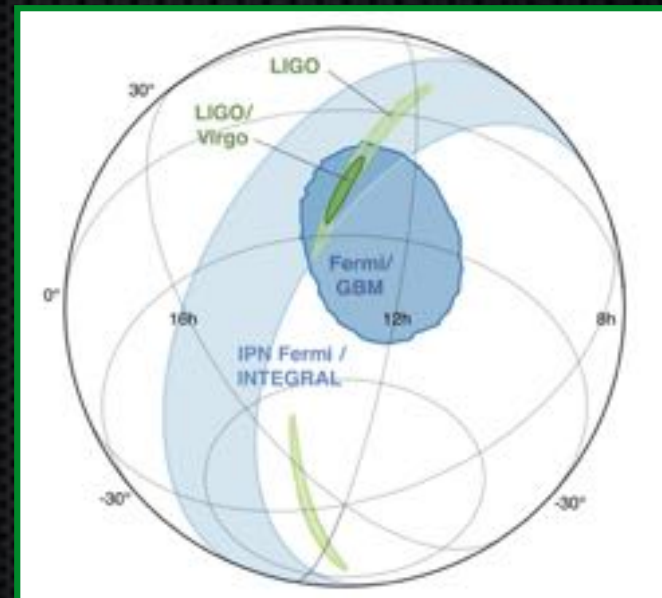






////////////////////////////////////

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/glg_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.



GBM Alert

First On-board GBM
Localization

LIGO Report of
coincident GW/GRB

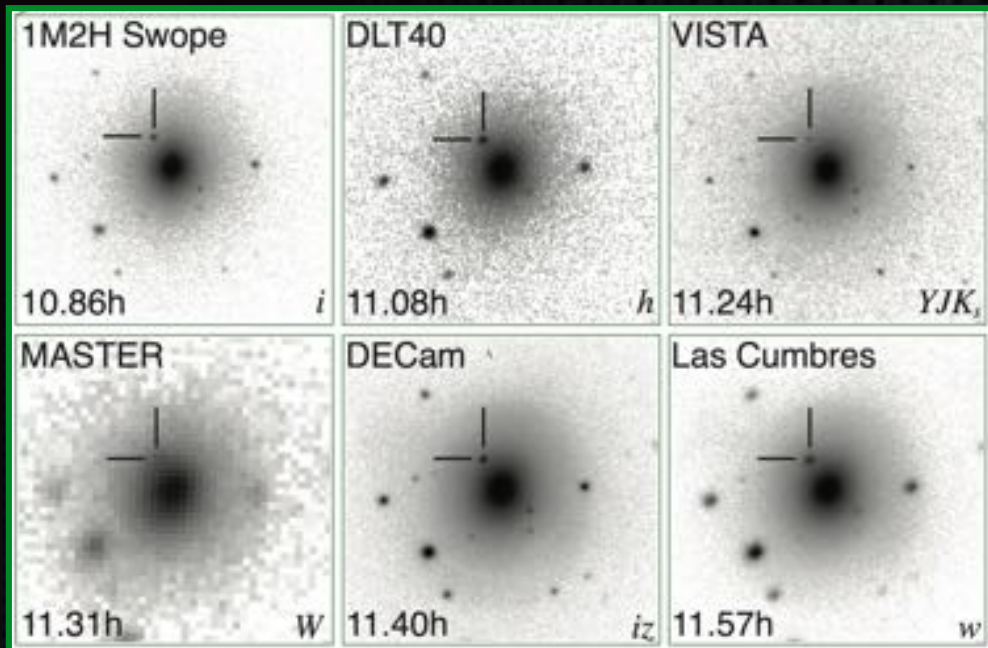
Joint LIGO/
Virgo sky map

+16 s

+27 s

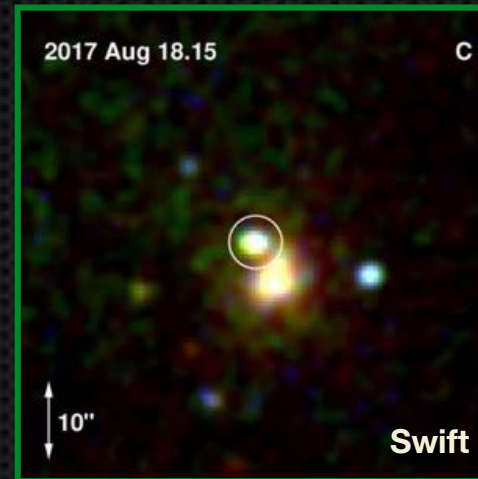
+45 min

+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 Smartt et al. (2017) who observed the region with the 1m Swope telescope at Las Campanas Observatory



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

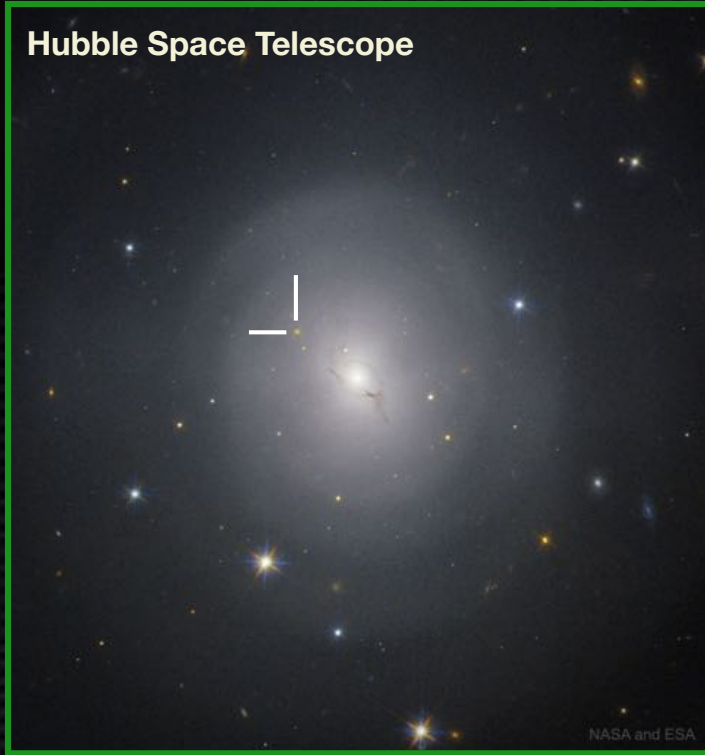
NuStar observations show no X-ray emission (Evans et al. 2017)

+12 hours

+13 hours

+14 hours

Hubble Space Telescope



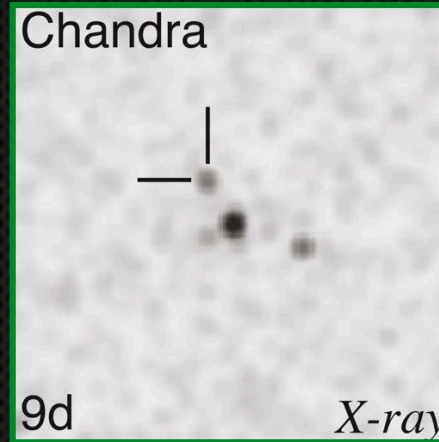
Hubble observations reveal a reddening source (Adams et al. 2017)

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

+2 days

+5 days

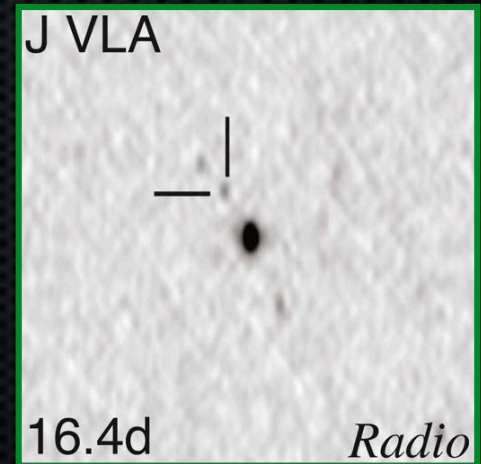
Chandra



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

+9 days

J VLA

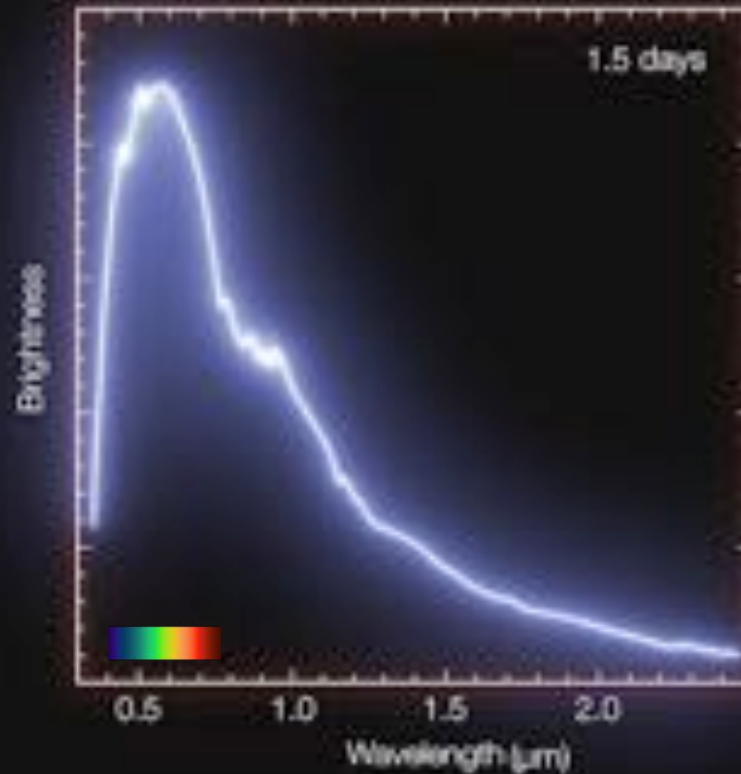


Radio counterpart reported by VLA (Mooley et al. 2017)

+16.4 days

Spectra

ESO-VLT/X-Shooter



Pian et al. 2017

- Very blue spectrum with a rapid fall off and quasi-thermal spectrum
- No evidence of line absorption common in supernova-like transients
- Evolves into the infrared with evidence of broad emission lines

Kilonova

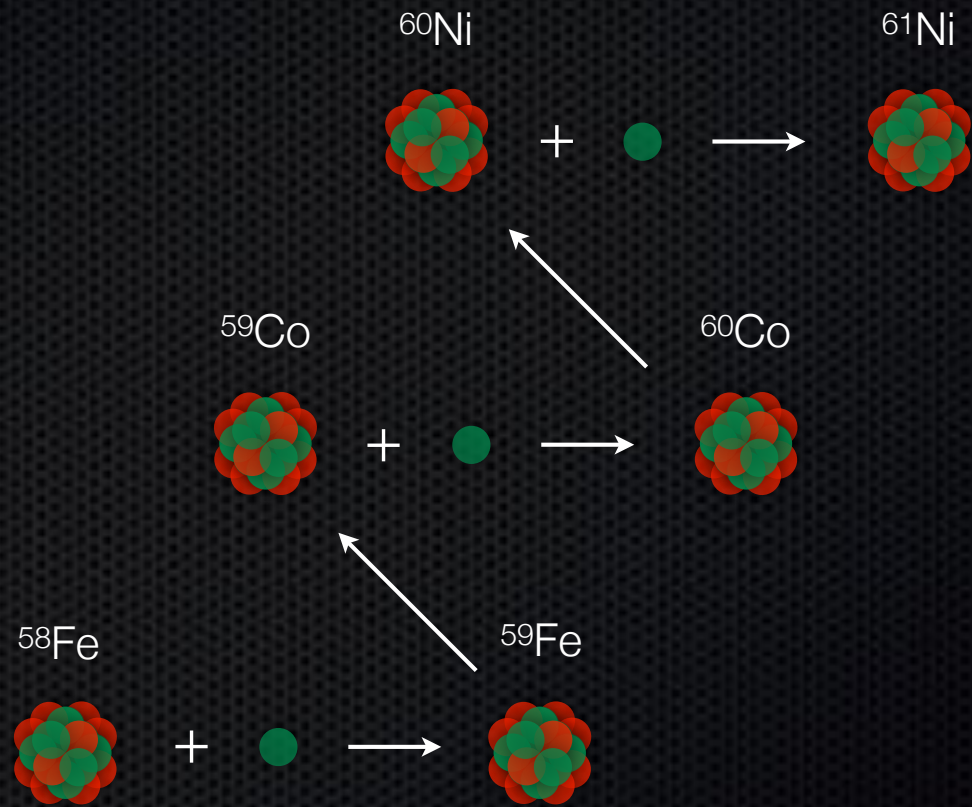


- The production of heavy elements through rapid neutron capture (r-process)
- Heavy elements are unstable and radioactively decay to emit light
- Predicted to be about 1000 times brighter than a stellar nova, hence the name kilonova

Neutron Capture



Neutron Capture



Element Origins

1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac	90 Th	91 Pa	92 U													

Merging Neutron Stars
Dying Low Mass Stars

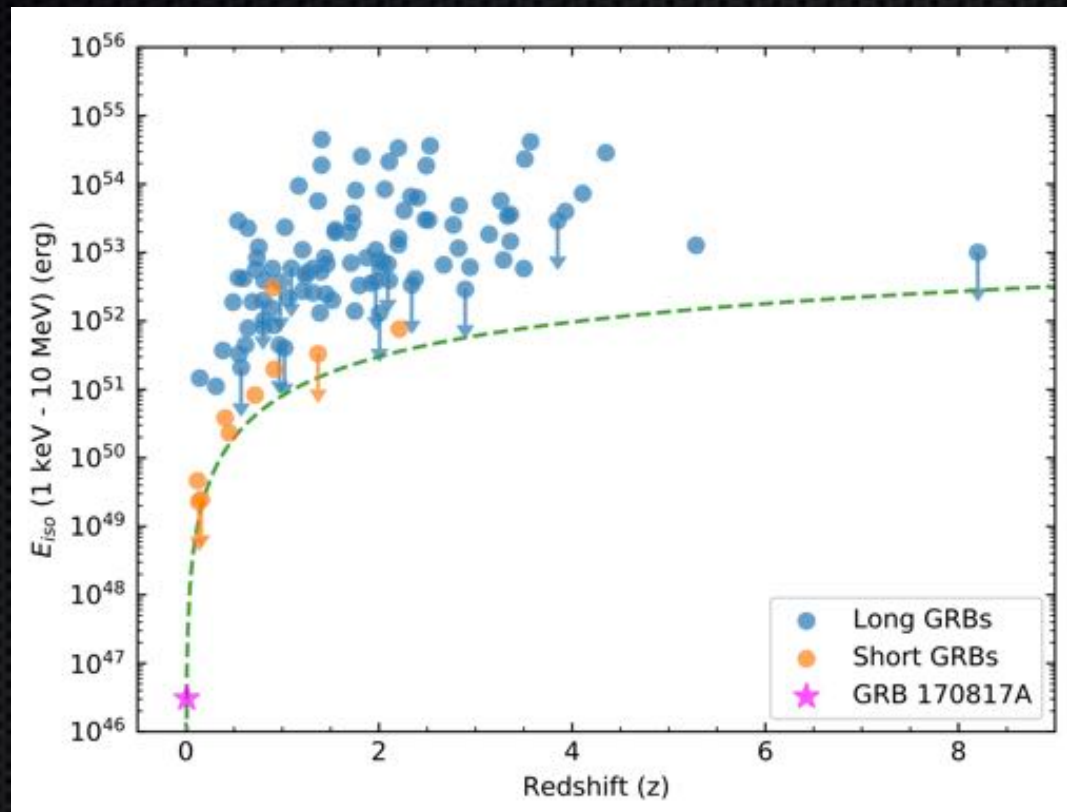
Exploding Massive Stars
Exploding White Dwarfs

Big Bang
Cosmic Ray Fission

Source: graphic created by Jennifer Johnson

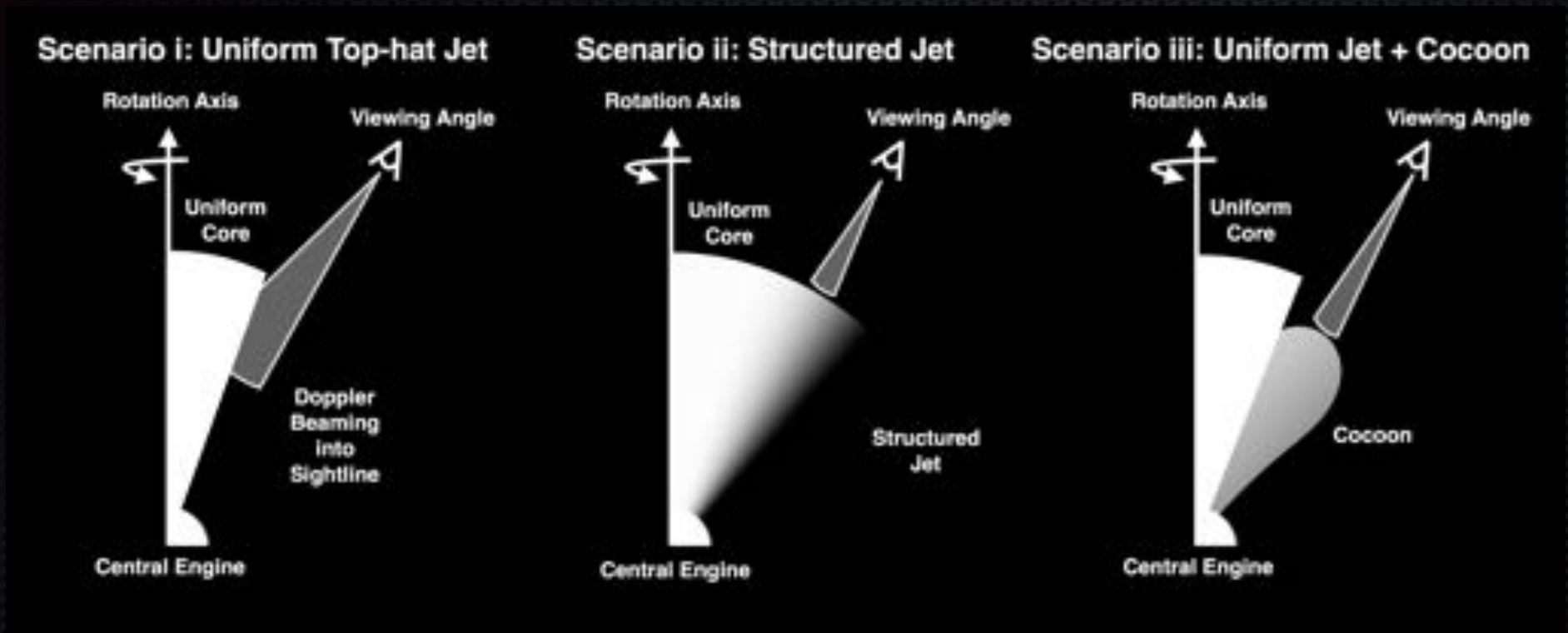
- Kilonova help explain the abundance of elements heavy elements like Ir, Pt, and Au
- Lanthanide elements are also almost exclusively produced via the r-process in Kilonova

Under-luminous Gamma-ray Emission



- GRB 170817 was extremely under luminous compared to other GRBs
- GRB 170817 was the closest and least luminous GRB every detected
- This observations, combined with the late time x-ray emission, shed light on the viewing geometry

Viewing Geometry



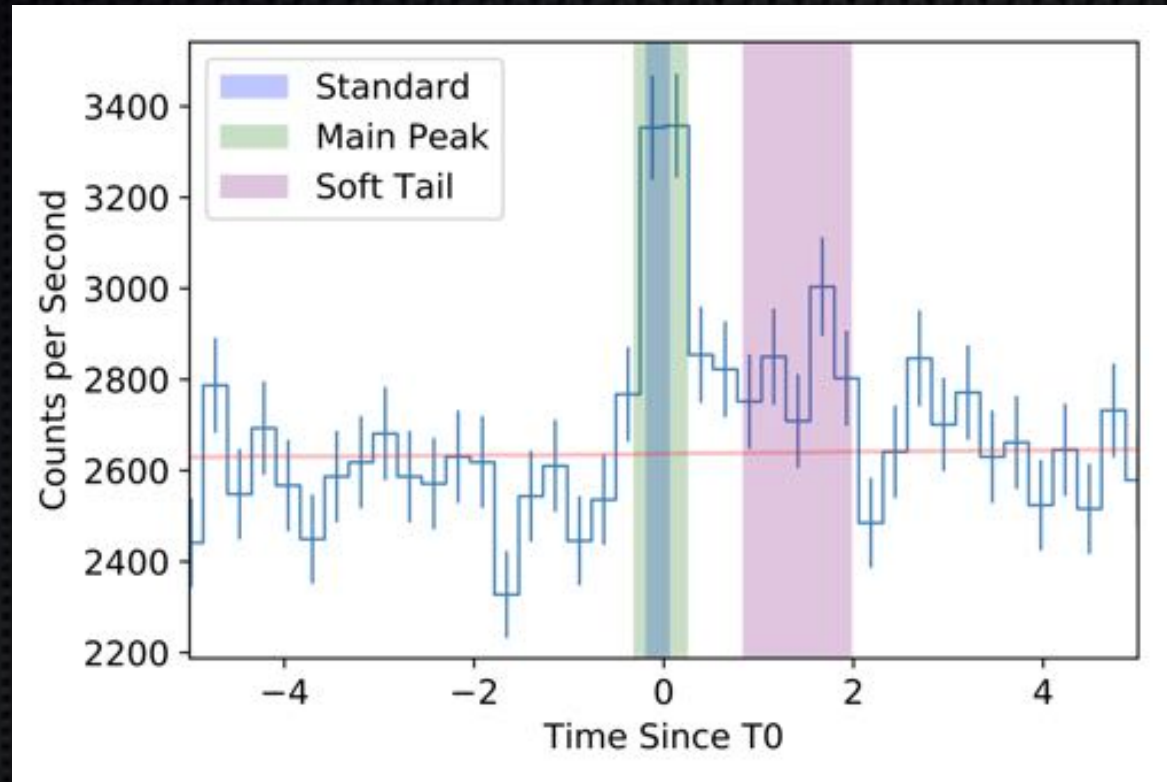
- We believe we observed GRB 170817 off-axis
- The off-axis jet is expected to be moving slower and therefore produce weaker gamma-ray emission
- The x-ray and radio emission from the jet is expected to rise and peak at later times

Off-Axis Jet



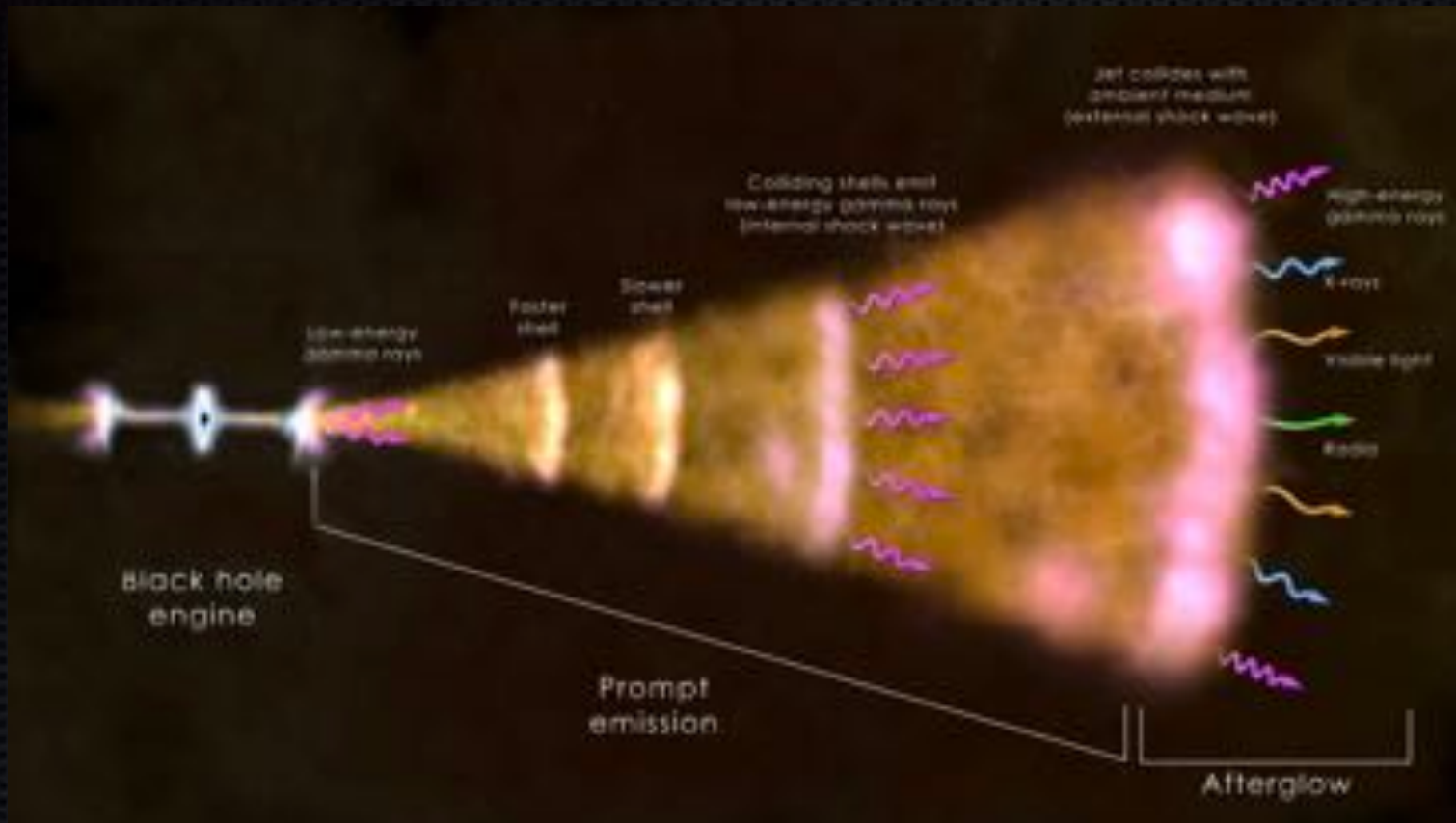
- We believe we observed GRB 170817 off-axis
- Jets viewed off-axis are less bright than jets viewed down the boresight
- X-ray and radio emission from the jet is expected to peak at later times because of relativistic beaming
- Off-axis jets could also allow us to see at the thermal photosphere in/around the jet

Origin of thermal emission?



- There was also evidence of a very prominent thermal emission
- Not typically observed as the primary component of GRB spectra

Origin of thermal emission?



- We can take observed luminosity and the GW-GRB delay (~ 2 s) and calculate the fireball expansion rate
- The fireball must have expanded at near the speed of light for ~ 800 s in its own frame
- Special relativistic effects makes that appear as a 2 s delay to the observer



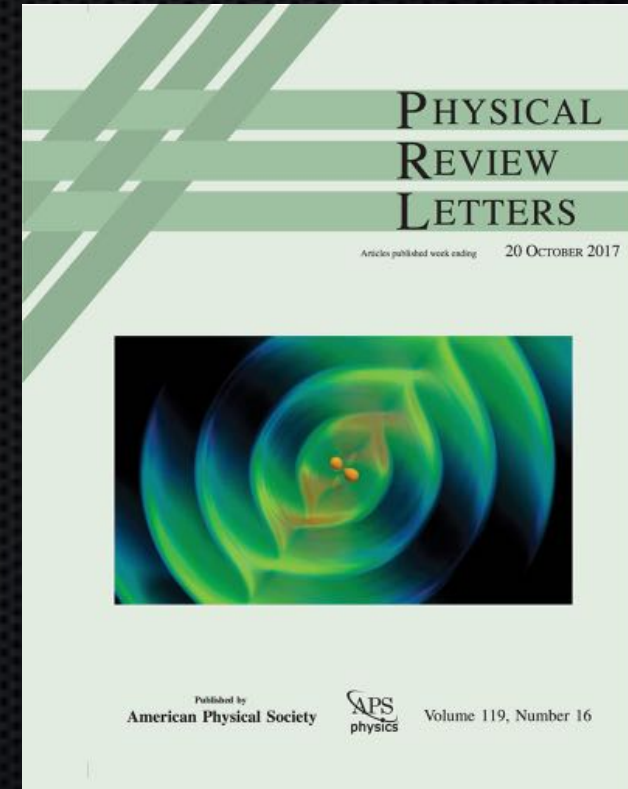
Speed of Gravity & Shapiro Delay



- The gravitational waves and gamma-rays traveled 130 million light years and arrived within 2 seconds
- Gravitational waves travel at the speed of light within one part in one quadrillion
- We can use this to test the equivalence principle (gravitational mass = inertial mass)
- Gravitational waves and light suffer the same Shapiro Delay in GR, but not in some MOND theories
- The tensor-vector-scalar gravity predicted a 1000 day delay in the arrival of GW - effectively ruling it out

Publications

- Staggering collaborative effort
 - >3500 Authors
 - >50 Teams
 - >900 Institutions
 - 45 Countries/Territories
 - 100% of Continents
- Staggering scientific output
 - >80 papers coordinated for release
 - ~50 accepted/published on 10/16
 - ApJL (29!)
 - Science (8)
 - Nature (7)
 - PRL (1)
 - MNRAS Letter (1)
 - A&A (1)



Very excited for the start of 3rd observing run in August of 2018!

Thank you!

