Multi-messenger Astronomy

A short overview

Contents

- ❑ Introduction - 3 detector localizations
- ❑ Historical background *from Initial to Advanced LIGO/Virgo*
- ❑ Communication System (Private) GCN
- ❑ BNS and short GRB association
- ❑ Astrophysical Implications

Welcome to the era of multimessenger astronomy with a network of advanced interferometers!

http://www.virgo-gw.eu/skymap.html

gw170814 map

GW170814 Interactive Skymap

J2000 01 32 11.259 -21 46 4.74

Using the skymap

Click on the various options below to display information relating to each detection.

Detection	Sky localisation	Label	Pop-up info
GW170814 - L1/H1 only	☑	☑	☐
GW170814 - L1/H1/V1	☑	☑	☑
GW170814 - refined skymap	☐	☐	☐
GW150914	☐	☐	☐
GW151226	☐	☐	☐
GW170104	☐	☐	☐

Backgrounds

If you want to see the extension of these sky regions through the constellations you can select an artistic background image ○ **Constellations.**

You can also select various background images at different wavelengths, combining the electromagnetic data with the gravitational-wave information: ◉ **Mellinger (default)** ○ **WISE** ○ **2MASS** ○ **DSS color** ○ **XMM** ○ **Fermi**

What you see

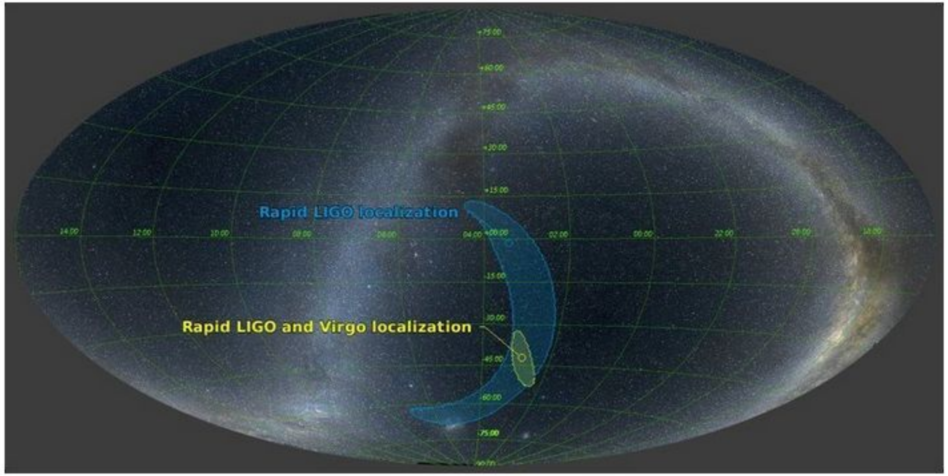
LIGO VIRGO

SECTIONS HOME SEARCH The New York Times SUBSCRIBE NOW LOG IN

SCIENCE

New Gravitational Wave Detection From Colliding Black Holes

By DENNIS OVERBYE SEPT. 27, 2017



The LIGO and Virgo detectors in the United States and Europe identified gravitational waves emitted by the [illegible] holes 1.8 billion light years away. The location of the black holes in the night skies is [illegible]p. LIGO/Virgo

4
ARTICLES REMAINING THIS MONTH

RELATED COVERAGE

Third Gravitational Wave Detection, From Black-Hole Merger 3 Billion Light Years Away JUNE 1, 2017

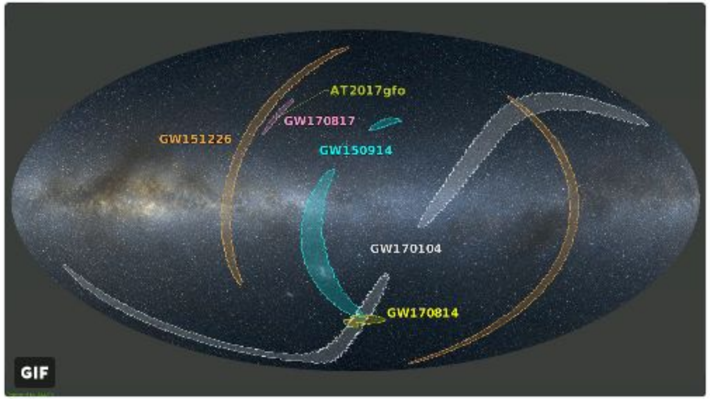
Press Statement from Dr. France A. Córdova at G7 Science Ministerial Meeting

LIGO @LIGO

Siguiendo

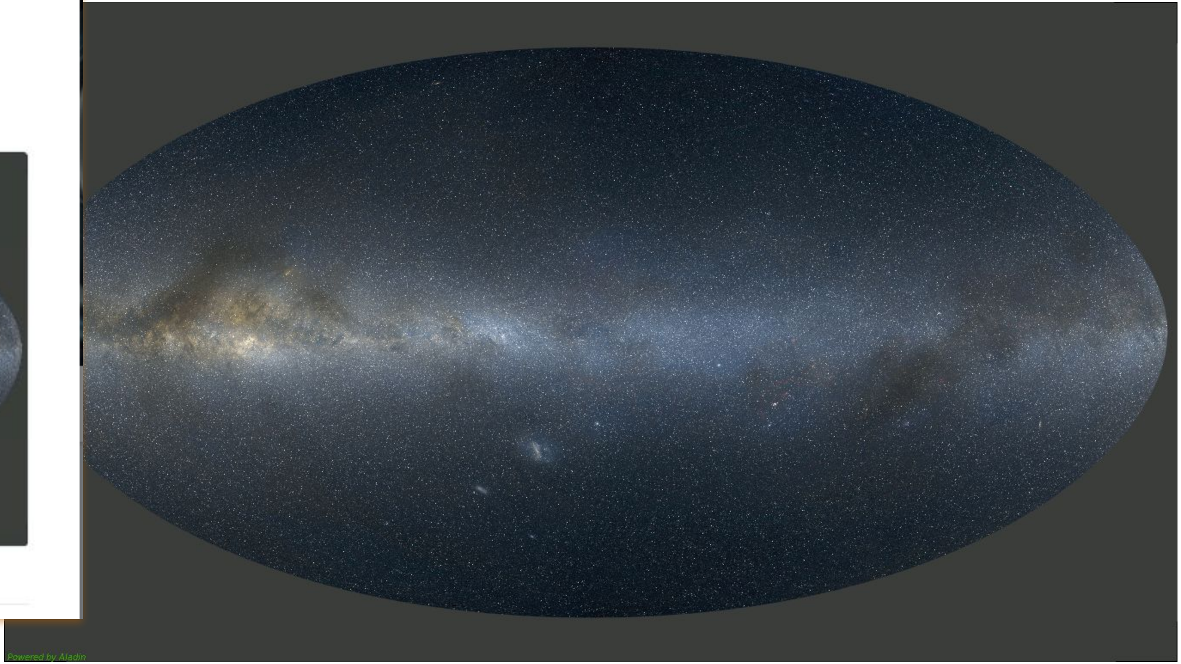
Watch how GW astronomy improves sky location of sources. @LIGO & @ego_virgo together point very well! #GW170814 #GW170817

Traducir del inglés



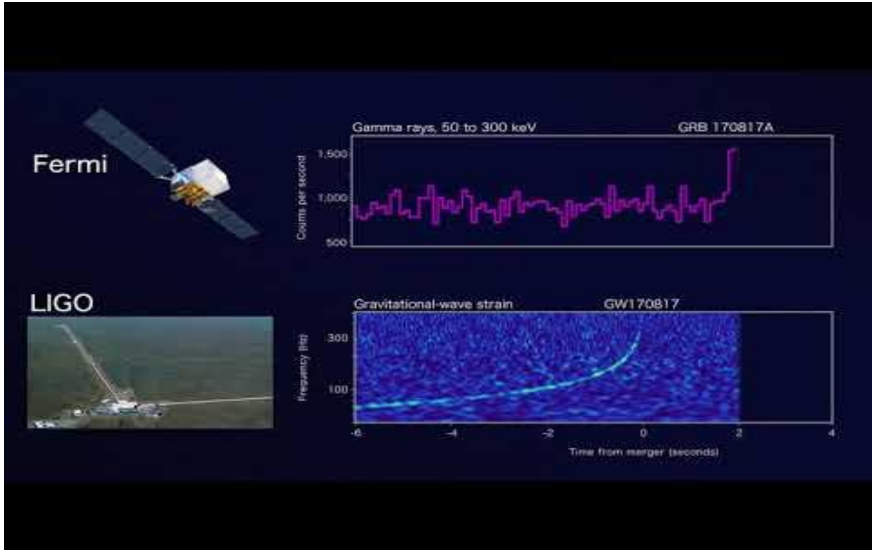
12:30 - 16 oct. 2017

Tweets	Siguiendo	Seguidores	Me gusta	Listas
3.649	165	74 K	1.095	1

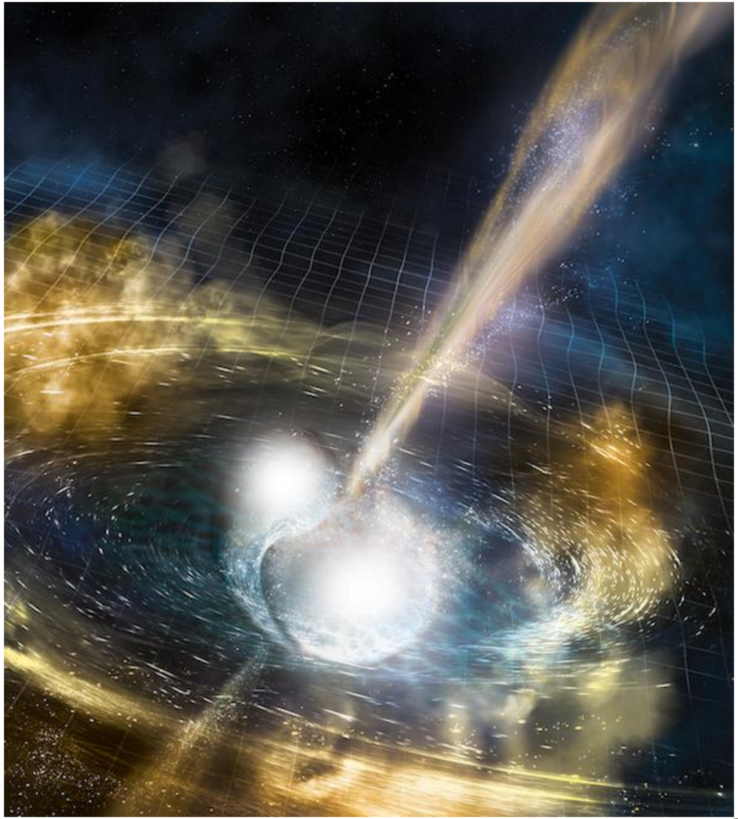


GW170817 - The first observation of gravitational-waves from a binary neutron star inspiral

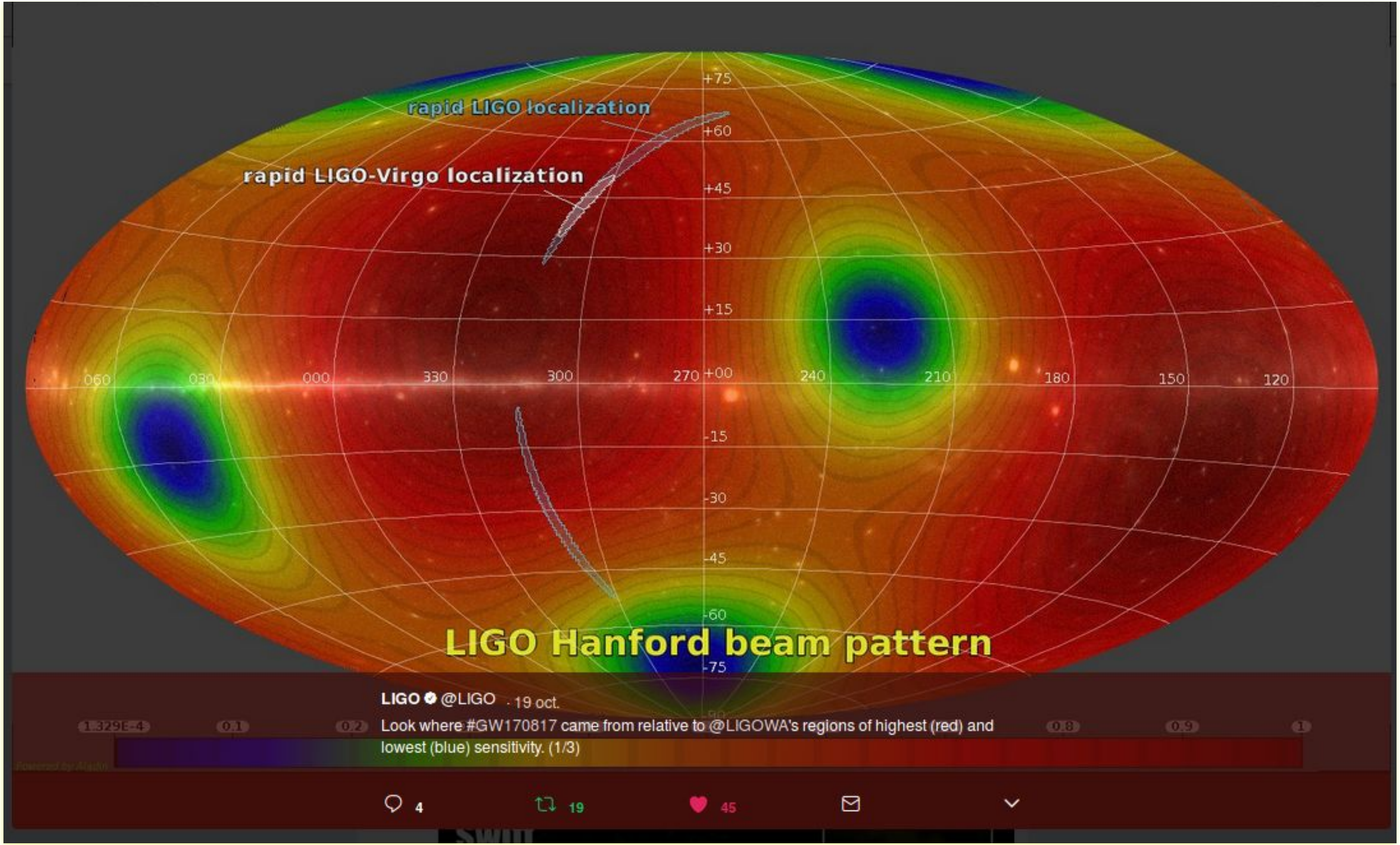
GW170817 marks a new era of multi-messenger astronomy, where the same event is observed by both gravitational waves and electromagnetic waves.



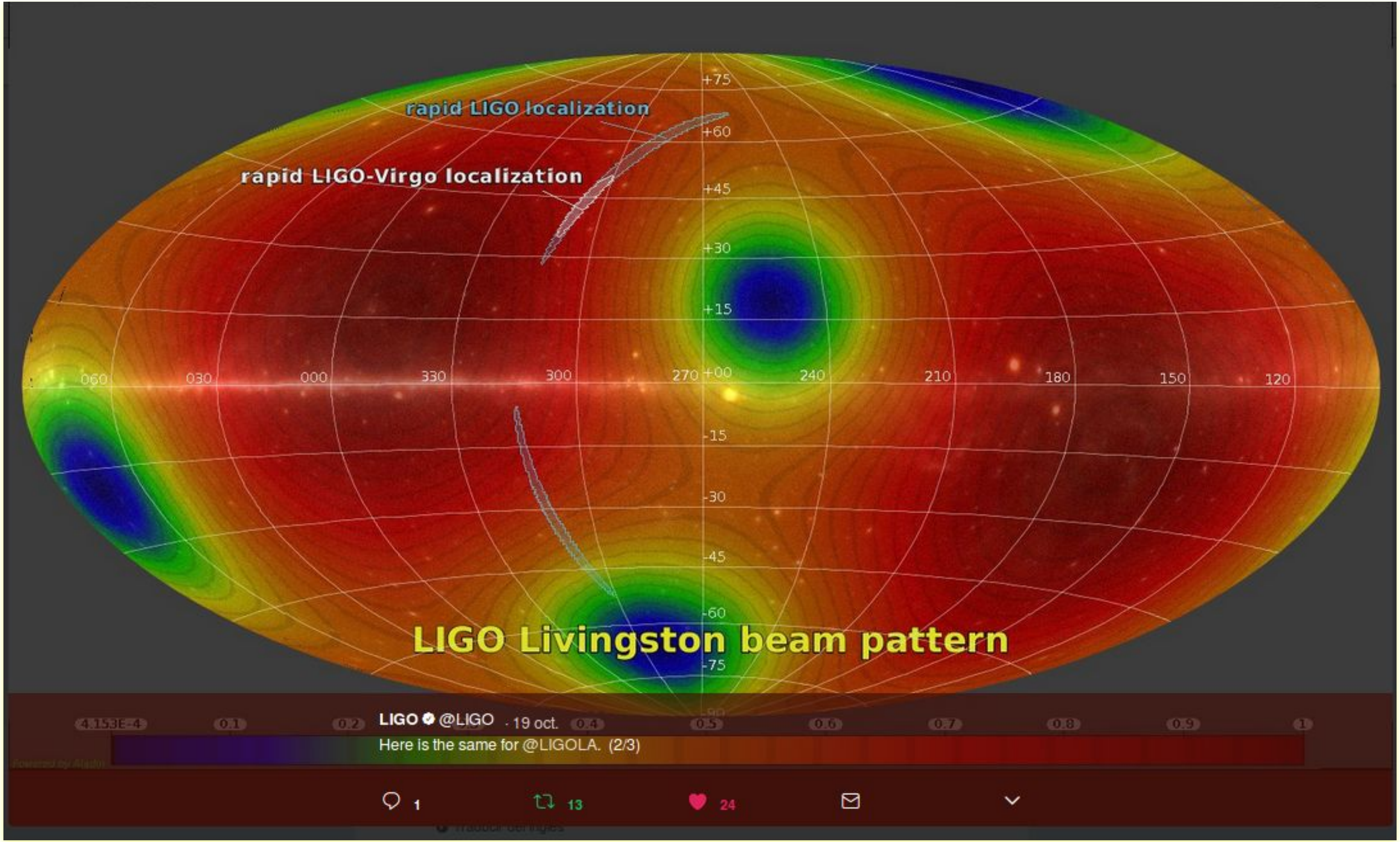
Credit: NASA GSFC & Caltech/MIT/LIGO Lab



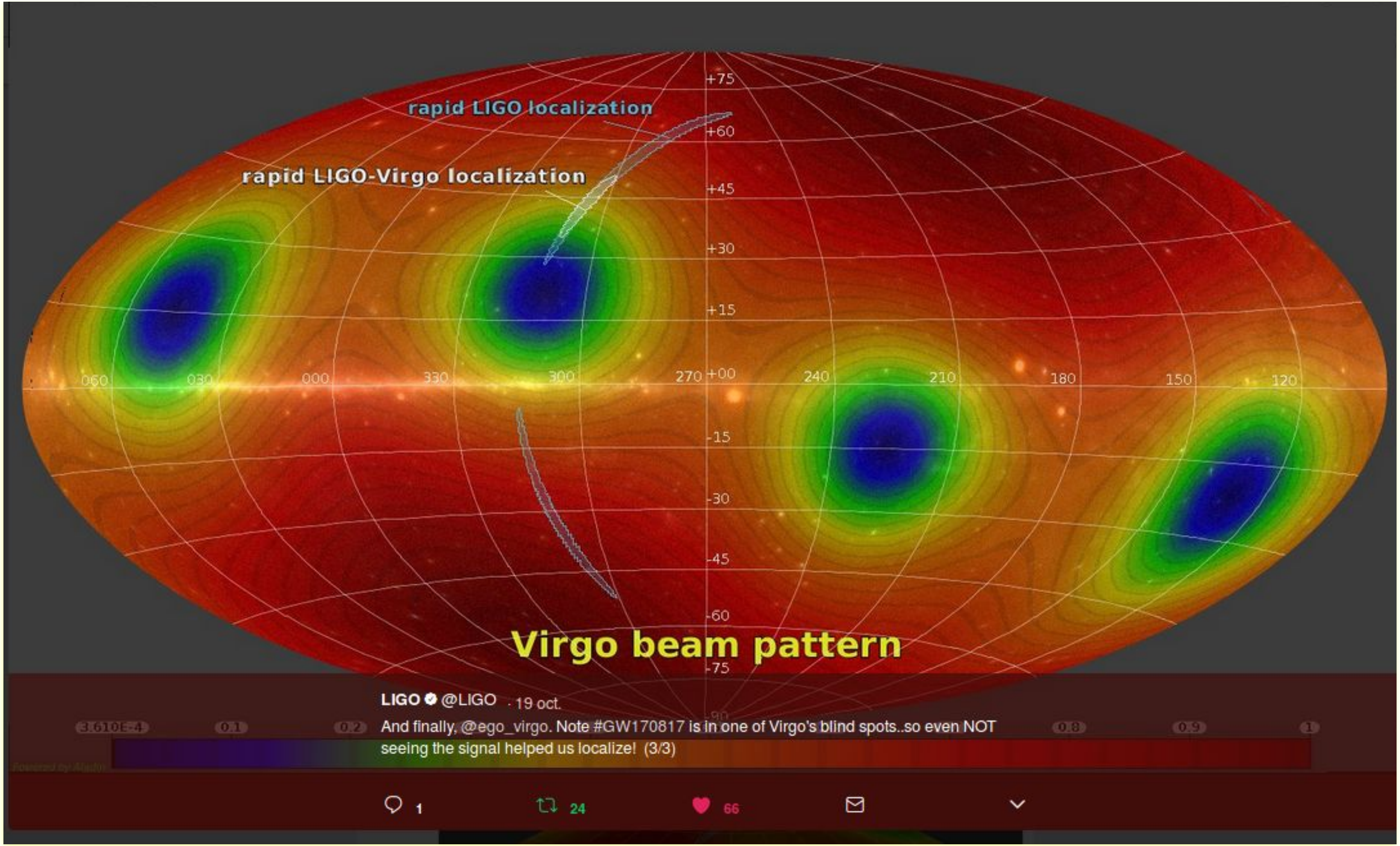
Credit: NSF/LIGO/Sonoma State University/A. Simonne



The sensitivity increases from blue to red



The sensitivity increases from blue to red



The sensitivity increases from blue to red

From *Initial* to *Advanced* LIGO and Virgo

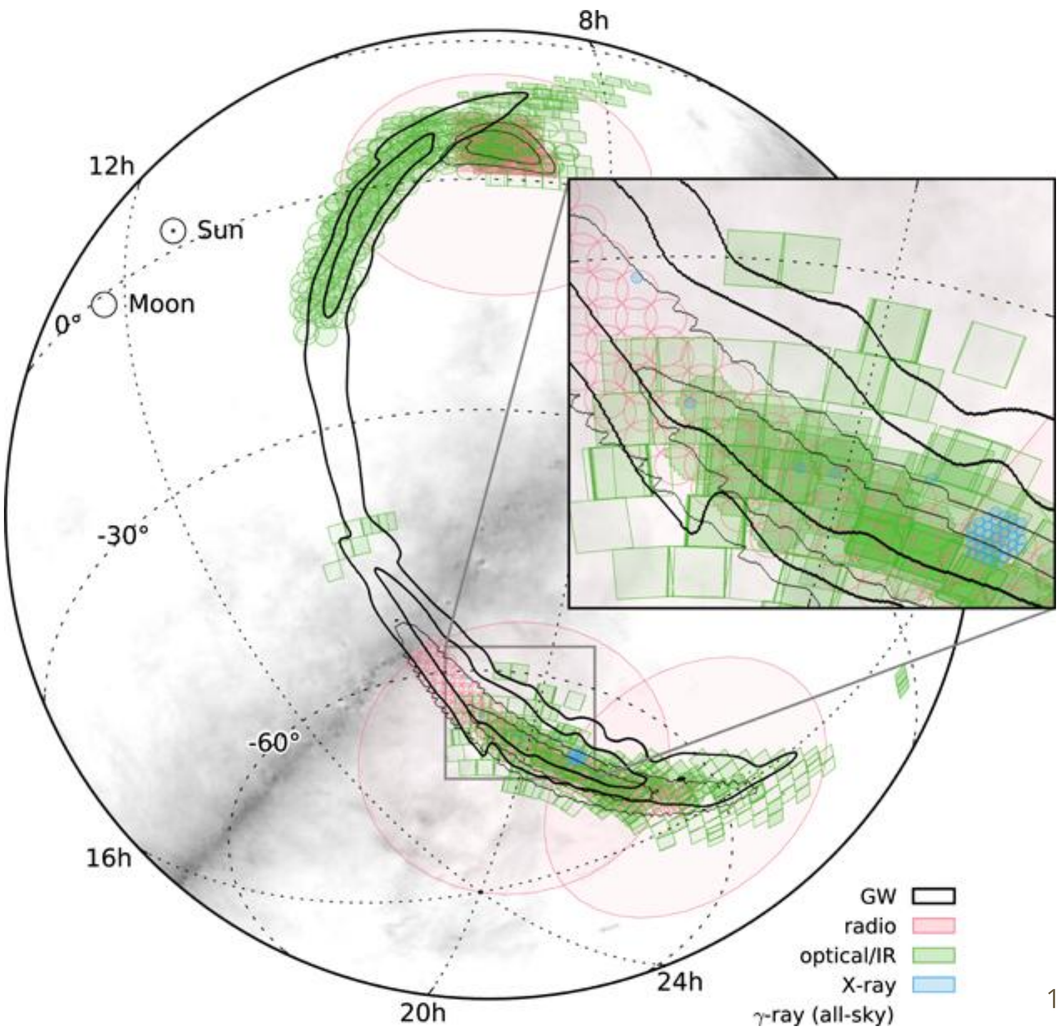
- ~ 12 ground optical and radio telescopes + Swift satellite
- Centrally planning; assignment of Field of View (FoV) tiles to EM facilities
- 8 GW candidates were followed although none of these were significant enough to constitute detection

- 160 (~200) instruments - satellites/world-wide ground-based telescopes
- Sky map localization (3D sky map and source classification for compact binary mergers)
- 6 Detections (5 **BH-BH** and 1 **NS-NS** mergers) + 1 event candidate. **First electromagnetic counterpart.**

EM-FollowUP of GW150914

Follow-up observations are reported by **25 teams** via private GCN Circulars.

The astronomer teams tiled portions of the GW sky maps. Some groups, considering the possibility of a NS merger or core-collapse SN, selected fields based on nearby galaxies or pointed at the Large Magellanic Cloud.



High-energy followUP of GW150914

No stellar-BBH EM emission expected due to the absence of the accreting material.

However some mechanisms that could produce unusual presence of matter around BHs recently discussed (*e.g.* Loeb 2016; Perna et al. 2016; Murase et al. 2016, Bartosetal.2016)

Future EM follow-ups of GW will shed light on the presence or absence of firm EM counterparts for BBH.

- Fermi-GBM, INTEGRAL, IPN **archival search** to detect prompt emission
- Fermi-LAT, MAXI, Swift-XRT to detect afterglow emission

From Abbott et al. 2016, arXiv:1602.08492

Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained probability (%) cWB	LIB	BSTR.	LALInf.	GCN
		erg cm^{-2} s^{-1}	Gamma-ray						
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100	18709
Fermi GBM	8 keV–40 MeV	$0.7–5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100	18339
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100	18354
IPN	15 keV–10 MeV	1×10^{-9}	(archival)	—	100	100	100	100	—
			X-ray						
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84	19013
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05	18331
		$2–4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26	18346

Evans et al. arXiv:1602.03868

Integral:

no signal but stringent upper limit

Savchenko et al. arXiv:1602.04180

Fermi-GBM sub-threshold search:

weak signal 0.4s after the event (t=1s)

Connaughton et al. arXiv:1602.03920

Communication System: *notice/circular*

GCN Notices automated, machine-readable packets. Available as VOEvent XML, binary, and plain text. Listen anonymously or pre-register for connection and delivery tracking.

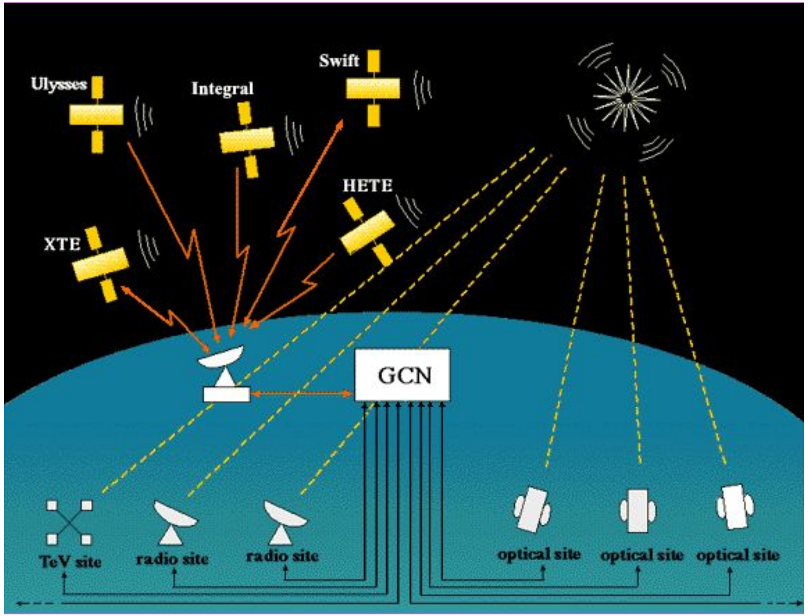
GCN Circulars human-readable, citable, non-refereed astronomical bulletins. Pre-register in order to receive and submit by email.

Preliminary
~ 3 min

Initial
~ 30 min

Update
Hours/days

Retraction at any stage



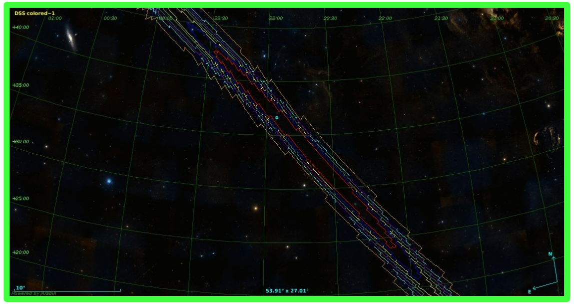
The Gamma-ray Coordinates Network

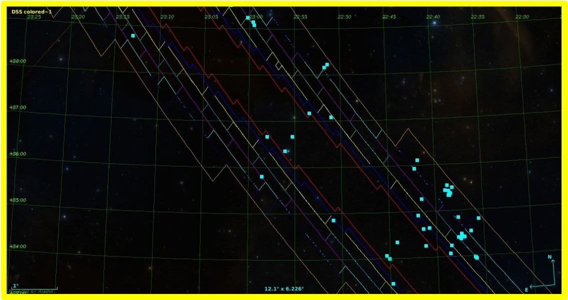
In O3 event candidates with high confidence will be shared immediately with the entire astronomy community!!!

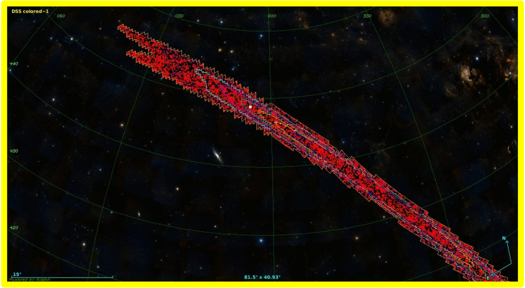
Reading an open public alert in O3 (GCN)

Alerts should contain all of the information that is useful to set an EM strategy for searching a counterpart - if there is.

1. **Tiling the sky map to maximize the enclosed localization probability**
2. **Ranked list of galaxies in 3D sky map**
3. **Targeting ranked FoV pointings**
4. **Set your own strategy combining GCN information with the telescope characteristics**







GCN Notices: Basic Info

	CBC	Burst
IVORN	ivo://nasa.gsfc.gcn/LVC#{G,M}*nnnnnn*-{1,2,3}-*Preliminary*,*Initial*,*Update*	
Who	LIGO Scientific Collaboration and Virgo Collaboration	
What	GraceDB ID: {G,M}*nnnnnn*	
Search group	CBC	Burst
Pipeline	{Gstlal,MBTA,PyCBC}	{CWB,LIB}
FAR	estimated false alarm rate in Hz	
Network	Flag for each detector (LHO_participated, etc.)	
Sky map	URL of HEALPix FITS localization file	
WhereWhen	Arrival time (UTC, ISO-8601), e.g., 2010-08-27T19:21:13.982800	

From Open LVEM Town Hall MIT held from 16 Mar 2018 to 17 Mar 2018 in MIT

GCN Notices: Inference (CBC only)

	CBC
What	GraceDB ID: {G,M}*nnnnnn*
...	...
Distance	a posteriori mean luminosity distance in Mpc
DistanceError	a posteriori standard deviation of luminosity distance in Mpc
ProbHasNS	Probability (0–1) that the less massive companion has a source-frame mass <3 $M_\odot$
ProbHasRemnant	EMBright: Probability (0–1) that the system ejected a significant amount of NS material, as calculated by method of Pannarale & Ohme (2014)

From Open LV EM Town Hall MIT held from 16 Mar 2018 to 17 Mar 2018 in MIT

Example Circulars of GW170817: GCN 21509

"A binary neutron star candidate was identified in data from the LIGO Hanford detector at gps time 1187008882.4457 (Thu Aug 17 12:41:04 GMT 2017). The signal is clearly visible in time-frequency representations of the gravitational-wave strain in data from H1. The current significance estimate of ~1/10,000 years is based on data from H1 alone. Information about this candidate is available in GraceDb here..."

Time, source classification, significance

GCN CIRCULARS: GCN 21513

"Investigation of L1 data identified a noise transient from a known class of instrumental glitches during the inspiral signal. The duration of this glitch is a small fraction of a second and does not appear to affect the signal at times away from the glitch. To make an improved preliminary estimate of the sky position, we re-analyzed the data, removing the L1 noise transient at GPS time 1187008881.389 by multiplying the strain data with a Tukey window, such that the total duration of the zeroed data is 0.2 s and the total duration of the Tukey window is 1.2 s.

Data quality assessment: Concise description of any instrument or data quality issues that affect significance estimates or parameter inference based on the GW data

GCN CIRCULARS: GCN 21513

"…An updated BAYESTAR sky map (Singer et al. 2016, ApJL 829, 15) that uses data from all three gravitational-wave observatories (H1, L1, and V1) is available for retrieval from the GraceDB page (https://gracedb.ligo.org/events/view/G298048): bayestar-HLV.fits.gz. The centroid (maximum a posteriori) sky location is R.A.=12h57m, Dec.=- 17d51m. The 50% credible region spans about 9 deg2 and the 90% region about 31deg2. The luminosity distance is 40 +/- 8 Mpc (all-sky a posteriori mean +/- standard deviation). This is the preferred sky map at this time…"

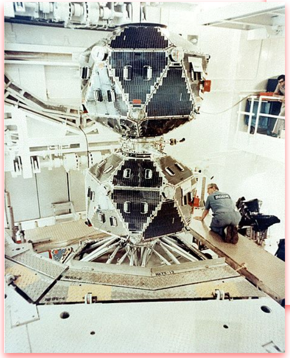
Localization, distance

GW170817/GRB170817/ AT2017gfo

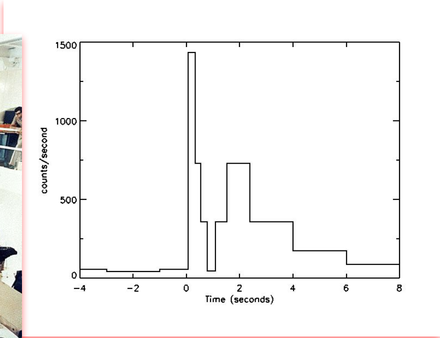
A Science Explosion

GRBs: Historical Perspective

- 1967: Discovery – Vela Satellites
- 1972-1991: A world of proposals (Local/Extragalactic/Cosmological Models).
- 1991: Constraining the theories – CGRO (BATSE) finds isotropic distribution.
- 1997: Localization - BeppoSAX - the first afterglow.

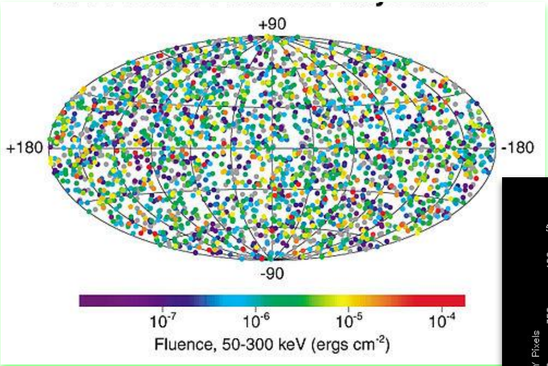


Vela-5A/B Satellite in Clean Room

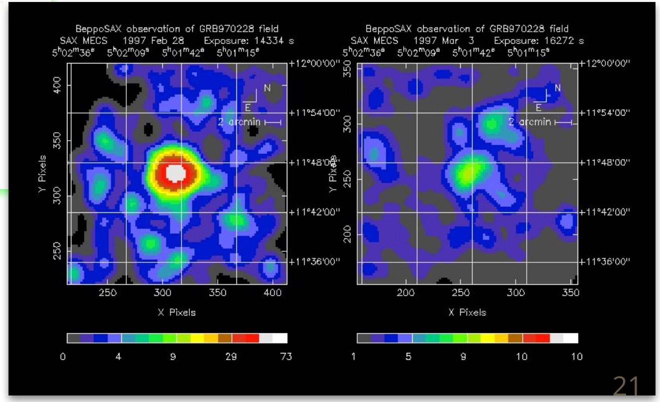


Event recorded by Vela 4a,b on July 2, 1967

By 1992, over 100 models Existed!



2704 BATSE Gamma-Ray Bursts

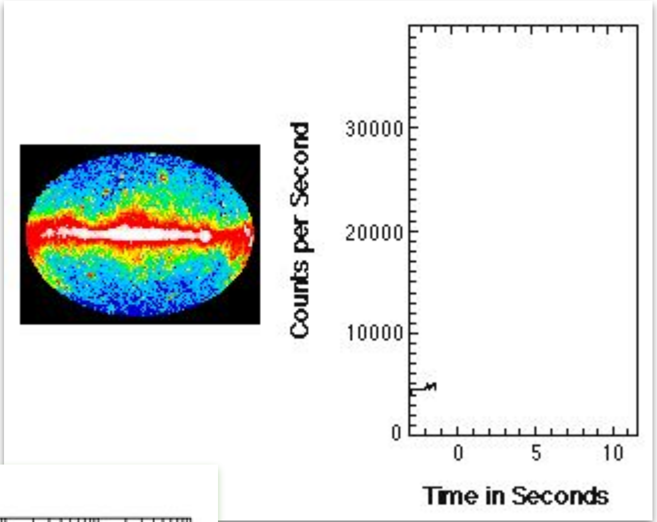


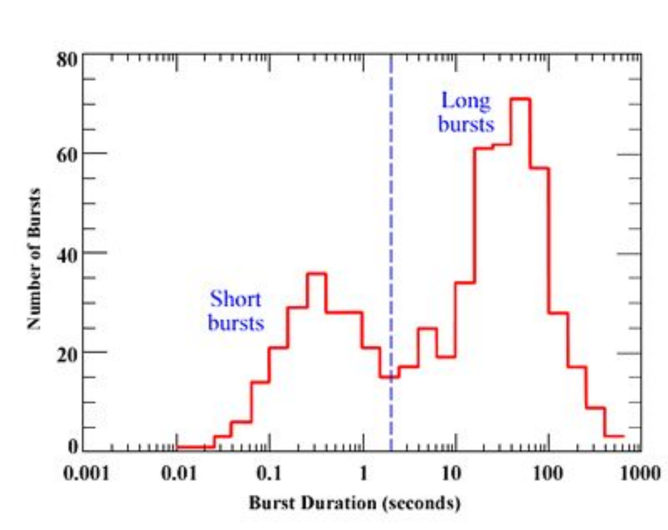
BeppoSAX observations of GRB 970228

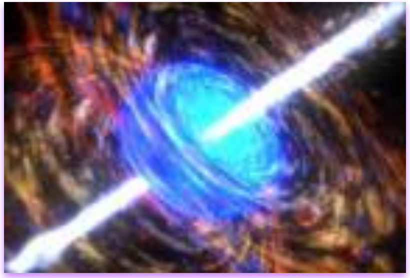
GRBs: short and long

GRBs are bright flashes of enormous gamma rays that appear suddenly in the sky and usually last only several to a few tens of seconds.

GRBs are (usually) followed by afterglow - lower energy, long lasting emission in the X-ray, optical and radio.

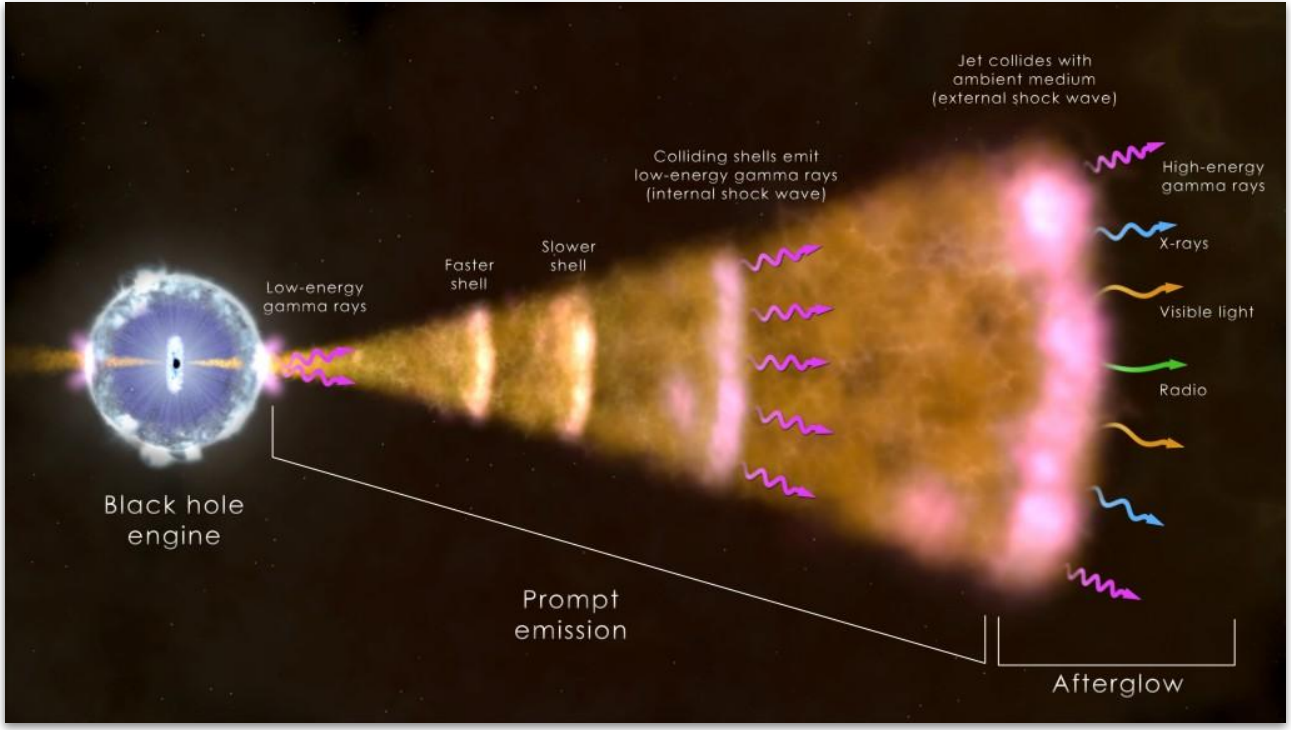






Fireball model

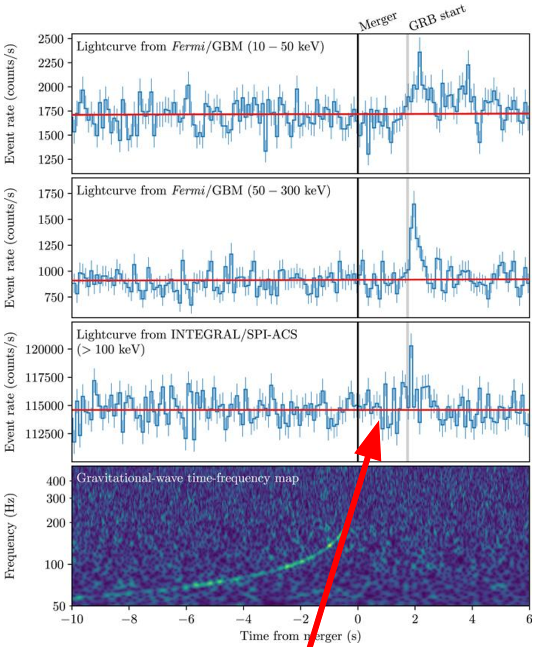
Schematic of the Fireball model, illustrating the production of the **prompt** and **afterglow** emission.

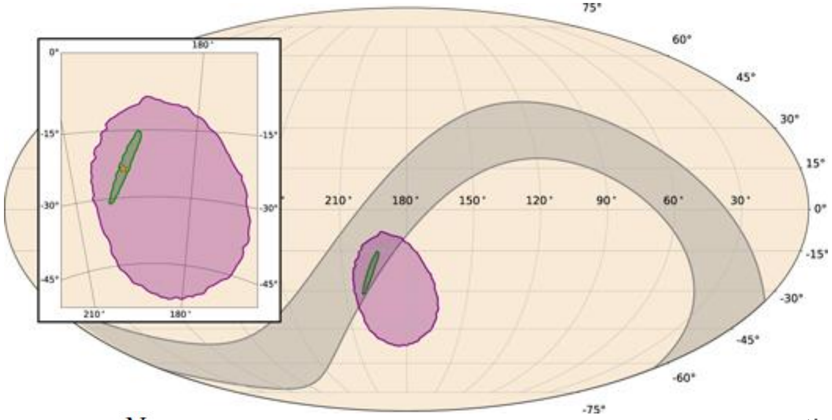


Credit: NASA

Unambiguous Association: GW170817 and GRB170817

From Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A; 2017ApJ...848L..13A





$$\mathcal{S} = \sum_{i=1}^{N_{\mathrm{pix}}} P_{1i} P_{2i}$$

Healpix pixel index

Posterior probabilities from GBM and LVC map

$$P_{\mathrm{spatial}} = 0.01$$

the two independent localizations agree this well by chance

$$P_{\mathrm{temporal}} = 2\Delta t_{\mathrm{SGRB-GW}} R_{\mathrm{GBM-SGRB}} = 2(1.74\ \mathrm{s})(351/3324\ \mathrm{days}/0.85) = 5.0 \times 10^{-6}$$

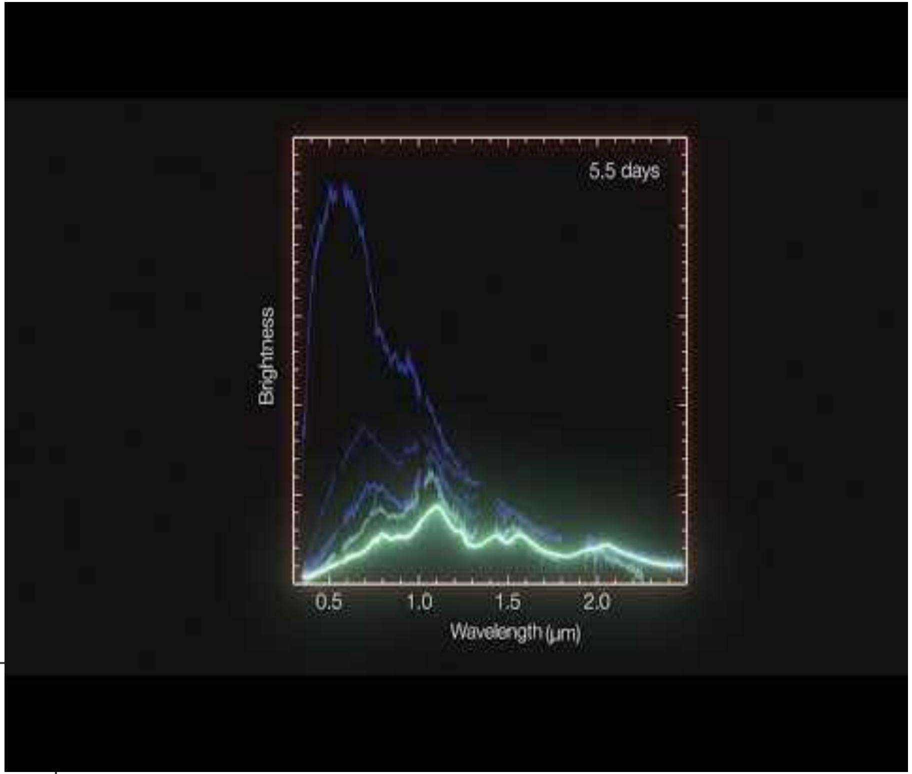
detection rate

$$P_{\mathrm{temporal}} \times P_{\mathrm{spatial}} = (5.0 \times 10^{-6}) \times (0.01) = 5.0 \times 10^{-8}$$

Animation of spectra of kilonova in NGC 4993

Swope and Magellan telescope optical and near-infrared images of the first optical counterpart to a gravitational wave source, SSS17a, in its galaxy, NGC 4993.

Credit: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley



This animation is based on a series of spectra of the kilonova in NGC 4993 observed by the X-shooter instrument on ESO's Very Large Telescope in Chile. They cover a period of 12 days after the initial explosion on 17 August 2017. The kilonova is very blue initially but then brightens in the red and fades.

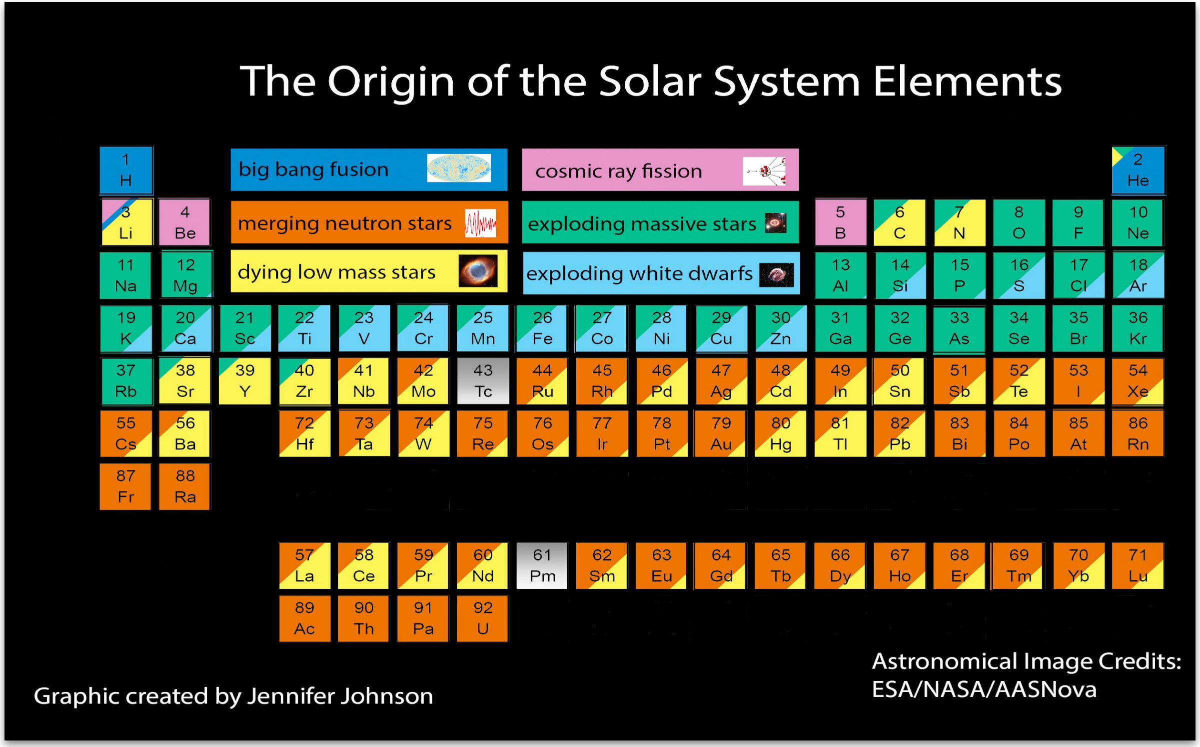
Credit: European Southern Observatory (ESO)

Neutron star mergers as an origin of heavy elements

<u>The cosmic origin of elements heavier than iron has long been uncertain.</u>

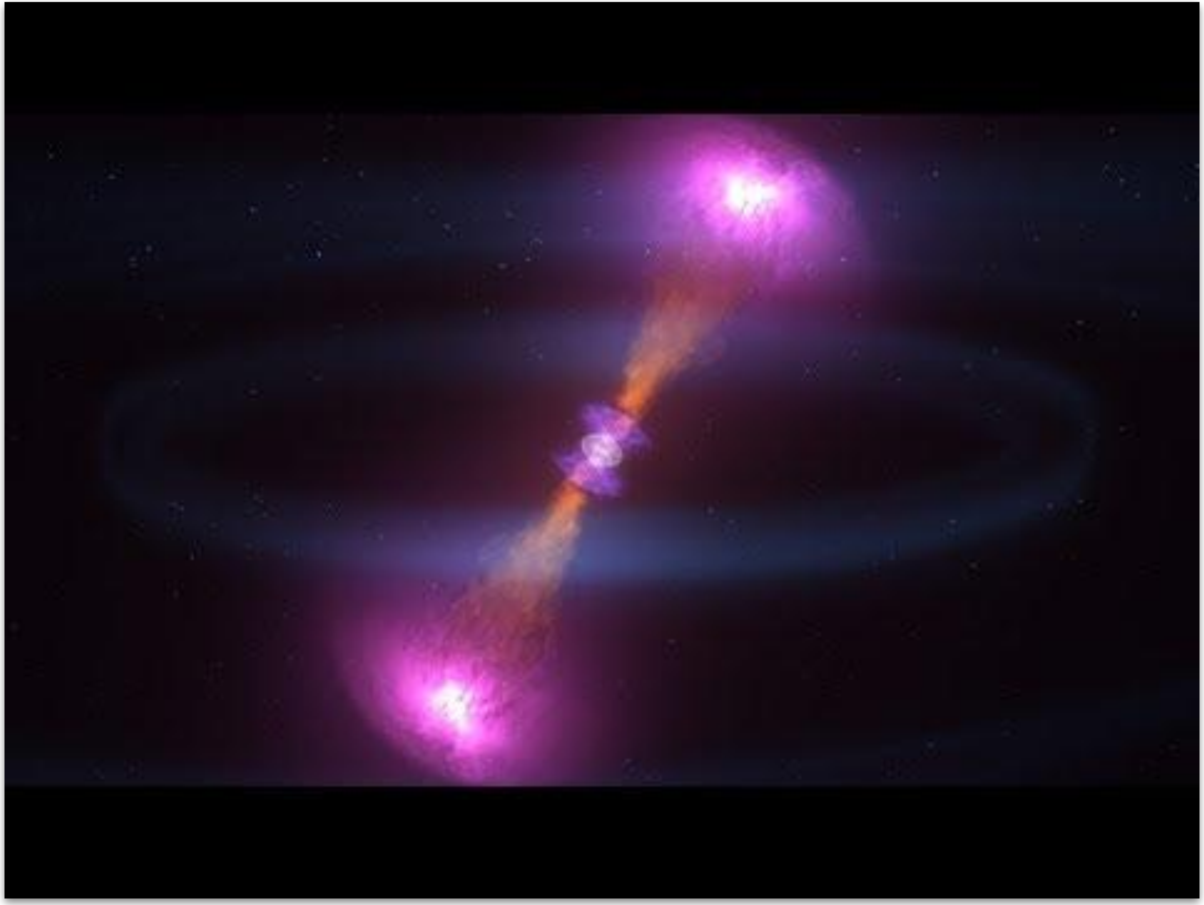
Theoretical modelling shows that the matter that is expelled in the violent merger of two neutron stars can produce heavy elements such as gold and platinum in a process known as rapid neutron capture (r-process) nucleosynthesis.

The radioactive decay of isotopes of the heavy elements is predicted to power a distinctive thermal glow *the kilonova.*



GW170817/GRB170817 represents the first opportunity to detect and study a sample of synthesized r-process elements.

Neutron Star Merger Create Blast of Light and Gravitational Waves



Credit: NASA Goddard

Astrophysical implications

First multi-messenger EM-GW detection

First Neutron star merger discovery

First short GRBs and GW connection

First heavy-element production associated in a neutron star merger

First relativistic outflow from a neutron star merger

First independent measurement of the Hubble constant

....

thanks