GW170817: the birth of MMA with GWs

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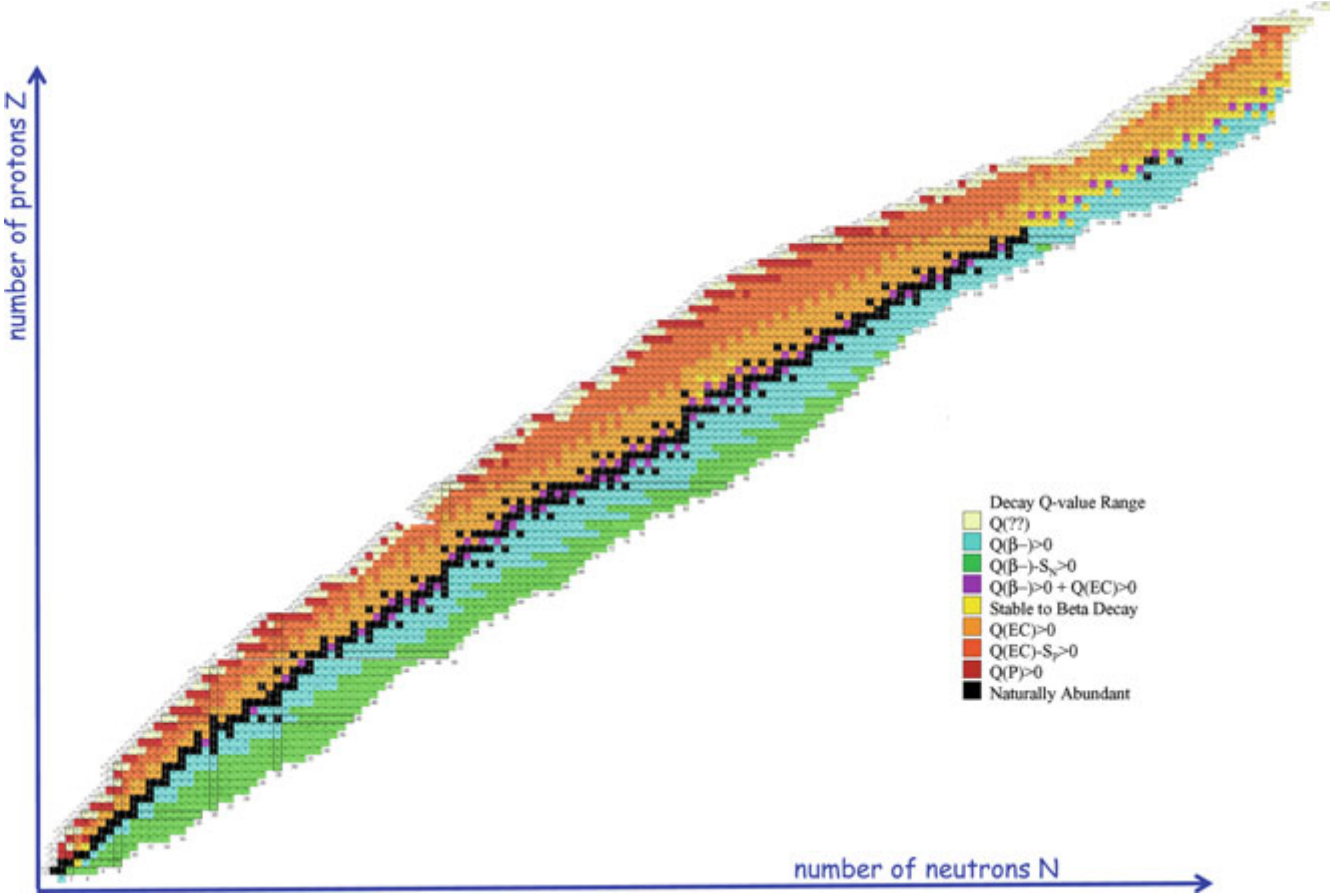
Stellar nucleosynthesis and the r-processes

Burbidge et al. and Cameron realized in 1957 that approximately half of the elements heavier than iron are synthesized via the capture of neutrons onto lighter seed nuclei like iron, in a dense neutron-rich environment in which the timescale for neutron capture is shorter than the β-decay timescale.

This ‘**rapid neutron-capture process**’, or **r-process**, occurs along a nuclear path which resides far on the neutron-rich side of the valley of stable isotopes. **Despite these works occurring over 70 years ago, the astrophysical environments giving rise to the r-process remains an enduring mystery, among the greatest in nuclear astrophysics.**

Adapted from B. D. Metzger, *Kilonovae*, Living Reviews in Relativity **23** (2020) 1



The table of isotopes, showing nuclei in a chart of neutron number (abscissa) versus proton number (ordinate). The stable elements are marked in black. All other isotopes are unstable, or radioactive, and will decay until a stable nucleus is obtained.

From Diehl, R.: Introduction to Astronomy with Radioactivity. Lect. Notes Phys. **812** (2011) 3–23

It has long been surmised that a suitable enviroment for r-processes could be created in collisions of neutron stars and the formation of the so-called kilonovae. **Kilonovae are thermal supernova-like transients lasting days to weeks, which are powered by the radioactive decay of heavy neutron-rich elements synthesized in the expanding merger ejecta**.

Table 1 Timeline of major developments in kilonova research

1974	Lattimer and Schramm: r-process from BH–NS mergers
1975	Hulse and Taylor: discovery of binary pulsar system PSR 1913+16
1982	Symbalisty and Schramm: r-process from NS–NS mergers
1989	Eichler et al.: GRBs from NS–NS mergers
1994	Davies et al.: first numerical simulation of mass ejection from NS–NS mergers
1998	Li and Paczyński: first kilonova model, with parametrized heating
1999	Freiburghaus et al.: NS–NS dynamical ejecta ⇒ r-process abundances
2005	Kulkarni: kilonova powered by free neutron-decay ("macronova"), central engine
2009	Perley et al.: optical kilonova candidate following GRB 080503
2010	Metzger et al., Roberts et al., Goriely et al.: "kilonova" powered by r-process heating
2013	Barnes and Kasen, Tanaka and Hotokezaka: La/Ac opacities ⇒ NIR spectral peak
2013	Tanvir et al., Berger et al.: NIR kilonova candidate following GRB 130603B
2013	Yu, Zhang, Gao: magnetar-boosted kilonova ("merger-nova")
2014	Metzger and Fernández: blue kilonova from post-merger remnant disk winds
2017	Coulter et al.: kilonova detected from NS–NS merger following GW-trigger

Table from B. D. Metzger, *Kilonovae*, Living Reviews in Relativity **23** (2020) 1

Wikipedia definitions:

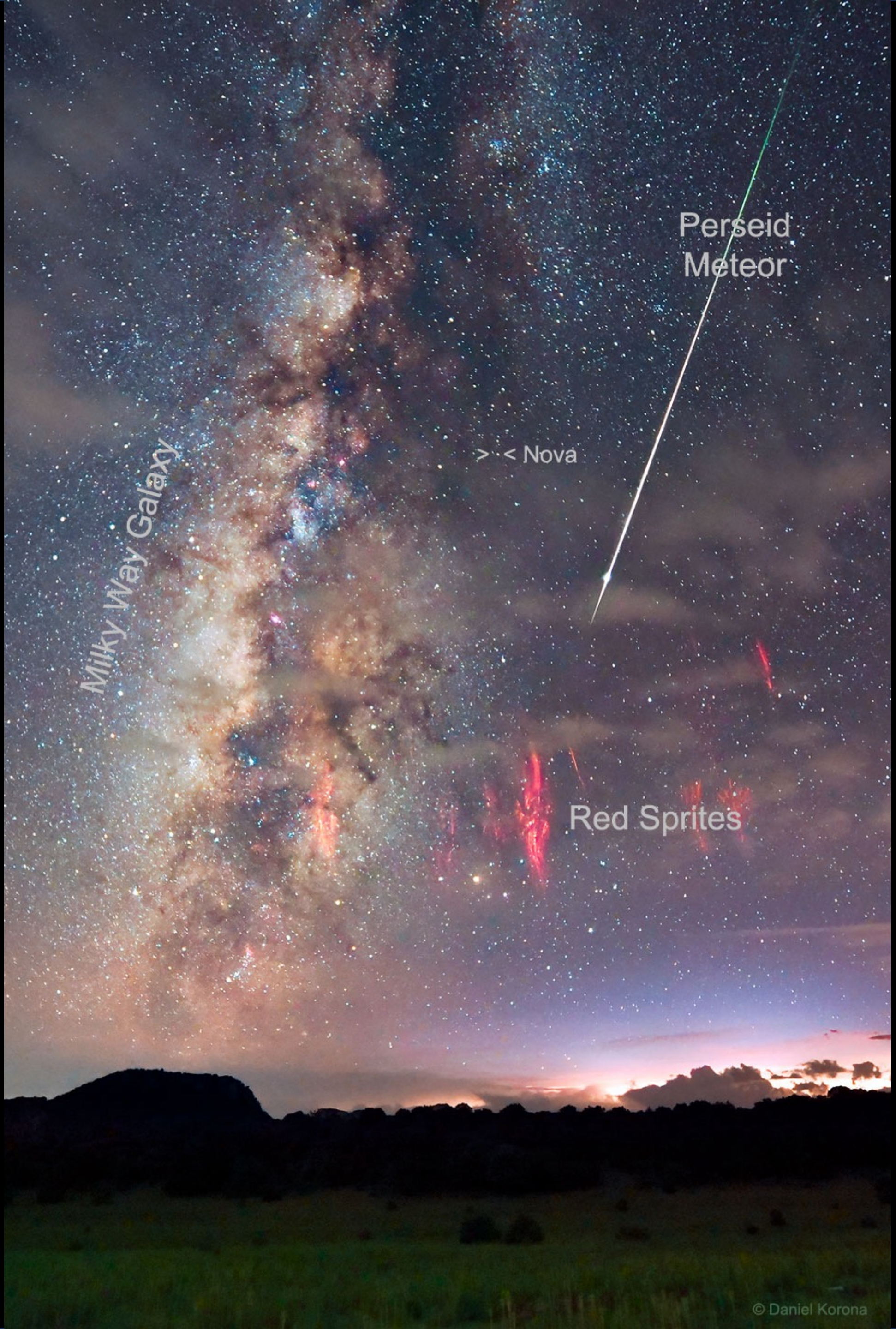
- **Nova**: a transient astronomical event that causes the sudden appearance of a bright, apparently "new" star that slowly fades over weeks or months. Causes of the dramatic appearance of a nova vary, depending on the circumstances of the two progenitor stars. All observed novae involve white dwarfs in close binary systems. The main sub-classes of novae are classical novae, recurrent novae (RNe), and dwarf novae. They are all considered to be cataclysmic variable stars.

  Classical nova eruptions are the most common type. They are likely created in a close binary star system consisting of a white dwarf and either a main sequence, subgiant, or red giant star. When the orbital period falls in the range of several days to one day, the white dwarf is close enough to its companion star to start drawing accreted matter onto the surface of the white dwarf, which creates a dense but shallow atmosphere. This atmosphere, mostly consisting of hydrogen, is thermally heated by the hot white dwarf and eventually reaches a critical temperature causing ignition of rapid runaway fusion.

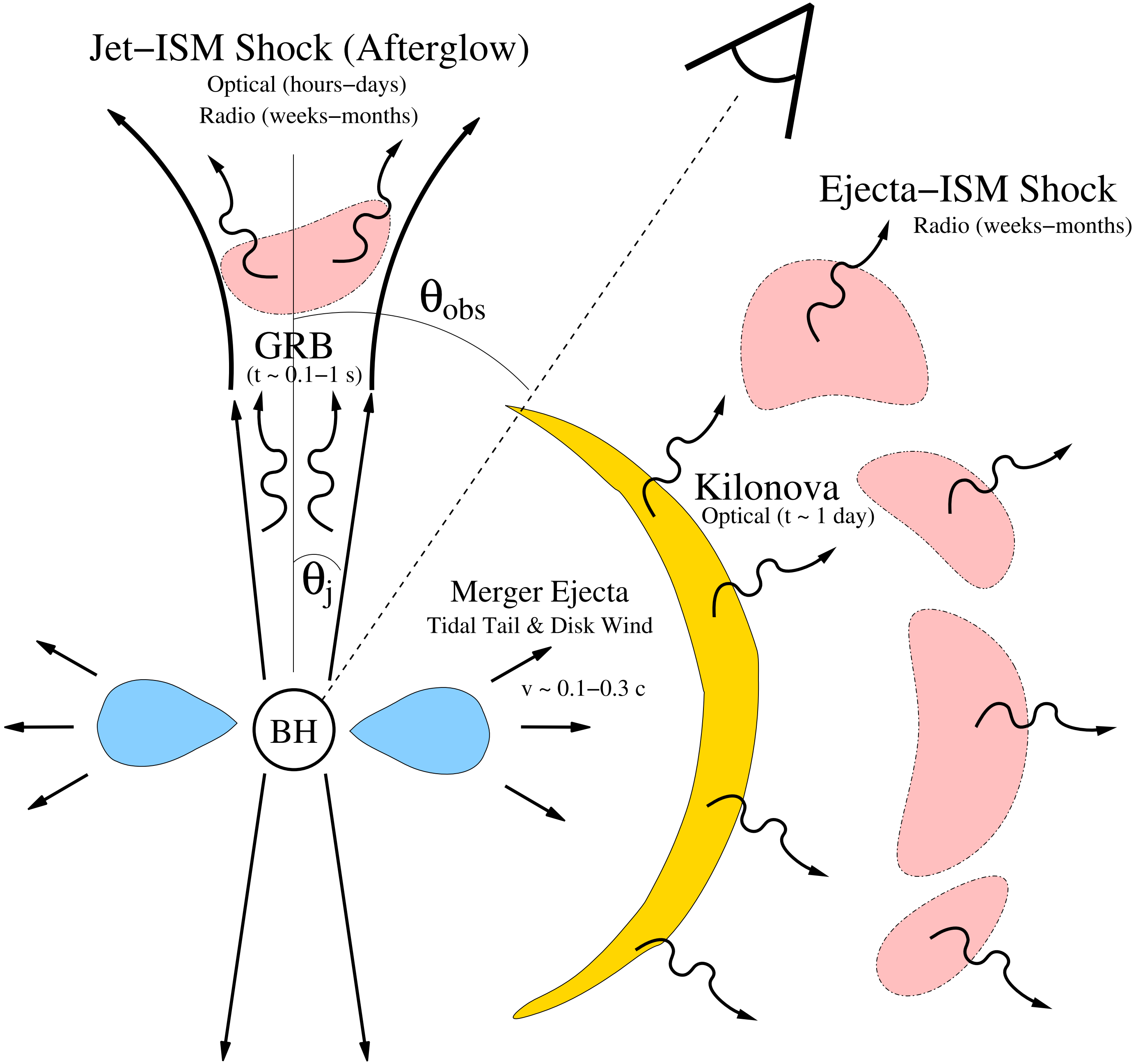
  The sudden increase in energy expels the atmosphere into interstellar space creating the envelope seen as visible light during the nova event.
  (List of recent galactic novae https://asd.gsfc.nasa.gov/Koji.Mukai/novae/novae.html)

- **Kilonova**: a transient astronomical event that occurs in a compact binary system when two neutron stars or a neutron star and a black hole merge. Neutron-rich matter released from such events undergoes rapid neutron capture (r -process) nucleosynthesis as it decompresses into space, enriching our universe with rare heavy elements like gold and platinum.

http://www.vcastro.com/contact.htm



https://apod.nasa.gov/apod/ap210816.html



Summary of the electromagnetic counterparts of NS–NS andBH–NS mergers and their dependence on the viewing angle with respect to the axis of the GRB jet.

The kilonova, in contrast to the GRB and its afterglow, is relatively isotropic and thus represents the most promising counterpart for the majority of GW-detected mergers.

Adapted from B. D. Metzger, *Kilonovae*, Living Reviews in Relativity **23** (2020) 1

THE ASTROPHYSICAL JOURNAL, 507:L59–L62, 1998 November 1

TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

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ABSTRACT

Mergers of neutron stars (NS + NS) or neutron stars and stellar-mass black holes (NS + BH) eject a small fraction of matter with a subrelativistic velocity. Upon rapid decompression, nuclear-density medium condenses into neutron-rich nuclei, most of them radioactive. Radioactivity provides a long-term heat source for the expanding envelope. A brief transient has a peak luminosity in the supernova range, and the bulk of radiation in the UV-optical domain. We present a very crude model of the phenomenon, and simple analytical formulae that can be used to estimate the parameters of a transient as a function of poorly known input parameters. The mergers may be detected with high-redshift supernova searches as rapid transients, many of them far away from the parent galaxies. It is possible that the mysterious optical transients detected by Schmidt et al. are related to neutron star mergers, since they typically have no visible host galaxy.

Subject headings: binaries: close — gamma rays: bursts — stars: neutron — supernovae: general

LP paper and notes

LETTER

doi:10.1038/nature12505

A 'kilonova' associated with the short-duration γ-ray burst GRB 130603B

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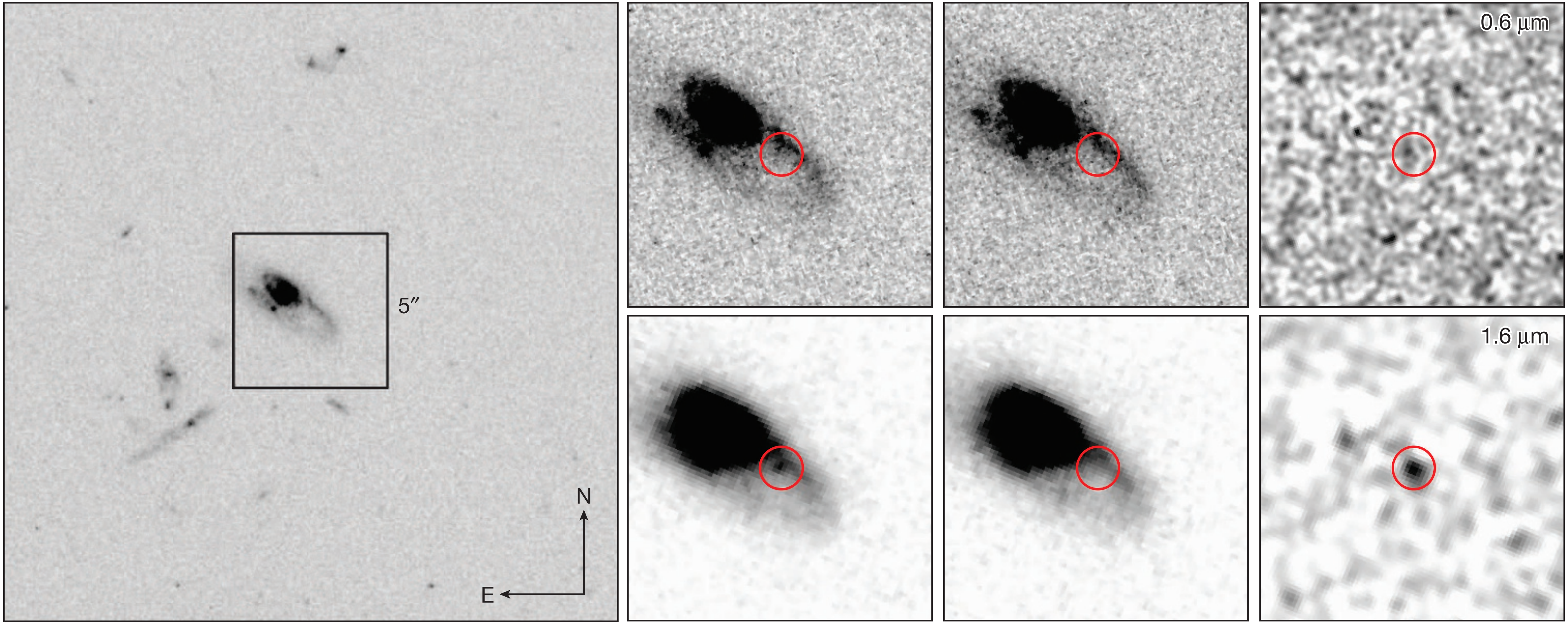
Short-duration γ-ray bursts are intense flashes of cosmic γ-rays, lasting less than about two seconds, whose origin is unclear[1,2]. The favoured hypothesis is that they are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). This is supported by indirect evidence such as the properties of their host galaxies[3], but unambiguous confirmation of the model is still lacking. Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species[4,5], whose decay should result in a faint transient, known as a 'kilonova', in the days following the burst[6–8]. Indeed, it is speculated that this mechanism may be the predominant source of stable r-process elements in the Universe[5,9]. Recent calculations suggest that much of the kilonova energy should appear in the near-infrared spectral range, because of the high optical opacity created by these heavy r-process elements[10–13]. Here we report optical and near-infrared observations that provide strong evidence for such an event accompanying the short-duration γ-ray burst GRB 130603B. If this, the simplest interpretation of the data, is correct, then it confirms that compact-object mergers are the progenitors of short-duration γ-ray bursts and the sites of significant production of r-process elements. It also suggests that kilonovae offer an alternative, unbeamed electromagnetic signature of the most promising sources for direct detection of gravitational waves.



HST imaging of the location of GRB 130603B. The position at which the SGRB occurred is marked as a red circle (right-hand panels), lying slightly off a tidally distorted spiral arm. The left-hand panel shows the host and surrounding field from the higher-resolution optical image. The right-hand panels show, from left to right, the epoch-1 and epoch-2 imaging and their difference (epoch 1 minus epoch 2; upper row, F606W/ optical; lower row, F160W/NIR). The difference images have been smoothed with a Gaussian of width similar to the point-spread function, to enhance any point-source emission. Although the resolution of the NIR image is inferior to that of the optical image, we clearly detect a transient point source that is absent in the optical.

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger*

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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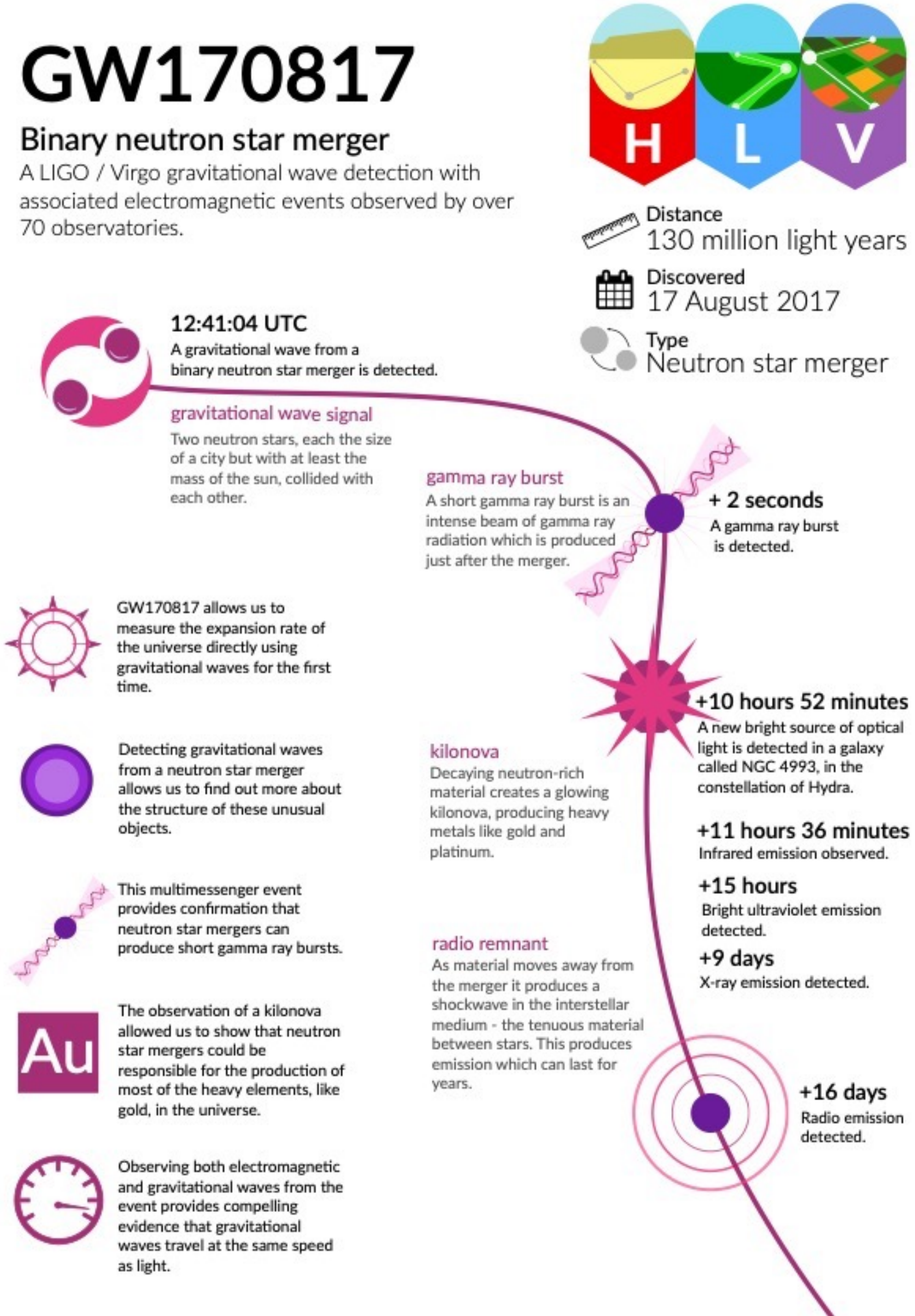
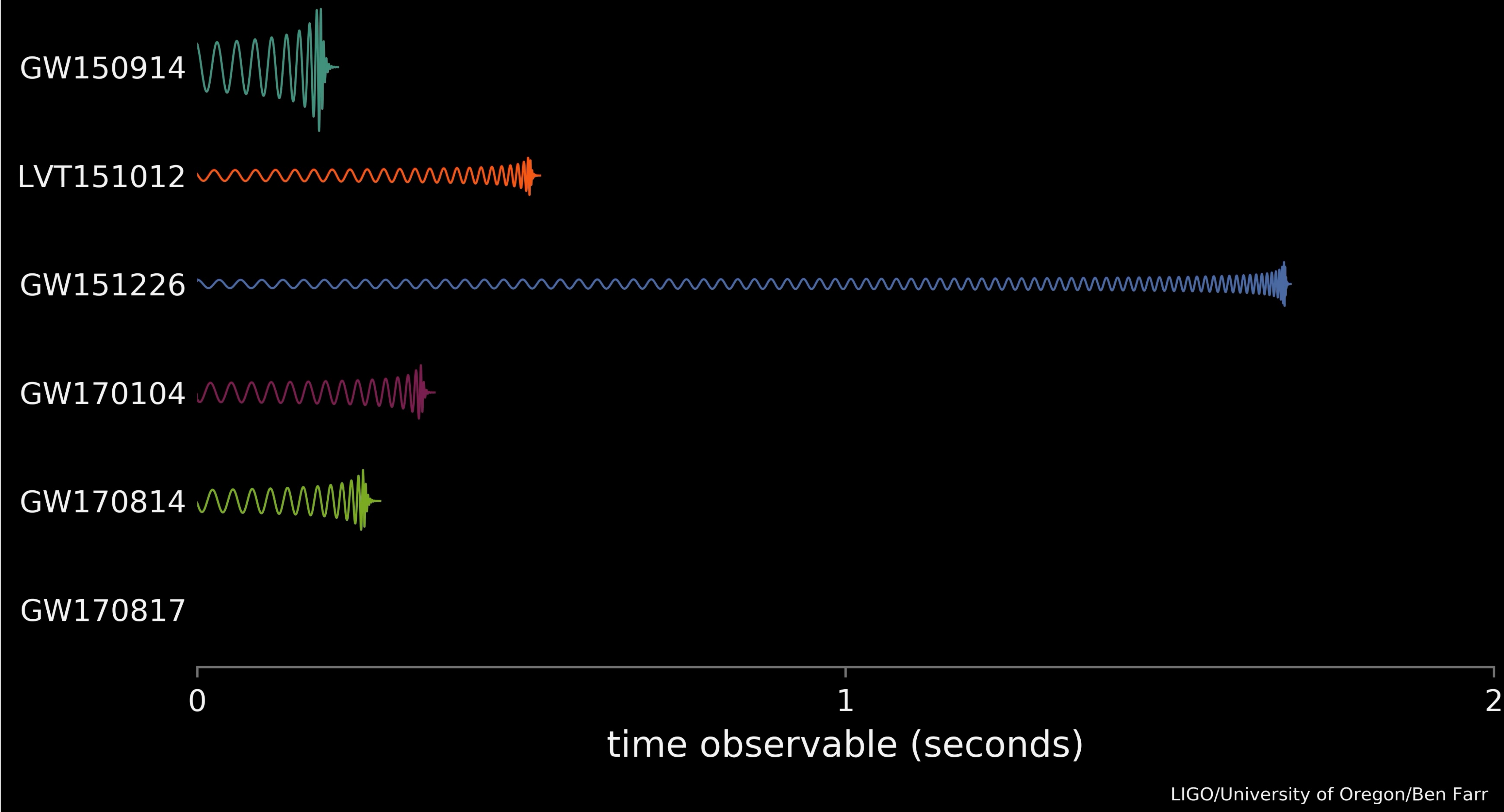
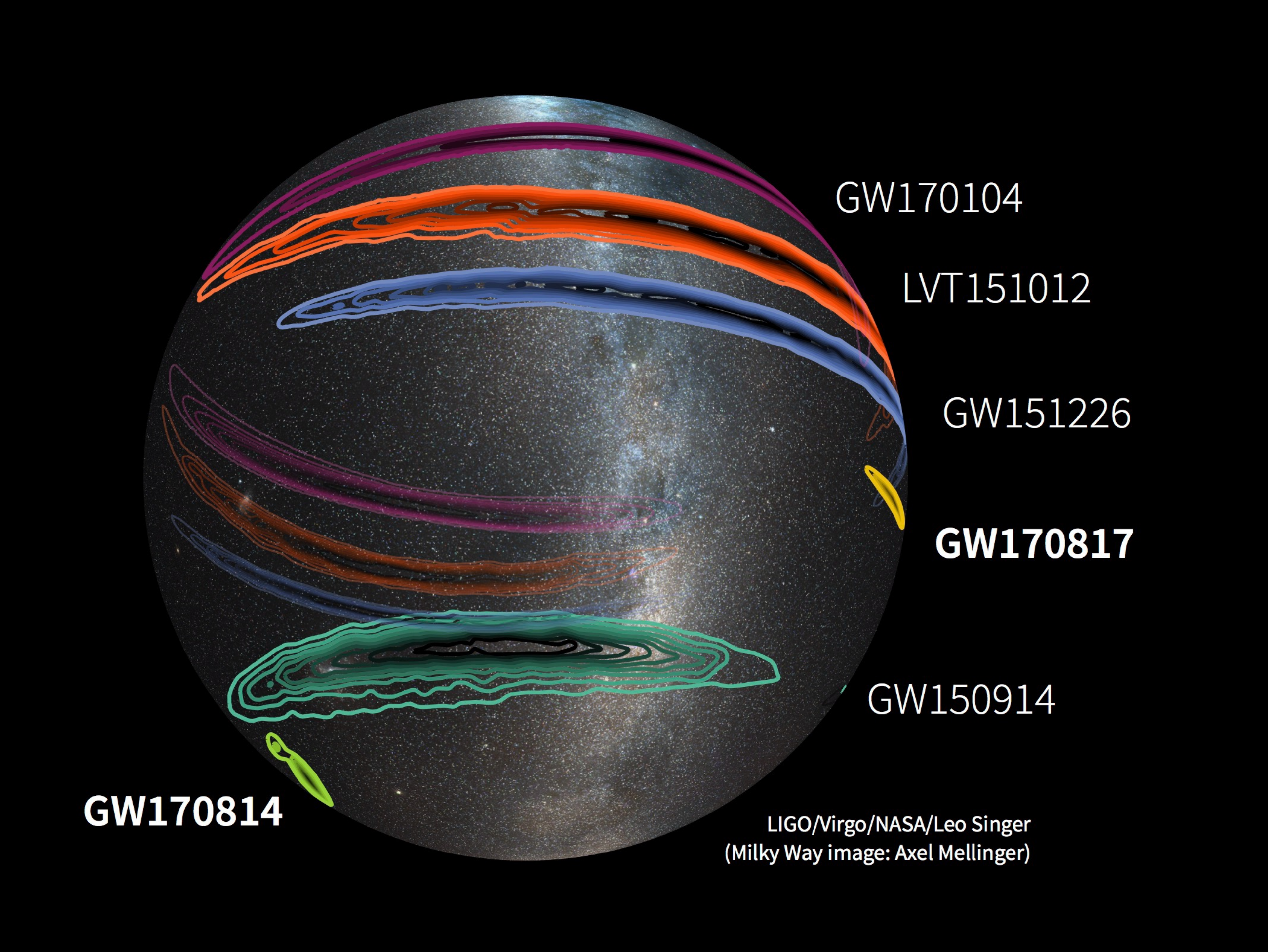
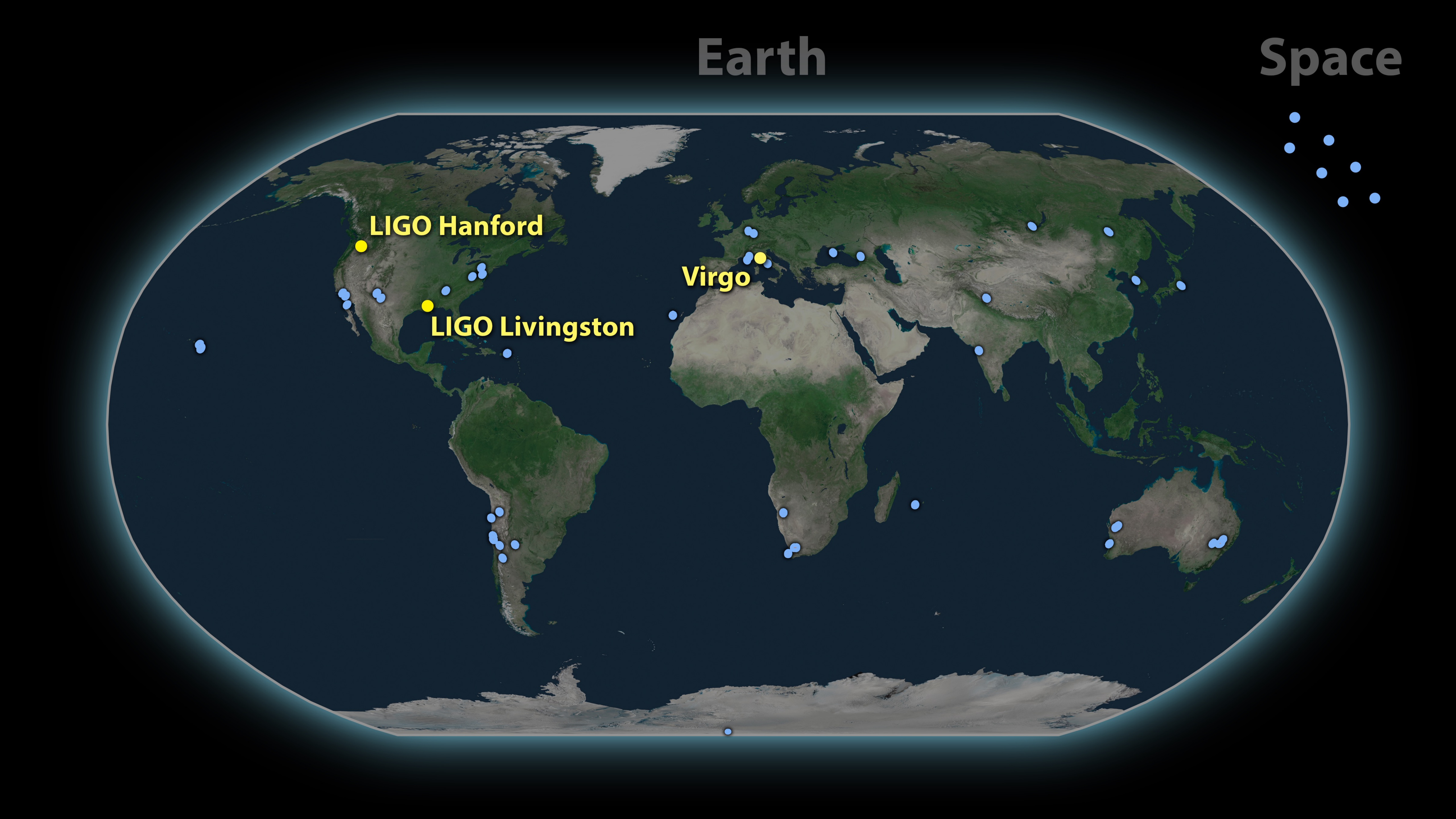
Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of $\sim$1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_\odot$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at $\sim$40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over $\sim$10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position $\sim$9 and $\sim$16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.


GW170817
Binary neutron star merger
A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.
H
L
V
Distance
130 million light years
Discovered
17 August 2017
Type
Neutron star merger
12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.
gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.
gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.
+ 2 seconds
A gamma ray burst is detected.
GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.
+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.
Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.
kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.
+11 hours 36 minutes
Infrared emission observed.
+15 hours
Bright ultraviolet emission detected.
This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.
radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.
+9 days
X-ray emission detected.
Au
The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of most of the heavy elements, like gold, in the universe.
+16 days
Radio emission detected.
Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

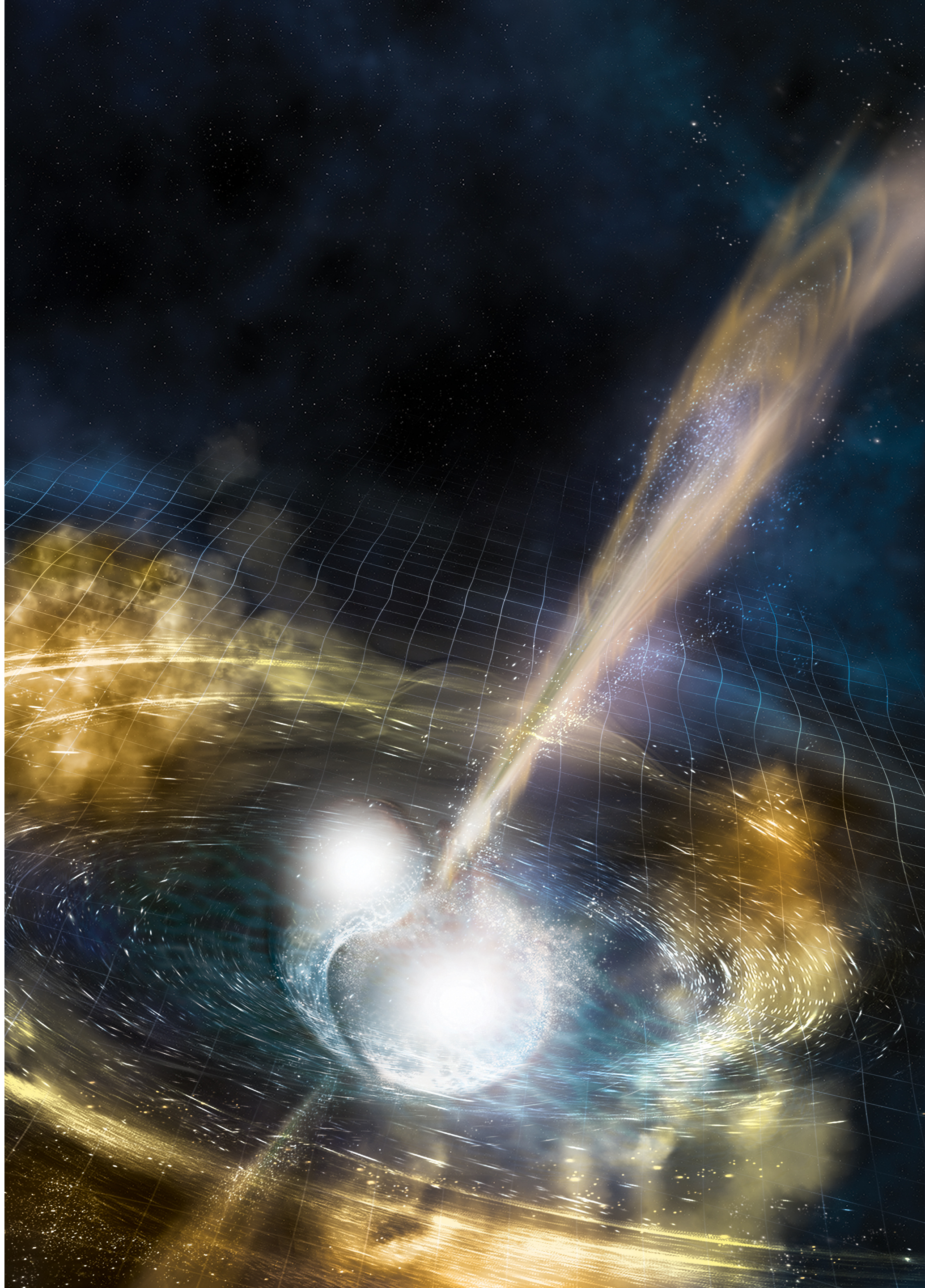

GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr


GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)


Earth
Space
LIGO Hanford
LIGO Livingston
Virgo

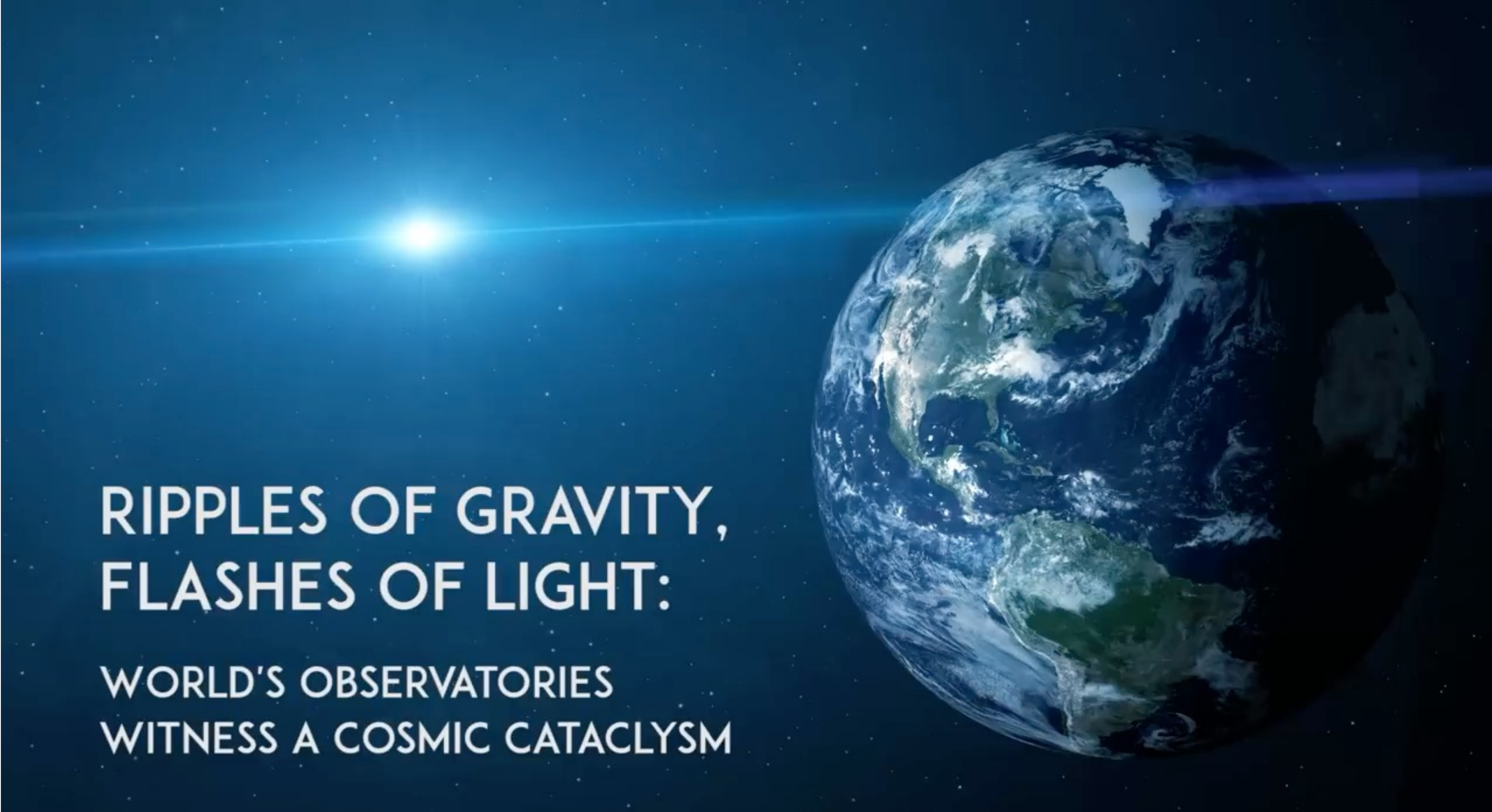
Video of GW170817 discovery and observations:

https://www.youtube.com/watch?v=EtIkOjq0_50&list=PLmX6l7z5IPlfpkHUzyGZ6d66Wu5k-AiZ0



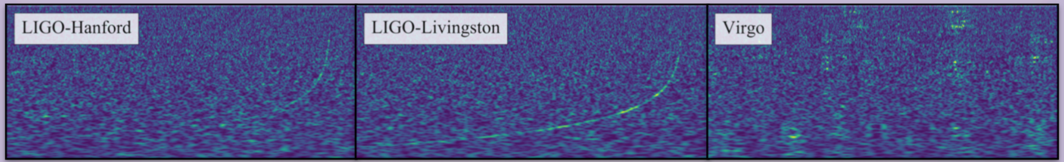
Artist’s illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light.

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet



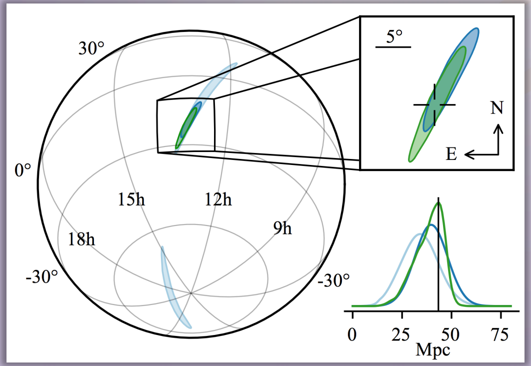
https://www.youtube.com/watch?v=EtIkOjq0_50&list=PLmX6l7z5IPlfpkHUzyGZ6d66Wu5k-AiZ0

GW170817 FACTSHEET



observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≲ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}



Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2x10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region

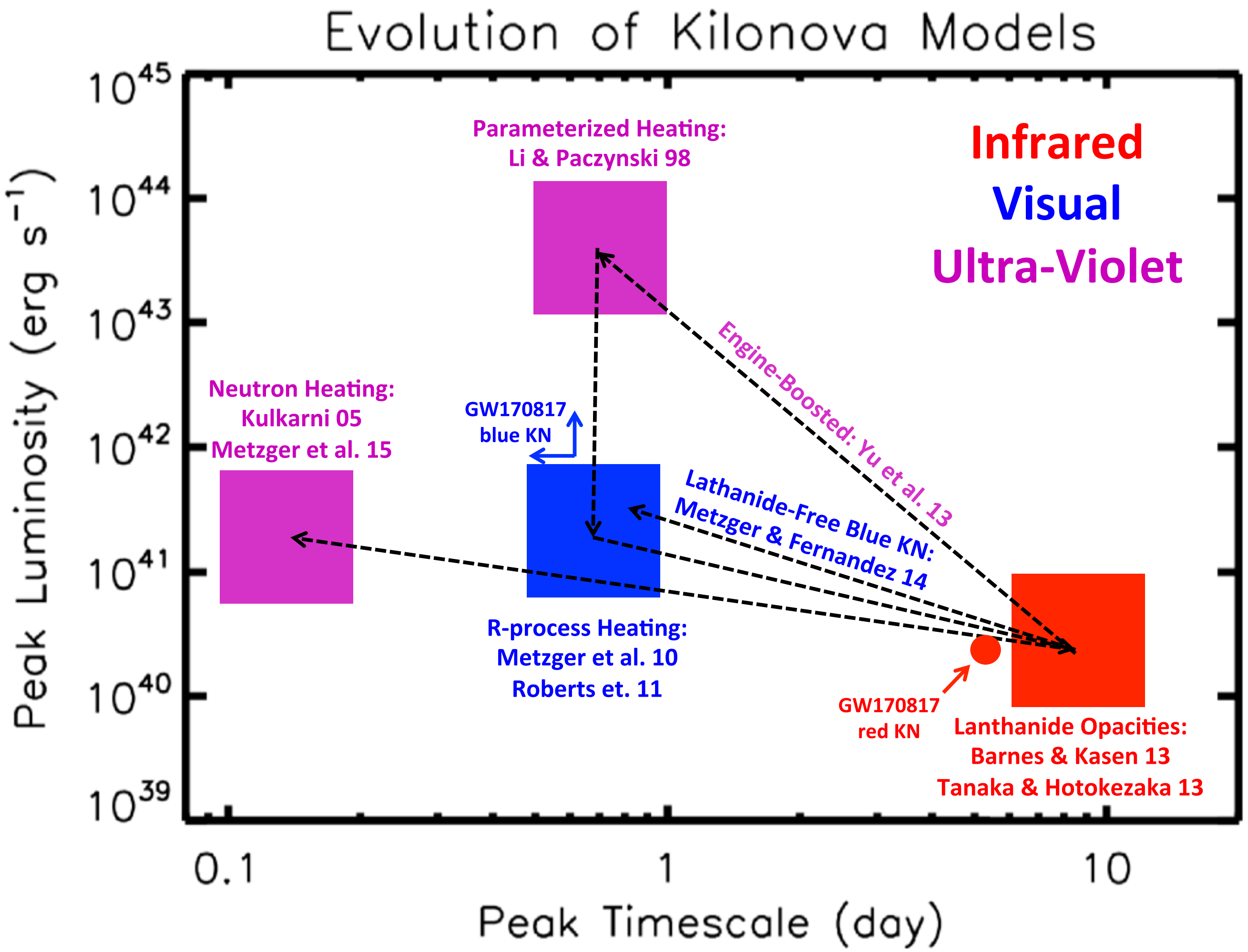
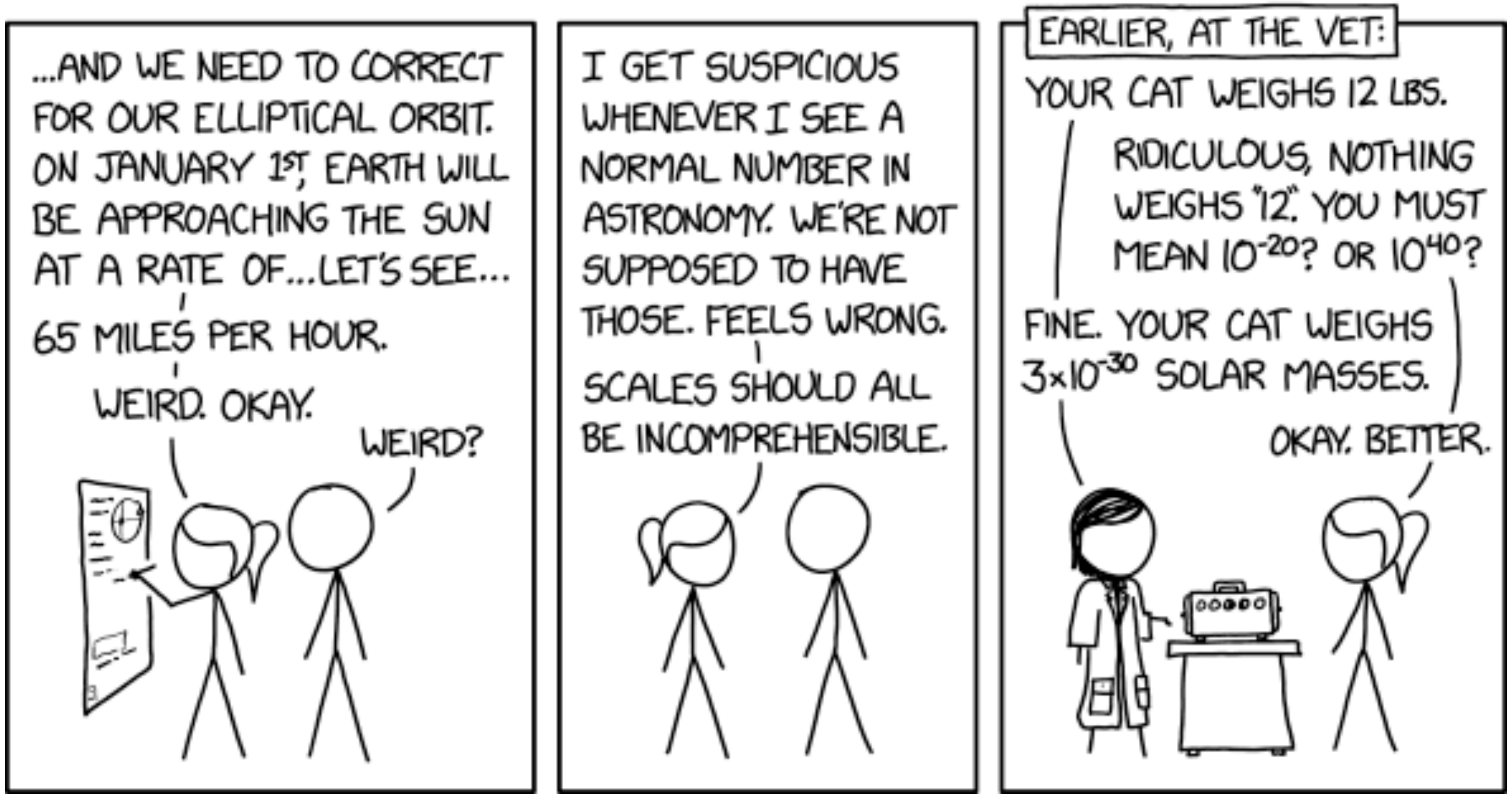


Fig. 2 Schematic timeline of the development kilonova models in the space of peak luminosity and peak timescale. The wavelength of the predicted spectral peak are indicated by color as marked in the figure. Shown for comparison are the approximate properties of the "red" and "blue" kilonova emission components observed following GW170817 (e.g., Cowperthwaite et al. 2017; Villar et al. 2017)


...AND WE NEED TO CORRECT FOR OUR ELLIPTICAL ORBIT. ON JANUARY 1ST, EARTH WILL BE APPROACHING THE SUN AT A RATE OF...LET'S SEE...
65 MILES PER HOUR.
WEIRD. OKAY.
WEIRD?
I GET SUSPICIOUS WHENEVER I SEE A NORMAL NUMBER IN ASTRONOMY. WE'RE NOT SUPPOSED TO HAVE THOSE. FEELS WRONG.
SCALES SHOULD ALL BE INCOMPREHENSIBLE.
EARLIER, AT THE VET:
YOUR CAT WEIGHS 12 LBS.
RIDICULOUS, NOTHING WEIGHS "12." YOU MUST MEAN 10^{-20}? OR 10^{40}?
FINE. YOUR CAT WEIGHS 3×10^{-30} SOLAR MASSES.
OKAY. BETTER.