Current status of GW-EM synergies

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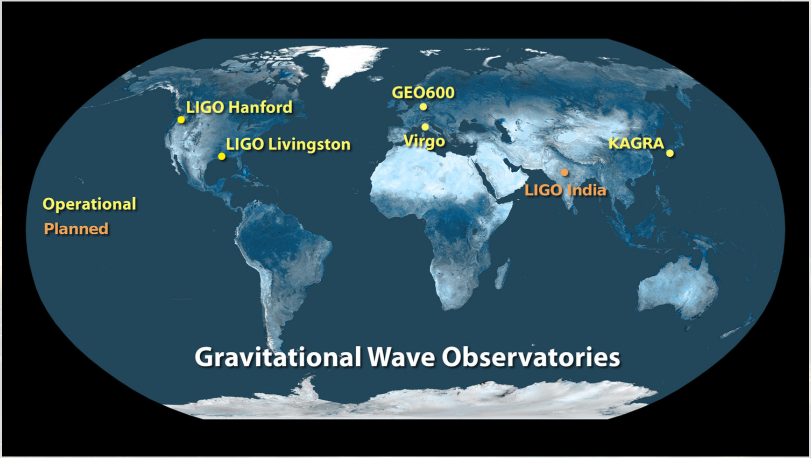
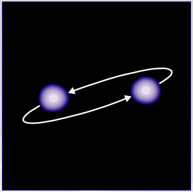
Outline

The 2nd generation GW detector network



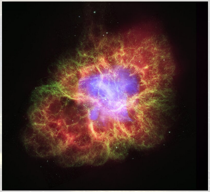
High frequency (10-1000 Hz) GW transient sources

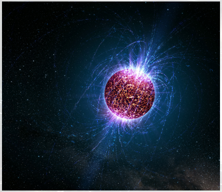
Coalescence of binary systems of NSs and/or BHs



- Accurate modeling of the GW signals
- Energy emitted in GWs (NS-NS): $\sim 10^{-2}$ $M_{\odot}c^2$

Core collapse of massive stars and Isolated neutron stars





- The modeling of the GW signal is complicated
- Energy emitted in GWs:
  $\sim 10^{-11}$- 10^{-7} $M_{\odot}c^2$ for core collapse*
  $\sim 10^{-16}$- 10^{-6} $M_{\odot}c^2$ for isolated NSs

* higher values are suggested by models exploring "extreme" GW emission scenarios

Associated multi-wavelength electromagnetic (EM) emission

NS-NS and NS-BH mergers

- Short Gamma-Ray Bursts (GRBs):
  - *Prompt* γ-ray emission (< 2 s).
  - Multiwavelegth *afterglow* emission: X-ray, optical and radio (minutes, hours, days, months).
- Kilonova: optical and NIR (days-weeks).
- Late blast wave emission: radio ($\sim$ months, years).

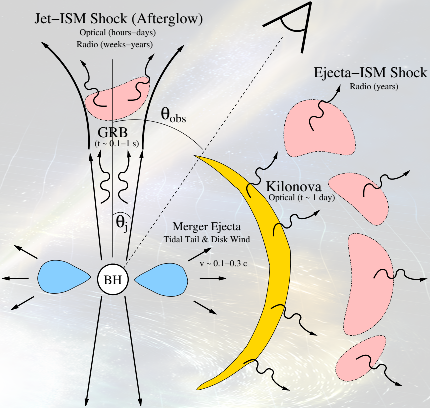


Image credit: Metzger & Berger 2012

Associated multi-wavelength EM emission

BBH mergers

?

- They are typically not expected to produce bright EM signal due to the absence of baryonic matter left outside the merger remnant...
- ... However, some rare scenarios which predict an unusual presence of matter around the BBH have been proposed in the last years, e.g.
  - the matter comes from the remnants of the stellar progenitors (Loeb 2016, Perna et al. 2016, Janiuk et al. 2017)
  - the matter comes from the tidal disruption of a star in triple system with two BHs (Seto & Muto 2011, Murase et al. 2016)
- In addition, **BBH mergers can take place in gas rich environment in the disks of active galactic nuclei** (AGN, Bartos et al. 2017, McKernan et al. 2019)

Associated multi-wavelength EM emission

Core collapse of massive stars

- supernovae (SNe):
  - X-rays, UV (minutes, days)
  - optical (week, months)
  - radio (years)

Image Credit: Avishay Gal-Yam

- long GRBs

Isolated neutron stars

- soft γ-ray repeaters
- radio/X-ray pulsar glitches

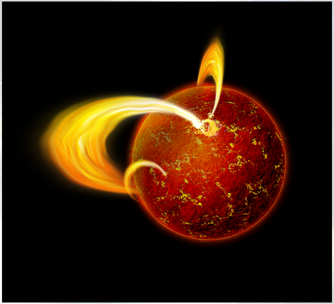


Image Credit: NASA, CXC, M. Weiss

Why multi-messenger astronomy with GWs?

GWs and photons provide complementary information about the physics of the source and its environment

GW

- *mass*
- *spin*
- *system orientation*
- *luminosity distance*
- *compact object binary rate*

EM

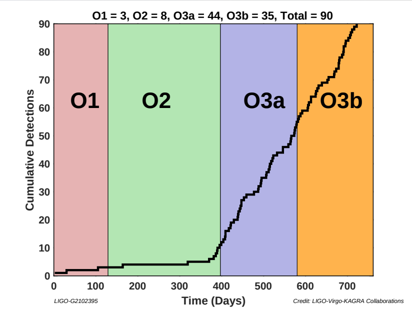
- *precise (arcsec) sky localization*
- *host galaxy*
- *redshift*
- *emission processes*
- *acceleration mechanisms*

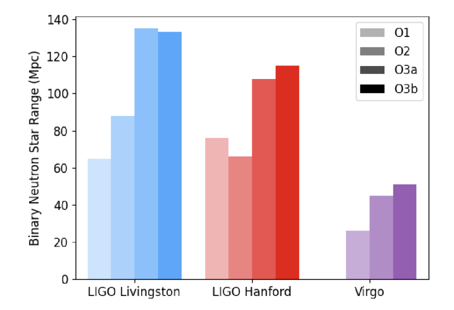
Where do we stand?

Credit: LIGO-Virgo-KAGRA

- *O1: September 2015 - January 2016*
  LIGO operating
- *O2: November 2016 - August 2017*
  Virgo joined the network on August 1
- *O3a: April 2019 - September 2019*
  O3b: November 2019 - March 2020
  Virgo and LIGO operating
- *O4a: May 2023 - January 2024*
  LIGO operating; KAGRA operating for 1 month
- *O4b: April 2024 - now*
  LIGO and Virgo operating; KAGRA expected to join before the end of the run

GW detections: O1+O2+O3 summary



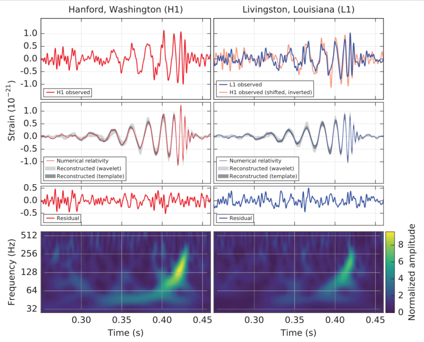


Credits: LIGO-Virgo-KAGRA Collaborations/Hannah Middleton/OzGrav

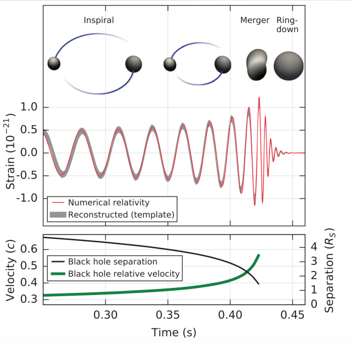
O1: The birth of GW astronomy

GW150914

The observation



The model

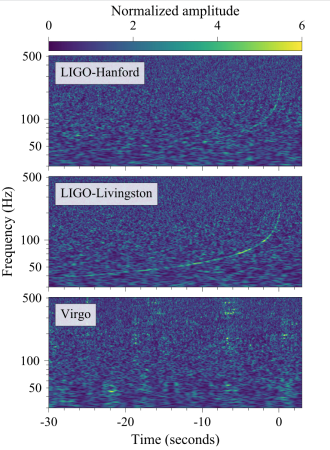


- BBHs can form in nature and merge within a Hubble time
- The two BH masses are $\sim 30\ M_\odot \Rightarrow$ First direct evidences for "heavy" stellar mass BHs ($> 25\ M_\odot$)

Abbott et al. 2016, PRL, 116, 061102

O2: the birth of multi-messenger astronomy with GWs

On August 17, 2017 at 12:41:04 UTC Advanced LIGO and Advanced Virgo made their **first observation of a binary neutron star inspiral**



- **GW170817** swept through the detectors' sensitive band for ~ 100 s ($f_{\mathrm{start}} = 24$ Hz)
- The signal-to-noise ratio (SNR) is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

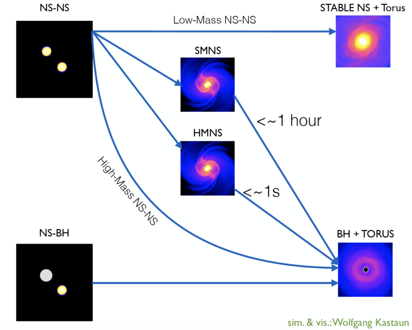
  the combined SNR is 32.4

  $\Rightarrow$ This is the loudest signal among the ones reported in GW catalogs

Abbott et al., PRL, 119, 161101 (2017)

The compact remnant

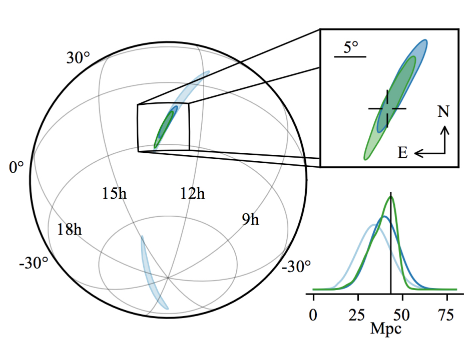
The outcome of a NS-NS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state (EOS) of nuclear matter.



- **Stable NS** (continuous-wave GW signal)
- **Supramassive NS (SMNS)** collapsing to a BH in 10 - 10^4 s (long-transient GW signal)
- **Hypermassive NS (HMNS)** collapsing to a BH in < 1 s (burst-like GW signal)
- **BH** prompt formation (high frequency quasi normal mode ringdown GW signal)

Searches for post-merger GW signals associated with GW170817 have not found any significant signal candidate (Abbott et al. 2017, 2019)

Where did the NS-NS merger occur?



Luminosity distance:

40^{+8}_{-14} Mpc

Sky localization:

- rapid loc., HL: 190 deg^2
- rapid loc., HLV: 31 deg^2
- final loc.*, HLV: 28 deg^2

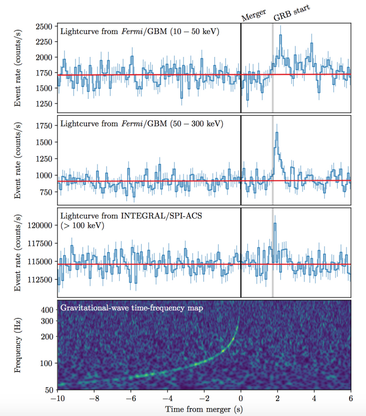
Virgo was essential in localizing the source to a single region of the sky

Abbott et al., PRL, 119, 161101 (2017)

* More refined analysis allowed to reduce the sky localization to 16 deg^2 (Abbott et al. 2019, PRX, 9, 031040; Abbott et al. 2019, PRX, 9, 011001)

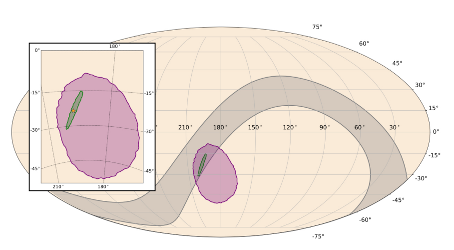
Gamma-rays: short GRB

A short GRB (GRB 170817A) was independently detected by Fermi-GBM and INTEGRAL



Abbott et al., ApJ, 848, 13 (2017)
Goldstein et al., ApJL, 848, 14 (2017)
Savchenko et al., ApJL, 848, 15 (2017)

GW170817/GRB 170817A association



90 % Fermi-GBM sky localization (1100 deg^2)

90 % sky localization from Fermi and INTEGRAL timing

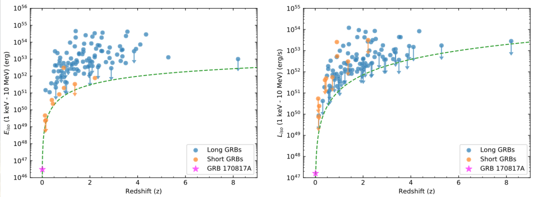
LIGO-Virgo 90 % credible region (28 deg^2)

The probability that GRB 170817A and GW170817 occurred this close in time and with this level of location agreement by chance is 5.0×10^{-8}: a 5.3 σ Gaussian-equivalent significance

$\Rightarrow$ First direct evidence that NS-NS mergers are progenitors of (at least some) short GRBs!

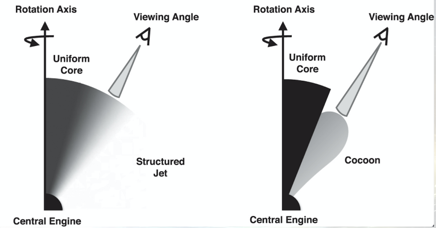
Abbott et al., ApJ, 848, 13 (2017)

GRB 170817A: energy and luminosity



GRB 170817A several orders of magnitude less energetic than other observed bursts with measured redshift.

- Intrinsically sub-luminous GRB?
- structured jet?
- cocoon emission?

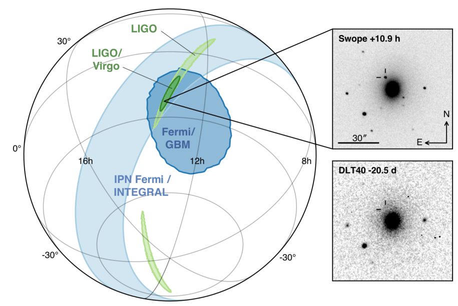


Abbott et al., ApJ, 848, 13 (2017)

The identification of the host galaxy

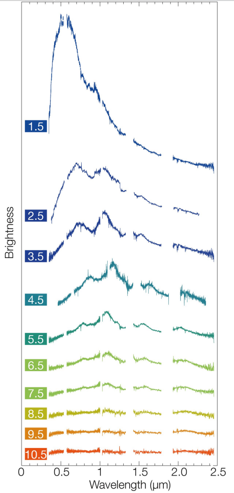
A wide-ranging EM follow-up campaign started in the hours immediately after the observation of GW170817 and GRB 170817A

- An associated **optical transient** (SSS17a/AT 2017gfo) has been discovered on August 18, 2017;
- the transient is located at $\sim 10''$ from the center of the galaxy NGC 4993, at a distance of 40 Mpc



Abbott et al., ApJ Letters, 848, 12 (2017)

The spectroscopic identification of the kilonova



Credit: ESO/E. Pian et al./S. Smartt & ePESSTO

- The first spectrum is well described by a blackbody spectrum of temperature $\sim$ 5000 K
- Later:
  - The maximum moved to longer wavelengths

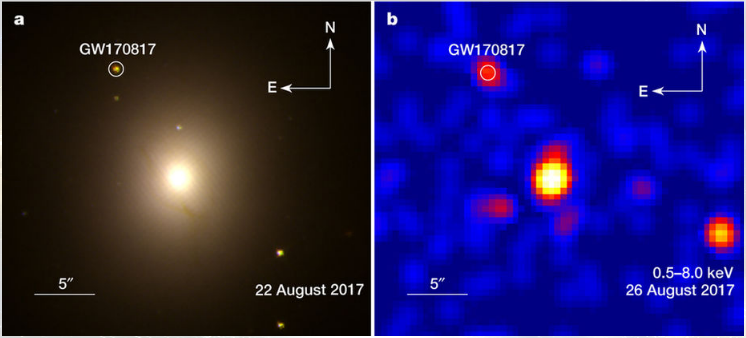
    $\Rightarrow$ rapid cooling of the ejecta;
  - Broad absorption-like lines appear on the spectral continuum

    $\Rightarrow$ atomic species produced by nucleosynthesis that occurs in the post-merger ejecta

First spectroscopic identification of a kilonova and evidence that NS-NS mergers can produce heavy r-process elements!

X-ray and radio observations

9 days and 16 days after the GW trigger, an X-ray and a radio counterparts have been discovered (Troja et al. 2017, Hallinan et al. 2017)



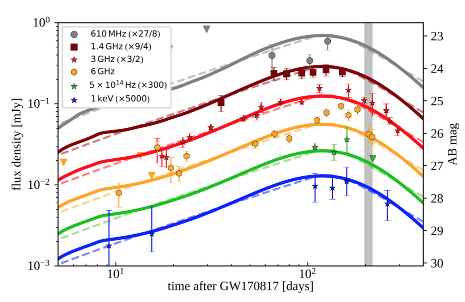
Source monitored for hundreds of days...

X-ray and radio observations

Two possible interpretations:

- - - cocoon emission
- — afterglow emission from a structured jet

Both models are consistent with the multiwavelength light curve... ⇒

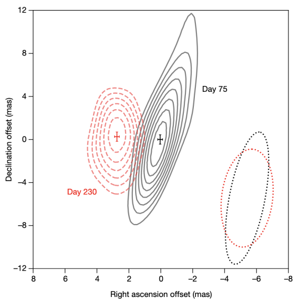


Ghirlanda et al. 2019

Radio observations

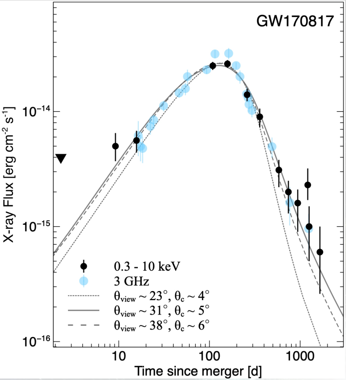
... But Very Long Baseline Interferometry observations allowed to break the degeneracy (Ghirlanda et al. 2019, Mooley et al. 2018)

- Apparent source size < 2.5 milliarcseconds
- Displacement of the source apparent position by 2.67 ± 0.3 milliarcseconds in 155 days



$\Rightarrow$ This excludes the isotropic outflow scenario and favor **the structured jet model**: a successful jet with a structured angular velocity and energy profile, featuring a narrow core (with $\theta_j < 5$ deg) seen from a viewing angle $\theta_{\text{view}} \leq 20$ deg.

The late X-ray emission



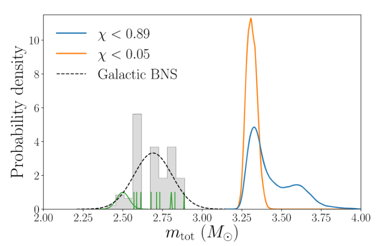
- Latest X-ray and radio emission deviate from early predictions of the jet model with $\theta_{\rm view} \sim 20$ deg
- Is there an additional component taking over the fading GRB afterglow?
  - Long lived magnetar?
  - Kilonova afterglow?

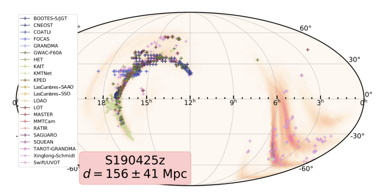
O'Connor & Troja 2022; Troja et al. 2022

see also Balasubramanian et al. 2021, Hajela et al. 2022

Continued monitoring at radio and X-ray wavelengths is key to identify the origin of such long-lasting emission from GW170817

GW190425: the second NS-NS merger





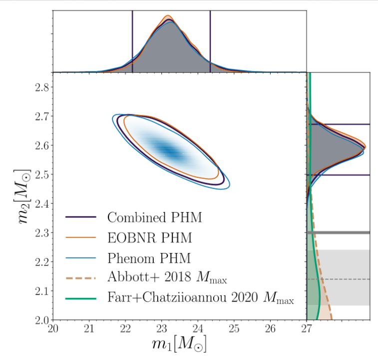
- GW event observed by LIGO-Livingston and Virgo
- The total mass is significantly larger than that of the other NS-NS systems...

  ... different formation channel?

- 90 % C.R.: 8284 deg^2; $\mathrm{D_L}$=159^{+69}_{-72} Mpc
- No EM counterpart (see, e.g., Hosseinzadeh et al. 2019)

Abbott et al. 2020, ApJL, 892, 3

GW190814: a BBH or a NS-BH?



- GW event observed by the two LIGO detectors and Virgo
- m_1: $23.2^{+1.1}_{-1.0}$ $\mathrm{M}_\odot$

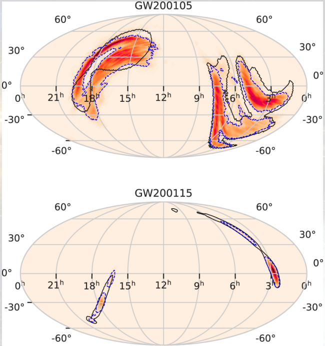
  $\mathbf{m}_2$: $2.59^{+0.08}_{-0.09}$ $\mathrm{M}_\odot$

  BBH or NS-BH merger?
- 90 % C.R.: 18.5 deg^2; $\mathrm{D_L}=241^{+41}_{-45}$ Mpc
- No EM counterpart (see, e.g., Ackley et al. 2020)

Abbott et al. 2020, ApJL, 896, 44

GW200105 and GW200115

	m_1	m_2	D_L	90 % C.R.
GW200105*	$8.9^{+1.2}_{-1.5}$ $M_\odot$	$1.9^{+0.3}_{-0.2}$ $M_\odot$	280^{+110}_{-110} Mpc	7200 deg^2
GW200115	$5.7^{+1.8}_{-2.1}$ $M_\odot$	$1.5^{+0.7}_{-0.3}$ $M_\odot$	300^{+150}_{-100} Mpc	600 deg^2

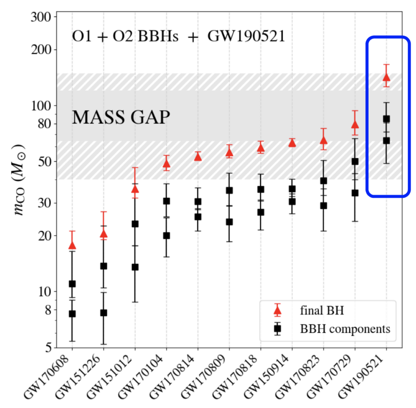


- No EM counterpart has been found...
- ... However, EM emission would have been difficult to detect, given the large distances and large error in the sky localization

Abbott et al. 2021, ApJL, 915, L5

* In the GWTC-3 analysis, GW200105 is found to have $p_{\rm astro}$ <0.5, but it remains a candidate of interest (Abbott et al. 2023, PRX, 13, 041039

GW190521



- GW event observed by the two LIGO detectors and Virgo
- m_1: 85^{+21}_{-14} $M_\odot$, m_2: 66^{+17}_{-18} $M_\odot$
- The primary falls in the mass gap by (pulsational) pair-instability SN

Challenge for stellar evolution

- Isolated binary evolution is disfavoured
- **Dynamical scenario?** e.g., hierarchical mergers in an AGN disk

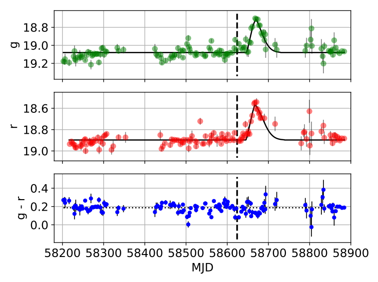
Abbott et al. 2020, PRL, 125, 101102

Abbott et al. 2020, ApJL, 900, 13

GW190521: an EM counterpart?

The Zwicky Transient Facility (ZTF) detected a candidate optical counterpart in AGN J124942.3+344929

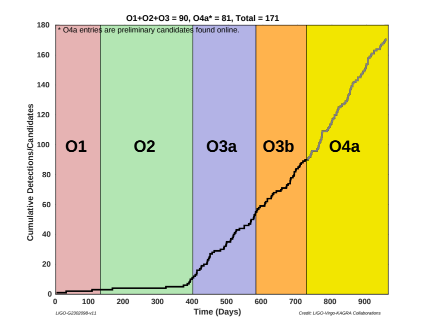
- GW sky localization: 765 deg^2 (90% C.R.)
- ZTF observed 48% of the 90% C.R. of the GW skymap
- An EM flare observed $\sim$ 34 days after the GW event
- It is consistent with expectations for a **BBH merger in the accretion disk of an AGN** (see McKernan et al. 2019, ApJL, 884, 50)



Graham et al. 2020, PRL, 124, 251102

Common origin of the two transients seems to be preferred with respect to random coincidence (Morton et al. 2023; see, however, Ashton et al. 2021, Palmese et al. 2021)

O4a: summary

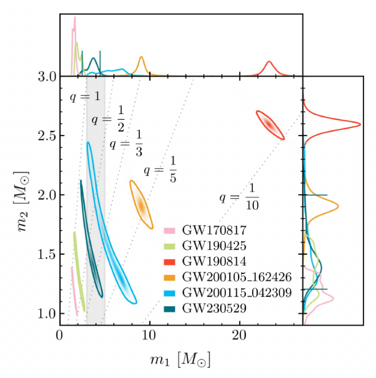


- $\sim$ 8 months of data taking
- 81 significant[a] detection candidates (92 Total - 11 Retracted)
- Almost all BBHs; no NS-NS; a couple of possible NS-BHs
  - **S230627c** - GraceDB
  - **GW230529**
- No EM counterpart so far

[a] Significant GW alerts: false alarm rate $<$ 1/month for CBC and 1/year for bursts

GW230529

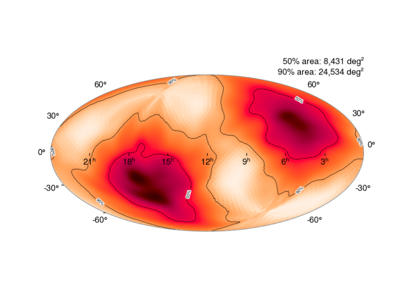
- Dedicated paper on arXiv on April 5, 2024
- Single-detector signal found by LIGO Livingston
- Primary: (2.5 - 4.5) $M_\odot$; Secondary: (1.2 - 2.0) $M_\odot$
- Most probable interpretation: merger of a NS with a BH with mass in the "lower mass gap" (3 - 5 $M_\odot$)



LVK Collaboration 2024, arXiv:2404.04248

GW230529

- Significantly more symmetric than other NSBHs
- More symmetric masses $\rightarrow$ more susceptible to tidal disruption $\Rightarrow$ EM counterpart
- 90 % C.R. $\sim 2 \times 10^4$ deg^2
- D_L=201$^{+102}_{-96}$ Mpc
- No EM counterpart reported so far



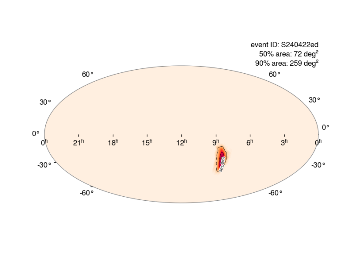
LVK Collaboration 2023, GCN 34148
LVK Collaboration 2024, arXiv:2404.04248

O4b: summary

O4b Significant Detection Candidates: 16 (19 Total - 3 Retracted)*

No BNS so far; 1 NSBH

- **S240422ed**
- NSBH (> 99 %)
- HasRemnant** > 99 %
- Luminosity Distance: (188 ± 43) Mpc
- GraceDB
- GCNs: 36236 and 36240
- No confirmed EM counterpart so far



*Updated on May 15 at 09:00 CEST

**Probability of having a non-zero amount of NS material outside the final remnant compact object

What we learned so far and open questions

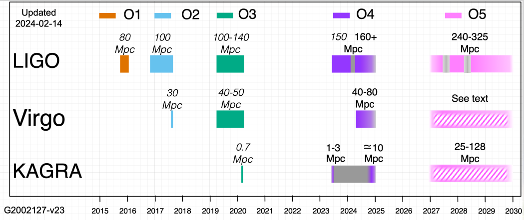
- *First direct evidence that NS-NS mergers are progenitors of at least a fraction of short GRBs*
- *First evidence for a structured jet for GRBs*
- *First unambiguous observational evidence for a kilonova*
- *First observation of a kilonova in association with both a short GRB and a GW event*
- *Evidence for NS-NS mergers as heavy element factories*

- *Do all NS-NS mergers produce short GRBs?*
- *Are Kilonovae associated to every short GRB?*
- *What is the GRB central engine/NS-NS merger outcome?*
- *Do NS-BH and BBH mergers have EM counterparts?*
- *...and much more!*

Waiting for new LIGO-Virgo-KAGRA observations

to shed light on these questions!

Current and next GW observing runs

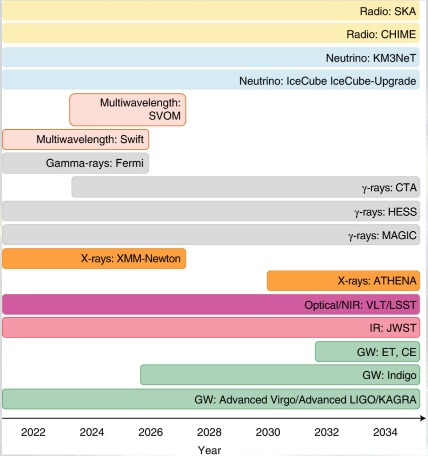


- O4b will run until February 2025
- KAGRA will possibly join the network by the end of the run
- A fifth observing run (O5) is planned to start in a few years

Updated observing run plans at https://observing.docs.ligo.org/plan/

In the future 2$^{\text{nd}}$ generation GW detectors will operate with increased sensitivity, in synergy with current and future EM facilities (e.g. SVOM, CTA, Vera Rubin Observatory etc)

Multi-messenger facilities in the next years



Cuoco, Patricelli et al. 2022, Nat Comput Sci 2, 479

Conclusions

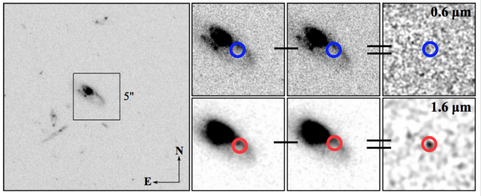
- $\sim$ three and a half observing runs so far
  - We had the first multi-messenger (GWs+photons) observation of a binary system of NSs
  - We observed an EM signal possibly associated with a BBH merger
- Other multi-messenger sources still to be detected (supernovae, pulsars...)
- O4b is currently ongoing; O5 will start in a few years
- New EM facilities will soon become operative, in sinergy with GW detectors

Many other GW and multi-messenger discoveries are expected in the near future... stay tuned!

Backup

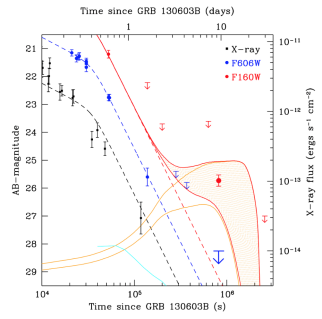
Backup slides

A kilonova detection for GRB 130603B?



F606W/optical

NIR/F160W

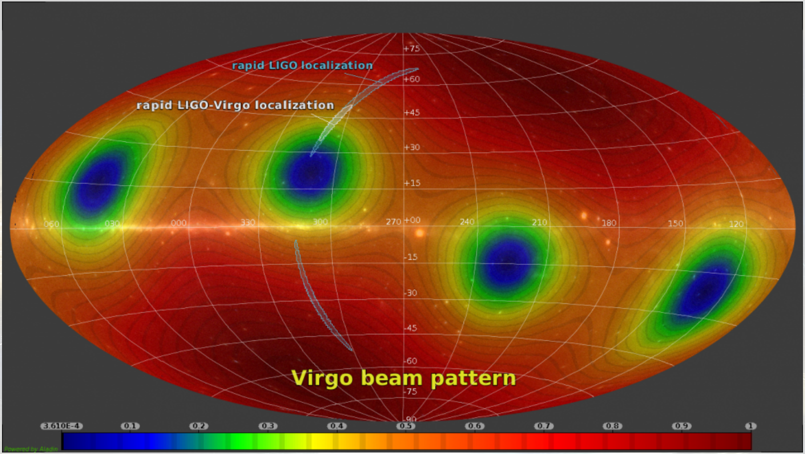


- dashed lines: afterglow model
- orange curves: kilonova NIR model

  ejected masses:
  10^{-2} $M_\odot$ and 10^{-1} $M_\odot$
- cyan curve: kilonova optical model
- solid red curves: afterglow+kilonova

Tanvir et al, Nature, 500, 547 (2013)

The role of Virgo in the sky localization



Credits: G. Greco, N. Arnaud, M. Branchesi, A. Vicere

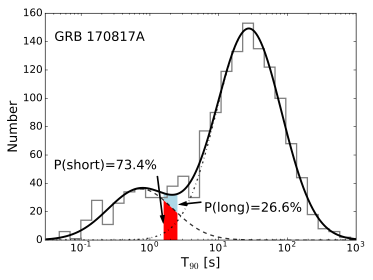
The role of Virgo in the sky localization

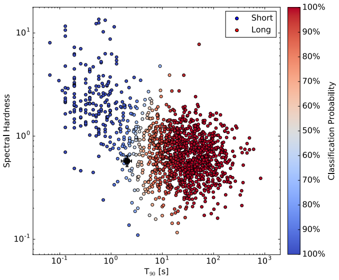
(Loading Video...)

Credit: L. Singer

GRB 170817A: duration and spectral hardness

To which GRB class does GRB 170817A belong?

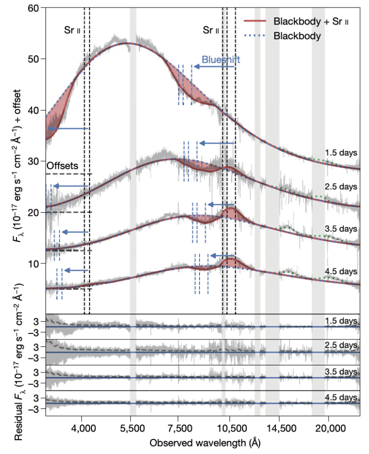




GRB 170817A is ∼ 3 times more likely to be a **short GRB** than a long GRB

Goldstein et al., ApJL, 848, 14 (2017)

Signature of heavy elements

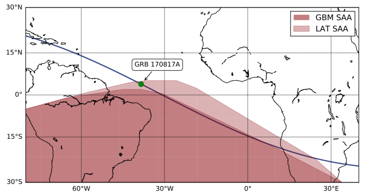


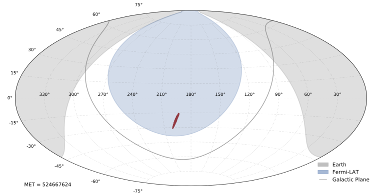
Watson et al. 2019, Nature, 574, 497

(see also Smartt et al. 2017, Domoto et al. 2021)

What's missing? High energy emission (HE, E $>$ 100 MeV)

- *Fermi*-LAT was entering the South Atlantic Anomaly at the time of the GW trigger
- Later, no significant EM counterpart at HE was detected by the LAT on timescales of minutes, hours, or days after the GW detection.

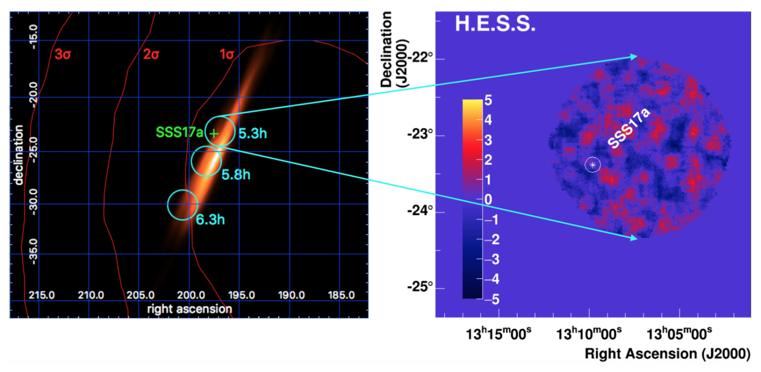




Fermi-LAT collaboration, ApJ, 861, 85 (2018)

What's missing? Very-high energy (VHE, E $>$ 100 GeV) emission

- H.E.S.S. started the observations 5.3h after the GW trigger
  $\Rightarrow$ it was the first ground-based instrument to observe the sky region containing the source
- No significant VHE gamma-ray emission has been found



Abdalla et al. 2017, ApJ, 850, 22

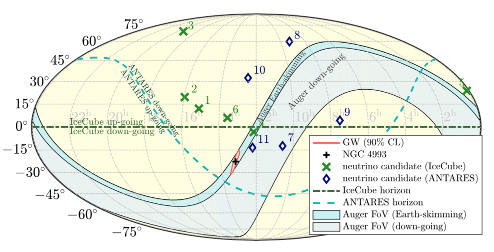
What's missing?

Search for coincident neutrino candidates with data of IceCube, ANTARES and Pierre Auger

Within ± 500 s of GW170817:

- ANTARES neutrino candidates: 5
- IceCube neutrino candidates: 6
- Pierre Auger neutrino candidates: 0

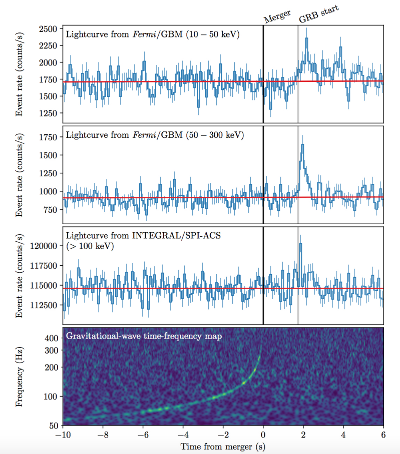
  - **No one directionally coincident with GW170817**



Albert et al., ApJ, 850, 35 (2017)

GW-GRB association: constraints on fundamental physics

The observed time delay between GRB 170817A and GW170817 (∼1.7 s) can be used to put constraints on fundamental physics:



Speed of gravity vs speed of light

$$\Delta\nu = \nu_{\mathrm{GW}} - \nu_{\mathrm{EM}}$$

$$\boxed{\frac{\Delta\nu}{\nu_{\mathrm{EM}}} \sim \frac{\nu_{\mathrm{EM}}\Delta t}{D}}$$

- lower limit on distance: D=26 Mpc
- Time delay: two cases considered
  - the EM and GW signals were emitted simultaneously
  - the EM signal was emitted 10 s later

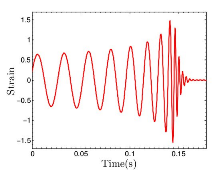
$$\boxed{-3\times10^{-15} \leq \frac{\Delta\nu}{\nu_{\mathrm{EM}}} \leq 7\times10^{-16}}$$

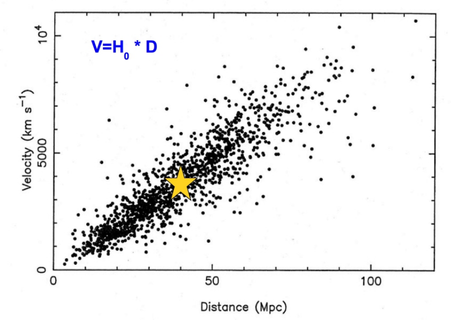
Abbott et al. 2017, ApJL, 848, 13

Implications for cosmology

The association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**

- Recession velocity of NGC4993 from spectroscopic measurements: 3017 ± 166 km s^{-1}
- Distance from GW signal



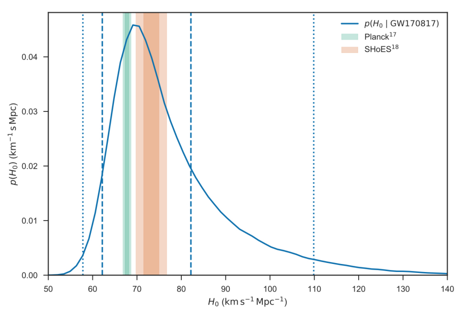


$$\boxed{H_0 = 70^{+12}_{-8}\ \text{km/s/Mpc}}$$

Abbott et al., Nature, 551, 85 (2017)

GW-NGC4993 association: implications for Cosmology

GW170817 as a standard siren:
the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**



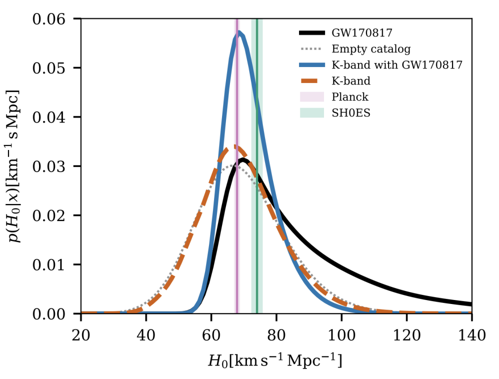
- $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}*
- $H_0 = 67.74^{\pm 0.46}$ km s^{-1} Mpc^{-1}
- $H_0 = 73.24^{\pm 1.74}$ km s^{-1} Mpc^{-1}

Abbott et al., Nature, 551, 85 (2017)

* More recent estimates, obtained assuming a priori that the GW source is in NGC 4993, are:
- $H_0 = 70^{+13}_{-7}$ km s^{-1} Mpc^{-1} (high-spin case)
- $H_0 = 70^{+19}_{-8}$ km s^{-1} Mpc^{-1} (low-spin case)

Abbott et al. 2019, PRX, 9, 011001

Hubble constant estimate with GWTC-3



BBHs + galaxy catalogs + GW170817: $\mathrm{H}_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}

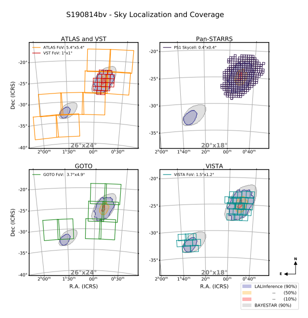
$\Rightarrow$ improvement of ~ 40 % with respect to the result obtained using only GW170817

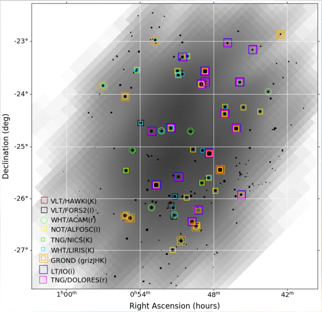
Abbott et al. 2023, ApJ, 949, 76

GW190814: the EM follow-up

Example: optical counterpart searches by ENGRAVE

ENGRAVE - Electromagnetic counterparts of gravitational wave sources at the Very Large Telescope



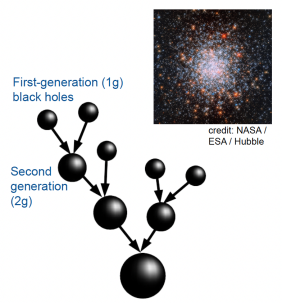


Non-detection of EM counterparts ⇒ **limits on the properties of the outflows** that could have been produced by the binary during and after the merger

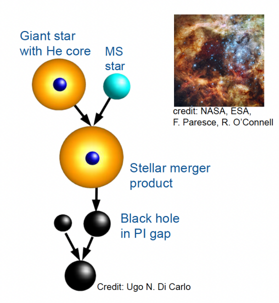
Ackley et al. 2020, A&A, 643, 113

Dynamical scenarios for GW190521

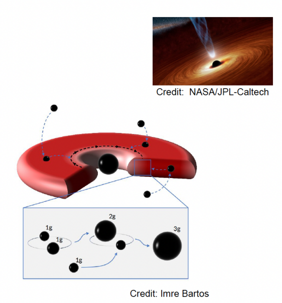
Hierarchical mergers



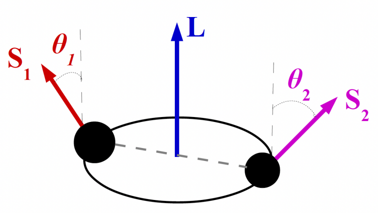
Stellar mergers in young star clusters



Active Galactic Nucleus (AGN) disks

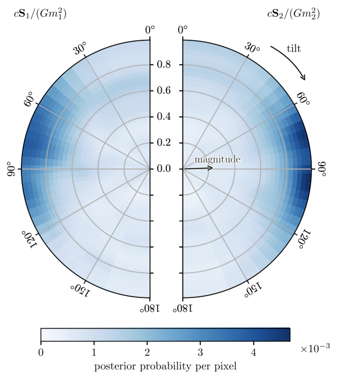


GW190521: the spin



$$\chi_\mathrm{i} = \frac{c\mathbf{S_i}}{Gm_i^2} \quad \text{Dimensionless spin}$$

$$\theta_i : \quad \text{Tilt angle}$$



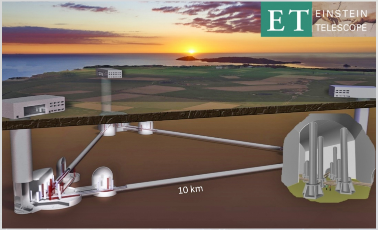
Mild evidence for large spins nearly in the orbital plane
… **dynamical origin of the system?**

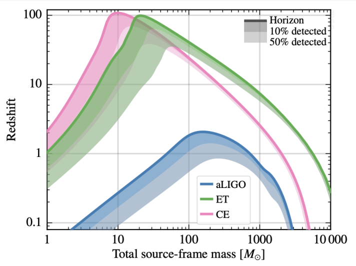
Abbott et al. 2020, PRL, 125, 101102

Abbott et al. 2020, ApJL, 900, 13

Prospects with 3$^{\rm rd}$ generation GW detectors

In the next decade, 3$^{\rm rd}$ generation GW detectors such as the Einstein Telescope (ET) or Cosmic Explorer (CE) will become operative





With ET:

- 10^5-10^6 BBHs/year
- BBHs with total mass in the range 20 - 100 $M_\odot$: up to z $\sim$ 20
- $\sim 10^5$ NS-NS/year
- NS-NS up to z$\sim$ 2-3

Maggiore et al. 2020, JCAP, 03, 050