GW and multi-messenger astronomy: lessons learned from the first three LVK observing runs

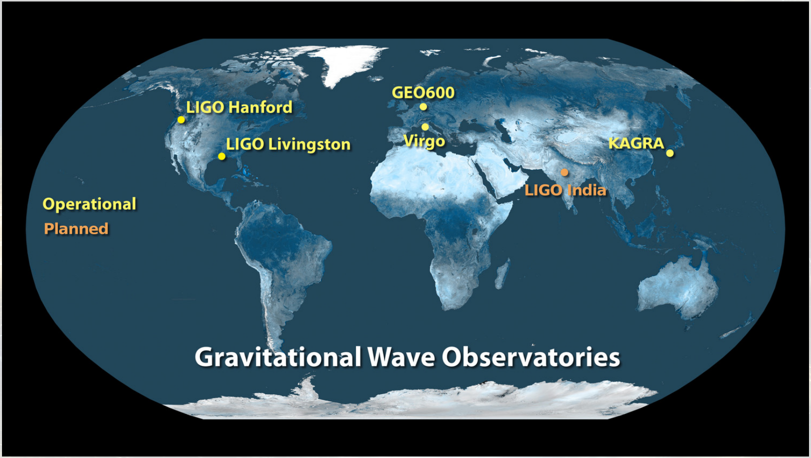
Barbara Patricelli[1,2,3]

[1] Physics Department - University of Pisa
[2] INFN - Sezione di Pisa
[3] INAF - Osservatorio Astronomico di Roma

Seventeenth Marcel Grossmann Meeting
July 7-12, 2024
Pescara, Italy

Outline

The 2nd generation GW detector network



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

  $\Rightarrow$ *This talk*

- *O4a: May 2023 - January 2024*

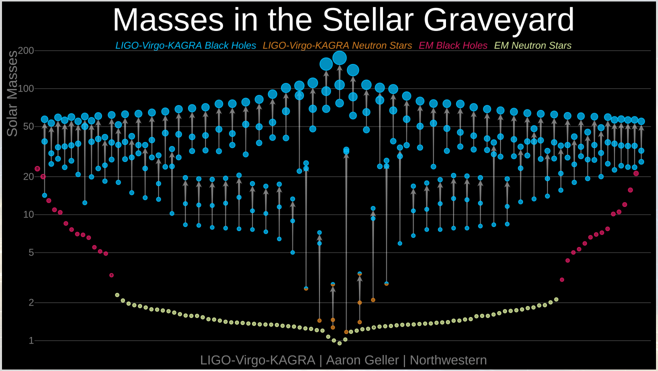
  LIGO operating; KAGRA ran for 1 month

- *O4b: April 2024 - now*

  LIGO and Virgo operating; KAGRA expected to join before the end of the run

  $\Rightarrow$ *Giacomo's talk*

GW detections: O1+O2+O3 summary

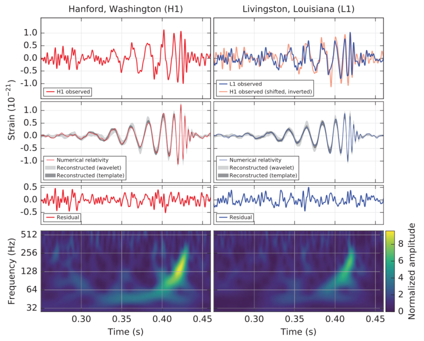


- Total number of candidates: 90
- Most are binary black holes (BBHs); some are neutron star - black hole (NSBH) binaries; two are binary neutron stars (BNSs)
- Four GW catalogs: GWTC-1 (O1+O2), GWTC-2 and GWTC-2.1 (O3a), GWTC-3 (O3b)

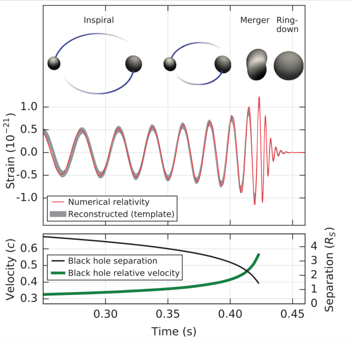
LVK Collaboration 2019, PRX, 9, 031040; LVK Collaboration 2021, PRX, 11, 021053; LVK Collaboration 2023, PRX, 13, 041039; LVK Collaboration 2024, PRD, 109, 022001

GW150914: The birth of GW astronomy

The observation



The model



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

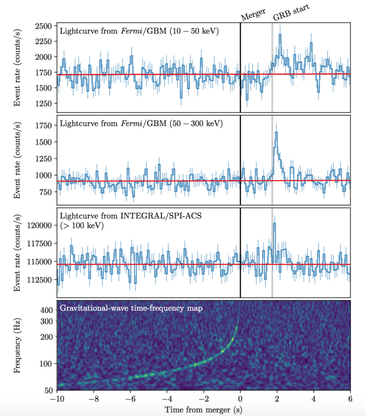
LVC 2016, PRL, 116, 061102

GW170817: the birth of multi-messenger astronomy with GWs

On August 17, 2017

- GW170817: **first observation of a binary neutron star inspiral** by Advanced LIGO and Advanced Virgo
- GRB 170817A: a **short GRB** was independently detected by Fermi-GBM and INTEGRAL in coincidence with GW170817

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



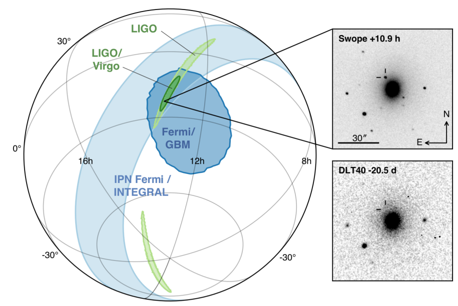
LVC 2017, PRL, 119, 161101, LVC 2017, ApJ, 848, 13, Goldstein et al. 2017, ApJL, 848, 14, Savchenko et al. 2017, ApJL, 848, 15

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, consistent with the luminosity distance of the GW signal.

$\Rightarrow$ First identification of the host galaxy of a GW event!



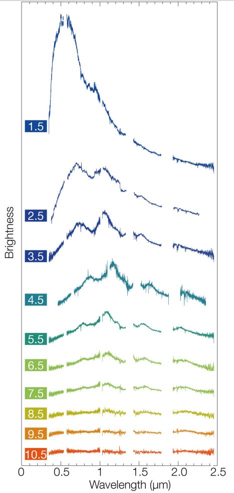
LVC 2017, ApJ Letters, 848, 12

The spectroscopic identification of the kilonova

- Source was monitored for days...
- ... Spectral temporal evolution consistent with a **kilonova**: optical/NIR emission powered by radioactive decay of heavy nuclei synthesized in the merger ejecta through r-processes

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

(Pian + BP et al. 2017, Smartt et al 2017)

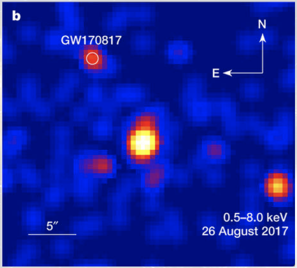


Credit: ESO/E. Pian et al./S. Smartt & ePESSTO

X-ray and radio observations

9 days and 16 days after the GW trigger: discovery of an X-ray and a radio counterparts

(Troja et al. 2017, Hallinan et al. 2017)



Source monitored for hundreds of days...

Very Long Baseline Interferometry observations ⇒ GRB afterglow emission from a **structured jet**

(Ghirlanda et al. 2019, Mooley et al. 2018)

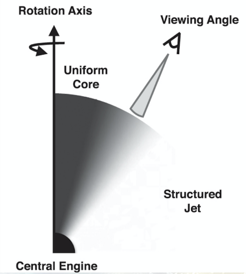
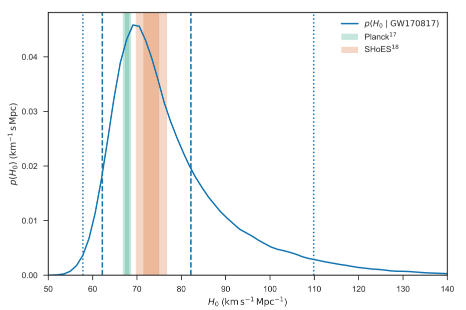


Image from: LVC 2017, ApJ, 848, 13

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**



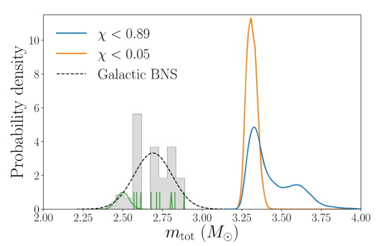
- $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}*
- $H_0 = 67.74^{\pm 0.46}$ km s^{-1} Mpc^{-1}
- $H_0 = 73.24^{\pm 1.74}$ km s^{-1} Mpc^{-1}

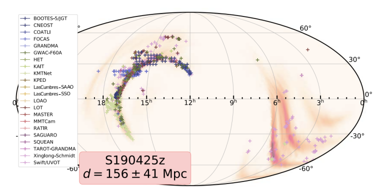
LVC 2017, Nature, 551, 85

* 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)

LVC 2019, PRX, 9, 011001

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...

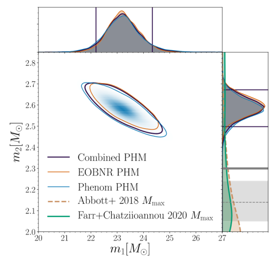
  ... different formation channel?

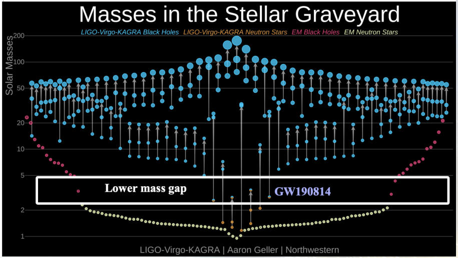
- 90 % C.R.: 8284 deg^2; $D_L = 159^{+69}_{-72}$ Mpc
- No EM counterpart (see, e.g., Hosseinzadeh et al. 2019)

LVC 2020, ApJL, 892, 3

GW190814: lower mass gap

- GW event observed by the two LIGO detectors and Virgo
- m_1: $23.2^{+1.1}_{-1.0}$ $M_\odot$
- **m_2: $2.59^{+0.08}_{-0.09}$ $M_\odot$ $\Rightarrow$ BBH or NS-BH?**

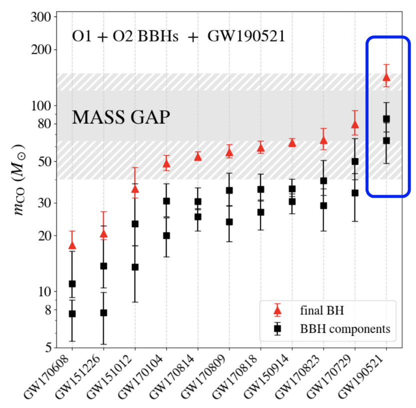




- 90 % C.R.: 18.5 deg^2; D_L=241^{+41}_{-45} Mpc
- No EM counterpart (see, e.g., Ackley + BP et al. 2020)

LVC 2020, ApJL, 896, 44

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

  $\Rightarrow$ **Challenge for stellar evolution**
- Isolated binary evolution is disfavoured

Dynamical scenario?

e.g., hierarchical mergers in an AGN disk

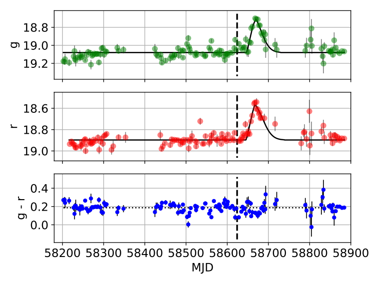
LVC 2020, PRL, 125, 101102

LVC 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)

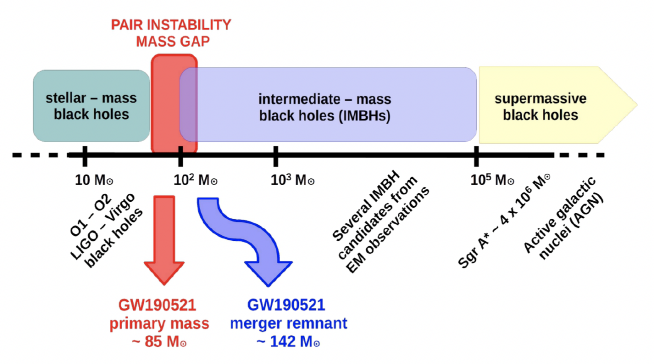


Graham et al. 2020, PRL, 124, 251102

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)

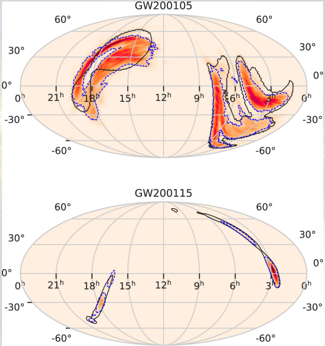
GW190521: the birth on a intermediate massive BH

The remnant BH mass is $\sim 142\ M_\odot \Rightarrow$ **First strong observational evidence for an intermediate-mass BH**: the missing link between stellar and supermassive BHs



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



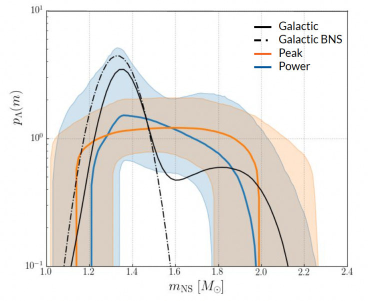
- No EM counterpart has been found...
- ... However, EM emission would have been difficult to detect, given the large distances and large error in the sky localization

LVK Collaboration 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 (LVK Collaboration 2023, PRX, 13, 041039

The astrophysical population of NSs

The mass distribution of NSs

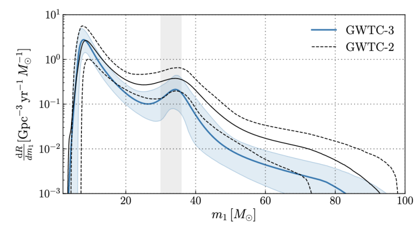


- The mass distribution of NSs observed in GWs is broader and has greater support for high-mass NSs with respect to the Galactic population
- Difference could result from:
  - distinct formation channels;
  - strong selection effects;
  - overlap of NS and BH mass distributions

LVK Collaboration 2023, PRX, 13, 011048

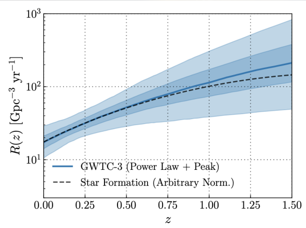
The population of BBH merging systems

Primary BH mass distribution



- BH mass distribution is non-uniform, with overdensities at BH masses of 10 $M_\odot$ and 35 $M_\odot$; tail up to 80 $M_\odot$

BBH merger rate



- BBH merger rate is observed to increase with redshift

LVK Collaboration 2023, PRX, 13, 011048; LVC 2021, ApJL, 913, L7

Conclusions

Highlights from the first three LVK runs:

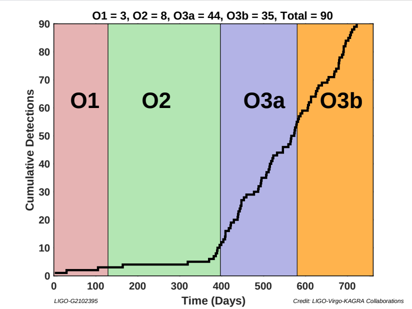
- BBHs can form in nature and merge within a Hubble time
- First observations of BHs in the pair-instability mass gap and of IMBHs
- First multi-messenger (GWs+photons) observation of a binary system of NSs; possible EM signal associated with a BBH merger
- First observations of NS-BH mergers
- Population studies
- Other multi-messenger sources still to be detected (supernovae, pulsars...)

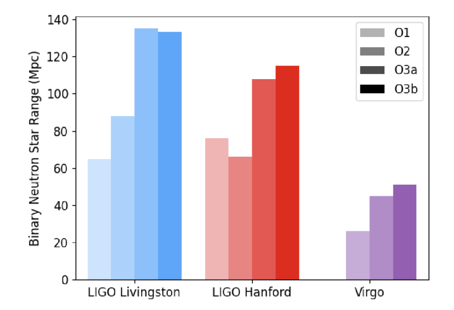
The fourth observing run is currently ongoing, and a fifth run is planned to start in a few years (see Giacomo's talk)...**Many other GW and multi-messenger discoveries are expected in the near future... stay tuned!**

Backup

Backup slides

GW detections: O1+O2+O3 summary

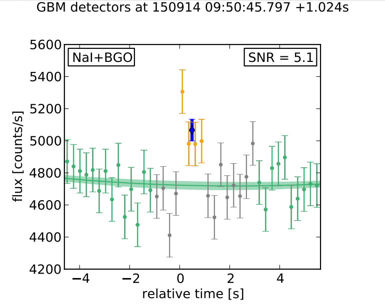




Credits: LIGO-Virgo-KAGRA Collaborations/Hannah Middleton/OzGrav

GW150914: an EM counterpart?

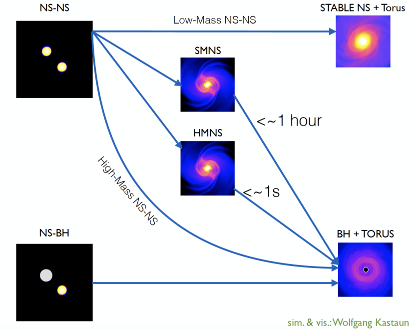
- *Fermi*-GBM: sub-threshold **weak signal above 50 keV 0.4 s after GW150914** (at 2.9 σ), consistent with a short GRB (Connaughton et al. 2016)



- Re-analysis of data shown that it is consistent with a background fluctuation (Greiner et al. 2016, Xiong 2016)
- Nevertheless, some rare scenarios that could explain an EM counterpart for BBH mergers have been proposed, such as:
  - 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)

The compact remnant

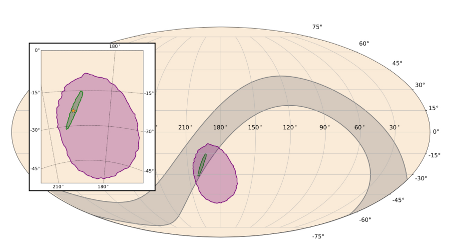
The outcome of a NS-NS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state (EOS) of nuclear matter.



- **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 (LVC 2017, 2019)

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

LVK 2017, Apj, 848, 13

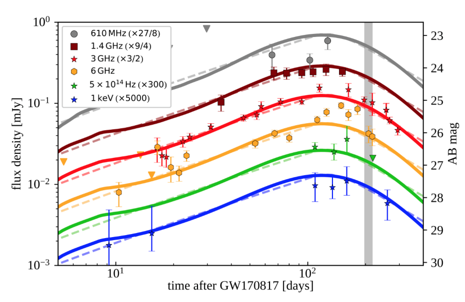
X-ray and radio observations

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...

Two possible interpretations:

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

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

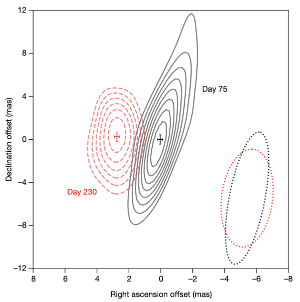


Ghirlanda et al. 2019

Radio observations

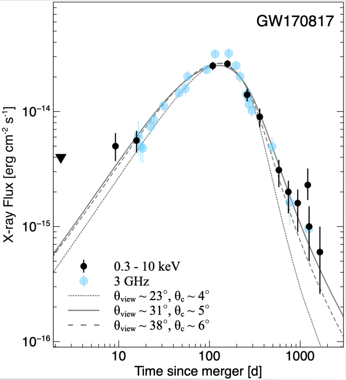
... But Very Long Baseline Interferometry observations allowed to break the degeneracy (Ghirlanda et al. 2019, Mooley et al. 2018)

- 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



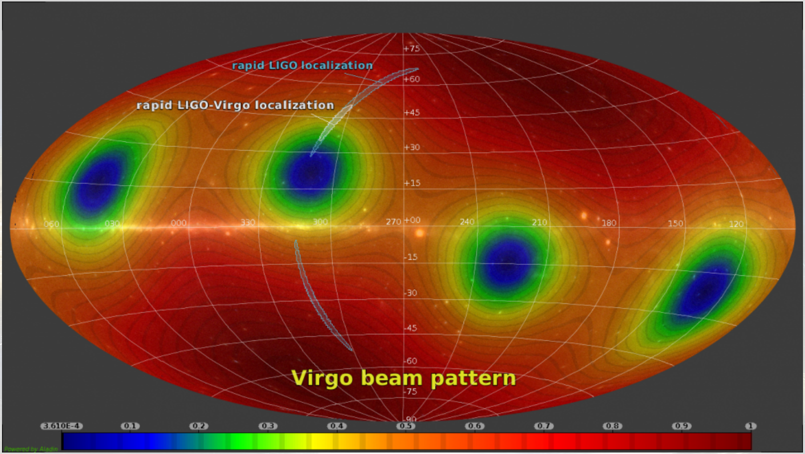
- Latest X-ray and radio emission deviate from early predictions of the jet model with $\theta_{\mathrm{view}} \sim 20$ deg
- Is there an additional component taking over the fading GRB afterglow?
  - Long lived magnetar?
  - Kilonova afterglow?

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

The role of Virgo in the sky localization

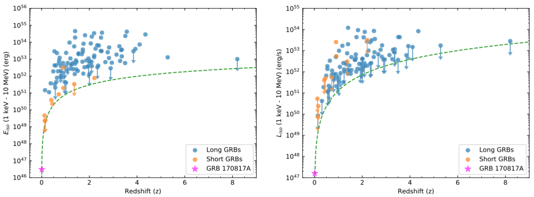


Credits: G. Greco, N. Arnaud, M. Branchesi, A. Vicere

The role of Virgo in the sky localization

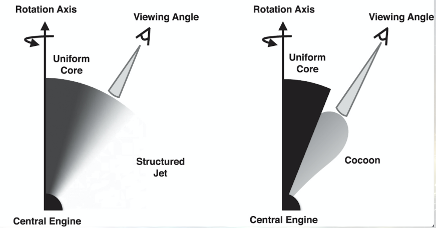
Credit: L. Singer

GRB 170817A: energy and luminosity



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

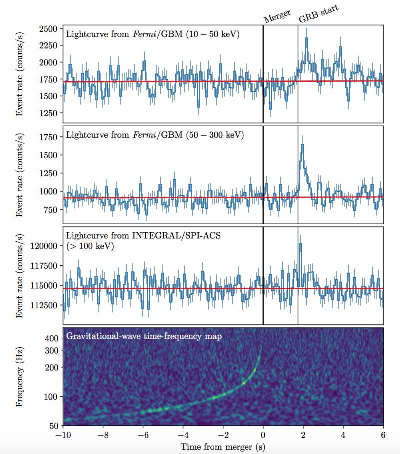
- Intrinsically sub-luminous GRB?
- structured jet?
- cocoon emission?



LVC 2017, ApJ, 848, 13

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

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

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

- 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

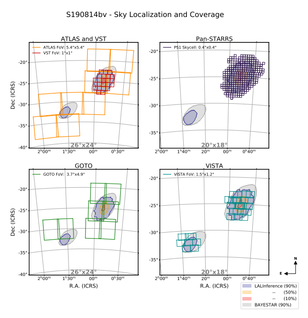
$$-3\times 10^{-15} \leq \frac{\Delta\nu}{\nu_{\rm EM}} \leq 7\times 10^{-16}$$

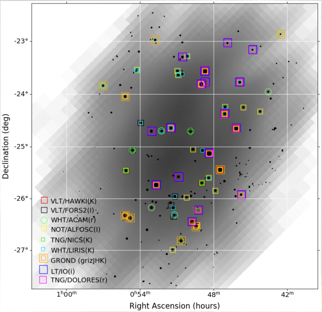
LVC 2017, ApJL, 848, 13

GW190814: the EM follow-up

Example: optical counterpart searches by ENGRAVE

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

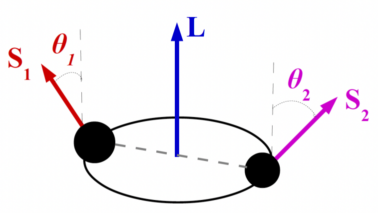




Non-detection of EM counterparts ⇒ **limits on the properties of the outflows** that could have been produced by the binary during and after the merger

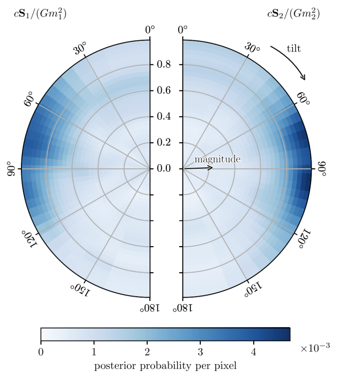
Ackley + BP et al. 2020, A&A, 643, 113

GW190521: the spin



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

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



Mild evidence for large spins nearly in the orbital plane

... **dynamical origin of the system?**

LVC 2020, PRL, 125, 101102

LVC 2020, ApJL, 900, 13

Astrophysical implications: the merger rates

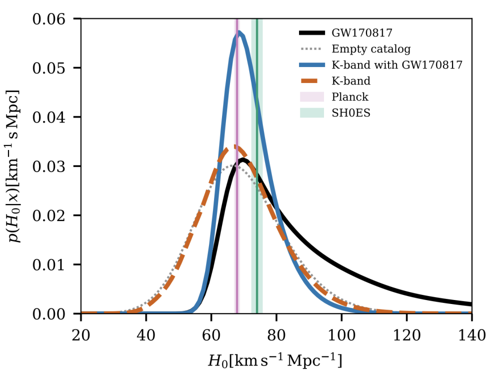
O1+O2+O3:

- BBH merger rate (z=0.2): 17.3 - 45 Gpc^{-3} yr^{-1}
- BNS merger rate: 13 - 1900 Gpc^{-3} yr^{-1}
- NS-BH merger rate: 7.4 - 320 Gpc^{-3} yr^{-1}

LVK Collaboration 2023, PRX, 13, 011048

→ Helpful to constrain population synthesis models

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

LVK Collaboration 2023, ApJ, 949, 76