Multi-messenger Physics

Barbara Patricelli[1,2,3] **and Massimiliano Razzano**[1,2]

[1] Physics Department - University of Pisa

[2] INFN - Sezione di Pisa

[3] INAF - Osservatorio Astronomico di Roma

MidTerm Review
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UNIVERSITÀ DI PISA

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Istituto Nazionale
Fisica Nucleare
Sezione di Pisa

PROBES
H2020 MSCA RISE 2020
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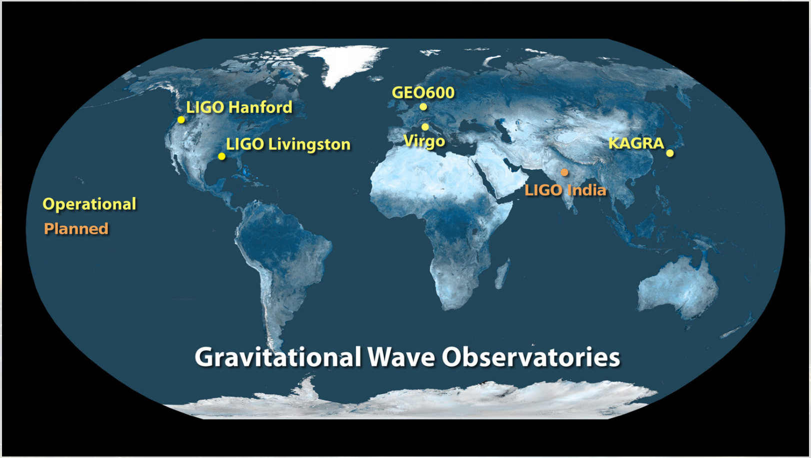
The 2nd generation GW detector network



Where do we stand?

Credit: LIGO-Virgo-KAGRA

- *O1: September 2015 - January 2016*

  Only the two LIGO detectors were operating

- *O2: November 2016 - August 2017*

  Virgo joined the network on August 1

- *O3a: April 2019 - September 2019*

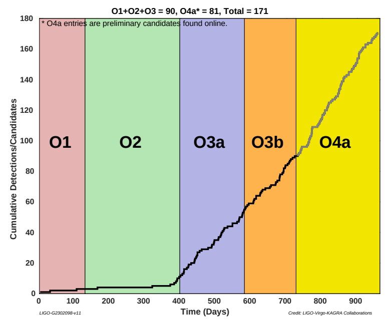
  O3b: November 2019 - March 2020

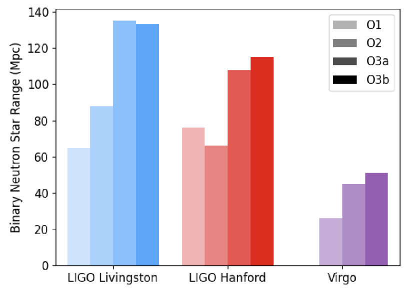
  Virgo and the two LIGO detectors were operating

- *O4a: May 2023 - January 2024*

  The two LIGO detectors were operating; KAGRA operating for 1 month

GW detections: summary



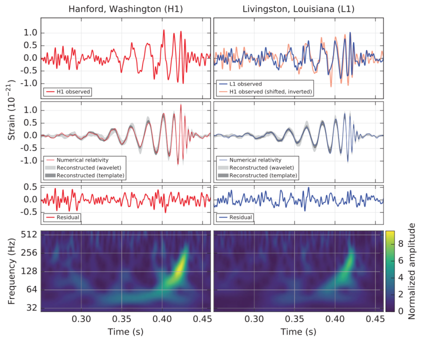


Credits: LIGO-Virgo-KAGRA Collaborations/Hannah Middleton/OzGrav

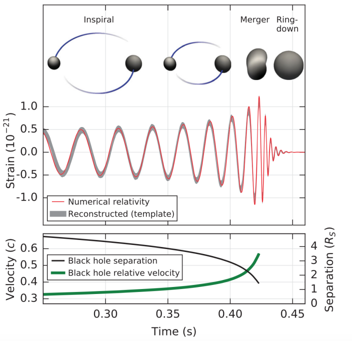
O1: The birth of GW astronomy

GW150914

The observation



The model

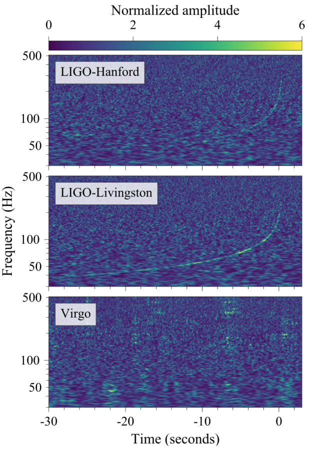


- Binary Black Holes (BBHs) can form in nature and merge within a Hubble time
- The two BH masses are $\sim 30\ \mathrm{M}_\odot \Rightarrow$ First direct evidences for "heavy" stellar mass BHs ($> 25\ \mathrm{M}_\odot$)

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 (BNS) inspiral**



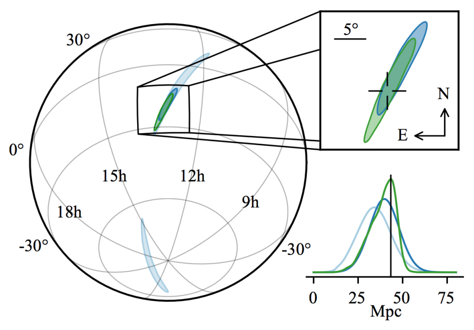
- **GW170817** swept through the detectors' sensitive band for ~ 100 s ($f_{\mathrm{start}} = 24$ Hz)
- The signal-to-noise ratio (SNR) is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

  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)

Where did the BNS 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)

Which were the expected EM counterparts?

- Short 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).

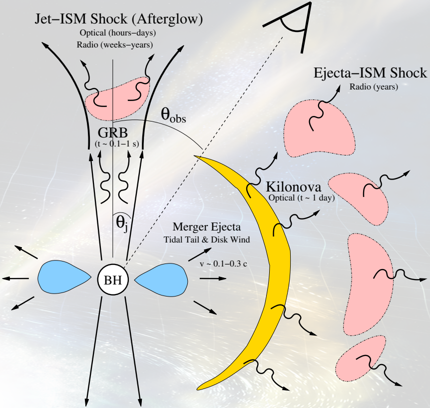
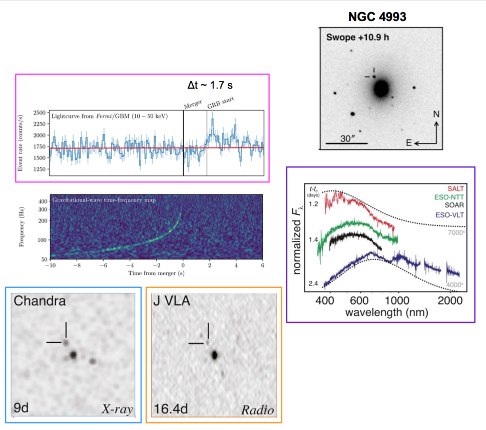


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

What did we observe?



- coincident short GRBs detected in gamma rays

  ⇒ first direct evidence that at least some **BNS mergers are progenitors of short GRBs**

- the **host galaxy** has been identified: NGC 4993

- an optical/infrared/UV counterpart has been detected

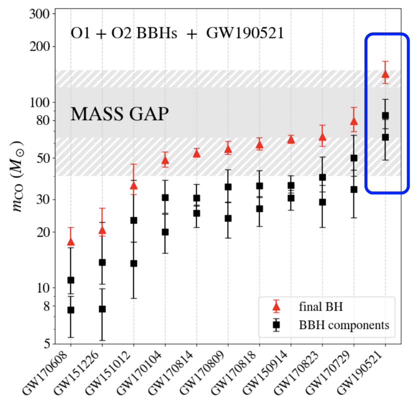
  ⇒ first spectroscopic **identification of a kilonova**

- An X-ray and a radio counterparts have been identified

  ⇒ **off-axis afterglow from a structured jet** (Ghirlanda et al. 2019, Mooley et al. 2018)

see Abbott et al., ApJ Letters, 848, 2 (2017) and refs. therein

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 Active Galactic Nucleus (AGN) disk

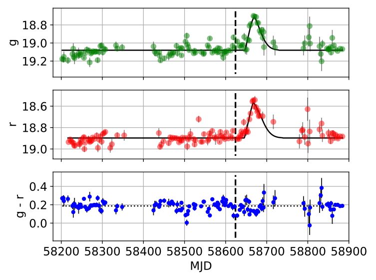
Abbott et al. 2020, PRL, 125, 101102

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[1] detection candidates (92 Total - 11 Retracted)
- Almost all BBHs; no BNS; a couple of possible NS-BH ($p \gtrsim 50\%$)
  - **S230529ay** `https://gracedb.ligo.org/superevents/S230529ay/view/`
  - **S230627c** `https://gracedb.ligo.org/superevents/S230627c/view/`
- No EM counterpart so far

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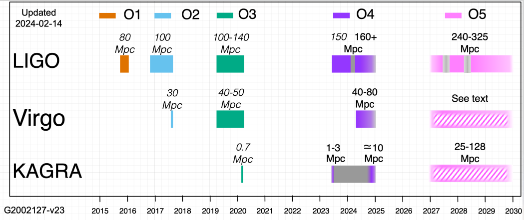
[1] Significant GW alerts: false alarm rate $<$ 1/month for CBC and 1/year for bursts

The next GW observing runs

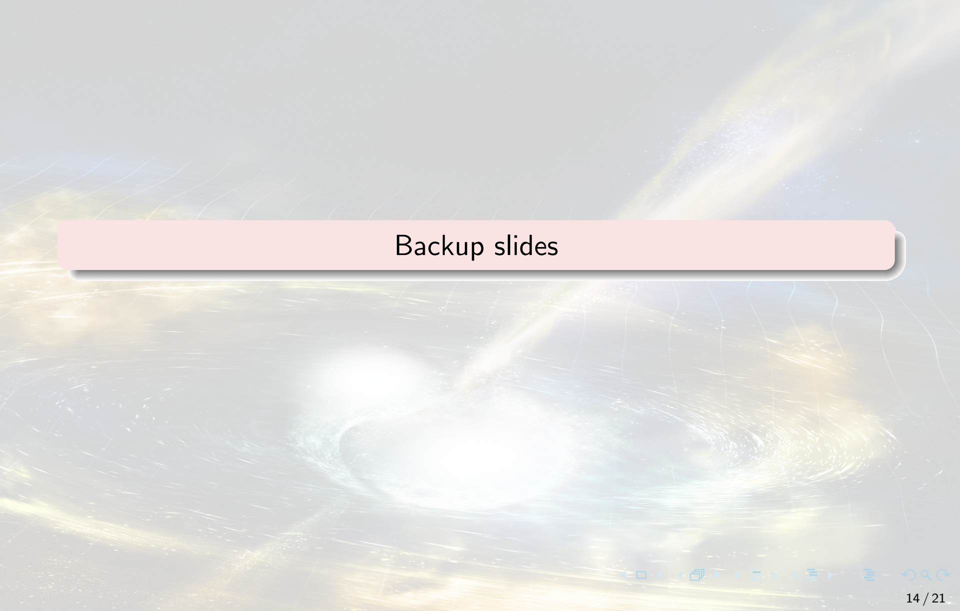


- Commissioning break is ongoing
- Planned starting date of O4b: April 3, 2024
- O4b duration: 9 months

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

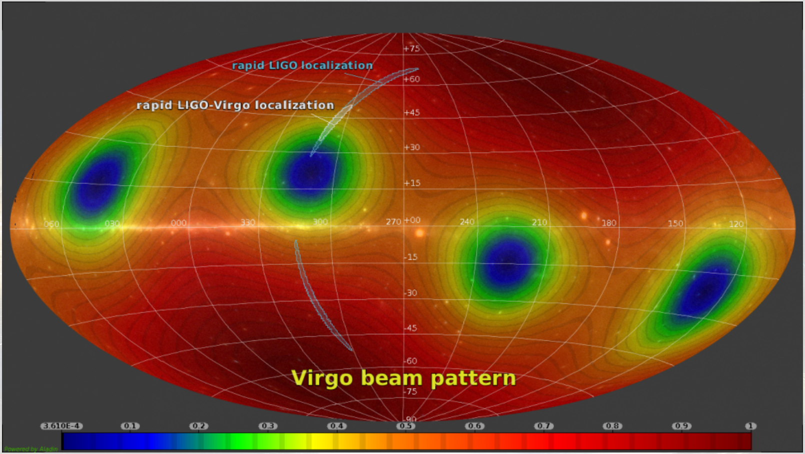
- In the future 2^{nd} generation GW detectors will operate with increased sensitivity, in synergy with current and future EM facilities (e.g. SVOM, CTA, Vera Rubin Observatory etc) $\Rightarrow$ increase in the data rates and in the data complexity
- Work is ongoing to develop new tools to make faster and more efficient the detection of the sources, their localization etc (e.g., Machine Learning)

Backup



Backup slides

The role of Virgo in the sky localization



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

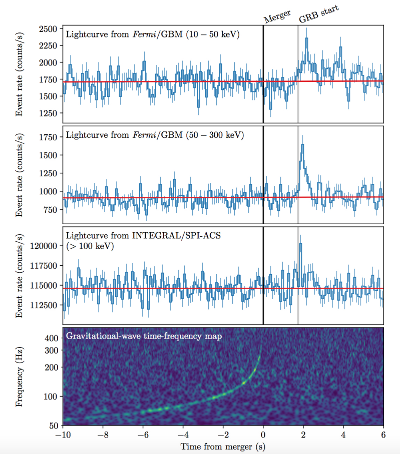
The role of Virgo in the sky localization

(Loading Video...)

Credit: L. Singer

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

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

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

- 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

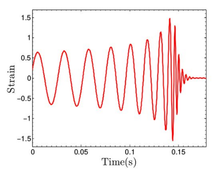
$$\boxed{-3\times10^{-15} \leq \frac{\Delta\nu}{\nu_{\rm EM}} \leq 7\times10^{-16}}$$

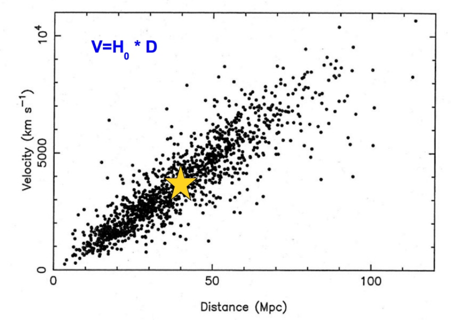
Abbott et al. 2017, ApJL, 848, 13

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



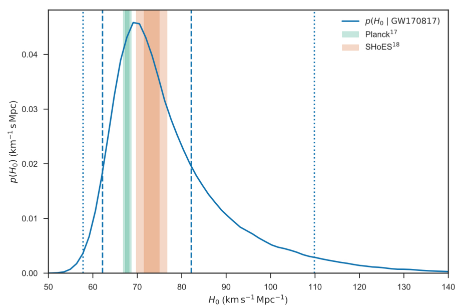


$$\boxed{H_0 = 70^{+12}_{-8}\ \text{km/s/Mpc}}$$

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**



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

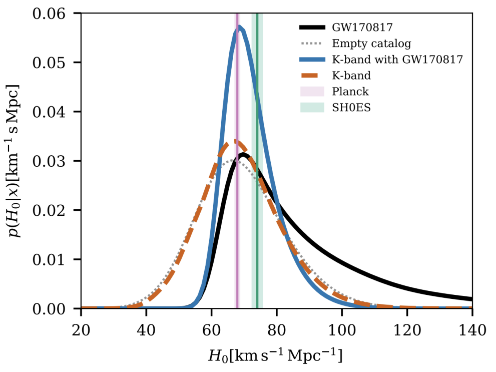
Abbott et al., Nature, 551, 85 (2017)

* More recent estimates, obtained assuming a priori that the GW source is in NGC 4993, are:

- $\mathrm{H_0}$=70^{+13}_{-7} km s^{-1} Mpc^{-1} (high-spin case)
- $\mathrm{H_0}$=70^{+19}_{-8} km s^{-1} Mpc^{-1} (low-spin case)

Abbott et al. 2019, PRX, 9, 011001

Hubble constant estimate with GWTC-3



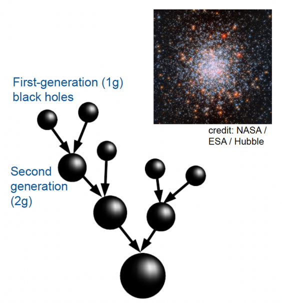
BBHs + galaxy catalogs + GW170817: $\mathrm{H}_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}

⇒ improvement of ∼ 40 % with respect to the result obtained using only GW170817

Abbott et al. 2023, ApJ, 949, 76

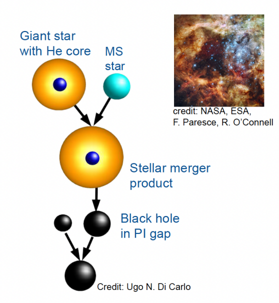
Dynamical scenarios for GW190521

Hierarchical mergers



credit: NASA / ESA / Hubble

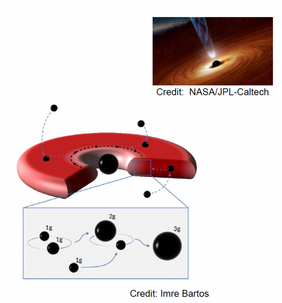
Stellar mergers in young star clusters



credit: NASA, ESA, F. Paresce, R. O'Connell

Credit: Ugo N. Di Carlo

Active Galactic Nucleus (AGN) disks



Credit: NASA/JPL-Caltech

Credit: Imre Bartos