The new exploration of the Universe through gravitational-wave and multi-messenger observations

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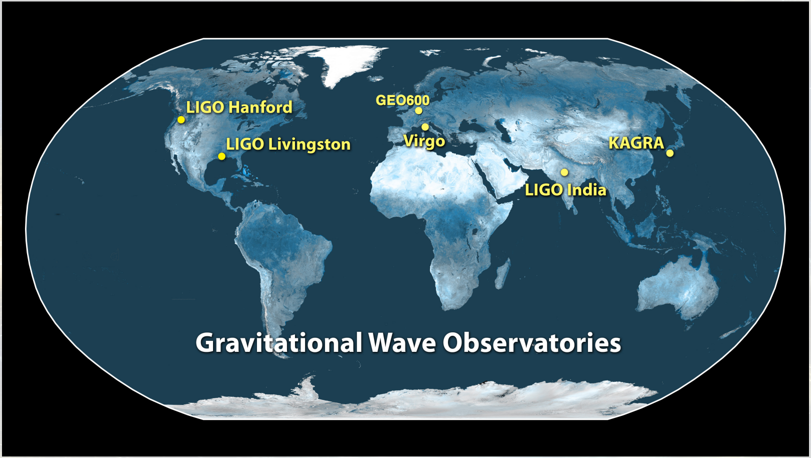
Meeting of the Cosmic Ray Division of the Mexican Physical Society

March 27-29, 2023

Outline

The 2nd generation GW detector network



Where do we stand?

Three observing runs so far

Credit: LIGO-Virgo

- *O1: September 2015 - January 2016*

  Only the two LIGO detectors were operating

- *O2: November 2016 - August 2017*

  Virgo joined the network on August 1

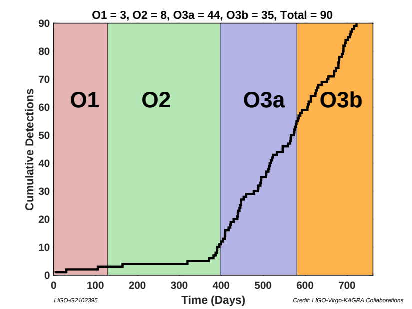
- *O3a: April 2019 - September 2019*

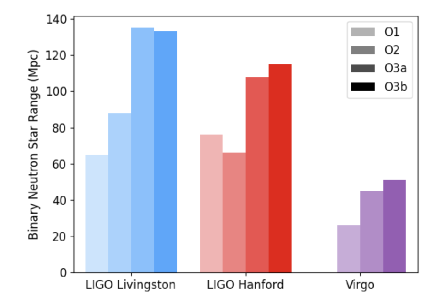
  O3b: November 2019 - March 2020

  Virgo and the two LIGO detectors were operating

GW detections: summary

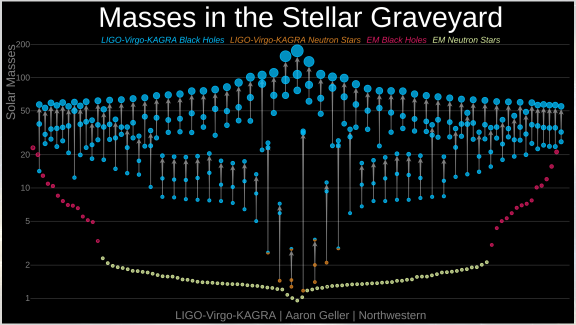
90 GW candidates detected so far





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

GW detections: summary



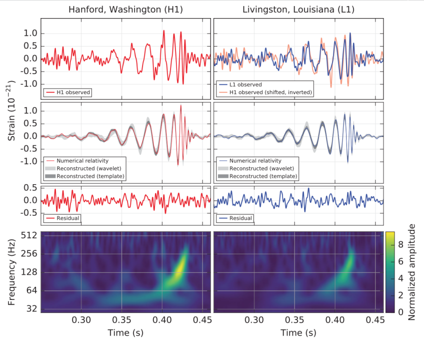
- Total number of candidates: 90
- Most are binary black holes (BBHs); some are neutron star - black hole (NSBH) binaries; two are binary neutron stars (BNSs)
- Four GW catalogs: GWTC-1 (O1+O2), GWTC-2 and GWTC-2.1 (O3a), GWTC-3 (O3b)

Abbott et al. 2019, PRX, 9, 031040; Abbott et al. 2021, PRX, 11, 021053;
Abbott et al. 2021, arXiv:2111.03606; Abbott et al. 2021, arXiv:2108.01045

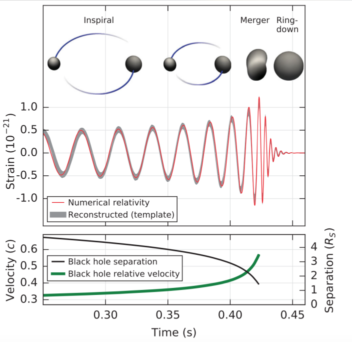
O1: The birth of GW astronomy

GW150914

The observation



The model

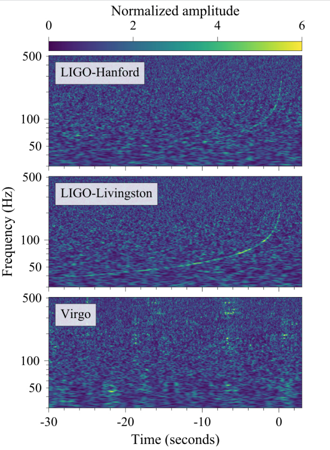


- BBHs can form in nature and merge within a Hubble time
- The two BH masses are $\sim 30\ M_\odot \Rightarrow$ First direct evidences for "heavy" stellar mass BHs ($> 25\ M_\odot$)

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**



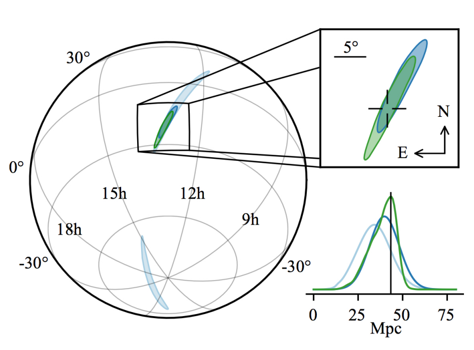
- **GW170817** swept through the detectors' sensitive band for $\sim$ 100 s (f_{start} = 24 Hz)
- The signal-to-noise ratio (SNR) is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

  the combined SNR is 32.4

  $\Rightarrow$ This is the loudest signal among the ones observed so far

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

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)

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).

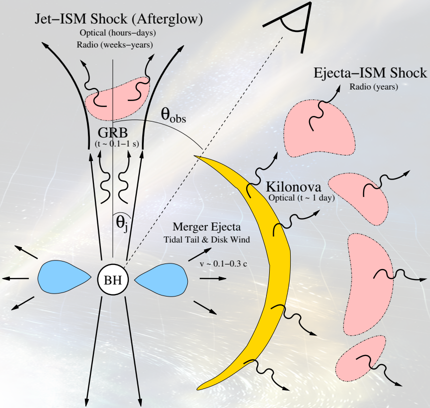
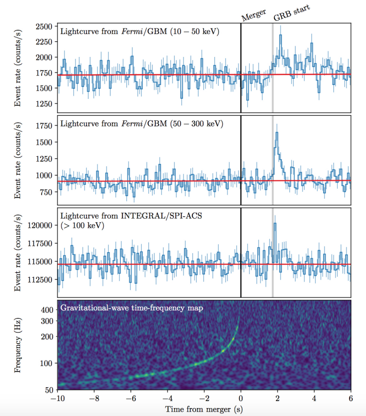


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

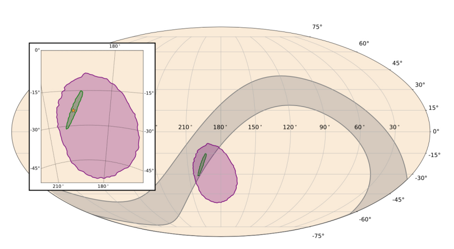
Gamma-rays: short GRB

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

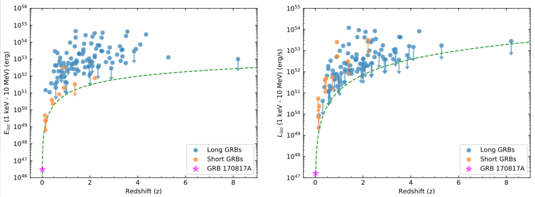
LIGO-Virgo 90 % credible region (28 deg^2)

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

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

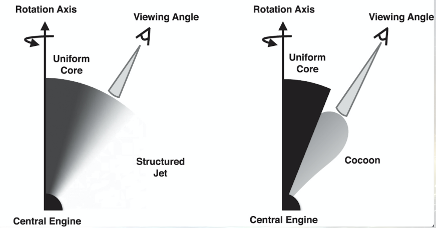
Abbott et al., ApJ, 848, 13 (2017)

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 EM follow-up campaign

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

(Loading Video...)

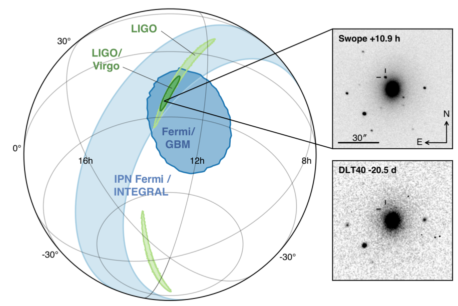
Credit: LIGO-Virgo

The identification of the host galaxy

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

The discovery has been reported by 6 teams:

- SWOPE (10.86 h)
- DLT40 (11.08 h)
- VISTA (11.24 h)
- MASTER (11.31 h)
- DECam (11.40 h)
- Las Cumbres (11.57 h)



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

The spectroscopic identification of the kilonova

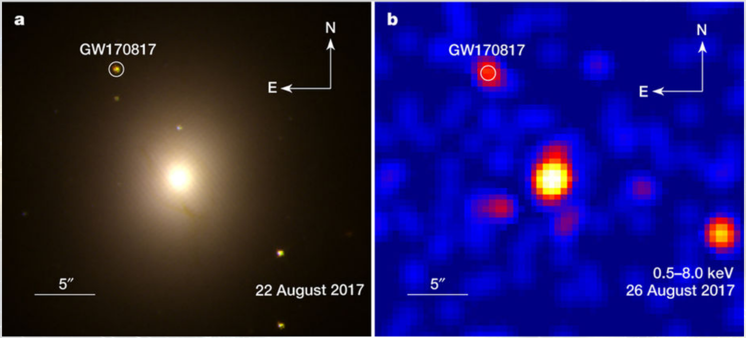
Following the detection of this source, an imaging and spectroscopic follow-up campaign at optical and NIR wavelengths started

(Loading Video...)

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

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)



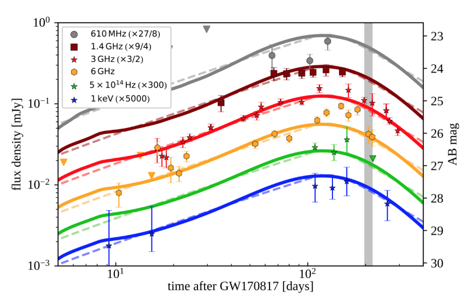
Source monitored for hundreds of days...

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... ⇒

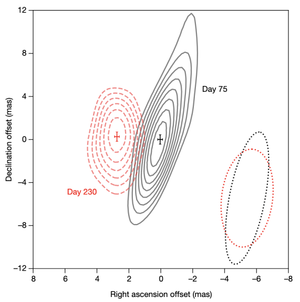


Ghirlanda et al. 2019

Radio observations

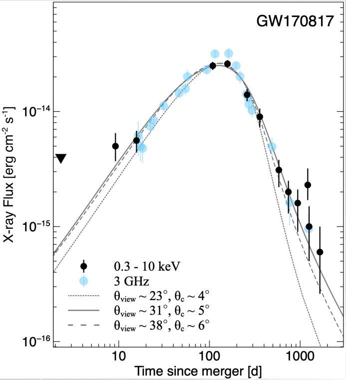
... But Very Long Baseline Interferometry observations allowed to break the degeneracy (Ghirlanda et al. 2019, Mooley et al. 2018)

- 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



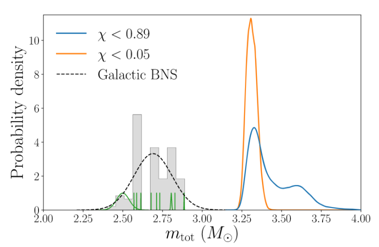
- Latest X-ray and radio emission deviate from early predictions of the jet model with $\theta_{\text{view}} \sim 20$ deg
- Is there an additional component taking over the fading GRB afterglow?
  - Long lived magnetar?
  - Kilonova afterglow?

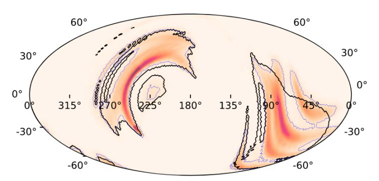
O'Connor & Troja 2022; Troja et al. 2022

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





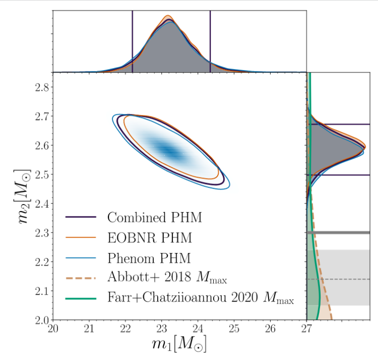
- GW event observed by LIGO-Livingston and Virgo
- GW signal most likely originated from a **NS-NS merger but...**

  ... **the total mass is significantly larger than that of the other NS-NS systems**

- 90 % C.R.: 8284 deg^2; $D_L = 159^{+69}_{-72}$ 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?



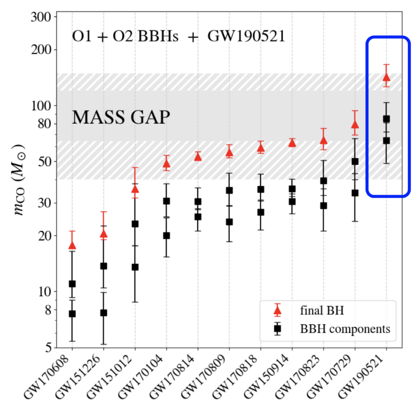
- GW event observed by the two LIGO detectors and Virgo
- $\mathrm{m_1}$: $23.2^{+1.1}_{-1.0}$ $\mathrm{M_\odot}$

  $\mathrm{m_2}$: $2.59^{+0.08}_{-0.09}$ $\mathrm{M_\odot}$

  BBH or NS-BH merger?
- Challenging for current formation scenarios
- 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

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

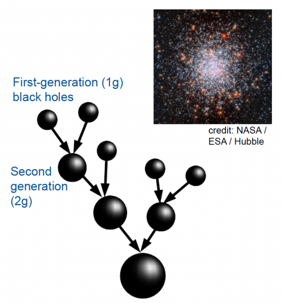
- Isolated binary evolution is disfavoured
- **Dynamical scenario?**

Abbott et al. 2020, PRL, 125, 101102

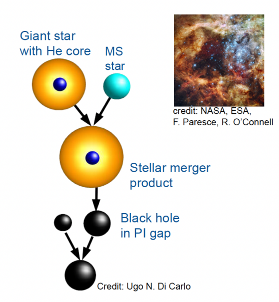
Abbott et al. 2020, ApJL, 900, 13

Dynamical scenarios for GW190521

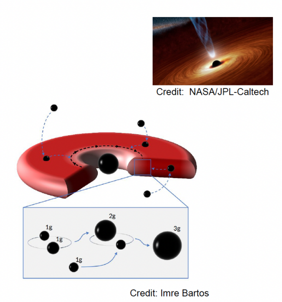
Hierarchical mergers



Stellar mergers in young star clusters



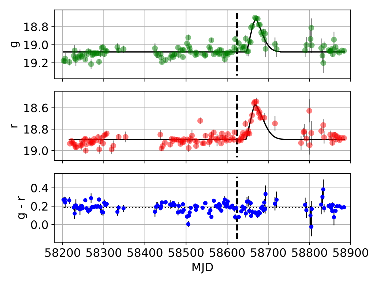
Active Galactic Nucleus (AGN) disks



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)

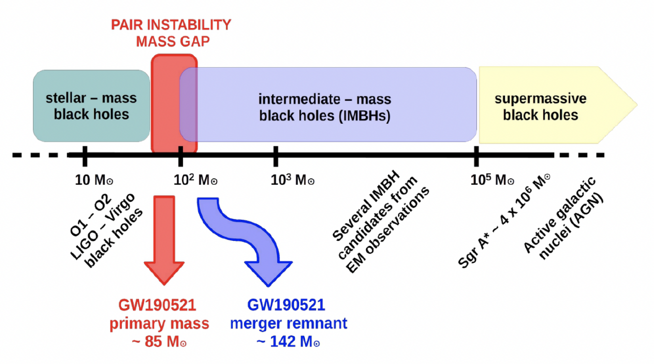


Graham et al. 2020, PRL, 124, 251102

However, this association is not yet clear and is under investigation (Ashton et al. 2021, CQG, 38, 235004, Palmese et al. 2021, ApJL 914, 34)

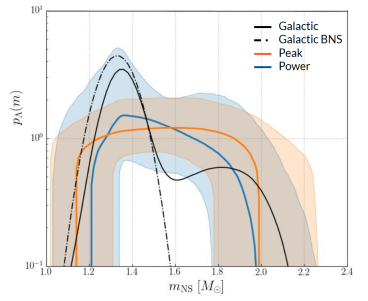
GW190521: the birth on a intermediate massive BH

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



The astrophysical population of NSs

The mass distribution of NSs

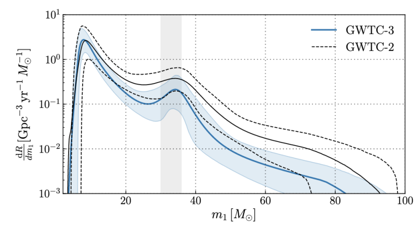


- The mass distribution of NSs observed in GWs is broader and has greater support for high-mass NSs with respect to the Galactic population
- Difference could result from:
  - distinct formation channels;
  - strong selection effects;
  - overlap of NS and BH mass distributions

Abbott et al. 2021, arXiv:2111.03634

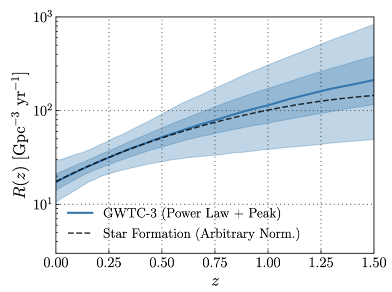
The population of BBH merging systems

Primary BH mass distribution



- Well described by a power-law plus a Gaussian peak at $34^{+2.3}_{-3.8}$ $M_\odot$
- A higher fraction of low mass and unequal mass binaries observed in GWTC-3

BBH merger rate



- BBH merger rate is observed to increase with redshift

Abbott et al. 2021, arXiv:2111.03634

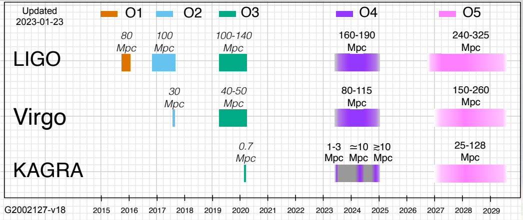
Astrophysical implications: the merger rates

O1+O2+O3:

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

Abbott et al. 2021, arXiv:2111.03634

The next GW observing runs



- Planned starting date of O4: May 24, 2023
  (this will be preceded by a 1-month engineering run)
- O4 duration: 18 months

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

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

Prospects for multi-messenger detections in O4

How many multi-messenger detections do we expect in the next LIGO-Virgo-KAGRA observing run?

- We generated a sample of synthetic NS-NS systems populating the local Universe up to z=0.11
  - MOBSE population-synthesis code (Mapelli et al. 2017, Giacobbo et al. 2018)
  - 3 sets of simulations, corresponding to 3 different choices of the common-envelope parameter α=1, 3 and 7 (model A1, A3 and A7)
- We simulated the associated GW signal and estimated the GW detection rates with the HLVK network
- We simulated the associated GRB emission considering a uniform and a structured jet, and estimated the joint GW and EM detection rates with different EM facilities

Patricelli et al. 2022, MNRAS, 513, 4159

(see also, e.g., Patricelli et al. 2016, 2018; Howell et al. 2019, MNRAS, 485, 1435; Colombo et al. 2022, ApJ, 937, 79; Perna et al. 2022, MNRAS, 512, 2654)

Prospects for multi-messenger detections in O4

GWs + GRB (prompt emission)

"Conservative approach" (SNR > 12, Ndet ≥ 2)

model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
	$\mathrm{Gpc^{-3}yr^{-1}}$	$\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$
A1	31	1	0.0006 (0.0023)	0.014-0.020	0.003 (0.013)	0.070-0.11	0.0001 (0.0004)	0.0024-0.0035	0.0005 (0.0019)	0.013-0.017
A3	258	5	0.003 (0.01)	0.07-0.10	0.017 (0.068)	0.35-0.54	0.0005 (0.002)	0.01-0.02	0.002 (0.01)	0.06-0.08
A7	765	13	0.008 (0.031)	0.18-0.26	0.045 (0.18)	0.91-1.42	0.001 (0.005)	0.031-0.046	0.006 (0.025)	0.17-0.22

"Optimistic approach" (SNR > 8, Ndet ≥ 1)

model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
	$\mathrm{Gpc^{-3}yr^{-1}}$	$\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$	uniform $\mathrm{yr^{-1}}$	structured $\mathrm{yr^{-1}}$
A1	31	5	0.002 (0.01)	0.05-0.08	0.014 (0.06)	0.27-0.46	0.0005 (0.002)	0.009-0.014	0.002 (0.008)	0.05-0.07
A3	258	22	0.01 (0.04)	0.24-0.37	0.06 (0.26)	1.17-2.00	0.002 (0.008)	0.04-0.06	0.009 (0.04)	0.22-0.32
A7	765	61	0.03 (0.12)	0.67-1.05	0.18 (0.74)	3.28-5.65	0.006 (0.02)	0.11-0.18	0.02 (0.10)	0.63-0.90

* Please note that the GW and GW+EM rates should be multiplied by 1.5 to get the expected number of detections in O4

- Depending on the population model considered and on the assumed GW SNR thresholds, we expect from 1 to 61 NS-NS merger detections per year in O4;
- **There is a realistic probability to observe at least another multi-messenger event during O4**

Patricelli et al. 2022, MNRAS, 513, 4159

Conclusions

- Three observing runs so far
- We observed GWs from merging binary BH and NS systems
- We had the first multi-messenger (GWs+photons) observation of a binary system of NSs
- Other multi-messenger sources still to be detected (supernovae, pulsars...)
- Advanced LIGO, Advanced Virgo and KAGRA will re-start soon to take data with increased sensitivity
- New EM facilities will soon become operative, in sinergy with GW detectors

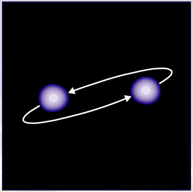
Many other GW and multi-messenger discoveries are expected in the near future... stay tuned!

Backup

Backup slides

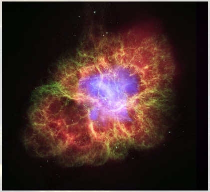
High frequency (10-1000 Hz) GW transient sources

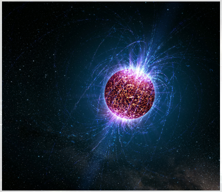
Coalescence of binary systems of NSs and/or BHs



GW signals accurately modeled by post-Newtonian approximation and numerical simulations → **Matched filter modeled searches**

Core collapse of massive stars and Isolated neutron stars





The modeling of the GW signal is complicated → **Unmodeled searches**

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).

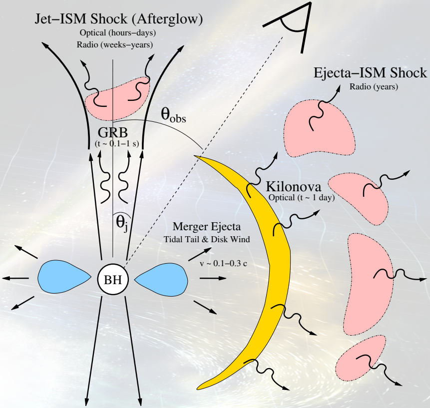


Image credit: Metzger & Berger 2012

Associated multi-wavelength EM emission

BBH mergers

?

- They are 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 recently been proposed, 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)
  - the BBH merger takes place in the gas rich environment in the disks of active galactic nuclei (AGN, Bartos et al. 2017)

Associated multi-wavelength EM emission

Core collapse of massive stars

- supernovae (SNe):
  - SBO 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

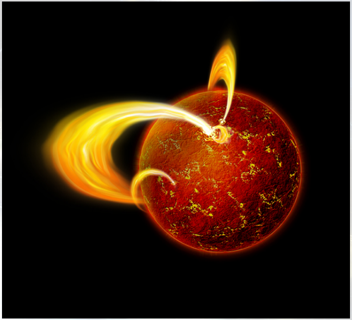


Image Credit: NASA, CXC, M. Weiss

Why multi-messenger astronomy?

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

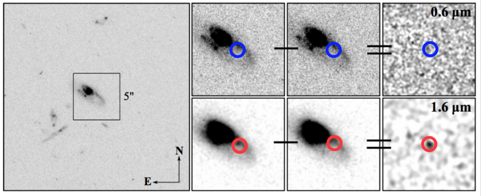
GW

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

EM

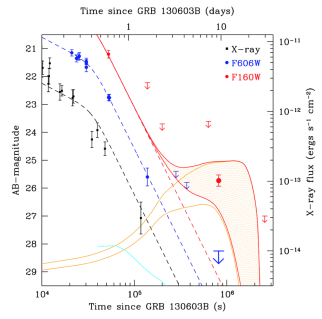
- *precise (arcsec) sky localization*
- *host galaxy*
- *redshift*
- *emission processes*
- *acceleration mechanisms*

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

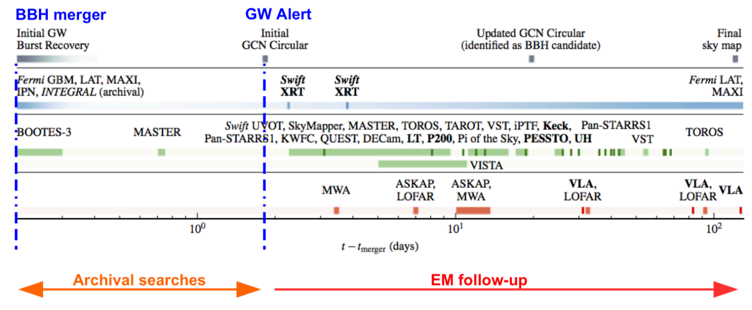
Tanvir et al, Nature, 500, 547 (2013)

GW150914: EM follow-up

High energy

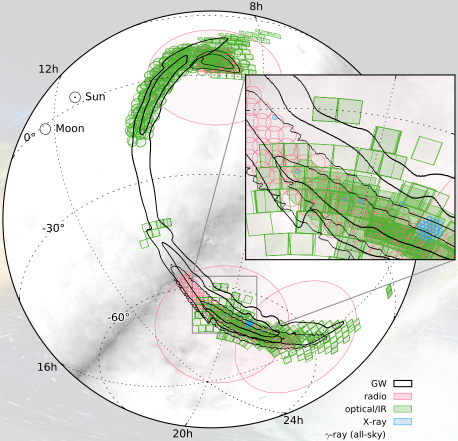
Optical

Radio



Abbott et al. 2016, ApJ Letters, 826, L13

GW150914 sky map coverage



Abbott et al. 2016, ApJ Letters, 826, L13

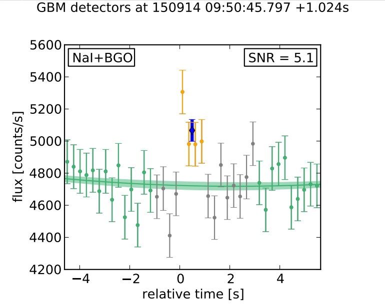
Covered sky map contained probabilty:

- Gamma-ray: 100 %
- Optical: over 50 %
- Radio: 86 %
- X-ray: $\sim$ 90 %
  (MAXI + *Swift*-XRT)

Several candidate counterparts have been found in optical, all identified to be normal population SNe, dwarf novae and AGN unrelated to GW150914

An EM counterpart for GW150914?

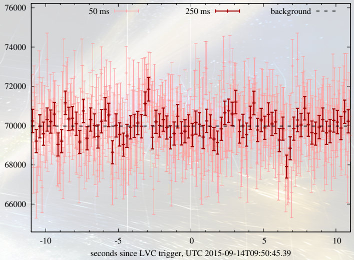
Fermi-GBM: sub-threshold **weak signal above 50 keV 0.4 s after GW150914** (at 2.9 σ), consistent with the direction of GW 150914



Its duration and spectrum are consistent with a weak short GRB (Connaughton et al. 2016).

but...

- no signal detected by INTEGRAL (Savchenko et al. 2016), AGILE (Tavani et al. 2016) and *Fermi*-LAT (Ackermann et al. 2016)

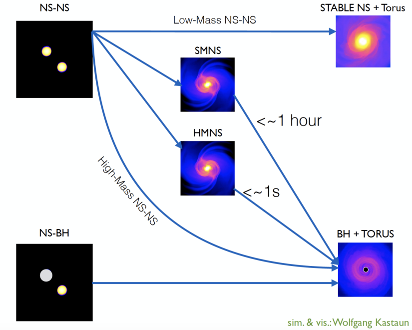


INTEGRAL data, Savchenko et al. 2016

- Greiner et al. 2016: GBM transient consistent with a background fluctuation (see also Xiong 2016)

The compact remnant

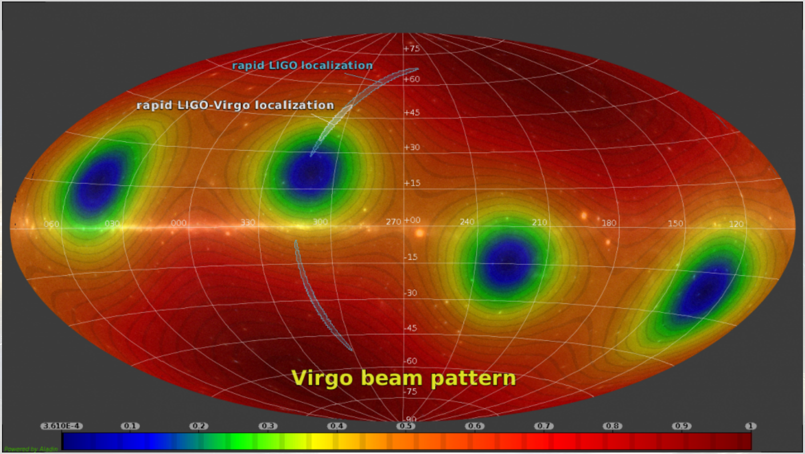
The outcome of a NS-NS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state (EOS) of nuclear matter.



- **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)

The role of Virgo in the sky localization



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

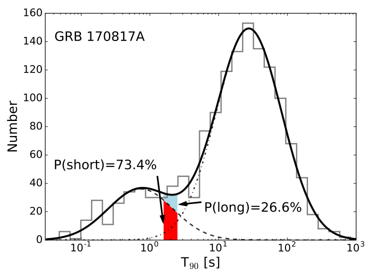
The role of Virgo in the sky localization

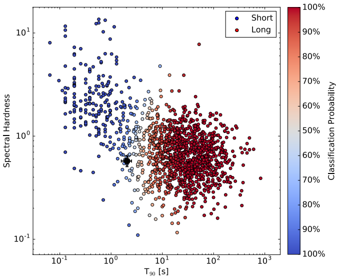
(Loading Video...)

Credit: L. Singer

GRB 170817A: duration and spectral hardness

To which GRB class does GRB 170817A belong?

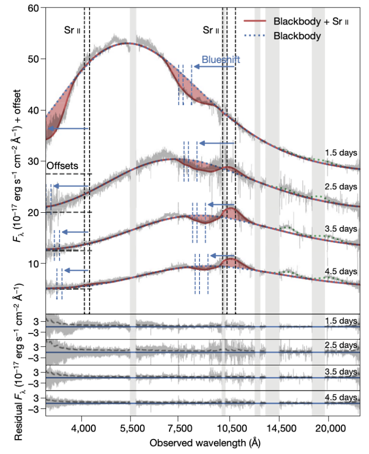




GRB 170817A is $\sim$ 3 times more likely to be a **short GRB** than a long GRB

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

Signature of heavy elements

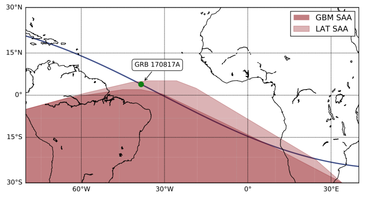


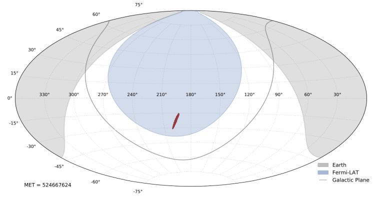
Watson et al. 2019, Nature, 574, 497

(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.

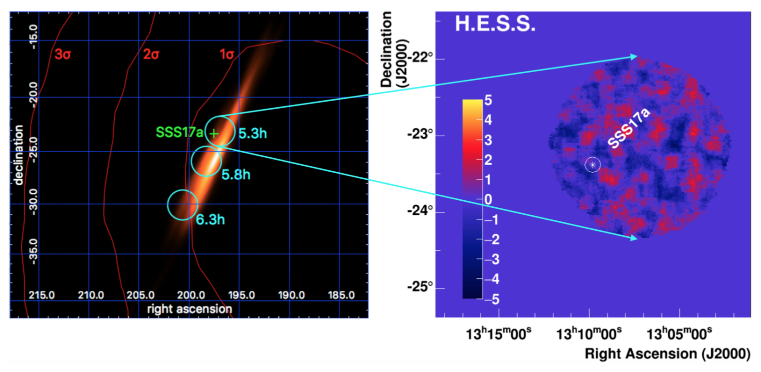




Fermi-LAT collaboration, ApJ, 861, 85 (2018)

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

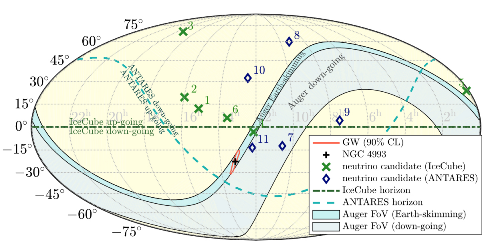
What's missing?

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

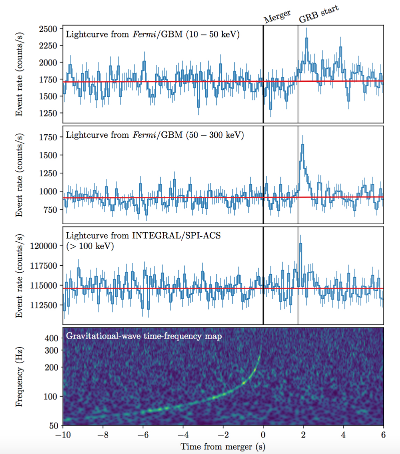
  - No one directionally coincident with GW170817



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

GW-GRB association: constraints on fundamental physics

The observed time delay between GRB 170817A and GW170817 ($\sim$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

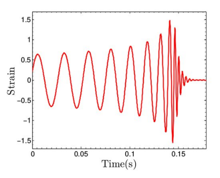
$$\boxed{-3\times10^{-15} \leq \frac{\Delta\nu}{\nu_{\rm EM}} \leq 7\times10^{-16}}$$

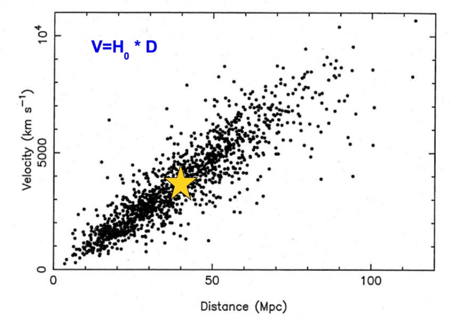
Abbott et al. 2017, ApJL, 848, 13

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

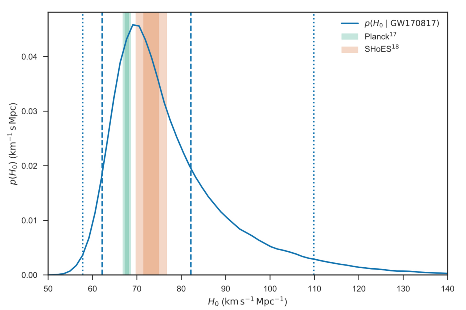




$\boxed{H_0 = 70^{+12}_{-8} \text{ km/s/Mpc}}$

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

Implications for Cosmology

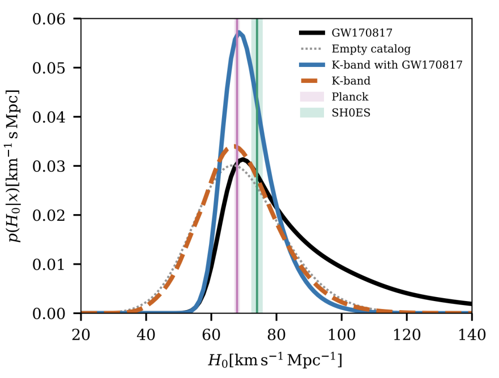


- $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}
- $H_0 = 67.74^{\pm 0.46}$ km s^{-1} Mpc^{-1}
- $H_0 = 73.24^{\pm 1.74}$ km s^{-1} Mpc^{-1}

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

* More recent estimates in Abbott et al. 2019, PRX, 9, 011001; see also Abbott et al. 2021, arXiv:2111.03604

Hubble constant estimate with GWTC-3



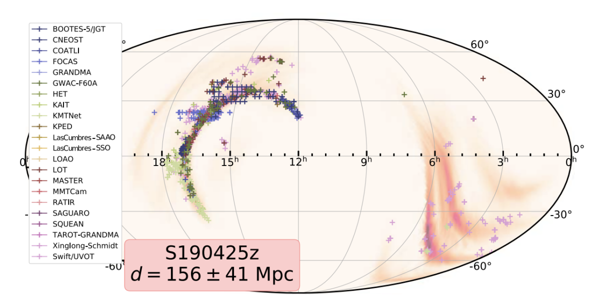
BBHs + galaxy catalogs + GW170817: $\mathrm{H_0} = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}

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

Abbott et al. 2021, arXiv:2111.03604

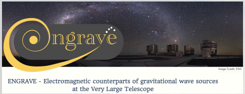
GW190425: the EM follow-up

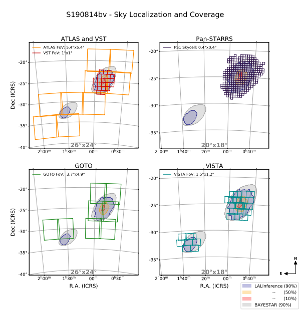
EM follow-up observations have been performed with several facilities, but no EM counterpart has been found (see, e.g., Hosseinzadeh et al. 2019)

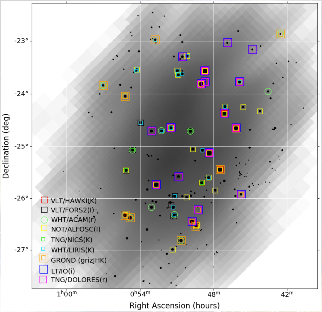


GW190814: the EM follow-up

Example: optical counterpart searches by ENGRAVE



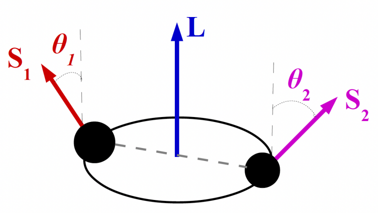




Non-detection of EM counterparts ⇒ limits on the properties of the outflows that could have been produced by the binary during and after the merger

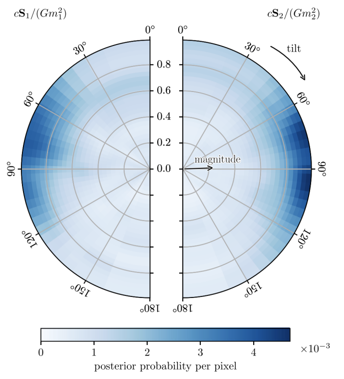
Ackley et al. 2020, A&A, 643, 113

GW190521: the spin



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

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

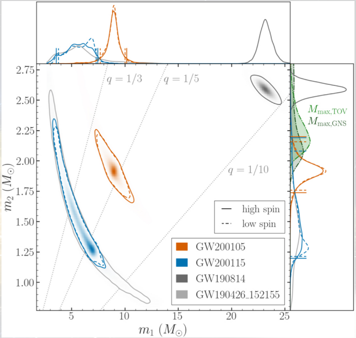


Mild evidence for large spins nearly in the orbital plane
... **dynamical origin of the system?**

Abbott et al. 2020, PRL, 125, 101102

Abbott et al. 2020, ApJL, 900, 13

GW200105 and GW200115



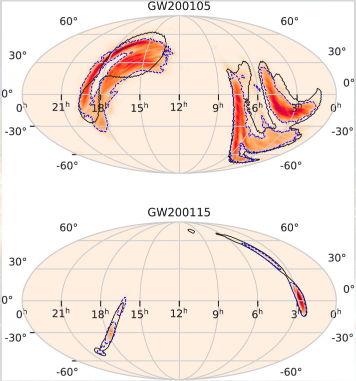
	m_1	m_2
GW200105*	$8.9^{+1.2}_{-1.5}$ $M_\odot$	$1.9^{+0.3}_{-0.2}$ $M_\odot$
GW200115	$5.7^{+1.8}_{-2.1}$ $M_\odot$	$1.5^{+0.7}_{-0.3}$ $M_\odot$

- m_1: consistent with BH masses predicted by population synthesis models for NSBHs
- m_2: consistent with the observed NS mass distribution of Galactic NS-NSs

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. 2021, arXiv:2111.03606)

GW200105 and GW200115

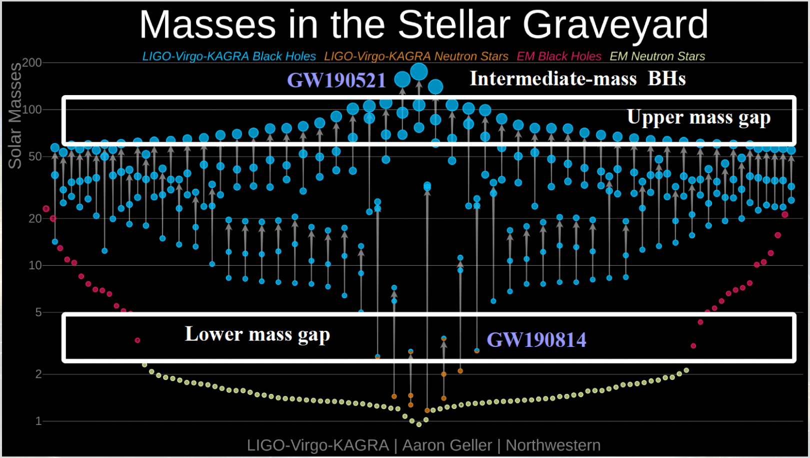


	D_L	90 % C.R.
GW200105	280^{+110}_{-110} Mpc	7200 deg^2
GW200115	300^{+150}_{-100} Mpc	600 deg^2

- 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

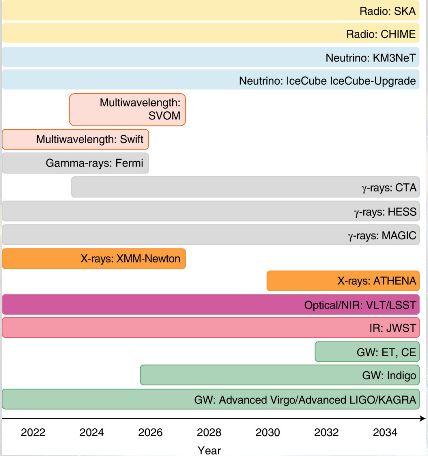
Abbott et al. 2021, ApJL, 915, L5

GW detections: summary



Abbott et al. 2021, arXiv:2111.03606

Multi-messenger facilities in the next years



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

The NS-NS population and the associated GW signals

We generated a sample of synthetic NS-NSs populating the local Universe up to z=0.11

- MOBSE population-synthesis code (Mapelli et al. 2017, Giacobbo et al. 2018)
- 3 sets of simulations corresponding to 3 different choices of the common-envelope parameter α=1, 3 and 7 (model A1, A3 and A7)

We gave these NS-NS systems:

- Isotropic and homogeneous distribution in space
- Random inclination of the orbital plane with respect to the line of sight

We simulated the associated GW signals using the TaylorT4 waveforms

Patricelli et al. 2022, MNRAS, 513, 4159

The GW detection

- Gaussian and stationary noise
- Advanced LIGO (aLIGO), Advanced Virgo (AdV) and KAGRA, O4 sensitivity
  `https://dcc.ligo.org/LIGO-T2000012/public`
- NS-NS range: 190 Mpc (aLIGO); 120 Mpc (AdV); 80 Mpc (KAGRA)
- GW detection - two scenarios:

"Conservative" approach

- *at least 2 detectors;*
- *combined SNR > 12*

(see, e.g., Abbott et al. 2020)

"Optimistic" approach

- *at least 1 detector;*
- *combined SNR > 8*

(see, e.g., Petrov et al. 2022)

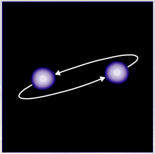
- Independent interferometer duty cycle: 70 %
- GW sky localization with BAYESTAR

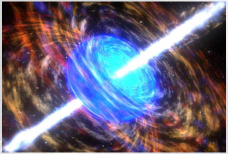
Matched filter pipeline and sky localization: `ligo.skymap` package
`https://lscsoft.docs.ligo.org/ligo.skymap/`

Patricelli et al. 2022, MNRAS, 513, 4159

The short GRB emission

- We assumed that all NS-NS mergers are associated with a short GRB





- We considered both the GRB prompt emission and afterglow emission
- We considered different electromagnetic facilities:

Swift, SVOM, INTEGRAL and *Fermi*

Patricelli et al. 2022, MNRAS, 513, 4159

The GRB prompt emission

- **Uniform jet** with θ_j=5°, 10°
  - On-axis short GRBs ($\theta_{\rm view} < \theta_j$);
  - The short GRB prompt emission is described by: $E_{\rm peak}$, $L_{\rm iso}$, $\theta_{\rm view}$, z:
    - $E_{\rm peak}$ from a broken power law distribution (model "a", Ghirlanda et al. 2016);
    - $L_{\rm iso}$ assuming $E_{\rm peak}$-$L_{\rm iso}$ (Yonetoku) correlation;
    - $\theta_{\rm view}$ and z same as NS-NS merger.
  - Spectrum: Band function* $S(E_{\rm peak},\alpha,\beta)$ with α=-0.6, β=-2.5, normalised to $L_{\rm iso}$
  - The photon flux ($P_{\rm pk}$) is calculated in the characteristic energy band for different instruments, and then compared with the detector sensitivity

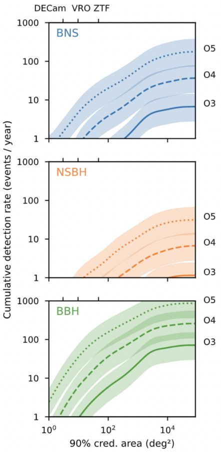
- **Structured jet** with θ_j=5° and a power-law/gaussian angular distribution of the radiated luminosity and the Lorentz factor
  - On-axis plus moderately off-axis ($5^\circ < \theta_{\rm view} < 35^\circ$) S-GRBs
  - Same procedure as for GRBs with uniform jet, but using the $L_{\rm iso}(\theta_{\rm view})$ and $E_{\rm peak}(\theta_{\rm view})$ as seen by an observer at $\theta_{\rm view}$

Patricelli et al. 2022, MNRAS, 513, 4159

*Band function: two power laws joined smoothly at a given break energy

Prospects for GW detections

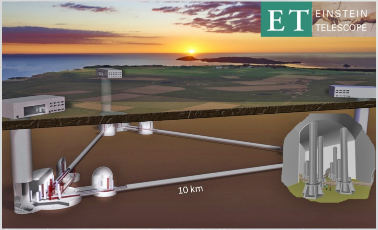
Observing run	Network	Source class		
		BNS	**NSBH**	**BBH**
Merger rate per unit comoving volume per unit proper time (Gpc^{-3} $year^{-1}$, log-normal uncertainty)				
		210^{+240}_{-120}	$8.6^{+9.7}_{-5.0}$	$17.1^{+19.2}_{-10.0}$
Annual number of public alerts (log-normal merger rate uncertainty × Poisson counting uncertainty)				
O4	HKLV	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	HKLV	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}
Median 90% credible area (deg^2, Monte Carlo uncertainty)				
O4	HKLV	1860^{+250}_{-170}	2140^{+480}_{-530}	1428^{+60}_{-55}
O5	HKLV	2050^{+120}_{-120}	2000^{+350}_{-220}	1256^{+48}_{-53}

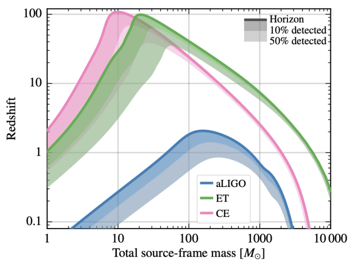


LVK Public Userguide

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

In the next decade, 3$^{\mathrm{rd}}$ 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