# Gravitational Waves and Multimessenger Astronomy

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UNIVERSITÀ DI PISA

INFN Istituto Nazionale Fisica Nucleare Sezione di Pisa

# Outline

# What is Multimessenger Astronomy?

Multimessenger Astronomy: study of the Universe through the combination of data from different types of cosmic messengers coming from the same astrophysical source

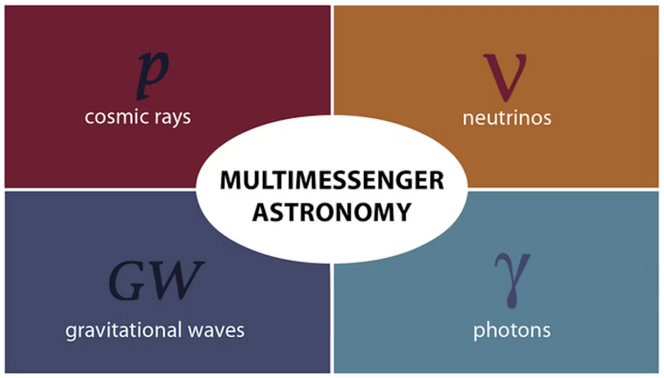
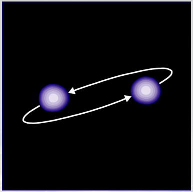



Figure from link

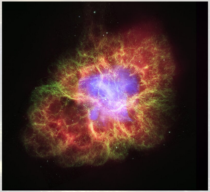
# High frequency (10-1000 Hz) GW transient sources

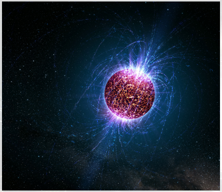
## Coalescence of binary systems of Neutron Stars (NSs) and/or Black Holes (BHs)



- 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* $\gamma$-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).

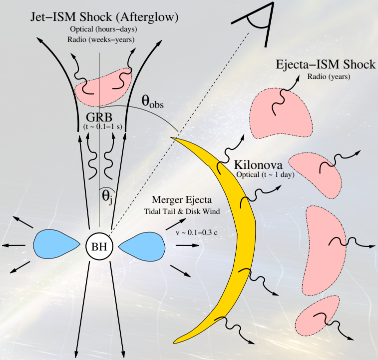



Image credit: Metzger & Berger 2012

**BBH mergers**

?

- They are typically not expected to produce bright EM signal, but some scenarios predicting EM counterparts have recently been proposed (see, e.g., 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 (prompt duration $> 2$ s)

## Isolated neutron stars

- soft $\gamma$-ray repeaters
- radio/X-ray pulsar glitches

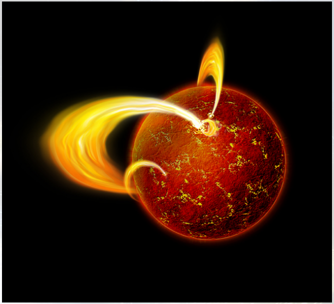


Image Credit: NASA, CXC, M. Weiss

# 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**

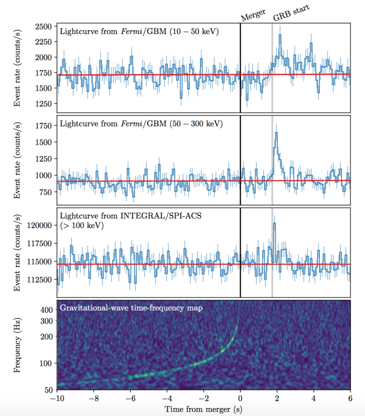
- *precise (arcsec) sky localization*
- *host galaxy*
- *redshift*
- *emission processes*
- *acceleration mechanisms*

# 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

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



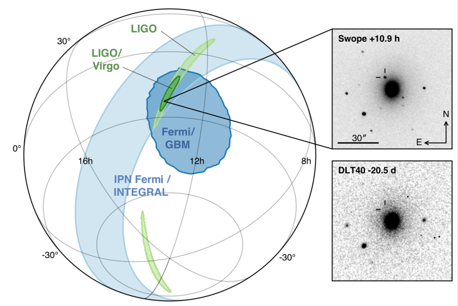

LVC 2017, PRL, 119, 161101, LVC 2017, ApJ, 848, 13, Goldstein et al. 2017, ApJL, 848, 14, Savchenko et al. 2017, ApJL, 848, 15

# 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

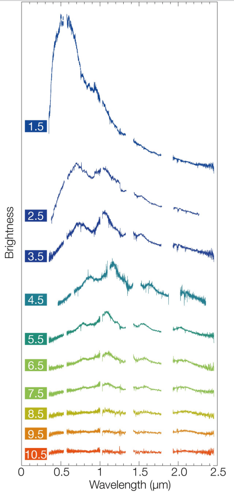
- An associated **optical transient** (SSS17a/AT 2017gfo) has been discovered on August 18, 2017;
- the transient is located at $\sim$ 10" from the center of the galaxy NGC 4993, at a distance of 40 Mpc, consistent with the luminosity distance of the GW signal.

**⇒ First identification of the host galaxy of a GW event!**




LVC 2017, ApJ Letters, 848, 12

# 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

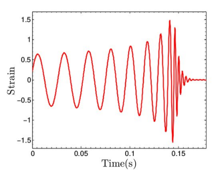
**First spectroscopic identification of a kilonova and evidence that NS-NS mergers can produce heavy r-process elements!**

Pian, D'Avanzo, ..., Patricelli et al. 2017,
Smartt et al 2017

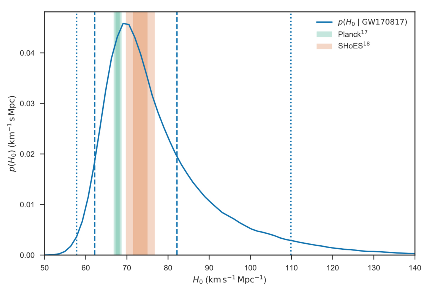
# GW-NGC4993 association: implications for Cosmology

GW170817 as a standard siren: **the Hubble constant**

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




$v = H_0 \cdot D \Rightarrow H_0 = 70^{+12}_{-8}$ km/s/Mpc



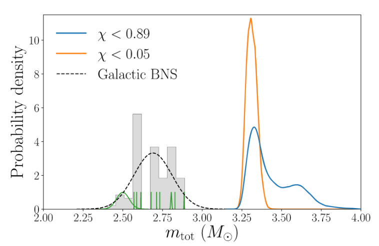

LVC 2017, Nature, 551, 85

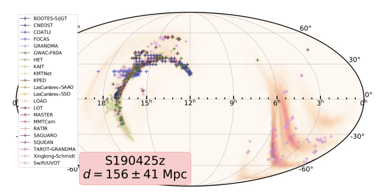
More recent estimates, obtained assuming a priori that the GW source is in NGC 4993, are:

- $H_0 = 70^{+13}_{-7}$ 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

# S250818k: a possible NS-NS merger

- Low-significant GW candidate with $p_{\mathrm{BNS}} = 29\%$
- Luminosity Distance ($D_{\mathrm{L}}$): $237 \pm 62$ Mpc
- H, L and V online
- Possible EM counterpart observed by the Zwicky Transient Facility

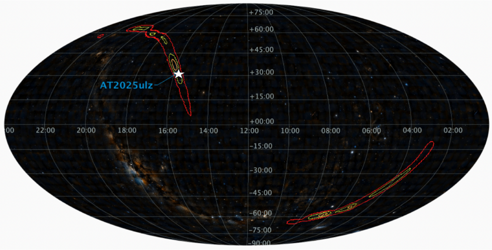
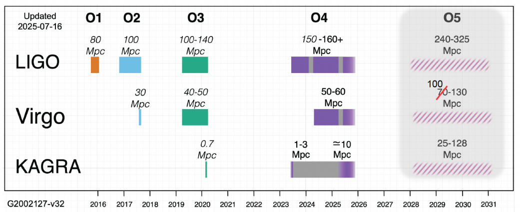



Image Credit: G. Greco

Initial data consistent with a kilonova! But later EM observations suggest AT2025ulz is a type II supernova (see, e.g., GCN 41532) unrelated to the GW event

# Observing plans




https://observing.docs.ligo.org/plan/

- O4 will end on November 18, 2025
- A fifth observing run (O5) is planned to start in a few years

In the future 2nd generation GW detectors will operate with increased sensitivity, in synergy with current and future EM facilities (e.g. CTAO, Vera Rubin Observatory etc)

# The Vera Rubin Observatory

- A key instrument for discovering EM counterparts to GW transient events
- Most promising class of sources for joint GW+EM searches: kilonovae
- Currently under commissioning phase, during which ToO* observations to follow-up GWs may be possible

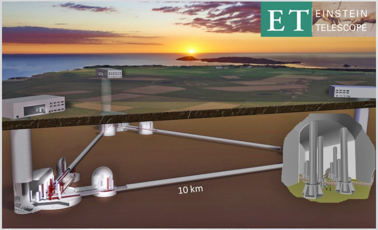
Image Credit: Rubin Obs./NSF/AURA

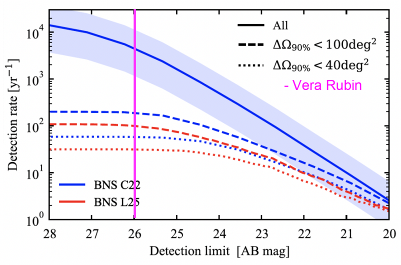
Proposal for a "Memorandum of Understanding" between LVK and Vera Rubin currently under review ⇒ **This will allow us to maximize the chance of future multimessenger discoveries and their scientific return!**

* Target of Opportunity

# Prospects with 3$^{rd}$ generation GW detectors

In the next decade, 3$^{rd}$ generation GW detectors such as the Einstein Telescope (ET, see Franco Frasconi's talk) will become operative



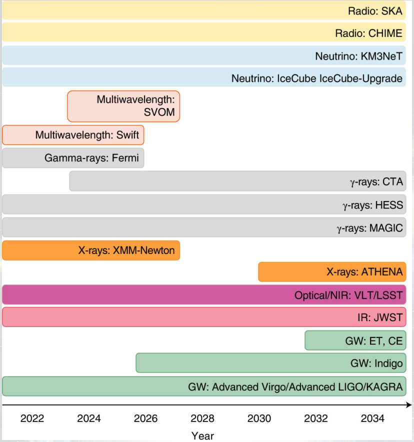




With ET:

- $\sim 10^5$ NS-NS/year, up to z$\sim$ 2-3
- For events with $\Delta\Omega_{90}\% < 100$ deg$^2$, the joint KN+GW detection rate is
  - $\sim$ 200 yr$^{-1}$ for KN model C22
  - $\sim$ 100 yr$^{-1}$ for KN model L25

Abac et al. 2025, arXiv:2503.12263

# Multimessenger facilities in the next years




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

**Many other GW and multi-messenger discoveries are expected in the near future...**

**stay tuned!**

# Backup slides

## Kilonovae

**NS-NS and NS-BH mergers**: → Kilonova

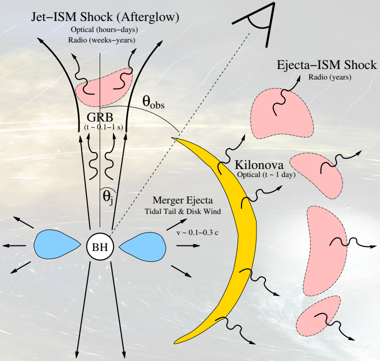



Image credit: Metzger & Berger 2012

- *Significant mass (0.01-0.1 $M_\odot$) is ejected during NS-NS NS-BH mergers at sub-relativistic velocity*
- *The neutron-rich ejecta undergoes rapid neutron capture (r-process) nucleosynthesis*
- *The radioactive decay of unstable nuclei powers a rapidly evolving, supernova-like transient: the* **"kilonova"**.

*r-process*: neutron capture much faster than beta decay; this requires special conditions:

T $> 10^9$ K, high neutron density $10^{22}$ cm$^{-3}$

# Associated multi-wavelength EM emission

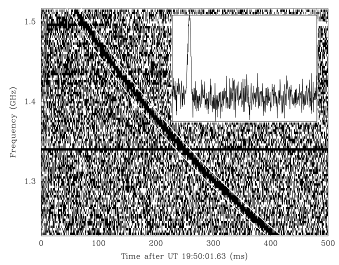
**BBH mergers**

**?**

- 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)

# Fast Radio Bursts (FRBs)

- Bright short duration (micro-milliseconds) radio pulses
- Isotropic energy $\sim 10^{38}$ - $10^{41}$ erg
- Distances $\sim$ 0.1 - 3 Gpc
- Some FRBs have been seen to repeat
- Physical origin still unknown; many theoretical models (see frbtheorycat), e.g.:



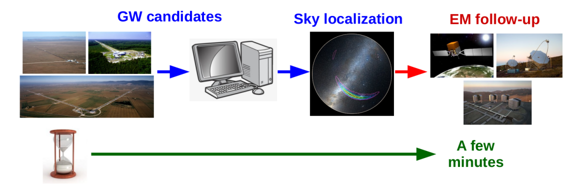

Lorimer et al. 2007

- FRB emission associated with magnetar flares $\rightarrow$ NS crust cracking $\Rightarrow$ GW emission is expected
- FRB emission associated with the collapse of a supramassive NS, that can be the outcome of NS-NS mergers $\Rightarrow$ merger and post-merger GW signals are expected

# Joint GW and EM/neutrino detections

Possible scenarios:

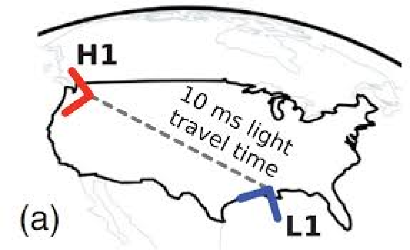
- **EM follow-up:** low-latency GW data analysis pipelines promptly identify GW candidates and send GW alerts to trigger prompt EM observations and start archival searches

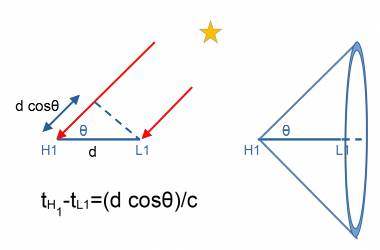



- **Externally-triggered GW searches:** an EM transient event is detected and GW data are analyzed to look for possible associated GW events.

# How can we localize GW signals?

Localization estimates can be obtained through "triangulation", based on timing information at the detector sites



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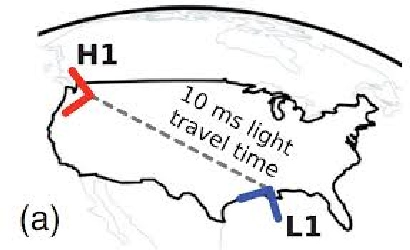
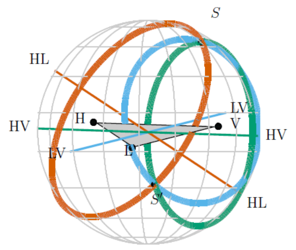
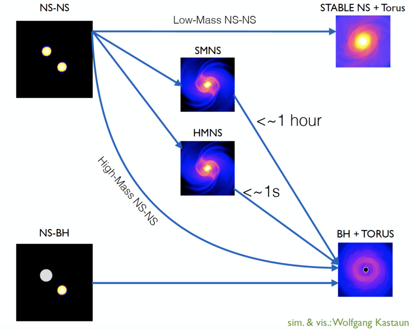


# The compact remnant

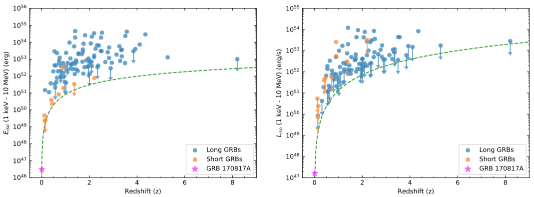
The outcome of a NS-NS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state (EOS) of nuclear matter.




- **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)

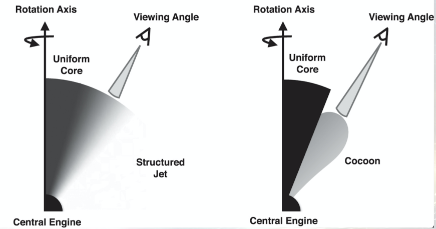
Searches for post-merger GW signals associated with GW170817 have not found any significant signal candidate (Abbott et al. 2017, 2019)

# 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

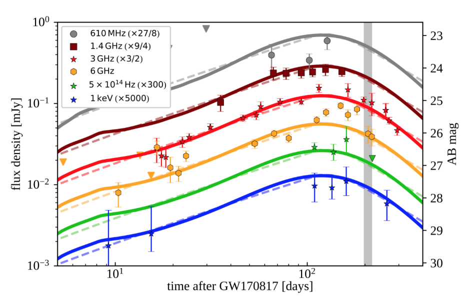
# X-ray and radio observations

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
- — GRB afterglow emission from a structured jet

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

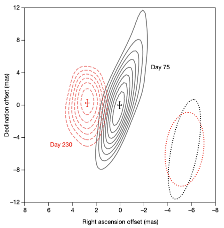



Ghirlanda et al. 2019

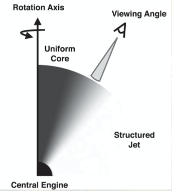
# Radio observations

... 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 $2.67 \pm 0.3$ milliarcseconds in 155 days

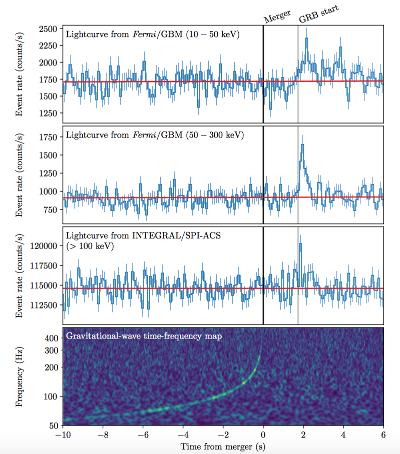



- This excludes the isotropic outflow scenario and favor **the structured jet model**: a successful jet with a structured angular velocity and energy profile, featuring a narrow core (with $\theta_j < 5$ deg) seen from a viewing angle $\theta_{\rm view} \leq 20$ deg.



# 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**

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

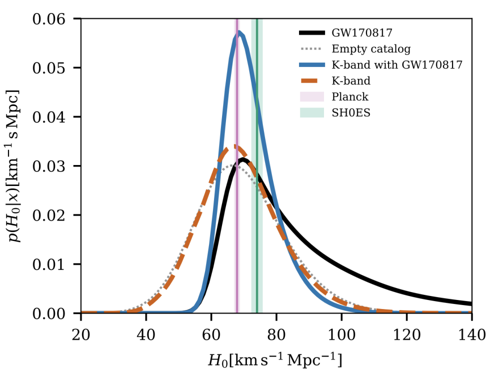
$$\frac{\Delta\nu}{\nu_{\rm EM}} \sim \frac{\nu_{\rm EM}\Delta t}{D}$$

- 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

# Hubble constant estimate with GWTC-3

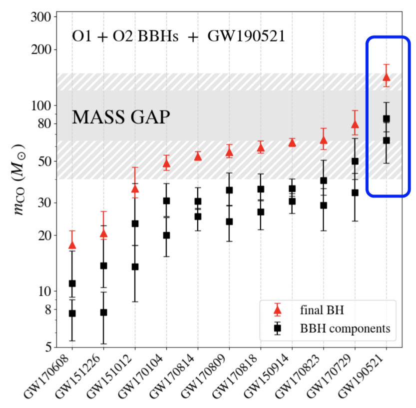



BBHs + galaxy catalogs + GW170817: $\mathrm{H_0} = 68^{+8}_{-6}$ km s$^{-1}$ Mpc$^{-1}$

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

LVK Coll. 2023, ApJ, 949, 76

# 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

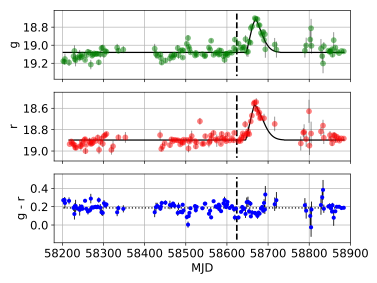
Abbott et al. 2020, PRL, 125, 101102

Abbott et al. 2020, ApJL, 900, 13

# GW190521

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)

# Externally-triggered GW searches: advantages

If an EM event has already been detected, then GW searches:

- know **when** to look at the GW data
- know **where** in the sky to look
- may know **what kind** of GW signal to search for
- may know the **distance** to the source

As a consequence:

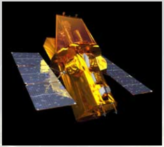
- Search sensitivity increases $\Rightarrow$ **weaker** GW signals can be confidently detected
- The **extra information** from the combined observations will reveal more about the astrophysics of the source
- Even in case of **non-detection** of a GW signal, we can still get interesting information, e.g. an upper limit on energy emitted in GWs

# Externally-triggered GW searches

Examples of **targets** used for externally-triggered GW searches

- Gamma-Ray Bursts
- Fast Radio Bursts
- Magnetar flares
- High energy neutrinos
- Supernovae

Swift



Palomar

IceCube

CHIME

# Externally triggered GW searches: GRBs

GRB prompt emission detection $\Rightarrow$ GW triggered search

Known GRB time and sky position:

- reduction in the search parameter space
- gain in sensitivity search

Two kind of searches:

**Short/Ambiguous GRBs**

- Modeled binary merger search (PyGRB)
- 'On-source' search window: $[-5, +1]$ s from the GRB trigger time

**All GRBs**

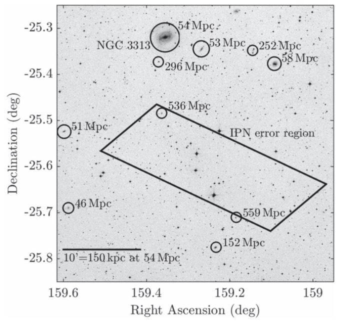
- Unmodeled generic GW transient search (X-pipeline)
- 'On-source' search window: $[-600, +\max(60, \mathrm{T90}))$ s from the GRB trigger time

No evidence for GW counterparts other than GW170817 in the first three observing runs. $\rightarrow$ **Non GW-detection result: lower bound on the progenitor distance**

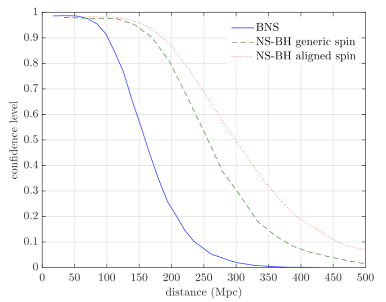
Abbott et al. 2017, ApJ 841 89 (O1), Abbott et al. 2019, ApJ, 886, 75 (O2), Abbott et al 2021 ApJ 915 86 (O3a),Abbott et al. 2022, ApJ, 928, 186 (O3b)

# Externally triggered GW searches: the case of GRB 150906B

- Short duration/hard spectrum GRB close to the galaxy NGC 3313 (D=54 Mpc)




- No evidence for NS-NS or NS-BH GW signals up to 102/170/186 Mpc




Abbott et al. 2017, ApJ, 841, 89

# FRBs and the Galactic magnetar SGR 1935+2154

- In April 2020, an FRB (FRB 20200428A) was detected from the Galactic magnetar SGR 1935+2154
- The event was notable for the simultaneous emission of both radio and X-ray bursts

  ⇒ First burst with a radio counterpart observed from a SGR!
- Other radio burst episodes observed later ⇒ FRB 20200428A is a repeater FRB

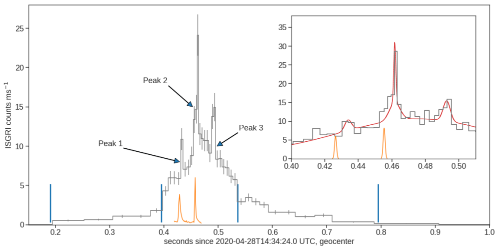


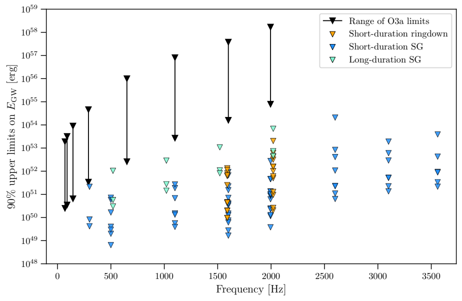

Image credit: Mereghetti et al. 2020

**First direct evidence supporting the theory that magnetars can produce FRBs!**

# Search for GW emission from the FRB+SGR 1935+2154

FRBs from SGR 1935+2154 were detected after the end of the third observing run of LIGO, Virgo, and KAGRA

- GEO600 detector was operating, although with a very low sensitivity
- Four periods of GW data from GEO600 coincident with four periods of FRB activity were analysed
- No significant GW emission from any of the events
- 90% upper limits on the emitted GW energy from SGR 1935+2154 coincident with FRBs

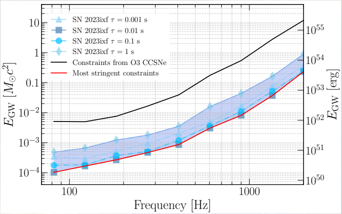


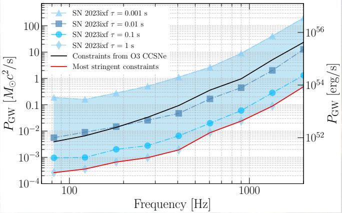

LVK collaboration 2024, ApJ, 977, 255

# SN 2023ixf

SN 2023ixf: supernova osservata nella galassia M101 (6.7 Mpc) il 19 Maggio 2023

- 15° Run Ingegneristico di LVK (ER15)
- Ricerca di un possibile segnale gravitazionale associato
- Nessun candidato significativo ⇒ Vincoli su:
  - energia e luminosità associate alle onde gravitazionali
  - ellitticità della proto-stella di neutroni formatasi dopo la supernova
- **Vincoli più stringenti rispetto a quelli ottenuti precedentemente!**

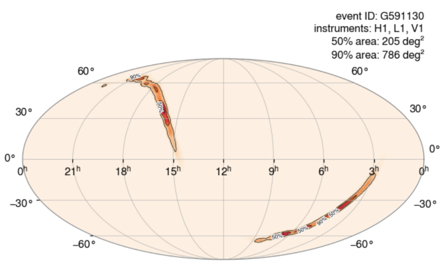



LVK Coll. 2025, accettato per la pubblicazione in ApJ (arXiv:2410.16565)

# S250818k

- $p_{\mathrm{BNS}} = 29\%$; $p_{\mathrm{terr}}=71\ \%$
- Luminosity Distance ($D_{\mathrm{L}}$): $259 \pm 74$ Mpc*
- H, L and V online
- GraceDB, GCN Notices
- Only automated data quality checks for low-significant events, but ...
- ... Possible EM counterpart observed by the Zwicky Transient Facility (ZTF)




Bayestar skymap

* Preliminary notice's value

# S250818k

ZTF observed $\sim$ 25 % of the GW skymap

- Transient source ZTF25abjmnps/AT2025ulz compatible with the GW sky localization (GCN 41414)
- Further observations with Keck (GCN 41436):
  - z=0.0848, consistent with the GW distance;
  - data consistent with a kilonova

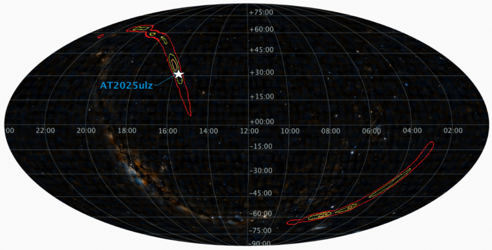



Image Credit: G. Greco

# S250818k

- Given the **special science case**, LVK released an Initial GCN Circular: GCN 41437
  - No evidence for glitches or data quality issues
  - Source chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$: highest probability in the bin (0.1, 0.87) $M_\odot$
- Update GCN Circular: GCN 41440
  - Updated 3D GW skymap; $D_L = 237 \pm 62$ Mpc
  - AT2025ulz position still consistent

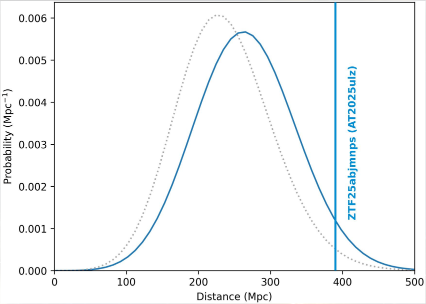



Image Credit: G. Greco

Later EM observations suggest AT2025ulz is a type II supernova (see, e.g., GCN 41532) unrelated to the GW event; other scenarios have also been proposed (see GCN 41541)

# 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 $\Rightarrow$ 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!**