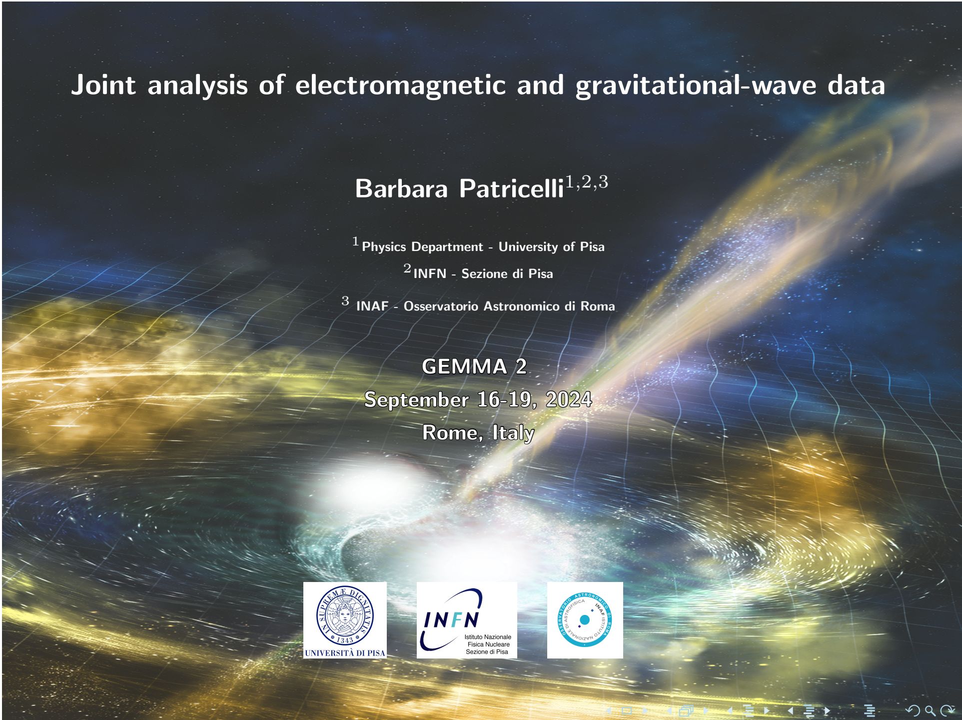


Joint analysis of electromagnetic and gravitational-wave data

Barbara Patricelli[1,2,3]

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

GEMMA 2
September 16-19, 2024
Rome, Italy

GW and multimessenger astronomy: where do we stand?

- Three LIGO-Virgo-KAGRA (LVK) observing runs (O1, O2, O3) have been completed;
- a fourth observing run (O4) is currently ongoing

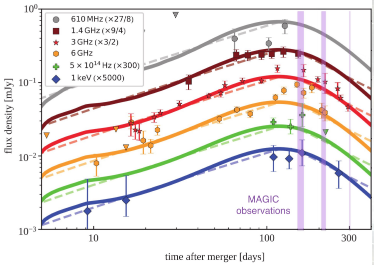
O1+O2+O3: 90 candidates, all consistent with compact binary mergers

- GW170817: the first multimessenger observation of a BNS merger (see Giancarlo's talk)
  - Does GRB 170817A have Very High Energy (VHE, E $>$ 100 GeV) emission?
  - Which is the GW170817 remnant/ the central engine of GRB 170817A?
- Other sources potentially interesting for multimessenger have also been observed

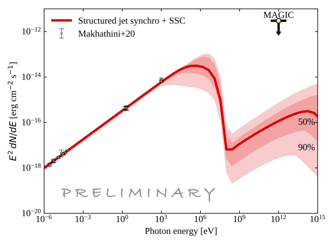
GW170817: VHE EM follow-up

GW170817: EM counterparts in many wavelenghts; **what about VHE?**

- In the last few years VHE emission has been observed in association with several GRBs
  ⇒ at least a fraction of GRBs has VHE emission
- H.E.S.S. performed prompt and long term EM follow-up; no significant VHE emission has been found (Abdalla et al. 2017, ApJL, 850, 22; Abdalla et al 2020 ApJL 894 L16)
- MAGIC follow-up observations were performed in 10 different nights from January to June 2018; no significant VHE emission has been found (Stamerra, Salafia, Patricelli et al. 2022, PoS(ICRC2021)944)

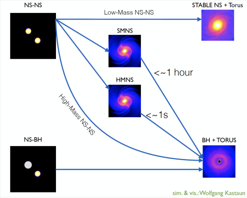


Adapted from Ghirlanda, Salafia, et al. 2019, Science, 363, 968



Which is the remnant of the BNS merger/the GRB central engine?

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



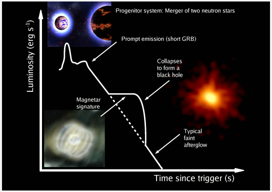
sim. & vis.: Wolfgang Kastaun

- **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)

◆ **Magnetars are competing with BHs as GRB central engine**; the magnetar scenario is supported by several observations of GRB emission, in particular of their X-ray emission (Dai & Lu 1998, Zhang & Meszaros 2001, Metzger et al. 2011)

- **late X-ray emission** (plateau), observed in $\sim 50\%$ of cases (see, e.g., Corsi & Meszaros 2006; see, however, Oganesyan et al. 2020)
- **extended emission**, observed in $\sim 15\%$ of cases (see, e.g., Metzger et al. 2008, Siegel & Ciolfi 2016a,b)

Image credit: Antonia Rowlinson/University of Leicester/NASA/Swift



Which is the remnant of the BNS merger/the GRB central engine?

Lessons learned from GW170817/GRB170817 A:

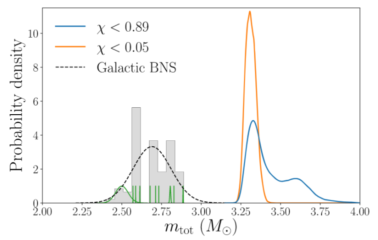
- Direct link between the short GRB central engine and the outcome of BNS mergers
- Rate of magnetars produced in BNS mergers (stable NS and SMNS) is high enough to power all the short GRBs for most EOSs; scenarios with only BHs as central engine seem to be disfavoured (Patricelli & Bernardini 2020; see also Piro et al. 2017)
- Searches for post-merger GW signals associated with GW170817 have not found any significant signal candidate (LVC 2017, ApJL, 851, L16; LVC 2019, ApJ 875 160)
- Thermal EM emission: kilonova properties suggests that the remnant was a HMNS (e.g. Shibata et al. 2017, Granot et al. 2017, Metzger et al. 2018, Gill et al. 2019, Ciolfi et al. 2020)
- Non thermal EM emission: is the X-ray emission flattening/rising?

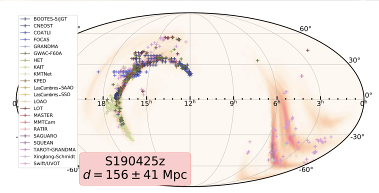
  ⇒ Kilonova afterglow? Long lived magnetar? see Giancarlo's talk

  (O'Connor et al. 2022; Troja et al. 2022, Balasubramanian et al. 2021, Hajela et al. 2022)

No final proof of the nature of the BNS merger remnant/GRB central engine yet

GW190425: the second BNS merger





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

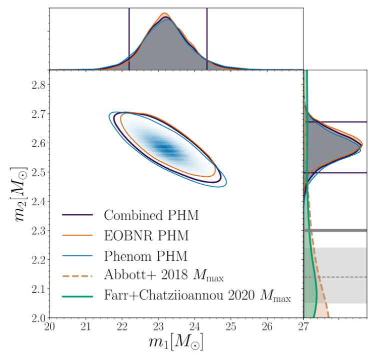
  ... different formation channel?

- 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: a BBH or a NS-BH?



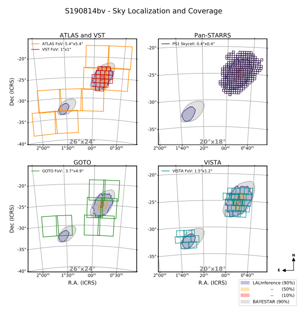
- GW event observed by the two LIGO detectors and Virgo
- m_1: $23.2^{+1.1}_{-1.0}$ $\mathrm{M}_\odot$

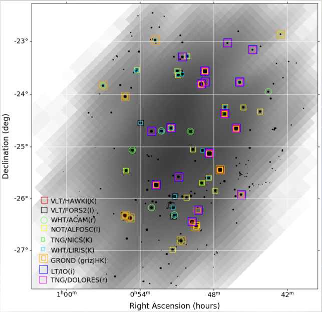
  m_2: $2.59^{+0.08}_{-0.09}$ $\mathrm{M}_\odot$

  BBH or NS-BH merger?
- Does this event have an electromagnetic counterpart?
- 90 % C.R.: 18.5 deg^2; $\mathrm{D_L}$=241^{+41}_{-45} Mpc

LVC 2020, ApJL, 896, 44

GW190814: the EM follow-up





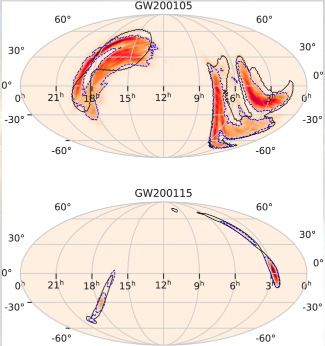
- 27 transients detected during the EM follow-up campaign
- No EM counterpart of the GW event identified

  ⇒ **limits on the properties of the outflows** that could have been produced by the binary during and after the merger

The ENGRAVE Coll. 2020, A&A, 643, 113
(see also Andreoni et al. 2019, Gomez et al. 2019)

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

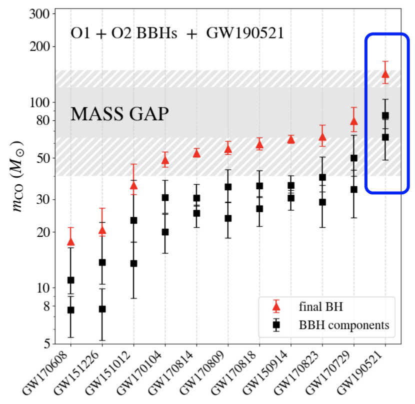


- No EM counterpart has been found...
- ... However, EM emission would have been difficult to detect, given the large distances and large error in the sky localization

LVK Coll. 2021, ApJL, 915, L5

* In the GWTC-3 analysis, GW200105 is found to have p_{astro} <0.5, but it remains a candidate of interest (LVK Coll. 2023, PRX, 13, 041039)

GW190521



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

Challenge for stellar evolution

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

LVC 2020, PRL, 125, 101102

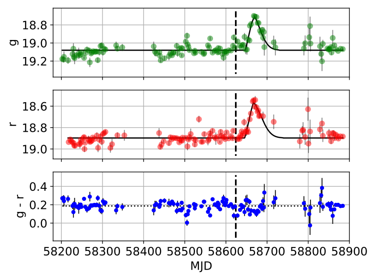
LVC 2020, ApJL, 900, 13

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)

What we learned so far and open questions

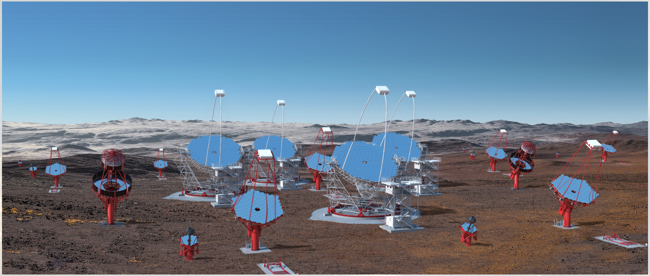
- *First direct evidence that BNS mergers are progenitors of at least a fraction of short GRBs*
- *First evidence for a structured jet for GRBs*
- *First unambiguous observational evidence for a kilonova*
- *No EM counterpart observed in association with NS-BH mergers*
- *Possible EM signal in association with a BBH merger*

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

Next generation instruments will be key to answer to these questions

The Cherenkov Telescope Array Observatory (CTAO)

A ground-based observatory for gamma-ray astronomy at very-high energies



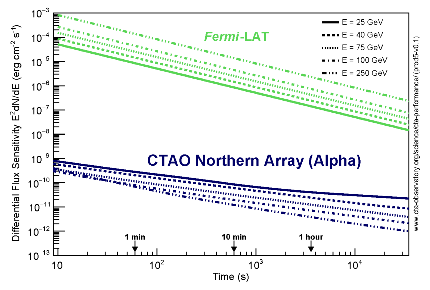
Southern Hemisphere Site Rendering; image credit: Gabriel Pérez Diaz, IAC / Marc-André Besel, CTAO

- Two arrays: one in the Northern hemisphere (La Palma), one in the Southern hemisphere (Chile) ⇒ **full-sky coverage**
- CTAO Alpha Configuration of the array in the North (South):
  - 4 (0) Large Size Telescopes (LSTs); 20 GeV - 150 GeV
  - 9 (14) Medium Size Telescopes (MSTs); 150 GeV - 5 TeV
  - 0 (37) Small Size Telescopes (SSTs); 5 TeV - 300 TeV

⇒ **wide energy coverage**

CTAO: a key instrument for the EM follow-up of GWs

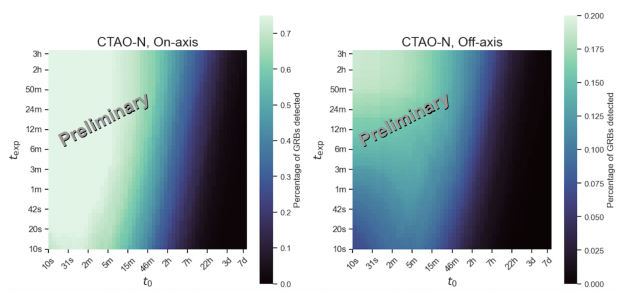
- Coincident observational schedule with 2nd generation GW detectors at their highest sensitivity (O5 LVK run)
- Large field of view (LST: 4.3 deg)
- Survey mode
- **Rapid response ($\leq$ 30 s) of LST**
- **Very high sensitivity**



Several studies have been done to investigate the capability of CTAO to perform the EM follow-up of GWs detected by 2$^{\text{nd}}$ generation GW detectors (Patricelli et al. 2018,2022; Green + Patricelli et al. 2024; Seglar-Arroyo + Patricelli et al. 2019; Bartos et al. 2014,2018,2019)

VHE EM follow-up of GWs: preliminary results (O5)

- We used the GW catalogs of simulated BNS mergers from Petrov et al. 2022, ApJ, 924, 54, that refers to O5
- We simulated the associated VHE GRB emission (structured jet), and investigate the detectability with CTAO



- $t_0 = 30$ s: 80 % (13 %) of on-axis (off-axis) GRBs can be detected with $T_{\rm exp} \sim 5$ mins
- $t_0 = 10$ mins: 69 % (14 %) of on-axis (off-axis) GRBs can be detected with $T_{\rm exp} \sim 10$ mins

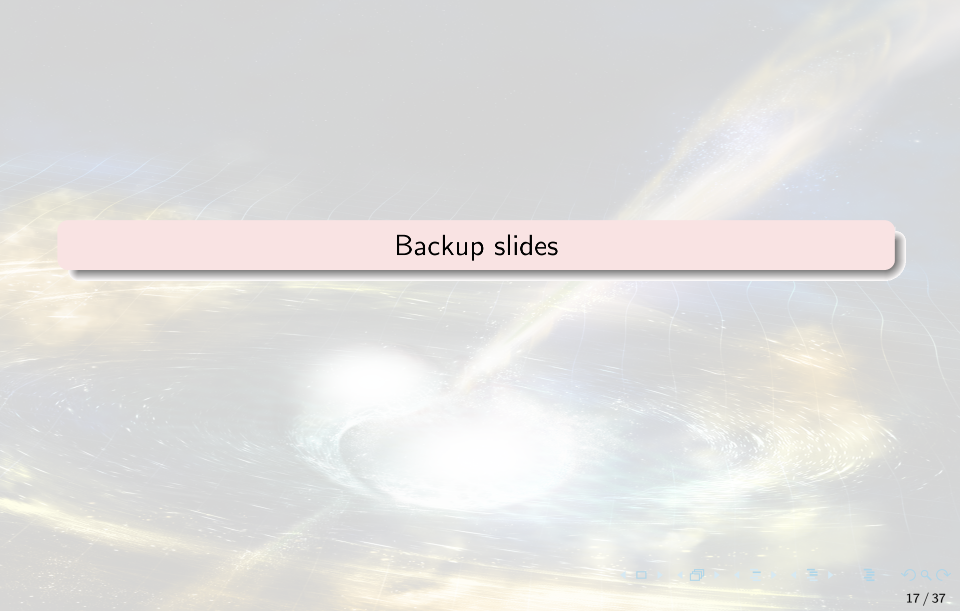
Green, Patricelli et al. 2024, PoS (ICRC2023) 1534;
CTAO Coll., in preparation

Conclusions

- First multi-messenger (GWs+photons) observation of a BNS
- No EM counterpart observed in association with NS-BH mergers
- Observation of an EM signal possibly associated with a BBH merger
- Other multi-messenger sources still to be detected (supernovae, pulsars...)
- New EM facilities will soon become operative, in sinergy with current/future GW detectors

Future multi-messenger observations will be key to probe the rich physics of transient phenomena in the Universe

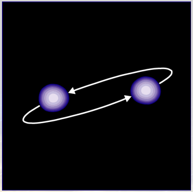
Backup



Backup slides

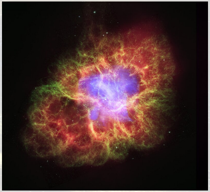
High frequency (10-1000 Hz) GW transient sources

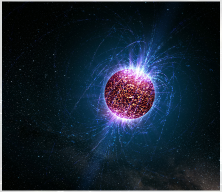
Coalescence of binary systems of NSs and/or BHs



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

Core collapse of massive stars and Isolated neutron stars





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

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

Associated multi-wavelength electromagnetic (EM) emission

NS-NS and NS-BH mergers

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

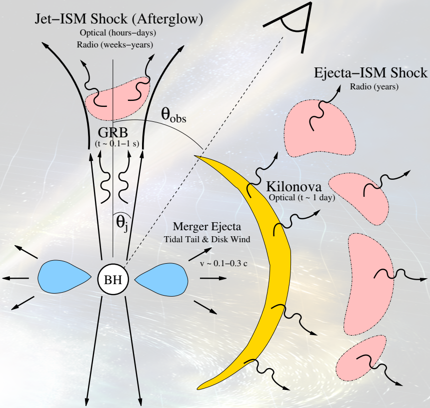


Image credit: Metzger & Berger 2012

Associated multi-wavelength EM emission

BBH mergers

?

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

Associated multi-wavelength EM emission

Core collapse of massive stars

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

Image Credit: Avishay Gal-Yam

- long GRBs

Isolated neutron stars

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

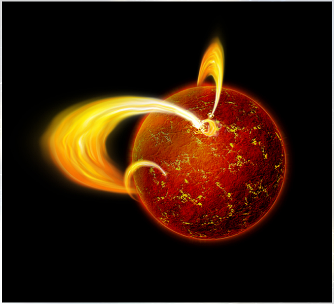


Image Credit: NASA, CXC, M. Weiss

Why multi-messenger astronomy with GWs?

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

GW

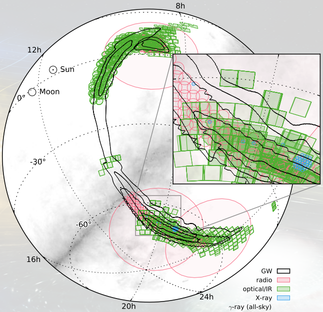
- *mass*
- *spin*
- *system orientation*
- *luminosity distance*
- *compact object binary rate*

EM

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

The EM follow-up of GW150914

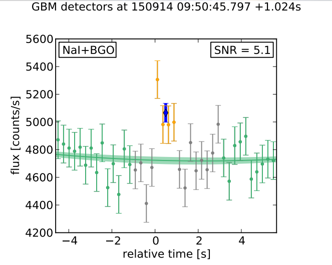
Very intense EM follow-up campaign covering the whole EM spectrum



Several candidate counterparts in optical, all unrelated to GW150914

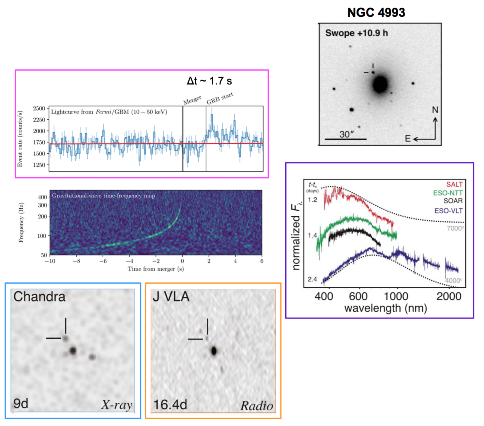
LVC 2016, ApJ Letters, 826, L13

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



...but re-analysis of data shown that the transient is consistent with a background fluctuation (Greiner et al. 2016, Xiong 2016)

GW170817: the beginning of multi-messenger astronomy with GWs



- GW170817: **first observation of a binary neutron star inspiral**
- coincident short GRBs detected in γ rays

  ⇒ first direct evidence that at least some **BNS mergers are progenitors of short GRBs**
- identification of the **host galaxy**: NGC 4993

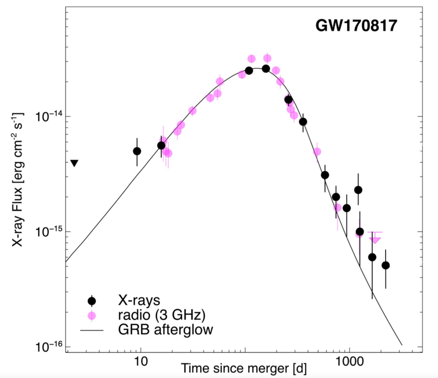
  ⇒ new, independent estimate of the Hubble constant
- an optical/infrared/UV counterpart has been detected

  ⇒ first spectroscopic **identification of a kilonova**
- An X-ray and a radio counterparts have been identified

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

see LVC 2017, ApJ Letters, 848, 2 and refs. therein

The late X-ray emission



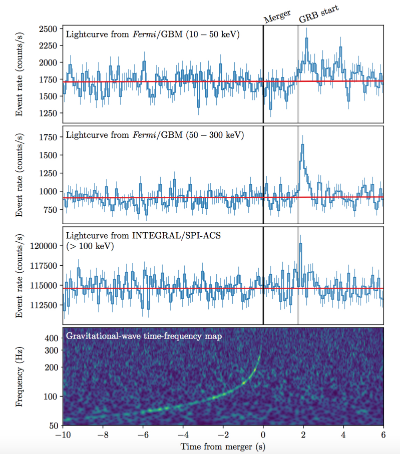
- Latest X-ray and radio emission deviate from early predictions of the jet model with $\theta_{\rm view} \sim 20$ deg
- Is there an additional component taking over the fading GRB afterglow?
    - Long lived magnetar?
    - Kilonova afterglow?

Troja et al. in prep.,
see also O'Connor & Troja 2022; Troja et al. 2022; 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

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

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

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

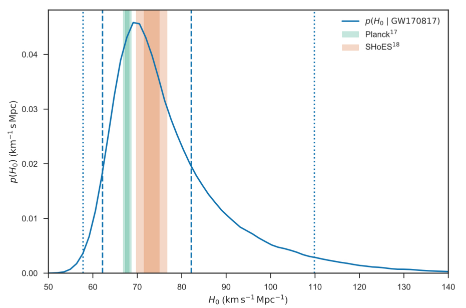
- lower limit on distance: D=26 Mpc
- Time delay: two cases considered
  - the EM and GW signals were emitted simultaneously
  - the EM signal was emitted 10 s later

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

LVC 2017, ApJL, 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**



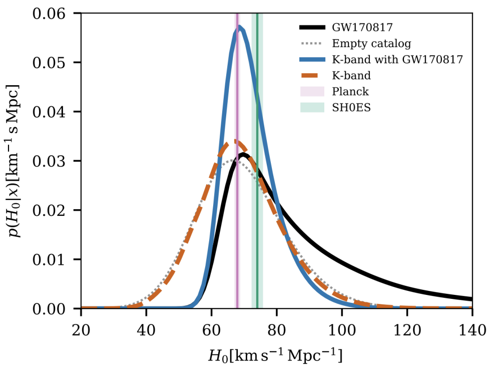
- $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}*
- $H_0 = 67.74^{\pm 0.46}$ km s^{-1} Mpc^{-1}
- $H_0 = 73.24^{\pm 1.74}$ km s^{-1} Mpc^{-1}

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

Hubble constant estimate with GWTC-3



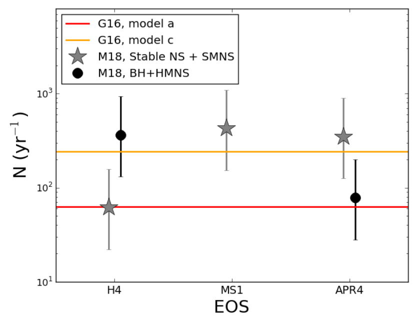
BBHs + galaxy catalogs + GW170817: $\mathrm{H}_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}

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

LVK Coll. 2023, ApJ, 949, 76

Can magnetars power all short GRBs?

- Catalog of BNS mergers by combining BNS merger rate and NS mass distribution inferred from Galactic BNSs
- Predict the number of BNS systems ending as magnetars (stable or SMNS) or BHs (formed promptly or after the collapse of a HMNS) for different EOSs
- Compare these outcomes with the observed rate of short GRBs



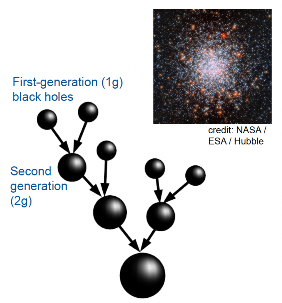
For most EOSs the rate of magnetars produced in BNS mergers is high enough to power all the short GRBs; scenarios with only BHs as possible central engine seem to be disfavoured

Patricelli & Bernardini 2020, MNRAS, 499, L96

(see also Piro et al. 2017, ApJ, 844, L30)

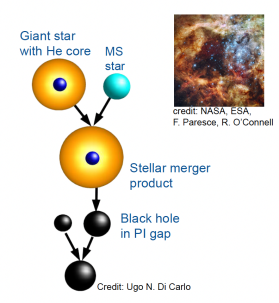
Dynamical scenarios for GW190521

Hierarchical mergers



credit: NASA / ESA / Hubble

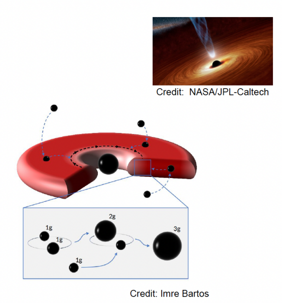
Stellar mergers in young star clusters



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

Credit: Ugo N. Di Carlo

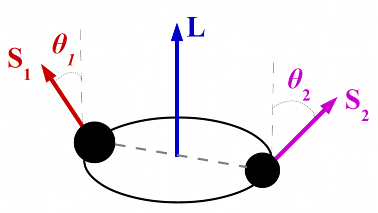
Active Galactic Nucleus (AGN) disks



Credit: NASA/JPL-Caltech

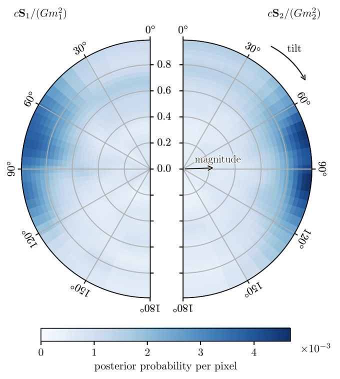
Credit: Imre Bartos

GW190521: the spin



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

θ_i : 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

Do GRBs have VHE emission?

The first observations of GRBs at VHE with IACTs have been reported starting from 2019:

- GRB 190114C, GRB 160821B, GRB 201216C and GRB 201015A (MAGIC - Acciari et al. 2019, 2021; Abe et al. 2024, Blanch et al. 2020)
- GRB 180720B and GRB 190829A (H.E.S.S. - Abdalla et al. 2019, 2021)
- GRB 221009A (LHAASO - Cao et al. 2023; see also Aharonian et al. 2023 for H.E.S.S.)

Several open questions:

- Which conditions are required to produce the VHE GRB emission? How common are they?
- Do BNS and NS-BH mergers have a VHE EM counterparts?
- Is the VHE emission dependent on the progenitor system (binary mergers or core collapsing massive stars)?
- How does the VHE emission depend on the environment of the source?

Why joint GW and VHE gamma-ray observations?

- The search for GRBs at VHE can take great advantage of the GW alerts:

  Current GW detectors are all-sky observatories for low redshift events ⇒ the associated VHE radiation is not expected to be severely attenuated by EBL

- At the same time, the search for EM counterparts to GWs can take advantage of VHE detectors:

  The γ-ray sky is less "crowded" ⇒ clearer association of an EM transient to the GW event

Joint GW and VHE detection could:

- Probe that BNS and NS-BH (and possibly BBH) mergers have VHE EM counterparts
- Allow us to better investigate the dependence of the VHE emission from the progenitor system and its environment

Prospects for multi-messenger detections in O4

The fourth LIGO-Virgo-KAGRA observing run is currently ongoing ...

how many multi-messenger detections do we expect?

Many investigations on this topic, e.g.: Patricelli et al. 2016, 2018, 2022; Howell et al. 2019, Colombo et al. 2022, Perna et al. 2022, Frostig et al. 2022

- 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

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	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	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	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	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

- GW detection rate between 1 and 13 (5 and 61) yr^{-1} for case a (case b)
- Maximum joint GW+EM detection rate with *Fermi*/GBM, structured jet
- *Swift*/BAT and SVOM/ECLAIRs have similar performances: working together they will almost double the possibilities to catch the S-GRB prompt emission

Patricelli et al. 2022, MNRAS, 513, 4159

Prospects for multi-messenger detections in O4

- Depending on the population model considered and on the assumed GW SNR thresholds, the expected number* of BNS merger detections is between 1 and 61 per year

  → Comparison with O4 observations would allow us to put constraints on population synthesis models

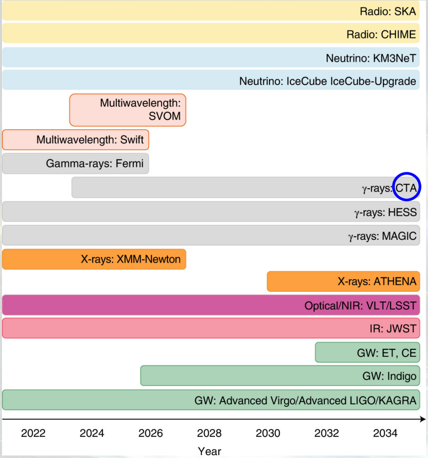
- Expected rate* of multimessenger detections higher when considering Fermi/GBM

  → Fermi/GBM represents a very efficient detector of counterparts to GWs

- New missions such as SVOM could play an important role for the discovery of S-GRB associated with BNS mergers

*NB: rates have been obtained assuming GW detector sensitivities higher than the current ones

Multi-messenger facilities in the next years



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