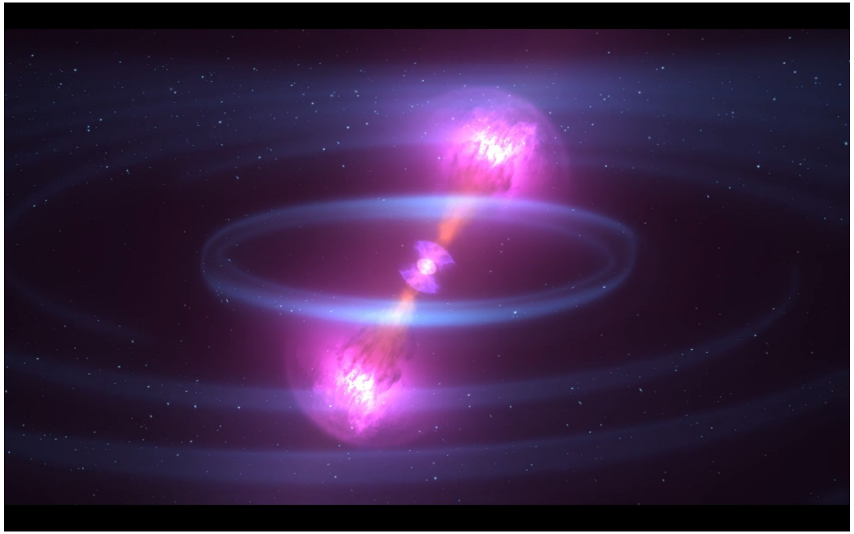
GW170817 : l'avènement de l'astrophysique multimessager



Eric Chassande-Mottin

AstroParticule et Cosmologie (APC)

CNRS Univ Paris Diderot

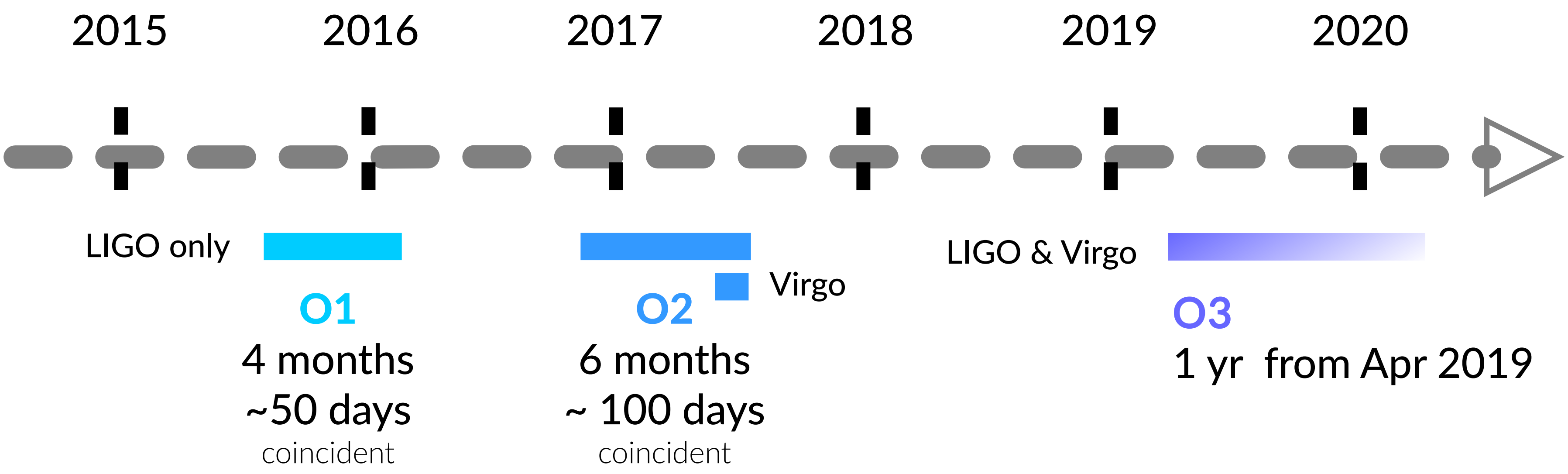
Plan de la présentation

- Un peu de contexte
- Le signal gravitationnel GW170817
- GW170817 et l'astronomie multi-messager
- Implications en physique, en astrophysique et en cosmologie
- Perspectives


LIGO Handford H1


LIGO Livingston L1


Virgo V1


2015
2016
2017
2018
2019
2020
LIGO only
O1
4 months
~50 days
coincident
Virgo
O2
6 months
~ 100 days
coincident
LIGO & Virgo
O3
1 yr from Apr 2019

~3000 km
(10 light-ms)

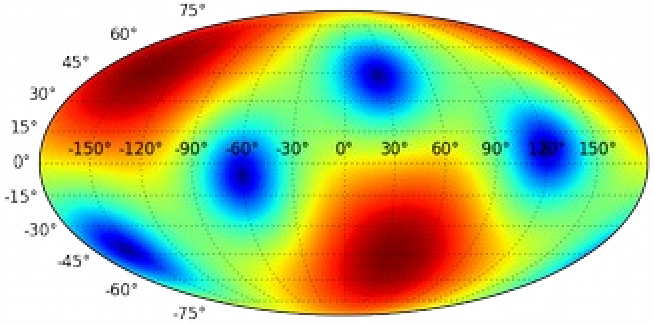
~10000 km
(30 light-ms)

BNS range

H1: 60 Mpc

L1: 80 Mpc

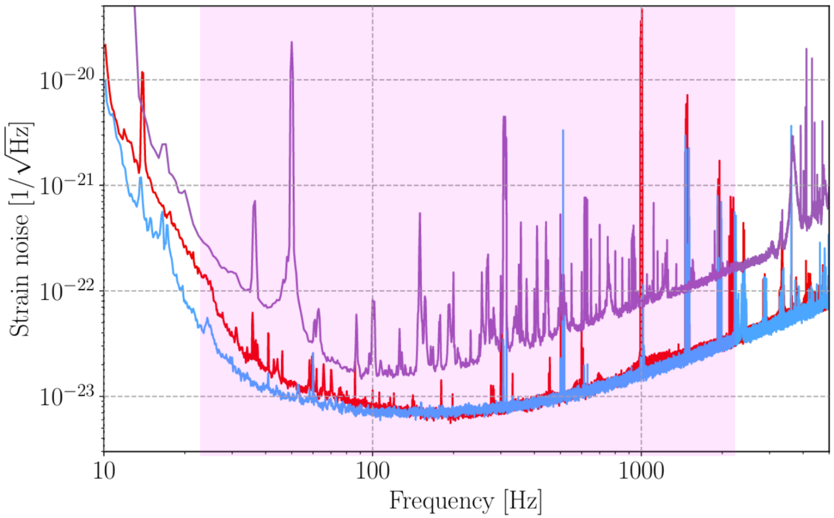
V1: 25 Mpc



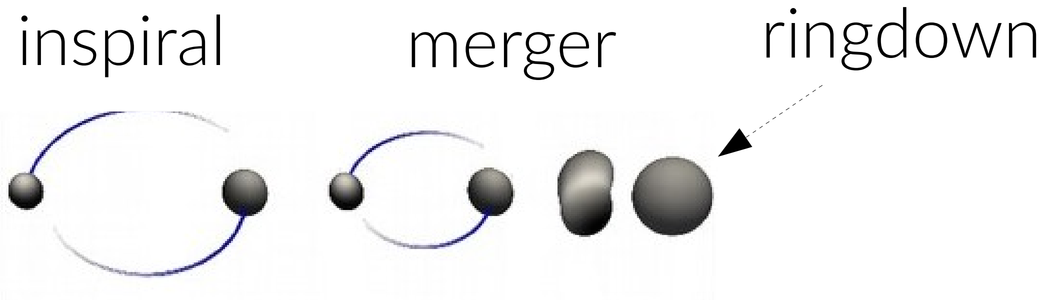
Quasi-omnidirectional

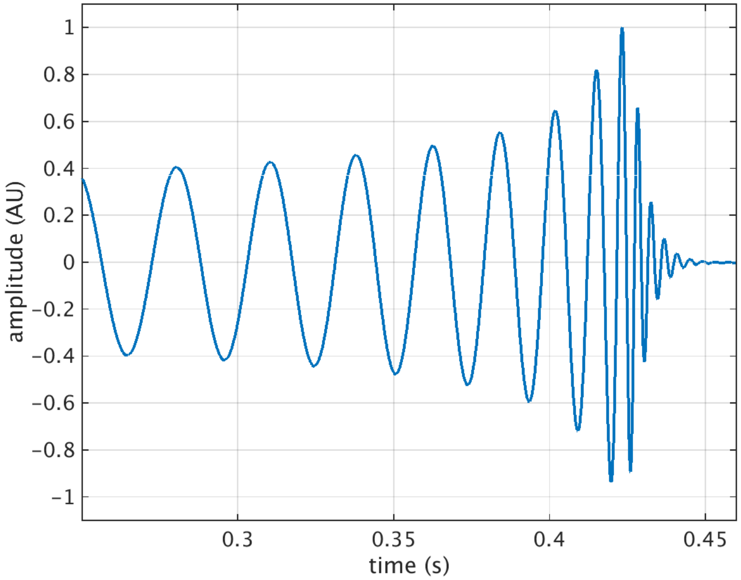
(no pointing)

Sensitivities during O2 (2017)



Compact binary merger





Characteristic waveform signature

The signal is described by **15 parameters**

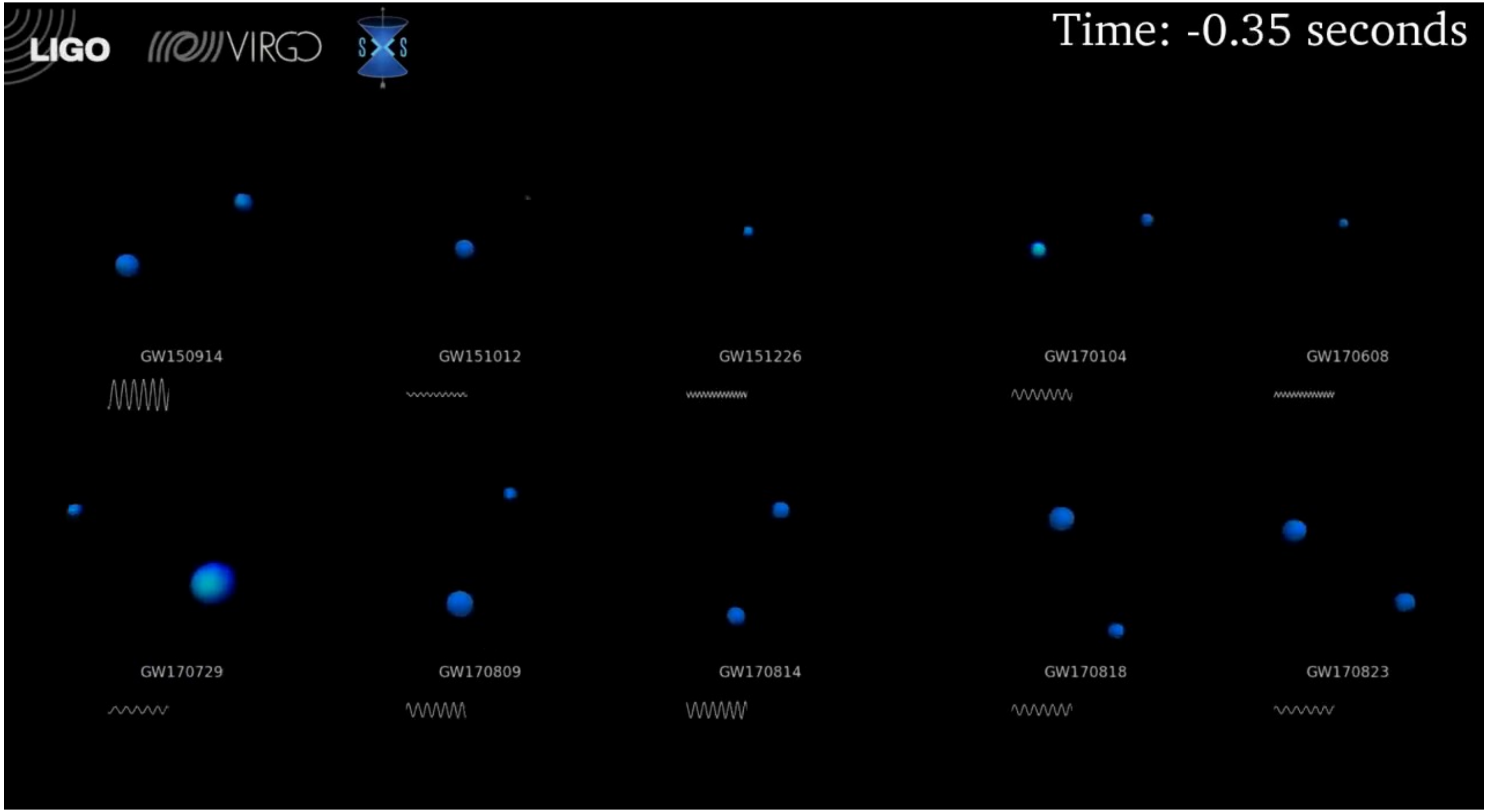
component masses and spins

time and geometry: space location and orientation

Chirp mass $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

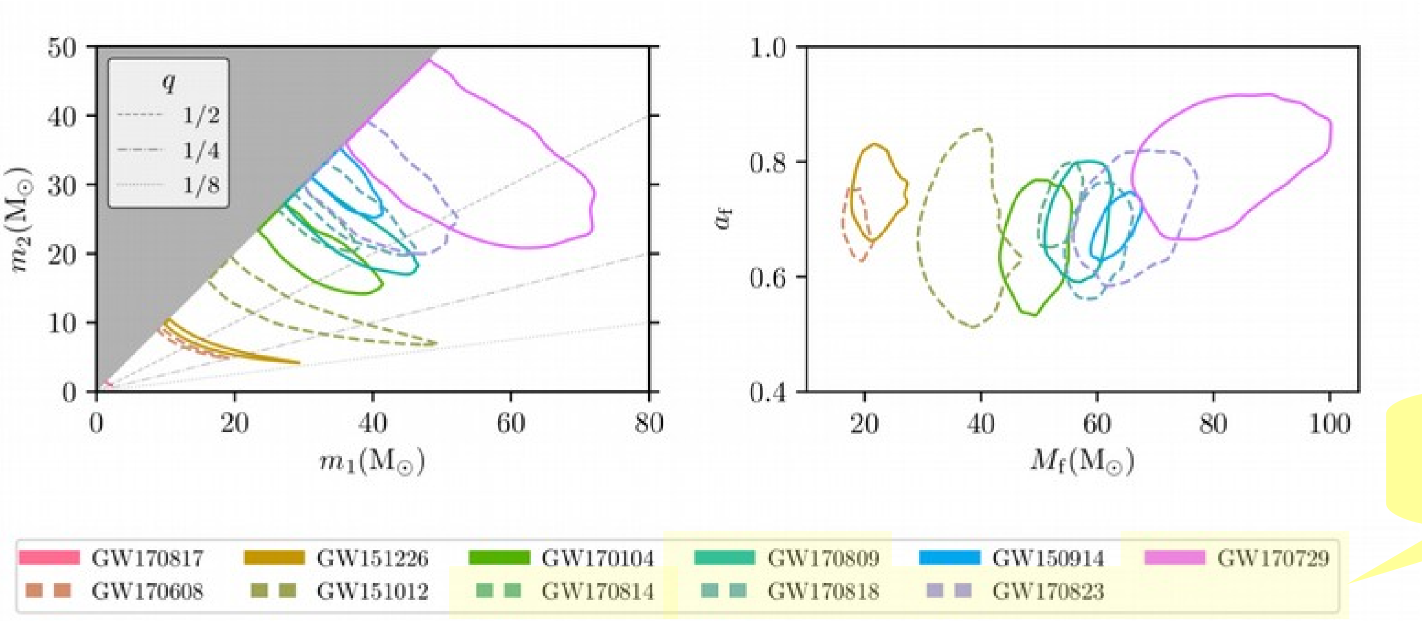
$$\mathcal{M}^{\mathrm{det}} = (1+z)\mathcal{M}$$

In-band duration $\tau \propto \mathcal{M}_{\mathrm{det}}^{-5/3}$


LIGO
VIRGO
SXS
Time: -0.35 seconds
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823

Catalog GWTC#1

Confident detections: 10 binary black hole mergers



include Virgo

population of objects hidden to conventional astronomy

arXiv:1811.12907, https://www.gw-openscience.org/catalogs/

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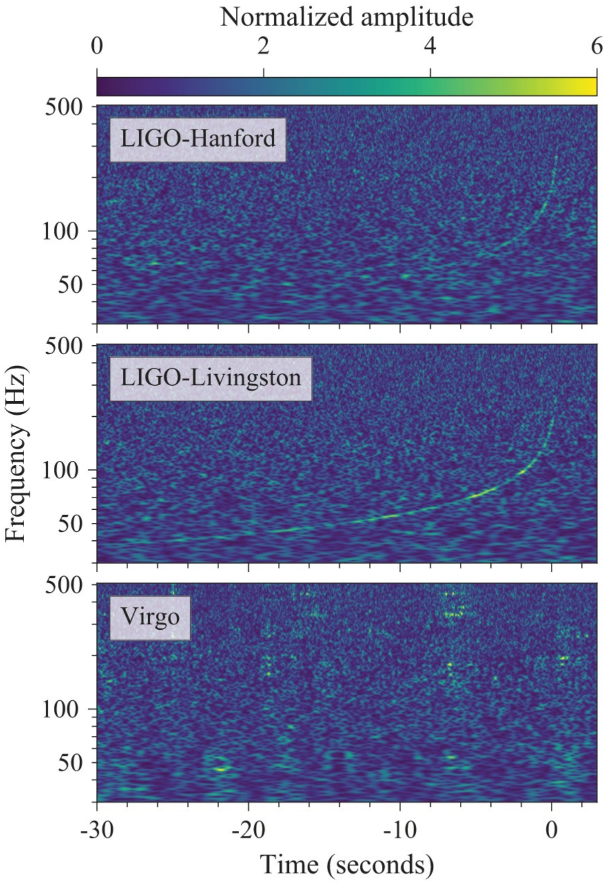
Aug 17, 2017



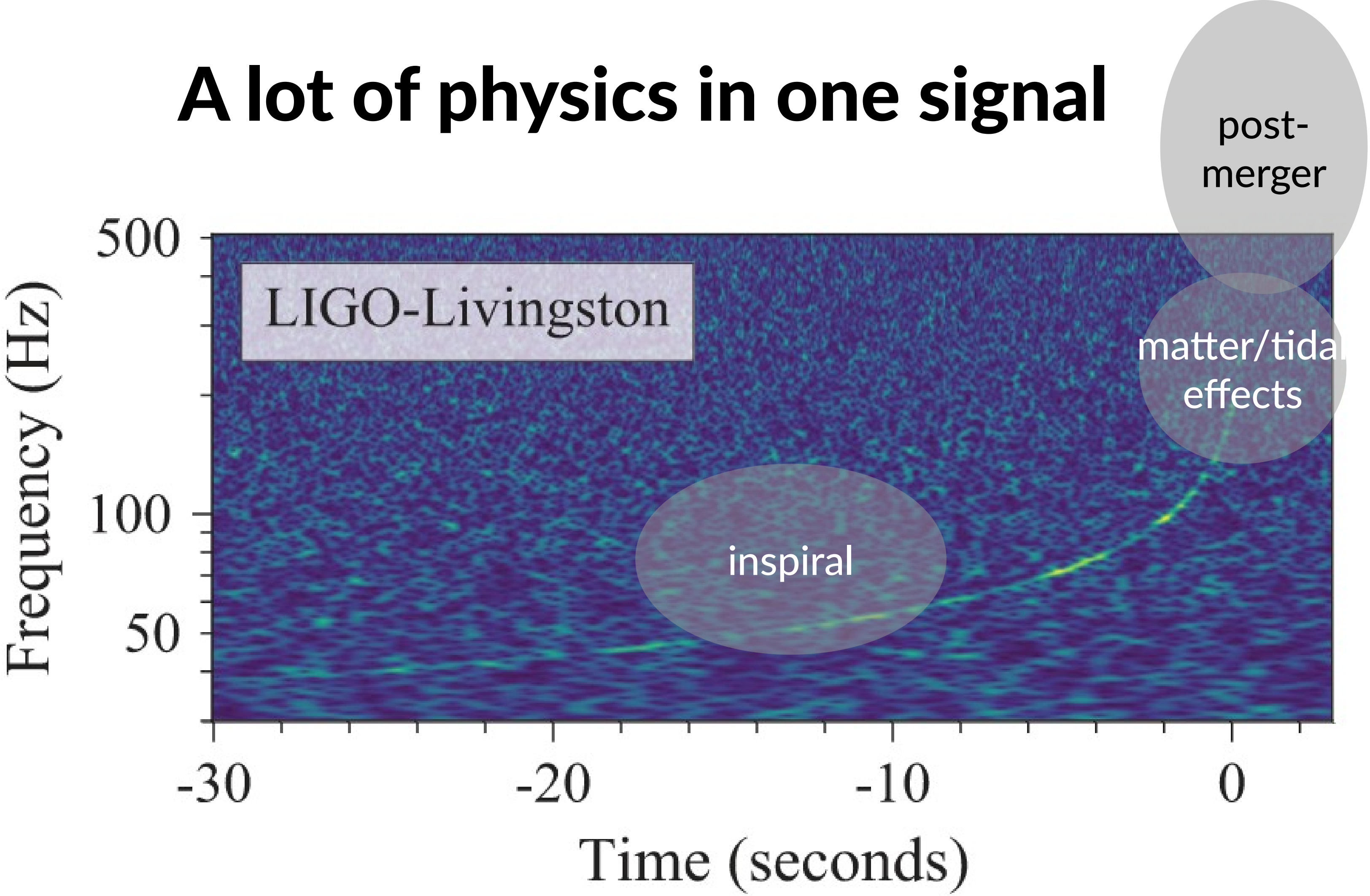
$$\tau \propto \mathcal{M}_{\rm det}^{-5/3}$$ chirp mass

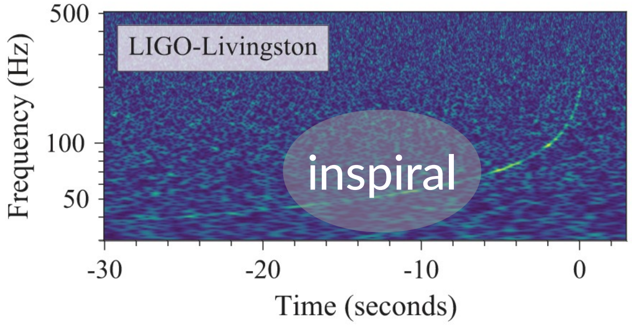
$\tau \lesssim 1\,\mathrm{s}$ for BBH

GW170817 $\tau \sim 100\,\mathrm{s}$

$$\mathcal{M}_{\rm det} \sim 1 M_\odot$$

A lot of physics in one signal



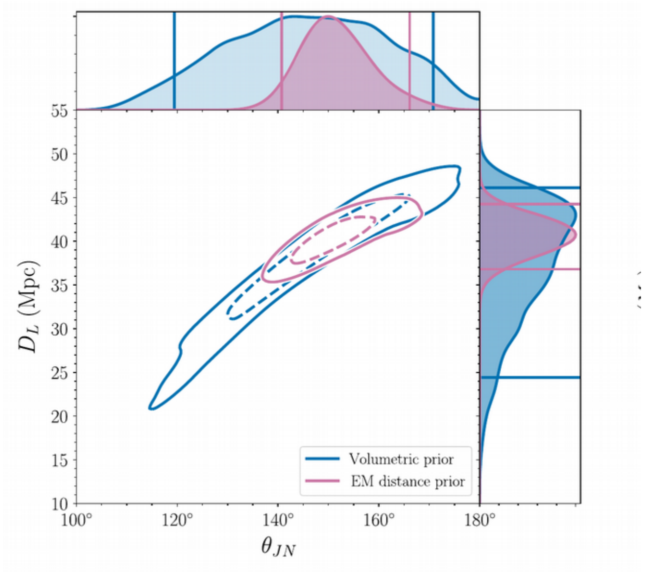


From signal phase, chirp mass estimate

Phase matching: measurement accuracy scales with $1/N_{cycles}$

$N_{cycles} \approx 3000$

detector-frame chirp mass $\mathcal{M}^{\rm det} = 1.1977\,\mathrm{M}_\odot \pm 0.07\%$



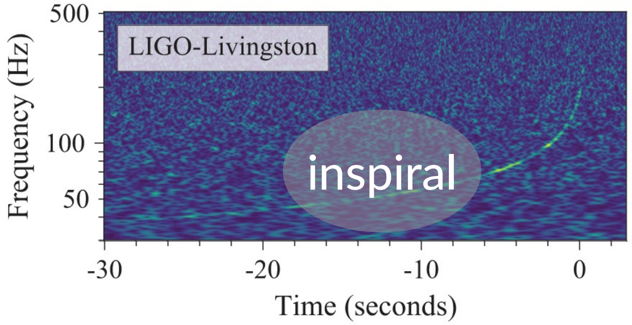
From signal amplitude, distance/inclination (degenerate)

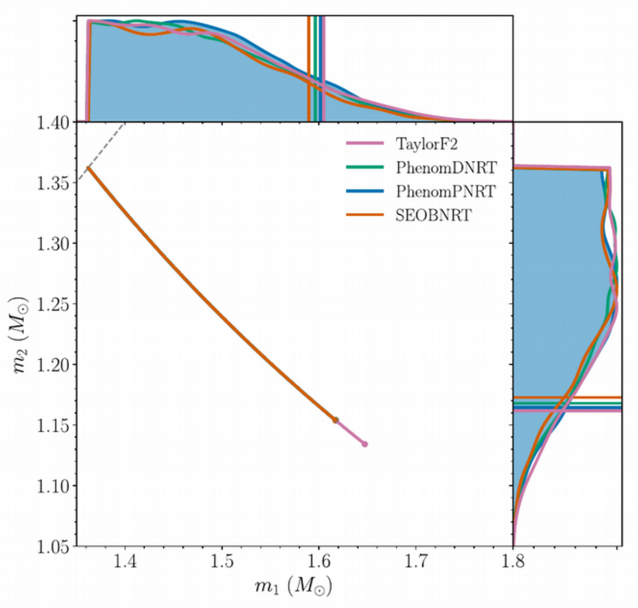
$$h_+ \propto \frac{1+\cos^2\theta_{JN}}{D_L} \qquad D_L = 40\,\mathrm{Mpc} \pm 35\%$$

Can be converted to source frame by assuming a ref. cosmology (Planck)

$$z = 0.008 \pm 37.5\%$$

$$\mathcal{M} = \mathcal{M}^{\rm det}/(1+z) \qquad \mathcal{M} = 1.188\,\mathrm{M}_\odot \pm 0.33\%$$





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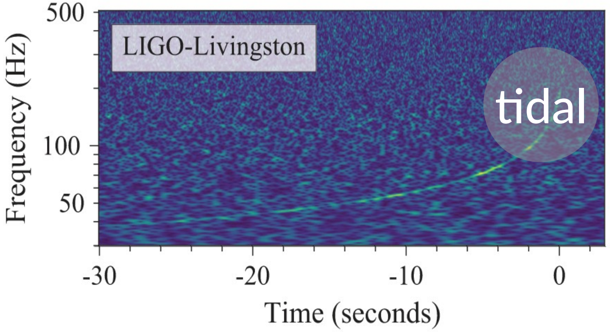
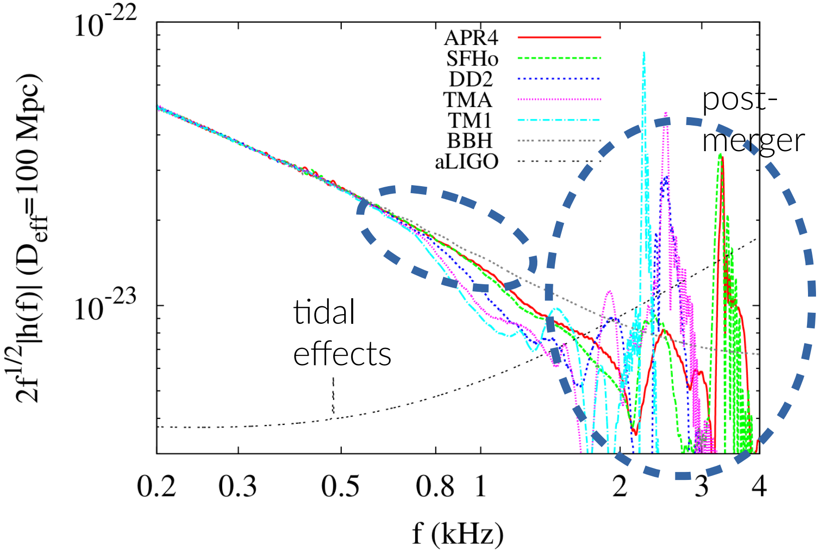
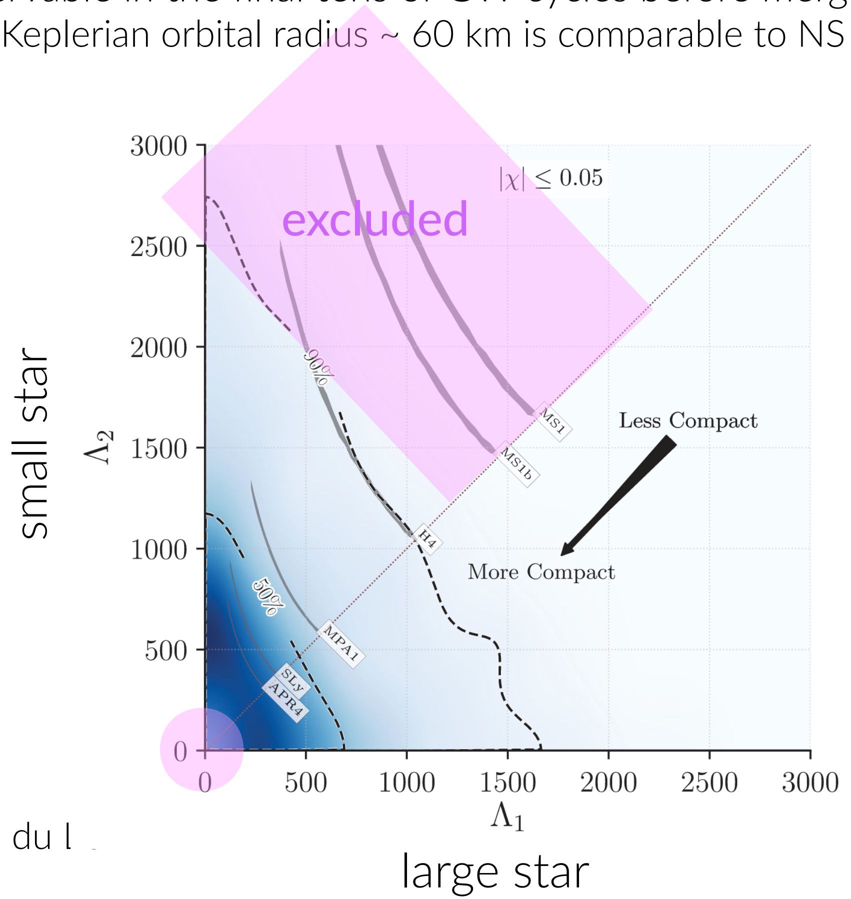


Tidal deformation by the gravity gradient due to companion

Effect observable in the final tens of GW cycles before merger

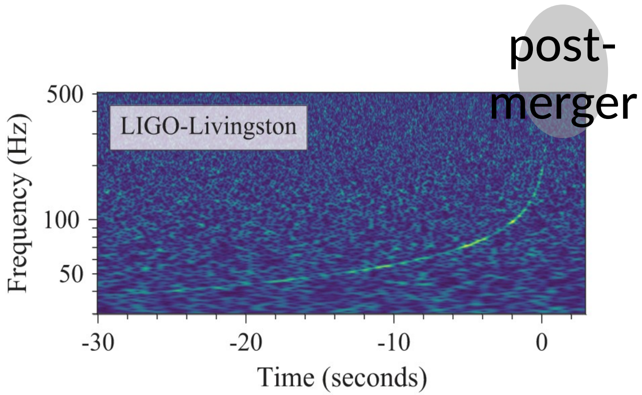
f_{GW} > 400 Hz – Keplerian orbital radius ~ 60 km is comparable to NS radius





Selection of EoS from J. S. Read et al
Phys. Rev. D79, 124032 (2009) and refs therein

Figure from arXiv:1603.01286



What is the remnant?

prompt collapse to a black hole — QNM at 6 kHz

hypermassive NS [preferred] — livetime ~ 1 s f-mode, 2-4 kHz

supramassive NS — livetime ~ $10-10^4$ s

stable NS — magnetar, bar mode or r-mode instability

No evidence for a post-merger signal
Not enough sensitivity at f > 2 kHz to conclude

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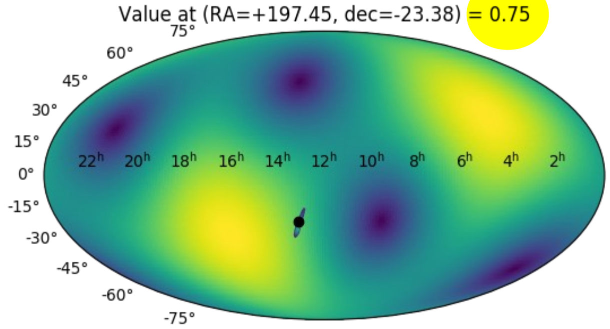
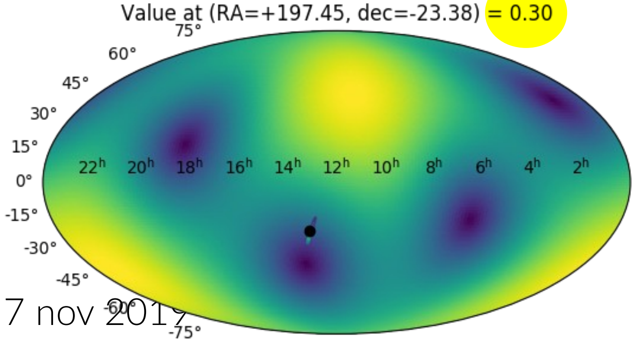
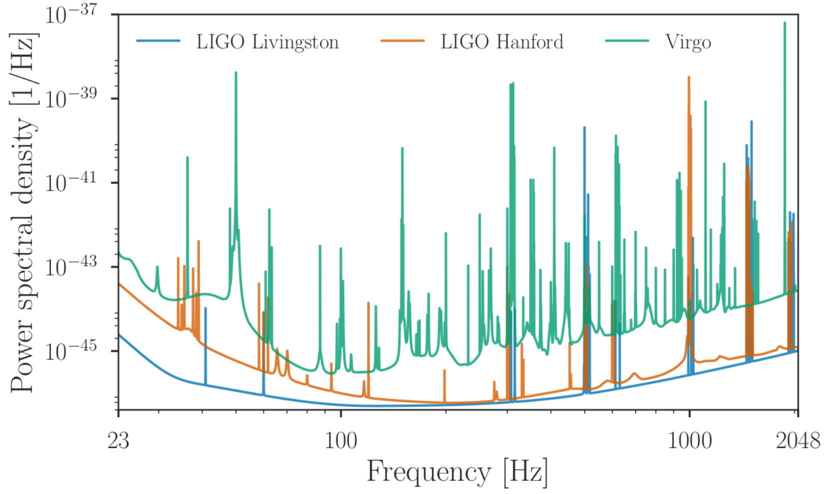
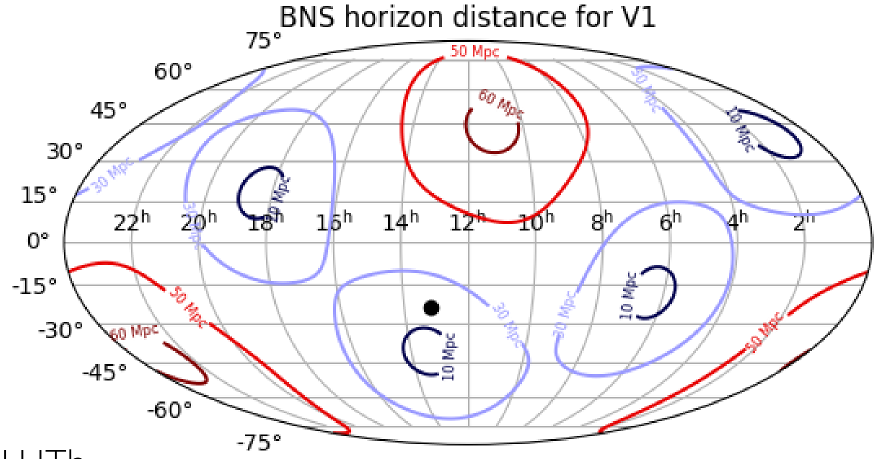
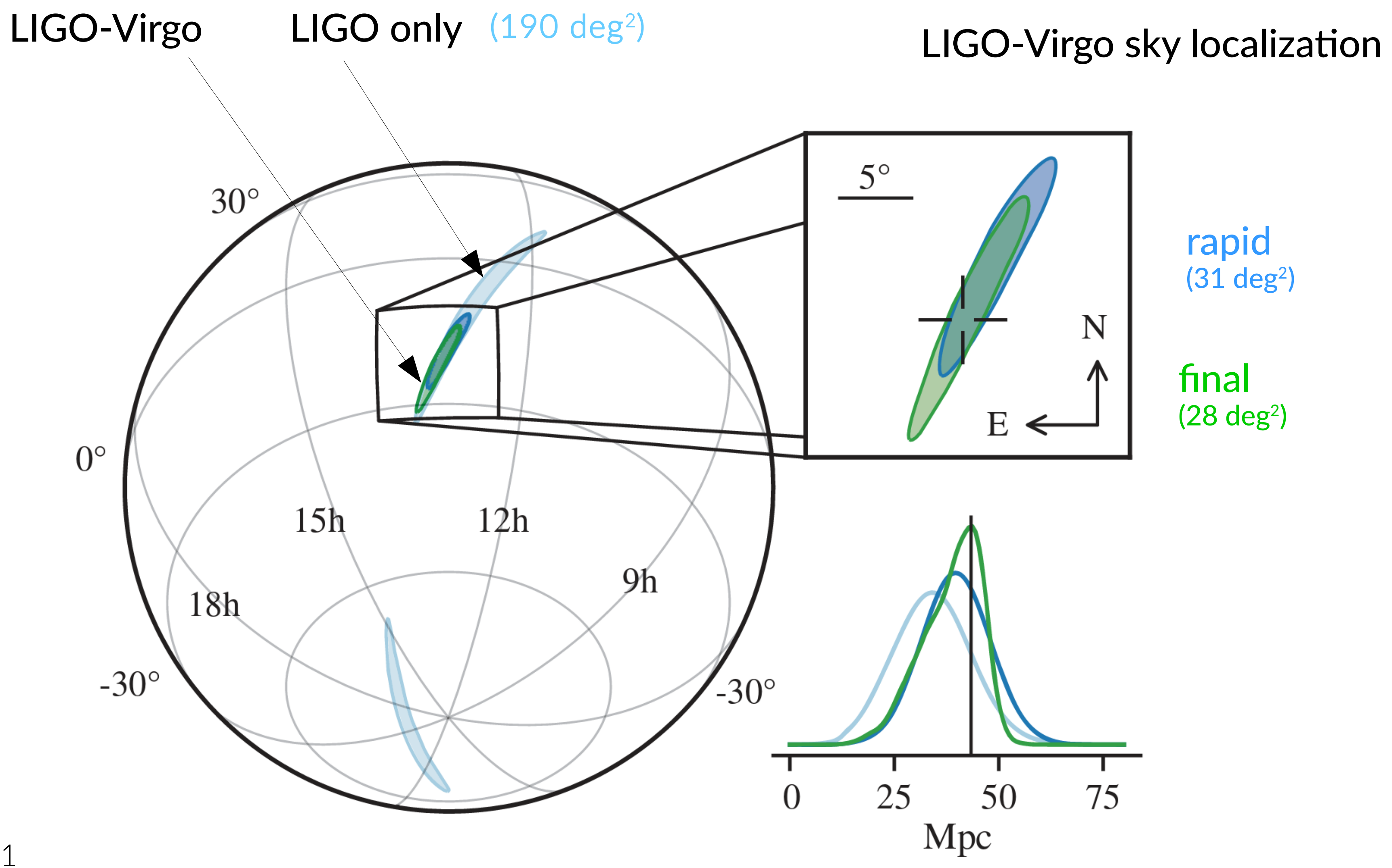
$$\mathrm{SNR}_{\mathrm{total}} = 32.4$$
$$\mathrm{SNR}_{H1} = 18.8$$
$$\mathrm{SNR}_{L1} = 26.4$$
$$\mathrm{SNR}_{V1} = 2.0$$

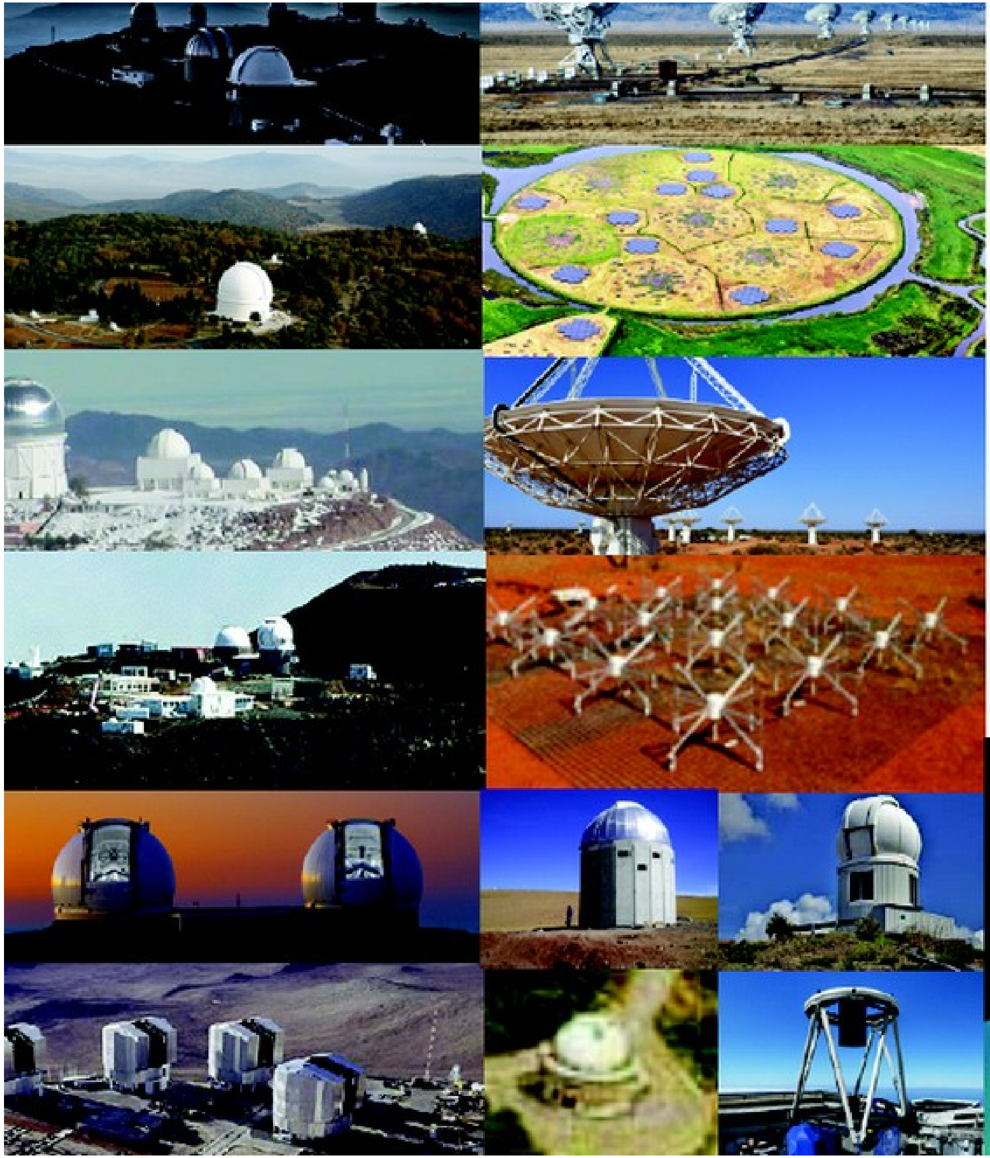


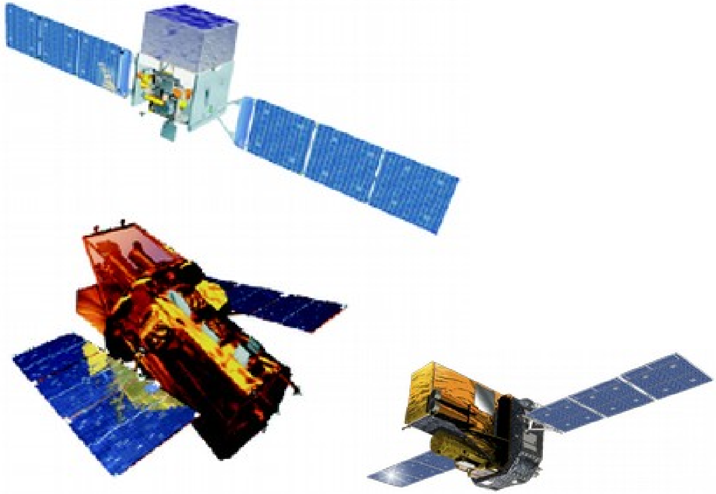


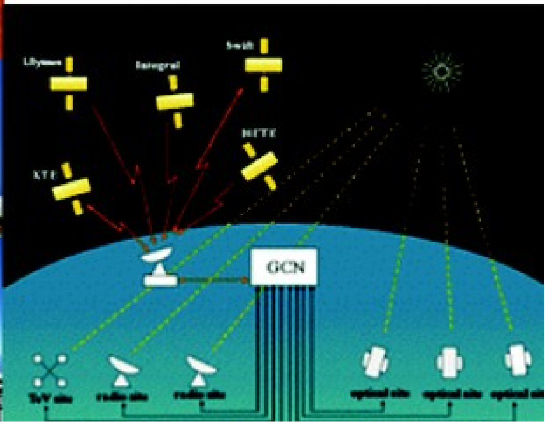





LIGO-Virgo
LIGO only
(190 deg²)
LIGO-Virgo sky localization
30°
0°
-30°
-30°
15h
12h
18h
9h
5°
N
E
rapid
(31 deg²)
final
(28 deg²)
0
25
50
75
Mpc






GCN

GW170817 follow-up

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

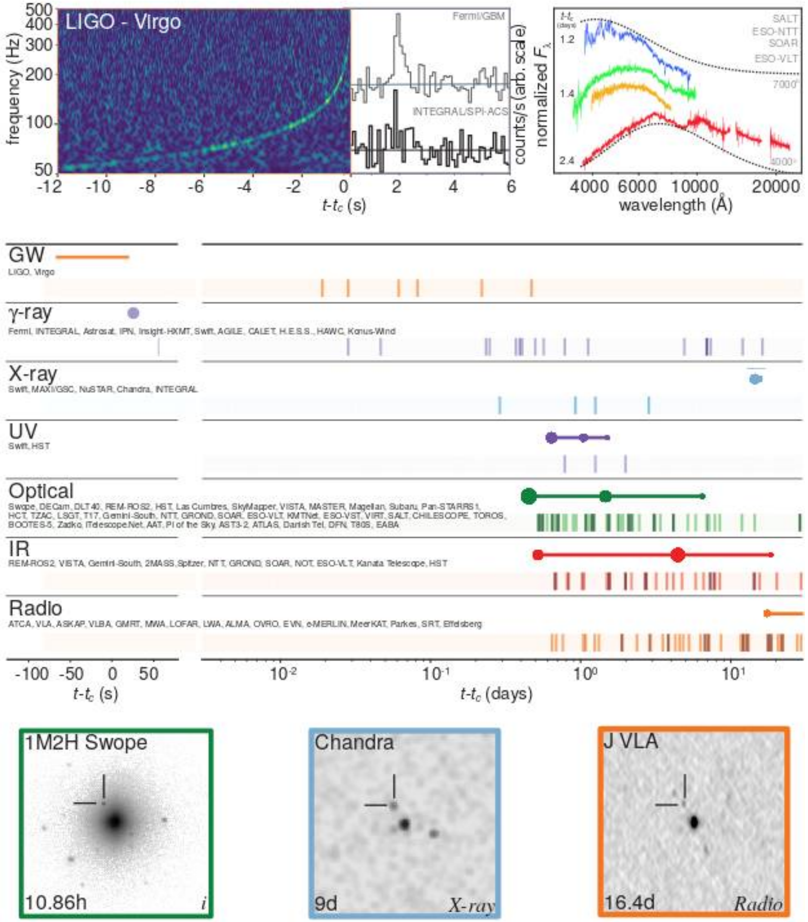
On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_\odot$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~9 and ~16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

Key words: gravitational waves – stars: neutron

1. Introduction

Over 80 years ago Baade & Zwicky (1934) proposed the idea of neutron stars, and soon after, Oppenheimer & Volkoff (1939) carried out the first calculations of neutron star models. Neutron stars entered the realm of observational astronomy in the 1960s by providing a physical interpretation of X-ray emission from Scorpius X-1 (Giacconi et al. 1962; Shklovsky 1967) and of radio pulsars (Gold 1968; Hewish et al. 1968; Gold 1969).

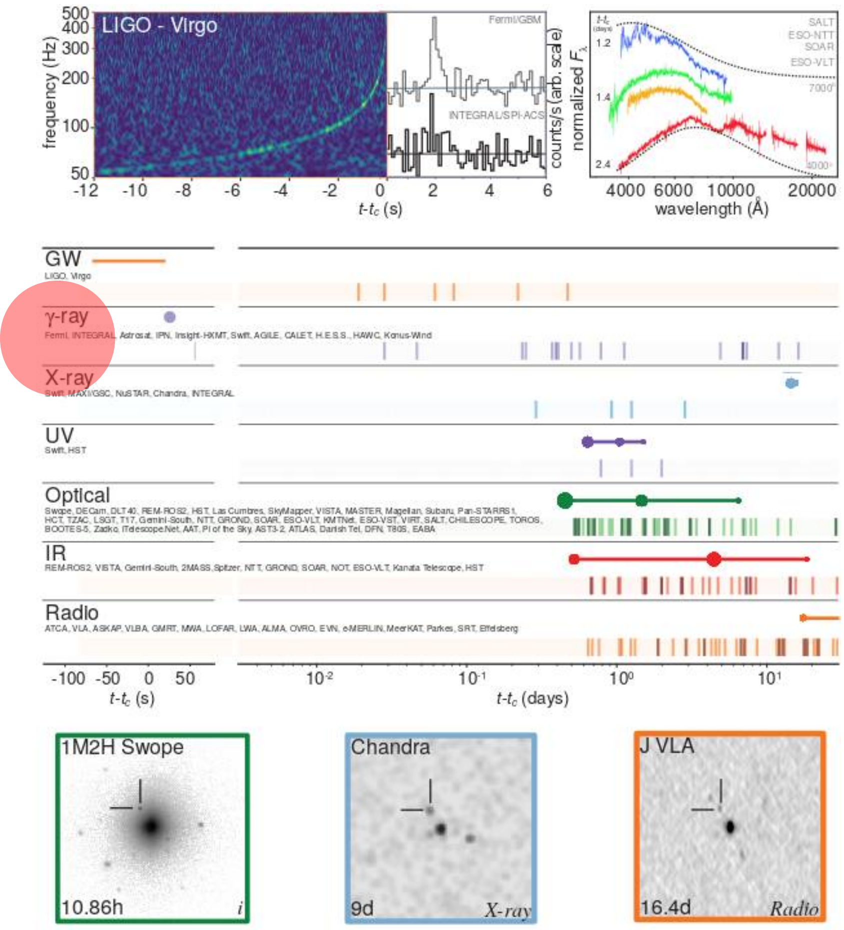
The discovery of a radio pulsar in a double neutron star system by Hulse & Taylor (1975) led to a renewed interest in binary stars and compact-object astrophysics, including the development of a scenario for the formation of double neutron stars and the first population studies (Flannery & van den Heuvel 1975; Massevitch et al. 1976; Clark 1979; Clark et al. 1979; Dewey & Cordes 1987; Lipunov et al. 1987; for reviews see Kalogera et al. 2007; Postnov & Yungelson 2014). The Hulse-Taylor pulsar provided the first firm evidence (Taylor & Weisberg 1982) of the existence of gravitational waves (Einstein 1916, 1918) and sparked a renaissance of observational tests of general relativity (Damour & Taylor 1991, 1992; Taylor et al. 1992; Wex 2014). Merging binary neutron stars (BNSs) were quickly recognized to be promising sources of detectable gravitational waves, making them a primary target for ground-based interferometric detectors (see Abadie et al. 2010 for an overview). This motivated the development of accurate models for the two-body, general-relativistic dynamics (Blanchet et al. 1995; Buonanno & Damour 1999; Pretorius 2005; Baker et al. 2006; Campanelli et al. 2006; Blanchet 2014) that are critical for detecting and interpreting gravitational waves (Abbott et al. 2016c, 2016d, 2016e, 2017a, 2017c, 2017d).



first month only

213 GCN Circulars
Peak 50/day

Three time scales: seconds

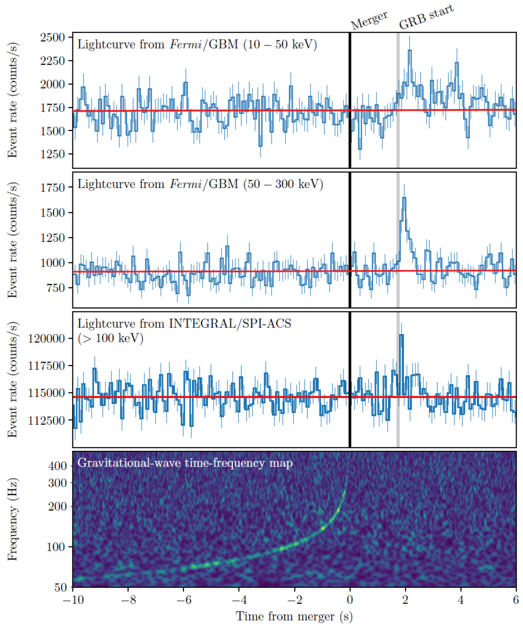


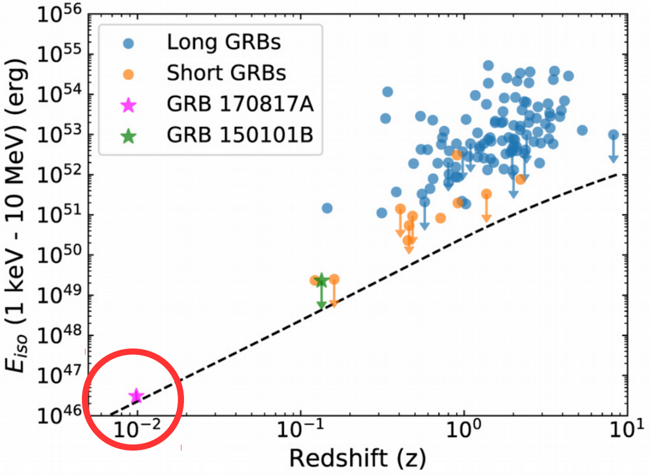
T0+1.7 s : gamma-ray burst

Short duration, ~ 2 sec

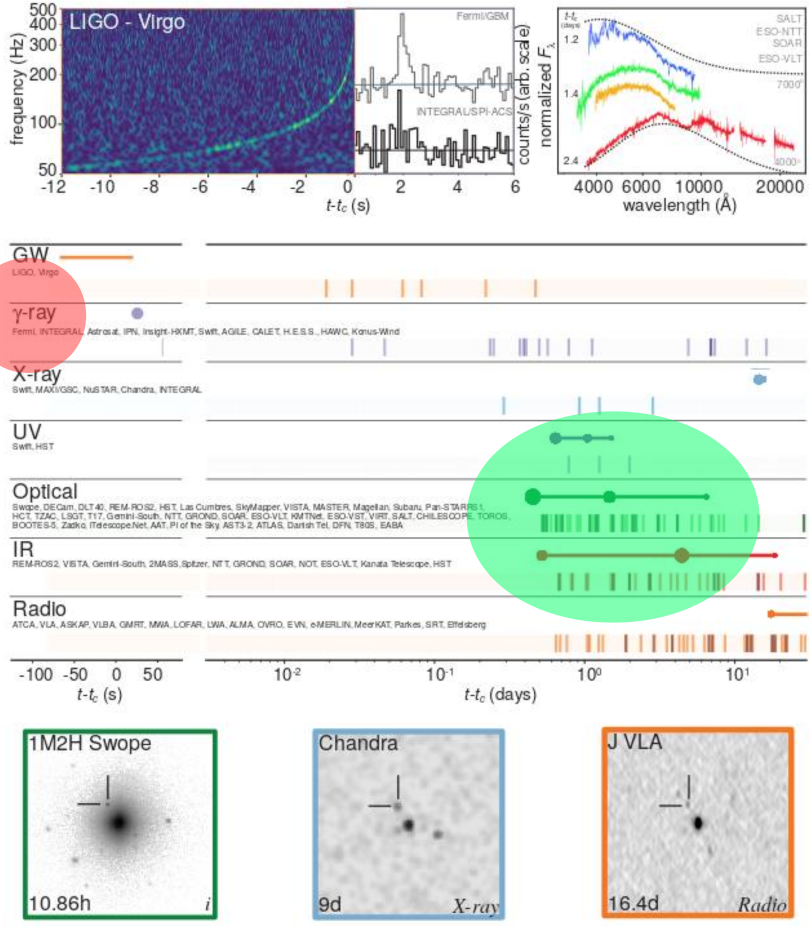
E_{iso} ~ 1.2 x 10^{46} erg (assuming D_L = 40 Mpc)

Atypical GRB: several orders of mag less energetic, softer spectrum





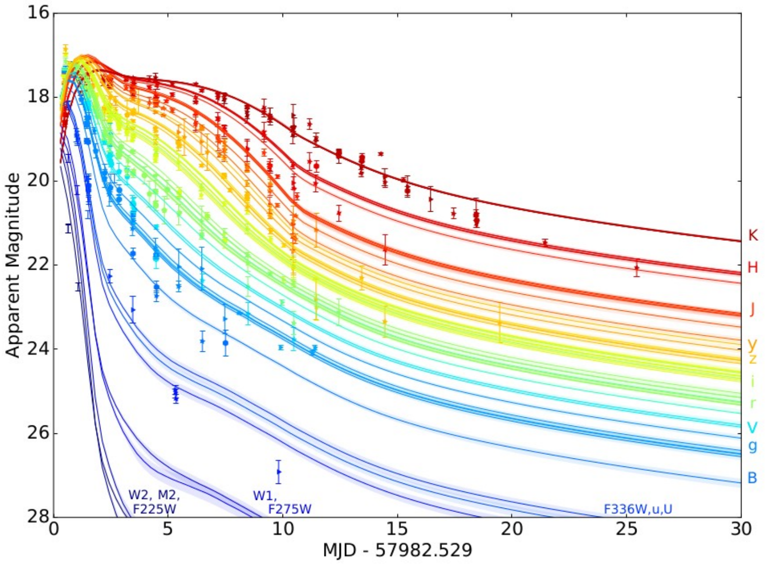
Three time scales: hours/day



T0+~1 d : UV, optical and IR

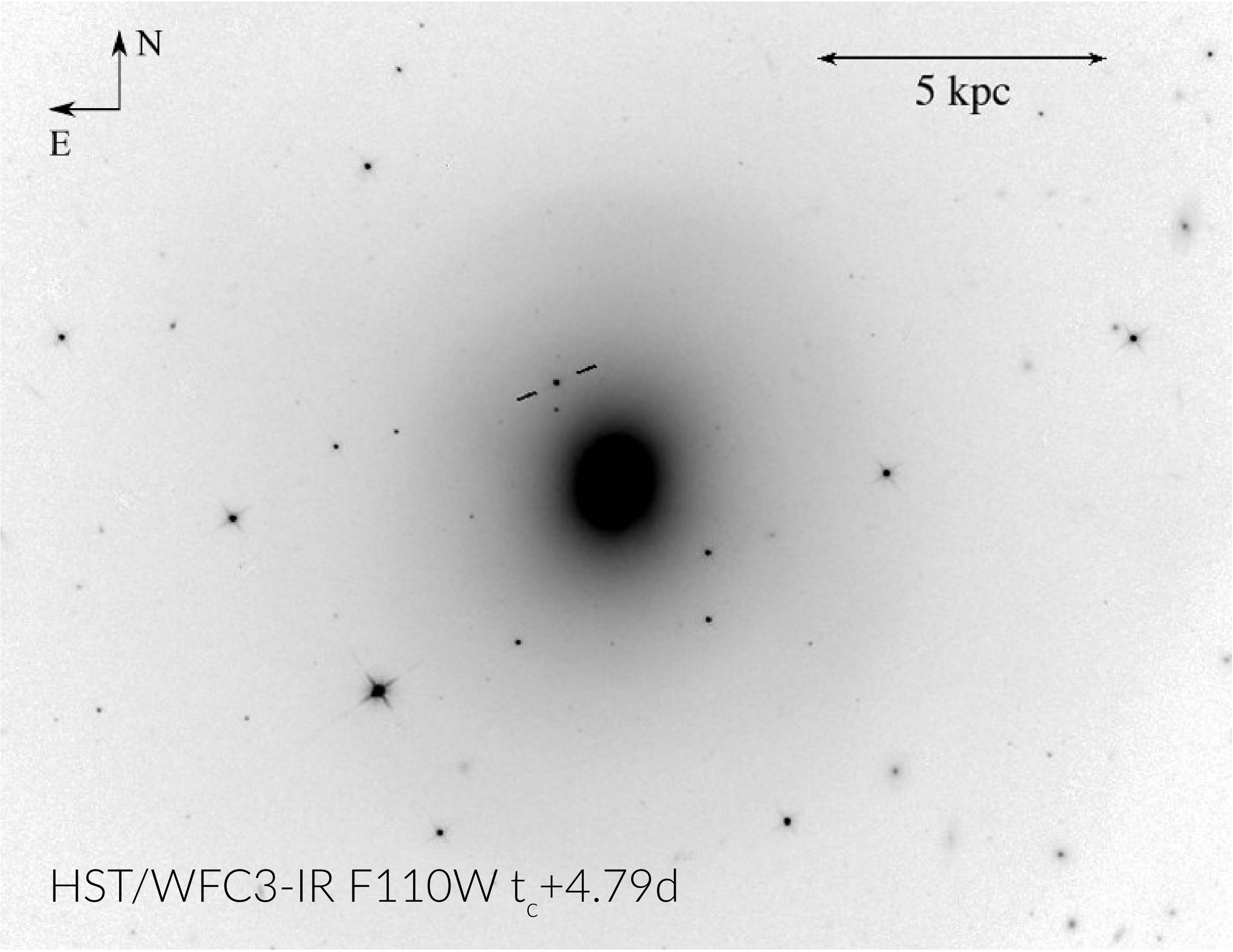
Host galaxy identification **NGC4933**

"**Kilonova**": radioactive-decay (r-process) powered emission from the merger ejecta



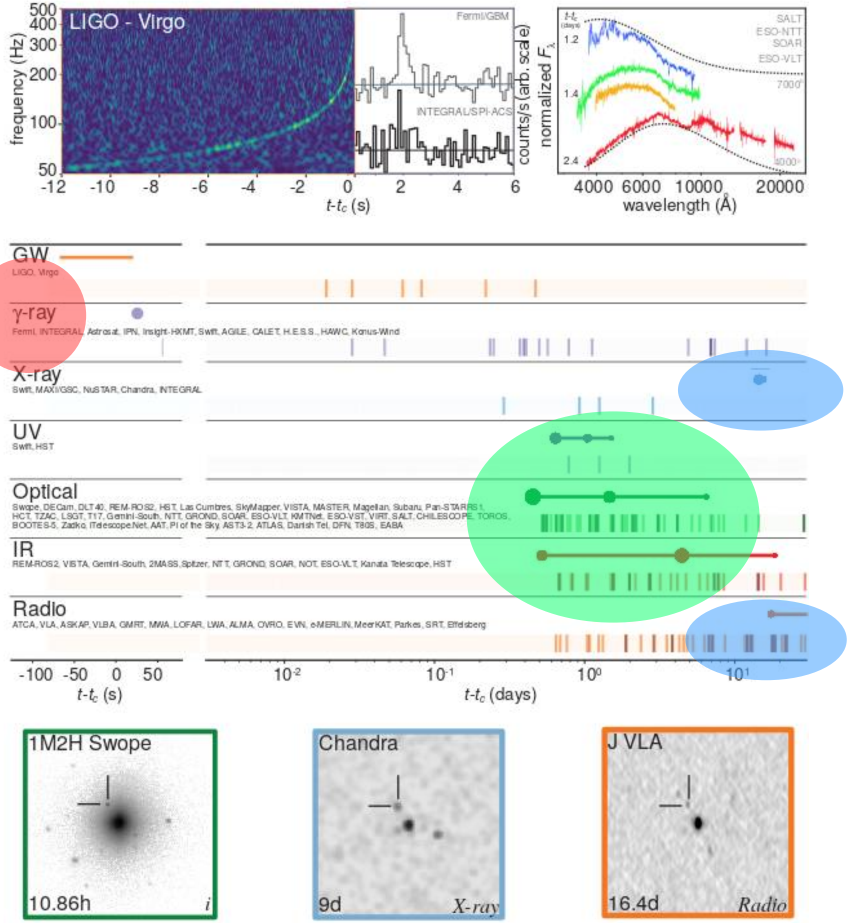
647 flux measurements from 18 papers and 46 instruments

V. Ashley Villar et al, arXiv:1710.11576



Tanvir et al, ApJL 848:L27 2017

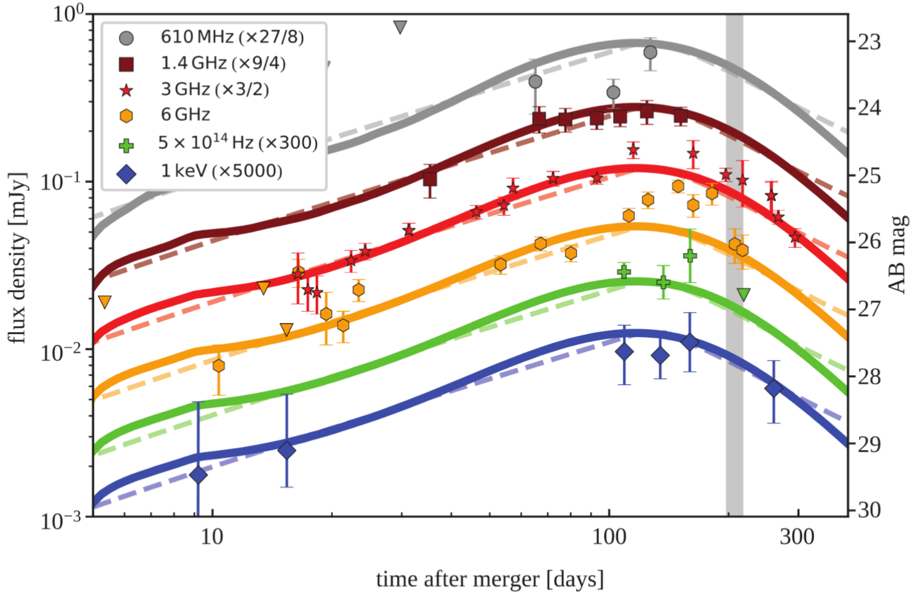
Three time scales: weeks/months



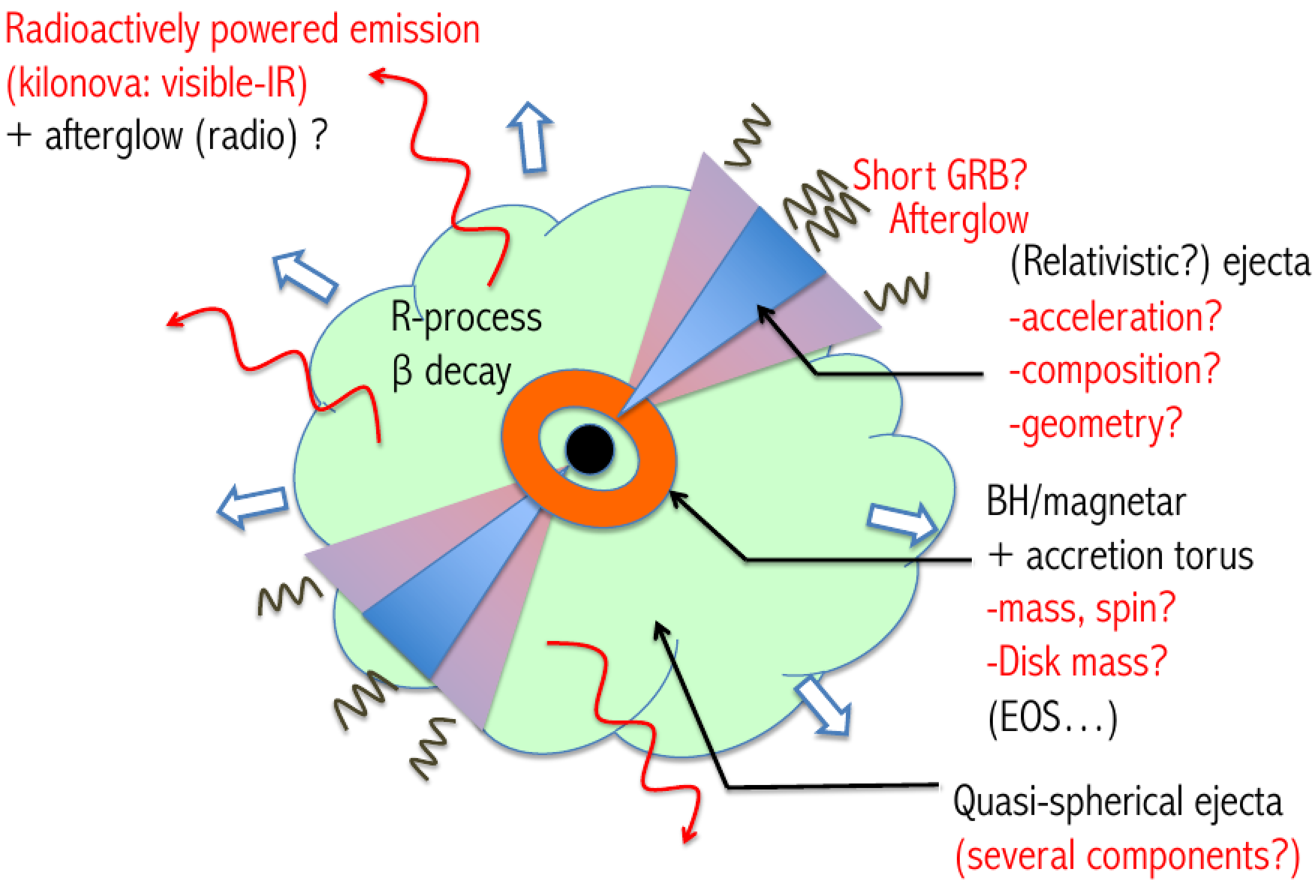
X-ray T0+9 d, radio T0+16 d

Peak in X-ray & radio (100 μJy) at T0+~150 d

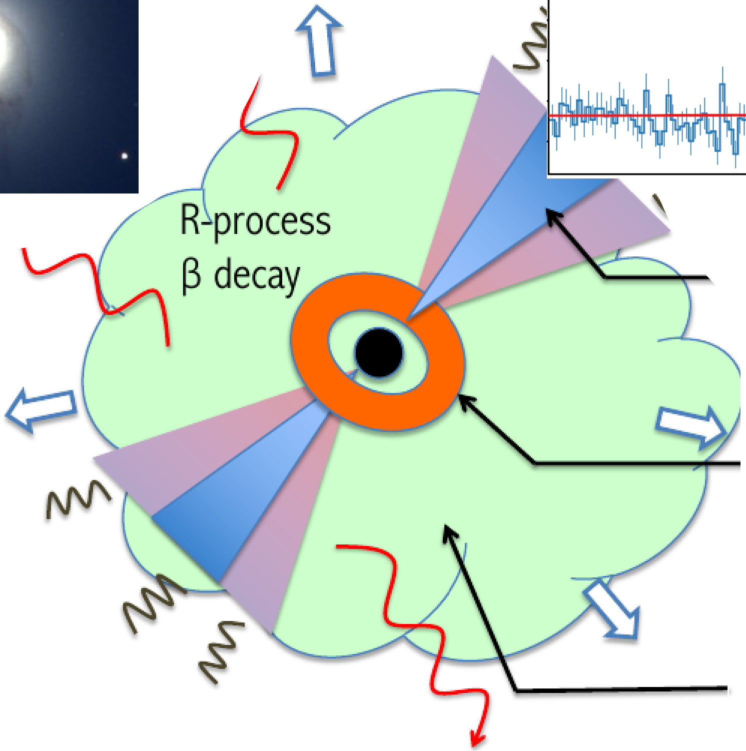
and optical (m=26.5) at T0+110 d

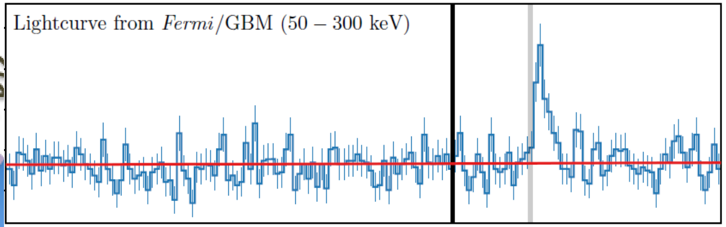


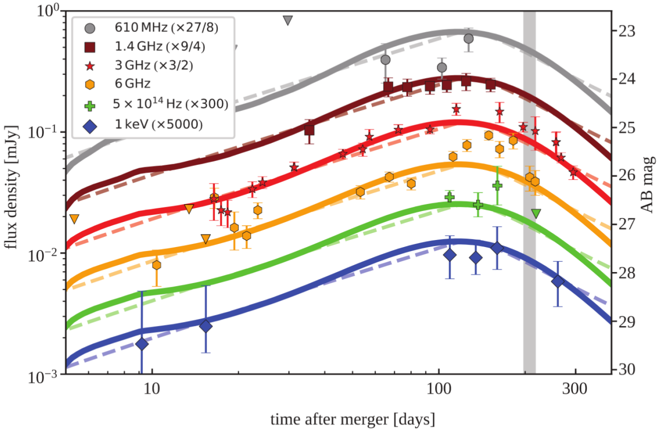
Ghirlanda et al. ArXiv:1808.00469



Credits: F Daigne







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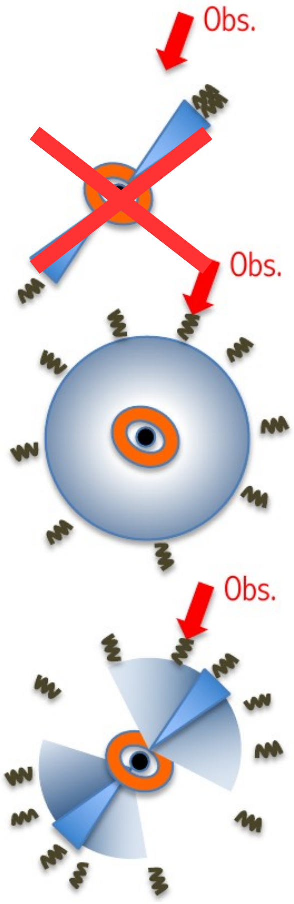
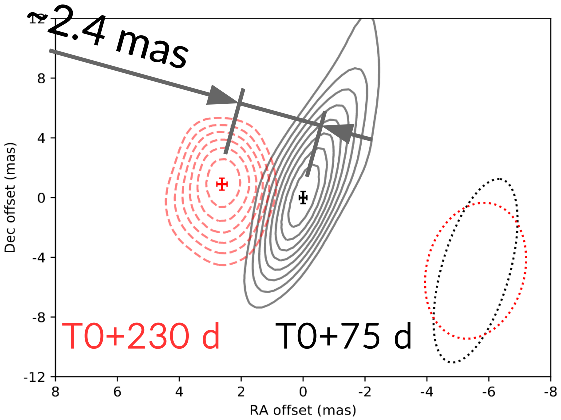


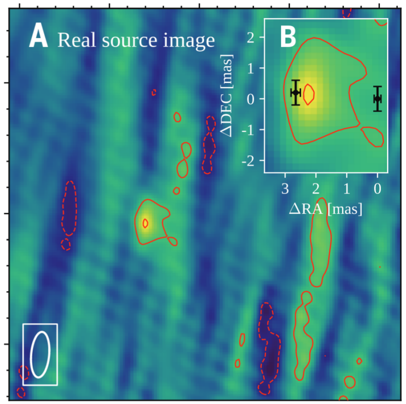
Jet seen off-axis

Quasi spherical outflow

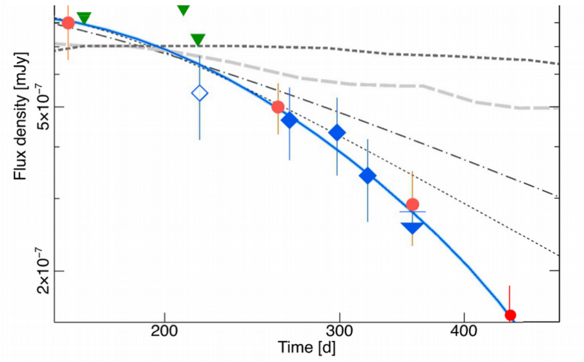
Jet with lateral structure

Evidence for a 'succesful' relativistic jet

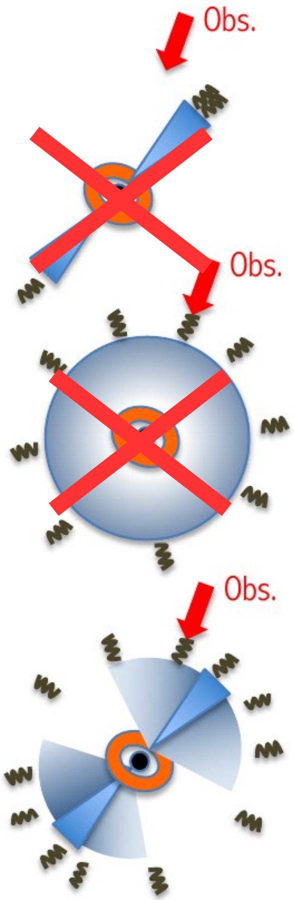




Mooley et al, ArXiv:1806.09693
Ghirlanda et al. ArXiv:1808.00469



- Mooley et al & Ghirlanda et al T0+ ~200 days
  - Very-long based interf [10 000 km] > 32 radiotelescopes [worldwide]
- Moving collimated jet **observed**
  - midly relativistic jet $\Gamma \sim 4$, $\theta_{jet} \sim 4°$
  - viewing angle $\theta_{obs} \sim 20°$



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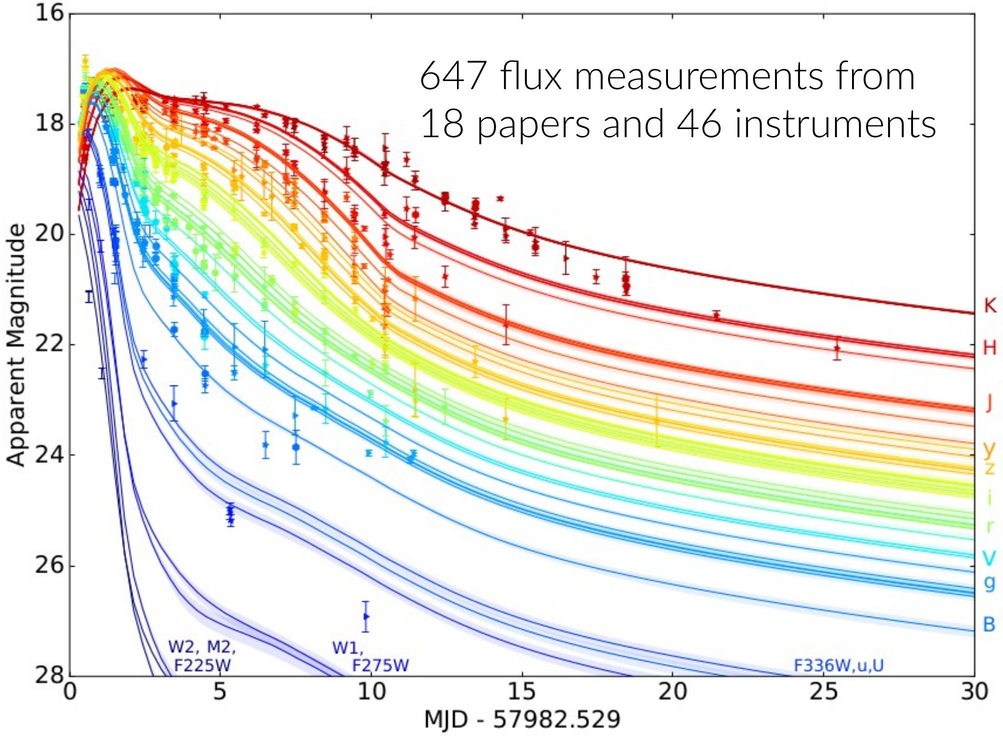
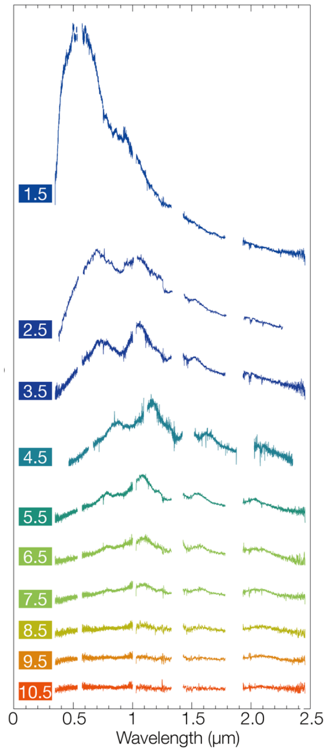
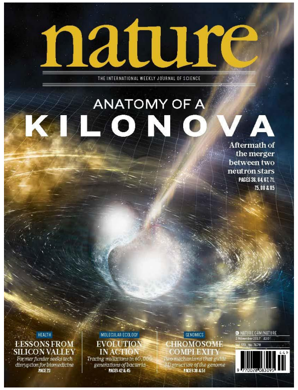
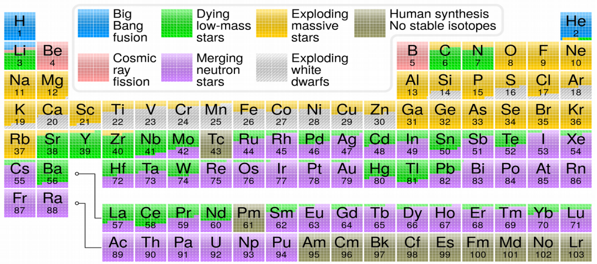
- Perspectives

Implications (1): nucleosynthesis









V. Ashley Villar et al, arXiv:1710.11576

Implications (1): nucleosynthesis

Identification of Strontium

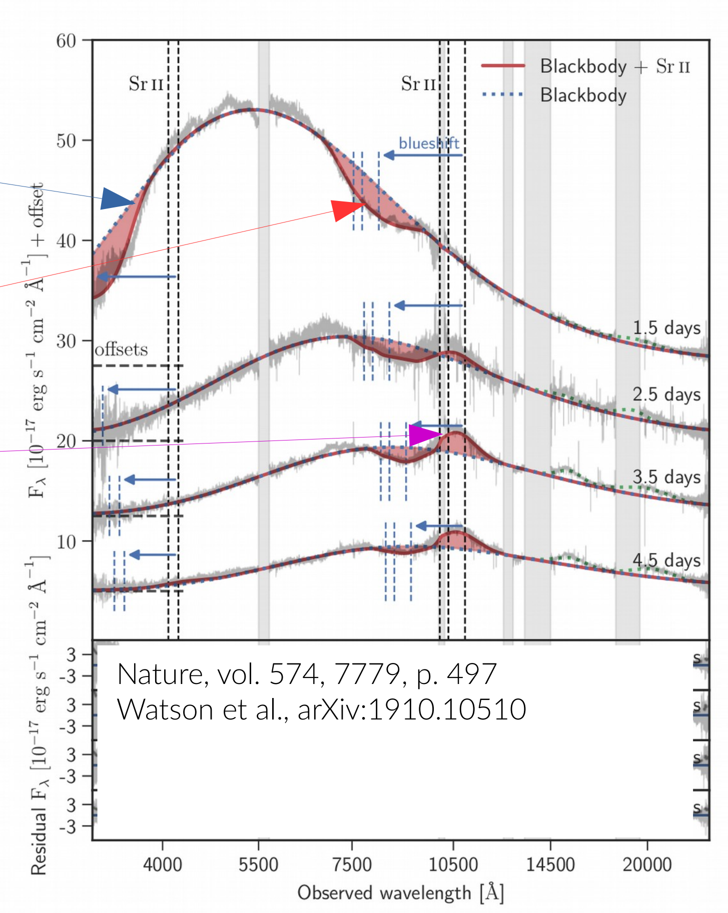
Sr = a few percent by mass of all *r*-process elements

kilonova = blackbody at 3,700 K

absorption lines broadened and blue-shifted due to the relativistic motion of the ejecta

P Cygni profiles develop in time for the Sr lines

The identification of an element that could only have been synthesised so quickly under an extreme neutron flux, provides ***the first direct*** *spectroscopic* ***evidence that neutron stars comprise neutron-rich matter.***



Nature, vol. 574, 7779, p. 497
Watson et al., arXiv:1910.10510

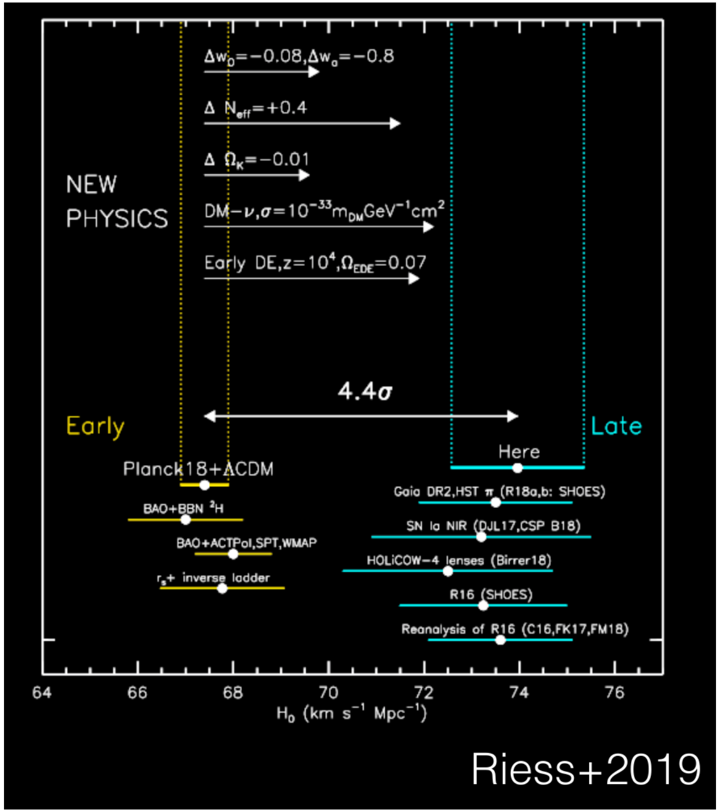
Implications (2): modified gravity

- Coincidence with GRB170817A within 1.7 s
- Very stringent constraints on the speed of gravity $|c/c_g - 1| < 5 \times 10^{-16}$
- Incompatible with a large set of alt. gravity scalar-tensor theories brought forward to explain dark energy

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity	quartic/quintic Galileons [13, 14]
	quintessence/k-essence [42]	Fab Four [15, 16]
	Brans-Dicke/$f(R)$ [43, 44]	de Sitter Horndeski [45]
	Kinetic Gravity Braiding [46]	$G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18]	quartic/quintic GLPV [19]
	Disformal Tuning (22)	DHOST [20, 48] with $A_1 \neq 0$
	DHOST with $A_1 = 0$	
	Viable after GW170817	Non-viable after GW170817

https://arxiv.org/abs/1710.05901
https://arxiv.org/abs/1710.05877

Implications (3): Cosmology



Tension in the current H_0 measurements from early/late times

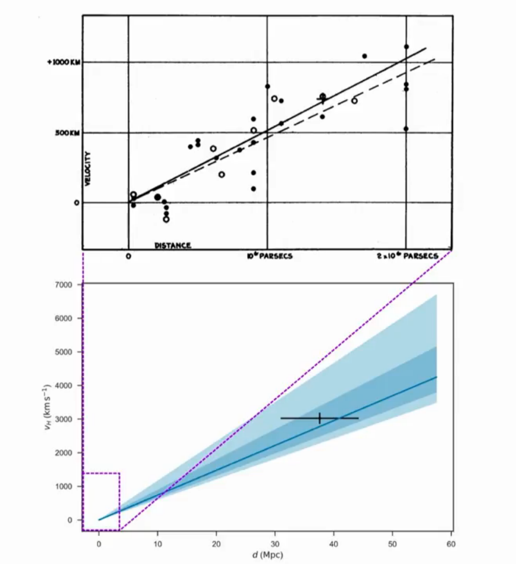
Implications (3): Cosmology

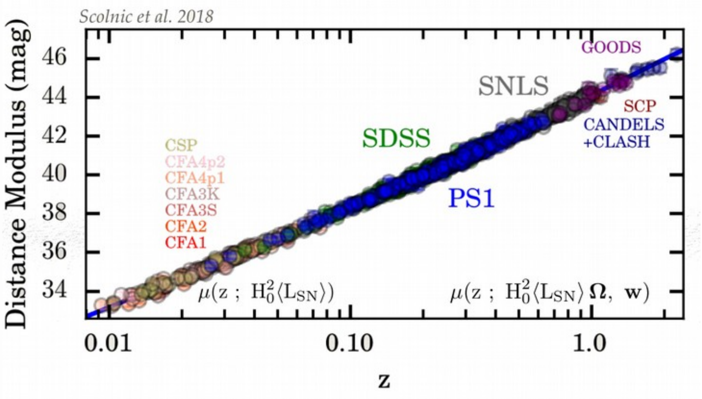
Hubble Lemaître law $v_H = c{\color{red}z} = H_0 {\color{blue}D_L}$

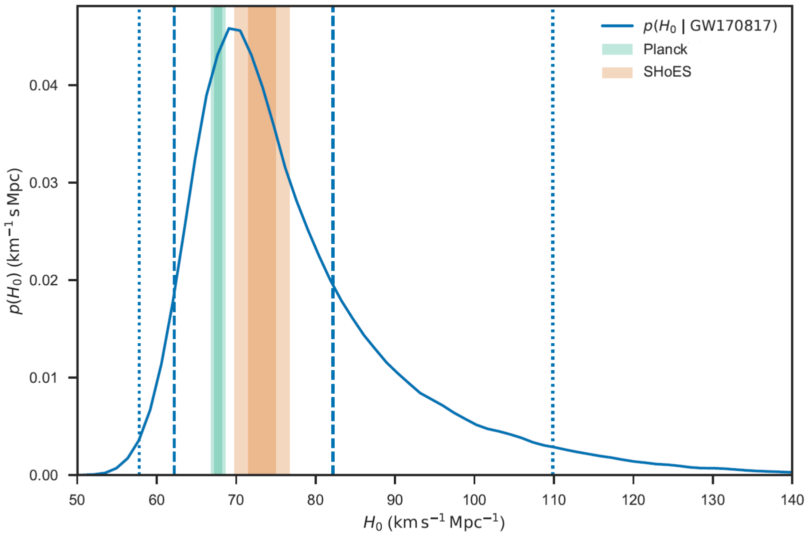
from host galaxy identif.

from GW signal amplitude
[no "cosmological ladder"!]

1929, distances from Cepheids variables



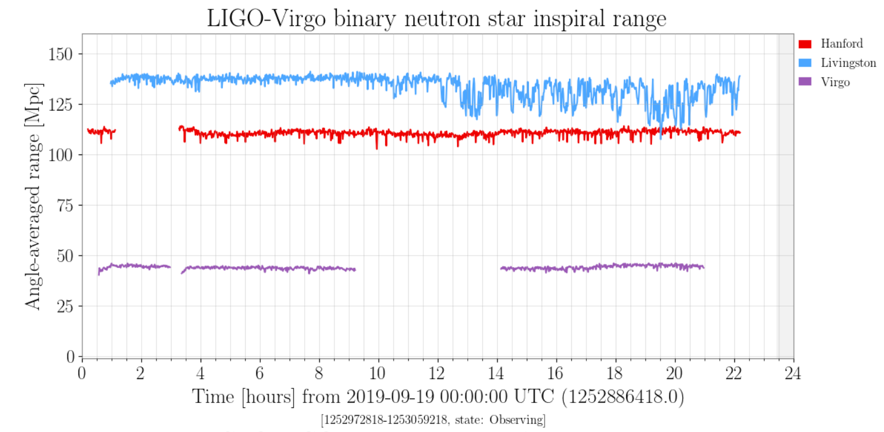


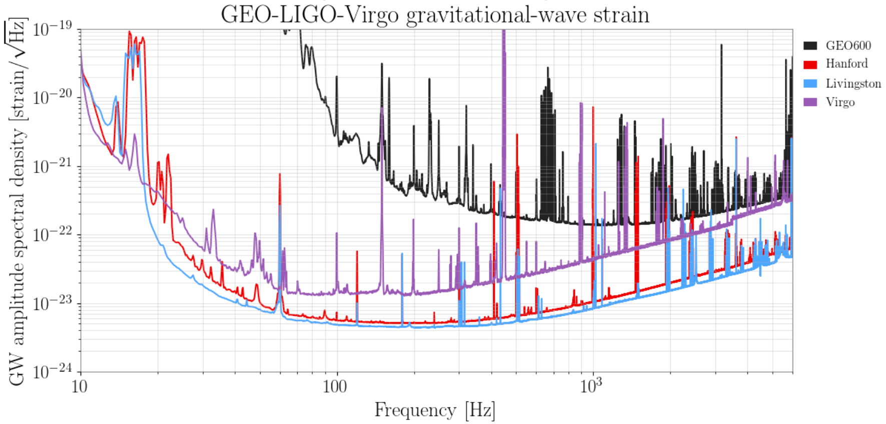


Plan de la présentation

- Un peu de contexte
- Le signal gravitationnel GW170817
- GW170817 et l'astronomie multi-messager
- Implications en physique, en astrophysique et en cosmologie
- Perspectives

GW astronomy today



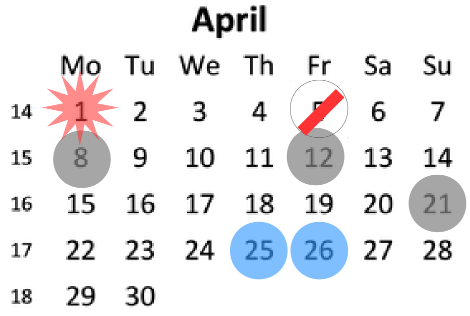


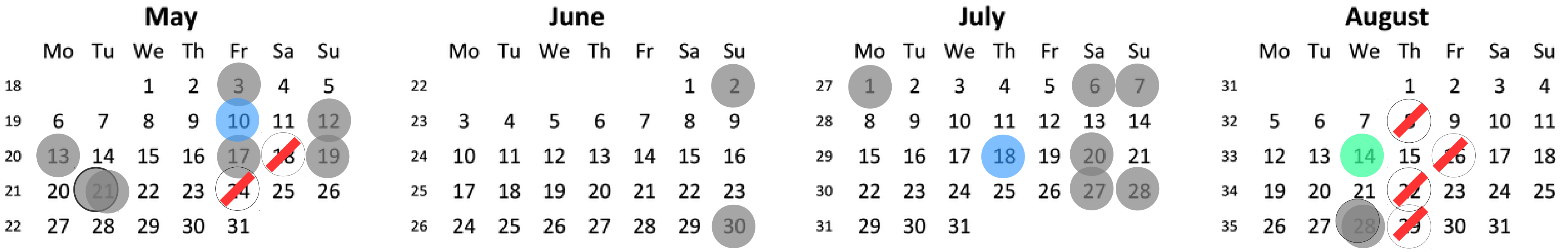
- **Advanced LIGO and Virgo observing**
  - Stable operation (~70 %) since April 1st 2019
  - Improved sensitivies wrt O2: Virgo x ~2, LIGO HL + 65 %
- **Public alerts within minutes**
  - 36 GW alerts – 7 retractions
  - 21 events classified as BBH, 4 as BNS and 2 events as **NS-BH**
  - *Now commissioning break for a month*
- **No electromagnetic counterpart detected so far**

O3a summary

~ 1 alert/week

- Binary black hole (21)
- Binary neutron star (6)
- Neutron star-black hole (4)
- "Mass gap" – 3 to 5 M_{sun} (2)
- Alert retracted





Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}

https://arxiv.org/abs/1304.0670

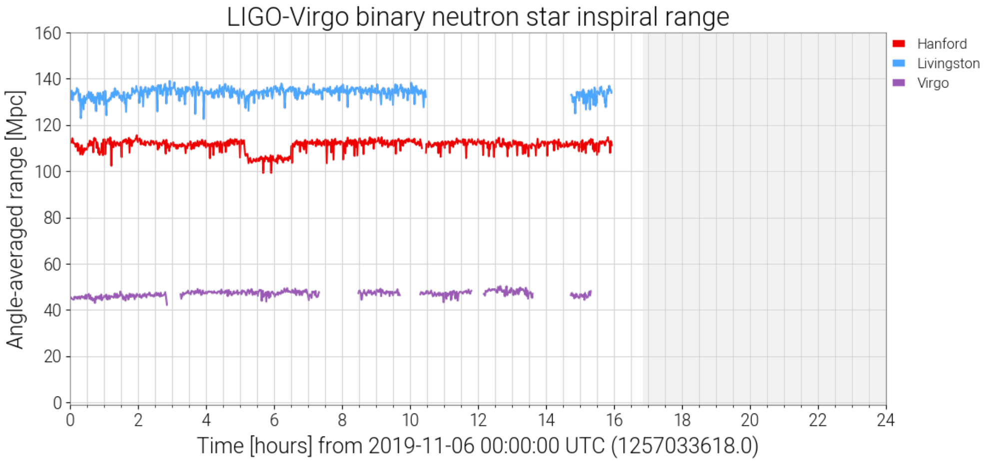
Current status

Gravitational Wave Detector Network

Operational Snapshot as of Nov 06, 17:24 UTC

Detector	Status	Duration
GEO 600	Unlocked	6:45
LIGO Hanford	Observing	6:55
LIGO Livingston	Observing	2:38
Virgo	Calibration	2:03
KAGRA	Future addition	

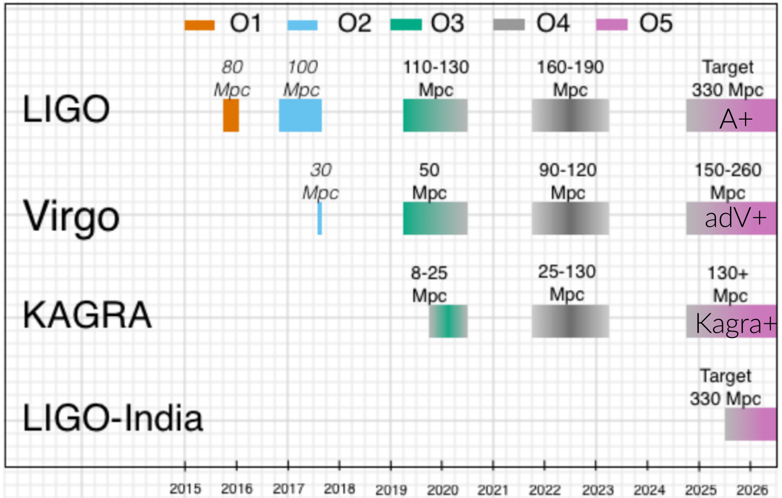
Detector status summary pages — LVC links



https://ldas-jobs.ligo.caltech.edu/~gwistat/gwistat/gwistat.html

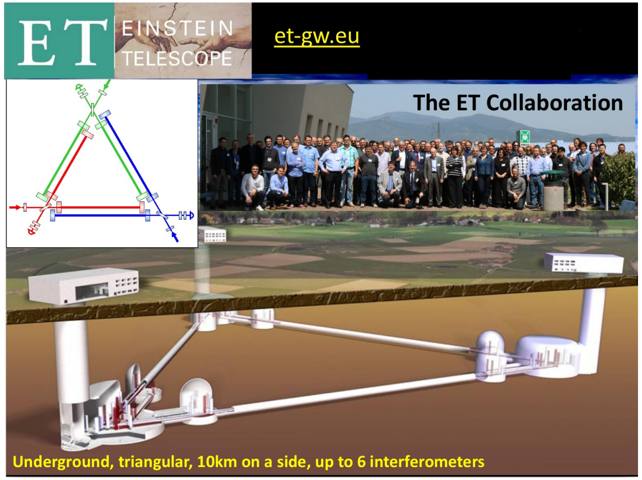
https://www.gw-openscience.org/

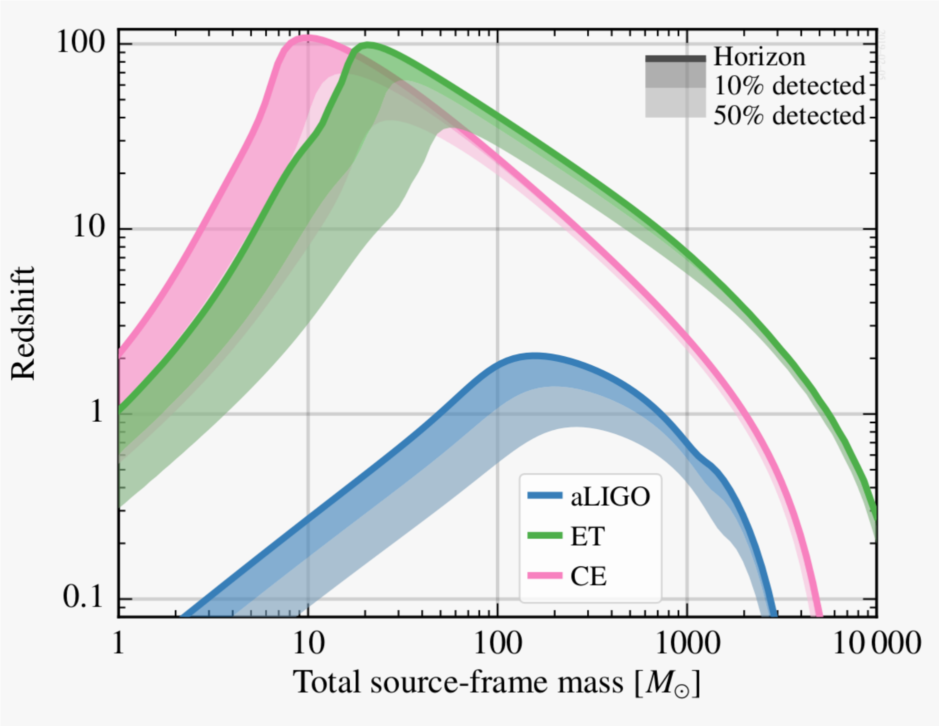
GW astronomy in 2025



- **Five large-scale detectors in operation**
  - Best BNS range ~ 300 Mpc – Horizon z ~ 0.15
  - ~3 x current sensitivity
    rough extrapolation from 03 → ~4 events/day (!)
  - O(100) BBH and O(10) BNS per year
    [rates will be revised after O3]
  - How many with an observed electromagnetic counterpart?

3^{rd} detector generation – post 2030





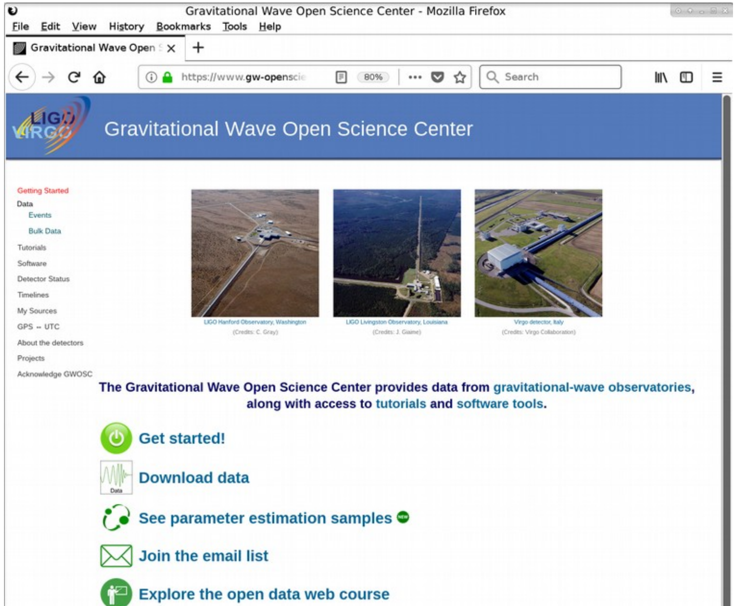
sub M_{sun} to ~1000 M_{sun}

> 10^5 BNS/yr →
+ 1 BNS every 5 mins
~50 % of all BNS mergers

10^6 BBH/yr →
1 BBH every 30 sec
~90 % of all BBH mergers

Baibhav et al, arxiv:1906.04197

gw-openscience.org



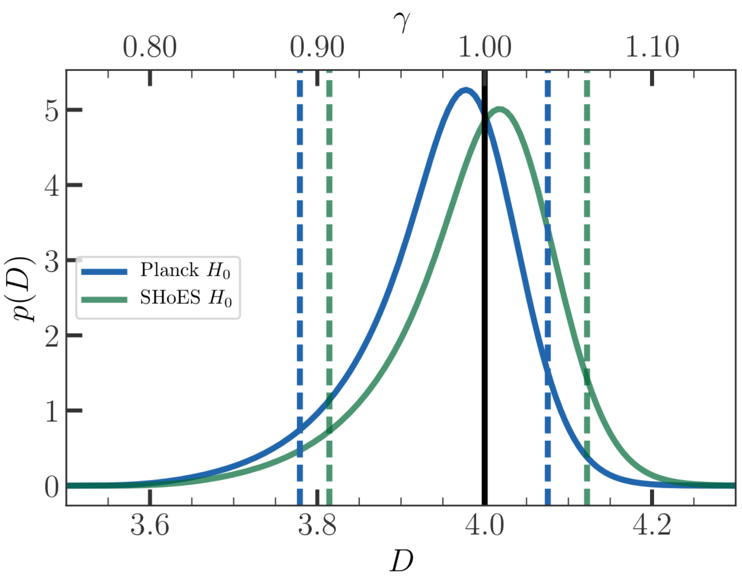
"Only days after they announced the first observation of gravitational waves, the LIGO and Virgo collaborations made public their data."

- Whole science-run data and GW event catalogs
  - ✓ 80+ papers using open data
- Documentation, usage recommendations
- Online training: video tutorials and Jupyter notebooks

Concluding remarks

- Multi-messenger astronomy in its infancy
  - Joint GW and EM signals allows unique tests in a range of fields
  - Many breakthroughs with only one event
- Is this going to happen again (during O3)?
  - In principle, yes but we probably got lucky with GW170817 (close source)
    Back-of-the-envelope calculation : ~3 % in six months
  - Major facilities in the next 10 years CTA; SVOM; LSST and JWST; SKA
    Game changer for electromagnetic follow-up
- Part of the Universe observable in GW is expanding very fast
  - Sensitivities ~+20 % / year (x 2 every four years)
  - More detectors around the globe soon (Japan, India)
- Very promising science program with large discovery potential!!

Implications (3): extra-dimensions



$$h_{GR} \propto \frac{1}{D_L} \quad \text{vs} \quad h_{alt} \propto \frac{1}{D_L^{\gamma}} \qquad \gamma = \frac{D-2}{2}$$

gravitational leakage

num of space-time dimensions

- **Test extra-dimensional theories of gravity**
  - Compare the luminosity distance extracted from the GW signal to the EM-measured distance of NGC4933

H_0 prior km s^{-1} Mpc^{-1}	γ	D
$H_0 = 73.24 \pm 1.74$ (Riess et al. 2016)	$1.01^{+0.04}_{-0.05}$	$4.02^{+0.07}_{-0.10}$
$H_0 = 67.74 \pm 0.46$ (Planck Collaboration et al. 2016)	$0.99^{+0.03}_{-0.05}$	$3.98^{+0.07}_{-0.09}$

 arXiv:1801.08160