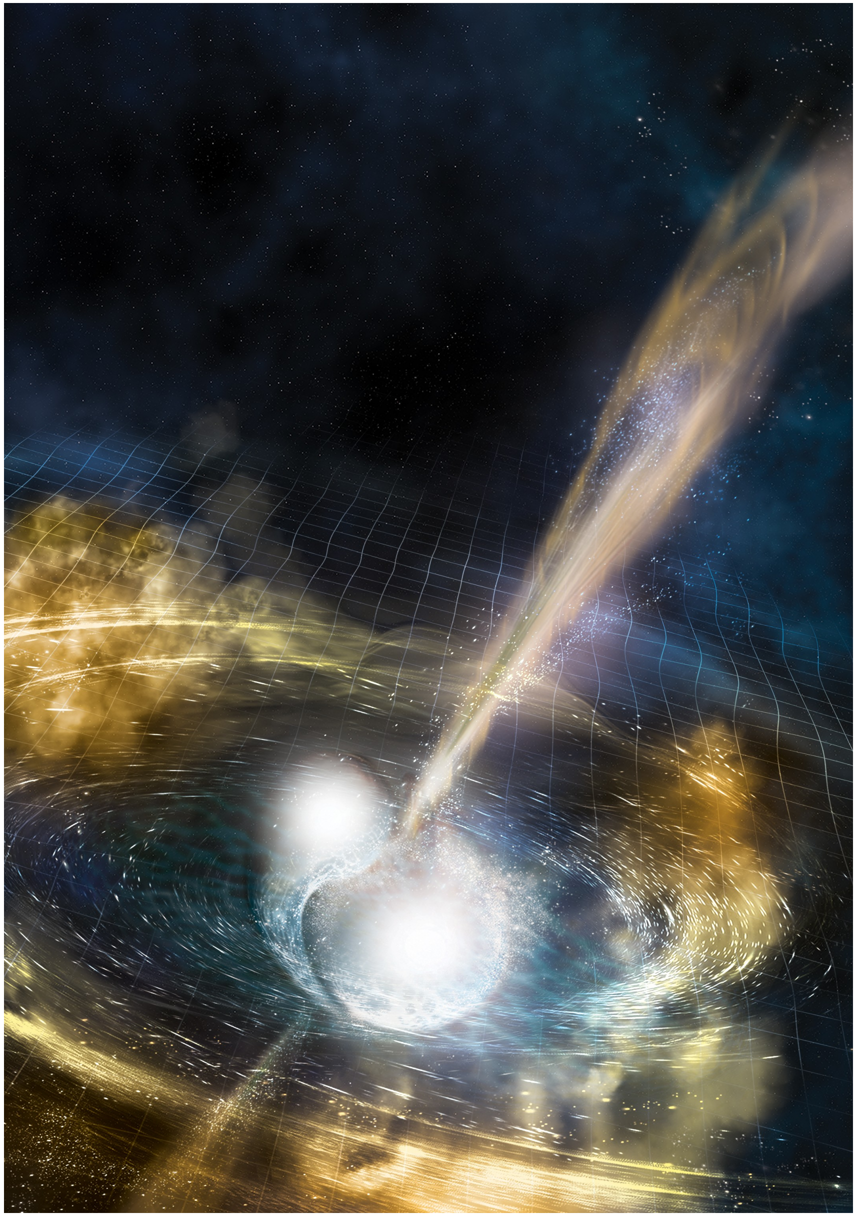
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral



Lazzaro Claudia
for the LIGO Scientific Collaboration
and the Virgo Collaboration

Padova 25 October 2017

GW170817

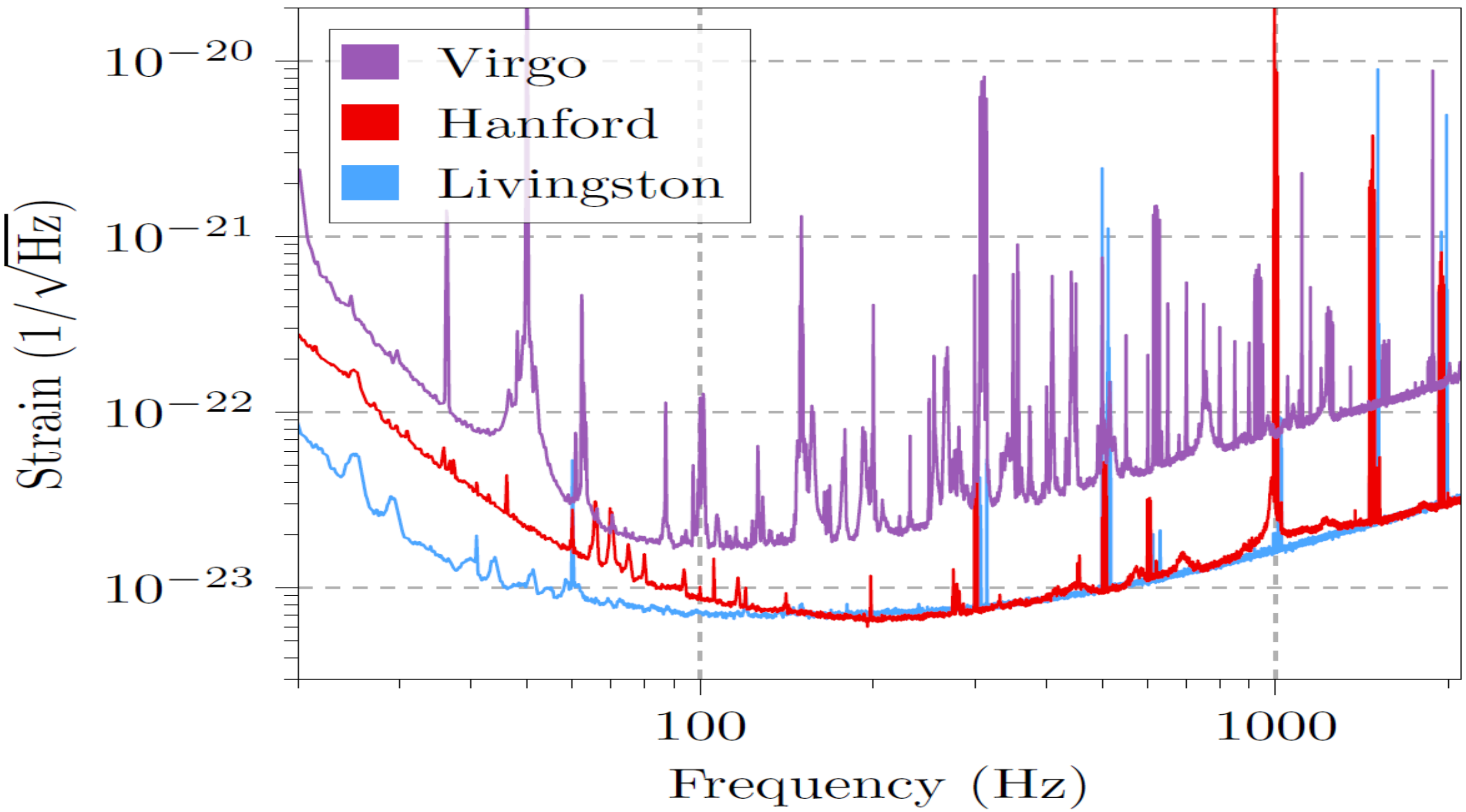
PhysRevLett.119.161101

On August 17, 2017, the LIGO-Virgo detector network observed a gravitational-wave signal from the inspiral of two low-mass compact objects consistent with a binary neutron star (BNS) merger.

- This gravitational-wave signal is the loudest yet observed, with a combined signal-to-noise ratio (SNR) of 32.4.
- After 100 s (starting from 24Hz) in the detectors' sensitive band, the inspiral signal ended
- In addition a gamma-ray burst was observed 1.7 s after the coalescence
- The combination of data from the LIGO and Virgo detectors allowed a precise sky position localization to an area of 28 deg^2.

O2 observing run

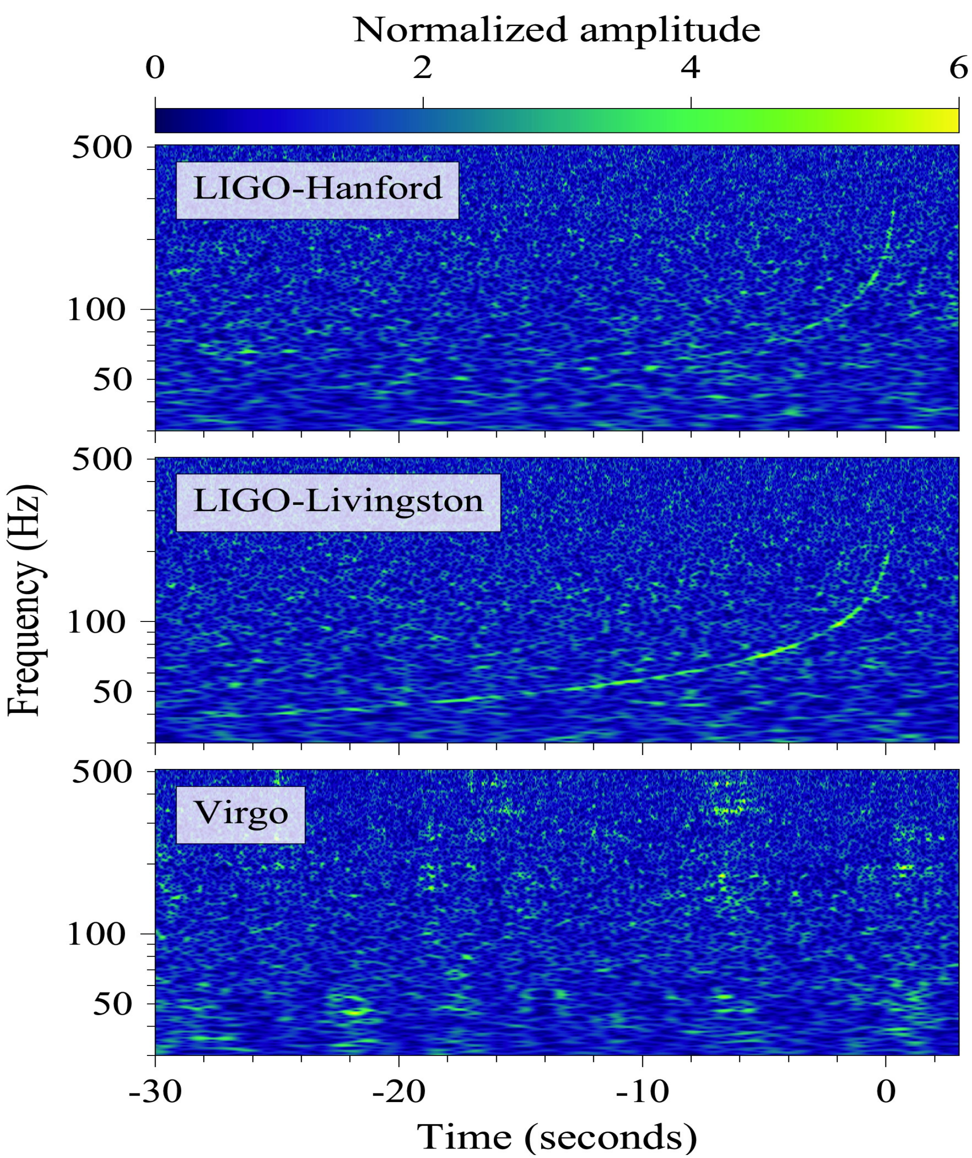
The second observing run (O2) of Advanced LIGO: November 30, 2016 - August 25, 2017, 117 days of simultaneous LIGO-detector observing time. Advanced Virgo joined the O2 run on August 1, 2017



Detector horizon (maximum distances at which the interferometer could detect a BNS system, SNR = 8): LIGO-Livigston 218Mpc, LIGO-Hanford 107Mpc, Virgo 58Mpc.

GW170817: data

GW170817 was initially identified as a single-detector event (LIGO-Hanford)



GW170817 in the detectors' sensitive band ~100 s (fstart = 24 Hz)

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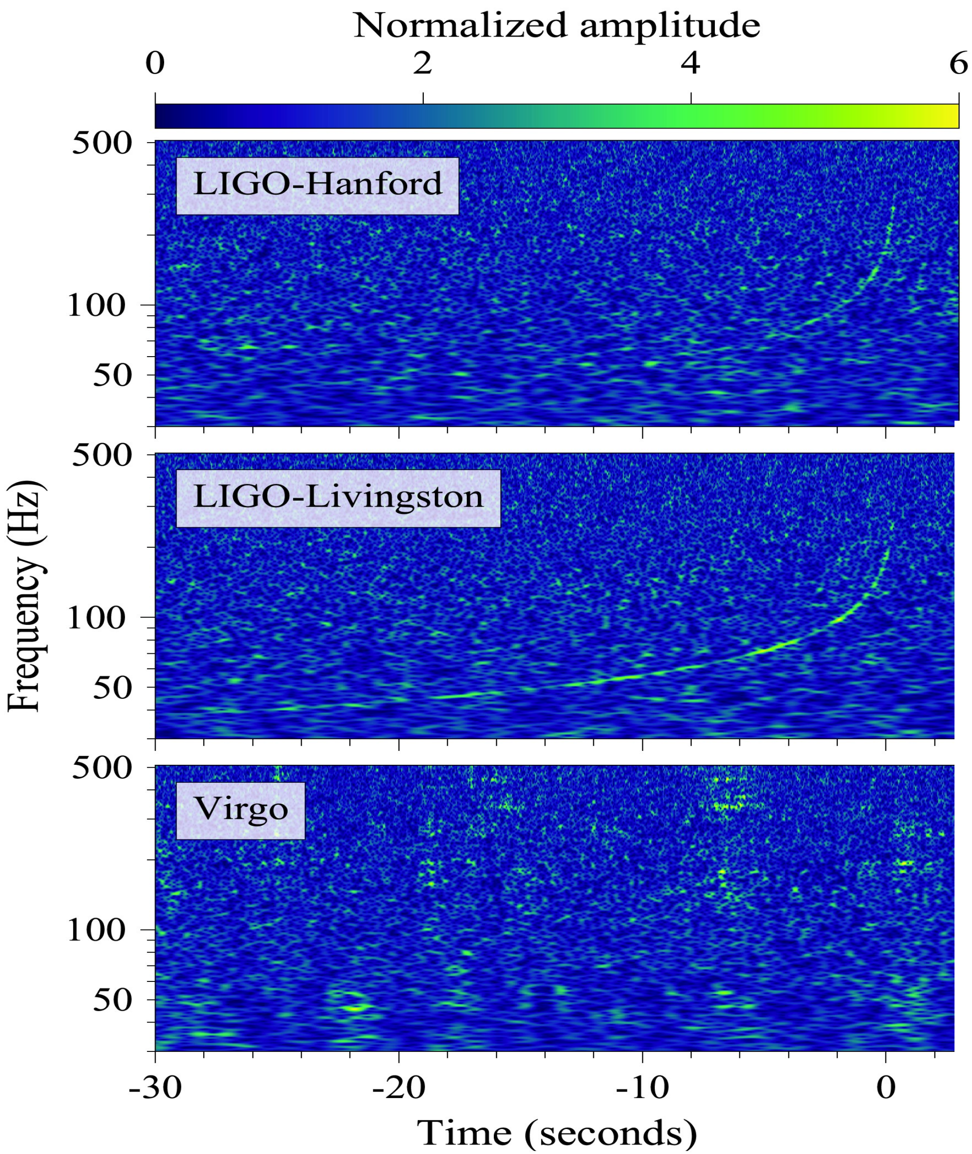

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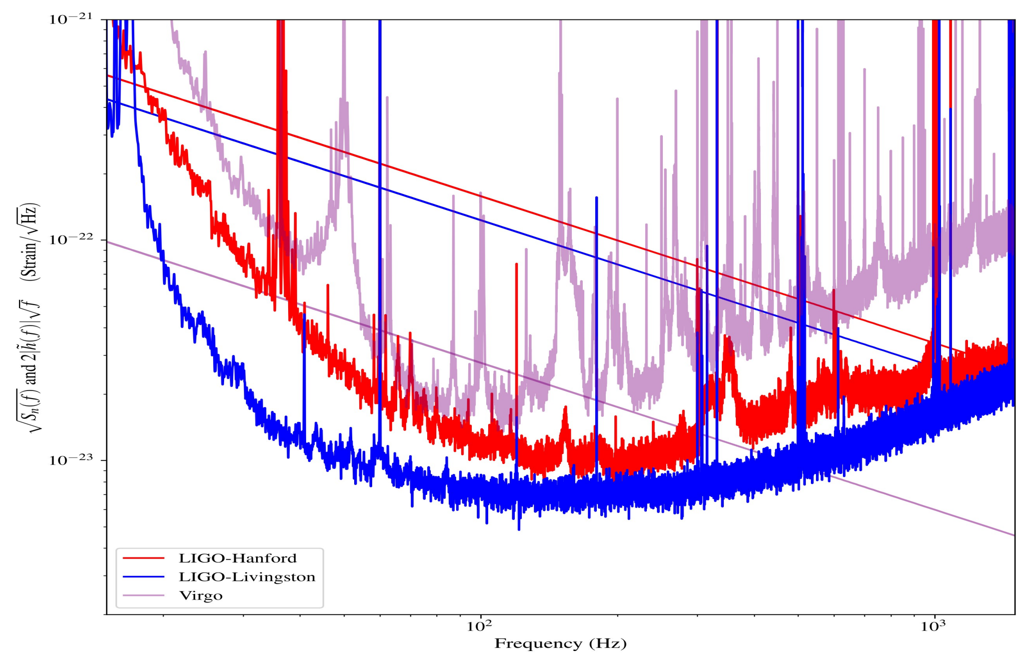
The combined SNR of GW170817 is estimated to be 32.4, with values 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data



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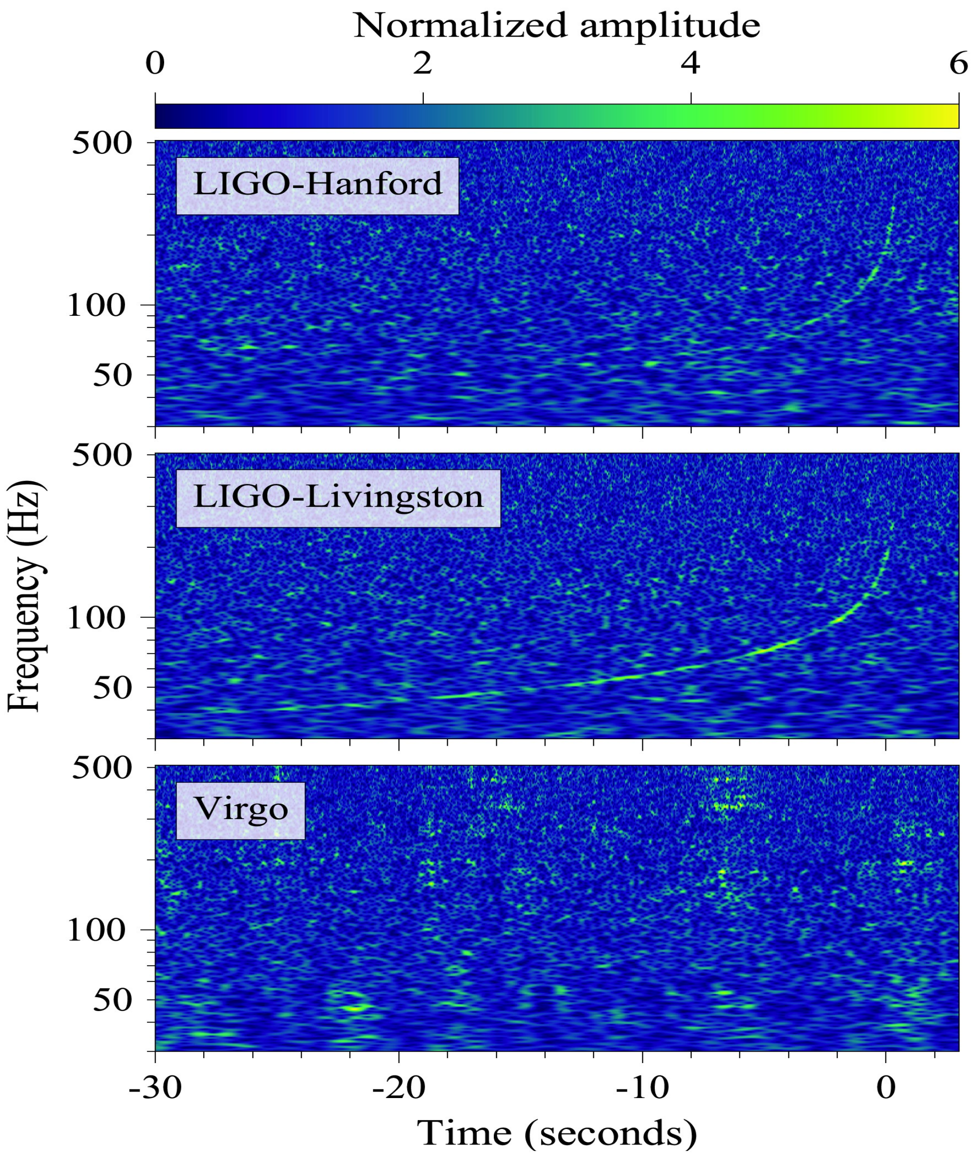

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Signal not visible in Virgo due to:
-lower detector horizon
-antenna pattern of Virgo

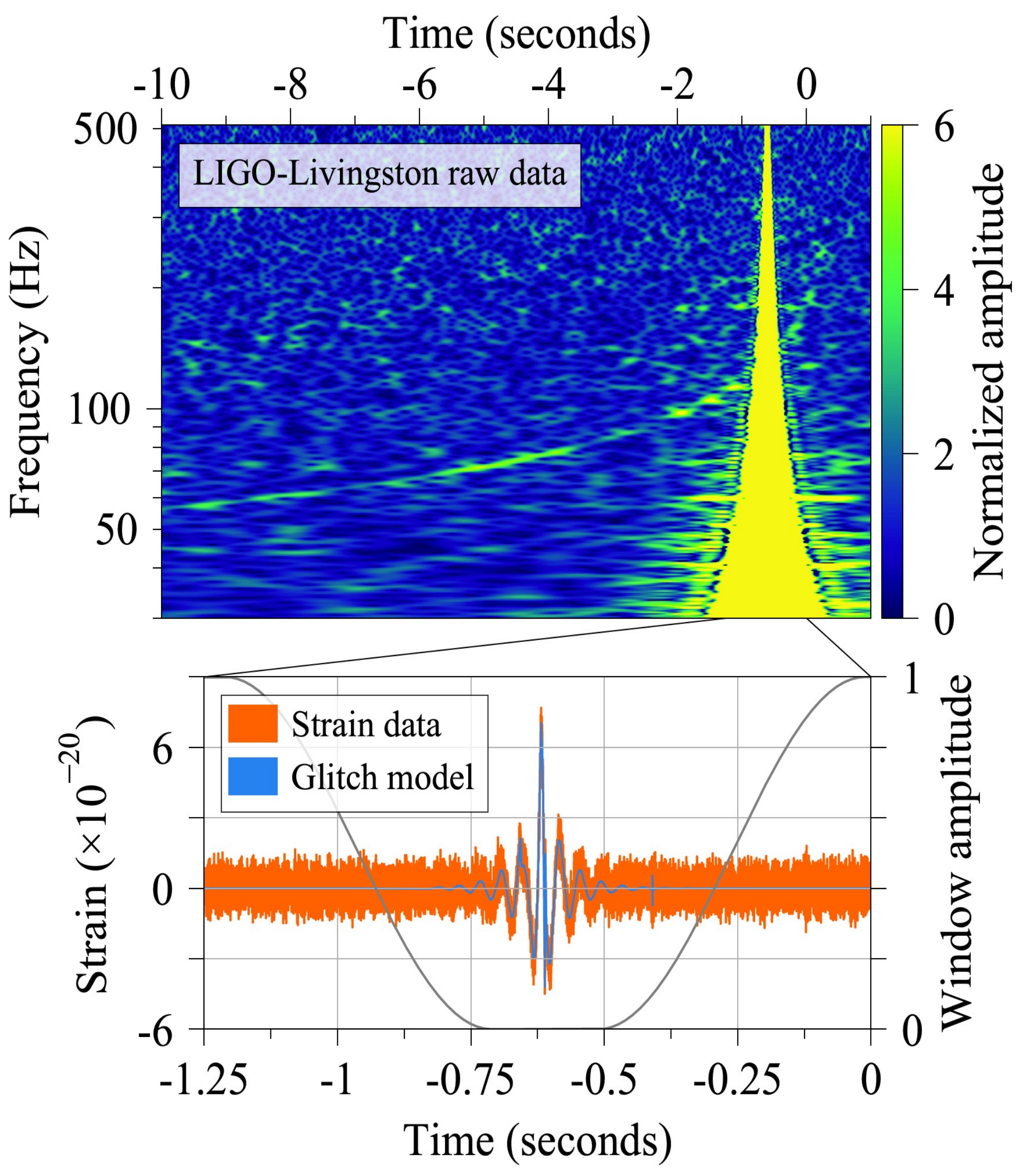
Virgo data used for sky localization and estimation of the source properties

GW170817: Livingston data

A short instrumental noise transient appeared in the LIGO-Livingston 1.1 s before the coalescence time

To mitigate the effect on the results:

- ✗ the search analyses applied a window function to zero out the data around the glitch
- ✗ in the measurement of the source's properties, a model of the glitch based on a wavelet reconstruction was subtracted from the data.



The coalescence time at time 0.4 s

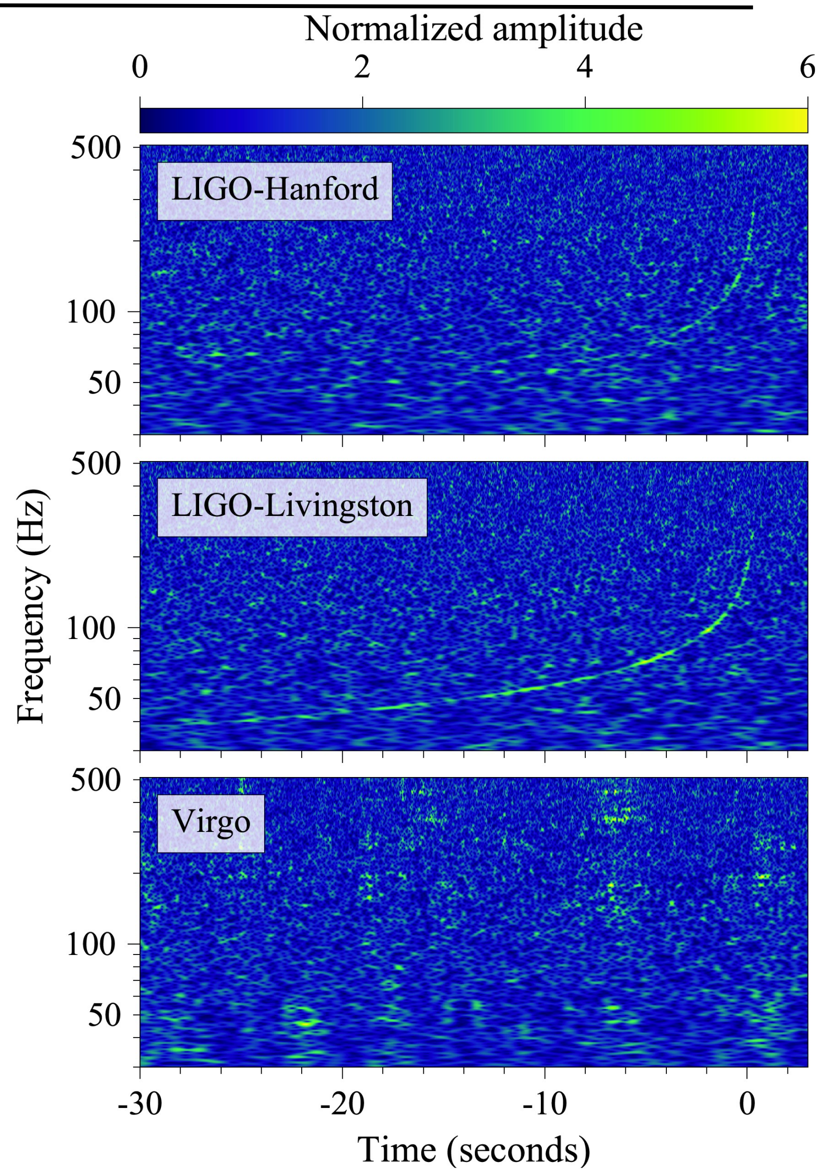
GW170817: detection significance

The searches analyzed 5.9 days of LIGO data (13-21 August)

Two matched-filter binary-coalescence searches targeting sources with total mass between 2 and 500 M_{sun}

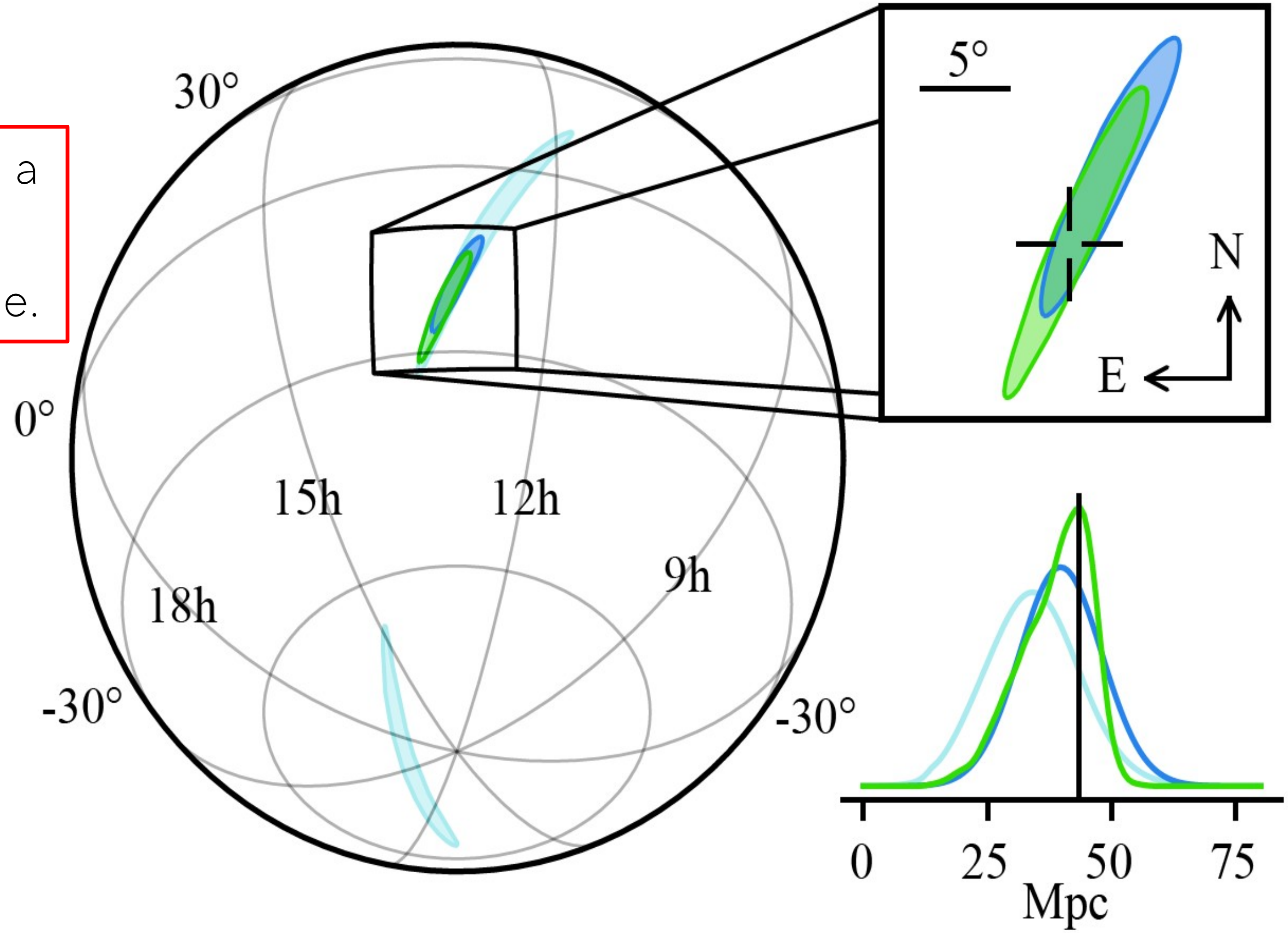
Background estimated by time shifting analysis

GW170817 was identified as the most significant event in the 5.9 days of data, with an estimated false alarm rate (FAR) of one in 1.1×10^6 years with one search and a consistent bound of less than one in 8.0×10^4 years for the other



GW170817: sky location

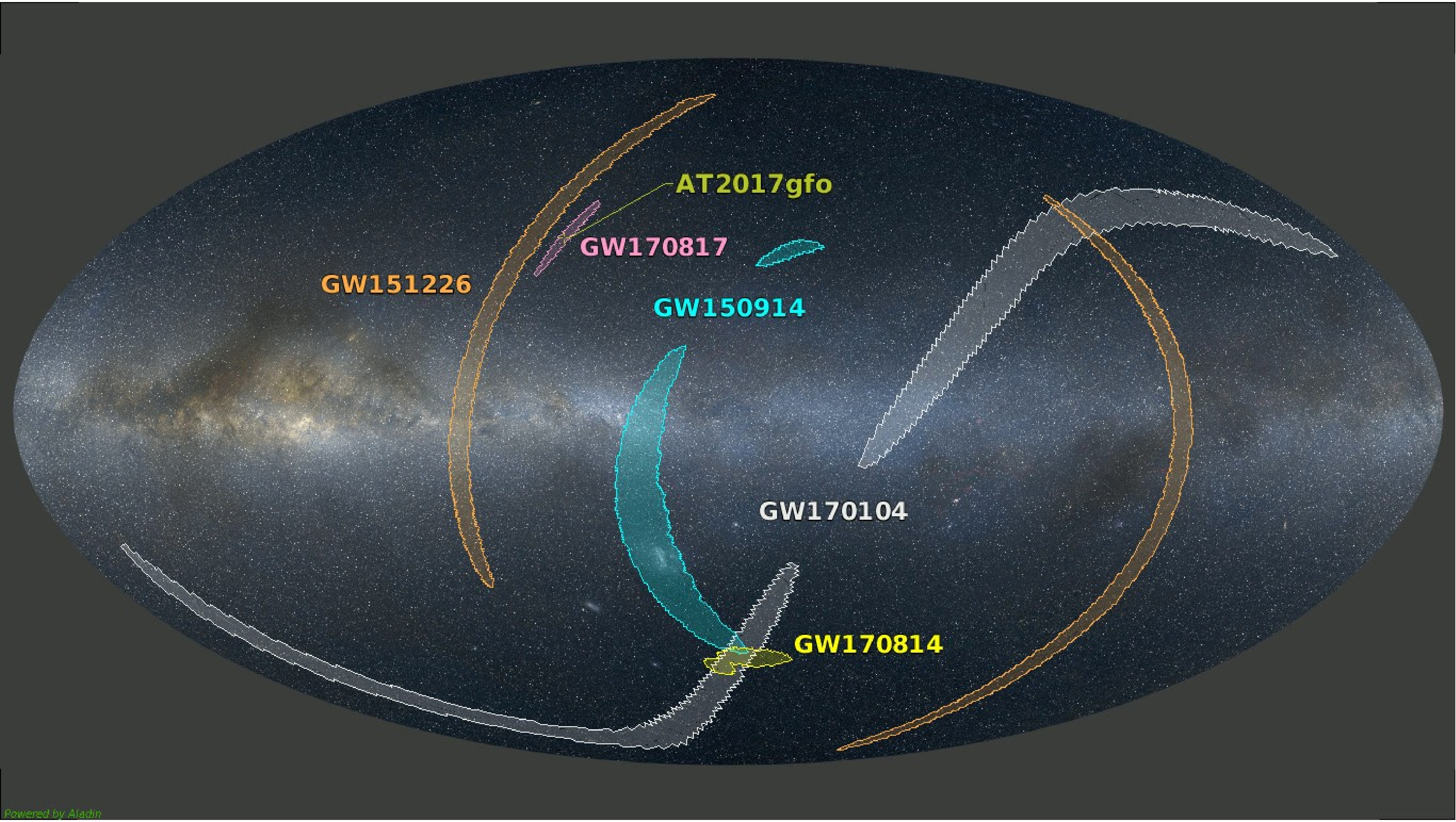
The source was localized to a region of the sky 28 deg^2 in area, and 380Mpc^3 in volume.



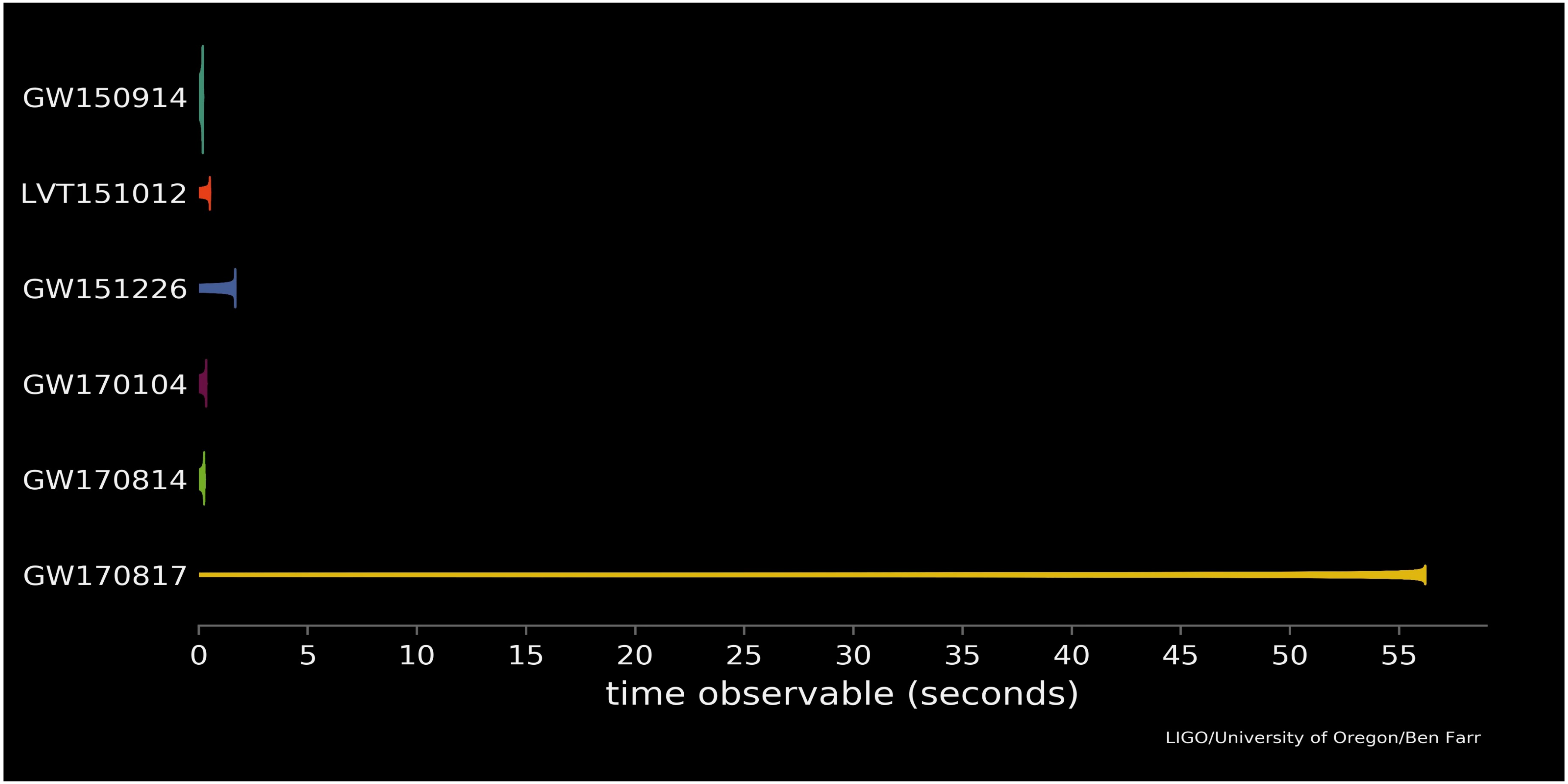
Sky location reconstructed for GW170817:

- ✗ rapid localization algorithm from a HL analysis: 190 deg^2, from a HLV analysis 31 deg^2
- ✗ higher latency HLV analysis improved the localization: 28 deg^2

GW170817: sky location



GW170817



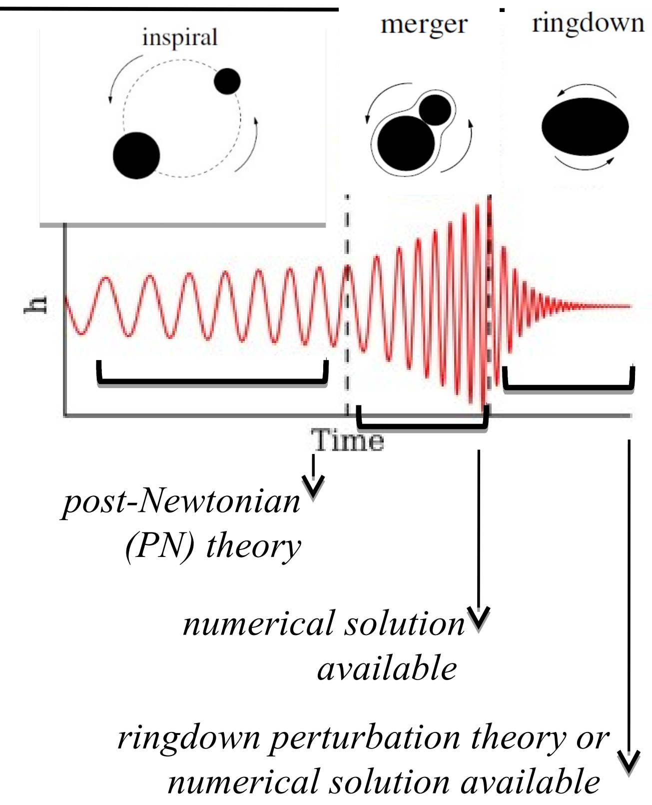
Properties of the source inferred by:

- ✗ matching data with predicted waveform: post Newtonian waveform models (including dynamical effect from tidal interactions, point mass spin-spin interactions)
- ✗ analysis performed in 30-2048Hz, including 1σ calibration uncertainties

GW170817: mass estimation

Chirp Mass estimated from gravitation-phase (3000 cycles in frequency range considered)

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



Source-frame chirp mass $M = 1.188^{+0:004}_{-0.002} M_{sun}$

The total mass of the system is between 2.73 and 3.29M_{sun}

The individual masses in 0.86- 2.26M_{sun}

This suggests a BNS as the source of the gravitational-wave signal

Moreover, although a neutron star-black hole system is not ruled out, the consistency of the mass estimates with the dynamically measured masses of known neutron stars in binaries, and their inconsistency with the masses of known black holes in galactic binary systems, suggests the source was composed of two neutron stars.

GW170817: component masses

Component masses estimation affected by the degeneracy between:

-mass ratio q (m_1/m_2)

-and the aligned spin component $|\chi_z|$

assuming $|\chi|<0.89$:

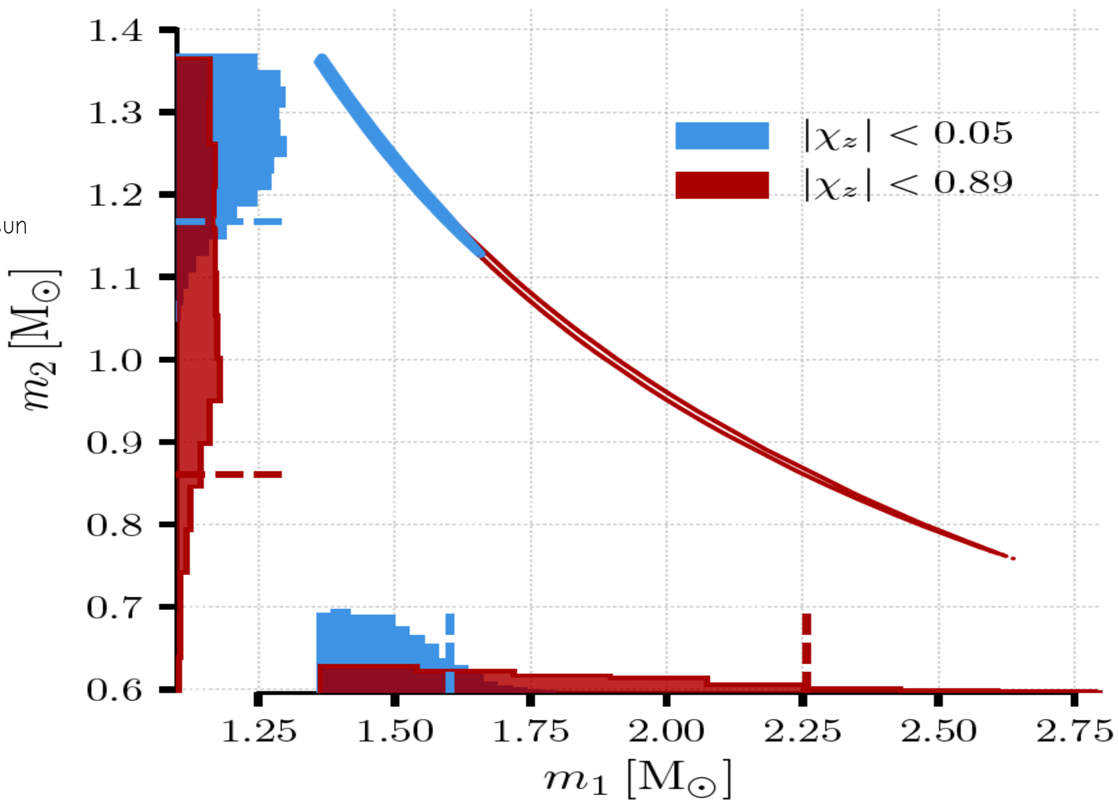
- q ∈[0.4, 1.1]
- m_1 ∈[1.36; 2.26] M_{sun} and m_2 ∈[0.86, 1.36,] M_{sun}

Fastest-spinning known neutron stars $|\chi|\leq 0.4$;
among BNS most extreme spin less ~ 0.04

assuming $|\chi|<0.05$:

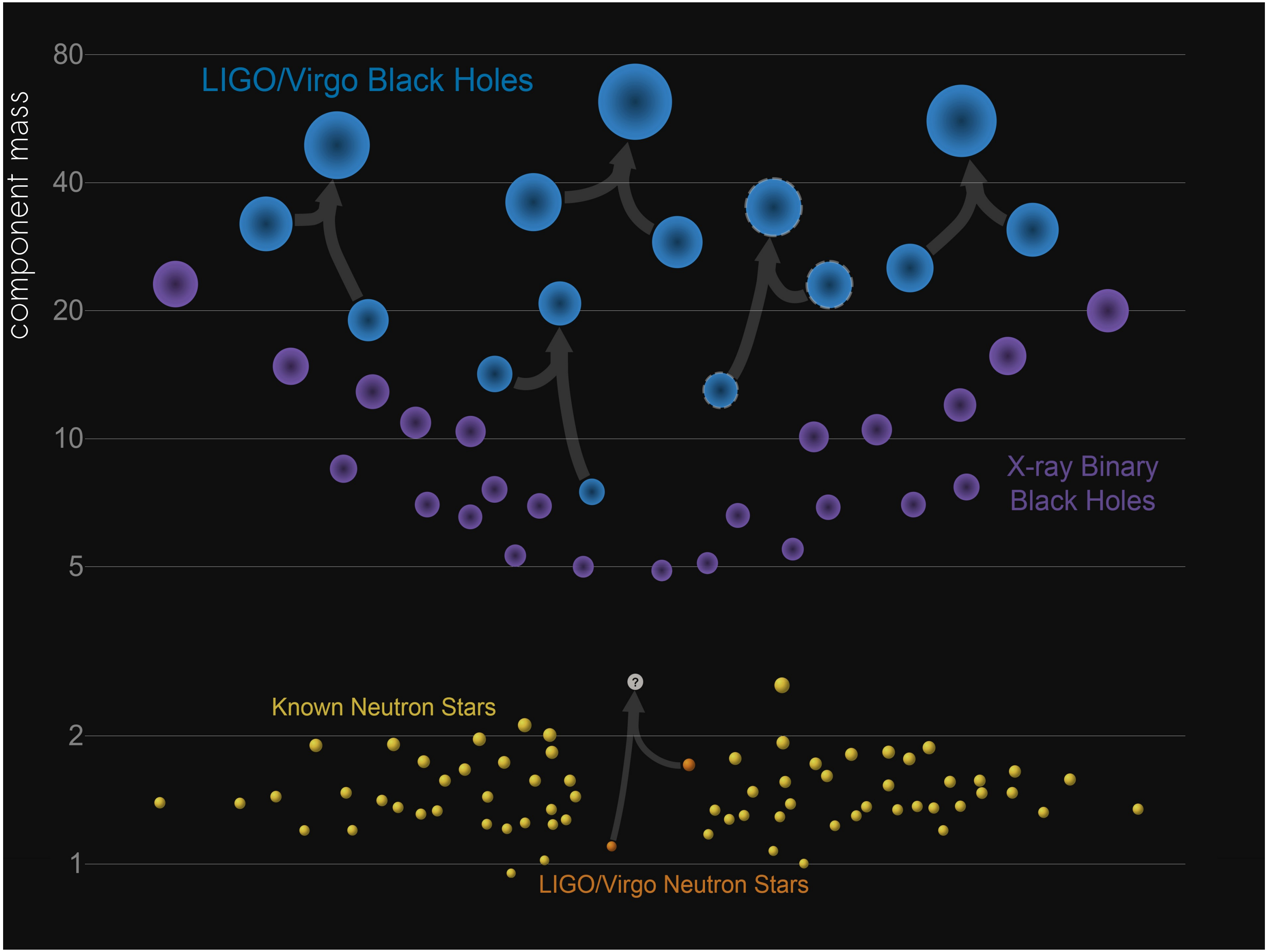
-q ∈[0.7, 1.0]

-m_1 ∈[1.36; 1.6] M_{sun} and m_2 ∈[1.17, 1.36,] M_{sun}



Posterior distribution for the two component mass.
Colored contours enclose 90% of the probability

BNS and BBH masses



Credits LIGO-Virgo/Northwestern/Frank Elavsky

GW170817: source properties

	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	$1.36 - 1.60\ M_\odot$	$1.36 - 2.26\ M_\odot$
Secondary mass m_2	$1.17 - 1.36\ M_\odot$	$0.86 - 1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002}\ M_\odot$	$1.188^{+0.004}_{-0.002}\ M_\odot$
Mass ratio m_2/m_1	$0.7 - 1.0$	$0.4 - 1.0$
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}\ M_\odot$	$2.82^{+0.47}_{-0.09}\ M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025\ M_\odot c^2$	$> 0.025\ M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55^\circ$	$\leq 56^\circ$
using counterpart location	$\leq 31^\circ$	$\leq 31^\circ$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

- Luminosity distance D_L correlated with inclination angle (viewing angle)
- Closest ever observed gw source
- Independent measurement of the distance obtained by the identification of host galaxy

LIGO Scientific Collaboration

VIRGO

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- Viewing angle: D_L is correlated with inclination angle, this degeneracy can be resolved using luminosity distance of the host galaxy

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- ✗ Radiated Energy depends critically on the EOS of neutron-star matter.
- ✗ Lower bound on the energy emitted before the onset of strong tidal effects at f_{GW} ~600 Hz

GW170817

For NSs the tidal field of the companion induces a mass-quadrupole moment

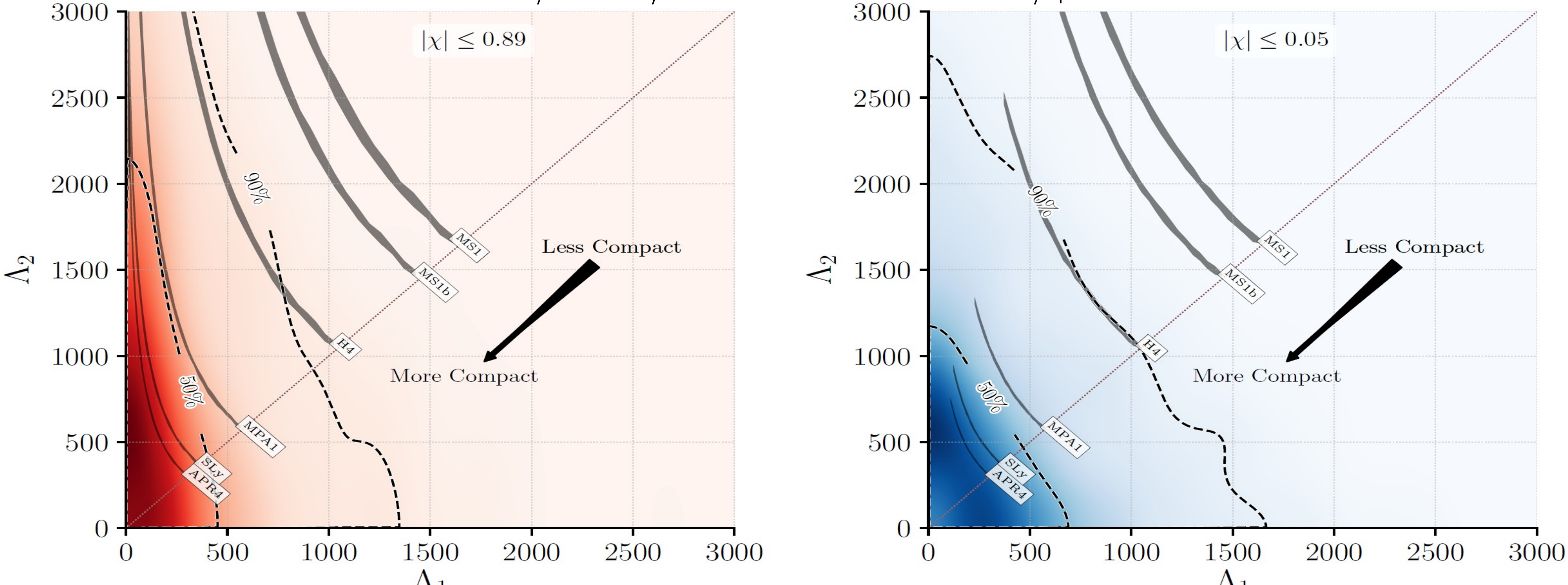
The ratio of the induced quadrupole moment to the external tidal field is proportional to the tidal deformability Λ

$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$

K_2= second Love number

R stellar radius

Probability density for the tidal deformability parameters



We find that our constraints on Λ_1 and Λ_2 disfavor equations of state that predict less compact stars, since the mass range we recover generates values outside the 90% probability region

GW170817: Astrophysics implications

Astrophysics rate: arXiv:1710.05837

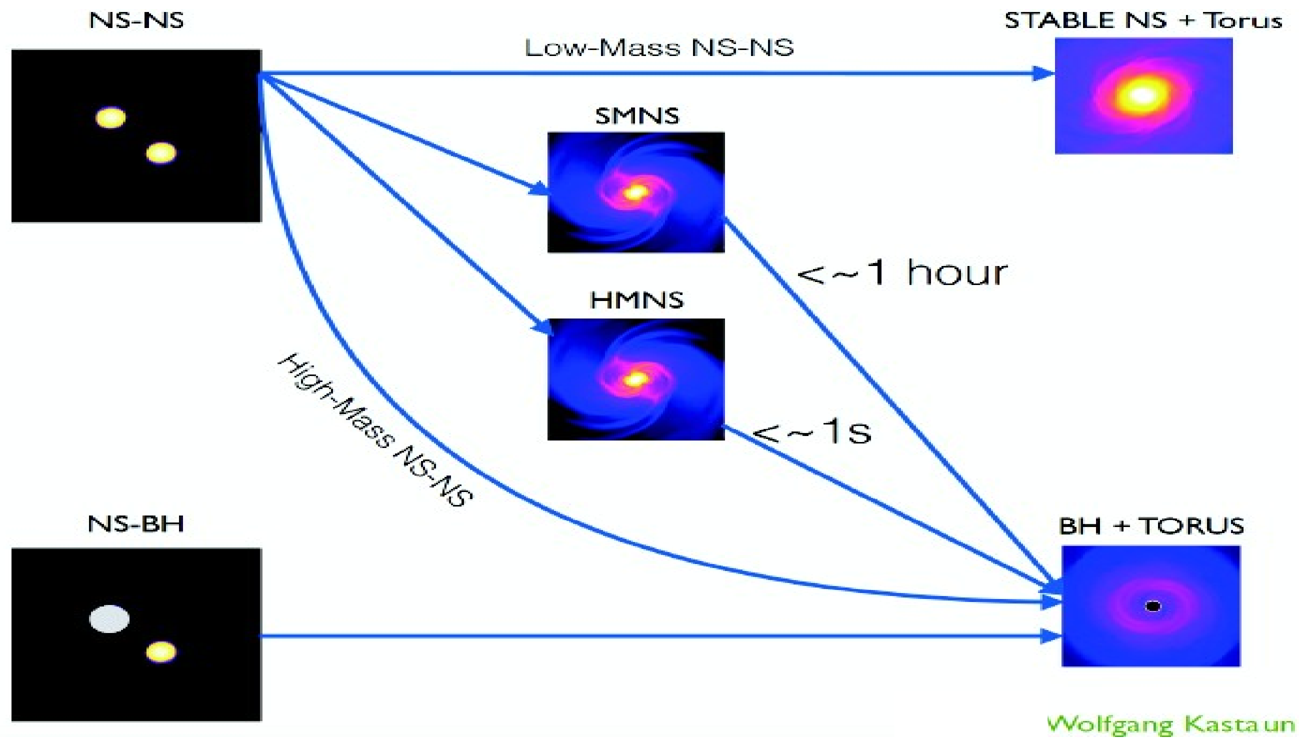
- ✗ Analyses identified GW170817 as the only BNS signal detected in O2 with a far < 1/100 yr.
- ✗ Infer the local coalescence rate density R of BNS systems = 1540^{+3200}_{-1200} Gpc^{-3}yr^{-1} (considering R= 12600Gpc^{-3}yr^{-1} from O1 analysis)
- ✗ The stochastic background of gravitational waves produced by BNS mergers should be comparable to the stochastic background produced by BBH mergers.
- ✗ Assuming the median merger rates, the background my be detected with SNR=3 after 40 months of accumulated observation time during the Design phase

Kilonova arXiv:1710.058376

- ✗ GW measurements provide constrains on the mass dynamical ejecta.
- ✗ Estimates depend on masses of components (spins), rotations, post-merger winds, magnetic fields..
- ✗ low spin configurations predict smaller ejecta masses (10^{-3} -10^{-2} M_{sun}), higher ejecta masses possible for higher spin (10^{-1} M_{sun})

→ See next talks (Cappellaro & Ciolfi)

GW170817: Post merger



BNS merger possible outcome:

- ✗ stable NS (τ_{GW} 10^2-10^5s)
- ✗ supramassive (SMNS) (τ_{GW} 10-100s)

→ Magnetar, bar-mode instabilities, r-mode instabilities

- ✗ hypermassive neutron star (HMNS) (τ_{GW} 10-100ms)

→PMNS GWs burst signals, dominant power in freq ~2-4 kHz, strongly depends on EOS.

- ✗ prompt collapse to BH →BH ringdown will be ~6-7 kHz (no detectable by Ligo-Virgo sensitivity)

GW170817: Post merger

- ✗ BNS mergers may result in a short- or long-lived neutron star remnant that could emit GW following the merger.

- ✗ Burst searches (without assumptions on the morphology signal):
  -for short (tens of ms) frequencies range 1- 4 kHz
  -for intermediate duration (≤ 500 s) GW signals from a NS remnant frequencies range 24-2048Hz
  .
- ✗ There is no evidence of a post-merger signal of astrophysical origin. However, upper limits placed on the strength of GW emission cannot definitively rule out the existence of a short- or long-lived post-merger neutron star.

Paper in progress

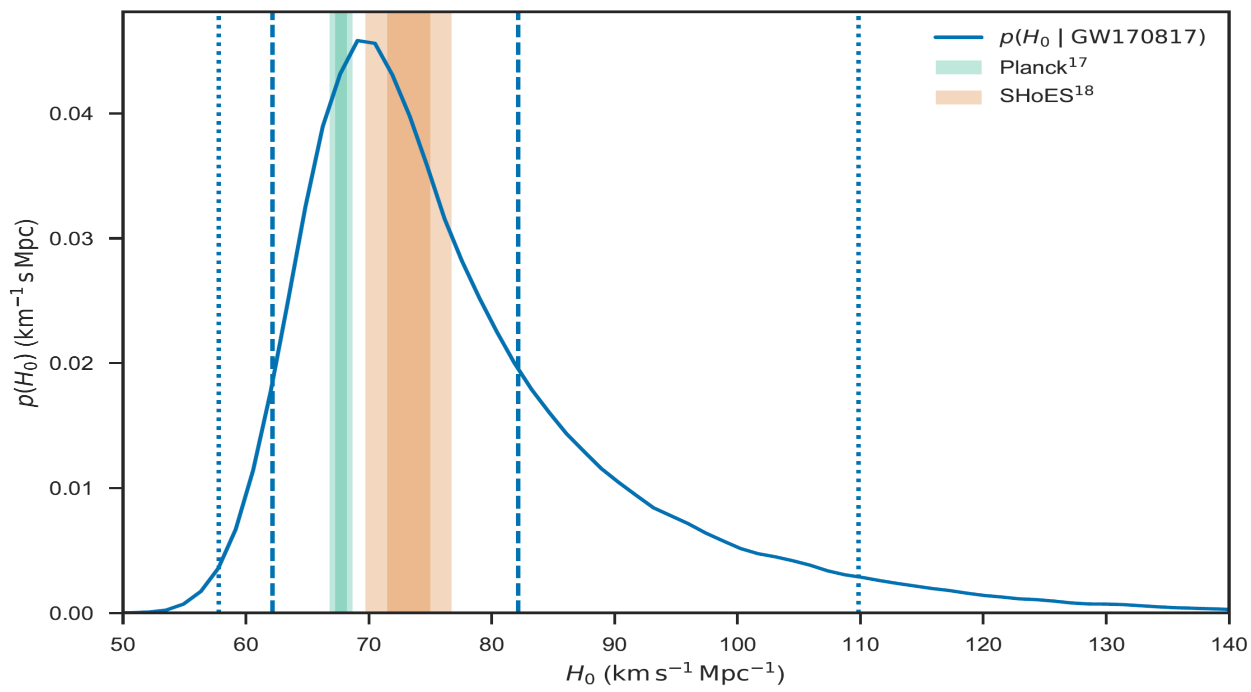
GW170817: Implications

Cosmology:

Using the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the Gravitational wave signal, the Hubble constant is inferred to be

$$H_0 = 70^{+12}_{-8} \ \mathrm{kms^{-1}Mpc^{-1}}$$

(most probable value and minimum 68.3% probability range, which can be compared to the value from Planck $H_0 = 67 \pm 0.55 \ \mathrm{kms^{-1}Mpc^{-1}}$



See Bartolo's talk

Conclusion

First detection of gravitational waves from the inspiral of a binary neutron star system

Gravitational-wave event GW170817, observed and localized by the two Advanced LIGO detectors and the Advanced Virgo detector, is the loudest gravitational wave signal detected to date.

This coalescence event was followed by a short burst of gamma rays observed with Fermi-GBM and INTEGRAL.

The coincident observation of a gravitational-wave signal and a gamma-ray burst appears to confirm the long-held hypothesis that BNS mergers are linked to short-gamma-ray bursts

Back up

GW170817: implications

Test of gravity:

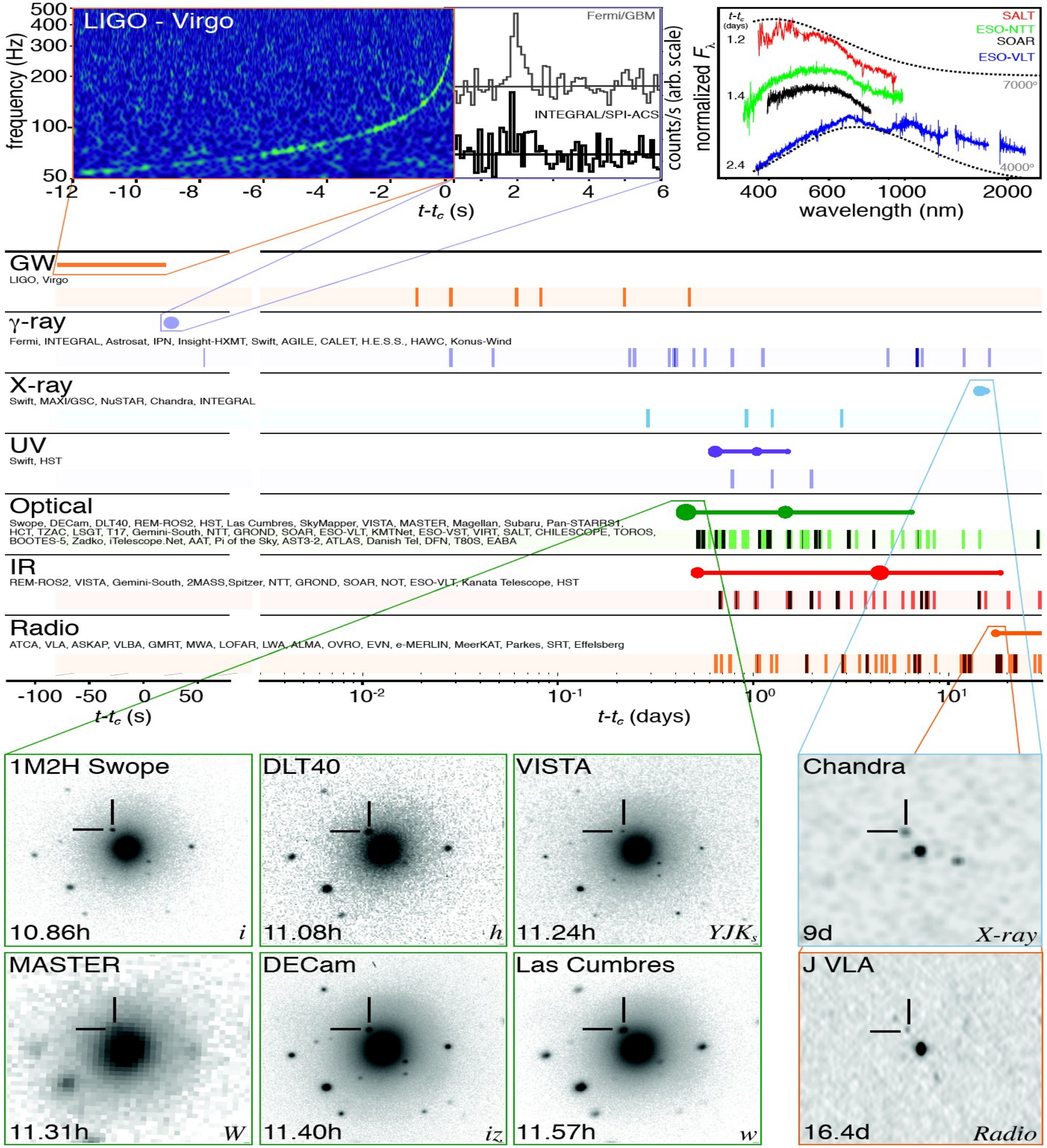
-Combining this delay with the knowledge of the source luminosity distance, strong constraints are placed on the fundamental physics of gravity: speed of gravity, Lorentz invariance, and tests of the equivalence principle

Speed of gravity:

- ✗ $\Delta v/v_{EM} \approx v_{EM}\Delta t/D$
- ✗ D=26Mpc (conservative)
- ✗ Upper bound determined by assumption that peak of GW signal and first photons emitted simultaneously
- ✗ Lower bound sGRB signal emitted 10s before GW

$$-3\times10^{-15} \leq \Delta v/v_{EM} \leq +7\times10^{-16}$$

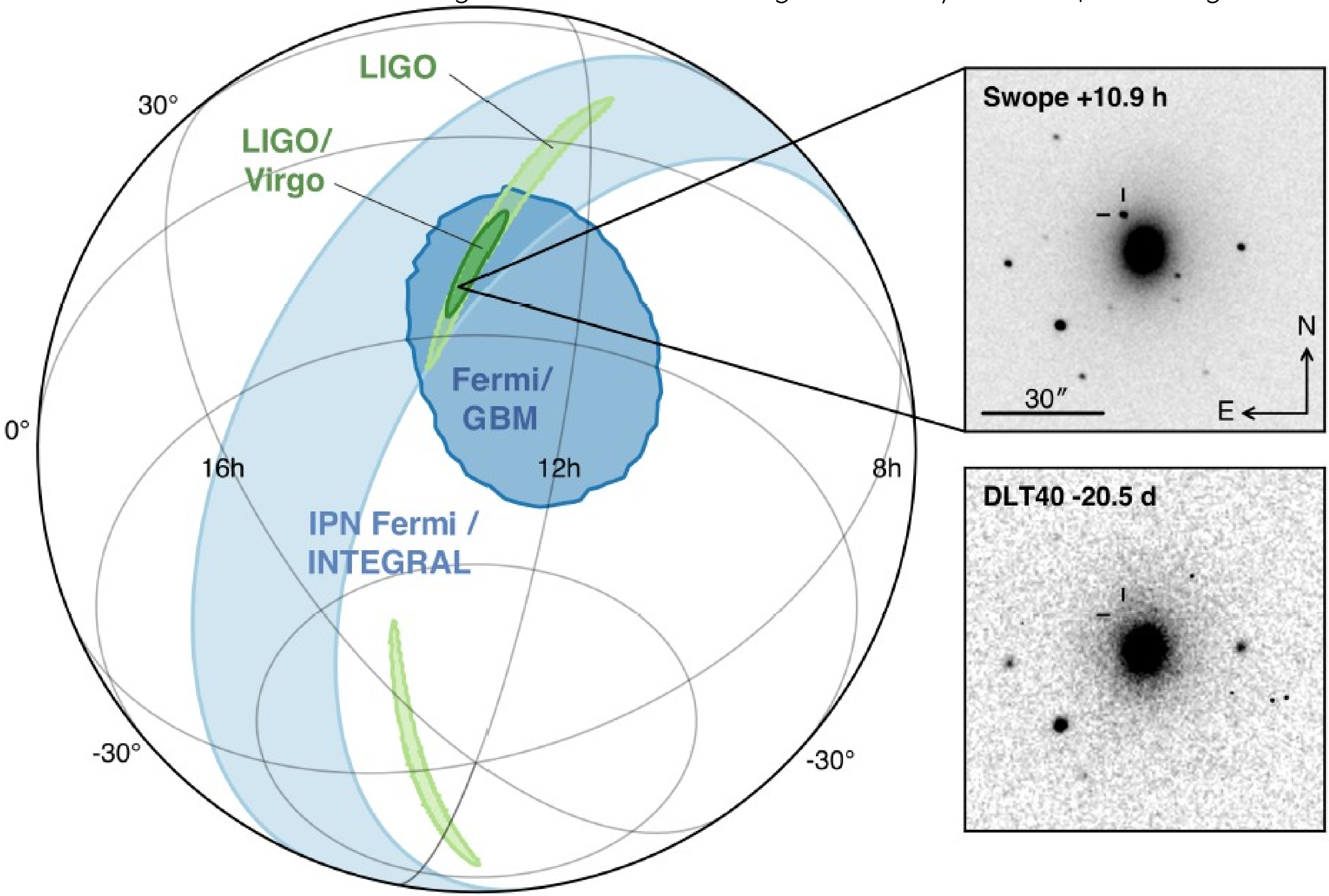
Multi-Messenger observation of BNS



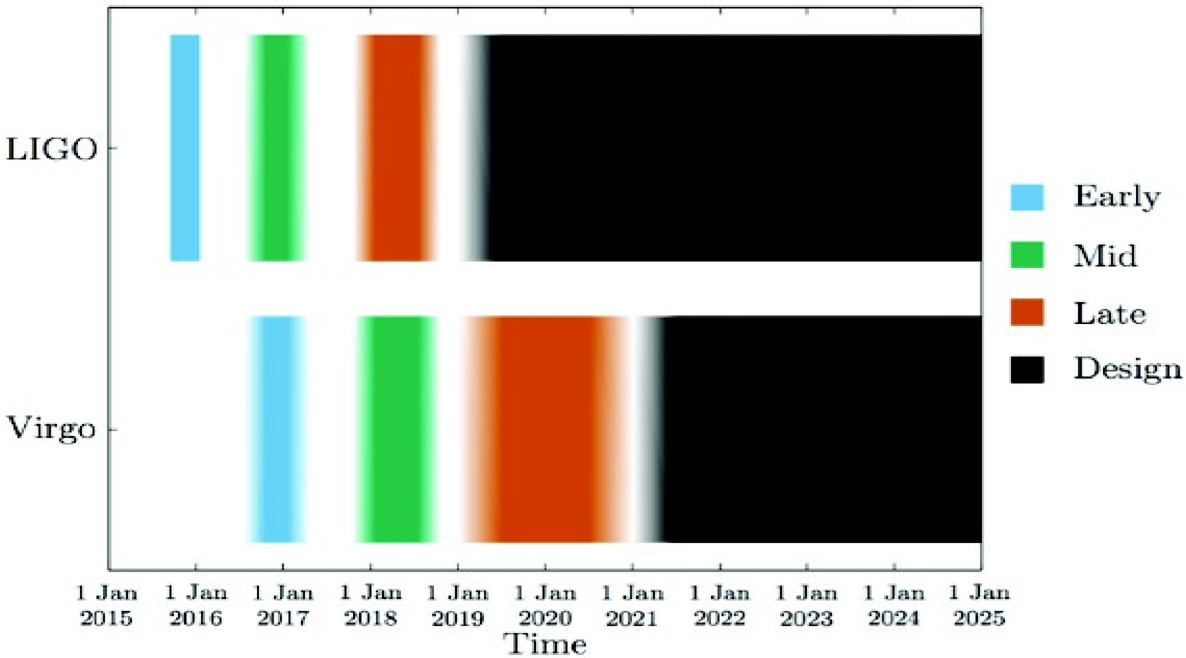
The time line of the discovery of GW170817, GRB170817A, SSS17a/AT 2017gfo and the follow-up observations are shown by messenger and wavelength relative to the time tc of the gravitational-wave event.

Multi-Messenger observation of BNS

Localization of the gravitational-wave, gamma-ray, and optical signals.



Near Future



Performance upgrades by steps, interleaved by scientific observation runs: O2, O3, design

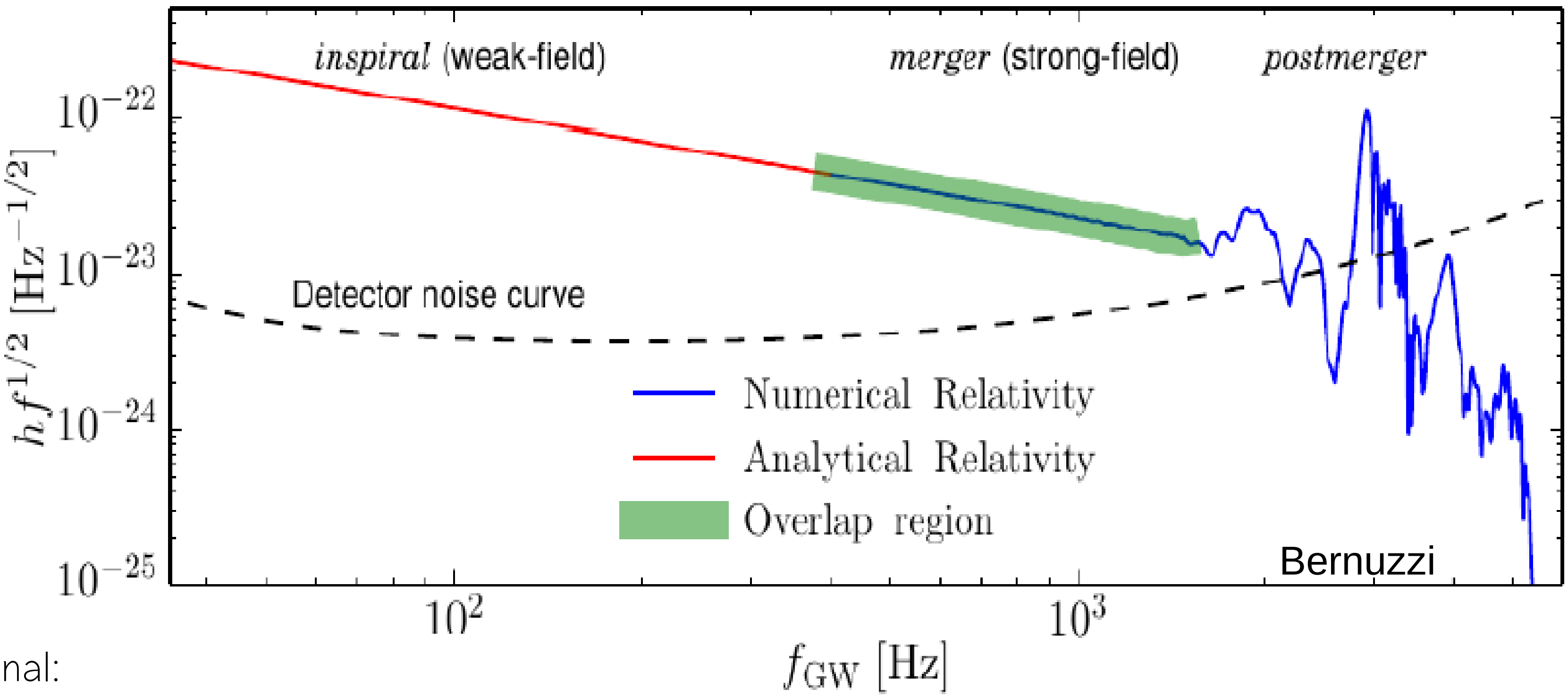
Data taking O2: ongoing

Epoch		2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration		4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc	LIGO	40 – 60	60 – 75	75 – 90	105	105
	Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200	200
	Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections		0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400

Design sensitivity:
Binary NS detection rate:
0.2-200 /year

Living Rev Relativ (2016)

Gravitational waves - PMNS



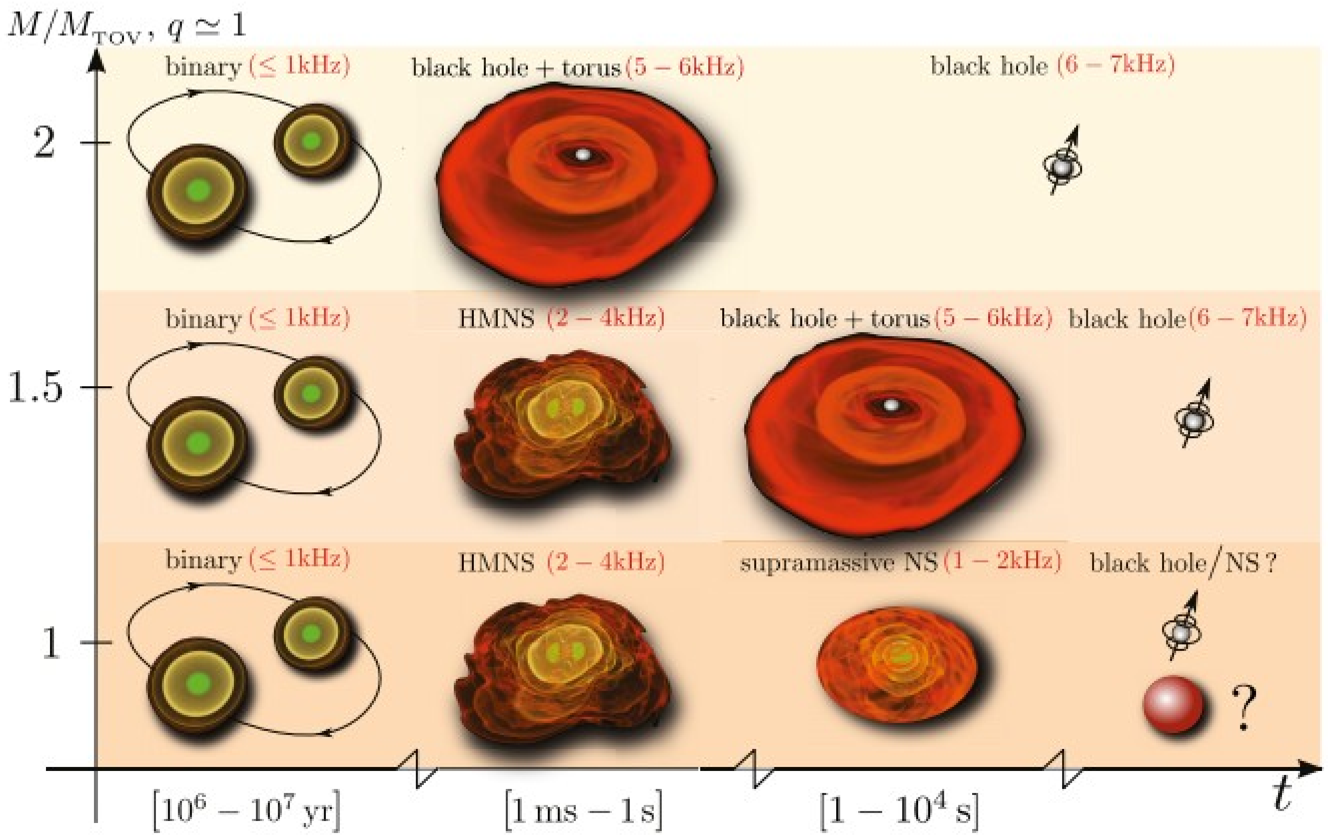
GW signal:

-Inspiral: well approximated by PN/EOB; tidal effects can be important at high PN order

-merger: analytic description possible, tidal effect are important, signature of neutron star EoS

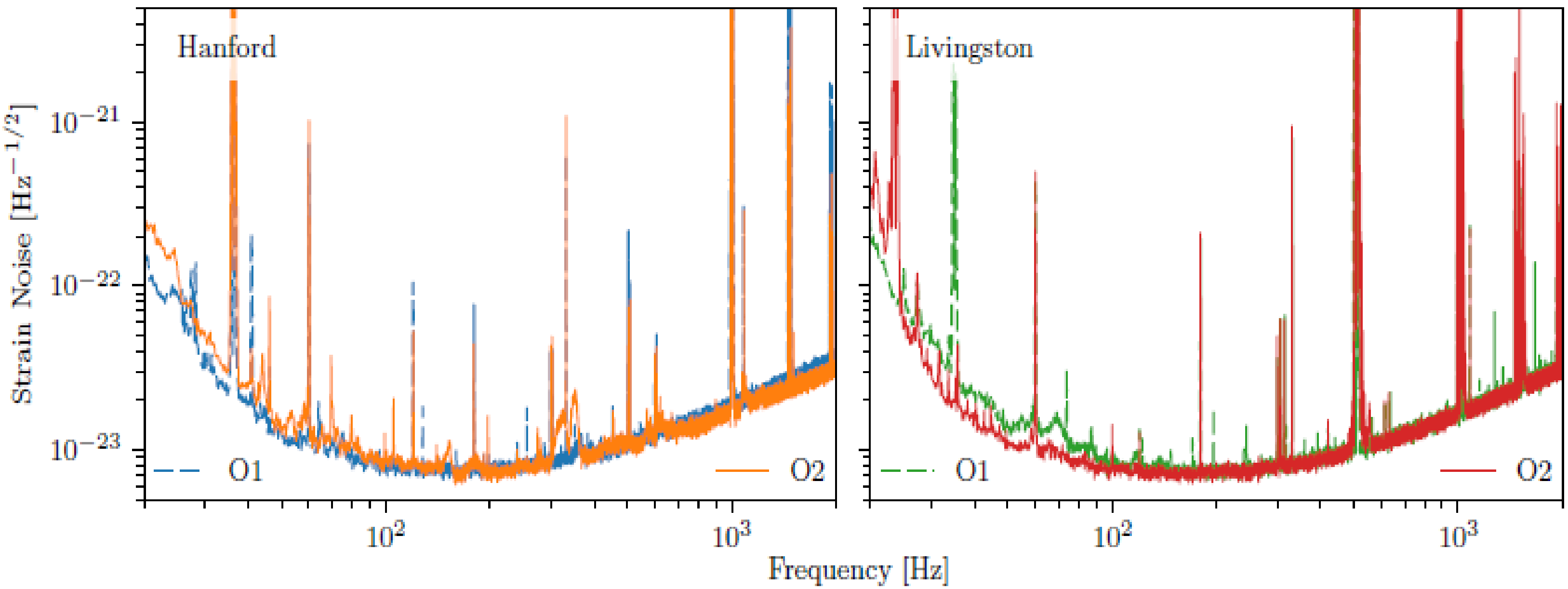
-post merger: among the excited modes, the fundamental (quadrupolar) mode of the NS is expected to produce a strong peak in the emitted GW, strong signature of neutron star EoS. Numerical relativity is needed

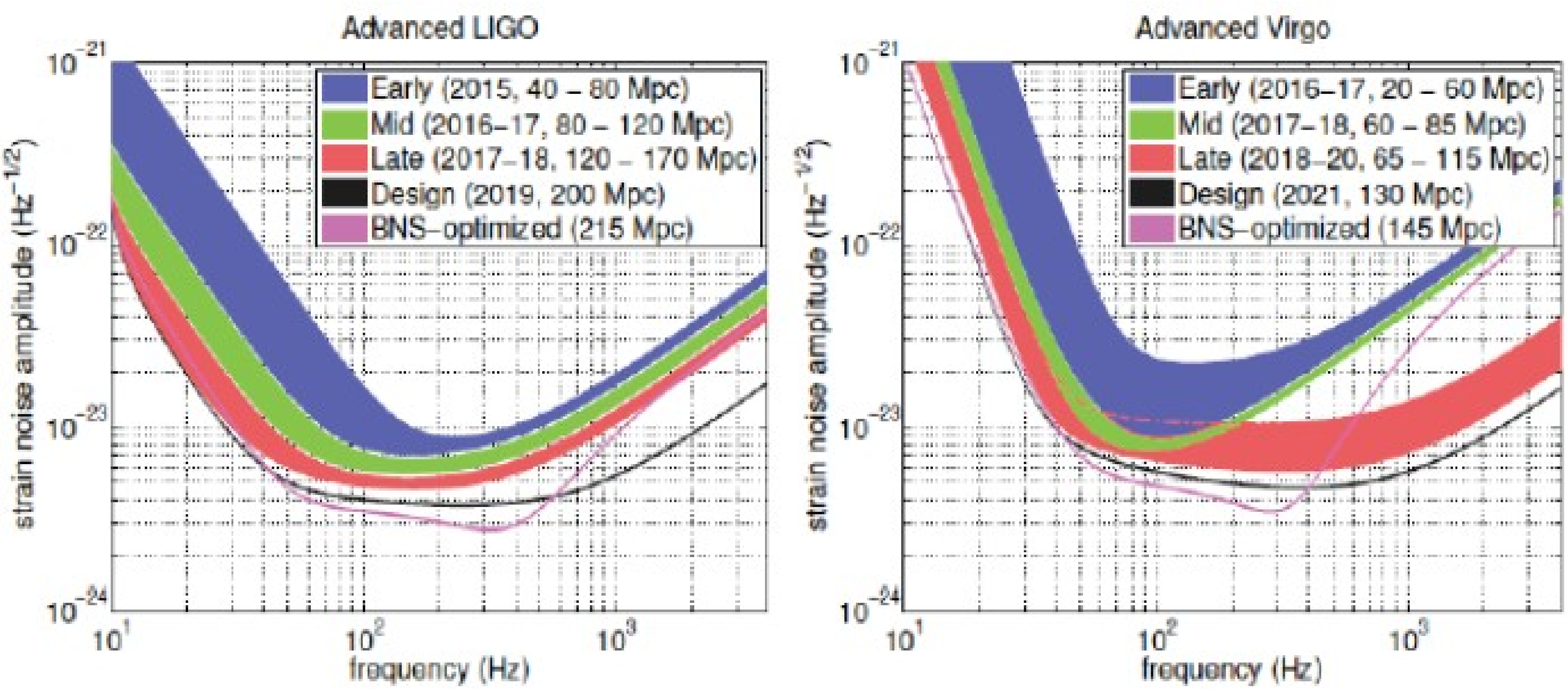
→ High computational cost to have full bank of templates
Accurate waveform models



M/M_{TOV}, $q \simeq 1$
binary (≤ 1kHz)
black hole + torus (5 – 6kHz)
black hole (6 – 7kHz)
2
binary (≤ 1kHz)
HMNS (2 – 4kHz)
black hole + torus (5 – 6kHz)
black hole (6 – 7kHz)
1.5
binary (≤ 1kHz)
HMNS (2 – 4kHz)
supramassive NS (1 – 2kHz)
black hole/NS ?
1
?
$[10^6 - 10^7$ yr$]$
[1 ms – 1 s]
$[1 - 10^4$ s$]$
t

Interferometers sensitivity O1 and O2

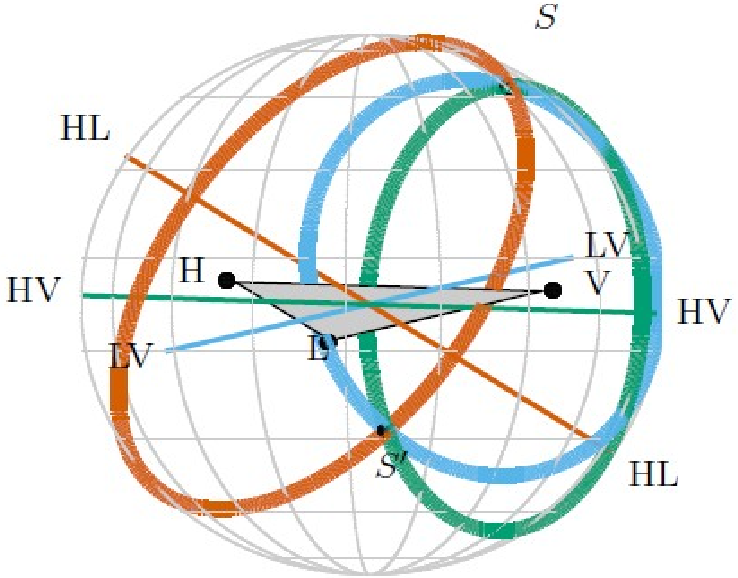




Benefit of three interferometers network: sky localization

Localization of the source position:

- ✗ Triangulation: measure time of flight with 2 or more detector sites and reconstruct ToF rings
- ✗ degeneracy along the rings can be reduce by using variability of antenna pattern



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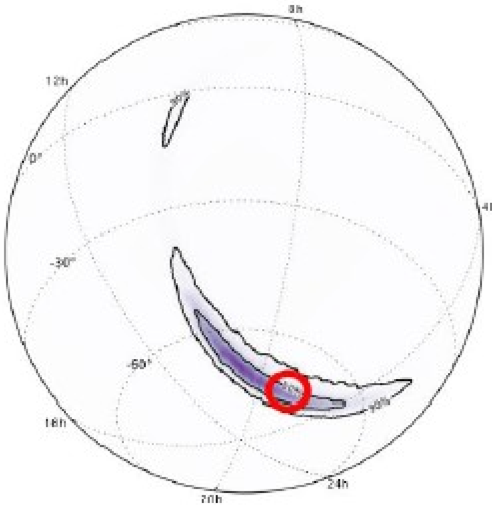


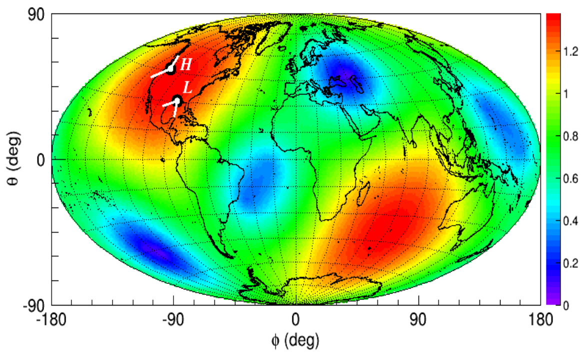
sky localization greatly improved
e.g. for GW150914:
L1H1: 600 deg2
L1H1V1: 20 deg2
expected reduction by ~30 times of sky area at 90% confidence

Benefit of three interferometers network

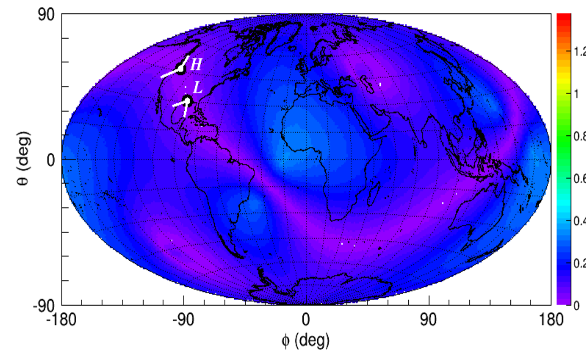
LIGOs arms are almost aligned → Sky coverage of LIGOs is very similar to that of a single detector, almost blind to one GW polarization per each direction

LIGO H1+LIGO L1

$|\vec{F}_{+}|$

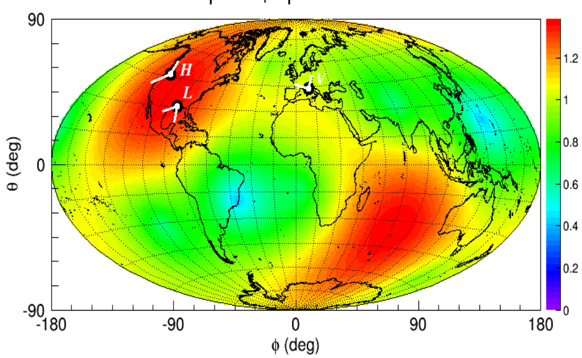


$|\vec{F}_{\times}|$



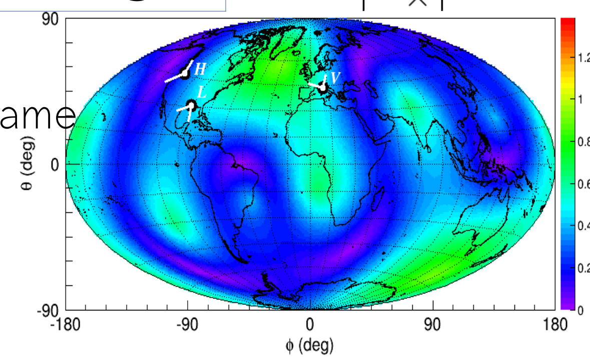
LIGO H1+LIGO L1+Virgo

$|\vec{F}_{+}|$



assuming same spectral sensitivity

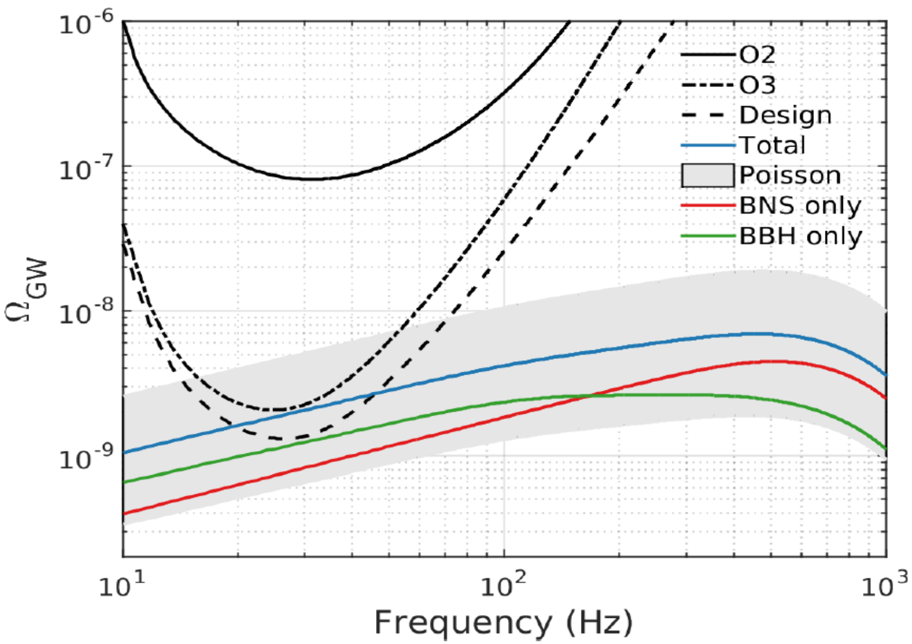
$|\vec{F}_{\times}|$

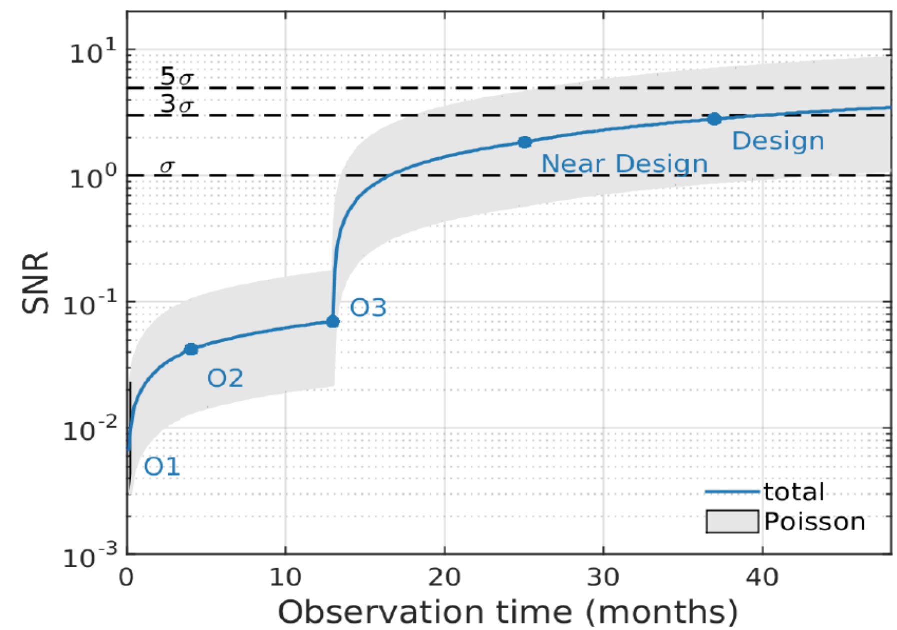


- Detection confidence: lower background and higher Signal-to-Noise Ratio
- coverage of sky and both GW polarizations, better waveform reconstruction
- Increased time coverage of the survey by detector pair

GW170817: Stochastic

arXiv:1710.05837





Estimates of the background energy density GW(f) at 25 Hz for each of the BNS, BBH and total background contributions, along with the 90% Poisson error bounds; and average time between events as seen by a detector in the frequency band above 10 Hz, and the number of overlapping sources at a given time .

	$\Omega_{GW}(25\text{ Hz})$	τ [s]	λ
BNS	$0.7^{+1.5}_{-0.6} \times 10^{-9}$	13^{+49}_{-9}	15^{+30}_{-12}
BBH	$1.1^{+1.2}_{-0.7} \times 10^{-9}$	223^{+352}_{-115}	$0.06^{+0.06}_{-0.04}$
Total	$1.8^{+2.7}_{-1.3} \times 10^{-9}$	12^{+44}_{-8}	15^{+31}_{-12}