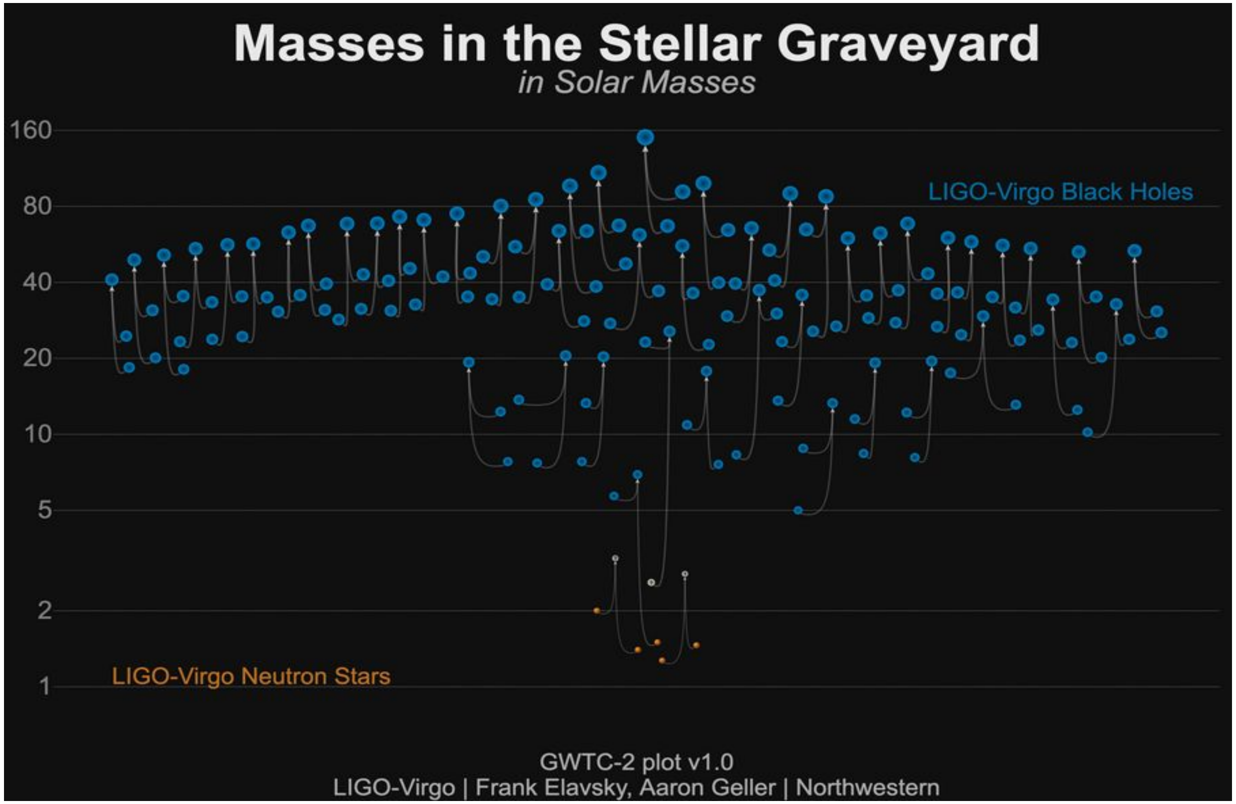
Gravitational waves searches in O3 Advanced LIGO and Advanced Virgo data



Lazzaro Claudia
on behalf of LVK Collaboration

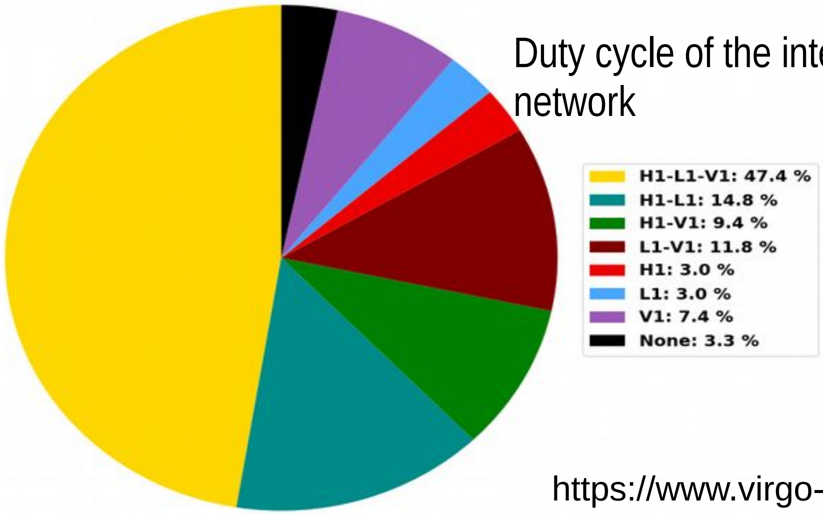
Outline

- Interferometers network in O3 data taking
- Gravitational Wave Transient Catalog 2 (GWTC-2) and test of general relativity with GWTC-2
- O3 data taking: GW exceptional events

O3 observing run

Three observing runs have happened to date:
O1: 12 Sep 2015 -20 Oct 2015
O2: 30 Nov 2016 - Aug 25th
O3a: 1 Apr 2019 - 1 Oct 2019
O3b: 1 Nov 2019 - 27 Mar 2020
O3b data taking ended due to the impact of COVID-19

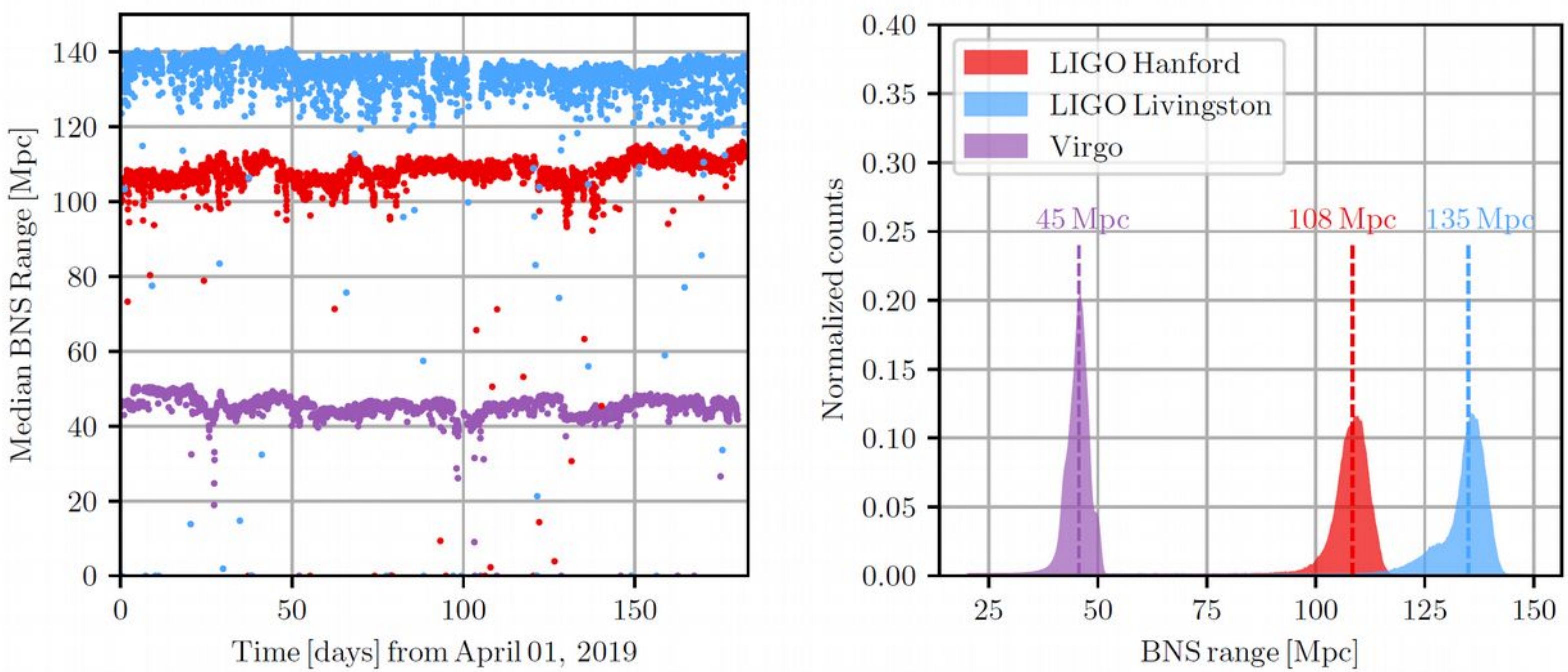
Duty cycle of the interferometer network



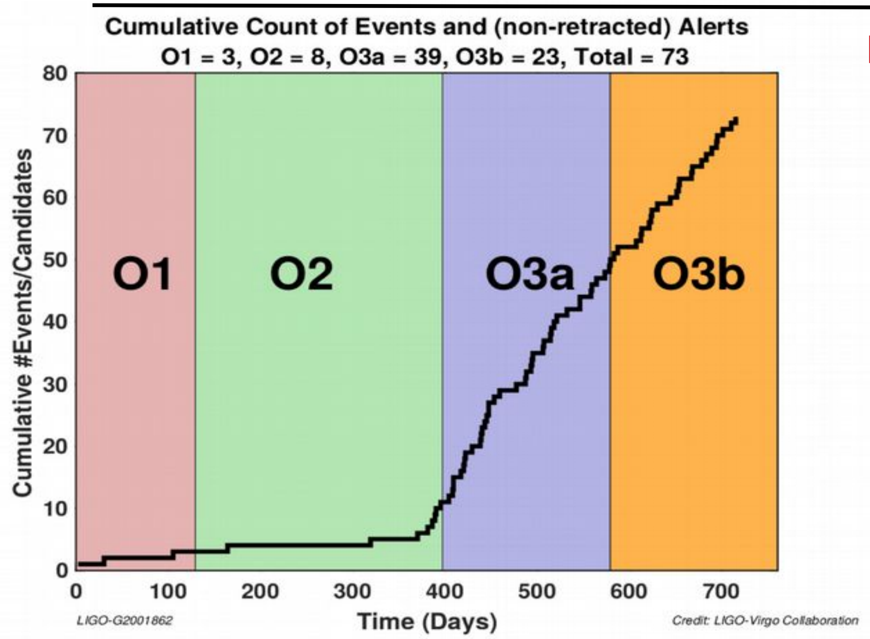
https://www.virgo-gw.eu/status.html

The sensitivity, quantified by Binary neutron star inspiral range for first phase of O3 (O3a)

- Hanford: 108 Mpc
- Livigstone 135 Mpc
- Virgo: 45 Mpc

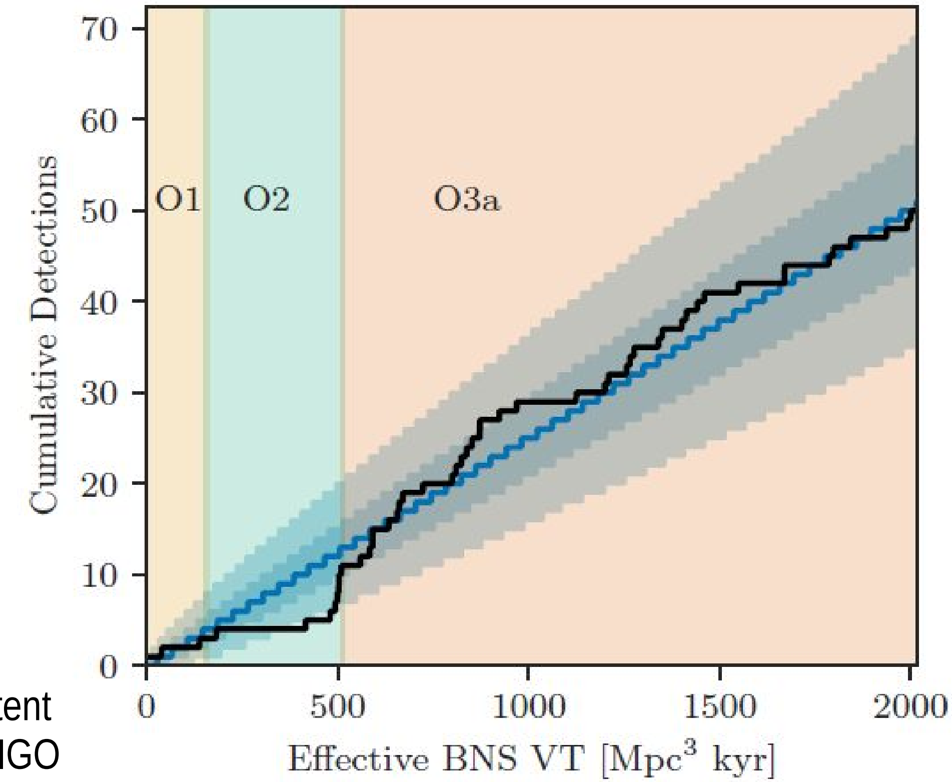


Gravitational-wave Transient Catalog-2



LIGO-G2001862

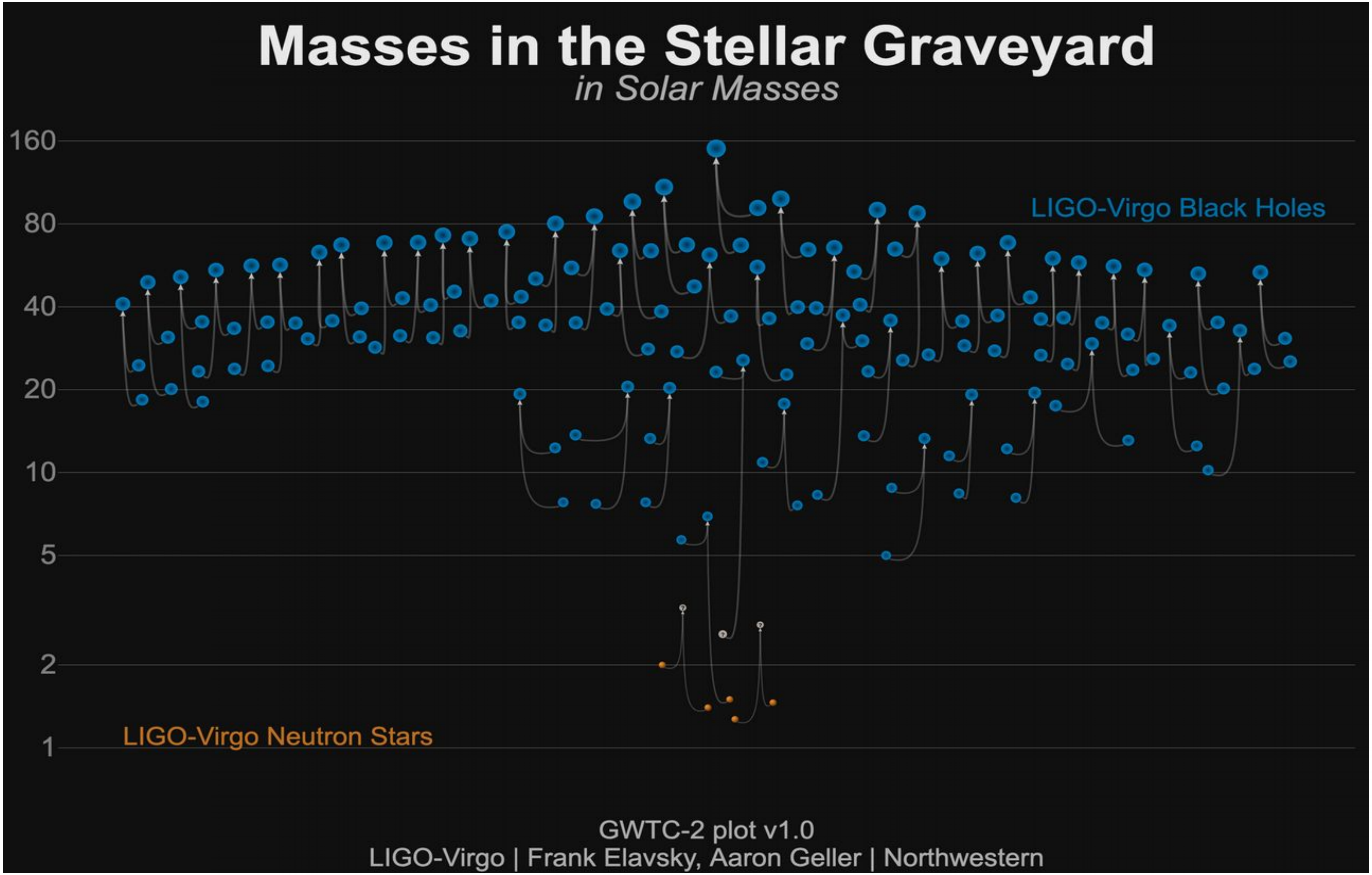
Compact binaries coalescence:
- O1-O2: detection ~every few months
- O3: detection ~weekly



- GWTC-1 (Physical review X 9, 031040, 2019):
  11 confident detections during 01 and O2
- GWTC-2 (Phys. Rev. X 11, 021053, 2021) :
  39 confident detections during O3a

The detection of 39 candidate events in 26 weeks is consistent with GWTC-1, given the increased sensitivity of Advanced LIGO and Advanced Virgo

Gravitational-wave Transient Catalog-2

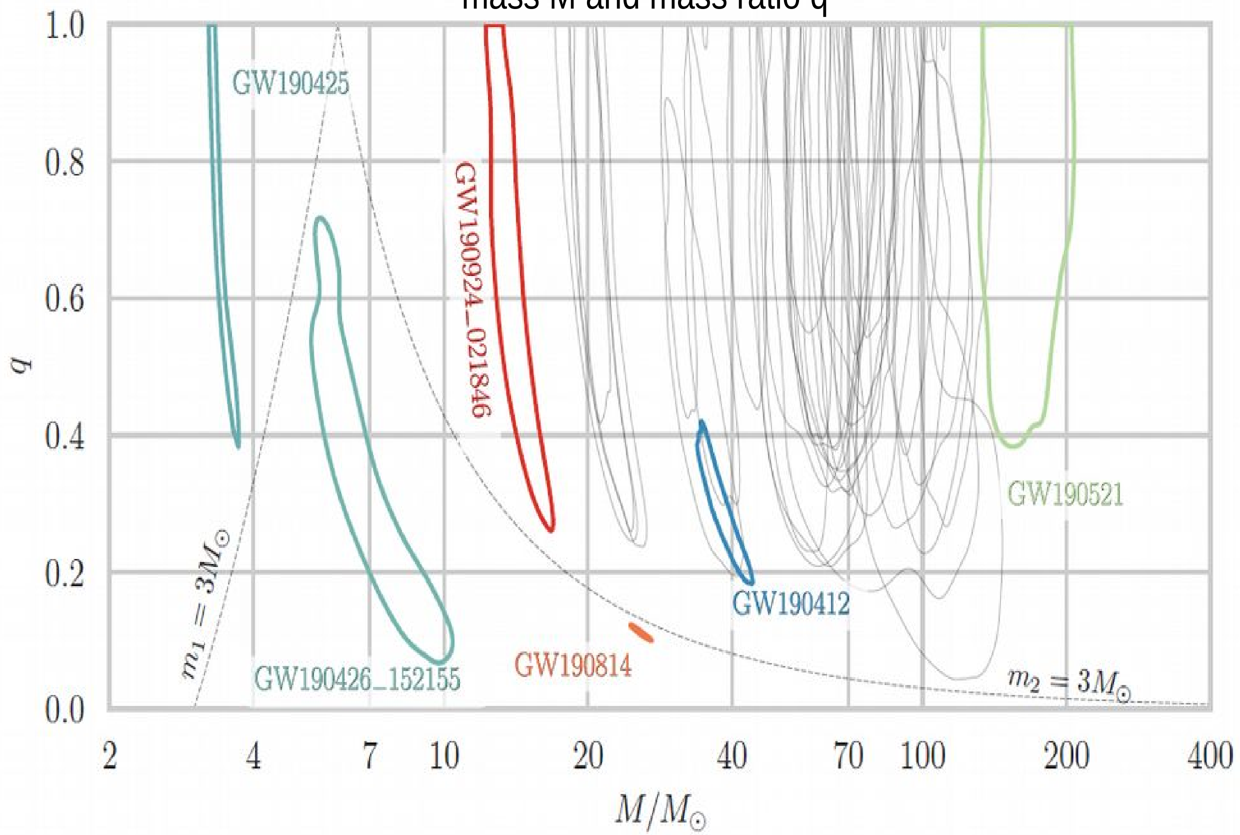


Gravitational-wave Transient Catalog-2

- reported 39 candidate GW imposing false alarm rate less than 2 per years (expected contamination fraction less than 10%)
- 4 search pipelines: 3 template searches, 1 unmodeled search

- Total masses of BBH system from 14M$_\odot$ for GW190924_021846 to 150M$_\odot$ for GW190521
- This catalog includes binary systems with significantly asymmetric mass ratios
- 11 of the 39 events detected have positive effective inspiral spins under our default prior (at 90% credibility), while none exhibit negative effective inspiral spin.

Credible region contours for all candidate events in the plane of total mass M and mass ratio q

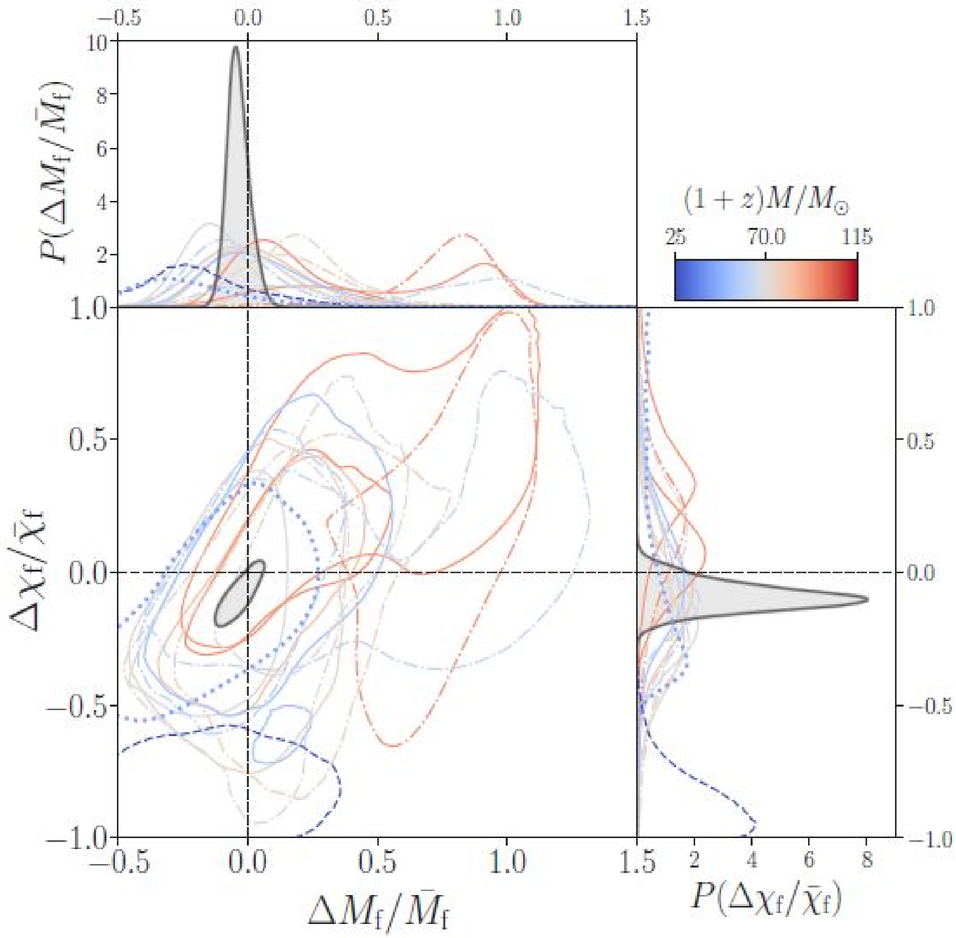


Testing general relativity

Phys. Rev D. 103, 122002 (2021)

Tests of general relativity in the highly dynamical and strong-field regime:

- Residuals from best-fit waveforms consistent with detector noise
- Consistency of parameters inferred from inspiral and ringdown phases of the signal

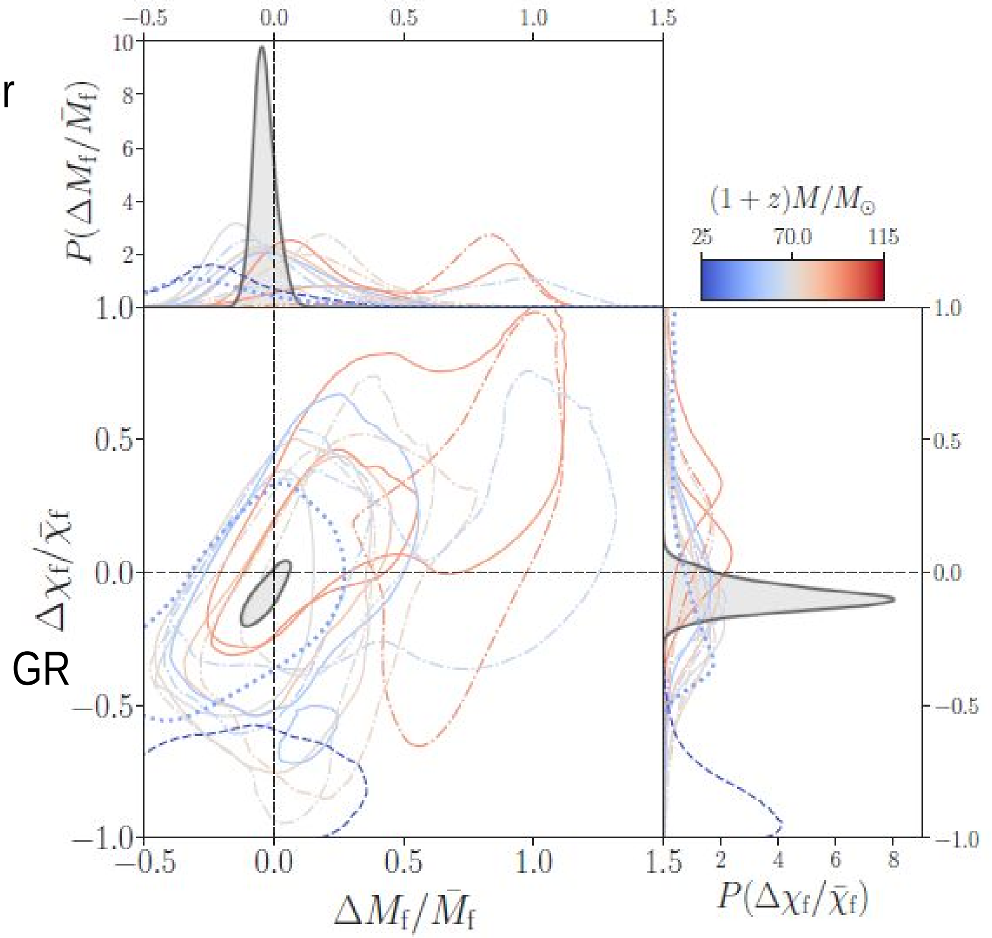


Testing general relativity

Phys. Rev D. 103, 122002 (2021)

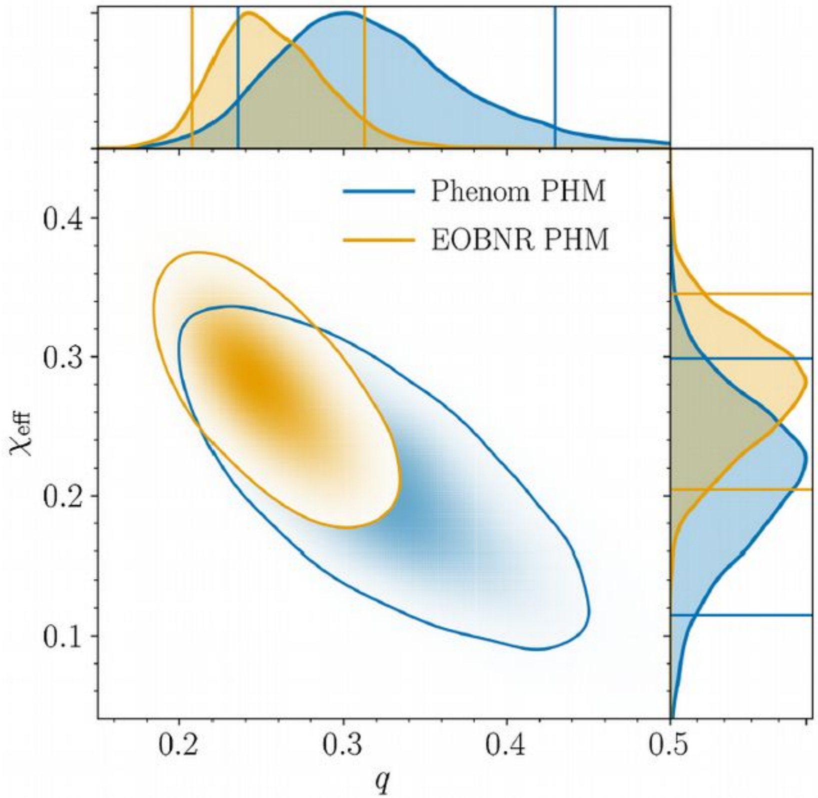
Tests of general relativity in the highly dynamical and strong-field regime:

- Residuals from best-fit waveforms consistent with detector noise
- Consistency of parameters inferred from inspiral and ringdown phases of the signal
- Measured PN coefficients consistency with GR
- Consistency with no dispersion of GWs and massless graviton
- Ringdown frequencies and damping times consistent with GR
- No detection of echoes
- No evidence for pure scalar or pure vector polarisations



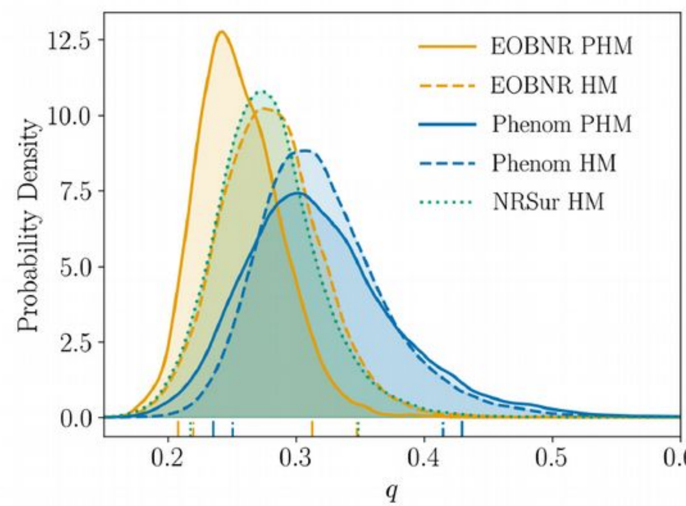
O3 exceptional events: GW190412

Phys. Rev. D 102, 043015 (2020)



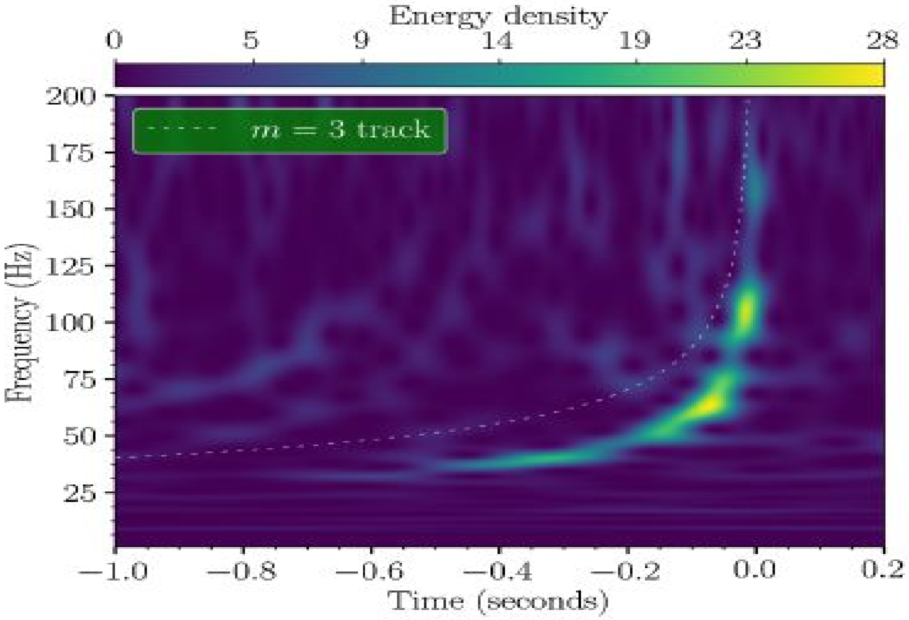
- First GW signal observed due to coalescences of two BHs with asymmetric masses of $30.1^{+4.6}_{-5.3}\,M_\odot$ and $8.3^{+1.6}_{-0.9}\,M_\odot$ black.
- Mass ratio $q = 0.28^{+0.12}_{-0.07}$ (median and 90% confidence intervals)
- Asymmetric systems are predicted to emit gravitational waves with stronger contributions from higher multipoles
- third BH binary identified with at least one non zero spin component, small value (<0.1) of precessing spin parameter X_p disfavored

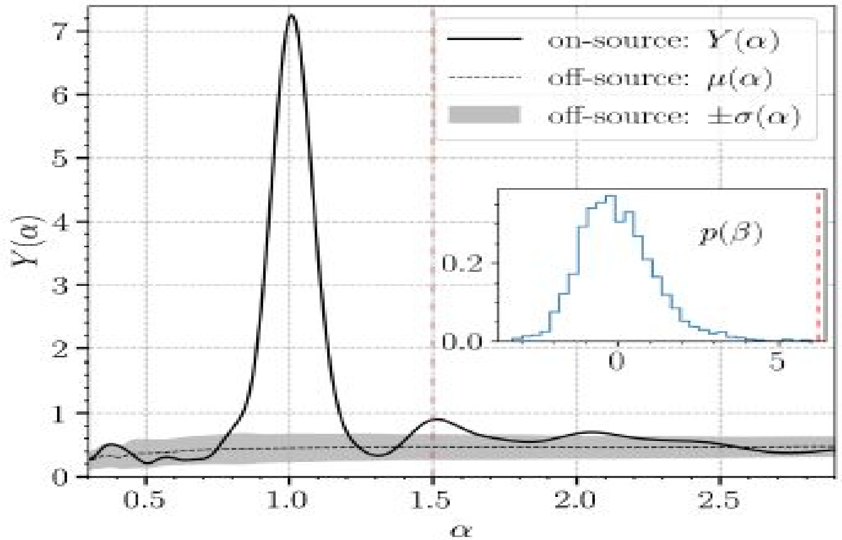
Mass-ratio measurement of GW190412 is robust against modeling systematic



O3 exceptional events: GW190412

Phys. Rev. D 102, 043015 (2020)



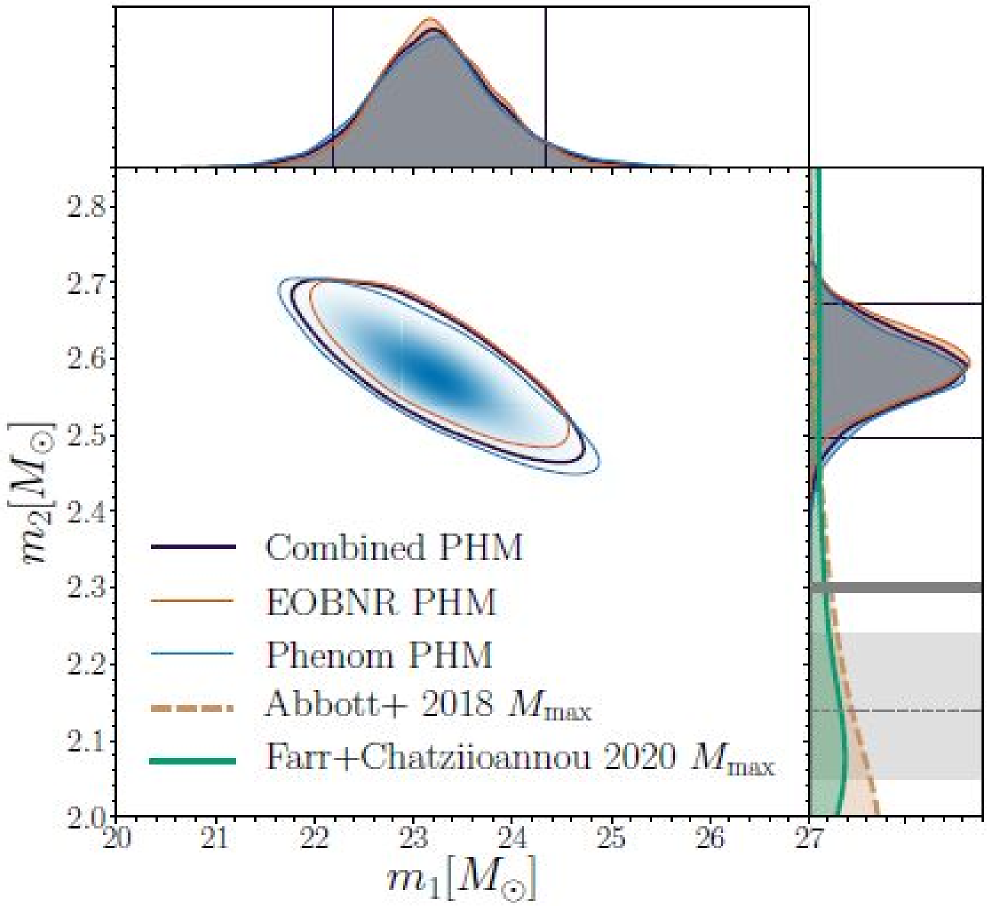


Higher multipoles:

- Many different statistical tests, all support existence of higher multipoles
- Time-frequency track methods: GW instantaneous frequency $f_{ml}(t)$ is related to the dominant mode one:
  $f_{ml}(t)= (m/2)f_{22}(t)$
- search of "secondary" track in the time frequency representation, looking to the energy along each track $f_{\alpha}(t)$

O3 exceptional events: GW190814

Astrophys. J. Lett. 896, L44 (2020)



- Livingstone-Hanford-Virgo observation with SNR of 25
- Masses in the range respectively: 22.2- 24.3 $M_\odot$ and 2.50- 2.67$M_\odot$
- secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system
- mass ratio of q = $0.112^{+0.008}_{-0.009}$ (most unequal ever observed with GW)
- no electromagnetic counterpart

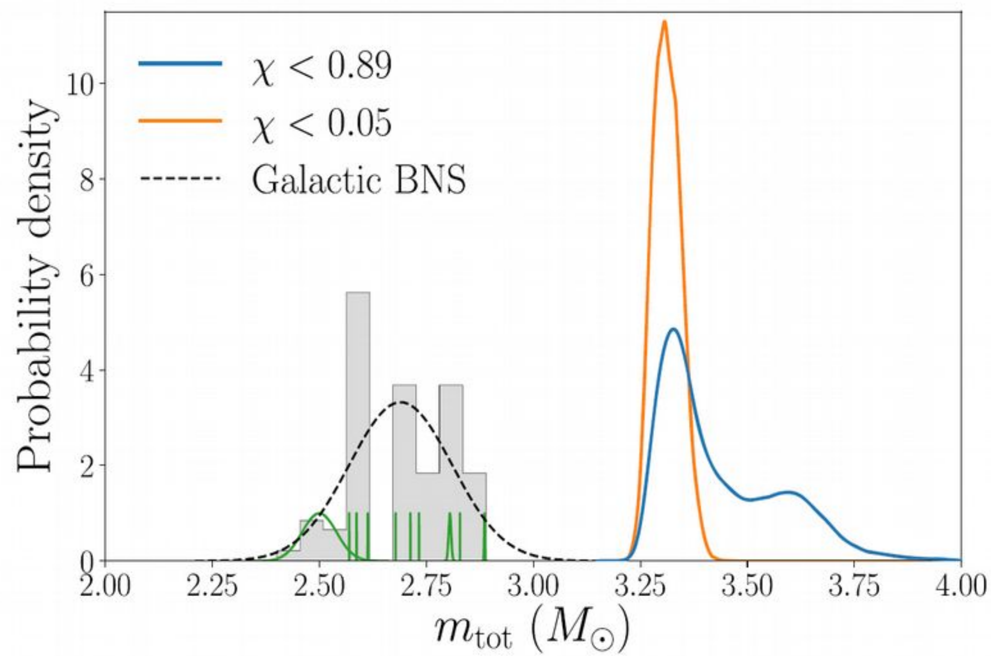
- Tests of general relativity reveal no measurable deviations from the theory
- prediction of higher-multipole emission is confirmed at high confidence
- Comparisons between the secondary mass and estimates of the maximum NS mass suggest that this signal is unlikely to originate in a NSBH coalescence.

O3 exceptional events: GW190425

Astrophys. J. Lett. 892, L3 (2020)

	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}$ $M_\odot$	$1.44^{+0.02}_{-0.02}$ $M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}$ $M_\odot$	$1.4873^{+0.0008}_{-0.0006}$ $M_\odot$
Mass ratio m_2/m_1	0.8 – 1.0	0.4 – 1.0
Total mass m_{tot}	$3.3^{+0.1}_{-0.1}$ $M_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$

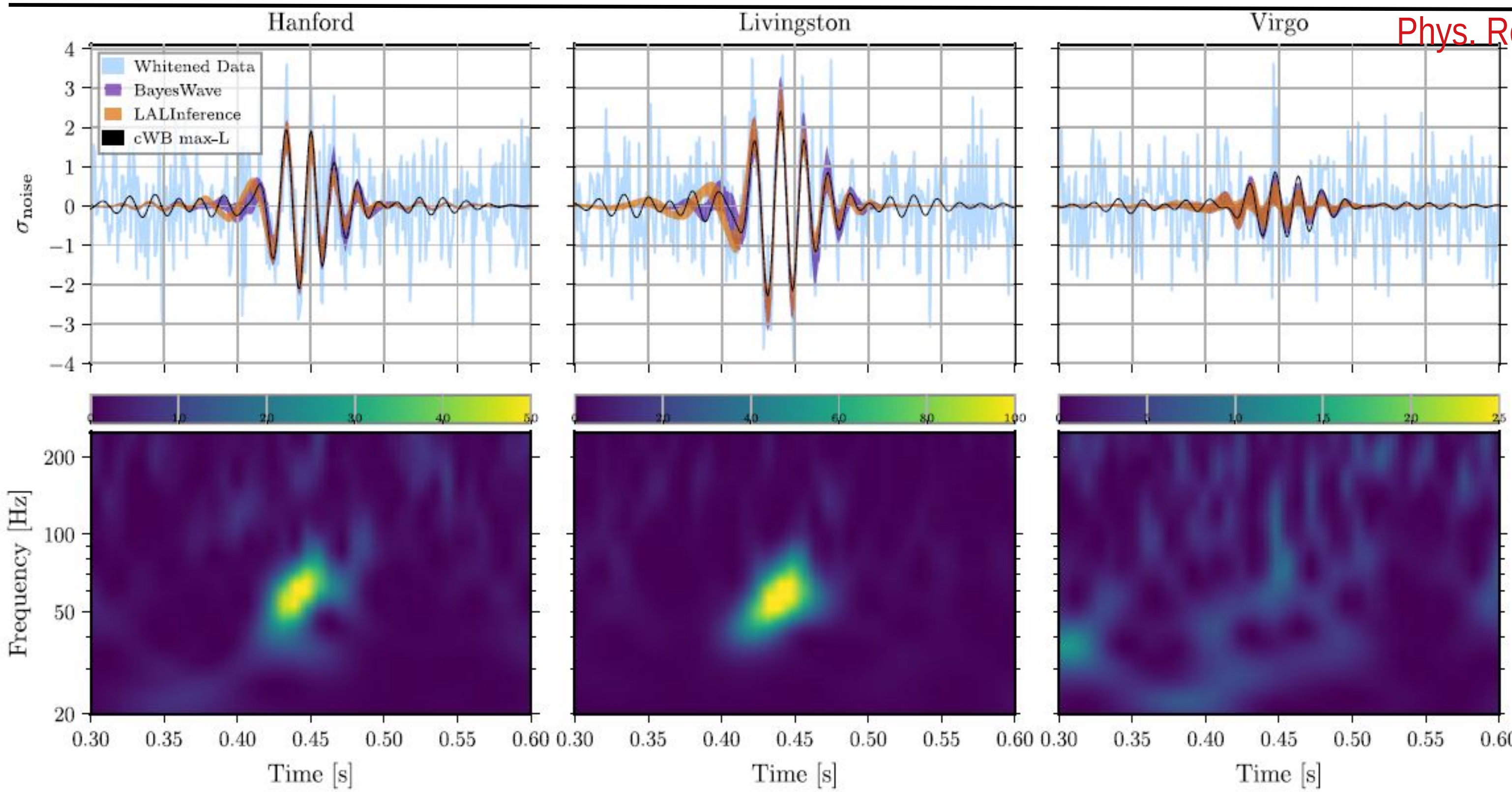
- compact binary coalescence observed by LIGO Livingstone only, SNR 12.9
- Both components have masses less than 3 $M_\odot$
- no clear detection of a counterpart has been reported (broad sky position region)



- component masses range from 1.12 to 2.52 $M_\odot$, consistent with the individual binary components being neutron stars.
- the total mass is significantly larger than those of known binary BNS system (5σ from mean of Galactic BNS)
- The possibility that one or both binary components are black holes cannot be ruled out

O3 exceptional events: GW190521

Phys. Rev. Lett. 125, 101102 (2020)

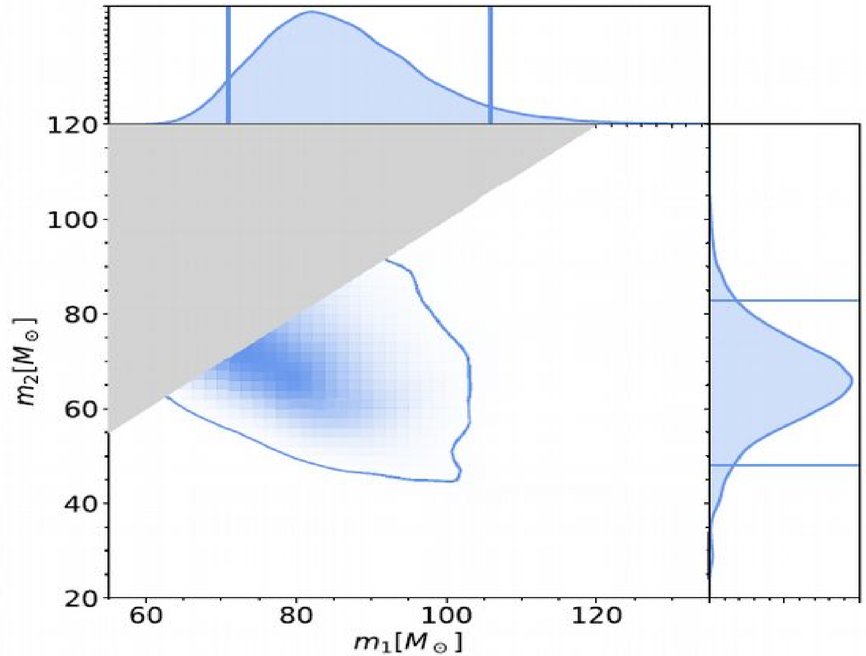


First clear detection of "intermediate mass" black hole

- short duration (few observable cycles) GW, three-detector network SNR: of 14.7
- estimated false-alarm rate of 1 in 4900 yr using cWB (indipendent model search) and of 1 in 829y and 1 in 0.94y by template searches GstLAL and PyCBC
- BH masses of $85^{+21}_{-14}\,M_\odot$ and $66^{+17}_{-18}\,M_\odot$ (heavier in PISN mass gap)
- BH remnant mass $142^{+28}_{-16}\,M_\odot$ (direct observation of formation of a IMBH)

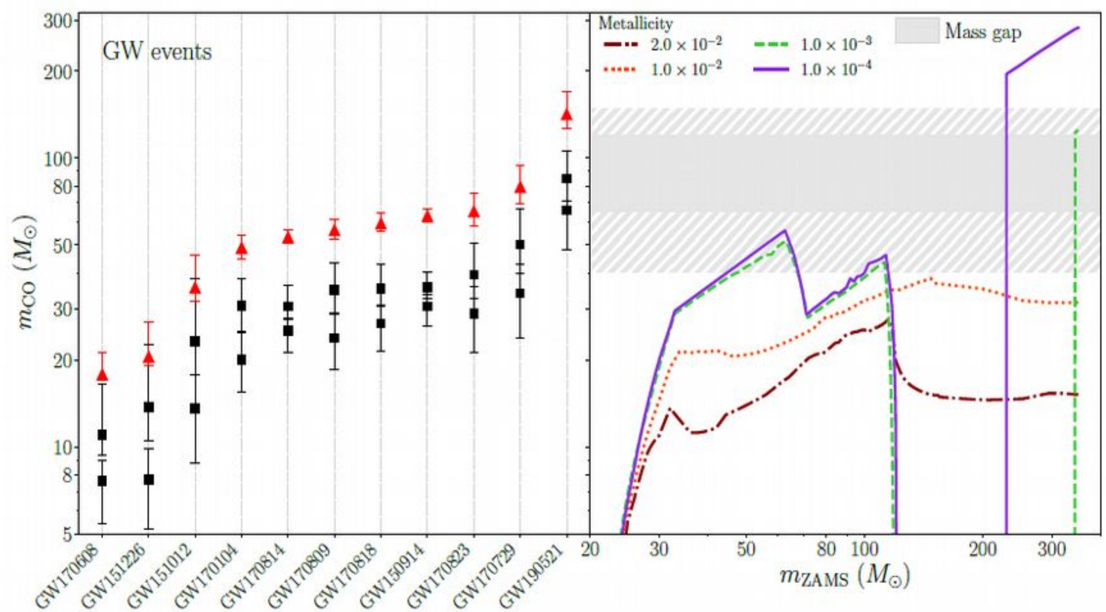
GW190521

Phys. Rev. Lett. 125, 101102 (2020)



- Posterior distribution for remnant BH mass shows no support below 100$M_\odot$
- Weak evidence for spinning BBH and precessing orbital plane obtained performing bayesian model selection including models omitting precession and spins
- No evidence for higher order modes

Astrophys. J. Lett. 900, L13 (2020)

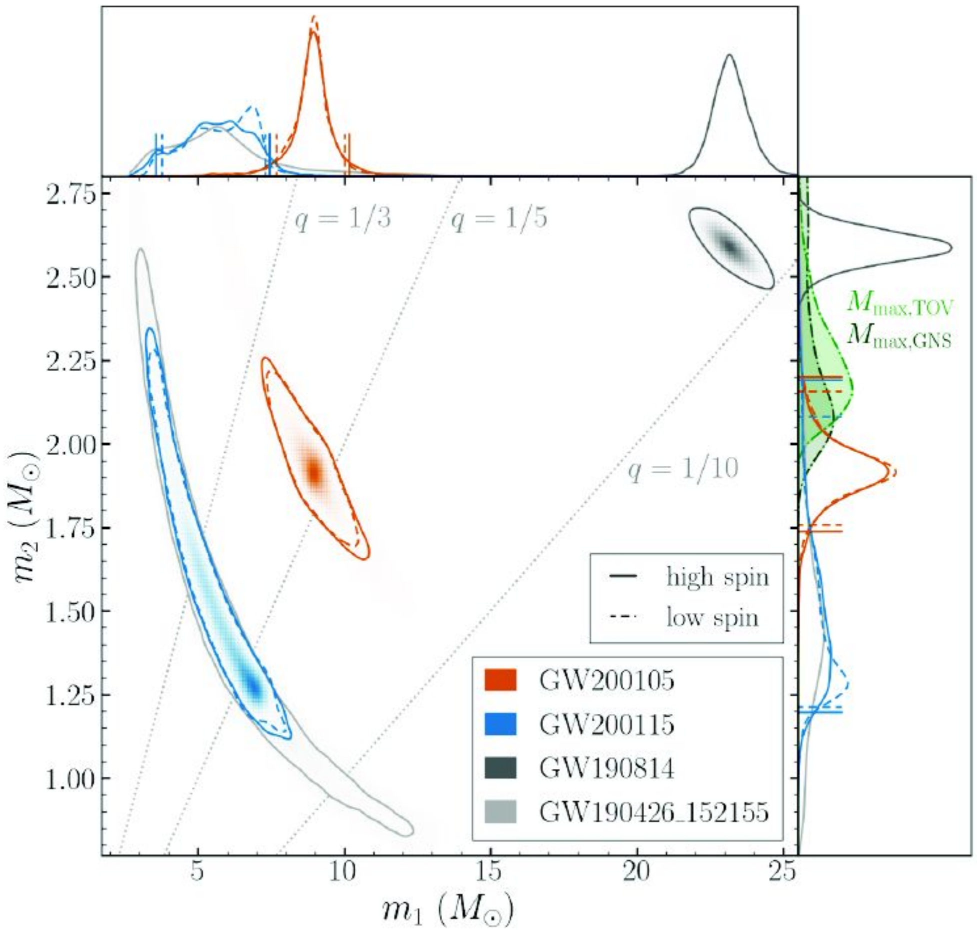


The possible formation of black holes in the pair-instability mass gap

- the formation from stellar collapse
- the primary BH might be the result of the merger of two smaller BHs (hierarchical scenario), or of two massive stars
- formation via isolated binary evolution appears disfavored.
- it is unlikely that GW190521 is a strongly lensed signal of a lower-mass black hole binary merger.

GW200105 and GW200115

ApJ Letters 915, L5 (2021)



- First detections of neutron star-black hole systems: GW200105 and GW200115
- GW200105 is a single-detector event (observed in LIGO Livingston) with an SNR of 13.9. (statistical confidence difficult to establish)
- GW200115 SNR of 11.6 and FAR of < 1/(1x10^5 yr).
- Component mass:
  GW200105: $8.9^{+1.2}_{-1.5}$ $M_\odot$ and $1.9^{+0.2}_{-0.3}$ $M_\odot$
  GW200115: $5.7^{+1.8}_{-2.1}$ $M_\odot$ and $1.5^{+0.7}_{-0.3}$ $M_\odot$
- GW200115: preference for spin to be anti-aligned with orbital angular momentum
- No EM counterpart observed (as expected)

Conclusions

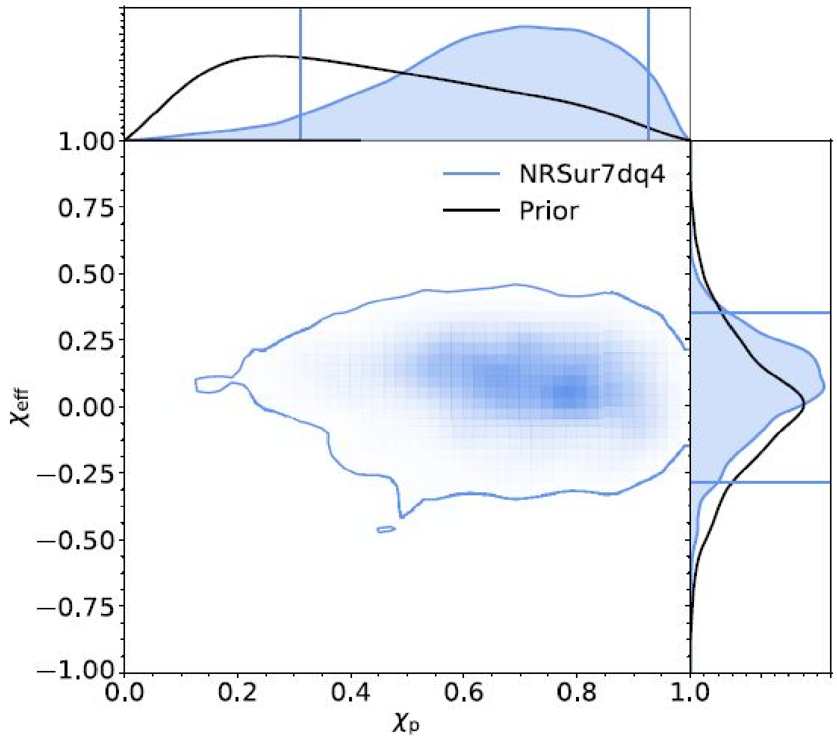
- GWCT-2: 39 GW detections due to compact binaries coalescences, from the analysis of the O3a data taking analysis
- For the first time, binary systems with significantly asymmetric mass ratios, BHNS systems and intermediate mass BHs have been reported
- Further investigations and results :
  - → "Population properties of compact objects from the second LIGO-Virgo Gravitational-Wave Transient Catalog" , ApJ Letters 913, L7 (2021)
  - → "Properties and astrophysical implications of the 150 Msun binary black hole merger GW190521", Astrophys. J. Lett. 900, L13 (2020)
  - → "O3a Search for Intermediate Mass Black Hole Binaries", arxiv:2105.15120

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Back up

GW190521

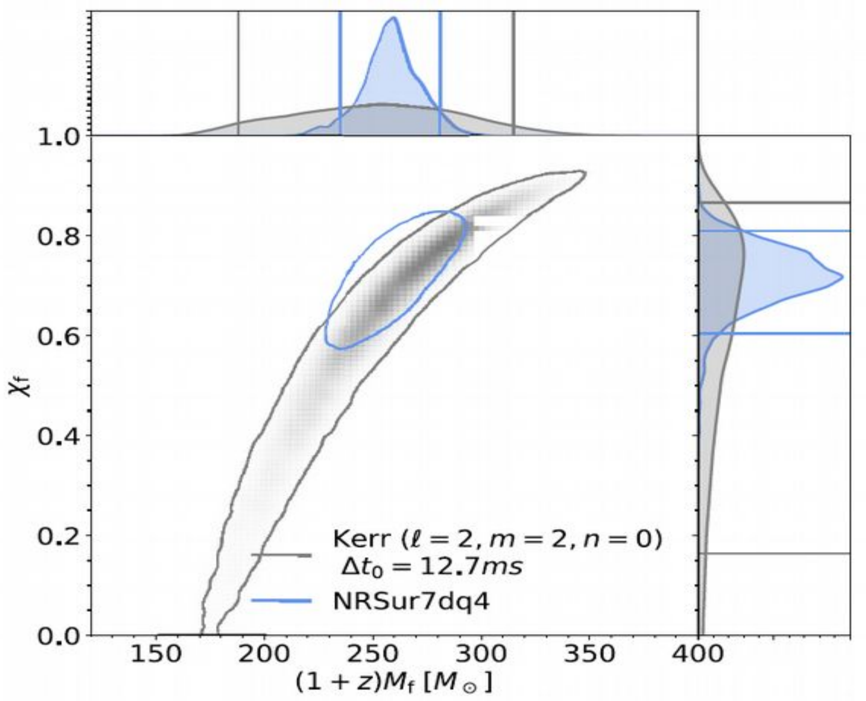
Phys. Rev. Lett. 125, 101102 (2020)



- Effective inspiral spin parameters χ_{eff} (spin components aligned with the orbital angular momentum) is estimated to be $0.08^{+0.27}_{-0.36}$ and effective precession spin parameters χ_p to be $0.68^{+0.25}_{-0.37}$
- Weak evidence for spinning BBH and precessing orbital plane obtained performing bayesian model selection including models omitting precession and spins
- No evidence for higher order modes

GW190521

Phys. Rev. Lett. 125, 101102 (20

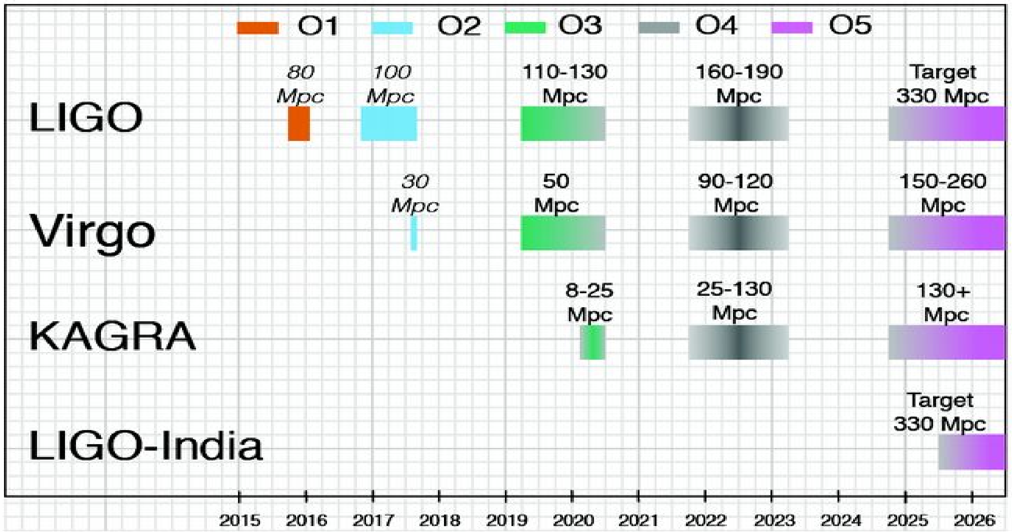


Redshifted remnant mass and spin inferred from the least-damped mode. Blue: 90% credible region of the prediction from the full-waveform analysis.

- Ringdown part of the signal has been analysed using a damped sinusoid mode; analysis estimates $f = 66^{+4}_{-3}$Hz and damping time τ 19^{+9}_{-7}ms, inferring the final redshifted mass and dimensionless spin to be $(1+z)M_f = 252^{+63}_{-64} M_\odot$ and $\chi_{f=}0.65^{+0.22}_{-0.48}$
- Results are consistent with the full-waveform analysis, the remnant ringdown signal is compatible with the full waveform analysis and GR

Signal reconstructions are obtained through a templated analysis (LALinference) and two signal-agnostic analyses (CWB and BayesWave). Reconstructions are in agreement: overlap between the CWB point estimate and the maximum-likelihood NRSur7dq4 template is 0.89, overlap between the median BayesWave waveform and the maximum likelihood NRSur7dq4 template is 0.93.

Interferometers networks near future



Living Reviews in Relativity 23, 3 (2020)

2022 O4: four-detector network

Late 2024/Early 2025 – 2026 O5: O5 will begin with a four-detector network incorporating the A+ upgrade for the aLIGO instruments and the AdV+ Phase 2 upgrade for Virgo.

Hardware update (Frequency independent squeezing, newtonian noise subtraction, improved coatings) will allow improvement in spectral sensitivity (low and high frequency)