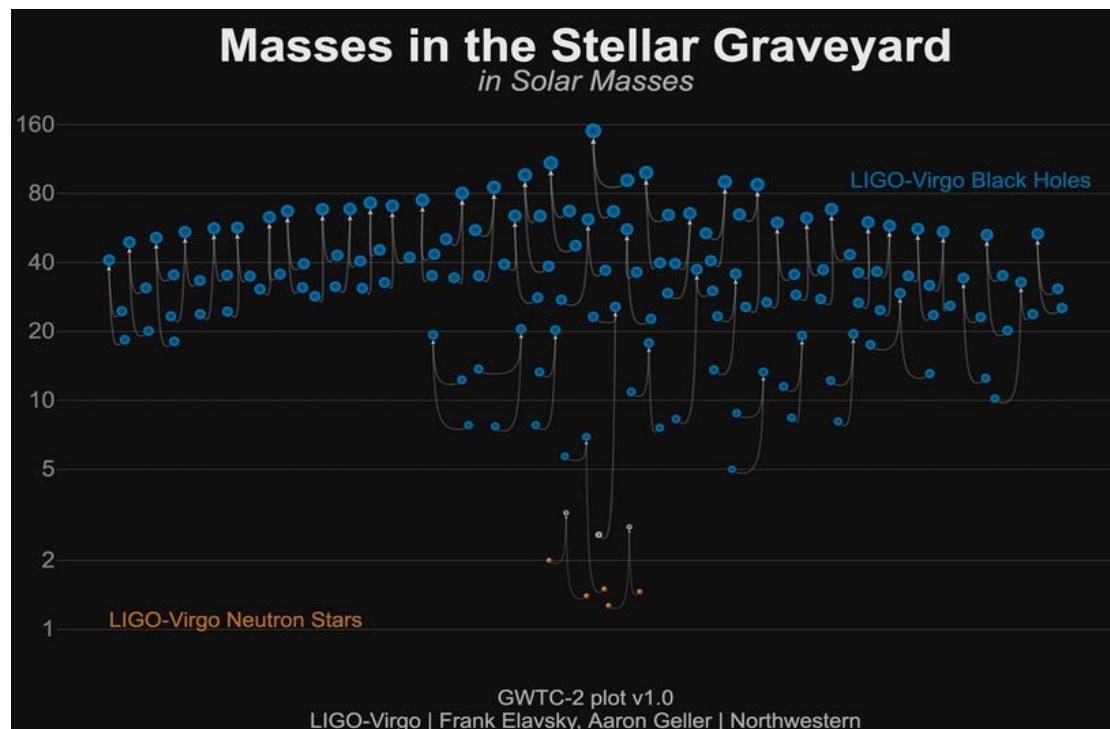




Gravitational-wave results from the last LIGO-Virgo observational run



10th International Conference on New Frontiers in Physics ICNFP 2021

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for the LVK Collaboration



UNIVERSITÀ
DEGLI STUDI
DI PADOVA



Outline

- Interferometers network during O3 data taking
- Gravitational Wave (GW) Transient Catalog 2 (GWTC-2) and test of general relativity with GWTC-2
- O3 detection of “exceptional” compact binaries coalescences:
 - binary black holes system with asymmetric masses: GW190412
 - asymmetric system with a secondary of uncertain type: GW190814
 - high mass binary black holes systems: GW190512
 - neutron star-black hole systems: GW200105 and GW200115
- Overview on other LVK GWs searches:
 - searches for continuous GWs
 - unmodeled searches for transient burst GWs
 - searches for GW background

O3 observing run

Three observing runs have happened to date:

O1: 12 Sep 2015 -20 Oct 2015

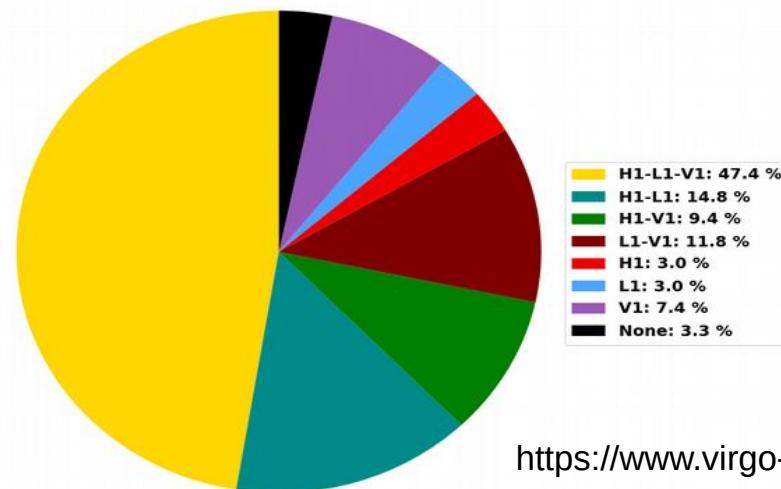
O2: 30 Nov 2016 - Aug 25th

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

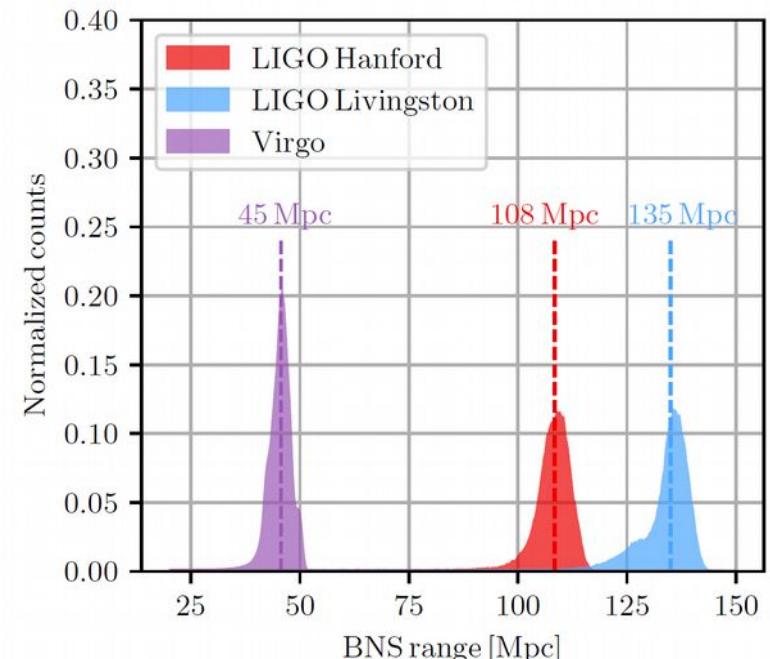
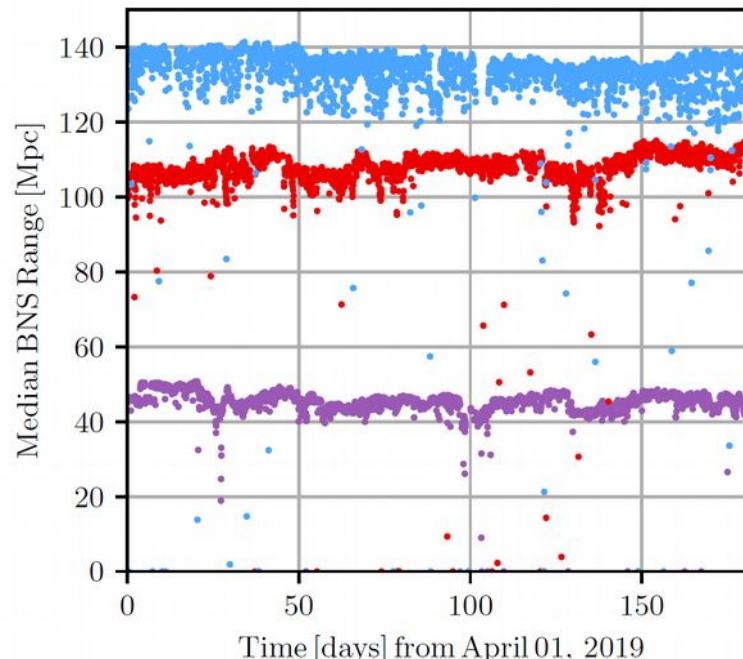
Duty cycle of the interferometer network



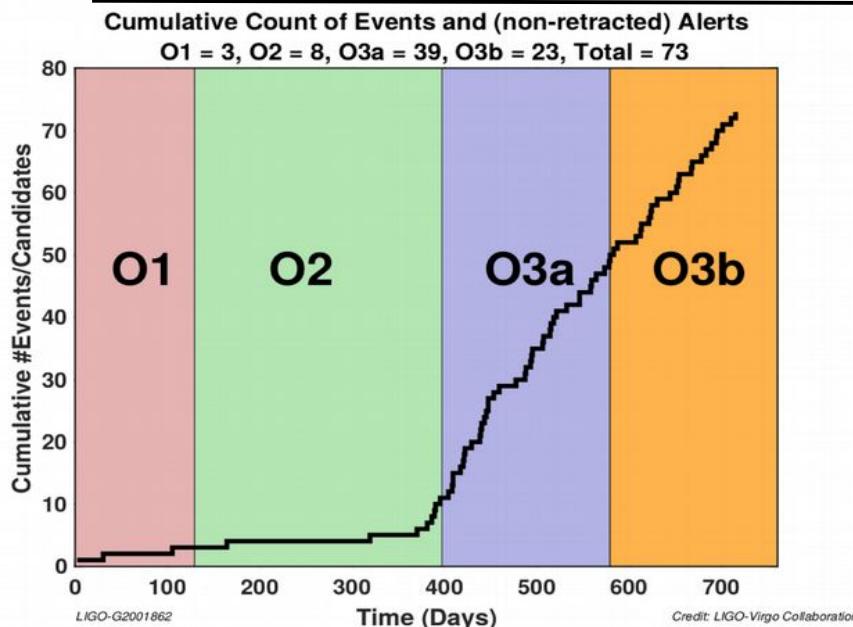
<https://www.virgo-gw.eu/status.html>

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

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



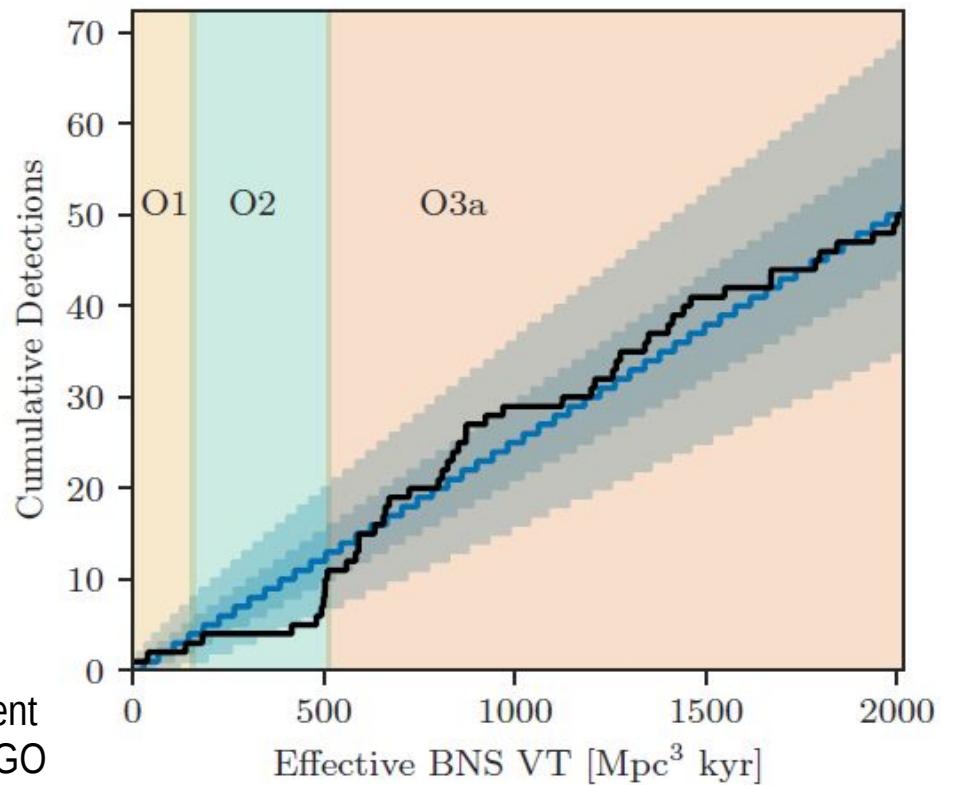
Gravitational-wave Transient Catalog-2



LIGO-G2001862

Compact binaries coalescence:

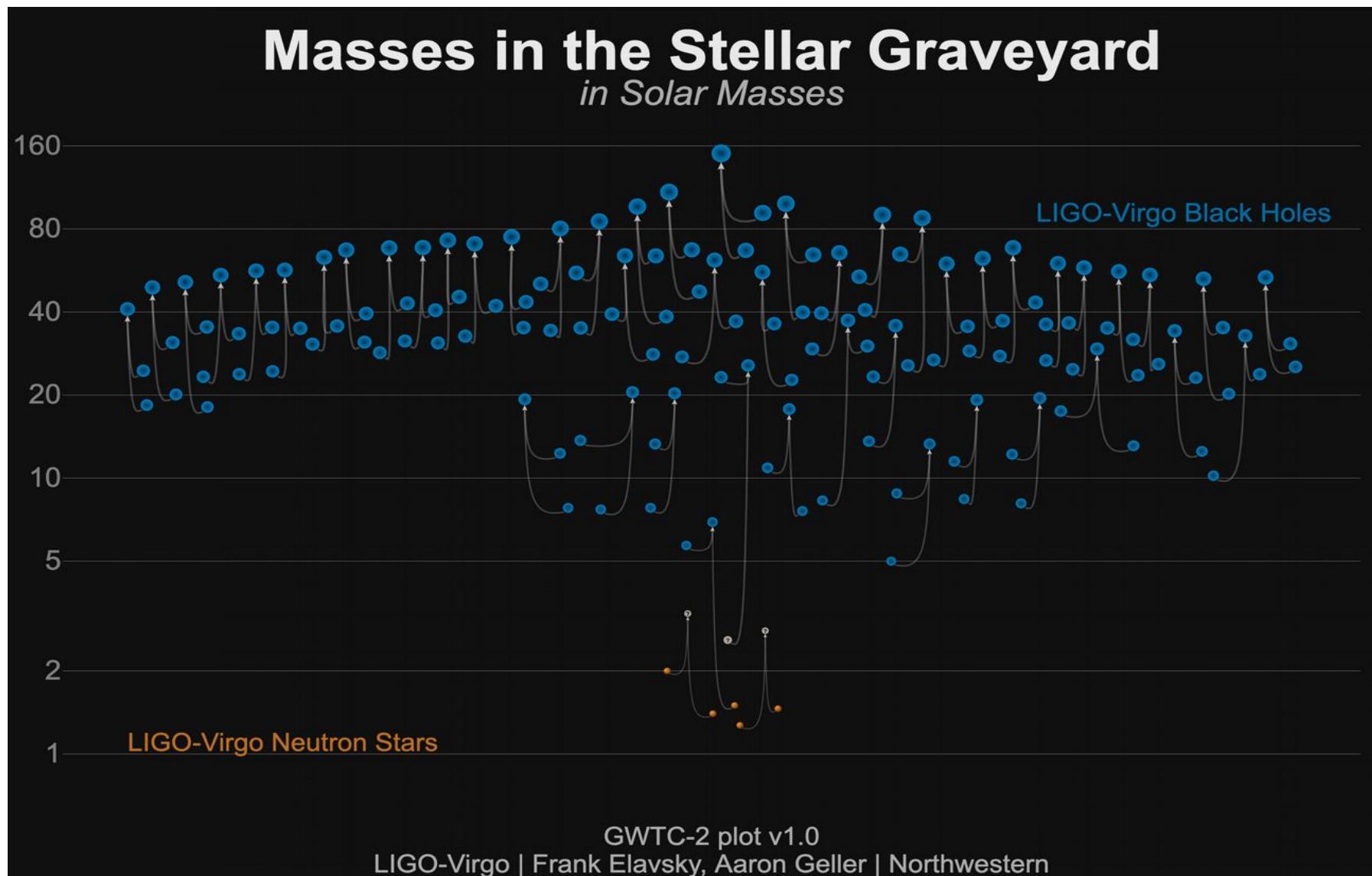
- O1-O2: detection ~every few months
- O3: detection ~weekly



- GWTC-1 (Physical review X 9, 031040, 2019):
11 confident detections during O1 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

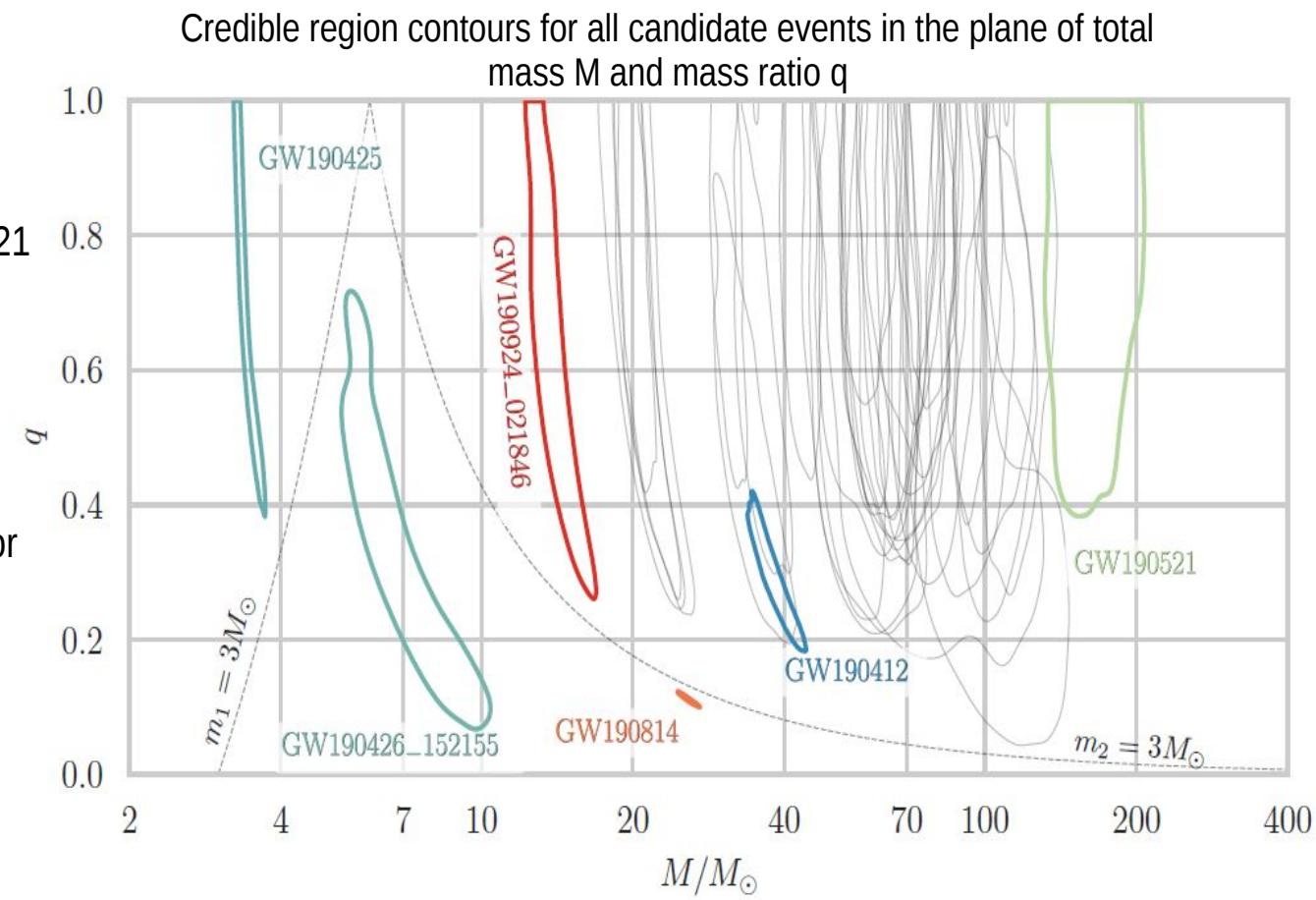
Gravitational-wave Transient Catalog-2



Gravitational-wave Transient Catalog-2

- O3a data analyzed, 4 search pipelines employed: 3 template searches, 1 unmodeled search
- reported 39 GW candidate imposing false alarm rate less than 2 per years (expected contamination fraction less than 10%)

- 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.



GWTC-2.1: Deep Extended Catalog

arXiv:2108.01045

GWTC-2.1 reports on a deeper list of candidate events observed over the same period of GWTC-2, analyzing final version of the strain data with improved calibration and better subtraction of excess noise:

- 8 new events that were not in GWTC-2 with probability of astrophysical origin > 0.5

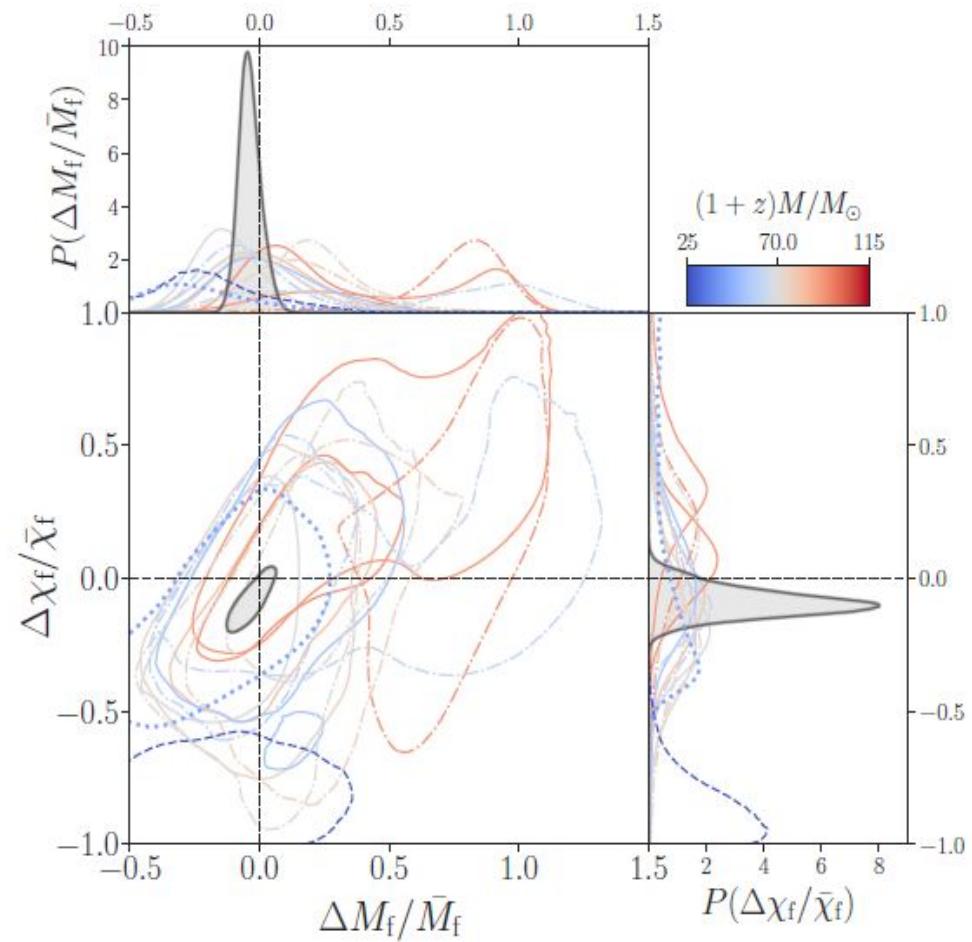
Event	M (M_{\odot})	\mathcal{M} (M_{\odot})	m_1 (M_{\odot})	m_2 (M_{\odot})	χ_{eff}	D_L (Gpc)	z	M_f (M_{\odot})	χ_f	$\Delta\Omega$ (deg 2)
GW190403_051519	$110.5^{+30.6}_{-24.2}$	$36.3^{+14.4}_{-8.8}$	$88.0^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.70^{+0.15}_{-0.27}$	$8.00^{+5.88}_{-3.99}$	$1.14^{+0.64}_{-0.49}$	$105.2^{+29.1}_{-24.1}$	$0.92^{+0.04}_{-0.11}$	5600
GW190426_190642	$184.4^{+41.7}_{-36.6}$	$77.1^{+19.4}_{-17.1}$	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$	$0.19^{+0.43}_{-0.40}$	$4.35^{+3.35}_{-2.15}$	$0.70^{+0.41}_{-0.30}$	$175.0^{+39.4}_{-34.3}$	$0.76^{+0.15}_{-0.15}$	8200
GW190725_174728	$18.2^{+4.2}_{-1.8}$	$7.4^{+0.6}_{-0.5}$	$11.5^{+6.2}_{-2.7}$	$6.4^{+2.0}_{-2.0}$	$-0.04^{+0.26}_{-0.14}$	$1.05^{+0.57}_{-0.46}$	$0.21^{+0.10}_{-0.09}$	$17.4^{+4.4}_{-1.8}$	$0.65^{+0.08}_{-0.07}$	2300
GW190805_211137	$80.1^{+22.5}_{-16.1}$	$33.5^{+10.1}_{-7.0}$	$48.2^{+17.5}_{-12.5}$	$32.0^{+13.4}_{-11.4}$	$0.35^{+0.30}_{-0.36}$	$5.31^{+4.10}_{-2.95}$	$0.82^{+0.48}_{-0.40}$	$75.8^{+21.2}_{-15.3}$	$0.81^{+0.09}_{-0.15}$	3900
GW190916_200658	$68.9^{+21.0}_{-14.0}$	$27.3^{+9.3}_{-5.5}$	$44.3^{+21.2}_{-13.3}$	$23.9^{+12.7}_{-10.2}$	$0.18^{+0.33}_{-0.29}$	$4.46^{+3.79}_{-2.52}$	$0.71^{+0.46}_{-0.36}$	$65.7^{+19.8}_{-13.4}$	$0.73^{+0.14}_{-0.23}$	4500
GW190917_114630	$11.4^{+3.0}_{-2.9}$	$3.7^{+0.2}_{-0.2}$	$9.3^{+3.4}_{-4.4}$	$2.1^{+1.5}_{-0.5}$	$-0.11^{+0.24}_{-0.49}$	$0.72^{+0.34}_{-0.31}$	$0.15^{+0.06}_{-0.06}$	$11.2^{+3.0}_{-2.9}$	$0.42^{+0.12}_{-0.06}$	2100
GW190925_232845	$37.0^{+3.8}_{-2.6}$	$15.8^{+1.1}_{-1.0}$	$21.2^{+6.9}_{-3.1}$	$15.6^{+2.6}_{-3.6}$	$0.11^{+0.17}_{-0.14}$	$0.93^{+0.38}_{-0.35}$	$0.19^{+0.07}_{-0.07}$	$35.2^{+3.8}_{-2.4}$	$0.72^{+0.07}_{-0.06}$	1200
GW190926_050336	$62.9^{+22.7}_{-11.9}$	$25.6^{+8.8}_{-5.3}$	$39.8^{+20.6}_{-11.1}$	$23.2^{+10.8}_{-9.7}$	$-0.04^{+0.28}_{-0.33}$	$3.78^{+3.17}_{-2.00}$	$0.62^{+0.40}_{-0.29}$	$60.5^{+21.8}_{-11.6}$	$0.65^{+0.14}_{-0.19}$	2500

Testing general relativity

Phys. Rev D. 103, 122002 (2021)

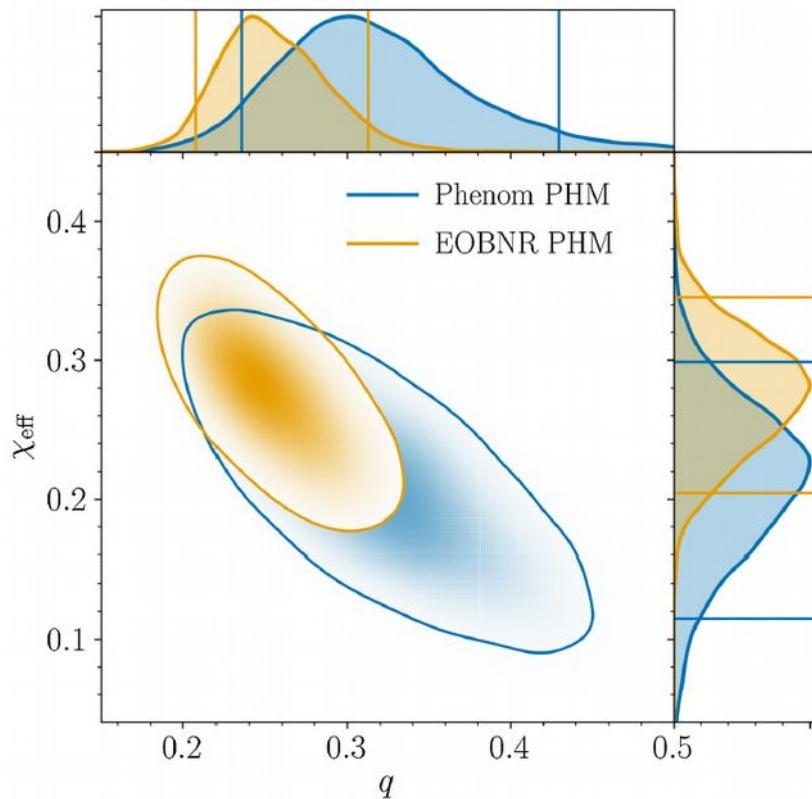
Tests of general relativity in the highly dynamical and strong-field regime:

- 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



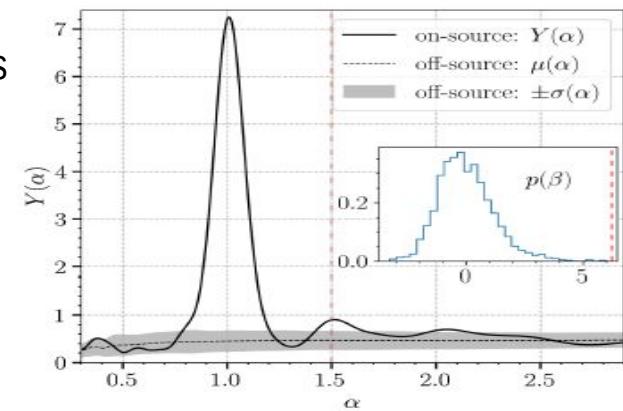
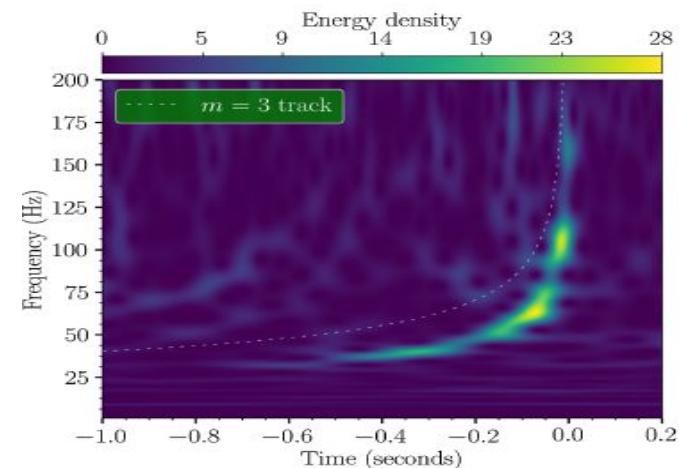
O3 exceptional events: GW190412

Phys. Rev. D 102, 043015 (2020)



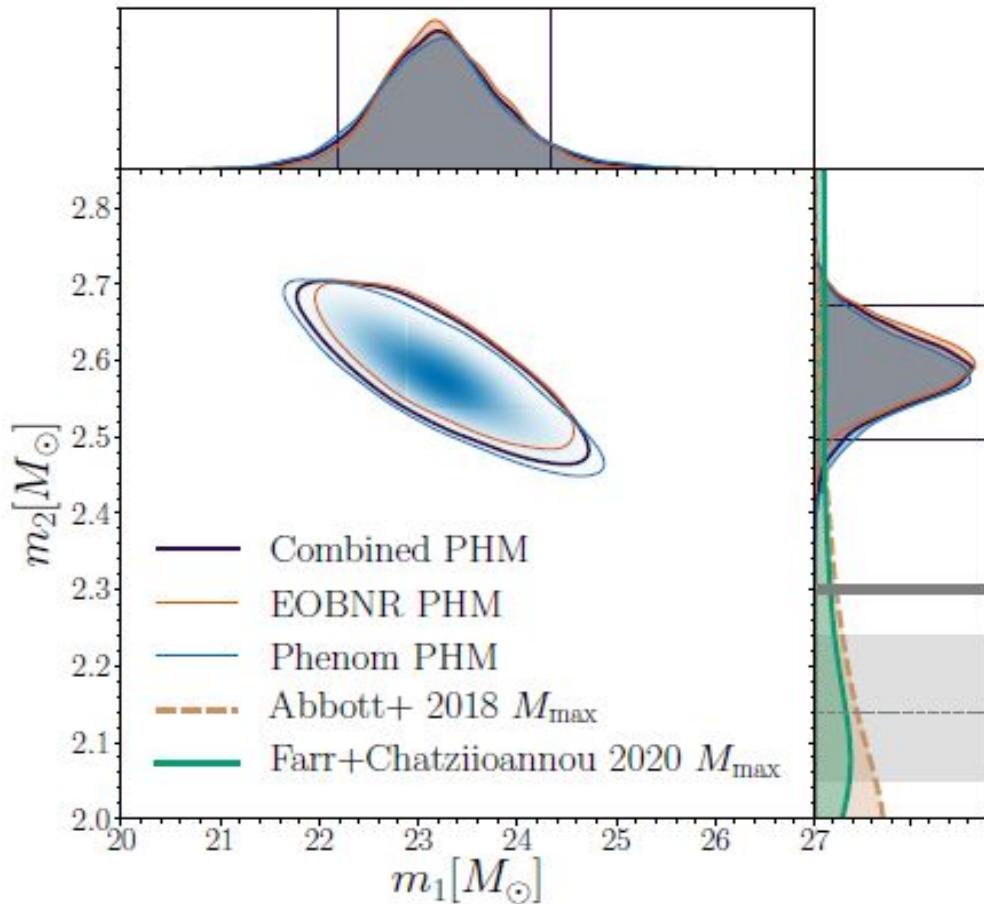
Higher multipoles:

- 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: $f_{ml}(t) = (m/2)f_{22}(t)$



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.

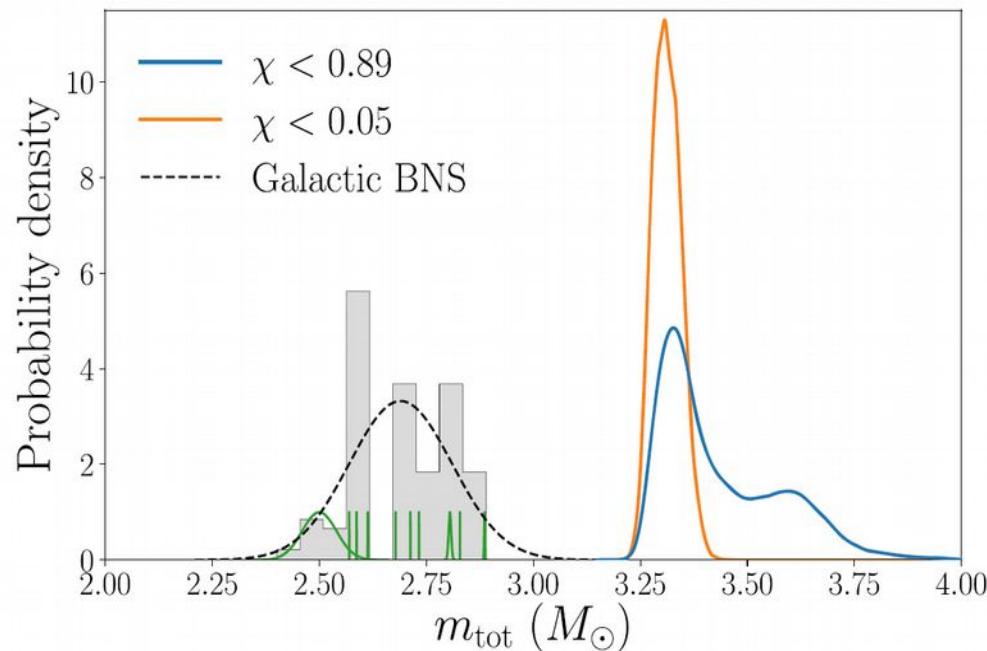
O3 exceptional events: GW190425

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

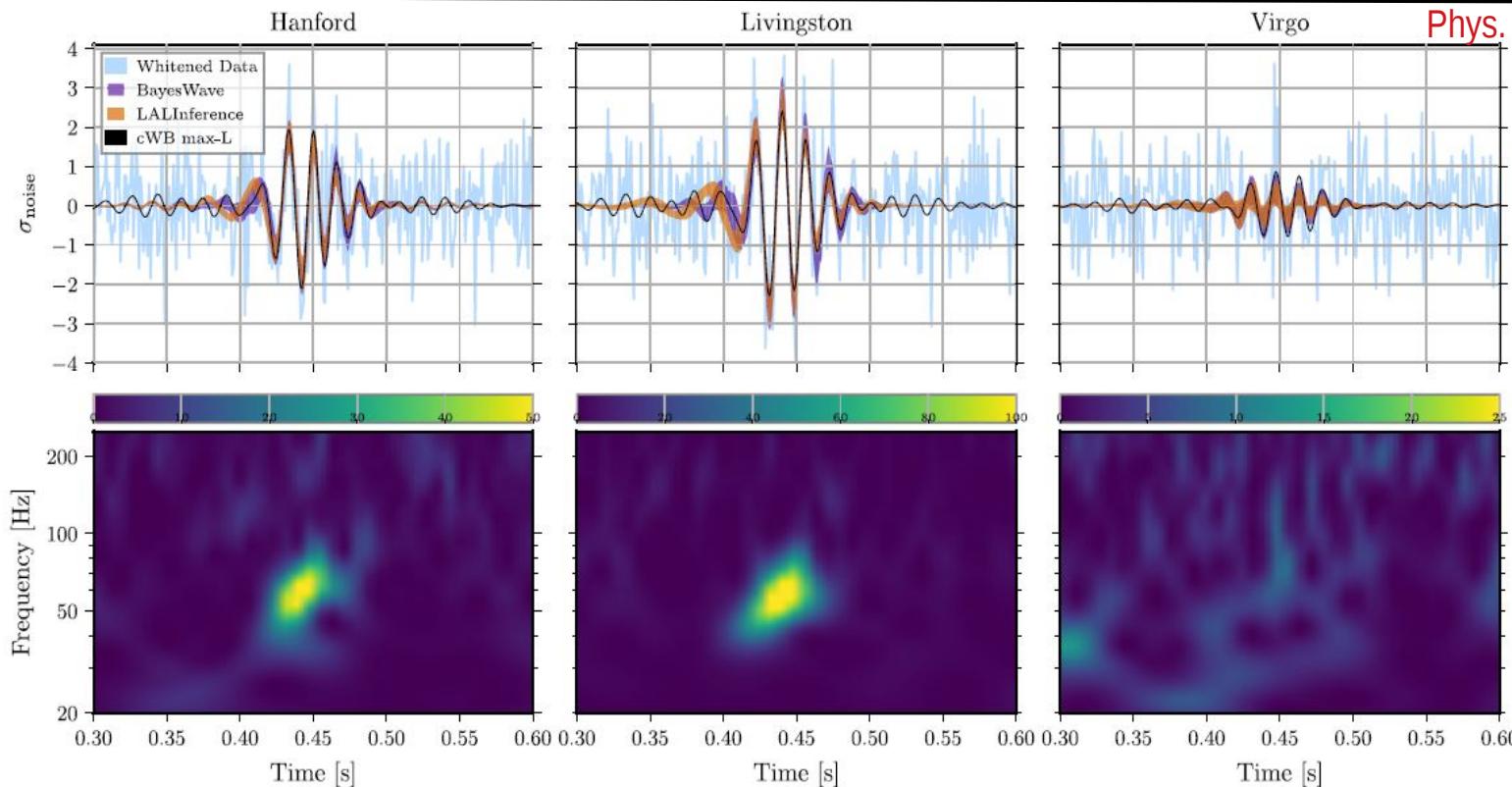
	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	$1.60\text{--}1.87 M_{\odot}$	$1.61\text{--}2.52 M_{\odot}$
Secondary mass m_2	$1.46\text{--}1.69 M_{\odot}$	$1.12\text{--}1.68 M_{\odot}$
Chirp mass \mathcal{M}	$1.44^{+0.02}_{-0.02} M_{\odot}$	$1.44^{+0.02}_{-0.02} M_{\odot}$
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}	$3.3^{+0.1}_{-0.1} M_{\odot}$	$3.4^{+0.3}_{-0.1} M_{\odot}$

- 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

- 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)



O3 exceptional events: GW190521



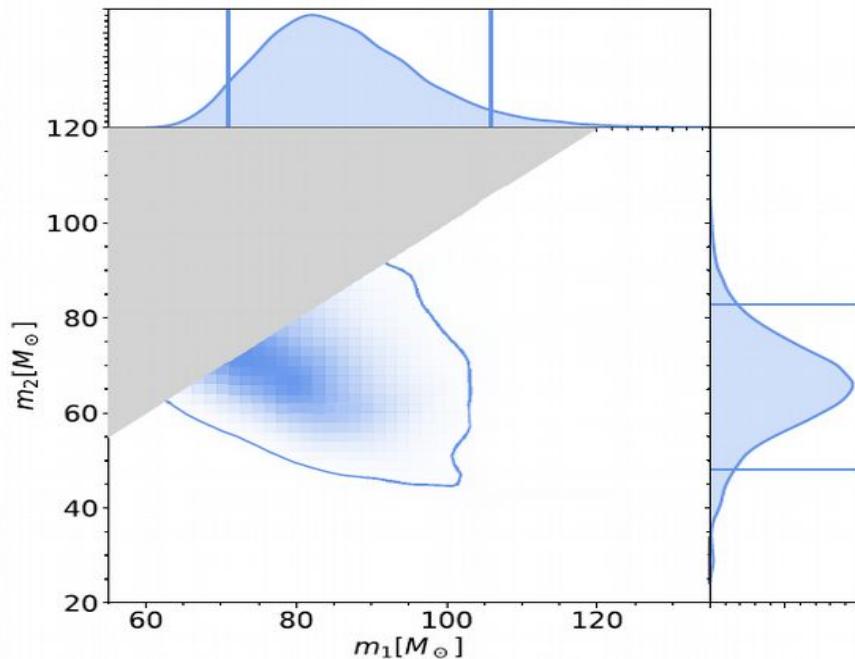
Phys. Rev. Lett. 125, 101102 (2020)

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 (independent 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)

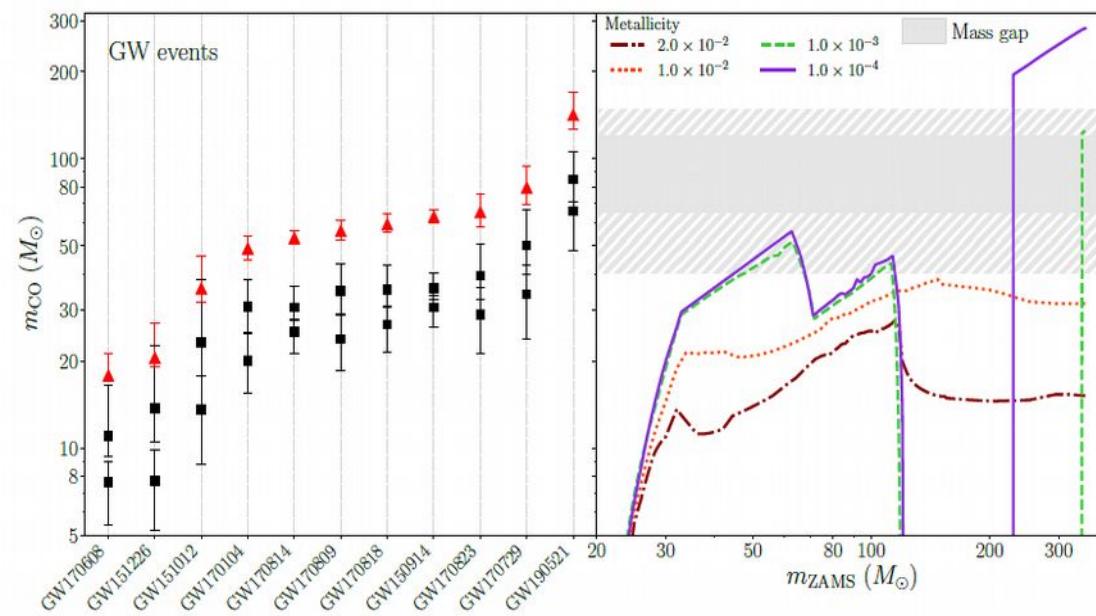
GW190521

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)

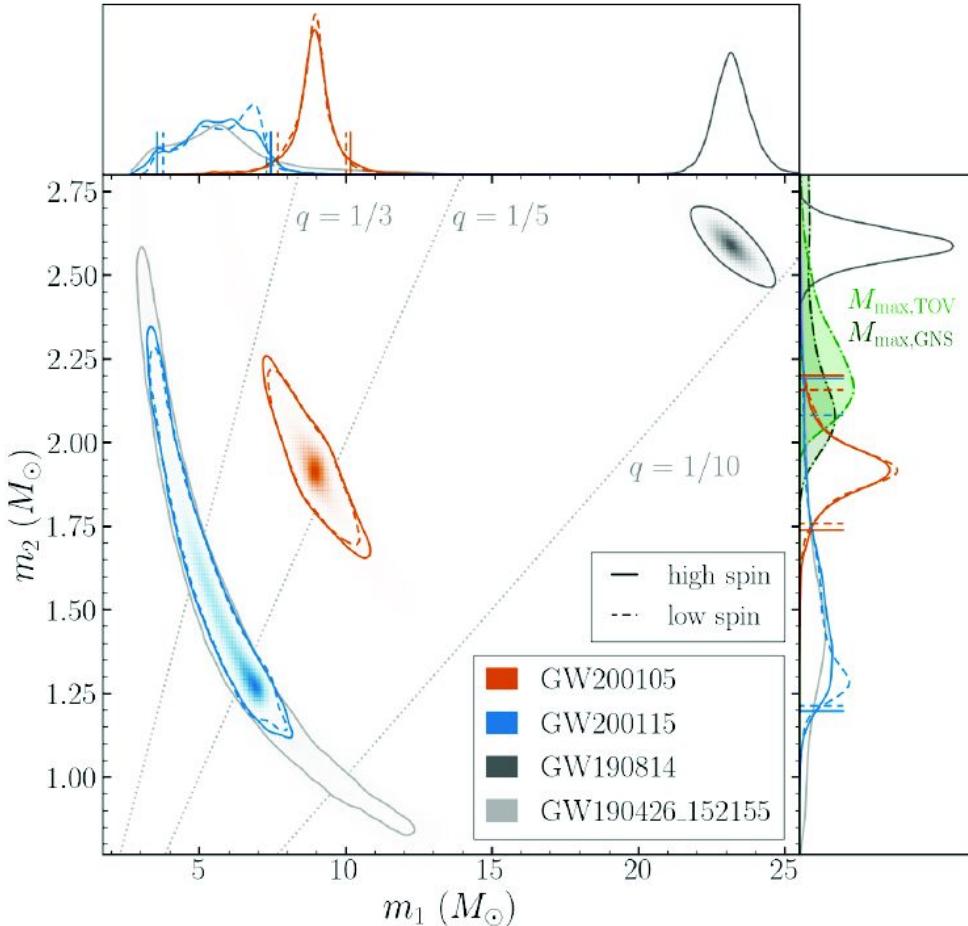


The possible formation of black holes in the pair-instability mass gap:

- 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 during O3b: 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 $< 1/(1 \times 10^5 \text{ yr})$.
- 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

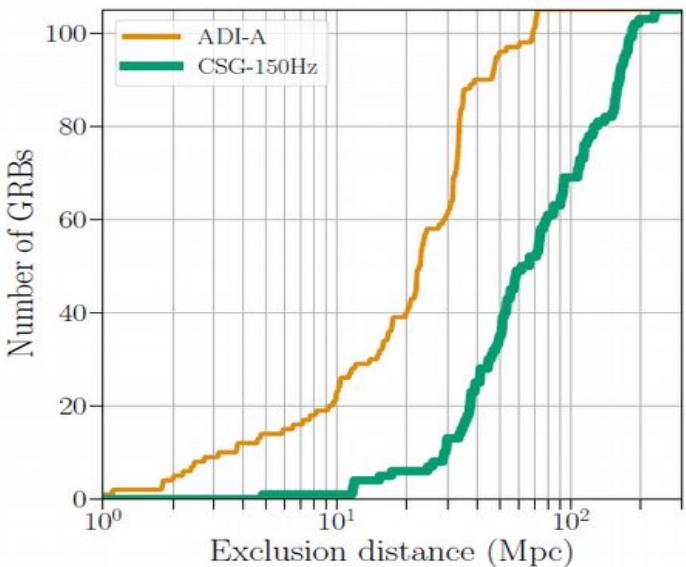
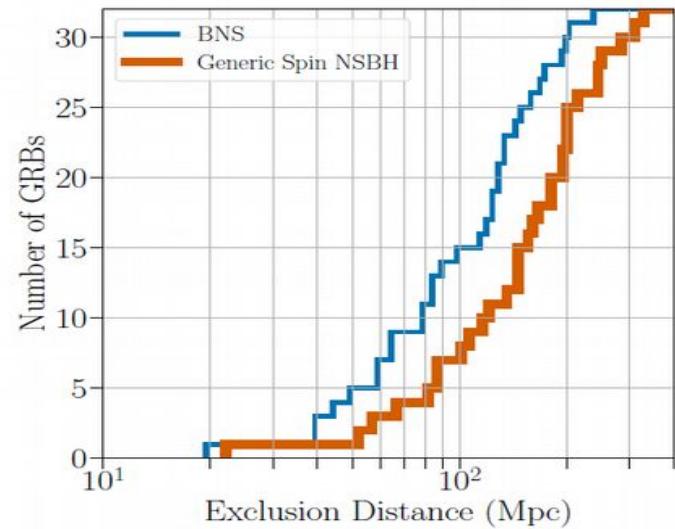
Other LVK highlights

Search for GWs associated with Gamma-Ray Burst

Astrophys. J. 915, 86 (2021)

targeted analyses for GWs associated to Fermi and Swift GRBs reported during the O3aLIGO-Virgo observing run:

- 105 gamma-ray bursts were analyzed using a search for generic GW transients, 32 gamma-ray bursts with a search specifically target neutron star binary mergers
- no GW signal in association with the GRBs followed up
- lower bounds on the distances to the progenitors of all GRBs analyzed for different emission models (exclusion distances achieved include the largest values published so far for some GRBs)

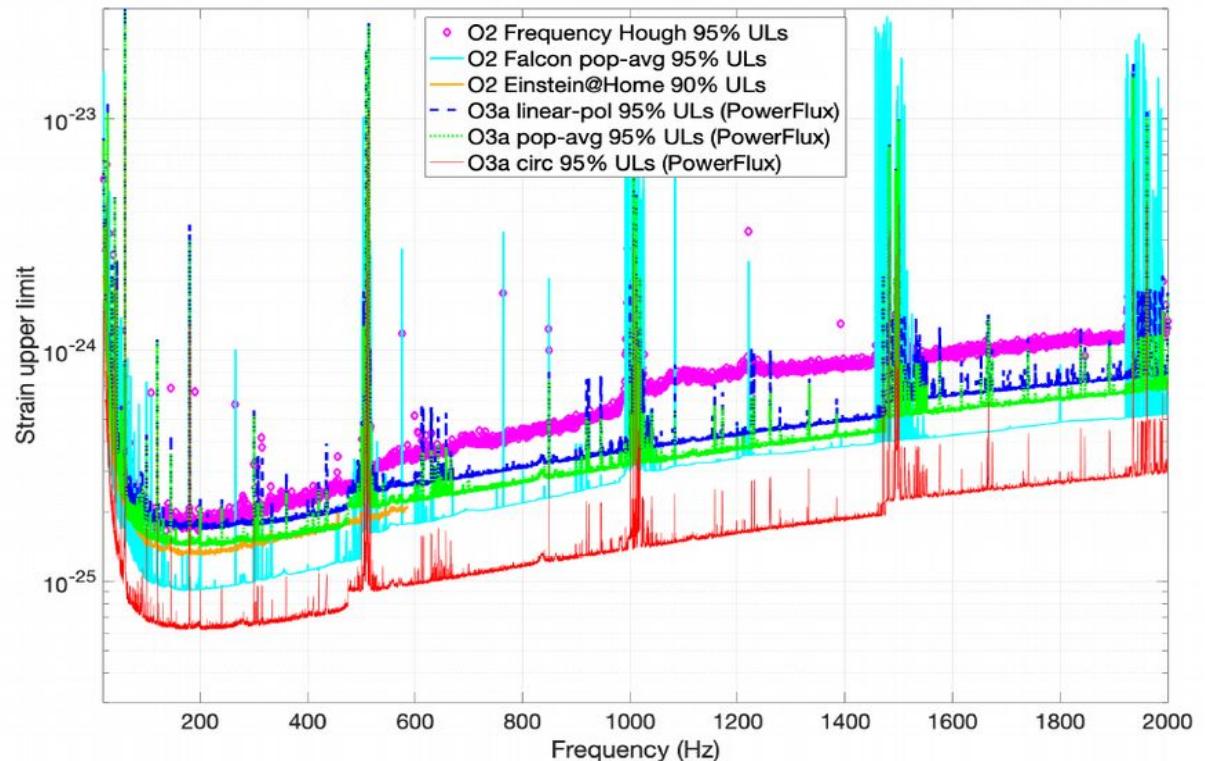


Search for continuous gravitational waves

arxiv:2107.00600

All-sky search for continuous GWs in the first six months of O3:

- Most sensitive search for unknown non-axisymmetric neutron stars with high allowed spin-down magnitudes (up to 10^{-8} Hz/s)
- No detections, upper limits estimations



Search for continuous GWs from 15 young supernova remnants in O3a data:

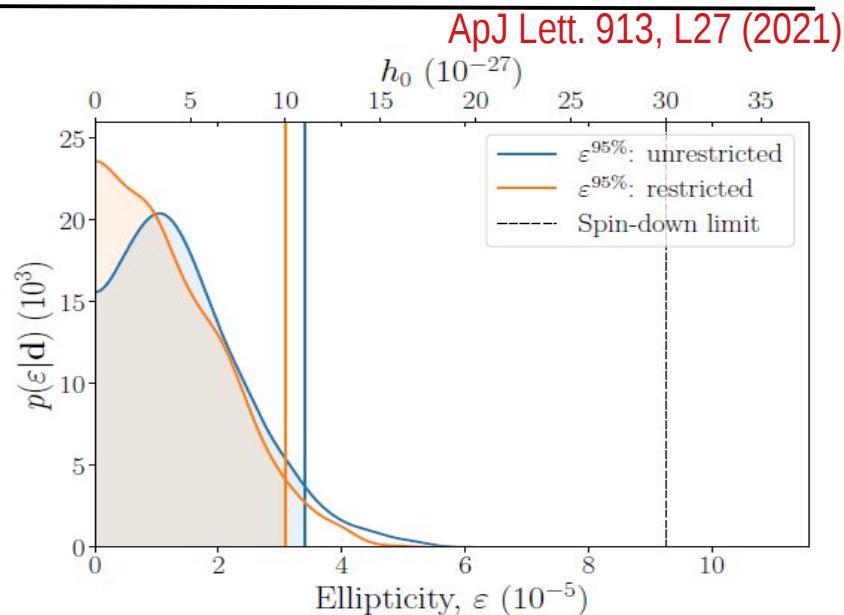
arxiv:2105.11641

- no evidence of signals from these sources
- 95% confidence constraints placed on the signal strain: 7.7×10^{-26} and 7.8×10^{-26} near 200 Hz for the supernova remnants G39.2–0.3 and G65.7+1.2
- constraints placed on ellipticities and r-mode oscillation amplitudes

Search for continuous gravitational waves (2)

Search for quasi-monochromatic GW from X-ray pulsar PSR J0537-6910:

- rapid spindown and frequent glitching (observed through X-rays)
- analyzed data from the second and third observing runs of LIGO and Virgo
- LVK and NICER collaboration
- No GW signal, upper limit on ellipticity is $< 3 \times 10^{-5}$ (95% confident)



Constraints on GW emission due to r-modes in the pulsar PSR J0537-6910:

arxiv:2104.14417

- LVK-NICER collaboration, using data from the second and third observing runs of LIGO and Virgo
- No GW signal detected
- upper limits on the amplitude of Gws from r-modes in J0537-6910 improved by a factor of up to 3

All-sky search for continuous GW signals from unknown neutron stars in binary systems

Phys. Rev. D 103, 064017 (2021)

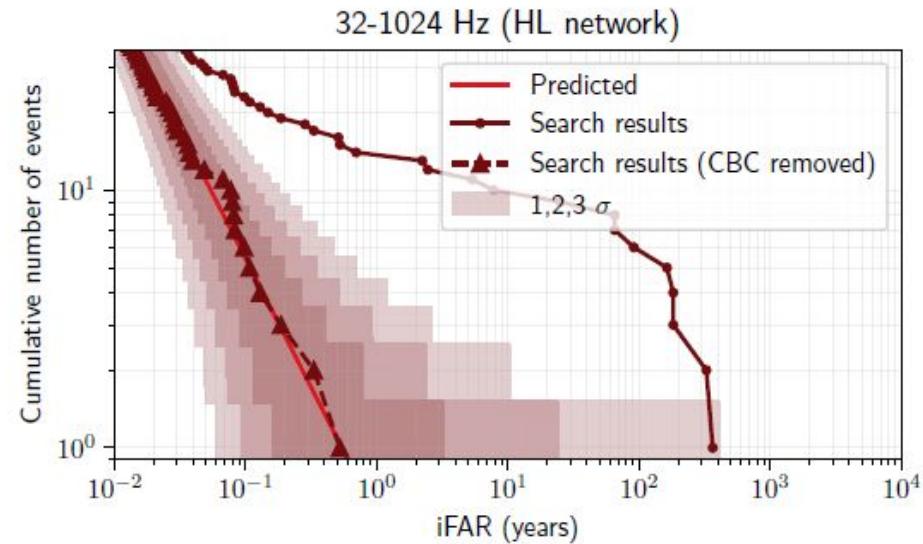
- analysed LIGO data from the first six months of O3 (in the most sensitive frequency band 50–300Hz)
- No detections are reported.
- minimum amplitude sensitivity: $(2.4 \pm 0.1) \times 10^{-25}$ ($f_0 = 149.5\text{Hz}$), a factor of ~ 1.6 lower than the searches in previous run

GW transients un-modeled searches

arxiv:2107.03701

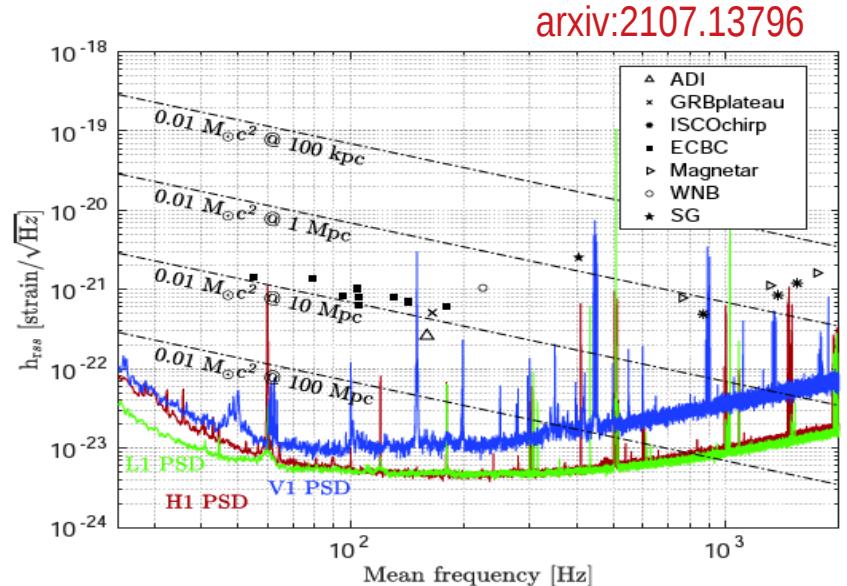
All-sky search for short GWs bursts. Astrophysics sources could include: BBH, CCSNe, cosmic strings, pulsar glitches.

- all sky unmodeled search for GW transients < 1s
- No new candidates found apart from CBC sources
- Set current upper limit (about one order of magnitude better than the previous O2 limit over most of the frequency bandwidth)



All-sky search for long GW bursts. Astrophysics sources could include: fallback accretion, accretion disk instabilities, newborn neutron stars from BNS merger or core-collapse supernovae, eccentric compact binary coalescences:

- all sky unmodeled search for GW transients 2-500 s
- no new candidates found
- amplitude sensitivity improved by a factor of 1.8 upon the analysis from the O2



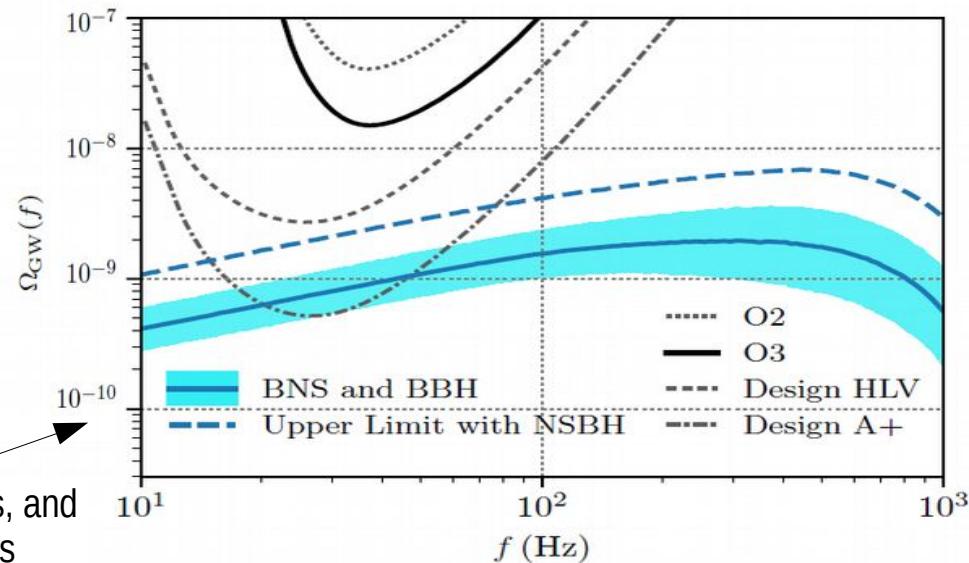
Searches for GW background

Phys. Rev. D 104, 022004 (2021)

Search for isotropic GW background (astrophysical and cosmological):

- O3 data from Advanced LIGO's and Advanced Virgo
- no significant evidence for a GW background
- up to date most stringent limits on strength of background (upper limits improved previous bounds by about a factor of 6.0 for a flat background)

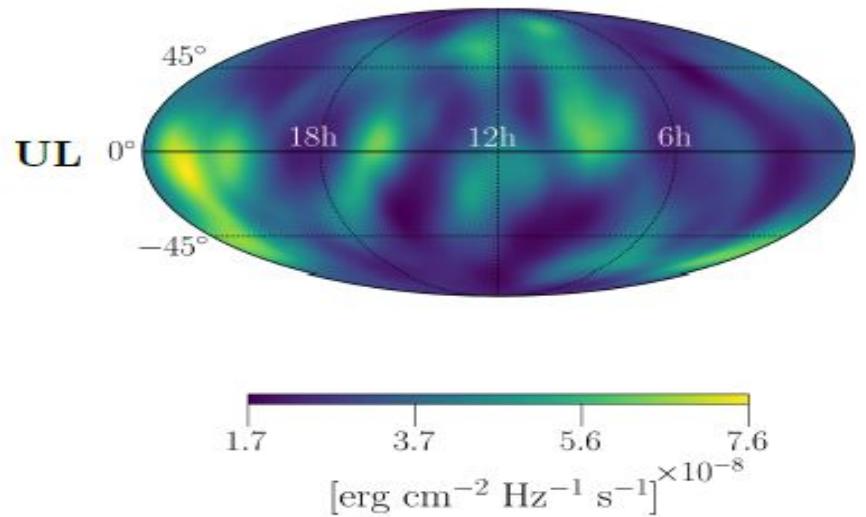
Fiducial model predictions for the GWB from BBHs, BNSs, and NSBHs, along with current and projected sensitivity curves



Phys. Rev. D 104, 022005 (2021)

Search for anisotropies stochastic in GW backgrounds:

- No significant evidence for a gravitational-wave background.
- direction-dependent upper limits set on GW emission, improving upon existing limits by a factor of ≥ 2.0



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
- Searches for unmodeled transient GW, continuous Gws, stochastic background have been performed for O3 observing run
- Many 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 \(2020\)](#)
 - “Search for intermediate mass black hole binaries in the third observing run of Advanced LIGO and Advanced Virgo”, [arxiv:2105.15120](#)

Conclusions

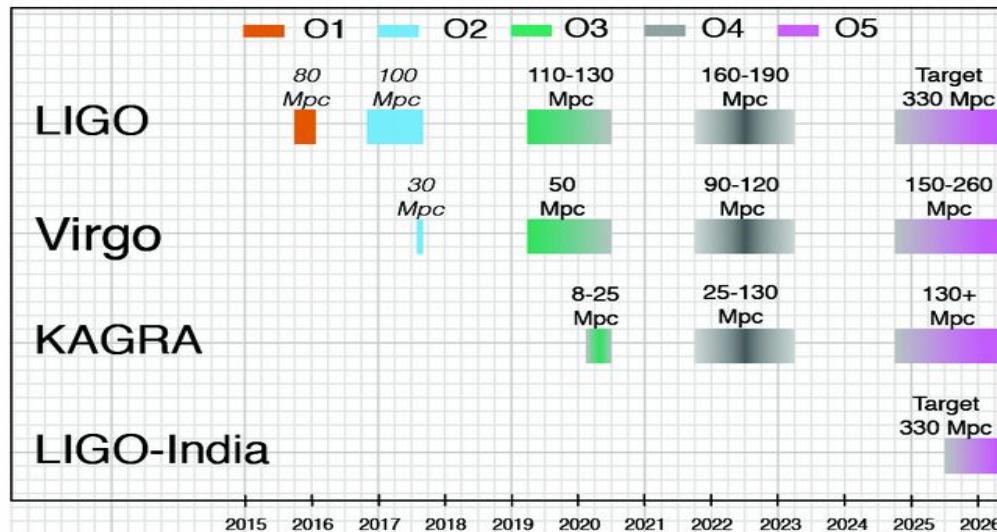
- “Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo’s third observing run” [arxiv:2105.06384](https://arxiv.org/abs/2105.06384)
- “Searching for dark photon dark matter in the third observing run of LIGO/Virgo”,
[arxiv:2105.13085](https://arxiv.org/abs/2105.13085)
- “Constraints on cosmic strings using data from the third Advanced LIGO-Virgo observing run”,
[Phys. Rev. Lett. 126, 241102 \(2021\)](https://doi.org/10.1103/PhysRevLett.126.241102)

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Back up

Interferometers networks near future

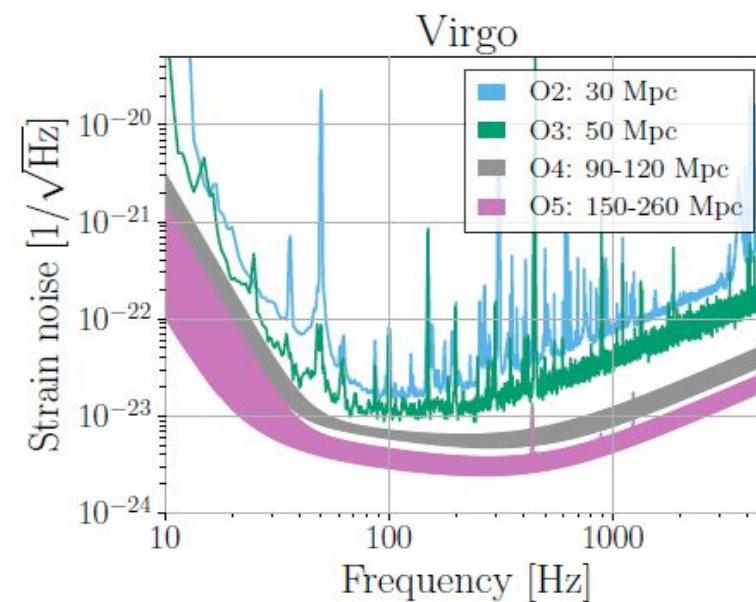
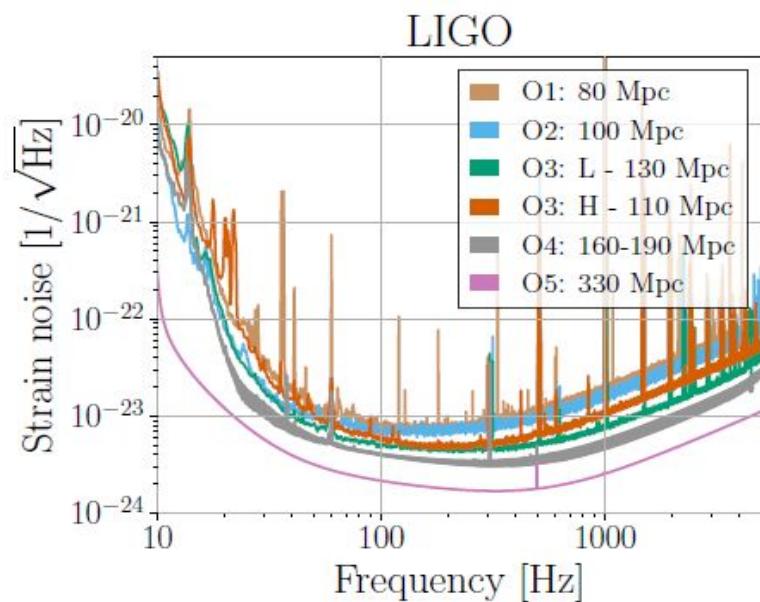


Living Reviews in Relativity 23, 3 (2020)

2022 O4: four-detector network

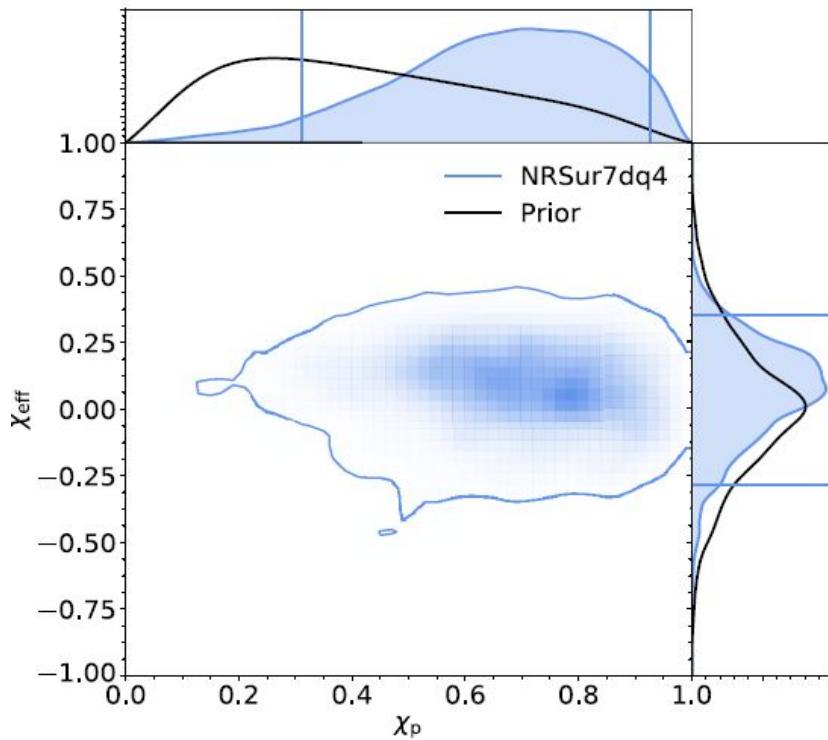
Late 2024/Early 2025 – 2026 O5: O5 will begin with a four-detector network incorporating the A+ upgrade for the aLIGO instruments and the AdV+ Phase 2 upgrade for Virgo.

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



GW190521

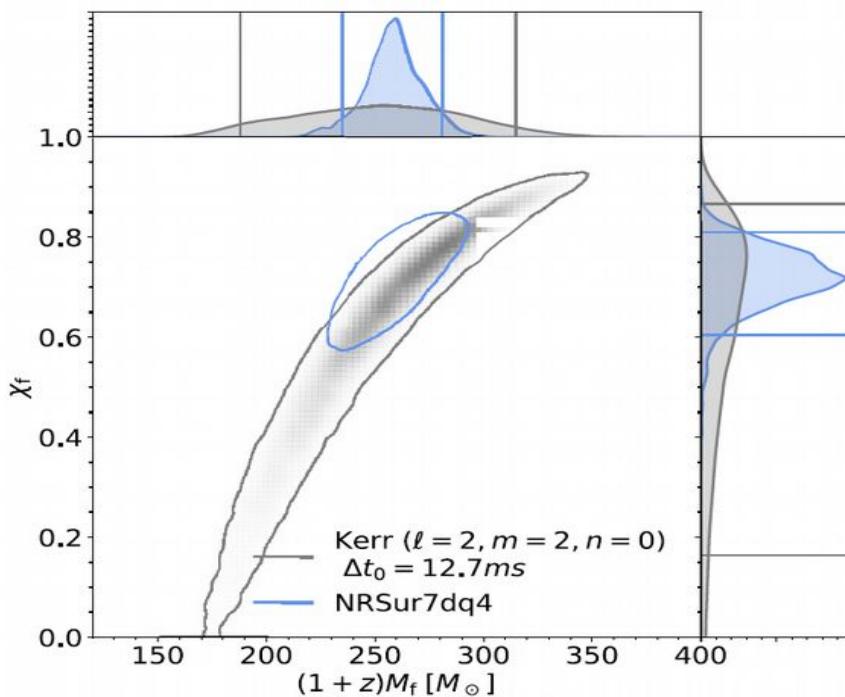
Phys. Rev. Lett. 125, 101102 (2020)



- 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

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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 $\tau = 19^{+9}_{-7m}$ s, 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.