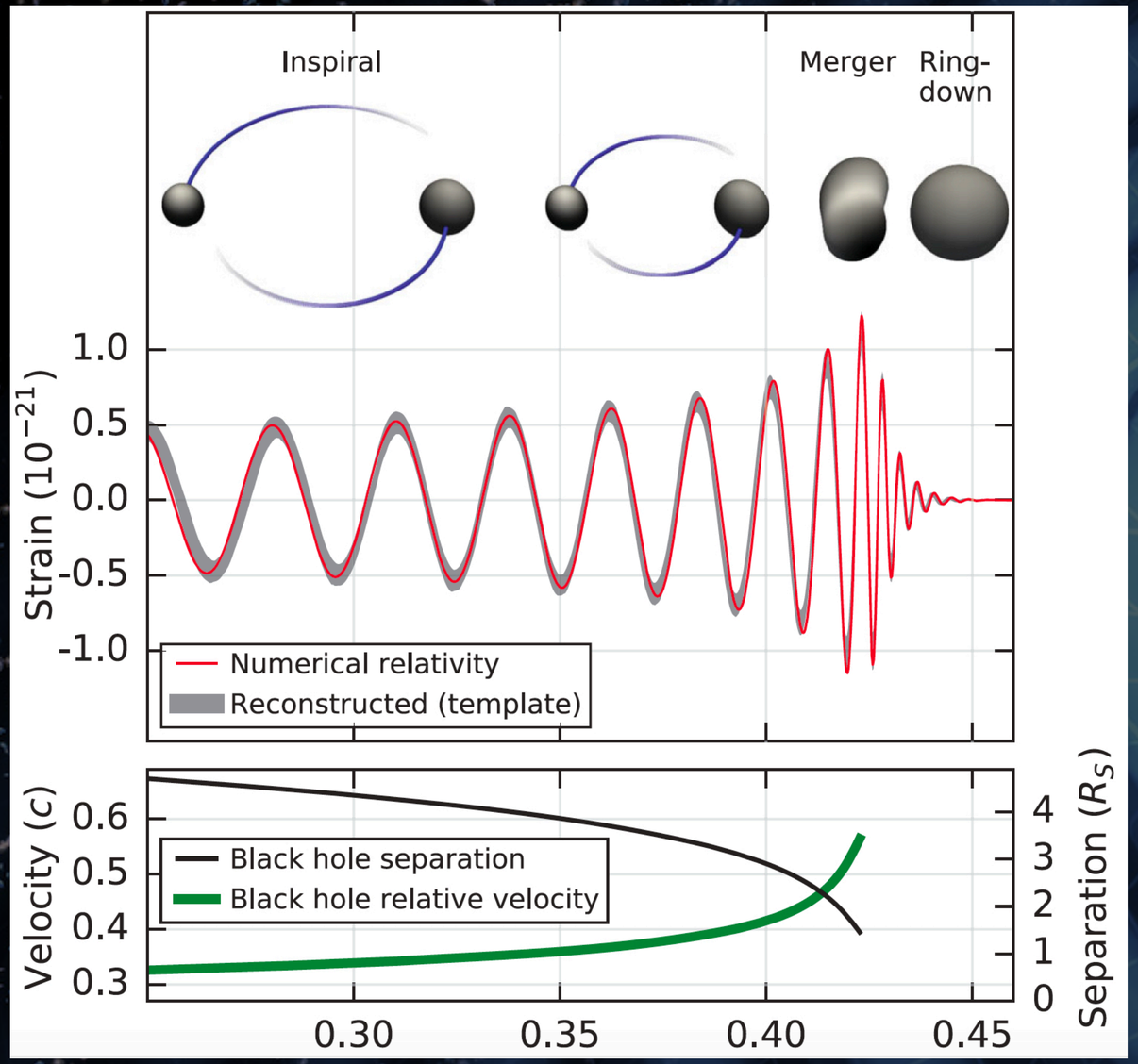
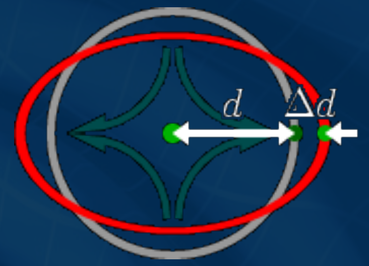
LIGO and Virgo: results, status and perspective

A. Trovato
Università di Trieste, INFN-Sezione Trieste

Gravitational waves (GW)



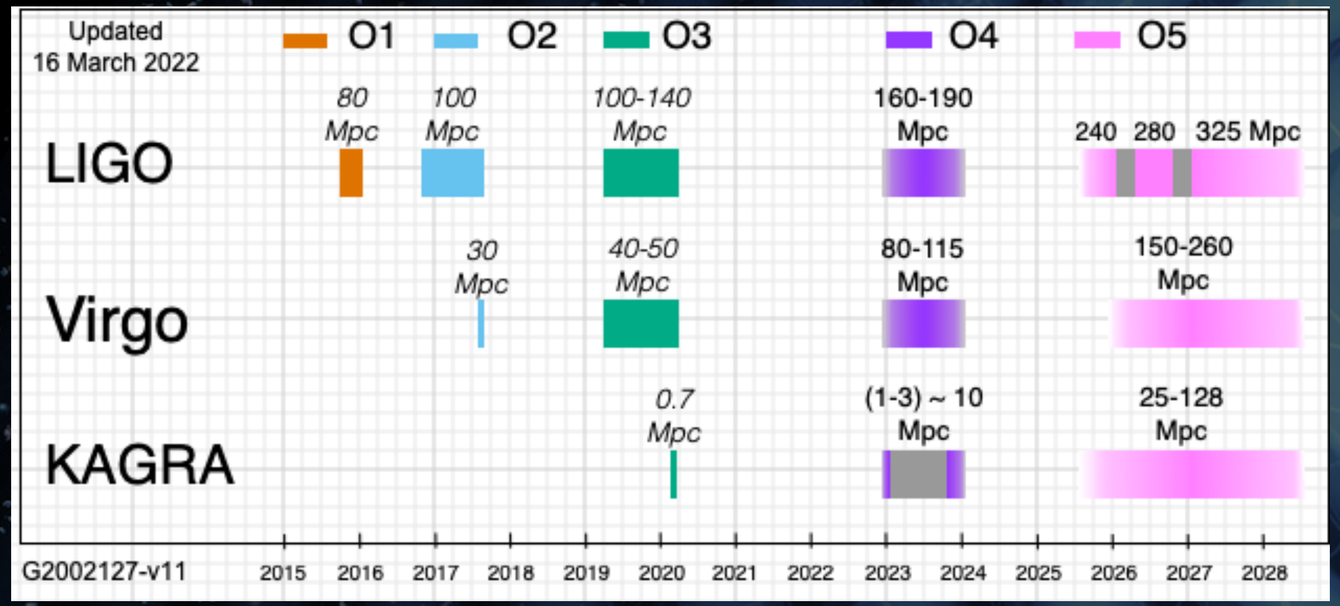
Reminder: strain



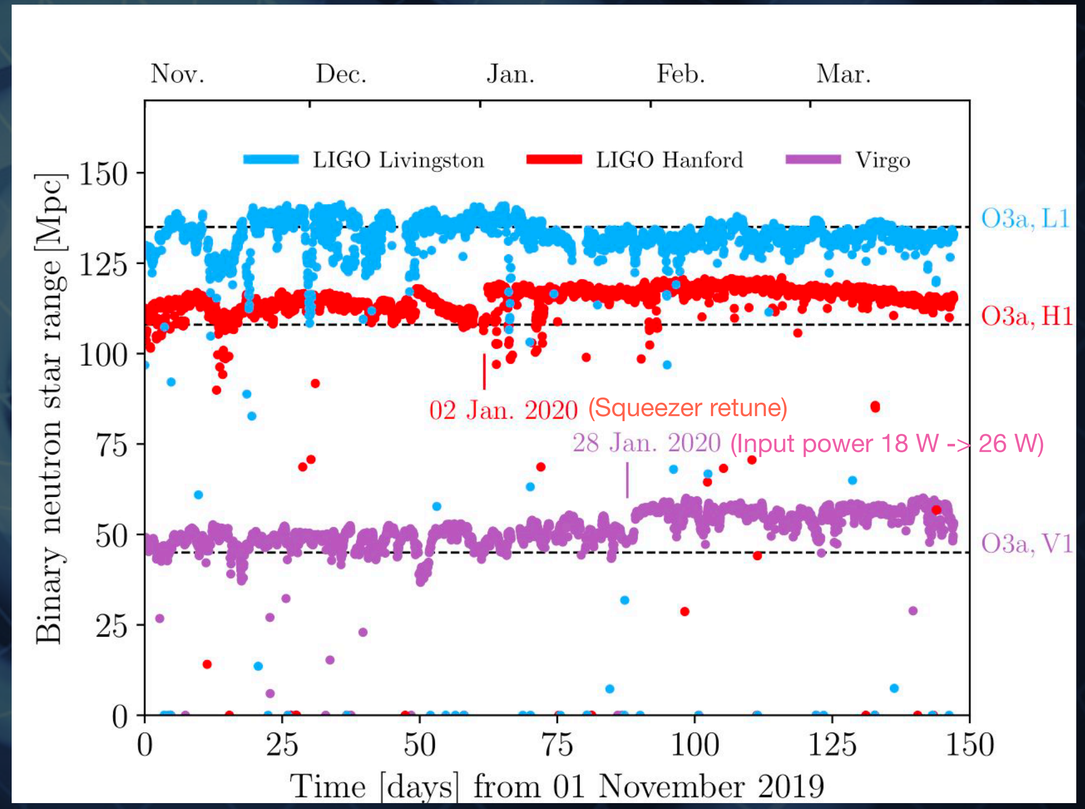
$$h = \frac{\Delta d}{d} = \frac{change\ in\ relative\ position}{separation}$$

Observing runs

The detectors alternate periods of data taking and periods of upgrades to the machines



*BNS range during O3

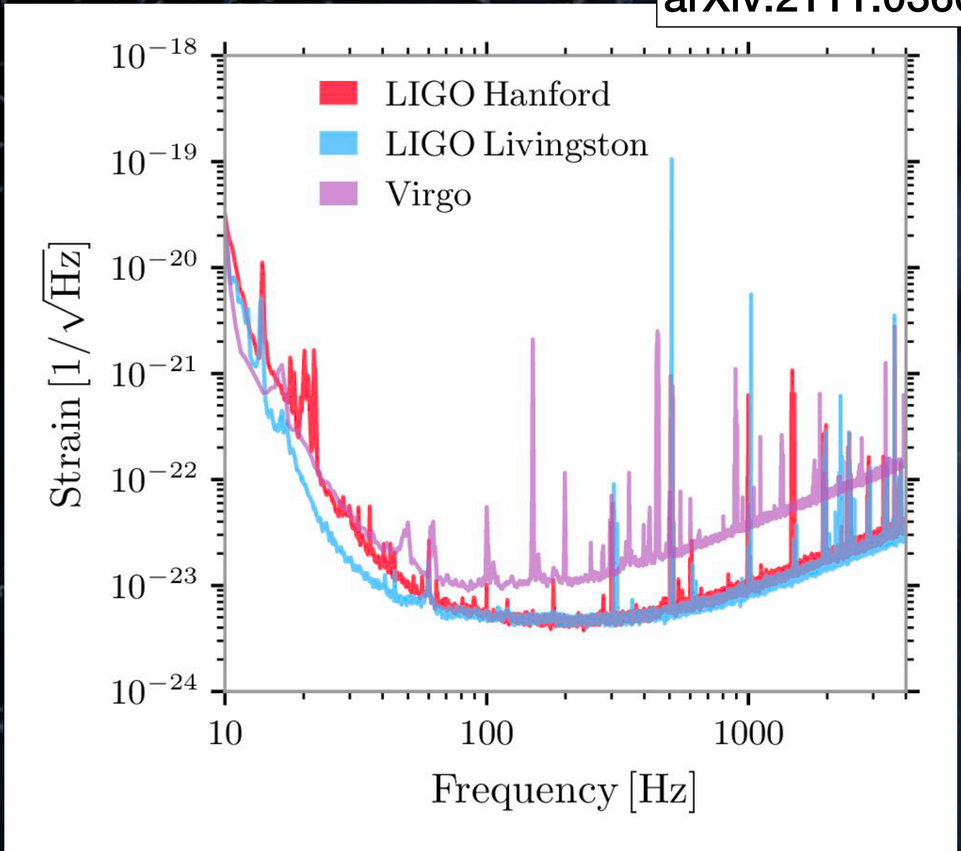


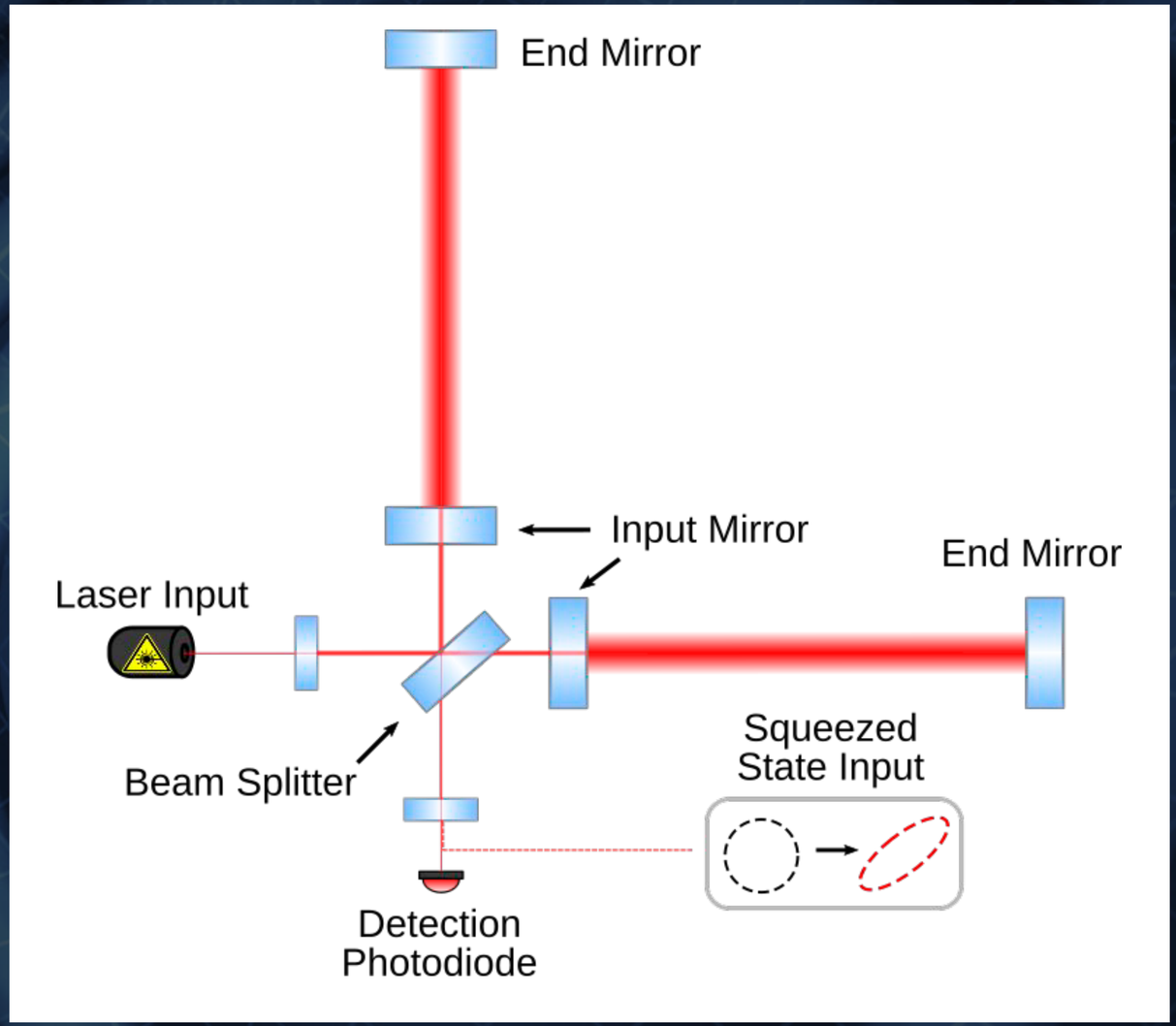
arXiv:2111.03606

**Binary Neutron Star Range*: average distance at which a fiducial 1.4 $M_\odot$ + 1.4 $M_\odot$ BNS could be detected with a signal-to-noise ratio of 8

GW detectors during O3

arXiv:2111.03606





Major upgrades of the detectors since O2:

- Increased laser power
- Squeezed light input
- New test masses and suspension wires

GWTC: Gravitational Waves Transient Catalog - 3

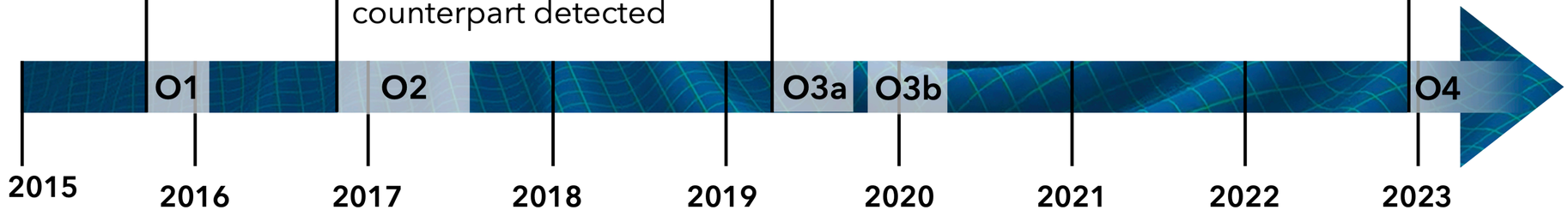
arXiv
1811.12907
2108.01045
2111.03606

3 GW detection during O1
- First direct detection of GW
- From coalescing binary systems of black holes

8 GW detection during O2
- 1 coalescing binary system of neutron stars: electromagnetic counterpart detected

79 GW detection during O3
- 44 during O3a, including 1 confirmed binary system of neutron stars
- 35 during O3b, including 2 confirmed systems of neutron stars - black holes
- No electromagnetic counterpart

O4 to start in 2022
- Planned for December



90 GW detections reported

Coalescence of compact objects (black holes, neutron stars)

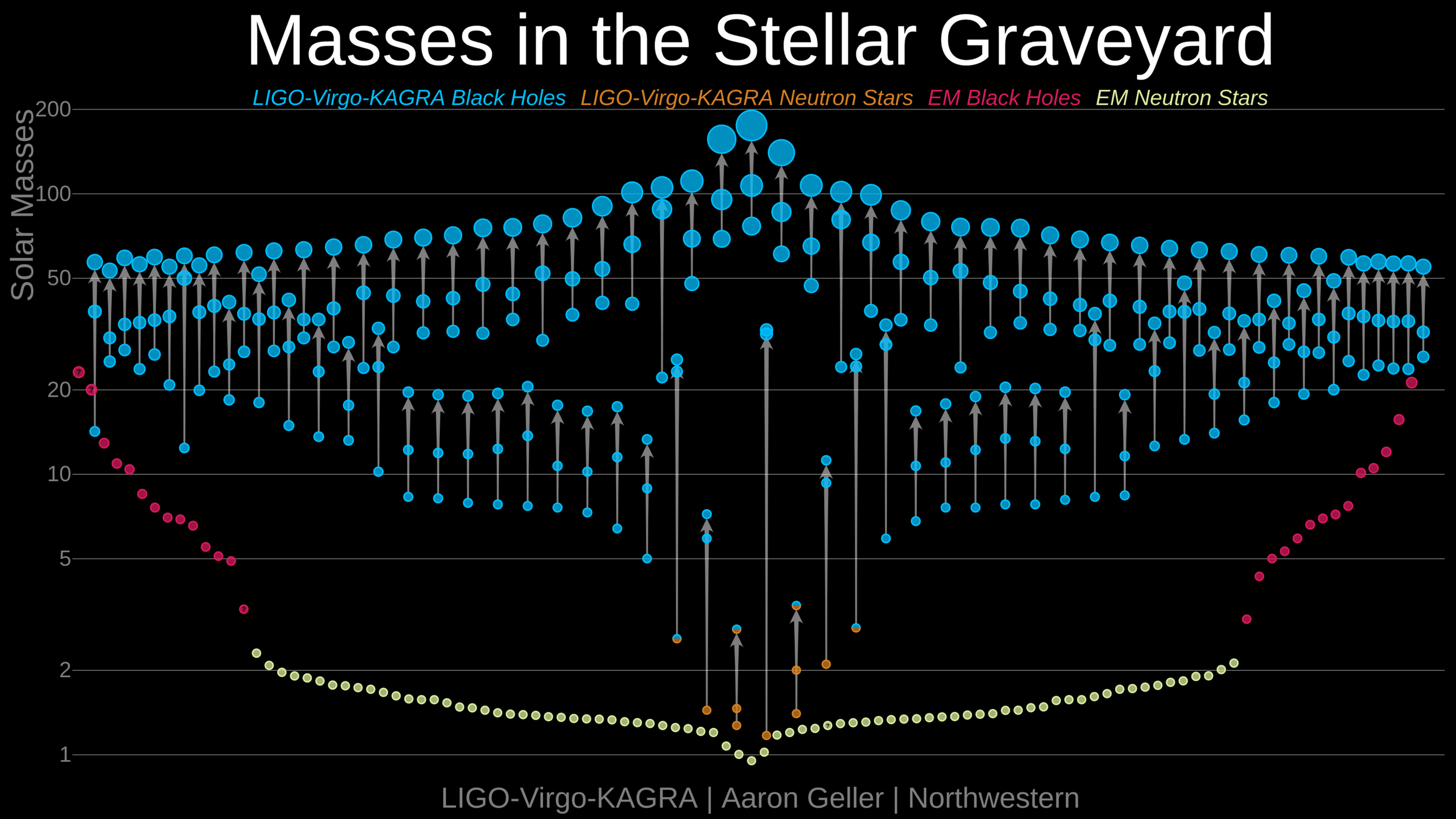
1 multimessenger event (GW + EM observation)

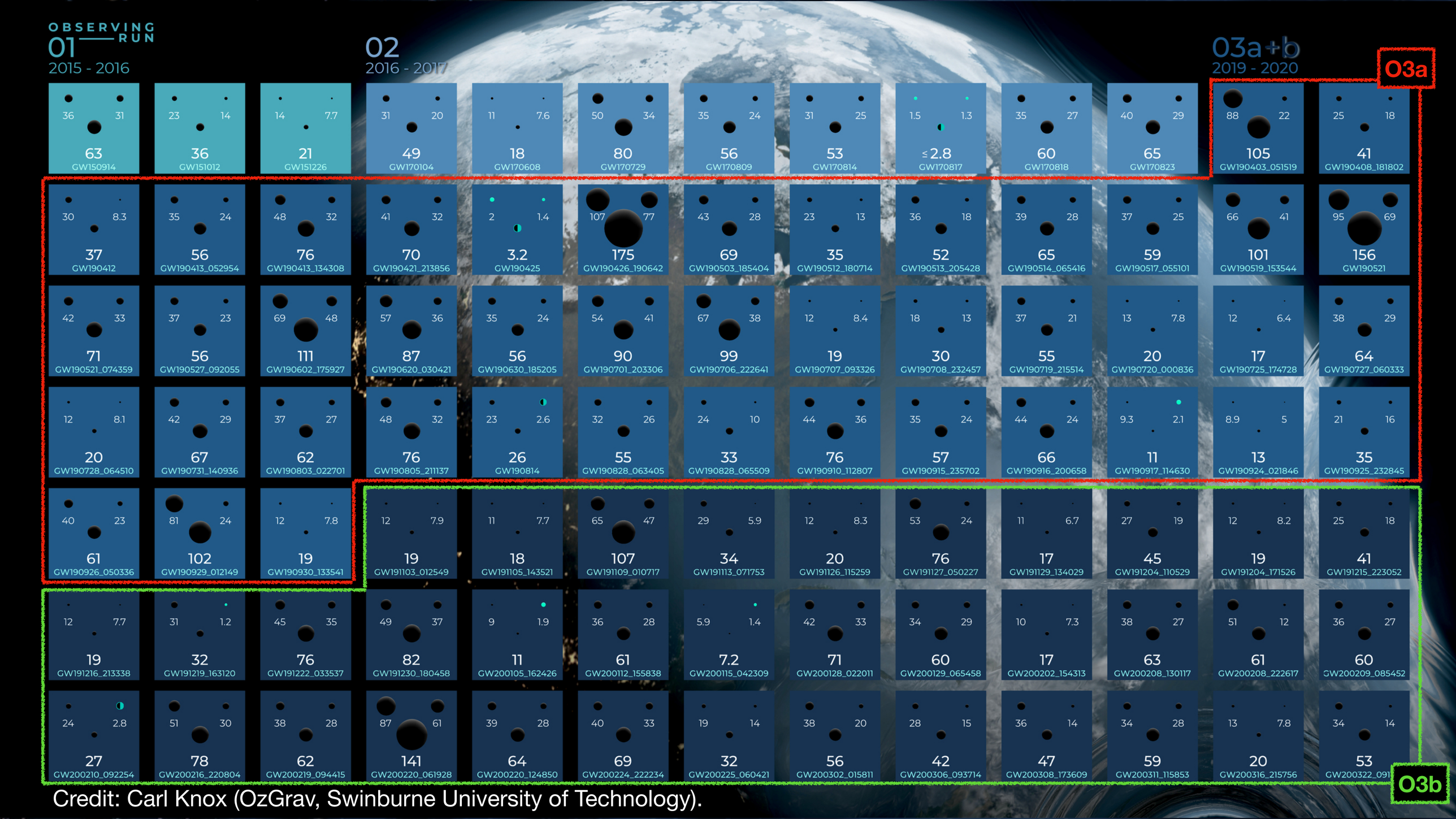
Mass range 1.2 → 107 $M_\odot$ (stellar)

Distance range 40 Mpc → 6 Gpc (z → 0.45)

Leïla Haegel

Masses in the Stellar Graveyard





Credit: Carl Knox (OzGrav, Swinburne University of Technology).

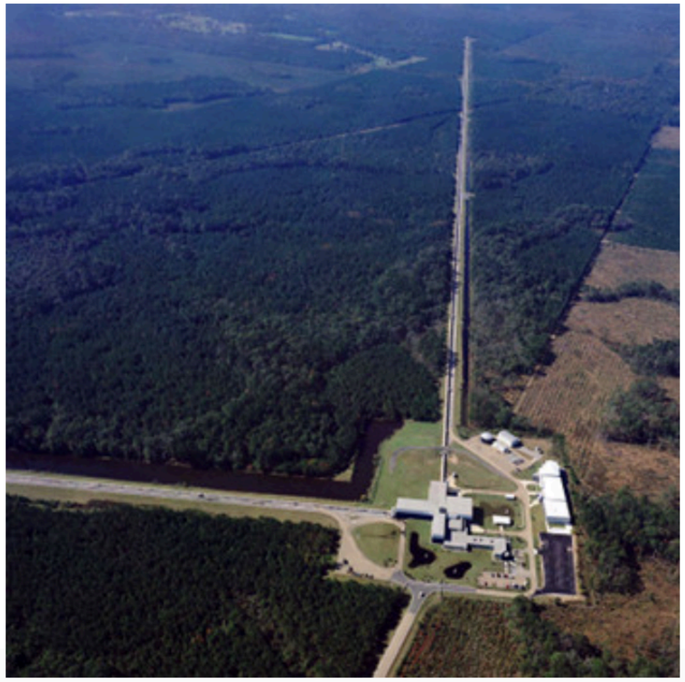
Gravitational Wave Open Science Center

www.gwosc.org

Data Software Online Tools Learning Resources About GWOSC

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

LIGO Hanford Observatory, Washington



LIGO Livingston Observatory, Louisiana

Virgo detector, Italy

Data releases for entire runs

Auxiliary Data Release

Time Range: 3 hours around event GW170814 (August 14, 2017)
Detectors: H1 and L1
Description: Around 1,000 channels that monitor the LIGO instruments and surrounding enviornment.

Auxiliary Data

www.gwosc.org/data

O3GK Data Release

O3GK Time Range: April 7, 2020 through April 21, 2020
Detectors: G1 and K1

4 kHz Data | 16 kHz Data | Documents | Timeline

O3b Data Release

O3b Time Range: November 1, 2019 through March 27, 2020
Detectors: H1, L1 and V1

4 kHz Data | 16 kHz Data | Documents | Timeline

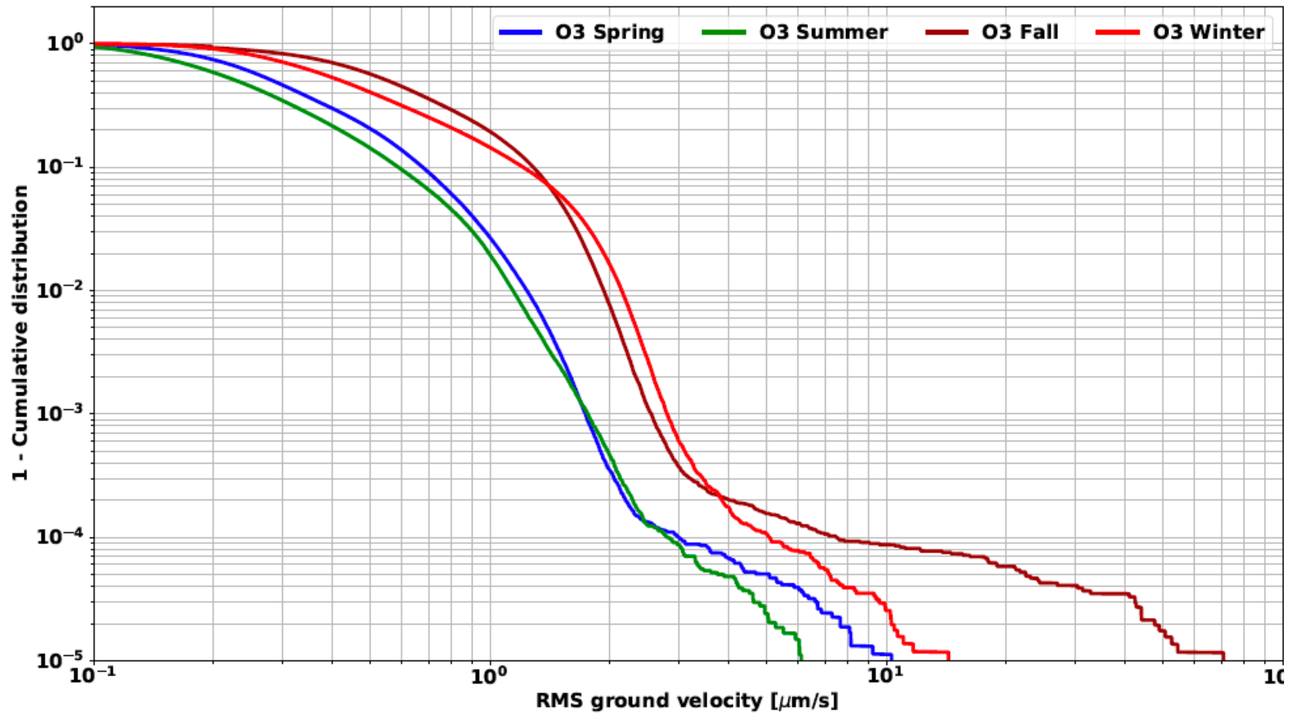
O3a Data Release

O3a Time Range: April 1, 2019 through October 1, 2019
Detectors: H1, L1 and V1

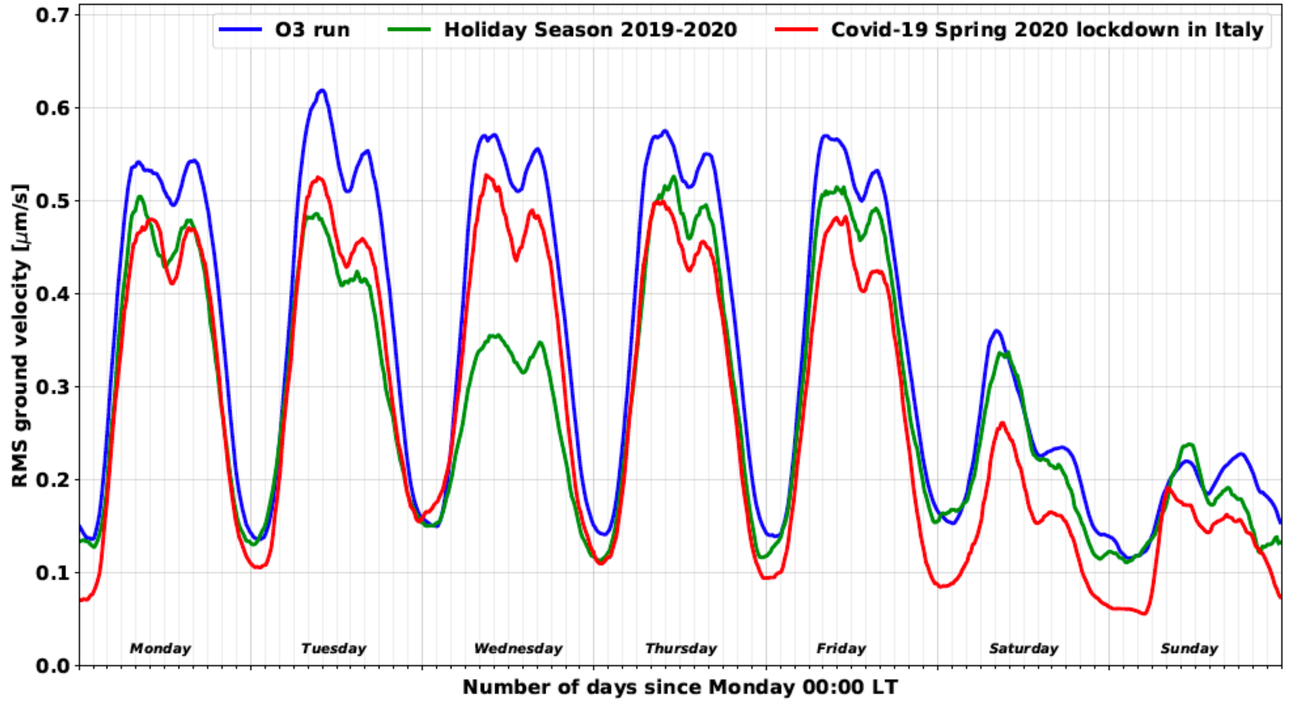
4 kHz Data | 16 kHz Data | Documents | Timeline

The GWOSC team is working on a release of O3 auxiliary channels (only for LIGO)

The Virgo O3 run and the impact of the environment (I)



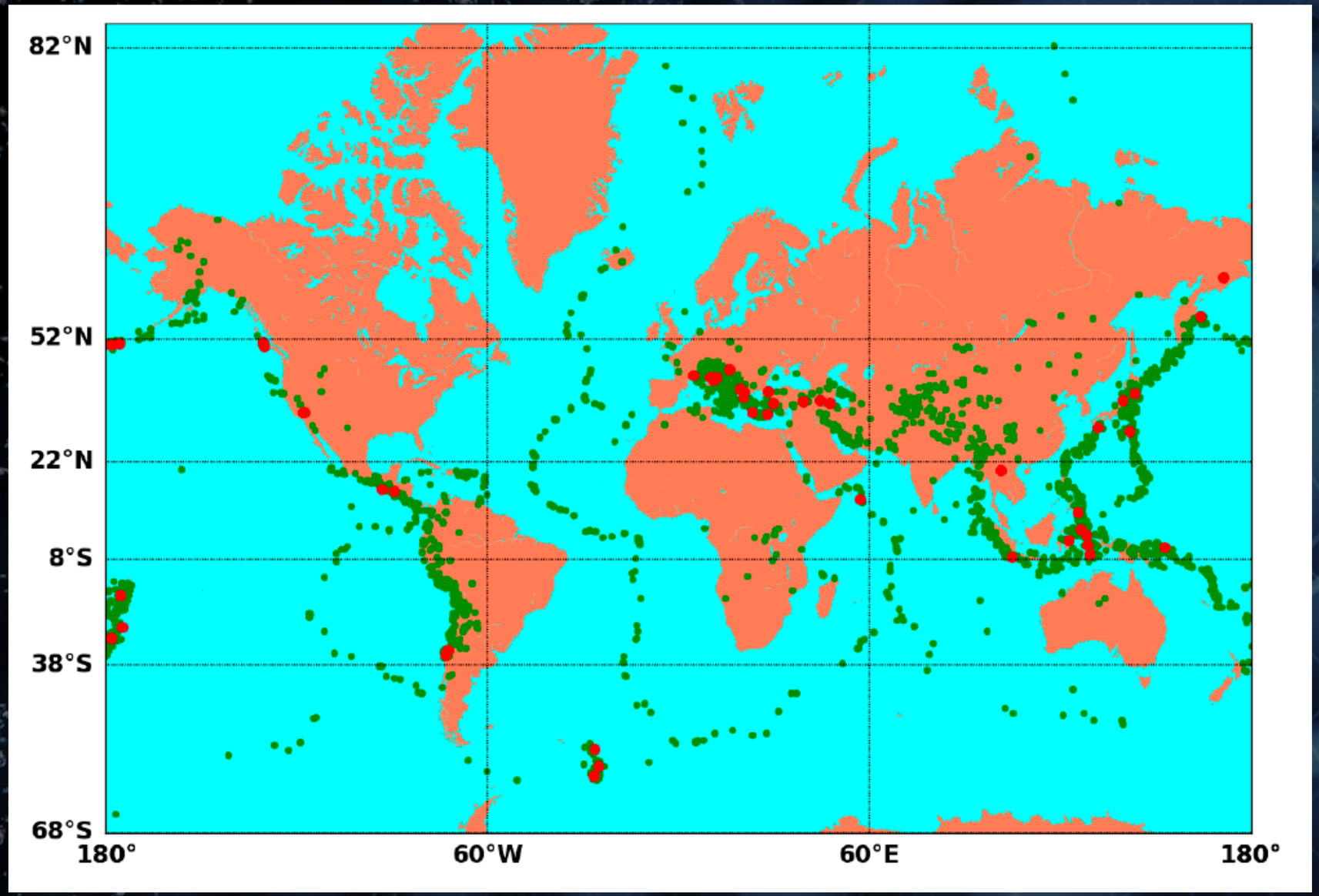
Cumulative distribution of microseism in the frequency band 0.1-1 Hz



Average evolution on a weekly basis of the seismic anthropogenic noise (frequency band: 1-5 Hz)

arXiv:2203.04014

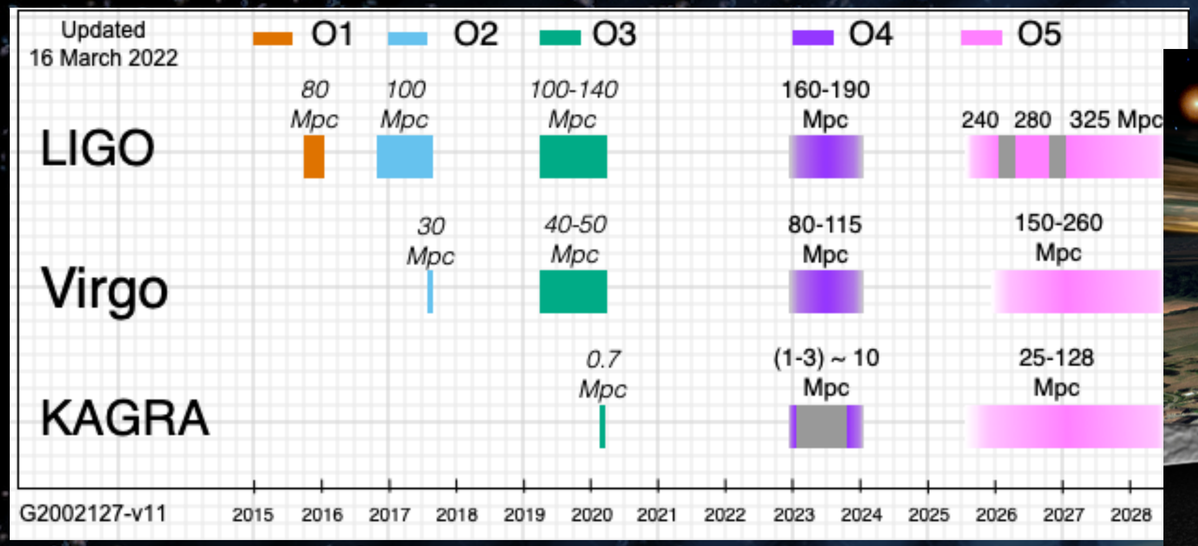
The Virgo O3 run and the impact of the environment (II)

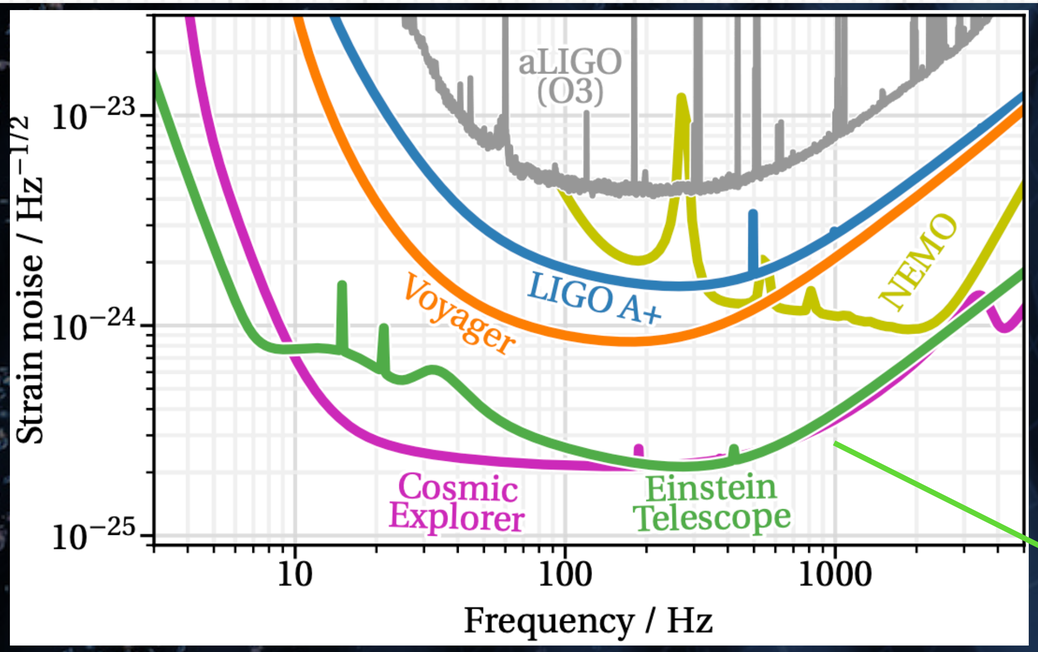


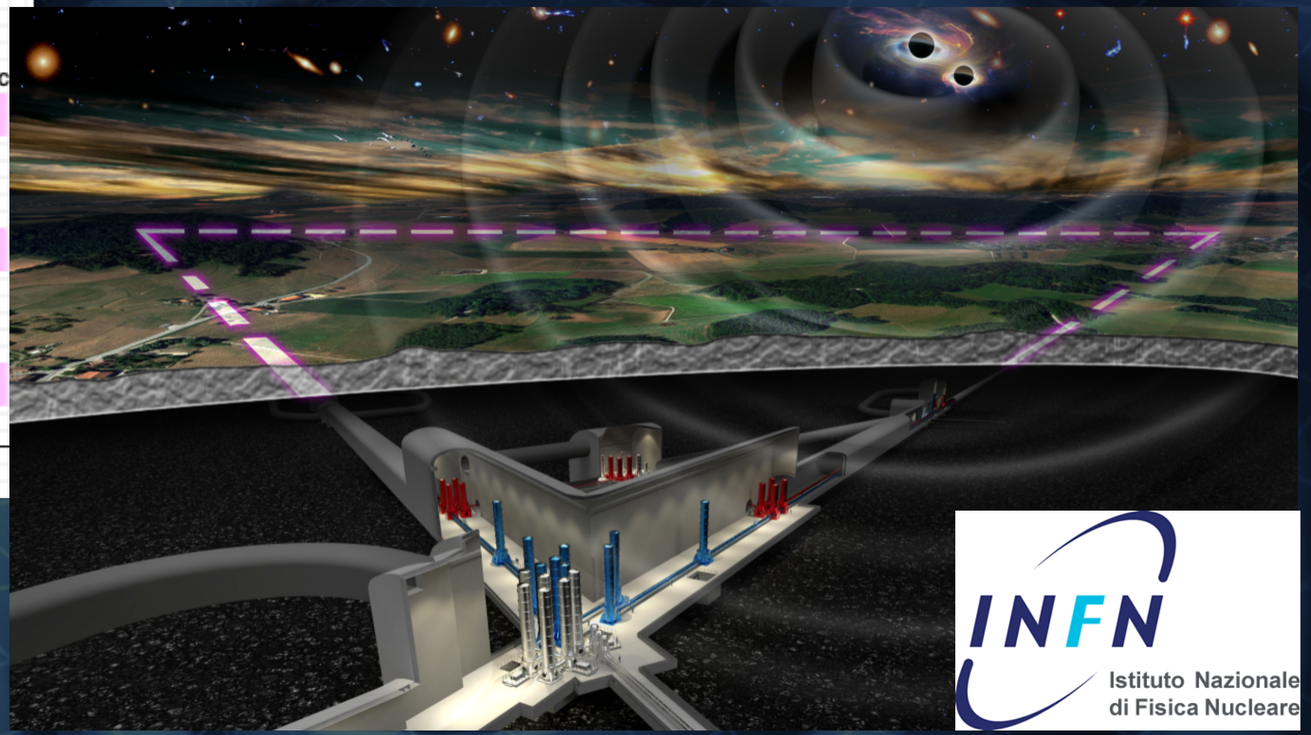
The earthquakes that caused a Virgo control loss (did not cause a control loss) are represented with red (green) dots.

arXiv:2203.04014

What happen next?







INFN Istituto Nazionale di Fisica Nucleare

Einstein Telescope

- 2026 - constructions starts
- 2035 - science run

10x sensitivity of today's observatories

Conclusions

- Observation of 90 gravitational wave signals from binary mergers
- Identification of several exceptional GW events
- Many additional results and analysis published
- Fourth observing run, starting mid December 2022, will lead to further interesting and unexpected observations!!!

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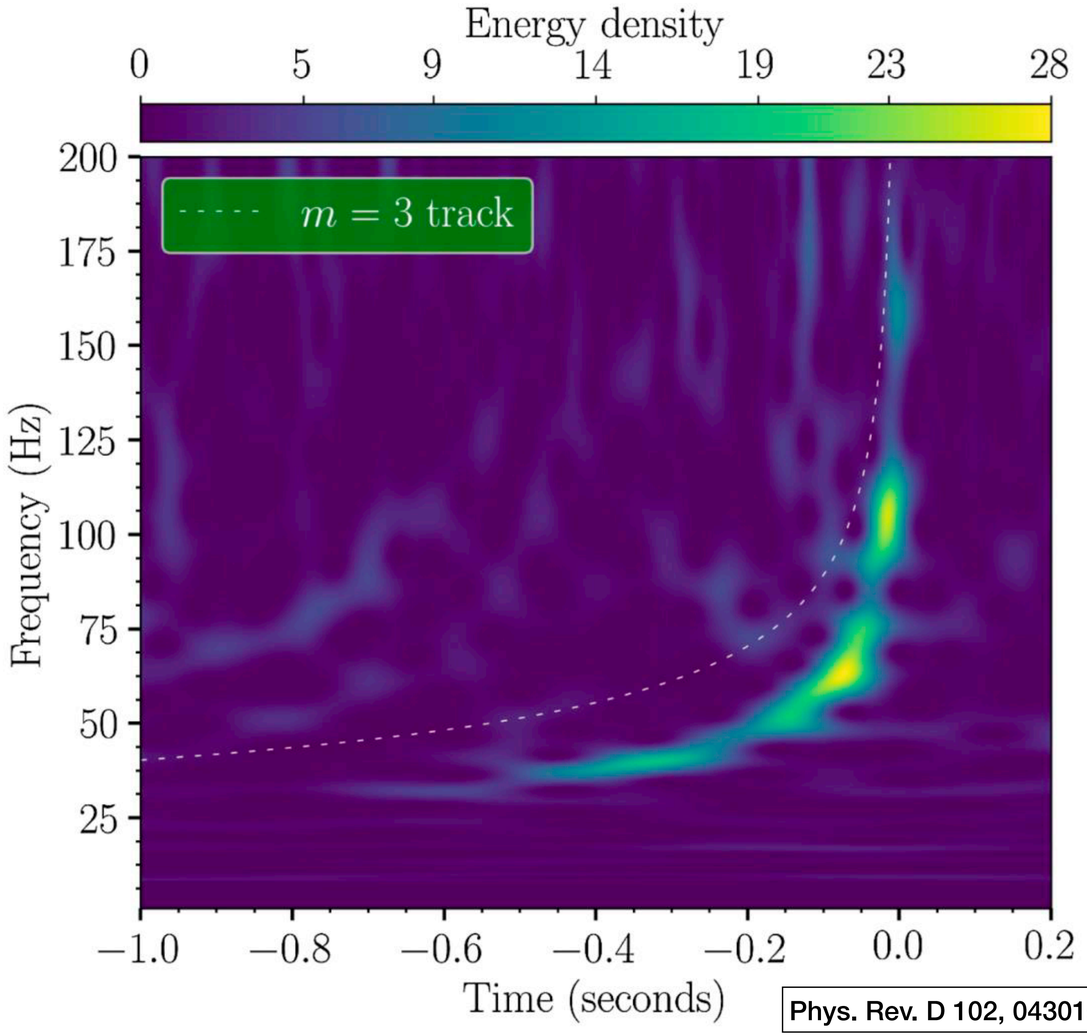
We would like to thank all of the essential workers who put their health at risk during the COVID-19 pandemic, without whom we would not have been able to complete this work.

GW190412: Unequal masses and higher GW harmonics



Phys. Rev. D 102, 043015 (2020)

Credit: Carl Knox (OzGrav, Swinburne University of Technology).

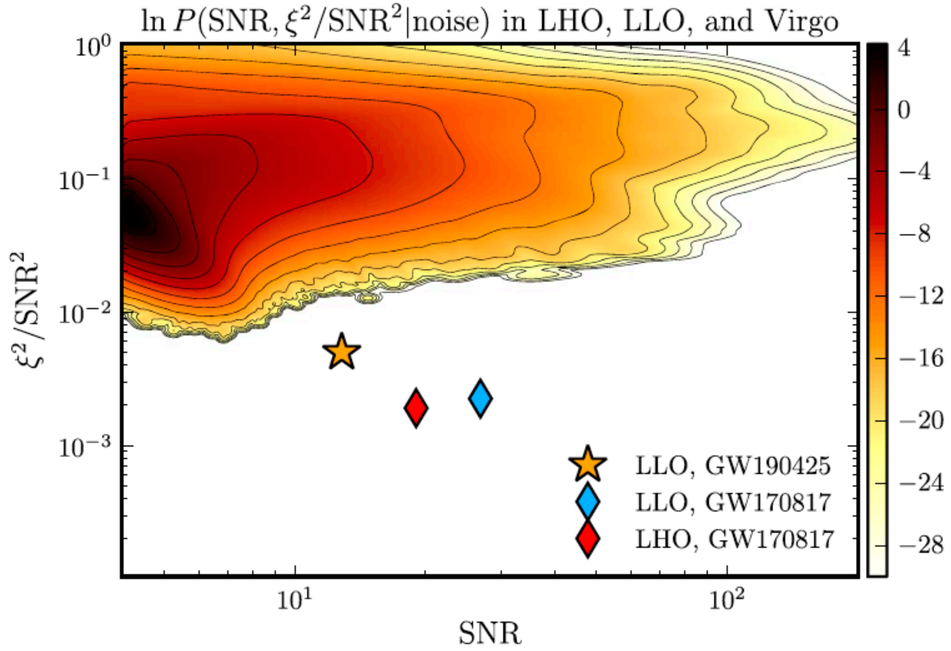
OBSERVING RUN 01
2015 - 2016

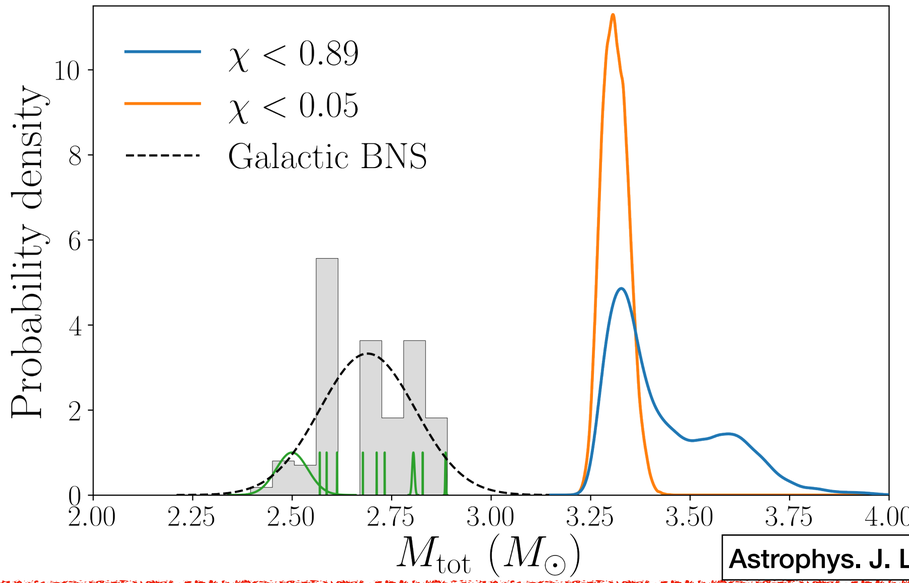
02
2016 - 2017

36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190[illegible]530_185205	54 41 90 GW190701_203306
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW[illegible]191109_010717
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155[illegible]38
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234

Credit: Carl Knox (OzGrav, Swinburne University of Technology).

GW190425: The heaviest BNS ever seen?





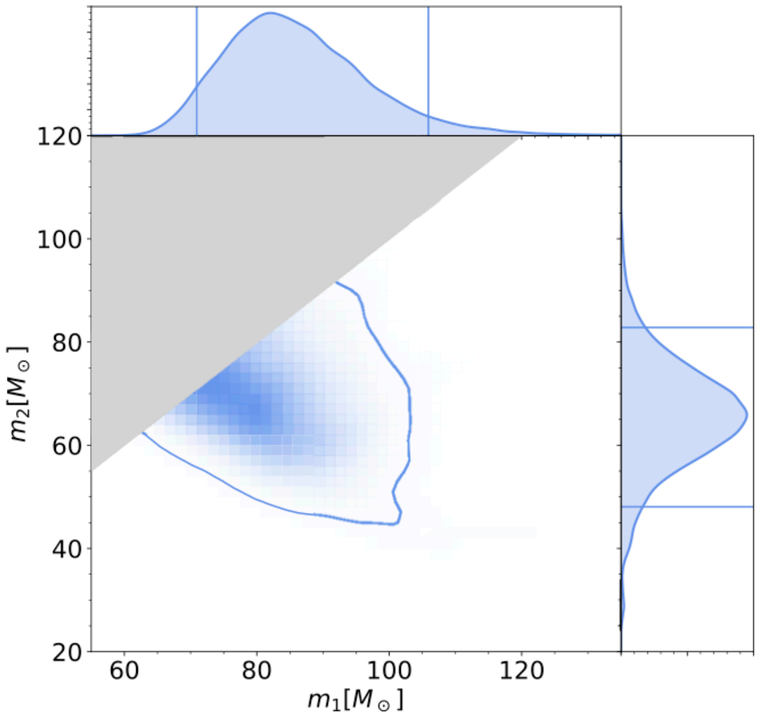
Astrophys. J. Lett. 892, L3 (2020)

OBSERVING RUN 01
2015 - 2016

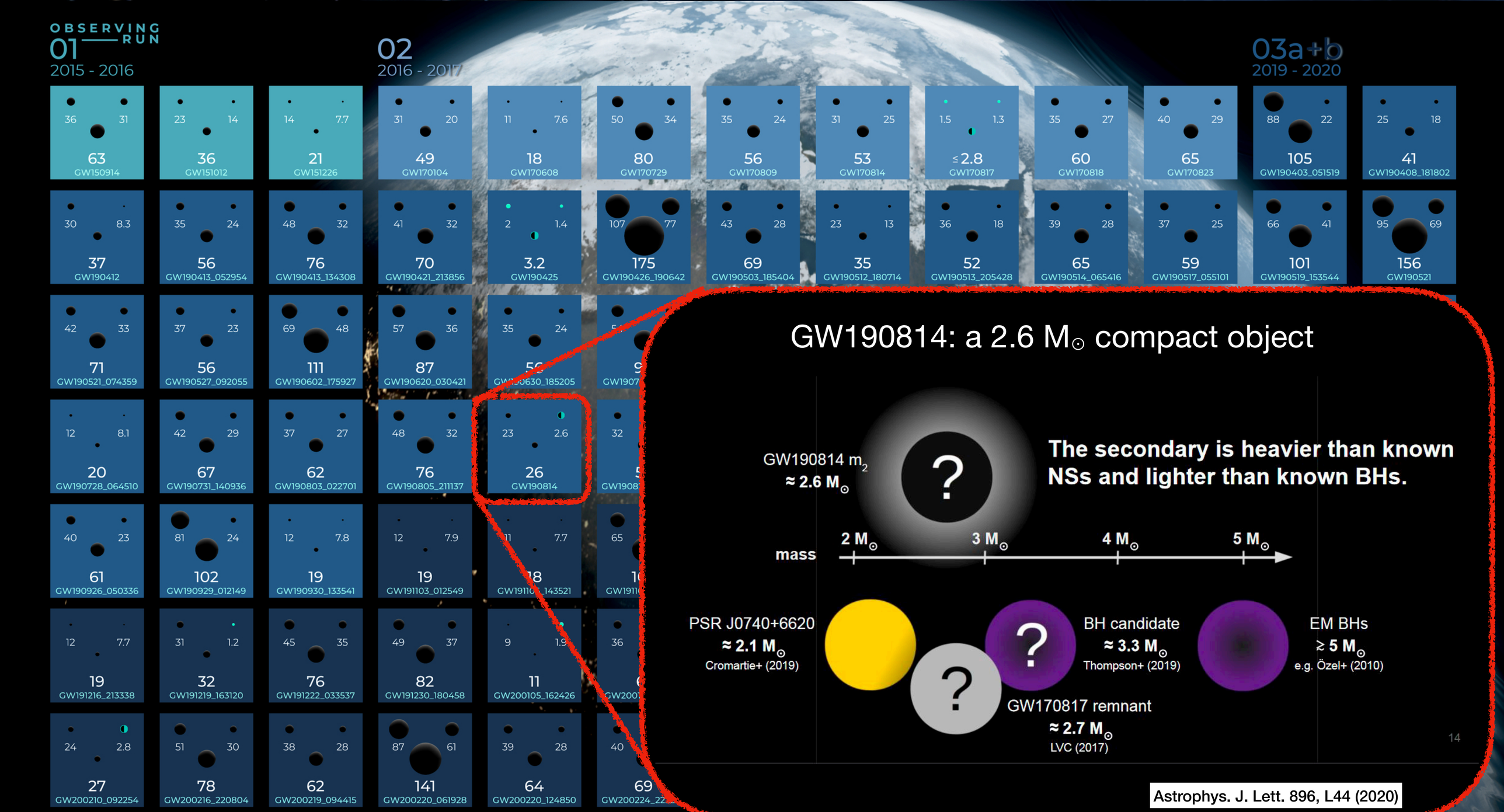
02
2016 - 2017

03a+b
2019 - 2020

GW190521: mass of the heavier binary component in the pair-instability supernova mass gap

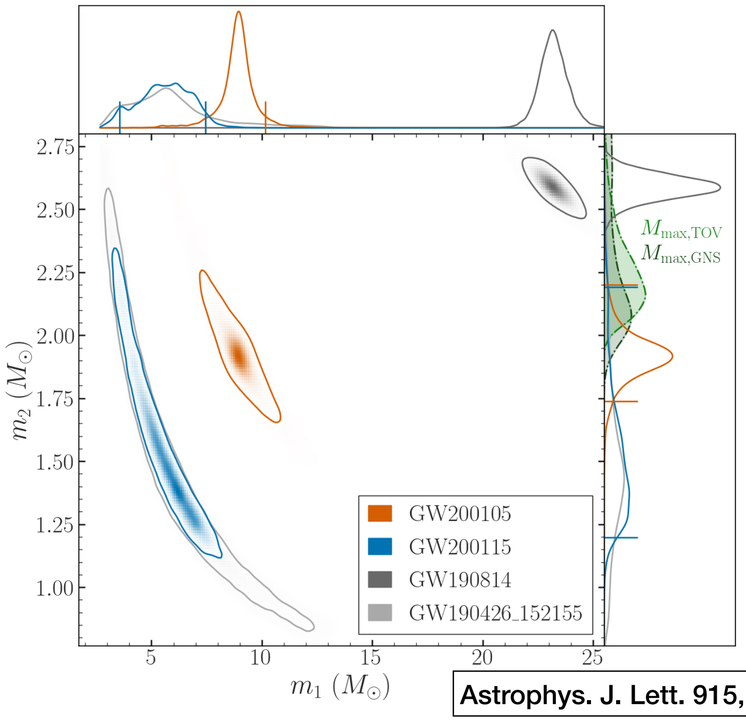


Credit: Carl Knox (OzGrav, Swinburne University of Technology)



Credit: Carl Knox (OzGrav, Swinburne University of Technology).

GW200105 and GW200115: First unambiguous observation of NS-BH system



Astrophys. J. Lett. 915, L5 (2021)

OBSERVING 01 RUN
2015 - 2016

03a+b
2019 - 2020

36 31 63 GW150914	23 14 36 GW151012	14 2 GW15	19 GW191103_012549	18 GW191105_143521	107 GW191109_010717	34 GW191113_071753	20 GW191126_115259	76 GW191127_050227	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 7 GW1904							39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 11 GW1906							37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 6 GW1908							44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7. 19 GW190930_133541							11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

Credit: Carl Knox (OzGrav, Swinburne University of Technology).

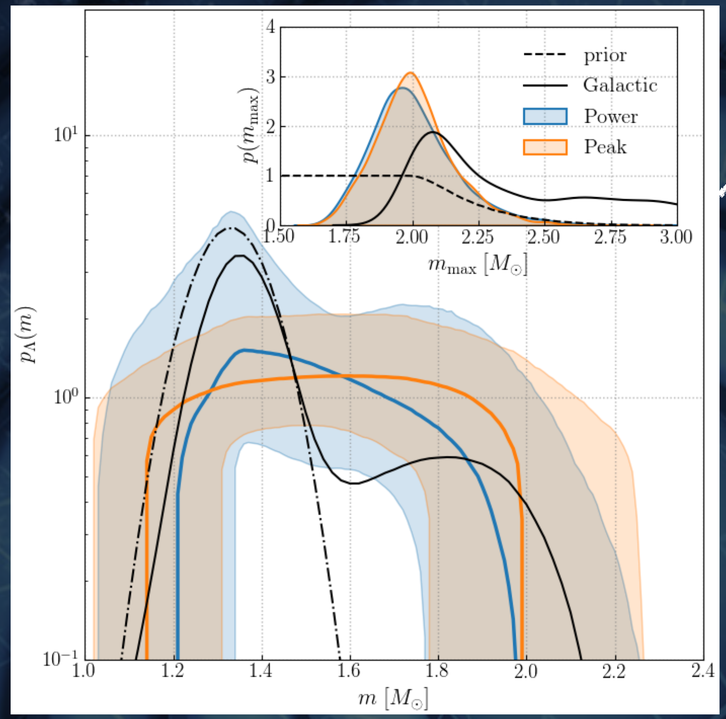
Population studies

arXiv:2111.03634

Merger rates

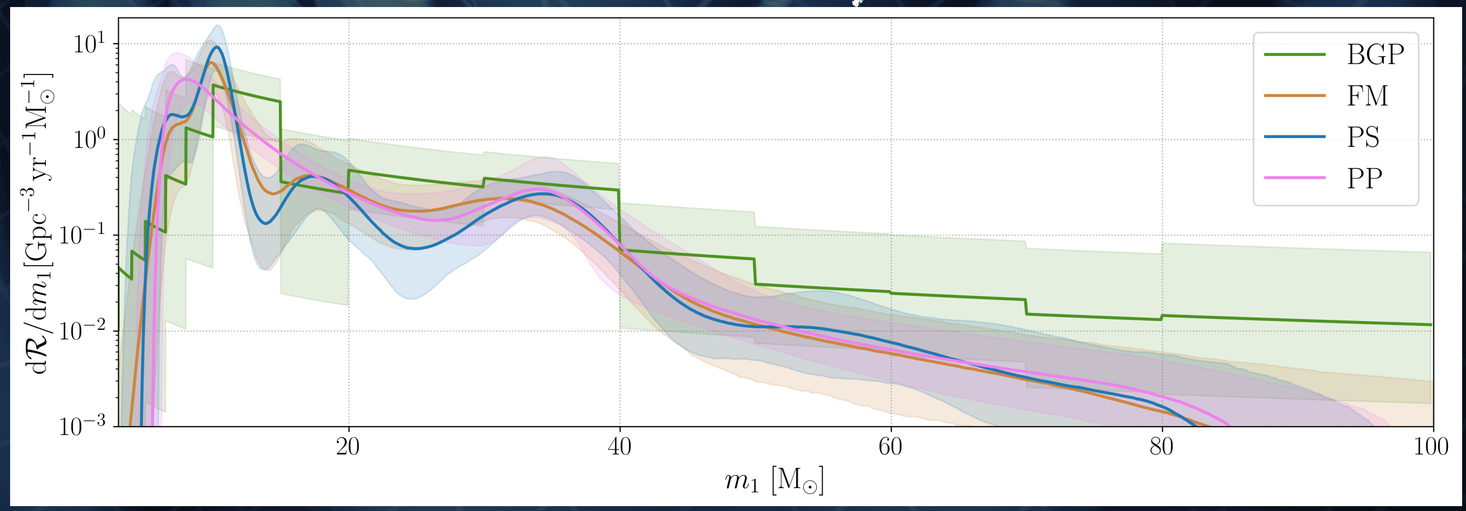
- BNS: 10 - 1700 $Gpc^{-3}\ yr^{-1}$
- NSBH: 7.8 - 140 $Gpc^{-3}\ yr^{-1}$
- BBH: 17.9 - 44 $Gpc^{-3}\ yr^{-1}$ (z=0.2)

BNS mass distribution: GW single-peak vs two-peaks from pulsars

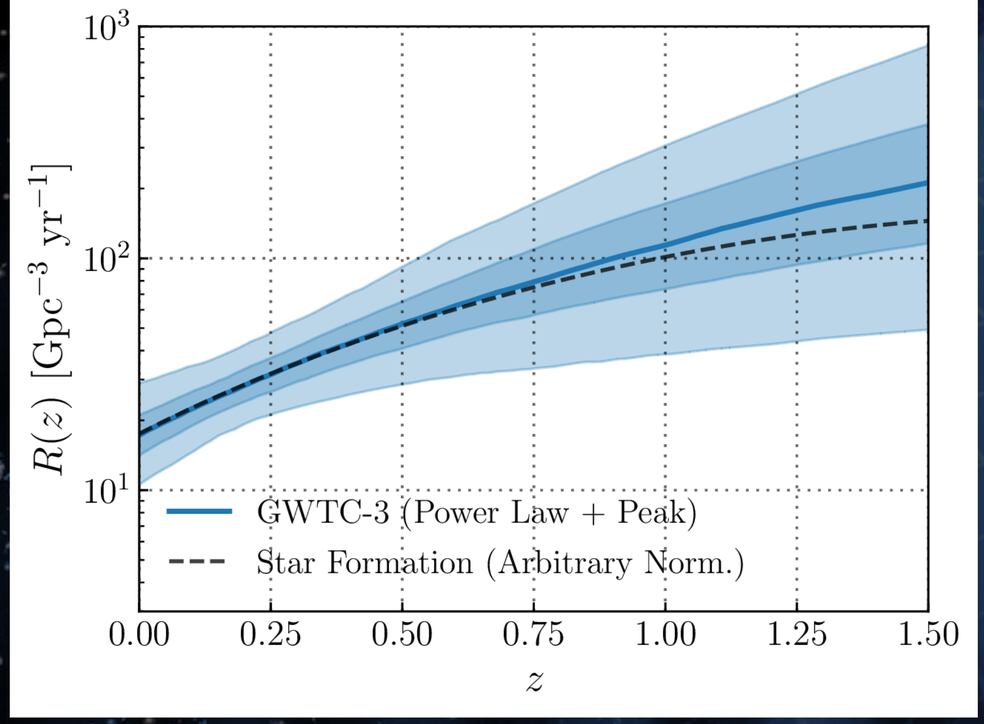


BBH primary mass distribution:

- peaks at ~10 and 35 (maybe also at 18)



BBH merger rate grows with redshift



Plenty of additional results

https://pnp.ligo.org/ppcomm/Papers.html

Release Date	Title	Keywords (clear filter)	Science Summary	Journal citation	arXiv Preprint	Public DCC
May 3, 2022 *Recent*	**Virgo Detector Characterization and Data Quality during the O3 run** (*by Virgo Collaboration*)	O3 Virgo DetChar	-	-	2205.01555	-
Apr 9, 2022 *Recent*	**Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO-Virgo data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2204.04523	P2100437
Mar 21, 2022 *Recent*	**Search for gravitational waves associated with Fast Radio Bursts Detected by CHIME/FRB During the LIGO-Virgo Observing Run O3a** (*by LSC, Virgo and KAGRA*)	O3 FRBs	summary	*Submitted to ApJ*	2203.12038	P2100124
Mar 2, 2022	**First international joint observation of an underground gravitational-wave observatory, KAGRA, with GEO 600** (*by LSC, Virgo and KAGRA*)	O3 CBC Burst	summary	*Accepted by PTEP*	2203.01270	P2100286
Jan 25, 2022	**Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2201.10104	P2100405
Jan 3, 2022	**All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2201.00697	P2100367
Dec 21, 2021	**Narrowband searches for continuous and long-duration transient gravitational waves from known pulsars in the LIGO-Virgo third observing run** (*by LSC, Virgo, KAGRA plus 28 radio astronomers and NICER science team members*)	O3 CW	summary	*Accepted by ApJ*	2112.10990	P2100267
Dec 13, 2021	**Tests of General Relativity with GWTC-3** (*by LSC, Virgo and KAGRA*)	O3 CBC TGR	summary	*Accepted by PRD*	2112.06861	P2100275
Nov 30, 2021	**Search of the Early O3 LIGO Data for Continuous Gravitational Waves from the Cassiopeia A and Vela Jr. Supernova Remnants** (*by LSC and Virgo*)	O3 CW	summary	Phys. Rev. D **105**, 082005 (2022)	2111.15116	P2100298
Nov 30, 2021	**All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	Phys. Rev. D **105**, 102001 (2022)	2111.15507	P2100343
Nov 25, 2021	**Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Accepted by ApJ*	2111.13106	P2100049
Nov 7, 2021	**Constraints on the cosmic expansion history from the third LIGO-Virgo-KAGRA Gravitational-Wave Transient Catalog** (*by LSC, Virgo and KAGRA*)	O3 Cosmology	summary	*Accepted by ApJ*	2111.03604	P2100185
Nov 7, 2021	**GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run** (*by LSC, Virgo and KAGRA*)	O3 CBC GWTC	summary	*Submitted to PRX*	2111.03606	P2000318
Nov 7, 2021	**Search for Gravitational Waves Associated with Gamma-Ray Bursts detected by Fermi and Swift during the O3b LIGO-Virgo Run** (*by LSC, Virgo and KAGRA*)	O3 GRBs	summary	Astrophys. J. **928**, 186 (2022)	2111.03608	P2100091
Nov 7, 2021	**The population of merging compact binaries inferred using gravitational waves through GWTC-3** (*by LSC, Virgo and KAGRA*)	O3 CBC	summary	*Submitted to PRX*	2111.03634	P2100239
Oct 19, 2021	**All-sky, all-frequency directional search for persistent gravitational waves from Advanced LIGO's and Advanced Virgo's first three observing runs** (*by LSC, Virgo and KAGRA*)	O3 Stochastic	summary	*Submitted to PRL*	2110.09834	P2100292
Sep 24, 2021	**Search for subsolar-mass binaries in the first half of Advanced LIGO and Virgo's third observing run** (*by LSC, Virgo, KAGRA, D. Jeong and S. Shandera*)	O3 CBC	summary	*Submitted to PRL*	2109.12197	P2100163
Sep 20, 2021	**Search for continuous gravitational waves from 20 accreting millisecond X-ray pulsars in O3 LIGO data** (*by LSC, Virgo, KAGRA plus A. C. Albayati, D. Altamirano, P. Bult, D. Chakrabarty, M. Ng, P. S. Ray, A. Sanna, and T. E. Strohmayer*)	O3 CW	summary	Phys. Rev. D **105**, 022002 (2022)	2109.09255	P2100221
Jul 21, 2021	**GWTC-2.1: Deep Extended Catalog of Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run** (*by LSC and Virgo*)	O3 CBC GWTC	summary	*Submitted to PRD*	2108.01045	P2100063
Jul 19, 2021	**All-sky search for long-duration gravitational-wave transients in the third Advanced LIGO observing run** (*by LSC, Virgo and KAGRA*)	O3 Burst	summary	Phys. Rev. D **104**, 102001 (2021)	2107.13796	P2100078
Jul 8, 2021	**All-sky search for short gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run** (*by LSC, Virgo and KAGRA*)	O3 Burst	summary	Phys. Rev. D **104**, 122004 (2021)	2107.03701	P2100045
Jul 1, 2021	**All-sky search for continuous gravitational waves from isolated neutron stars in the Early O3 LIGO Data** (*by LSC and Virgo*)	O3 CW	summary	Phys. Rev. D **104**, 082004 (2021)	2107.00600	P2000334
Jun 29, 2021	**Observation of gravitational waves from two neutron star-black hole coalescences** (*by LSC and Virgo*)	O3 CBC GW200105 GW200115	summary	Astrophys. J. Lett. **915**, L5 (2021)	2106.15163	P2000357
May 31, 2021	**Search for intermediate mass black hole binaries in the third observing run of Advanced LIGO and Advanced Virgo** (*by LSC, Virgo and KAGRA*)	O3 CBC Burst	summary	Astronomy & Astrophysics **659**, A84 (2022)	2105.15120	P2100025
May 27, 2021	**Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	Phys. Rev. D **105**, 063030 (2022)	2105.13085	P2100098
May 25, 2021	**Searches for continuous gravitational waves from young supernova remnants in the early third observing run of Advanced LIGO and Virgo** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	Astrophys. J. **921**, 80 (2021)	2105.11641	P2000479
May 13, 2021	**Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run** (*by LSC and Virgo*)	O3 CBC	summary	Astrophys. J. **923**, 14 (2021)	2105.06384	P2000400
Apr 29, 2021	**Constraints from LIGO O3 data on gravitational-wave emission due to r-modes in the glitching pulsar PSR J0537-6910** (*by LSC, Virgo, KAGRA plus D. Antonopoulou, Z. Arzoumanian, T. Enoto, C. M. Espinoza, and S. Guillot*)	O3 CW J0537-6910	summary	Astrophys. J. **922**, 71 (2021)	2104.14417	P2100069
Mar 15, 2021	**Search for anisotropic gravitational-wave backgrounds using data from Advanced LIGO's and Advanced Virgo's first three observing runs** (*by LSC, Virgo and KAGRA*)	O3 Stochastic	summary	Phys. Rev. D **104**, 022005 (2021)	2103.08520	P2000500
Jan 28, 2021	**Constraints on cosmic strings using data from the third Advanced LIGO-Virgo observing run** (*by LSC, Virgo and KAGRA*)	O3 Stochastic Burst	summary	Phys. Rev. Lett. **126**, 241102 (2021)	2101.12248	P2000506
Jan 9, 2021	**Upper limits on the isotropic gravitational-wave background from Advanced LIGO and Advanced Virgo's third observing run** (*by LSC, Virgo and KAGRA*)	O3 Stochastic	summary	Phys. Rev. D **104**, 022004 (2021)	2101.12130	P2000314
Dec 23, 2020	**Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537-6910** (*by LSC, Virgo, KAGRA plus D. Antonopoulou, Z. Arzoumanian, T. Enoto, C. M. Espinoza, and S. Guillot*)	O3 CW J0537-6910	summary	Astrophys. J. Lett. **913**, L27 (2021)	2012.12926	P2000407
Dec 22, 2020	**All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems** (*by LSC and Virgo*)	O3 CW	summary	Phys. Rev. D **103**, 064017 (2021)	2012.12128	P2000298
Oct 28, 2020	**GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run** (*by LSC and Virgo*)	O3 CBC GWTC	summary	Phys. Rev. X **11**, 021053 (2021)	2010.14527	P2000061
Oct 28, 2020	**Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog** (*by LSC and Virgo*)	O3 CBC TGR	summary	Phys. Rev. D **103**, 122002 (2021)	2010.14529	P2000091
Oct 28, 2020	**Population properties of compact objects from the second LIGO-Virgo Gravitational-Wave Transient Catalog** (*by LSC and Virgo*)	O3 CBC	summary	Astrophys. J. Lett. **913**, L7 (2021)	2010.14533	P2000077
Oct 28, 2020	**Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift during the LIGO-Virgo Run O3a** (*by LSC and Virgo*)	O3 GRBs	summary	Astrophys. J. **915**, 86 (2021)	2010.14550	P2000040
Sep 2, 2020	**GW190521: A Binary Black Hole Merger with a Total Mass of 150 Msun** (*by LSC and Virgo*)	O3 GW190521	summary	Phys. Rev. Lett. **125**, 101102 (2020)	2009.01075	P2000020
Sep 2, 2020	**Properties and astrophysical implications of the 150 Msun binary black hole merger GW190521** (*by LSC and Virgo*)	O3 GW190521	summary	Astrophys. J. Lett. **900**, L13 (2020)	2009.01190	P2000021
Jul 28, 2020	**Gravitational-wave constraints on the equatorial ellipticity of millisecond pulsars** (*by LSC, Virgo, and radio astronomers*)	O3 CW	summary	Astrophys. J. Lett. **902**, L21 (2020)	2007.14251	P2000029
Jun 23, 2020	**GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object** (*by LSC and Virgo*)	O3 GW190814	summary	Astrophys. J. Lett. **896**, L44 (2020)	2006.12611	P190814
Apr 17, 2020	**GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses** (*by LSC and Virgo*)	O3 GW190412	summary	Phys. Rev. D **102**, 043015 (2020)	2004.08342	P190412
Feb 26, 2020	**Trigger Data to Accompany "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs"** (*by LSC and Virgo*)	O2 O1 CBC GWTC	-	-	-	P1900392
Jan 6, 2020	**GW190425: Observation of a compact binary coalescence with total mass ~3.4 Msun** (*by LSC and Virgo*)	O3 GW190425	summary	Astrophys. J. Lett. **892**, L3 (2020)	2001.01761	P190425