Gravitational-wave Astronomy
with the LIGO-Virgo Detector Network

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Full professor

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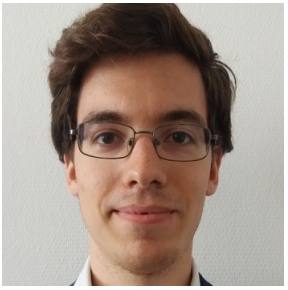
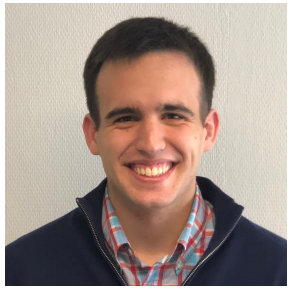


Gergely Dálya
PhD student

András Molnár
PhD student



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MSc student

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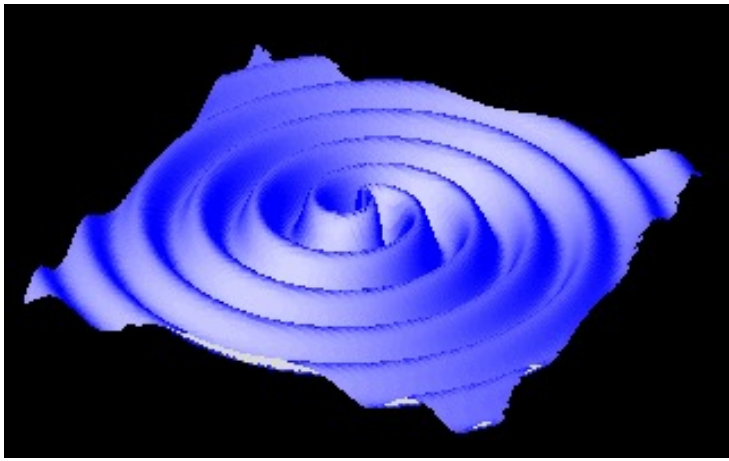
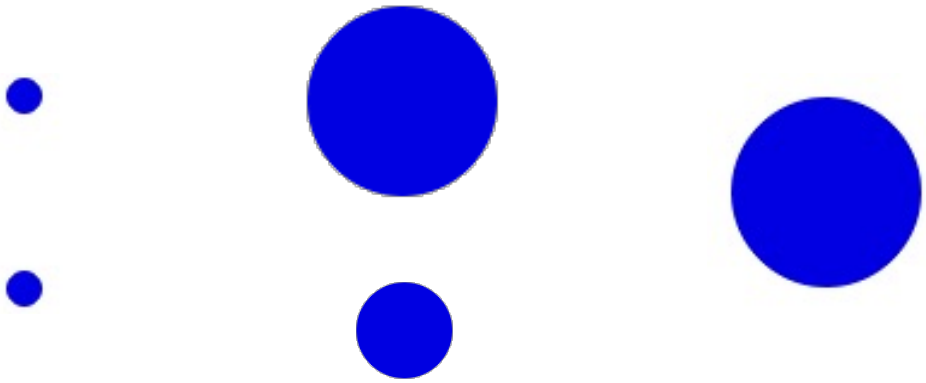
egrg.elte.hu

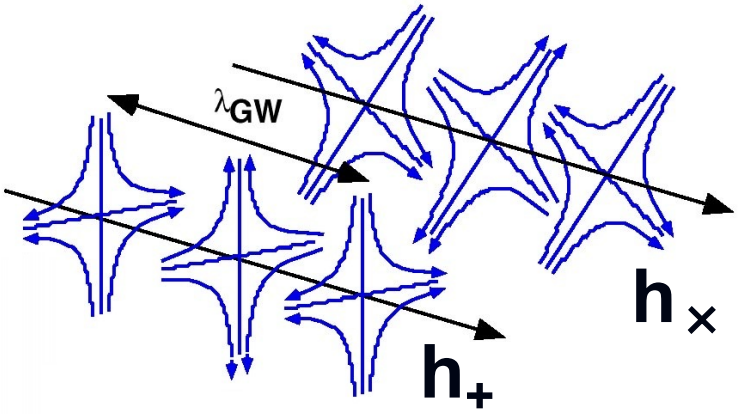
Gravitational Waves (GW)

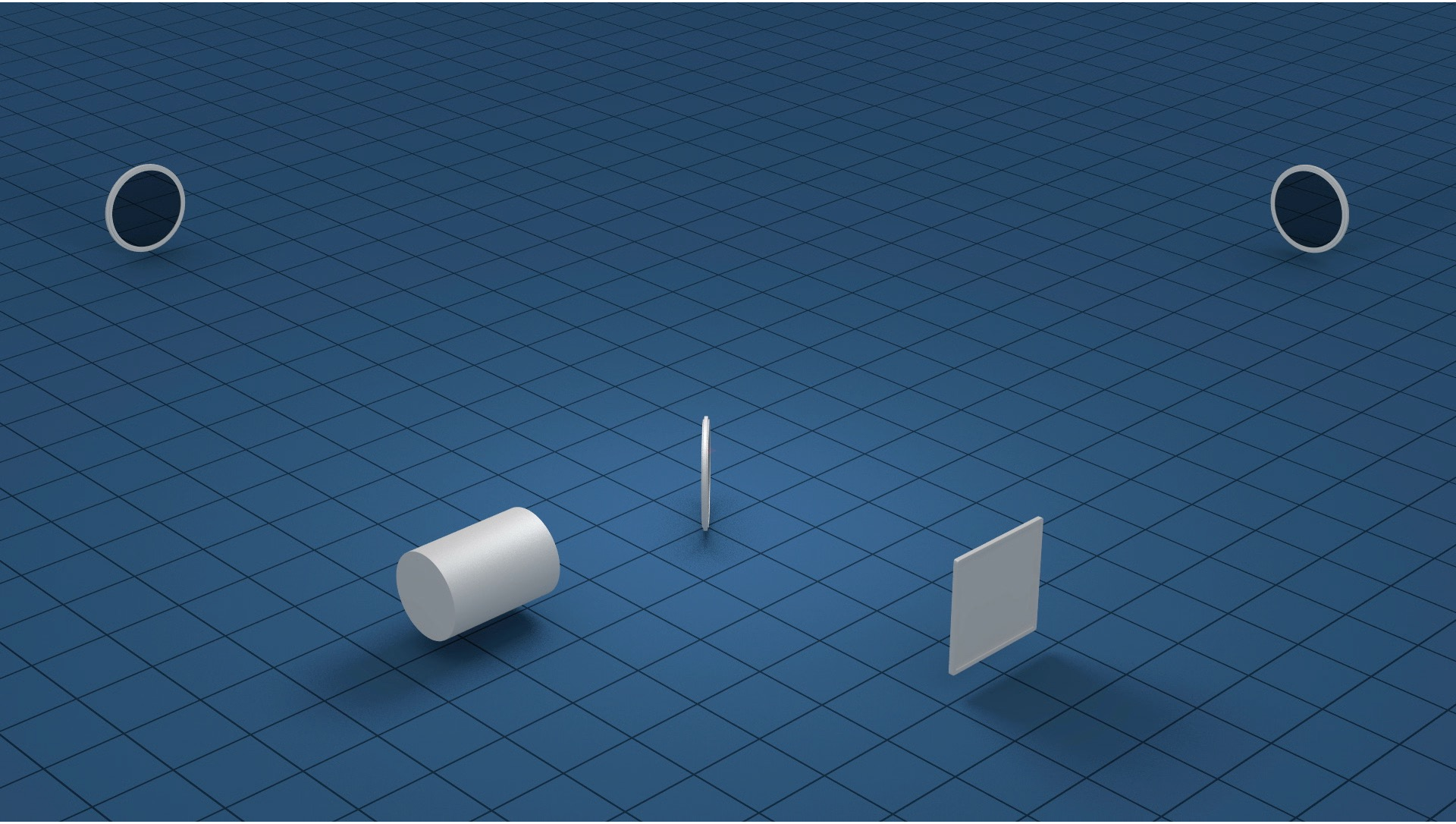
- **Theoretical solutions of Einstein's vacuum equation**
- **Transverse waves with two independent poralization states (+ and ×)**
- **GW propagation speed is *c***
- **Emitted by accelerating mass quadrupole moments**
- **Cause strain deformation of h~1/D**

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

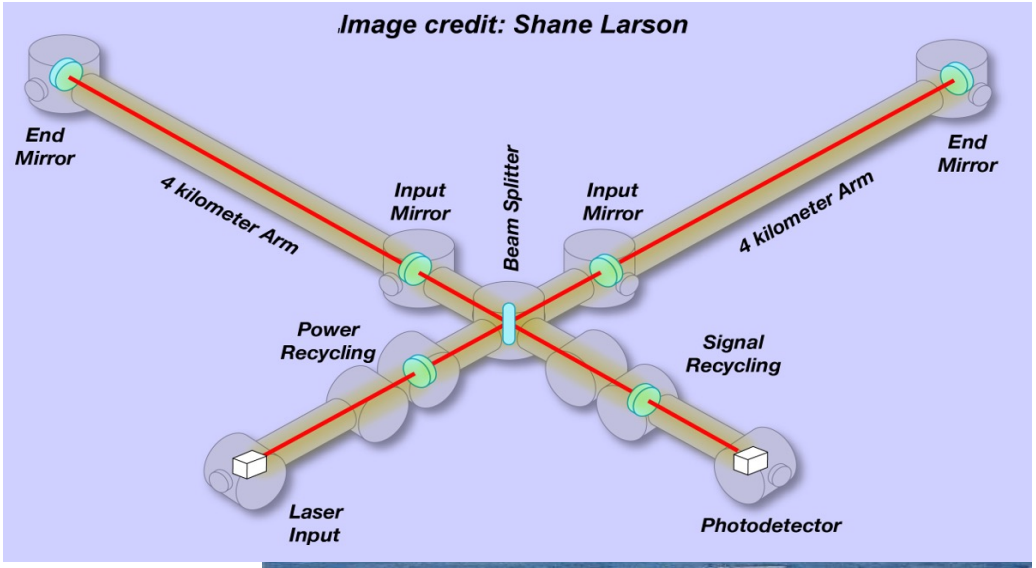


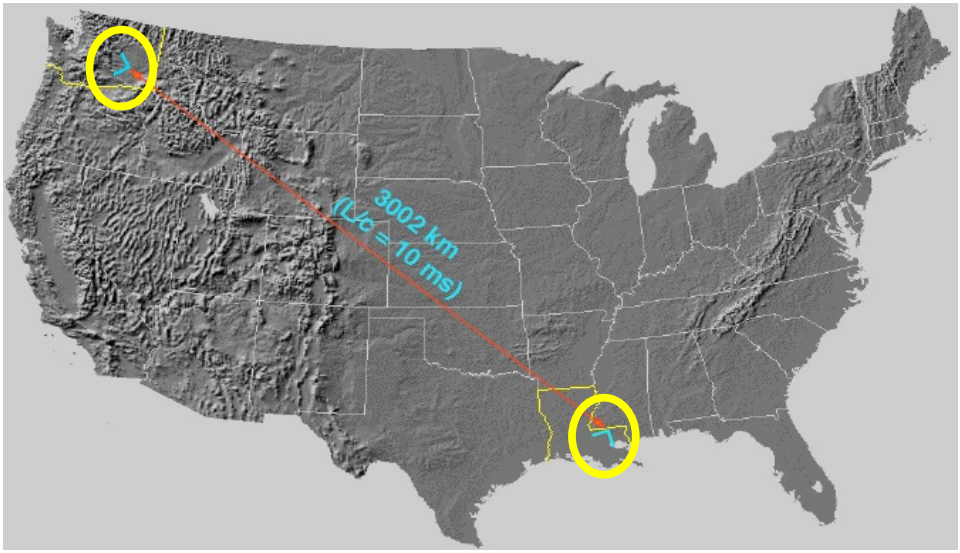


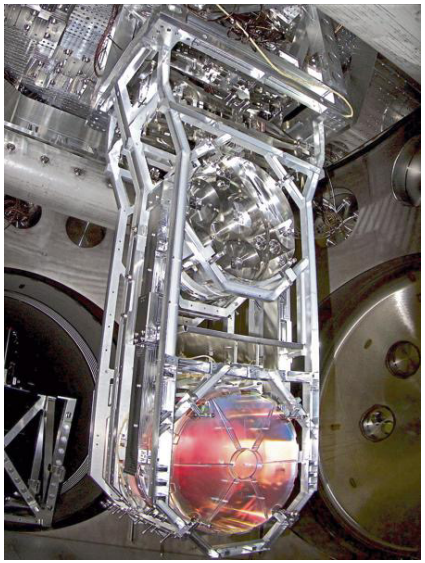


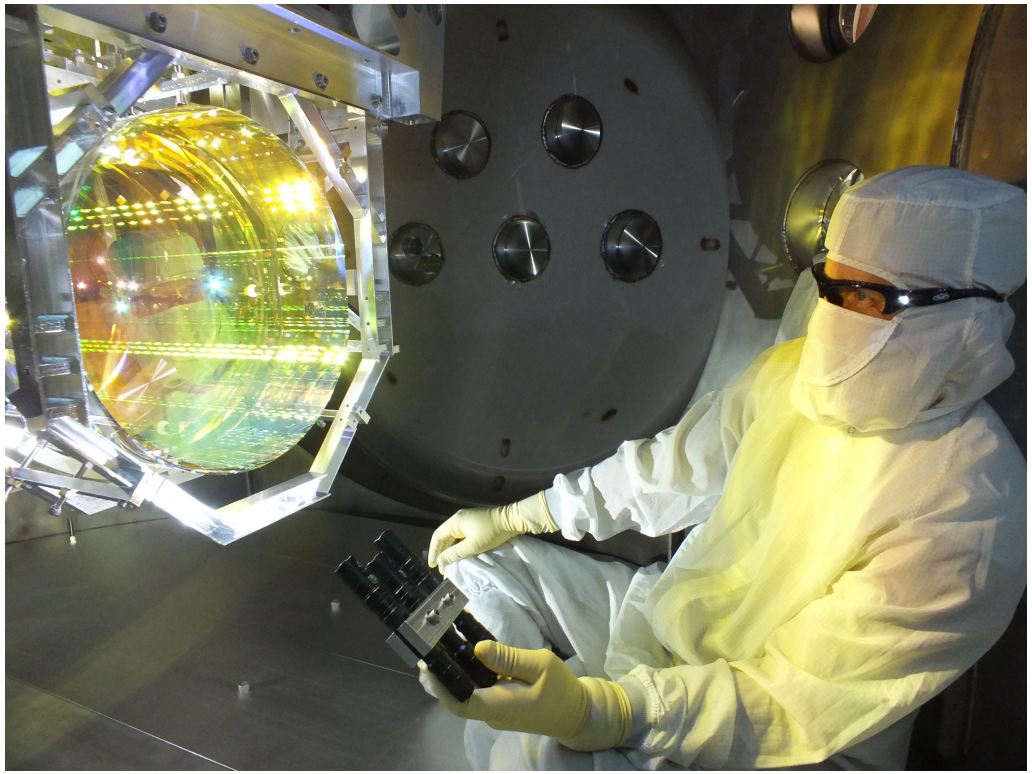


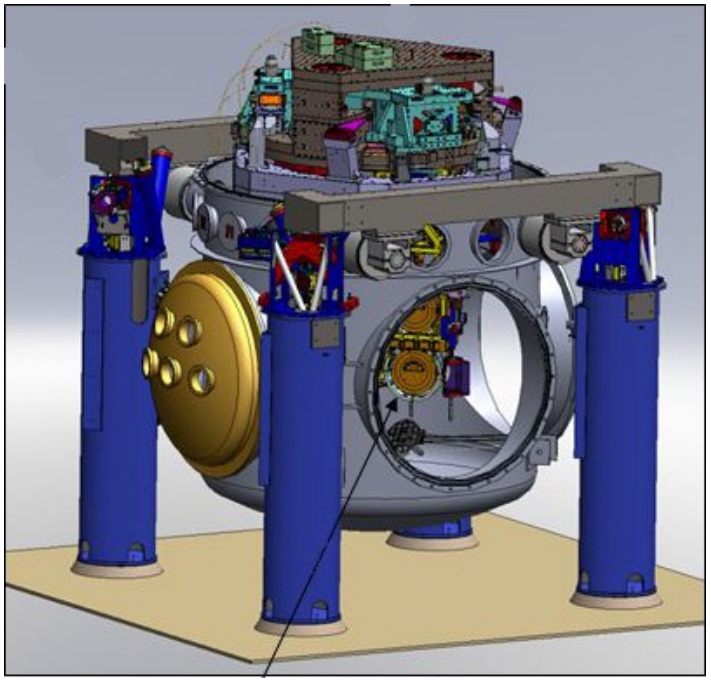
Laser Interferometer Gravitational-wave Observatory (LIGO)



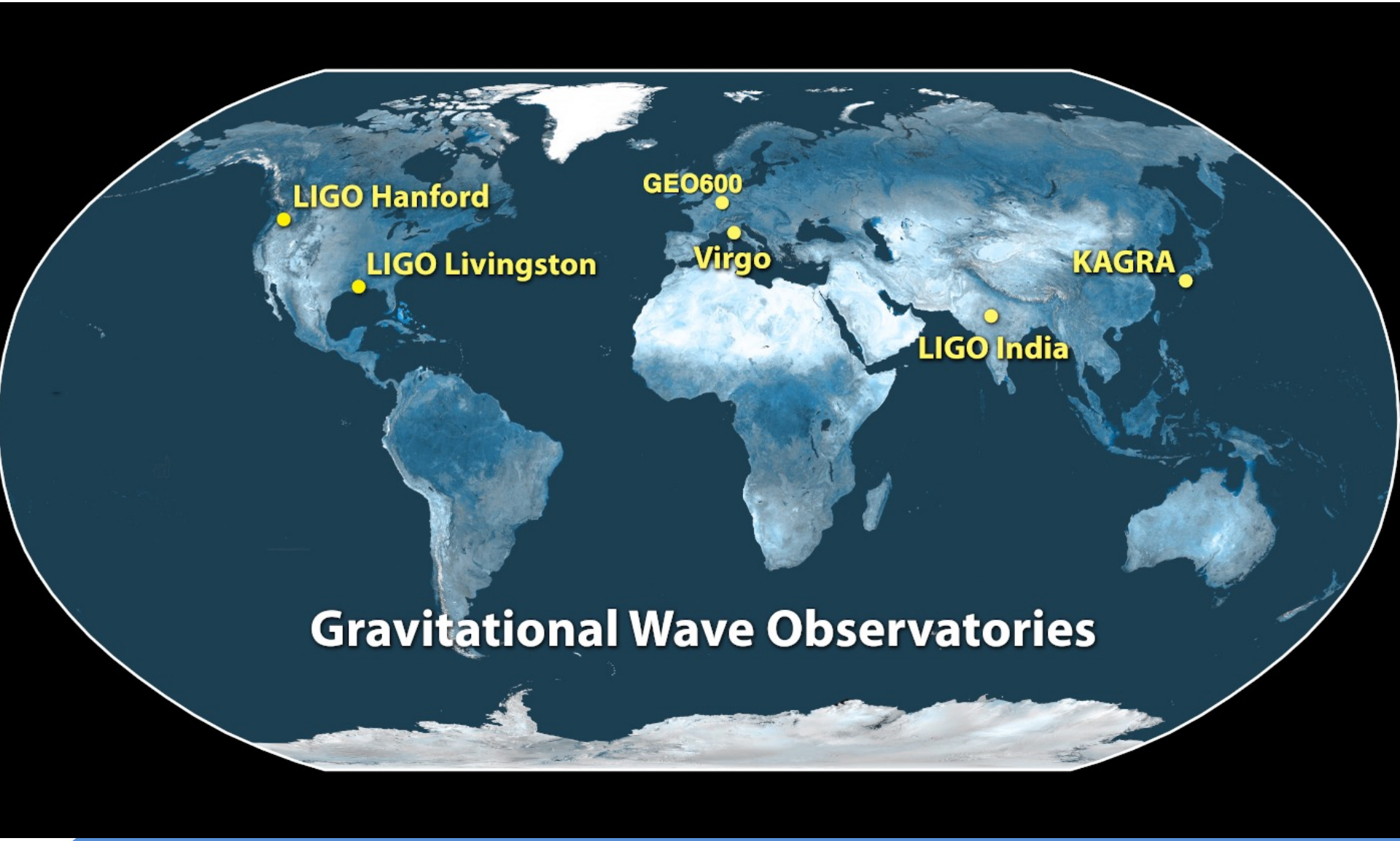


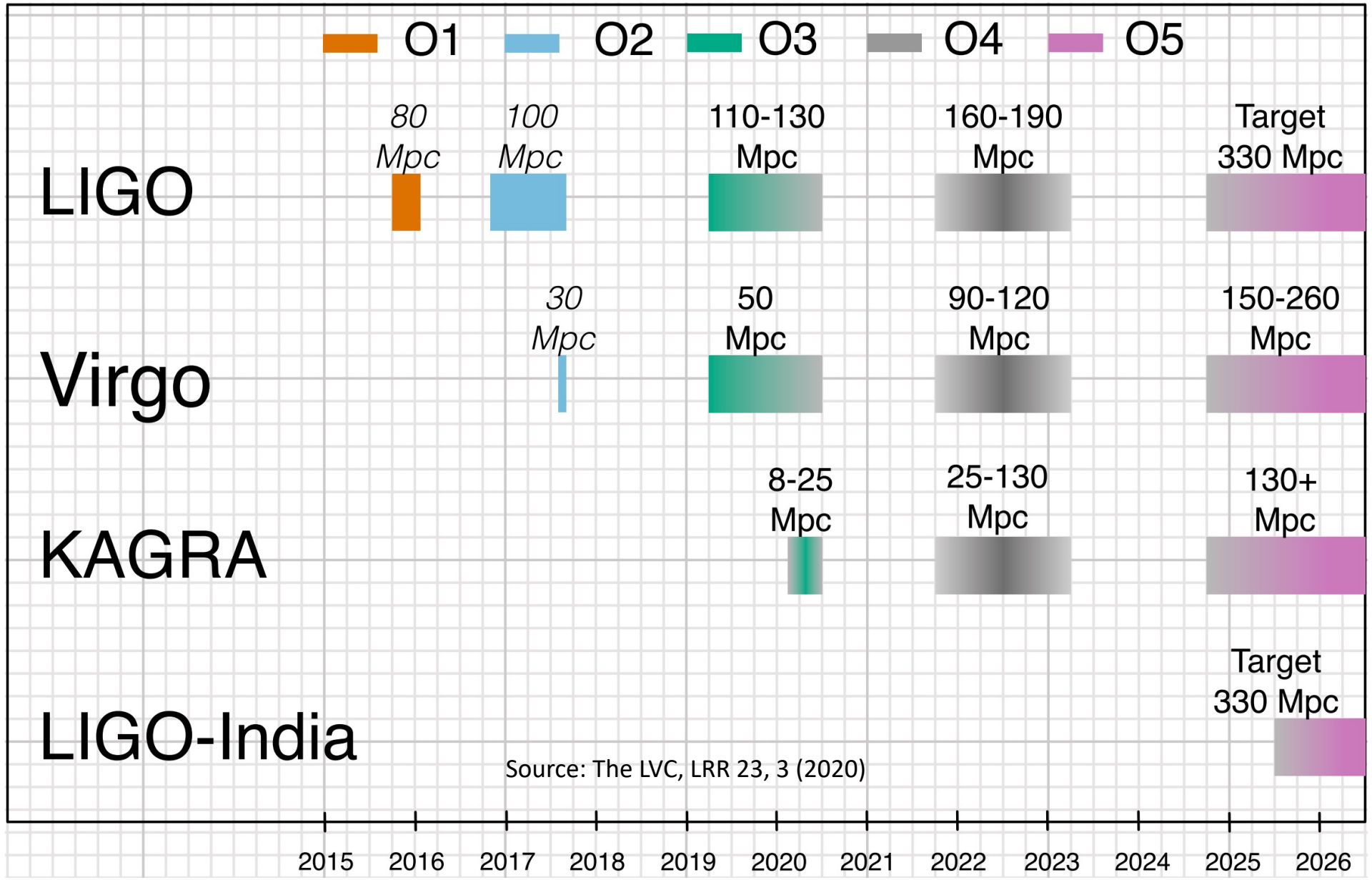


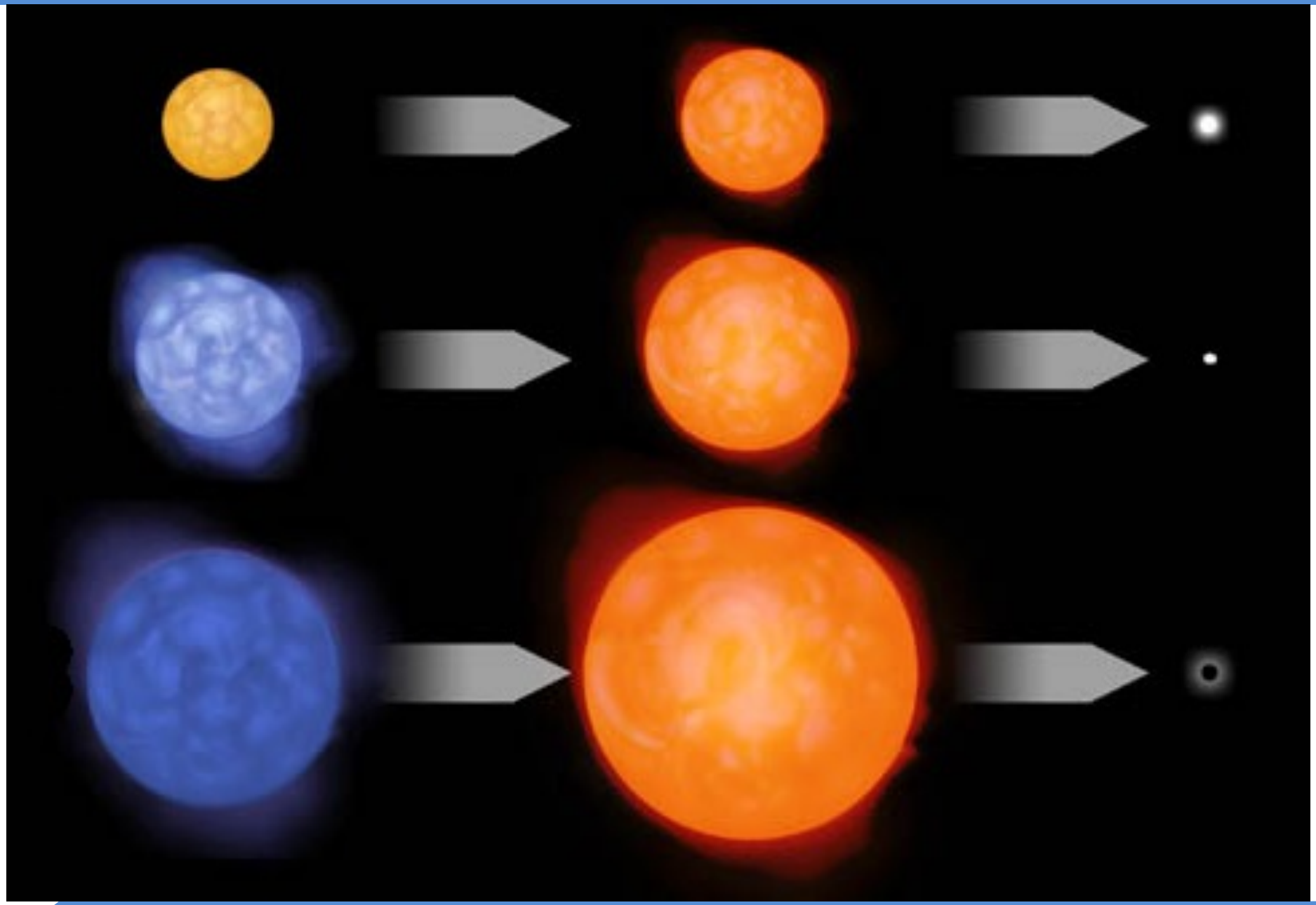




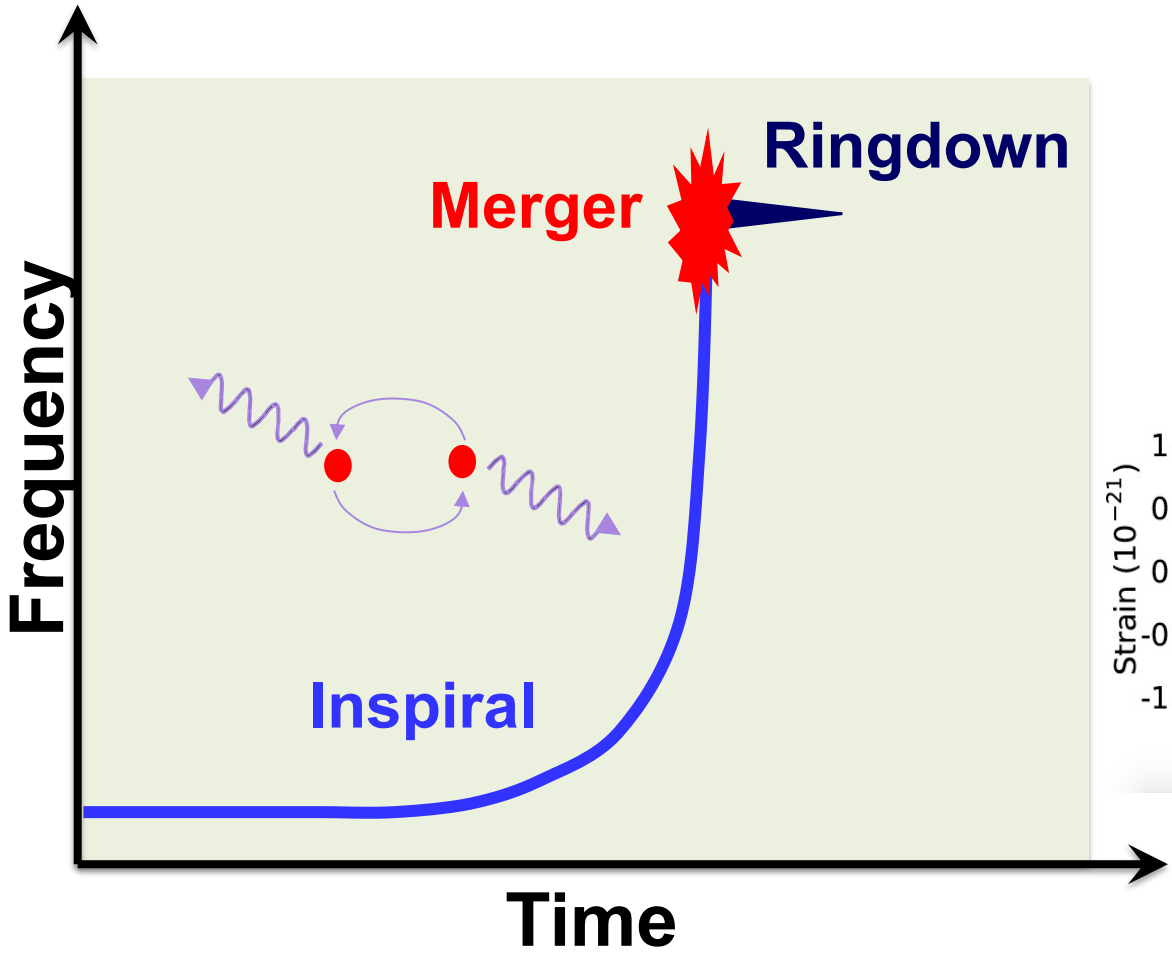
Detectors today and in the near future

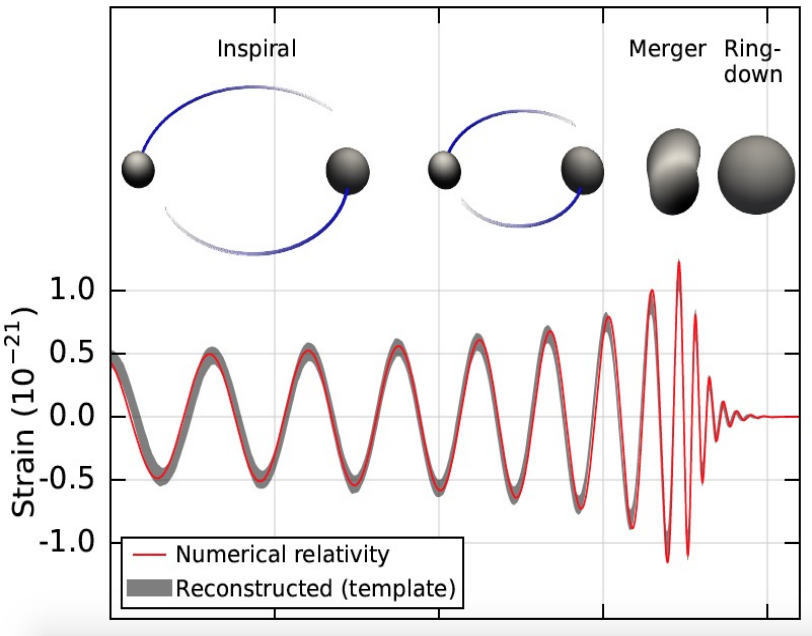



O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
110-130 Mpc
160-190 Mpc
Target 330 Mpc
Virgo
30 Mpc
50 Mpc
90-120 Mpc
150-260 Mpc
KAGRA
8-25 Mpc
25-130 Mpc
130+ Mpc
LIGO-India
Target 330 Mpc
Source: The LVC, LRR 23, 3 (2020)
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026



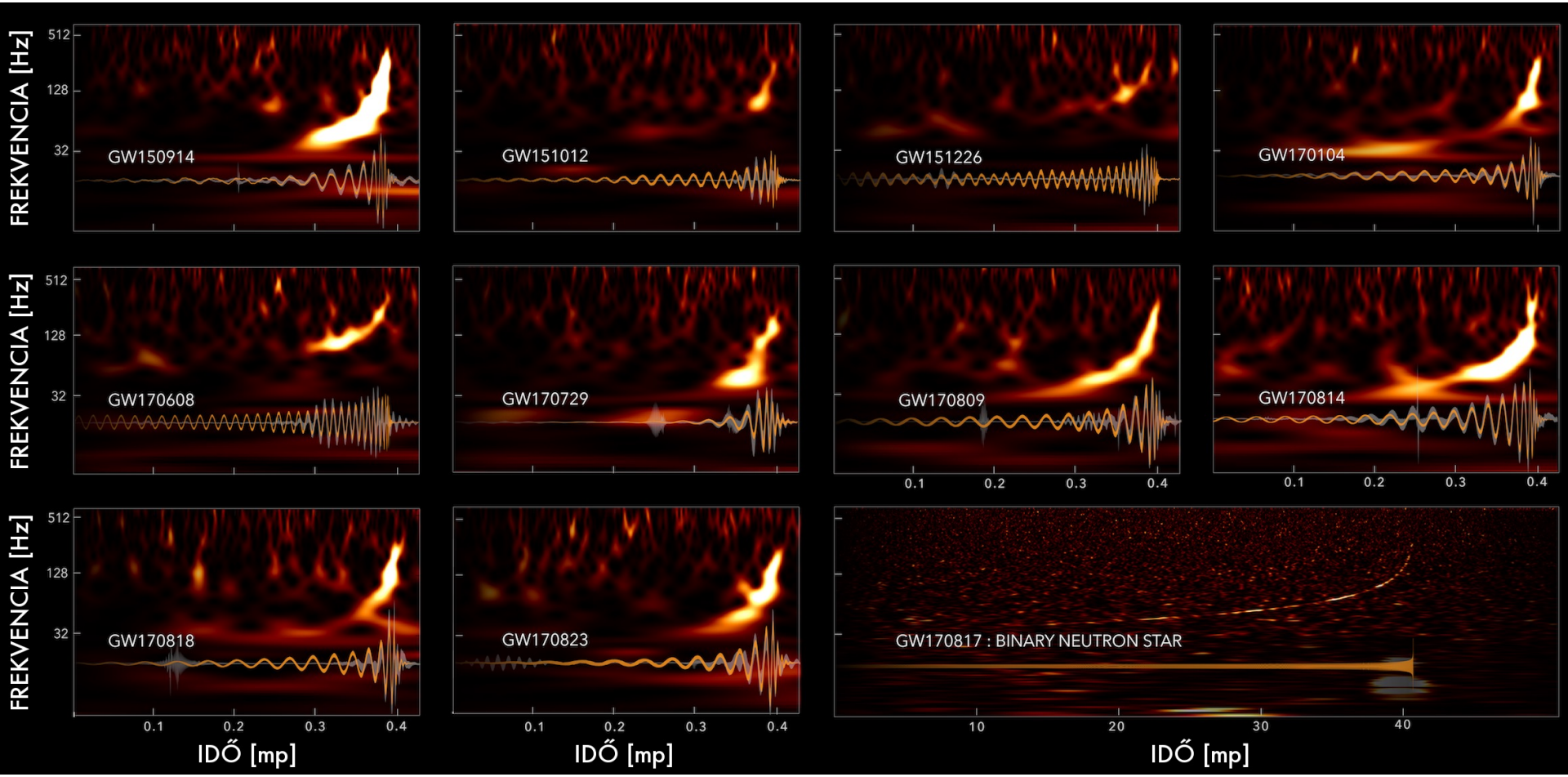
Compact Binary Coalescence (CBC)





Source: The LVC, PRL 116, 061102 (2016)

Detections (so far…)



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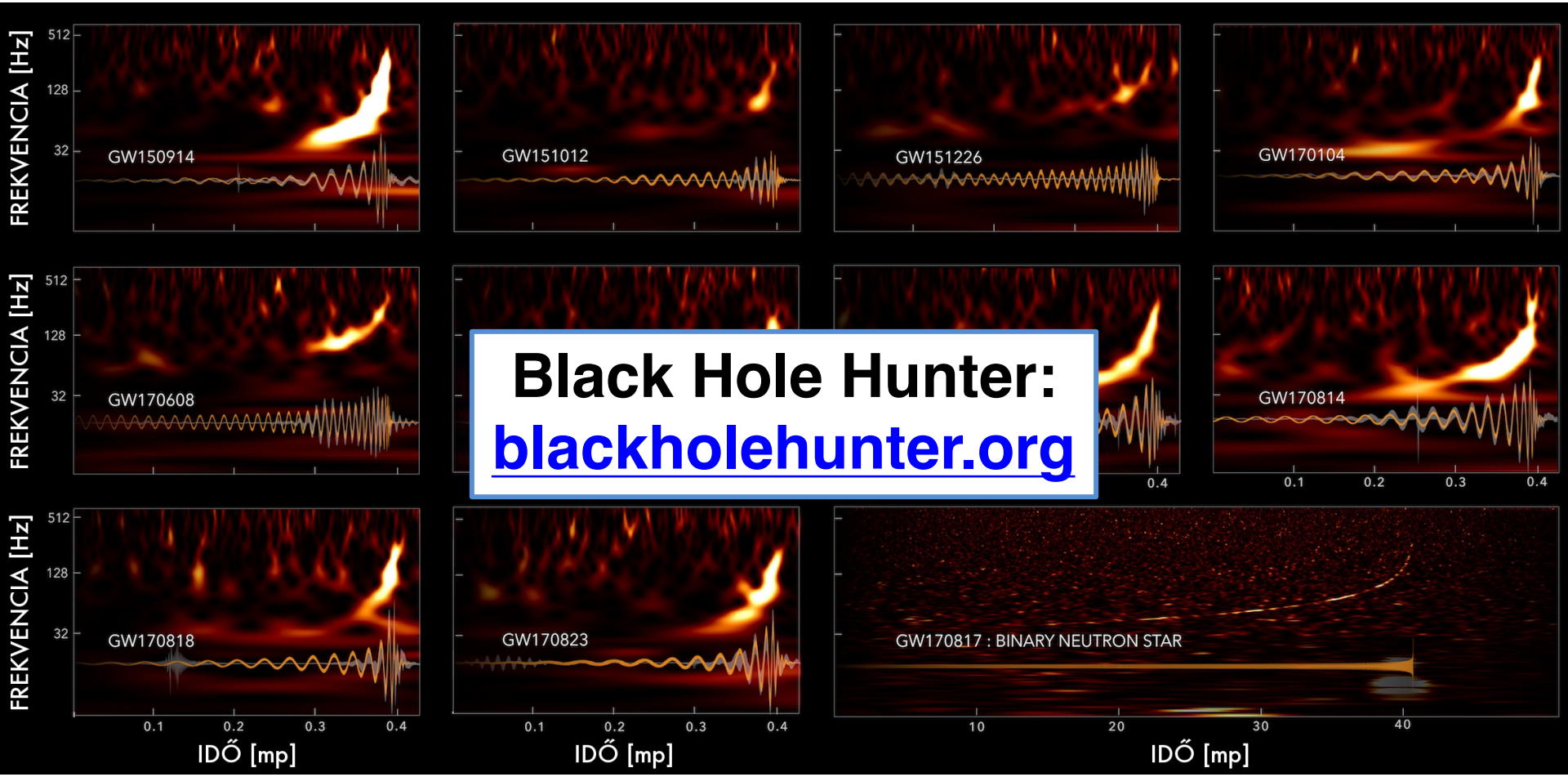
+39 and 17 candidates since April 1st 2019:
gracedb.ligo.org/superevents/public/O3/

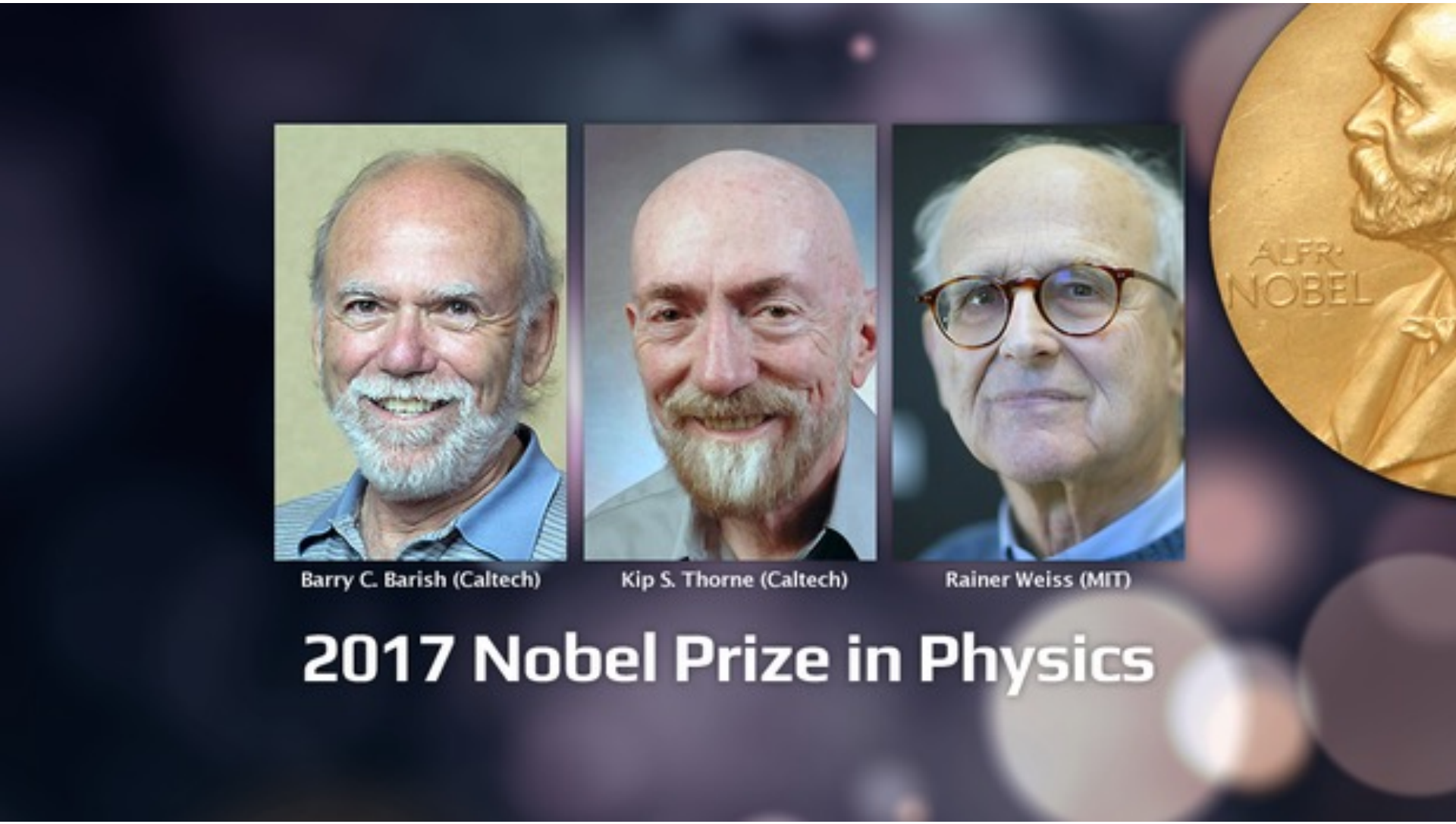
Detections (so far…)



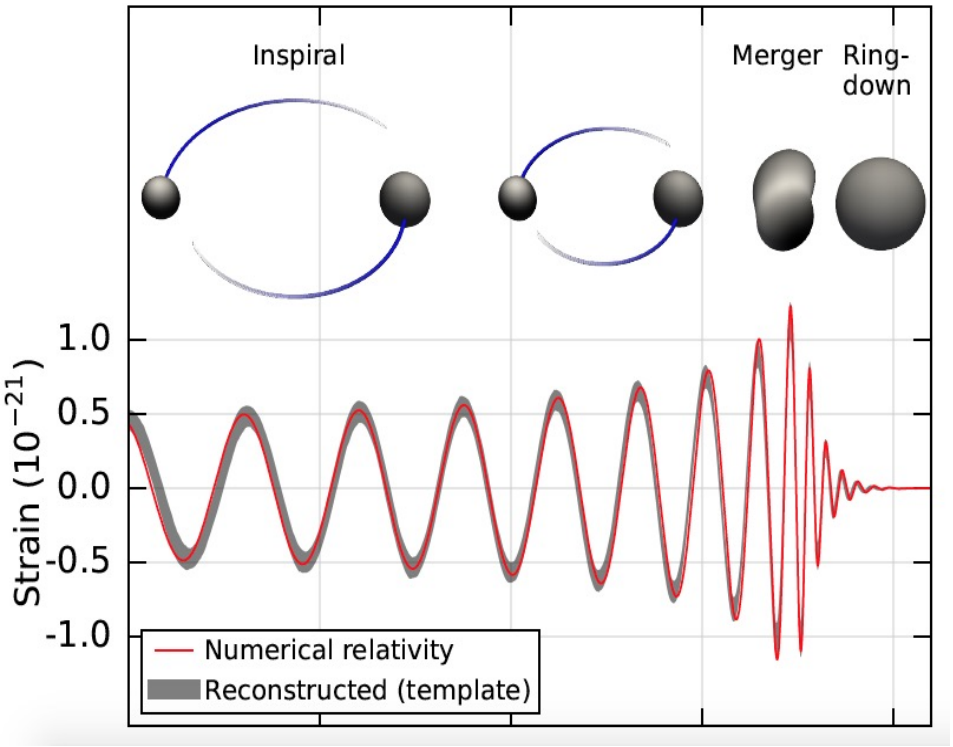
Black Hole Hunter:
blackholehunter.org

ligo.elte.hu

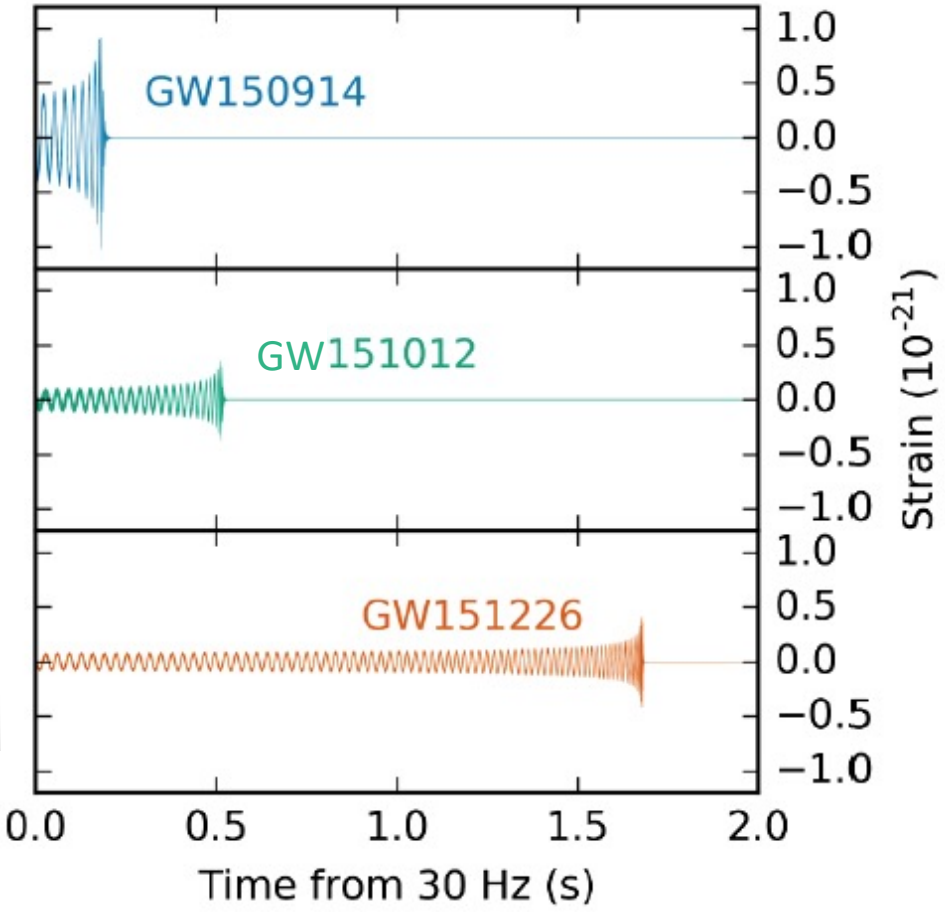
+39 and 17 candidates since April 1st 2019:
gracedb.ligo.org/superevents/public/O3/


Barry C. Barish (Caltech)
Kip S. Thorne (Caltech)
Rainer Weiss (MIT)
2017 Nobel Prize in Physics

What do we detect?

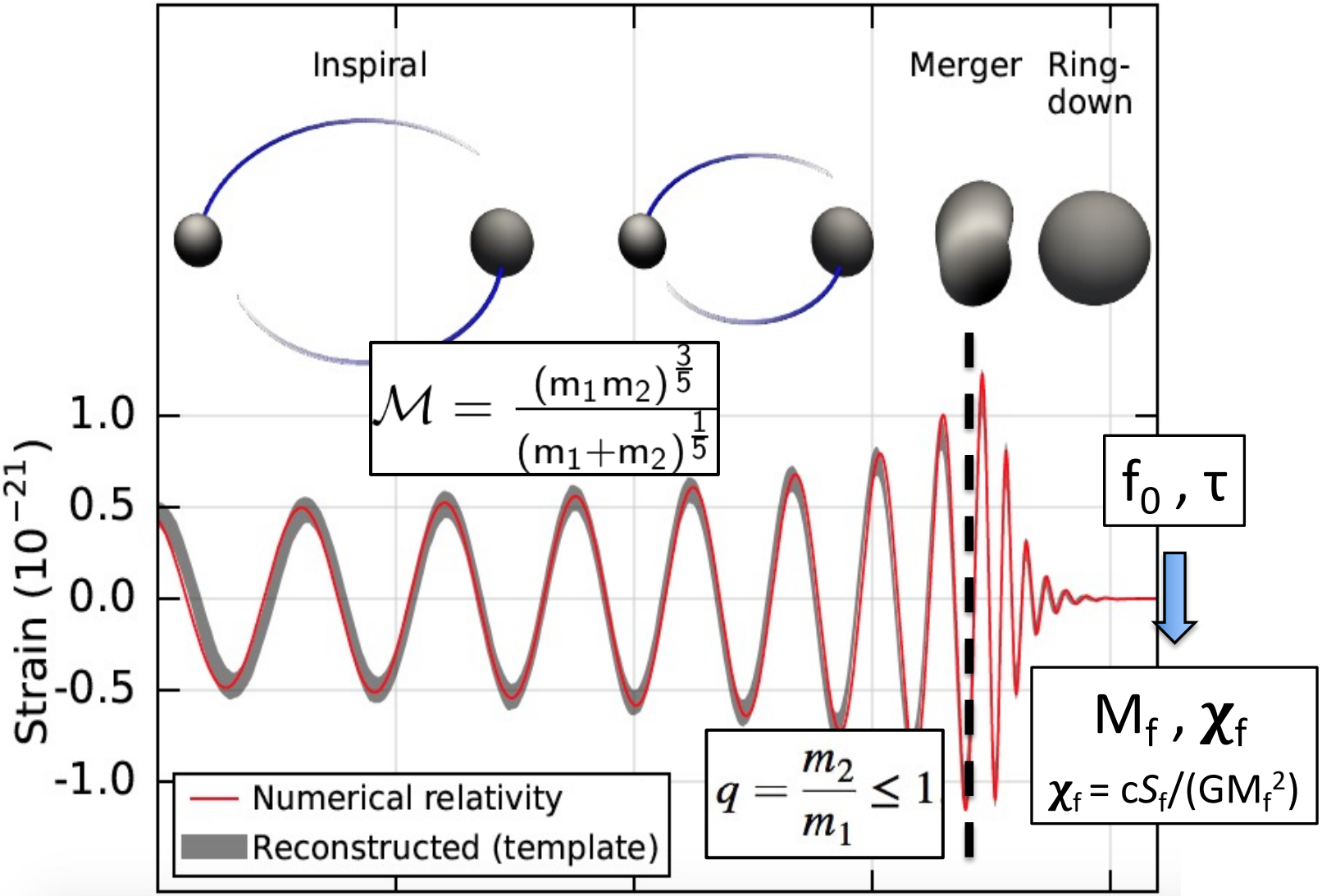


Source: The LVC, PRL 116, 061102 (2016)



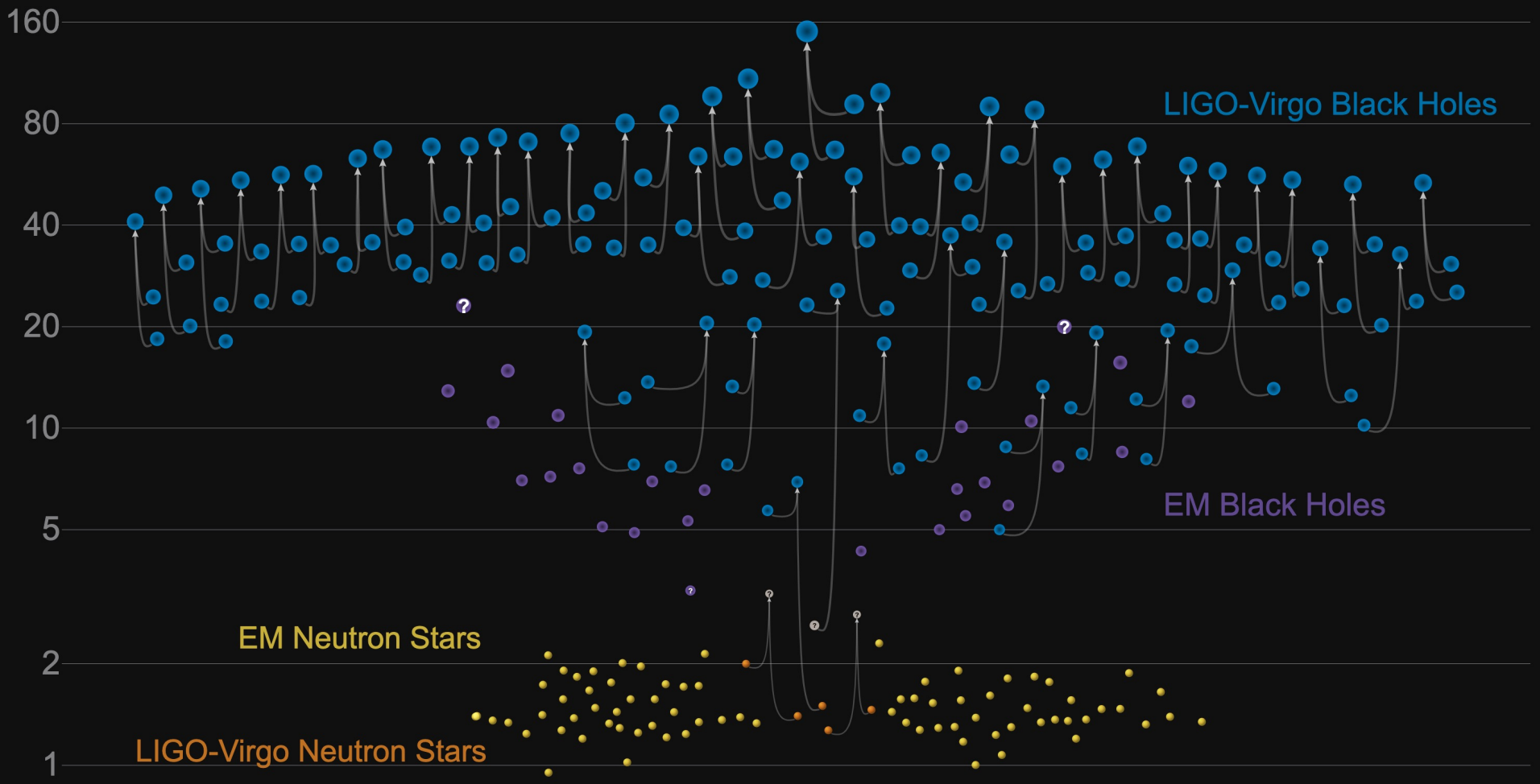
Source: Abbott et al. PRX 6, 041015 (2016)

Binary parameters (ignoring initial spins)



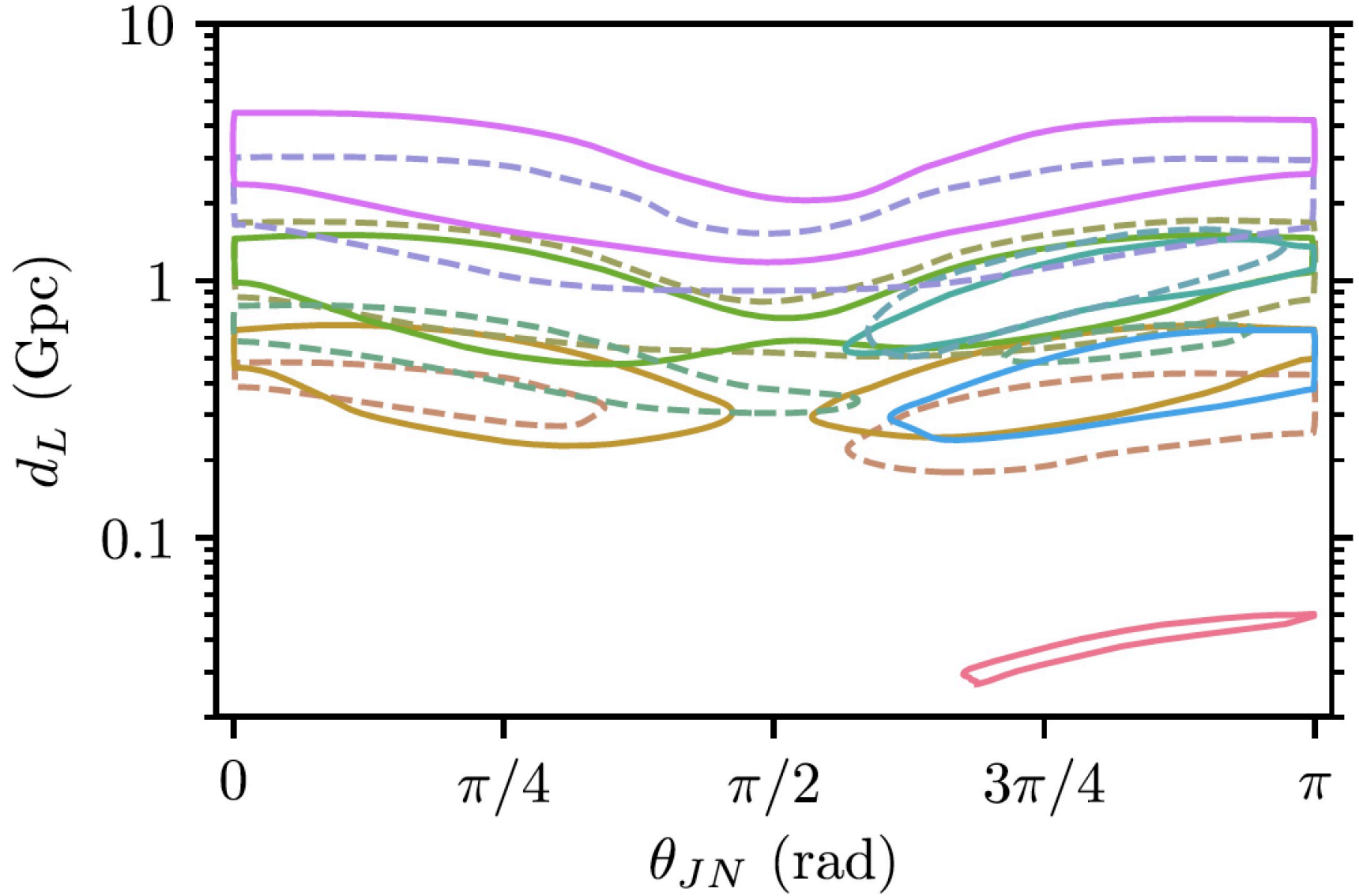
Masses in the Stellar Graveyard

in Solar Masses



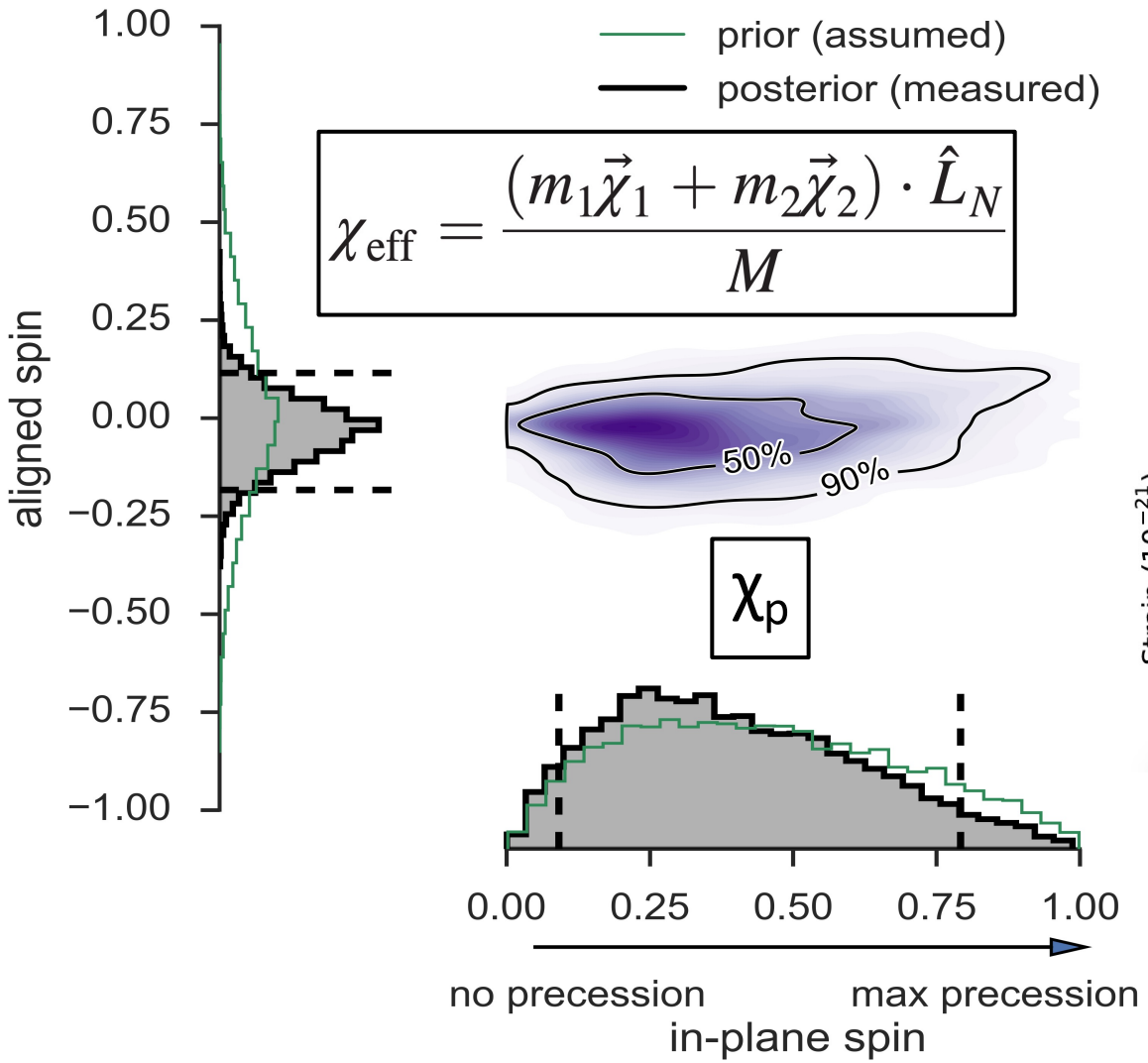
GWTC-2 plot v1.0

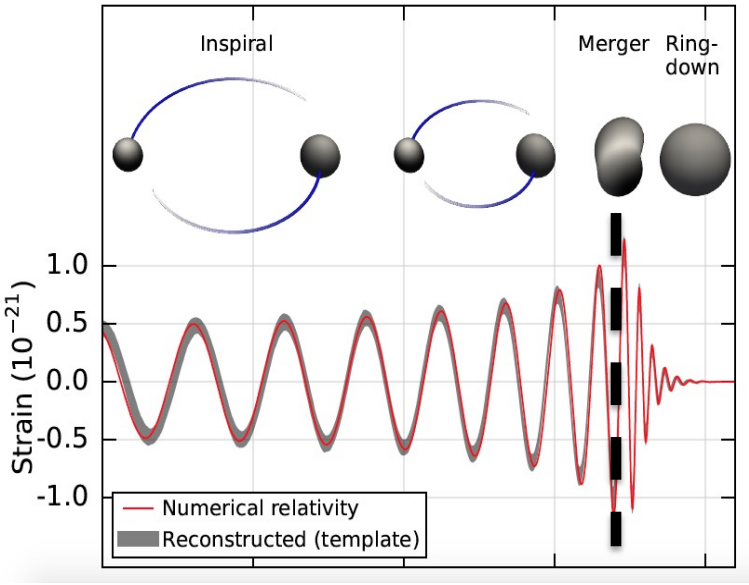
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



Original figure: Abbott et al. PRX 9, 031040 (2019)

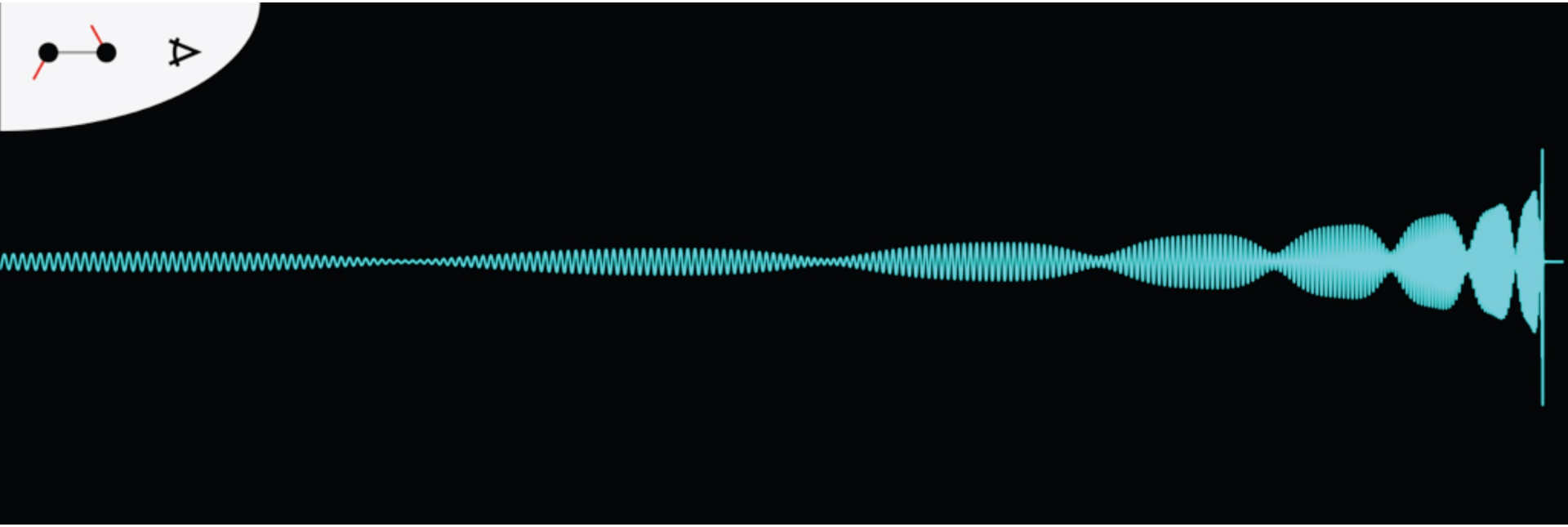
Constraining black hole spins

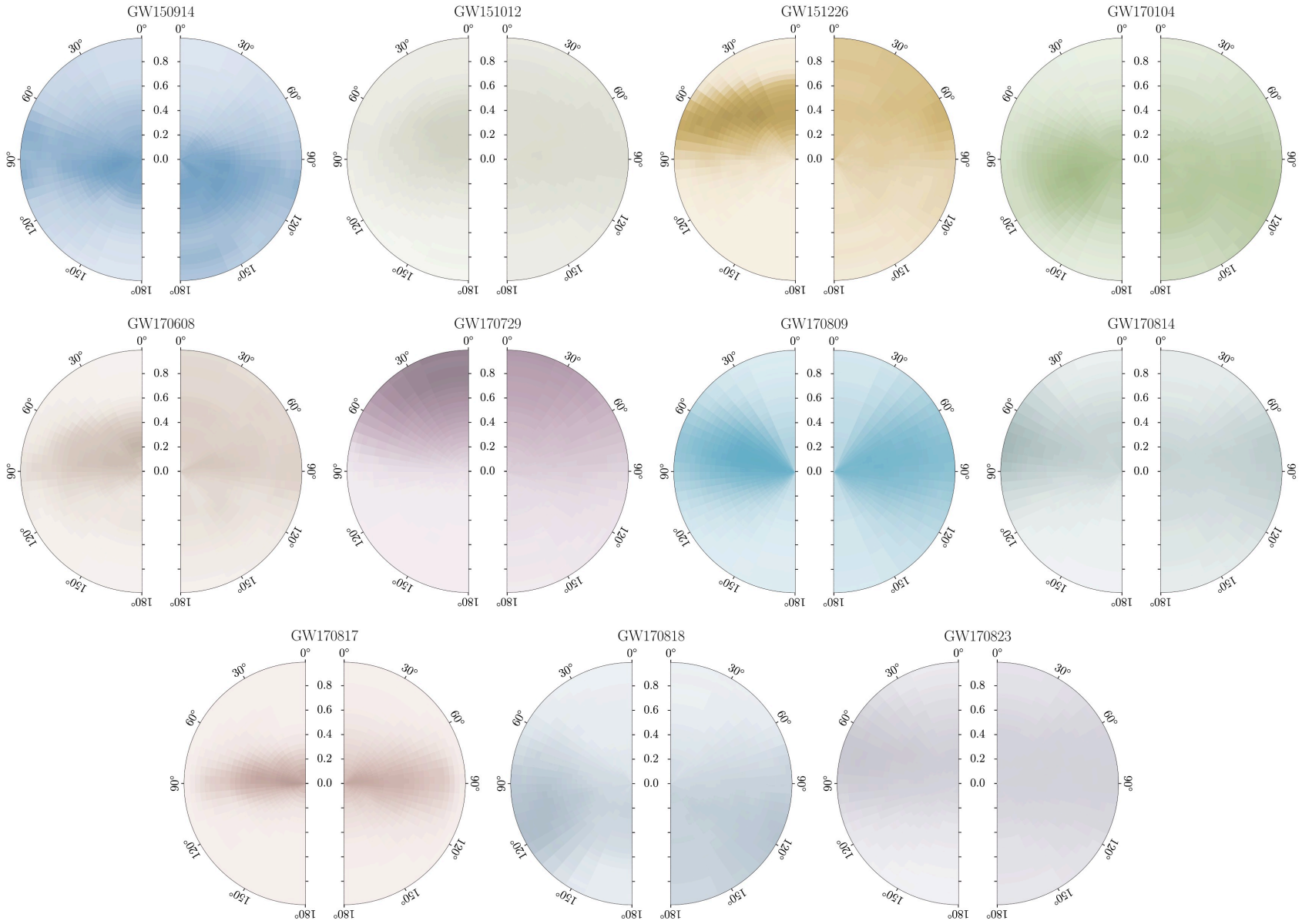




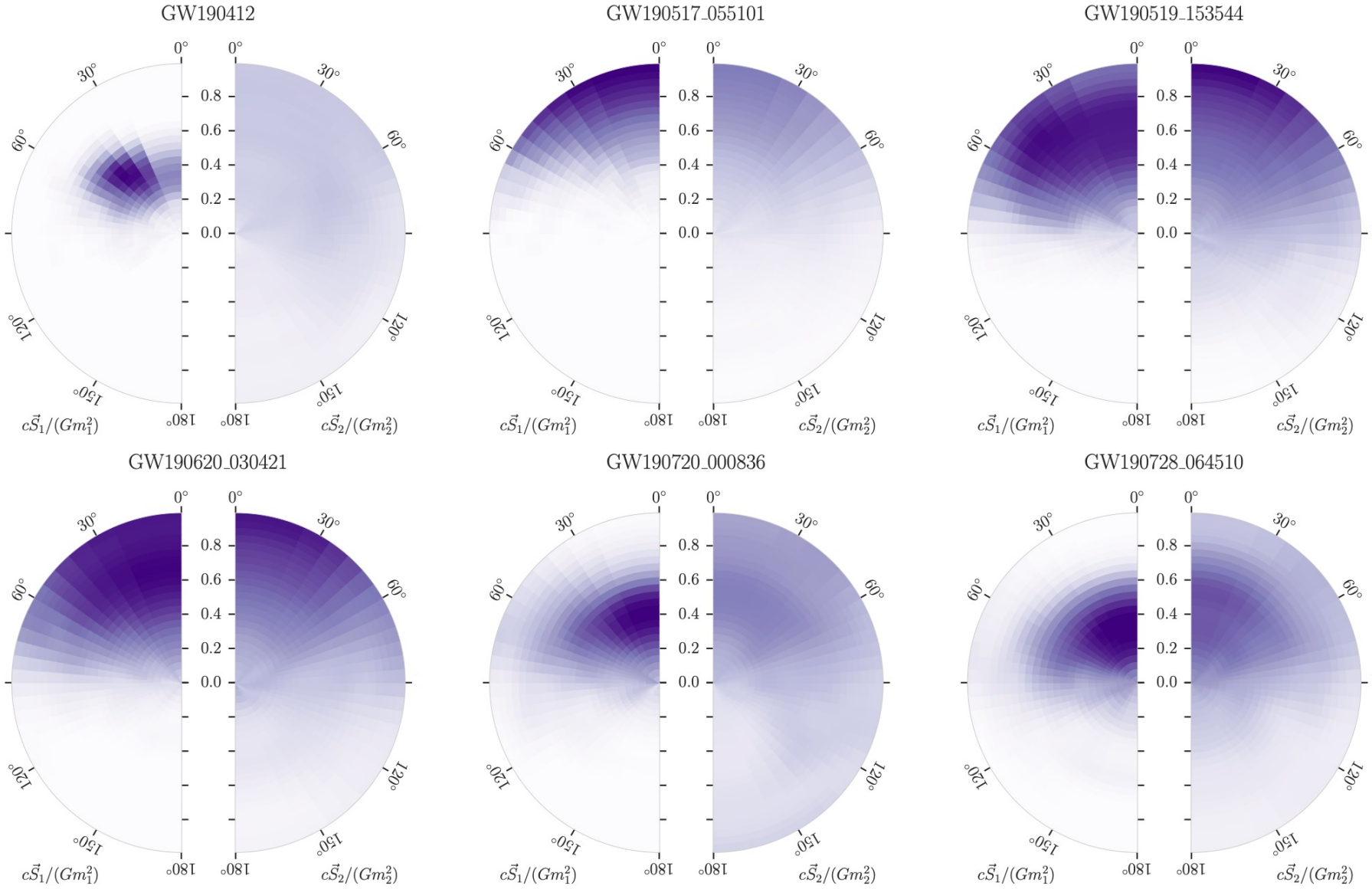
Precession spin parameter

Equal-mass binary:



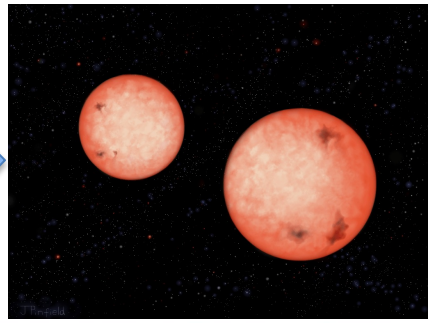


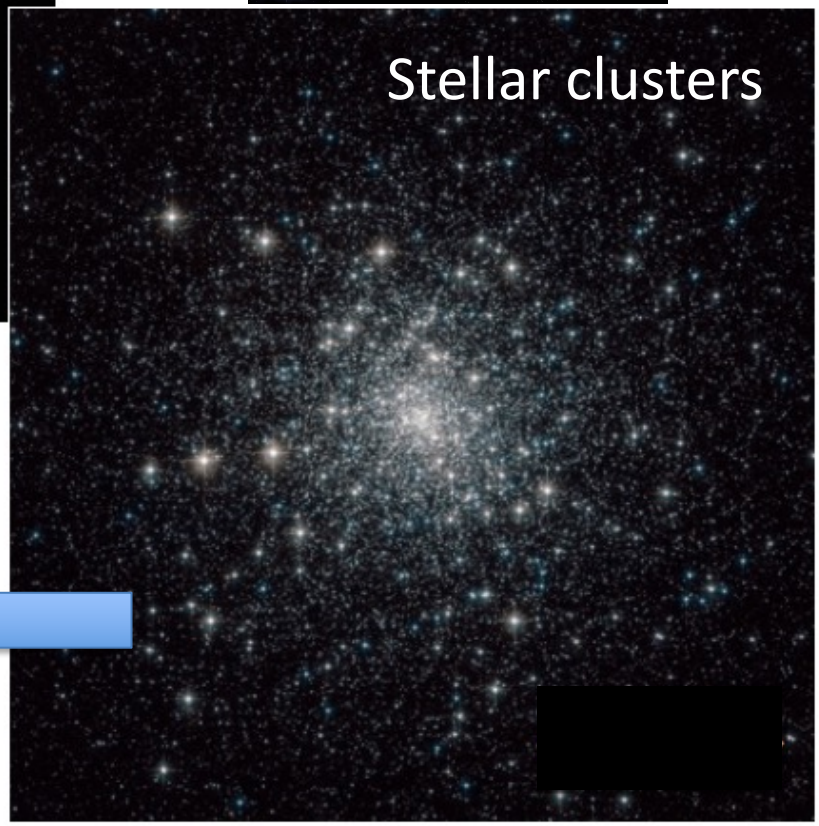
Original figure: Abbott et al. PRX 9, 031040 (2019)

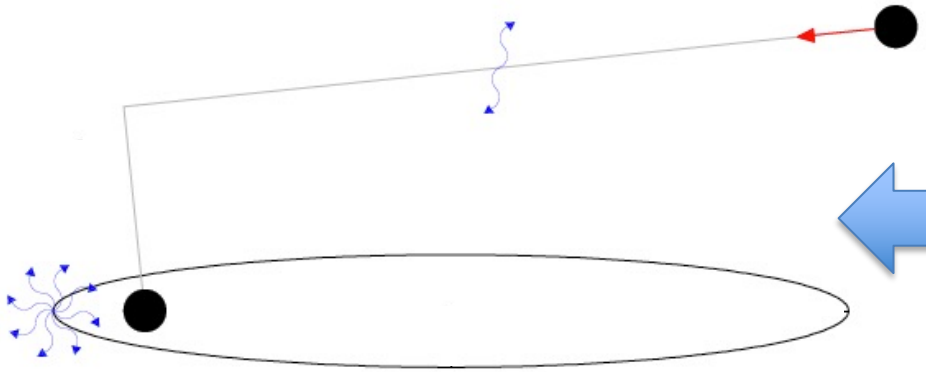


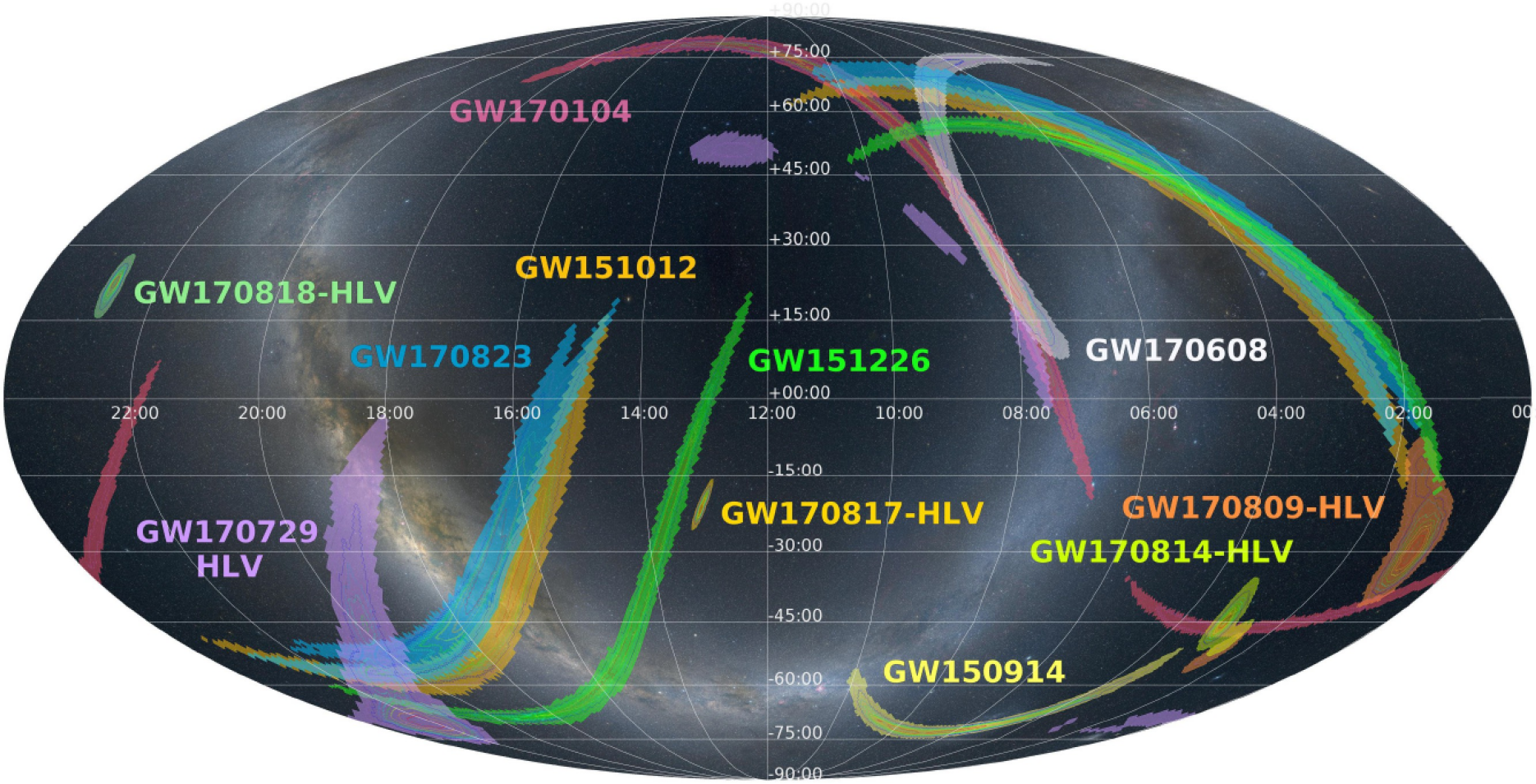
Forrás: Abbott et al. arXiv: 2010.14527 (2020)

How do these binaries form?

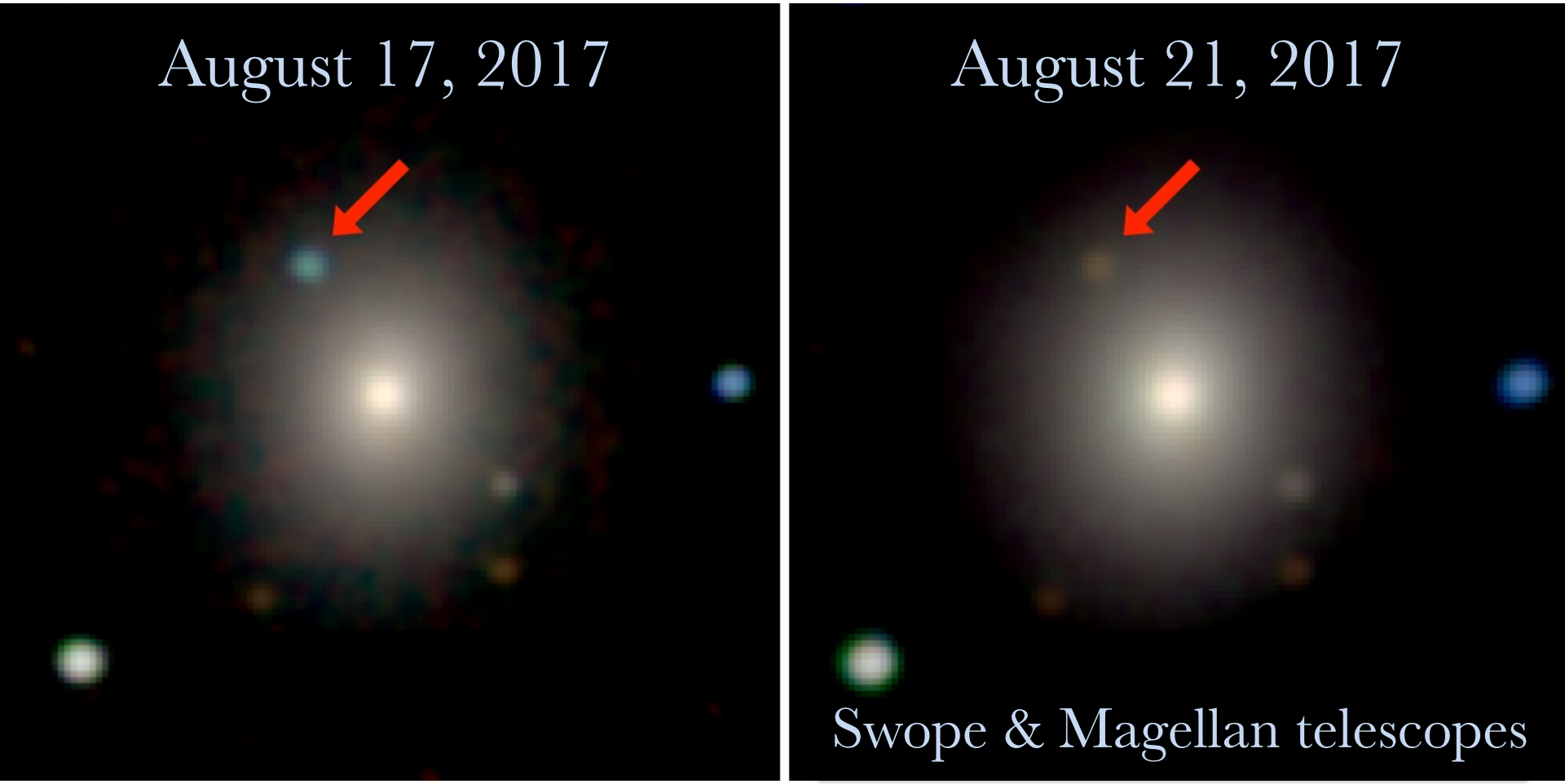




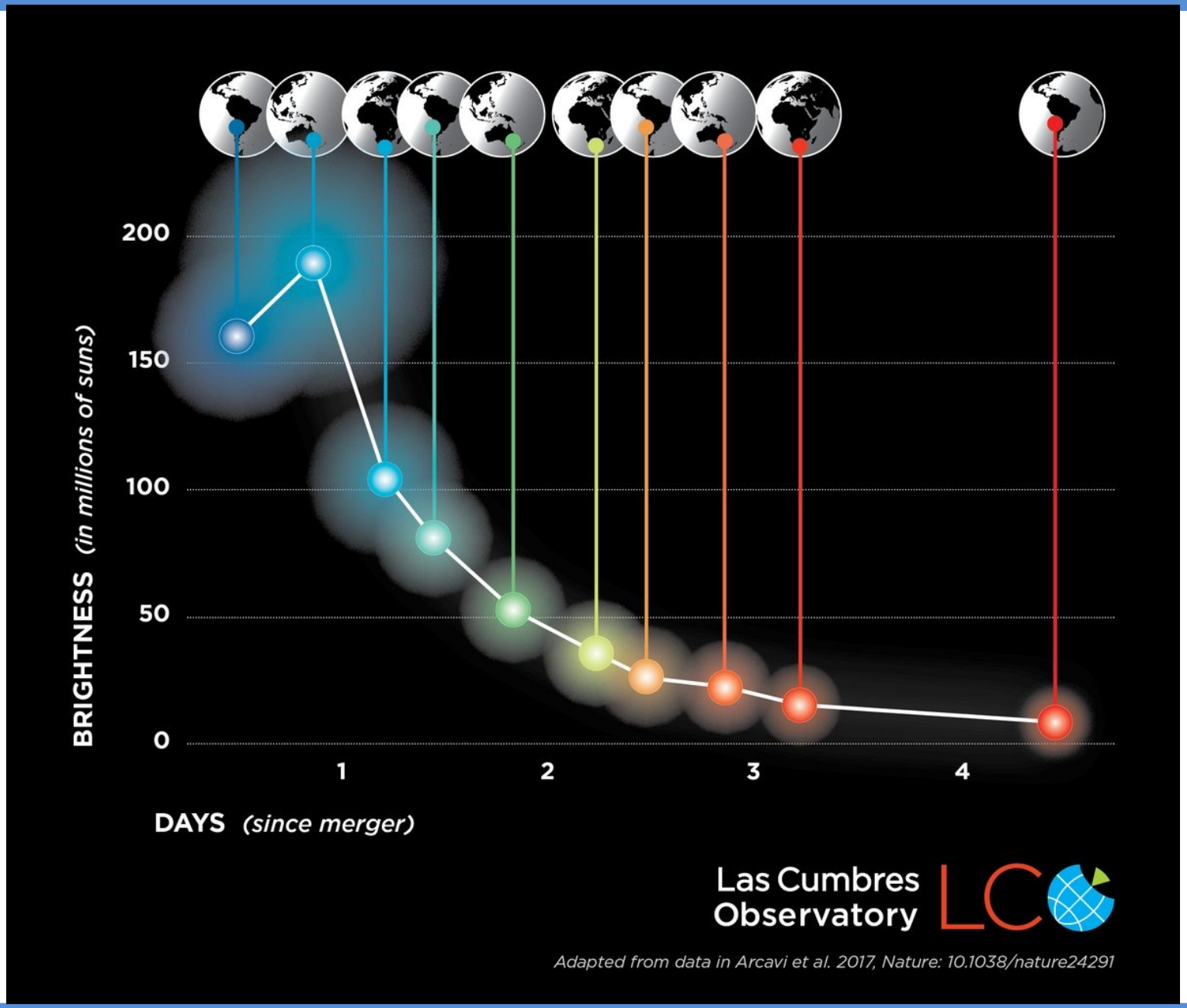


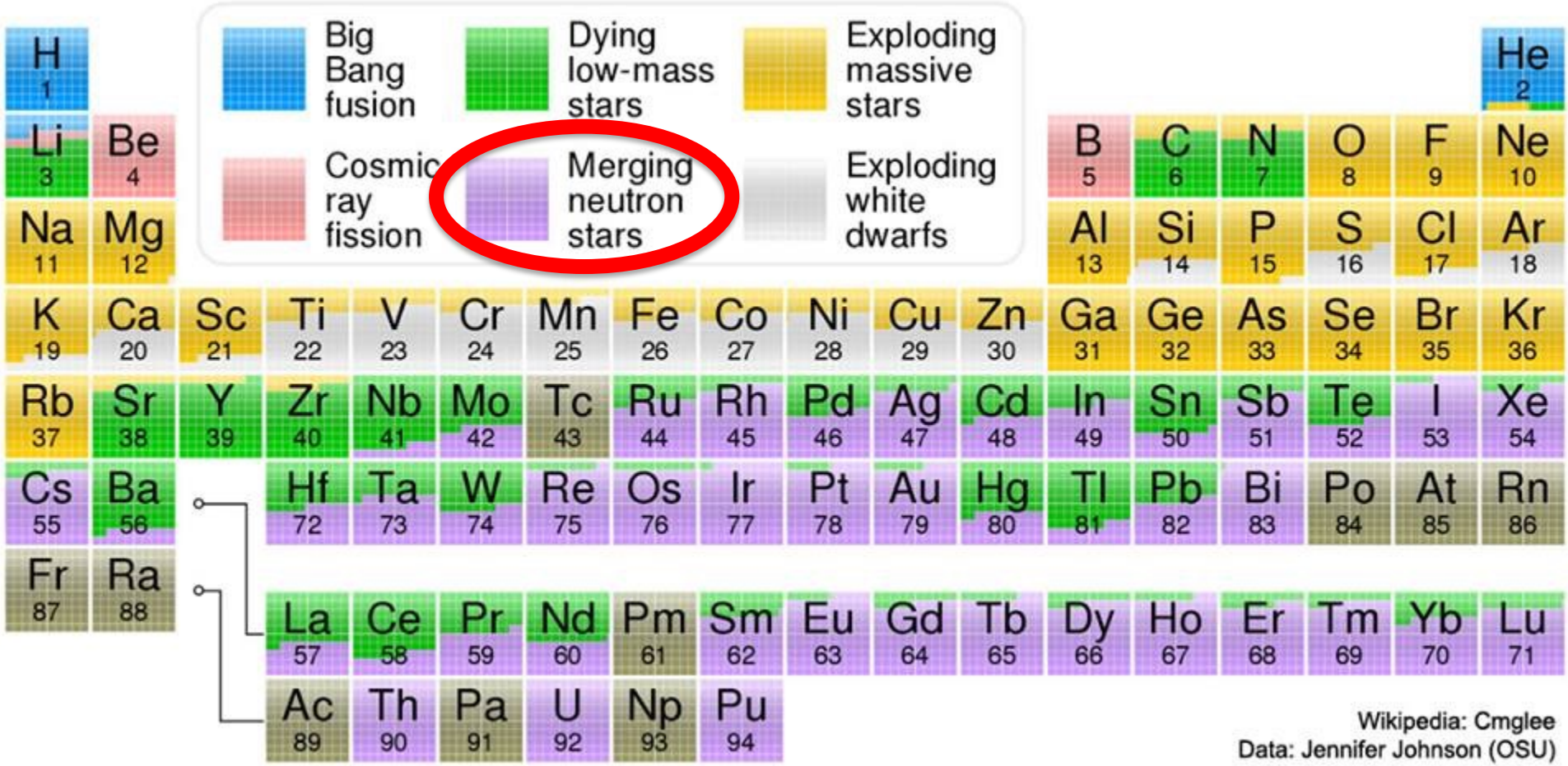


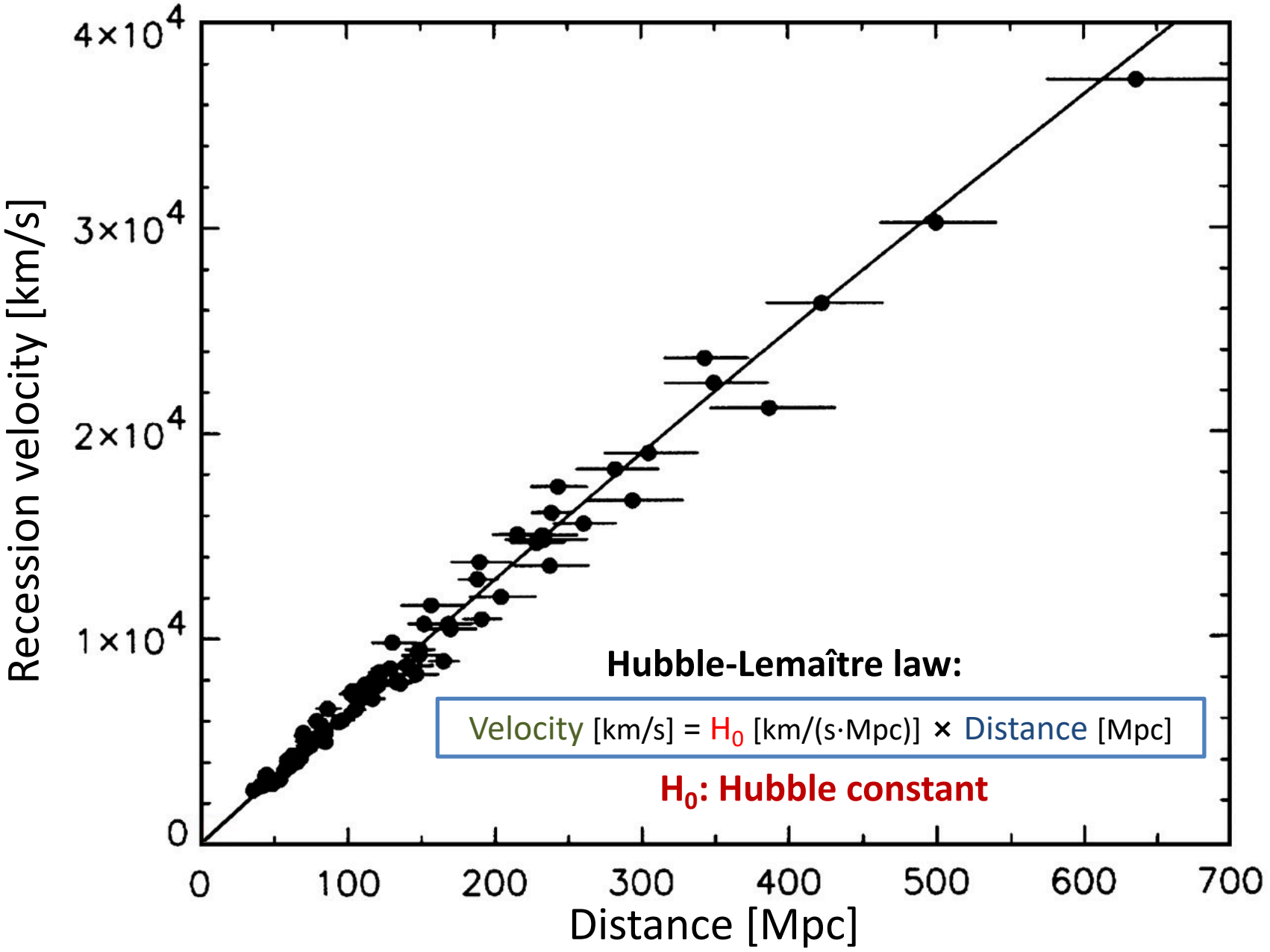
Source: The LVC, LRR 23, 3 (2020)

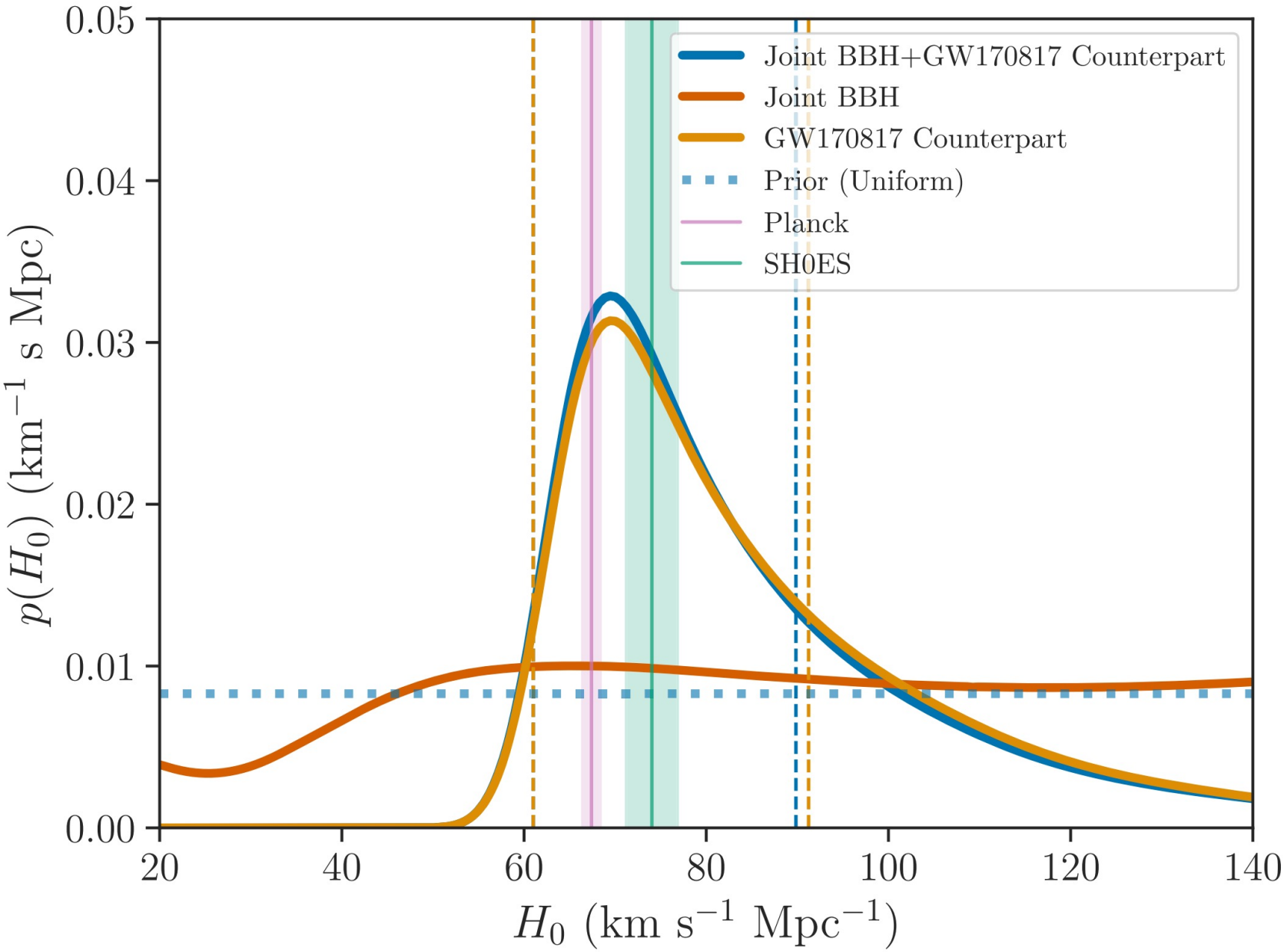


Source: 1M2H, Swope Telescope, Ryan Foley


200
150
100
50
0
BRIGHTNESS (in millions of suns)
1
2
3
4
DAYS (since merger)
Las Cumbres Observatory
LCO
Adapted from data in Arcavi et al. 2017, Nature: 10.1038/nature24291

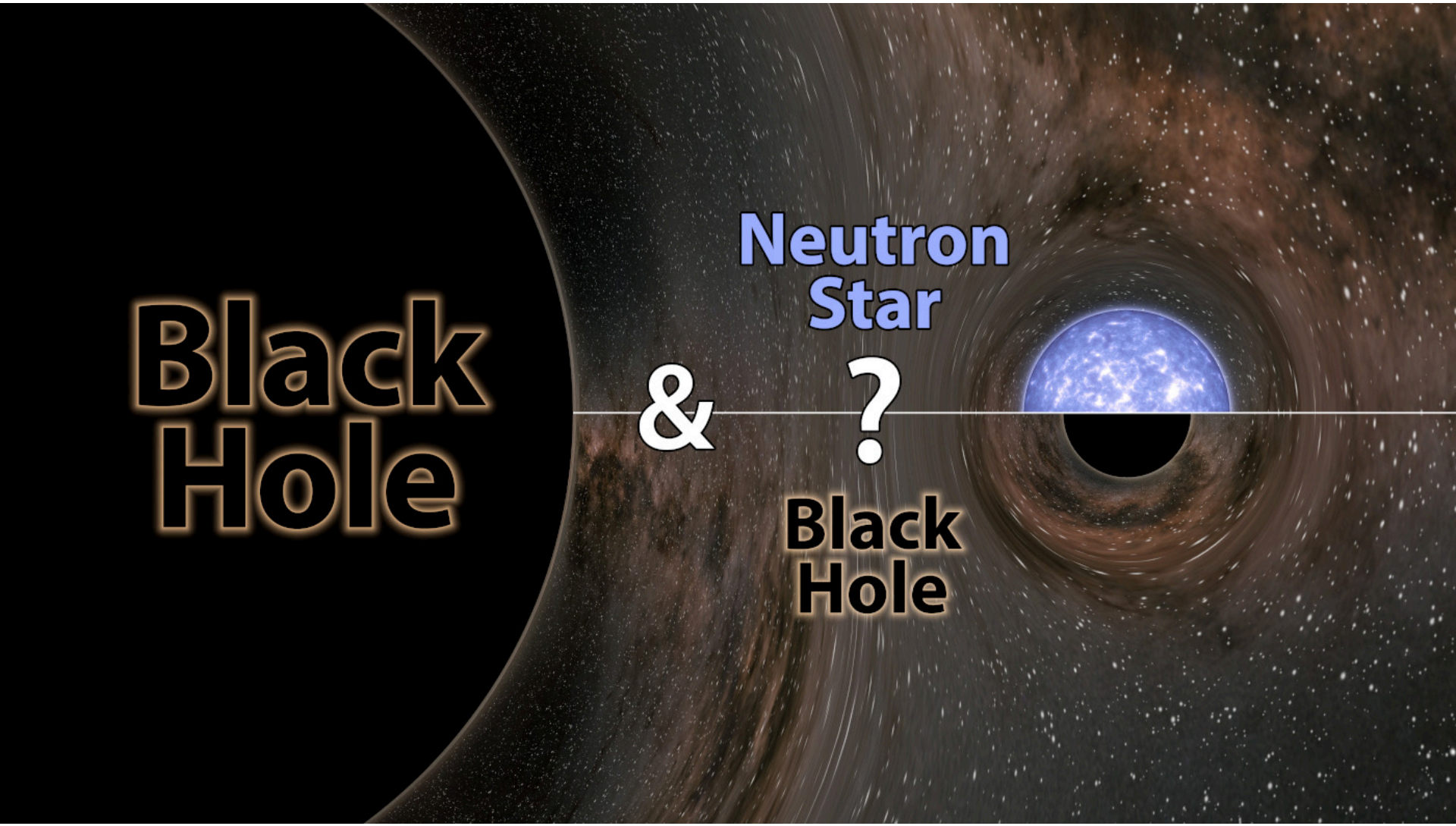

Big Bang fusion
Dying low-mass stars
Exploding massive stars
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)


Recession velocity [km/s]
4×10^4
3×10^4
2×10^4
1×10^4
0
0
100
200
300
400
500
600
700
Distance [Mpc]
Hubble-Lemaître law:
Velocity [km/s] = H0 [km/(s·Mpc)] × Distance [Mpc]
H0: Hubble constant



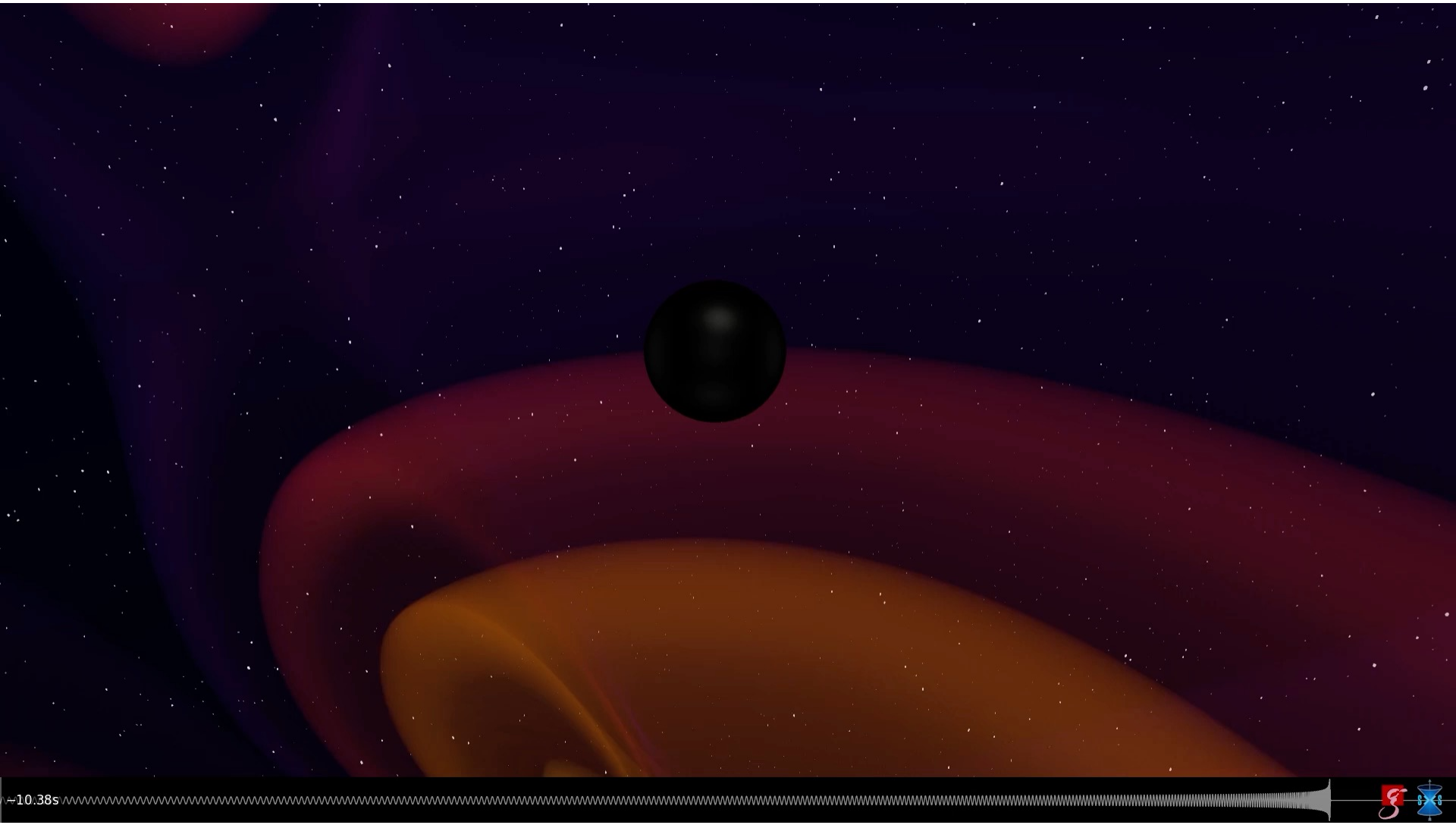
Source: The LVC, ApJ 909, 2, 218 (2021)

GW190814



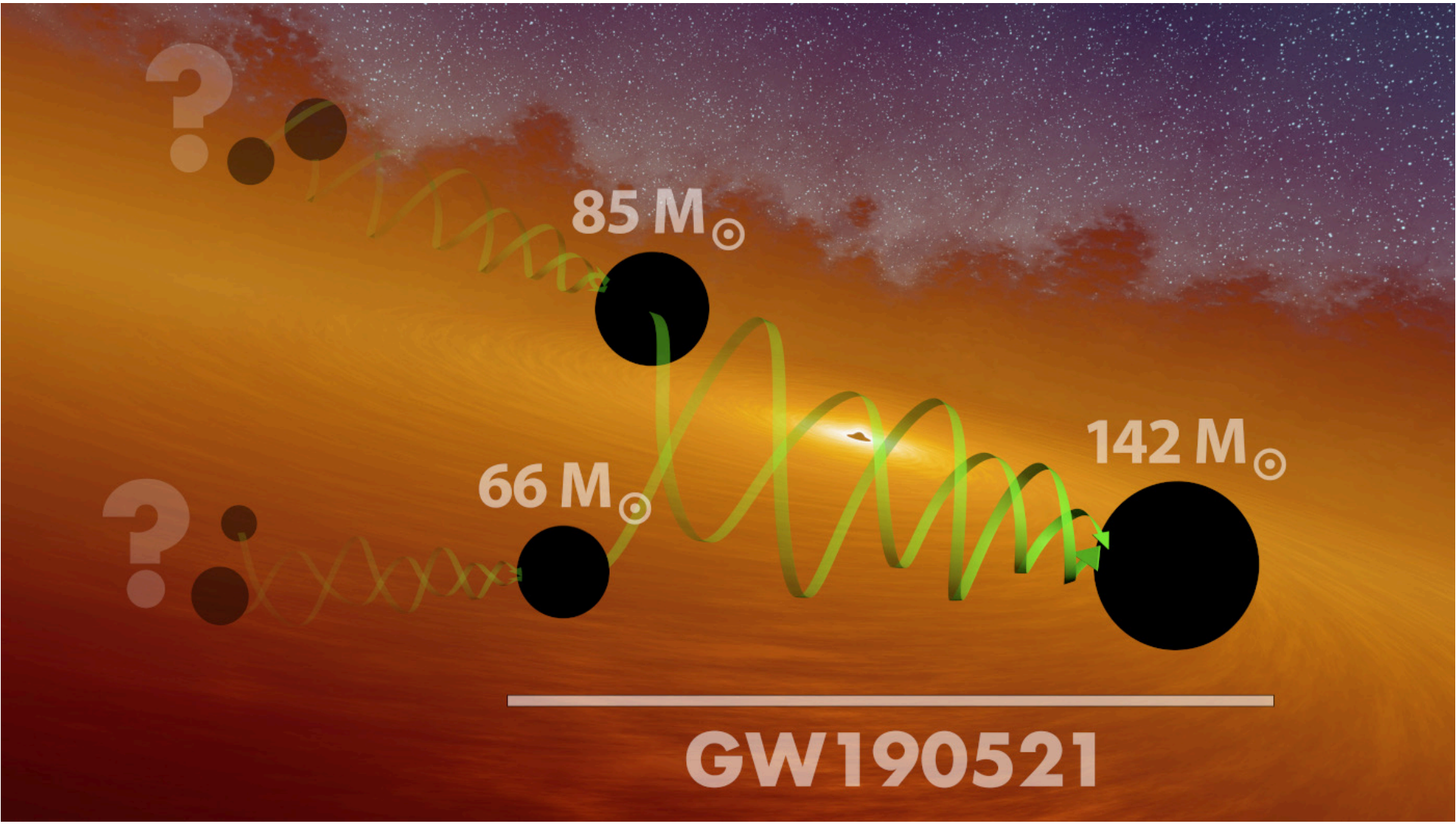
Source: JPL-Caltech/R. Hurt

GW190814



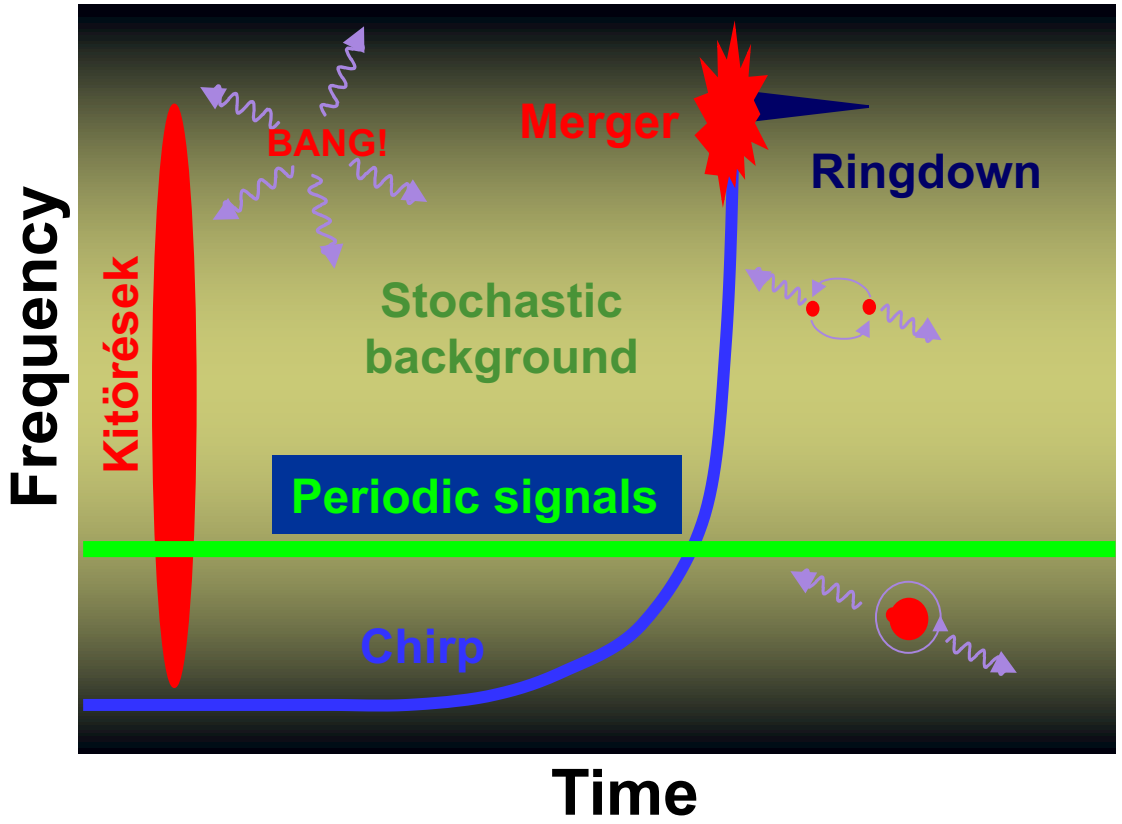
Source: Max Planck Institute for Gravitational Physics/Simulating eXtreme Spacetimes (SXS) Collaboration/N. Fischer, S. Ossokine, H. Pfeiffer, A. Buonanno

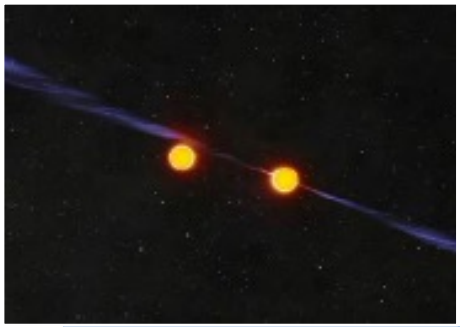
GW190521

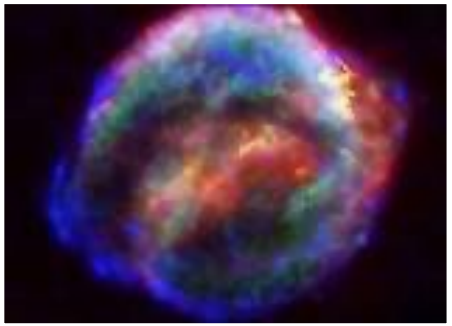


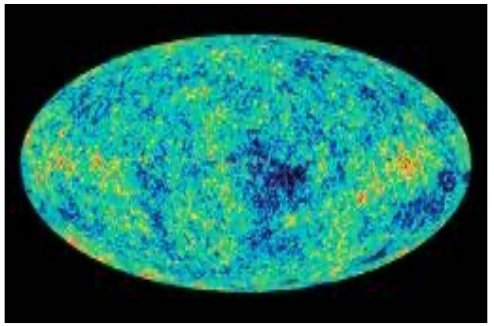
Source: LIGO/Caltech/MIT/R. Hurt (IPAC).

What else do we expect?









pnp.ligo.org/ppcomm/Papers.html

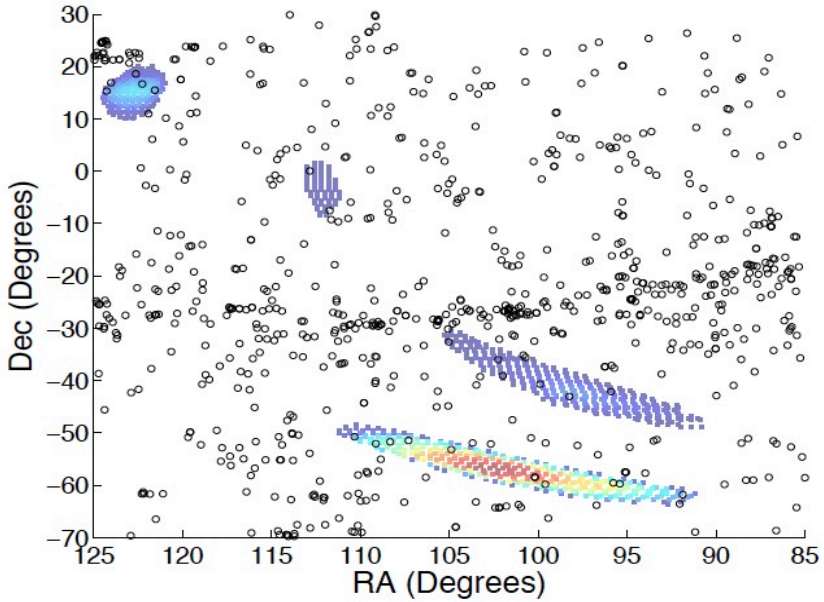
Publications of the LIGO Scientific Collaboration and Virgo Collaboration

Note: The LSC and Virgo collaborations have been co-authoring observational result papers since 2010. Beginning in 2021, the KAGRA collaboration too is co-authoring observational results from the full O3 run.

Highlighting: Event discoveries Multi-messenger

Click to toggle doi information | BibTeX file for these papers

Release Date	Title	Keywords	Science Summary	Journal citation	arXiv Preprint	Public DCC
May 31, 2021 *Recent*	**Search for intermediate mass black hole binaries in the third observing run of Advanced LIGO and Advanced Virgo**	O3 CBC Burst	summary	*Submitted to A&A*	2105.15120	P2100025
May 27, 2021 *Recent*	**Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run**	O3 CW	summary	*Submitted to PRL*	2105.13085	P2100098
May 25, 2021 *Recent*	**Searches for continuous gravitational waves from young supernova remnants in the early third observing run of Advanced LIGO and Virgo**	O3 CW	summary	*Submitted to ApJ*	2105.11641	P2000479
May 13, 2021 *Recent*	**Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run**	O3 CBC	summary	*Submitted to ApJ*	2105.06384	P2000400
Apr 29, 2021 *Recent*	**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	summary	*Submitted to ApJ*	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**	O3 Stochastic	summary	*Submitted to PRD*	2103.08520	P2000500
Jan 28, 2021	**Constraints on cosmic strings using data from the third Advanced LIGO-Virgo observing run**	O3 Stochastic Burst	summary	*Accepted by PRL*	2101.12248	P2000506
Jan 9, 2021	**Upper Limits on the Isotropic Gravitational-Wave Background from Advanced LIGO's and Advanced Virgo's First Three Observing Runs**	O3 Stochastic	summary	*Submitted to PRD*	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**	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**	O3 CBC	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**	O3 CBC	summary	*Accepted by PRD*	2010.14529	P2000091
Oct 28, 2020	**Population properties of compact objects from the second LIGO-Virgo Gravitational-Wave Transient Catalog**	O3 CBC	summary	Astrophys. J. Lett. **913**, L7 (2021)	2010.14533	P2000077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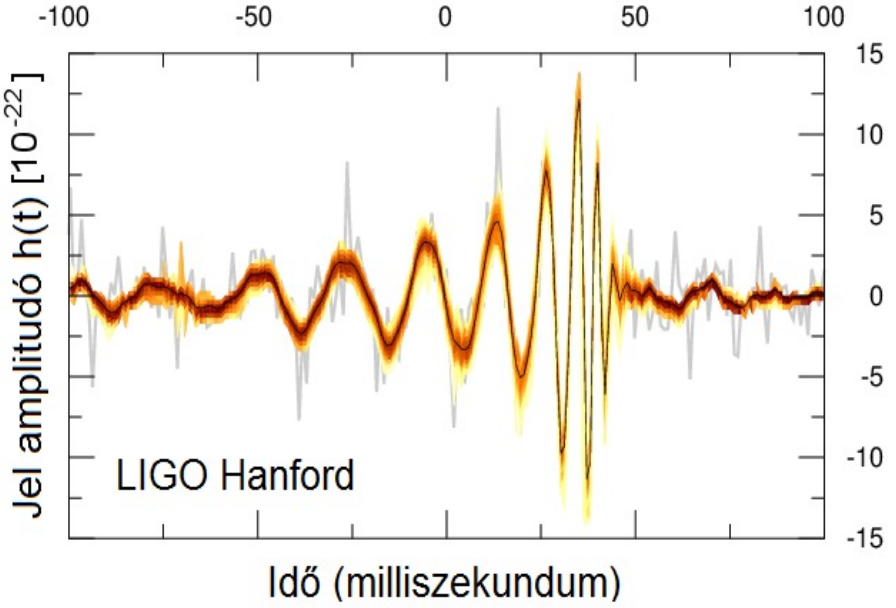
Jel amplitudó h(t) [10-22]
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LIGO Hanford
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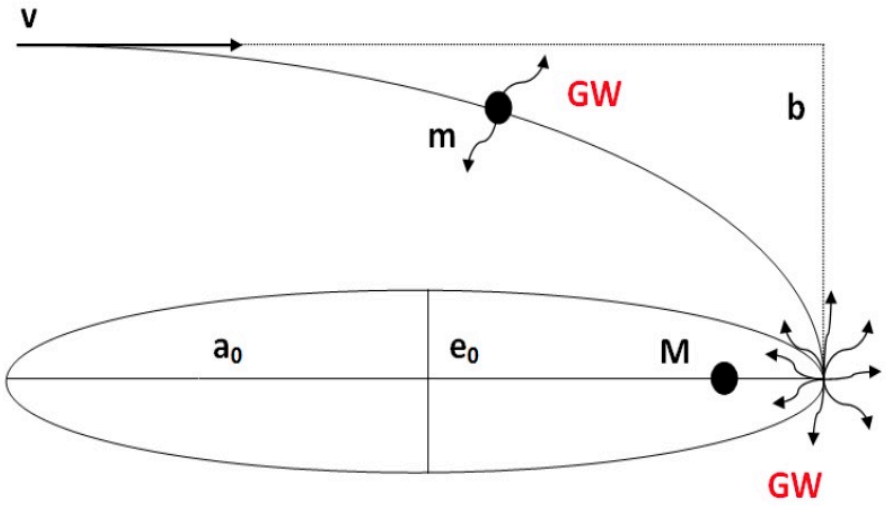
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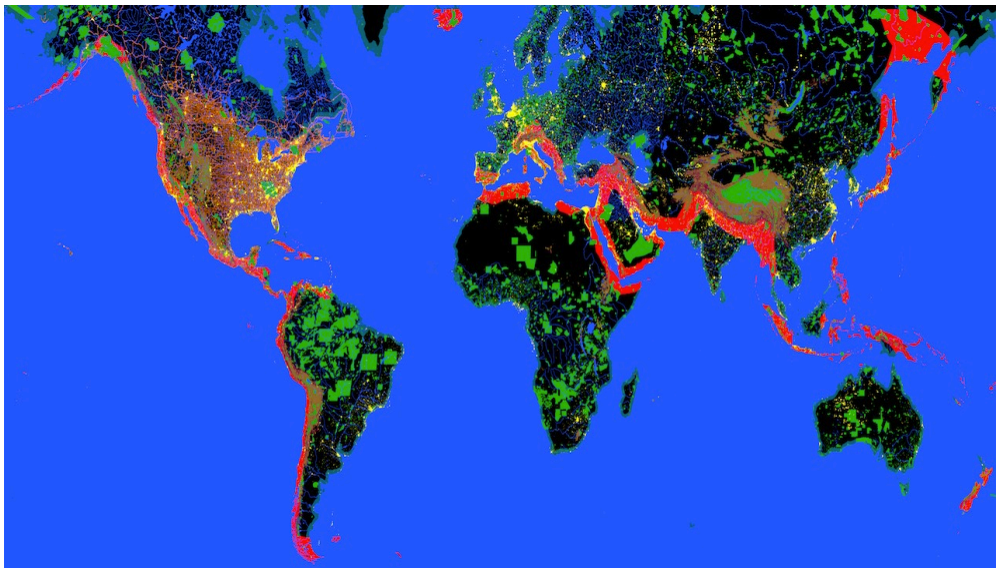


LIGO-related publications of the Eötvös University group in the past 5 years

Refereed short-authorlist publications:

- Dálya, G., Raffai, P., & Bécsy, B.; *"Bayesian reconstruction of gravitational-wave signals from binary black holes with nonzero eccentricities"*, CQG 38, 6 (2021)
- Bécsy, B., Raffai, P., Gill, K., Littenberg, T., Millhouse, M., & Szczepanczyk, M.; *"Interpreting gravitational-wave burst detections: constraining source properties without astrophysical models"*, CQG 37, 10 (2020)
- Takátsy, J., Bécsy, B., & Raffai, P.*; "Eccentricity distributions of eccentric binary black holes in galactic nuclei"*, MNRAS 486, 1, 570 (2019)
- Fishbach, M., et al. (+55 authors & The Virgo Collaboration); *"A Standard Siren Measurement of the Hubble Constant from GW170817 without the Electromagnetic Counterpart"*, ApJL 871, 1, L13 (2019)
- Dálya, G., Galgóczi, G., Dobos, L., et al. (+6 authors); *"GLADE: A Galaxy Catalogue for Multi-Messenger Searches in the Advanced Gravitational-Wave Detector Era"*, MNRAS 479, 2, 2374 (2018) [+VizieR Online Data Catalog: GLADE v2.3 catalog (Dalya+, 2018), VII/281.]
- Gondán, L., Kocsis, B., Raffai, P., & Frei, Z.; *"Eccentric Black Hole Gravitational-wave Capture Sources in Galactic Nuclei: Distribution of Binary Parameters"*, ApJ 860, 1, 5 (2018)
- Gondán, L., Kocsis, B., Raffai, P., & Frei, Z.; *"Accuracy of Estimating Highly Eccentric Binary Black Hole Parameters with Gravitational-wave Detections"*, ApJ 855, 1, 34 (2018)
- Bécsy, B., Raffai, P., Cornish, N. J., et al. (+6 authors); *"Parameter Estimation for Gravitational-wave Bursts with the BayesWave Pipeline"*, ApJ 839, 1, 15 (2017)
- Szölgyén, Á., Dálya, G., Gondán, L., & Raffai, P.; *“Target-based optimization of advanced gravitational-wave detector network operations”*, CQG 34, 7 (2017)

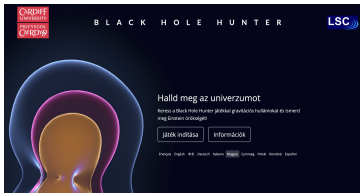
LSC publications we made significant contributions to:

- Abbott, B. P., et al. (+1187 authors); *"A Gravitational-wave Measurement of the Hubble Constant Following the Second Observing Run of Advanced LIGO and Virgo"*, ApJ 909, 2, 218 (2021)
- Abbott, B. P., et al. (+1253 authors); *"GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object"*, ApJL 896, 2, L44 (2020)
- Abbott, B. P., et al. (+1313 authors); *"A gravitational-wave standard siren measurement of the Hubble constant”*, Nature, doi:10.1038/nature24471 (2017)
- Abbott, B. P., et al. (+3620 authors); *"Multi-messenger Observations of a Binary Neutron Star Merger"*, ApJL 848, L12 (2017)
- Abbott, B. P., et al. (+935 authors); *"Search for Gravitational Waves Associated with Gamma-Ray Bursts During the First Advanced LIGO Observing Run and Implications for the Origin of GRB 150906B"*, ApJ 841, 2 (2017)
- Abbott, B. P., et al. (+935 authors); *"All-sky search for long-duration gravitational wave transients with initial LIGO"*, PRD 93, 4, 042005 (2016)

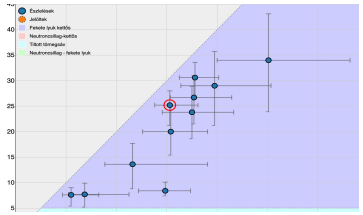
Stay tuned for more:

LIGO news and detections: **ligo.elte.hu**

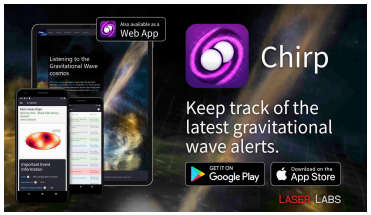
András Molnár
PhD student



Black Hole Hunter game: **blackholehunter.org**



LIGO-Virgo Compact Binary Catalog:
catalog.cardiffgravity.org/?lang=hu



- GraceDB site: **gracedb.ligo.org/superevents/public/O3/**
- **"Chirp"** application for tablets and smartphones

to follow live LIGO-Virgo alerts (from Fall 2021).