NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

Filling mass gaps in stellar graveyard by LIGO-Virgo data

Adam Zadrożny

NCBJ Yearly Seminar 2020

Warszawa, 15 December 2020

LSC LIGO Scientific Collaboration

VIRGO

Presentation is based on following articles

- GW190521: A Binary Black Hole Merger with a Total Mass of 150 Msun, Phys. Rev. Lett. 125, 101102 (2020)
- Properties and astrophysical implications of the 150 Msun binary black hole merger GW190521, Astrophys. J. Lett. 900, L13 (2020)
- GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object, Astrophys. J. Lett. 896, L44 (2020)
- GW190425: Observation of a compact binary coalescence with total mass ~3.4 Msun, Astrophys. J. Lett. 892, L3 (2020)
- GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run, arXiv:2010.14527
- Population properties of compact objects from the second LIGO-Virgo Gravitational-Wave Transient Catalog, arXiv: 2010.14533

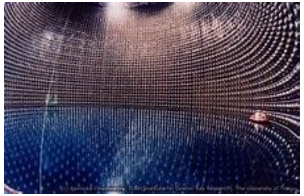
Ways to observe universe

- Electromagnetic
  - Visible light
  - Radio frequencies
  - Infra-red
  - …

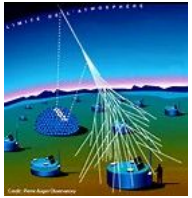
Credit: CAMK

Credit: Pi of the Sky

- Neutrinos … and cosmic rays



Credit: Super Kamiokande Team



- Gravitational waves (from 2015)

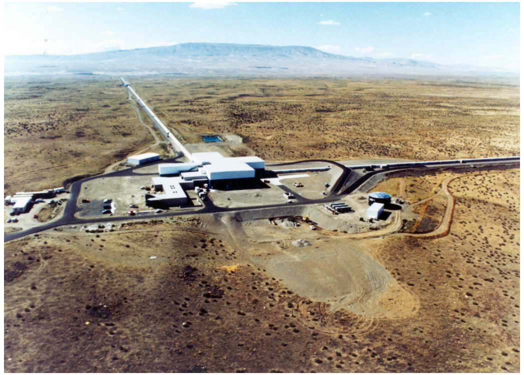
Credit: Virgo

Credit: LIGO

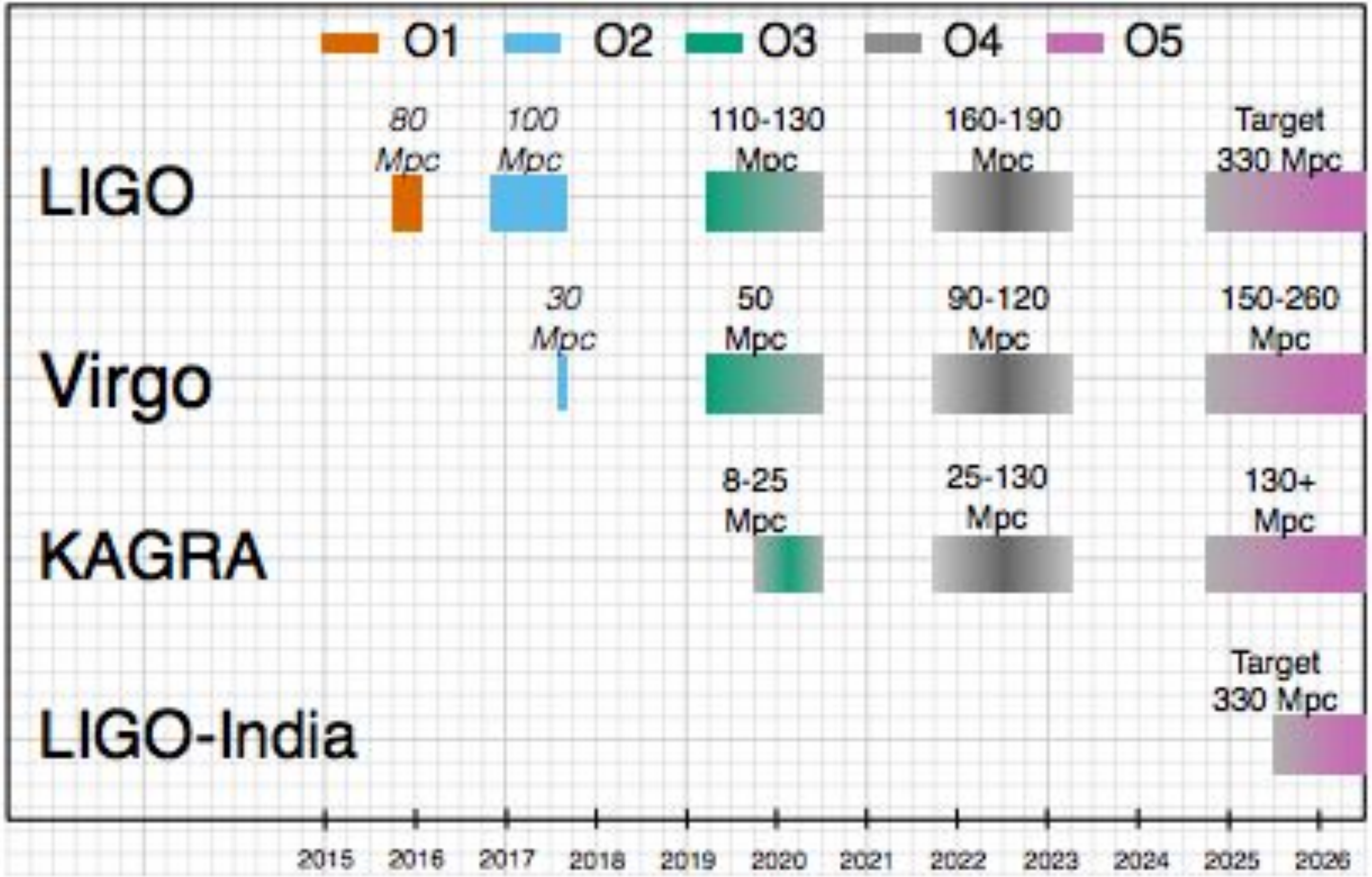
Gravitational Wave Detectors

LIGO Livingston

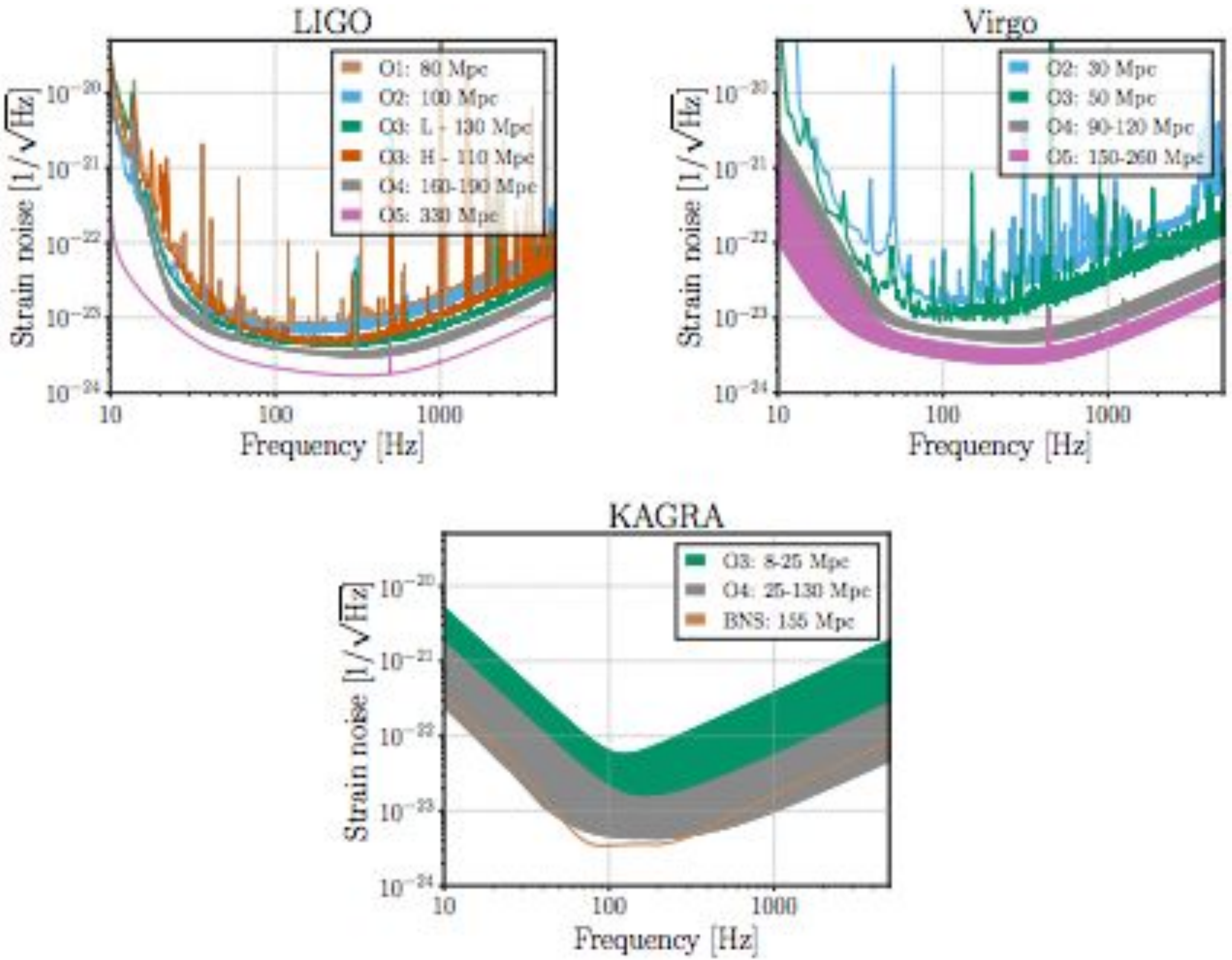
LIGO Hanford

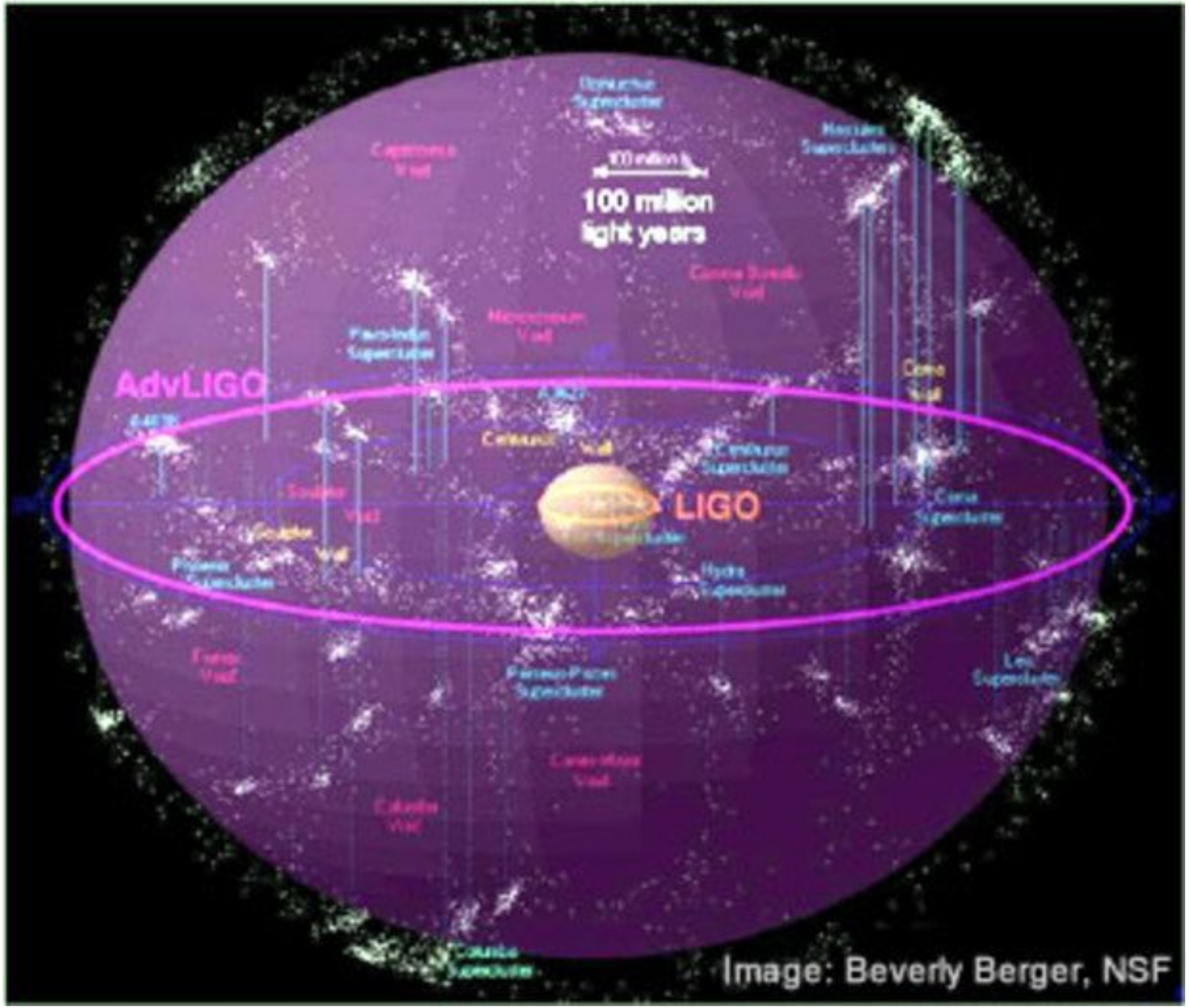


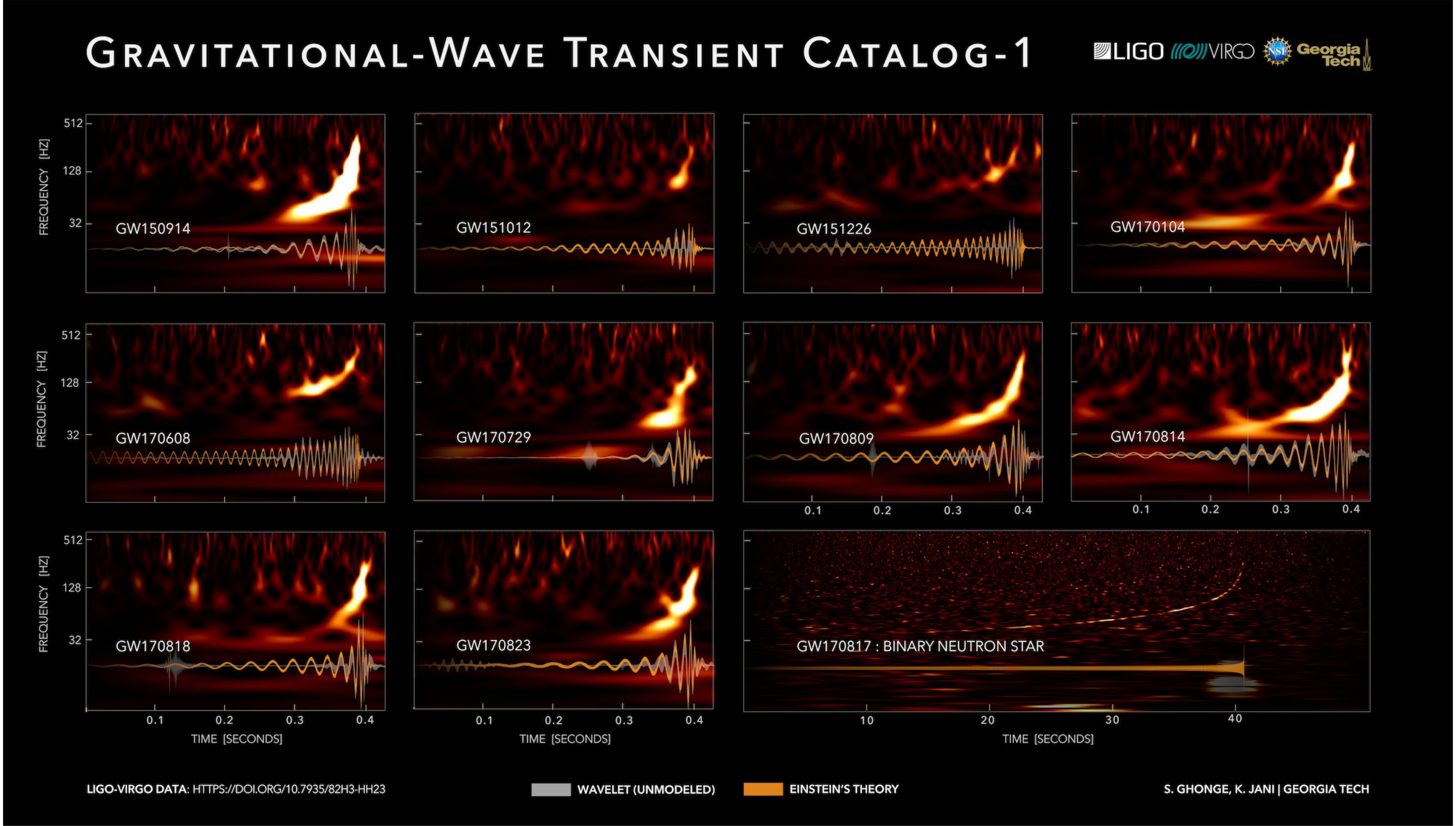
Virgo



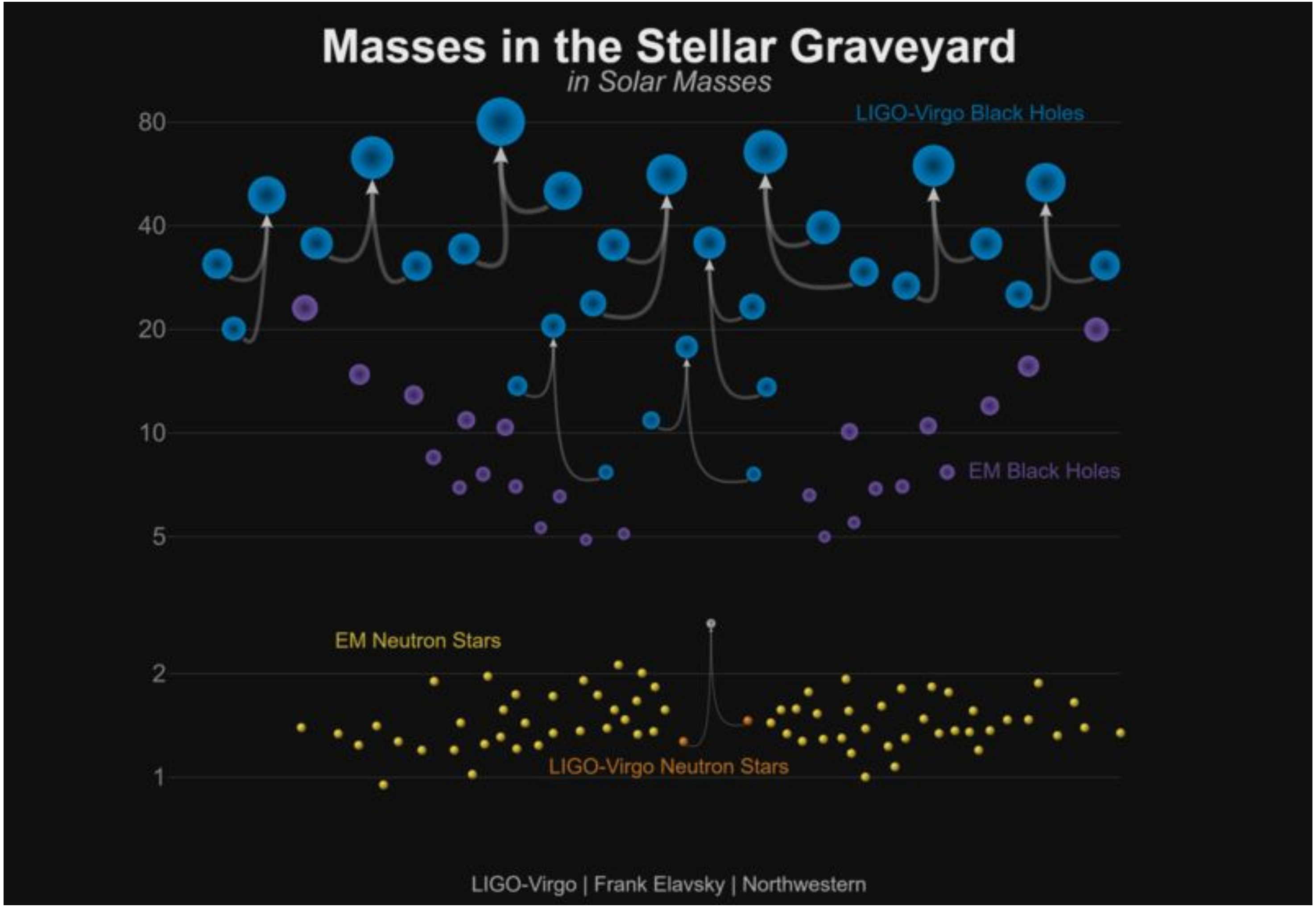
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
110-130 Mpc
160-190 Mpc
Target 330 Mpc
Virgo
30 Mpc
50 Mpc
90-120 Mpc
150-260 Mpc
KAGRA
8-25 Mpc
25-130 Mpc
130+ Mpc
LIGO-India
Target 330 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026


LIGO
O1: 80 Mpc
O2: 100 Mpc
O3: L - 130 Mpc
O3: H - 110 Mpc
O4: 160-190 Mpc
O5: 330 Mpc
Strain noise [1/√Hz]
Frequency [Hz]
Virgo
O2: 30 Mpc
O3: 50 Mpc
O4: 90-120 Mpc
O5: 150-260 Mpc
Strain noise [1/√Hz]
Frequency [Hz]
KAGRA
O3: 8-25 Mpc
O4: 25-130 Mpc
BNS: 155 Mpc
Strain noise [1/√Hz]
Frequency [Hz]


100 million
light years
AdvLIGO
LIGO
Image: Beverly Berger, NSF


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO
VIRGO
NSF
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH

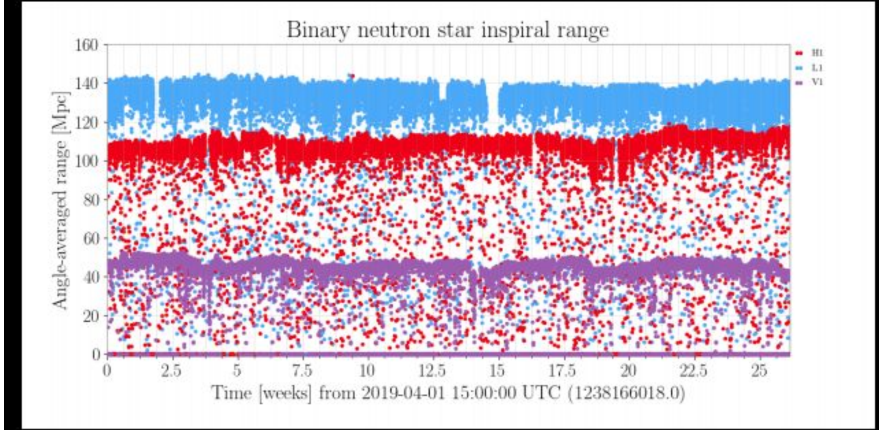
Prior to O3



Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

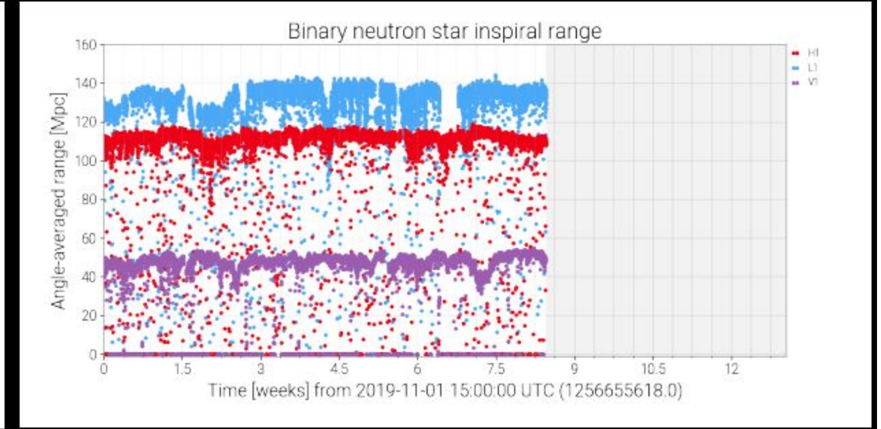
LIGO-Virgo's 3rd Observation Run

O3a



April 1 – October 1, 2019

O3b



November 1, 2019 – April 2020

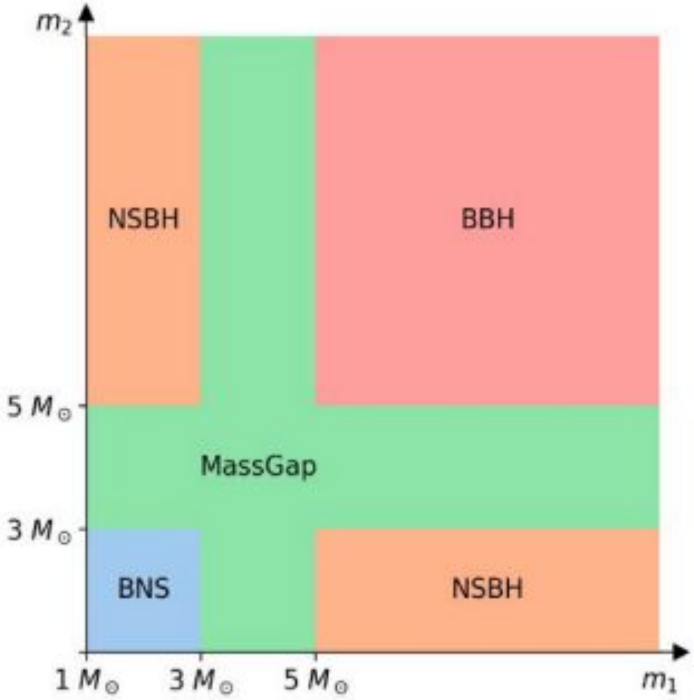
https://www.gw-openscience.org/detector_status/ LIGO-G1901973

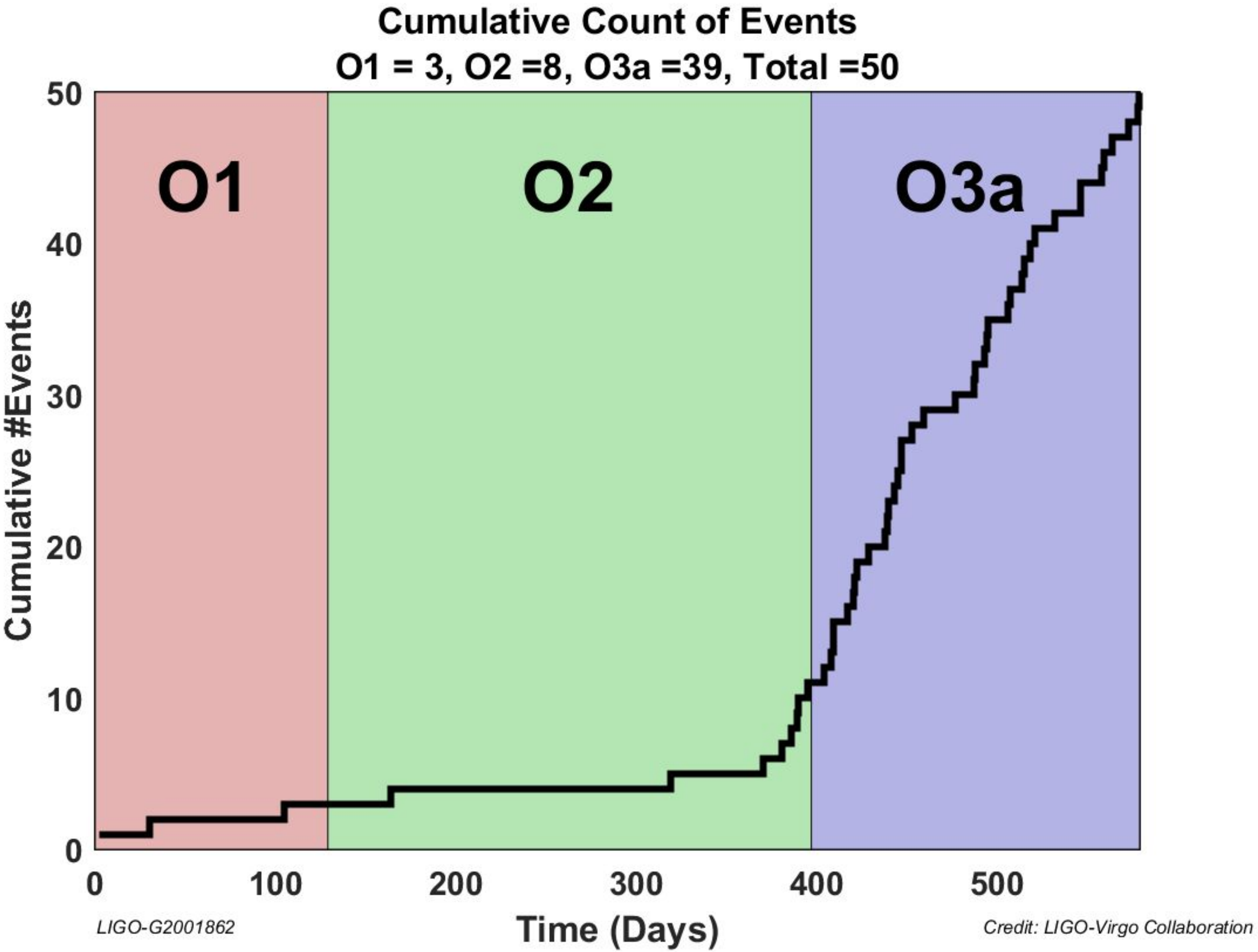
3rd observation run (O3)

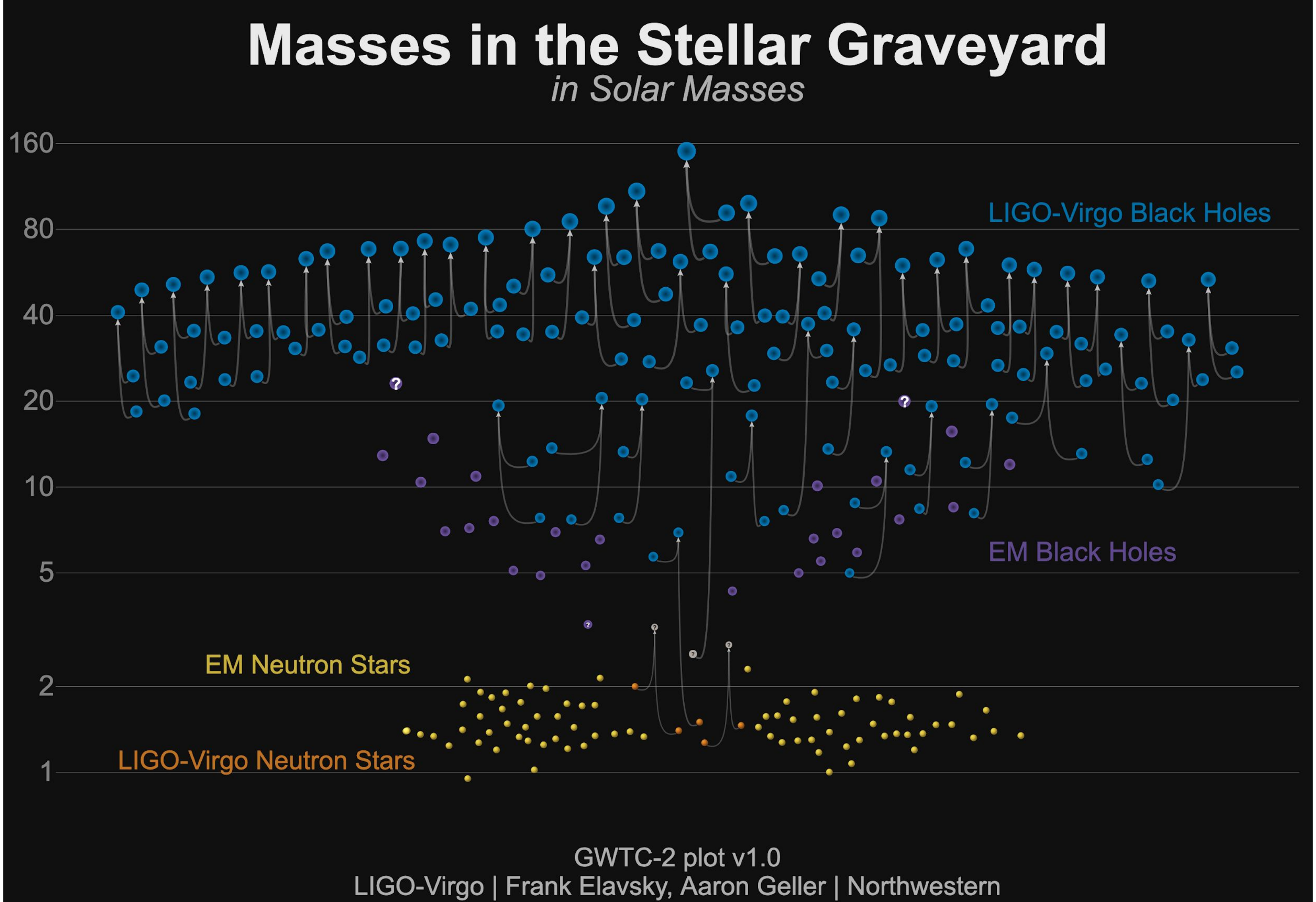
- The O3 run
  - Start: 1 April 2019
  - Break: Oct 2019
  - End: 30 April 2019
- LIGO/Virgo low-latency public alerts for transient event candidates
  - Notices and circulars available through the Gamma-ray Coordinates Network (GCN) https://gcn.gsfc.nasa.gov/gcn3_archive.html
- Event candidates will be publicly available
  - https://gracedb.ligo.org
- Japanese KAGRA detector to joined in Feb 2020

Inference: classification

- Five numbers, summing to unity, giving probability that the source belongs to the following five categories:
  - Terrestrial, BNS, MassGap, NSBH, BBH
  - GW150914: 5e-40, 0.00, 0.06, 0.01, 0.93
  - GW170817: 1e-48, 1.00, 0.00, 0.00, 0.00

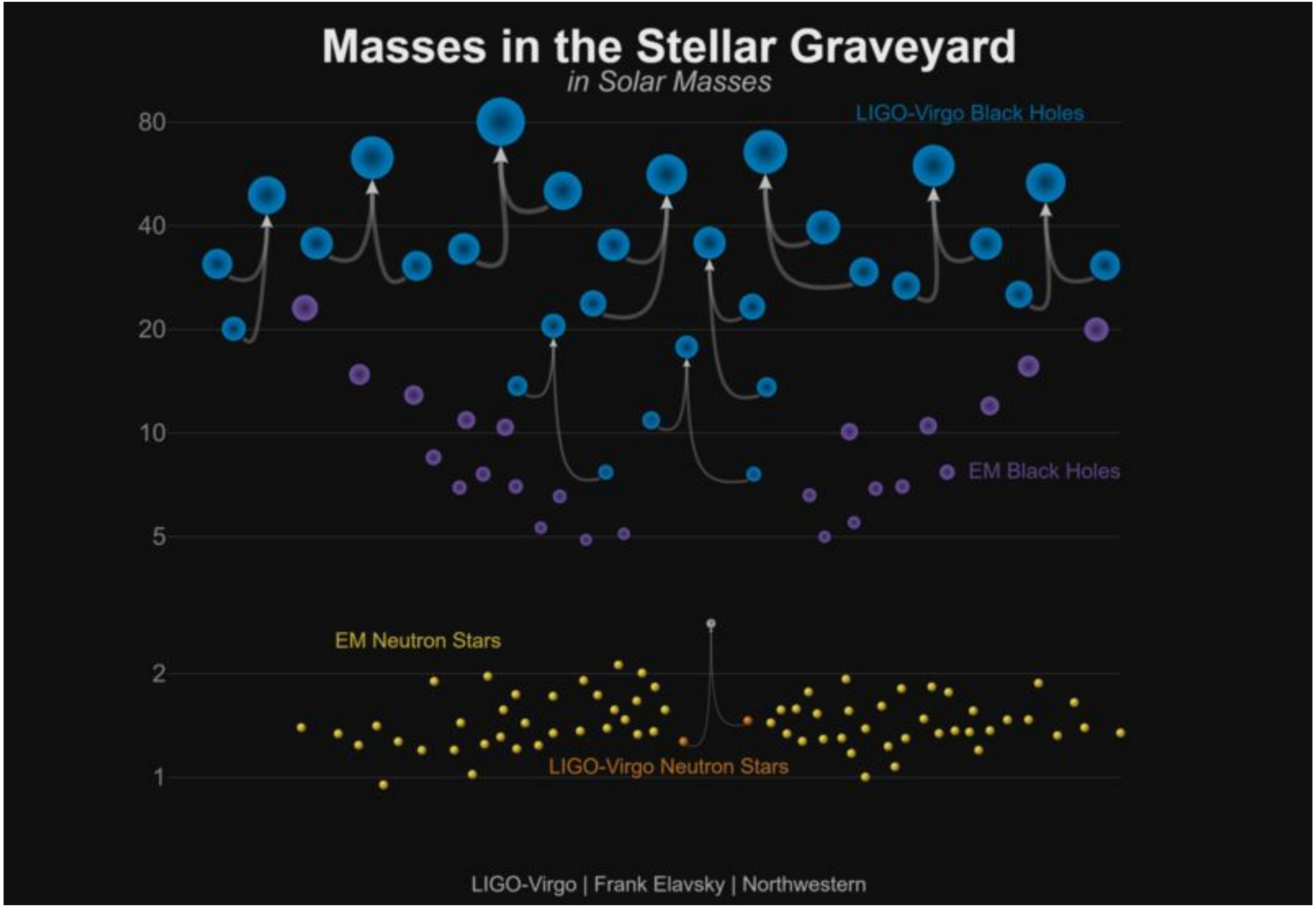



Cumulative Count of Events
O1 = 3, O2 =8, O3a =39, Total =50
O1
O2
O3a
Cumulative #Events
0
10
20
30
40
50
0
100
200
300
400
500
Time (Days)
LIGO-G2001862
Credit: LIGO-Virgo Collaboration



Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Prior to O3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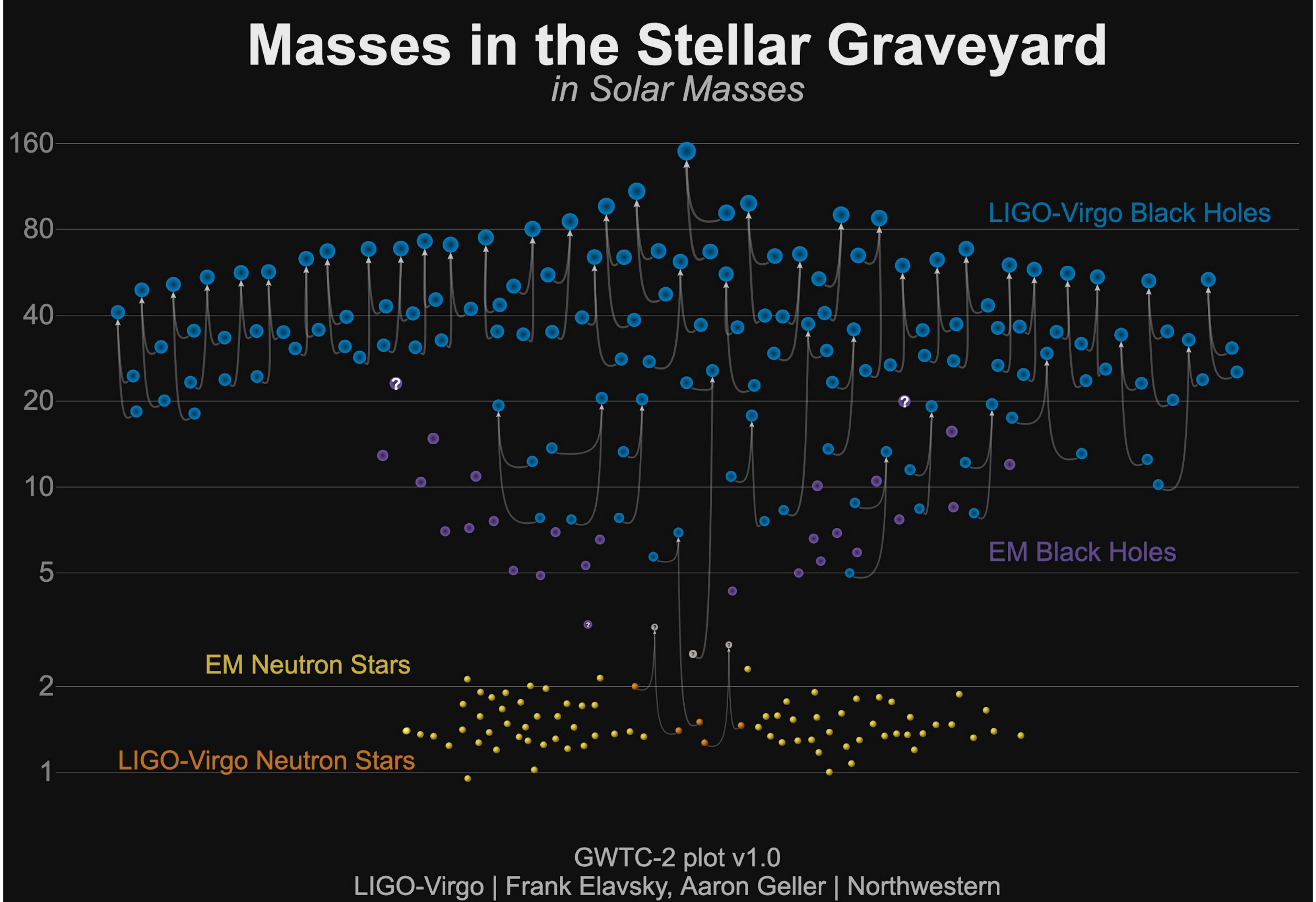
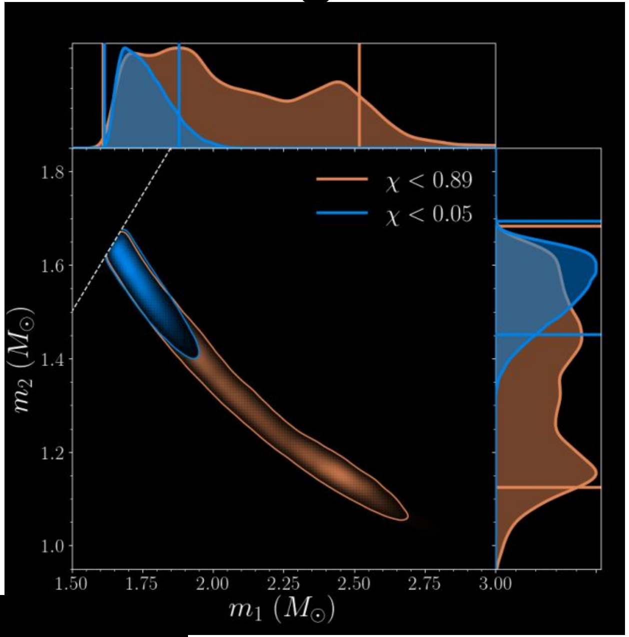
LIGO-Virgo | Frank Elavsky | Northwestern

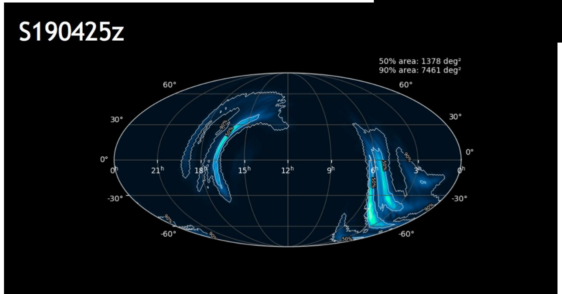


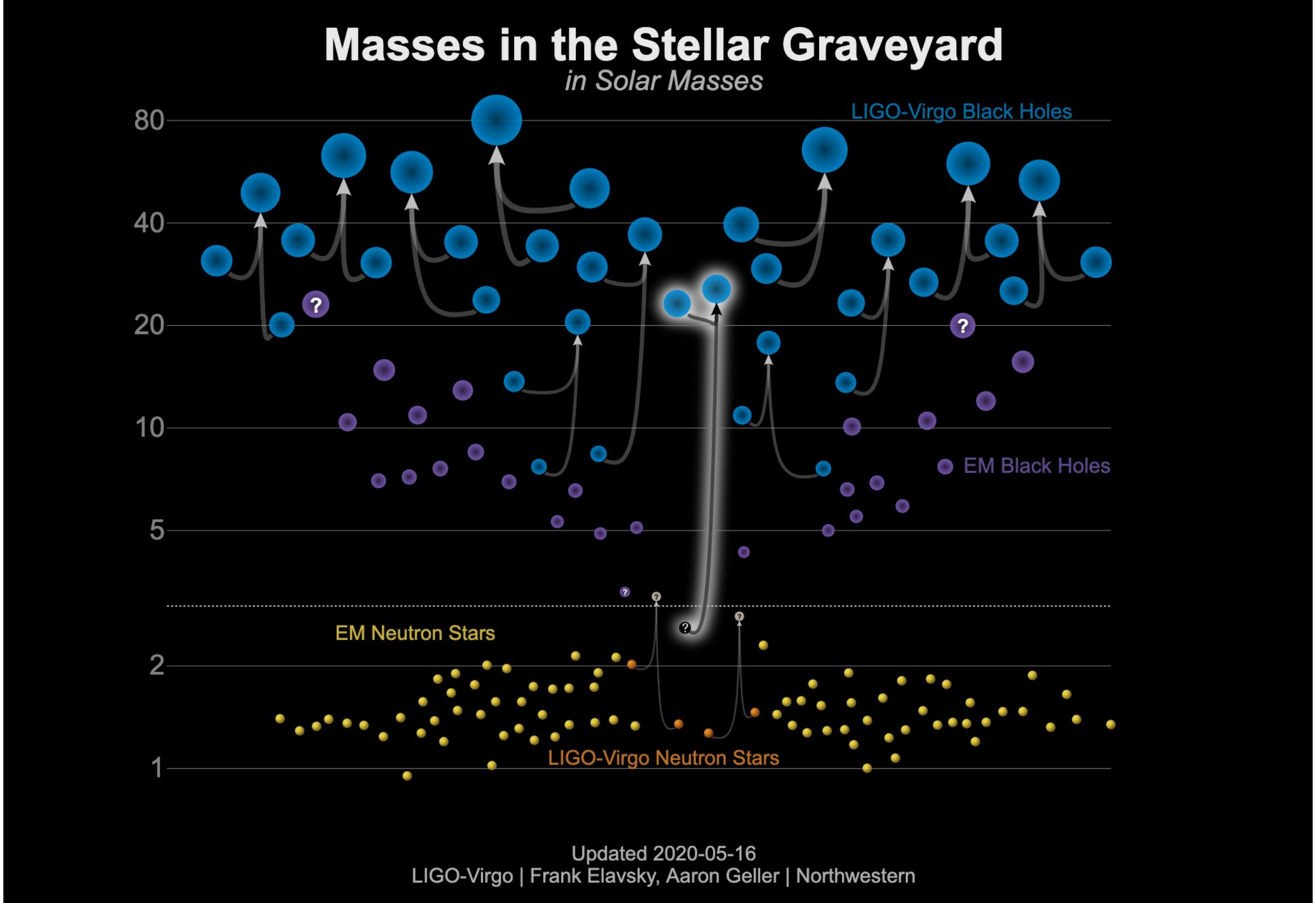
Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190425 - second binary neutron star merger

- Second BNS observed
- Components
  - First: 1.61 - 2.52 Msun
  - Second: 1.12 - 1.68 Msun
  - Total mass: 3.3 - 3.7 Msun
- Result object in massgap region
- Poor localization
- No GRB counterpart
- No matter effects observed



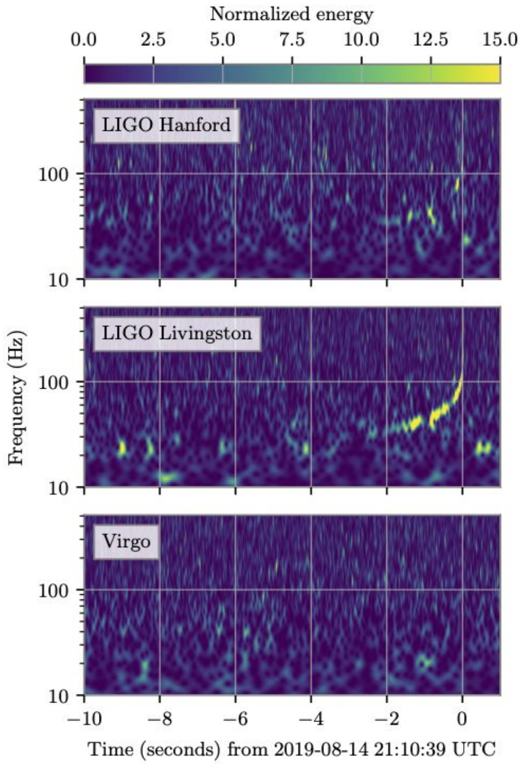




Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

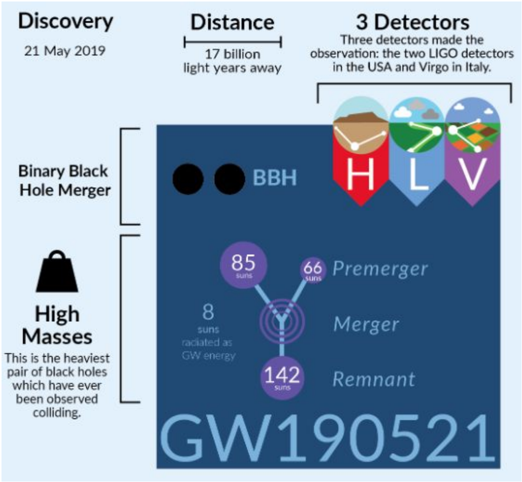
GW190814 - gravitational waves from an atypical coalescing binary

- Heavier component has 23 solar masses
- Lighter component has between 2.5 and 3 solar masses
- Mass ratio 1:9
- The legither component is either
  - an heaviest NS
  - or a lightest BH
- Higher GW modes were observable
- New GR tests weere possible



GW190521 - most massive BBH merger up to date

- component masses
  - 66 Msun
  - 85 Msun [!!!]
    - this cannot be a result of a core-collapse due to pair instability
- most massive merger up to date
- first intermediate black hole observed in LIGO 100-1000 Msun mass
- ApJL 900,L13 (2020)



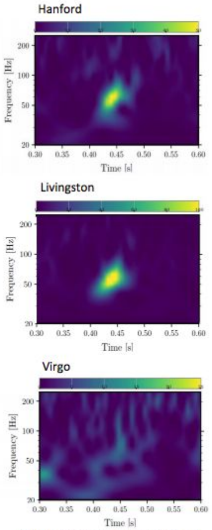
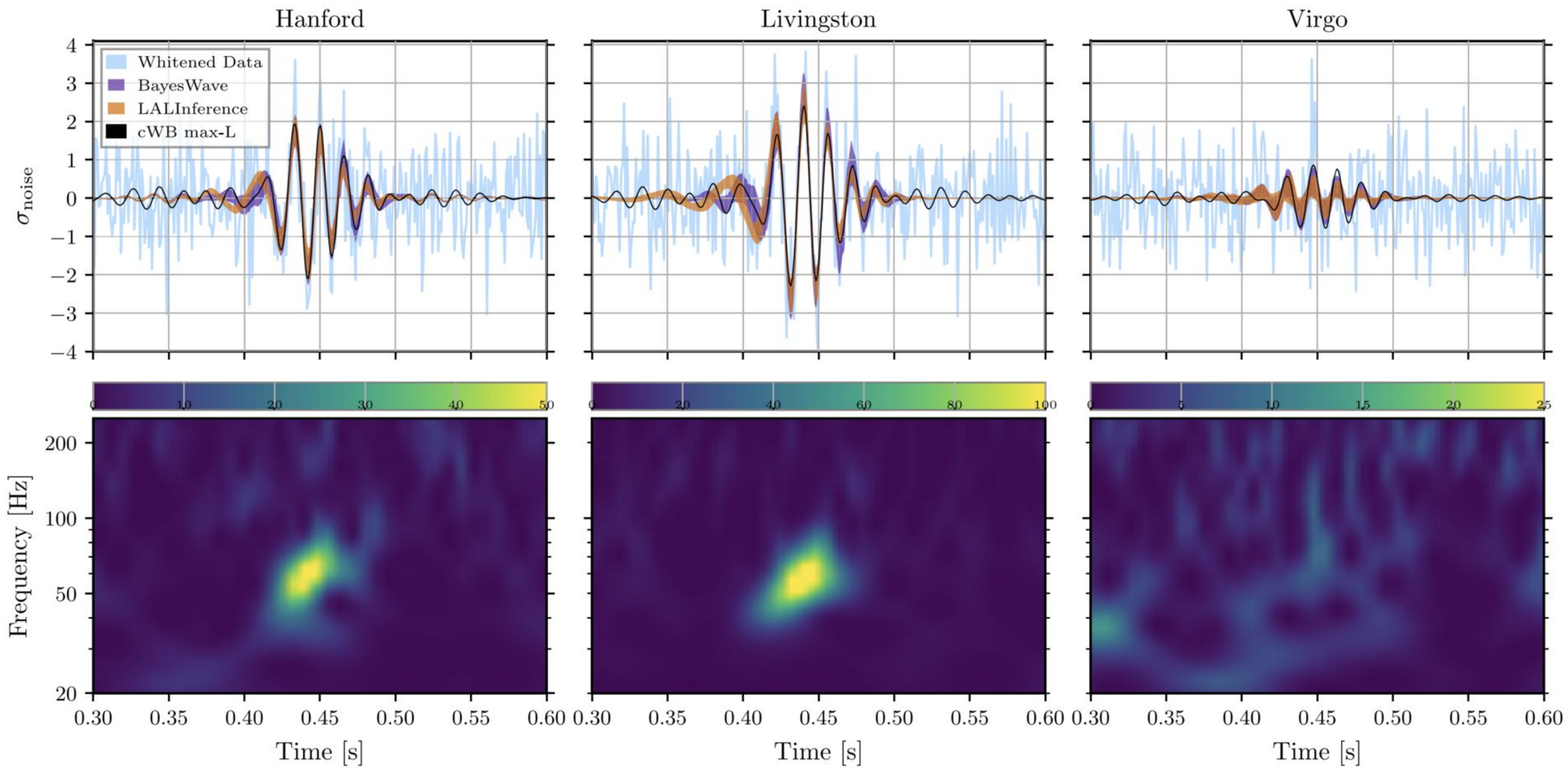


Figure 1. Time–frequency representations of data containing the GW190521 signal, observed by LIGO Hanford (top), LIGO Livingston (middle), and Virgo (bottom). Times are shown relative to 03:02:29 UTC on May 21, 2019. The energy in a certain time-frequency bin is represented by the color palette. Note the signal's extremely short duration and its peak frequency of about 60 Hz. (Adapted from Fig. 1 of our GW190521 discovery paper)

GW190521


Hanford
Livingston
Virgo
Whitened Data
BayesWave
LALInference
cWB max-L
σ_{noise}
Frequency [Hz]
Time [s]

GW190521

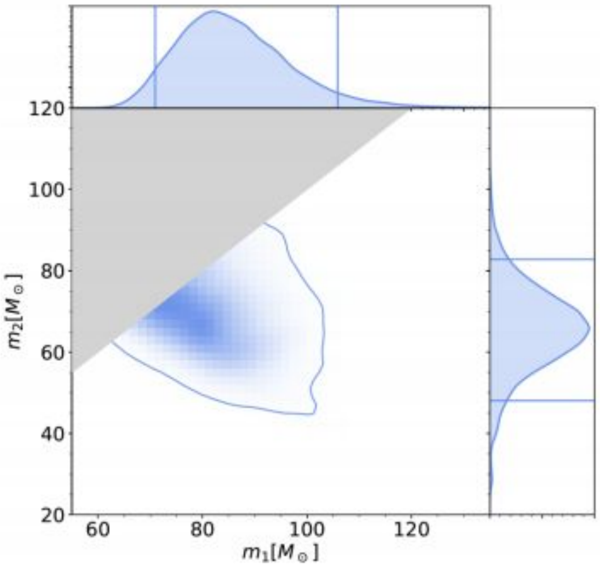


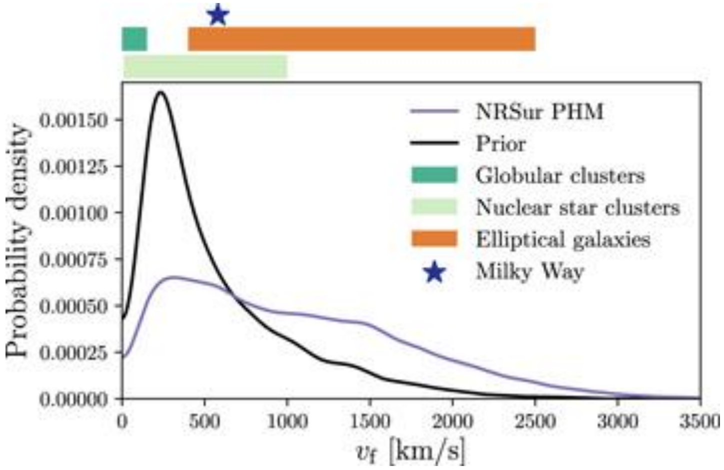
Figure 2. *Measured masses of the colliding black holes that produced the gravitational wave signal GW190521 shown as probability distributions. According to the LIGO-Virgo analysis, the true values of the black hole masses have a 90% probability of being located inside the solid blue contour in the central plot (which shows the joint probability for both masses). The same is true for the solid vertical and horizontal lines in the bell-shaped curves to the top and right of the figure, which show the mass measurements for the individual black holes. The grayed-out region of the central plot is due to the LIGO-Virgo convention that the "primary" mass m_1 is always of equal or greater value than the "secondary" mass m_2. (Reproduced from Fig. 2 of our [GW190521 discovery paper])*

Table 1

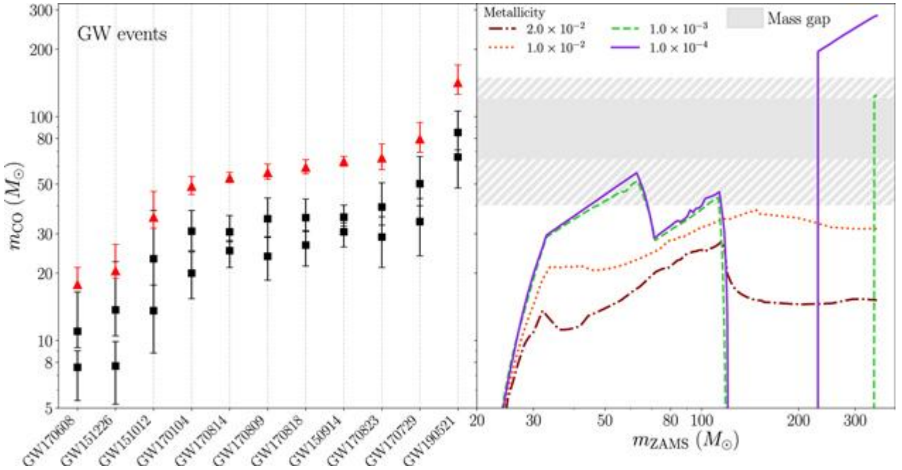
Source Properties for GW190521: Median Values with 90% Credible Intervals That Include Statistical Errors

Waveform Model	NRSur PHM	Phenom PHM	SEOBNR PHM
Primary BH mass m_1 ($M_\odot$)	85^{+21}_{-14}	90^{+23}_{-16}	99^{+42}_{-19}
Secondary BH mass m_2 ($M_\odot$)	66^{+17}_{-18}	65^{+16}_{-18}	71^{+21}_{-28}
Total BBH mass M ($M_\odot$)	150^{+29}_{-17}	154^{+25}_{-16}	170^{+36}_{-23}
Binary chirp mass $\mathcal{M}$ ($M_\odot$)	64^{+13}_{-8}	65^{+11}_{-7}	71^{+15}_{-10}
Mass ratio $q = m_2/m_1$	$0.79^{+0.19}_{-0.29}$	$0.73^{+0.24}_{-0.29}$	$0.74^{+0.23}_{-0.42}$
Primary BH spin χ_1	$0.69^{+0.27}_{-0.62}$	$0.65^{+0.32}_{-0.57}$	$0.80^{+0.18}_{-0.58}$
Secondary BH spin χ_2	$0.73^{+0.24}_{-0.64}$	$0.53^{+0.42}_{-0.48}$	$0.54^{+0.41}_{-0.48}$
Primary BH spin tilt angle θ_{LS_1} (deg)	81^{+64}_{-53}	80^{+64}_{-49}	81^{+49}_{-45}
Secondary BH spin tilt angle θ_{LS_2} (deg)	85^{+57}_{-55}	87^{+63}_{-58}	93^{+61}_{-60}
Effective inspiral spin parameter χ_{eff}	$0.08^{+0.27}_{-0.36}$	$0.06^{+0.31}_{-0.39}$	$0.06^{+0.34}_{-0.35}$
Effective precession spin parameter χ_p	$0.68^{+0.25}_{-0.37}$	$0.60^{+0.33}_{-0.44}$	$0.74^{+0.21}_{-0.40}$
Remnant BH mass M_f ($M_\odot$)	142^{+28}_{-16}	147^{+23}_{-15}	162^{+35}_{-22}
Remnant BH spin χ_f	$0.72^{+0.09}_{-0.12}$	$0.72^{+0.11}_{-0.15}$	$0.74^{+0.12}_{-0.14}$
Radiated energy E_{rad} ($M_\odot c^2$)	$7.6^{+2.2}_{-1.9}$	$7.2^{+2.7}_{-2.2}$	$7.8^{+2.8}_{-2.3}$
Peak Luminosity ℓ_{peak} (erg s^{-1})	$3.7^{+0.7}_{-0.9} \times 10^{56}$	$3.5^{+0.7}_{-1.1} \times 10^{56}$	$3.5^{+0.8}_{-1.4} \times 10^{56}$
Luminosity distance D_L (Gpc)	$5.3^{+2.4}_{-2.6}$	$4.6^{+1.6}_{-1.6}$	$4.0^{+2.0}_{-1.8}$
Source redshift z	$0.82^{+0.28}_{-0.34}$	$0.73^{+0.20}_{-0.22}$	$0.64^{+0.25}_{-0.26}$
Sky localization $\Delta\Omega$ (deg^2)	774	862	1069

GW190521



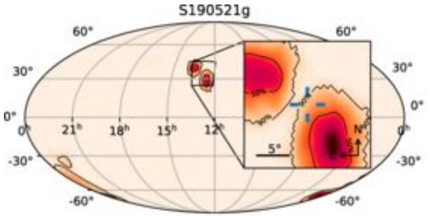
NRSur PHM
Prior
Globular clusters
Nuclear star clusters
Elliptical galaxies
Milky Way
Probability density
0.00000
0.00025
0.00050
0.00075
0.00100
0.00125
0.00150
0
500
1000
1500
2000
2500
3000
3500
v_f [km/s]

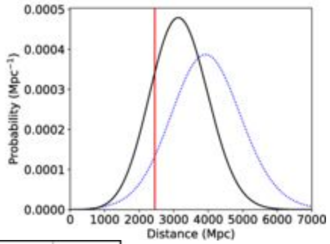


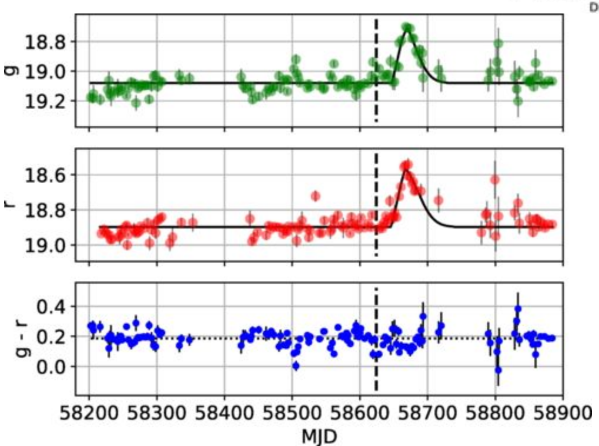
GW events
m_{CO} ($M_\odot$)
5
8
10
20
30
50
80
100
200
300
GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729
GW190521
Metallicity
2.0×10^{-2}
1.0×10^{-2}
1.0×10^{-3}
1.0×10^{-4}
Mass gap
20
30
50
80
100
200
300
m_{ZAMS} ($M_\odot$)

GW190521 - EM candidate S190521g

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.251102







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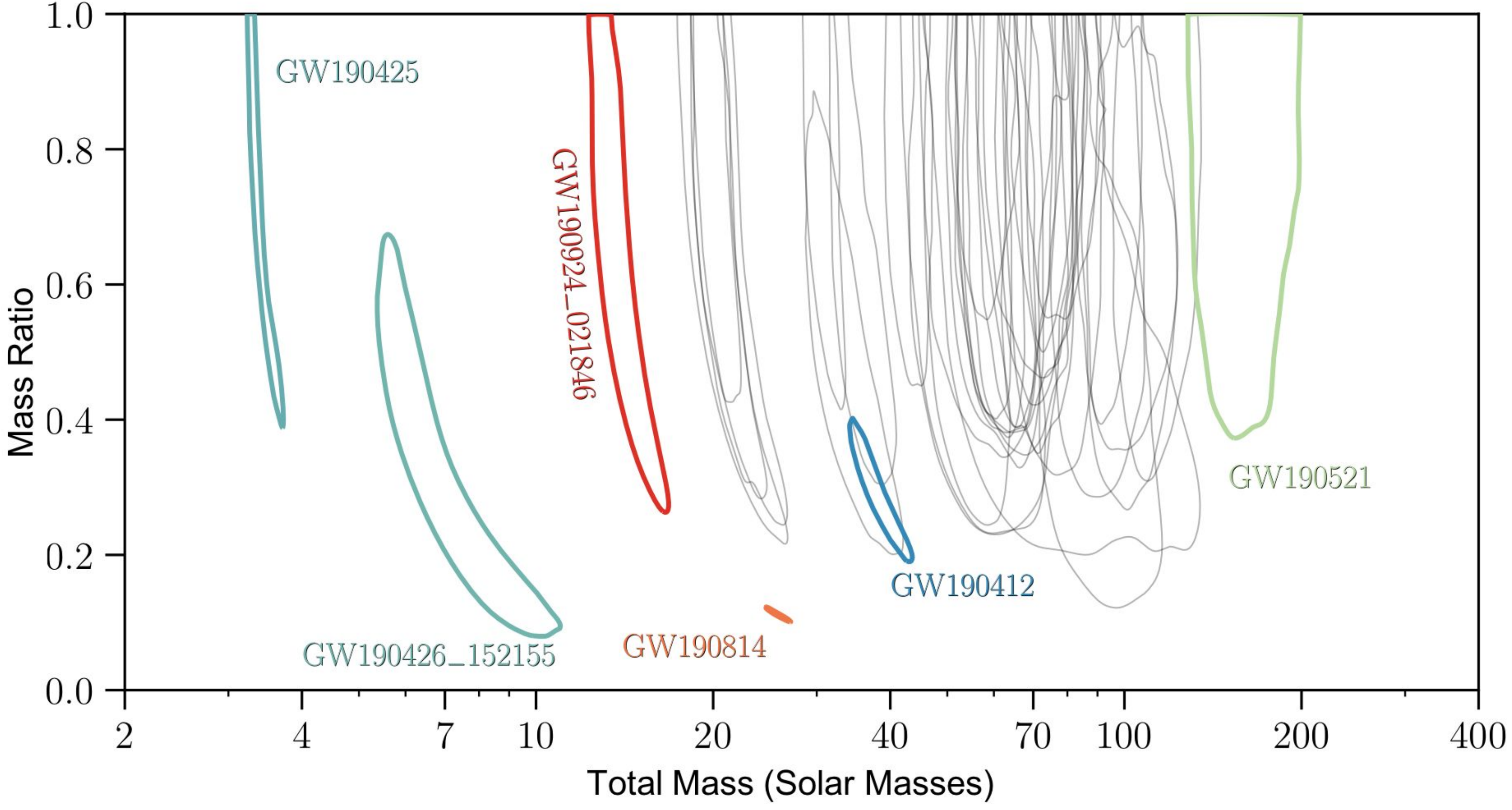
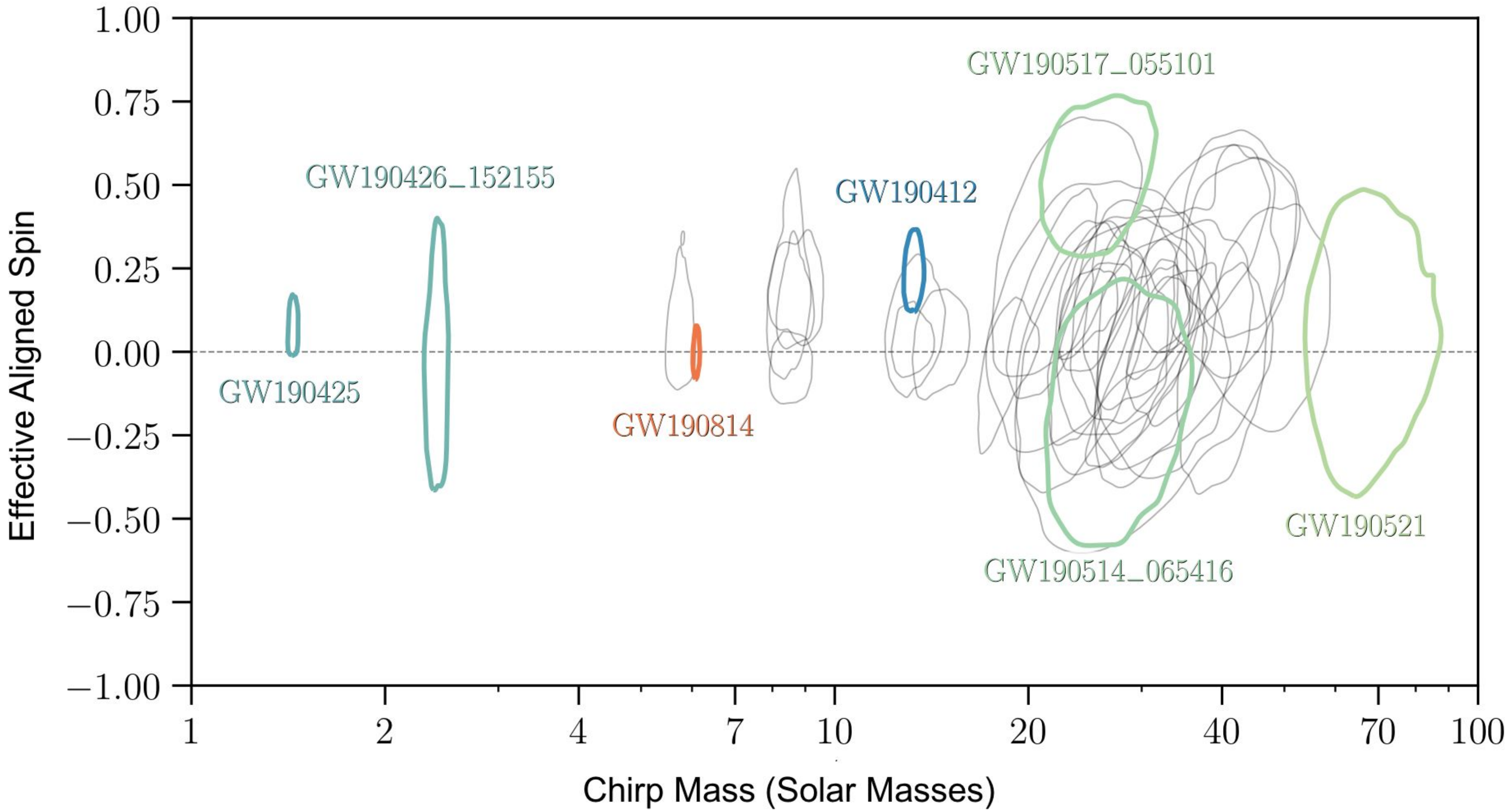


GW190425
GW190924_021846
GW190426_152155
GW190814
GW190412
GW190521
Mass Ratio
1.0
0.8
0.6
0.4
0.2
0.0
2
4
7
10
20
40
70
100
200
400
Total Mass (Solar Masses)



Effective Aligned Spin
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
GW190426_152155
GW190425
GW190814
GW190412
GW190517_055101
GW190514_065416
GW190521
1
2
4
7
10
20
40
70
100
Chirp Mass (Solar Masses)

Summary

- We started to filling gaps in stellar graveyard
- First observation of intermediate back hole 100-100 Msun
- First observation of objects from massgap (3-5 Msun)
- What's more there were 39 detections of GW in O3a
- We can start population studies