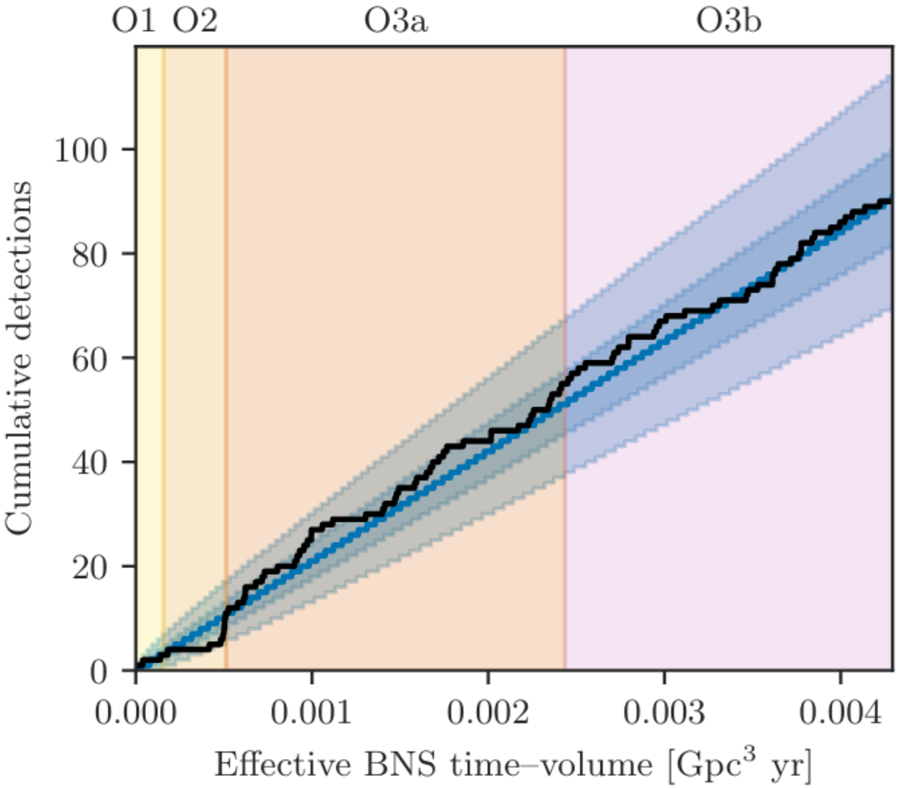
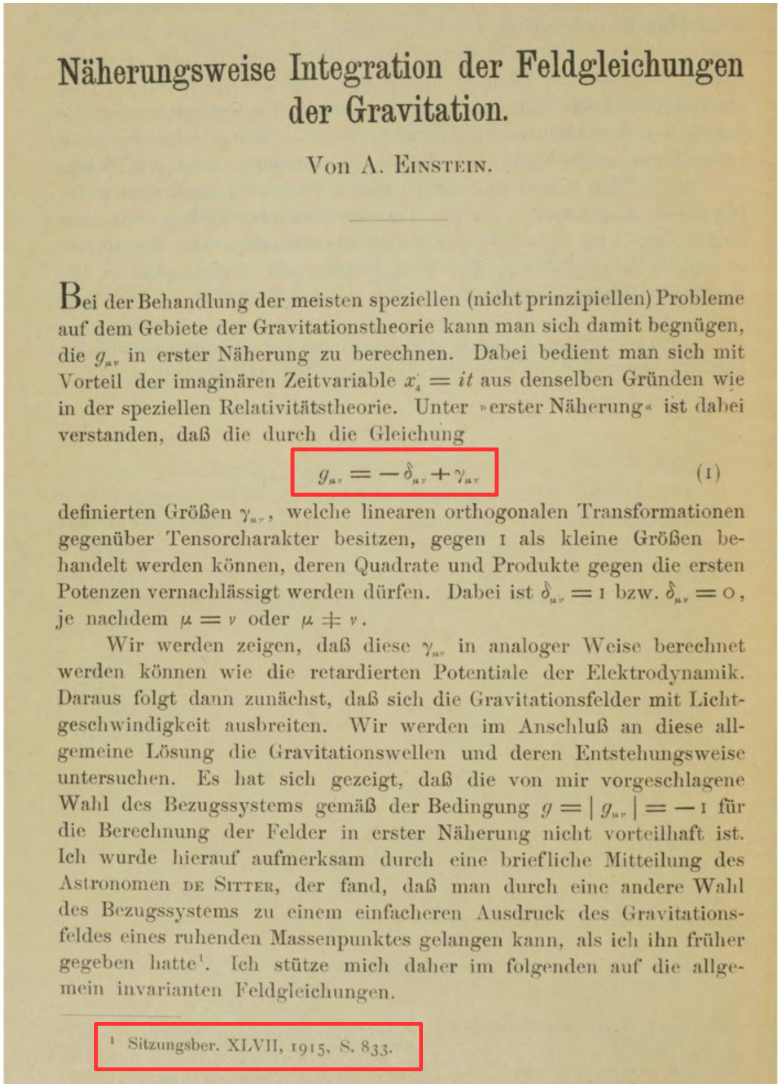


Recent results from gravitational-wave searches

Florent Robinet

Gravitational waves



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$\boxed{g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}} \qquad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen de Sitter, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihn früher gegeben hatte[1]. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

---

[1] Sitzungsber. XLVII, 1915, S. 833.

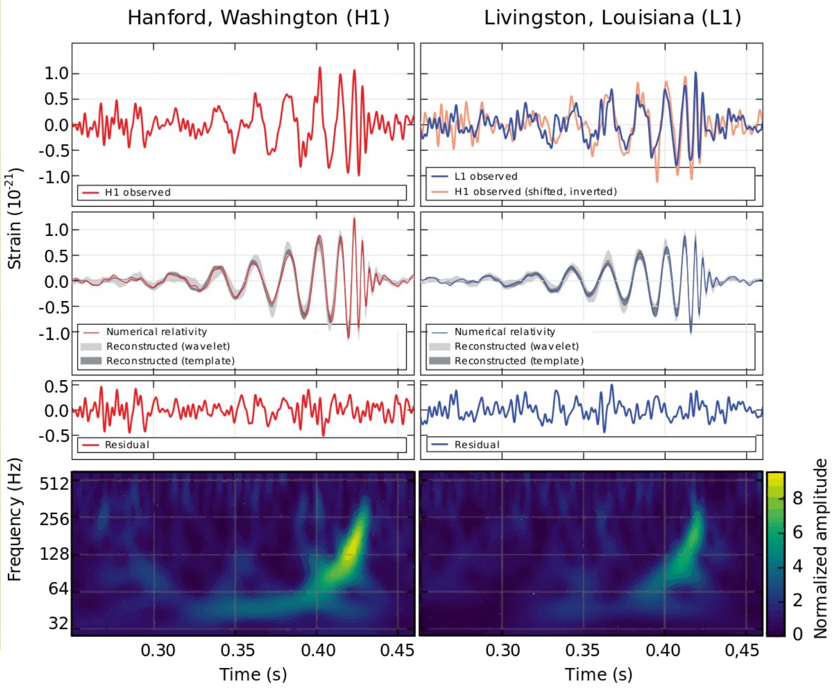
Minkowski metric + small perturbation

$$\eta^{\mu\nu}\partial_\mu\partial_\nu\bar{h}_{\alpha\beta} = -\frac{16\pi G}{c^4}T_{\alpha\beta}$$

→ gravitational waves
speed of light + 2 polarizations

$$\bar{h}_{\mu\nu}(x^\alpha) = A_{\mu\nu}e^{ik_\sigma x^\sigma}$$

First detection: 2015



Hanford, Washington (H1)

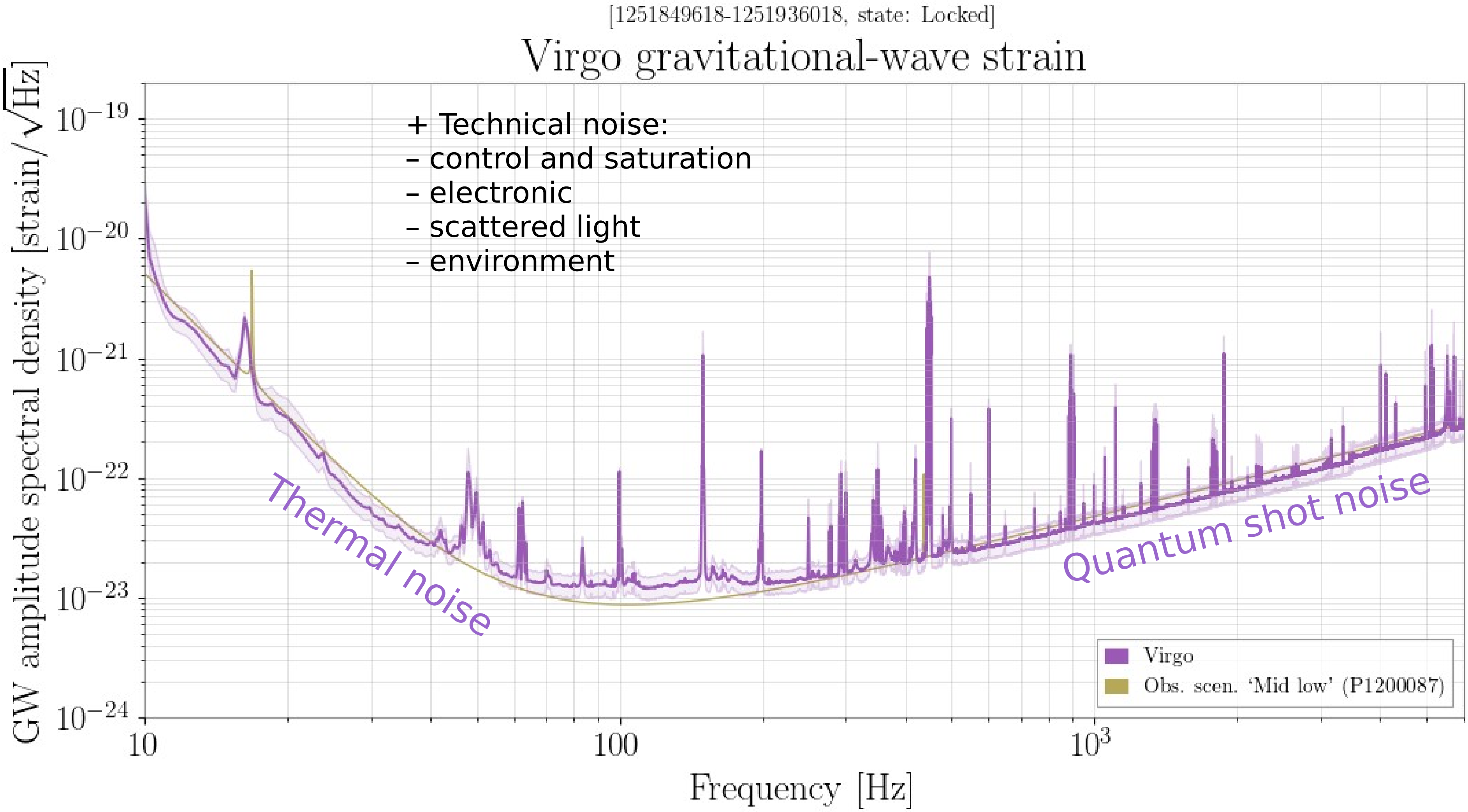
Livingston, Louisiana (L1)

LIGO Livingston (USA)

LIGO Hanford (USA)

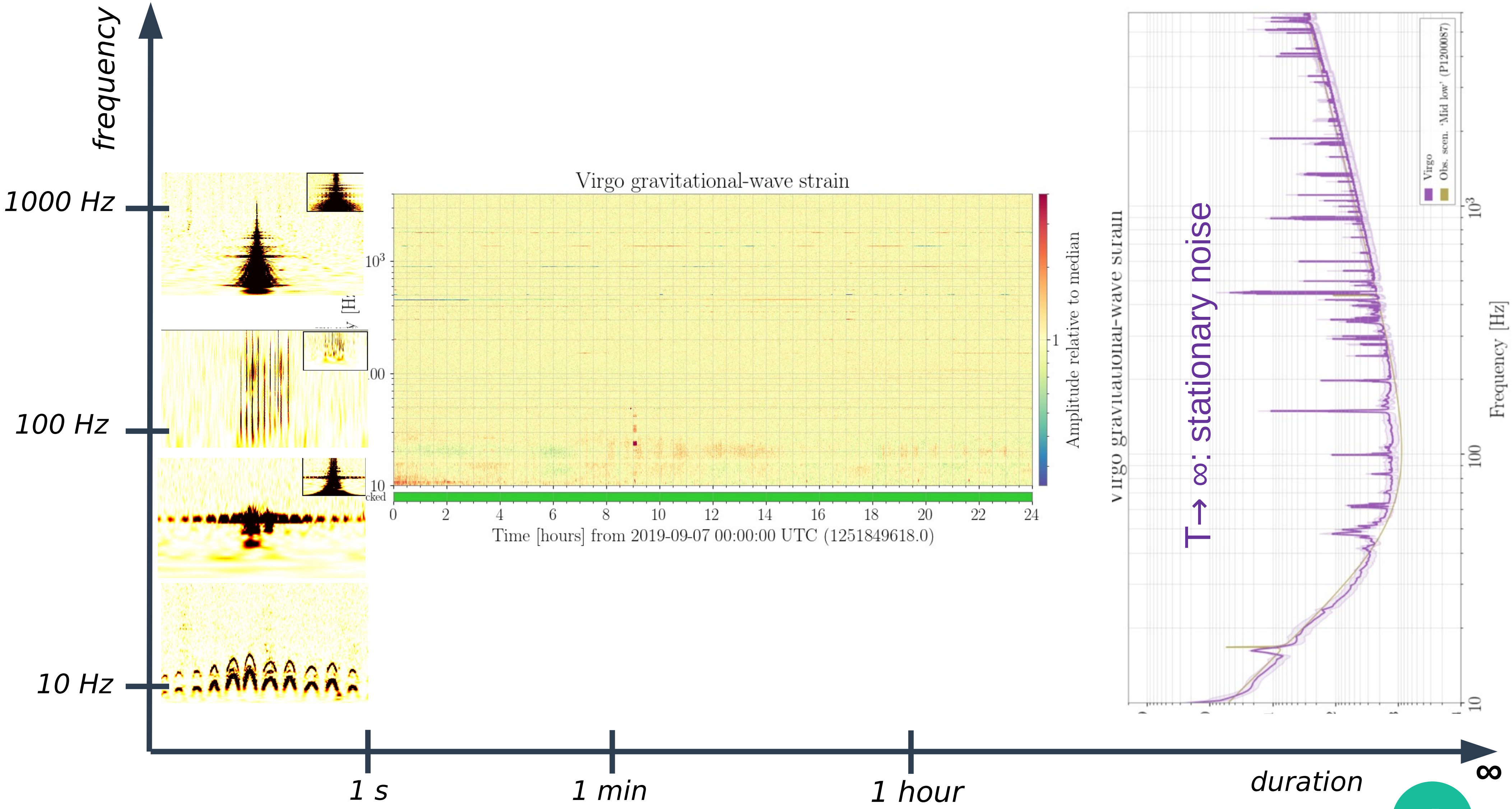
Virgo (Italy)

Sensitivity to gravitational waves

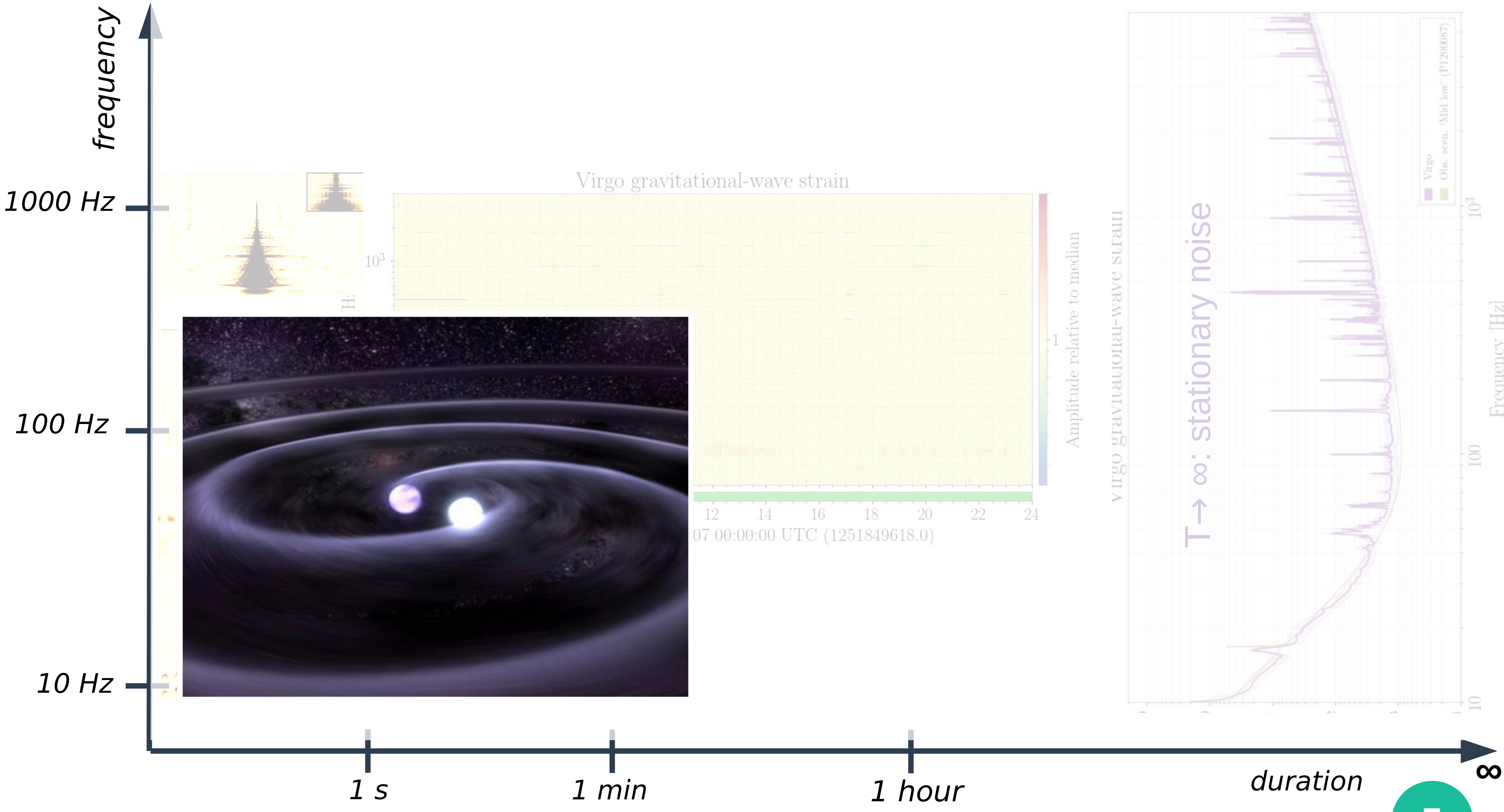


+ Technical noise:
- control and saturation
- electronic
- scattered light
- environment

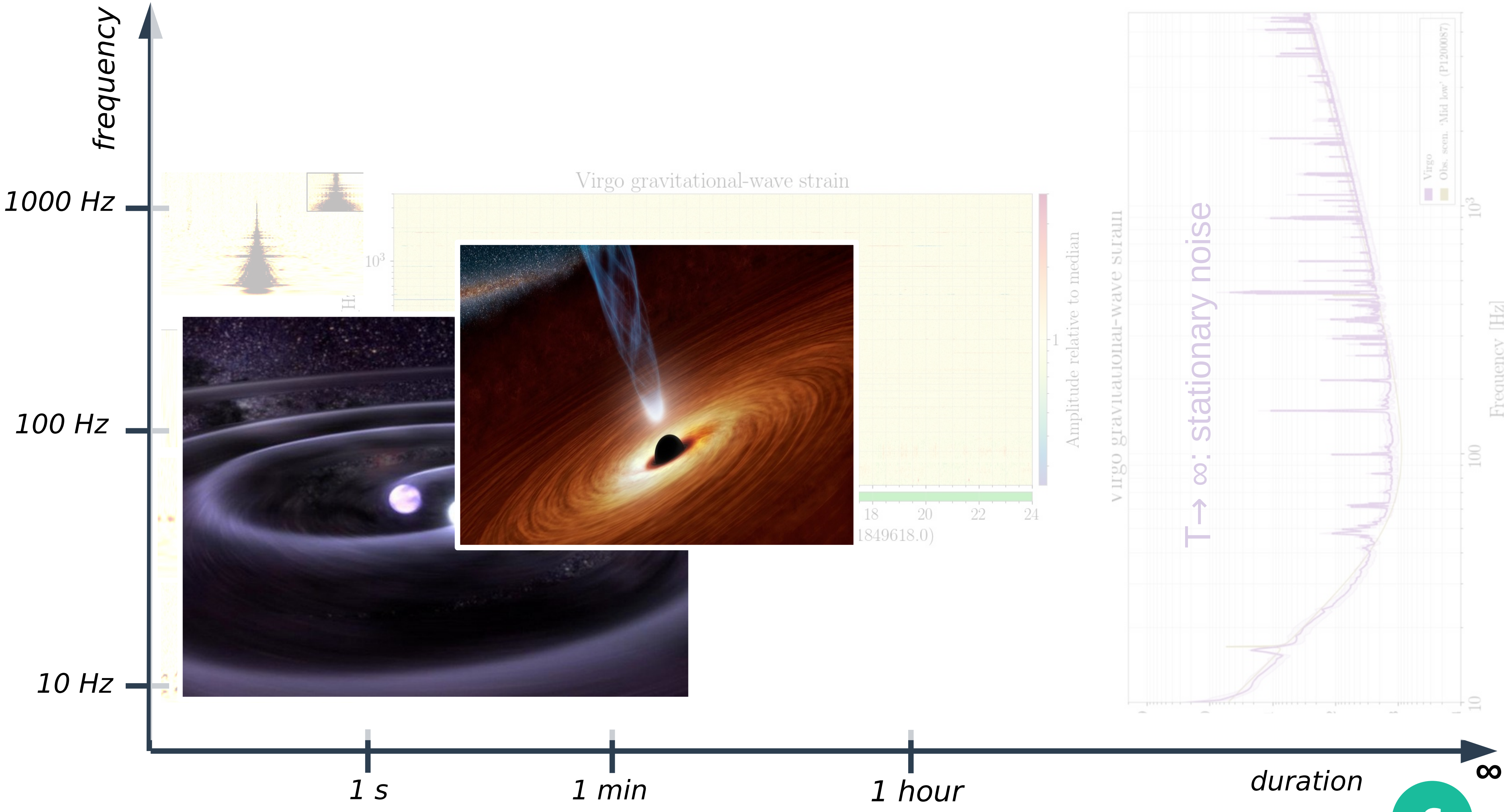
Detector noise



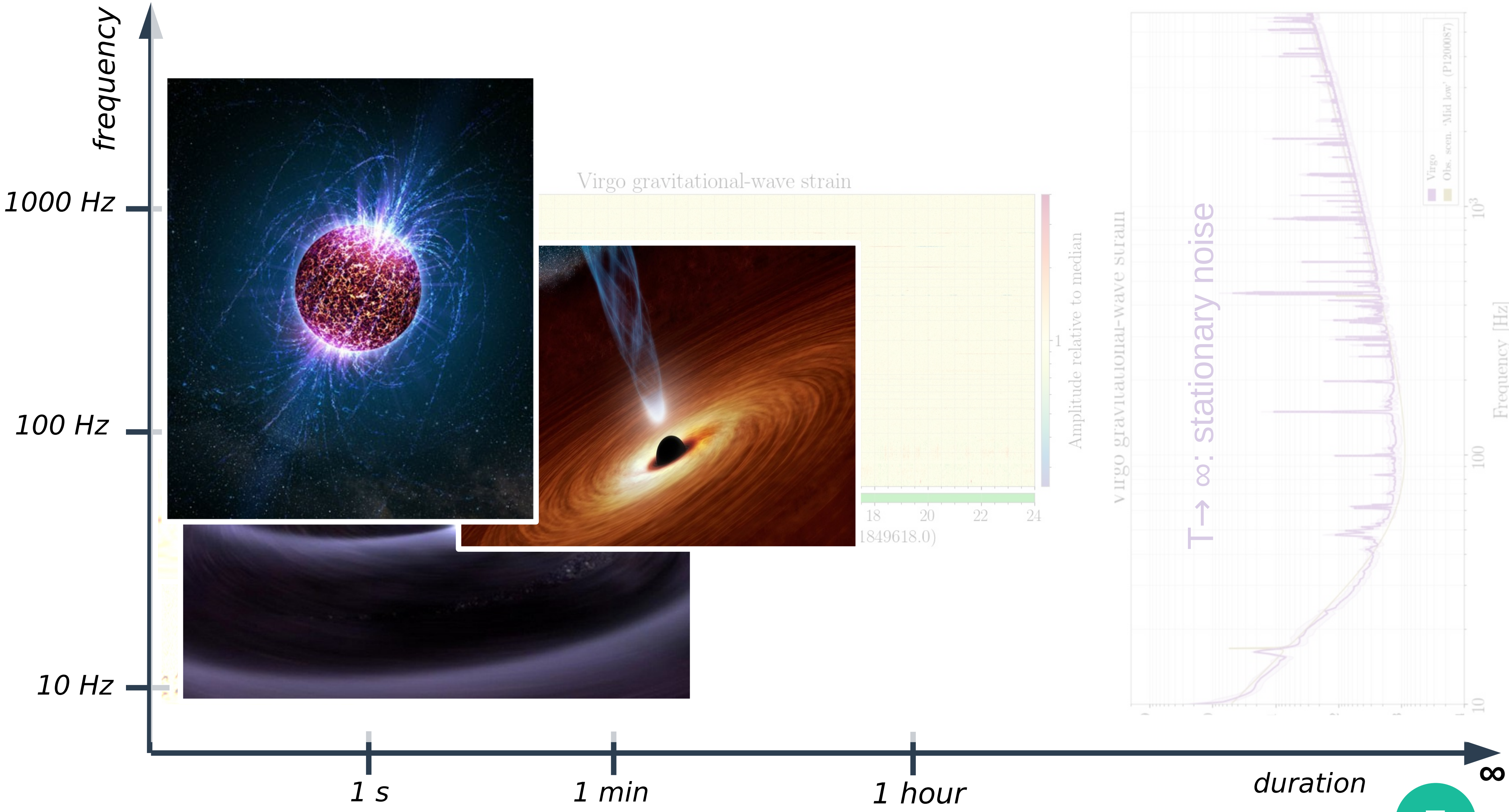
Gravitational-wave sources



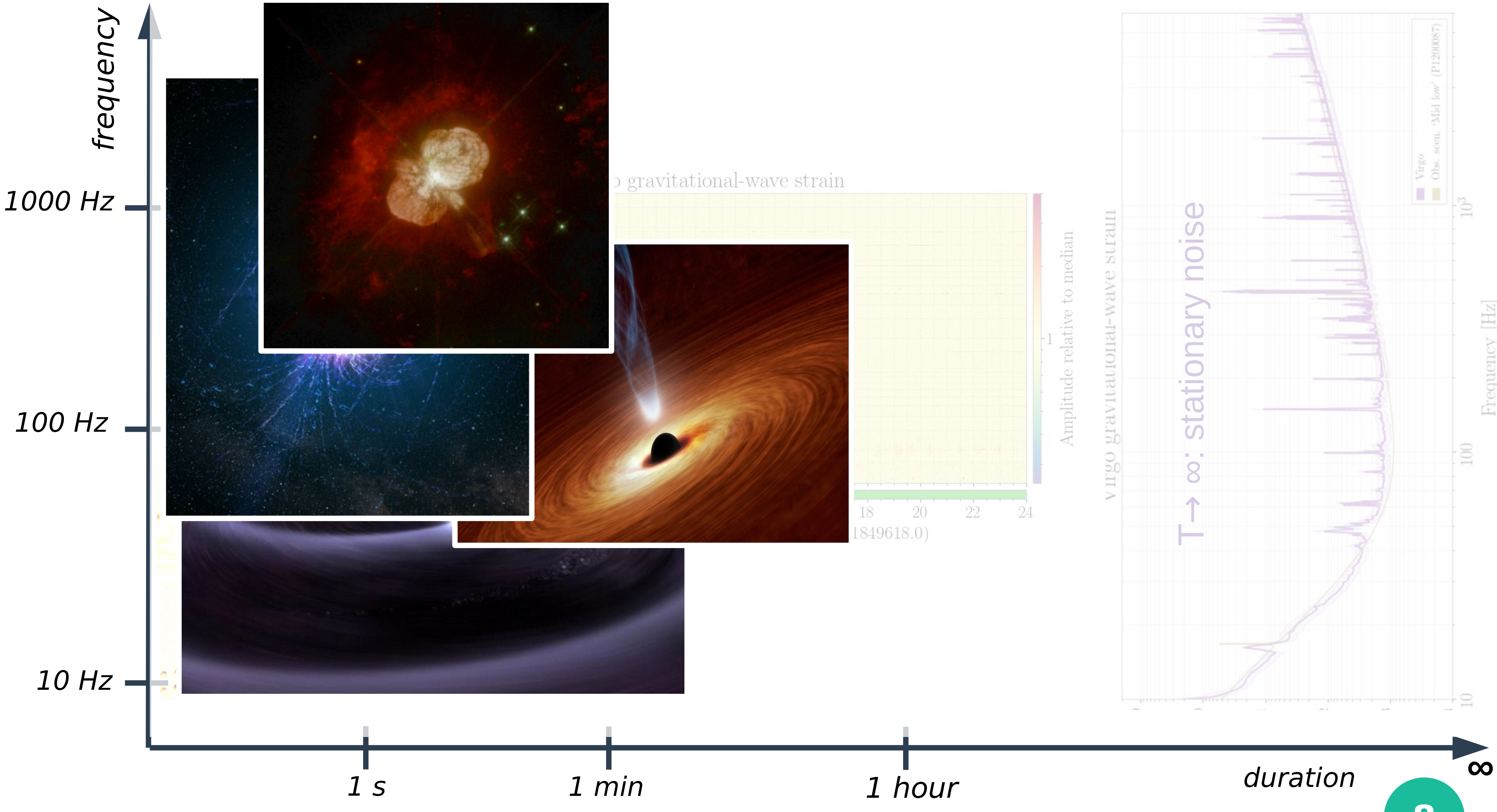
Gravitational-wave sources



Gravitational-wave sources

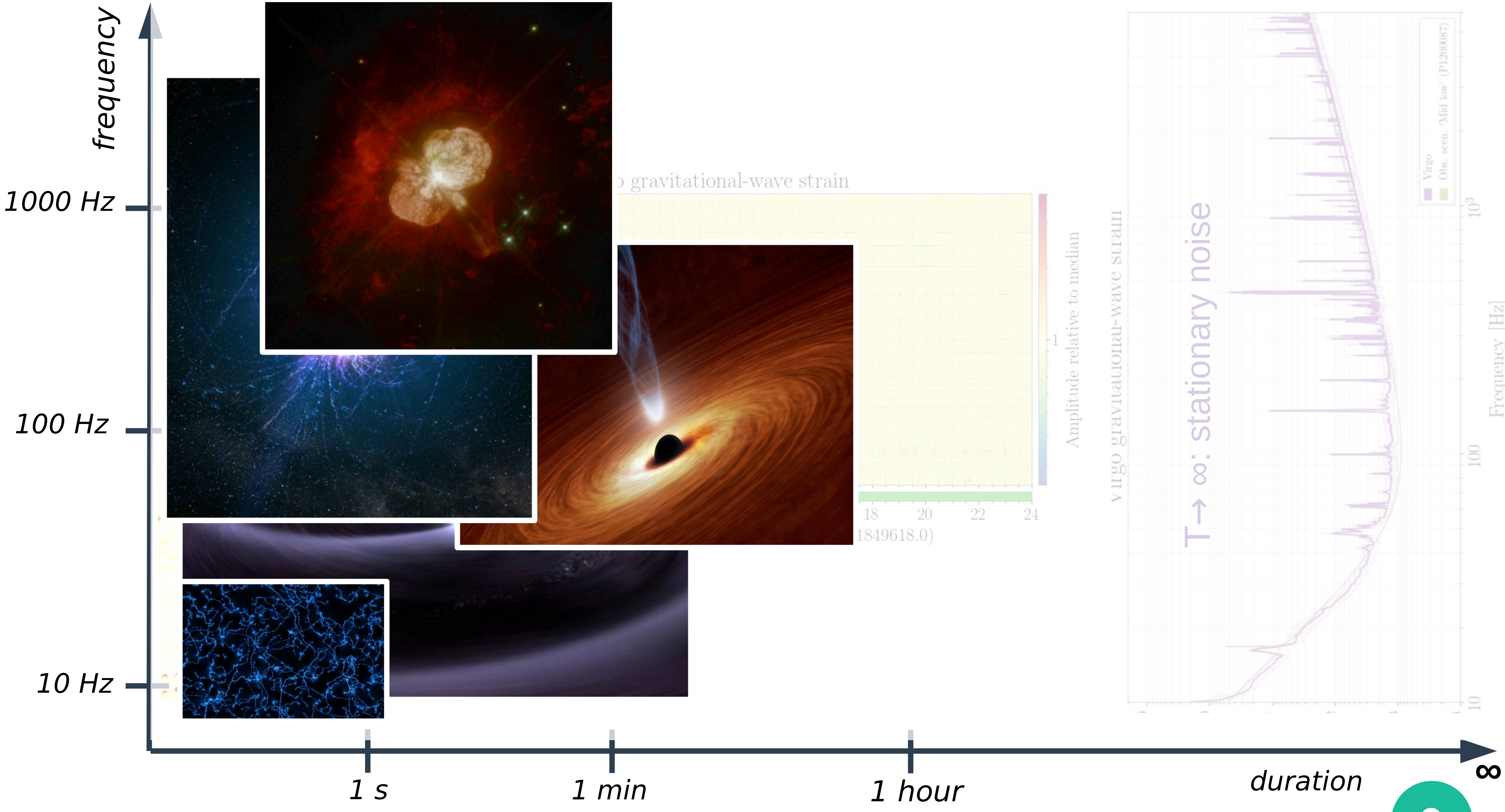


Gravitational-wave sources

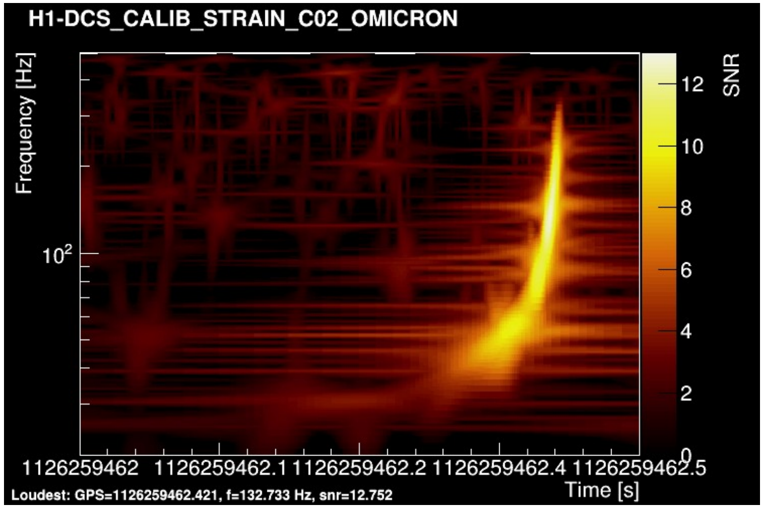


T→ ∞: stationary noise

Gravitational-wave sources



Historical events



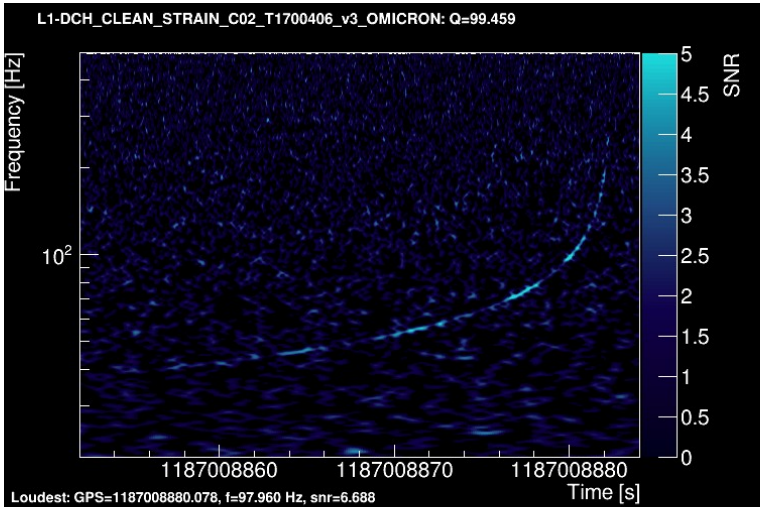
GW150914

→ Gravitational-wave discovery
  - – Direct observation
  - – Existence of a black-hole binary
  - – First evidence of high-mass stellar black holes (> 25 M_{sun})

→ Parameter estimation
  - – 36 M_{sun} + 29 M_{sun} → 63 Msun
  - – Spin not well-constrained (short signal)

→ First opportunity to test GR in a strong-field regime

→ In-depth review of instrumental and environmental noise

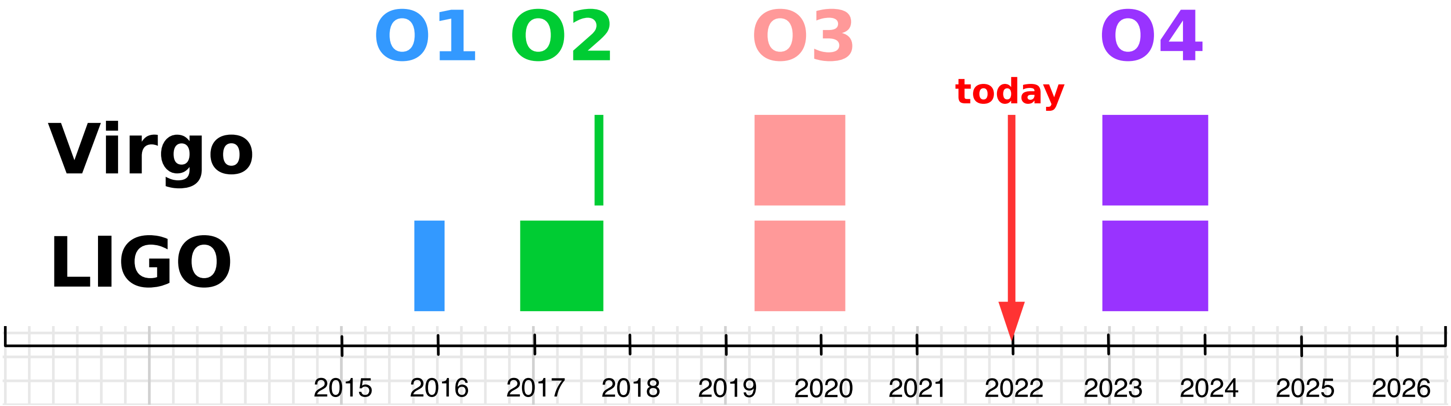


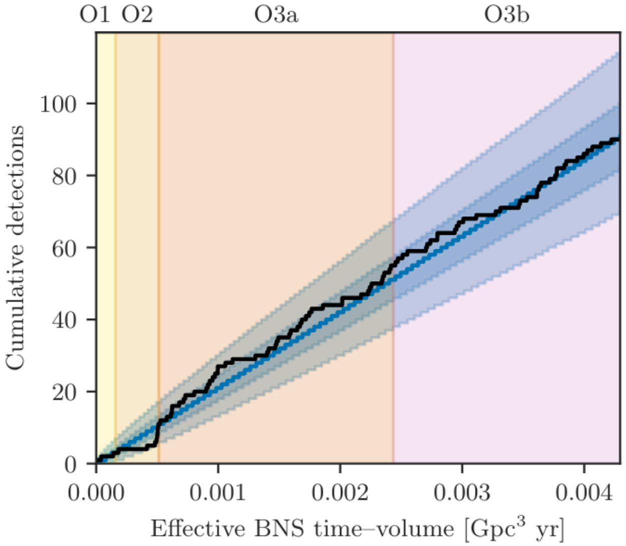
GW170817

→ First gravitational-wave signal from the merger of 2 neutron stars
→ Birth of multi-messenger astronomy with gravitational waves
→ Observed in coincidence with a short gamma-ray burst
→ Kilonova followed-up over months in all wavelengths

→ Tests of GR (PN coefficients, Lorentz invariance, massive gravitons...)
→ Standard siren to measure the Hubble constant
→ Star equation of state and tidal effects
→ Source of heavy elements (via r-process nucleosynthesis)

LIGO-Virgo data sets

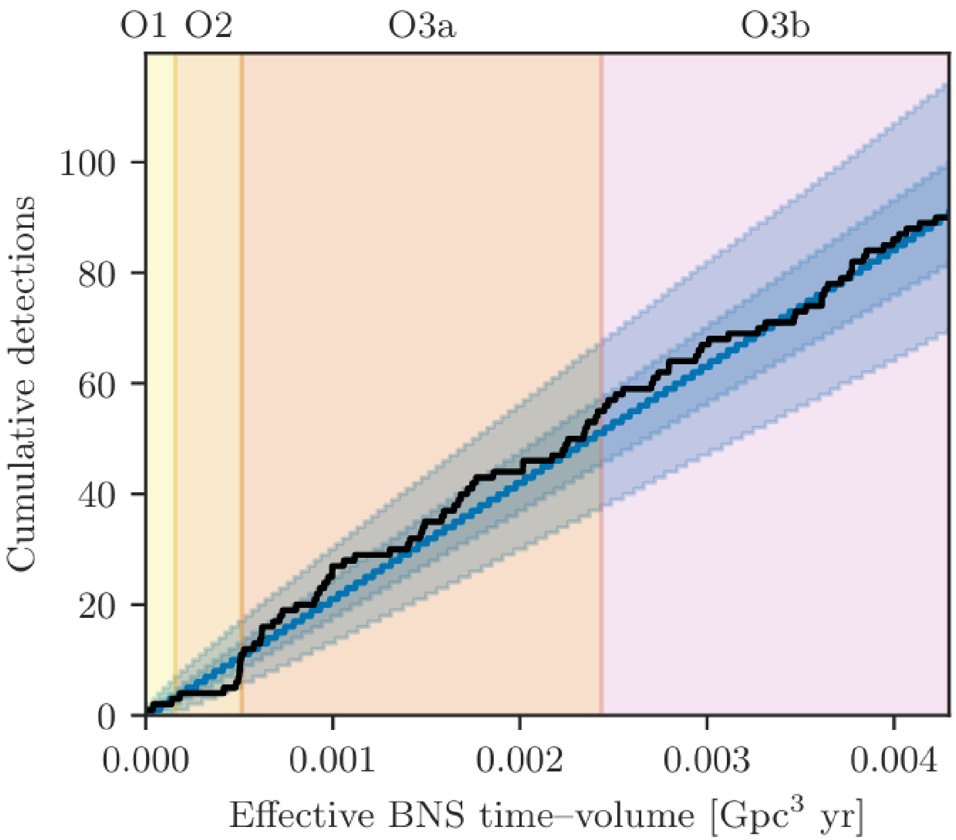




→ O3 run = O3a (Apr-Oct 2019) + O3b (Nov. 2019 – Mar. 2020)
→ Binary neutron star range improvement: x 1.5 (LIGO), x 1.75 (Virgo) / O2

→ O4 will start in Dec. 2022 with more sensitive LIGO and Virgo detectors
→ Event rate x 10 → ~1 CBC event / day
→ KAGRA (Japan) will join the network with a limited sensitivity (>1Mpc)

O3 results

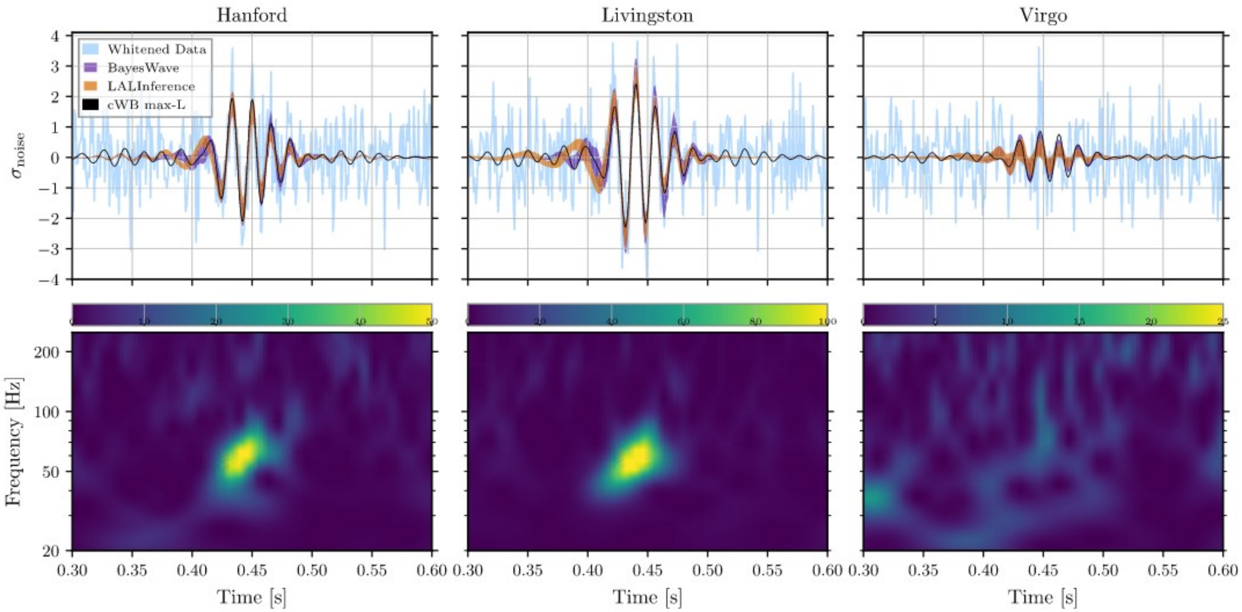


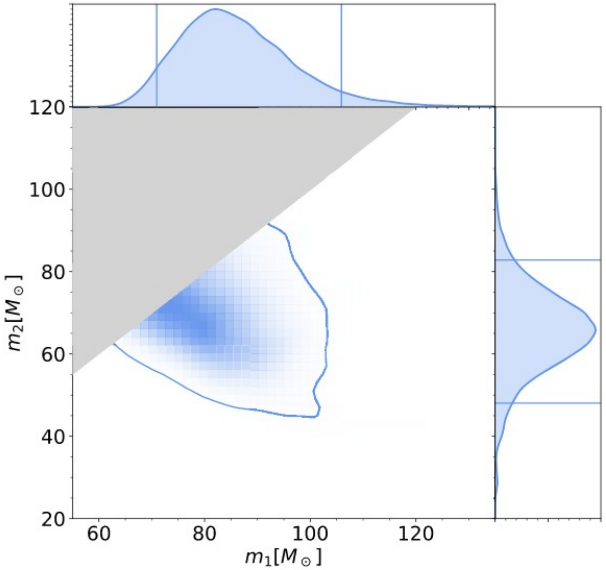
Increased statistic of you detection set → access “corners” of your parameter space:
“Exceptional” events

GW190521: High-mass black holes

Phys.Rev.Lett. 125 (2020) 10, 101102

Astrophys.J.Lett. 900 (2020) 1, L13





→ Shortest signal detected so far (~ 100 ms) → Only ~4 cycles between 30 Hz and 80 Hz

→ Heaviest progenitor: 85 M_{sun} + 66 M_{sun} → 142 M_{sun}

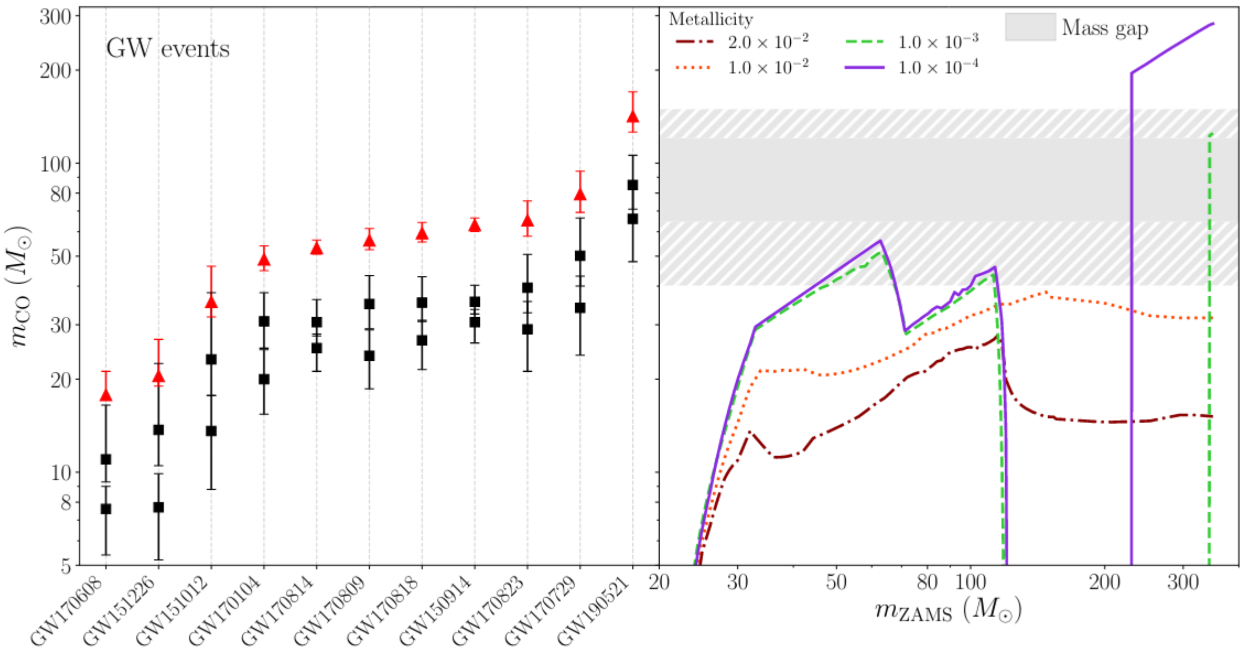
→ Cosmological distance: 5.3 Gpc

→ Could match signals from other sources?
Alternative scenarios: orbital eccentricity, gravitational lensing, primordial black holes, cosmic strings, core-collapse supernova

GW190521: High-mass black holes

Phys.Rev.Lett. 125 (2020) 10, 101102

Astrophys.J.Lett. 900 (2020) 1, L13



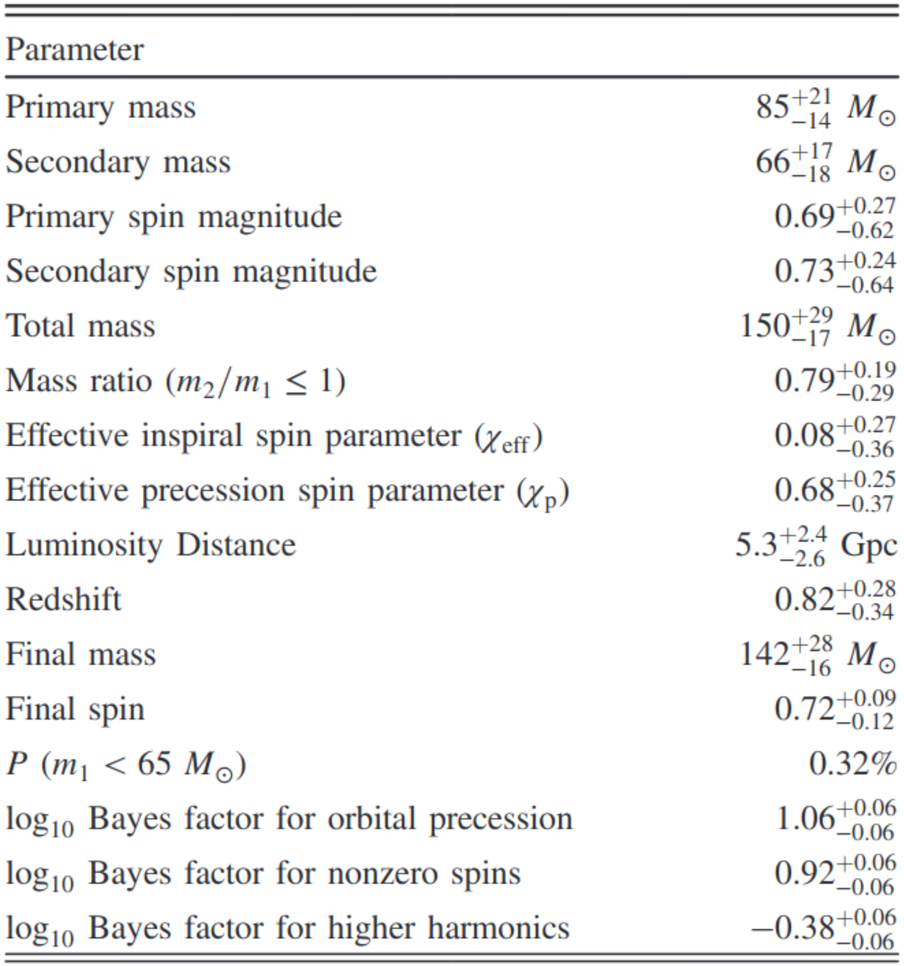
Mass gap predicted by pair-instability (PI) supernova theory : 65 – 120 M_{sun}
→ Low likelihood for the primary black holes to originate from stellar collapse

Final black hole = intermediate mass (100 – 10^5 M_{sun})
→ First detection in this mass range

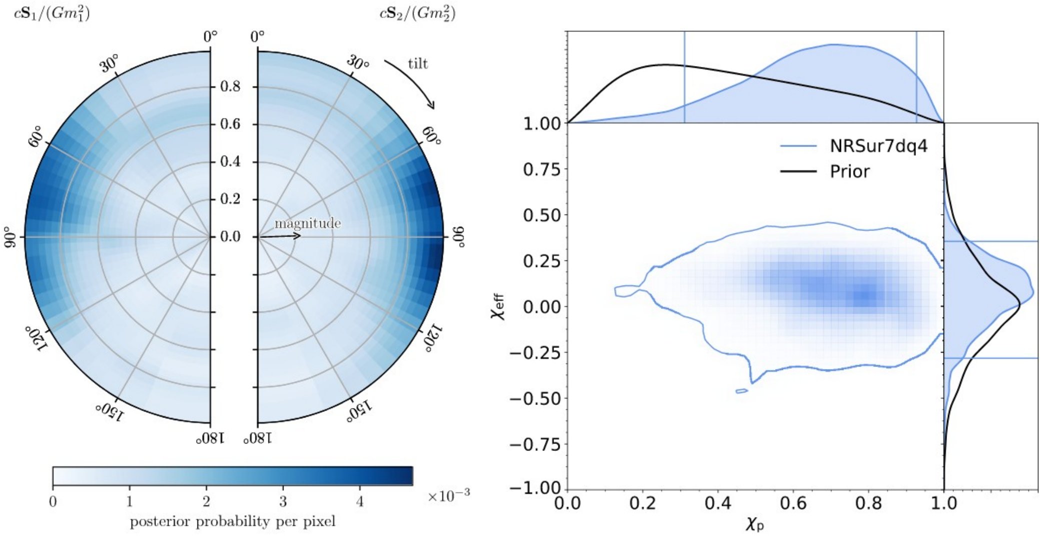
GW190521: High-mass black holes

Phys.Rev.Lett. 125 (2020) 10, 101102

Astrophys.J.Lett. 900 (2020) 1, L13



Parameter	
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Primary spin magnitude	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude	$0.73^{+0.24}_{-0.64}$
Total mass	$150^{+29}_{-17}\ M_\odot$
Mass ratio ($m_2/m_1 \leq 1$)	$0.79^{+0.19}_{-0.29}$
Effective inspiral spin parameter ($\chi_{\rm eff}$)	$0.08^{+0.27}_{-0.36}$
Effective precession spin parameter ($\chi_{\rm p}$)	$0.68^{+0.25}_{-0.37}$
Luminosity Distance	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift	$0.82^{+0.28}_{-0.34}$
Final mass	$142^{+28}_{-16}\ M_\odot$
Final spin	$0.72^{+0.09}_{-0.12}$
$P\ (m_1 < 65\ M_\odot)$	0.32%
$\log_{10}$ Bayes factor for orbital precession	$1.06^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for nonzero spins	$0.92^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for higher harmonics	$-0.38^{+0.06}_{-0.06}$



Evidence for large initial spins + large misalignment with the orbital angular momentum

→ orbital precession
→ indication of a capture formation mechanism

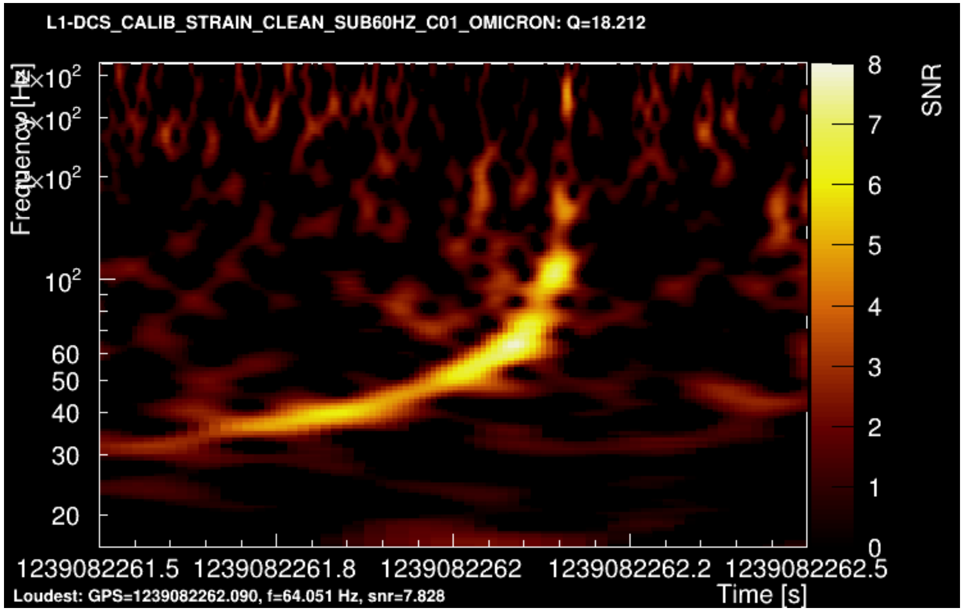
GW190412: asymmetric masses

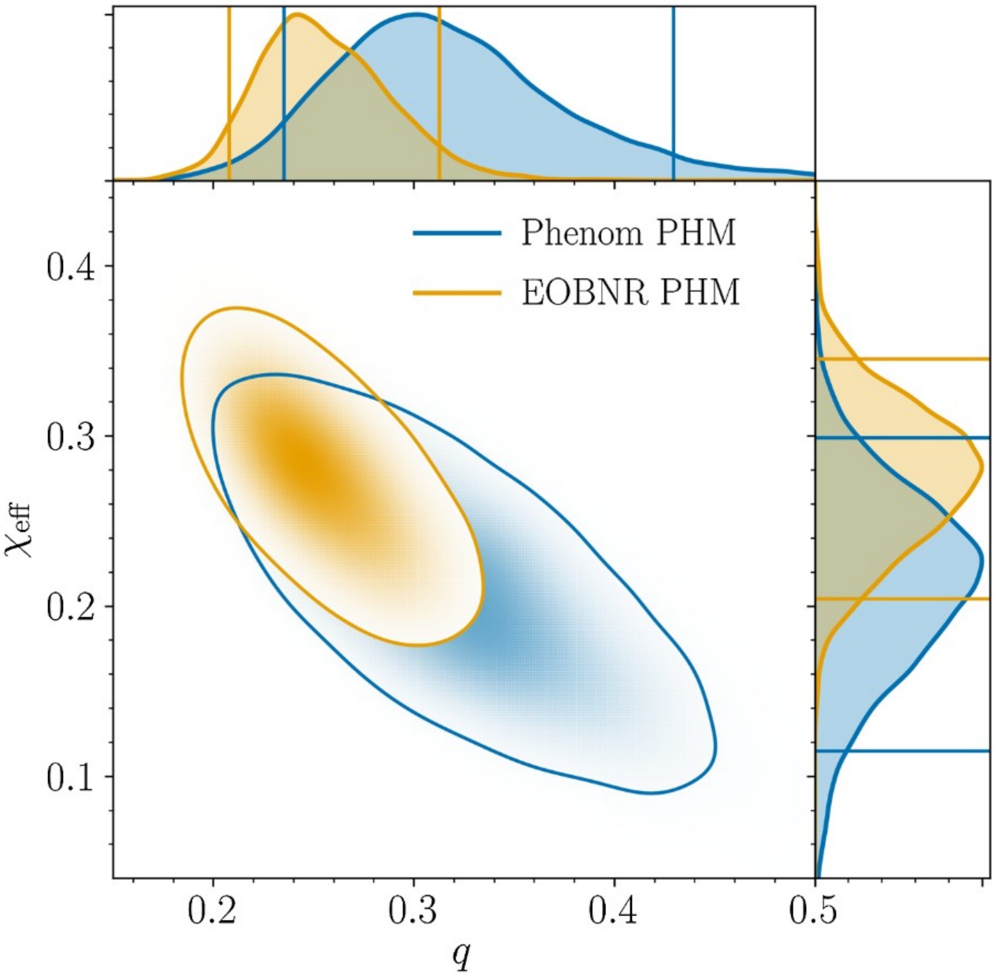
Phys.Rev.D 102 (2020) 4, 043015

For the first time: $q = m_2/m_1 = 8.0/31.7 < 1$

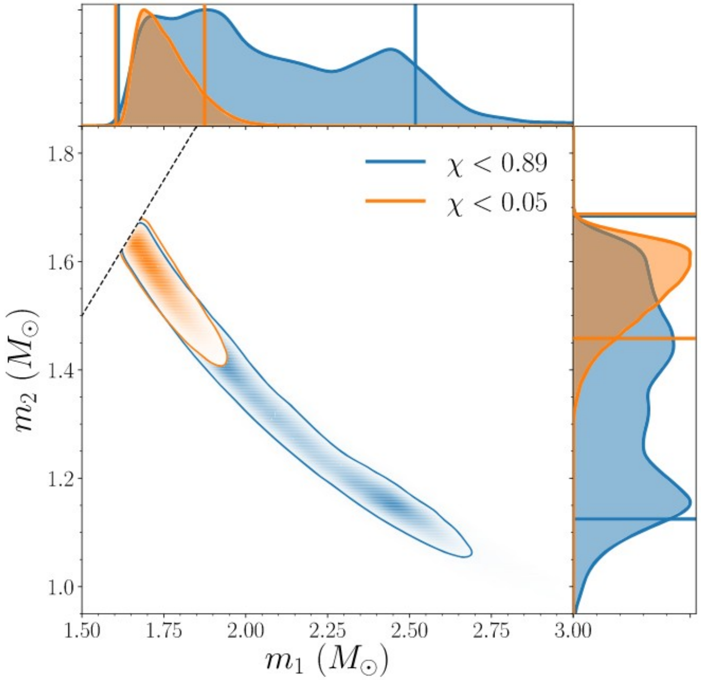
Detectable signal from higher-multipole (above the quadrupole)

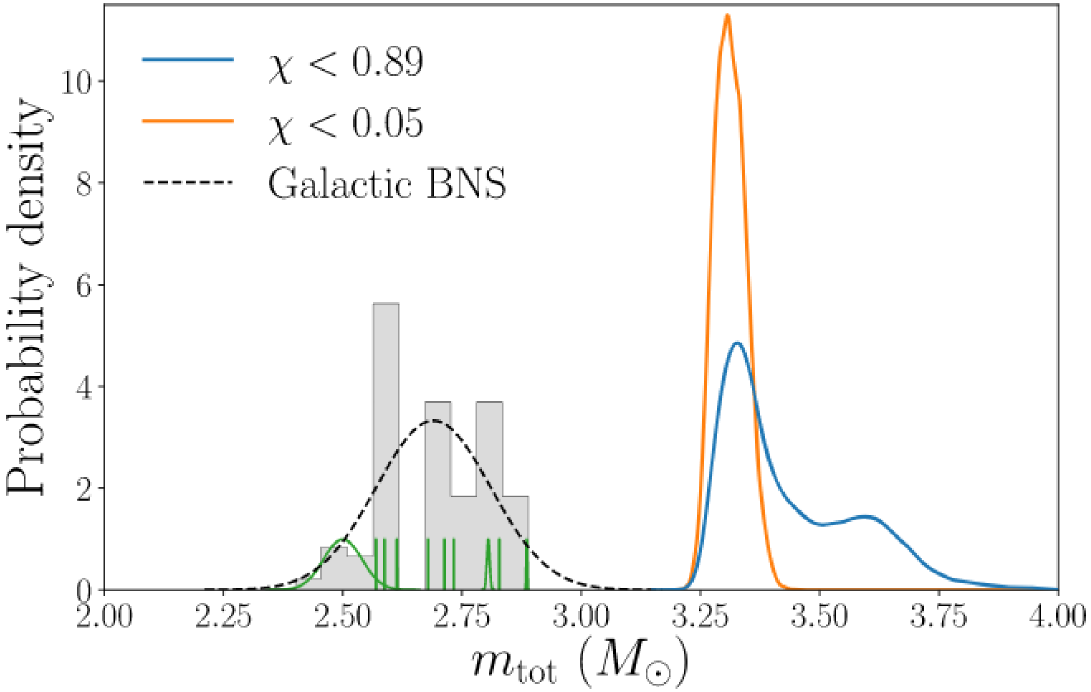
GR tests in a new regime





GW190425: massive neutron stars (?)



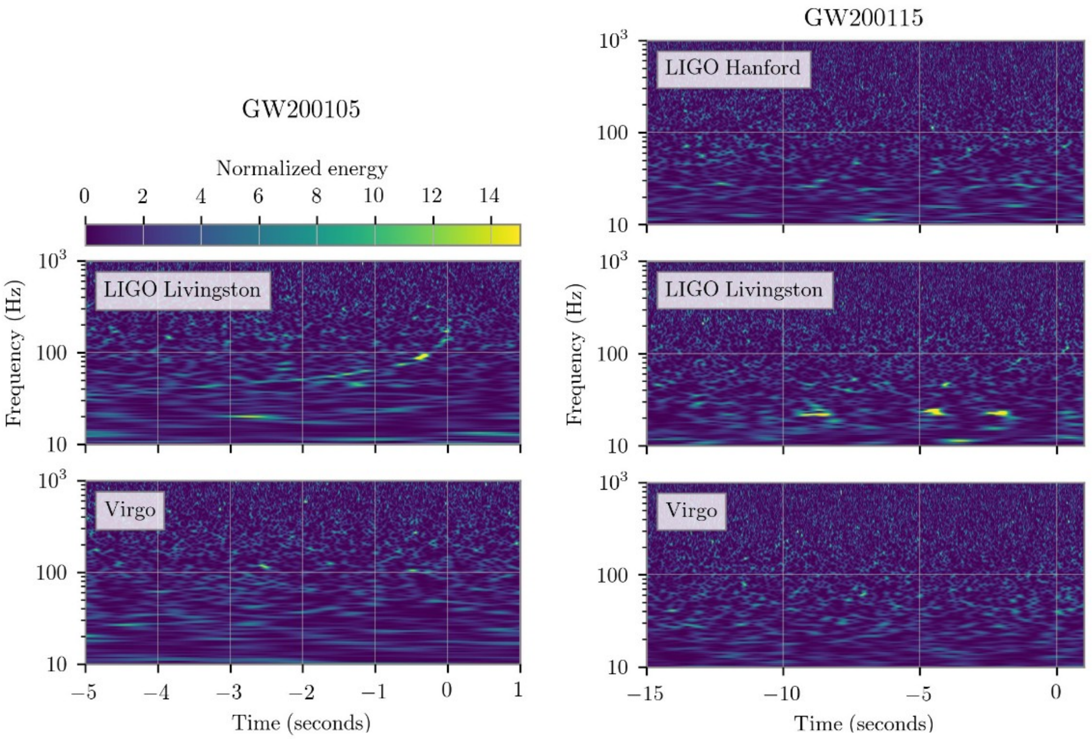


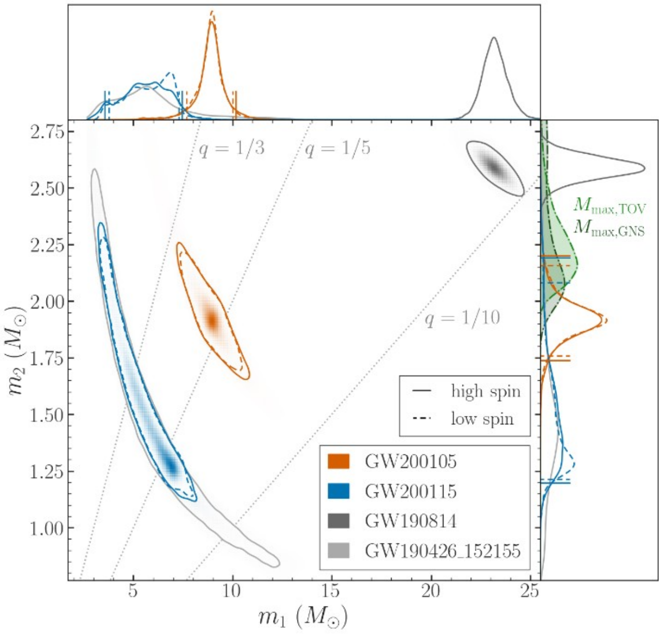
→ Probably the second merger of 2 neutron stars (?)
→ Single-detector event
→ Detected with low-latency but no EM counterpart was found (GRB signal in INTEGRAL data?)
→ Total mass is higher than what is known from galactic binaries
→ No evidence of tidal effects
→ Light black holes ?

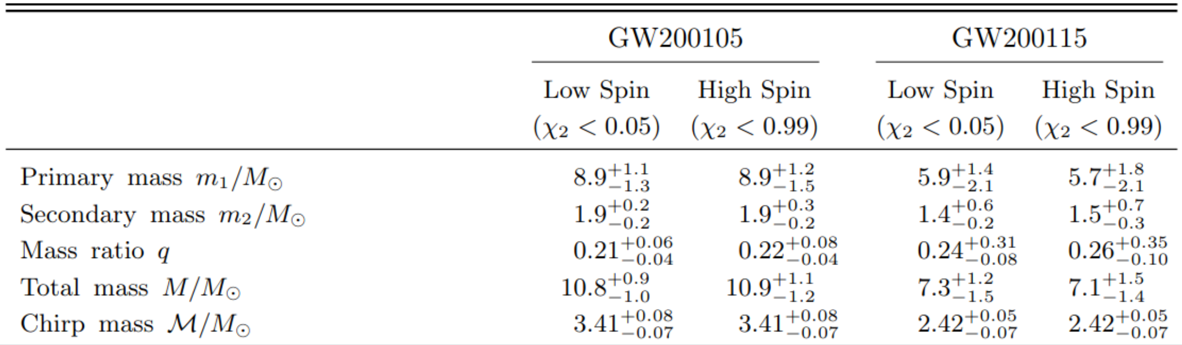
GW200115 & GW200105

Astrophys.J.Lett. 915 (2021) 1, L5

The “missing” gravitational-wave source: BBH (2015) → BNS (2017) → NSBH (2020)

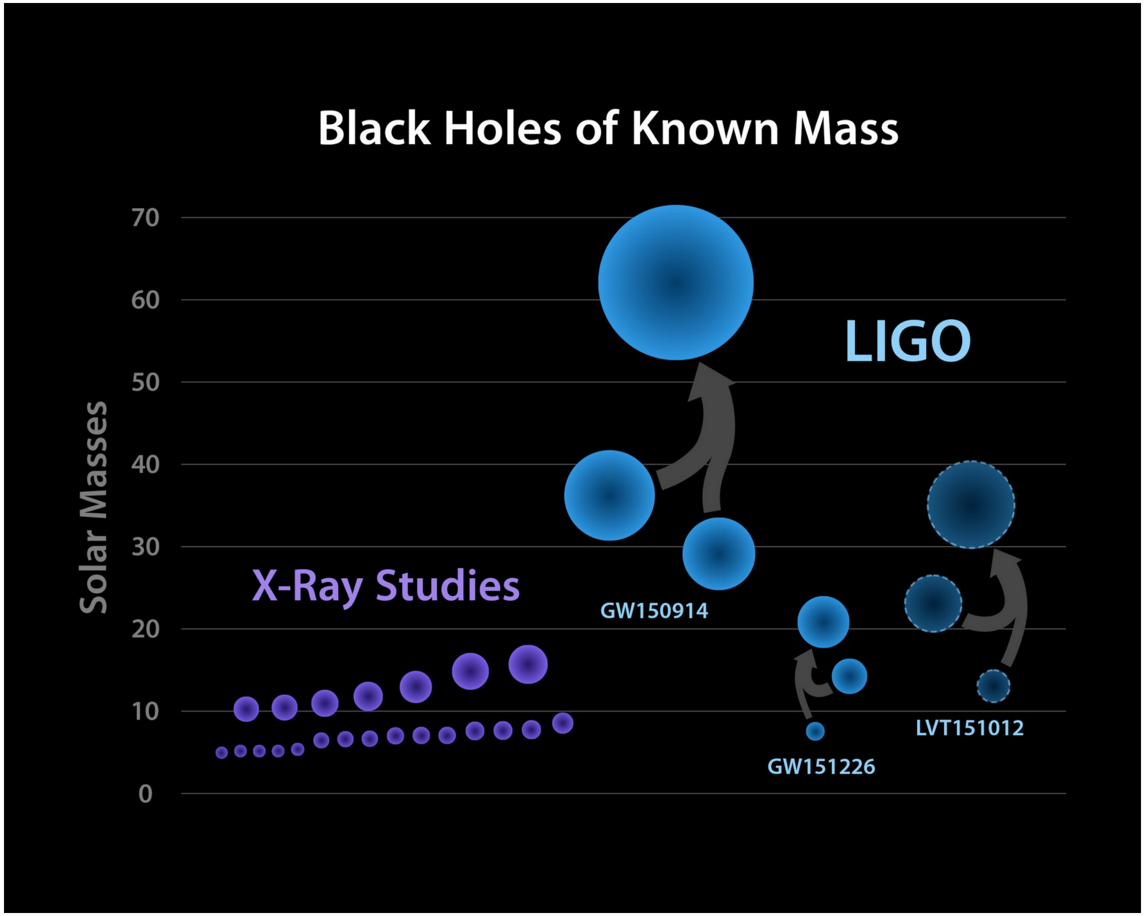






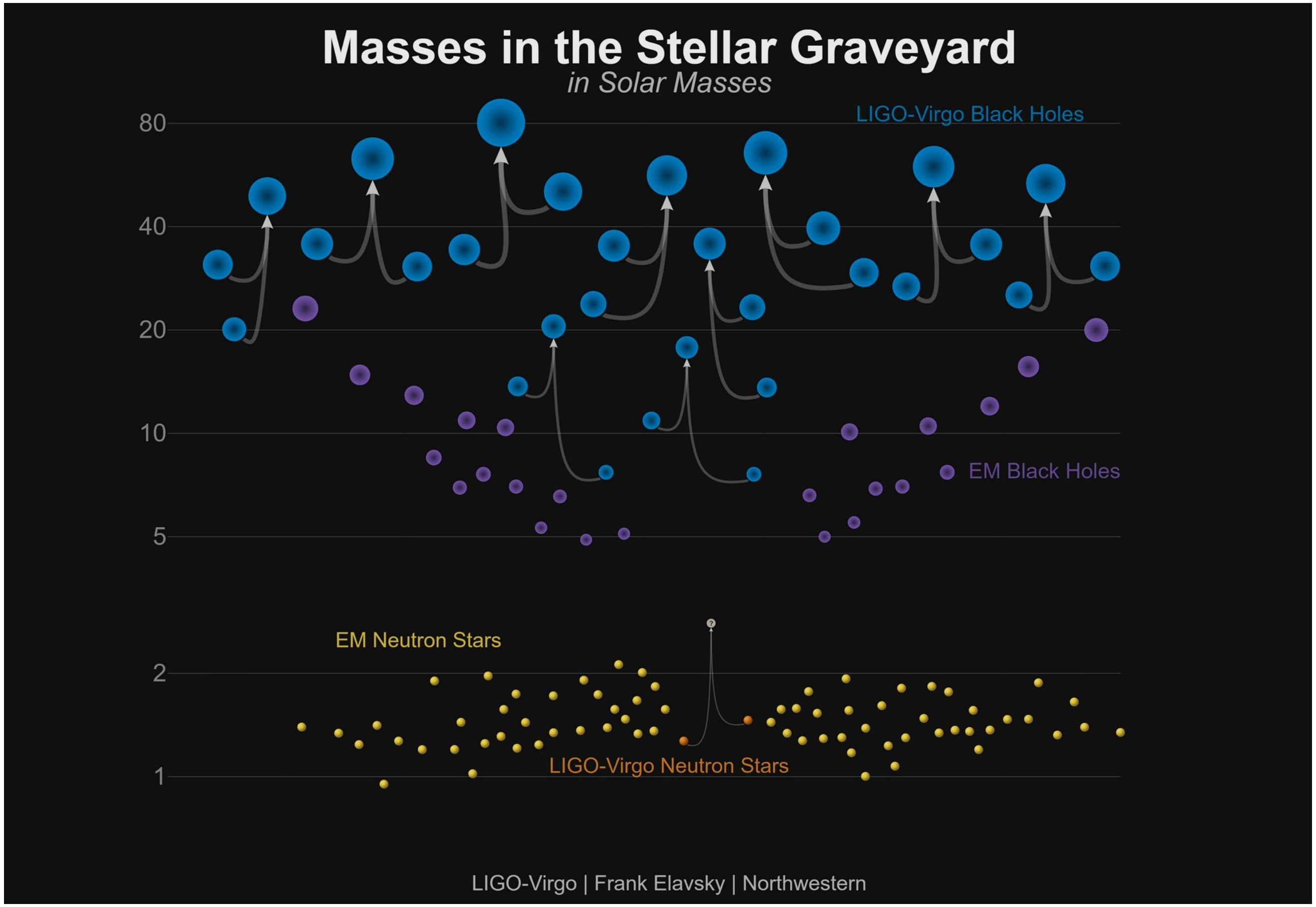
	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
Mass ratio q	$0.21^{+0.06}_{-0.04}$	$0.22^{+0.08}_{-0.04}$	$0.24^{+0.31}_{-0.08}$	$0.26^{+0.35}_{-0.10}$
Total mass $M/M_\odot$	$10.8^{+0.9}_{-1.0}$	$10.9^{+1.1}_{-1.2}$	$7.3^{+1.2}_{-1.5}$	$7.1^{+1.5}_{-1.4}$
Chirp mass $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$

O1: first discoveries



2015 (O1)

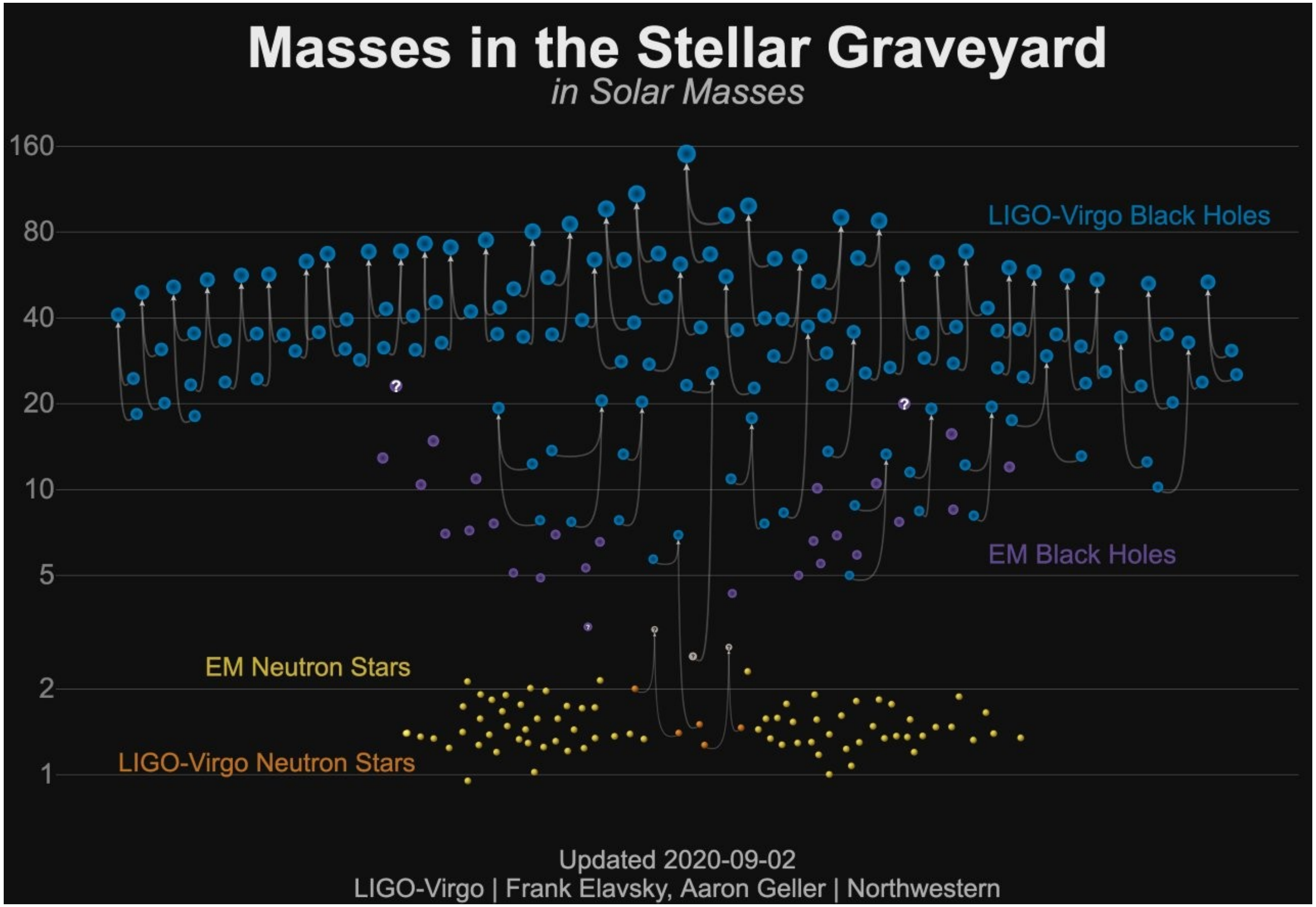
O2: first catalog GWTC1



LIGO-Virgo | Frank Elavsky | Northwestern

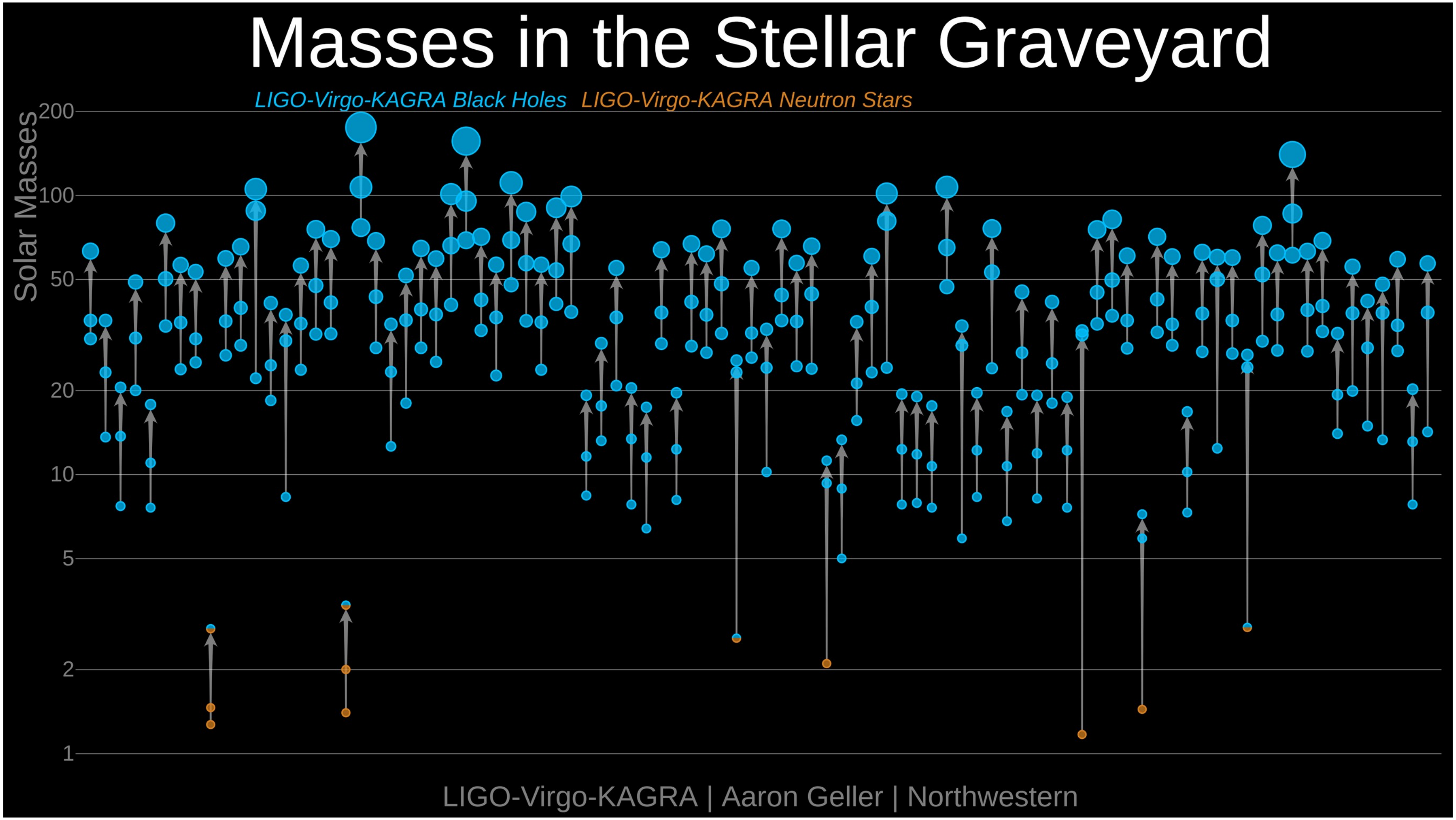
2018 (O1+O2)

O3a: second catalog GWTC2



2020 (O1 – O3a)

O3b: third catalog GWTC3



2021 (O1 – O3)

O3b: third catalog GWTC3

e-Print: 2111.03606 [gr-qc]

→ Events are listed in the catalog if $p_{astro} > 0.5$ (~10-15 % false alarm)

→ 90 events (35 in O3b)

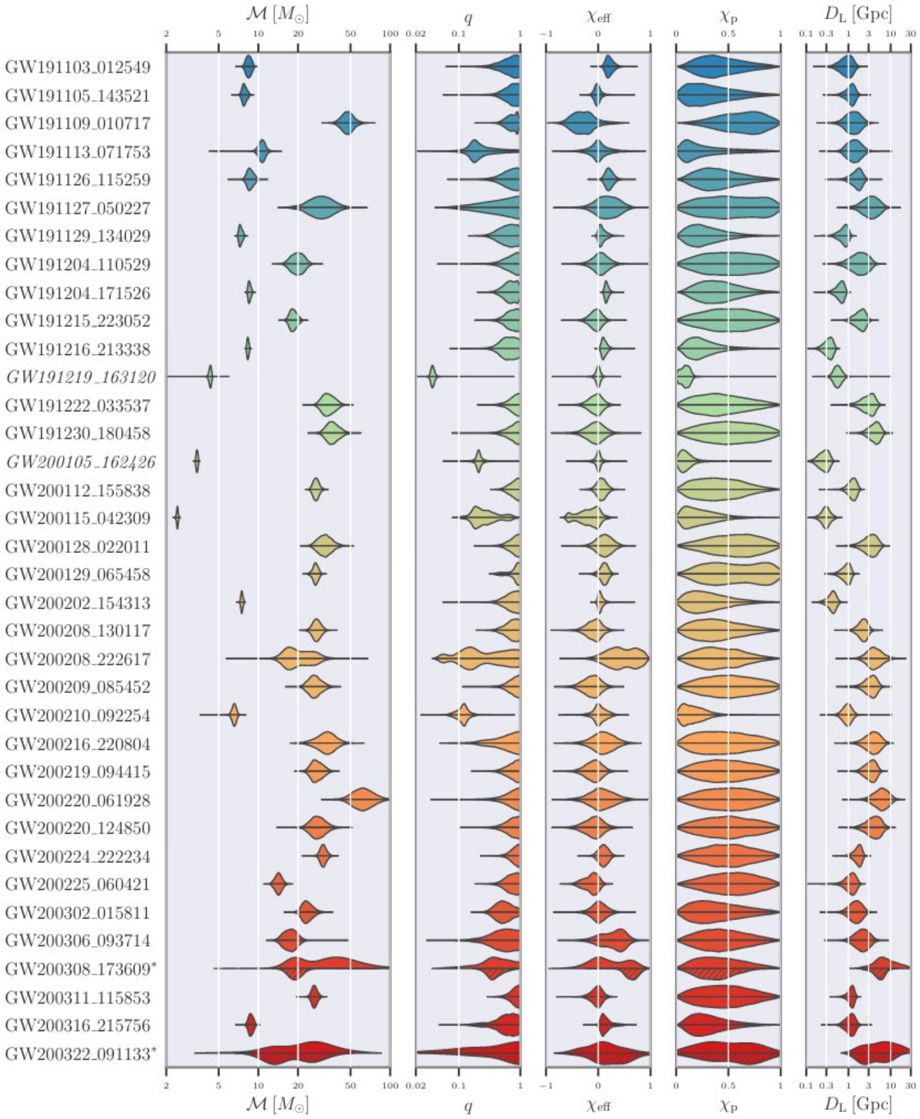
→ + ~1000 sub-threshold events

→ Final calibration + in-depth data quality studies and noise subtraction

→ 3 CBC- template searches + 1 unmodeled search

→ Parameter estimation studies
  – high spins ($\chi > 0.8$)
  – extreme mass ratio ($q < 0.1$)

→ Waveform models start to be limited



Population studies

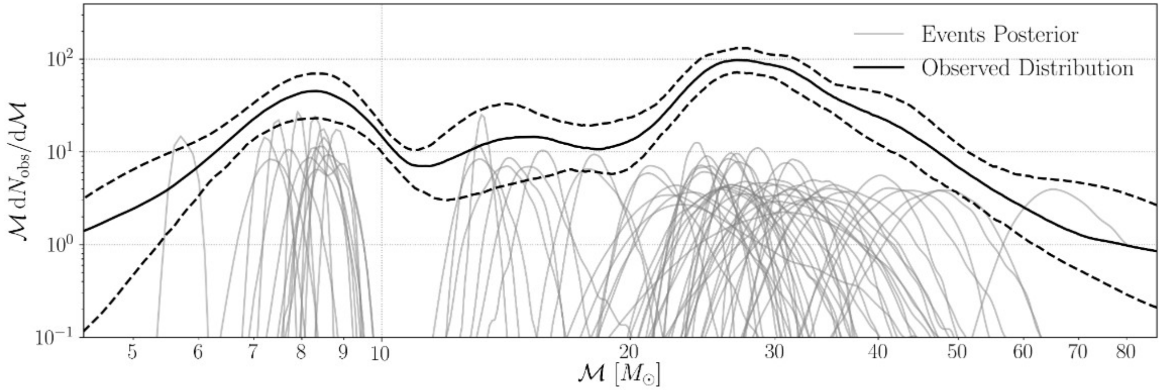
E-Print: 2111.03634 [astro-ph.HE]

→ Gravitational-wave events from the catalog are used to infer merger rates

– BNS: 13 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ – 1900 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (95%)

– NSBH: 7.4 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ – 320 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (95%)

– BBH: 16 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ – 130 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (95%)



→ Entering the high-statistical regime

→ Parameters can be binned!

→ Merger rates as a function of mass

→ Merger rates as a function of redshift: ~$(1+z)^{2.7}$ for $z < 1$

→ Correlation studies (spin magnitude vs. mass ratio)

→ Formation scenarios

Unmodeled searches

Phys.Rev.D 104 (2021) 10, 102001

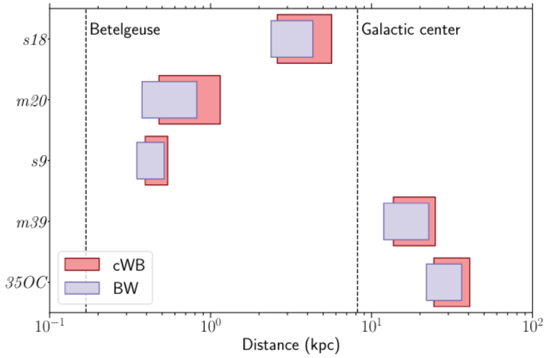
E-Print: 2107.03701 [gr-qc]

→ Various sources of gravitational waves with poorly-modeled waveforms
Core-collapse supernovae, isolated deformed neutron stars, BH accretion disk instabilities, eccentric binaries…

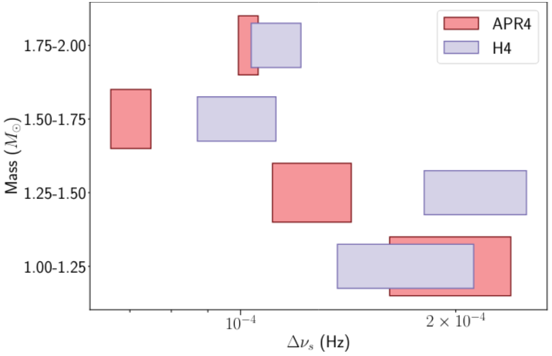
→ Wide parameter space

→ All-sky and all-time searches based on excess-power methods

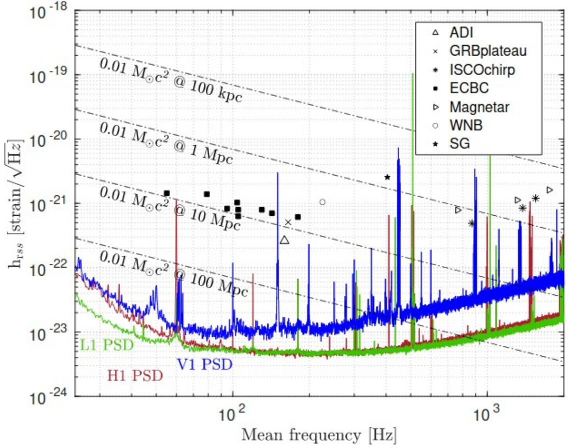
CCSN waveform models



NS glitch waveform models



long-duration waveform models

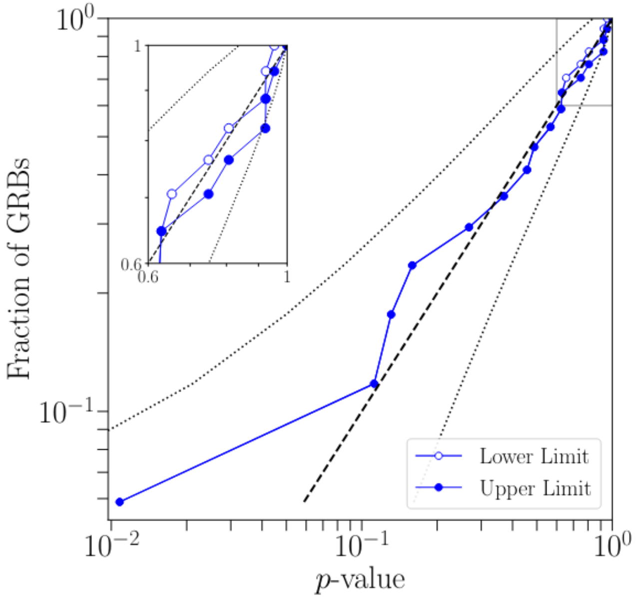


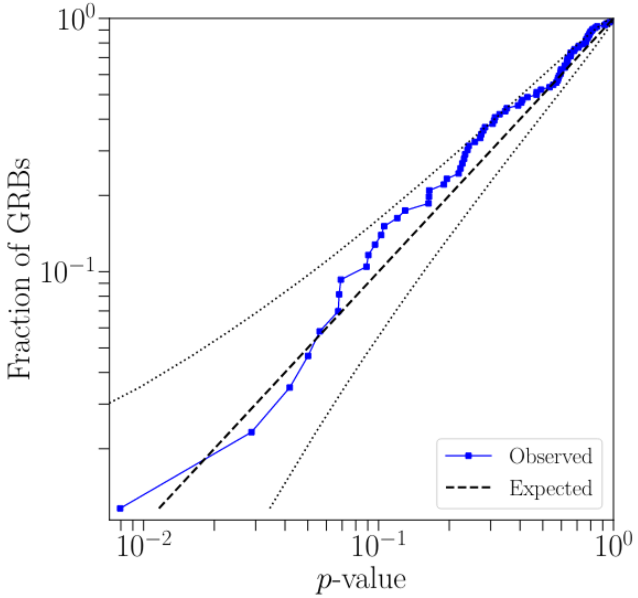
Targeted searches

E-Print: 2111.03608 [astro-ph.HE]

→ Use triggers from other channels to target gravitational-wave searches
Gamma-ray bursts, neutrinos, Magnetar flares, fast-radio bursts

→ GRB triggers: Use both CBC-modeled and unmodeled searches





→ No detections: exclusion distance, population studies

Conclusion

→ Many O3 results have been released:
  - New discoveries (NSBH, intermediate-mass BH...)
  - "Exceptional" events used to derive important science
  - Major step in terms of number of detections → population studies
  - Cosmology implications: H_0 estimate

→ Disappointment: no new multi-messenger event :-(

→ Upcoming science with O3 data
  - Testing GR with CBC events
  - Searches targeting FRB, Magnetar flares, high-energy neutrino...

→ O3 dataset is publicly available

→ O4 (2023), O5 (2025)

→ Post-O5 Virgo detector

→ LISA and Einstein telescope (2035)