

## 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

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

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 ihm früher gegeben hatte<sup>1</sup>. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

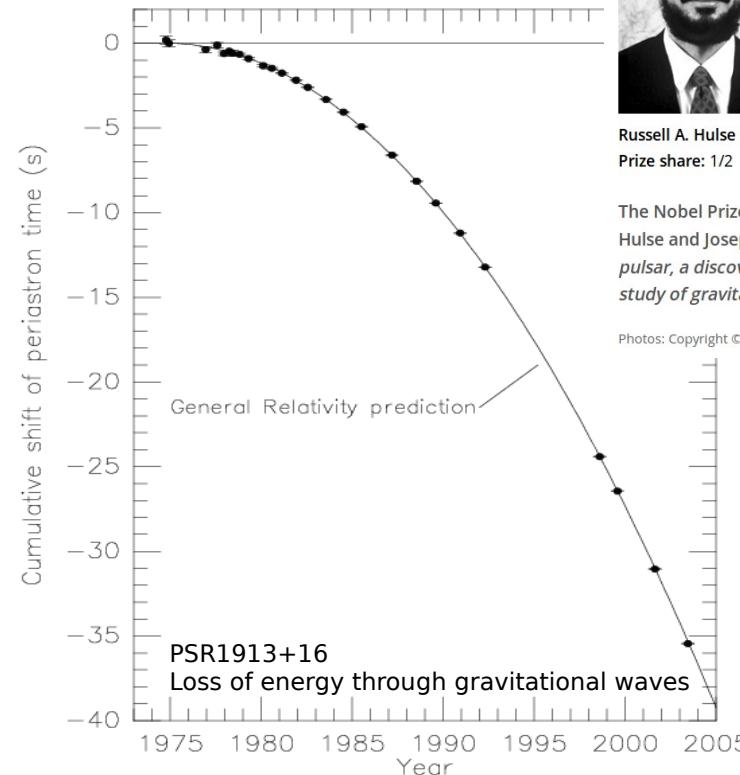
<sup>1</sup> Sitzungsber. XLVII, 1915, S. 833.

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

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



## The Nobel Prize in Physics 1993



Russell A. Hulse  
Prize share: 1/2



Joseph H. Taylor Jr.  
Prize share: 1/2

The Nobel Prize in Physics 1993 was awarded jointly to Russell A. Hulse and Joseph H. Taylor Jr. "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

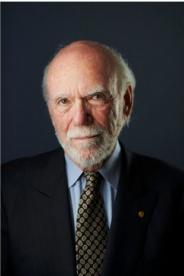
Photos: Copyright © The Nobel Foundation

# Gravitational-wave detectors

## The Nobel Prize in Physics 2017



© Nobel Media AB. Photo: A. Mahmoud  
Rainer Weiss  
Prize share: 1/2



© Nobel Media AB. Photo:  
A. Mahmoud  
Barry C. Barish  
Prize share: 1/4



© Nobel Media AB. Photo:  
A. Mahmoud  
Kip S. Thorne  
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves."

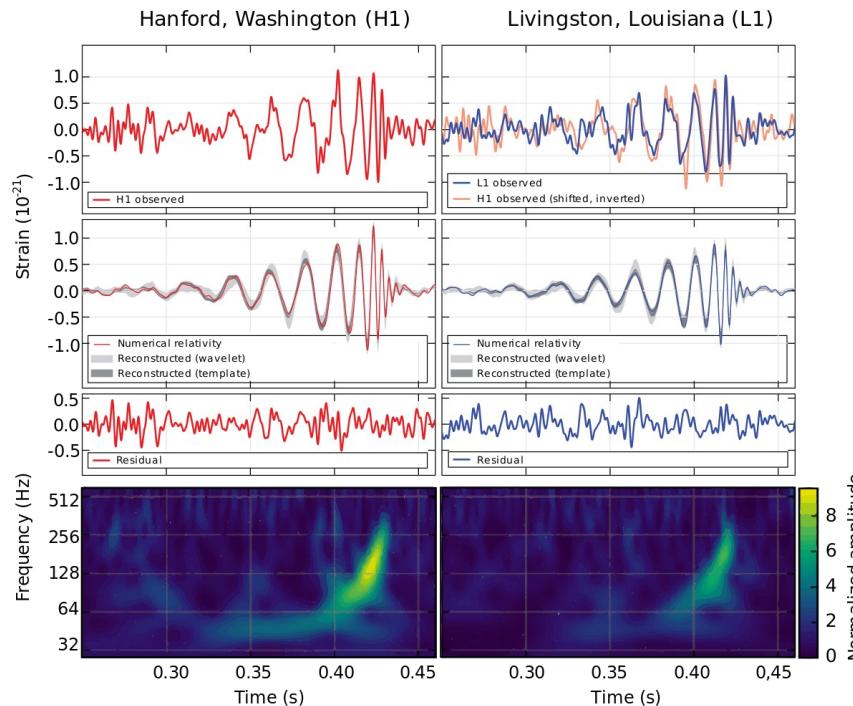


Kilometer-scale Michelson interferometric detectors

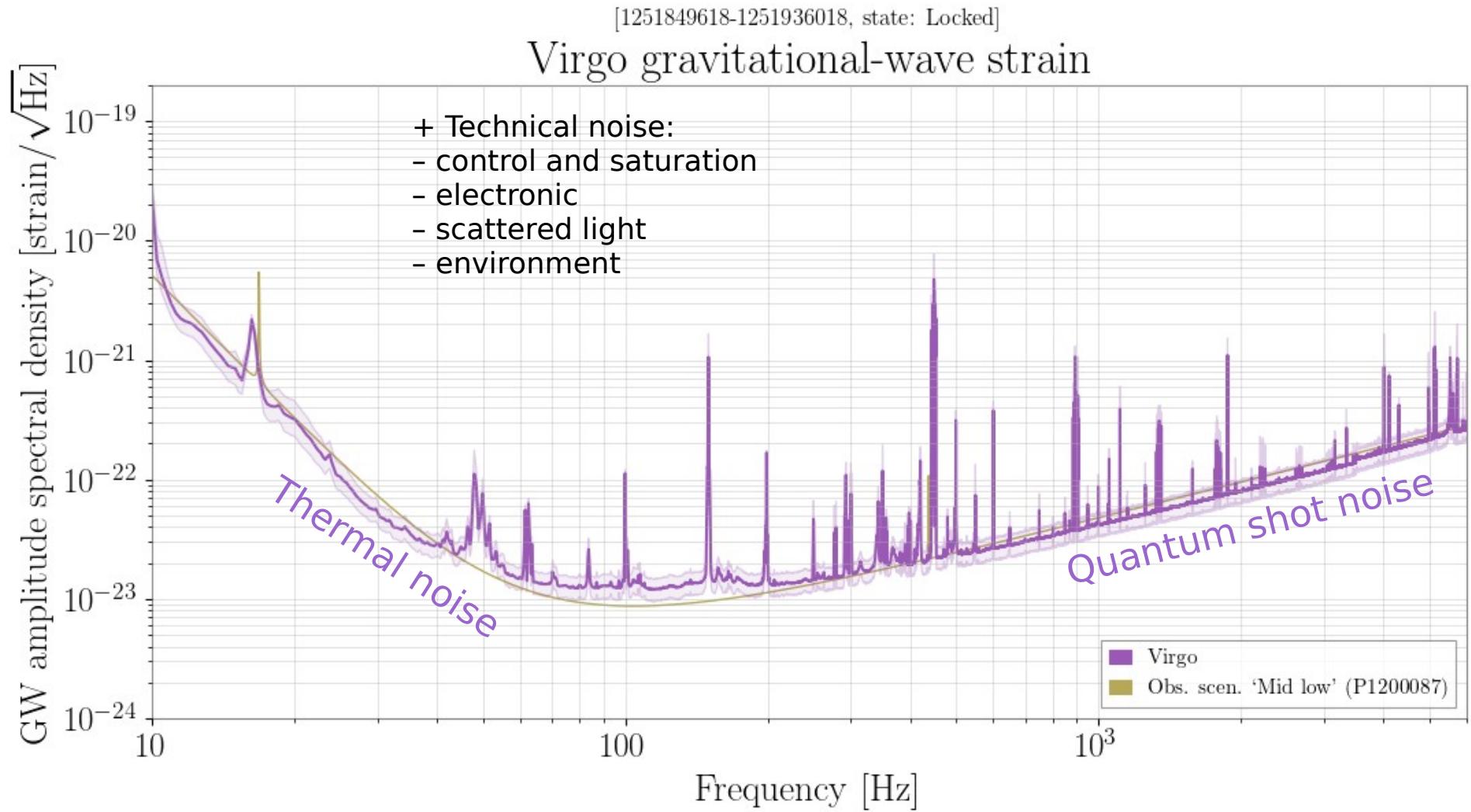
The detectors are designed to sense gravitational waves from astrophysical sources

GW150914: First gravitational-wave event detected by LIGO

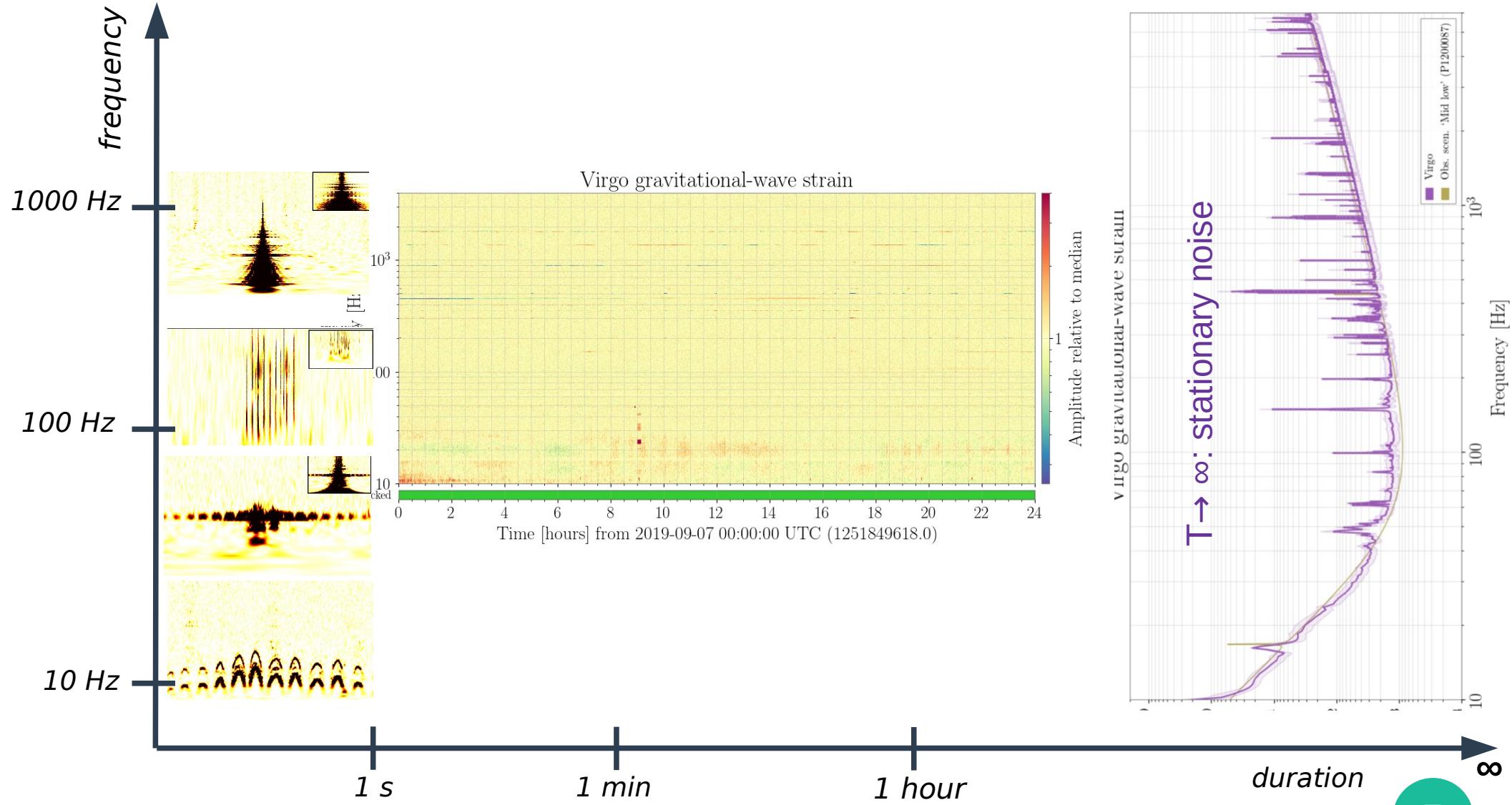
The signal is produced by the merger of 2 black holes



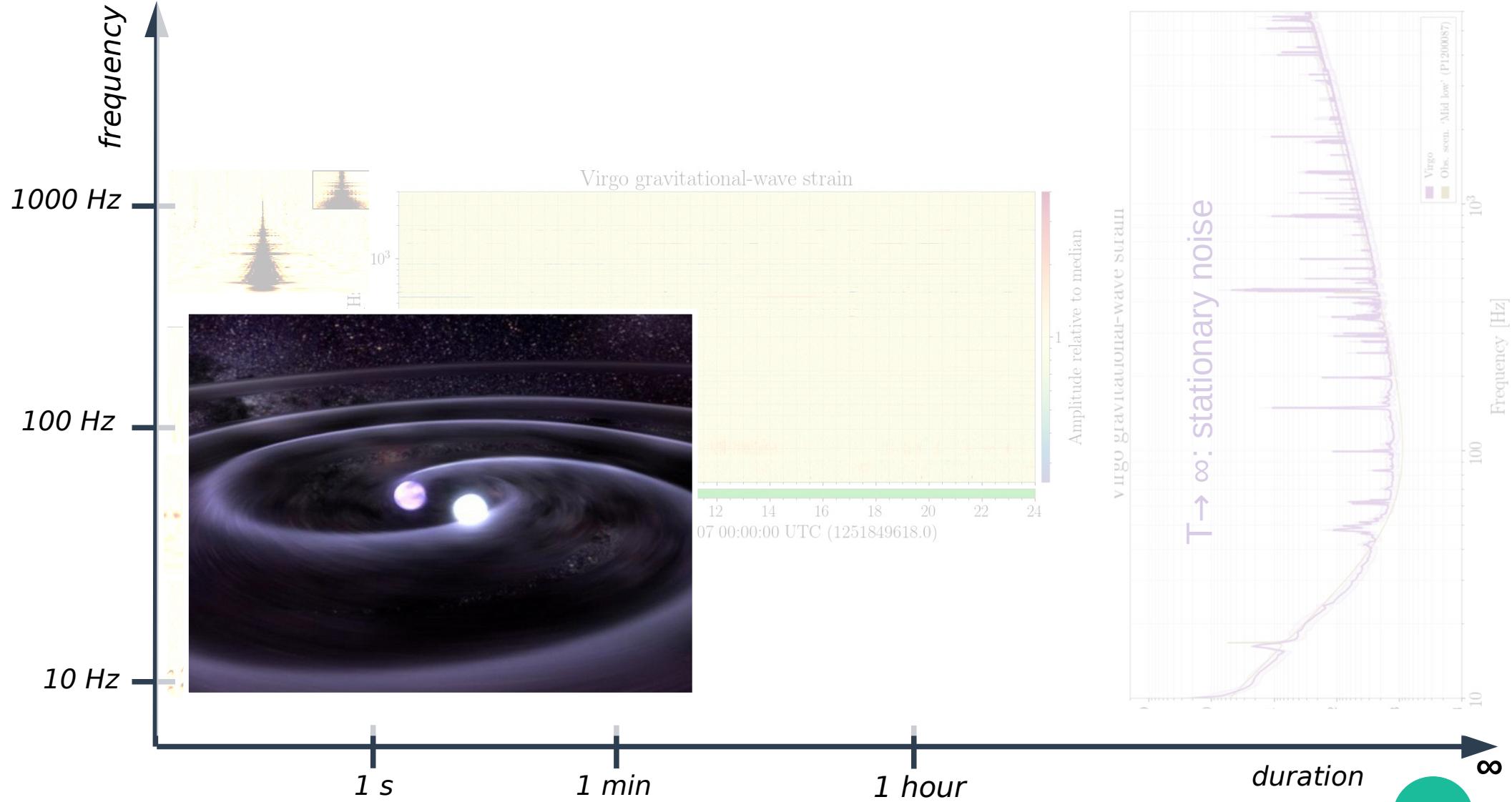
# Sensitivity to gravitational waves



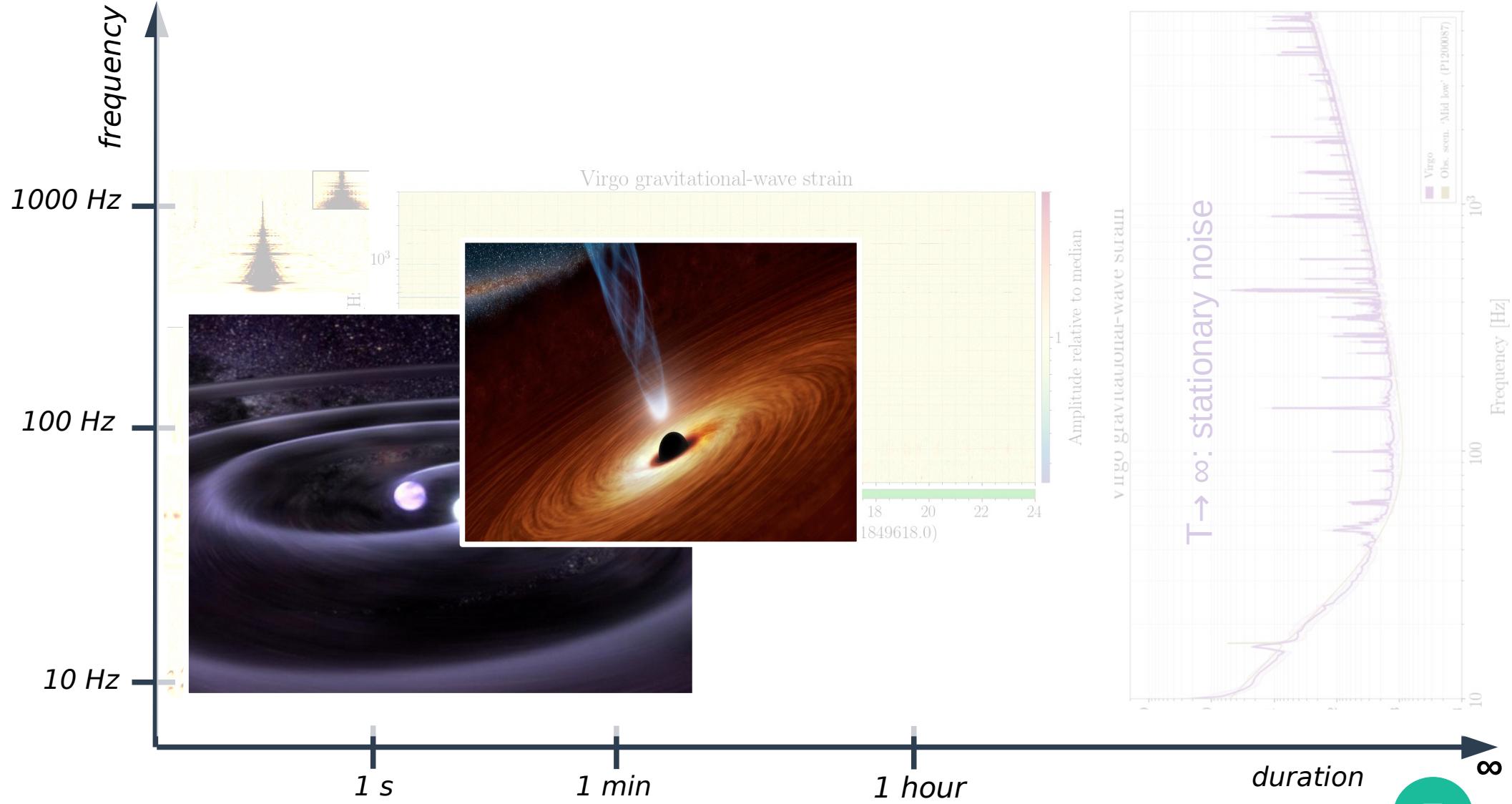
# Detector noise



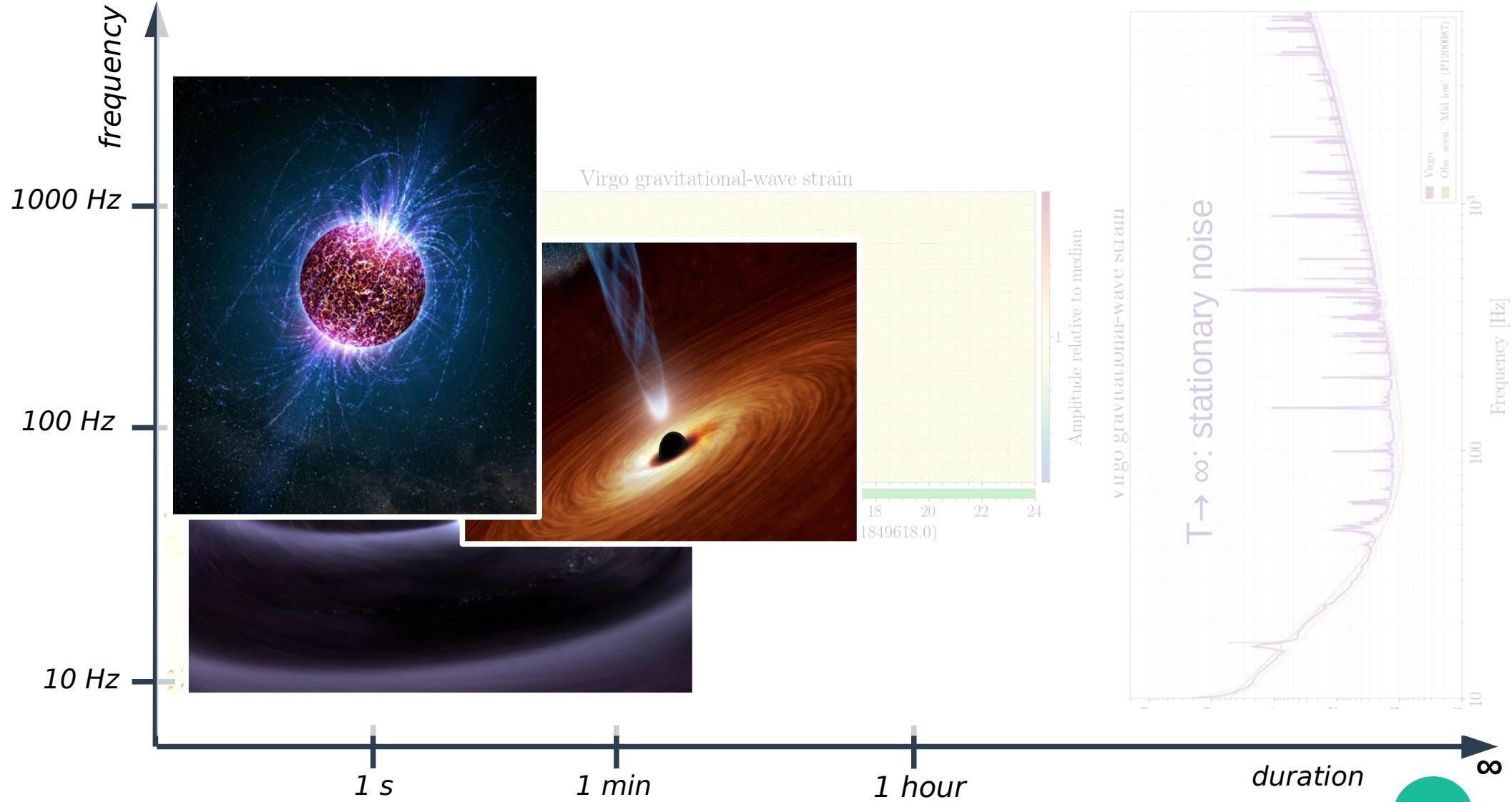
# Gravitational-wave sources



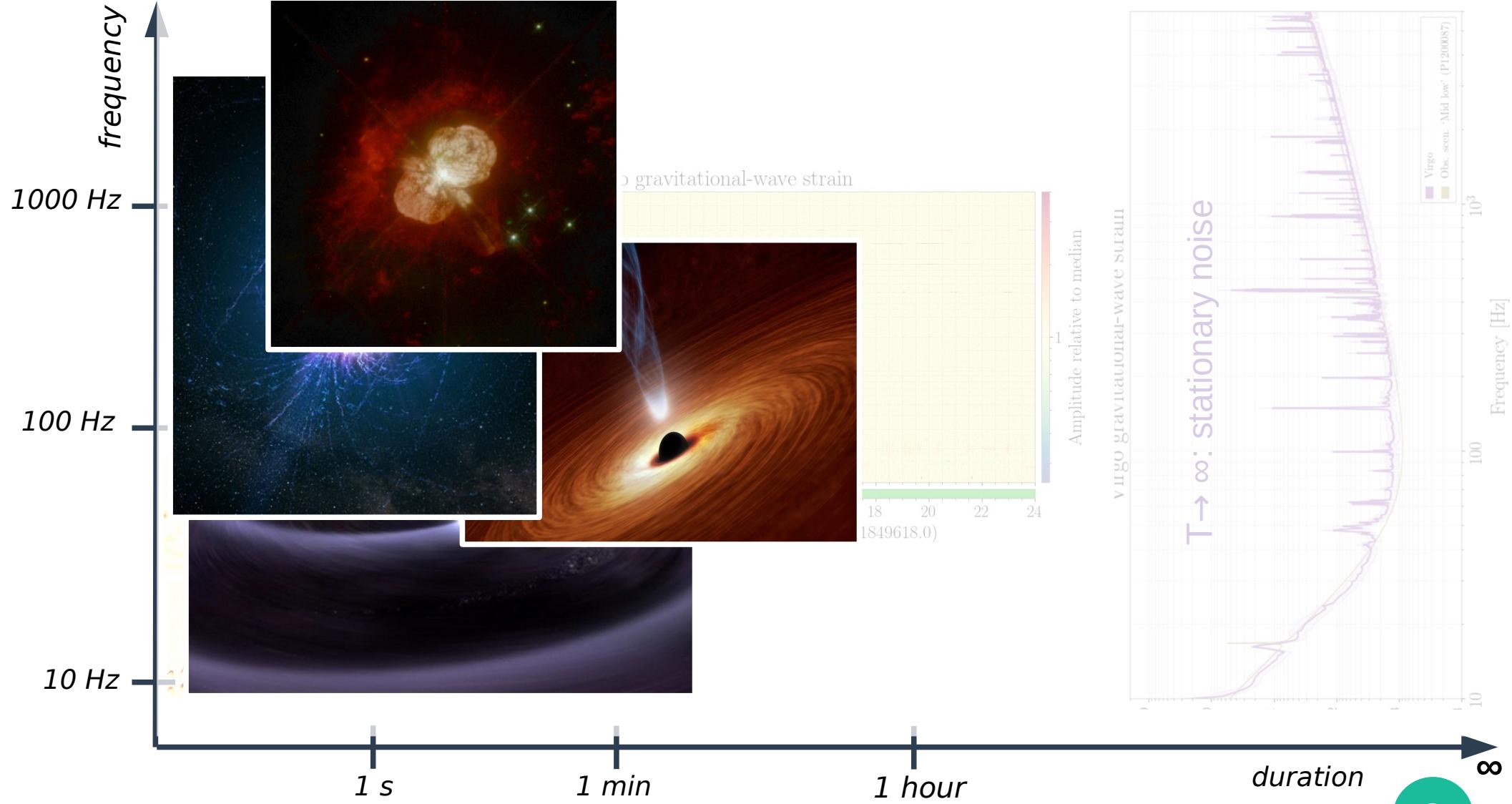
# Gravitational-wave sources



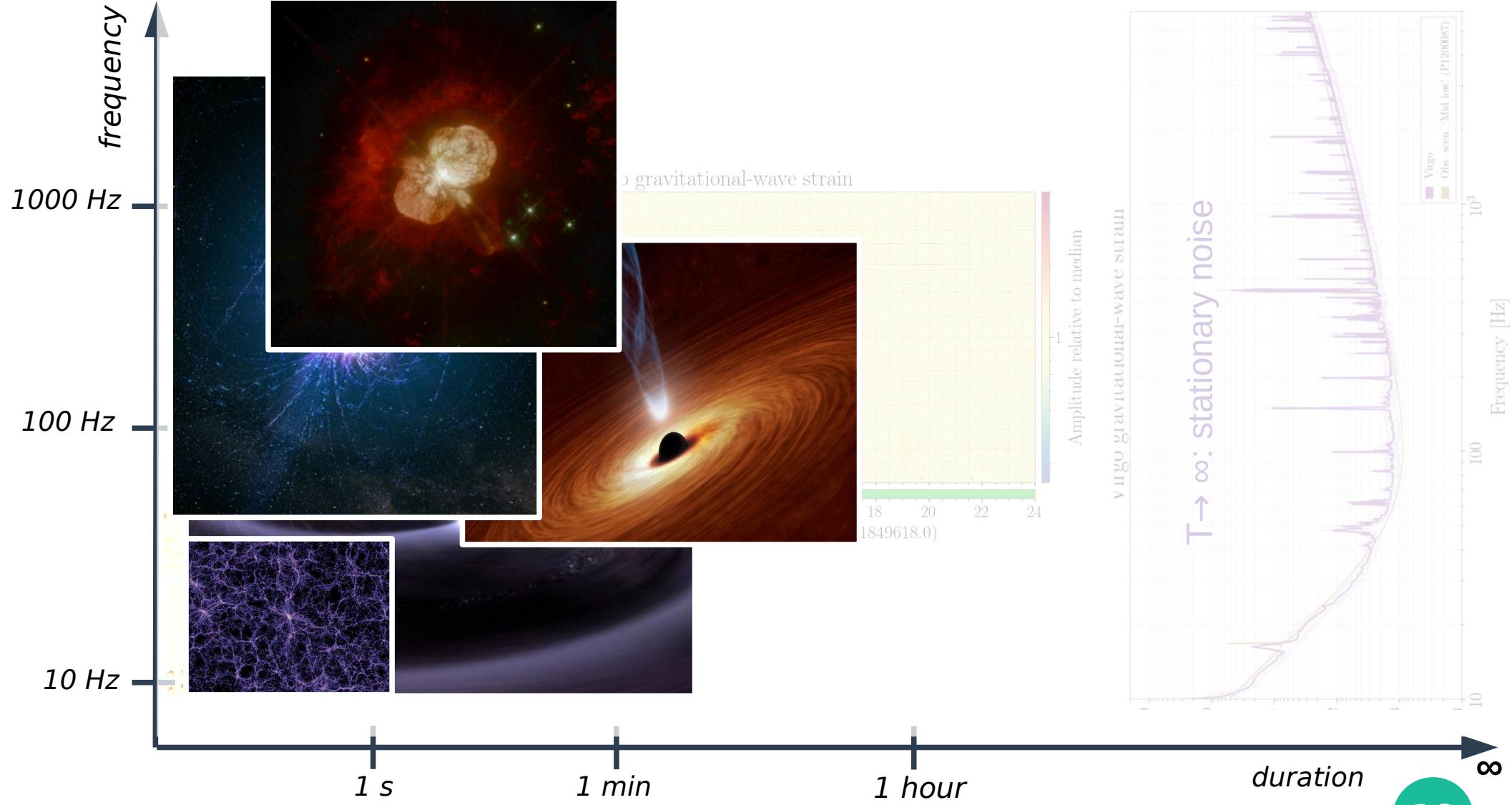
# Gravitational-wave sources



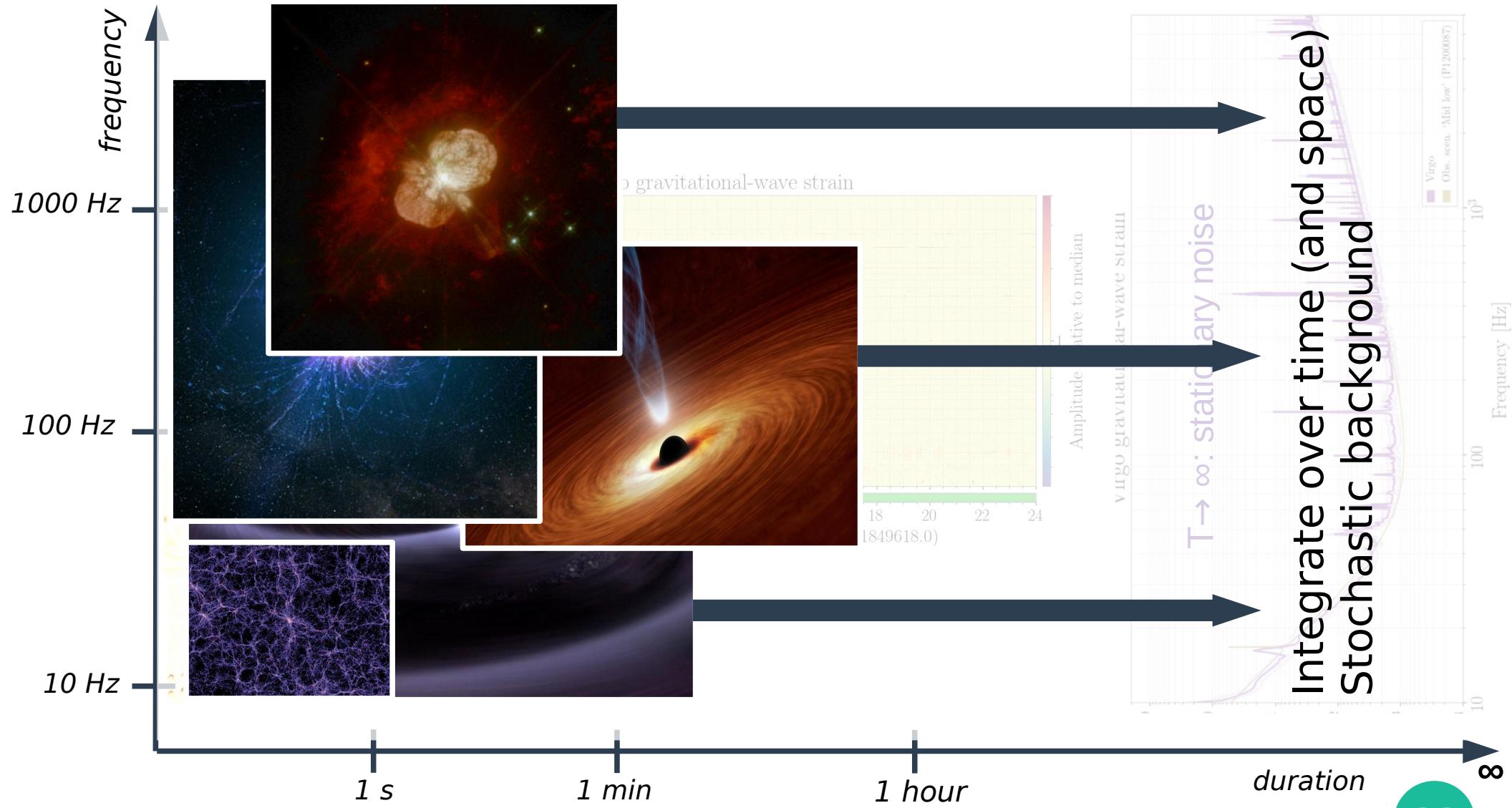
# Gravitational-wave sources



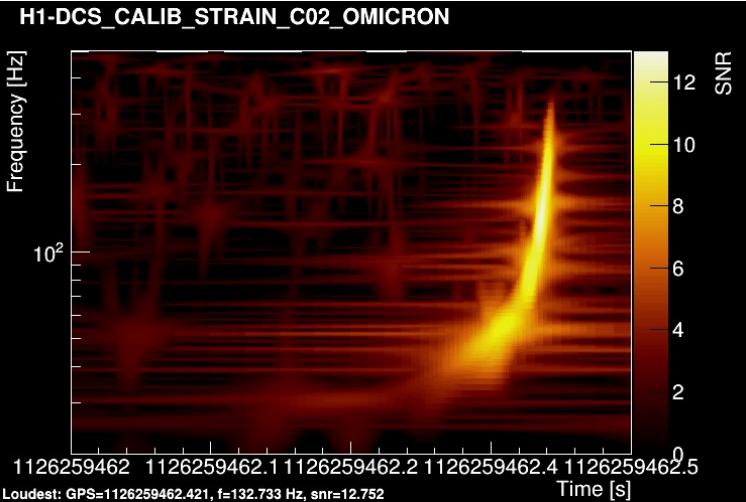
# Gravitational-wave sources



# Gravitational-wave sources

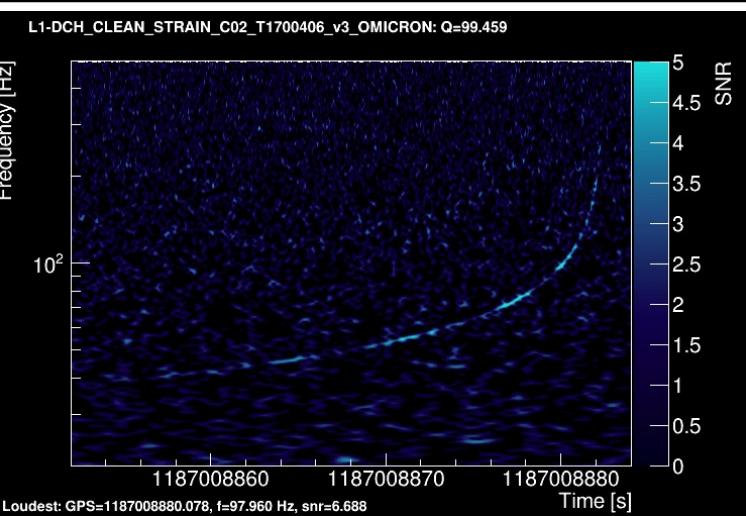


# Historical events



## GW150914

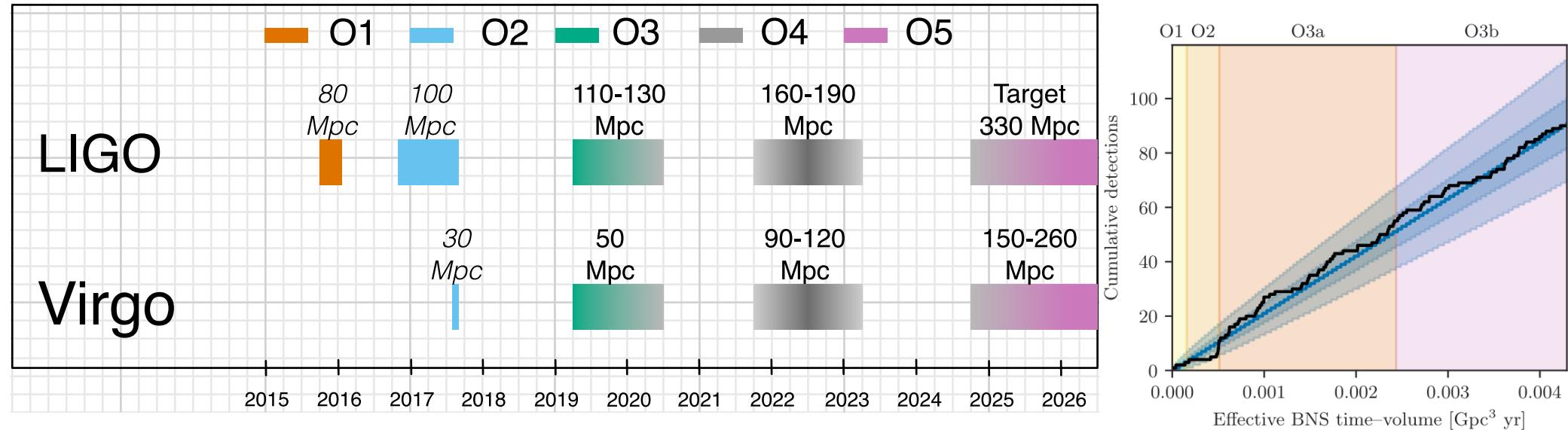
- Gravitational-wave discovery
  - Direct observation
  - Existence of a black-hole binary
  - First evidence of high-mass stellar black holes ( $> 25 M_{\text{sun}}$ )
- Parameter estimation
  - $36 M_{\text{sun}} + 29 M_{\text{sun}} \rightarrow 63 M_{\text{sun}}$
  - Spin not well-constrained (short signal)
- First opportunity to test GR in a strong-field regime
- In-depth review of instrumental and environmental noise



## GW170817

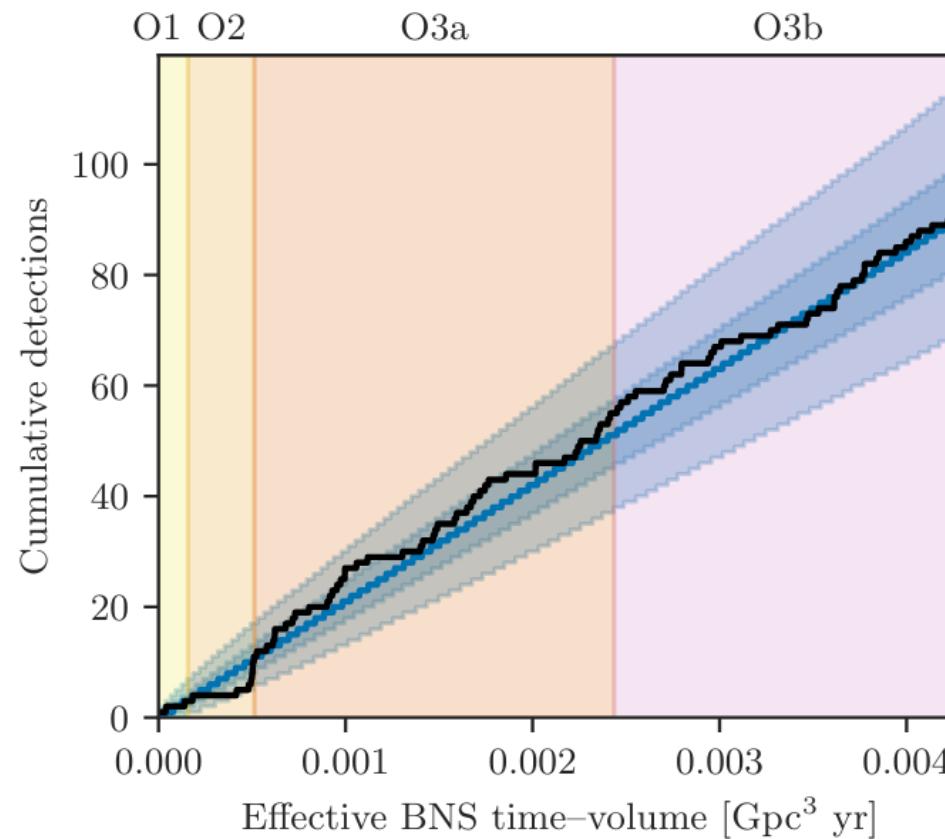
- First gravitational-wave signal from the merger of 2 neutron stars
- Birth of multi-messenger astronomy with gravitational waves
- Observed in coincidence with a short gamma-ray burst
- Kilonova followed-up over months in all wavelengths
- Tests of GR (PN coefficients, Lorentz invariance, massive gravitons...)
- 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

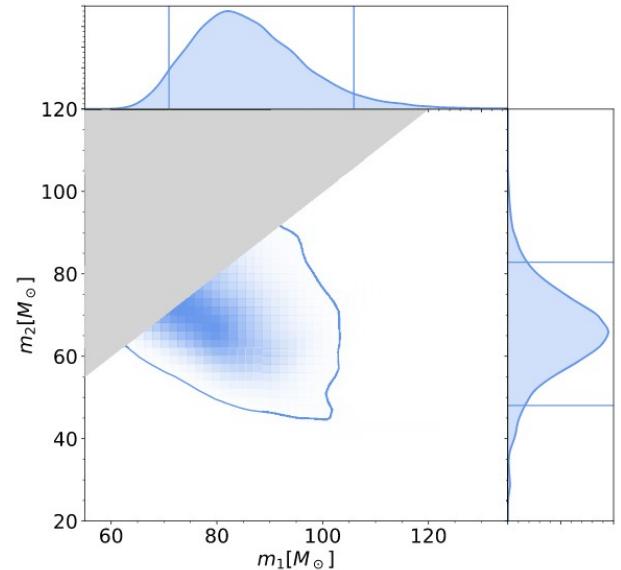
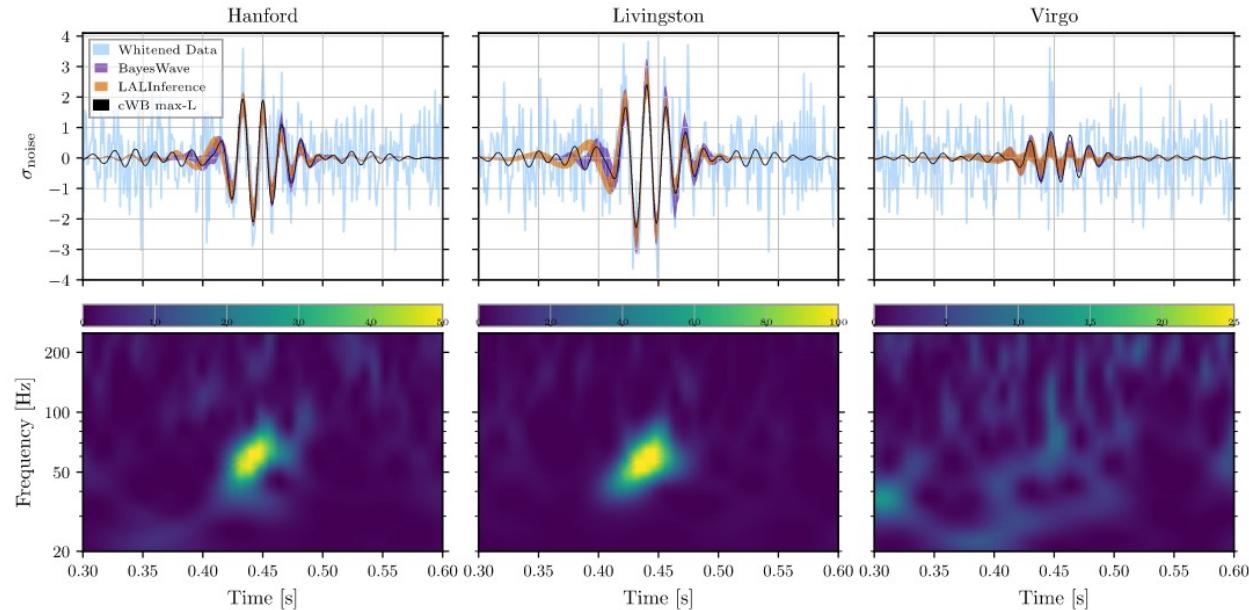


Increased statistic of your detection set → access “corners” of your parameter space:  
**“Exceptional” events**

# GW190521: High-mass black holes

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

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

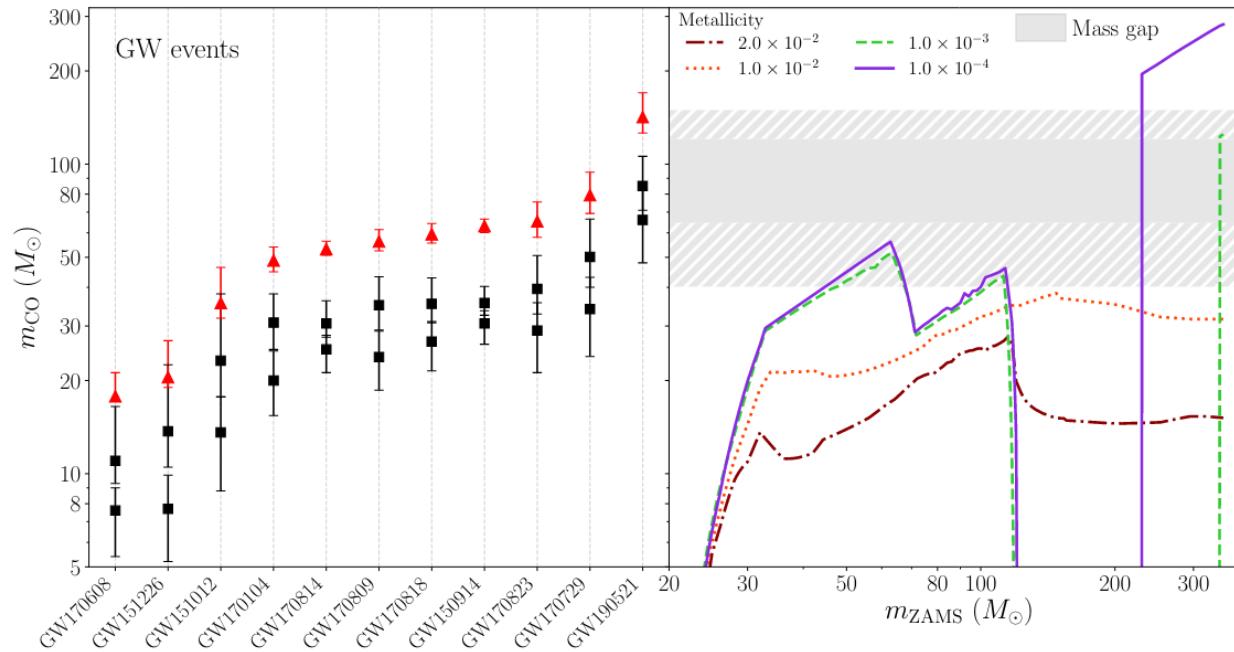


- Shortest signal detected so far ( $\sim 100$  ms) → Only  $\sim 4$  cycles between 30 Hz and 80 Hz
- Heaviest progenitor:  $85 M_\odot + 66 M_\odot \rightarrow 142 M_\odot$
- Cosmological distance: 5.3 Gpc
- Could match signals from other sources?  
Alternative scenarios: orbital eccentricity, gravitational 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 :  $65 - 120 M_{\odot}$   
→ Low likelihood for the primary black holes to originate from stellar collapse

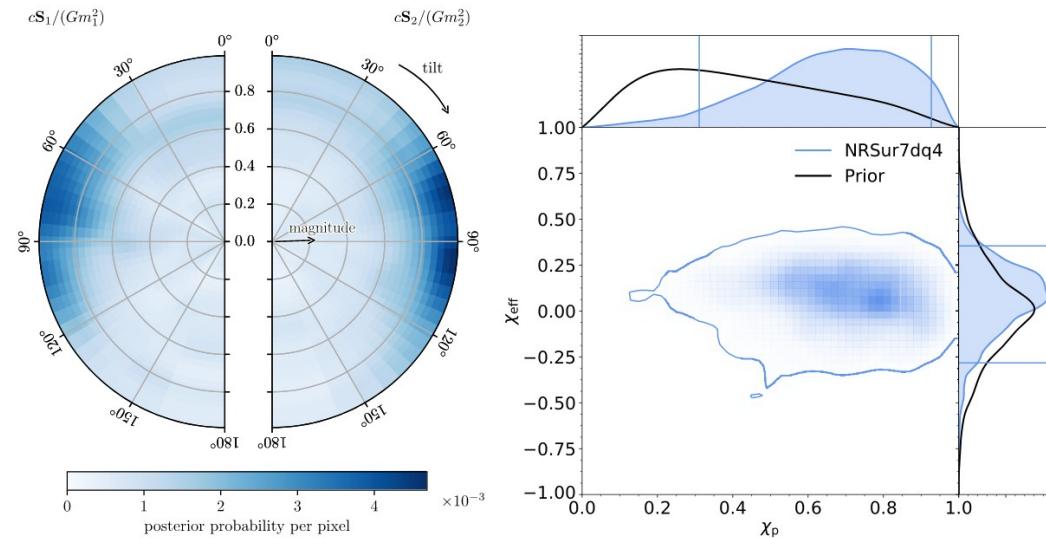
Final black hole = intermediate mass ( $100 - 10^5 M_{\odot}$ )  
→ First detection in this mass range

# 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 ( $\chi_{\text{eff}}$ )	$0.08^{+0.27}_{-0.36}$
Effective precession spin parameter ( $\chi_p$ )	$0.68^{+0.25}_{-0.37}$
Luminosity Distance	$5.3^{+2.4}_{-2.6} \text{ Gpc}$
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

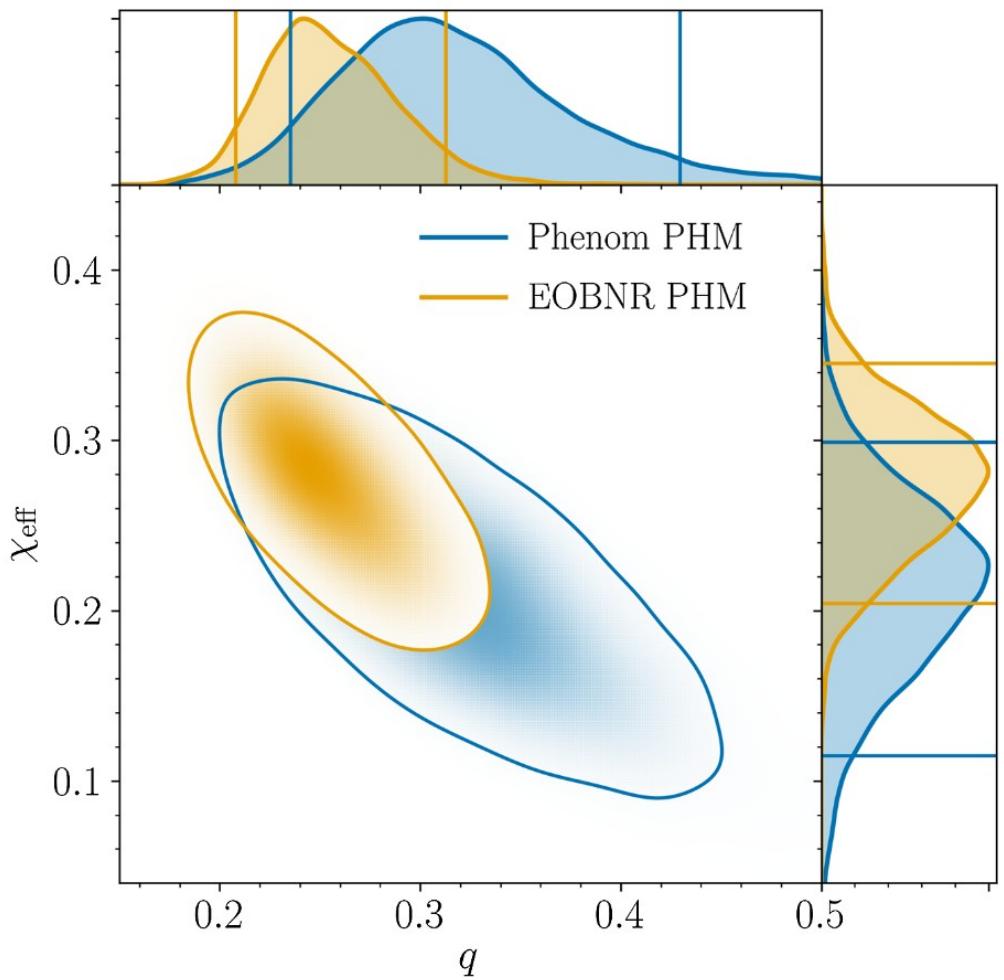
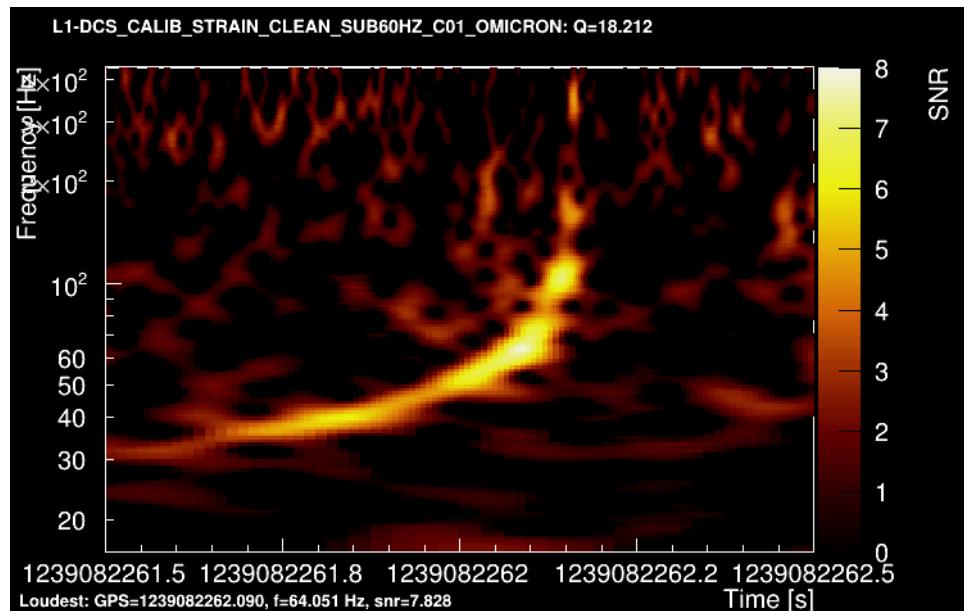
# GW190412: asymmetric masses

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

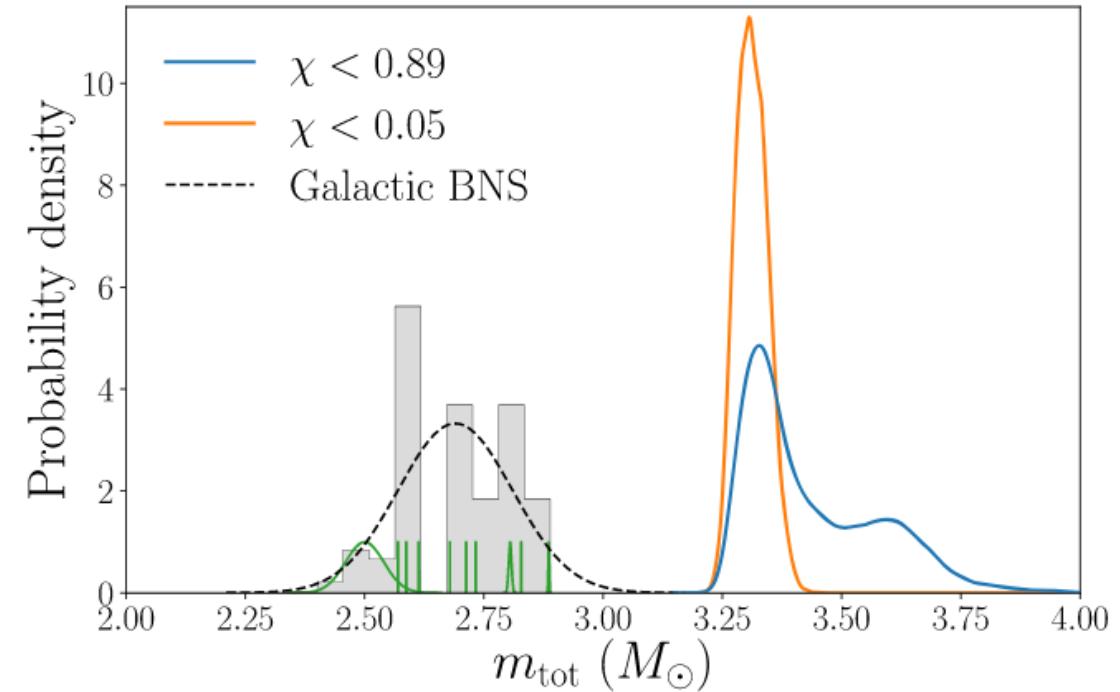
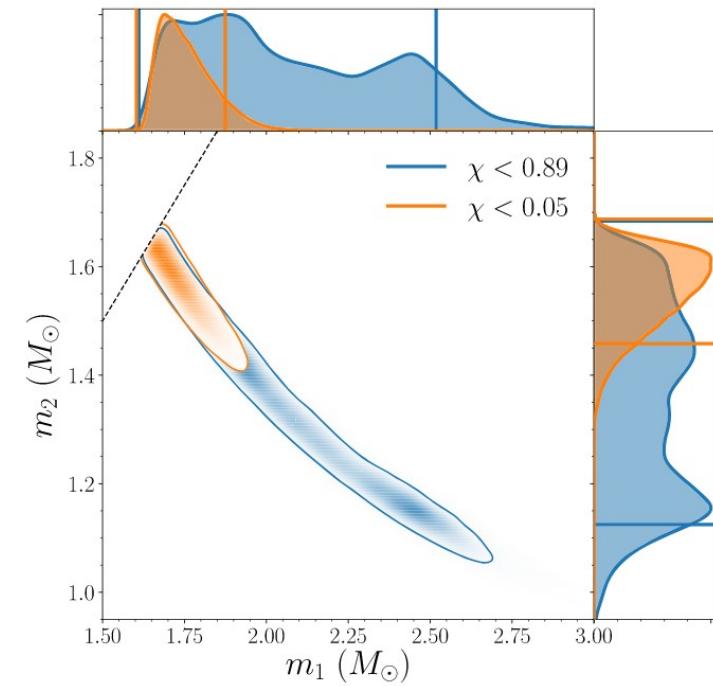
For the first time:  $q = m_2/m_1 = 8.0/31.7 < 1$

Detectable signal from higher-multipole  
(above the quadrupole)

GR tests in a new regime



# GW190425: massive neutron stars (?)

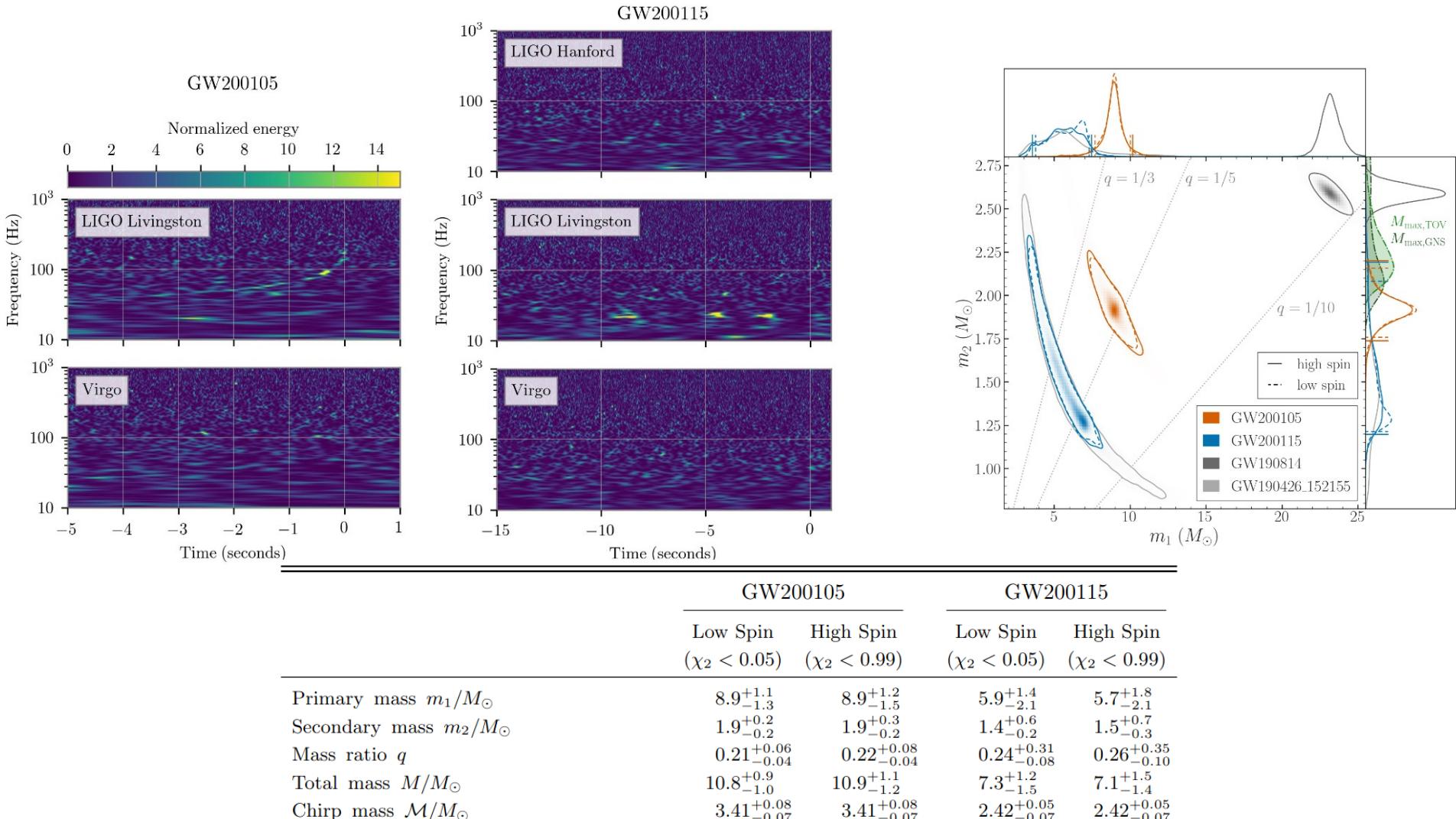


- Probably the second merger of 2 neutron stars (?)
- Single-detector event
- Detected with low-latency but no EM counterpart was found (GRB signal in INTEGRAL data?)
- Total mass is higher than what is known from galactic binaries
- No evidence of tidal effects
- Light black holes ?

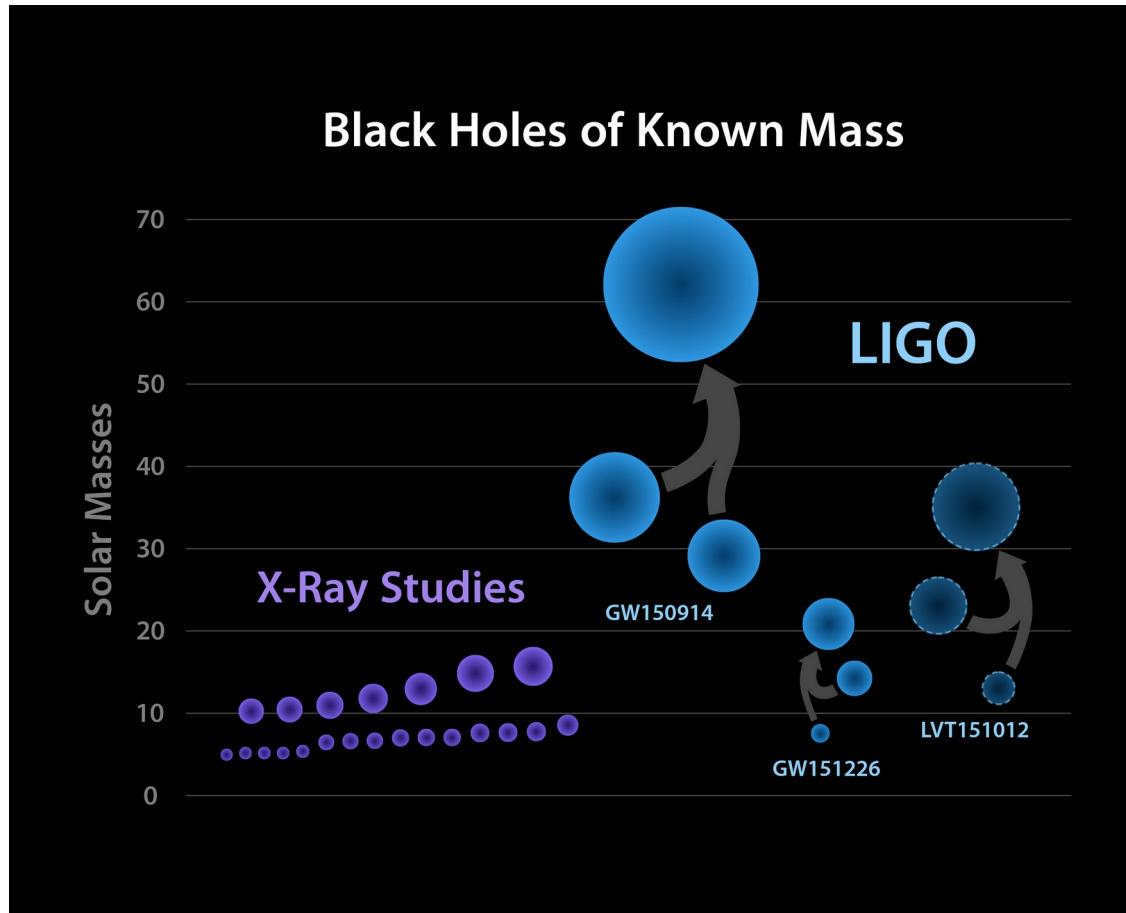
# GW200115 & GW200105

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

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

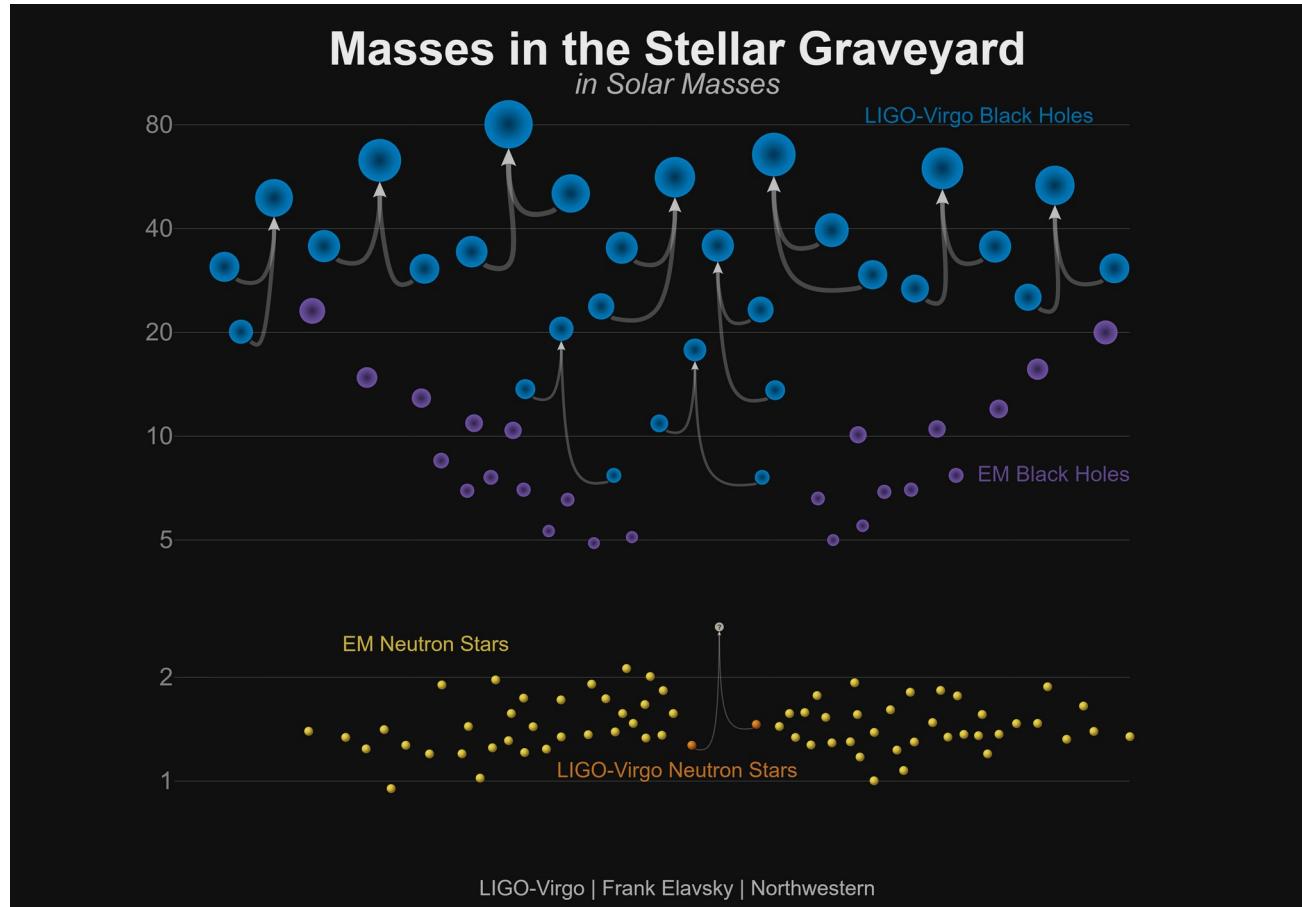


# O1: first discoveries



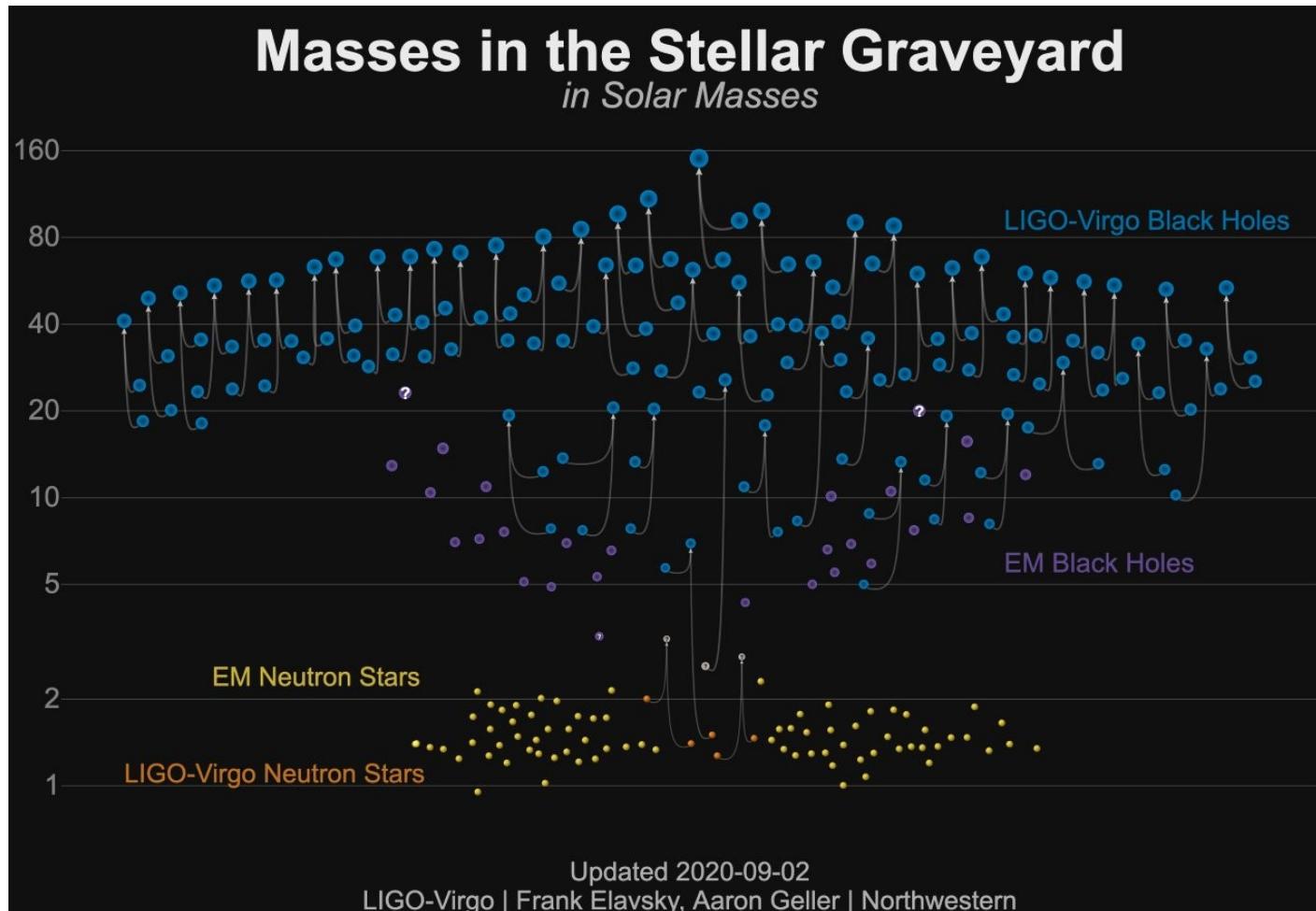
2015 (O1)

# O2: first catalog GWTC1



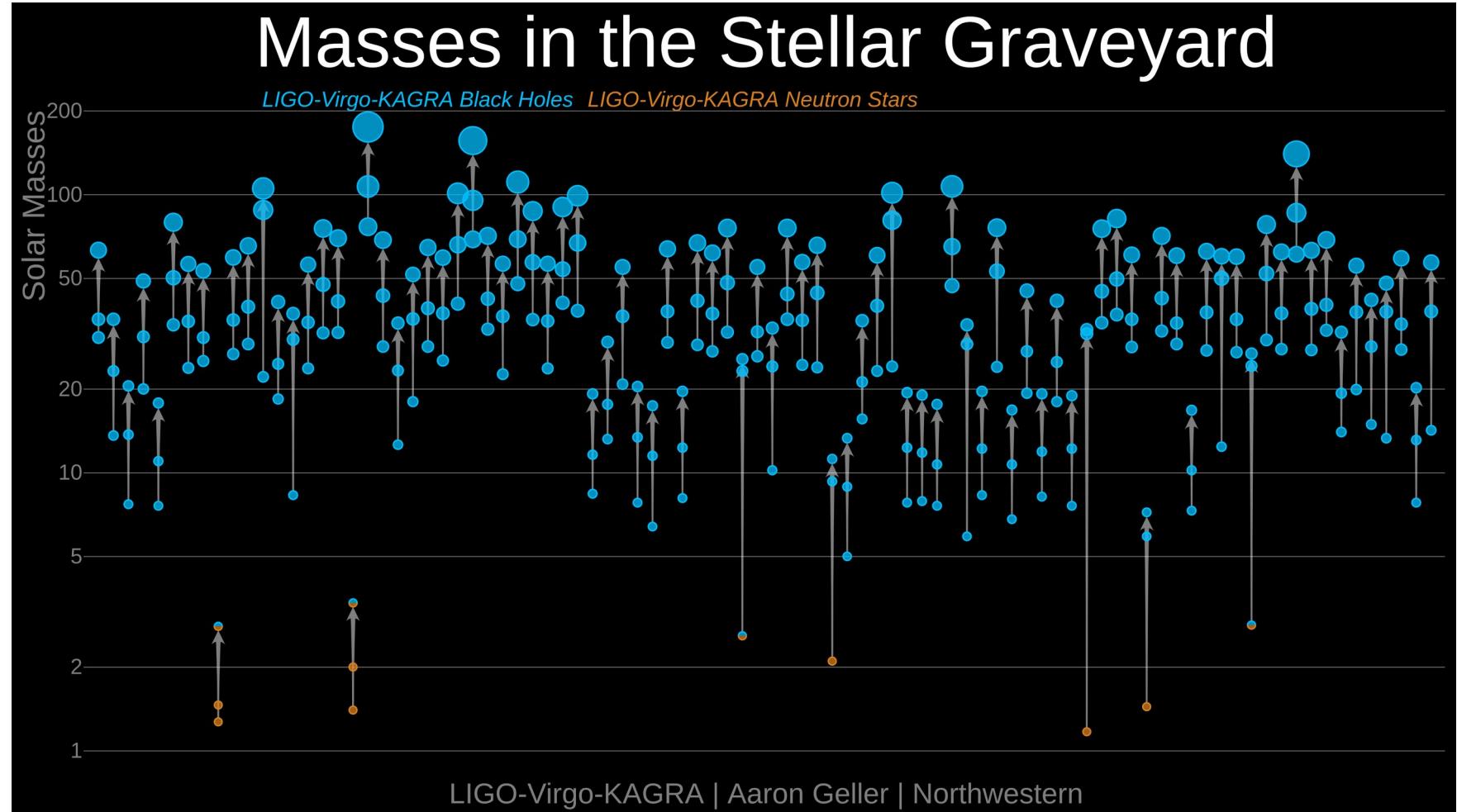
**2018 (O1+O2)**

# O3a: second catalog GWTC2



**2020 (O1 - O3a)**

# O3b: third catalog GWTC3

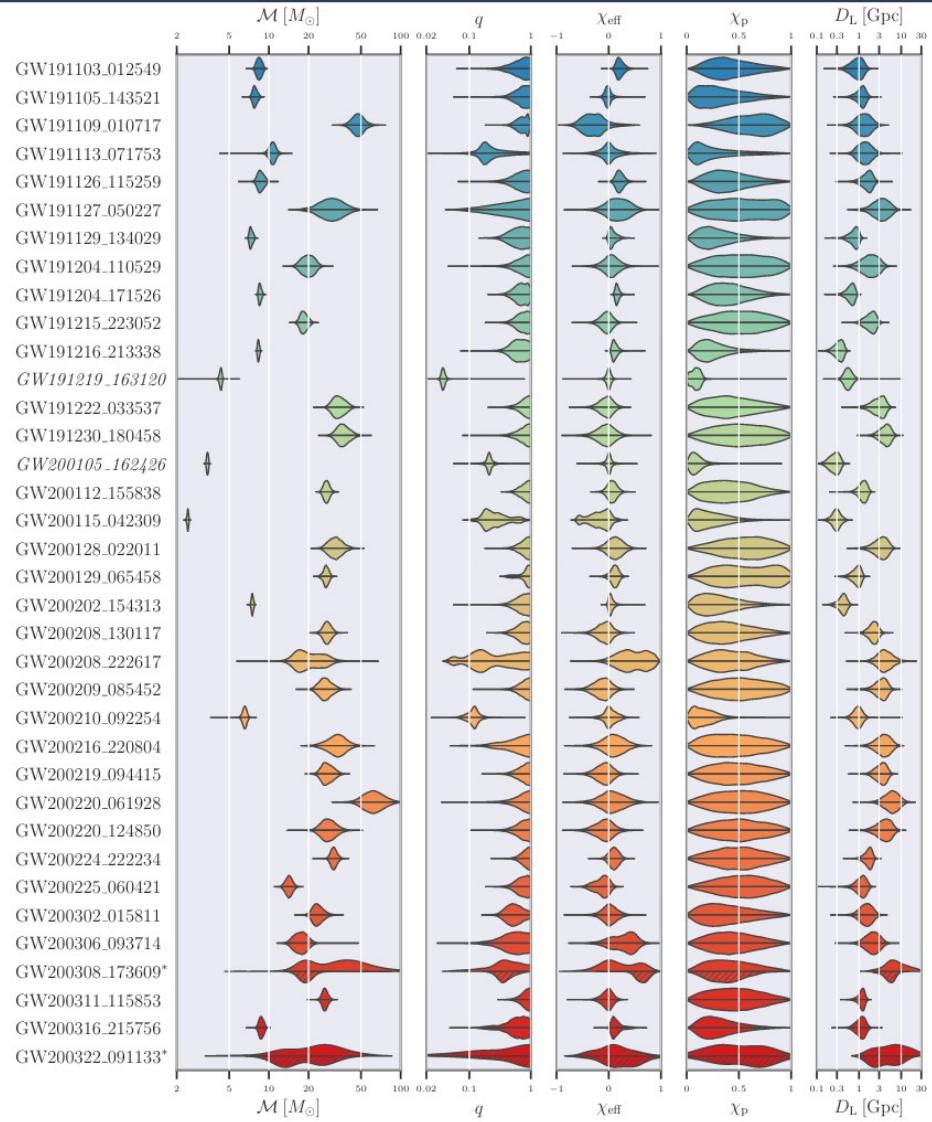


2021 (O1 - O3)

# O3b: third catalog GWTC3

e-Print: 2111.03606 [gr-qc]

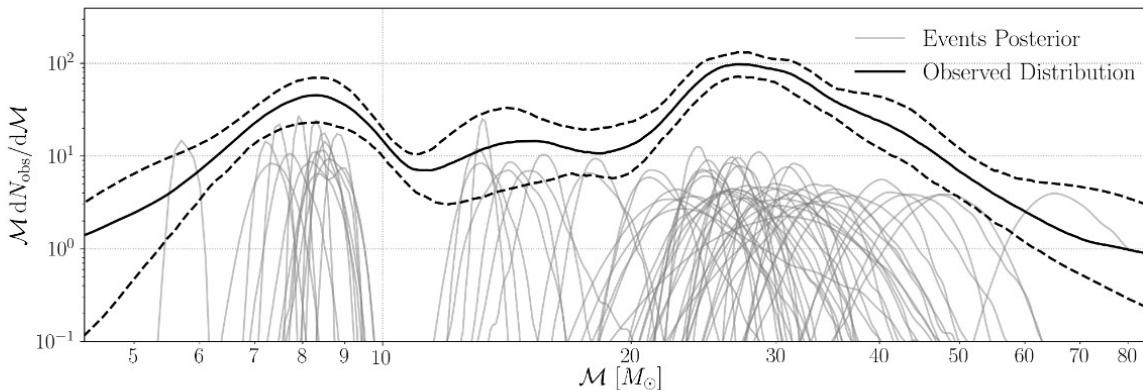
- Events are listed in the catalog if  $p_{\text{astro}} > 0.5$  ( $\sim 10\text{-}15\%$  false alarm)
- 90 events (35 in O3b)
- +  $\sim 1000$  sub-threshold events
- Final calibration + in-depth data quality studies and noise subtraction
- 3 CBC- template searches + 1 unmodeled search
- Parameter estimation 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:  $13 \text{ Gpc}^{-3} \text{ yr}^{-1}$  –  $1900 \text{ Gpc}^{-3} \text{ yr}^{-1}$  (95%)
  - NSBH:  $7.4 \text{ Gpc}^{-3} \text{ yr}^{-1}$  –  $320 \text{ Gpc}^{-3} \text{ yr}^{-1}$  (95%)
  - BBH:  $16 \text{ Gpc}^{-3} \text{ yr}^{-1}$  –  $130 \text{ Gpc}^{-3} \text{ yr}^{-1}$  (95%)



- Entering the high-statistical regime
- Parameters can be binned!

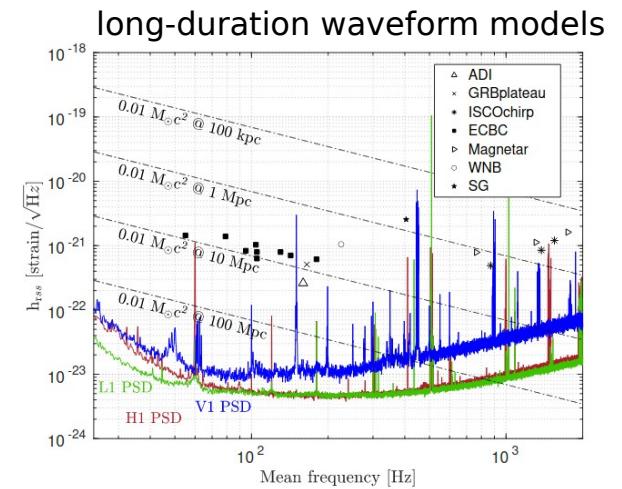
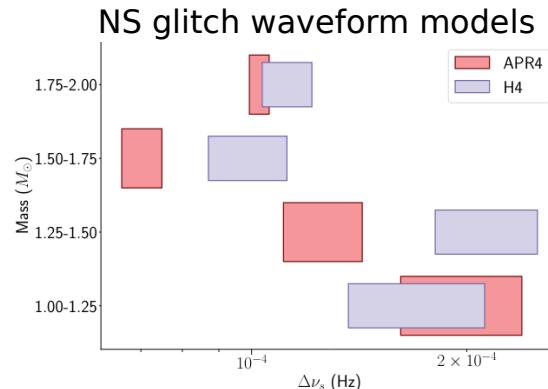
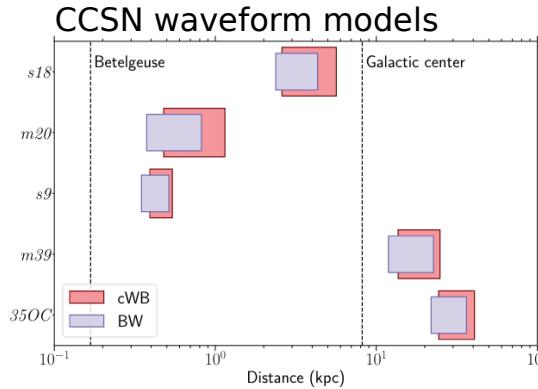
- Merger rates as a function of mass
- Merger rates as a function of redshift:  $\sim(1+z)^{2.7}$  for  $z < 1$
- Correlation studies (spin magnitude vs. mass ratio)
- Formation scenarios

# Unmodeled searches

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

E-Print: 2107.03701 [gr-qc]

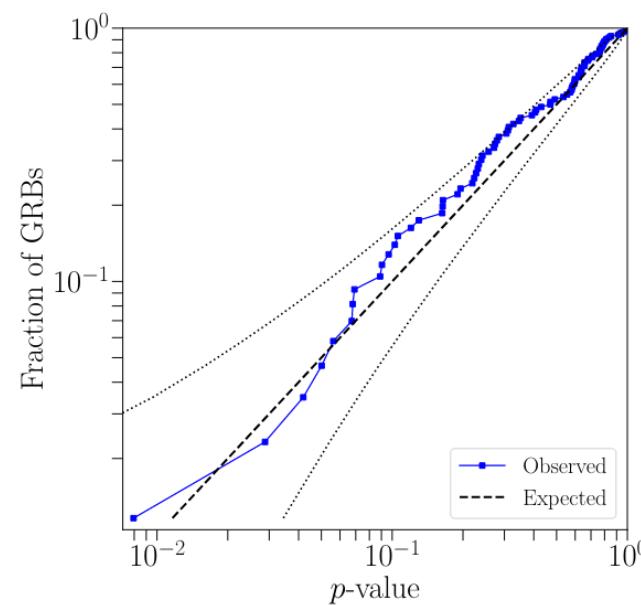
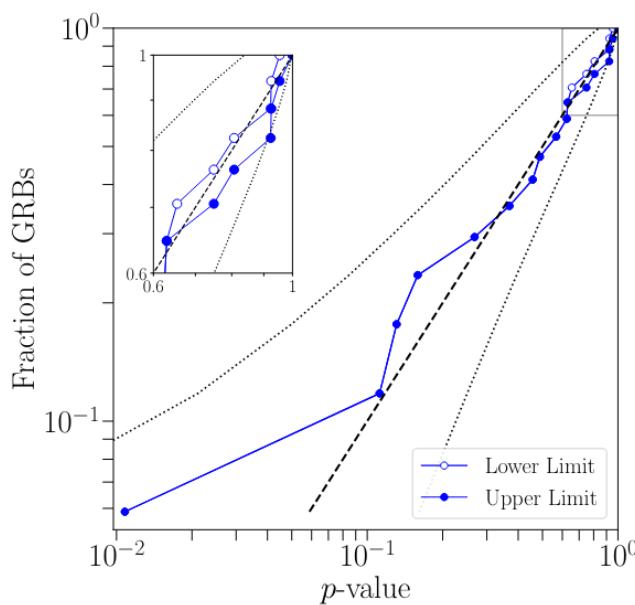
- Various sources of gravitational waves with poorly-modeled waveforms  
Core-collapse supernovae, isolated deformed neutron stars, BH accretion disk instabilities, eccentric binaries...
- Wide parameter space
- All-sky and all-time searches based on excess-power methods



# Targeted searches

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

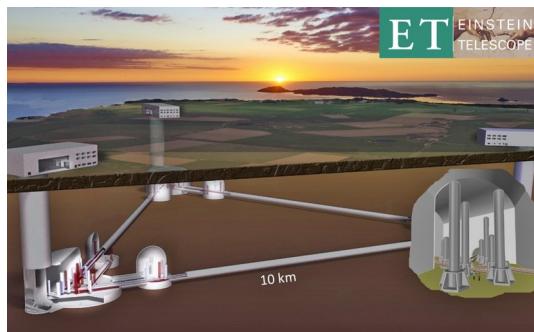
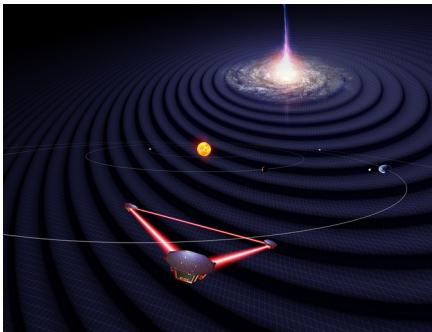
- Use triggers from other channels to target gravitational-wave searches  
Gamma-ray bursts, neutrinos, Magnetar flares, fast-radio bursts
- GRB triggers: Use both CBC-modeled and unmodeled searches



- 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



→ Future prospects: see Tito's talk