

“O3” Results

The O3 run, public alerts and published events

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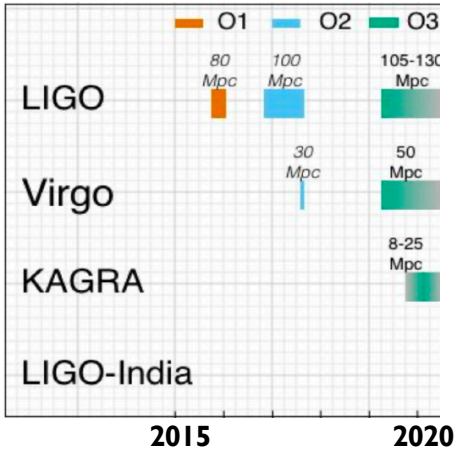
IPHC-Strasbourg

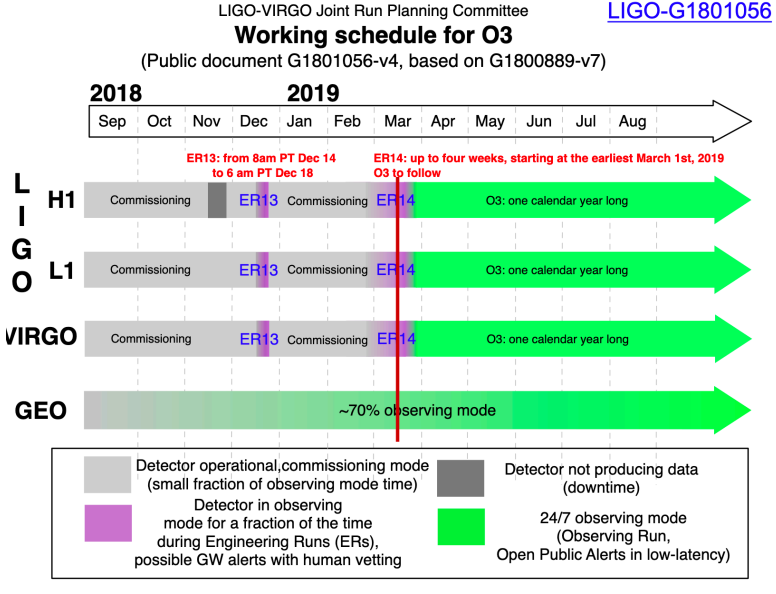
October 14, 2020

Troisième assemblée générale du GdR Ondes Gravitationnelles

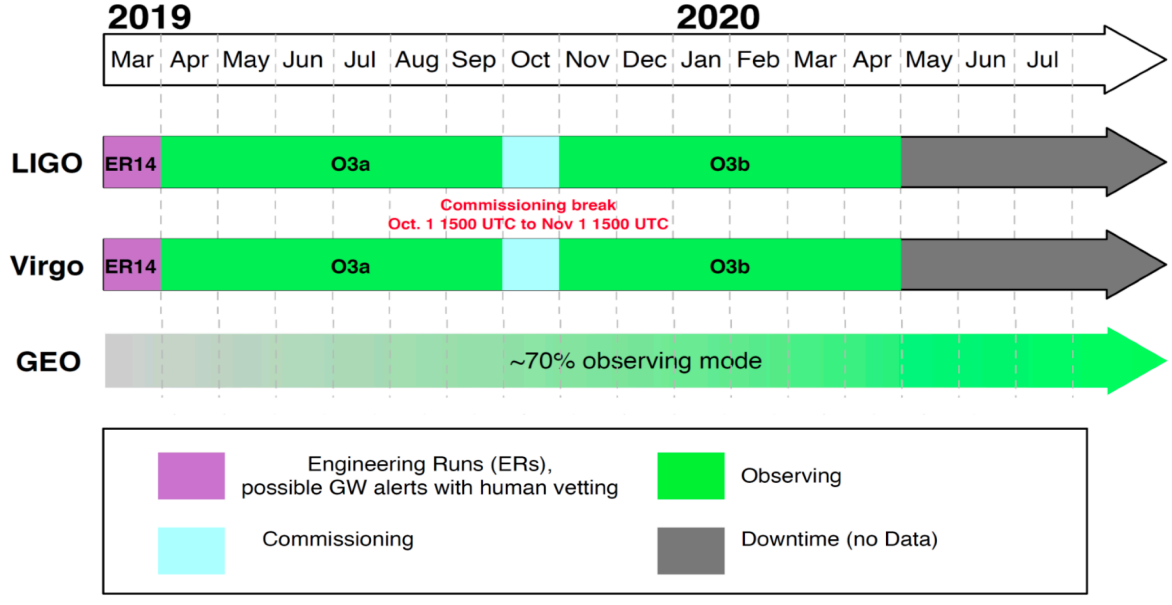
Preparing the O3 run

- GW detectors follow a cycle of detector upgrade and data taking
- Main upgrades O2 to O3:
  - Squeezing,
  - Increase laser power,
  - Stray light control improvements
  - Improvement to various control systems
  - Replace 5/8 test masses (LIGO: better coating, high absorbing point removed)
  - New reaction mass (LIGO)
  - Monolithic signal recycling (LIGO)
  - Monolithic suspension (Virgo)
  - Improve mirror ROC with TCS (Virgo)
  - …
- Commissioning time needed
  - Not so predictable period
- O3 started on April 1, 2019





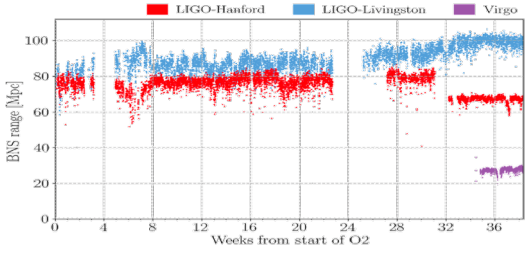
O3: April 1, 2019 to March 27, 2020



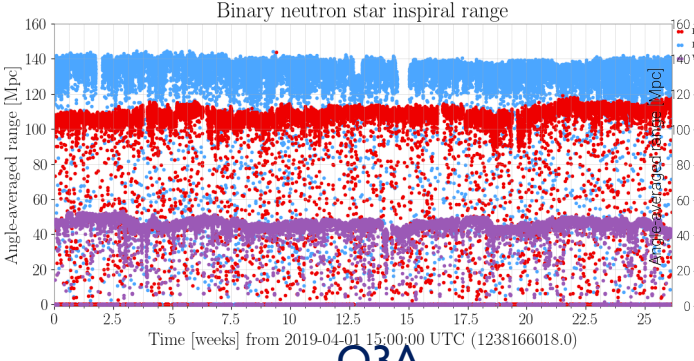
- Scheduled for 2x6 months of data taking: O3A and O3B
- 1 month of commissioning from Oct 1. to Nov 1.
- O3b suspended/end on March 27 due to COVID-19
  - No more activity at the site → start O4 preparation
- KAGRA best sensitivity approached 1 Mpc end of March

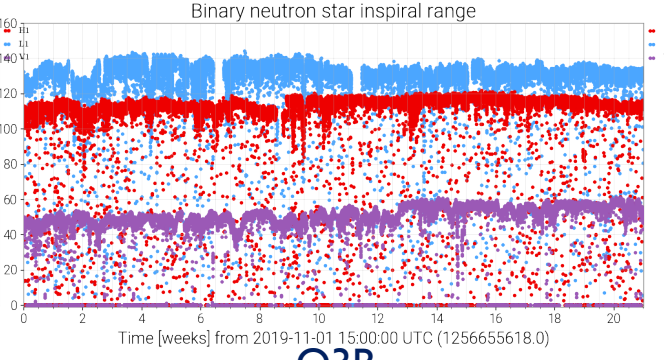
O3 sensitivity: BNS range

- Significant improvement compared to O2
- Some improvement during the run, especially for Virgo



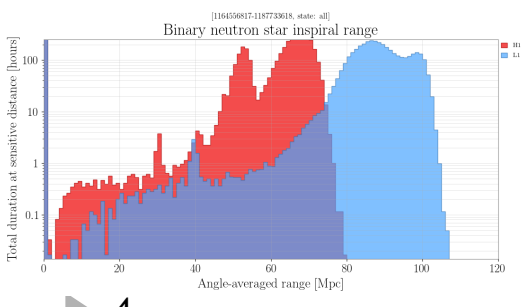
O2

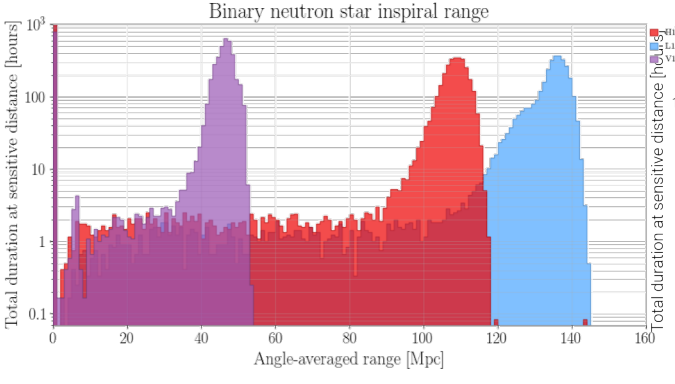


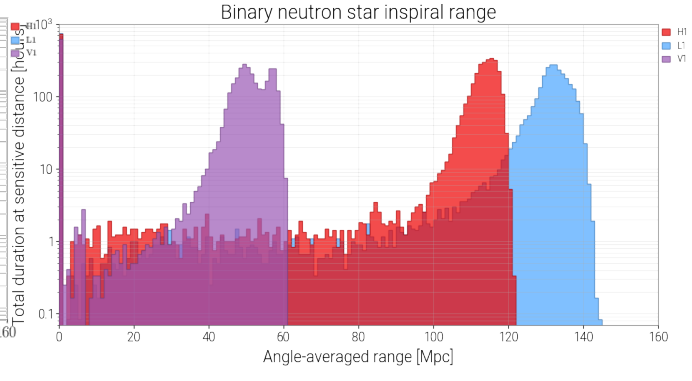


O3A

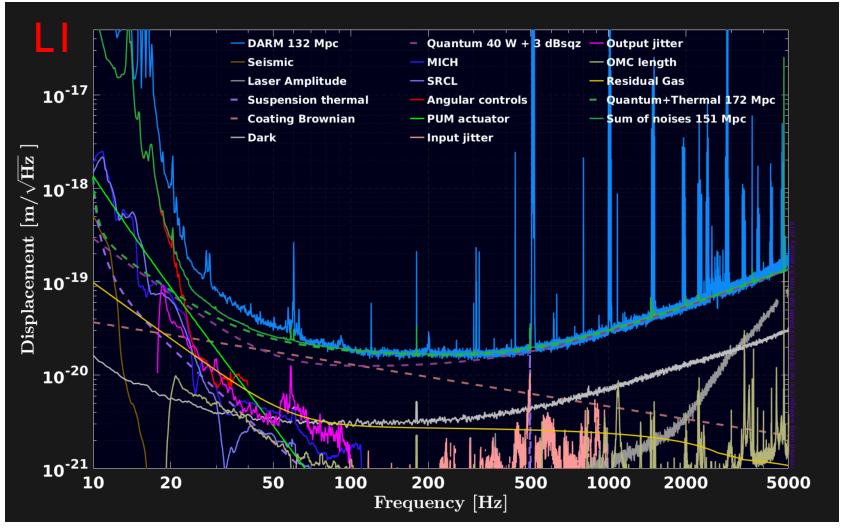
O3B

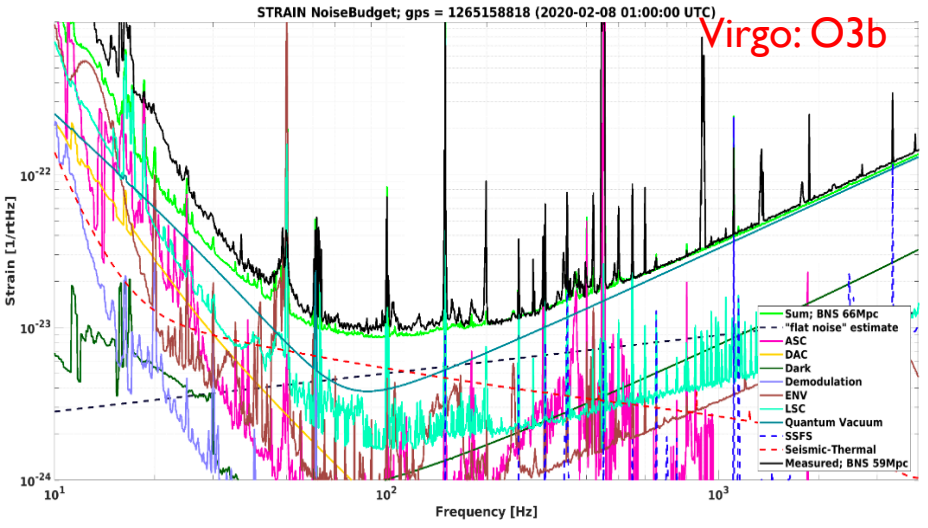






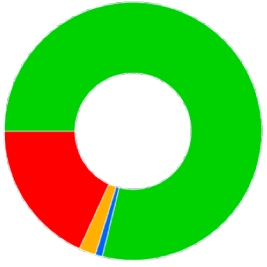
Sensitivity: noise budgets during O3





- Goal: try to understand the detector
  - A guide for the commissioning and detector improvements
- A good but not perfect understanding; BNS ranges:
  - L1 known noises: 151 Mpc, observed: 132 Mpc
  - V1 known noises: 66 Mpc, observed: 59 Mpc
- Main messages: detectors are complex;
  - The low frequency is difficult (high mass/redshift), but could be improved

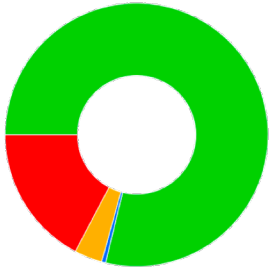
O3 Duty cycles



H1 operational state
O3b

- Observing [78.8%]
- Ready [0.9%]
- Locked [2.1%]
- Not locked [18.2%]

78.8% VS 71.2 in O3a



L1 operational state
O3b

- Observing [78.8%]
- Ready [0.5%]
- Locked [3.4%]
- Not locked [17.3%]

78.8% VS 75.8

Virgo operational state
O3b

- Observing [75.6%]
- Locked [6.9%]
- Not locked [17.5%]

75.6% VS 76.3

- Single detector duty cycles improved for O3 and during O3
  - Duty cycles were 61% for H1/L1 during O2
- Coordination between sites
  - To maximize 3-IFO operation
  - To have at least one instrument tries to remain online at any given time:

O3A Network duty factor

[1238166018-1253977218]

- Triple interferometer [44.5%]
- Double interferometer [37.4%]
- Single interferometer [15.0%]
- No interferometer [3.2%]

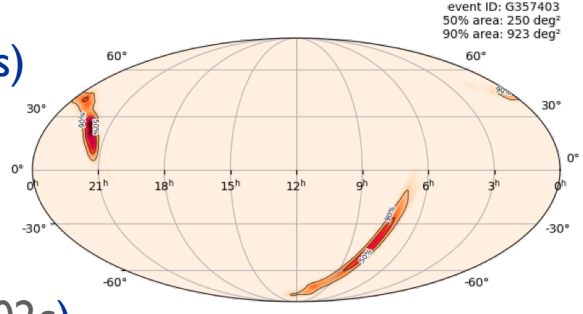
O3B Network duty factor

[1256655618-1269363618]

- Triple interferometer [51.0%]
- Double interferometer [34.3%]
- Single interferometer [11.2%]
- No interferometer [3.4%]

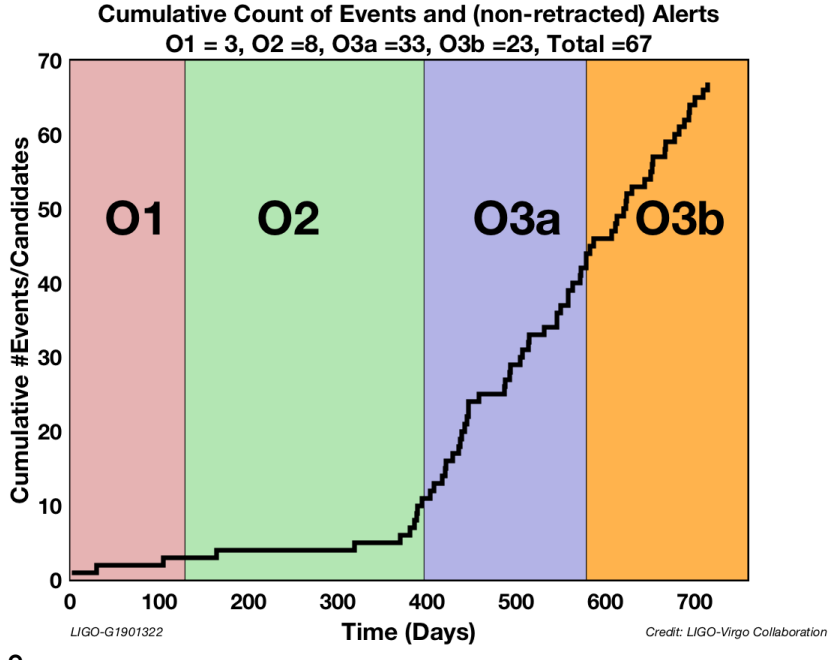
Public alerts setting for O3

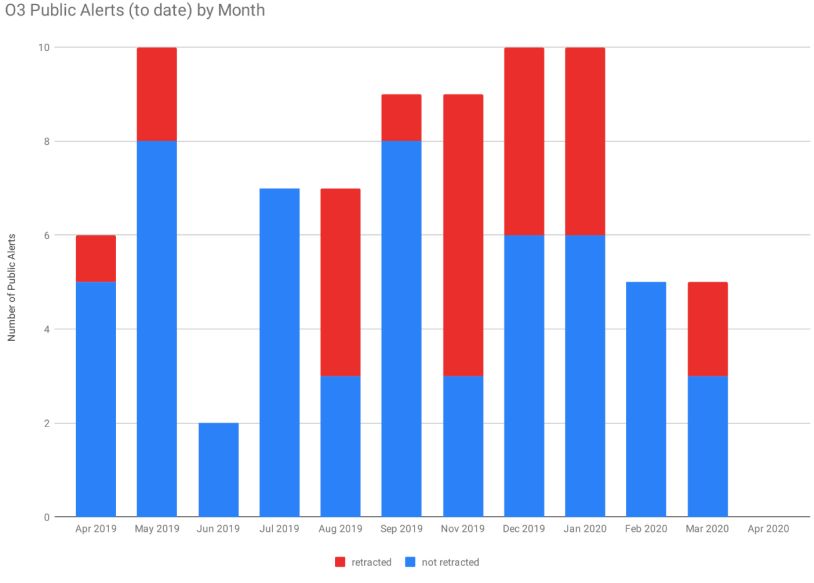
- https://gracedb.ligo.org/superevents/public/O3/
- Distributed by public GCN
- Automated
  - Automated GCN Notice(s) + human update with circular(s)
  - Content:
    - 3d sky map
    - FAR
    - Rough classification: NS/NSBH/BBH/has remnant
  - Latency for the first notice as low as 2 minutes (see S200302c)
    - Start prototyping the early warning at the end of O3
- False Alarm Rate (FAR) Thresholds:
  - 1/2 months for CBC events
    - Four searches running in parallel: GstLAL, MBTA, PyCBC, SPIIR
  - 1/year for Burst search: only one search running during O3
  - RAVEN: coincidence between sub-threshold GW candidates and GRB/SNEWS alerts



Public alerts during O3

- 11 events at the end of 02
- 56 (non retracted) online candidates for 03
- Large increase due to sensitivity, duty cycles and search pipelines improvement (single detector trigger)

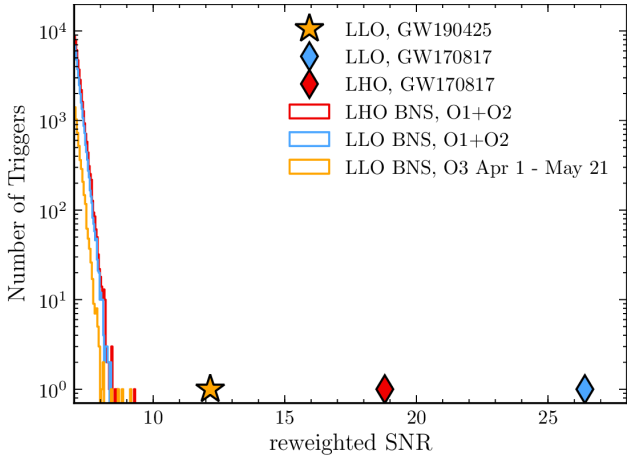


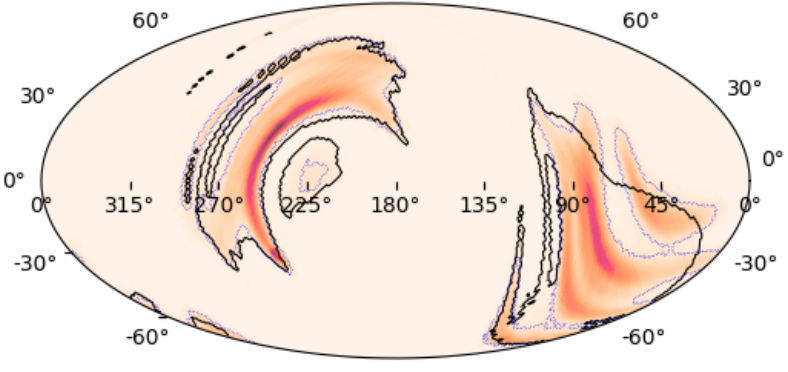


Observation of a compact binary coalescence with total mass ~3.4 Msun, Astrophys. J. Lett. **892**, L3 (2020)

GW190425: detection

- Published on Jan 6, 2020
- 2nd BNS (most likely) after GW170817
- Detected online as a single detector event
  - SNR in L1: 12.9
  - SNR in Virgo: 2.5
    - noise level, but used for parameter estimation
  - FAR = 1/69000 years
  - Alert sent 43 minutes after the trigger
  - First sky map 10200 deg^2 (90% CL)
  - Improved sky map: 8284 deg^2 (90% CL)
  - Distance: 159^{+69}_{-71} Mpc

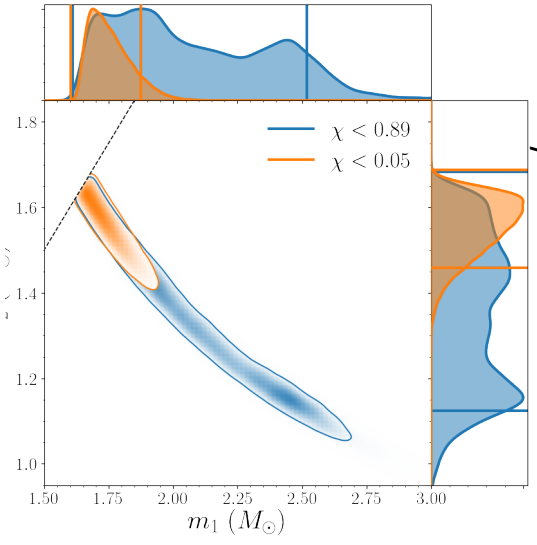


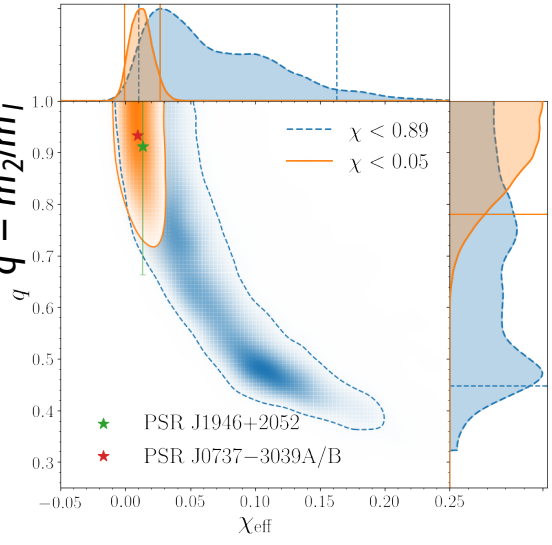


GW190425: parameters

Source Properties for GW190425

	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	$1.60–1.87\ M_\odot$	$1.61–2.52\ M_\odot$
Secondary mass m_2	$1.46–1.69\ M_\odot$	$1.12–1.68\ M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}\ M_\odot$	$1.44^{+0.02}_{-0.02}\ M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}\ M_\odot$	$1.4873^{+0.0008}_{-0.0006}\ M_\odot$
Mass ratio m_2/m_1	$0.8 - 1.0$	$0.4 - 1.0$
Total mass $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}\ \mathrm{M}_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.012^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance $D_{\rm L}$	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leqslant 600$	$\leqslant 1100$



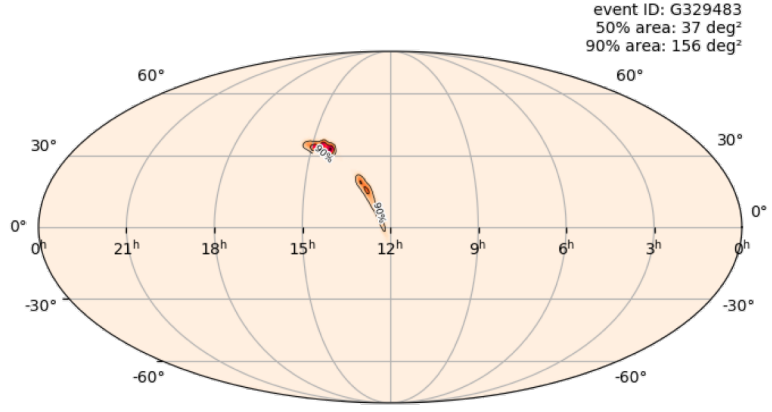


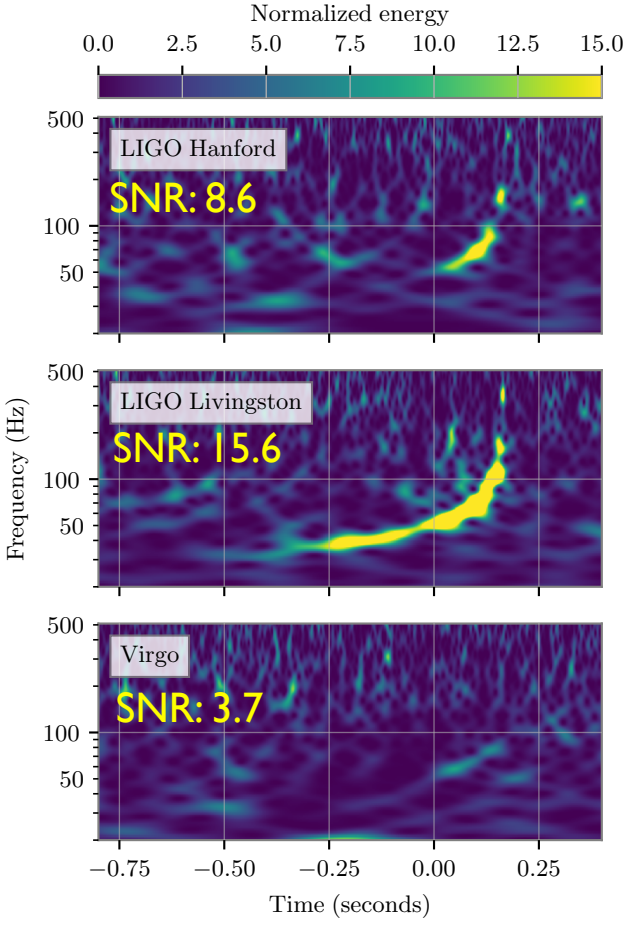
- Total mass ~ 3.4 $M_\odot$
  - Cannot rule out BBH or NSBH from GW data
  - See next talk for astrophysical implications

GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses Phys. Rev. D **102**, 043015 (2020)

GW190412: detection

- Publish on April 17, 2020
- First significantly asymmetric BBH
- Detected online by all pipelines
  - Network SNR ~ 19
  - Alert sent 60 minutes after event
  - Credible area: 156 deg^2 (90% CL)

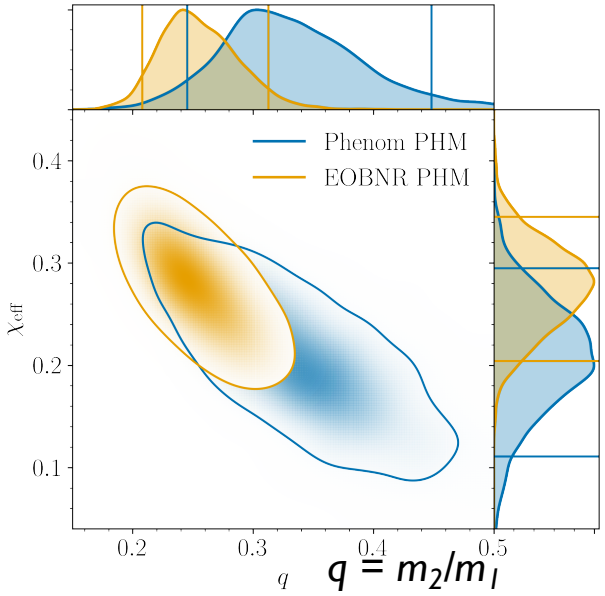


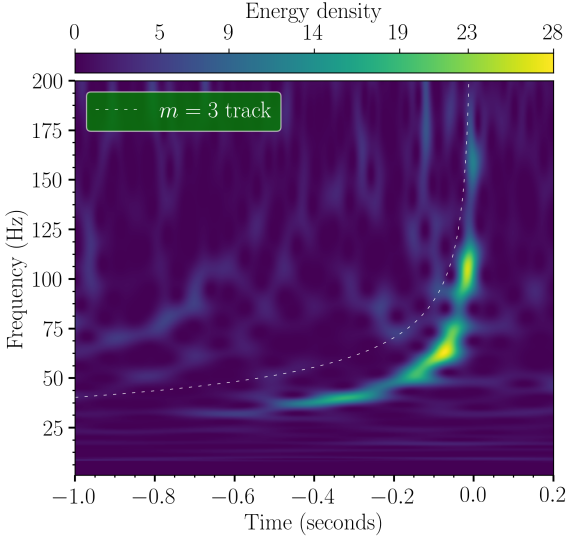


GW190412: Source properties

Parameter[a]	EOBNR PHM	Phenom PHM	Combined
$m_1/M_\odot$	$31.7^{+3.6}_{-3.5}$	$28.1^{+4.8}_{-4.3}$	$30.1^{+4.6}_{-5.3}$
$m_2/M_\odot$	$8.0^{+0.9}_{-0.7}$	$8.8^{+1.5}_{-1.1}$	$8.3^{+1.6}_{-0.9}$
D_L/Mpc	740^{+120}_{-130}	740^{+150}_{-190}	740^{+130}_{-160}
z	$0.15^{+0.02}_{-0.02}$	$0.15^{+0.03}_{-0.04}$	$0.15^{+0.03}_{-0.03}$
$\hat{\theta}_{JN}$	$0.71^{+0.23}_{-0.21}$	$0.71^{+0.39}_{-0.27}$	$0.71^{+0.31}_{-0.24}$

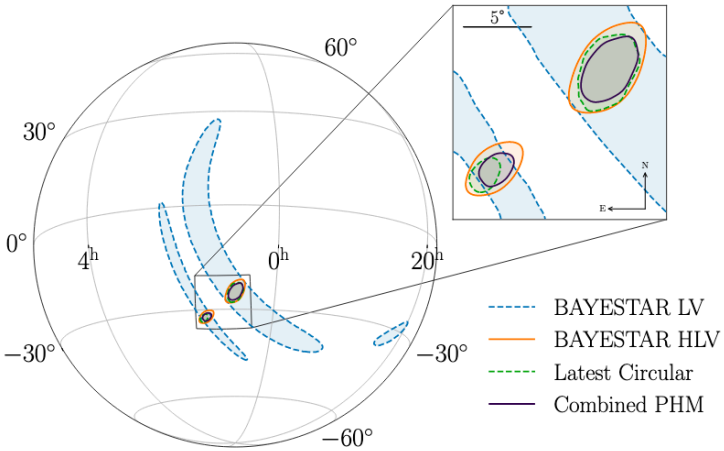
- Both models include precession and higher multipoles
  - Slightly different, yet largely consistent results
- Asymmetric BBH
- Effective spin of the more massive BH is the largest so far: $\chi_1 = 0.44^{+0.16}_{-0.22}$
- Moderate support for precession
- Higher harmonics
  - SNR increase by ~ one unit (from 18 to 19)
  - Break the degeneracy between luminosity distance and inclination angle



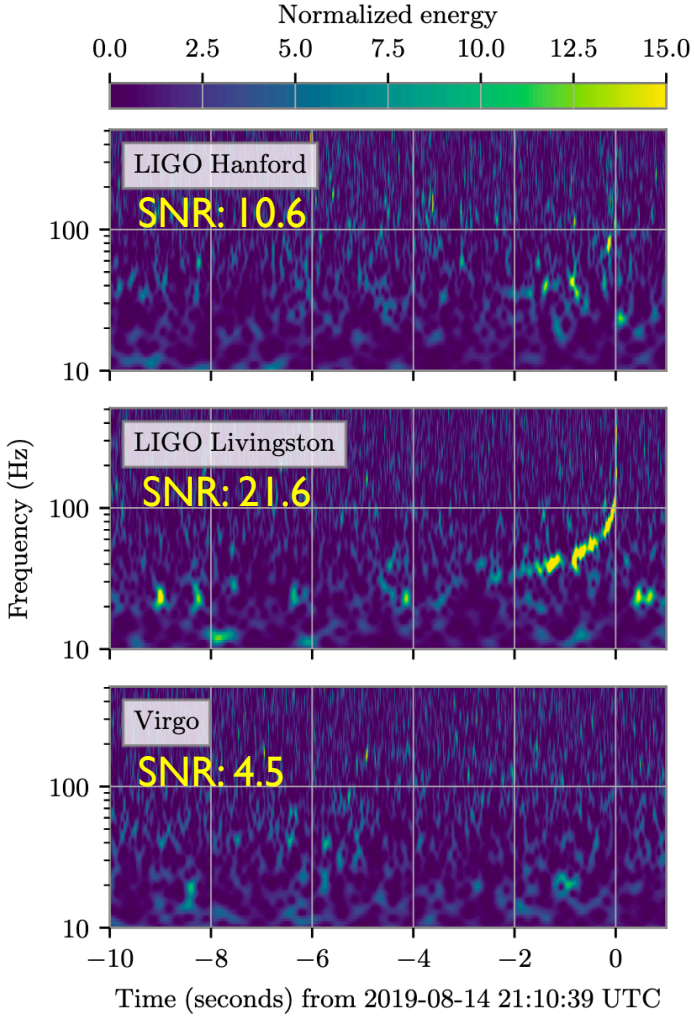


GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object Astrophys. J. Lett. **896**, L44 (2020)

- Publish on June 23, 2020
- BH + NS or BH ?
- Detected online by one pipeline
  - H1 not in observing mode but good data
  - Alert sent 20 minutes after event
- Offline analysis:
  - Network SNR ~ 25
  - Credible area: 18 deg^2 (90% CL)
  - Distance: 241^{+41}_{-45} Mpc

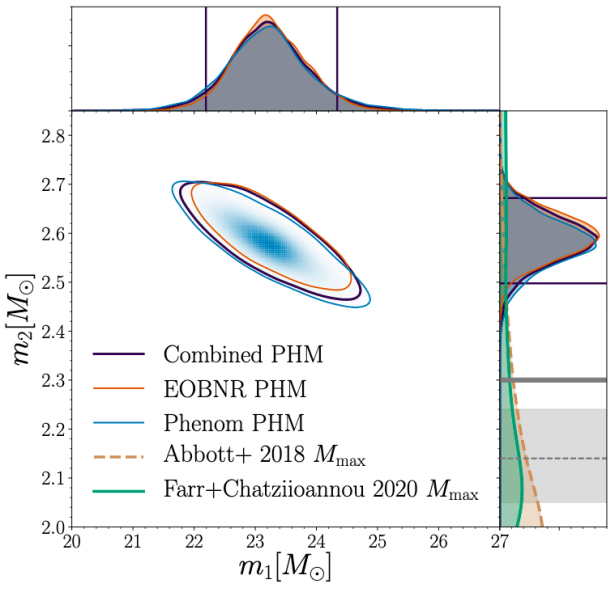


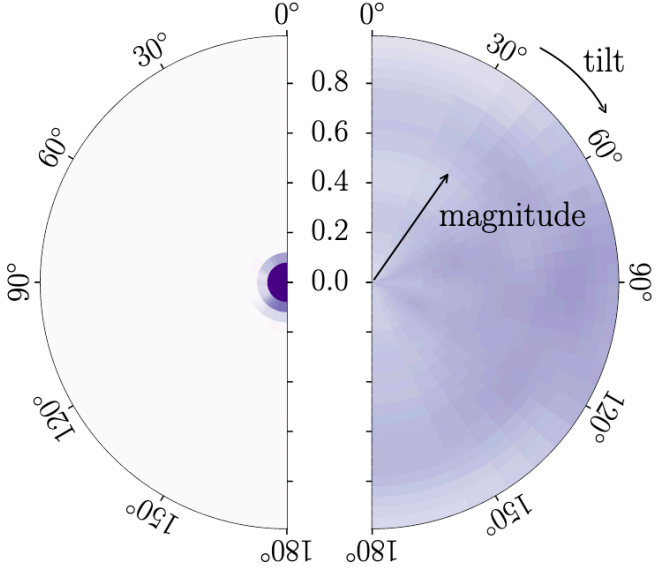
GW190814: detection



GW190814: source properties

- Individual masses well measured: 23 + 2.6 $M_\odot$
  - Most unequal mass ratio observed with GW
- Strongest constrain on a BH primary spin: $\chi_1 \leq 0.07$
- Stronger evidence than GW190412 for higher multipoles in the signal



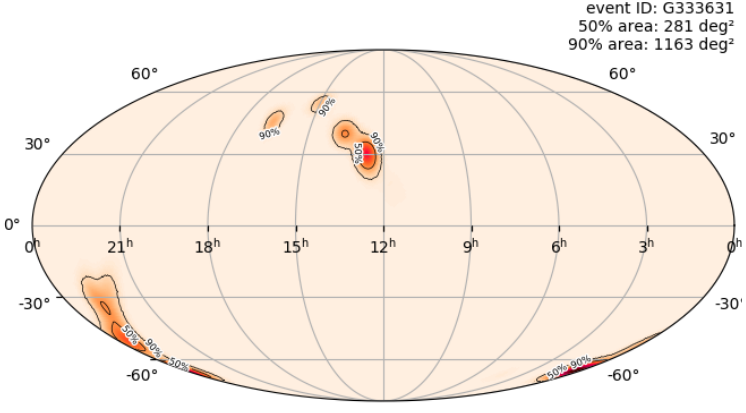


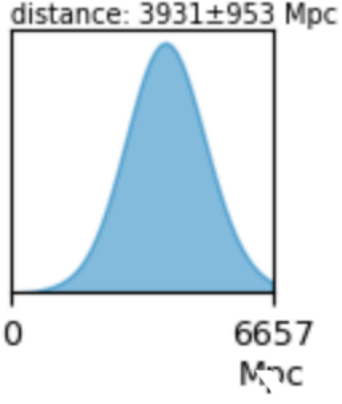
Title angle and spin magnitude
for the primary object (left) and secondary (right)

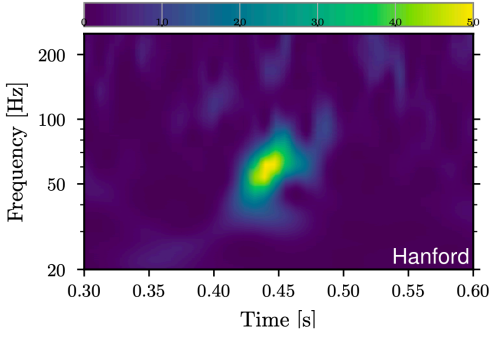
GW190521: A Binary Black Hole Merger with a Total Mass of 150 Msun [Phys. Rev. Lett. **125**, 101102 (2020)]

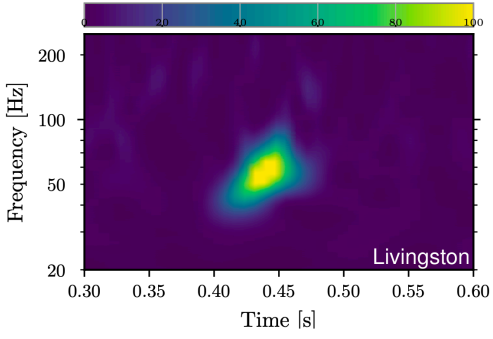
GW190521: detection

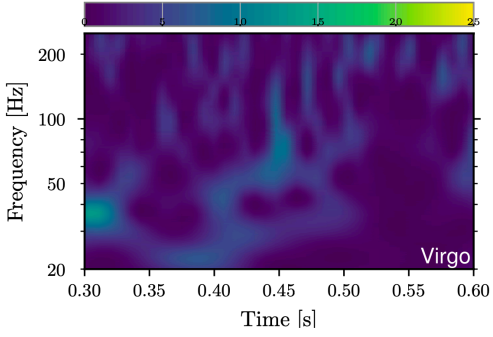
- Publish on Sep 2, 2020
- The heaviest BBH
- Detected online by burst and CBC pipelines
  - Network SNR ~ 15
  - Only few cycles: merge at ~ 60 Hz
  - Alert sent 6 minutes after event
  - Remark: another GW event reported on the same day
    - No overlapping sky positions
  - Credible area: 1163 deg^2 (90% CL)





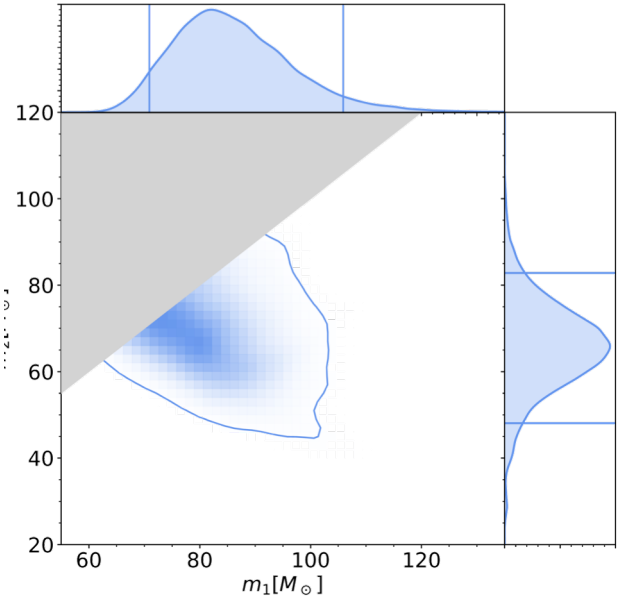


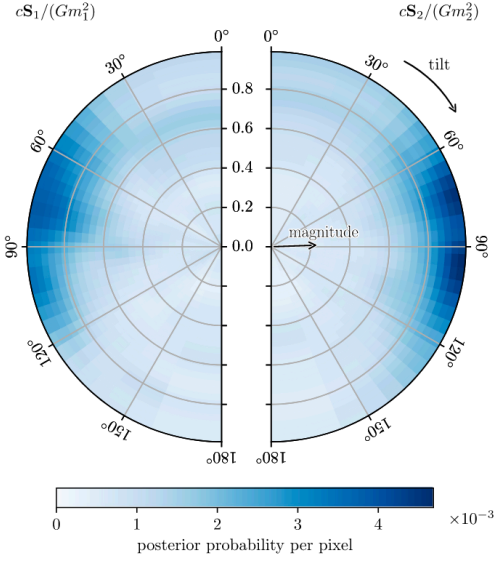




GW190521: source properties

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%





- Large masses,
- Probability spin vs no-spin: 8.3
- Probability precessing vs nonprecessing: 11.5
- Inclination angle: sin(θ) < 0.79 at 90 % CL → disfavor higher order multipoles

Summary

- O3: large improvements compared to O2
  - Detector sensitivity, duty cycle, data analysis
- 56 Public Alerts
- 4 new special events already published
- More papers to come
- O4 will be even more exciting!