LIGO-Virgo-KAGRA Observational Results and Outlook

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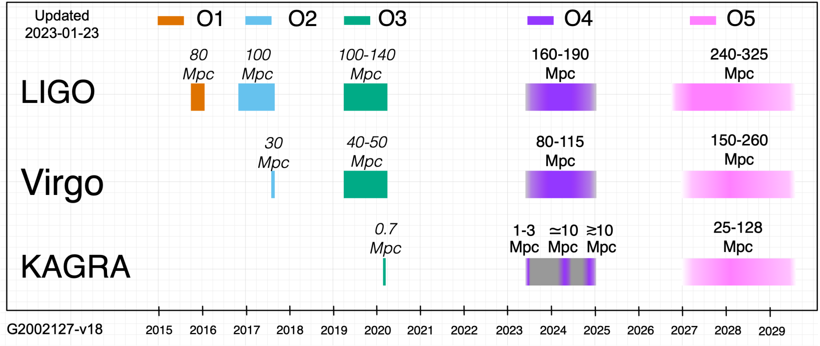
Gravitational-Wave Astronomy

- What are gravitational waves?
- Sources of gravitational waves?
- What sort of things can we learn from them?
- No time to discuss this, lots of presentations at this meeting about gravitational-wave astrophysics,
- let's assume you've heard these things already and dive right in ...

LIGO-Virgo-KAGRA Observation Schedule



- See https://observing.docs.ligo.org/plan/

O3 Observations — Compact Object Collisions

See https://pnp.ligo.org/ppcomm/Papers.html

- arXiv:2105.06384 [gr-qc]: "**Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run**"
- arXiv:2105.15120 [astro-ph.HE]: "**Search for intermediate mass black hole binaries in the third observing run of Advanced LIGO and Advanced Virgo**"
- arXiv:2106.15163 [astro-ph.HE]: "**Observation of gravitational waves from two neutron star–black hole coalescences**"
- arXiv:2111.03604 [astro-ph.CO]: "**Constraints on the cosmic expansion history from GWTC–3**"

O3 Observations — Compact Object Collisions

- arXiv:2111.03606 [gr-qc]: "**GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run**"
- arXiv:2111.03634 [astro-ph.HE]: "**The population of merging compact binaries inferred using gravitational waves through GWTC-3**"
- arXiv:2112.06861 [gr-qc]: "**Tests of General Relativity with GWTC-3**"
- arXiv:2212.01477 [astro-ph.HE]: "**Search for subsolar-mass black hole binaries in the second part of Advanced LIGO's and Advanced Virgo's third observing run**"

O3 Observations — Associated with EM Transients

- arXiv:2111.03608 [astro-ph.HE]: "**Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift During the LIGO-Virgo Run O3b**"
- arXiv:2203.12038 [astro-ph.HE]: "**Search for Gravitational Waves Associated with Fast Radio Bursts Detected by CHIME/FRB During the LIGO–Virgo Observing Run O3a**"
- arXiv:2210.10931 [astro-ph.HE]: "**Search for gravitational-wave transients associated with magnetar bursts in Advanced LIGO and Advanced Virgo data from the third observing run**"

O3 Observations — Stochastic GWs

- arXiv:2103.08520 [gr-qc]: "**Search for anisotropic gravitational-wave backgrounds using data from Advanced LIGO and Advanced Virgo's first three observing runs**"
- arXiv:2110.09834 [gr-qc]: "**All-sky, all-frequency directional search for persistent gravitational-waves from Advanced LIGO's and Advanced Virgo's first three observing runs**"
- arXiv:2201.10104 [gr-qc]: "**Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data**"
- arXiv:2209.02863 [astro-ph.HE]: "**Model-based Cross-correlation Search for Gravitational Waves from the Low-mass X-Ray Binary Scorpius X-1 in LIGO O3 Data**"

O3 Observations — More

- CW GWs from spinning neutron stars.
- Other GW transients (“bursts”), *e.g.* supernovæ, neutron star crust disruptions.
- Exotica, *e.g.* bursts from cosmic strings, GW interactions with scalar bosons, dark photos

O3 Highlights — KAGRA Joins (Sort of)

- Pandemic caused early termination of LIGO/Virgo O3 operations, before KAGRA could begin observations.
- A brief period of coincident operation with the GEO600 detector in Germany was accomplished.
- KAGRA sensitivity was far too low for a detection.
- Nevertheless, a useful exercise forcing end-to-end completion of the analysis
  - Stable observatory operations.
  - Automated data collection, calibration, distribution.
  - Detection software upgrades to support 4 detector network.
- We're ready, now we just need the detector sensitivity improved.

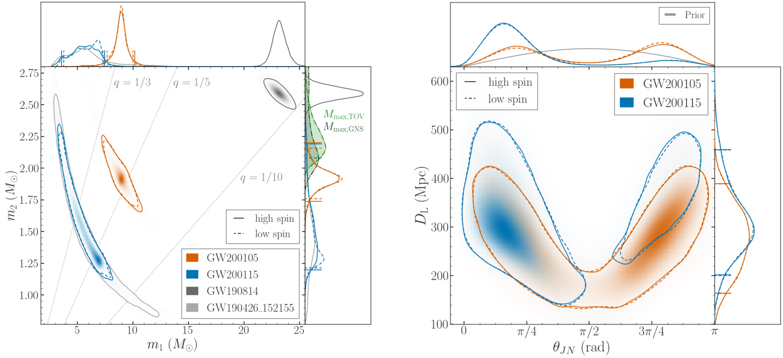
O3 Highlights — Neutron Star-Black Hole Collisions

- GW200105 and GW200115 (arXiv:2106.15163 [astro-ph.HE])
- First confident (?) identification of this class of binary system.
- Observed approximately 10 days apart near end of O3.
- NOTE: there is insufficient SNR to observe matter effects in the GWs.
- NOTE: no electromagnetic transients have been associated with either.
- Designation as "neutron star-black hole" collisions based purely on component masses inferred from GWs, and the assumption that all objects with those masses are neutron stars and black holes respectively.

O3 Highlights — Neutron Star-Black Hole Collisions

- GW200105 was initially not considered significant.
- Hanford was off, insufficient SNR in Virgo for detection: only detectable in Livingston ...
- ... and only the GstLAL detection system was capable of making single-detector signal identifications.
- Late in O3 GstLAL's model for the noise process had, over time, become contaminated with genuine signals diminishing the system's ability to distinguish between signals and noise.
- A prototype system running in parallel with experimental improvements to better clean signals contamination from the noise model assessed the signal to have a much higher significance.
- Manual follow-up by other detection tools confirmed the signal's presence.

O3 Highlights — Neutron Star-Black Hole Collisions



From LSC, Virgo, KAGRA, arXiv:2106.15163 [astro-ph.HE]

- Mass and distance (and orbit inclination) posterior PDFs.

O3 Highlights — Neutron Star-Black Hole Collisions

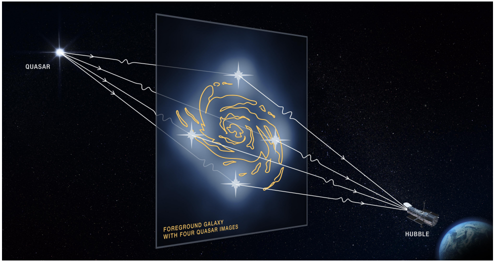
	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
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 $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$3.619^{+0.006}_{-0.006}$	$3.619^{+0.007}_{-0.008}$	$2.580^{+0.006}_{-0.007}$	$2.579^{+0.007}_{-0.007}$
Primary spin magnitude χ_1	$0.09^{+0.18}_{-0.08}$	$0.08^{+0.22}_{-0.08}$	$0.31^{+0.52}_{-0.29}$	$0.33^{+0.48}_{-0.29}$
Effective inspiral spin parameter χ_{eff}	$-0.01^{+0.08}_{-0.12}$	$-0.01^{+0.11}_{-0.15}$	$-0.14^{+0.17}_{-0.34}$	$-0.19^{+0.23}_{-0.35}$
Effective precession spin parameter χ_p	$0.07^{+0.15}_{-0.06}$	$0.09^{+0.14}_{-0.07}$	$0.19^{+0.28}_{-0.17}$	$0.21^{+0.30}_{-0.17}$
Luminosity distance D_{L}/Mpc	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

From LSC, Virgo, KAGRA, arXiv:2106.15163 [astro-ph.HE]

- Summary of NSBH properties.

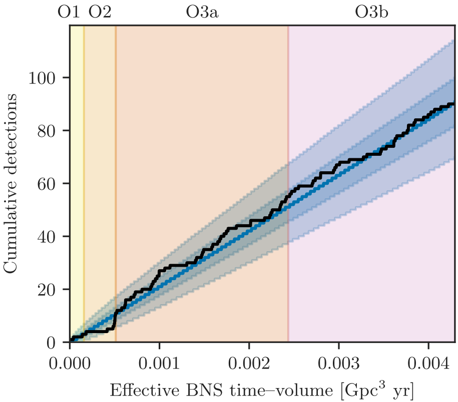
O3 Highlights — Neutron Star-Black Hole Collisions

- Lensed echoes?
- Because the two signals were seen just days apart after many observational runs, there was initial speculation that they were echoes of one another: a lensed GW signal.
- After proper parameter estimation, the inconsistency of the mass posteriors has ruled out this possibility: true lensed echoes would appear to be nearly identical.



NASA

O3 Highlights — Lots of Detections



From arXiv:2111.03606 [gr-qc]

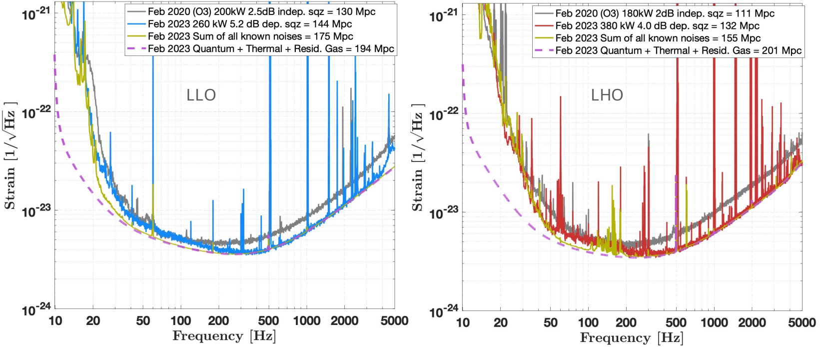
- NOTE: this plot mostly for entertainment purposes.
- Signal naming convention expanded to include time-of-day: *e.g.* "GW200105_162426", first potential NSBH discovery.

Coming in O4

- Both LIGO-Hanford and LIGO-Livingston have the goal of significantly increasing the laser power in the arm cavities.
- Nearly double, to 400 kW, or more.
- Close to this has been achieved for O(days) at a time, but still a work in progress.

Coming in O4

- Both LIGO-Hanford and LIGO-Livingston have improved optical squeezing: compared to O3, 25% reduction in strain noise amplitude for GW frequencies above about 400 Hz.
- Better measurements of properties of matter in neutron star collisions.



From Driggers, *et al.*, LIGO-G2300201, "NSF Annual Review of LIGO Laboratory & LSC"

Coming in O4 — New Discoveries?

With decreasing certainty:

- Early warning alerts. Machinery exists, is tested, but plumbing and procedures are not in place. Almost certainly will be seen before end of O4.
- A second joint GW-EM observation of a compact object collision. Duration of O4 extended to increase chances of this, but nothing can be guaranteed.
- Detection of an astrophysical stochastic background of GWs. Expected to *not* be observed this science run, but it might be close.

Bonus

Essentials of GW Detection

- Neymann-Pearson criterion and lemma:
    - when performing a hypothesis test between two point hypotheses, choose the discriminant that maximizes the detection efficiency given a fixed false-alarm probability;
    - the likelihood-ratio test satisfies this criterion.
- $$\Lambda(\theta) = \frac{P(\theta|\text{signal})}{P(\theta|\text{no signal})} \tag{1}$$

  where θ are your data, whatever it is you've observed.
- Choose a threshold: "$\Lambda(\theta) >$ threshold" extremizes detection efficiency for the false-positive rate corresponding to that choice of threshold.

Essentials of GW Detection

$$\Lambda(\theta) = \frac{P(\theta|\text{signal})}{P(\theta|\text{no signal})} \tag{2}$$

where θ are your data, whatever it is you've observed.

- What have we "observed", what's our data?
- Whole archive of strain time series not practical to work with.
- We convolve the data against a template bank of model waveforms — the "matched filter" algorithm — and use peak finding or threshold crossings to select data of interest.
- Yields a stream of candidates at a rate of several $\times 1\,\mathrm{MHz}$

Essentials of GW Detection

$$\Lambda(\theta) = \frac{P(\theta|\text{signal})}{P(\theta|\text{no signal})} \tag{3}$$

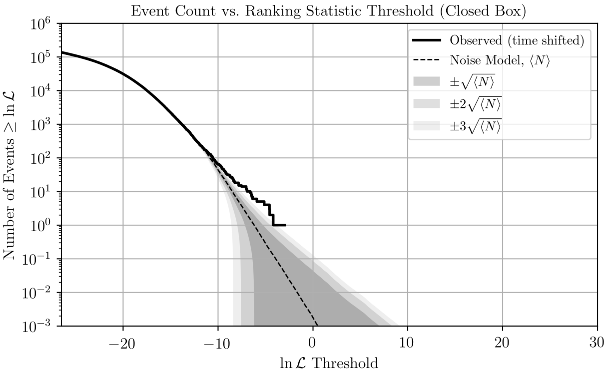
- For each candidate the “data”, θ, is not the strain, it’s a collection of parameters measured from the strain:
  - Which waveform template produced the candidate?
  - Which detectors produced a threshold crossing or peak and at precisely what time?
  - What were all detectors’ sensitivities to that waveform model? (Including the ones that didn’t report it.)
  - At what mean rate had each detector been producing candidates (false-positives).
  - With what amplitude, or “SNR”, was it seen in each detector that saw it?
  - For multi-phase waveforms, with what phase was seen in each detector?
  - If subtracted from each detector’s data, what sum-of-square residuals is observed in each detector? (usually called “χ squared”, but not always a χ^2-distributed RV)

Essentials of GW Detection

$$\Lambda(\theta) = \frac{P(\theta|\text{signal})}{P(\theta|\text{no signal})} \tag{4}$$

- Need
  - $P(\theta|\text{signal})$: construct analytically and/or numerically. Computationally expensive, and complex.
  - $P(\theta|\text{no signal})$: measure from data (assume noise-dominated regime). Noise processes are independent so models are simple, but need to exclude real signals using agnostic approach that does not introduce a self-selection bias, so gets tricky.
- For compact object merger search details, see C. Messick, *et al.*, Physical Review D, 95, 042001 (2017).

What Do We Do With It?



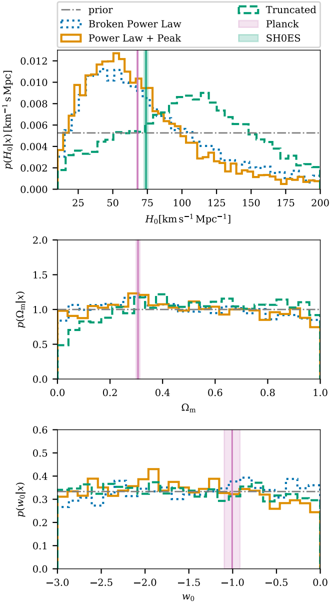
- Using $P(\theta|\text{no signal})$, predict $P(\Lambda > \Lambda_{\text{threshold}}|\text{no signal})$.
- Compare to observed fraction of events above threshold.
- Excess → detection.

What Do We Do With It?

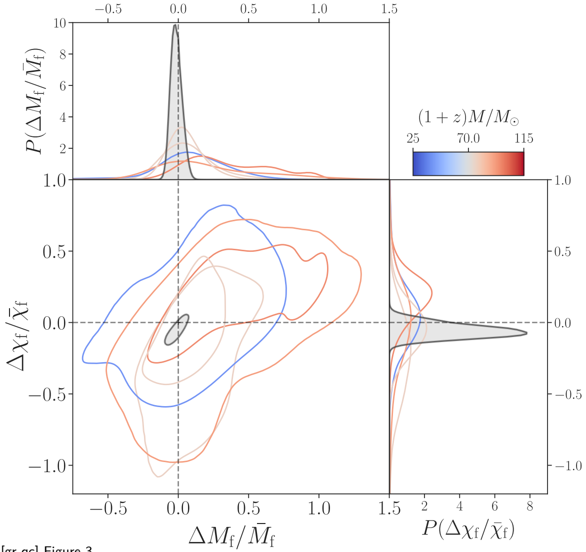
Estimate signal rate

$$P(R_\mathrm{s}, R_\mathrm{n}) \propto \left[\prod_{i=1}^{N} \left(\frac{R_\mathrm{s}}{R_\mathrm{n}}\Lambda(\theta_i) + 1\right)\right] R_\mathrm{n}^N \exp[-(R_\mathrm{s} + R_\mathrm{n})] \frac{1}{\sqrt{R_\mathrm{s} R_\mathrm{n}}}$$

- $R_\mathrm{s} = \#$ signal events/experiment
- $R_\mathrm{n} = \#$ noise events/experiment
- See W. Farr, *et al.*, “Counting And Confusion: Bayesian Rate Estimation With Multiple Populations”, Physical Review D, 91, 023005 (2015).



arXiv:2111.03604 [astro-ph.CO] Figure 4



arXiv:2112.06861 [gr-qc] Figure 3