The LIGO-Virgo Low-latency Campaign & Public Alerts In The Third Observing Run

ICTS Seminar
Bengaluru, India

Deep Chatterjee [1] [2]

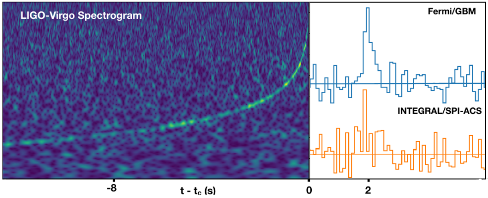
[1]University of Wisconsin – Milwaukee

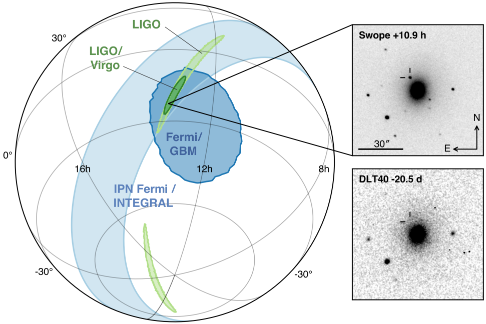
[2]LIGO–Virgo Collaboration

January 28, 2020

Premise

GW170817



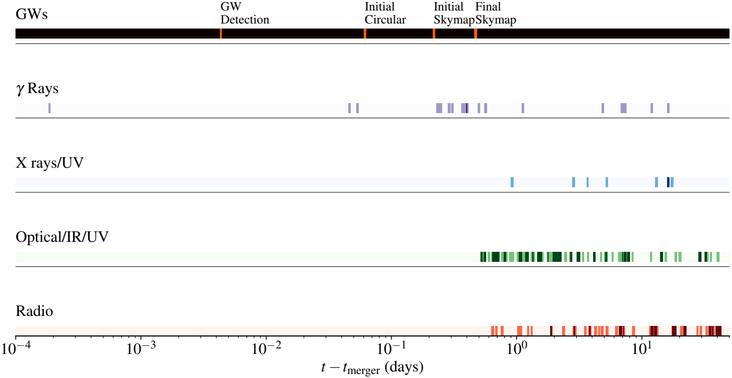


GW170817 (Abbott et al., 2017c)
GRB 170817A (Goldstein et al., 2017; Abbott et al., 2017b)

SSS17a
EM170817
⋮
AT 2017gfo (Abbott et al., 2017d)

Notice Timeline

Unprecedented Follow-up Operations



Radio, X-ray follow-up operations $\sim$ 1yr.

Speed of gravity $= c$?

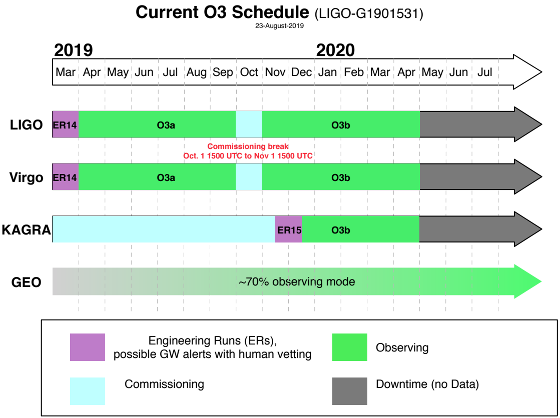
On August 17, it was established correct up to 15 decimal places!

The Story it Told...

Astronomy, Astrophysics & Cosmology

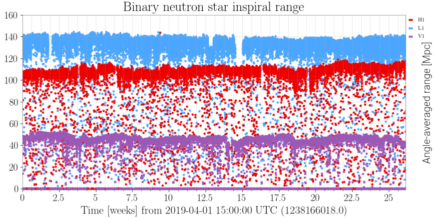
- Physics of "kilonova" (Abbott et al., 2017a,d)
- Independent measurement of H_0 (The LIGO Scientific Collaboration et al., 2017)
- Tidal deformability & neutron star equation of state (Abbott et al., 2018)
- Progenitor model (Abbott et al., 2017e)
- Post-merger remnant (Abbott et al., 2017f; Abbott et al., 2019b)
- Merger rates (Abbott et al., 2019a)

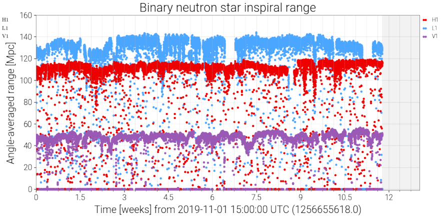
Third Observing Run **O3**



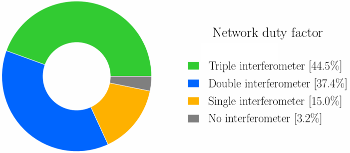
33 public GW candidates in LIGO-Virgo O3a
14 public GW candidates in O3b so far

Detectors in O3



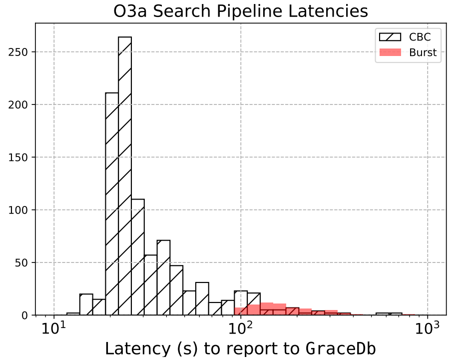


Detector	BNS range (Mpc)
LIGO-Livingston	~ 135
LIGO-Hanford	~ 110
Virgo	~ 50



KAGRA expected to join in O3b

Search Pipelines



- Compact Binary Coalescence (CBC) searches: `GstLAL`, `PyCBC`, `MBTAOnline`, `SPIIR`
  - Most CBC candidates processed in $\lesssim 1$ minute.
- Unmodeled Burst searches: `cWB`
  - Three independent searches: `AllSky`, `BBH`, `IMBH`.
  - Candidates reported $\simeq$ minutes.

Superevents

Unification of candidates corresponding to the same physical event.

UID	Labels	Preferred Event	GW events
S191129u	EM_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	G355916	G355991, G355990, G355989, G355988, G355987,
S191124be	ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	G355462	G355462
S191120at	ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	G355100	G355101, G355100, G355099

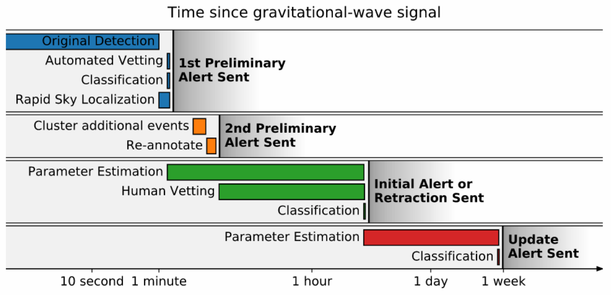
`S200128abc`: prefix, UTC date, incremental suffix (`a, b, ..., aa, ...`)

Preferred event selection criteria

1. CBC candidates preferred over Burst candidates.
2. Among CBC, prefer higher number of participating interferometers.
3. Further tie is broken by a detection statistic.

Open Public Alerts

For the first time, LIGO-Virgo Alerts are public!



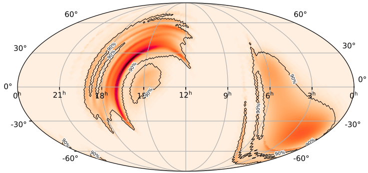
Public alert threshold False Alarm Rate (FAR)

- CBC: FAR $\leq 1/(2 \text{ months}) \xrightarrow[\text{Effectively}]{\text{4 searches}} \leq 1/(8 \text{ months})$
- Burst: FAR $\leq 1/(1 \text{ years}) \xrightarrow[\text{Effectively}]{\text{3 searches}} \leq 1/(3 \text{ years})$

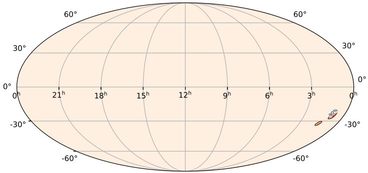
Human vetting could lead to a *retraction*.

Data Products

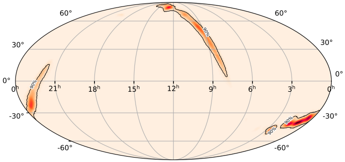
Sky Localization



(a) S190425z

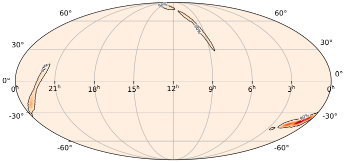


(b) S190814bv



(c) S191105e Initial

$\Rightarrow$

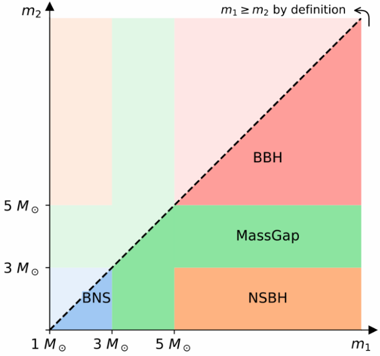


(d) S191105e Updated

Supplied with initial & update notices.

Source Classification in **O3**

Classification based on trigger history



Λ_0: Terrestrial trigger counts

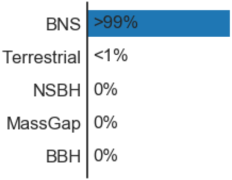
Λ_α: Astrophysical trigger counts; $\alpha \in \{\text{BNS, NSBH, BBH, MassGap}\}$

$$p(\Lambda_0, \Lambda_\alpha | \vec{x}_N) \propto p(\Lambda_0, \Lambda_\alpha) \times \prod_{j=1}^{N} [\underbrace{b(x_j)}_{\text{background}} \Lambda_0 + \underbrace{f_\beta(x_j)}_{\text{foreground}} \Lambda_\beta] e^{-\Lambda_0 - \sum_\beta \Lambda_\beta}$$

$$P_\alpha(x_{N+1} | \vec{x}_N) = \frac{\langle \Lambda_\alpha \rangle_N \overset{f_\alpha / b}{K_\alpha}(x_{N+1})}{\langle \Lambda_0 \rangle_N + \langle \Lambda_\beta \rangle_N K_\beta(x_{N+1})}$$

(see Farr et al., 2015; Kapadia et al., 2019).

Source Classification in **O3**

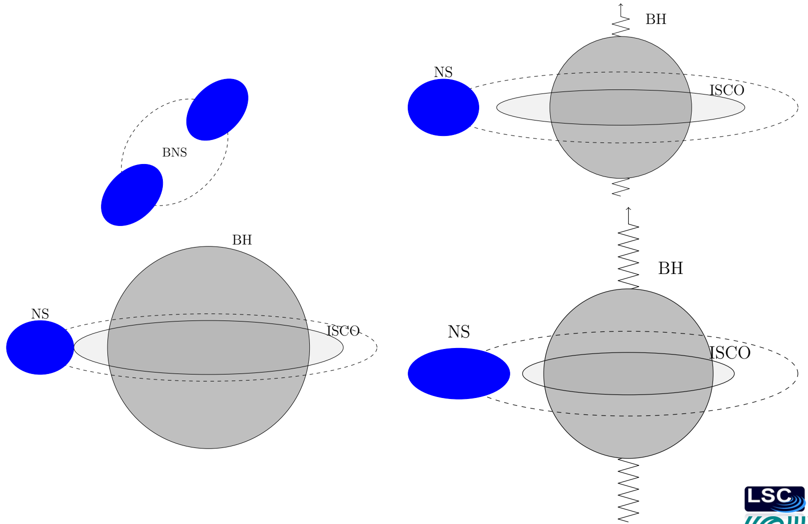


Values for S190425z

- Reported as a part of the notices in **O3**
- 5 values summing up to unity: $P_{\mathrm{BNS/NSBH/BBH/MassGap/Terrestrial}}$

Source Properties in O3

Possibility of Electromagnetic Counterparts



HasNS & HasRemnant

HasNS

$$m_2 \leq 3M_\odot$$

Model independent.

HasRemnant

Remnant disk mass $\rightarrow$ tidal disruption, potential of counterparts
Calculated using fit due to Foucart et al. (2018):

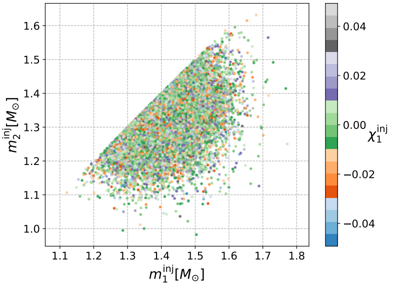
$$M_{\text{rem}}(\underbrace{m_1, m_2, \chi_1^z}_{\text{GW template}}) = M_{\text{rem}}(\underset{\substack{\uparrow \\ \text{needs EoS}}}{C_{\text{NS}}}, \eta, R_{\text{ISCO}}) > 0M_\odot$$

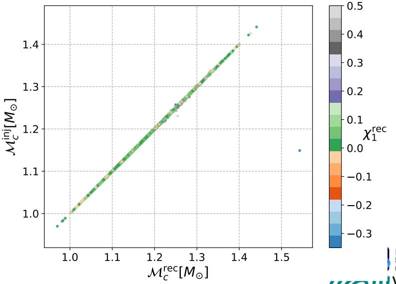
More constrained, requires compactness, EoS dependent.[1]

[1] Currently, 2H Kyutoku et al. (2010) EoS being used.

Inference From Online Searches

- GW template based analyses.
- Detect GW candidates ∼ sub-minute latency.
- Maximize detection efficiency at fixed false alarm.
- *Accurate parameter recovery* is left to bayesian parameter inference. [1]



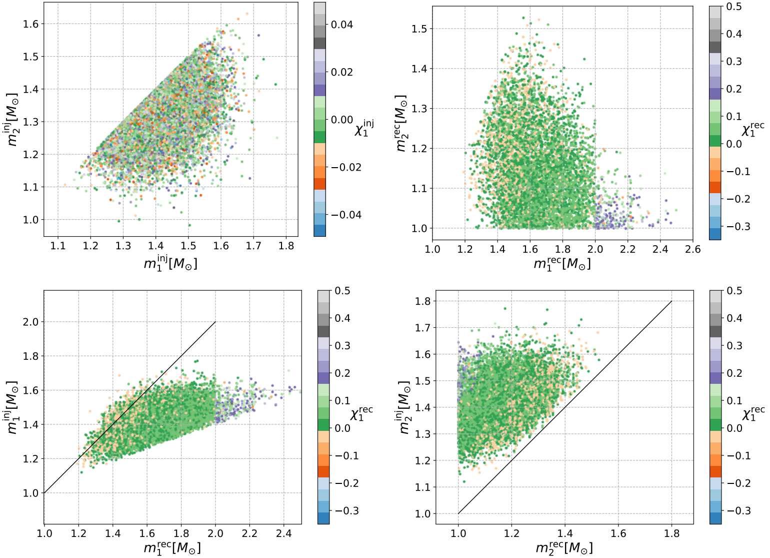


[1] LALInference software library Veitch et al. (2015)

[2] Plots are for the GstLAL search

Inference From Online Searches

Component masses and spins



LIGO Scientific Collaboration

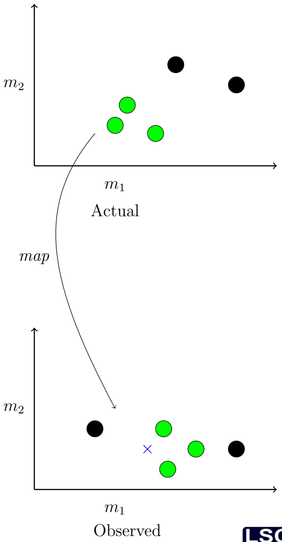
VIRGO

Supervised Binary Classification

Feature space

$$\beta = \{\underbrace{m_1, m_2}_{\text{masses}}, \overbrace{\chi_1^z, \chi_2^z}^{\text{spins}}, \underset{\text{SNR}}{\underset{\uparrow}{\rho}}\}.$$

- `KNeighborsClassifier` from `scikit-learn` library.
- Non-parametric.
- Intuition of a *map*.
- Use 11 $(2 \times \# \text{ dims} + 1)$ neighbors to fit.

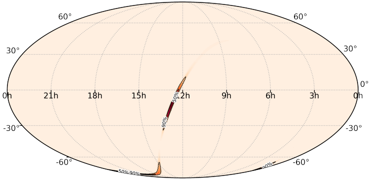


Chatterjee et al. (2019).

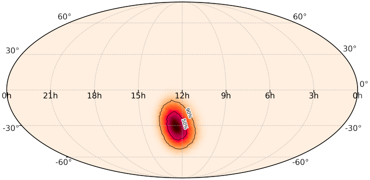
Recent Alerts in **O3**

Superevent	HasNS	HasRemnant
https://gracedb.ligo.org/superevents/S190930t/	1.0	0.0
https://gracedb.ligo.org/superevents/S190930s/	0.0	0.0
https://gracedb.ligo.org/superevents/S190928c/	–	–
https://gracedb.ligo.org/superevents/S190924h/	0.3	0.0

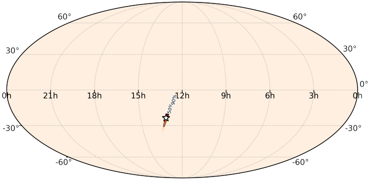
External Coincidences and Combined skymaps



(a) GW170817 (HL)



(b) Fermi GBM

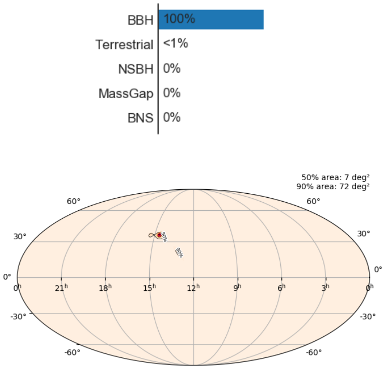


(c) Combined

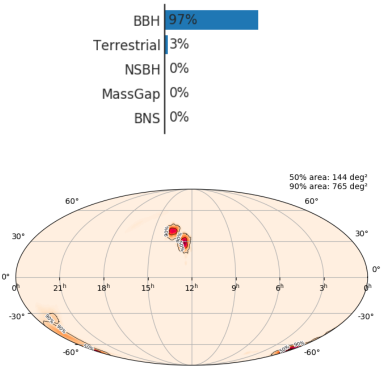
Subthreshold GW candidates elevated above public threshold via external coincidences.

Candidates From O3a: 33 Total

Working on individual papers for some



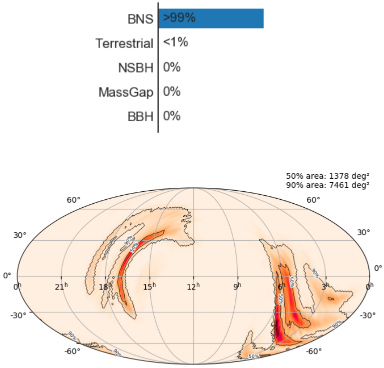
S190412m



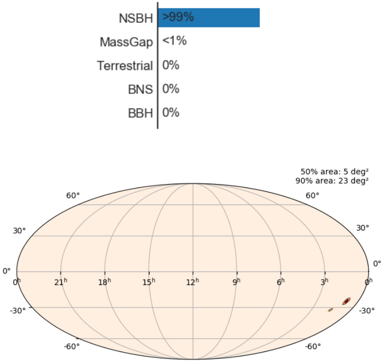
S190521g

Candidates From **O3**a: 33 Total

Working on individual papers for some



S190425z[2]



S190814bv

[2] (see The LIGO Scientific Collaboration et al., 2020)

No Counterparts Observed Yet

Extensive follow-up for S190425z, S190426c, S190814bv

P. Kuin et al. LIGO/Virgo S190425z: Swift UVOT - no new sources identified, and a summary of the Swift UVOT processing of GW triggers. GRB Coordinates Network, 24673, 2019.

B. Gendre et al. LIGO/Virgo S190425z: No counterpart candidate in Zadko-GRANDMA observations. GRB Coordinates Network, 24767, 2019.

L Singer et al. LIGO/Virgo S190814bv: No candidates from the Zwicky Transient Facility. GRB Coordinates Network, 25343, 2019.

S. Yang et al. LIGO/Virgo S190814bv: No counterpart candidate after completion of GRAWITA VST-ESO PARANAL transient survey. GRB Coordinates Network, 25748, 2019.

Some potential candidates, but possibly unrelated:

I. Andreoni et al. LIGO/Virgo S190814bv: DECam-GROWTH detection of an optical counterpart to the radio source AT2019osy. GRB Coordinates Network, 25488, 2019.

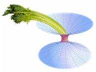
K. Herner et al. LIGO/Virgo S190814bv: DESGW non-detection of AT2019osy/ASKAP 005547-270433. GRB Coordinates Network, 25495, 2019.

No convincing candidates observed.[3]

[3] https://gcn.gsfc.nasa.gov/gcn3_archive.html

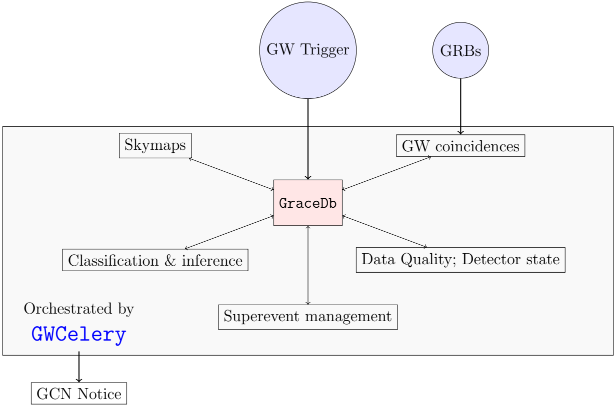
Software Infrastructure

Orchestrating using GWCelery[4]



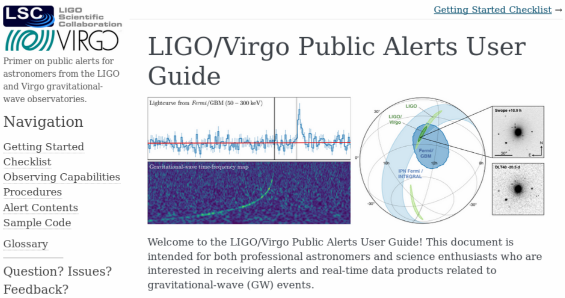
GWCelery

GWCelery is a simple and reliable package for annotating and orchestrating LIGO/Virgo alerts, built from widely used open source components.



4 https://gwcelery.readthedocs.io/

Userguide for alerts in **O3**


Getting Started Checklist →

LIGO Scientific Collaboration

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

Navigation

- Getting Started Checklist
- Observing Capabilities
- Procedures
- Alert Contents
- Sample Code
- Glossary

Question? Issues? Feedback?

LIGO/Virgo Public Alerts User Guide

Welcome to the LIGO/Virgo Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

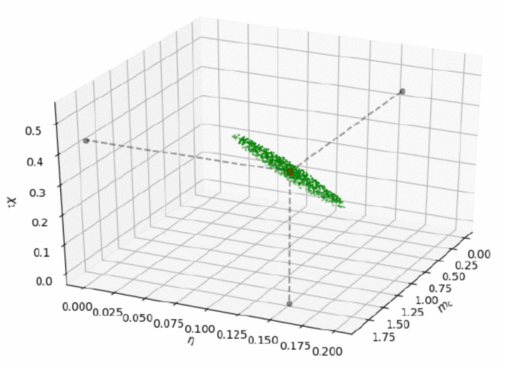
https://emfollow.docs.ligo.org/userguide/

Extra Slides

Method of ellipsoids, used during LIGO-Virgo O2

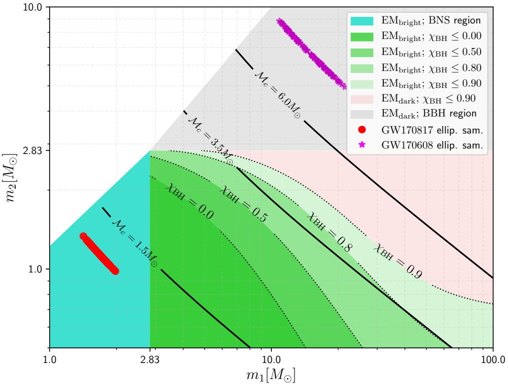
- Ambiguity ellipsoid constructed using Fisher approximation
- 90% confidence region populated with *ellipsoid* samples
- Fraction of *bright* samples gives probability

Statistical uncertainties ✓
Search systematics ✗



Extra Slides

Source-classification detailed



Abbott, B. P., Abbott, R., Abbott, T. D., et al. (2019a). Binary black hole population properties inferred from the first and second observing runs of advanced LIGO and advanced virgo. *The Astrophysical Journal*, 882(2):L24.

Abbott, B. P., Abbott, R., Abbott, T. D., et al. (2019b). Search for gravitational waves from a long-lived remnant of the binary neutron star merger GW170817. *The Astrophysical Journal*, 875(2):160.

Abbott, B. P. et al. (2017a). Estimating the contribution of dynamical ejecta in the kilonova associated with GW170817. *The Astrophysical Journal*, 850(2):L39.

Abbott, B. P. et al. (2017b). Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. *The Astrophysical Journal Letters*, 848:L13.

Abbott, B. P. et al. (2017c). GW170817: Observation of gravitational waves from a binary neutron star inspiral. *Phys. Rev. Lett.*, 119:161101.

Abbott, B. P. et al. (2017d). Multi-messenger Observations of a Binary Neutron Star Merger. *ApJ Lett.*, 848:L12.

Abbott, B. P. et al. (2017e). On the progenitor of binary neutron star merger GW170817. *The Astrophysical Journal*, 850(2):L40.

Abbott, B. P. et al. (2017f). Search for Post-merger Gravitational Waves from the Remnant of the Binary Neutron Star Merger GW170817. *ApJ Lett.*, 851:L16.

Abbott, B. P. et al. (2018). GW170817: Measurements of Neutron Star Radii and Equation of State. *Phys. Rev. Lett.*, 121:161101.

Chatterjee, D., Ghosh, S., Brady, P. R., Kapadia, S. J., Miller, A. L., Nissanke, S., and Pannarale, F. (2019). EM Bright: Supervised learning based source property inference for compact binary mergers. *submitted to ApJ*.

Farr, W. M., Gair, J. R., Mandel, I., and Cutler, C. (2015). Counting and confusion: Bayesian rate estimation with multiple populations. *Physical Review D*, 91(2).

Foucart, F., Hinderer, T., and Nissanke, S. (2018). Remnant baryon mass in neutron star-black hole mergers: Predictions for binary neutron star mimickers and rapidly spinning black holes. *Phys. Rev. D*, 98:081501.

Goldstein, A. et al. (2017). An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi-GBM Detection of GRB 170817A. *ApJL*, 848:L14.

Kapadia, S. J., Caudill, S., Creighton, J. D. E., Farr, W. M., Mendell, G., Weinstein, A., Cannon, K., Fong, H., Godwin, P., Lo, R. K. L., Magee, R., Meacher, D., Messick, C., Mohite, S. R., Mukherjee, D., and Sachdev, S. (2019). A self-consistent method to estimate the rate of compact binary coalescences with a Poisson mixture model. *arXiv e-prints*, page arXiv:1903.06881.

Kyutoku, K., Shibata, M., and Taniguchi, K. (2010). Gravitational waves from nonspinning black hole-neutron star binaries: dependence on equations of state. *Phys. Rev.*, D82:044049. [Erratum: Phys. Rev.D84,049902(2011)].

The LIGO Scientific Collaboration, the Virgo Collaboration, and Abbott (2020). GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_{\odot}$. *arXiv e-prints*, page arXiv:2001.01761.

The LIGO Scientific Collaboration, The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM

Collaboration, The DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration, and The MASTER Collaboration (2017). A gravitational-wave standard siren measurement of the Hubble constant. *Nature*, 551(7678):85–88.

Veitch, J., Raymond, V., Farr, B., Farr, W., Graff, P., Vitale, S., Aylott, B., Blackburn, K., Christensen, N., Coughlin, M., Del Pozzo, W., Feroz, F., Gair, J., Haster, C.-J., Kalogera, V., Littenberg, T., Mandel, I., O'Shaughnessy, R., Pitkin, M., Rodriguez, C., Röver, C., Sidery, T., Smith, R., Van Der Sluys, M., Vecchio, A., Vousden, W., and Wade, L. (2015). Parameter estimation for compact binaries with ground-based gravitational-wave observations using the lalinference software library. *Phys. Rev. D*, 91:042003.