Gravitational wave observations: What have we learned so far?

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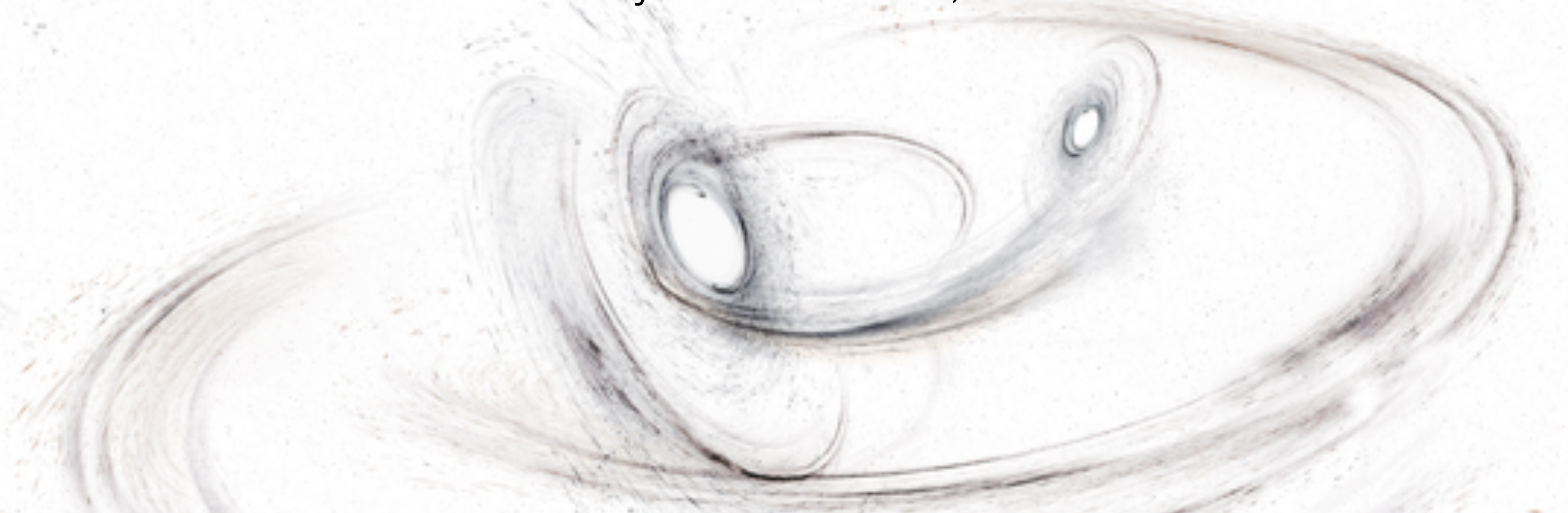


Chennai Symposium on Gravitation and Cosmology

February 4, 2022

Background image credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

Caltech

UNIVERSITY of WISCONSIN UWMILWAUKEE

LSC LIGO Scientific Collaboration

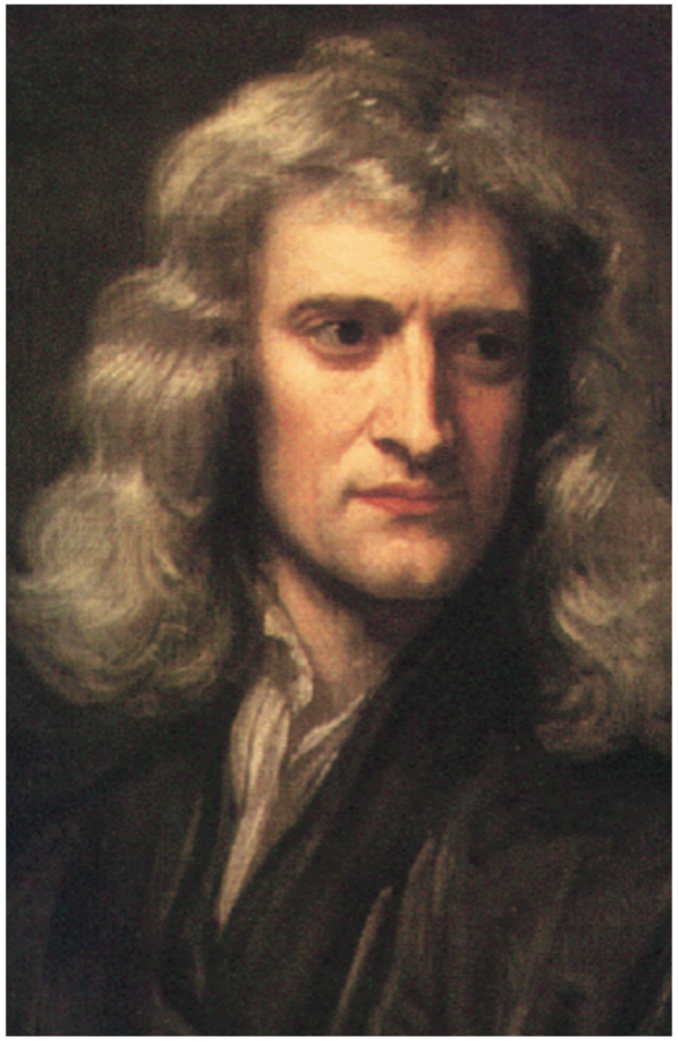
VIRGO

NSF

Outline

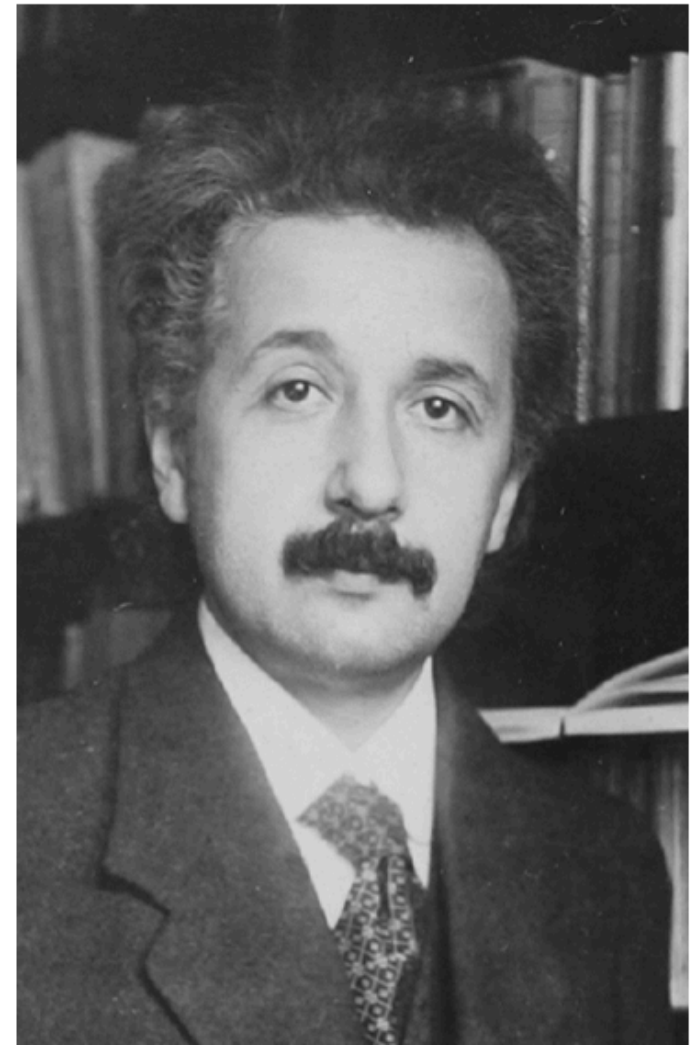
- Gravitational waves
- Compact Binary Coalescences
- Analysis workflow of Advanced LIGO and Virgo data
- Highlights from the third observing run
- Going Forward - Near Term - Multi-messenger astronomy
- What we have learned from GW observations

Gravitational Waves



$$F = m_1 a = G\frac{m_1 m_2}{r^2}$$

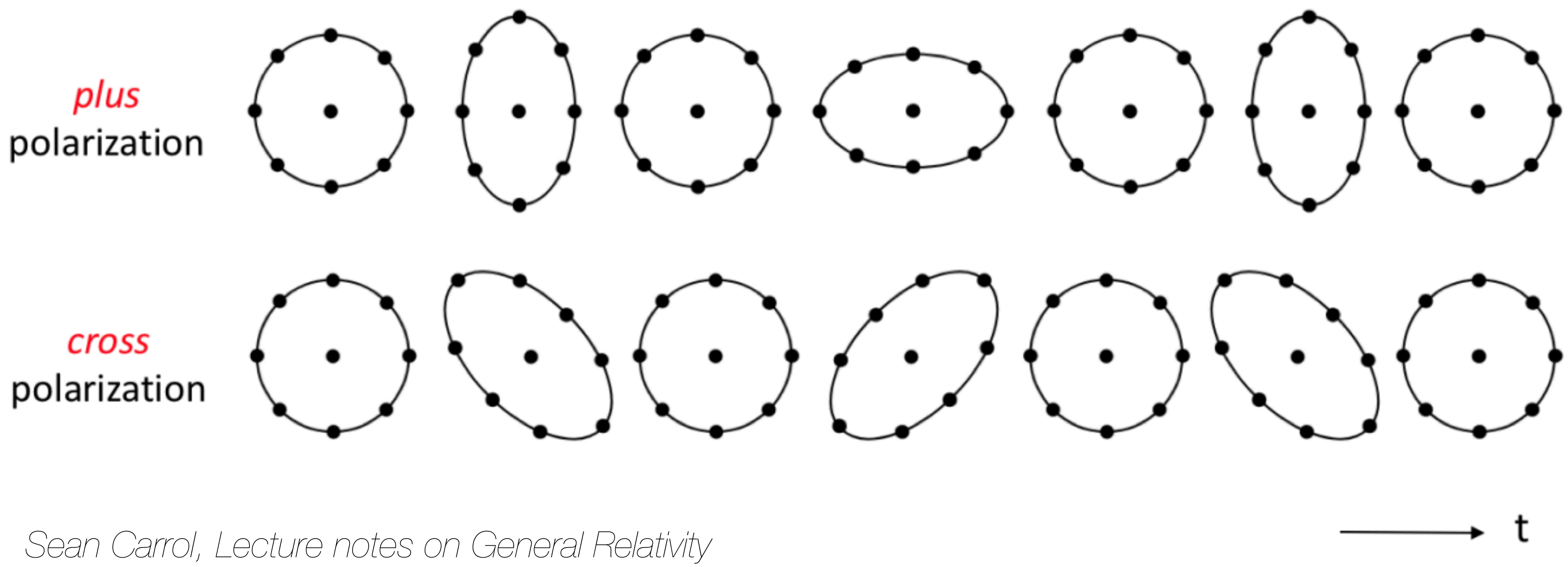
Instantaneous action
at a distance



$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Information about changing gravitational field is carried by gravitational radiation **at the speed of light**

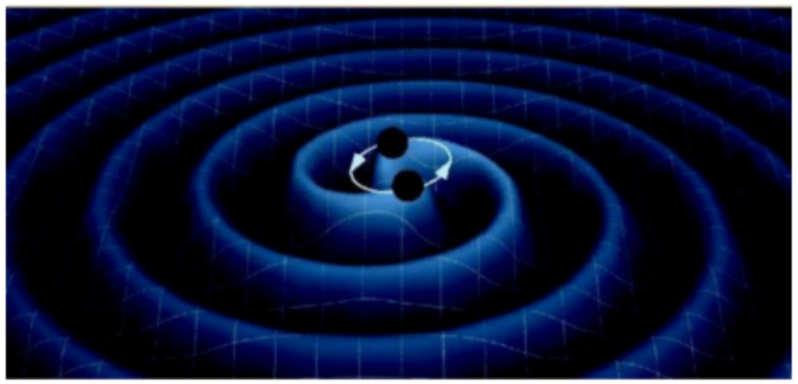
Effect of gravitational waves



Sean Carrol, Lecture notes on General Relativity

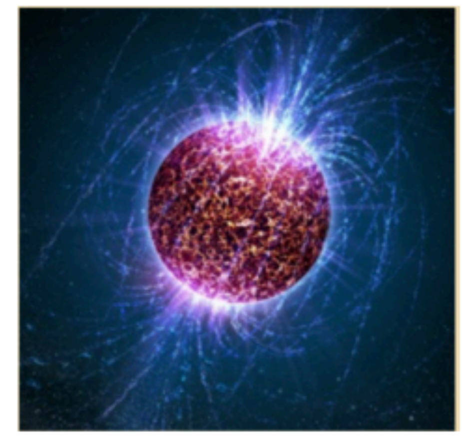
$$h \sim \frac{\Delta L}{L}$$

Binary megers



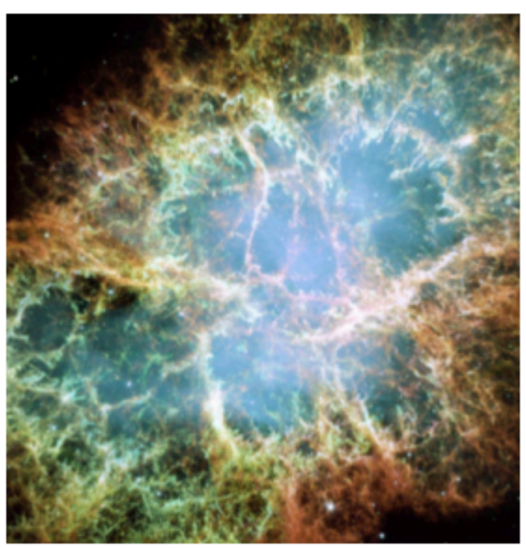
Binary Neutron Stars, Neutron Star Black Holes, Binary Black Holes

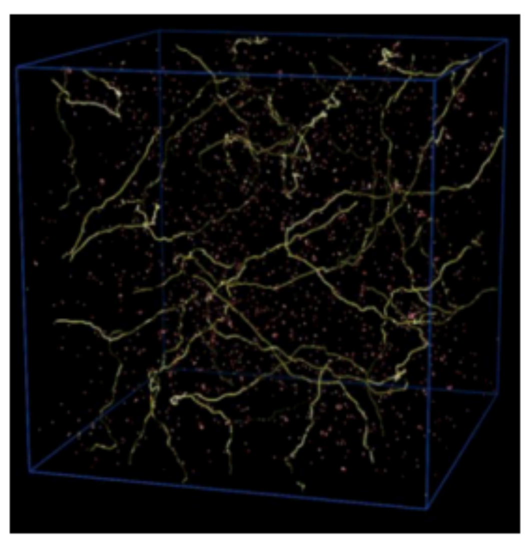
Continuous waves



Non-axisymmetric pulsars

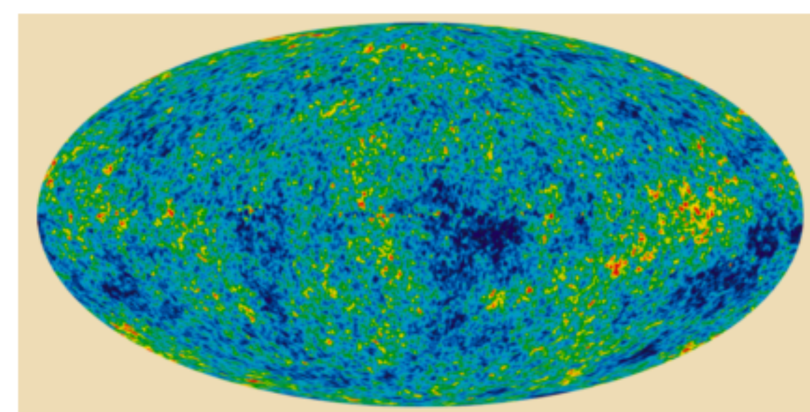
Burst





Supernovae

Stochastic



Radiation from early universe, superposition of CBCs

LIGO, Virgo, KAGRA

$$h \sim \frac{\Delta L}{L}$$

Binary Neutron Star (BNS) range in O3:

LIGO Hanford: ~ 110 Mpc
LIGO Livingston: ~ 135 Mpc
Virgo: ~ 45–50 Mpc

Expected in O4:

LIGO: ~ 160–190 Mpc
Virgo: ~ 80–115 Mpc
KAGRA: > 1 Mpc

BNS range is the distance at which on average a $1.4 : 1.4\ M_\odot$ source would produce an SNR of 8.

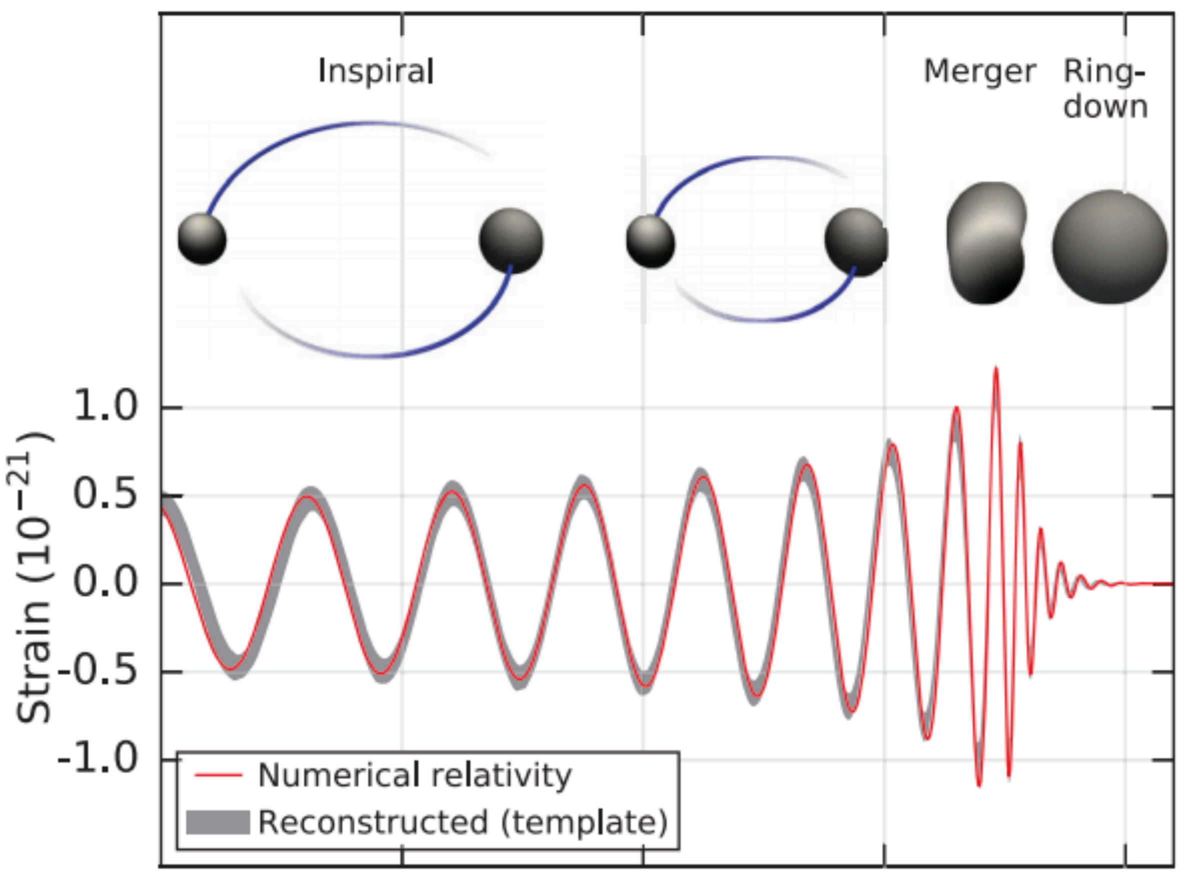
KAGRA, illustrated at top right, will join a network of gravitational-wave observatories that includes LIGO Hanford (top left), LIGO Livingston (bottom right), and Virgo (bottom left). Image credit: ICRR, Univ. of Tokyo/LIGO Lab/Caltech/MIT/Virgo Collaboration.

First Observing Run

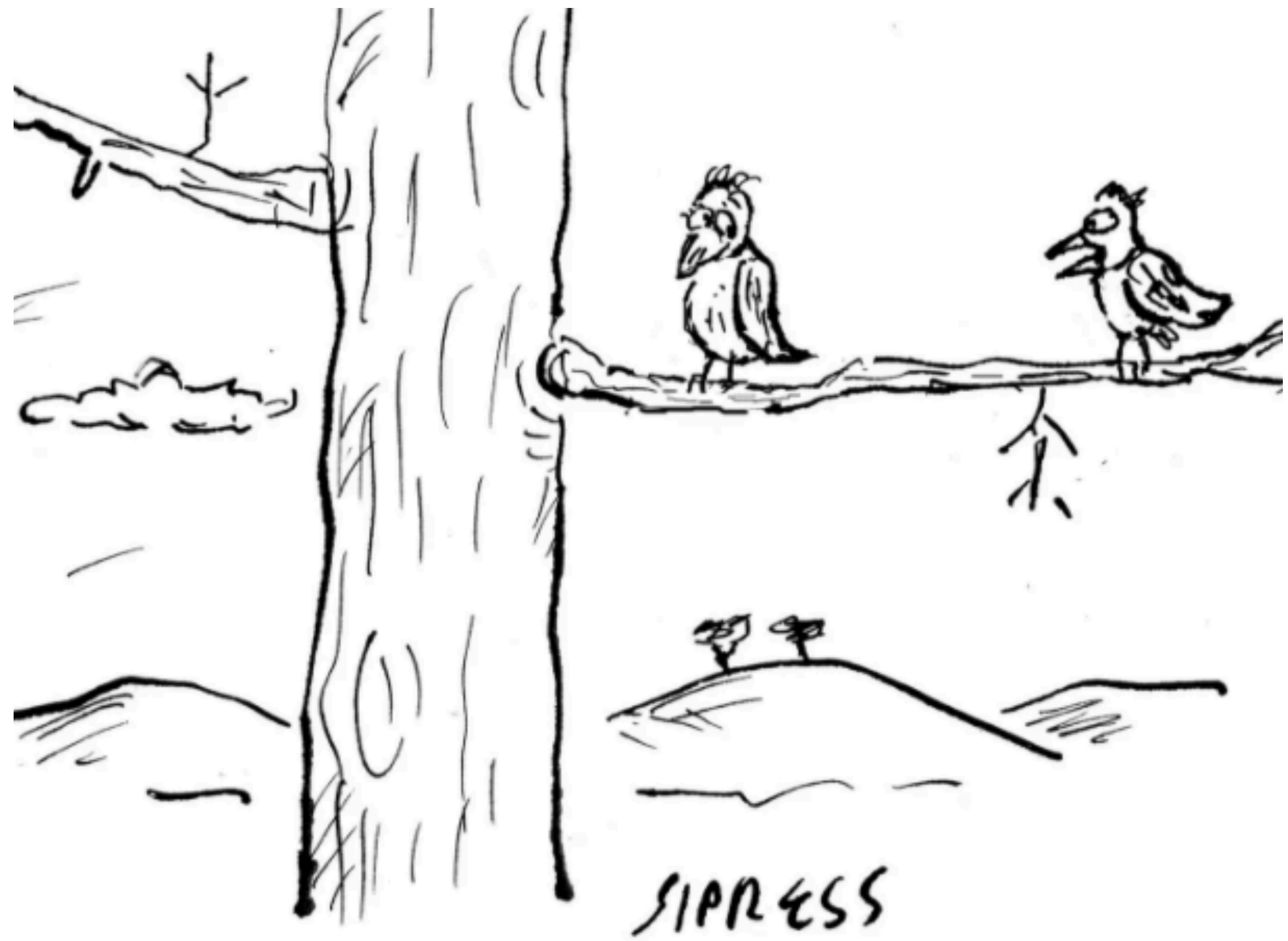
O1: September 12, 2015 to January 19, 2016

Start of GW astronomy

First BBH detection: GW150914

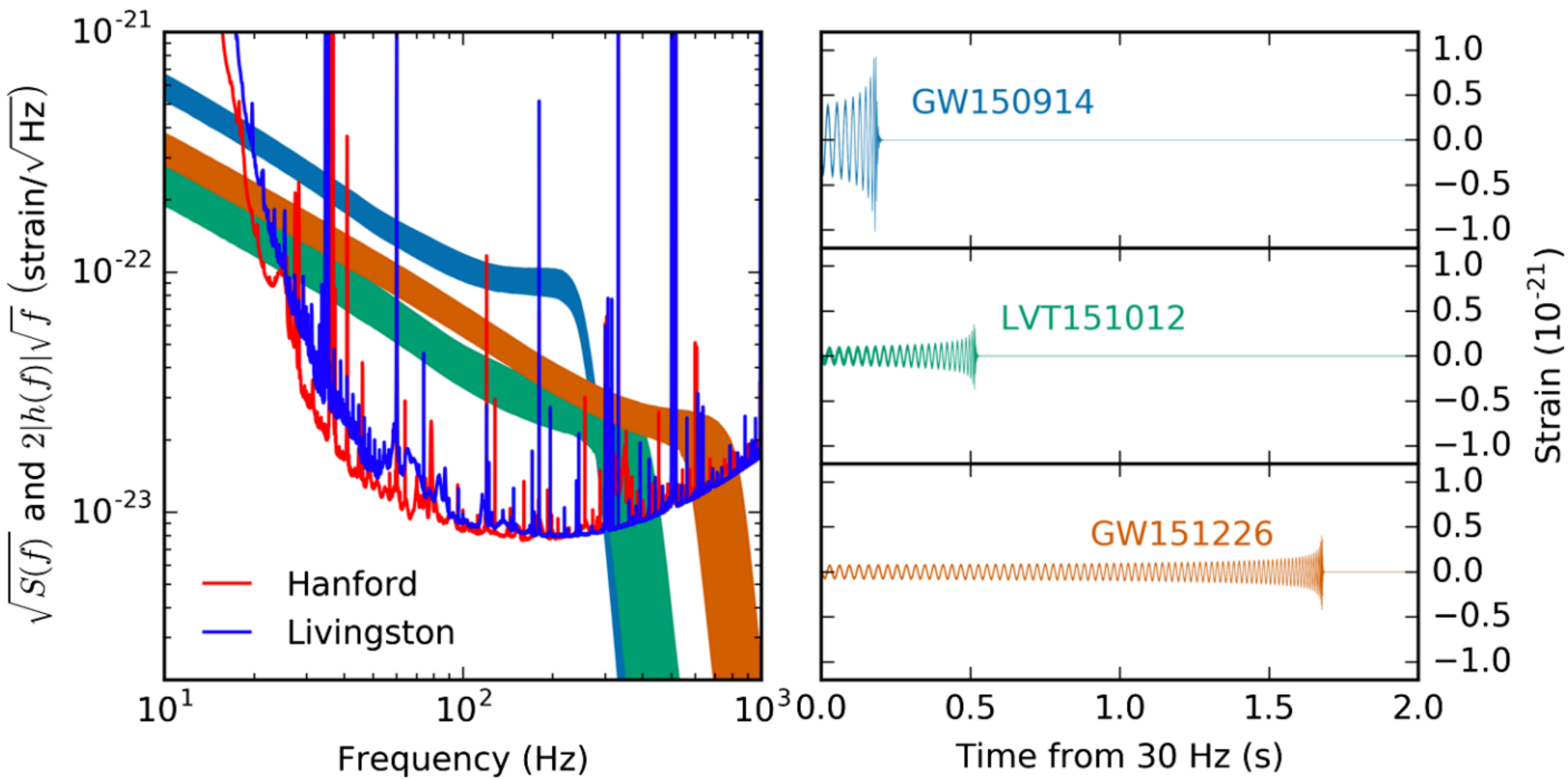


PRL 116, 061102 (2016)



"Was that you I heard just now, or was it two black holes colliding?"

THE NEW YORKER, Feb 12, 2016

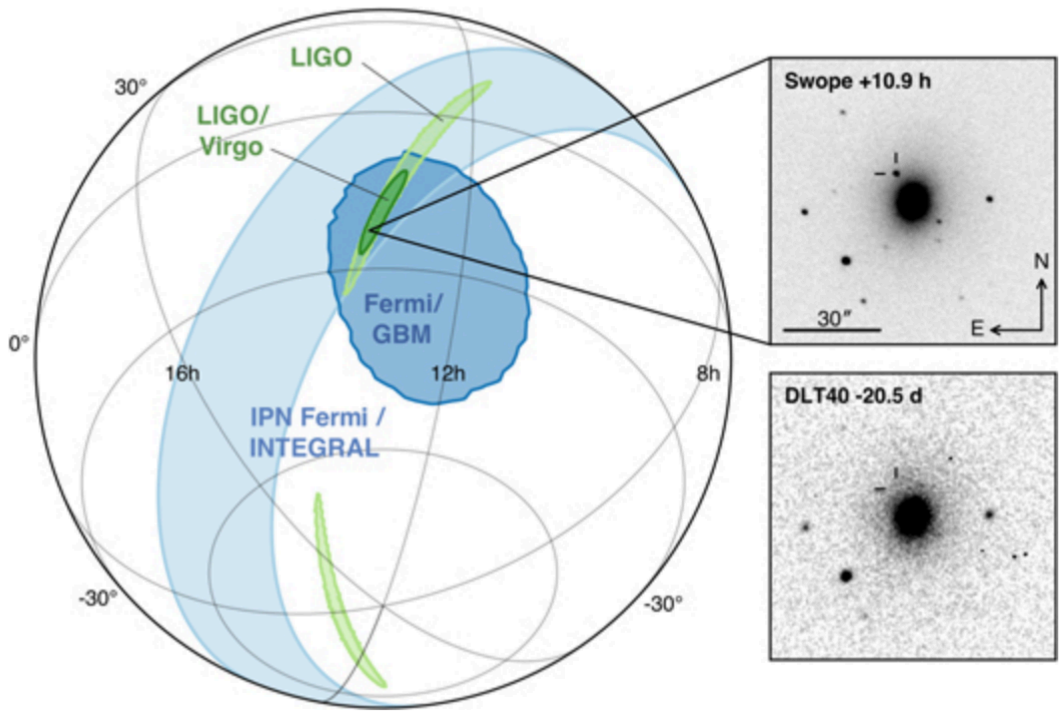


Phys. Rev. X 6, 041015 (2016)

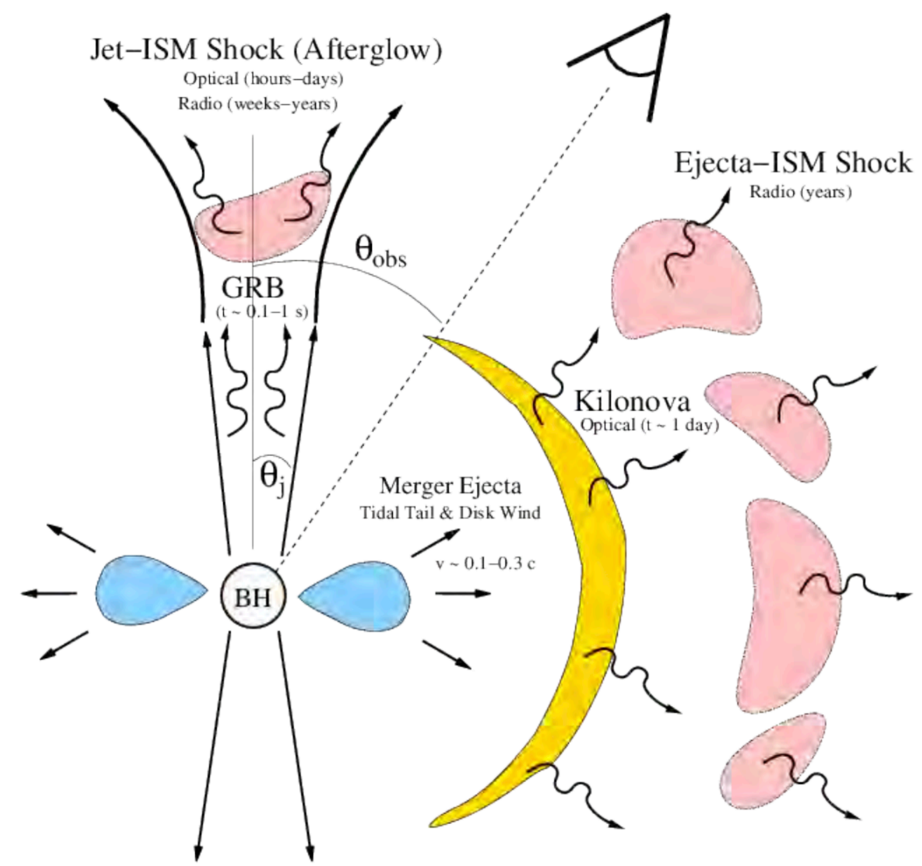
Second Observing Run

O2: November 30, 2016 to August 25, 2017

Virgo joins the observing run
Start of multi-messenger astronomy



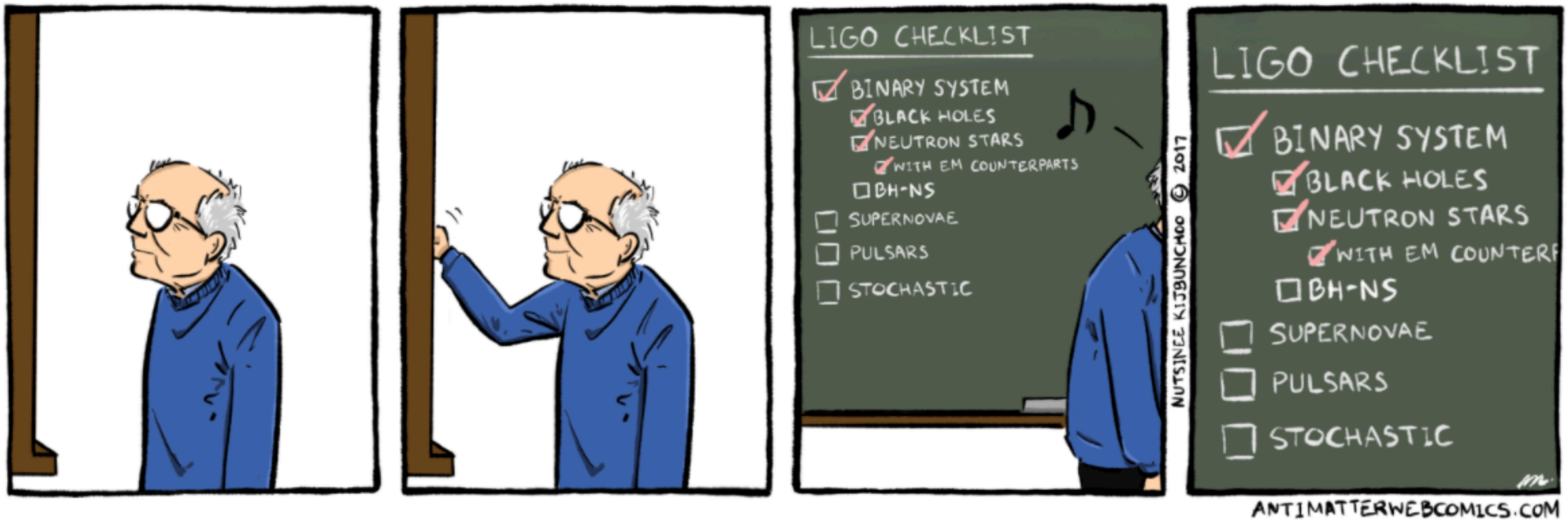
B. P. Abbott et al 2017 ApJL 848 L12



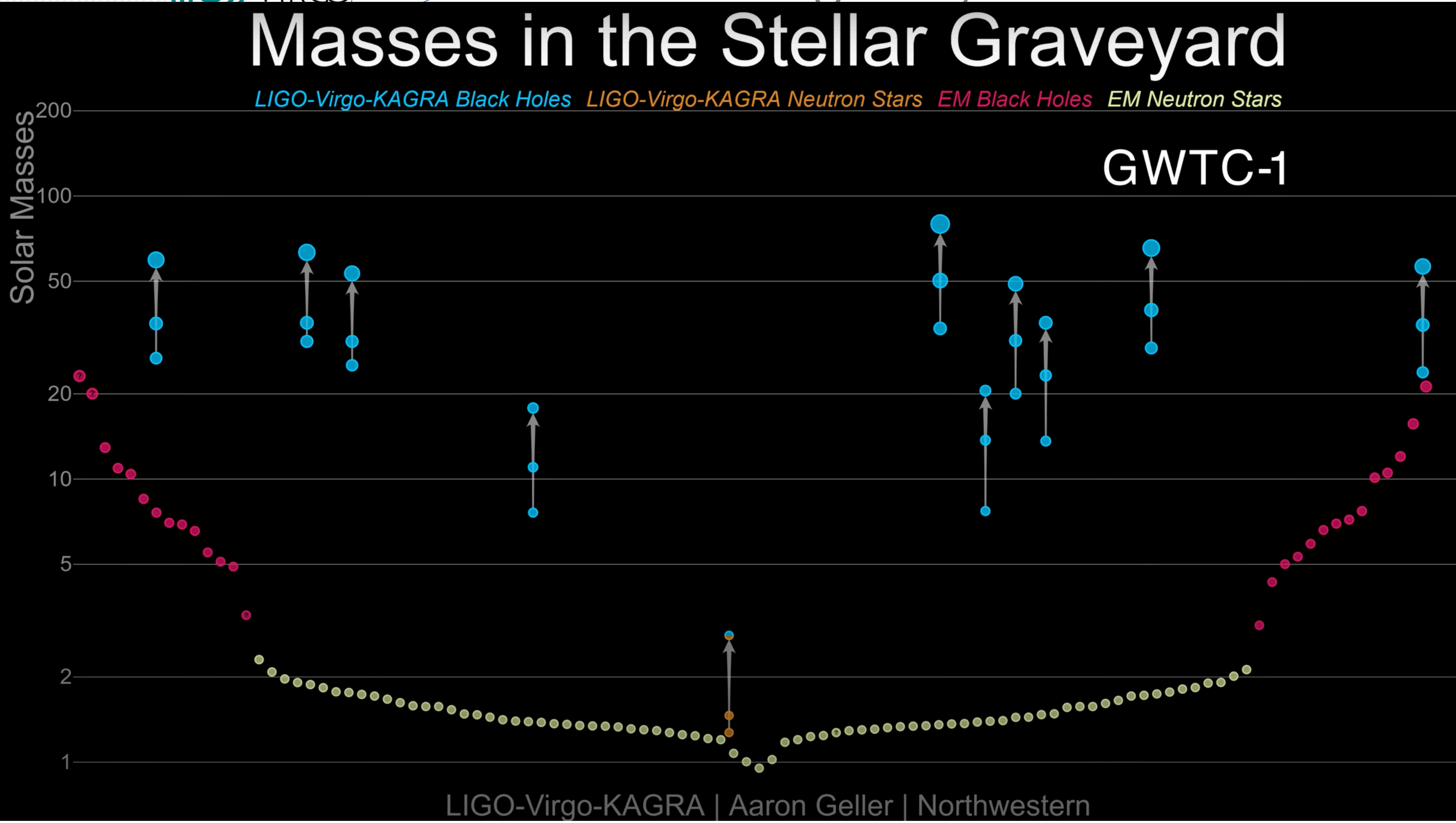
- Understand how the **short Gamma Ray Bursts (GRB)** are powered
- Study the **kilonova** light curve
- Measure the **Hubble constant**
- Compare the **speed of gravity** to light
- Production site for elements heavier than Fe

GW170817

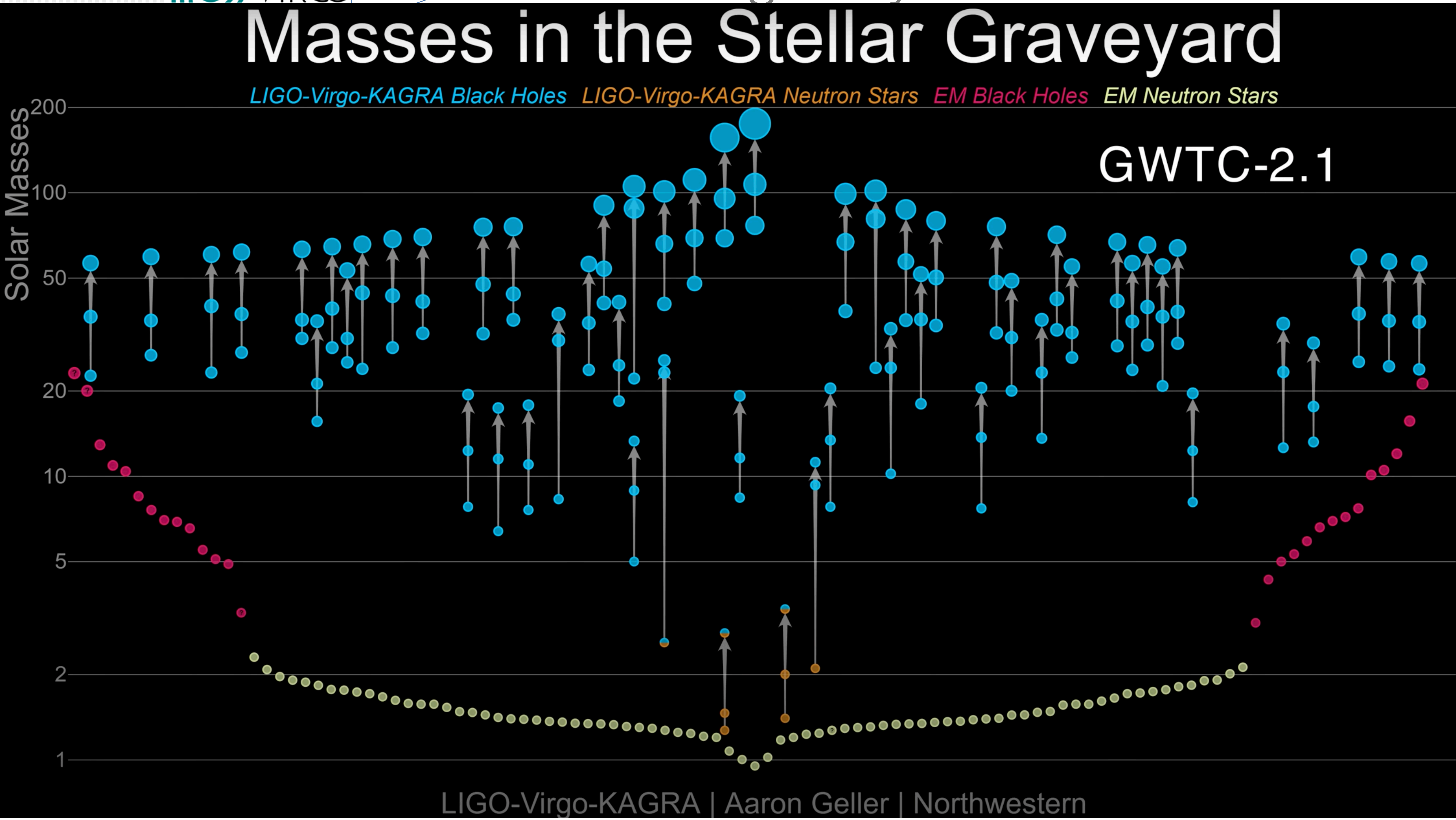
Nutsinee Kijbunchoo



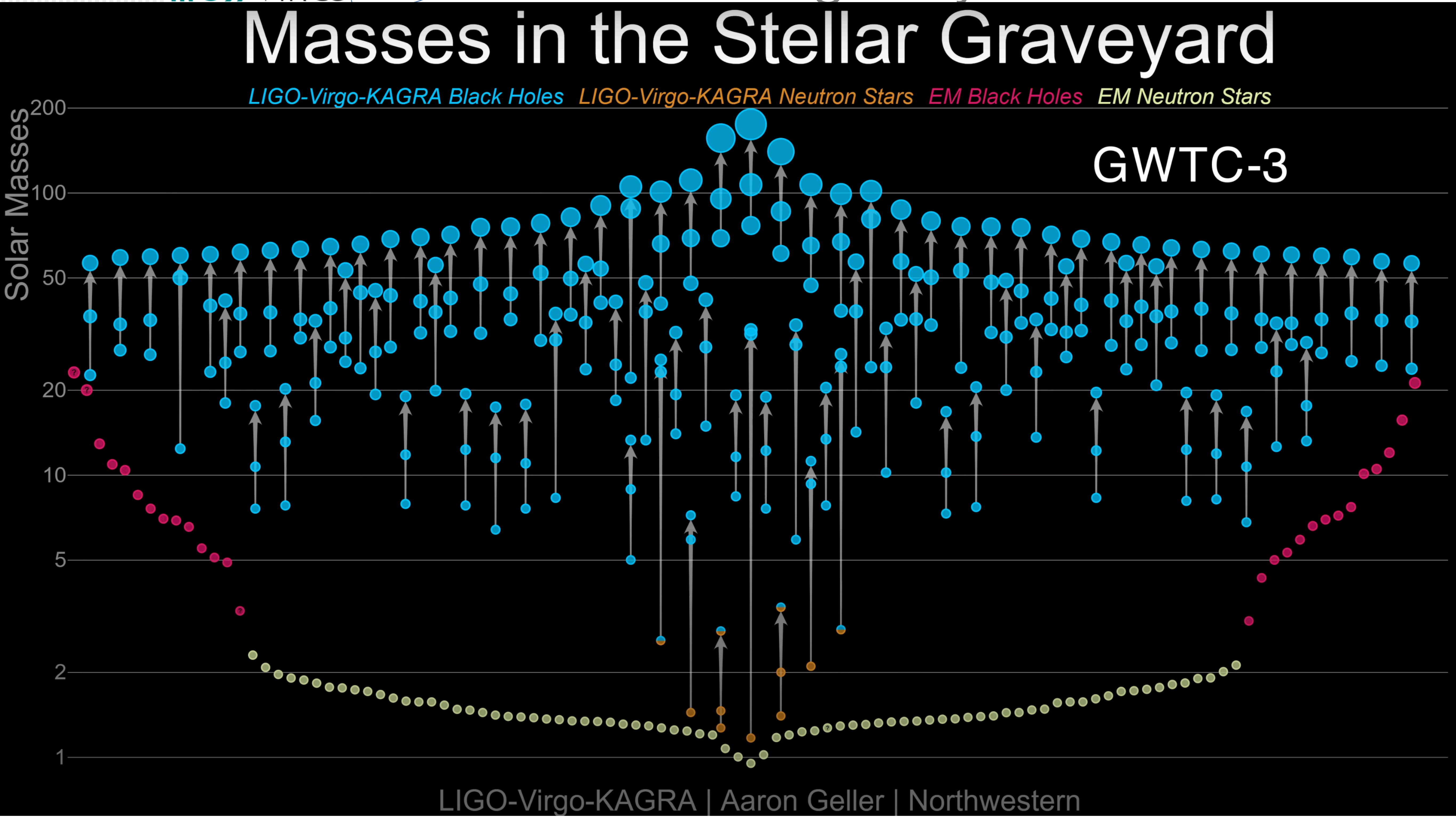
Stellar graveyard:GWTC-1



Stellar graveyard: GWTC-2.1



Stellar graveyard GWTC-3



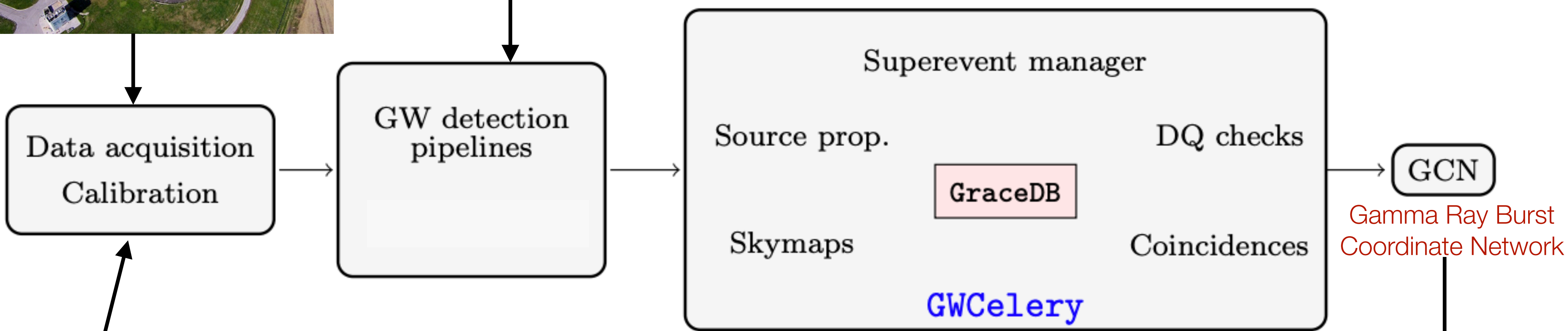
Third Observing Run

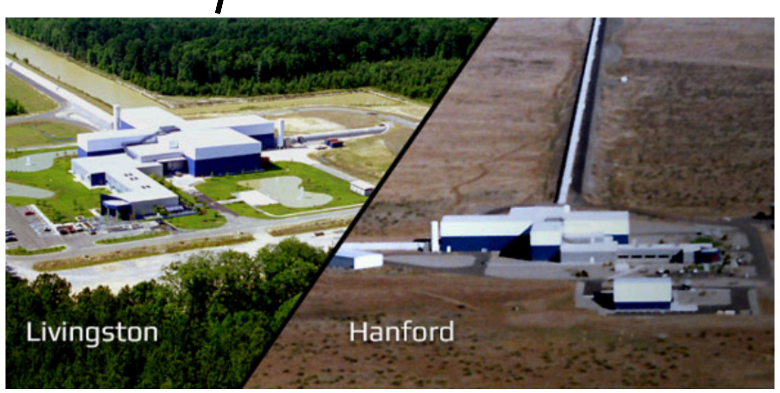
- April 1, 2019 1500 UTC:
  start of **Advanced LIGO's** and **Advanced Virgo's third** observing run
- April 2, 2019 20:00 UTC:
  start of **public alerts**
- One month break in October
- Suspension of O3 on March 27, 2020

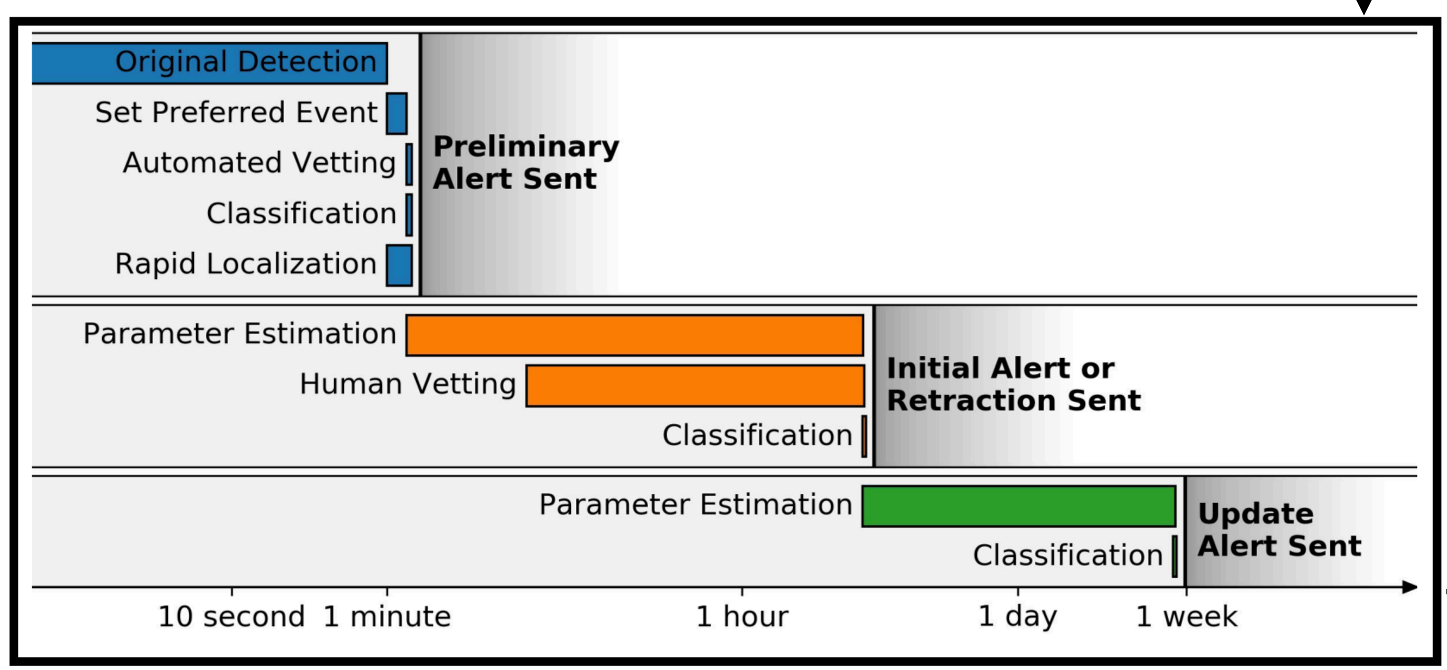
Detection Workflow

Modified from Ryan Magee et al 2021 ApJL 910 L21

GstLAL, pyCBC, MBTA, SPIIR, cWB





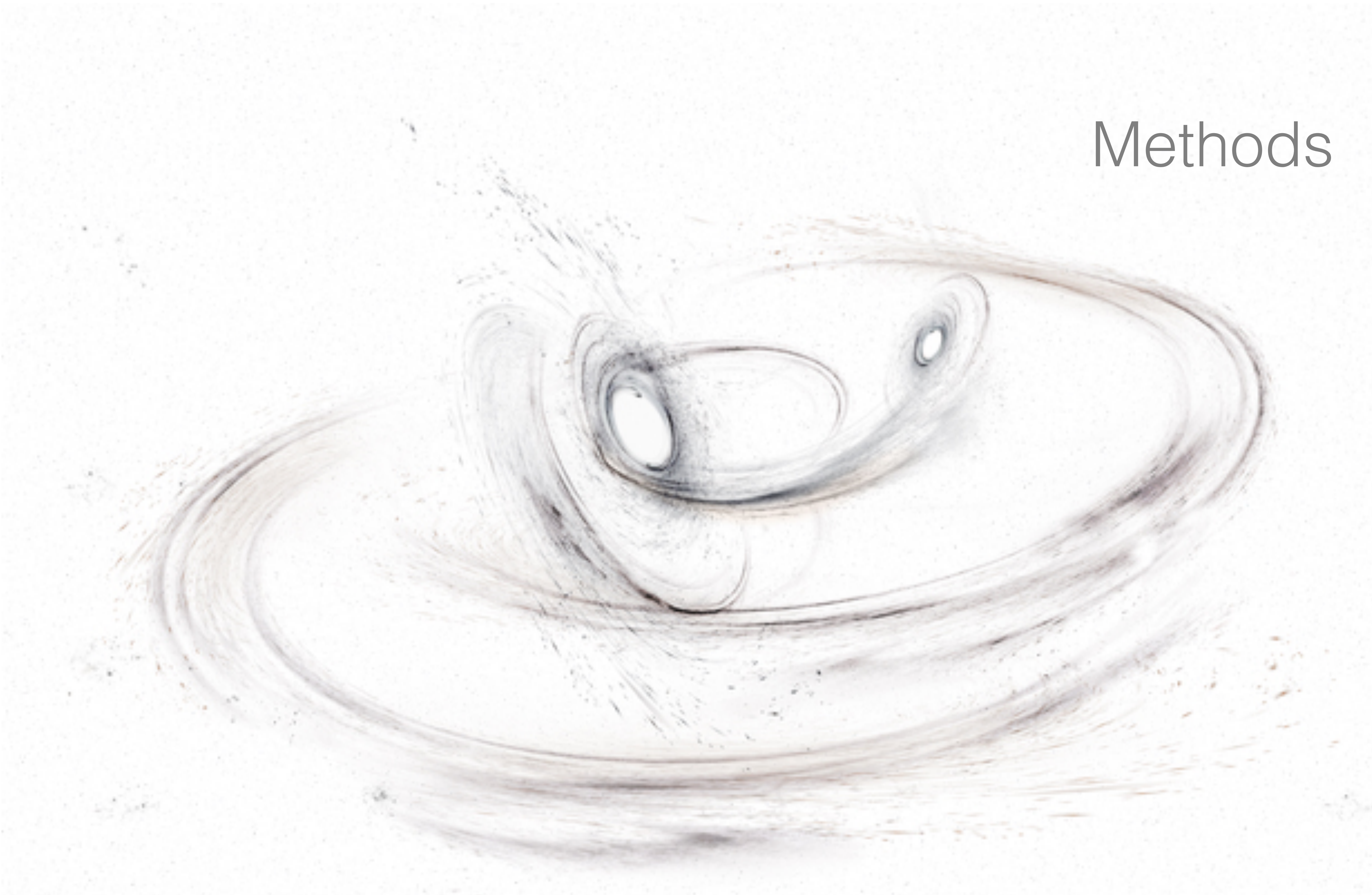


From LIGO DCC G1802186

Offline reanalysis/ GW catalogs

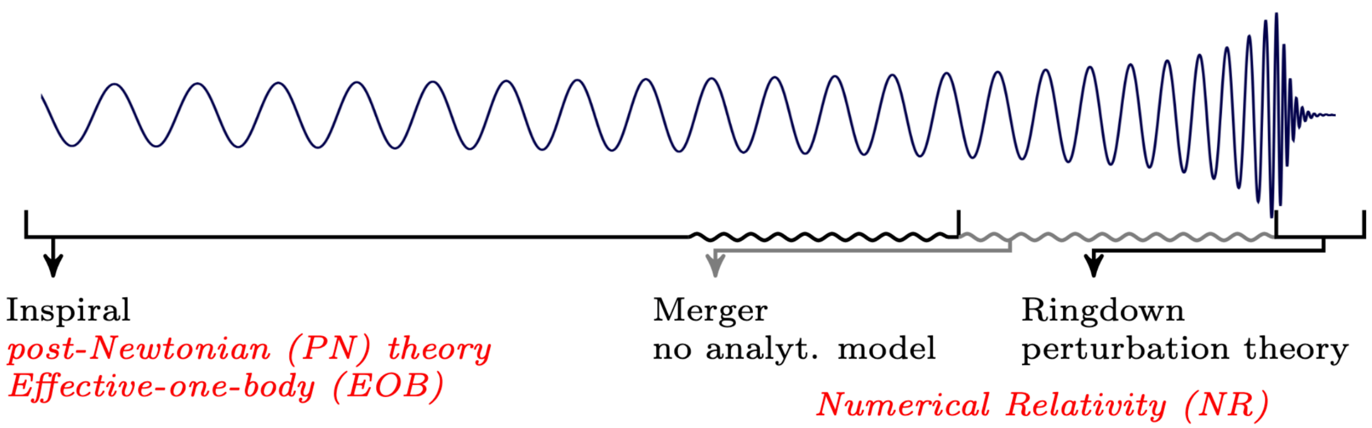
O(months)

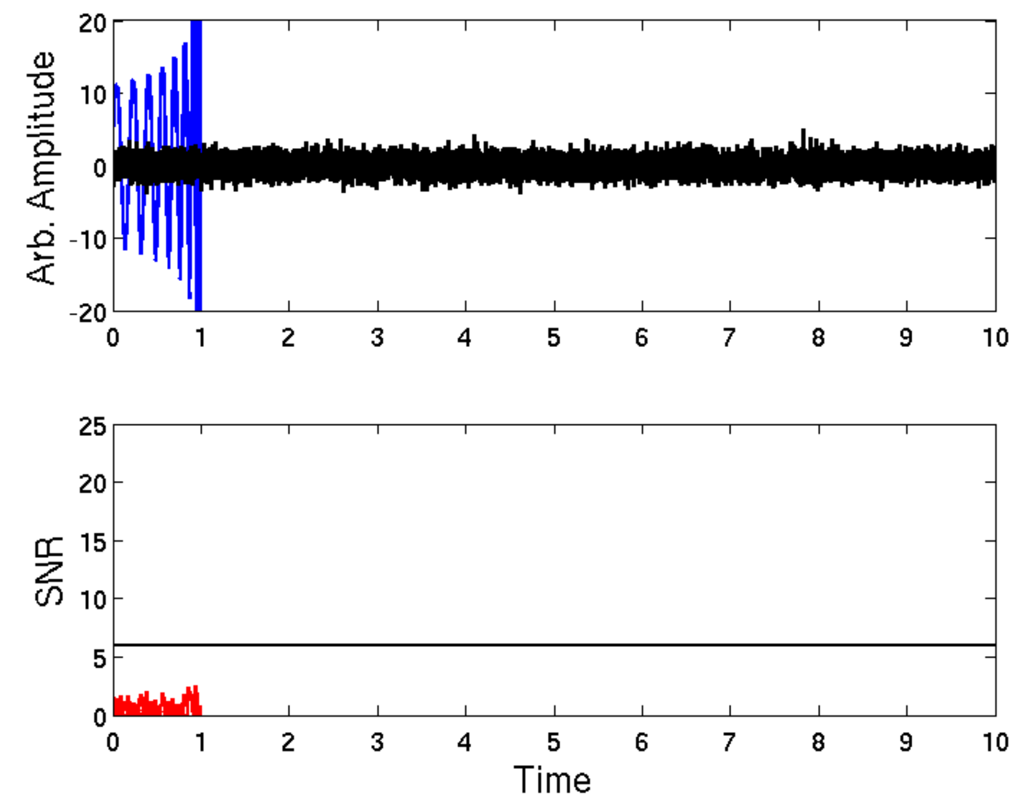
Methods



Matched-Filtering

Frank Ohme 2012 CQG 29 124002





Credit: Chad Hanna

Noise hypothesis: $s(t) = n(t)$

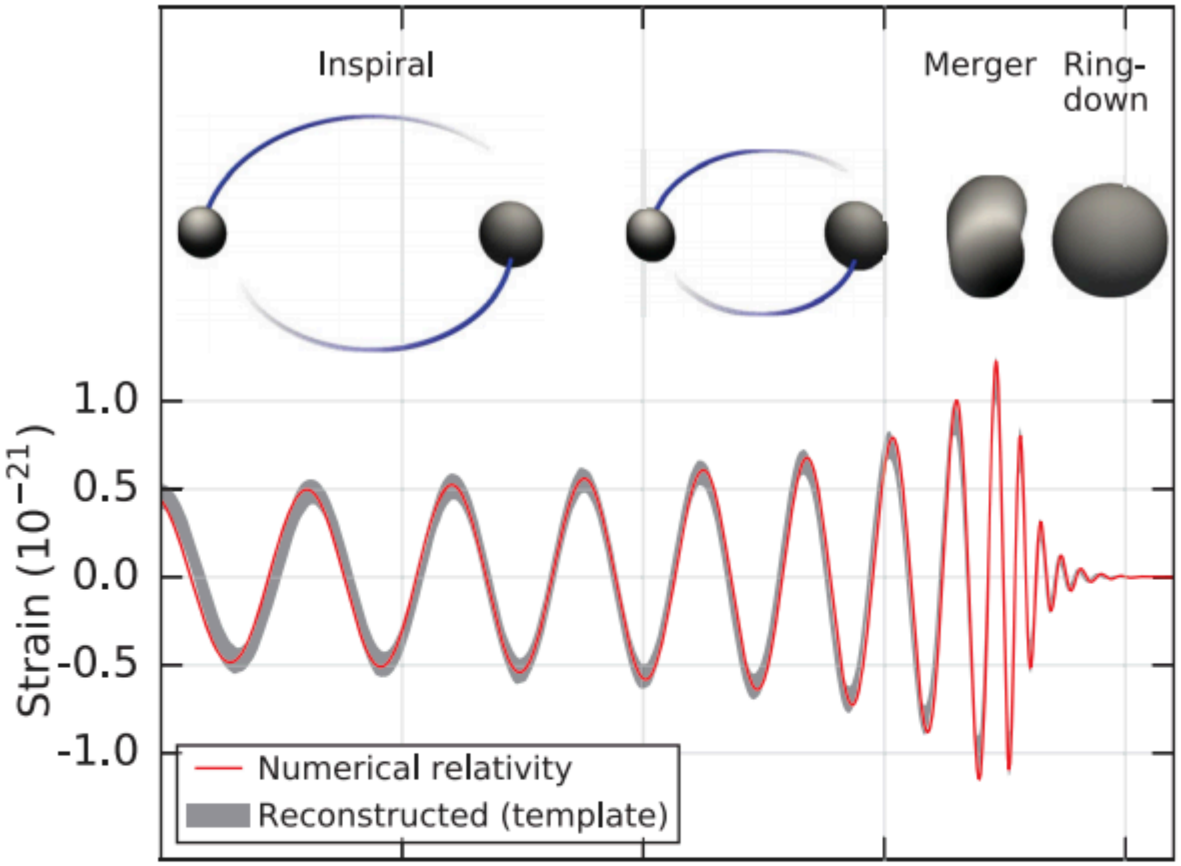
Signal hypothesis: $s(t) = n(t) + h(t)$

A powerful technique in signal processing,
used to extract signals from noisy data,
if we know the signal form we are looking for

Matched-filtering searches

Intrinsic

- m_1, m_2 : masses
- $s_{1x}, s_{1y}, s_{1z}, s_{2x}, s_{2y}, s_{2z}$: spins



Extrinsic

- α, δ : right ascension, declination
- i, Ψ : inclination, polarization angle
- D : luminosity distance
- $\Phi_{\rm coal}$: coalescence phase
- $t_{\rm coal}$: coalescence time

Complex SNR time series:

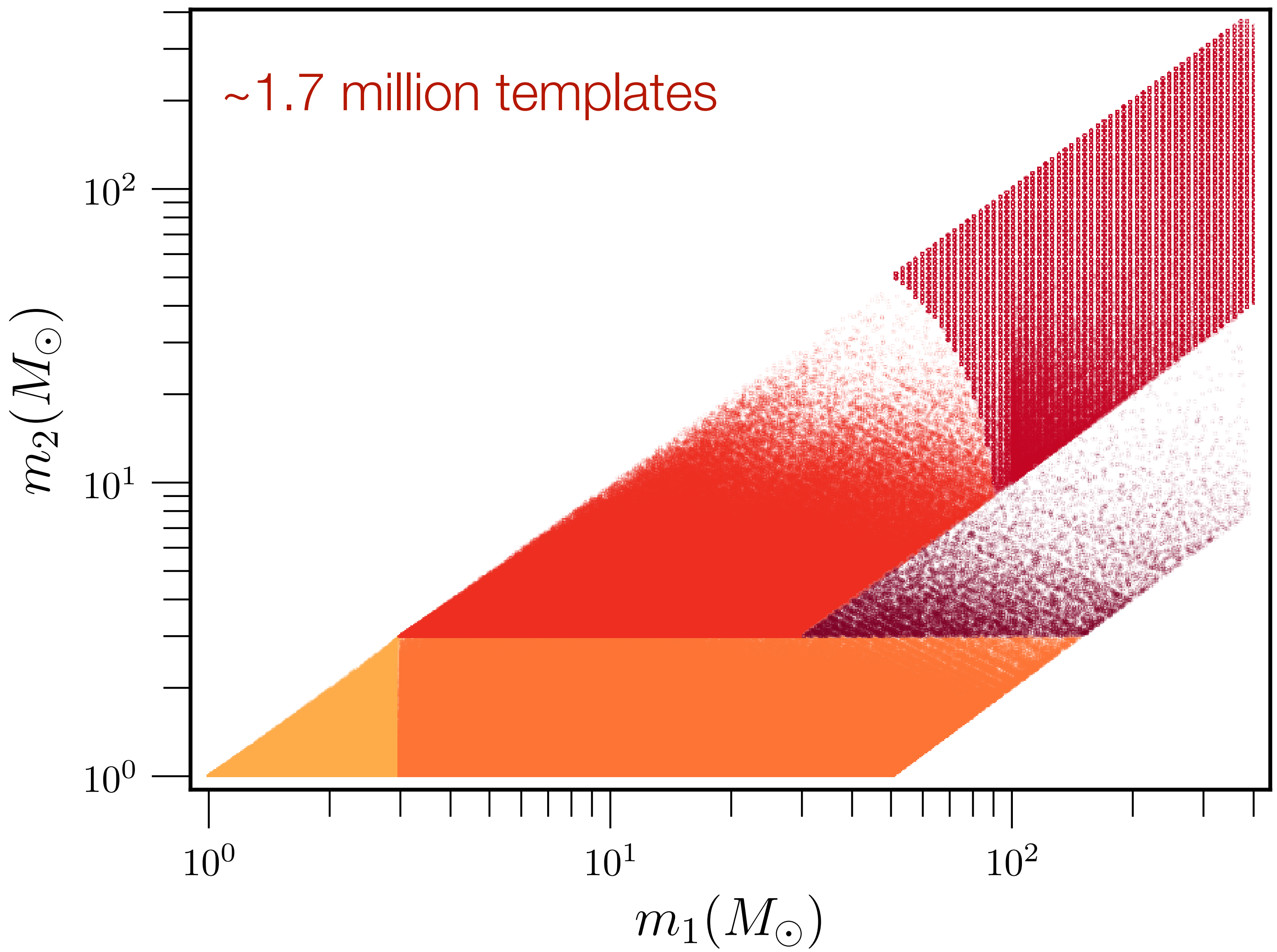
$$z(t) = 4\int_0^\infty \frac{\tilde{s}*(f)\tilde{h}(f)}{S_n(f)} e^{2\pi i f t} df$$

SNR maximized over phase and time:

$z = \max_t |z(t)|$

Template bank

- Template bank used by `GSTLAL` in O3
- During O3, in low latency, the bank was divided into two banks, by separating every other template
- The banks were run in different computing clusters - CIT and UWM - `checkerboarding`
- If one cluster goes down, lose some sensitivity but not all



Significance

- If noise were stationary & Gaussian, SNR could be used as a ranking statistic
- Noise is not Gaussian, we use **likelihood-ratio** $\mathcal{L}$ instead

$$\mathcal{L} = \frac{P(\vec{D_H}, \vec{O}, \vec{\rho}, \vec{\xi^2}, \vec{\phi}, \vec{t} \,|\, \mathrm{s})}{P(\vec{D_H}, \vec{O}, \vec{\rho}, \vec{\xi^2}, \vec{\phi}, \vec{t} \,|\, \mathrm{n})}$$

- Noise is estimated from non-coincident triggers, and signal from semi-analytical models
- $P(\mathscr{L}/\mathrm{n})$ is estimated by sampling the noise distributions and used to assign FAR (false alarm rate) to candidates

Prob. of astrophysical origin

- FAR is calculated using the background distribution of the ranking statistic used by the search pipeline
- p_{astro} also considers the foreground distribution of the ranking statistic
- Searches estimate membership probabilities for astrophysical source classes:

$$p_{\mathrm{astro}} = p_{\mathrm{BNS}} + p_{\mathrm{NSBH}} + p_{\mathrm{BBH}} = 1 - p_{\mathrm{terr}}$$

- Class membership is based on component masses only, no necessary implication that the objects are actually BHs or NSs
- Since the foreground rate of binary black holes (BBH) is higher compared to that of binary neutron stars (BNS) and neutron star - black holes (NSBH), the astrophysical probability inferred at a fixed FAR is greater for BBH than for BNS and NSBH

Parameter Estimation

- **Posteriors** on parameters: Masses and 3D spins, location, orientation of the binary
- Incorporate **more physics**, such as spin-induced precession effects, and sub-dominant multipole moments
- Mass, spin, redshift distribution of the binaries give us a clue to the formation channel of the binaries
- Non-GR and tidal parameters can be added to the waveforms to perform **tests of GR** and to infer **NS equation-of-state (EoS)**

$$p(\theta|d) = \frac{p(d|\theta)\,p(\theta)}{p(d)}$$

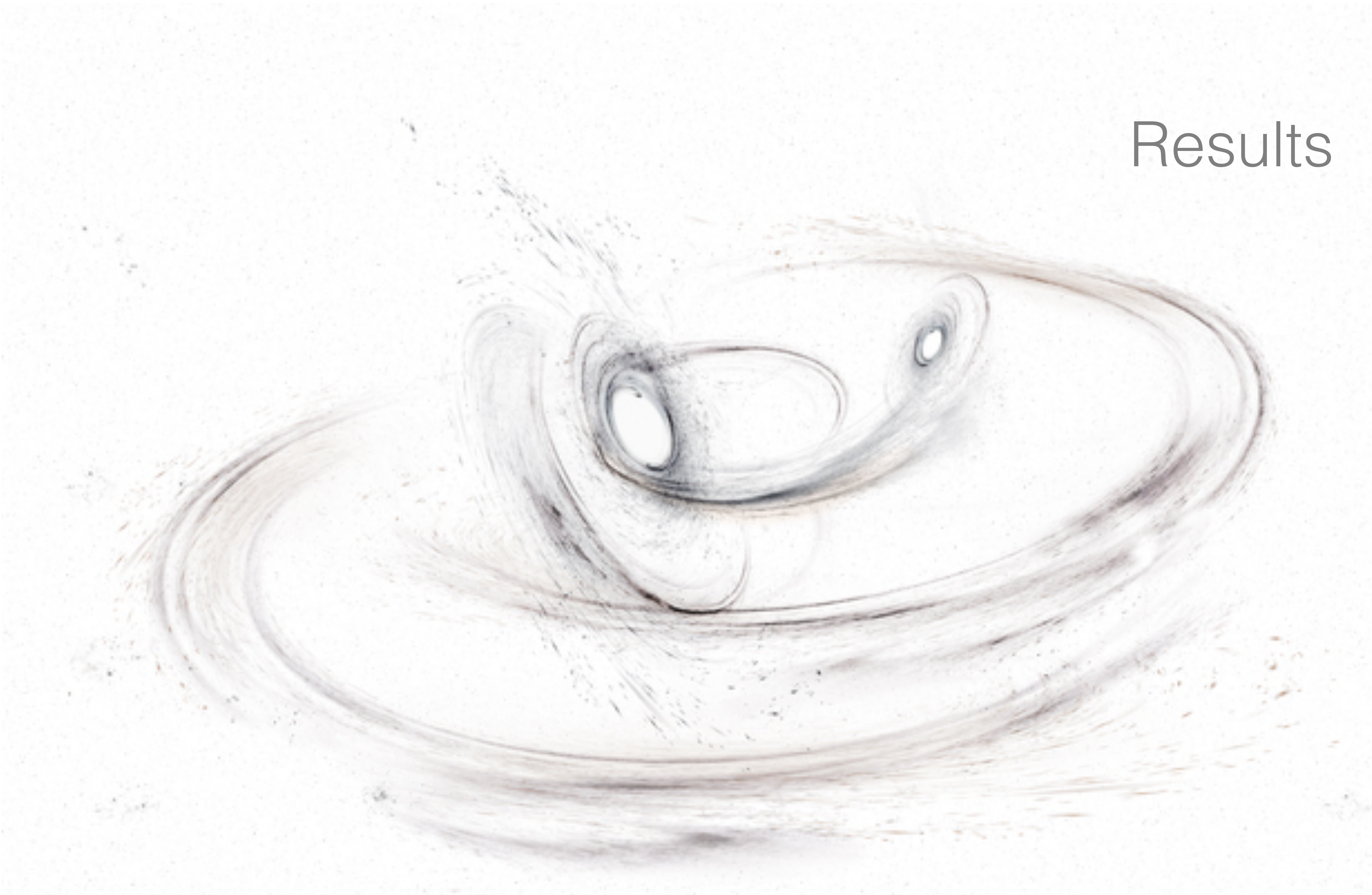
Likelihood

Prior

Posterior

Evidence

Results

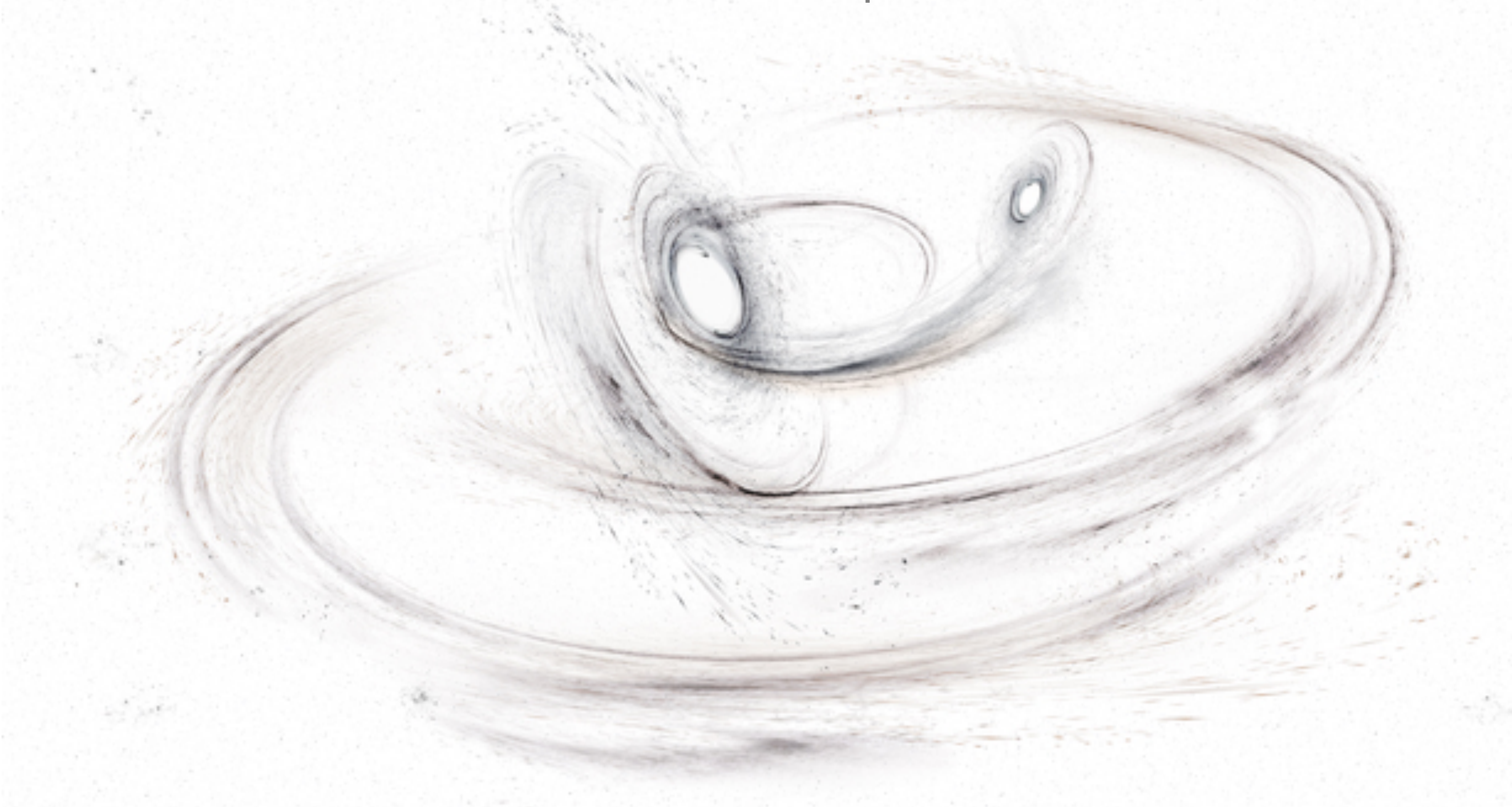


Search results

- **90** events so far with p_{astro} > **0.5**:
  11 in GWTC-1, 44 added in GWTC-2.1, 35 added in GWTC-3
- ~10 % contamination
- **Cross-correlation** studies of **sub-threshold candidates** between different astrophysical surveys could lead to a **multi-messenger** discovery
- We also released deep sub-threshold list; 2194 total events in O3 with $p_{\mathrm{astro}} < 0.5$ and FAR < 2/day
- ~1–2 % purity in the sub-threshold list of candidates
- Search results and sky localizations are available via Zenodo:

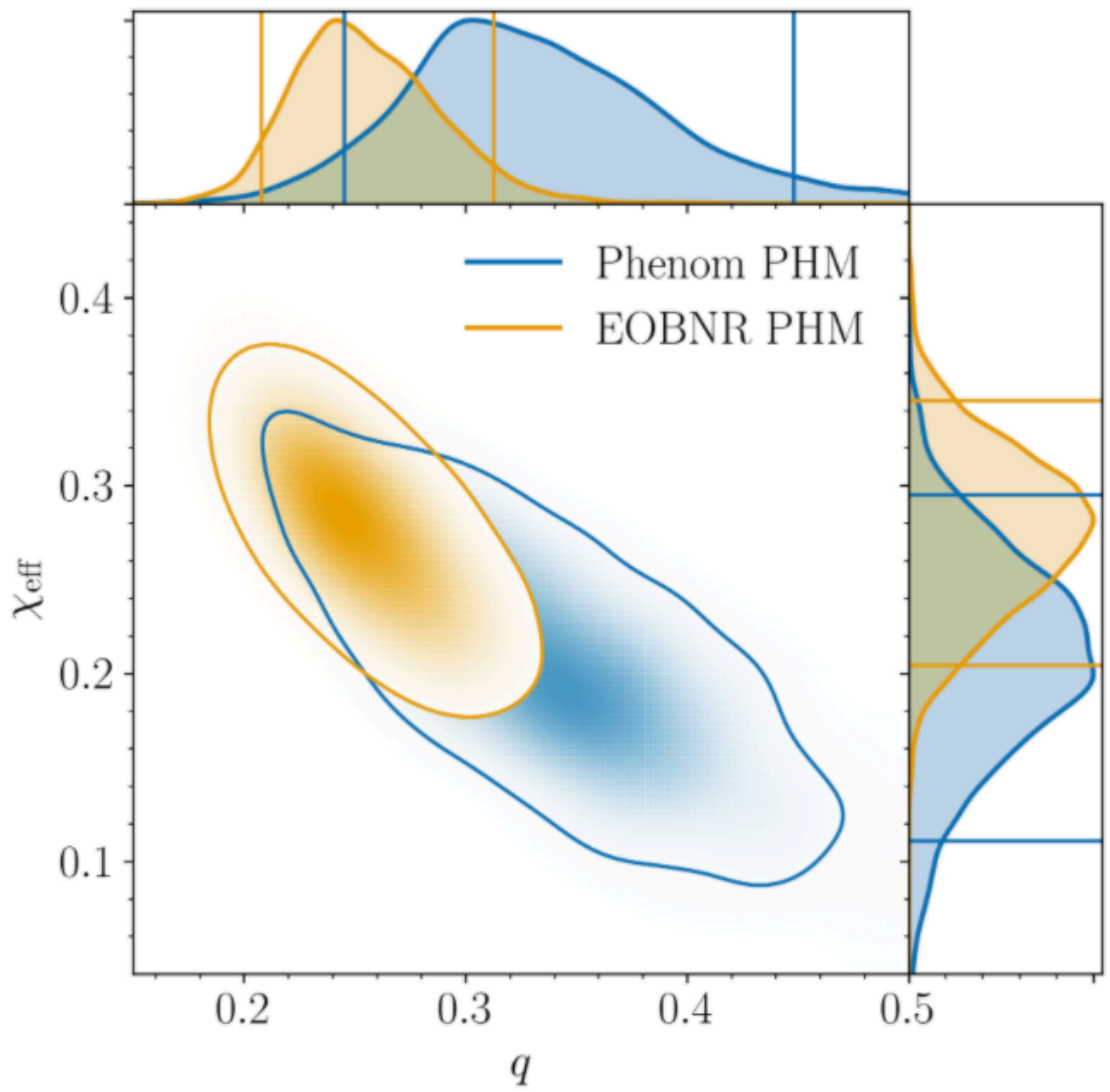
  O3a - 10.5281/zenodo.5148739
  O3b - 10.5281/zenodo.5546665

Exceptional events in O3



Abbott et al. Astrophys. J. Lett. 896, L44 (2020)

mass ratio $q = m_2/m_1 = 0.28^{+0.12}_{-0.07}$

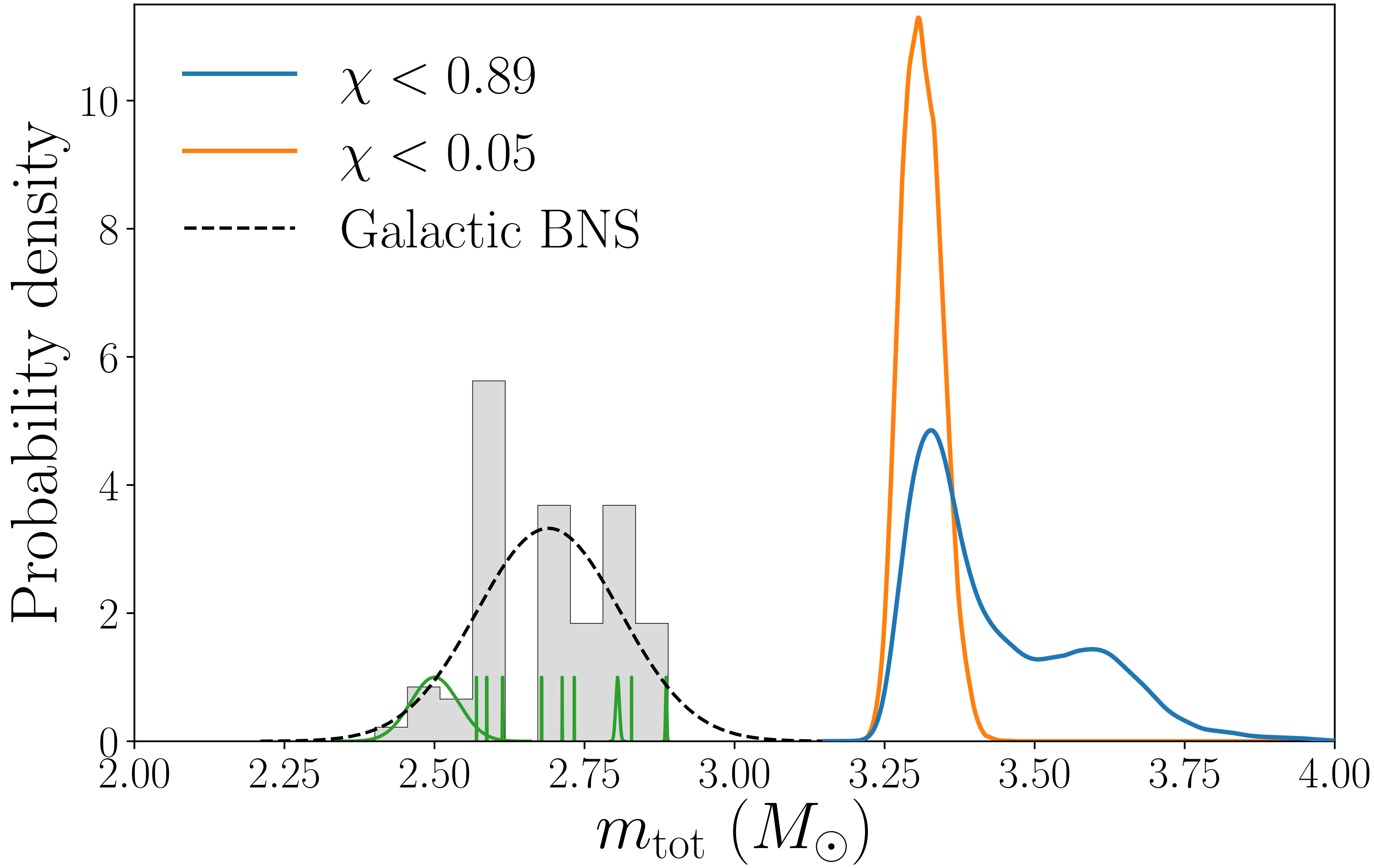


- **First detection with unequal masses**
- **First evidence for sub-dominant, higher order multipole moments**

$$\chi_{\rm eff} = \frac{m_1 s_{1z} + m_2 s_{2z}}{m_1 + m_2}$$

Astrophys. J. Lett. 892, L3 (2020)

Second BNS observation



Galactic binaries:

$M_{\rm tot}$: 2.50 to 2.89 $\mathrm{M}_\odot$

m: 1.12 to 1.24 $\mathrm{M}_\odot$

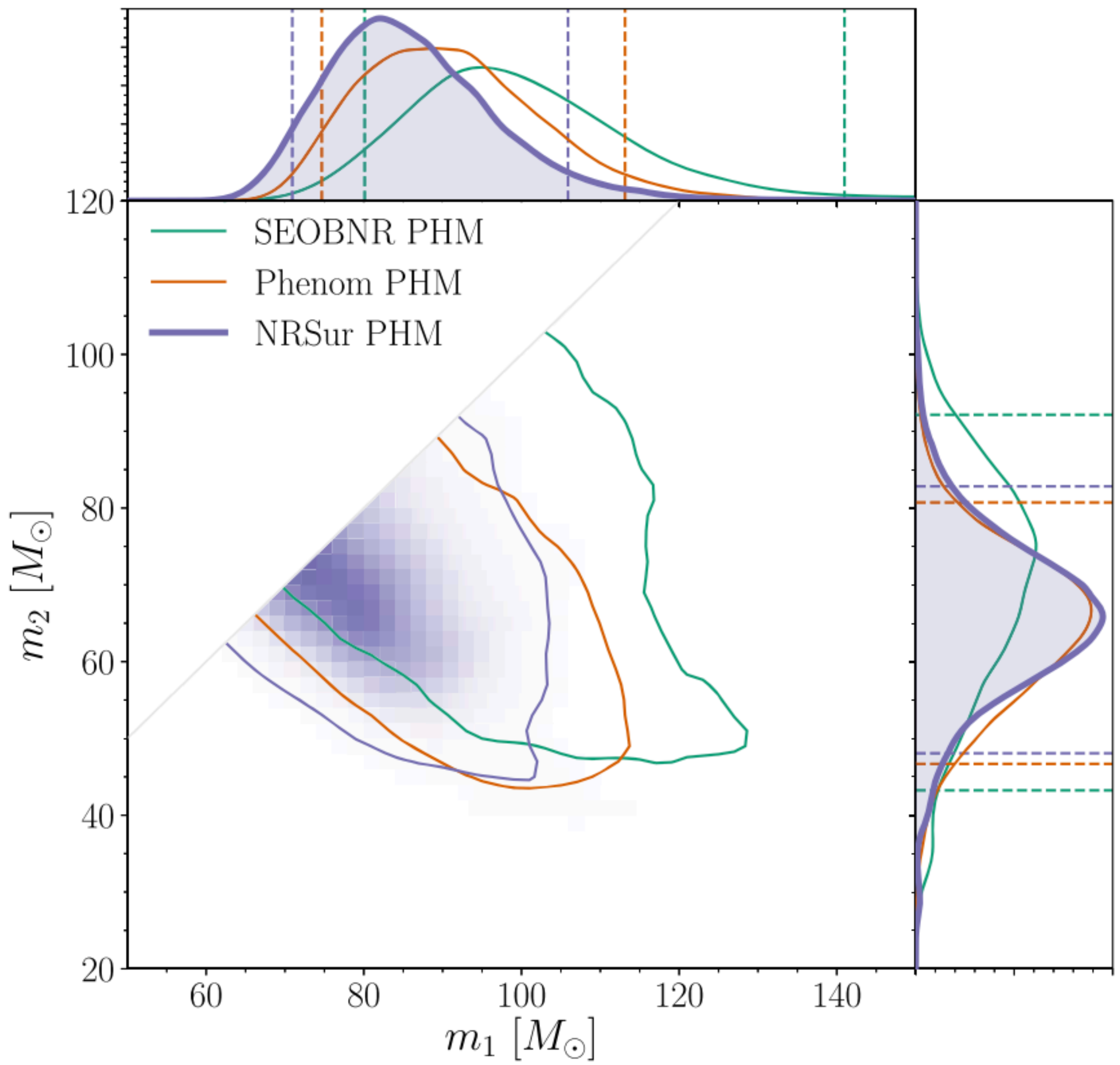
Gaussian fit to $M_{\rm tot}$ for galactic binaries:

2.69 ± 0.12 $\mathrm{M}_\odot$

Nicholas Farrow et al 2019 ApJ 876 18

GW190521

Abbott et al. Phys. Rev. Lett. 125, 101102



Masses within the pair instability gap

$P(m_1 < 65 M_\odot) = 0.32\%$

$P(m_1 \in [65,120]\ M_\odot) = 99\ \%$

$m_1 = 85^{+21}_{-14} M_\odot \qquad m_2 = 66^{+17}_{-18} M_\odot$

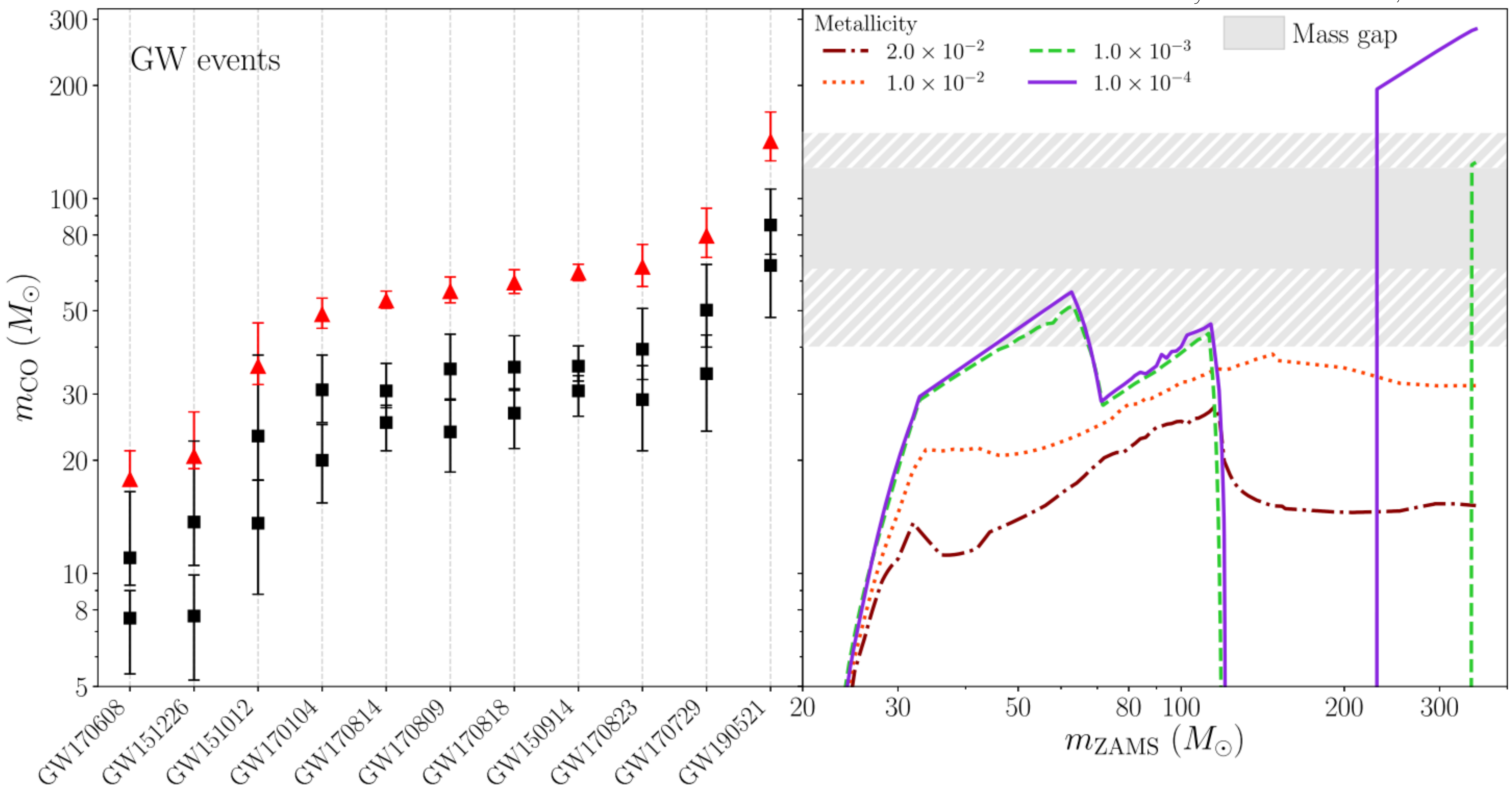
First evidence of an intermediate mass black hole (IMBH)

$M = 150^{+29}_{-17} M_\odot \qquad m_2/m_1 = 0.79^{+0.19}_{-0.29}$

Pair Instability Mass Gap: Mass gap of range $65 - 120 M_\odot$ due to pulsational pair instability supernovae, outer layers of the star are ejected, leaving no remnant or a lighter remnant

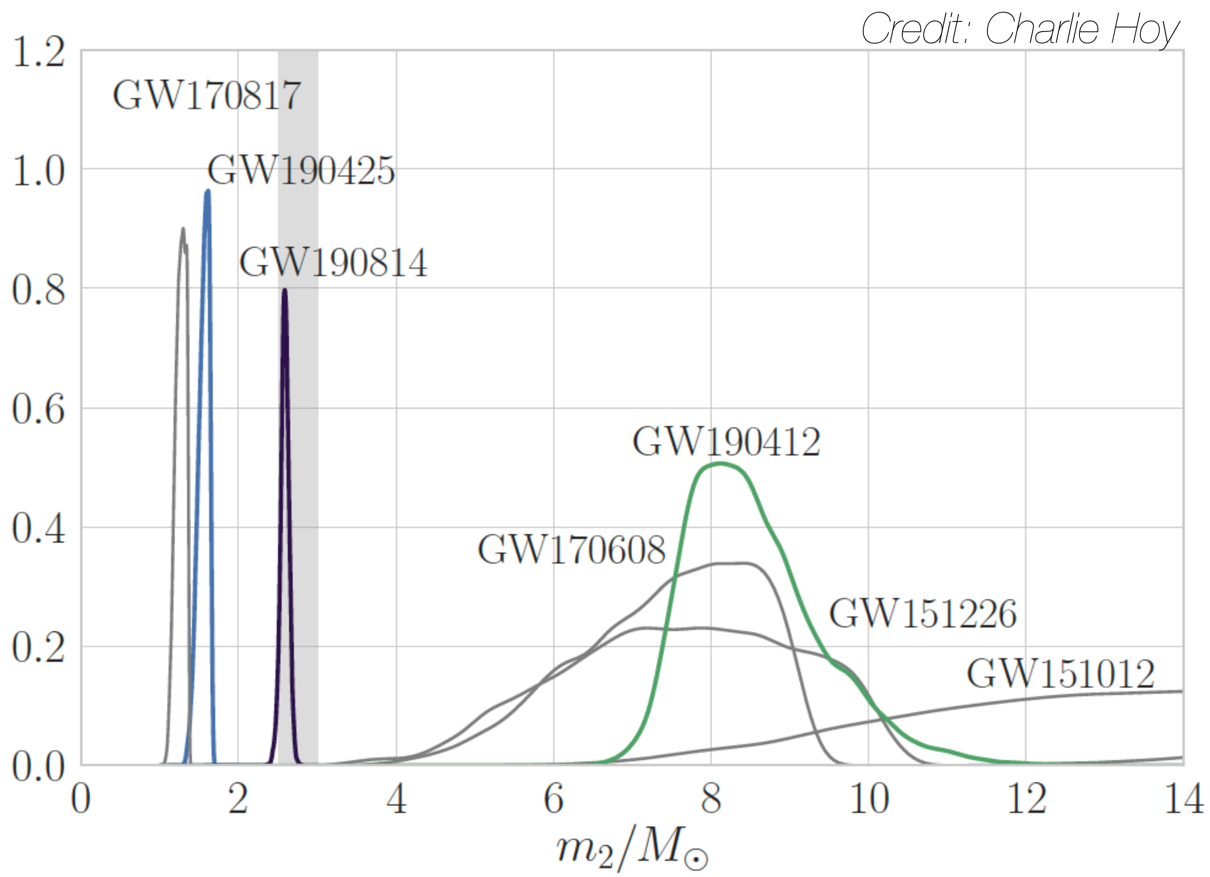
Pair Instability Mass-Gap

Abbott et al. Phys. Rev. Lett. 125, 101102



Inferred rate of 190521-like systems : $R = 0.13^{+0.30}_{-0.11}$ Gpc^{-3} yr^{-1}

Secondary in putative mass gap



- Mass gap of $\sim 3 - 5\,\mathrm{M}_\odot$ is observed between most massive NSs and least massive BHs
- Secondary of GW190814 lies in this mass gap
- We cannot say for certain whether it is a black hole or a neutron star

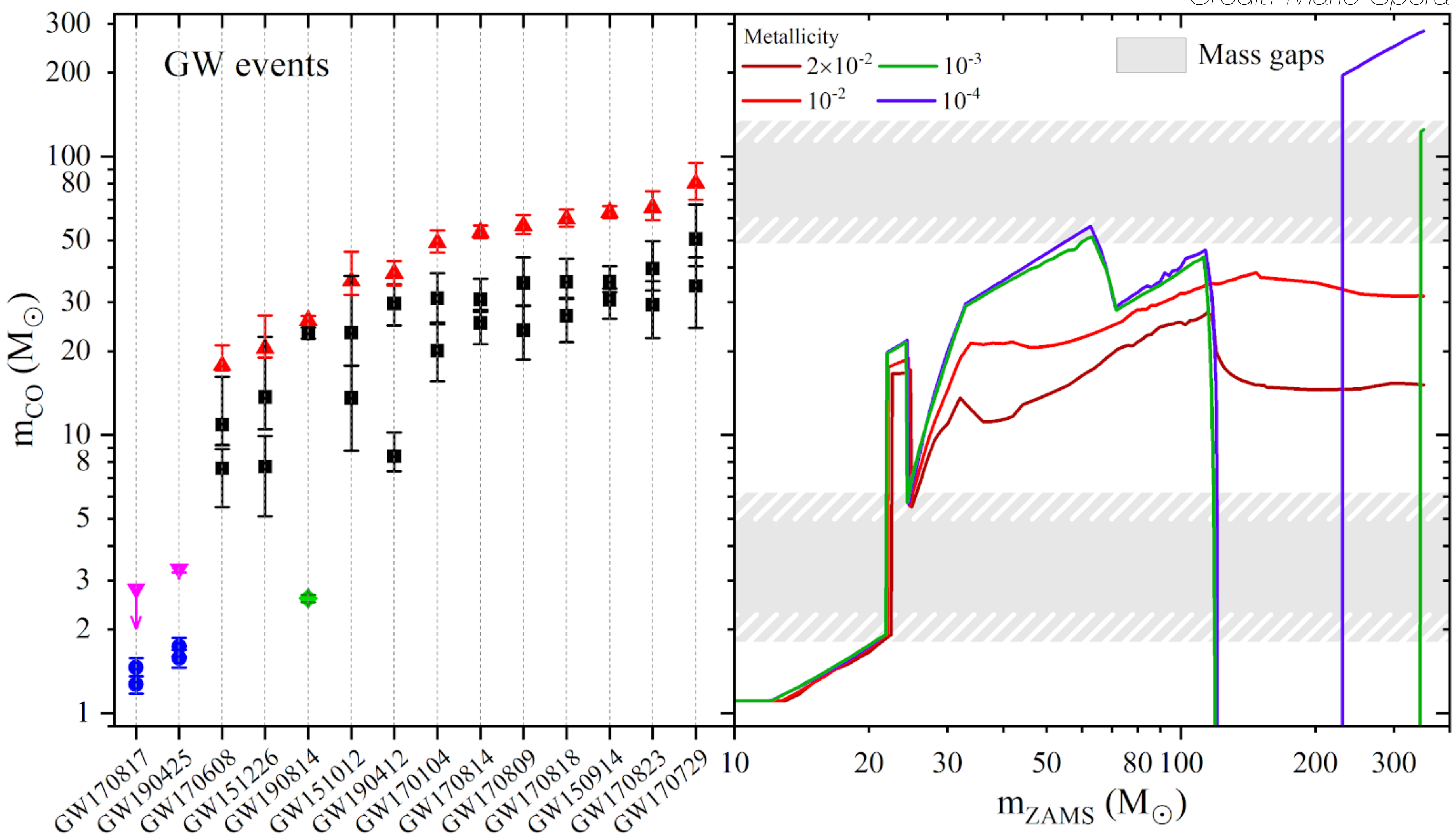
Lowest mass-ratio detection so far

Strongest evidence for higher order modes, best dark siren

LVC 190425 (2020) + LVC 190412 (2020) + LVC 190814 (2020) + LVC GWTC-1 (2019)

Forming GW190814

Credit: Mario Spera



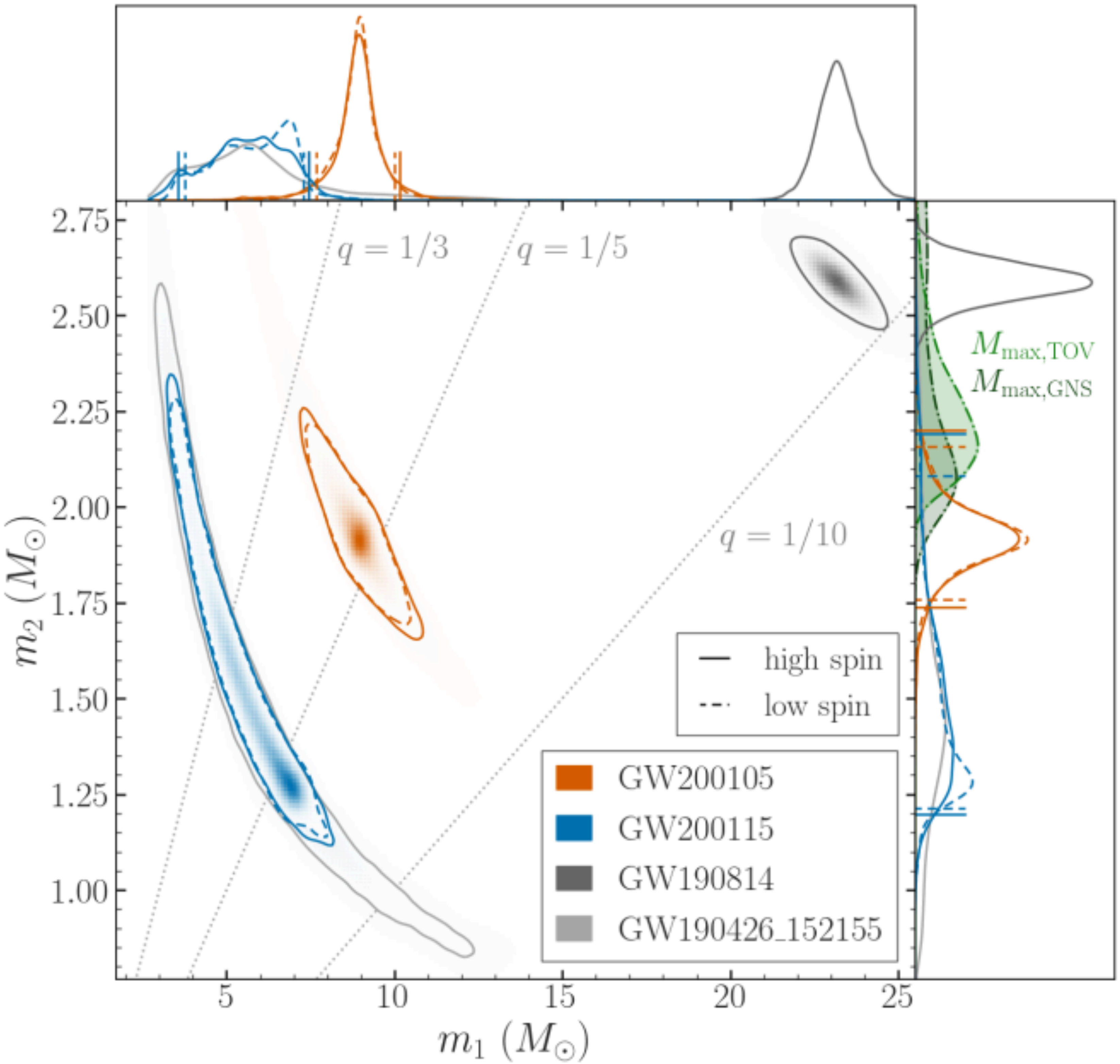
$m_2 \sim 2.6\,\mathrm{M}_\odot$

$q \sim 0.1$

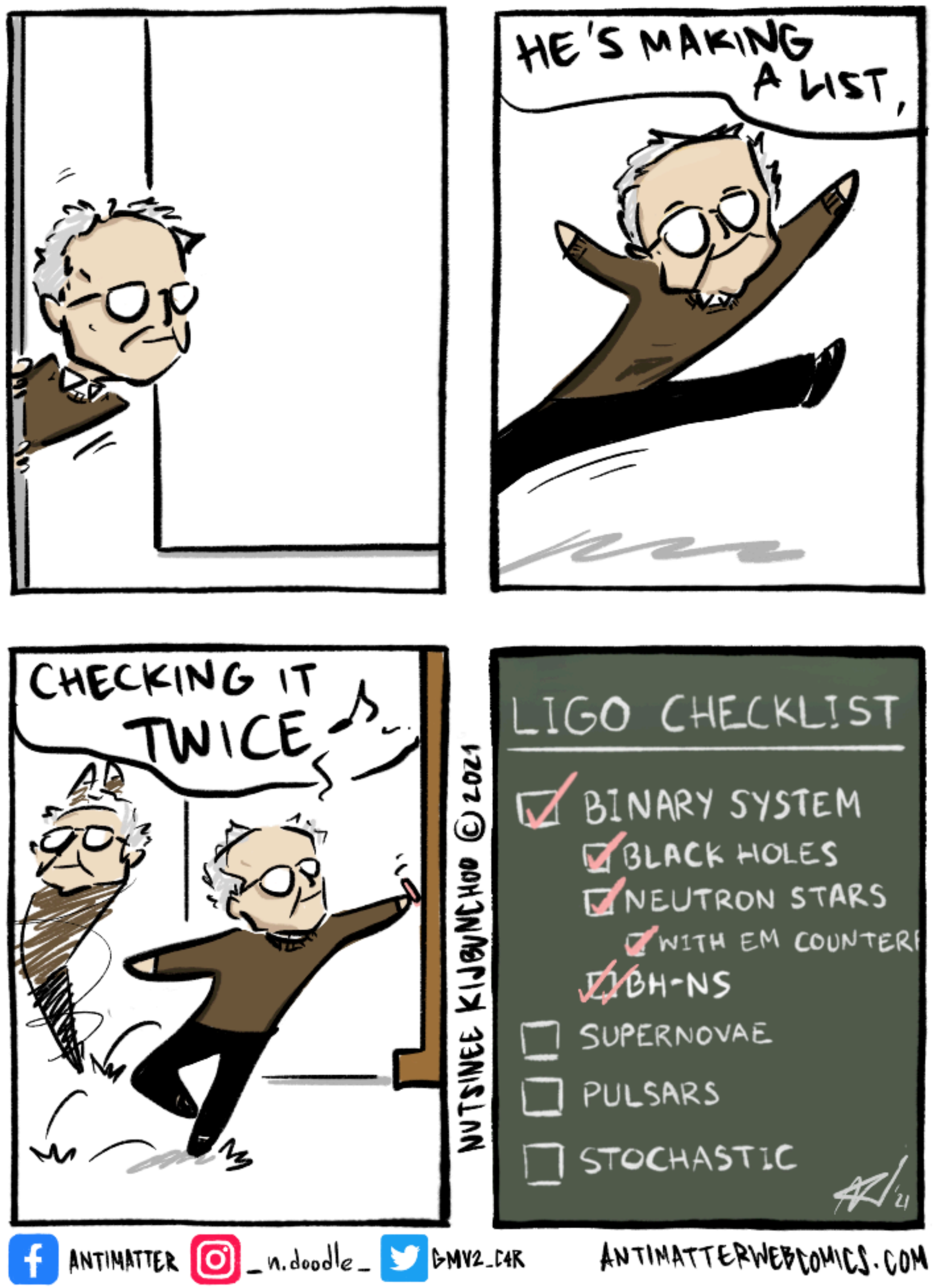
$R \sim 1 - 23\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Challenges most population synthesis models

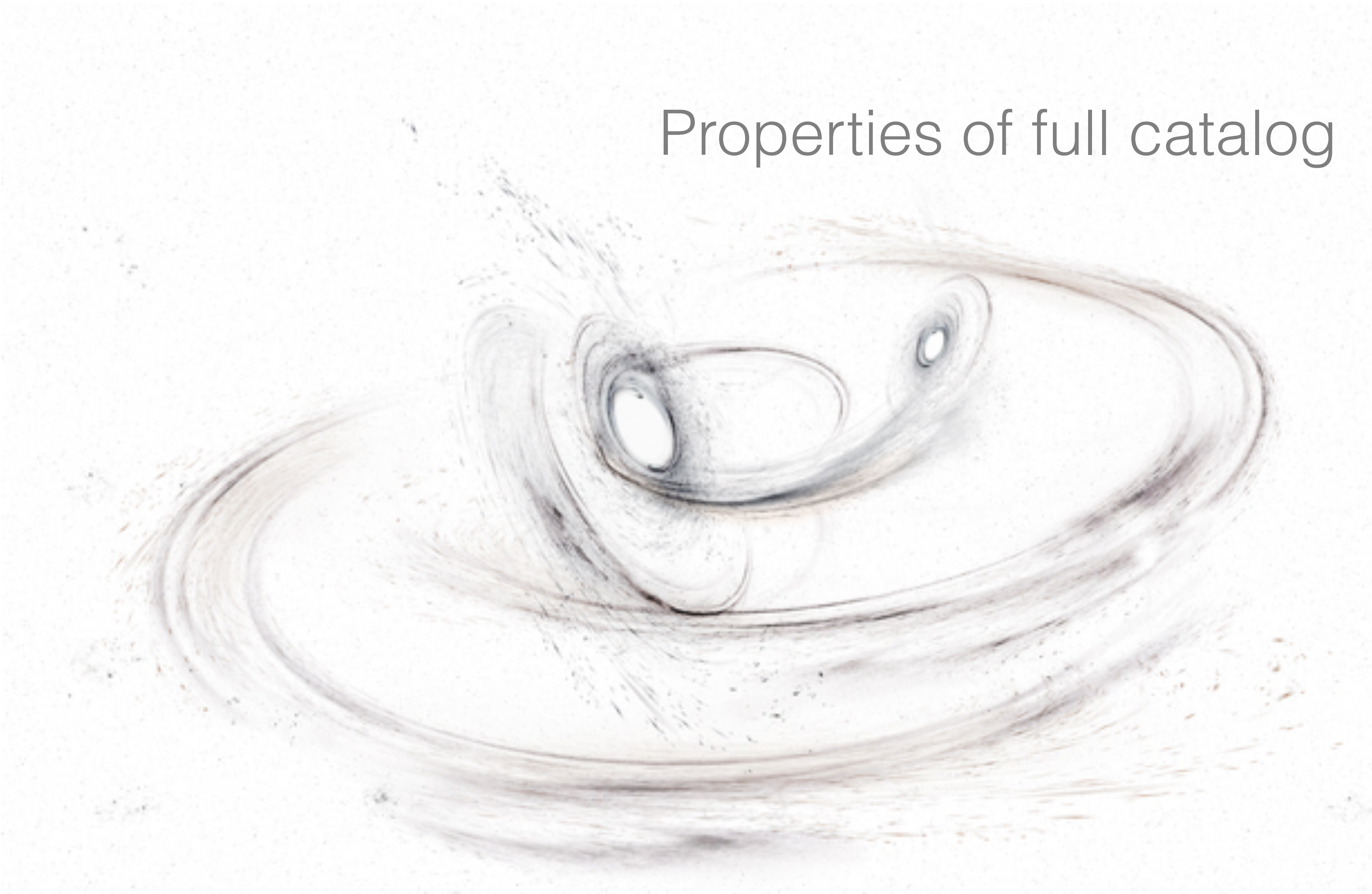
Neutron Star - BH Binaries



Neutron Star - BH Binaries

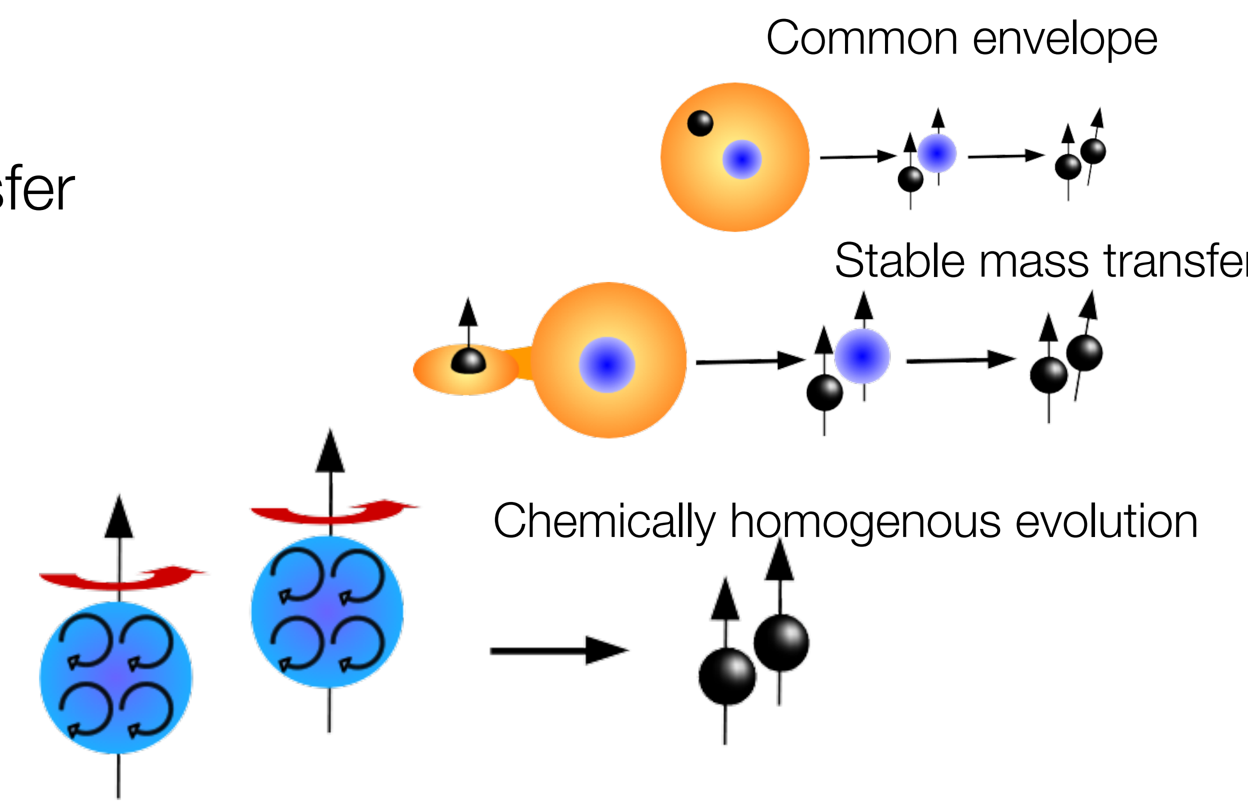


Properties of full catalog



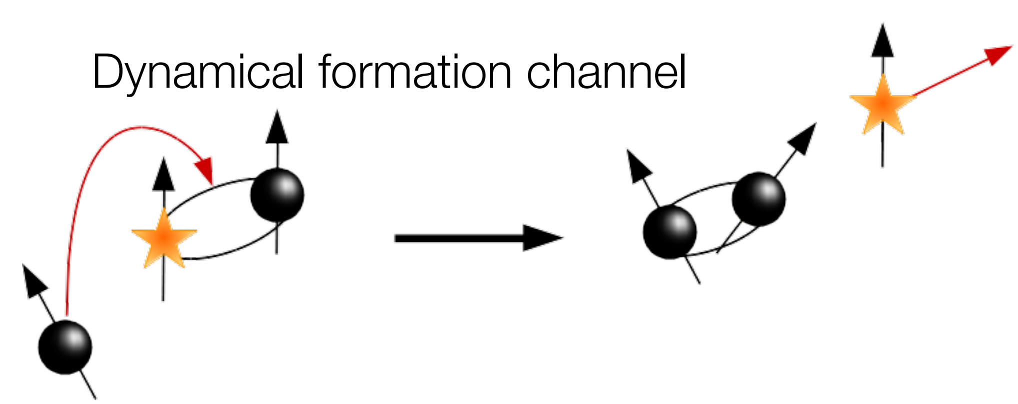
Isolated formation channel

1. Via common envelope or stable mass transfer
    1. Preference for **equal mass**
    2. Preference for **aligned spins**
2. Chemically homogeneous evolution
    1. **Equal mass**
    2. **Aligned spins**

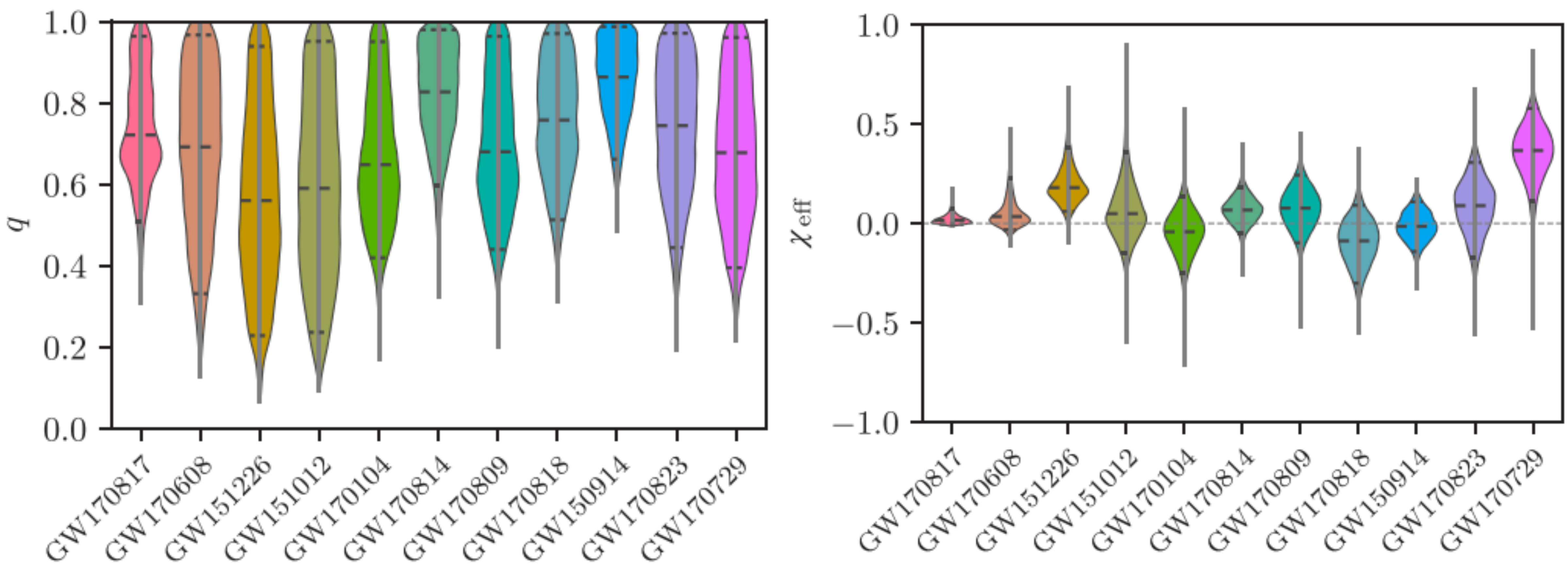


Dynamical formation channel

- **Higher masses** than isolated channel
- **Lower mass ratios** more likely
- **Spins isotropically** distributed



GWTC-1 Phys. Rev. X 9, 031040 (2019)



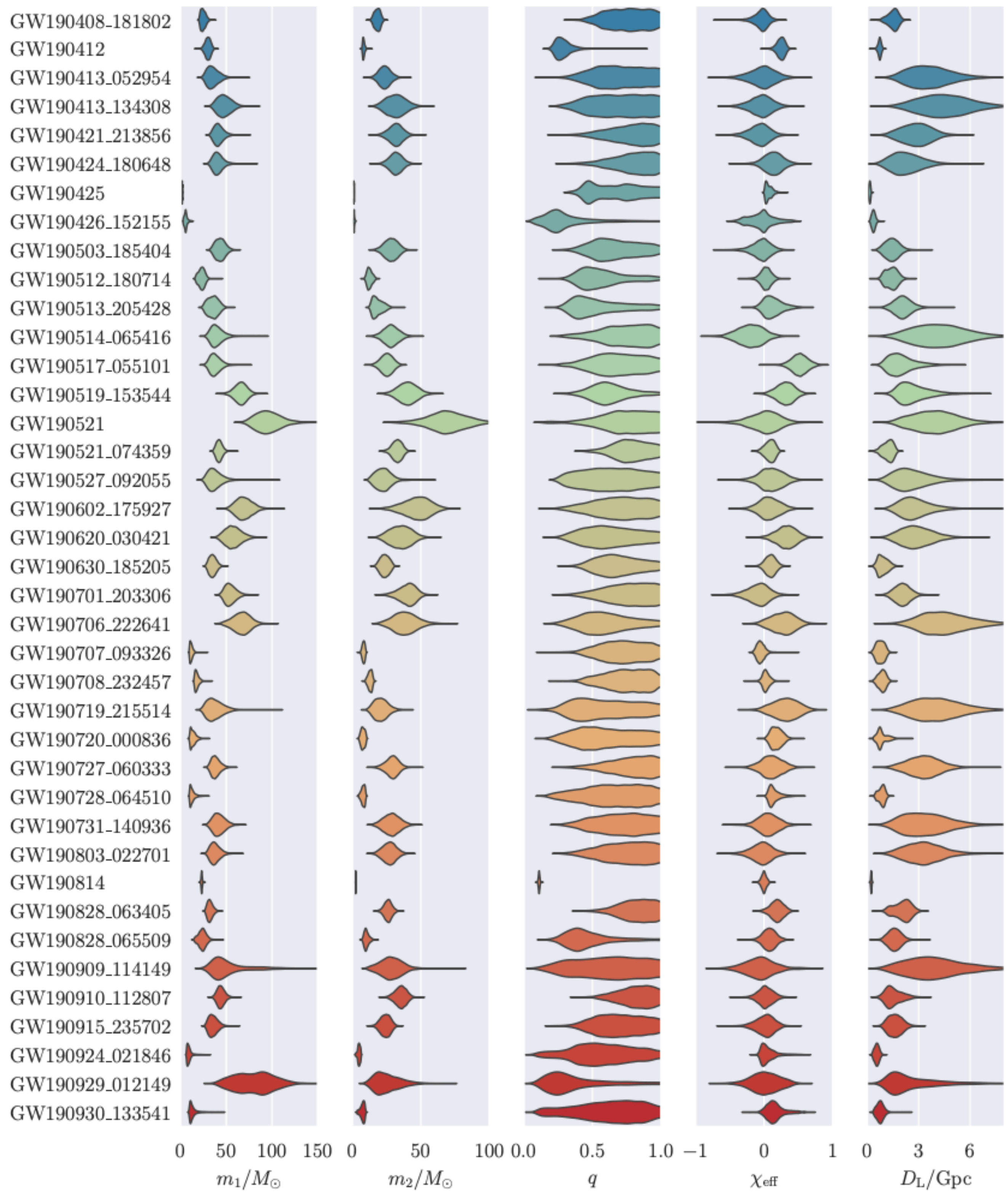
- All the events are consistent with having equal masses
- Small spins - Only two events hint at $\chi_{\text{eff}} > 0$
- Consistent with the isolated binary formation channel

GWTC-2

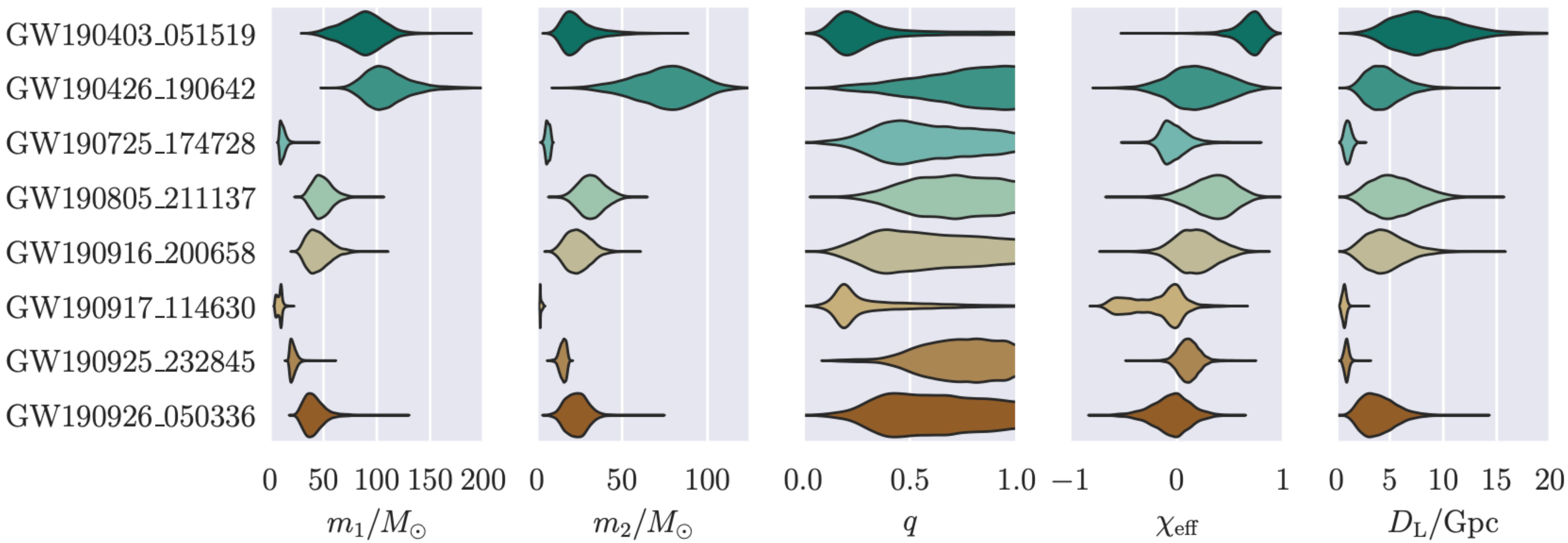
Events of Note

Event	Description
GW190521	**Most massive** binary system with total mass = 157.9 $M_\odot$
GW190425	**Least massive system & Closest event** Total Mass = 3.4 $M_\odot$; Distance = 0.16 Gpc
GW190426_152155	**Second lowest** total mass (M = 7.2 $M_\odot$), **NSBH or BBH**
GW190814	Most extreme mass ratio **q = 0.11, NSBH or BBH**
GW190924_021846	**Least massive** definite **BBH** system with total Mass = 13.9 $M_\odot$
GW190514_065416	**Lowest effective spin** perpendicular to orbital plane: χ_{eff} = -0.16
GW190517_055101	**Highest effective spin** perpendicular to the orbital plane: χ_{eff} = 0.53
GW190909_114149	**Most distant event** Luminosity distance = 4.77 Gpc; Redshift = 0.75
GW190412	First event with evidence of **higher multipole mode** contribution Aside from GW190814, most unequal mass ratio: **q = 0.28**

R.Ewing, R. Huxford, D. Singh, Pennsylvania State Univeristy



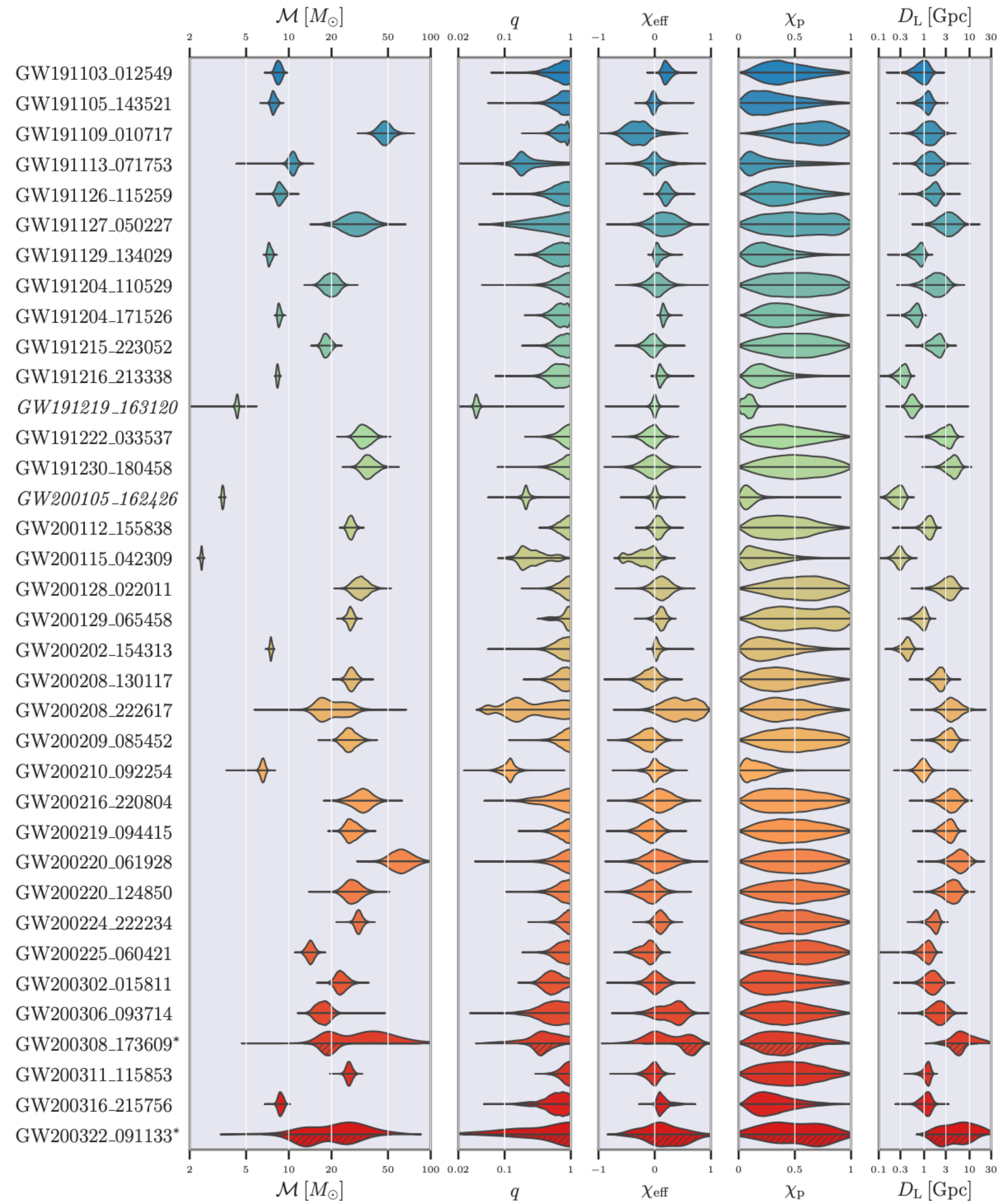
Abbott et al. Phys. Rev. X 11, 021053 (2021)



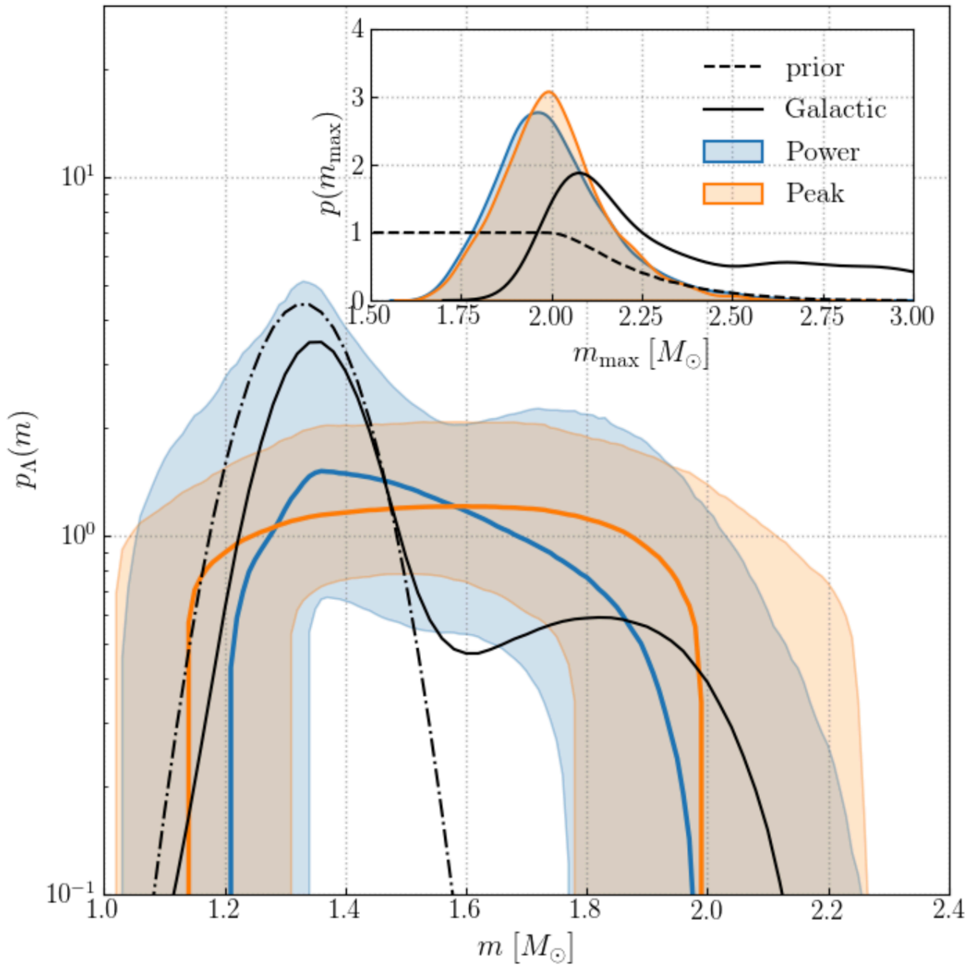
- Two additional events, *GW190403_051519* and *GW190426_190642*, besides *GW190521* with component **masses in the PISN mass gap.**
- *GW190917_114630* has inferred parameters consistent with an NSBH, however, had it originally been classified as an NSBH by the detection pipeline, its $p_{\rm astro}$ would have been smaller than 0.5.

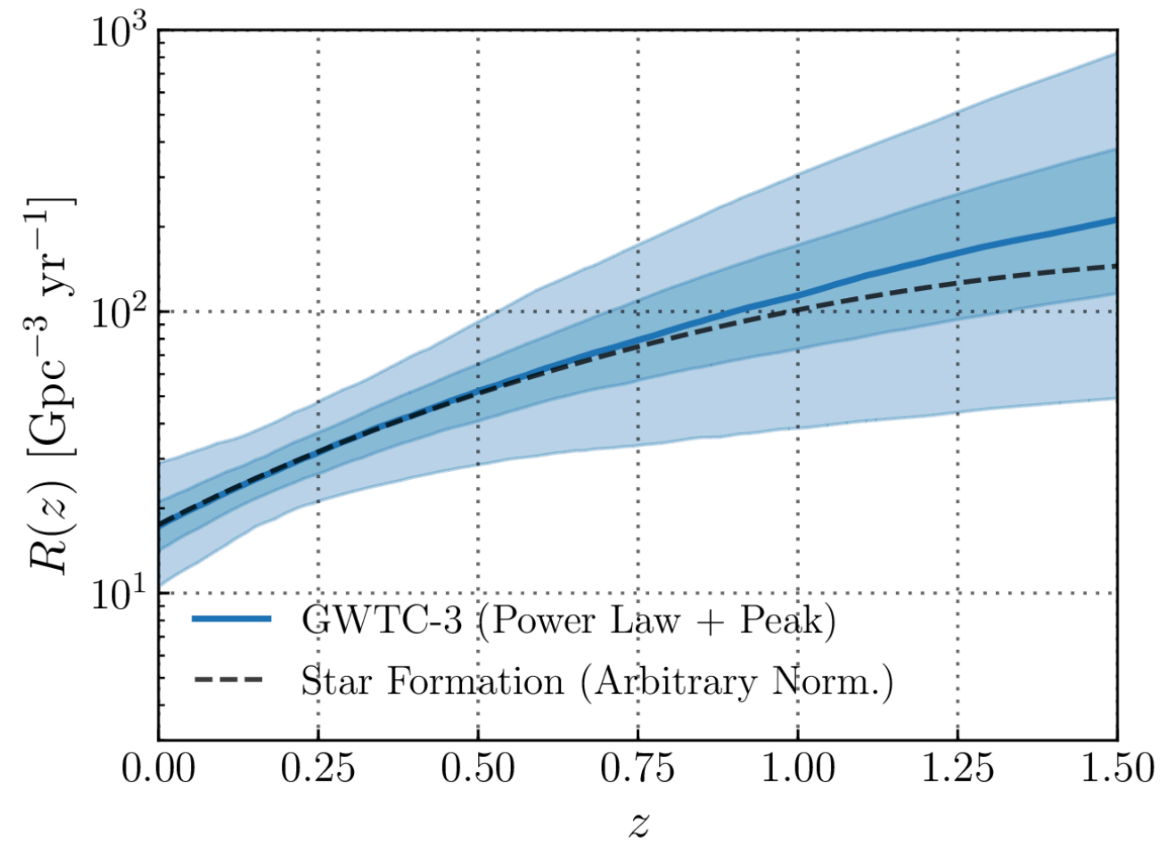
GWTC-3

- Three candidates consistent with NSBHs
- Three candidates have the primary mass posterior partially overlapping with the PISN mass gap
- Two candidates showing significant support for $\chi_{\rm eff} < 0$
- One event showing significant support for mis-aligned spin



Binary populations

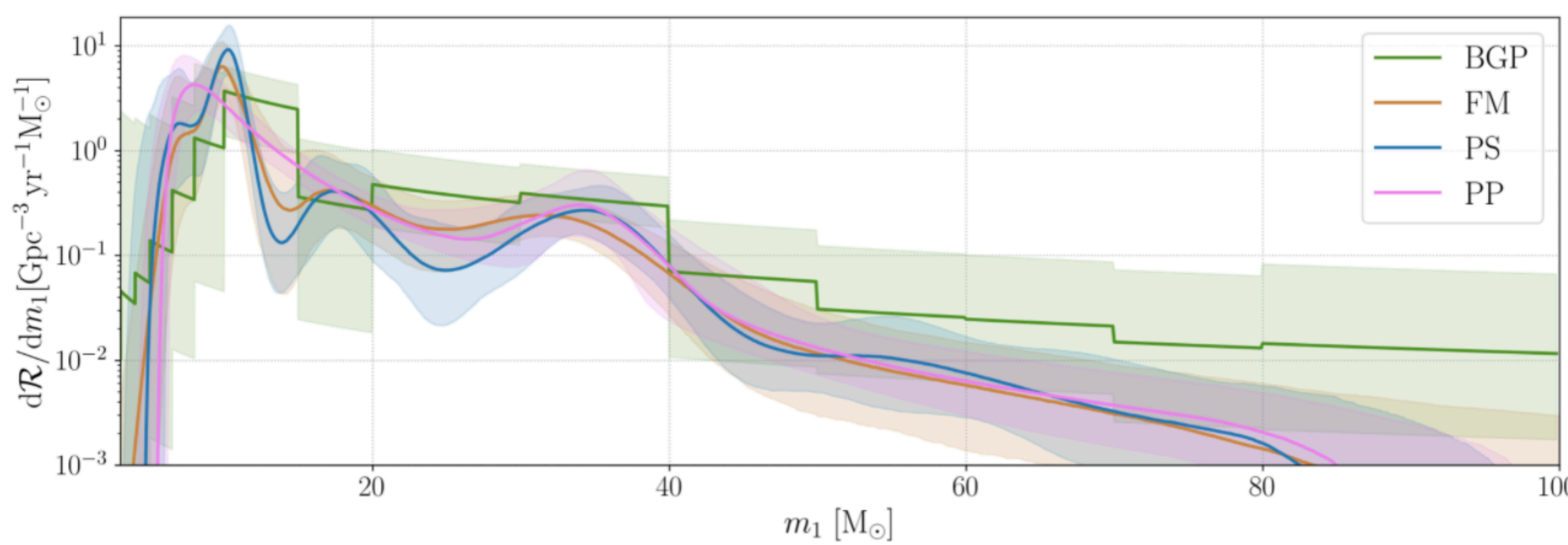




$$R_{\mathrm{BBH}} = 17.3 - 45\,\mathrm{Gpc^{-3}yr^{-1}}$$

$$R_{\mathrm{BNS}} = 13 - 1900\,\mathrm{Gpc^{-3}yr^{-1}}$$

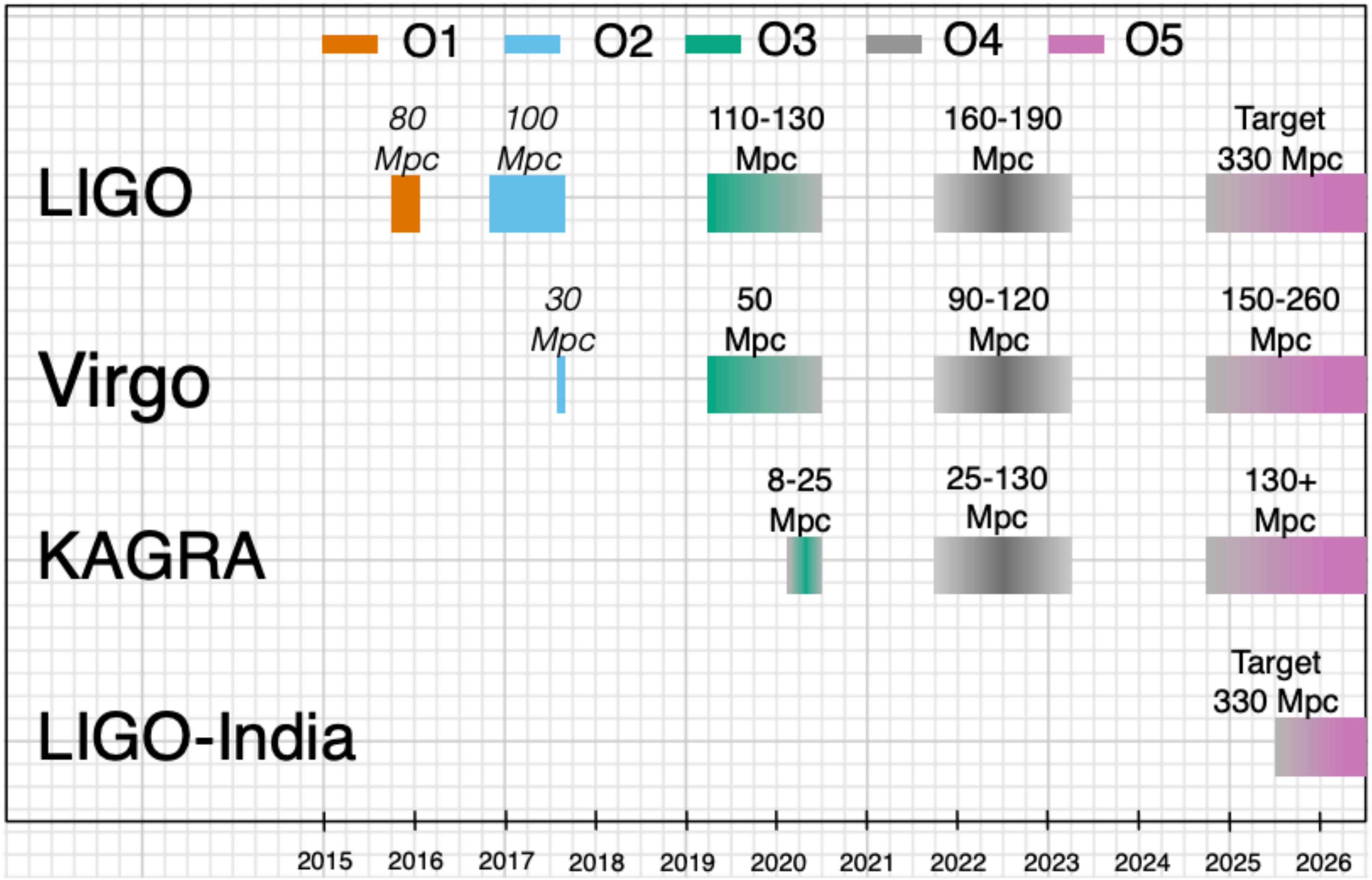
$$R_{\mathrm{NSBH}} = 7.4 - 320\,\mathrm{Gpc^{-3}yr^{-1}}$$

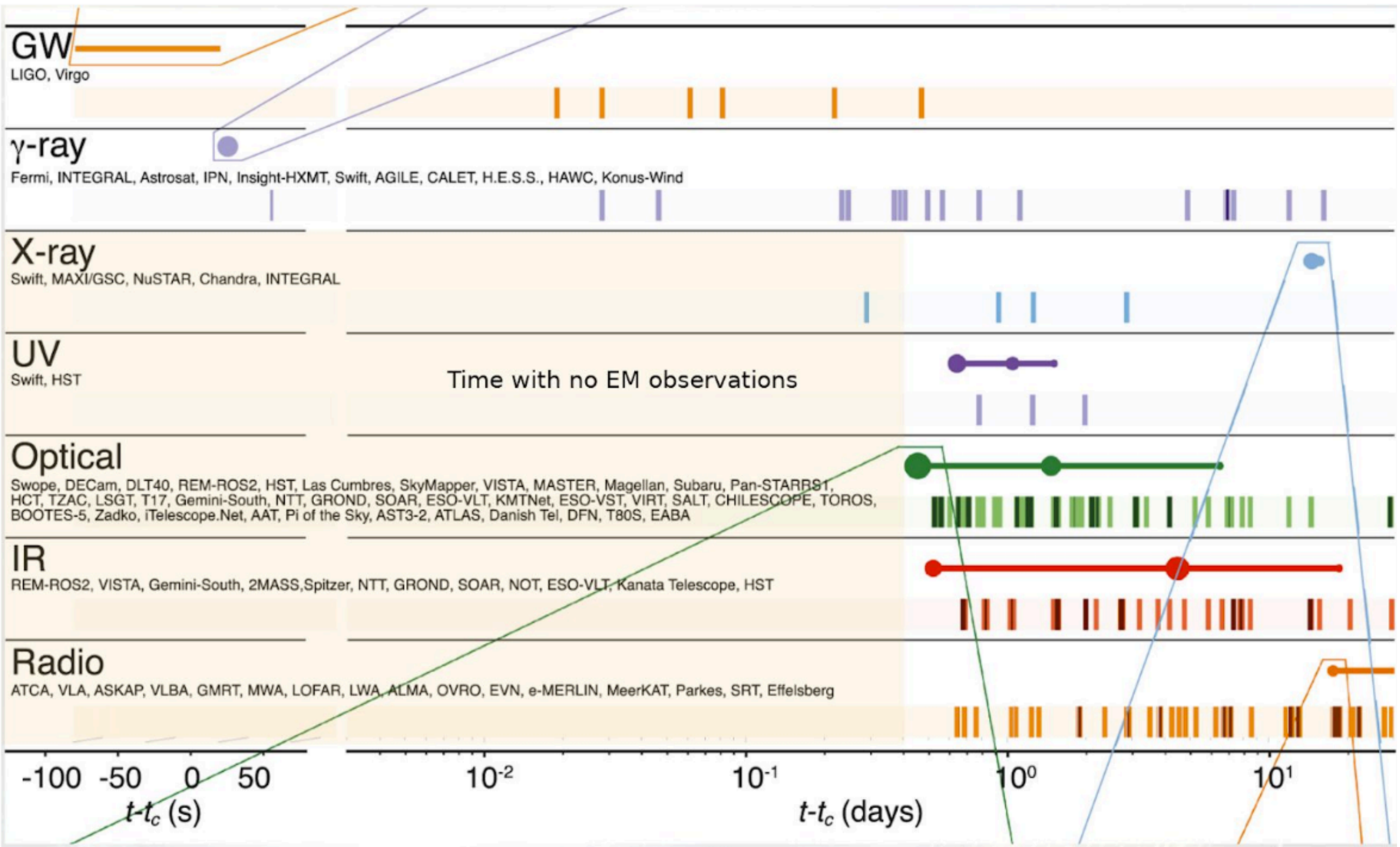


arXiv: 2111.03634

Going Forward - Near Term

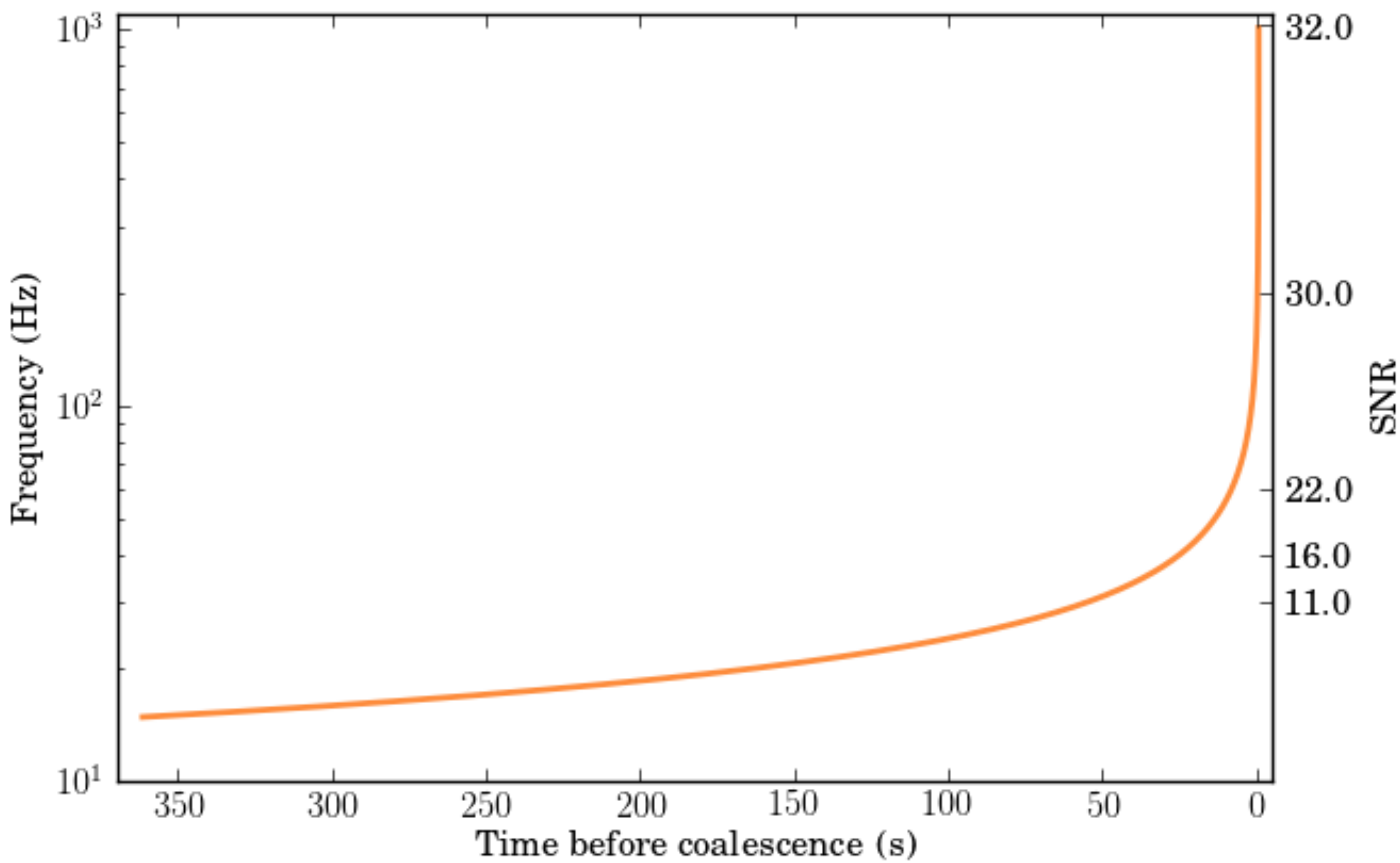
LIGO DCC P1200087-v58





Modified from ApJL 848:L12

NS-NS Time Frequency

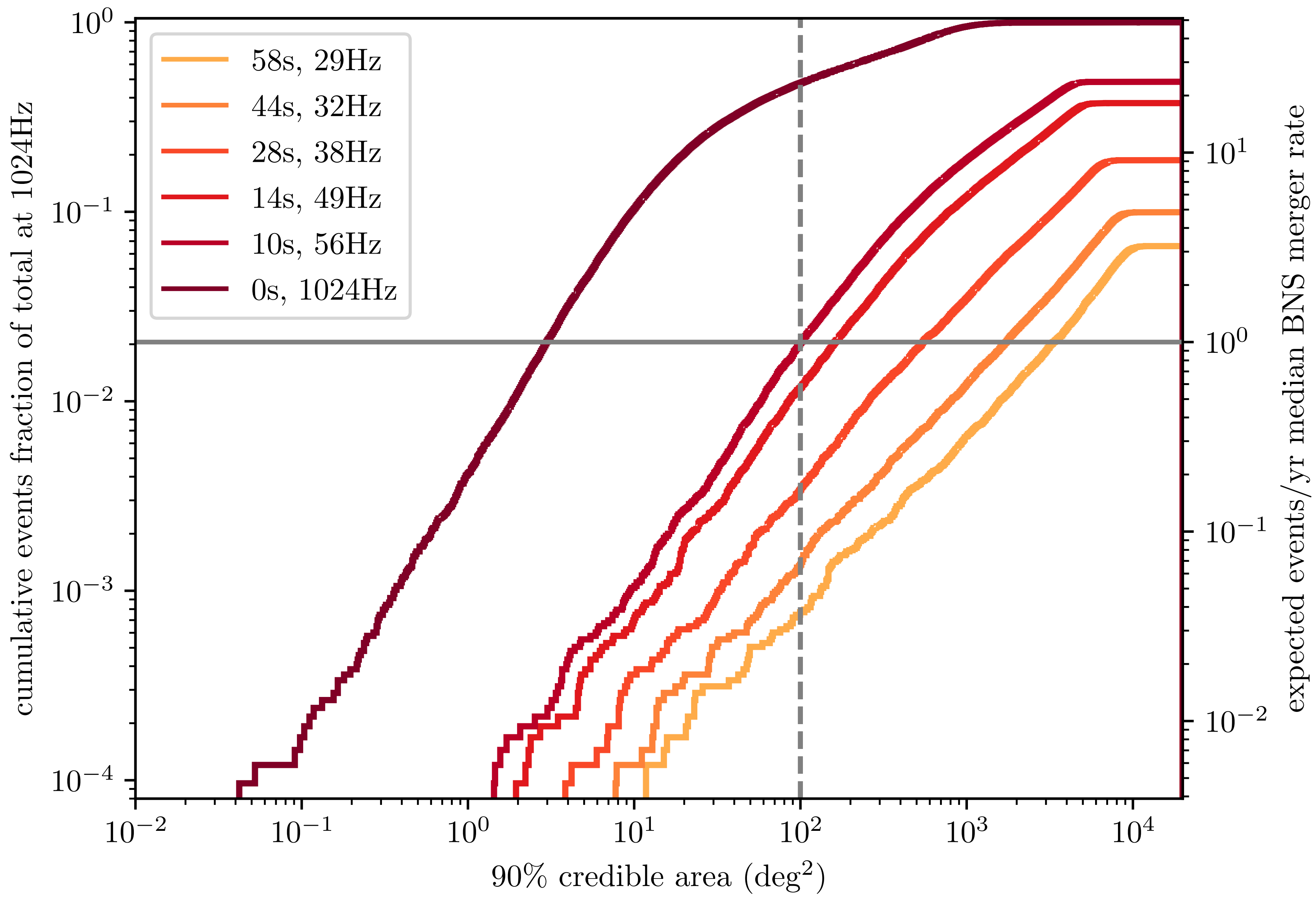


Early Warning: Motivation

- Prompt radio emission
  short coherent radio pulse near the instant of merger
  Usov & Katz 2000; Hansen & Lyutikov 2001; Pshirkov & Postnov 2010; Lai 2012; Lyutikov 2013; Totani 2013; Ravi & Lasky 2014; Metzger & Zivancev 2016; Wang et al. 2016; Lyutikov 2018; Wang et al. 2018
- Early UV/optical observations
  properties of shock-heated ejecta, jet formation,…
  Metzger et al 2017 (arXiv:1710.05931)
- X-ray signatures
  prior to merger from NS-NS magnetosphere interaction, crust breaking
  immediately after merger, extended emission or X-ray plateaus
  in case of a long-lived post-merger NS, there may be X-ray/UV emissions
  Ciolfi & Siegel 2015; Metzger & Piro 2014; Siegel & Ciolfi 2015
- GRBs
  O(s)

Early Warning: Predictions

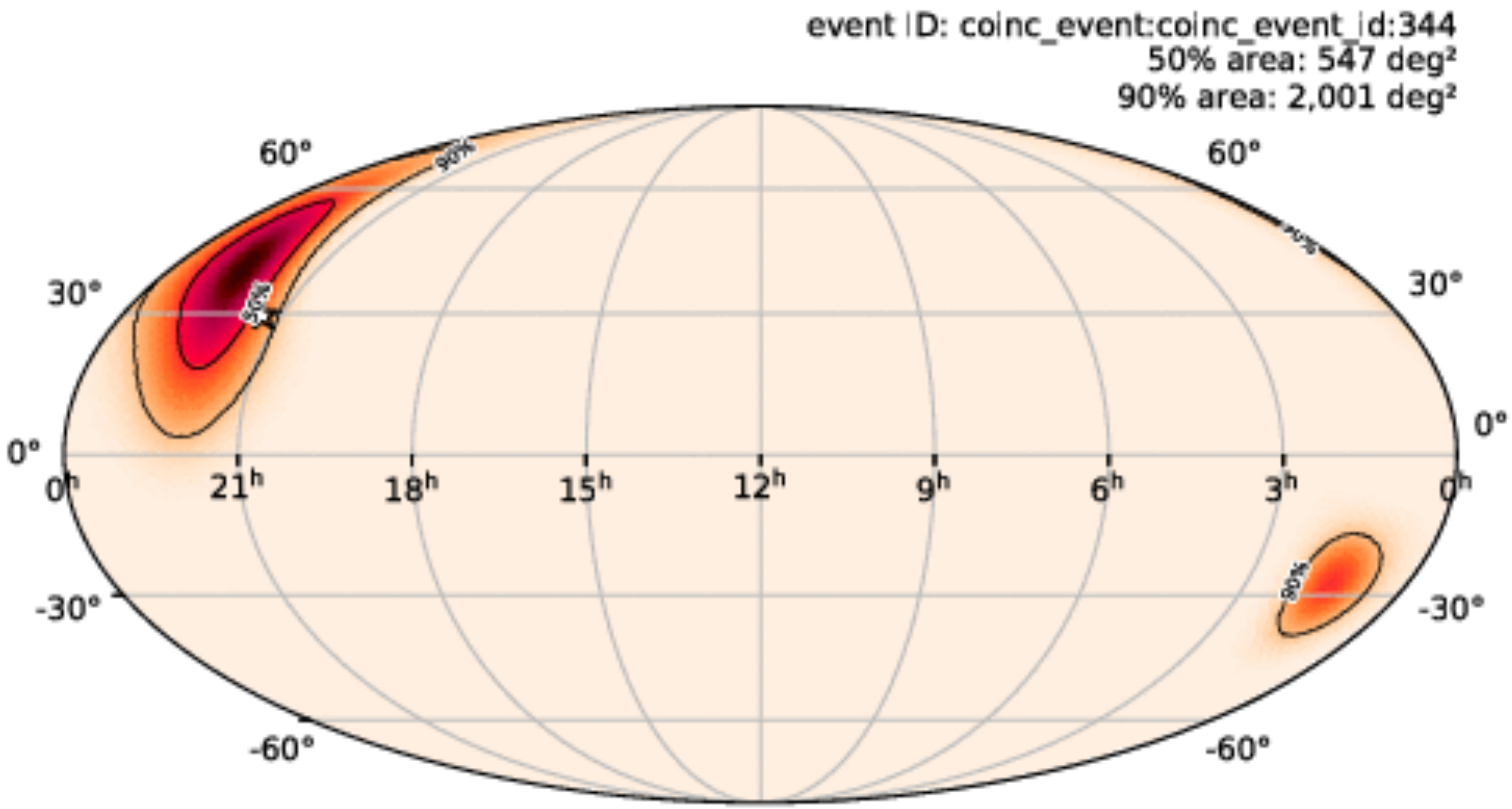
Sachdev et al 2020 ApJL 905 L25



We expect at least **1 pre-merger event/year** localized to **< 100 deg²** (90% interval)

Several pre-merger events/year: **24 (3) detected 10s (60s) before merger** with larger localizations

Evolving sky localization



Early Warning: Data Release

https://gstlal.docs.ligo.org/ewgw-data-release/

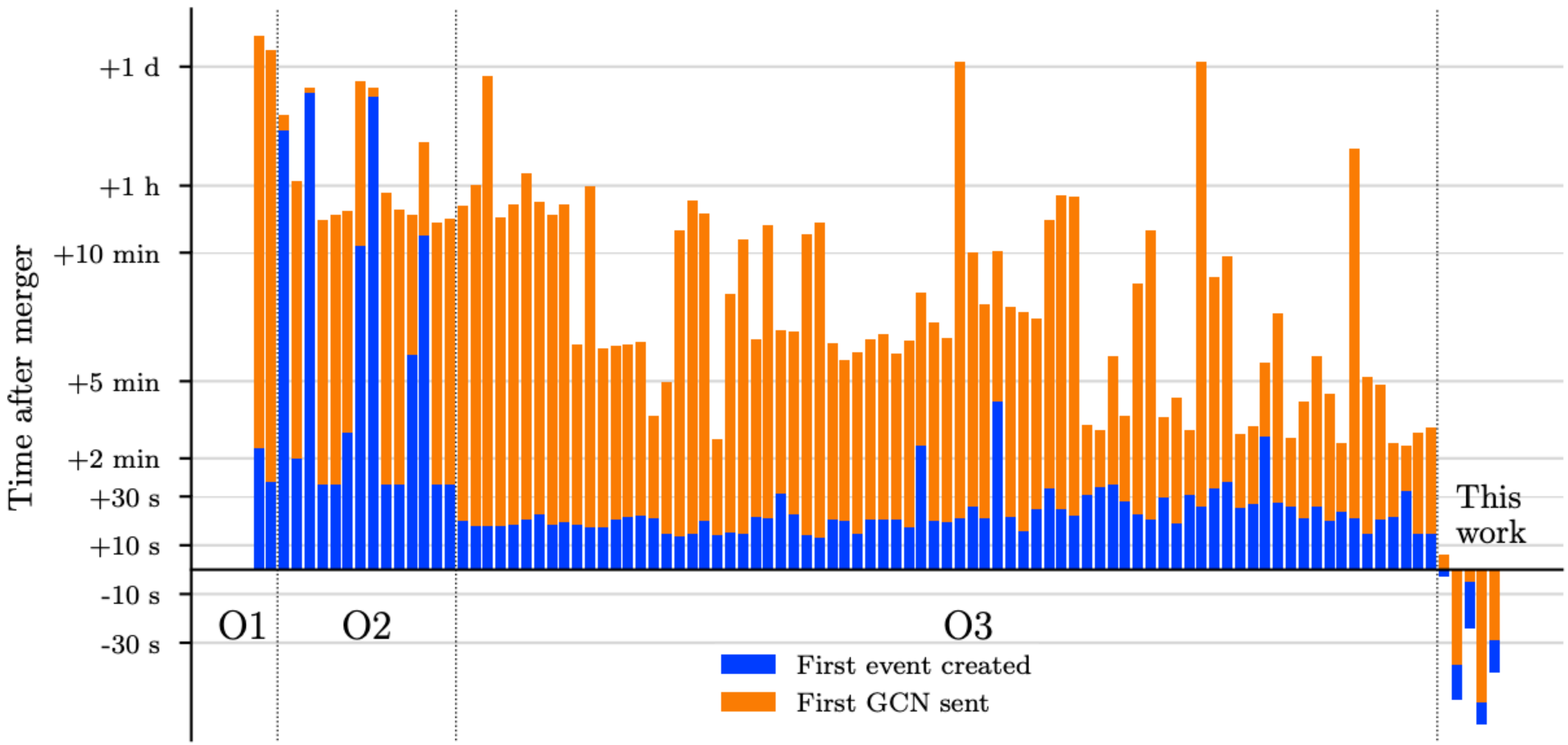
Early Warning: Replay Test

Magee-Chatterjee-Singer-Sachdev et al.
ApJL 910 L21

- 11 June 2020 - 19 June 2020
- Data from O3 were replayed to replicate online conditions
- EW alert threshold set to 1 per day
- 5 EW alerts were sent out and later retracted

Early Warning: Replay Test

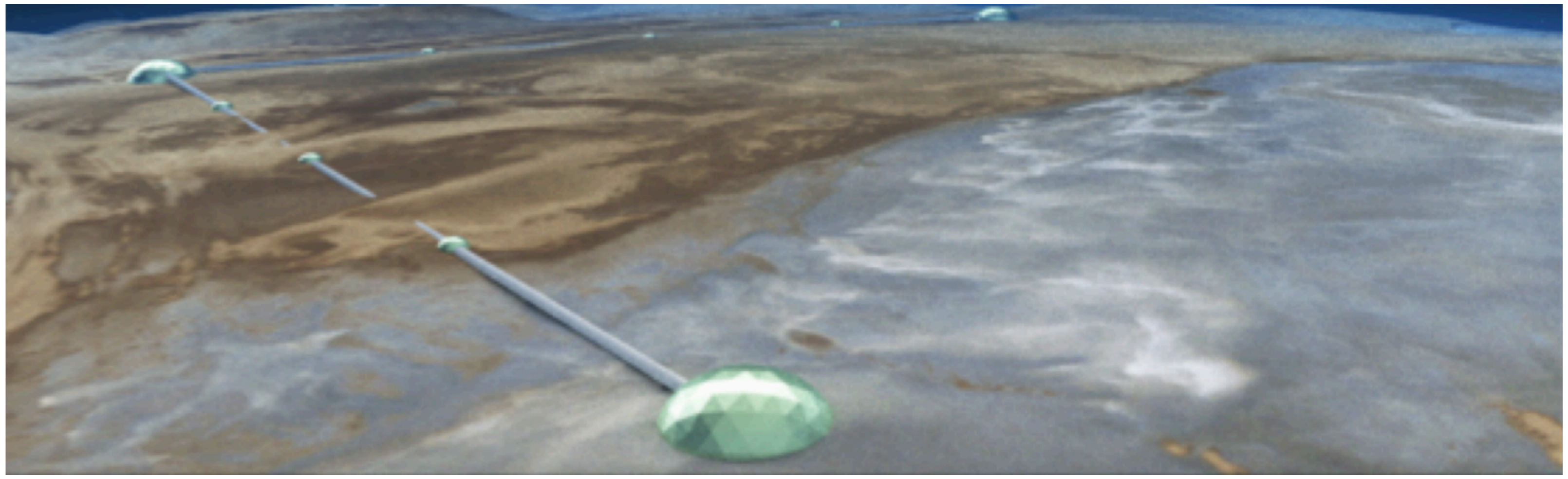
Magee-Chatterjee-Singer-Sachdev et al.
ApJL 910 L21



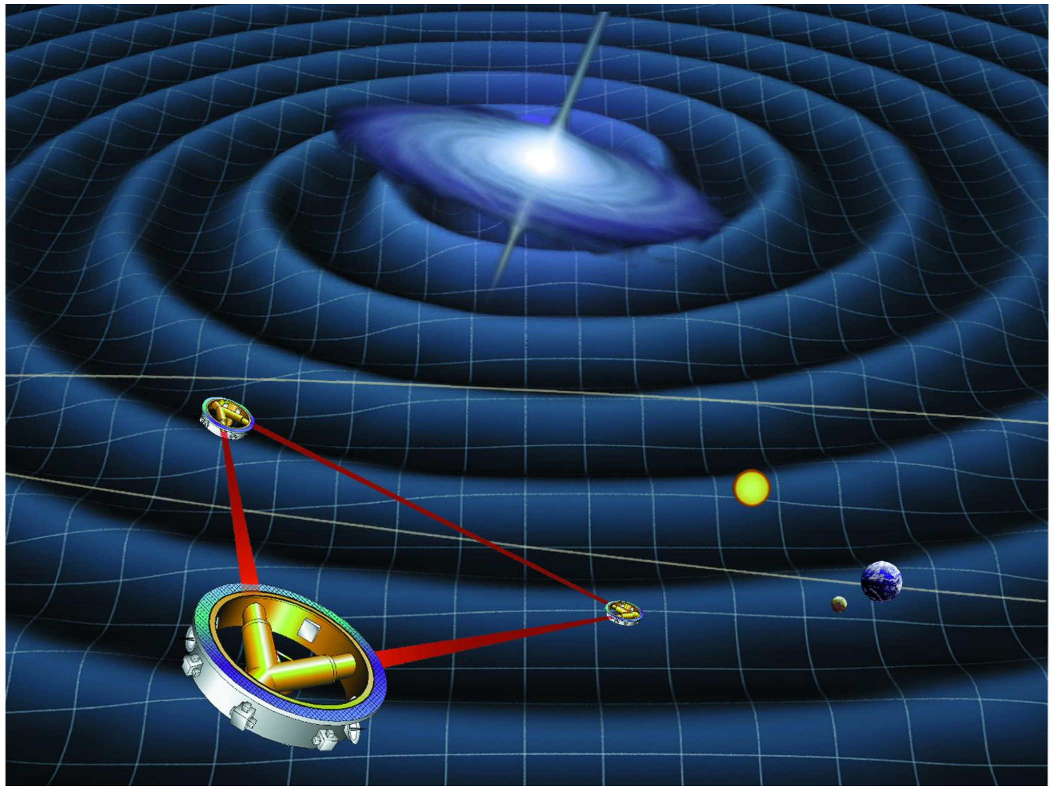
Conclusions

- Since the first discovery of gravitational waves, Advanced LIGO and Virgo have observed a several dozens of black holes
- We have detected at least one BNS event (+ likely another BNS, and 2 NSBH events)
- BNS mergers are progenitors of short GRBs
- We have discovered BHs in both mass gaps, although it is not clear if these BHs were formed via conventional mechanisms
- BBH mass distribution shows several sub-features of potentially different formation mechanisms, possibly some of them being formed in dynamical environments
- NS in compact binaries mass distribution is different from that of NSs observed in the galaxy
- GWs can be used to measure the Hubble constant
- No evidence of sub-solar mass / primordial black holes yet
- No violations of GR have been observed
- No matter effects have been observed

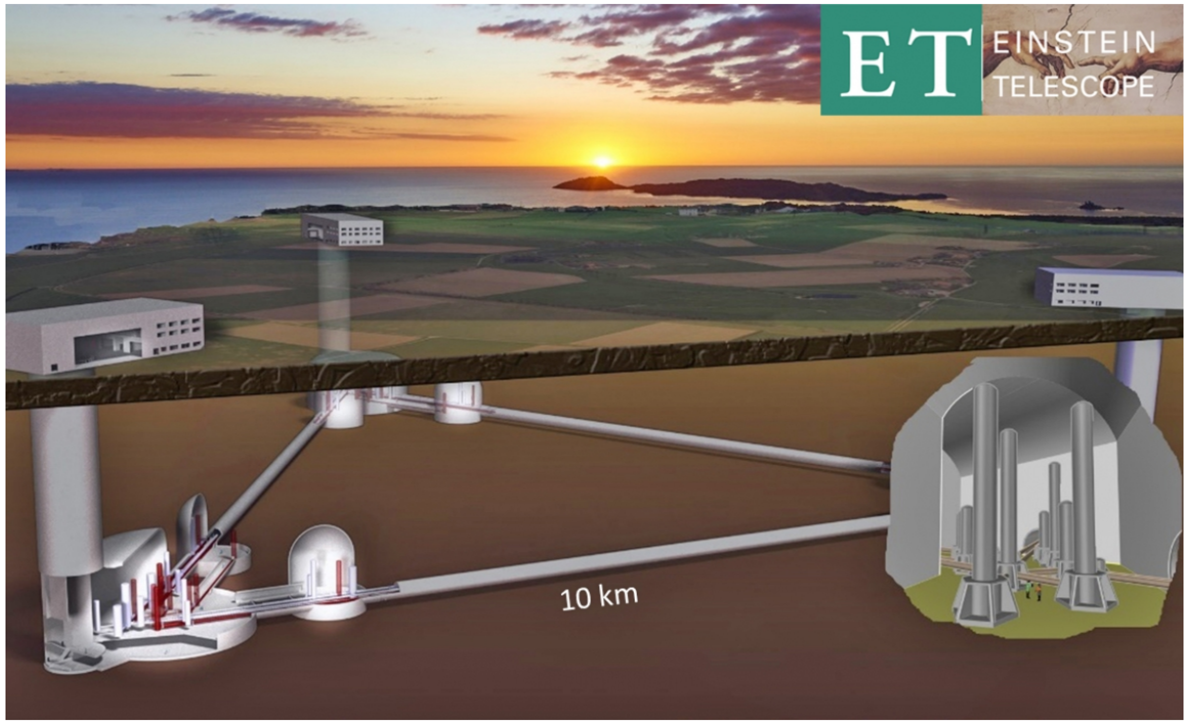
Future detectors



http://cosmicexplorer.org



http://lisa.jpl.nasa.gov/gallery/lisa-waves.html



https://www.ego-gw.it/

Acknowledgements

Thank you ☺