Overview of binary detections

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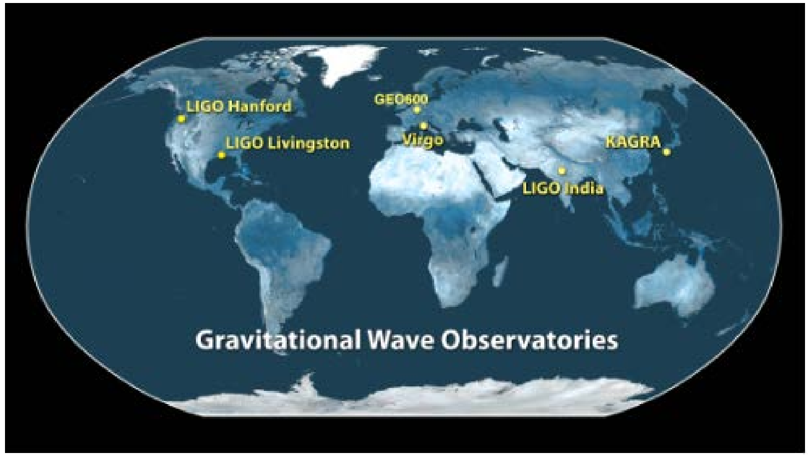
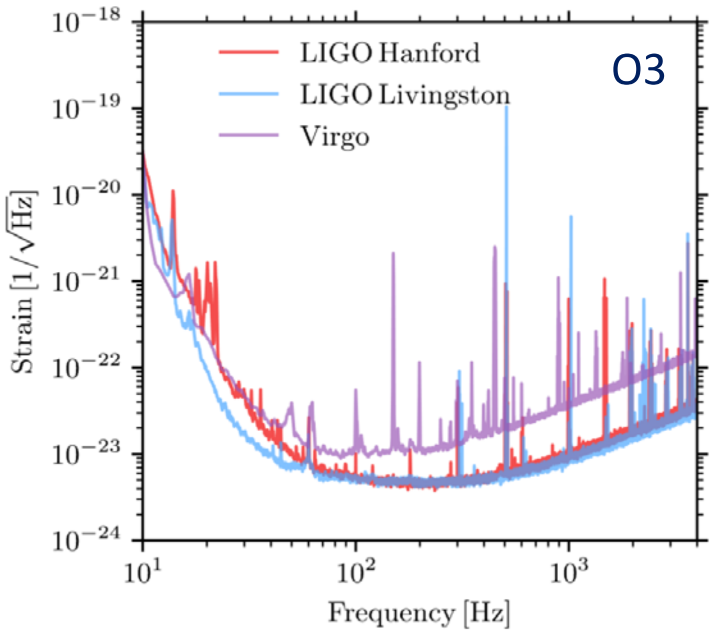
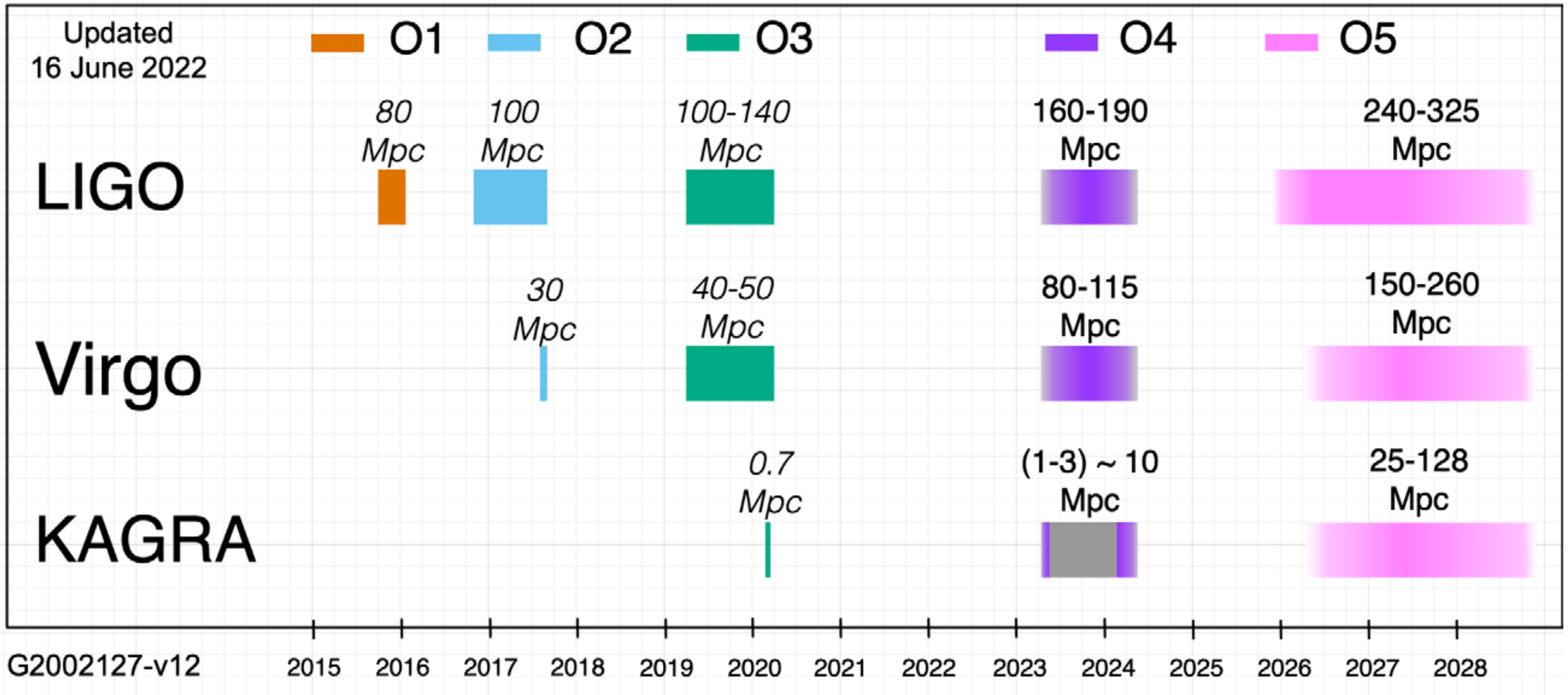
On behalf of the LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration

TMEX, January 7th, 2023

Detectors and observing runs

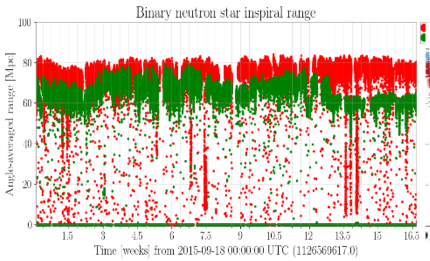




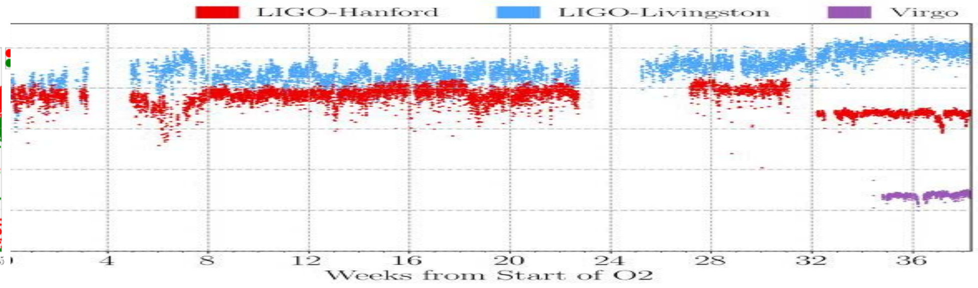


Improved sensitivity and longer runs…

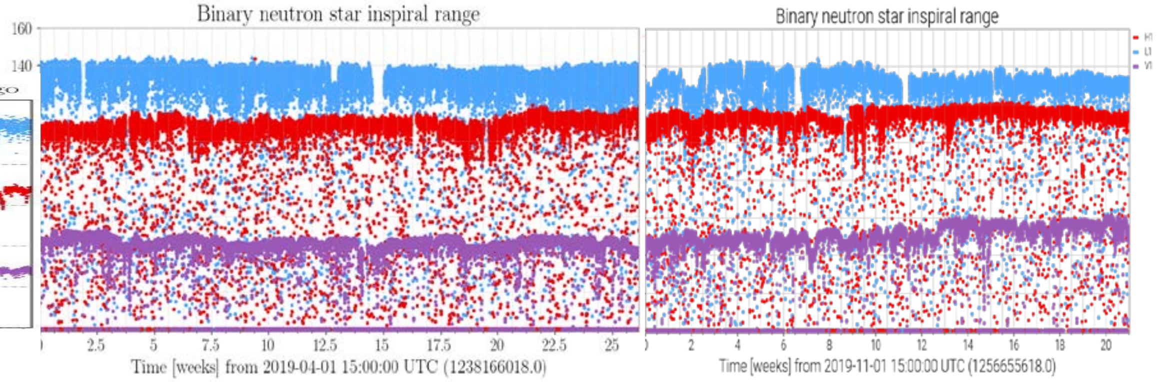
O1 (2015)



O2 (2017)

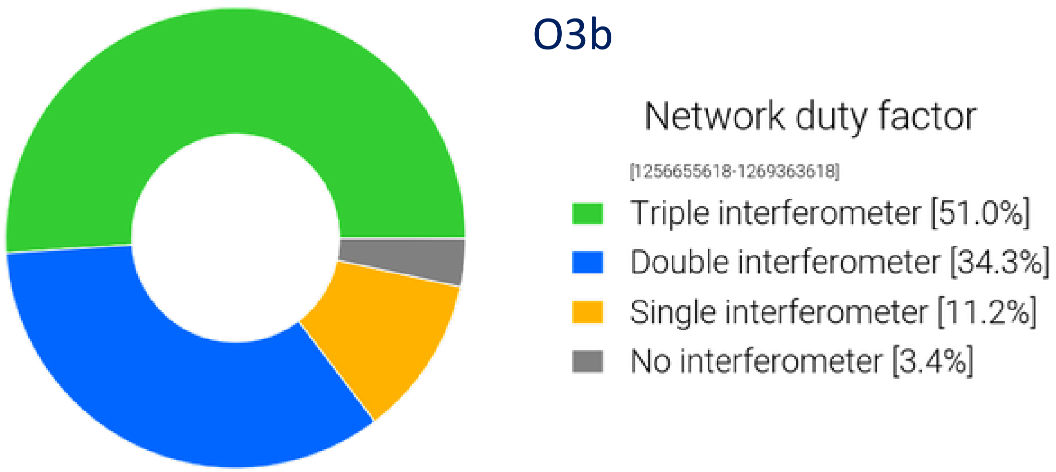


O3a (2019-2020) O3b

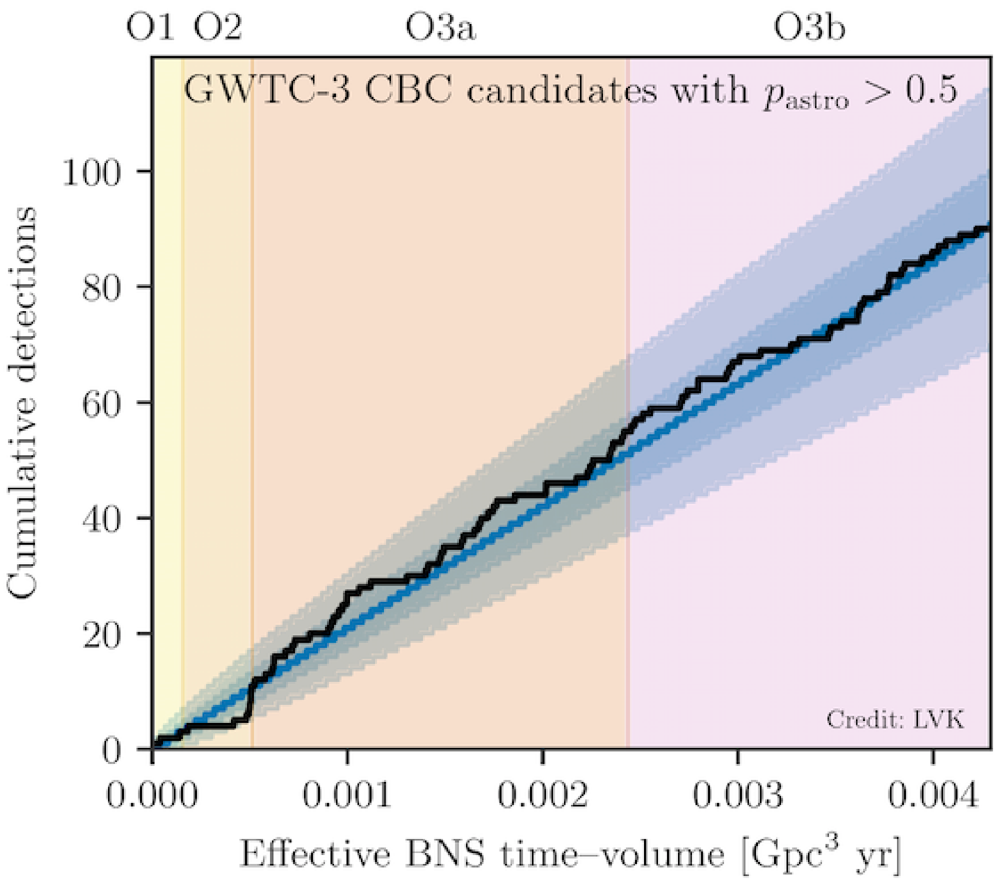


- BNS range
  - Typical detection reach for binary neutron star mergers with signal to noise ratio of 8

O3b



… provide more and more detections



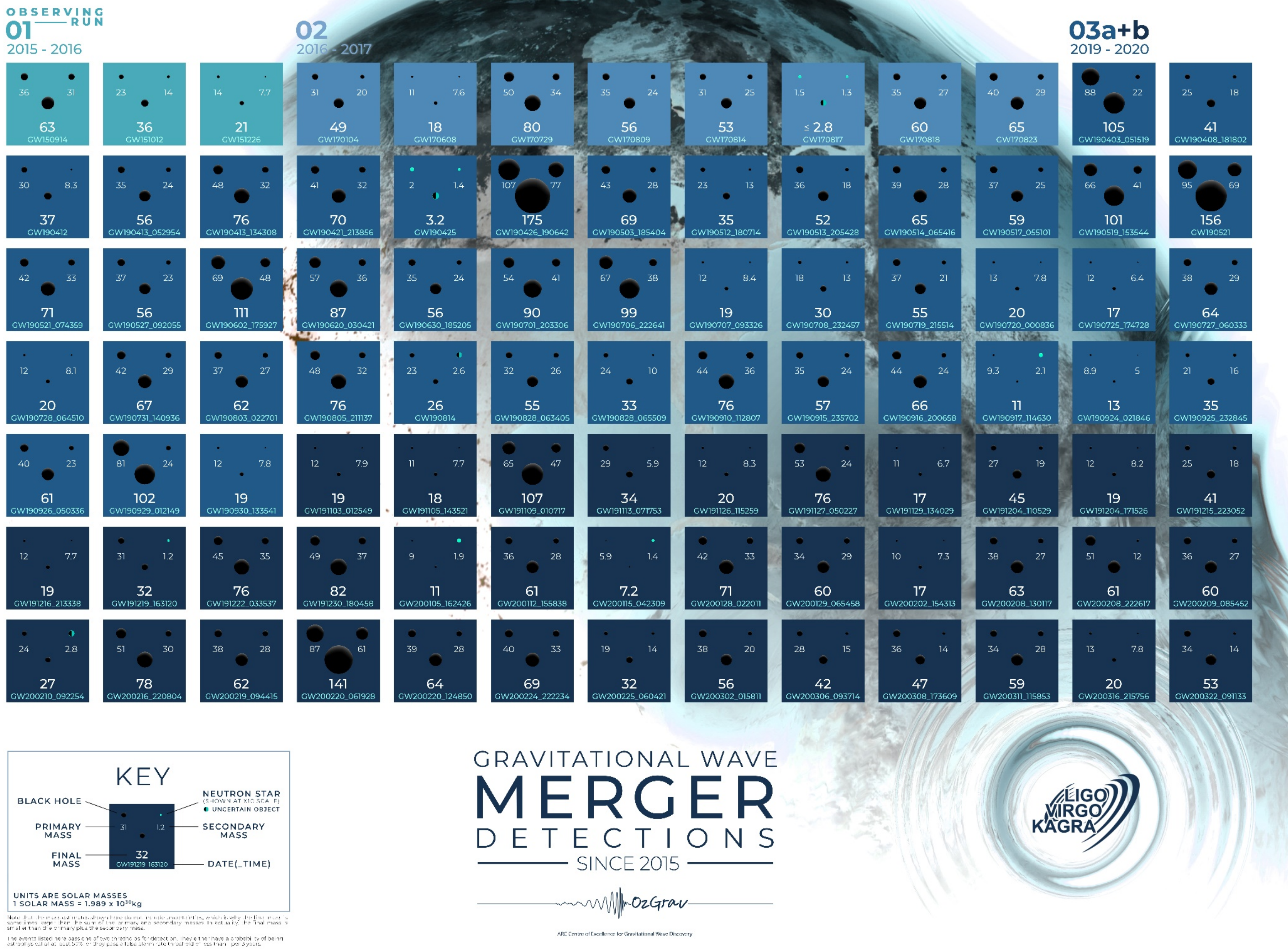
- All detections so far are from compact binary coalescences
  - Other types of sources also searched by LIGO-Virgo-KAGRA
- Searches are done on two timescales
  - Low latency ➔ public alerts
  - Offline re-analysis of archival data
- Latest catalog of detections through O3 reported in GWTC-3 arXiv 2111.03606
- Bulk data released at gravitational wave open science center
  - Additional candidates reported by external groups

Searches in a nutshell

- Searches use cleaned, calibrated data with data quality information
- Two types of searches used to search for signals from compact binary coalescences
  - Modeled searches – several pipelines
    - Assume source is compact binary coalescence
    - Use matched filtering and banks of template waveforms with varying parameters to find signals in data
      - Masses, (anti-)aligned spins
    - Look for coincidences
      - One pipeline also considers single-detector candidates
  - Minimally modeled search
    - Search for generic, short transients
    - Identify coherent excess power in time-frequency representations of data

Estimating significance

- False alarm rate (FAR)
  - How often do we expect noise to produce a trigger with same or higher ranking statistic?
  - Does not take into account any astrophysical information
- Probability of astrophysical origin (p_{astro})
  - Assess significance by comparing foreground and background ranking statistic distributions, informed by estimated astrophysical rates
  - $$p_{\mathrm{astro}} = p_{\mathrm{BNS}} + p_{\mathrm{NSBH}} + p_{\mathrm{BBH}} = 1 - p_{\mathrm{terr}}$$
- Event validation to check for possible instrumental origin



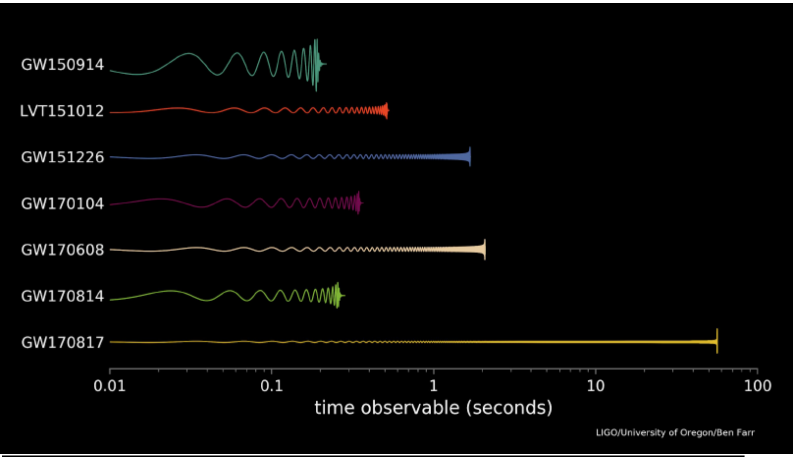
91 candidates, including

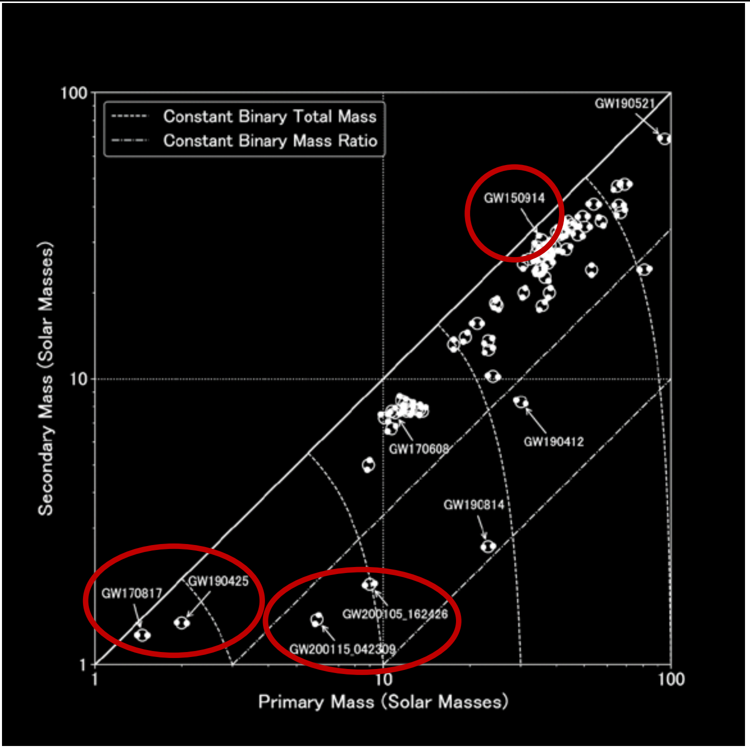
- 10-15% contamination from noise
- 76 used in population studies

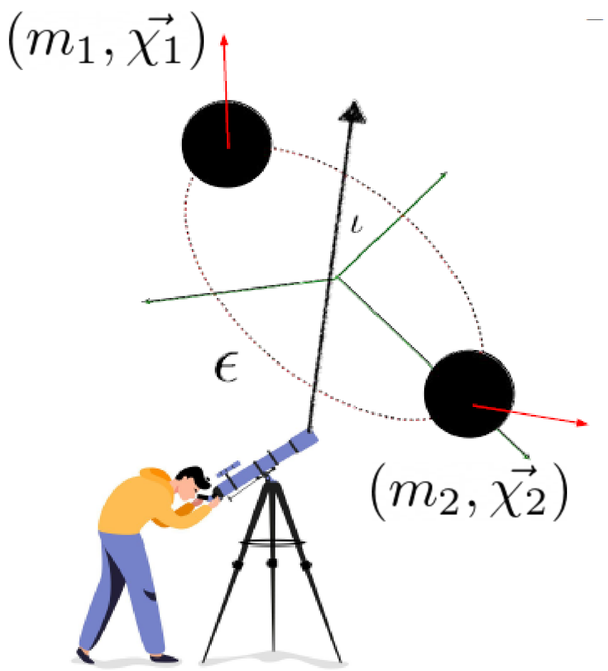
Science from:

- Remarkable, individual events
- Multi-messenger events
- Event populations

Source diversity



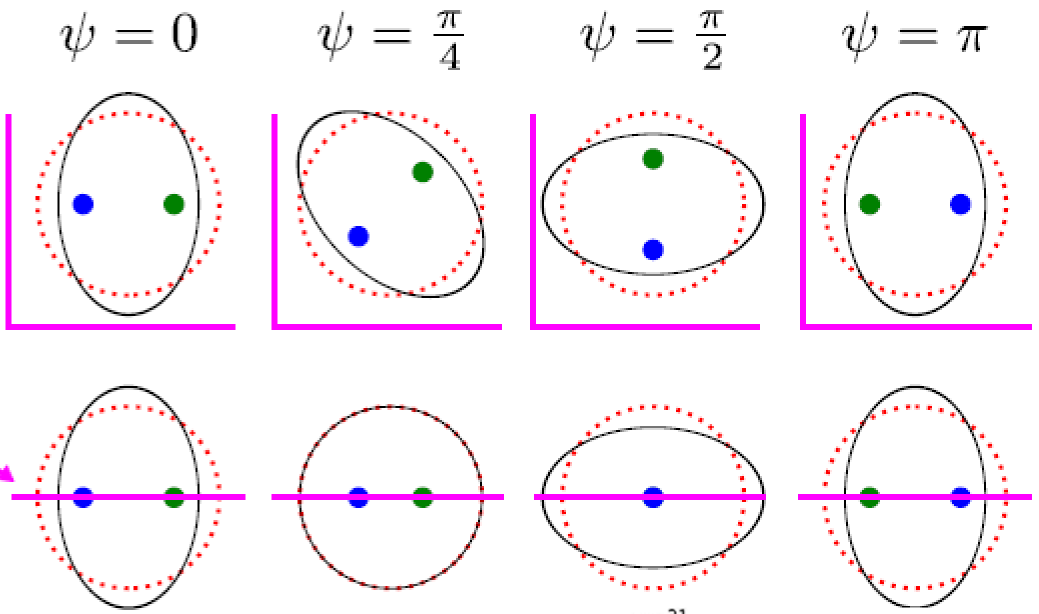




- ❑ Source parameter estimation
  - ➢ Coherent analysis of signal measured by detector network
  - ➢ Identify parameters best matching signal
    - ▪ Multidimensional parameter space
    - ▪ Some parameter degeneracies
    - ▪ Needs complete, reliable waveform models
- ❑ Up to 19 parameters
  - ➢ Intrinsic
    - ▪ Masses (2)
    - ▪ Spins (6)
    - ▪ Deformability for neutron stars (2)
    - ▪ Eccentricity (2)
  - ➢ Extrinsic
    - ▪ Location : luminosity distance, right ascension, declination (3)
    - ▪ Orientation: inclination, polarization (2)
    - ▪ Time and phase at merger (2)

- ❑ Many binary black hole (BBH) mergers
  - ➢ Most with ~ equal masses
  - ➢ Discovery signal GW150914 turned out to be quite typical
- ❑ 2 binary neutron star (BNS) mergers
- ❑ 2 neutron star – black hole (NSBH) mergers

Signal basic features



circular polarization

linear polarization

Dominant frequency

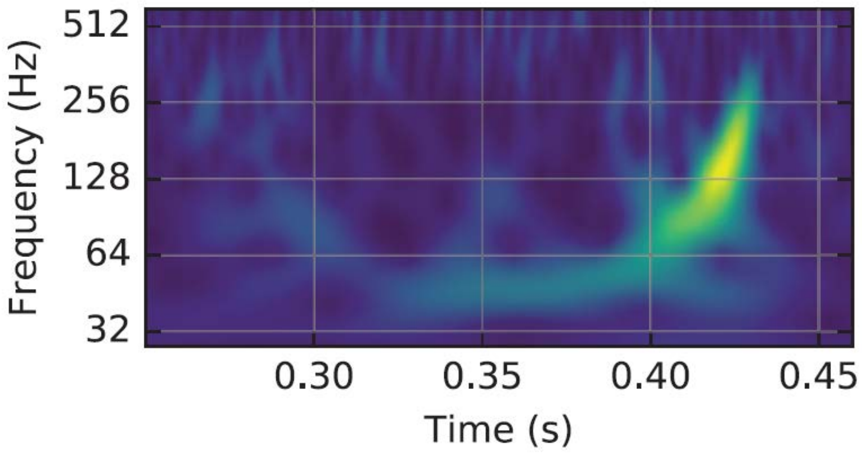
$$f_{\rm GW} = 2\, f_{\rm orbital}$$

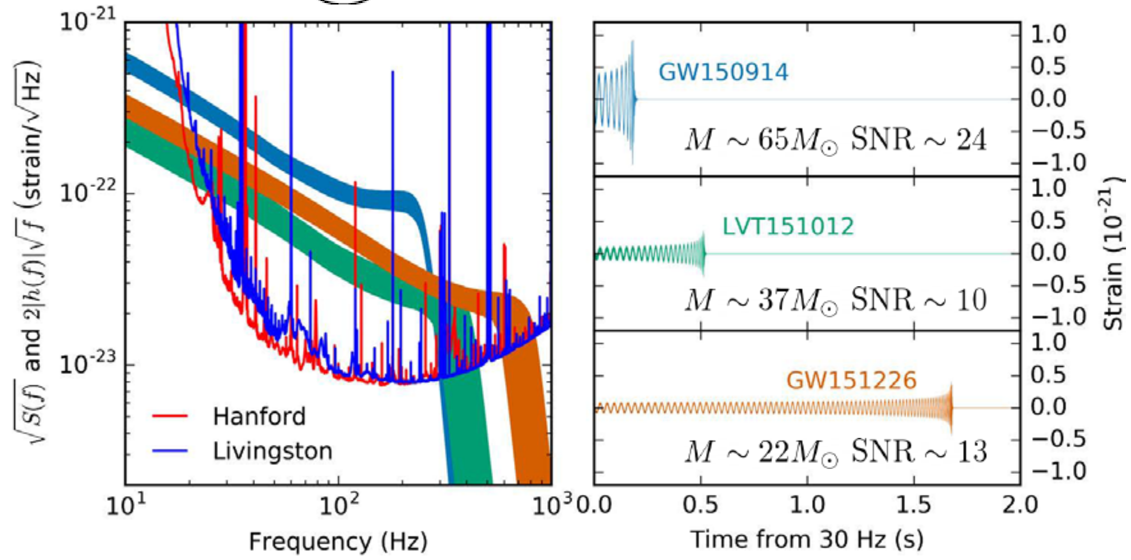
Last stable orbit

$$f_{\rm ISCO} \sim \frac{3M_\odot}{M}\ 1500\ \mathrm{Hz}$$

$M(1+z)$ actually

GW150914

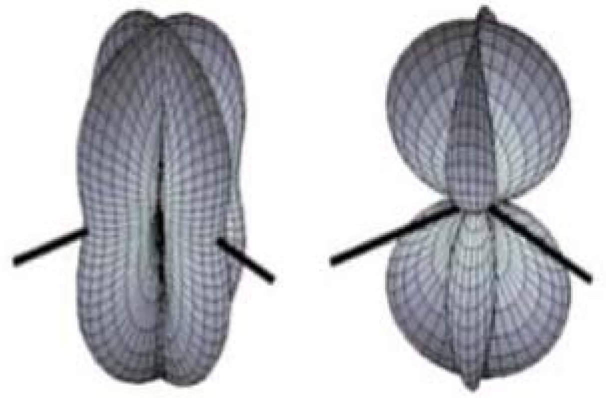




Extrinsic parameters

$$h = F_+ h_+ + F_\times h_\times$$

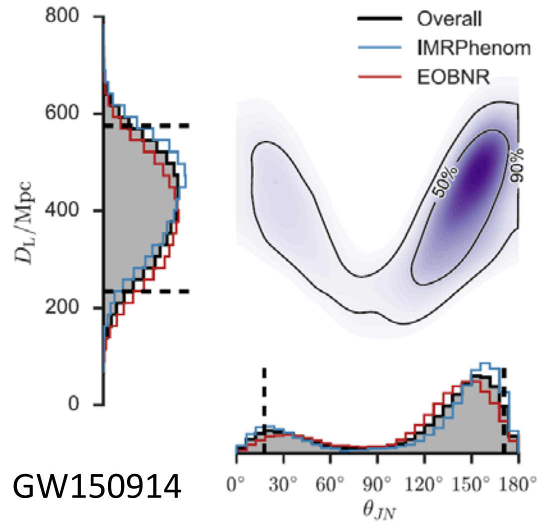
Detector response
- Depends on source direction and polarization



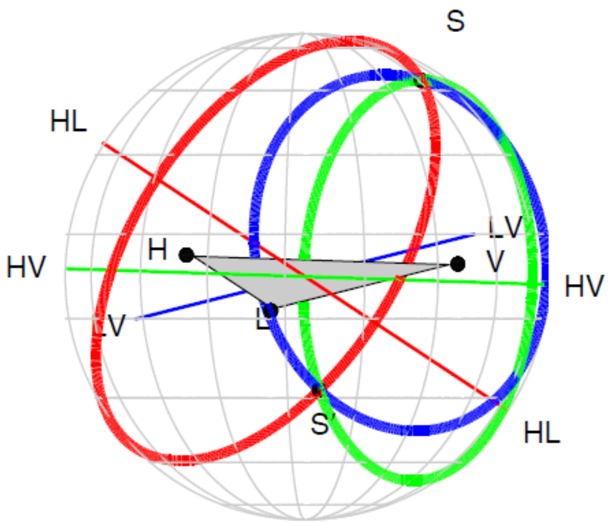
\+   X

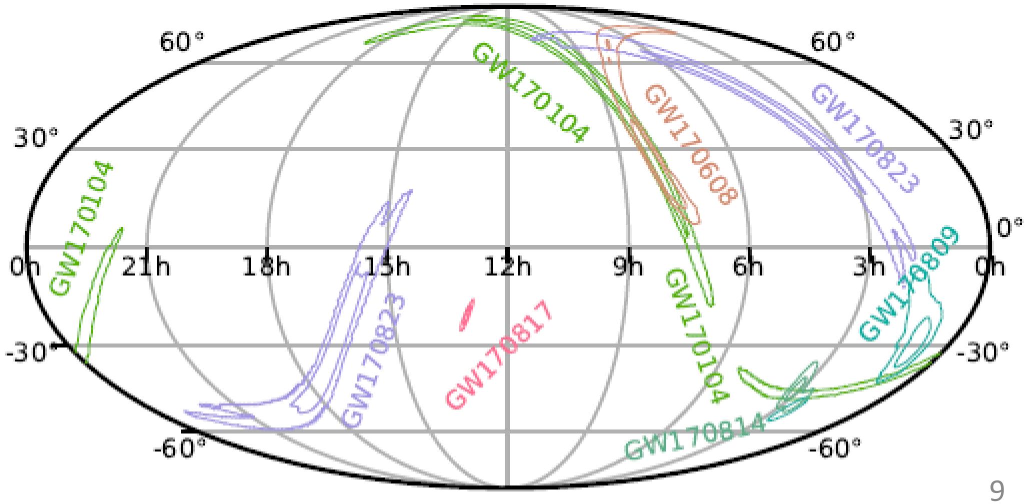
$$h_{+,\times} \propto \frac{1}{D_L}$$

Distance - inclination correlation

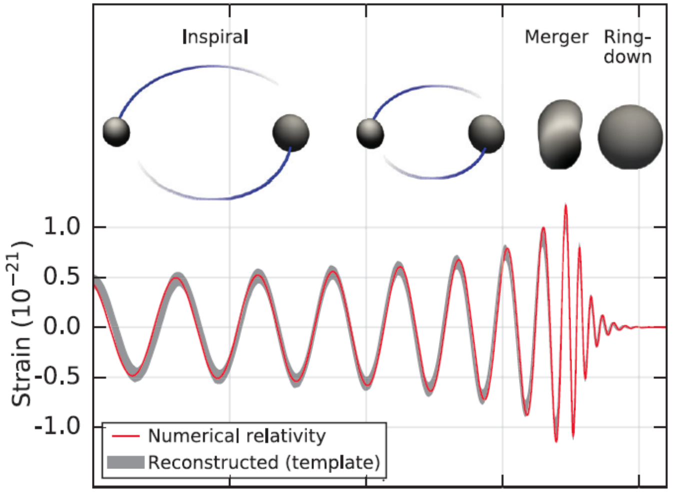


Sky localization from time of flight between detectors
\+ relative amplitude and phase

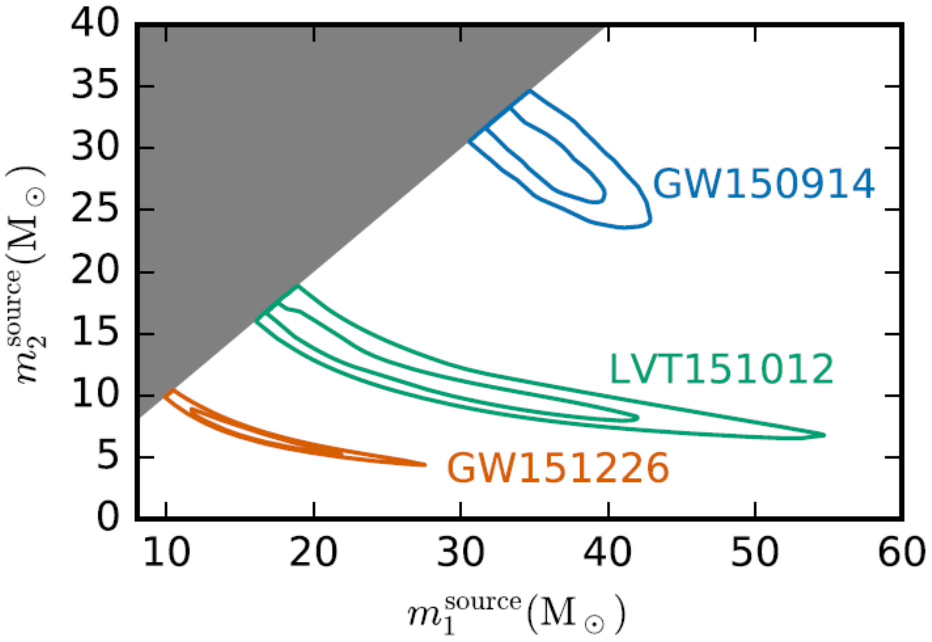




Inspiral dynamics



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



At leading order: driven by chirp mass

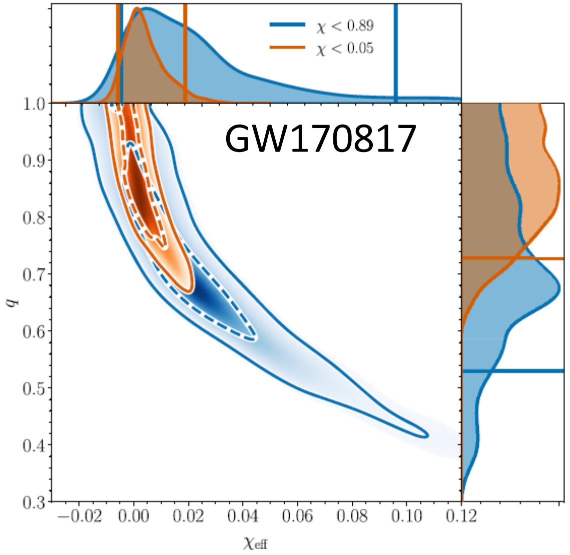
- $\mathcal{M}$ precisely measured
- m_1 and m_2 correlated

At higher orders

- Mass ratio q
- Effective spin $\chi_{\rm eff}$
- q and $\chi_{\rm eff}$ correlated

$$q = m_2/m_1$$

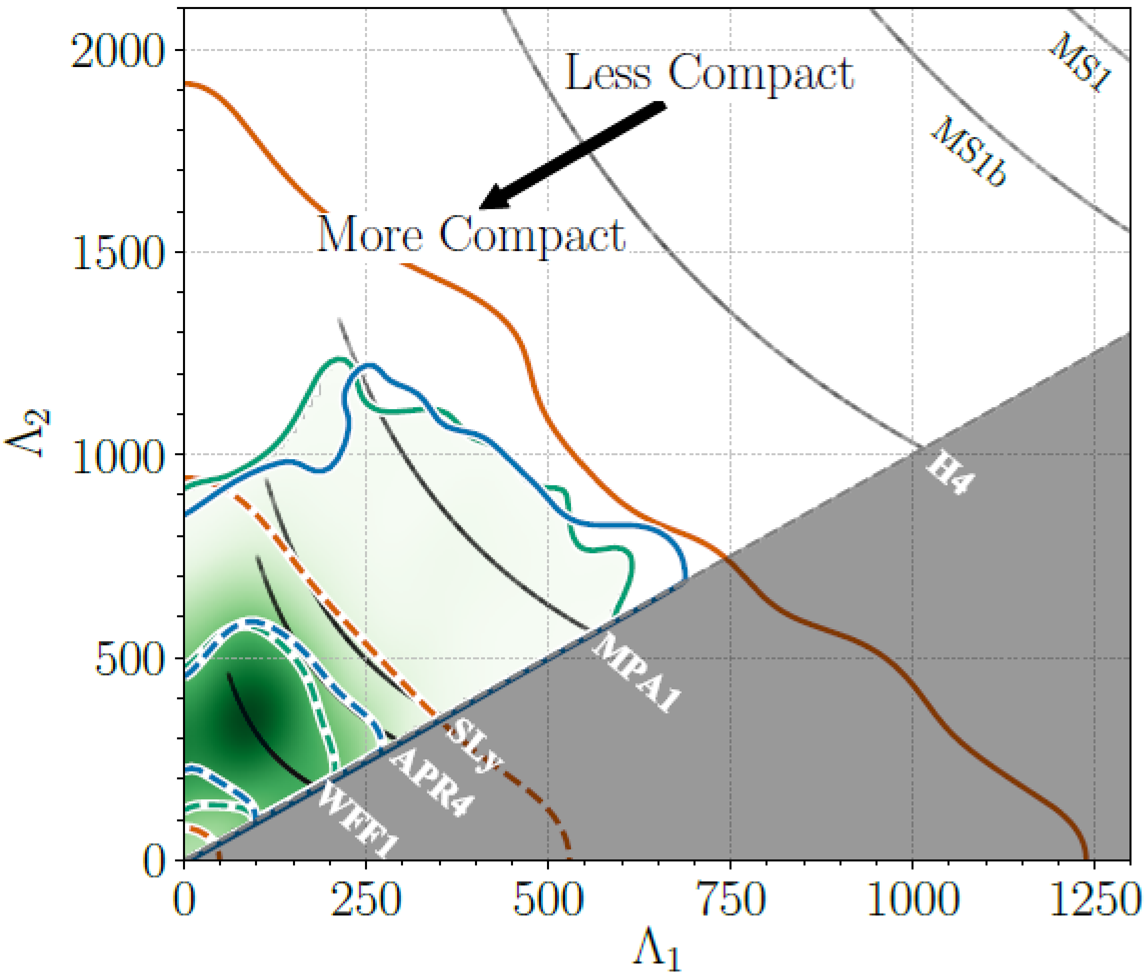
$$\chi_{\rm eff} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \cdot \hat{L}_{\rm N}}{M}$$



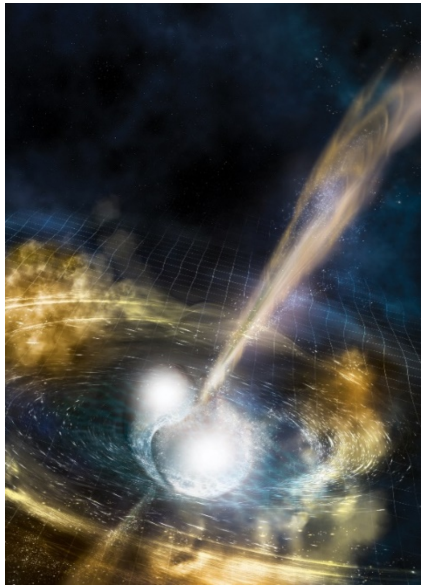
More signal structure: matter effects

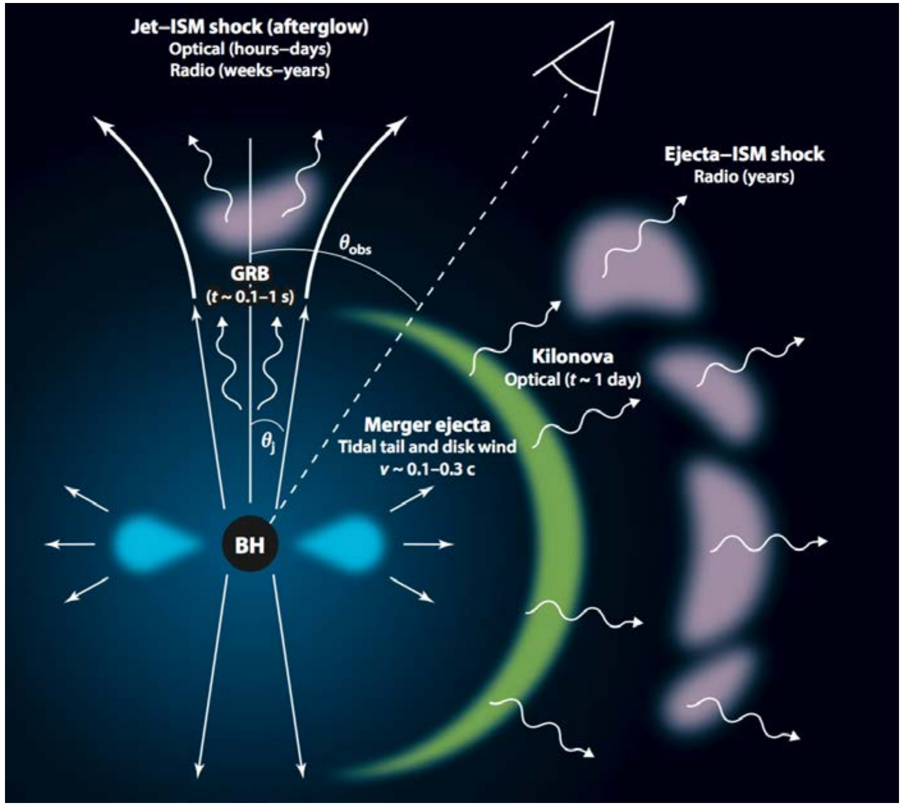
- ❑ Point-mass approximation in BNS or NSBH binaries breaks down before end of inspiral
- ❑ Neutron star tidal deformation from companion's gravitational field accelerates inspiral
  - ➢ Depends on neutron star tidal deformability
  - ➢ Subtle effect, becomes significant above 600 Hz – potentially measurable
- ❑ Upper limits on deformability constrain NS radii and equation of state

GW170817



GW170817





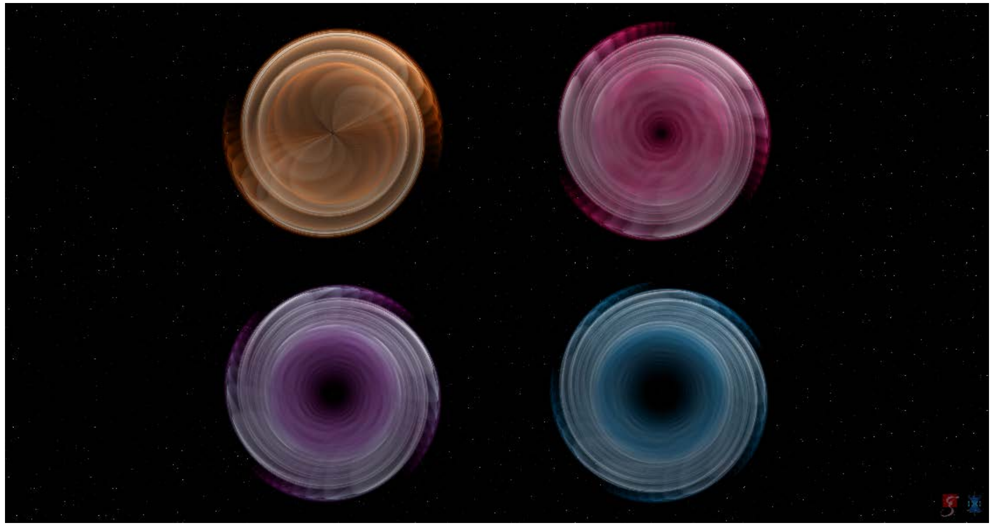
Metzger 2019

- 1st binary neutron star merger
  - Strong signal (signal-to-noise ratio 32)
  - Well-localized source (2+1 detectors, 28 deg^2)
- With counterparts identified across EM spectrum
  - Short Gamma-ray burst and afterglow + kilonova

- Structure of extreme matter in neutron stars
- Short Gamm-ray burst progenitor
- First confirmed kilonova observation
- Production of heavy elements in ejecta
- Gravitational waves propagate at the speed of light
- Hubble constant measurement

More signal structure: higher order modes

$$h_+ - i h_\times = \sum_{l\geq 2} \sum_{m=-l}^{l} {}_{-2}Y_{lm}(\iota, \phi_c) h_{lm}$$

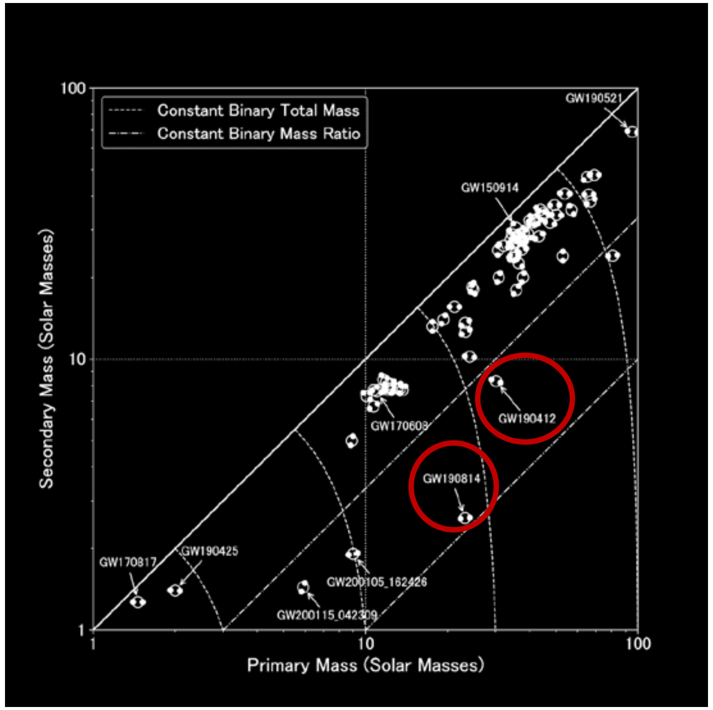


Dominant quadrupolar mode

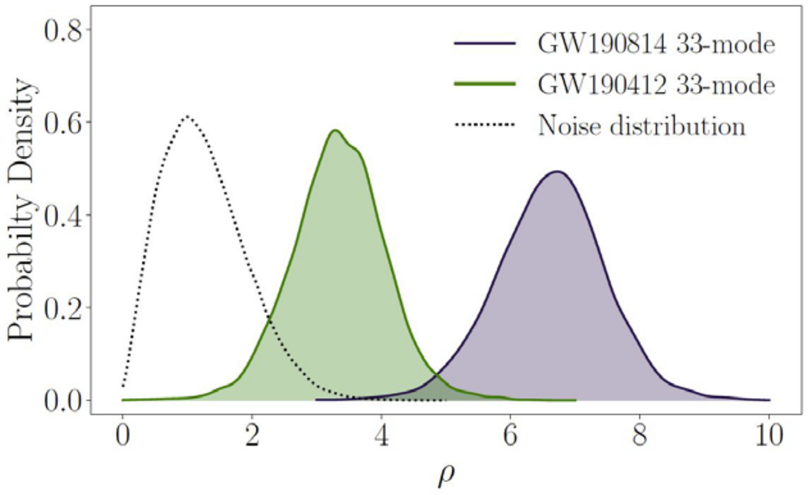
$$l = 2 \quad m = \pm 2$$

Higher-order modes significant

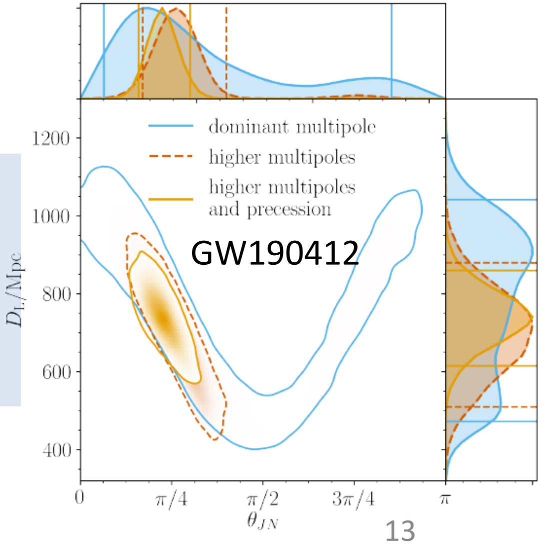
- For asymmetric systems
- For systems seen edge-on



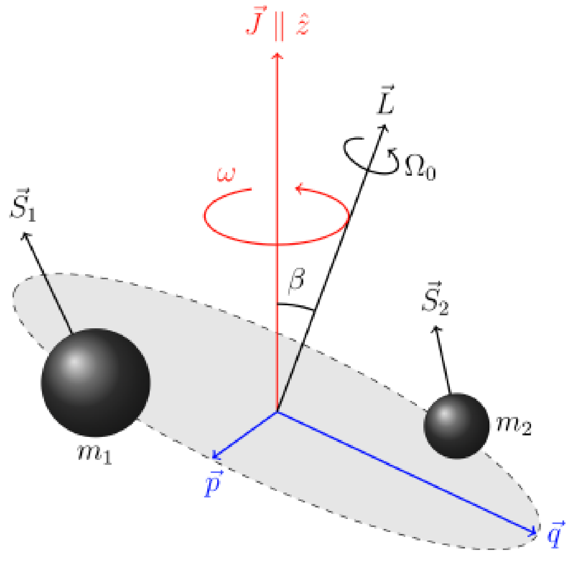
Signal-to-noise ratio in mode 33



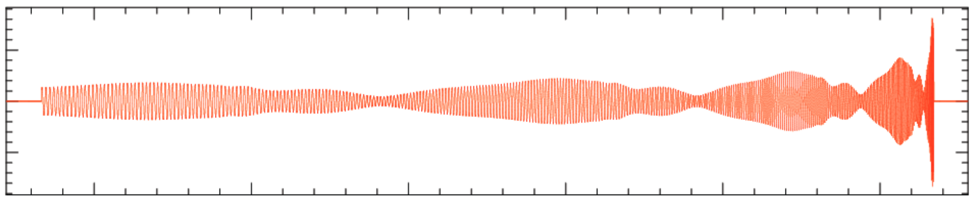
Helps lifting degeneracy between distance and inclination

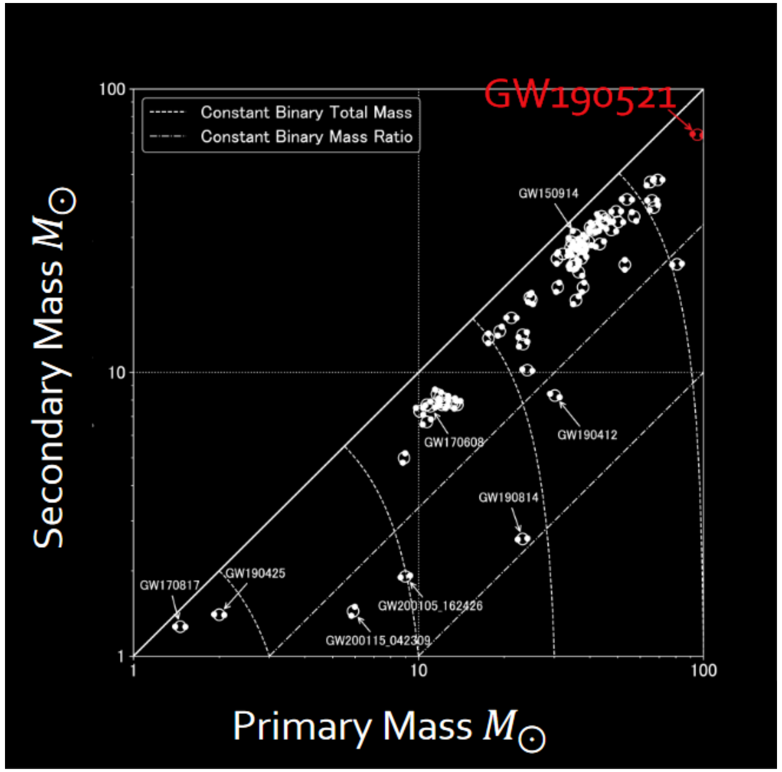


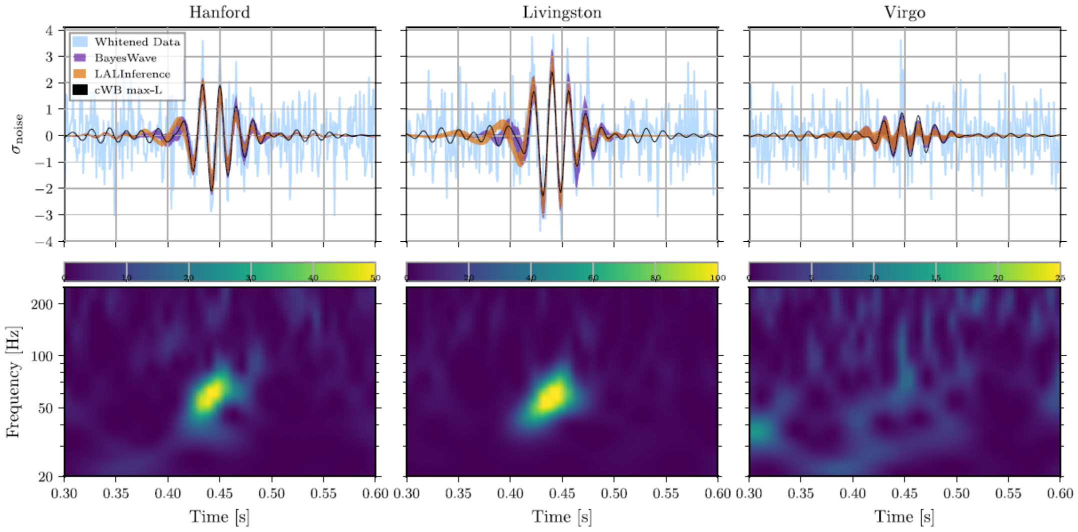
More signal structure: precession



- Orbital plane precession
  - If significant in-plane spin component
  - Time varying inclination induces amplitude and phase modulation of signal
  - Observable for edge-on binaries





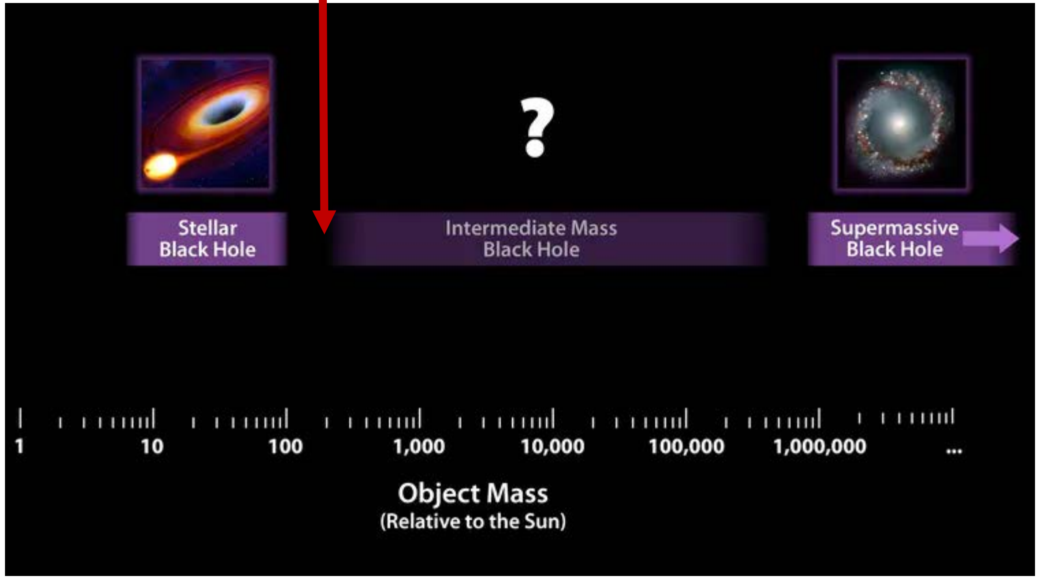


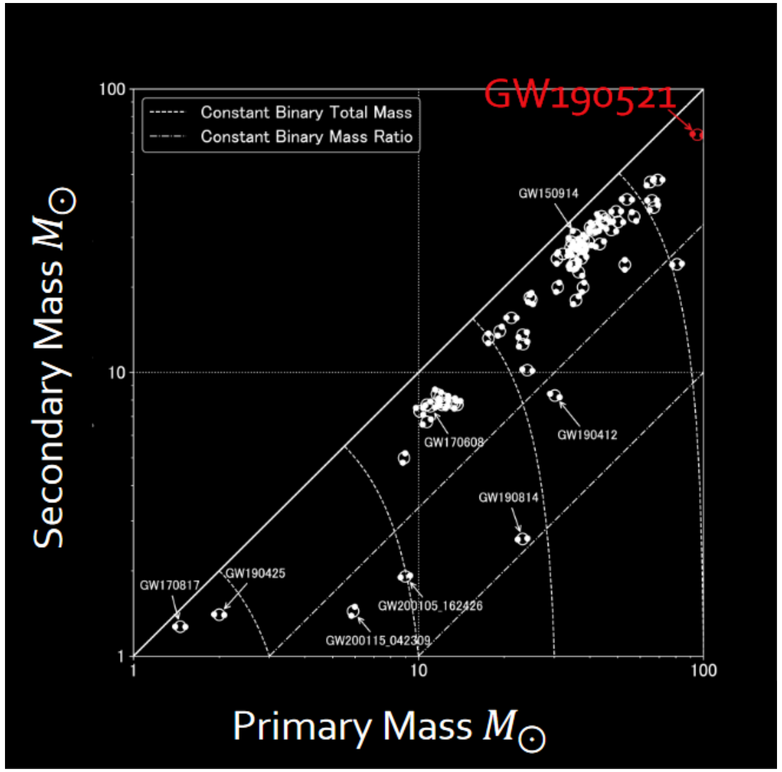
- Few cycles observed, dominated by merger and ringdown
- Many interpretations of GW190521
  - Precessing, quasi-circular binary
  - Eccentric binary +/- precessing
  - Dynamical capture of black holes
  - Merger of boson stars

GW190521 as the heaviest source to date

Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Luminosity Distance	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift	$0.82^{+0.28}_{-0.34}$
Final mass	$142^{+28}_{-16}\ M_\odot$

- ❑ At least one object in high-mass gap expected from pair-instability supernovae
- ❑ Merger remnant is intermediate-mass black hole

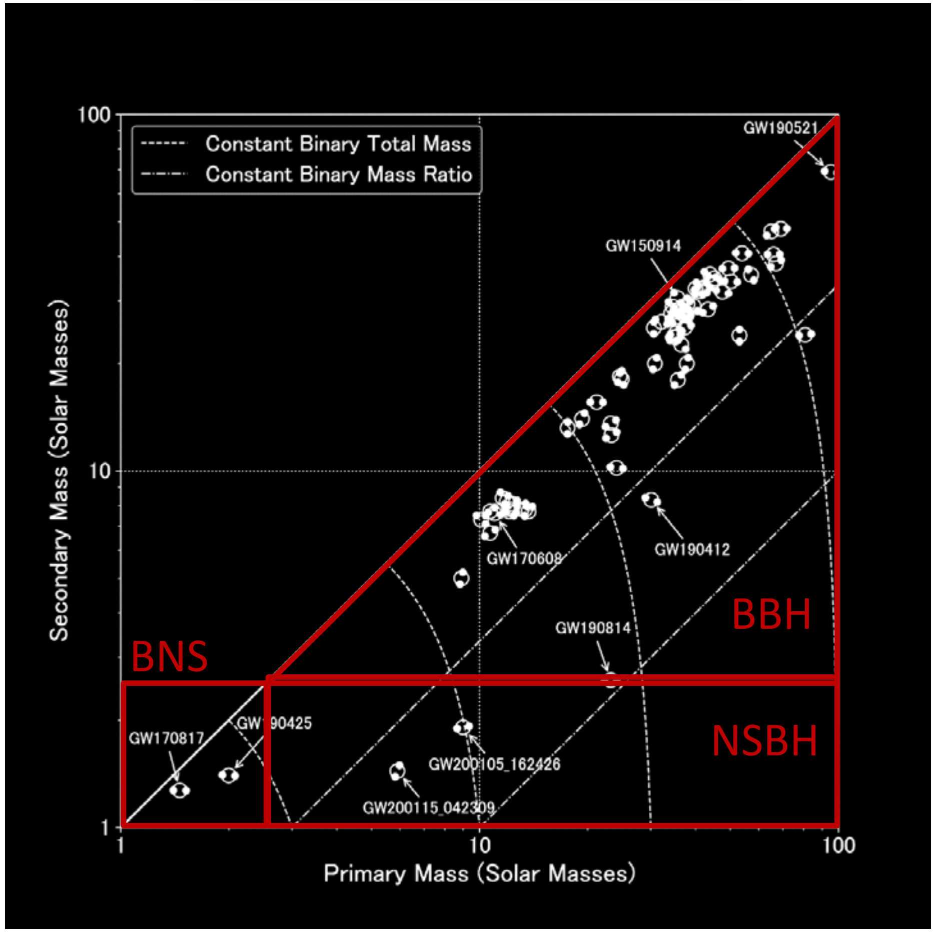




Merger rates

Detection efficiency

Observed sample



Merger rates

$$\mathcal{R}_{\mathrm{BNS}} = 13 \text{ - } 1900 \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

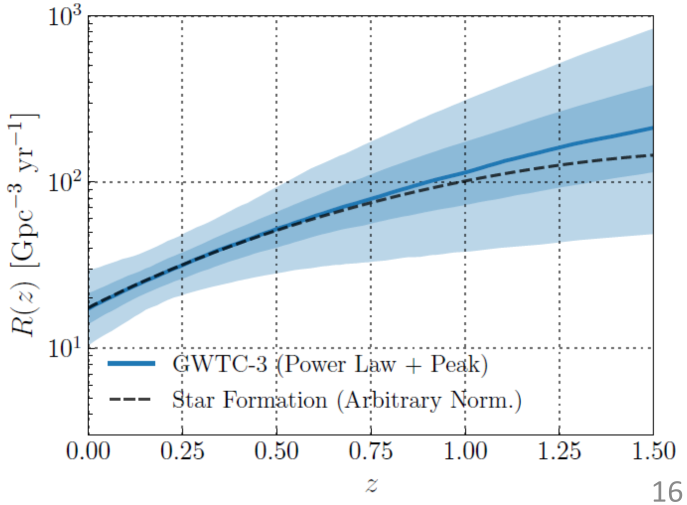
$$\mathcal{R}_{\mathrm{NSBH}} = 7.4 \text{ - } 320 \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

$$\mathcal{R}_{\mathrm{BBH}} = 16 - 130 \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

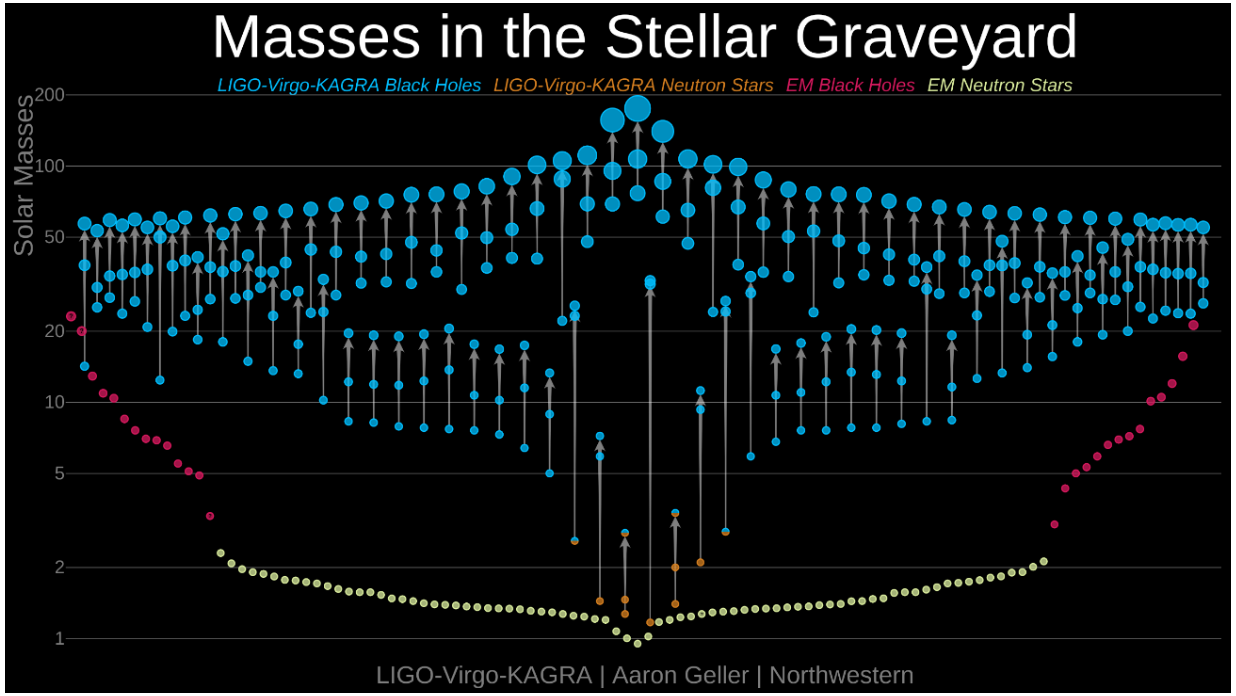
Intrinsically rarer but dominate observed sample – louder sources detectable at larger distances

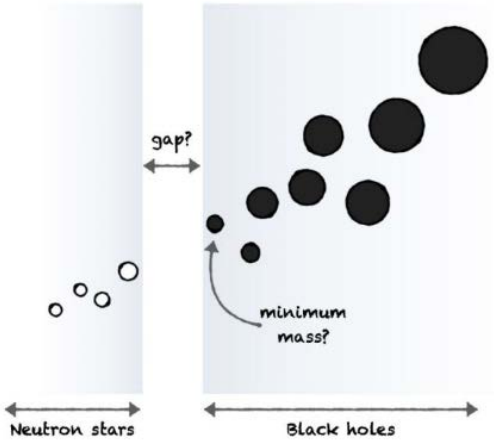
Uncertainties:
statistical
+
population mass distribution

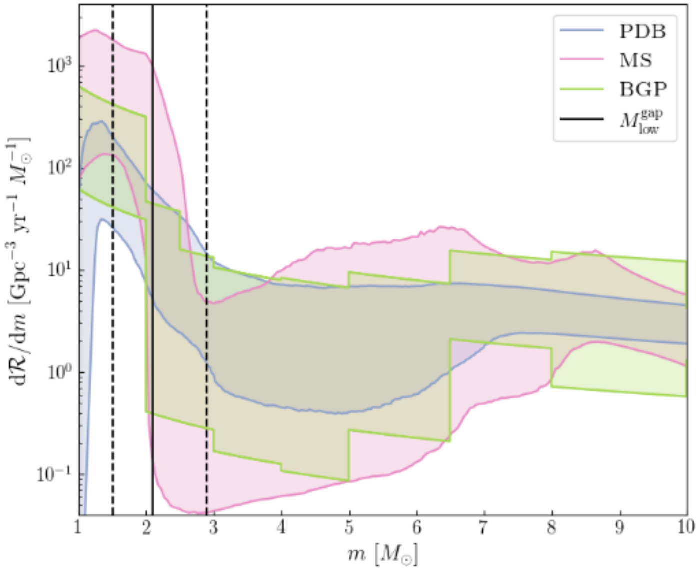
BBH merger rate increases with redshift



Masses





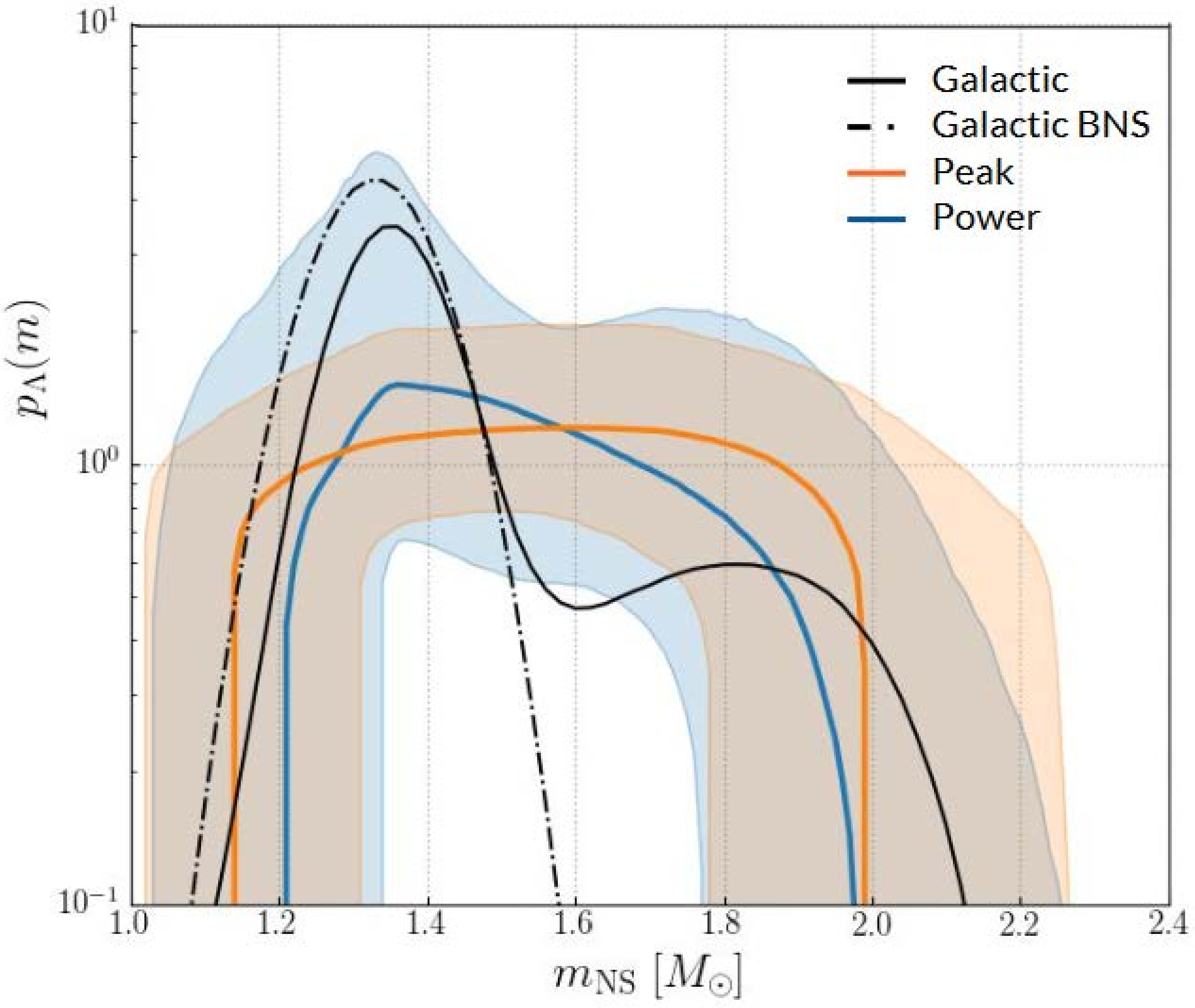


- ❑ Heavy stellar-mass black holes, pointing to low-metallicity environments

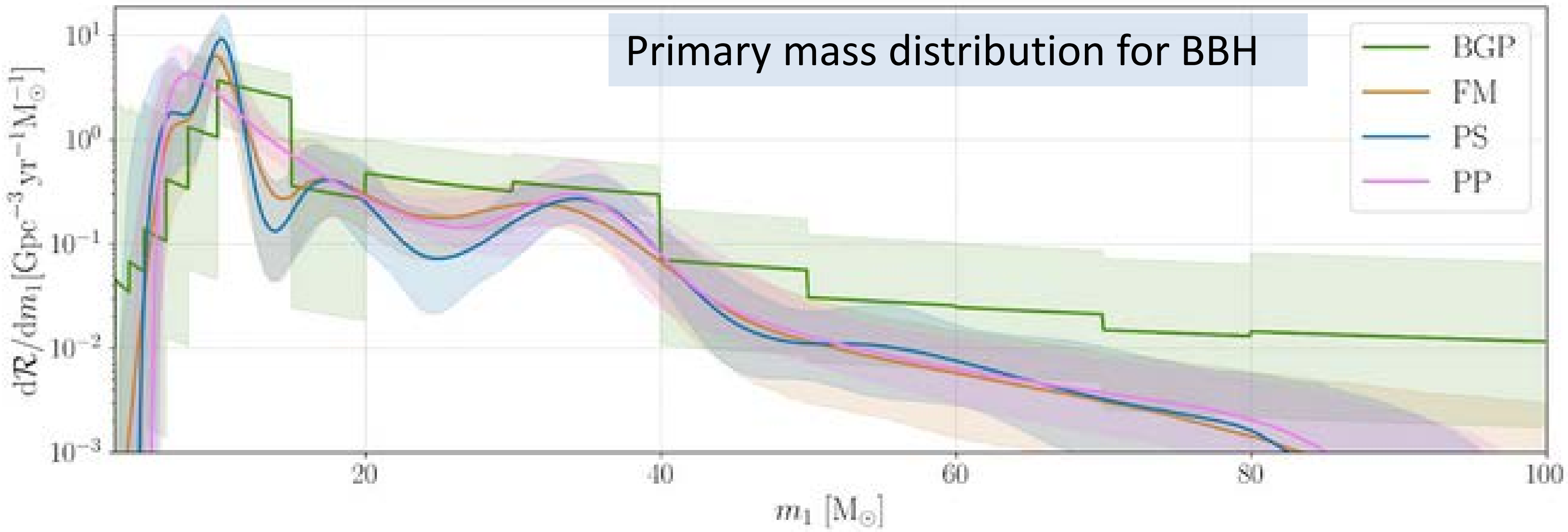
- ❑ Steep drop-off in merger rate above neutron star-like masses
- ❑ Potential mass gap but may not be empty
  - ➢ e.g., GW190814 has $m_2 = 2.59^{+0.08}_{-0.09}\, M_\odot$

Masses: neutron stars

- Broad mass distribution with more support for heavy NSs than Galactic population
- Gaussian Peak model does not recover sharp peak at 1.35 $M_\odot$
- Power law model consistent with uniform distribution



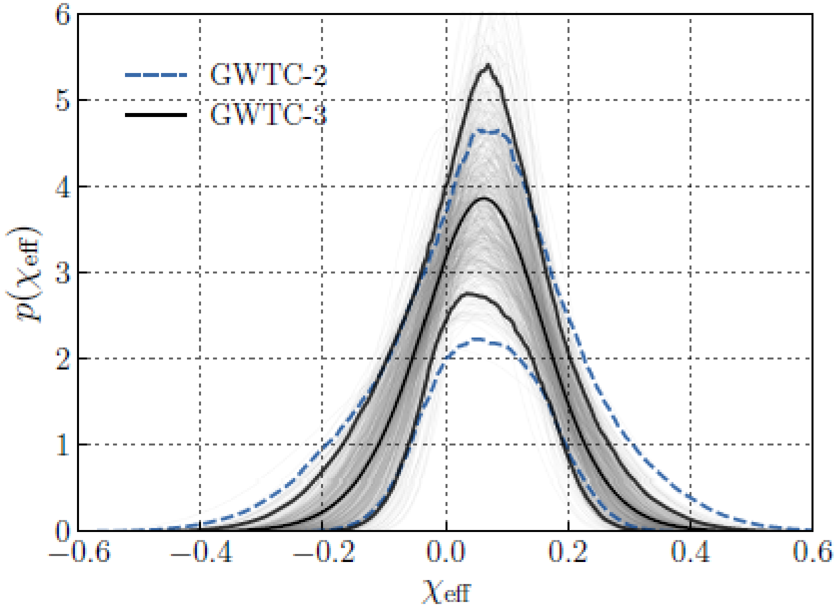
Masses: black holes

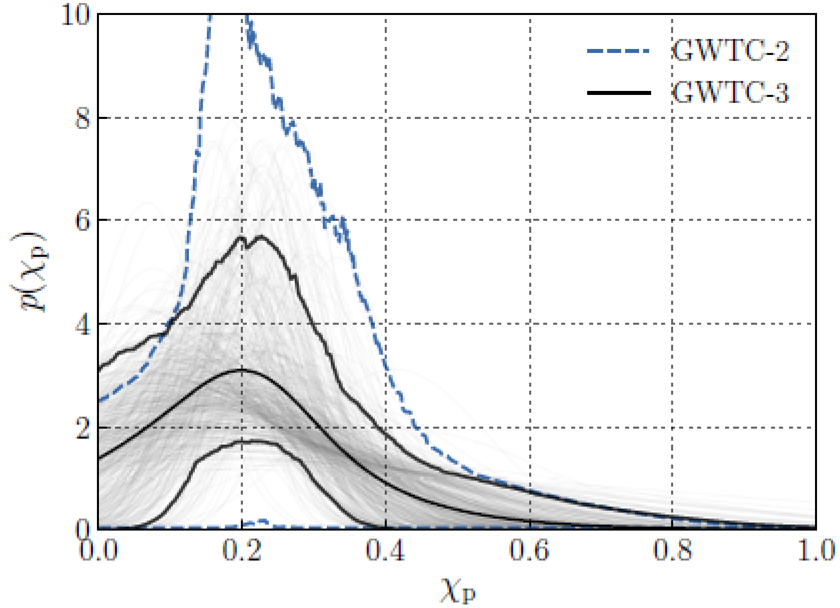


- Distribution has structure
  - Overdensity at ~10 $M_\odot$ – contributes biggest fraction to merger rate
  - Overdensity at ~35 $M_\odot$ – contributes biggest fraction to observed mergers
  - Tentative additional overdensity at ~18 $M_\odot$
- No evidence for an upper mass gap
  - No sharp cutoff at ~50 $M_\odot$

Black hole spins

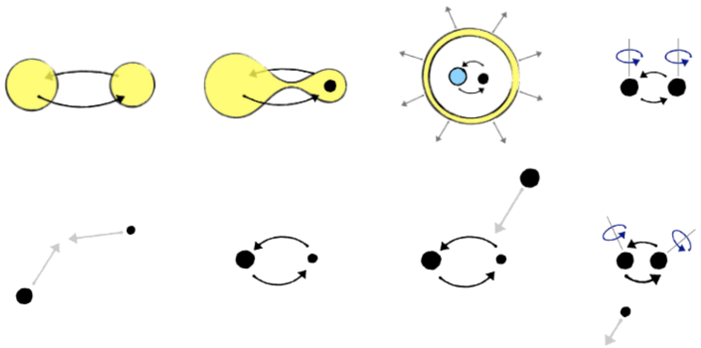
$\chi_{\rm eff}$ ~ average spin parallel to orbital axis
$\chi_{\rm p}$ ~ dominant spin perpendicular to orbital axis





- ❑ Spin magnitudes generally small but non-vanishing
- ❑ Significant support at $\chi_{\rm eff} < 0$
- ❑ Non-vanishing spin-tilt misalignment angles

BBH spin orientations probe binary formation

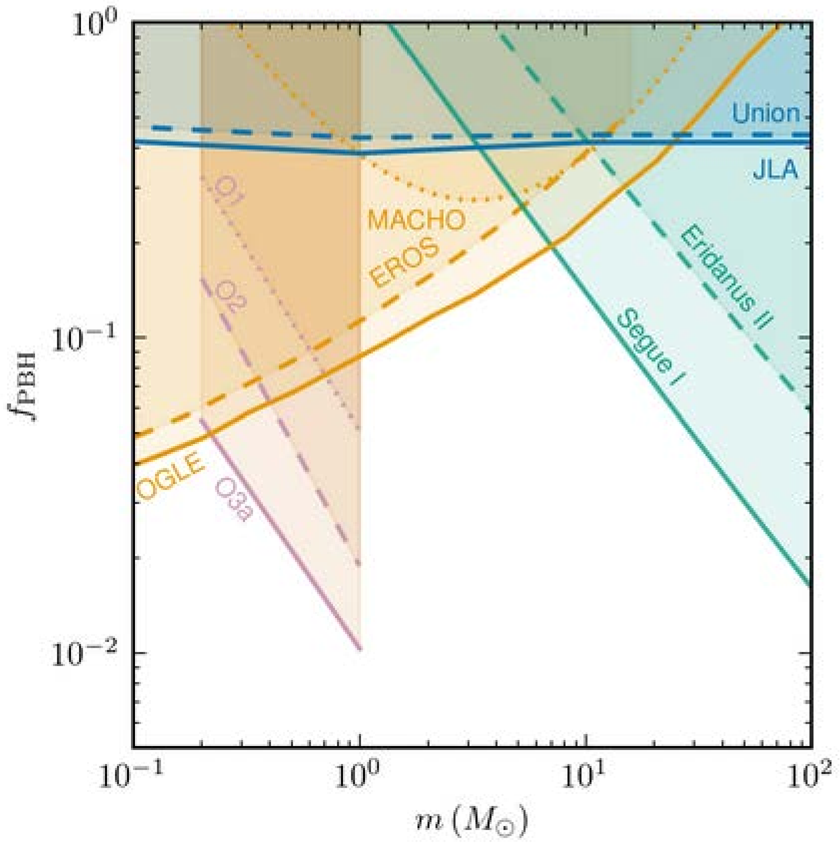


Isolated field binaries: preferentially aligned spins

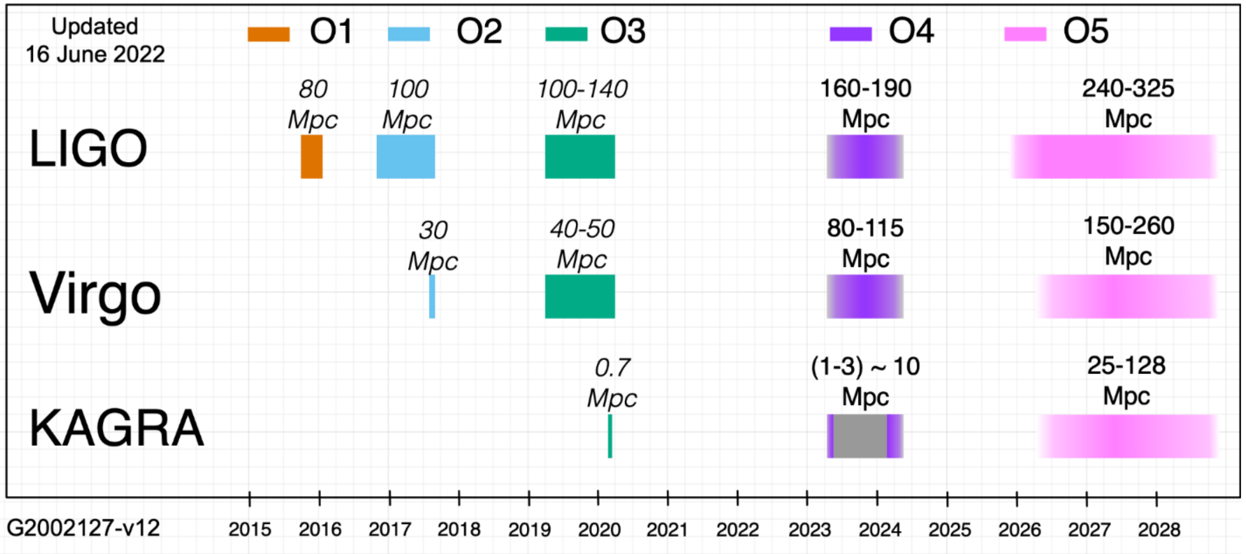
Dynamical assembly in clusters: isotropically aligned spins

Further searches

- Sub-solar mass binaries
  - Targeting new physics
    - e.g., primordial black holes or black holes from collapse of dissipative dark matter
  - No detection so far
- Intermediate mass black hole binaries
  - GW190521 only detection so far
- Gravitationally lensed merger signals
  - Variety of expected lensing effects on merger signals
    - Amplification, multiple signals, signal distortion
  - Unlikely with current detector reach, no detection so far
- Dedicated searches associated to GRBs
  - GW170817 only detection so far
- ...



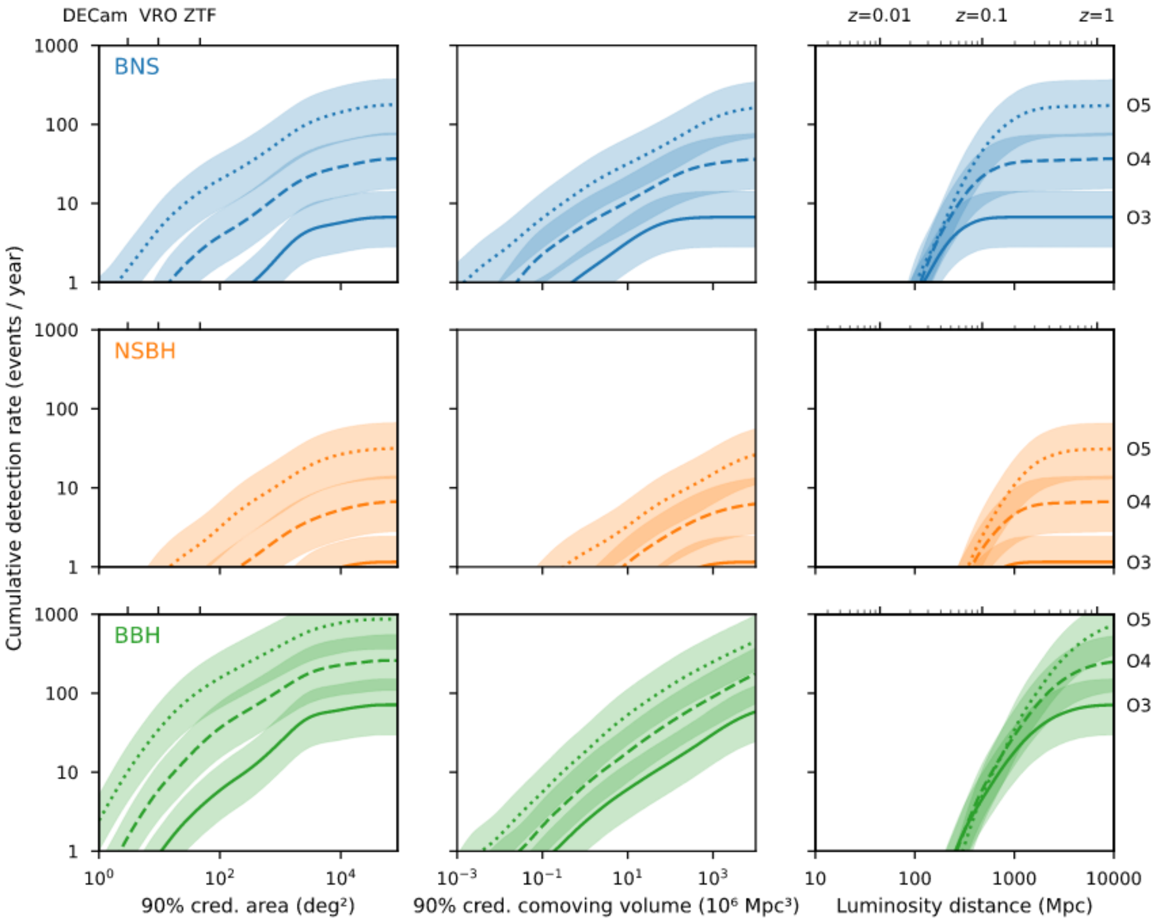
Future prospects



Estimated yearly rate of public alerts

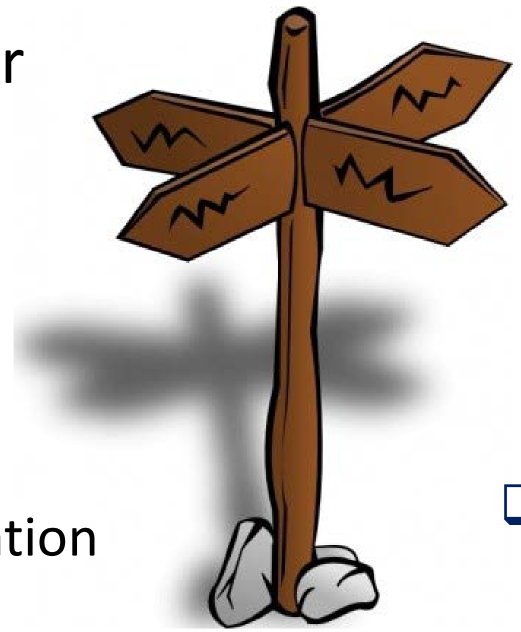
		BNS	NSBH	BBH
O4	HKLV	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	HKLV	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}

[Public alerts user guide]



More sensitive detectors for more science

- **Sensitivity**
  - More statistics to characterize source populations
  - Higher signal-to-noise ratio for exceptional events
- **Bandwidth**
  - Low-frequency sensitivity
    - High-mass BBH mergers
    - More accurate parameter estimation
  - High-frequency sensitivity
    - Post-merger signal
    - Black hole spectroscopy



- **Network size and robustness**
  - Duty cycle
  - 3-detector observations
    - Improved sky localization
- **Multi-messenger approach**
  - Low-latency alerts
    - Possibly early warning

Conclusion

- Observations with ever more sensitive detectors has brought tally of compact merger detections to 91 candidates
  - A goldmine for fundamental physics, astrophysics, cosmology
  - Stay tuned to other talks in this session to hear more about the beautiful science they enable
- Exciting O4 run coming soon
  - More statistics and more discoveries around the corner
    - Hopefully including more multi-messenger events