Earth-based Gravitational-Wave Experiments
Part II: Sources, data analysis, science

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SIGRAV International School 2024 - Measuring Gravity

PANORAMA OF GW SOURCES AND DATA ANALYSIS TECHNIQUES

GW emission

- Quadrupole formula

$$h_{ij} = \frac{G}{c^4}\,\frac{2}{r}\,\frac{d^2Q_{ij}}{dt^2} \qquad Q_{ij} = \int \rho\, x_i\, x_j\, d^3x$$

- Expected strength of signal

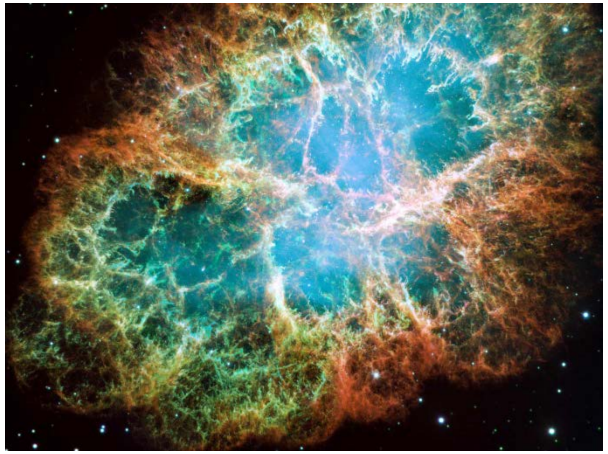
$$h \sim \underbrace{\epsilon}_{\text{source asymmetry}}\ \overbrace{\frac{G}{c^4}}^{8.3 \times 10^{-45}\,\frac{\mathrm{s}^2}{\mathrm{kg\ m}}}\ \frac{1}{\underbrace{r}_{\text{distance to observer}}}\ \underbrace{M}_{\text{mass}}\ \underbrace{v^2}_{\text{characteristic speed}}$$

Sources detectable from Earth

Transient signals

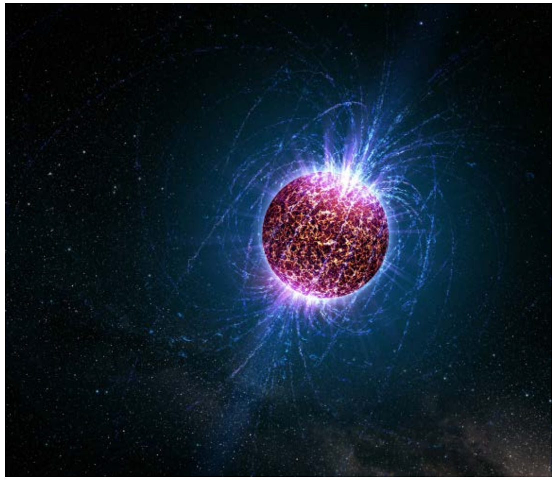
Merging black holes, neutron stars

Burst sources

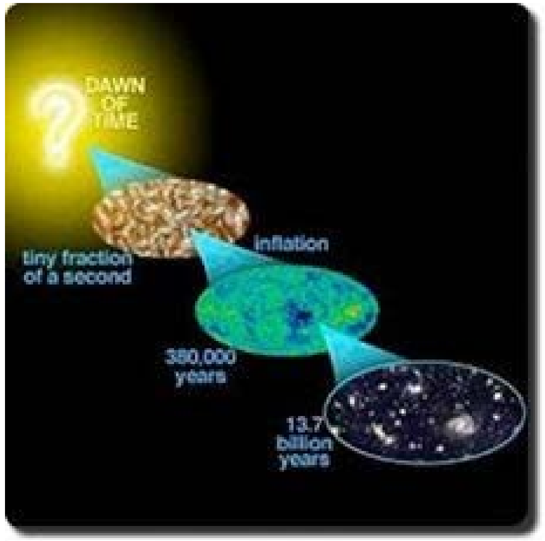


- Two broad classes
  - Transient signals
  - Persistent signals
- Search strategies
  - Waveform known
  - Waveform unknown

Spinning neutron stars

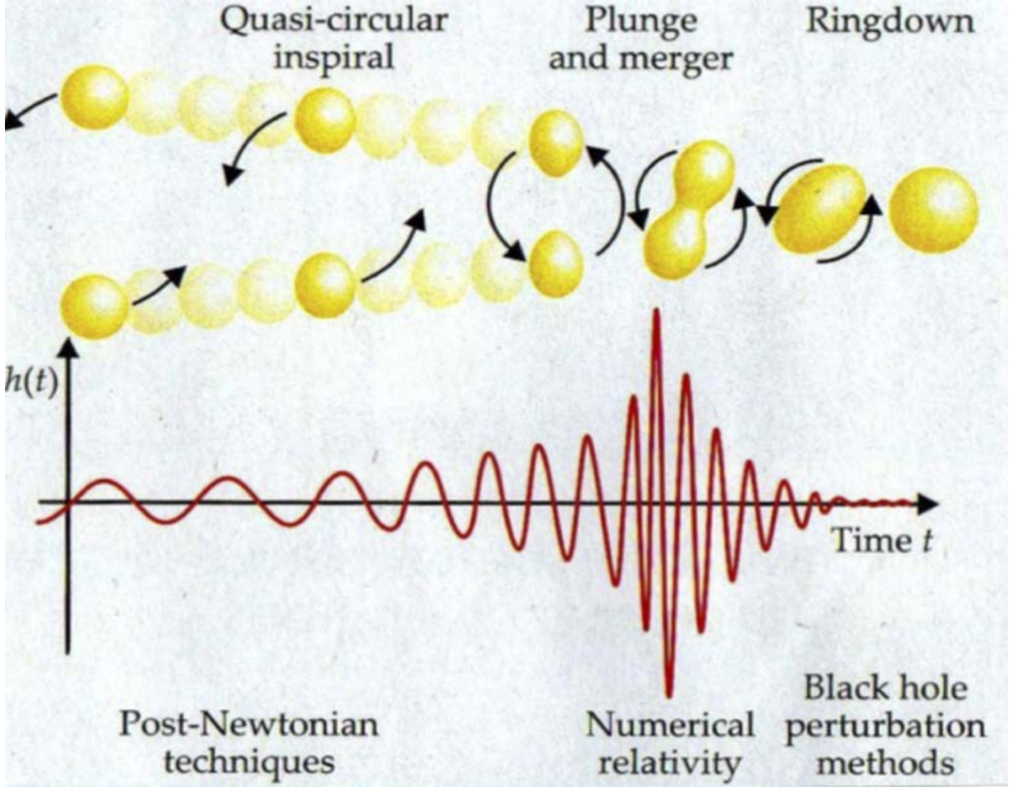


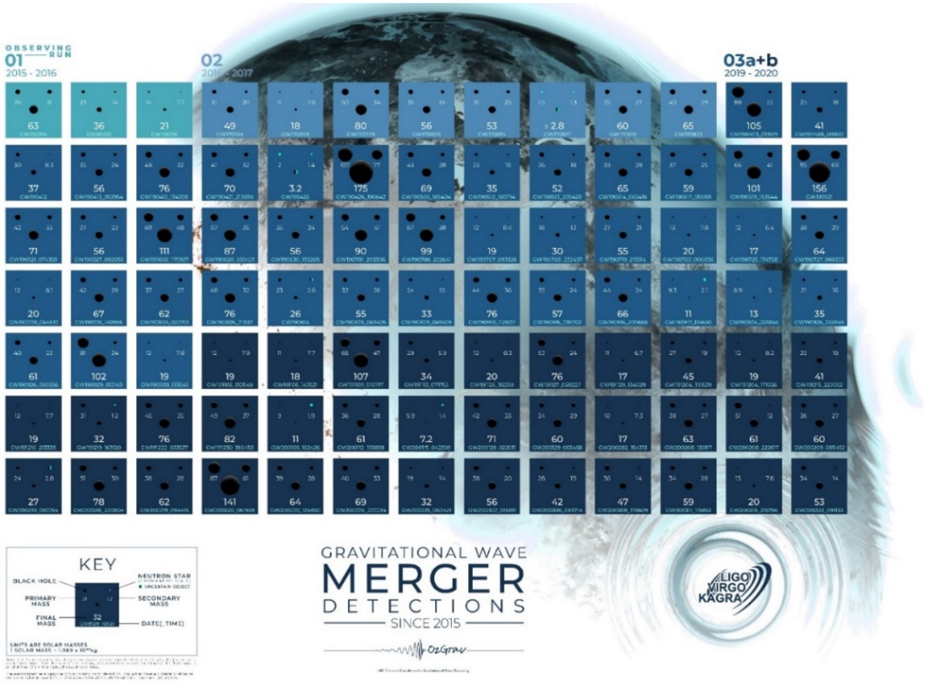
Stochastic backgrounds

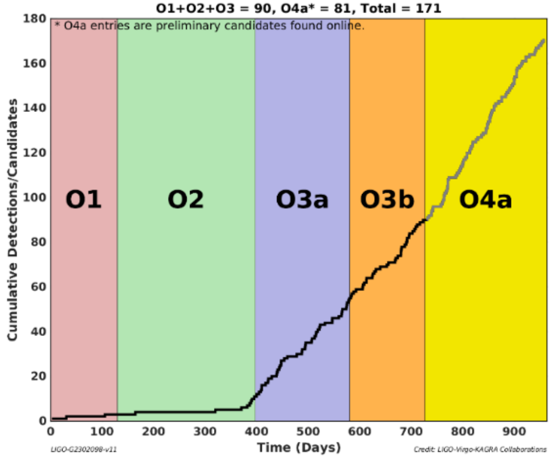


Persistent signals

Compact binary coalescences







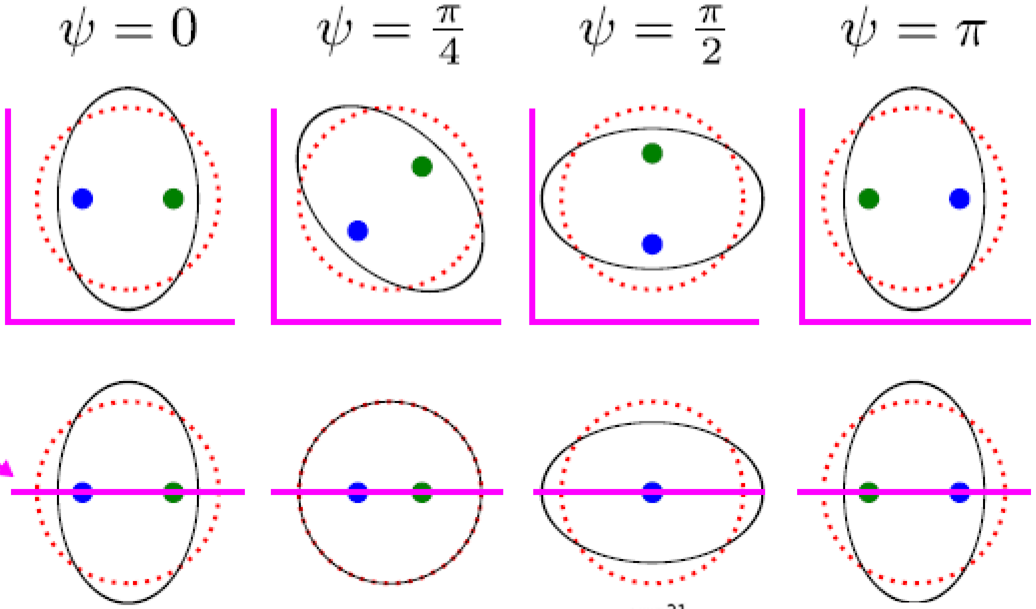
- ❑ 91 detection candidates in O1-O2-O3 data
  - ➢ Many binary black holes
    - Most with ~ equal masses
    - Discovery signal GW150914 turned out to be quite typical
  - ➢ Binary neutron stars: GW170817, GW190425
  - ➢ Neutron star-black hole: GW200105, GW200115

The (inspiral) signal in a nutshell

top view

orbital plane

side view



circular polarization

linear polarization

Dominant frequency

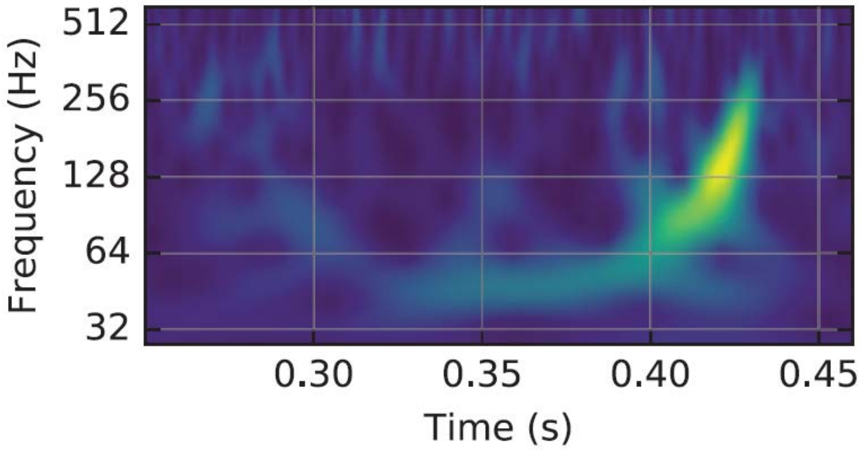
$$f_{\rm GW} = 2\; f_{\rm orbital}$$

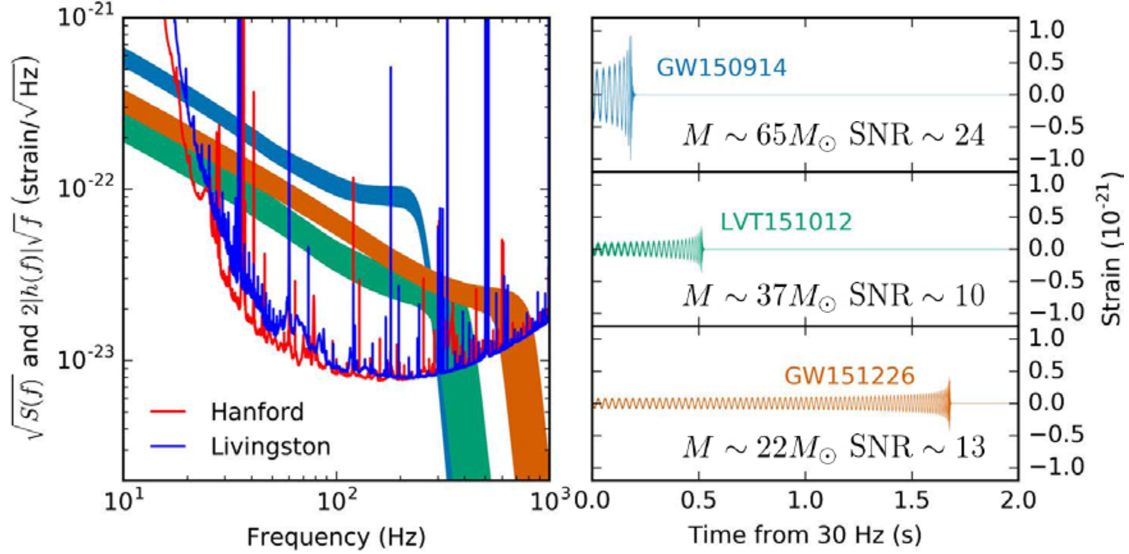
Last stable orbit

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

$M(1+z)$ in practice

GW150914





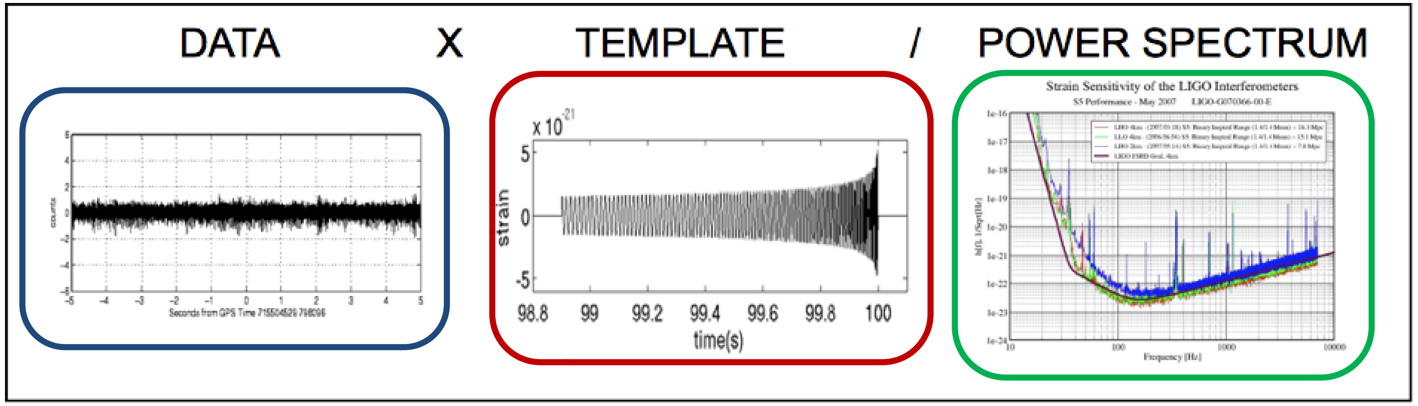
Matched filtering

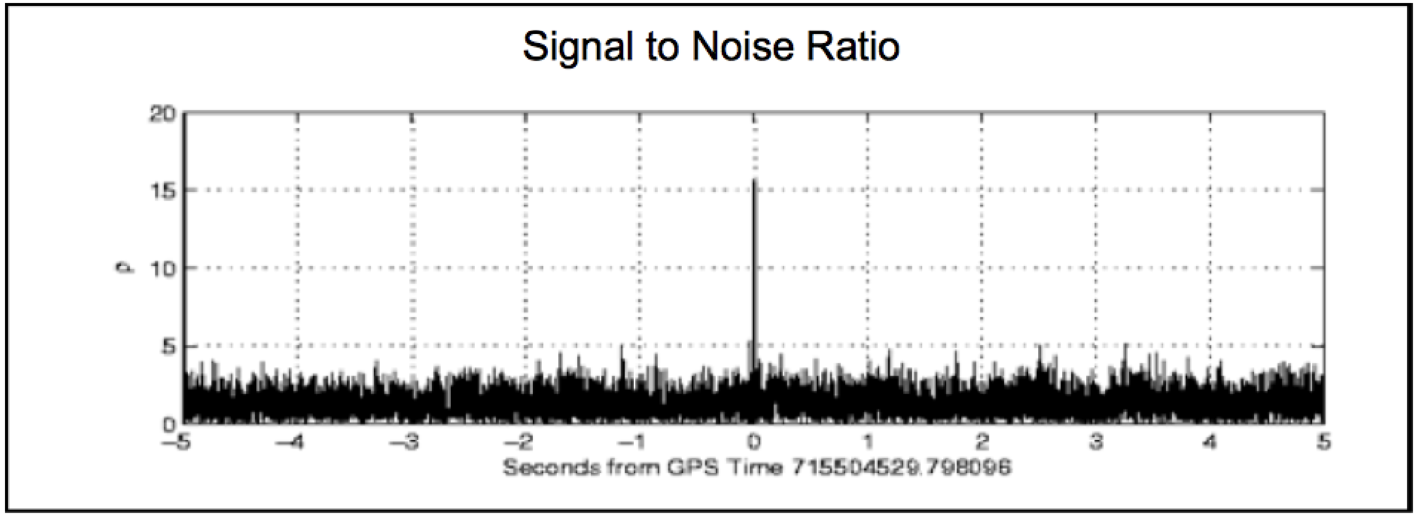
$$S = (s|T) = 4\int_0^\infty \frac{\boxed{\tilde{s}(f)}\,\boxed{\tilde{T}^*(f)}}{\boxed{S_n(f)}}\,df$$

- ❑ If we know what we're looking for, and we know the properties of detector noise
- ❑ Correlation of data with expected signal, weighted by sensitivity curve

$$E[S] = \alpha \quad \text{if} \quad \tilde{s} = \alpha\,\tilde{T} + \tilde{n}$$

and T is properly normalized


DATA X TEMPLATE / POWER SPECTRUM


Signal to Noise Ratio

Matched filtering (cont.)

- ❑ As a function of the (unknown) arrival time

$$S(t_c) = 4\int_0^\infty \frac{\tilde{s}(f)\tilde{T}^*(f)}{S_n(f)} e^{-i2\pi f t_c} df$$

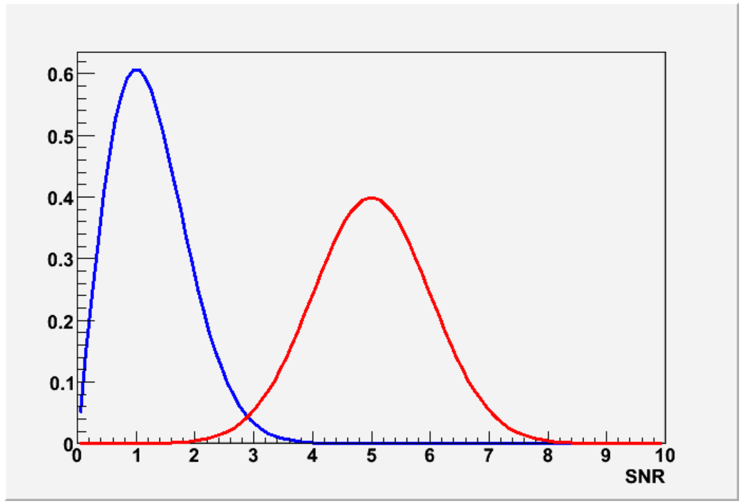
- ❑ Maximize over unknown phase

$$S(t_c) = 4\left|\int_0^\infty \frac{\tilde{s}(f)(\tilde{T}_{0^\circ}(f) - i\tilde{T}_{90^\circ}(f))^*}{S_n(f)} e^{-i2\pi f t_c} df\right|$$

- ❑ Record *trigger* at t_c if $S(t_c)$ exceeds some threshold

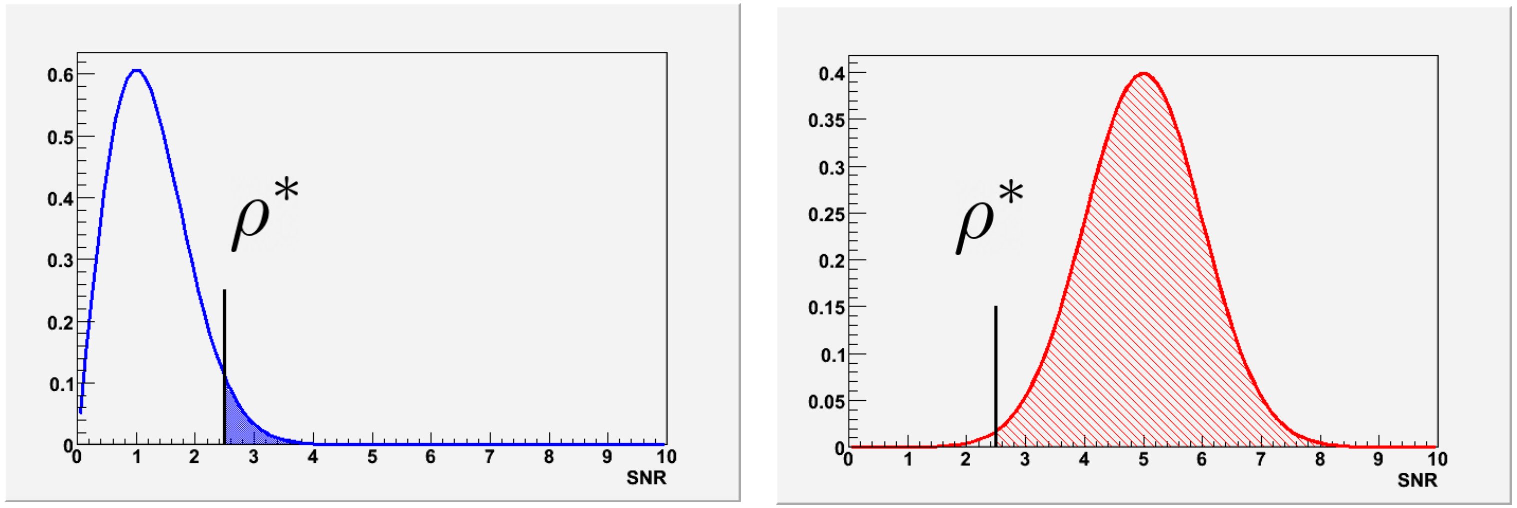
Matched filtering is "optimal"

In Gaussian, stationary noise with known PSD…



- ☐ Noise SNR distribution: χ^2 with 2 degrees of freedom
- ☐ Signal SNR distribution: non-central χ^2 distribution ~ Gaussian distribution if signal strong enough

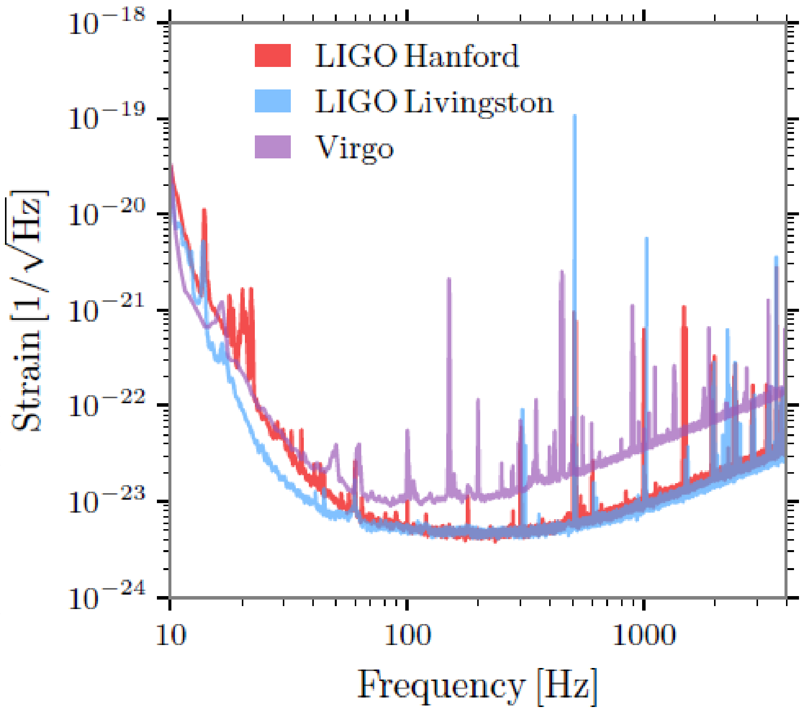
- ☐ Matched filter optimizes SNR $\mathrm{SNR} = \dfrac{E[S]}{\sqrt{E[(S - E[S])^2]}}$



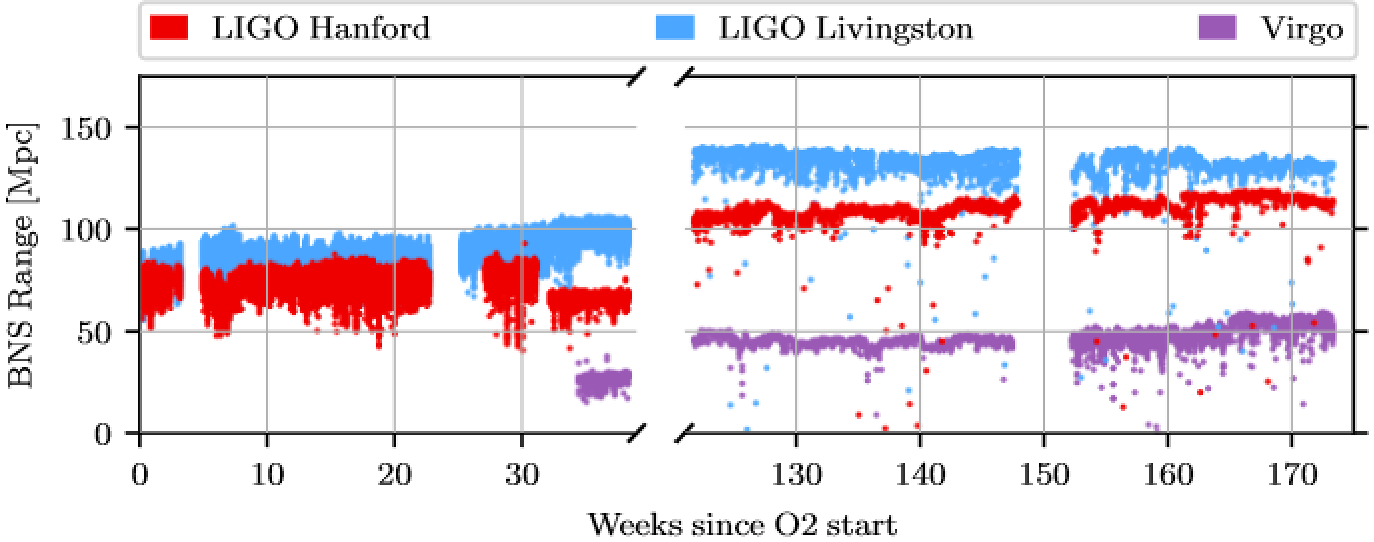
- ☐ Selecting triggers by setting threshold on SNR $\rho > \rho^*$ guarantees lowest false alarm probability for given detection probability

But…

Noise spectrum

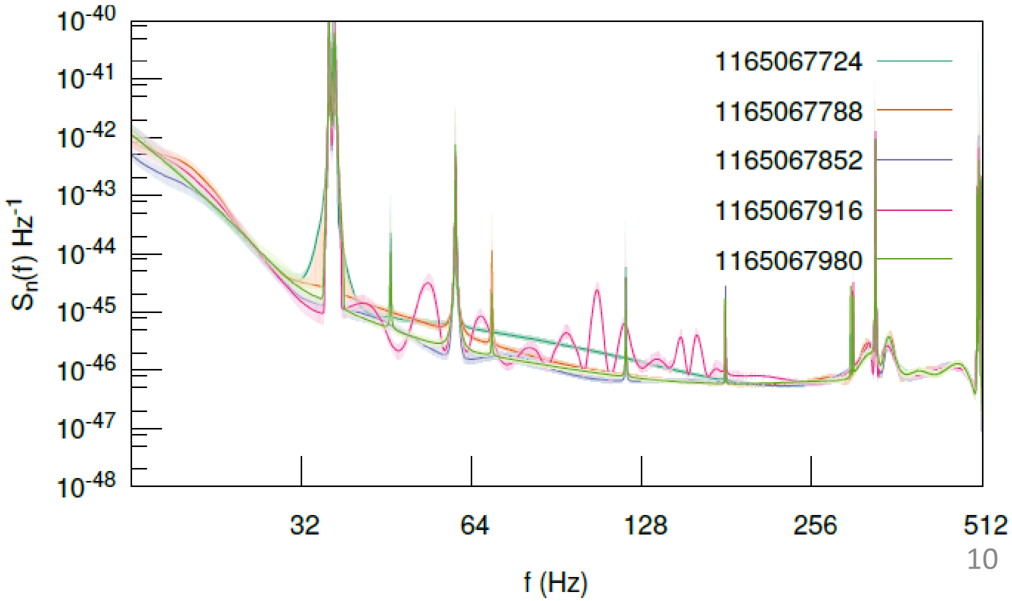


arXiv:2111.03606



arXiv:2101.11673

- ❑ Detector noise spectrum has complex structure
  - ➢ Broadband noise
  - ➢ Narrow features
  - ➢ Large dynamic range
- ❑ Noise spectrum is not stationary
- ❑ Estimated by averaging consecutive FFTs
  - ➢ Over time large enough to get smooth estimate, short enough to follow medium-term variations



CQG 37 055002 (2020)

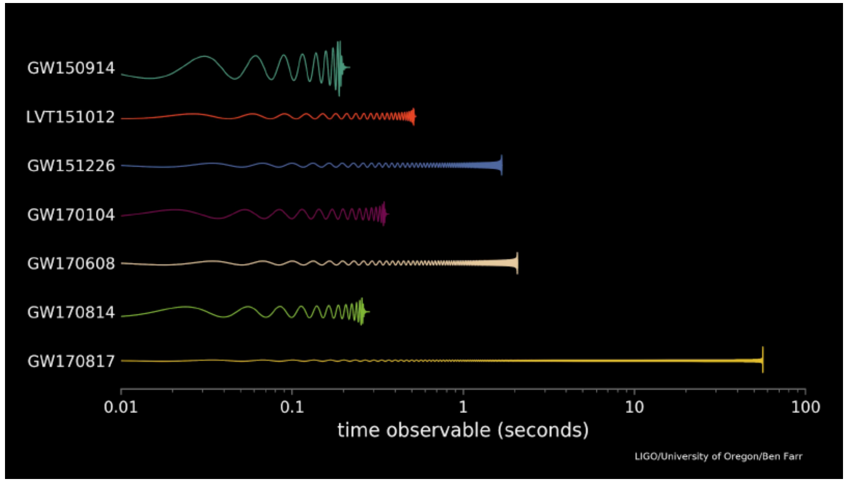
Waveforms

- ❑ Approximate analytical solutions
  - ➢ Perturbative approaches
    - ▪ Post-Newtonian expansion
    - ▪ Effective-one-body approach
    - ▪ Final black hole ringdown
  - ➢ Accurate for inspiral and ringdown, loses accuracy close to merger

- ❑ Numerical solutions
  - ➢ Solving Einstein’s equations directly with numerical evolution methods
  - ➢ Computationally expensive
    - ▪ Cannot be used to model many orbits
  - ➢ Can model merger

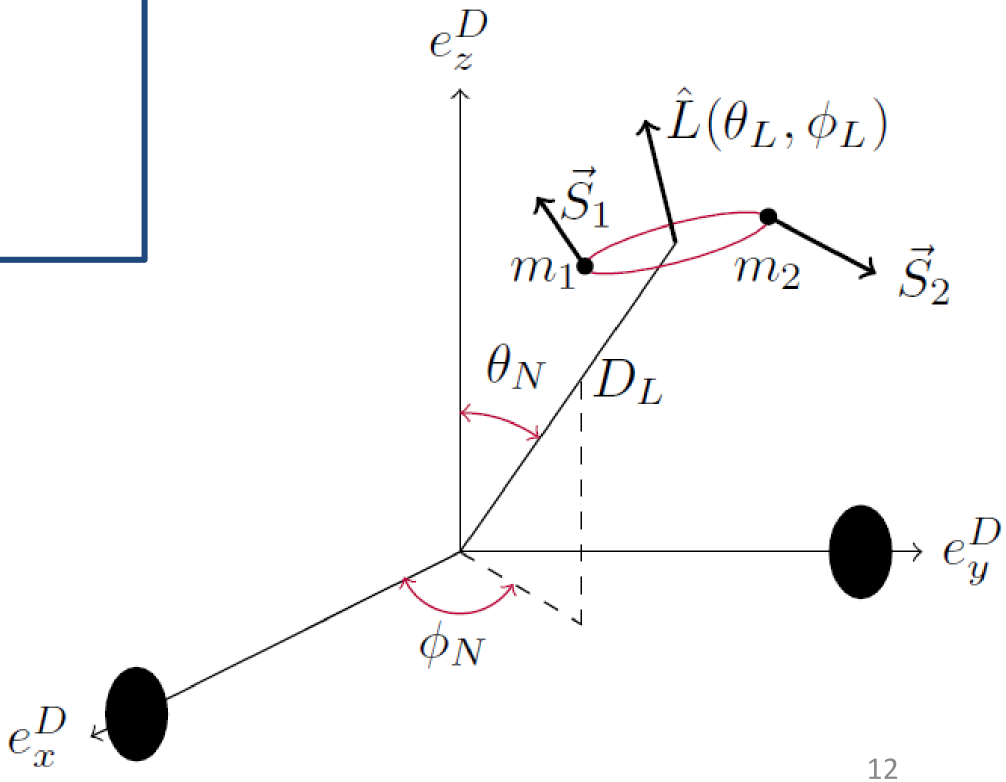
- ❑ Hybrid models
  - ➢ Combining results from analytical and numerical approaches
  - ➢ Provide full inspiral-merger-ringdown waveforms

Parameters

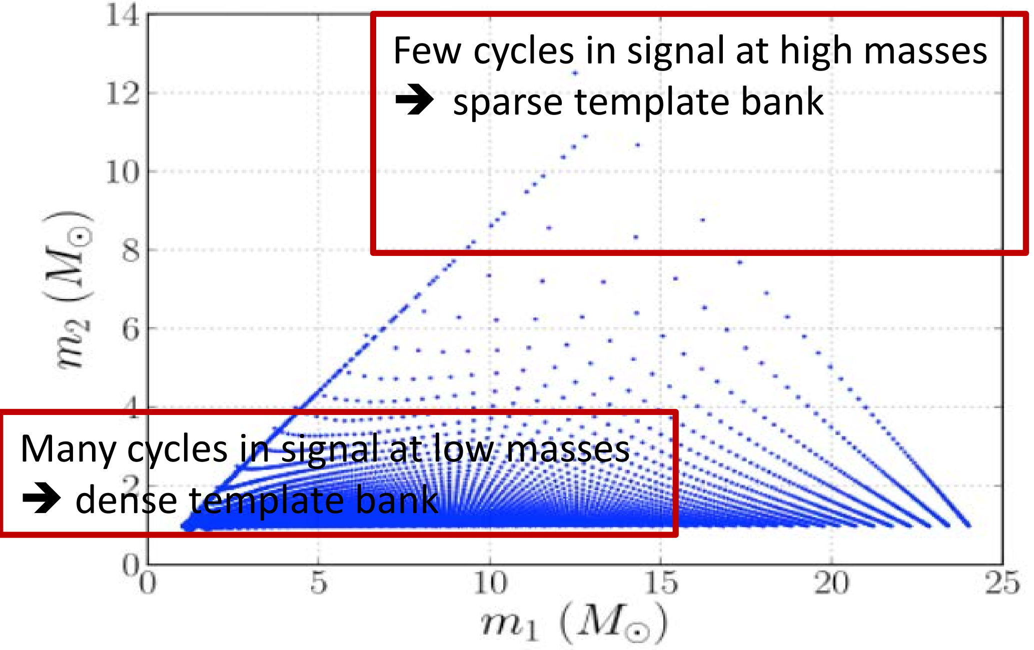


- In general, compact binary is described by up to 19 parameters
  - Intrinsic parameters drive system dynamics
    - Masses (2)
    - Spins (6)
    - Deformability for neutron stars (2)
    - Eccentricity (2)
  - Extrinsic parameters impact measured signal
    - Position : luminosity distance, right ascension, declination (3)
    - Orientation: inclination, polarization (2)
    - Time and phase at coalescence (2)

- Searching a reduced parameter space
  - Assume that there is no eccentricity
  - Assume that there is no precession of the orbital plane
  - Assume that both bodies are black holes
  - Restrict to the dominant, quadrupolar mode of the signal
  - Orientation and location parameters now enter as overall scale, time or phase shifts, easily maximized over
  - Scan a 4-dimensional space: m_1, m_2, S_{1z}, S_{2z}

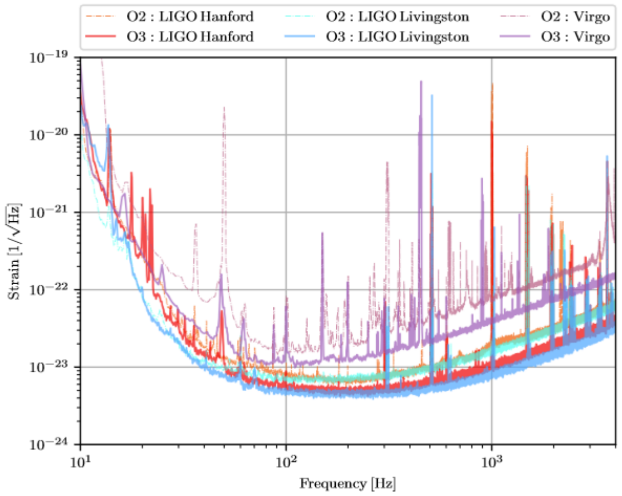


Search parameter space



Few cycles in signal at high masses
➔ sparse template bank

Many cycles in signal at low masses
➔ dense template bank



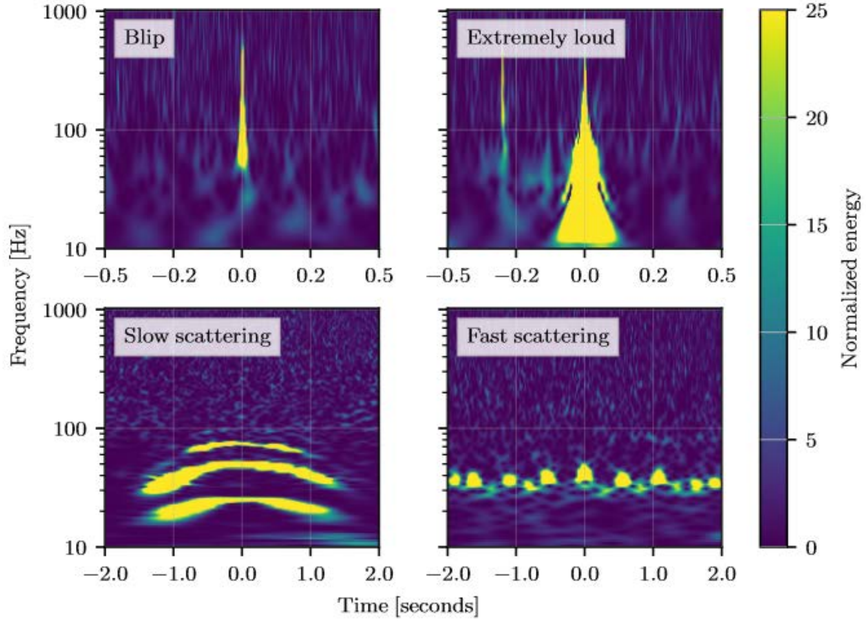
arXiv:2101.11673

- Detected masses are redshifted
  - For given (source-frame) parameter space, search parameter space needs to extend to higher masses as detector reach increases
- Number of observed cycles impacts density of template banks
  - For given parameter space, number of templates increases as low-frequency detector sensitivity improves and lower frequency cutoff decreases

- Main CBC search
  - $2 \leq M/M_\odot \leq\sim 500$
  - Template bank size ~ 4 10^5 (O2), ~ 8 10^5 (O3)
- Sub-solar mass search
  - $0.2 \leq m_1/M_\odot \leq 10 \quad 0.2 \leq m_2/M_\odot \leq 1$
  - Template bank size ~ 1.9 10^6 $f_{\rm low} = 45{\rm Hz}$
- Intermediate-mass BH search
  - $50 \leq M/M_\odot \leq 600$
  - Template bank size ~ 10^3

Noise is not Gaussian

- Environmental or instrumental artefacts are common in the data
  - Aka *glitches*
  - Responsible for long tails in SNR distributions
- Coping strategies
  - Use data quality tools to diagnose and flag issues where possible
  - Go beyond SNR by considering additional observables to distinguish between astrophysical signals and glitches
    - Combine SNR with outcome of signal consistency tests to rank triggers
  - Estimate background from data
    - Requiring coincidence between detectors both reduces the background and provides ways to estimate it



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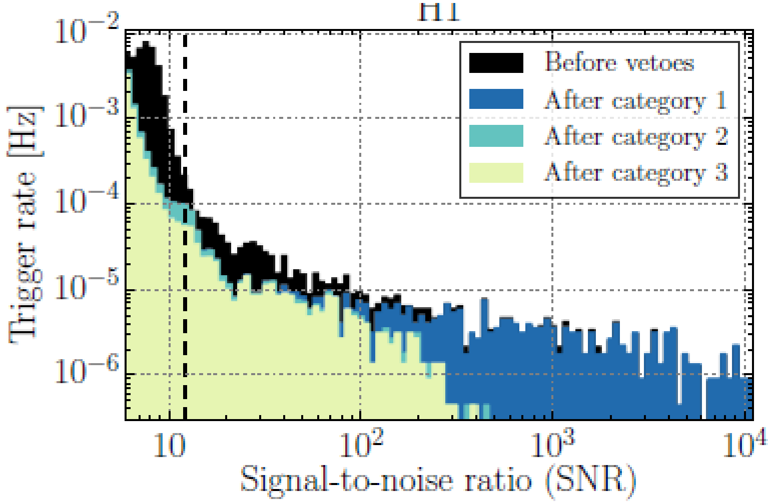
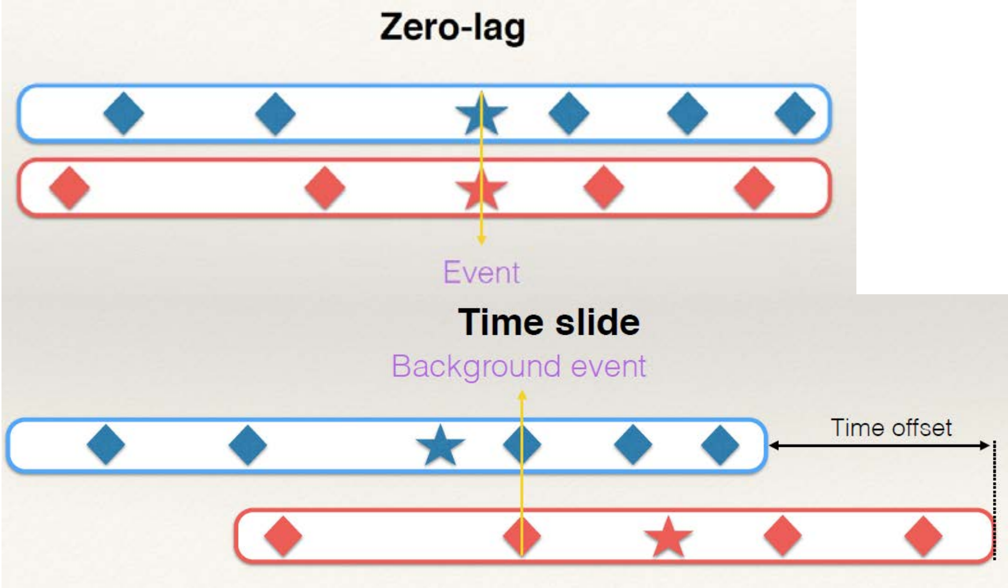


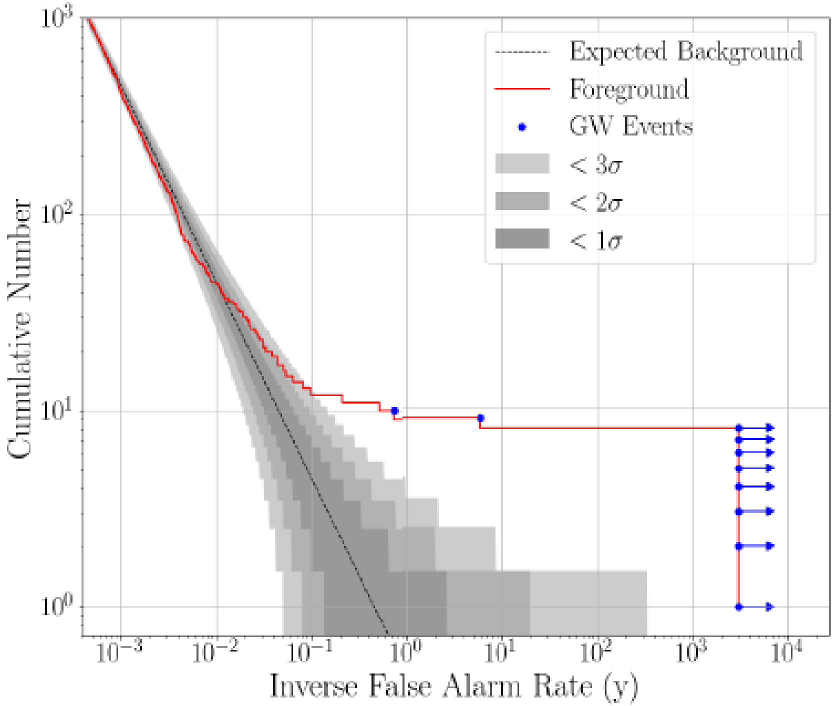
CQG 33 134001

Background estimation & IFAR plots

- ❑ With time slides



- ❑ Without time slides
  - Use all pairs of single-detector triggers
    - Account for probability that they could form a coincidence



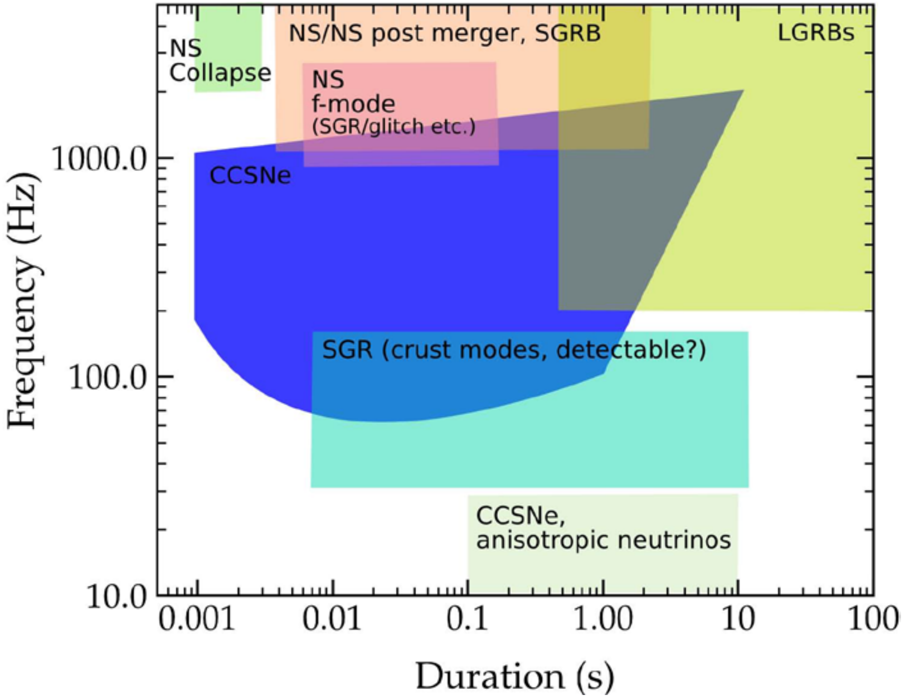
- ❑ Cumulative number of triggers with IFAR ≥ x-axis value
  - Average background distribution follows $n = T/\text{IFAR}$
  - Foreground candidate events appear as outliers

Burst sources

- Generic GW Bursts with < ~1 – 10 s duration
  - Some long-lived transient signals considered too, duration < 10^4 s
- Many poorly modeled transient sources
  - CBC post-merger signal
  - Core-collapse supernovae
  - Long Gamma-ray bursts
  - Neutron star instabilities
  - Soft Gamma-ray repeater flares
  - …
  - ???
- Some well modeled (speculative) sources
  - Cosmic strings

    Cusps $\tilde{h} \propto f^{-4/3}$ Kinks $\tilde{h} \propto f^{-5/3}$

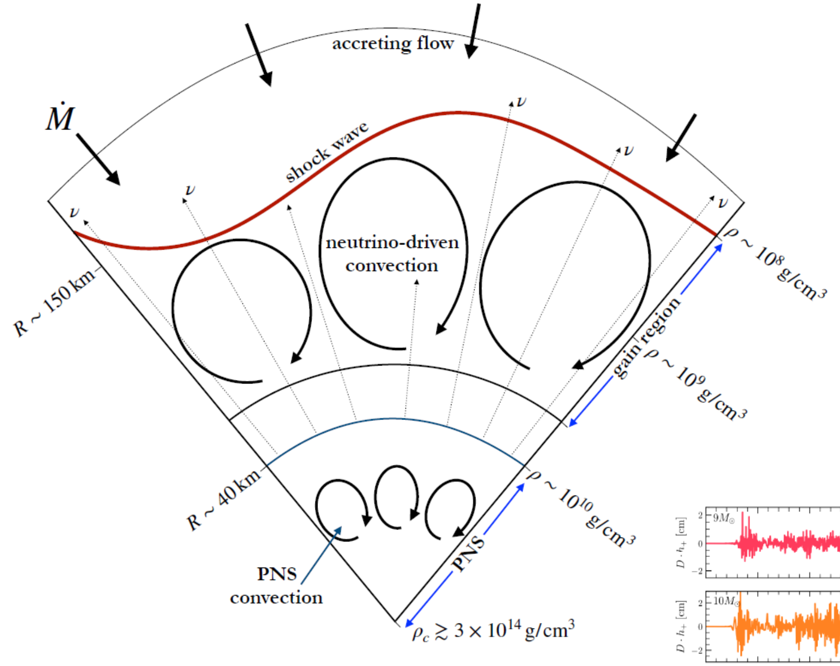
Ott 2010

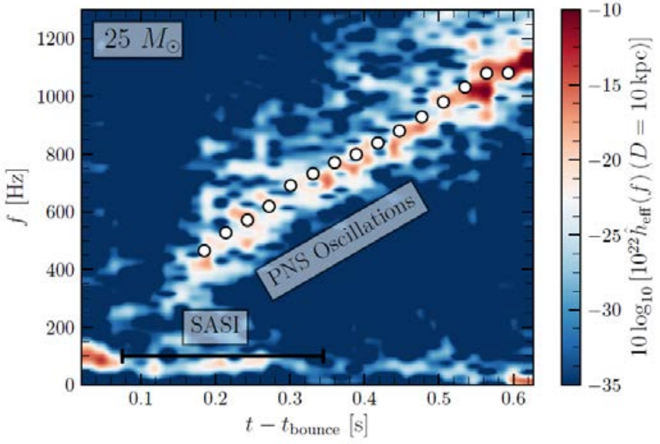


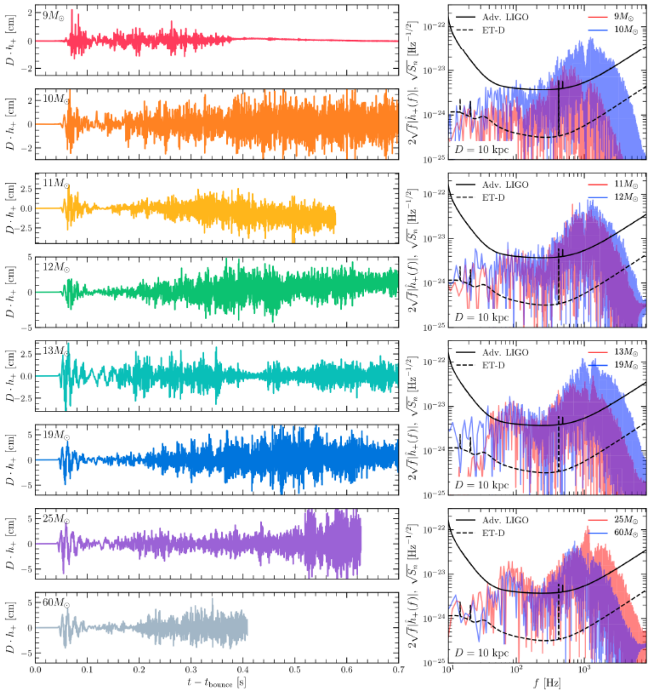
- Robust search paradigm
  - Look for excess power in time-frequency space
    - Using Fourier or wavelet decomposition
  - Require coherent signals in multiple detectors
    - Common features at ~same time, consistent with single sky location
      - Using direction-dependent antenna response

Core-Collapse Supernovae (i)

- ❑ Process still poorly understood
- ❑ GW expected, mainly from protoneutron star oscillations
  - ➢ Oscillations excited by multi-dimensional hydrodynamic instabilities
    - Convection
    - Possibly large-scale non-radial oscillations of shock (SASI)
  - ➢ GW carry information about dynamics of central engine



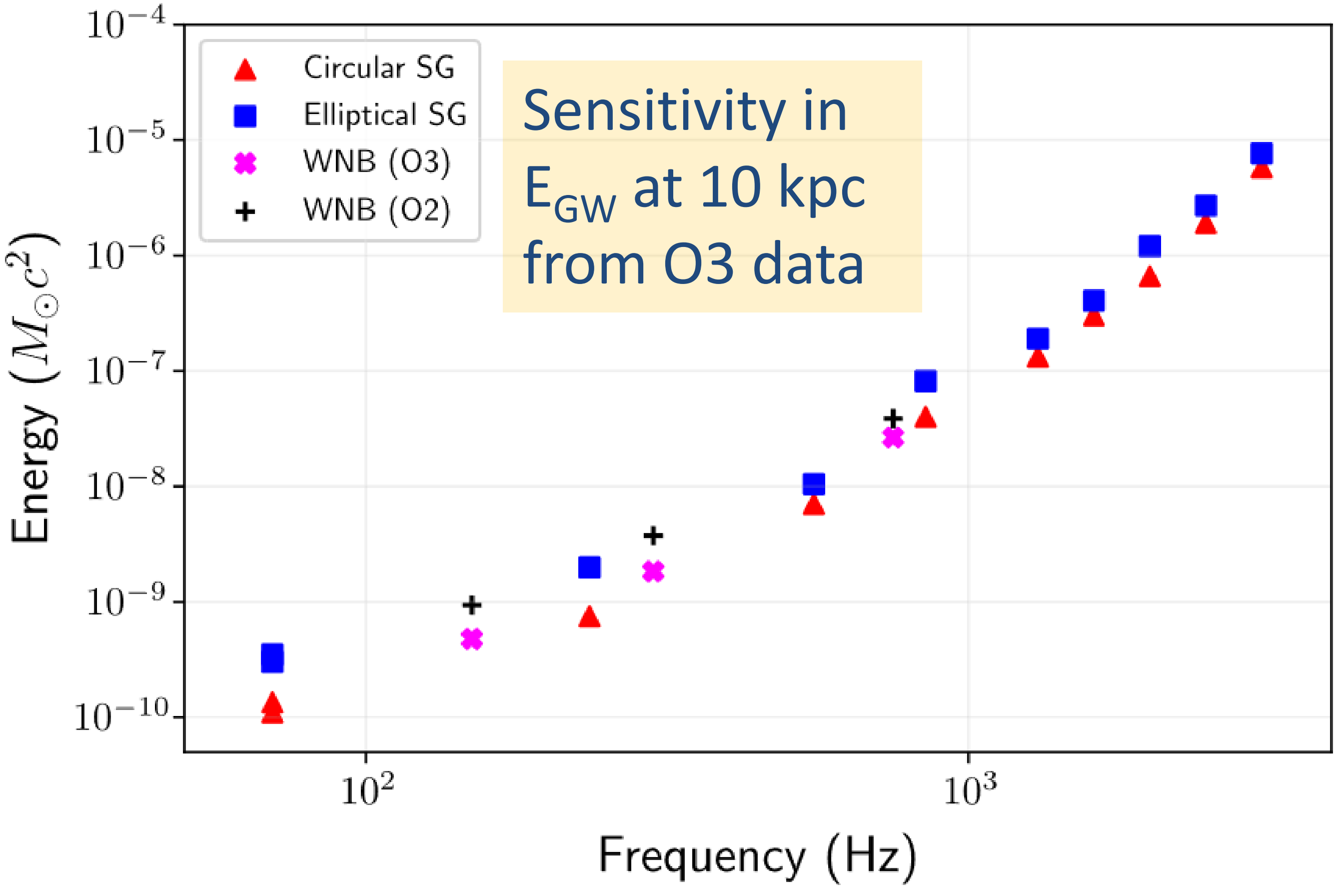




- ❑ GW waveform hard to predict
  - ➢ Efficiency of GW emission strongly parameter and model dependent
    - $E_{GW} \sim 10^{-11} - 10^{-7}\ M_\odot c^2$

Core-Collapse Supernovae (ii)

Phys. Rev. D 104, 122004 (2021)



Sensitivity in E_{GW} at 10 kpc from O3 data

- O3 sensitivity

$$h_{\rm rss} = \sqrt{\int (h_+(t)^2 + h_\times(t)^2)\; dt} \;\sim\; 10^{-22}/\sqrt{\rm Hz}$$

  - E_{GW} ~10^{-10} $M_\odot c^2$ @ 10 kpc, ~100 Hz
- Could detect GW signal from Galactic supernova for some models
- Put constraints on extreme scenarios for supernova in the local group
- Next-gen detectors needed for robust and detailed observations

Multi-messenger searches

- ❑ Triggered searches
  - ➢ Search for GW signals in coincidence wit remarkable events
    - GRBs, Magnetar flares, Pulsar glitches, Supernovae, High energy neutrinos…
  - ➢ Are more sensitive than their all-sky counterparts

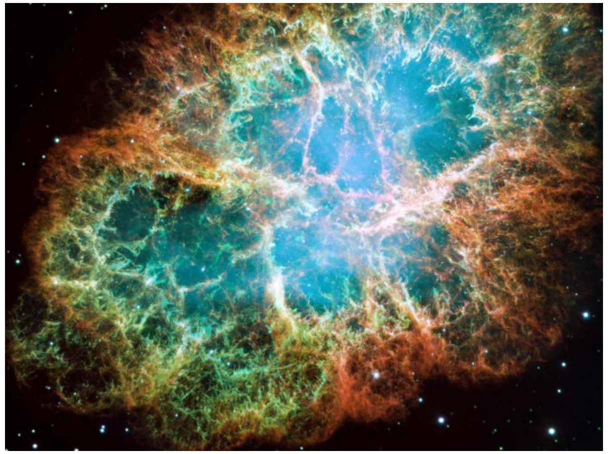
- ❑ The electromagnetic follow-up program
  - ➢ Agreements with partners allowed successful follow-up in O1/O2
    - Spectacular results for GW170817
  - ➢ Moved to open public alerts since O3 run

Sources detectable from Earth

Transient signals

Merging black holes, neutron stars

Burst sources



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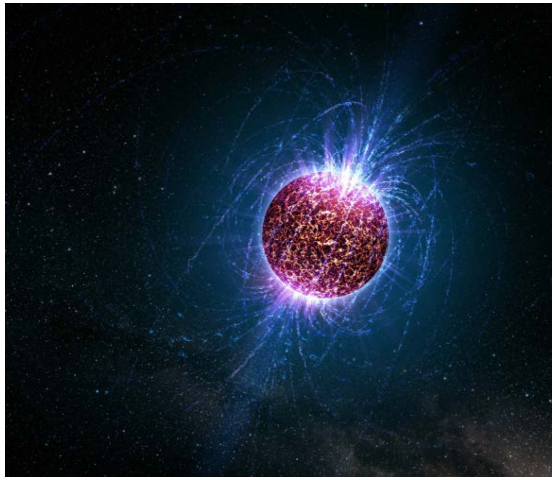
Spinning neutron stars



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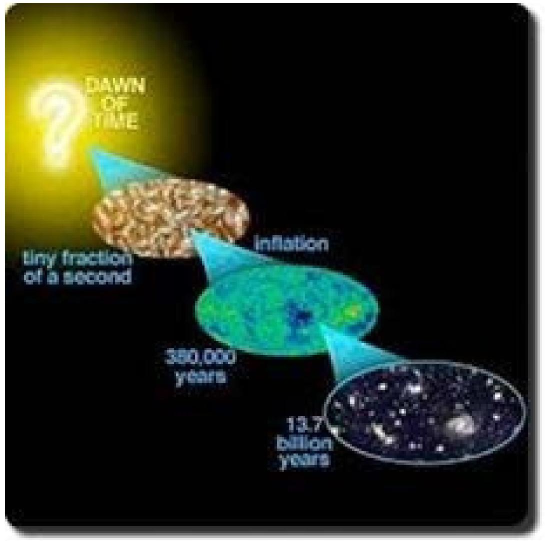
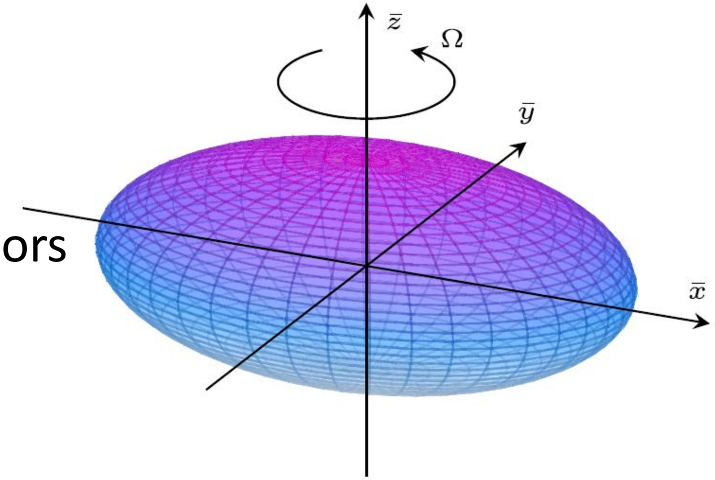


Persistent signals

Continuous wave sources

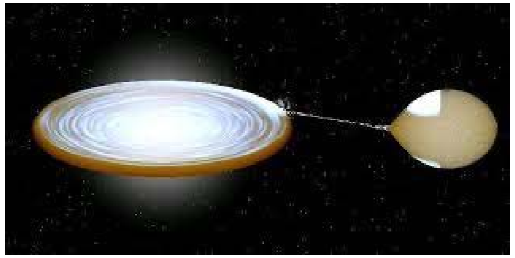


- GW signal from non axisymmetric rotating neutron star
  - O(10^6 - 10^7) neutron stars within 5 kpc
  - ~2000 known pulsars, ~ 10% in frequency band of ground-based detectors

$$h = 3.10^{-27}\left(\frac{\epsilon}{10^{-6}}\right)\left(\frac{10\ \mathrm{kpc}}{D}\right)\left(\frac{I}{10^{45}\ \mathrm{g\ cm}^2}\right)\left(\frac{f}{200\ \mathrm{Hz}}\right)^2$$

- Amplitude of GW signal driven by ellipticity, many uncertainties
  - Maximum sustainable ε depends on NS structure $\epsilon \leq 10^{-7}$–10^{-5}
  - Processes to produce/sustain ε
    - NS born with bumpy crust
    - Strong internal magnetic fields
    - Accretion ± unstable r-mode oscillations
    - Free precession

$$\sim 10^{-12} < \epsilon <\sim 10^{-5}$$



- Emission frequency
  - Depends on emission mechanism $f = 2\ f_{\mathrm{rot}}, f_{\mathrm{rot}} \dots$
- Amplitude very small, but integrating signal over time makes SNR grow $\propto T^{1/2}$

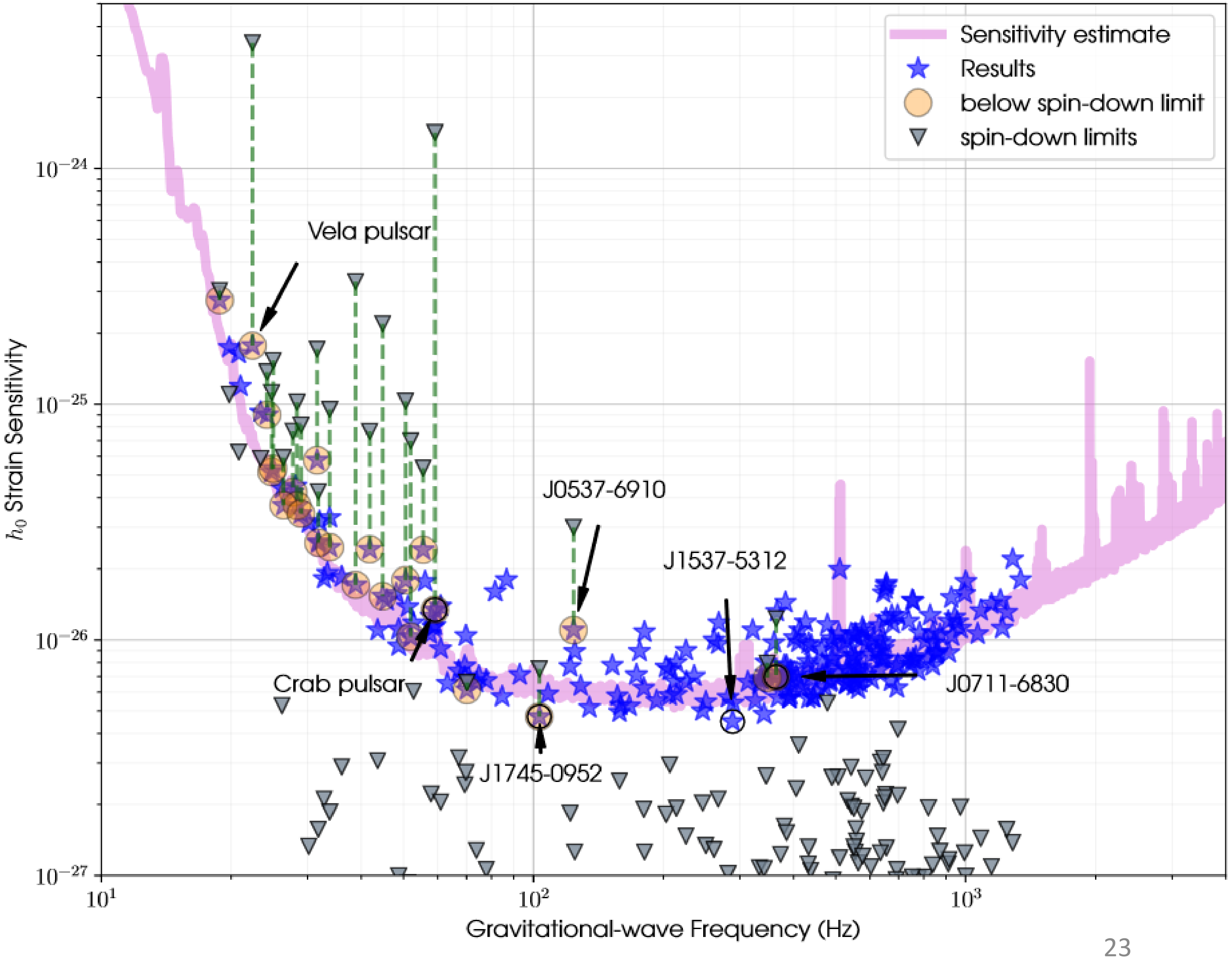
CW search challenges

- Computationally limited searches
  - Coherent analysis needs to account for Doppler modulation of signal due to Earth motion
  - Need to scan an enormous parameter space
    - Sky location x Frequency x Frequency derivative(s) x Inclination x Polarization
  - Coherent analysis is expensive
    - Cost α (coherence time)^6 x (band upper frequency)^3
- Pick your battles: choose your search mix well
  - Coherent / Semi-coherent, Targeted/Directed/All sky, Isolated neutron stars / In binaries (accretion!)
- Data quality
  - Chase wandering lines of instrumental or environmental origin
- Electromagnetic information
  - Pulsar ephemerides, glitches…

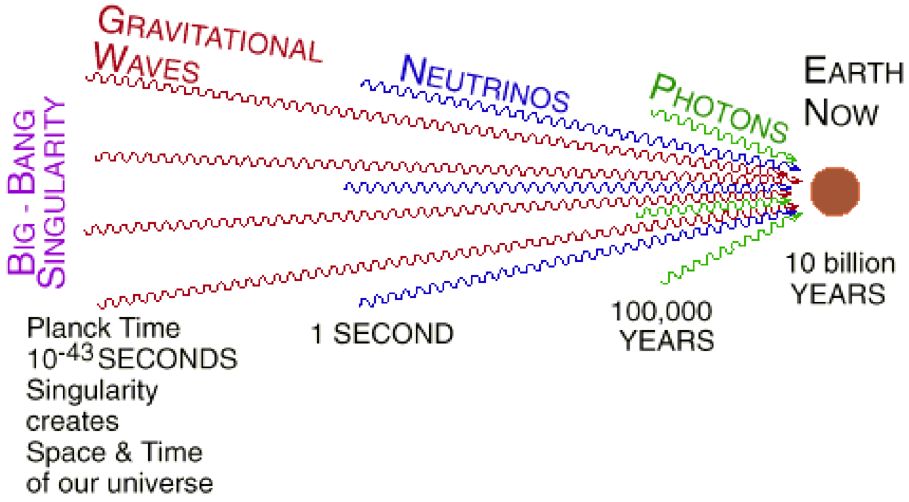
Known pulsars: upper limits

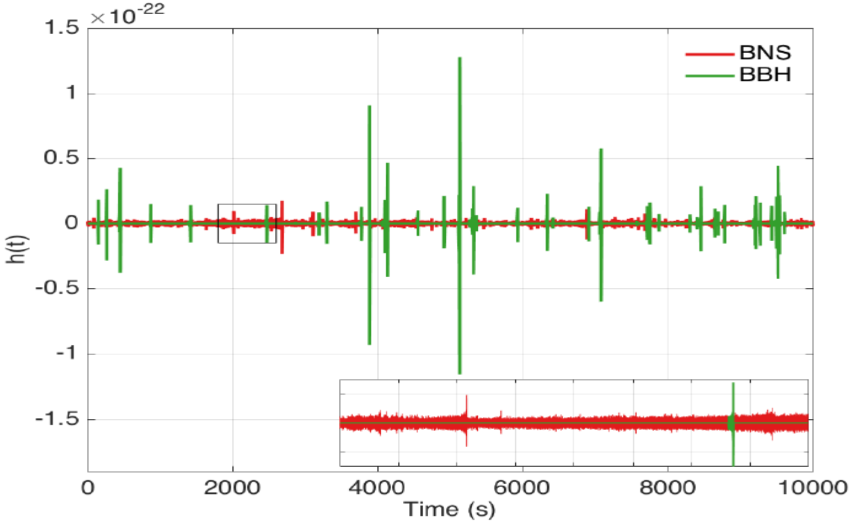
- Spin-down limit surpassed for 23 pulsars
- GW emission <0.009% of spin-down luminosity for Crab pulsar
  - Mountains < 2 cm
- J1745−0952: smallest upper limit on GW amplitude
  - *h* < 4.72 10^{-27}
- J0711−6830: smallest upper limit on ellipticity
  - $\varepsilon < 5.26\ 10^{-9}$

Astrophys. J. 935, 1 (2022)



Stochastic gravitational wave backgrounds





- ❑ Stochastic gravitational-wave backgrounds expected from
  - ➢ Cosmological sources
    - Inflation models, Cosmic strings, Phase transitions…
    - Production processes typically involve energies inaccessible to particle colliders
      - – Discovery window
  - ➢ Astrophysical sources
    - Superposition of unresolved sources
      - – Pulsars in Milky Way
      - – BNS and BBH mergers in Universe

Searching for stochastic backgrounds

- Search for isotropic background by cross-correlating data streams from detector pairs
  - Optimal filter
  - Assume power law spectrum for signal

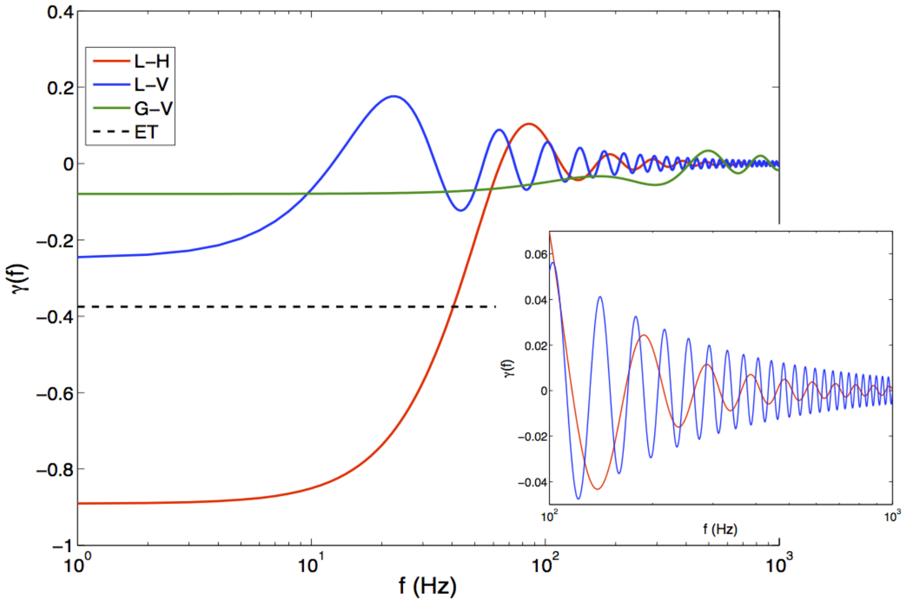
$$\Omega_{\mathrm{GW}}(f) = \Omega_\alpha \left(\frac{f}{f_{\mathrm{ref}}}\right)^\alpha$$

    - α = 0 (cosmologically motivated)
    - α = 3 (astrophysically motivated)
    - α = 2/3 (dominated by CBC sources)
  - Optimal filter depends on detector pair overlap function *γ(f)*
    - Determined by network geometry

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df}$$

$$Y = \int \tilde{s_1}^*(f)\tilde{Q}(f)\tilde{s_2}(f)df$$

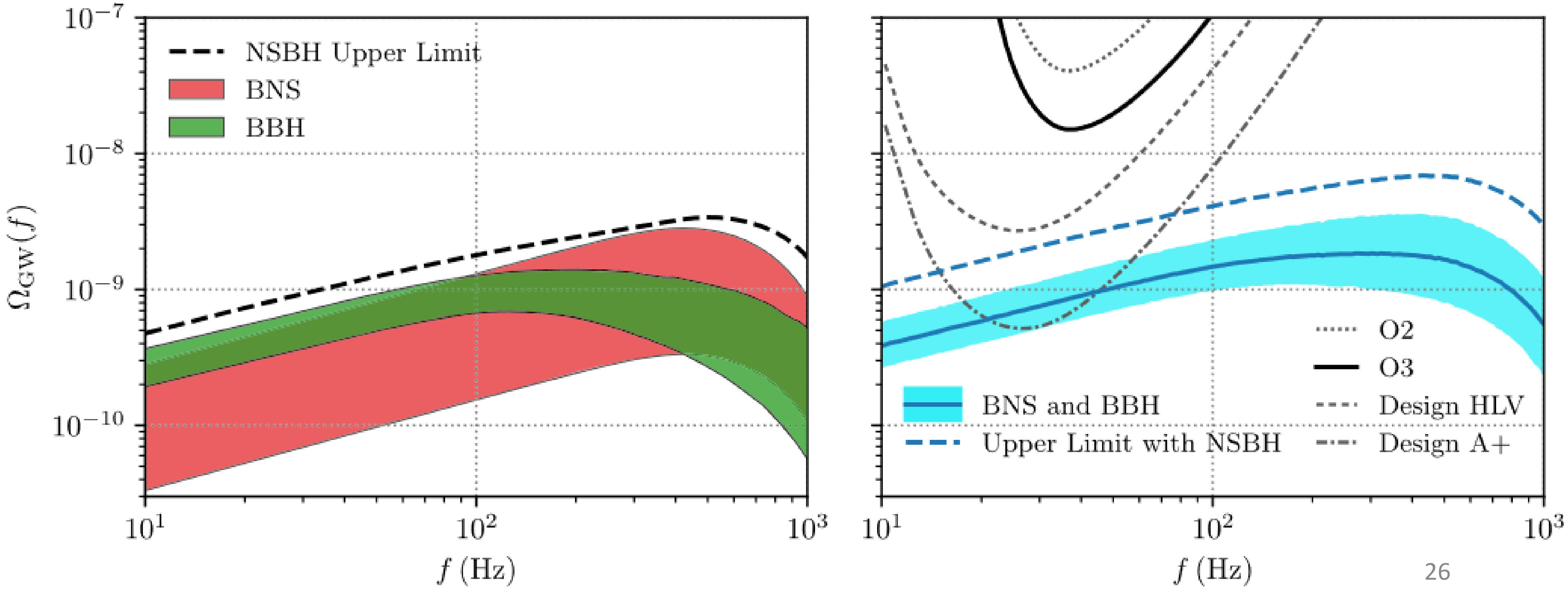
$$\tilde{Q}(f) \propto \frac{\gamma(f)\,\Omega_{\mathrm{GW}}(f)}{f^3\,S_1(f)\,S_2(f)}$$



Background from compact binaries

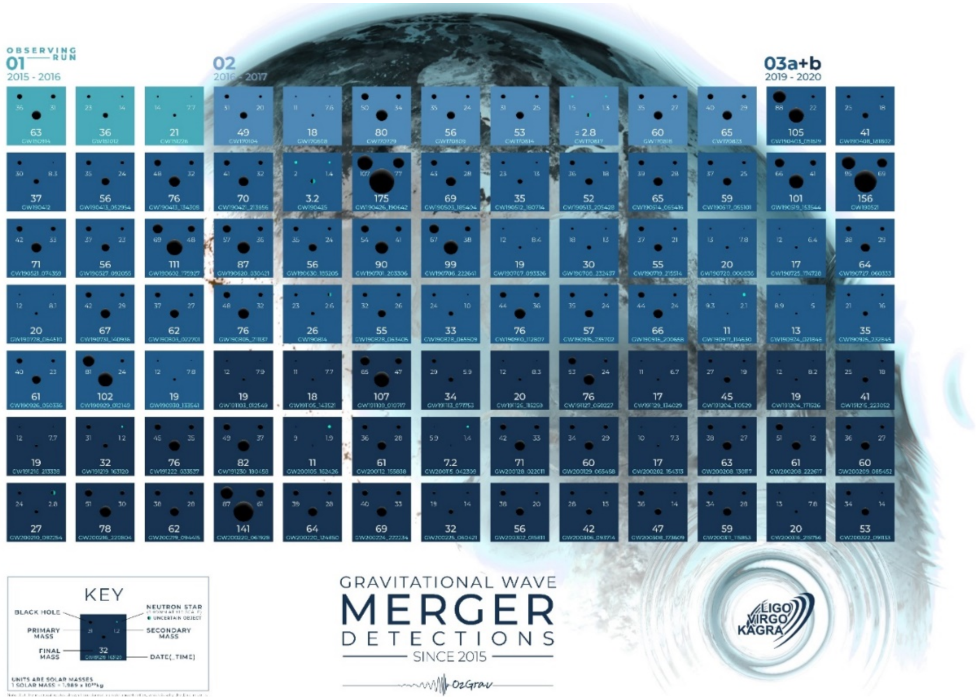
- ❑ Detections have revealed population of BBH with relatively high mass
  - ➢ Boosts expected background from BBH
    - ▪ Dominated by inspiral phase

- ❑ Significant contribution from BNS and possibly NSBH



FOCUS ON COMPACT BINARY COALESCENCES

From signals to sources to science



- ❑ Detailed features of signal reveal source properties
  - ➢ Used for astrophysics, cosmology, fundamental physics

- ❑ Characterizing sources, extracting science: mostly through Bayesian analyses of
  - ➢ Individual events
  - ➢ Collections of events

Parameter estimation via Bayesian inference

- Assume data **d** are described by model *M* with parameters $\vec{\theta}$
- Use Bayes' theorem to infer posterior probability distribution for parameters $\vec{\theta}$, given data **d**

likelihood

prior

a priori knowledge about $\vec{\theta}$

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

posterior

a posteriori knowledge about $\vec{\theta}$

evidence

Likelihood $p(\mathbf{d}|\vec{\theta}, M)$

- ❑ Model for data $$d = R[h] + n$$

available (calibrated) data

detector response to GW signal *h*

detector noise

Assumptions
- ✓ Gaussian
- ✓ Stationary
- ✓ Uncorrelated across detectors
- ✓ Characterized by known PSD

- ❑ $p(d|\vec{\theta})$ is probability of drawing residual $d - R[h]$ from noise distribution
- ❑ Once we have a signal model, the noise model defines the likelihood

$$p(n) \propto e^{-\frac{1}{2}(n|n)} \qquad (n|n) \equiv 4\int_0^\infty \frac{\tilde{n}(f)\tilde{n}^*(f)}{S_n(f)}df$$

Prior, posterior, evidence

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

Prior
Potentially influential choices

Posterior
Sampling algorithm provides set of (n-dim) parameter values that together give a fair representation of the posterior pdf

- ➢ n-dim posterior samples are end result of inference

Evidence = marginal likelihood

$$p(\mathbf{d}|M) = \int_{\Omega_{\vec{\theta}}} p(\mathbf{d}|\,\vec{\theta}\,, M)\,p(\,\vec{\theta}\,|M)\,d\,\vec{\theta}$$

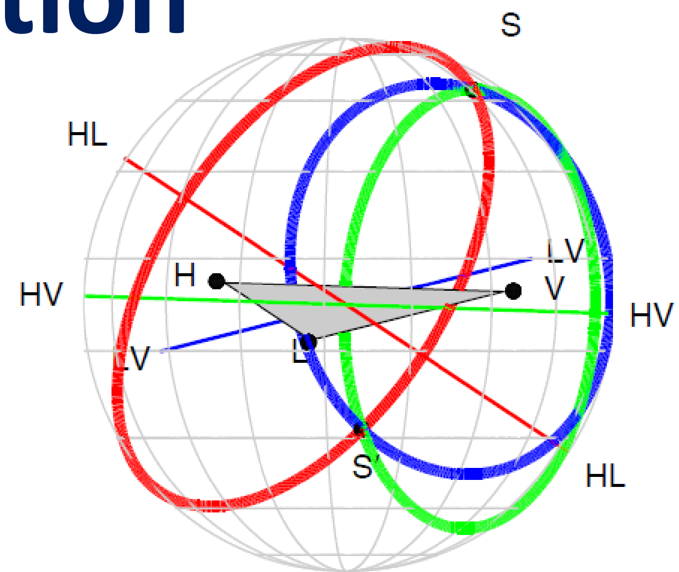
Important for model selection

Results often presented using 2-D corner plots

- ➢ Marginalizing on other parameters, e.g. $p(m_1, m_2|\mathbf{d}) = \int_{\vec{\theta}_{\rm other}} p(\vec{\theta}_{\rm other}, m_1, m_2|\mathbf{d})\; d\vec{\theta}_{\rm other}$
- ➢ Parameter correlations

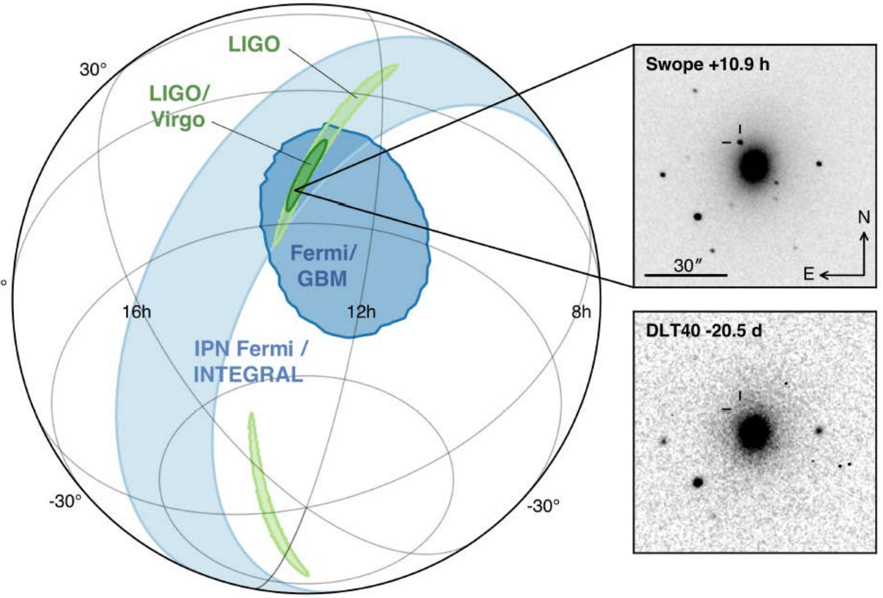
Rapid parameter estimation

- ❑ Parameter estimation requires long computing times
  - ➢ A few hours for short BBH signals
  - ➢ Weeks for BNS signals
  - ➢ Driven by evaluating likelihood (including computing waveform) at each step



- ❑ Low-latency localization of sources for electromagnetic follow-up
  - ➢ Focus is on extrinsic parameters
    - ▪ Fix intrinsic parameters to values reported by search pipelines
  - ➢ Information crucial for localization is encapsulated in matched-filter estimates of times, amplitudes, and phases on arrival at the detectors
  - ➢ Compute posterior distribution of extrinsic parameters, provide (good!) approximate marginal posterior distribution of sky location within minutes

GW170817



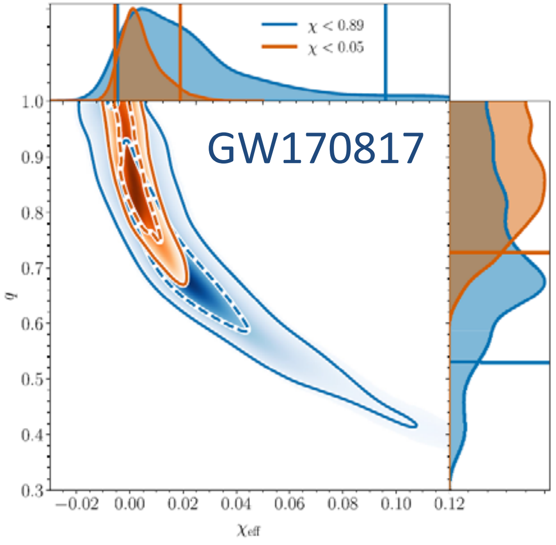
ApJL 848 L12 (2017)

BAYESTAR – Singer & Price Phys. Rev. D 93, 024013 (2016)

System dynamics & intrinsic parameters

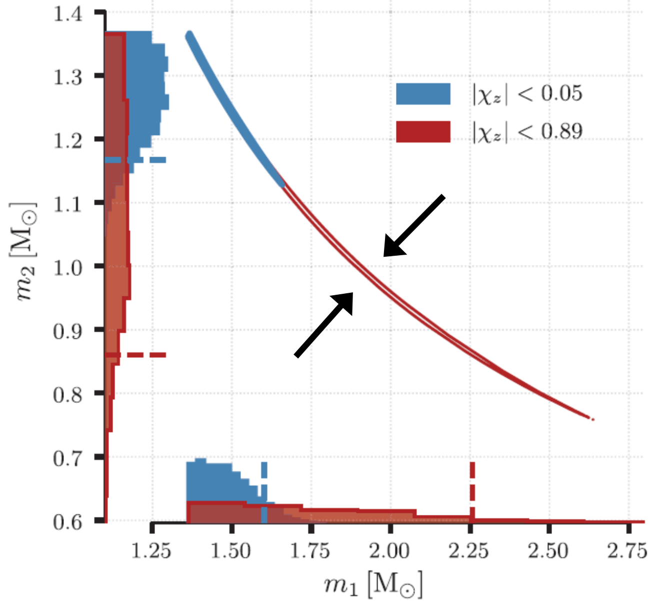
- ❑ Inspiral phase evolution: post-Newtonian expansion in powers of $(v/c)^2$
- ❑ At leading order: driven by chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$
- ❑ At higher orders
  - ➢ Mass ratio $q = m_2/m_1$
  - ➢ Effective spin $\chi_{\text{eff}} = \frac{m_1 \chi_{1z} + m_2 \chi_{2z}}{m_1 + m_2}$
- ❑ Correlations
  - ➢ Between m_1 and m_2
  - ➢ Between q and χ_{eff}
- ❑ For high-mass systems, merger-ringdown significant part of signal, driven by total mass

PRX 9, 011001 (2019)

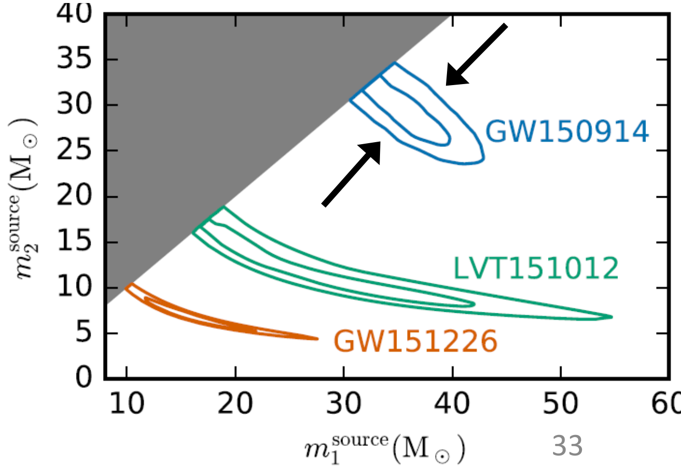


GW170817

PRL 119, 161101 (2017)



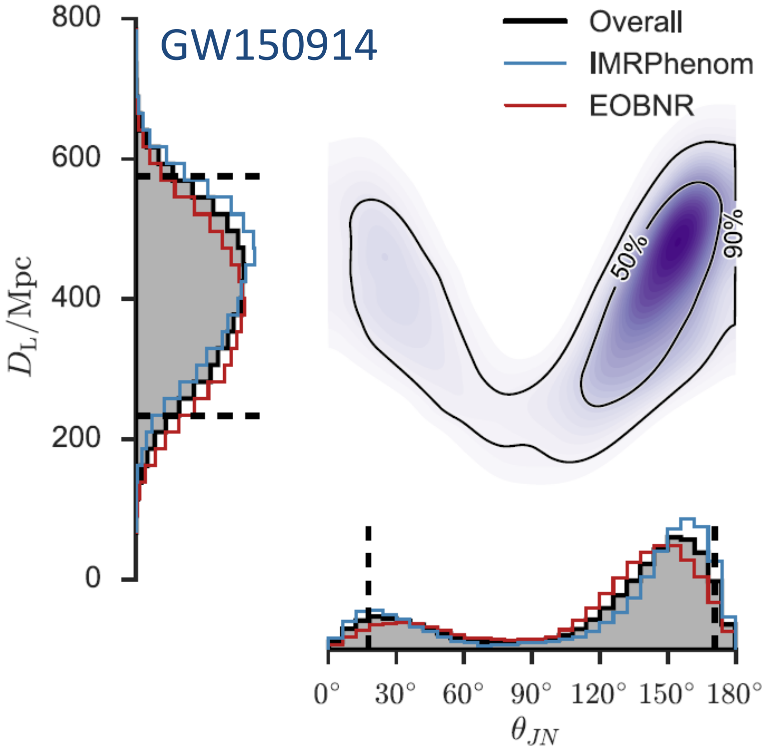
PRX 6, 041015 (2016)



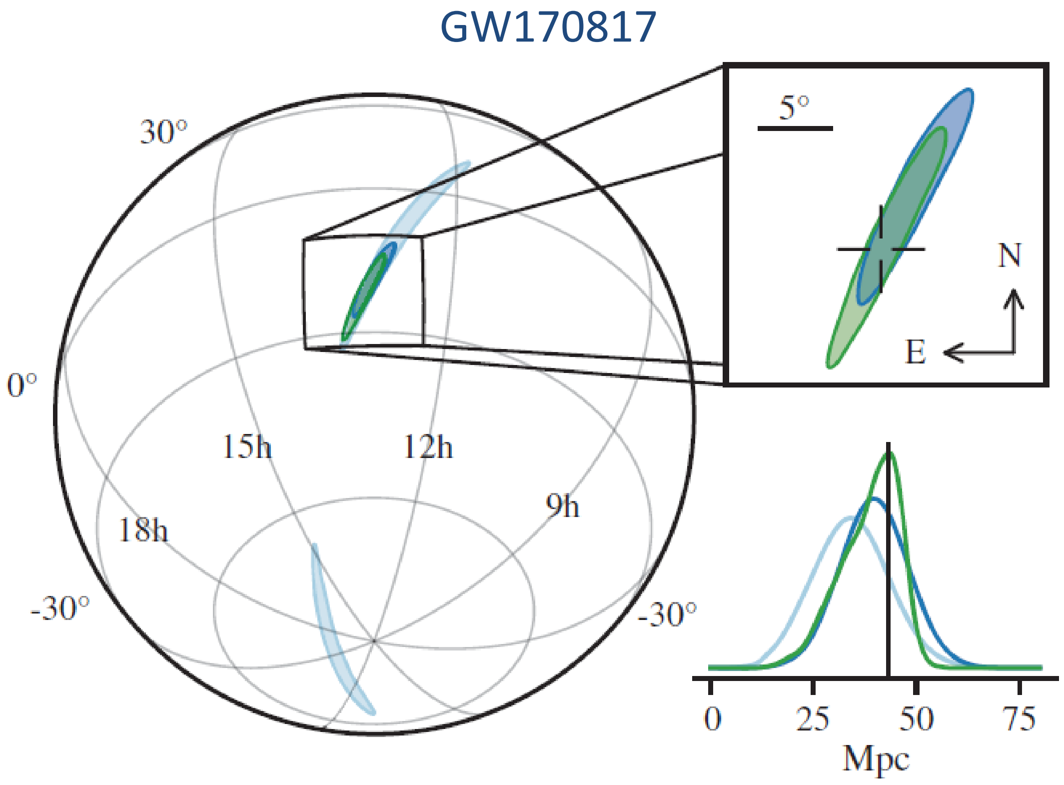
Extrinsic parameters

- ❑ From GW signal, difficult to distinguish distant, well-oriented source from nearby, ill-oriented source
  - ➢ Correlation between luminosity distance and inclination (and direction)

PRL 116, 241102 (2016)



inclination



PRL 119, 161101 (2017)s

More features: higher-order modes

See movie

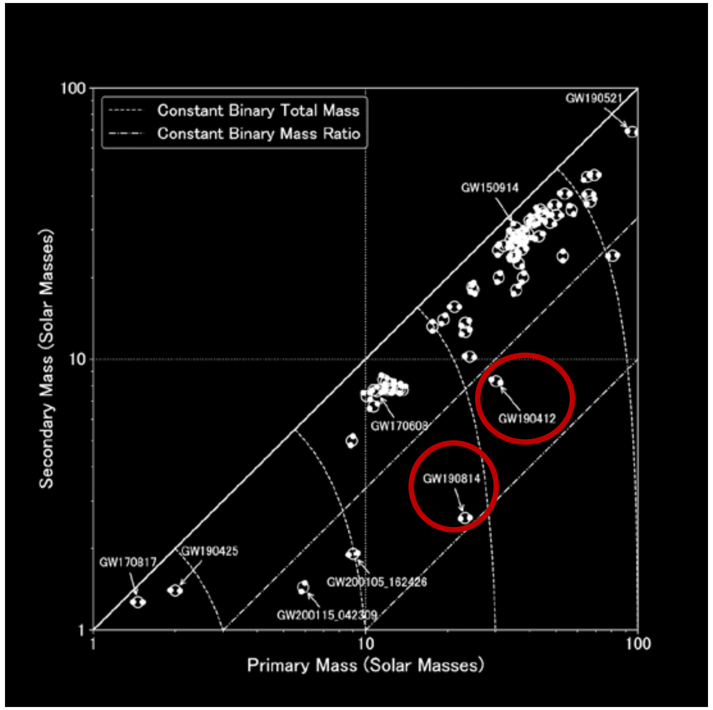
$$h_+ - i h_\times = \sum_{l \geq 2} \sum_{m=-l}^{l} {}_{-2}Y_{lm}(\iota, \phi_c) h_{lm}$$

Quadrupolar mode dominates

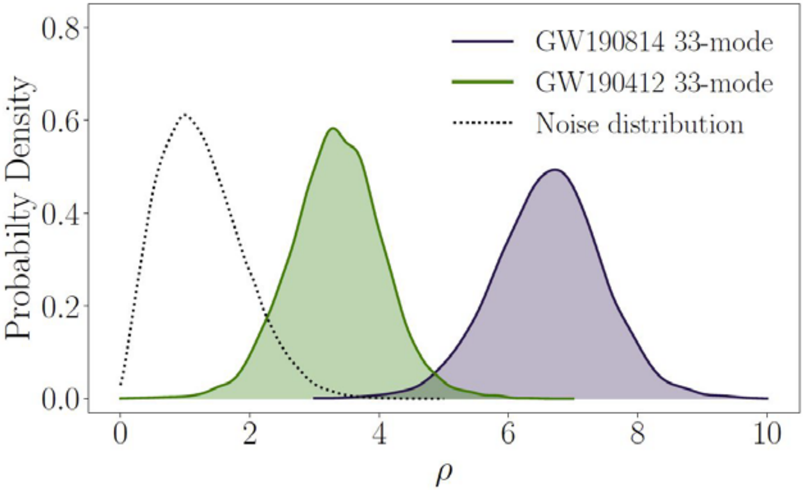
$$l = 2 \; m = \pm 2$$

Higher-order modes significant

- For binaries with asymmetric masses
- For binaries seen edge-on

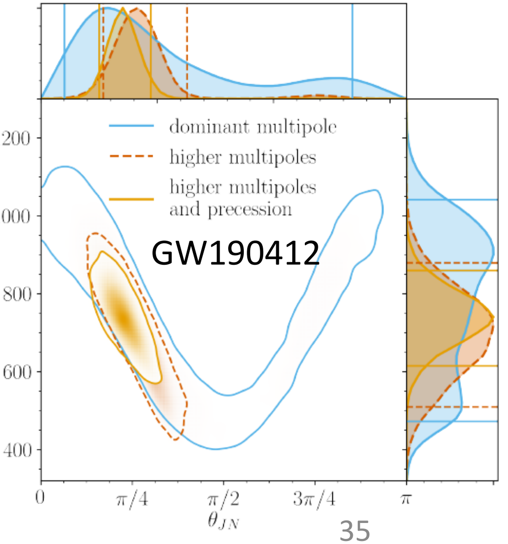


Signal-to-noise ratio in 33 mode



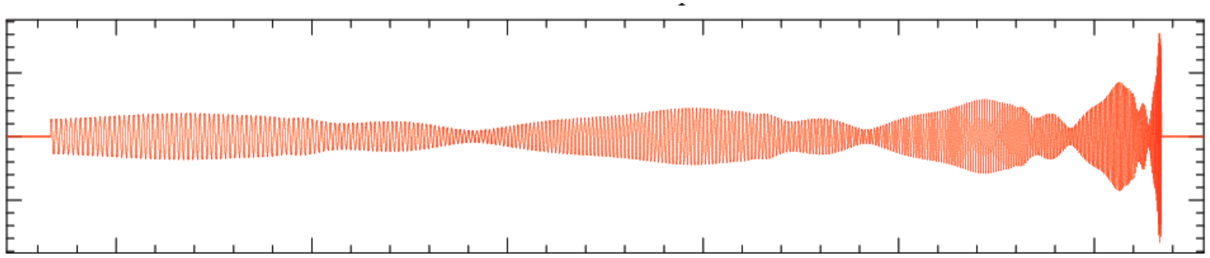
Asymmetric system GW190412

- 30+8 $M_\odot$
- Presence of higher-order modes helps lifting degeneracy between distance and inclination

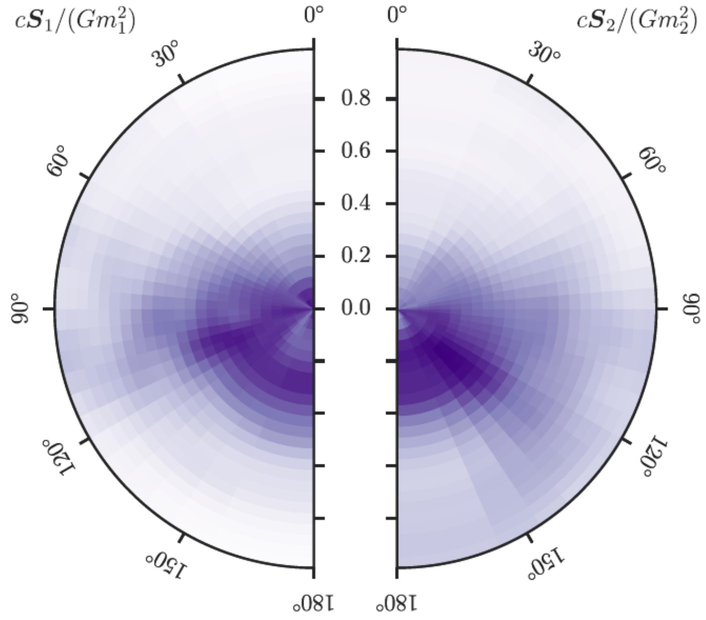


More features: precession

- Spins enter at higher order in system dynamics and have subtle effects on GW waveform
  - Difficult to measure
  - Unless precession changes inclination over time and induces spectacular amplitude and phase modulation
    - If significant spin component in orbital plane
    - Most easily observable for edge-on binaries

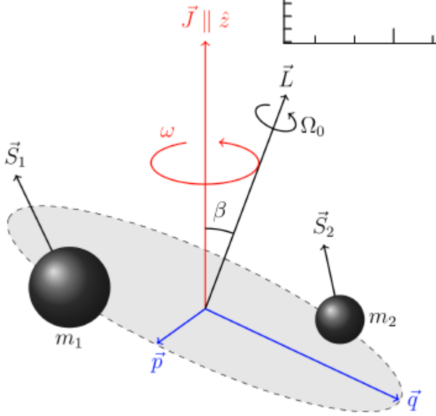


GW150914 spin aligned with orbital angular momentum



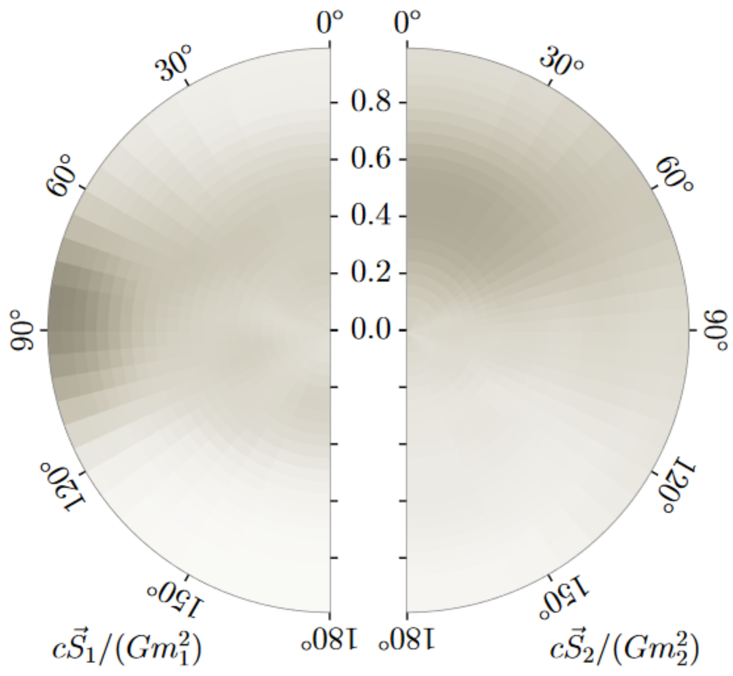
spin anti-aligned with orbital angular momentum

PRL 116, 241102 (2016)



- 2D posterior probability for tilt angle and spin magnitude for each object
- Tiles constructed linearly in spin magnitude and cosine of tilt angle (identical prior probability)
- Color indicates posterior probability per pixel, marginalized over azimuthal angle

GW200129_065458



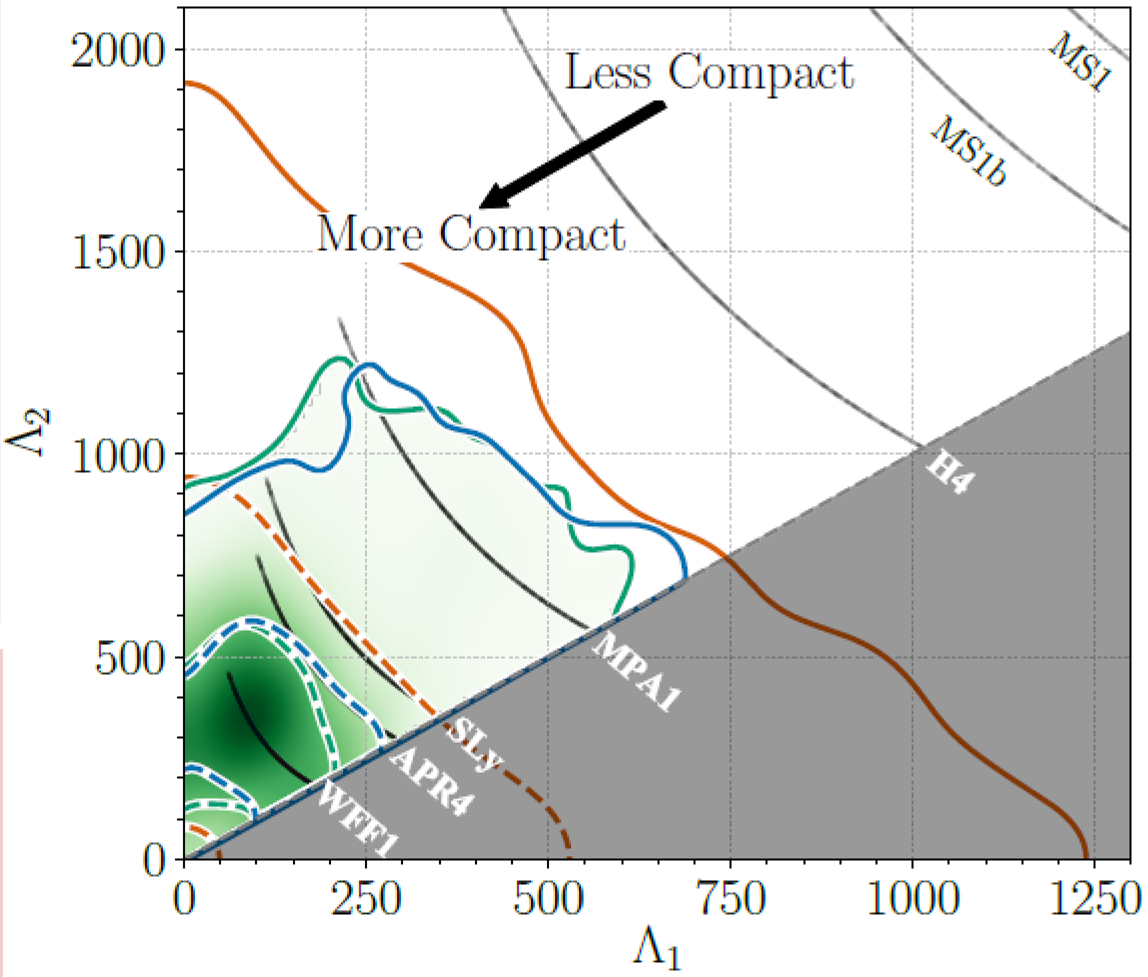
PRX 13, 041039 (2023)

More features: matter effects

- Relevant for BNS and NSBH binaries
- Point-particle approximation breaks down before end of inspiral
- Tidal field of companion induces mass-quadrupole moment and accelerates inspiral
  - Induced quadrupole moment depends on unknown NS tidal deformability Λ
  - Impact on waveform phase potentially observable above a few hundred Hz

- Upper limits on Λ constrain NS compactness and radius
- GW170817
  - Equations of state predicting less compact stars are disfavored
  - NS radii ~12 km

GW170817



More features: post-merger signal

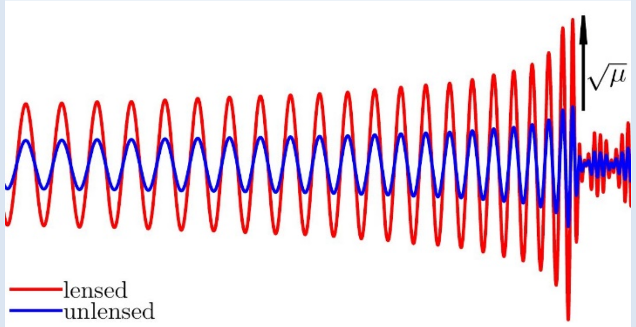
- Black hole ringdown
  - Merger remnant likely BH in most cases
  - Reaches equilibrium by radiating GW quasinormal modes
    - Superposition of exponentially damped sinusoidal oscillations
    - Frequencies and damping times determined by mass and spin of remnant BH
    - Energy radiated via ringdown < ~1% M_{BH}
- BNS case
  - Prompt BH formation
  - Formation of a short-lived or long-lived NS
    - NS oscillations potentially excited and detectable

Black holes have no hair (?)

More features: lensing?

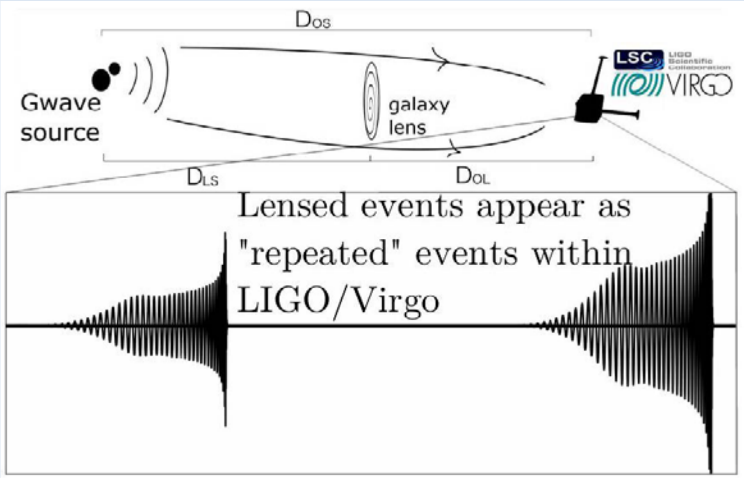
- ❑ Like electromagnetic waves, gravitational waves can be gravitationally lensed
- ❑ Lenses rare in universe probed with current sensitivities ➔ unlikely
  - ➢ Expected for $1 : 10^{3-4}$ events
- ❑ Various signatures

Signal amplification



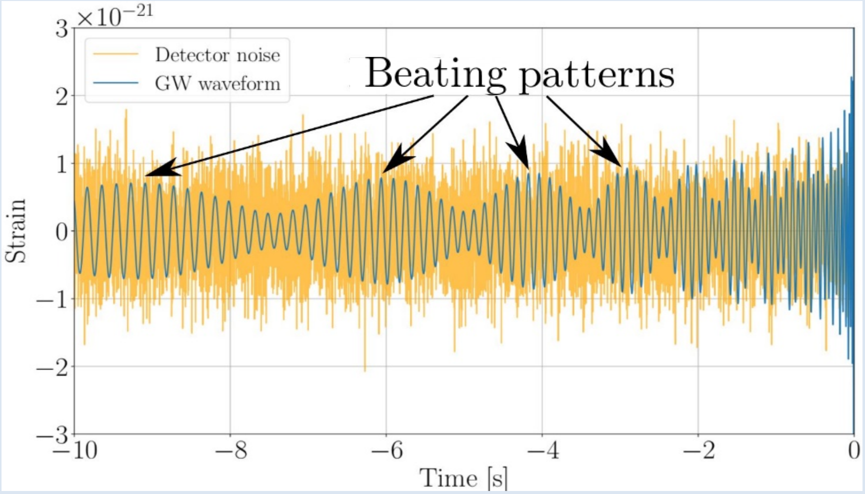
Multiple images

Time delays: minutes, months, years



Lensed events appear as "repeated" events within LIGO/Virgo

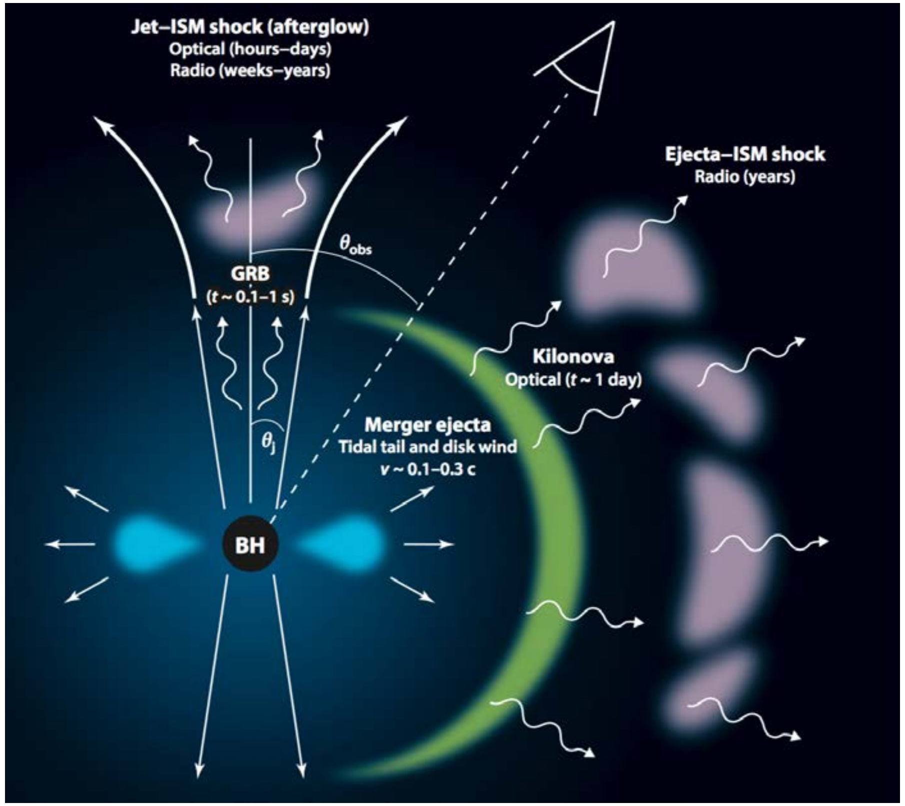
Waveform distortion from microlensing



Beating patterns

Multi-messenger counterparts

- Counterparts expected for BNS and some NSBH mergers
  - Electromagnetic emission
  - Possibly neutrinos
- The famous case of GW170817
  - Coincident with a short Gamma-ray burst
  - Extensive follow-up led to discovery of optical transient, then X-ray, radio
  - Optical transient linked to kilonova
    - Nucleosynthesis of heavy elements in ejecta



Standard sirens & Hubble constant

- ❑ GW signal provides luminosity distance – standard sirens
- ❑ Universe expansion rate: recession velocity / distance
- ❑ GW signal typically does not provide redshift
  - ➢ Full mass-redshift degeneracy for inspiral
- ❑ How do we get the redshift ?
  - ➢ From possible electromagnetic counterpart – GW170817!
  - ➢ Statistically, from reliable galaxy catalog
  - ➢ Statistically, from known features in NS / BH mass distribution
  - ➢ From tidal effects if NS equation of state is known
  - ➢ From post-merger signal if observed and NS EoS is known
- ❑ High statistics will provide precise measurements

Present

Future

Source population: merger rates

Detection efficiency

Merger rates

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

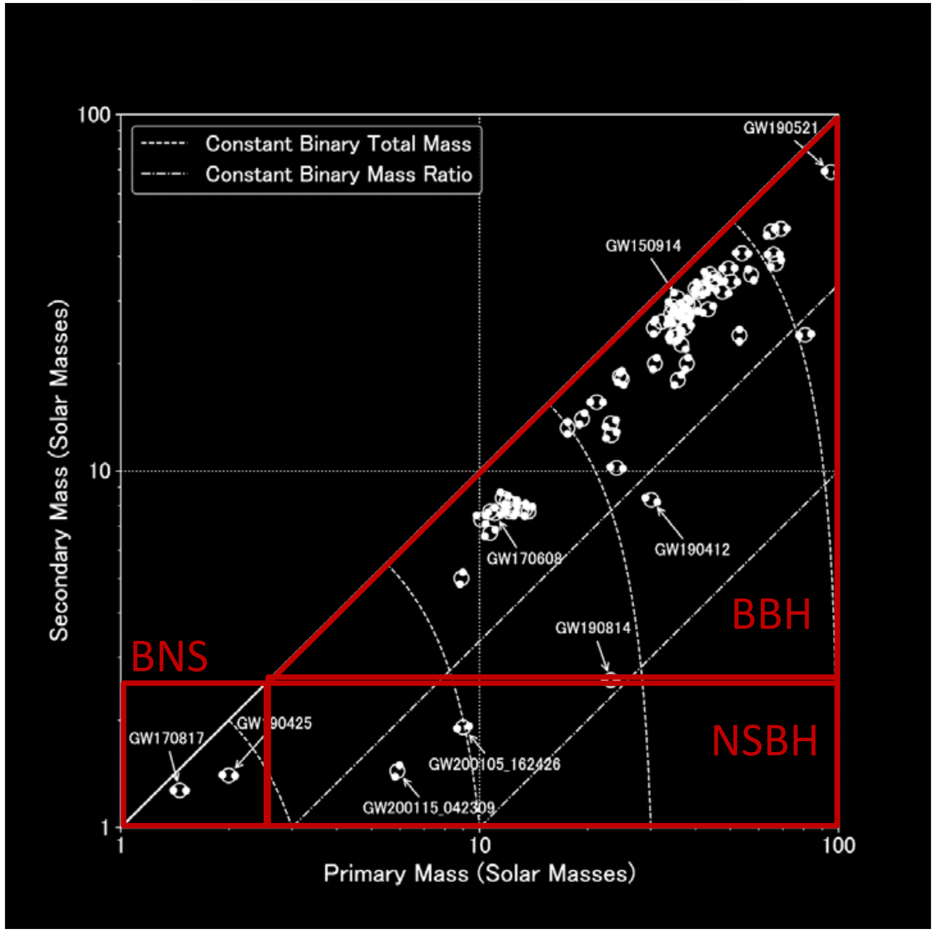
$$\mathcal{R}_{\rm NSBH} = 7.4 \text{ - } 320 \ {\rm Gpc}^{-3}{\rm yr}^{-1}$$

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

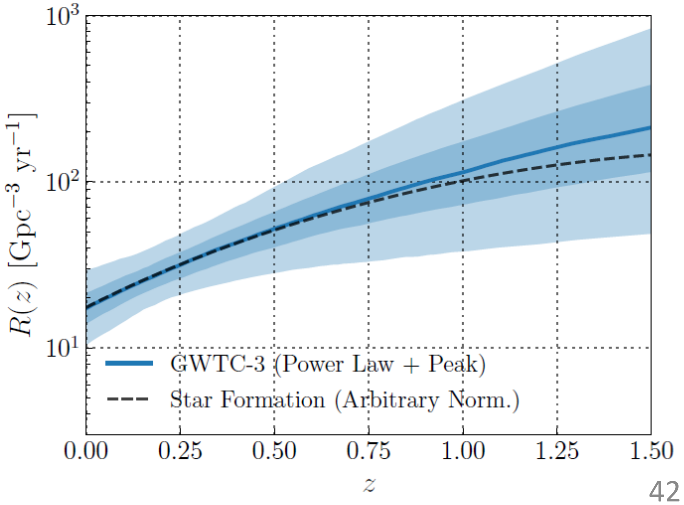
Intrinsically rarer but dominate observed sample – louder sources detectable at larger distances

Uncertainties:
statistical
+
population mass distribution

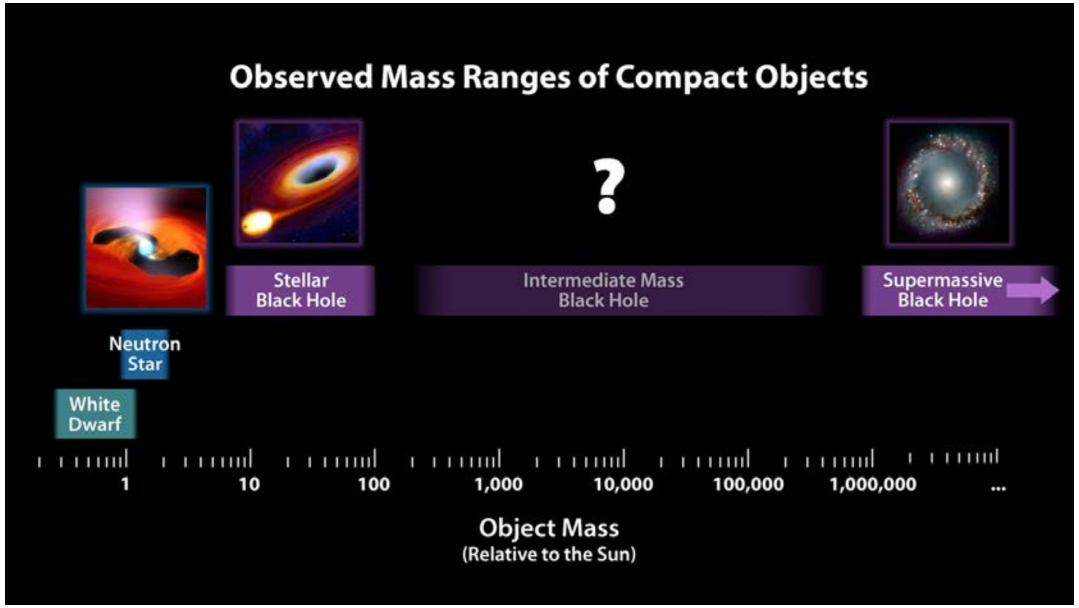
Observed sample



BBH merger rate increases with redshift

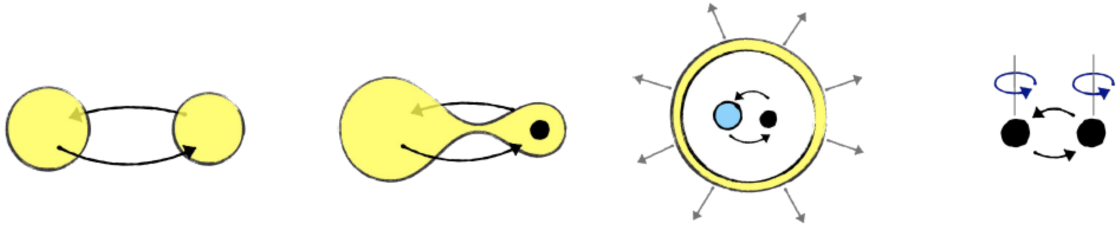


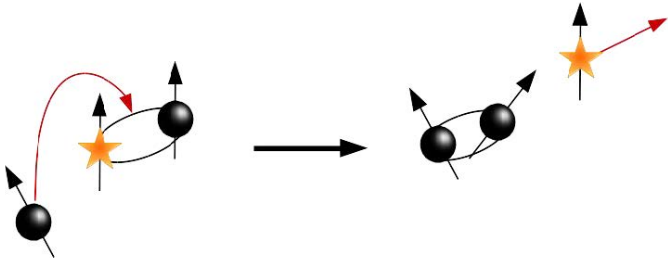
Source population: formation scenarios



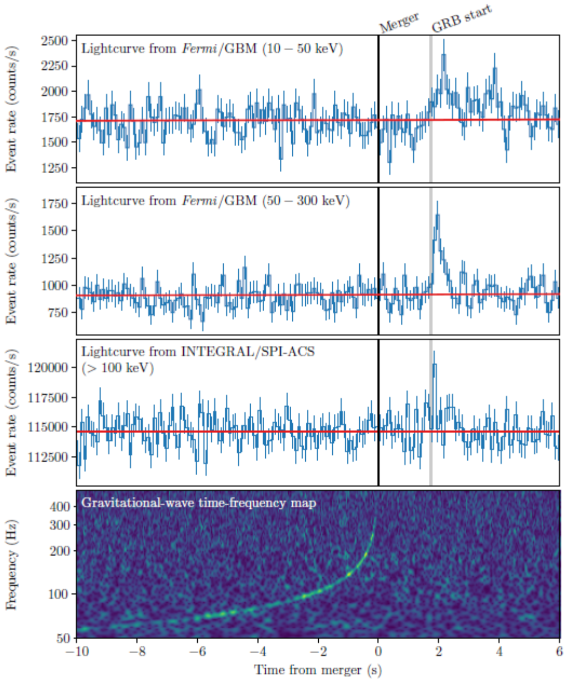
- ❑ Understanding binary formation and evolution of progenitor stars
  - ➢ Merger rates
  - ➢ Mass distribution
  - ➢ Spin distribution
- ❑ Two main classes of formation channels for merging binaries
  - ➢ Isolated binary evolution
  - ➢ Dynamical formation

- ❑ GW190521: challenges and clues
  - ➢ 66 + 85 ⇨142 $M_\odot$
  - ➢ How were the initial BHs formed?
  - ➢ Remnant is an intermediate-mass BH





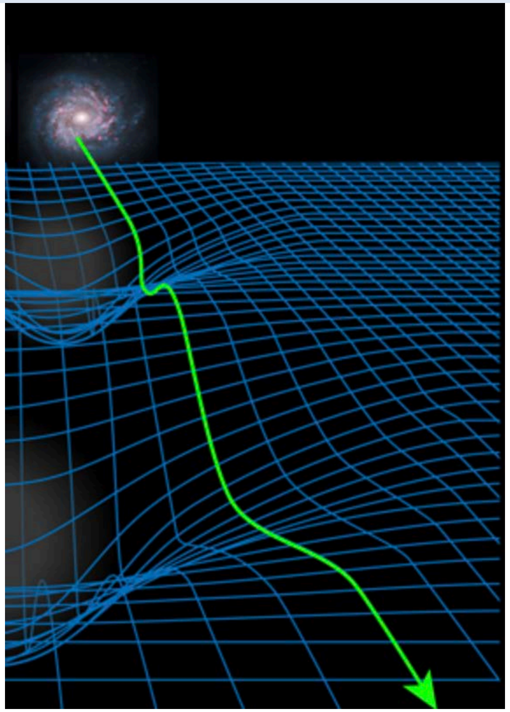
Testing some GR cornerstones



- ❑ GW propagation speed
  - GW170817 – GRB 170817A: delay of 1.74 ± 0.05 s over > 85 million years propagation
  - Assume γ emission delayed by [0,10]s

$$-3\times10^{-15} \leq \frac{v_{\mathrm{GW}}-v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq 7\times10^{-16}$$

Astrophys. J. Lett. **848**, L13 (2017)



APS/Alan Stonebraker

- ❑ Equivalence principle
  - EM radiation and GWs affected by background gravitational potentials in the same way ?
  - Shapiro delay $\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3}\int_{\mathbf{r}_{\mathrm{e}}}^{\mathbf{r}_{\mathrm{o}}} U(\mathbf{r}(l))dl$

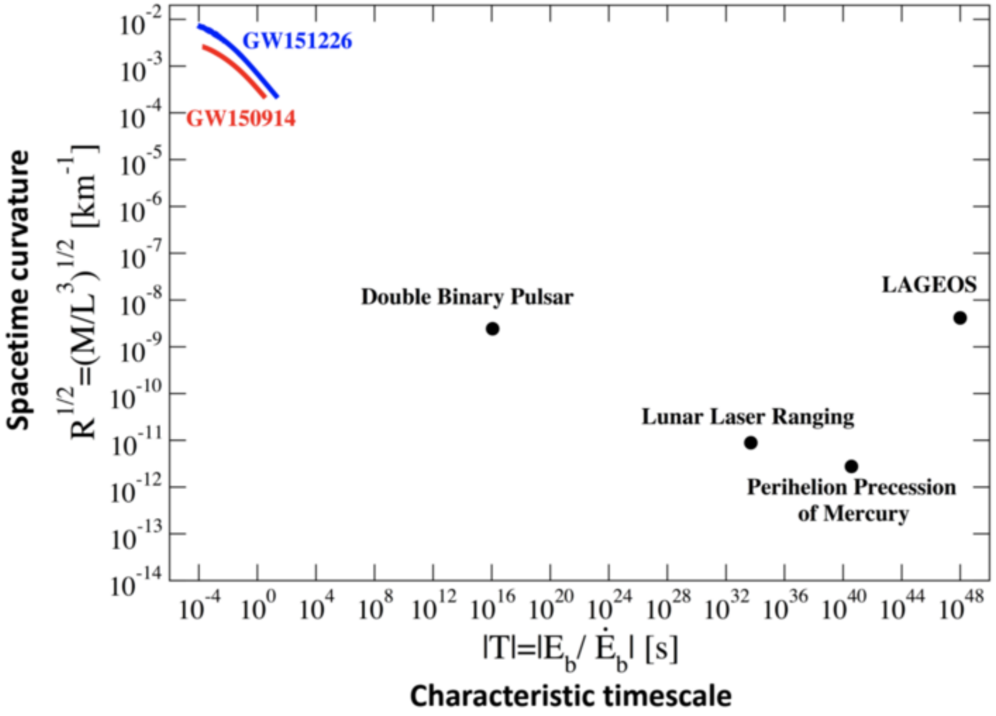
$$-2.6\times10^{-7} \leq \gamma_{\mathrm{GW}}-\gamma_{\mathrm{EM}} \leq 1.2\times10^{-6}$$

Many alternative theories of gravity ruled out

Further tests of GR

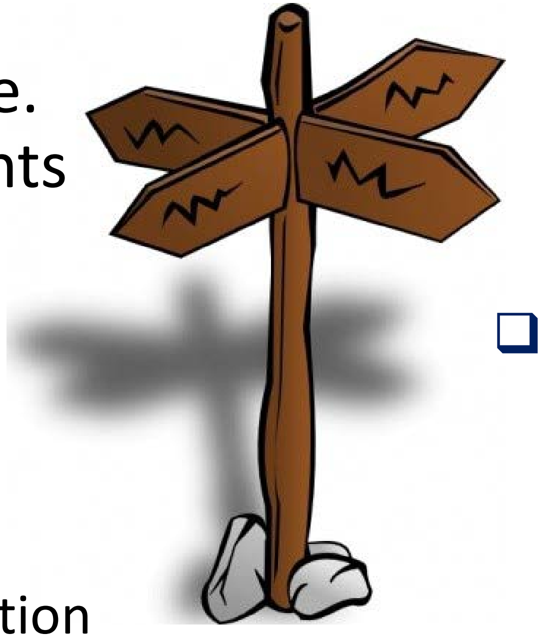
- GW polarization
  - Are signals recorded in different detectors consistent with two tensor polarizations?
- Dispersion
  - Any sign of waveform distortion due to different frequencies propagating at different speeds?
- Source dynamics
  - Consistency of inspiral waveform with GR prediction
  - Consistency of inspiral and ringdown parts of signal
  - Test of BH no-hair theorem with ringdown spectroscopy

Phys. Rev. D 94, 084002 (2016)



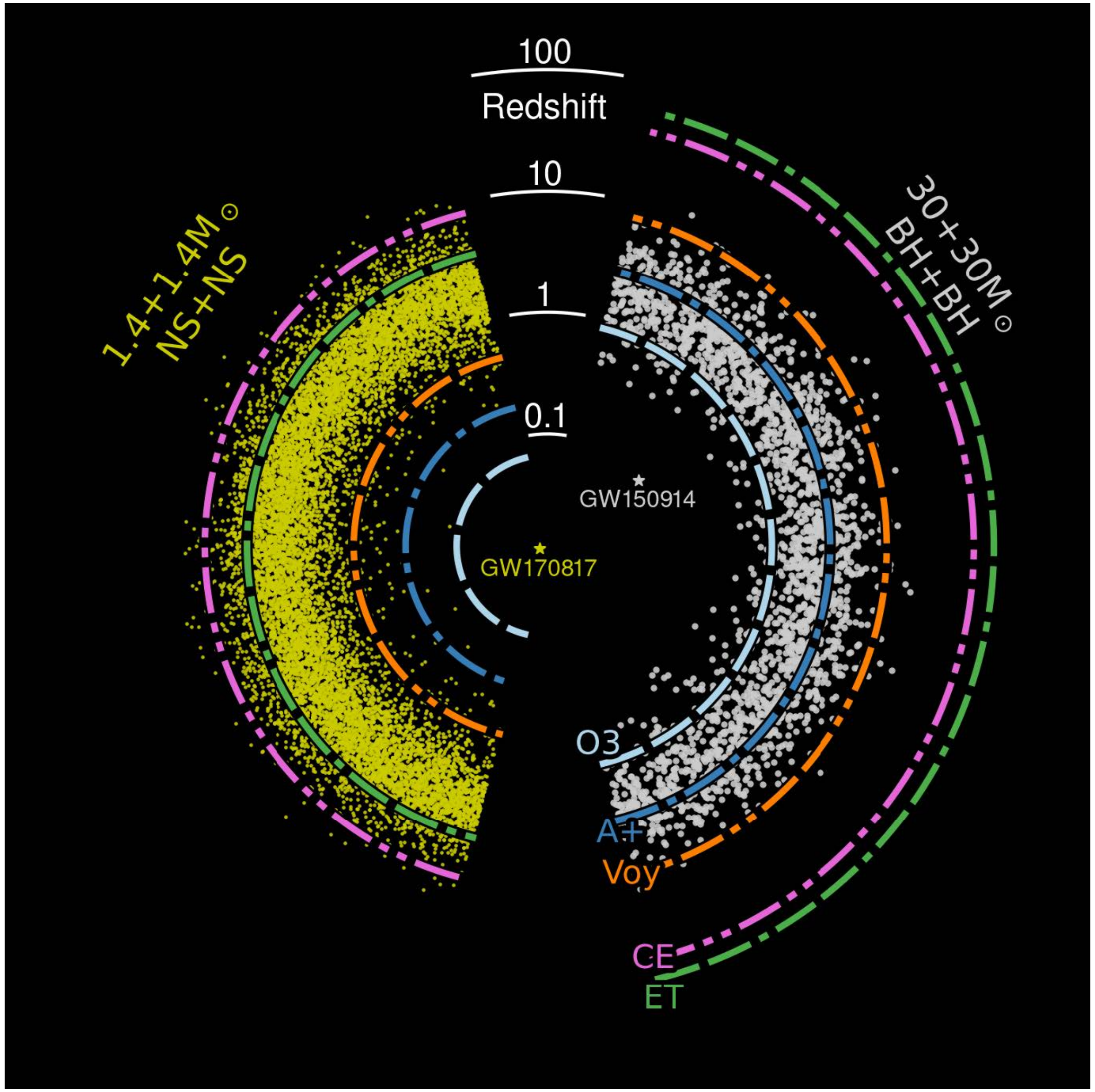
CLOSING THE LOOP : SCIENCE & DETECTORS

More sensitive detectors for more science



- ❑ Sensitivity
  - ➢ More statistics to characterize source populations
  - ➢ Higher signal-to-noise ratio, i.e. precision, for exceptional events
  - ➢ Potential for new discoveries
- ❑ Bandwidth
  - ➢ Low-frequency sensitivity
    - ▪ High-mass BBH mergers
    - ▪ More accurate parameter estimation
  - ➢ Mid- and high-frequency sensitivity
    - ▪ Black hole spectroscopy
    - ▪ Post-merger signal
- ❑ Network size and robustness
  - ➢ Duty cycle
  - ➢ 3-detector observations
    - ▪ Improved sky localization
- ❑ Multi-messenger approach
  - ➢ Low-latency alerts
    - ▪ Possibly early warning
  - ➢ And multi-wavelength
    - ▪ Some sources expected to be visible from space then from Earth

Potential of next-gen detectors re. BNS & BBH



- ❑ Stellar-mass BHs and NSs throughout cosmic time
  - ➢ Map population of compact objects across time
  - ➢ Remnants of first stars

Further reading

- Two recent Scholarpedia articles
  - [Gravitational Waves: Ground-Based Interferometric Detectors]
  - [Gravitational Waves: Science with Compact Binary Coalescences]