The Binary Universe In Gravitational Waves

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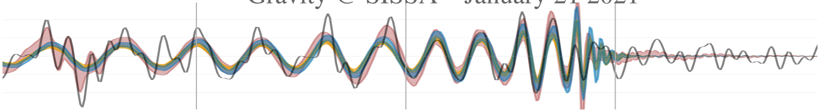
Hannover, Germany

Gravity @ SISSA – January 21 2021



LIGO-G2002166v1

Binary Merger
Observations &
Numerical Relativity

LIGO Scientific Collaboration

LIGO

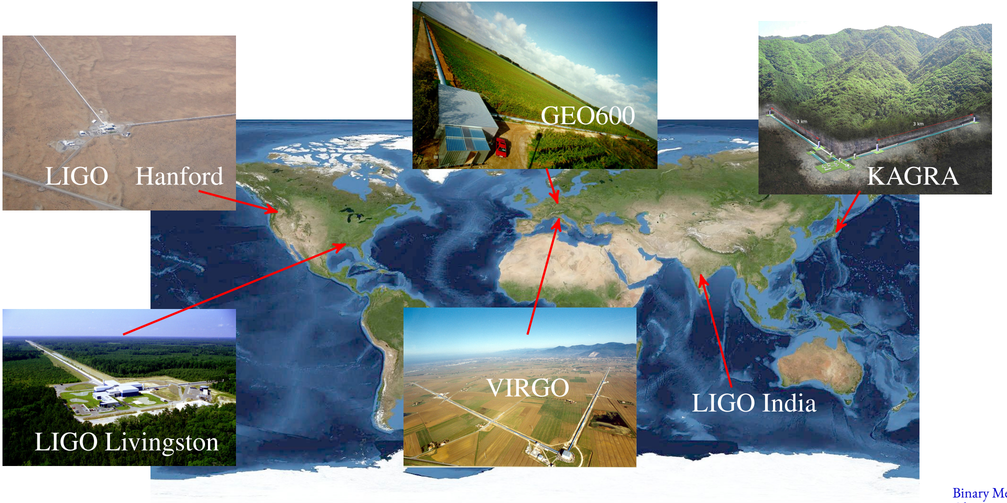
LSC

Binary Merger Observations & Numerical Relativity

Interferometer

Binary Merger Observations & Numerical Relativity

Detector network



Binary Merger Observations & Numerical Relativity

[GWTC-2, 2010.14527]

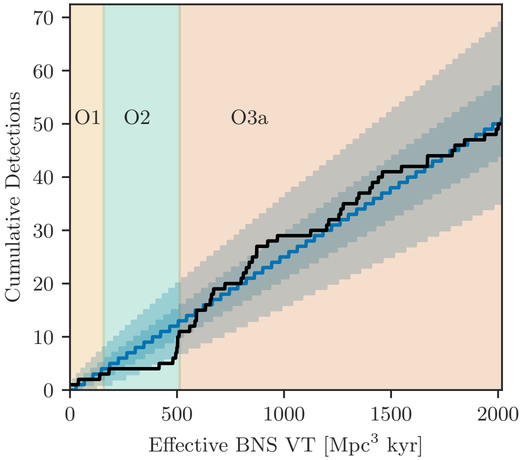
O1 09/2015 – 01/2016
3 binary black holes (BBHs)

O2 10/2016 – 08/2017
7 BBHs + 1 binary neutron star (BNS)

O3 04/2019 – 03/2020 (suspended)

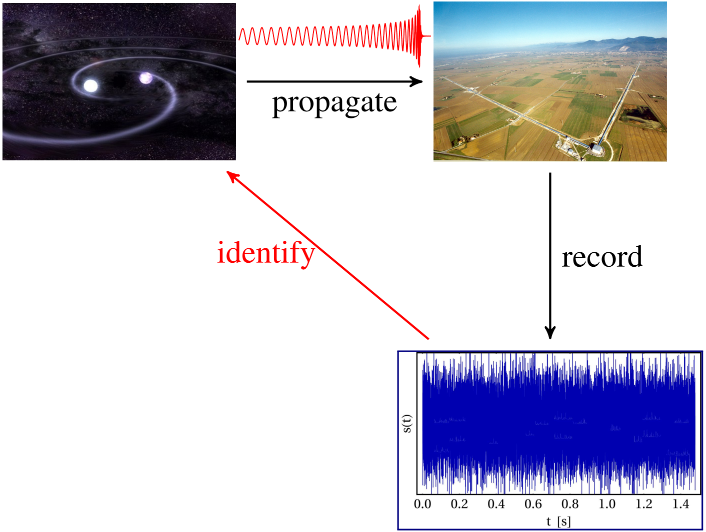
O3a 37 BBHs + 1 BNS + 1 NSBH (candidates)

O3b ☐ BBHs + ☐ BNSs + “#..;’?@

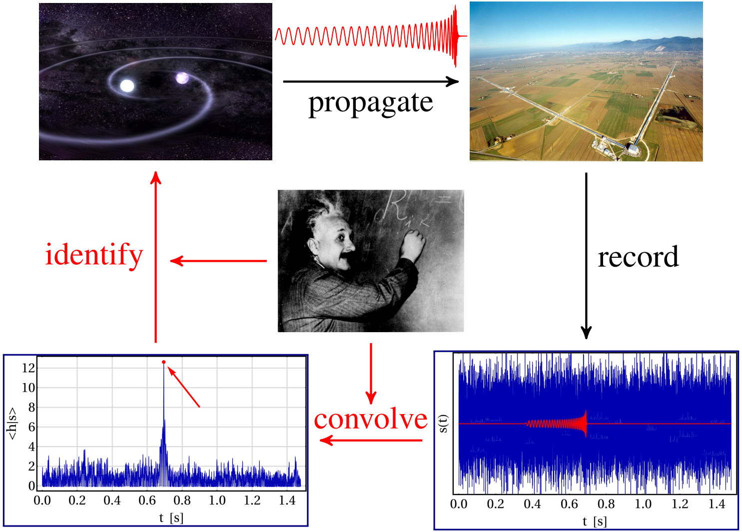


see also [Zackay+ 1902.10331, 1910.09528; Venumadhav+ 1904.07214; Nitz+ 1910.05331, 1811.01921]

The Analysis Challenge



Binary Merger Observations & Numerical Relativity



Binary Merger
Observations &
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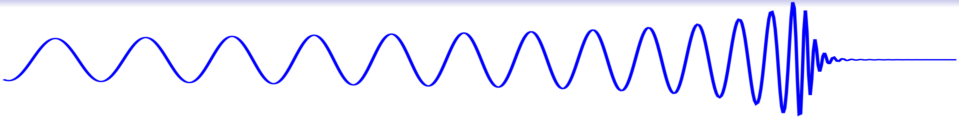

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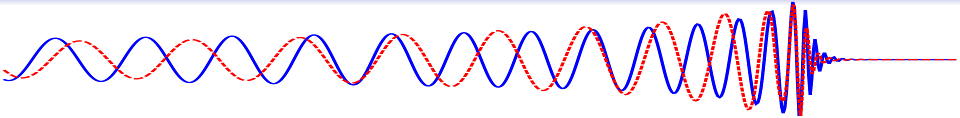
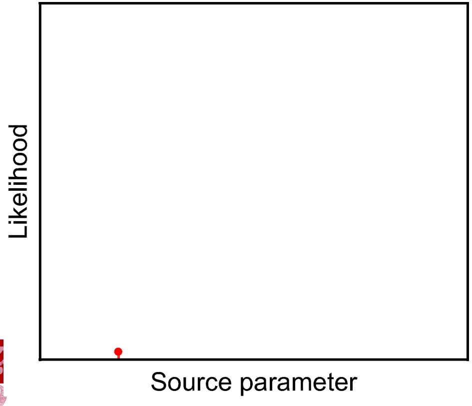
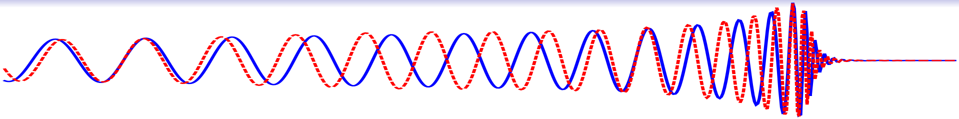
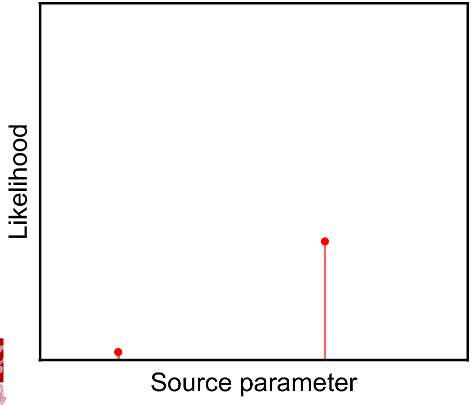




- $\langle h|s\rangle = 4\,\mathrm{Re}\int \frac{\tilde{h}(f)\,\tilde{s}^*(f)}{S_n(f)}\,df$
- ϑ : Source parameters
- $\Lambda(s|\vartheta) \sim \exp(-\frac{1}{2}||s-h(\vartheta)||^2)$
- **Posterior probability**$(\vartheta|s)$ $\sim \Lambda(s|\vartheta)\times \mathit{prior}(\vartheta)$

Binary Merger Observations & Numerical Relativity





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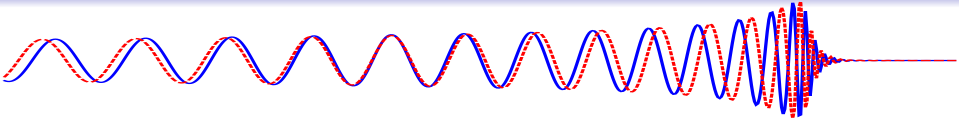

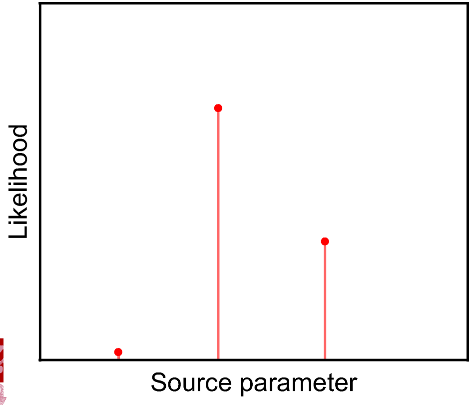

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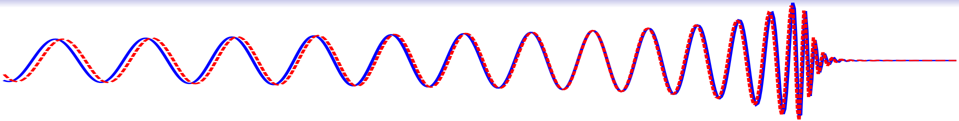

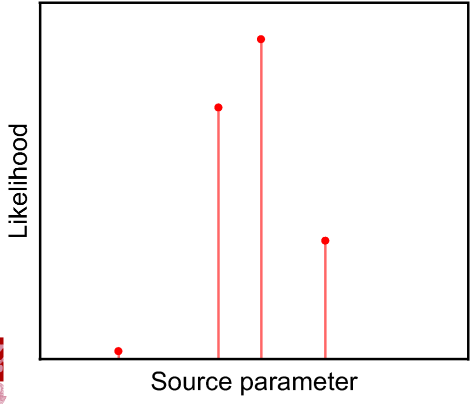

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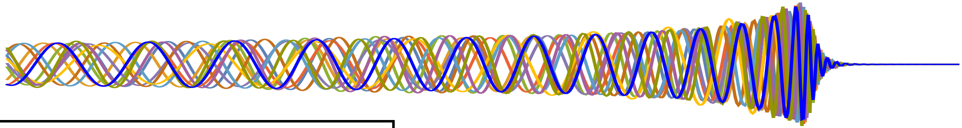
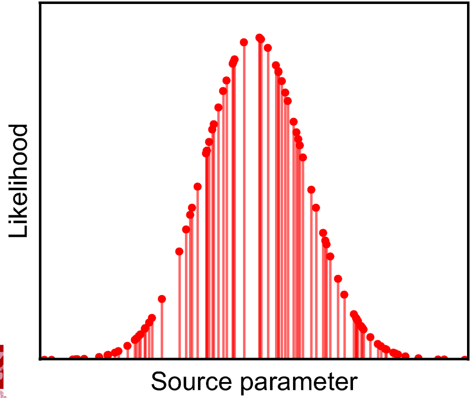
Binary Merger Observations & Numerical Relativity





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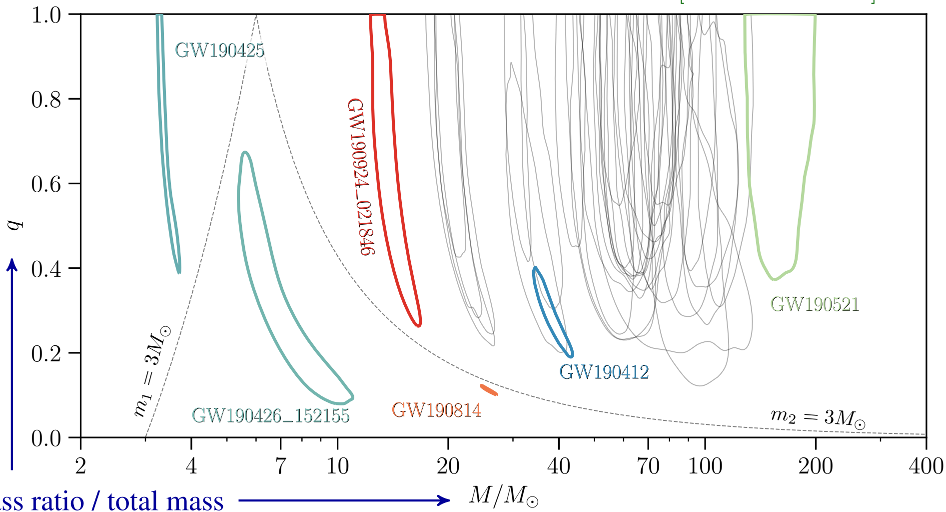
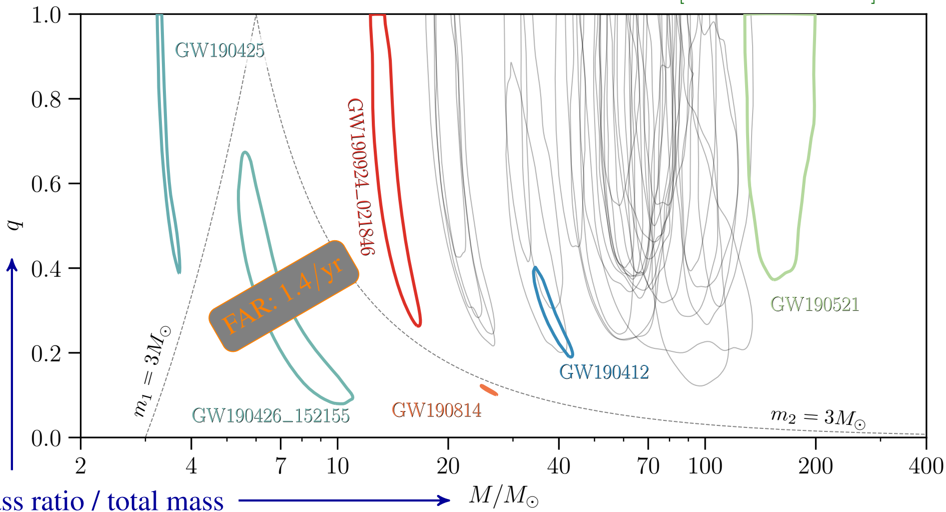
[GWTC-2 2010.14527]



mass ratio / total mass

[GWTC-2 2010.14527]



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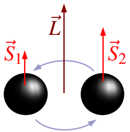
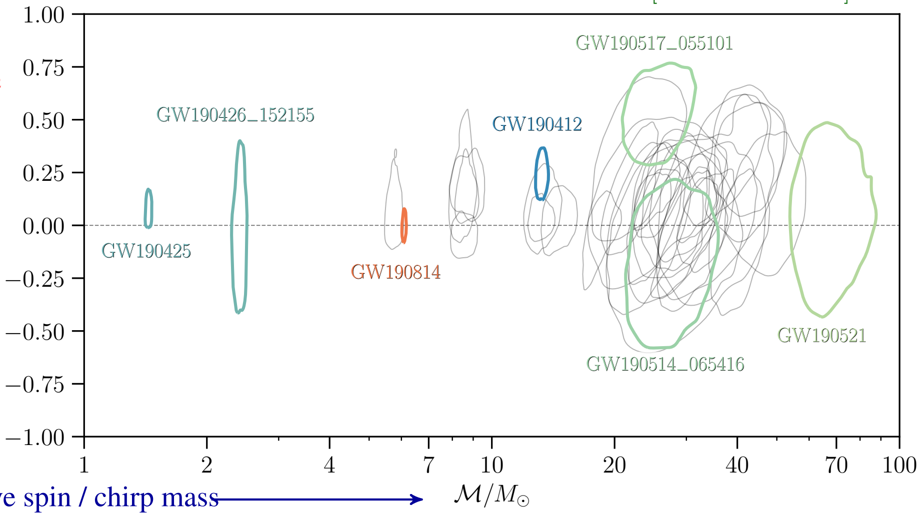
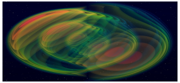
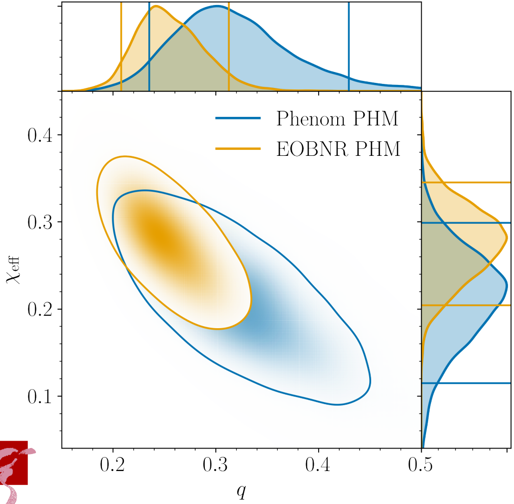




effective spin / chirp mass

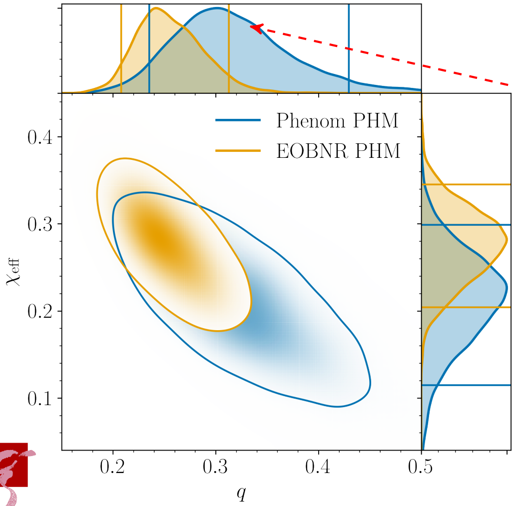
GW190412



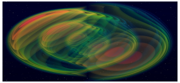


[LVC 2004.08342]

Binary Merger Observations & Numerical Relativity



GW190412



mass ratio $q \sim 0.3$

[LVC 2004.08342]

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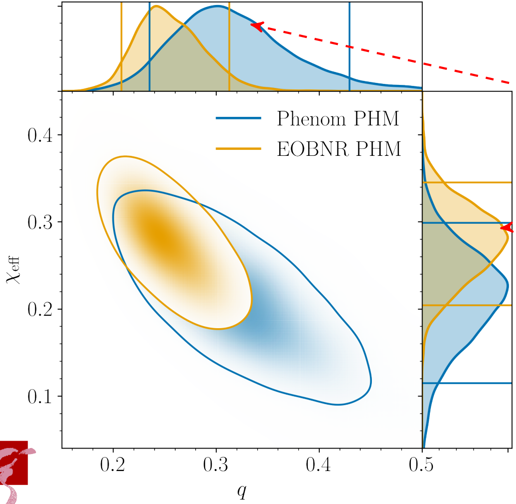

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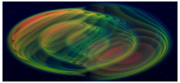

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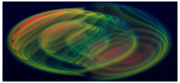
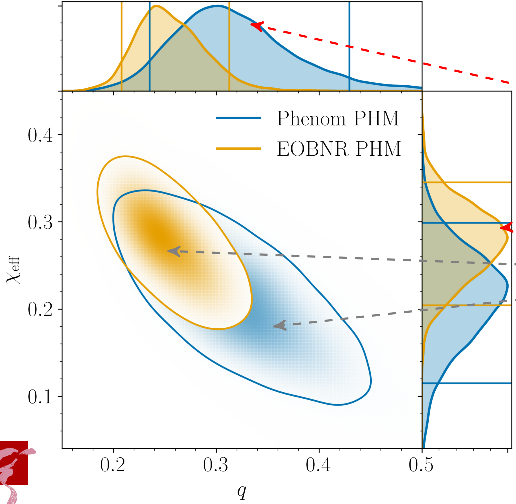
significant spin

[LVC 2004.08342]

Binary Merger Observations & Numerical Relativity

GW190412





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non-negligible systematics

[LVC 2004.08342]

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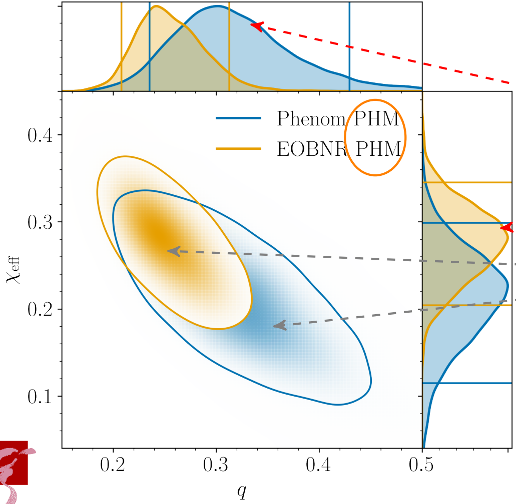

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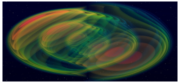


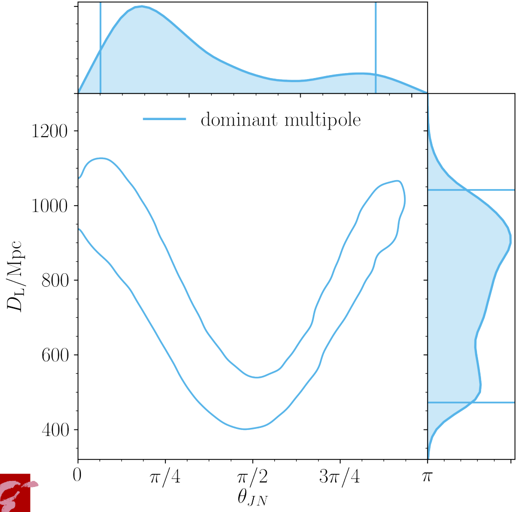
mass ratio $q \sim 0.3$

significant spin

non-negligible systematics

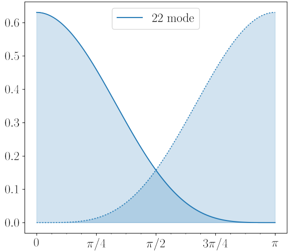
models including precession and higher multipoles

[LVC 2004.08342]

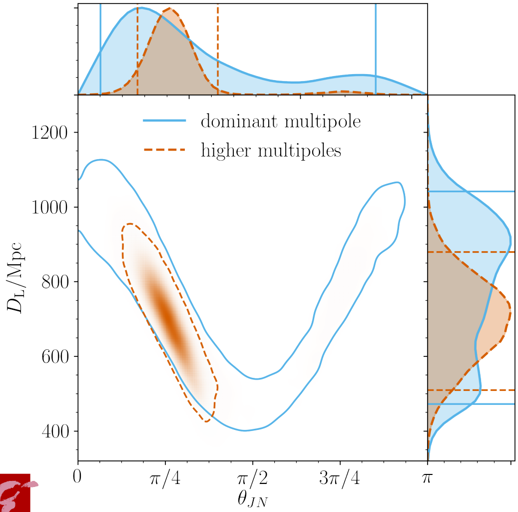


- Inclined systems are intrinsically quieter

$\rightarrow$ degenerate with distance



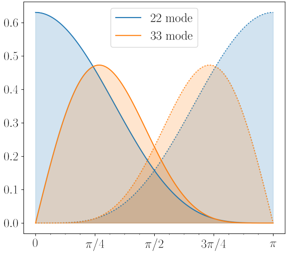
Distance and Inclination

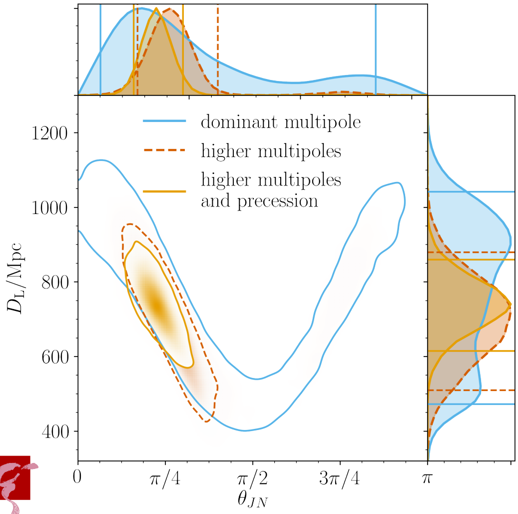


- Inclined systems are intrinsically quieter

→ degenerate with distance

- $h_+ - ih_\times = \sum_{\ell,m} h_{\ell m}(t, \vartheta)\ {}_{-2}Y_{\ell m}(\theta, \phi)$





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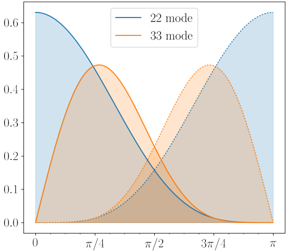
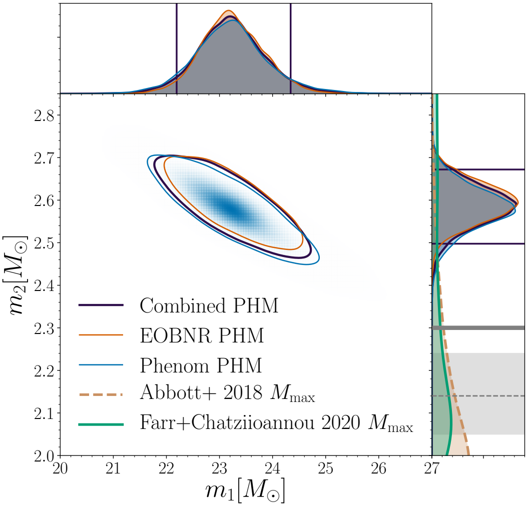


✓ Strong evidence for higher multipoles

? Strong precession disfavoured

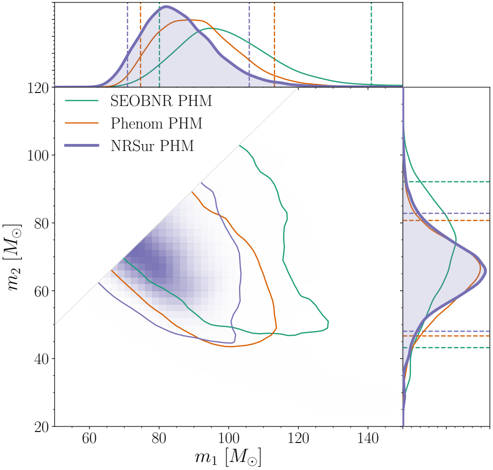
- Loud, unambiguous detection with SNR$\approx$ 25
- Most asymmetric masses observed so far, $q = 0.112^{+0.008}_{-0.009}$
- Object 1 clearly a black hole, but nature of object 2 unclear ($m_2 = 2.59^{+0.08}_{-0.09} M_\odot$)
- Strongest evidence of higher multipoles ($\rho_{33} \gtrsim 6$, Bayes factor $\sim 10^9$)
- Strong spin constraint $\chi_1 < 0.07$
- Challenging for standard formation channels

GW190814 [LVC 2006.12611]



GW190521 [LVC 2009.01075, 2009.01190]

- Short (0.1 s), low frequency signal of SNR$\approx$ 15, highest significance [FAR$= 1/4900\,$yr)] from generic transient search
- BBH: Masses in pair instability mass gap
- Hints of precession
- Candidate counterpart [Graham+ 2006.14122], association inconclusive [Ashton+ 2009.12346]
- Many suggested formation mechanisms: hierarchical mergers in dense environment (globular clusters, AGN disks), stellar merger, more exotic scenarios, high-mass ratio merger



GW190521 [Nitz+ 2010.12558]

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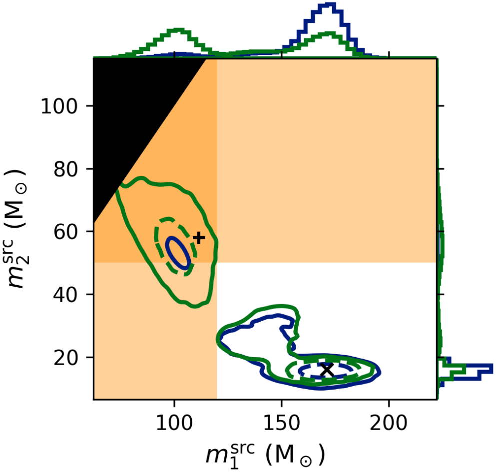
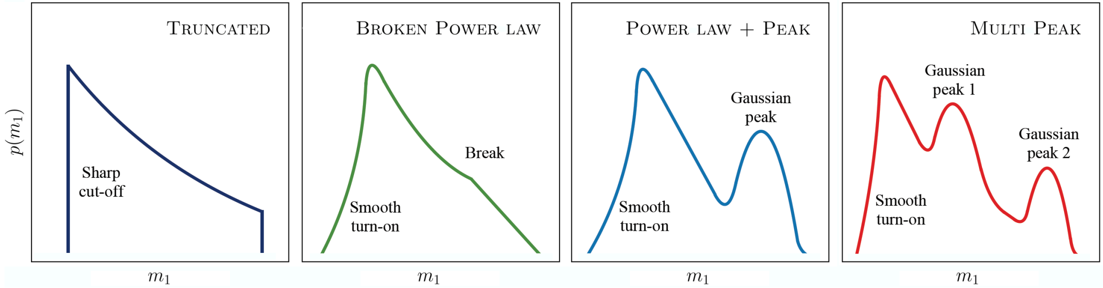
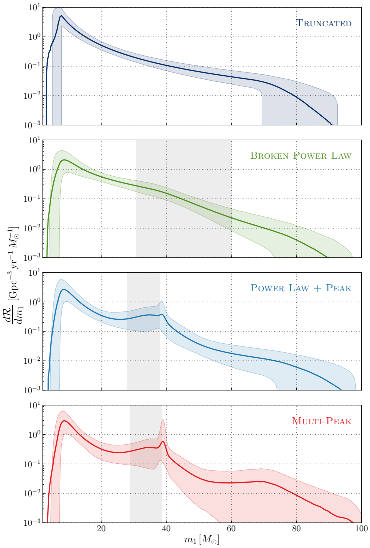


Black hole population [LVC 2010.14533]

1. Assume parametric model for population of black hole masses, mass ratio and spins
2. For each model, calculate likelihood of observing GWTC-2
3. Bayes' theorem: obtain posterior probabilities for population hyperparameters



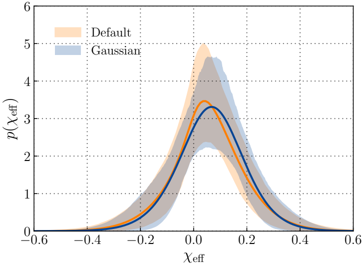


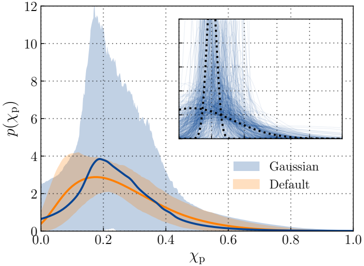
Masses

- Truncated power law insufficient
- Boundaries dominated by GW190814, GW190521
- Extra feature around $m_1 \lesssim 40 M_\odot$

Spins

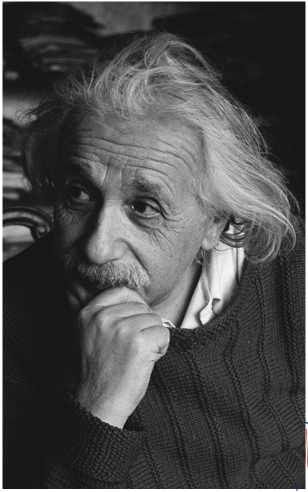
- Some (small) fraction of spins misaligned
- Completely aligned spin population disfavoured
- $\approx 30\%$ with $\chi_{\rm eff} < 0$





GR is the correct theory, or is it not?

Conclusively proving GR as the correct theory is impossible, only ruling it (GR or alternatives) out.

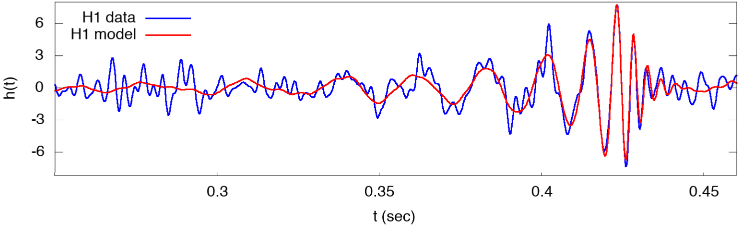


Test categories

1. Is what we observe consistent with GR?
   Is there something we cannot explain?
2. Can we measure generic deviations from GR?
3. Can we observe features of specific alternatives to GR?

Anything unusual in the data?

[LIGO-Virgo 1908.11170]



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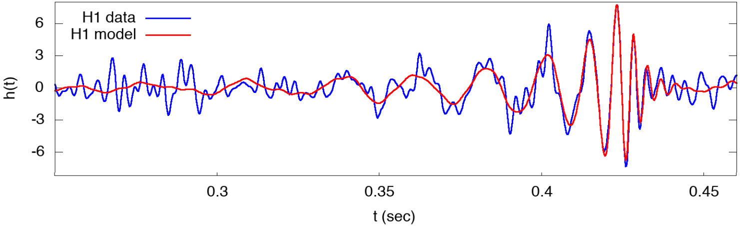
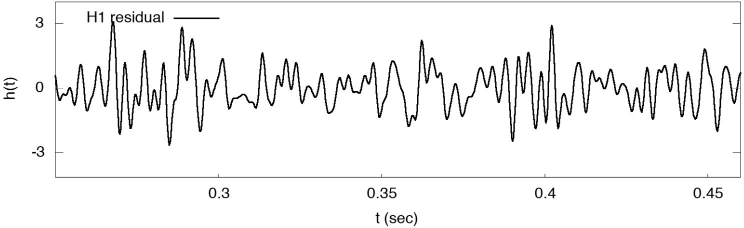
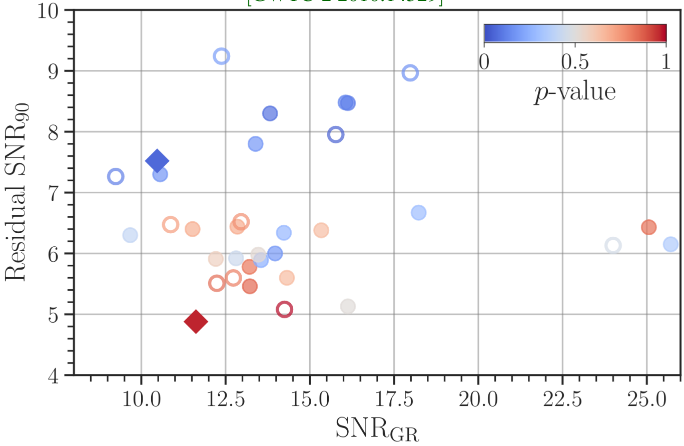




Residuals

[GWTC-2 2010.14529]



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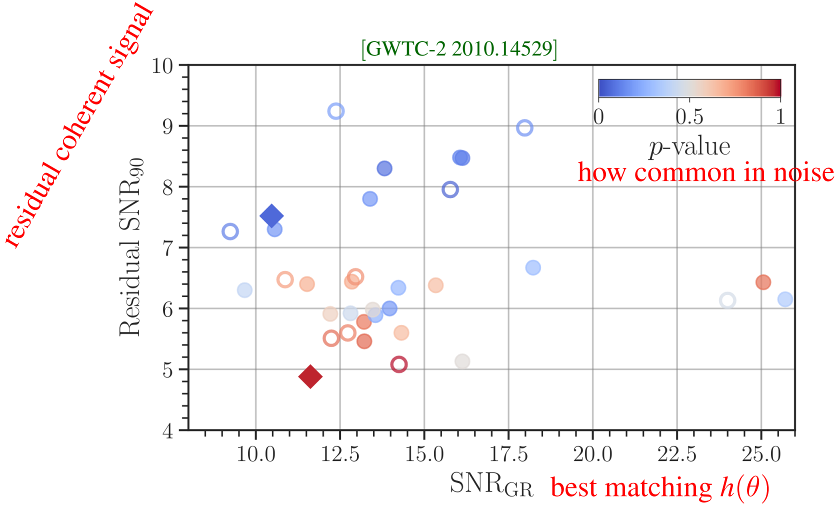
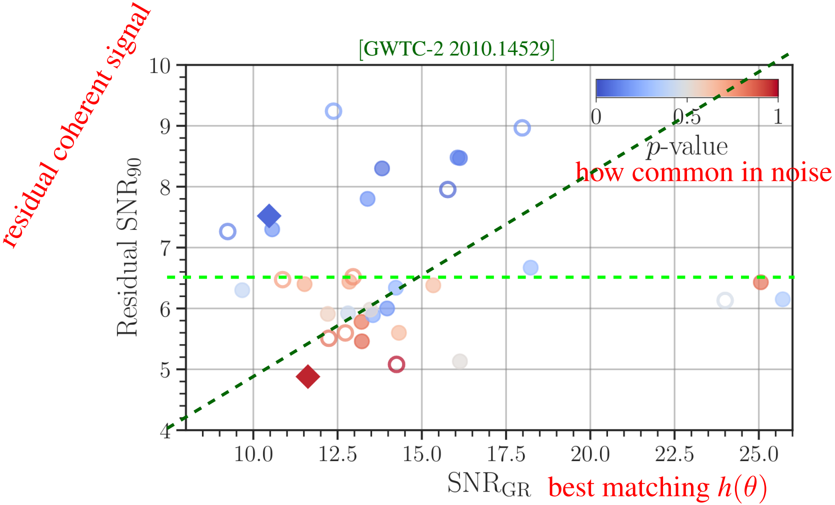

residual coherent signal
[GWTC-2 2010.14529]
Residual SNR_{90}
$\mathrm{SNR}_{\mathrm{GR}}$
best matching $h(\theta)$
p-value
how common in noise
0
0.5
1
10
9
8
7
6
5
4
10.0
12.5
15.0
17.5
20.0
22.5
25.0



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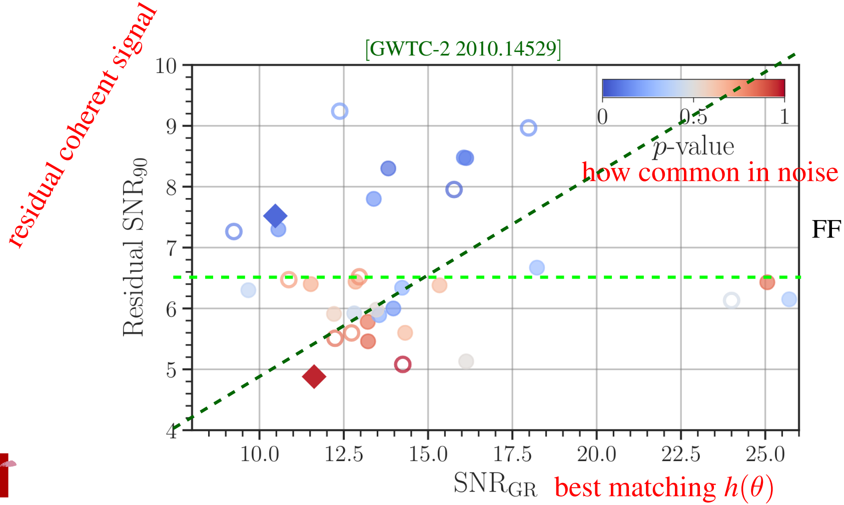


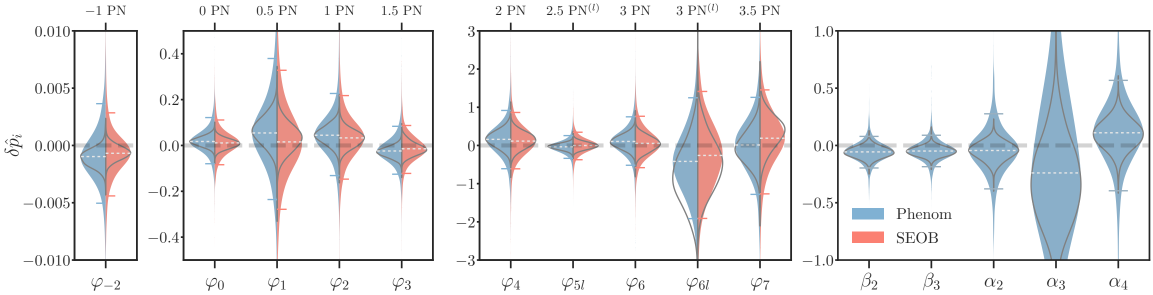
$$\mathrm{FF} = \frac{\mathrm{SNR}_{\rm GR}}{\sqrt{\mathrm{SNR}_{\rm GR}^2 + \mathrm{SNR}_{90}^2}}$$

$$\approx 0.8 \ldots 0.9 \quad (\text{LIGO})$$

$$\approx 0.9999 \quad (\text{ET})$$

Post-Newtonian Phase

$$\phi(v) = \sum_{k=0} \varphi_k(\eta, \vec{S}_1, \vec{S}_2) \cdot \left(\frac{v}{c}\right)^{k-5}$$



[GWTC-2 2010.14529]

Binary Merger Observations & Numerical Relativity

- BH mimickers react differently to their own spin and the companion's tidal field

$\Rightarrow$ spin-induced quadrupole moment coefficient entering at 2PN order can test BH nature

[Krishnendu+ 1701.06318, 1811.00317]

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Observations &
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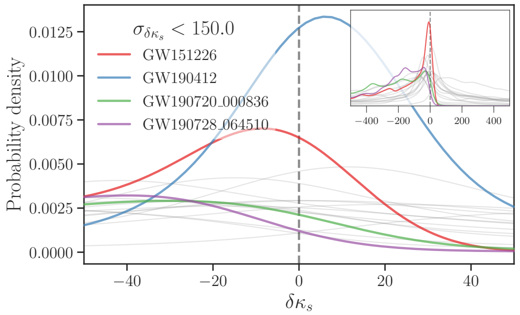
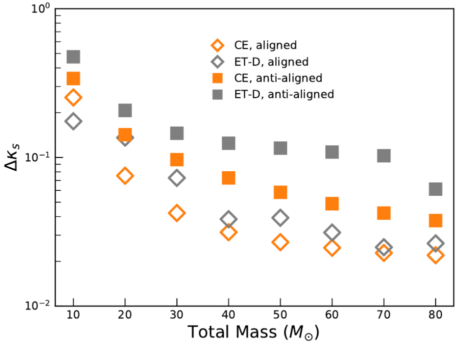
- BH mimickers react differently to their own spin and the companion's tidal field

⇒ spin-induced quadrupole moment coefficient entering at 2PN order can test BH nature
[Krishnendu+ 1701.06318, 1811.00317]

[GWTC-2 2010.14529]



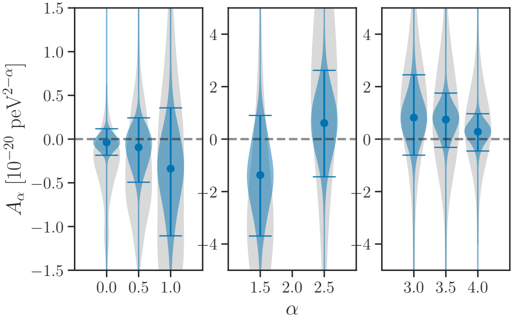
Measurement accuracy



- Modified theories may violate Lorentz invariance, leading to a modified dispersion relation

$$E^2 = p^2\, c^2 + A_\alpha\, p^\alpha\, c^\alpha$$

- Modified dispersion leads to different gravitational-wave phasing [Mirshekari+ 1110.2720]

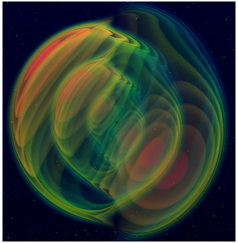


$$m_g\, c^2 = \sqrt{A_0} < 1.8 \times 10^{-23}\,\mathrm{eV}$$

[GWTC-2 2010.14529]

Binary Merger Observations & Numerical Relativity

- Every Observing Run delivered new science
- Digging deeper into neutron star and black hole populations
- Binaries show (surprising?) diversity – multiple formation channels?
- Important interactions with EM observers, stellar modeling, fundamental physics communities etc.
- Groups outside the LIGO-Virgo collaborations analyze data and report new events
- Open public alerts, strain data and posterior samples released
- Stay tuned for more news from O3 and the gravitational-wave universe



Binary Merger Observations & Numerical Relativity