(MIS)INTERPRETING GRAVITATIONAL WAVES
from binary compact objects

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GRAVITATIONAL WAVES FROM BINARY BLACK HOLES

how do we interpret them?

The signal describes its source!
...if you know how to read it...
Gravitational waves
how do we interpret them?

data = signal + noise

With added uncertainties due to: noise, signal model, parameter correlations...

Ashton et al. 2018, IRS et al. 2021
Binary biographies

Pathways to merger

90 events so far, but how do they form?

Isolated

Dynamical

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Binary biographies

Decoding binary formation

- Aligned
- Precessing, may be more rapid
- Isolated
- Circular
- Mass
- Eccentricity
- Dynamical

Mass can be eccentric.

Spin can have upper limit.

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Both eccentricity and spin-induced precession are signatures of dynamical formation...

...but we expect all dynamical BBH to have misaligned spins (if they are spinning), and only about 5% to be eccentric, so the fraction of the population forming dynamically is uncertain if the two effects are confused.

most events are vanilla, i.e., circular and non-spinning

high mass $\rightarrow$ short signal

See, e.g., IRS, Lasky, Thrane & Calderon Bustillo 2020; Calderon Bustillo et al 2020, 2021
Can compare hypotheses, but not analytically simultaneously.

GW190521

Livingston

"better described" : ratio of Bayesian evidences = Bayes factor
Log B = 1.8 for eccentricity vs precession
Log B = 8 required for confident statement

Possible eccentricity

While the original LIGO/Virgo data analysis assumed a quasi-circular inspiral waveform model, subsequent publications claimed that this source could have been significantly eccentric. Romero-Shaw et al. showed that the data is better described by a non-precessing eccentric waveform with $e_{10\text{Hz}} \geq 0.1$ than a spin-precessing quasi-circular model.\cite{16}
(Mis)interpreting gravitational waves

eccentricity or precession? - cycles

Can distinguish eccentric systems from precessing systems if signal is long enough, i.e., system is low-mass.

Need longer signals for lower eccentricity.

If highly eccentric, can distinguish eccentric from precessing system with only a few cycles in-band.

How much eccentric hypothesis preferred over circular, precessing hypothesis.

Grey area shows log $B < 8$.

How many orbital cycles are in the observed signal (higher mass $\Rightarrow$ shorter).

IRS, Gerosa & Loutrel 2023.
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eccentric or circular? - biases

Inject circular, recover with different circular models:

Inject eccentric, recover with different circular models:

Dangers of ignoring eccentricity illustrated with low-mass injections

Divyajyoti et al. incl. IRS in press. 2023
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other exotic physics? - biases

Injected:
Binary boson star merger
Mass 1: 40 Msol
Mass 2: 40 Msol
Spin 1: 0.0
Spin 2: 0.0

Recovered:
Binary black hole merger
Mass 1: 56 Msol
Mass 2: 40 Msol
Spin 1: 0.9 (close to max.)
Spin 2: 0.0

Evsatfyeva et al. incl. IRS
in prep. 2024
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other exotic physics? – biases

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Mergers of exotic objects successfully masquerade as BBH mergers...

Recovered:
Binary black hole merger
Mass 1: 56 Msol
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...and PE confidently infers incorrect properties (unequal mass, high spin)

Evsatfeyeva et al. incl. IRS in prep. 2024
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machine learning to the rescue?

Look out for Ravichandran et al. incl. IRS 2024

Ravichandran et al. 2023
INTERPRETING GRAVITATIONAL WAVES

outlook

• Gravitational waves must be modelled correctly to be understood.
• Incomplete or incorrect models can lead to confident inferences of incorrect physics...
• ...which can lead to inferences of incorrect merger object identities...
• ...and inferences of incorrect formation channels!
• Machine learning can help us find the right path - Work In Progress.
• Students, postdocs, ECRs at KICC / DAMTP are working hard to deduce BBH origins!
$\theta_{JN} = \pi/4$

maximal spin precession

quasi-circular spin-precessing

aligned spins

eccentric aligned spins

non-spinning

anti-aligned spins