Addressing the challenge of overlapping signals in the 3G era

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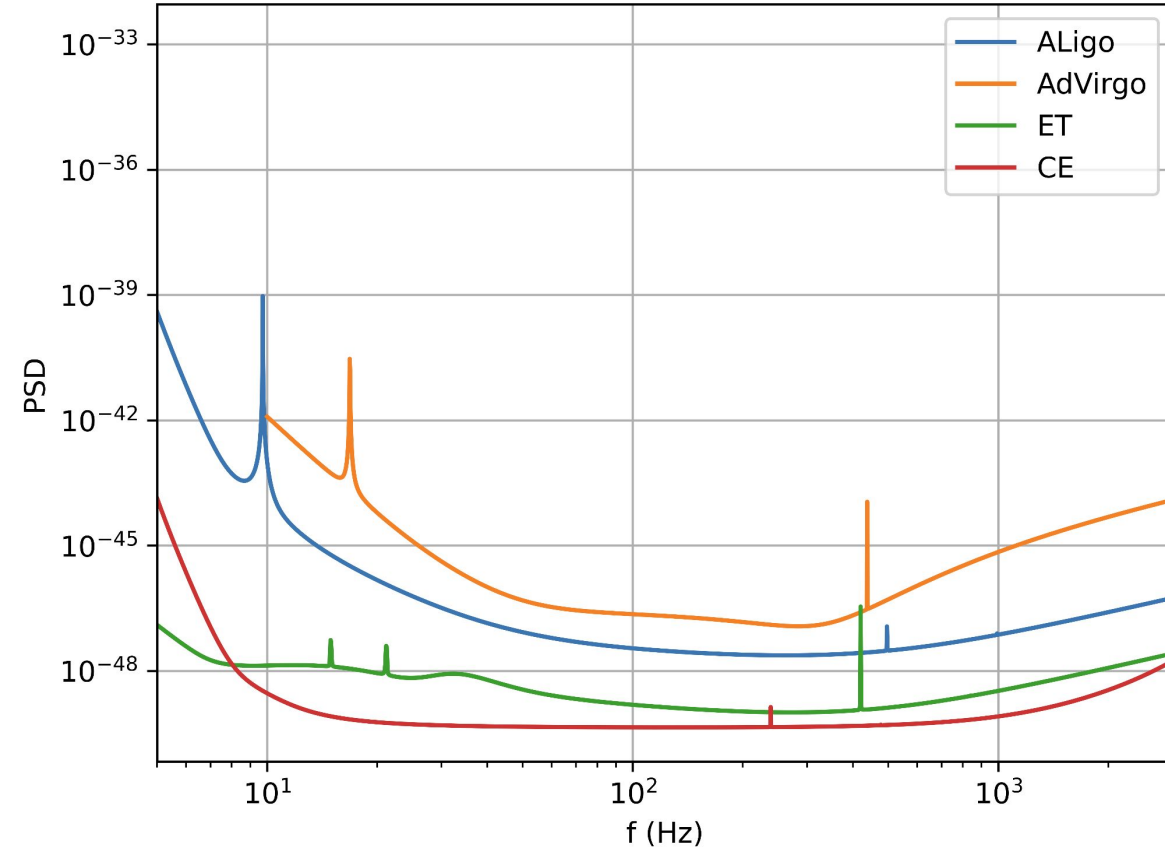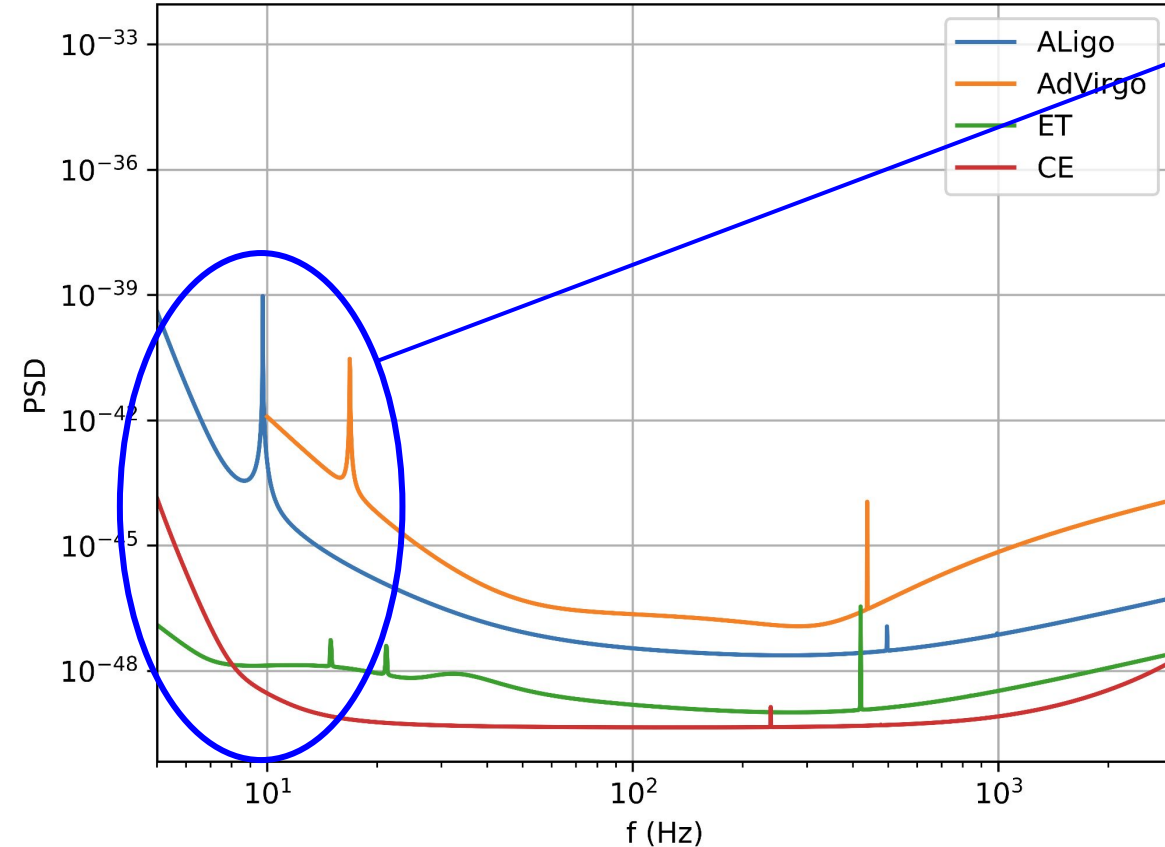
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Nikhef

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Why are overlaps likely?

Improved power-spectral densities in 3G detectors
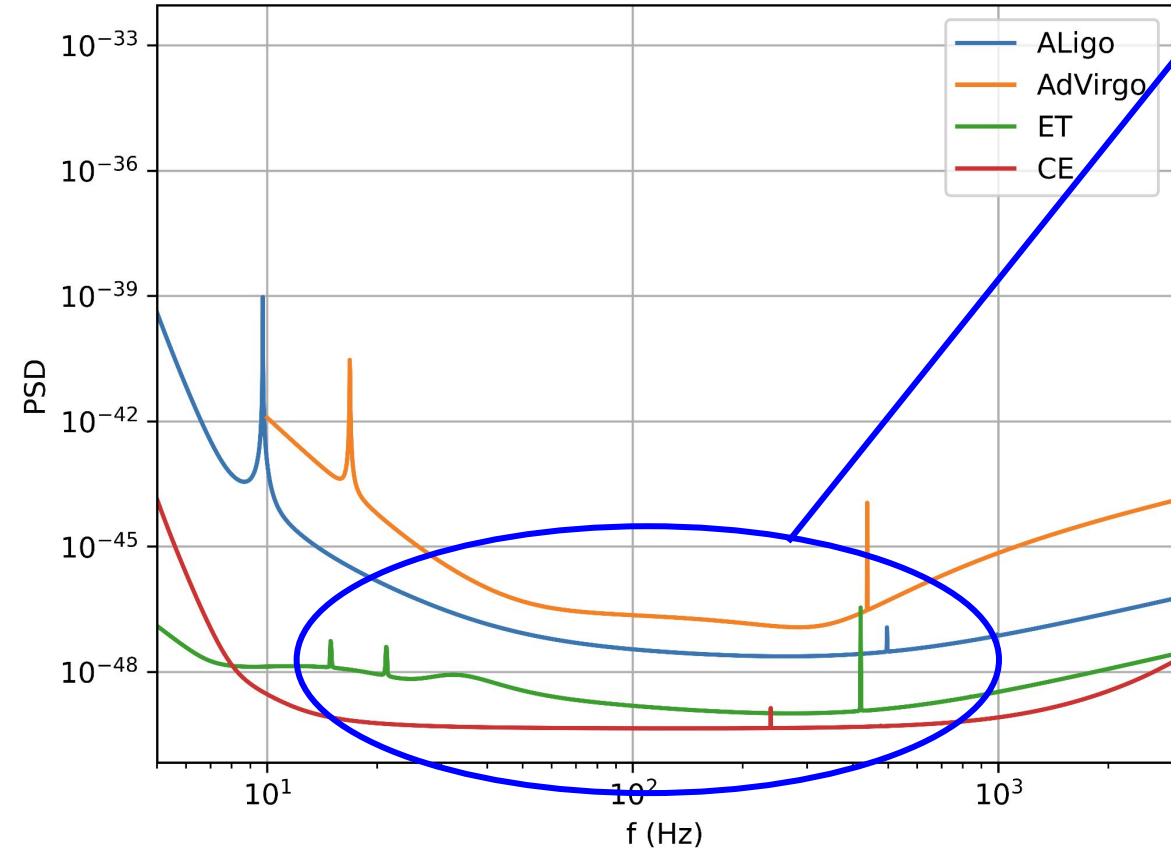
Why are overlaps likely?
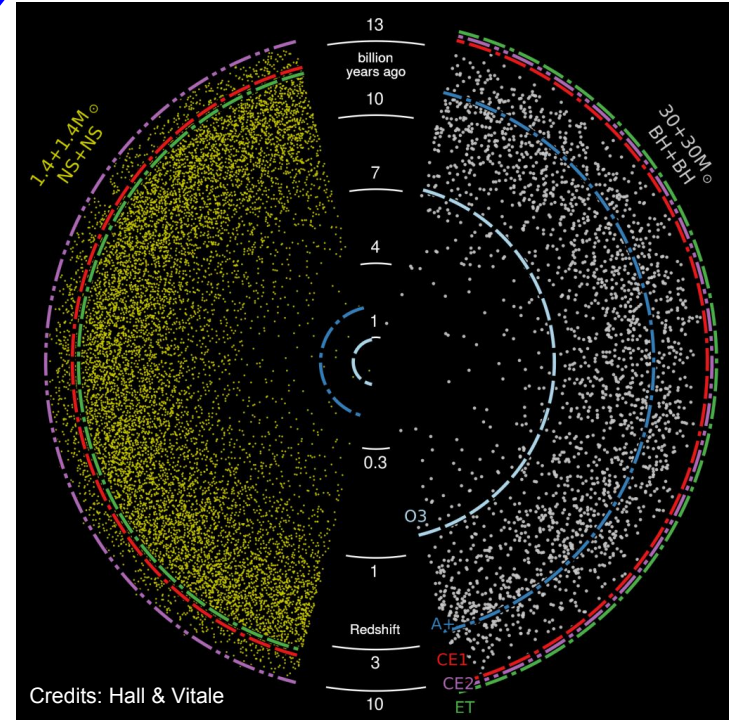
Improved power-spectral densities in 3G detectors

Enhanced low frequency sensitivity → Longer duration signals

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Why are overlaps likely?

Improved power-spectral densities in 3G detectors
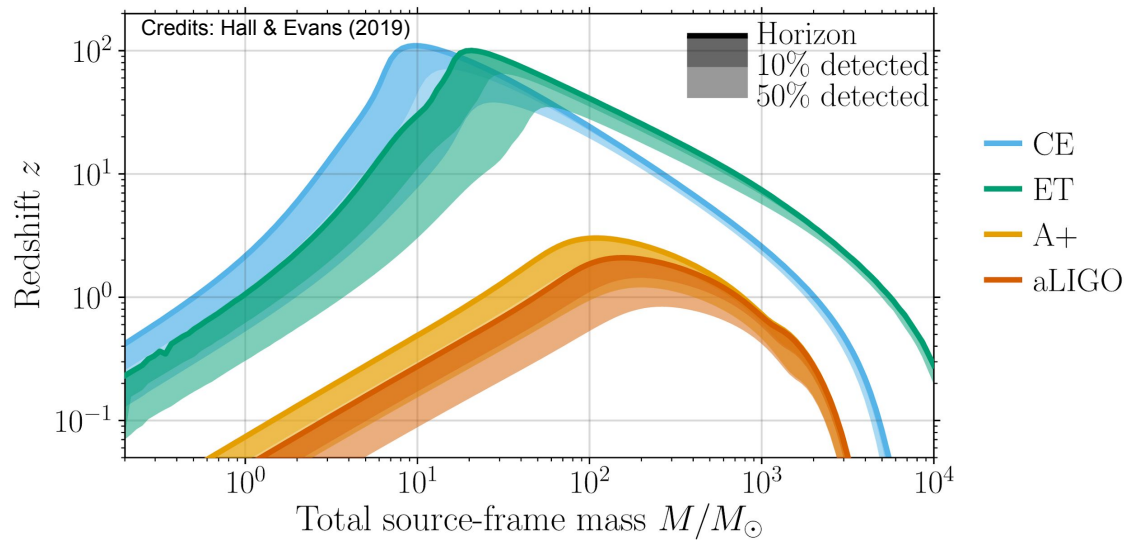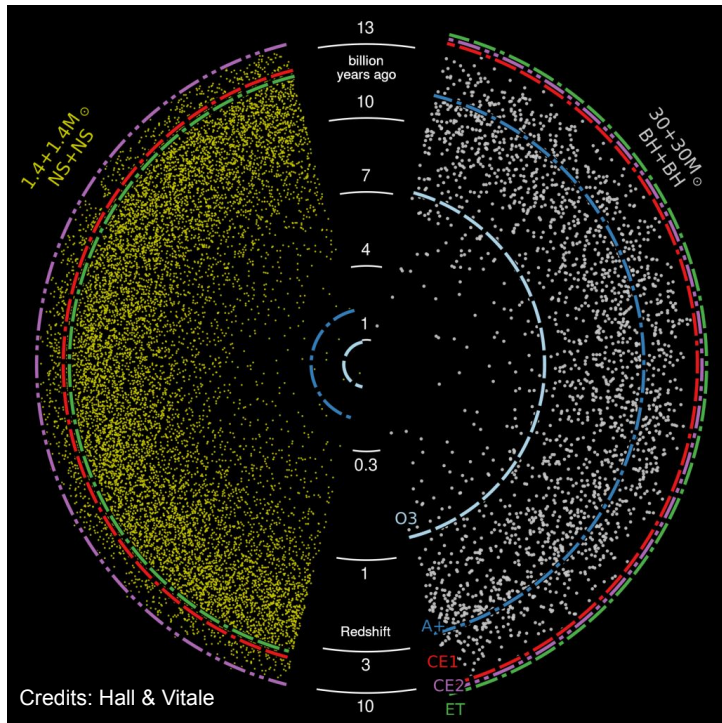
Enhanced overall sensitivity → Increased number of detections

Credits: Hall & Vitale

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Why are overlaps likely?

**Longer** duration signals + **More** detectable signals → Seems possible they start **overlapping**

Overlaps, really?

Several independent studies have looked at the probability to have overlapping signals:

- Regimbau & Hughes, 2009: Based on vanilla events, check the noise regime
- Samajdar et al, 2021: Simulate one year of data and look at the observed overlaps
- Pizzati et al, 2021: Assuming a Poisson process, look at the overlap rate

→ All agree: **overlaps will be quite common in the 3G detector era**

Fraction of BNS with a given number of overlaps
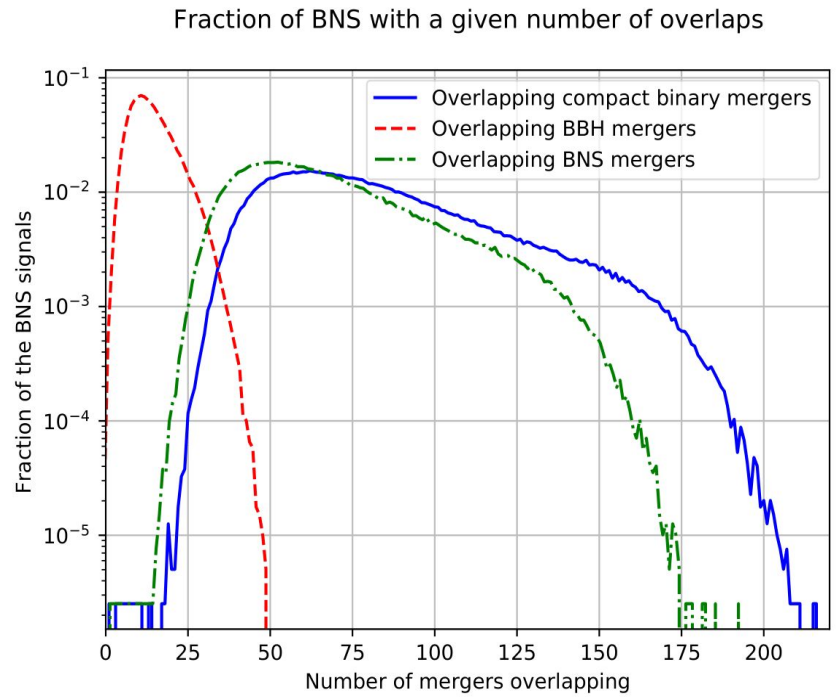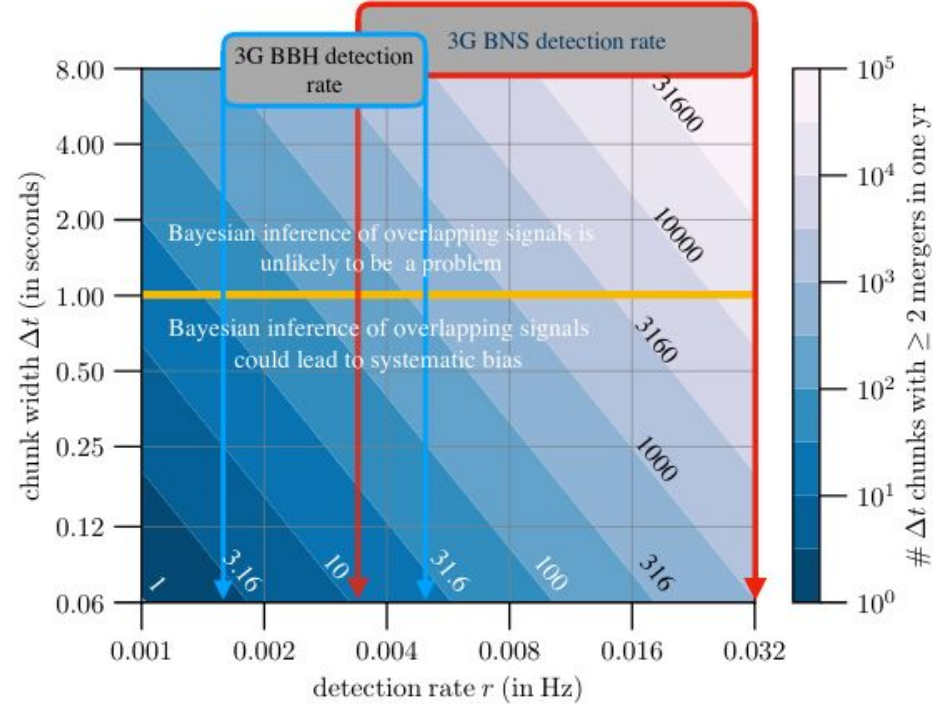
Should we be worried about overlaps?

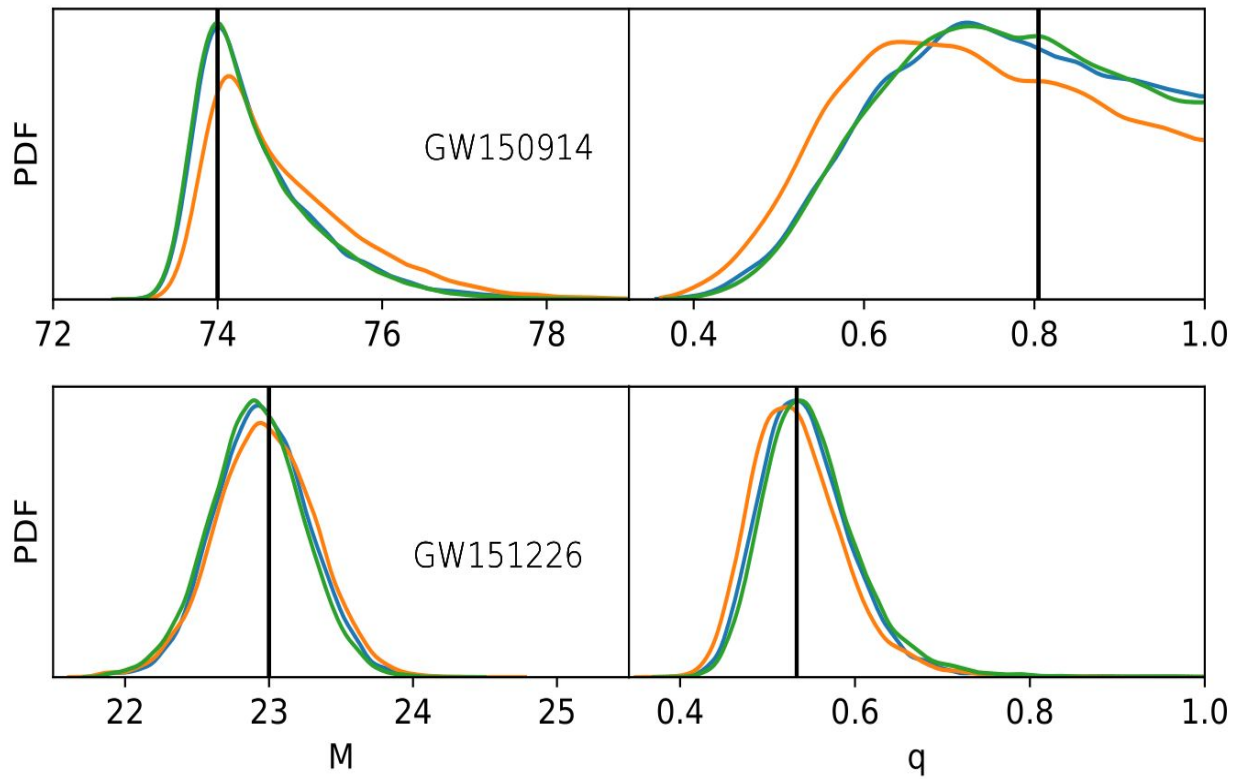It depends: in some cases, overlaps do not lead to major consequences, in others, results can be biased.

Here, we focus on the results from Samajdar et al, 2021, where we consider 3 scenarios
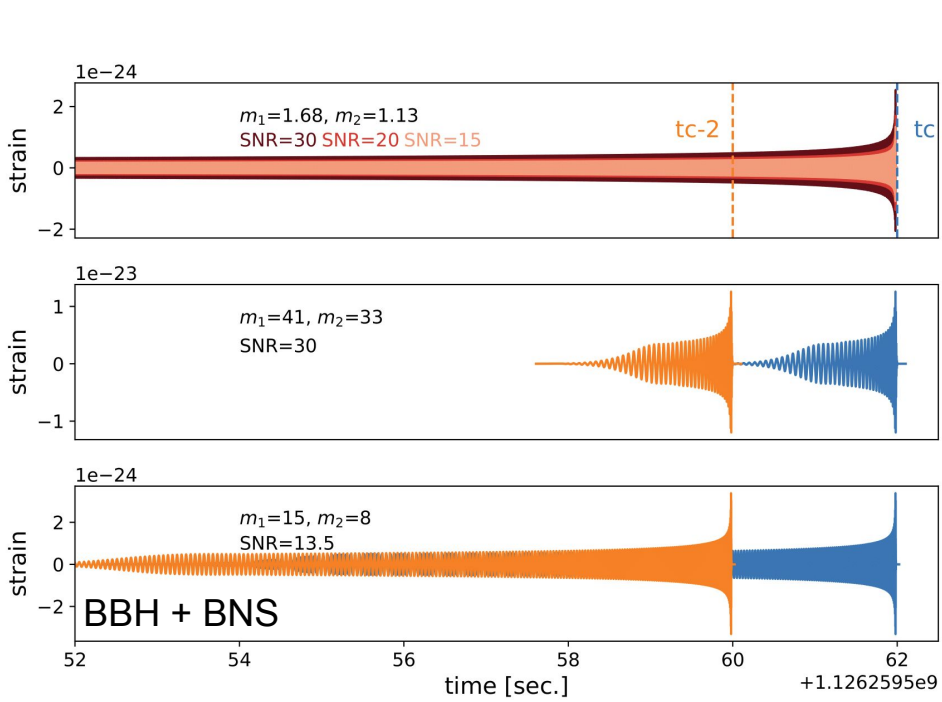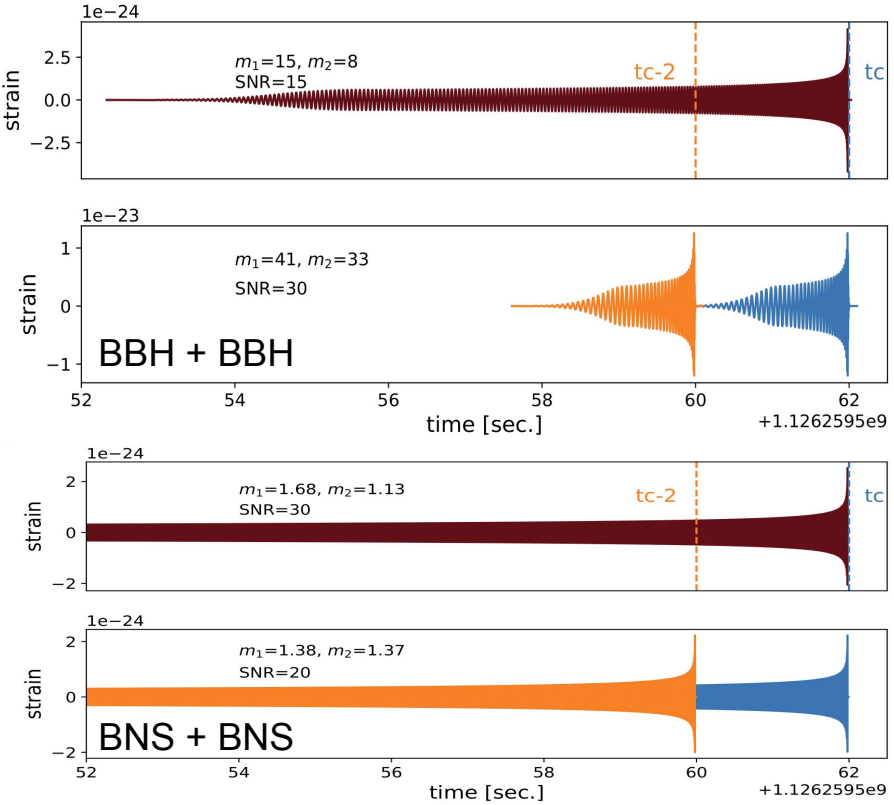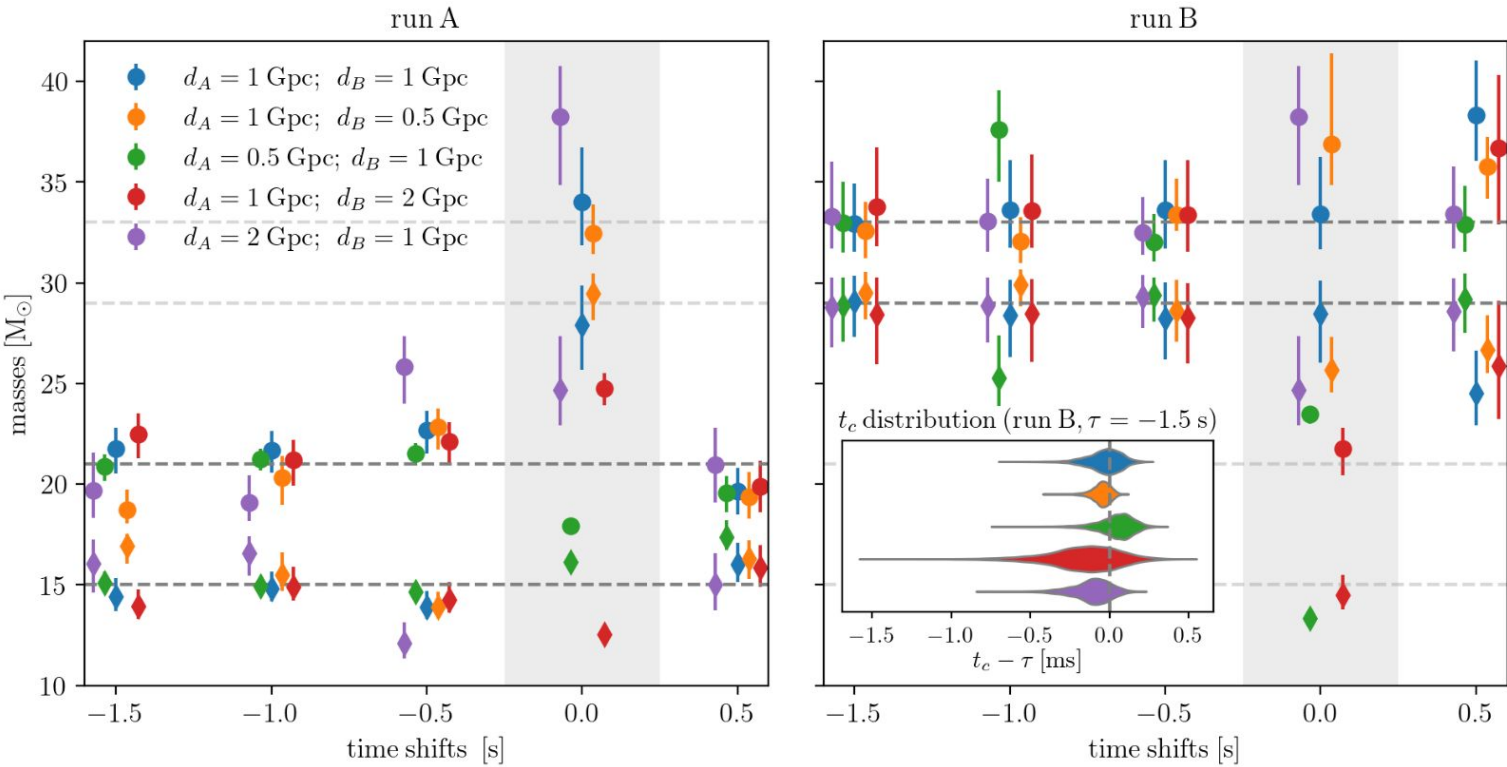
Overlapping BBHs:

SNR(GW50914-like) = 30
SNR(GW151226-like) = 15

tc   tc-2   BBH

No bias observed, regardless of the difference in time. Probably due to the very different characteristics and duration of the signals

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Overlapping BBHs, other scenarios:
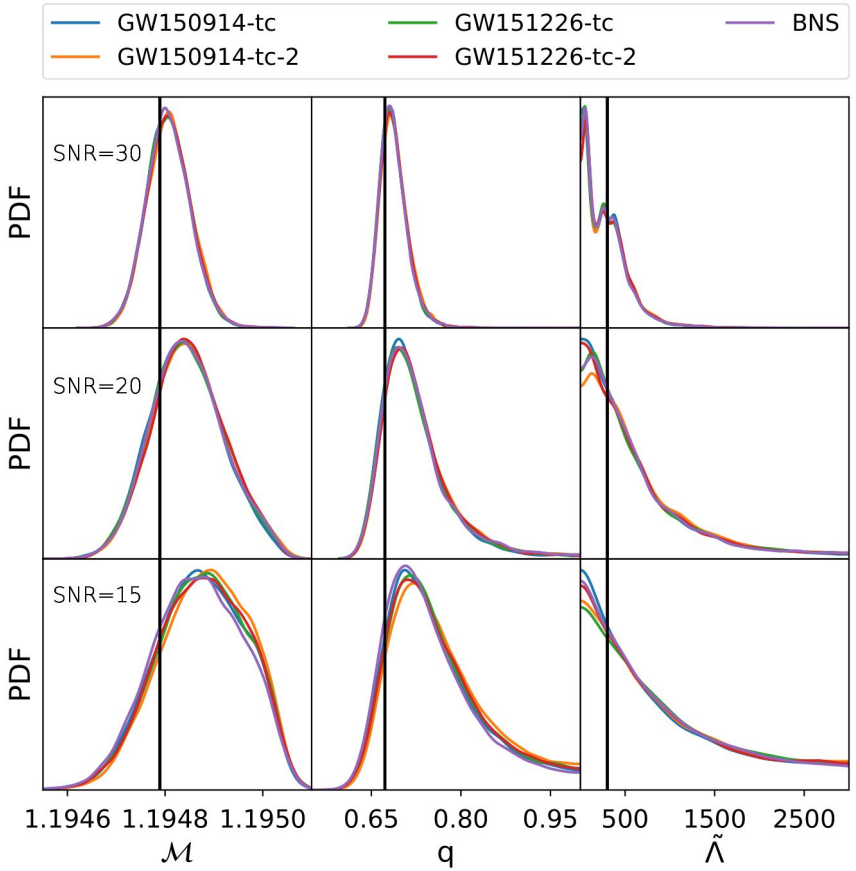
E.g Pizzati et al, 2021

When the signals characteristics are close, bias can happen when BBHs merger within 0.1s

→ The exact effect of the overlap **depends on the exact signals involved** (also confirmed by Relton et al, 2022)
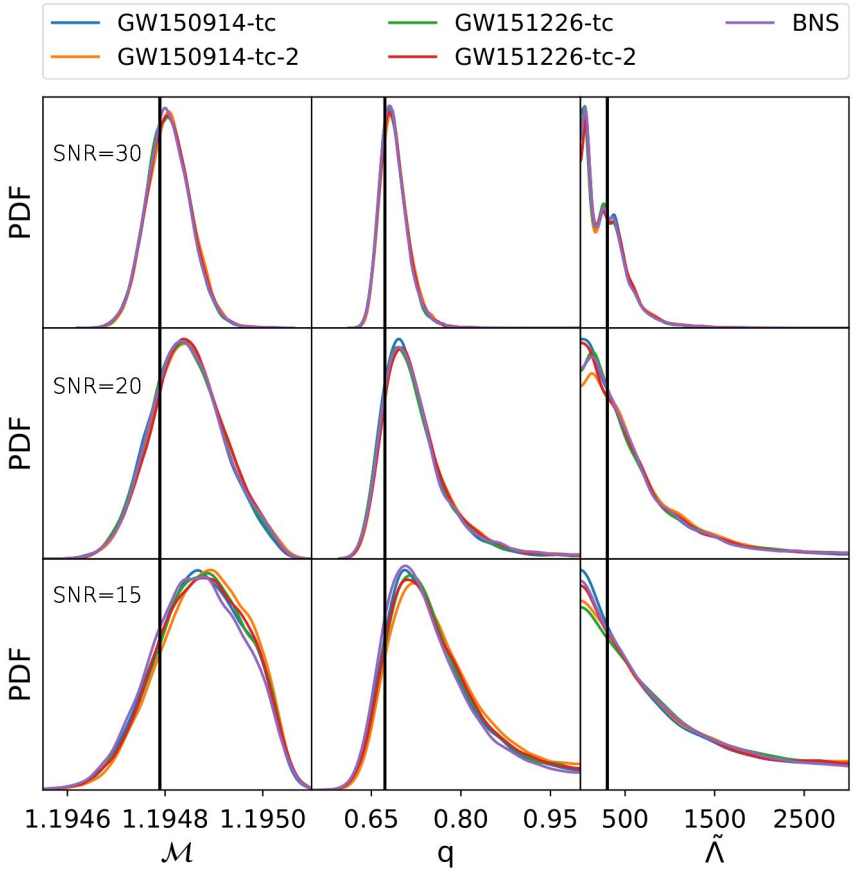
BBH overlapping with a BNS
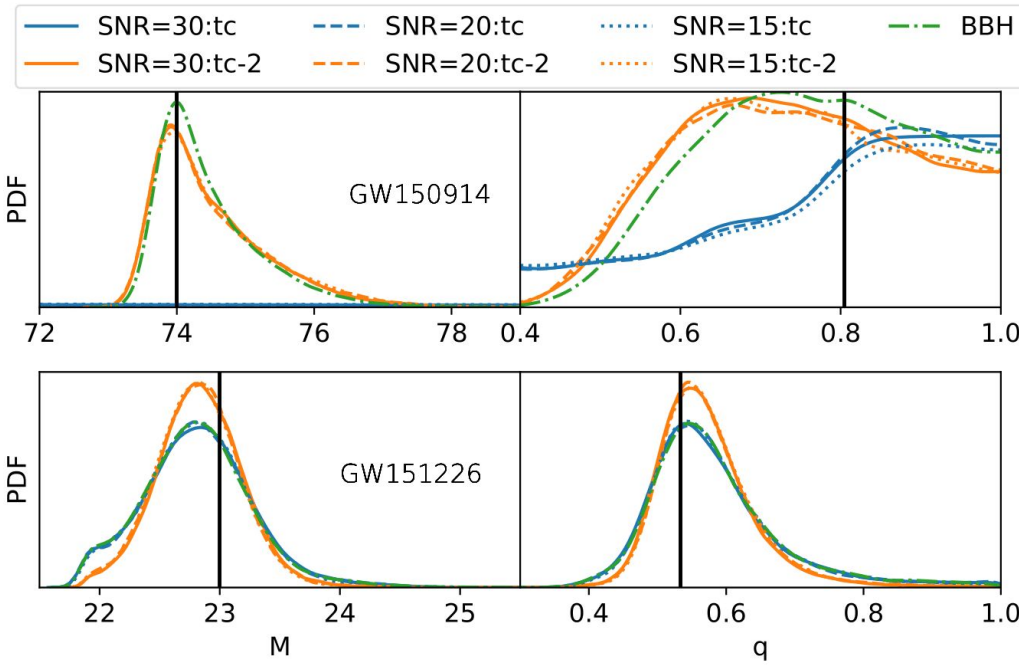
For the BNS recovery: **No bias** observed

BBH overlapping with a BNS

For the BNS recovery: No bias observed

For the BBH recovery:
- High-mass BBH **not recovered**
- Low-mass BBH **recovered with some variance**

Overlapping BNS signals
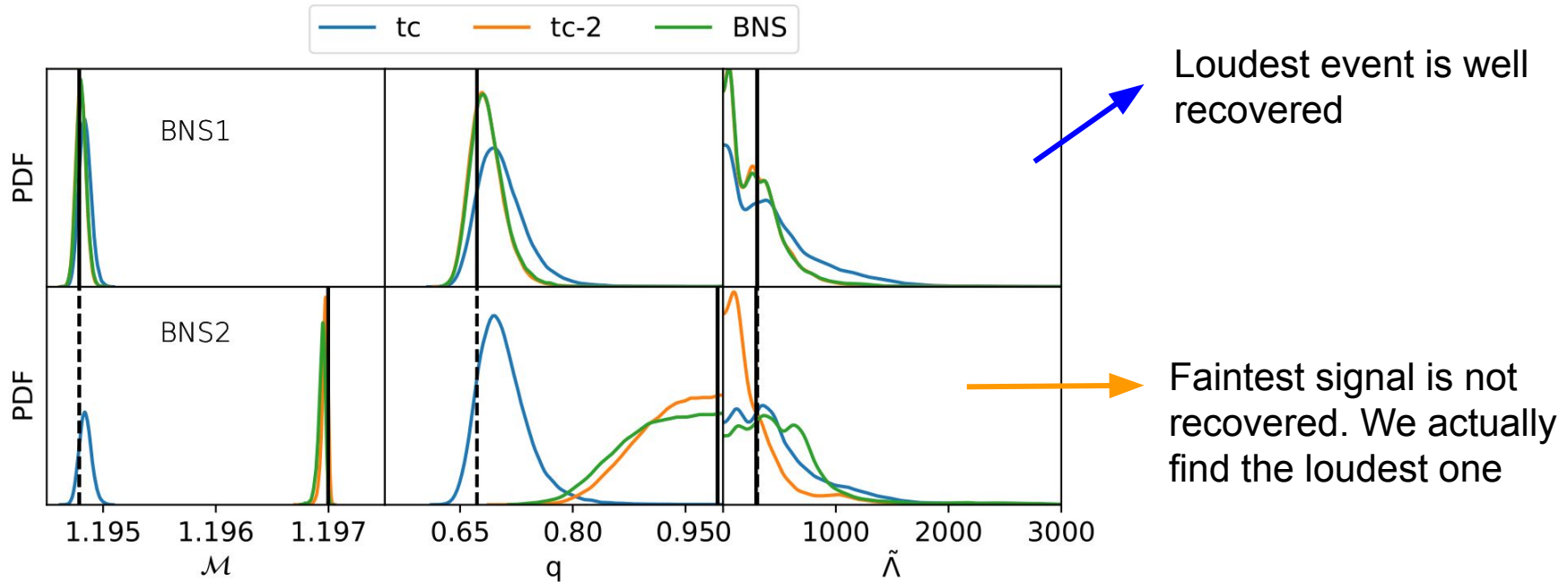
→ The Bias could be due to the closely related properties of the signals, generally not so much bias expected

In the end…

Different studies (e.g. Regimbau & Hughes, 2009; Samajdar et al, 2021; Pizzati et al, 2021; Himemoto et al, 2021; Relton et al, 2022; Antonelli et al, 2022) have been undertaken with different approaches, all conclude that **bias can occur in some cases, especially when events have close merger times.**

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Different studies (e.g. Regimbau & Hughes, 2009; Samajdar et al, 2021; Pizzati et al, 2021; Himemoto et al, 2021; Relton et al, 2022; Antonelli et al, 2022) have been undertaken with different approaches, all conclude that **bias can occur in some cases, especially when events have close merger times.**

Number of seconds in the year with at least 2 mergers occuring

Rate \ case	N_{sec} > 2 BBH	N_{sec} > 2 BNS	N_{sec} > 2 Events
Lowest	48	155	374
Median	127	2412	3663
Highest	303	15581	20149

Depending on the exact rate, it can go from a few on a year to many of them.

So what?

Overlapping signals will happen and we will need to deal with them:
- Direct consequences on science cases if not accounted for (ex: testing GR (Hu & Vietch, 2023))
- Indirect consequences on tests requiring subtracting foreground sources (ex: search for GWB (Sachdev et al, 2020))

So what?

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- Direct consequences on science cases if not accounted for (ex: testing GR (Hu & Vietch, 2023))
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$\rightarrow$ We need to introduce adapted data analysis methods able to deal with this scenarios.

Focus on the overlap of two signals for now, we tested (Janquart et al, 2022; Langendorff et al, 2022), focusing on BBH signals starting at 20Hz:
- **Hierarchical subtraction**: analyze one signal, subtract it, and then analyze the other

- **Joint parameter estimation**: fit the two signals jointly using an adapted Bayesian likelihood

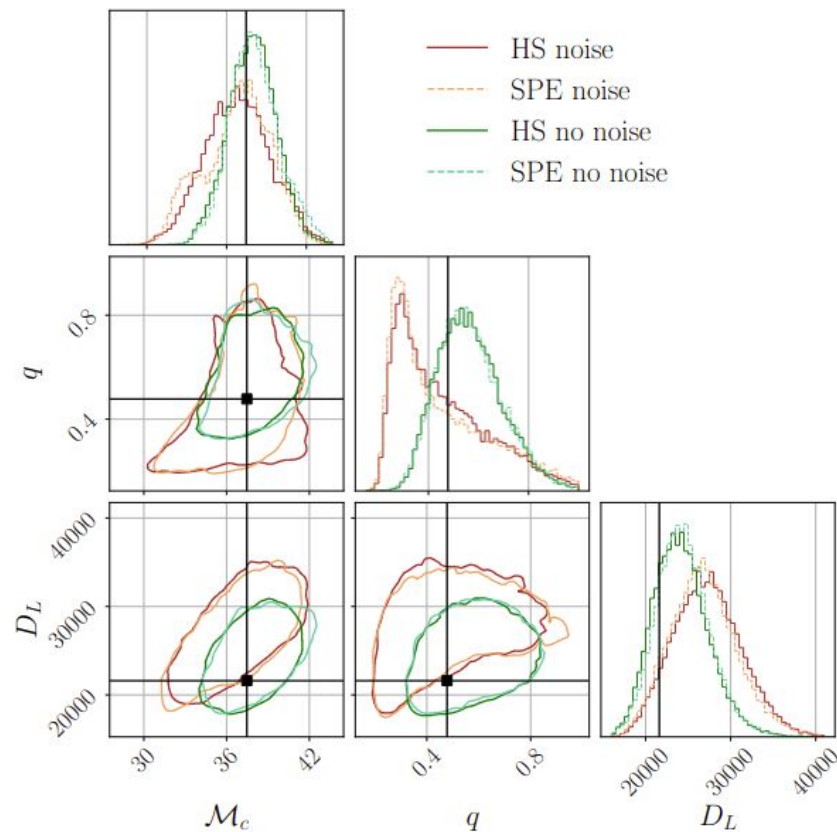- **Machine learning**: normalizing flows approach providing posteriors for the two events

Hierarchical subtraction
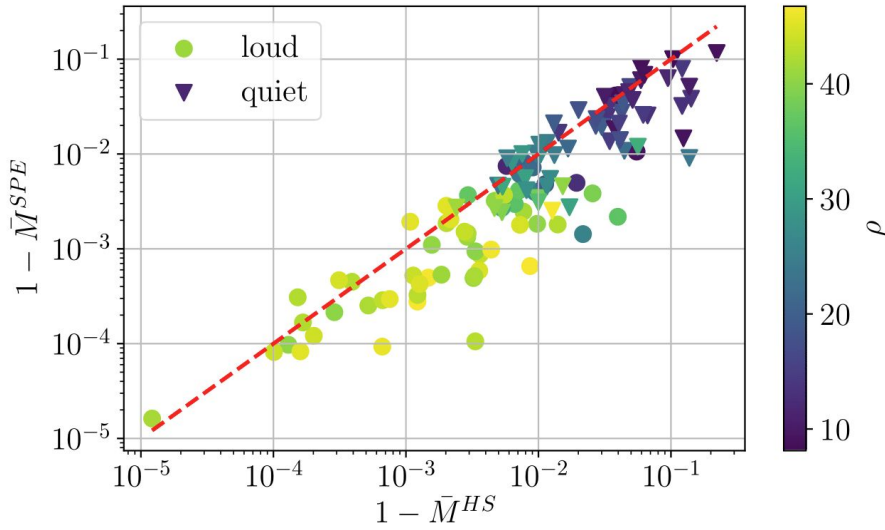
2 main situations:

HS is biased w.r.t SPE
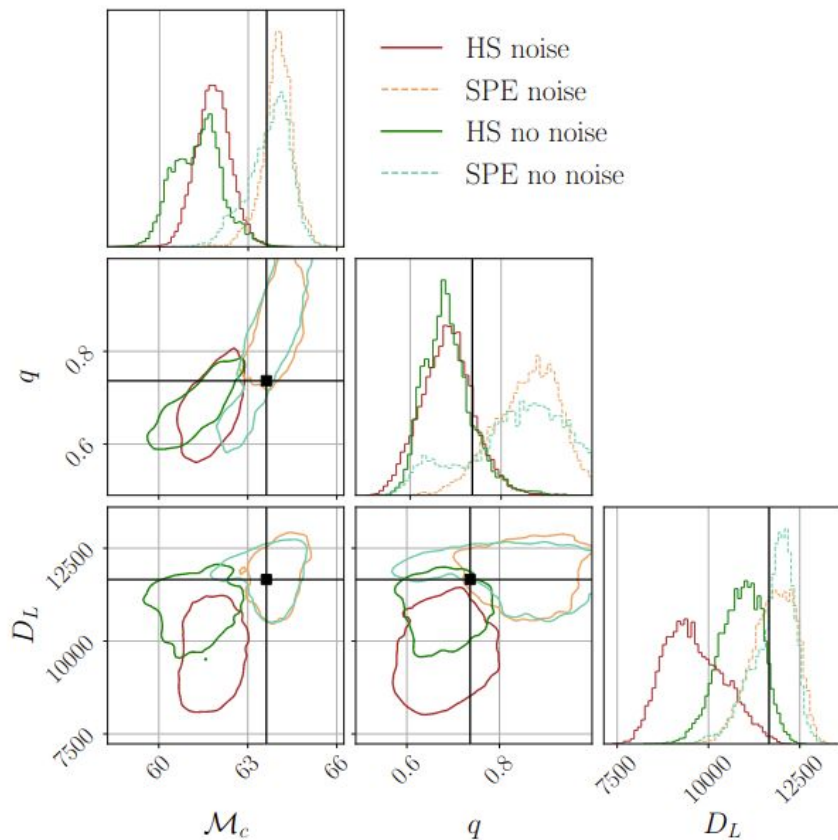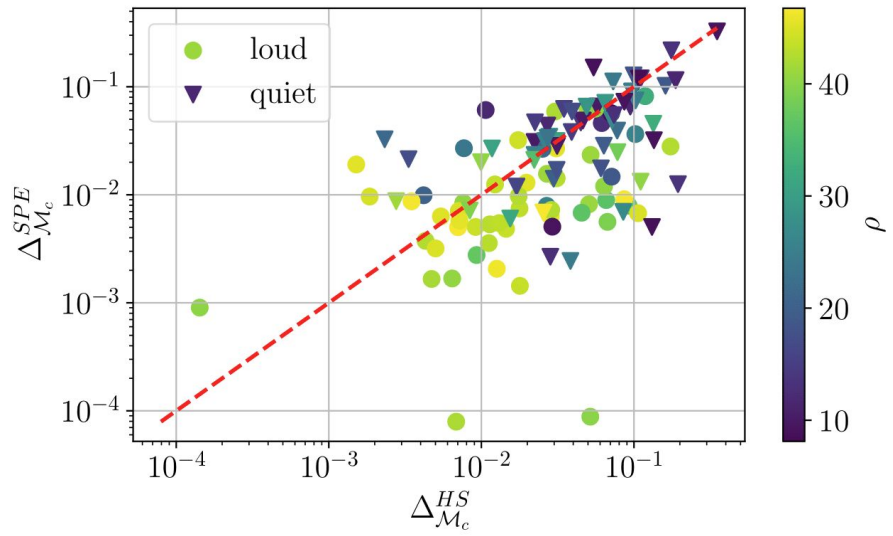
HS is comparable to SPE

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Hierarchical subtraction, comparison with no overlap

Mismatch for the maximum likelihood recovery

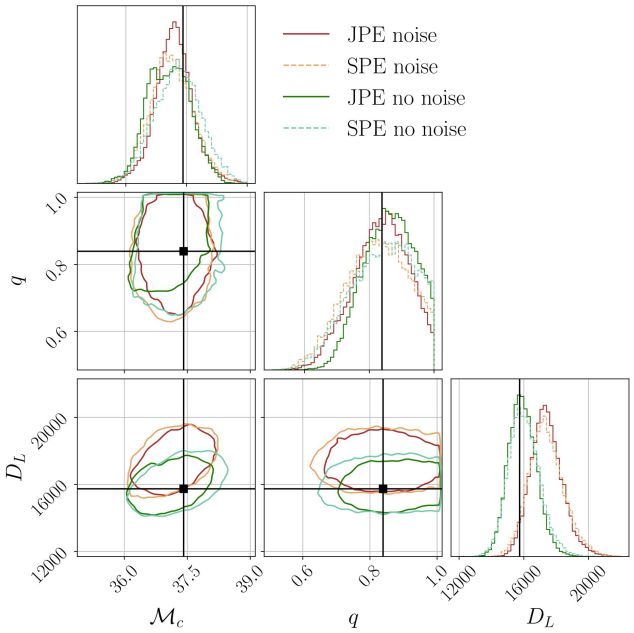Measure of the bias (normalized distance between the median and injected value)

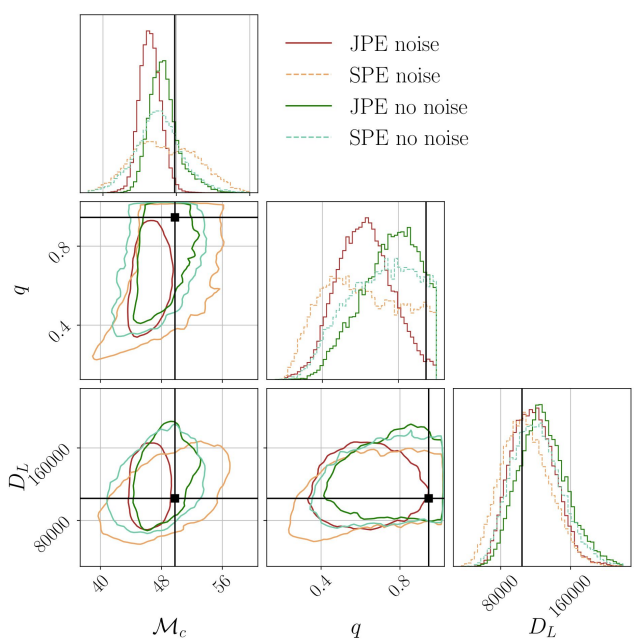On average, hierarchical subtraction is less precise and more prone to bias than without overlap

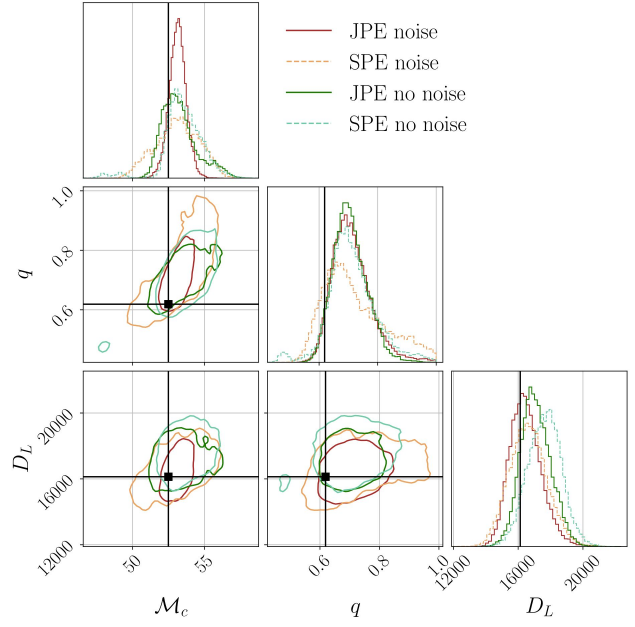→ Expected since imperfect noise realization

Joint parameter estimation
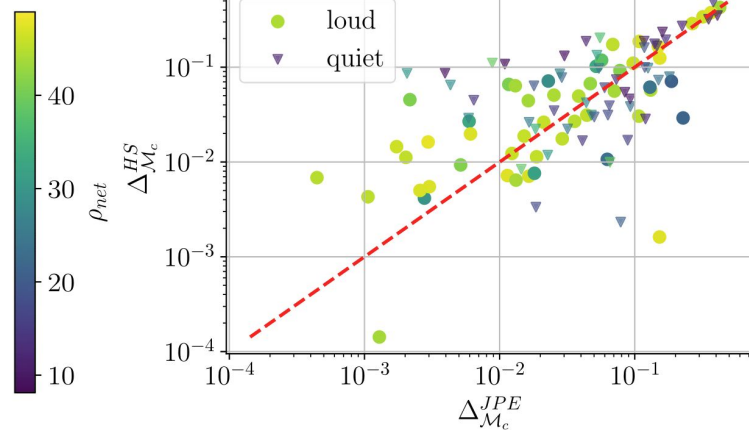

JPE and SPE are equivalent
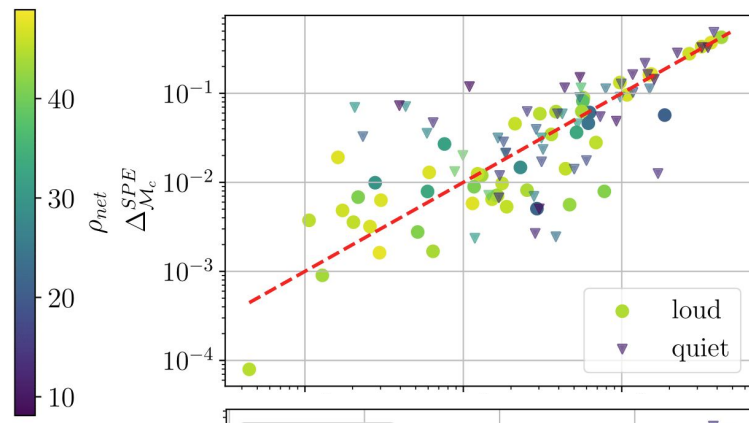
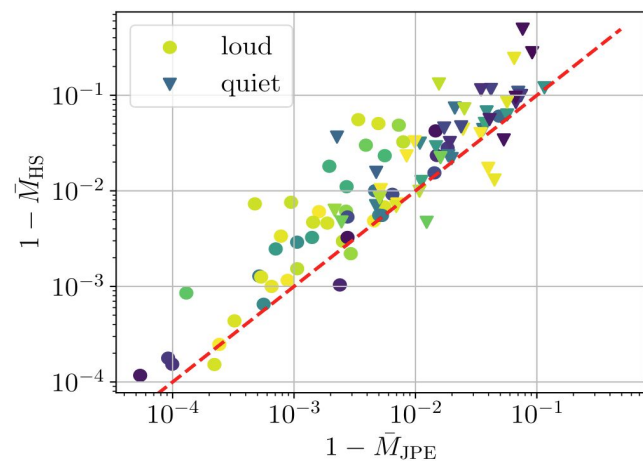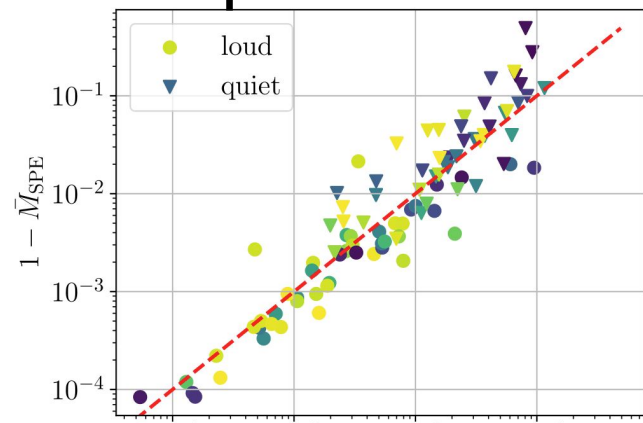JPE is biased w.r.t SPE

JPE is better than SPE

More diversity in the recoveries are observed, probably due to the cross term in the joint likelihood.
More extended studies are needed to fully grasp the behavior

Comparison with hierarchical subtraction and without overlap

Joint parameter estimation is more accurate than hierarchical subtraction, but slightly less precise than without overlap

Overview Bayesian analysis methods

Joint posterior overlap is **better suited** than hierarchical subtraction for close-by mergers

Joint parameter estimation is **more variable** than without overlap

→ It is possible to use Bayesian frameworks to analyze two overlapped signals

Overview Bayesian analysis methods

Joint posterior overlap is **better suited** than hierarchical subtraction for close-by mergers

Joint parameter estimation is **more variable** than without overlap

→ It is possible to use Bayesian frameworks to analyze two overlapped signals

BUT

- Not optimal yet
- Not yet tested on more types of signals due to heavy analyses
- Would not be able to keep up the pace with predicted detection rate
- We have not accounted for the difficulties in noise modeling or many overlapping mergers
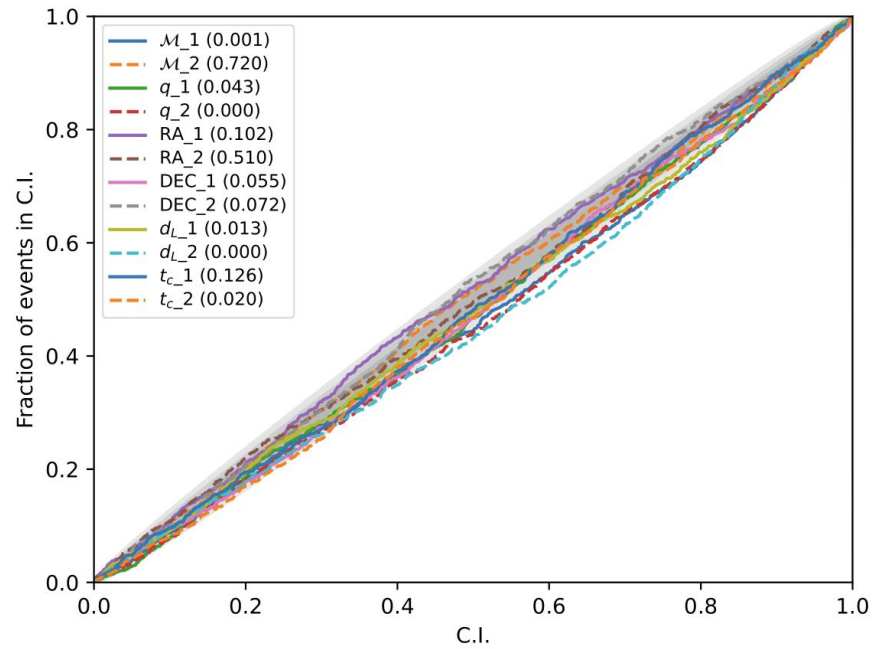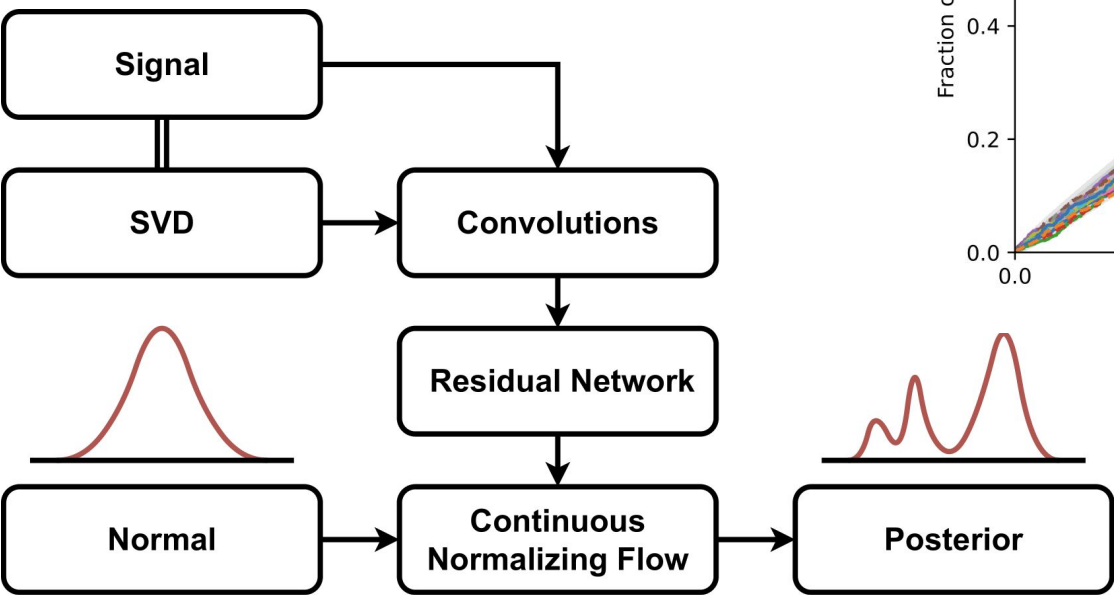
Can we try something else?

Machine learning based approach

Event A

Event B
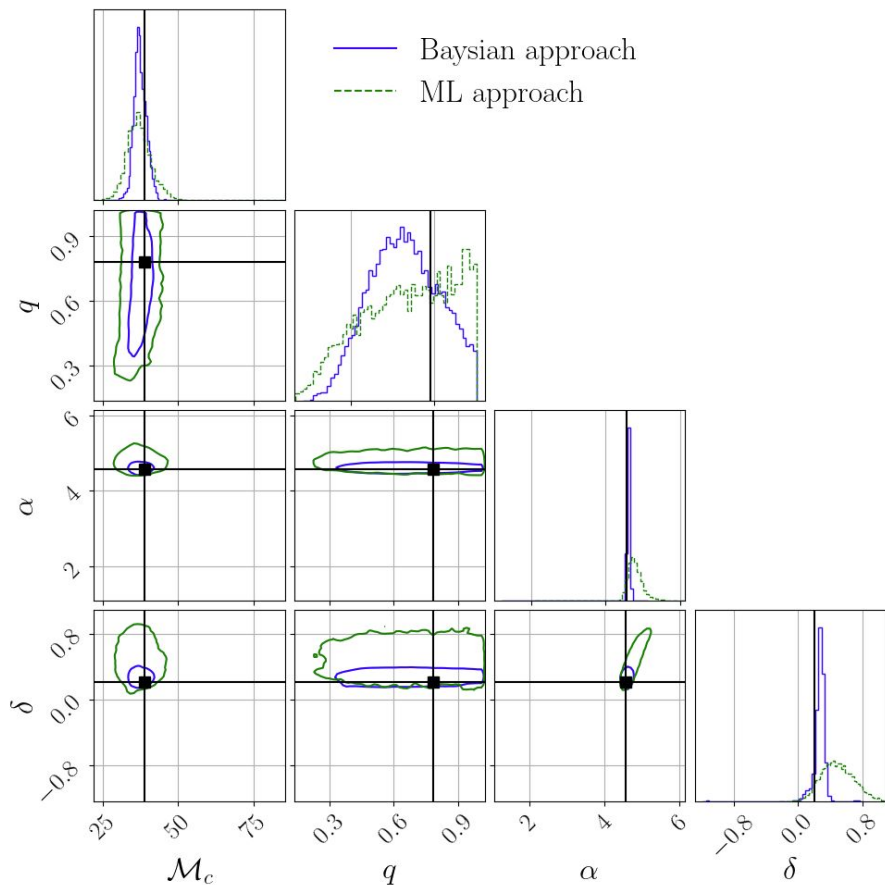
CNN + NFs

1 second
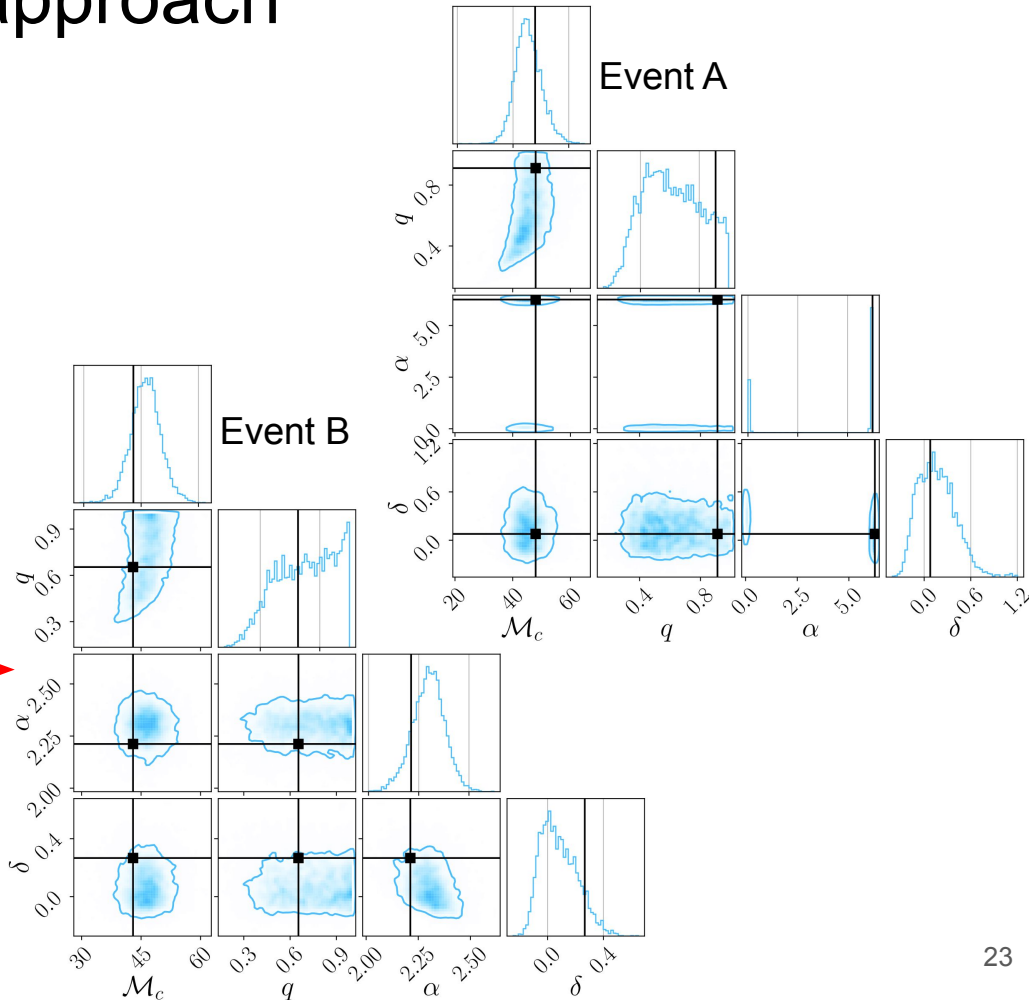
Machine learning based performance

Stable results throughout the parameter space, with a good speed

Machine learning vs Bayesian

Machine learning is **less prone to bias** but has regularly **larger posteriors** than Bayesian joint parameter estimation

Possible cause: **small network** compared to other

Possible solutions:
Make the network **bigger**
Use **importance sampling** in the output

Conclusions and Outlook

In the 3G era, **overlaps will happen** and be **quite common** (Samajdar et al, 2021)

Overlaps raise **several issues** and can lead to biased, negatively impacting science studies

In our works, we have presented **several avenues to tackle the issue:**
- Hierarchical subtraction (Janquart et al, 2022)
- Joint parameter estimation (Janquart et al, 2022)
- Machine learning based joint parameter estimation (Langendorff et al, 2023)

Up to now, these techniques have been **limited** to overlapping BBHs due to computational restrictions
They are **not optimal yet but can be improved**

In the future:
Work to **more realistic scenarios** with more background signals, more signal types and higher SNRs