A recipe to find Black holes and Neutron stars

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PhD seminar

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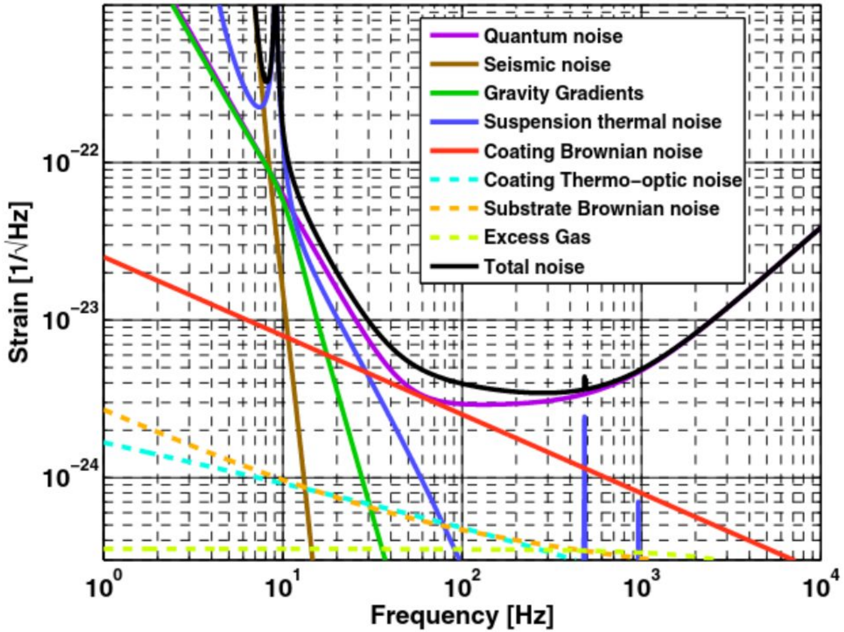
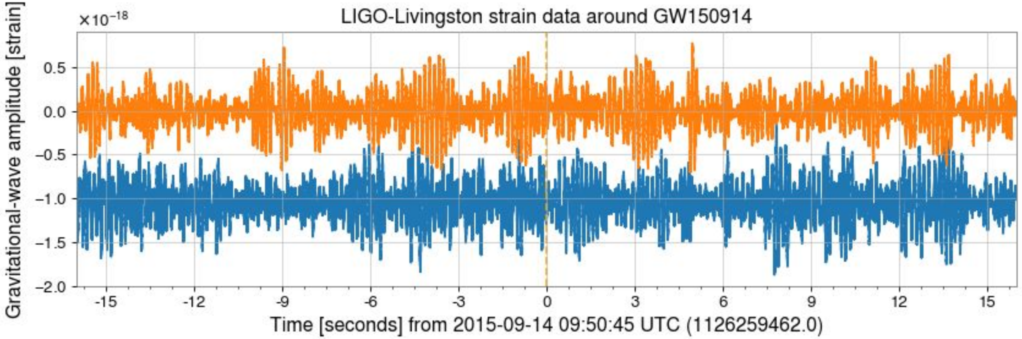
Disclaimer



Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo-optic noise
Substrate Brownian noise
Excess Gas
Total noise
Strain [1/√Hz]
Frequency [Hz]



LIGO-Livingston strain data around GW150914
Gravitational-wave amplitude [strain]
Time [seconds] from 2015-09-14 09:50:45 UTC (1126259462.0)

The problem of GW astronomy

1. Search for a signal u(t) buried in stationary, frequency dependent, gaussian noise n(t).
   NOTE: we will focus on the case of signals u(t) of known morphology.

2. Decide whether it is of astrophysical origin or not

Hypothesis 1

$$h(t) = n(t)$$

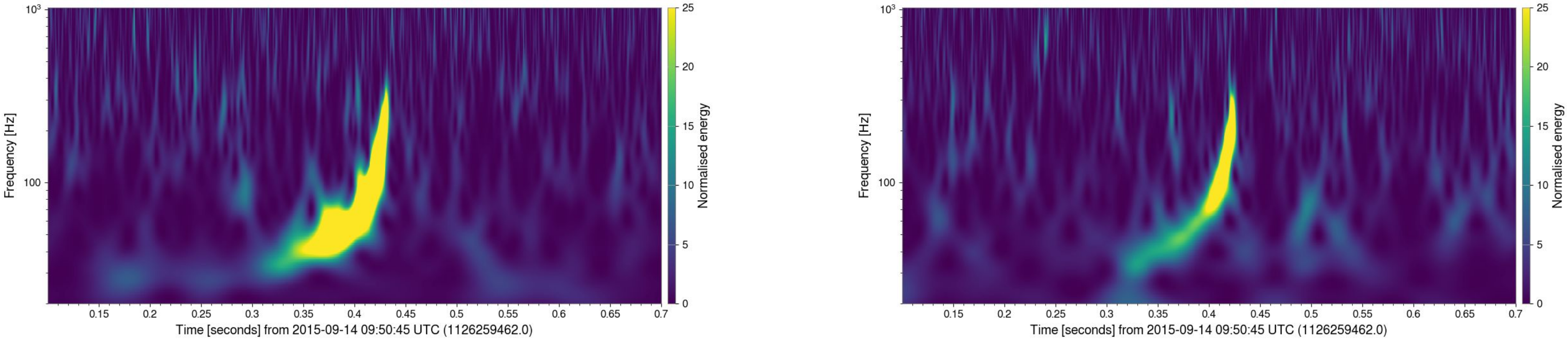
Hypothesis 2

$$h(t) = u(t) + n(t)$$

Note: not only very sensitive detectors are required, but optimal and computationally affordable data analysis techniques.

The popular q-scans are based on generic gaussian wavelet filtering.

Extremely useful, flexible and fast. But … suboptimal.



GW150914 Handford and Livingston.
Source: GOWSC

- The theory of linear filtering can take 1. as input, and give us:

Quote 1: “ The optimal detection statistic when one looks for signals of known/partially known morphology in the presence of gaussian stationary noise is:”

The Matched Filter

Note: This is an optimization problem solved in the 60s. see ***L. A. Wainstein and V. D. Zubakov. Extraction of Signals from Noise***

The matched filter is the key to sentences like:

“... My model is great because, the signal to noise ratio(SNR) is above…”

“... LIGO/Virgo should see my favorite source, because their sensitivity will reach XYZ megaparsec.”

“... I want a grant because X-generation detectors will see this exotic source with SNR of 8.”

Quote 1, can be put in simpler terms as:

Template

If we have an estimation of detector's power spectral density.
And If we believe q(t) is the best model for the signal u(t)

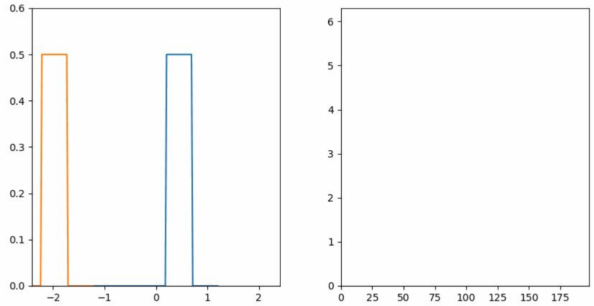
-> <u>The optimal</u> linear filter to find q in a noisy frequency dependent data stream h(t) is:

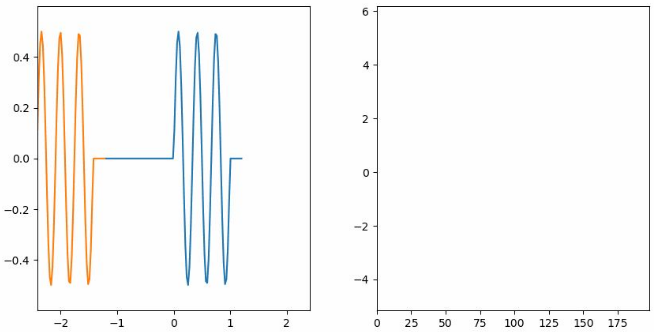
$$\langle h, q \rangle = 4Re\left(\int_0^\infty \frac{h(f) \cdot q^*(f)}{S_n(f)} \cdot df\right)$$

$$\langle n(f), n(f') \rangle = \delta(f' - f) \cdot S_n(f)$$

$$\int_{-\infty}^{\infty} x(t) \cdot y(t-\tau) d\tau = \int_{-\infty}^{\infty} X(f) \cdot Y(f) e^{i2\pi f\tau} df$$

$$\int_{-\infty}^{\infty} x^*(t) \cdot y(t+\tau) d\tau = \int_{-\infty}^{\infty} X^*(f) \cdot Y(f) e^{-i2\pi f\tau} df$$





- A “sort of” complex valued noise weighted cross correlation:

$$\langle h, qe^{i(2\pi f\tau+\phi_0)}\rangle_{\phi_0=\phi_{opt}} = 4\cdot\left(\left|\int_{-\infty}^{\infty}\theta(f)\frac{h(f)\cdot q^*(f)}{S_n(|f|)}\cdot e^{i2\pi f\tau}df\right|\right)$$

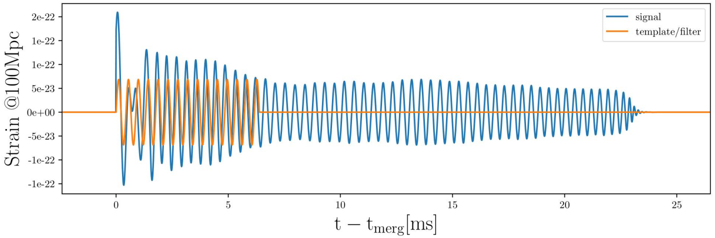
$$\rho(\tau) = \frac{\langle h, qe^{i(2\pi f\tau+\phi_0)}\rangle_{\phi_0=\phi_{opt}}}{\sqrt{\langle q,q\rangle}}$$

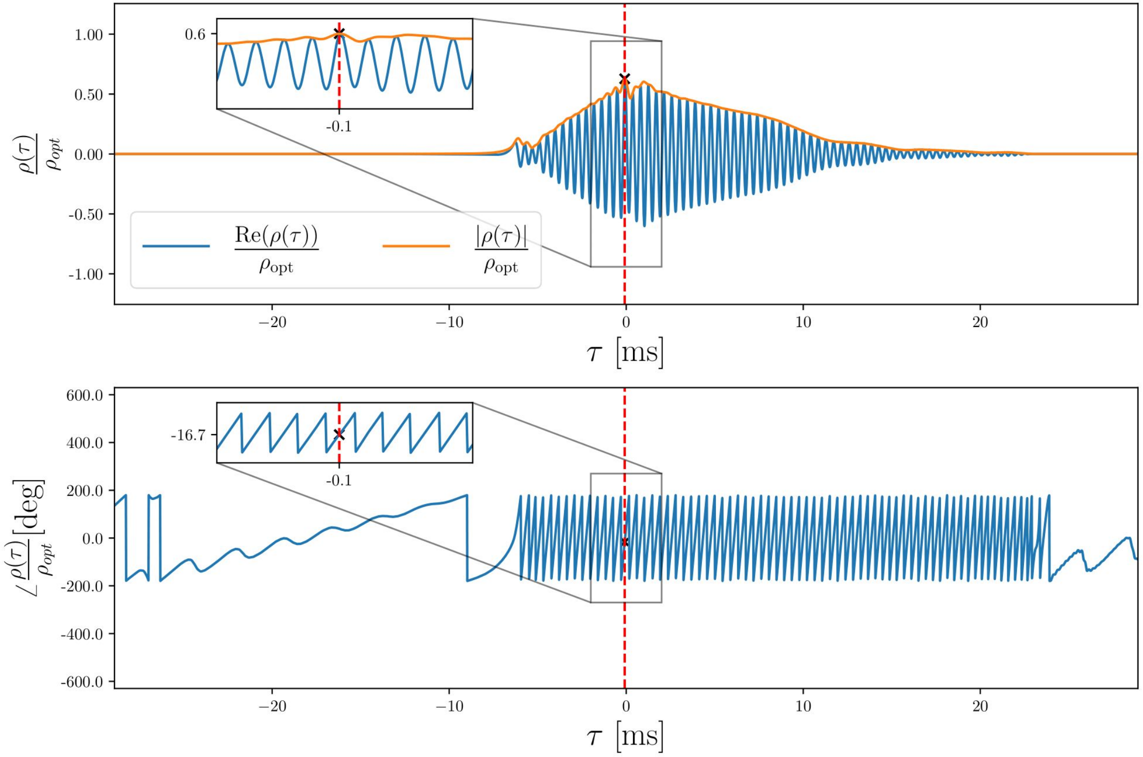
Signal-to-noise ratio “SNR”

(Its a complex timeseries, not a single scalar quanity)

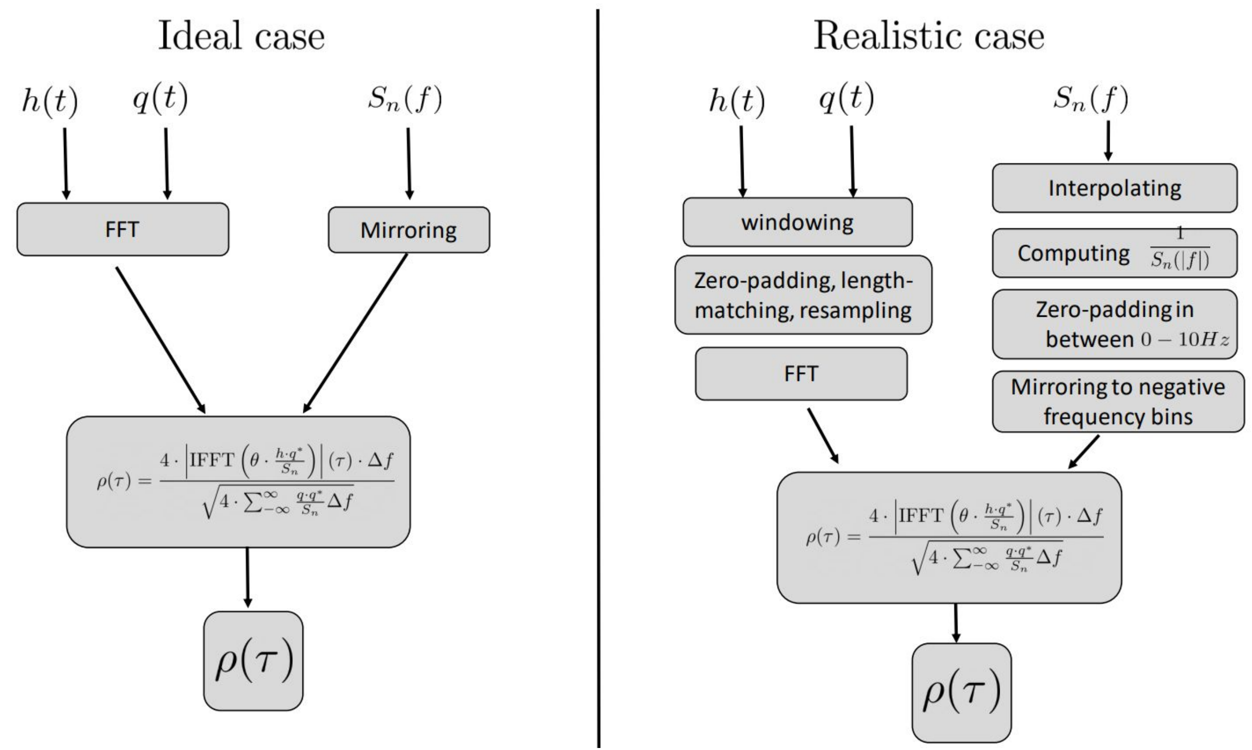
$$\rho(\tau) = \frac{4\cdot\left|\text{IFFT}\left(\theta\cdot\frac{h\cdot q^*}{S_n}\right)\right|(\tau)\cdot\Delta f}{\sqrt{4\cdot\sum_{-\infty}^{\infty}\frac{q\cdot q^*}{S_n}\Delta f}}$$

- Gives info about:
    - Signal power
    - Signal phase***





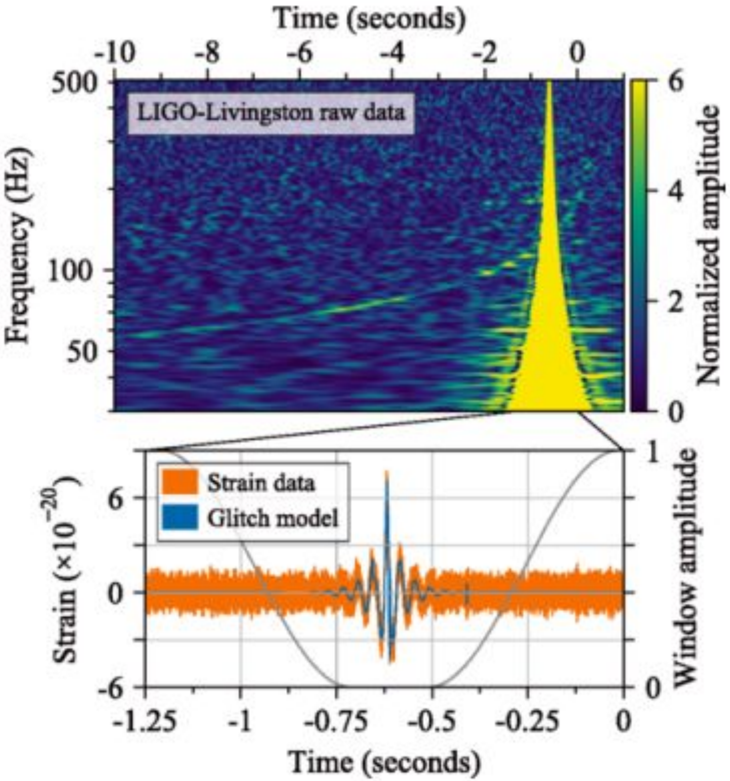
In a real search…



1. h(t) may have deviations from the "gaussian stationary" case. We call them glitches.

2. Signals h(t), q(t) have to discretely sampled and must have compact support.

- Vetoing
- Zero-padding
- resampling
- Windowing
- Length matching
- Mirroring



BNS event GW170817: LIGO Livingston

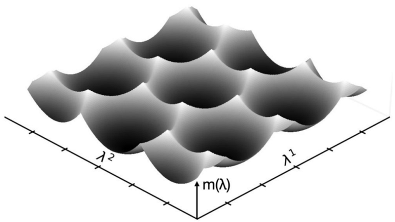
Doing a real search becomes high dimensional problem

$$\langle h, qe^{i(2\pi f\tau+\phi_0)}\rangle_{a_1,\ldots,a_n,\phi_0=\phi_{opt}} = 4\cdot\left(\left|\int_{-\infty}^{\infty}\theta(f)\frac{h(f)\cdot q^*_{a_1,\ldots,a_n}(f)}{S_n(|f|)}\cdot e^{i2\pi f\tau}df\right|\right)(\tau)$$

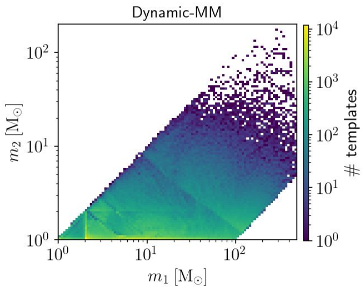
$$q_{a_1,\ldots,a_n}(t)$$

Template banks

- Can not be defined continuously at every point of $a_1 \times a_2 \ldots \times a_n$
- Geometrically motivated ways have been invented to sample that space discretely without losing too much SNR. (Using manifold theory)



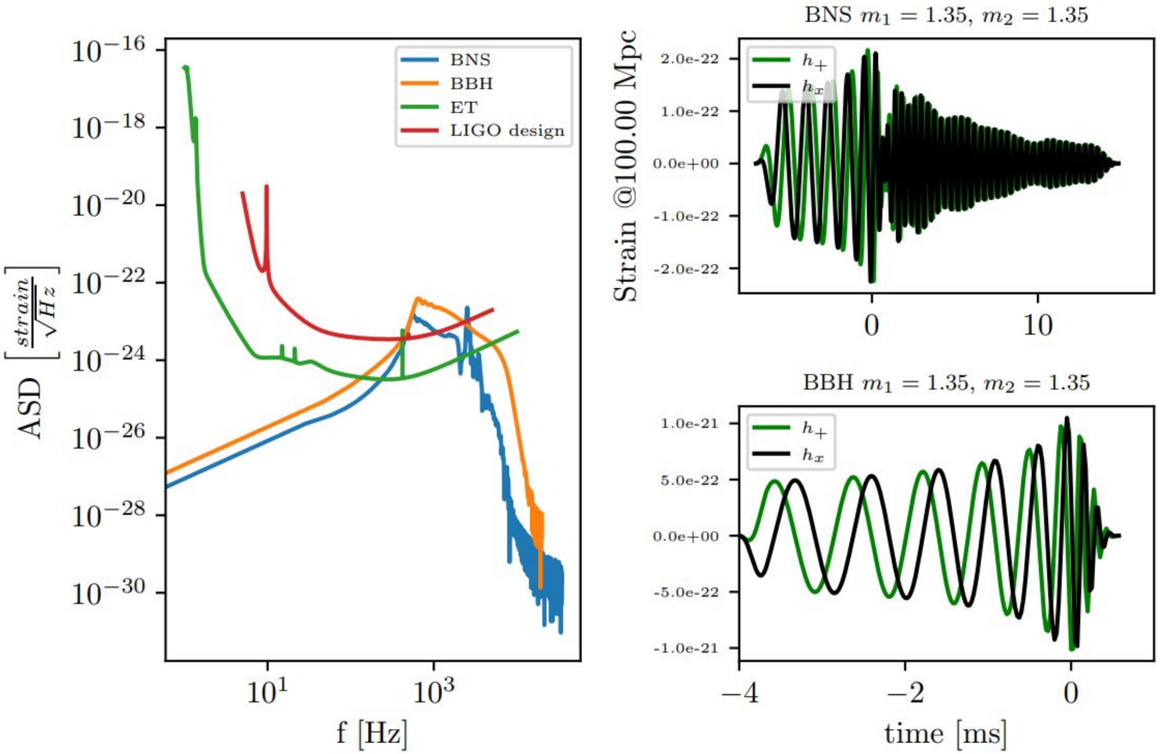
B. Allen 2021



LVK collaboration 2023

Searching for black holes and neutron star mergers

- We know their GW signature!



- We can get exact solutions to the 3+1 Einstein's Field equations
- There are several methods to extract accurately gravitational radiation from such simulated events.
- As of today, using the most powerful supercomputers and large amounts of RAM. It is possible to complete one simulation run in weeks of clock time.

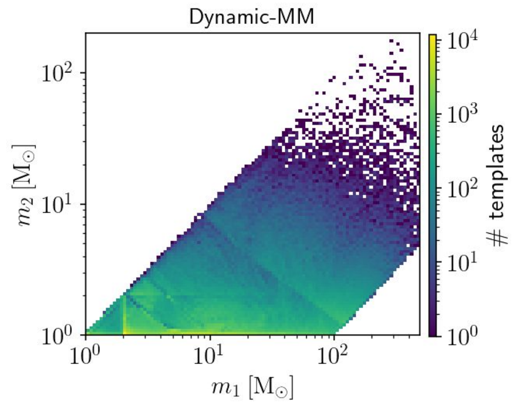
The problem:

- Template banks require hundreds of thousands of signals. This is not computationally achievable.

A solution:

- Find analytical/semianalyical expressions to model the “easy part”.
- We need fewer numerical solutions to “calibrate” this models.

- Inspiral phenomenological waveforms:
  - BBH: yes
  - BNS: yes

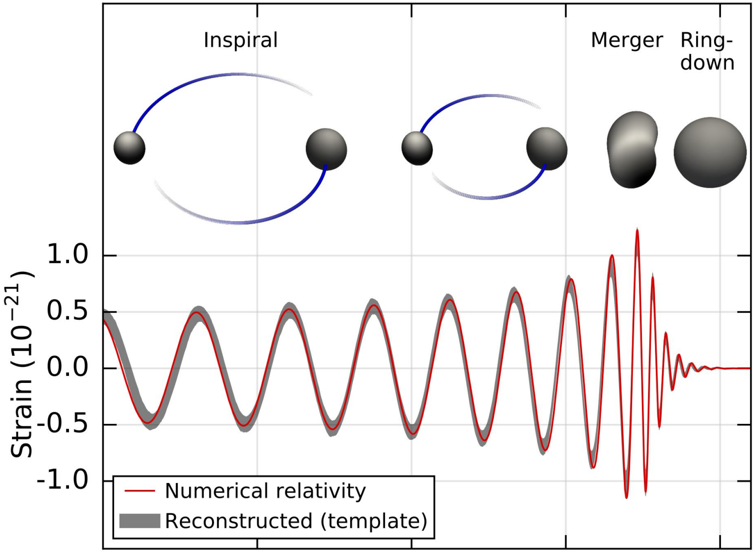


LVK O4a template bank:
approx. 700 thousand templates

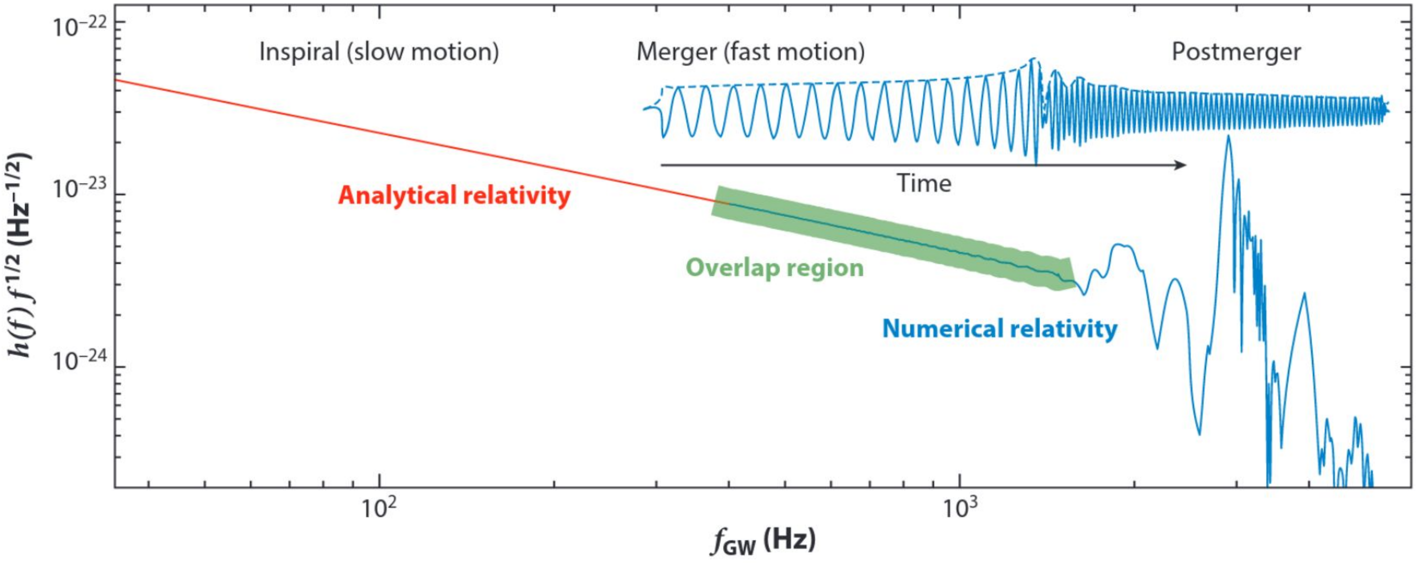
An incomplete solution:

Quasicircular inspiral-merger-postmerger waveforms:

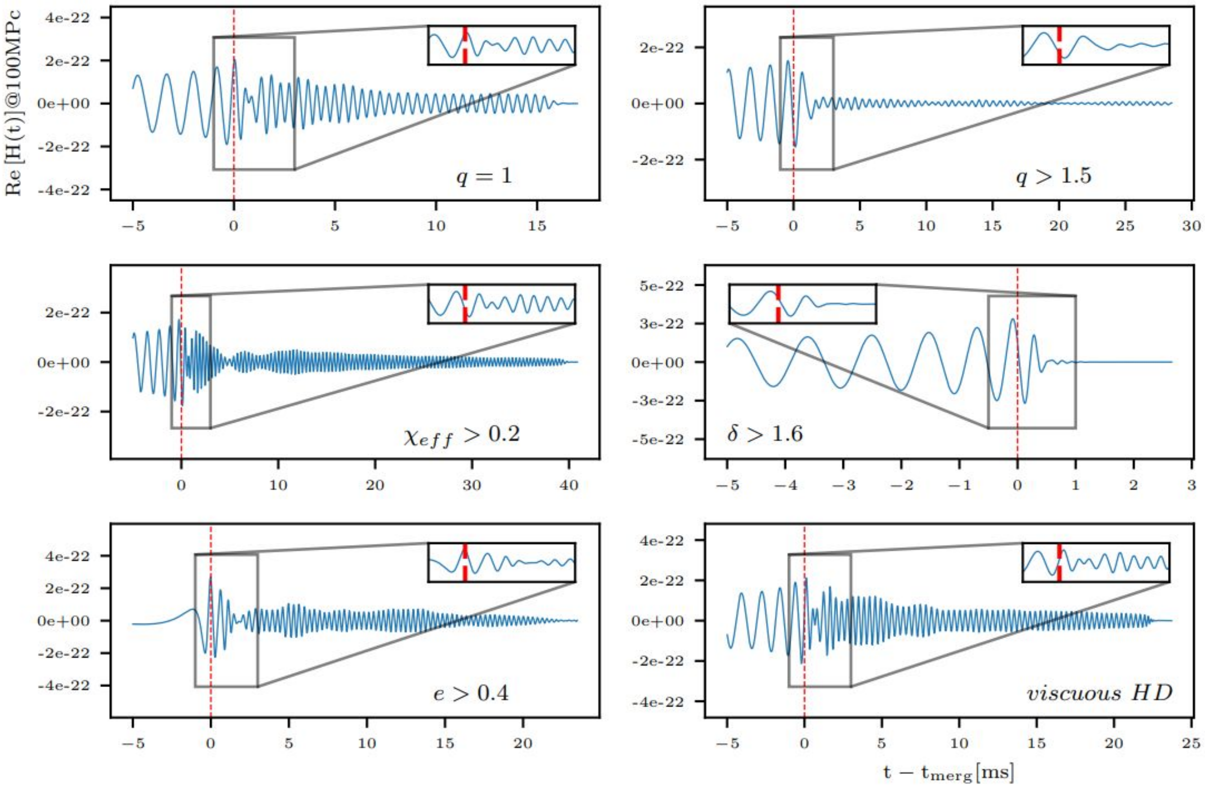
- BBH and yes, but…



- BNS: Not ready



source: Radice et. al. 2020



source: CoRe BNS catalog


FUN WITH CREAM
WHATCHA COOKIN?

Recipe

Ingredients:

- 1 spoon of NR waveforms(a few hundred)
- 1 template bank with enough waveforms
- A few days of detector data
- A bowl of CPU cores
- A highly paralellized matched filtering engine

Directions:

- step1 Grab a phenomenological waveform model.
- step2. Use the spoon of NR waveforms to calibrate it. And build a template bank.
- step3. Stir your detector data while removing glitches, zeropadding its edges and resampling it as needed.
- step4. Estimate the PSD at runtime.
- step5. Put everything together in the bowl of CPU cores.
- step6. Let the MF engine burn a few thousand cores.
- step7. Collect your astrophysically interesting triggers

Conclusions:

- Matched filtering, requires:
    - Theory(phenomenological models)
    - Numerics(to solve Einstein's equations)
    - Highly parallelized signal processing Techniques.
- Implementing this operations in modern computers is a very challenging task:
    - Many cores doing fast fourier transforms are needed.
- Numerical relativity is still needed, otherwise we would not know for sure how good are our banks.
- Looking for "complete" waveforms is beyond the capabilities current computational infrastructure. Specially the BNS case.
- Find tutorials for doing this yourself in:

  https://github.com/gwastro/PyCBC-Tutorials