Title: New Developments In Gravitational Wave Data Analysis For Compact Binary Mergers

Speakers: Liang Dai

Series: Strong Gravity

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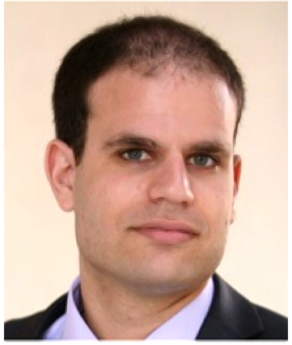
Abstract: Ground-based gravitational wave observatories have begun to uncover a large number of compact binary coalescences in the universe through gravitational wave signals. I will discuss novel and effective techniques we have developed recently to analyze the publicly available LIGO/Virgo bulk strain data from scratch. Built on simple ideas and easy to implement, those address the questions of template bank construction, signal processing, trigger ranking, and fast parameter estimation. Applying those techniques, we searched for compact binary mergers during the LIGO/Virgo O1 and O2 runs, and detected a few binary black hole mergers in addition to what have been reported in the literature.

# New Developments in Analyzing Gravitational Wave Data For Compact Binary Mergers

**Liang Dai (IAS)**

Strong Gravity Seminar, Perimeter Institute
May 2019

# Major Collaborators at IAS/Princeton



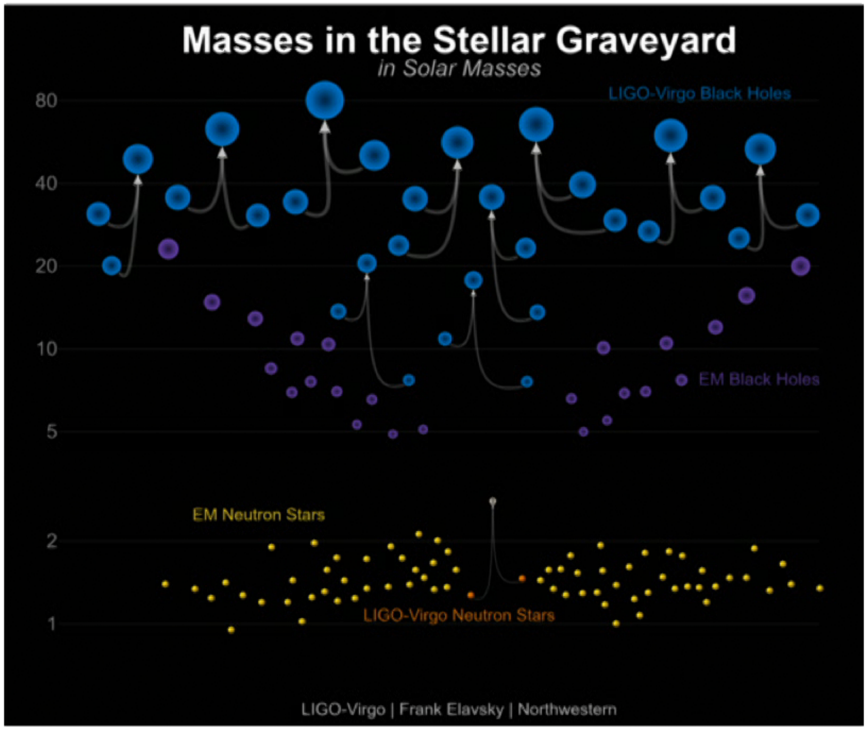
Barak Zackay (IAS)

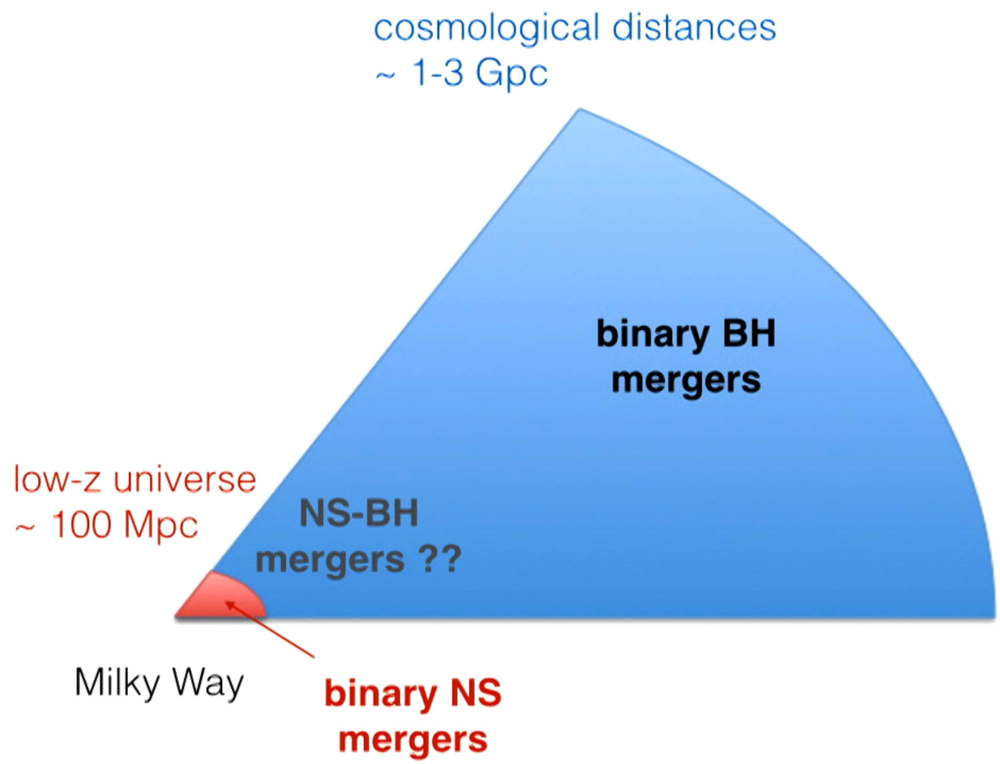
Javier Roulet (Princeton)

Tejaswi Venumadhav (IAS)

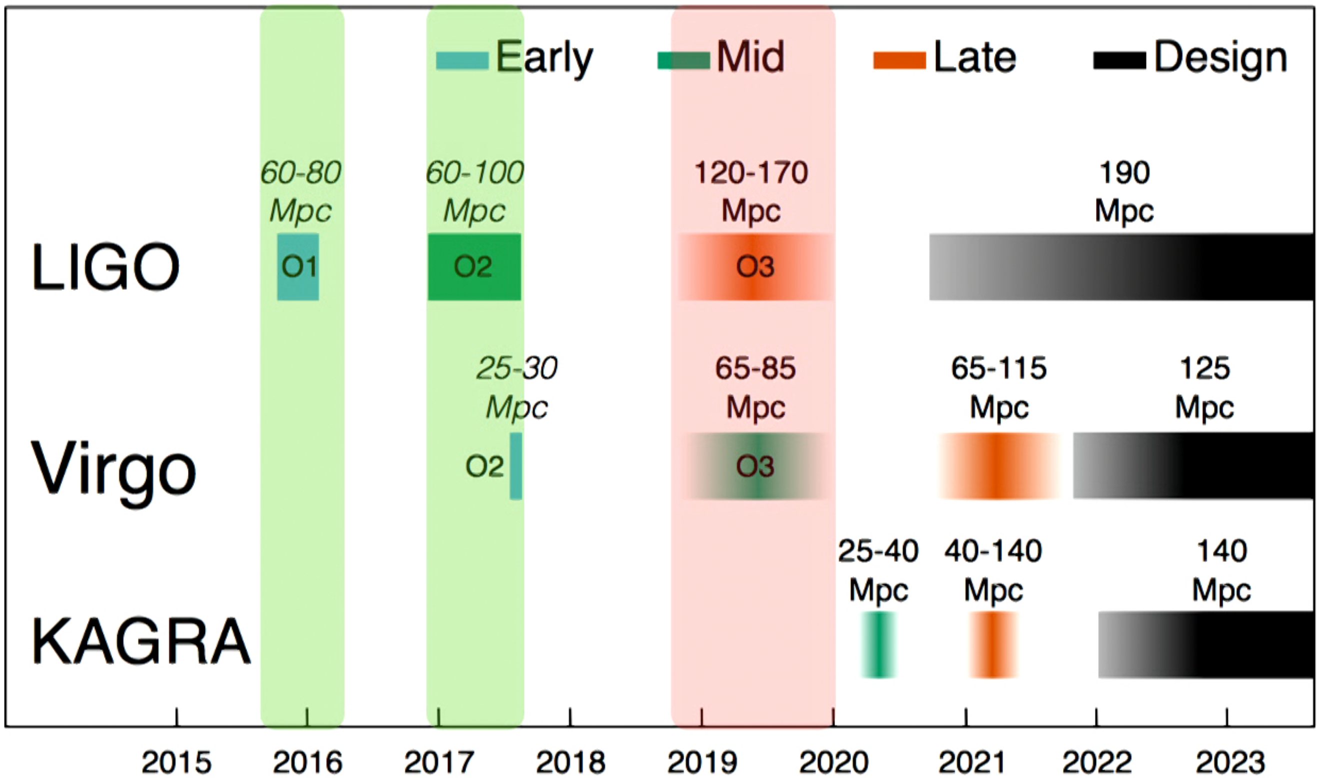
Matias Zaldarriaga (IAS)

# Compact Binary Mergers



# Science Runs at LIGO/Virgo

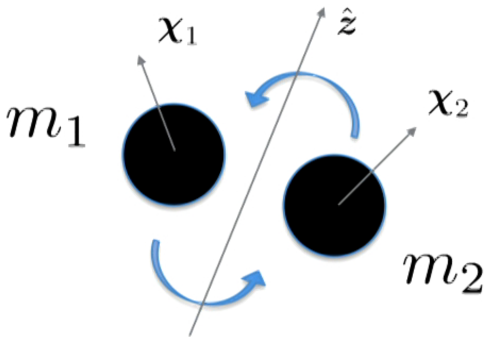


# Bottom Line

- We aimed to understand how accessible and useful bulk strain data are to ordinary astrophysicists.
- We developed an independent, full-fledged pipeline.
- We aimed to verify the results from LIGO/Virgo. We also wanted to see if there were fainter events so that more would be learned about source populations.
- We analyzed O1 and O2 bulk data release for compact binary merger signals.
- We found 1 new BBH event from O1, and 6 new BBH events from O2.

# Parameters For Binary Mergers

## Intrinsic parameters




component masses
and spins

"chirp" mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$ $\dot{f} \sim \mathcal{M}^{5/3} f^{11/3}$

In detector frame $\mathcal{M}^{\rm det} = \mathcal{M}\,(1+z)$

effective spin parameter $\chi_{\rm eff} = \frac{m_1\,\chi_{1z} + m_2\,\chi_{2z}}{m_1 + m_2}$

## Extrinsic parameters

(Geocentric) arrival time
Luminosity distance
Orbital phase
Inclination
Sky position: RA, Dec
Roll angle of the orbit on the sky

# Parameter Estimation

Parameter estimation is important to address many astrophysics questions

## Intrinsic parameters

Component mass distribution?
Mass cutoff (e.g. due to pair-instability SNe)?
Mass ratio?

Fast spinning or slowly/non-spinning?
(Binary stellar evolution? Dynamic formation?)
Spins aligned, anti-aligned, or random?

Identify NS-BH mergers ?!

## Extrinsic parameters

(RA, Dec) for EM follow-ups

Luminosity distance for understanding **redshift evolution** of the mergers;
And for the **standard siren** test.

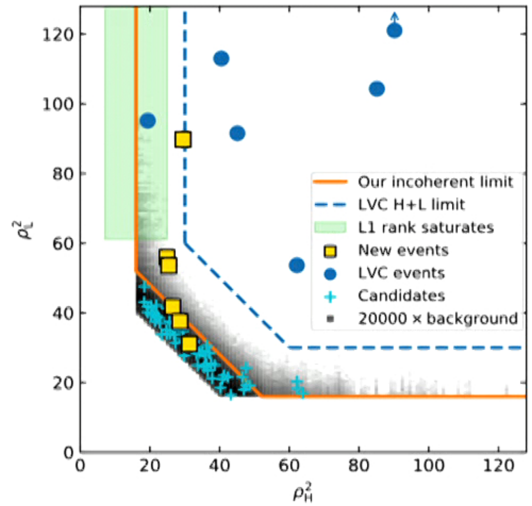
Inclination has important implications for the luminosity distance, mass ratio measurement, and spin-precession effect.

# New BBH Events Uncovered

| | Flat $\chi_{\rm eff}$ prior | Isotropic spin prior |
|---|---|---|
| Chirp mass $\mathcal{M}^{\rm det}$ | $31^{+2}_{-3}\,M_\odot$ | $29^{+2}_{-2}\,M_\odot$ |
| Primary mass $m_1$ | $31^{+13}_{-6}\,M_\odot$ | $38^{+11}_{-11}\,M_\odot$ |
| Secondary mass $m_2$ | $21^{+5}_{-6}\,M_\odot$ | $16^{+6}_{-3}\,M_\odot$ |
| Mass ratio $m_2/m_1$ | $0.7^{+0.3}_{-0.3}$ | $0.4^{+0.3}_{-0.1}$ |
| Total mass $M$ | $52^{+9}_{-6}\,M_\odot$ | $54^{+10}_{-8}\,M_\odot$ |
| Primary aligned spin $\chi_{1z}$ | $0.86^{+0.12}_{-0.27}$ | $0.73^{+0.18}_{-0.28}$ |
| Secondary aligned spin $\chi_{2z}$ | $0.79^{+0.19}_{-0.65}$ | $0.30^{+0.51}_{-0.46}$ |
| Effective aligned spin $\chi_{\rm eff}$ | $0.81^{+0.15}_{-0.21}$ | $0.60^{+0.16}_{-0.18}$ |
| Cosine of inclination $\lvert\cos\iota\rvert$ | $0.81^{+0.18}_{-0.52}$ | $0.81^{+0.18}_{-0.51}$ |
| Luminosity distance $D_L$ | $2.4^{+1.2}_{-1.1}$ Gpc | $2.1^{+1.0}_{-0.9}$ Gpc |
| Source redshift $z$ | $0.43^{+0.17}_{-0.17}$ | $0.38^{+0.15}_{-0.15}$ |

Zackay+ 1902.10331

O1 analysis

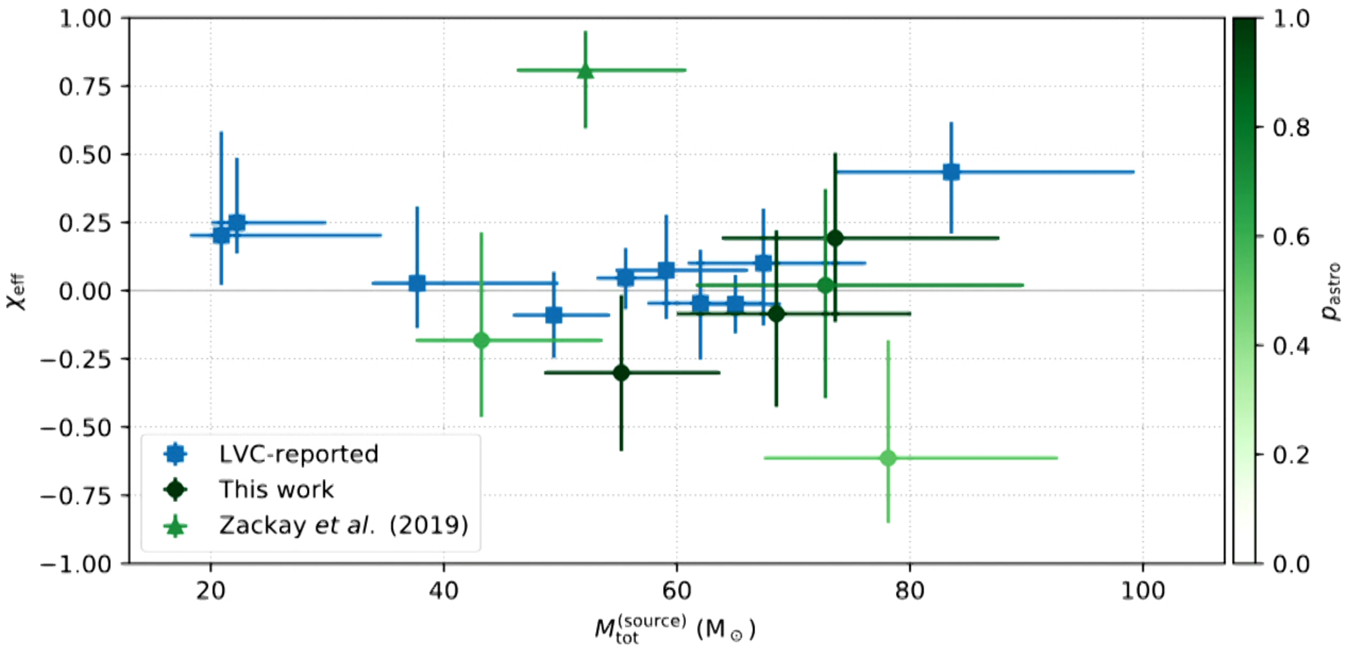



| Name | Bank | $\mathcal{M}^{\rm det}(\mathrm{M}_\odot)$ | $\chi_{\rm eff}$ | $z$ | GPS time[a] | $\rho_{\rm H}^2$ | $\rho_{\rm L}^2$ | FAR$^{-1}$(O2)[b] | $\frac{W(\text{event})}{\mathcal{R}(\text{event}\mid\mathcal{N})}$ (O2) | $p_{\rm astro}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| GW170121 | BBH (3,0) | $29^{+4}_{-3}$ | $-0.3^{+0.3}_{-0.3}$ | $0.24^{+0.14}_{-0.13}$ | 1169069154.565 | 29.4 | 89.7 | $2.8 \times 10^3$ | $> 30$ | $> 0.99$ |
| GW170304 | BBH (4,0) | $47^{+8}_{-7}$ | $0.2^{+0.3}_{-0.3}$ | $0.5^{+0.2}_{-0.2}$ | 1172680691.356 | 24.9 | 55.9 | 377 | 13.6 | 0.985 |
| GW170727 | BBH (4,0) | $42^{+6}_{-6}$ | $-0.1^{+0.3}_{-0.3}$ | $0.43^{+0.18}_{-0.17}$ | 1185152688.019 | 25.4 | 53.5 | 370 | 11.8 | 0.98 |
| GW170425 | BBH (4,0) | $47^{+26}_{-10}$ | $0.0^{+0.4}_{-0.5}$ | $0.5^{+0.4}_{-0.3}$ | 1177134832.178 | 28.6 | 37.5 | 15 | 0.65 | 0.77 |
| GW170202 | BBH (3,0) | $21.6^{+4.2}_{-1.4}$ | $-0.2^{+0.4}_{-0.3}$ | $0.27^{+0.13}_{-0.12}$ | 1170079035.715 | 26.5 | 41.7 | 6.3 | 0.25 | 0.68 |
| GW170403 | BBH (4,1) | $48^{+9}_{-7}$ | $-0.7^{+0.5}_{-0.3}$ | $0.45^{+0.22}_{-0.19}$ | 1175295989.221 | 31.3 | 31.0 | 4.7 | 0.23 | 0.56 |

O2 analysis

Venumadhav+ 1904.07214

# BBH population properties




Zackay+ 1902.10331

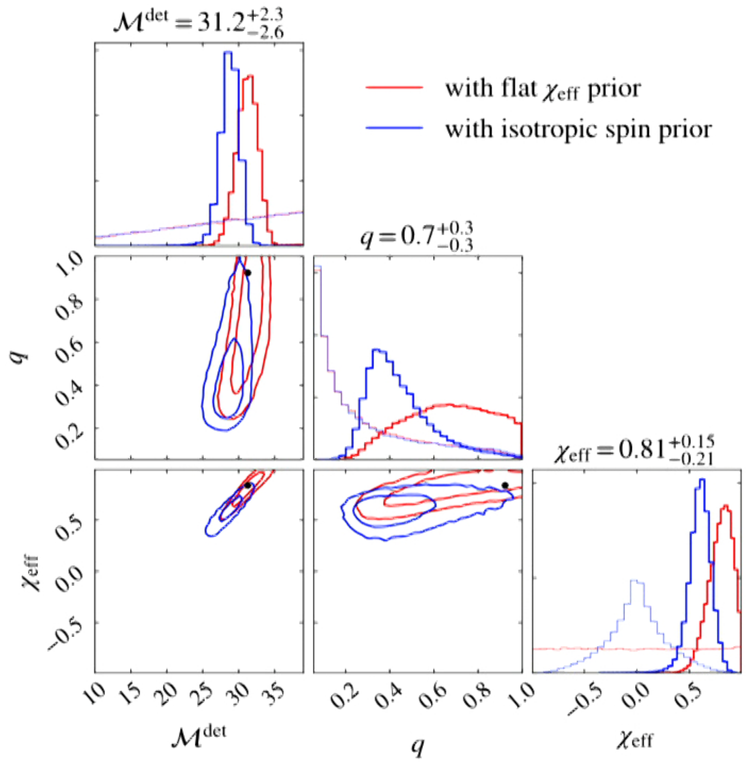
Venumadhav+ 1904.07214

## Secure BBH events:

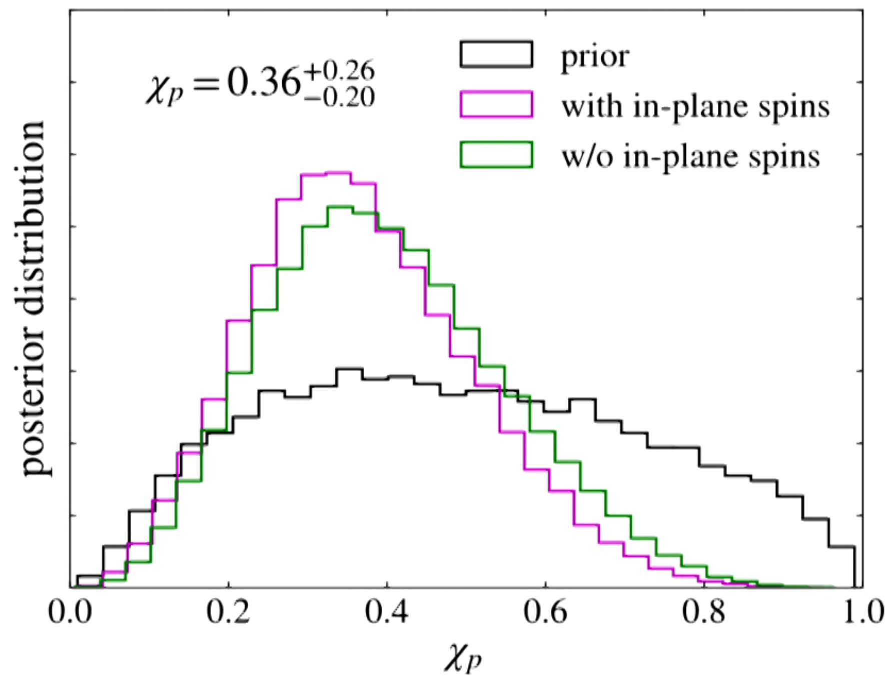
- Heavier than X-ray Binaries ??
- Consistent with a BH mass cutoff
- Consistent with comparable component masses
- Consistent with non-spinning or slowly-spinning

# Priors Play Tricks

Candidate GW event from O1:
GW151216




Test spin precession

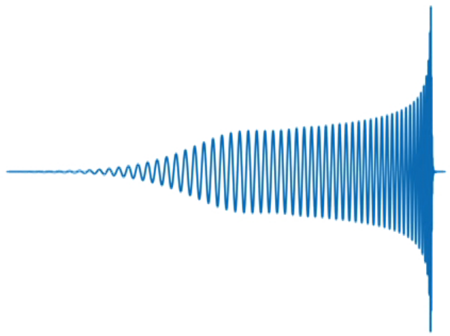



Zackay+ 1902.10331

# GW Signal Detection

strain signal
expected from GR
**waveform**
**“template”**

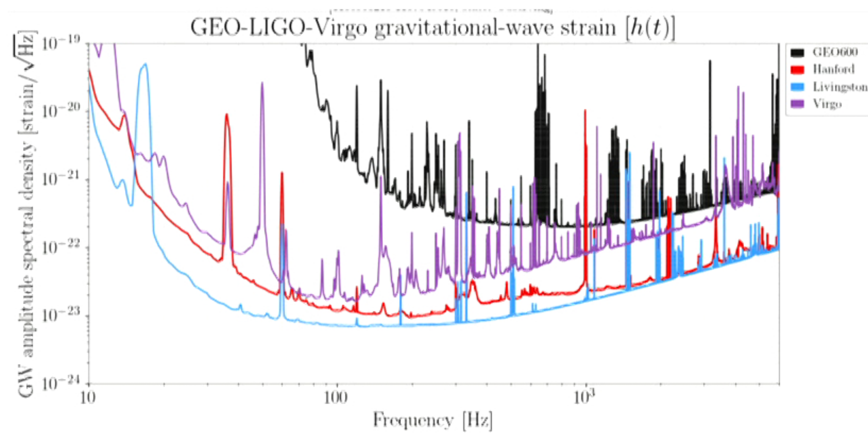
$$h(t)$$



To find the needle in the haystack, use the technique of **matched filter**

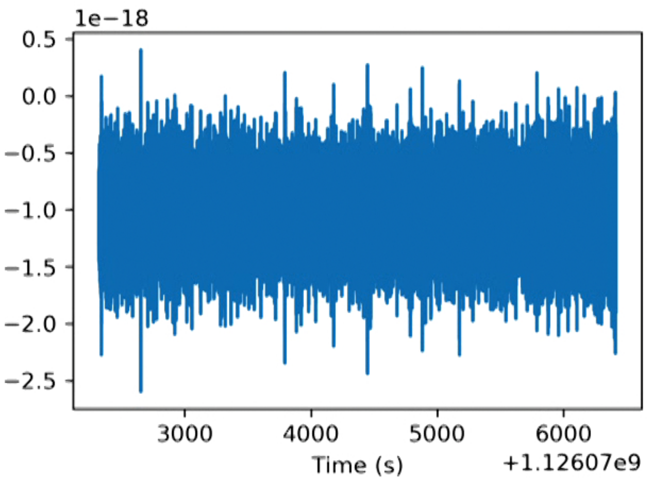
$$(d(t)|h(t+\tau)) := \sum_f \frac{d(f)\,h^*(f)\,e^{i\,2\pi\,f\,\tau}}{S_N(f)/4}$$

noise **power spectral density** (PSD)




strain data as
recorded in detector

$$d(t)$$



# Likelihood Evaluation

Need to calculate the "overlap"

$$(d(t)|h(t+\tau)) := \sum_f \frac{d(f)\, h^*(f)\, e^{i\, 2\pi\, f\, \tau}}{S_N(f)/4}$$

To analyze a chunk of **T** seconds at a sampling rate **Fs** Hz, perform ing FFT on a regular frequency grid requires **O(N log N)** flops, where **N = T*Fs**

Parameter estimation may require us to evaluate the above FFT for **O($10^6$–$10^8$)** parameter combinations.

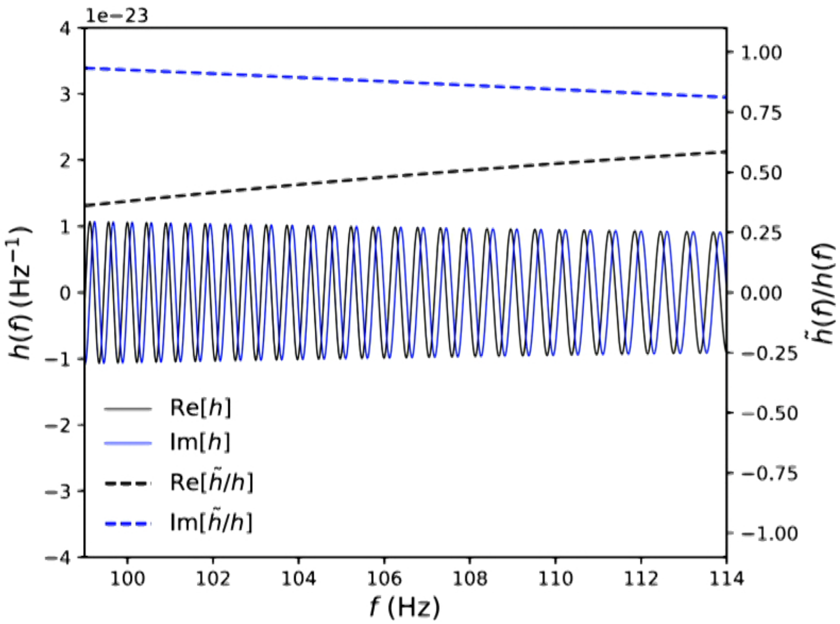
Become increasingly challenging when events are visible in band for a very long period of time.

# Fast Likelihood Evaluation: Relative Binning

Binary neutron star merger GW170817

$$\mathcal{M}^{\rm det} = 1.1975 \pm 0.0001\, M_\odot$$

Let us compare
$$\mathcal{M}^{\rm det} = 1.1975\, M_\odot$$
$$\mathcal{M}^{\rm det} = 1.1985\, M_\odot$$




Compute (frequency-domain) **waveform ratio** only on a sparse frequency grid

$$r(f) = \frac{h(f)}{h_0(f)} = r_0(h, \mathrm{b}) + \mathrm{r}_1(\mathrm{h}, \mathrm{b})\,(\mathrm{f} - \mathrm{f}_\mathrm{m}(\mathrm{b})) + \cdots$$

Match can be approximated as

$$Z(d,h) = 4 \sum_f \frac{d(f) h^*(f)}{S_n(f)/T}$$
$$\approx \sum_{\mathrm{b}} \left[A_0(\mathrm{b})\, r_0^*(h,\mathrm{b}) + A_1(\mathrm{b})\, r_1^*(h,\mathrm{b})\right]$$

Pre-compute moments (on FFT grid, but for once)

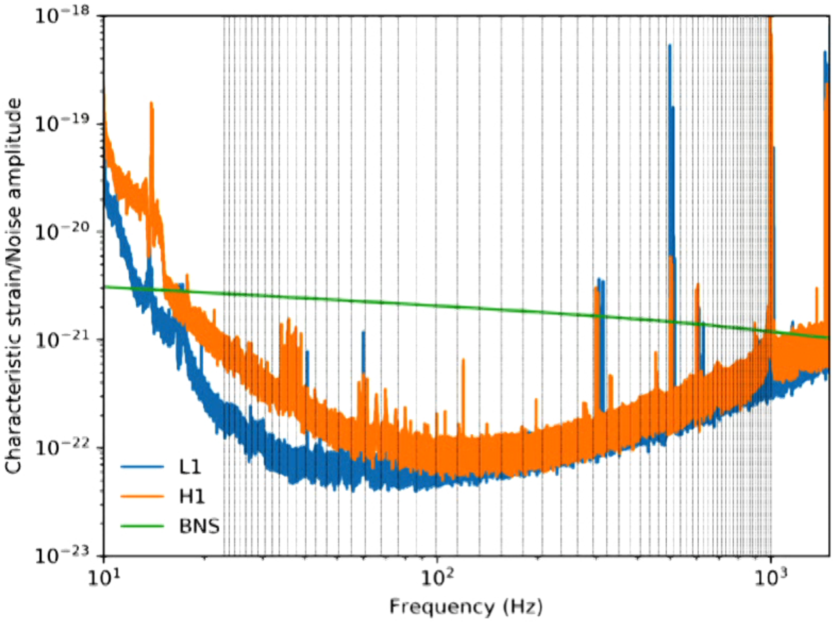
$$A_0(\mathrm{b}) = 4 \sum_{f\in \mathrm{b}} \frac{d(f)\, h_0^*(f)}{S_n(f)/T}$$
$$A_1(\mathrm{b}) = 4 \sum_{f\in \mathrm{b}} \frac{d(f)\, h_0^*(f)}{S_n(f)/T} (f - f_\mathrm{m}(\mathrm{b}))$$

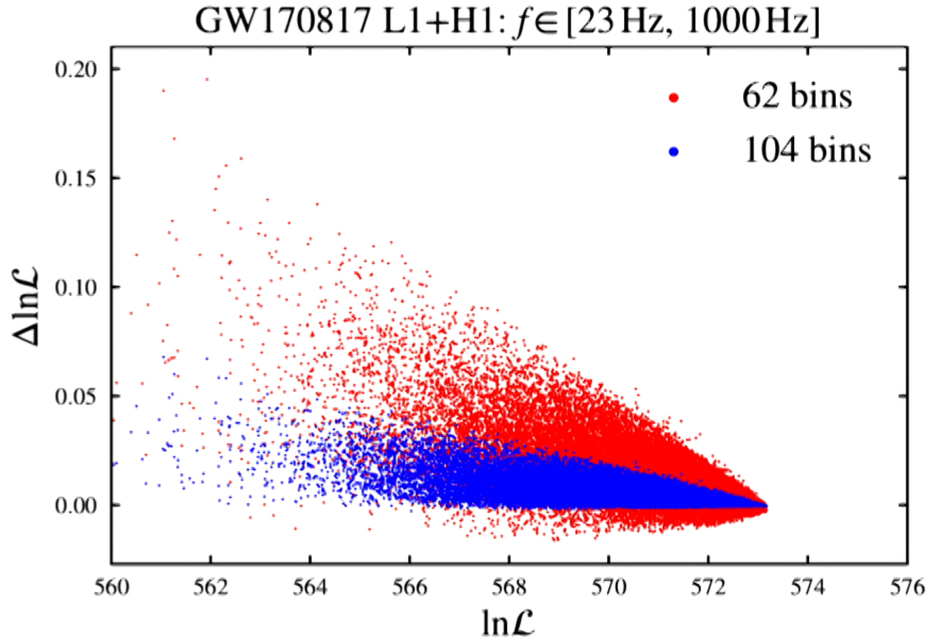
# Relative Binning: GW170817

Zackay, Dai & Venumadhav 1806.08792
Also see earlier exploration:
Tanaka & Tagoshi (2000)
N. Cornish 1007.4820

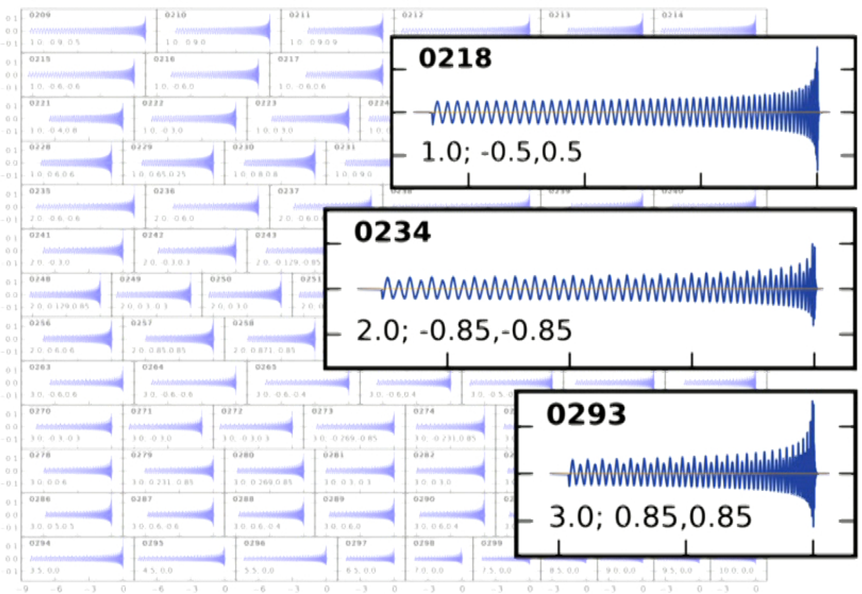
Absolute error on the log likelihood under control
Use O(100) frequency bins

Non-uniform frequency bins



# Template Bank



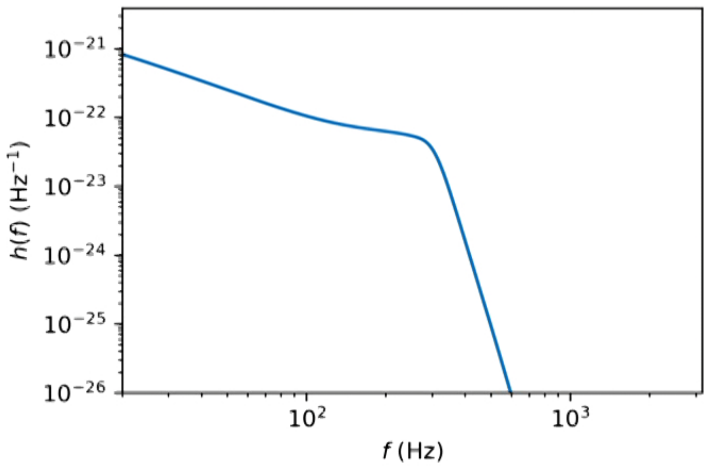

- Necessary to try out a large number of waveform templates
- Should not try out templates that cannot be realized in any physical binary sources
- Should not repeat trying out templates that are indistinguishable from each other at given noise level.
- Should not repeat trying out templates that correspond to different source parameters but are actually (nearly) identical

Need an economic but effectual template bank !!

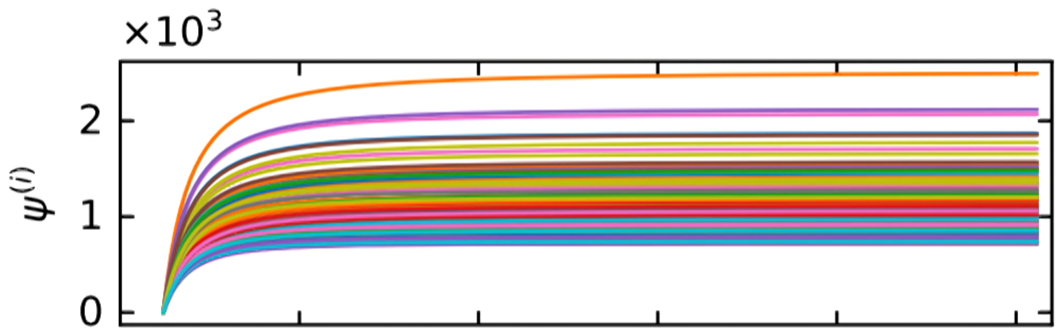
# Template Bank: Amplitude and Phase

In frequency domain

$$h(f;\boldsymbol{p}) = \underbrace{\boxed{A(f;\boldsymbol{p})}}_{\text{amplitude profile}} e^{i\overbrace{\boxed{\phi(f;\boldsymbol{p})}}^{\text{(unwrapped) phase profile}}}$$




Amplitude is smooth and non-oscillatory




The (unwrapped) phase evolves over many many radian.

Need to track to within a small fraction of an radian

Otherwise, “match” is lost.

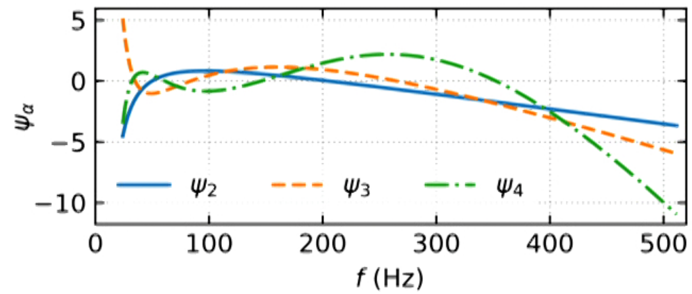
# A Geometric Solution

Roulet+ 1904.01683

Construct a linear space of phases

$$\phi(f) = c_0 + c_1\, f + \sum_{\alpha=2}^{n} c_\alpha\, \psi_\alpha(f)$$

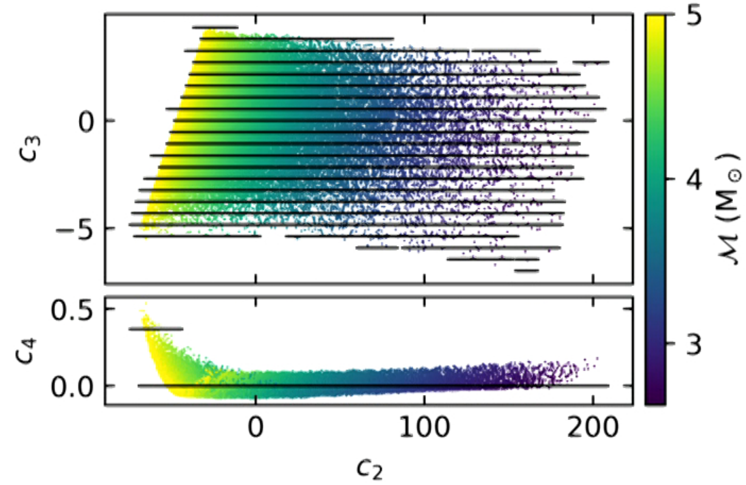
Only a few extra bases are needed




Orthonormalize the basis phase profiles

$$\langle \psi_\alpha, \psi_\beta \rangle = \sum_f \frac{\bar{A}^2(f)}{S_N(f)/4}\, \psi_\alpha(f)\, \psi_\beta(f) = \delta_{\alpha\beta}$$

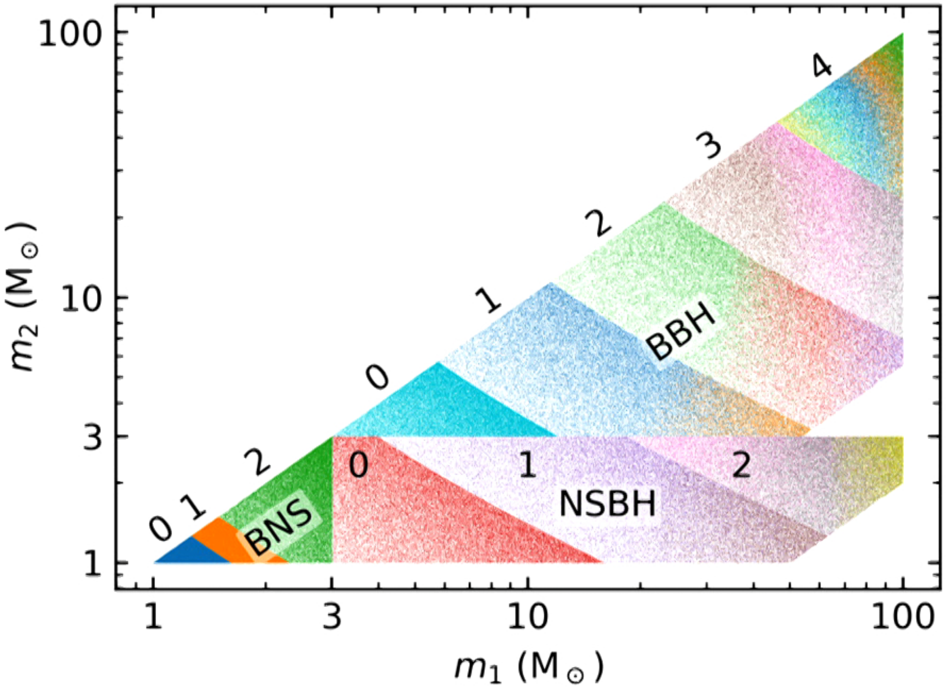
The bank is defined as a lattice




Such that the "Euclidean" distance in terms of the c-coefficients measure "mismatch"

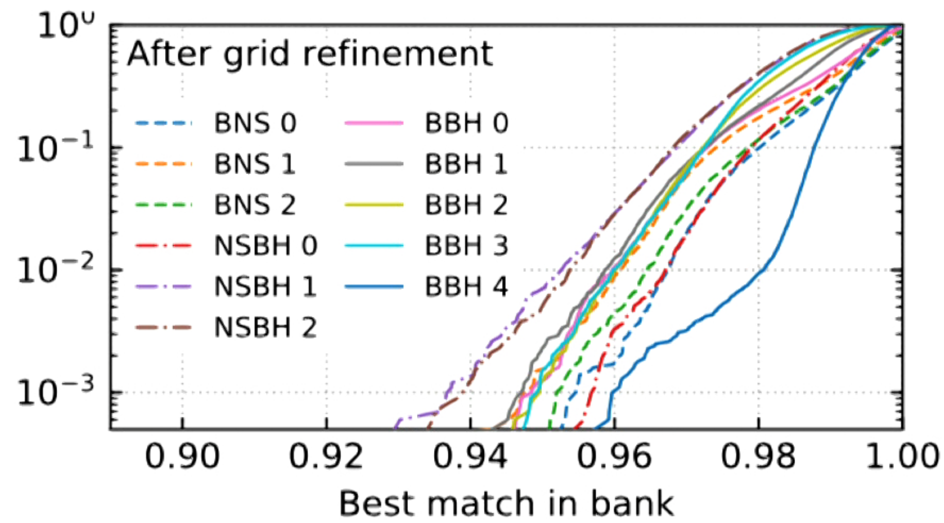
# Template Banks According to Amplitude

Construct this metric space of phases for a group of waveforms that share similar amplitude profiles.




If used in search, only lose **a few percent in SNR² (i.e. match)**

Roulet+ 1904.01683



# Matched Filter: Trigger Statistics

A template waveform only needs to be defined up to:

Babak+ 2013
Abbott+ 2017

An amplitude normalization;
A phase constant;
The time of arrival.

$$h(f) \longrightarrow A\, e^{i\,\phi_c + i\,2\pi\, f\, t_c}\, h(f)$$

For normalized template

$$(h|h) = \sum_f \frac{|h(f)|^2}{S_N(f)/4} = 1$$

Define trigger score

$$Z(d|h) := (d|h) = \sum_f \frac{d(f)\, h^*(f)}{S_N(f)/4}$$

If perfect stationary gaussian noise, Z has **chi-square statistics with 2 DOF**
Astrophysical signals would stand out of the tail (decay exponentially with $|Z|^2$)

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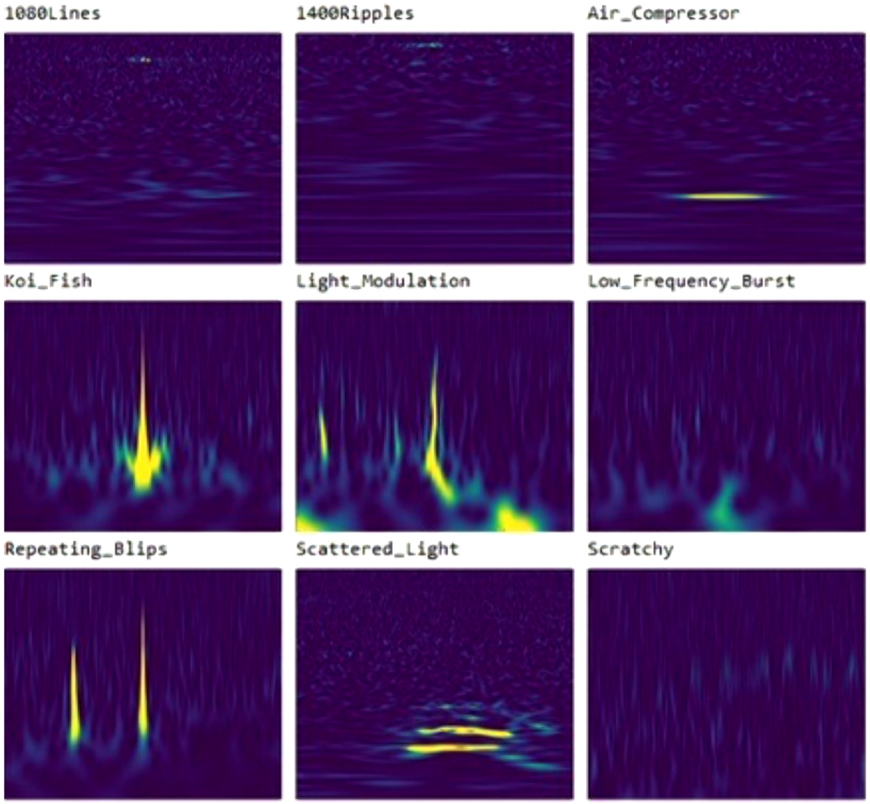
# Noise Transients ("Glitches")

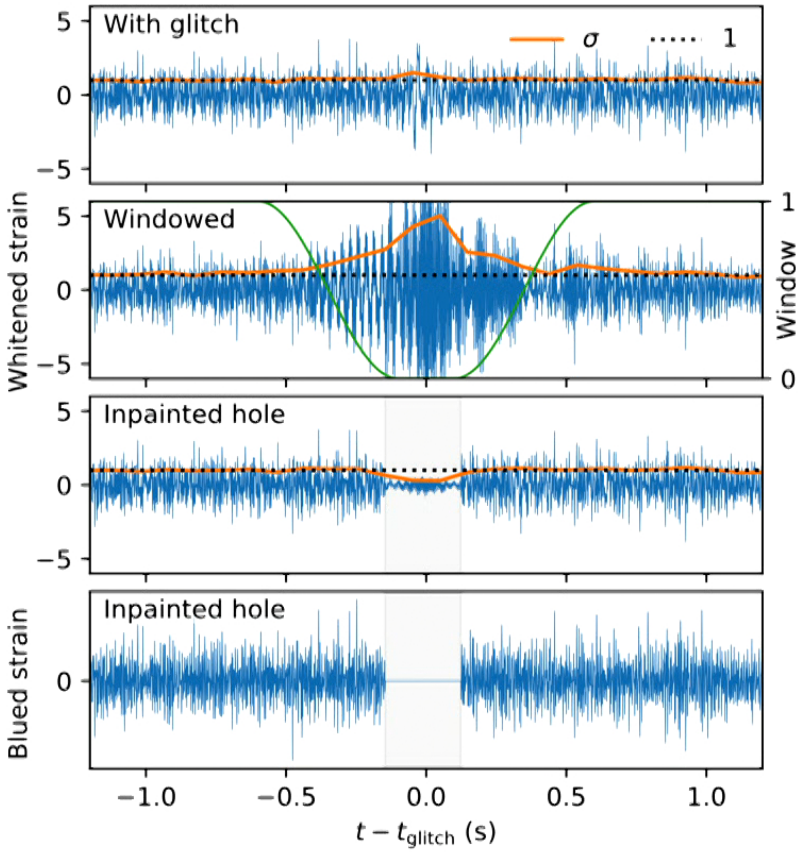



Abbott+ 2017

We identify and mask out bad seconds

| Test type | Frequency band | Excess duration (s) | Hole duration (s) |
|---|---|---|---|
| Whitened outlier | [20, 512] | $10^{-3}$ | 0.6 |
| | [20, 512] | 0.2 | 0.2 |
| | [20, 512] | 1 | 1 |
| | [55, 65] | 1 | 1 |
| | [70, 80] | 1 | 1 |
| | [40, 60] | 1 | 1 |
| Excess power | [40, 60] | 0.5 | 0.5 |
| | [20, 50] | 1 | 1 |
| | [100, 180] | 1 | 1 |
| | [25, 70] | 0.1 | 0.1 |
| | [20, 180] | 0.05 | 0.05 |
| | [60, 180] | 0.025 | 0.025 |
| | [25, 70] | 0.2 | 1 |
| | [55, 65] | - | 0.1 |
| | [20, 60] | - | 0.1 |
| | [100, 140] | - | 0.1 |
| Sine-Gaussian[a] | [50, 150] | - | 0.1 |
| | [70, 110] | - | 0.1 |
| | [50, 90] | - | 0.1 |
| | [125, 175] | - | 0.1 |
| | [75, 125] | - | 0.1 |

# Careful Treatment of Masked Data




Matched filter is **not local in time**

Zeroing the bad samples in time causes leakage of ringing artifacts

Conventional to apply smooth windows.

We solve a linear algebra problem to guarantee no leakage
(analogous to inpainting the masked CMB sky within the Galactic plane)

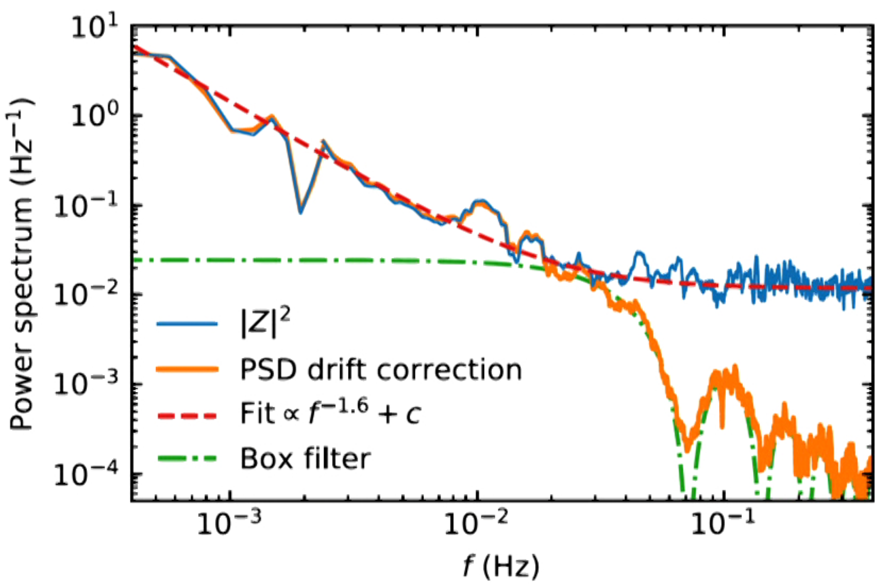
$$(d|h) = \sum_f \boxed{\frac{d(f)}{S_N(f)/4}} h^*(f)$$

Should just zero **the blued strain**

# PSD Drift

In order to well resolve the lines in the PSD, need to measure over **O(1000) seconds of data**

Empirically, we found that the PSD is changing over O(10) seconds, by ~ 10%




Tail of the Z distribution is badly over-produced !

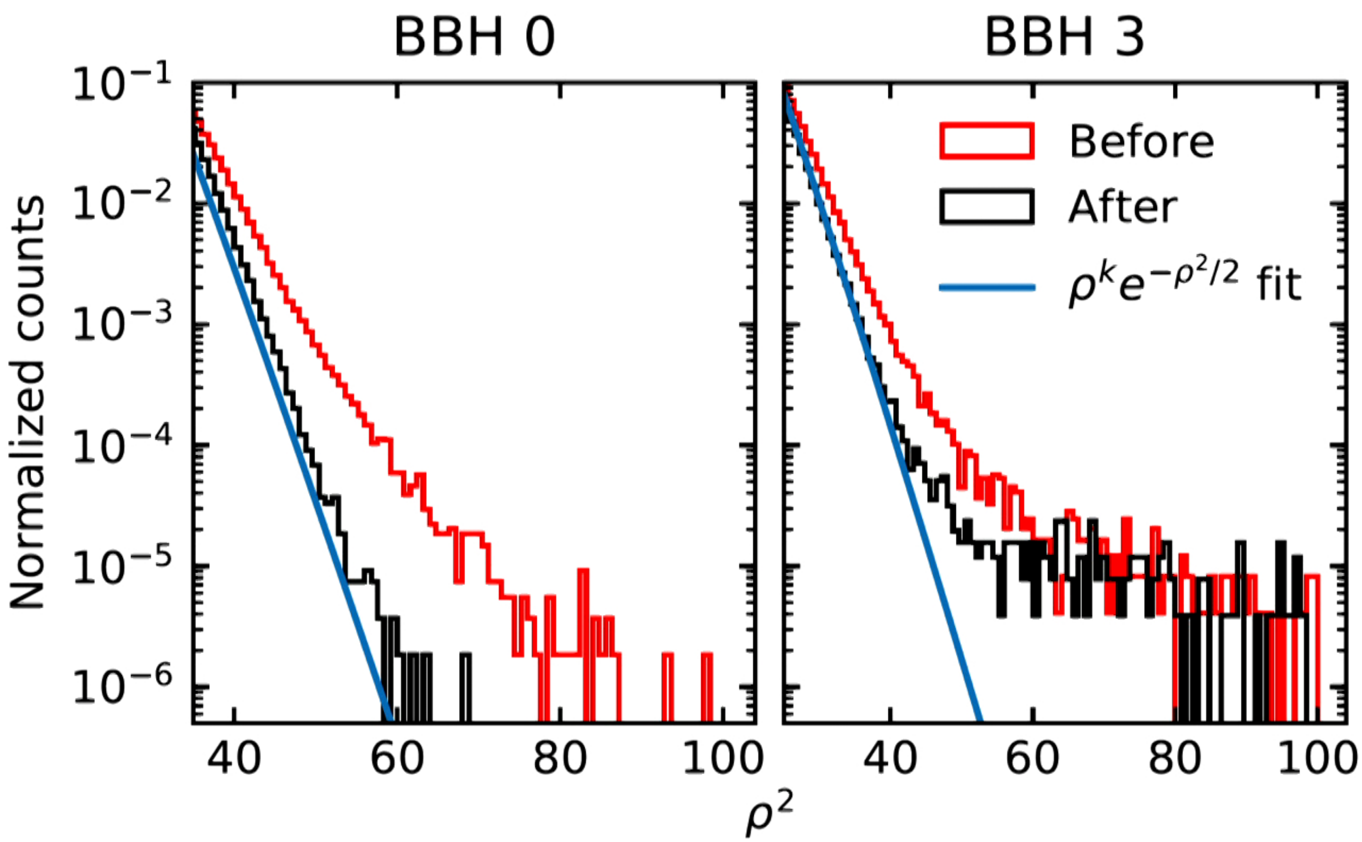
$$Z(d|h) := (d|h) = \sum_f \frac{d(f)\, h^*(f)}{S_N(f)/4}$$

**Solution:**
We track the std of Z to ~ 1% precision on time scales of O(10) seconds!

**This correction only depends on the amplitude profile of h(f), but not the phase!**

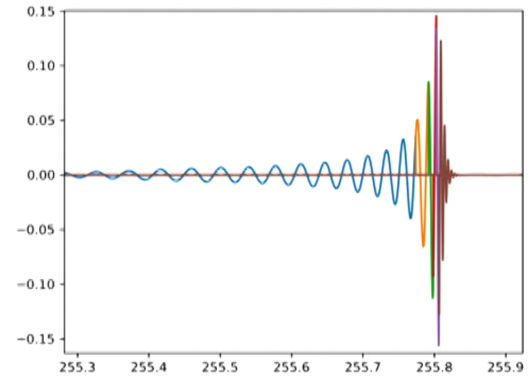
**We therefore track PSD drift bank by bank.**

# Trigger Distribution After PSD Drift Correction



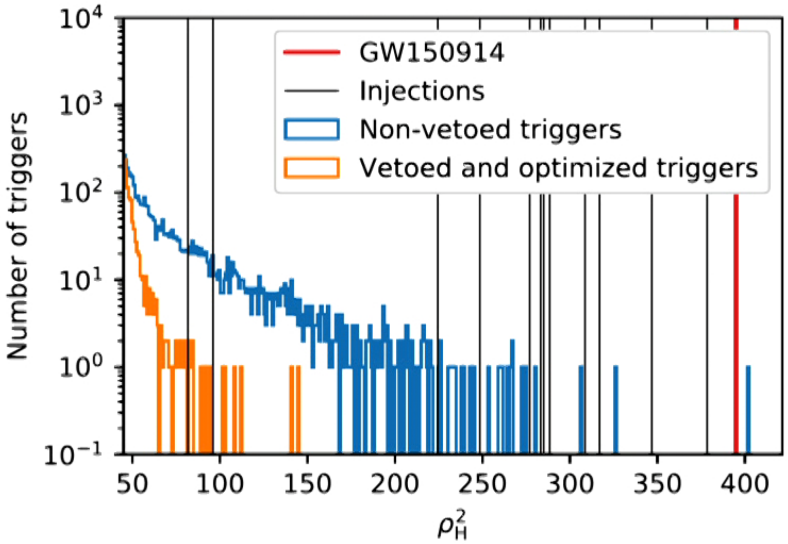
# Vetoing Triggers

Check if different frequency ranges contribute to the “match” according to theoretical expectations

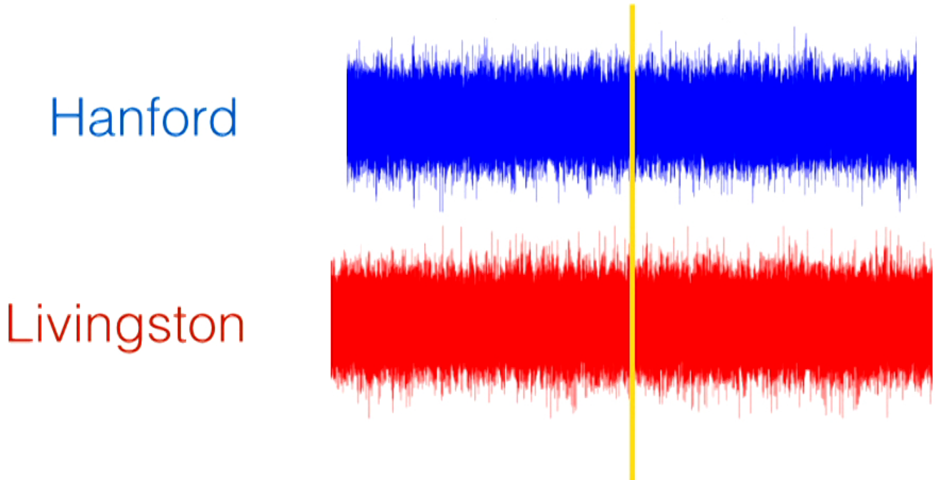


Promise:

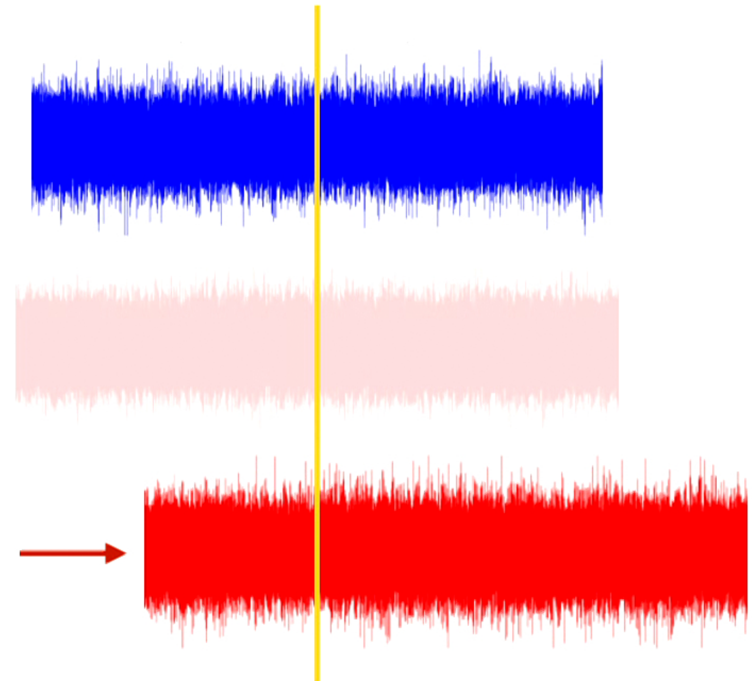
- **False positive rate** < 1% for perfect Gaussian noise
- Robust to **PSD drift** and to **template bank inefficiency**



# Search For Coincidence




Zero time lag

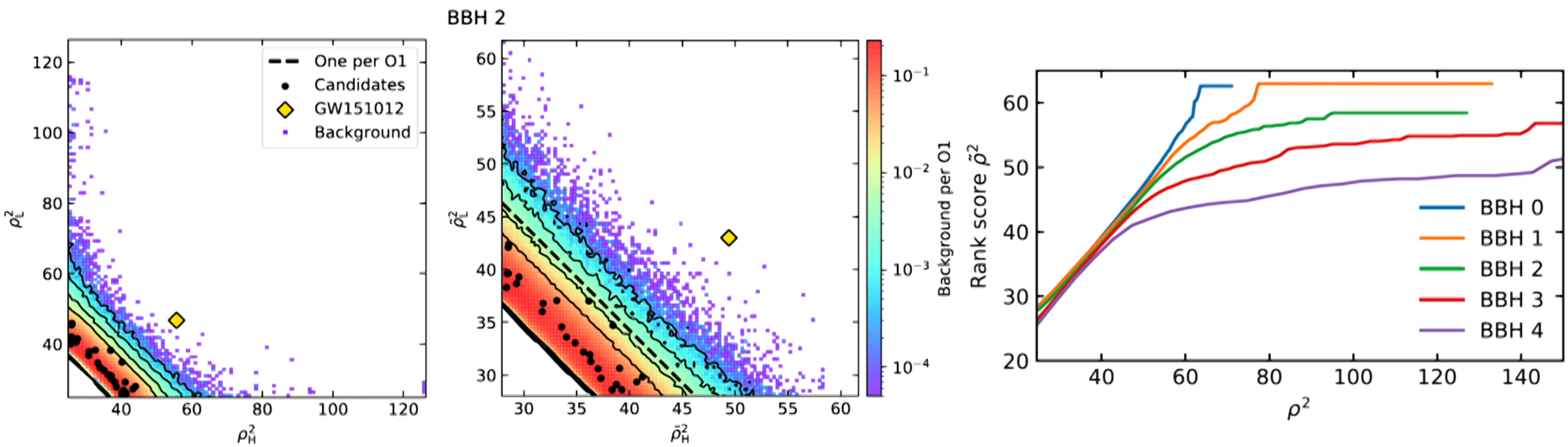


Record if the same template matches in two detectors at (nearly) the same time.

Genuine GW signal is subject to **a maximal time delay** between any two detectors

Unphysical time lags provide an empirical way to generate coincidences of **uncorrelated noise transients**.

# (Incoherent) Ranking Score




In this way we calculate the false alarm rate (FAR)

# Probability of Astrophysical Origin

Need to compare the **GW hypothesis** $H_1$ to the **noise hypothesis** $H_0$

$$p_{\rm astro}(\text{event}|\mathcal{R}_{\rm GW}) = \frac{\mathcal{R}(\text{event}|H_1)}{\mathcal{R}(\text{event}|H_0) + \mathcal{R}(\text{event}|H_1)}$$

Noise hypothesis
measure empirically

$$\mathcal{R}(\text{event} \mid H_0) = \mathcal{R}_{\rm bg} P(\Delta t, \Delta\phi, \rho_{\rm H}^2, \rho_{\rm L}^2 \mid H_0)$$
$$= \mathcal{R}_{\rm bg} \frac{P(\rho_{\rm H}^2 \mid H_0) P(\rho_{\rm L}^2 \mid H_0)}{2\pi T}.$$

GW hypothesis

$$\mathcal{R}(\text{event}|H_1) = \boxed{\mathcal{R}_{\rm GW}} P\left(\Delta t, \Delta\phi, \rho_{\rm H}^2, \rho_{\rm L}^2 | H_1\right)$$

**GW rate normalization is a free parameter subbank by subbing**

Bayesian inference for rate normalization

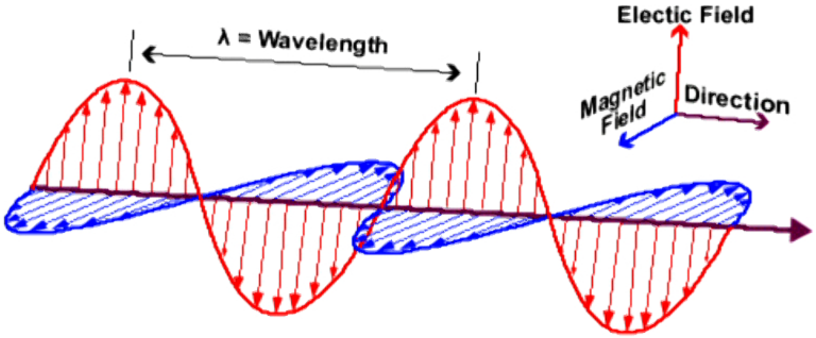
$$\mathcal{L}(\mathcal{R}_{\rm GW}) \sim e^{-\mathcal{R}_{\rm GW}} \prod_{\text{events}} \left[\mathcal{R}(\text{event}|H_0) + \mathcal{R}(\text{event}|H_1)\right]$$

Marginalized probability

$$p_{\rm astro}(\text{event}) = \int d\mathcal{R}_{\rm GW}\, P(\mathcal{R}_{\rm GW})\, p_{\rm astro}(\text{event}|\mathcal{R}_{\rm GW})$$

# A New Window Into the Universe

Electromagnetic waves




Gravitational waves:

Transverse sinusoidal distortion in the **space-time metric**