Detecting Gravitational waves on the public O1/O2 data

Barak Zackay
Tejaswi Venumadhav, Javier Roulet, Liang Dai and Matias Zaldariaga
Institute for Advanced Study, Princeton

Bottom line

- We have a full fledged pipeline for detecting gravitational wave mergers.
- LVC had announced 10 BBH mergers in the first two observing runs.
- We have detected 9 more events.
  - 7 published, 2 more will join soon.
  - More surprises to come!
- We have a method for fast parameter estimation, that allows fast and cheap parameter estimation.

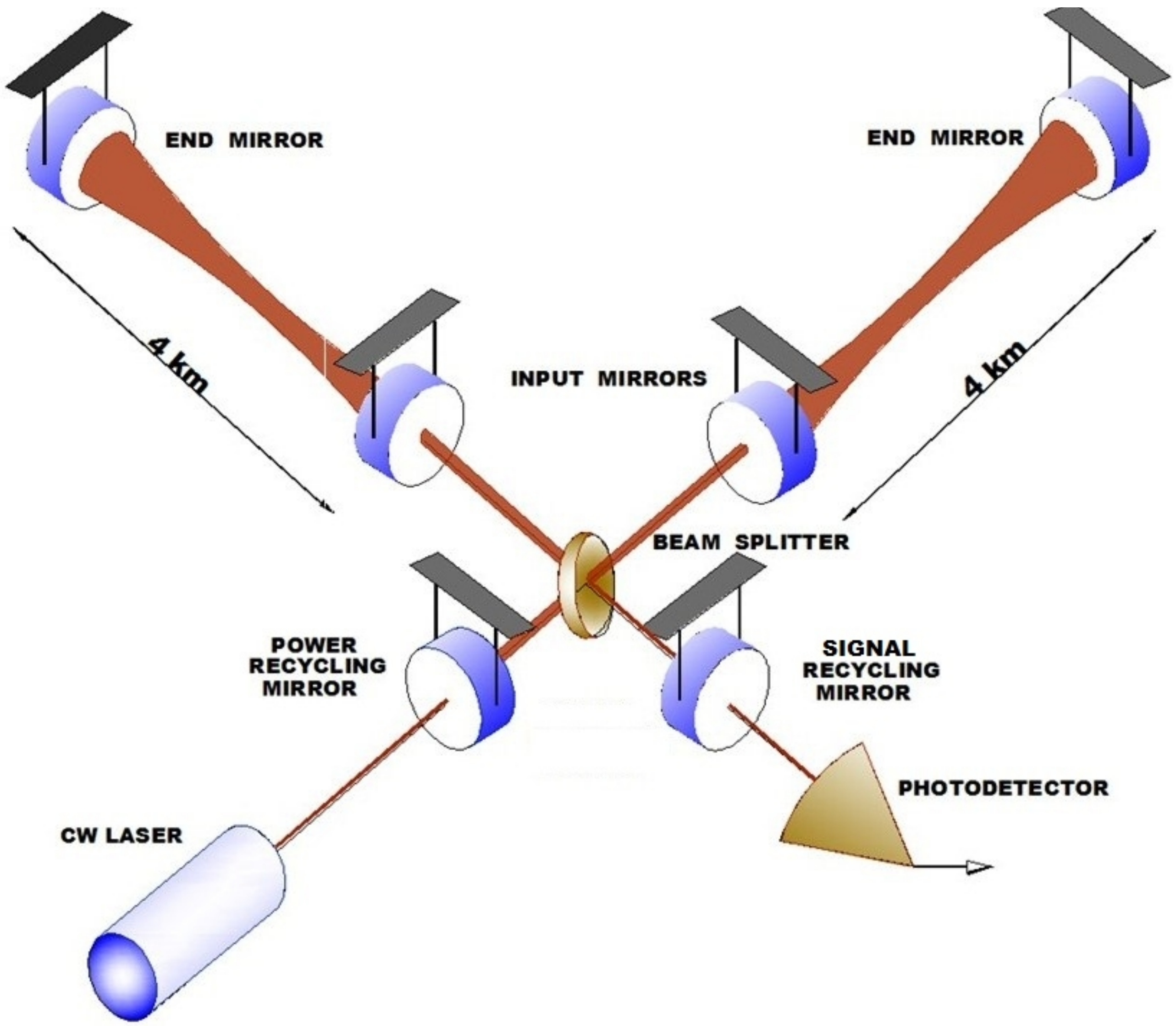
Similarity to LVC pipelines

- Matched filtering based (akin to pyCBC, GSTLAL)
- Coherent combination of the detectors (akin to pyCBC, GSTLAL)
- Empirical determination of final statistic (akin to GSTLAL)
- Significance based on time slides (akin to pyCBC)

Differences from LIGO data analysis

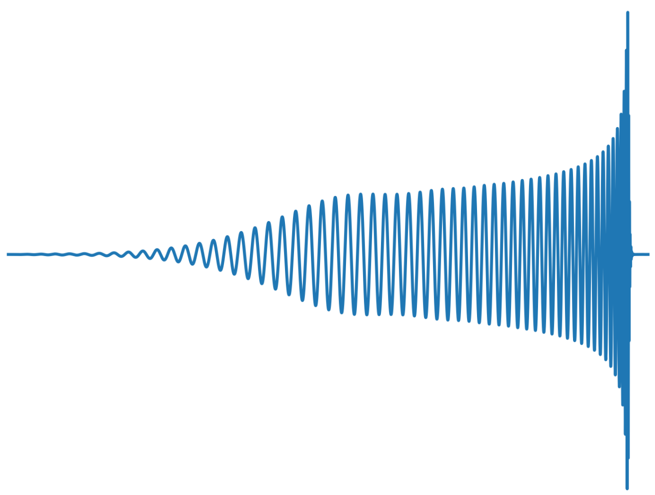
- Novel template bank construction.
- Automatic routines to detect bad data segments (``glitches") and insulate good data from them.
- Proper accounting for the non-stationary nature of the detector noise
- New signal-quality vetoes at the single-detector level, with rigorously computed False negative.
- New ways to combine results from multiple detectors.
- New way to “Fish” single detector candidates accompanied by a very weak counter signal in the other detector.
- Fast way to compute likelihood values for parameter estimation.

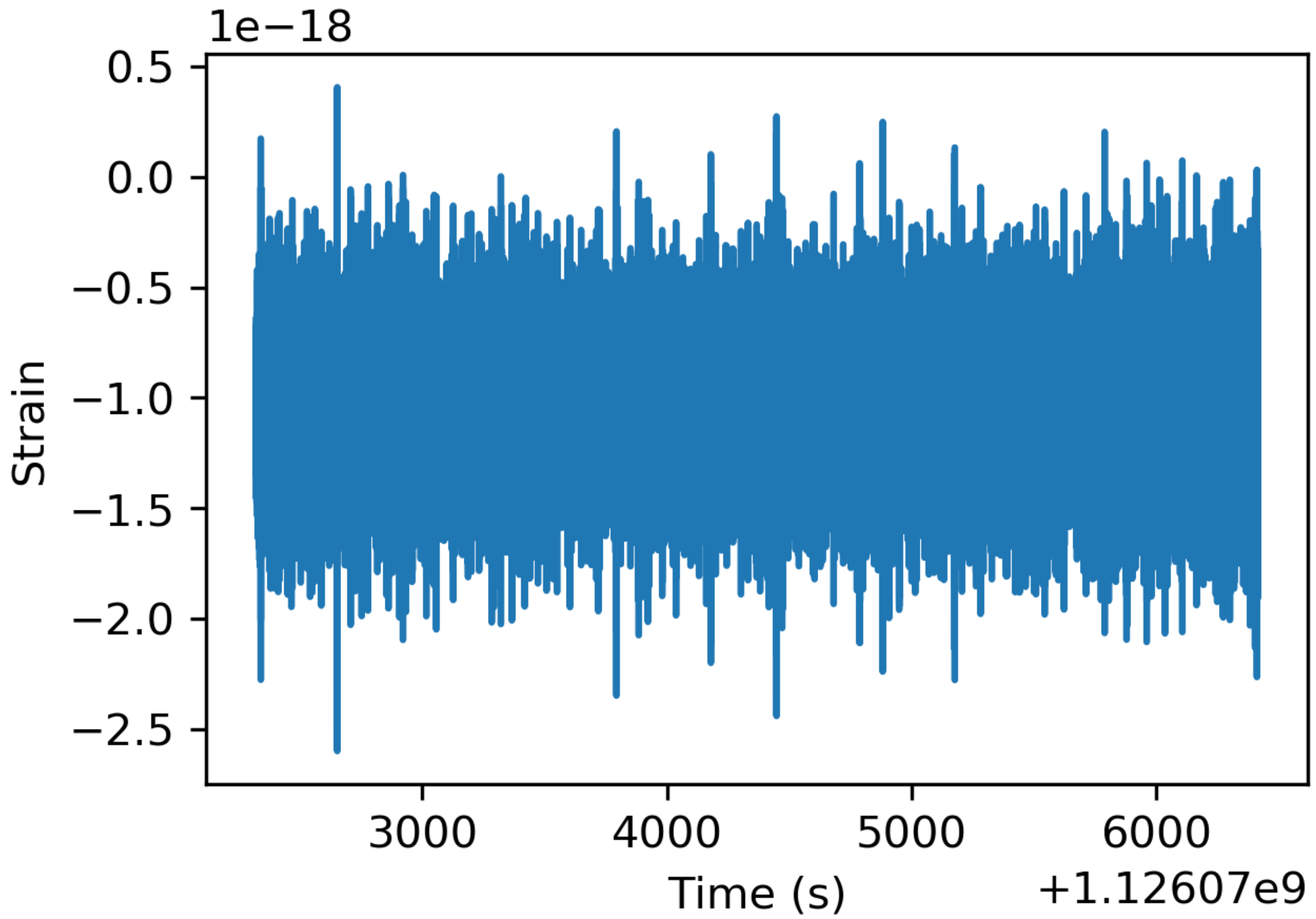
LIGO-VIRGO Detectors



Credit: Carruthers and Reitze (2015)

Looking for GWs



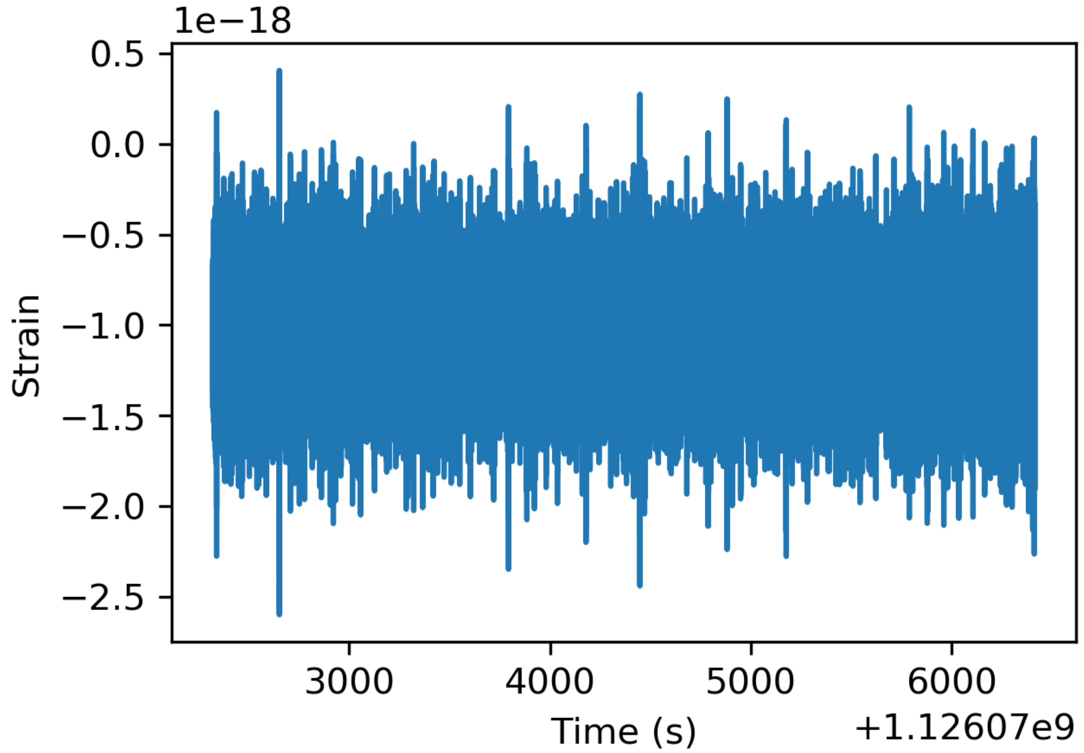


Need a noise model, simplest case is stationary Gaussian random noise

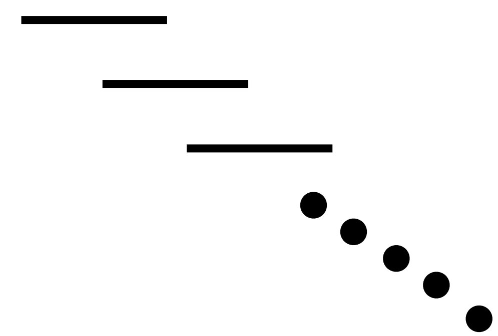
$$\langle s(t+\tau)s(t)\rangle = C(\tau)$$

FT of $C(\tau)$ **is the PSD** $S(f) \sim \sigma_f^2 \equiv \langle |s(f)|^2 \rangle$

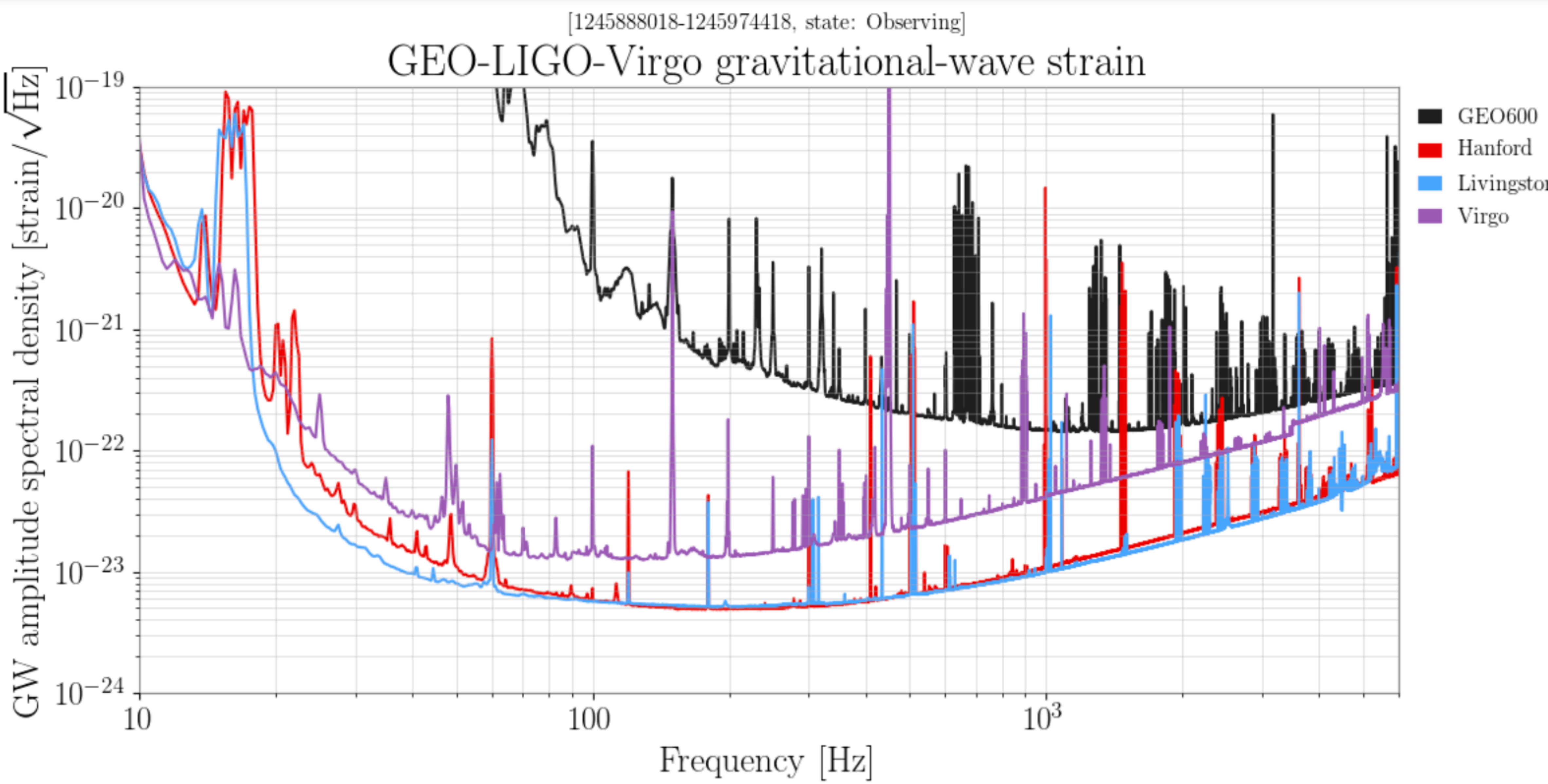
No one tells you what $S(f)$ **is! Have to measure, and compare to your guess**



PSD Measurement



Welch's method



Matched Filtering

Suppose you measure a $\sigma^2(f)$ on data d and want to look for a waveform h

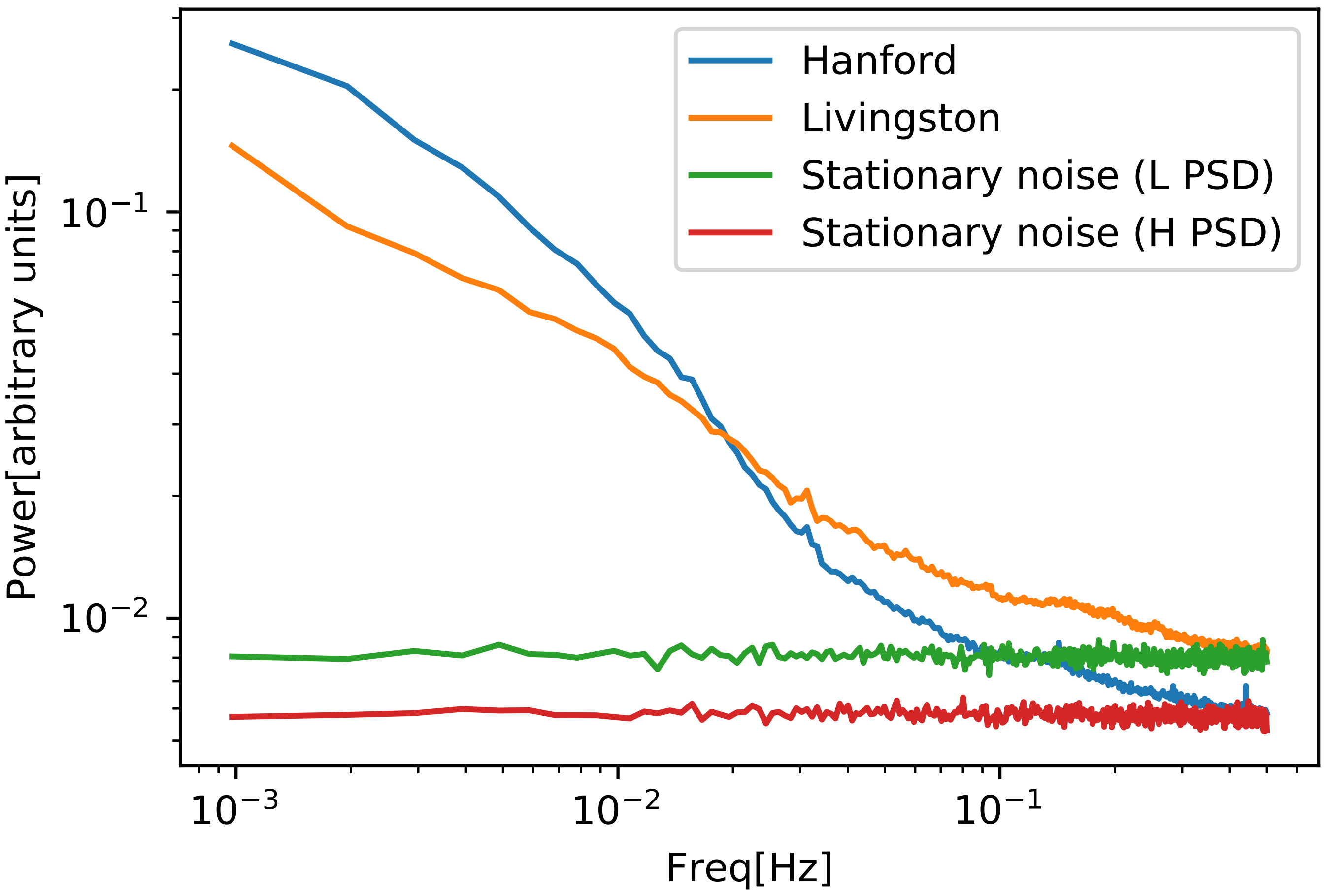
Gaussian noise is uncorrelated between frequencies, so compute the inverse-variance-weighted overlap of the data and the waveform in the frequency domain

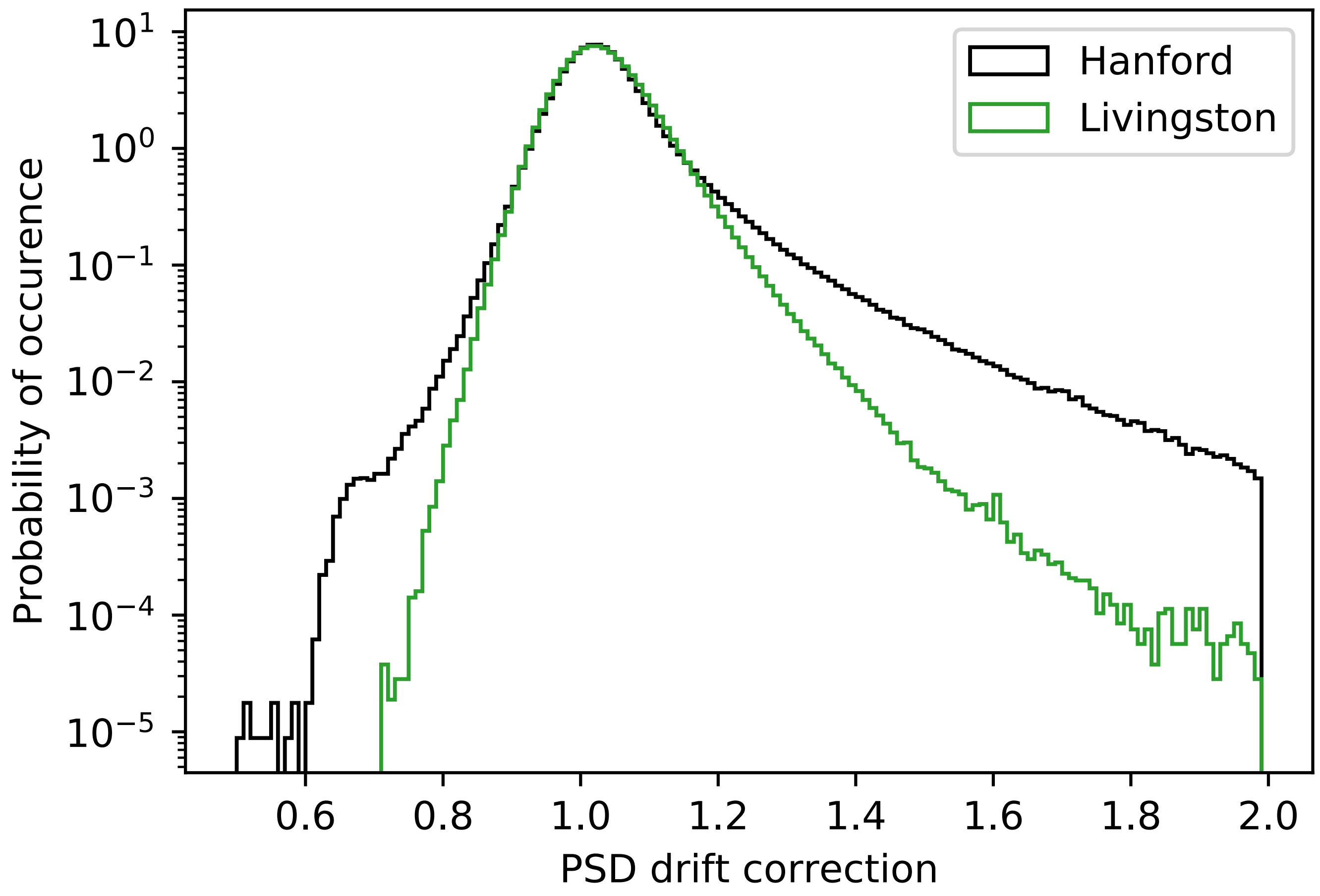
$$Z(h) = \sum_f \frac{d(f)h^\star(f)}{\sigma^2(f)}$$

$$\rho \equiv \mathrm{SNR} = \frac{Z(h)}{\langle Z(h)^2 \rangle^{1/2}} = \frac{\dfrac{\sum_f d(f)h^\star(f)}{\sigma^2(f)}}{\left[\dfrac{\sum_f |h(f)|^2}{\sigma^2(f)}\right]^{1/2}}$$

If everything is OK, the SNR^2 should be distributed according to a chi-squared distribution

The PSD drifts





PSD drift correction

$$\frac{Z}{\sigma_Z} = \frac{\sum_f \frac{h^*(f)d(f)}{S_n(f)}}{\sqrt{\sum_f \frac{|h(f)|^2}{S_n(f)}}}$$

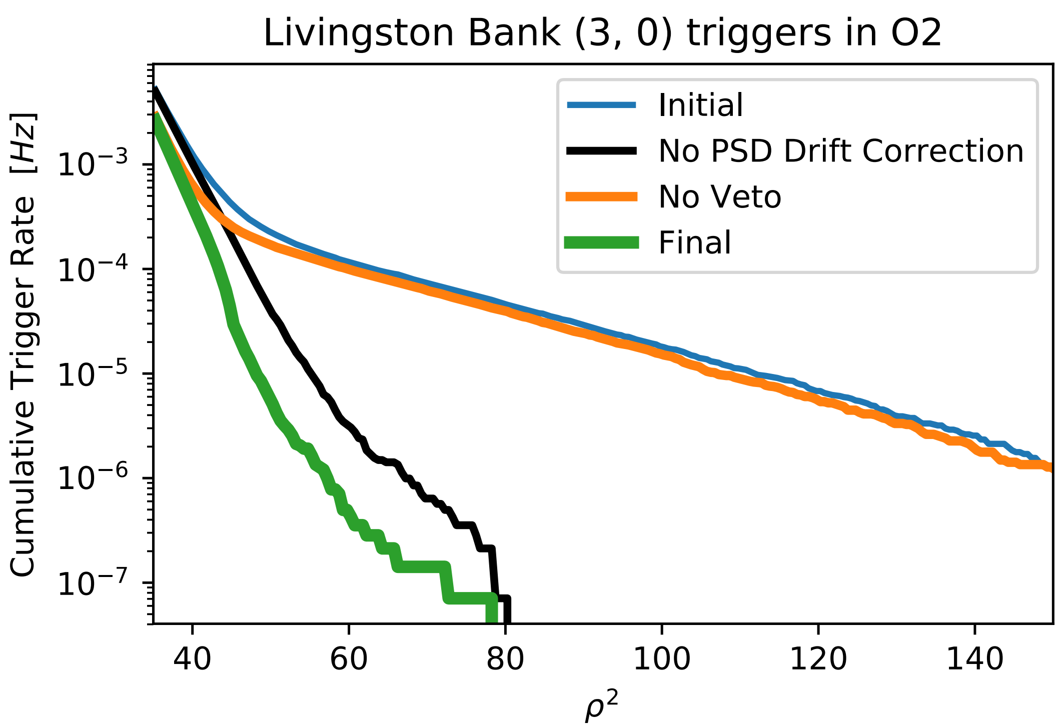
- PSD estimation requires ~1000s of seconds
- But PSD changes on time-scales of 10s of seconds.
- What happens when adding variables with incorrect coefficients?
- SNR is reduced by $O(\epsilon^2)$
- But standard deviation changes by $O(\epsilon)$

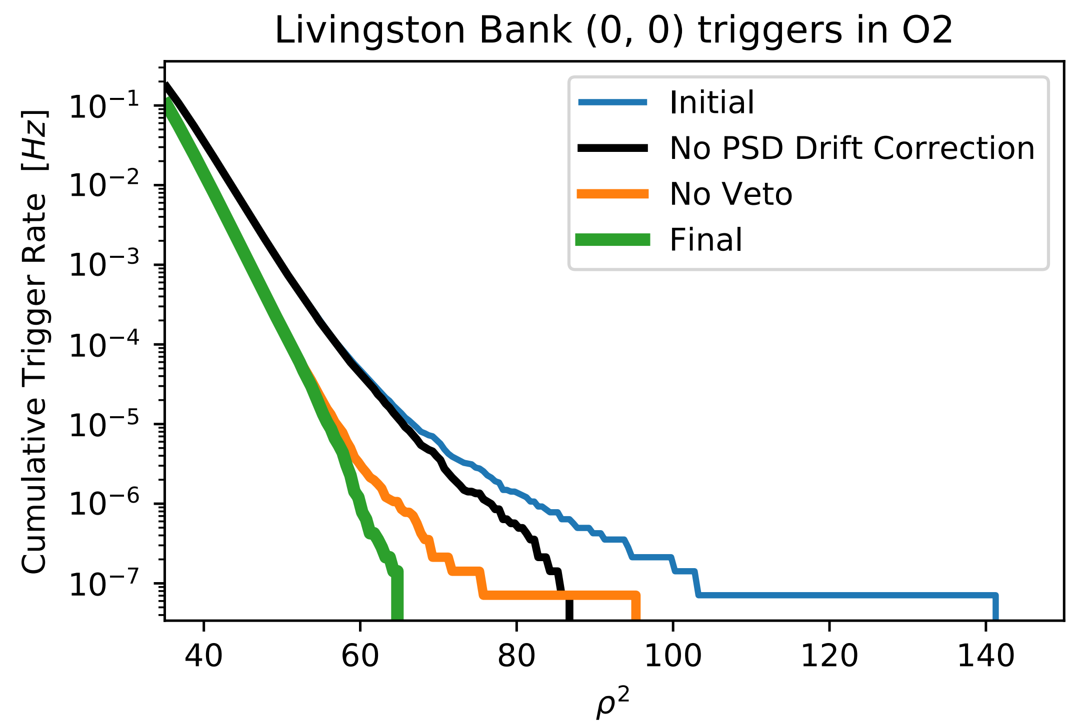
$$S_{\text{opt}} = X1 + X2$$

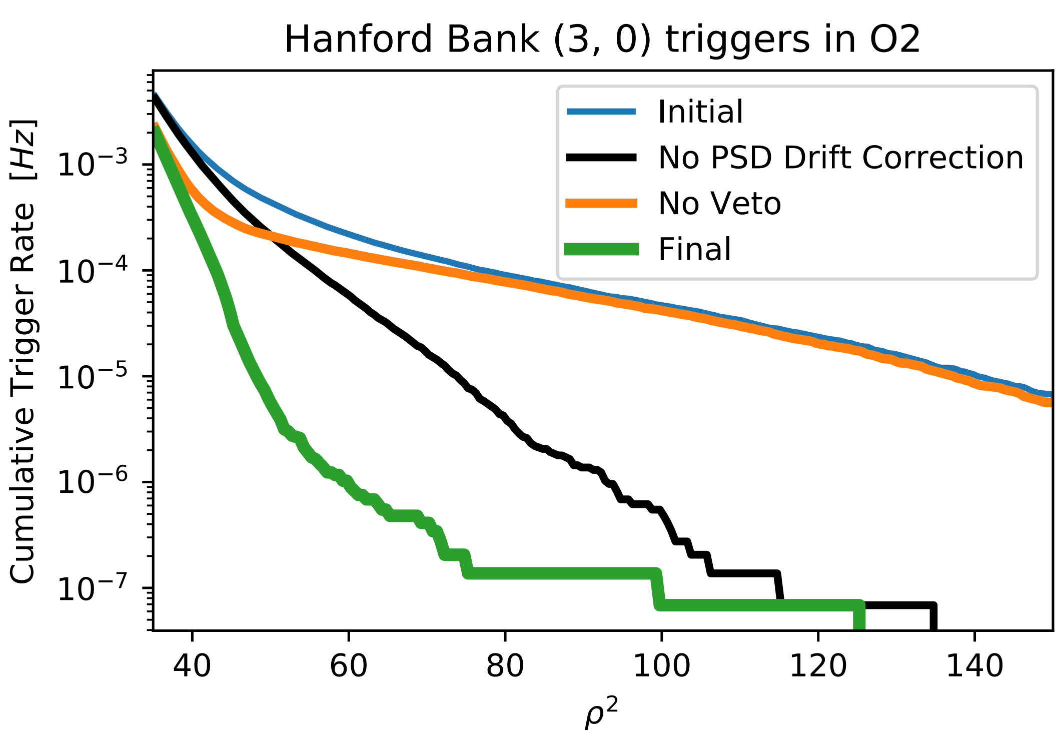
$$\downarrow$$

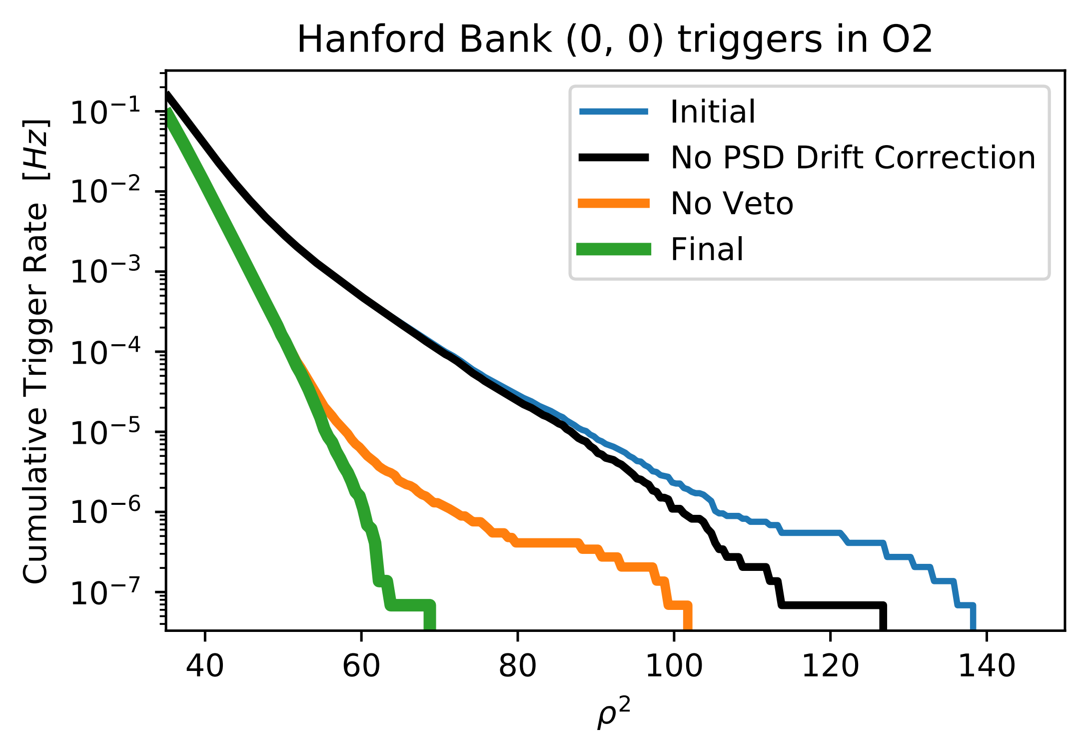
$$S_{\text{practical}} = X1 + (1+\epsilon)X2$$

Trigger distributions





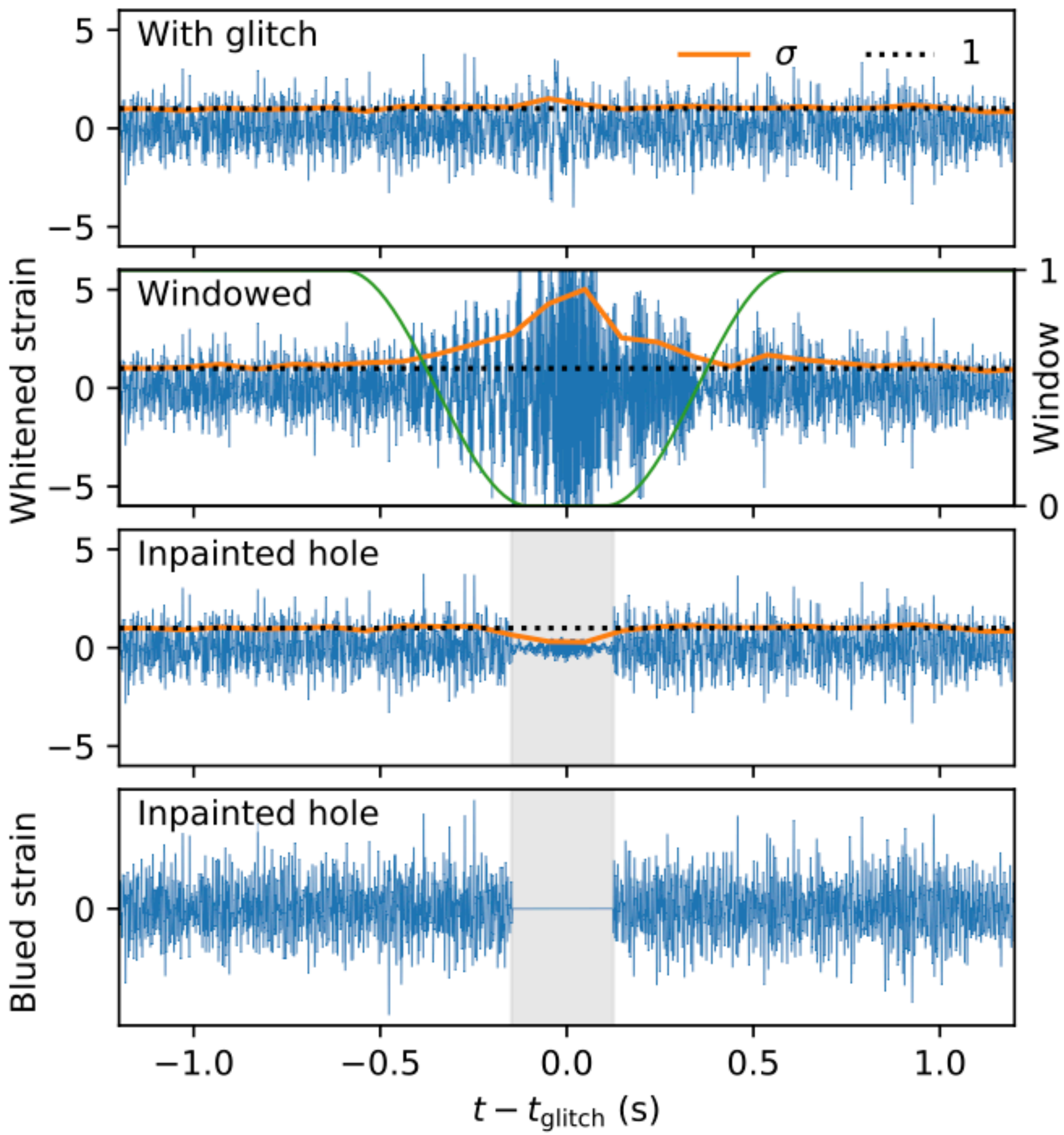


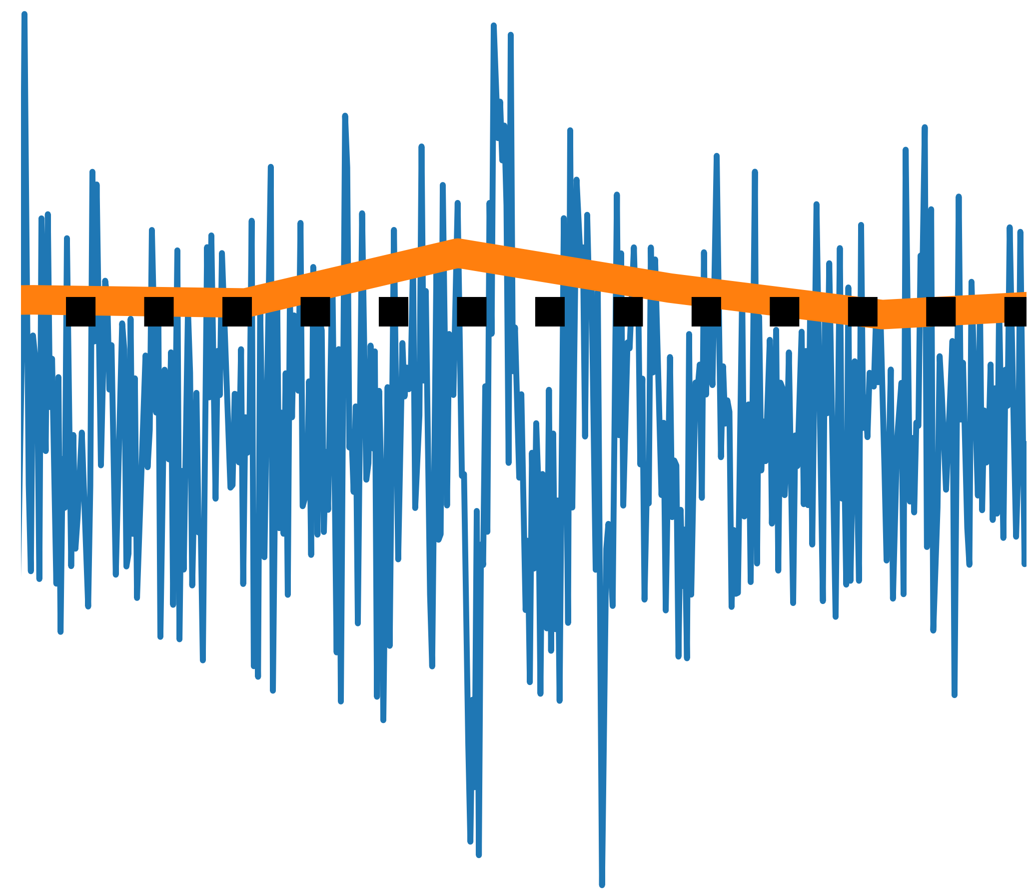


What do we do with holes?

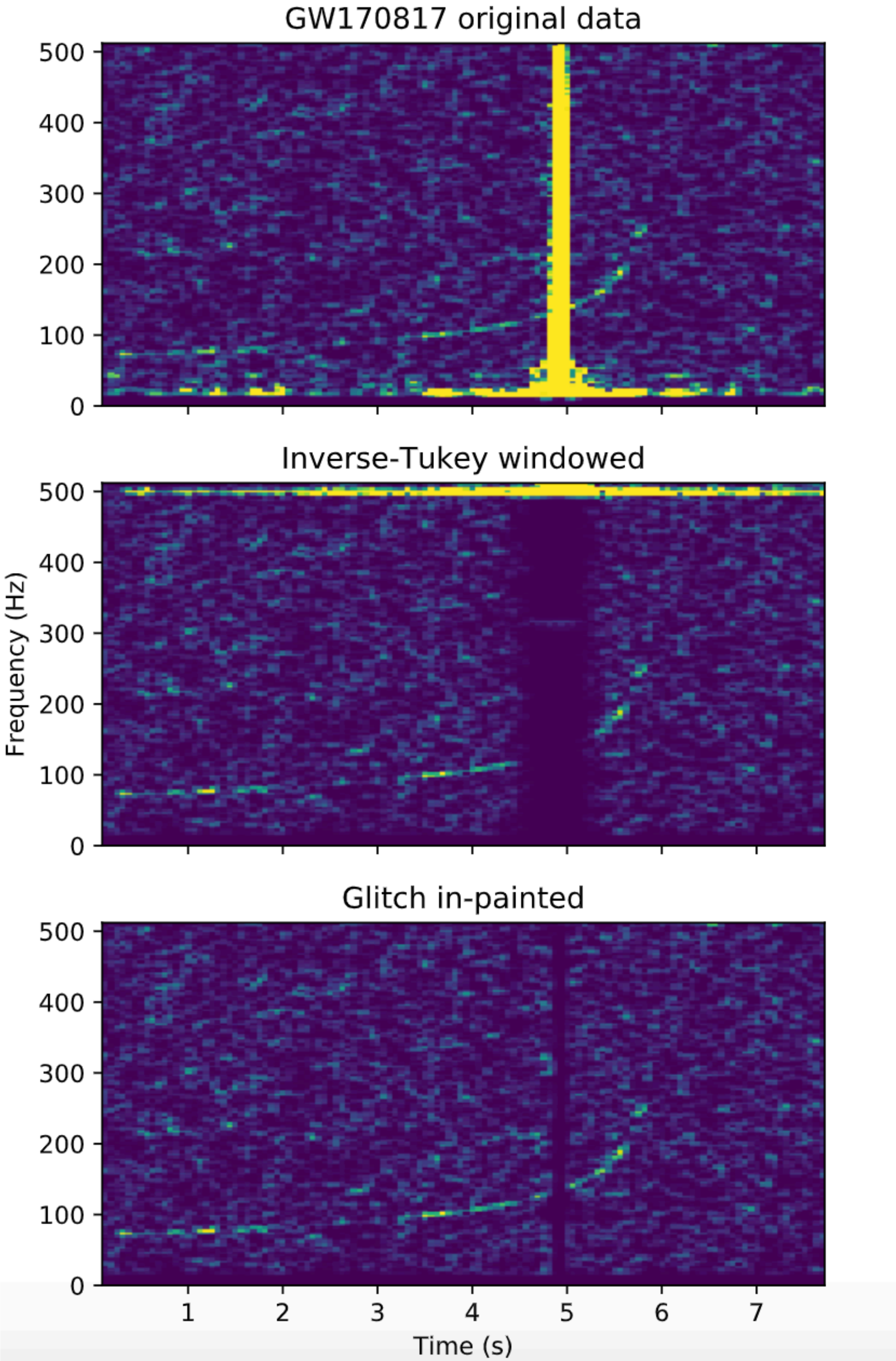
- Must not “remove samples” - Lines would leak out
- Rephrasing of the problem:
    - Insertion of an infinitely loud white noise process added to the bad segment.
    - Solve the least squares linear algebra problem of measuring amplitude.
    - Identify the relevant data equivalent
    - Solution: Inpaint the samples in the bad segment to the value expected by the rest of the data

Hole correction in practice





$$\frac{Z}{\sigma_Z} = \frac{\sum_f \frac{h^*(f)d(f)}{S_n(f)}}{\sqrt{\sum_f \frac{|h(f)|^2}{S_n(f)}}}$$



Applied to GW170817

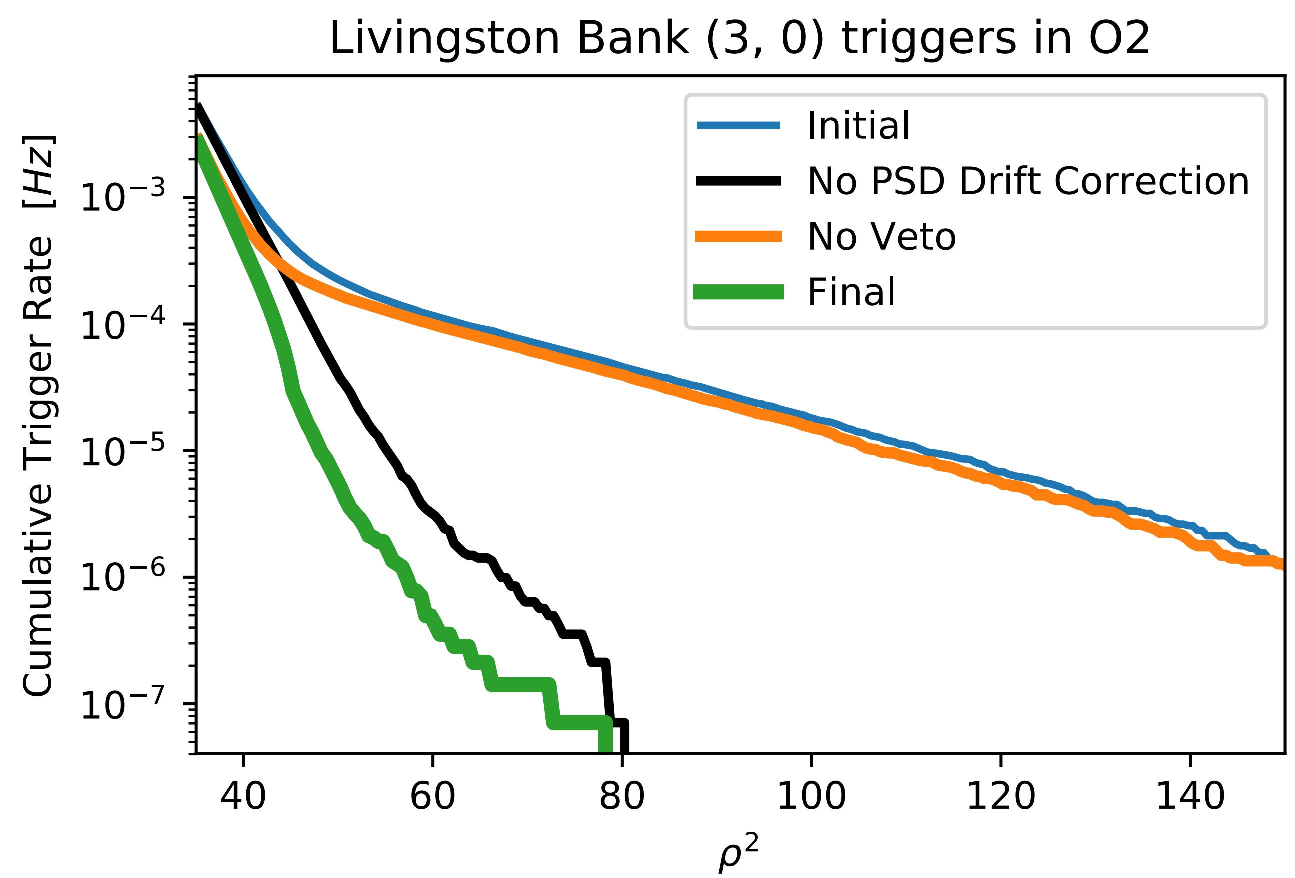
Vetoing Candidates

- Check for consistency between frequency bands

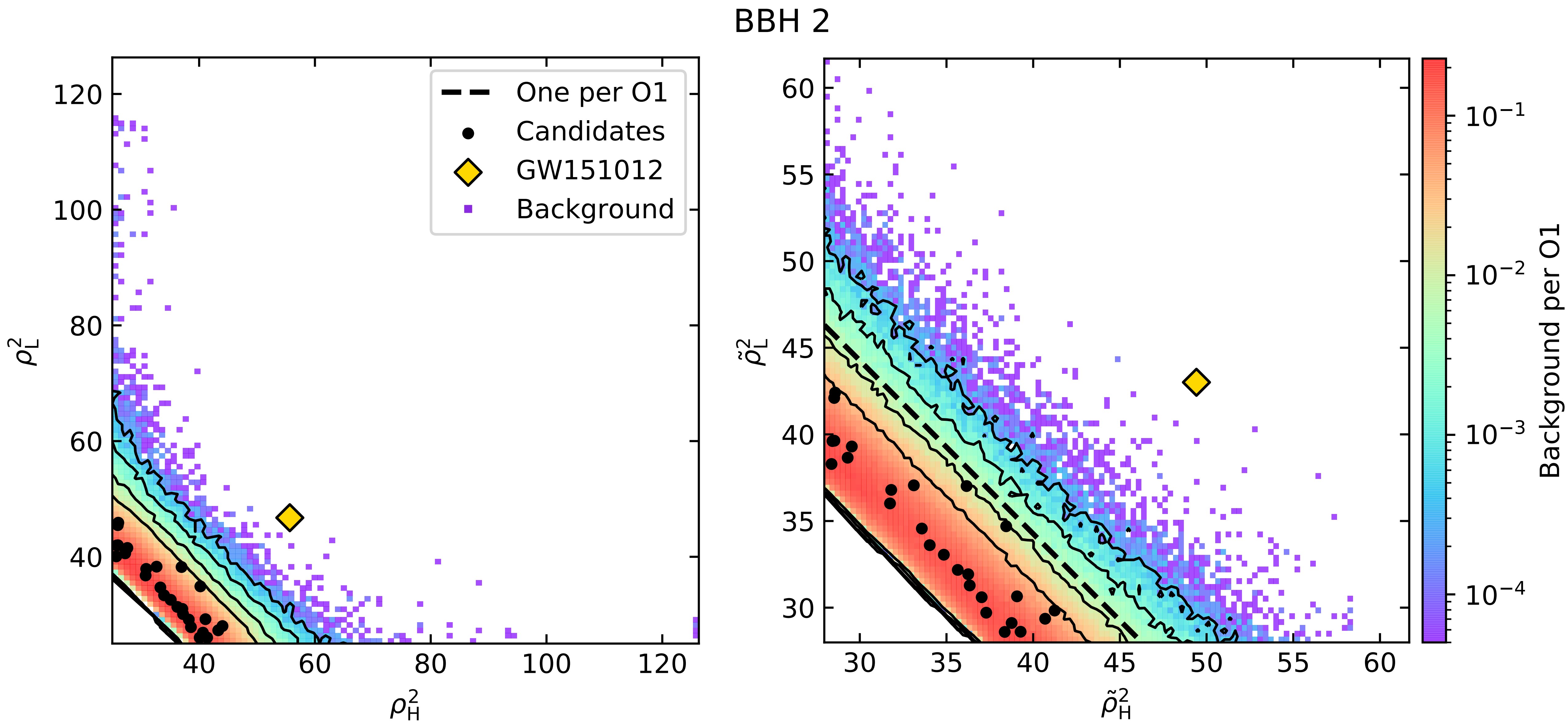
- Promise:

    - False negative rate is smaller than 1% on Gaussian noise

    - Robust to PSD drift and to template-bank inefficiency



Ranking Score



Coherent Score

Rank background + candidates according to the ratio

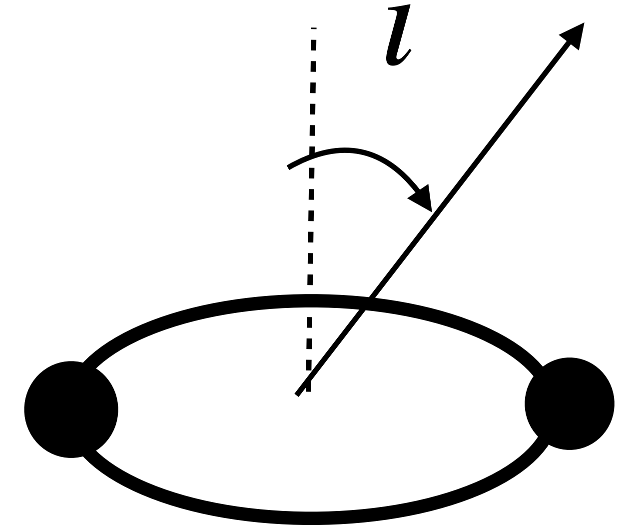
$$\frac{p(\rho_1^2, \rho_2^2, \Delta t, \Delta\phi \,|\, H1)}{p(\rho_1^2, \rho_2^2, \Delta t, \Delta\phi \,|\, H0)}$$

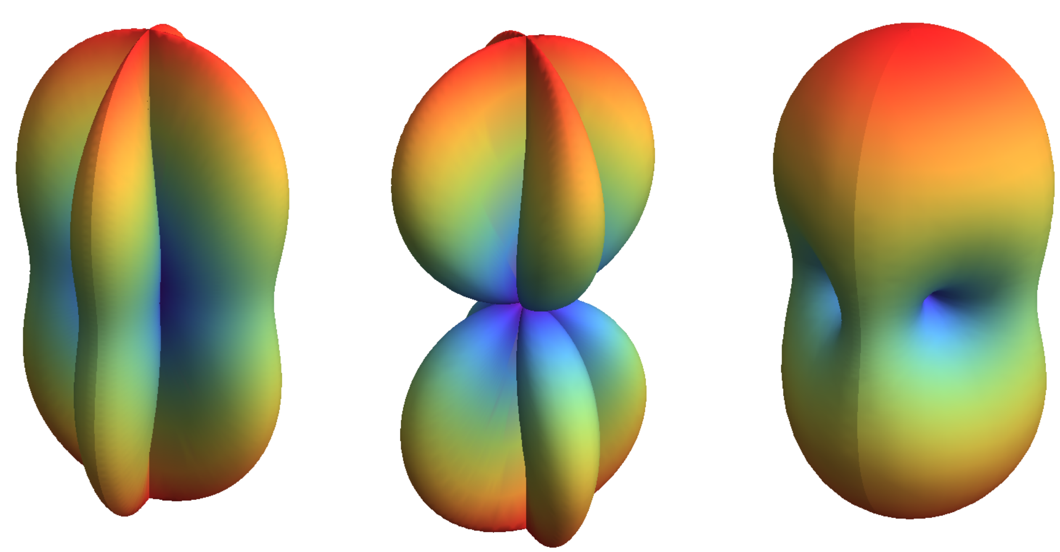
Account for the different sensitivities of the detectors, etc
We use Monte-Carlo estimates for the numerator

$$h_+ = A(1 + \cos^2 \iota)\ \cos \phi_{\mathrm{GW}}$$

$$h_\times = -\,2A \cos \iota\ \sin \phi_{\mathrm{GW}}$$

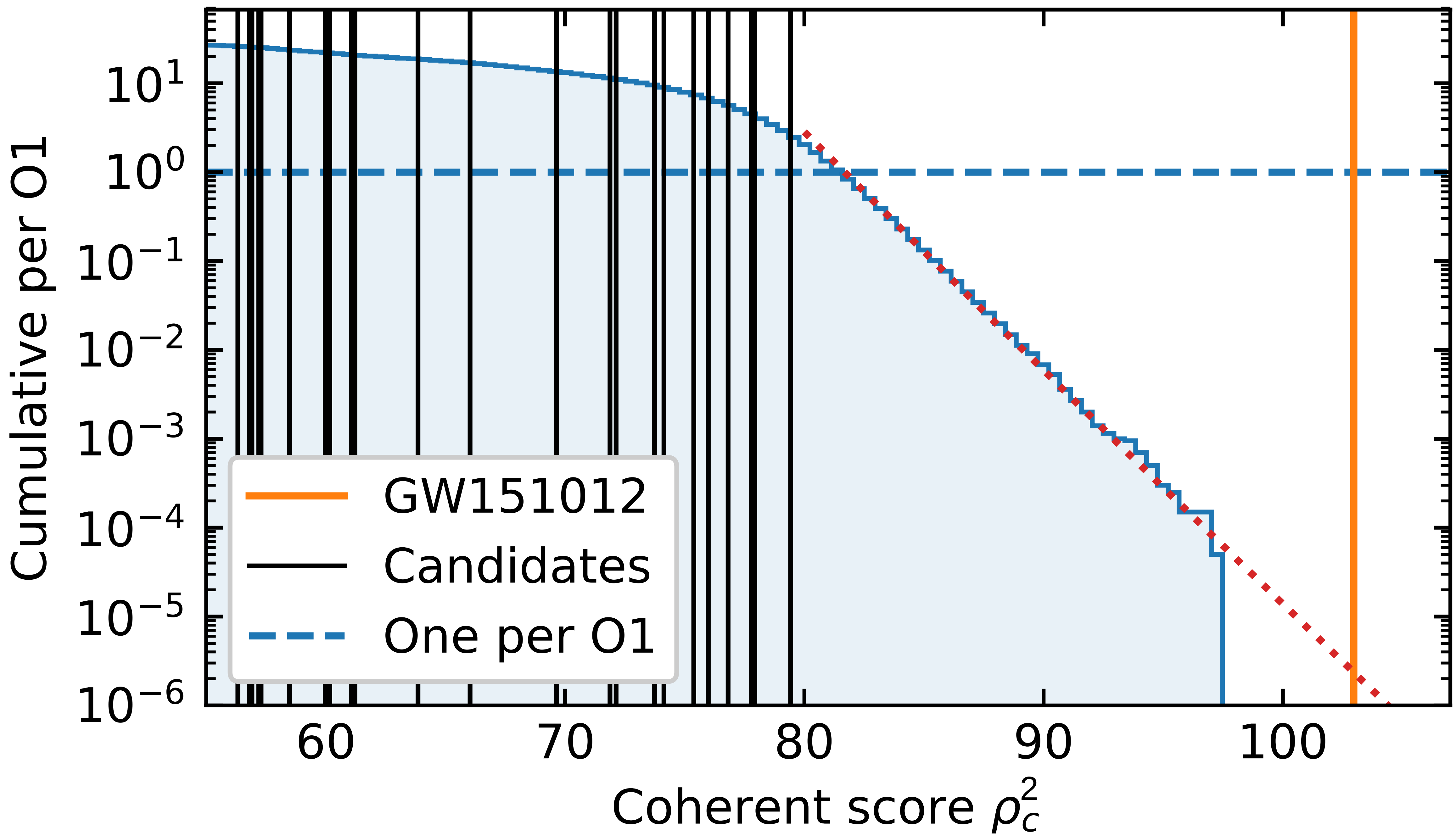
$$h = h_+ F_+ + h_\times F_\times$$





Adhikari, R., (2013)

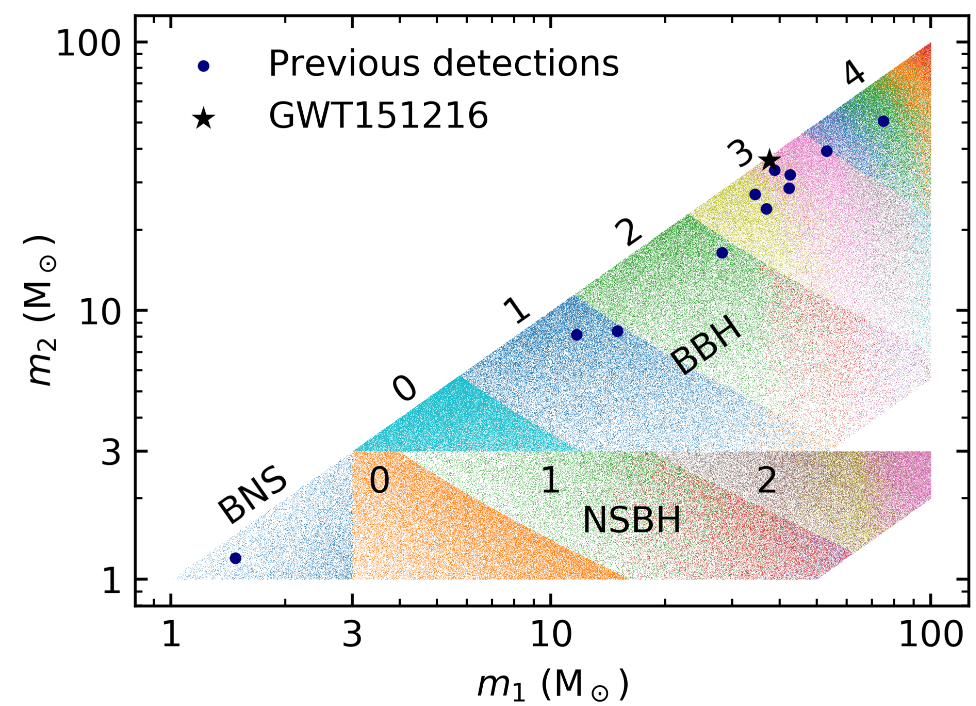
Coherent Score



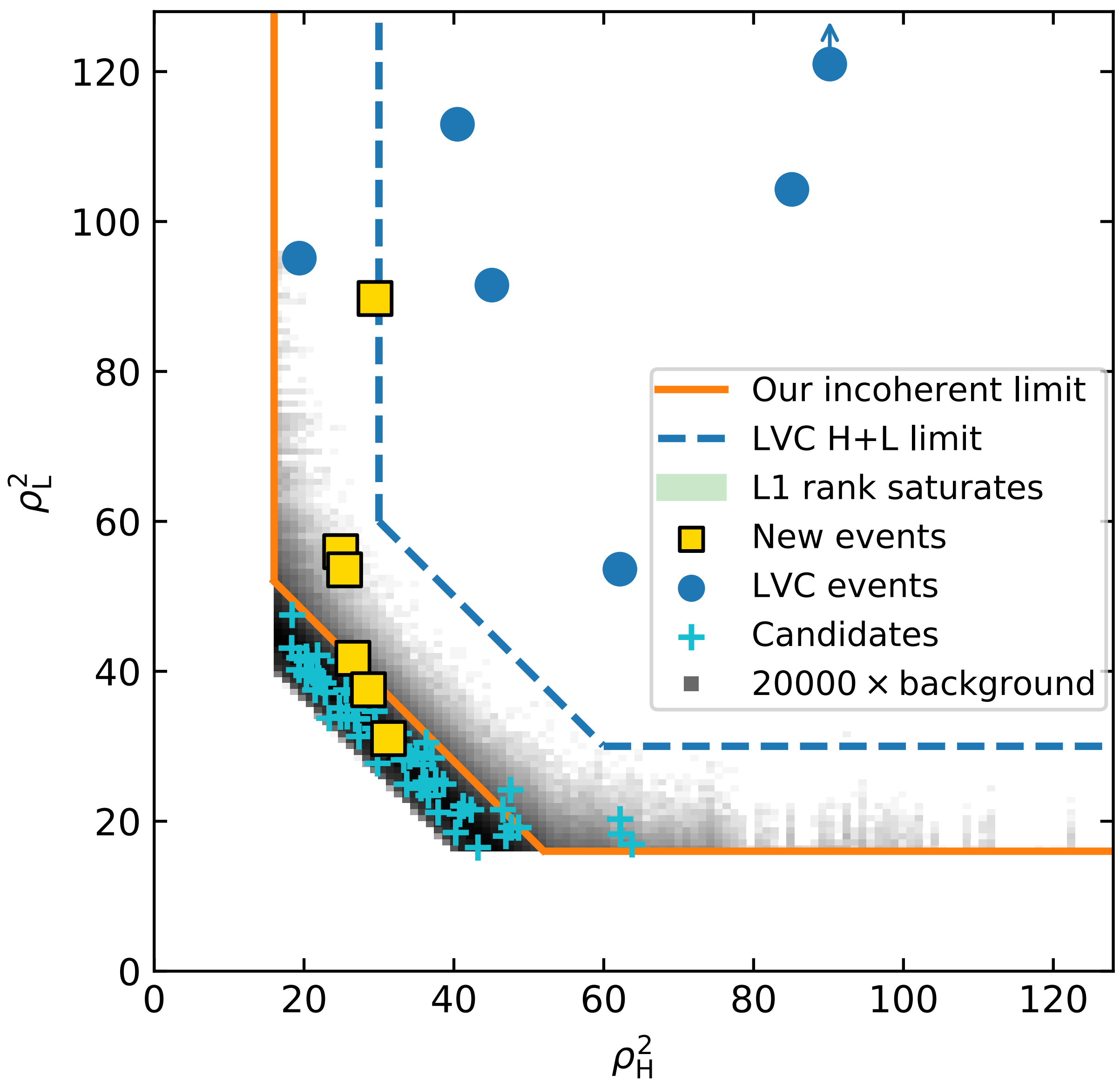
Splitting results to banks

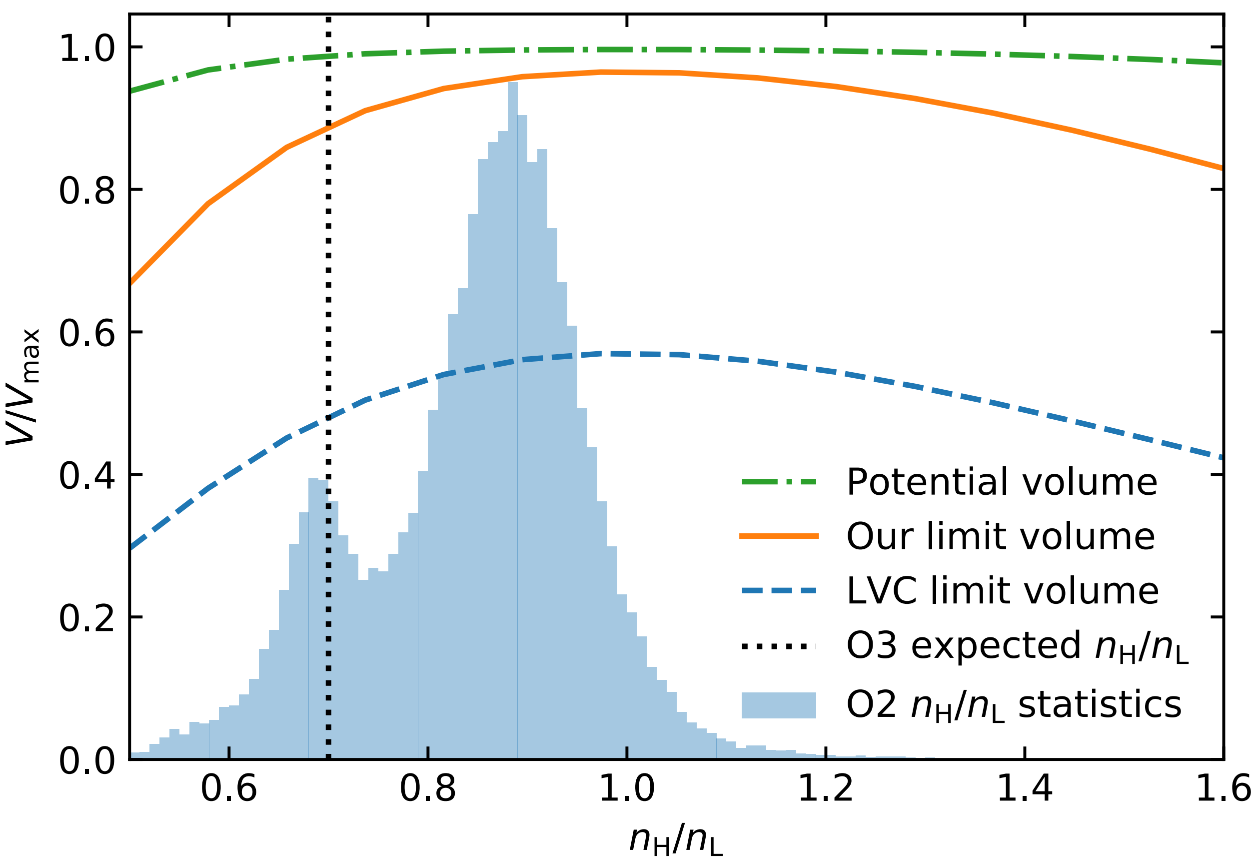
Bank	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	$q_{\min}$	$\lvert\chi_{1,2}\rvert_{\max}$	ζ	Δc_α	N_{subbanks}	d_{subbanks}	$L_{\max,\text{subbanks}}$	$N_{\text{templates}}$
BNS 0			< 1.1					1	2	777.0	48 806
BNS 1	$(1, 3)$	$(1, 3)$	$(1.1, 1.3)$	—	0.99	0.05	0.55	1	2	434.3	23 856
BNS 2			> 1.3					1	2	824.6	43 781
NSBH 0			< 3					1	4	753.4	84 641
NSBH 1	$(3, 100)$	$(1, 3)$	$(3, 6)$	1/50	0.99	0.05	0.5	2	6, 6	259.5, 166.8	85 149
NSBH 2			> 6					3	5, 4, 4	87.5, 61.2, 9.4	15 628
BBH 0			< 5				0.55	1	3	270.6	8246
BBH 1			$(5, 10)$				0.55	2	4, 4	113.7, 50.0	4277
BBH 2	$(3, 100)$	$(3, 100)$	$(10, 20)$	1/18	0.99	0.05	0.5	3	3, 4, 3	41.5, 33.5, 10.3	1607
BBH 3			$(20, 40)$				0.45	3	2, 2, 2	11.7, 10.8, 4.9	225
BBH 4			> 40				0.35	5	2, 2, 2, 1, 1	2.9, 2.0, 1.1, 0.7, 0.5	46
Total											316 262

- BBH3 has 40 times fewer templates than BBH0 while having most events.
- Prevalence of glitches is very different
- Data cleaning thresholds (and approaches) very different



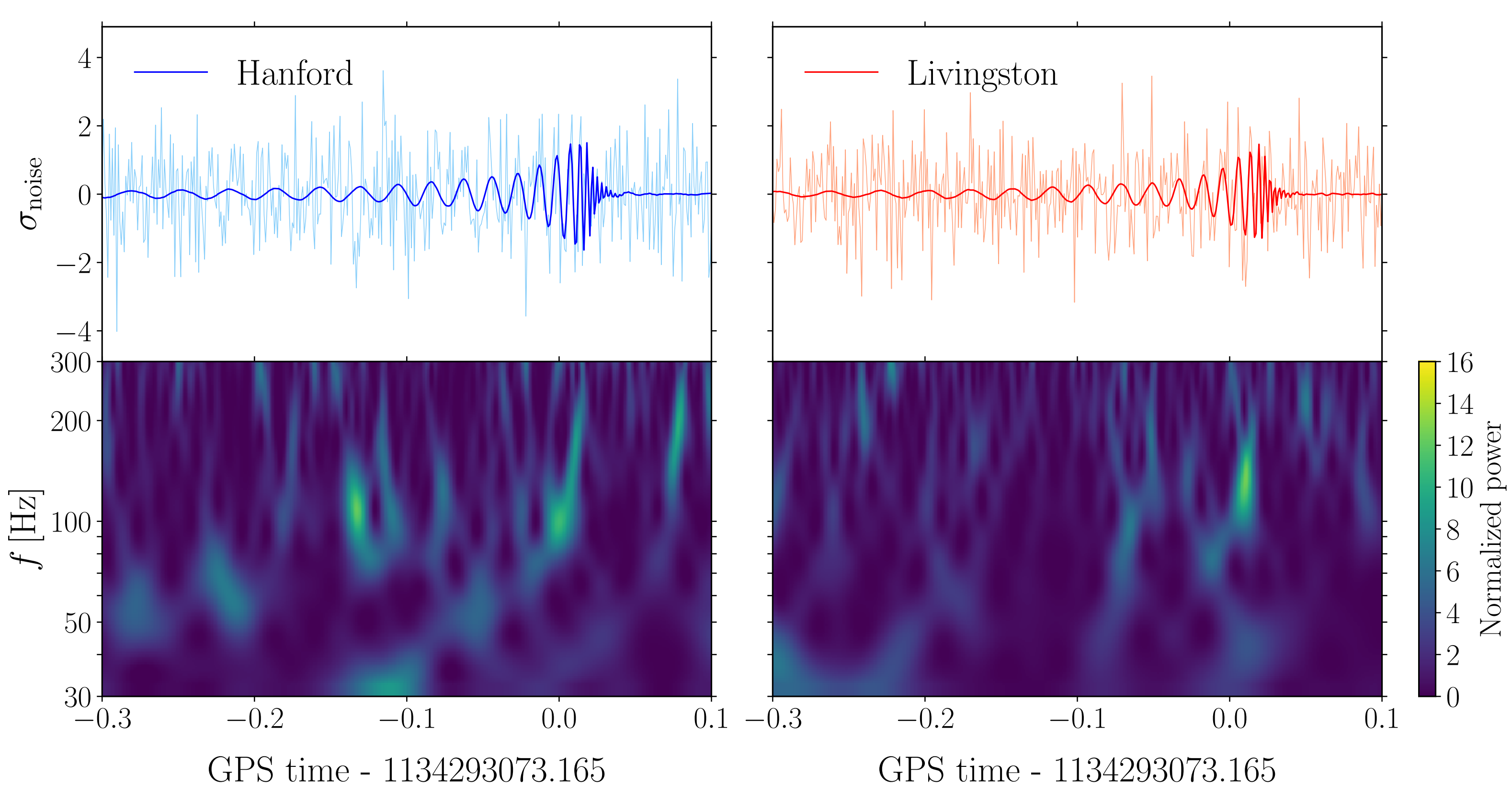
Volume improvement





New Events!

New event in O1!



	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_1/m_2	$1.5^{+1.4}_{-0.4}$	$2.4^{+1.4}_{-1.1}$
Total mass M	$52^{+9}_{-6}\,M_\odot$	$54^{+10}_{-8}\,M_\odot$
Primary aligned spin χ_{1z}	$0.86^{+0.12}_{-0.27}$	$0.73^{+0.18}_{-0.28}$
Secondary aligned spin χ_{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	$0.43^{+0.17}_{-0.17}$	$0.38^{+0.15}_{-0.15}$

- Highest spinning system so far !

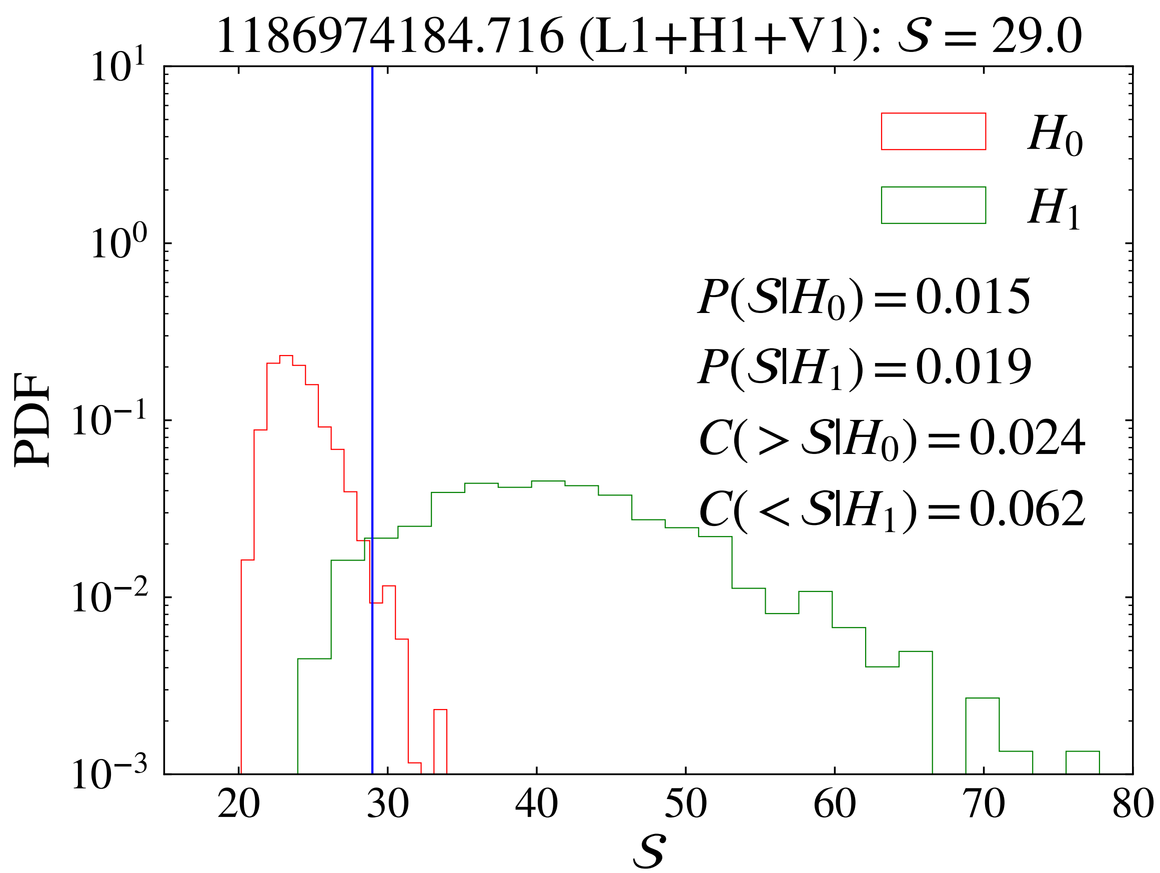
Six new events in O2!

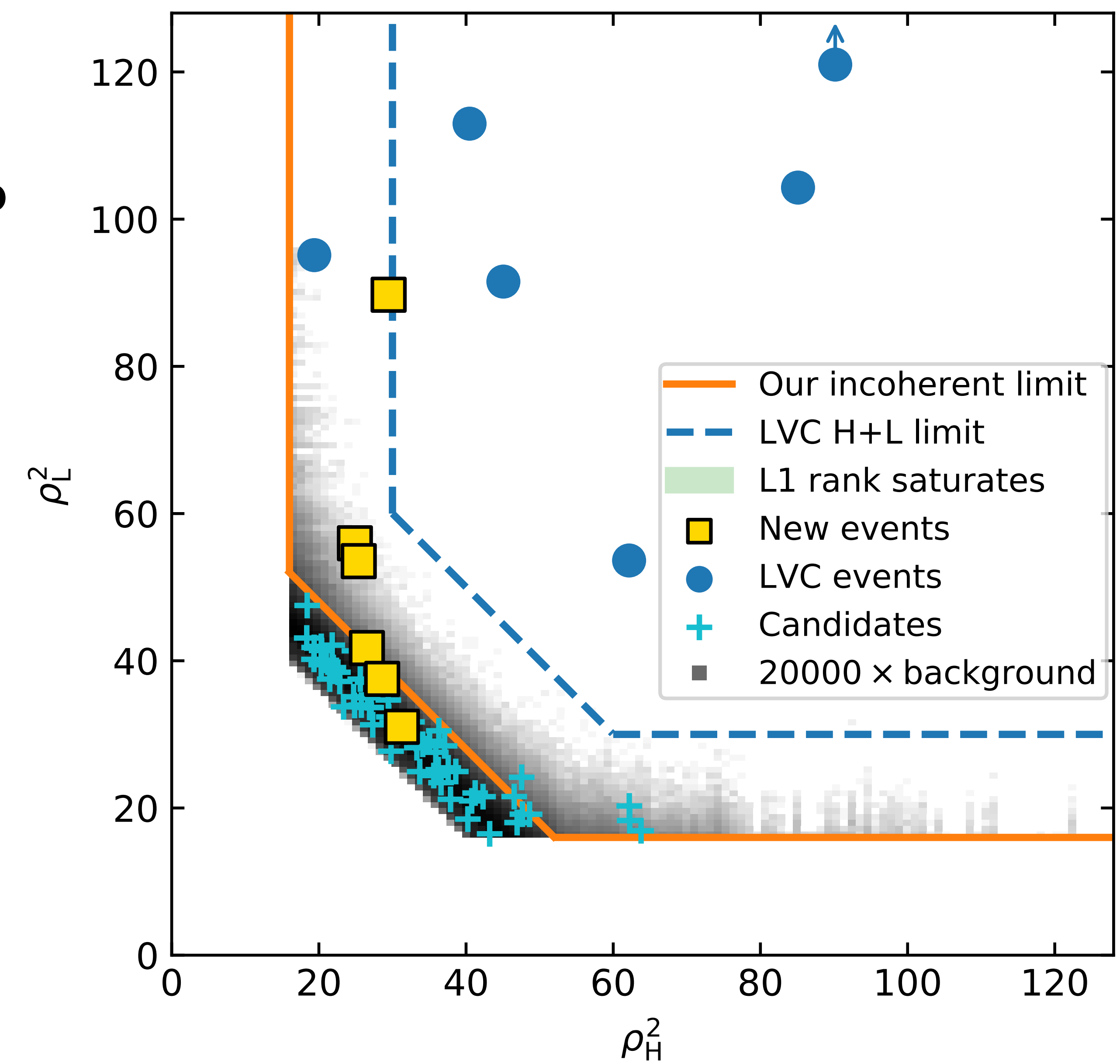
Name	Bank	GPS time[a]	ρ_H^2	ρ_L^2	$\mathrm{FAR}^{-1}(\mathrm{O2})^b$	$\frac{W(\text{event})}{\mathcal{R}(\text{event}\vert\mathcal{N})}$ (O2)	p_{astro}
GW170104	BBH (3,0)	1167559936.582	85.1	104.3	$> 2 \times 10^4$	> 100	> 0.99
GW170809	BBH (3,0)	1186302519.740	40.5	113	$> 2 \times 10^4$	> 100	> 0.99
GW170814	BBH (3,0)	1186741861.519	90.2	170	$> 2 \times 10^4$	> 100	> 0.99
GW170818	BBH (3,0)	1187058327.075	19.4	95.1	1.7[c]	—	—[c]
GW170729	BBH (3,1)	1185389807.311	62.1	53.6	$> 2 \times 10^4$	> 100	> 0.99
GW170823	BBH (3,1)	1187529256.500	46.0	90.7	$> 2 \times 10^4$	> 100	> 0.99

Name	Bank	$\mathcal{M}^{\text{det}}(M_\odot)$	χ_{eff}	z	GPS time[a]	ρ_H^2	ρ_L^2	$\mathrm{FAR}^{-1}(\mathrm{O2})^b$	$\frac{W(\text{event})}{\mathcal{R}(\text{event}\vert\mathcal{N})}$ (O2)	p_{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	2.8×10^3	> 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

Fishing two more signals!

- Framework does not apply to shaded area.
- Criterion for ranking candidates **according to L1 alone** - number of “similar” glitches observed.
- Exact evidence integral over the sky

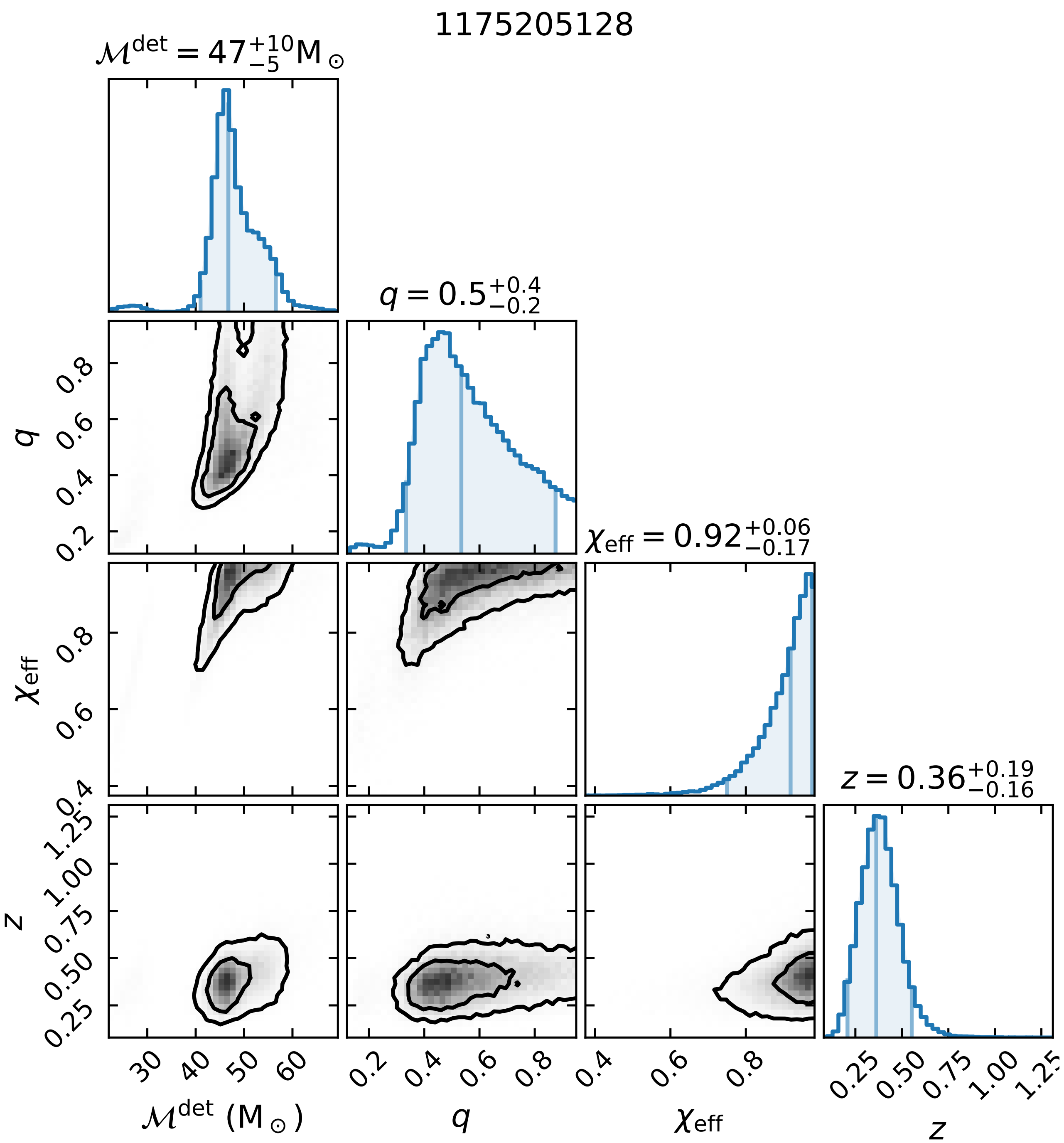


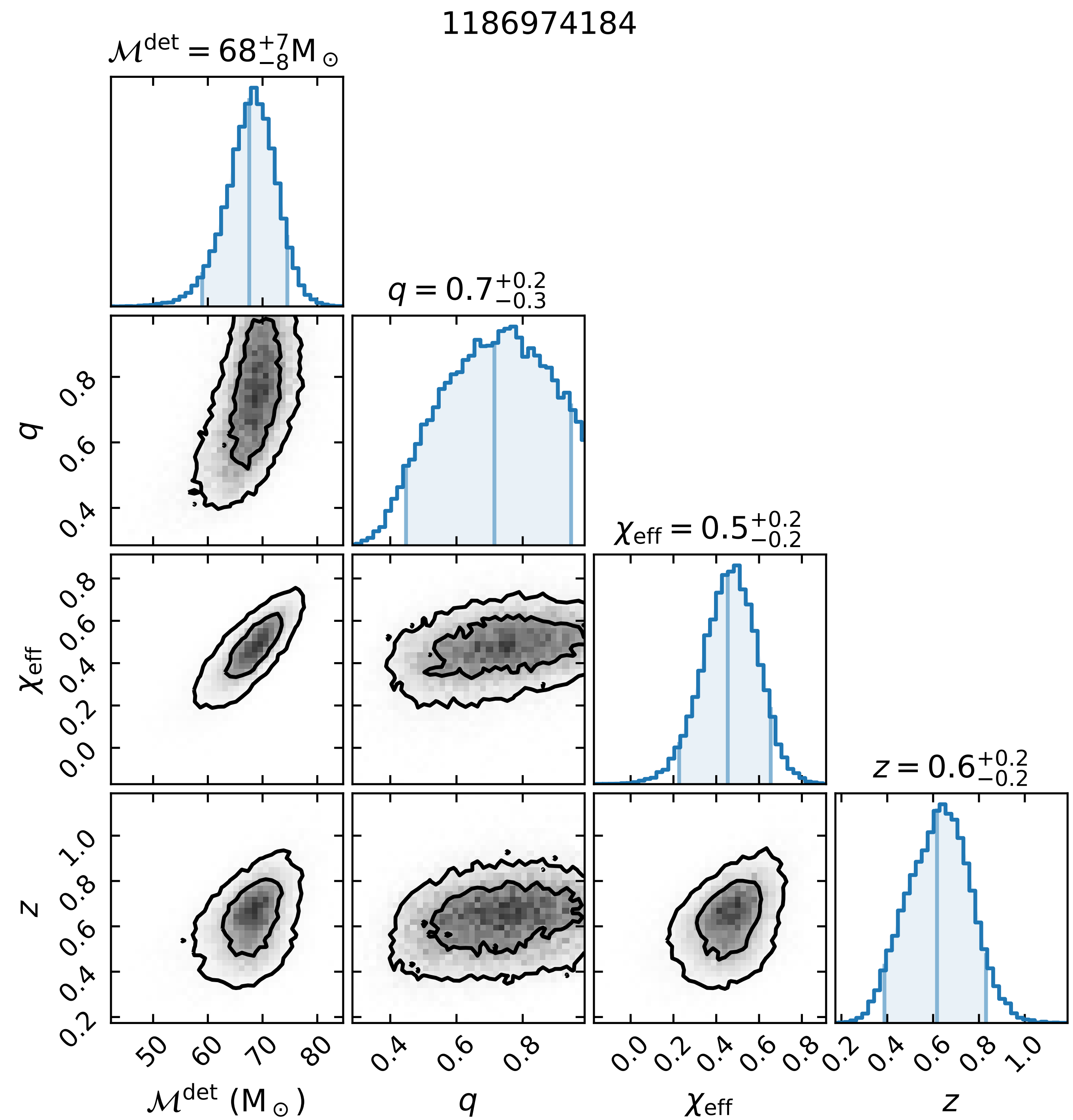


More events!

L1 based rank	GPS time	ρ_L^2	# similar glitches	Bank ID	$C(\mathcal{S}\|H_0)$	$C(\mathcal{S}\|H_1)$	$\frac{P(\mathcal{S}\|H_1)}{P(\mathcal{S}\|H_0)}$	Comment
1	1187058327.068	95.1	0	(3, 0)	$< 10^{-3}$	0.16	37	GW170818[a]
2	1187529256.504	92.4	0	(4, 0)	0	-	-	GW170823
3	1169069154.564	89.7	0	(3, 0)	0	-	-	GW170121
4	1186741861.51	172.5	1	(3, 0)	0	-	-	GW170814
5	1186302519.731	114.7	1	(3, 0)	0	-	-	GW170809
6	1167559936.584	105.7	1	(3, 0)	0	-	-	GW170104
7	**1175205128.565**	**74.1**	**1**	**(3, 0)**	**0.015**	**0.022**	**0.547**	**GW170402**
8	**1186974184.716**	**100.6**	**5**	**(4, 2)**	**0.028**	**0.055**	**0.98**	**GW170817B**
9	1174043898.842	74.3	9	(4, 3)	0.36	0.001	0.008	-
10	1181567025.654	66.6	12	(3, 1)	0.34	0.009	0.015	-
11	1178083239.592	75.9	24	(3, 1)	0.34	0.003	0.016	-
12	1170885005.109	65.3	25	(3, 1)	0.49	0.003	0.013	-
Removed[b]	1173477193.704	73.8	1	(3, 1)	0.38	0.014	0.011	Artifacts present

And they are highly spinning!

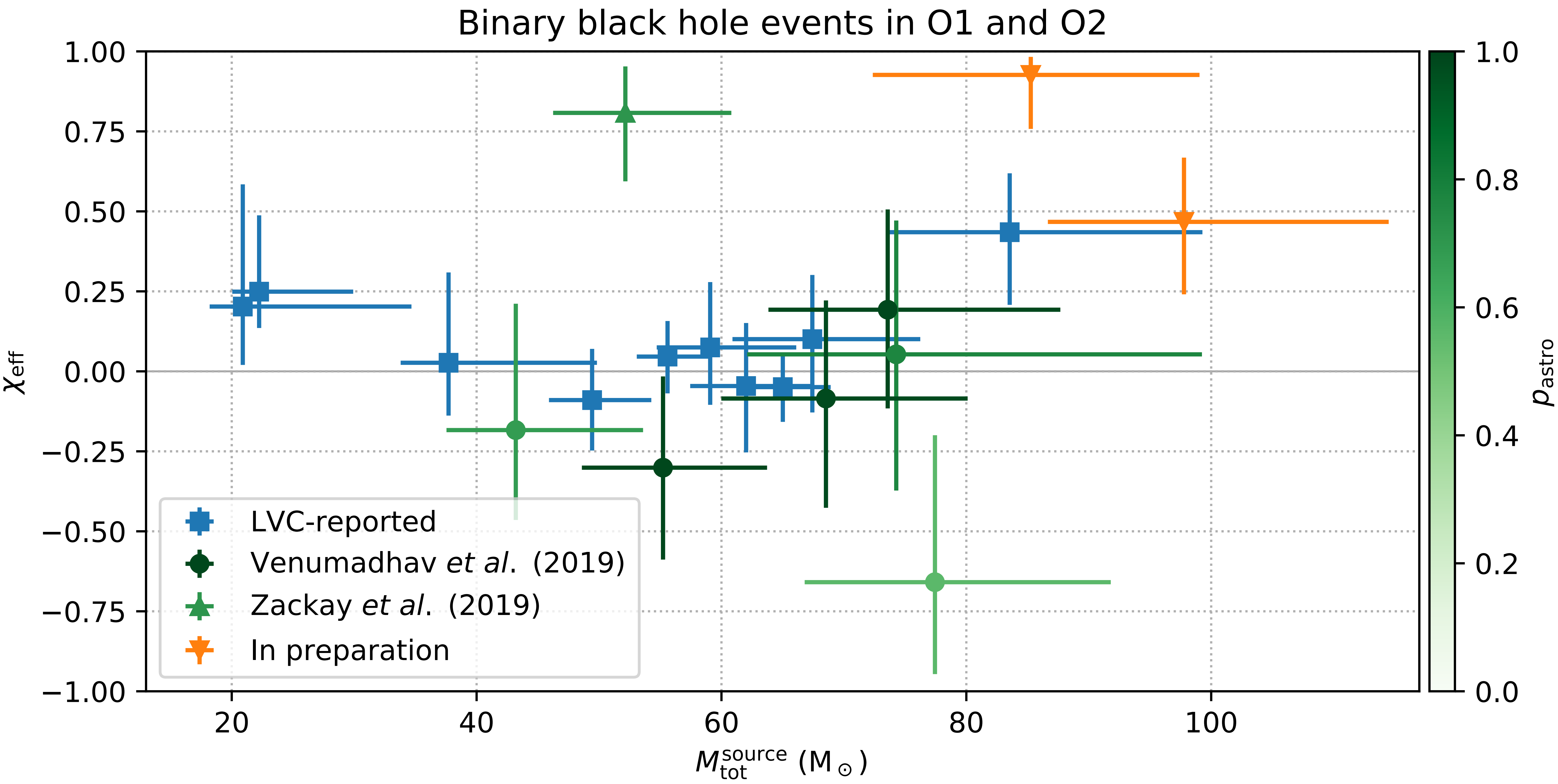




Summary

- The availability of the LIGO data gives the community an opportunity to try new ideas and propose new methods. We are very grateful to the LVC.
- We have developed a new, independent pipeline for detecting (and PE) GW mergers, that we estimate it has twice the detection volume compared to previous pipelines.
- We have found 9 new GW events in O2 data.
  - Two are very highly spinning - strong indication for non-dynamical formation.
  - Highest mass observed to date
  - An event with substantial negative spin.
- Ongoing:
  - Population study
  - BNS/NSBH searches

Do you see what I see?



Relative Binning
Parameter Estimation
Template Bank Construction

Barak Zackay,
Liang Dai, Tejaswi Venumadhav, Javier Roulet, Mattias Zaldarriaga
Institute for Advanced Study, Princeton

Parameter estimation for BNS

Why is parameter estimation for BNS mergers hard?

$$Z(d, h, \Delta t) = 4 \sum_f \frac{d(f) h^*(f)}{S_n(f)/T} e^{if\Delta t}$$

Frequency resolution set by $T \gtrsim 2\,\mathrm{min}$ for O2, and $f_{\max} = 2048\,\mathrm{Hz}$, say.

If we pick $T = 256\,\mathrm{s}$, we have $N \approx 2^{20} \approx 10^6$ frequencies.

The FFT requires $O(N \log N) \approx 10^7$ flops.

Parameter estimation requires us to evaluate the FFT above for many ($\sim 10^8$) parameter choices

Speeding up parameter estimation

- Speeding up template generation
  - Analytical frequency domain waveforms
  - Reduced order modeling (e.g., Pürrer 2014).
  - Multi-band interpolation (Vinciguerra, S., et. al., (2018))

- Speeding up matched filtering
  - Reduced order quadrature (Smith, R., et. al. (2016))

- Speeding up the sampling method
  - Separating variables as much as possible.
  - Using sophisticated sampling methods.

Are CBC templates smooth?

- Not in time domain $$A(t)e^{i(\alpha_1 t^{\gamma_1}+\alpha_2 t^{\gamma_2}+\ldots)}$$
- Not in frequency domain $$A(f)e^{i(\alpha_1 f^{\gamma_1}+\alpha_2 f^{\gamma_2}+\ldots)}$$
- But when you **phase unwrap:**

$$\phi(f) = (\alpha_1 f^{\gamma_1} + \alpha_2 f^{\gamma_2} + \ldots)$$

Waveform with high overlap are "similar"

- Not in physical parameters - that's why we need parameter estimation

- Rule of thumb: templates with high overlap do not lose phase (inside the sensitive band)

$$|\phi(f) - \phi_0(f)| < 1$$

- $$\frac{A(f)}{A_0(f)} e^{i(\phi(f)-\phi_0(f))} = \frac{A(f)}{A_0(f)} e^{i((\alpha-\alpha_0)f^\gamma+\ldots}$$

Template ratios are smooth and low dimensional

For GW170817, the detector frame chirp mass

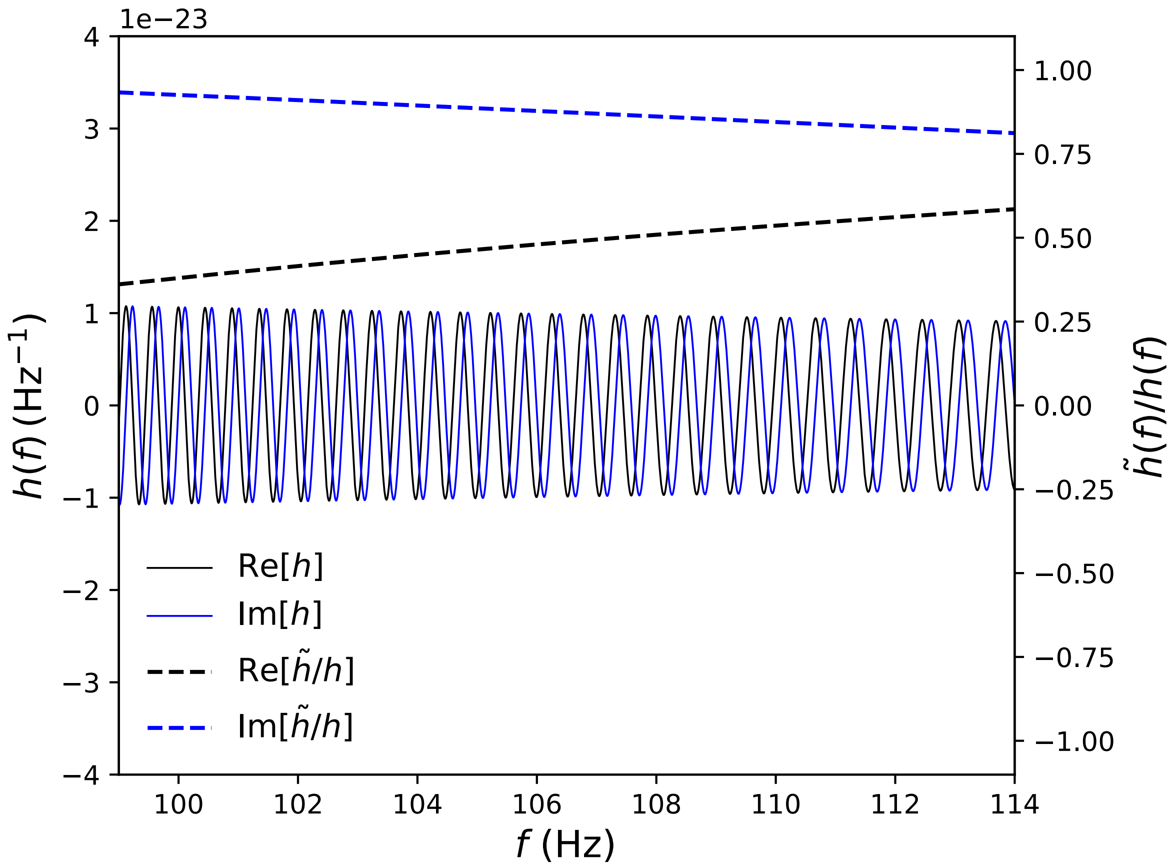
$$\mathscr{M}^{\mathrm{det}} = 1.1975 \pm 0.0001\, M_{\odot}$$

(LVC, arXiv 1805.11579)

$$\mathscr{M}^{\mathrm{det}} = 1.1975\, M_{\odot}$$

and

$$\mathscr{M}^{\mathrm{det}} = 1.1985\, M_{\odot}$$



Relative binning

Compute $r(f) = \dfrac{h(f)}{h_0(f)} = r_0(h, \mathrm{b}) + \mathrm{r_1(h, b)\,(f - f_m(b))} + \cdots$

on a coarse set of frequency bins, for a fiducial template

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

where

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

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

are computed once and for all on a fine frequency grid.

Choosing bin-boundaries to control approximation accuracy

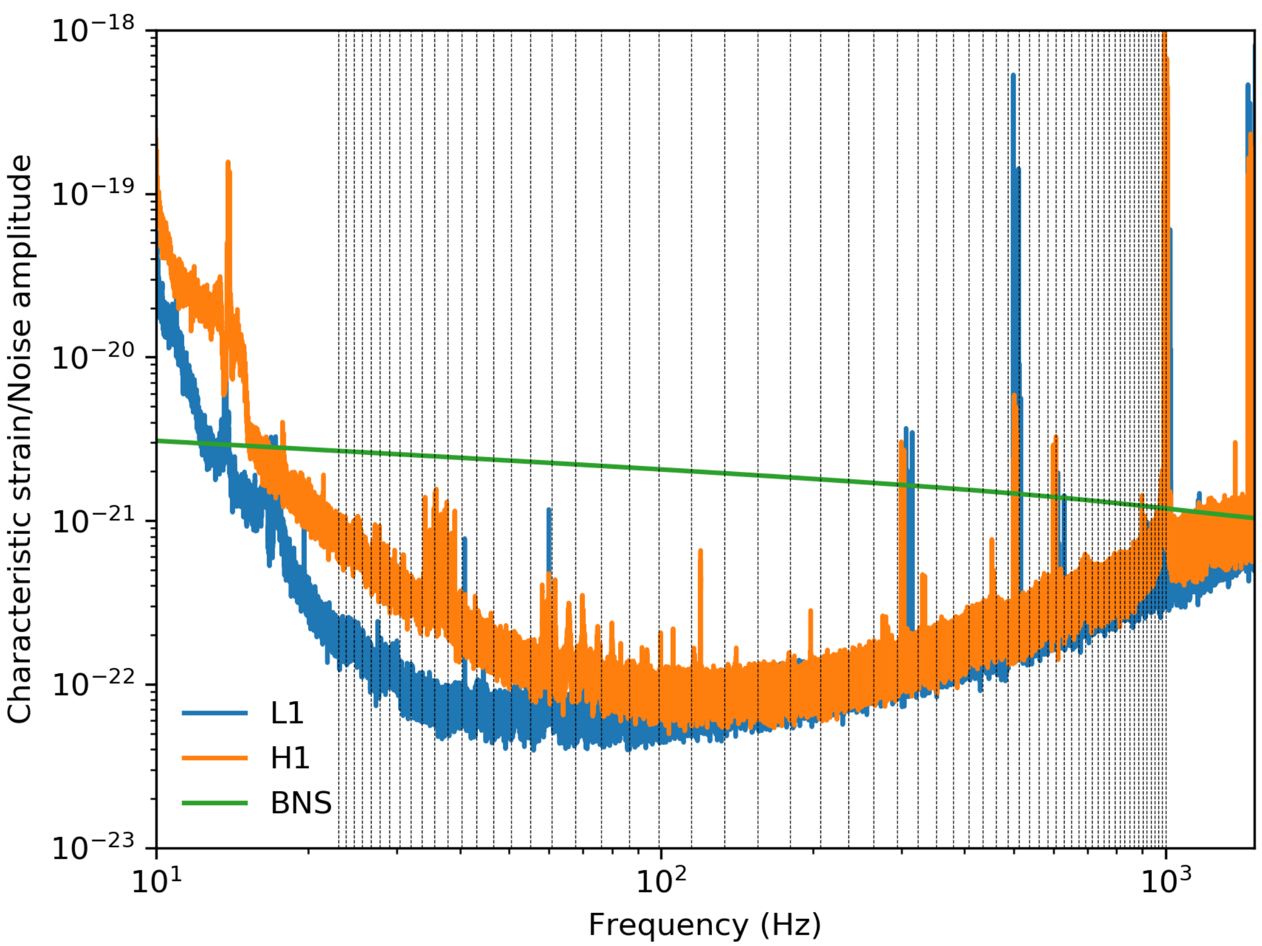
- No reason to chose equal spacing
- Spacing chosen such that total deviation of each component in the PN expansion to < 0.5 rad.

$$\phi(f) = (\alpha_1 f^{\gamma_1} + \alpha_2 f^{\gamma_2} + ...)$$

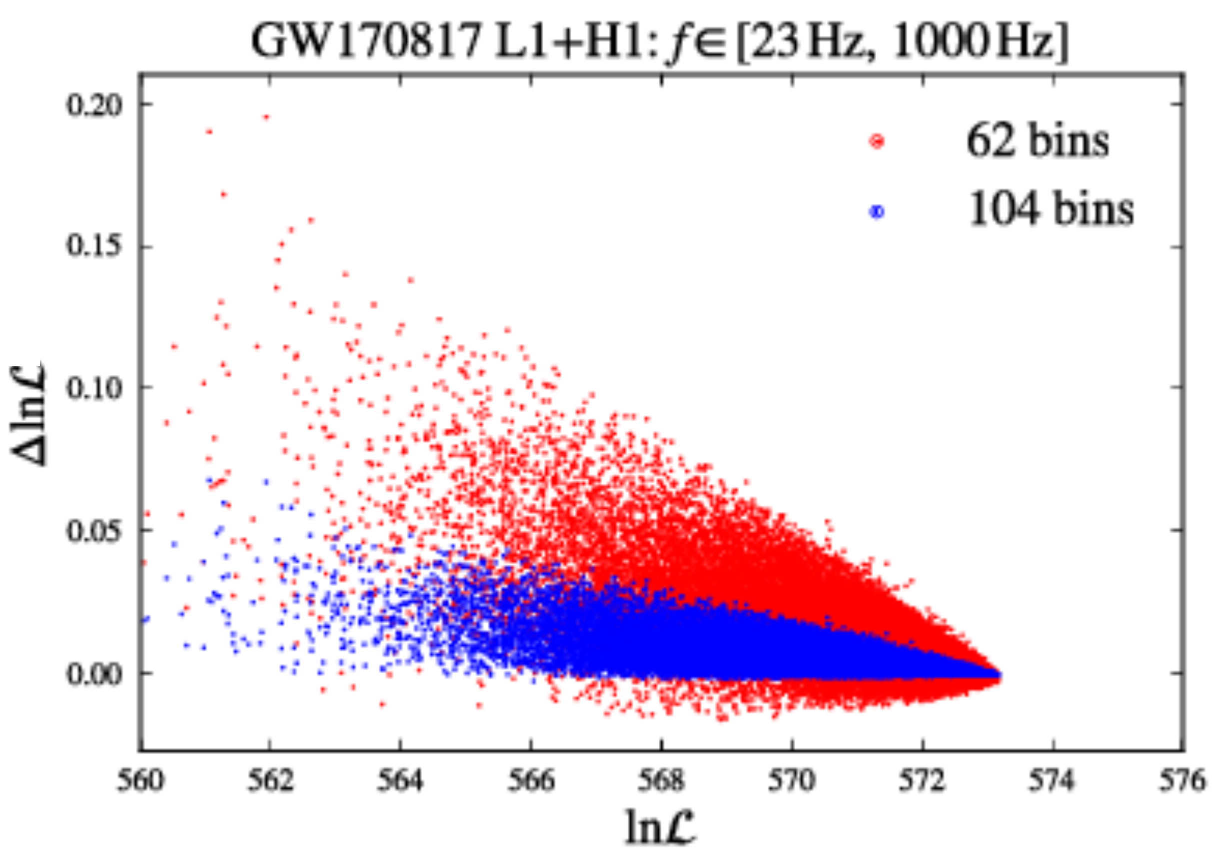
- Assume that a waveform is sampled by parameter estimation if

$$|\phi(f) - \phi_0(f)| < 2\pi$$

Relative binning

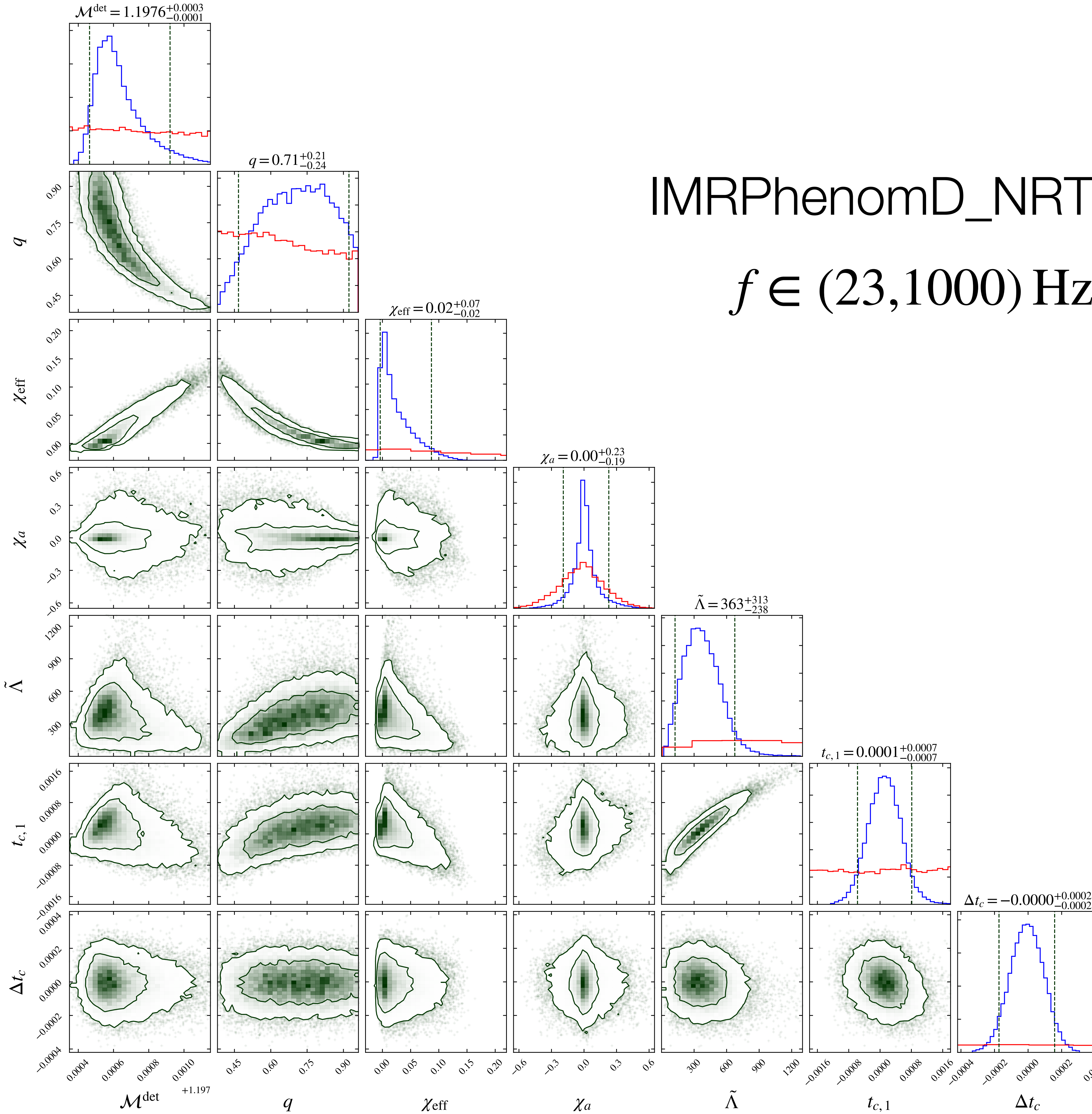


Likelihood accuracy



~60 Frequency bins

$O(10^2)$ flops per likelihood evaluation



IMRPhenomD_NRTidal

$f \in (23, 1000)$ Hz

Building a template bank using this understanding

- Can apply “reduced order modeling” on phase unwrapped waveforms
  - Trivially low dimension.
  - Very few examples required.
- Can build optimally gridded template banks by applying SVD on unwrapped waveform phases.
  - Similar to Tanaka & Tagoshi (2000).
  - Does not require analytical understanding of $\phi(f)$

Outlook

- Parameter estimation speed up at little cost for any reasonable accuracy.

- Will become essential for longer waveforms. O3 BNS, A+, ET, LISA parameter estimation.

    - Without relative binning - $N_{\rm bins} \sim N_{\rm cycles} \sim 10^6$

    - With relative binning - $N_{\rm bins} \sim 60$

Refs:
Zackay, B. Dai, L., TV, arXiv:1806.08792
Dai, L., TV, Zackay B., arXiv:1806.08793
Code at https://bitbucket.org/dailiang8/gwbinning