A New Independent Analysis of LIGO Data: New Mergers in the O1/O2 Runs

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Collaborators

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- Introduction to compact binary mergers and searches in gravitational wave data
- Developments in search methods:
  - Construction of template banks
  - Correcting for non-stationary noise
  - Identifying and mitigating glitches
- Results: New mergers in O1 and O2 data

The Gravitational Wave Spectrum

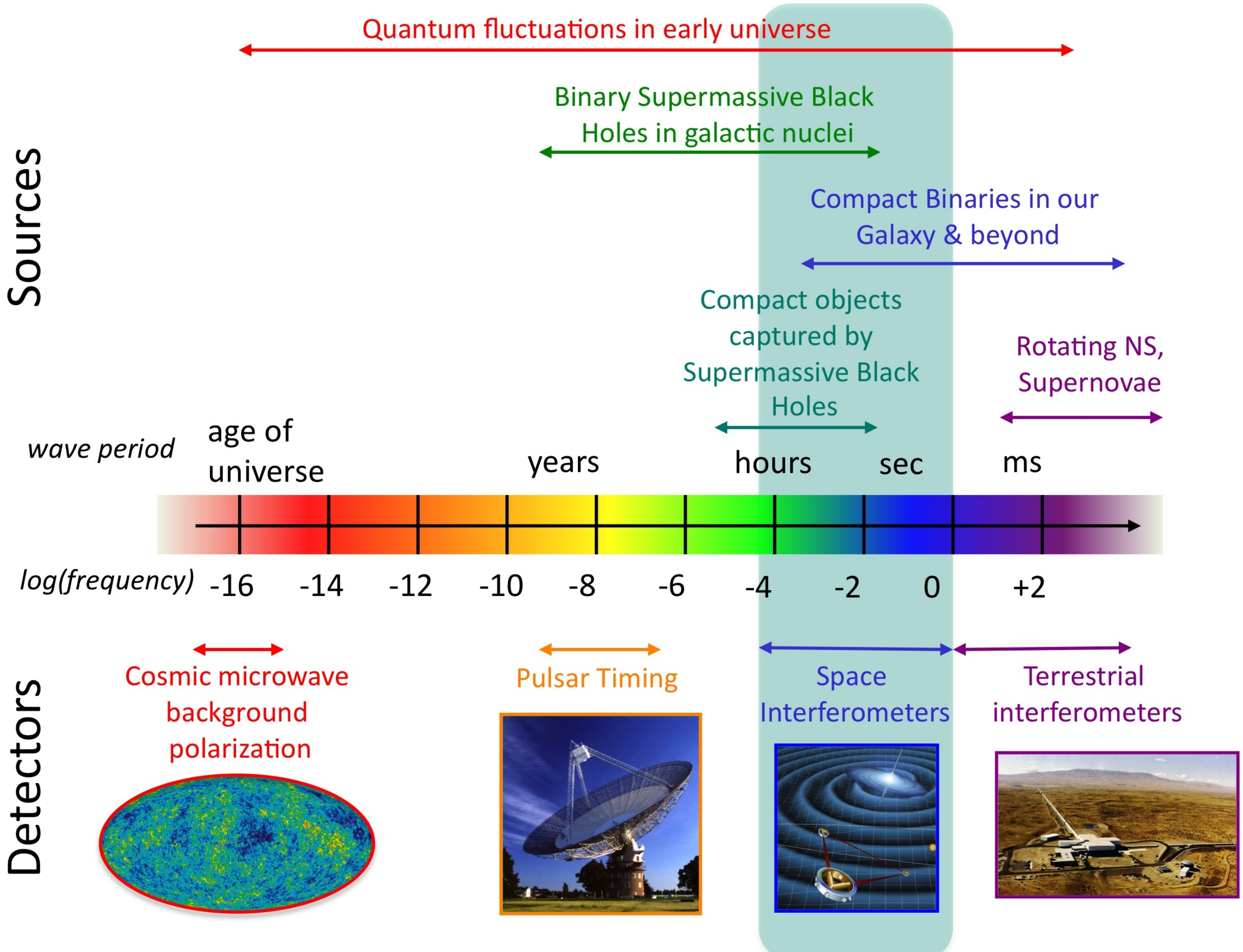

Image: NASA GSFC

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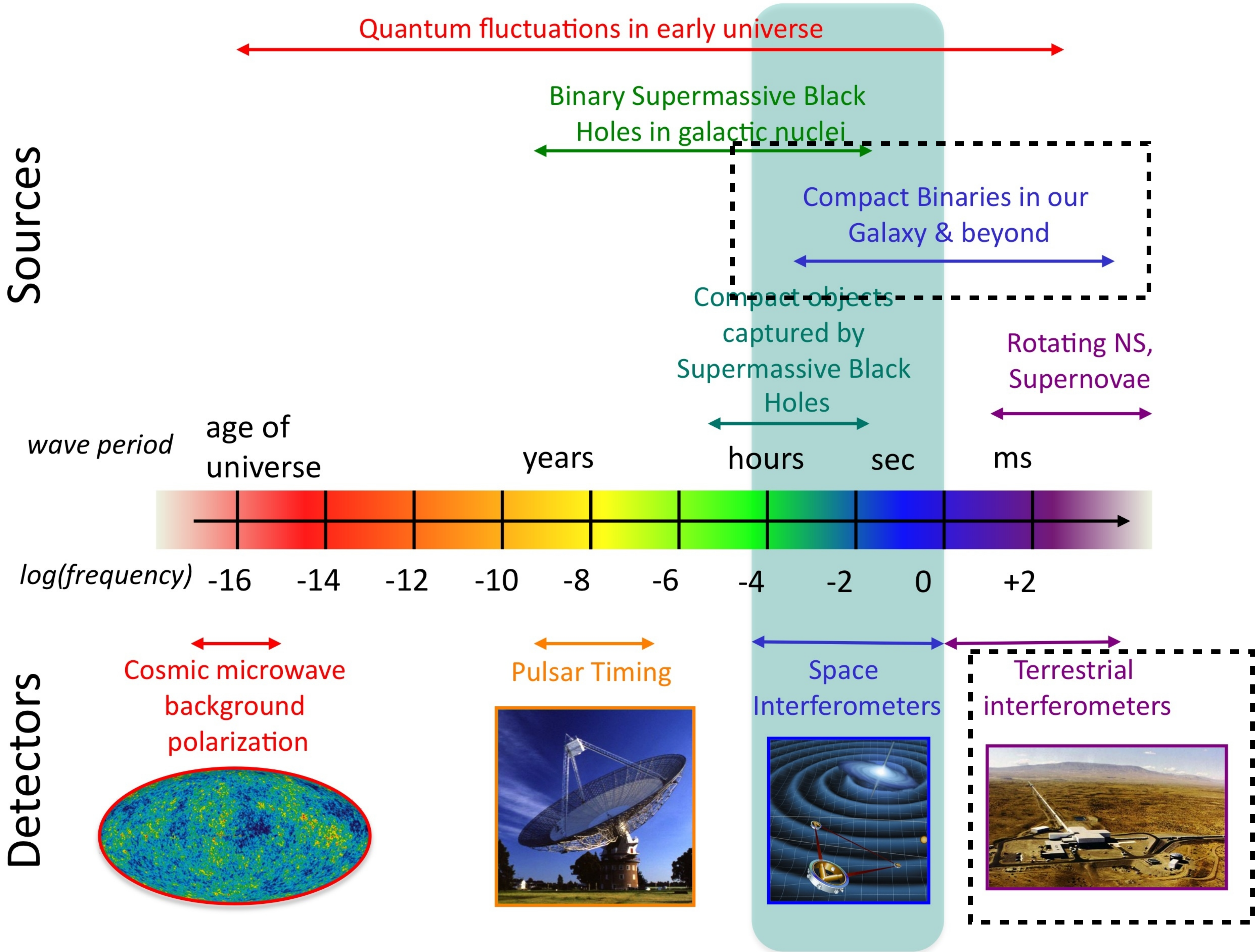

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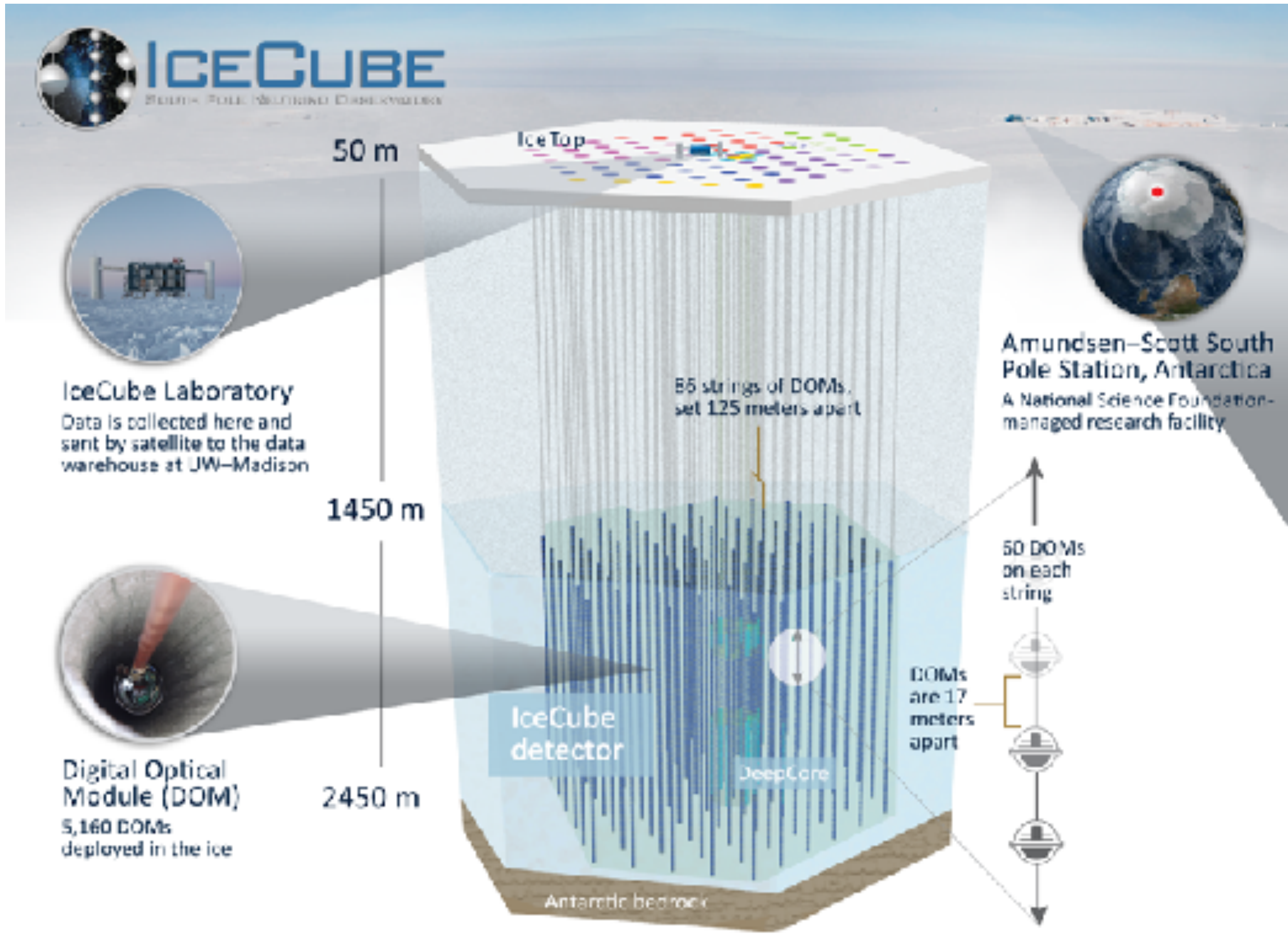
Searching for GW



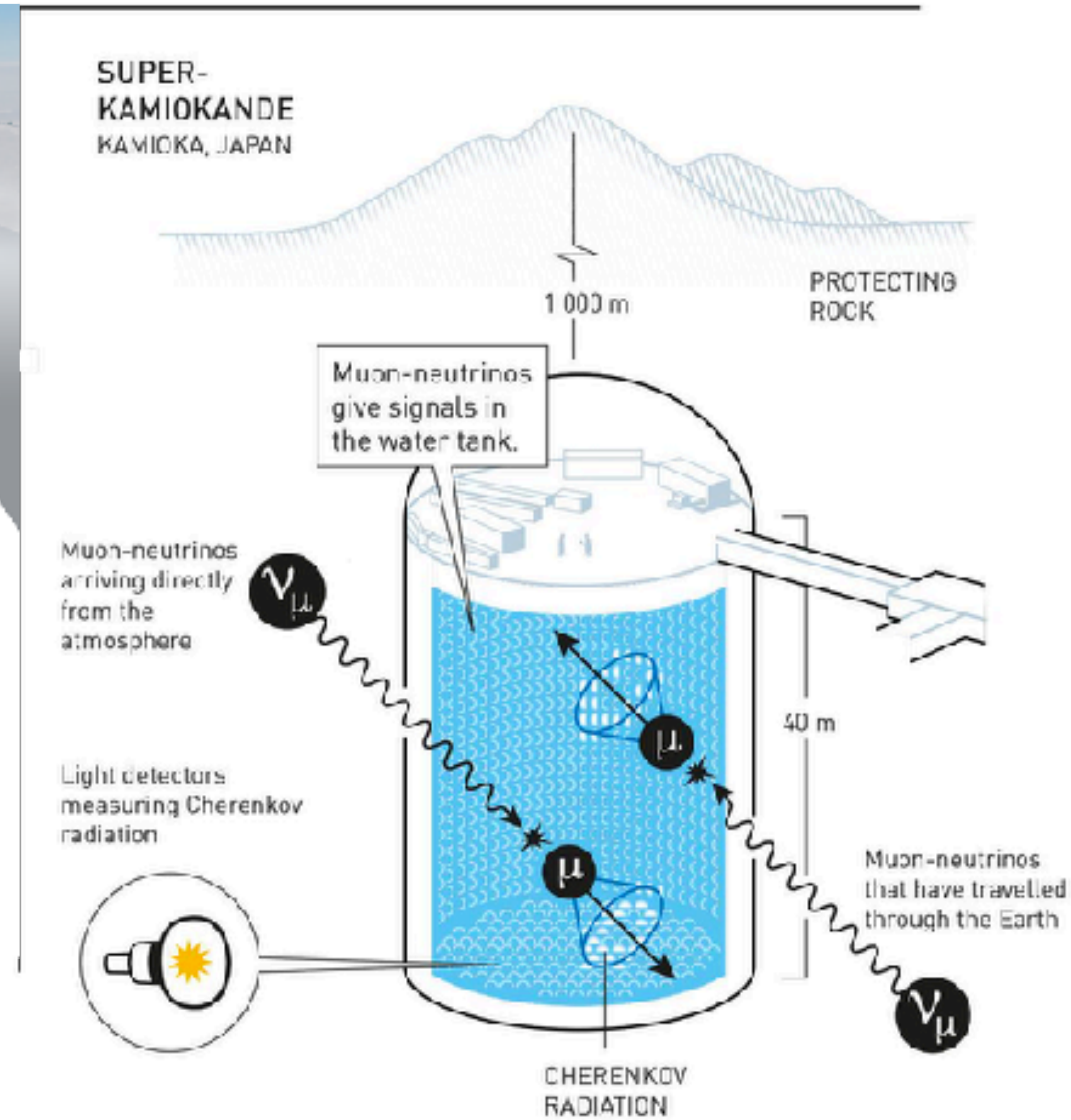


Image: icecube.wisc.edu

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

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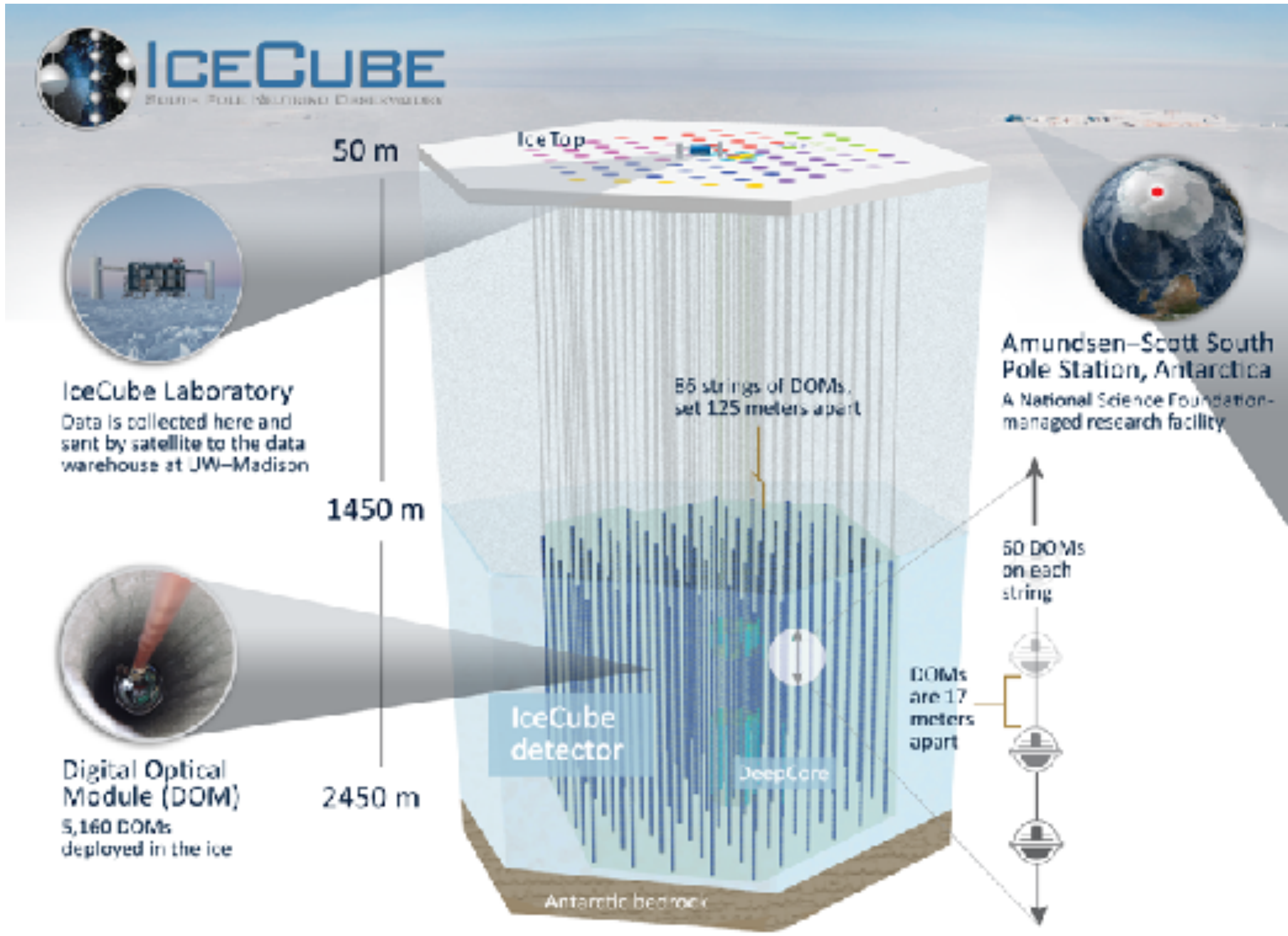

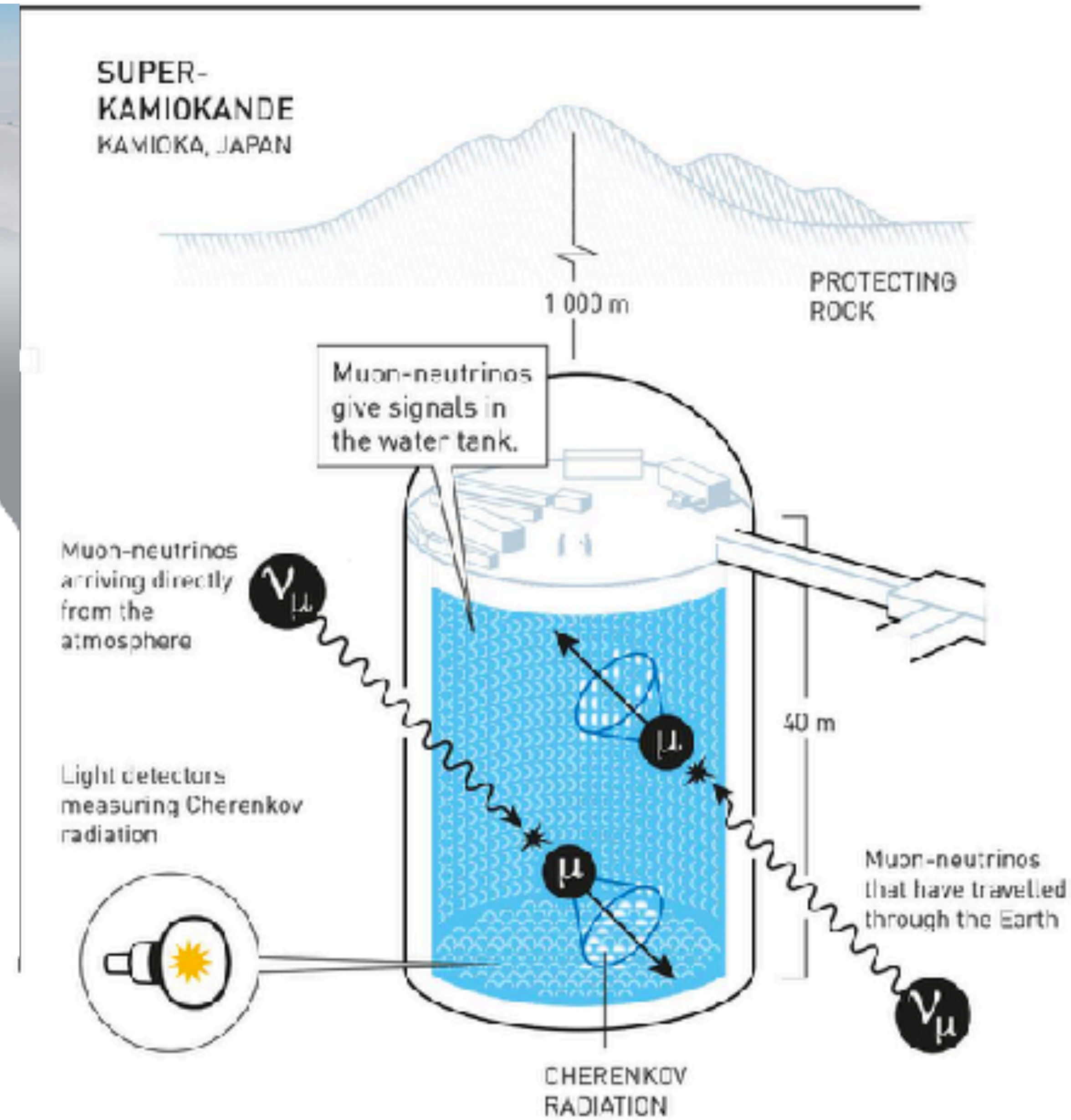

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1. **Source model: parameter space:**
   $S = \left\{ h_{+/\times}(m_1, m_2, \ldots, \theta, \phi, i, \ldots) \,|\, (m_1, m_2, \cdots) \in \mathcal{I}, (\theta, \phi, i, \ldots) \in \mathcal{E} \right\}$
2. **Detector + test statistic/signal: d(t) and matched-filter**
3. **Noise (background) model**

GW From Binaries: Amplitude

Quadrupole approximation

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$$\sim \frac{1}{R}\omega_{\rm GW}^{2/3} \left(M\eta^{3/5} \right)^{5/3}$$

$M\eta^{3/5} \rightarrow$ "chirp" mass M_c

$$\sim 10^{-21} \left(\frac{\omega_{GW}}{100\,\mathrm{Hz}} \right)^{2/3} \left(\frac{M_c}{25\,M_\odot} \right)^{5/3} \left(\frac{400\,\mathrm{MPc}}{R} \right)$$

GW From Binaries: Frequency Evolution

Orbital energy: $$E \sim -\frac{m_1 m_2}{a} \sim -\frac{M^2\eta}{\left(M/\omega_{\rm GW}^2\right)^{1/3}} \sim -M_c^{5/3}\omega_{\rm GW}^{2/3}$$

GW "Larmor formula": $$P \sim \dddot{q}^2 \sim \omega_{\rm GW}^6 \left(M_c^{5/3}\omega_{\rm GW}^{-4/3}\right)^2 \sim \left(M_c\omega_{\rm GW}\right)^{10/3}$$

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$$t_0 - t_{\rm min} \sim \frac{1}{M_c^{5/3}\omega_{\rm GW,min}^{8/3}} \approx 0.5\, s \left(\frac{25\, M_\odot}{M_c}\right)^{5/3} \left(\frac{20\,{\rm Hz}}{\omega_{\rm min}}\right)^{8/3}$$

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Cutoff at ISCO $\omega_{\rm max} \sim 100\,{\rm Hz}\left(\frac{50\,M_\odot}{M}\right)$

GW From Binaries: Waveforms

Orbital phase: $$\phi(\omega_{\rm GW}) \sim \int \omega_{\rm GW}(t)\, dt \sim \boxed{\left(\frac{1}{M_c\, \omega_{\rm GW}}\right)^{5/3}}$$

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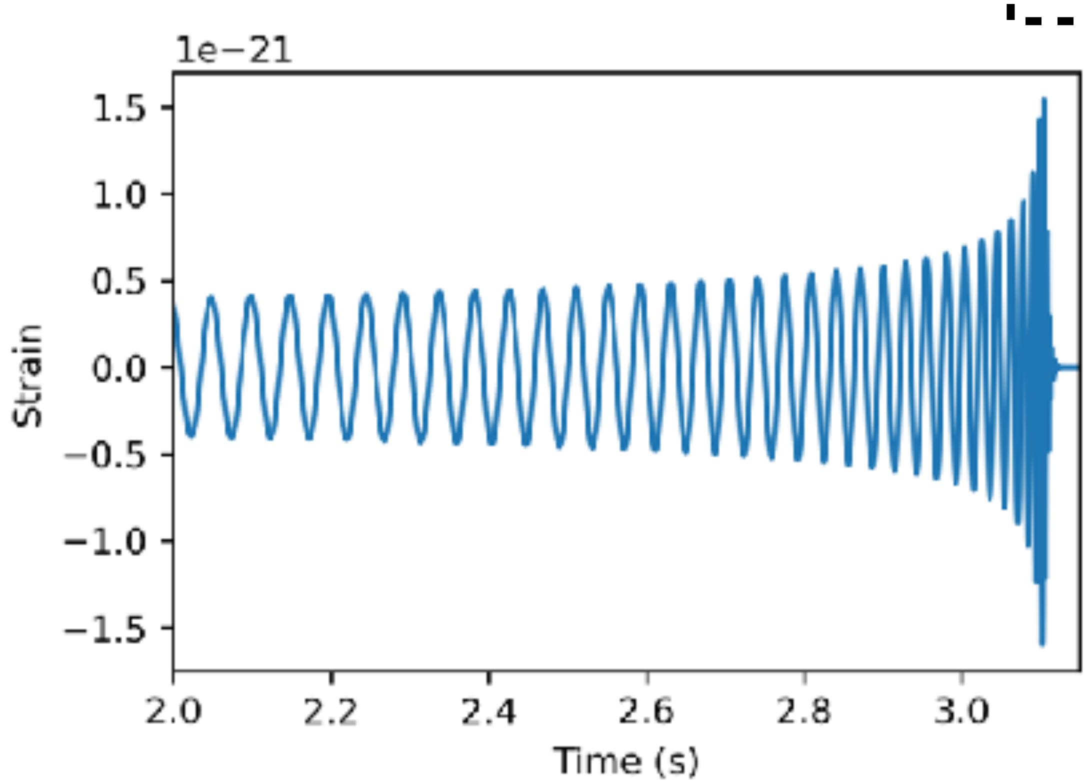
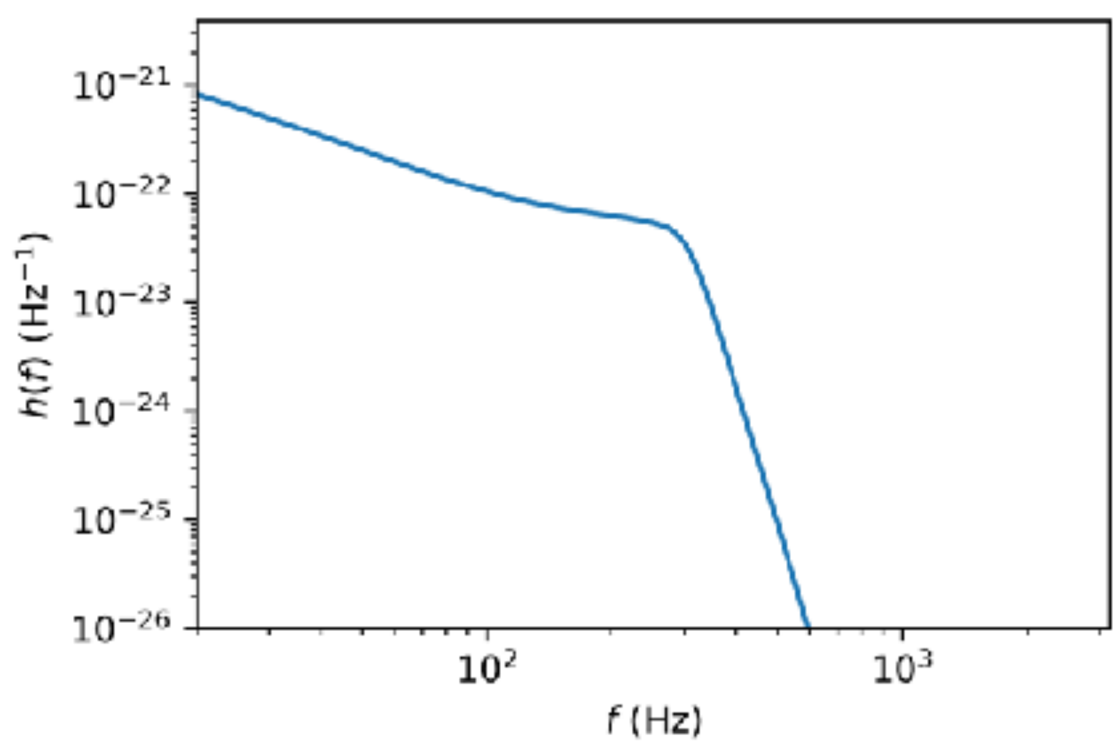
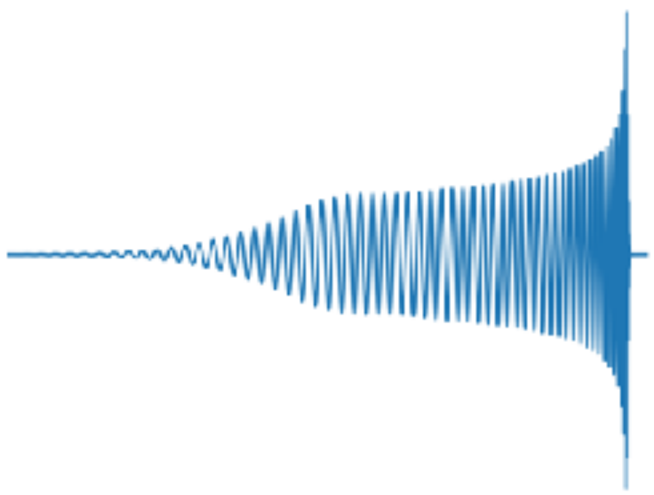
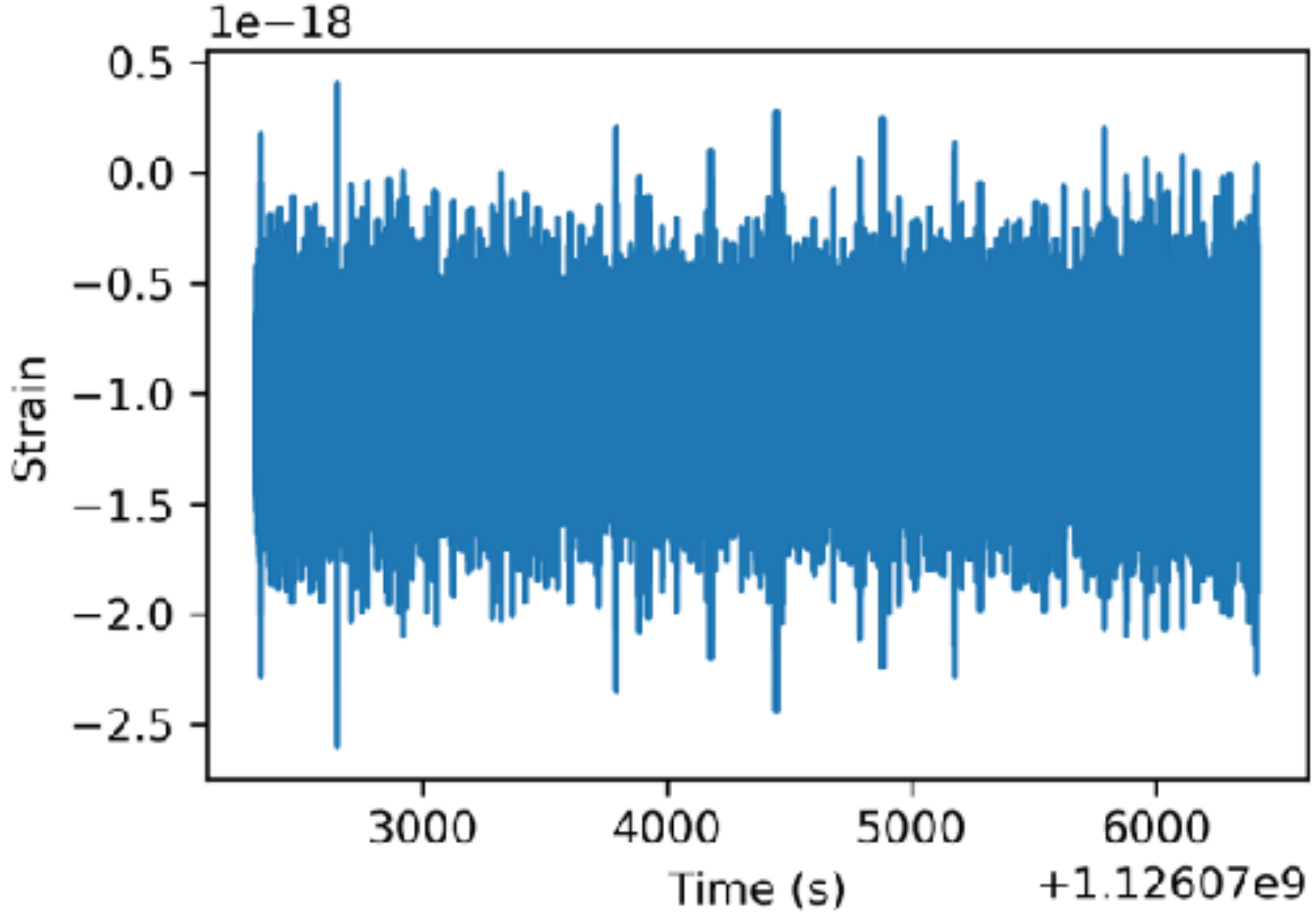




Matched Filtering





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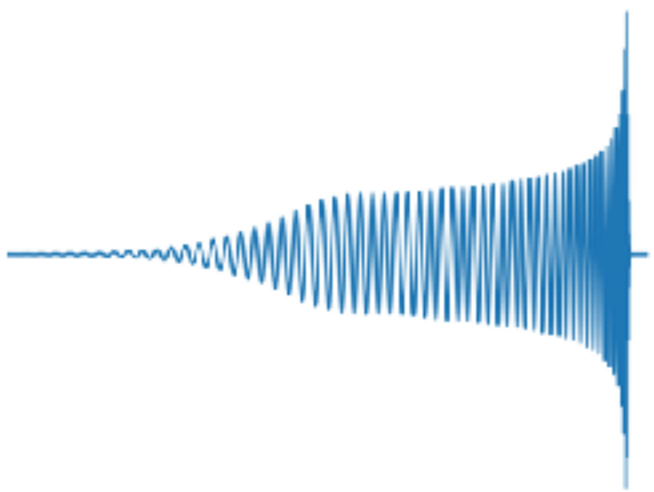

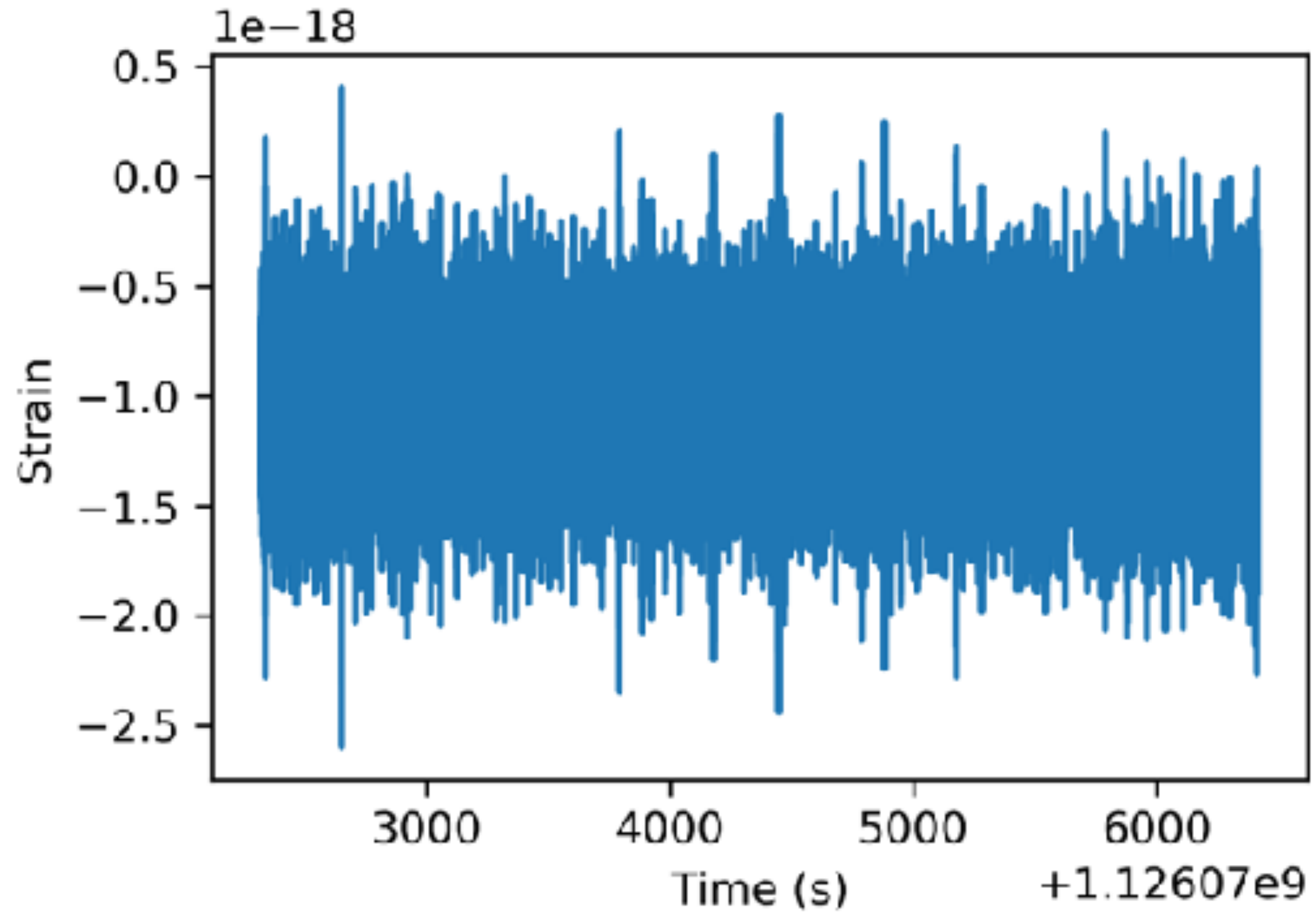

Need a noise model, simplest case is stationary Gaussian random noise

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

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

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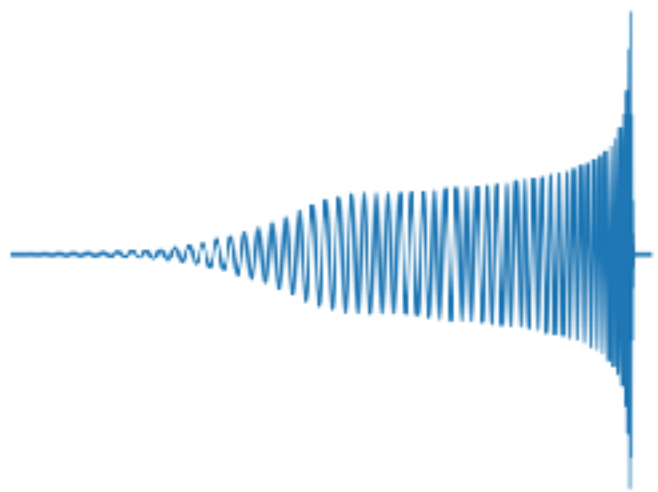

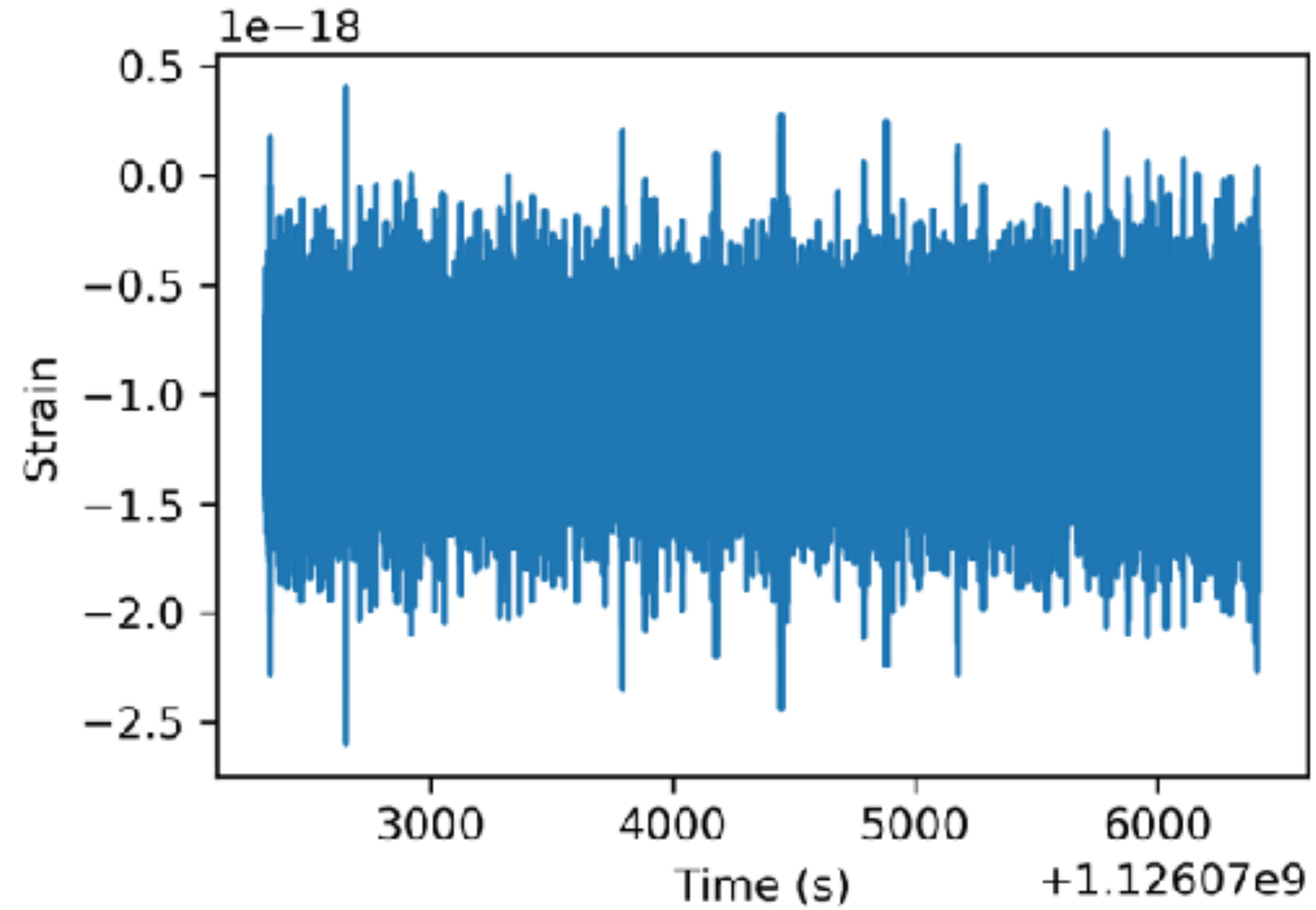

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No one tells you what $S(f)$ is! Have to measure it for yourself

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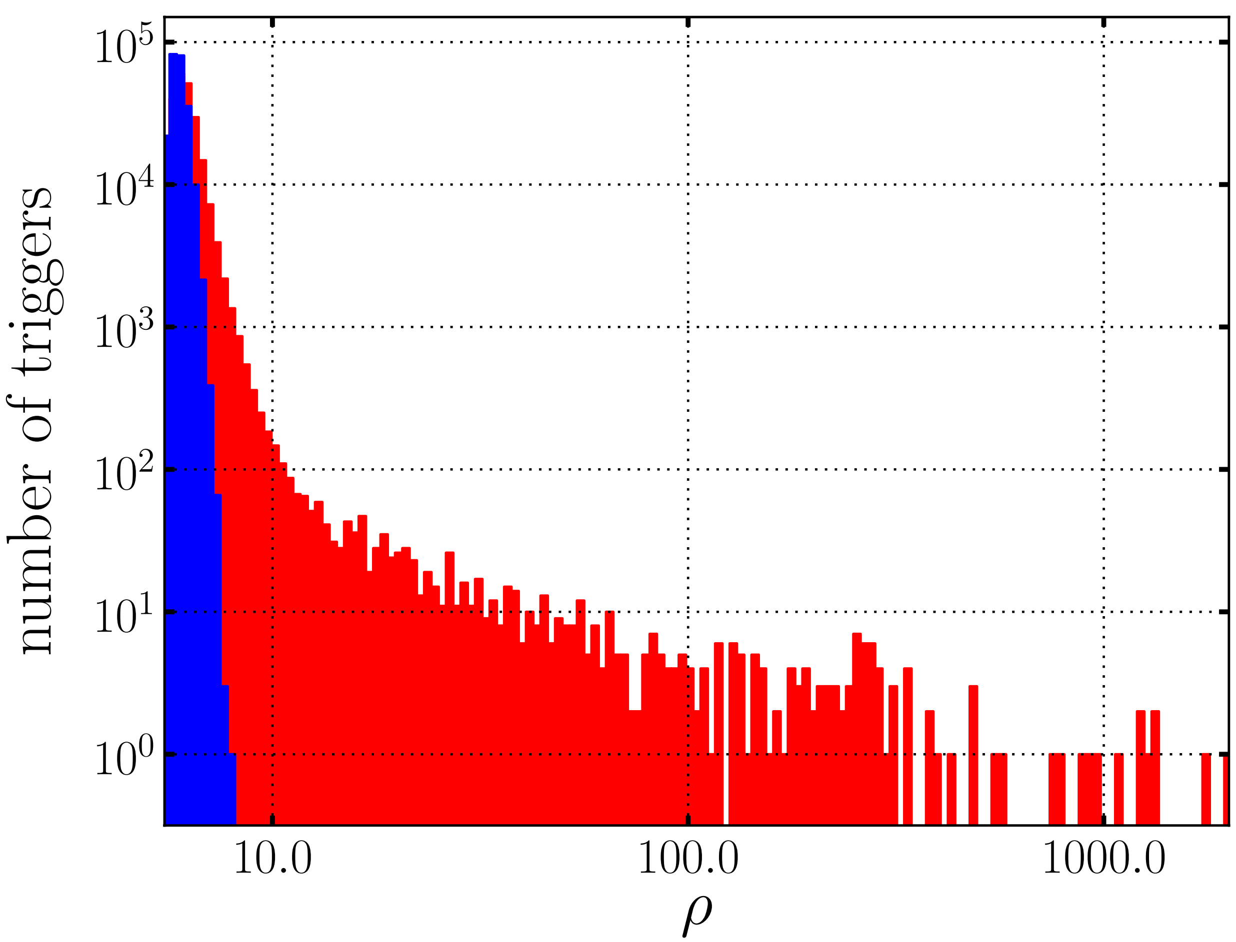
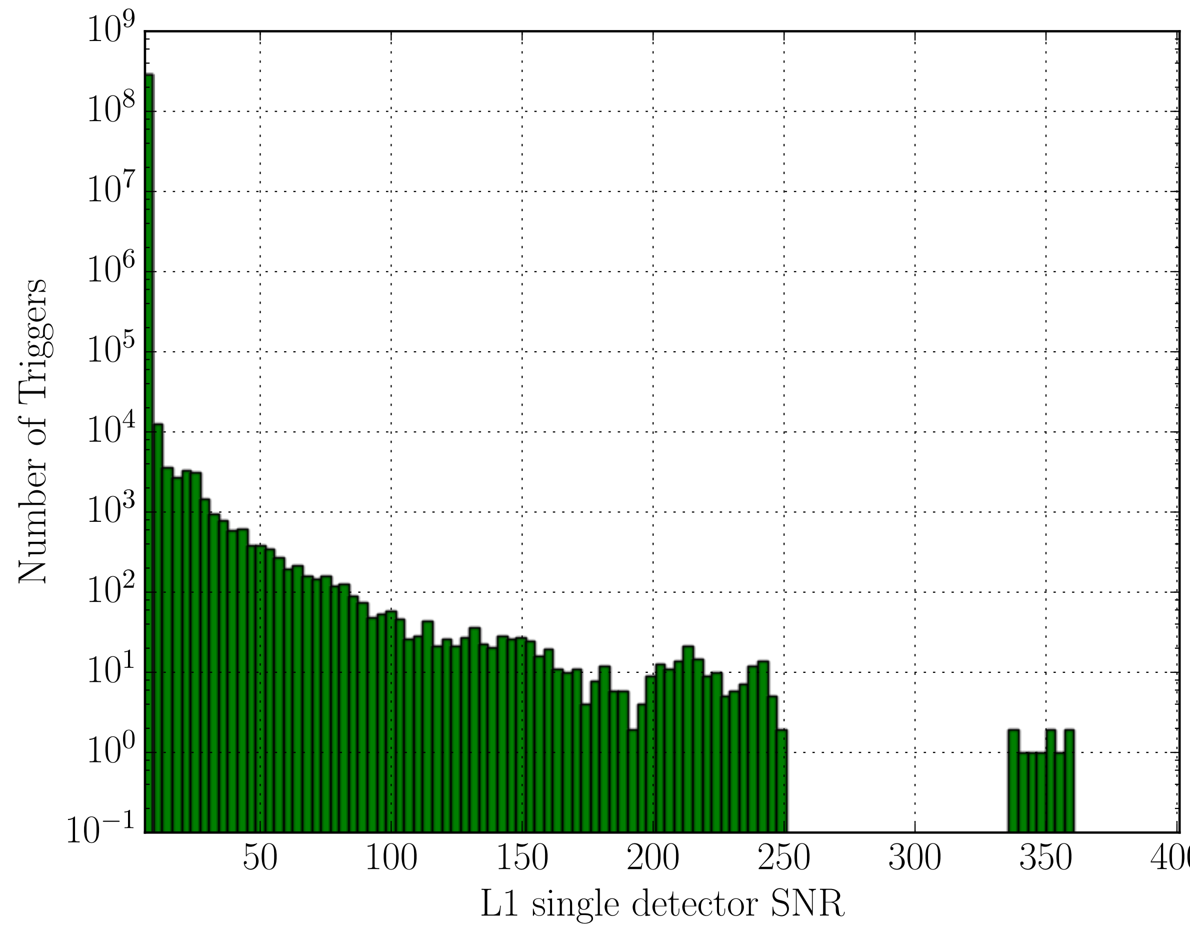
Linear
with amplitude

Distributions of Matched Filtering Scores

S5



O1



S5: Babak et. al. (2013)
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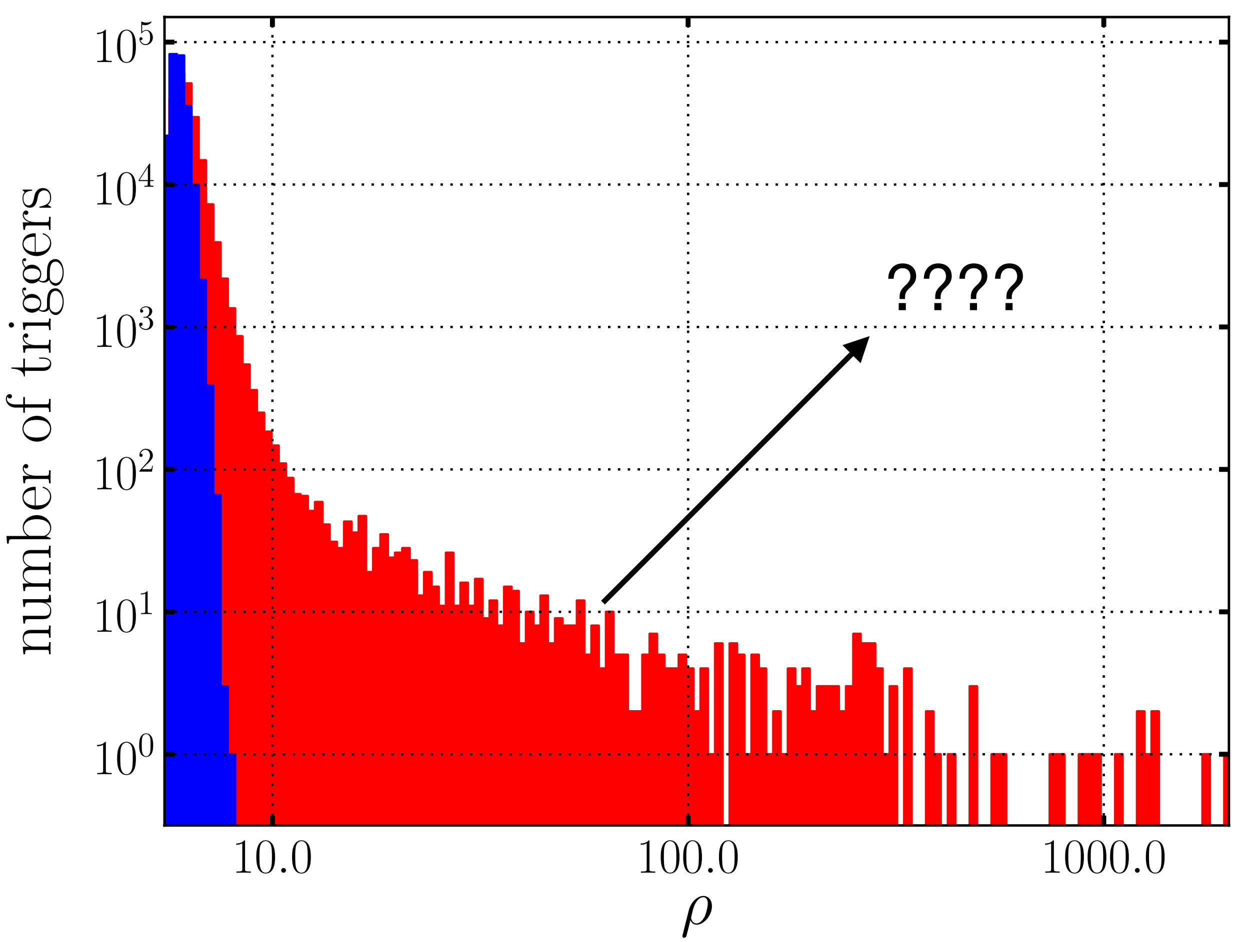

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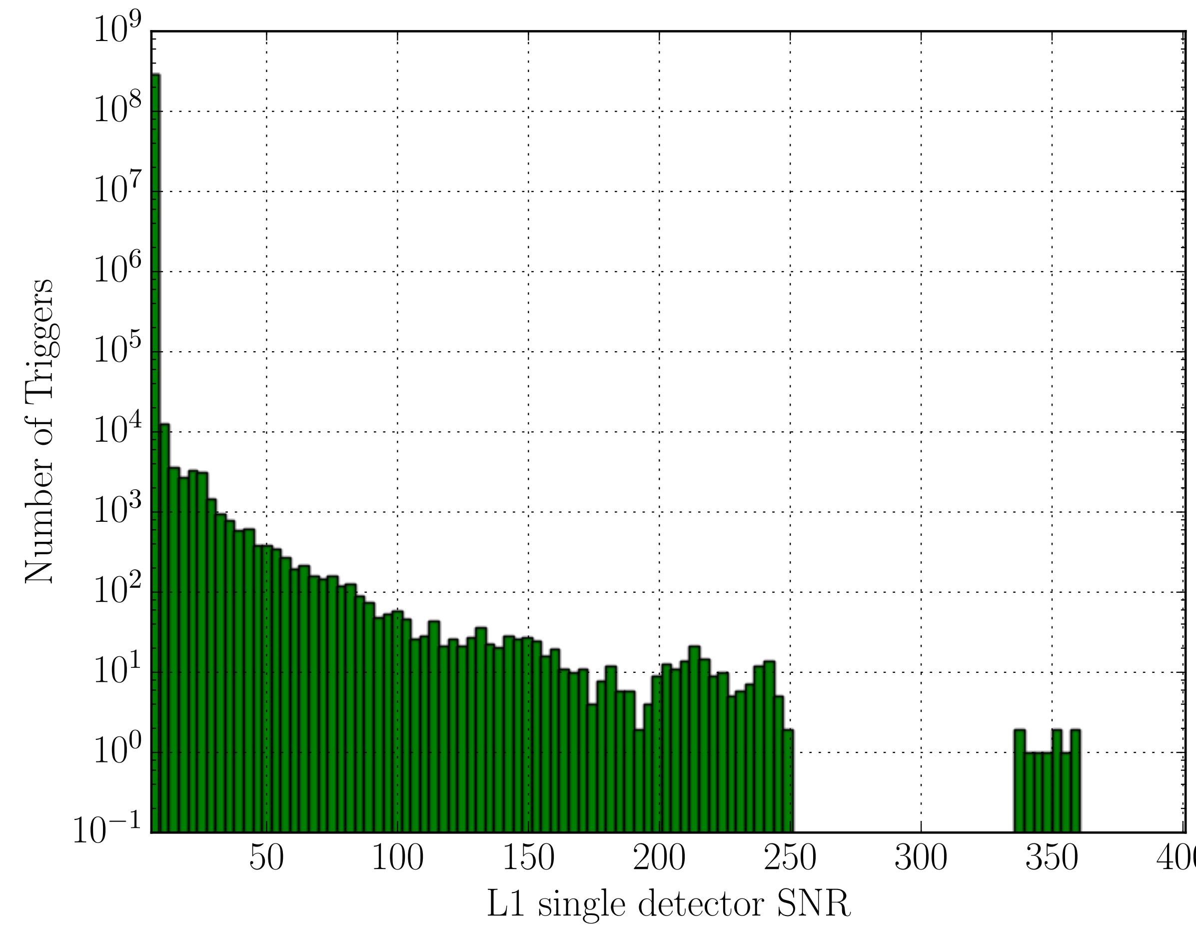

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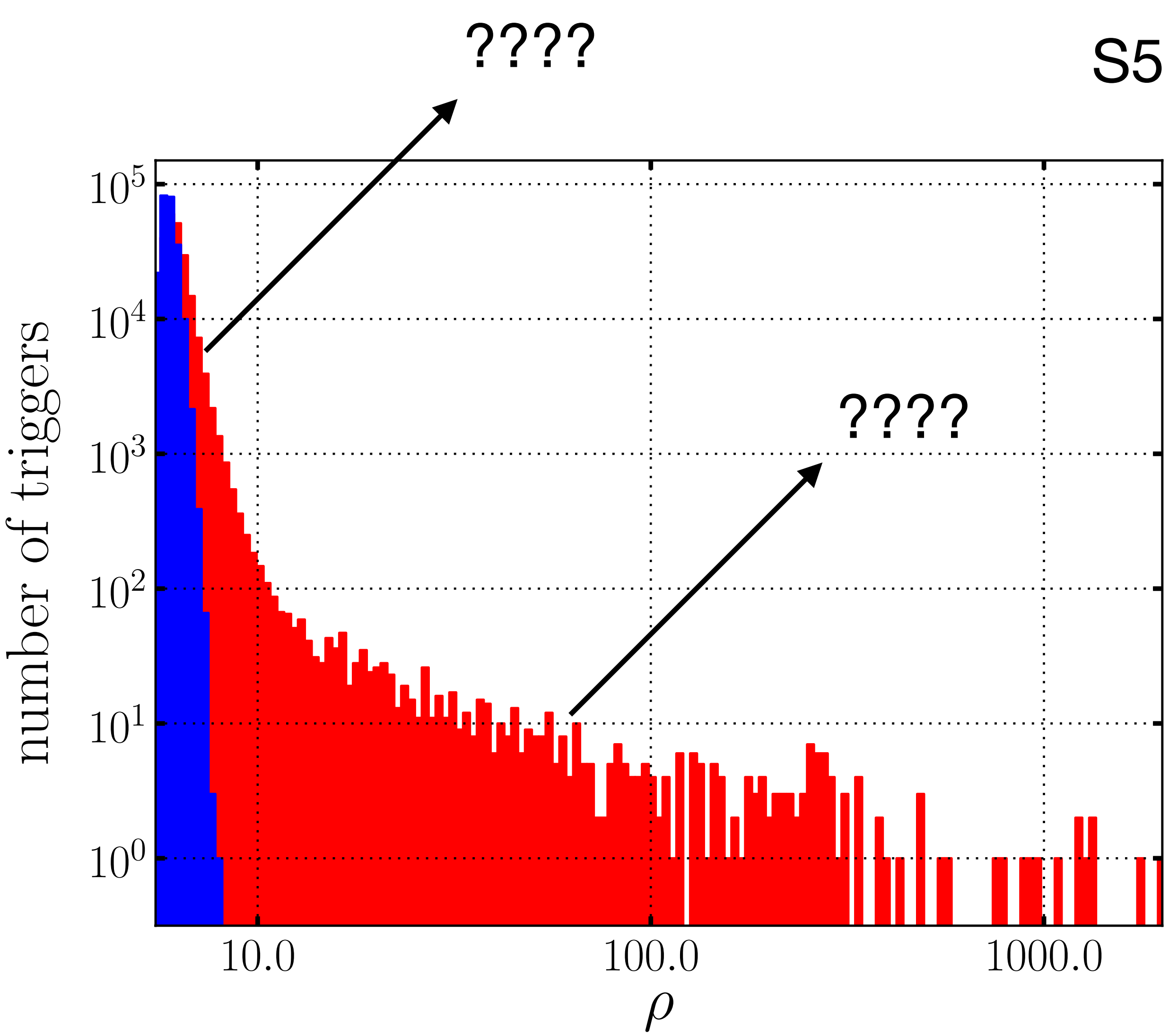

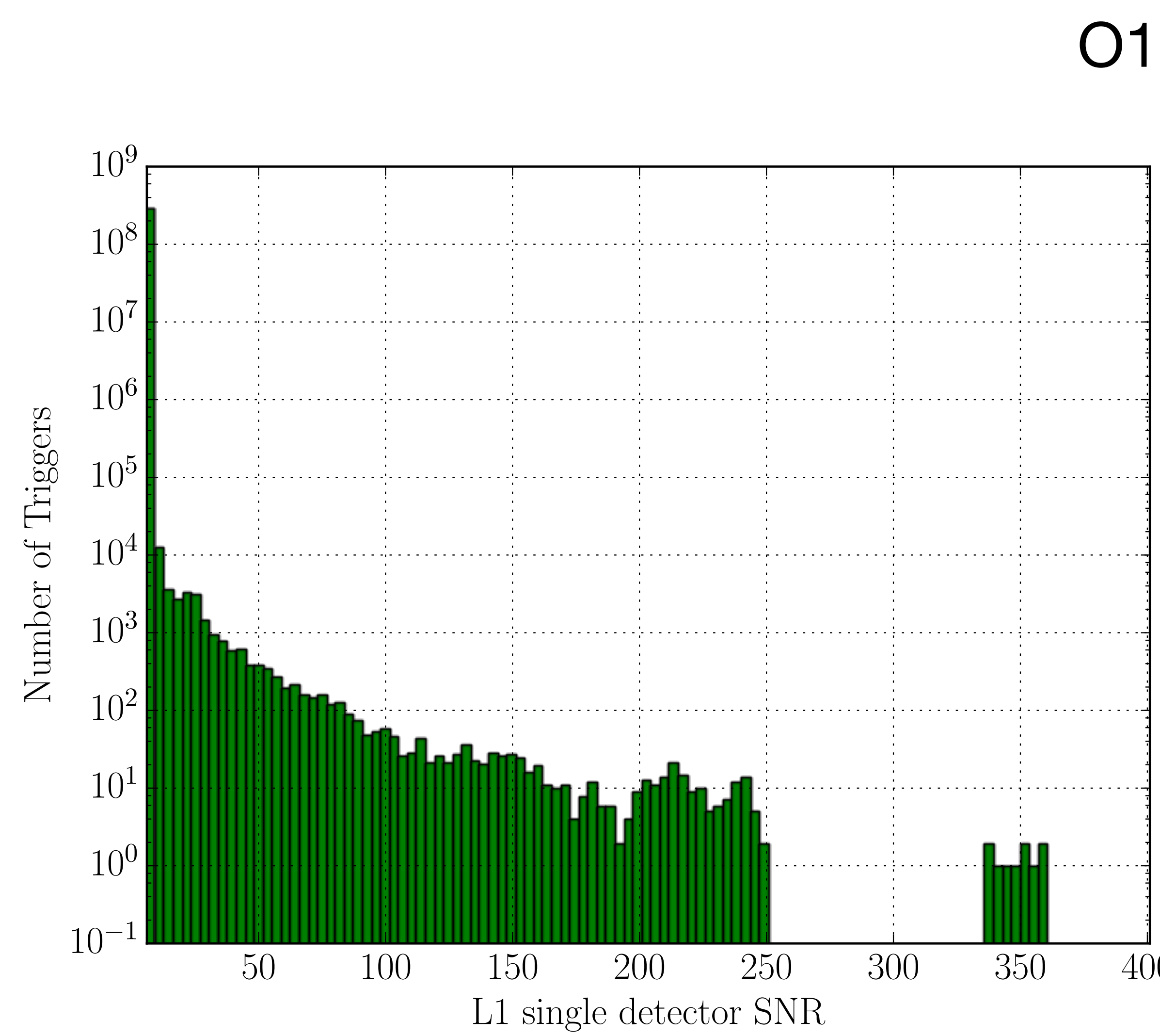

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If everything is OK, the whitened data stream

- has unit variance, and
- the data points are independent

Glitches in Whitened Data

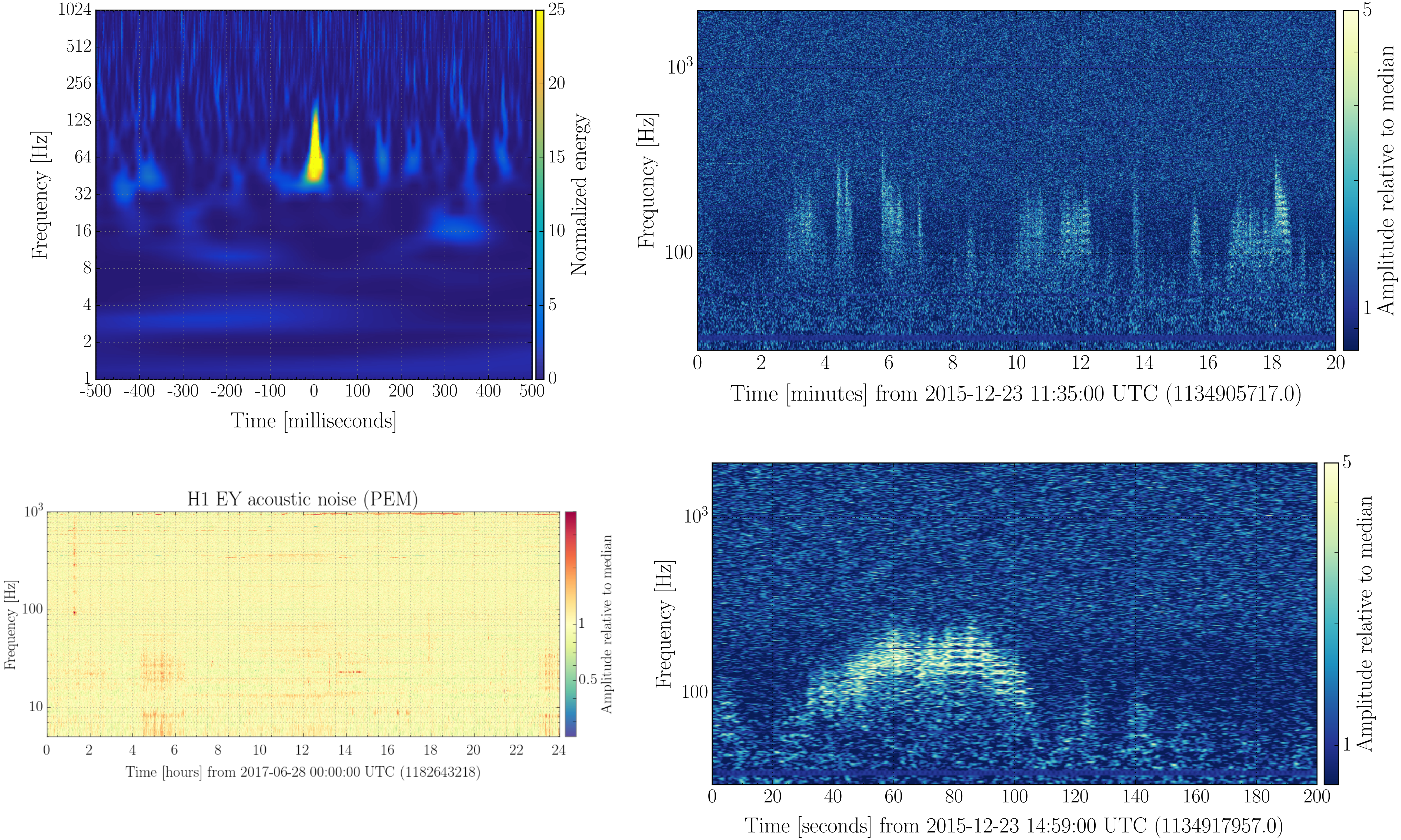

Image: Beverly Berger

Abbott et. al. (2017)

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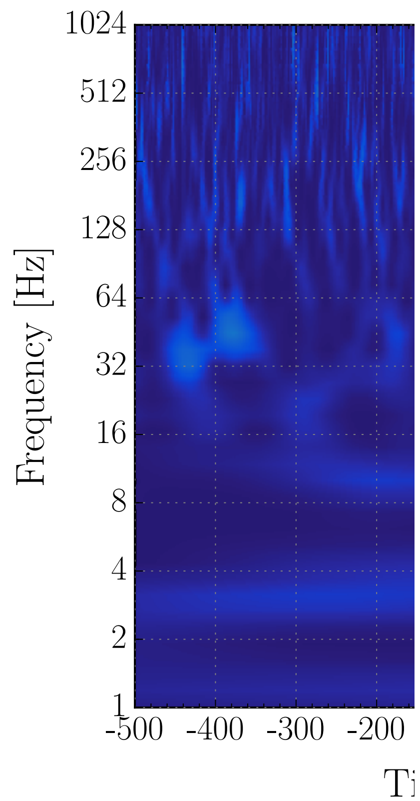

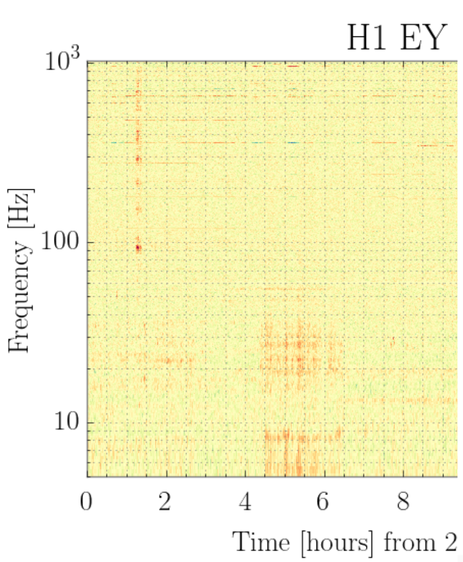

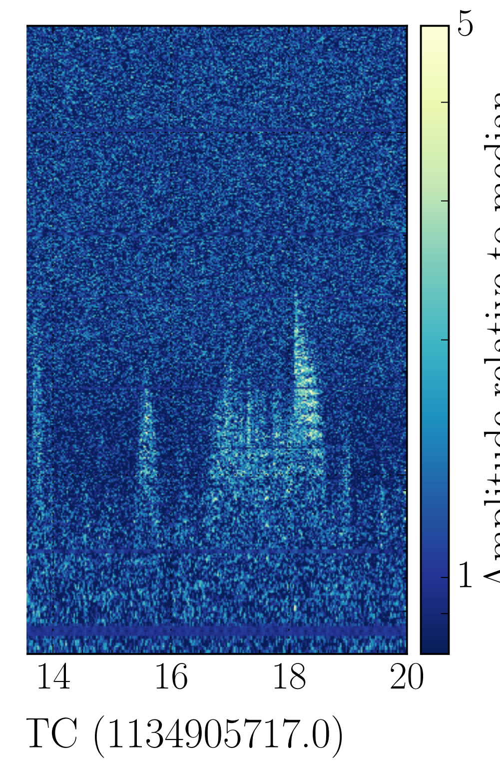

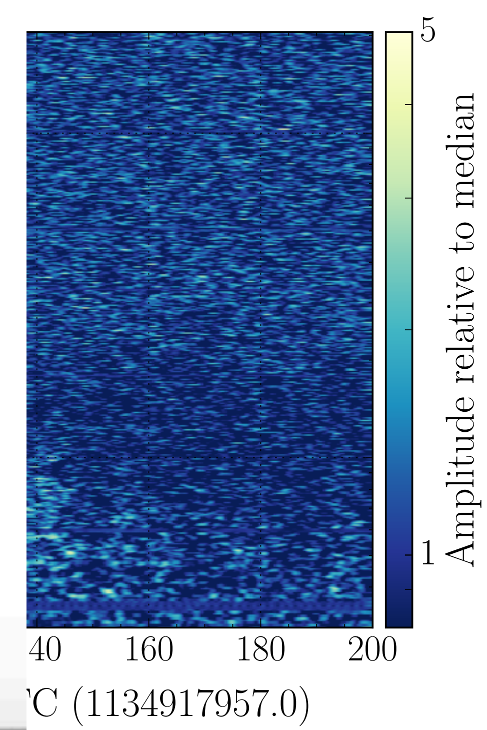

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Criteria for Detection

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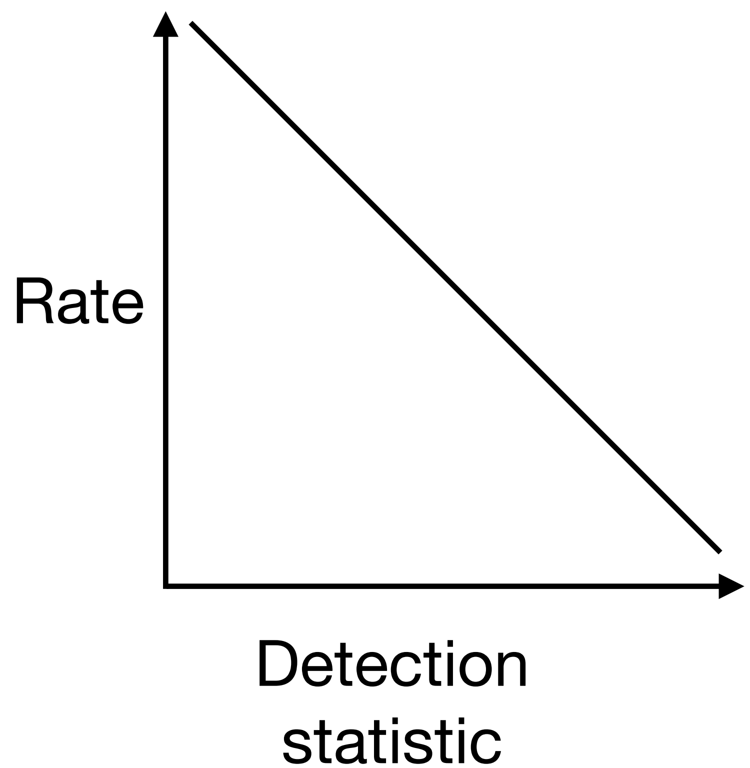

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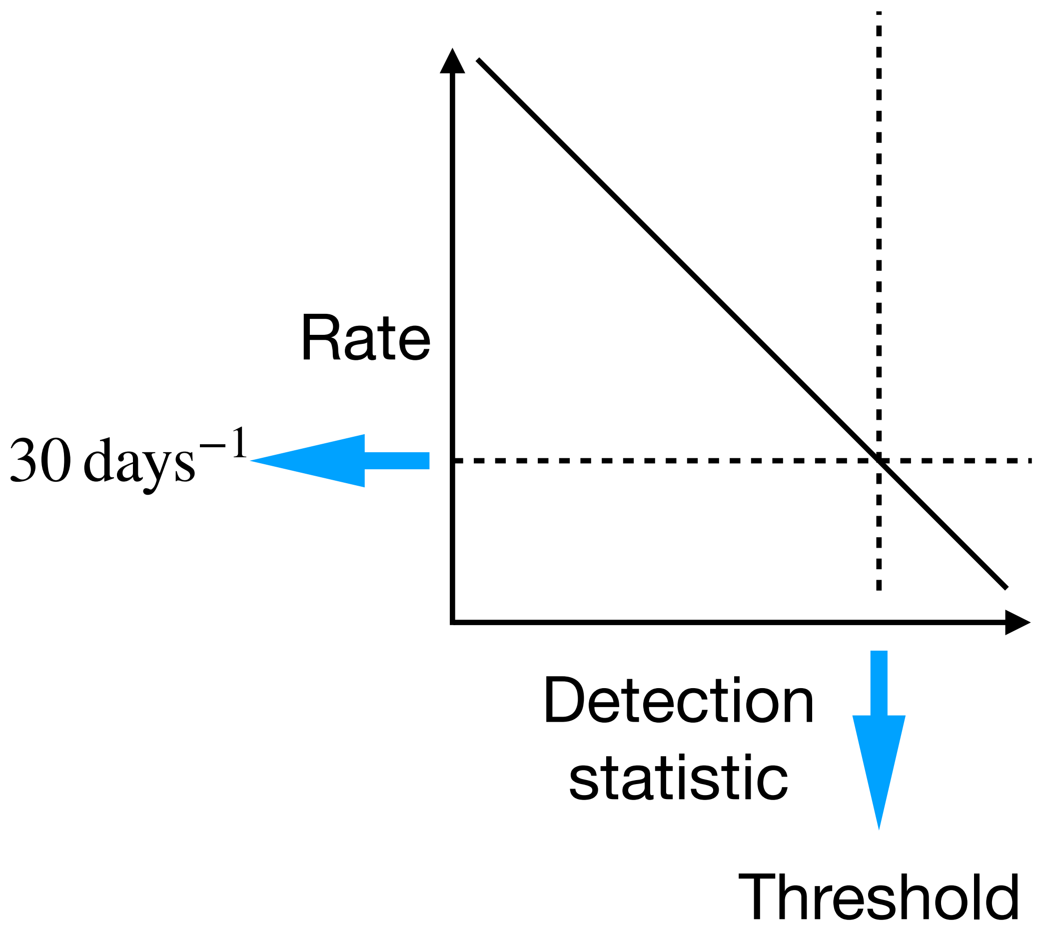

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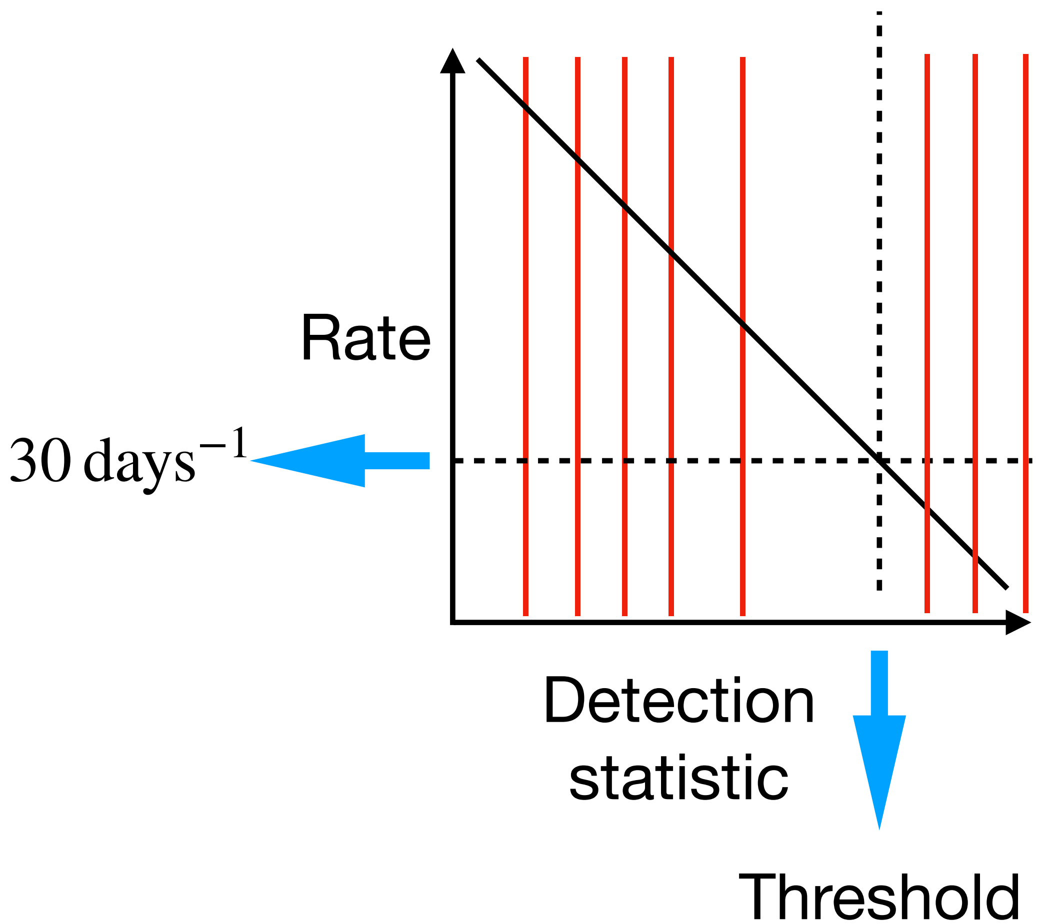

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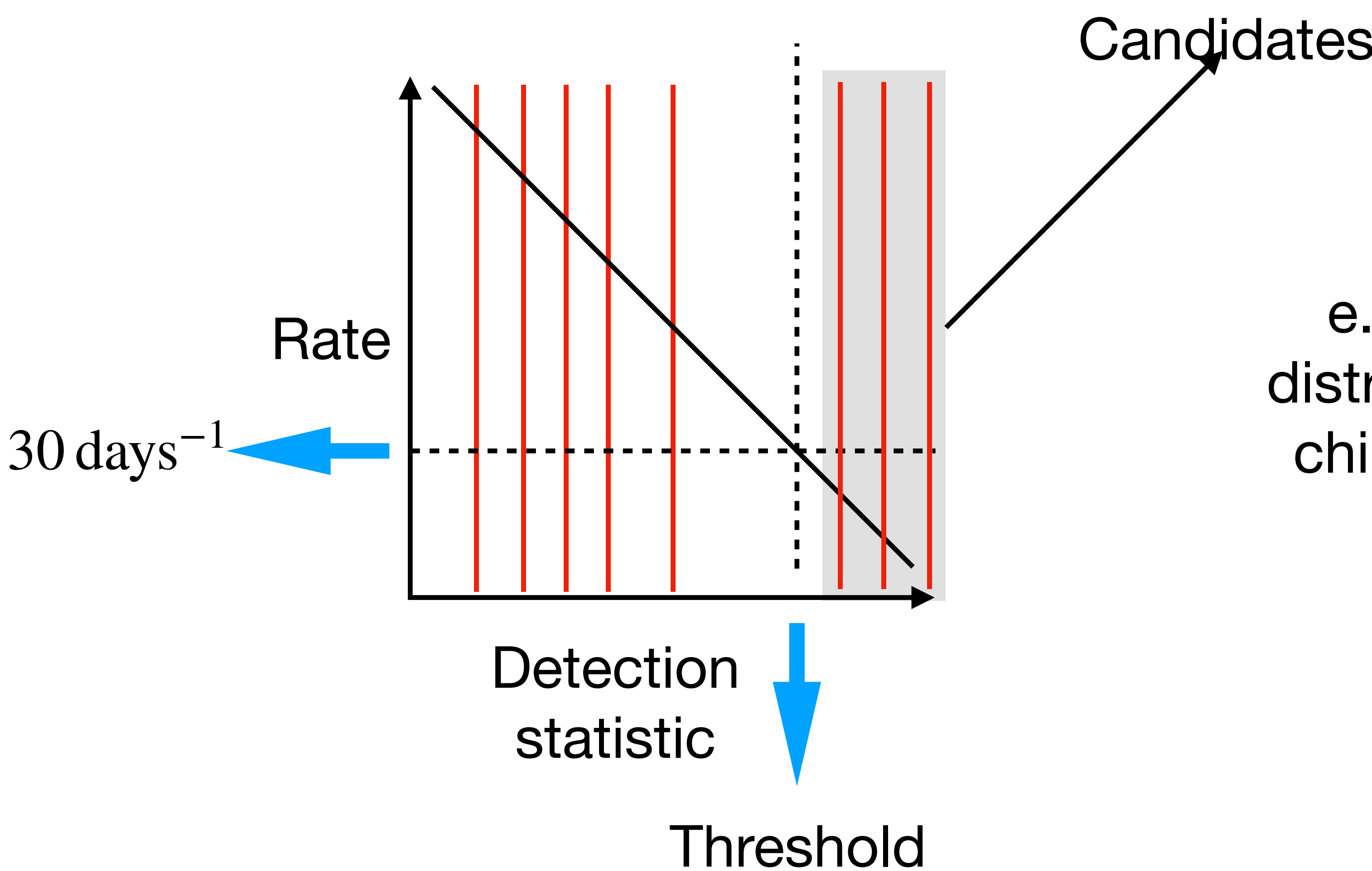

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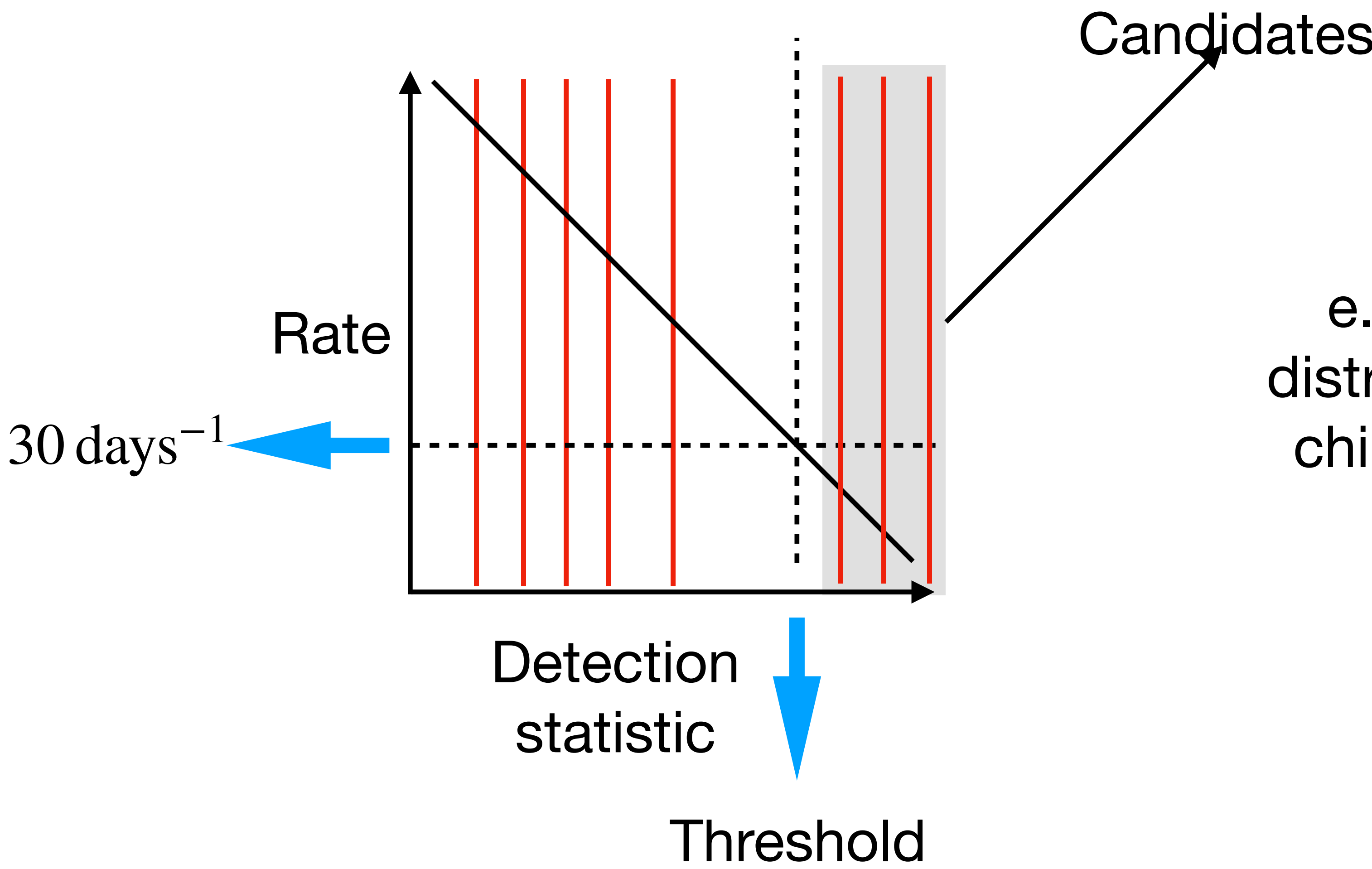

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2. $$p_{\text{astro}} = \frac{R\left(\text{candidate} \mid \mathcal{S}\right)}{R\left(\text{candidate} \mid \mathcal{N}\right) + R\left(\text{candidate} \mid \mathcal{S}\right)} > 0.5$$

LIGO-VIRGO Published Detections

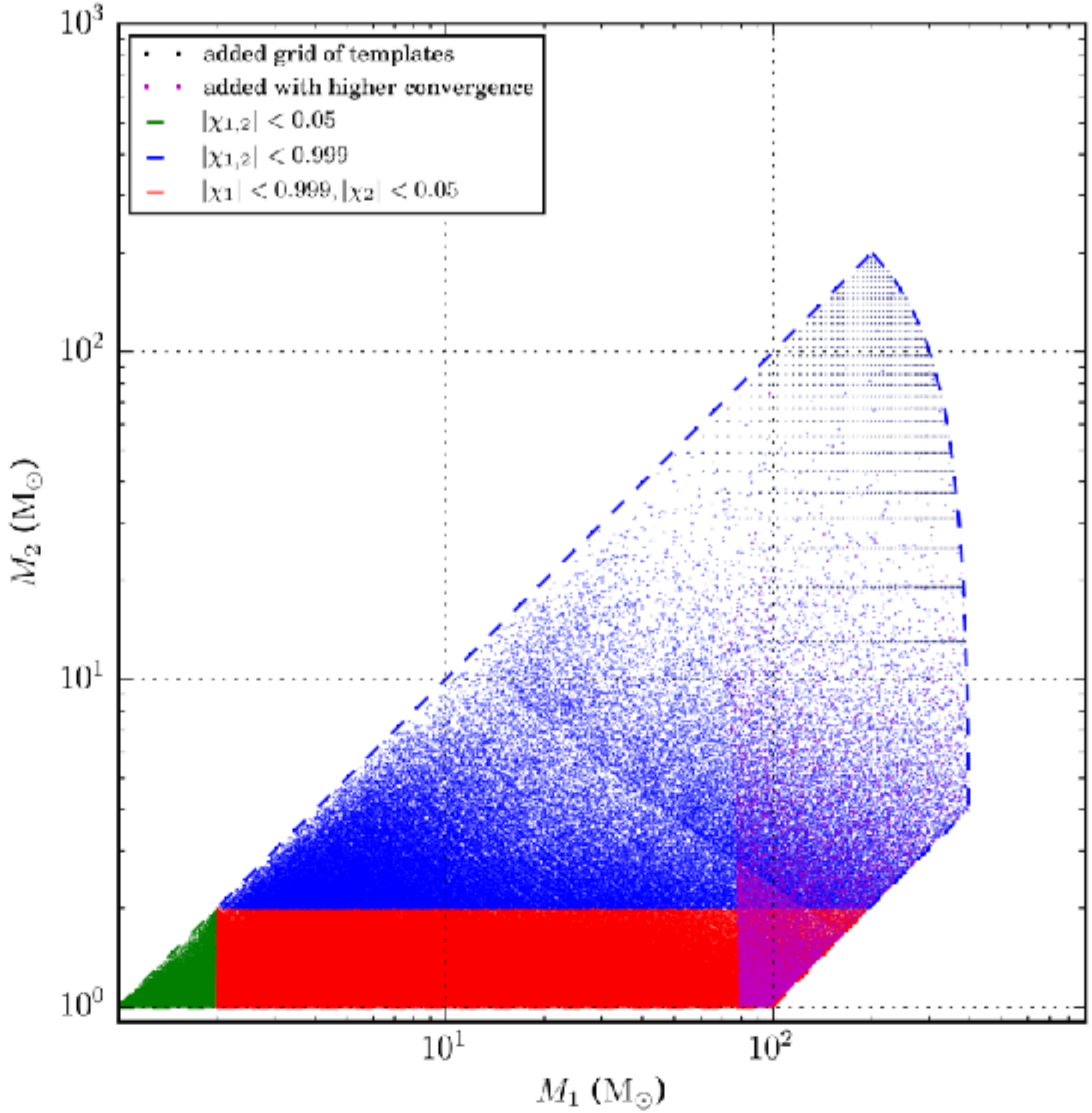
Two observing runs with detections:

1. O1 run: Sep 2015 to Jan 2016
   - ~50 days of coincident runtime
   - Two confirmed detections of GWs from merging BBHs, and one candidate (LVT151012)

2. O2 run: Nov 2016 to Aug 2017
   - 118 days of coincident data between H and L
   - 15 days with VIRGO
   - A BNS merger detected
   - With more confirmed events, and a better handle on the rates, criteria for detection were defined. 7 new BBH mergers, and LVT, added to the list of events.

Happening right now: O3 …

LIGO-VIRGO Published Detections



arxiv: 1901.08580

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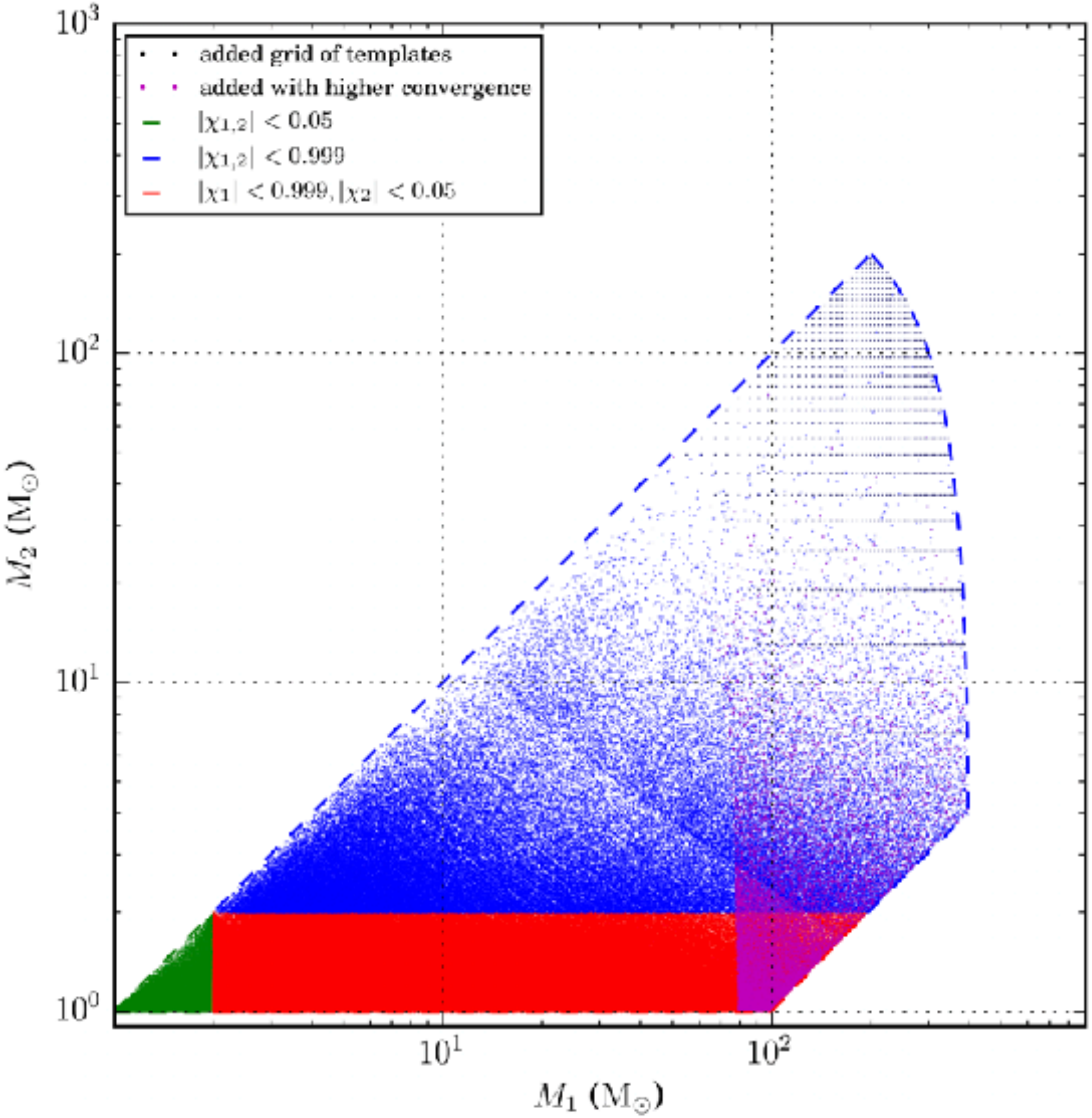
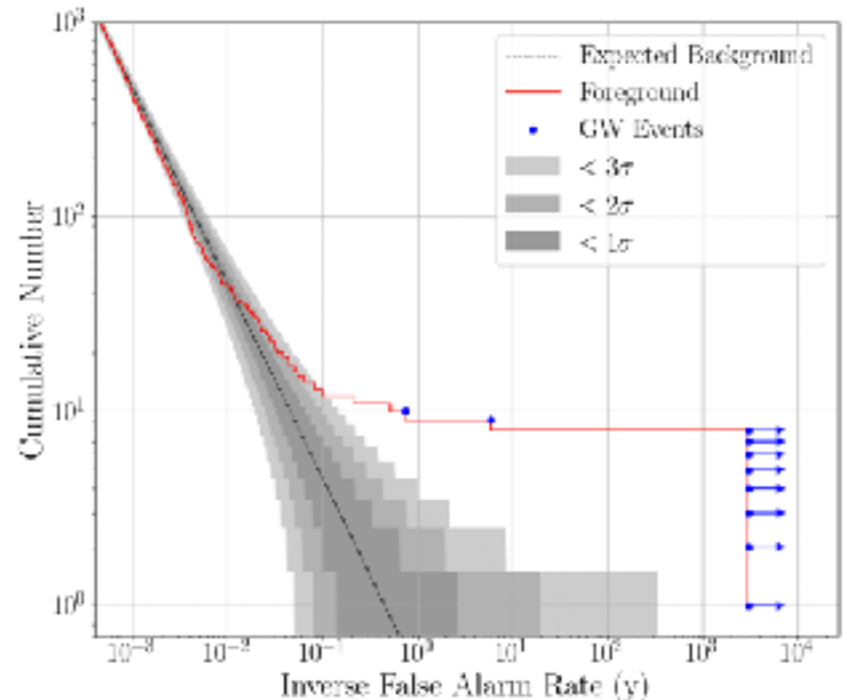
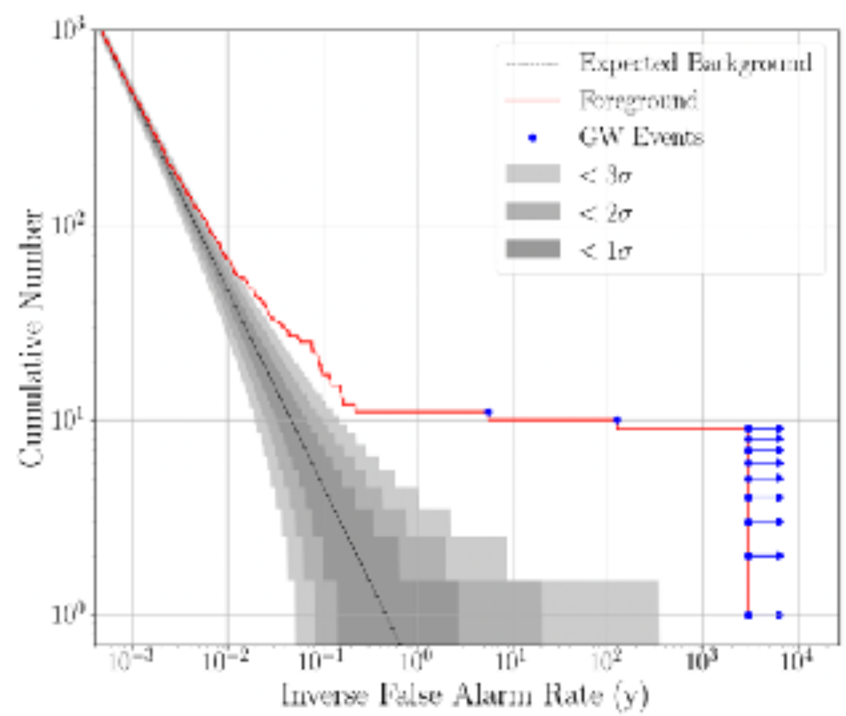


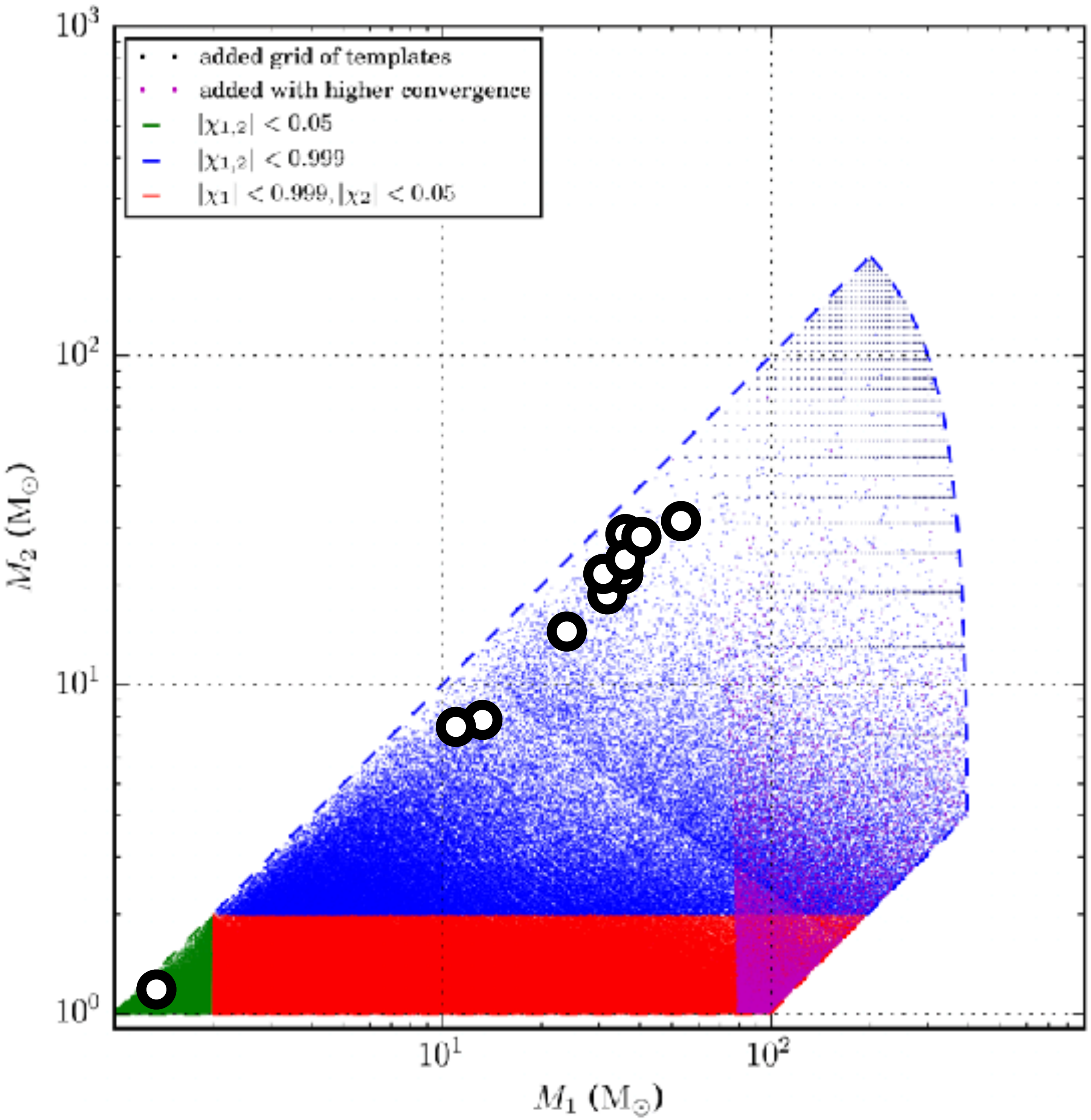




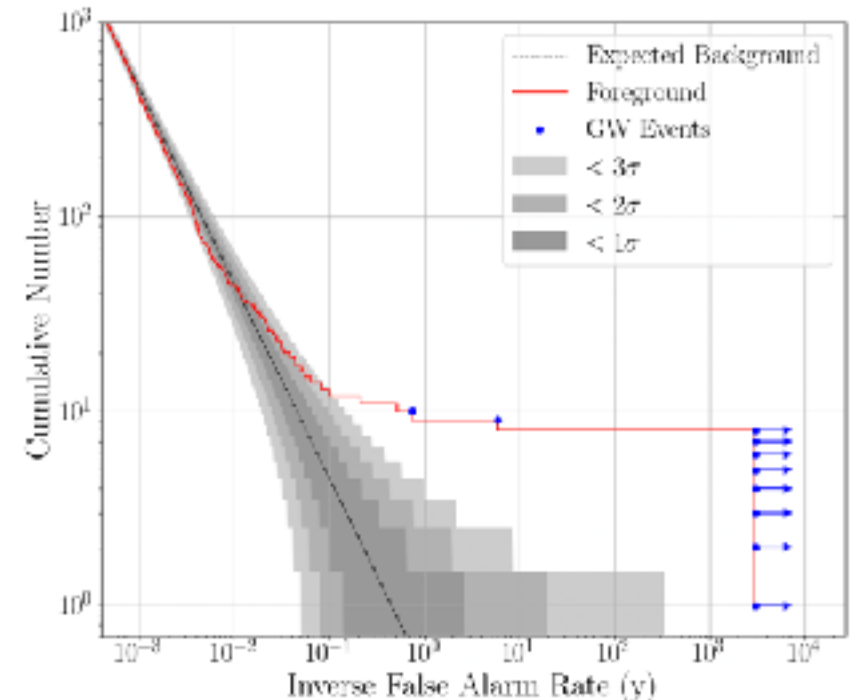
arxiv: 1901.08580

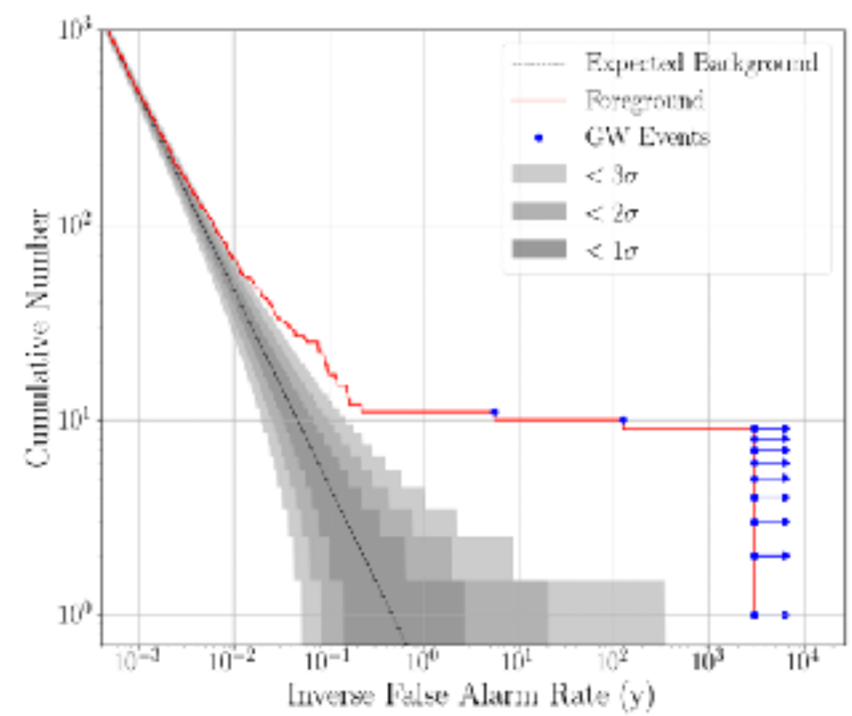
arxiv: 1811.12907

LIGO-VIRGO Published Detections



arxiv: 1901.08580





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Our Search

- Construct template banks
- Whiten and clean the data
- Generate triggers and correct for non-stationary noise
- Collect coincident triggers and veto remaining glitches
- Coherently analyze remaining coincident triggers

Our Search

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

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Template bank

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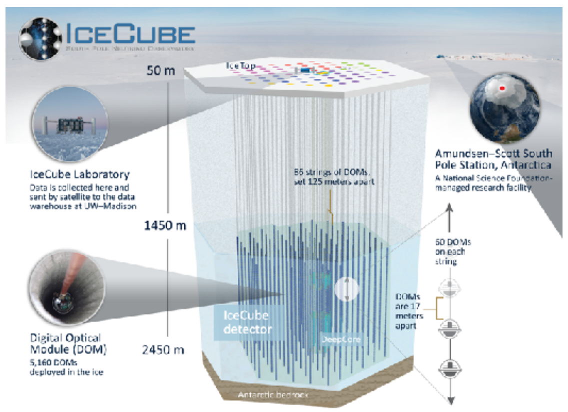

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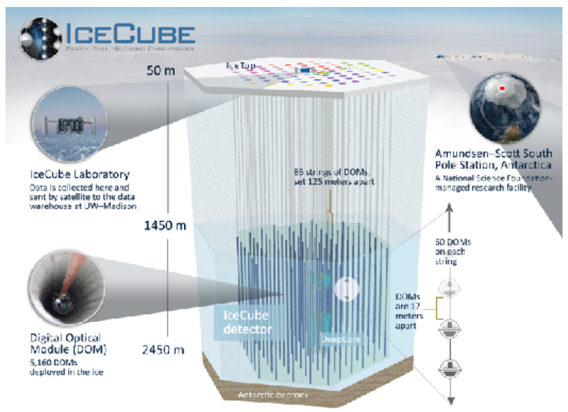

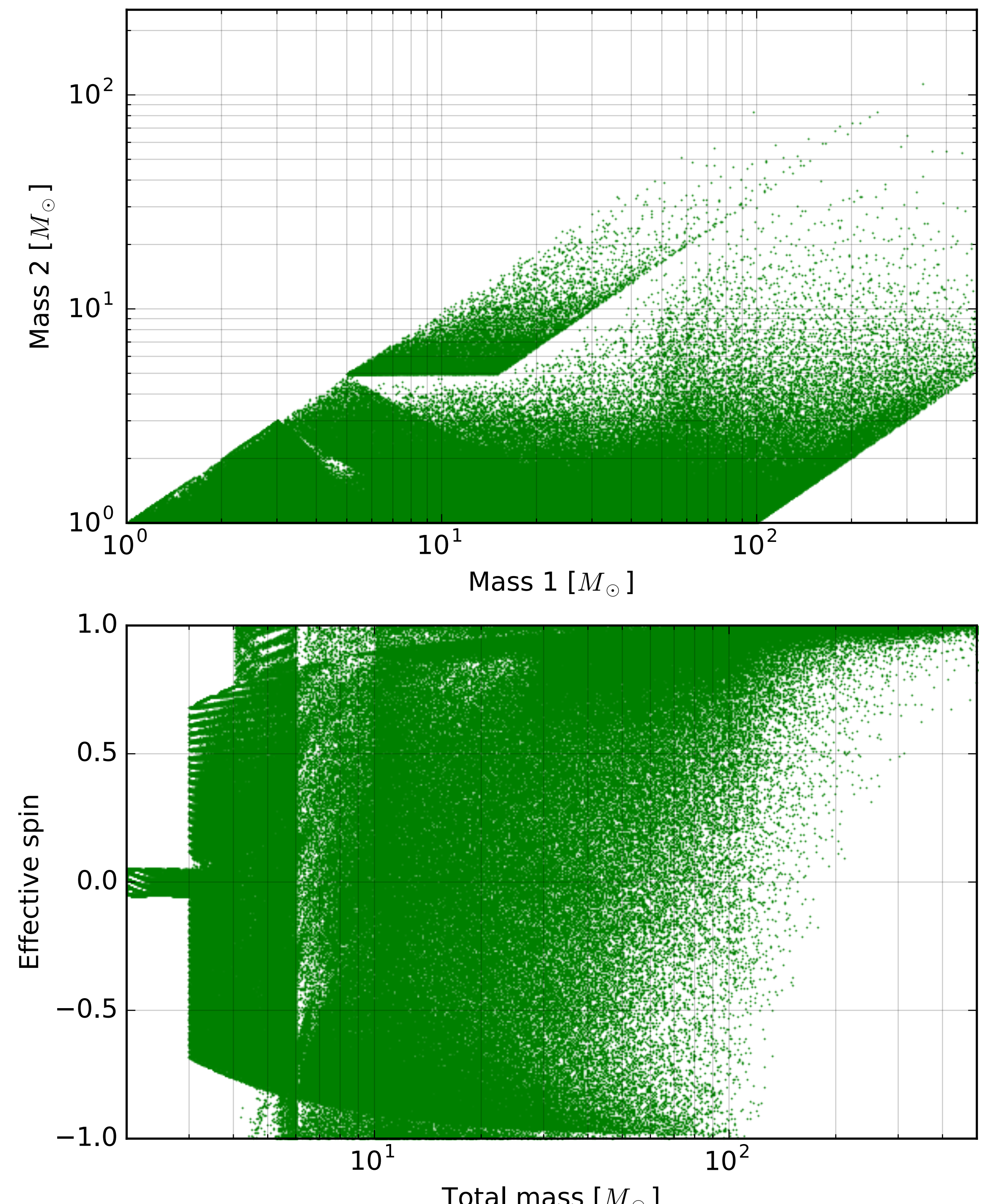

$$\chi_{\rm eff} = \frac{m_1\chi_{1,z} + m_2\chi_{2,z}}{m_1 + m_2}$$

Canton and Harry (2017)

Template bank

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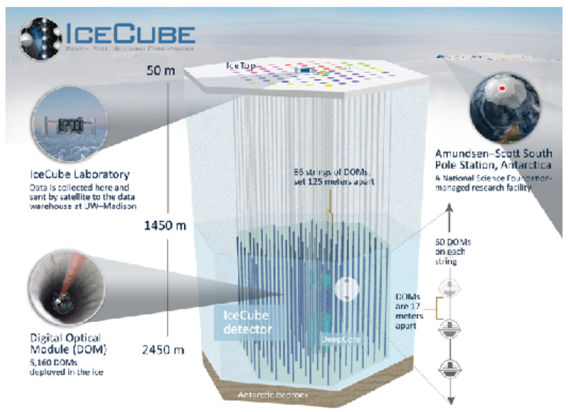
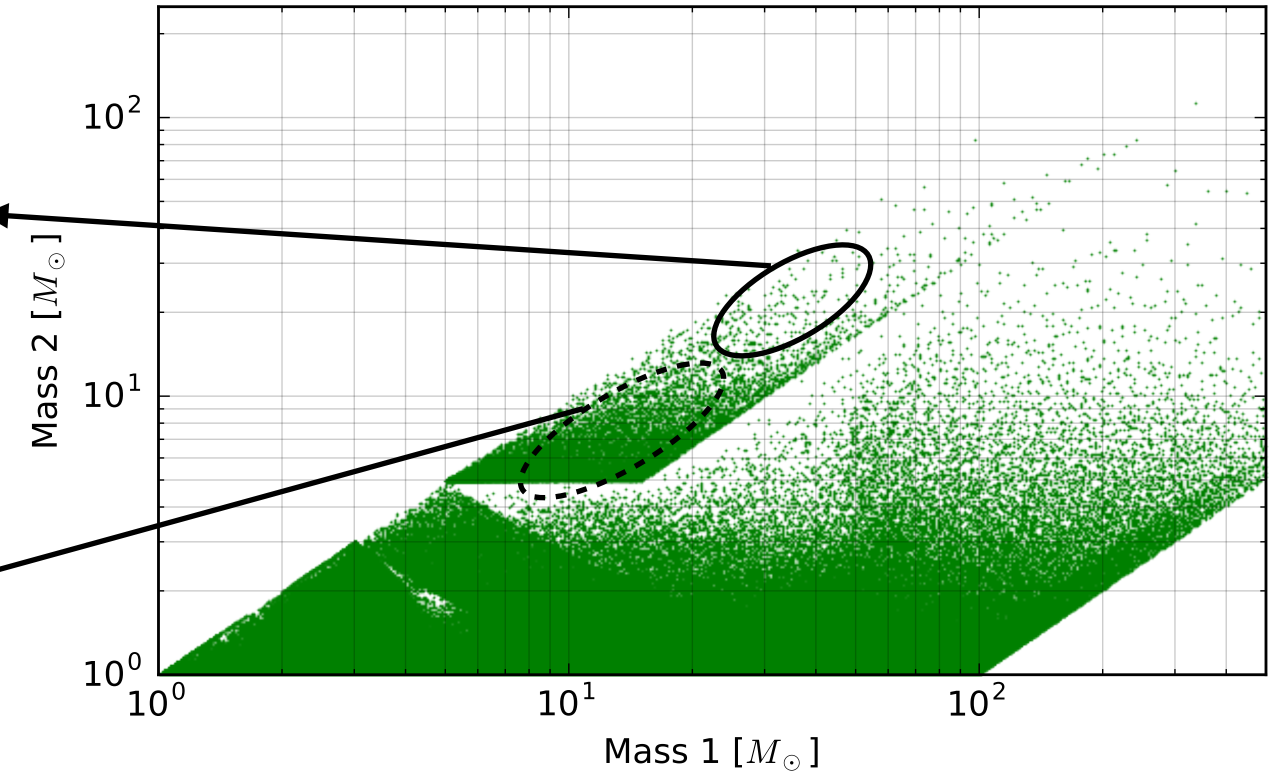
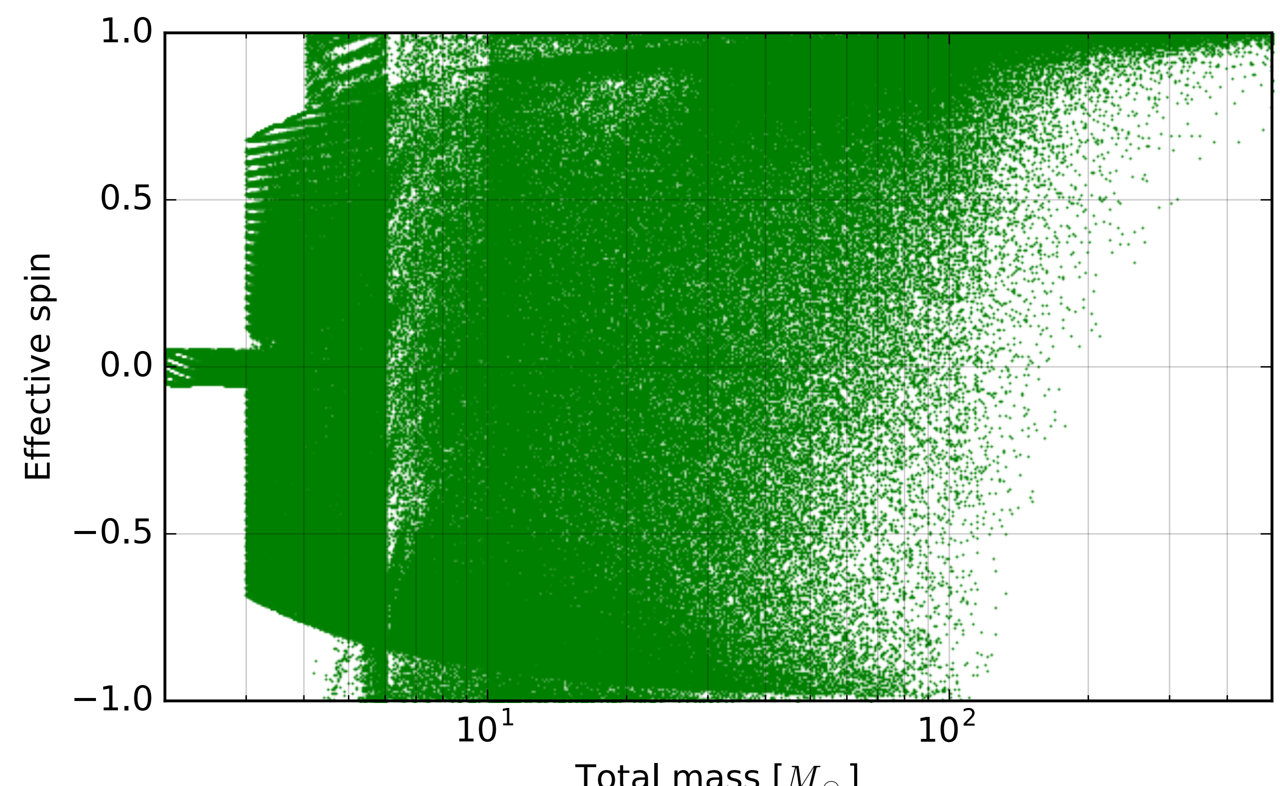


LVC detections

??





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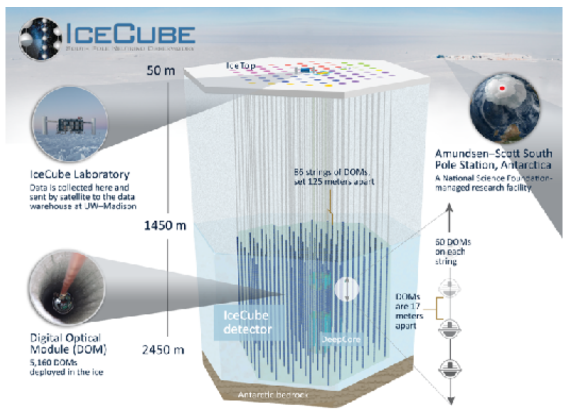
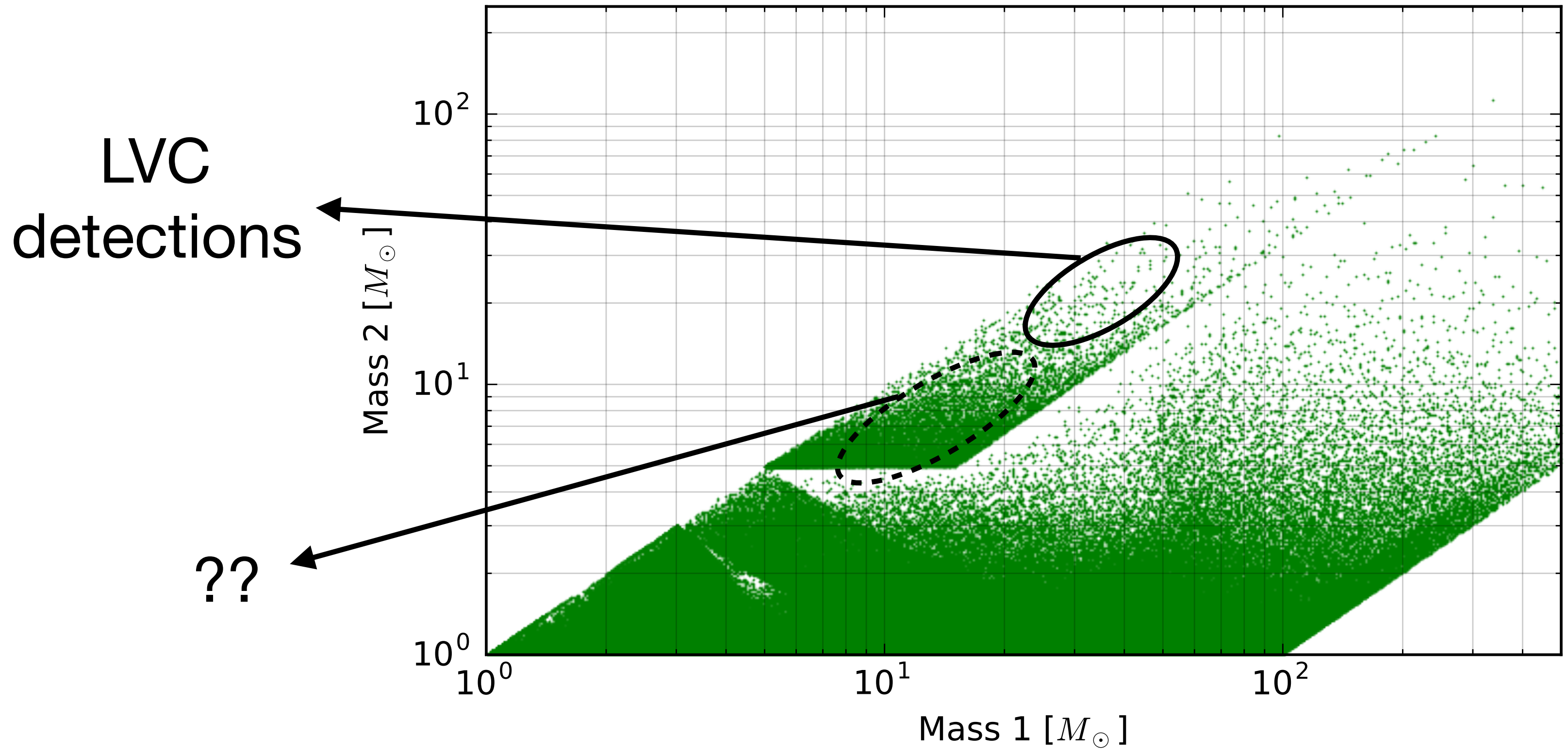
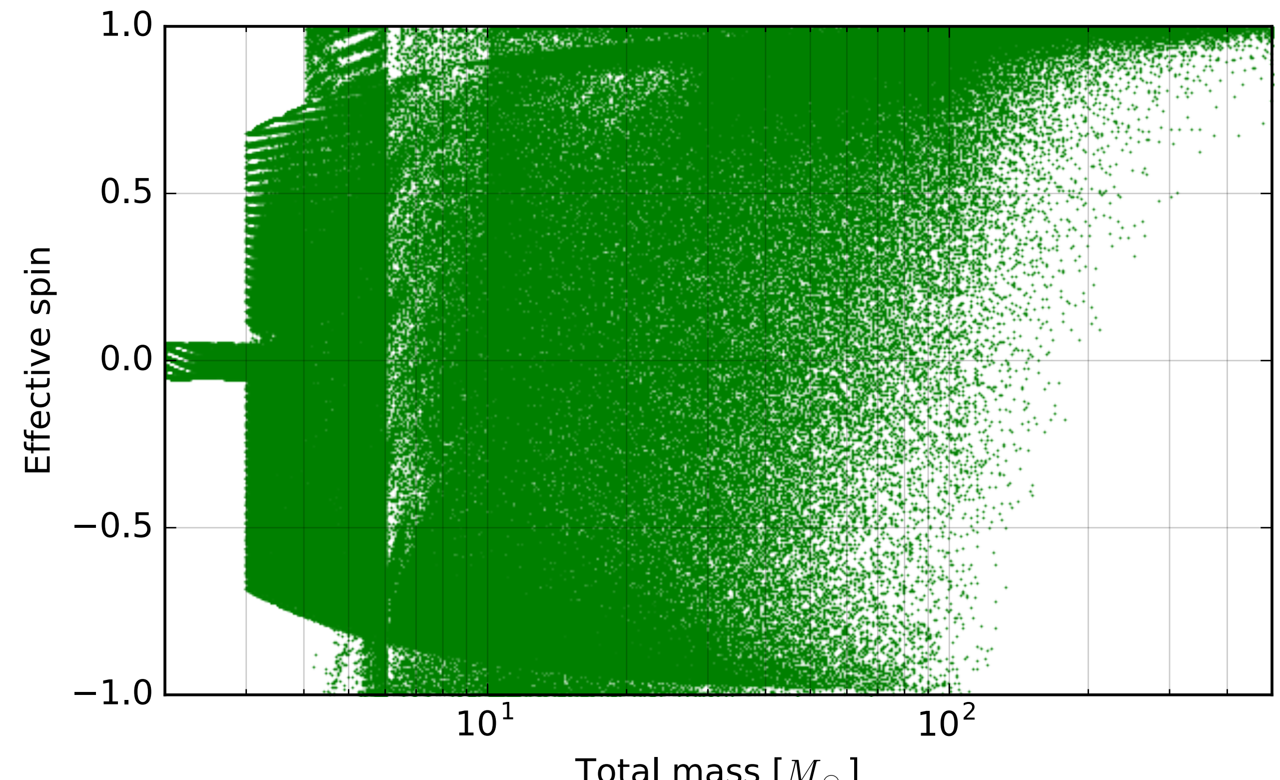




$$\phi \sim \frac{1}{\left(M_c f_{\min}\right)^{5/3}}$$

$$\frac{dN}{d\ln M_c} \sim \left(M_c f_{\min}\right)^{-5/3}$$



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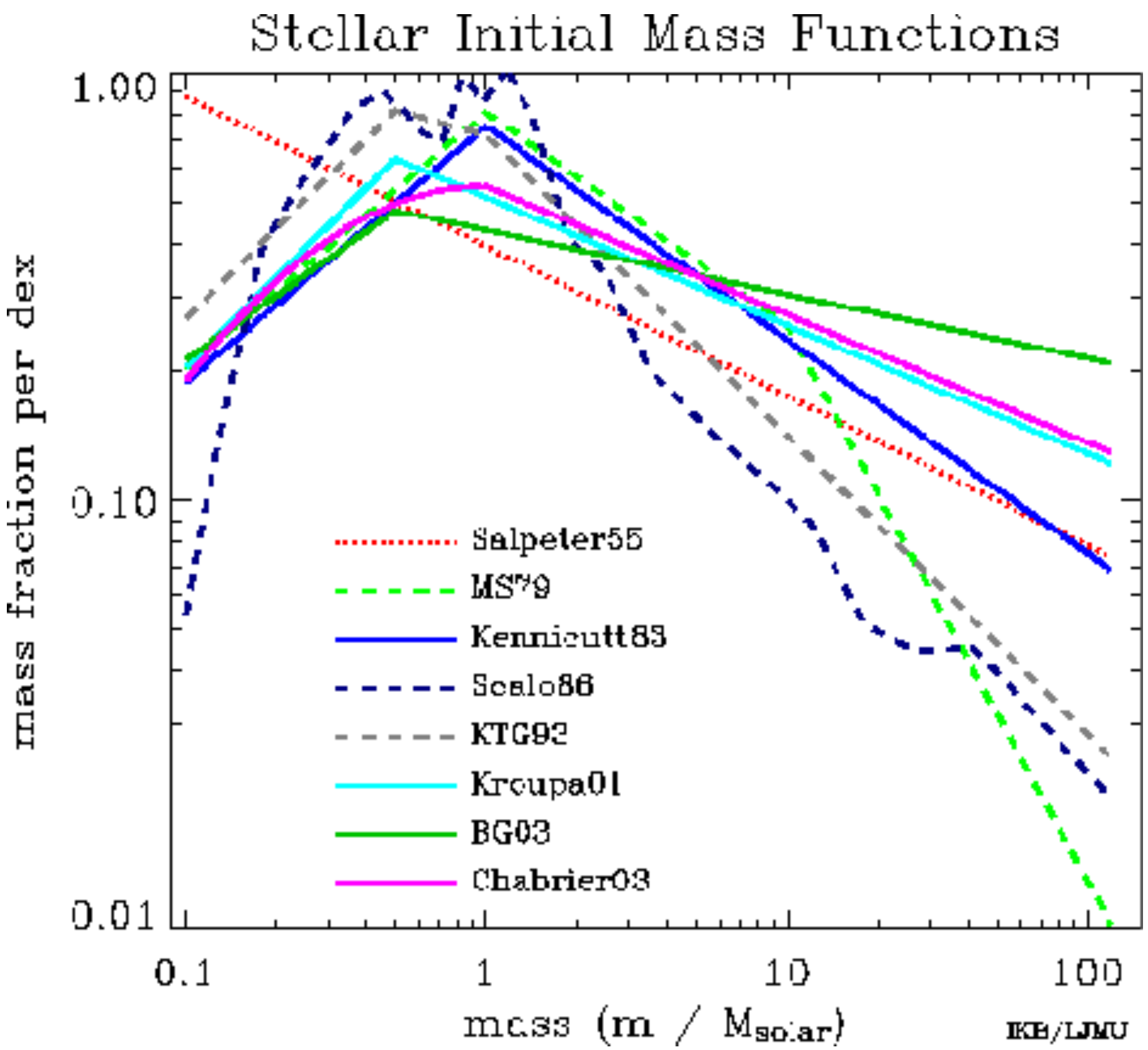
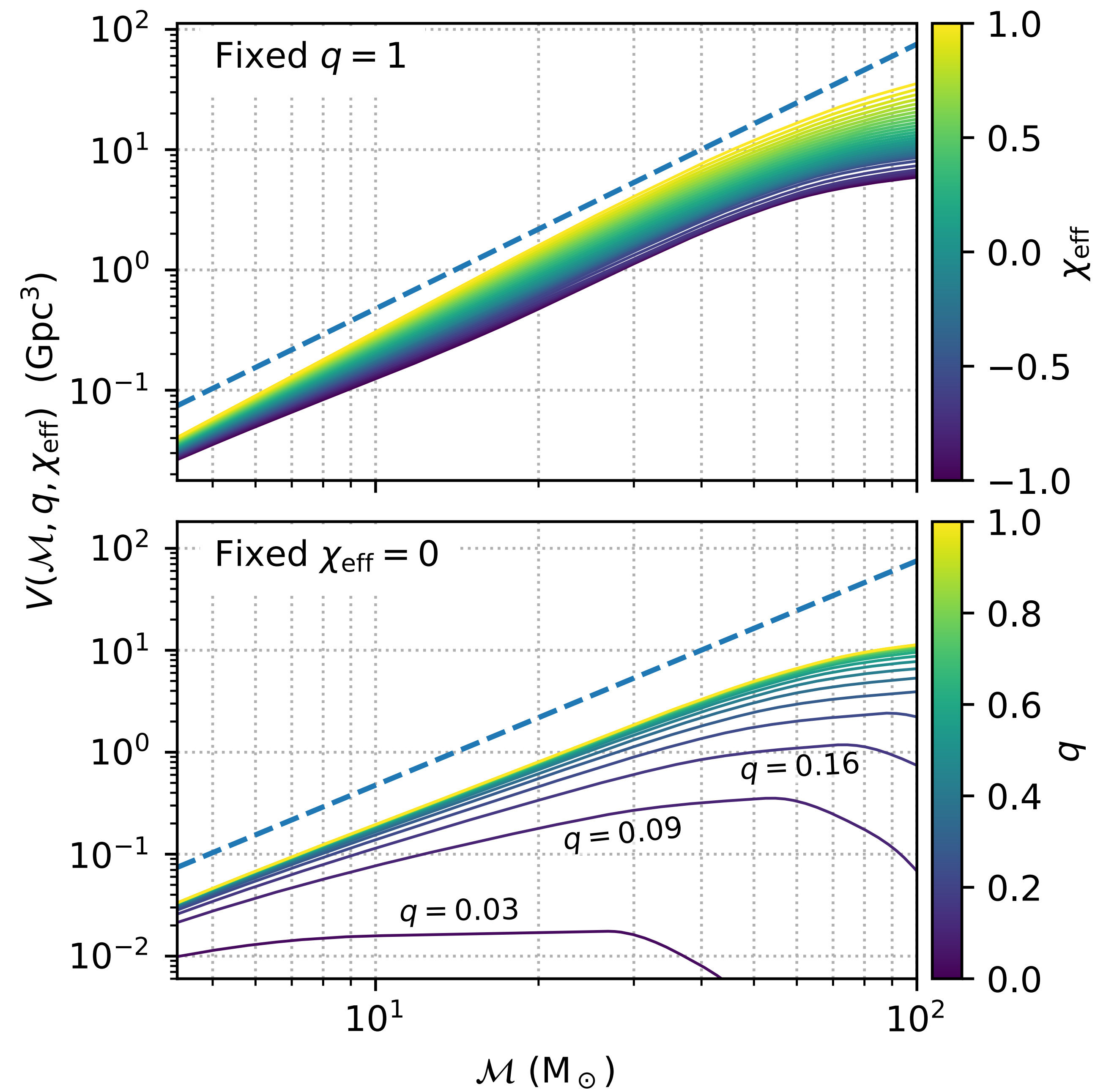
Canton and Harry (2017)

Estimated Astrophysical Distribution



$$\frac{dN}{dM} \sim M^{-2.35}$$

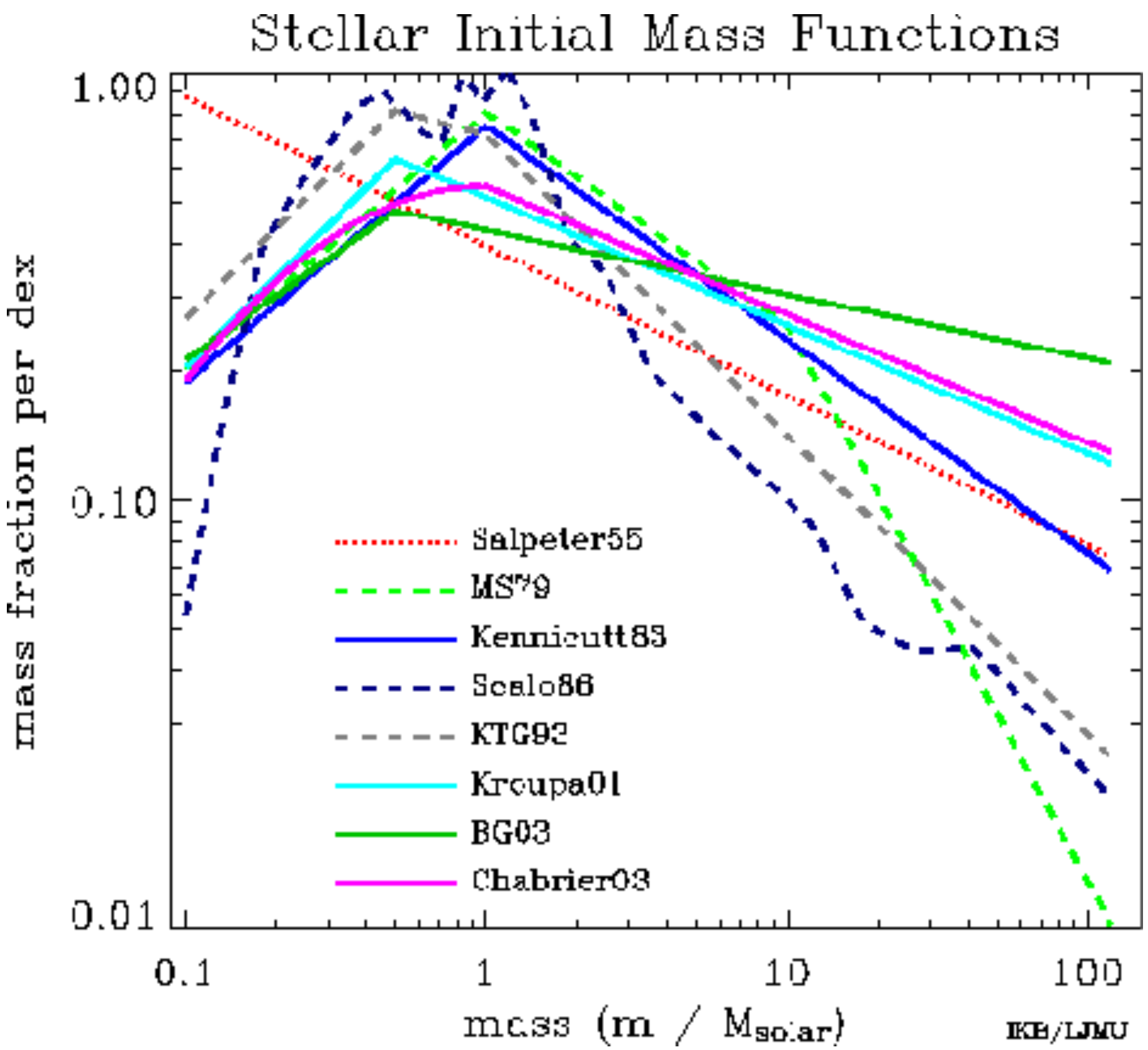
Image: Ivan Baldry

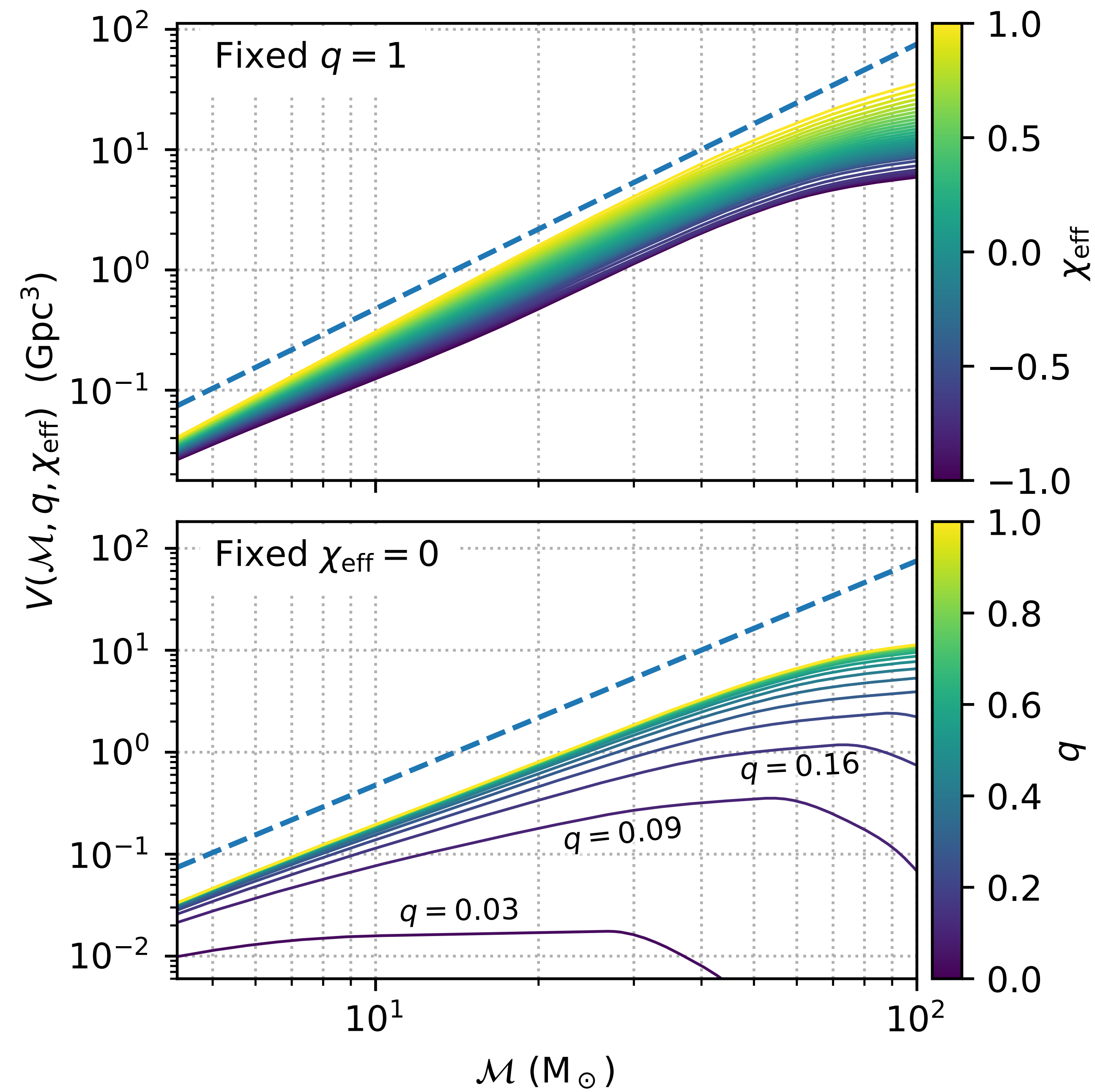


$$V\left(M_c\right) \sim M_c^{2.2}$$

Roulet and Zaldarriaga, (2018)

Estimated Astrophysical Distribution





$$\frac{d\mathrm{N}}{dM} \sim M^{-2.35}$$

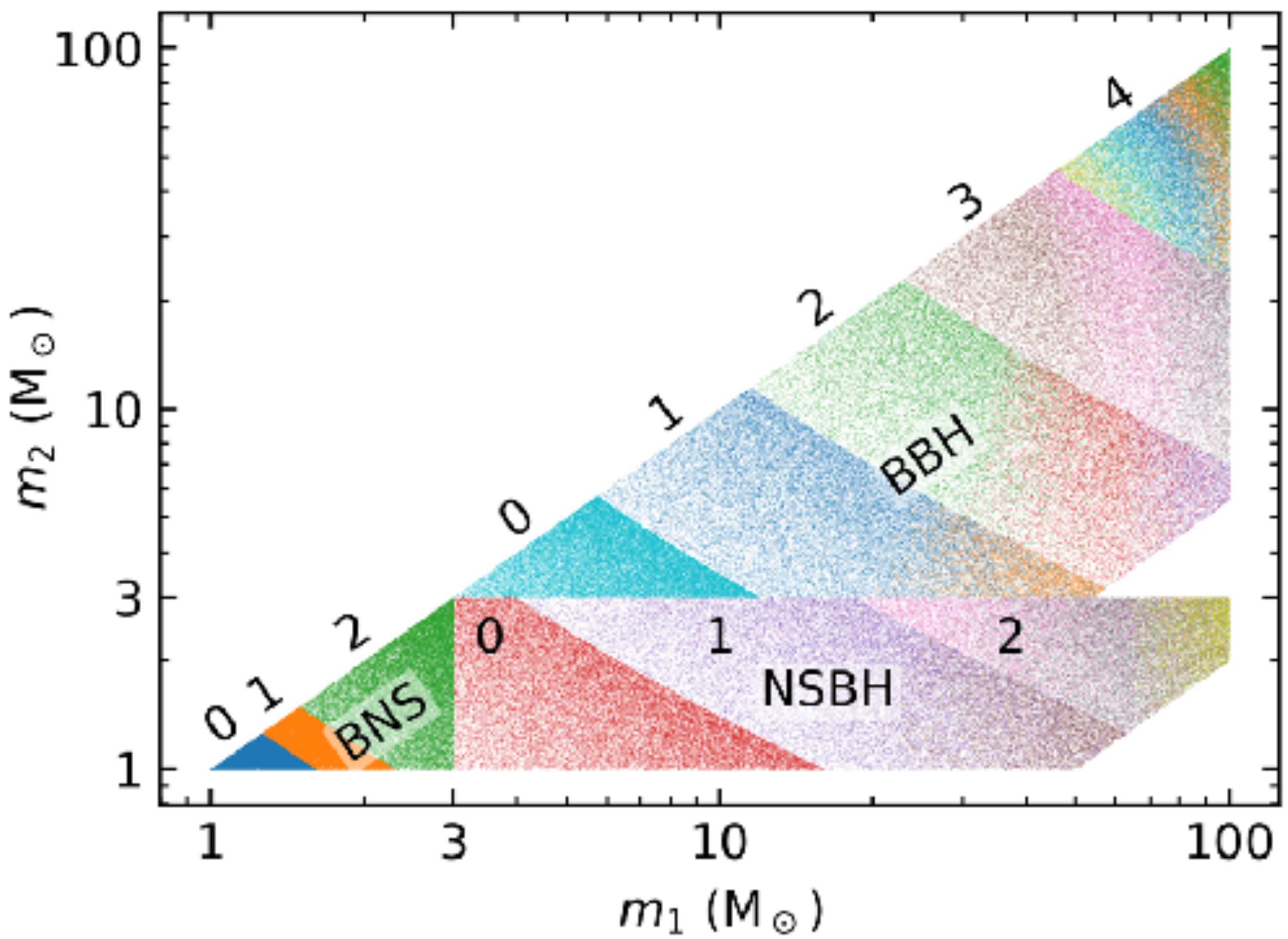
$$V\left(M_{\rm c}\right) \sim M_{\rm c}^{2.2}$$

$$\frac{d\mathrm{N}}{d\ln M_{\rm c}} \sim M_{\rm c}^{0.85}$$

Image: Ivan Baldry

Roulet and Zaldarriaga, (2018)

Solution: Split Template 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

Roulet et. al., (2018)

Correlations Between Templates

Parameter space

$$S = \left\{ h_{+/\times}(m_1, m_2, \ldots, \theta, \phi, i, \ldots) \,|\, (m_1, m_2, \cdots) \in \mathcal{I}, (\theta, \phi, i, \ldots) \in \mathcal{E} \right\}$$

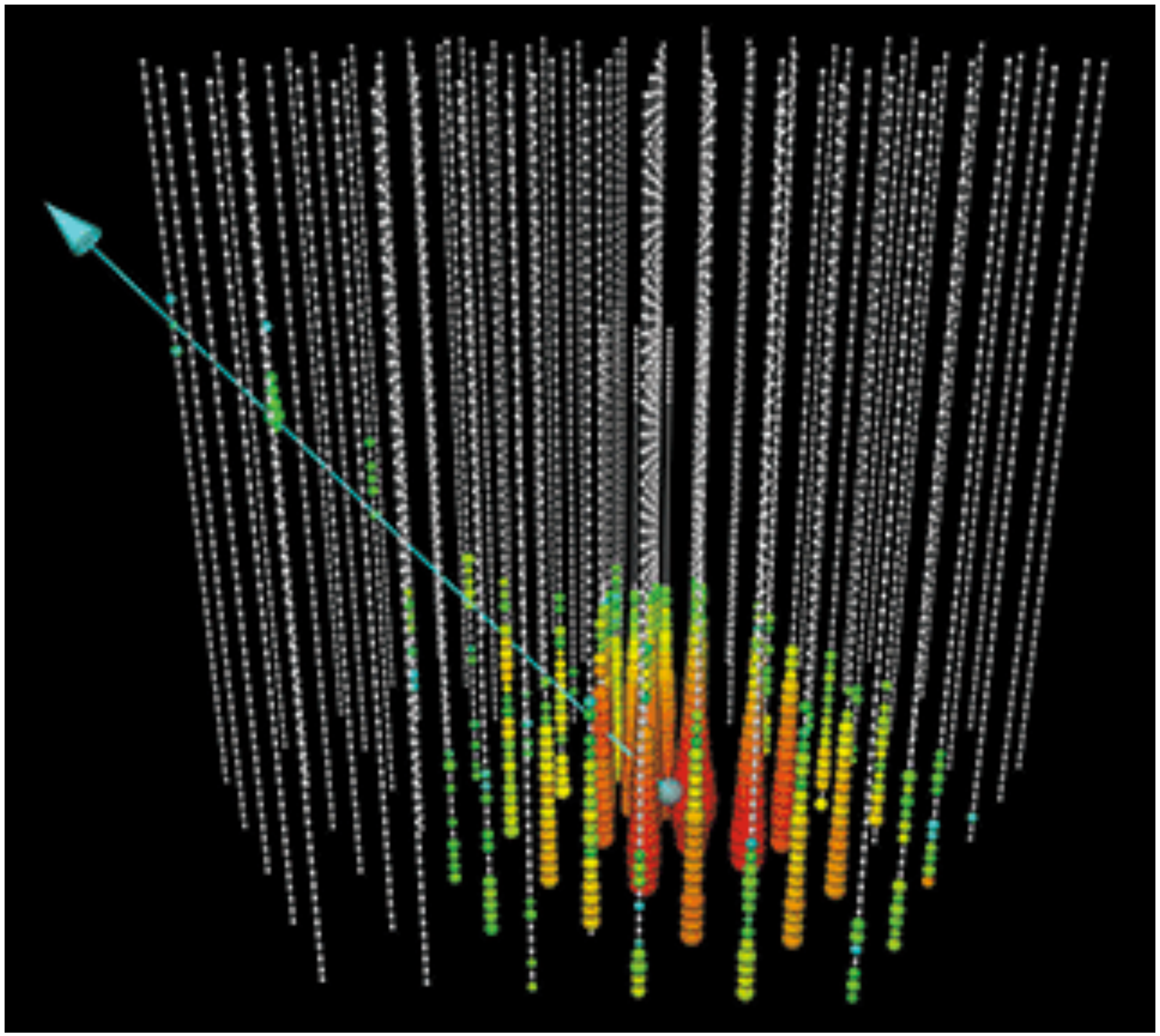


Image: Science

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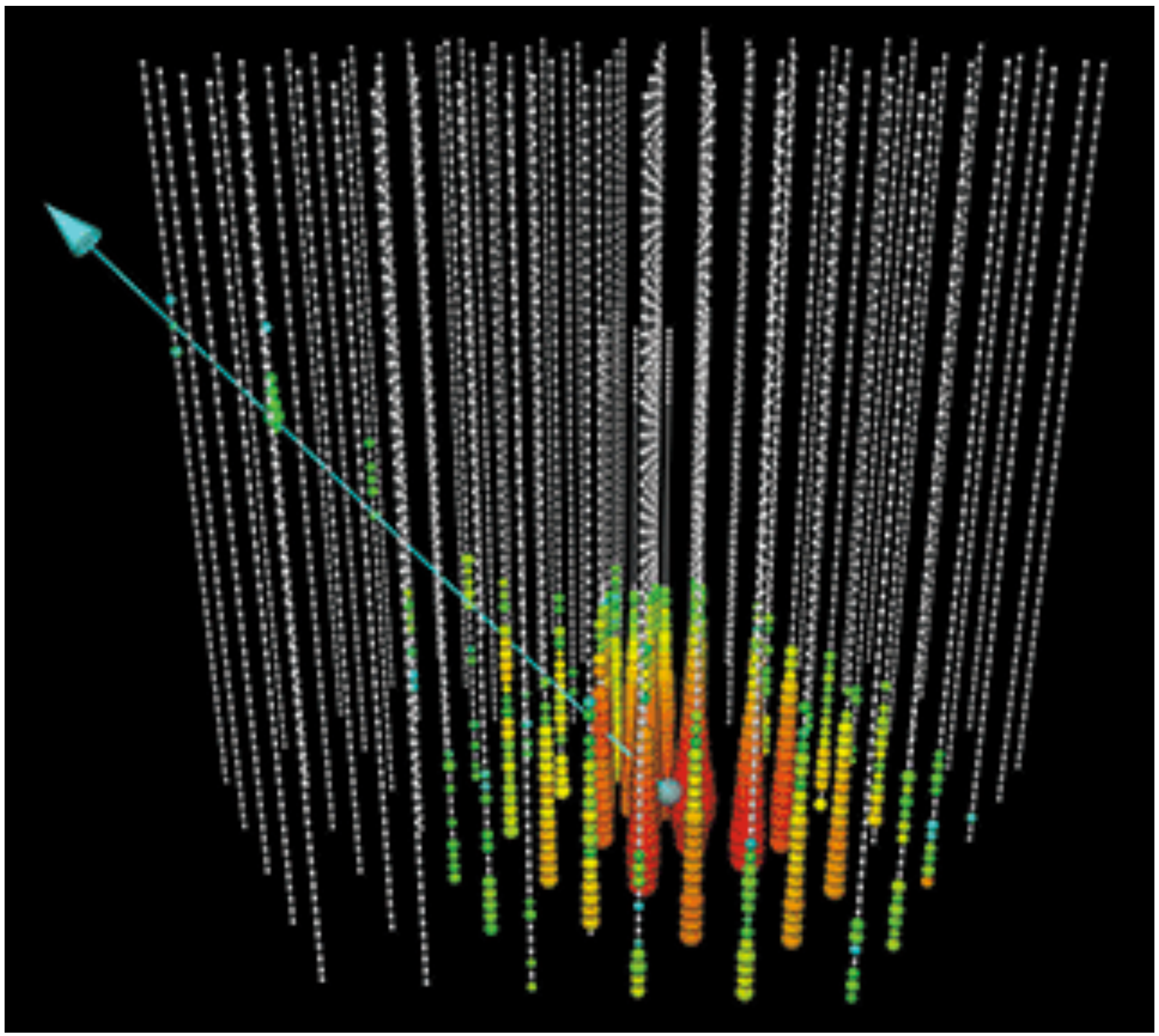


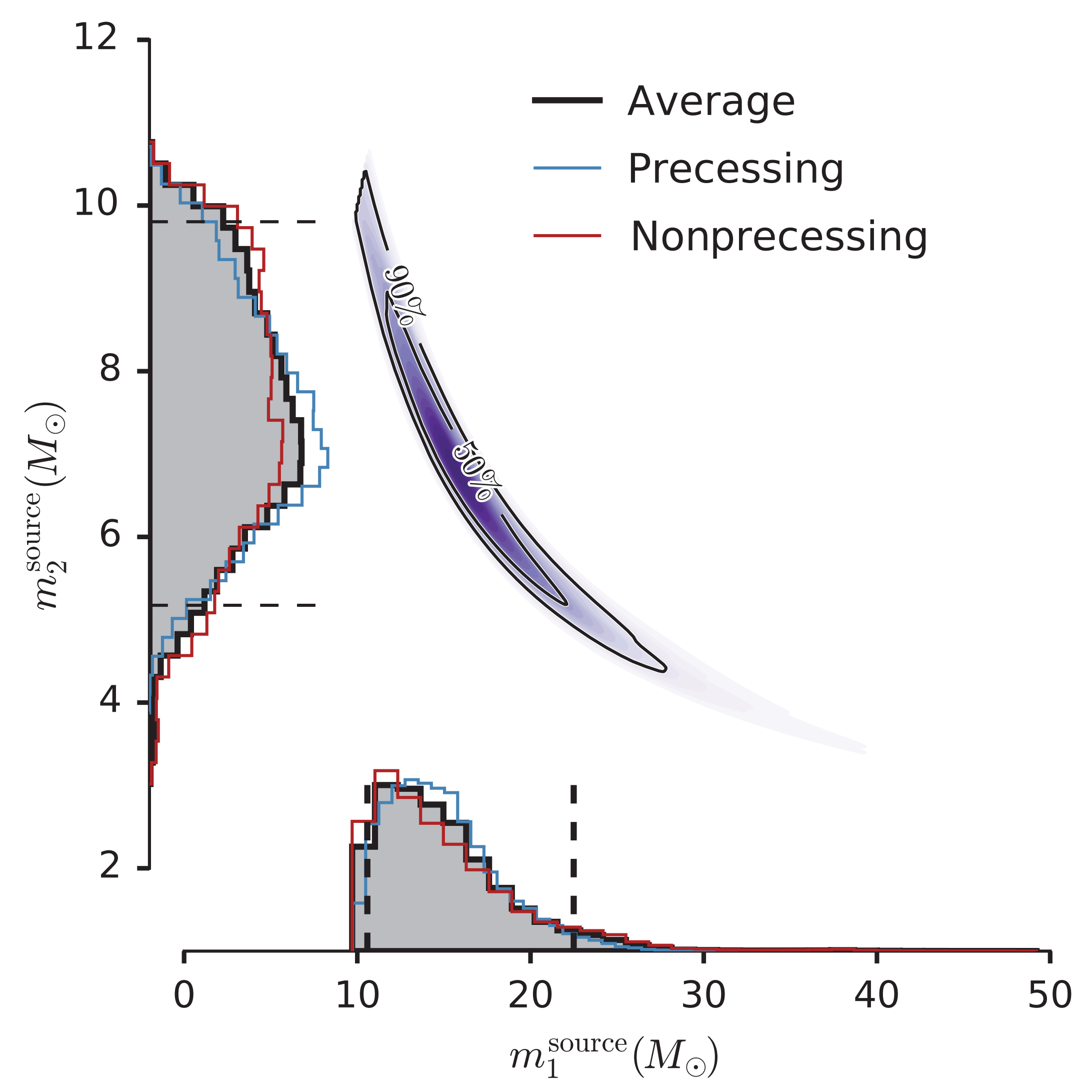
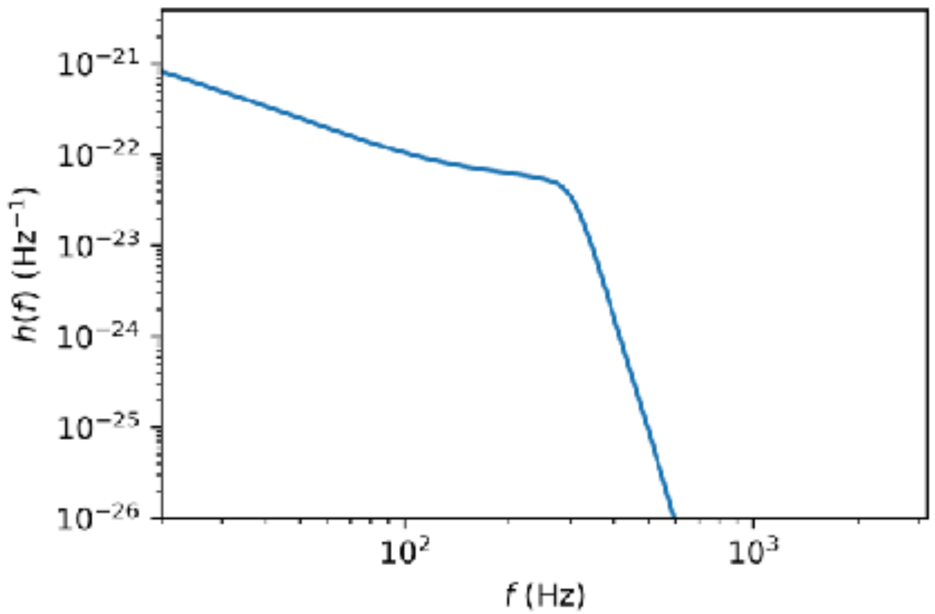
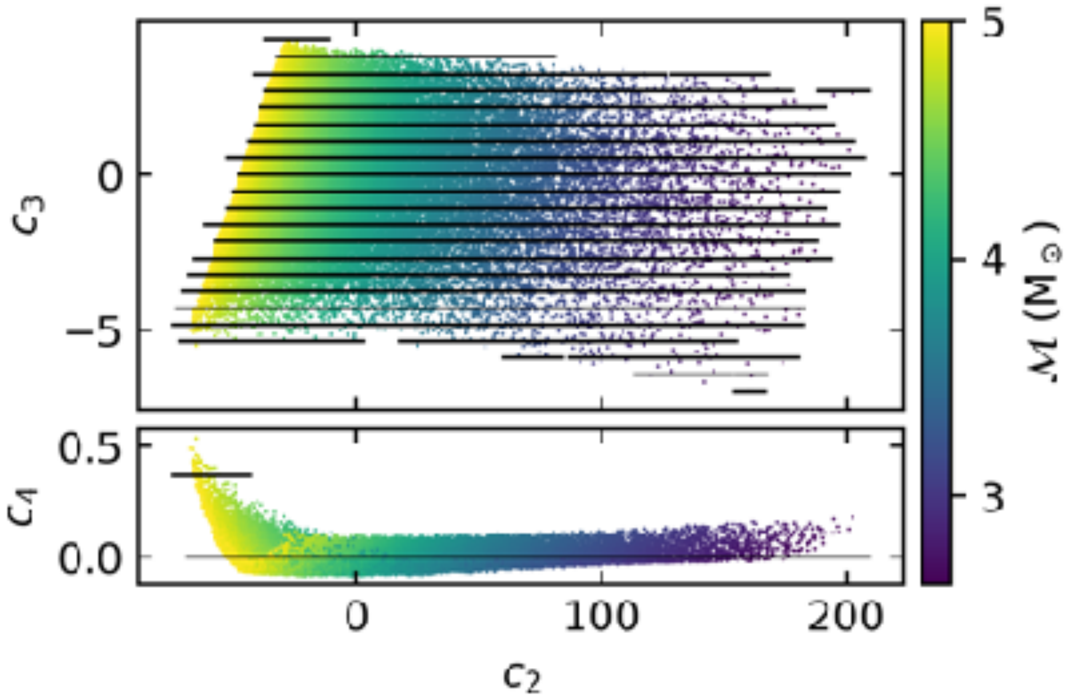


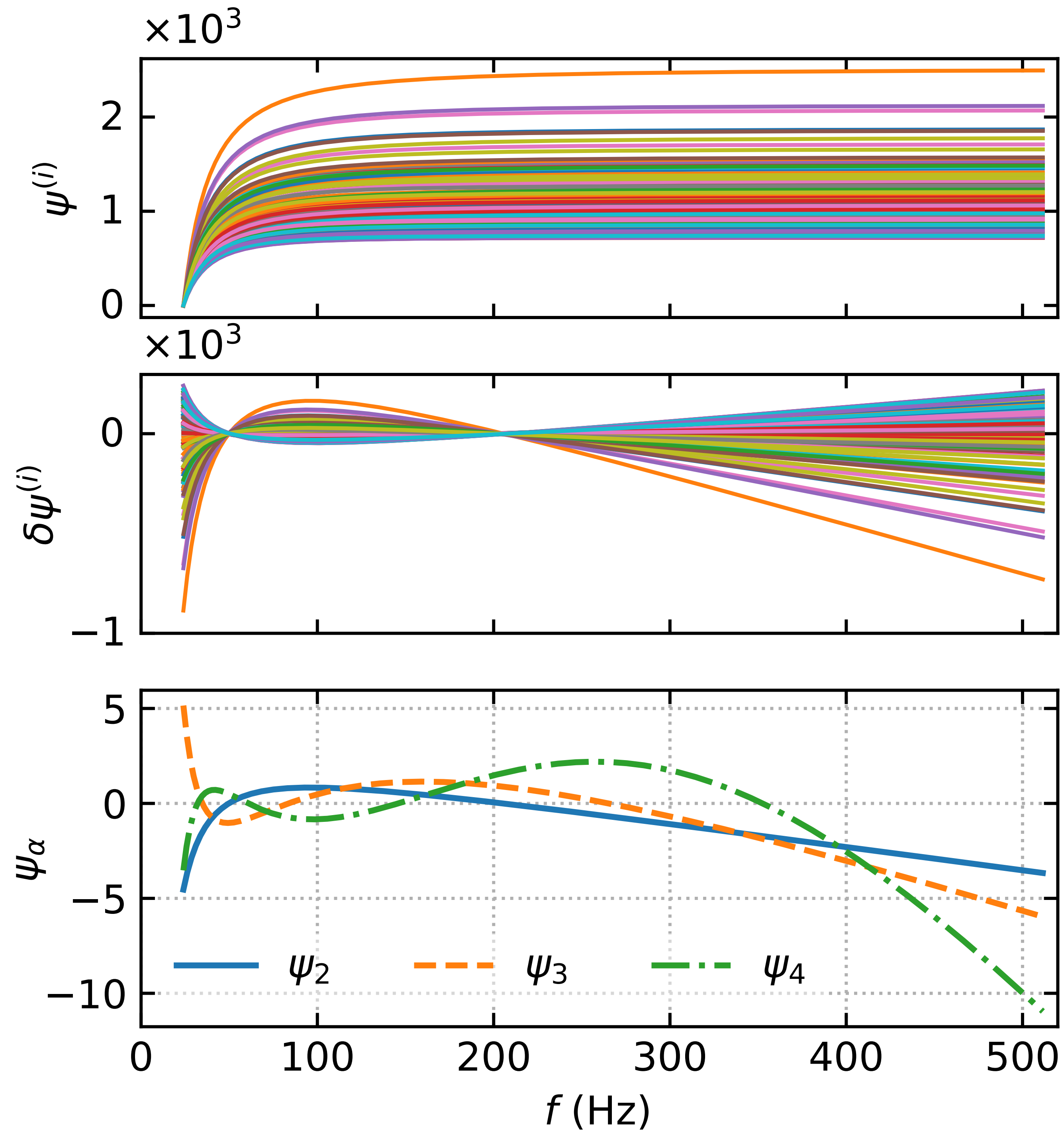
Image: Science

PRL 116, 241103 (2016)

Choice of Template Basis

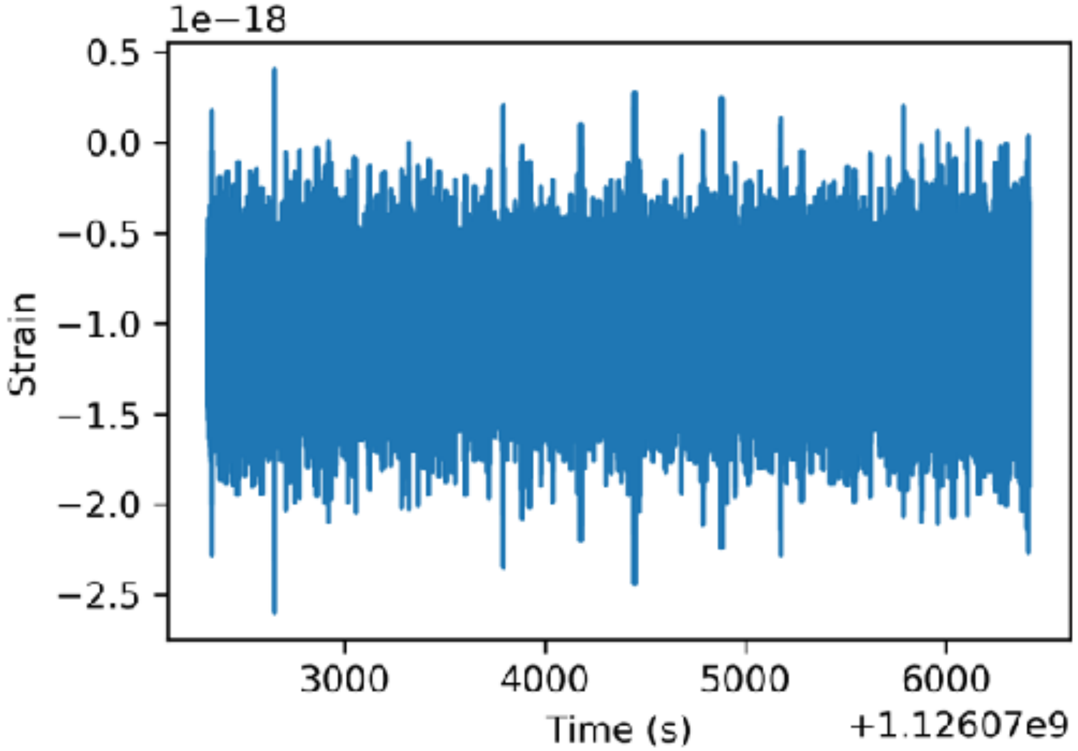






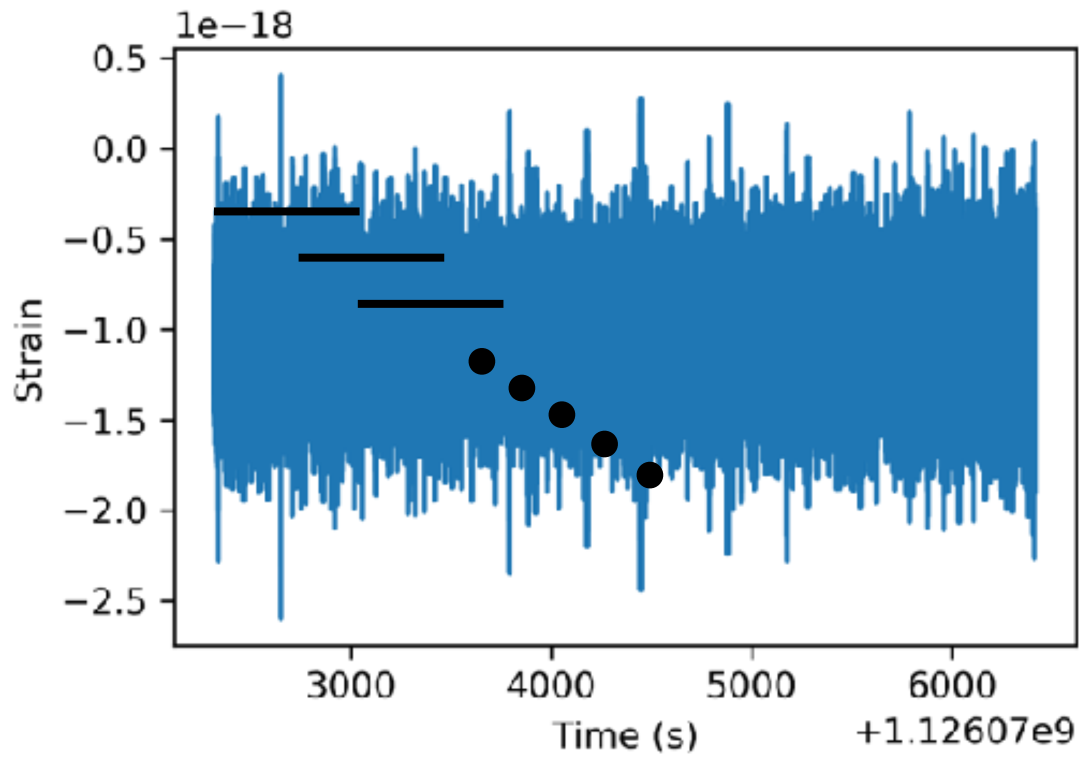
Roulet. et. al. (2019)

Non-stationary Noise

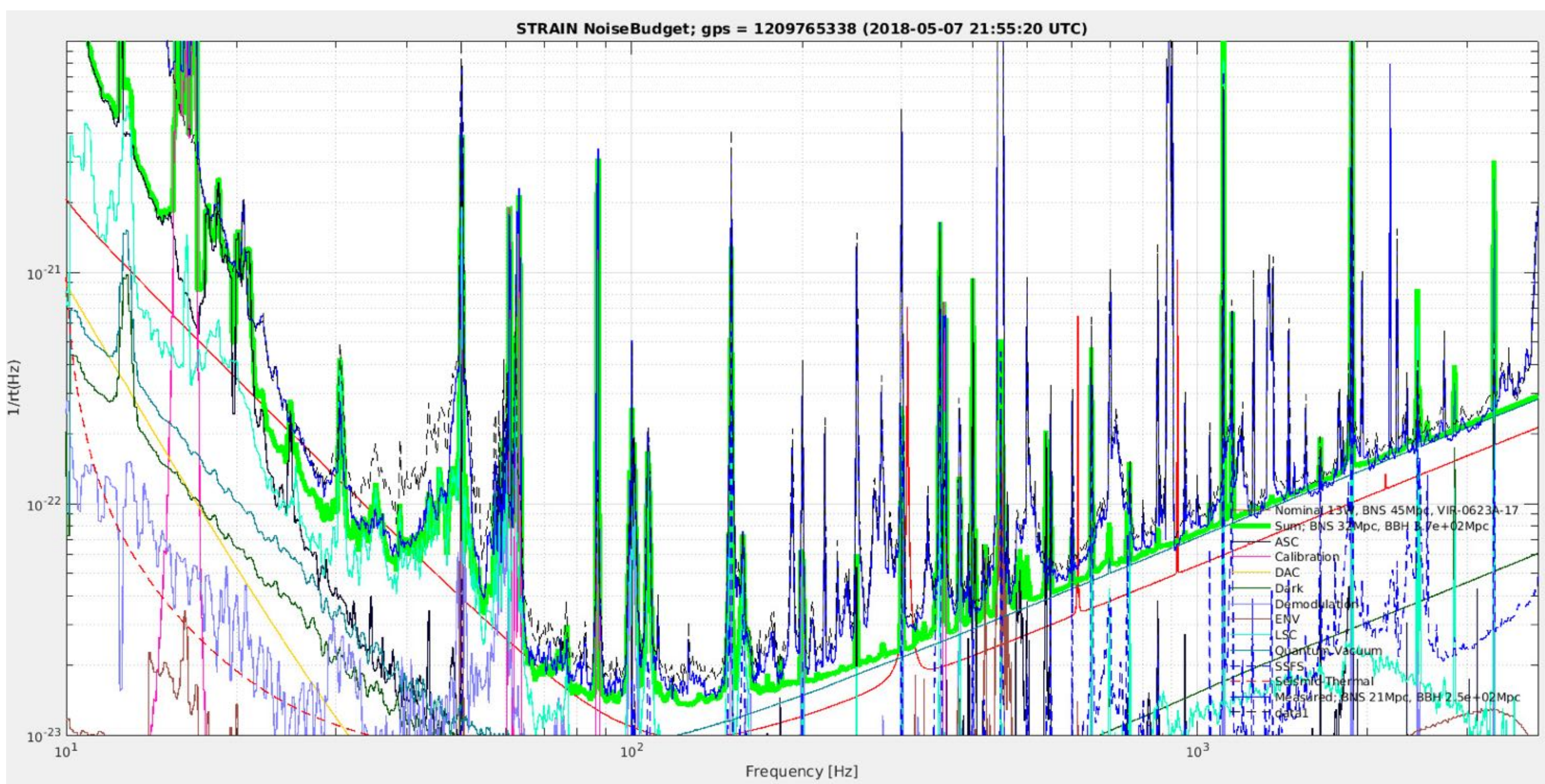


$$Z(h) = \sum_f \frac{d(f)h^\star(f)}{\sigma^2(f)}$$

Non-stationary Noise



PSD: Welch's method



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Credit: Giovanni Losurdo

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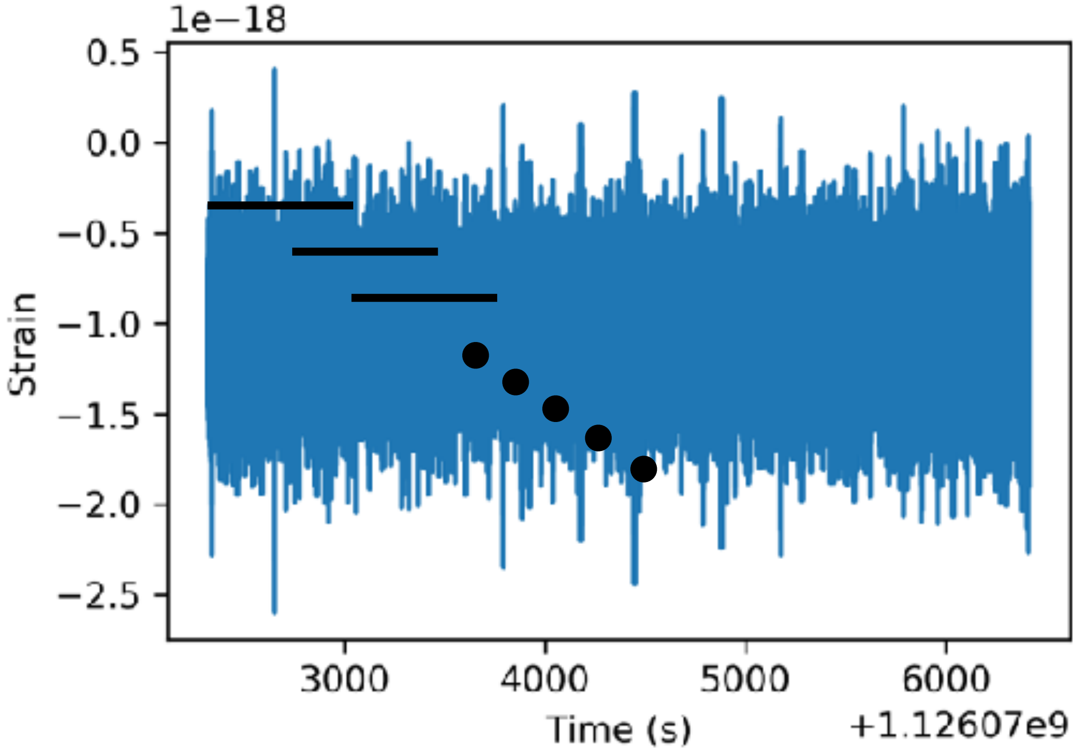

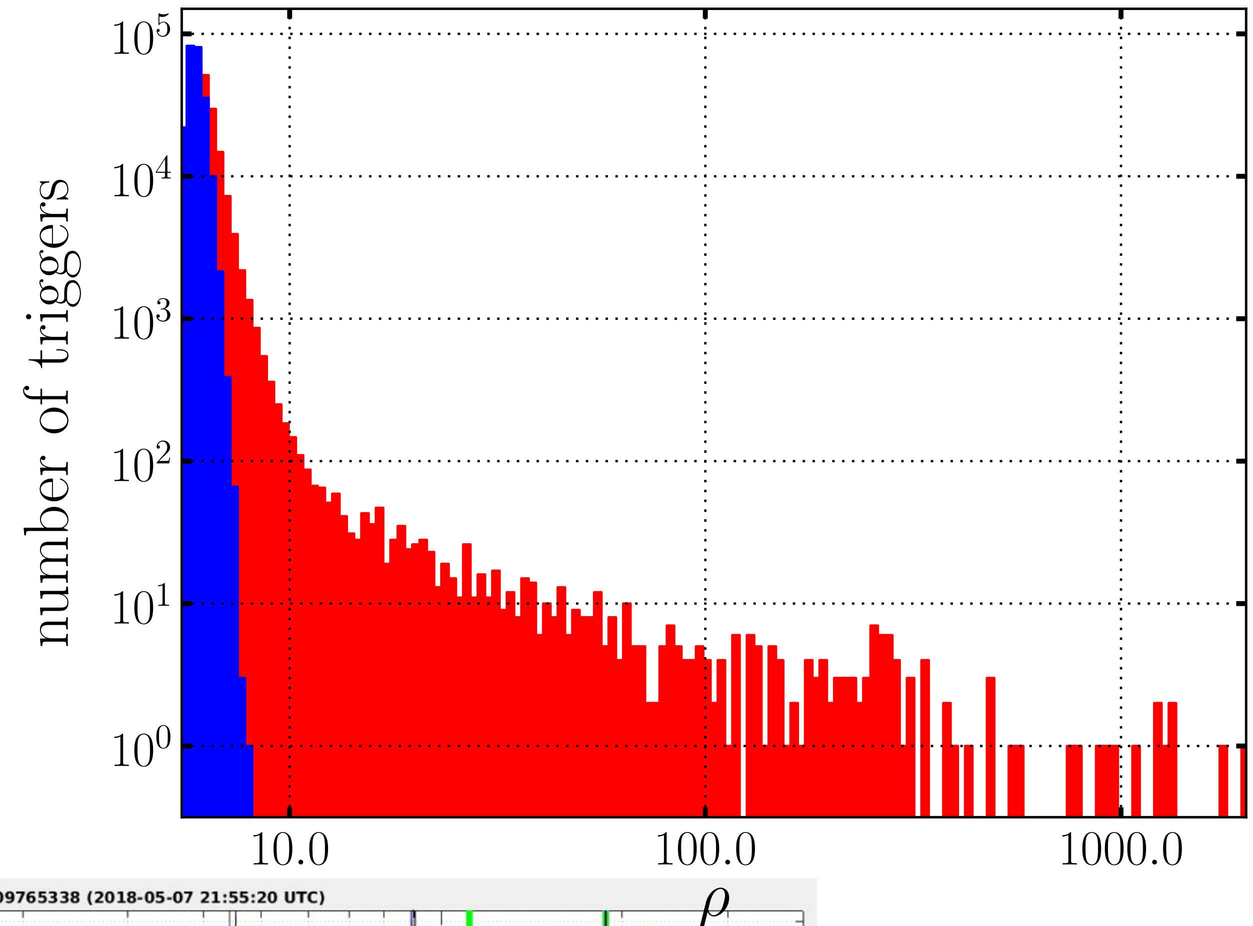

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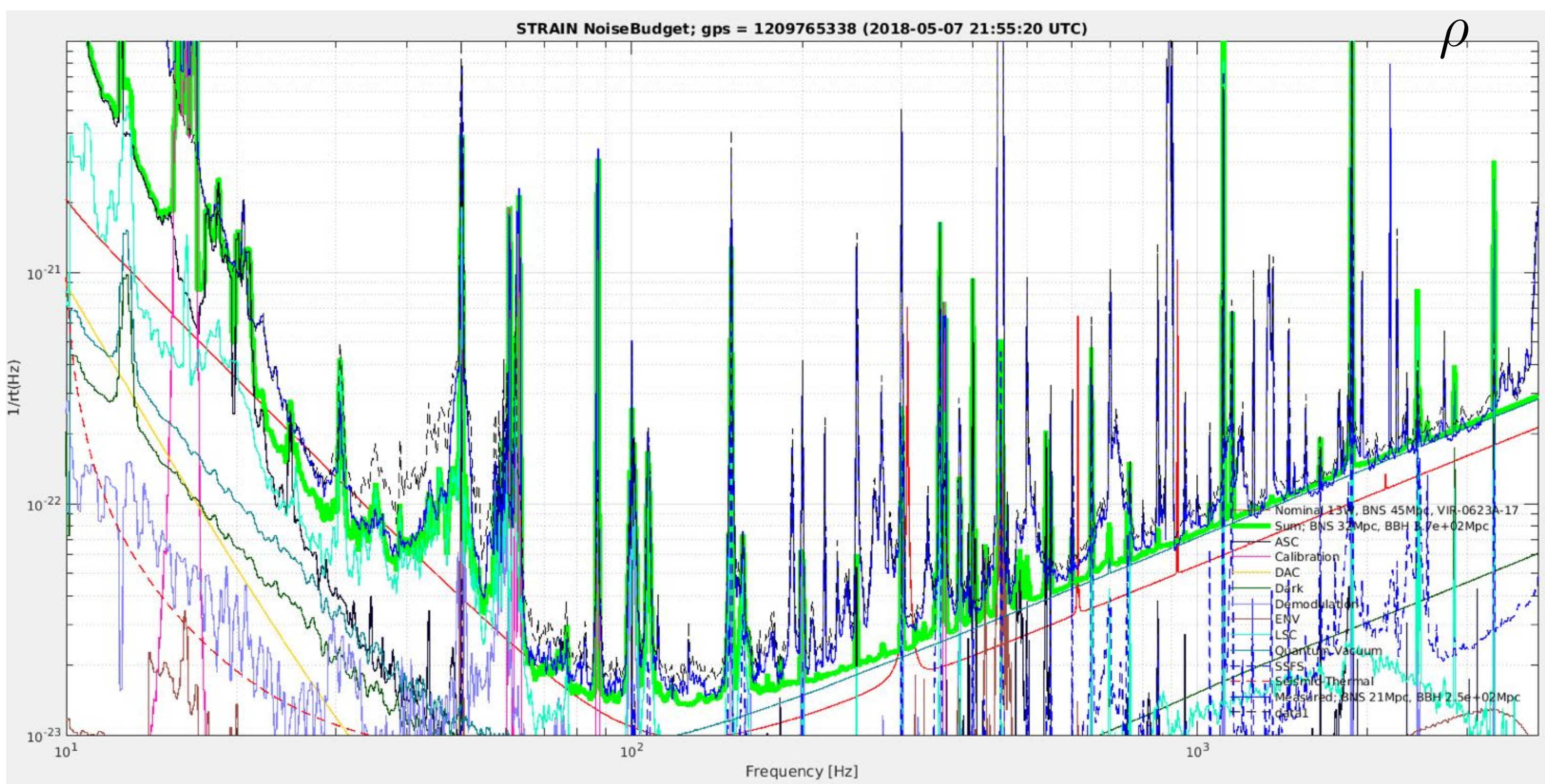

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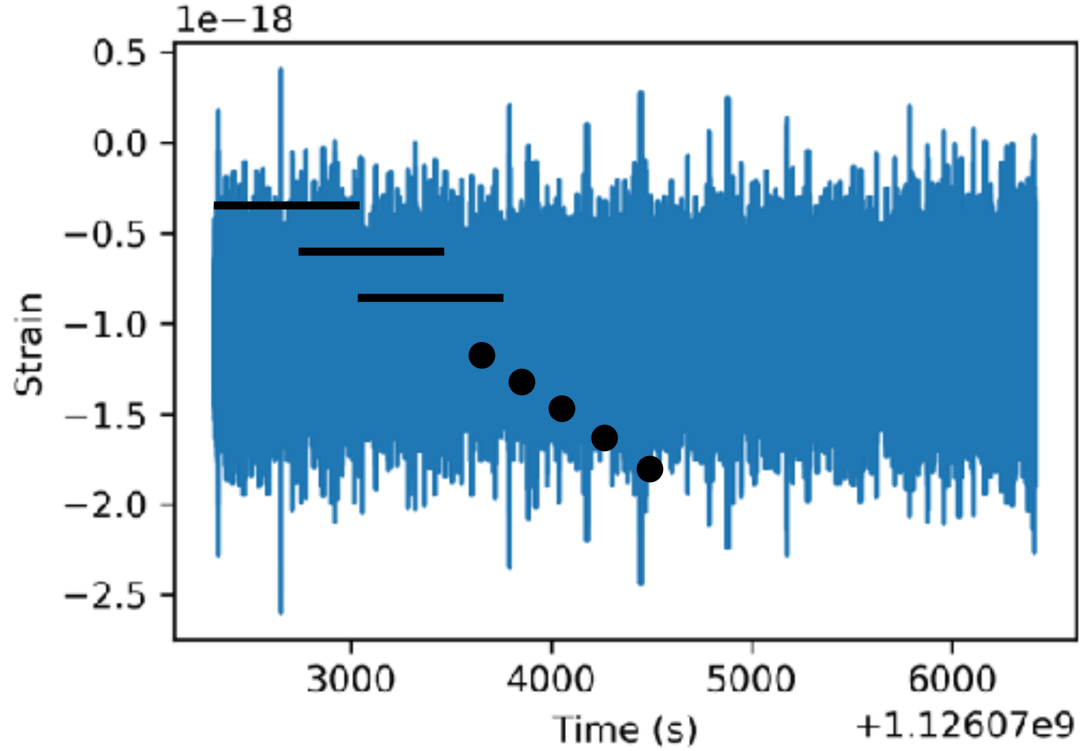
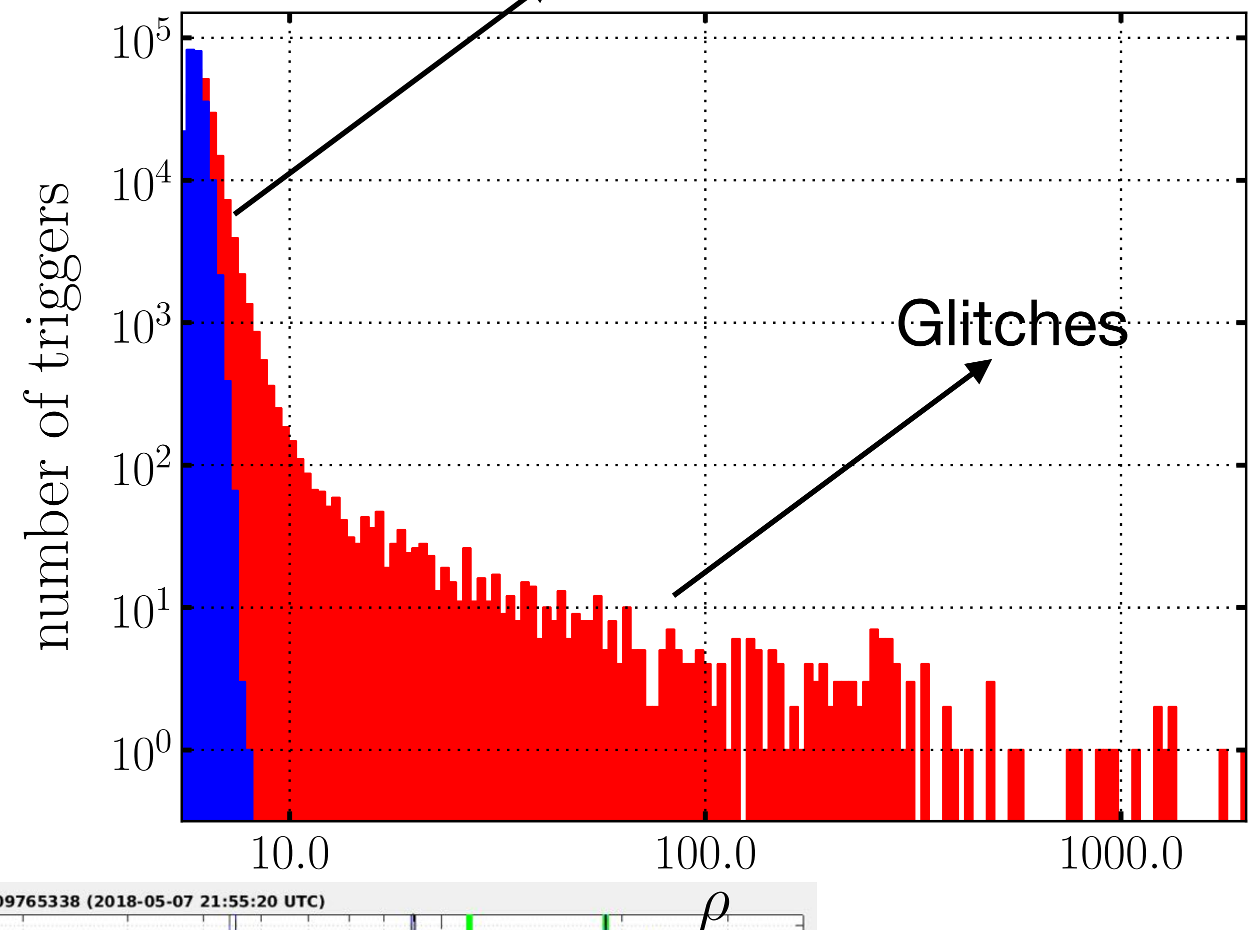


Incorrect PSD

Glitches



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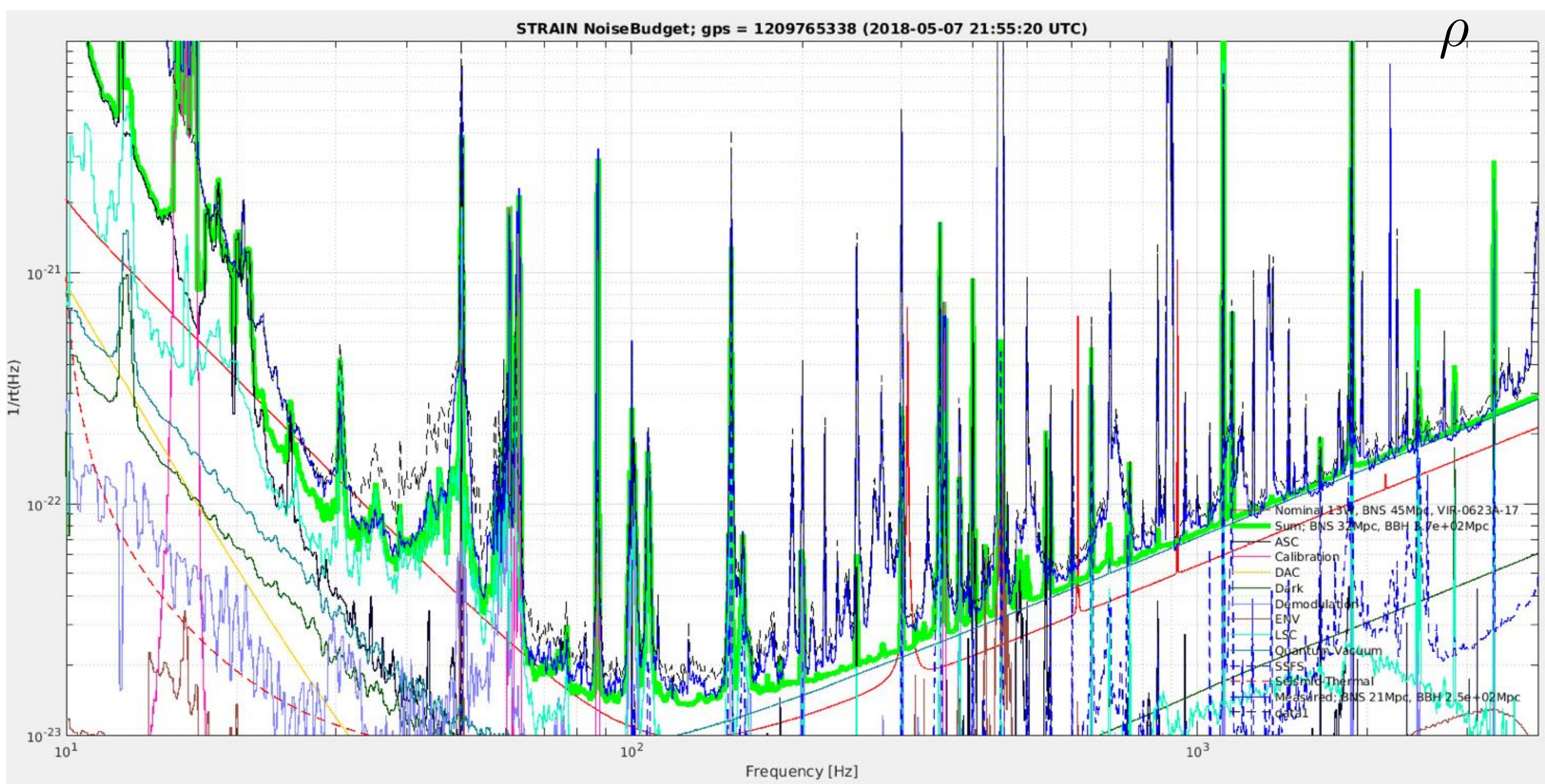

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PSD Drift

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- PSD estimation requires ~1000s of seconds to have acceptable error bars on SNR

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

$$\downarrow$$

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

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Analogy: Peak-background split

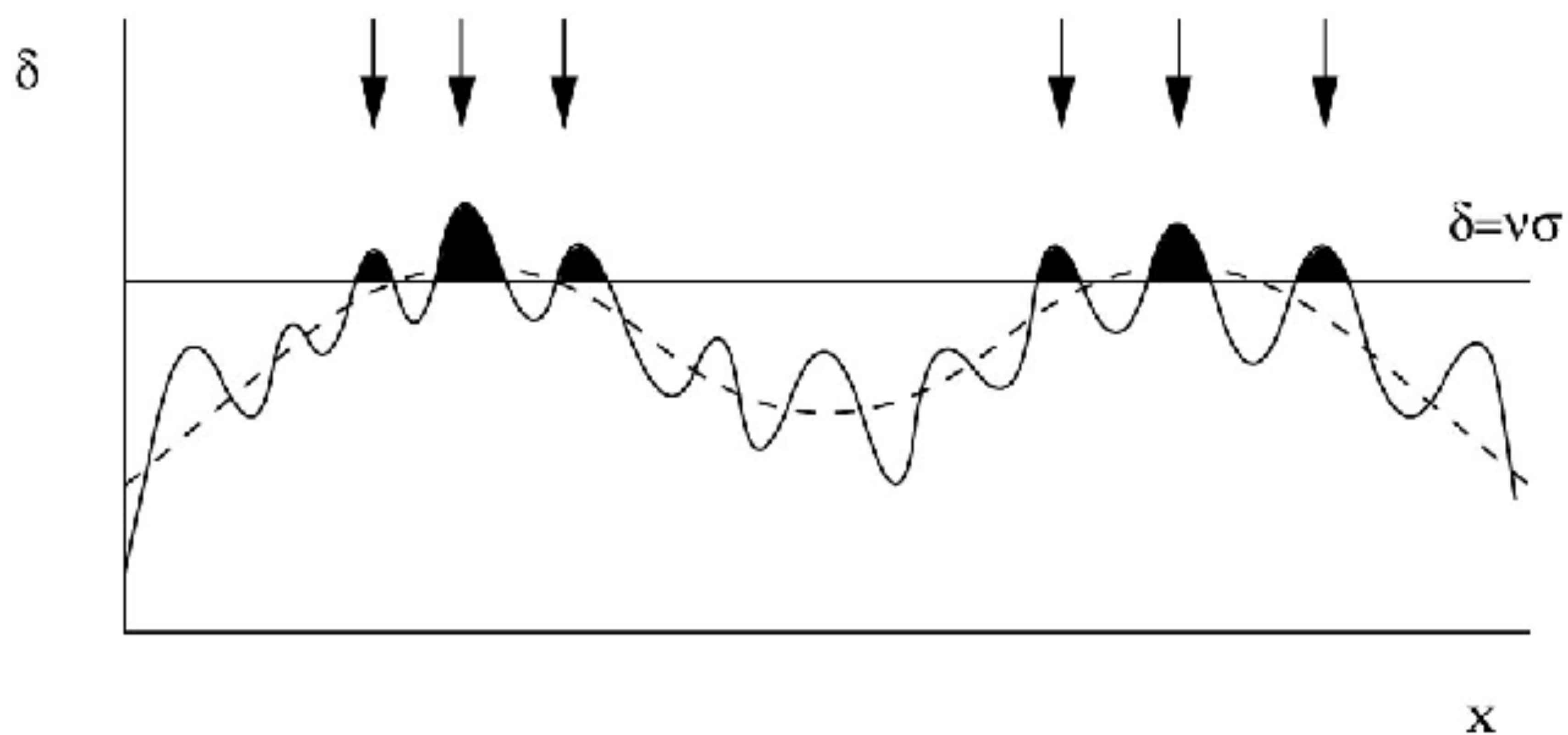
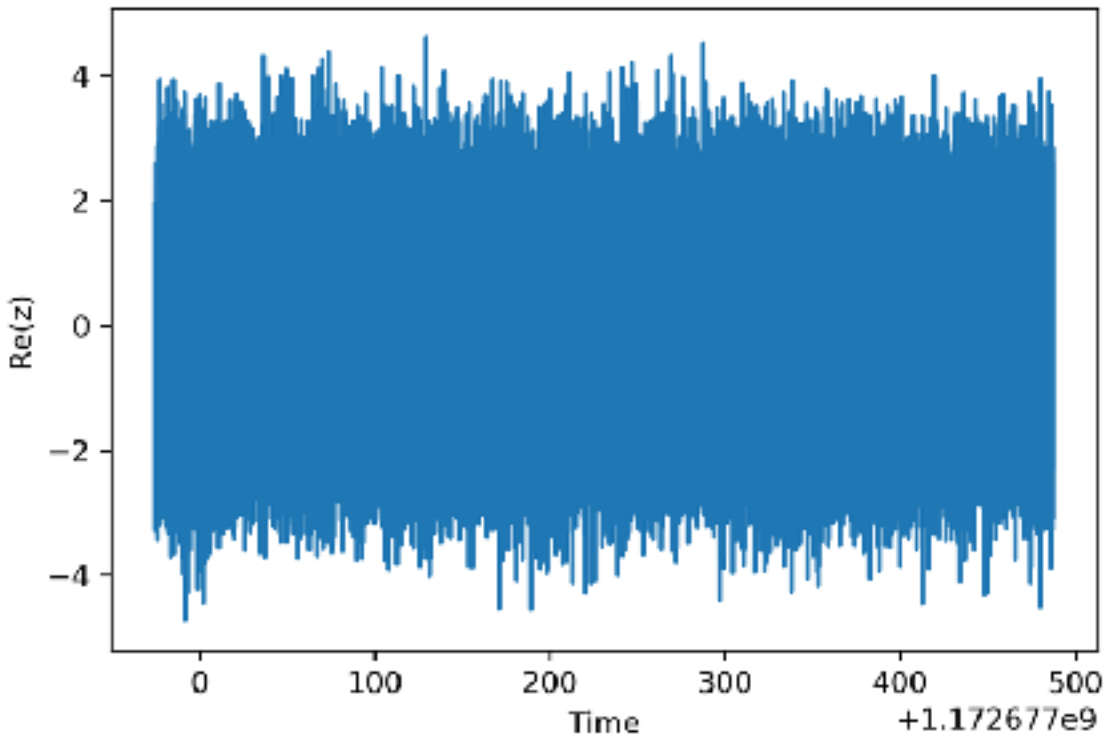
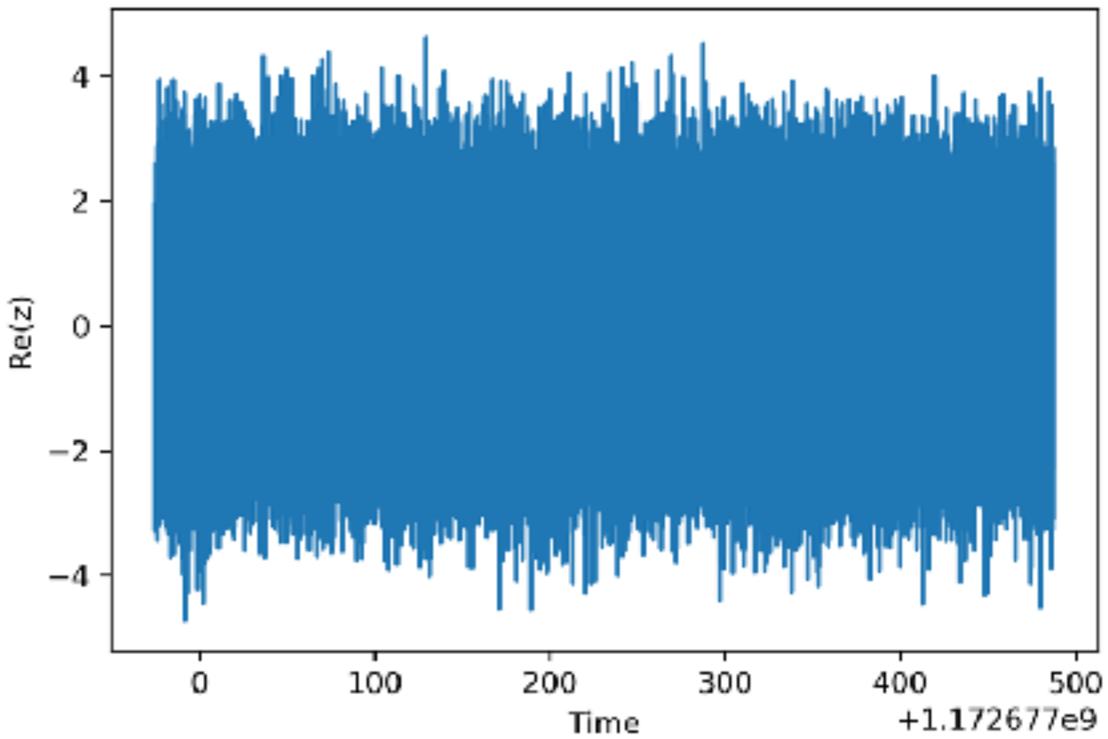


Image: ned.ipac.caltech.edu

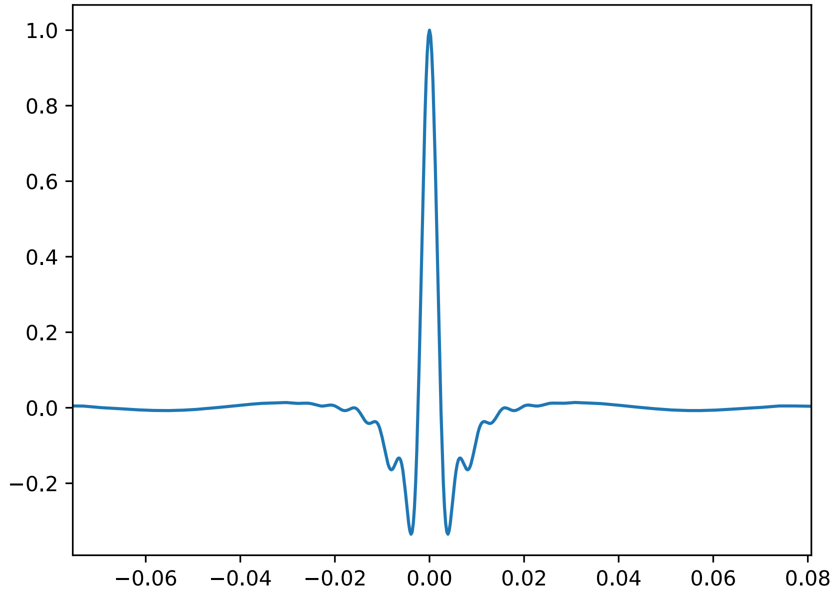
PSD drift: Evidence and Correction



PSD drift: Evidence and Correction



$$S_{z^2}(f) = 4\Delta t \left| \widetilde{h_\mathrm{w} \circledast \overleftarrow{h}_\mathrm{w}} \right|^2 (f)$$



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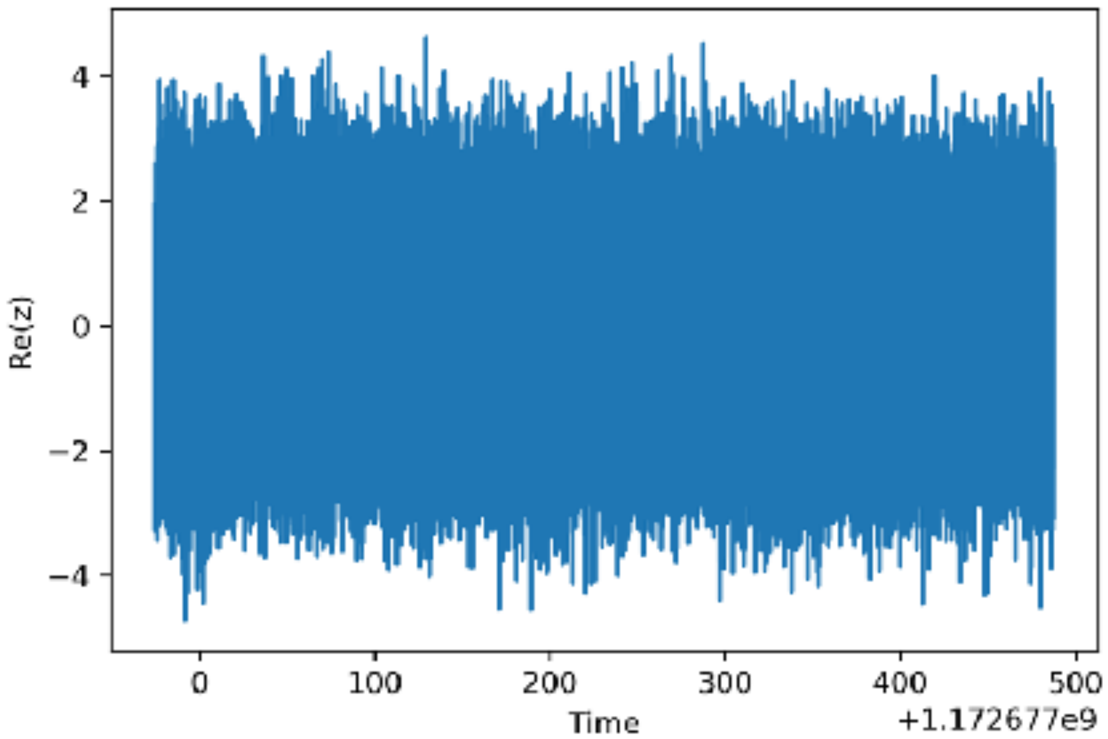

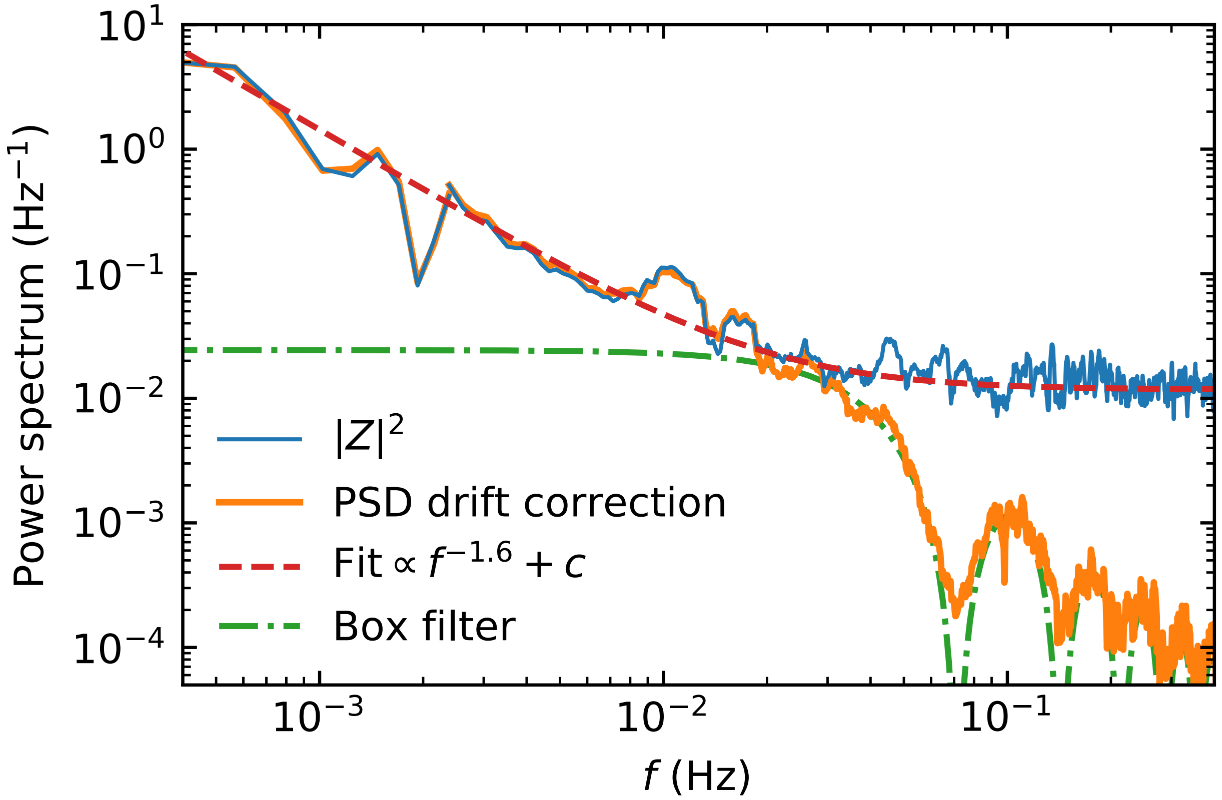

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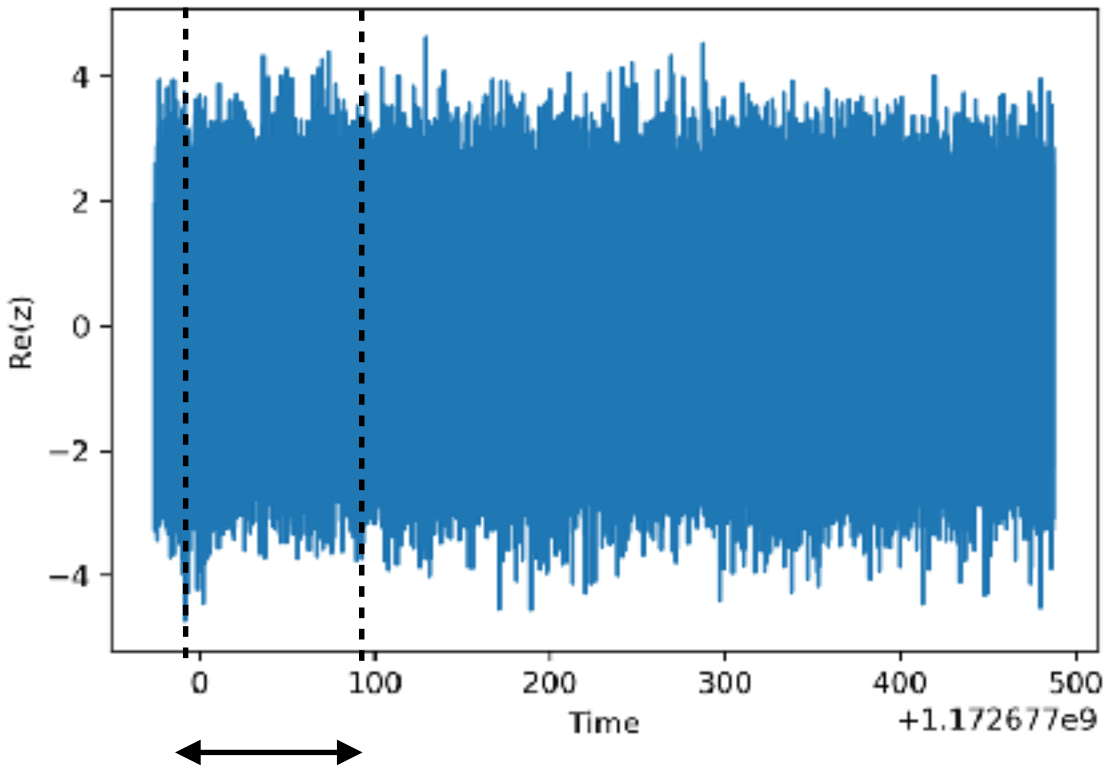

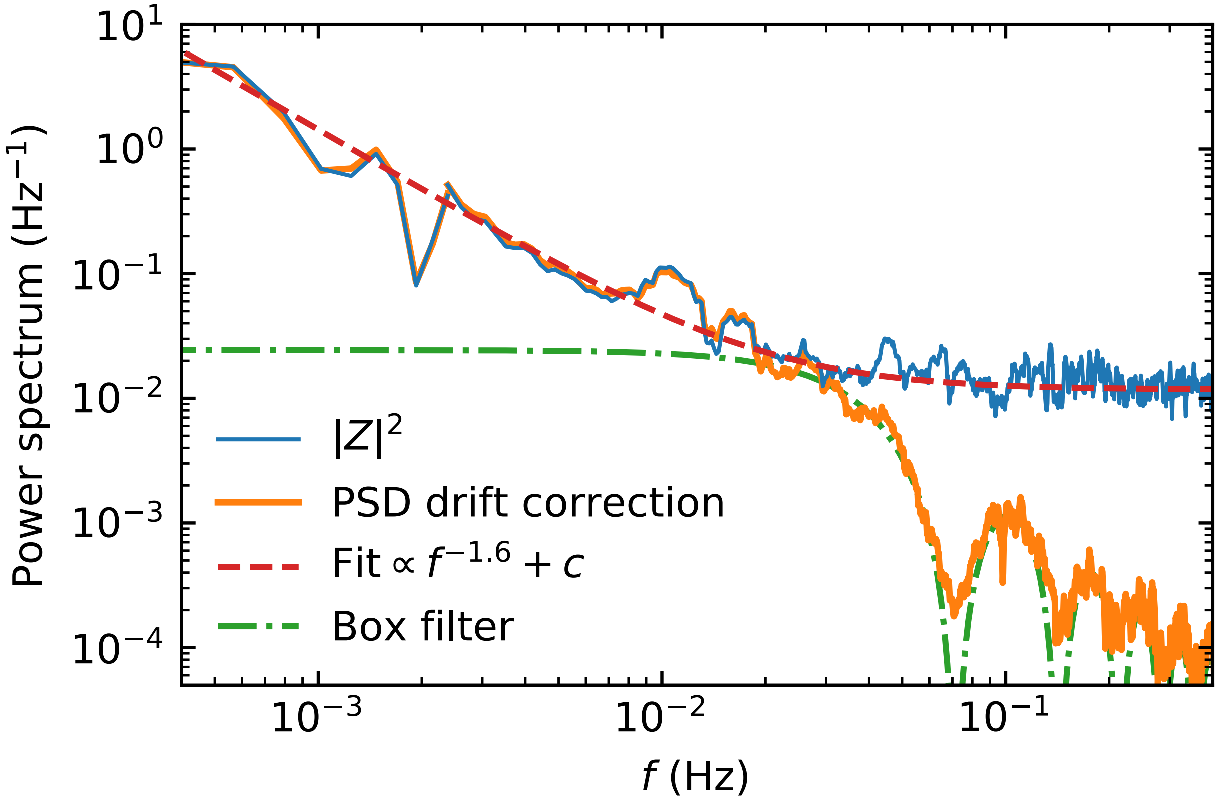

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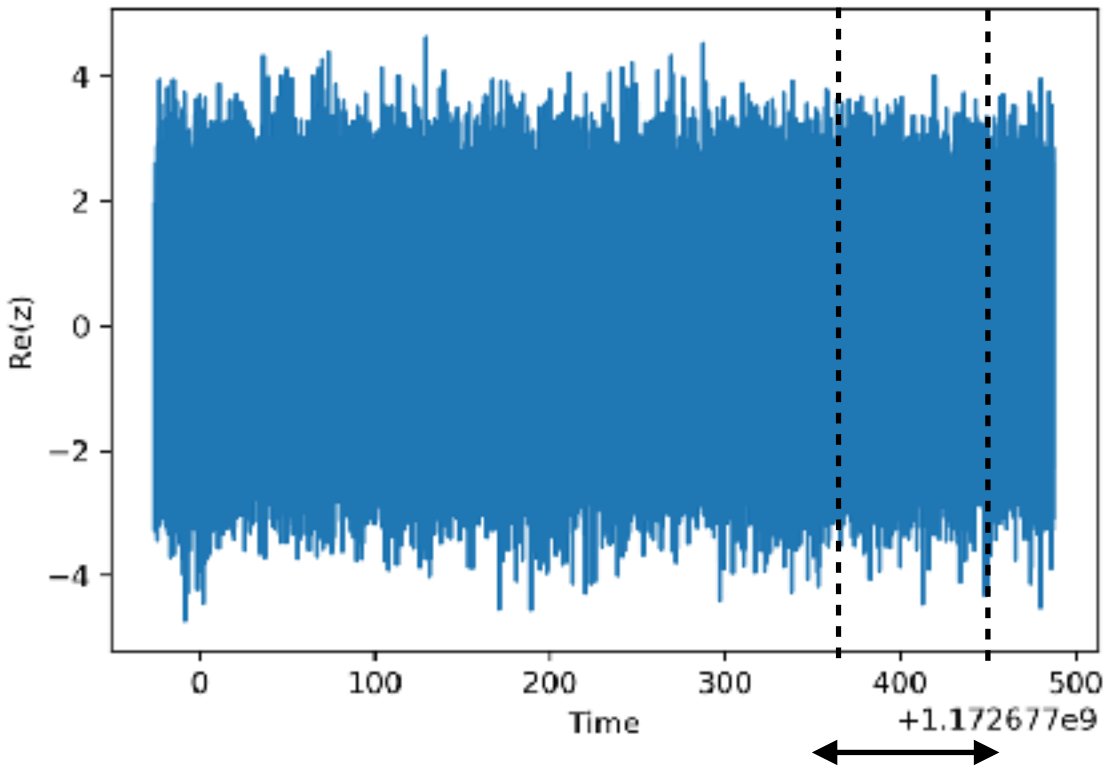
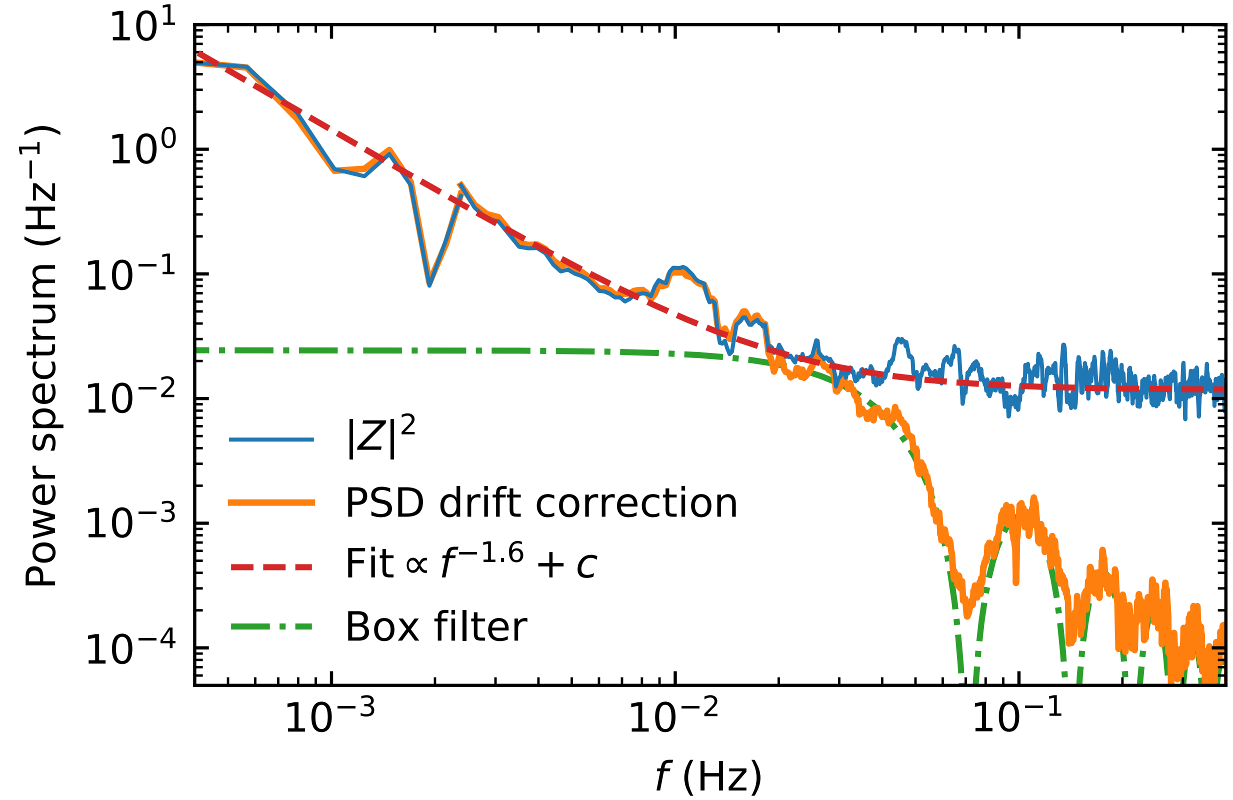
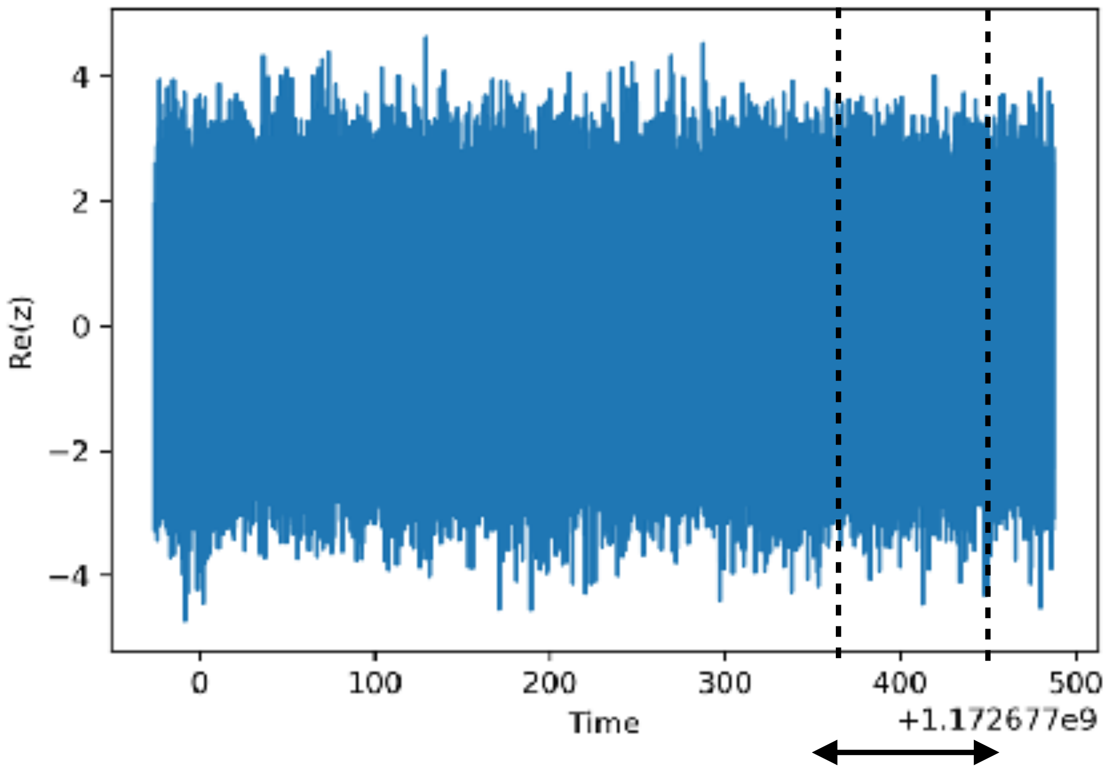
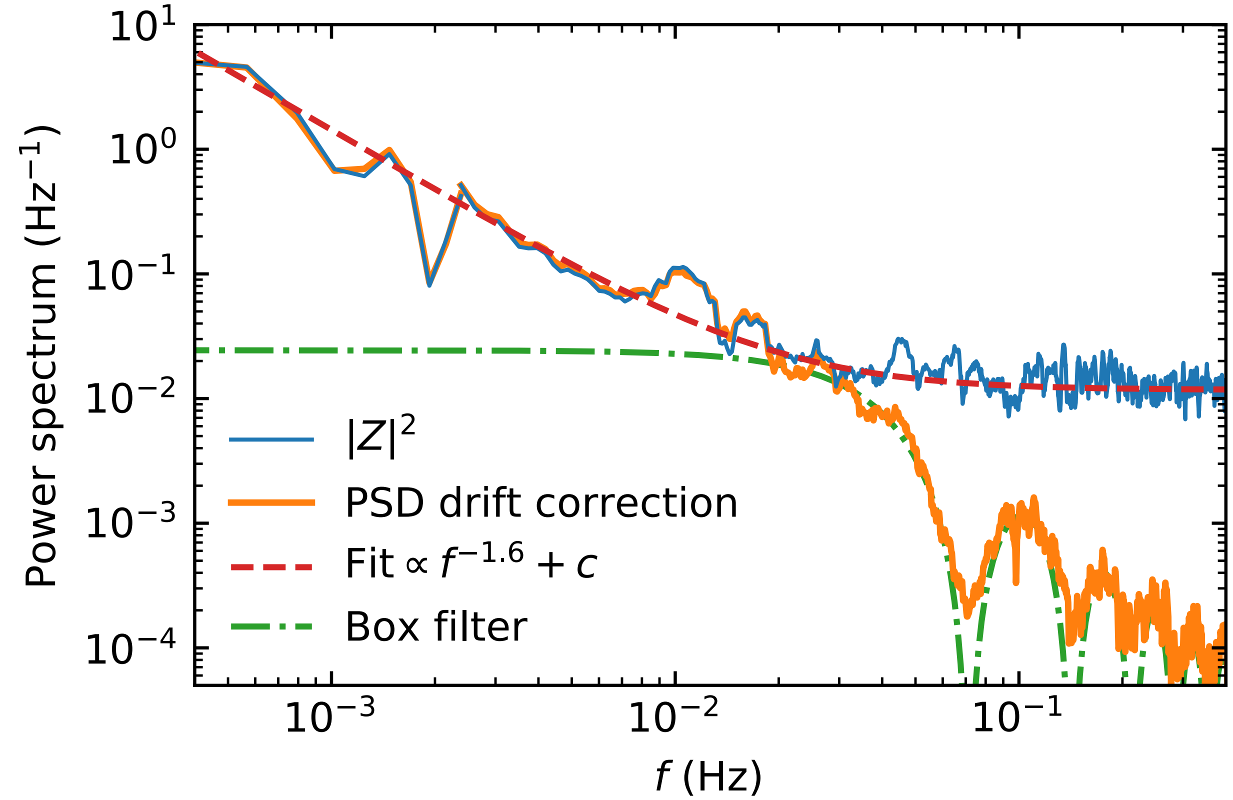




Can track the std of the score to 1% precision on scales of tens of seconds

PSD drift: Evidence and Correction





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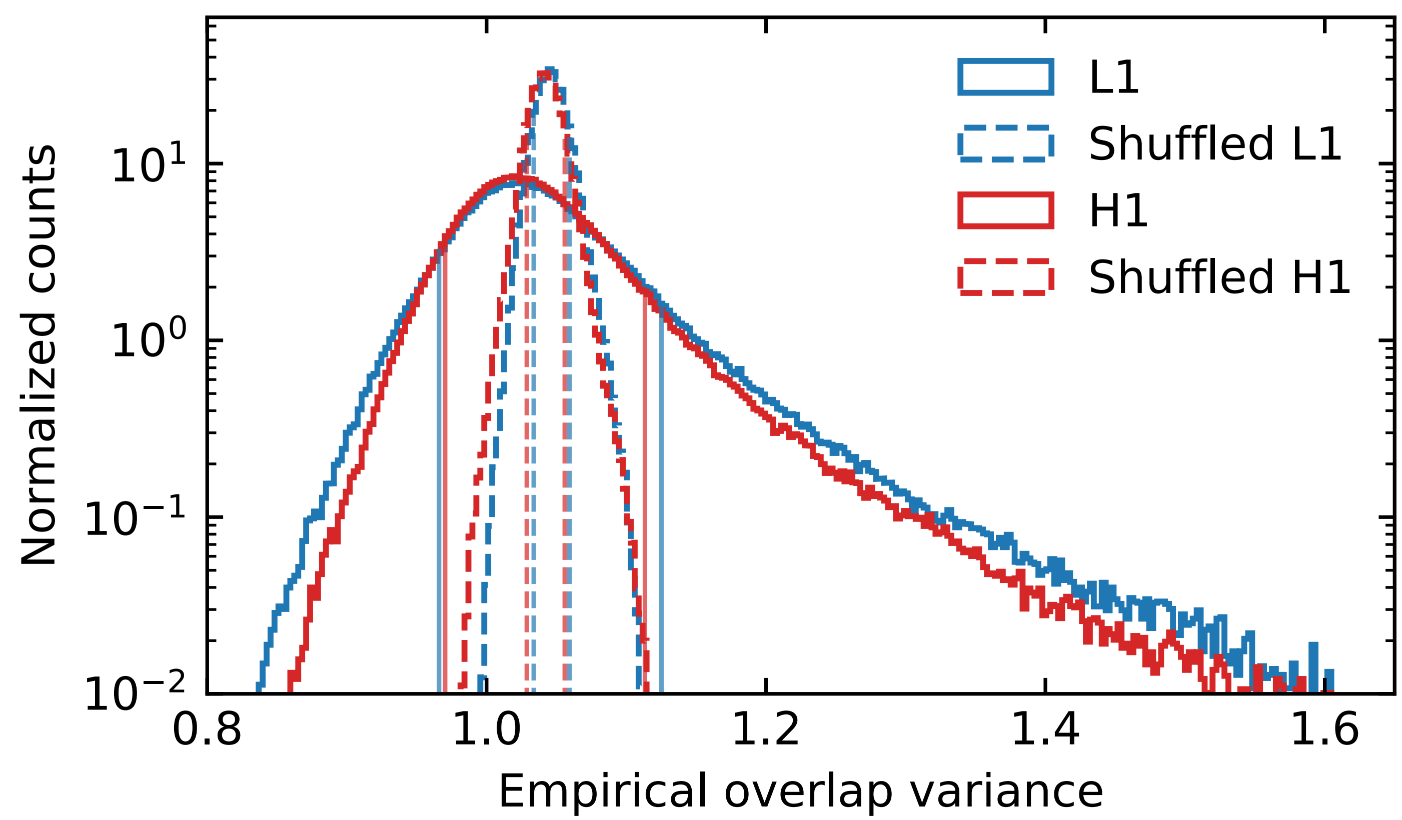

Effect of the PSD Drift Correction

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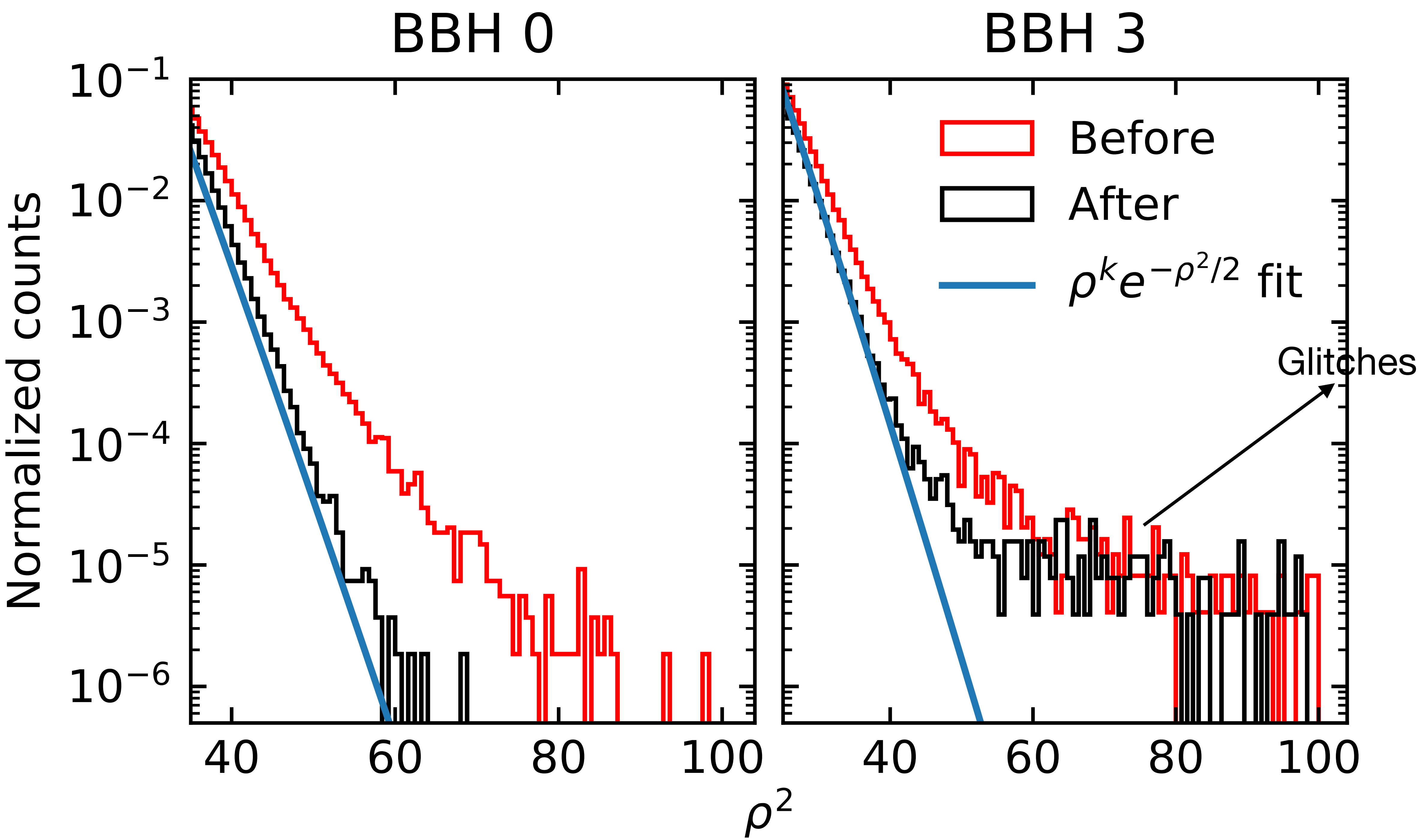
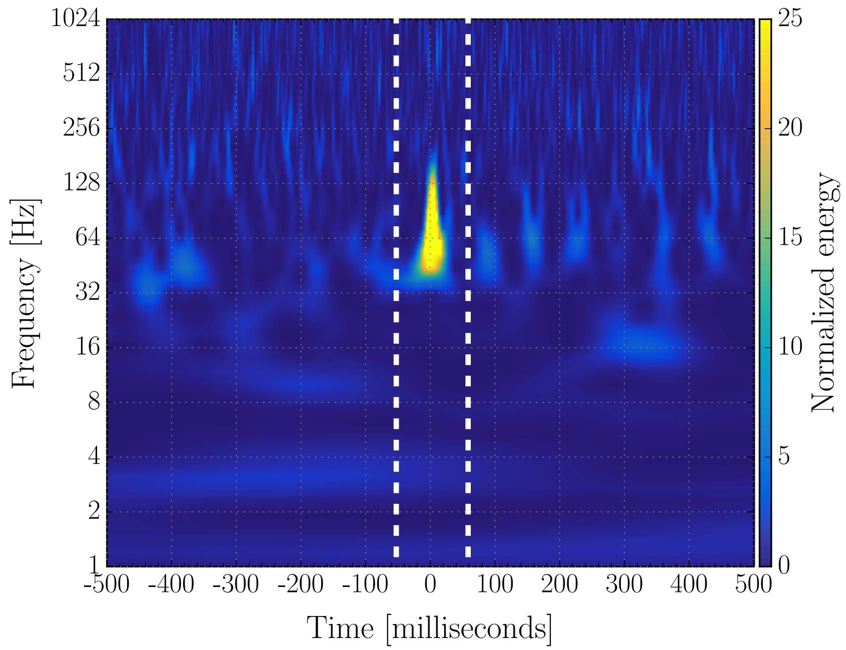


Mitigating Glitches

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



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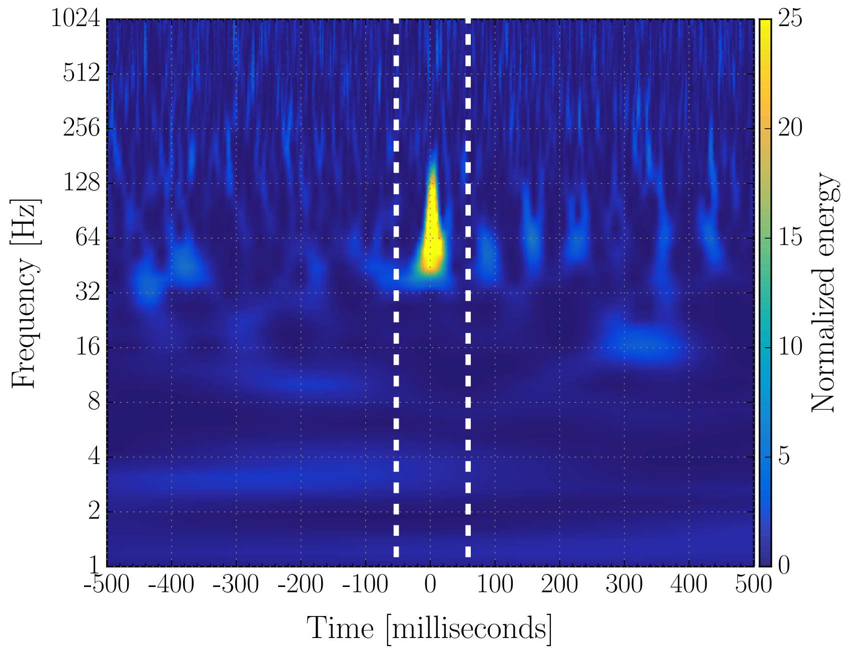
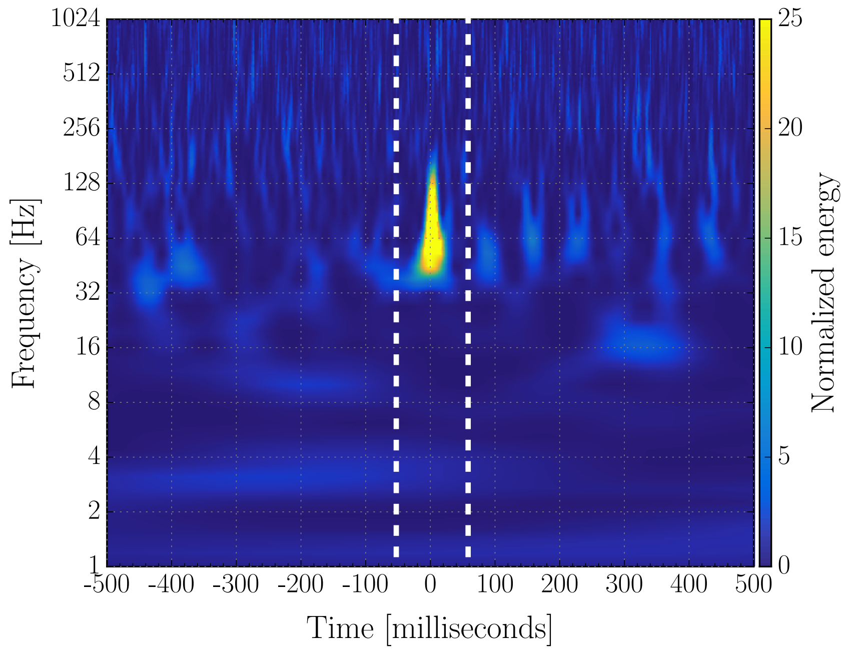


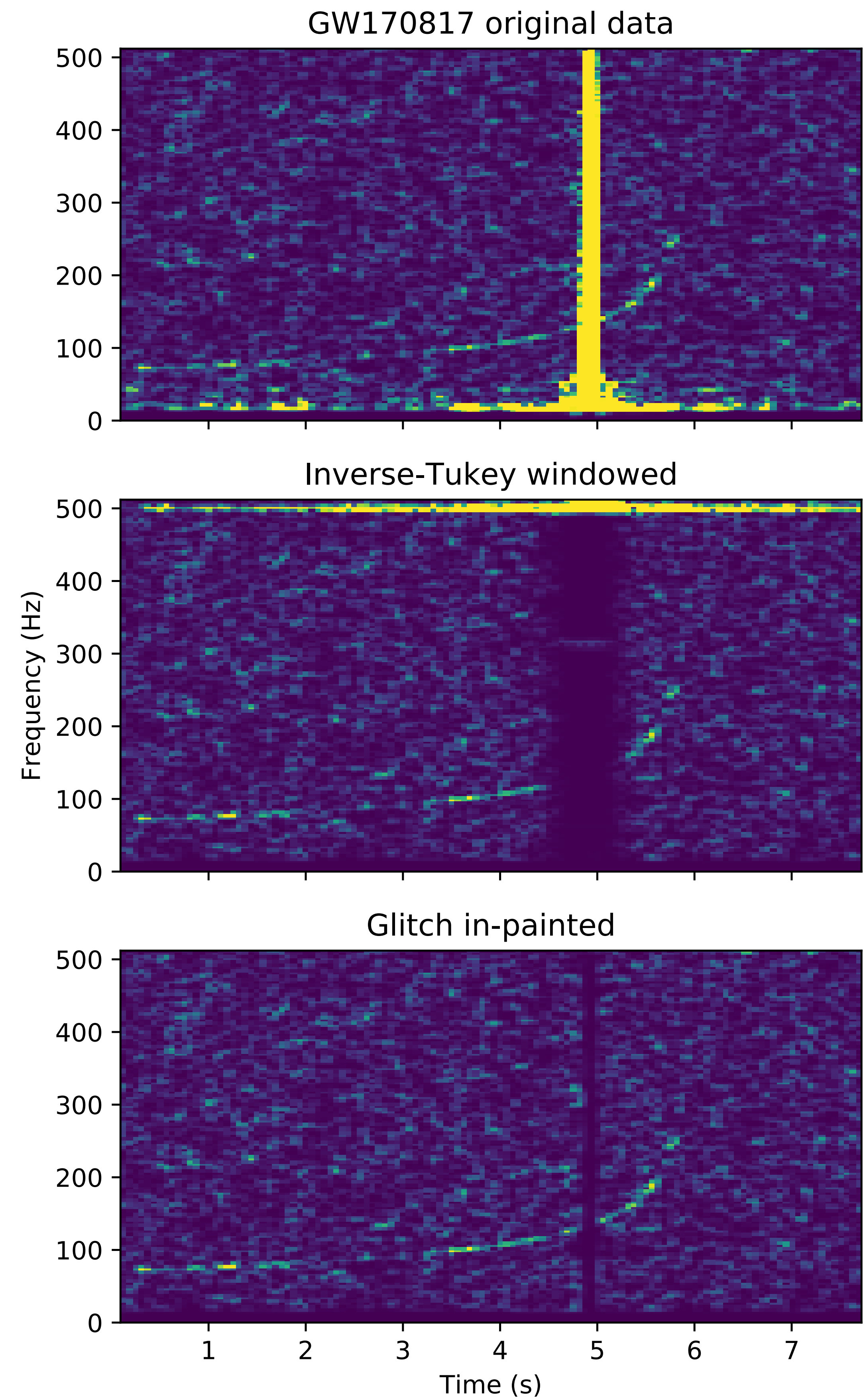
- Must not “remove samples” - Lines will leak out
- Rephrase the problem:
  - Replace the bad segment with an infinitely loud white noise process.
  - Solve the least squares linear algebra problem of measuring amplitude, and identify the equivalent data
  - Solution: Inpaint the samples in the bad segment to the value expected by the rest of the data
- Does not generate new triggers
- Preserves existing triggers (like the BNS GW170817)

Mitigating Glitches

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



- Must not “remove samples” - Lines will leak out
- Rephrase the problem:
  - Replace the bad segment with an infinitely loud white noise process.
  - Solve the least squares linear algebra problem of measuring amplitude, and identify the equivalent data
  - Solution: Inpaint the samples in the bad segment to the value expected by the rest of the data
- Does not generate new triggers
- Preserves existing triggers (like the BNS GW170817)

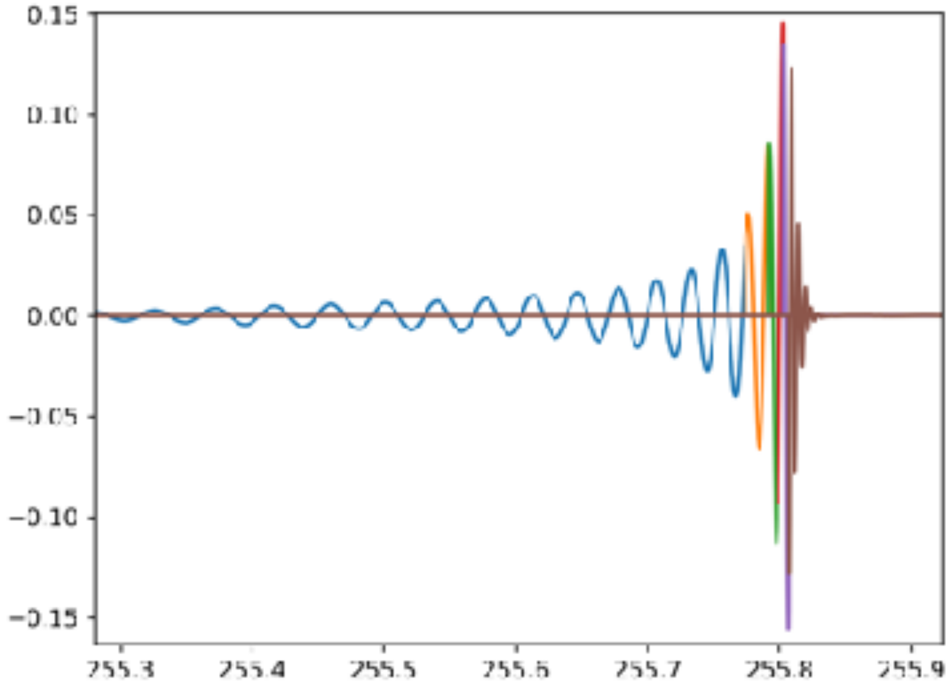


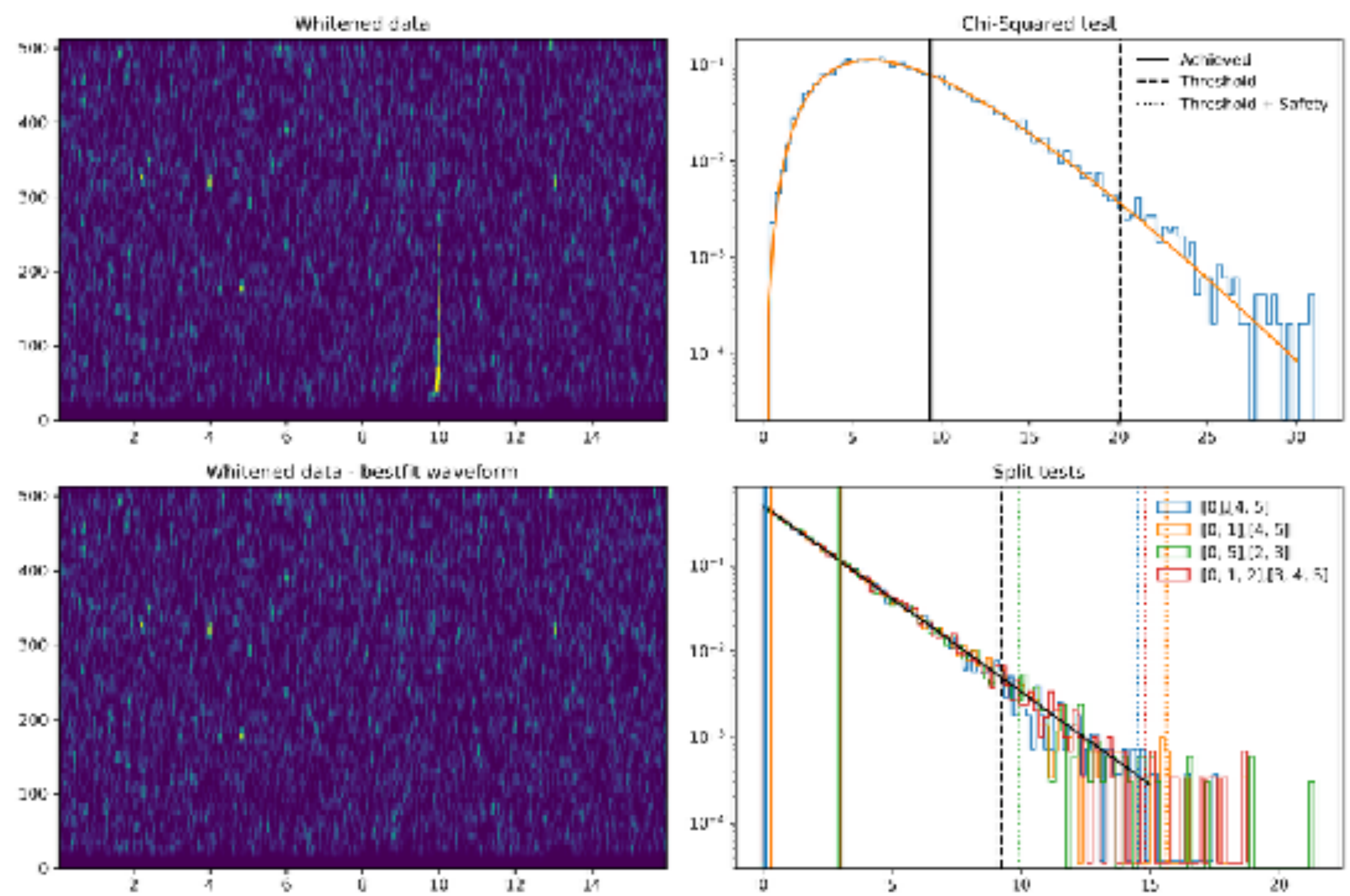
Mitigating Glitches

Check for consistency between different parts of the overlaps, and veto on this

Requirements:

- False positive rate ~ 1% on Gaussian noise
- Robust to
    A. PSD drift
    B. Inefficiency in the template bank

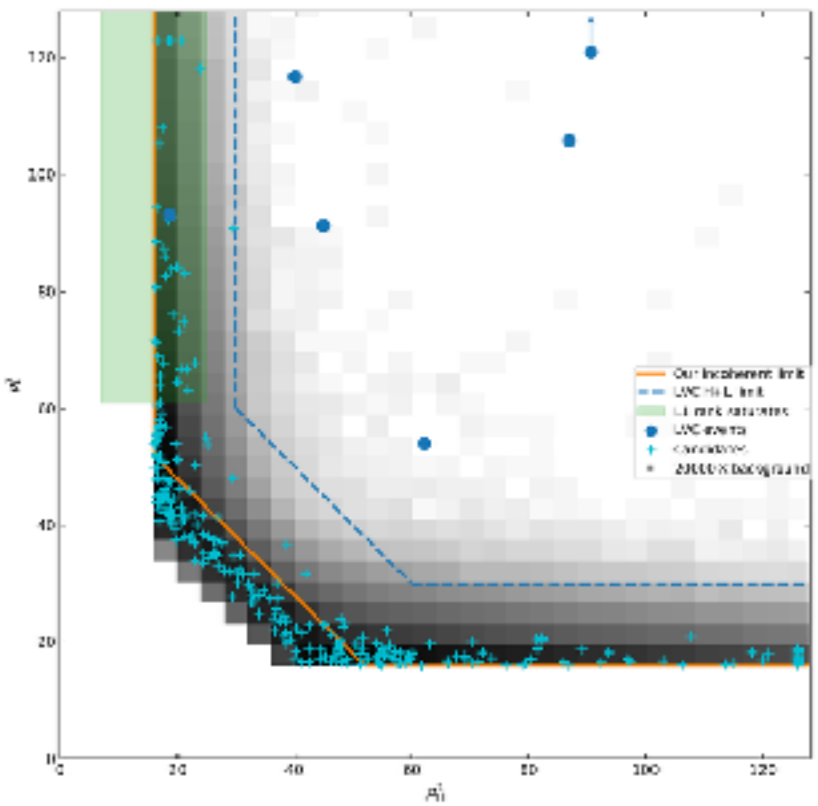




Effect of Mitigating Glitches

Background

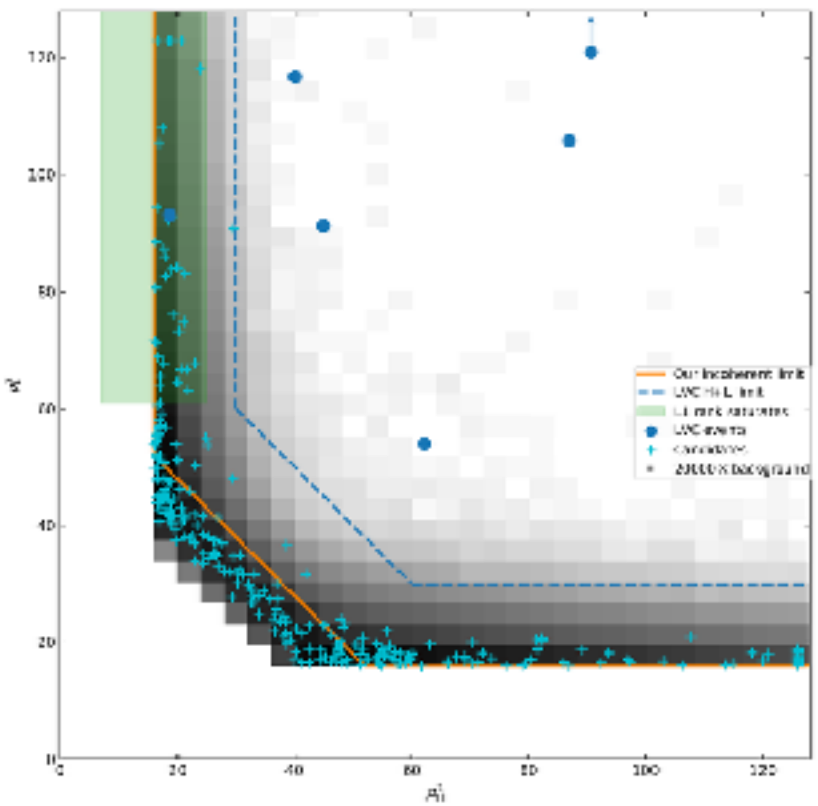
No vetoes

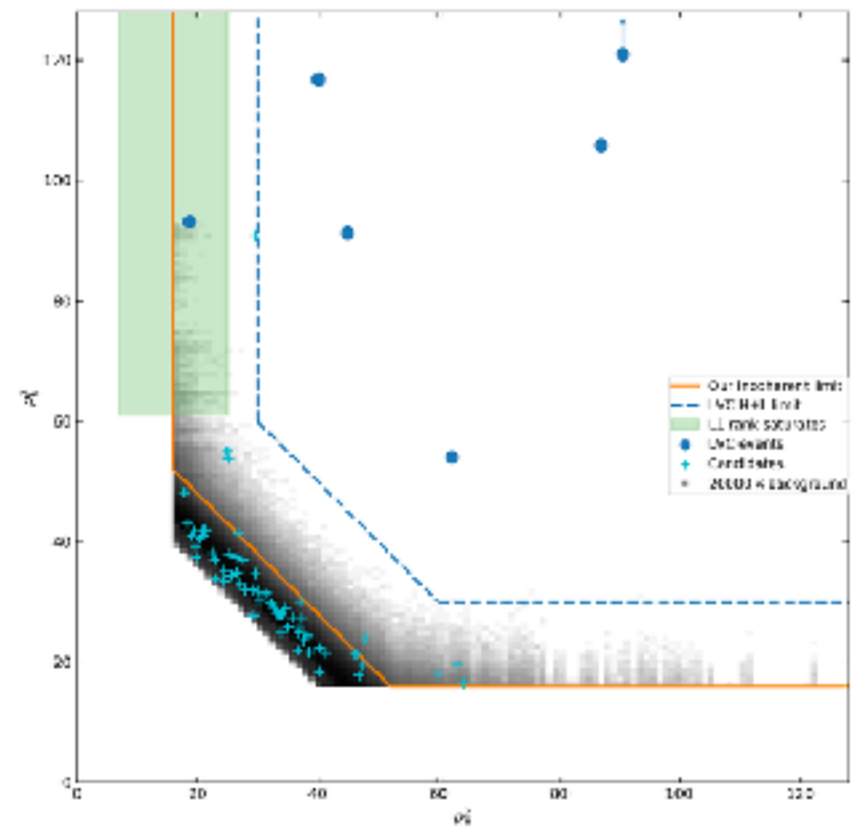


Effect of Mitigating Glitches

Background

No vetoes



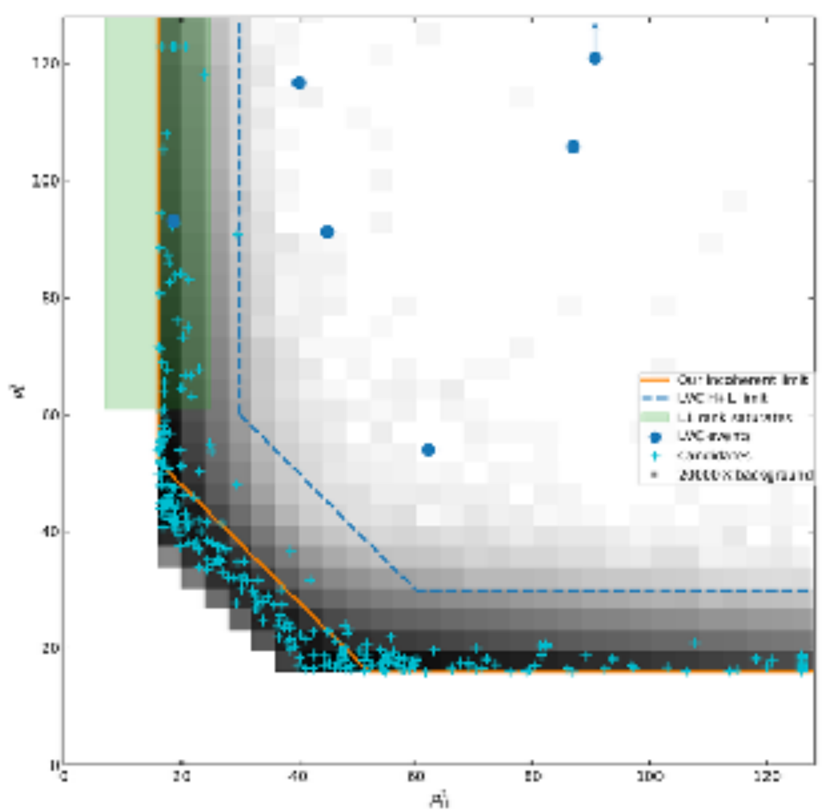


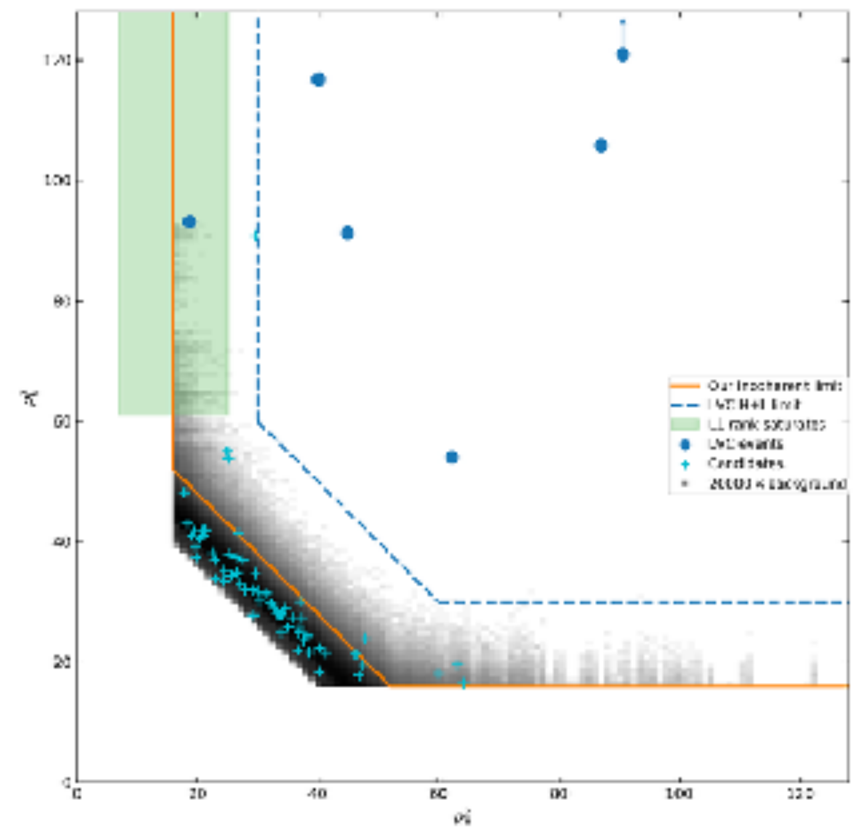
With vetoes

Effect of Mitigating Glitches

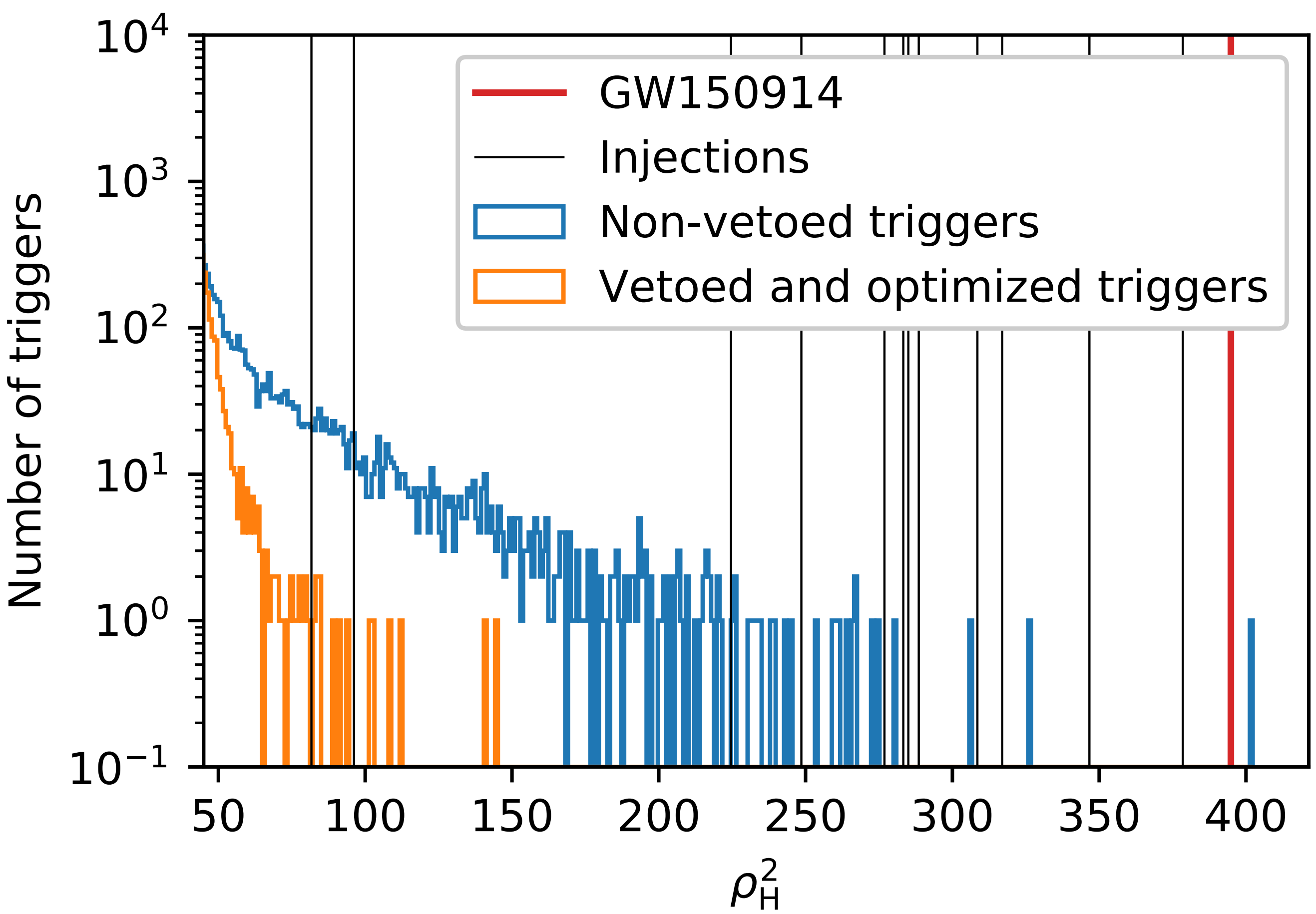
Background

No vetoes





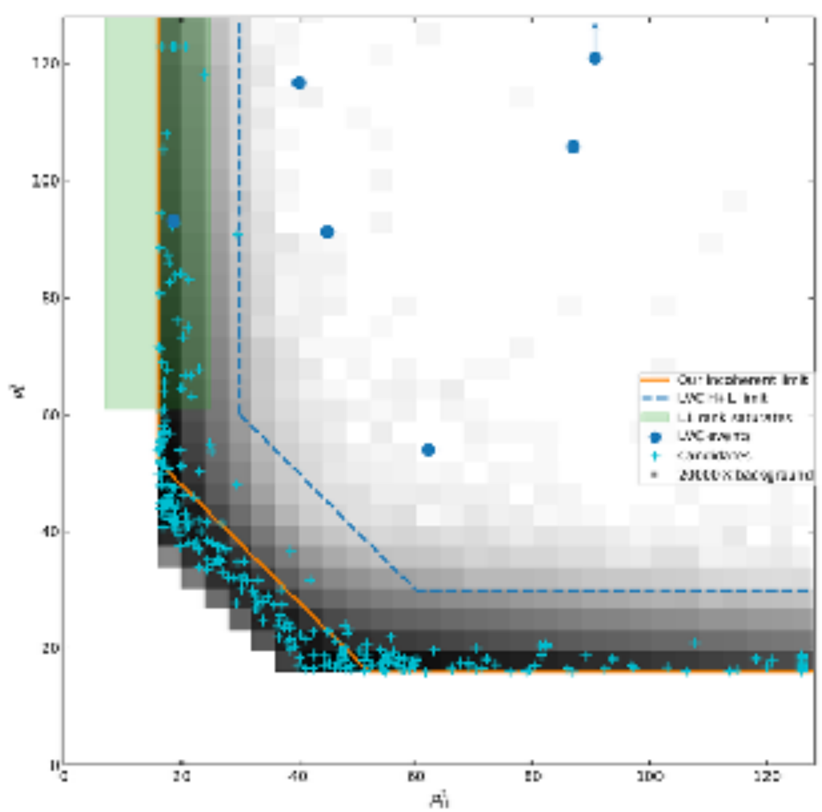
With vetoes

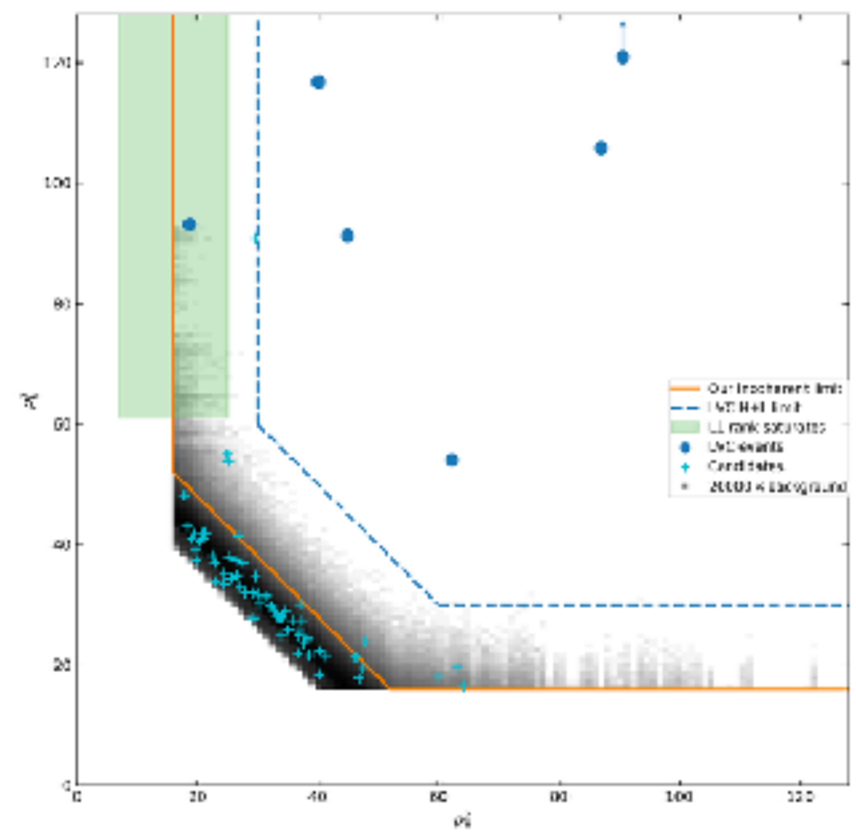


Effect of Mitigating Glitches

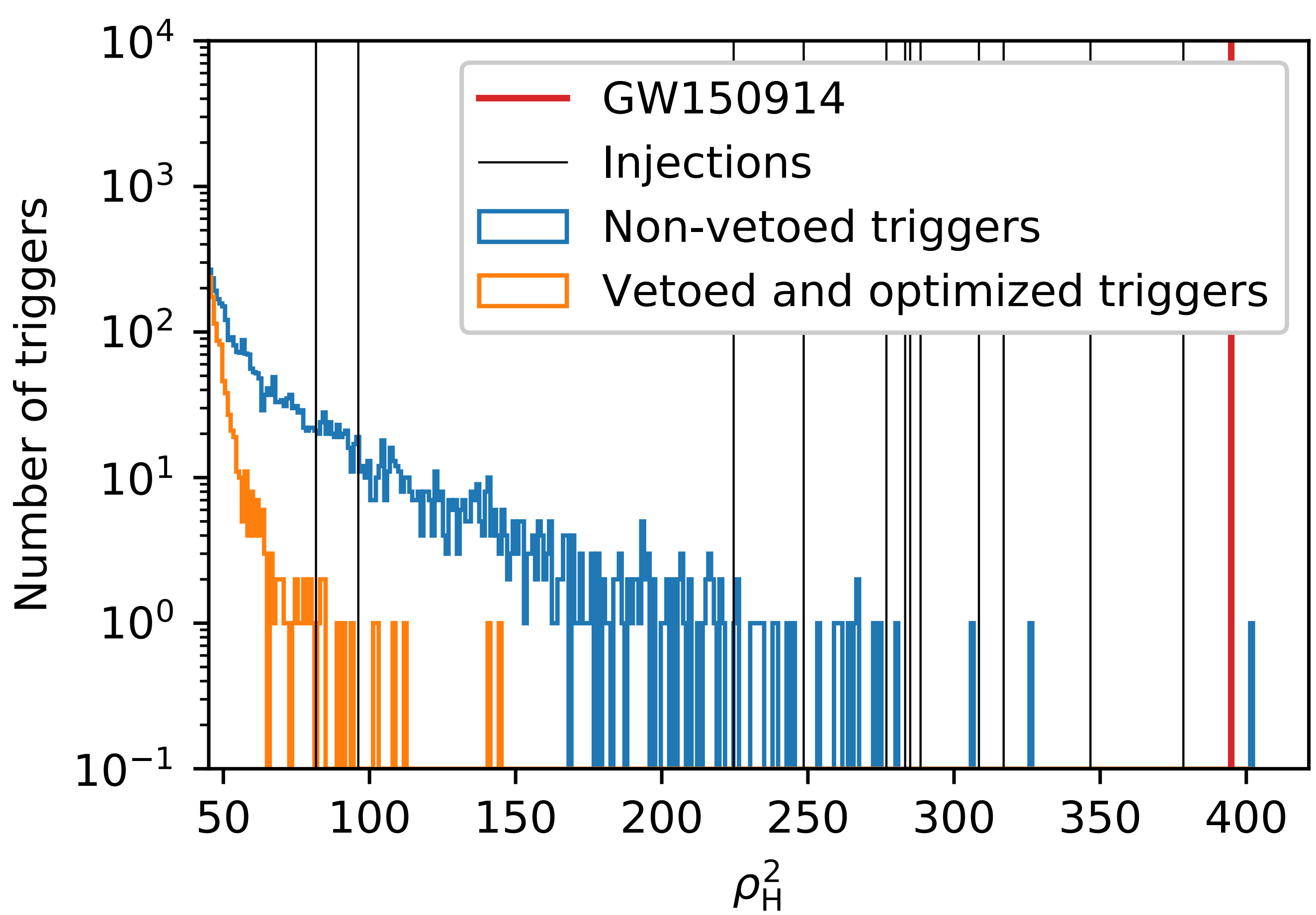
Background

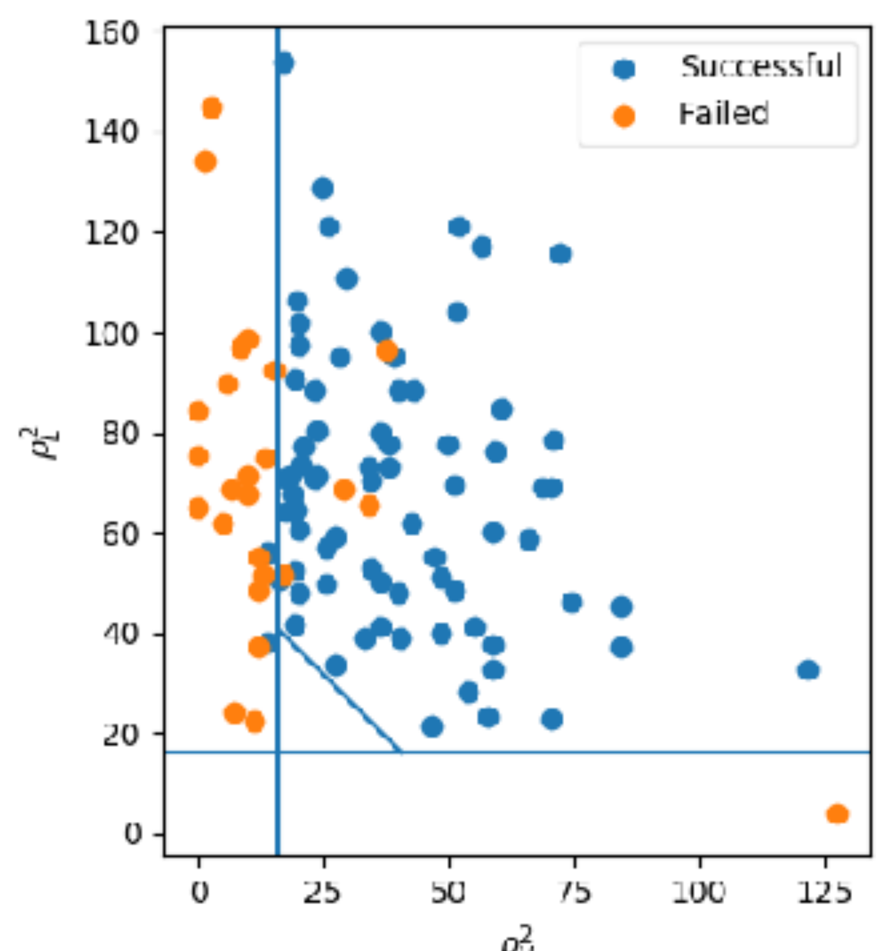
No vetoes





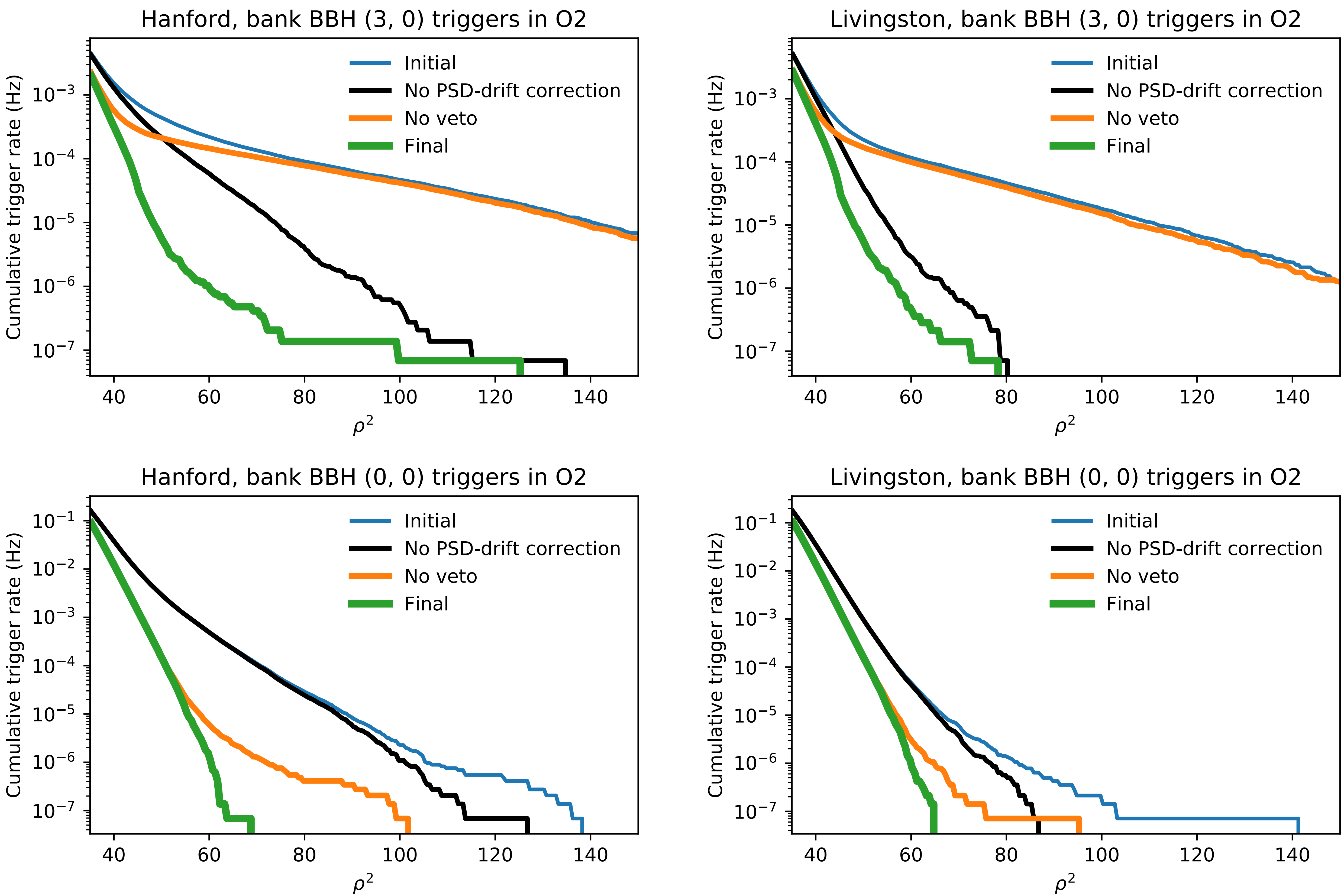
With vetoes





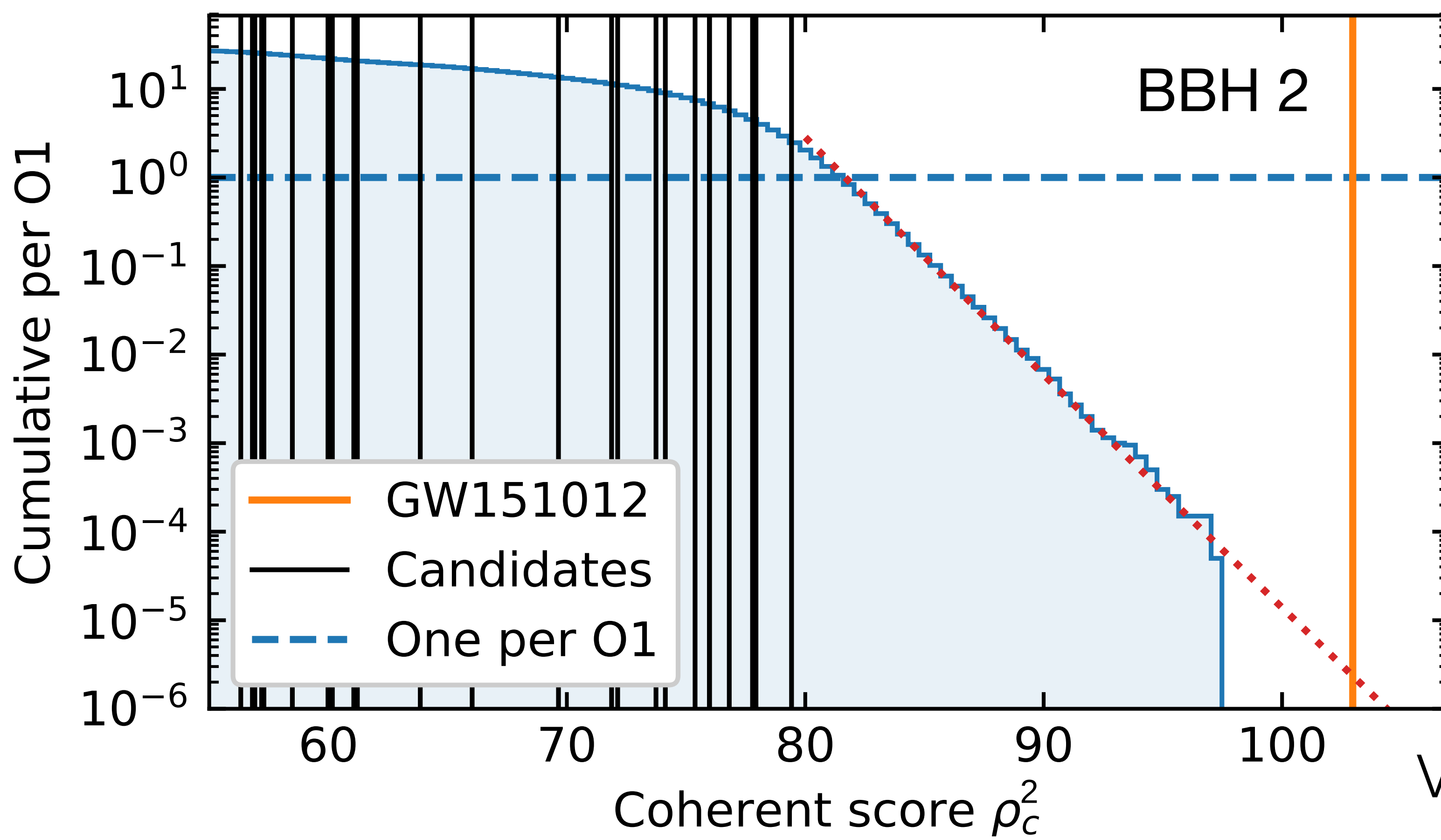
Signals

Impact of Cleaning + PSD Drift Correction + Vetoes



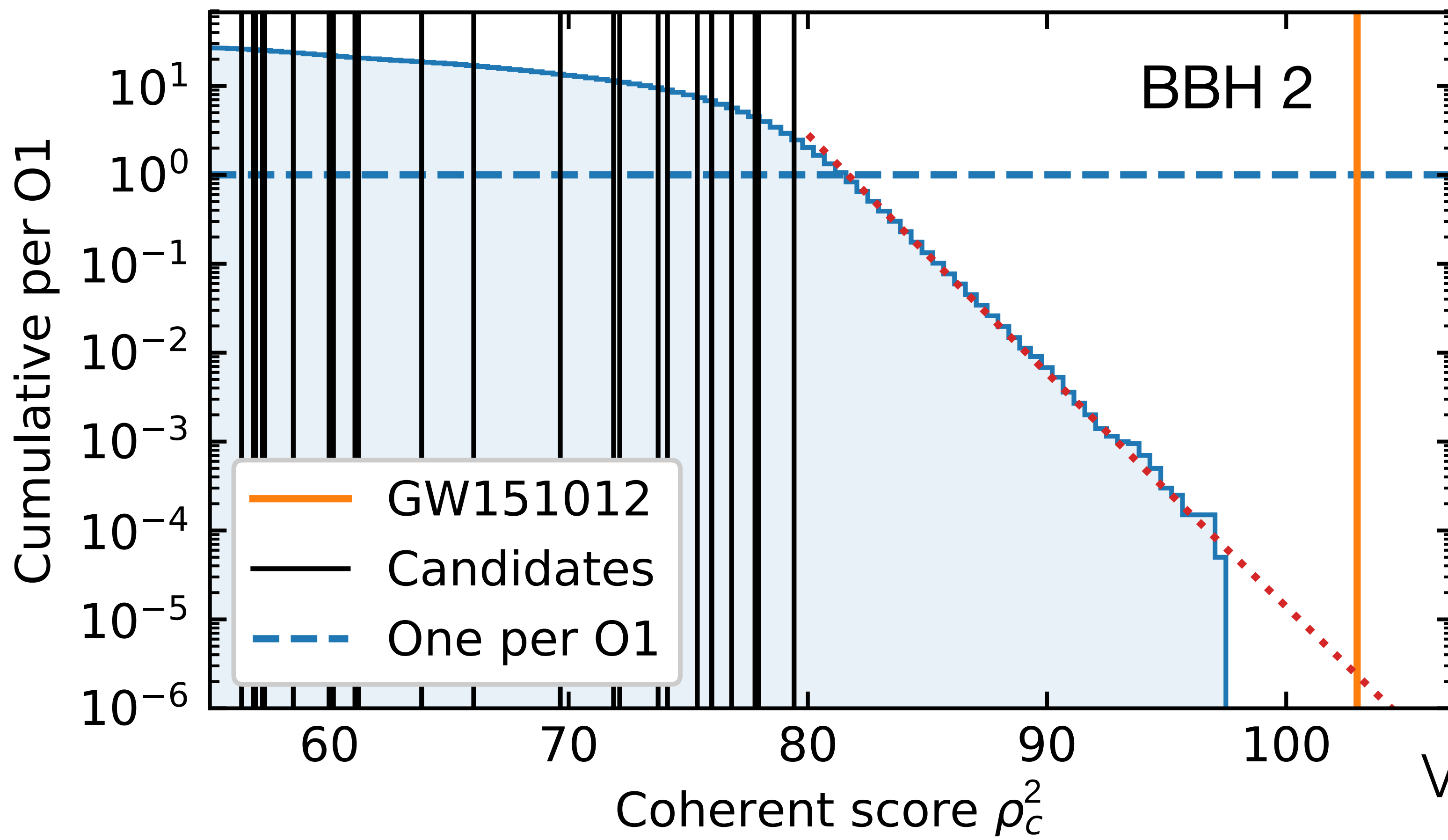
arXiv: 1908.05644

Improved Background on O1: GW151012



Venumadhav et. al., (2019)

Improved Background on O1: GW151012



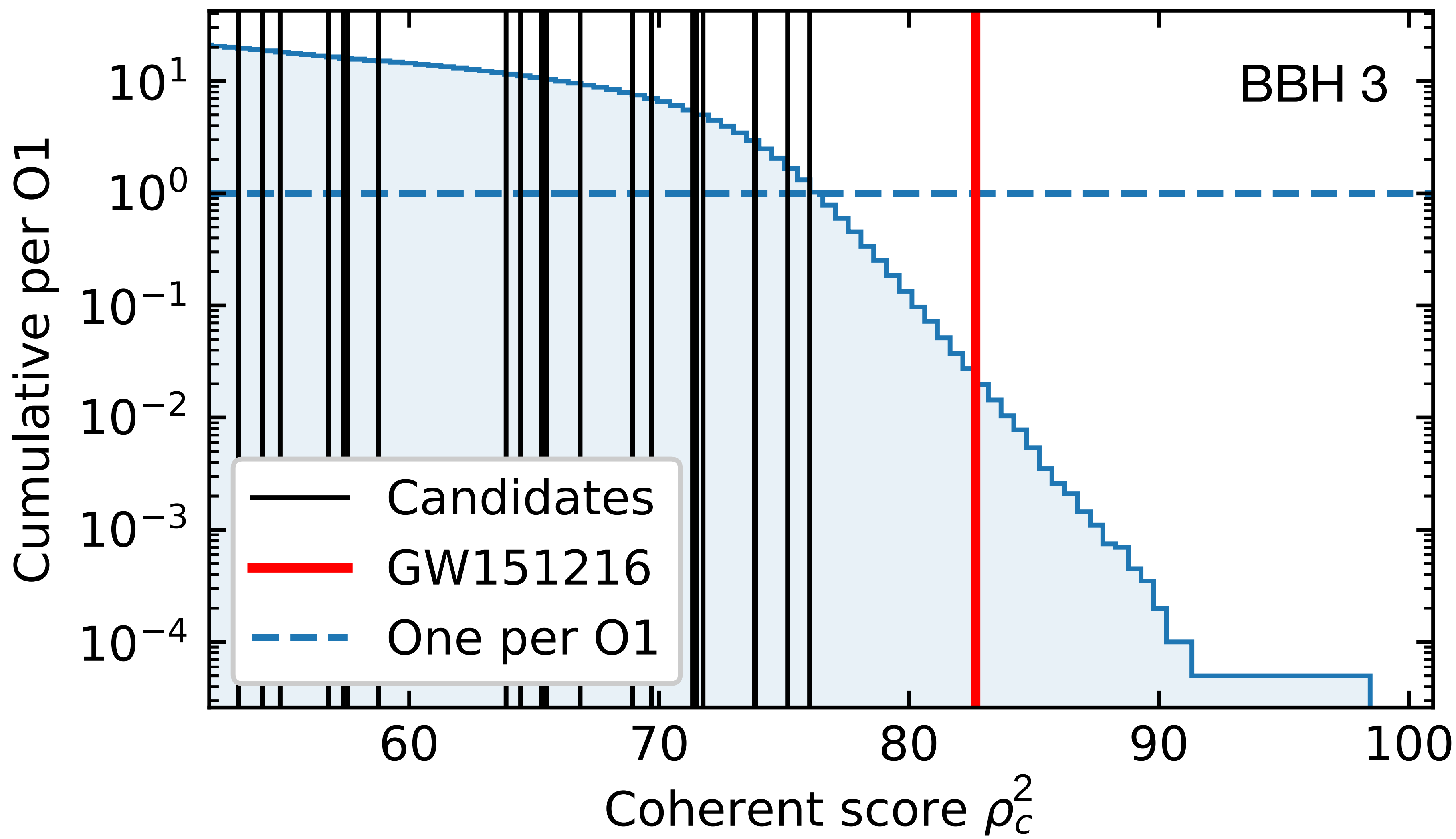
Venumadhav et. al., (2019)

Event	UTC Time	FAR [y^{-1}] PyCBC	GstLAL	cWB	Network SNR PyCBC	GstLAL	cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
GW170823	13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

TABLE I. Search results for the eleven GW events. We report a false-alarm rate for each search that found a given event; otherwise, we display

Abbott et. al., (2018)

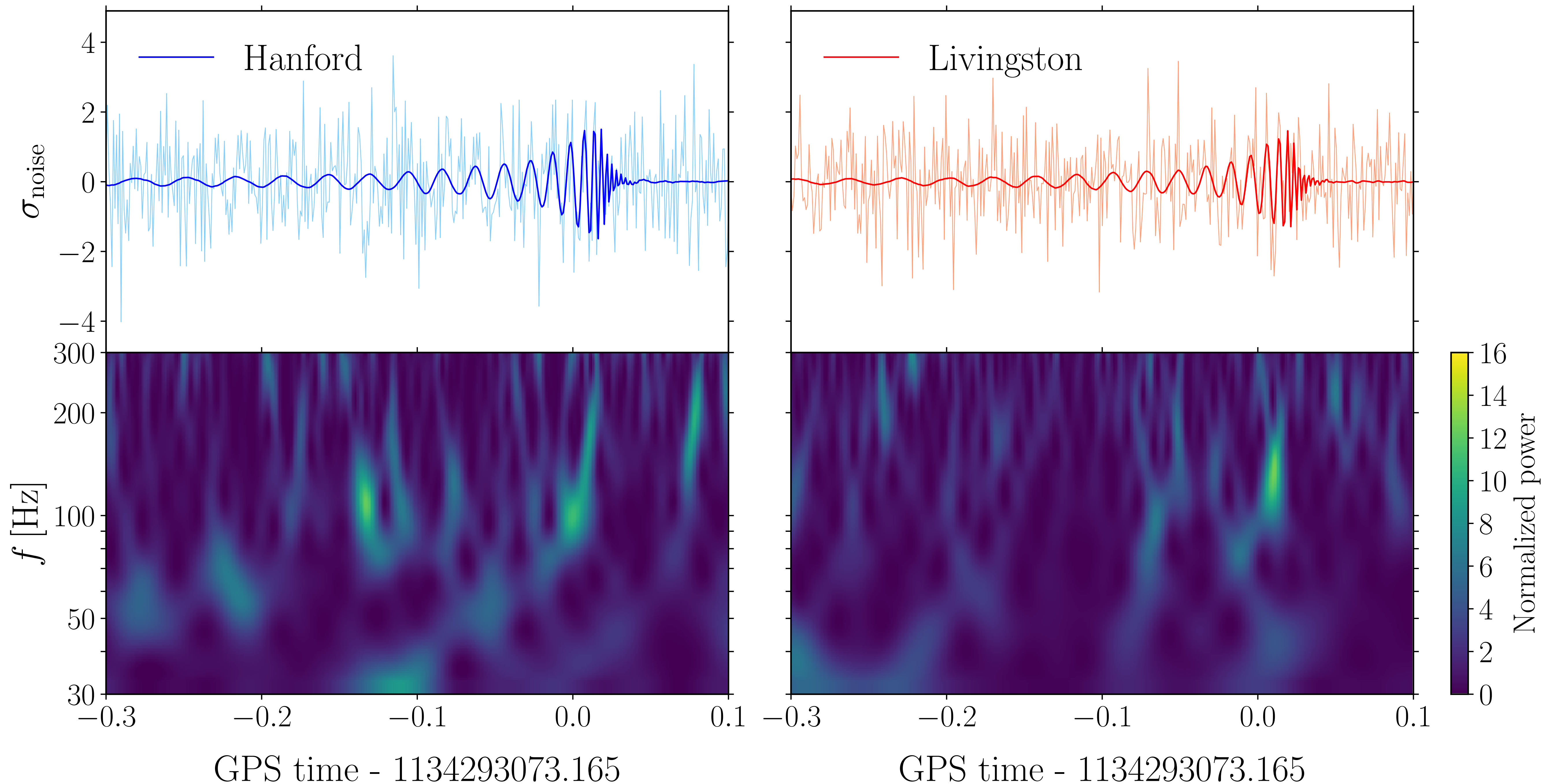
O1: New Event in Bank 3



Name	Bank	$\mathcal{M}(M_\odot)$	GPS time[a]	ρ_{H}^2	ρ_{L}^2	$\mathrm{FAR}^{-1}(\mathrm{O1})$[b]	$\frac{W}{\mathcal{R}(\mathrm{event}\mid H_0)}$ (days)	$\mathcal{R}_{>100}(\mathrm{days}^{-1})$	p_{astro}
GW151226	BBH 1	9.74	1135136350.585	120.0	52.1	> 20 000	–[c]	–	1[c]
GW151012	BBH 2	18	1128678900.428	55.66	46.75	> 20 000	7×10^5 [d]	0.01	0.9998[d]
GW150914	BBH 3	28	1126259462.411	396.1	184.3	> 20 000	–[c]	–	1[c]
GW151216[e]	BBH 3	29	1134293073.164	39.4	34.8	52	74 ± 2	0.033	0.71
151231	BBH 3	30	1135557647.145	37.5	25.2	0.98	5.4 ± 0.4	0.033	0.15
151011	BBH 4	58	1128626886.595	24.5	39.9	1.1	16 ± 1	0.01	0.14

Venumadhav et. al., (2019)

O1: GW151216



Zackay et. al., (2019)

Improved Background on O2

LVC events: our analysis (O2 = 118 days)

Name	Bank	GPS time[a]	$\rho_{\rm H}^2$	$\rho_{\rm L}^2$	$\mathrm{FAR}^{-1}(\mathrm{O2})^{\rm b}$	$\frac{W(\mathrm{event})}{\mathcal{R}(\mathrm{event}\vert\mathcal{N})}$ (O2)	$p_{\rm astro}$
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	$1.7^{\rm c}$	—	—[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

Venumadhav et. al., (2019)

LVC analysis

Event	UTC Time	FAR [y^{-1}] PyCBC	FAR [y^{-1}] GstLAL	FAR [y^{-1}] cWB	Network SNR PyCBC	Network SNR GstLAL	Network SNR cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
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Abbott et. al., (2018)

Improved Background on O2

LVC events: our analysis (O2 = 118 days)

Name	Bank	GPS time[a]	ρ^2_{H}	ρ^2_{L}	$\mathrm{FAR}^{-1}(\mathrm{O2})^{\mathrm{b}}$	$\frac{W(\mathrm{event})}{\mathcal{R}(\mathrm{event}\|\mathcal{N})}$ (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

Venumadhav et. al., (2019)

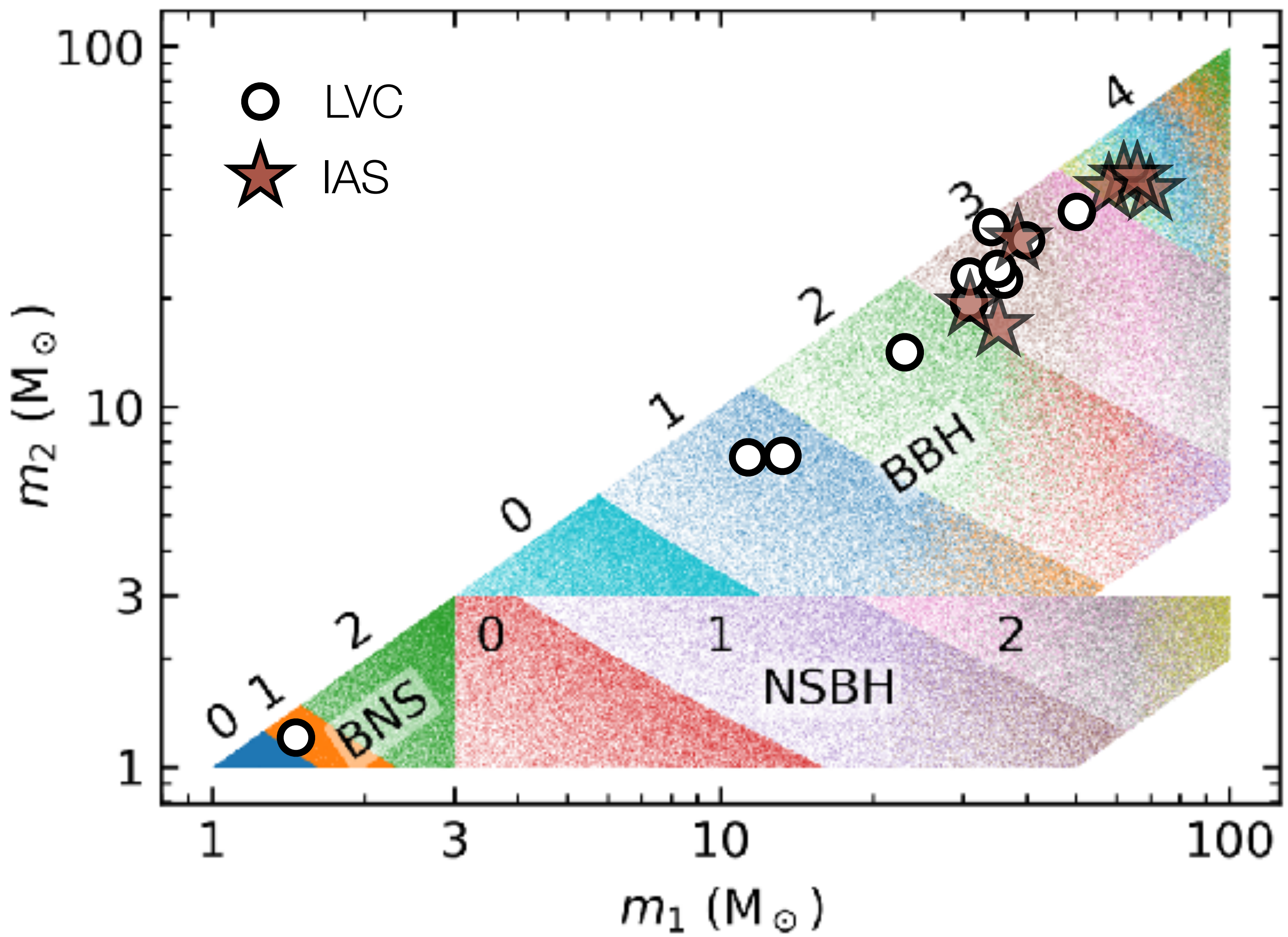
LVC analysis

Event	UTC Time	FAR [y^{-1}] PyCBC	FAR [y^{-1}] GstLAL	FAR [y^{-1}] cWB	Network SNR PyCBC	Network SNR GstLAL	Network SNR cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
GW170823	13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

TABLE I. Search results for the eleven GW events. We report a false-alarm rate for each search that found a given event; otherwise, we display

Abbott et. al., (2018)

O2: Six New Events in Banks 3 and 4

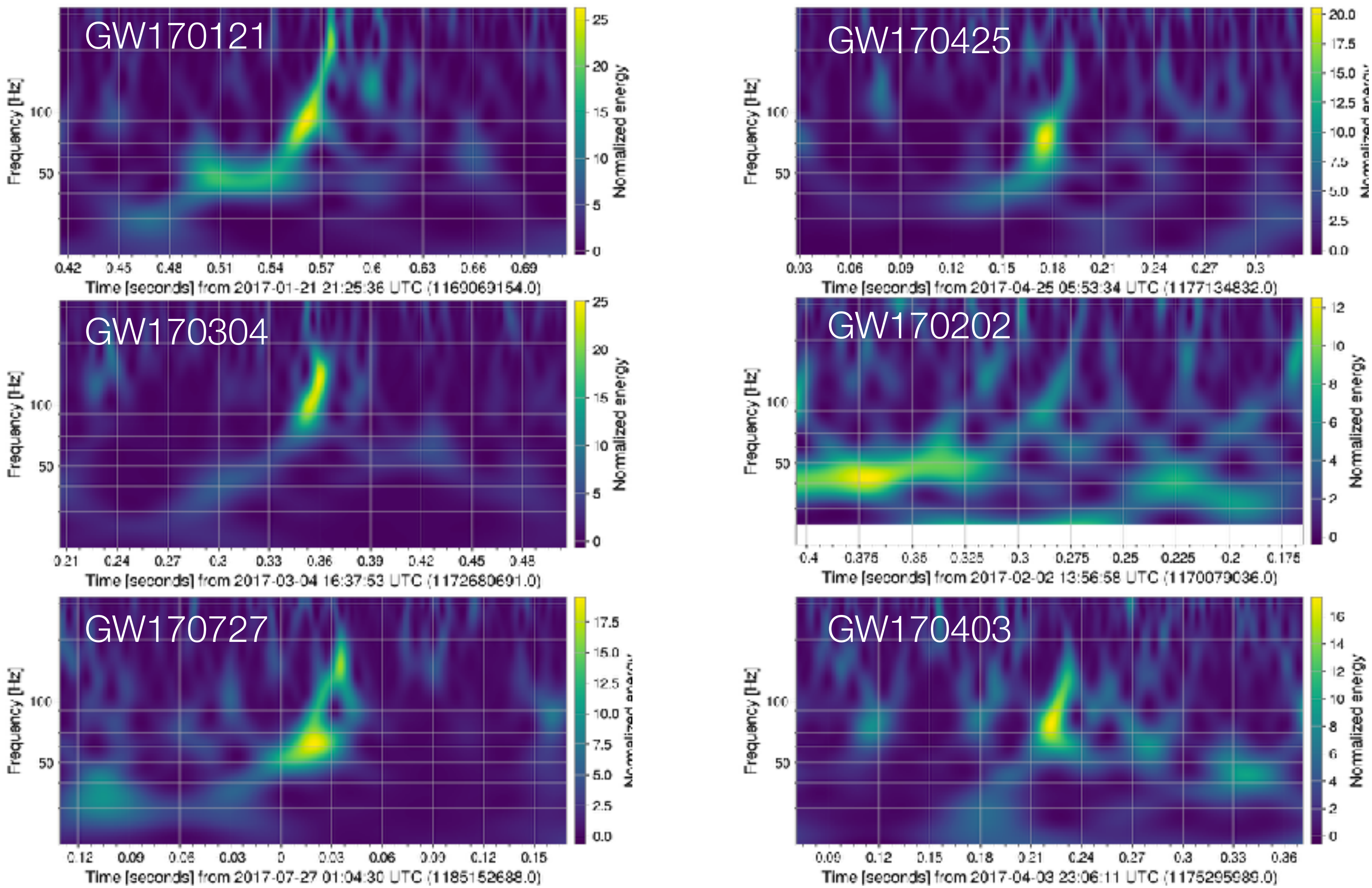


Name	Bank	$\mathcal{M}^{\rm det}(M_\odot)$	$\chi_{\rm eff}$	z	GPS time[a]	$\rho^2_{\rm H}$	$\rho^2_{\rm L}$	FAR^{-1}(O2)[b]	$\frac{W(\text{event})}{\mathcal{R}(\text{event}\mid\mathcal{N})}$ (O2)	$p_{\rm astro}$
GW170121	BBH (3,0)	29^{+4}_{-3}	$-0.3^{+0.3}_{-0.3}$	$0.24^{+0.14}_{-0.13}$	1169069154.565	29.4	89.7	2.8×10^3	> 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

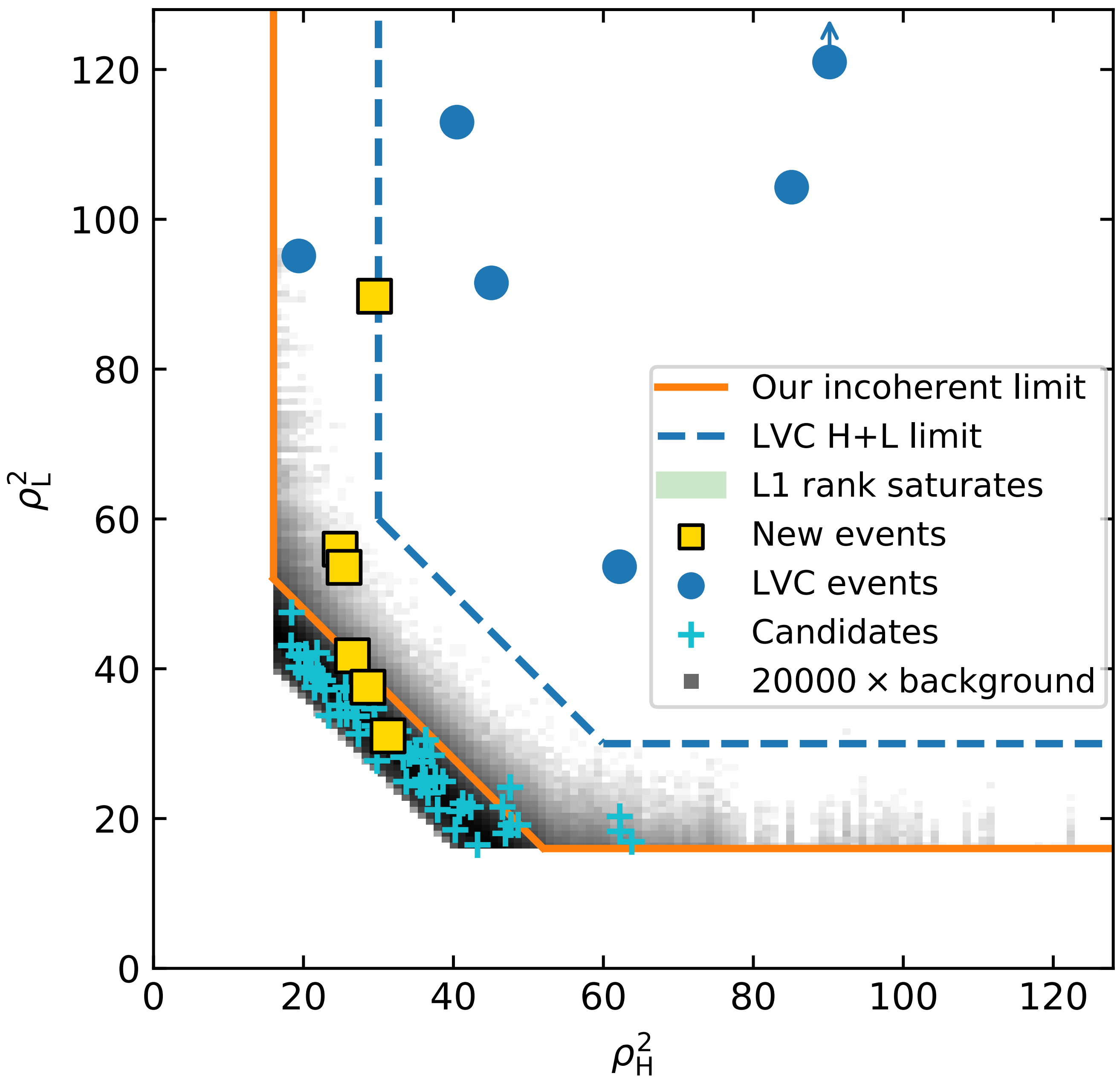
(O2 = 118 days)

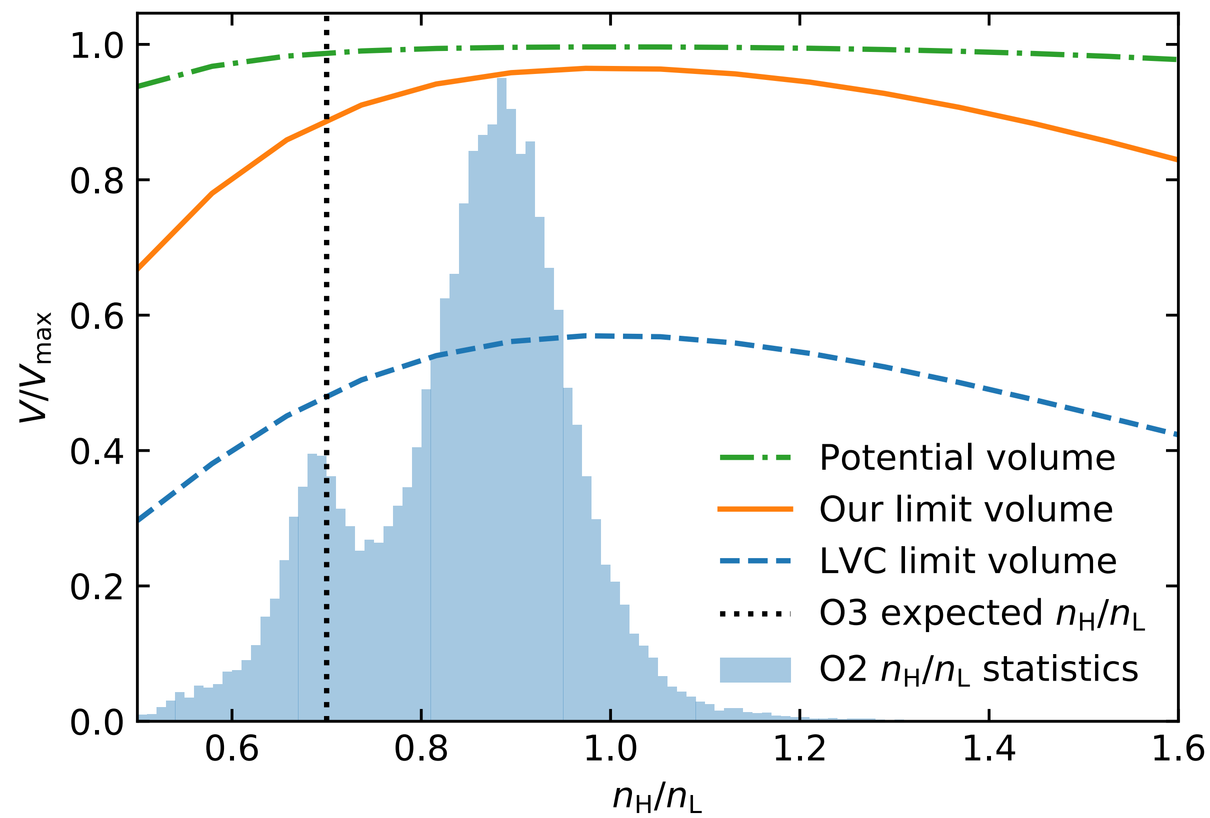
Venumadhav et. al., (2019)

New O2 events



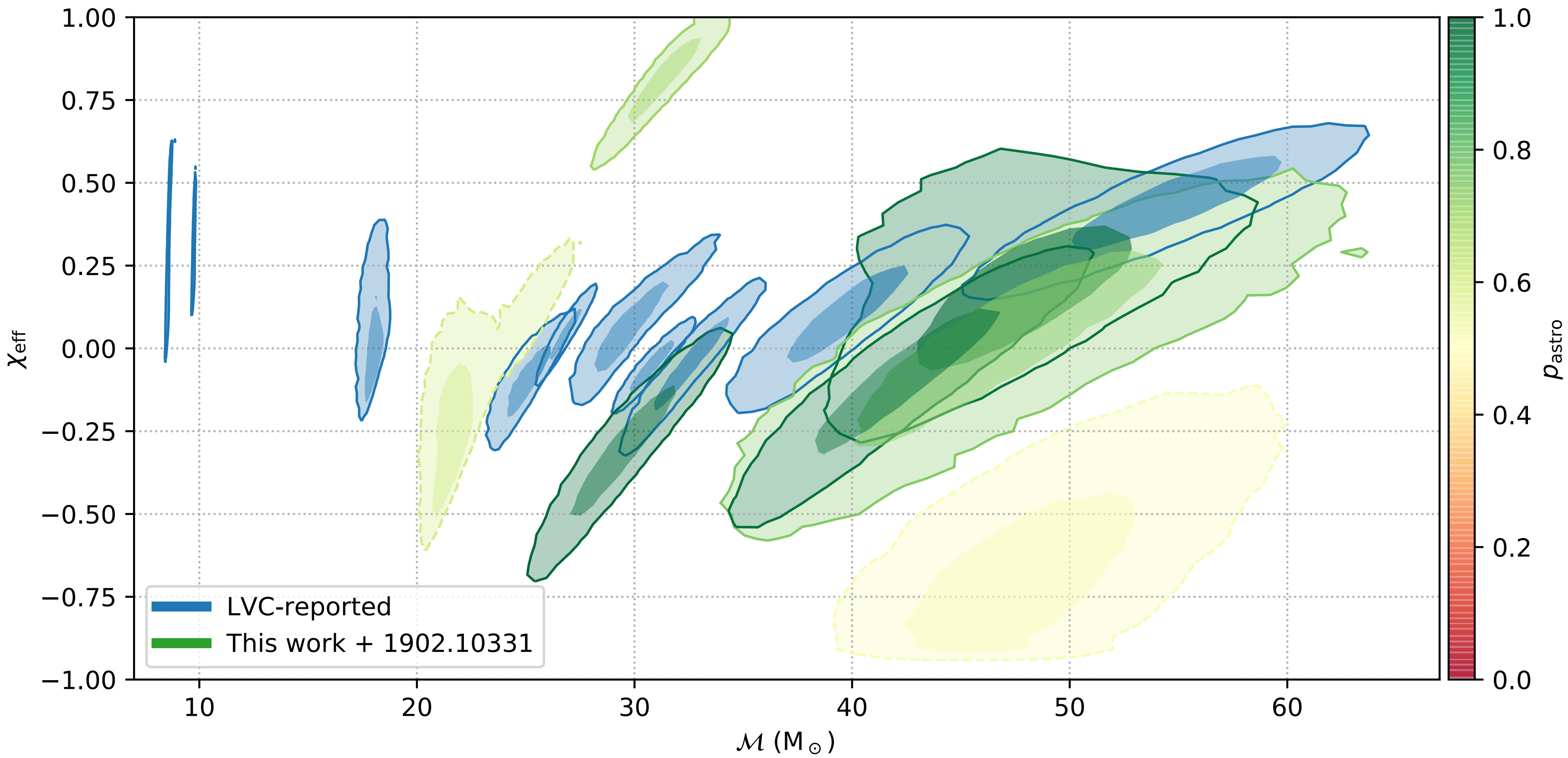
Increase in Sensitivity

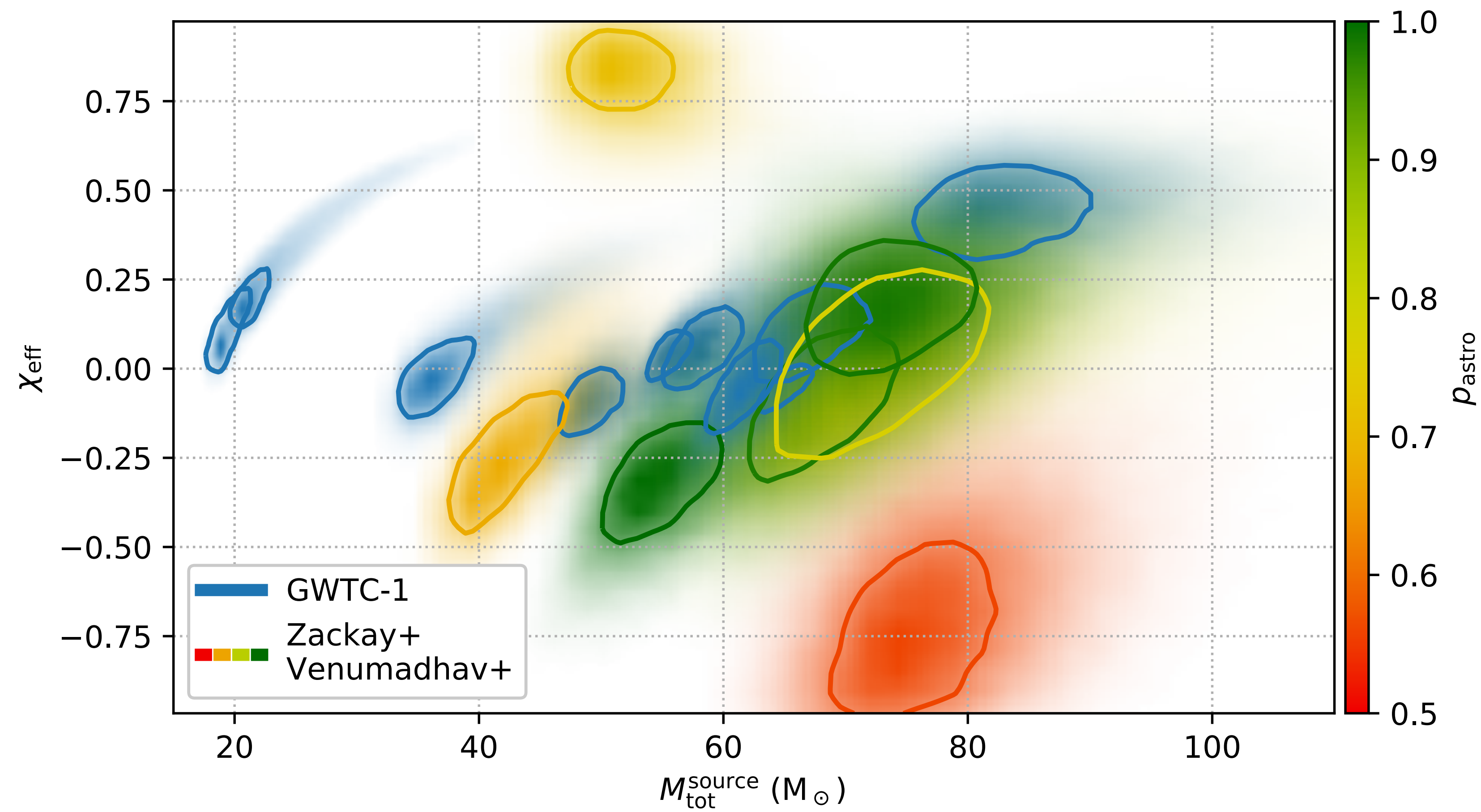




Equivalent to reducing the strain noise amplitude by ~ 25 %

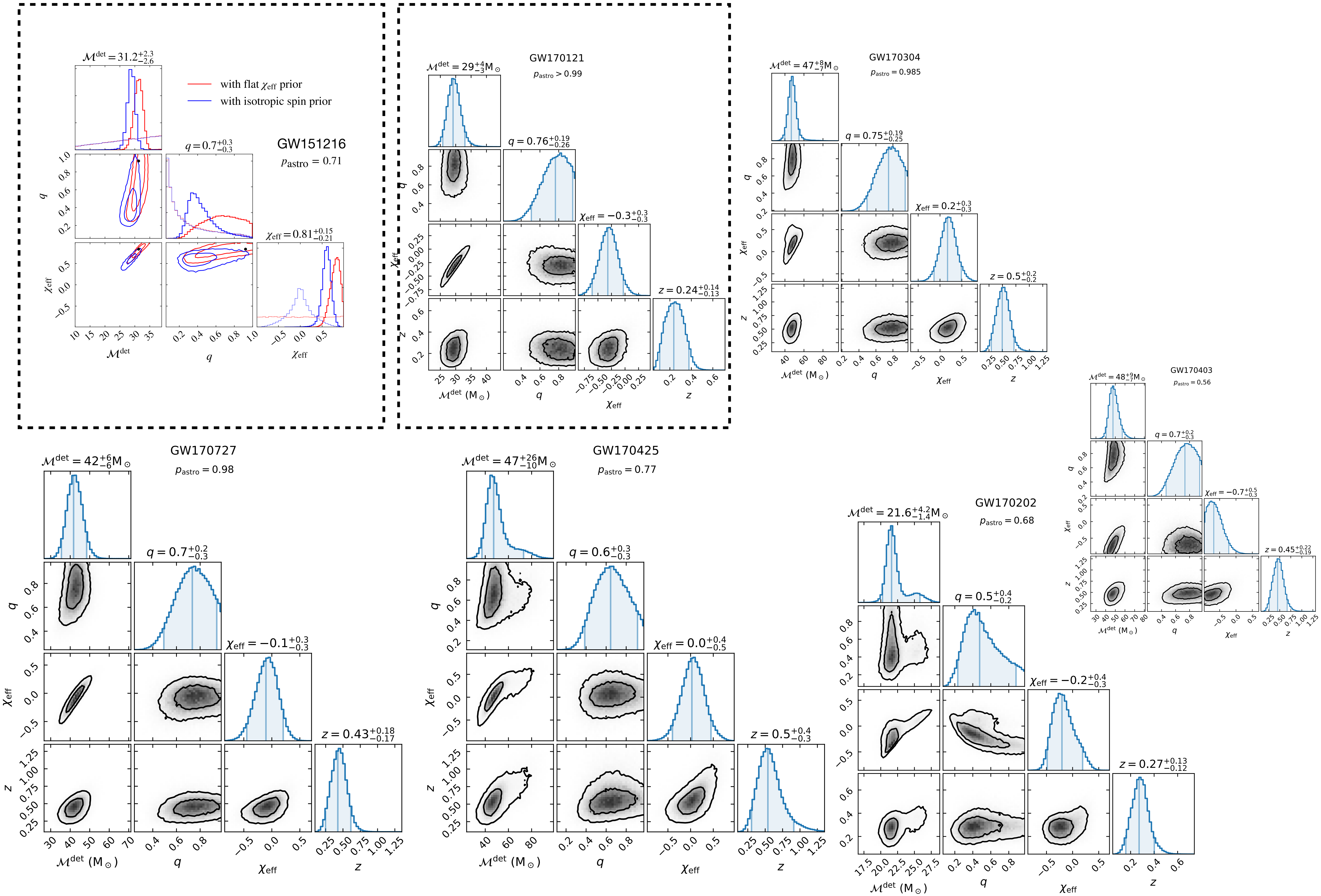
Parameters of the New Events



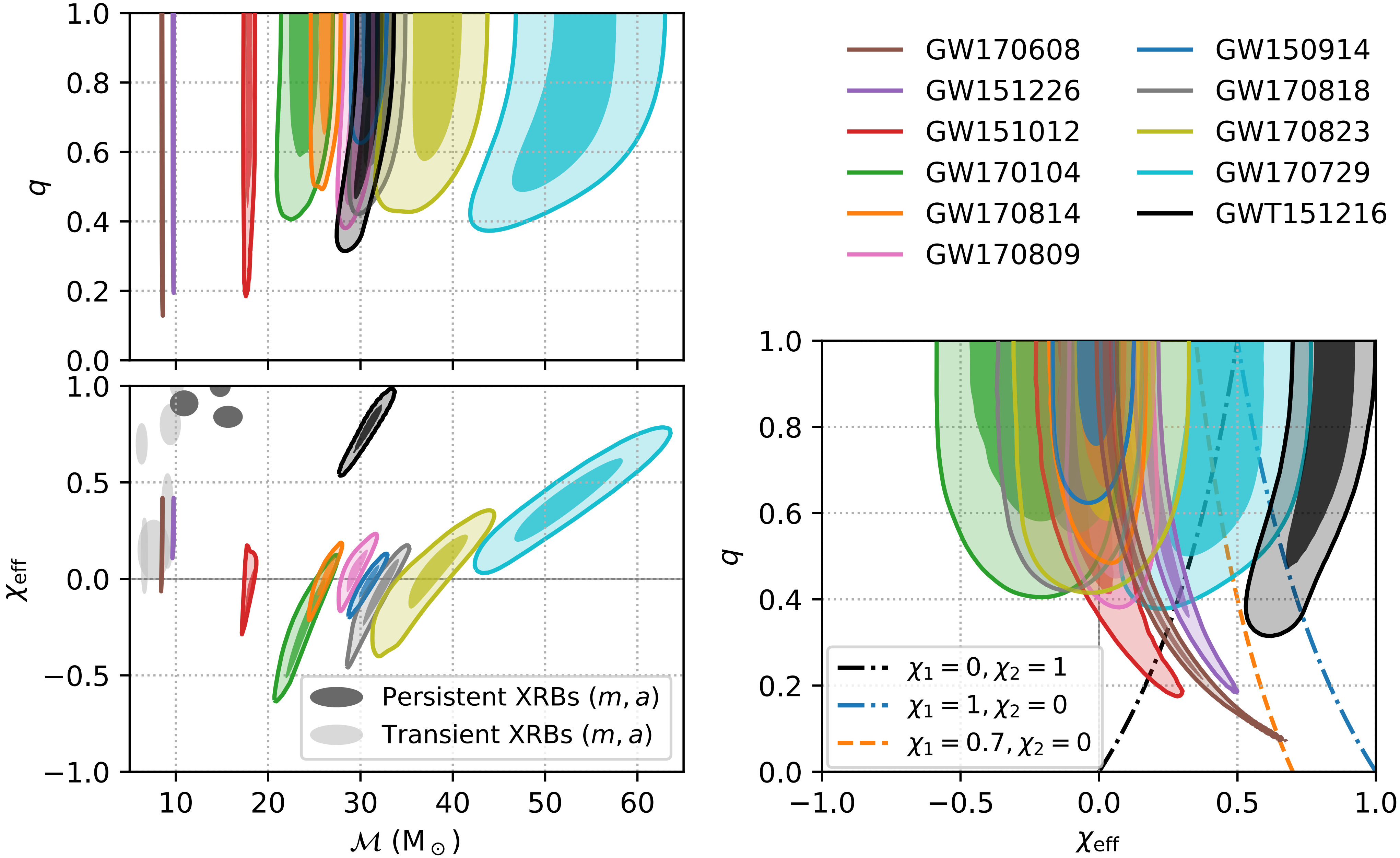


Venumadhav et. al., (2019)

Parameters of the New Events

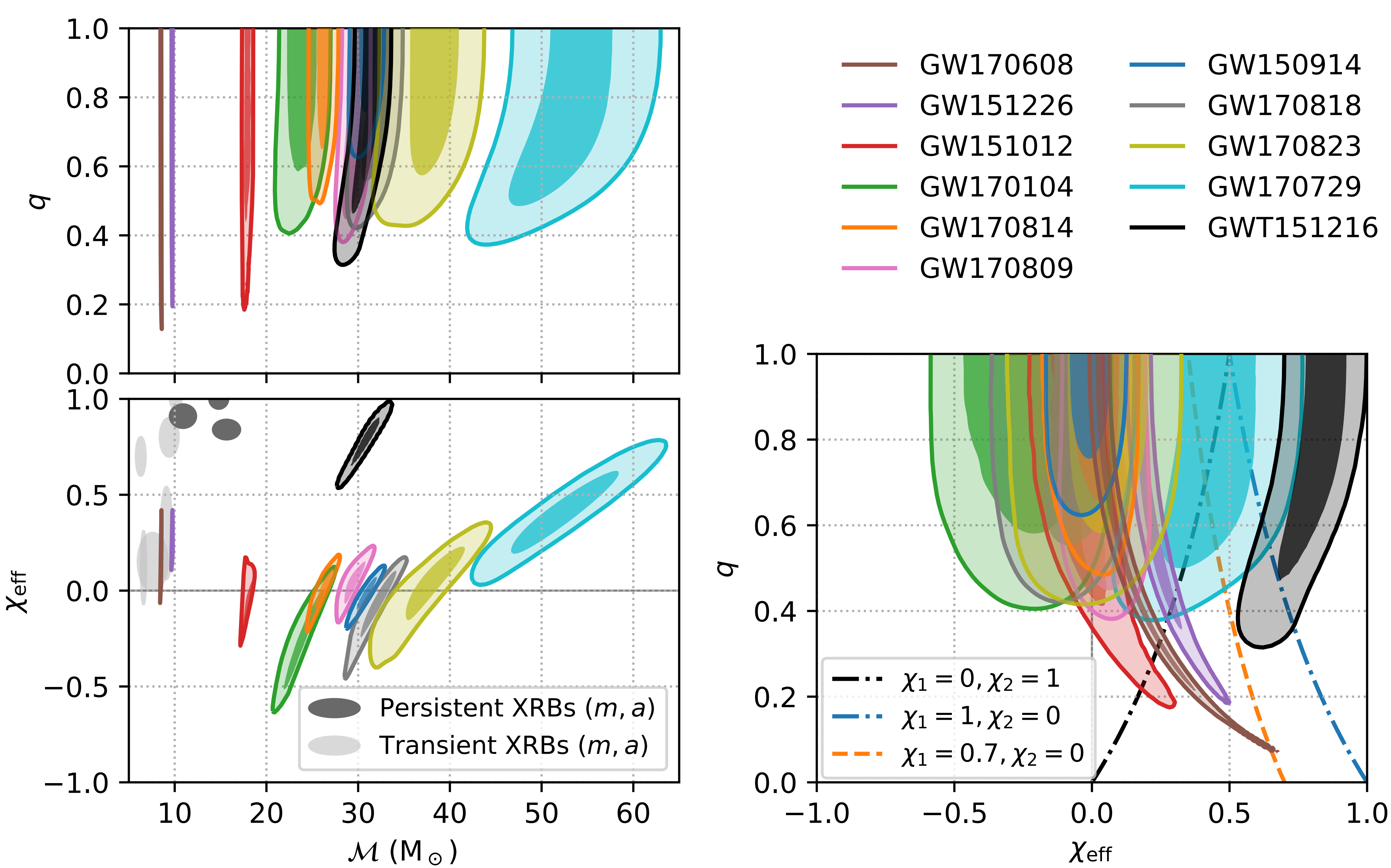


Astrophysical implications of GW151216



High spin points to this system being formed through binary evolution
Inconsistent with the isotropic prior (i.e., ML outside 95% contours)
Obviously outlier with respect to spin

Astrophysical implications of GW151216



$$\chi_{\rm eff} = \frac{\chi_{1,z} + q\chi_{2,z}}{1+q}$$

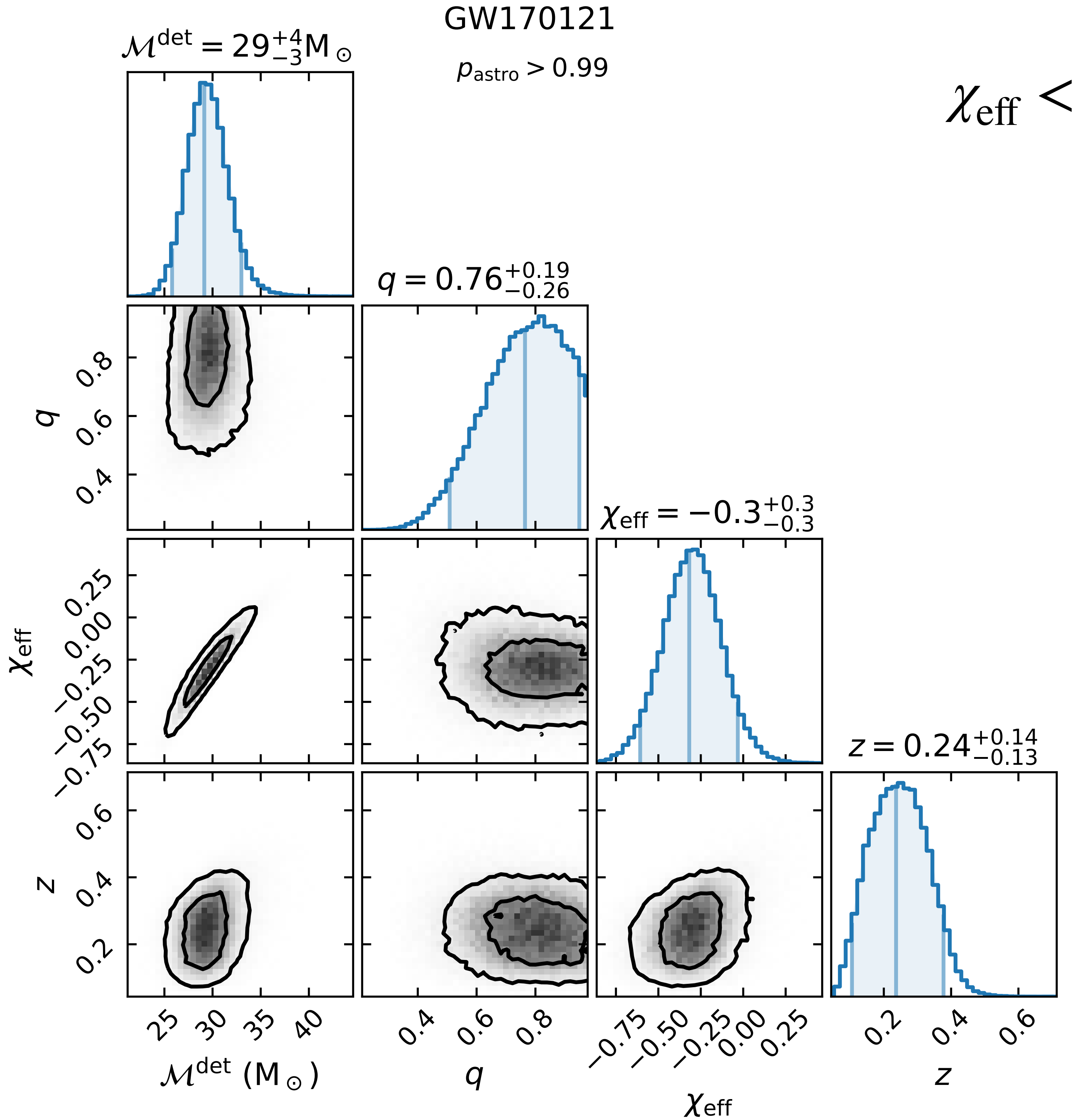
High spin points to this system being formed through binary evolution

Inconsistent with the isotropic prior (i.e., ML outside 95% contours)

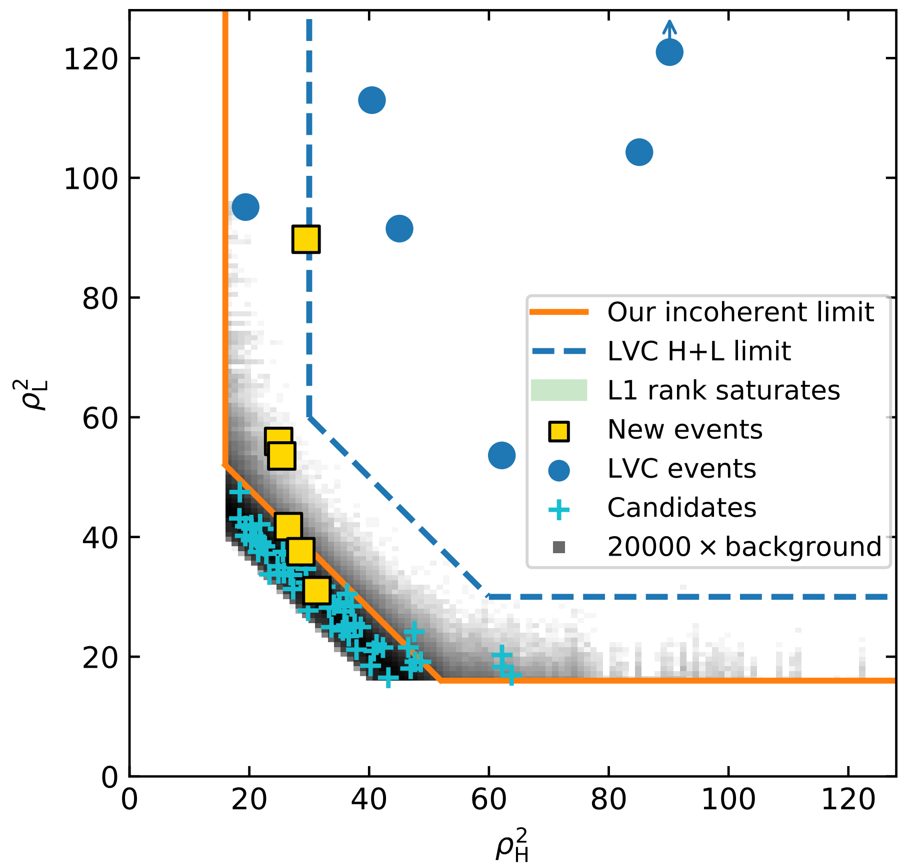
Obviously outlier with respect to spin

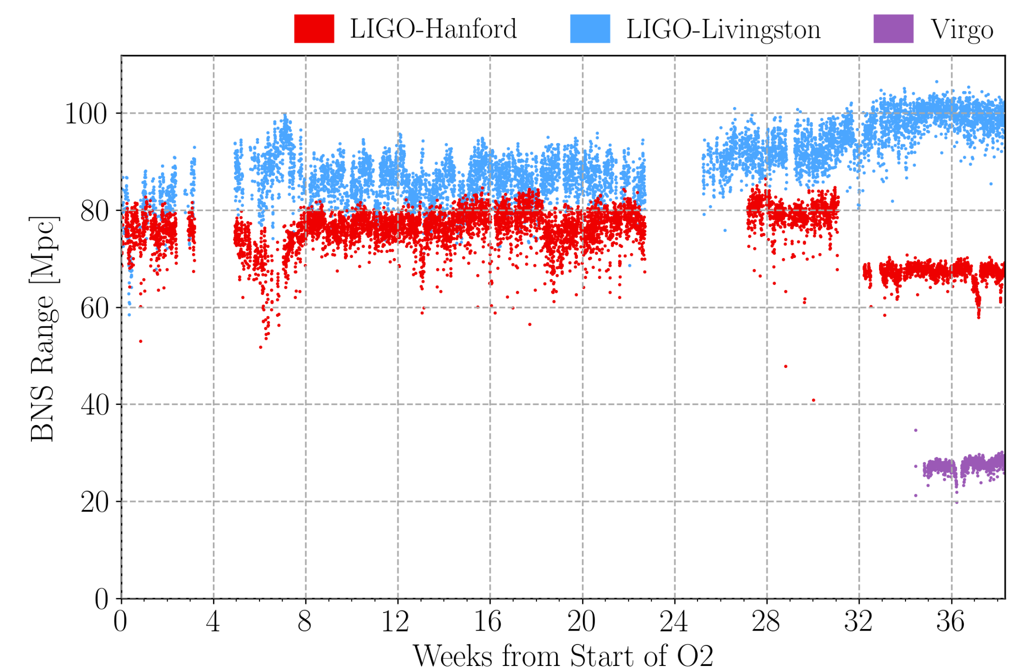
Astrophysical implications of GW170121

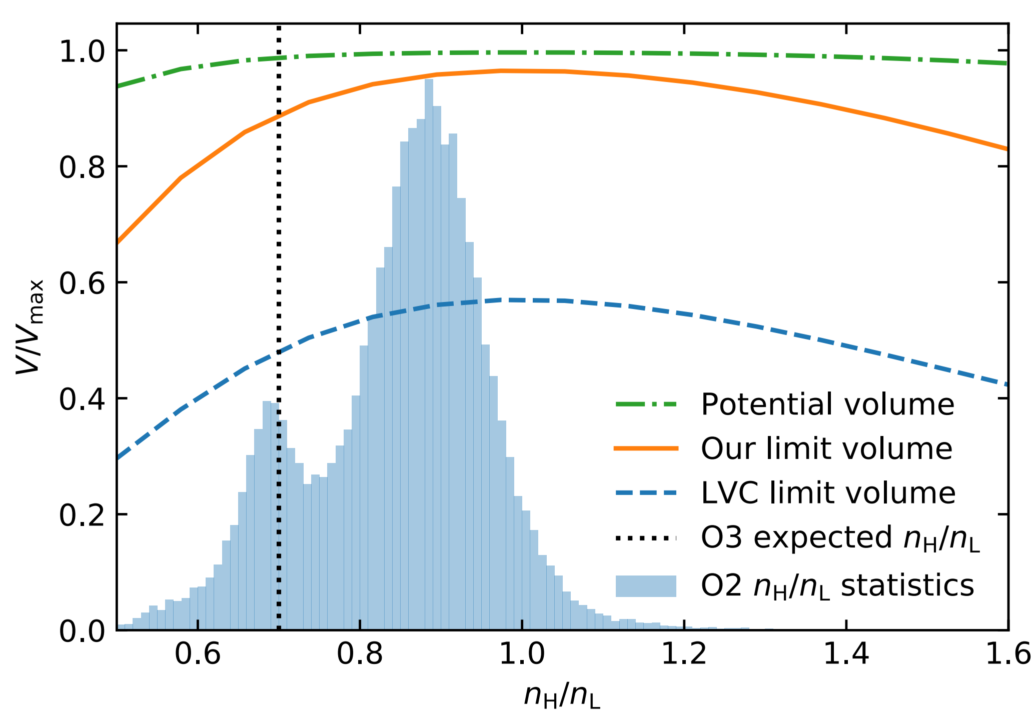
$\chi_{\rm eff} < 0$ at ~96% confidence

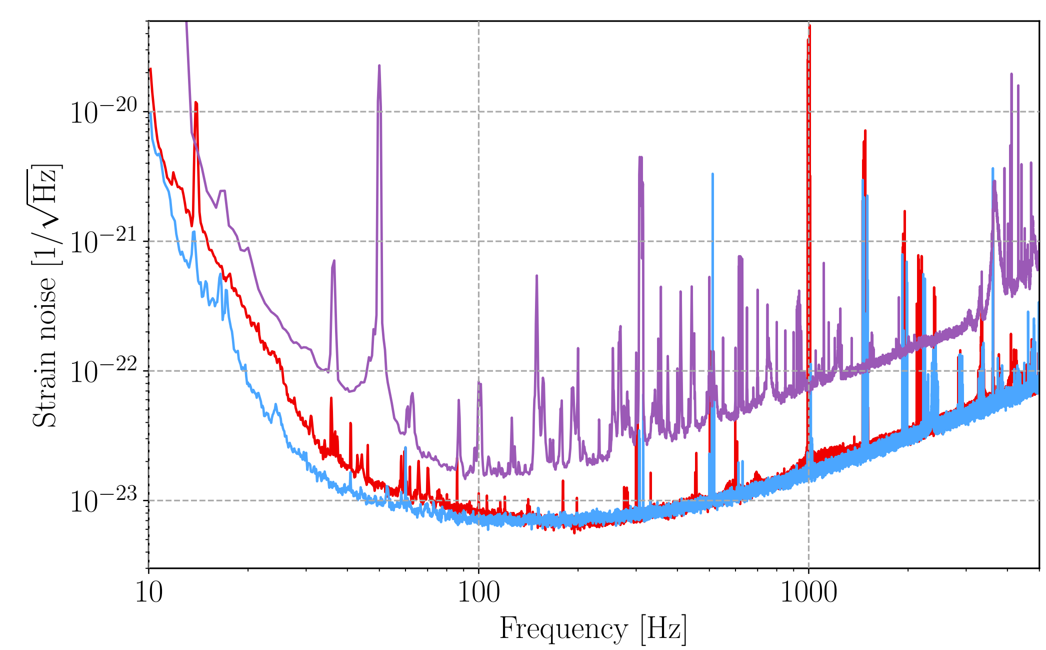


Events lost due to detector asymmetry





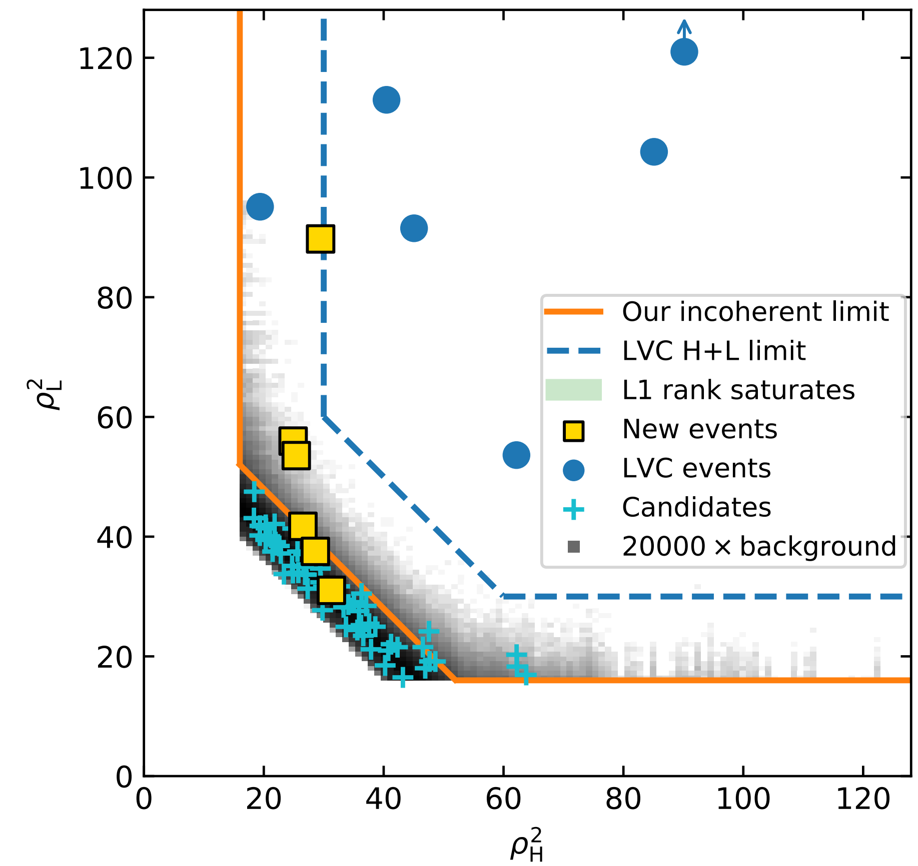


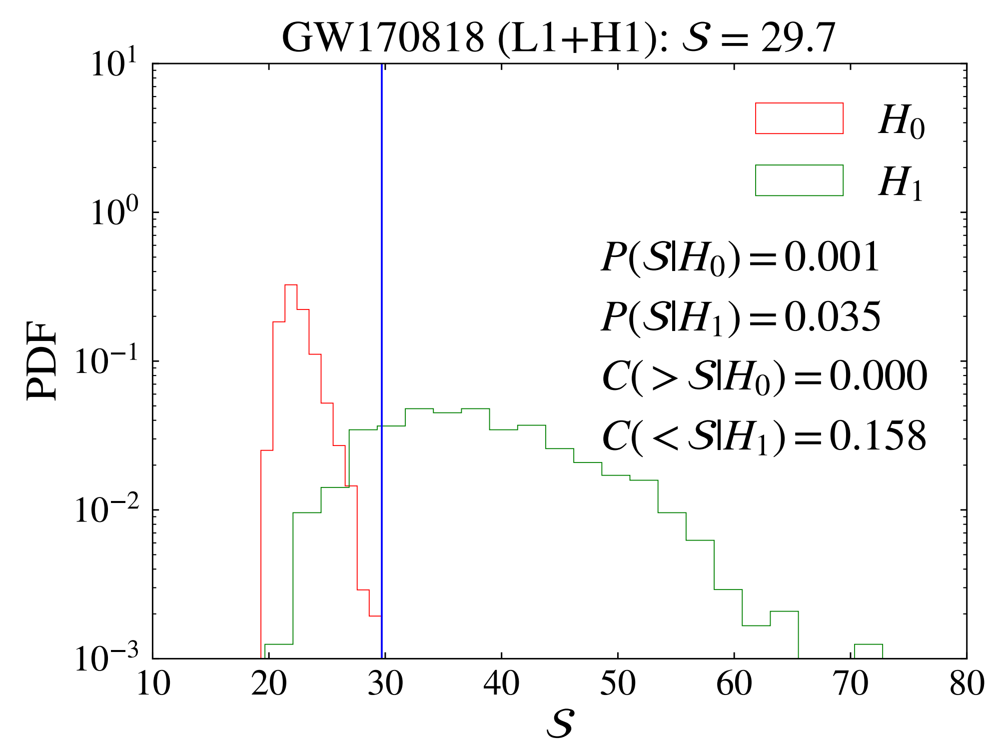


arxiv: 1811.12907

Solution: Follow up single detector triggers

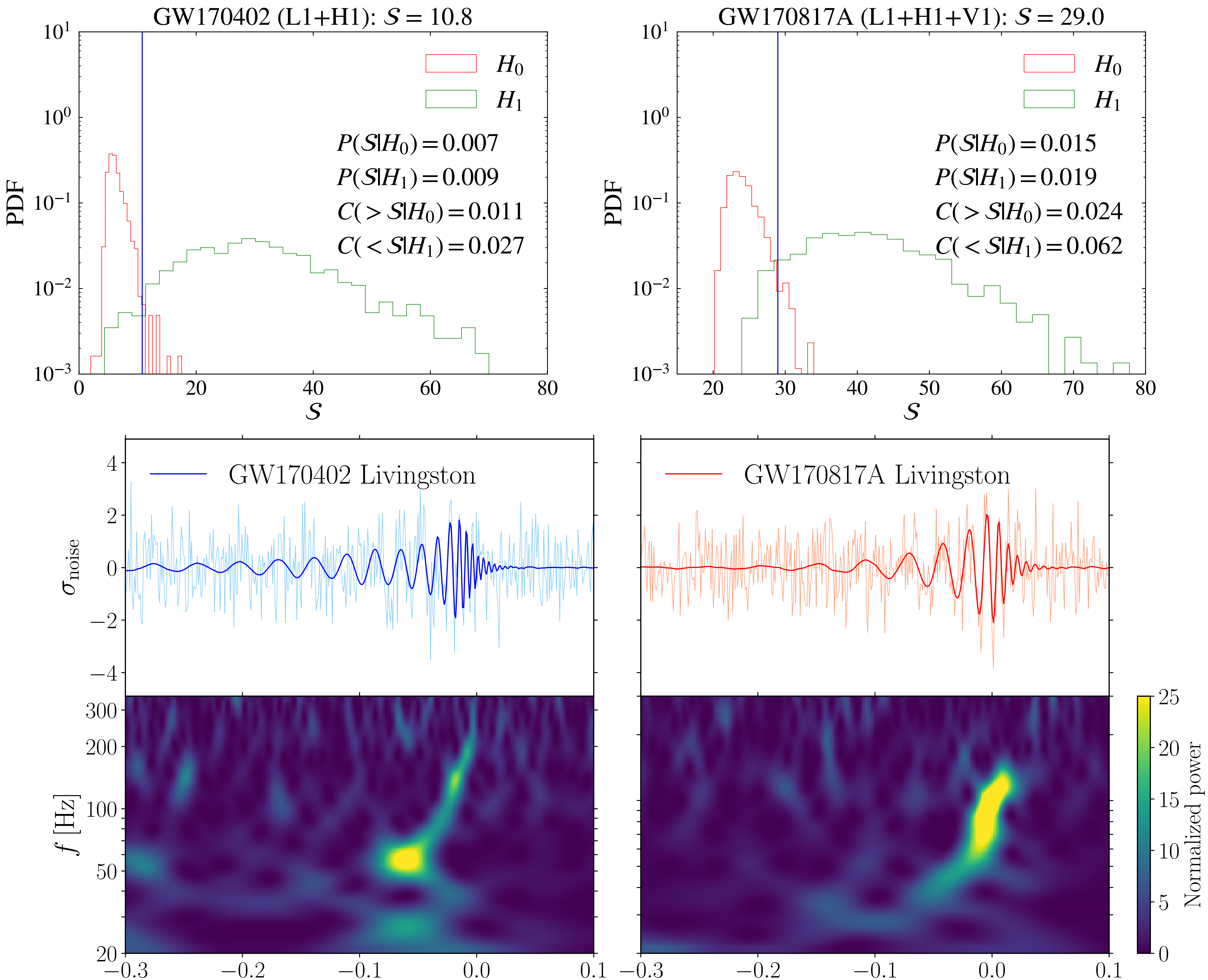
1. Collect all triggers of interest (TOI), which are veto-passing L1 triggers with $\rho_{\rm L}^2 \geq 65$, and best-fit $m_{\rm c} \geq 20\, M_\odot$
2. Make a list of glitches ($\rho_{\rm L}^2 \geq 55$) that are not declared GW events
3. Rank TOI by number of similar glitches (quantified by match between templates), and $\rho_{\rm L}^2$
4. Look for evidence from H1
$$e^{\mathcal{S}} = \int \mathcal{D}\boldsymbol{\Theta}_{\rm ext} \Pi(\boldsymbol{\Theta}_{\rm ext}) \mathcal{L}(\boldsymbol{d} \,|\, \boldsymbol{\Theta}_{\rm intr}, \boldsymbol{\Theta}_{\rm ext})$$
5. Understand distributions of $\mathcal{S}$ in the null hypothesis (H_0) using time slides
6. Understand distributions of $\mathcal{S}$ in the signal hypothesis (H_1) using injections





Two new ~1.5 detector events

Preliminary



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 pipeline and tried to incorporate several new elements: a new geometric template bank algorithm, PSD drift correction, aggressive data masking and hole filling, objective vetoing of triggers, coherent combination of detectors, etc
- We achieve a significant improvement in sensitive volume
- We have one new event in O1, and six new events in O2 above the thresholds for detection as defined by the LVC
- We see a rapidly spinning merger in O1, and a negatively spinning merger in O2 (at the 96% confidence level)
- Working on the rates, and implications for the astrophysical population

Bonus slides

Where did merging BHs form?

$$t_0 - t_{\rm min} \sim \frac{1}{M_c^{5/3}\omega_{\rm GW,min}^{8/3}} \sim \frac{a^4}{M^3\eta}$$

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$$a_{\min} \sim \left(\eta\, M^3 t_{\mathrm{H}}\right)^{1/4}$$
$$\sim 15\, R_\odot \times \left(\frac{M}{60\, M_\odot}\right)^{3/4} \left(\frac{t_{\mathrm{H}}}{10\,\mathrm{Gyr}}\right)$$

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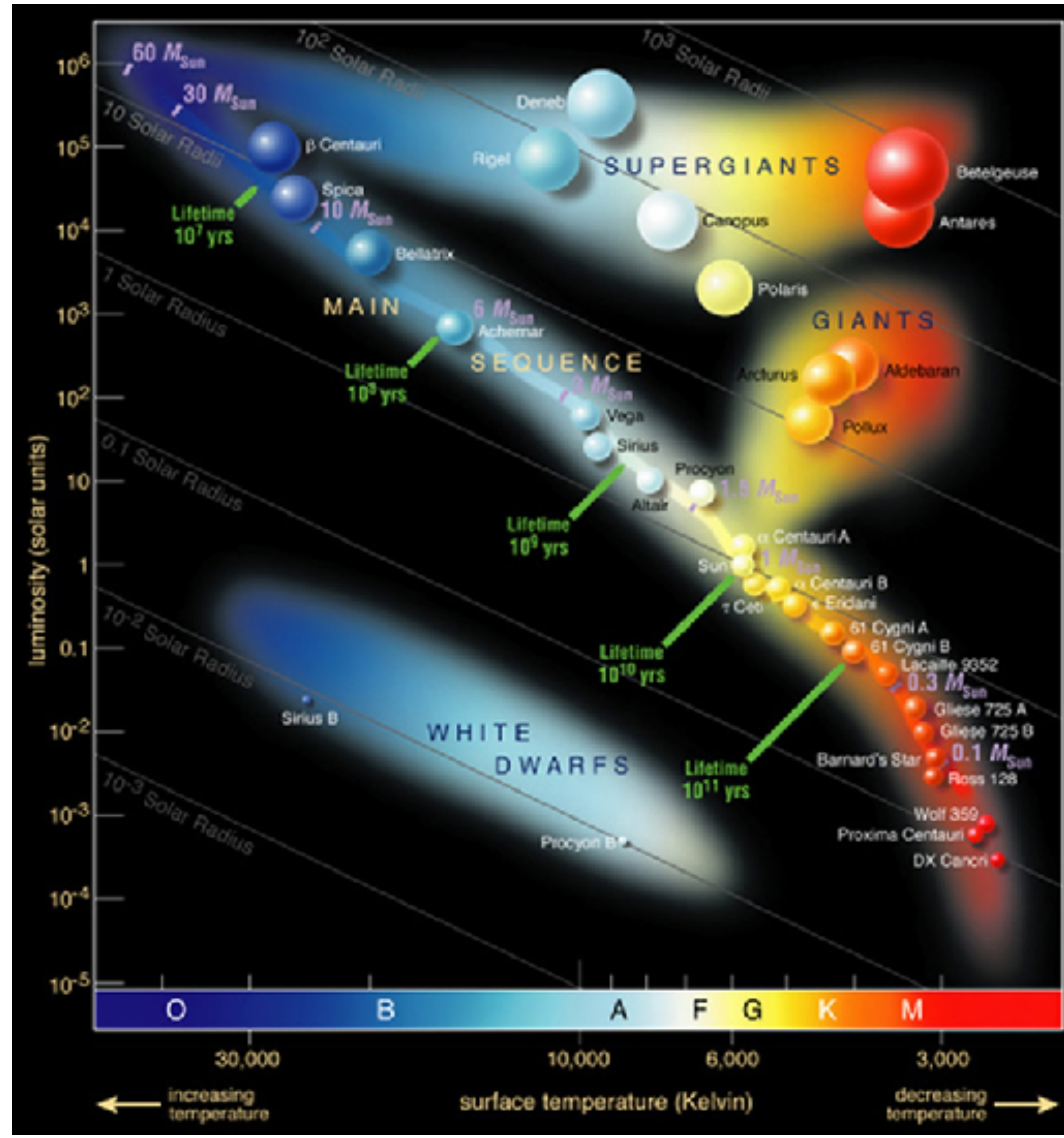

Image: ESO

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Binary evolution?
Chemically homogenous evolution?
Few-body interactions in the field?
Globular clusters?
Nuclear star clusters?
AGN disks?
Primordial black holes?

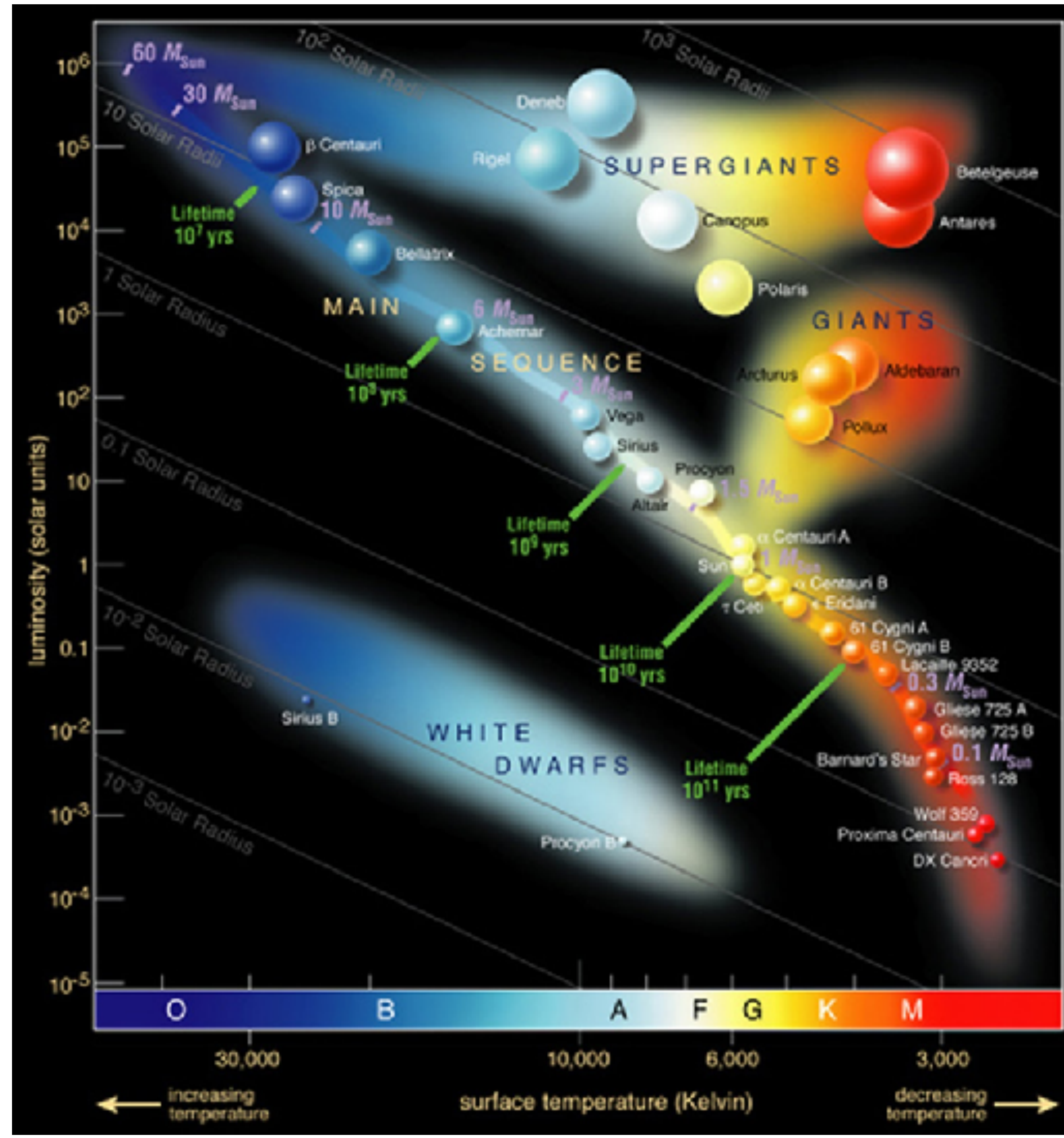

Image: ESO

Re-weighted SNR

Split waveform into p bands with equal SNR^2

$$\chi_r^2 = \frac{p}{2p-2}\sum_{i=1}^{p}\left(\rho_i - \frac{\rho}{p}\right)^2$$

Rank according to

$$\hat{\rho} = \begin{cases} \rho[(1+(\chi_r^2)^3)/2]^{-1/6} & \text{if } \chi_r^2 > 1 \\ \rho & \text{if } \chi_r^2 \leq 1 \end{cases}$$

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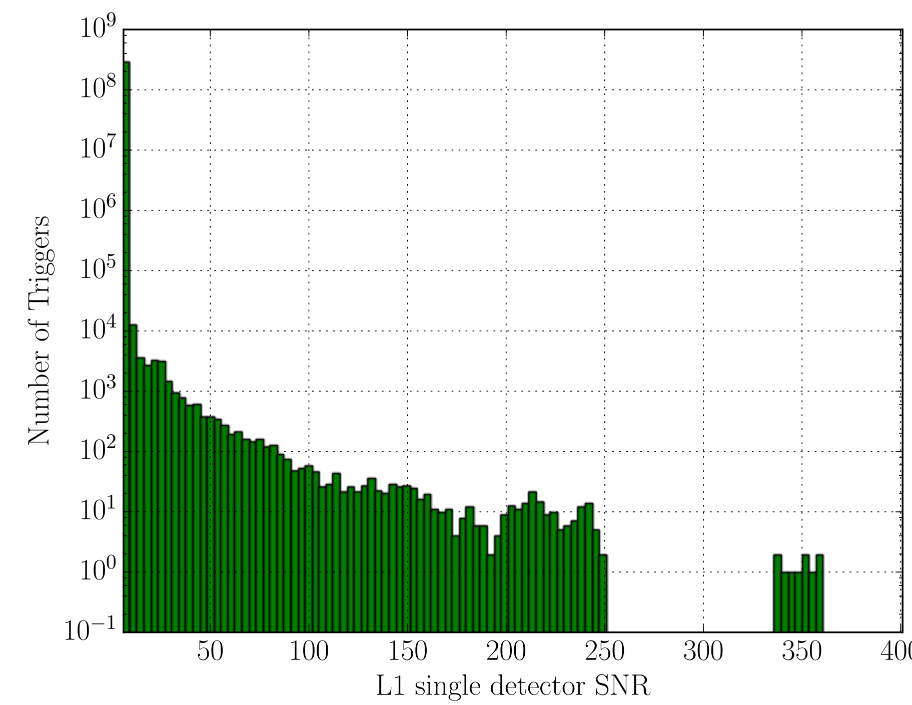

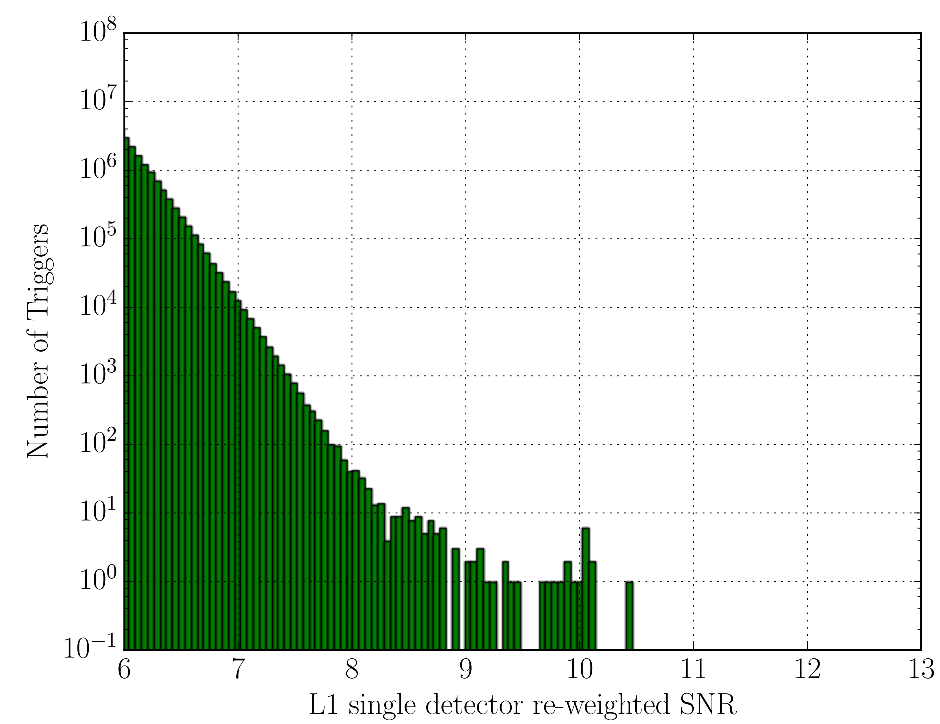

O1: Abbott et. al. (2017)

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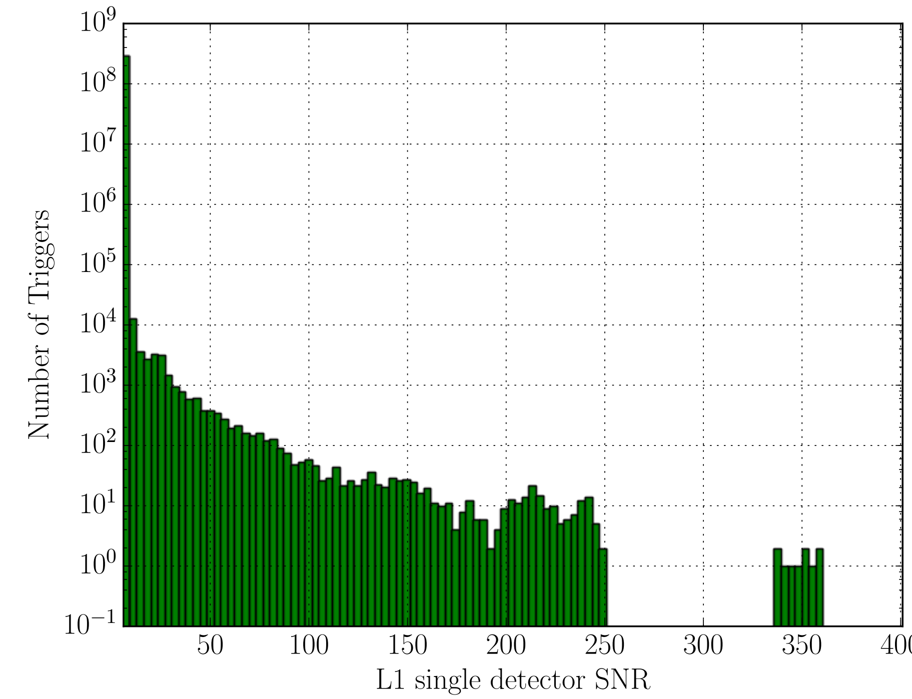

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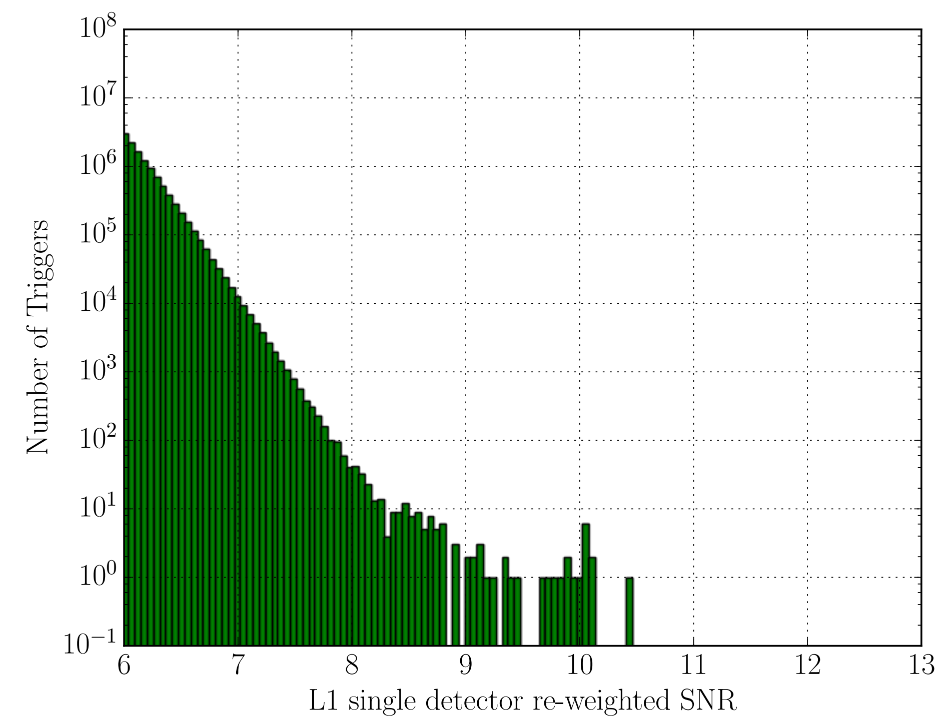
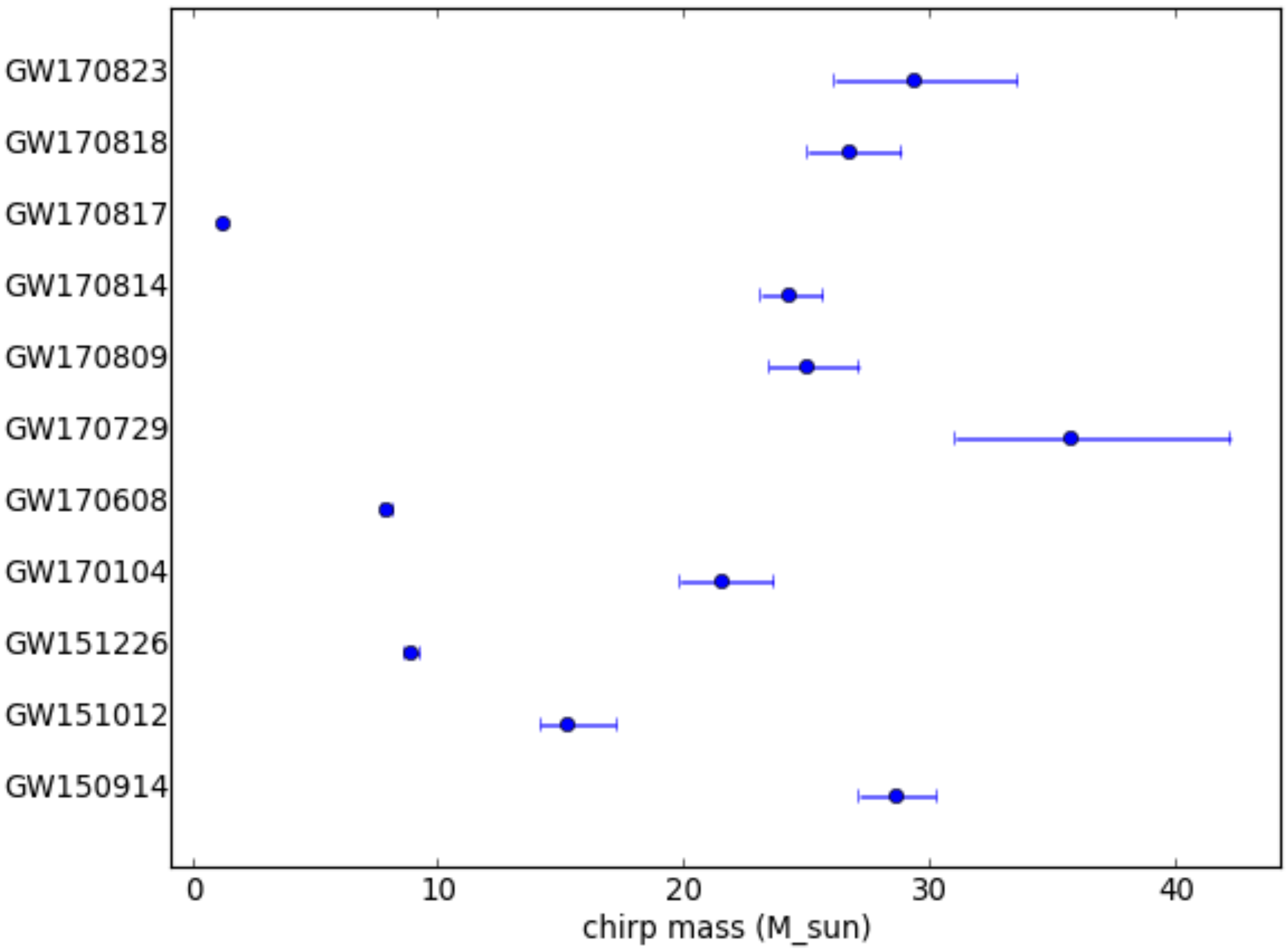
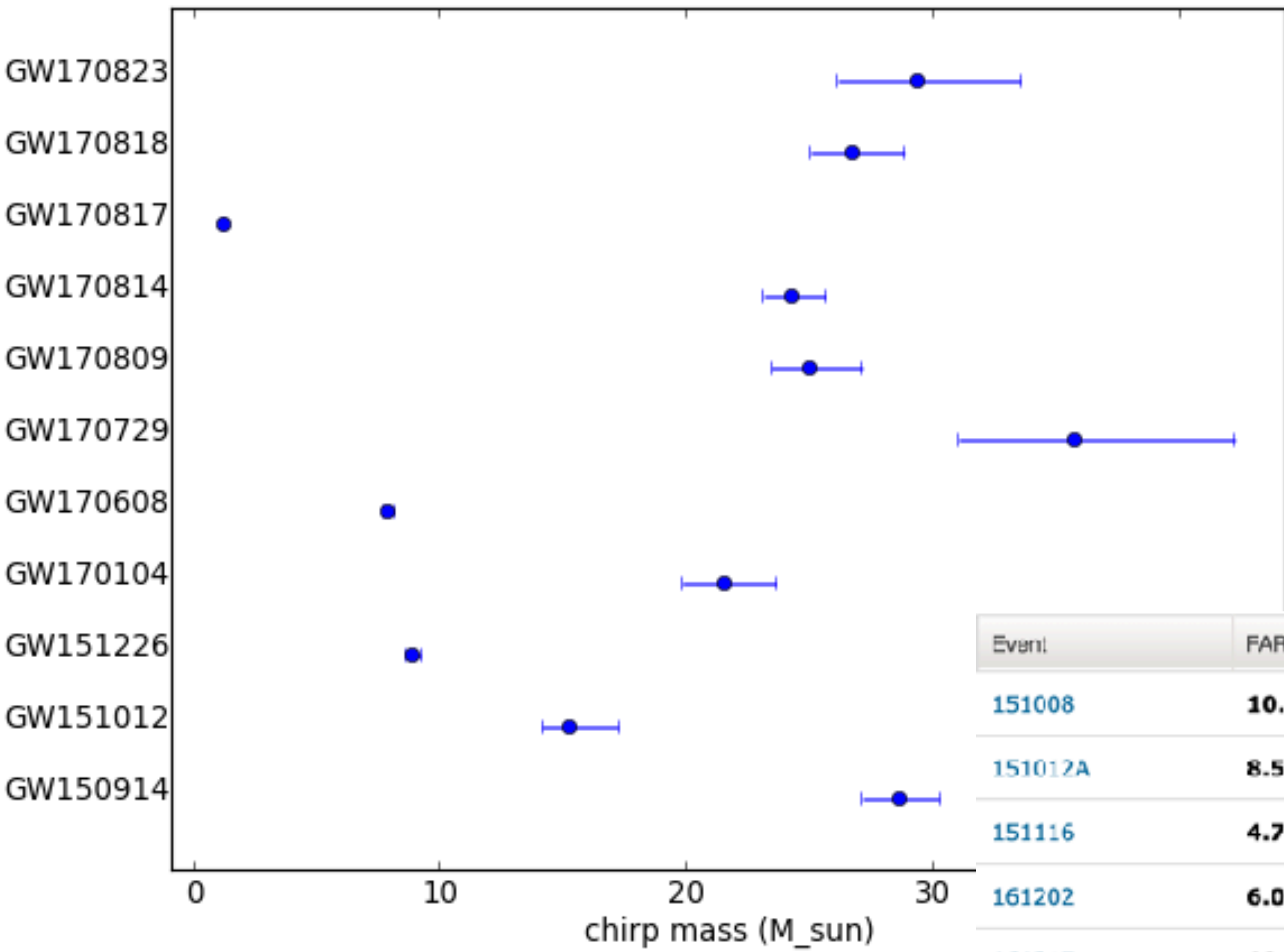


1. Keeps glitches in
2. Touches the Gaussian part
3. At low SNR, the distribution is not Gaussian even after, are glitches really this frequent?

O1: Abbott et. al. (2017)


GW170823
GW170818
GW170817
GW170814
GW170809
GW170729
GW170608
GW170104
GW151226
GW151012
GW150914
0
10
20
30
40
chirp mass (M_sun)

Detections

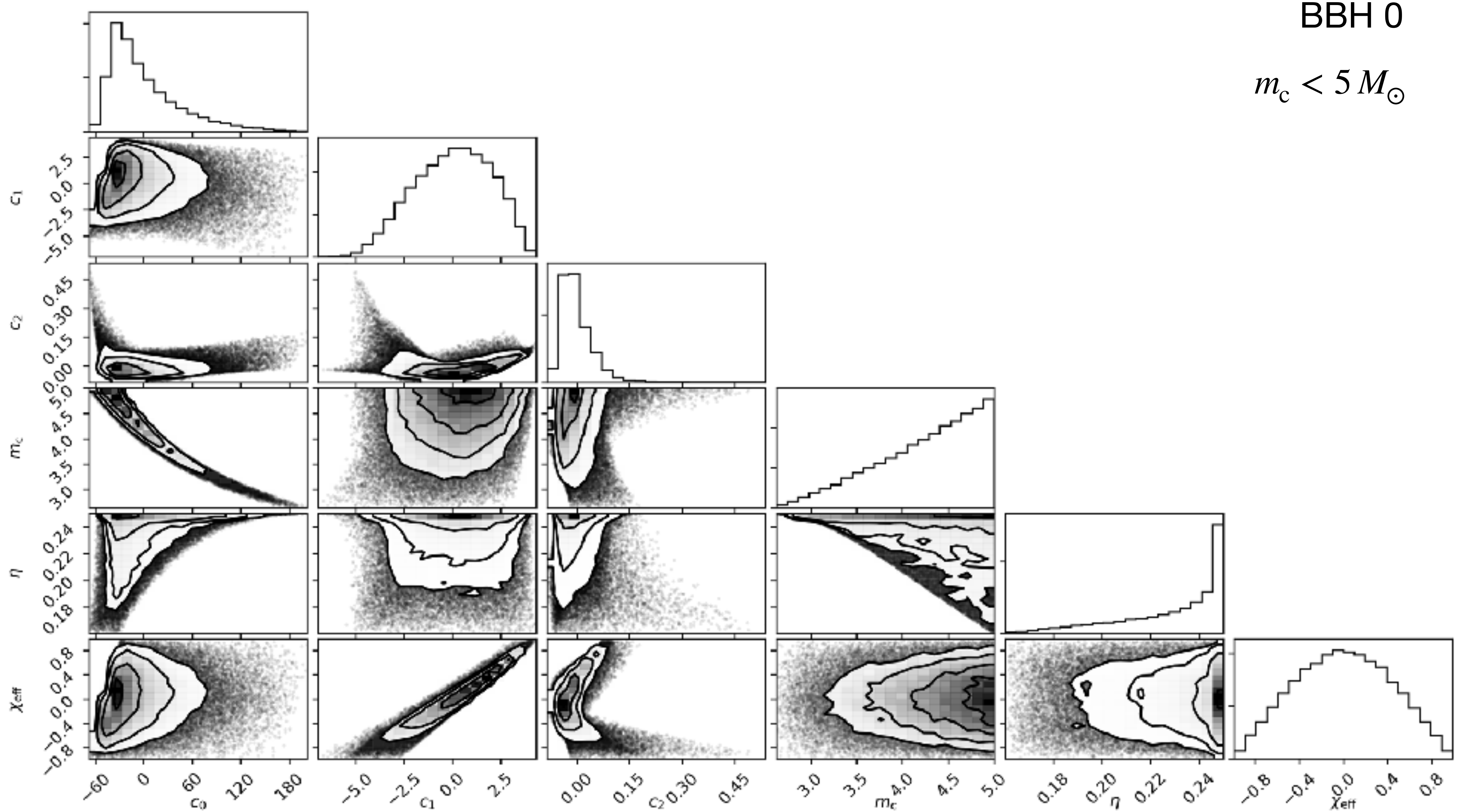


Detections

Sub-threshold events

Event	FAR (yr^-1)	Network SNR	Detector frame chirp mass (M_sun)
151008	10.17	8.8	5.12
151012A	8.56	9.6	2.01
151116	4.77	9.0	1.24
161202	6.00	10.5	1.54
161217	10.12	10.7	7.86
170208	11.18	10.0	7.39
170219	6.26	9.6	1.53
170405	4.55	9.3	1.44
170412	8.22	9.7	4.36
170423	6.47	8.9	1.17
170616	1.94	9.1	2.75
170630	10.46	9.7	0.90
170705	10.97	9.3	3.40
170720	10.75	13.0	5.96

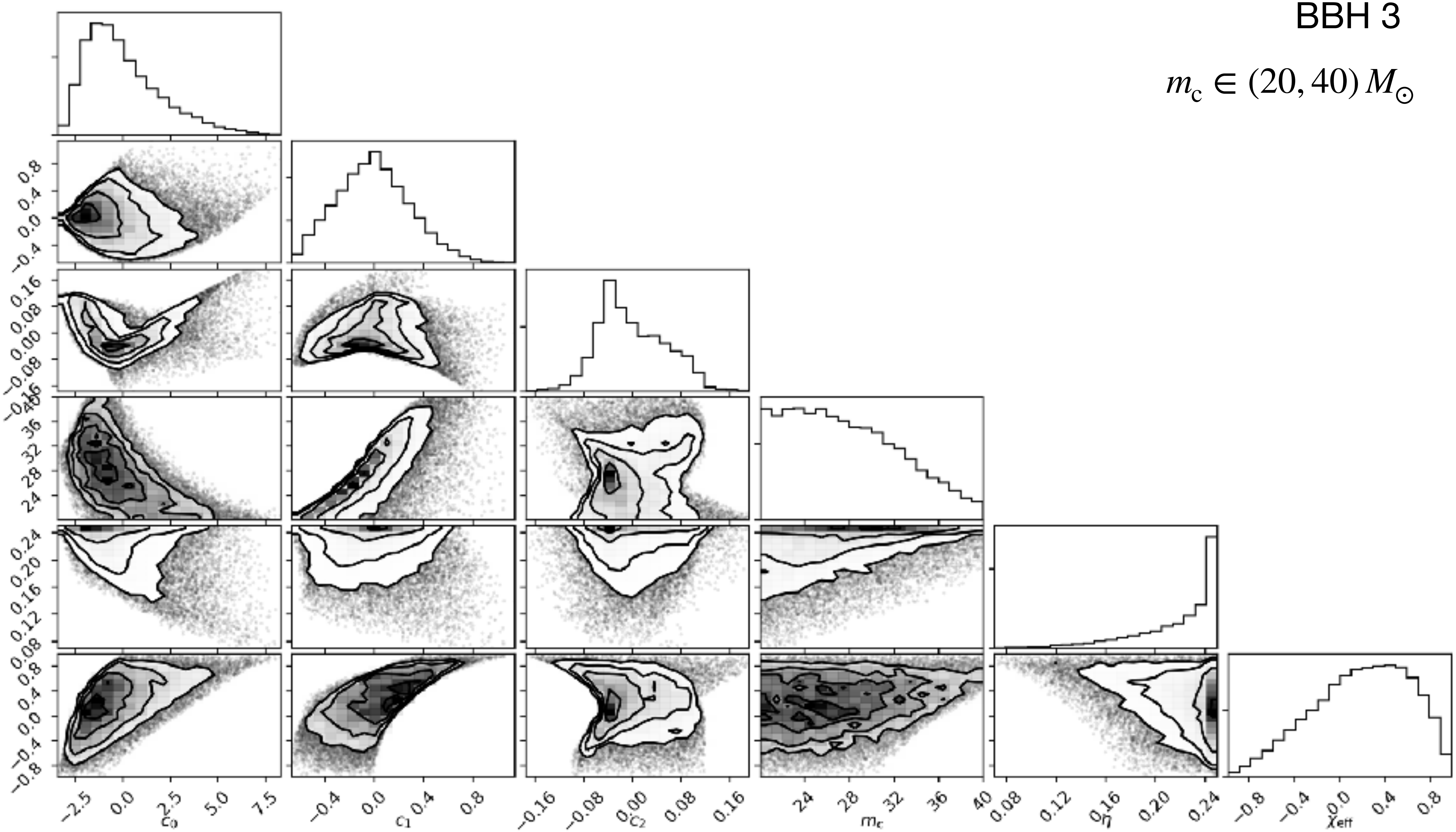
Coefficients and Parameters



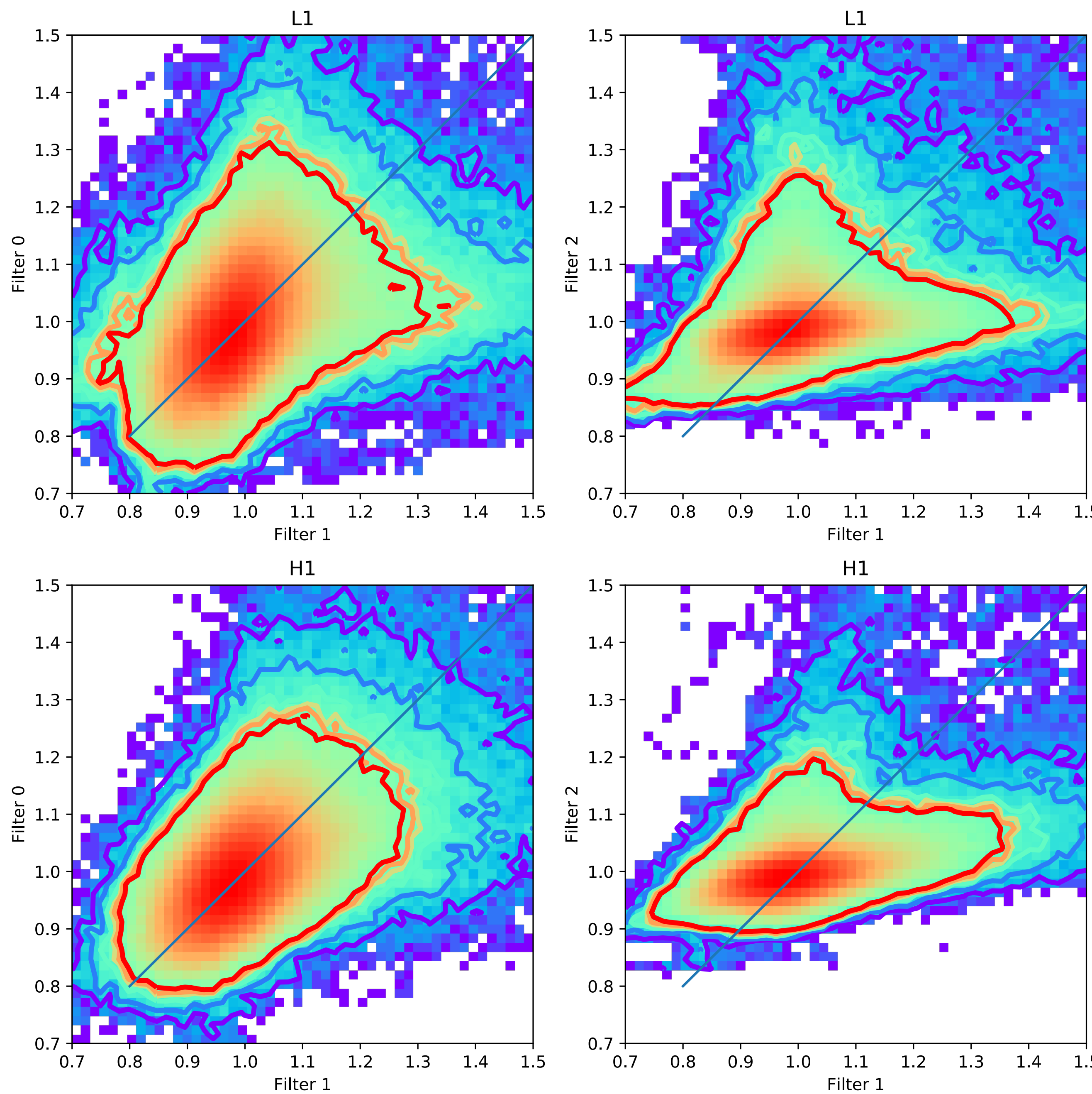
Coefficients and Parameters

BBH 3

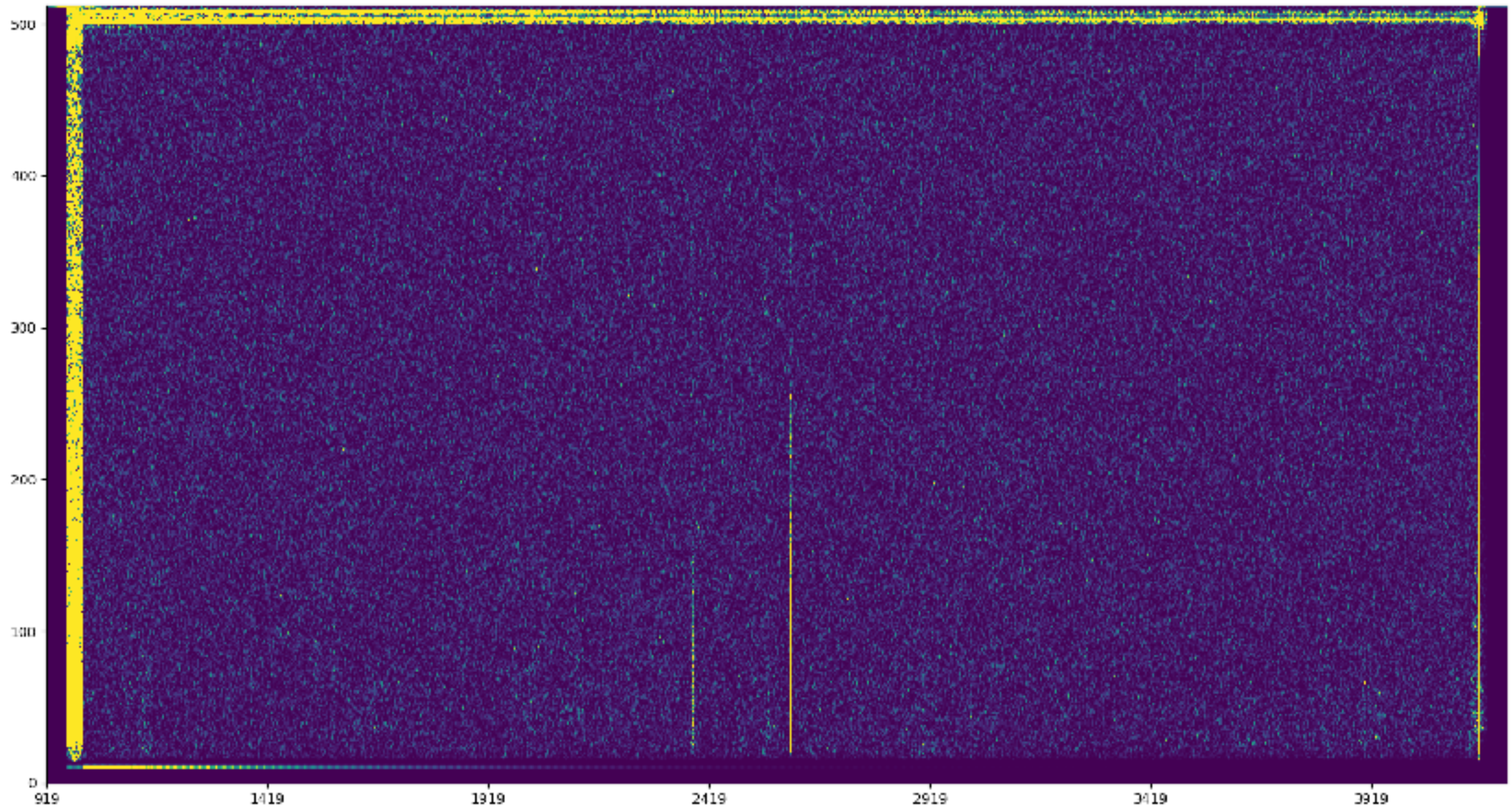
$m_c \in (20, 40)\, M_\odot$



Banded PSD drift



Impact of Cleaning + PSD Drift Correction



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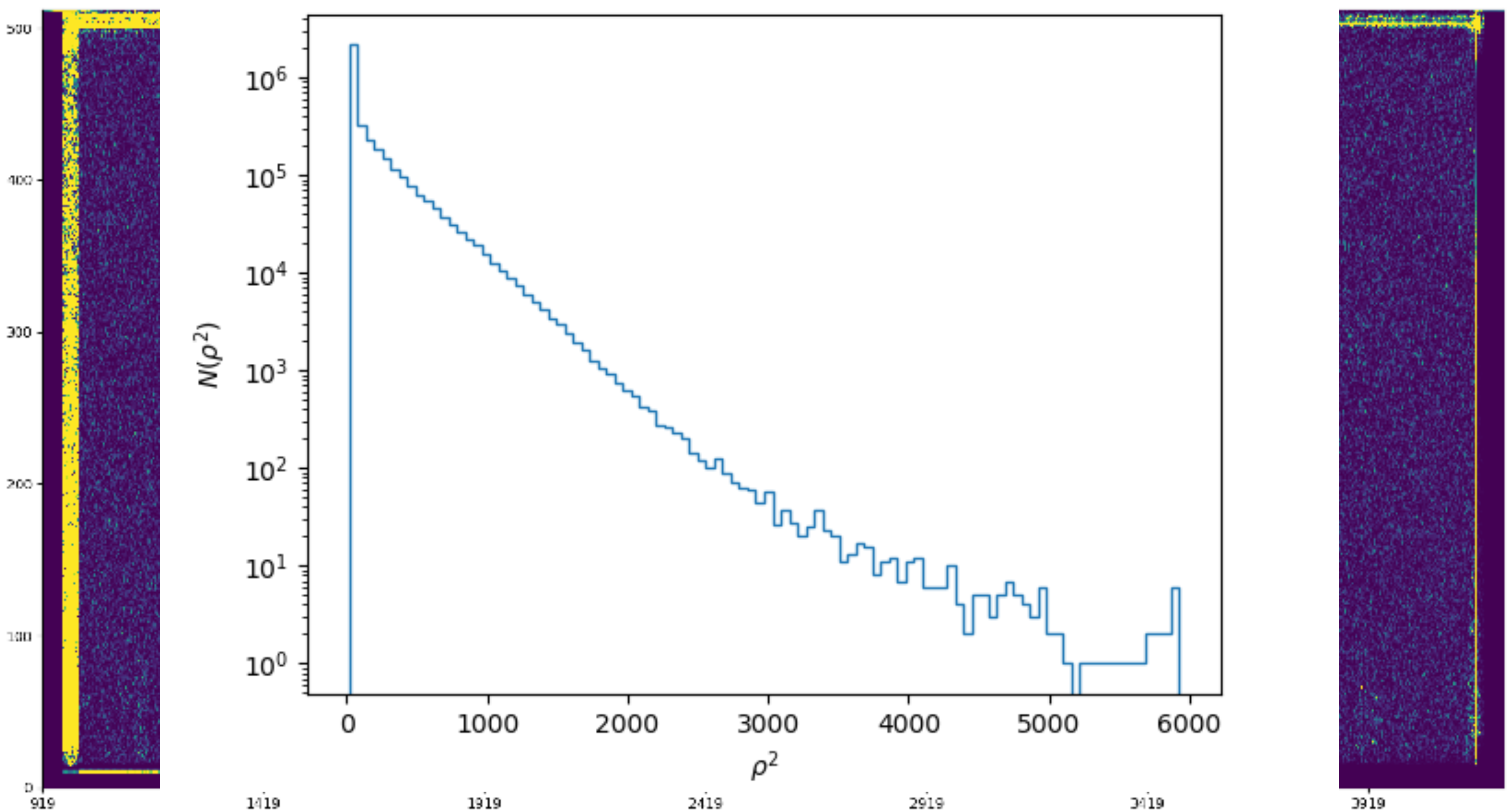

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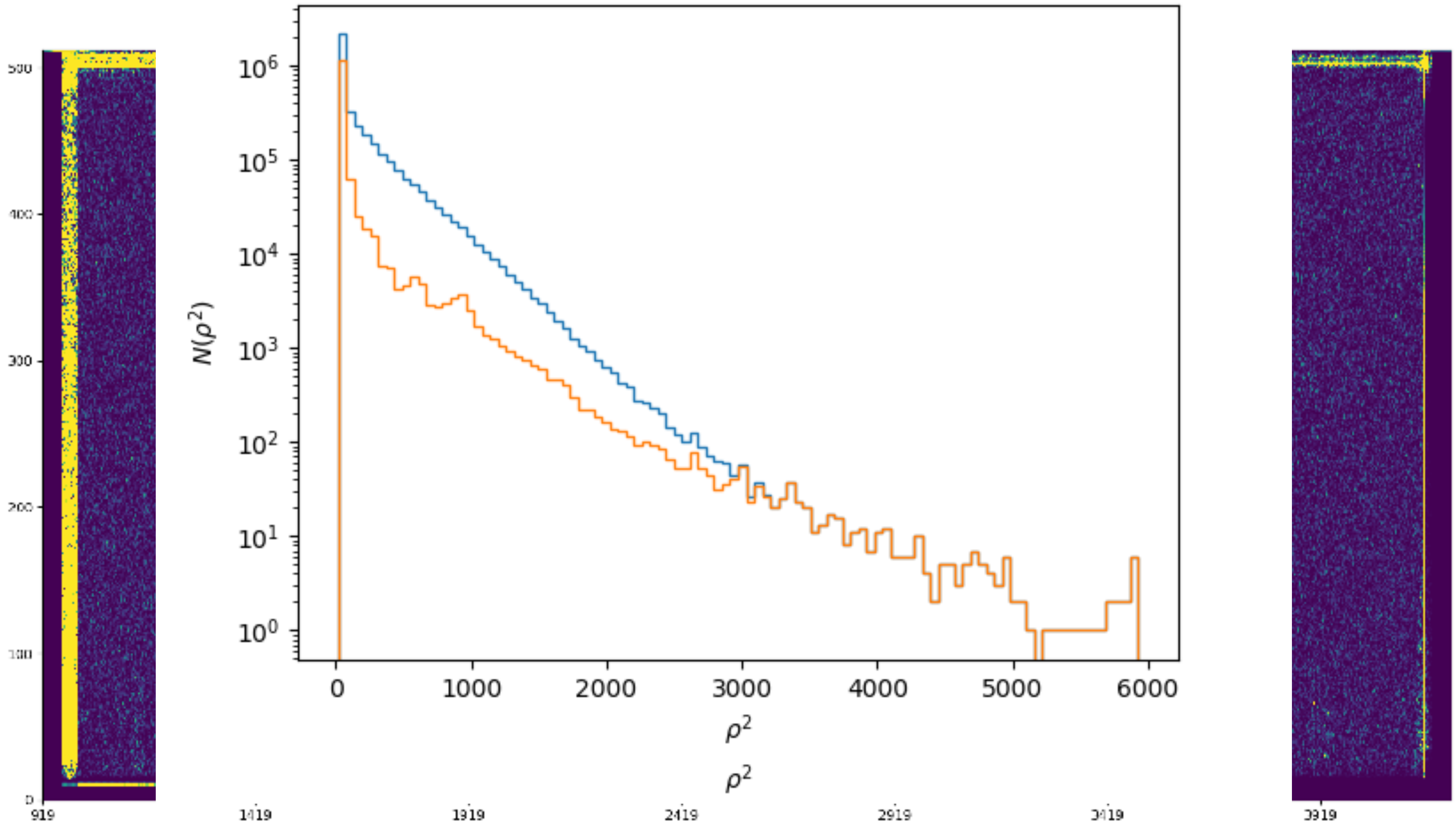

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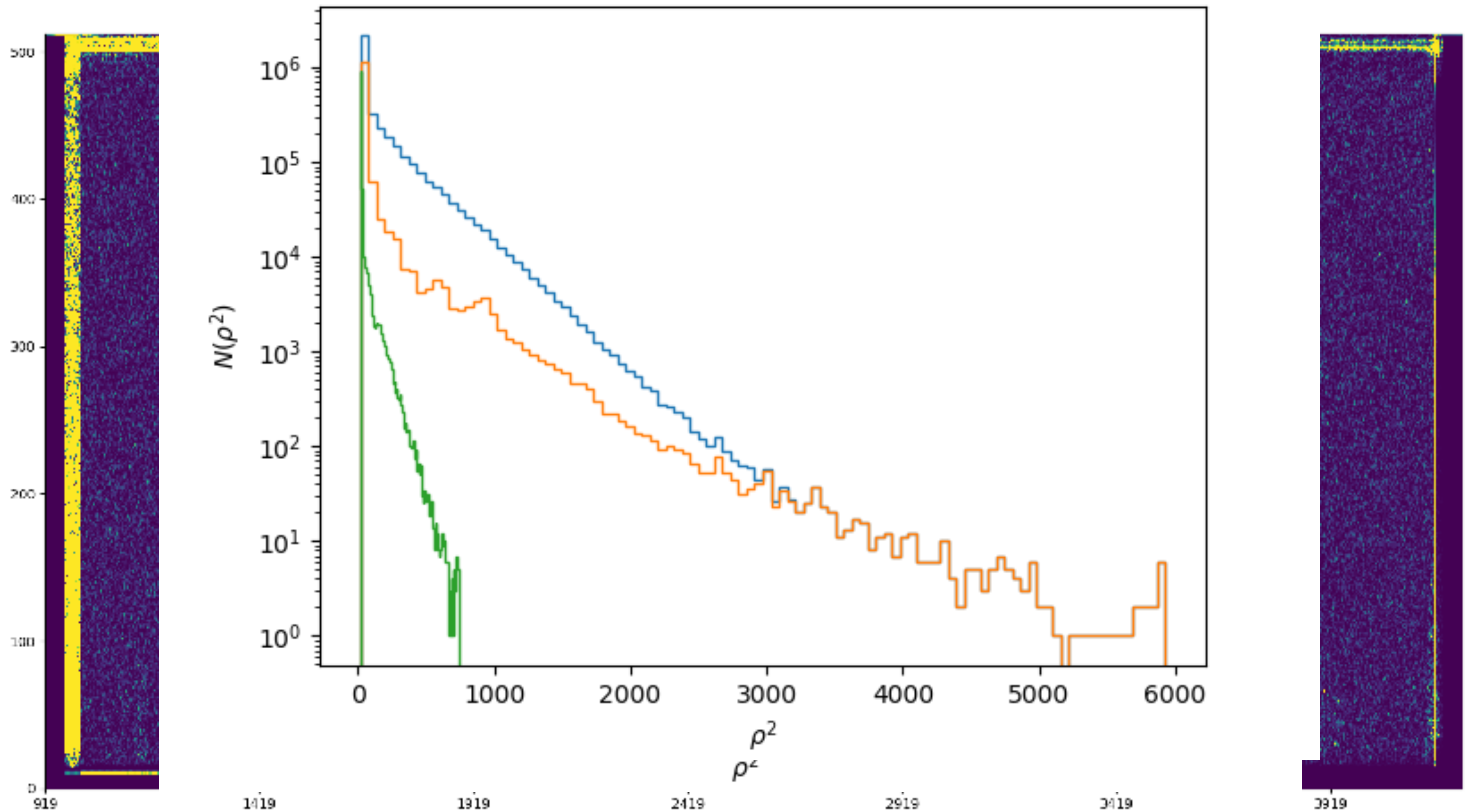

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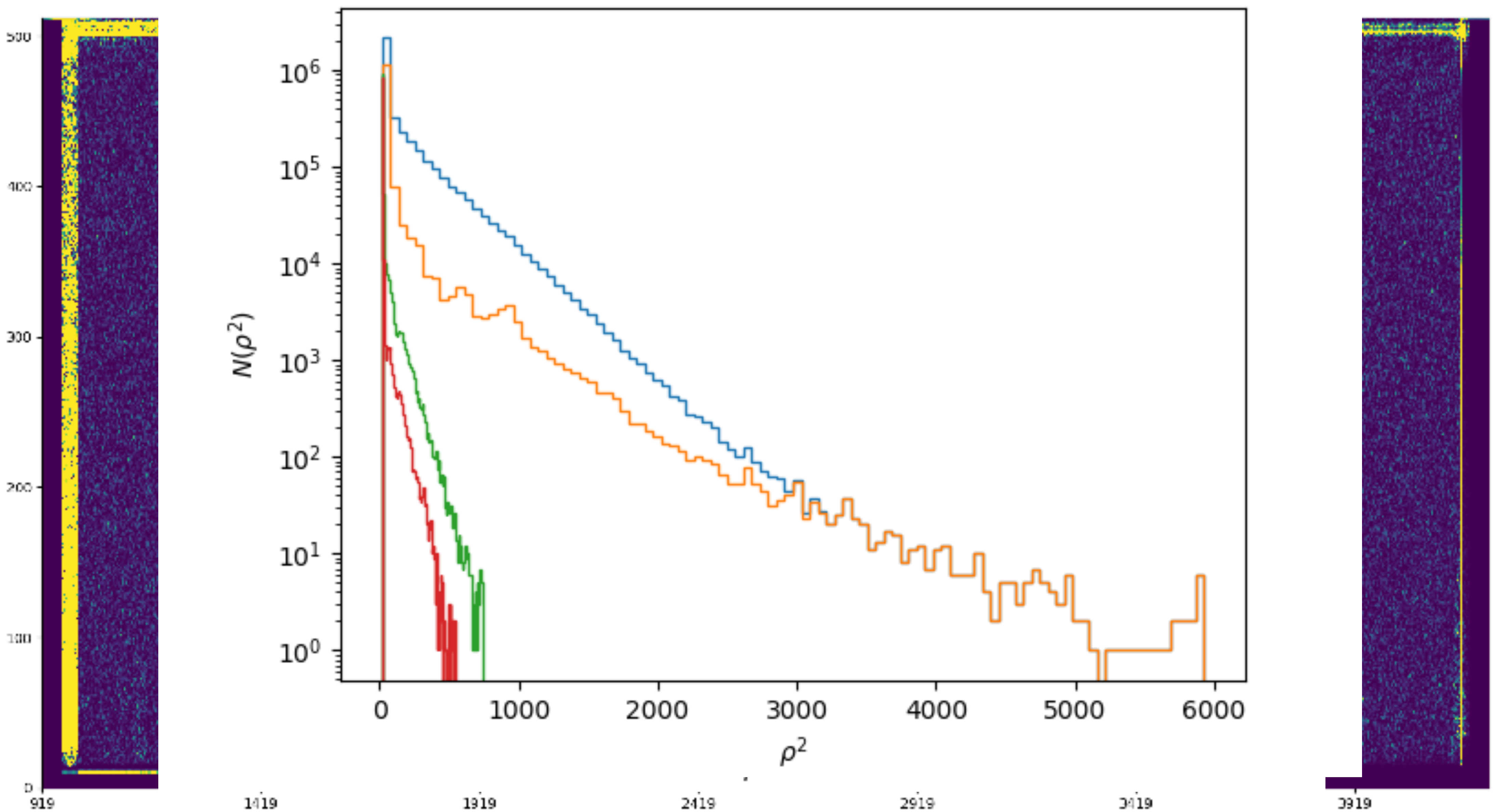

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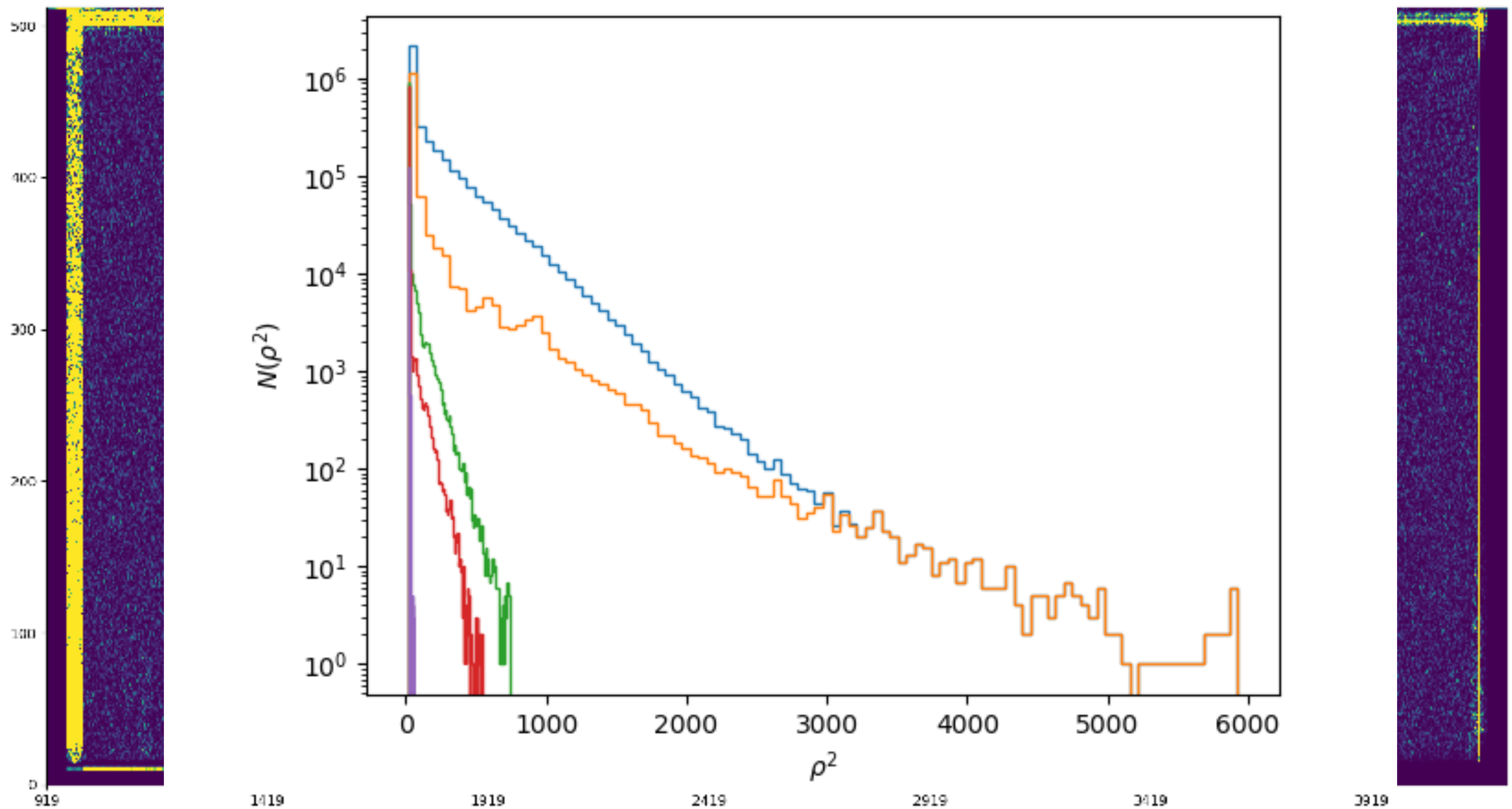

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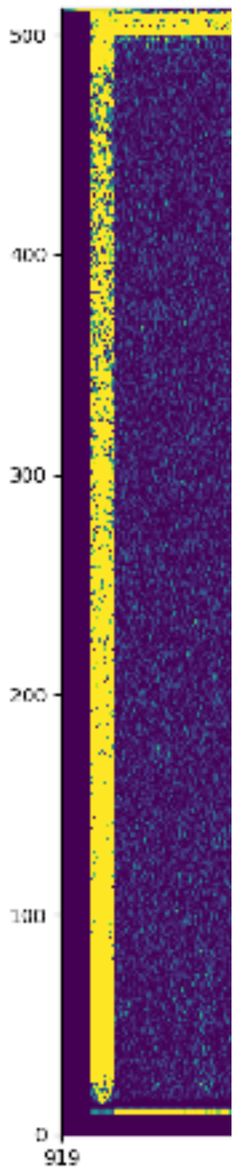

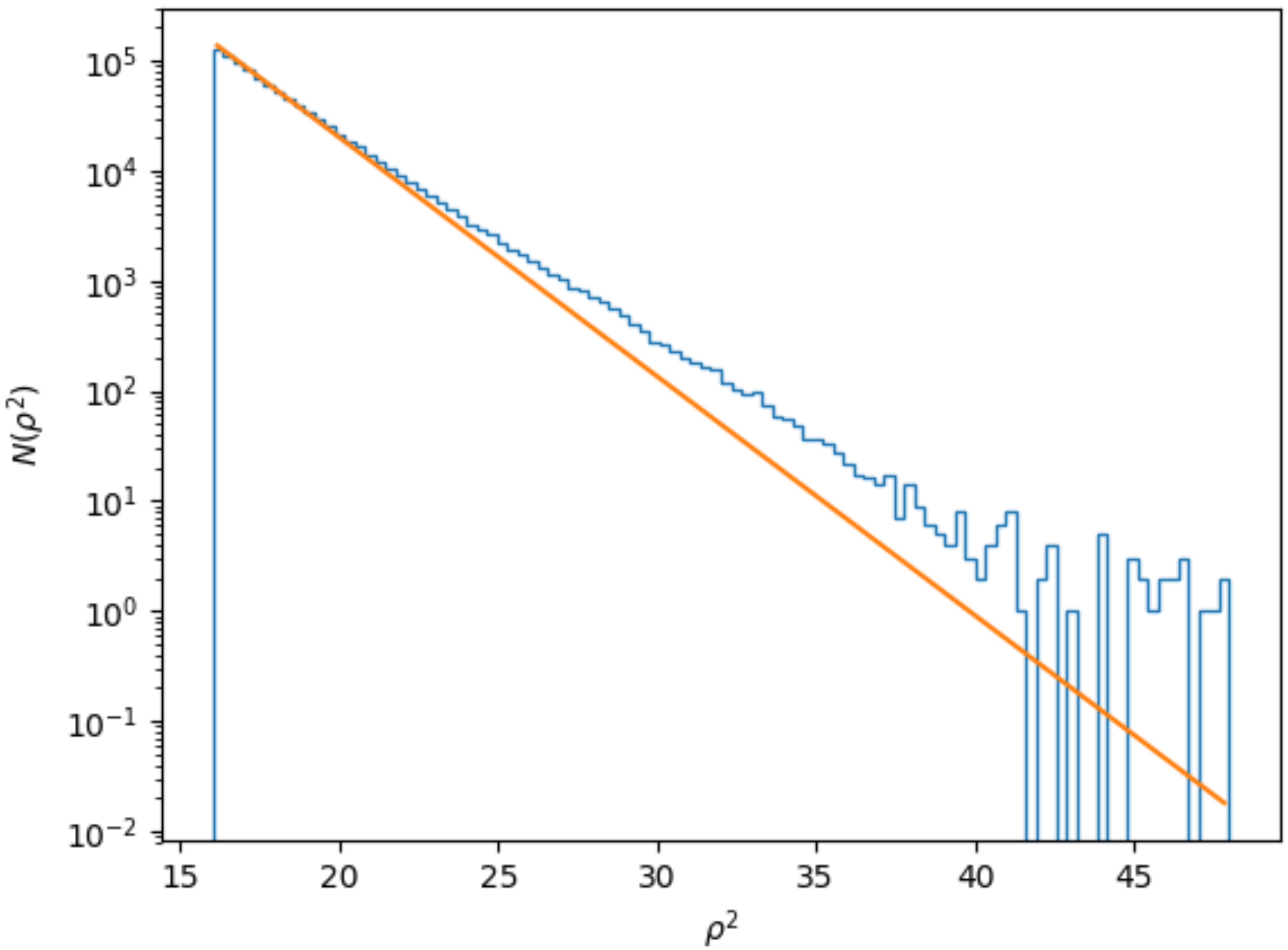

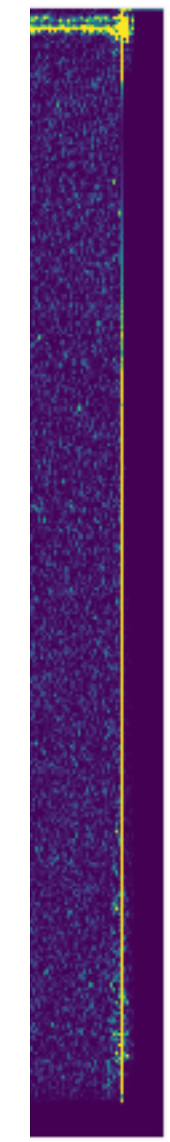

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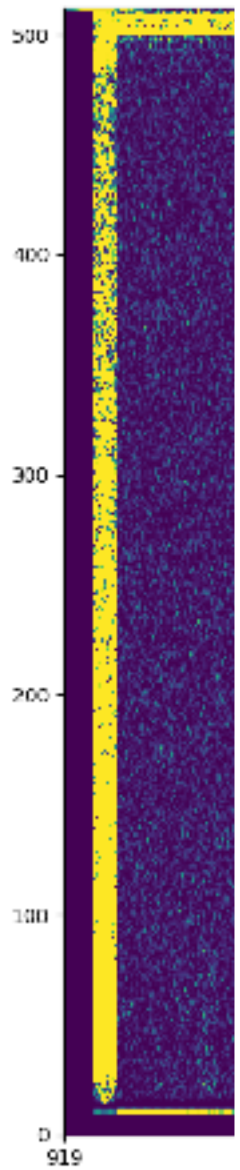
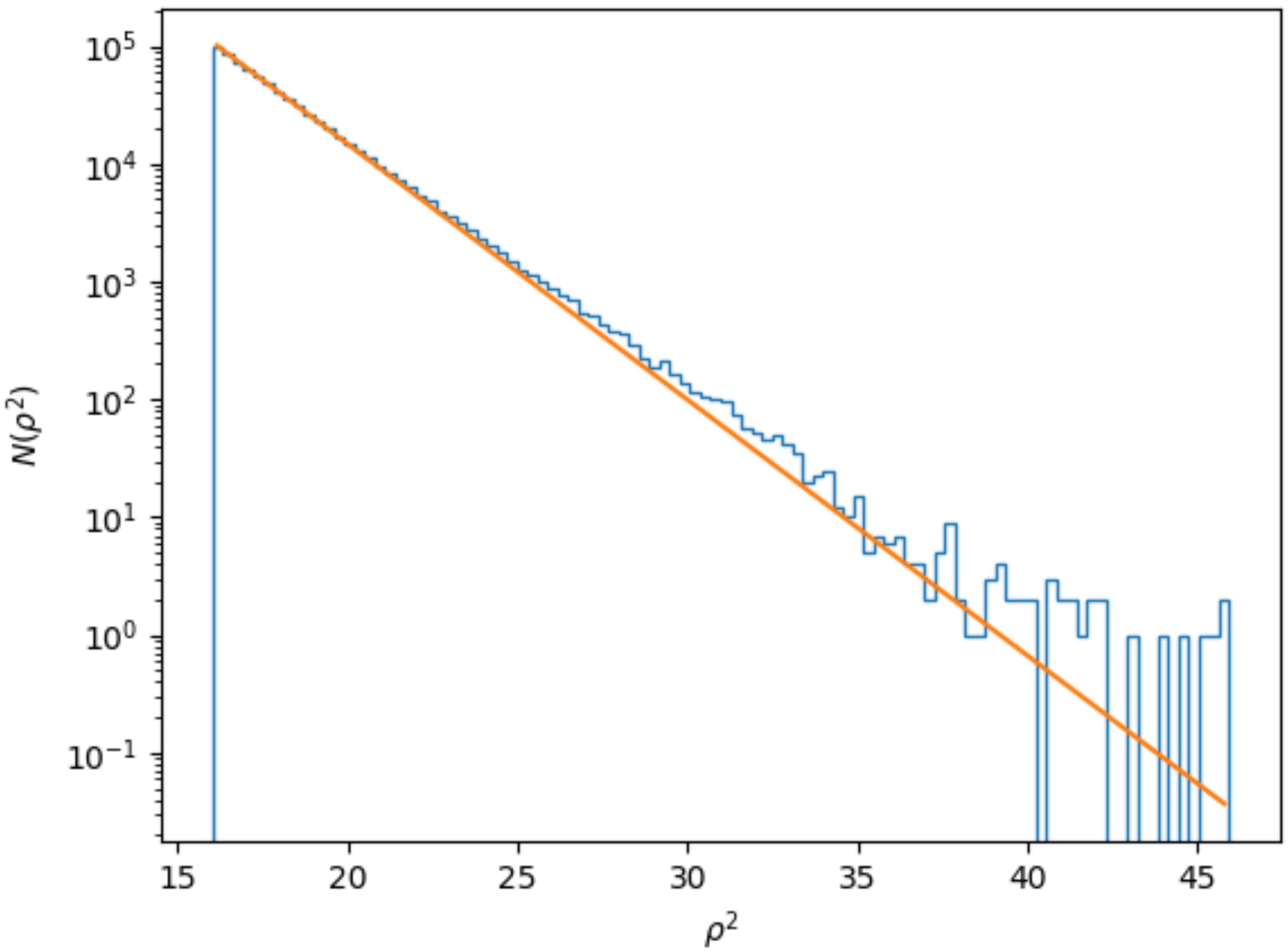
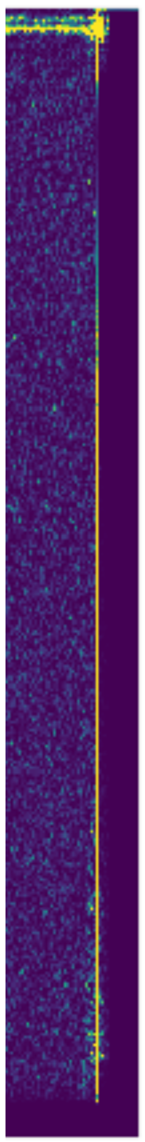
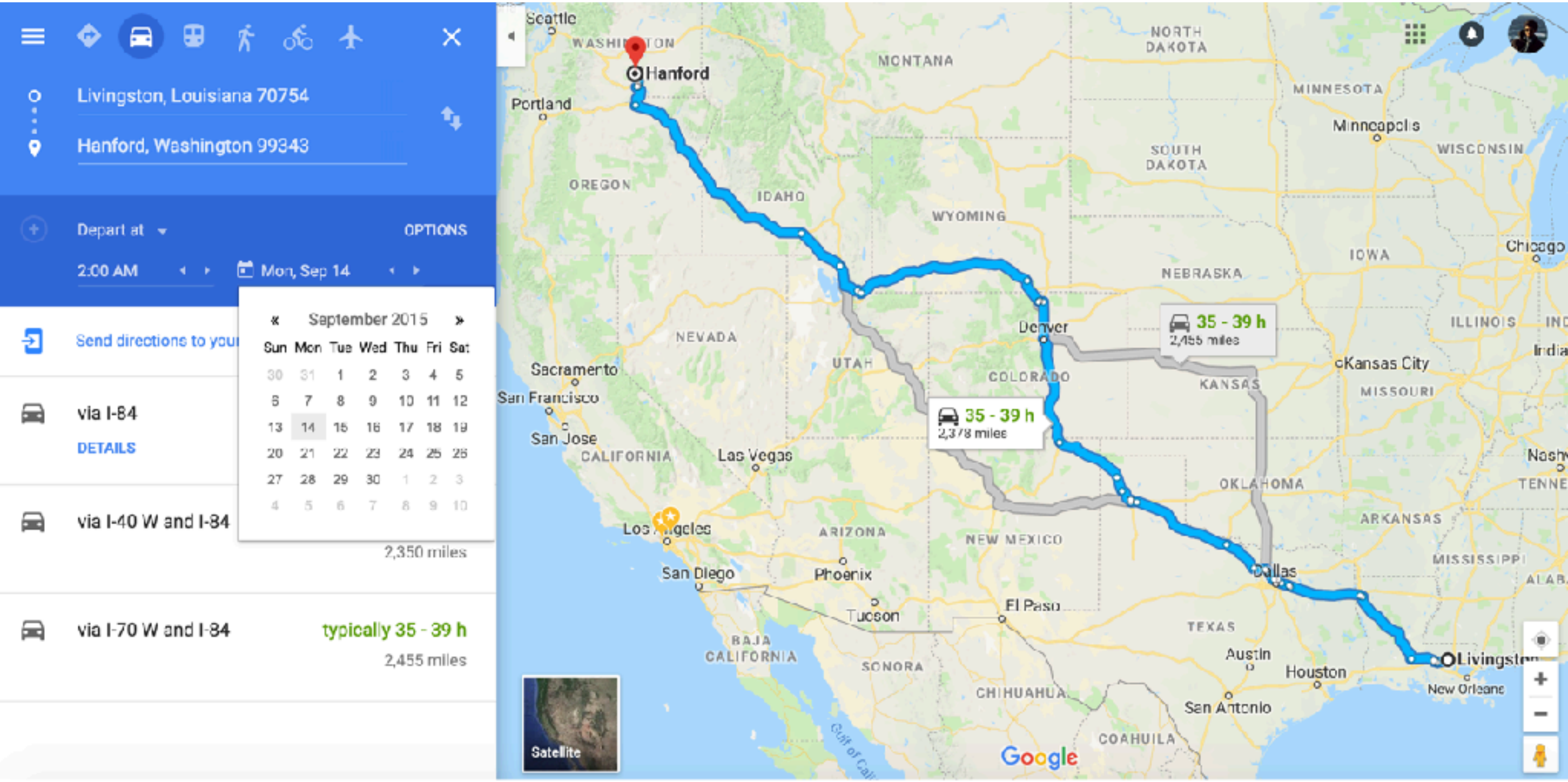






Collect Coincident and Background Events



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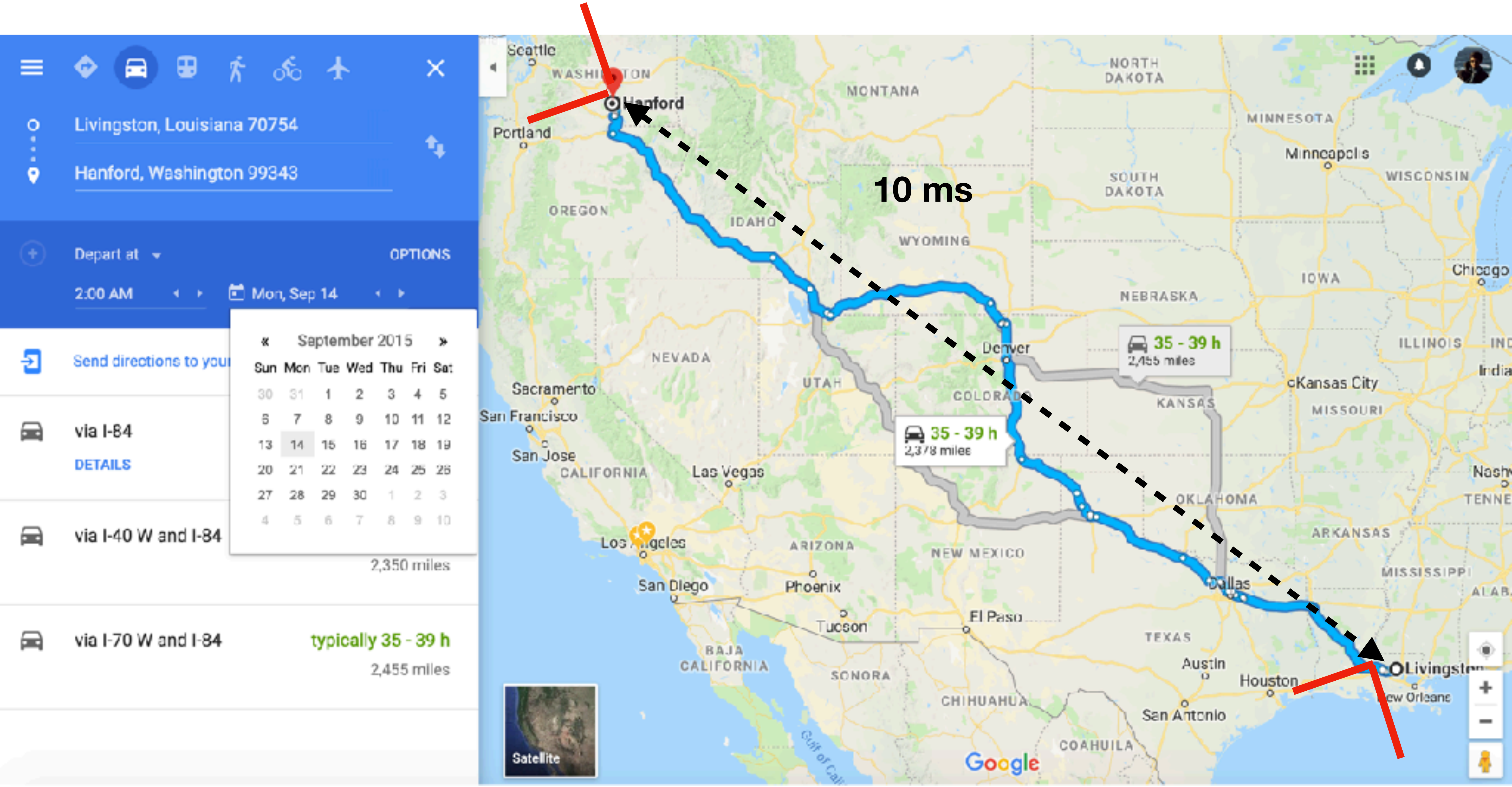

Shift data stream by t > 10 ms to estimate background

Coherent Ranking of Triggers

Rank background + candidates according to the ratio

$$\frac{p(\rho_1^2, \rho_2^2, \Delta t, \Delta\phi \mid \mathscr{S})}{p(\rho_1^2, \rho_2^2, \Delta t, \Delta\phi \mid \mathscr{N})}$$

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

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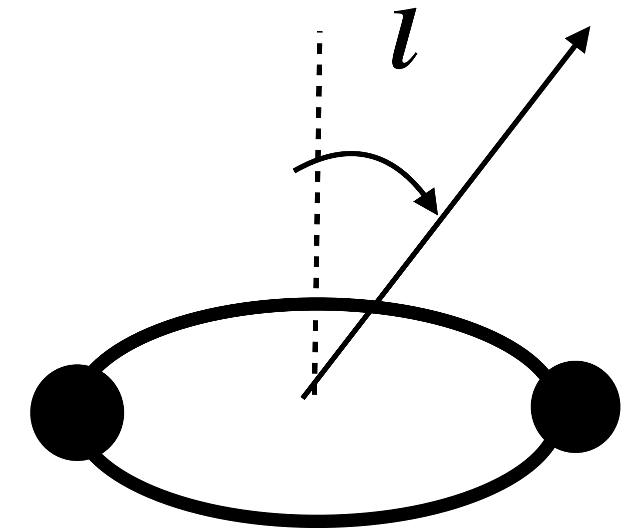
$$h_+ = A(1 + \cos^2 \iota)\ \cos\phi_{\mathrm{GW}}$$

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



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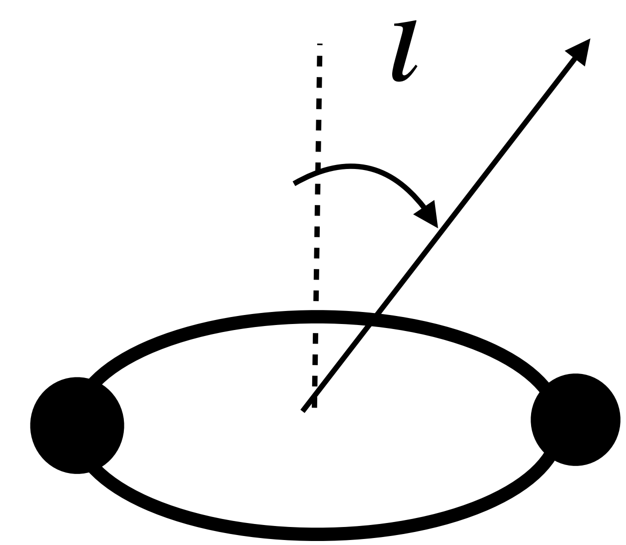
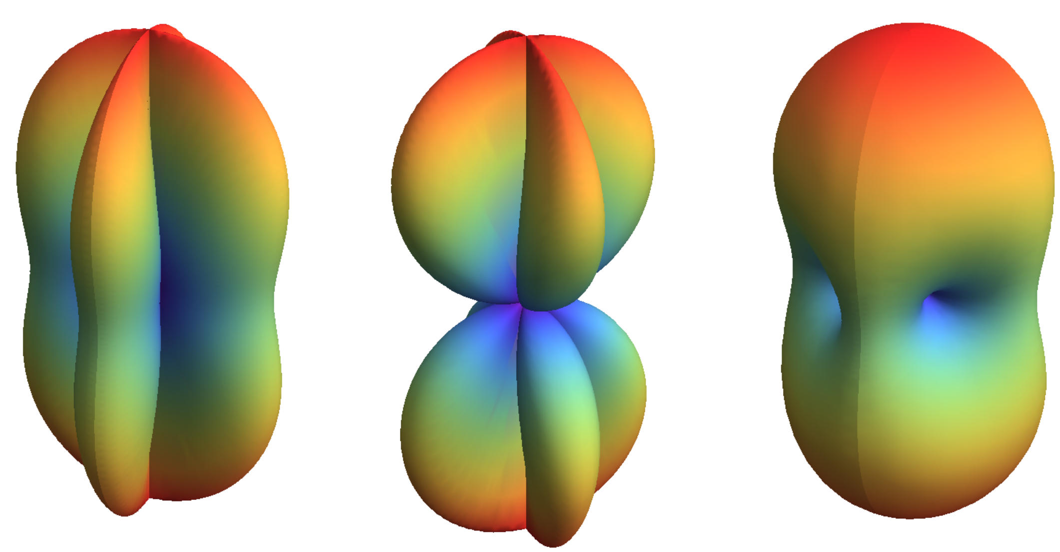
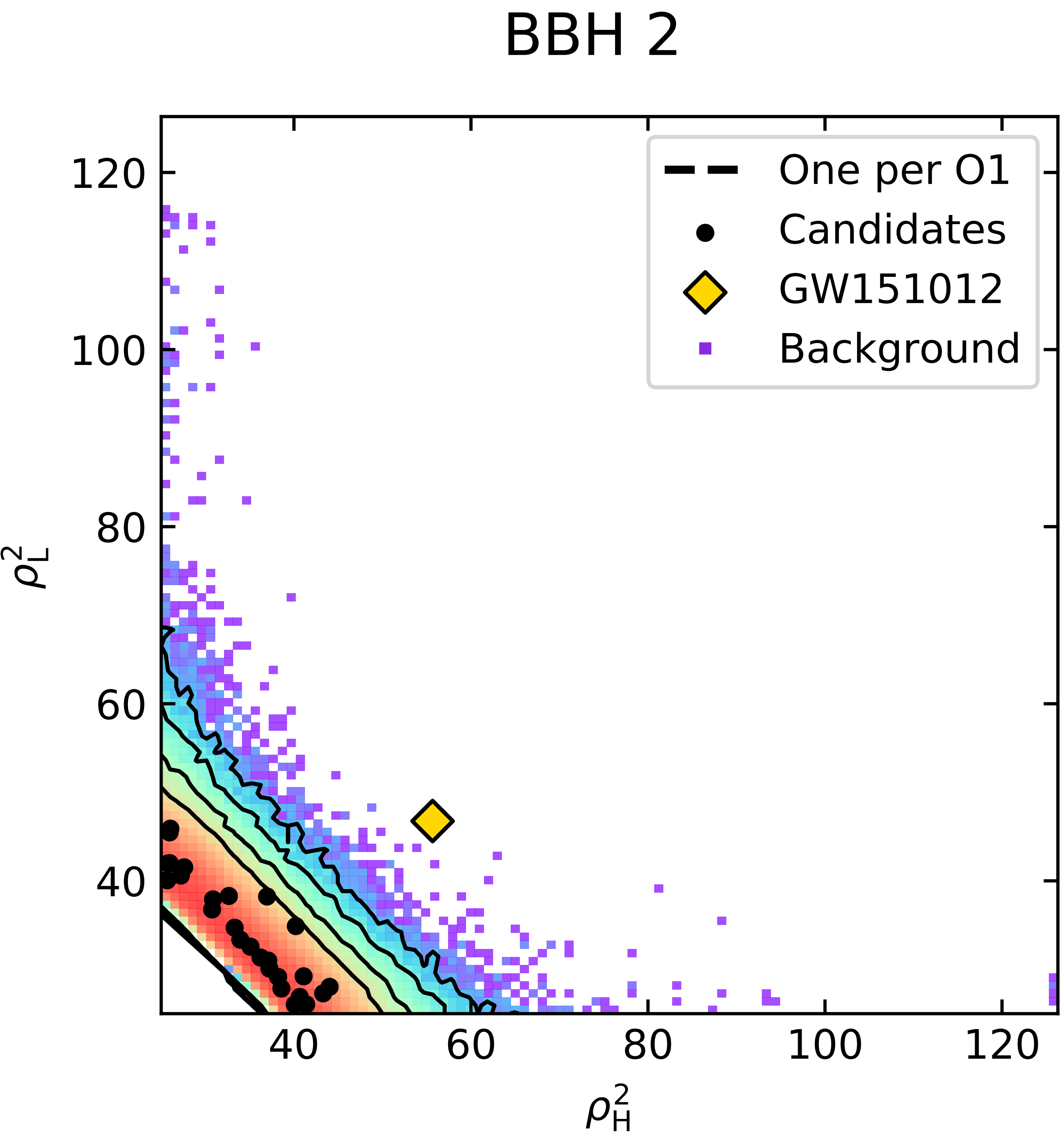
$$h = h_+ F_+ + h_\times F_\times$$





Adhikari, R., (2013)

Incoherent Ranking of Triggers



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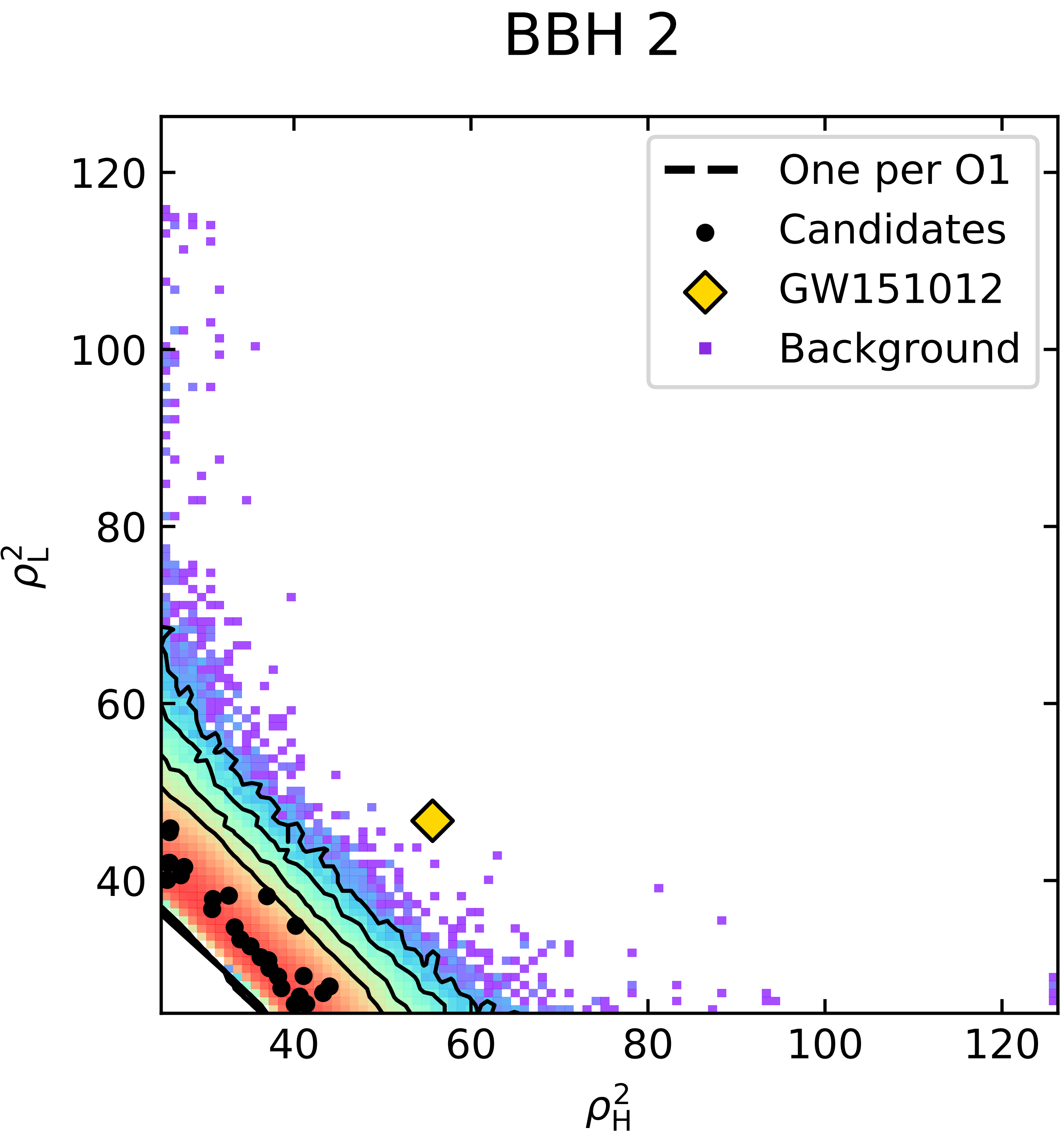
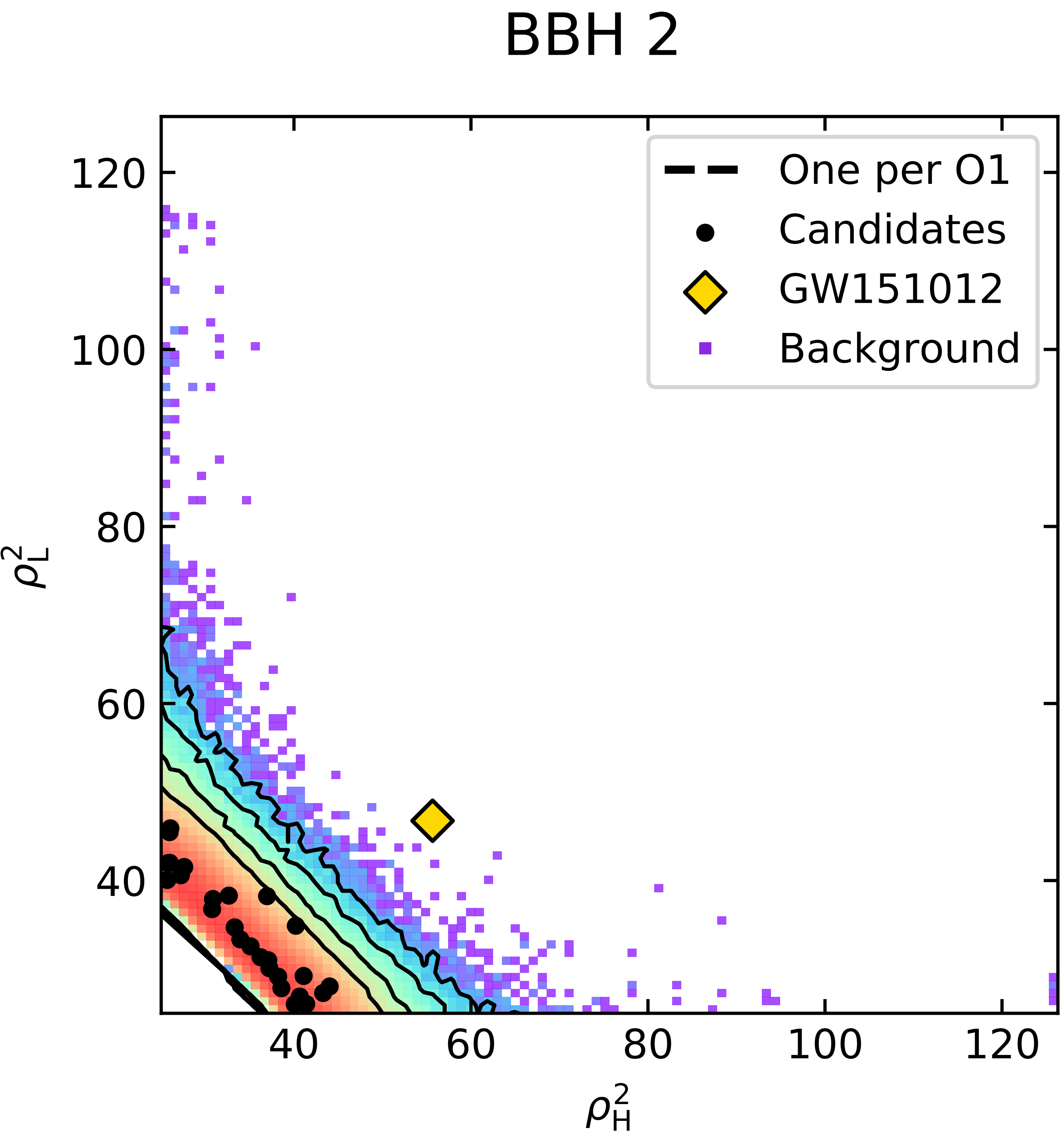
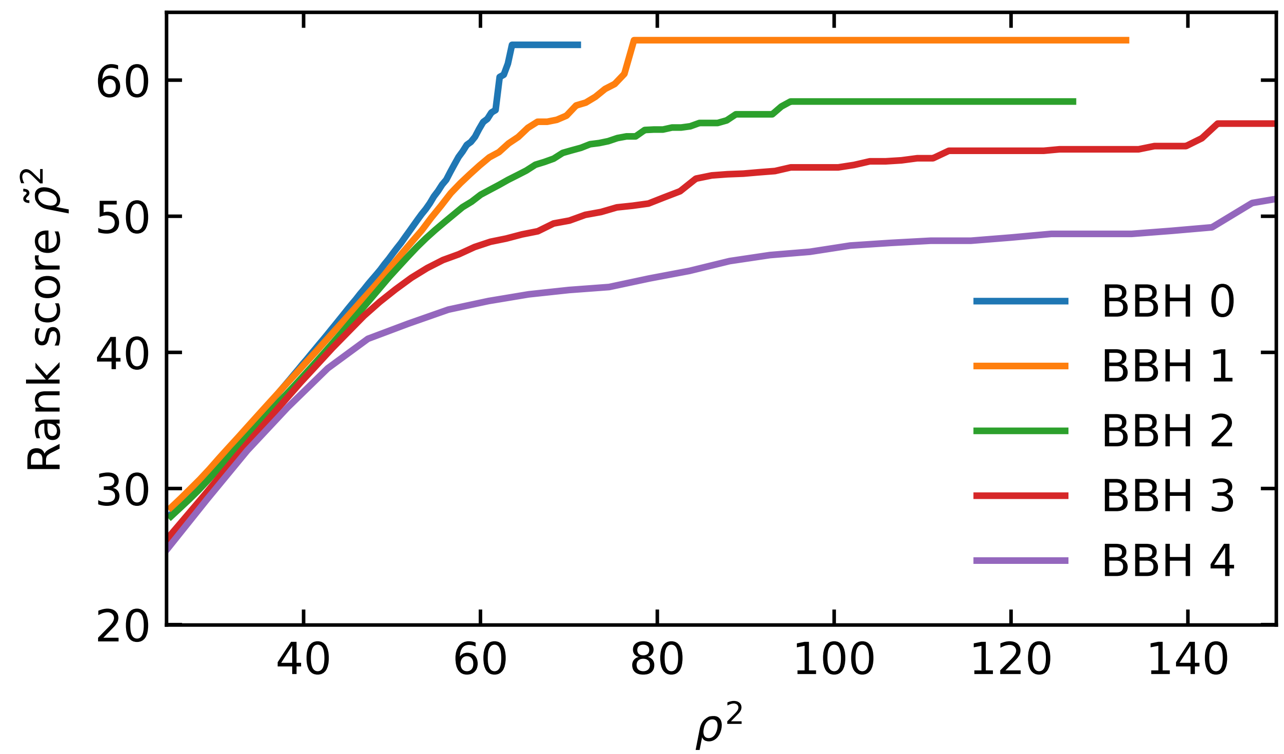


$$p(\rho_1^2, \rho_2^2 \mid \mathcal{N}) = p(\rho_1^2 \mid \mathcal{N})\, p(\rho_2^2 \mid \mathcal{N})$$

Incoherent Ranking of Triggers





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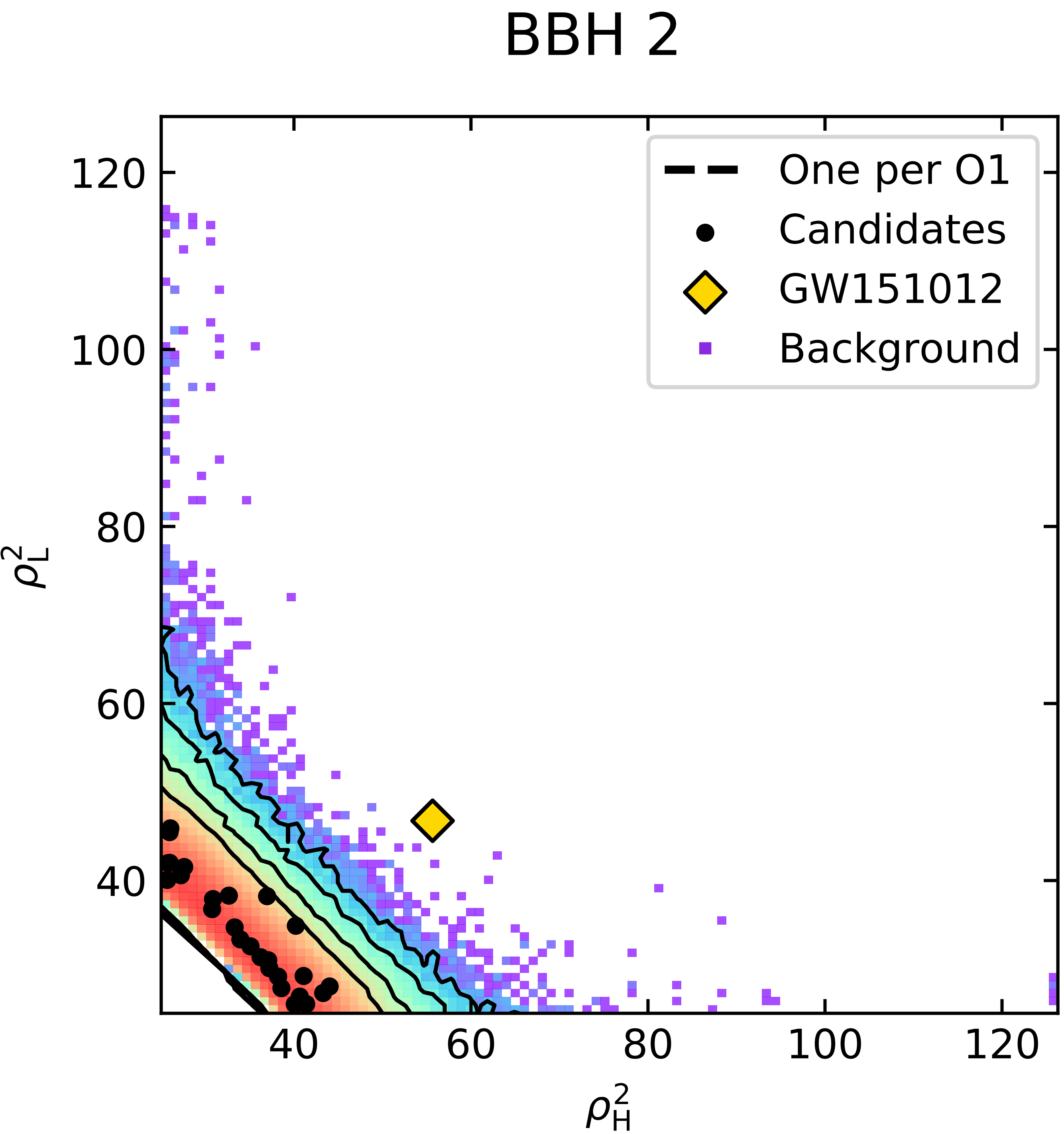

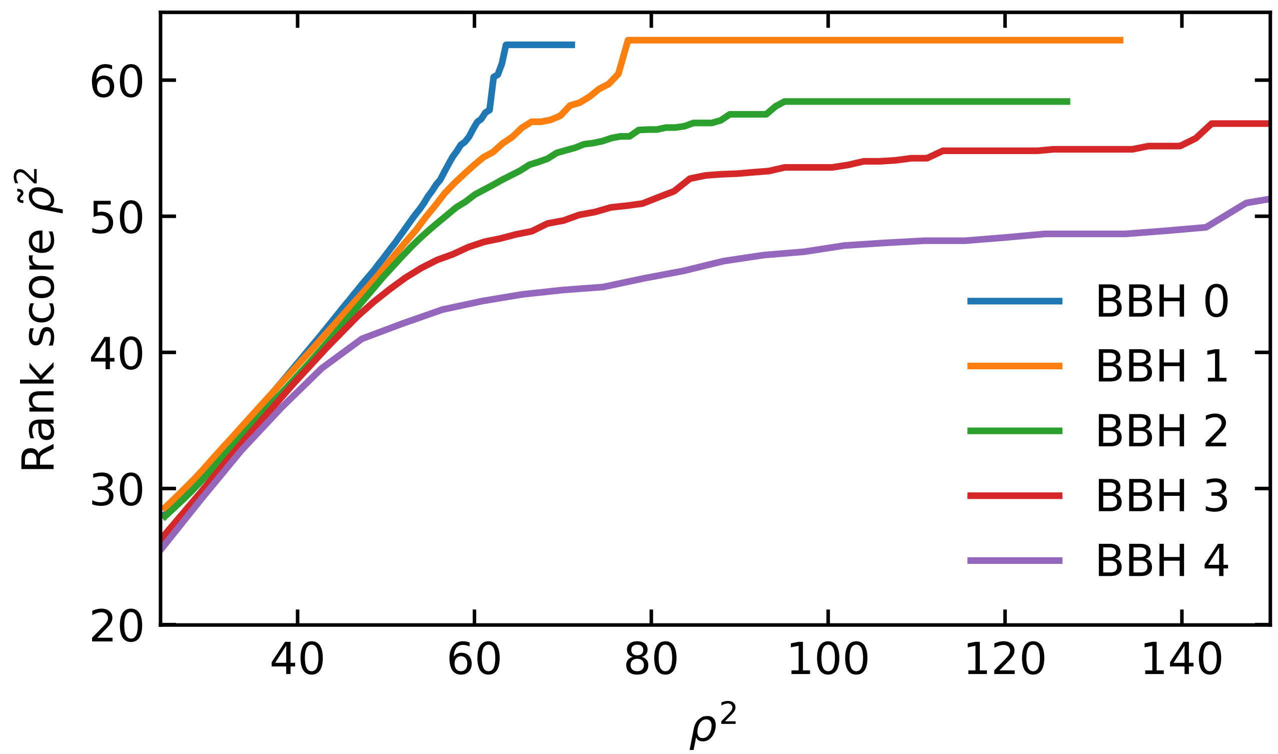

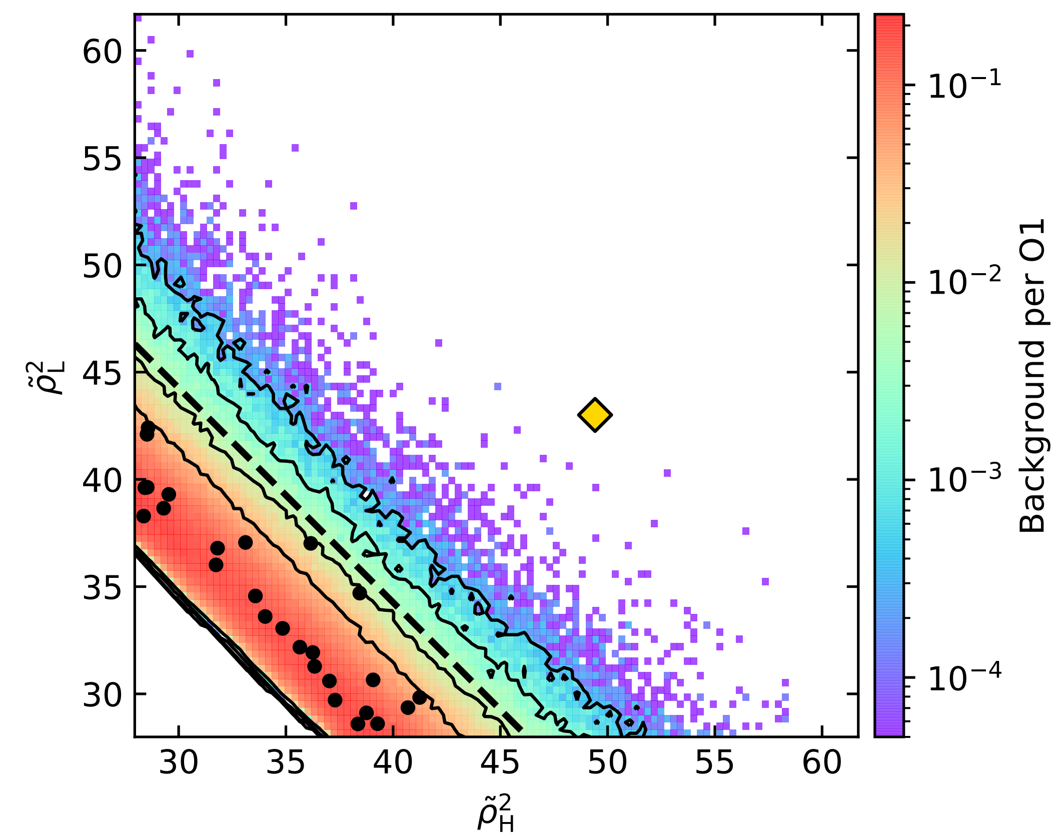

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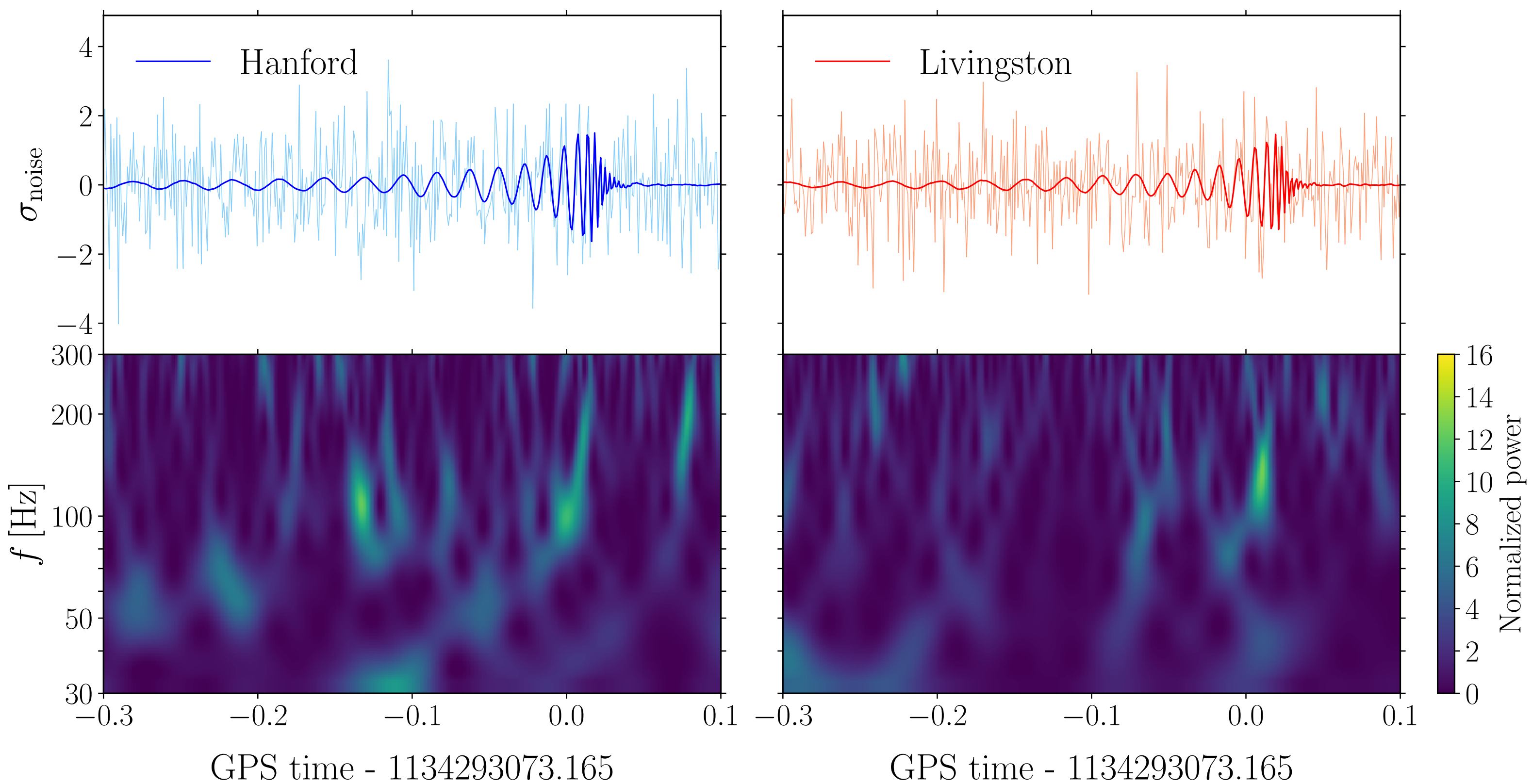
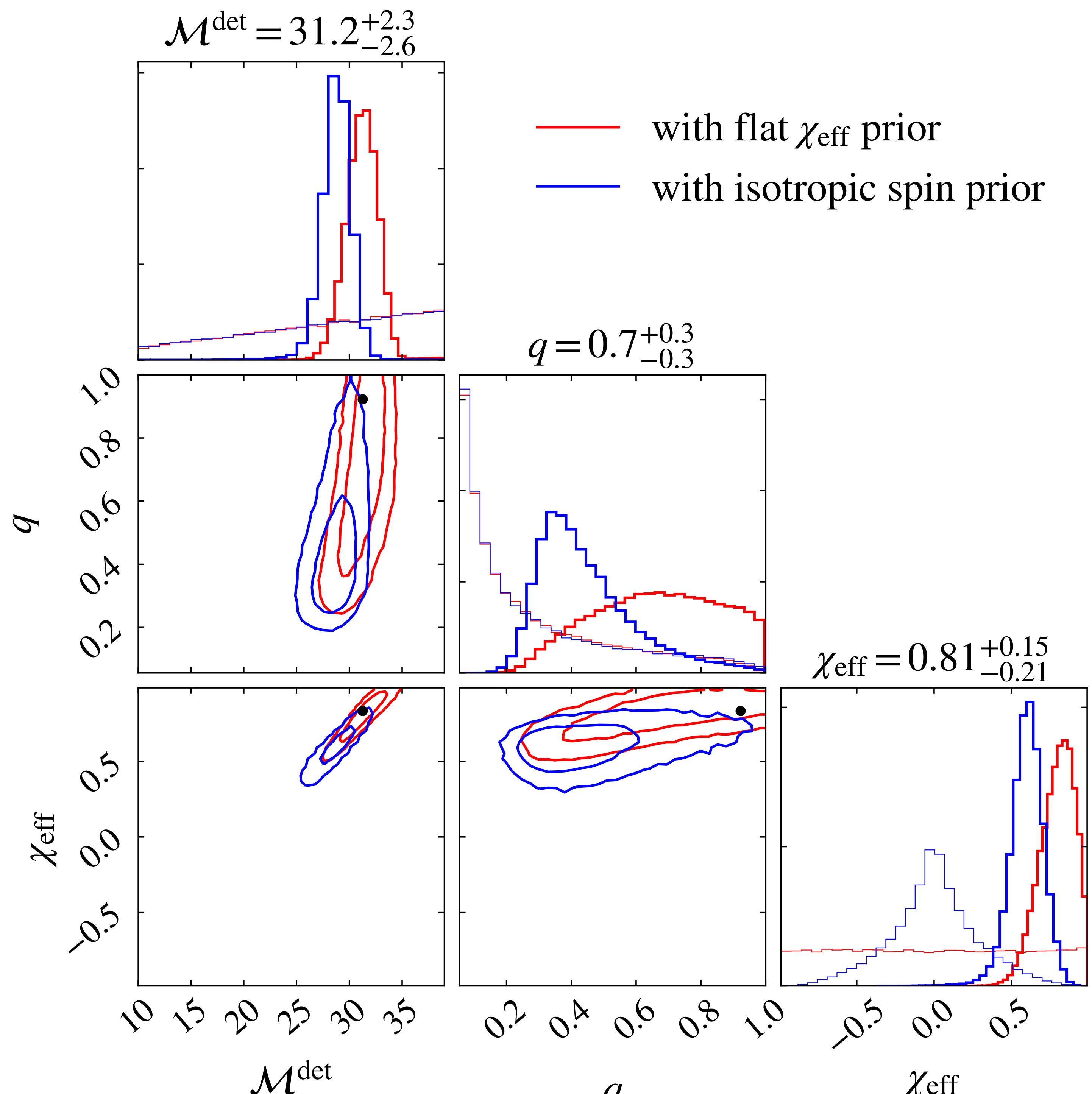
GW151216



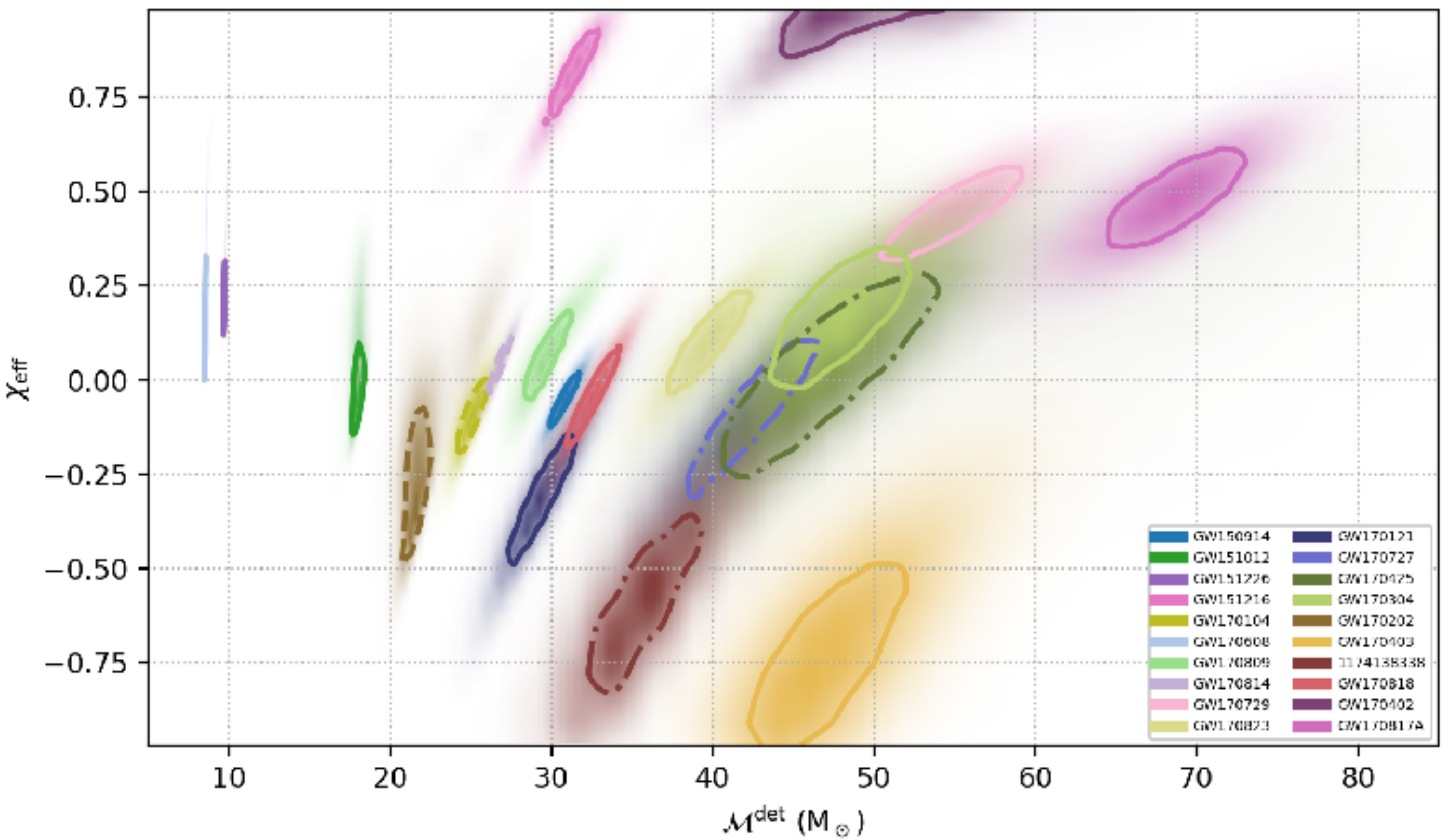
	Flat χ_{eff} prior	Isotropic spin prior
Chirp mass $\mathcal{M}^{\text{det}}$	$31^{+2}_{-3}\,M_\odot$	$29^{+2}_{-2}\,M_\odot$
Primary mass m_1	$31^{+13}_{-6}\,M_\odot$	$38^{+11}_{-11}\,M_\odot$
Secondary mass m_2	$21^{+5}_{-6}\,M_\odot$	$16^{+6}_{-3}\,M_\odot$
Mass ratio m_1/m_2	$1.5^{+1.4}_{-0.4}$	$2.4^{+1.4}_{-1.1}$
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 χ_{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.
- In terms of mass it is unremarkable
- Far away due to its low SNR and high spin
- Consistent with both BHs spinning rapidly but not with only the secondary spinning fast.

GW151216



$\mathcal{M}^{\rm det} = 31.2^{+2.3}_{-2.6}$
$q = 0.7^{+0.3}_{-0.3}$
$\chi_{\rm eff} = 0.81^{+0.15}_{-0.21}$
with flat $\chi_{\rm eff}$ prior
with isotropic spin prior
$\mathcal{M}^{\rm det}$
q
$\chi_{\rm eff}$
10 15 20 25 30 35
0.2 0.4 0.6 0.8 1.0
−0.5 0.0 0.5



0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
$\chi_{\rm eff}$
10
20
30
40
50
60
70
80
$\mathcal{M}^{\rm det}$ (M$_\odot$)
GW150914
GW151012
GW151226
GW151216
GW170104
GW170608
GW170809
GW170814
GW170729
GW170823
GW170121
GW170727
GW170425
GW170304
GW170202
GW170403
1174138338
GW170818
GW170402
GW170817A