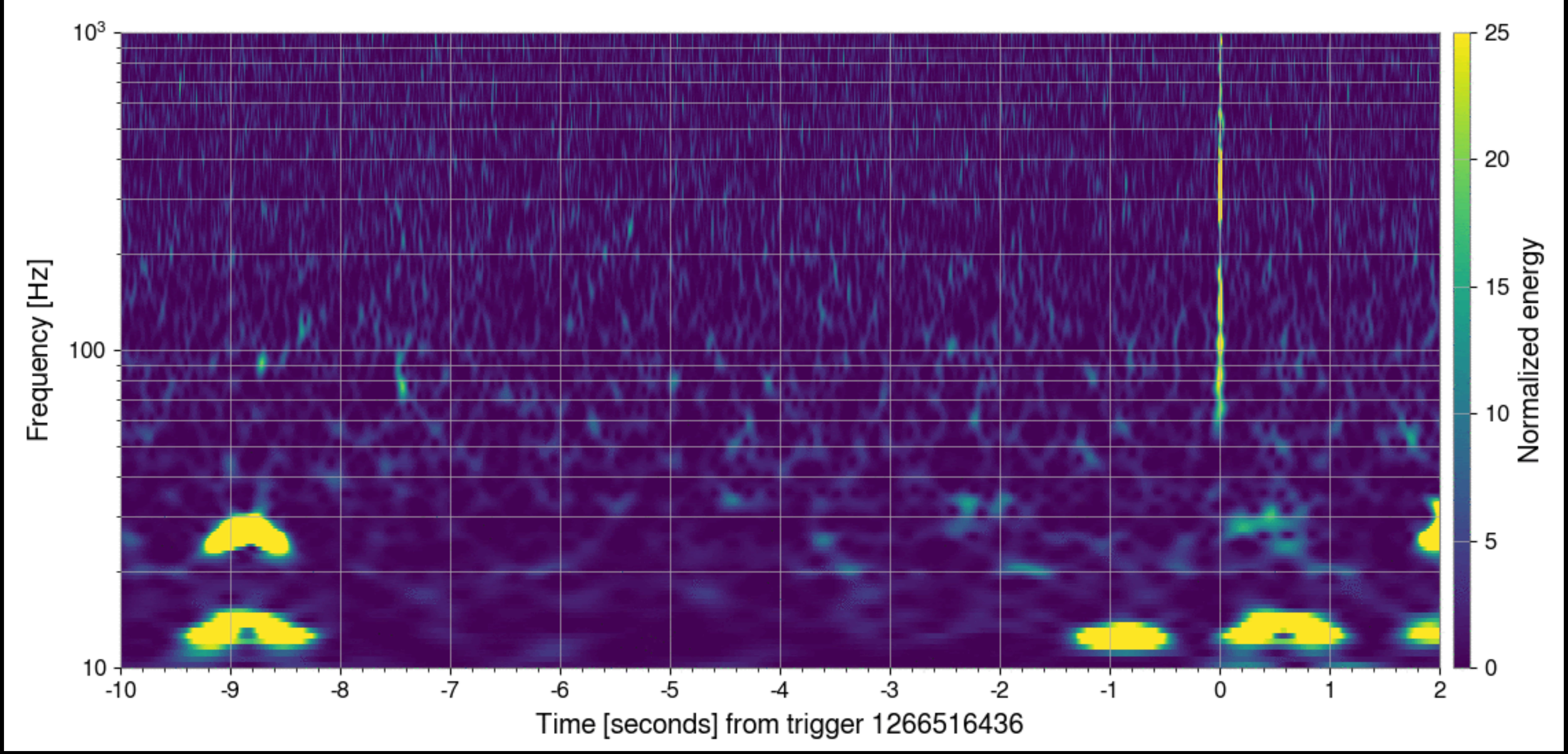
Rapid glitch mitigation for near-future GW detectors



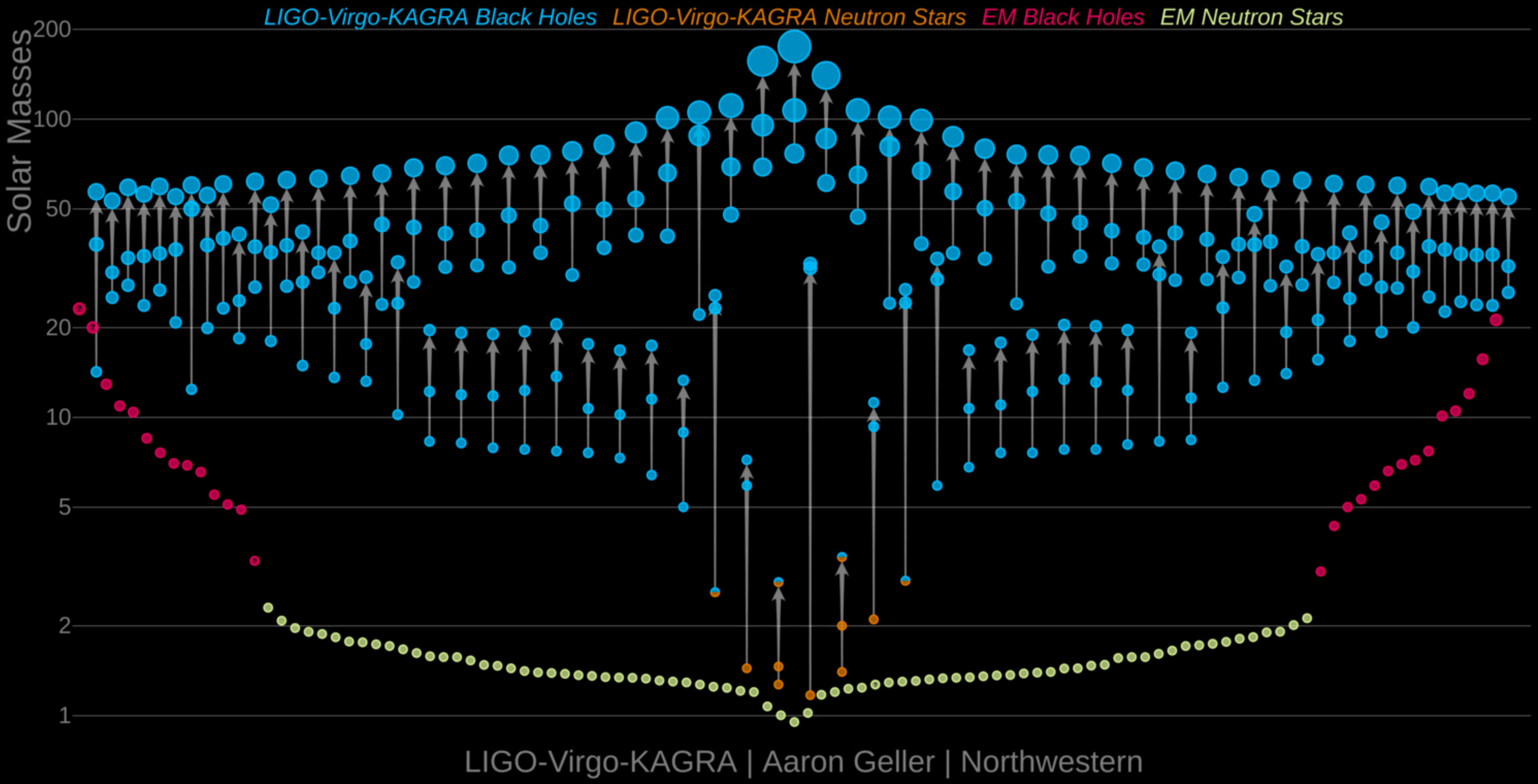
Dr. Jess McIver for the LVK

IPAM Workshop: Big Data in Multi-Messenger Astrophysics

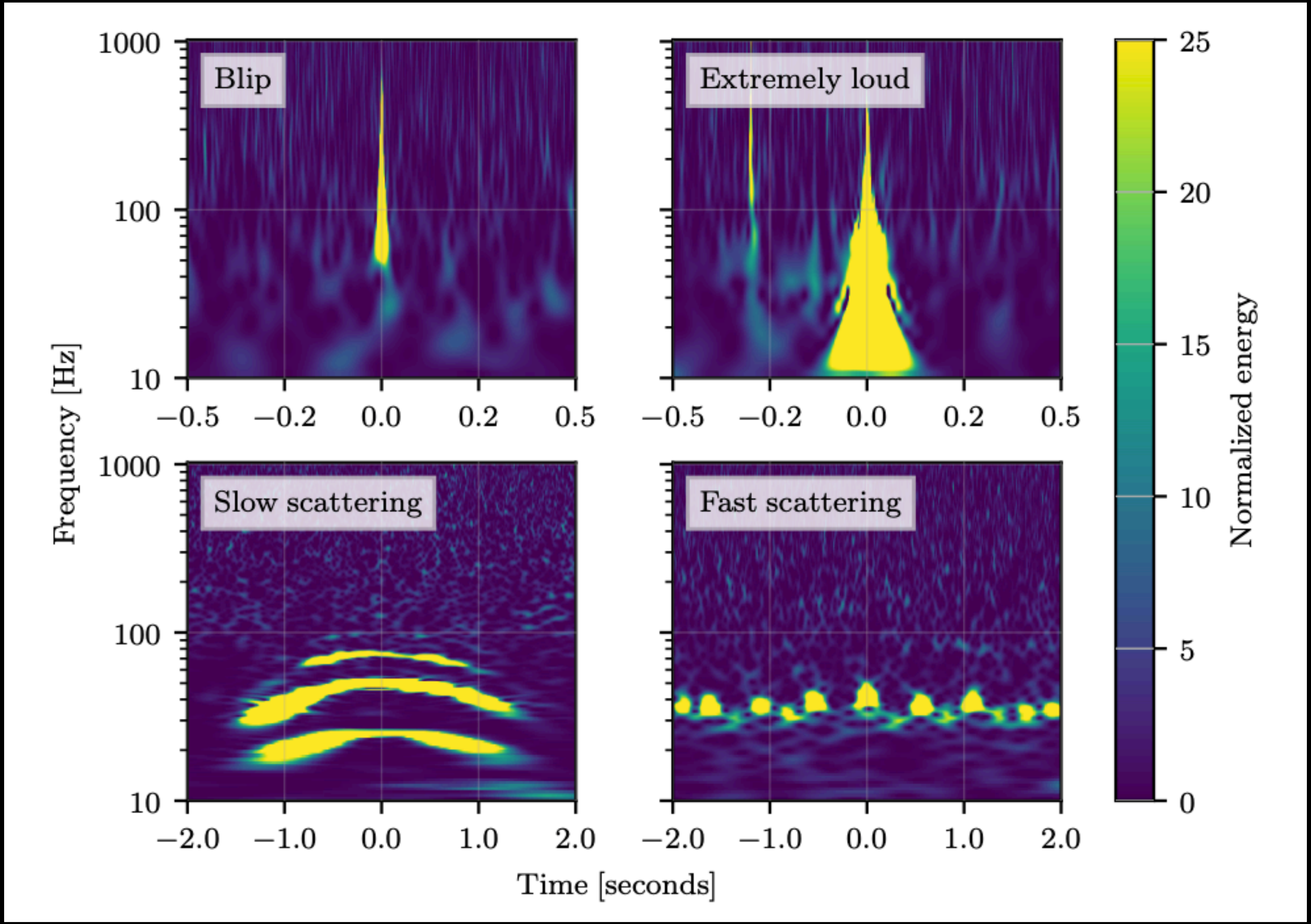
December 2, 2021

LIGO DCC G2102260

GWTC-3

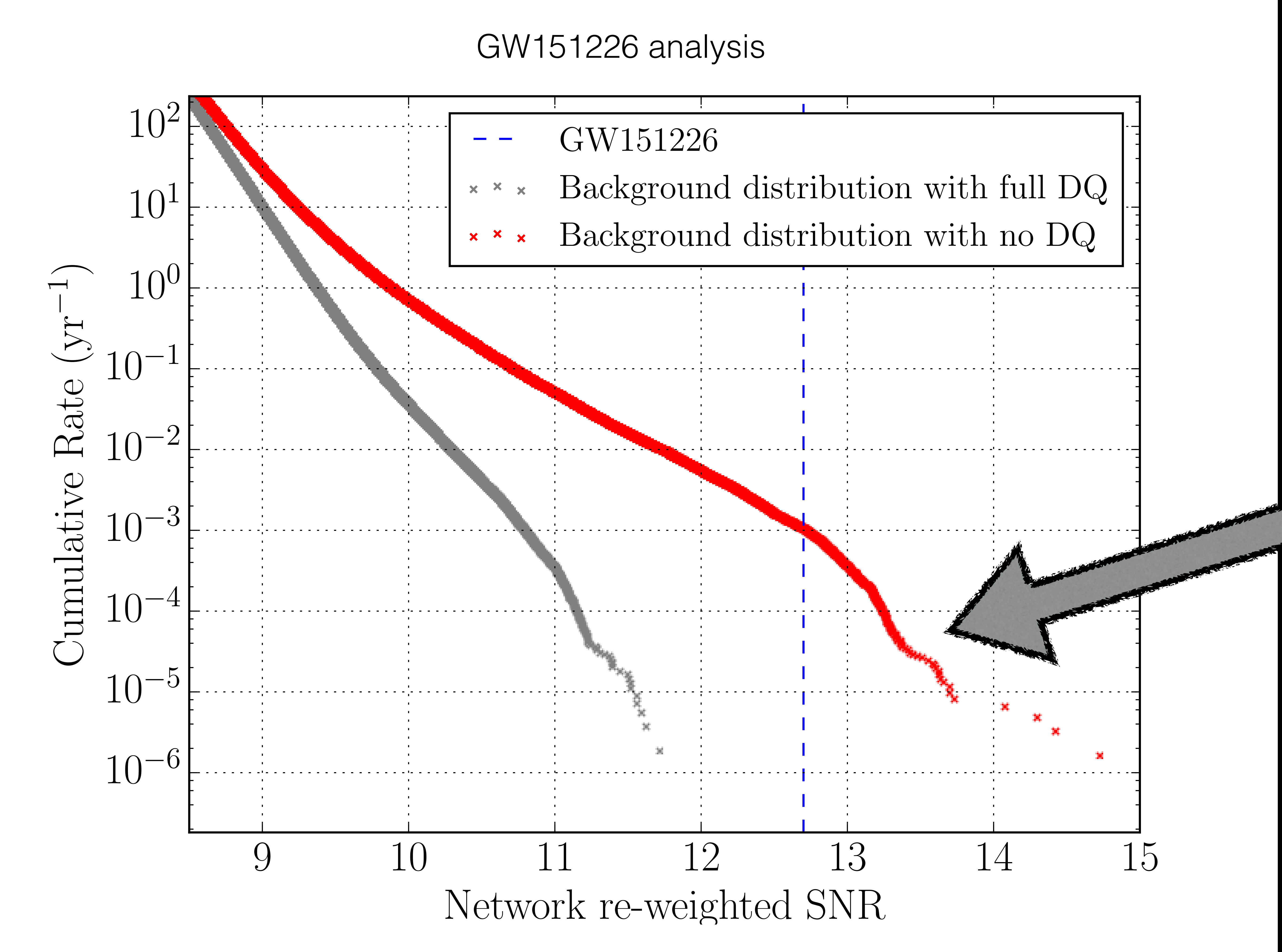

LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

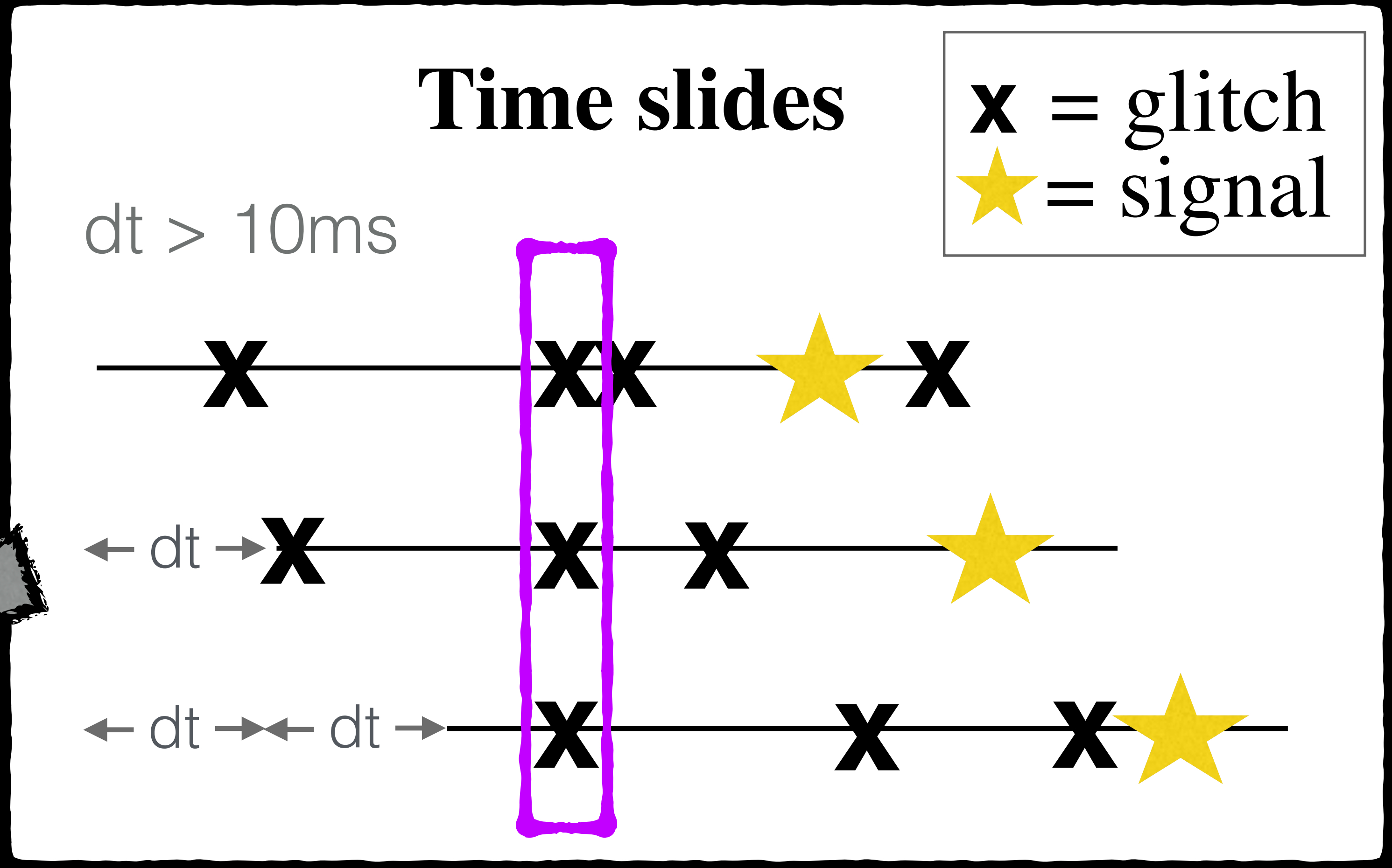
Challenge: GW detector transient noise



Davis et al. CQG 38 11673 (2021)

Glitches and the significance of a detected event

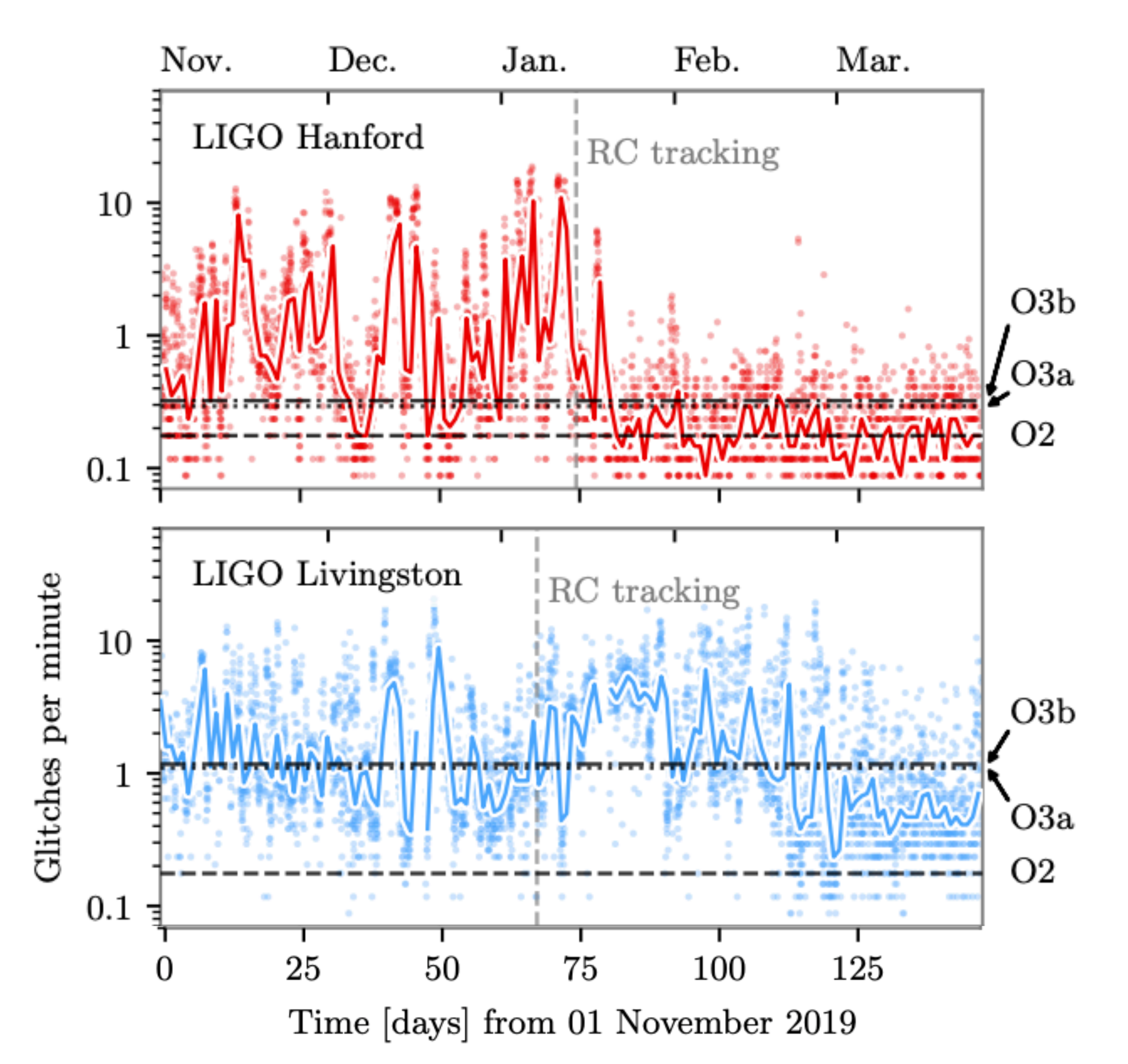


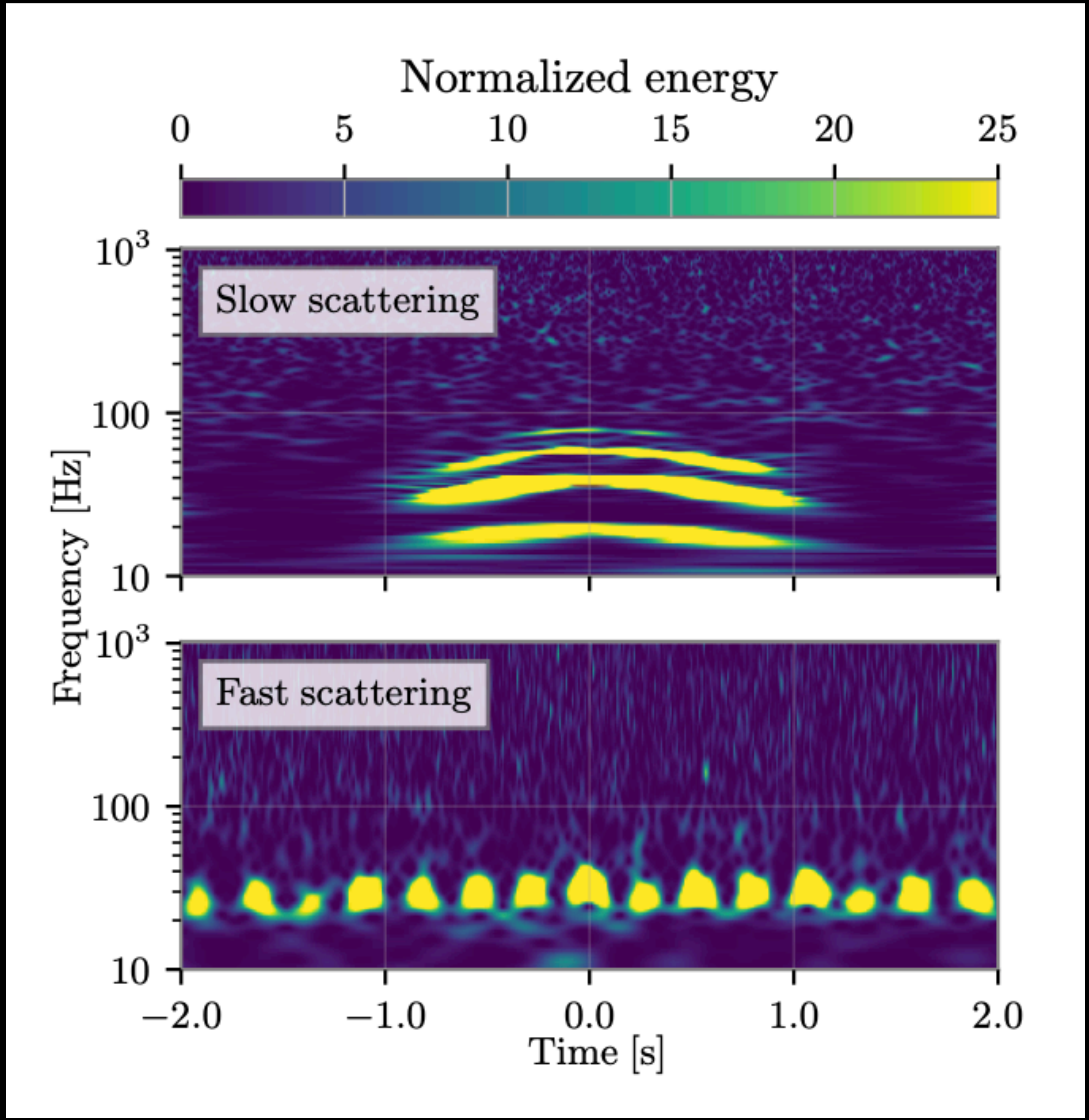


Estimating the coincident noise event rate with time slides

B.P Abbott et al. CQG (2018)

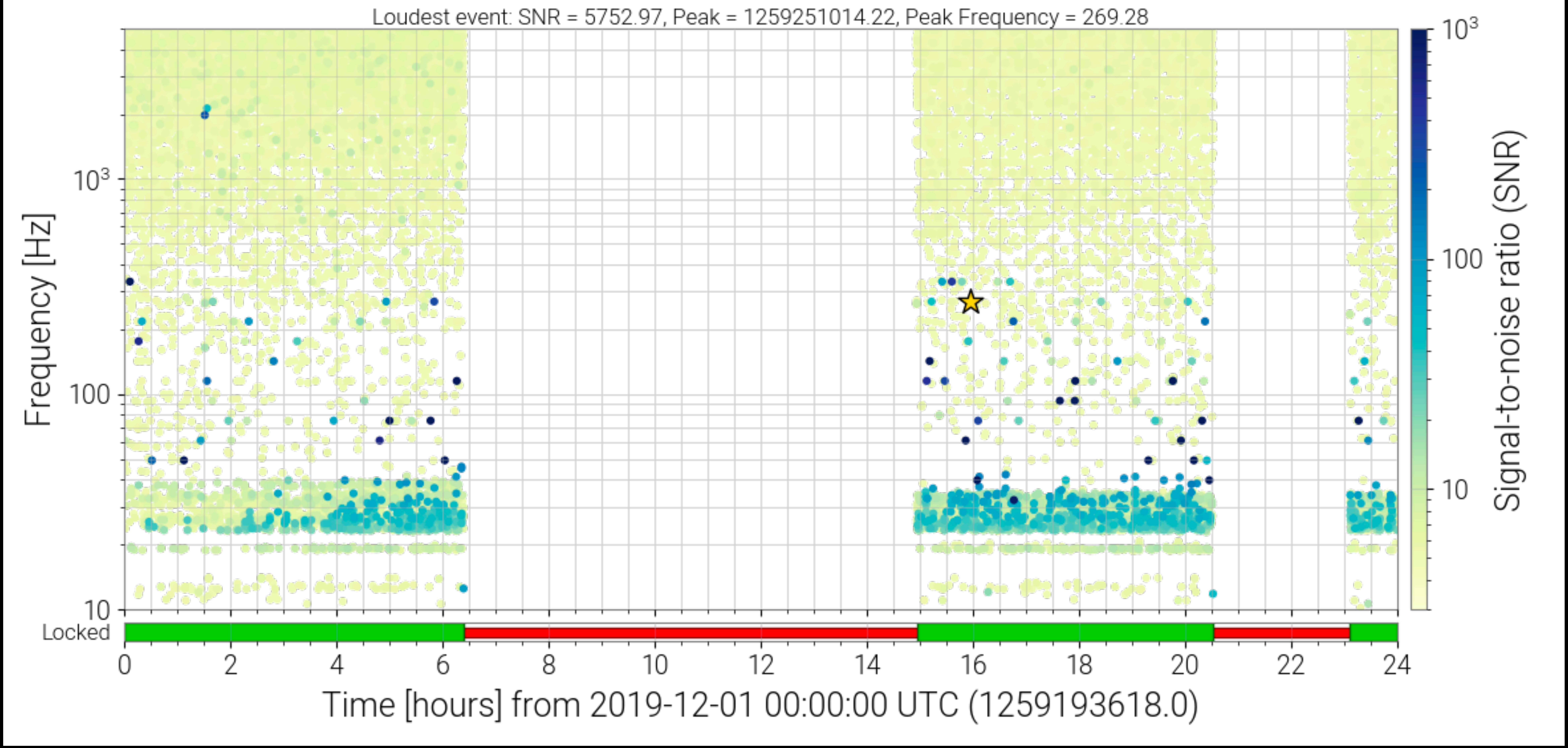
Challenge: Transient noise, as seen in GWTC-3





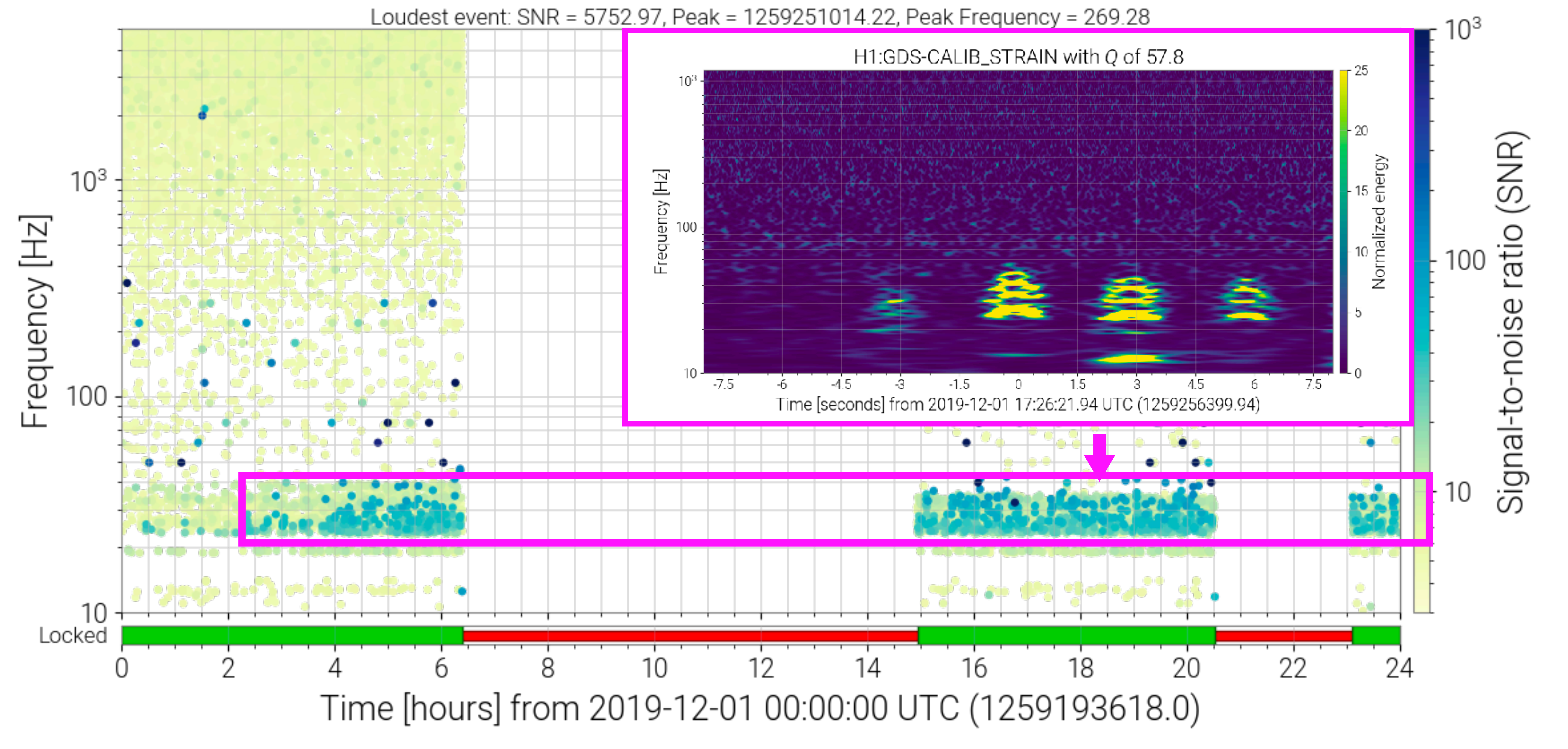
GWTC-3: arXiv 2111.03606 (2021)

Challenge: GW detector transient noise



The LIGO summary pages

Challenge: GW detector transient noise



The LIGO summary pages

GWTC candidates found to be due to noise

GWTC-1 arXiv 1811.12907

Date	UTC	Data quality
151008	14:09:17.5	No artifacts
151012.2	06:30:45.2	Artifacts present
151116	22:41:48.7	No artifacts
161202	03:53:44.9	Artifacts possibly caused
161217	07:16:24.4	Artifacts possibly caused
170208	10:39:25.8	Artifacts present
170219	14:04:09.0	No artifacts
170405	11:04:52.7	Artifacts present
170412	15:56:39.0	Artifacts possibly caused
170423	12:10:45.0	No artifacts
170616	19:47:20.8	Artifacts present
170630	16:17:07.8	Artifacts present
170705	08:45:16.3	No artifacts
170720	22:44:31.8	Artifacts possibly caused

4 marginal candidate events (but $p_{astro} < 0.5$ for all analyses)

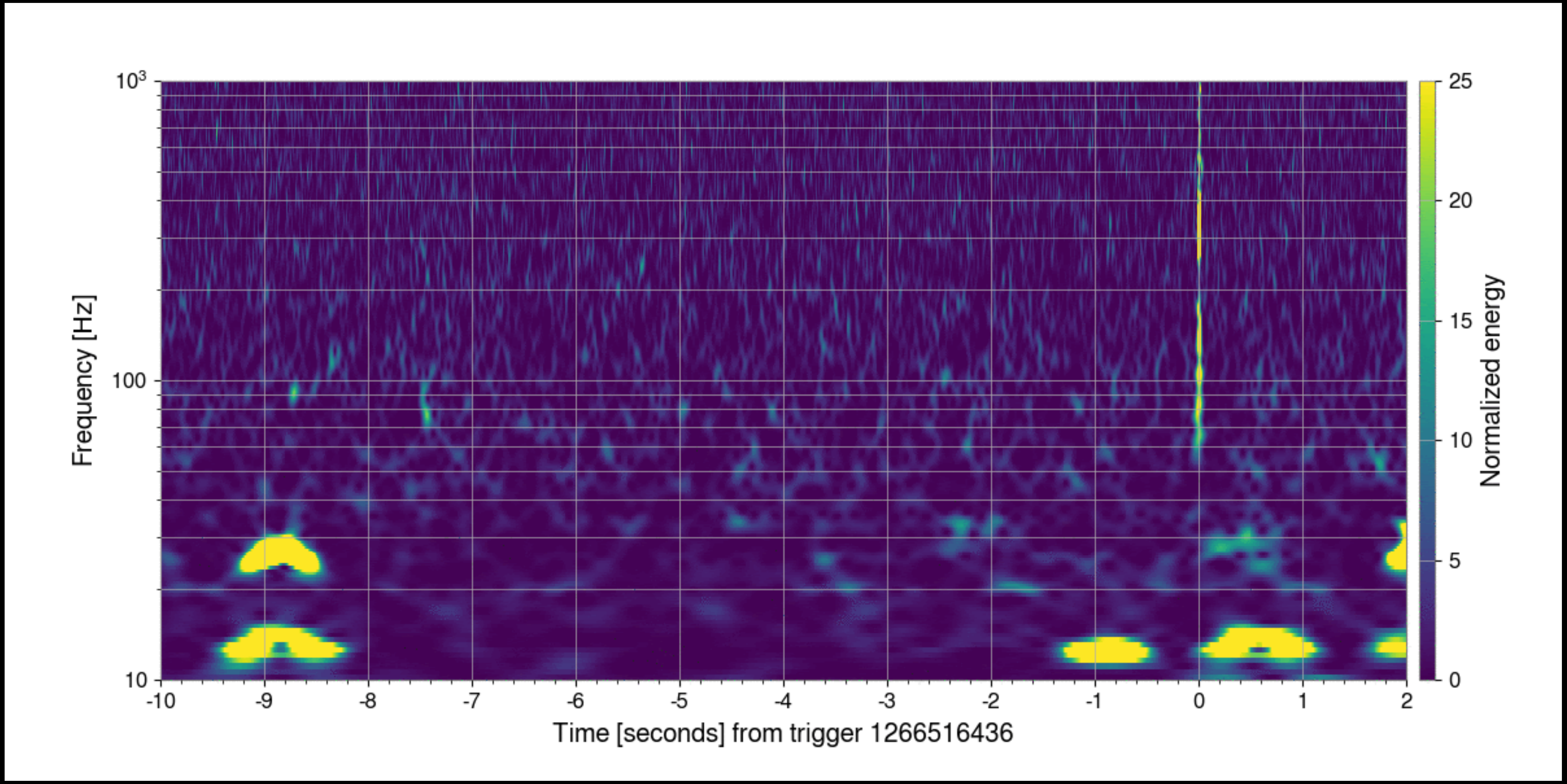
GWTC-3 arXiv 2111.03606

Name	Inst.
GW191118_212859	LV
GW200105_162426	LV
200121_031748*	HV
GW200201_203549	HLV
200214_224526*	HLV
200219_201407*	HLV
GW200311_103121	HL

3 marginal candidates with FAR below a threshold of 2.0 yr^{-1} in at least one analysis (but $p_{astro} < 0.5$)

GWTC-3: example of instrument origin

S200223aw - LIGO Hanford



Gif by Derek Davis

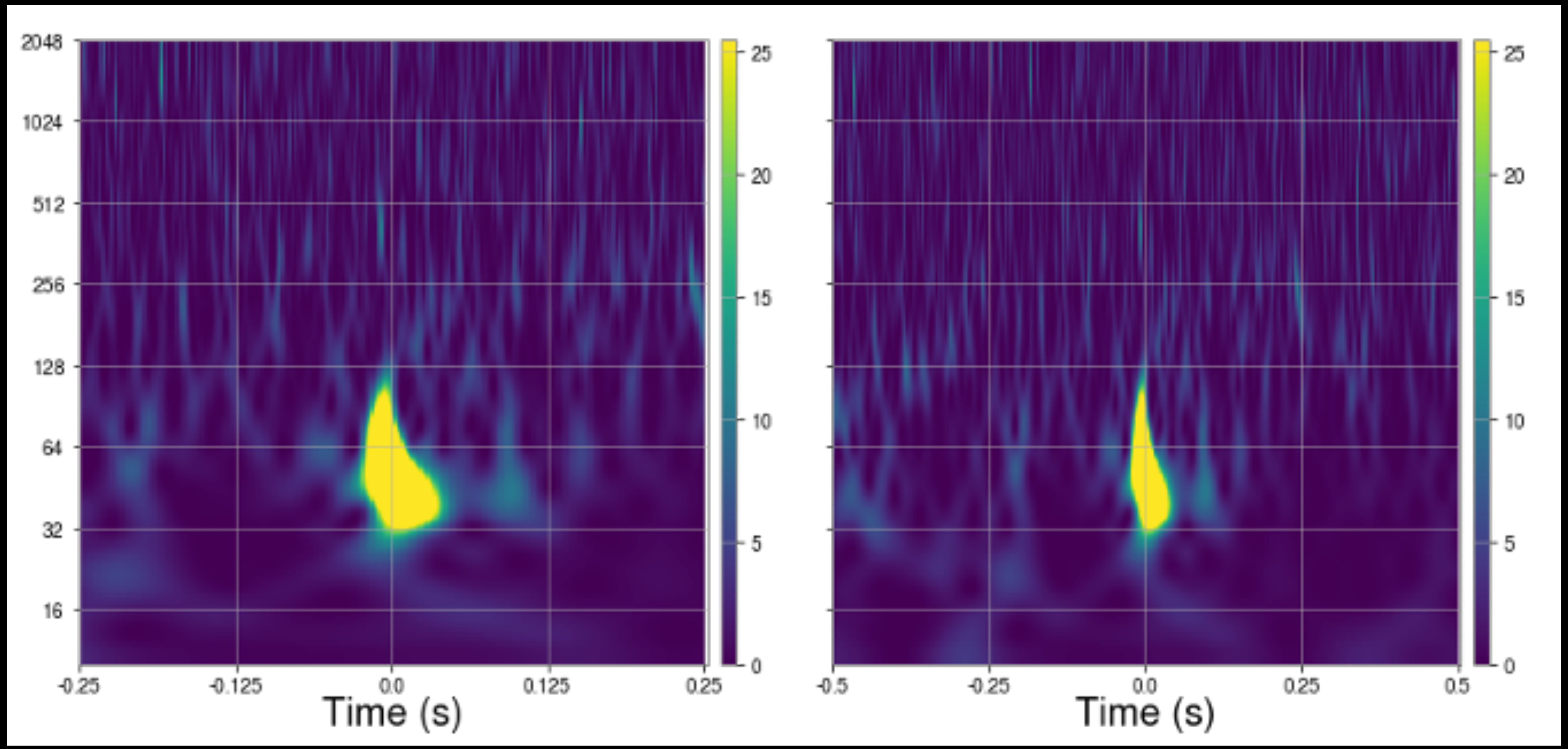
Distinguishing GW signals from glitches with GravitySpy

Study led by Seraphim Jarov, UBC student and 2021 NSERC USRA awardee, with many LSC contributions

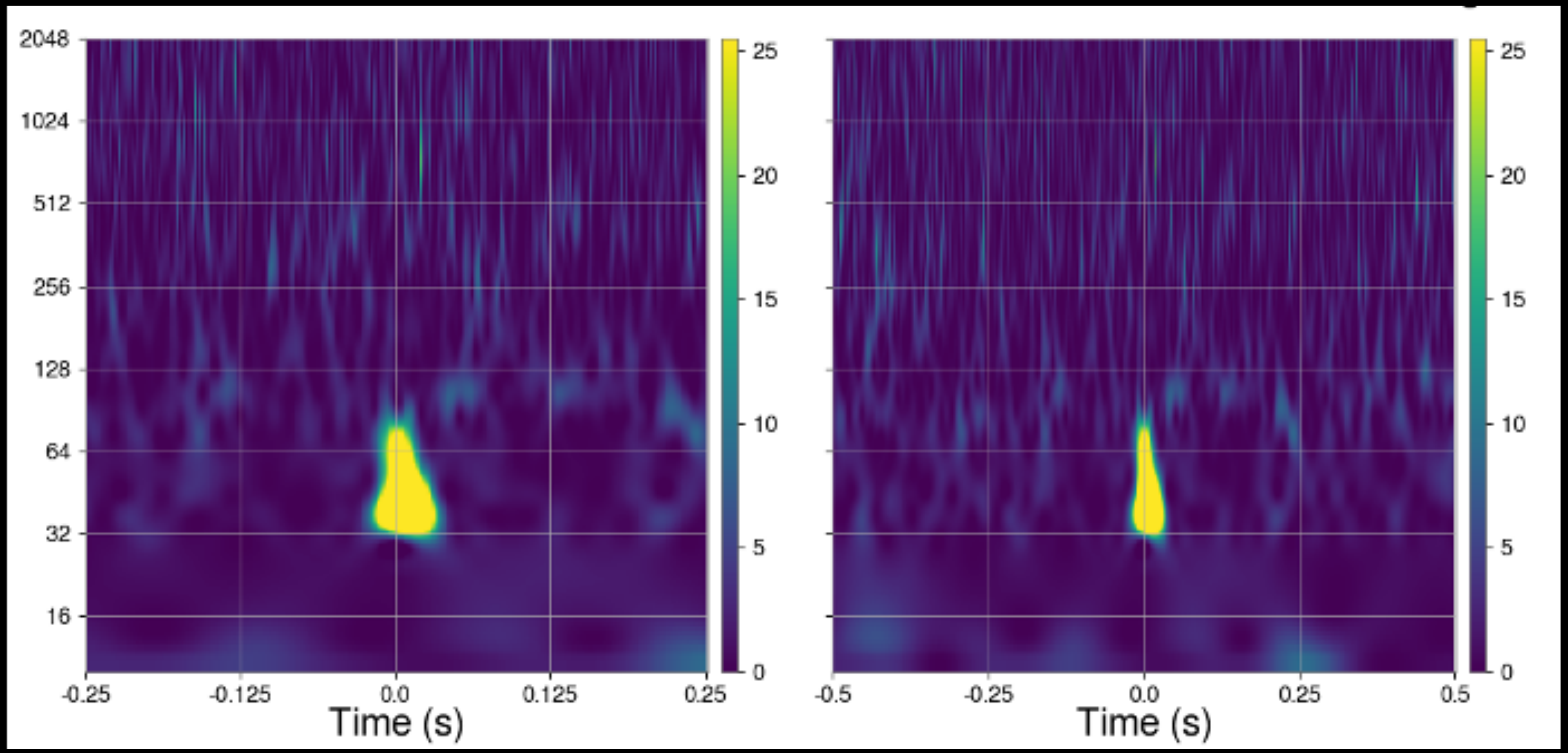
GravitySpy is a powerful CNN for classifying GW detector glitches based on time-frequency morphology

Can we confidently distinguish signals from glitches based on *morphology alone*?

Simulated GW signal (total mass 360 M_sol)



"Low frequency blip" glitch in LIGO-Livingston



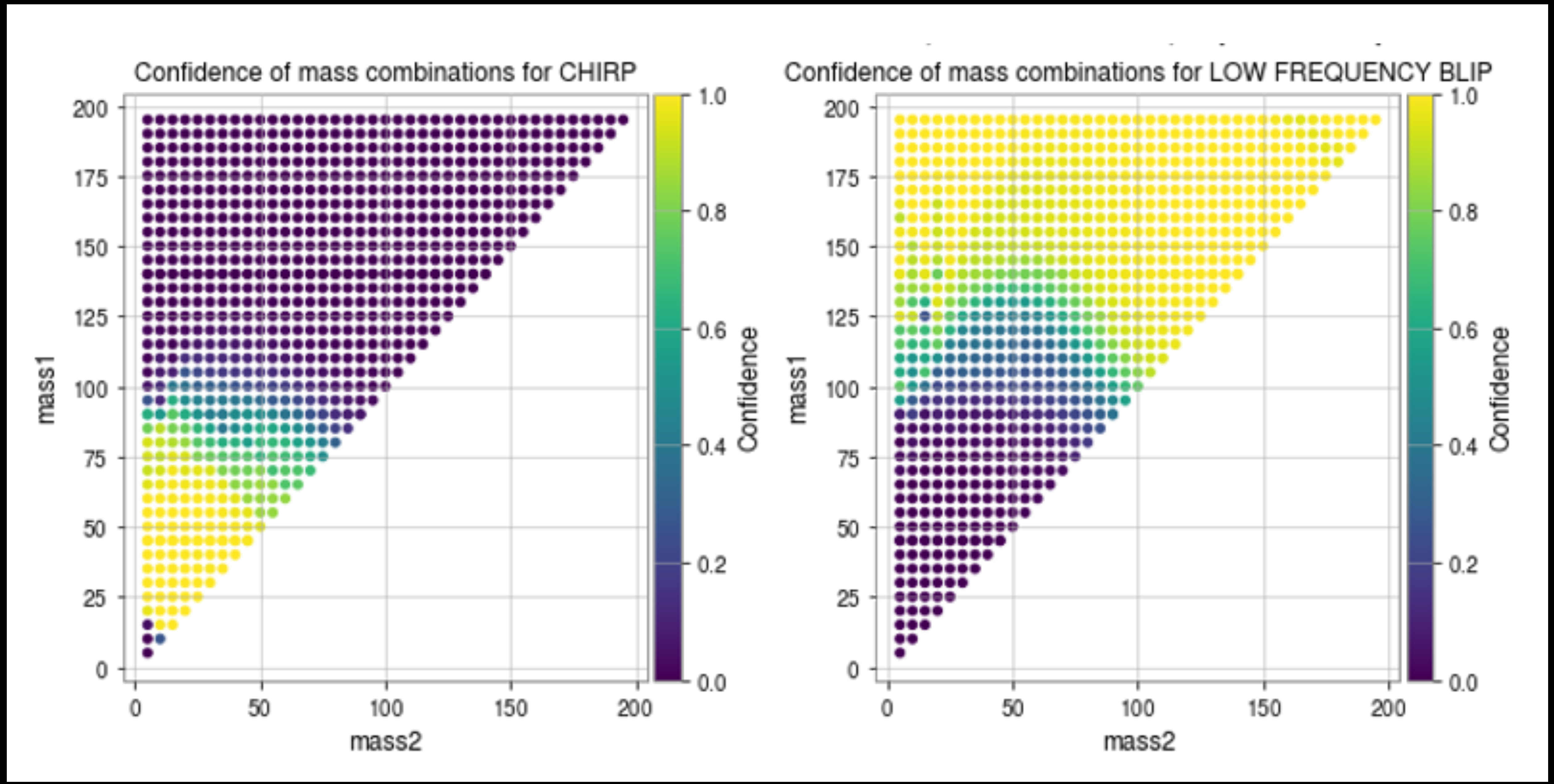
An application of the **Gravity Spy** algorithm: Zevin at al 2016 (arXiv 1611.04596).
Study originally conceived by Rikako Hatoya (Caltech LIGO SURF program) and Derek Davis (Caltech), with contributions from Sidd Soni (LSU/MIT) and Sarah Thiele (UBC).

Distinguishing GW signals from glitches with GravitySpy

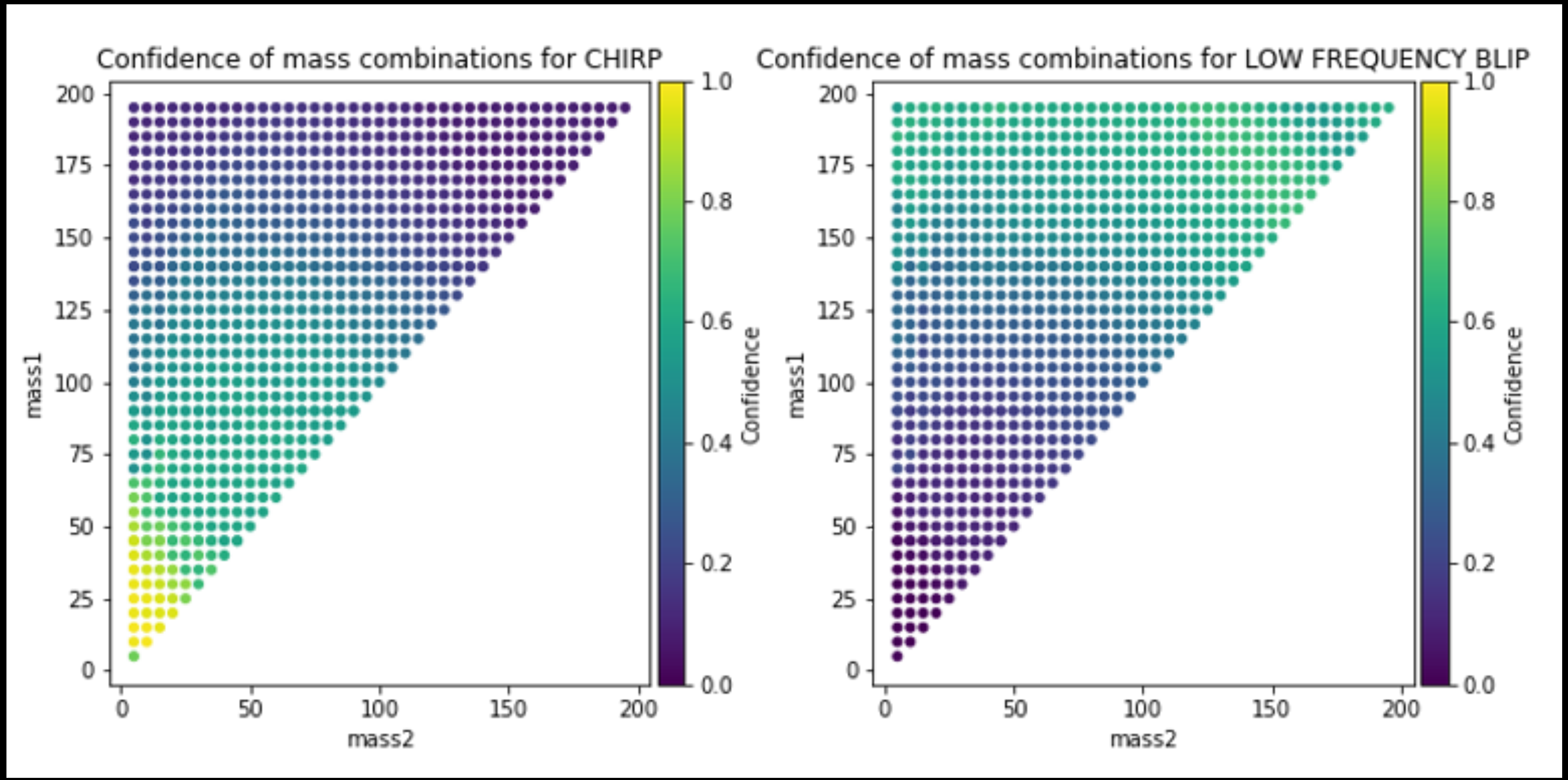
Study led by Seraphim Jarov, UBC student and 2021 NSERC USRA awardee, with many LSC contributions

The O3-era GSpy model only contained ~60 examples of simulated signals, all with total mass below 100 M_sol.
Approach: supplement the GSpy training set with more examples of high mass signals and retrain the GSpy model.

O3-era GSpy model



Re-trained GSpy model



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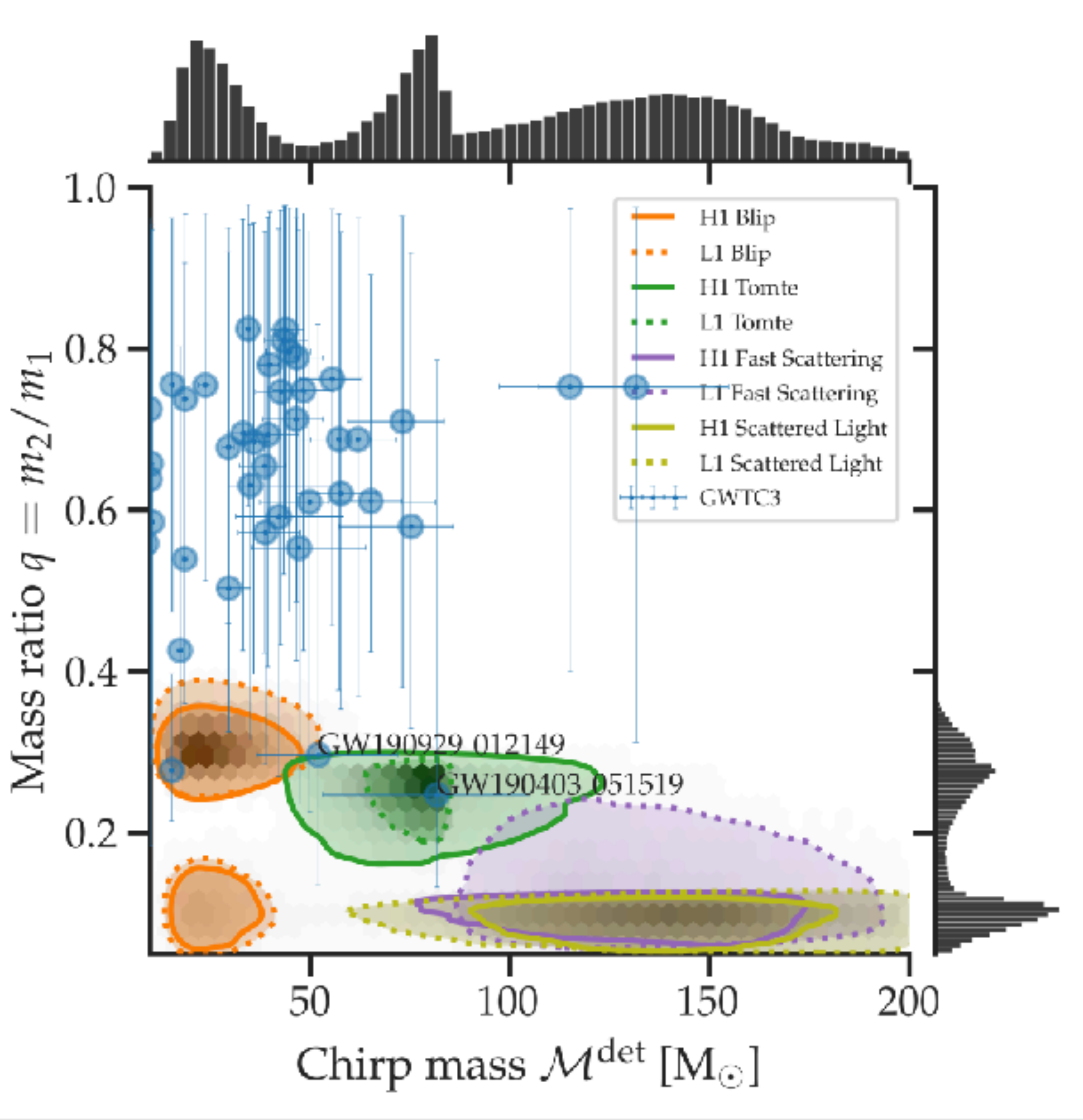
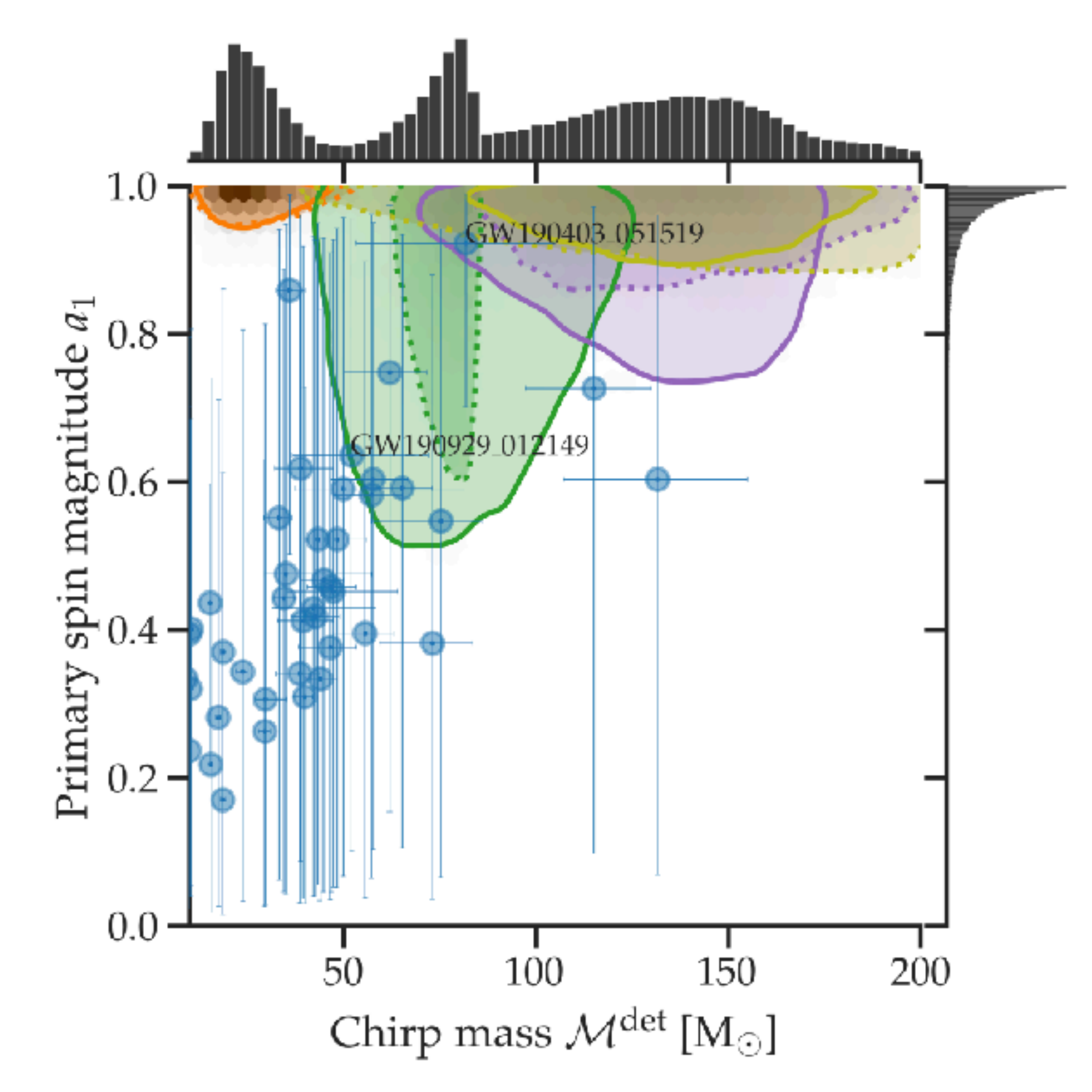
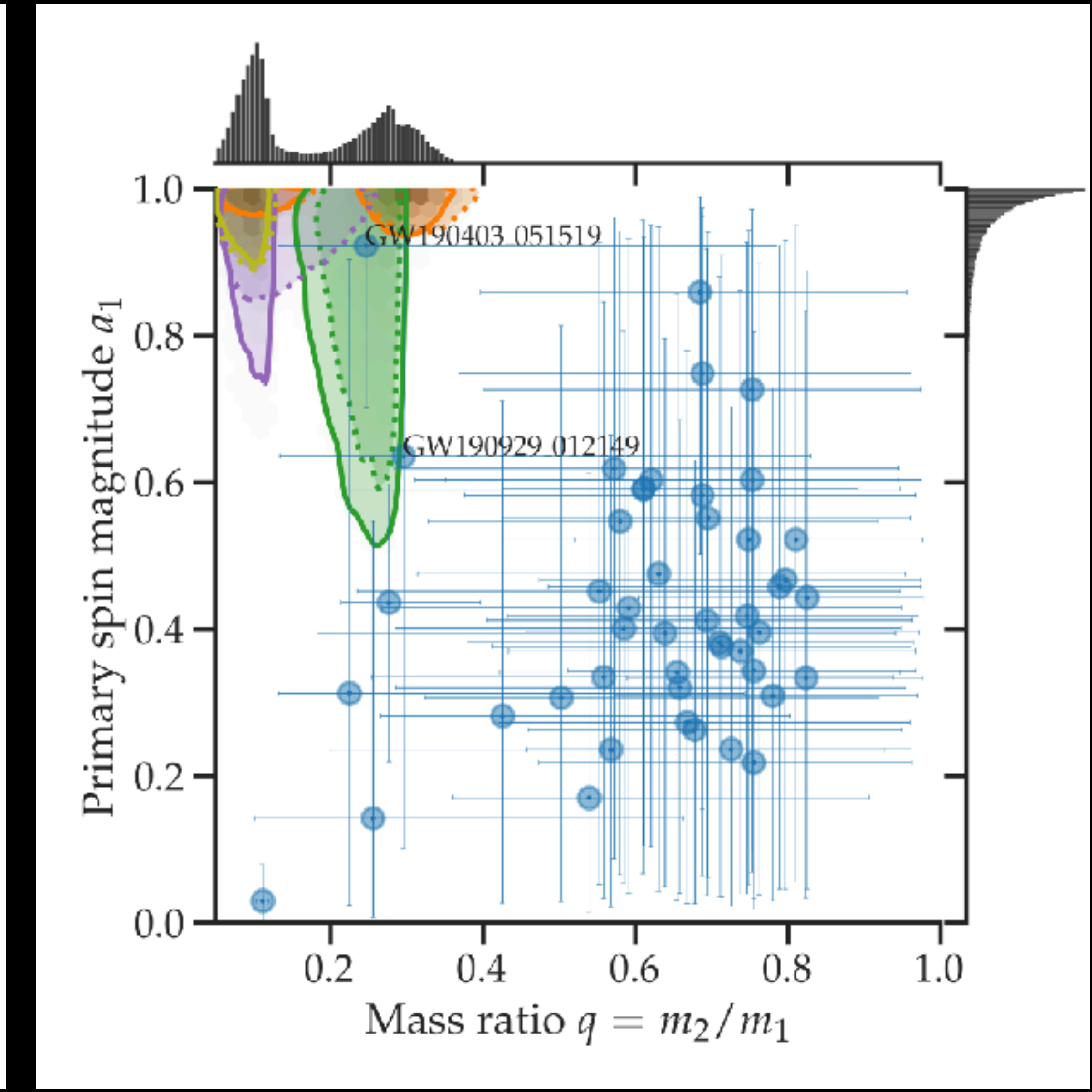
Study originally conceived by Rikako Hatoya (Caltech LIGO SURF program) and Derek Davis (Caltech), with contributions from Sidd Soni (LSU/MIT) and Sarah Thiele (UBC).

Distinguishing GW signals from glitches with PE

Study led by Greg Ashton (Royal Holloway)
with contributions from UBC students Sarah Thiele and Niko Lecoeuche, and others





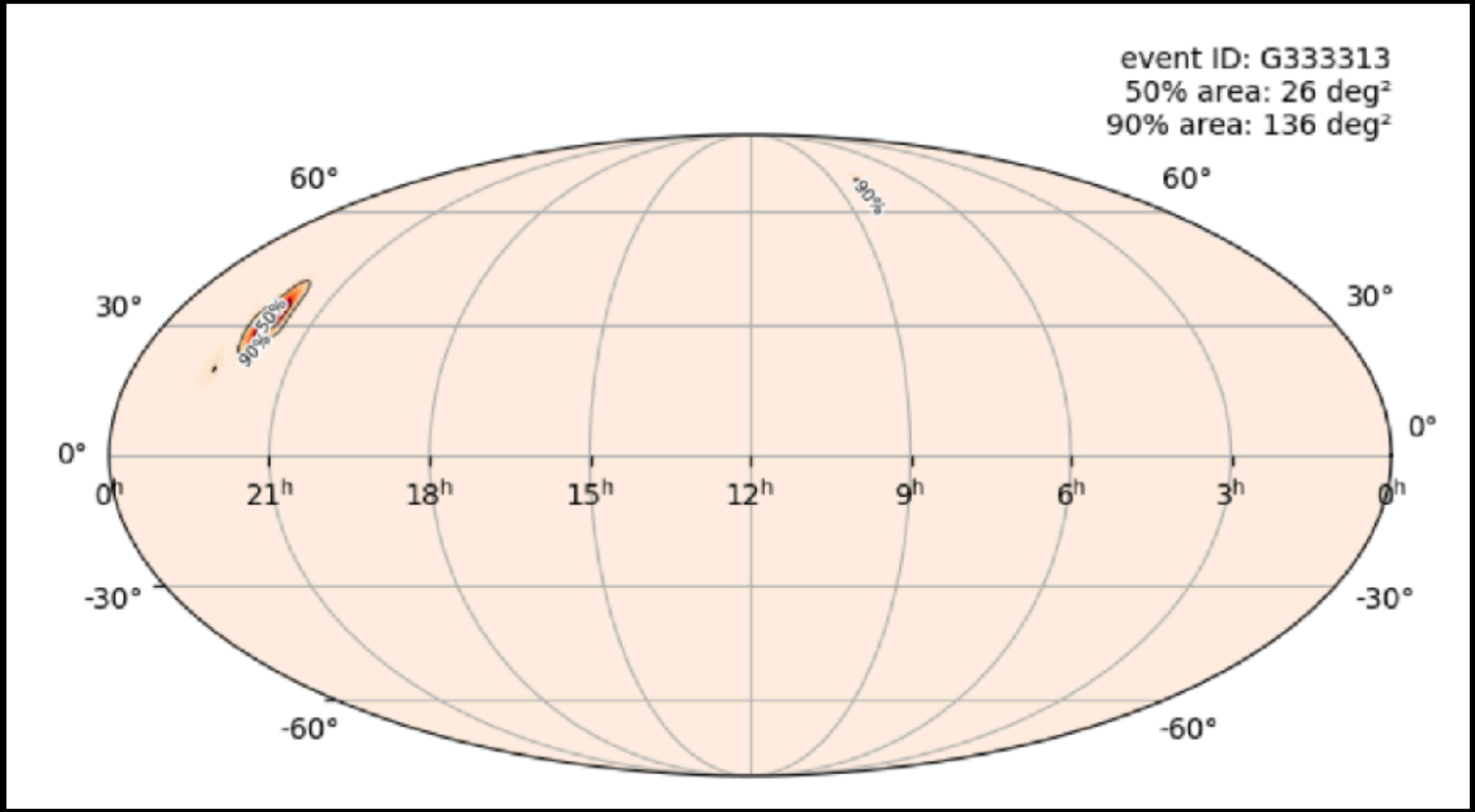


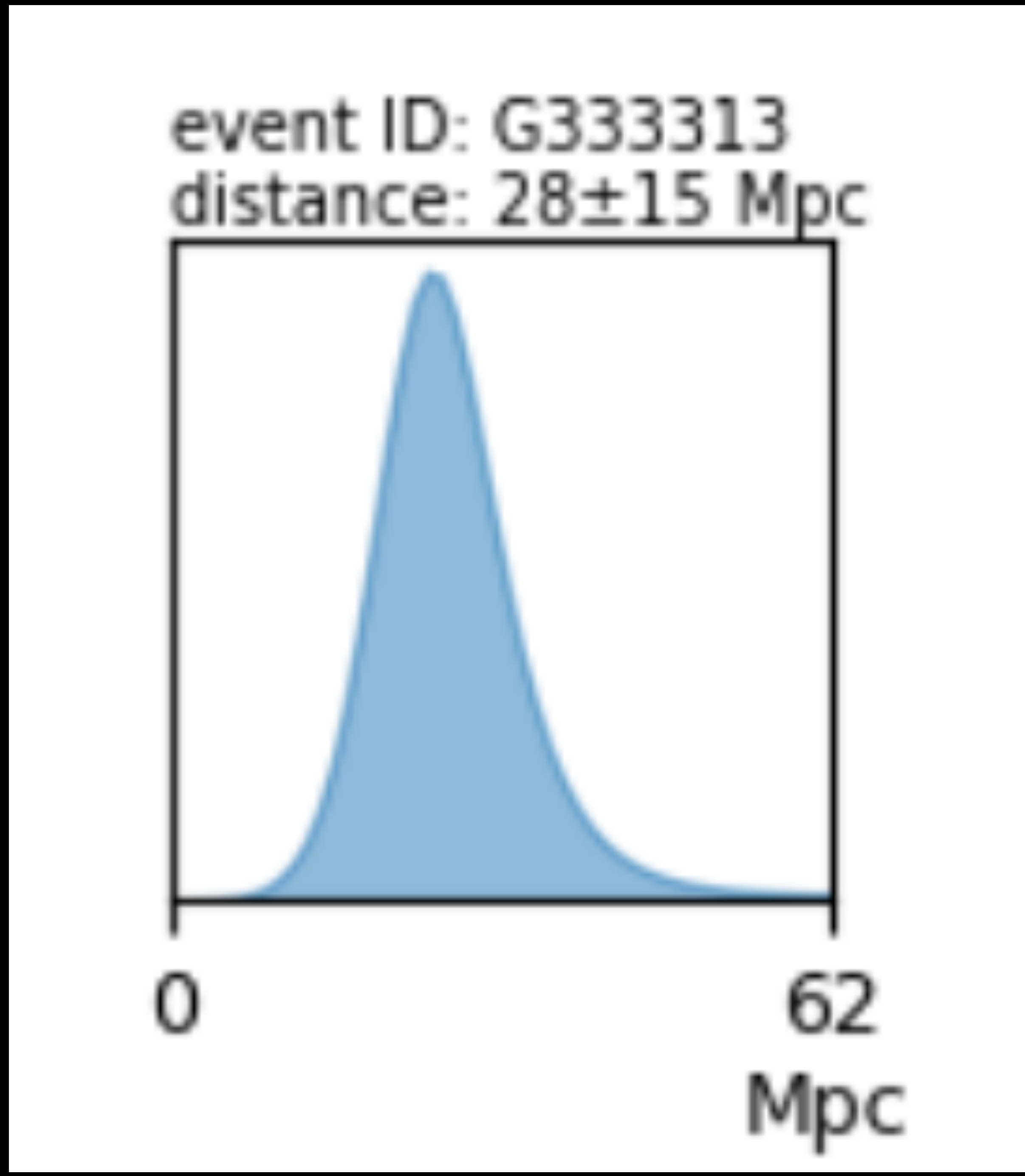
Ashton, Thiele, Lecoeuche, McIver, Nuttall (2021) arXiv 2110.02689
Also a study in the works by the RIFT team at RIT using rapid PE methods.

Challenge: S190518bb case study

Automatic Preliminary Notice sent ~6 minutes after the event:

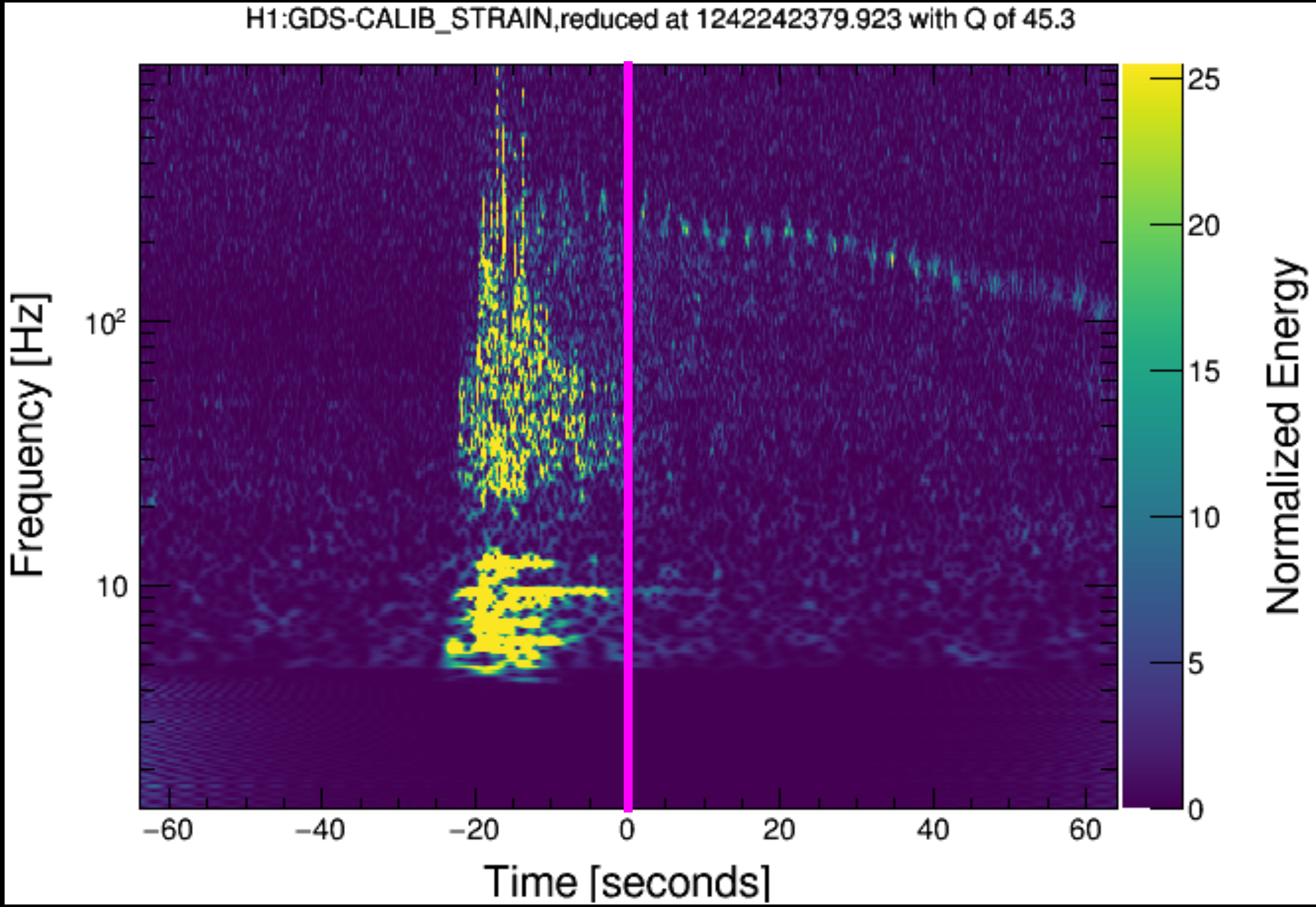
False Alarm Rate: 1.004e-08 [Hz] (one per ~3 years)
Probability system contains a neutron star: 100%
Probability the system is a binary neutron star merger: 75%
Probability the candidate is a detector glitch: 24%





LIGO-Virgo: GRAvitational-wave Canadidate Event DataBase (GraceDB.ligo.org)

Challenge: S190518bb case study



LIGO DCC G1900994: https://dcc.ligo.org/LIGO-G1900994/public

Characterizing noise outliers with the Temporal Outlier Factor

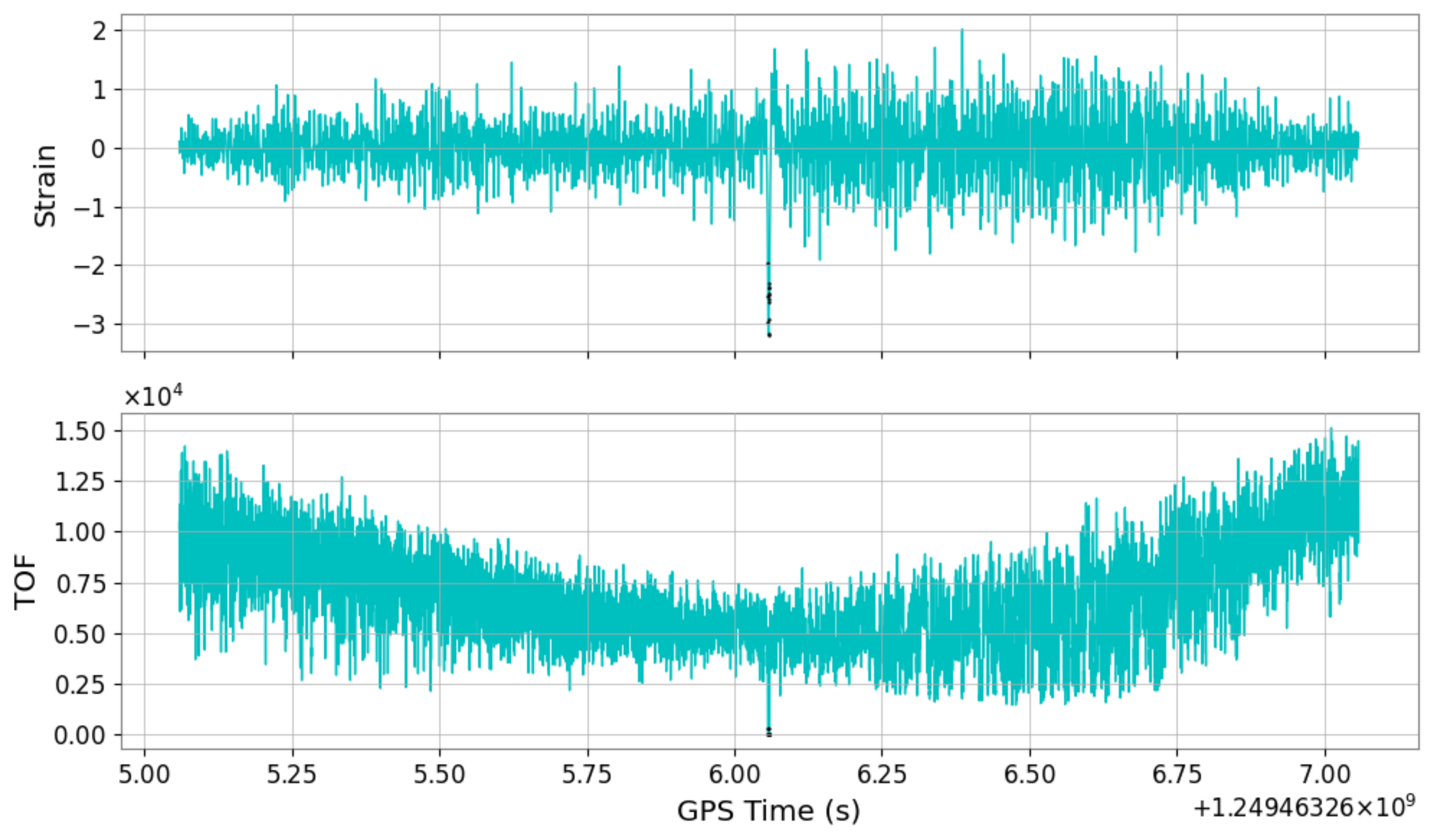
Study led by Julian Ding, UBC student and 2021 NSERC USRA awardee

An application of the **Temporal Outlier Factor** algorithm: Benkö et al. 2021 (arXiv 2004.11468)

$$\mathrm{TOF}(t) = \sqrt[q]{\frac{1}{k}\sum_{i=1}^{k}|t - t_i|^q}$$

For k nearest neighbours.

A small TOF indicates a “unique” feature in the analyzed time series.



Ding, Ng, McIver arXiv 2111.09465 (2021)

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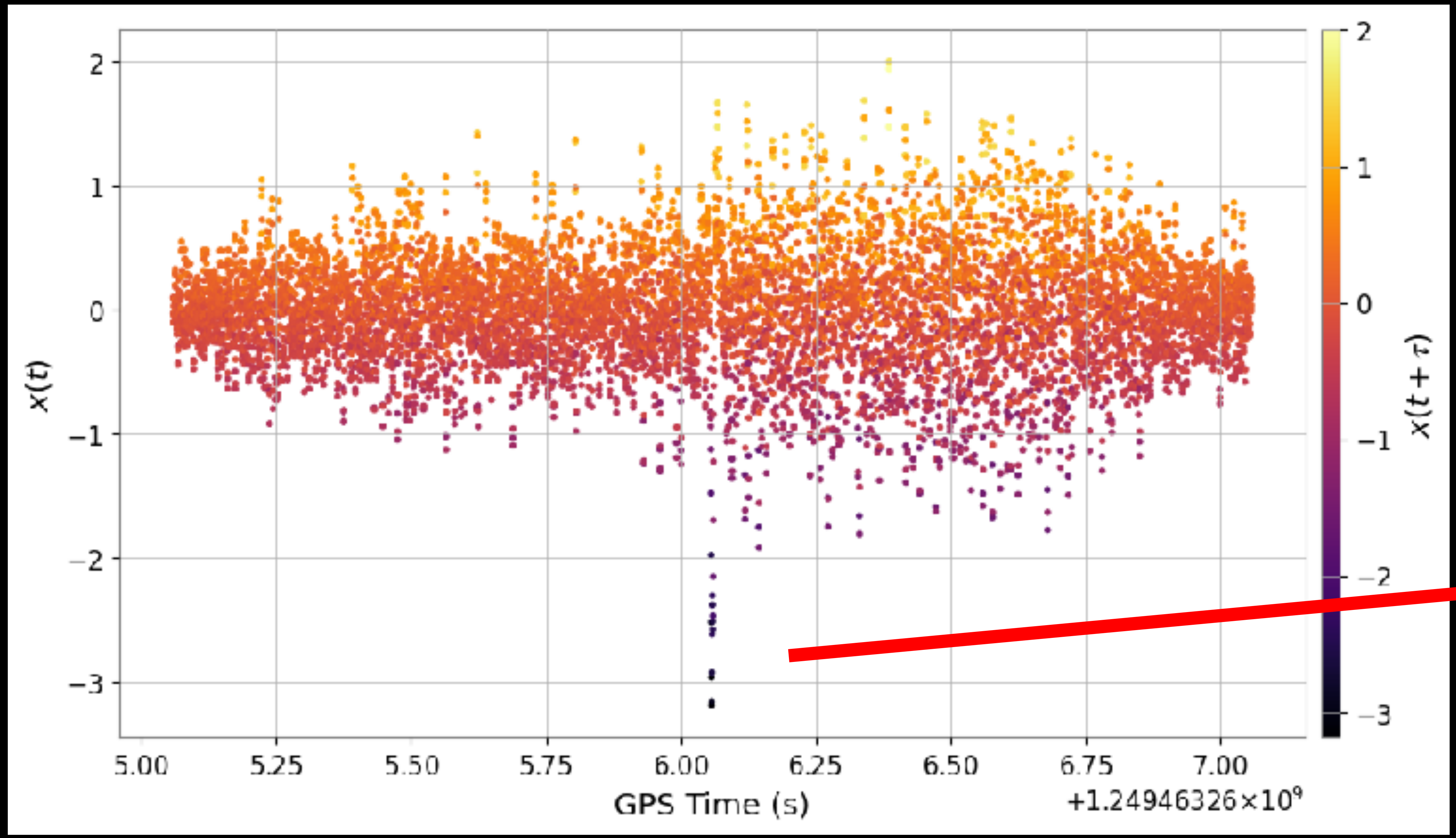

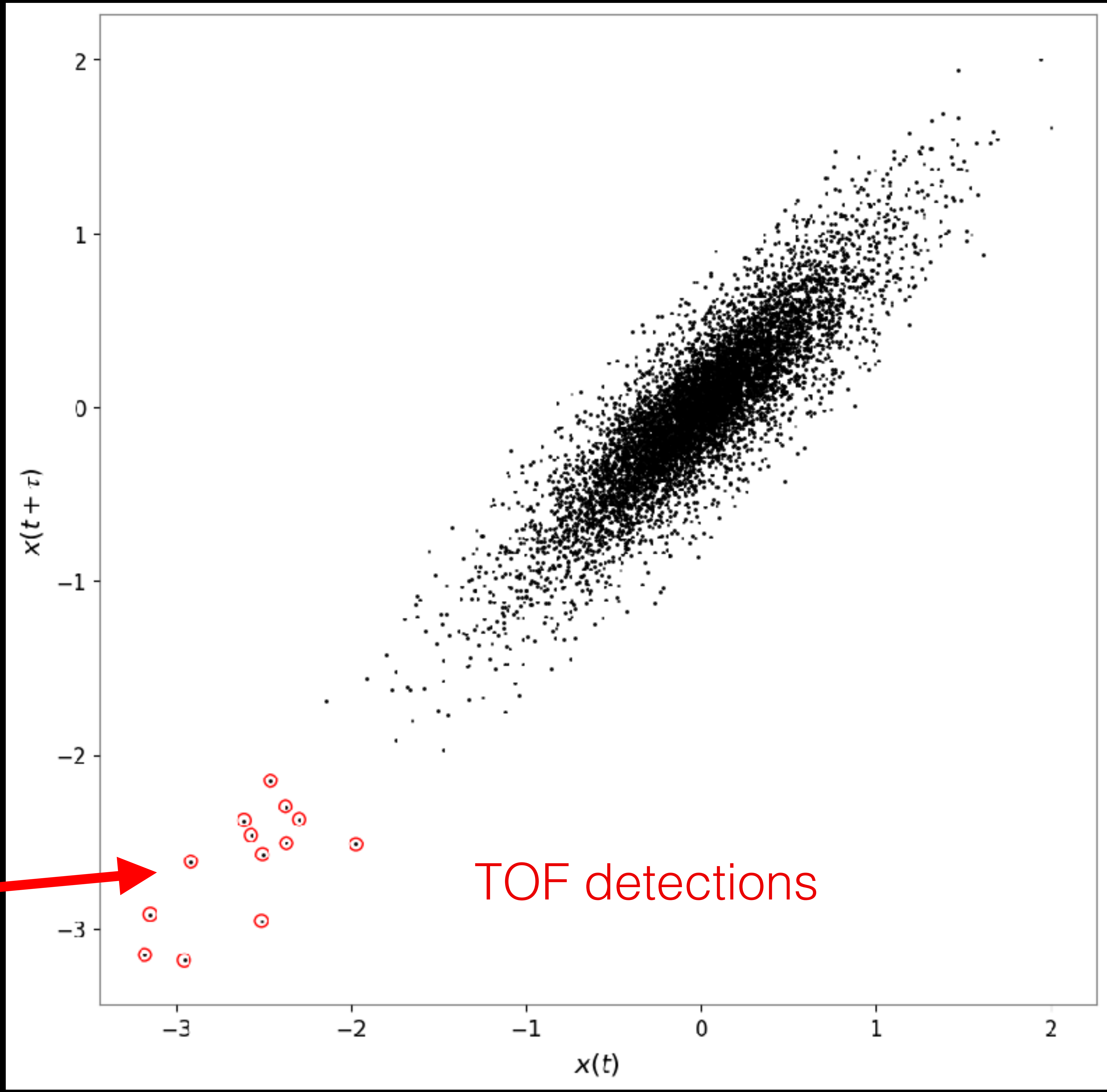

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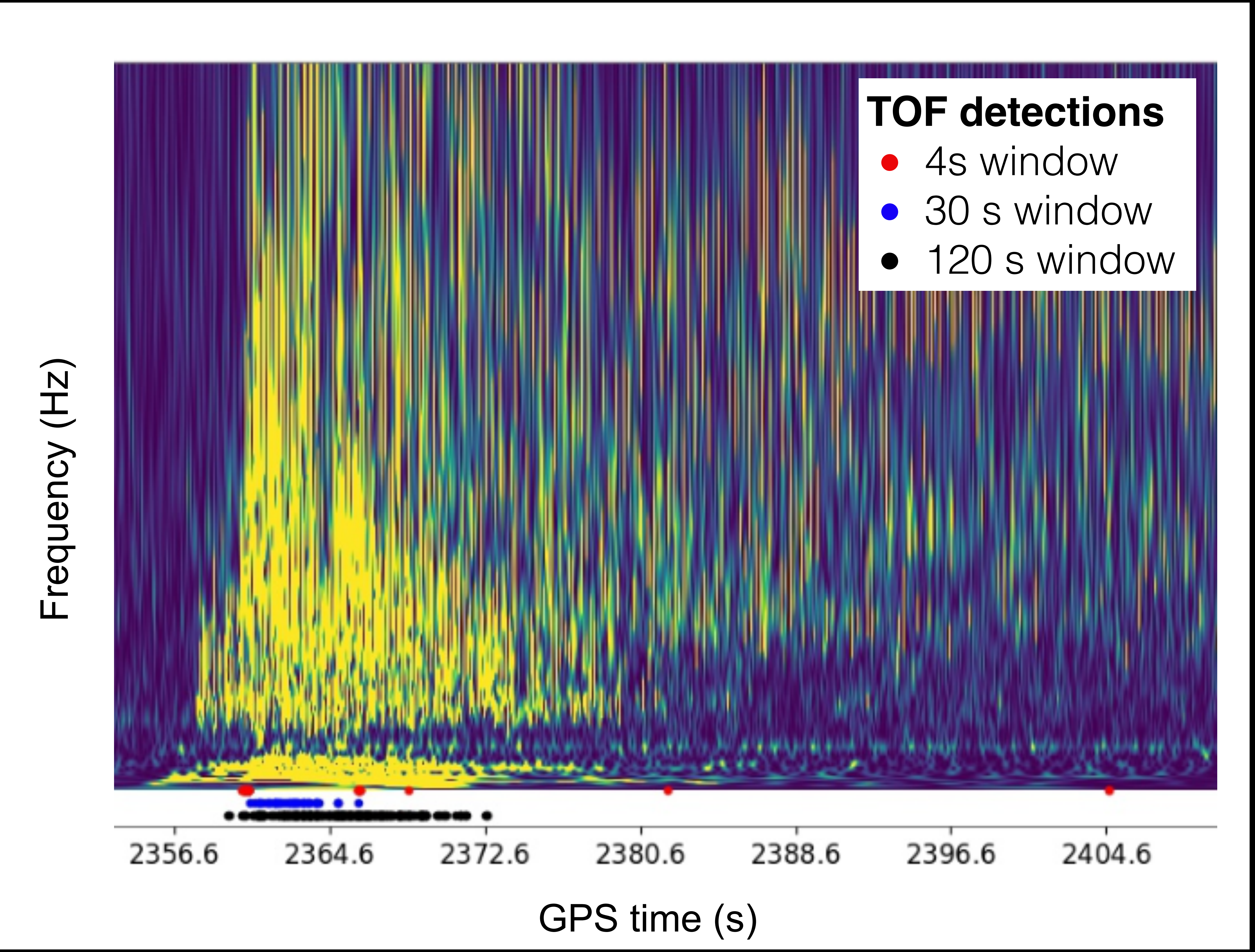


Ding, Ng, McIver arXiv 2111.09465 (2021)

GWSkyNet: ML classifier to distinguish real GW events from glitches

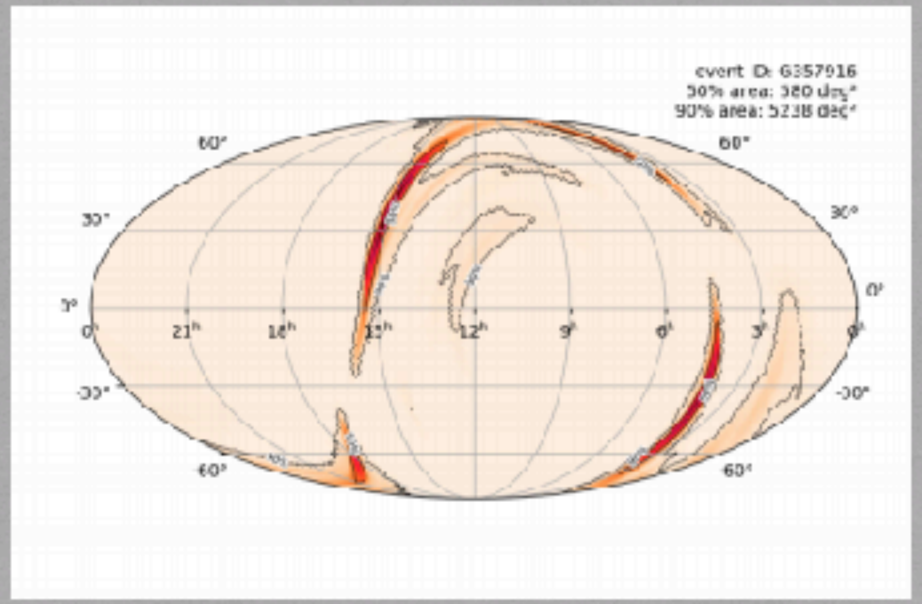
Study led by Dr. Miriam Cabero: Cabero, Mahabal, McIver (2020). ApJL. arXiv 2010.11829

Context and motivation:

Retracted event examples

S191220af: BNS

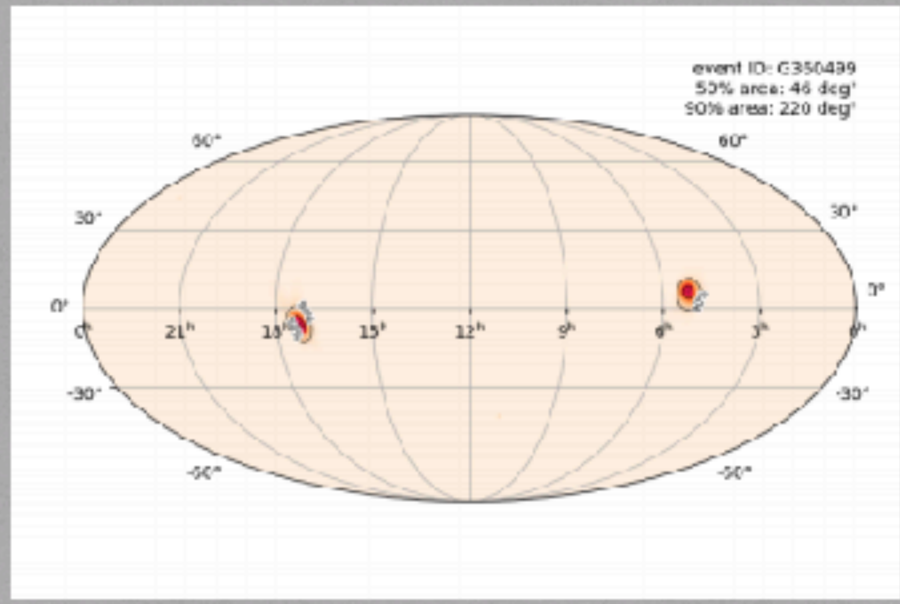
FAR: 1 per 80 yrs
d ~ 166 Mpc



- 1st followup: 13 mins
- Retraction: 32 mins

S200116ah: NSBH

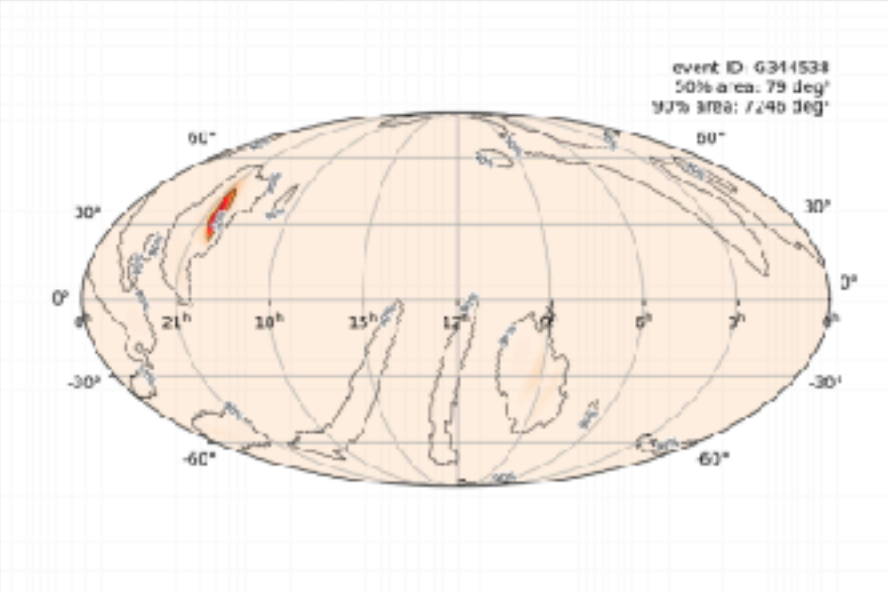
FAR: 1 per 15618 yrs
d ~ 31 Mpc



- 1st followup: 85 s
- Retraction: 19 mins

Unretracted event examples

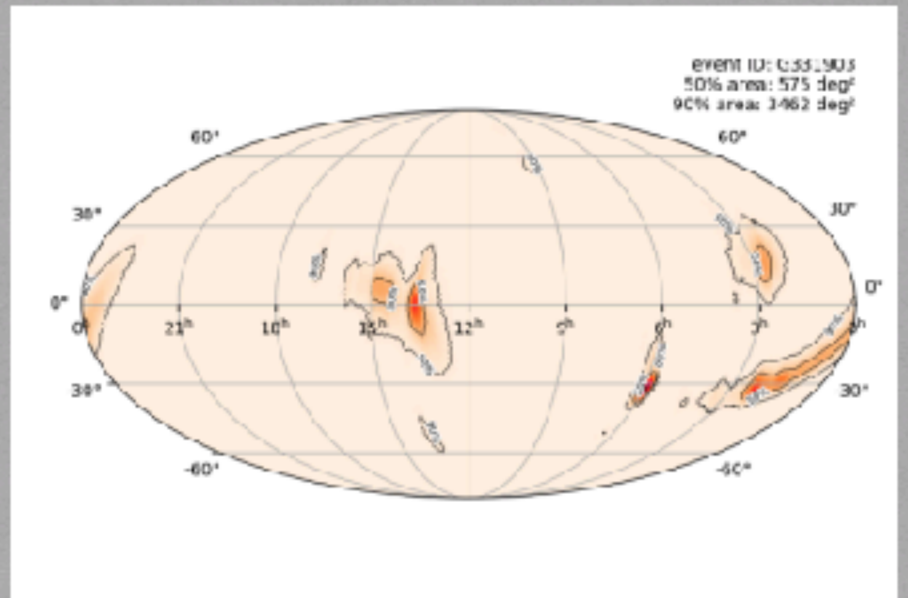
S190718y:
98% terrestrial



FAR: 1 per yr

1st followup:
25 mins

S190510g:
58% terrestrial



FAR: 1 per 3.6 yrs

1st followup:
18 mins

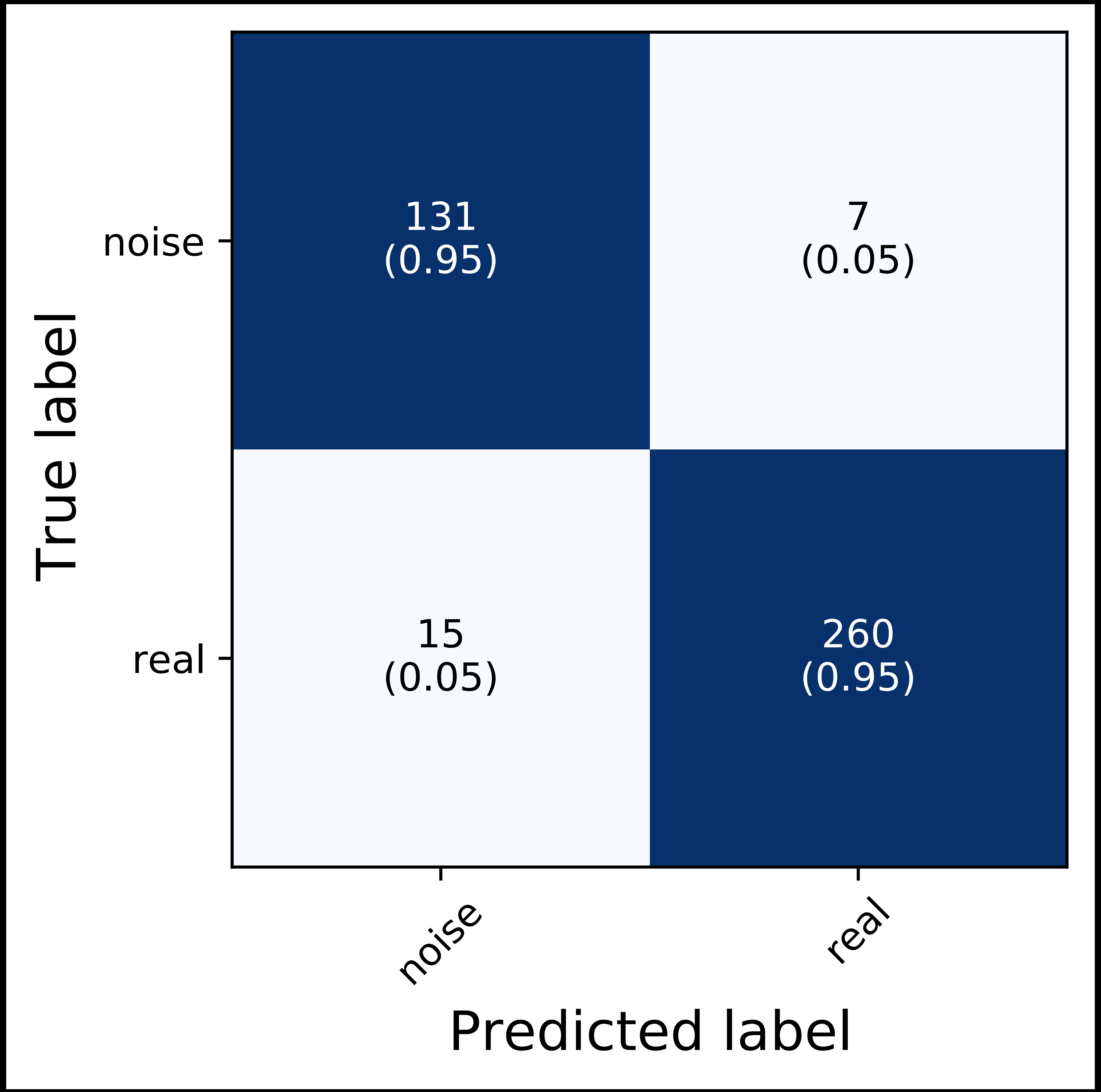
LIGO-Virgo: GRAvitational-wave Canadidate Event DataBase (GraceDB.ligo.org)

GWSkyNet: ML classifier to distinguish real GW events from glitches

Study led by Dr. Miriam Cabero.

Training features:
- Skymap image produced with BAYESTAR (Singer et al. 2016)
- Stacked sky volume images
- Detector network
- Normalization factors

Performance:
GWSkyNet correctly classified as terrestrial:
- 10/22 O3a retracted events (~50% improvement!)
- 6/6 unretracted O3a events



Cabero, Mahabal, McIver (2020). ApJL. arXiv 2010.11829

Patrick Godwin's talk tomorrow will discuss important methods that make use of auxiliary sensors

See also talks this week by Gaby Gonzalez,
Guillermo Valdes, Jenne Driggers, and Gabriele Vajente

Bayesian inference of GW properties: noise assumptions

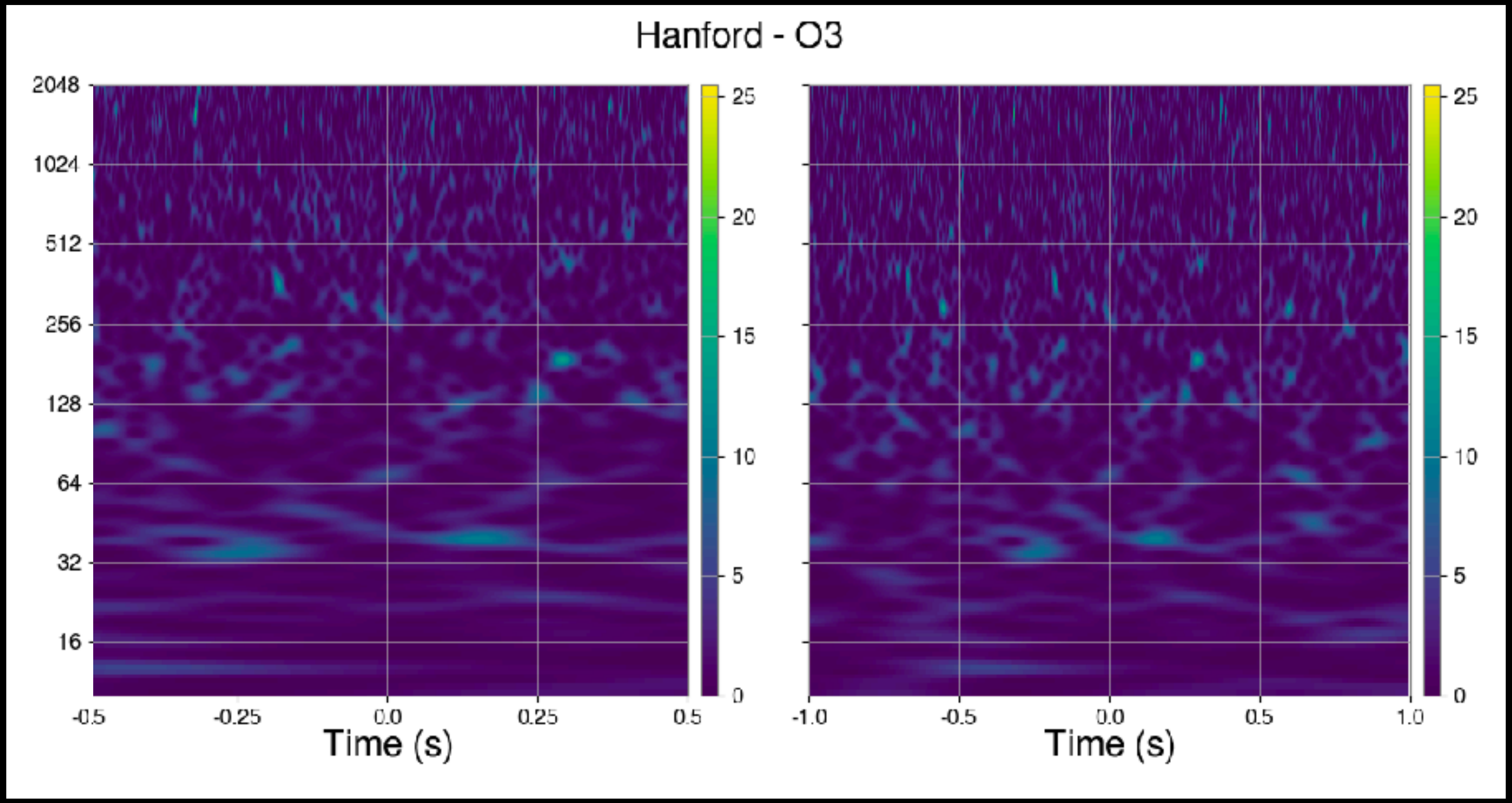
$$\boldsymbol{d} = \boldsymbol{h} + \boldsymbol{n}.$$

Data model, d = signal (through lens of detector network), h + detector noise, n

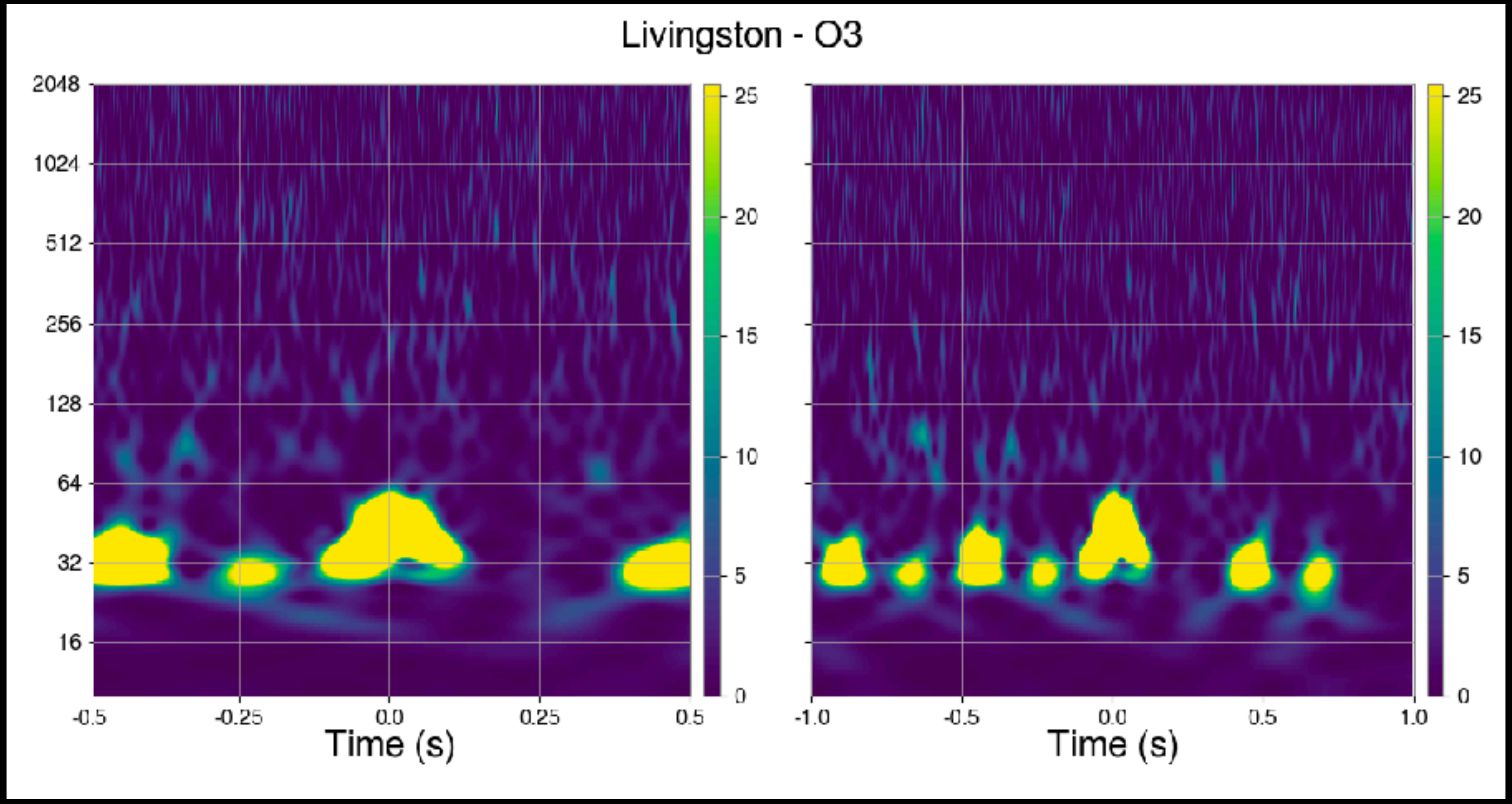
$$p(\mathbf{d}|H_N, S_n(f)) = \exp \sum_i \left[-\frac{2|\tilde{d}_i|^2}{T S_n(f_i)} - \frac{1}{2}\log(\pi T S_n(f_i)/2) \right]$$

Likelihood: we expect the residual of d-h to be *consistent with Gaussian noise*

Gaussian

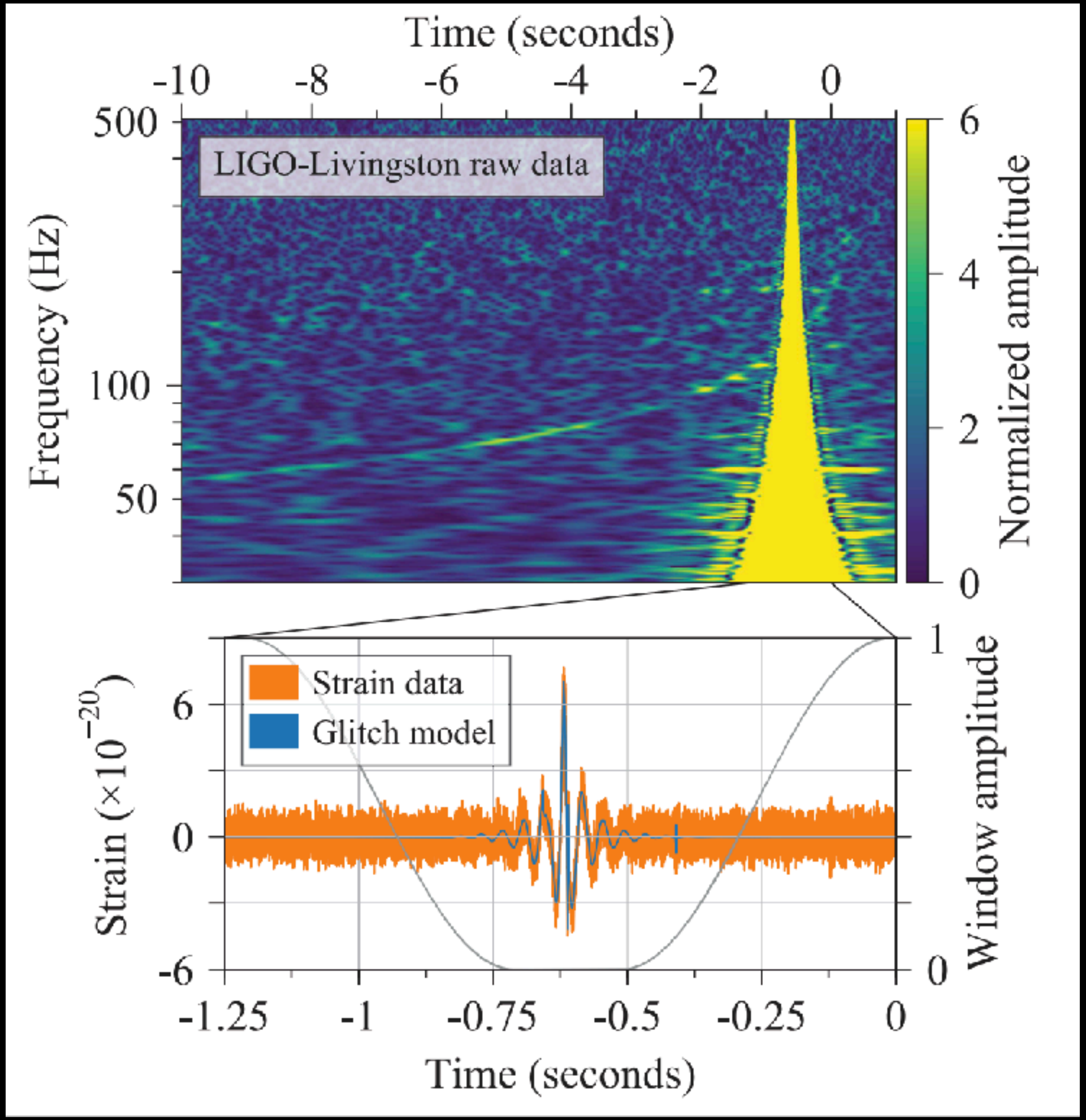


Non-Gaussian!



Images from LigoDVweb's GlitchDB, classified by GravitySpy

GW170817 and our most famous mitigated glitch



B.P. Abbott et al. PRL 119 161101 (2017) arXiv 1710.05832

Loud, short-duration glitches are the ***easiest case*** to mitigate (either through modelling and subtraction, gating, or other means).

GWTC candidates that have required glitch mitigation

GWTC-2 arXiv 2010.14527

Name	Mitigation
GW190413_134308	L1 glitch subtraction, glitch-only model
GW190424_180648	L1 glitch subtraction, glitch-only model
GW190425	L1 glitch subtraction, glitch-only model
GW190503_185404	L1 glitch subtraction, glitch-only model
GW190513_205428	L1 glitch subtraction, glitch-only model
GW190514_065416	L1 glitch subtraction, glitch-only model
GW190701_203306	L1 glitch subtraction, glitch+signal model
GW190727_060333	L1 $f_{\rm min}$: 50 Hz
GW190814	L1 $f_{\rm min}$: 30 Hz; H1 non-observing data used
GW190924_021846	L1 glitch subtraction, glitch-only model

10 of 39 candidate events (passing the FAR threshold of 2.0 yr^{-1})

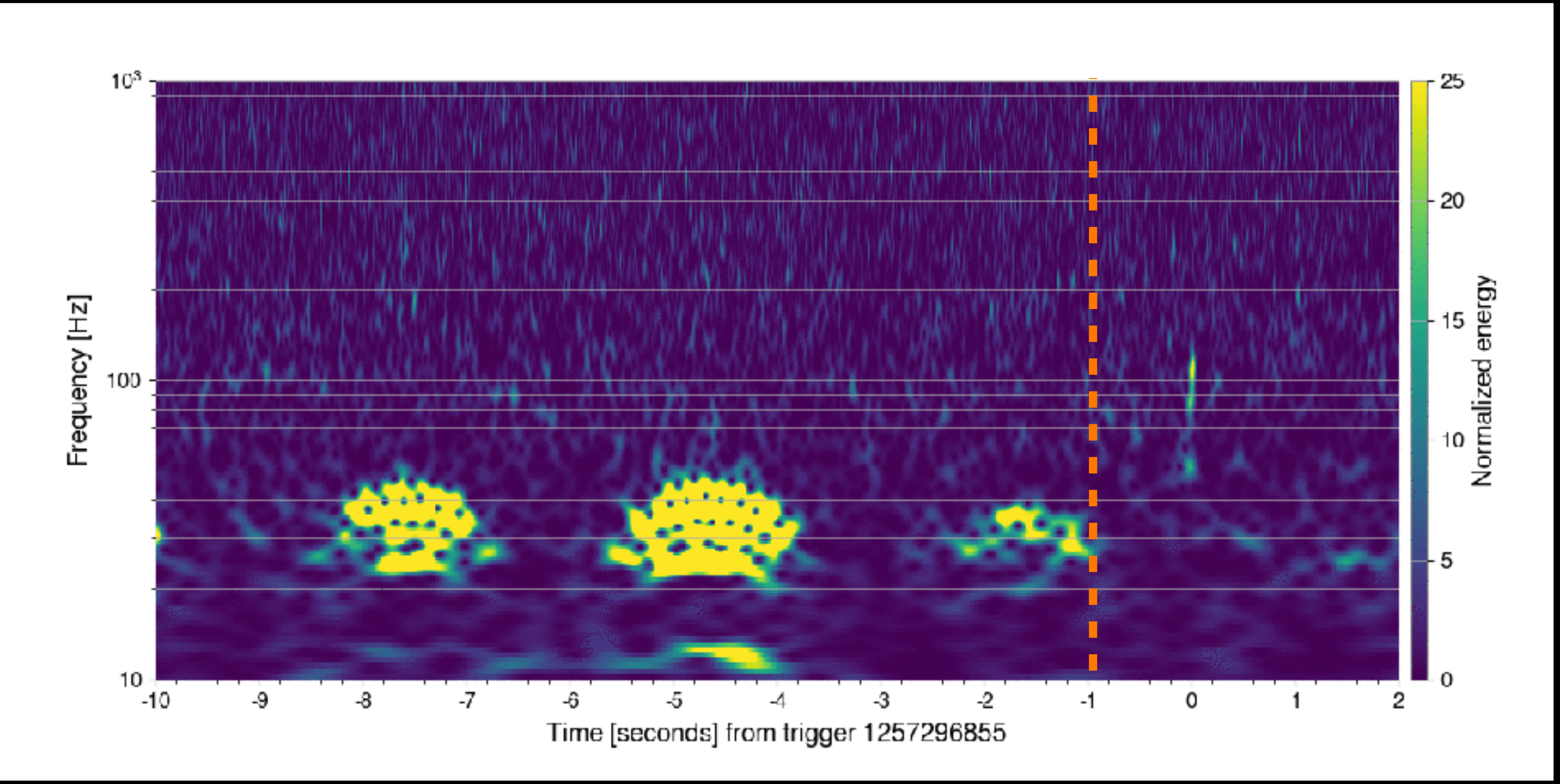
GWTC-3 arXiv 2111.03606

Event	Affected detectors	Mitigation
GW191105_143521	Virgo	BayesWave deglitching
GW191109_010717	Hanford, Livingston	BayesWave deglitching
GW191113_071753	Hanford	BayesWave deglitching
GW191127_050227	Hanford	BayesWave deglitching
GW191219_163120	Hanford, Livingston	BayesWave deglitching
GW200105_162426	Livingston	BayesWave deglitching
GW200115_042309	Livingston	BayesWave deglitching
GW200129_065458	Livingston	Linear subtraction

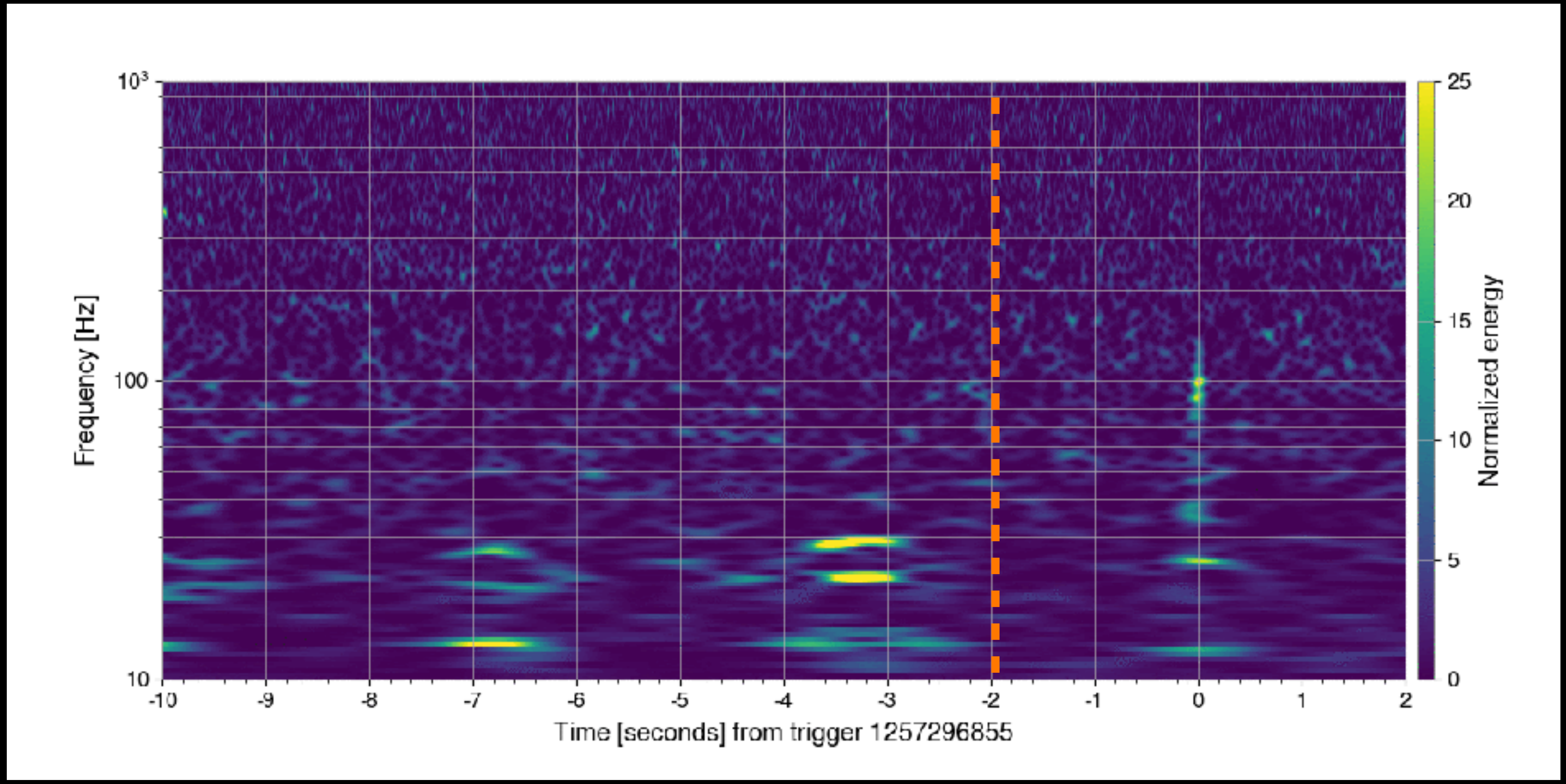
8 of 39 candidate events (passing the threshold $p_{astro} > 0.5$)

GWTC-3 candidates that have required glitch mitigation

S191109d - LIGO Hanford



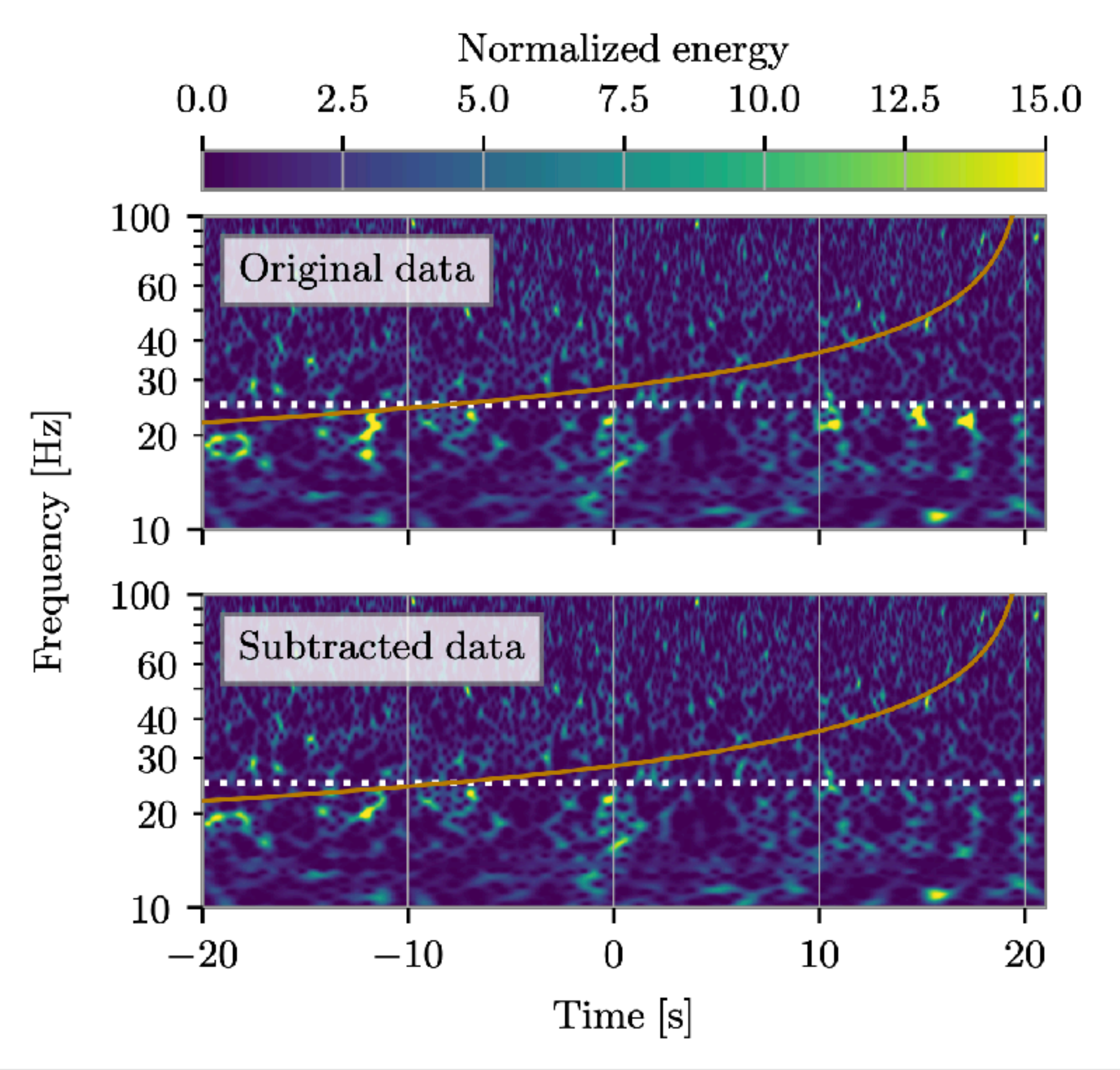
S191109d - LIGO Livingston



Gifs by Derek Davis

GWTC-3 candidates that have required glitch mitigation

GW200115_042309 - LIGO Livingston



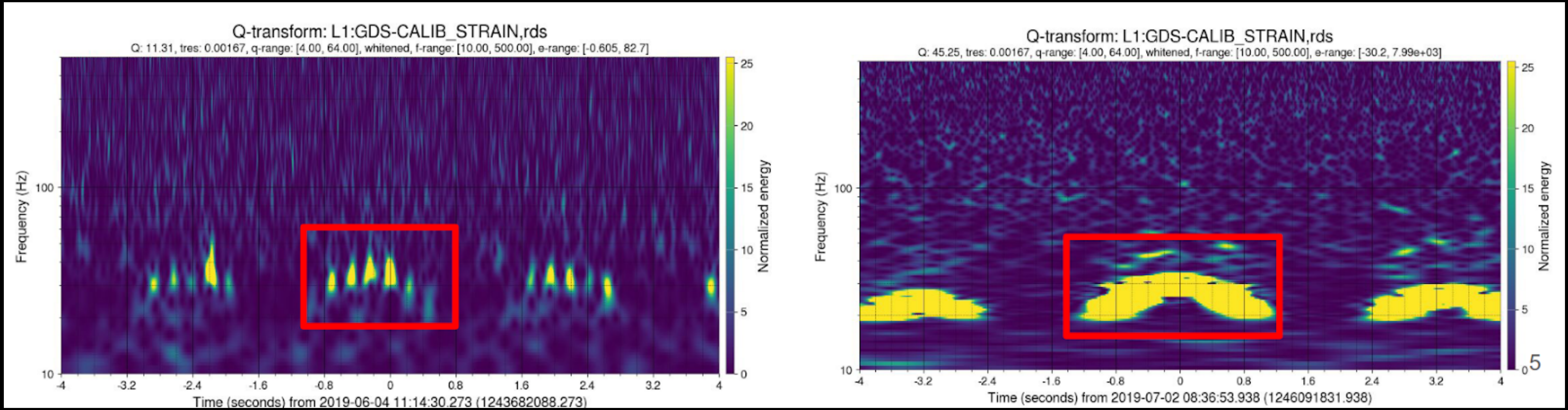
NSBH discovery analysis used low frequency cutoff of 25 Hz (arXiv 2106.15163)

GWTC-3 analysis used glitch-subtracted frames (arXiv 2111.03606)

GWTC-3: arXiv 2111.03606

How Gaussian is "Gaussian enough"?

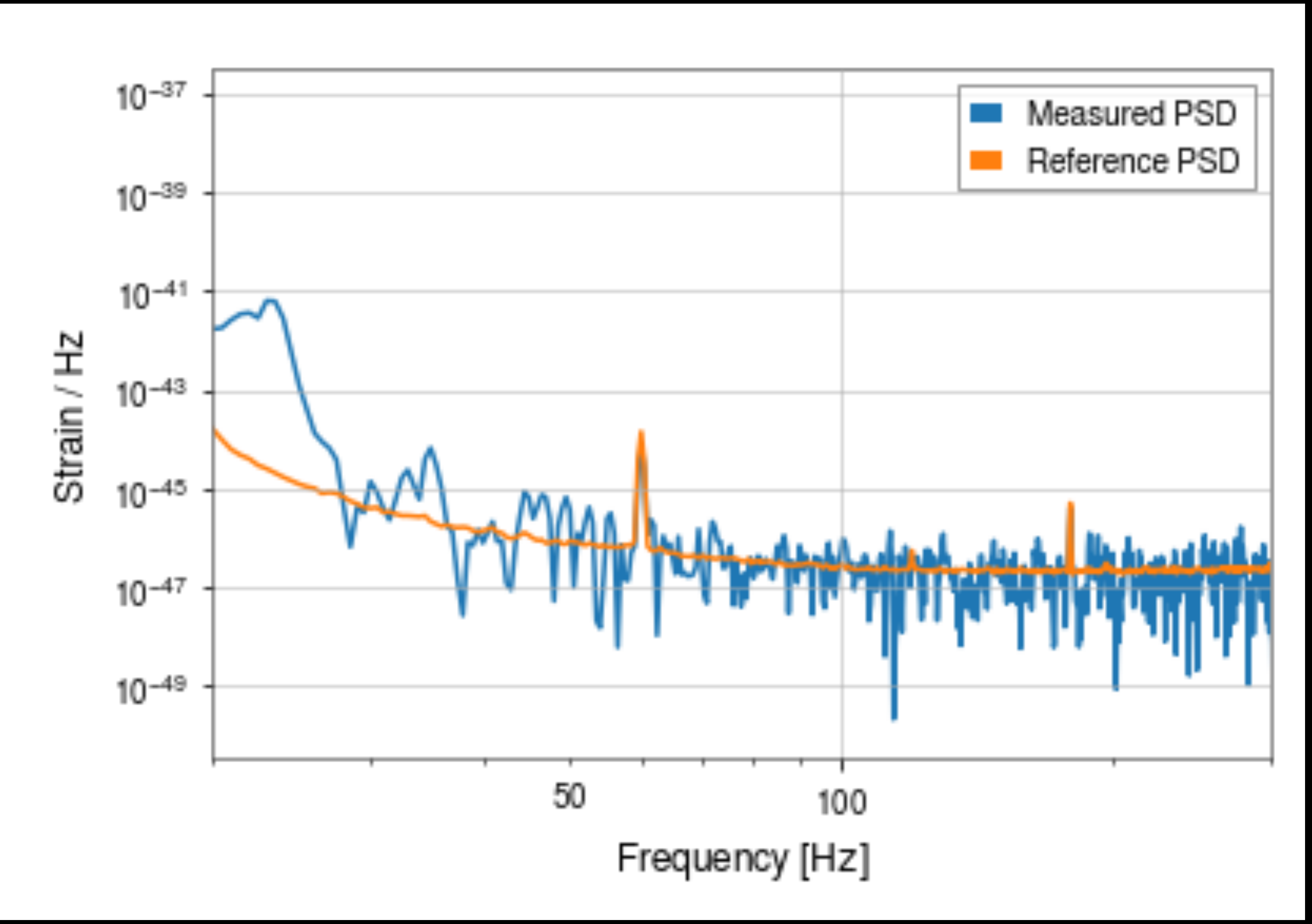
Step 1: Identify glitches that could overlap with analysis window

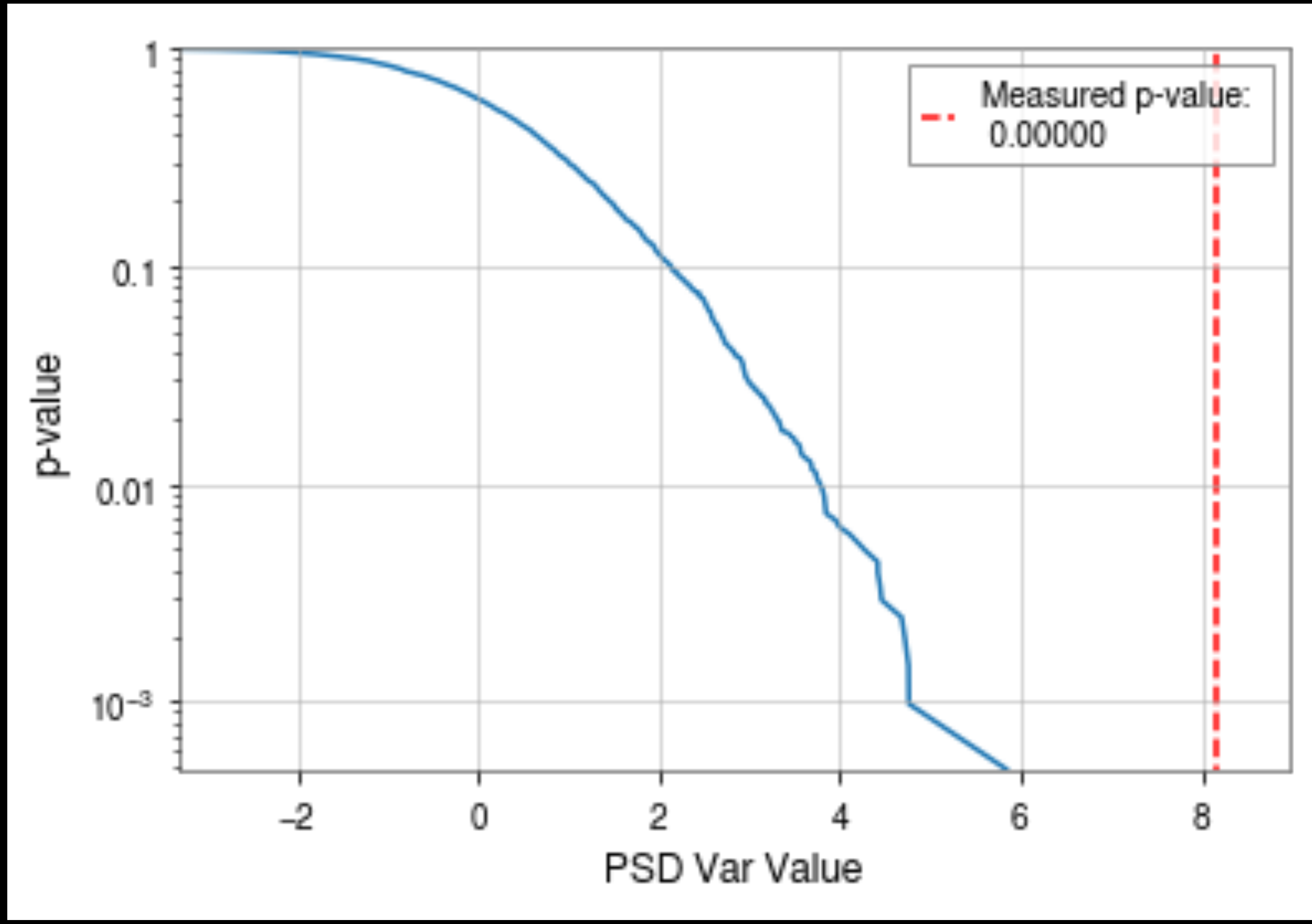


In O3 this step was produced by humans. Automation is a long term goal.

How Gaussian is "Gaussian enough"?

Step 2: Compare PSD in that time-frequency region to some reference time.
p-test: *Are differences consistent with Gaussian noise?*





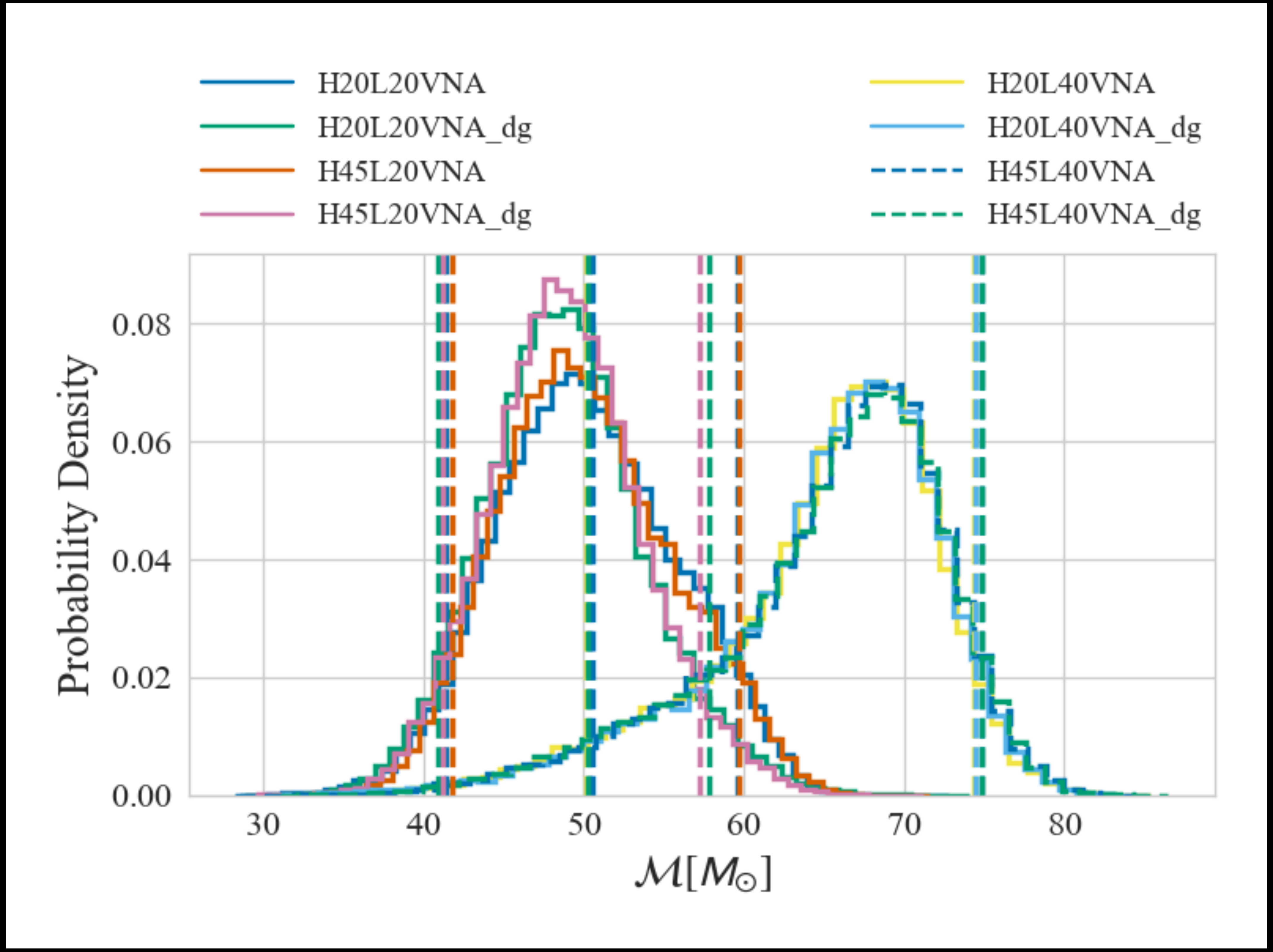
In O3 this step was largely automated.

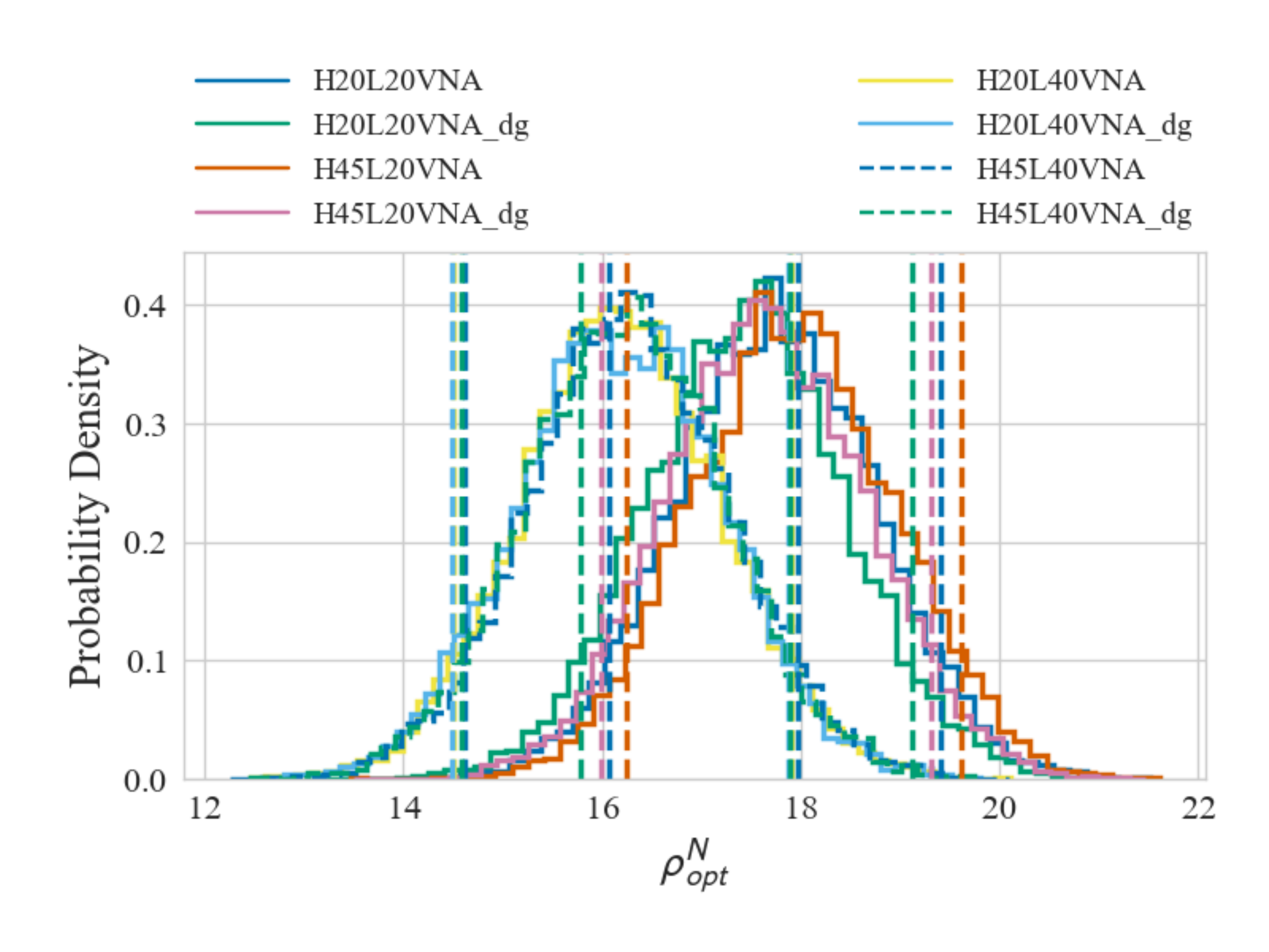
Test development and automation by Derek Davis, based on the method by
S. Mozzon et al. Class. Quantum Grav. 37 215014 (2020)

Which mitigation method: impact on PE runs

Step 3: Compare PE runs with alternate glitch mitigation methods to raw data.
Does mitigation impact the estimated parameters? Does it reduce recovered SNR?

f_low settings [Hz]		
H1	L1	V1
20	20	-
45	20	-
20	40	-
45	40	-

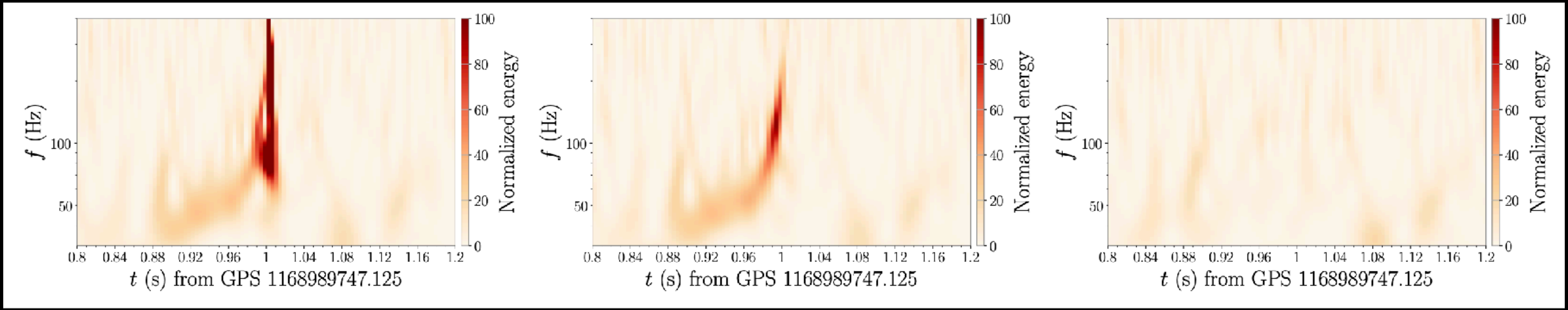


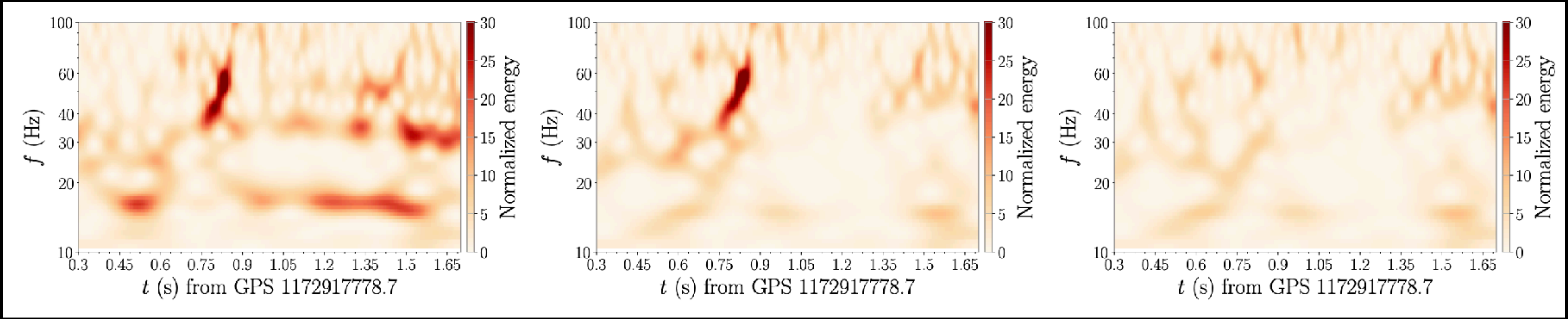


In O3 this step was produced by ~~humans~~ Isobel (plots by Isobel Romero-Shaw)

Prospects for rapid glitch mitigation: CBC signal models

Simulated signal + glitch ⟶ Glitch model subtracted ⟶ Signal model subtracted



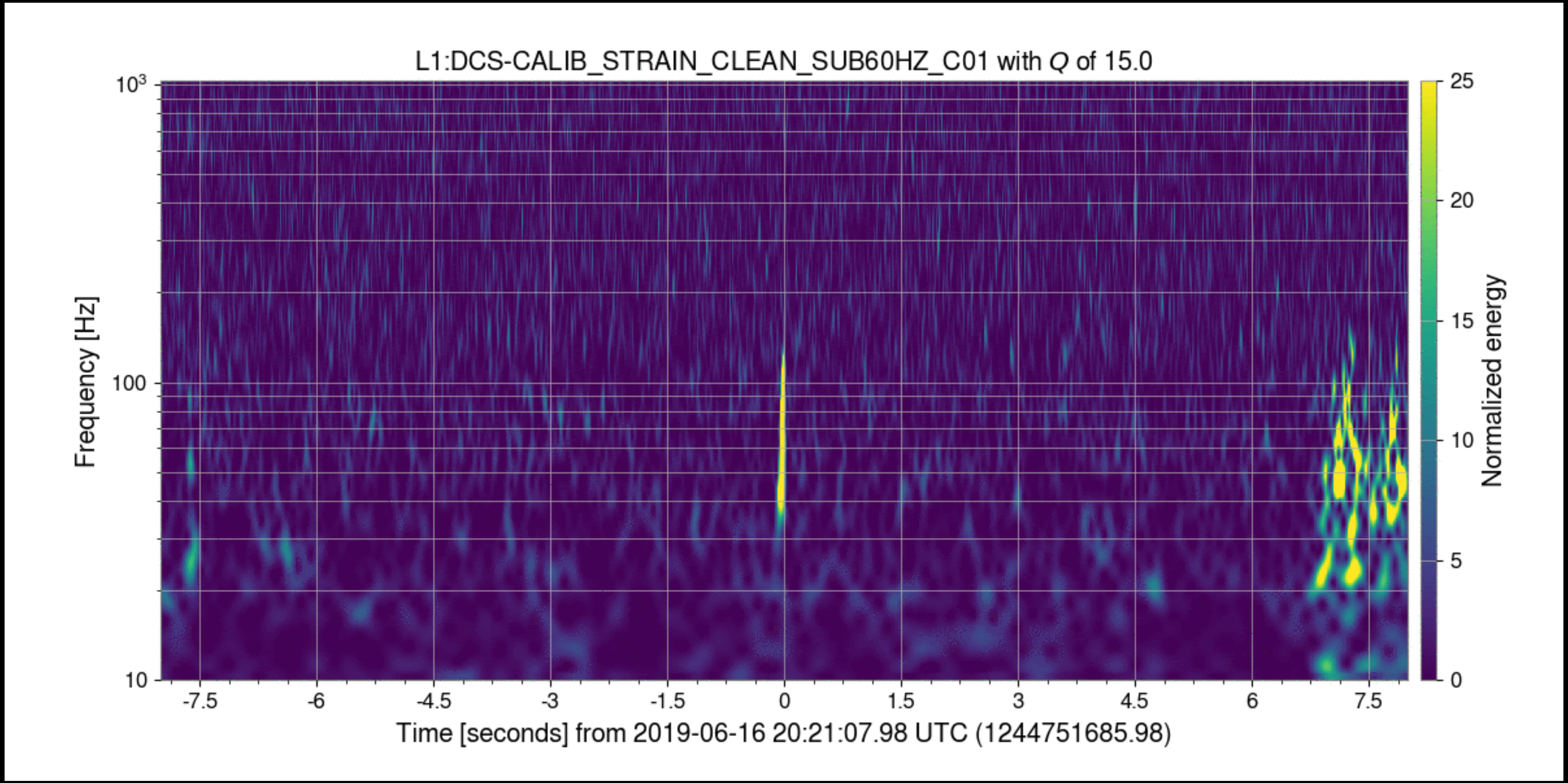


Katerina Chatziioannou et al. Phys Rev D 103, 044013 (2021) arXiv 2101.01200

Characterizing source property estimation for GWs+glitches

Study led by Yannick (Niko) Lecoeuche, UBC grad student, with many LSC contributions

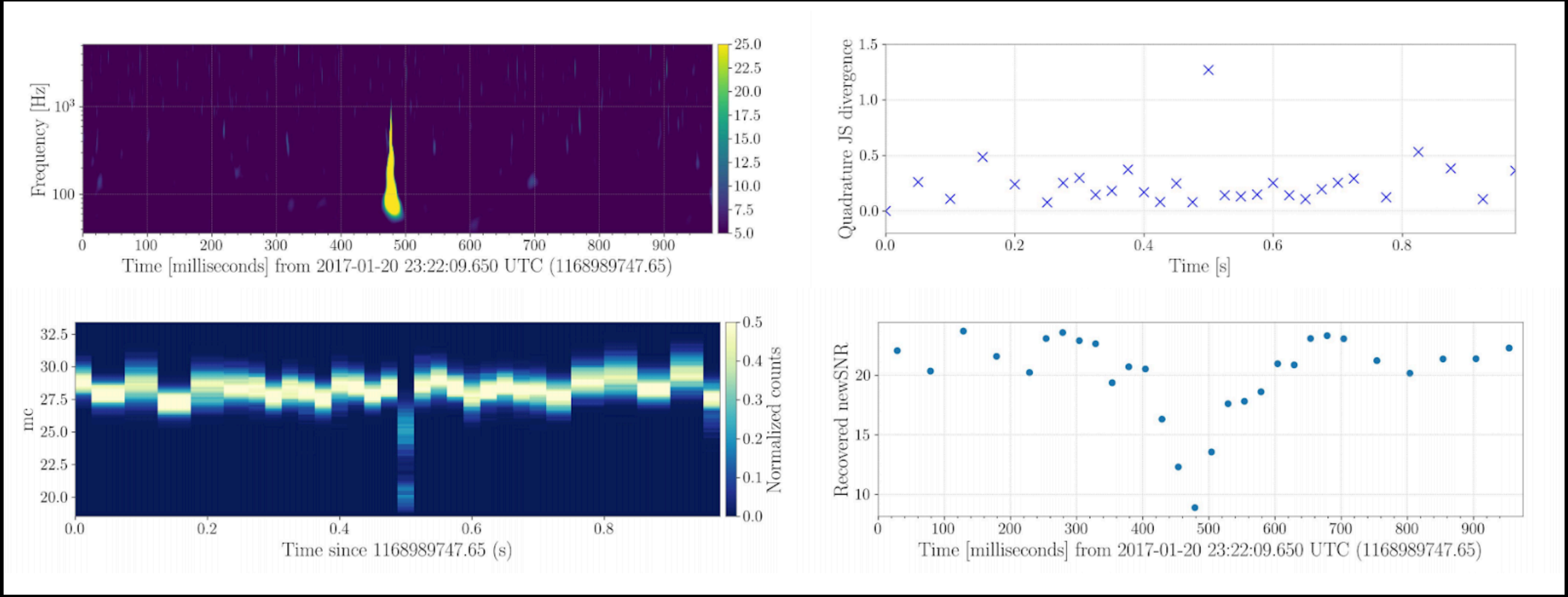
Goal: characterize the impact of overlap between glitches and true signals on source property estimation



Characterizing source property estimation for GWs+glitches

Study led by Yannick (Niko) Lecoeuche, UBC grad student, with many LSC contributions

How far away in time do glitches need to be from signals in order for us to safely ignore their effects?



See Pankow et al. 2018 and Chatziioannou et al. 2021 for studies on glitch mitigation.
See Powell 2018 for study on glitch amplitude. Study in prep by Ronaldas Macas et al characterizing online PE and skymaps.

Conclusions

Mitigating glitches in GW detector data is difficult, but vital.

Expected increase in event rate will require further automation.

Recent developments look promising, to that end. **There are many more great efforts working toward this goal with the LVK.**
See talks this week by Gaby, Guillermo, Patrick, Marco, and others.

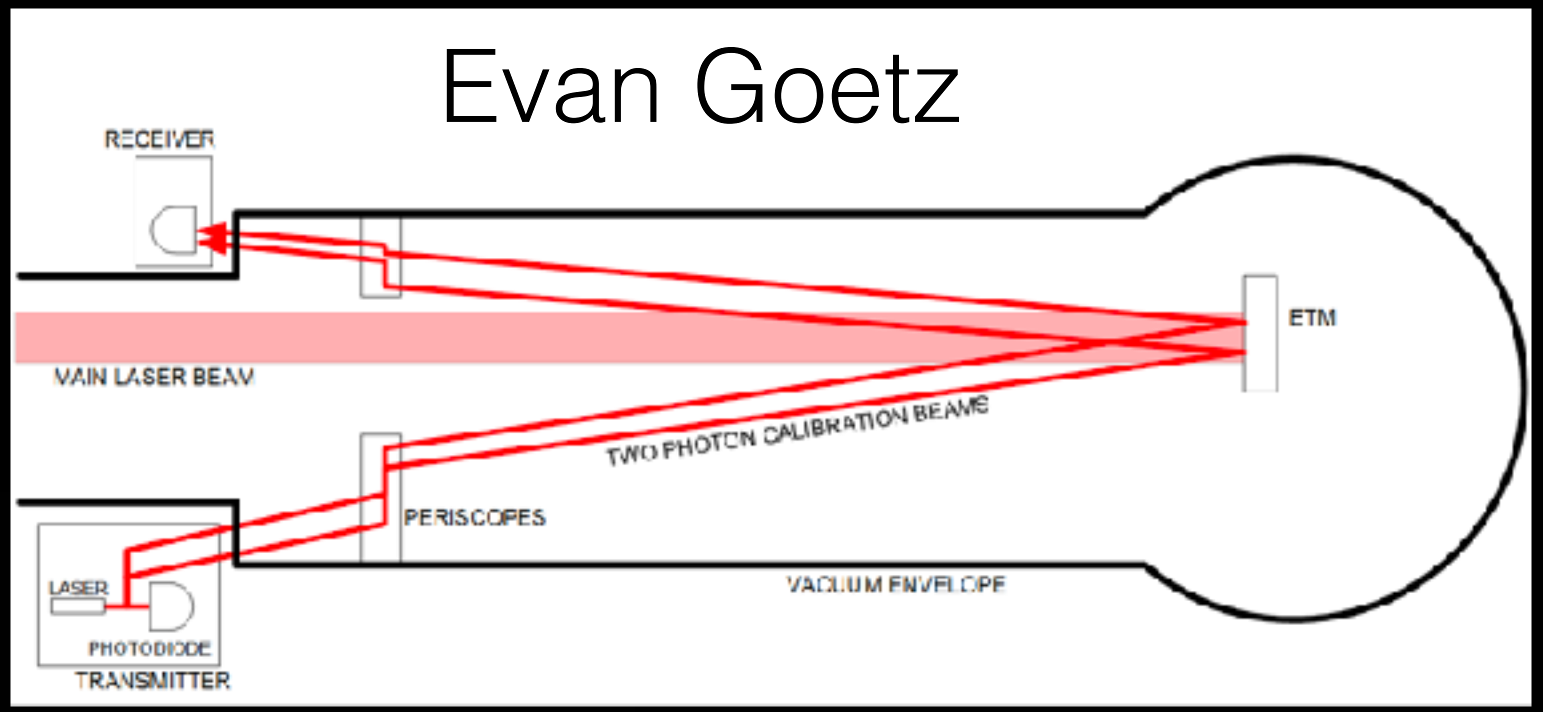
Looking forward to O4 and beyond!

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Extra slides

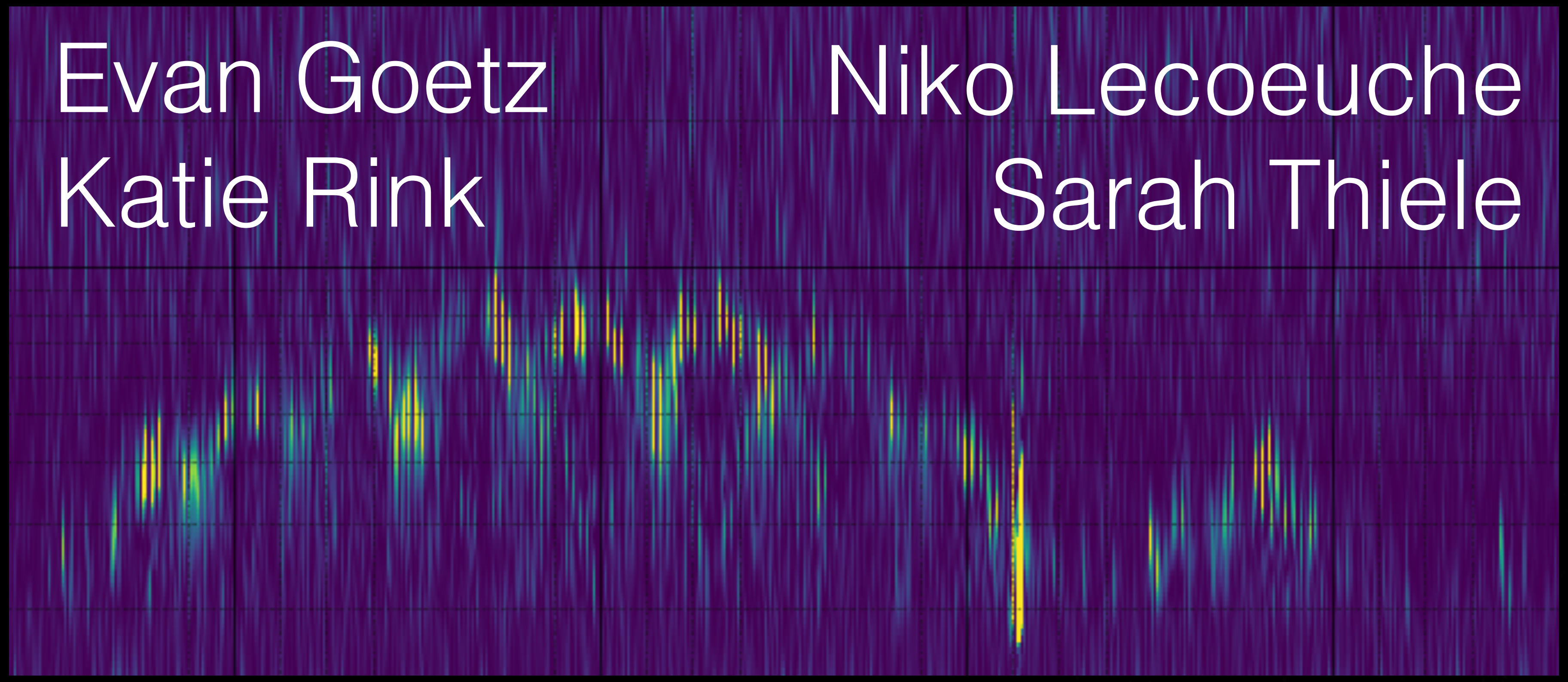
The UBC GW astrophysics group

Evan Goetz



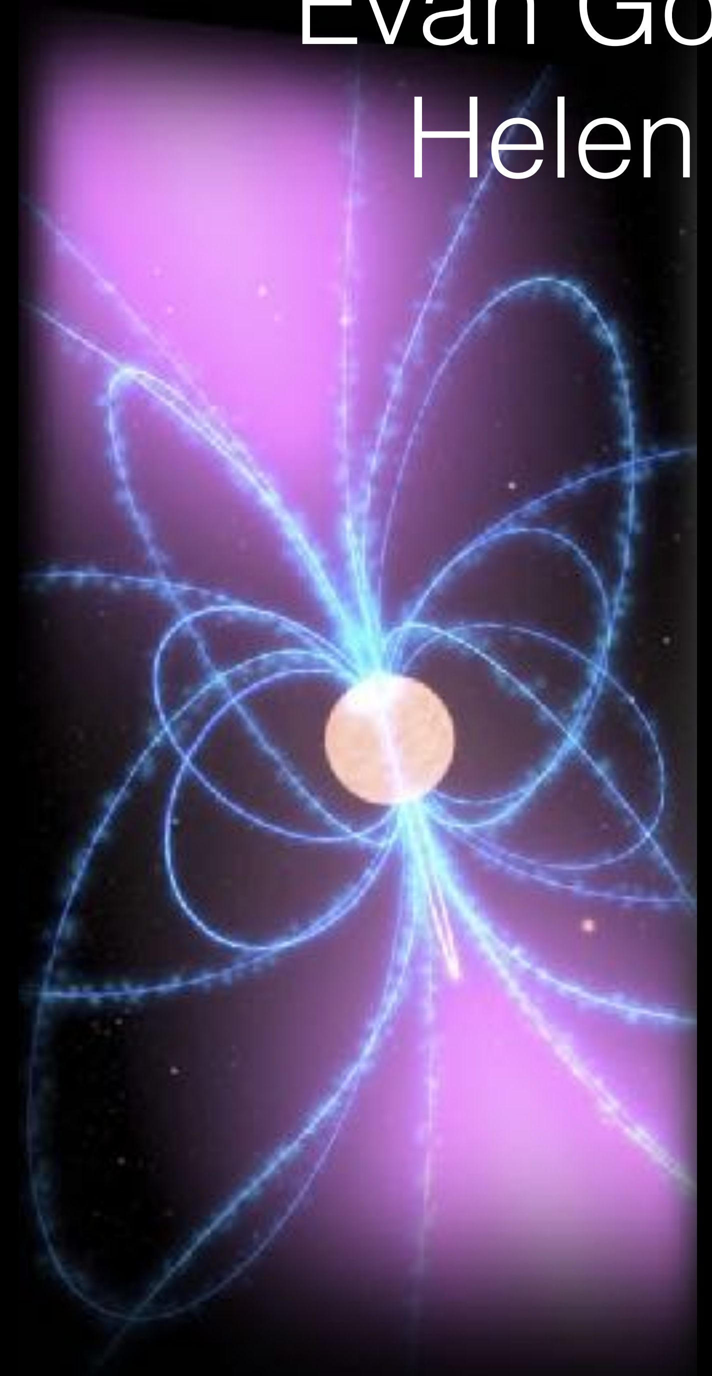
Evan Goetz
Katie Rink

Niko Lecoeuche
Sarah Thiele

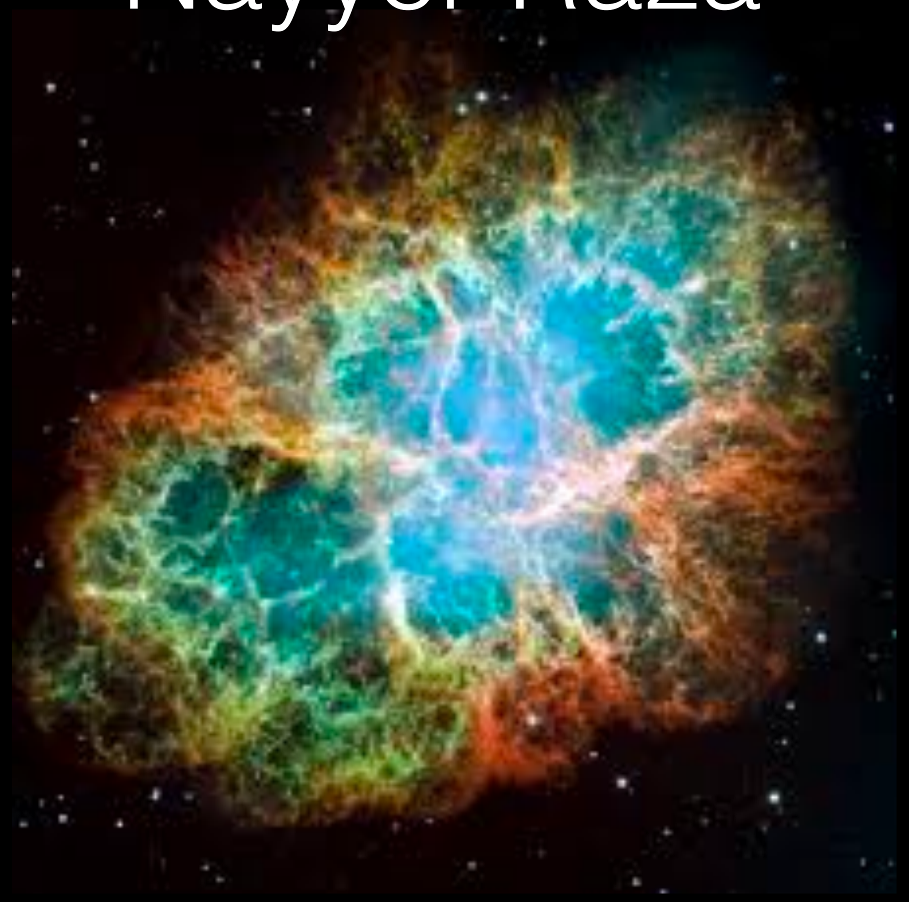


Evan Goetz, Seraphim Jarov
Julian Ding, Sabiha Bhuiyan

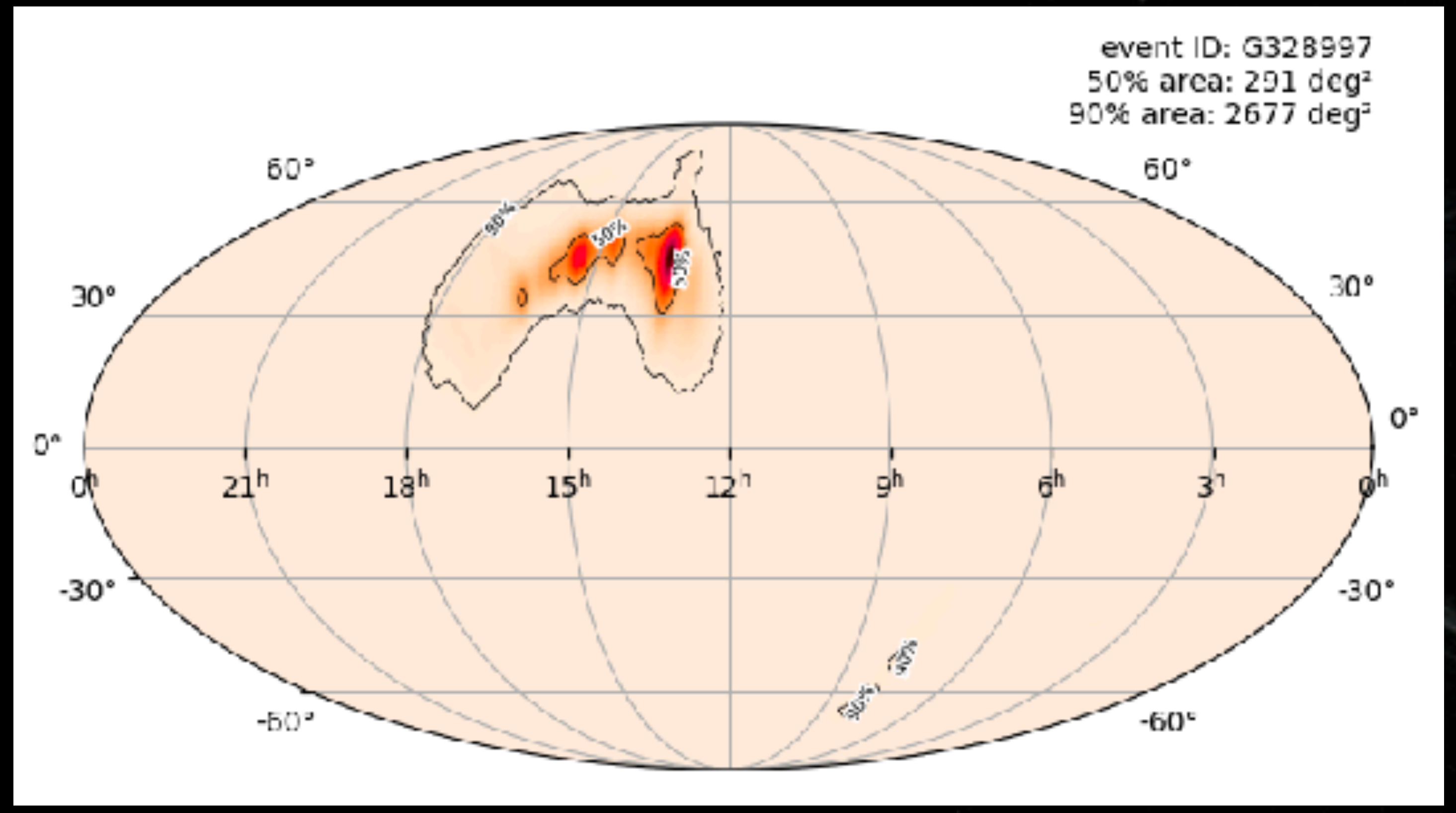
Evan Goetz
Helen Du



Nayyer Raza



Miriam Cabero, Mervyn Chan



Miriam Cabero
Alan Knee
Nikolas Boily