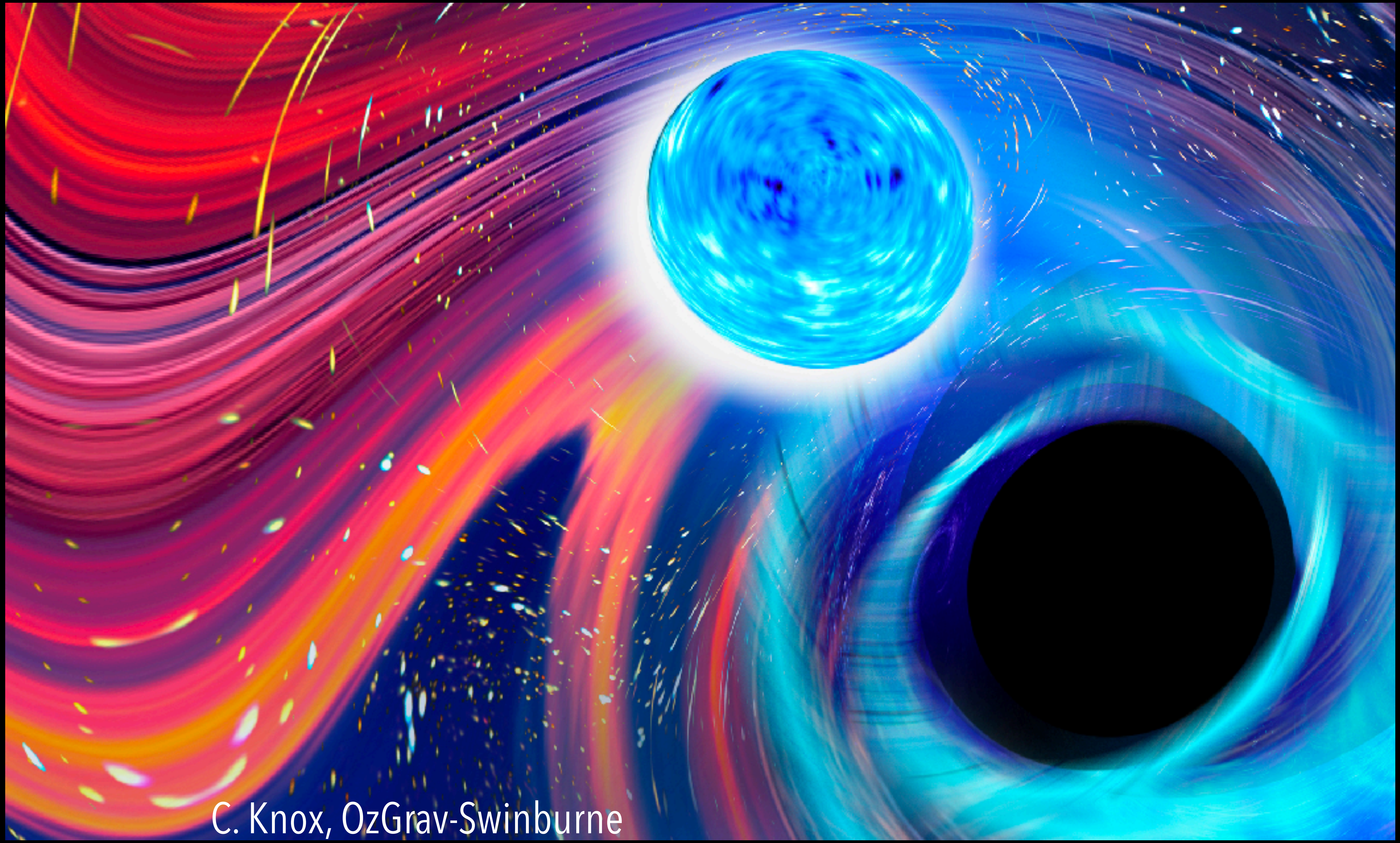
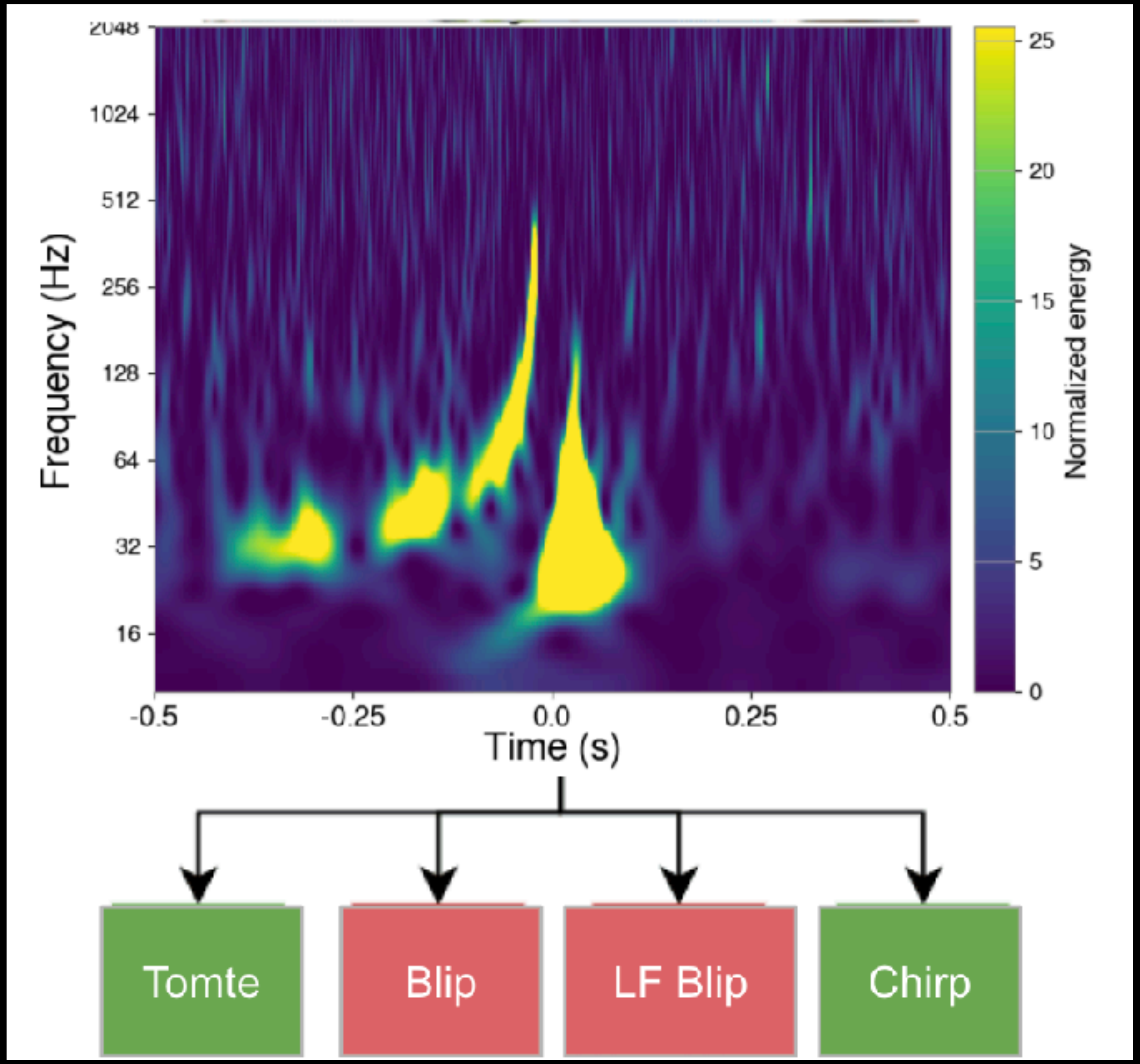
Challenges for multi-messenger astronomy with gravitational waves





Dr. Jess McIver for the LVK

CAP Congress

June 20, 2023

LIGO DCC G2301191

NASA

Independent measurement of Hubble constant

Insight into the nature of highly dense matter

See Phil Landry’s talk this afternoon!

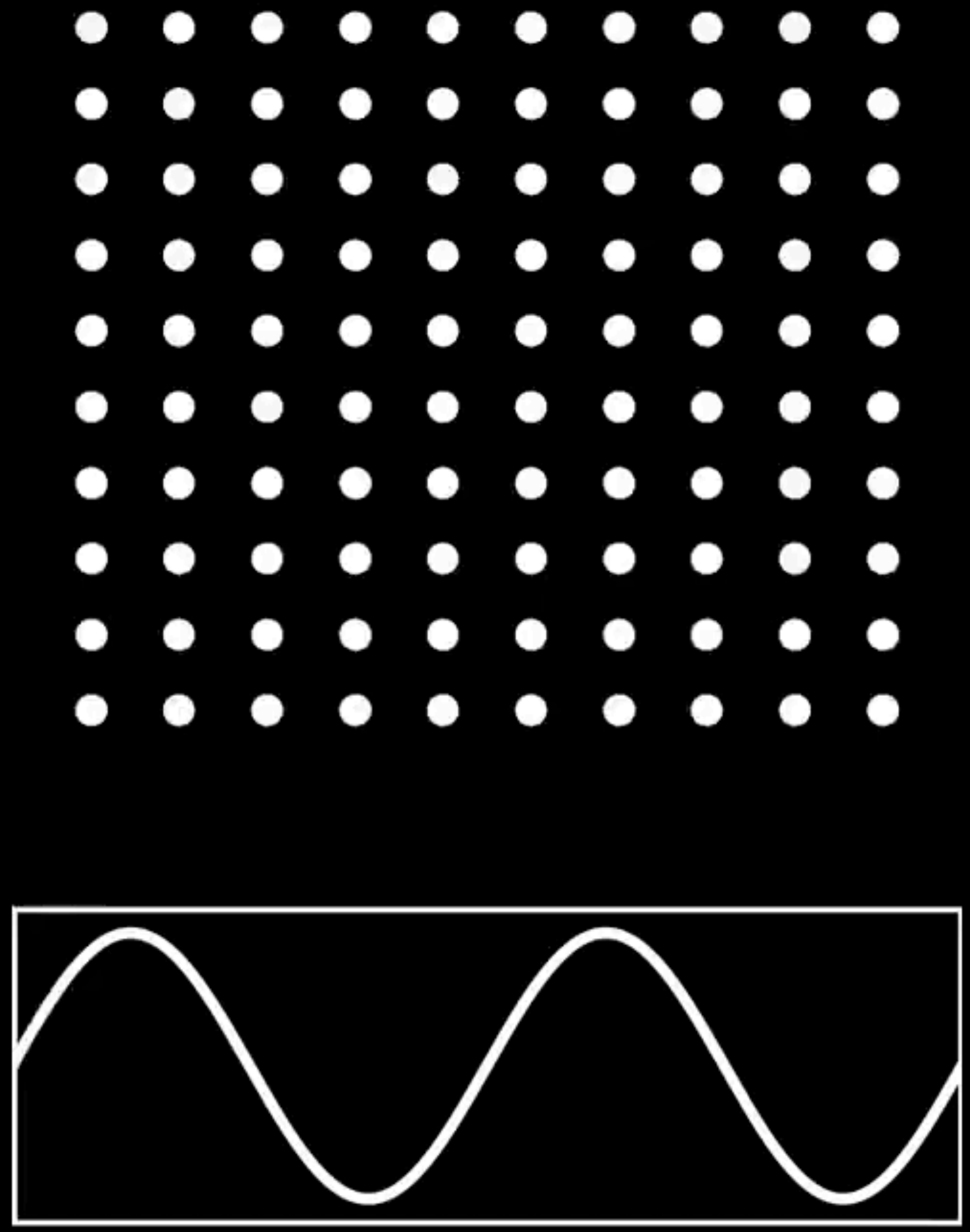
Tests of general relativity in extreme spacetime curvature

Census of stellar remnants

Gravitational wave strain

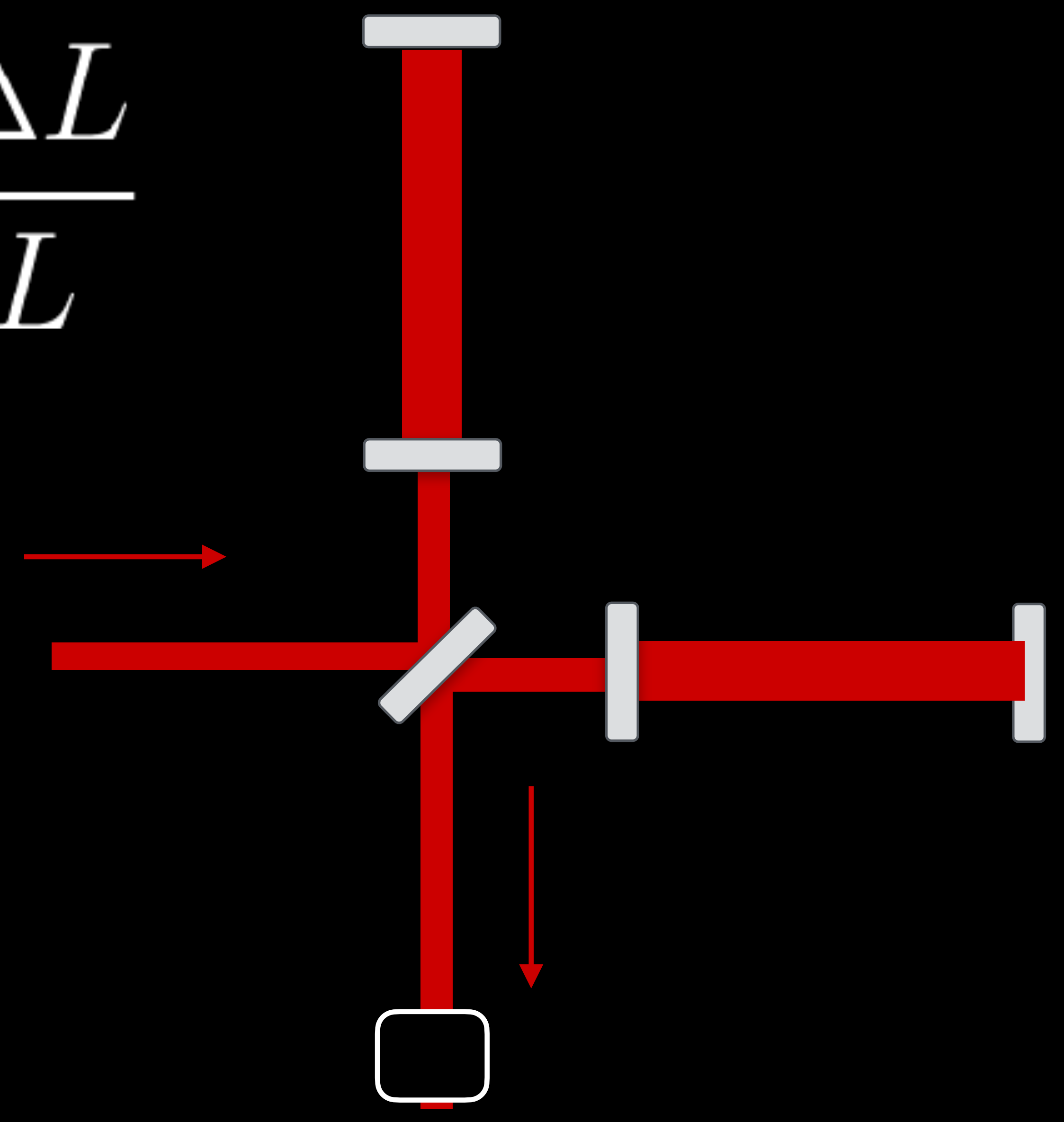
Induced spacetime strain h(t)

$$h_{ij}(t) \propto \frac{G}{c^4 r} \frac{d^2 I_{ij}}{dt^2}$$



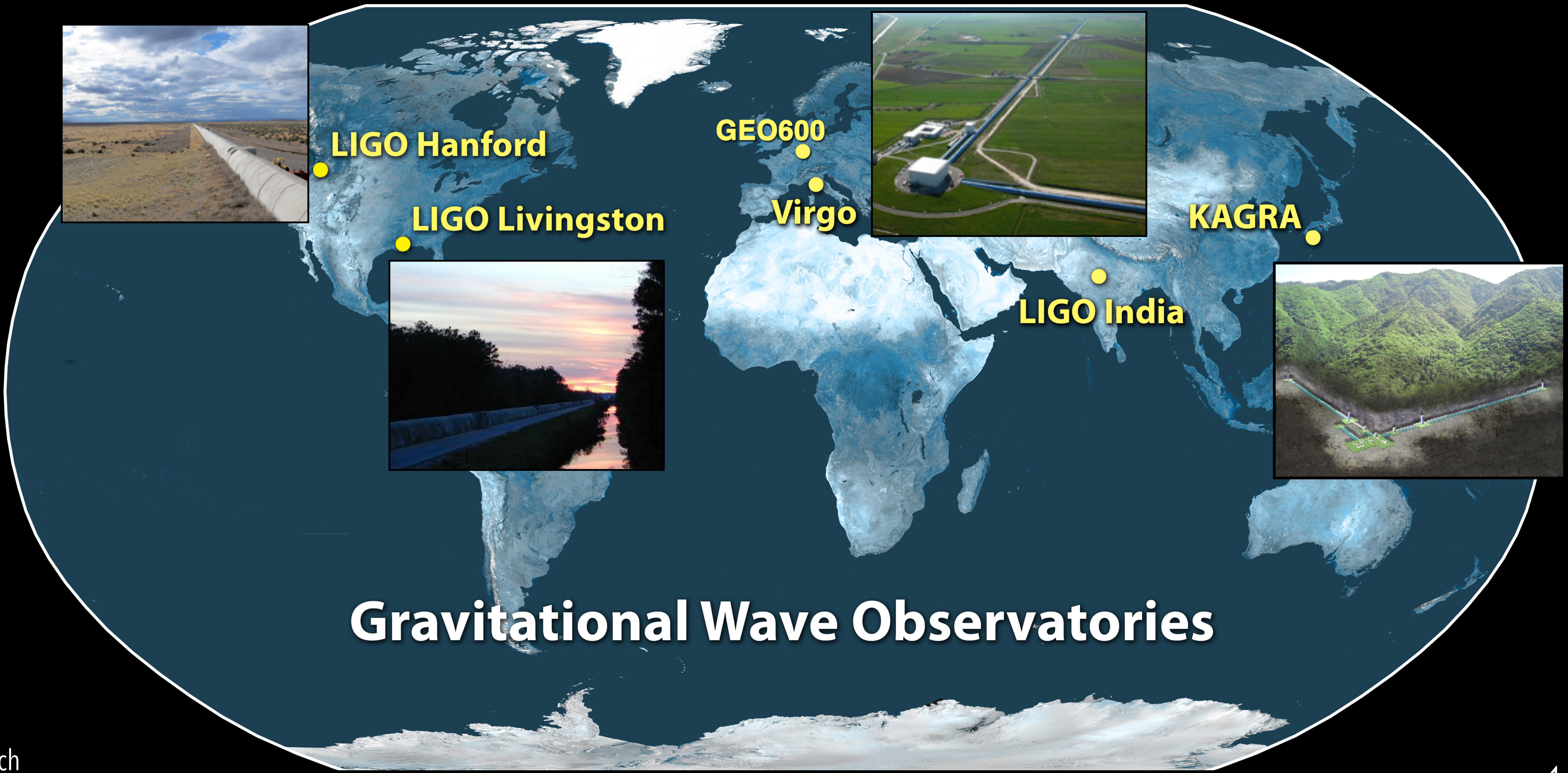
Measured spacetime strain h(t)

$$\frac{\Delta L}{L}$$



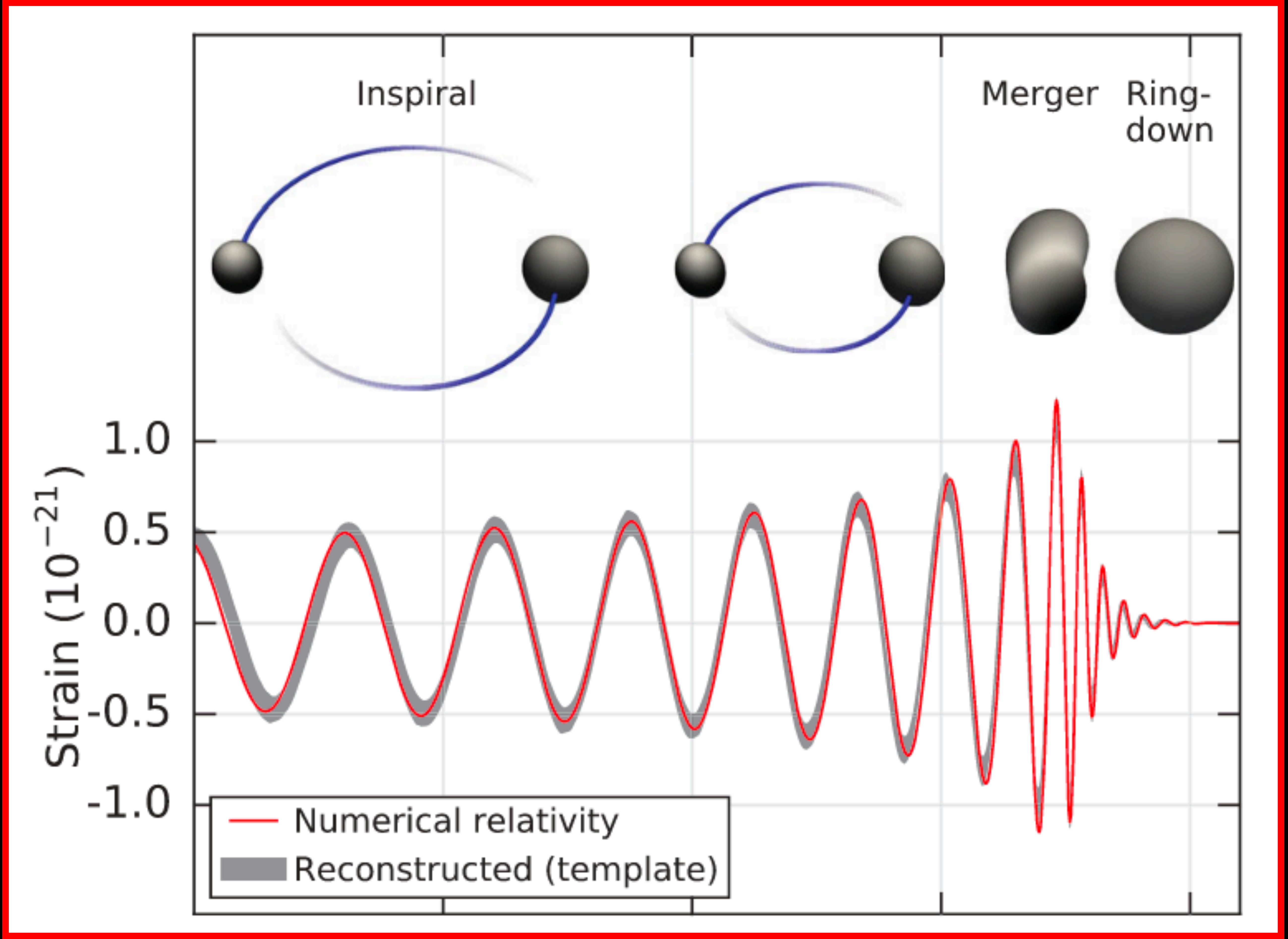
Movie: Carl Rodriguez

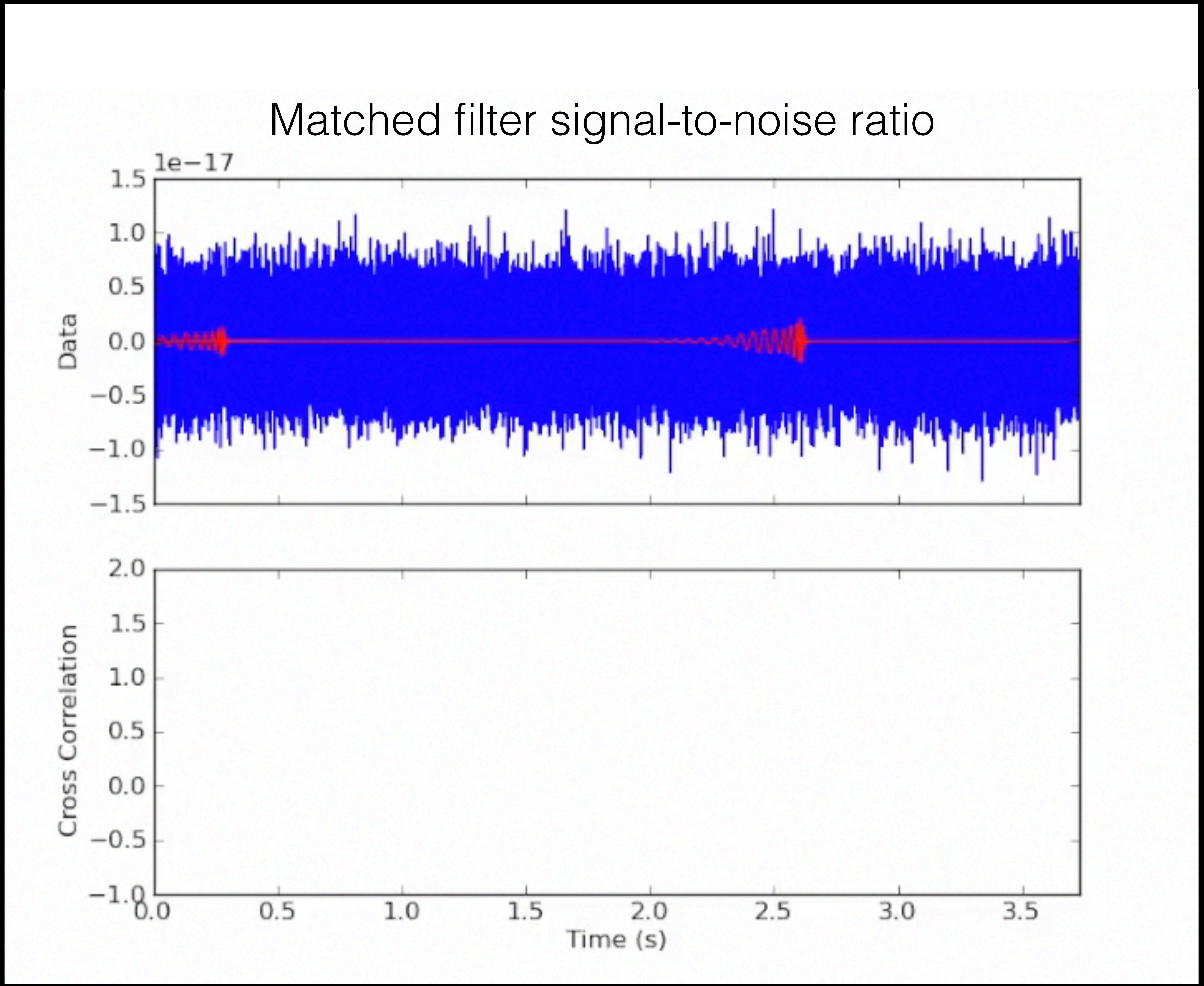
Current GW detector network (IGWN)



LIGO/Caltech

Searching for signals with matched filtering

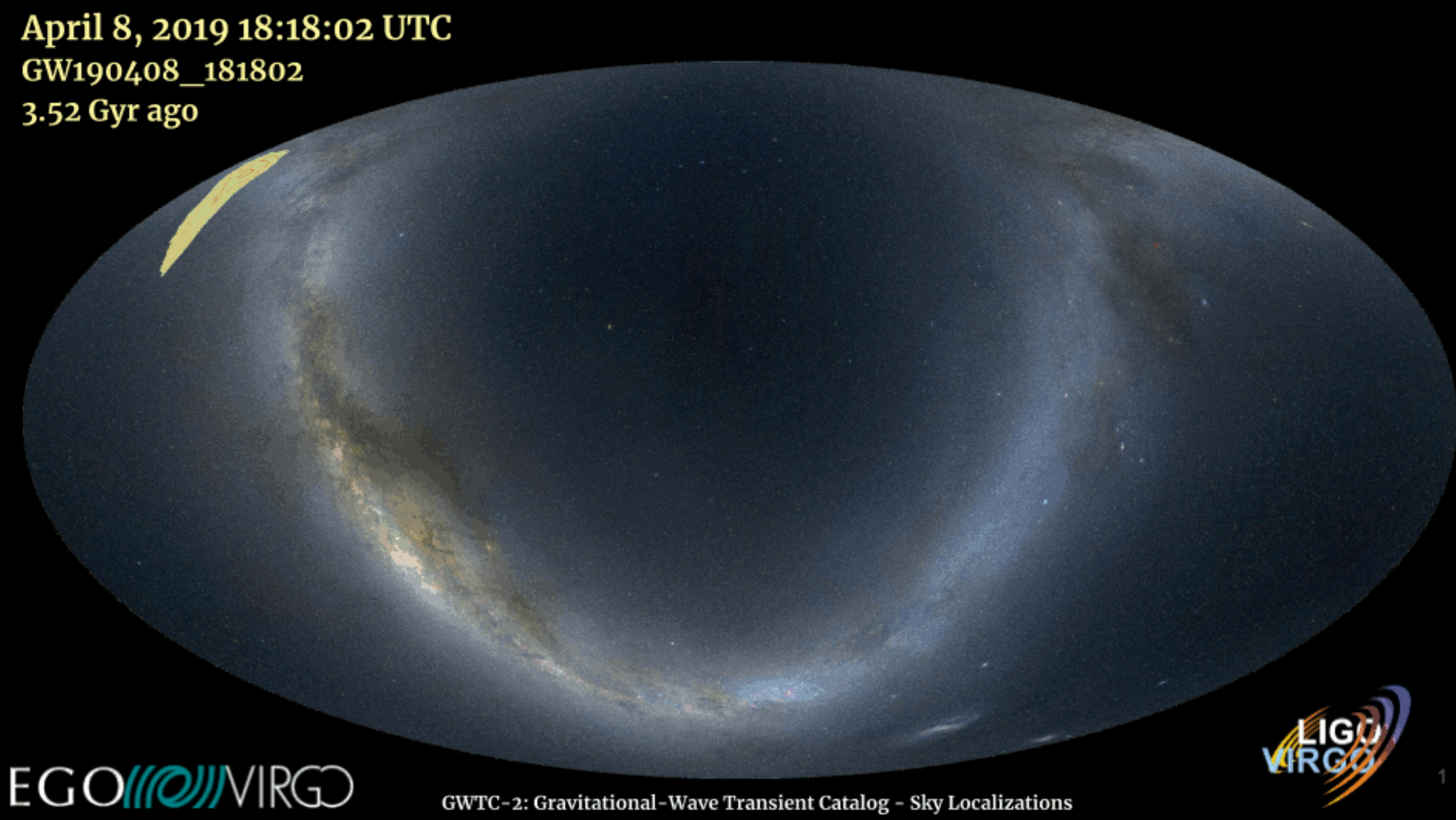




B. P. Abbott et al. Phys. Rev. Lett. (2016)

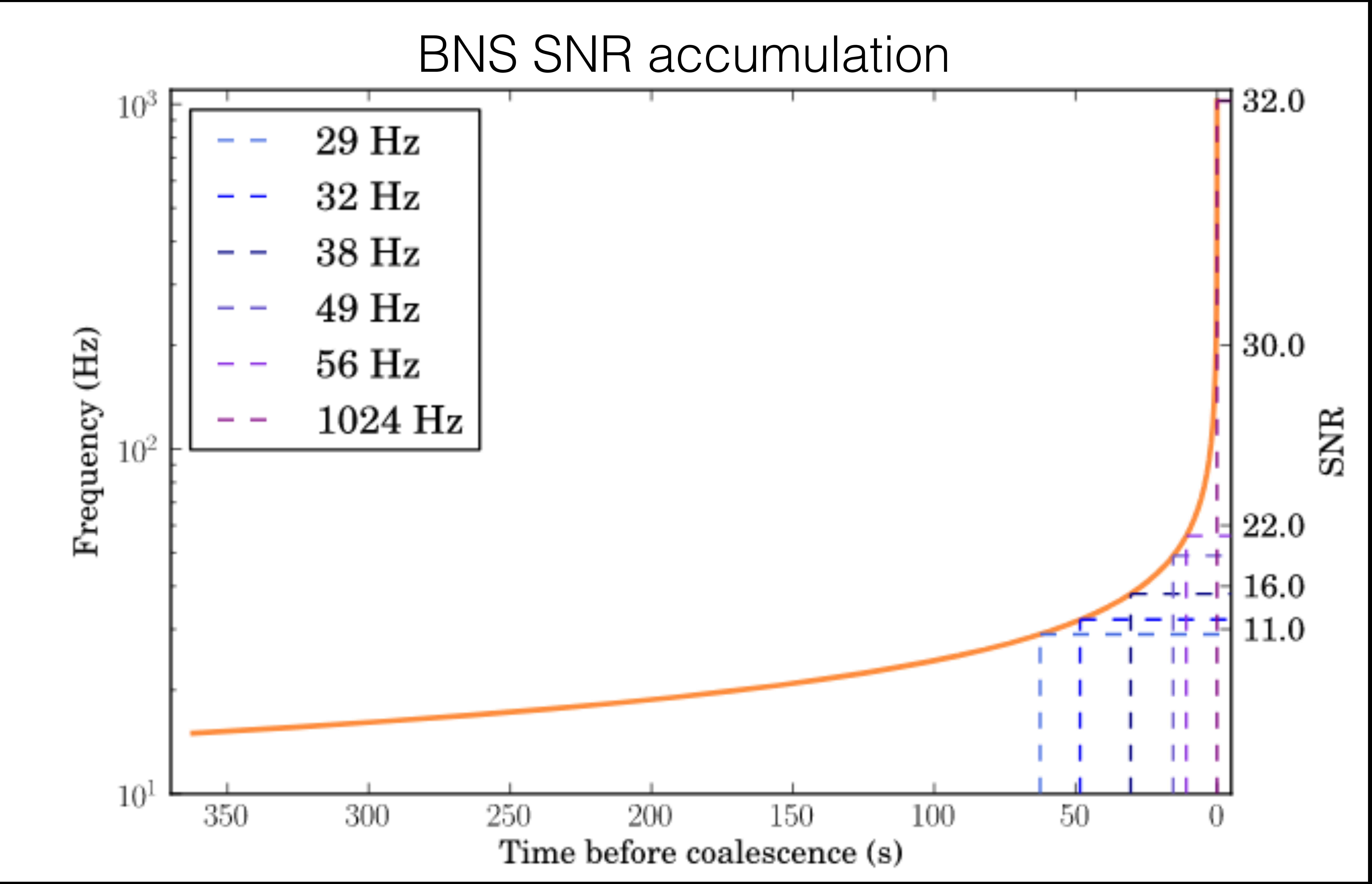
S. Caudill

Typical GW sky localizations (examples from GWTC-2)



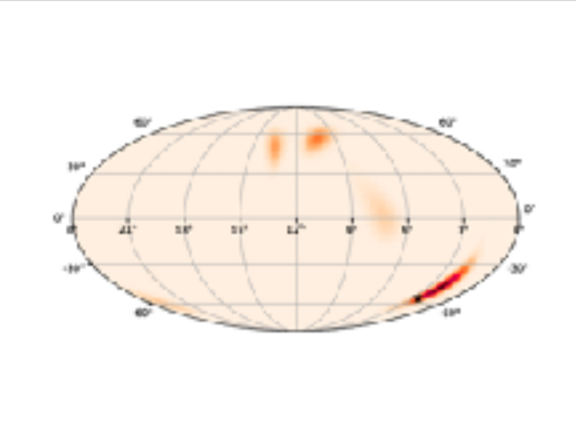
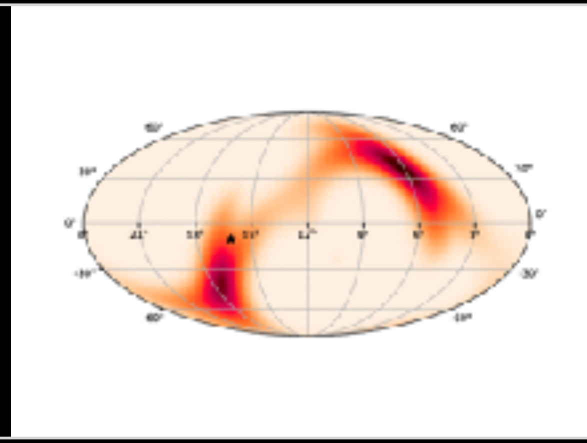
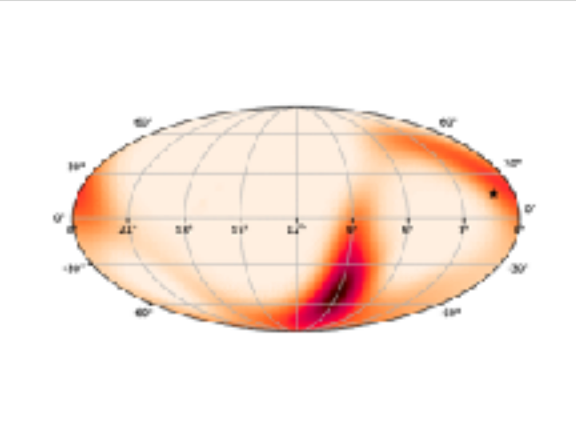
NASA/Goddard Space Flight Center/CI Lab

Prospects for early warning alerts for binary neutron stars



IGWN Public Alerts User Guide

Prospects for early warning alerts for binary neutron stars

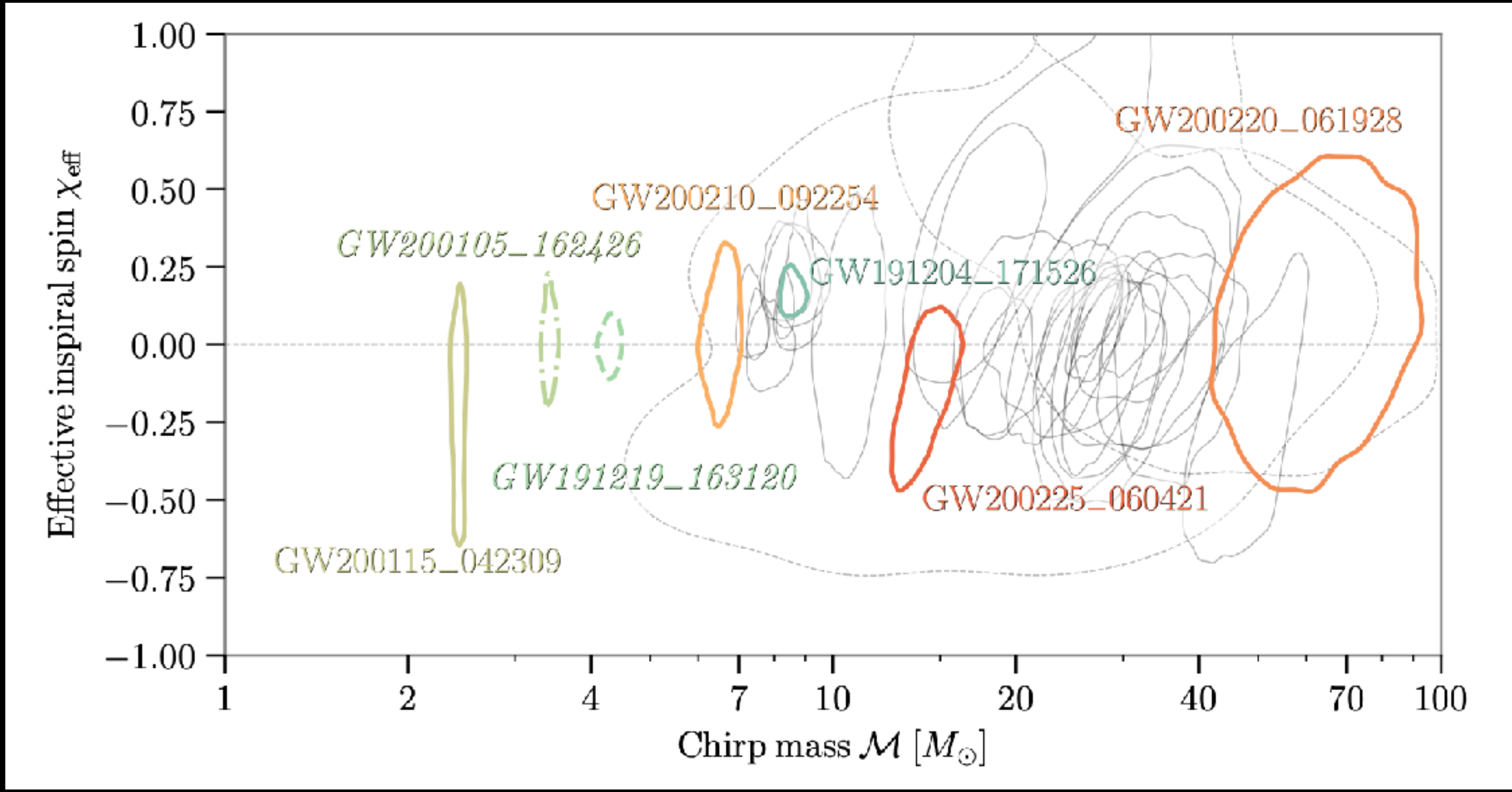
Final SNR	**11**	**18**	**25**
Distance	**250 Mpc**	**210 Mpc**	**160 Mpc**
Sky map (animated GIF)			
29 Hz	Not detected	Not detected	12000 deg^2
32 Hz			10000 deg^2
38 Hz		9200 deg^2	8200 deg^2
49 Hz	2300 deg^2	1000 deg^2	730 deg^2
56 Hz	1000 deg^2	700 deg^2	250 deg^2
1024 Hz	10 deg^2	31 deg^2	5.4 deg^2

IGWN Public Alerts User Guide

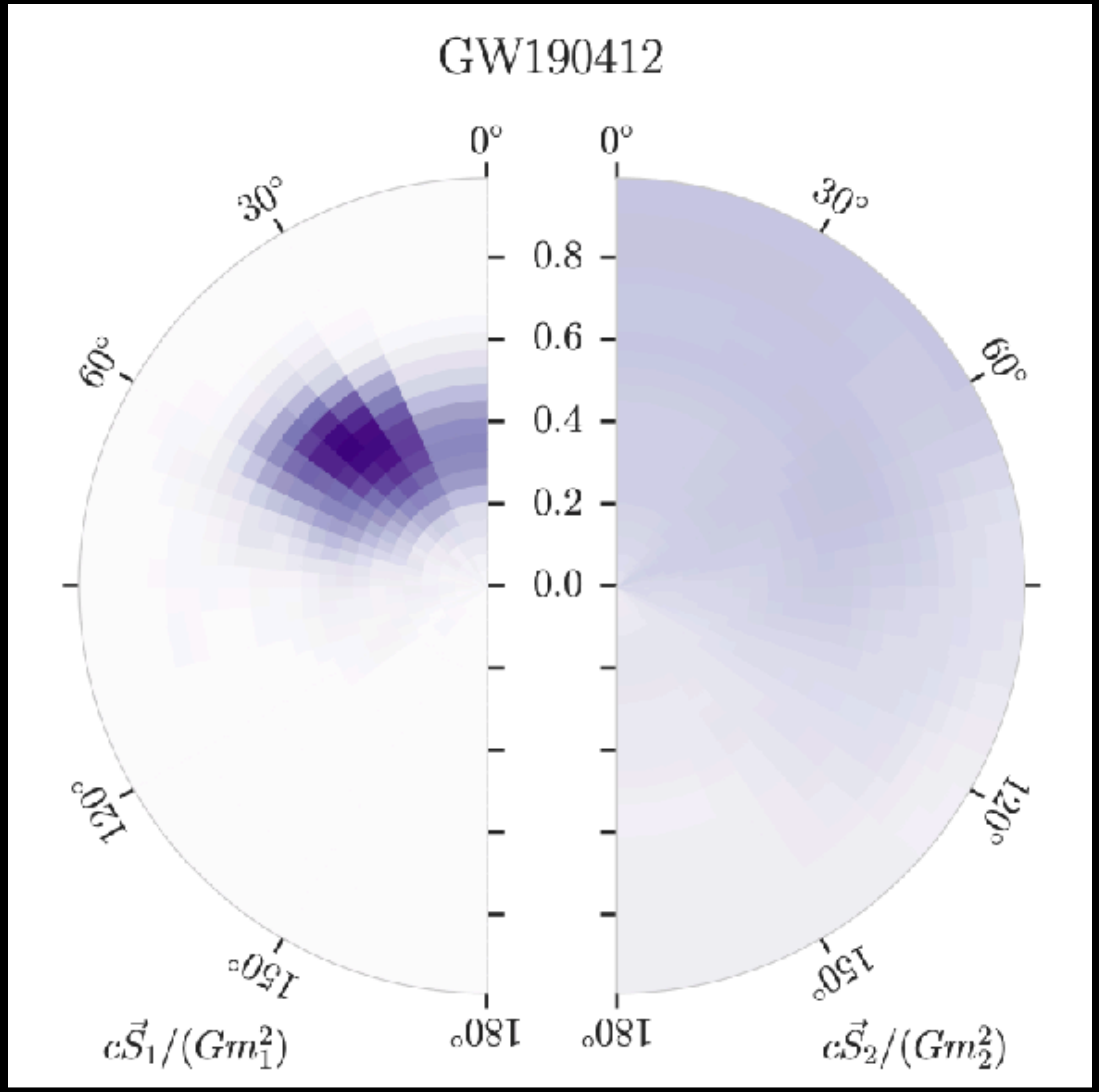
Inference of source properties

$$d = h + n.$$ ⟵ 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

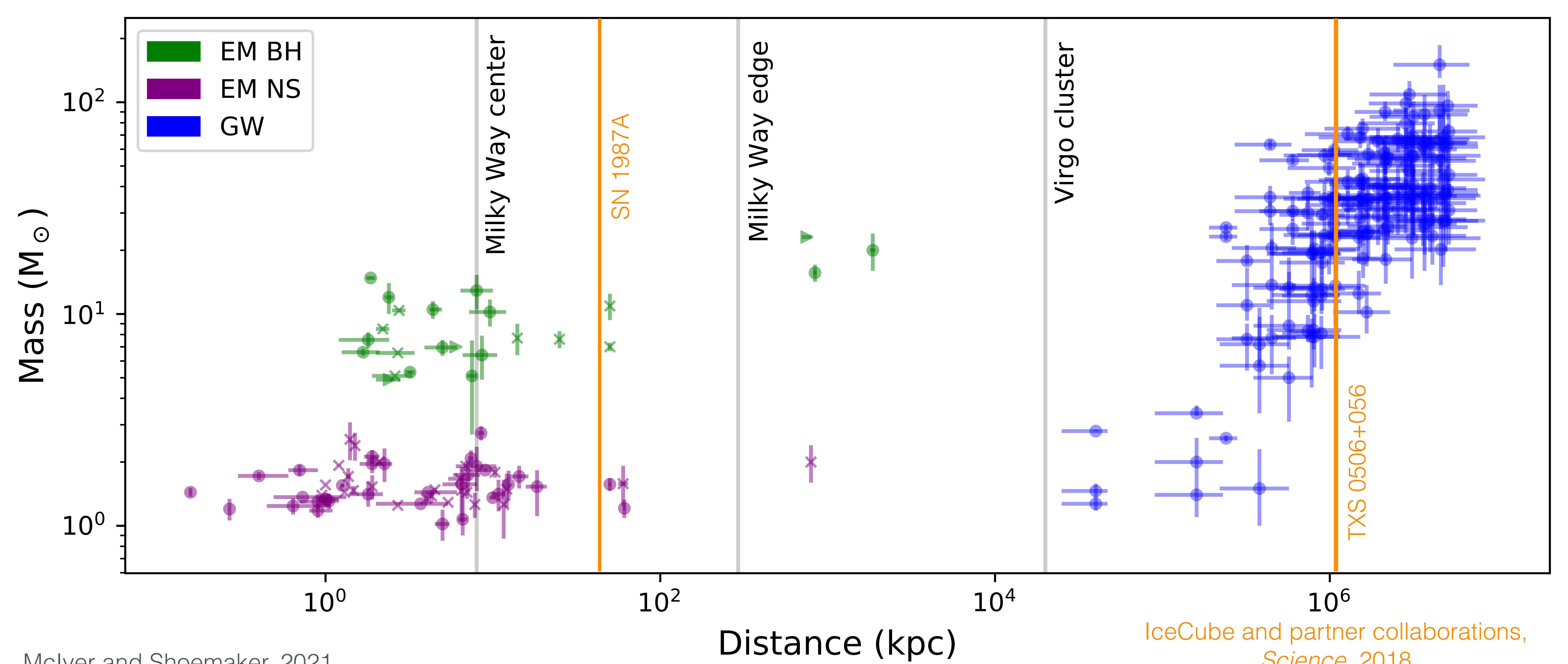


LIGO/Virgo GWTC-3 (2021)



LIGO/Virgo GWTC-2 (2020)

Known compact object masses vs. estimated distance



McIver and Shoemaker, 2021

IceCube and partner collaborations, *Science*, 2018

NASA

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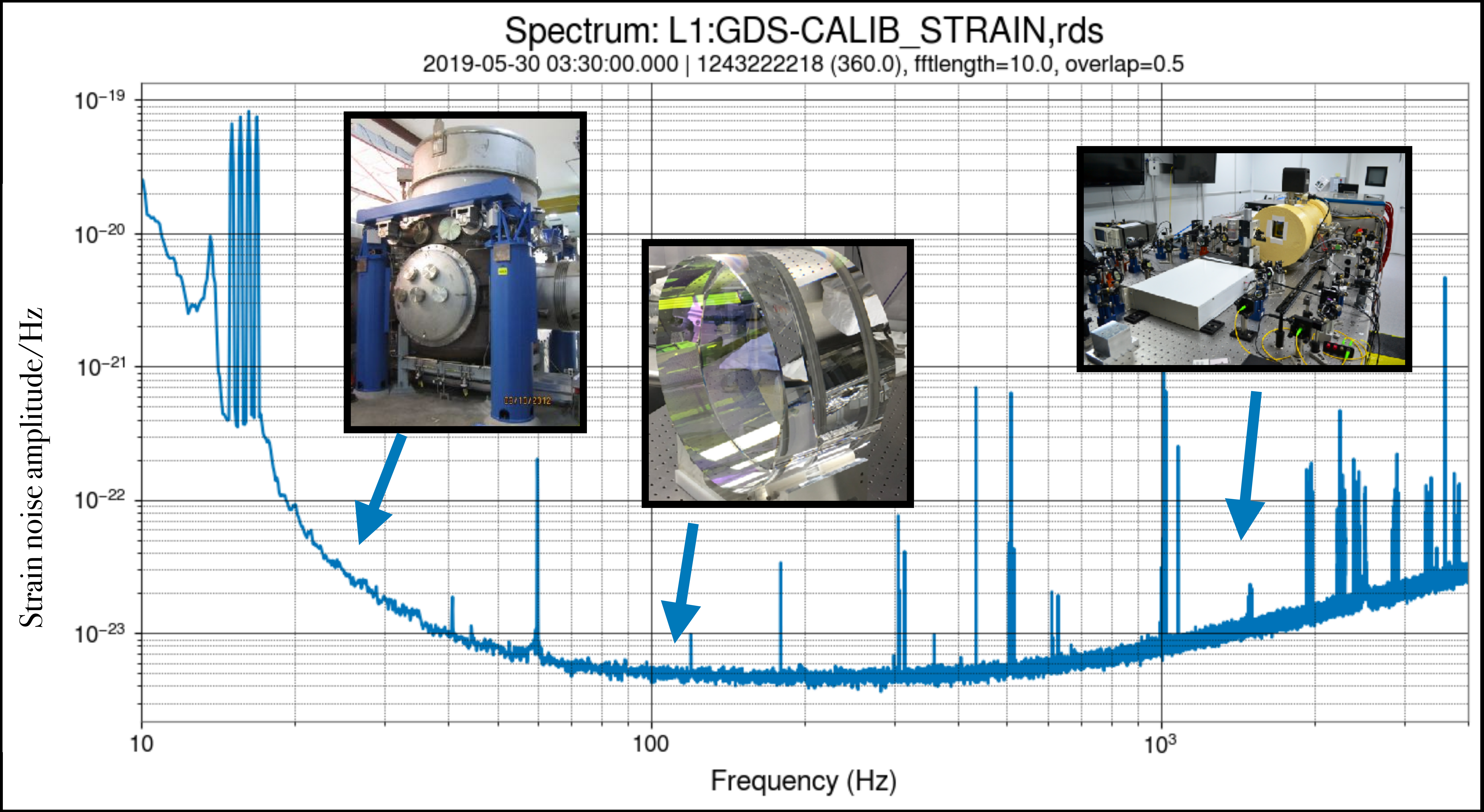
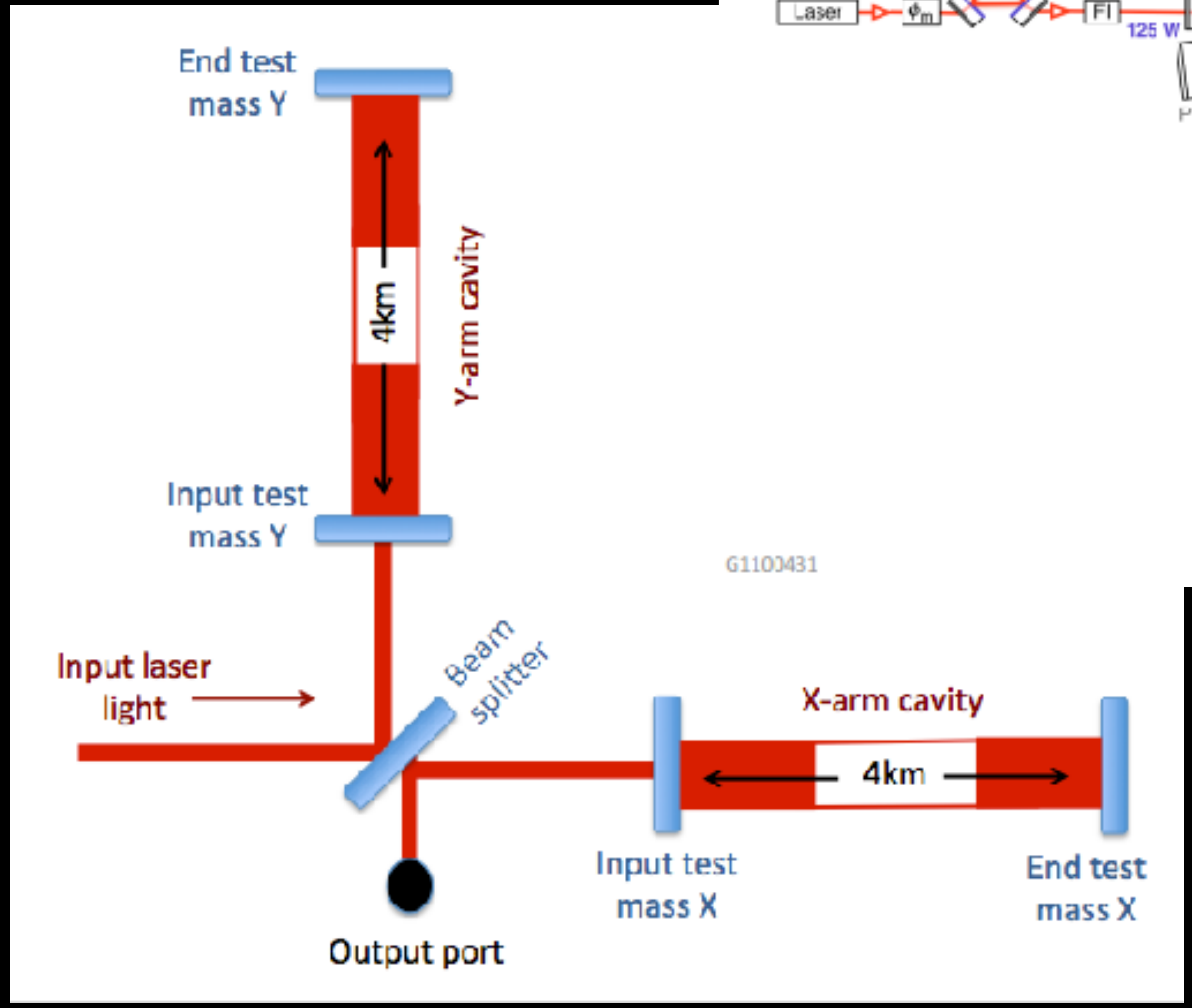
Kai Staats

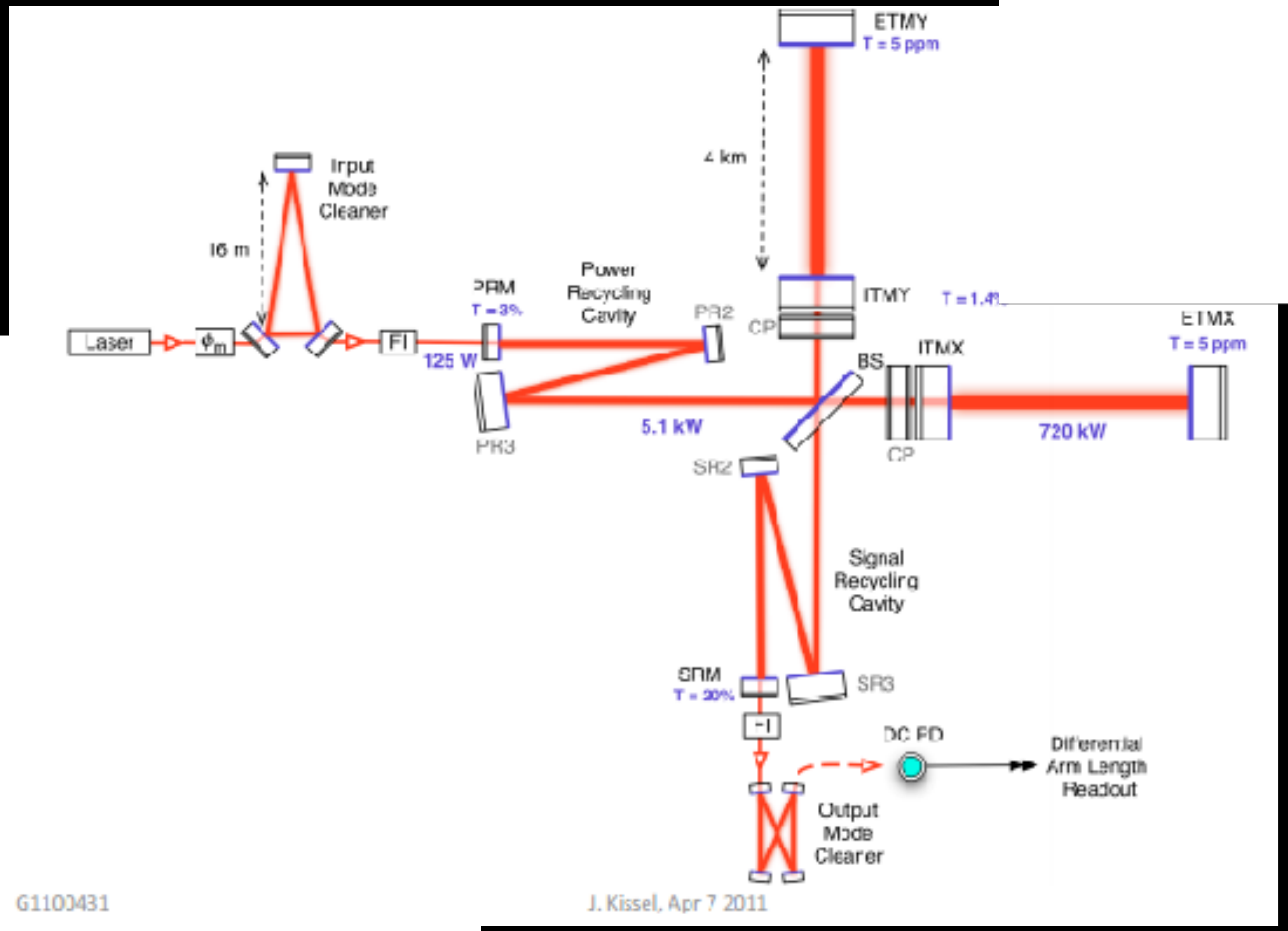

Science
AAAS

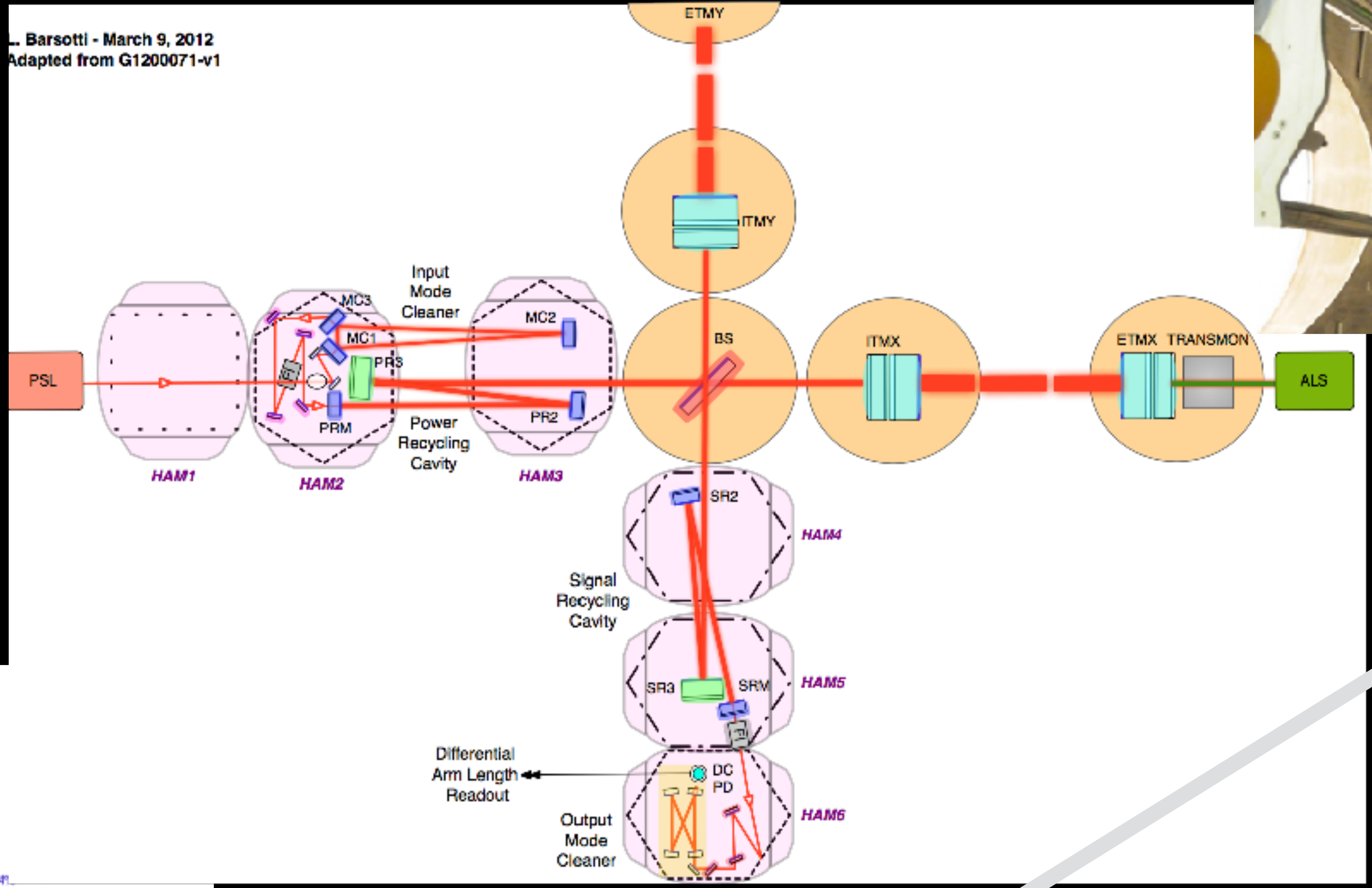
Advanced LIGO noise



Interferometric GW detectors are extremely complex.







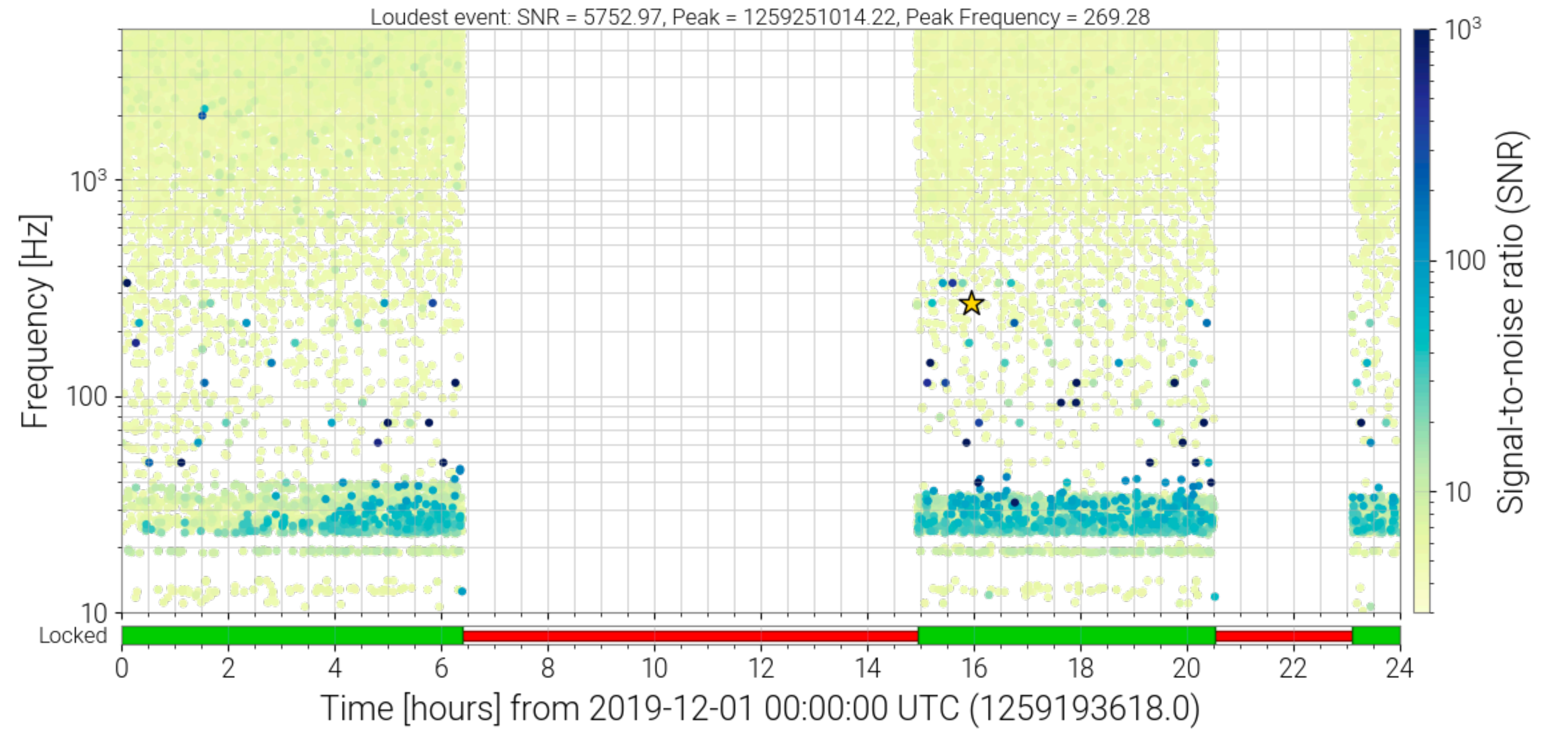
Reality

Adapted from D. Shoemaker

Challenge: known causes of GW detector glitches

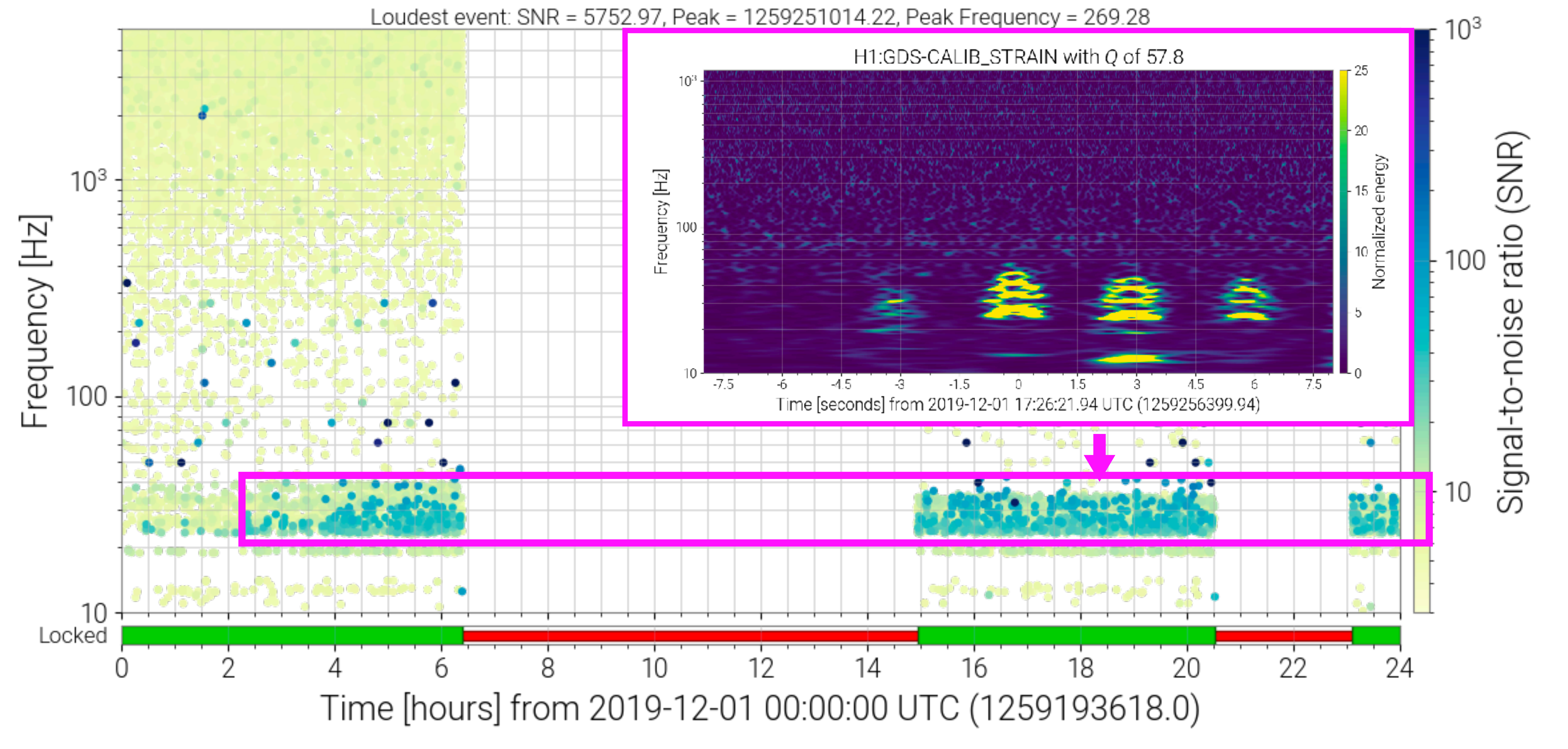
Lightning	Birds	Refrigerators	Radio contamination
Ocean waves	Earthquakes	Air conditioners	Telephones
Low humidity	Trains	Snow plows	Thunder
Forklifts	Helicopters	Airplanes	Logging

Challenge: GW detector transient noise



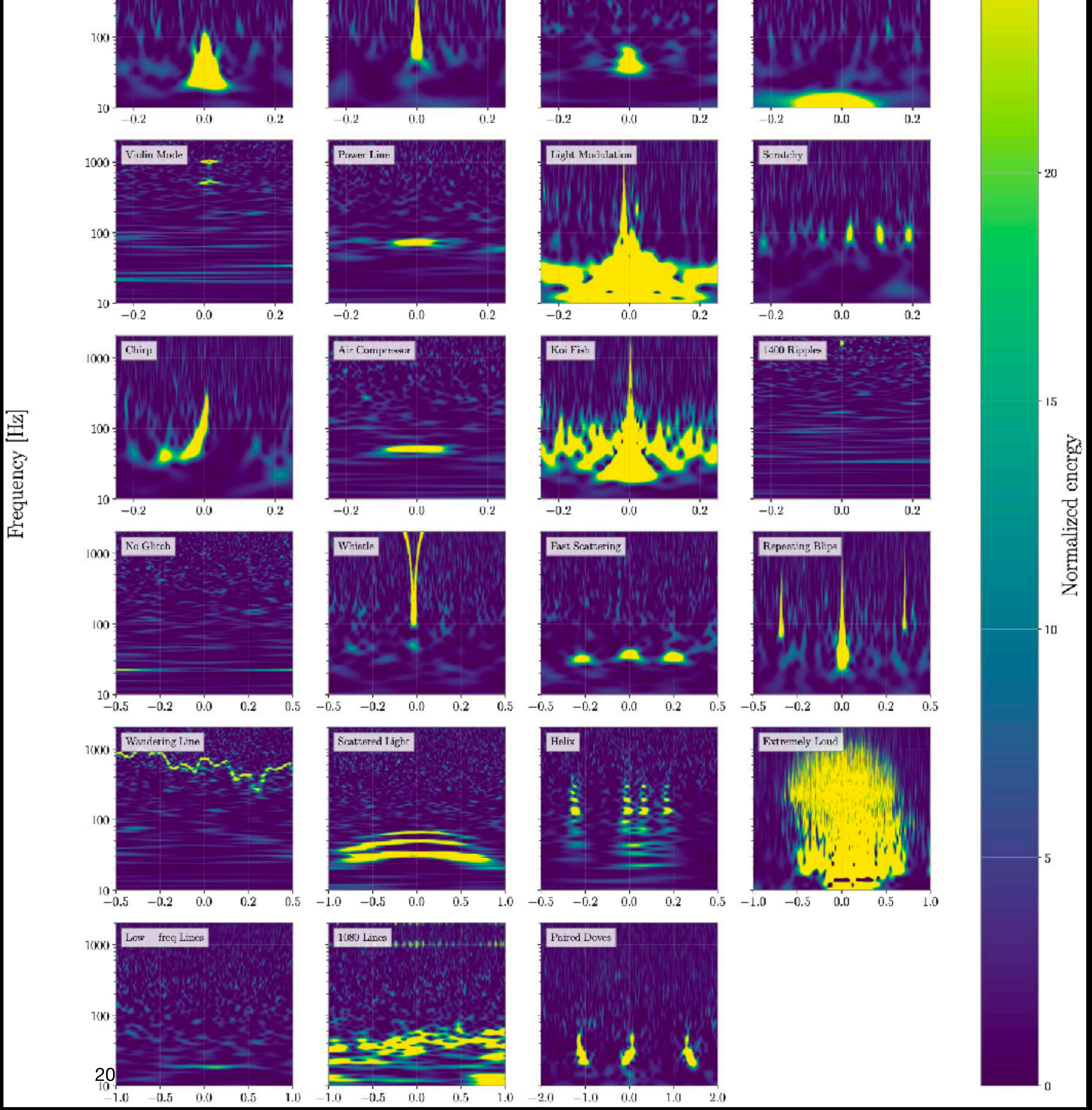
The LIGO summary pages

Challenge: GW detector transient noise



The LIGO summary pages

A menagerie of GW detector glitches



Time-frequency visualizations used for training Gravity Spy
M.. Zevin et al.,CQG (2017).

Different tools for different problems

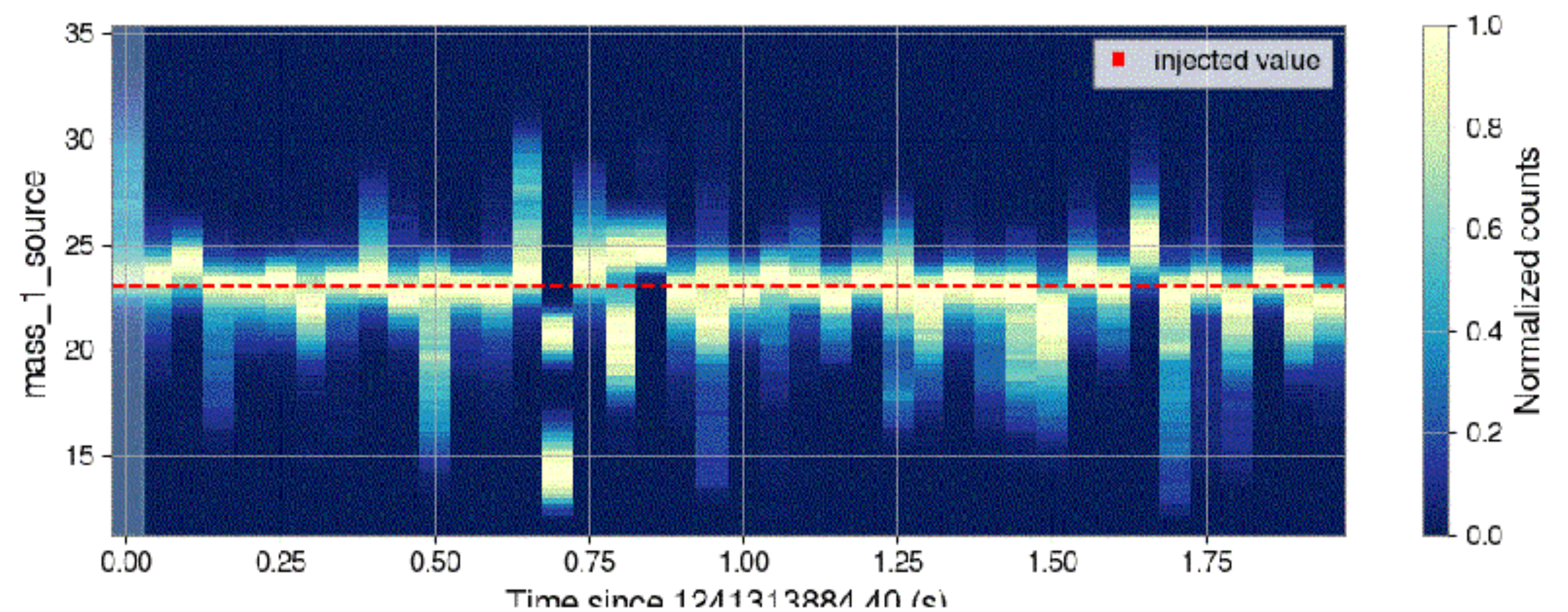
1. Is a candidate real (astrophysical)?
2. If real, is parameter estimation accurate? (Is the Gaussian noise assumption valid?)

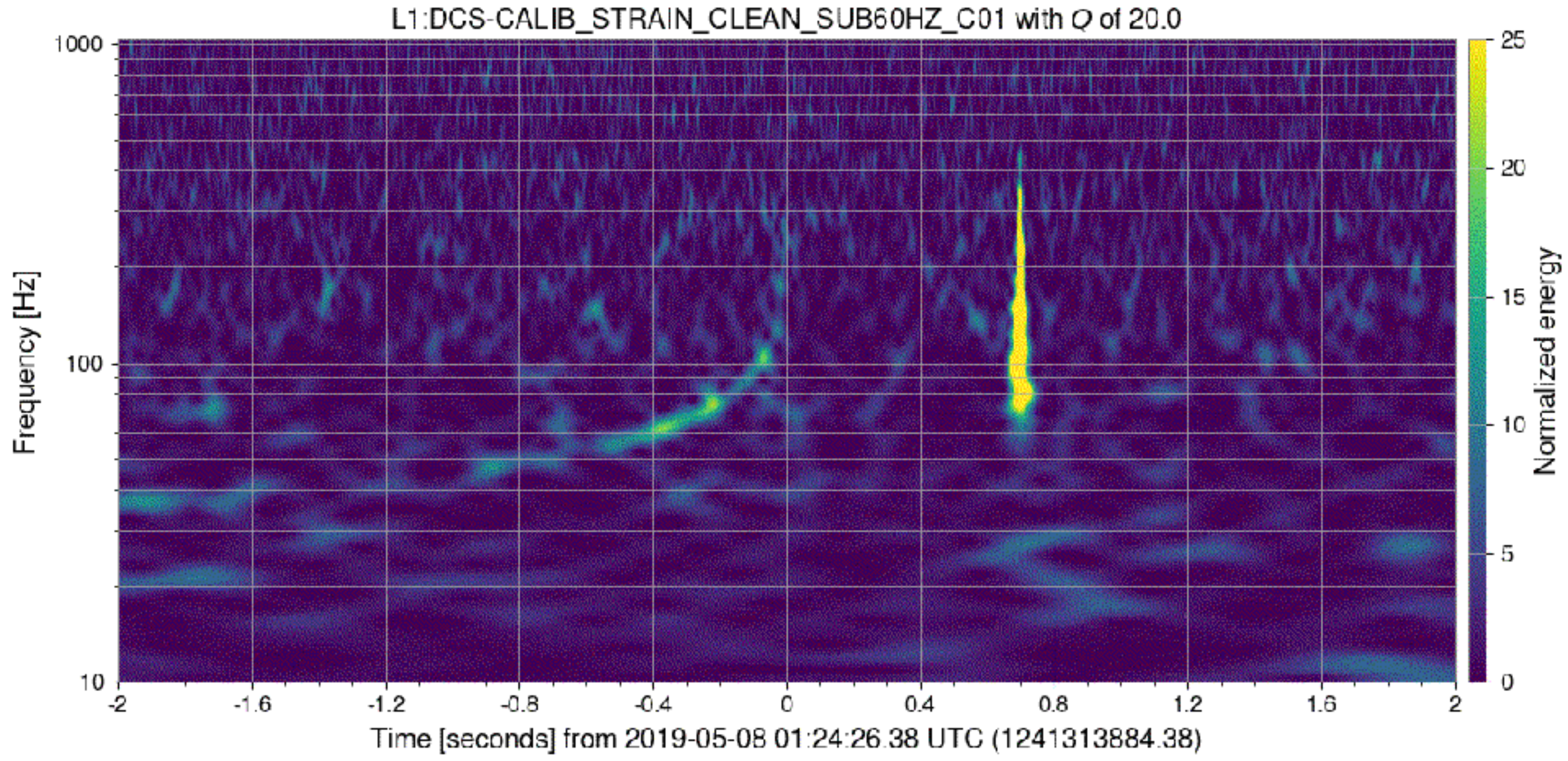
Plots by D. Davis. Glitch modelling and subtraction using **BayesWave**: Cornish & Littenberg 2014 & 2020; Davis et al 2021.

What impact do glitches have on parameter estimation?

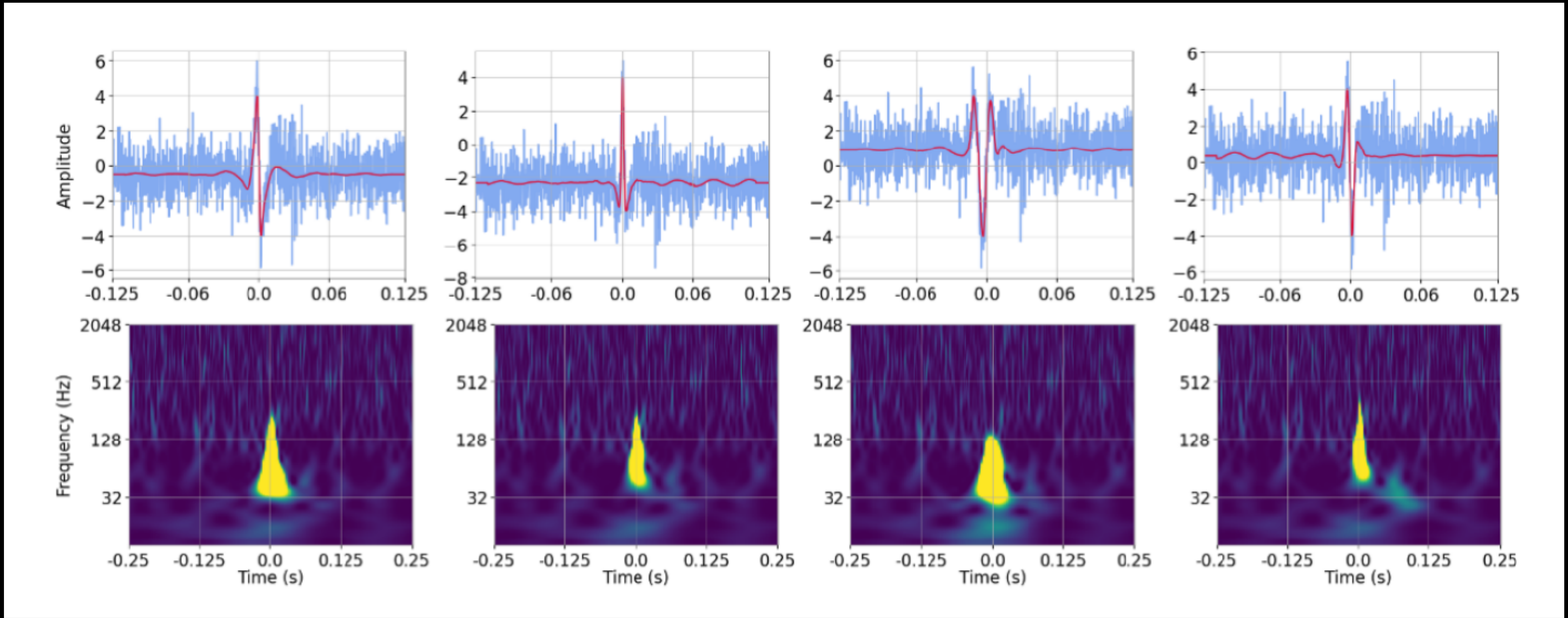
Niko Lecoeuche
UBC PhD student

- Simulated GW signal injected at different points in time relative to detector glitch
- GW source parameter estimation produced for signal at each injection merger time
- Posterior distributions compared to determine which parameters affected most, what constitutes a “safe” time separation between signal and glitch
- See also recent skymap study; Macas et al 2022.





Next level: simulated glitches



Simulated blips from **Melissa Lopez**'s 2022 Phys Rev D paper.

See also J. Powell et al. 2022 arXiv 2207.00207

- Recent work using ML to generate simulated glitches will allow us to have much more control over the transient noise used in this study
- Simulated Gaussian noise plus a simulated glitch will allow us to much better understand the impact of lower SNR glitches

The curious case of GW200129 - signs of precession?

EXPRESS

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Colliding black holes produce most extreme 'wobble' ever seen in 'one-in-1,000' event

This is the first time that this effect - known as precession - has been seen with black holes, where the "wobble" is 10 billion times faster than in observations o other bodies.

SciTechDaily

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Most Extreme "Wobbling Black Hole" Ev Detected – Exotic Phenomenon Predicte Einstein's Theory of Gravity

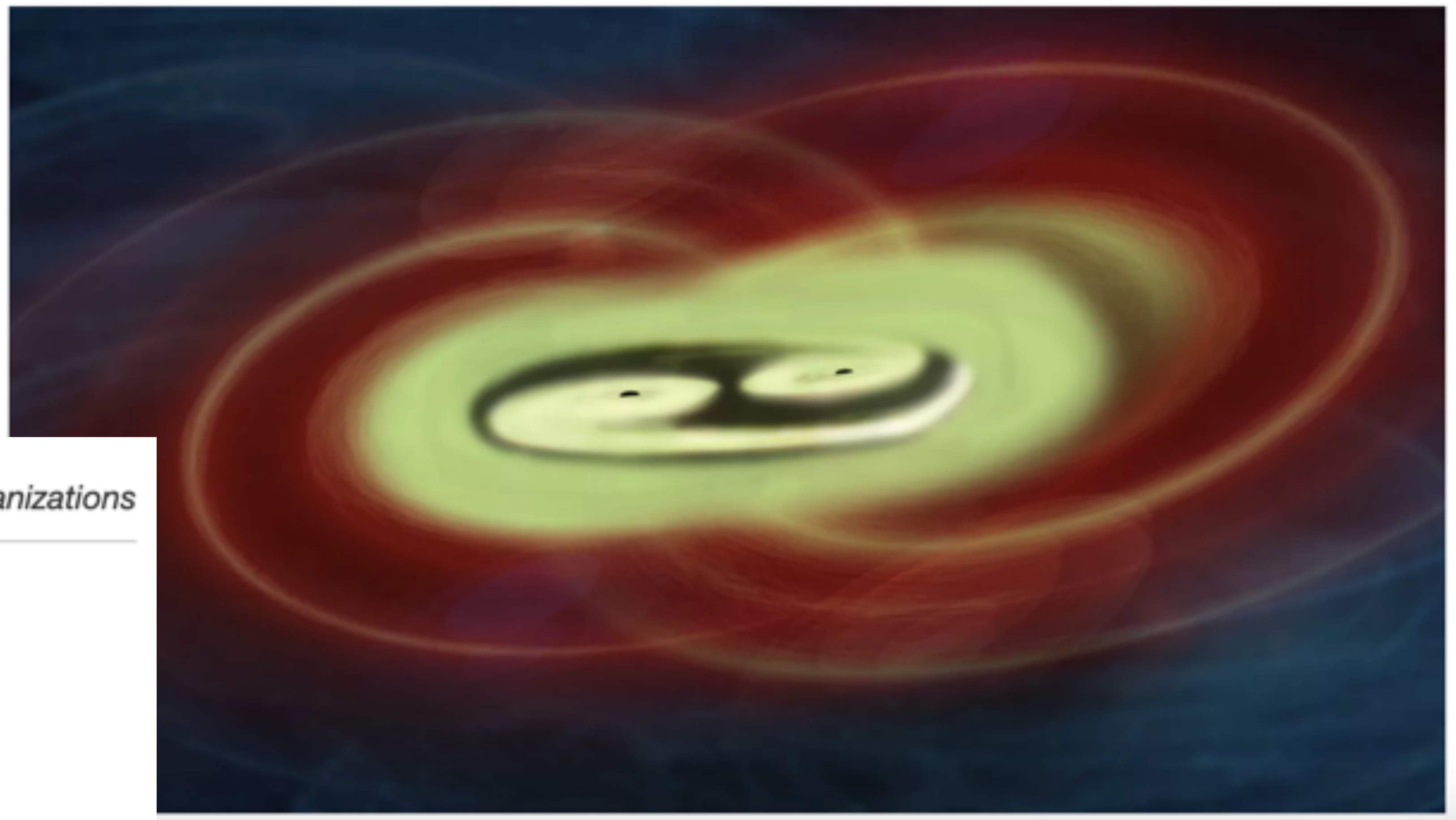
TOPICS: Astrophysics Black Hole Cardiff University Gravitational Waves

Home > News

One of the most extreme black hole collisions in the universe just proved Einstein right

By Brandon Speckter published October 12, 2022

The black hole twisted 10 billion times faster than any ever observed.



Science News *from research organizations*

'Wobbling black hole' most extreme example ever detected

Gravitational waves identify what could be a rare one-in-1000 event

Date: October 12, 2022

Source: Cardiff University

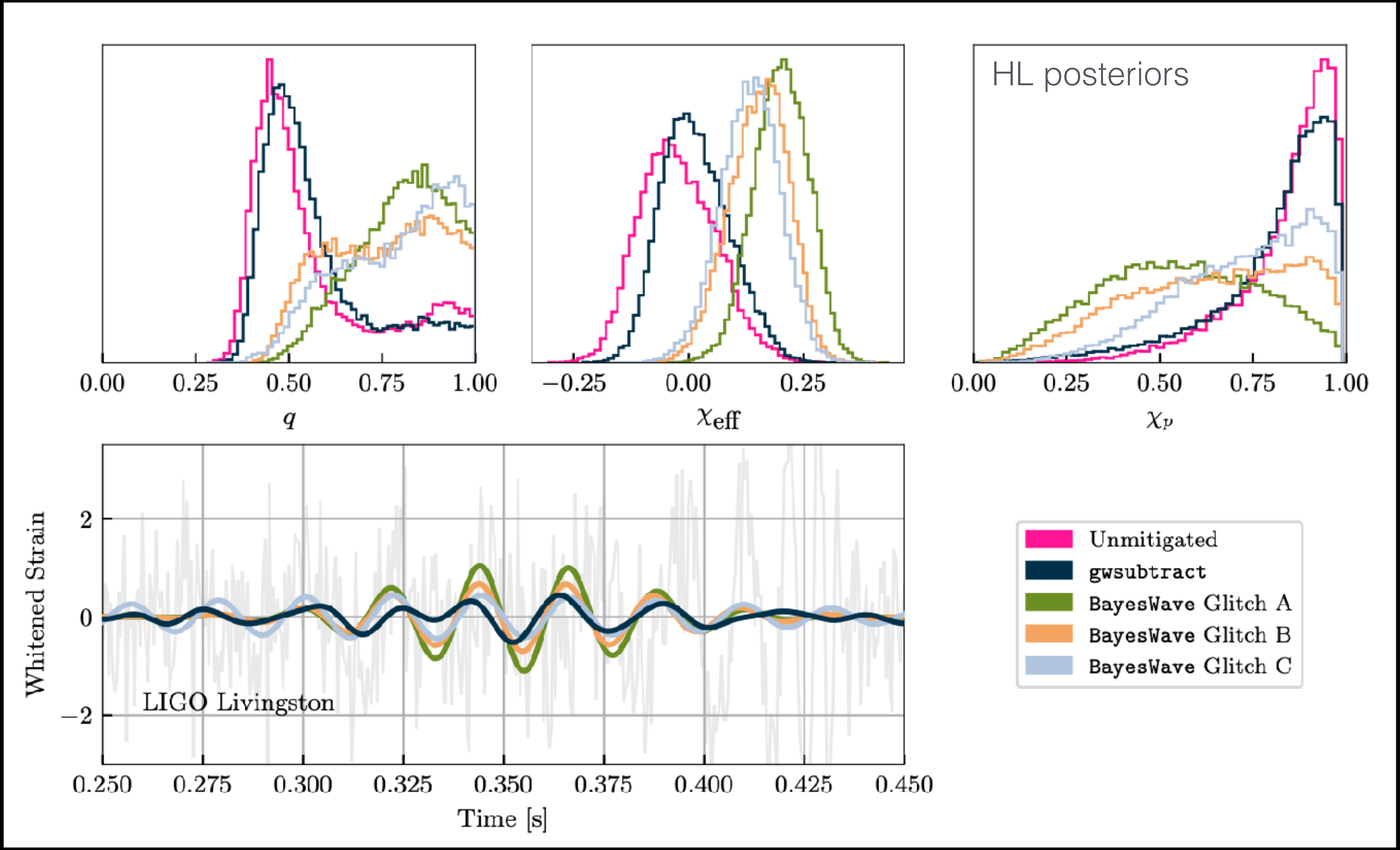
Summary: Researchers have identified a peculiar twisting motion in the orbits of two colliding black holes, an exotic phenomenon predicted by Einstein's theory of gravity. Their study reports that this is the first time this effect, known as precession, has been seen in black holes, where the twisting is 10 billion times faster than in previous observations.

Hannam et al, Nature, 2022

The curious case of GW20129

Plots by Derek Davis; Davis et al 2022.

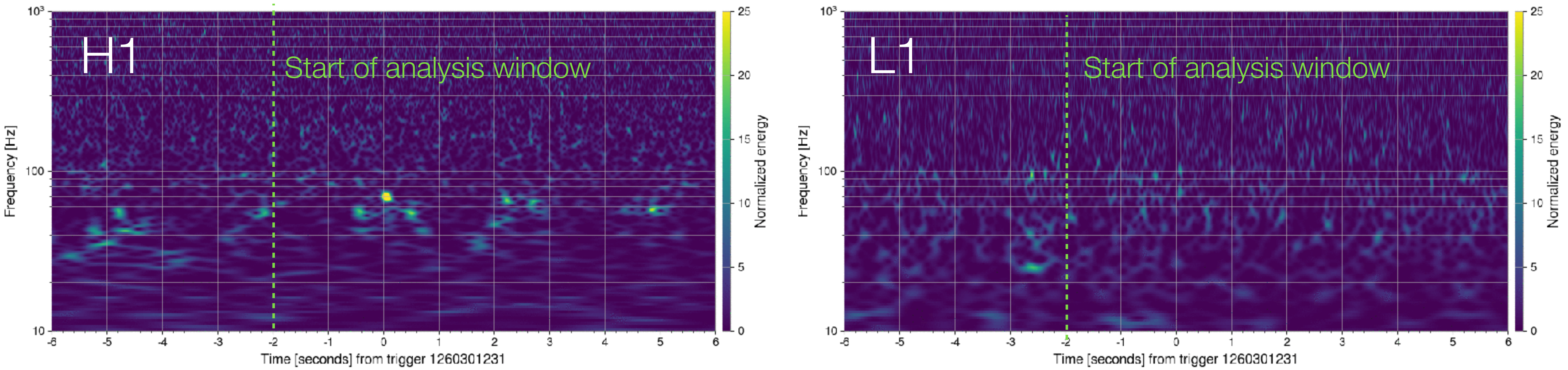
The curious case of GW200129



Payne et al. Phys Rev D. 2022

Example of more subtle noise features: S191213bb

S191213g was found in low latency by matched filter search GstLAL in both LIGO Hanford and LIGO Livingston with FAR of 1.1 yr^{-1}.



Plots by D. Davis

The need for automation

O4 candidates: ~100

O5 candidates: expected >600 !

Higher detection rate and *longer observing run*

H1 result: Pass Observing

Task	IFO	Status	P-value	Result
rayleigh	H1	Done	0.25	Pass
stationarity	H1	Done	0.984375	Pass
gspynettree	H1	Done	0.99584	Pass
glitchfind	H1	Done	0.99952813	Pass
lockcheck	H1	Done	1.0	Pass

The LVK data quality report, J. Areeda, D. Davis et al.

Danger: pass candidates with glitches to downstream analyses (testing general relativity, rates and pop, etc)

Introducing GSpyNetTree: signal-vs-glitch classifier for single detector GW data


Sofía Alvarez


Seraphim Jarov


Julian Ding


Sarah Thiele


Annduesh Liyanage


Dr. Mervyn Chan

With Raymond Ng, UBC Data Science Institute Director

Gravity Spy's original architecture consists of a single classifier for all glitches (+ 1 GW class)

→

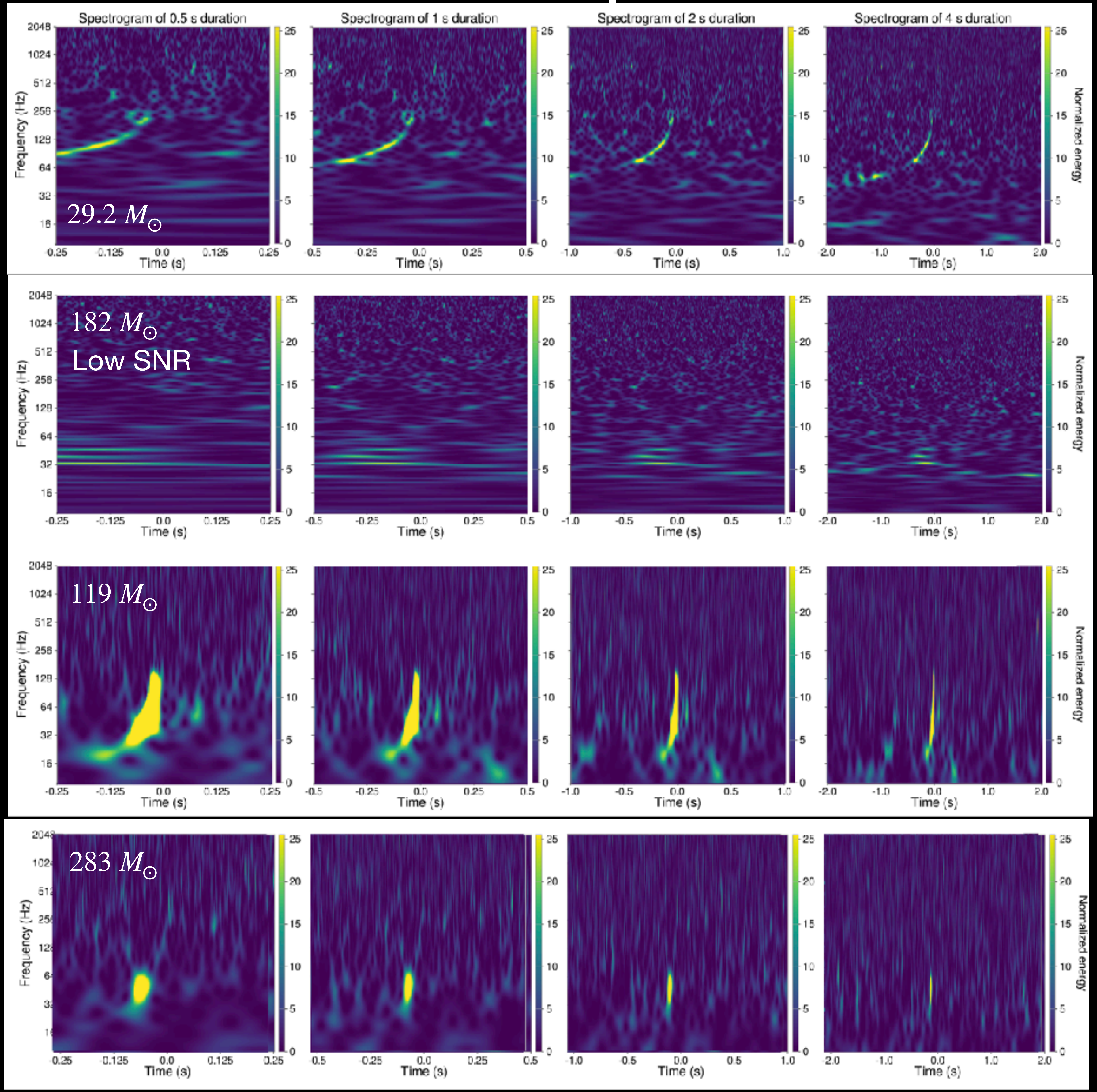
GSpyNetTree considers three classifiers, one per mass range, along with morphologically similar glitches.

Low mass CNN	High mass CNN	Extremely high mass CNN
1. GW (5-50 $M_{\odot}$)	1. GW (50-250 $M_{\odot}$)	1. GW (250-350 $M_{\odot}$)
2. Blip	2. Blip	2. Blip
3. Low Frequency Blip	3. Low Frequency Blip	3. Low Frequency Blip
4. No Glitch	4. No Glitch	4. No Glitch
5. Scratchy	5. Koi Fish	
	6. Tomte	

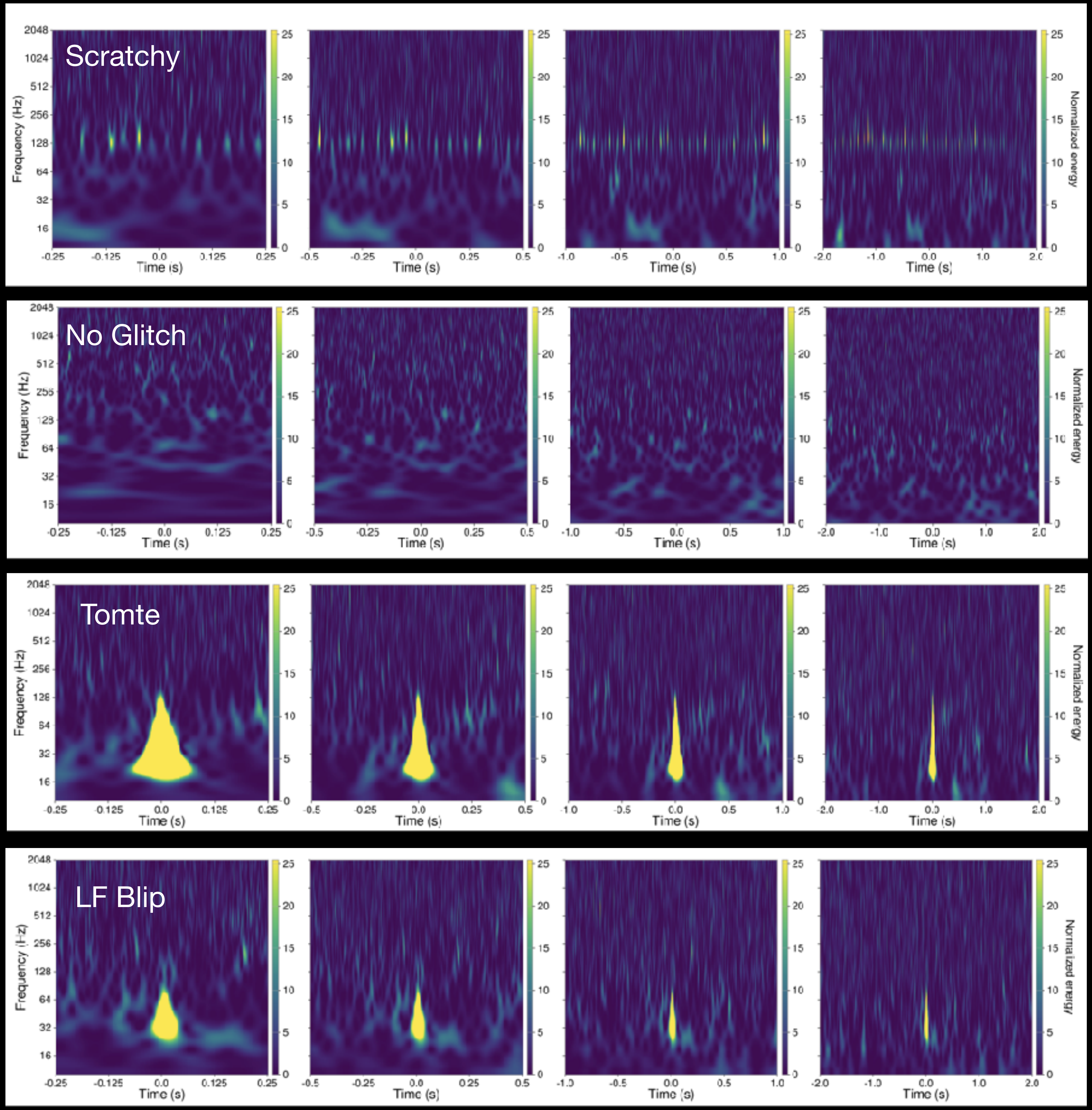
Builds on the original GravitySpy architecture and training set: M. Zevin et al. 2017 CQG (arXiv 1611.04596)

Jarov S., et al., "A new method to distinguish gravitational-wave signals from detector glitches with Gravity Spy", (in prep).
Álvarez-López et al., "GSpyNetTree: A signal-vs-glitch classifier for gravitational-wave event candidates", arXiv 2304.09977 (2023)

GW examples

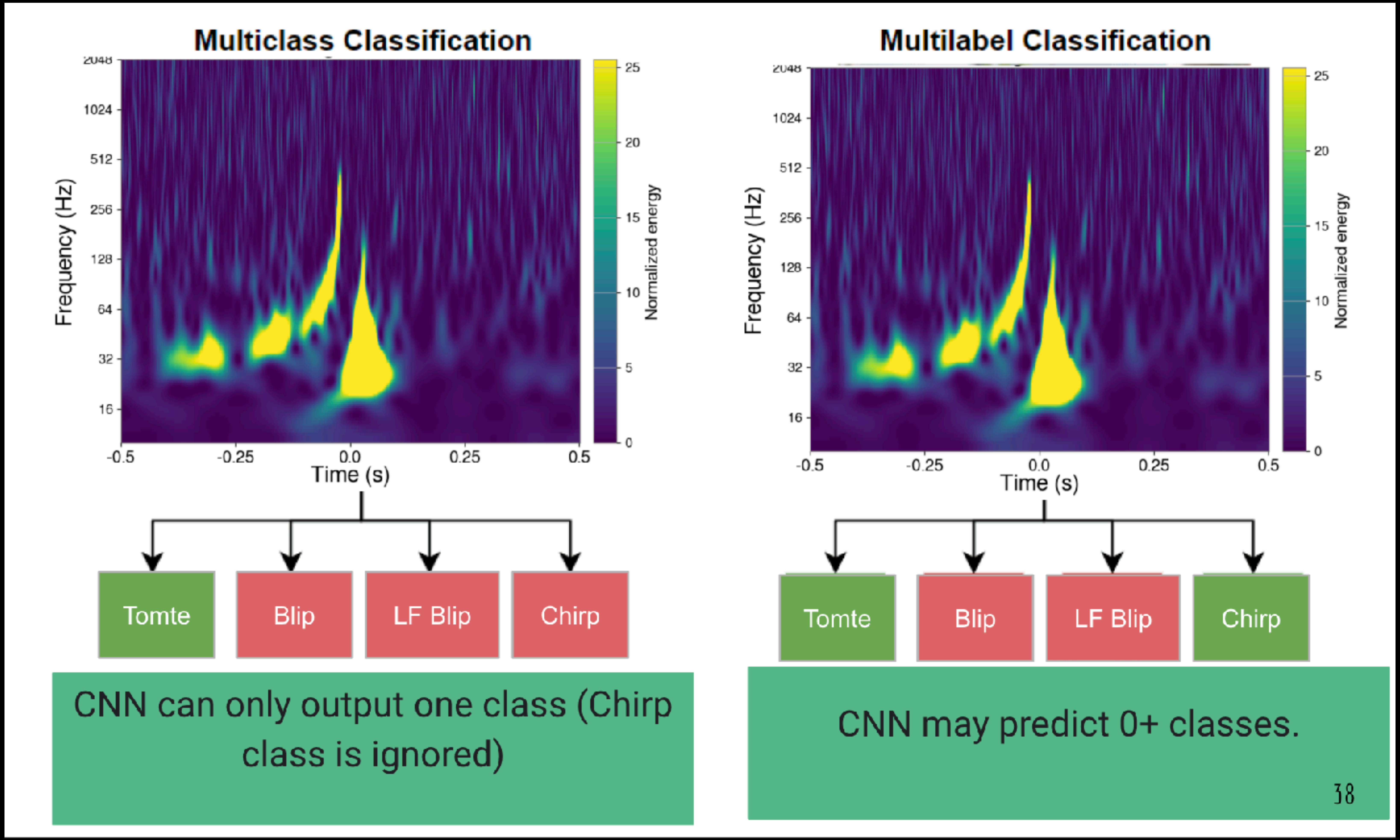


Glitch examples



Álvarez-López et al., "GSpyNetTree: A signal-vs-glitch classifier for gravitational-wave event candidates", arXiv 2304.09977 (2023)

A solution for robustness to glitches near signals: a multi-label classifier



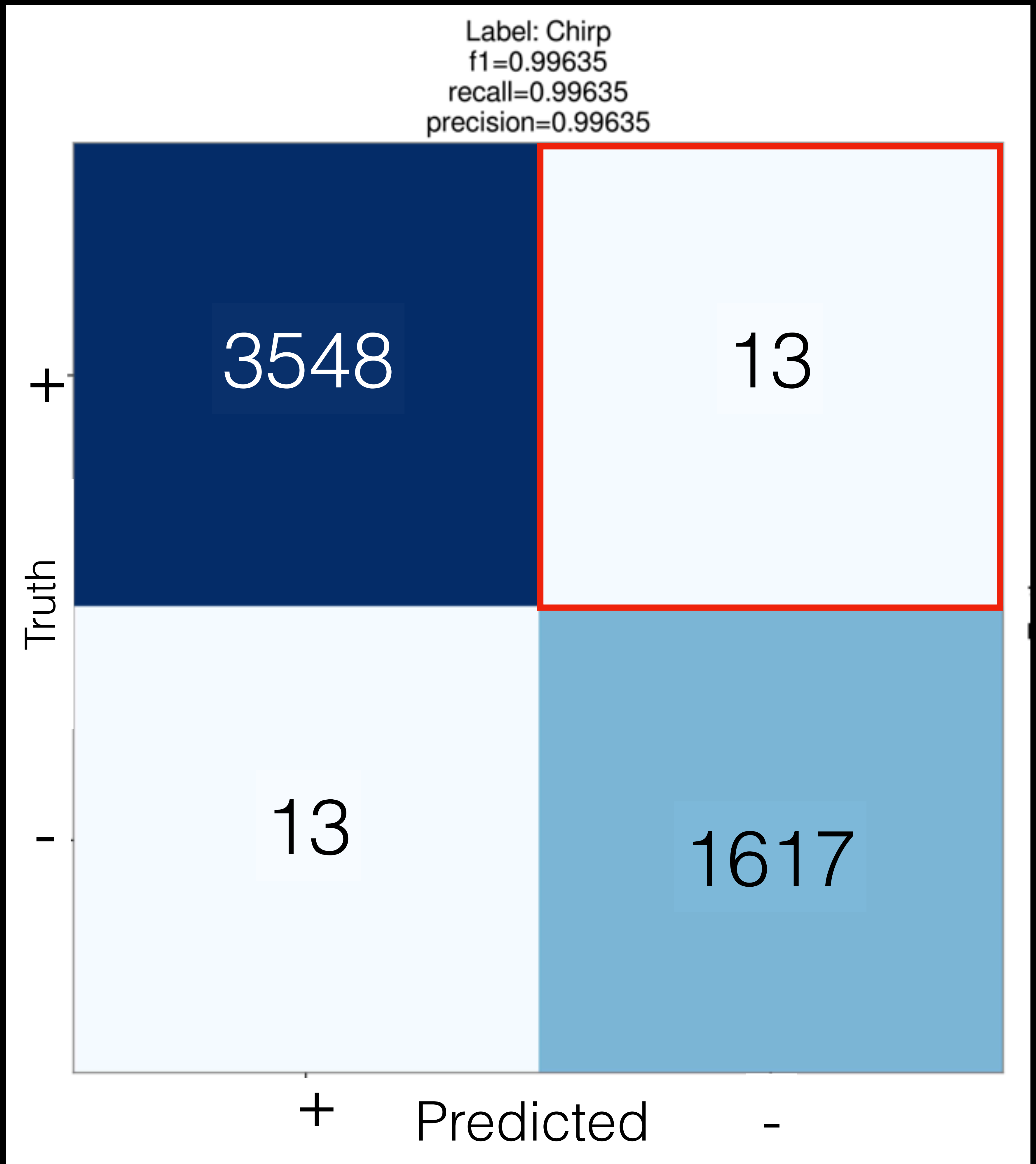
Álvarez-López et al., arXiv 2304.09977 (2023)

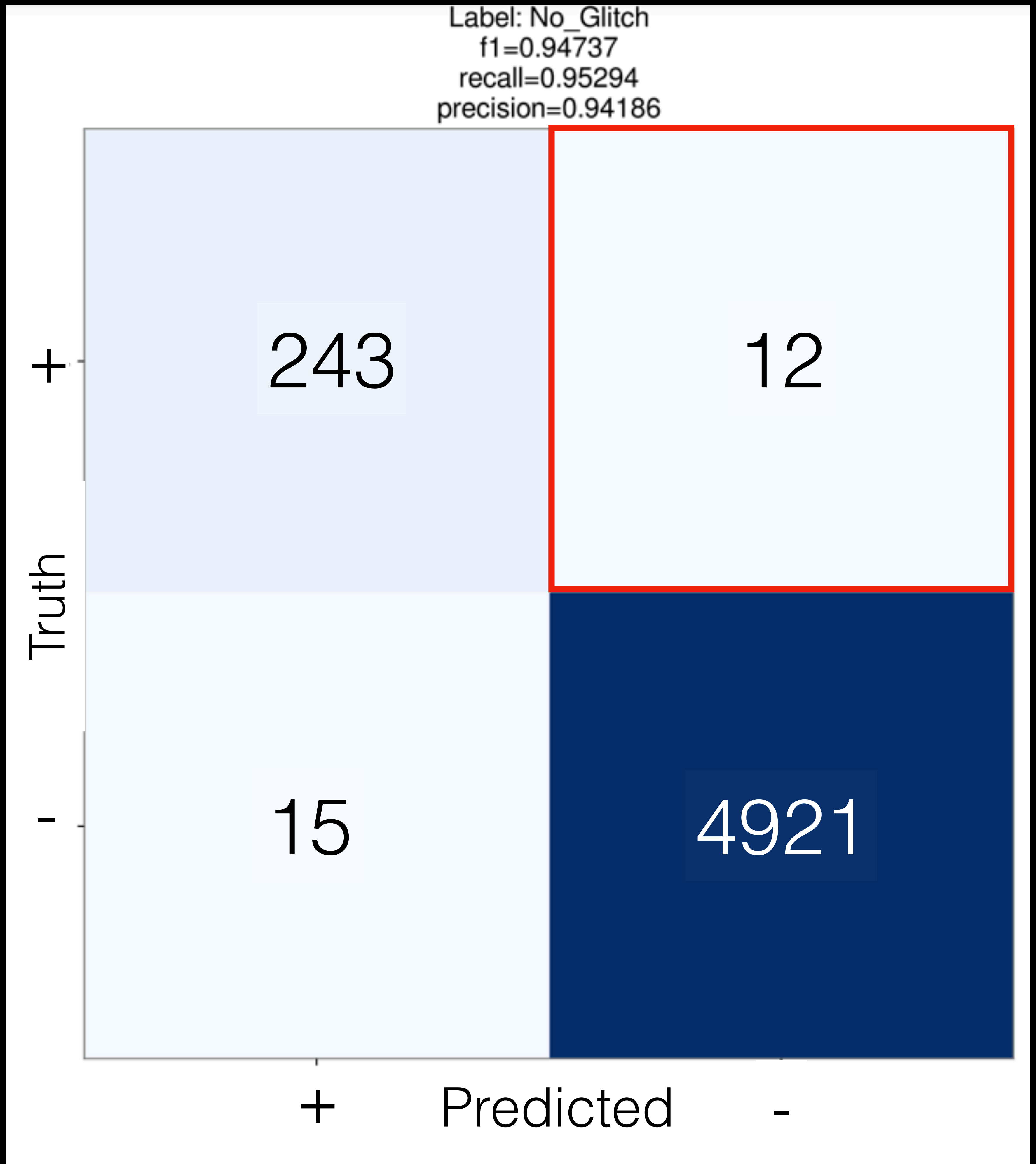
How well does GSpyNetTree perform?

>98% recall in all classifiers, in all classes!

The most commonly confused classes are GWs and no glitches; this is expected, and an equivalent result

Low mass classifier recall



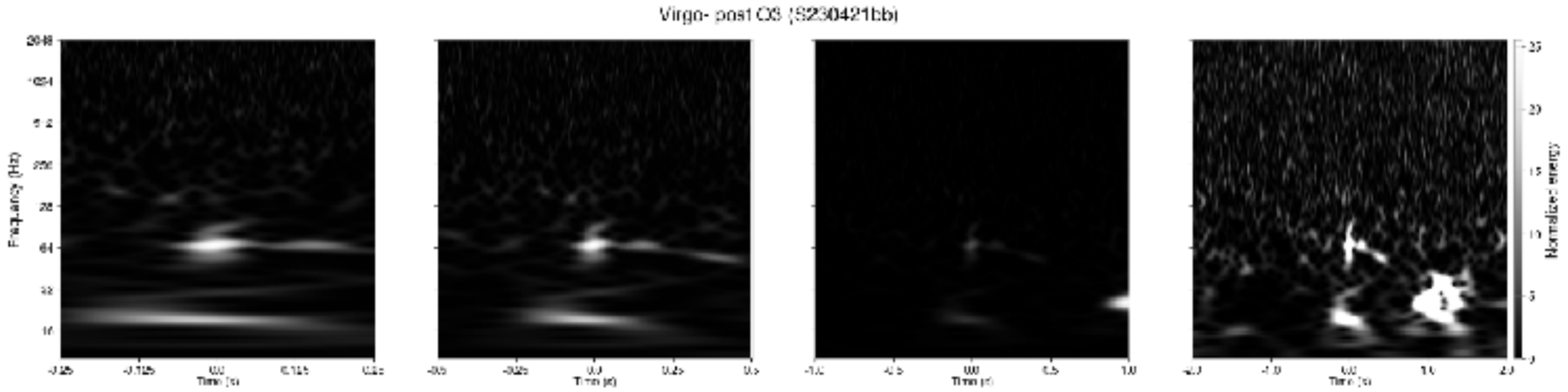


Álvarez-López et al., arXiv 2304.09977 (2023)

An example of where GSpyNetTree does well

GSpyNetTree result: DQ issue

(S230421bb) GSpyNetTree prediction on V1



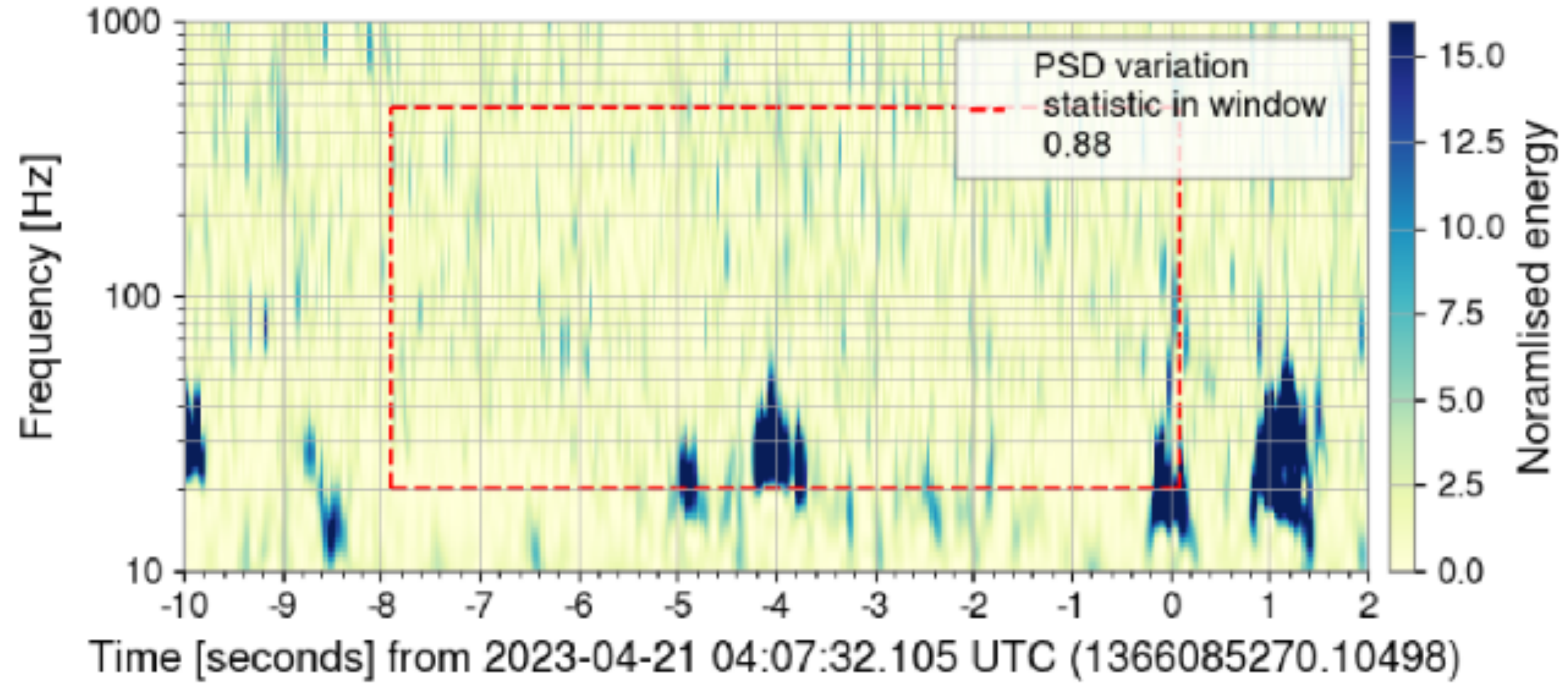
Parameters

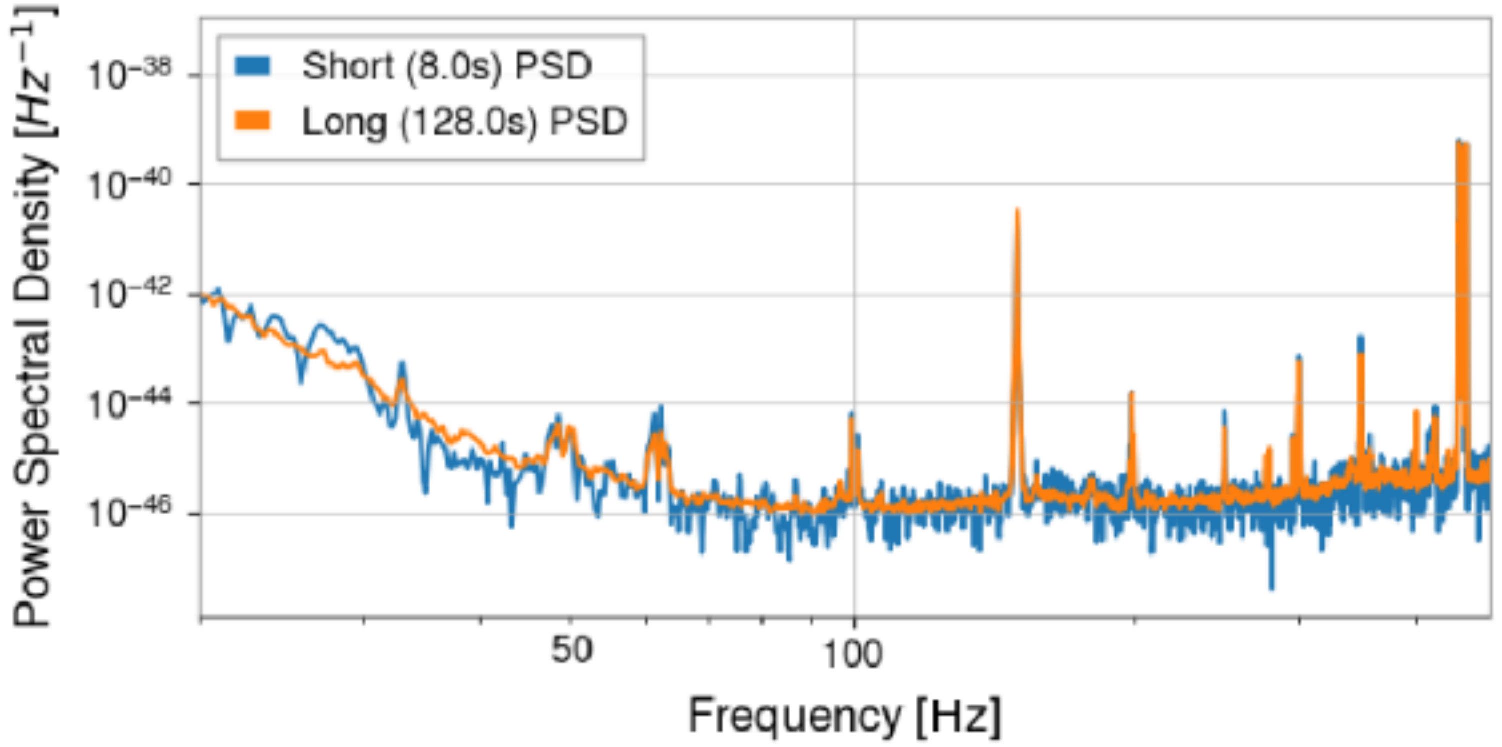
Start time (UTC)	2023-04-21 04:07:30.104980 (1366085268.10498)
End time (UTC)	2023-04-21 04:07:34.104980 (1366085272.10498)
Event ID	S230421bb
Window start (UTC)	2023-04-21 04:07:30.104980 (1366085268.10498)
Window end (UTC)	2023-04-21 04:07:34.104980 (1366085272.10498)
Channel	V1:Hrec_hoft_16384Hz_INJ1_O3Replay
Class probabilities	{'Blip': '0.00000', 'Blip_Low_Frequency': '0.00000', 'Chirp': '0.22620', 'Fast_Scattering': '0.00 '0.00001', 'Tomte': '0.00002'}
Predicted labels	Light_Scattering
Glitch p-value	0.00589

Stationarity test: PASS

V1 Stationarity for GPS Time 136608

Plotting Results





LVK
DQR

Challenge: detection

S190518bb case study

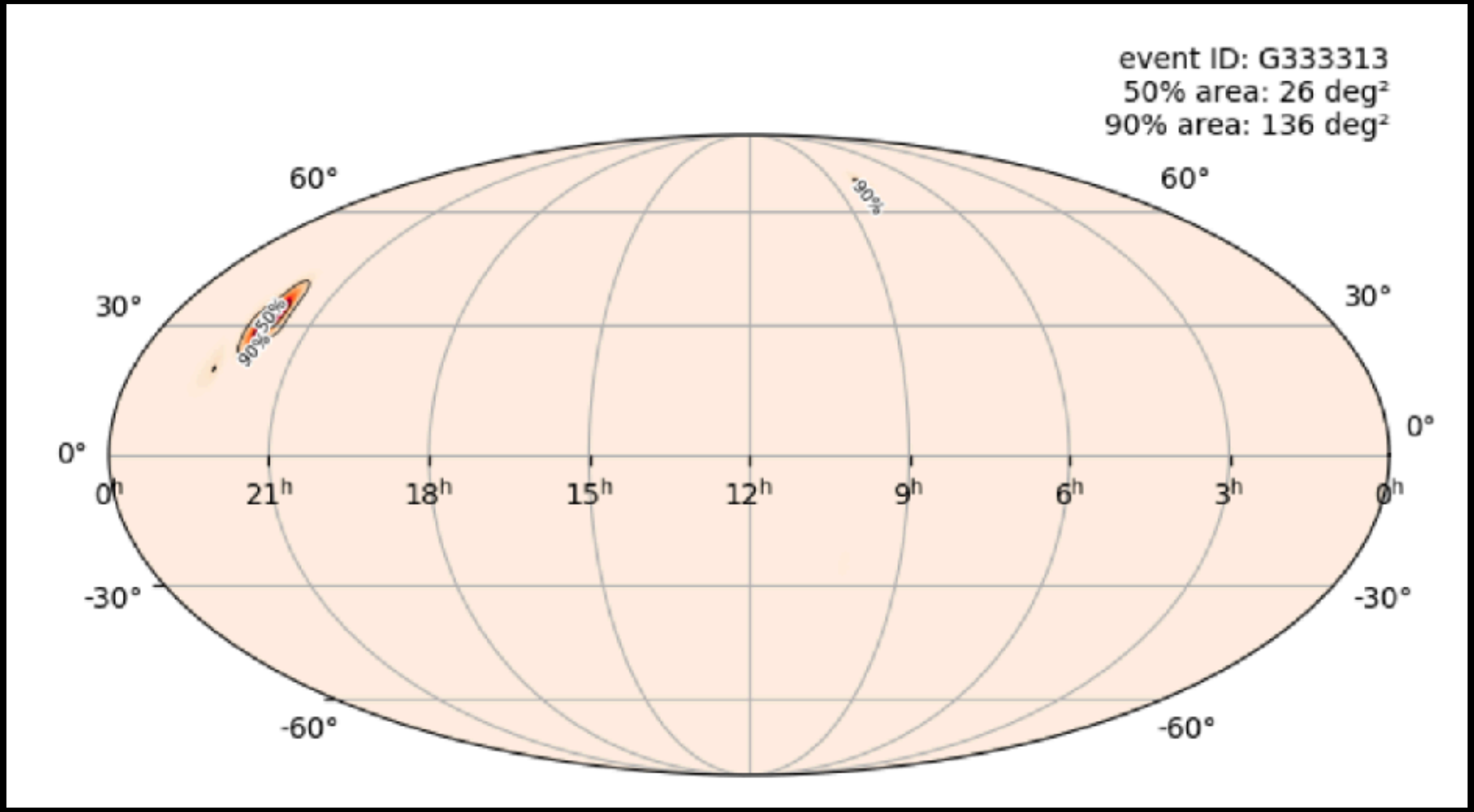
Automatic Preliminary Notice sent ~6 minutes after the event:

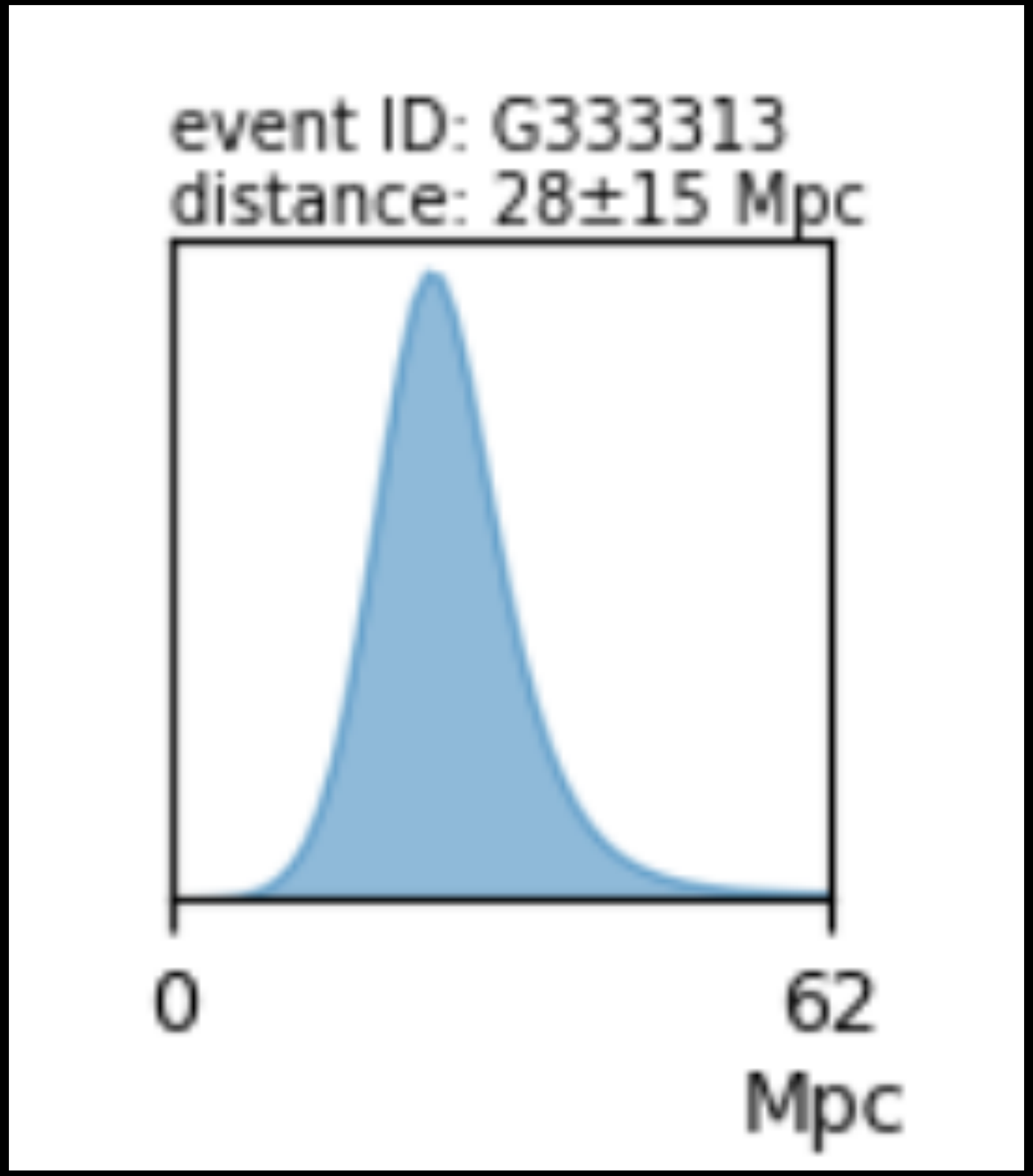
False Alarm Rate: 1.004e-08 [Hz] (one per ~3 years)

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%

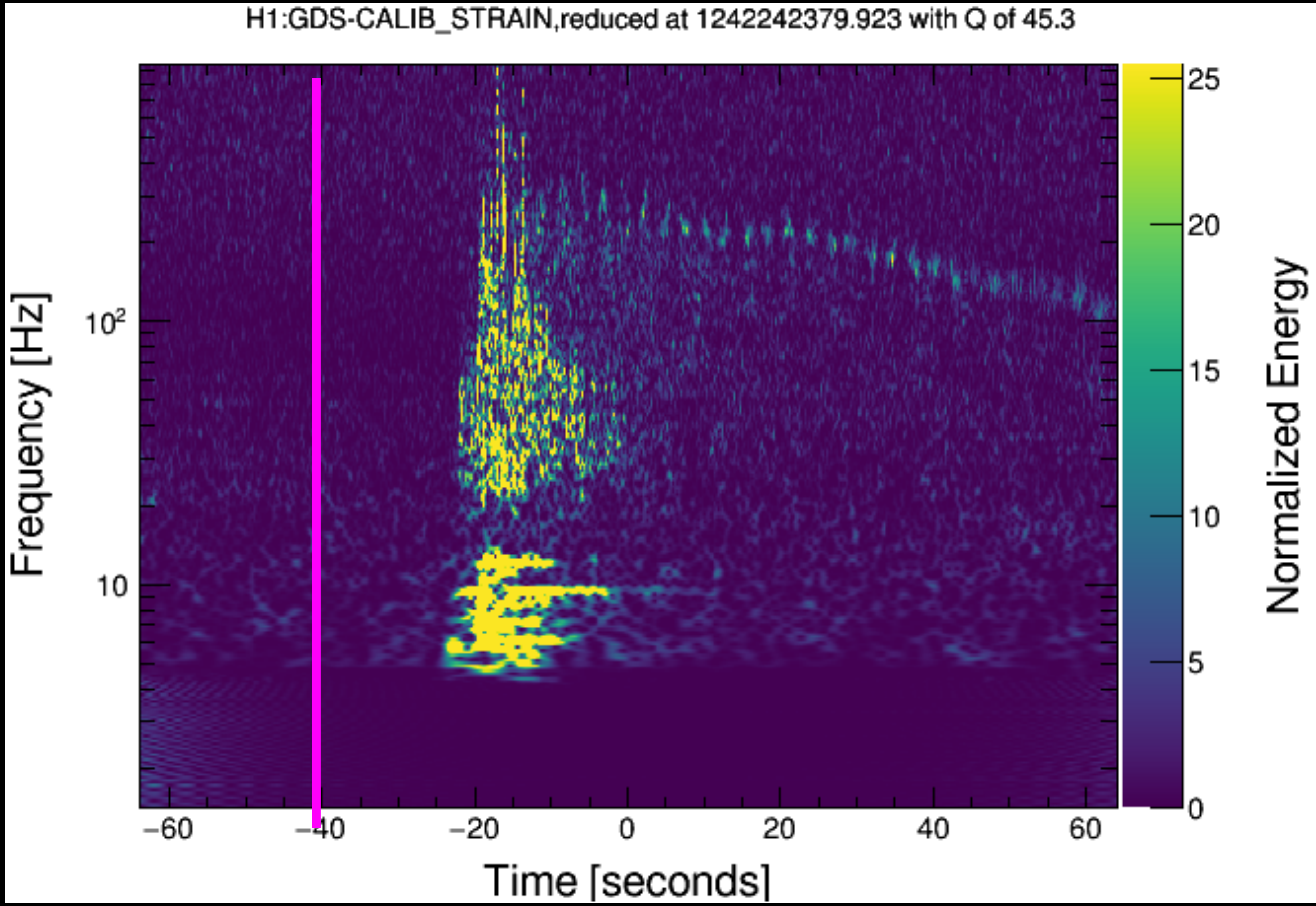




Challenge: S190518bb case study

Perspective of astronomers engaged in GW alert follow-up.

Idea from CIFAR G&EU 2019: additional noise screening is needed! What can we do with information that is available via alerts?

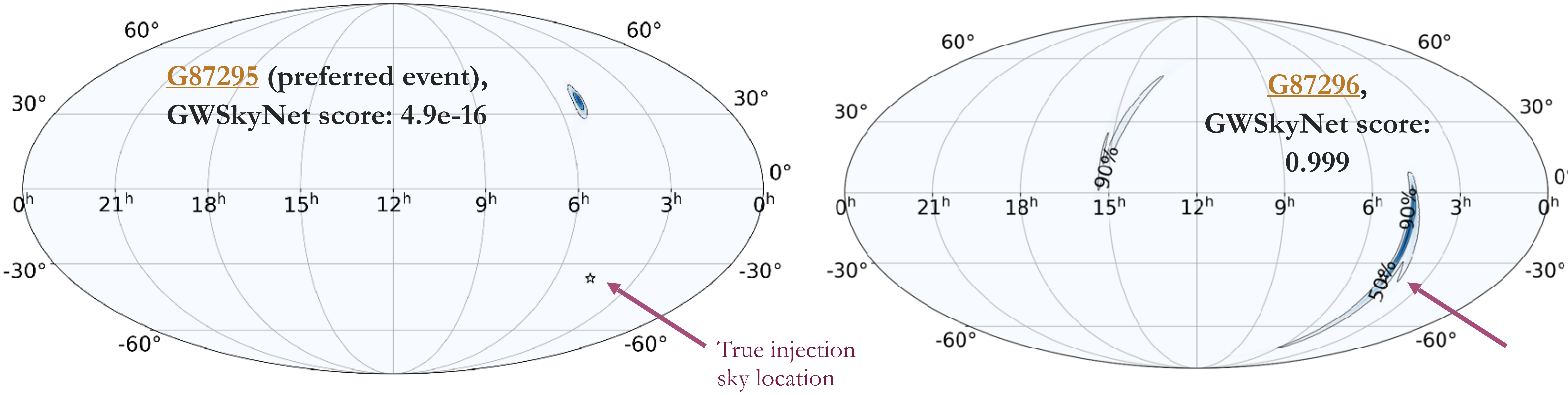


LIGO DCC G1900994

GWSkyNet: leveraging skymap information

Dr. Meryvn Chan

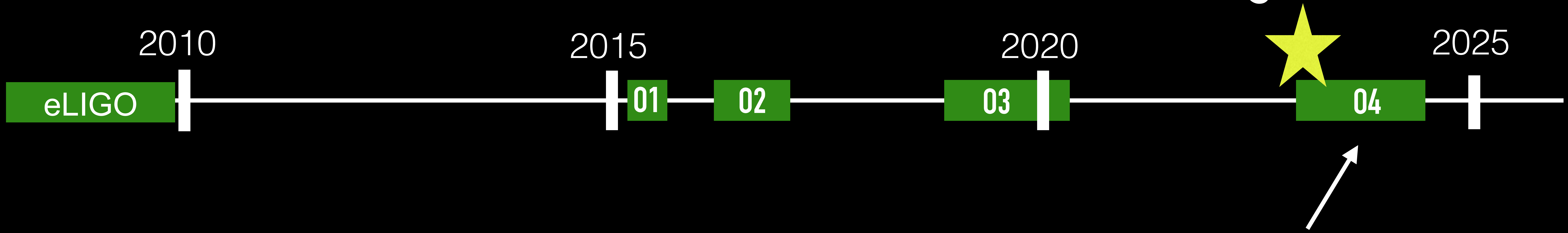
Two candidate triggers for the same “superevent” (i.e. nearby in time)



Miriam Cabero et al. ApJL, 2020

GWSkyNet results available for O4 to LVK members via GraceDB.

Timeline of Advanced LIGO and Advanced Virgo



Observing run 4 (O4)

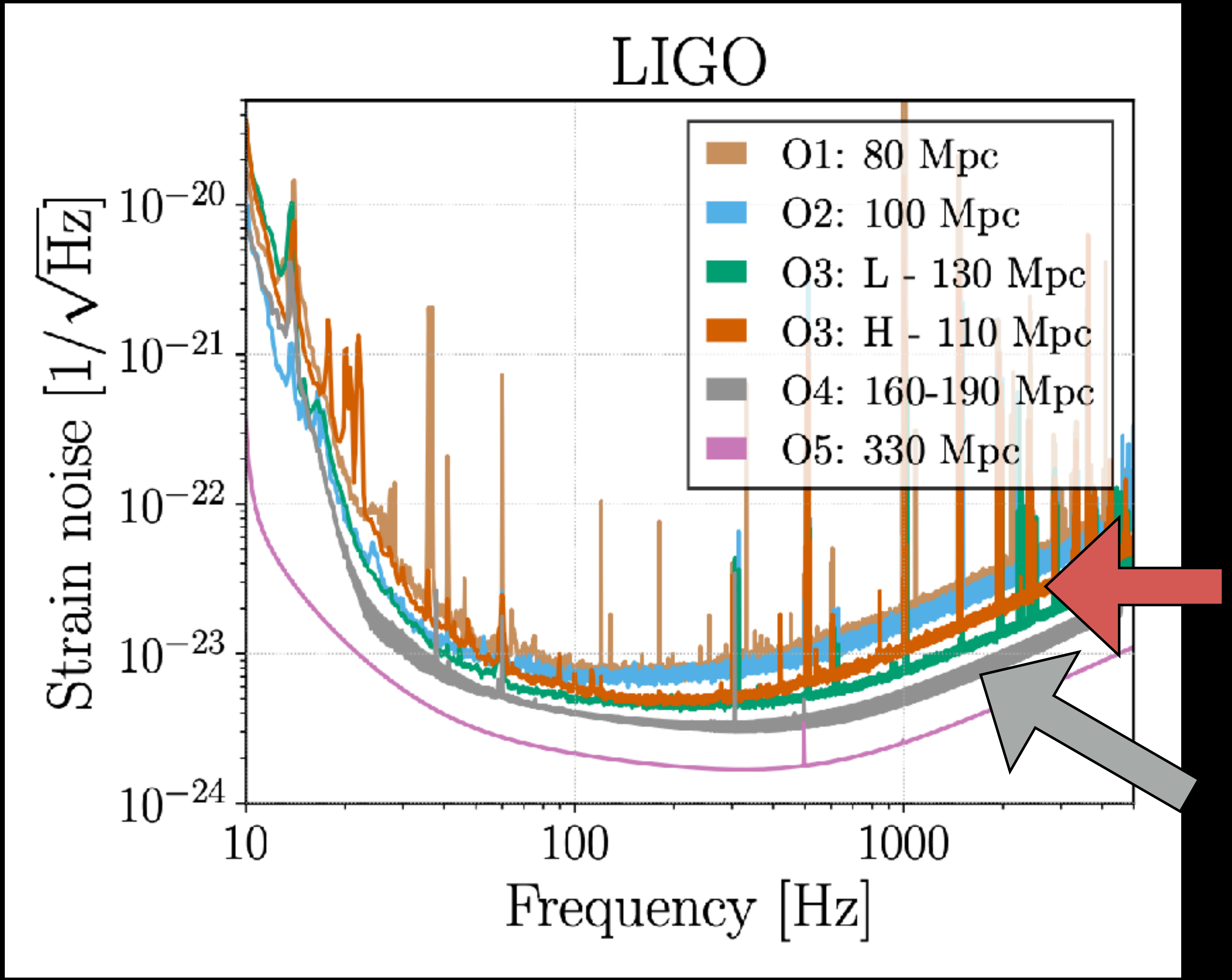
- Started May 24 with improved detector sensitivity (2 LIGO detectors)
- Target: Advanced LIGO and Advanced Virgo at improved sensitivity
- KAGRA also plans to join at a reduced sensitivity

Pre-O4 updates for Advanced LIGO

Slide by Dave Reitze

Looking ahead

As the GW detection rate increases, automation will become more important.



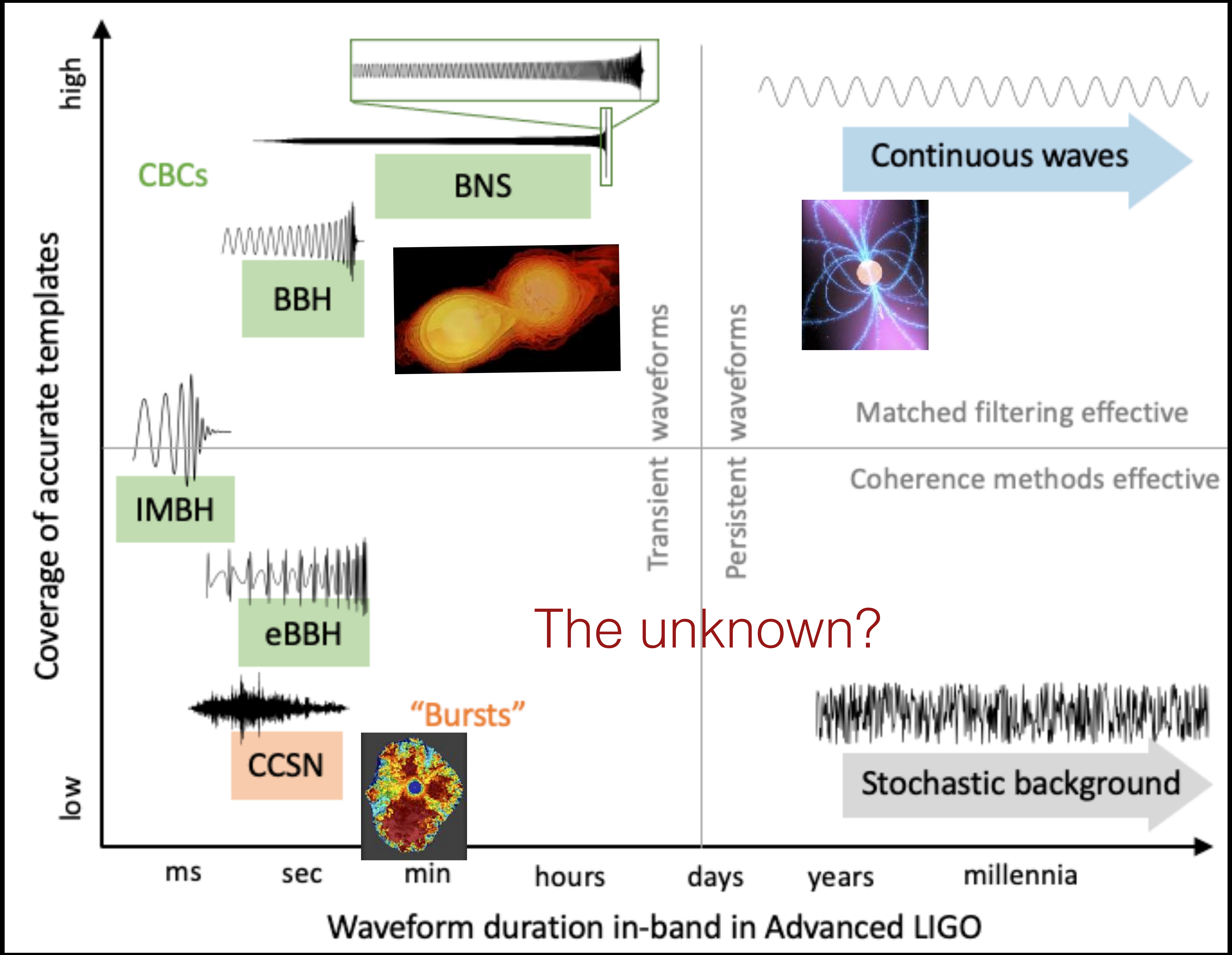
O4 started on May 24!

Expectation for the third LIGO observing run (O3) **1 signal/week!**

O4 expectation: up to a few signals per week

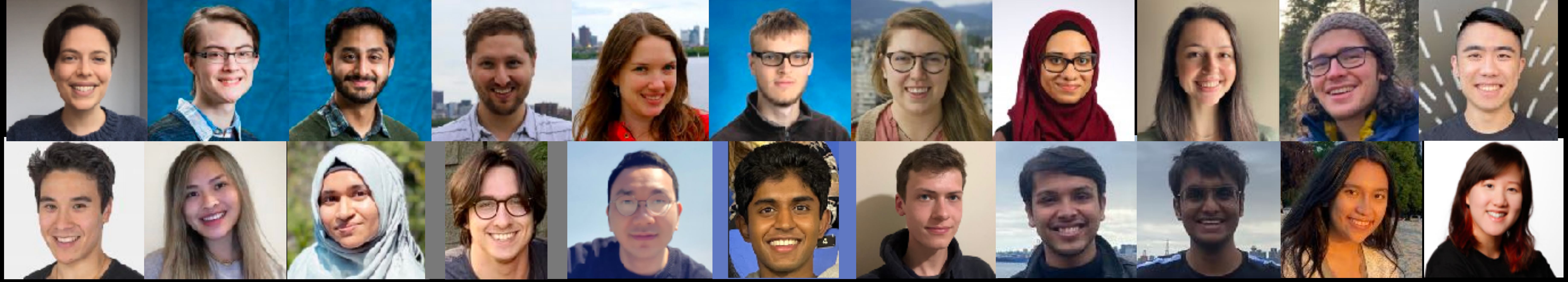
LIGO-Virgo arXiv 1304.0670 v11

What else might we detect with current detectors?

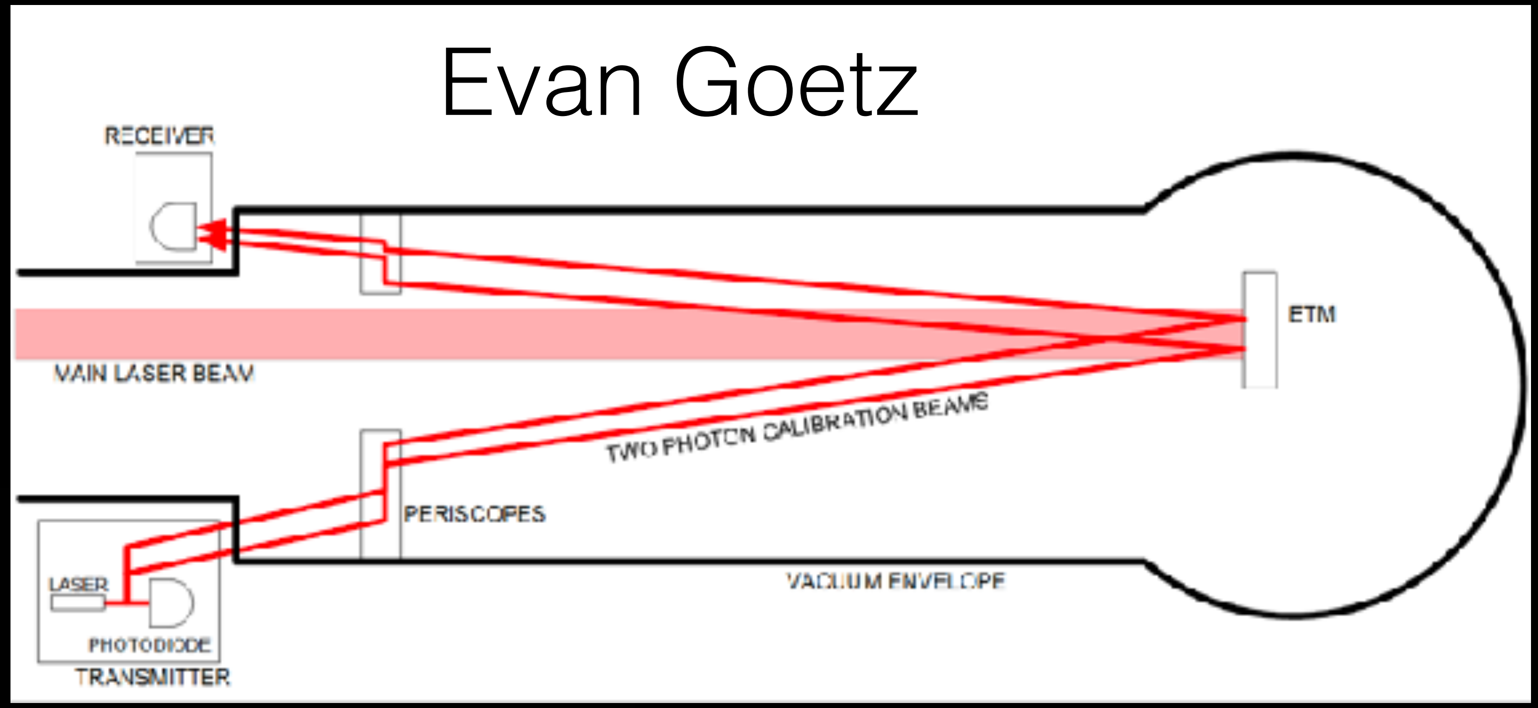


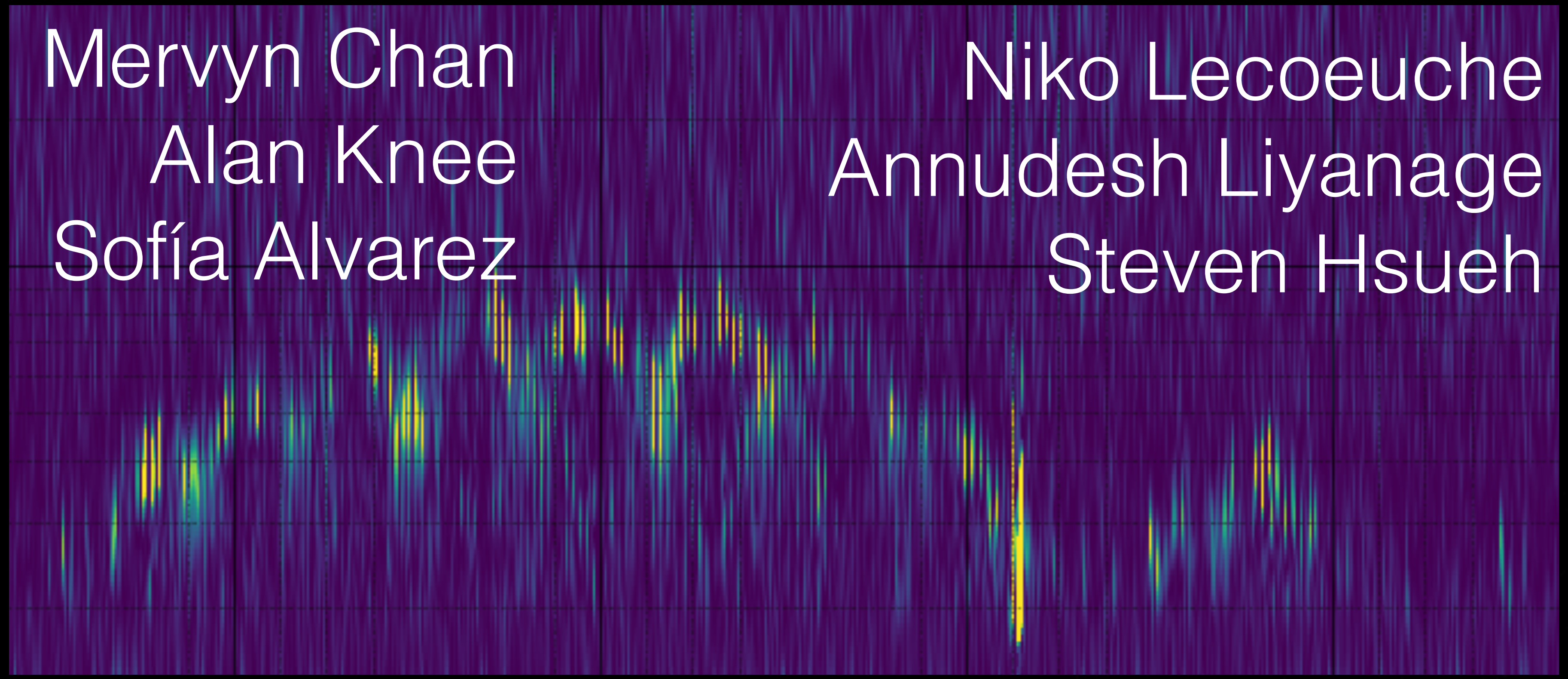
McIver and Shoemaker, 2021

The UBC GW astrophysics group



Evan Goetz





Mervyn Chan
Alan Knee
Sofía Alvarez

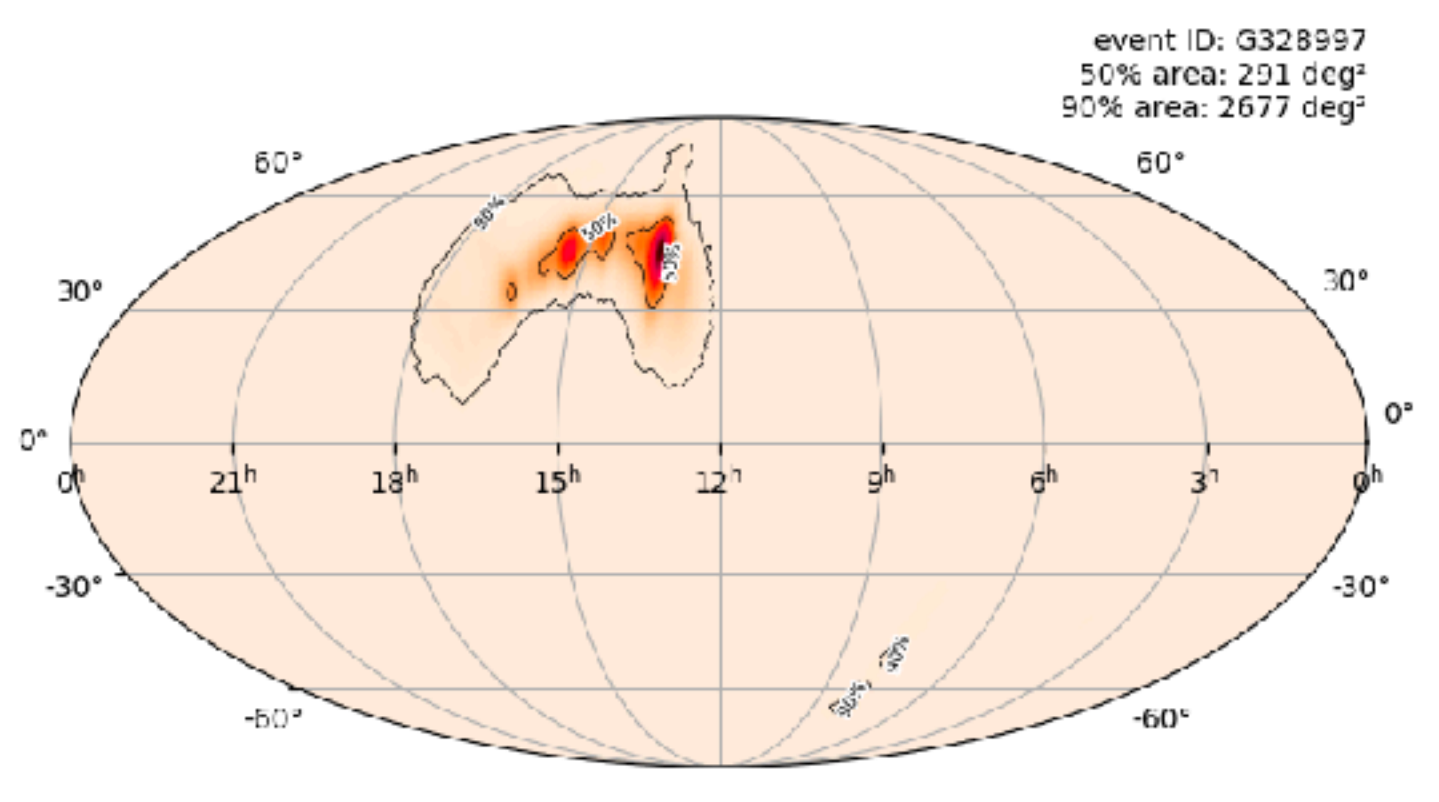
Niko Lecoeuche
Annudesh Liyanage
Steven Hsueh

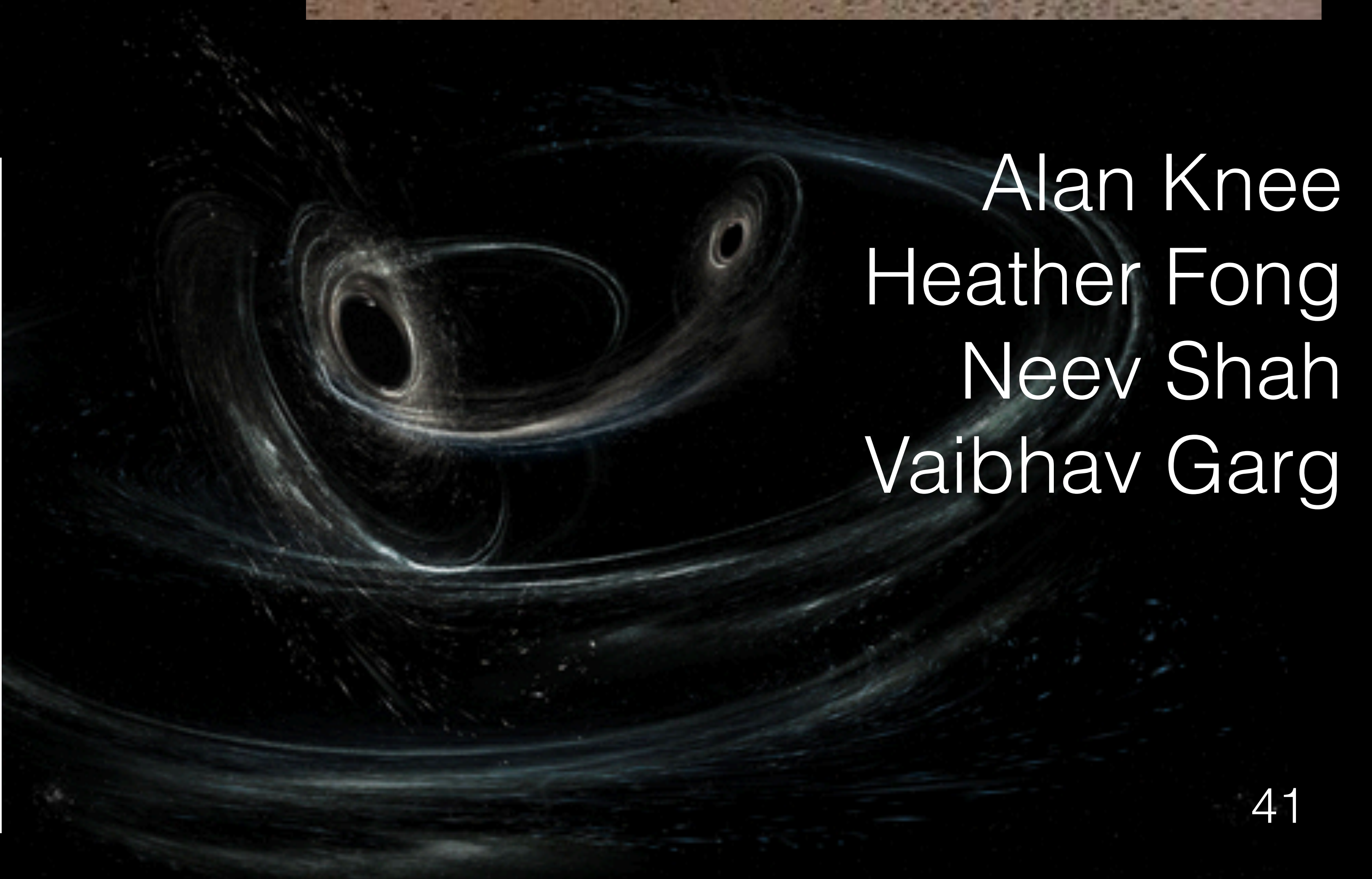
Evan Goetz, Alan Knee, Neev Shah, Kat Nell

Evan Goetz
Helen Du
Alan Knee

Nayyer Raza

Mervyn Chan, Miriam Cabero





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