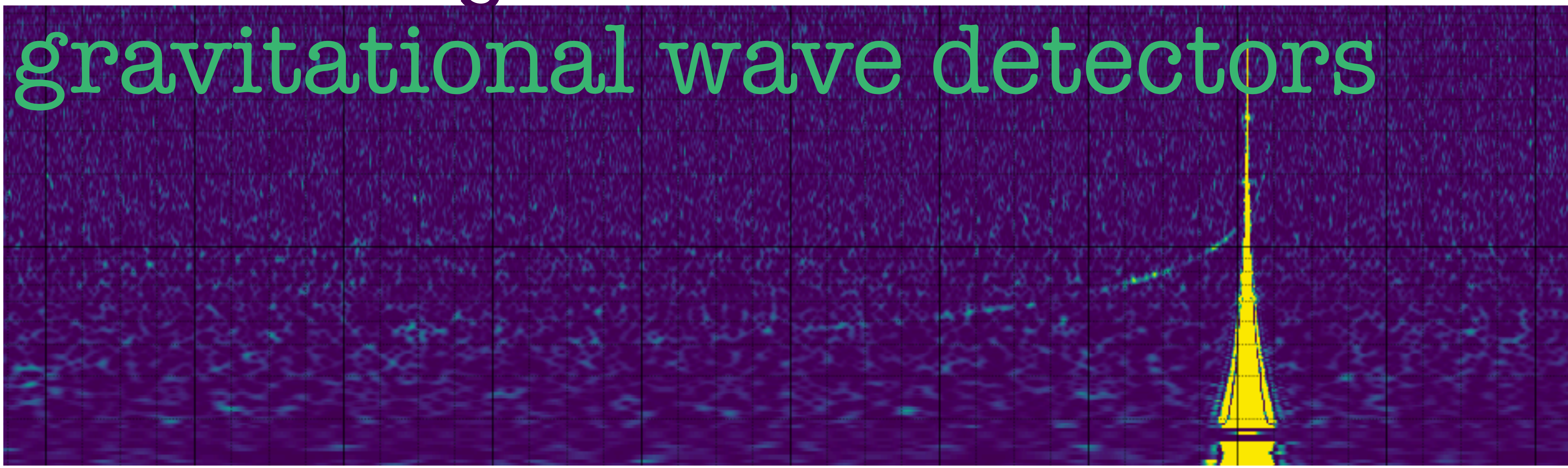
Noise mitigation methods for gravitational wave detectors



Made with GWpy: gwpy.github.io

Dr. Jess McIver

AstroInformatics 2019

June 26, 2019

LIGO DCC G1901218

NSF Caltech LIGO LSC THE UNIVERSITY OF BRITISH COLUMBIA

Outline

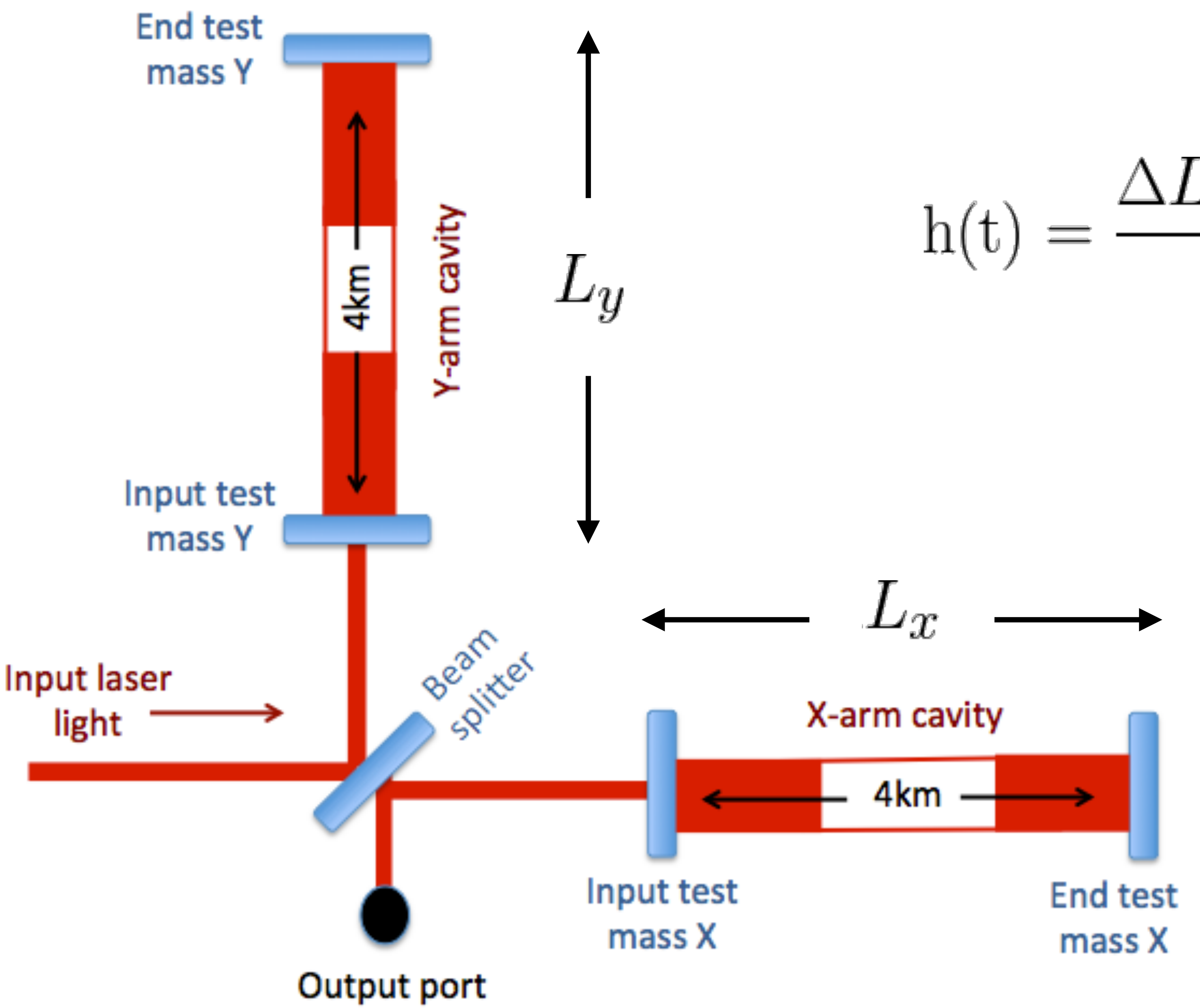
LIGO detector noise

Noise mitigation

- Improving GW search sensitivity
- Maximizing duty cycle

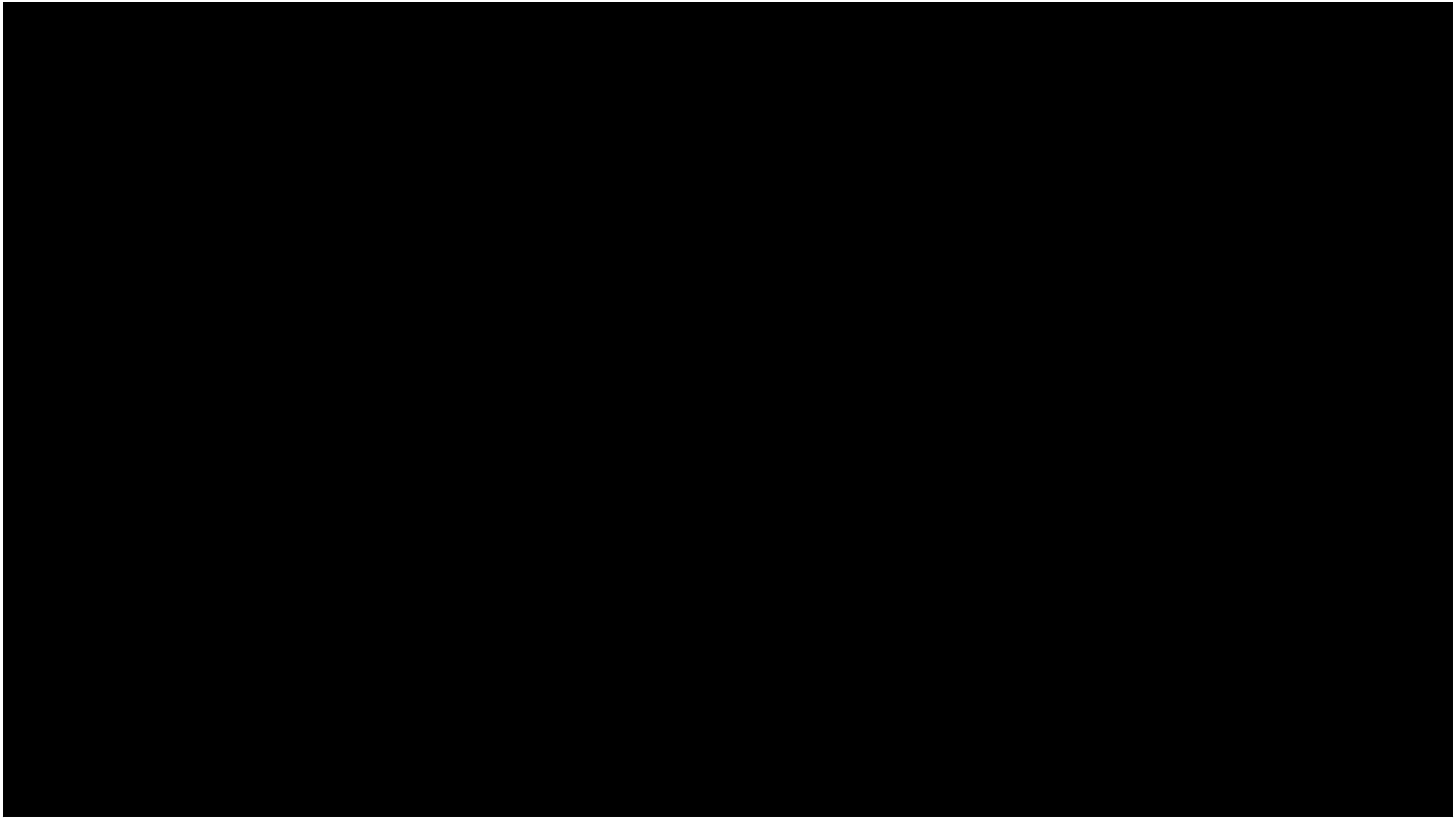
Conclusions

LIGO: the basics



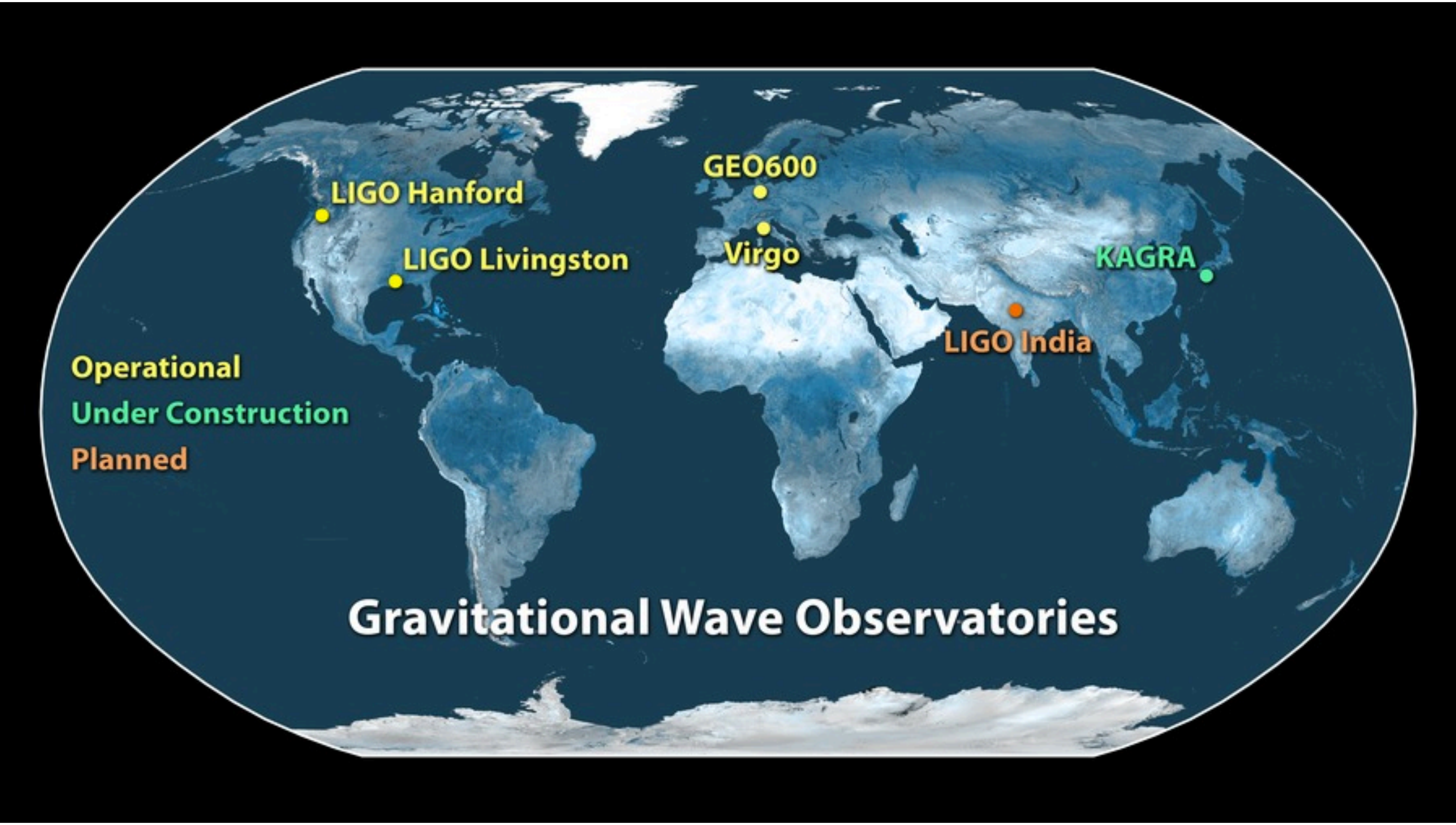
$$h(t) = \frac{\Delta L_y - \Delta L_x}{L}$$

LIGO: a more detailed view



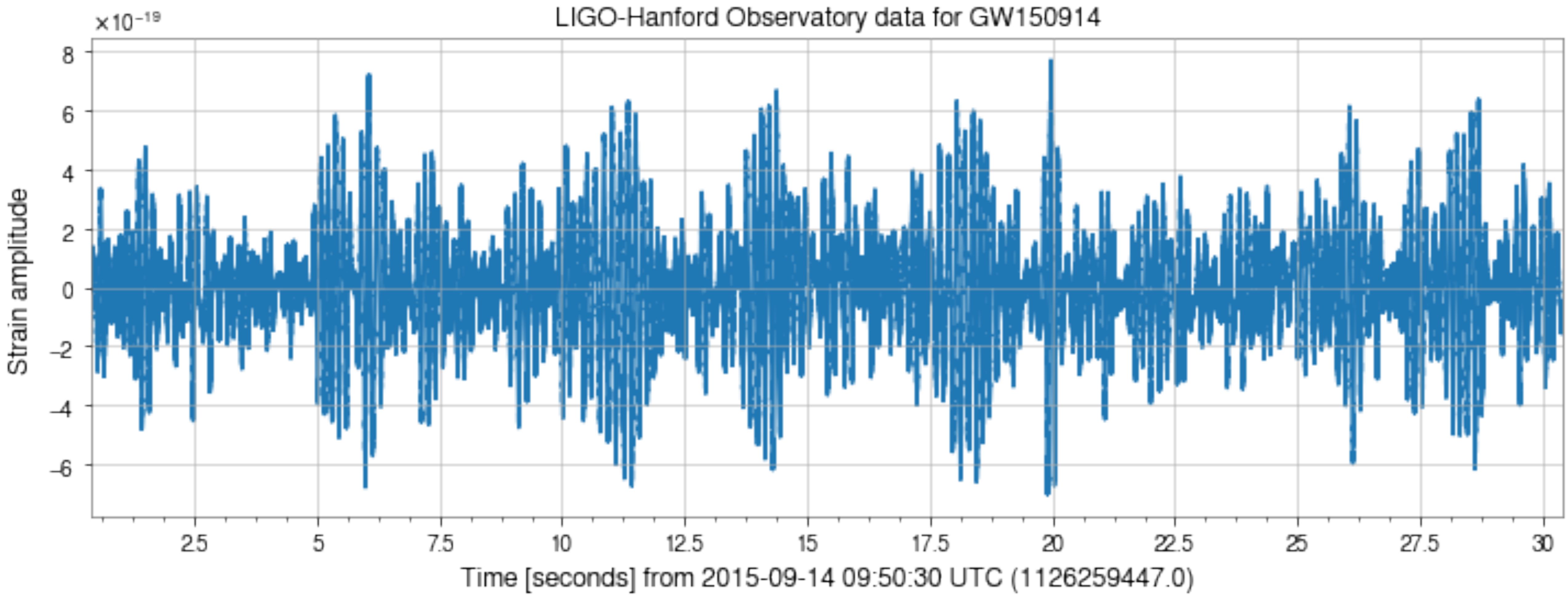
Kai Staats

The global network of current gen interferometers



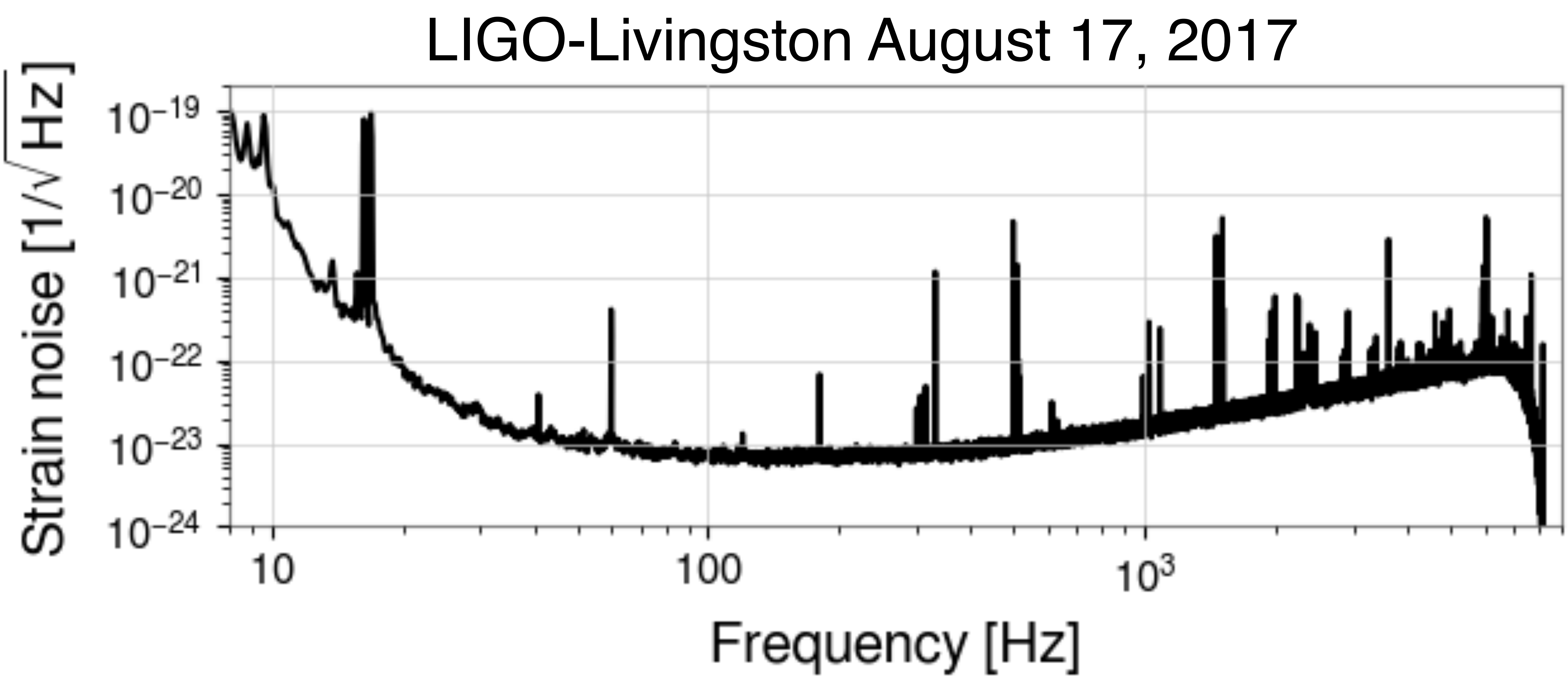
LIGO/Caltech

What does LIGO data look like?

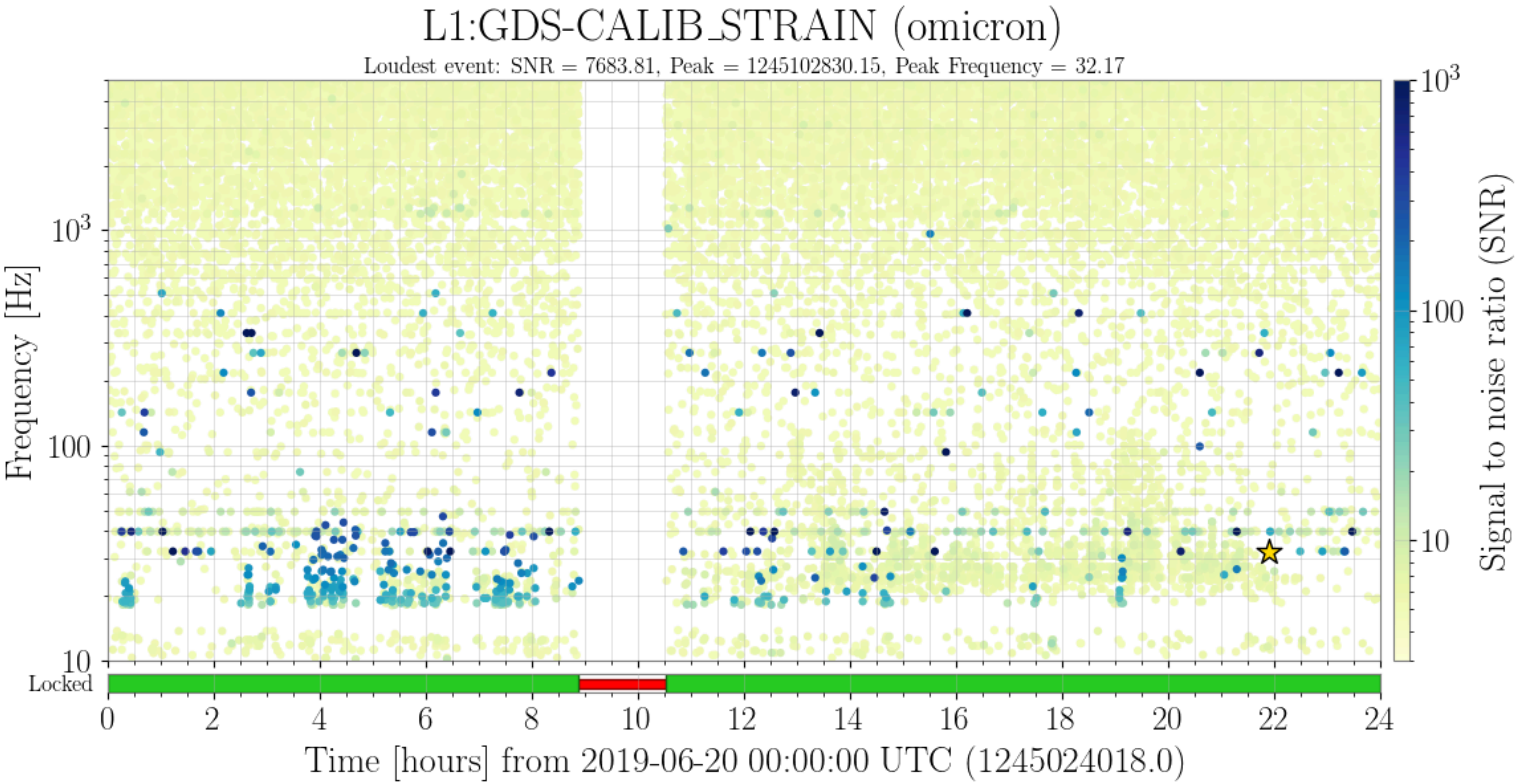


Made with GWpy!

Properties of averaged LIGO noise

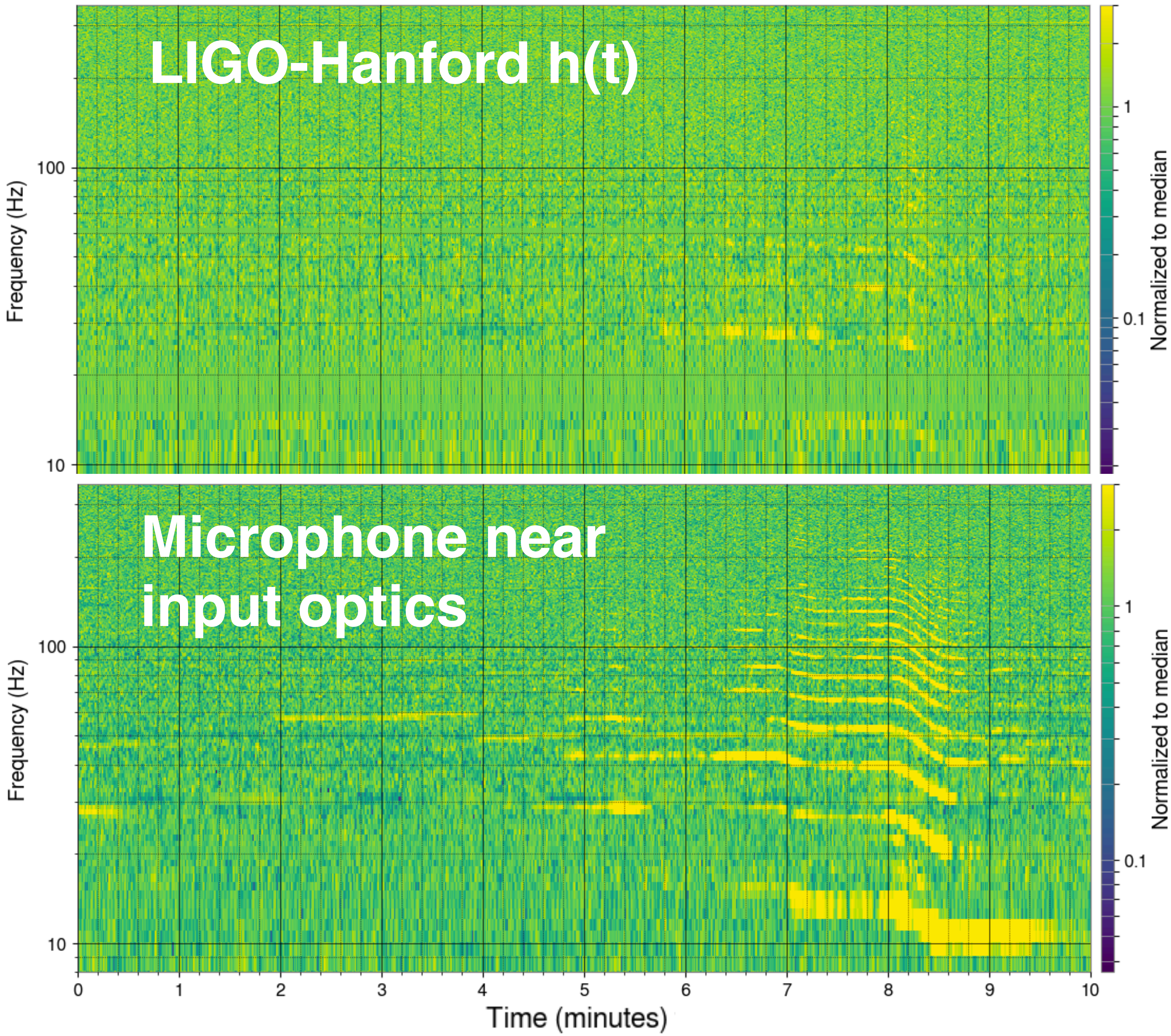


LIGO data is non-stationary!



https://ldas-jobs.ligo-la.caltech.edu/~detchar/summary/

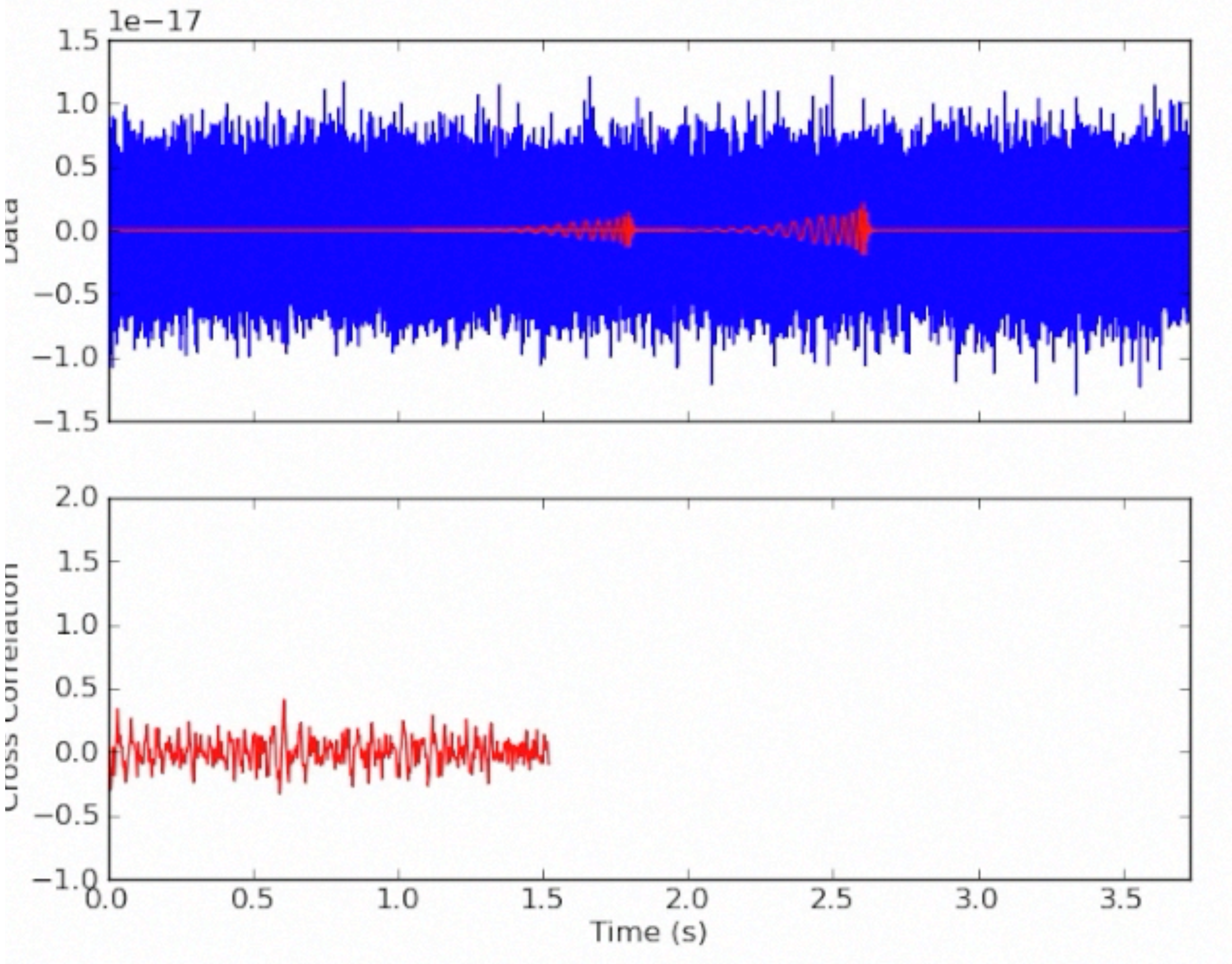
New noise feature in O3!



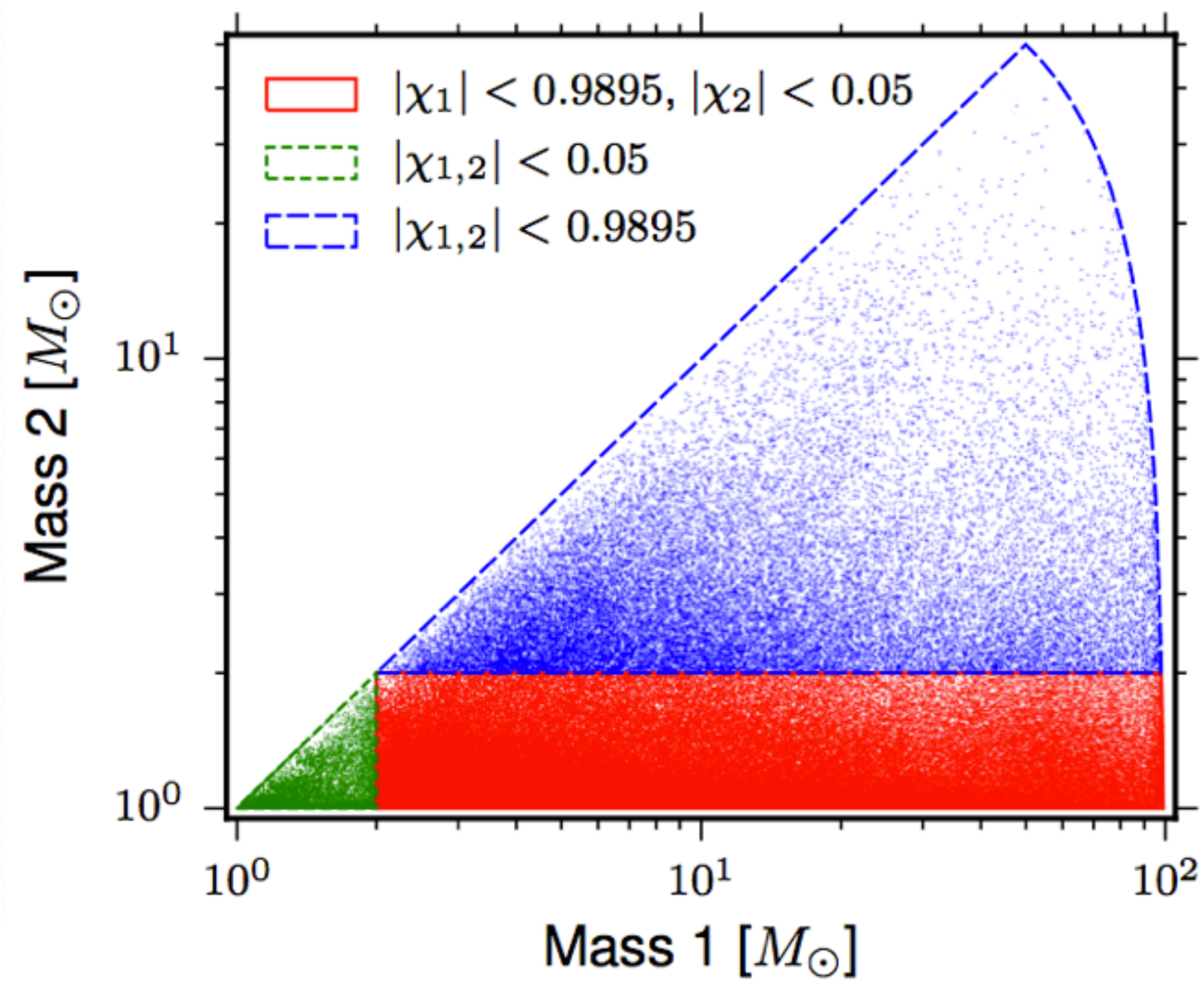
Searching for signals with matched filtering

Slide adapted from S. Caudill

Matched filter signal-to-noise ratio

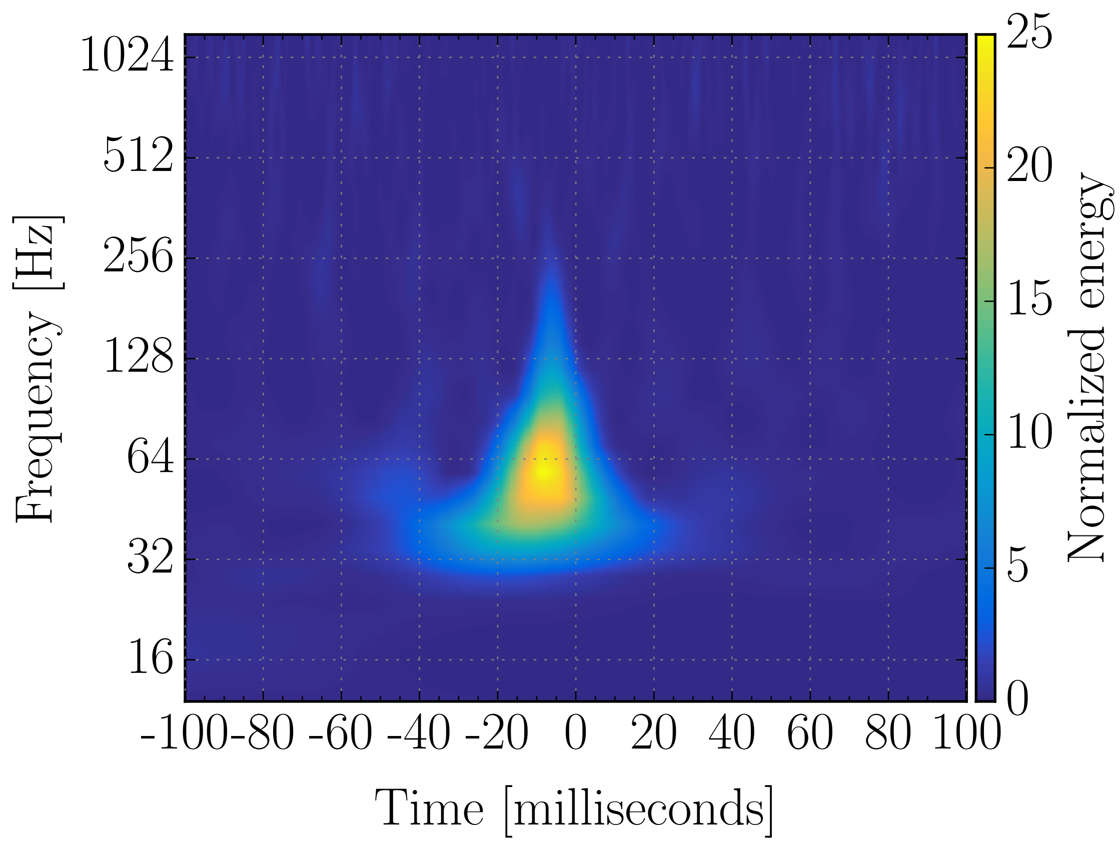


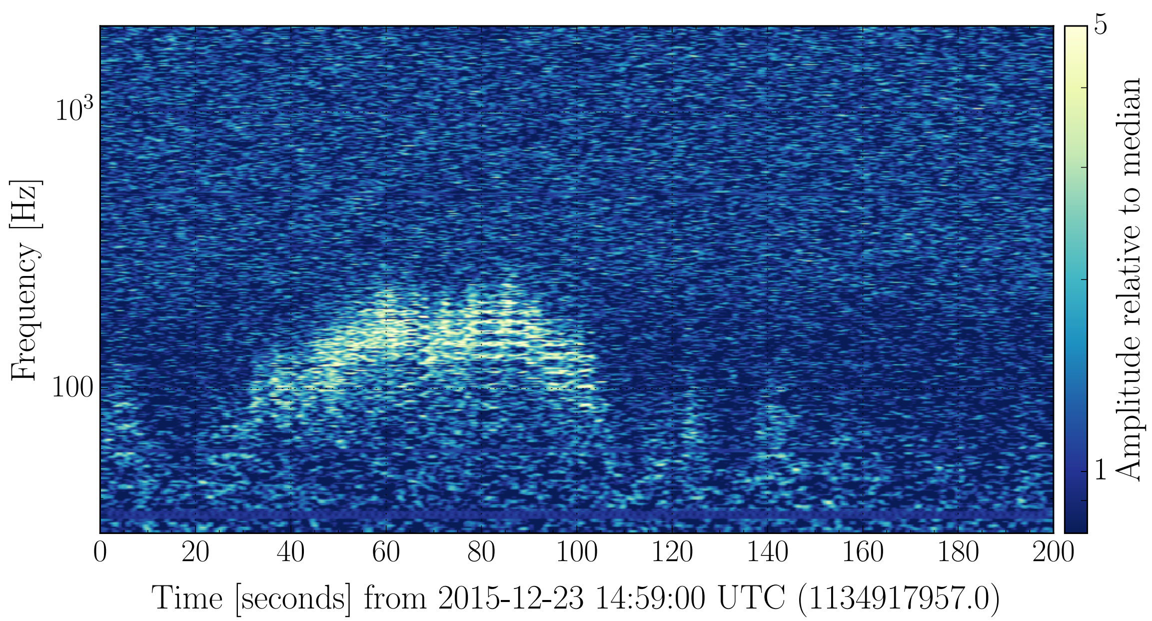
Template Bank

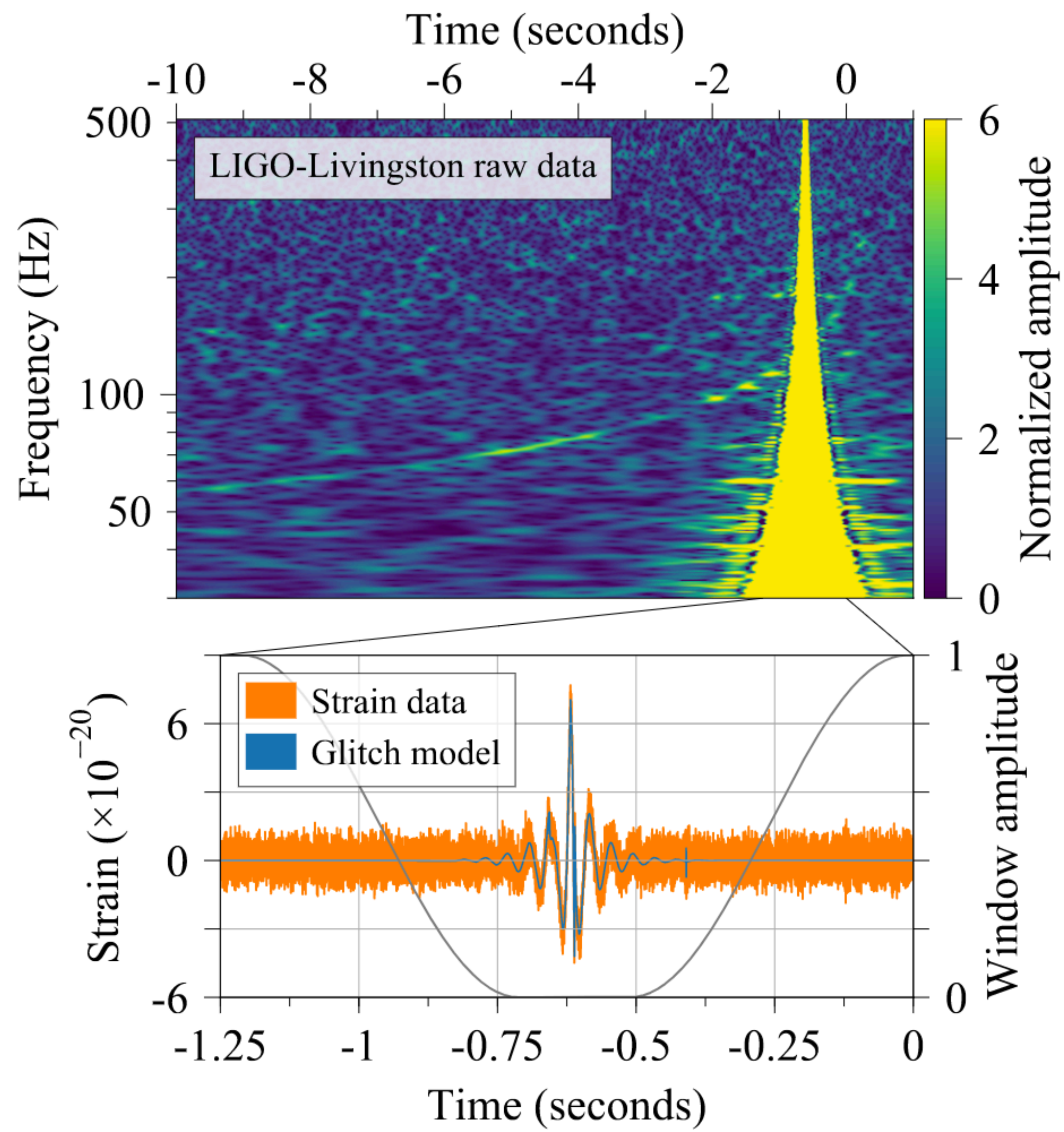


B. P. Abbott et al. Phys. Rev. X (2016)

Challenge: non-Gaussianity





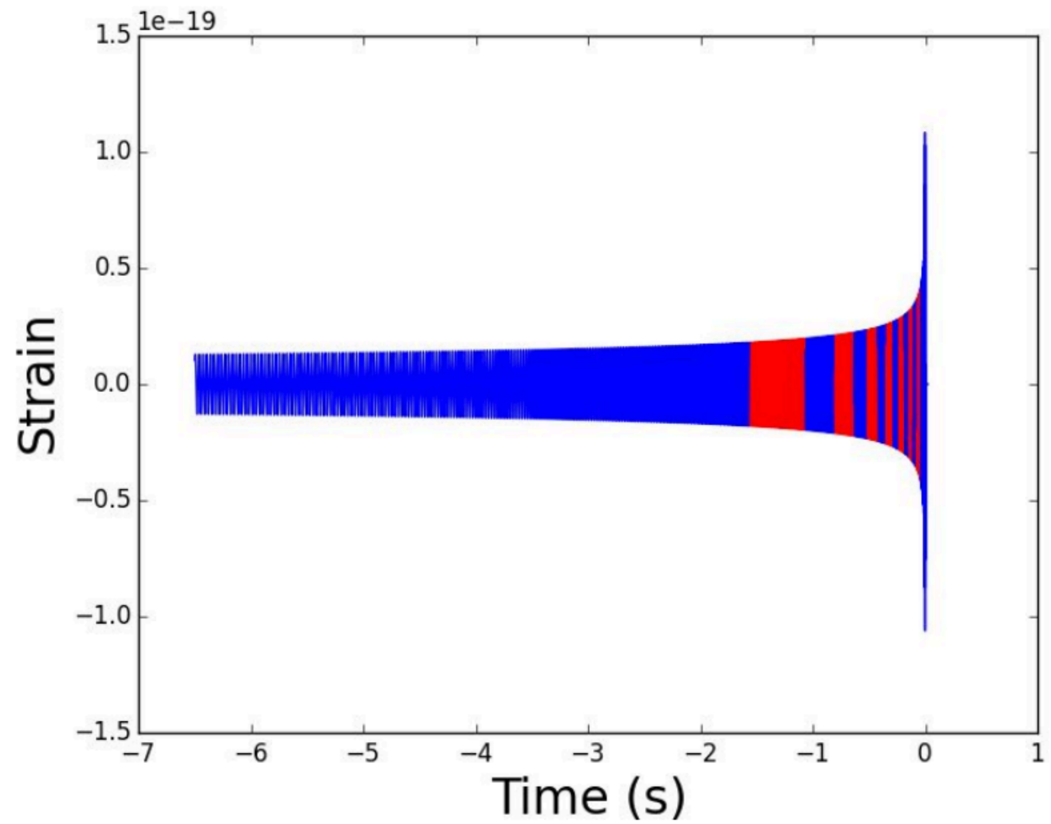


B.P Abbott et al. CQG (2018)

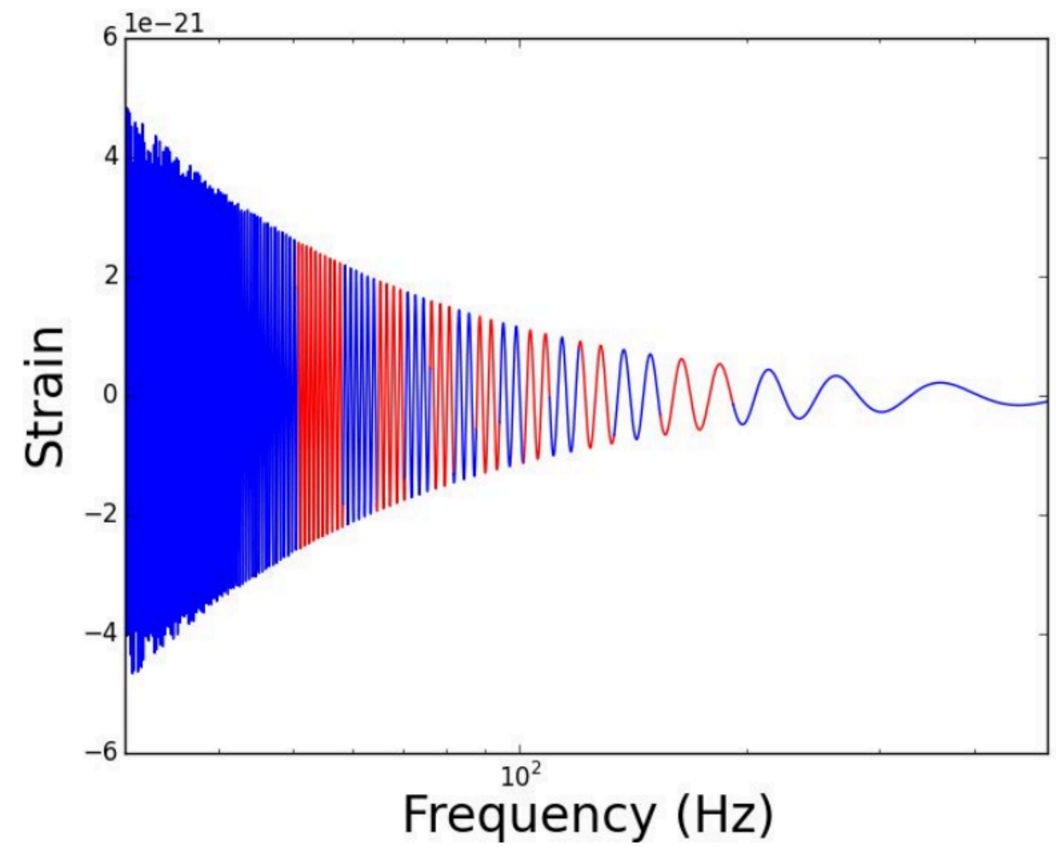
B.P. Abbott et al PRL. (2017)

The Chi-squared test

Time domain



Frequency domain



Divide the template into frequency bands of equal expected power

$$\chi^2 \propto \sum (\rho_l - \rho / N_{bins})^2$$

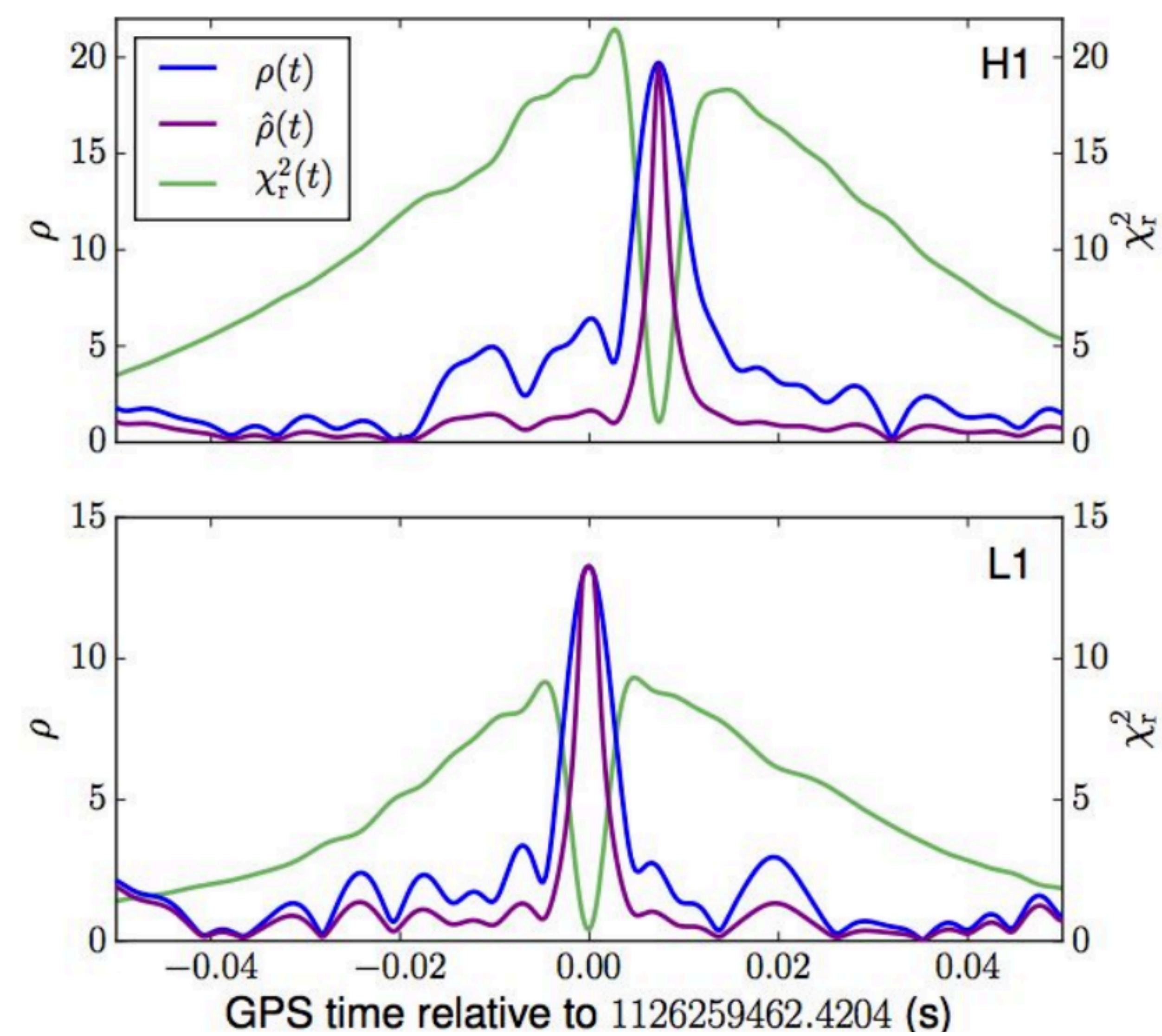
Adapted from slide by Alex Nitz

Chi-squared re-weighting

Redefine SNR to downweight the SNR of triggers with high Chi-squared

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

GW150914: an example

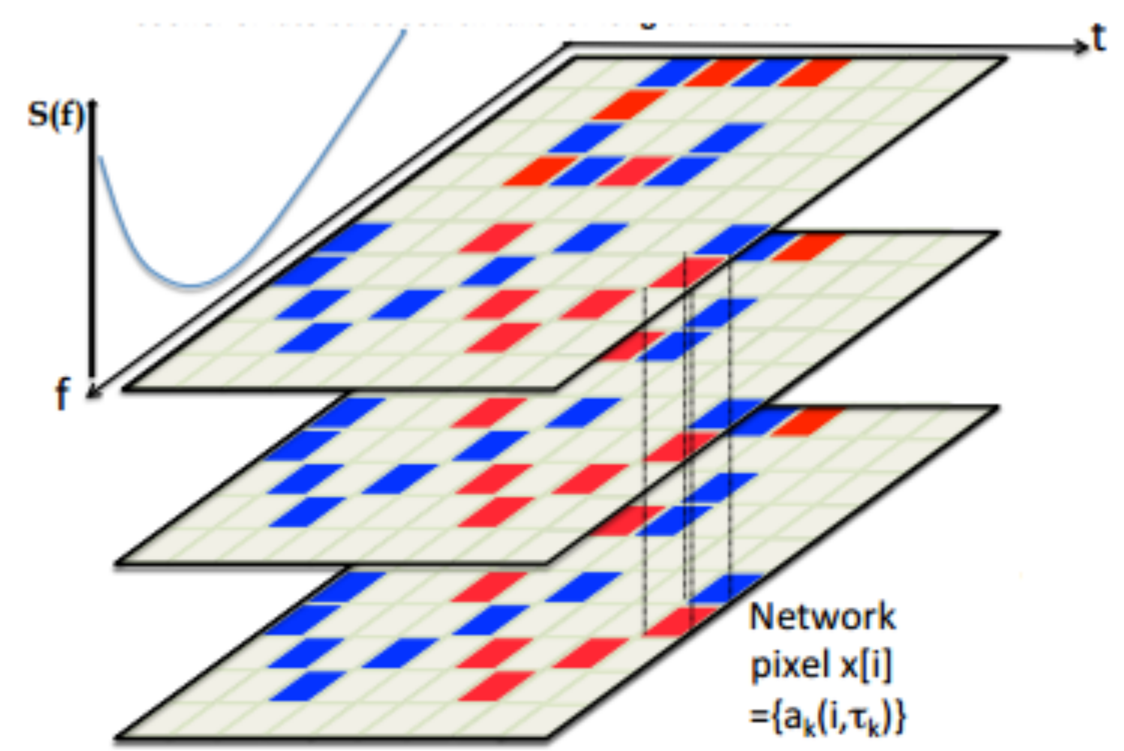


Adapted from slides by Alex Nitz

"Un-modeled" burst searches

cWB - an all-sky coherent burst search

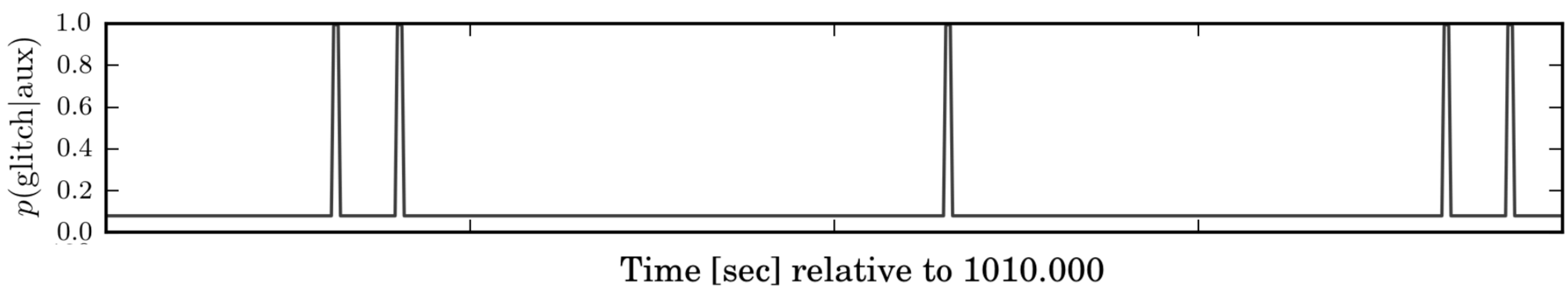
- Projects the data onto a Meyer wavelet basis.
- Extracts significant events using a coherent likelihood statistic maximized over all potential sky positions.



Klimenko et al. CQG 2011

Low latency glitch correlations: iDQ

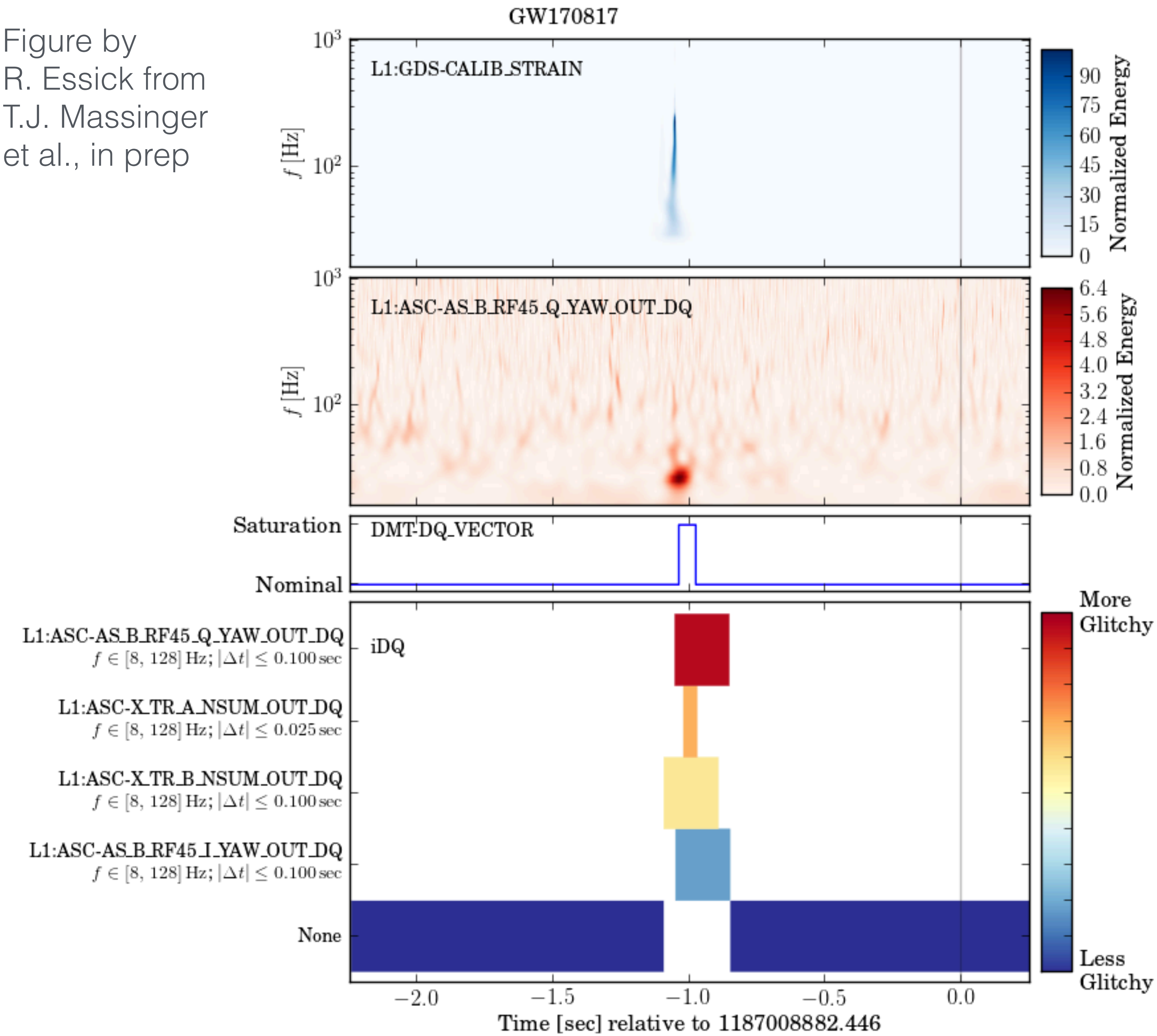
- iDQ is an **engine for statistical inference**
- Will produce a time series of the probability of a glitch in h(t) in the LIGO detectors based on auxiliary channel information in O3 — a **key data quality product that will inform Open Public Alerts**
- iDQ supports a variety of supervised learning techniques
- Broadly useful architecture for streaming classification



R. Essick et al. CQG (2013)

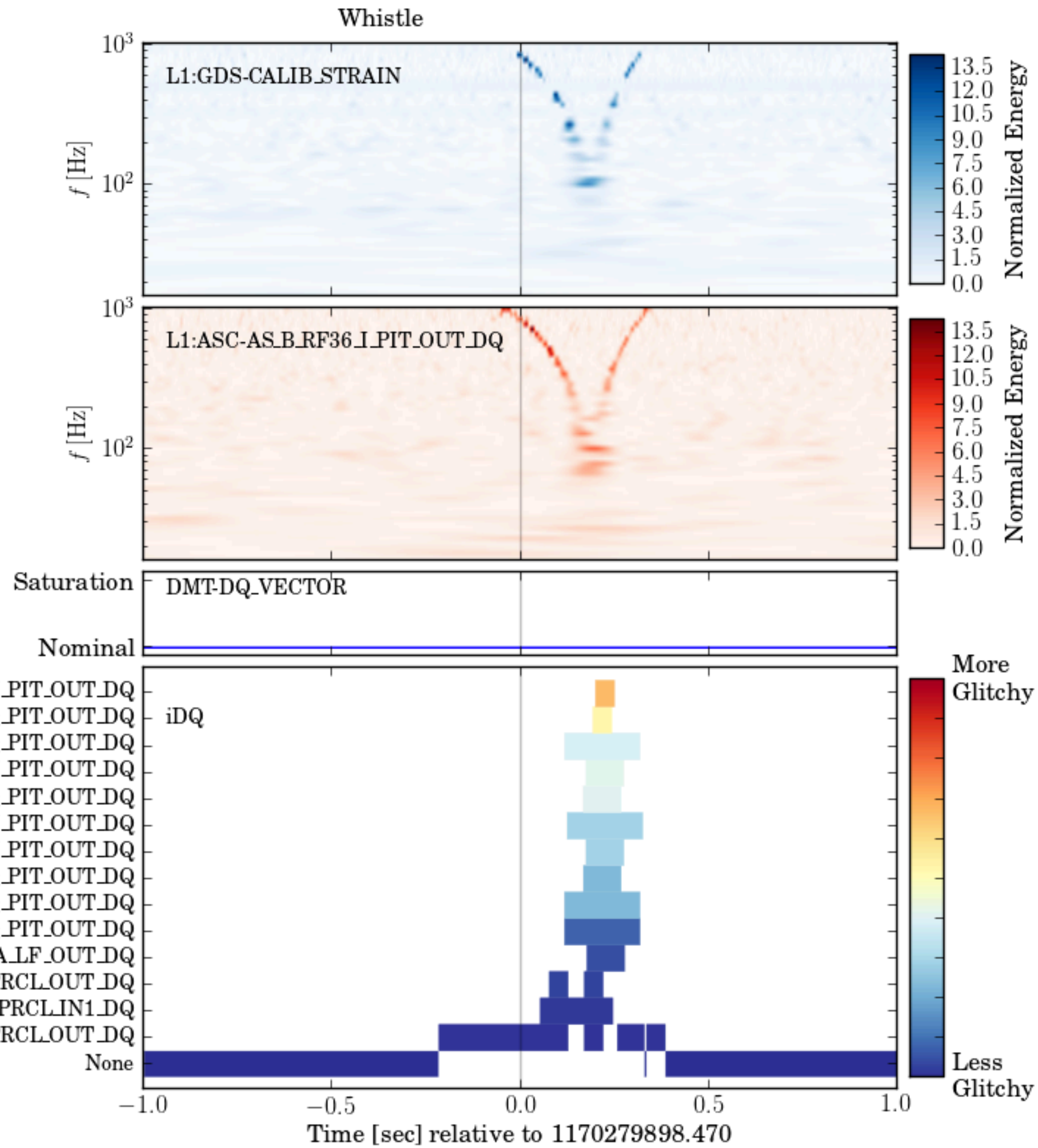
Low latency DQ mitigation

Figure by R. Essick from T.J. Massinger et al., in prep



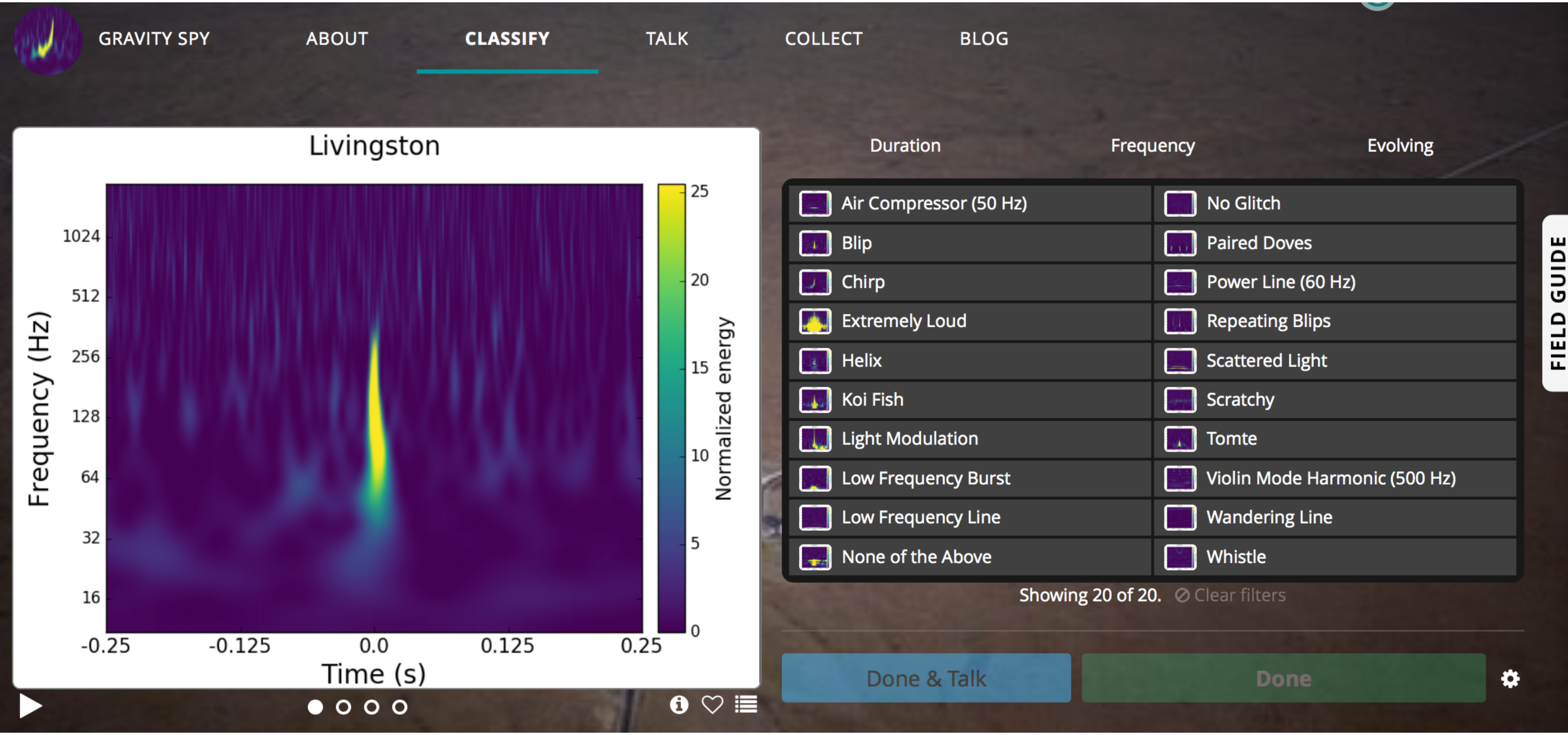
Low latency DQ mitigation

Figure by
R. Essick from
T.J. Massinger
et al., in prep



Citizen science and machine learning

gravityspy.org



Zevin et al, 2017, CQG

Identifying glitches by type

LigoDV-Web — *v0.1.07 Glitch DB*

Welcome Jessica McIver (admin)

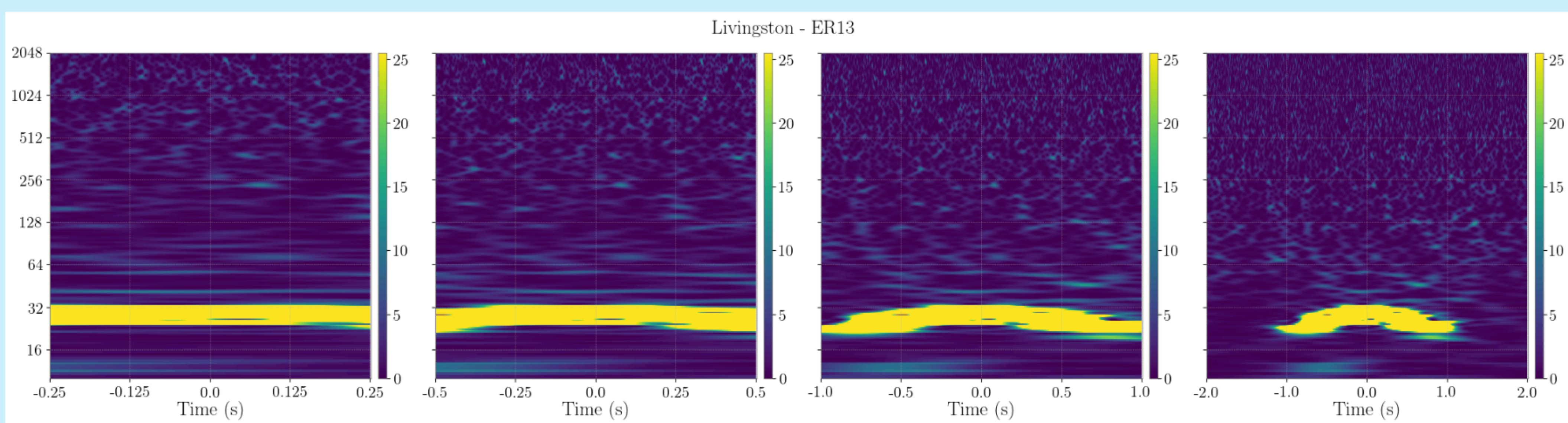
Home | History | Status | Glitch DB | Batch | Help | Admin

Link to this search

< Page: 1 of 3 Go > Save comments

249 matches found.

Unique Id	tihveWX1dQ
GPS Time	1229057821.313
UTC Time	2018-12-17 04:56:43
Pipeline	GravitySpy
Class	Scattered_Light
Status	testing
Ifo	L1
SNR	80.946
Amplitude	1.89e-21
Peak freq	28.117
Central freq	3977.720



J. Areeda et al. Astronomy and Computing (2017), S. Coughlin et al *in prep*

GWTC-1: confident detections

Eleven total events
10 BBHs
1 BNS

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	V	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	V	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	V	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	V(G)	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	V	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

B.P. Abbott et al. arXiv 1811.12907 (2018)

GW candidates in O3 thus far

16 alerts issued since April 1st.
14 un-retracted events in 8.5 weeks!

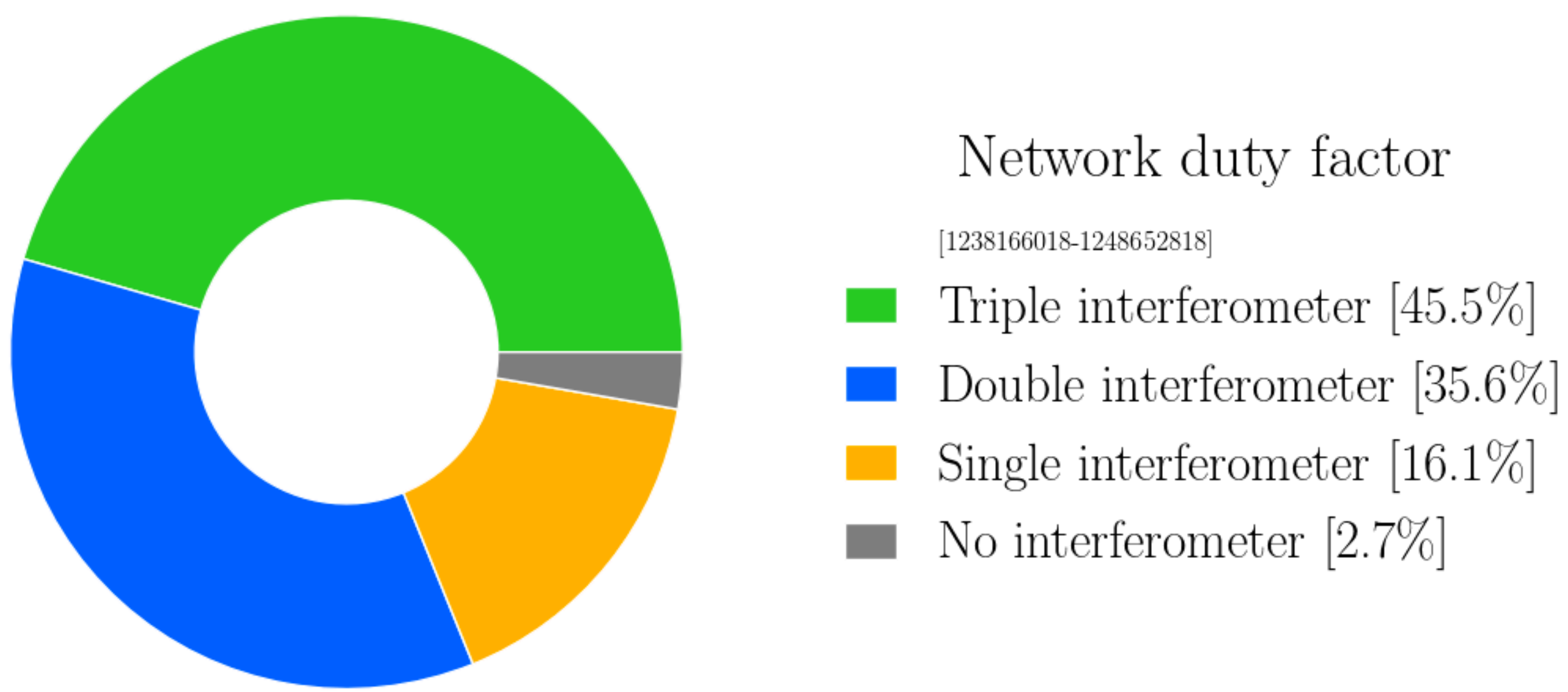
UID	Labels	FAR
S190602aq	PE_READY ADVOK SKYMAP_READY I	1.90052750535e-09
S190521r	PE_READY ADVOK SKYMAP_READY I	3.16754584224e-10
S190521g	PE_READY ADVOK SKYMAP_READY I	3.80105501069e-09
S190519bj	PE_READY ADVOK SKYMAP_READY I	5.70158251604e-09
S190517h	PE_READY ADVOK SKYMAP_READY I	2.37290998502e-09
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_F	3.73400311637e-13
S190512at	PE_READY ADVOK SKYMAP_READY I	1.90052750535e-09
S190510g	ADVOK SKYMAP_READY EMBRIGHT_F	8.8335691573e-09
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_F	1.63611159504e-09
S190426c	PE_READY ADVOK SKYMAP_READY I	1.94694181763e-08
S190425z	ADVOK SKYMAP_READY EMBRIGHT_F	4.53764787126e-13
S190421ar	PE_READY ADVOK SKYMAP_READY I	1.48874654585e-08
S190412m	PE_READY ADVOK SKYMAP_READY I	1.68289586112e-27
S190408an	PE_READY ADVOK SKYMAP_READY I	2.81096164616e-18

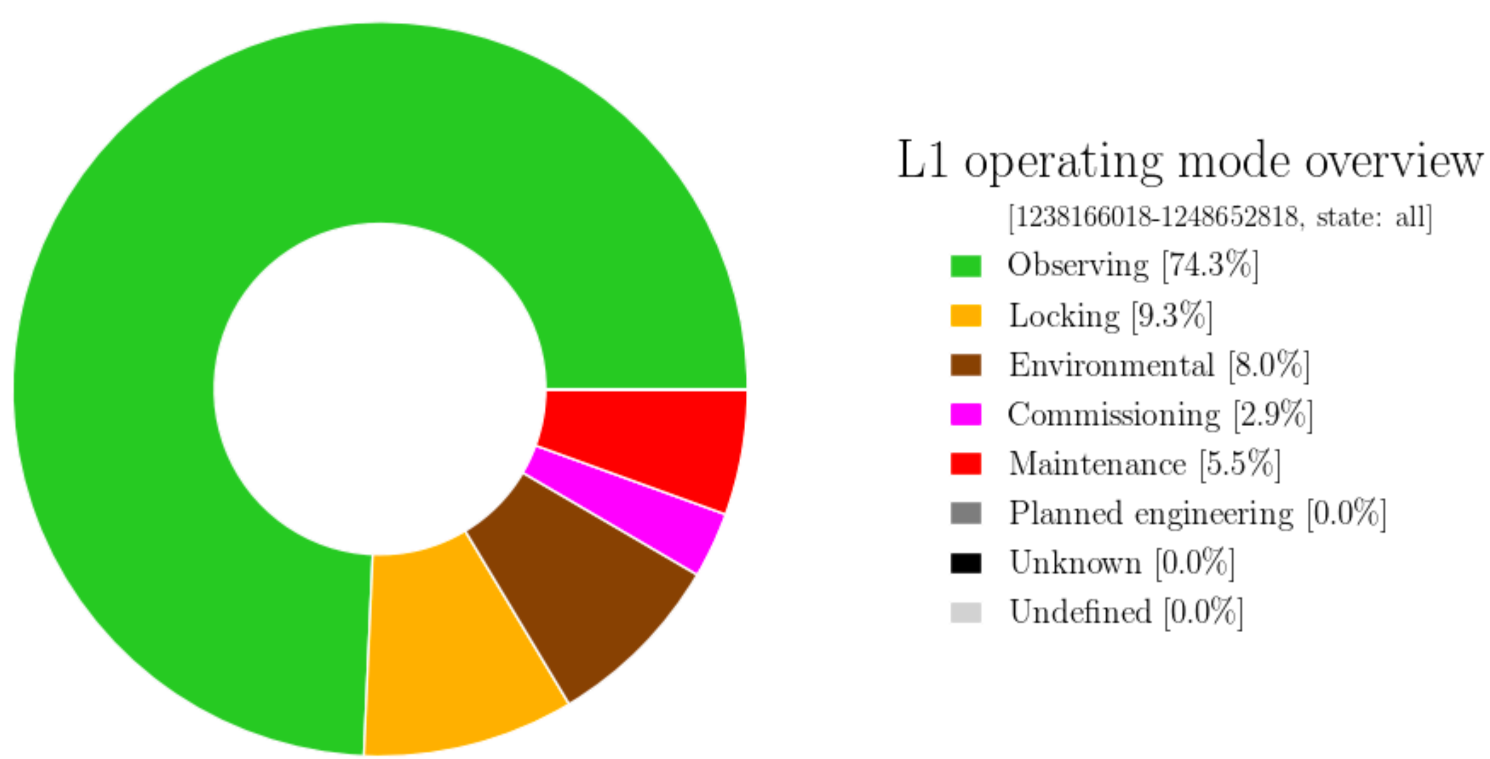
- 11 likely BBHs
- 2 BNSs (one likely, one 58% terrestrial)
- 1 potential NSBH candidate
- (BNS (49%), MassGap (24%), NSBH (13%), Terrestrial (14%))

Outline

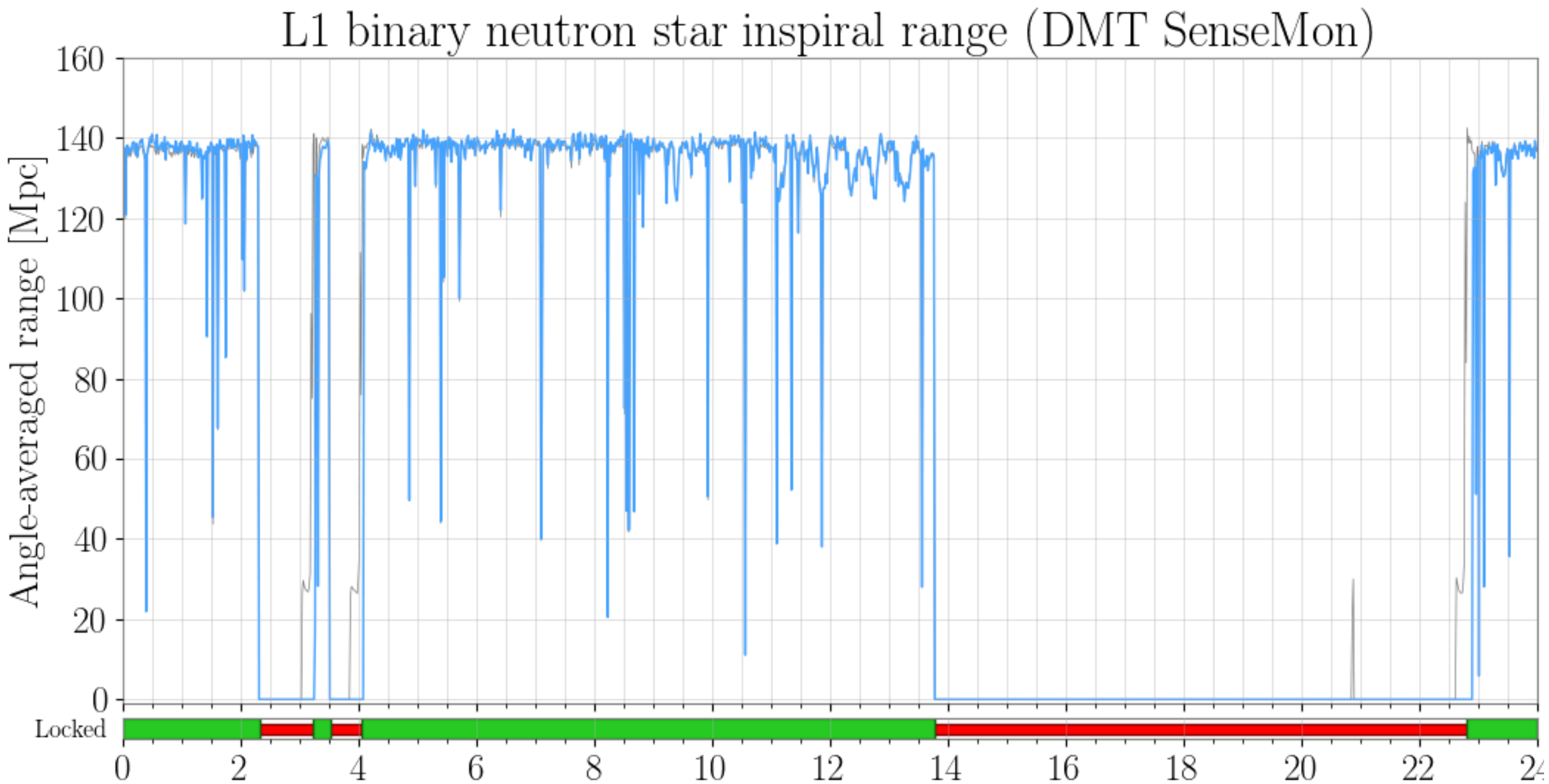
- Gravitational waves
- LIGO detector noise
- Noise mitigation
  - Improving GW search sensitivity
  - Maximizing duty cycle
- Conclusions

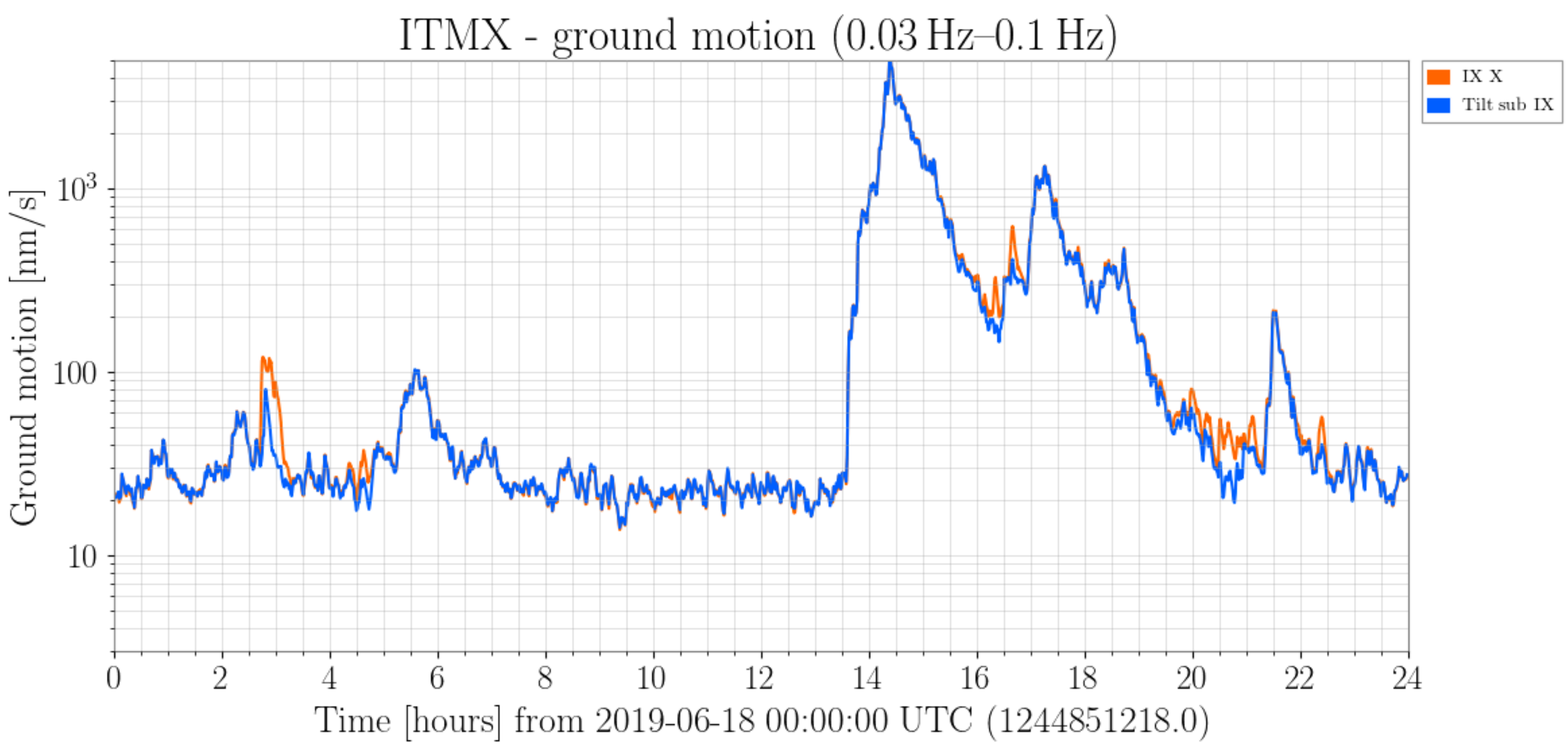
LIGO-Virgo duty cycle





Ground motion and “lock loss”





Improving LIGO duty cycle with machine learning

Ayon Biswas, Jess McIver, Ashish Mahabal

Study of ~1000 LIGO lock loss times during O2.

Goals of our work:

Can we diagnose the detector mechanisms for lock losses to increase uptime?

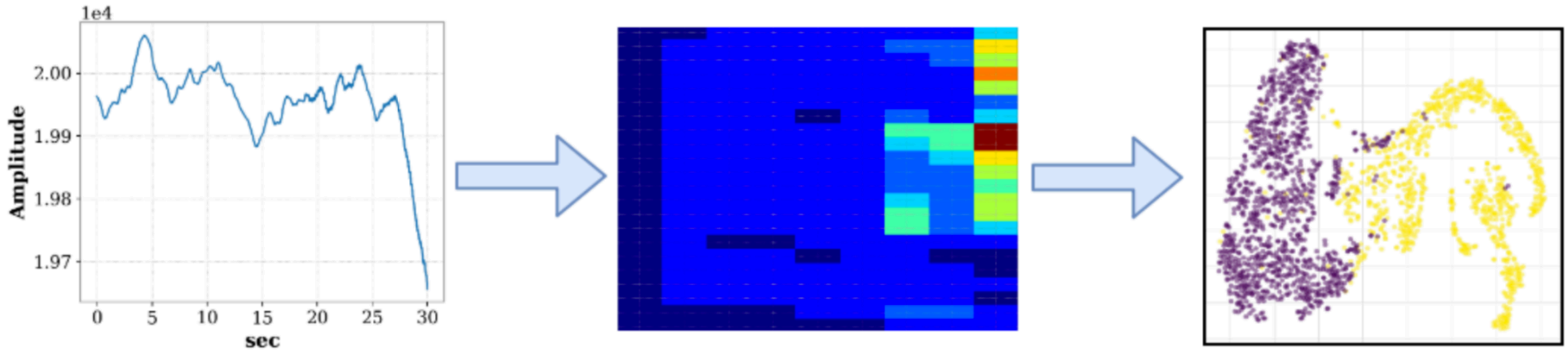
- What is the minimum number of auxiliary witnesses needed to correctly predict a lock loss?

Can we predict a lock loss *before it happens*?

- Could we automatically change the interferometer state to compensate, as we do for earthquake mitigation?

Approach 1/3: clustering algorithm (t-SNE) with *dmdt*

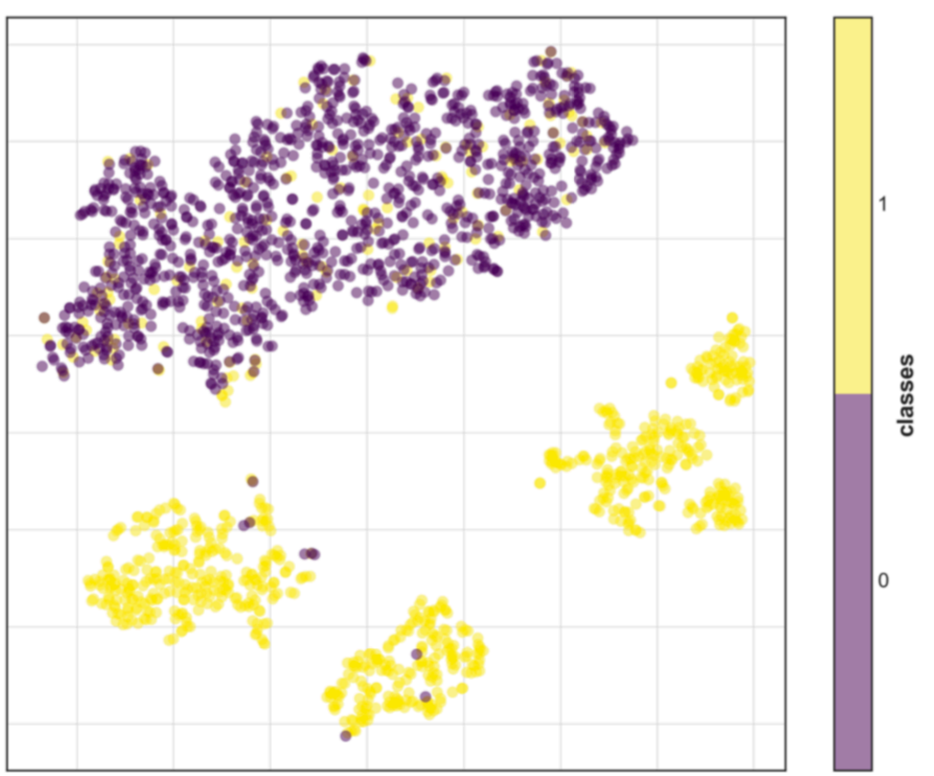
Biswas et al. In prep.



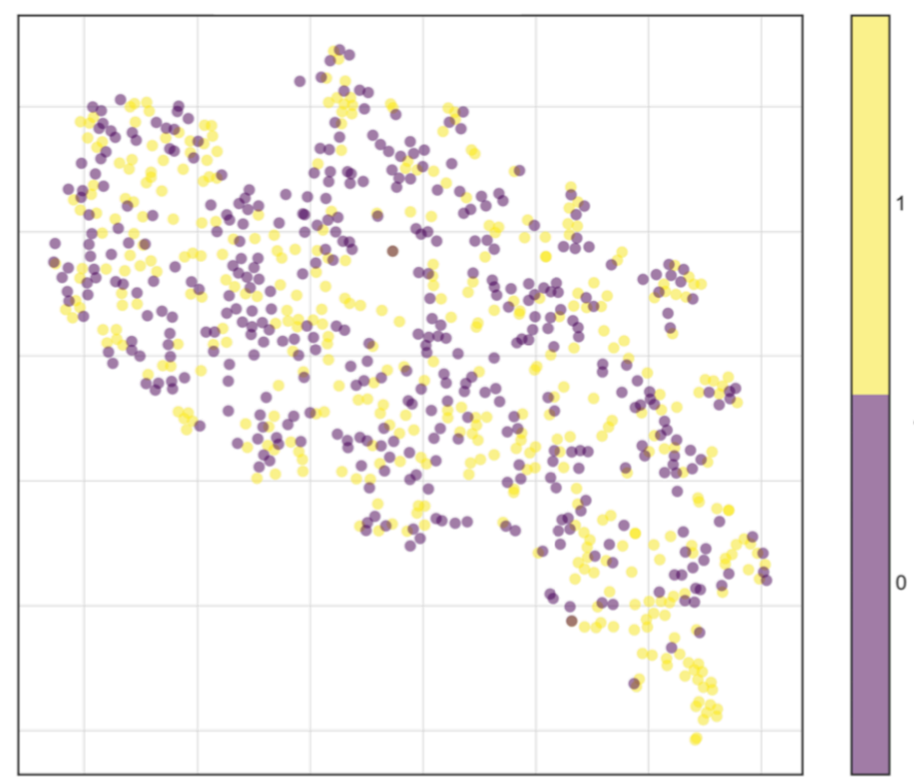
Time Series **dmdt features** **t-SNE**

Optic cavity channels are better predictors than ground motion!

Signal recycling cavity length

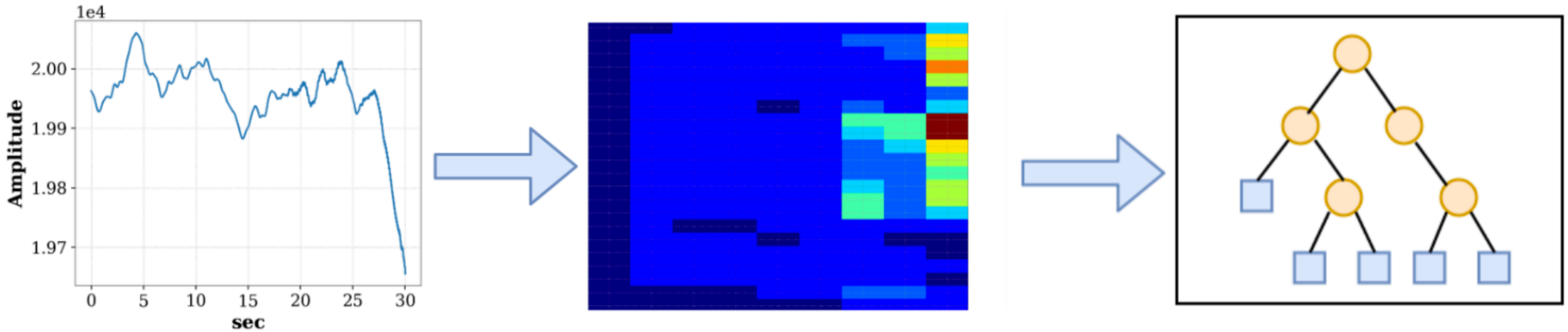


0.03-0.1 Hz ground motion



Approach 2/3: random forest with *dmdt* features

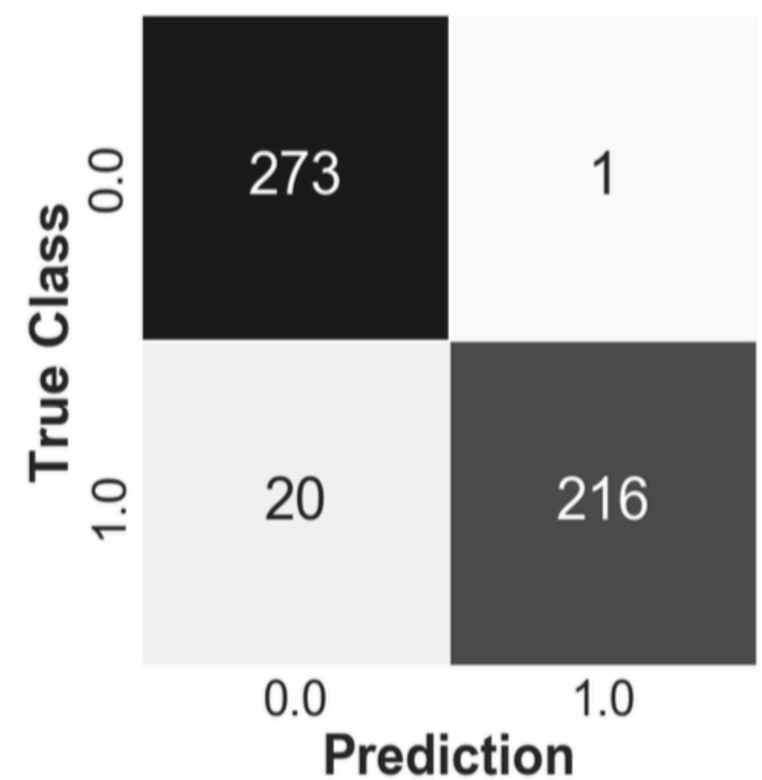
Biswas et al. In prep.



Time Series **dmdt features** **Decision trees**

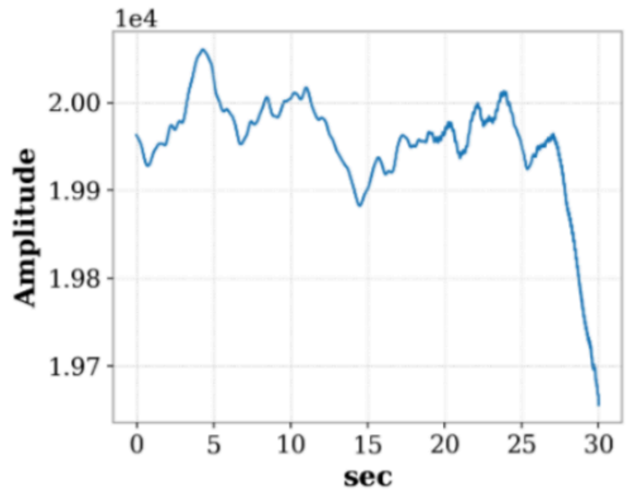
Combination of cavity sensing and control channels (majority vote) yields 0.95 accuracy.

Channel	Test accuracy
IMC_MC2+LSC_REFL+LSC_POP	0.92
MICH + SRCL + PRCL	0.94
All the above	0.95

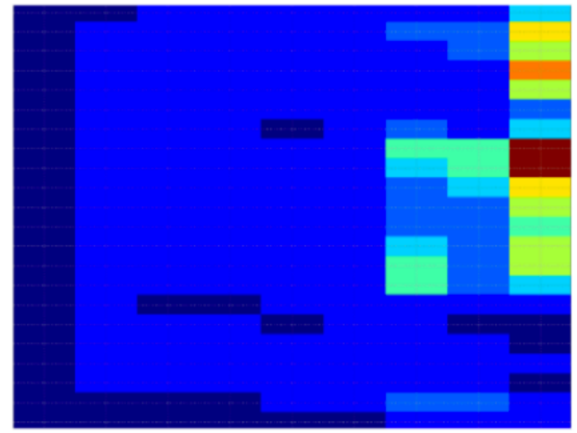


Approach 3/3: CNN with stacked *dmdt*

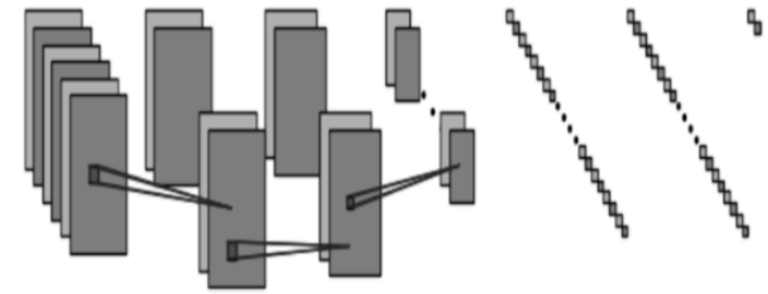
Biswas et al. In prep.



Time Series



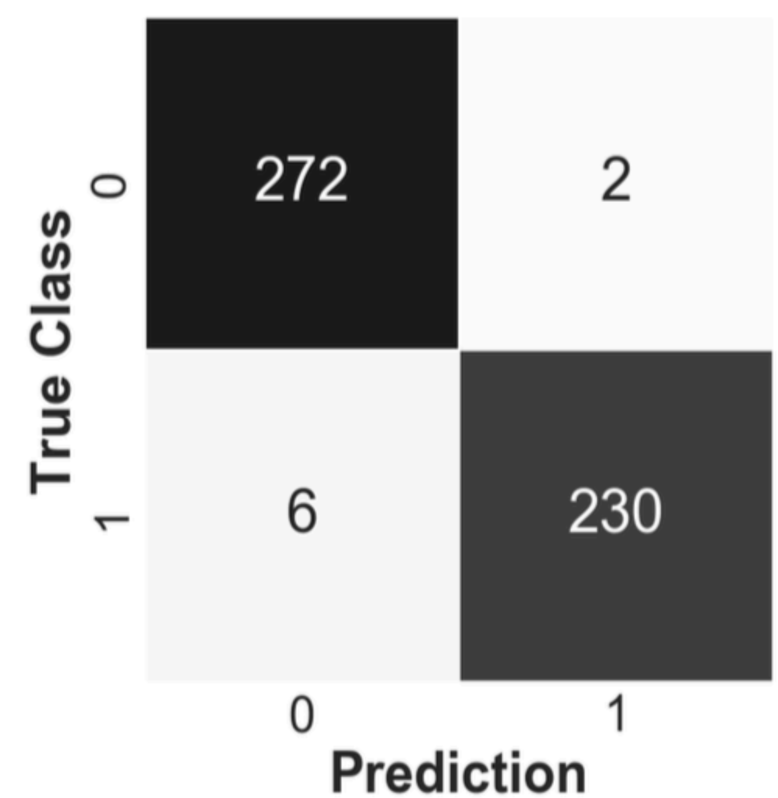
dmdt features



Convolutional neural network

Stacked dmdt features of channel combinations yields > 0.98 accuracy!

channels	Test accuracy	Test loss
IMC_MC2+LSC_REFL+LSC_POP	0.910	0.280
MICH + SRCL + PRCL	0.968	0.111
All the above	0.986	0.080



Study findings (preliminary)

Biswas et al. In prep

A subset of just three channels, MICH, LSC POP, and SRCL, predict > 97% of all LIGO-Livingston lock losses during O2!

Using those three channels, lock losses can be accurately predicted 10-15 prior to losing lock.

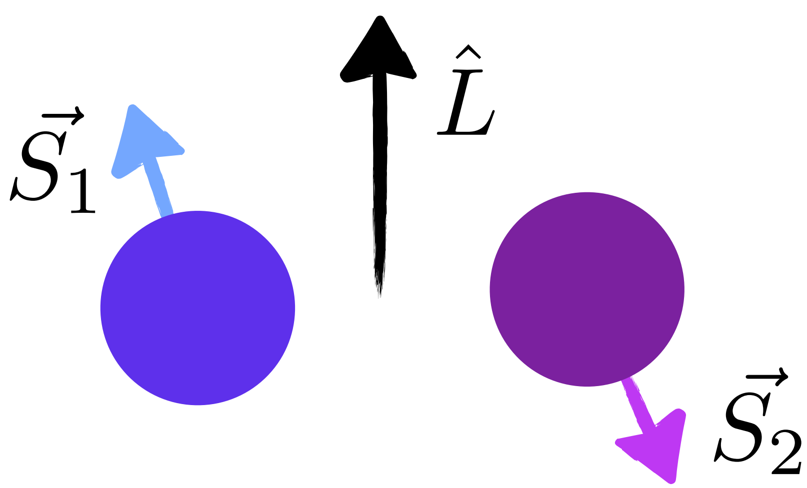
Ground motion channels alone are not good predictors of lock loss!

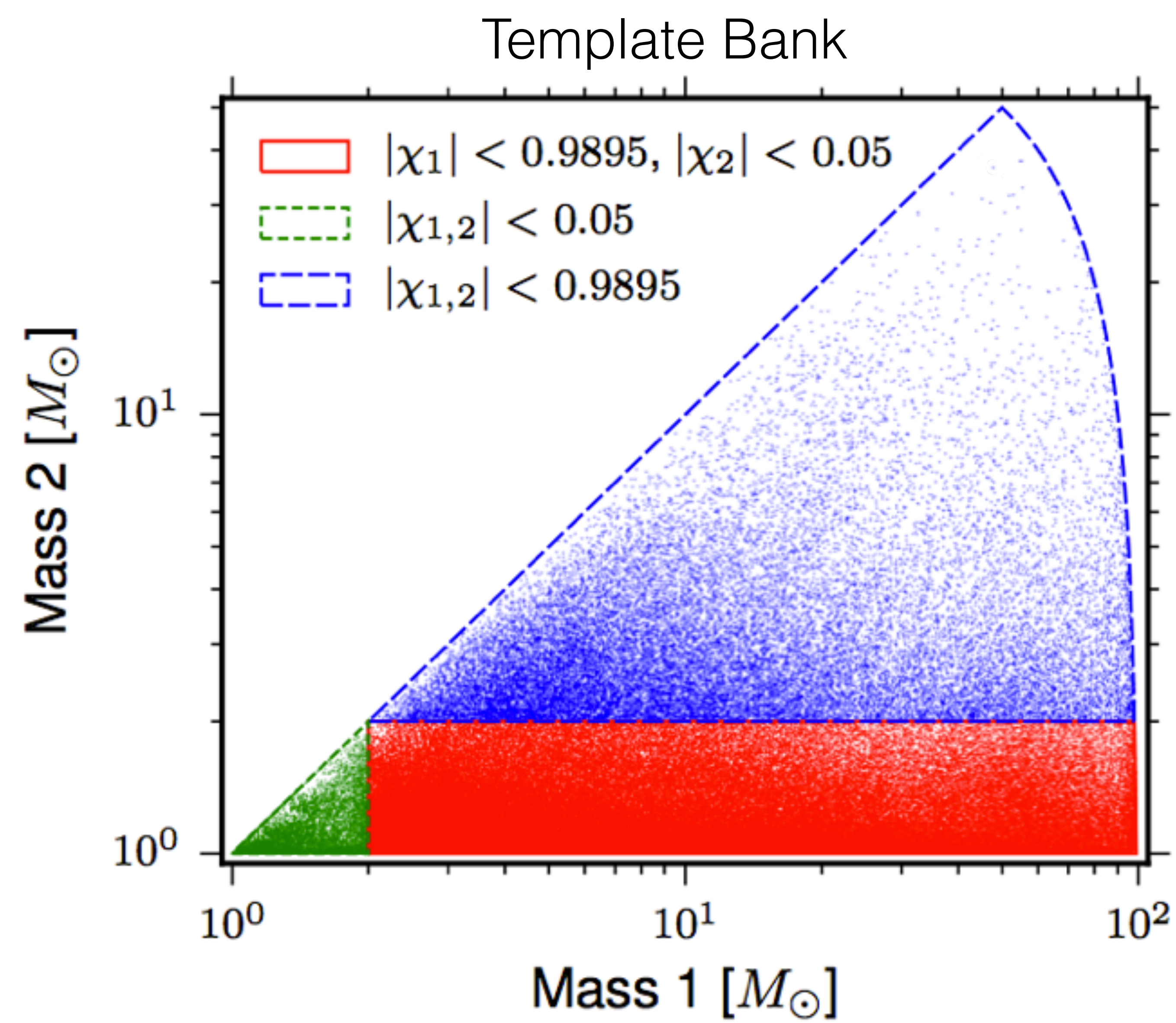
Overall conclusions

- Transient noise in gravitational wave detector data presents a major challenge for the astrophysical analyses
- Computational solutions have allowed us to successfully extract astrophysical signals with higher confidence and more accuracy.
- Investment in understanding causes of lock loss will allow us to improve detector duty cycle— crucial for sky localization!
- As the detectors progress toward design sensitivity, new and different noise sources will be unearthed!
- **Novel approaches will be needed!**

Searching for known GW signals
Step 1: Building a template bank

$$\chi_{1,2} \propto \vec{S_{1,2}} \cdot \hat{L}$$



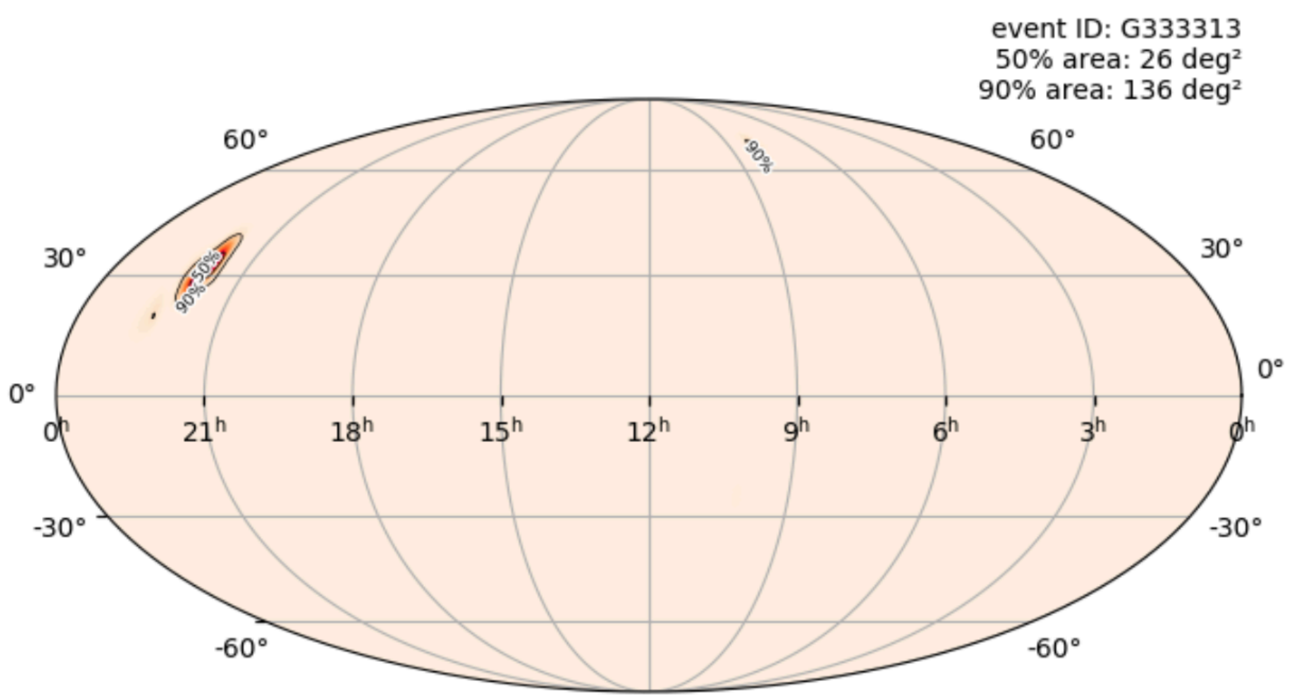


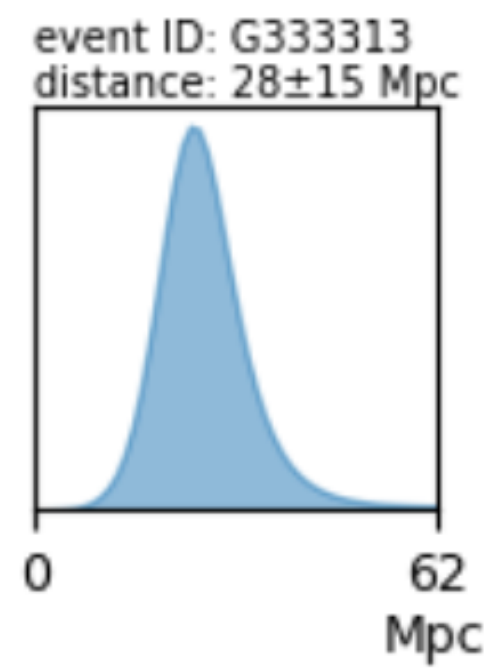
B. P. Abbott et al. Phys. Rev. X (2016)

Challenge: S190518bb case study

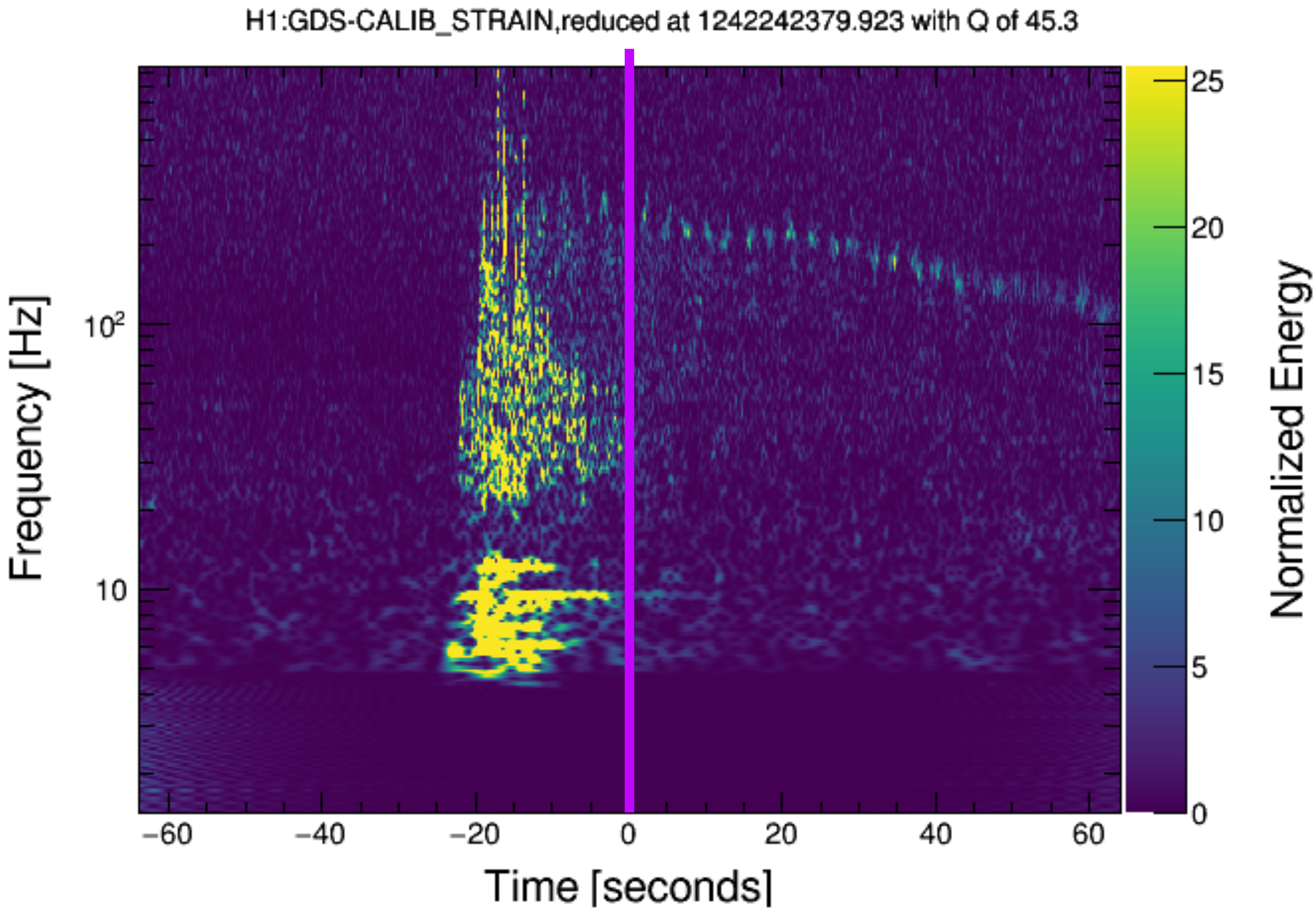
Automatic Preliminary Notice sent ~6 minutes after the event:

FAR: 1.004e-08 [Hz] (one per ~3 years)
PROB_NS: 1.00 [range is 0.0-1.0]
PROB_REMNANT: 1.00 [range is 0.0-1.0]
PROB_BNS: 0.75 [range is 0.0-1.0]
PROB_TERRES: 0.24 [range is 0.0-1.0]



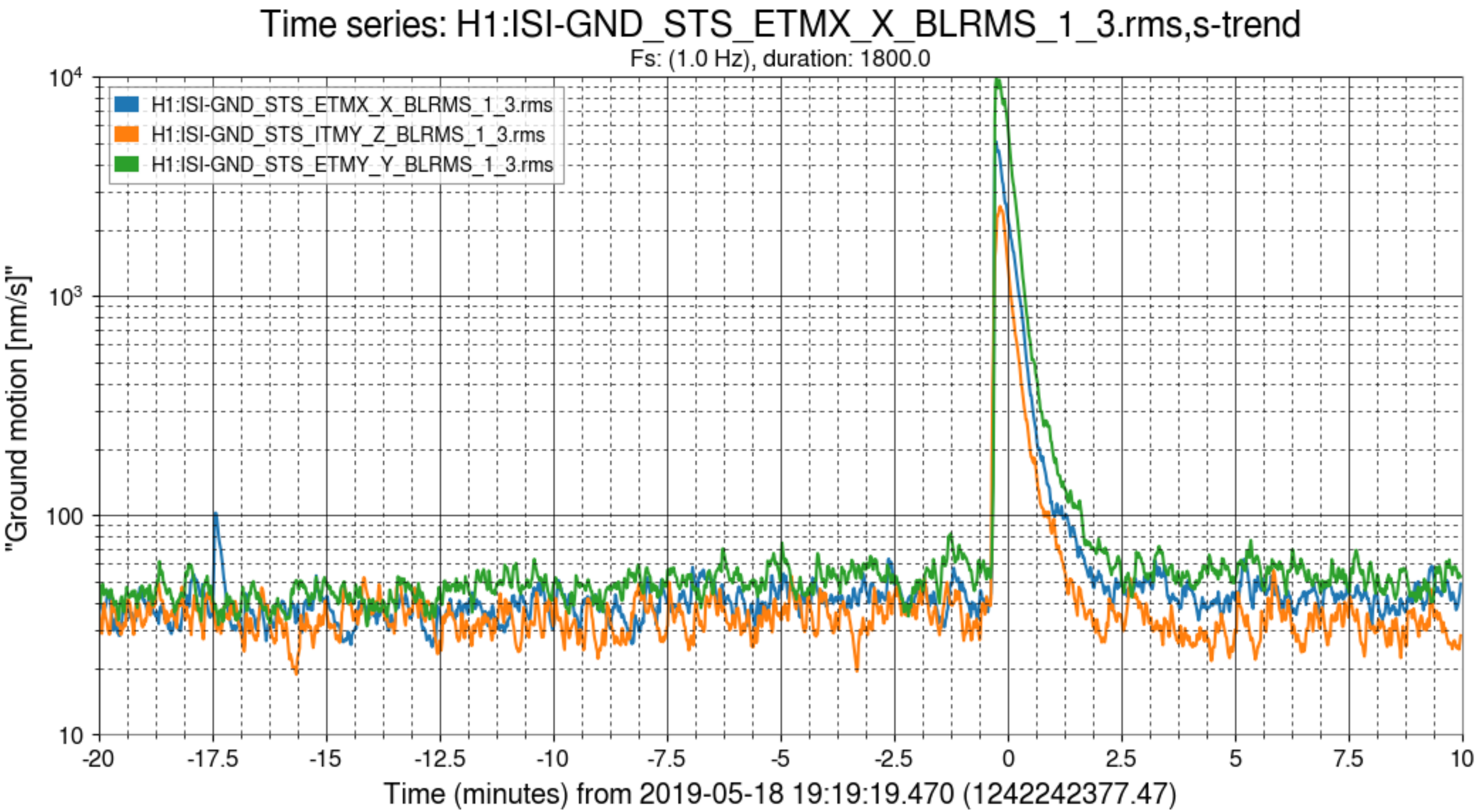


Challenge: S190518bb case study



LIGO DCC G1900994

Challenge: S190518bb case study



LIGO DCC G1900994