Addressing the challenges of characterizing gravitational-wave interferometers with machine learning

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Caltech LIGO

Timeline of Machine Learning references in LVK papers

S6 (published 2015)	**“MLA Statistical Inference of Glitches”** (Biswas+)
GW150914 (published 2016)	**“MLA Statistical Inference of Glitches”** (Biswas+)
GWTC-1 (published 2018)	**Gravity Spy**: Glitch Classification (Zevin+)
GWTC-3 (published 2020)	**NonSens:** Noise Subtraction (G. Vajente+) **iDQ:** Statistical Inference of Glitches (Essick+) **Gravity Spy:** Identifying New Glitch Classes (Soni+) **Gravity Spy:** Glitch Classification (Zevin+) **HasNS/HasRemnant:** A Machine Learning Based Source Property Inference (Chatterji+)
O4 online (as of now)	**GSpyNetTree:** A signal-vs-glitch spectrogram classifier (Alvarez-Lopez+) **GWSkyNet:** A signal-vs-glitch skymap classifier (Cabero+) **cWB-XGBoost:** coherent WaveBurst Search enhanced with machine learning (Michra+) **MLy:** Unmodelled GW transient search with CNNs (Skliris+)

Timeline of Machine Learning references in LVK papers

Detector Characterization ML References

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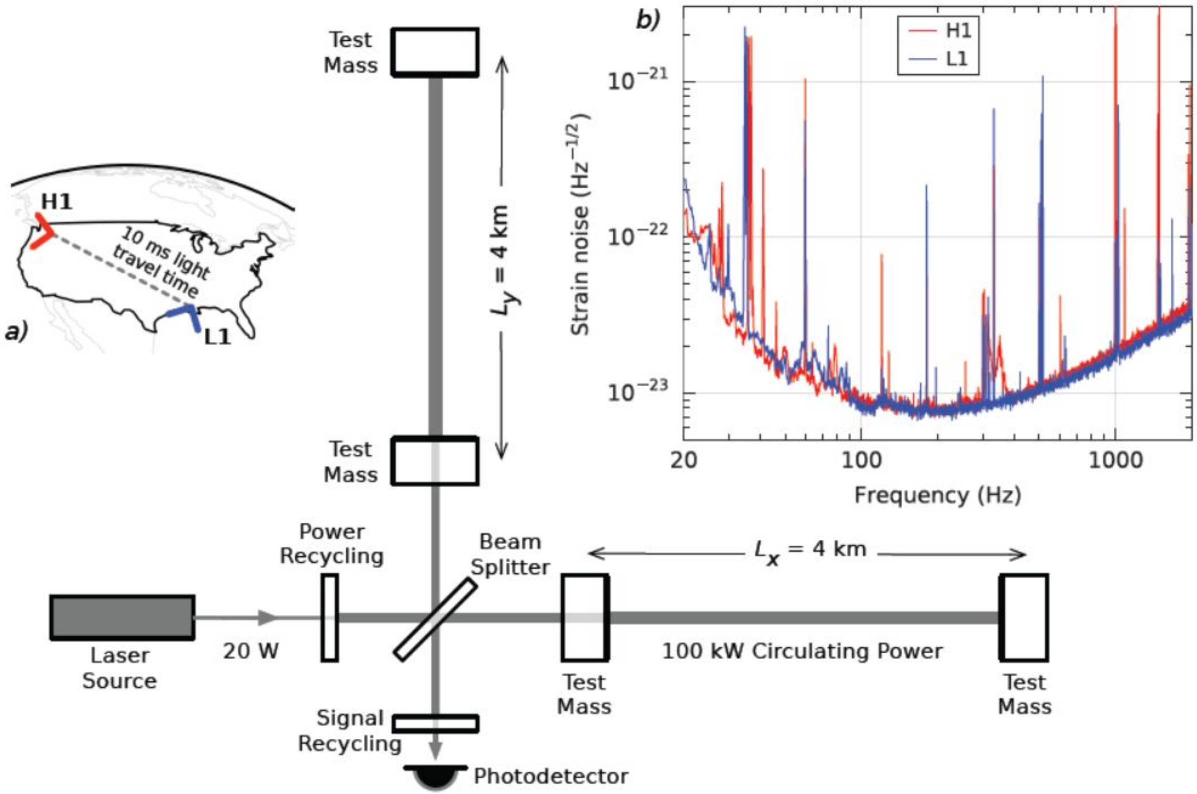
What is Detector Characterization?

Gravitational-wave detectors: **Expectation**



Gravitational-wave detectors: **Reality**

Vent Recovery: First locking attempts, can go to CARM 5 pm

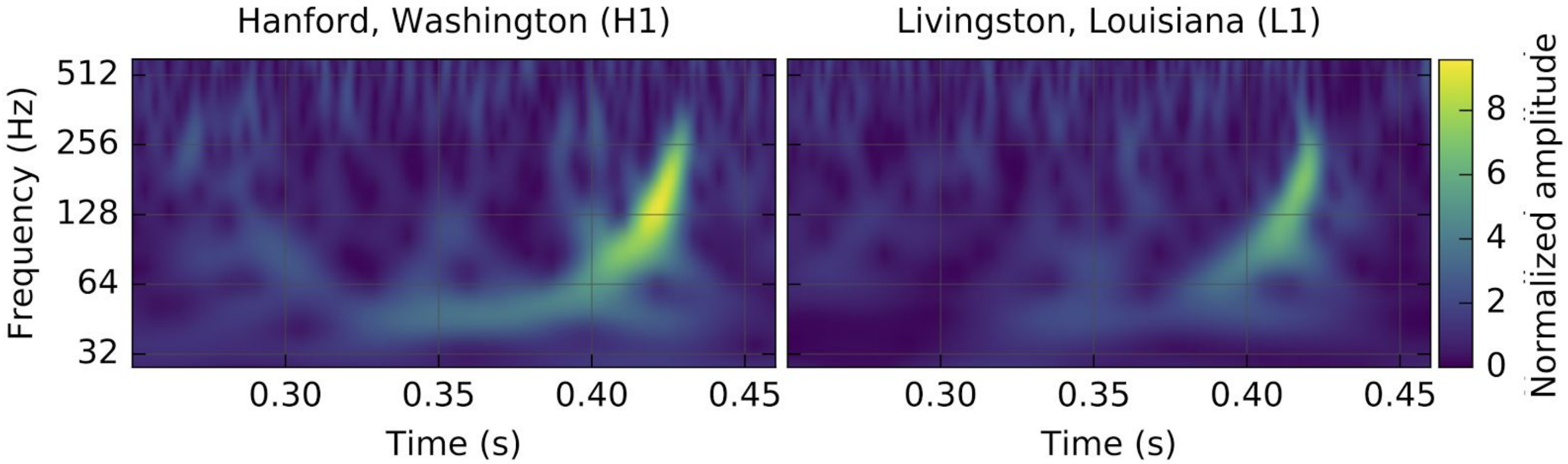
Ibrahim, Elenna

In summary, we can make it to CARM to REFL!

Here are some notes about recovering lock. I am bolding the ones that I think are urgent/should be read by anybody who next attempts to lock this IFO.

- **Before we even started this process, I set all DRMI and PRMI ASC to false except MICH ASC.**
- Locking green arms is a very "smooth" process (read: ALSY sucks a normal amount)
- Locking ALS proceeded without any hitch, as well as the find and check IR states.
- I first had problems with acquiring DRMI, even though at first glance the POPAIR flashes looked good. I tried PRMI, with good flashes, still no luck. I eventually had to go through MICH fringes, even though we had just run a successful initial alignment.
- **Any state where the power needs to change requires manualing in one or more guardians- the laser power guardian stalls because it gets stuck in some "10W idle" state.**
    - This is likely due to miscalibration in the rotation stage. If you get stuck, just manual to the power you need!
- After MICH fringes I went back to PRMI, and moved the PRM endlessly with no luck until I nudged the beamsplitter and everything immediately locked. Puzzling, because we had run at least two different MICH alignments at this point.
- Even with PRC1 disabled in PRMI ASC, the guardian still runs WFS centering on ALL WFS, which means it will error because the WFS centering isn't working well on the REFL WFS right now. I again had to manual around the WFS centering stage so it could offload MICH alignment.
    - this ended up being an SDF error which I fixed, see further notes
- Manualing around in ISC_DRMI seemed to stall things out, and since I was playing fast and loose with the guardian, caused a lockloss when I clicked "init" (I was trying to remanage guardians).
- Next lock went fine and I went straight to DRMI lock. (no need for PRMI or MICH fringes)
- **when DRMI caught lock, the AS AIR camera started shaking. Ibrahim saw that it was the beamsplitter, specifically F2 and F3 osems seemed to briefly saturate. I averted this problem by turning the LSC MICH gain down by 10% (MICH2 gain from 1 to 0.9).**
- Guardian got stuck in acquire DRMI 1f because the WFS centering on REFL failed again. I manualed over again to avoid it.
- Everything proceeded very well, the alignment looked great, I ran all the way to "CARM to REFL" and something started shaking.
    - At lockloss, there was a beamsplitter saturation warning, so I think something is funky in either the MICH LSC or ASC loop.

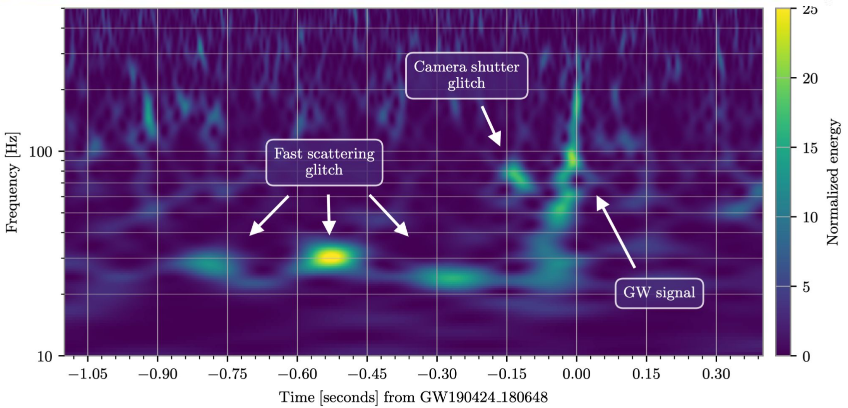
Gravitational-wave signals: **Expectation**



Gravitational-wave signals: **Reality**

Hanford, Washington (H1)

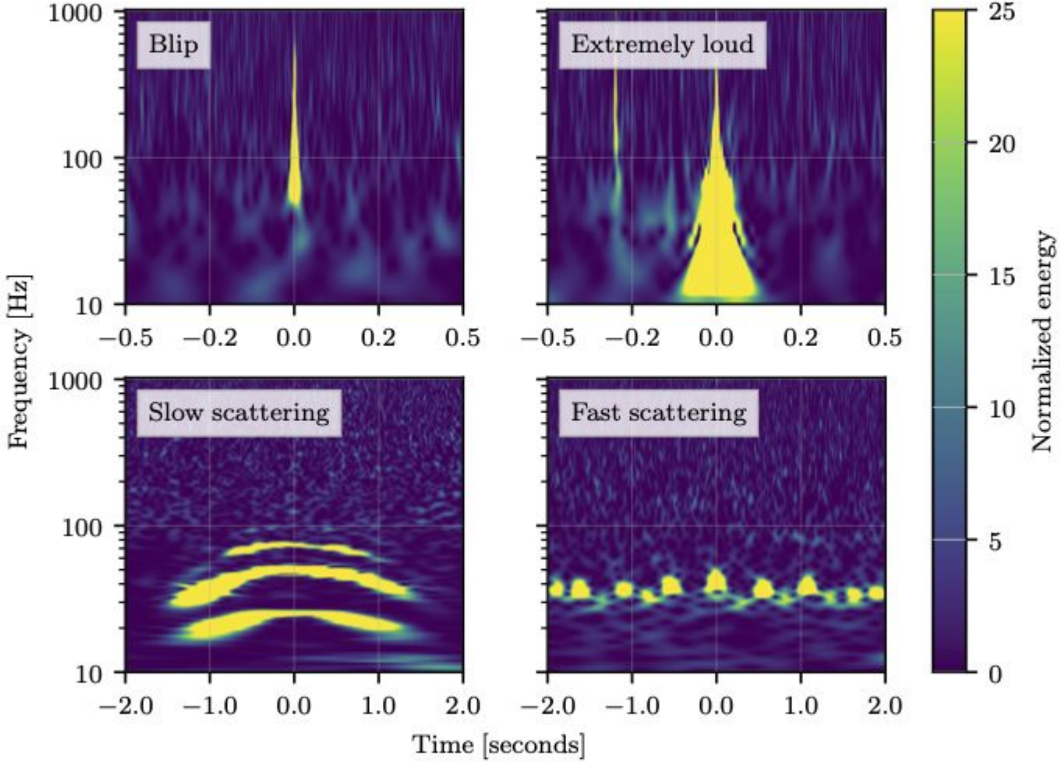
Livingston, Louisiana (L1)



Davis & Walker 2022

Glitches present in data

Instrumental artifacts are present in the data, including a large number of short duration noise transients we call *glitches*

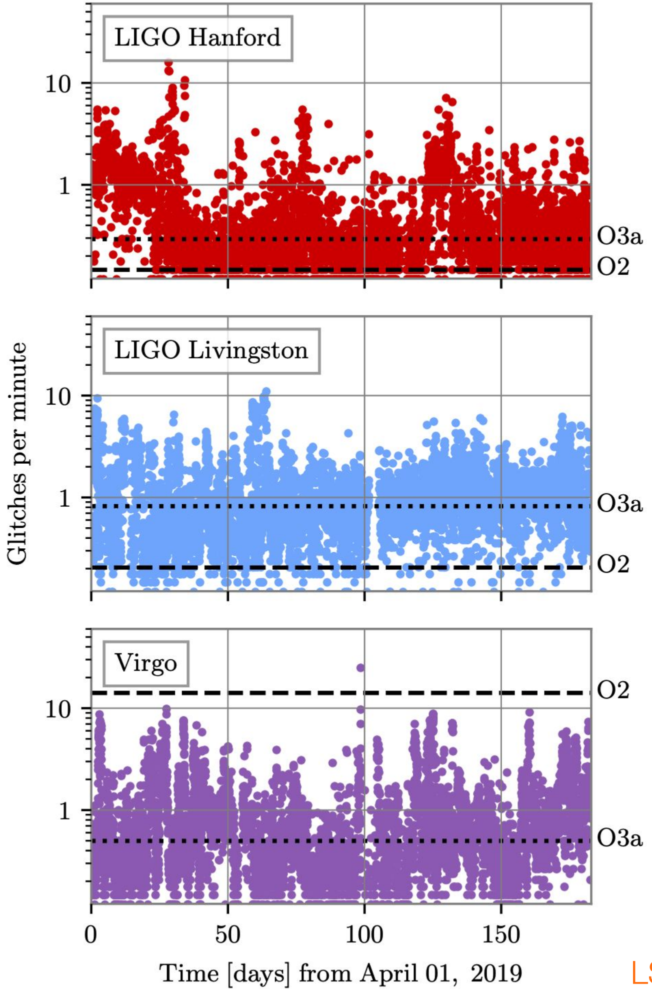


Davis+ 2021

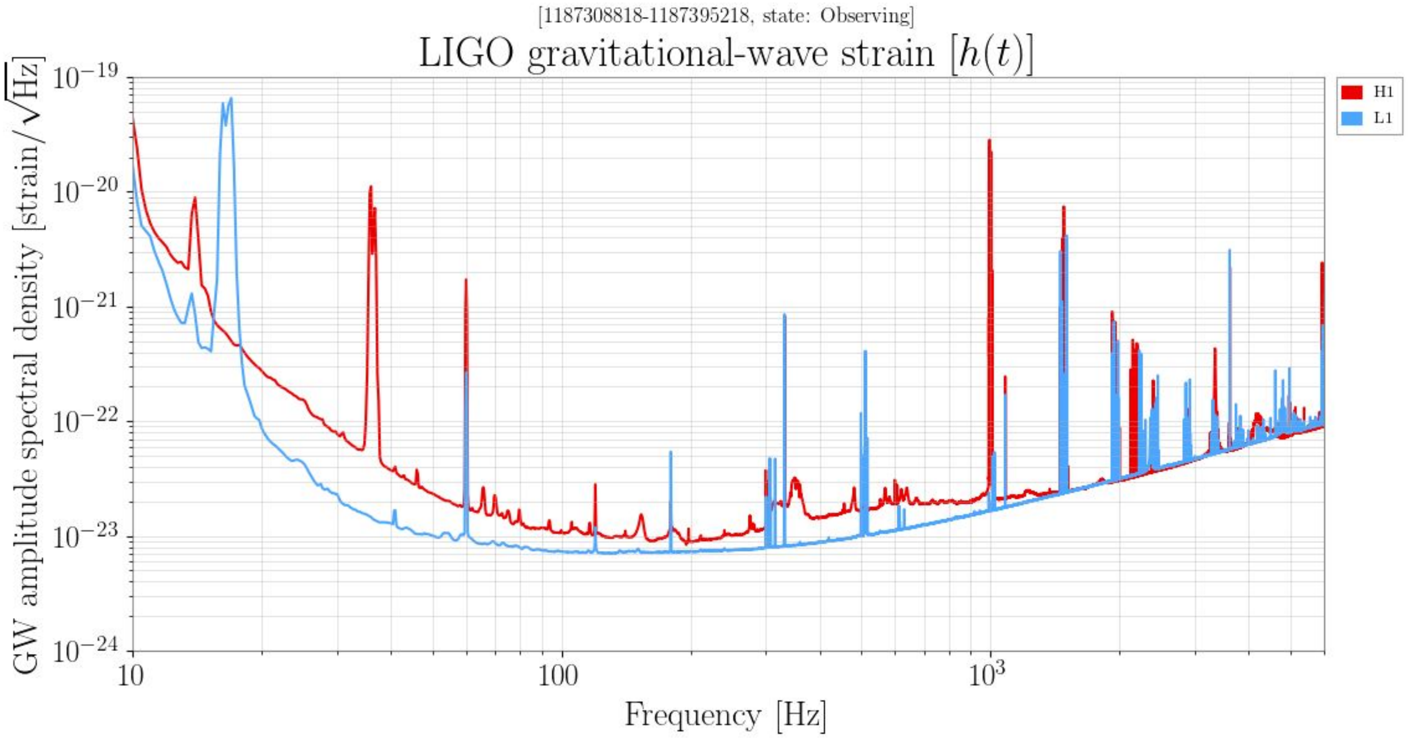
Lots of them in fact!

Much higher in the most recent observing run than in the past

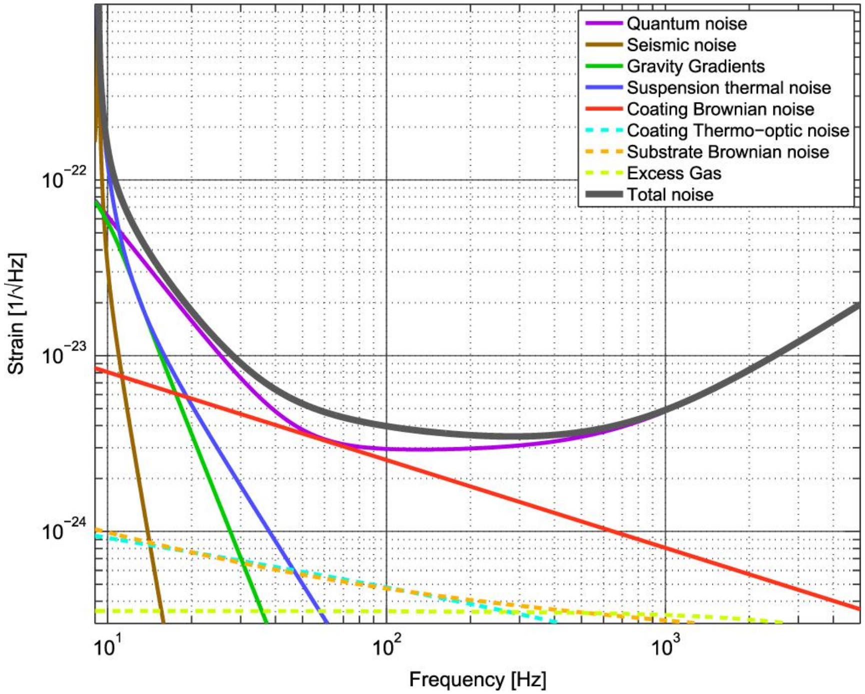
But O4 looks to be a bit better than O3!

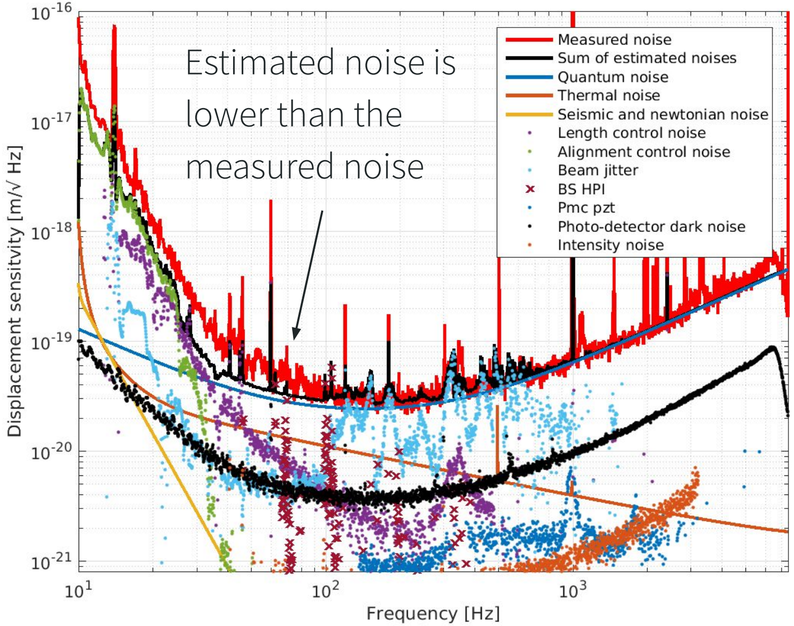


Lines present in the data



Something present in the data





Doing this correctly is vital for our science

Article | Published: 12 October 2022

General-relativistic precession in a black-hole binary

Mark Hannam, Charlie Hoy, ... Aaron Zimmerman + Show authors

Evidence of Large Recoil Velocity from a Black Hole Merger Signal

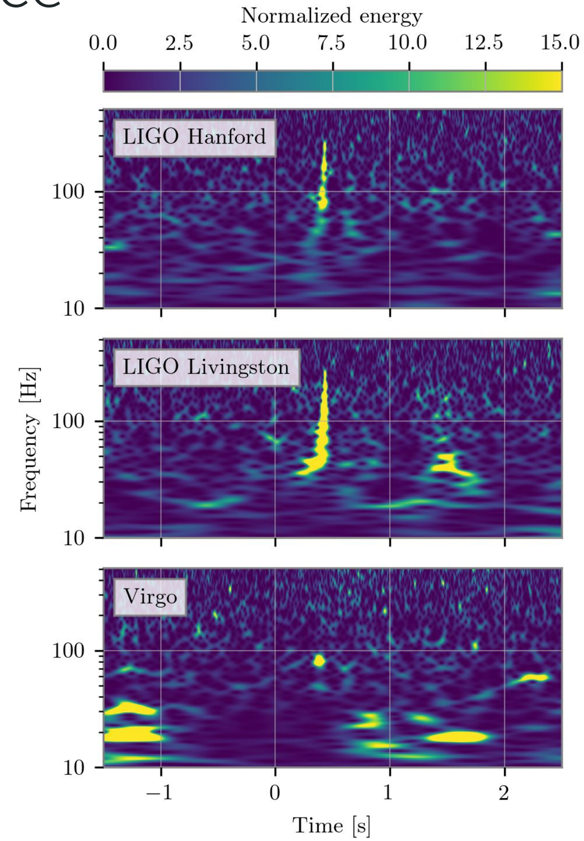
Vijay Varma[1,*], Sylvia Biscoveanu[2,3], Tousif Islam[4,5], Feroz H. Shaik[4,5], Carl-Johan Haster[2,3], Maximiliano Isi[6], Will M. Farr[7,6], Scott E. Field[4,5], and Salvatore Vitale[2,3]

[Submitted on 22 Apr 2024 (v1), last revised 27 Aug 2024 (this version, v2)]

Evidence for eccentricity in the population of binary black holes observed by LIGO–Virgo–KAGRA

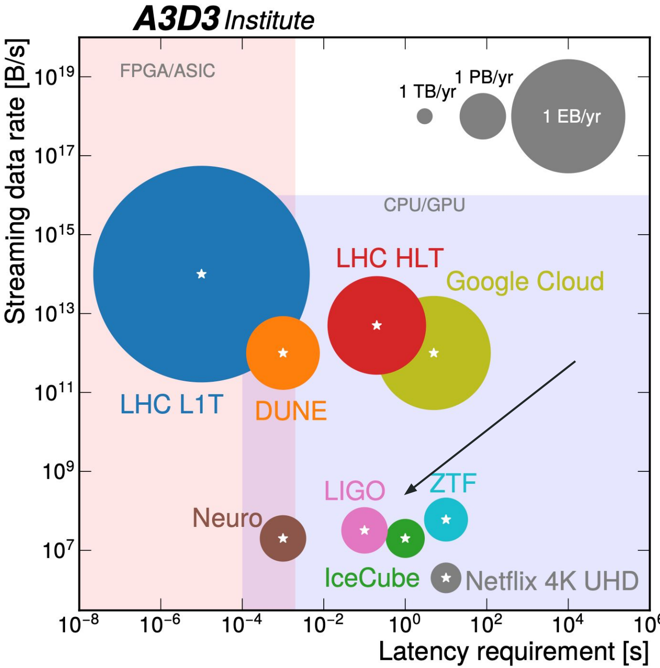
Nihar Gupte, Antoni Ramos-Buades, Alessandra Buonanno, Jonathan Gair, M. Coleman Miller, Maximilian Dax, Stephen R. Green, Michael Pürrer, Jonas Wildberger, Jakob Macke, Isobel M. Romero-Shaw, Bernhard Schölkopf

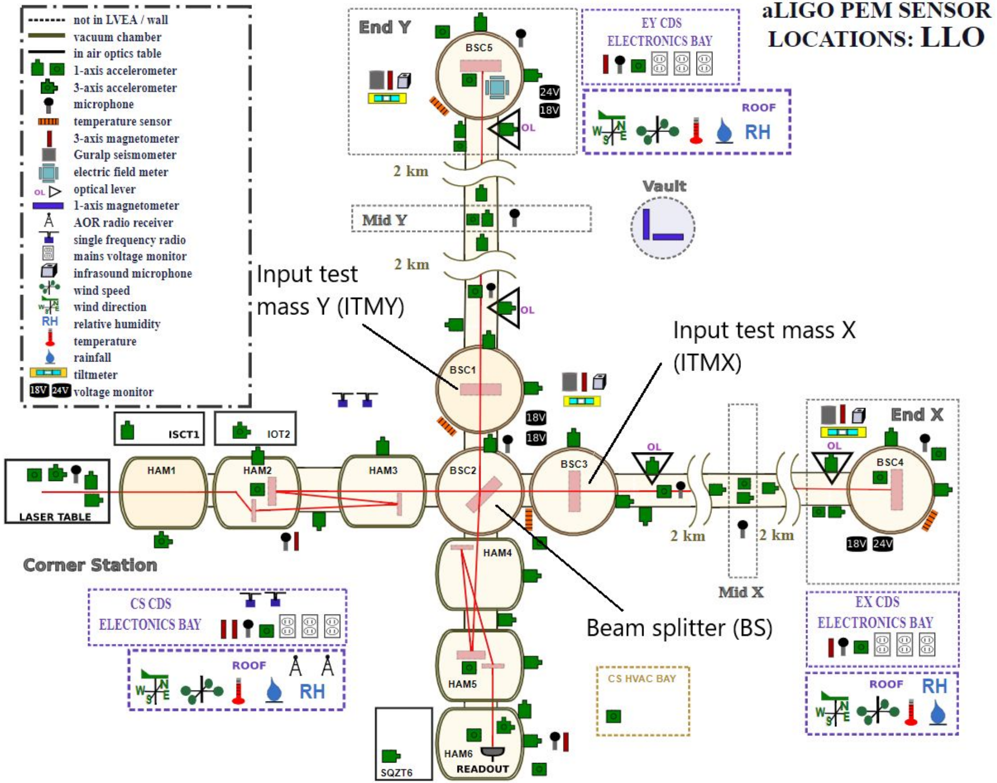
Or just glitches?



What makes this a good fit for machine learning?

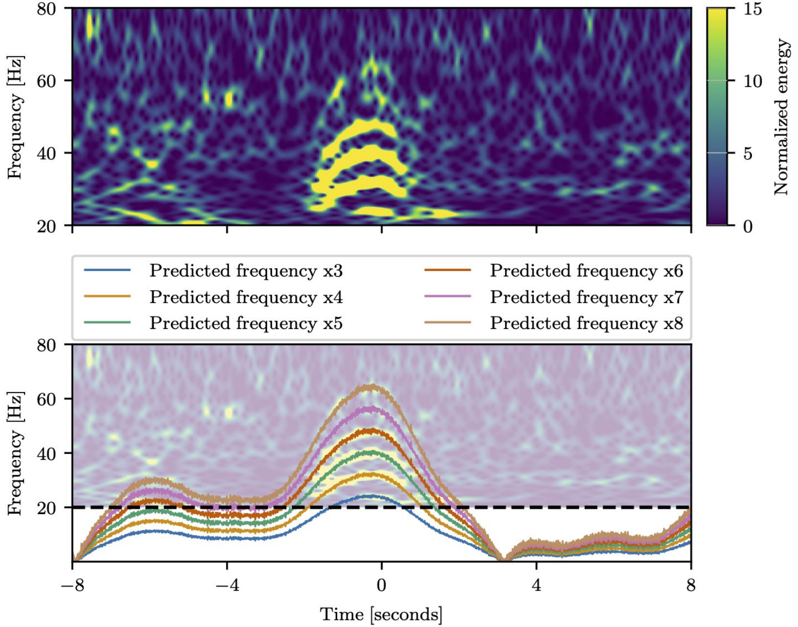
Large, complicated dataset



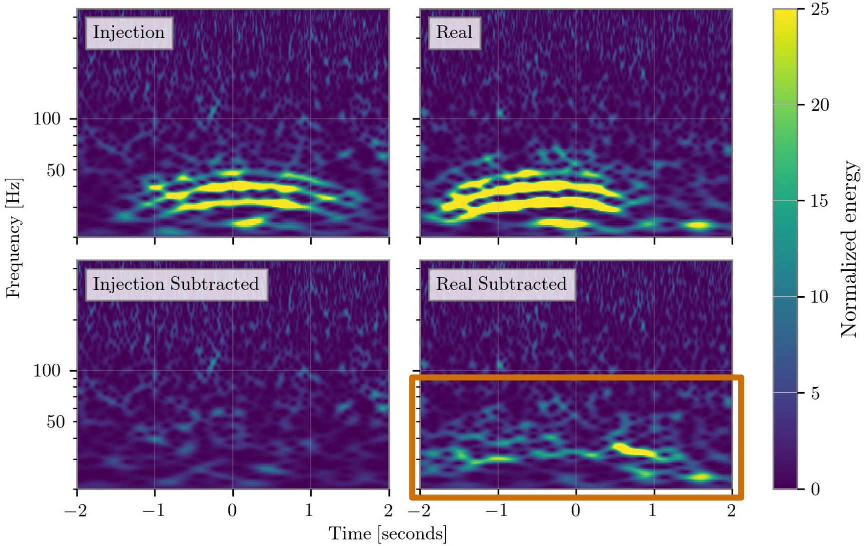


Nguyen+ 2021

Many problems that are difficult to address analytically



Scattering model



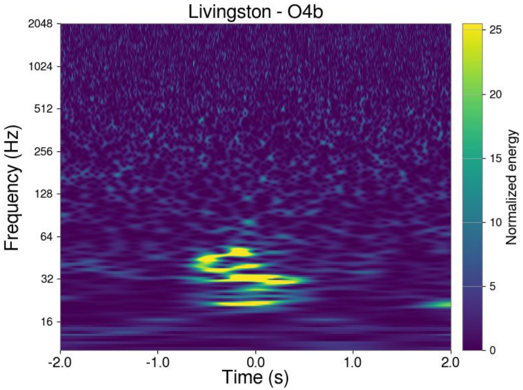
Simulation test

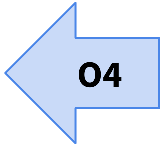
Real-life test

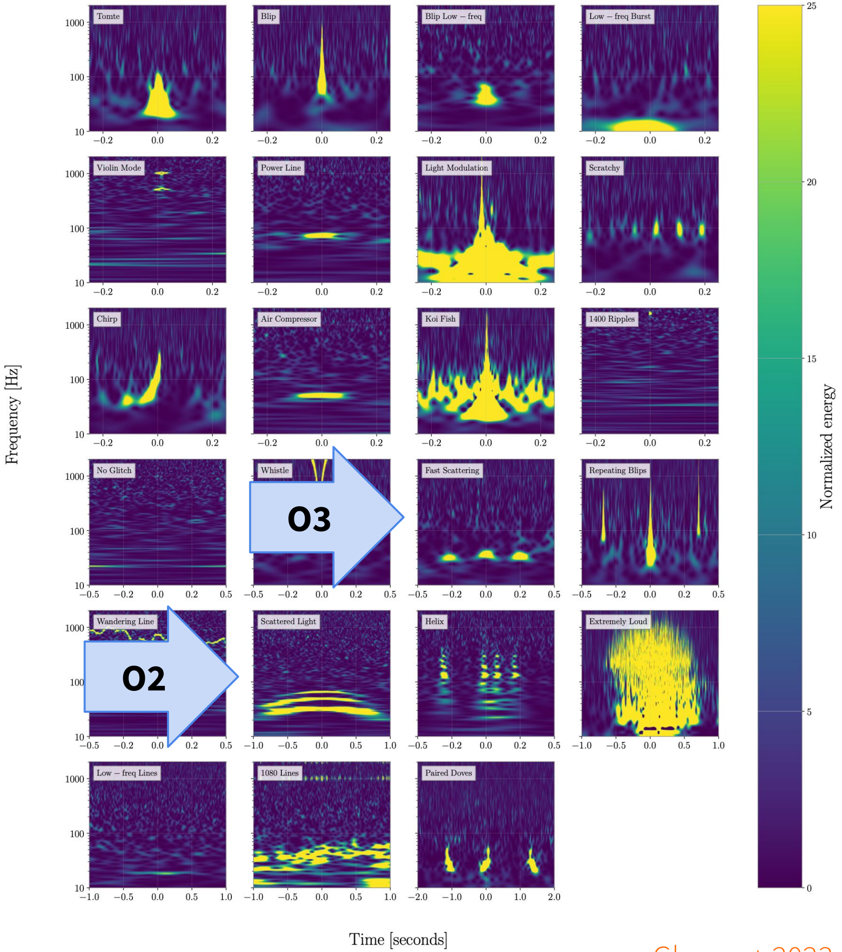
Udall & Davis 2023

Lots of variety

Scattered light glitches have changed a lot over the years!

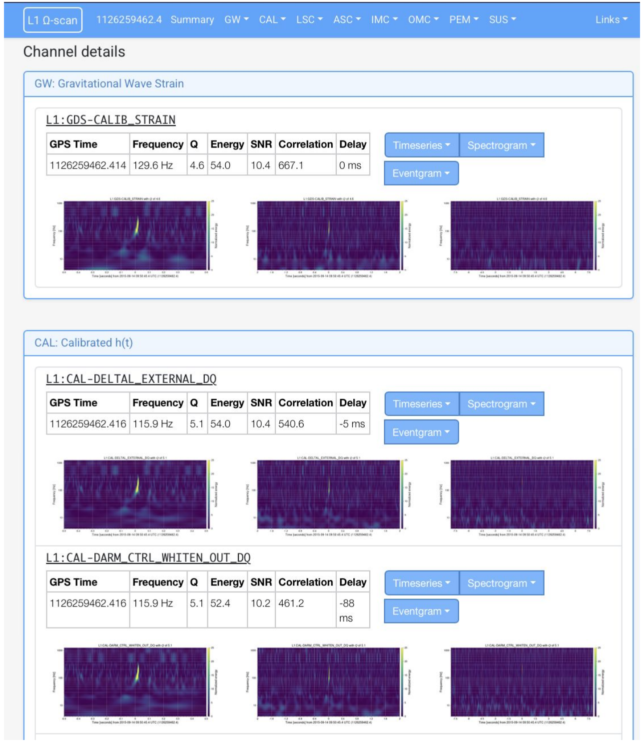


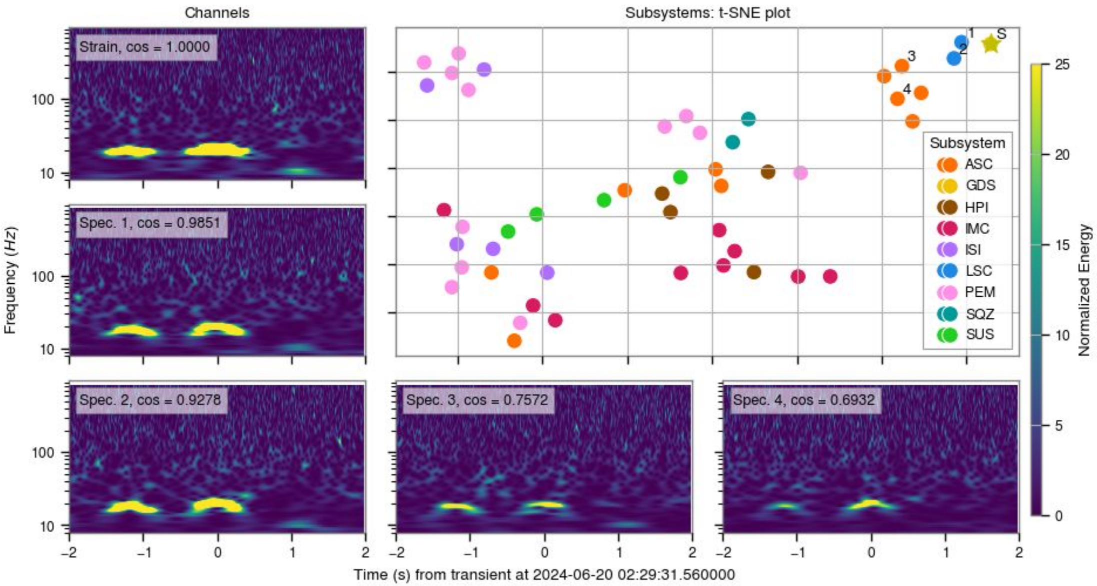




Glanzer+ 2023

Lots of manual intervention





The flip side of these benefits

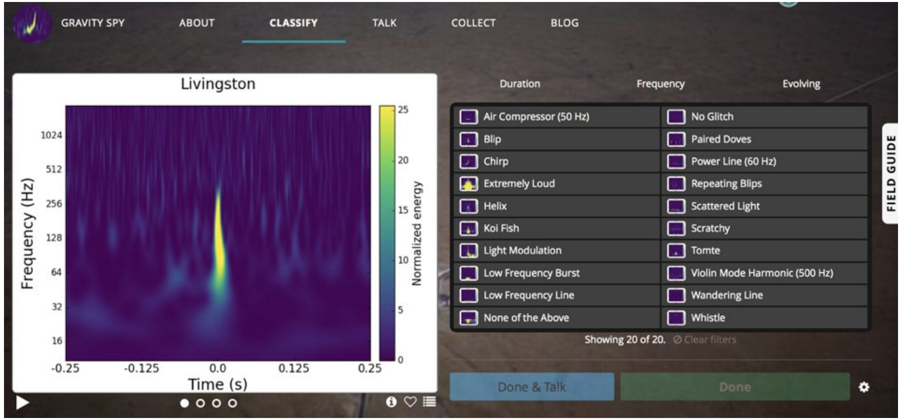
Large, complicated dataset	Many problems we don't have enough data to solve, there's a finite number of sensors
Few analytic Solutions	It is very challenging to develop simulated datasets for testing or performance evaluations
Lots of variety	Problem is constantly changing, solutions need to be targeted but also generic
Lots of manual intervention	Wide variety of best practices have been developed that are qualitative and hard to emulate

★ = I am here this week!

What is around?

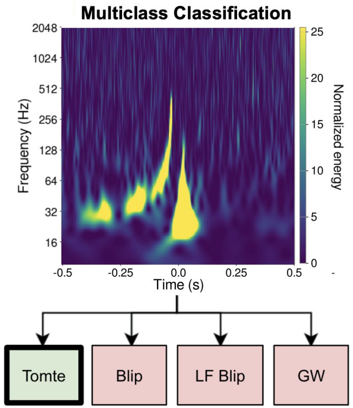
Note this is far from an exhaustive list

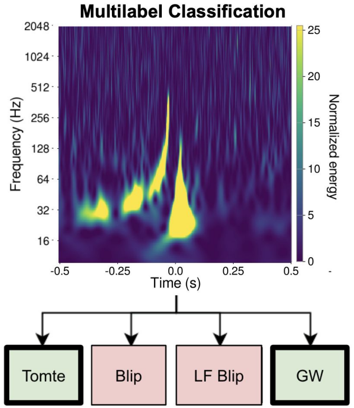
Classifying Glitches



Gravity Spy
Zevin+ 2016

GspyNetTree
Alvarez-Lopez+ 2023

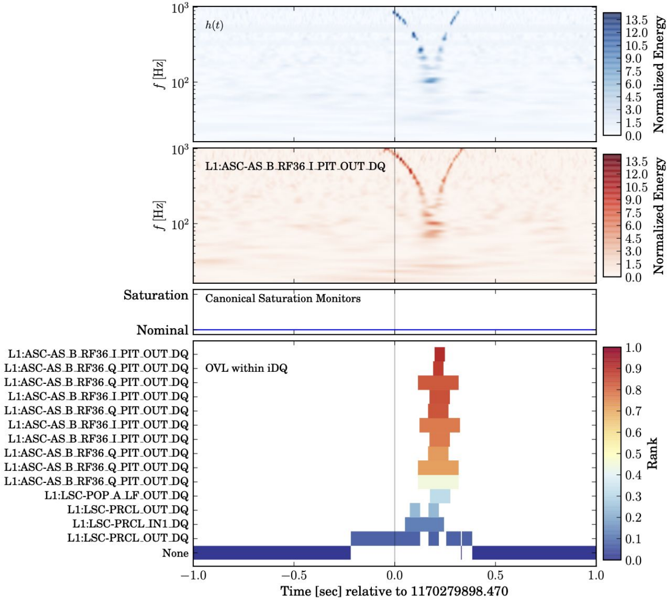




See also:

- Soni+ 2021
- George+ 2021
- Fernandes+ 2023
- Razzano+ 2023
- Chatterji+ 2024

Identifying
Noise Sources

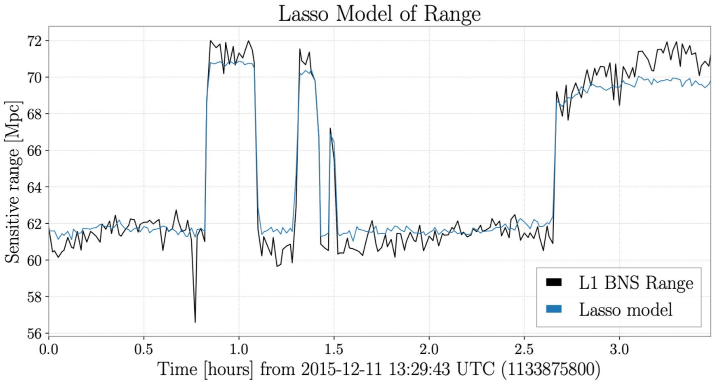


iDQ

Essick+ 2020

LASSO

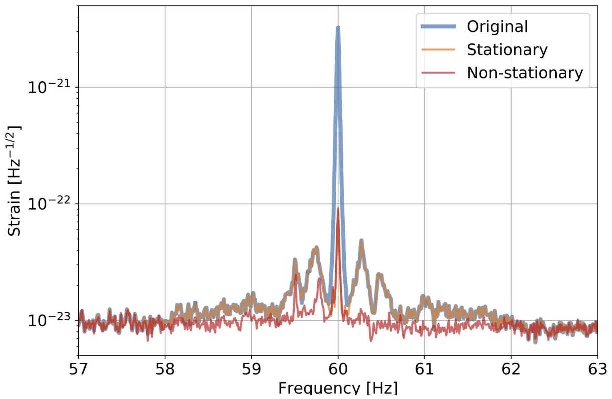
Walker+ 2018

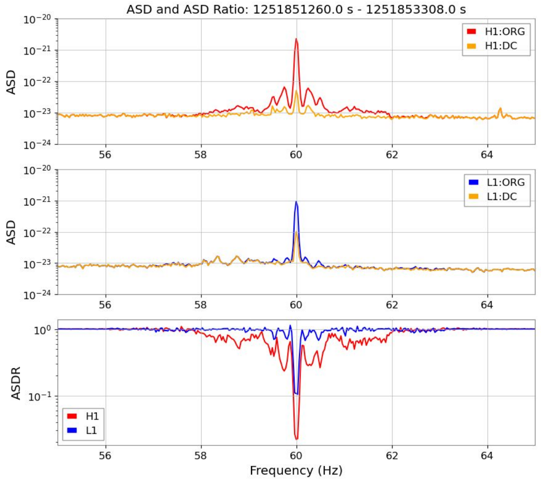


See also:

- Colgan+ 2019
- Gurav+ 2024

Subtracting Noise





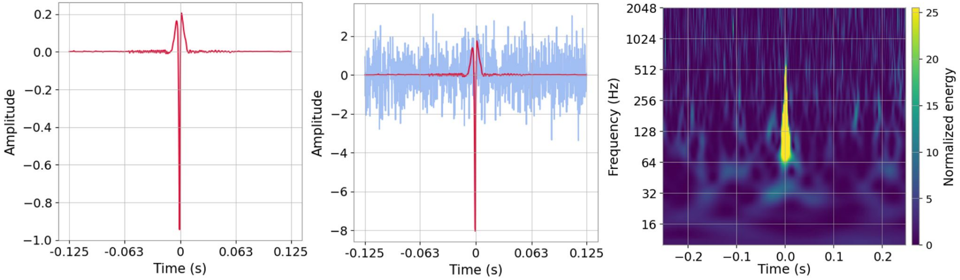
NonSens
Vajente+ 2019

DeepClean
Saleem+ 2023

See also:

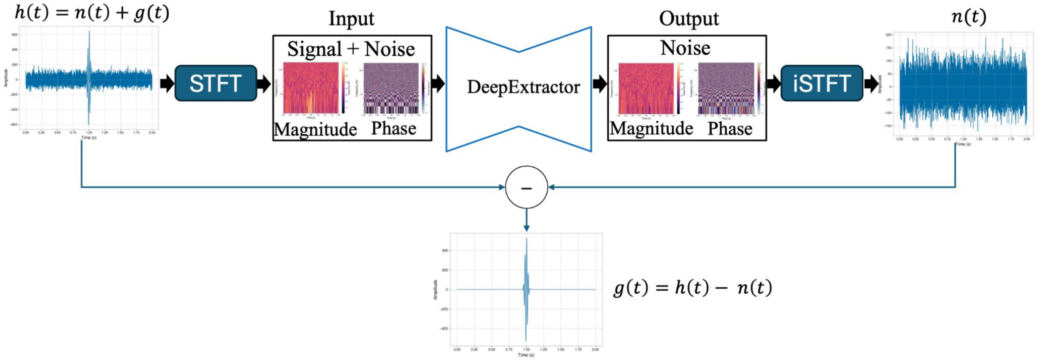
- Ormistan+ 2020
- Yu+ 2021
- Reissel+ 2025

Simulating
Glitches



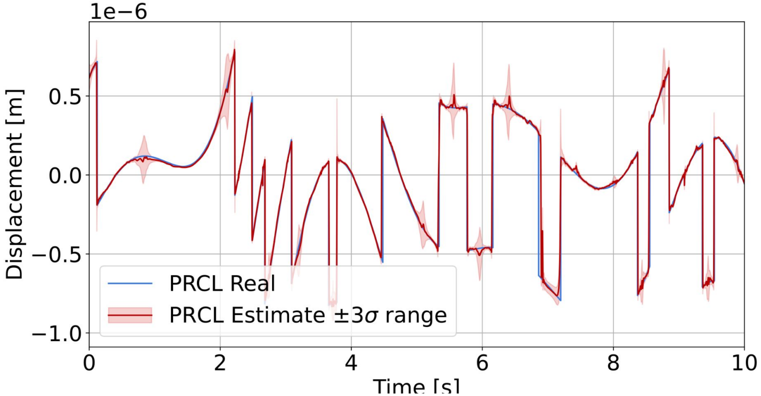
Gengli
Lopez+ 2022

DeepExtractor
Dooney+ 2025



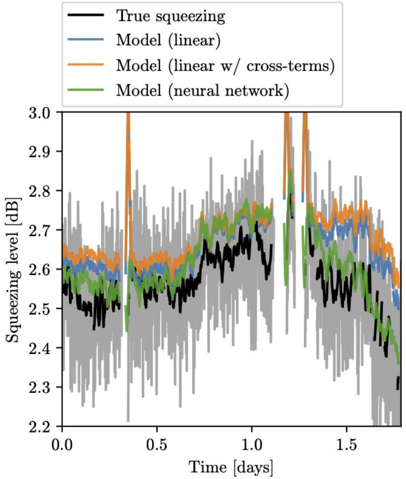
See also:
- Chatterji+ 2024
- Powell+ 2022

Improving Interferometer Perfromance



Non-linear Controls

Ma+ 202



Squeezing Predictions

Whittle+ 2023

See also:

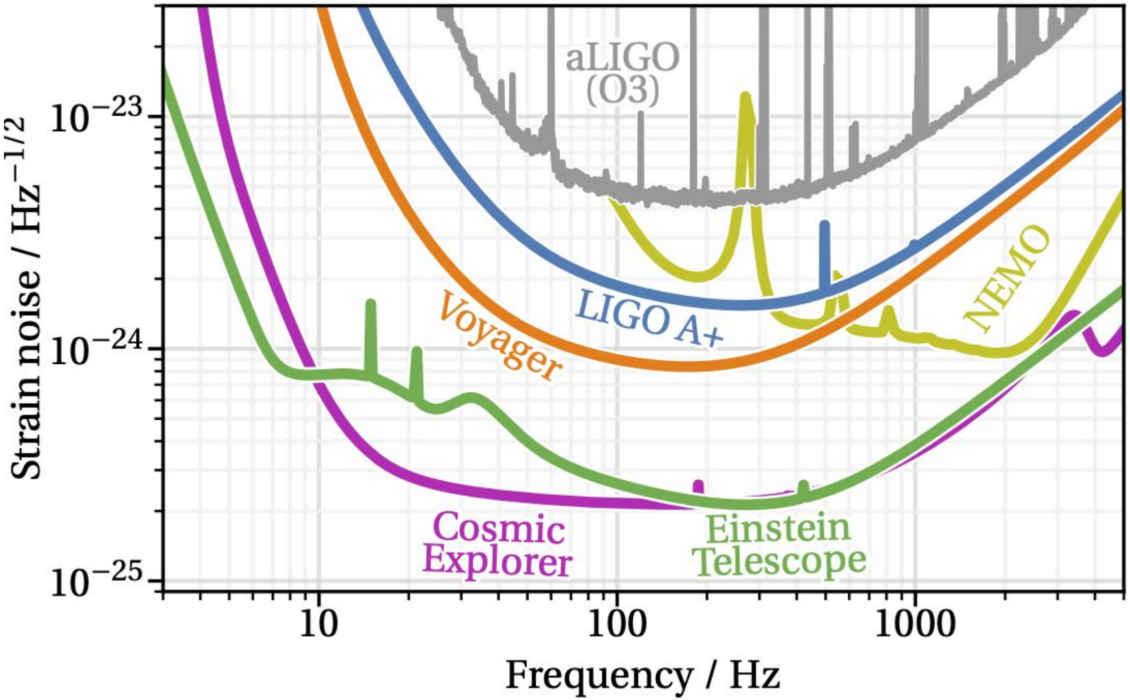
- Goode+ 2024
- Gurav+ 2024
- Krenn+ 2023

Where to go next?

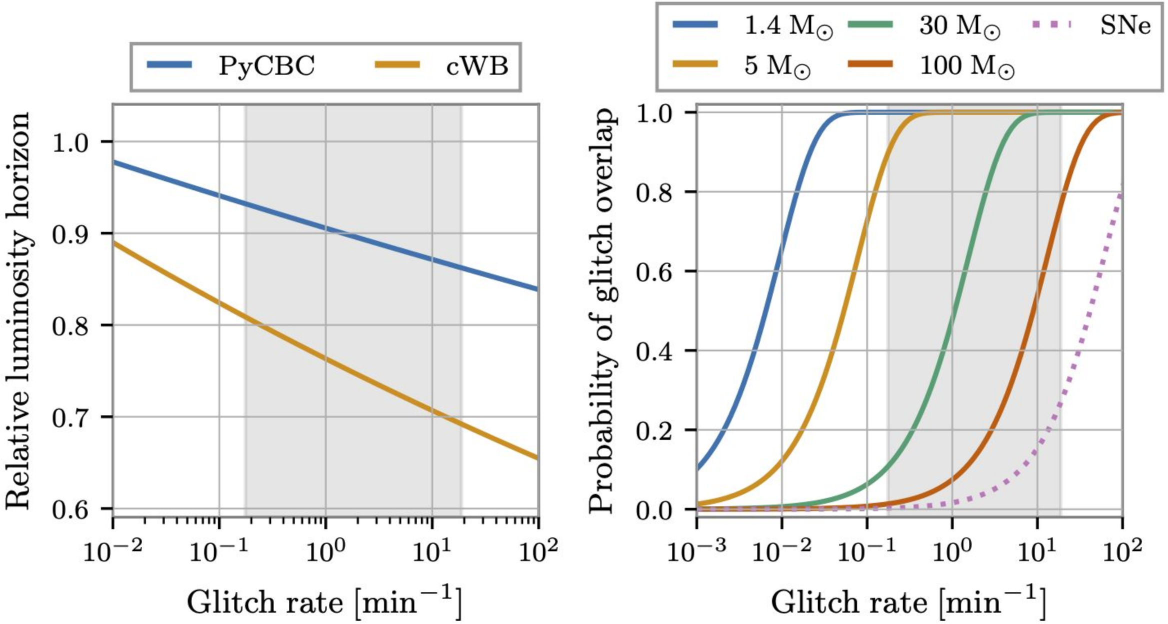
How do we adapt even more sensitive detectors?

Future observatories will be orders of magnitude more sensitive!

How do we deal with the practical realities of operating detectors and analyzing the data?



Example: Will glitches be a problem in the future?



Unless we reduce the rate of glitches, 100% of BNS signals will overlap glitches!

Can we develop robust methods for dealing with these problems?

Capote, Dartez, Davis 2024

Suggestions for new Detchar-ians

- There's lots of room for more growth in this field! Please come join us
- These types of problems will only grow in importance as gravitational-wave astronomy becomes more precise
- Understanding the field is an important part of making a significant contribution - hands on experience is best
- There's no "silver bullet" to many of these problems, but making some progress is often enough to be helpful

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