How are the LVK gravitational wave searches doing, and where are they headed?

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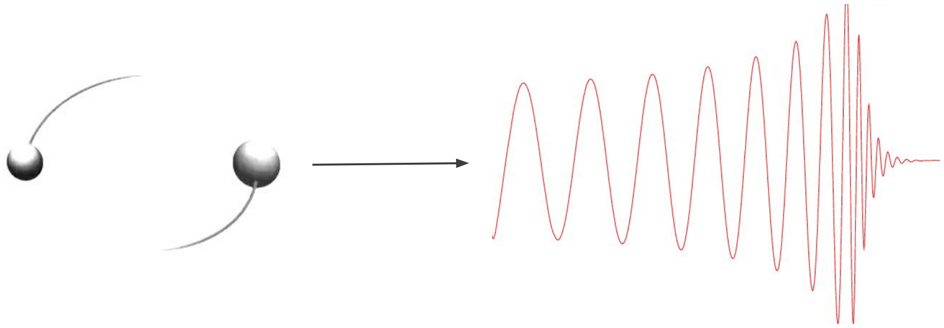
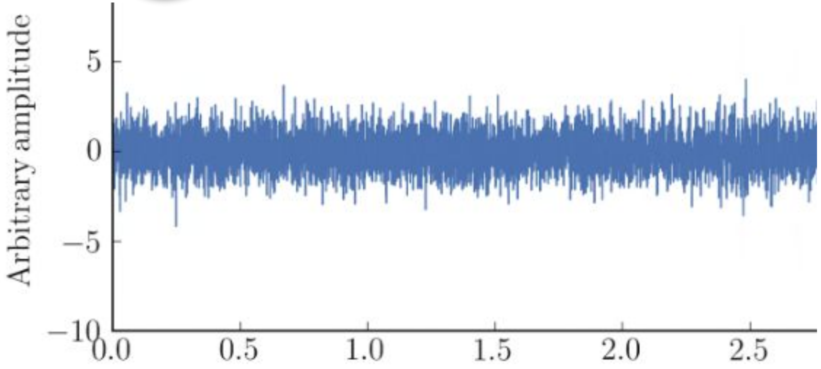
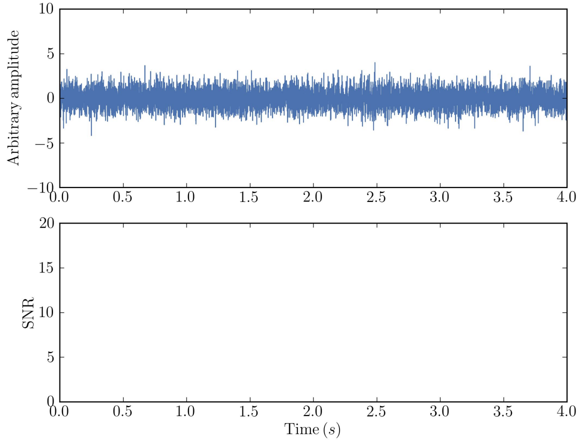
How do searches for compact binaries work?



BUT!!
Real data
looks
like this





Credit: Ryan Magee

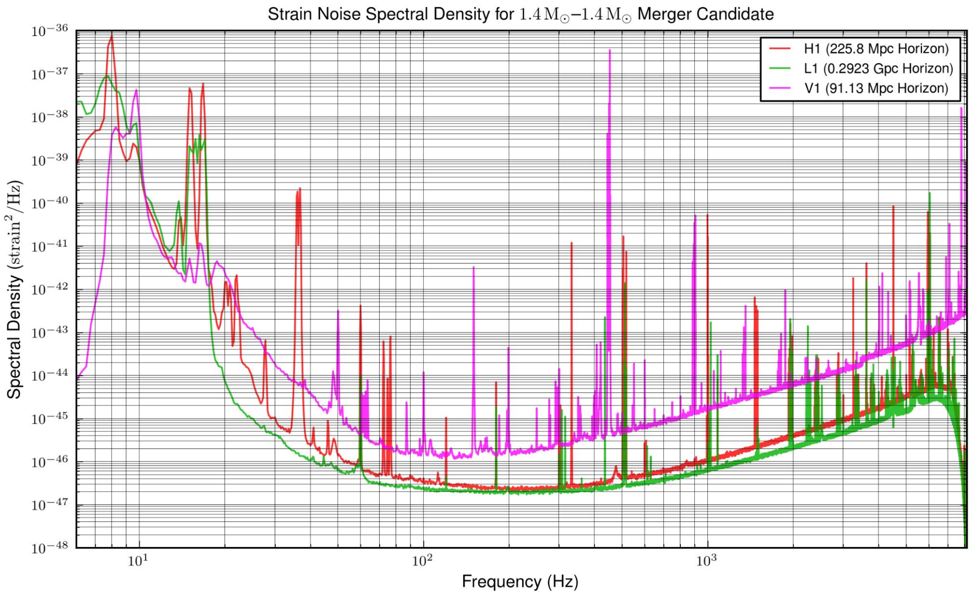
Solution:
Matched filtering!

SNR = $\langle \tilde{d} | \tilde{h} \rangle$

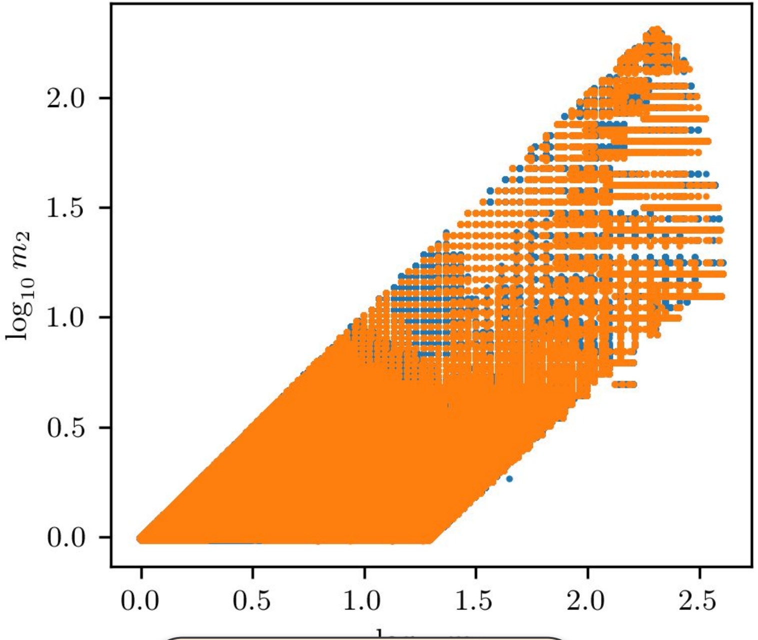
SNR is the inner product of (whitened) data and (whitened) template

$$\tilde{d}(f) = \frac{\tilde{d}(f)}{\sqrt{S_n(f)}}$$

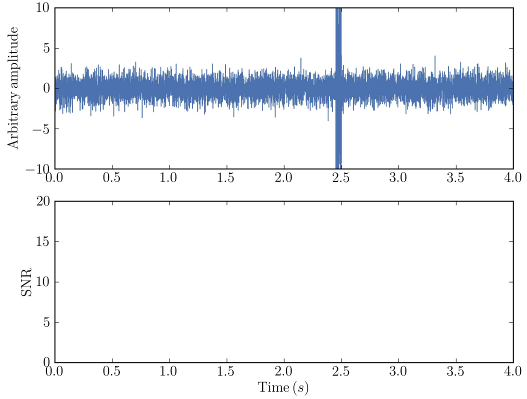
$$\tilde{h}(f) = \frac{\tilde{h}(f)}{\sqrt{S_n(f)}}$$



The PSD ($S_n(f)$) is used to remove frequency correlations in a process called whitening



We form “banks” of templates in intrinsic parameter space to find *all* the GWs out there



Credit: Ryan Magee

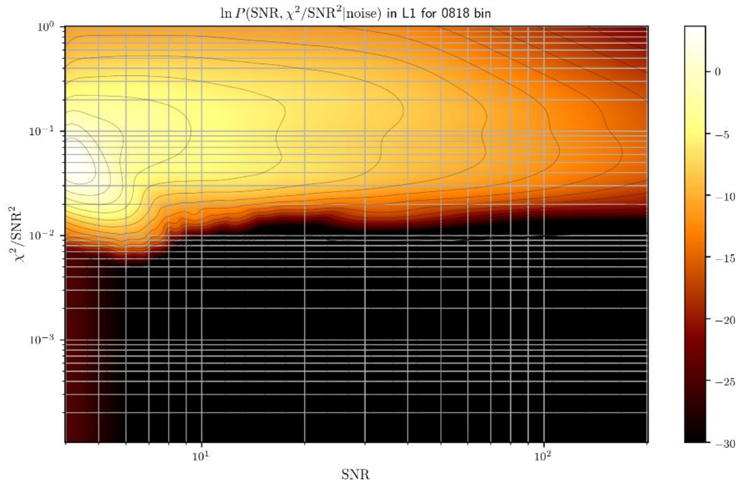
SNR isn’t always the perfect criteria for a GW

First solution: Form “coincidences” of triggers across detectors

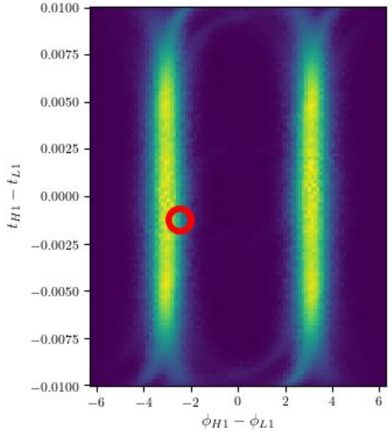
Trigger = a time when SNR > 4 is a particular detector

Second solution: create a better statistic than SNR to rank candidates

- This ranking statistic should consider things like background statistics, expected signal distributions, etc
- A common quantity used as an input to this ranking statistic is a χ^2 statistic to evaluate signal consistency across time/frequency
- The ranking statistic should consider the likelihood of relative arrival times (dt) and phases($d\phi$) of the GW at different detectors



An example background collected by a GstLAL analysis (top) and an example calculated dt-$d\phi$ (right)



The False Alarm Rate (FAR) of a candidate describes how frequently such a candidate will be produced from noise

How do we know noise statistics for such a long time?

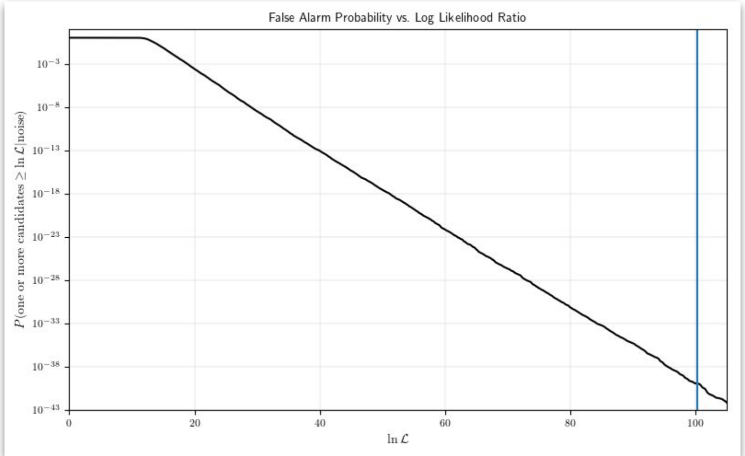
P(astro) considers the FAR and a prior astrophysical distribution to evaluate the probability of astrophysical origin

Event Information	
UID	G495305
Labels	PASTRO_READY EMBRIGHT_READY SKYMAP_READY
Group	CBC
Pipeline	MBTA
Search	AllSky
Instruments	H1,L1,V1
Event Time ▾	1403034677.425
FAR (Hz)	4.004e-20
FAR (yr^{-1})	1 per 7.9146e+11 years
SNR	27.837
Links	Data
Submitted ▾	2024-06-21 19:51:20 UTC

Solution: Create new "fake" noise triggers from existing noise triggers

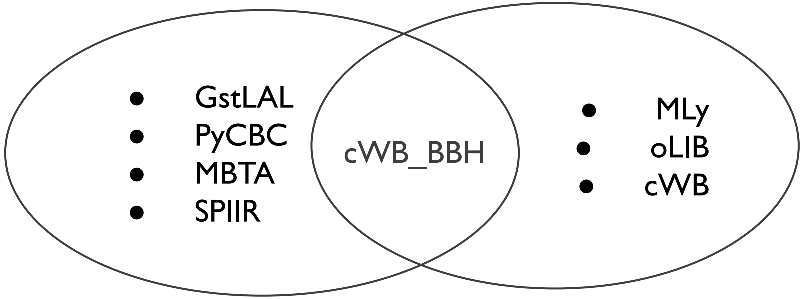
Common methods:

- Time slides
- Sampling from the noise background



Evaluating the FAR of a candidate with ranking statistic 100

Searches running during O4

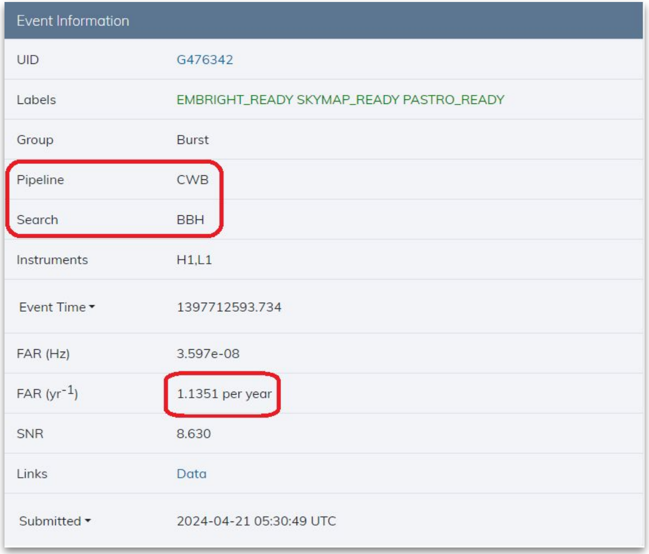


CBC pipelines

Burst pipelines

Online searches:

- AllSky
- Early Warning
- Sub-Solar Mass



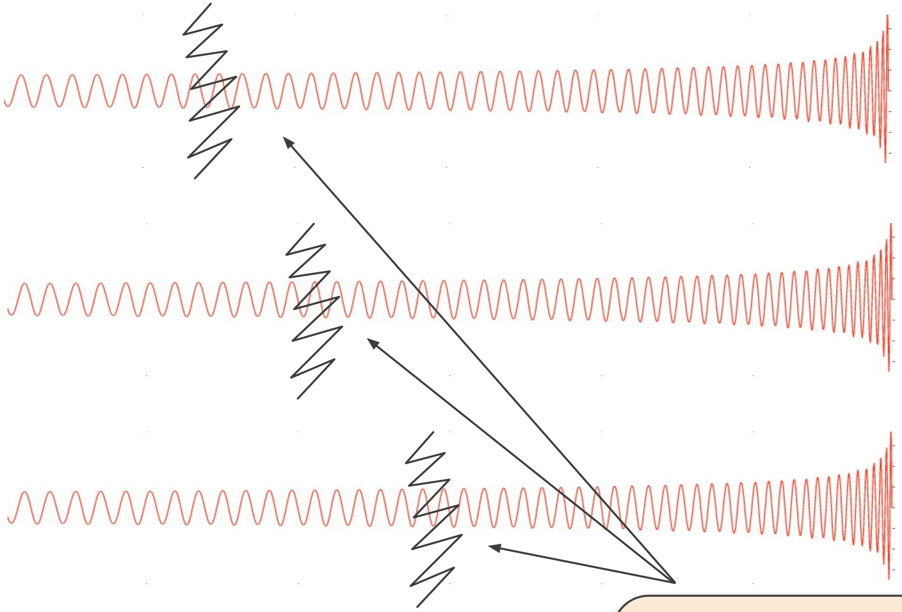
Event Information	
UID	G476342
Labels	EMBRIGHT_READY SKYMAP_READY PASTRO_READY
Group	Burst
Pipeline	CWB
Search	BBH
Instruments	H1,L1
Event Time ▾	1397712593.734
FAR (Hz)	3.597e-08
FAR (yr^{-1})	1.1351 per year
SNR	8.630
Links	Data
Submitted ▾	2024-04-21 05:30:49 UTC

CBC searches use templates; Burst searches are unmodeled

Offline searches:

- AllSky
- Sub-Solar Mass
- Intermediate-mass Black Hole

Early Warning Search

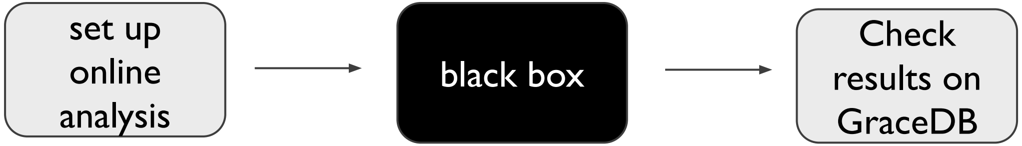


Basic Event Information	
UID	G710163
Labels	EMBRIGHT_READY SKYMAP_READY
Group	CBC
Pipeline	gstlal
Search	EarlyWarning
Instruments	H1,L1,V1
Event Time ▾	1347725130.154
FAR (Hz)	2.724e-04
FAR (yr^{-1})	8596.7 per year
Latency (s)	-57.770
Links	Data
Submitted ▾	2022-09-20 16:04:14 UTC
Superevent	S220920agw

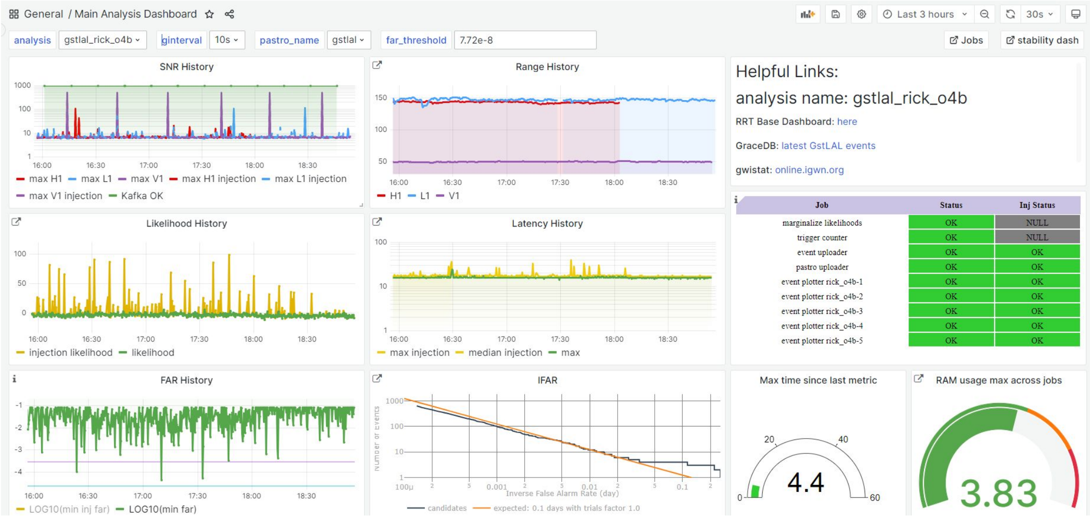
Cut off the template at different points, and try to predict the merger time before it happens

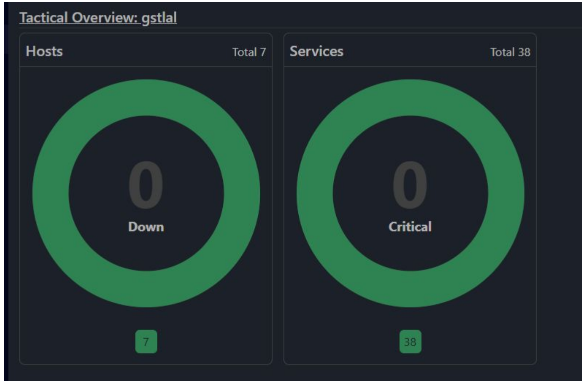
Only searches the low mass (BNS) space
Crucial for multi-messenger astronomy

Improvements in O4: monitoring

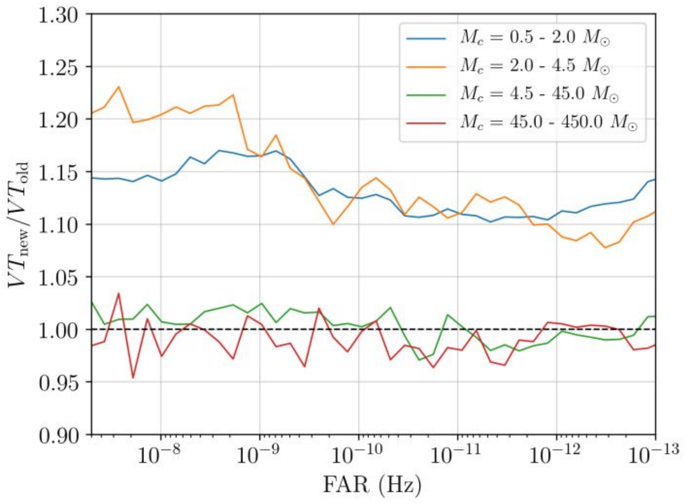


Traditional way of running an online search (top) vs the modern way (bottom)





Improvements in O4: sensitivity and reliability



VT, the sensitive volume-time is a measure of the sensitivity of a pipeline

O4 Results

	O3	O4a	O4b
Detections (FAR < 1/month)		81	31
Retractions	23	8	5
Duration (months)	11	8	3*

*still in progress

Due to multiple pipelines running, we have a trials factor on what qualifies far a public alert

Trials factors for O4b:

- AllSky: 5
- Early Warning: 3
- Sub-Solar Mass: No alerts
- Burst: 4

A retraction is a GW candidate that we sent out an alert for, but later on lost confidence in

Source classifications for public alerts in O4

No BNS!

	BBH	NSBH	BNS	Noise
Number	78	1	0	2

O4a

	BBH	NSBH	BNS	Noise
Number	28	1	0	2

O4b

Interesting candidates: GW230529

Observation of Gravitational Waves from the Coalescence of a 2.5–4.5 $M_\odot$ Compact Object and a Neutron Star

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration

ABSTRACT

We report the observation of a coalescing compact binary with component masses 2.5–4.5 $M_\odot$ and 1.2–2.0 $M_\odot$ (all measurements quoted at the 90% credible level). The gravitational-wave signal GW230529_181500 was observed during the fourth observing run of the LIGO–Virgo–KAGRA detector network on 2023 May 29 by the LIGO Livingston observatory. The primary component of the source has a mass less than 5 $M_\odot$ at 99% credibility. We cannot definitively determine from gravitational-wave data alone whether either component of the source is a neutron star or a black hole. However, given existing estimates of the maximum neutron star mass, we find the most probable interpretation of the source to be the coalescence of a neutron star with a black hole that has a mass between the most massive neutron stars and the least massive black holes observed in the Galaxy. We estimate a merger rate density of 55^{+127}_{-47} Gpc^{-3} yr^{-1} for compact binary coalescences with properties similar to the source of GW230529_181500; assuming that the source is a neutron star–black hole merger, GW230529_181500-like sources constitute about 60% of the total merger rate inferred for neutron star–black hole coalescences. The discovery of this system implies an increase in the expected rate of neutron star–black hole mergers with electromagnetic counterparts and provides further evidence for compact objects existing within the purported lower mass gap.

https://arxiv.org/abs/2404.04248

- Probable NSBH during O4a
- Single detector candidate
- Provides support for objects in the lower mass gap
- Has implications for merger rates

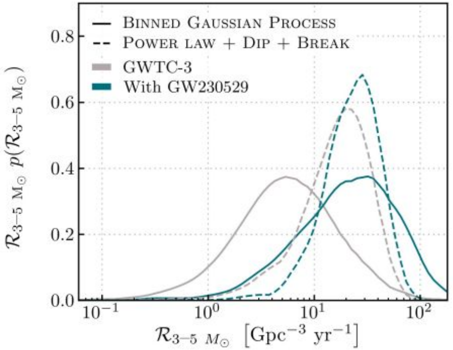
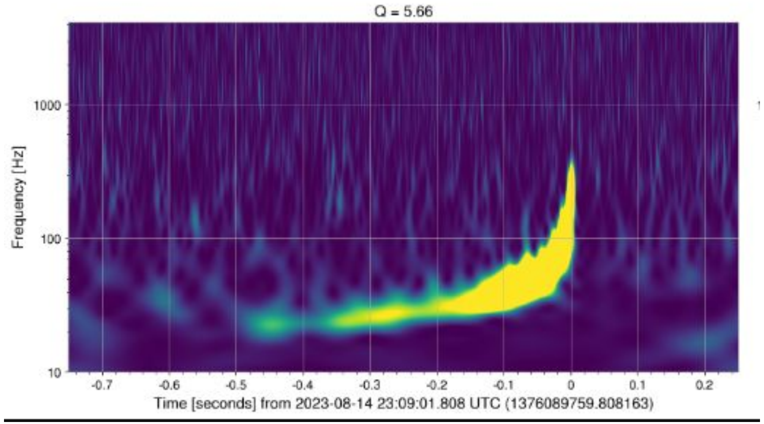
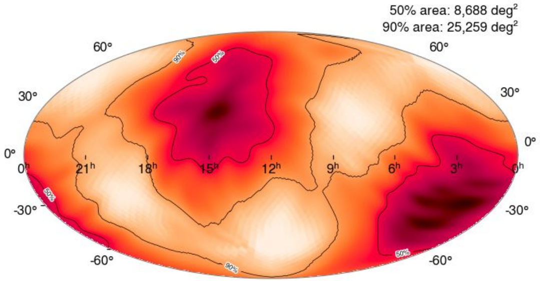


Figure 5. Posterior on the merger rate of binaries with one or both components between 3–5 $M_\odot$. The solid curves show the results from the Binned Gaussian Process analysis and the dashed curves show the results from the Power law + Dip + Break analysis. Both models analyze the full black hole and neutron star mass distribution. The teal and grey curves show the analysis results with and without GW230529, respectively.

Interesting candidates: S230814ah

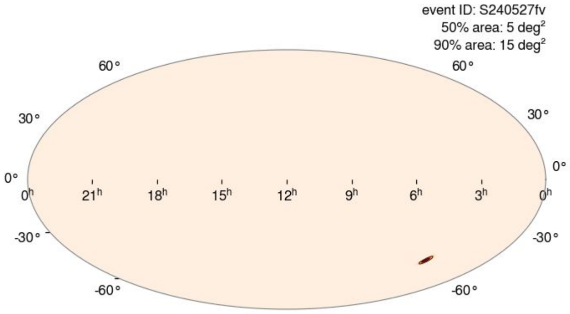
Single Inspiral Table	
IFO	L1
Channel	GDS-CALIB_STRAIN_CLEAN
End Time (GPS)	1376089759.810 s
Template Duration	17.0 s
Effective Distance	
Coa. Phase	0.68369401 rad
Mass 1	42.603889 $M_\odot$
Mass 2	24.745056 $M_\odot$
η	0.23242138
F Final	1024.0 Hz
SNR	42.375404
χ^2	0.99601358
χ^2 DOF	1
spin1z	0.01546875
spin2z	0.01546875

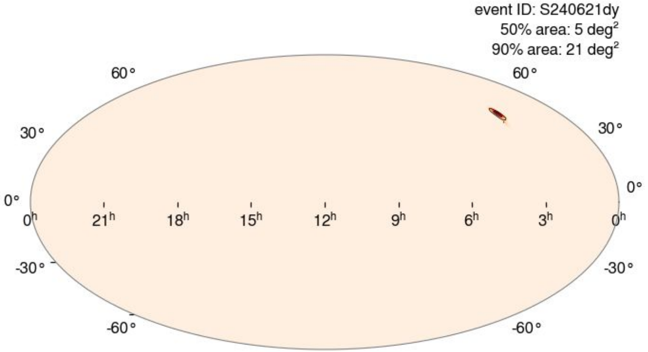


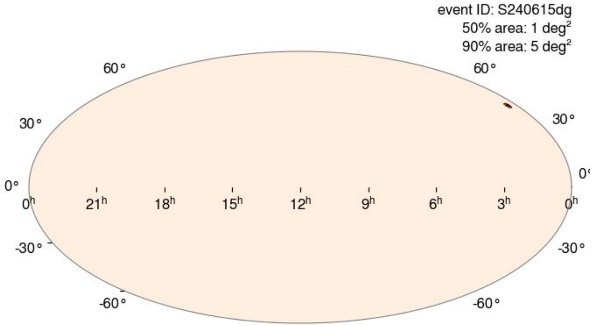


Unfortunately, only L1 was observing

Interesting candidates: S240527fv, S240615dg, S240621dy







Virgo data has helped a lot in sky localization

New SNR Optimization techniques also help make skymaps more accurate

Future Directions

- Searches keep getting more robust, more flexible, and more efficient
- We are now more prepared than ever to participate in the next multi-messenger event
- Making a burst detection would be huge
- Precession and higher order modes are the next frontier to conquer for searches

Gravitational-wave template banks for novel compact binaries

Stefano Schmidt [1,2,*] Bhooshan Gadre [2] and Sarah Caudill [3,4]
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[2] *Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, Princetonplein 1, 3584 CC Utrecht, The Netherlands*
[3] *Department of Physics, University of Massachusetts, Dartmouth, MA 02747, USA*
[4] *Center for Scientific Computing and Visualization Research, University of Massachusetts, Dartmouth, MA 02747, USA*

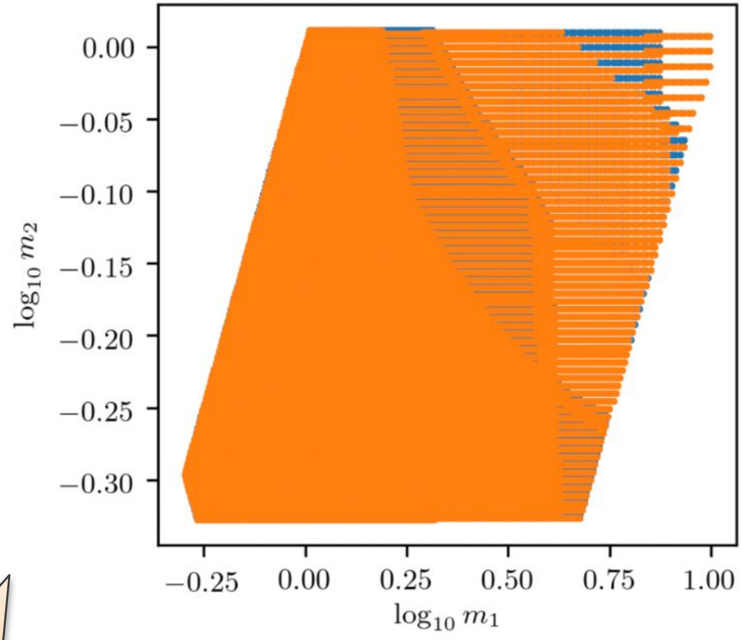
We introduce a novel method to generate a bank of gravitational-waveform templates of binary black hole (BBH) mergers for matched-filter searches in LIGO, Virgo and Kagra data. We derive a novel expression for the metric approximation to the distance between templates, which is suitable for precessing BBHs and/or systems with higher-order modes (HM) imprints and we use it to meaningfully define a template probability density across the parameter space. We employ a masked autoregressive normalizing flow model which can be conveniently trained to quickly reproduce the target probability distribution and sample templates from it. Thanks to the normalizing flow, our code takes a few *hours* to produce random template banks with millions of templates, making it particularly suitable for high-dimensional spaces, such as those associated to precession, eccentricity and/or HM. After validating the performance of our method, we generate a bank for precessing black holes and a bank for aligned-spin binaries with HMs: with only 5% of the injections with fitting factor below the target of 0.97, we show that both banks cover satisfactorily the space. Our publicly released code `mbank` will enable searches of high-dimensional regions of BBH signal space, hitherto unfeasible due to the prohibitive cost of bank generation.

https://arxiv.org/pdf/2302.00436

Sub-Solar Mass Search

- Searches for compact binaries with at least one component below 1 solar mass
- A very computationally expensive search, in terms of both number of templates and calculations per template
- Pipelines are running online searches as well as more comprehensive offline searches

New Physics!!!



GstLAL's online SSM bank

THANK YOU!