Searching for exceptional gravitational-wave sources in the LIGO-Virgo-KAGRA data

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Return to Poland

- Ph.D., ~5 years: Embry-Riddle Aeronautical University (Arizona)
- Postdoc, ~5 years: University of Florida
- Assistant Professor, present: University of Warsaw (permanent position and a Polish Returns grant)

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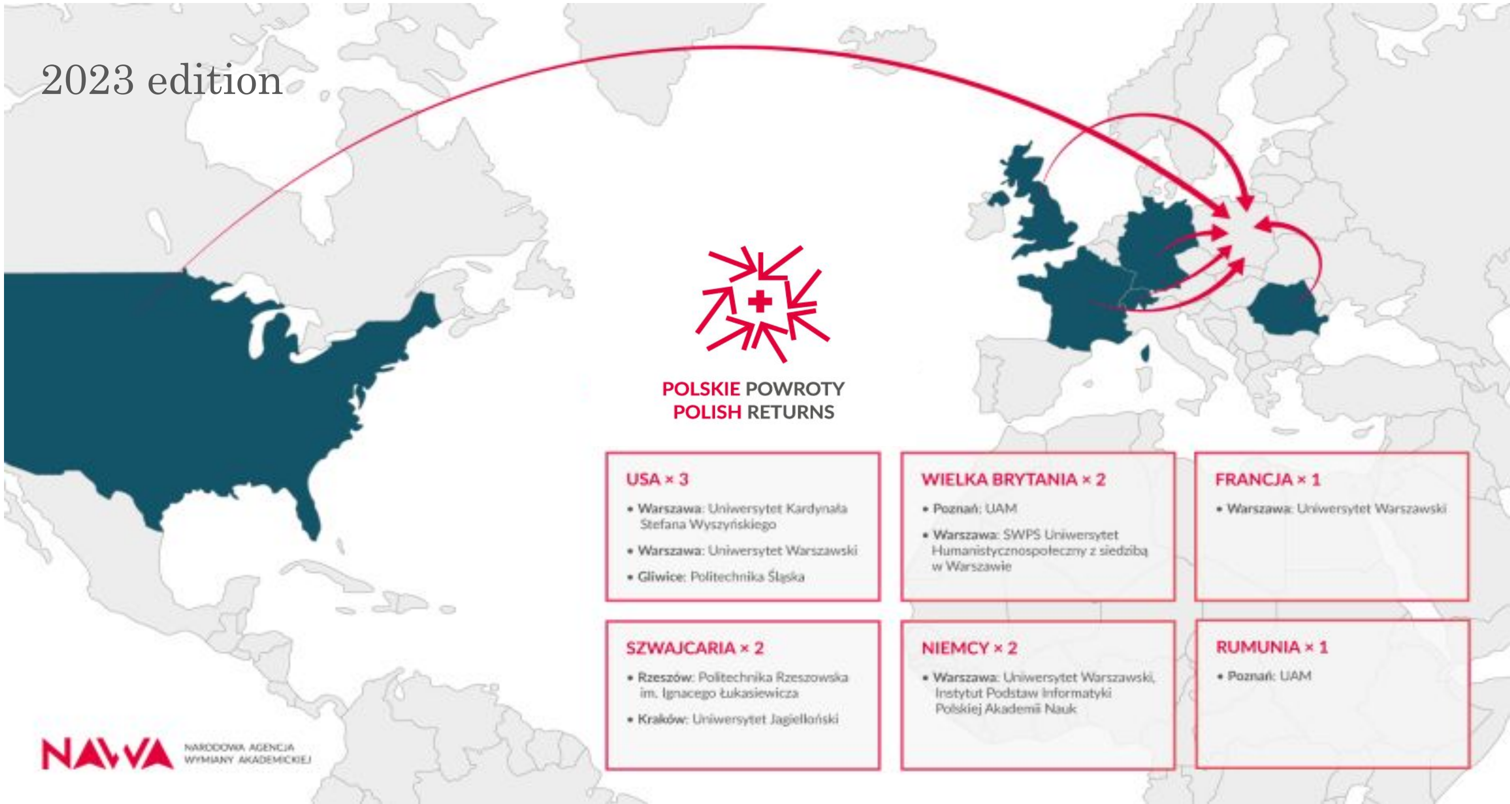


Outline

- Exceptional GW sources
- Model-independent searches
- Observing Run 4
- Summary

See also today's GW talks by:

- Tom Dent
- Christine Lee

Exceptional GW sources

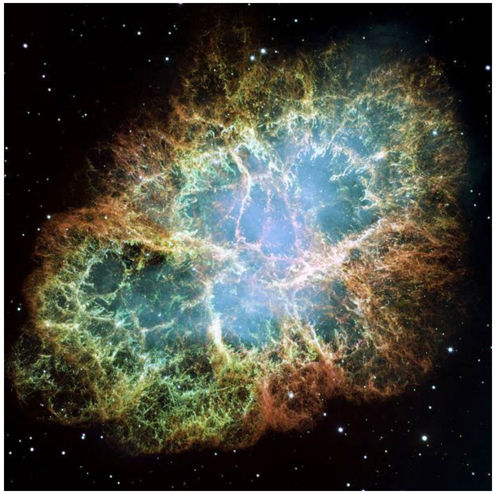
Exceptional astrophysical sources might play the key role in our endeavor of exploring the Universe.

- **New GW source populations**:
  - Compact binaries: binaries with eccentric orbits, hyperbolic encounters, head-on collisions, sub-solar mass binaries, extreme mass ratio
  - GW bursts: core-collapse supernovae, neutron star or pulsar glitches, cosmic strings
- **Multi-messenger GW sources (electromagnetic waves, neutrinos, cosmic rays)**: BNS, NSBH, BNS post-merger
- **GW sources with new phenomena (usually weaker effects)**:
  - GR: pre- and post-merger higher harmonics, GW cross-polarization, black hole kicks, GW memory, effects of precession, high spins, black hole formation etc.
  - Beyond GR: GW echo, beyond-quadrupolar GW polarizations,

GW searches

- Types:
  - **Model-dependent (template based):** binary black holes (BBH), binary neutron stars or binary black hole - neutron star
  - **Model-independent (template-independent) or “burst”:** for example core-collapse supernovae, cosmic strings, as well as regular or special binaries, such as heavy/eccentric BBHs
- Latency:
  - **Low-latency**: rapid (within seconds to minutes) identification of the GW sources and preliminary validation (within hour) for quick astronomical follow-up.
  - **Offline**: identification of GWs after data acquisition, weeks or even years.

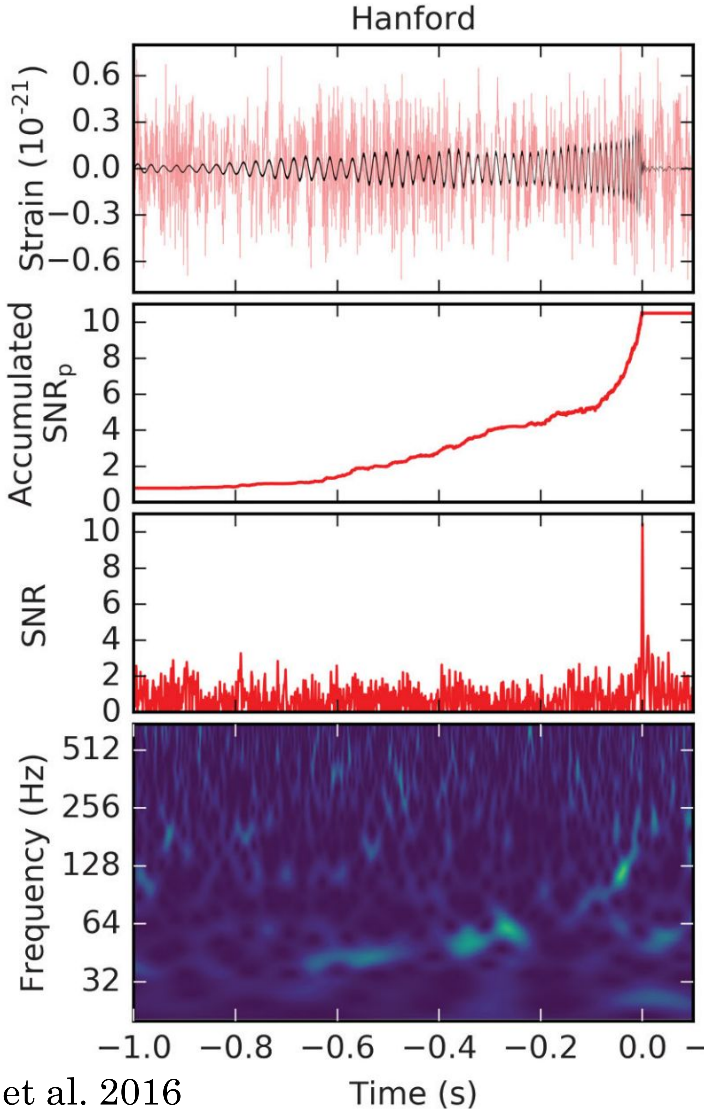
Image: NSF/LIGO/Sonoma/A. Simonnet



Crab Nebula

Model-dependent searches
Matched-filtering

- The template signals from compact binaries are derived from General Relativity.
- **Cross-correlating data with waveform templates**
- The method requires accurate waveform models. To the leading order, the waveform morphology depends on the chirp mass and effective spin.
- Missing parameter space or having an inaccurate model may result in missing a detection.
- Example algorithms: GstLAL, PyCBC, SPIIR, MBTA



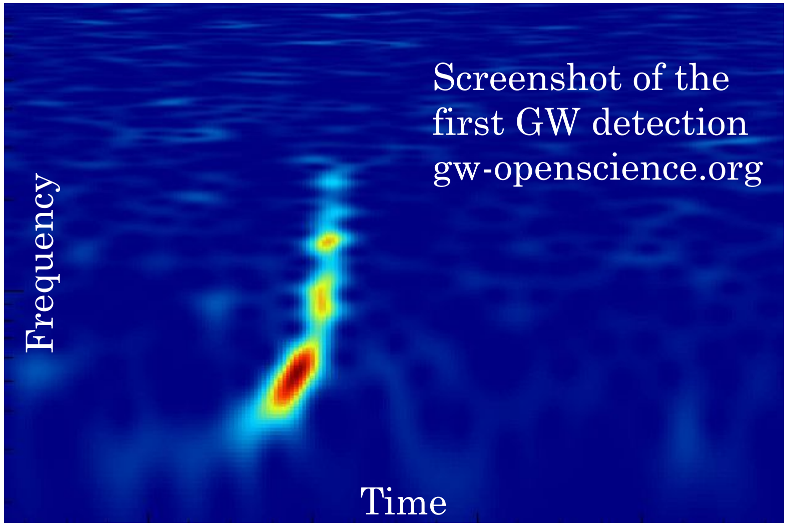
Abbott et al. 2016

Model-independent searches
coherent WaveBurst

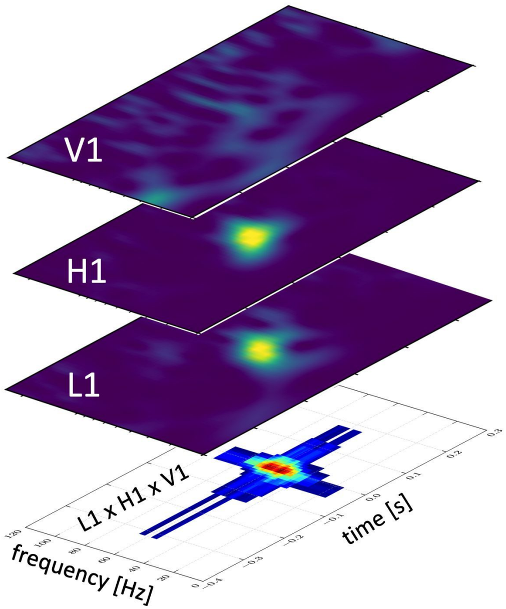
- **Coherent WaveBurst** (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
- cWB uses minimal assumptions, for example growing frequency over time in case of binaries
- Complementing matched filtering
- cWB has detected:
  - **GW150914 - the very first GW (PRL 116, 061102)**
  - **GW190521 - an intermediate mass binary black hole (PRL 125, 101102)**
  - several GWs together with template based searches
- **The cWB is the most sensitive burst algorithm in O4**

coherent WaveBurst
an open source software for gravitational-wave data analysis

https://gwburst.gitlab.io/



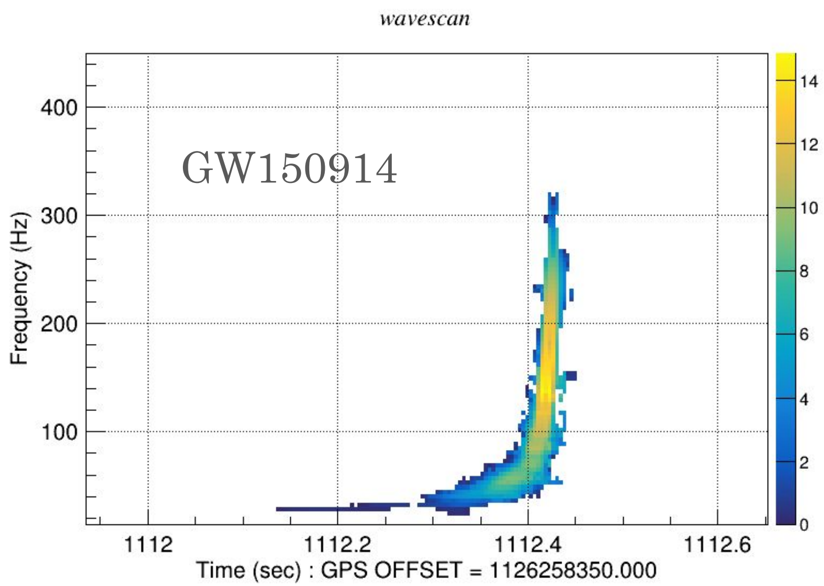
coherent WaveBurst (cWB)



x(t) —Wavelet Transform→

- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

—Inverse Wavelet Transform→ h(t)

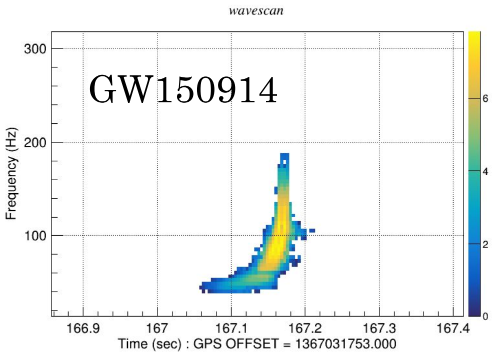


Model-independent searches classification

Compact binary searches (minimally modeled)

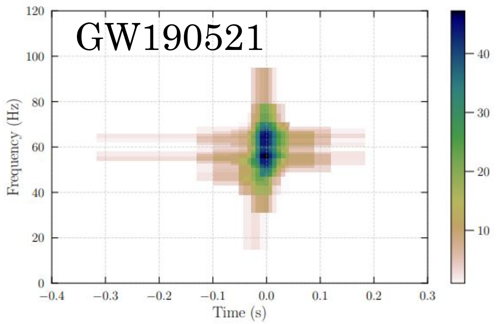
Generic searches (unmodeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



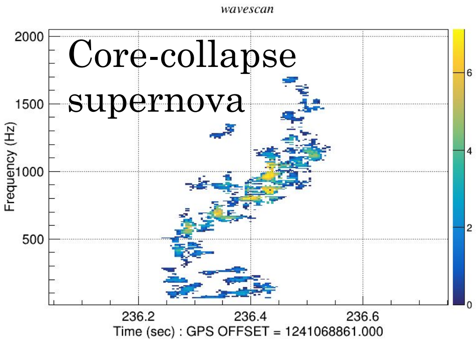
e.g. Mishra+23 (2201.01495)

Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



e.g. MS+21 (2009.11336)

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



e.g. MS+24 (2305.16146)

Low-latency searches

Public alerts for multi-messenger observations: electromagnetic, cosmic rays, and neutrino

e.g. Chaudhary+24 (2308.04545)

Searches for new phenomena

Higher harmonics
GW cross-polarization
Deviations from GR

e.g. Vedovato+22 (2108.13384)

Observing Run 4

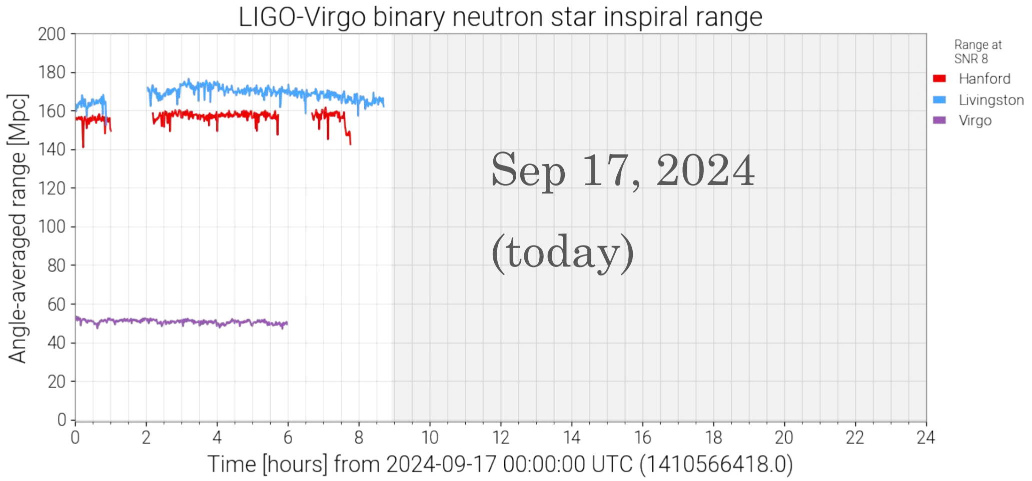
- O4: 24 months total, until Jun 2025
- BNS ranges: up to 180 Mpc (LIGO), around 55 Mpc (Virgo)
- The duty cycle for Hanford and Livingston is around 70-80% and 80% for Virgo
- Public communication about the observing run:
  - OpenLVEM: https://wiki.gw-astronomy.org/OpenLVEM
  - Latest plans: https://observing.docs.ligo.org/plan/

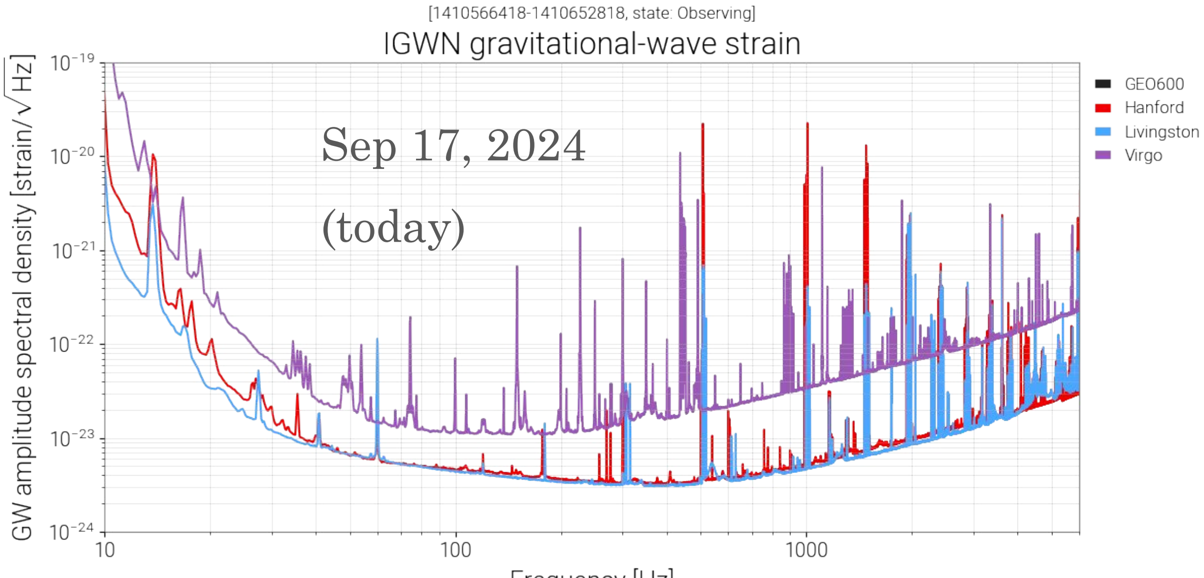
- KAGRA:
  - Hit by 7.6 magnitude earthquake on Jan 1
  - Planned joining before the end of O4 with 10 Mpc

gw
astro

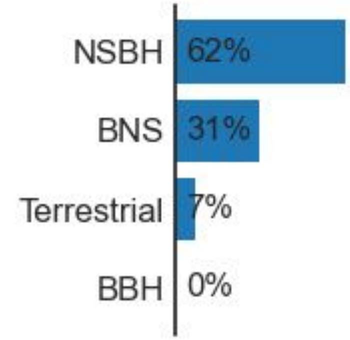
Observing Run 4

- Live detector status: https://online.igwn.org/
- Daily detector status: https://gwosc.org/detector_status/
- Public data release is 18 months after data collection





Observing Run 4



S230529ay

- GW candidates: 81 (O4a) and 24 (O4b so far)
- Detection rate: **3 per week**
- Almost all events are BBHs
  - NSBH/BNS: 15 events with non-zero probability
- Matched filtering: GstLAL, PyCBC, SPIIR, MBTA
- GW Bursts: cWB, (oLIB)
  - cWB-generic: generic searches for GW bursts
  - cWB-BBH: compact binaries

GW230929 (Abbott+25)

- 2.5-4.5 Mo Compact Object and a Neutron Star

https://gracedb.ligo.org/

O4 Significant Detection Candidates: **130** (146 Total - 16 Retracted)

O4 Low Significance Detection Candidates: **2371** (Total)

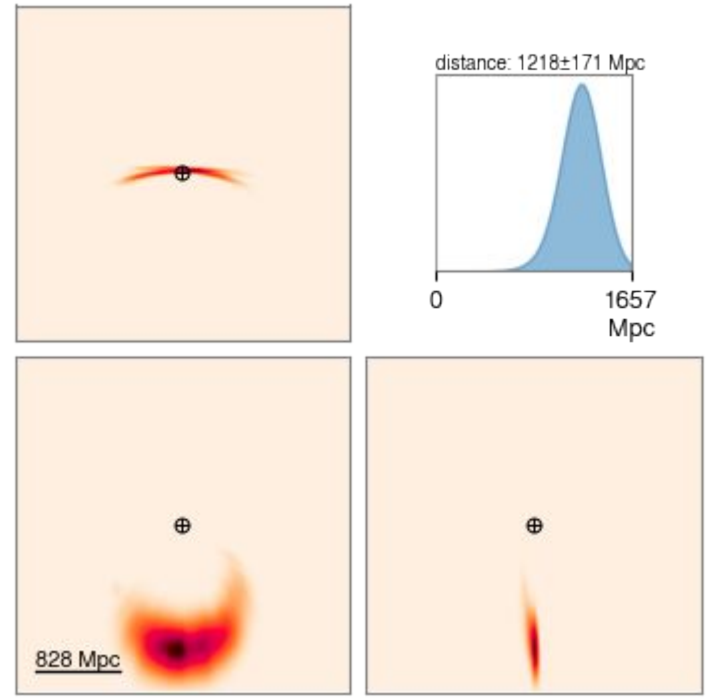
Observing Run 4
cWB-BBH search

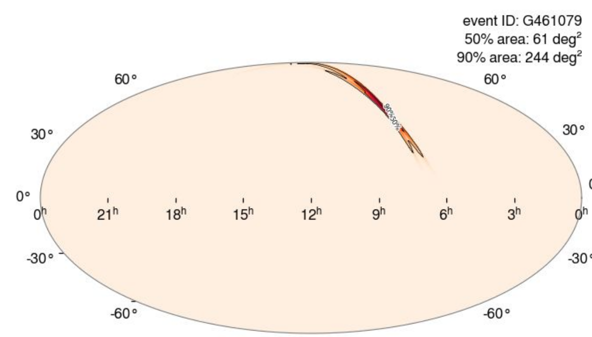
cWB-BBH search:

- Search for stellar- and intermediate-mass black holes.
- **It's capable to detect "vanilla" and special/exceptional compact binaries (e.g. GW150914 or GW190521)**
- Complementing matched filtering
- It detects around 80% of BBHs identified by matched filtering searches (for the Hanford-Livingston network)
- So far 3 alerts were sent publicly (non-significant)

Public alerts

- Binaries (example plots: S231226av):
  - Sky localization
  - Distance
  - Source classification
- Burst event alerts:
  - "Fluence" ~ GW energy
  - Peak frequency
  - Duration
- S200114f - a burst public alert in O3, later classified as noise
- No burst public alerts so far in O4





Summary

- Gravitational-Wave Astrophysics
  - The exceptional GW sources may play a key role in exploring the Universe and fundamental physics
- Gravitational-wave searches
  - Model-independent searches are suitable for observing exceptional events
  - Observing Run 4: around 130 GW events so far