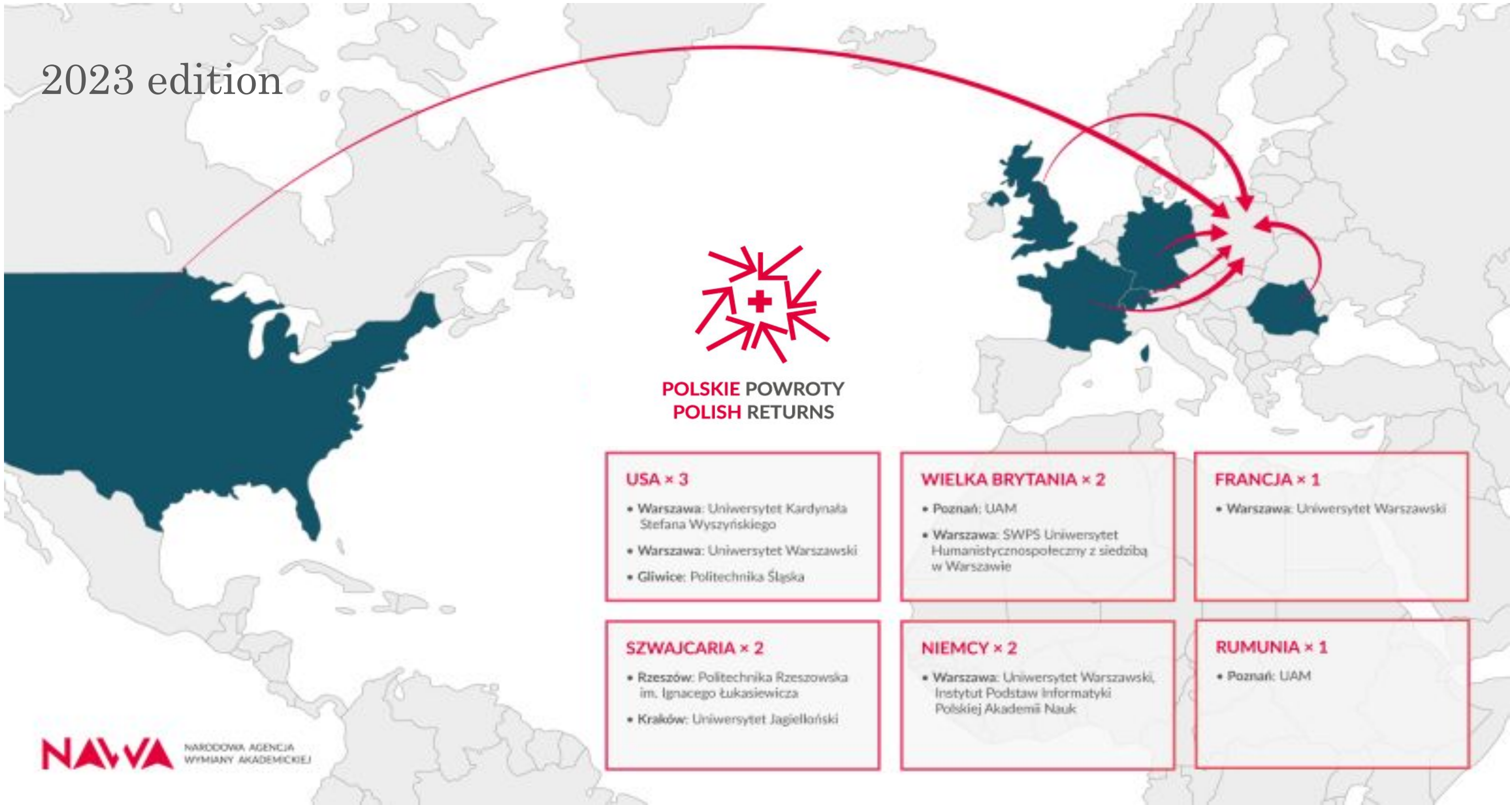
Searching for exceptional gravitational-wave sources in LIGO/Virgo/KAGRA

Marek Szczepańczyk
Department of Physics, University of Warsaw

Relativity Seminar
Institute of Theoretical Physics
Warsaw, 14.06.2024

Return to Poland

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



Outline

- Gravitational-Wave Astrophysics
  - Exceptional GW sources
- Gravitational-wave searches
  - Model-independent searches
  - Observing Run 4
  - Higher harmonics
- Summary

Gravitational-Wave Astrophysics

The Dynamic Universe

Quadrupole formula for GW production:

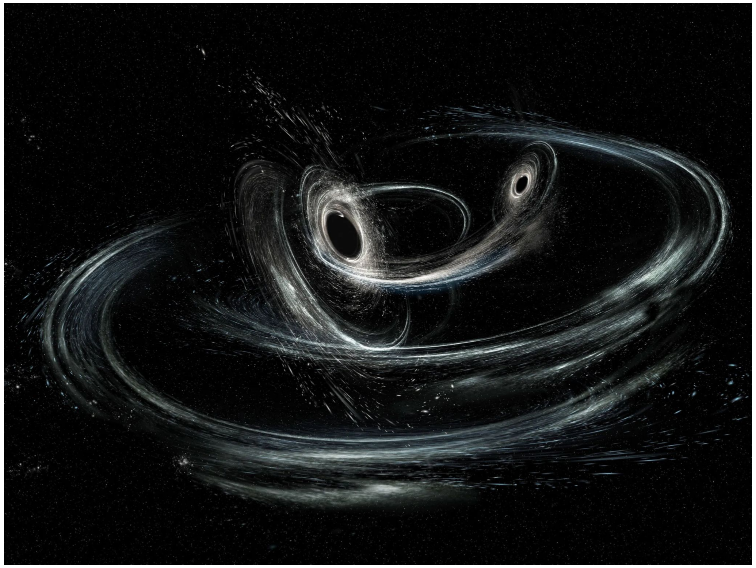
$$\mathbf{h}_{ij}^{TT}(t, \mathbf{x}) = \frac{1}{D}\ddot{Q}_{ij}(t - D/c, \mathbf{x})$$

We need aspherical mass-energy movement.

Image: NSF/LIGO/Sonoma/A. Simonnet

GW sources:

- "Vanila", e.g. stellar-mass binary black holes
- **Exceptional!**



AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

Exceptional GW sources

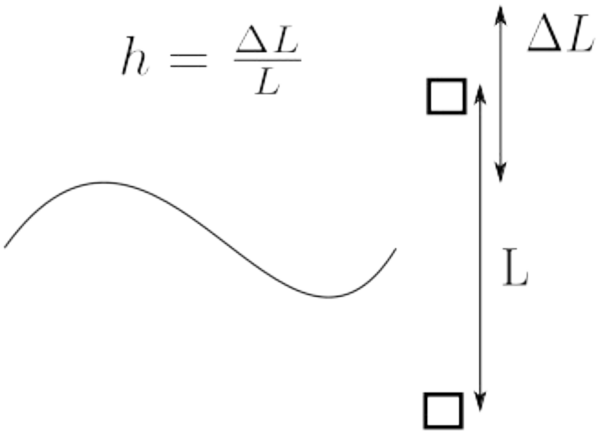
Exceptional astrophysical sources might play the key role in our endeavor of exploring the Universe.

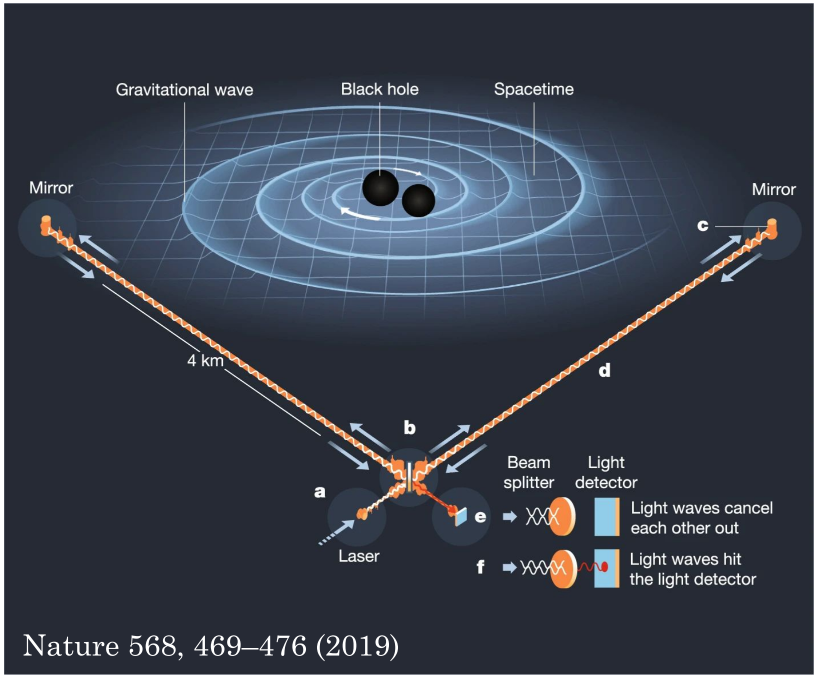
- **New GW source populations**:
  - Compact binaries: binaries with eccentric orbits, hyperbolic encounters, head-on collisions, sub-solar mass binaries, extreme mass ratio
  - GW bursts: core-collapse supernovae, neutron star or pulsar glitches, cosmic strings
- **Multi-messenger GW sources (electromagnetic 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,

Gravitational-Wave detectors

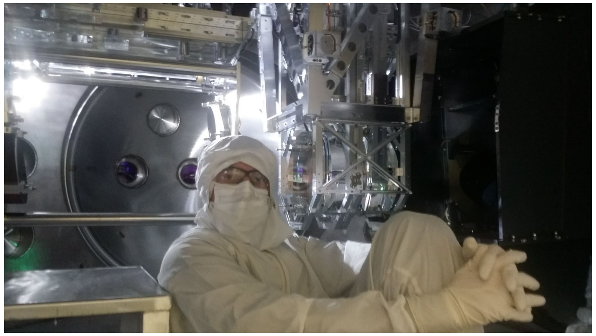
- GWs passing through two objects change distance between them.
- GW detectors: interferometers (the longer, the more sensitive)
- Preferably far away from human activities.

$$h = \frac{\Delta L}{L}$$

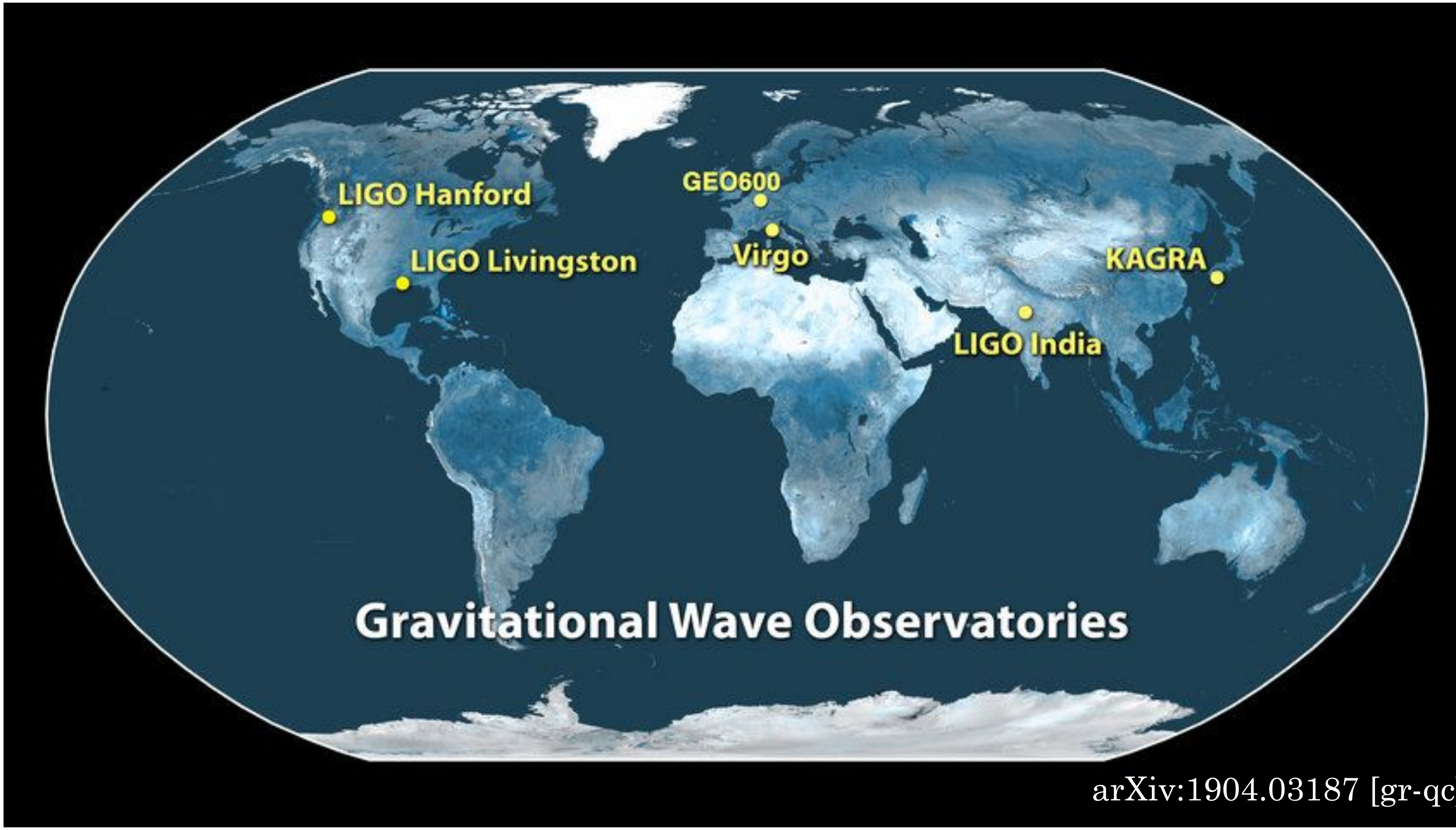




Nature 568, 469–476 (2019)



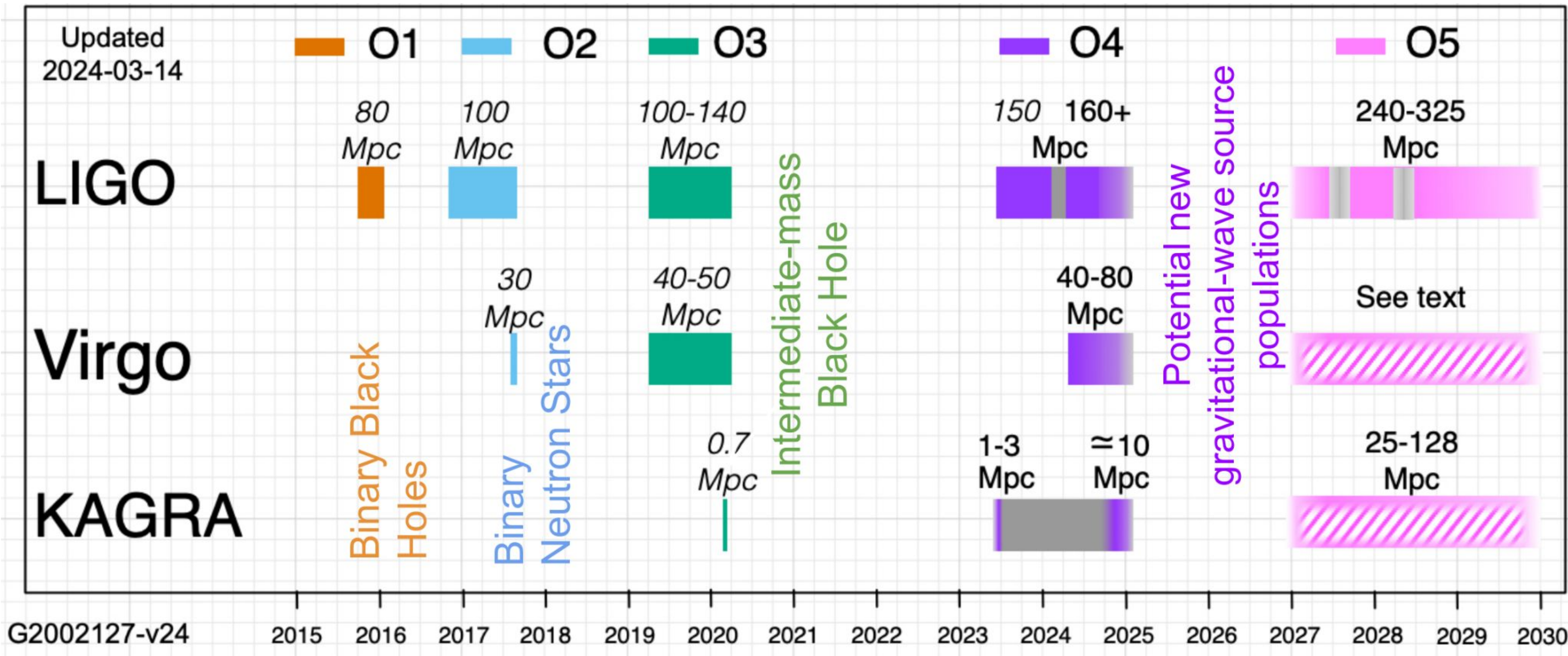
Detectors network



arXiv:1904.03187 [gr-qc]

- GEO and KAGRA - recently joined observations
- LIGO India - under construction
- NEMO - planned Australian high-frequency detector

Observing Timeline

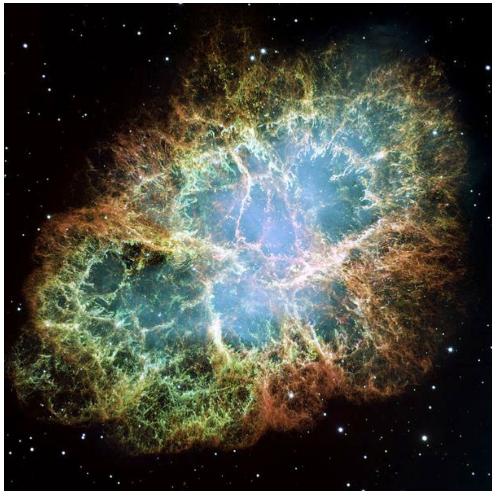


Gravitational-wave searches

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.

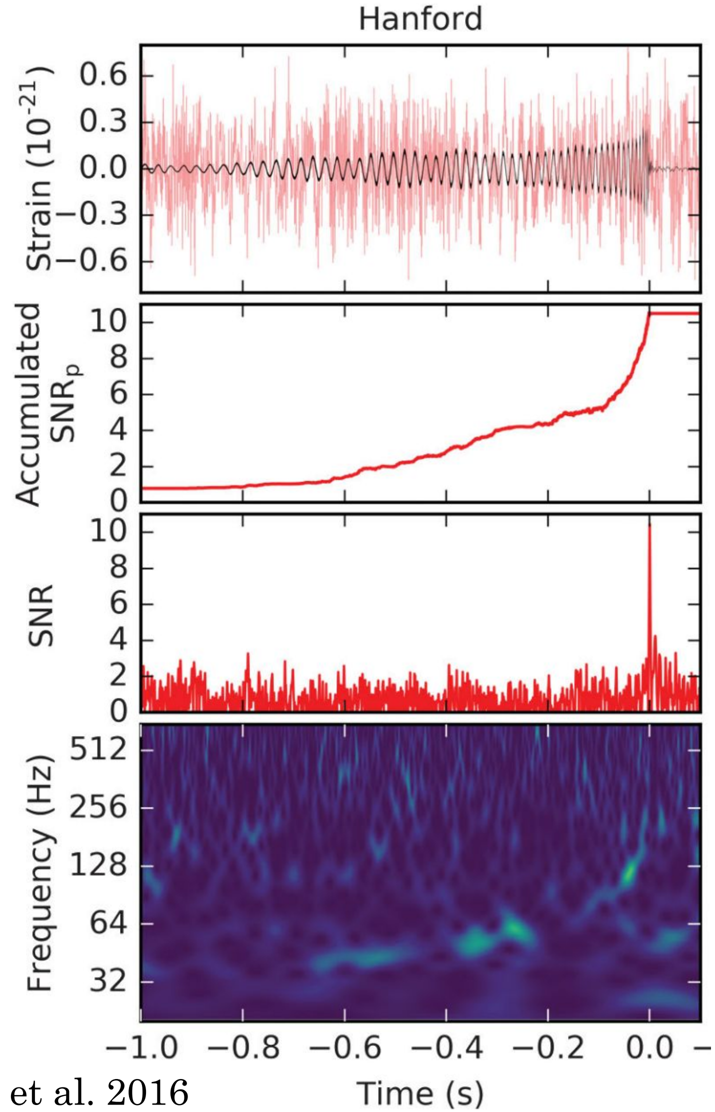
Image: NSF/LIGO/Sonoma/A. Simonnet



Crab Nebula

Model-dependent searches
Matched-filtering

- **Cross-correlating data with waveform templates**
- The template signals from compact binaries are derived from General Relativity.
- 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

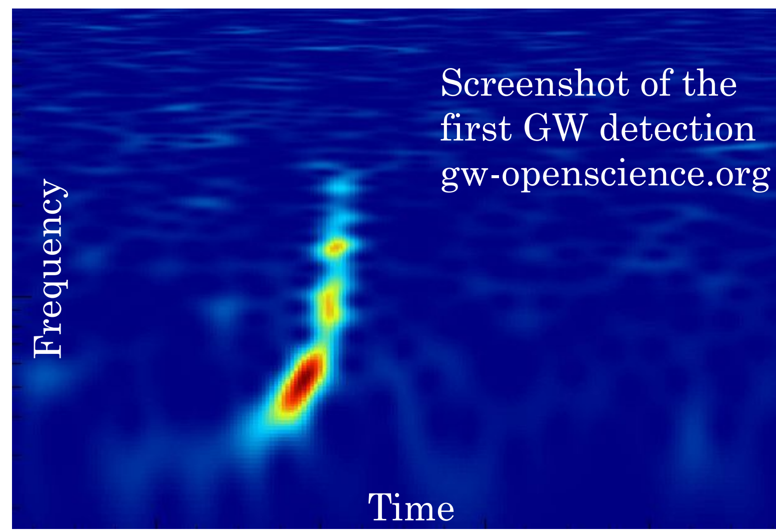
- cWB uses minimal assumptions, for example growing frequency over time in case of binaries

- Complementing matched filtering

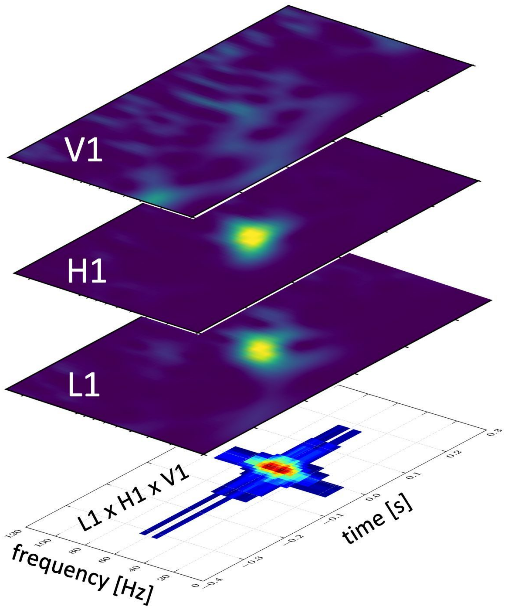
- cWB has detected:
    - **GW150914 - the very first GW (PRL 116, 061102)**
    - **GW190521 - an intermediate mass binary black hole (PRL 125, 101102)**
    - several GWs together with template based searches

- **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/



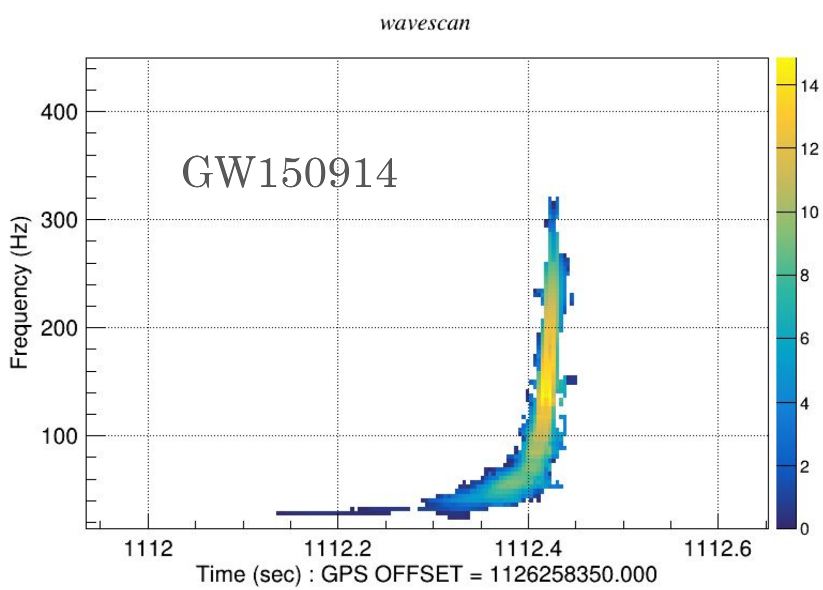
coherent WaveBurst (cWB)



x(t) —Wavelet Transform→

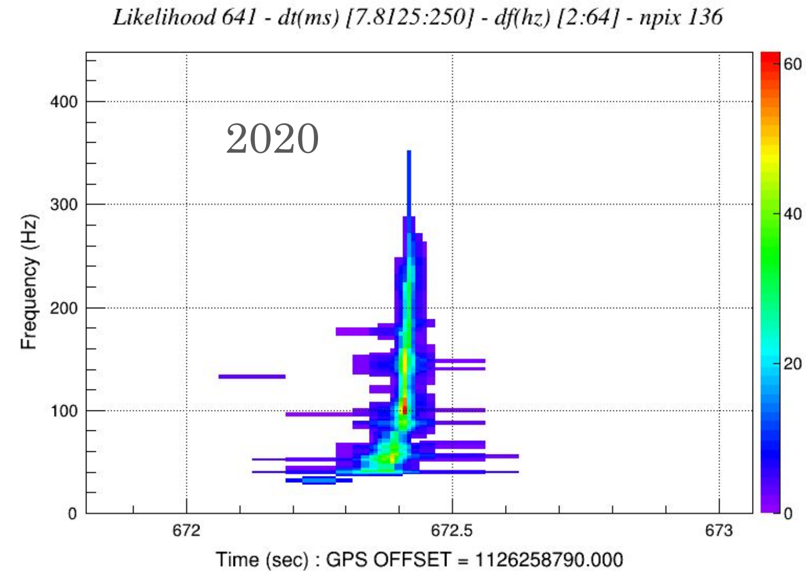
- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

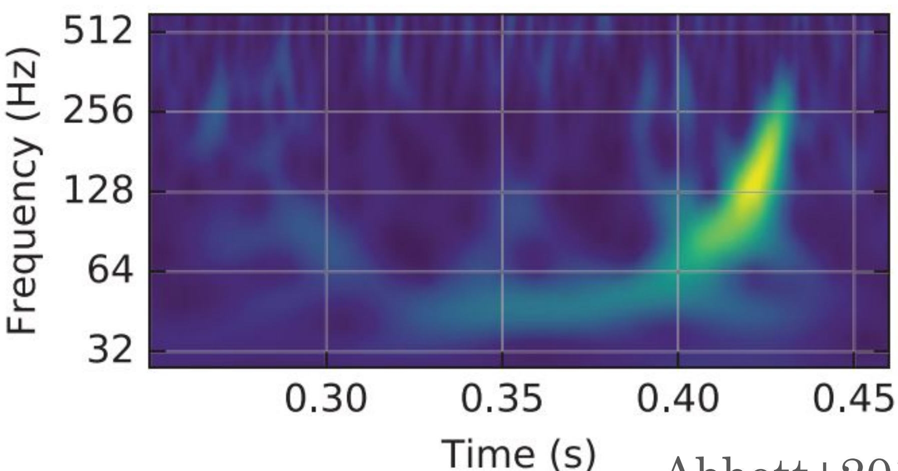
—Inverse Wavelet Transform→ h(t)



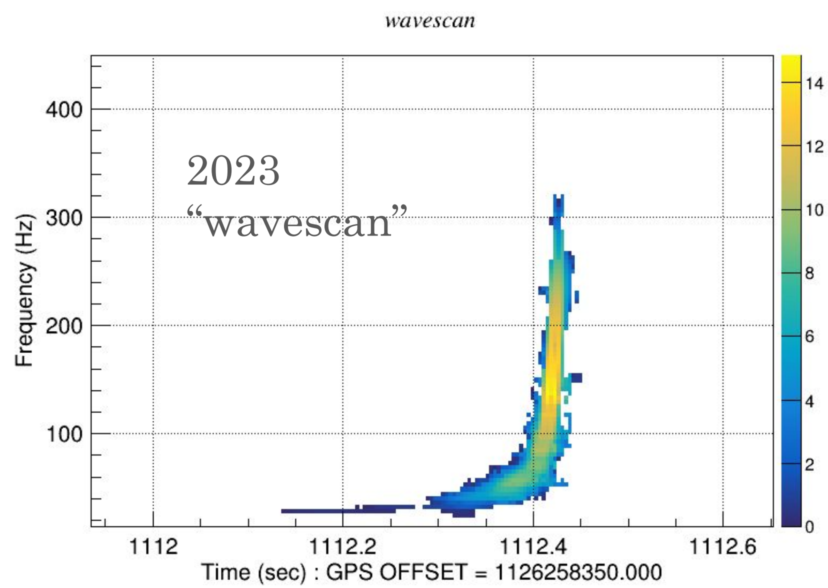
Time-frequency maps (GW150914 example)

- Challenges:
  - Temporal leakage (time domain)
  - Spectral leakage (frequency domain)
  - Combining resolutions
- Latest developments on high-resolution time-frequency transform and minimizing leakage:
  Klimenko+22 "wavescan" ([2201.01096](2201.01096))





Abbott+2016

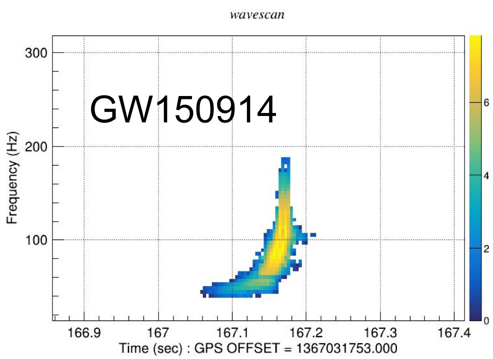


Model-independent searches classification

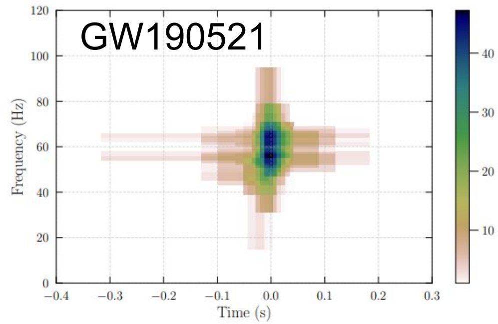
Compact binary searches (minimally modeled)

Generic searches (unmodeled)

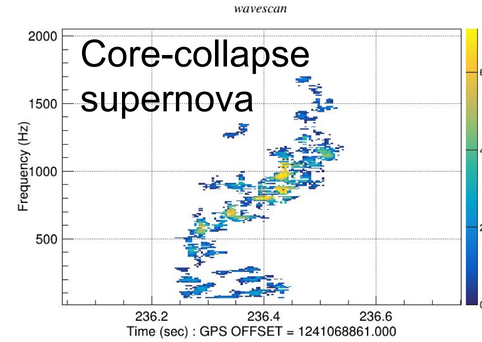
Binary black holes
Binary neutron stars
Black hole - neutron star



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



Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



Low-latency searches

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

Searches for new phenomena

Higher harmonics
GW cross-polarization
Deviations from GR

Observing Run 4

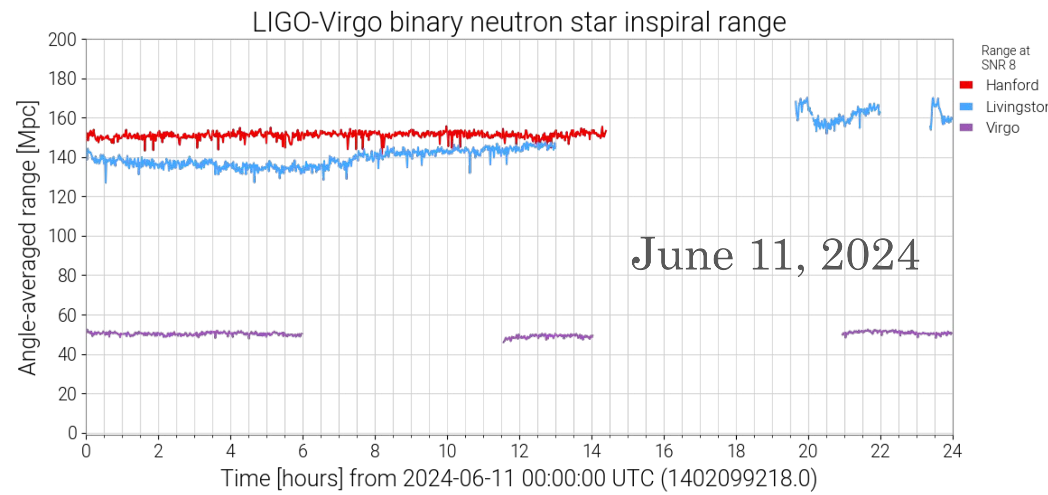
- O4: 20 months total, until Feb 2025
  - Possible extension of a few months.
- BNS ranges: 140-180 Mpc (LIGO), around 55 Mpc (Virgo)
- The duty cycle for Hanford and Livingston is around 70-80%.
- Public communication about the observing run:
  - OpenLVEM: https://wiki.gw-astronomy.org/OpenLVEM
  - Latest plans: https://observing.docs.ligo.org/plan/

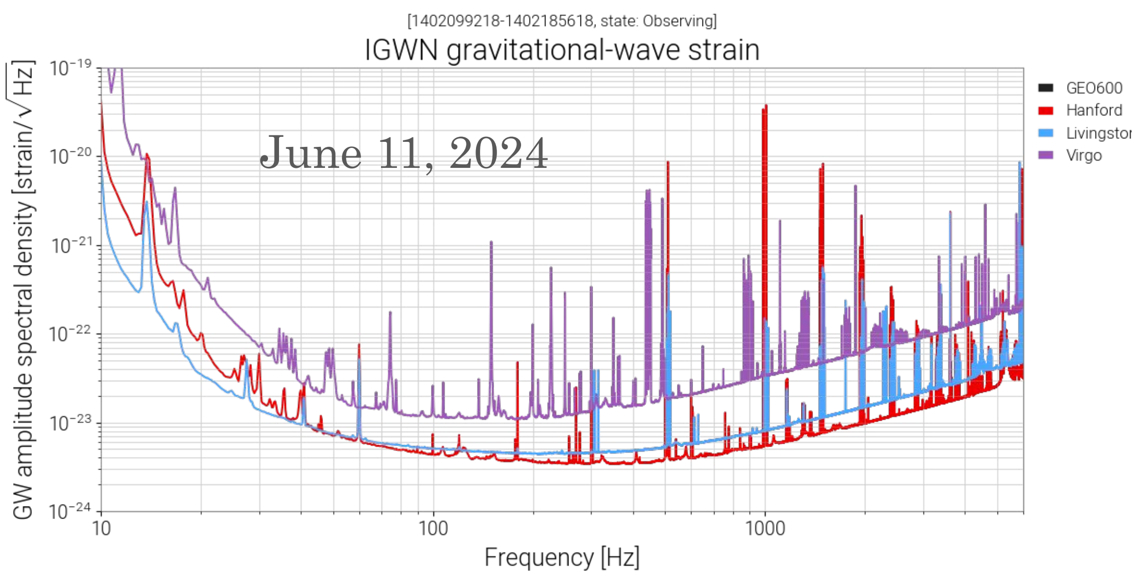
- KAGRA:
  - **Hit by 7.6 magnitude earthquake**
  - Several months delay

gw astro

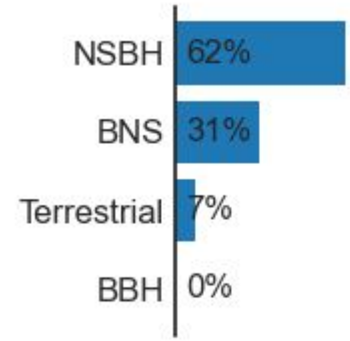
Observing Run 4

- 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](S230529ay)

- GW candidates: 81 (O4a) and 24 (O4b so far)
- Detection rate: **3 per week**
- Almost all events are BBHs
  - NSBH/BNS: 9 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: **105** (119 Total - 14 Retracted)

O4 Low Significance Detection Candidates: **1987** (Total)

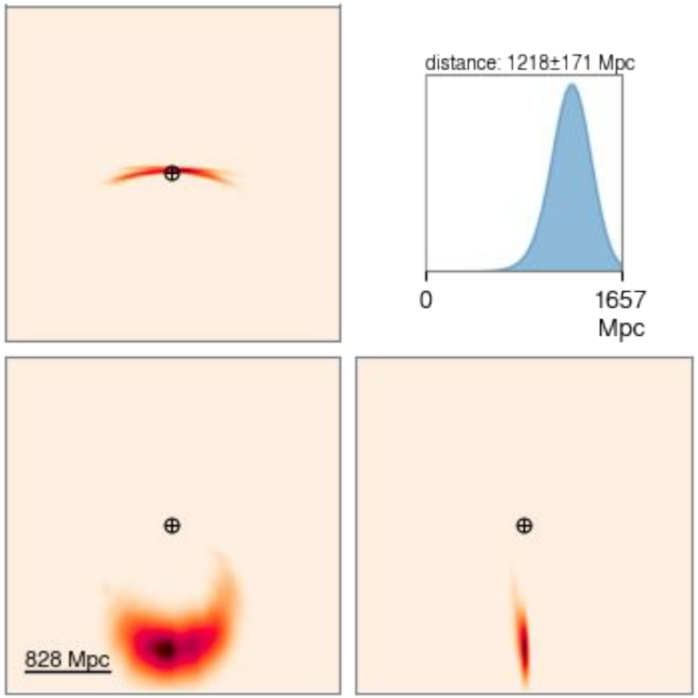
Observing Run 4
cWB-BBH search

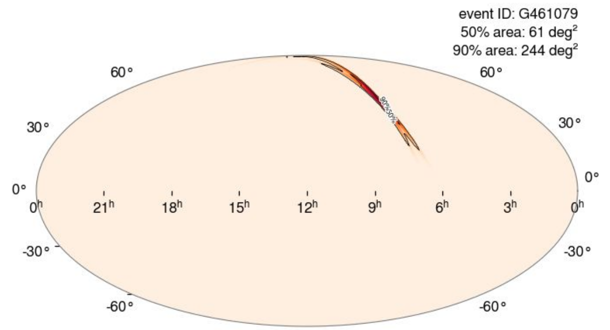
cWB-BBH search:

- 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

- General (example plots: S231226av):
  - Sky localization
  - Distance
  - Source classification
  - Detection pipeline
- Additional information for 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





Higher harmonics

- GWs are a sum of a dominant mode (2,2), and higher harmonics

$$h_+ - ih_\times = \sum_{\ell \geq 2} \sum_{-\ell \leq m \leq \ell} \frac{h_{\ell m}(t, \boldsymbol{\lambda})}{D_\mathrm{L}} {}_{-2}Y_{\ell m}(\theta, \phi)$$

- Higher harmonics carry a detailed information about the source, and they allow testing GR (e.g. no-hair theorem)!
- Their strength increases with an asymmetry of the binary system, depending primarily on:
  - Mass ratio, spins, precession, eccentricity, inclination angle
- So far, the first higher harmonic mode was detected in two events: GW190412 and GW190814
- The higher signal-to-noise ratio GWs the stronger effects we may observe

GW190412 and GW190814

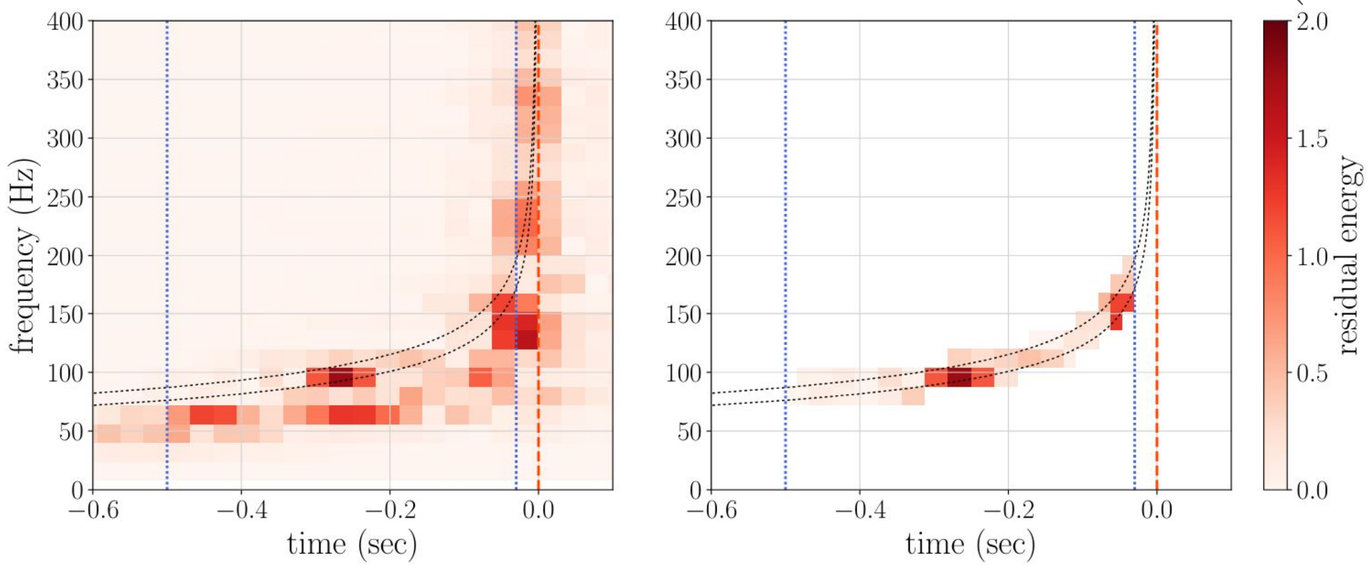
- Minimally modeled search for higher harmonics:

  Vedovato et al (MS) 2021 (arXiv: 2108.13384)
- Frequency evolution of the (3,3) mode with respect to dominant (2,2):

$$f_{\ell,m}(t) \approx \frac{m}{2} f_{22}(t)$$

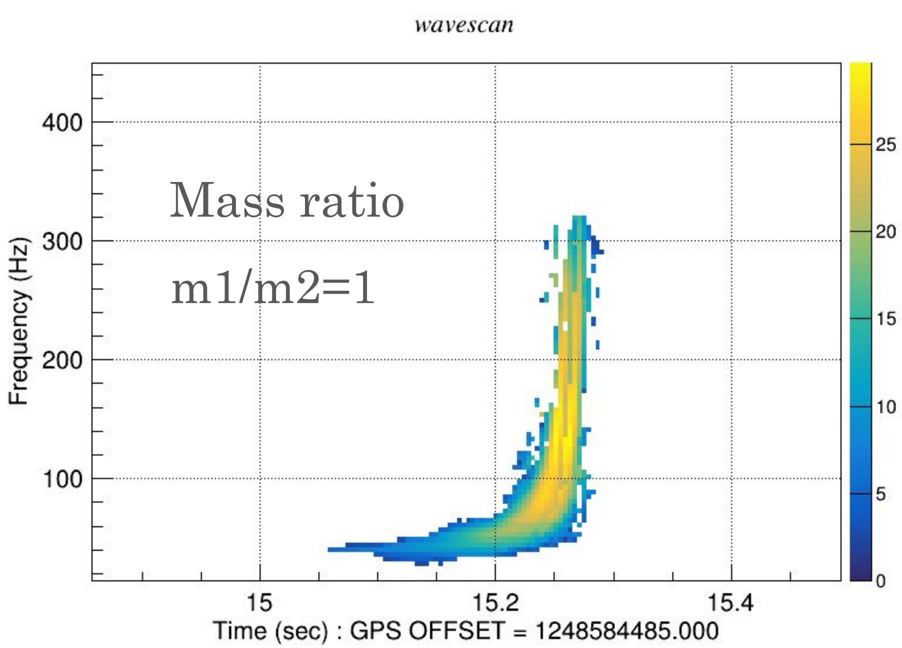
- GW190412: mass ratio ~0.28
- GW190814: mass ratio ~0.11
- Strong evidence of higher order modes

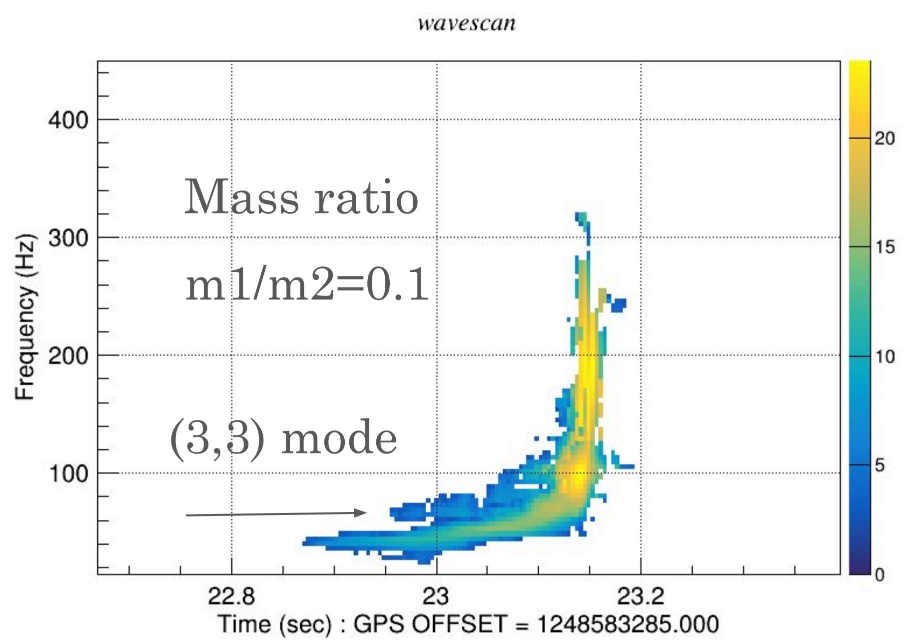
Vedovato et al (MS) 2021



Detecting higher harmonics

- Detecting higher harmonics is challenging
- The strongest emission of higher harmonics come with high mass ratio binaries
- Summer project of Chance Jackson (University of Florida) and Kya Schluterman (Embry-Riddle Aeronautical University):
    - (Rapid) identification of sources that have high mass ratio, hence higher harmonics.





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: 105 GW events so far
  - Higher harmonics: studying GW sources and testing theories