Observing gravitational waves from astrophysical sources

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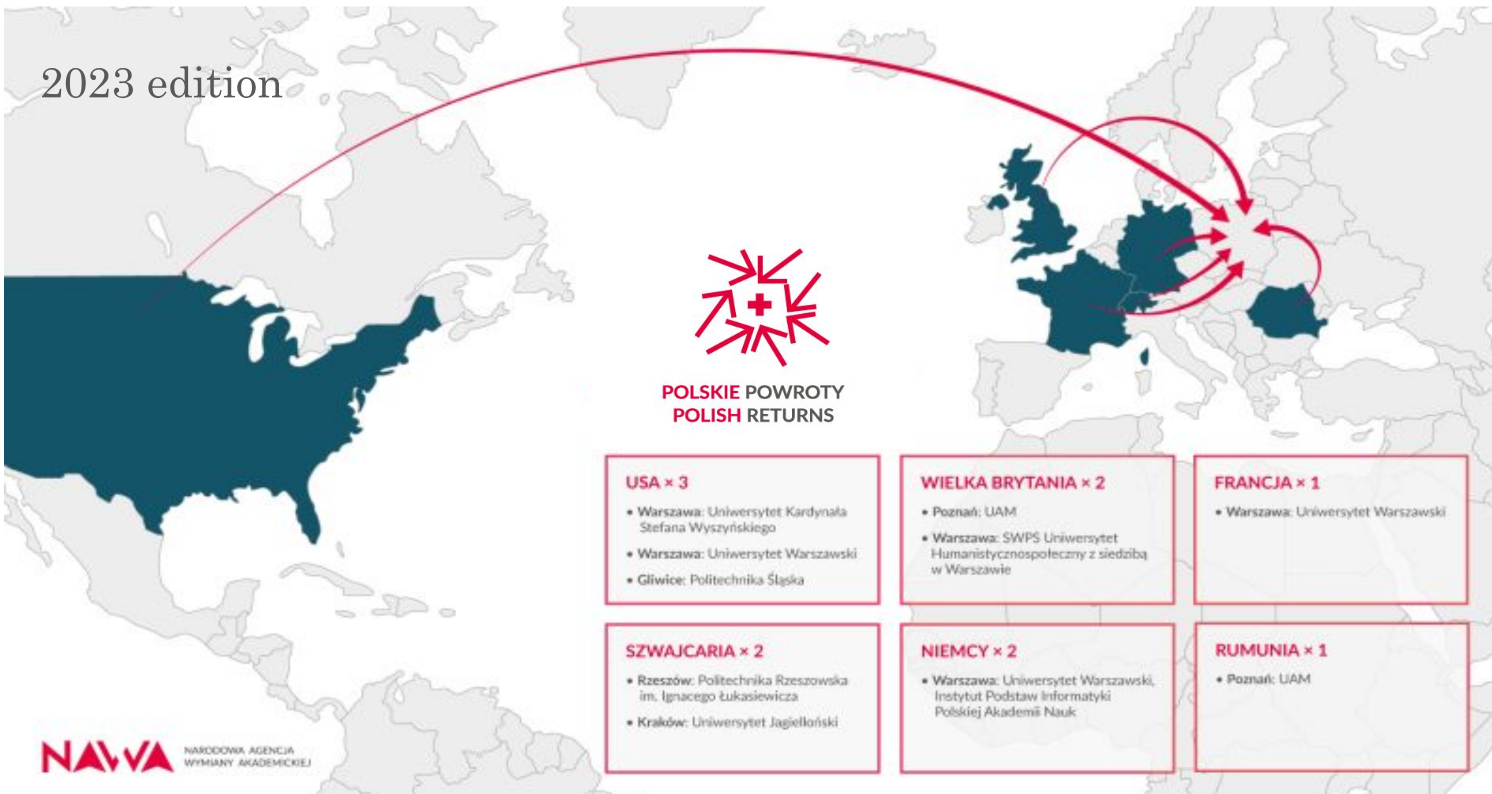
Return to Poland

- Ph.D., ~5 years: Embry-Riddle Aeronautical University (Arizona)
- Postdoc, ~5 years: University of Florida
- Assistant Professor, present (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
- Gravitational-wave searches for core-collapse supernovae
- Summary

Gravitational-Wave Astrophysics

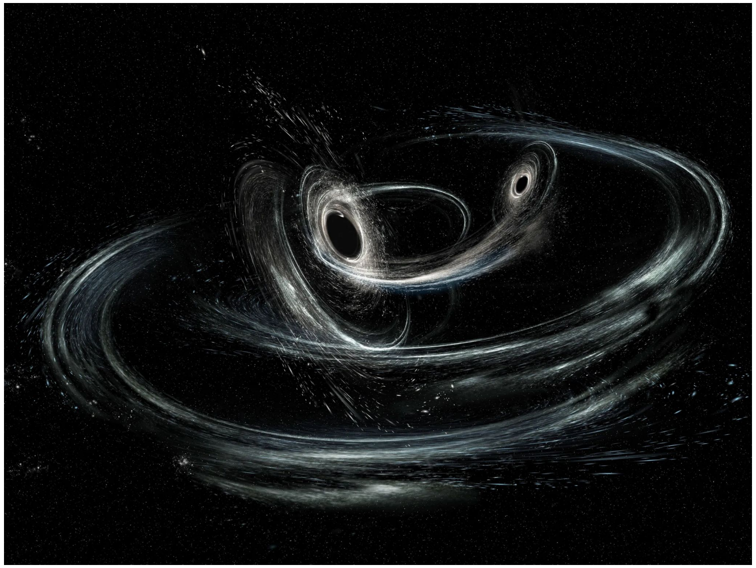
The Dynamic Universe

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



AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

GW sources:

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

Exceptional GW sources

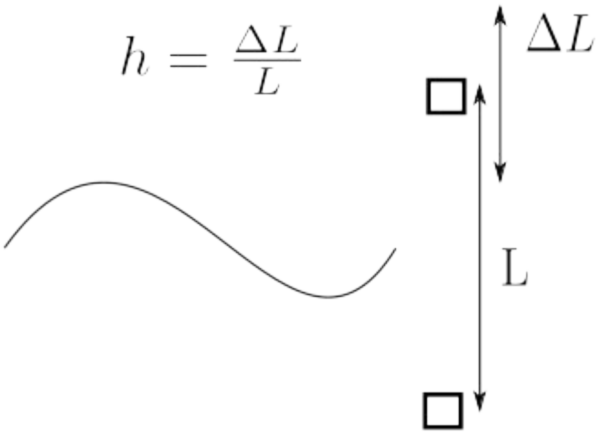
Exceptional astrophysical sources might play the key role in our endeavor of exploring the Universe.

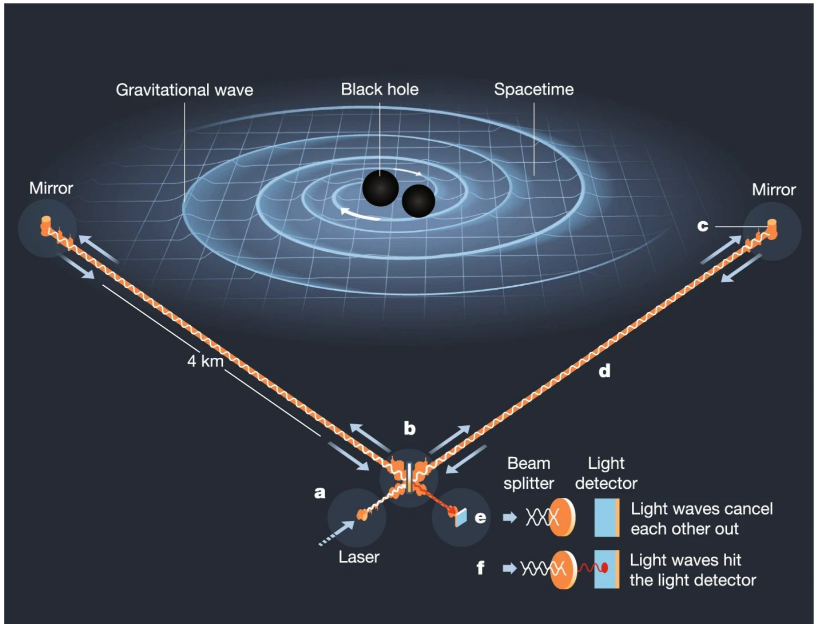
- **New GW source populations**:
  - Compact binaries: binaries with eccentric orbits, hyperbolic encounters, head-on collisions, sub-solar mass binaries, extreme mass ratio
  - GW bursts: core-collapse supernovae, neutron star or pulsar glitches, cosmic strings
- **Multi-messenger GW sources (electromagnetic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

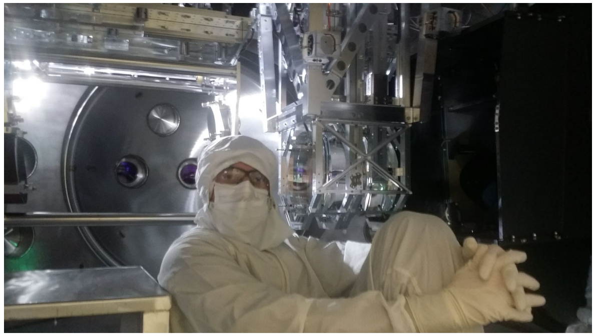
$$h = \frac{\Delta L}{L}$$



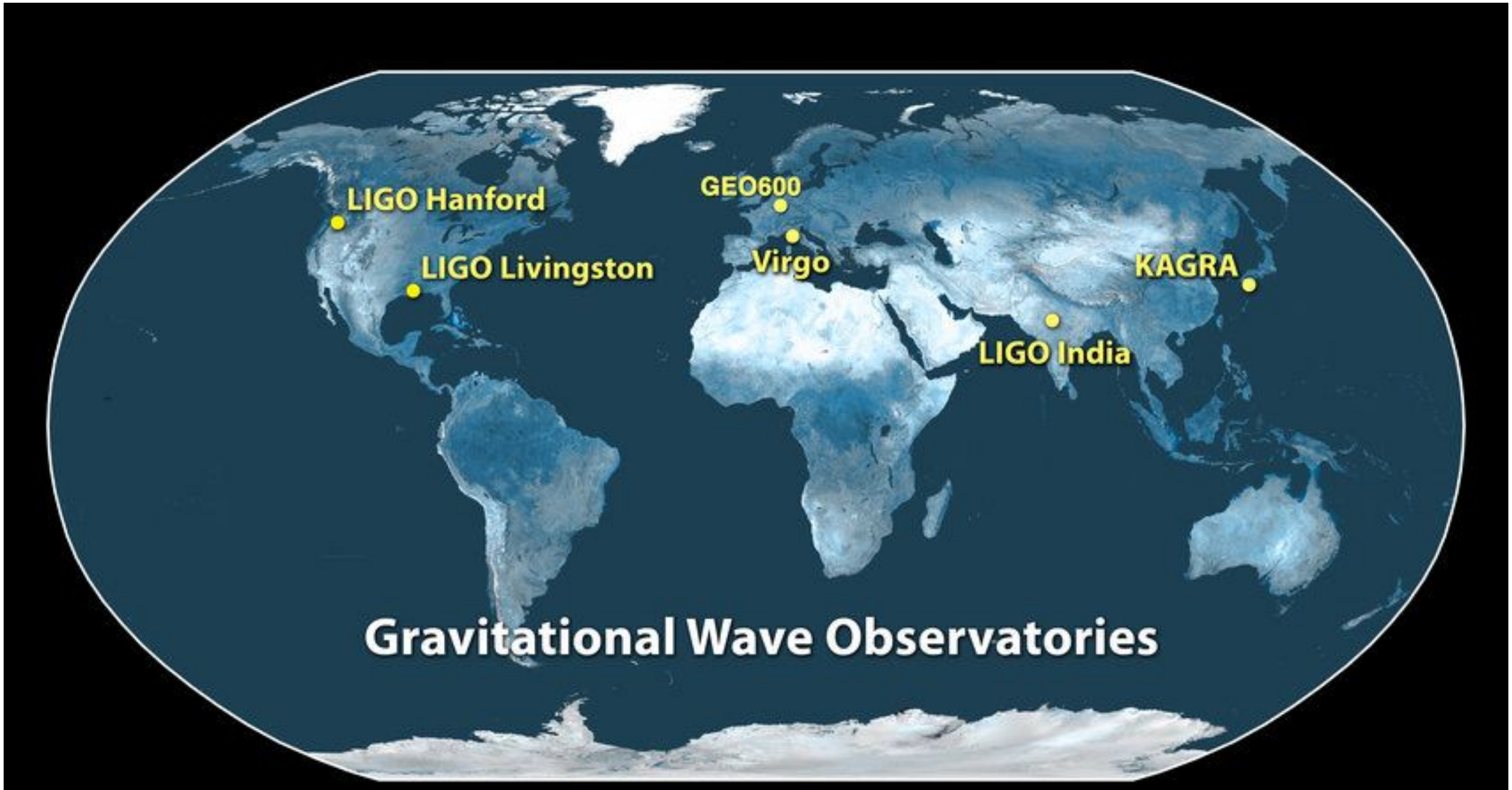


Nature 568, 469–476 (2019)


LIGO Hanford



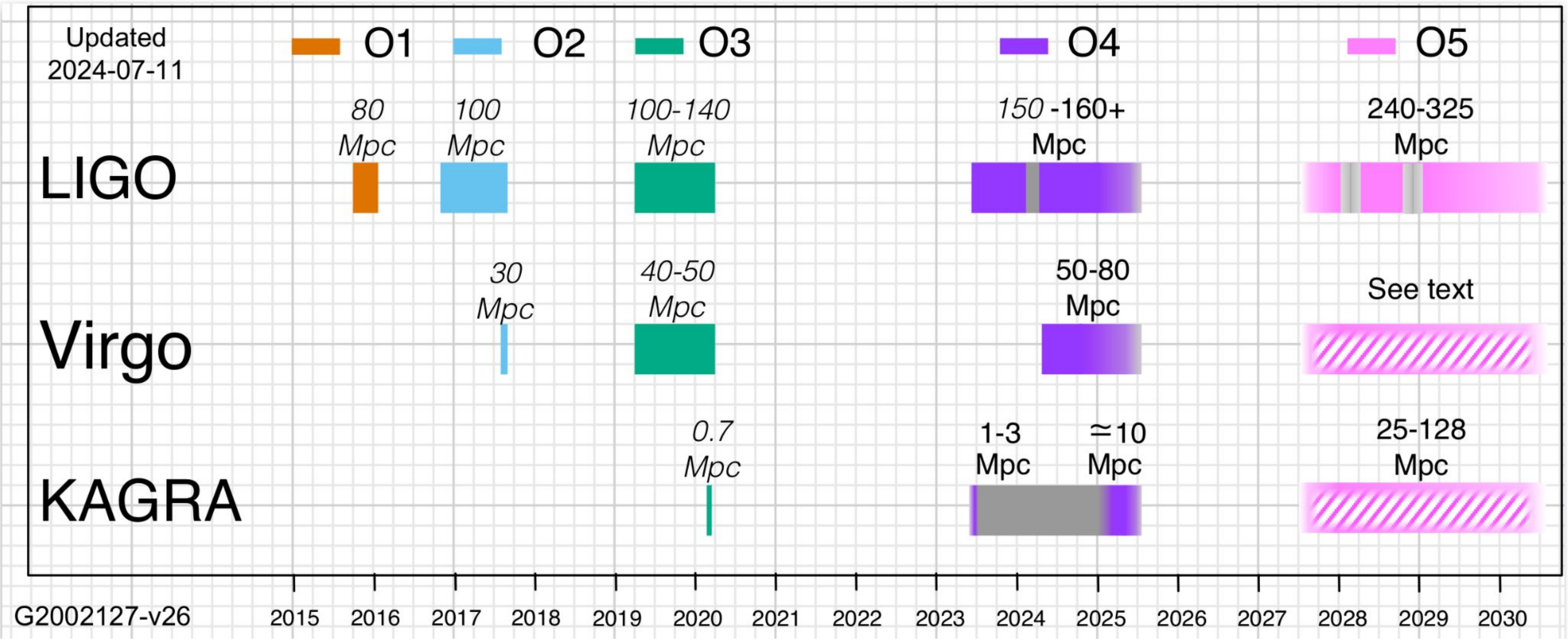
Detectors network



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.

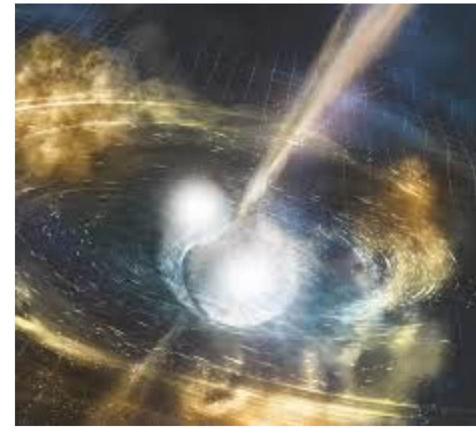
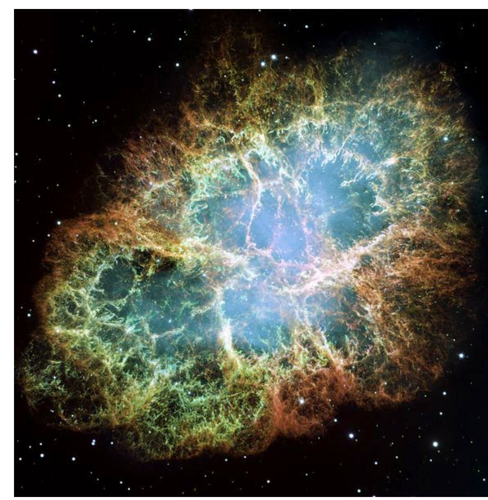


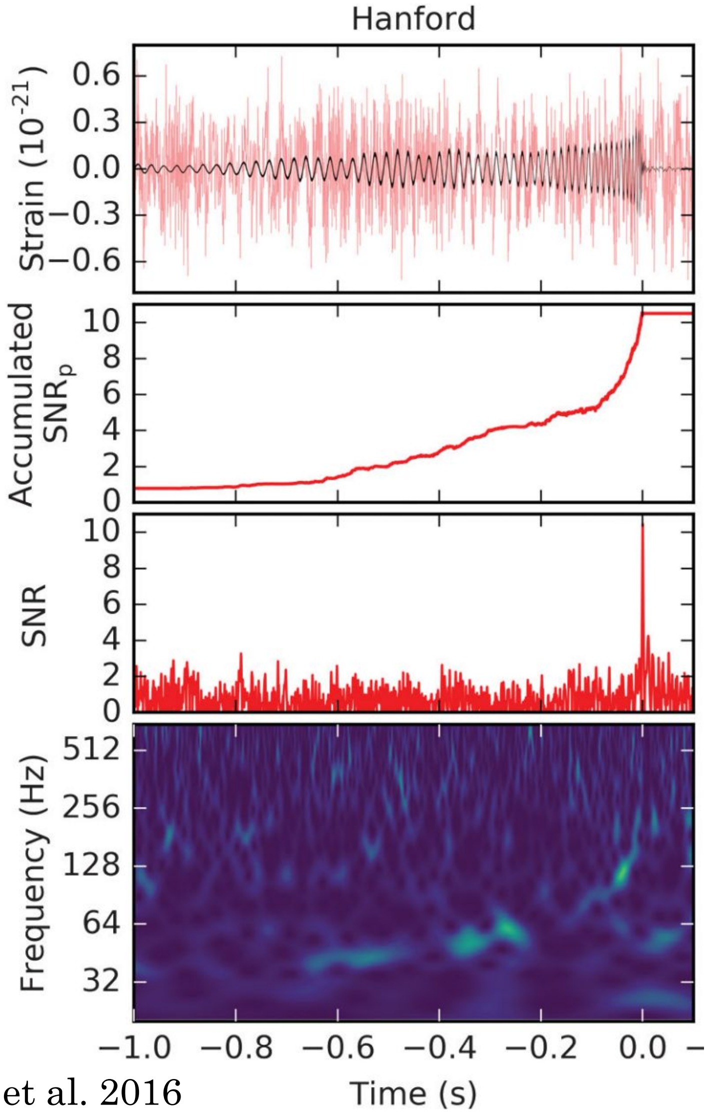
Image: NSF/LIGO/Sonoma/A. Simonnet



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

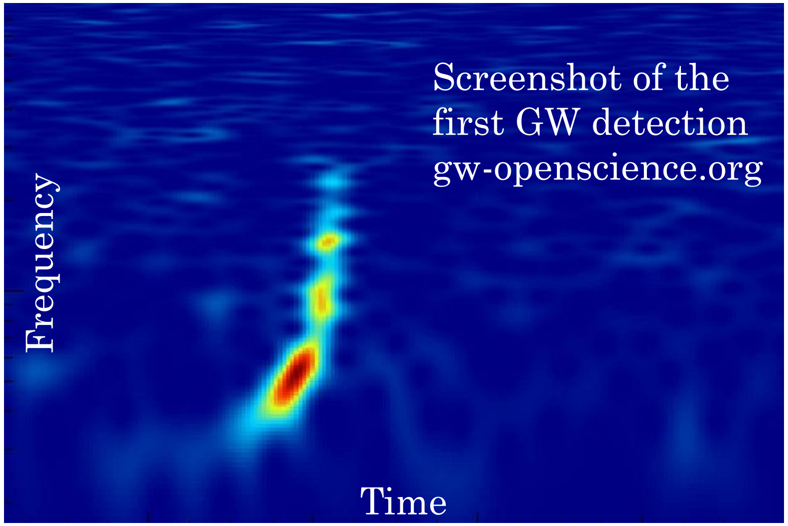


Abbott et al. 2016

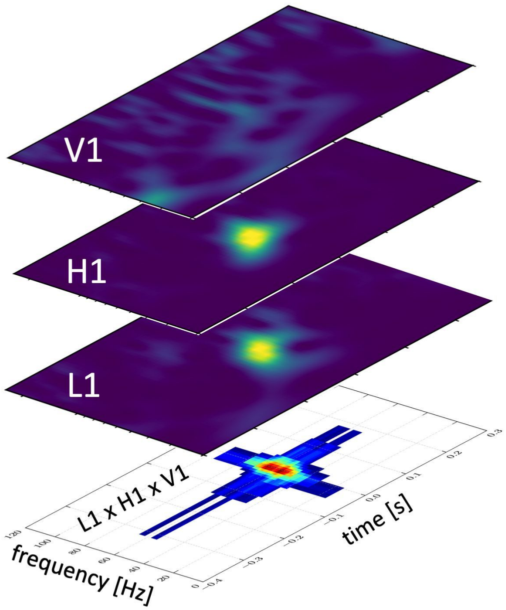
Model-independent searches
coherent WaveBurst

- **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**

WB coherent WaveBurst
an open source software for gravitational-wave data analysis
https://gwburst.gitlab.io/



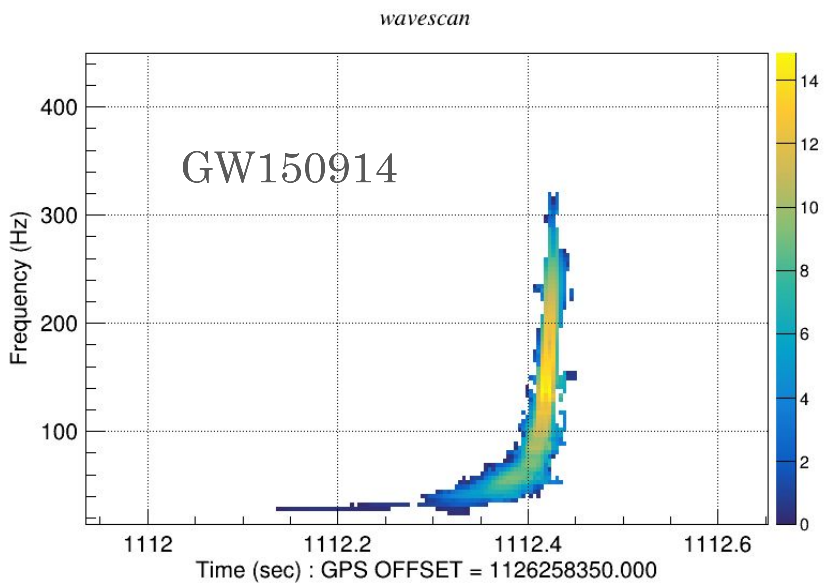
coherent WaveBurst (cWB)



x(t) $\xrightarrow{\text{Wavelet Transform}}$

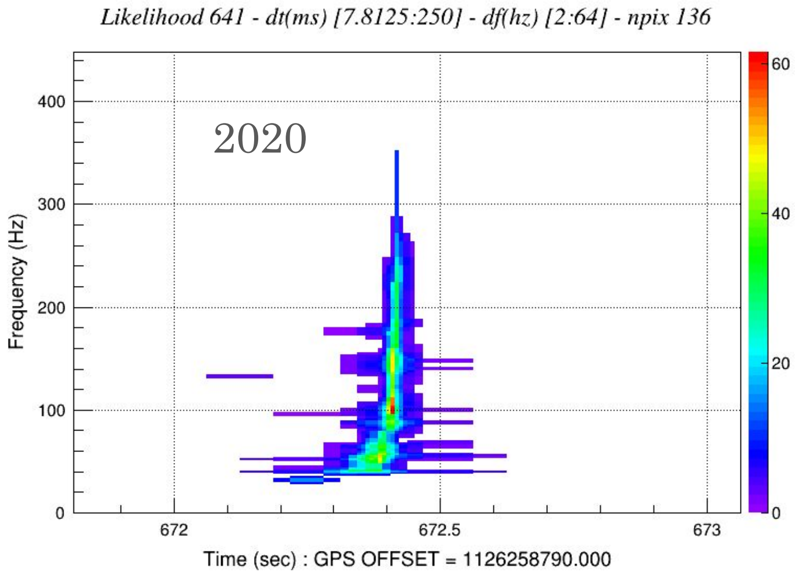
- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

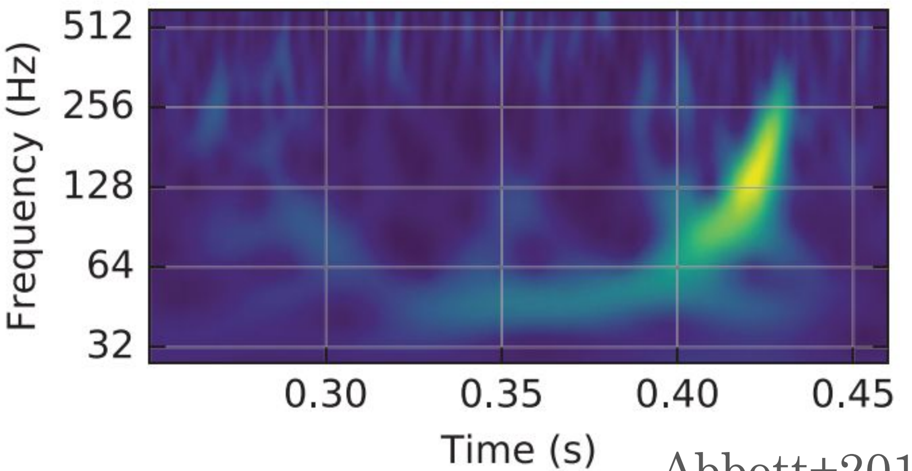
$\xrightarrow{\text{Inverse Wavelet Transform}}$ h(t)



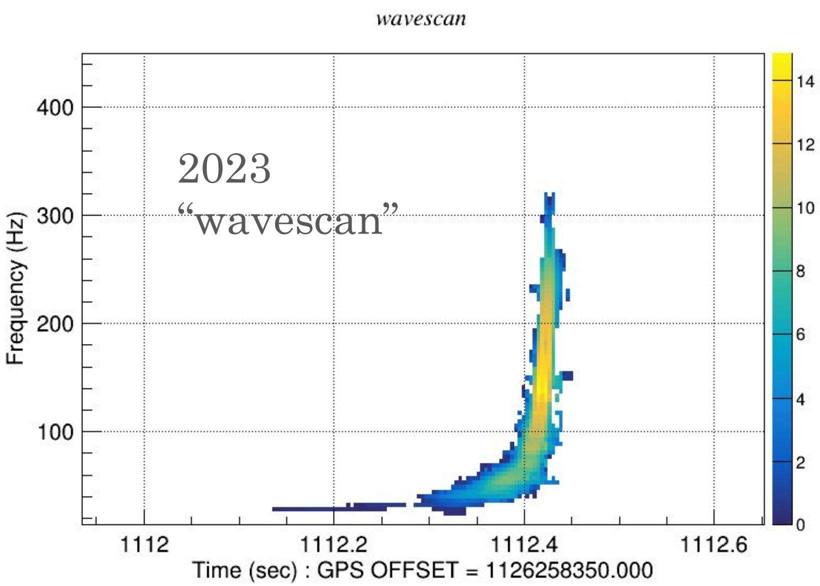
Time-frequency maps (GW150914 example)

- 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))





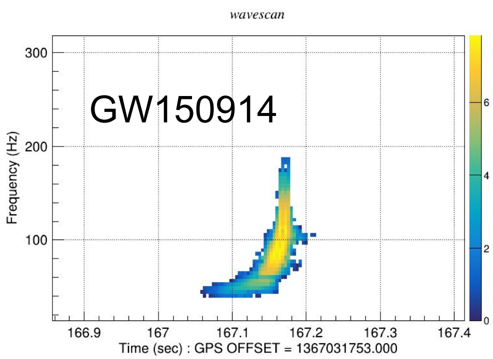
Abbott+2016



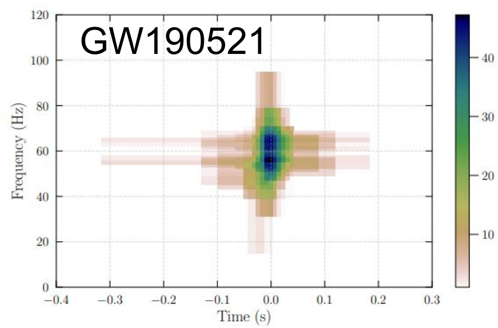
Model-independent searches classification

Compact binary searches (minimally modeled)

Binary black holes
Binary neutron stars
Black hole - neutron star

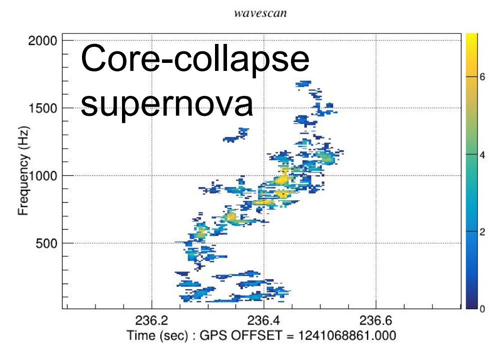


Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



Generic searches (unmodeled)

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

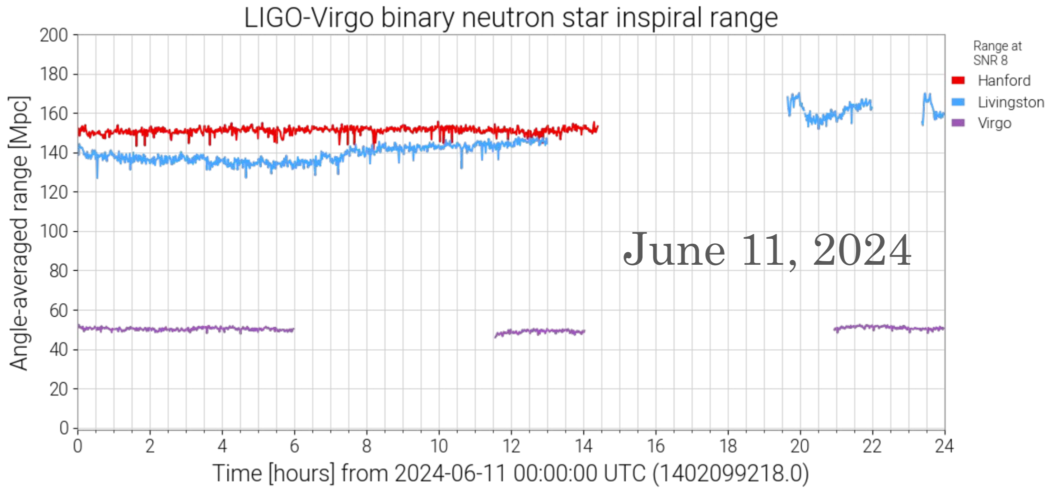
- O4: 24 months total, until Jun 2025
- BNS ranges: 140-180 Mpc (LIGO), around 55 Mpc (Virgo)
- The duty cycle for Hanford and Livingston is around 70-80%.
- Public communication about the observing run:
  - OpenLVEM: https://wiki.gw-astronomy.org/OpenLVEM
  - Latest plans: https://observing.docs.ligo.org/plan/

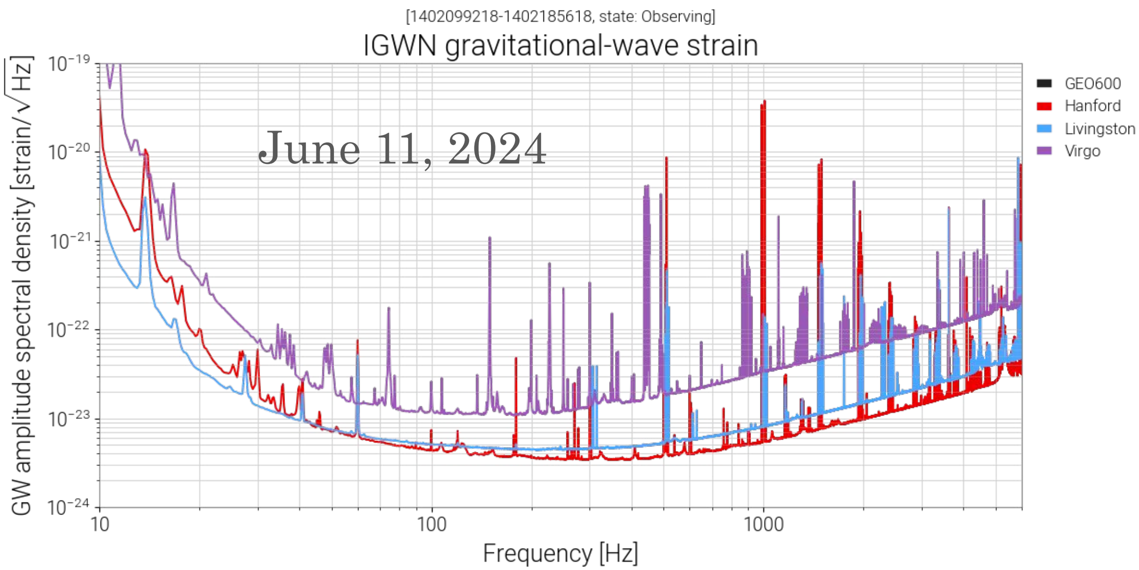
- KAGRA:
  - **Hit by 7.6 magnitude earthquake**
  - Several months delay

gw
astro

Observing Run 4

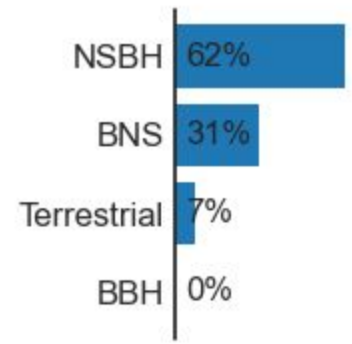
- Live detector status: https://online.igwn.org/
- Daily detector status: https://gwosc.org/detector_status/
- Public data release is 18 months after data collection





Observing Run 4

- 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



S230529ay

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)

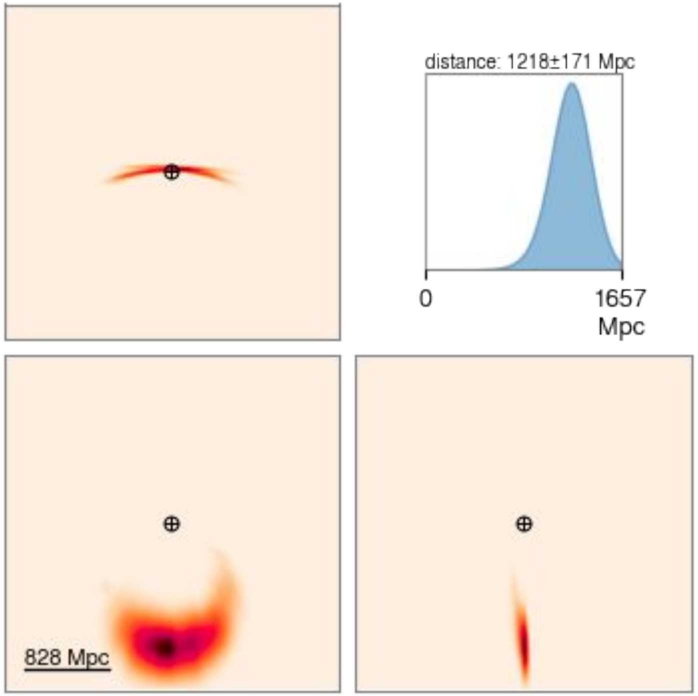
Observing Run 4
cWB-BBH search

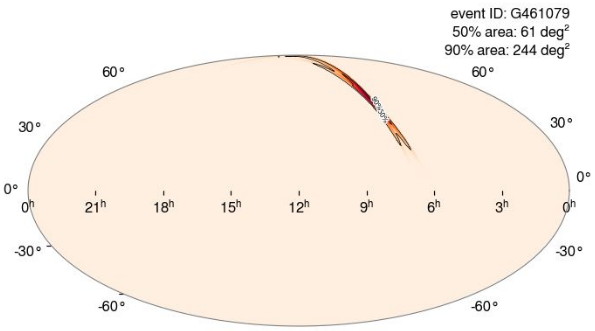
cWB-BBH search:

- 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





Searches for Core-Collapse Supernovae

Optically Targeted searches

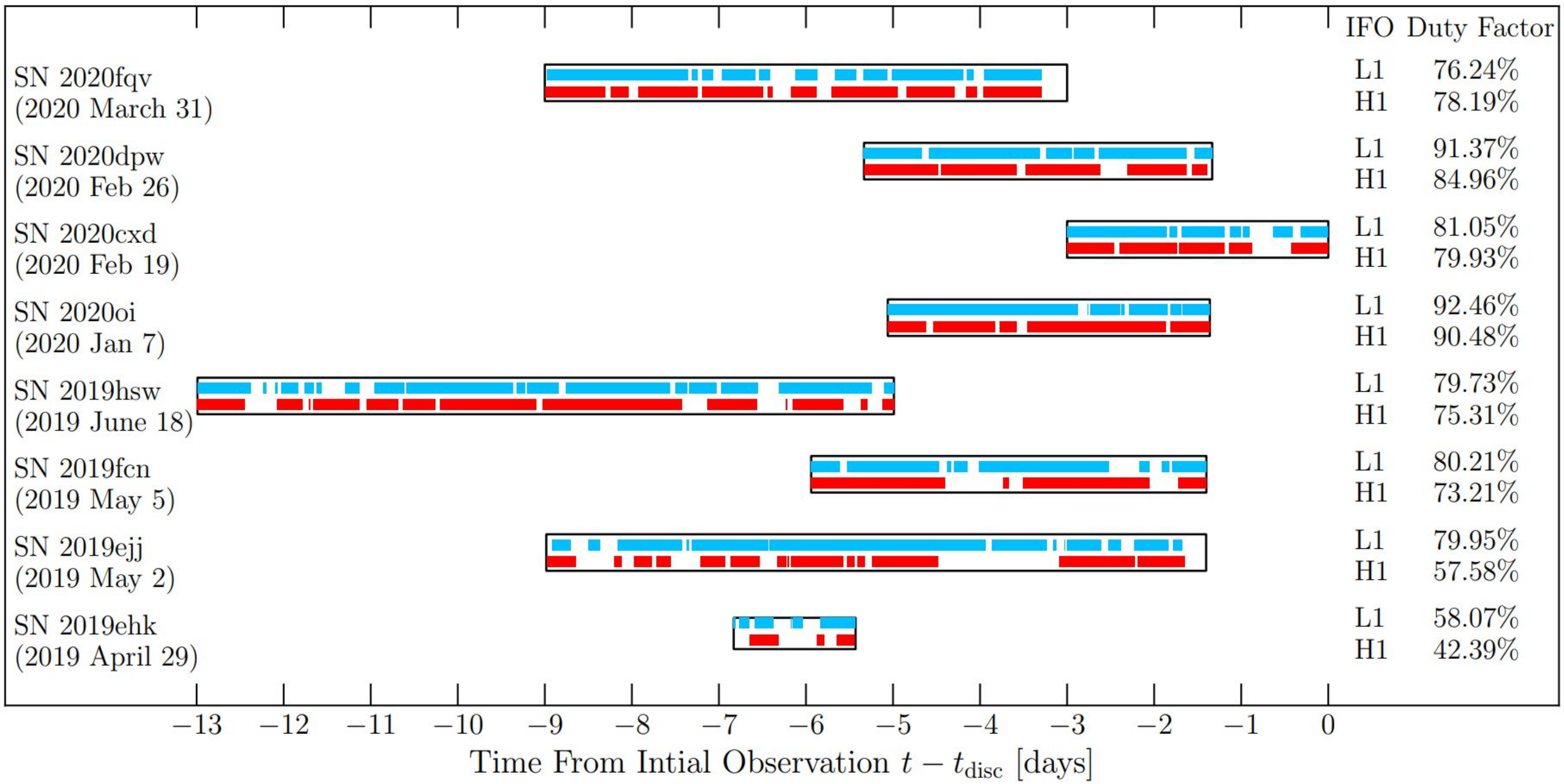
While waiting for the Galactic event, we search for GWs from extra-Galactic CCSNe (targets).

O1-O2 data (5 CCSN up to 20 Mpc, 1908.03584):

- First constraints of CCSN engine

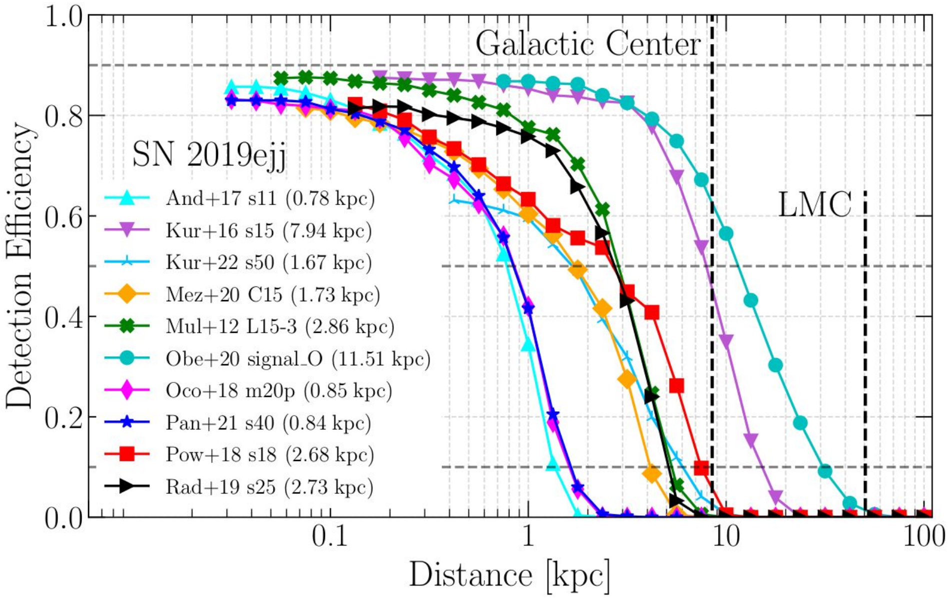
O3 data (9 CCSN up to 30 Mpc, 2305.16146):

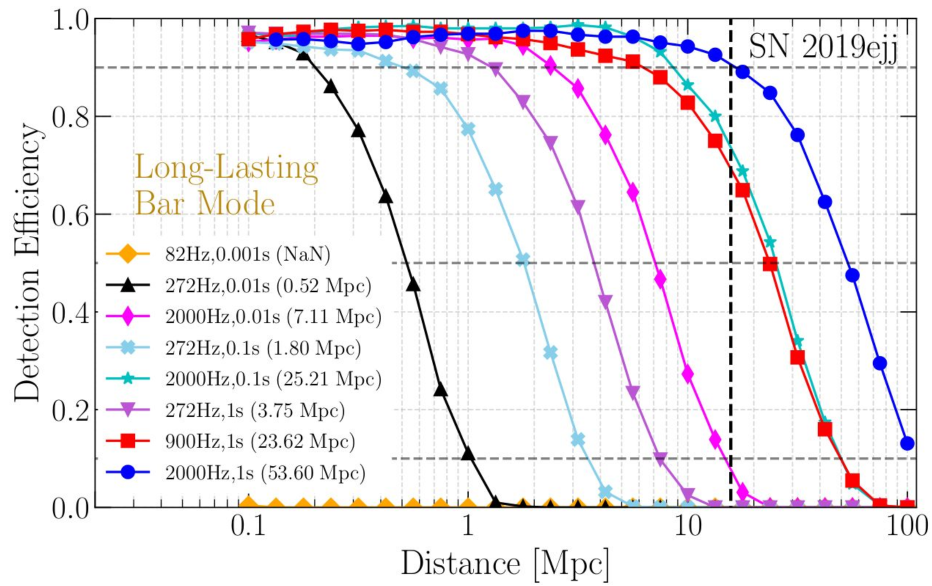
- First upper limits on GW power and ellipticity
- Continuation of constraining extreme emission models



O3 Optically Targeted search
(Szczepanczyk et al. 2023)

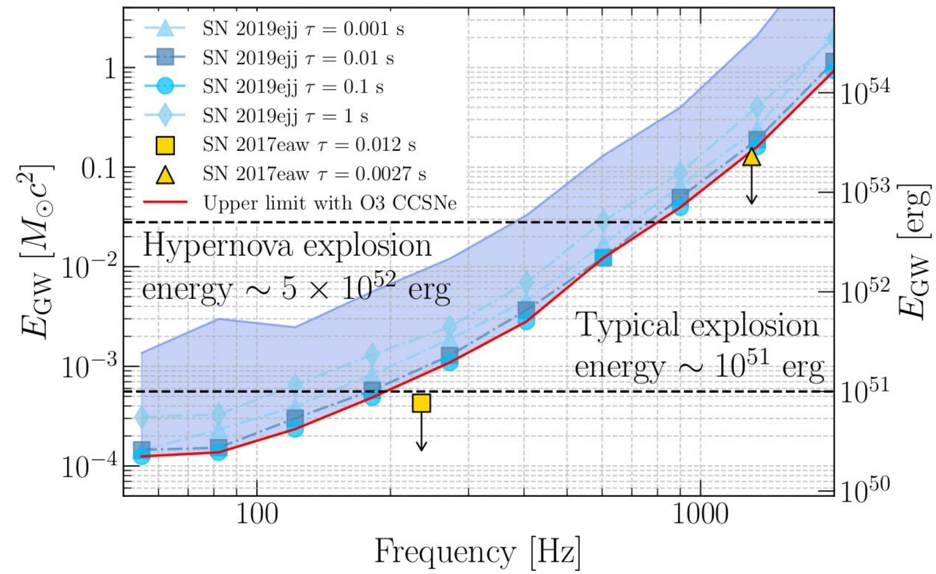
- No GW detection so far
- Most significant event for SN 2020fqv: 2.8 sigma significance
- Detection range: distance at 50% detection efficiency
  - Neutrino-driven explosions: up to 13.7 kpc
  - Magnetorotationally-driven explosions: up to 15.9 kpc
  - QCD phase transition: up to 2.1 kpc
  - Black hole formation: up to 0.8 kpc
  - Extreme emission models: several Mpc

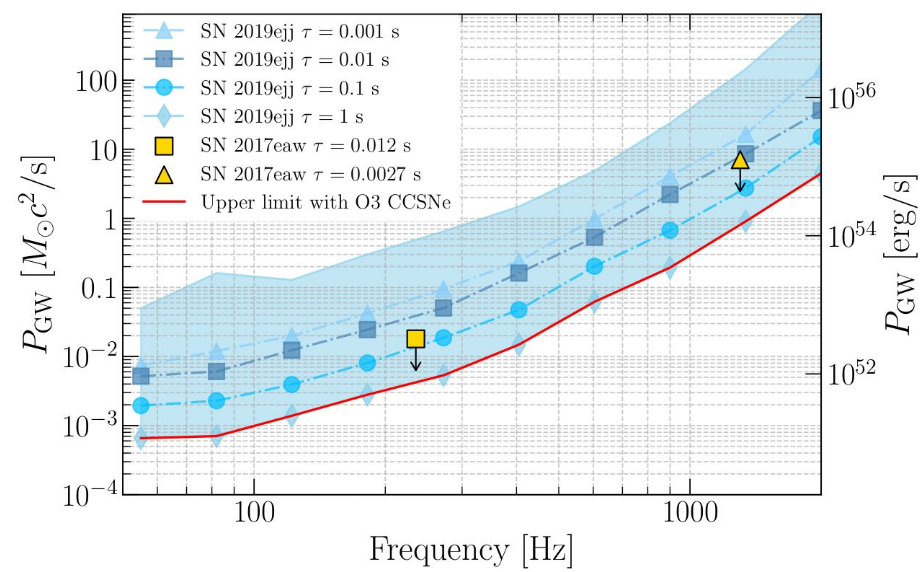




O3 Optically Targeted search
(Szczepanczyk et al. 2023)

- Extensive constraints of the CCSN engine.
  - Assuming monochromatic (narrowband) emission
- GW energy constraints
  - Isotropic emission
  - Stringest: **1x10^{-4} M$_{\odot}$c^{2}**
- GW power (luminosity) constraints
  - First observational constraints
  - Stringest: **5x10^{-4} M$_{\odot}$c^{2}/s**

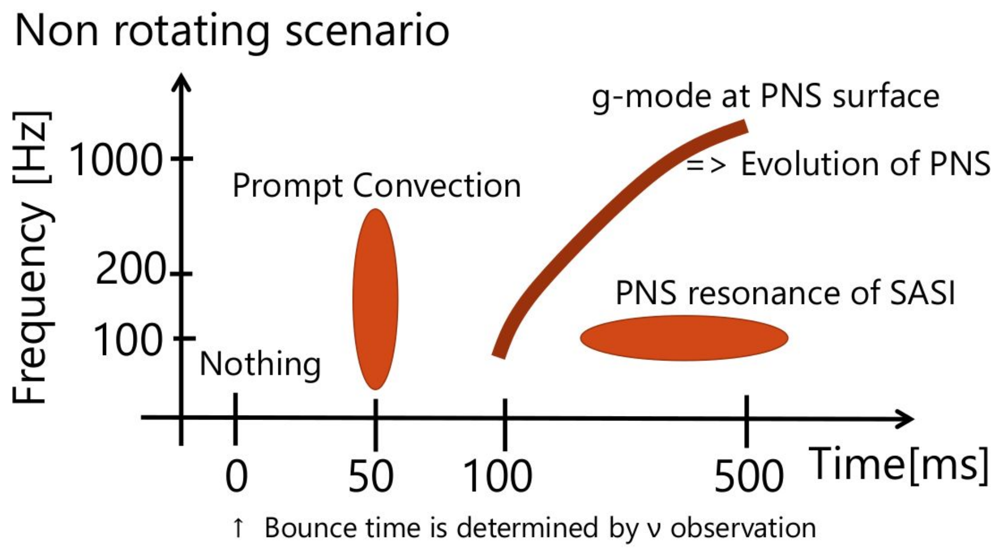




Parameter Estimation

Recently a lot of efforts to extract physical parameters from CCSN. See review in Mezzacappa&Zanolin+24 (2401.11635), examples:

- Proto-neutron star (PNS) evolution: Casallas-Lagos+23 (2304.11498), Bizouard+21 (2012.00846),
- Equation of State: Edwards+21 (2009.07367),
- SN kicks (GW memory): Richardson+21 (2109.01582)
- Standing Accretion Shock Instability: Takeda+21 (2107.05213)
- PNS rotation: Chan+21 (ADS), Hayama+18 (1802.03842)
- Rotation properties: Pastor-Marcos+23 (2308.03456), Villegas+23 (2304.01267)



Credit: Takiwaki

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 GW events so far
- Core-collapse supernovae are rare but golden events.