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

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Birthday Edition

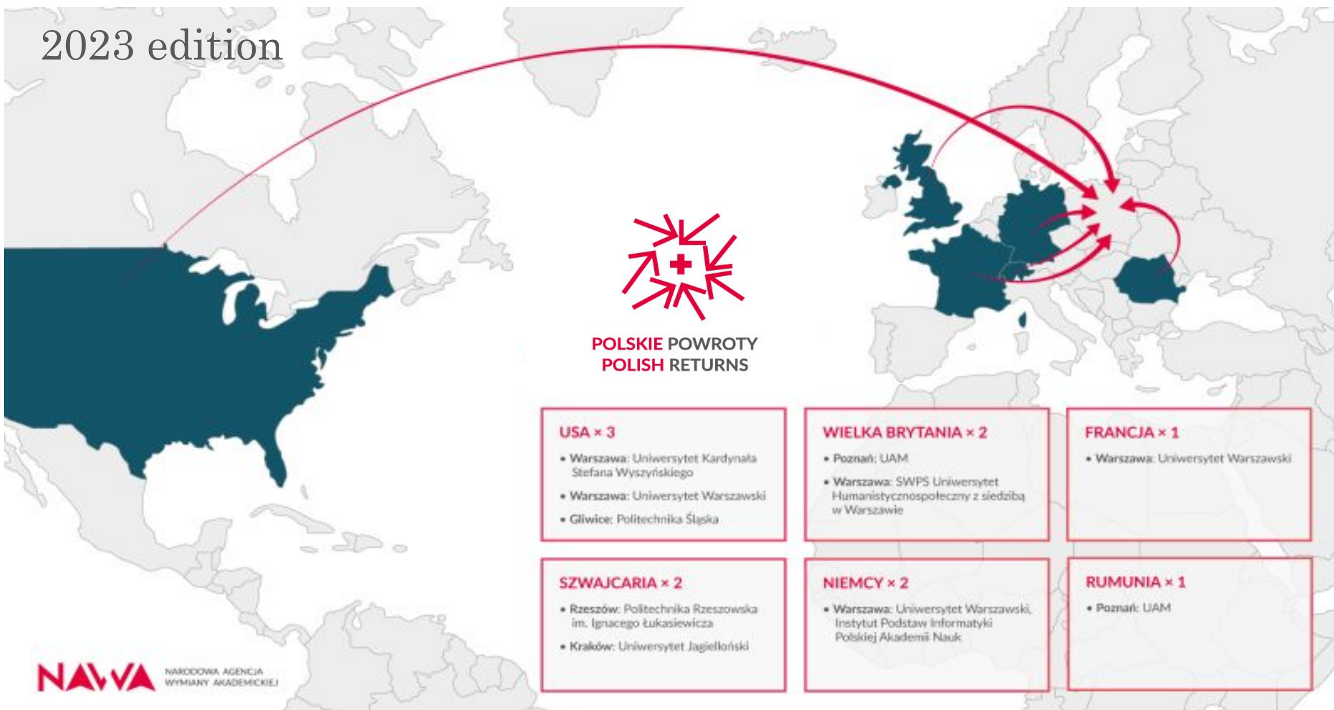
Astronomical Observatory
University of Warsaw, 14.01.2025

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)

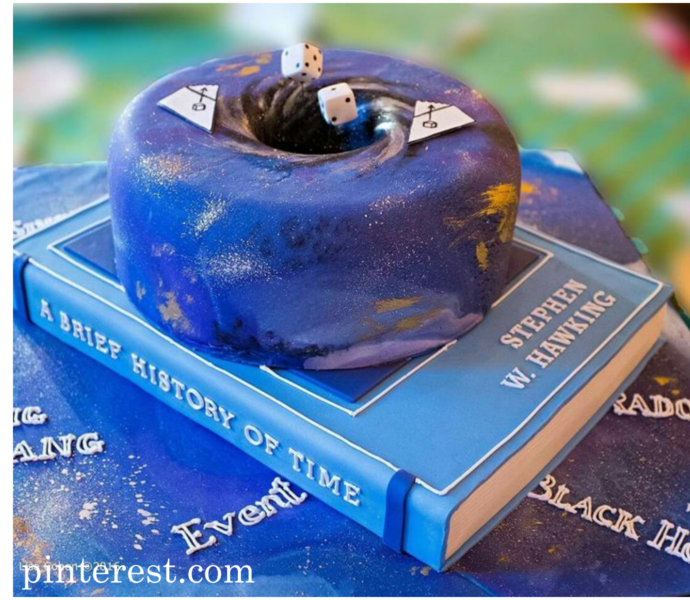
Prof. Jerzy Lewandowski was my Inviting Scientist for Polish Returns grant

Homepage: https://www.fuw.edu.pl/~mszczepanczyk/



Outline

- Gravitational-Wave Astrophysics
  - Introduction
  - Observing Run 4
- Searching for exceptional GW sources
  - Model-independent searches
- Core-Collapse Supernova
  - Properties, results
  - Announcement: LVK workshop on CCSNe, summer 2025



Gravitational-Wave Astrophysics

The Dynamic Universe

Quadrupole formula for GW production:

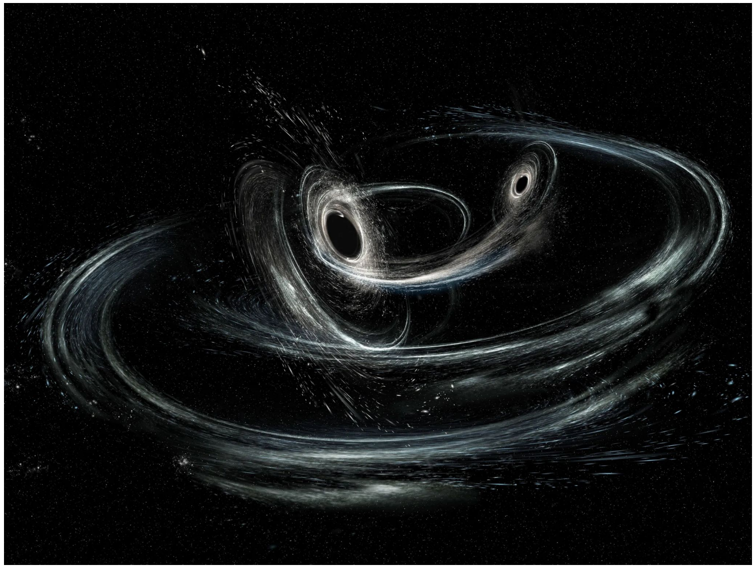
$$\mathbf{h}_{ij}^{TT}(t,\mathbf{x}) = \frac{1}{D}\ddot{Q}_{ij}(t - D/c, \mathbf{x})$$

We need aspherical mass-energy movement.

Image: NSF/LIGO/Sonoma/A. Simonnet

GW sources:

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

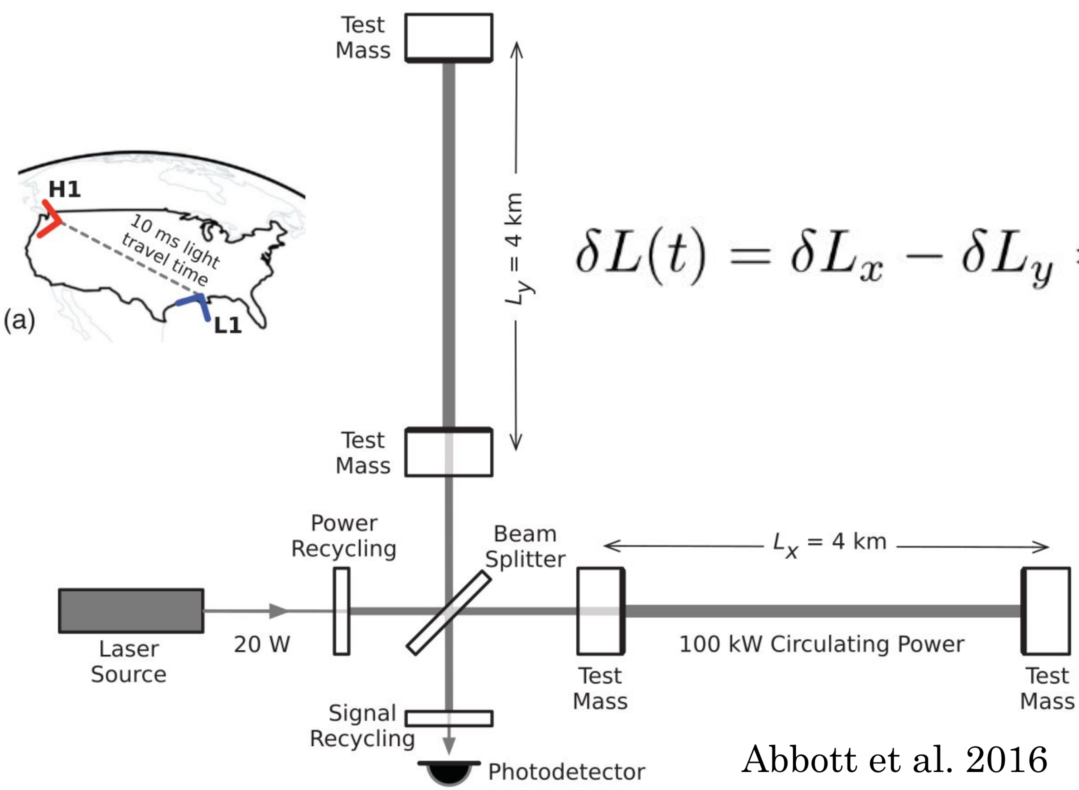


AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

Gravitational-Wave detectors

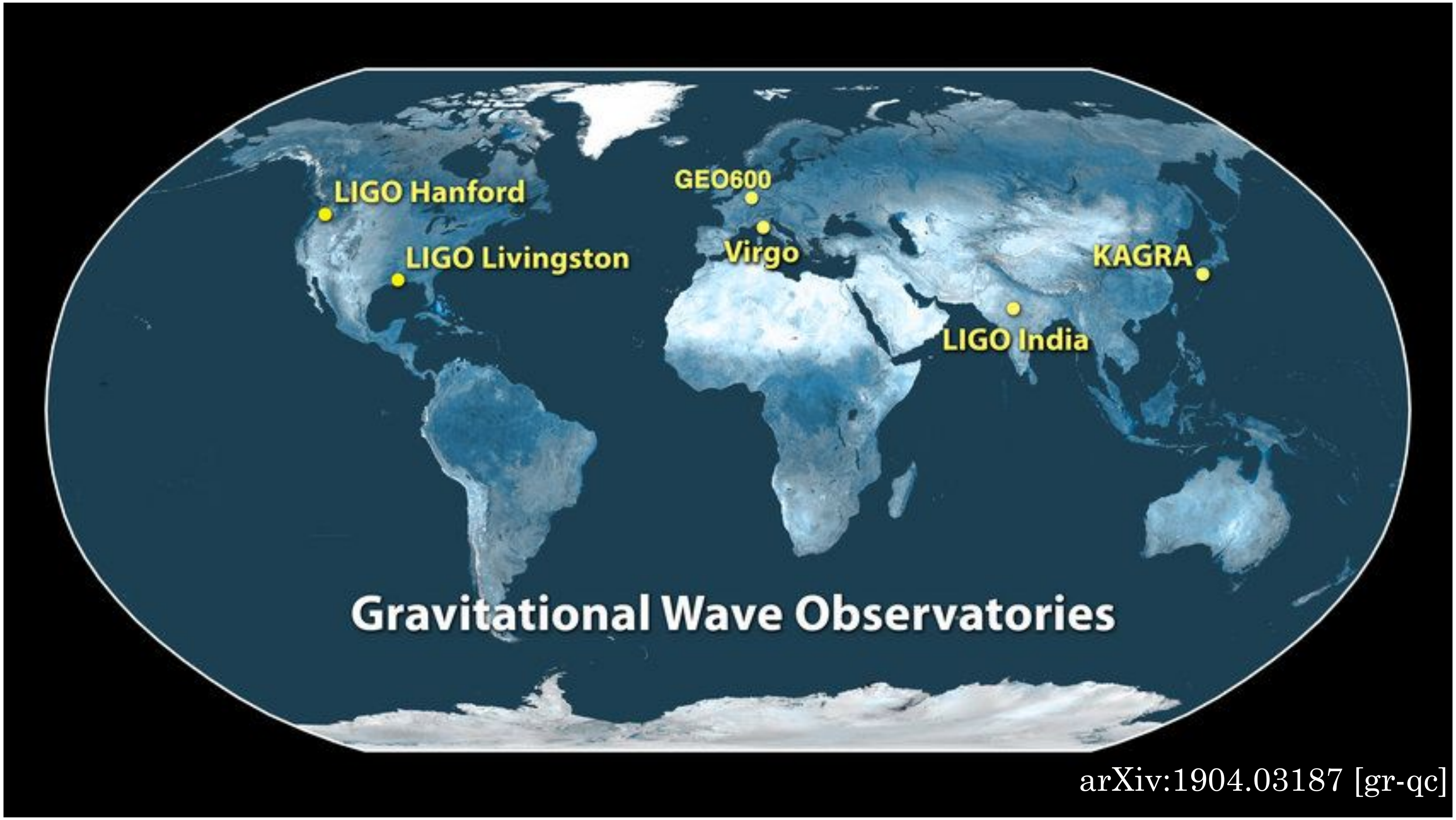
- GW detectors: interferometers
  (the longer the more sensitive)
- Preferably far away from human activities.
  But noise is inevitable…

$$\delta L(t) = \delta L_x - \delta L_y = h(t) L$$



Abbott et al. 2016

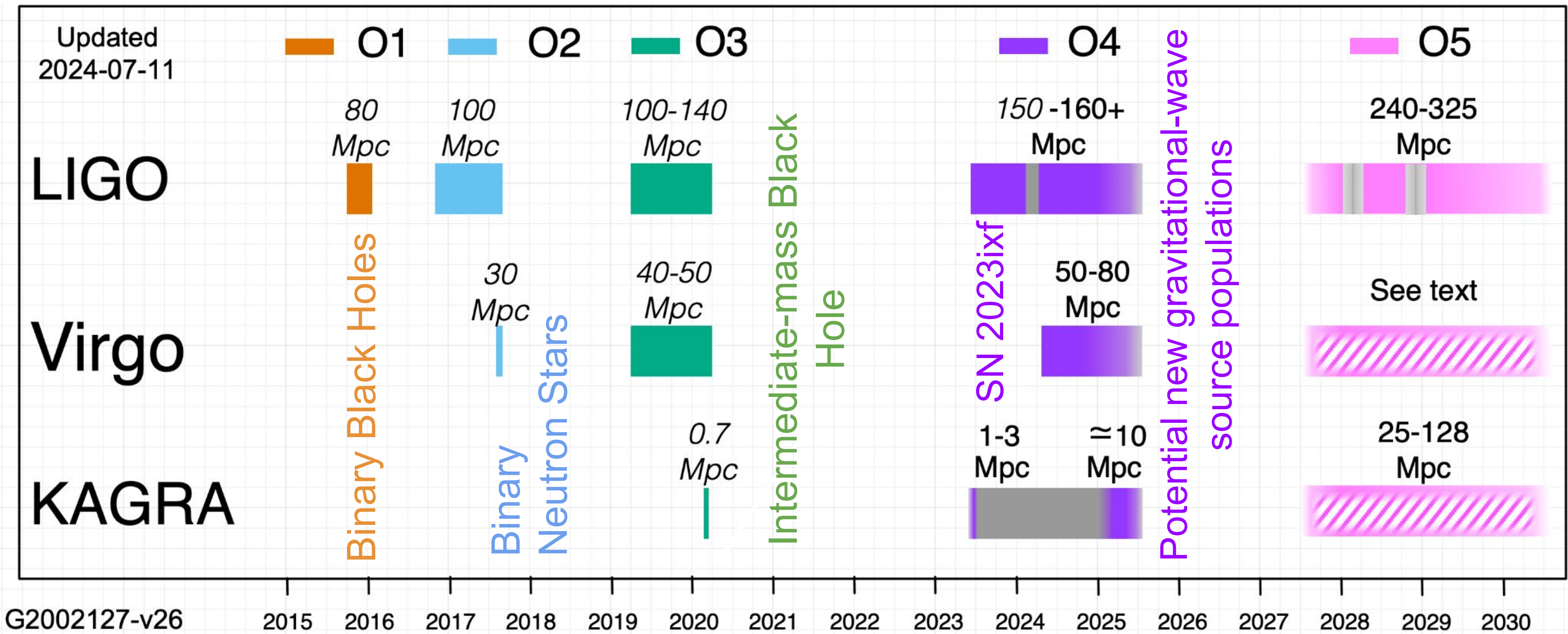
Detectors network



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

Later: status of detectors observing in O4

Observing Timeline



Prof. Szczepańczyk

Ph.D. expertise: Core-collapse supernova (CCSN)

University of Florida. expertise: compact binaries, low-latency

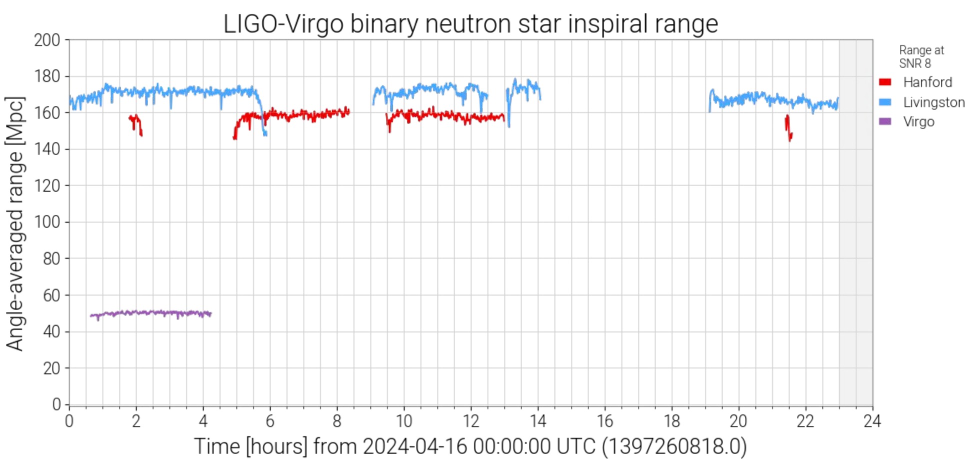
University of Warsaw

O4 and low-latency searches

- 24 months total, until June 2025
- GW candidates: 180 so far **(3 per week)**
- Searches:
  - Model-dependent
  - **Model-independent**
- Public alert for GW bursts:
  - False Alarm Rate, sky localization
  - “Fluence” (~luminosity), peak frequency, duration
- S200114f - a burst public alert in O3, later classified as noise
- No burst public alerts so far in O4

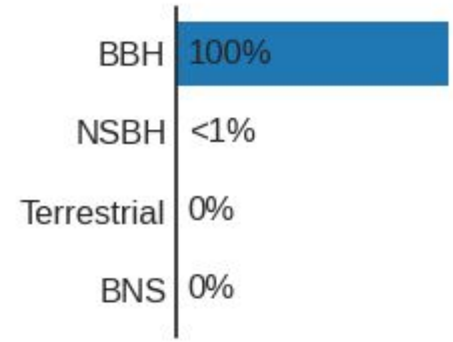
Useful resources:

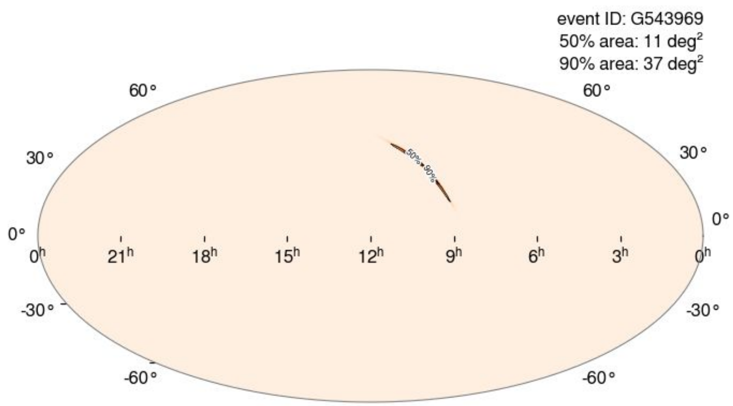
- https://gracedb.ligo.org/superevents/public/O4/
- https://emfollow.docs.ligo.org/userguide/
- https://wiki.gw-astronomy.org/OpenLVEM
- https://gwosc.org/detector_status/
- https://observing.docs.ligo.org/plan/
- https://online.igwn.org/

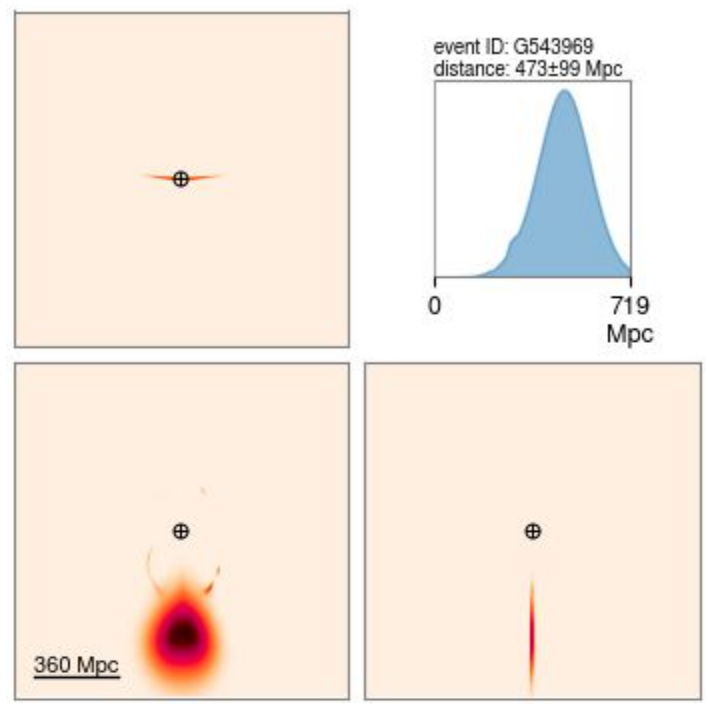


O4 and low-latency searches

- Today's event [S250114ax]
- Very well localized and significant event False Alarm Rate is 1 per 7e+18 years

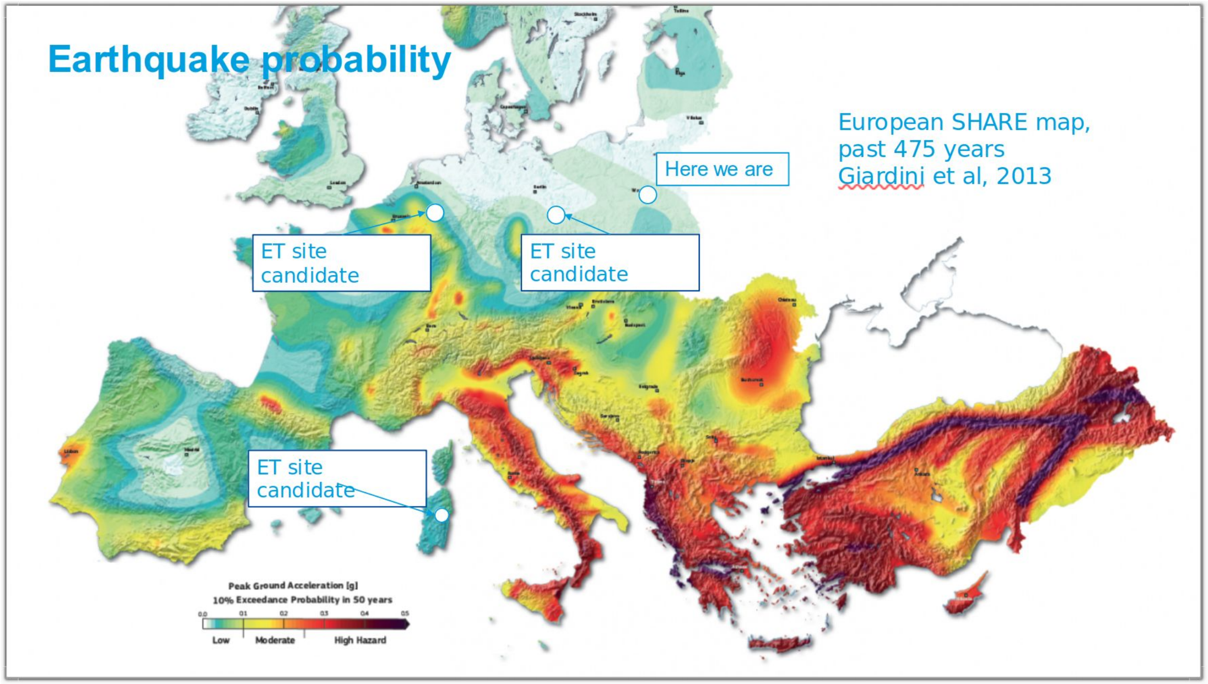






Einstein Telescope - 3G observatory

- 3rd Annual Meeting in Warsaw:
  - https://indico.ego-gw.it/event/764/
  - 3 possible sites for ET
- Challenges:
  - L vs triangular shape
  - Location



Searches for exceptional GW sources

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,

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

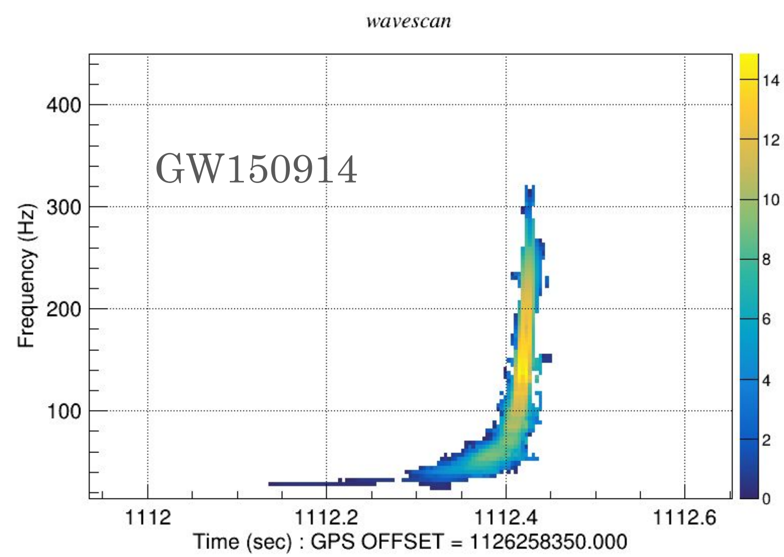
- Complementing matched filtering

- 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

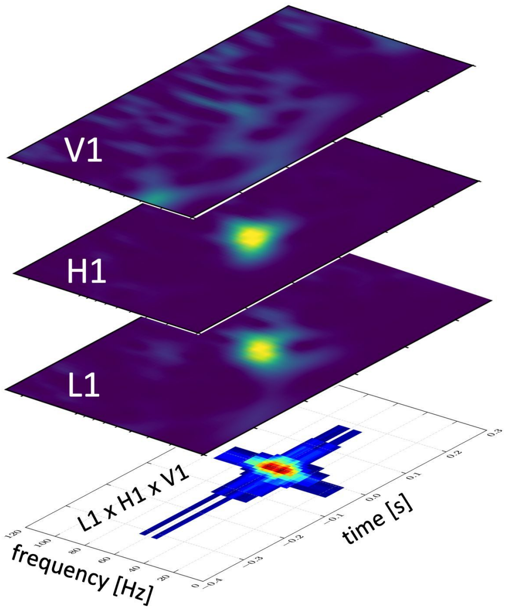
- **The cWB is the most sensitive burst algorithm in O4**

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

https://gwburst.gitlab.io/



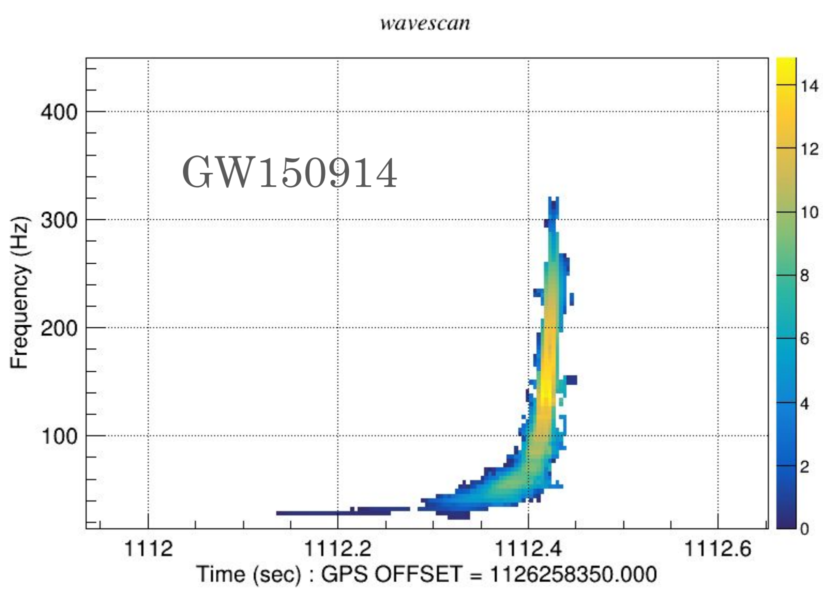
coherent WaveBurst (cWB)



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

- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

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

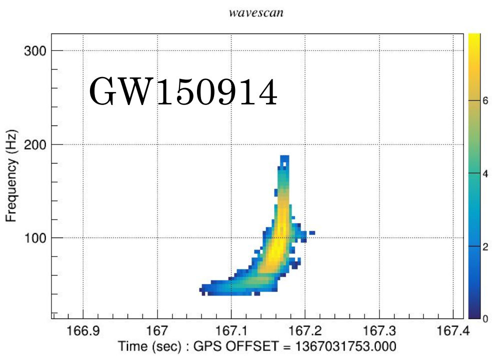


Model-independent searches classification

Compact binary searches (minimally modeled)

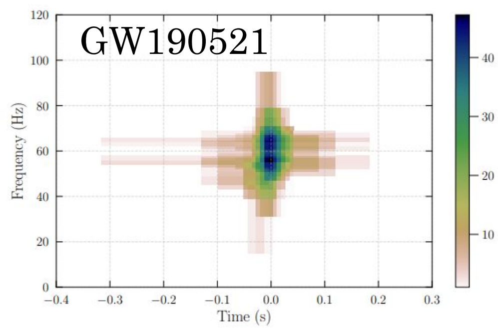
Generic searches (unmodeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



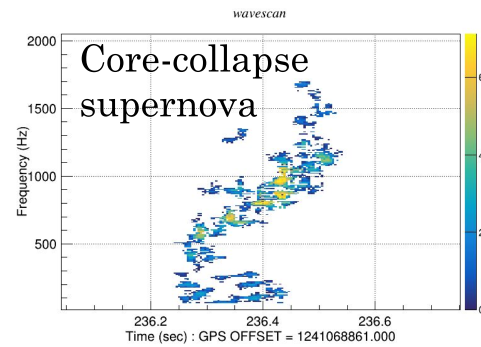
e.g. Mishra+23 (2201.01495)

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)

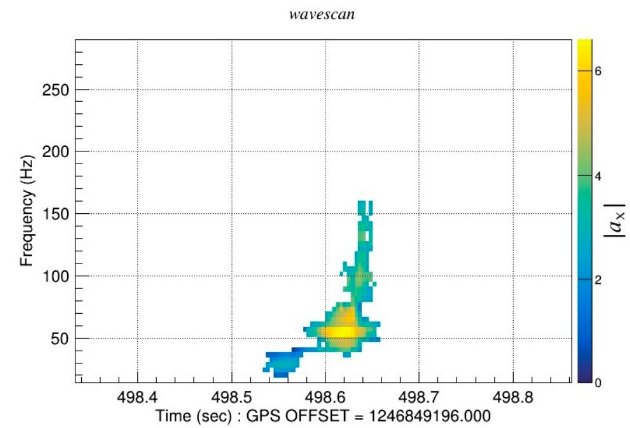
Searches for new phenomena

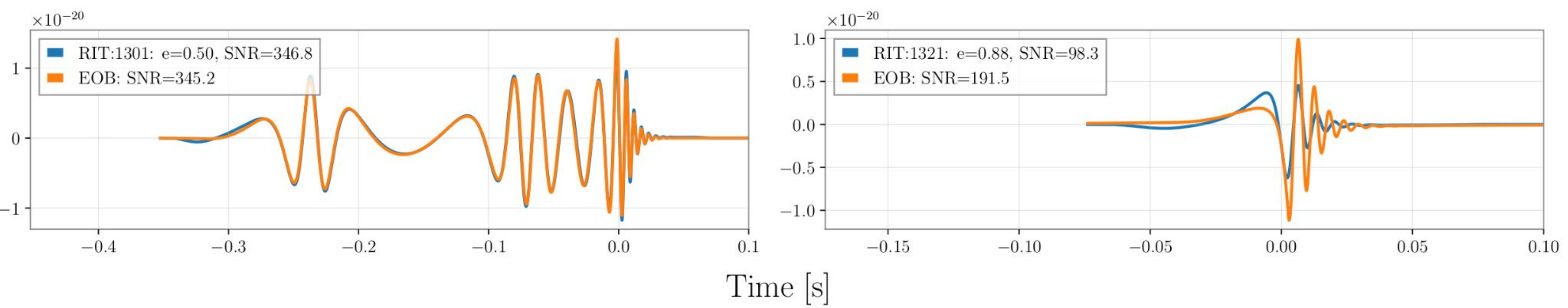
Higher harmonics
GW cross-polarization
Deviations from GR

e.g. Vedovato+22 (2108.13384)

Eccentric binaries

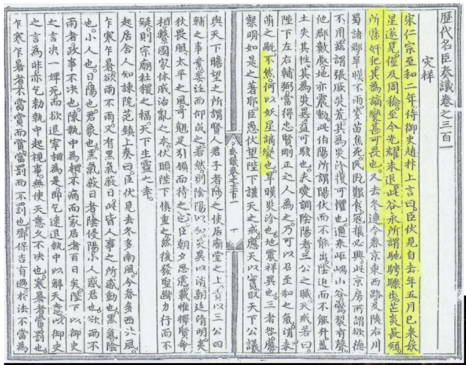
- Eccentric binaries: compact binaries elliptical orbits.
  - Dynamical formation
  - They could be the next LVK discovery
- Mishra et al (MS) 2024 ([2410.15191]())
  - O3 data reanalysis
  - 3 new GWs: consistent with stellar BHs, one event has large mass-ratio (possible dynamic formation)
- Bhaumik et al (MS) 2024 ([2410.15192]())
  - Comparison between waveform models
  - Sensitivity studies

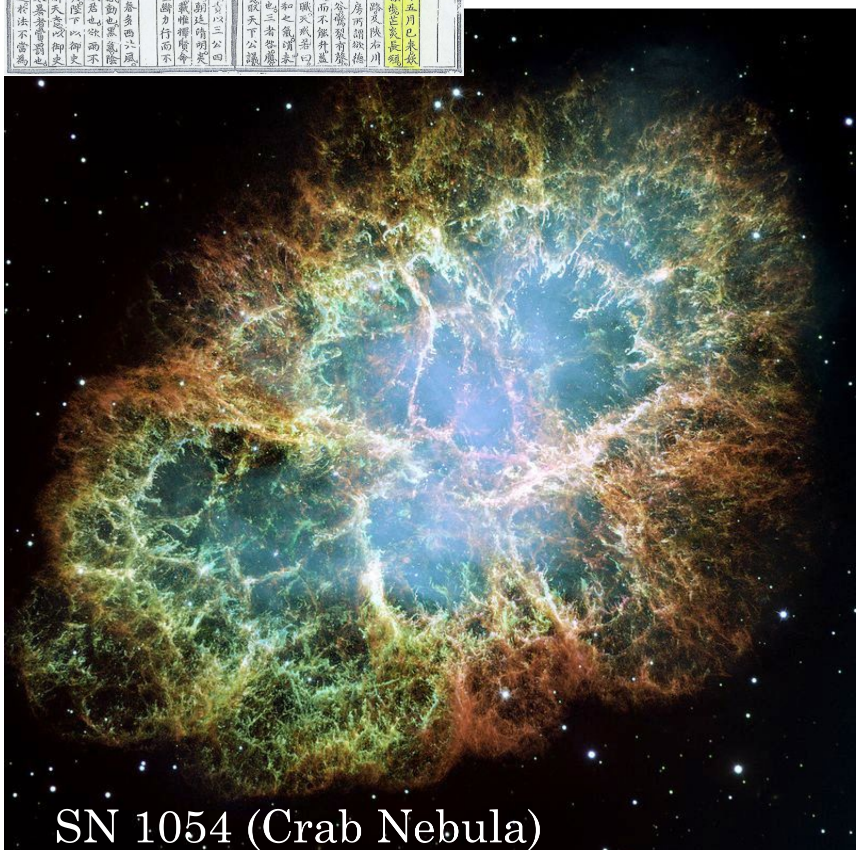




Core-Collapse Supernova

Core-Collapse Supernova (CCSN)



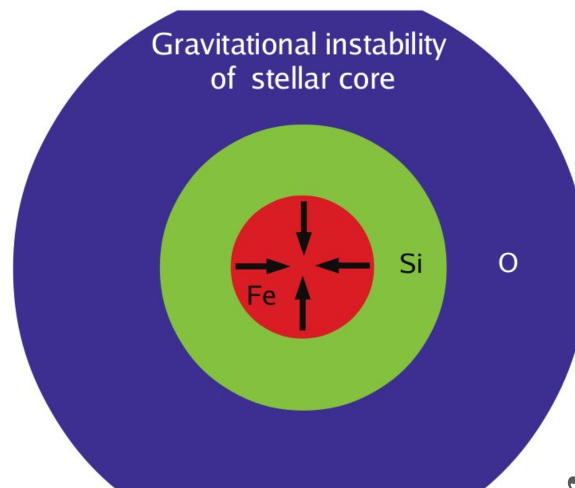


SN 1054 (Crab Nebula)

Nova on the sky!
1-2 per century in Milky Way (?)

- Burning of a star: H → He → … → Fe
- After exceeding Chandrasekhar mass of 1.4 Sun mass the iron core collapses.
- 99% of explosion energy escapes with neutrinos!

Explosion mechanism is still unknown

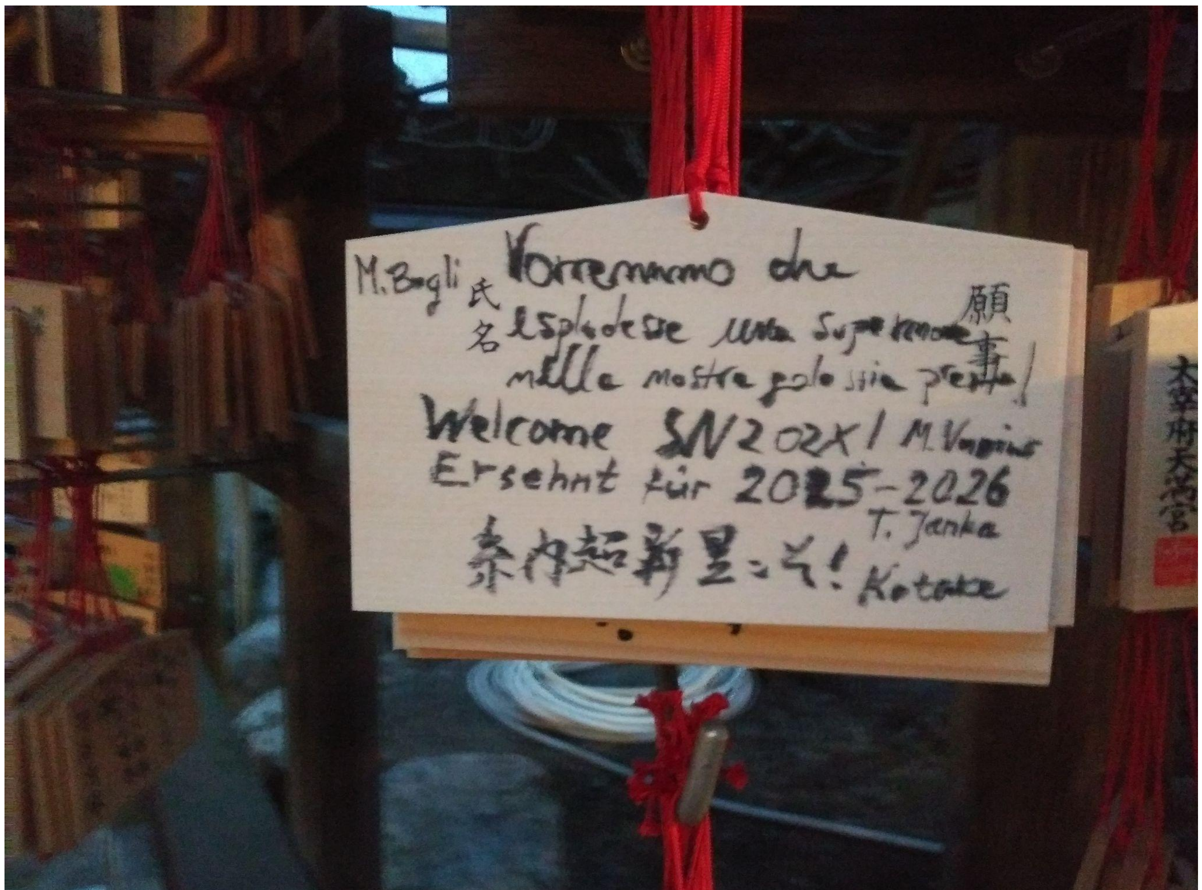


Janka+12

CCSN - the next big GW discovery

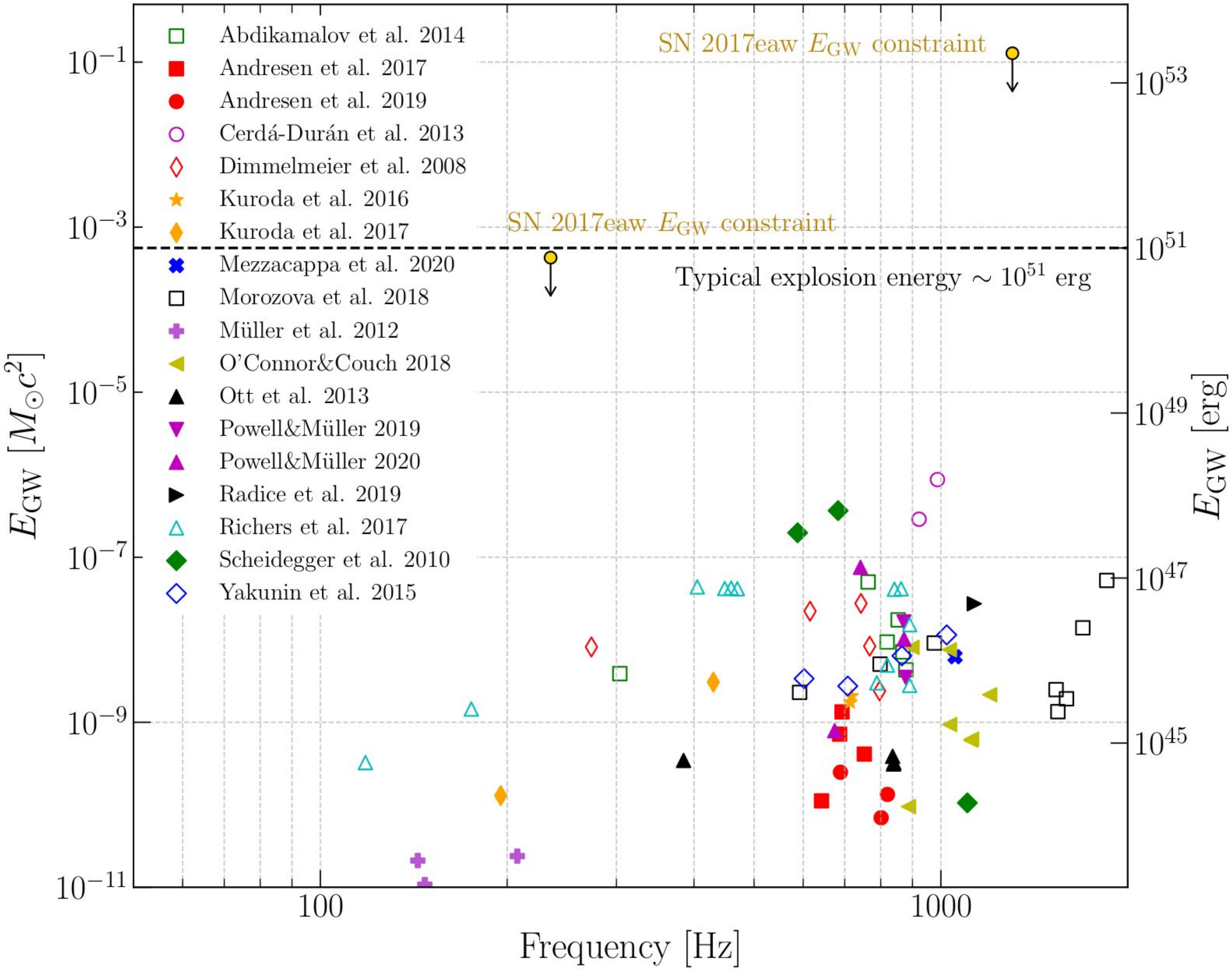
"Welcome SN 202X! Long-awaited for 2025-2026"

Fukuoka Temple, 2019.10.23

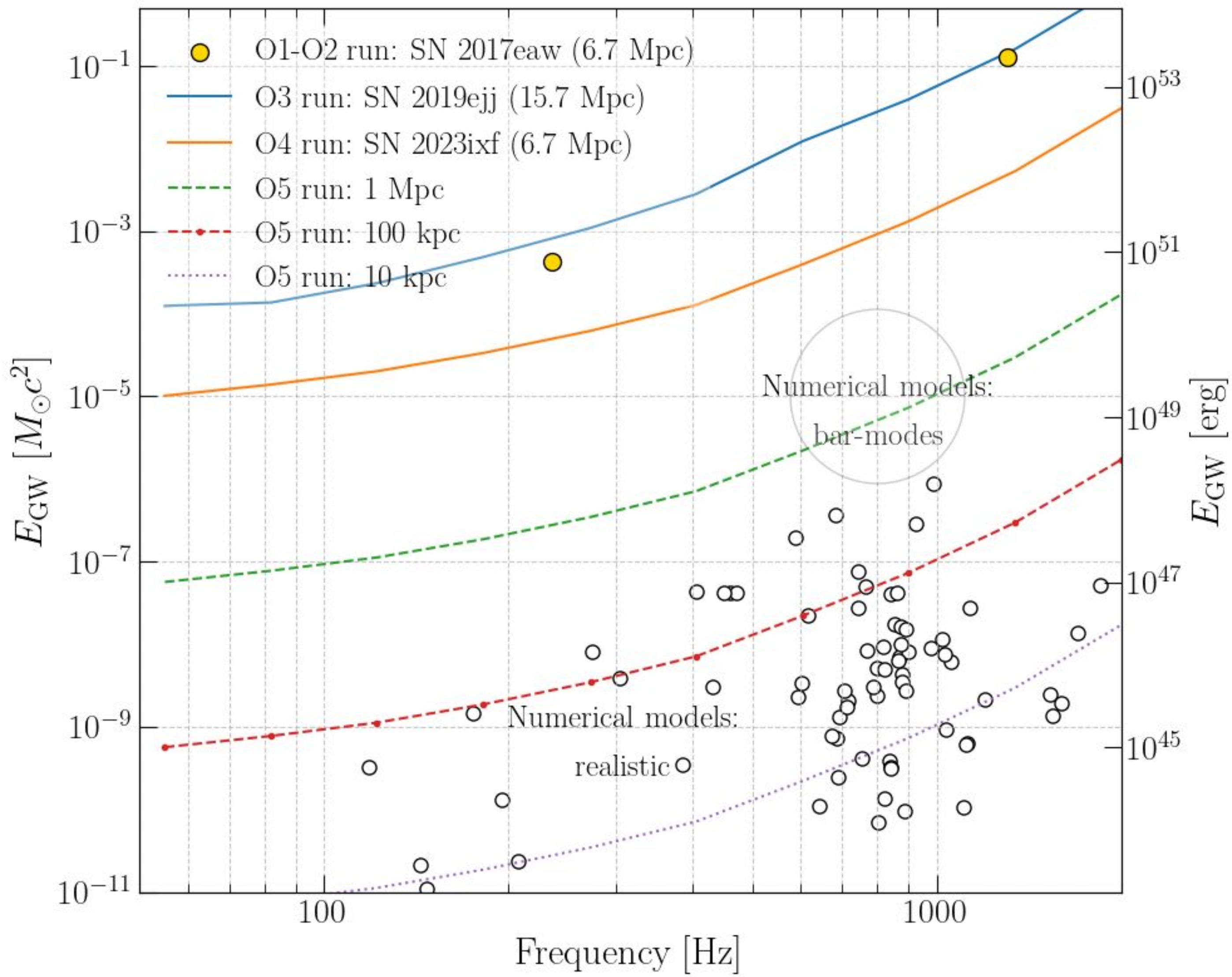


Core-Collapse Supernova Properties

Szczepanczyk et al 2021 ([2104.06462](https://arxiv.org/abs/2104.06462))



How far are we from a discovery?
(realistically: Galactic CCSN)



Optically Targeted searches

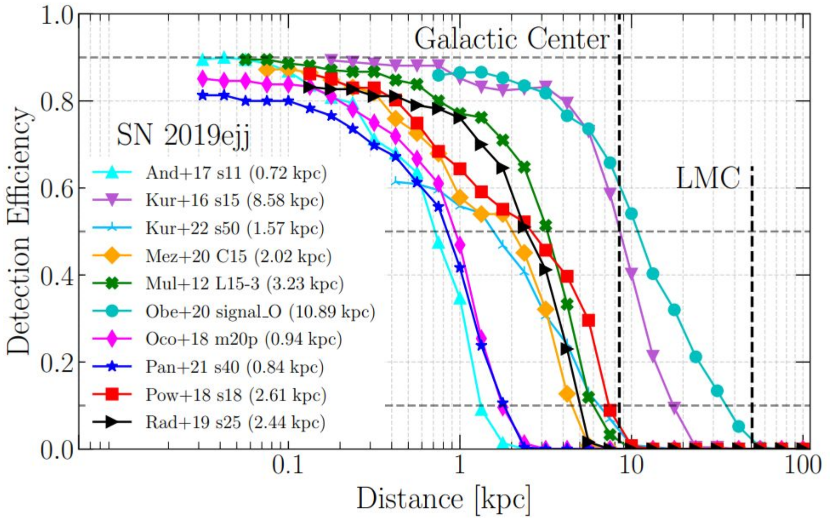
While waiting for the Galactic event, we search for GWs from extra-Galactic CCSNe (targets).

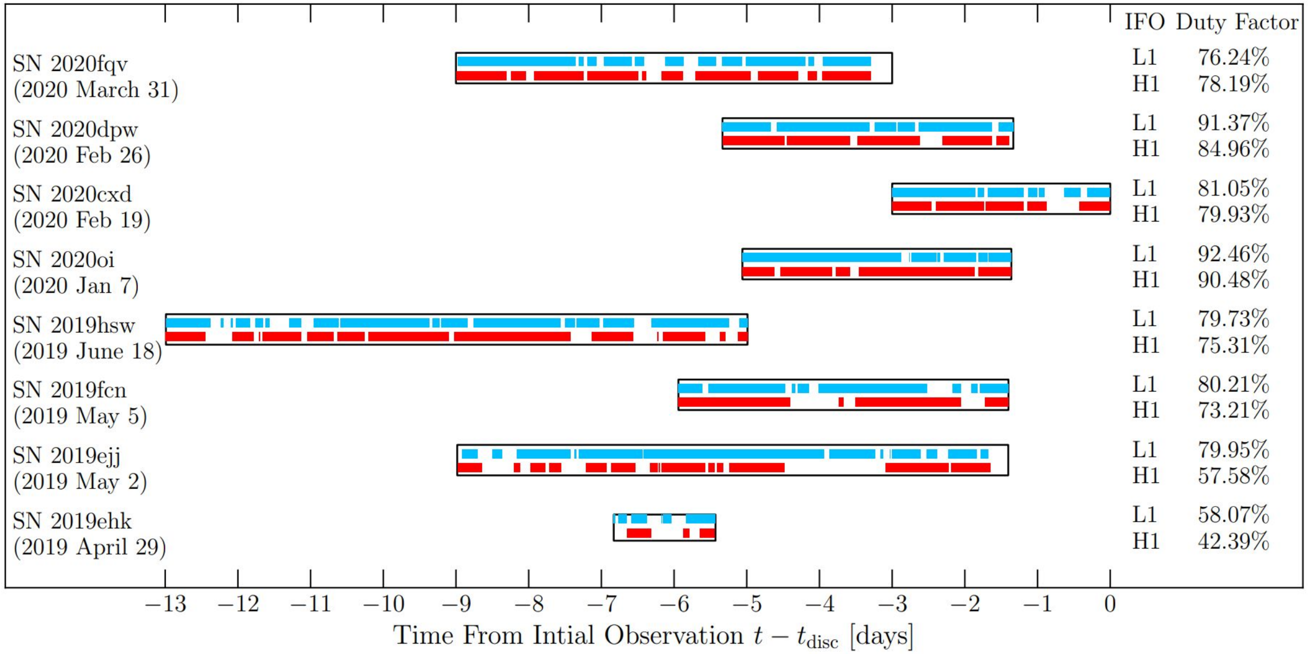
O1-O2 data (5 CCSN up to 20 Mpc, [1908.03584](1908.03584)):

- First constraints of CCSN engine

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

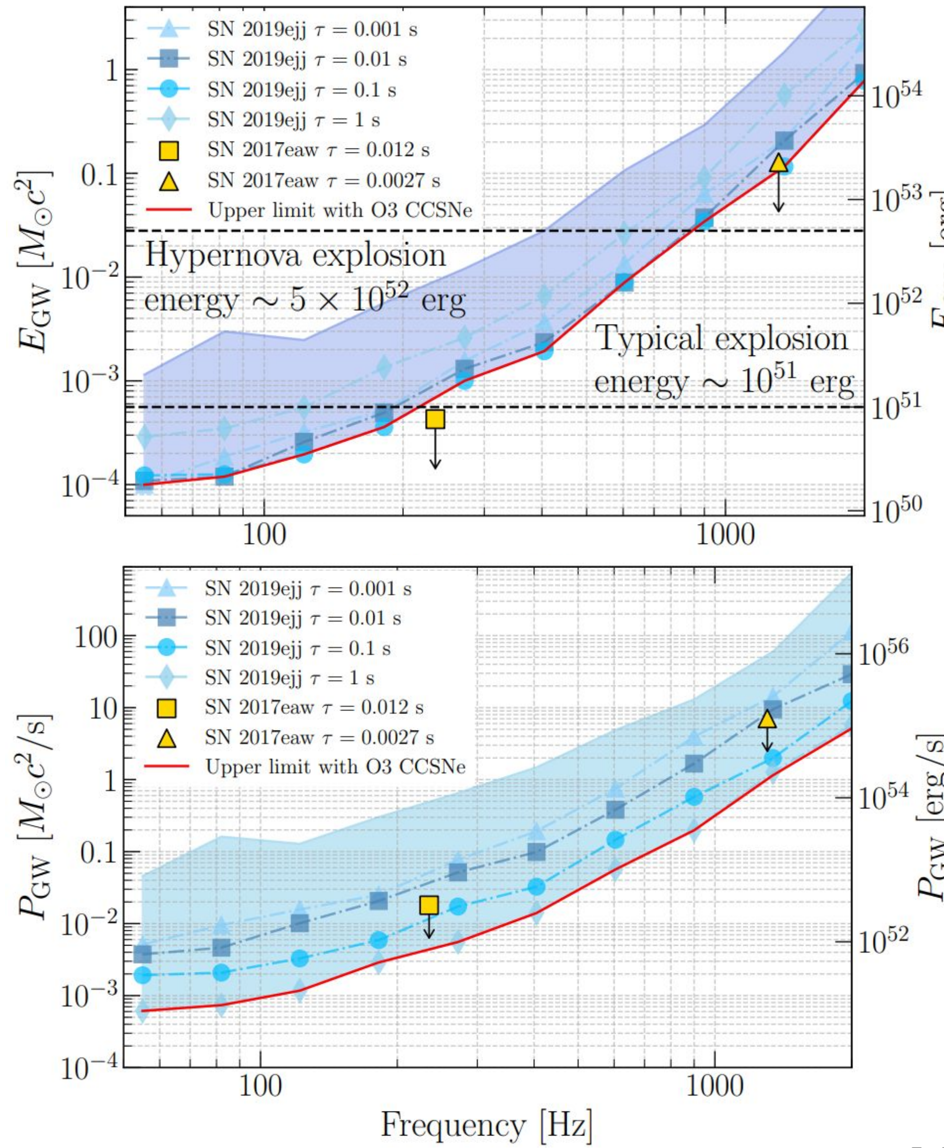
- First upper limits on GW power and ellipticity
- Continuation of constraining CCSN engine





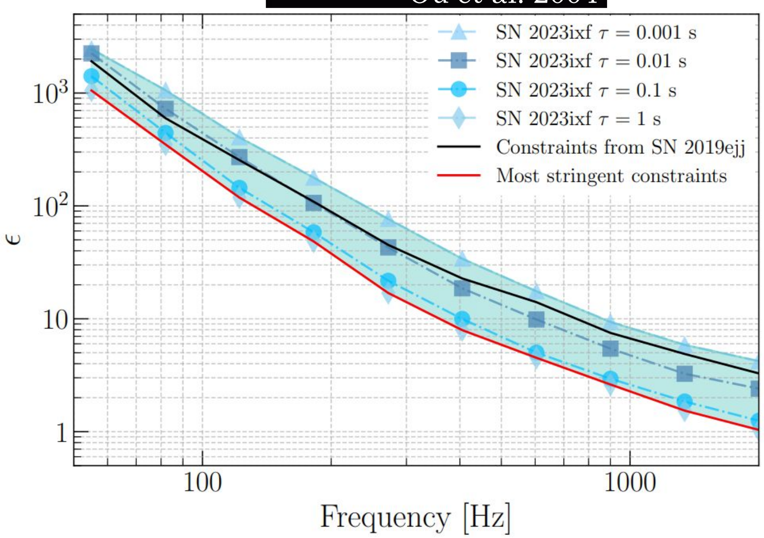
O3 Optically Targeted search
(Szczepanczyk et al. 2023)

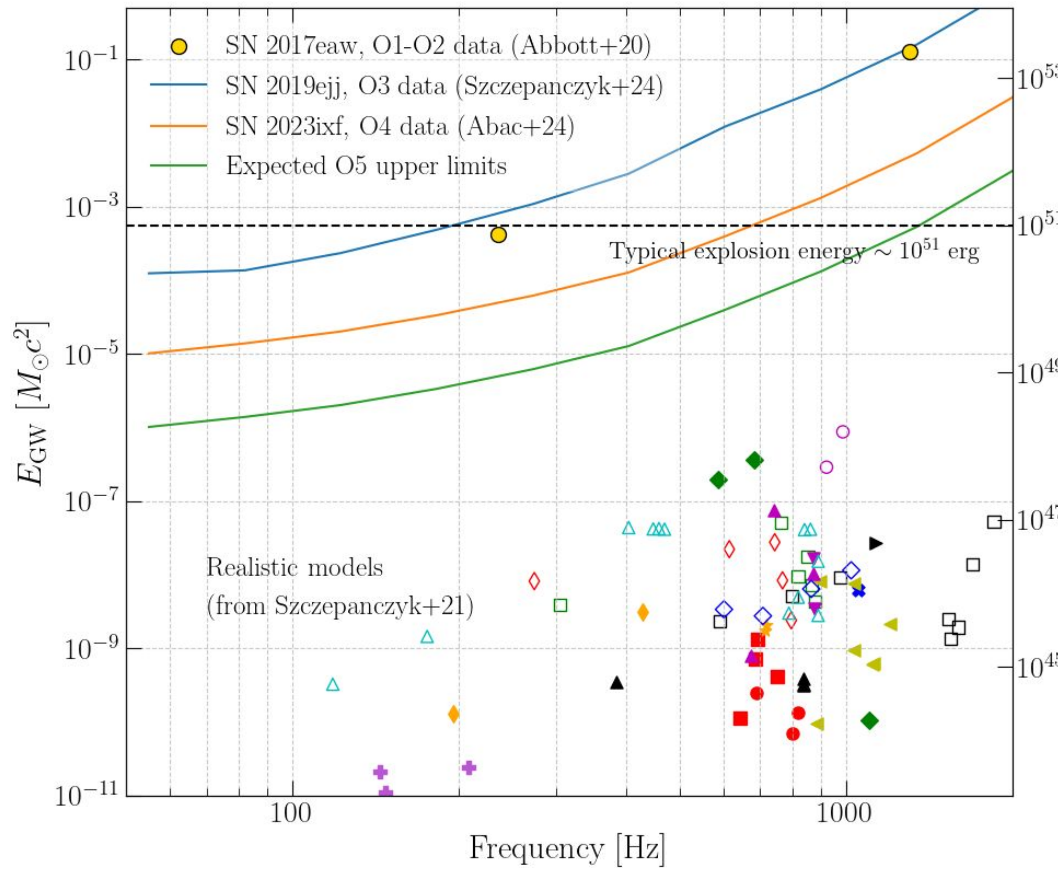
- Extensive constraints of the CCSN engine.
  - Assuming monochromatic (narrowband) emission
- GW energy constraints
  - Isotropic emission
  - Stringest: $\mathbf{1x10^{-4}\ M_{\odot}c^{2}}$
- GW power (luminosity) constraints
  - First observational constraints
  - Stringest: $\mathbf{5x10^{-4}\ M_{\odot}c^{2}/s}$



SN 2023ixf

- Special LVK paper: [2410.16565]
- GW energy emission: order of magnitude better constraints
- Core deformations upper limits: 2 orders of magnitude higher than for most energetic CCSN simulations.

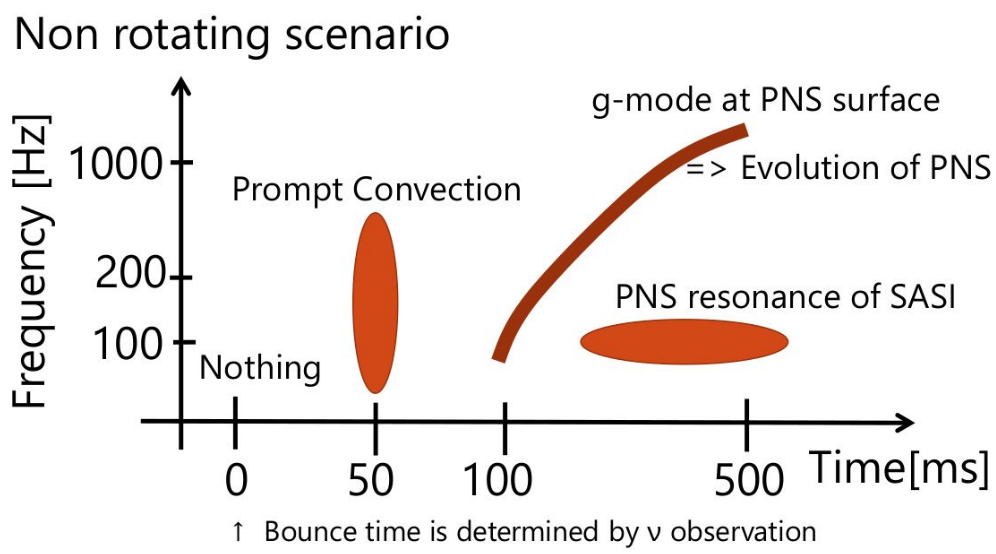




Parameter Estimation

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)

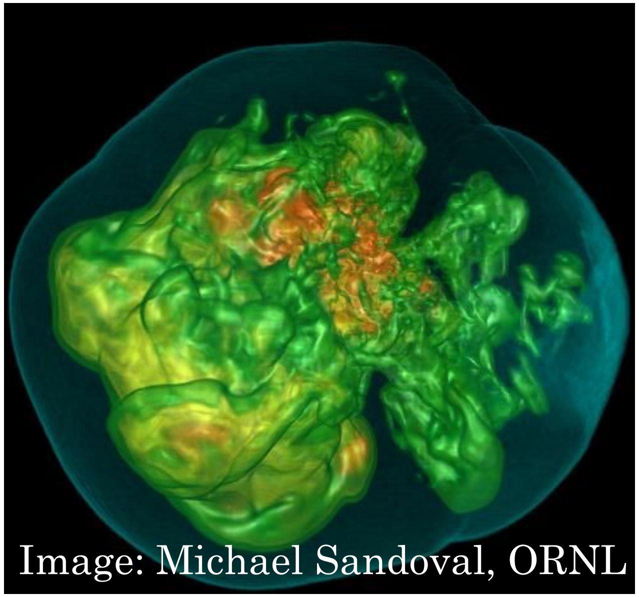


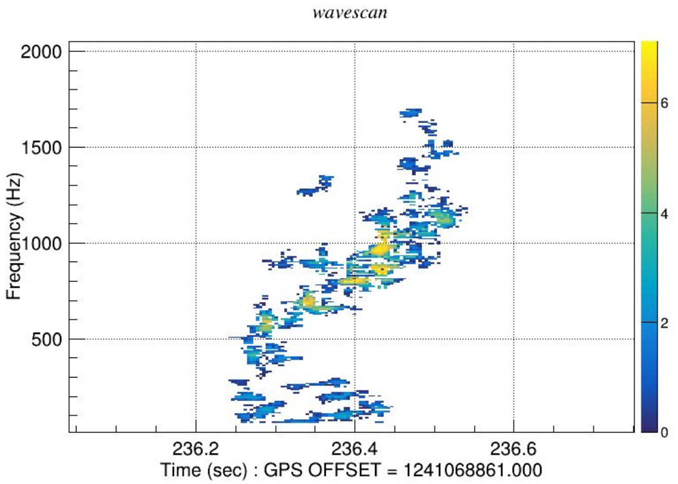
Credit: Takiwaki

LVK and CCSN Theory

Example: Mezzacappa et al 2023

- CCSNe are the most challenging astronomical events to model:
  - All four fundamental forces are important
  - Neutrino transport
  - Computational challenges
- A joint workshop between LVK and CCSN modellers happened at Caltech in 2017
  - Supernova Multimessenger Consortium is created





Next LVK workshop: summer 2025 in Warsaw - stay tuned!

Summary

- Core-Collapse Supernova
  - “Supernova problem”: why do the stars explode?
  - Gravitational Waves can bring an answer!
- GW burst searches
  - Optically targeted searches: constraining SN engine
  - Parameter Estimation - a lot of effort
- **LVK workshop with CCSN theorists: summer 2025 in Warsaw**

Slides: fuw.edu.pl/~mszczepanczyk/news.html