Detecting Gravitational Waves from a nearby Core-Collapse Supernova

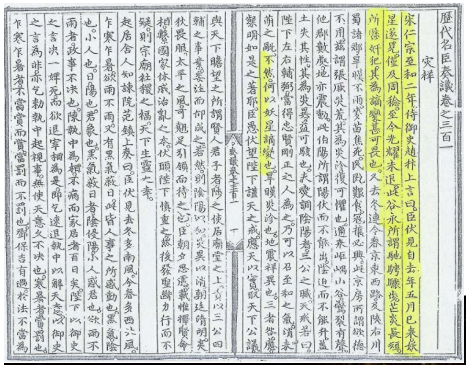
Marek Szczepańczyk
Department of Physics, University of Warsaw

Theory meeting experiment (TMEX)
Quy Nhon, Vietnam, 5-11.01.2025

Outline

- Core-Collapse Supernova
  - Properties
  - Predictions
- Observing Run 4
- Model-independent searches
  - Types
  - Optically targeted
  - Parameter Estimation
- LVK workshop: summer 2025

Core-Collapse Supernova (CCSN)

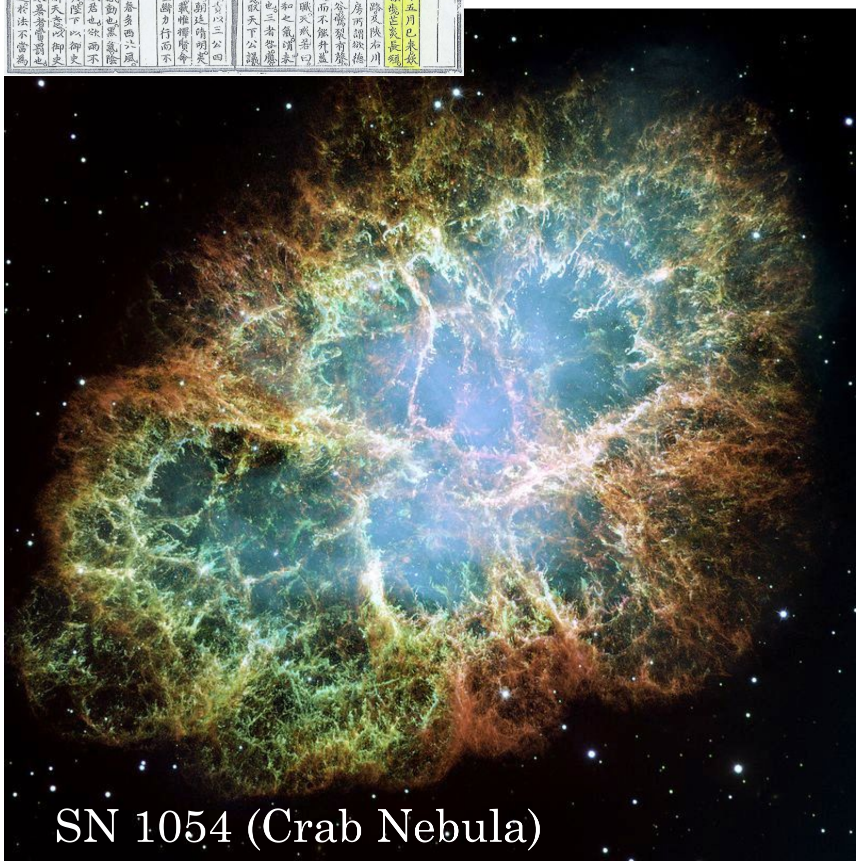


See also Irene's talk

Nova on the sky!

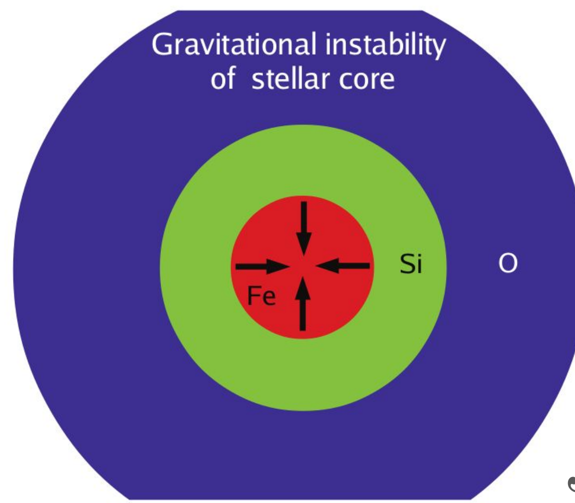
1-2 per century in Milky Way (?)

- 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!



SN 1054 (Crab Nebula)

Explosion mechanism is still unknown

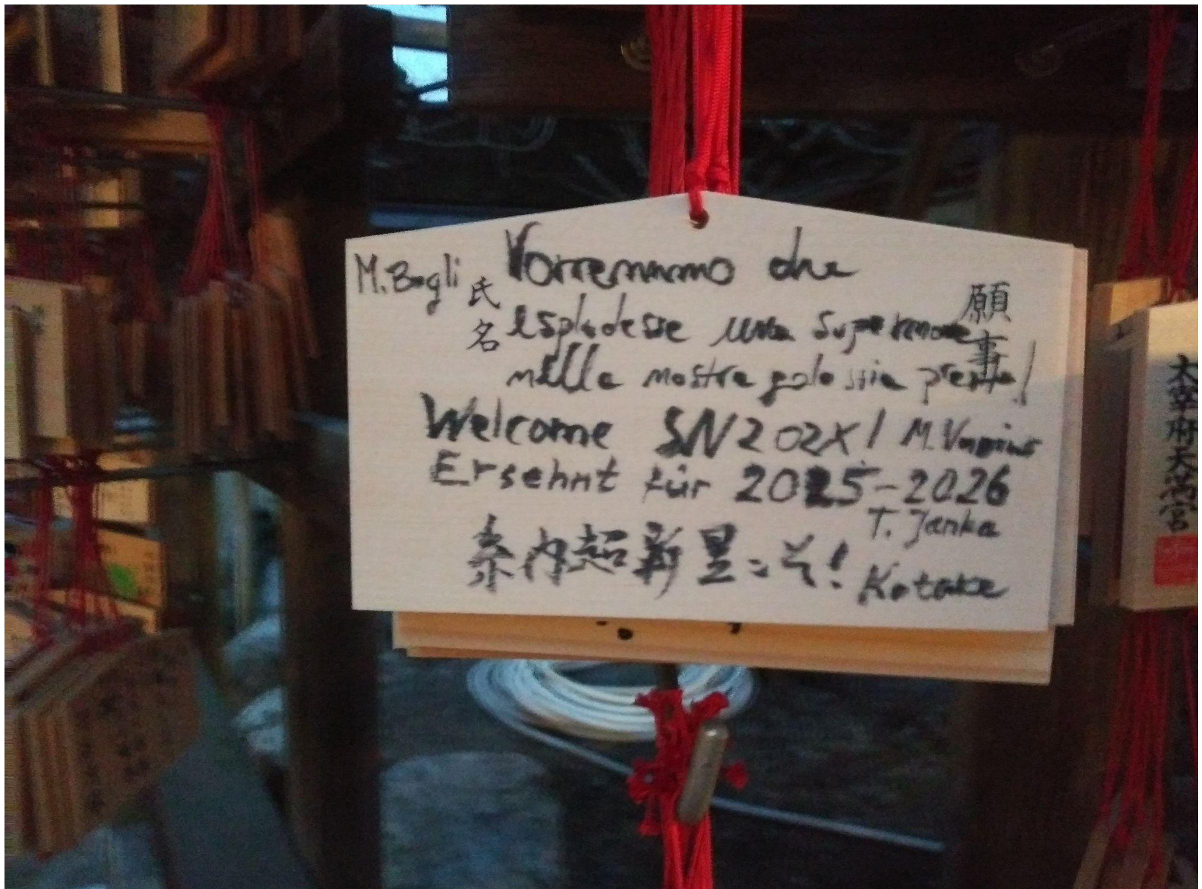


Janka+12

CCSN - the next big GW discovery

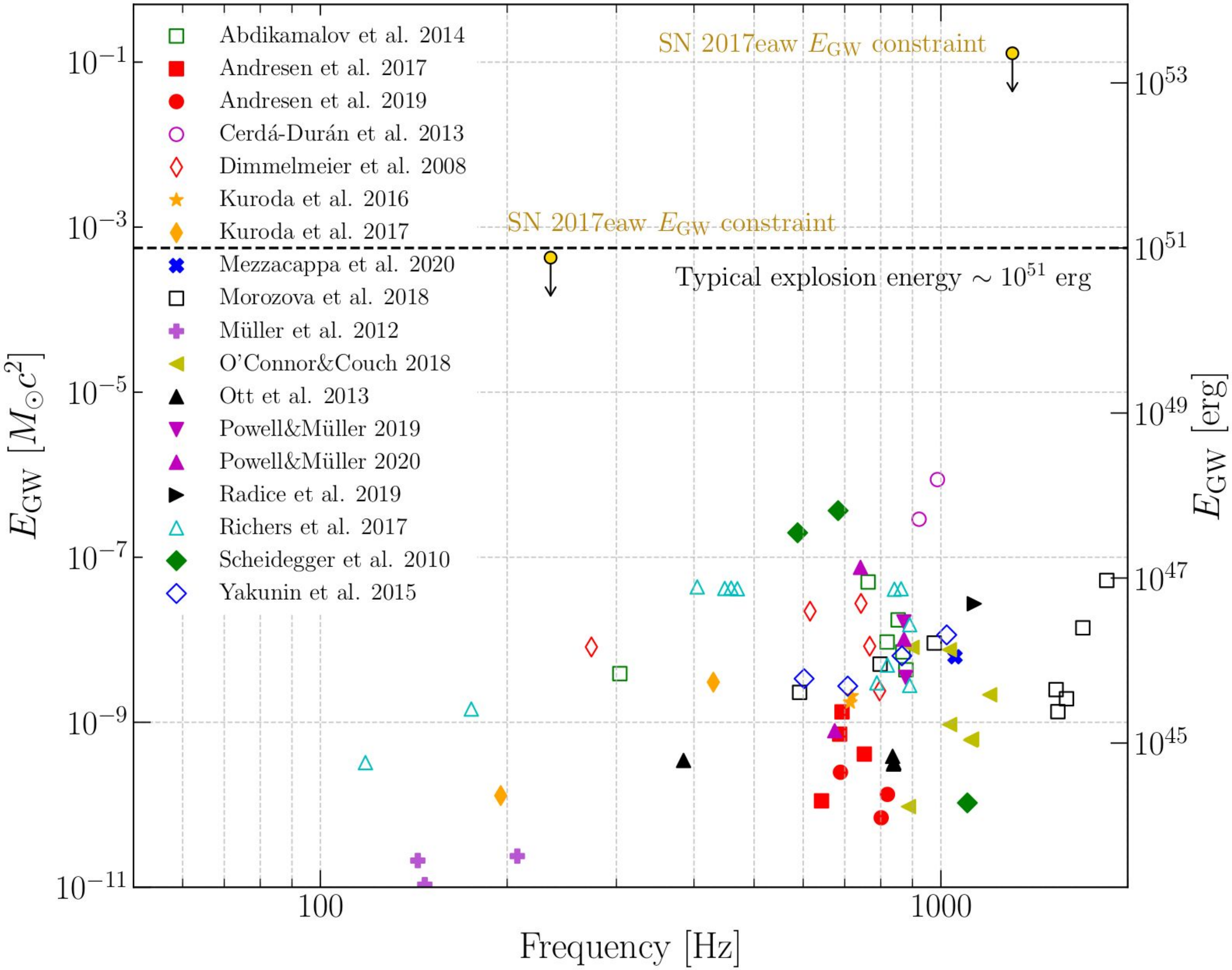
"Welcome SN 202X! Long-awaited for 2025-2026"

Fukuoka Temple, 2019.10.23

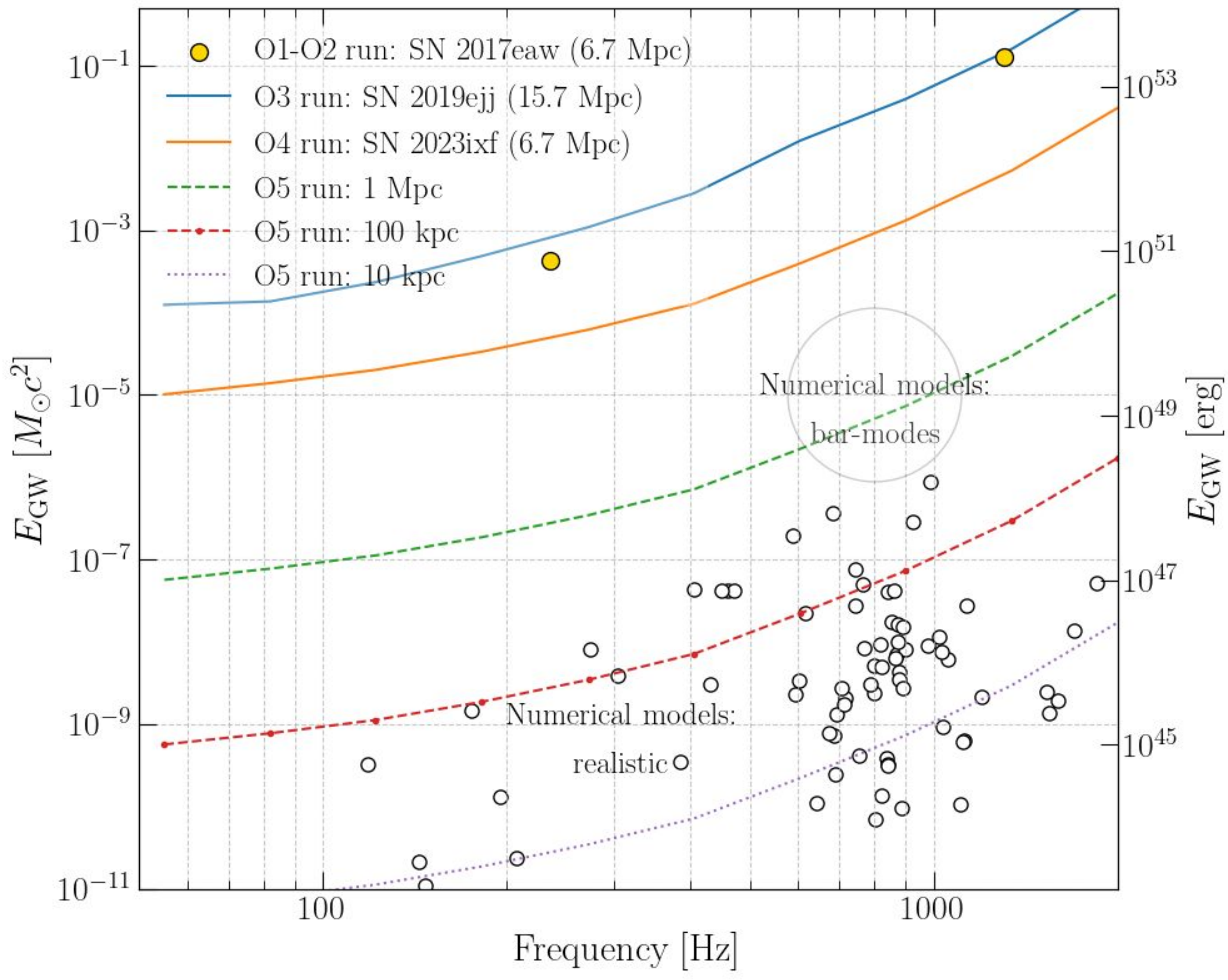


Core-Collapse Supernova Properties

Szczepanczyk et al 2021 ([2104.06462](2104.06462))



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

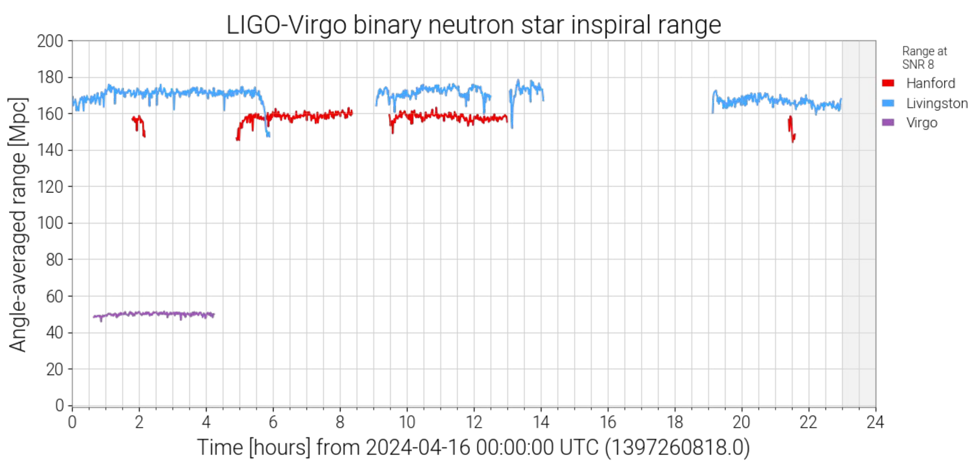


O4 and low-latency searches

- 24 months total, until June 2025
- GW candidates: 178 so far **(3 per week)**
- Searches:
  - Model-dependent
  - **Model-independent**
- Public alert for GW bursts:
  - False Alarm Rate, sky localization (cWB),
  - "Fluence" (~luminosity), peak frequency, duration

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/

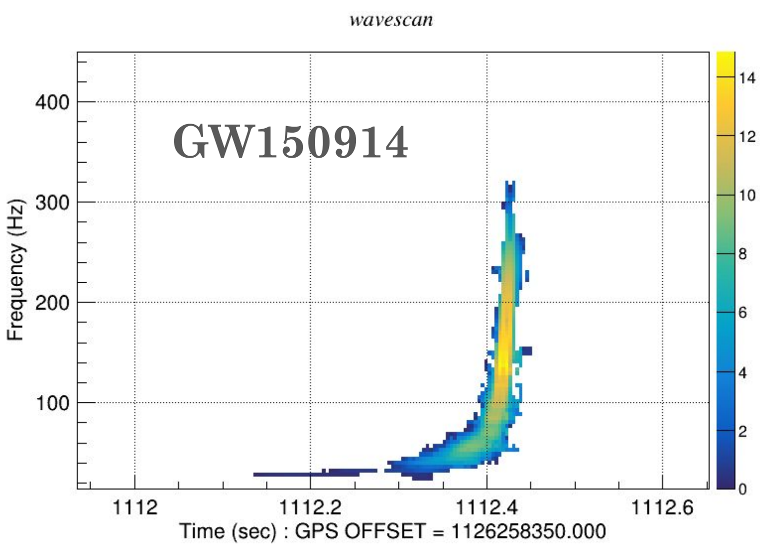


Model-independent searches

- **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

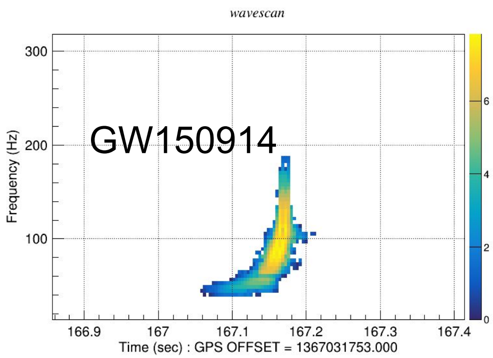
https://gwburst.gitlab.io/



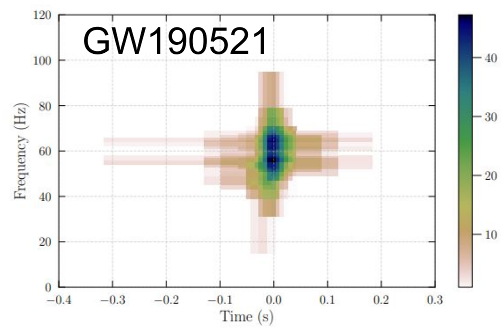
Model-independent searches

Compact binary searches (minimally modeled)

Binary black holes
Binary neutron stars
Black hole - neutron star

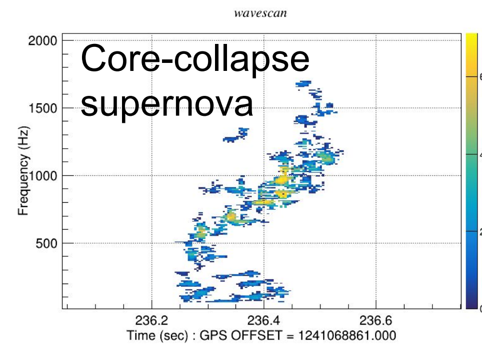


Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



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

CCSN Parameter Estimation:
Proto-neutron star evolution, shock properties, rotational rate etc.

Optically Targeted searches

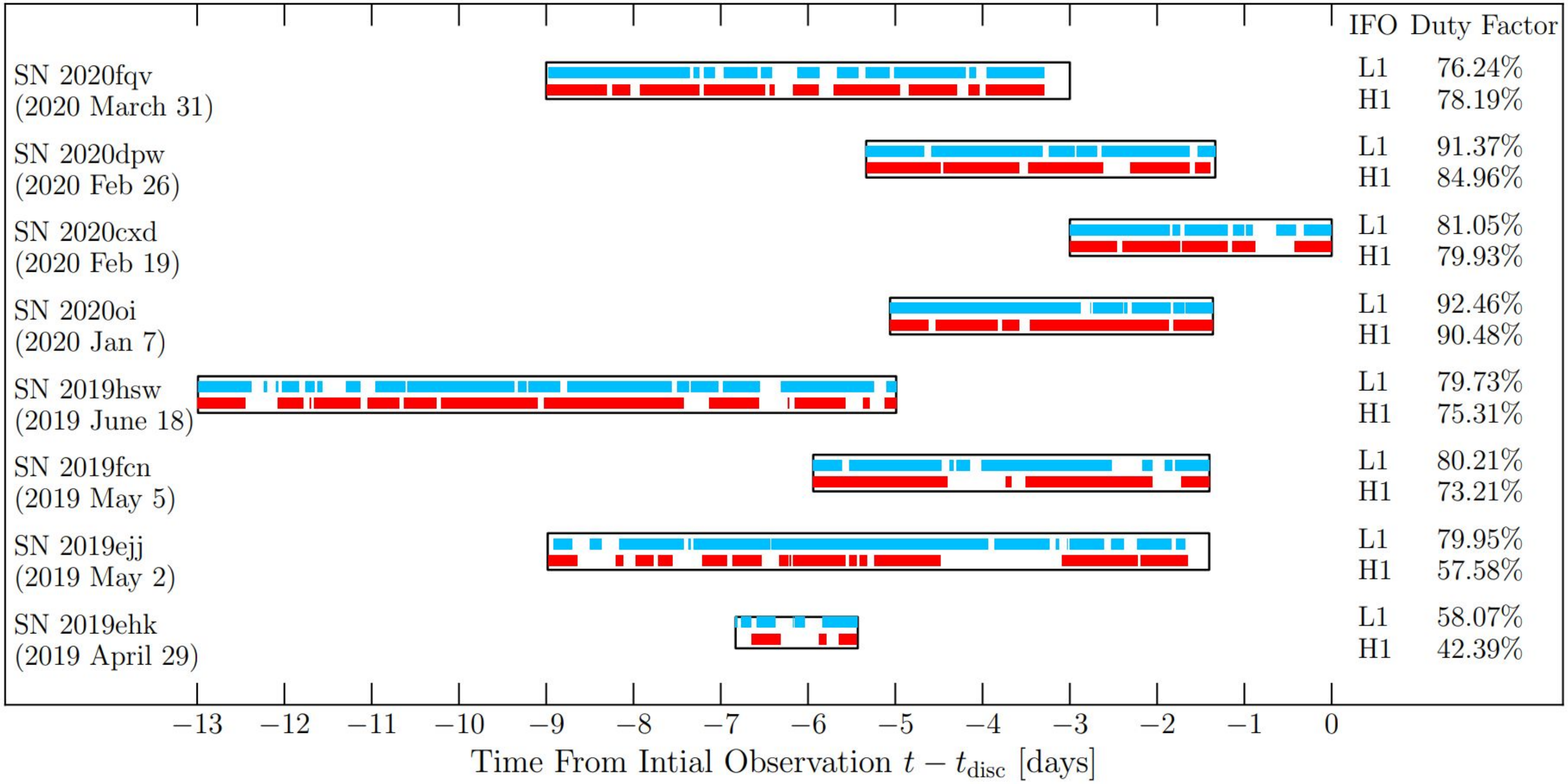
While waiting for the Galactic event, we search for GWs from extra-Galactic CCSNe (targets).

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

- First constraints of CCSN engine

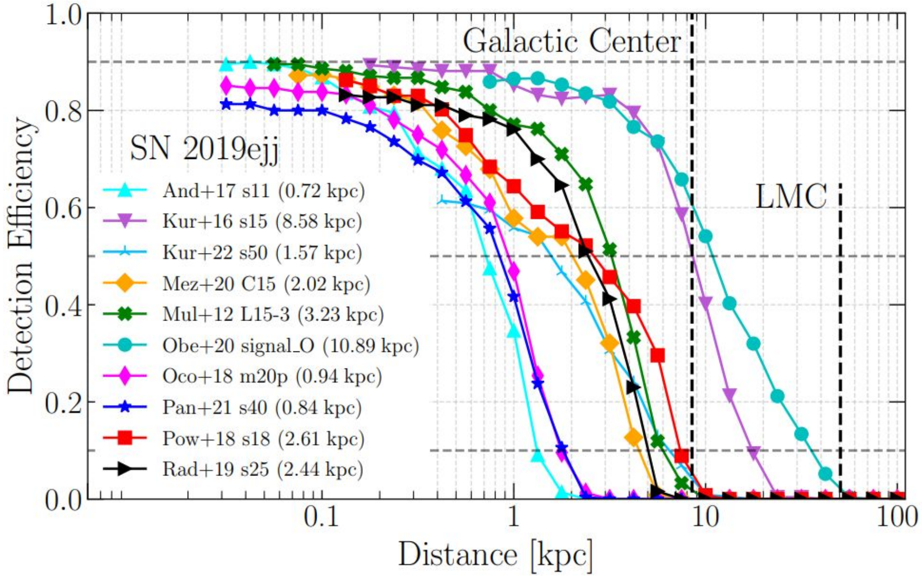
O3 data (9 CCSN up to 30 Mpc, 2305.16146):

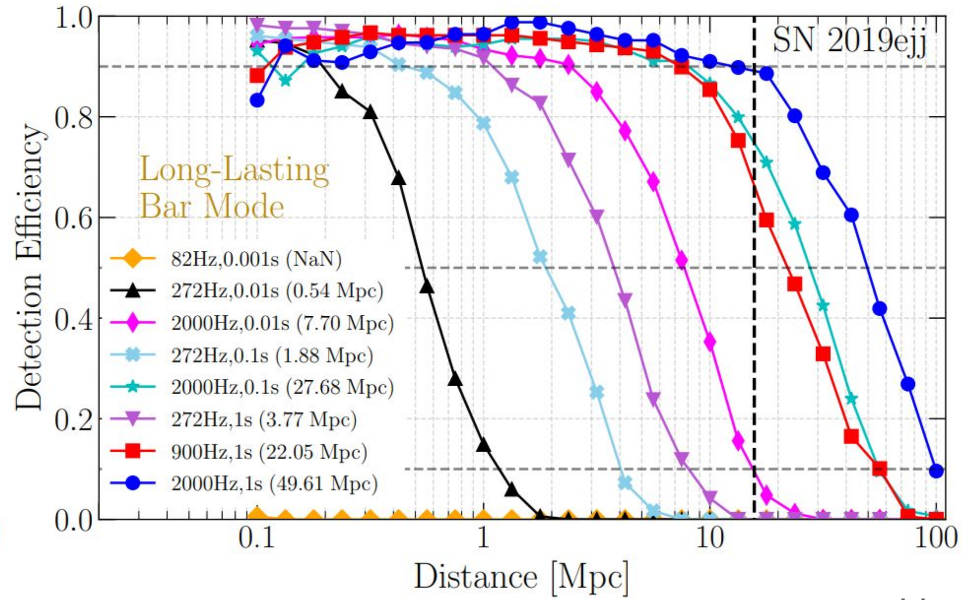
- First upper limits on GW power and ellipticity
- Continuation of constraining extreme emission models



O3 Optically Targeted search
(Szczepanczyk et al. 2023)

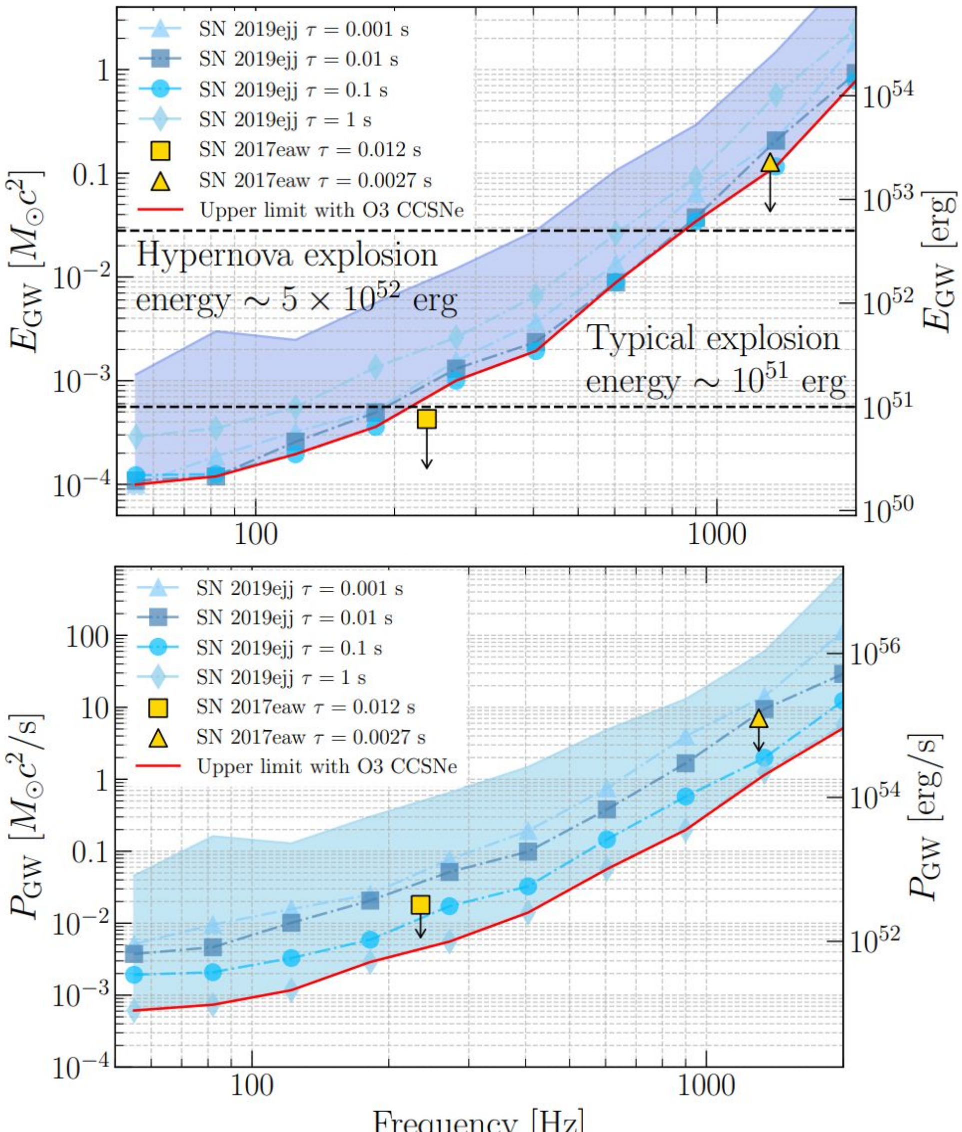
- No GW detection so far
- Most significant event for SN 2020fqv: 2.8 sigma significance
- Detection range: distance at 50% detection efficiency
  - Neutrino-driven explosions: up to 13.7 kpc
  - Magnetorotationally-driven explosions: up to 15.9 kpc
  - QCD phase transition: up to 2.1 kpc
  - Black hole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





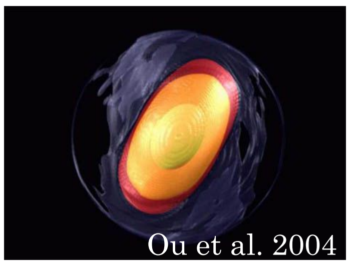
O3 Optically Targeted search
(Szczepanczyk et al. 2023)

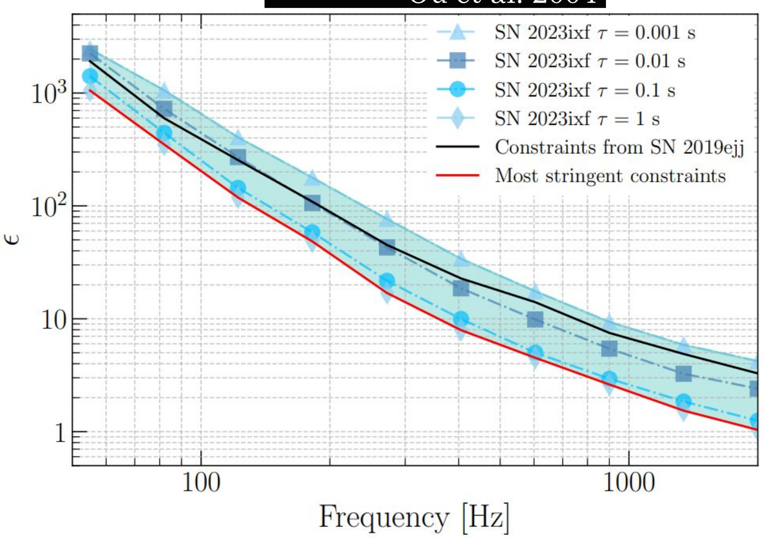
- Extensive constraints of the CCSN engine.
  - Assuming monochromatic (narrowband) emission
- GW energy constraints
  - Isotropic emission
  - Stringest: **1×10^{-4} $M_{\odot}c^2$**
- GW power (luminosity) constraints
  - First observational constraints
  - Stringest: **5×10^{-4} $M_{\odot}c^2/s$**

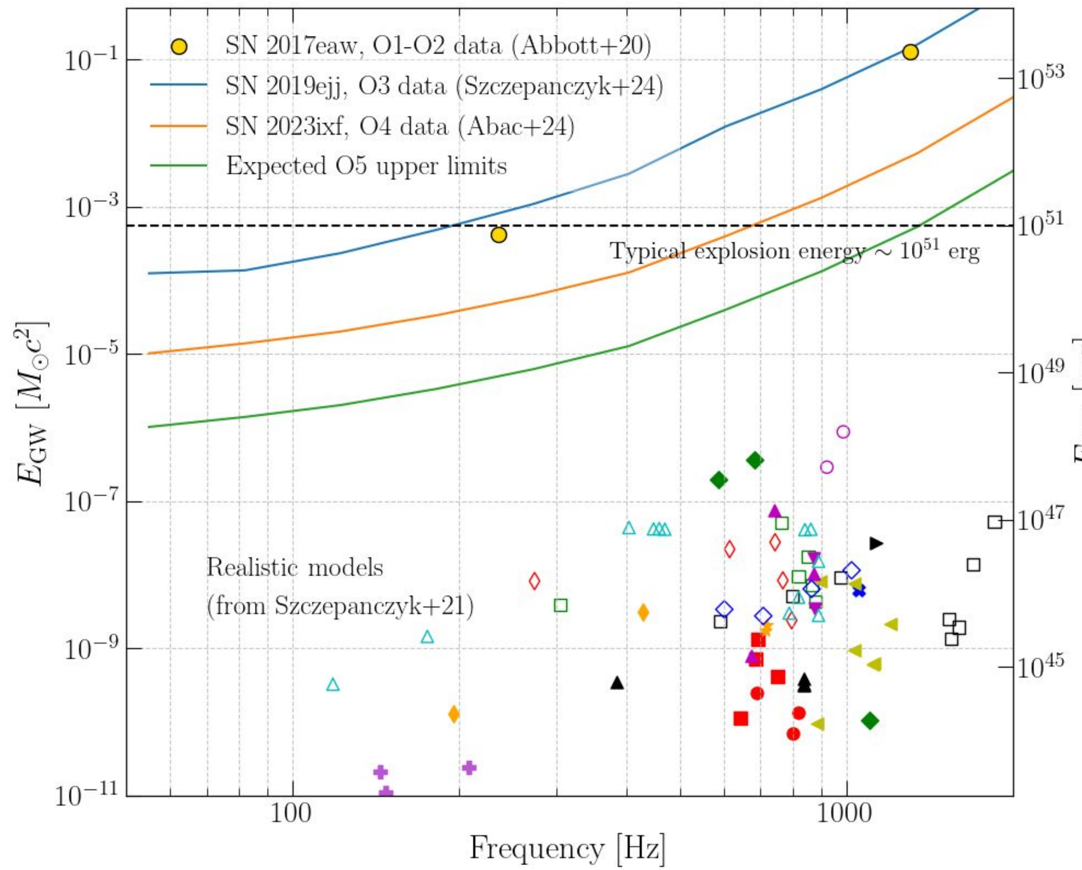


SN 2023ixf

- 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.



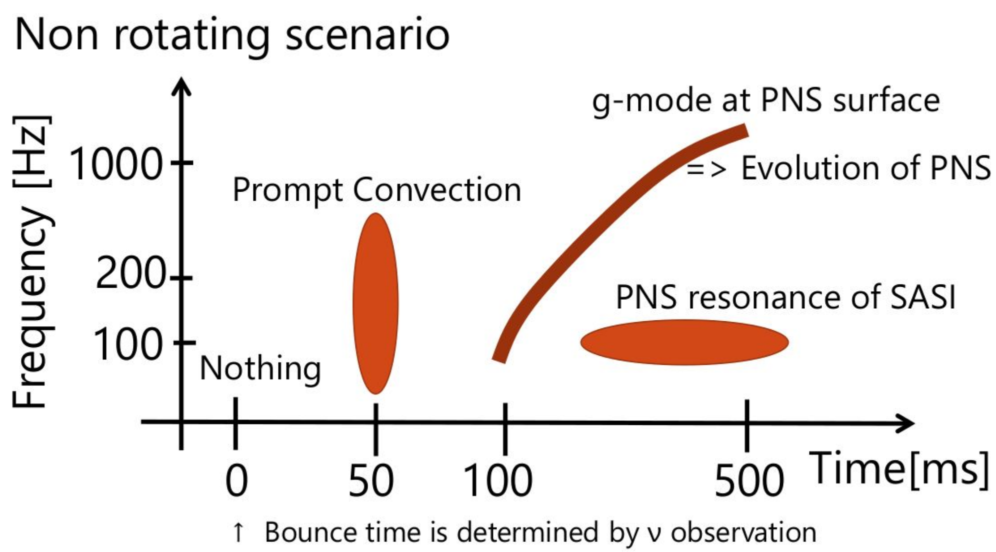




Parameter Estimation

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)

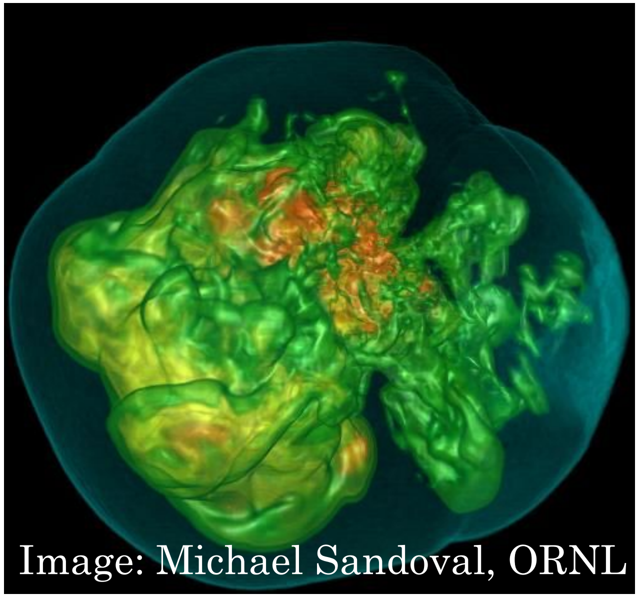


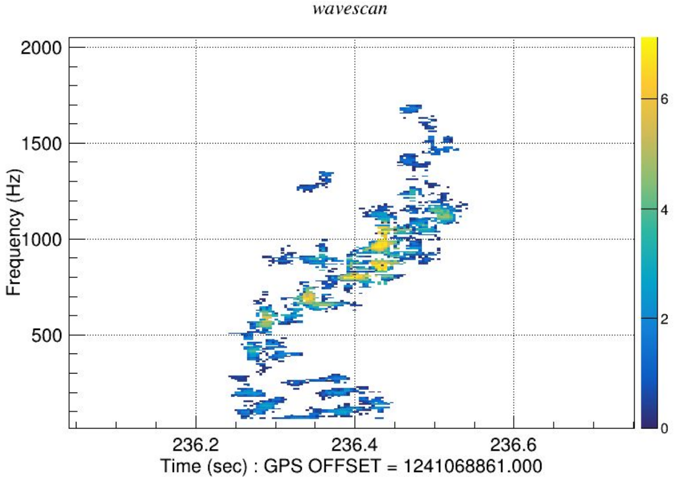
Credit: Takiwaki

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