# The next ten years of core-collapse supernova gravitational-wave astronomy

Slides:

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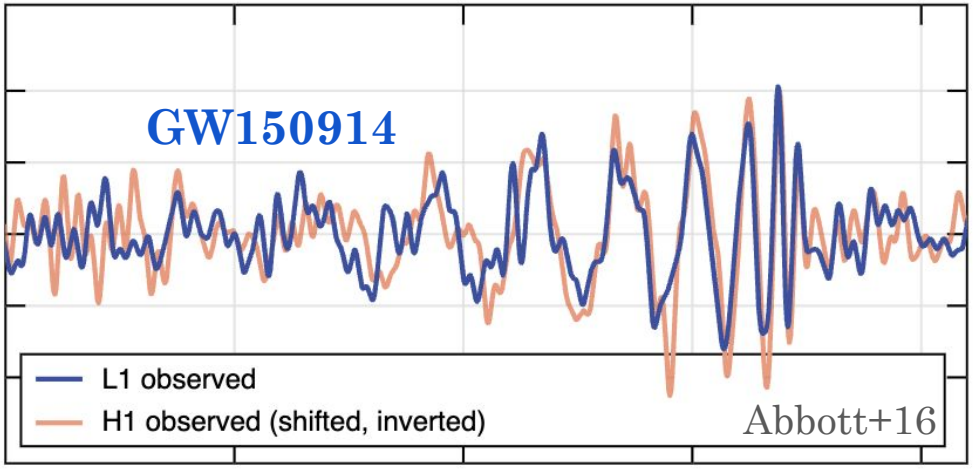
Stellar Populations and their Explosions:
Bridging the Gap
Schloss Ringberg, Tegernsee, 13.11.2025

# 10 years of Gravitational-Wave Astronomy!

**GW150914**: discovery of gravitational waves on 14 Sep 2015

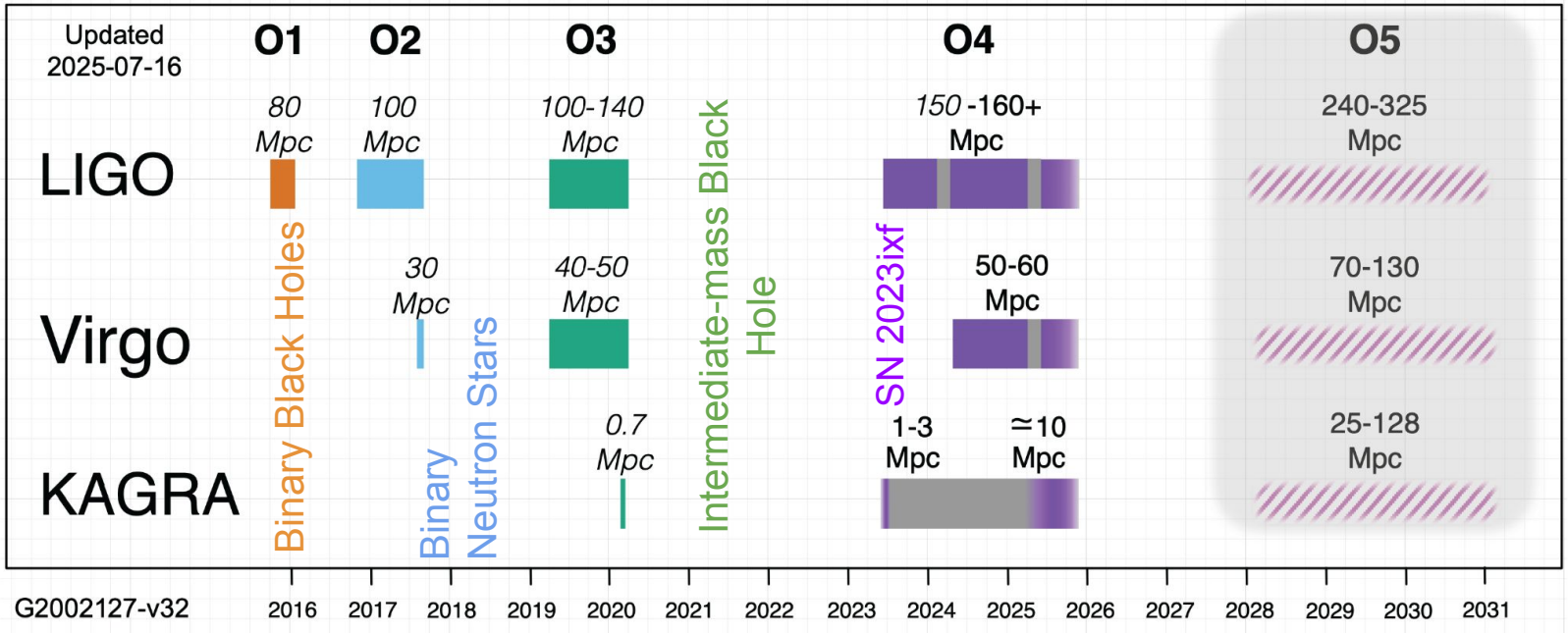
**What's next?**



# Outline

- Preliminaries
  - Observing timelines
  - Detection distance
- Are we ready (as communities) for a nearby CCSN?
  - SN2025gw IGWN Symposium
  - Some lessons learned

# Past and Future 10 years




**O6 (?)**

- pushing facilities
- 3G pathfinders

A# (400-600 Mpc)

Virgo_nEXT (260-500Mpc)

KAGRA+

Past 10 years

Future 10 years

- https://observing.docs.ligo.org/plan/
- O4: 24 months total, until 18 Nov 2025
- LIGO: up to 180 Mpc, currently 160 Mpc
- Virgo: around 55 Mpc
- KAGRA: reached 7.5 Mpc, observed briefly

- Also: GEO600, a few Mpc
- LIGO-India - under construction
- Possible an Australian detector

# Binaries and binaries so far…

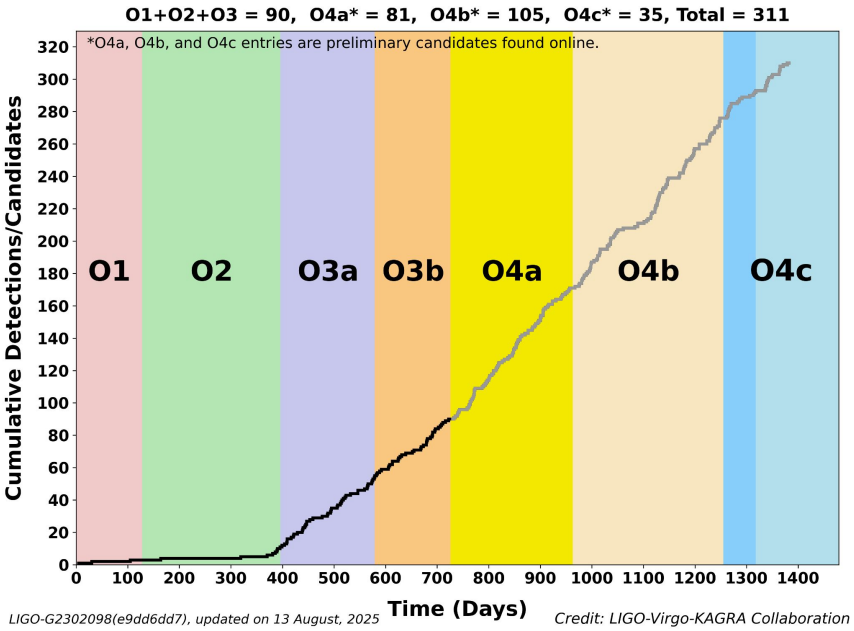
- Low-latency searches are crucial for astronomical observations, resources:
  - https://gracedb.ligo.org
  - https://emfollow.docs.ligo.org/userguide/
- Published results:
  - 21 papers and counting!
  - GWTC-4, O4a catalog (2508.18082)
  - Search with SN 2023ixf, a core-collapse supernova at 6.7 Mpc (2410.16565)

GW candidates so far **(3 per week)**:

O4a: 128 GWs

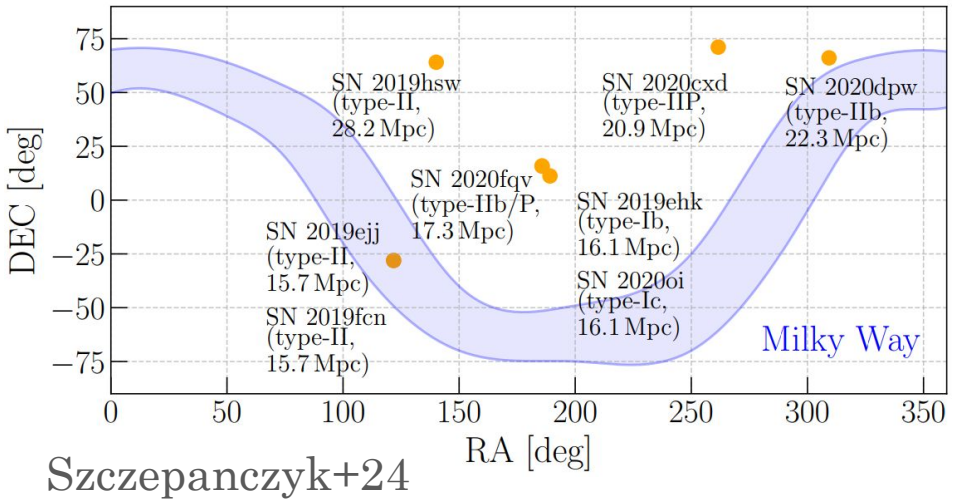
O4b: 105 GW candidates

O4c: 66 GW candidates

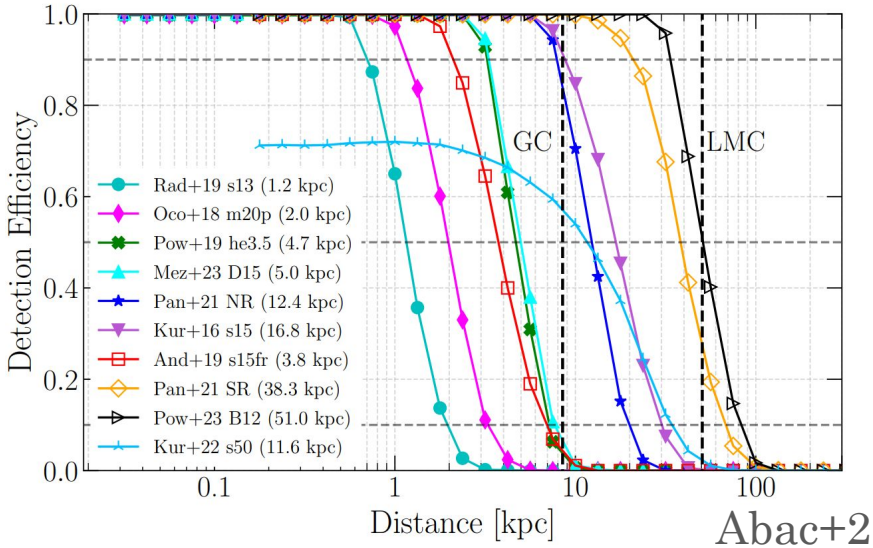


# Optically targeted searches

- While waiting for a Galactic CCSN, we can systematically constrain its engine with CCSNe at MPc range -> **optically targeted searches**
- **O1-O2 search** (Abbott+19, 1908.03584):
  - First observational constraints of a CCSN engine
- **O3 search** (Szczepanczyk+24, 2305.16146):
  - We could not beat the previous upper limits
- **SN 2023ixf search** (Abac+24, 2410.16565, special O4 paper):
  - GW energy emission: constraints improved by an order of magnitude

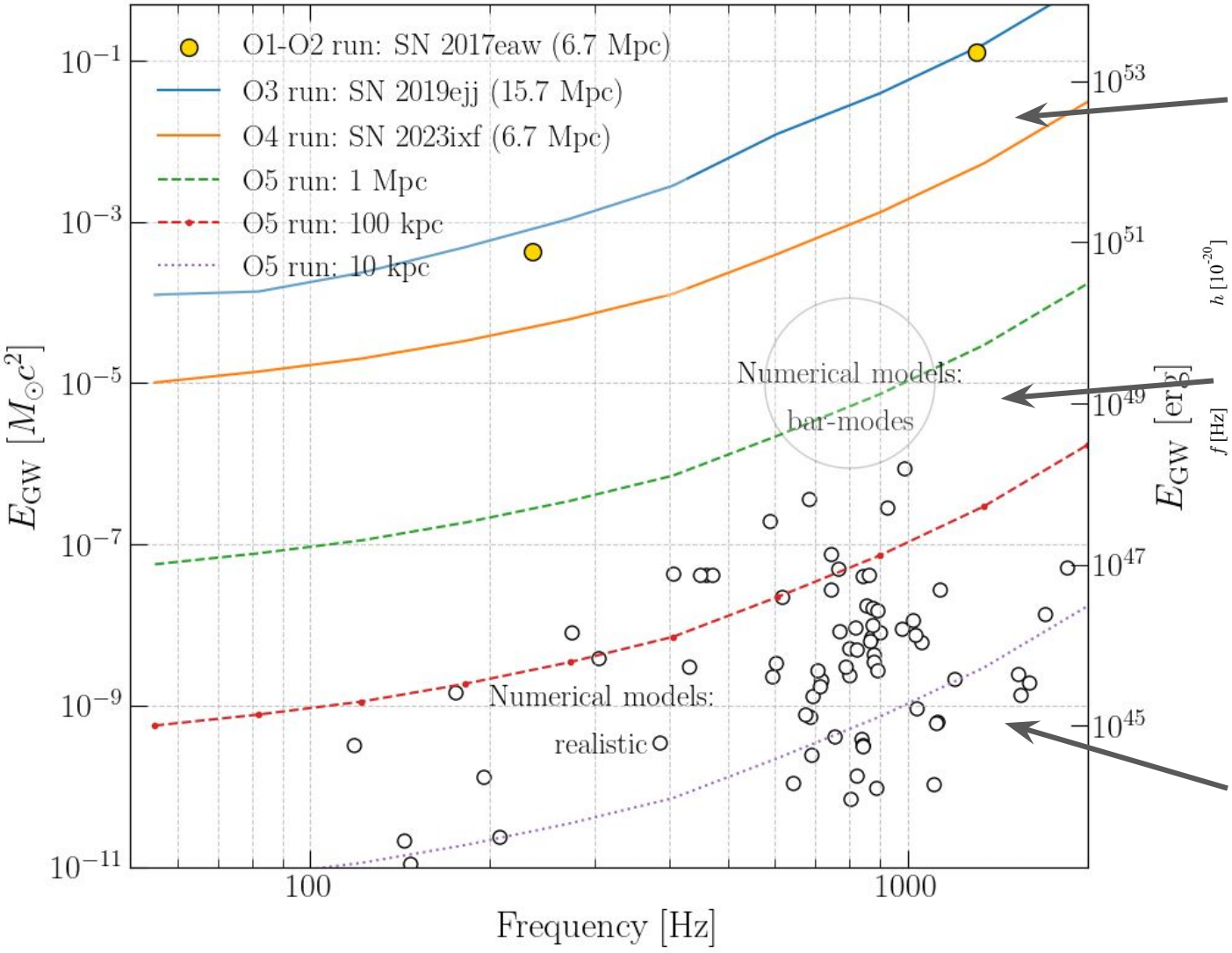


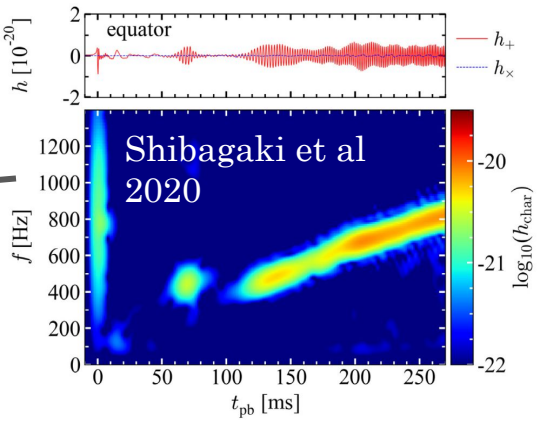
Szczepanczyk+24

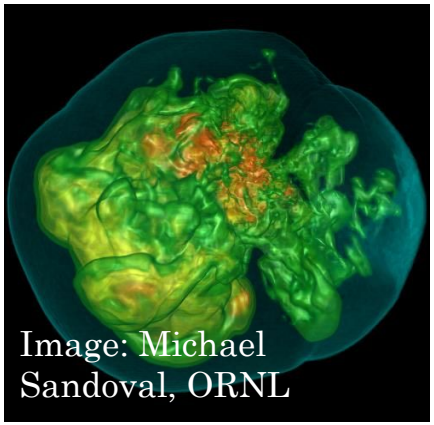


Abac+24

# When will we discover GWs?
## (realistically: Galactic CCSN)

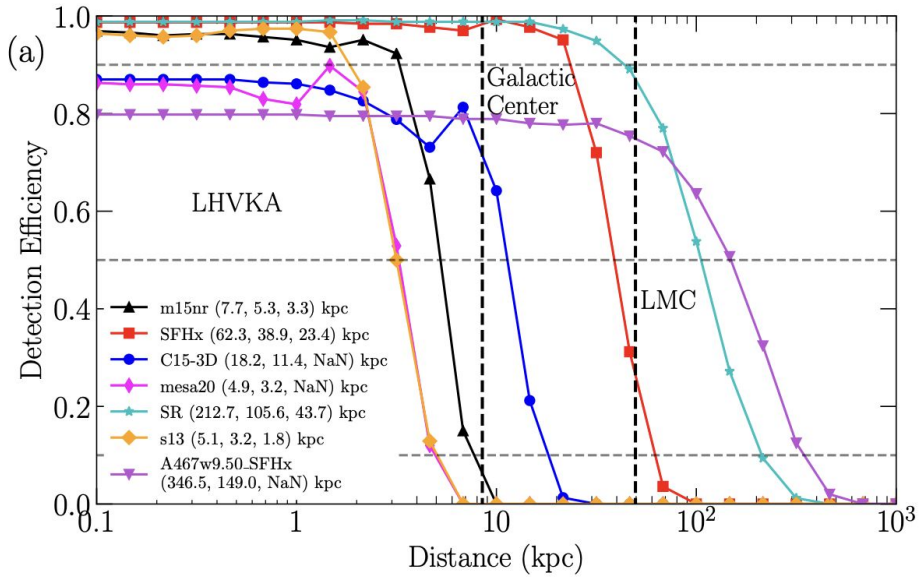


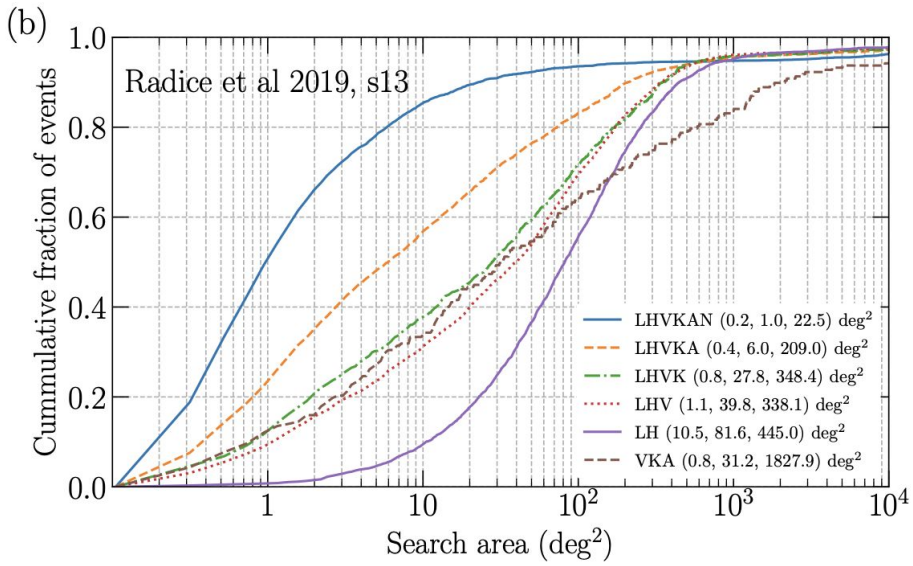


# 2.5G detectors (post-O5, before 3G)

- Szczepańczyk&Zanolin 2022 *Gravitational Waves from a Core-Collapse Supernova: Perspectives with Detectors in the Late 2020s and Early 2030s*, Galaxies 2022, 10(3), 70
- Detectors: LIGO Hanford, LIGO Livingston, LIGO India, Virgo, KAGRA, NEMO/Australia (?)
- Factor of 2 with respect to 2G detectors (conservative)
- Improved sky localization



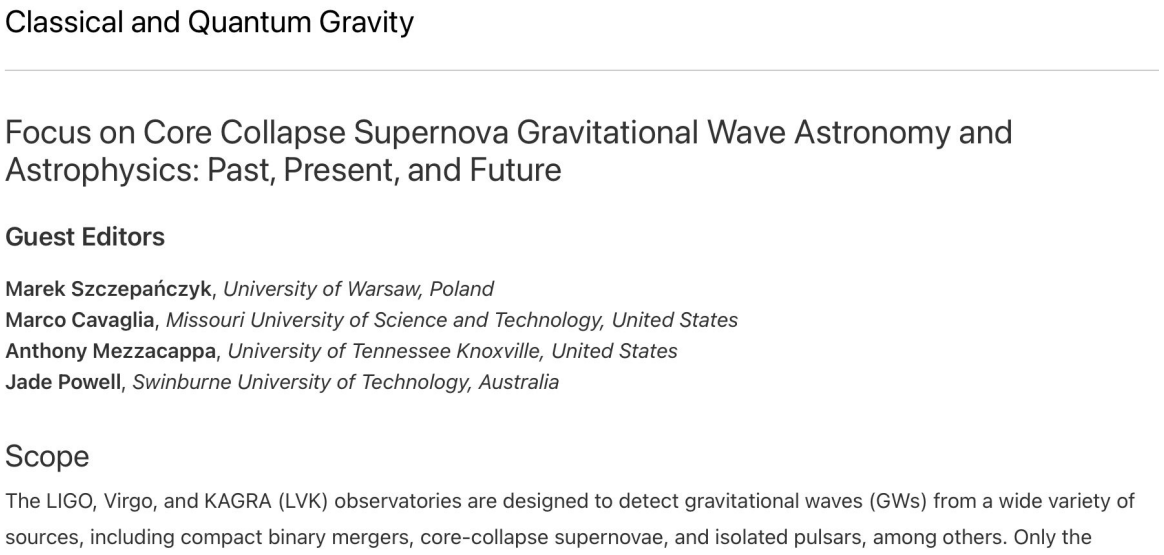
Are we ready, as communities, for a CCSN in Milky Way (or nearby)?

# SN2025gw: IGWN Symposium on CCSNe Bridging the Gap

- IGWN - International Gravitational-Wave Network, to replace LVK
- Symposium webpage: https://indico2.fuw.edu.pl/event/17/overview
- CCSNe are the most challenging astronomical events to model
  - Theory, GW, neutrino, EM, next 10 years
- Slack channel: please ask me to add you
- Youtube: playlist
- Large attendance of the Symposium: **Galactic CCSN - the next big thing?**

# SN2025gw: IGWN Symposium on CCSNe

- Classical and Quantum Gravity focus issue proceedings and White Paper (in progress): https://iopscience.iop.org/collections/cqg-250513-841
- A White Paper will summarize the state of the art of the fields and provide recommendations
- **Everybody can contribute**, regardless of attending the Symposium:
  - Regular articles
  - Proceedings papers
- Deadline (likely soft): 31 Dec 2025



Classical and Quantum Gravity

Focus on Core Collapse Supernova Gravitational Wave Astronomy and Astrophysics: Past, Present, and Future

**Guest Editors**

**Marek Szczepańczyk**, *University of Warsaw, Poland*
**Marco Cavaglia**, *Missouri University of Science and Technology, United States*
**Anthony Mezzacappa**, *University of Tennessee Knoxville, United States*
**Jade Powell**, *Swinburne University of Technology, Australia*

Scope

The LIGO, Virgo, and KAGRA (LVK) observatories are designed to detect gravitational waves (GWs) from a wide variety of sources, including compact binary mergers, core-collapse supernovae, and isolated pulsars, among others. Only the

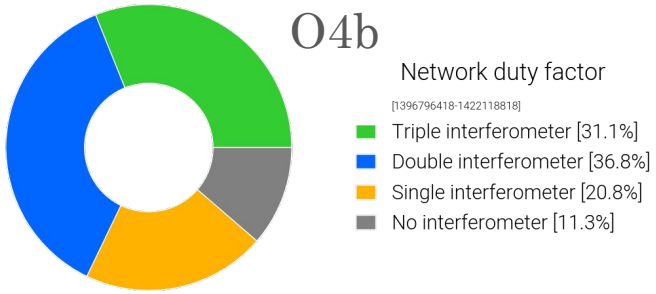
# SN2025gw: IGWN Symposium on CCSNe

Some lessons learned (work in progress on a White Paper):

- **A multimessenger (GW+nu+EM) detection program** for CCSNe is underway. Detailed discussion/decisions needed on the conditions for declaring a detection with a CCSN candidate (statistical significance, morphological constraints).
- **A multimessenger (GW+nu+EM) parameter estimation program** for CCSNe is underway. More areas can be expanded further like multi feature.
- **The interaction between EM, nu and GW communities could be improved**, for example what will we do explicitly if we have a Galactic CCSNe?
- While there is a consensus on predicted GWs, it is still not known what waveform amplitudes we may expect.
- Many uncertainties (**progenitor structure**...) and hidden assumptions (**transport treatment**...) are baked into the multi-physics supernova problem.
- Important to consider how supernova modelling needs to **evolve technically and organisationally** to make further progress and aid gravitational wave and multi-messenger astronomy.

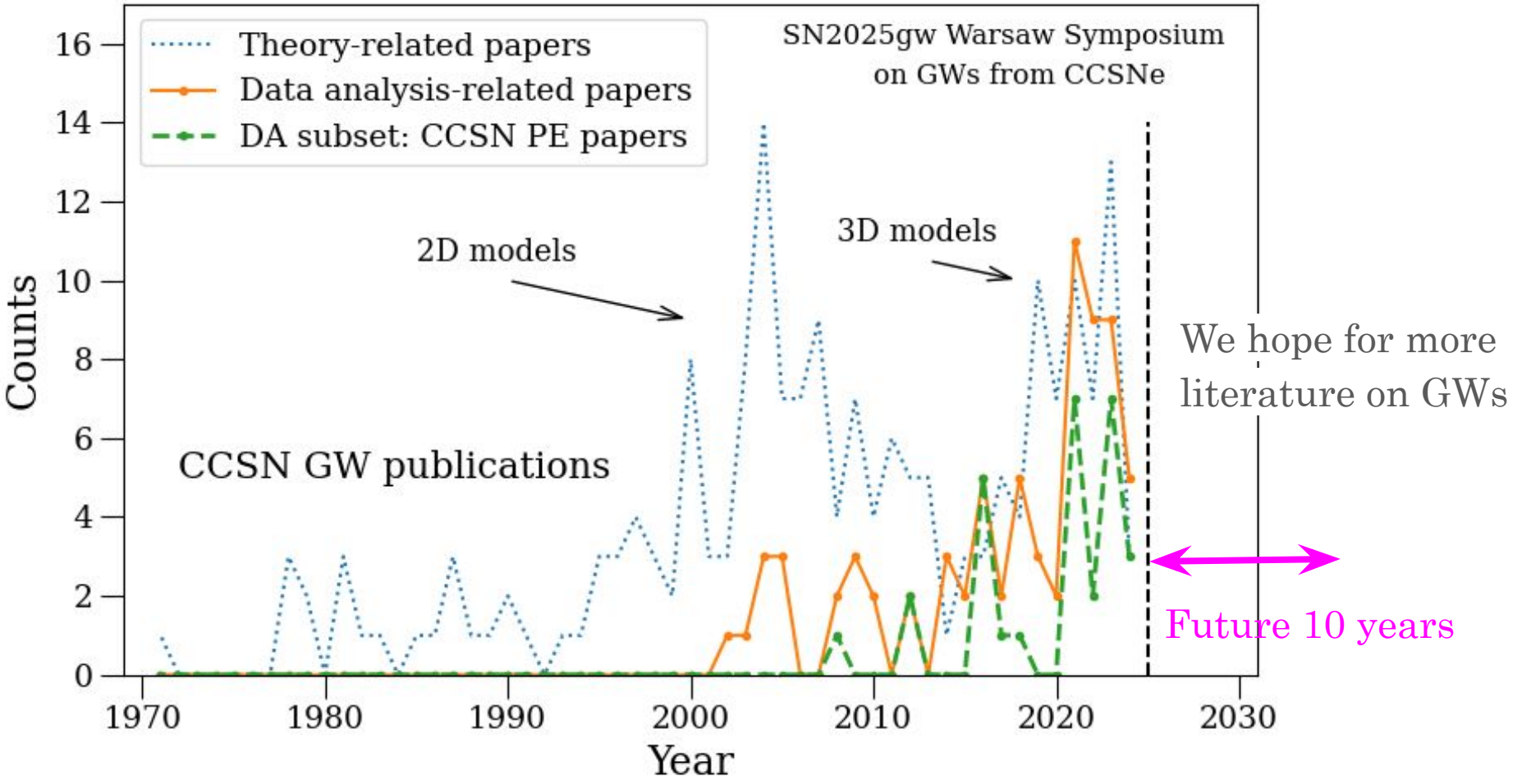
# FAQ: can LVK run continuously?
# Short answer: (we wish it too but) no…, because

- **„You cannot eat cookie and have cookie”**: you either make observations at a given sensitivity or do breaks between runs to improve the sensitivity (we do not want to run at O1 sensitivity for 20 years)
- **Detector upgrades**: replacing hardware, testing, calibrating
- **Interruptions during a run**: weather, maintenance, cleaning, equipment failures/malfunctioning, replenishing technical gases, locking etc.
- **Coincidence duty factor**: synchronizing detectors to get double and triple coincidence
- **Single detector data**: hard case for GW bursts (e.g. Cavaglia+20)




It may definitely help!

# Papers on GWs from CCSN

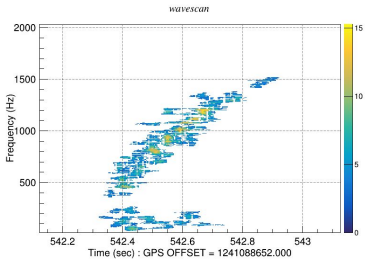



CCSN GW Literature, by Ewald Mueller:
https://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

# Low-latency Physical Inference work in progress

**Approach:**

**Implement in low-latency** **Existing methods**




Prompt convection

PNS oscillations

SASI/convection

Physical inference

30-60s: LVK public alert

Current infrastructure: human involvement for the physical inference

GW burst

second minute hour day week month

Time after core-collapse [sec]

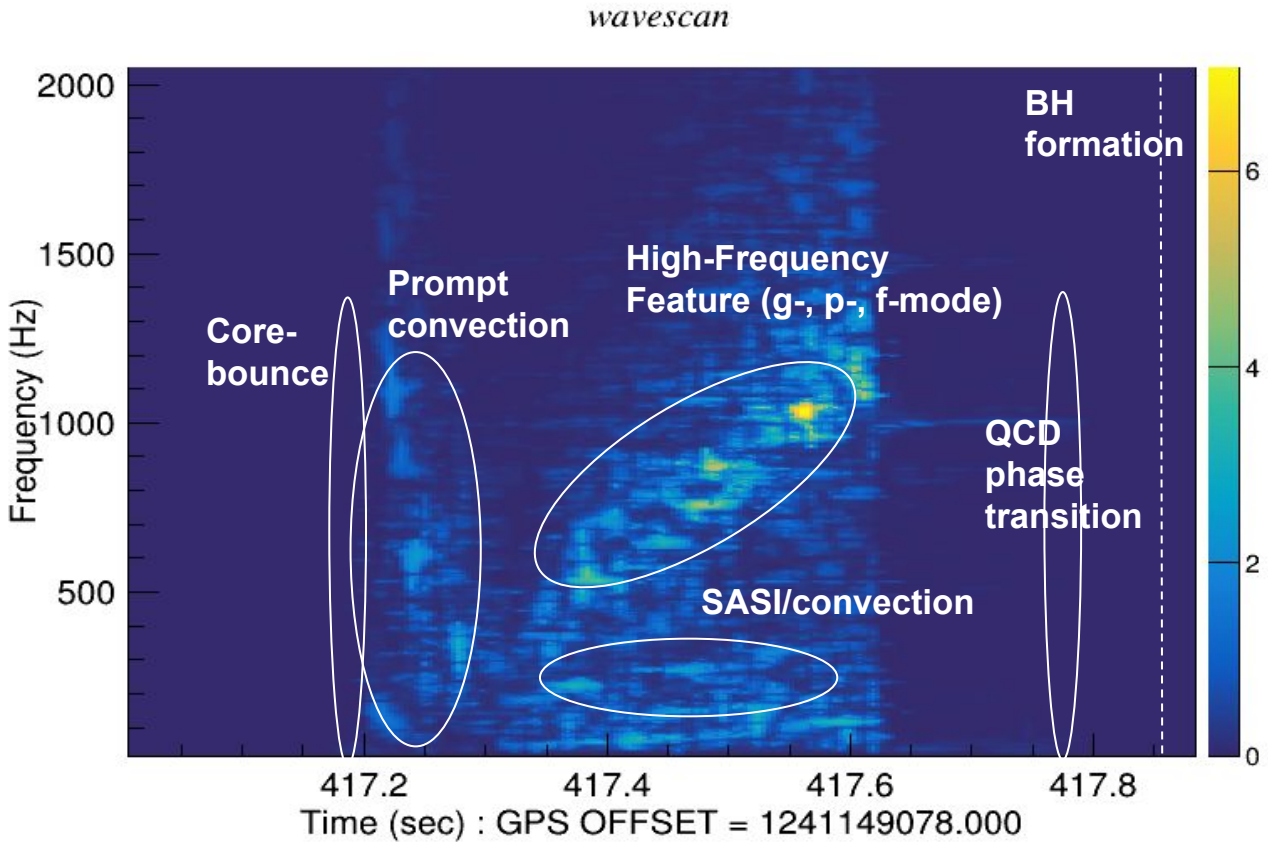
# Summary

- Next 10 years of GW detectors
  - Pushing facilities and prepare for ET/CE
- Are we ready?
  - *SN2025gw: IGWN Symposium on CCSNe*, first such a meeting of multimessenge community, likely first meeting of a series
  - White paper and proceedings in progress. Everybody is welcome to contribute!

***"Welcome SN 202X! Long-awaited for 2025-2026"***
Fukuoka Temple, 2019.10.23

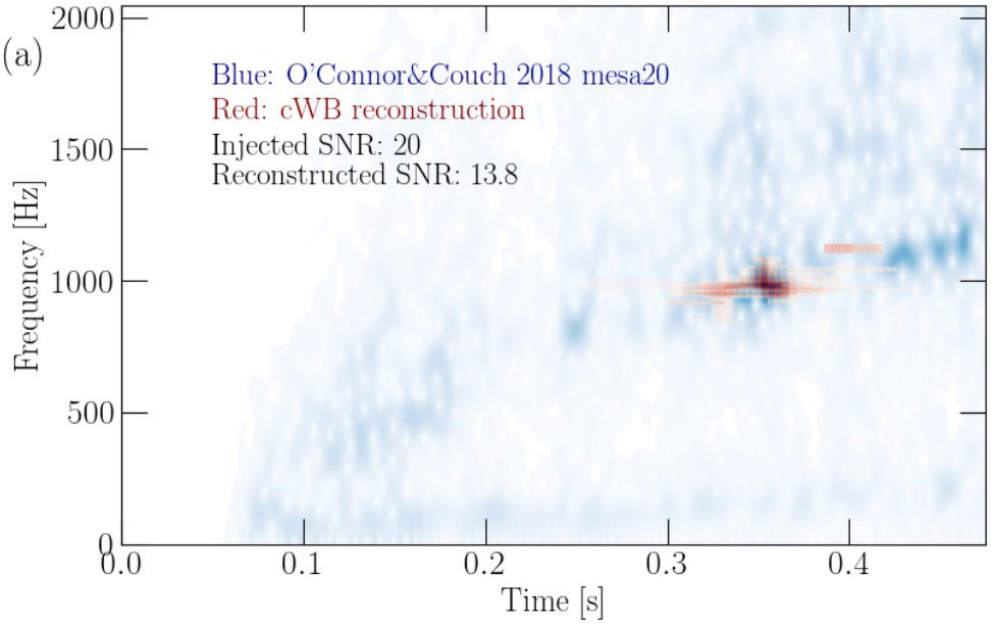
# Extras

# CCSN - parameter estimation



# GW detection challenges

More details: Szczepańczyk+21 (2104.06462)



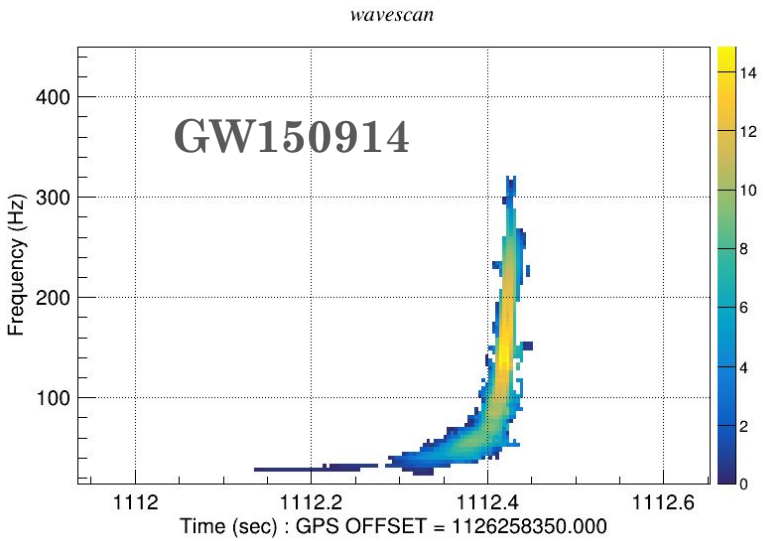

- Large time-frequency area, in contrast to GWs from BBHs
- Detectable signal-to-noise ratio of 20-30

# 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 template-based searches**
- cWB has detected:
  - **GW150914** - the very first GW (PRL 116, 061102)
  - **GW190521** - an intermediate mass binary black hole, 150 Msun (PRL 125, 101102)
  - **GW231123** - ~200 Msun BH (2507.08219)
  - It regularly detects GWs together with template-based searches
- The cWB contributes results to several LVK papers during each observing run.

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

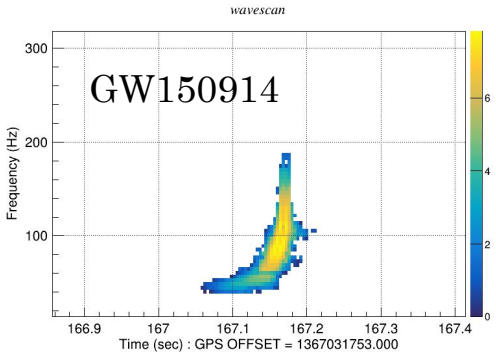
https://gwburst.gitlab.io/



# Model-independent searches classification

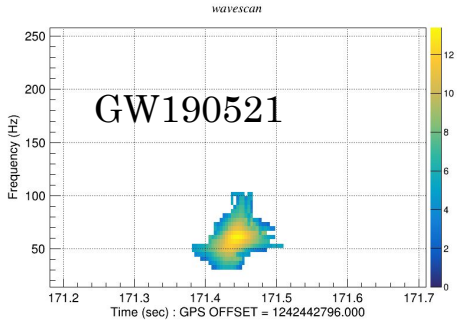
**Compact binary searches (minimally modeled)**

Binary black holes
Binary neutron stars
Black hole - neutron star




e.g. Mishra+23 (2201.01495)

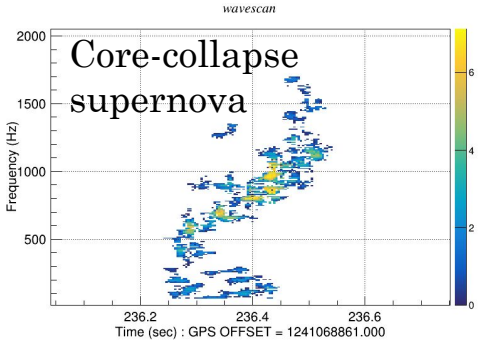
Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio




e.g. MS+21 (2009.11336)

**Generic searches (unmodeled)**

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



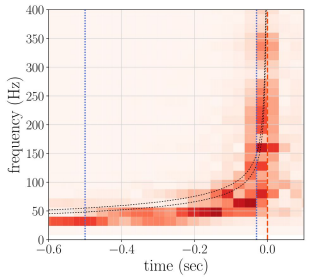

e.g. MS+24 (2305.16146)

**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)

# IGWN Symposium on CCSNe
## (IGWN - International GW Network)

Some lessons learned (work in progress on a White Paper):

- 2D simulations can be reliable for computing the frequency of the high-frequency feature, 3D are needed for the correct amplitudes.
- There is more effort in computing the GW emission for rapid rotation CCSNe. This is better than a few years ago, but we need to have quantitative comparisons
- The Core Bounce Phase of rapid rotation is templetable (still a few percent uncertainty in the amplitude).
- Some debate on the relationship of the SASI frequency in the GW and neutrino channel (f_gw twice f_nu is the leading expectation).
- Which mode is related to the high-frequency feature depends on the progenitor and simulations. Not clear yet how well we can distinguish between f and g modes from GW (modal analysis can be used to interpret the frequency evolution if the mode is established, but does not predict amplitudes)
- Usage of EM information is still in early phase. We currently use light curved for estimating the time of the shock breakout but many other areas can be used/expanded for MMA with CCSNe (spectra, progenitor mass estimation, nucleosynthesis).
- Some people are starting to work on “less unmodelled” configurations for CCSNe GW searches.

# Neutrino data

Simulation:

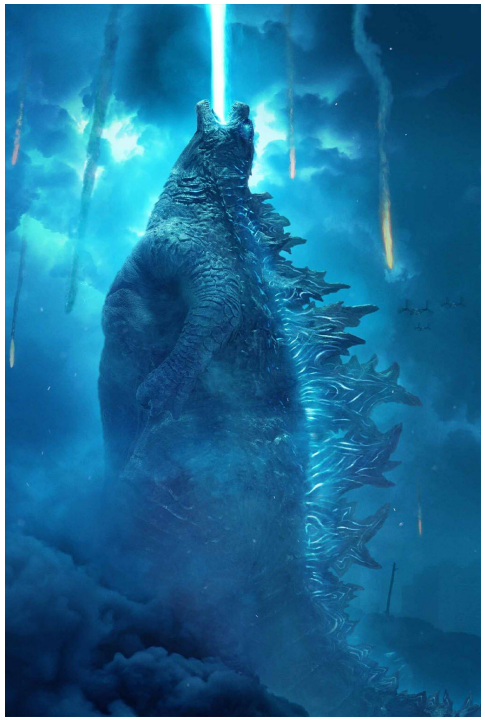
200 GB

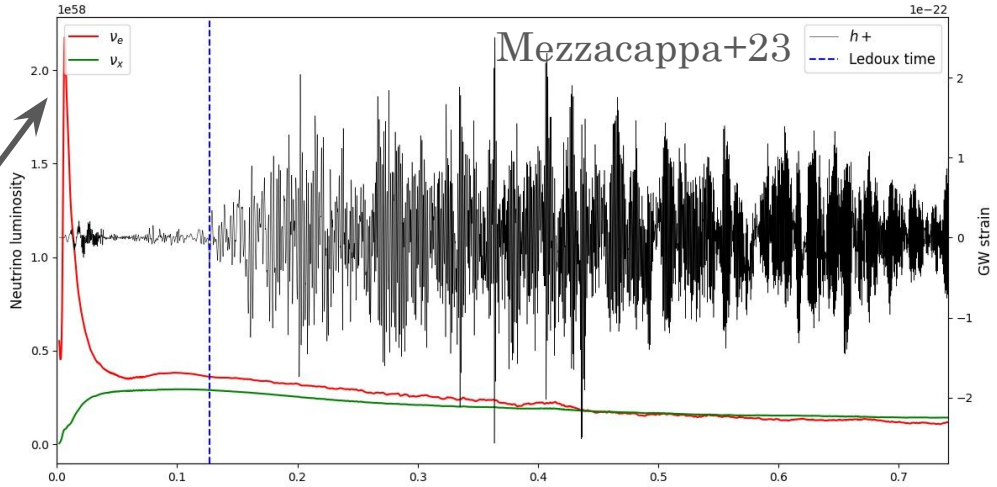
Reduced Data:

5 GB

Marek needs:

2 Bytes



(Observational)

time of the collapse