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

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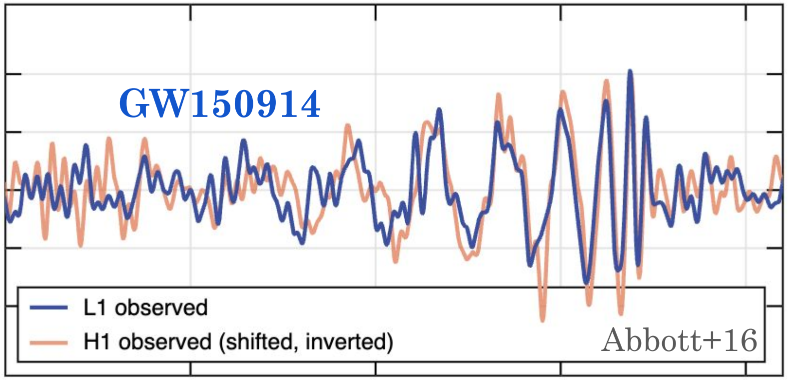
The 12th Conference of the Polish Society on Relativity
Będlewo, 02-07.08.2026

10 years of Gravitational-Wave Astronomy!

GW150914: discovery of gravitational waves on 14 Sep 2015



What's next?

Today's Talk: Core-Collapse Supernova (CCSN)

Common consensus:
Next CCSN in Milky Way will be one of the most important astronomical events of the century

Outline

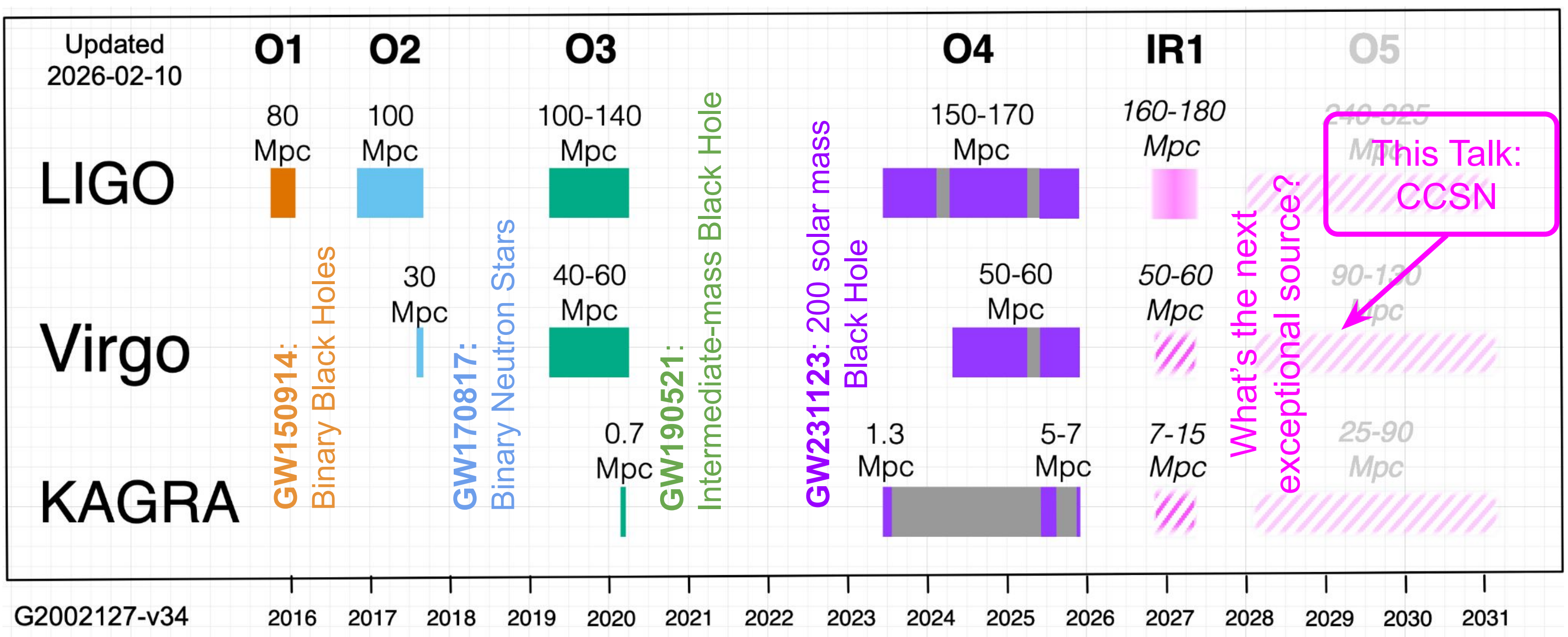
- GW Astronomy: Past and Future
- Core-Collapse Supernova (CCSN)
- Are we ready (as communities) for a nearby CCSN?
    - SN2025gw IGWN Symposium
    - Some lessons learned

GW Astronomy: Past and Future

Observing Timeline

Past 10 years

Future 10 years



O6 Goals:

1. pushing facilities
2. 3G pathfinders

A# (400-600 Mpc)

Virgo_nEXT (260-500Mpc)

KAGRA+

Australian detector?

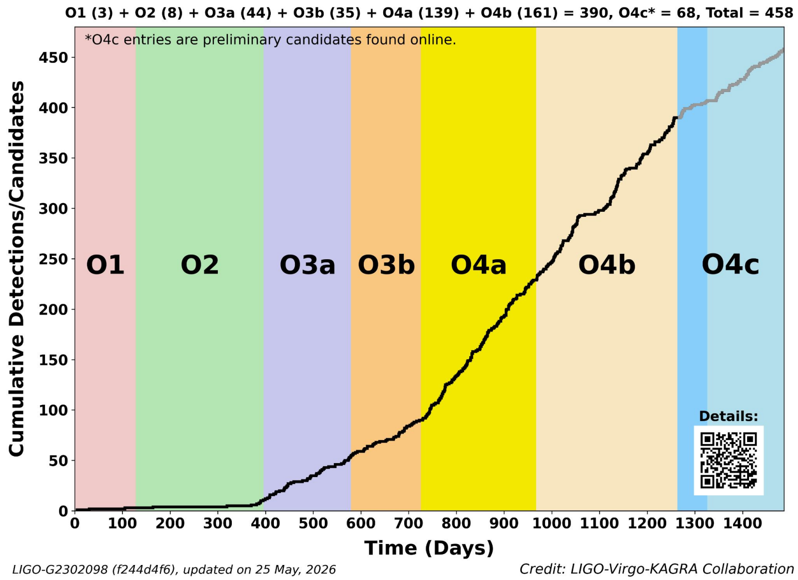
- O4: 24 months total, until 18 Nov 2025
- LIGO: up to 180 Mpc, around 160 Mpc
- Virgo: around 55 Mpc
- KAGRA: reached 7 Mpc

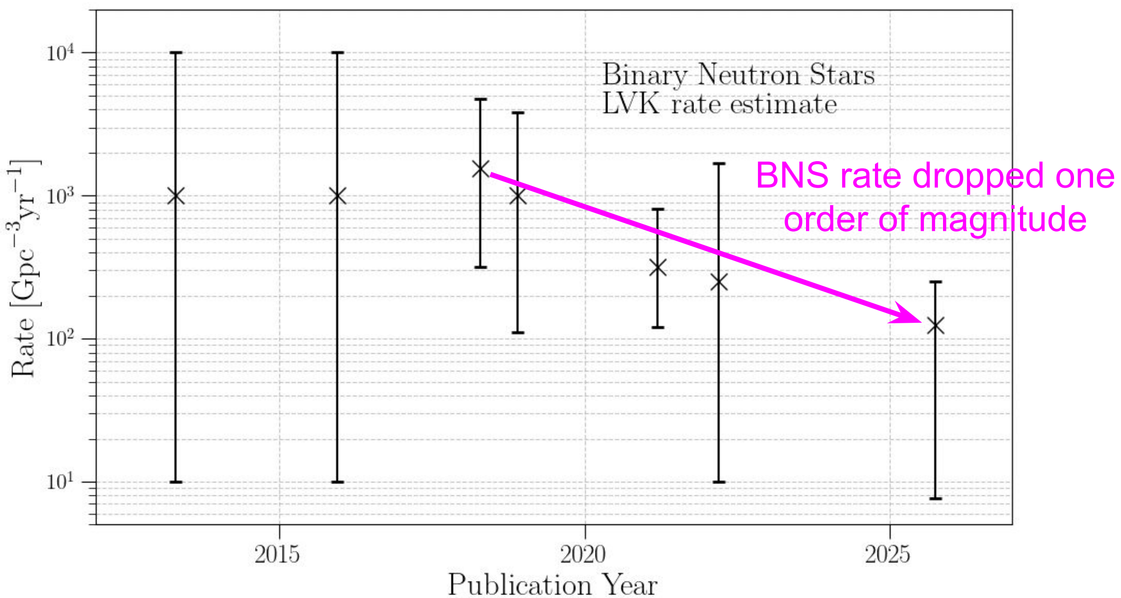
Observing news:
https://observing.docs.ligo.org/plan/

LVK papers:
https://pnp.ligo.org/ppcomm/Papers.html

Binaries and binaries so far…

- We have 458 GW events:
  - O1 - O4b: 390 GWs
  - O4c: 68 GW candidates
- Case of Binary Neutron Star (BNS) GW170817
  - Astronomers and Astrophysicists are so ready for the next multimessenger BNS
  - Optimistic rate - motivation for a new Australian detector
  - However, the estimated rate dropped one order of magnitude…





Potential new GW sources

Exceptional/special astrophysical sources might play an important role in our endeavor of exploring the Universe.
Potential targets:

- GW lensing
- Eccentric binaries
- Pulsar glitches
- Core-collapse supernovae

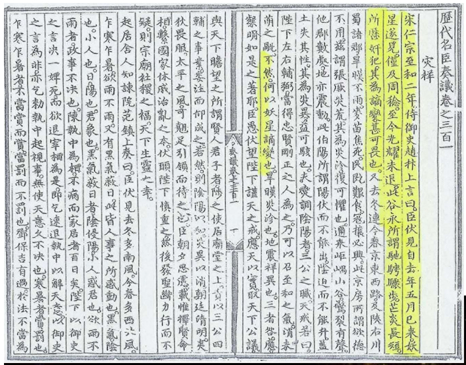
This Talk

But also:
- Hyperbolic encounters
- Multi-messenger: GWs and GRBs

Eager to discuss options!

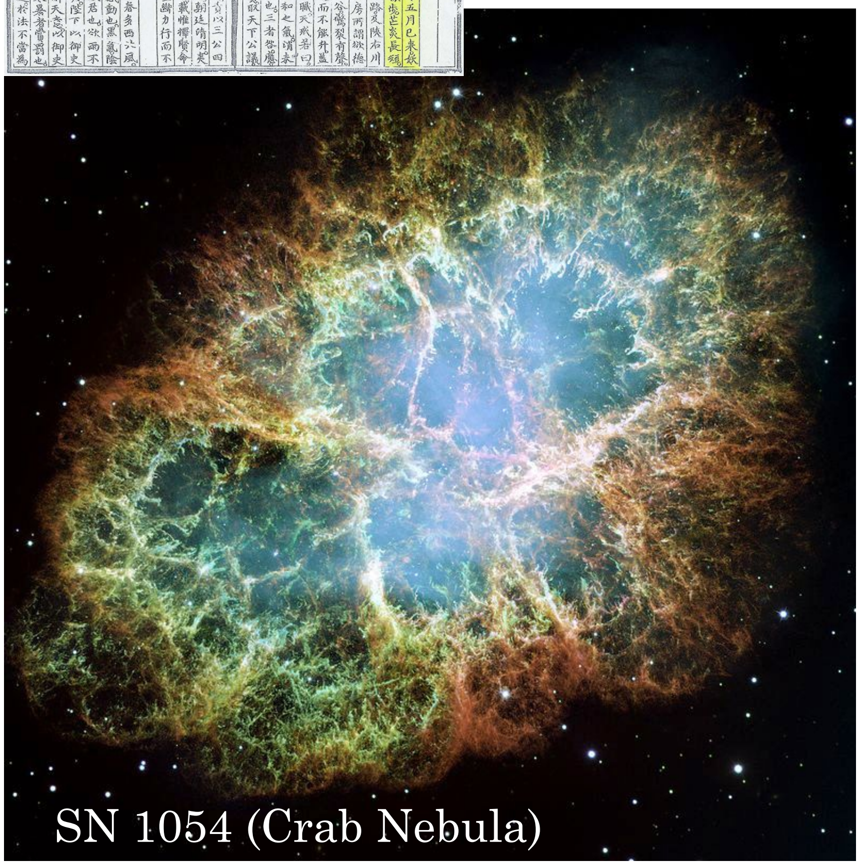
Core-Collapse Supernova

Core-Collapse Supernova (CCSN)



"Guest star"

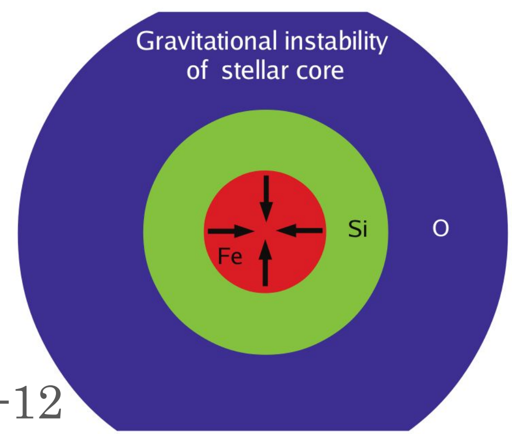
Zhao Bian's memorial to Emperor Renzong



SN 1054 (Crab Nebula)

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

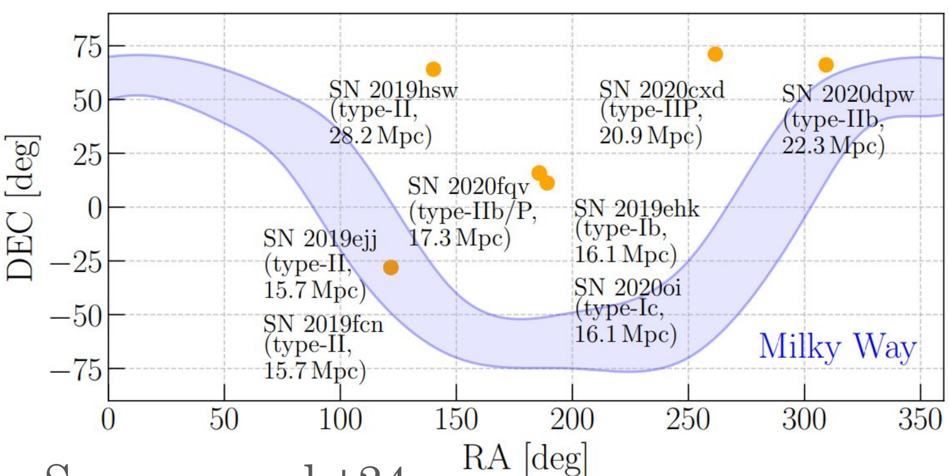
- Burning of a star: H → He → … → Fe
- After exceeding Chandrasekhar mass of 1.4 $M_{\odot}$ the iron core collapses.
- 99% of explosion energy escapes with neutrinos!
- Supernova problem: **why do the stars explode?**
- Explosion mechanism(s) is still unknown
- GWs are the only messengers to probe deep interiors of an exploding star



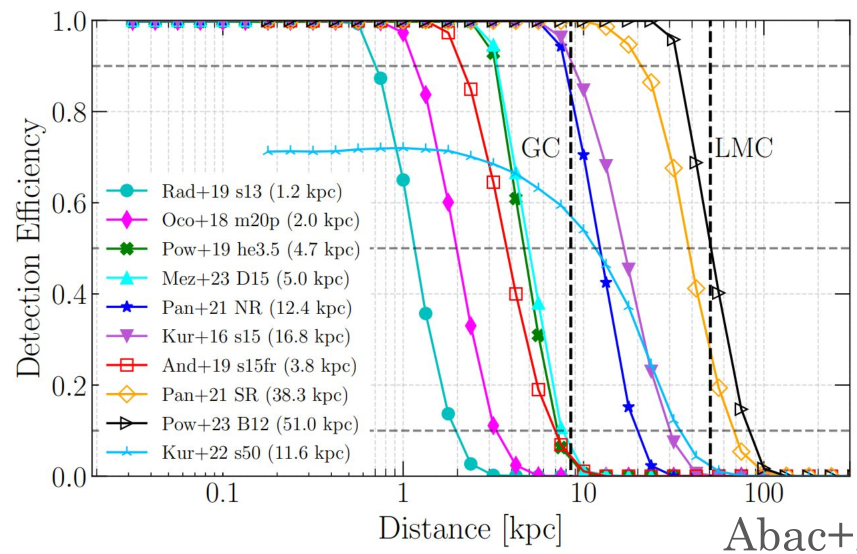
Janka+12

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](1908.03584)):
  - First observational constraints of a CCSN engine
- **O3 search** (Szczepanczyk+24, [2305.16146](2305.16146)):
  - We could not beat the previous upper limits
- **SN 2023ixf search** (Abac+24, [2410.16565](2410.16565), special O4 paper):
  - GW energy emission: constraints improved by an order of magnitude

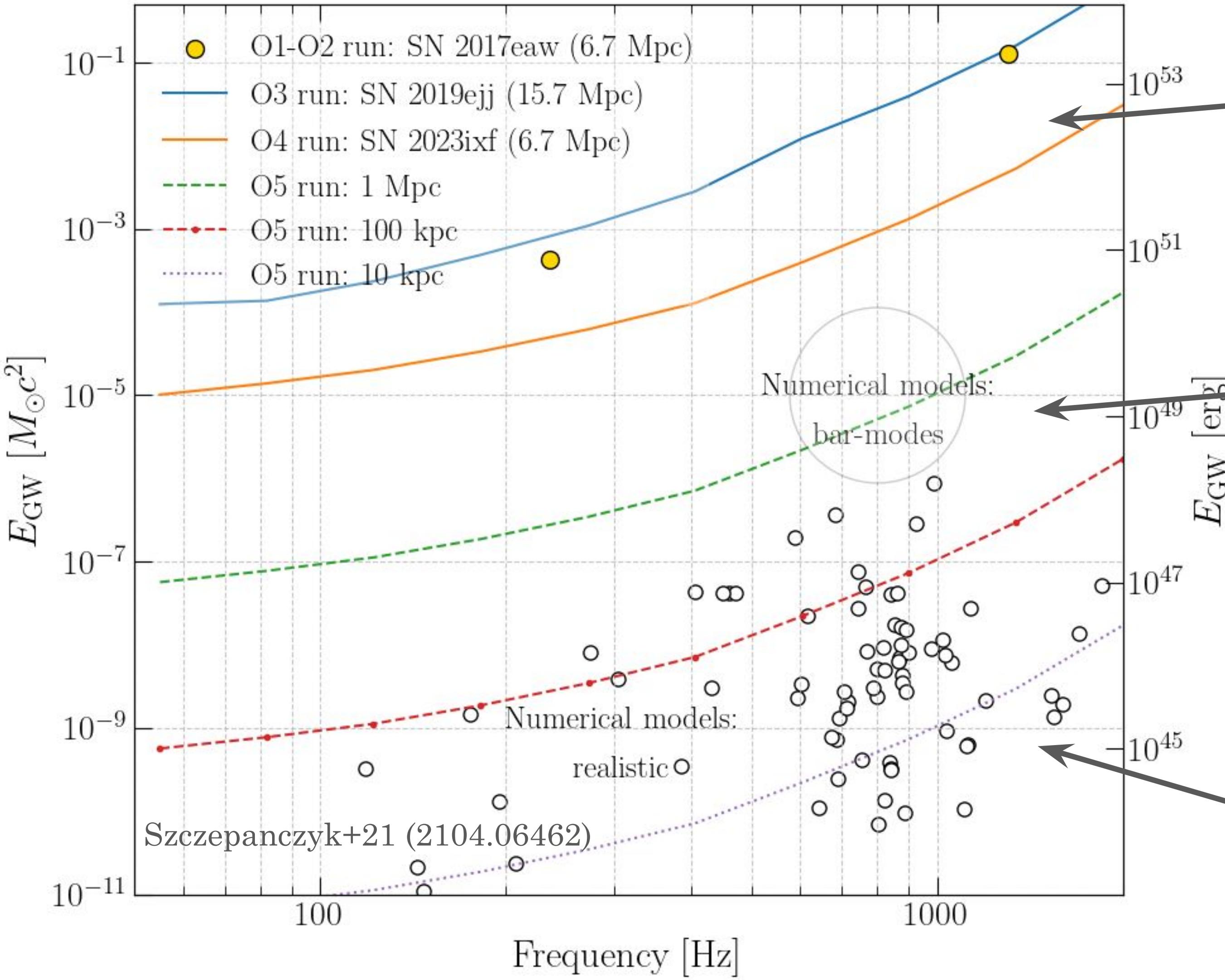


Szczepanczyk+24

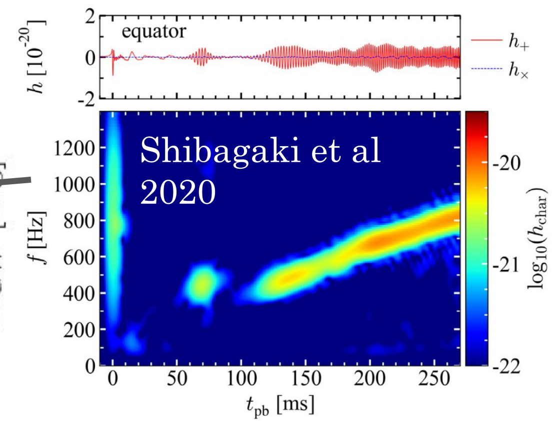


Abac+24

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




Ou et al 2004



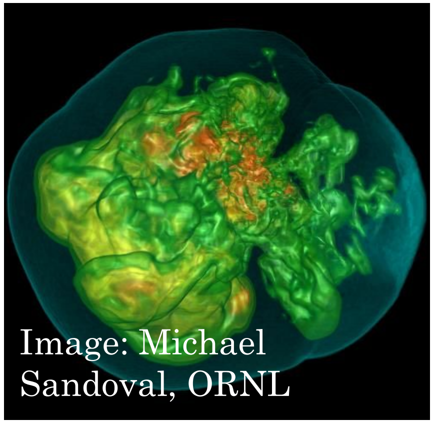
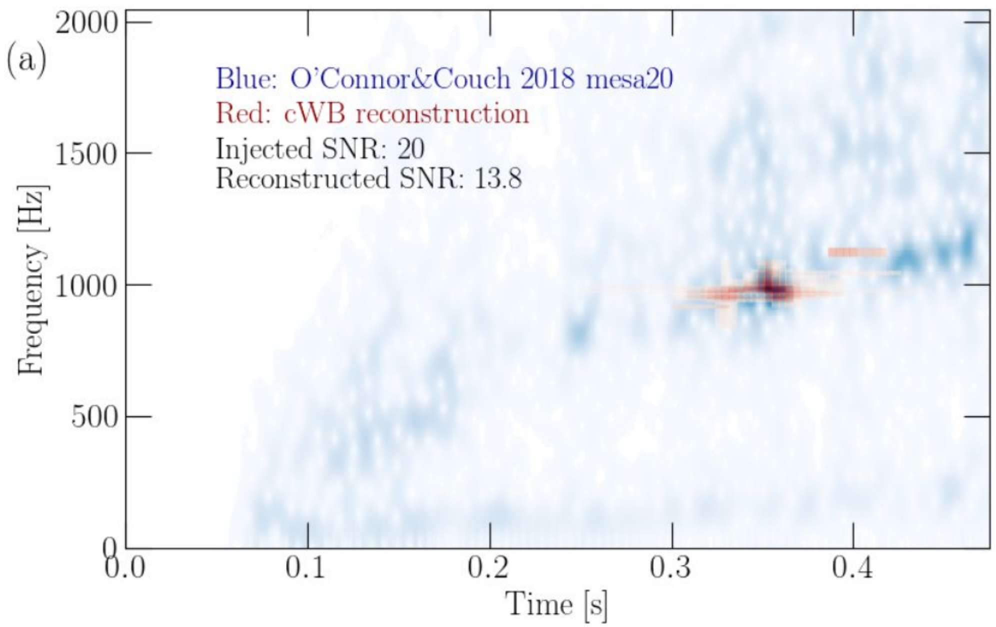


Image: Michael Sandoval, ORNL

GW detection challenges

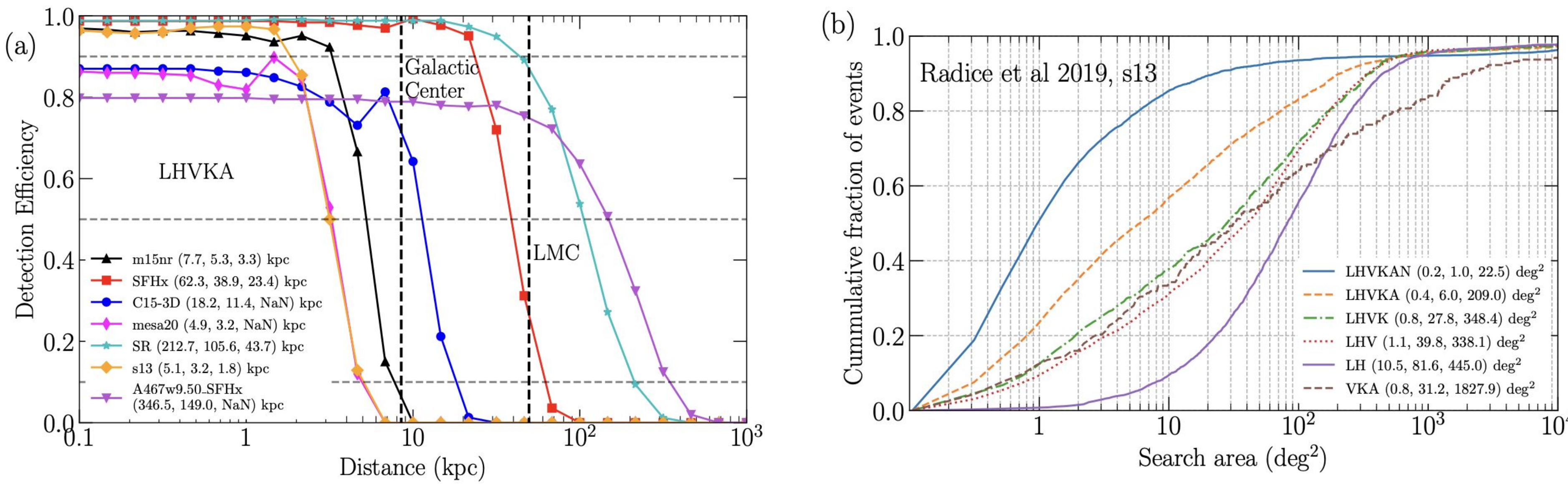
More details: Szczepańczyk+21 (2104.06462)



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

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
- 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: https://iopscience.iop.org/collections/cqg-250513-841
- Focus issue papers:
  - Expected almost 30 papers (successful focus issue!)
  - 9 papers are already published
- Work in progress on a **White Paper** that will summarize the state of the art of the field and provide recommendations

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

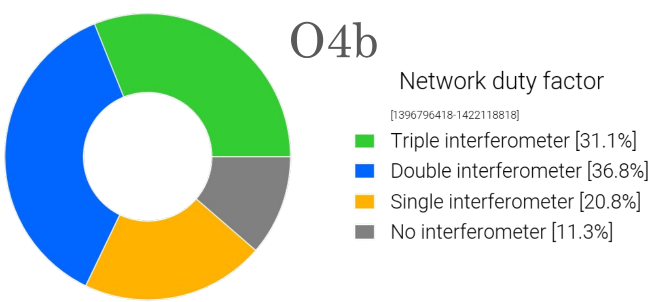
Some lessons learned (work in progress on a White Paper):

- **A multi-messenger (GW, neutrino and electromagnetic waves) 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 multi-messenger (GW, neutrino and electromagnetic waves) parameter estimation program** for CCSNe is underway. More areas can be expanded further. There are indications that GW memory could be detected as well (thanks also to current hardware improvements).
- **The interaction between electromagnetic, neutrino 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** (e.g., progenitor star structure) and hidden assumptions (e.g., neutrino transport treatment) are baked into the multi-physics supernova problem.
- Important to consider how supernova modeling needs to **evolve technically and organizationally** to make further progress and aid GW and multi-messenger astronomy.

FAQ: can LVK run continuously?
Short answer: (we wish yes 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)

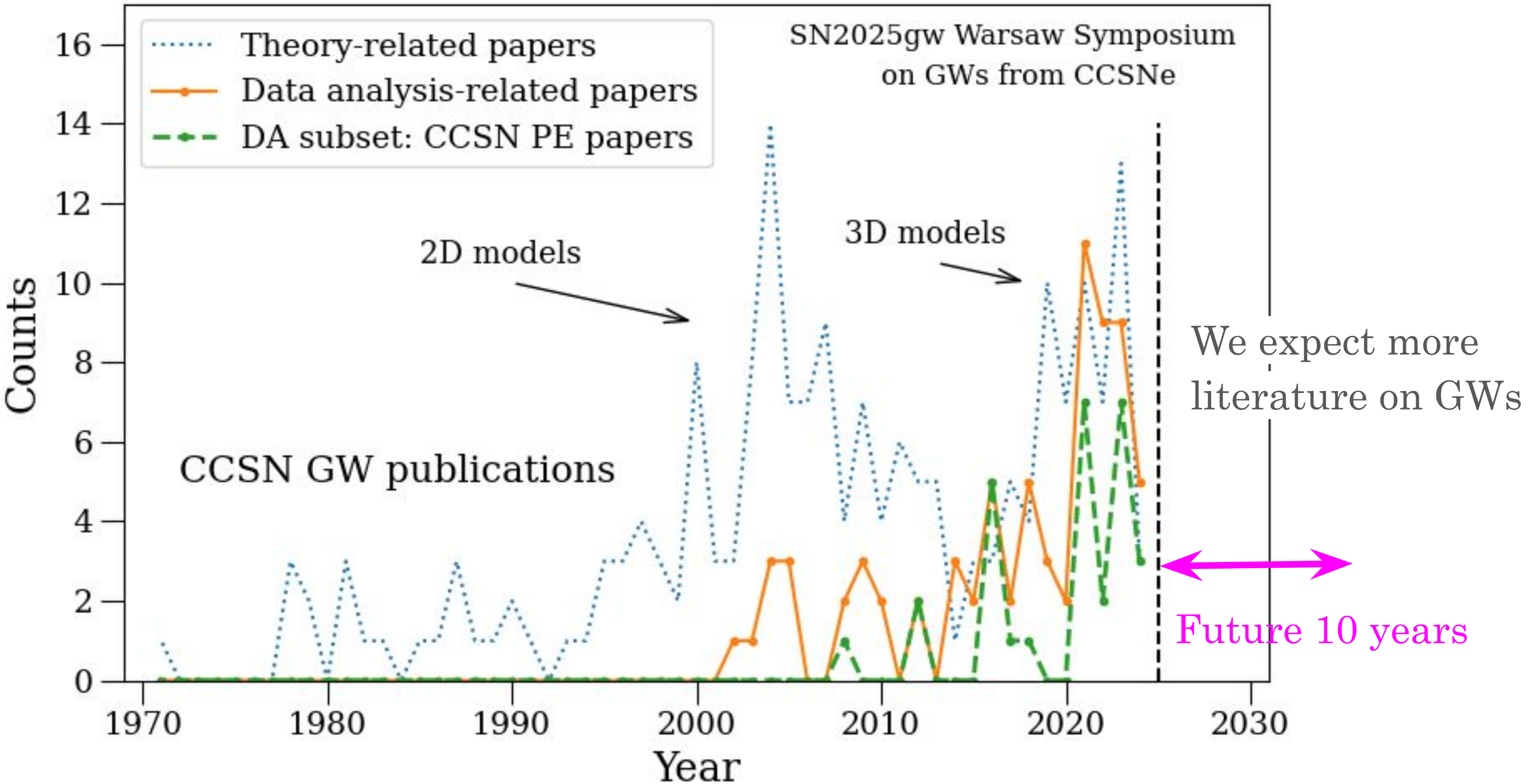
O4b



It may definitely help!

shutterstock.com

Papers on GWs from CCSN

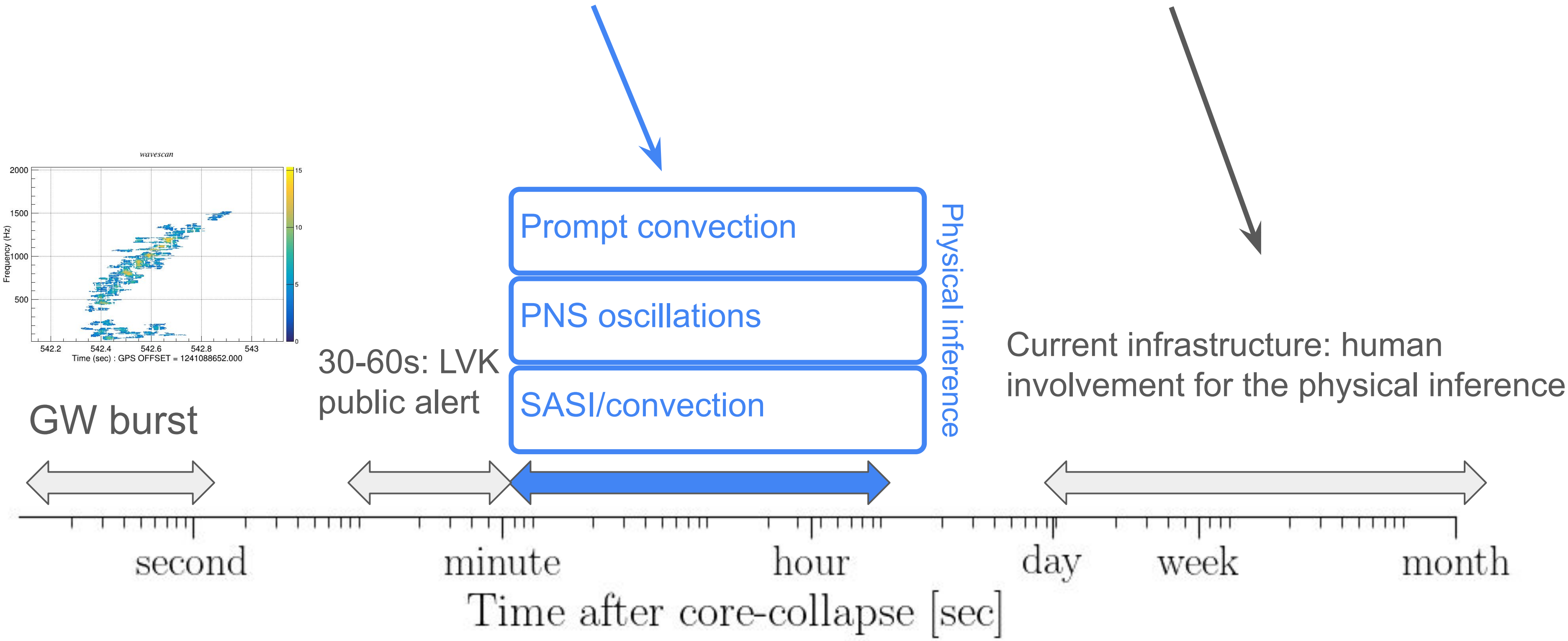


CCSN GW Literature, by Ewald Mueller:
https://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

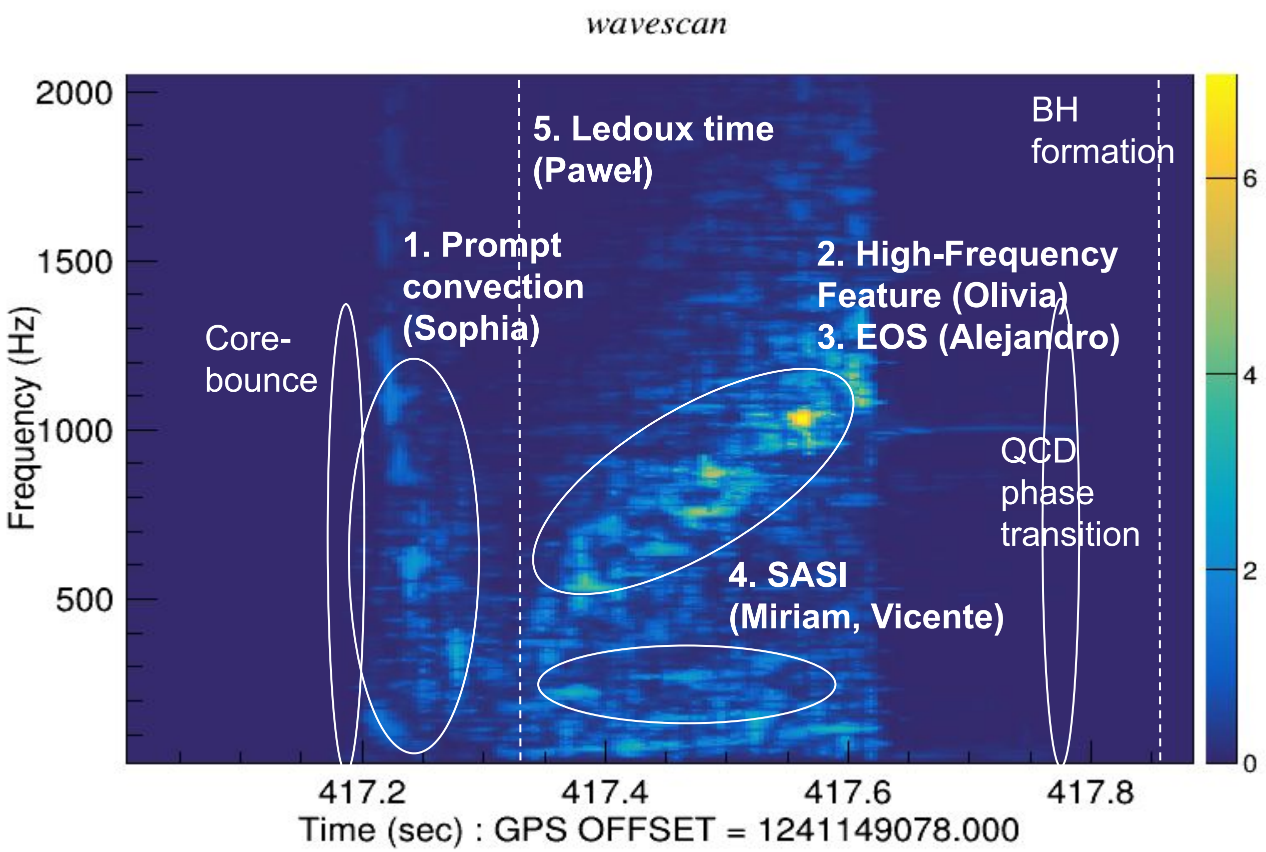
Low-latency Physical Inference
work in progress

Approach:

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



SN2025gw: Physical inference and Warsaw group contribution

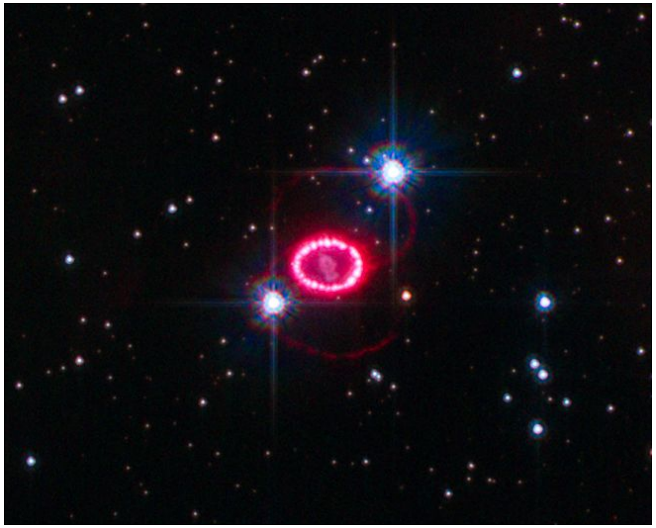


6. Emission Regions (Brajesh)
7. GW energy (Sreeta)
8. Source Orientation (Pratul)
9. CCSN Sound (Jan)
10. GW Representation (Stanisław)

Announcement:

SN2027gw: Second IGWN Symposium on CCSNe

- Date: 24 - 28 May 2027
- Place: Knoxville, Tennessee, USA
- 40th anniversary of SN 1987A



Summary

- Next 10 years of GW Astronomy
  - Special GW sources will likely drive the field
  - Pushing facilities and prepare for ET/CE
- Core-Collapse Supernova:
  - Next CCSN in Milky Way will be one of the most important astronomical events of the century
- Are we ready?
  - *SN2025gw: IGWN Symposium on CCSNe*, first such a meeting of multimessenger community
  - White paper and proceedings in progress
  - *SN2027gw: IGWN Symposium on CCSNe*, second meeting in Knoxville (USA) on 24-28 May 2027

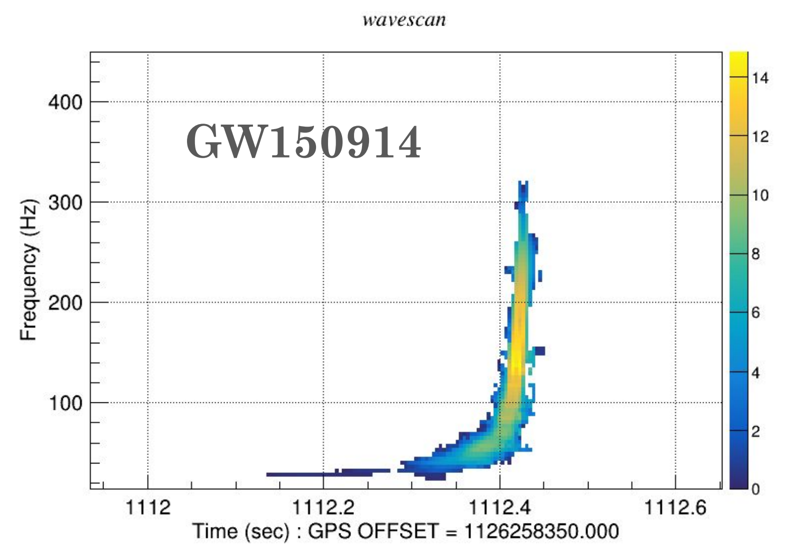
"Welcome SN 202X! Long-awaited for 2025-2026"
Fukuoka Temple, 2019.10.23

Extras

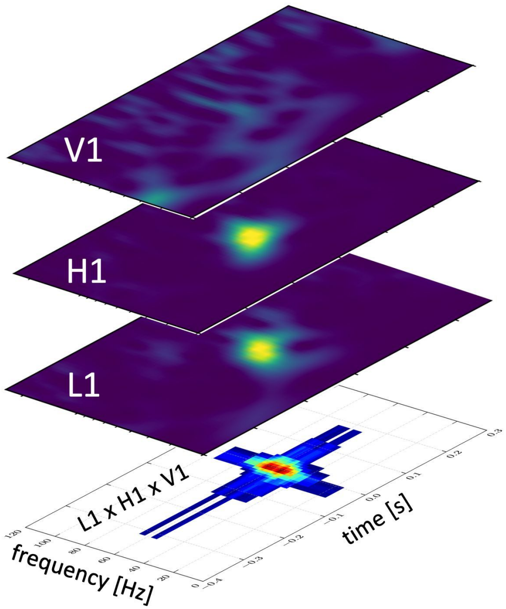
Model-independent searches

- **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 may use **minimal assumptions**, for example growing frequency over time in case of binaries
- **Complementary with template-based searches**
- cWB has detected:
  - **GW150914** - the very first GW
  - **GW190521 and GW231123** - intermediate-mass binary black holes
  - It regularly detects GWs together with template-based searches
- The cWB contributes results to several LVK papers during each observing run.

https://gwburst.gitlab.io/



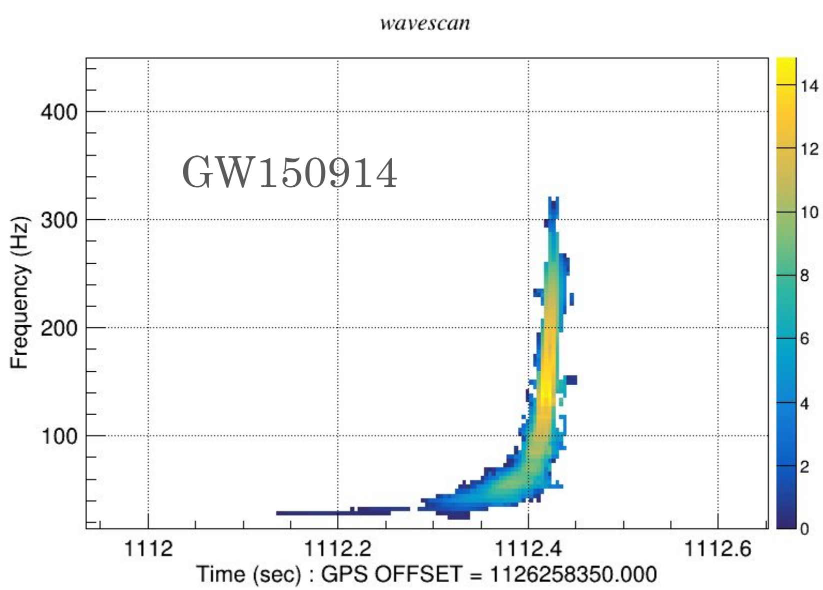
coherent WaveBurst (cWB)



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

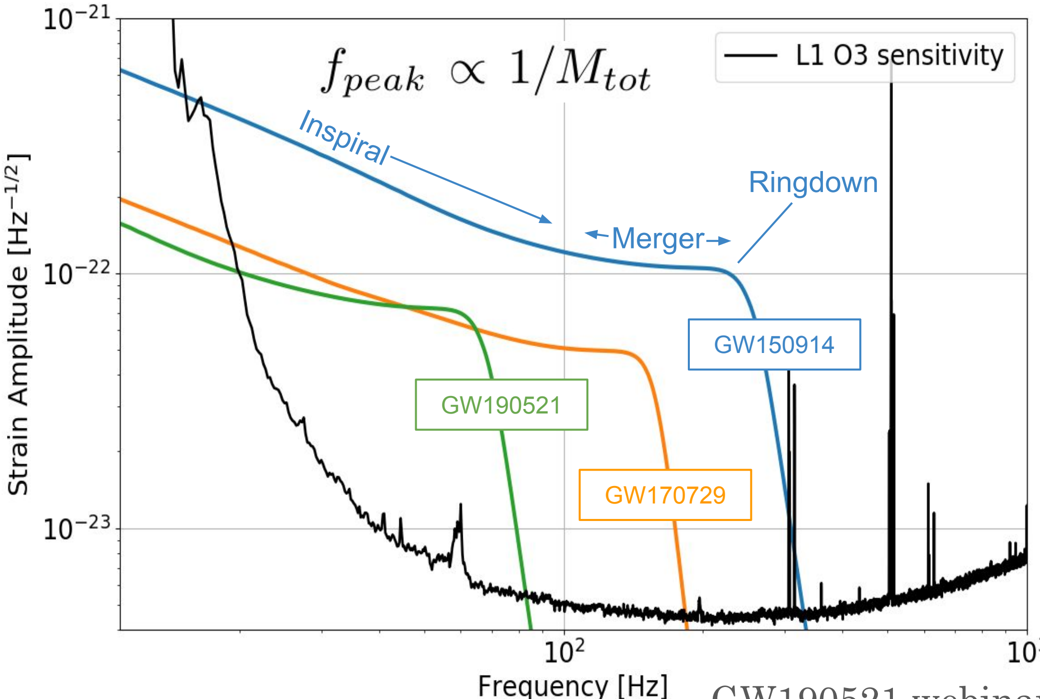
- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

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

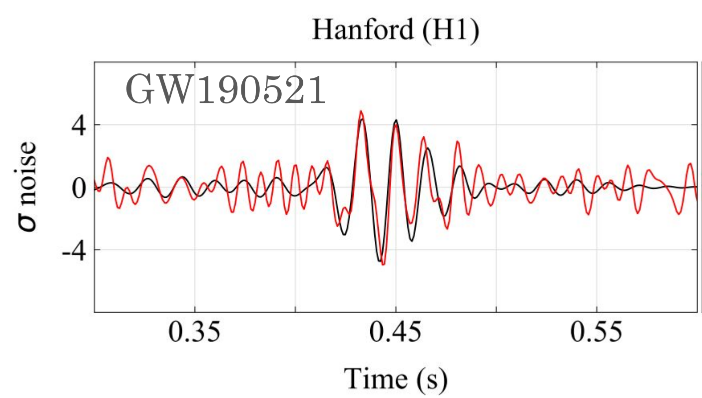


Intermediate-mass black holes, GW190521 and GW231123

- **Intermediate-mass black holes** (IMBHs) - between stellar mass (100 $M_\odot$) and supermassive (10^5 $M_\odot$). The origin is not yet well understood. Exploring:
  - Probing pair-instability mass gap (Stars with He mass in (64 $M_\odot$, 135 $M_\odot$)
  - Formation channels
  - Most distant GW sources
- No chirping structure
- Peak frequency is inversely proportional to the total mass.
- **GW190521** - first conclusive evidence of an IMBH (see MS+21, [2009.11336](2009.11336))
- **GW231123** - the heaviest black hole detected so far.

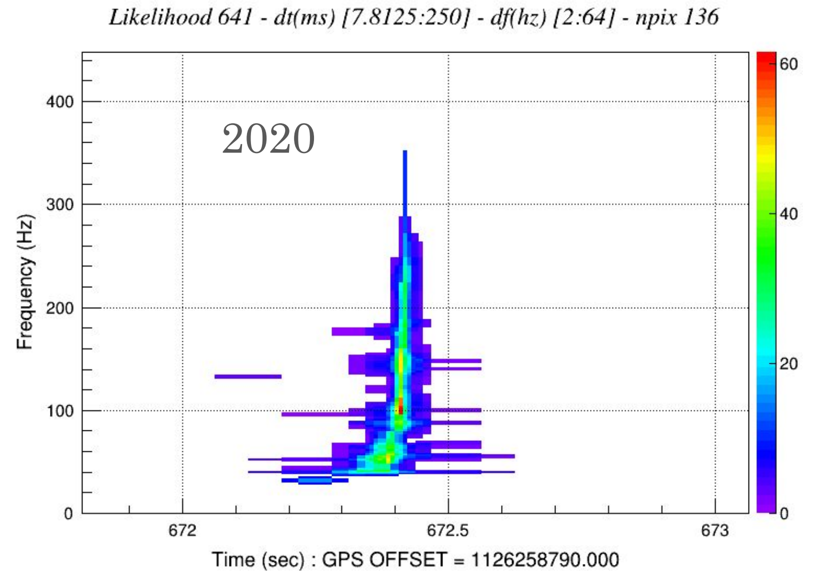


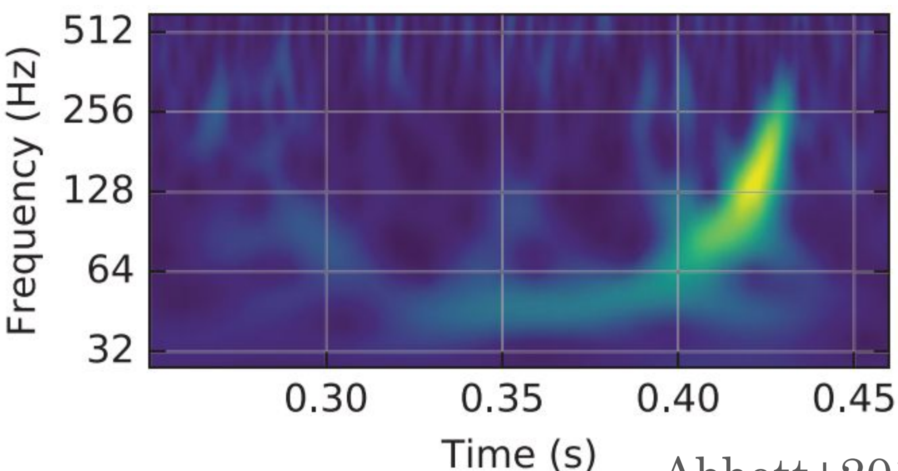
GW190521 webinar



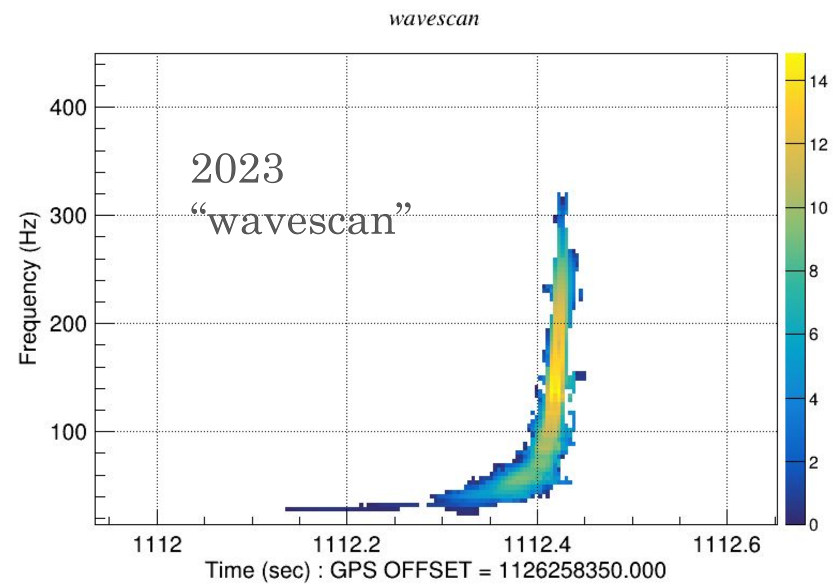
Time-frequency maps (GW150914 example)

- 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))





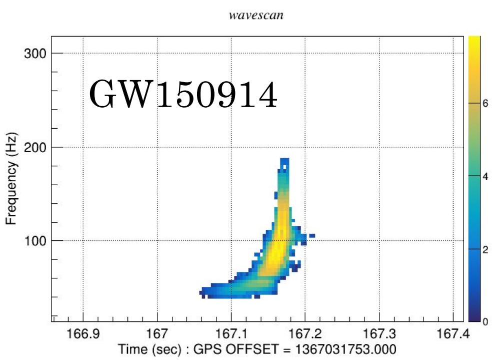
Abbott+2016



Model-independent searches classification

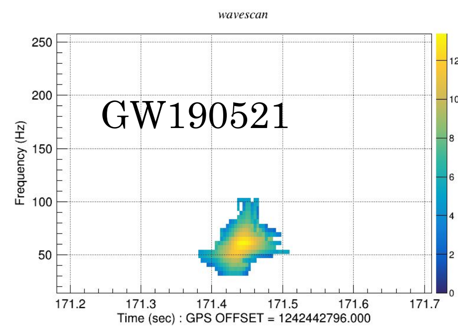
Compact binary searches (minimally modeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



e.g. Mishra+23 (2201.01495)

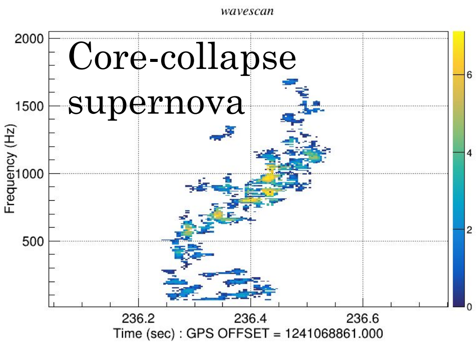
Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



e.g. MS+21 (2009.11336)

Generic searches (unmodeled)

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



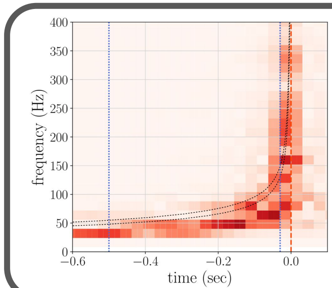
e.g. MS+24 (2305.16146)

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)

Exceptional/special GW sources
(and my top pics for O5 in blue)

Exceptiona/special astrophysical sources might play an important role in our endeavor of exploring the Universe.

- **New GW source populations**:
  - Compact binaries: binaries with eccentric orbits, hyperbolic encounters, head-on collisions, extreme mass ratio, sub-solar mass binaries, lensed binaries
  - GW bursts: core-collapse supernova (CCSN), neutron star or pulsar glitches, cosmic strings High-risk high-reward, the second part of my talk
- **Multi-messenger GW sources** (electromagnetic waves, neutrinos, cosmic rays): CCSN, binary neutron stars merger and post-merger, neutron-star - black hole
- **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
  - Beyond GR: GW echo, beyond-quadrupolar GW polarizations

Is it possible to model accurately every GW source? Not really…

→ **Model-independent (GW bursts) searches**

IGWN Symposium on CCSNe

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.