

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

Marek Szczepańczyk

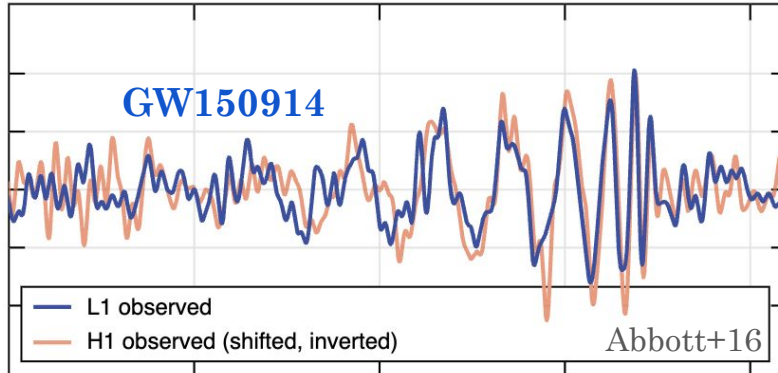
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Three-days of brainstorming workshop - multimessenger astrophysics with core-collapse supernovae and binary neutron star mergers,
Wrocław 09-11.09.2026

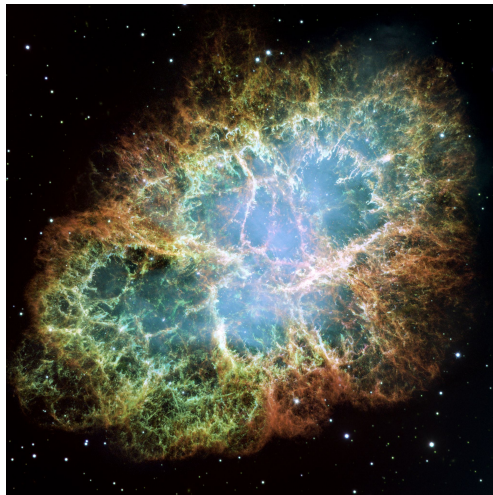
10 years of Gravitational-Wave Astronomy!

GW150914: discovery of gravitational waves on 14 Sep 2015



What's next?

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



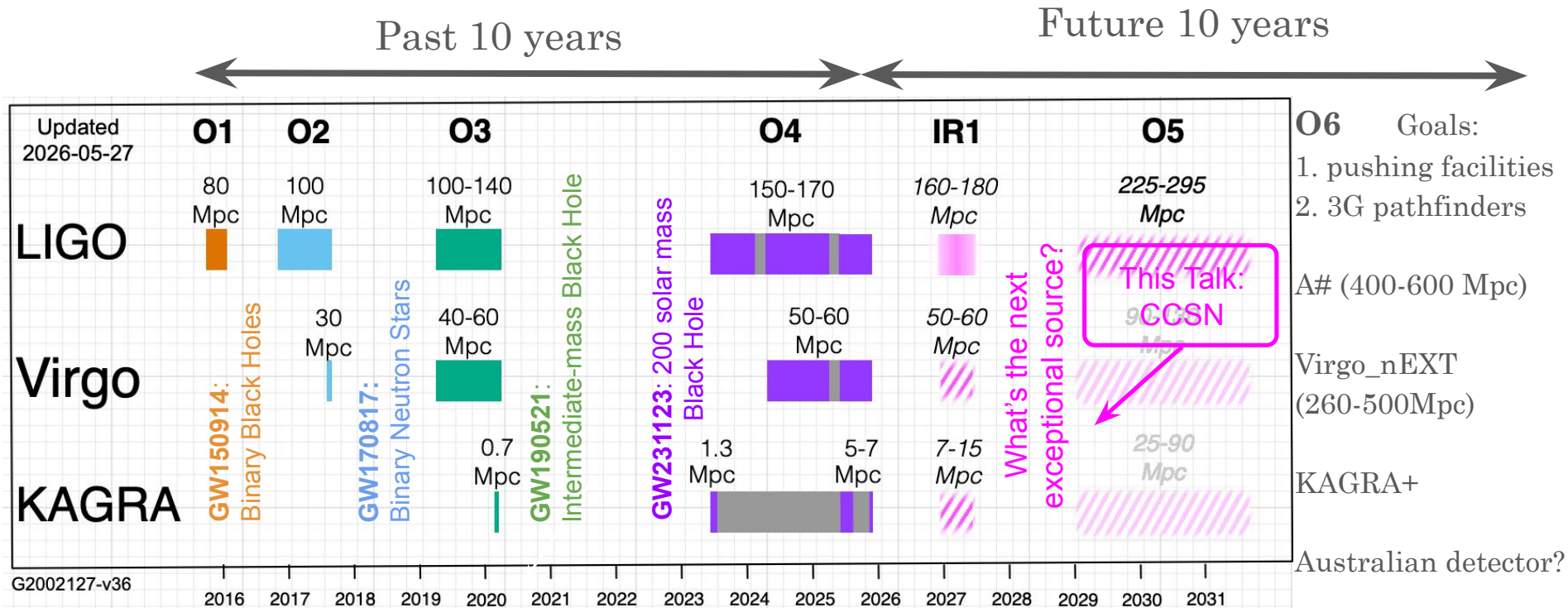
Common consensus:
*Next CCSN in Milky Way will be
one of the most important
astronomical events of the century*

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



- 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>

Exceptional/special GW sources

(and my top pics for O5 in blue)

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

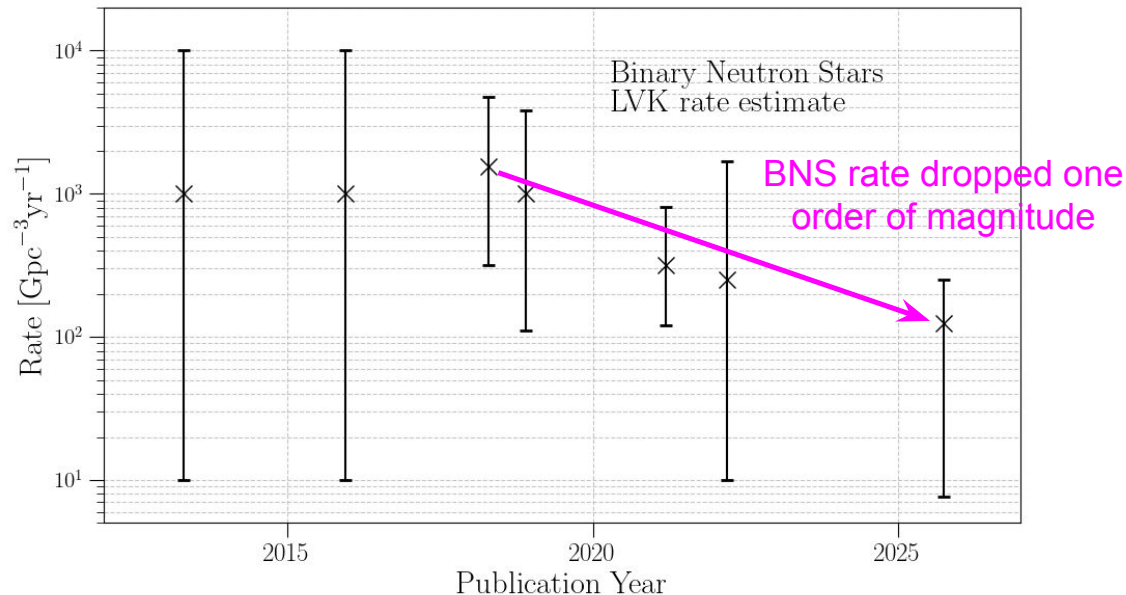
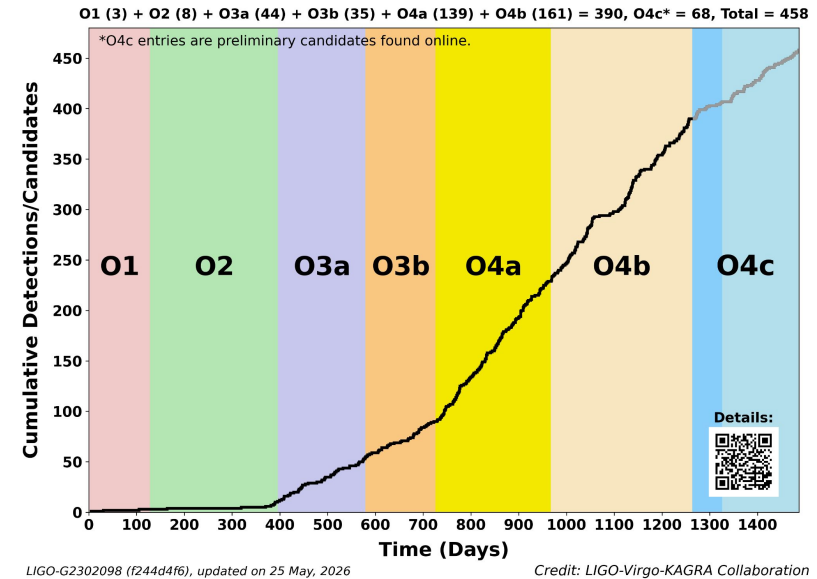
- **New GW source populations:**
 - Compact binaries: **binaries with eccentric orbits**, hyperbolic encounters, head-on collisions, extreme mass ratio, sub-solar mass binaries, **lensed binaries**
 - GW bursts: **core-collapse supernova (CCSN)**, neutron star or pulsar glitches, cosmic strings **High-risk high-reward**
- **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**

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

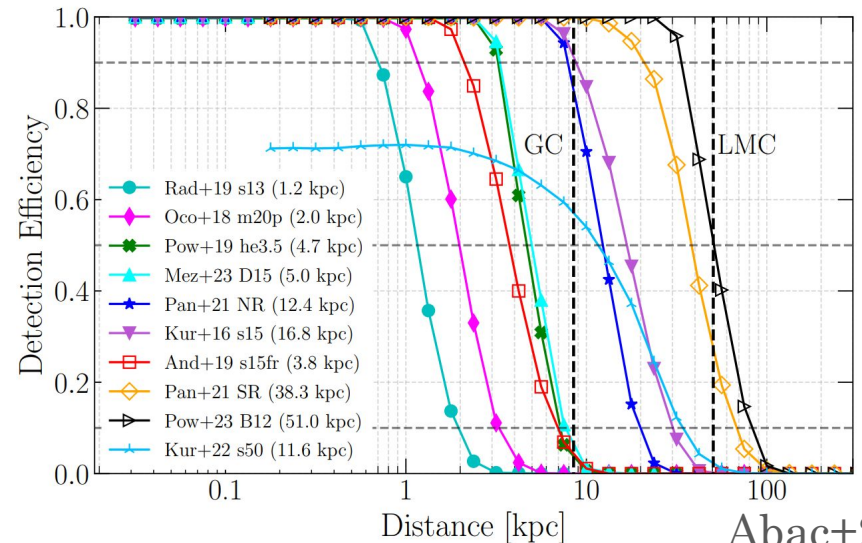
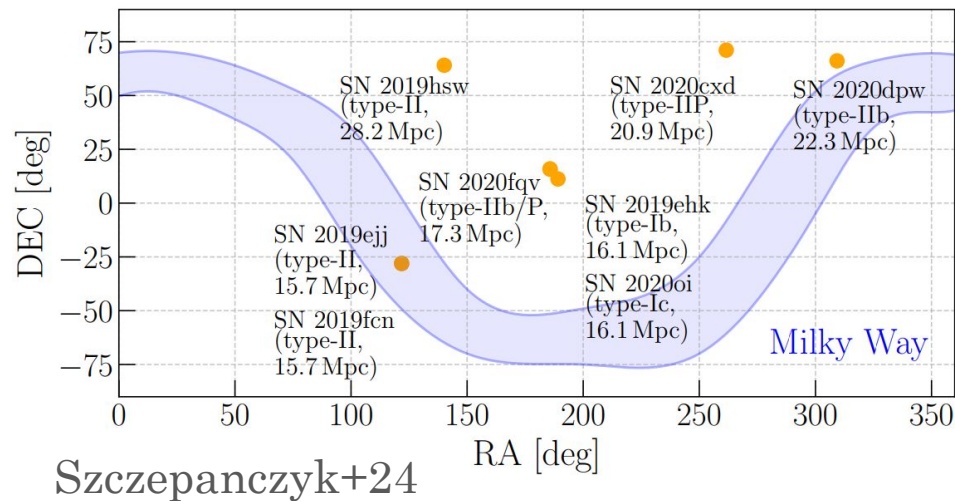
Searches for GWs from CCSNe

Optically targeted searches:

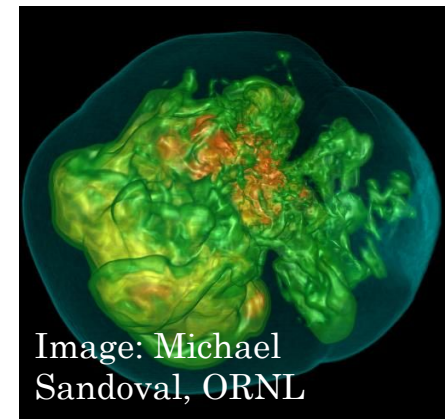
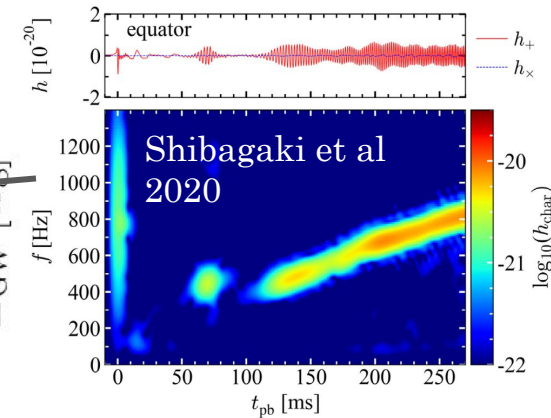
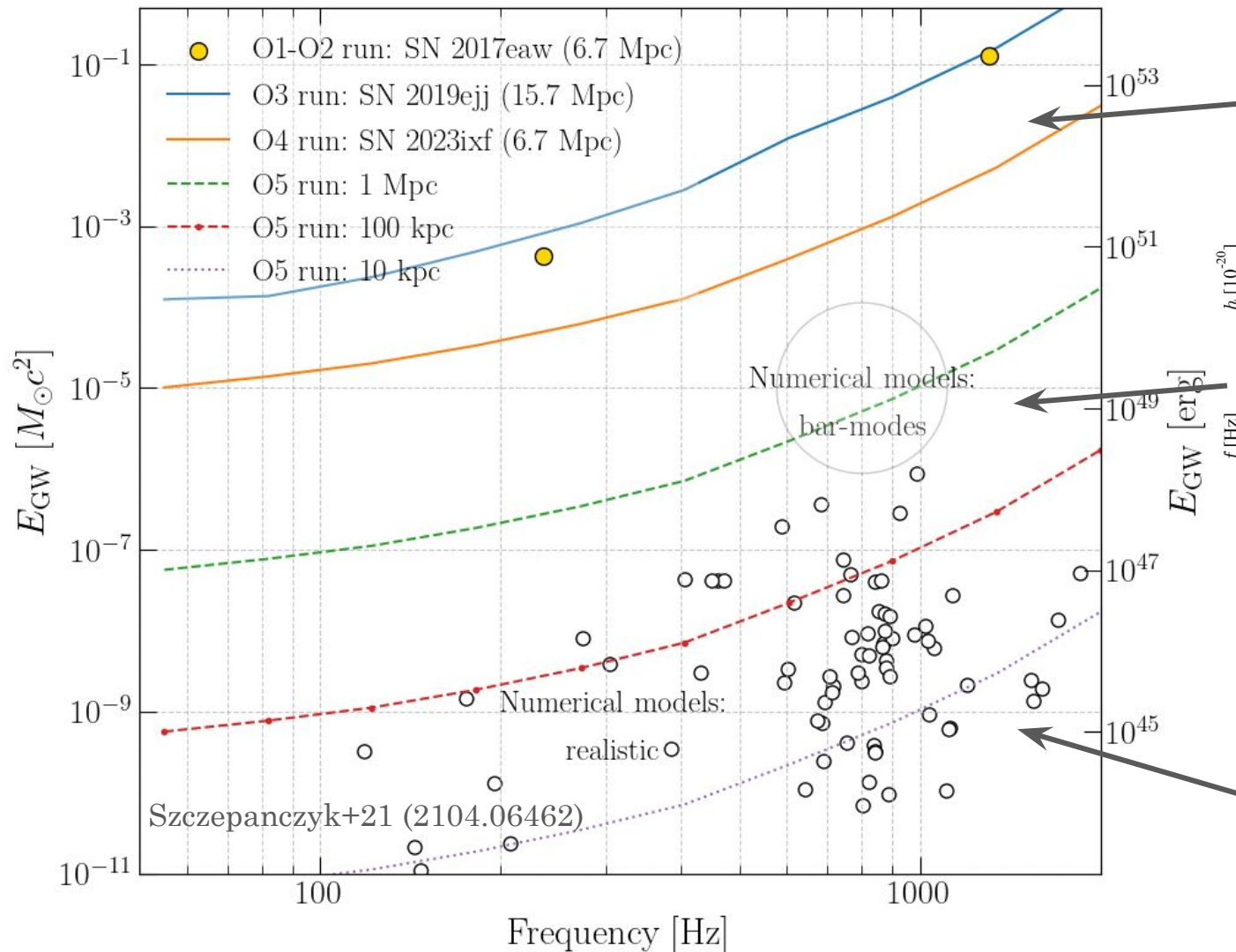
- **O4 Search:** on-going
- **SN 2023ixf search** (Abac+24, [2410.16565](#), special O4 paper):
 - GW energy emission: constraints improved by an order of magnitude
- **O3 search** (Szczepanczyk+24, [2305.16146](#)):
 - We could not beat the previous upper limits
- **O1-O2 search** (Abbott+19, [1908.03584](#)):
 - First observational constraints of a CCSN engine

Generic searches:

- Short-duration all-sky searches, for example Abac+25 ([2507.12374](#))



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



Neutrino and GWs

Neutrinos give us timing of the GW transient:

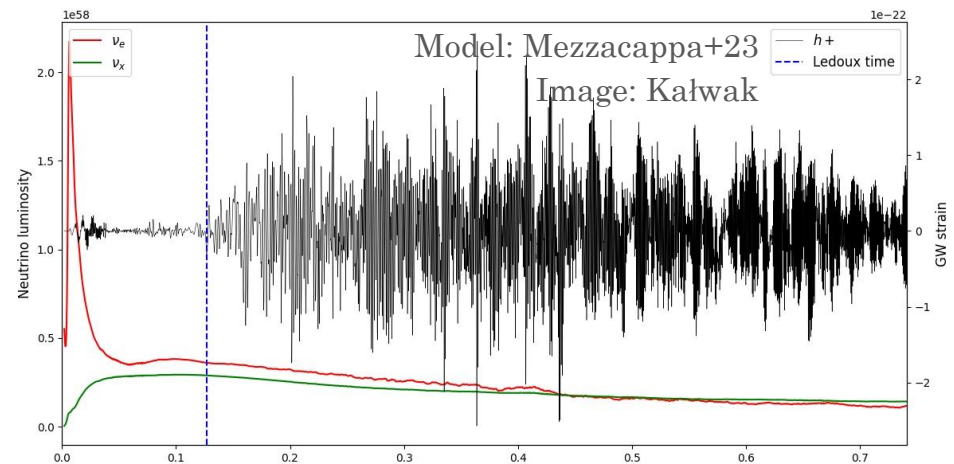
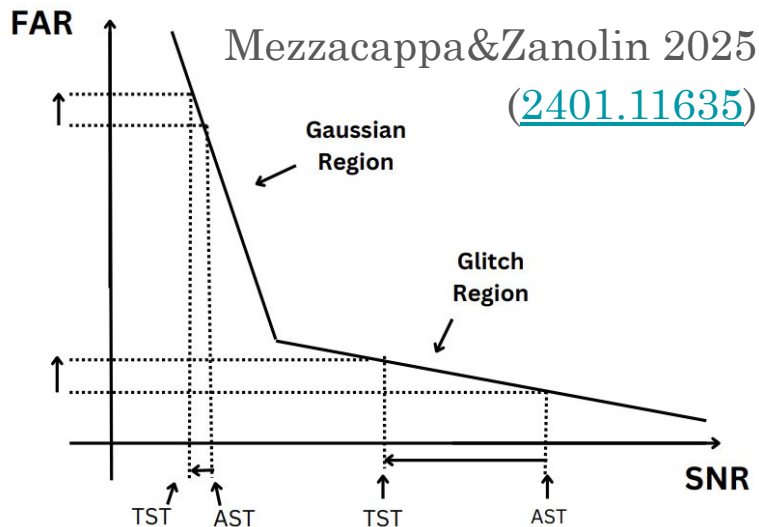
$$\text{FAP} = T * \text{FAR}$$

- FAP: False Alarm Probability
- FAR: False Alarm Rate
- T: time window to find GW:
 - TST - Targeted Search Threshold
 - AST - All-Sky Search Threshold

Timing from SNEWS will allow us further threshold reduction.

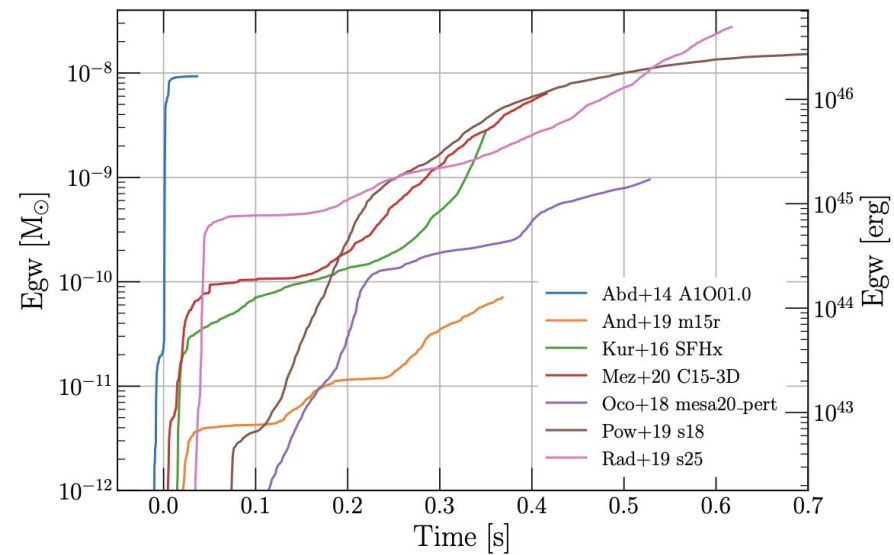
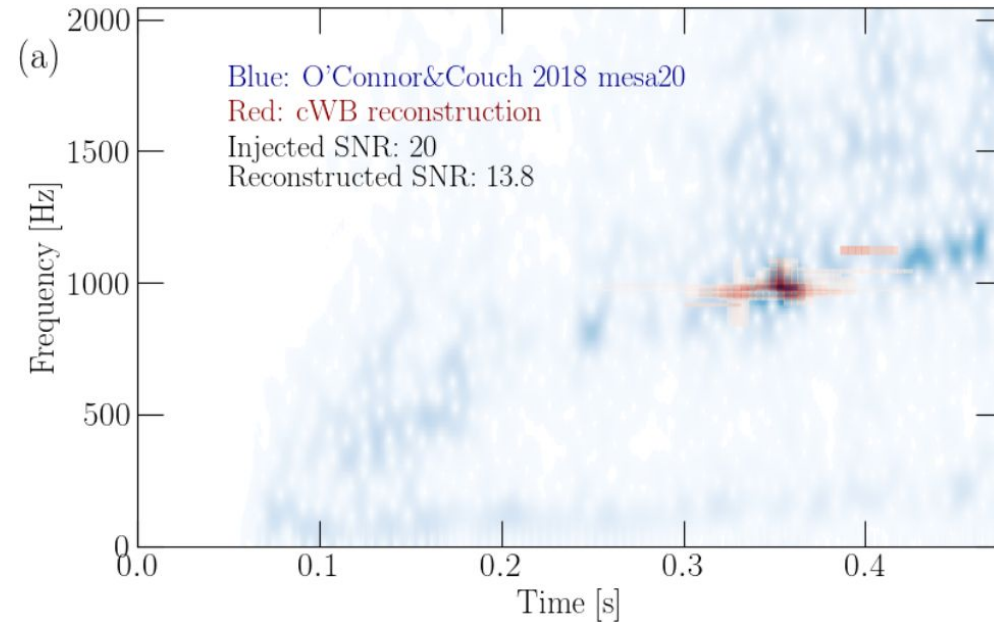
ACME workshop with SNEWS, registration until Sep 12:

<https://acme-snews-work.sciencesconf.org/>



GW detection challenges

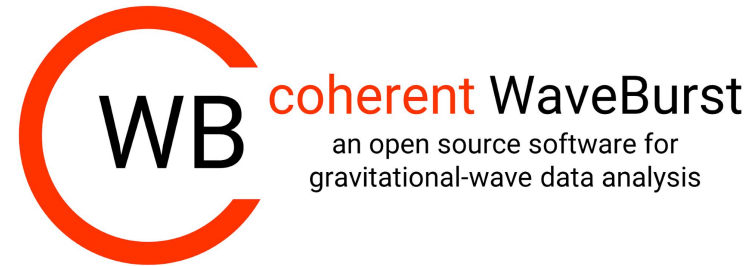
More details: Szczepańczyk+21 ([2104.06462](#))



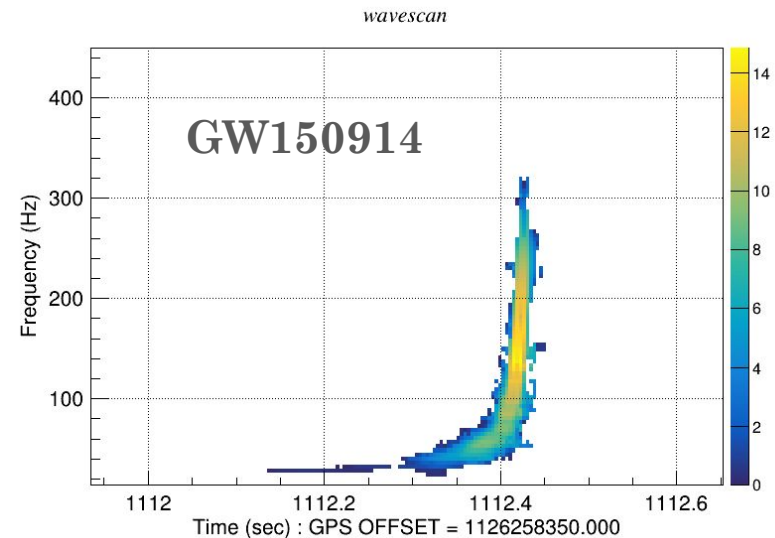
- Large time-frequency area, in contrast to GWs from BBHs
- Detectable signal-to-noise ratio of 20-30
- Cumulative energy is growing

Model-independent searches

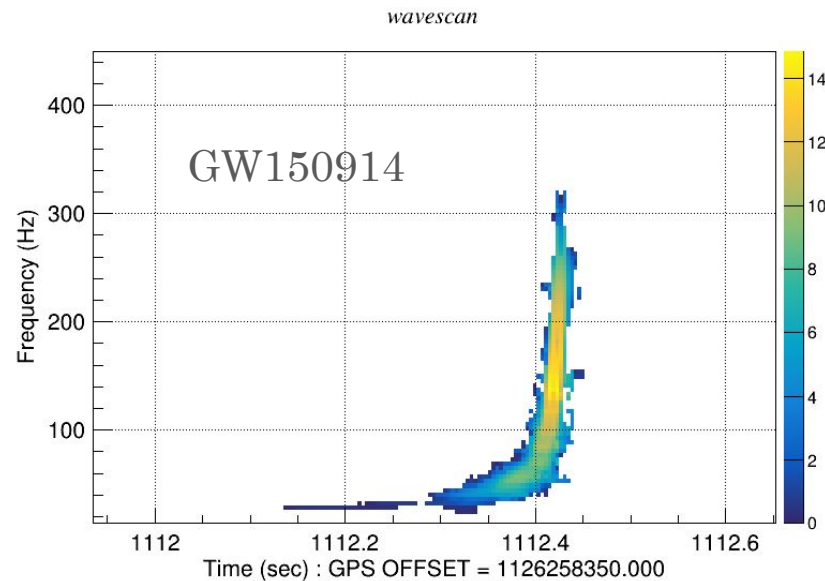
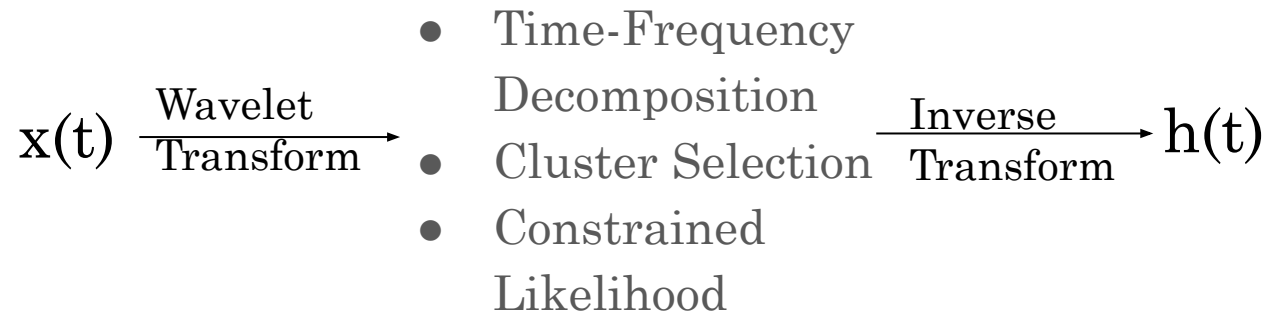
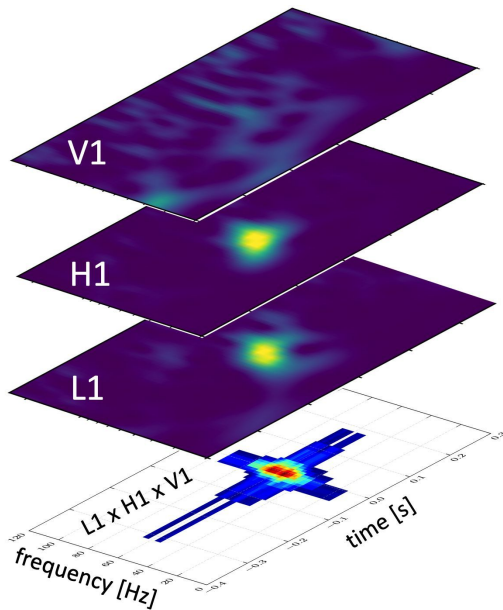
- **Coherent WaveBurst** (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
- cWB may use **minimal assumptions**, for example growing frequency over time in case of binaries
- **Complementary with template-based searches**
- 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/>



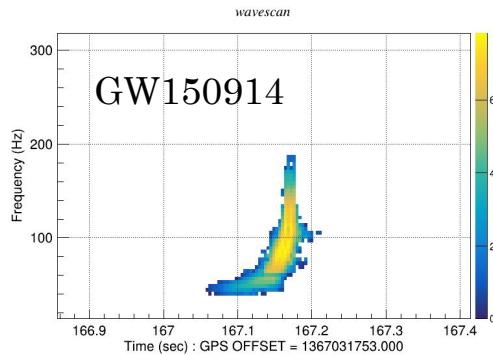
coherent WaveBurst (cWB)



Model-independent searches classification

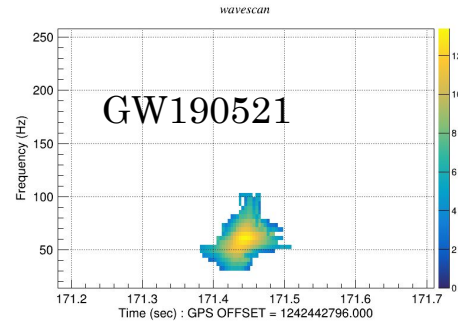
Compact binary searches (minimally modeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



e.g. Mishra+23 ([2201.01495](#))

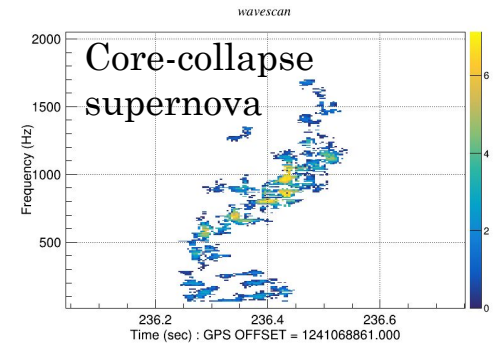
Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



e.g. MS+21 ([2009.11336](#))

Generic searches (unmodeled)

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



e.g. MS+24 ([2305.16146](#))

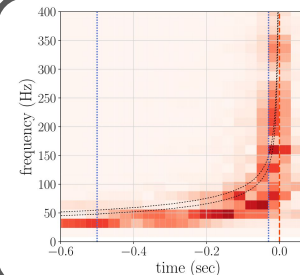
Low-latency searches



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](#))

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](#)
- Classical and Quantum Gravity focus issue proceedings and White Paper (in progress): <https://iopscience.iop.org/collections/cqg-250513-841>
- Pretty successful (23 submissions and 12 papers are published)



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

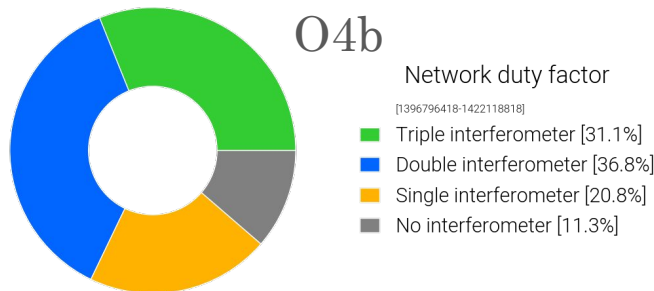
Some lessons learned (work in progress on a White Paper):

- **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. CCSN models advanced enough in the recent years to allow building more detailed tools.
- 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.
- **The interaction between electromagnetic, neutrino and GW communities could be improved**, for example what will we do explicitly if we have a Galactic CCSNe?
- 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)



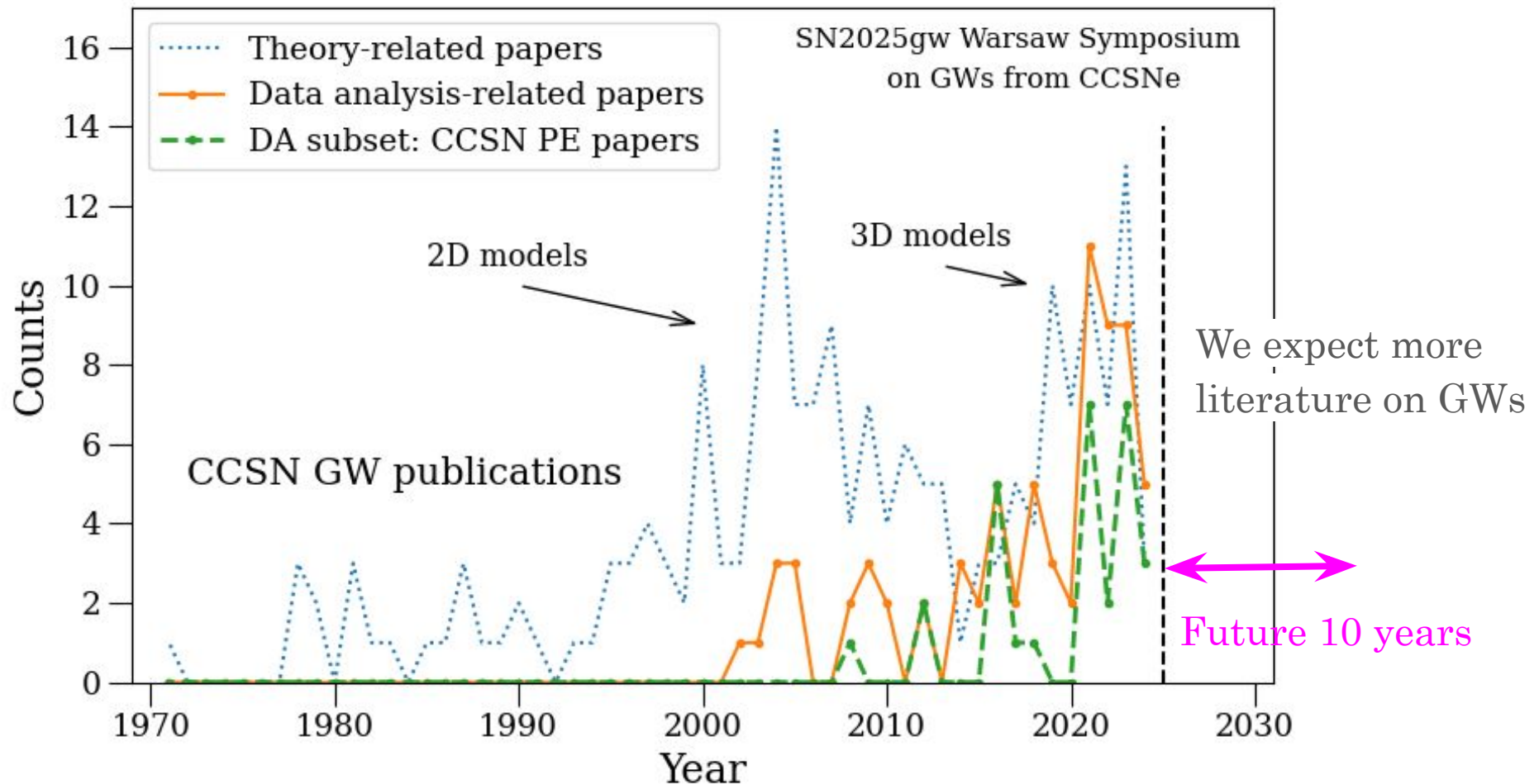
It may definitely help!



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Papers on GWs from CCSN



CCSN GW Literature, by Ewald Mueller:

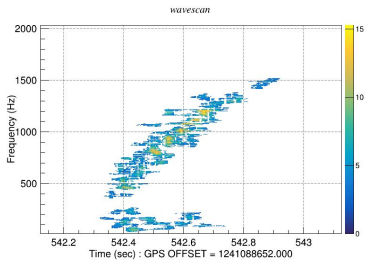
https://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

Low-latency Physical Inference work in progress

Approach:

Implement in low-latency

Existing methods



GW burst

30-60s: LVK
public alert

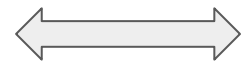
Prompt convection

PNS oscillations

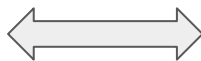
SASI/convection

Physical inference

Current infrastructure: human
involvement for the physical inference



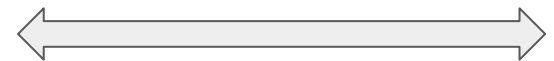
second



minute



hour



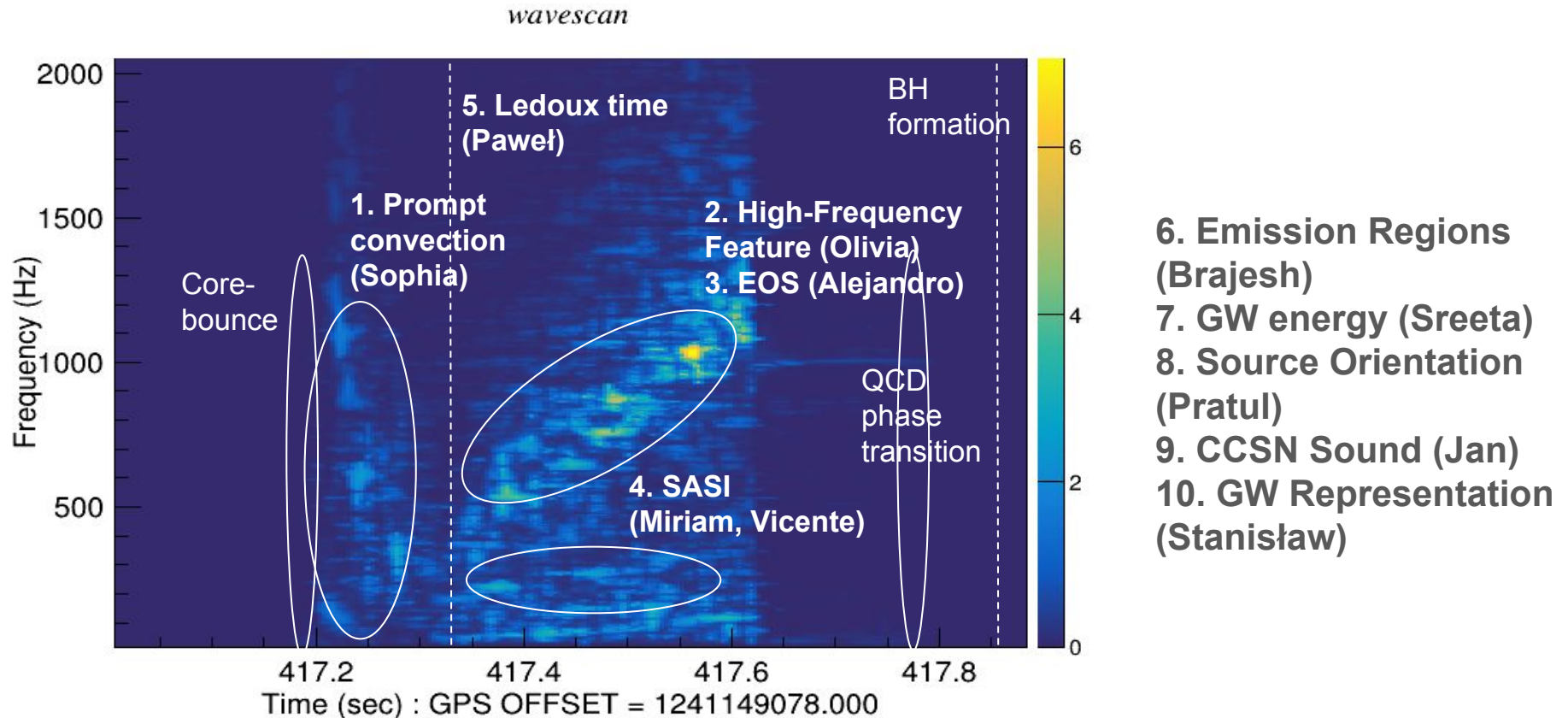
day

week

month

Time after core-collapse [sec]

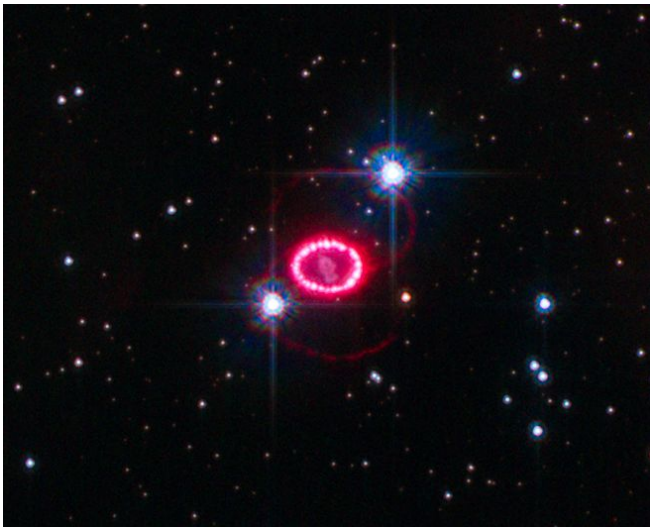
SN2025gw: Physical inference and Warsaw group contribution



Announcement:

SN2027gw: Second IGWN Symposium on CCSNe

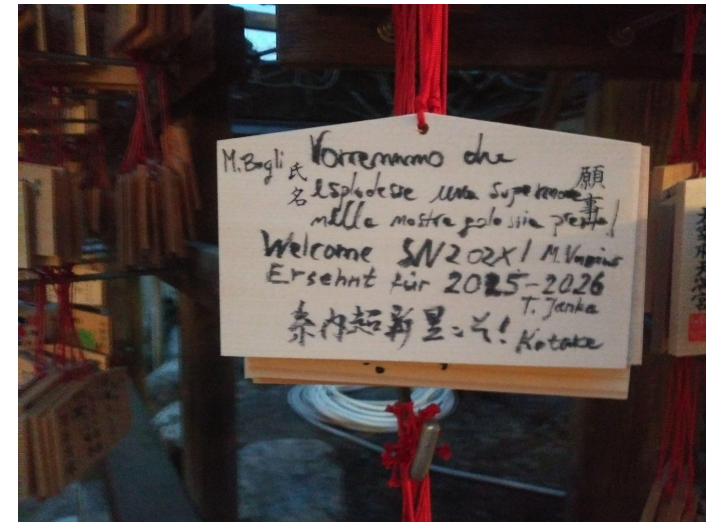
- Date: 24 - 28 May 2027
- Place: Knoxville, Tennessee, USA
- 40th anniversary of SN 1987A



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

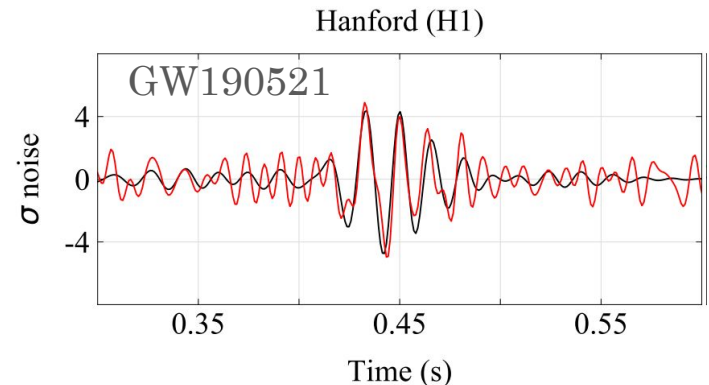
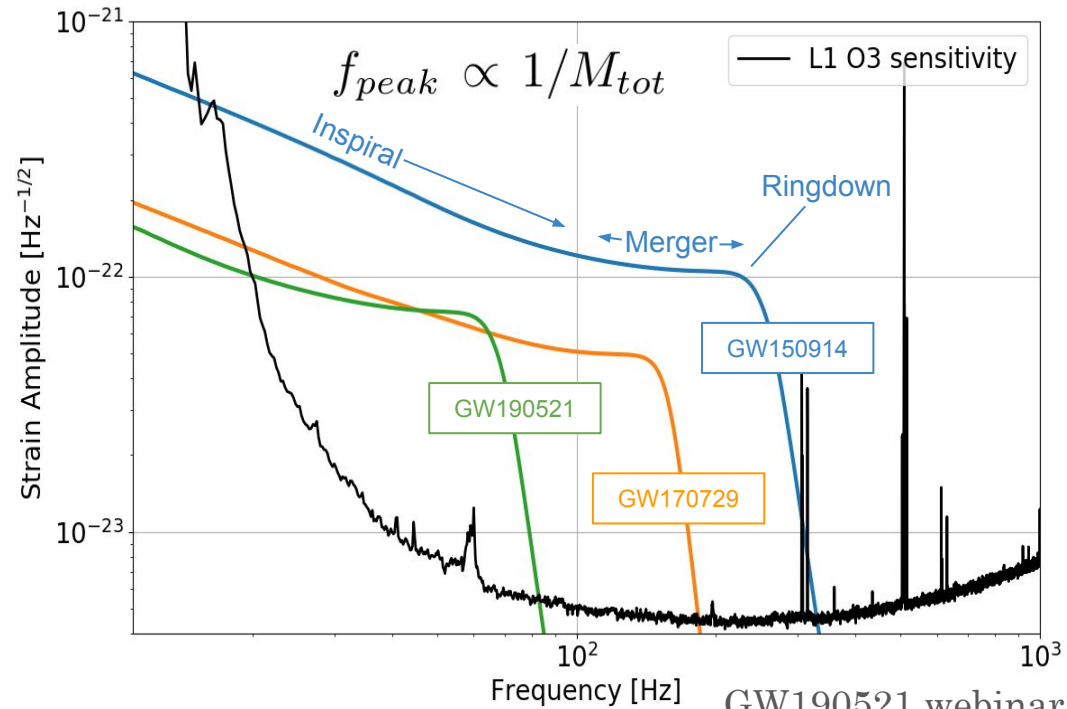
“Welcome SN 202X! Long-awaited for 2025-2026”
Fukuoka Temple, 2019.10.23



Extras

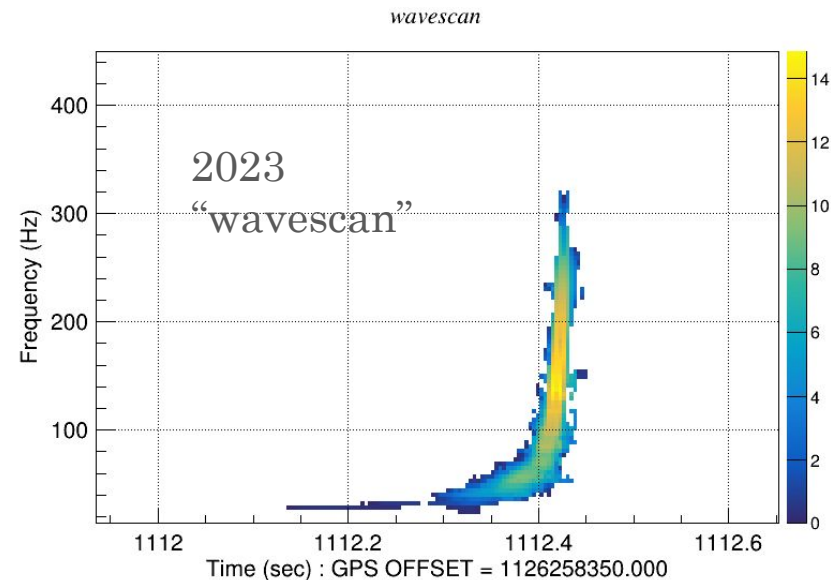
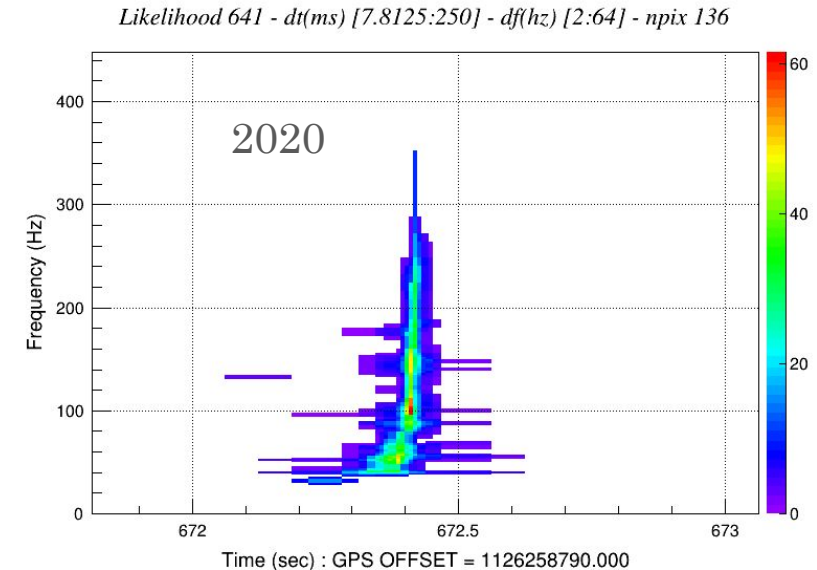
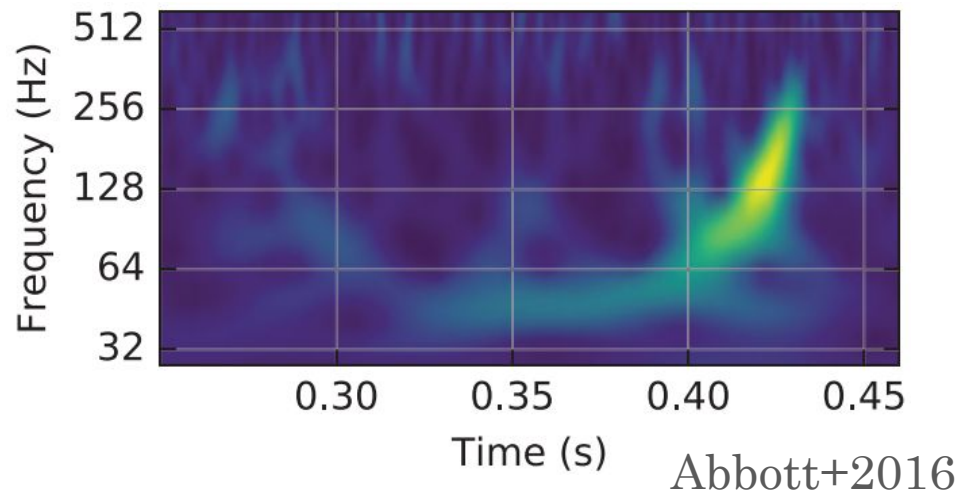
Intermediate-mass black holes, GW190521 and GW231123

- **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](#))
- **GW231123** - the heaviest black hole detected so far.



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](#))



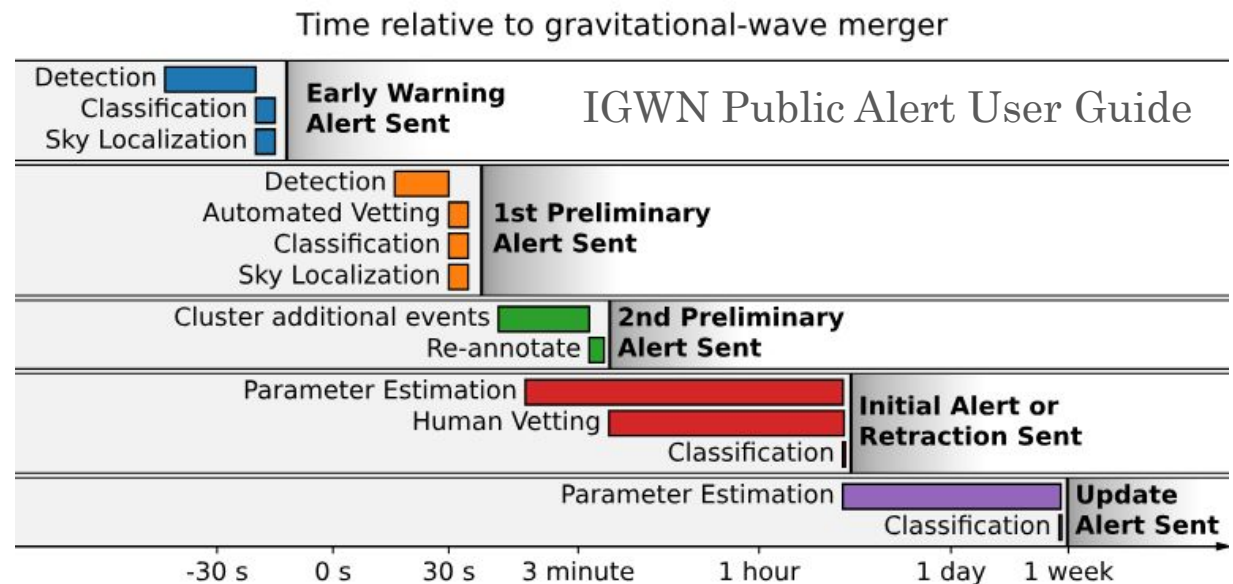
Burst public alerts

IGWN Public Alert User Guide: [link](#)

- Burst searches in O4: cWB-AllSky and MLy
- External coincidences: [RAVEN](#)
- Thresholds:
 - Significant events: $\text{FAR} < 1$ per year
 - Low-significance events: $\text{FAR} < 4$ per day
- Alert Timeline (for CBC):

Data products for an automatic public alert:

- False Alarm Rate
- Sky location
- Event Time
- Event Frequency



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

