The quest to detect (exceptional) gravitational-wave sources

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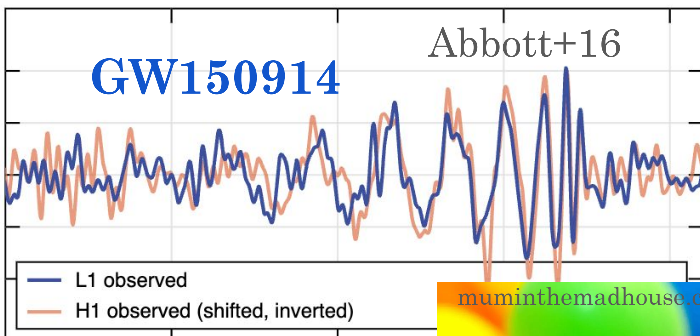


Main theme: what's next?

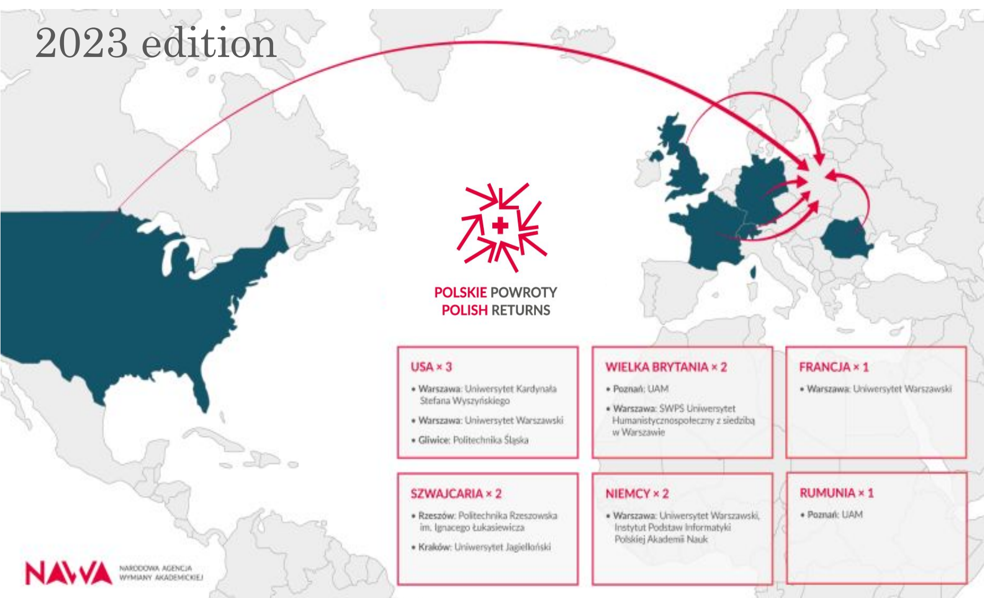
Slides:
fuw.edu.pl/~mszczepanczyk/news.html

Center of Gravity of the Niels Bohr Institute
Copenhagen, 07.04.2026

Return to Poland

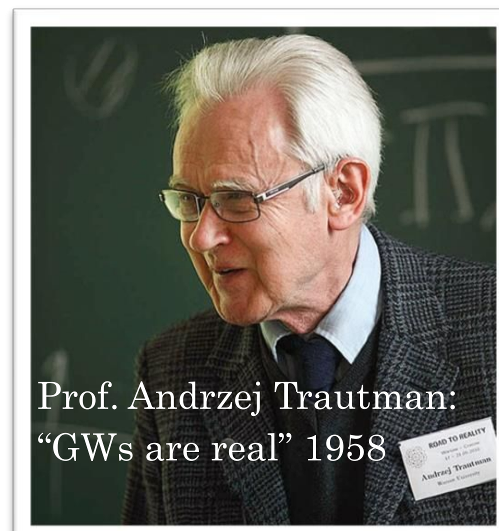
- Ph.D., ~5 years: ERAU (Arizona)
- Postdoc, ~5 years: University of Florida
- Assistant Professor, present:
  University of Warsaw (permanent position and a Polish Returns grant)

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



Chair of Theory of Relativity and Gravitation

- Classical and Quantum Gravity
- Proof that GWs are real
  (prof. Andrzej Trautman, the story)
- Loop Quantum Gravity (prof. Lewandowski, prof. Ashtekar at Princeton)
- Isolated and Dynamic Horizons (prof. Lewandowski, prof. Ashtekar at Princeton)
- Einstein–Infeld–Hoffmann equations
  (prof. Infeld with Einstein)
- Growing interest in Numerical Relativity


Prof. Andrzej Trautman:
“GWs are real” 1958

Outline

- Model-independent searches
  - Exceptional GW sources
  - Coherent WaveBurst
  - Searches
- Core-Collapse Supernova
  - Properties, predictions
  - SN2025gw: IGWN Symposium in Warsaw (21-25 July 2025)

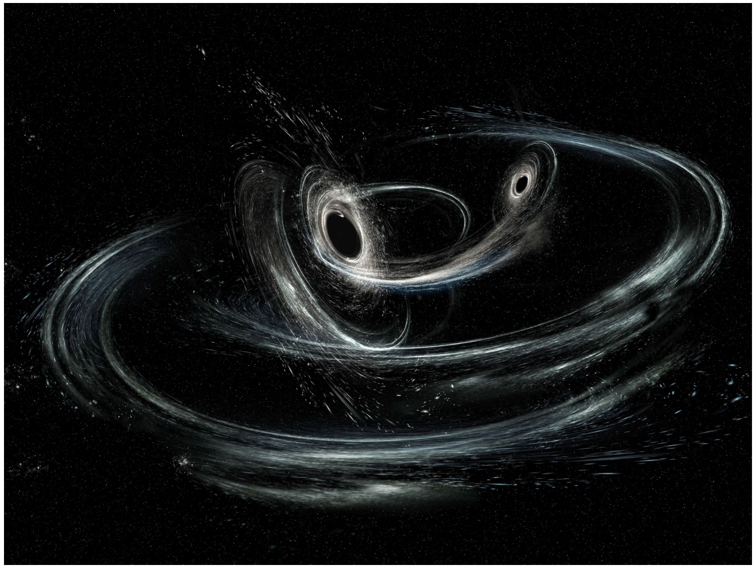
Model-independent searches

The Dynamic Universe

- **"Conventional" or time-domain Astronomy** ("looking" at the Universe): observing Universe using electromagnetic waves (e.g. visible light), cosmic rays or neutrinos.
- **"Gravitational-Wave" Astronomy** ("listening" to the Universe): observing Universe using gravitational-waves, the ripples of spacetime
  - Priority science area of **"New windows on the Dynamic Universe"** - the study of neutron stars, white dwarfs, collisions of black holes, and stellar explosions – Astro 2020 Survey

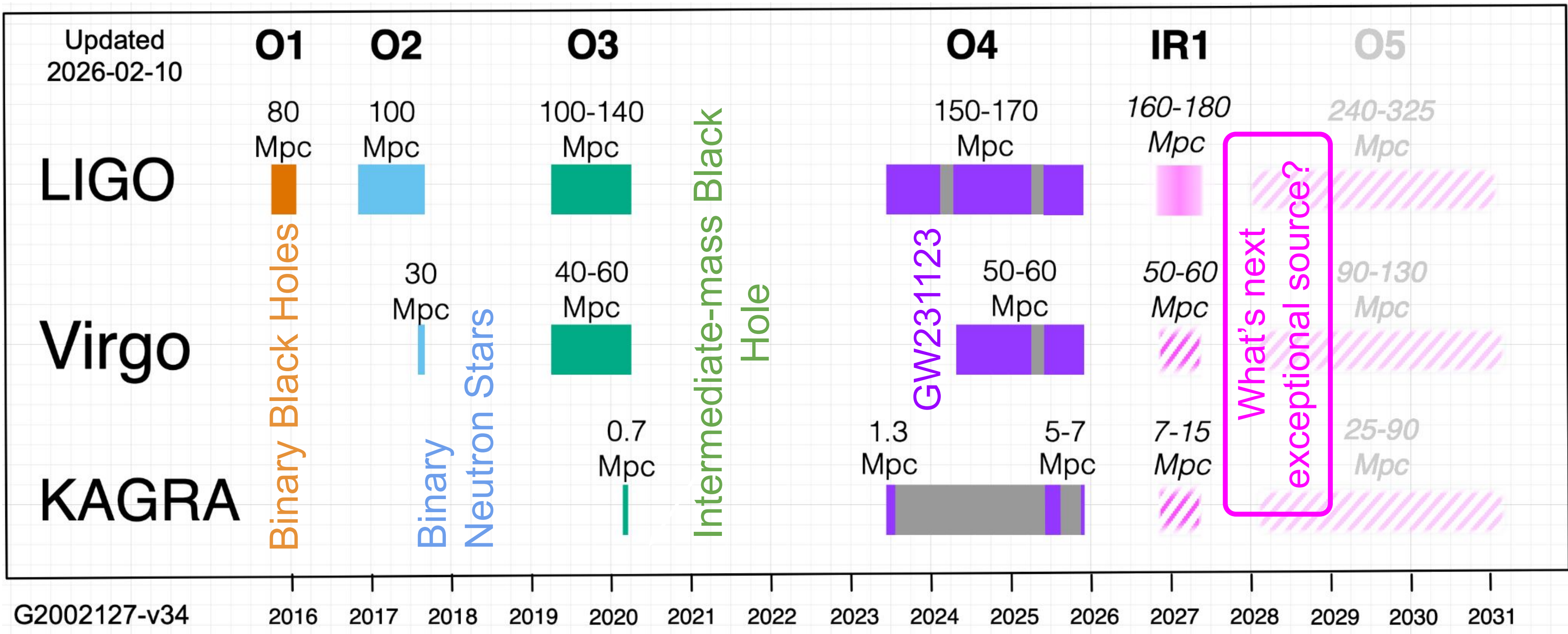
GW sources (need aspherical mass-energy movement):

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



AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

Observing Timeline



- O4: 24 months total, until 18 Nov 2025 https://observing.docs.ligo.org/plan/
- LIGO: up to 180 Mpc, around 160 Mpc
- Virgo: around 55 Mpc
- KAGRA: up to 10 Mpc, not yet observing, reached 7 Mpc

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

GW Sources and Searches

	Model-independent searches (also, GW burst)	Model-dependent searches (also, templated-based)
Long GWs	Stochastic GWs (e.g. sum of pulsars in Milky Way)	Pulsars, continuous waves
Short GWs	This Talk GW bursts (compact binaries, supernovae)	Compact binaries (black holes, neutron stars)

Table 1. Candidate GW signals from O4a with a FAR $\leq 1\,\mathrm{yr}^{-1}$ in at least one analysis and for which $p_{\mathrm{astro}} > 0.5$.

Complementary searches

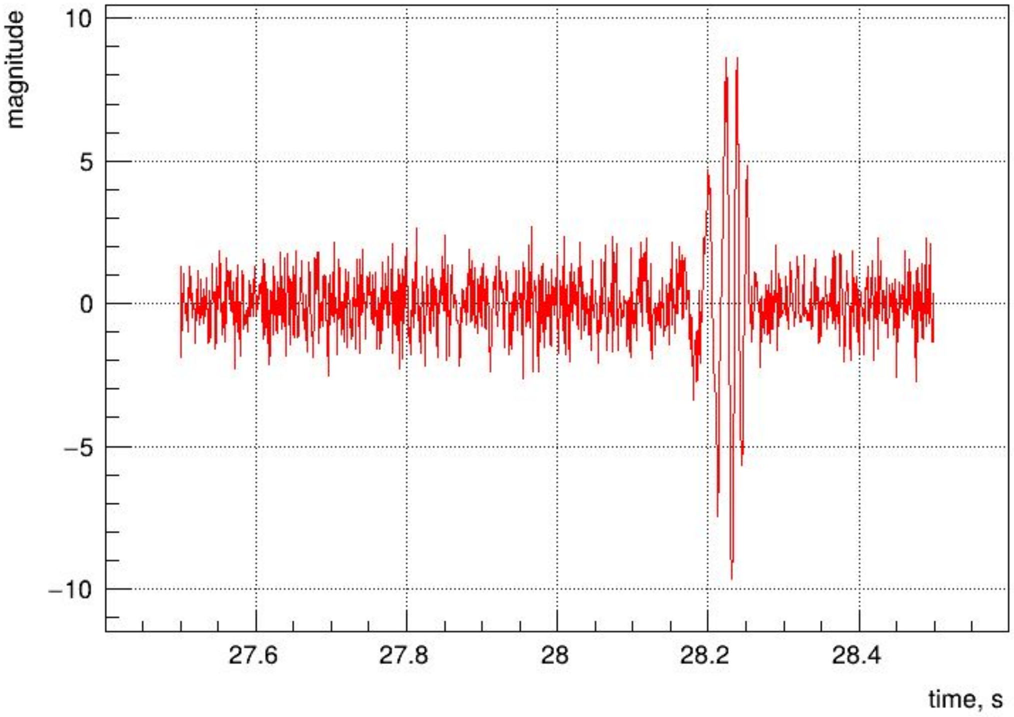
Candidate	Inst.	cWB-BBH			GstLAL			MBTA			PyCBC		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}

Abbott et al 2025, GWTC-4

GW Bursts

Bursts – short-duration transients. Examples:

- Electromagnetic: gamma ray burst, fast radio burst, optical, X-ray, etc.
- Neutrino bursts
- Cosmic rays
- **GW Bursts ← how to search for them?**



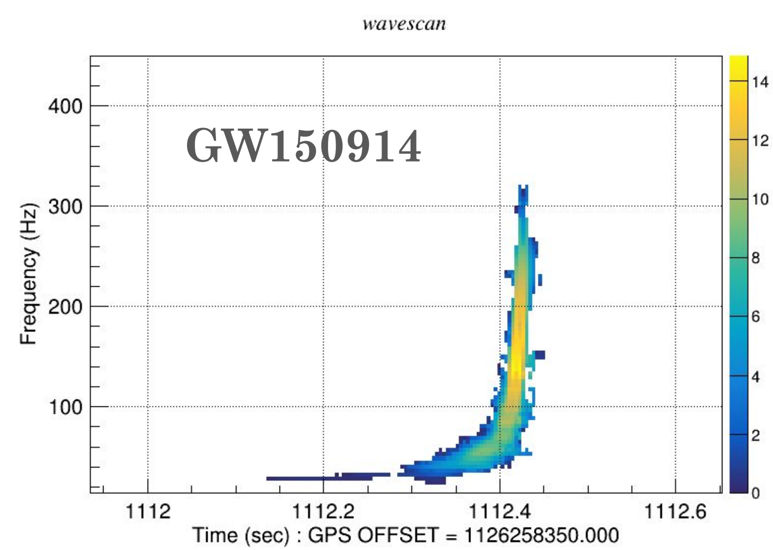
Example of binary black hole in the data, signal-to-noise ratio of around 30 (very strong)

Model-independent searches

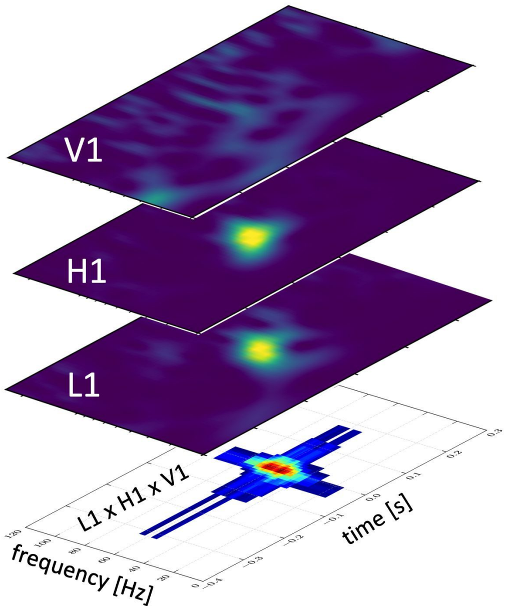
- **Coherent WaveBurst** (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
- cWB may use **minimal assumptions**, for example growing frequency over time in case of binaries
- **Complementing template-based searches**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

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

https://gwburst.gitlab.io/



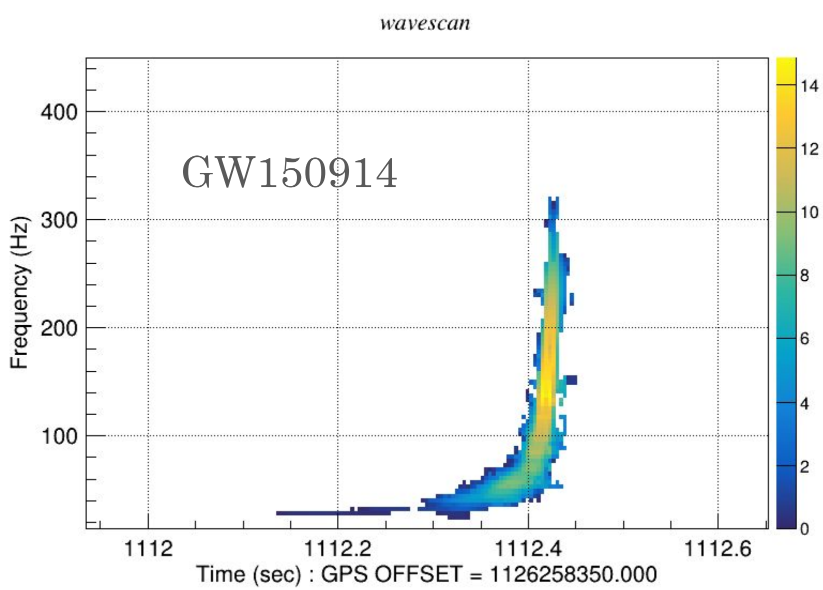
coherent WaveBurst (cWB)



x(t) —Wavelet Transform→

- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

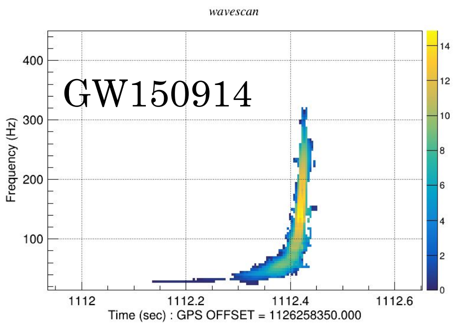
—Inverse Transform→ h(t)



Model-independent searches classification

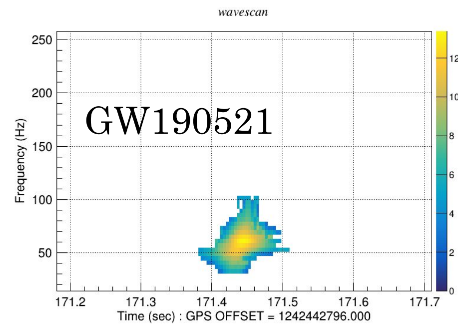
Compact binary searches (minimally modeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



e.g. Mishra+23 (2201.01495)

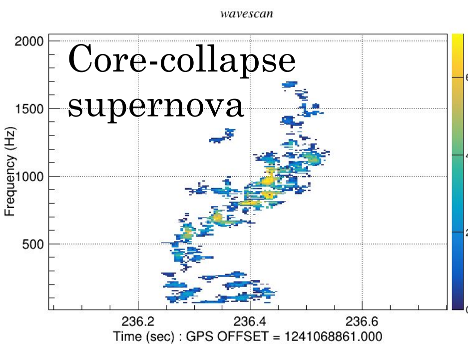
Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



e.g. MS+21 (2009.11336)

Generic searches (unmodeled)

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



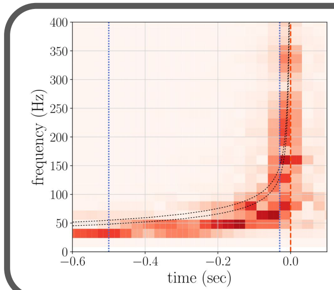
e.g. MS+24 (2305.16146)

Low-latency searches

Public alerts for
multi-messenger observations:
electromagnetic, cosmic rays,
and neutrino

e.g. Chaudhary+24 (2308.04545)

Searches for new phenomena

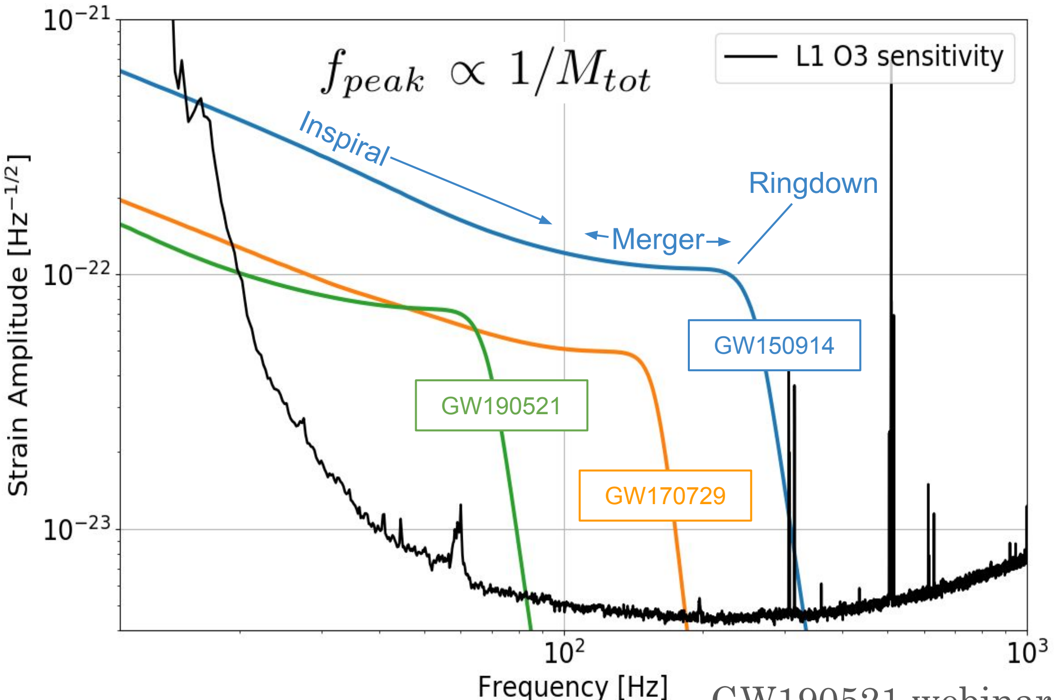


Higher harmonics
GW cross-polarization
Deviations from GR

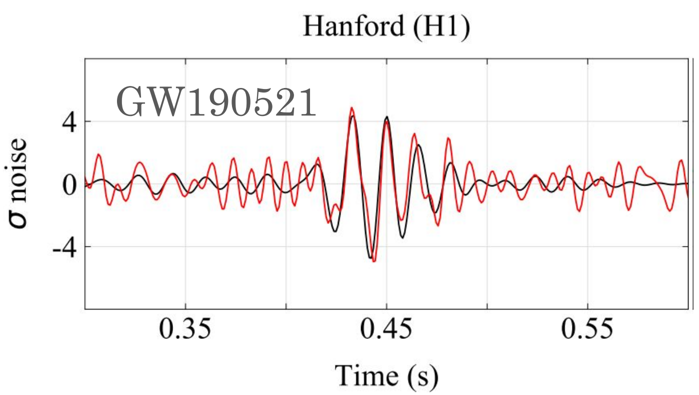
e.g. Vedovato+22 (2108.13384)

GW190521 and GW231123

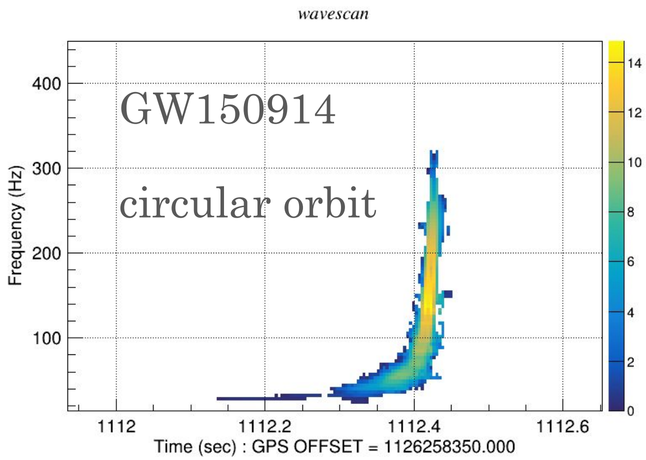
- **Intermediate-mass black holes** (IMBHs) - between stellar mass (100 $M_\odot$ and supermassive (10^5 $M_\odot$). The origin is not yet well understood. Exploring:
  - Probing pair-instability mass gap (Stars with He mass in (64 $M_\odot$, 135 $M_\odot$)
  - Formation channels
  - Most distant GW 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



Eccentric binaries



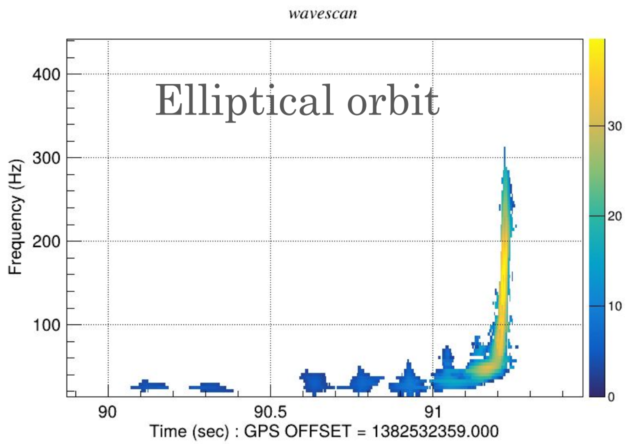
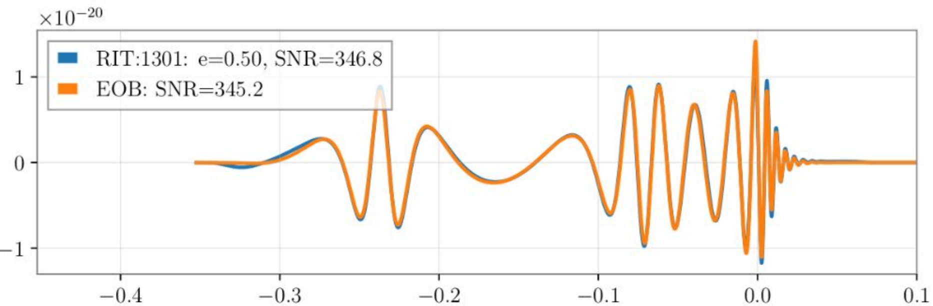
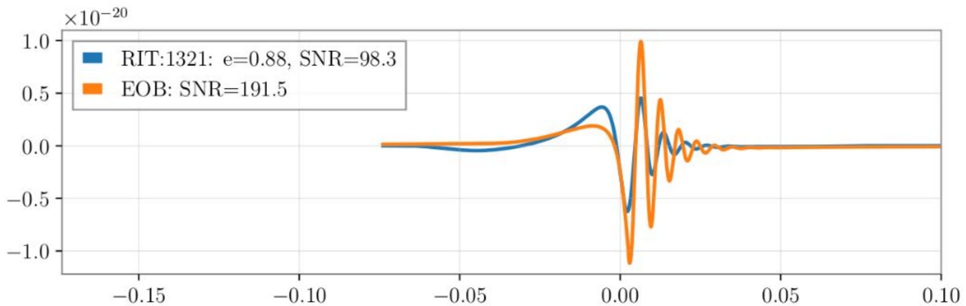


Image: Bhaumik

- Eccentric binaries: compact binaries elliptical orbits. “Smoking gun” of the dynamical formation
- Bhaumik et al (MS) 2024 ([2410.15192](2410.15192))
  - Comparison between waveform models
  - Sensitivity studies and recommendations



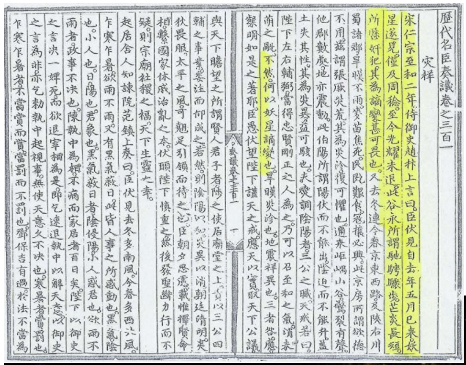


Time [s]

Core-Collapse Supernova

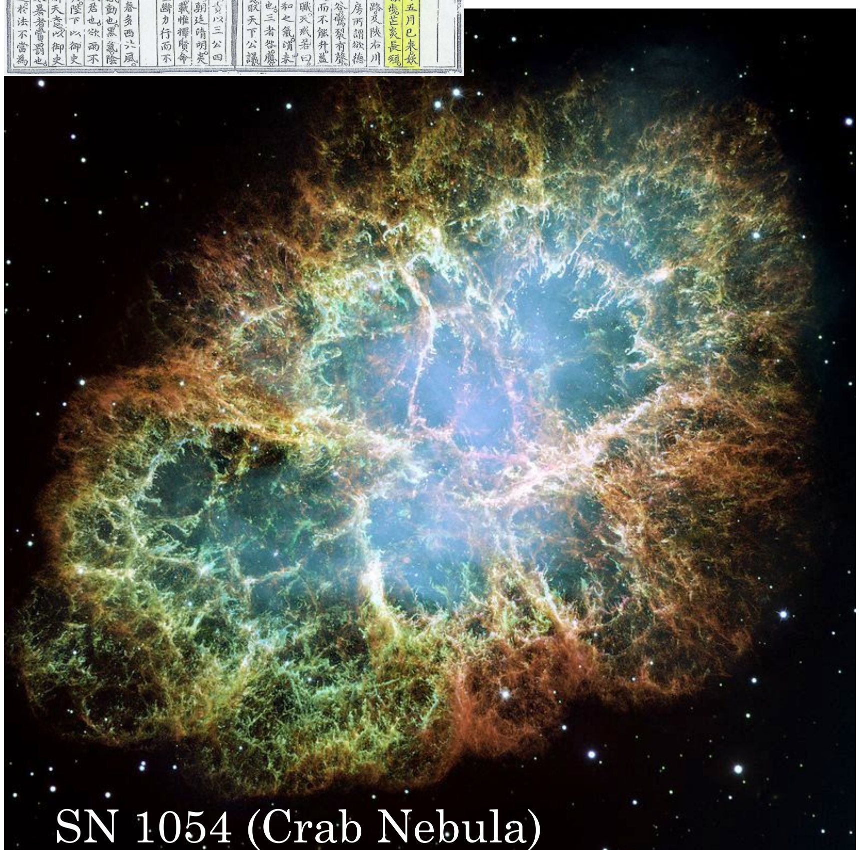
Are we ready, as communities, for a CCSN in Milky Way (or nearby)?

Core-Collapse Supernova (CCSN)



"Guest star"

Zhao Bian's memorial to Emperor Renzong

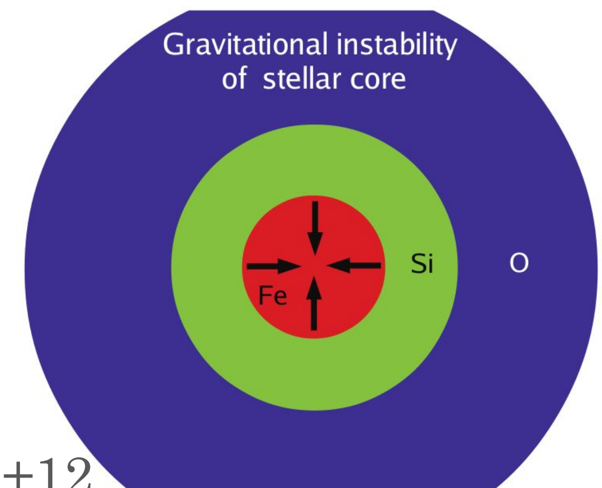


SN 1054 (Crab Nebula)

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

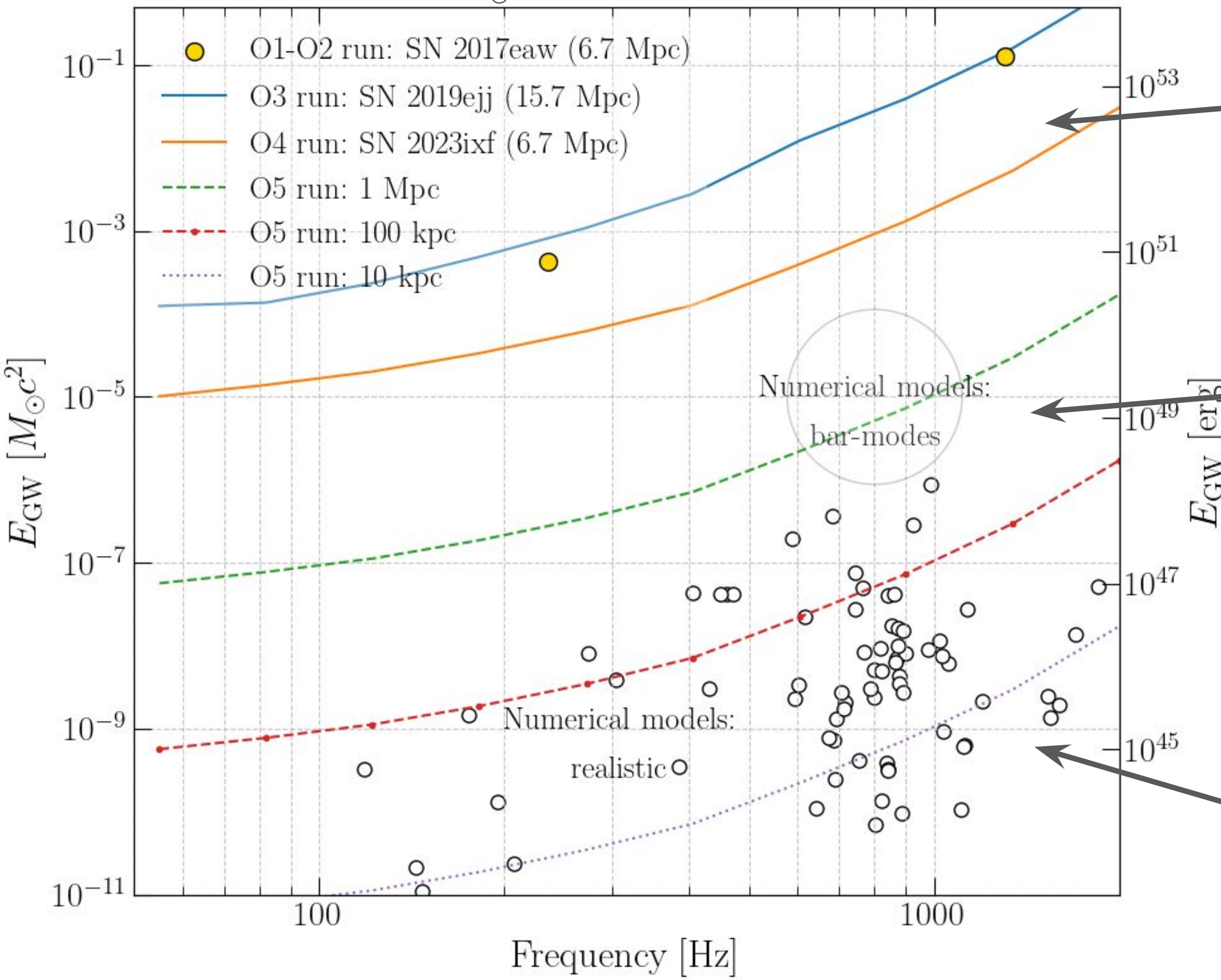


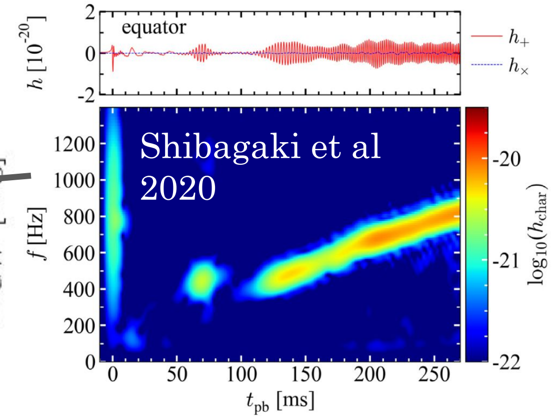
Janka+12

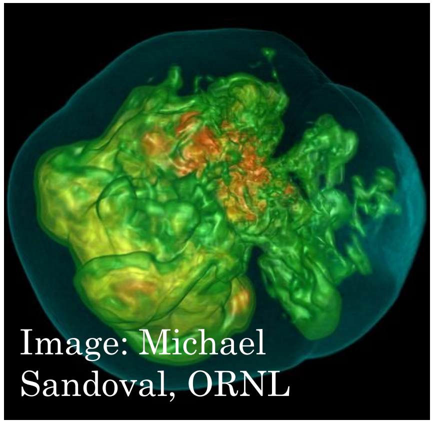
When will we discover GWs?

(realistically: Galactic CCSN)

Binary black holes: ~3 $M_\odot c^2$

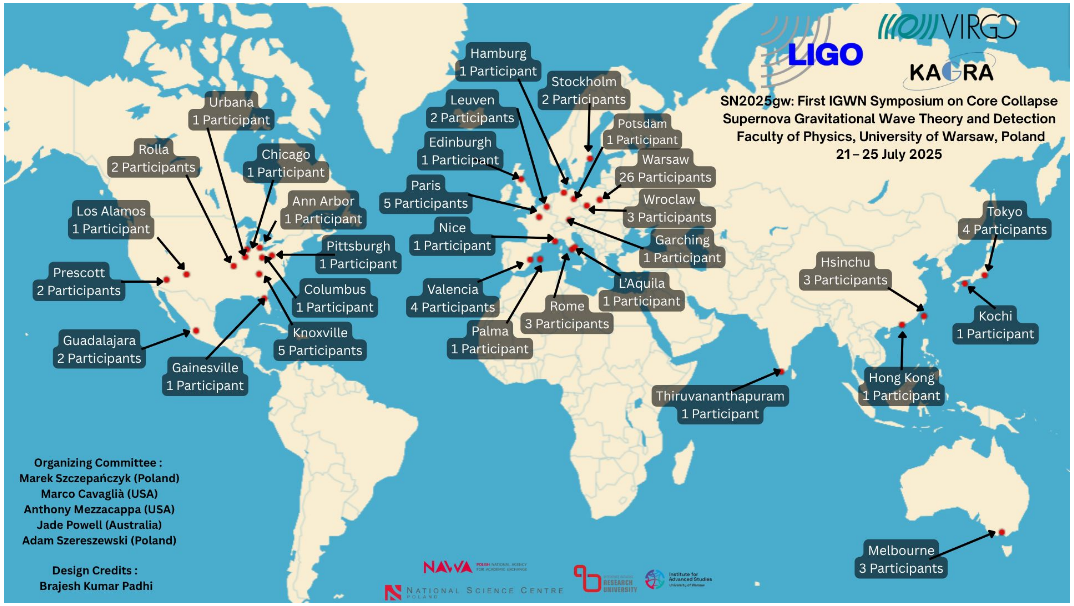






SN2025gw: IGWN Symposium on CCSNe Bridging the Gap

- 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: proceedings and White Paper

- 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
- Pretty successful (12 submissions so far and around 10 to be submitted)

Classical and Quantum Gravity

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

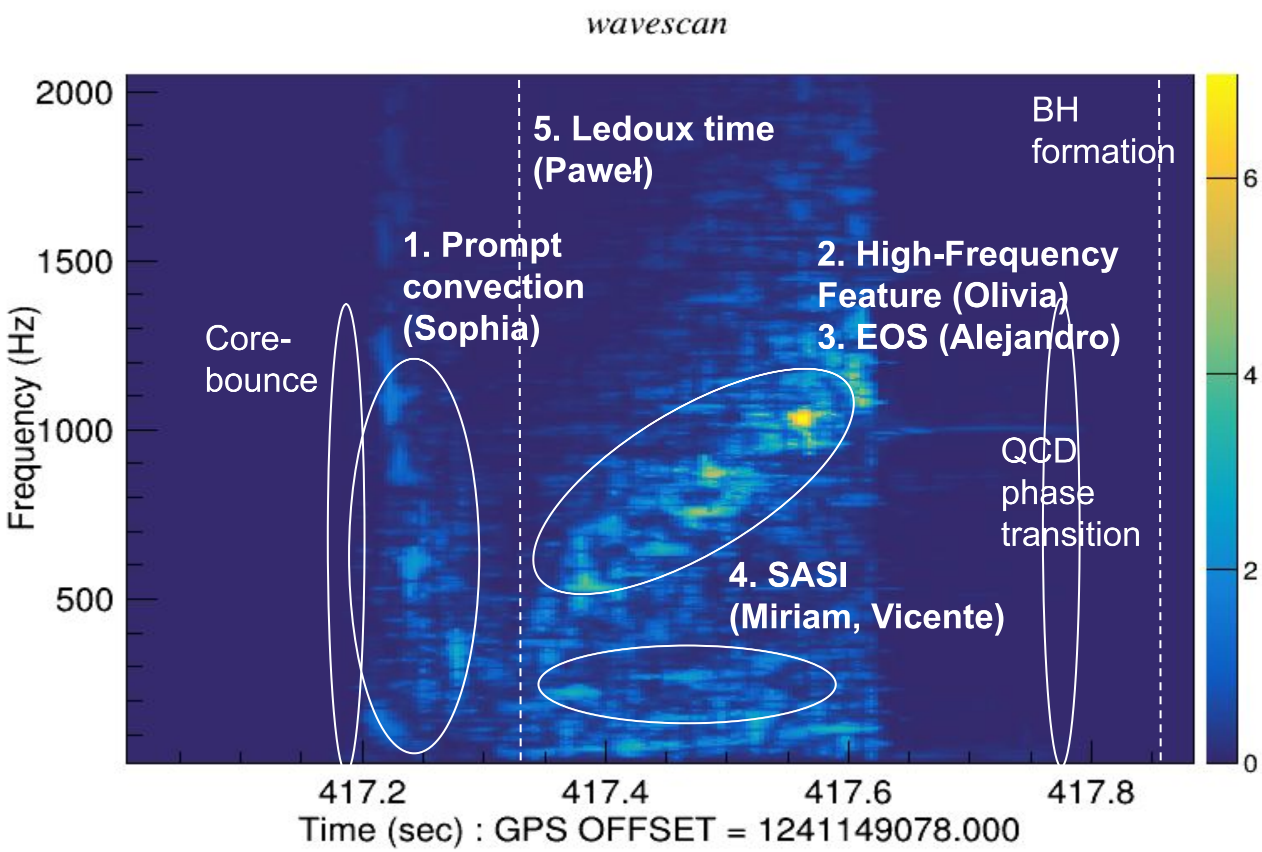
Guest Editors

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

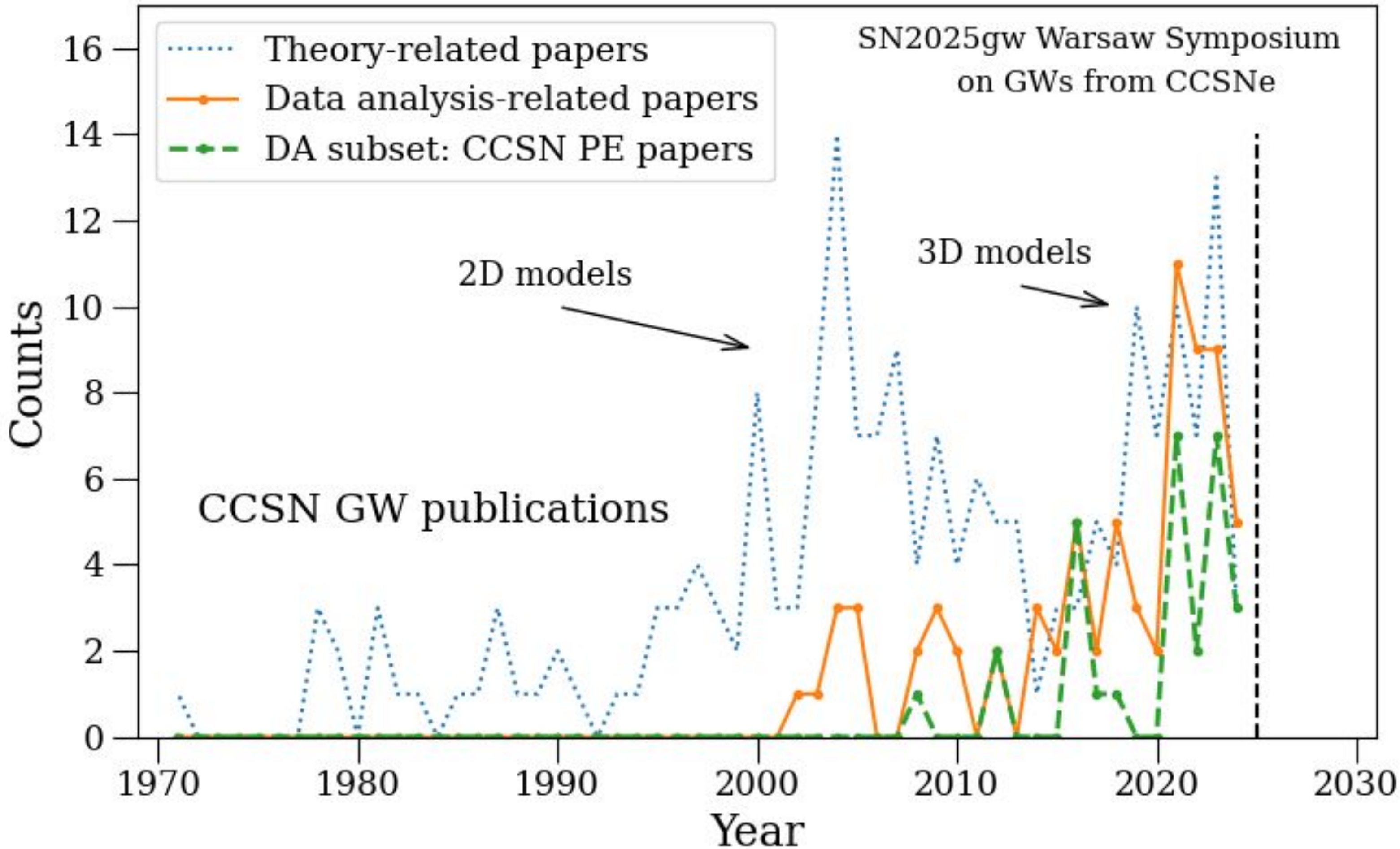
The LIGO, Virgo, and KAGRA (LVK) observatories are designed to detect gravitational waves (GWs) from a wide variety of sources, including compact binary mergers, core-collapse supernovae, and isolated pulsars, among others. Only the

SN2025gw: 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)

SN2025gw: maturity of CCSN models



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

SN2025gw: some lessons learned

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

- **Maturity of the 3D models.** However, 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.
- **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. There are indications that GW memory could be detected as well (thanks also to current hardware improvements).
- **The interaction between EM, nu and GW communities could be improved**, for example what will we do explicitly if we have a Galactic CCSNe?
- Important to consider how supernova modelling needs to **evolve technically and organisationally** to make further progress and aid gravitational wave and multi-messenger astronomy.

Summary

- Model-independent searches
  - Preparing for exceptional/special GW sources
  - Suitable for discoveries
  - Complement template-based searches
- Core-Collapse Supernova
  - "Supernova problem": why do the stars explode?
  - "Are we ready?":
    SN2025gw: IGWN Symposium in Warsaw
- "What's next?" - we have a few clues, but we need to wait for Mother Nature to answer it with our ears wide open

Extras

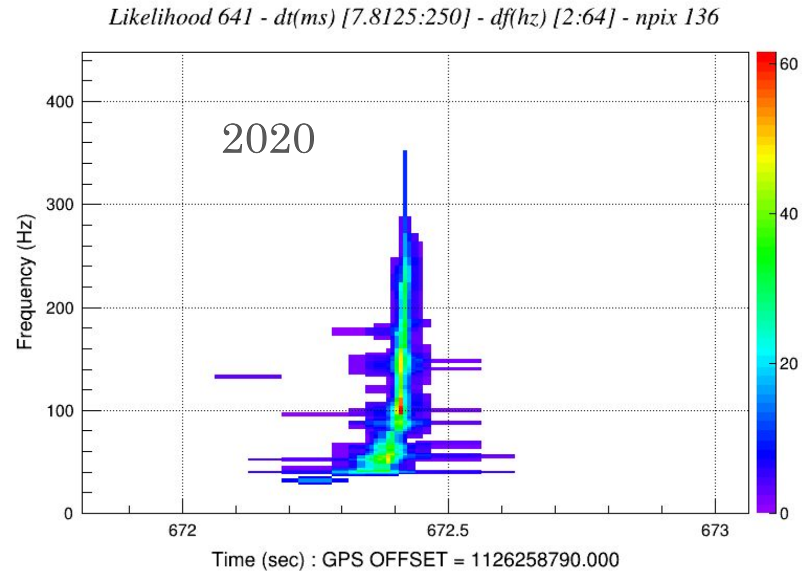
Polgraw

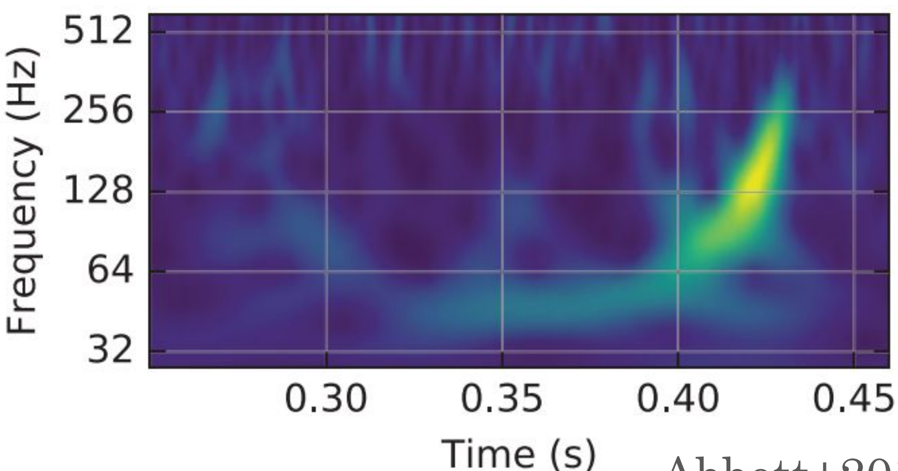
- Currently 24 people. Group leader: prof. Królak
    - https://polgraw.camk.edu.pl/
- Funding member of Virgo and ET
- Example achievements:
    - Correct prediction of LIGO's first detection (prof. Belczyński, prof. Bulik)
    - Correct prediction of IMBH discovery (prof. Belczyński, prof. Bulik)
      Continuous waves - mathematical foundation for data analysis (prof. Królak, prof. Jaranowski)
- Recent and future GW events:
    - Sep 2019 - LVK Meeting
    - Nov 2024 - 3rd ET Annual Meeting
    - Jul 2025 - LVK workshop on supernovae (last slide)
    - Spring 2027 - LVK Meeting

3rd ET Annual Meeting LOC

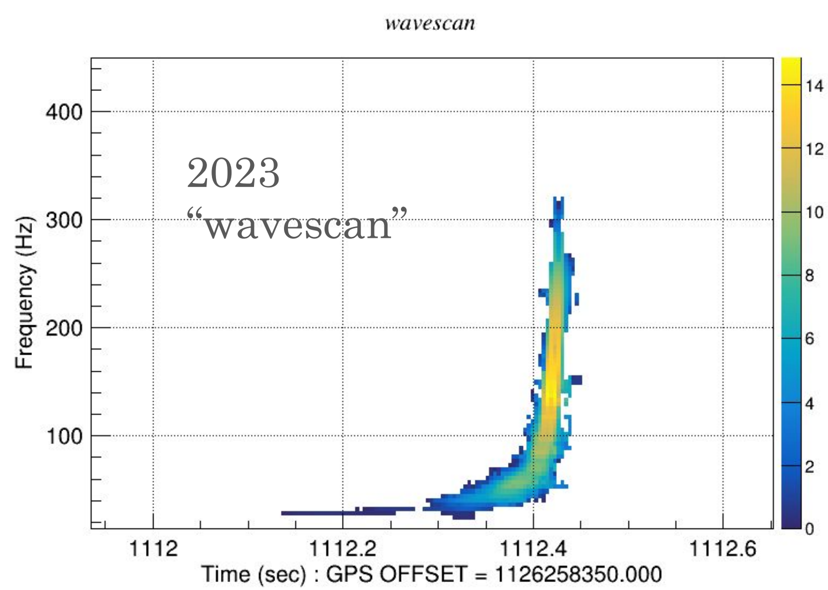
Time-frequency maps (GW150914 example)

- 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))



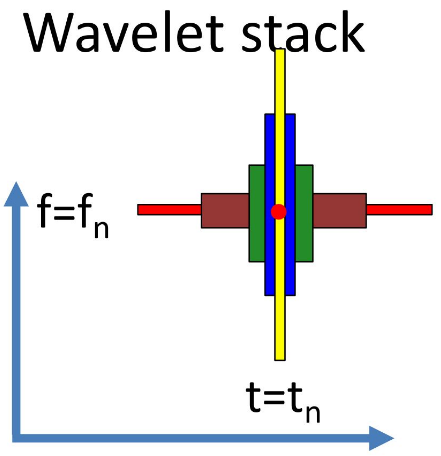


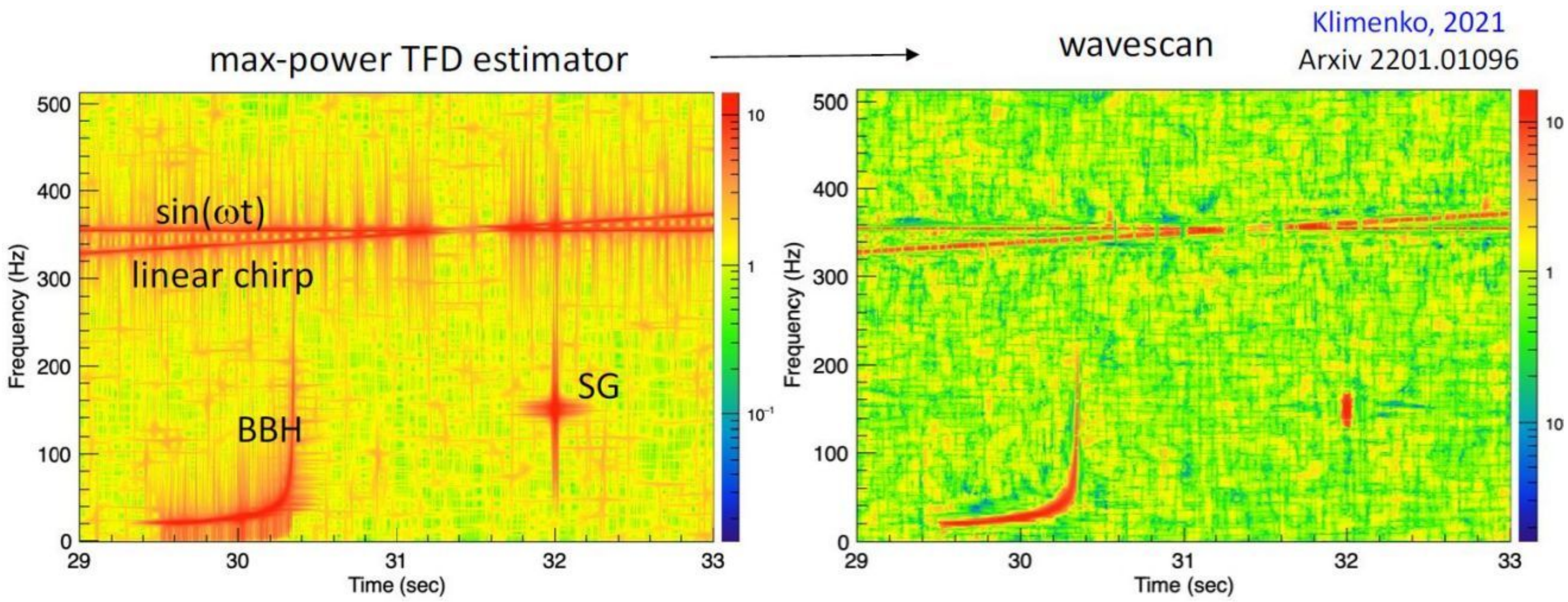
Abbott+2016



Wavescan

- Wavescan (Klimenko+22, [2201.01096](2201.01096)): high-resolution time-frequency transform
- Heisenberg rule for signal processing: $\sigma_t^2 \sigma_\omega^2 \geq \frac{1}{4}$
  - Multiresolution analysis and wavelet stack
- Wavescan transform combines the maps from different resolution into a single time-frequency map
  - Spectral and temporal leakage is minimized.



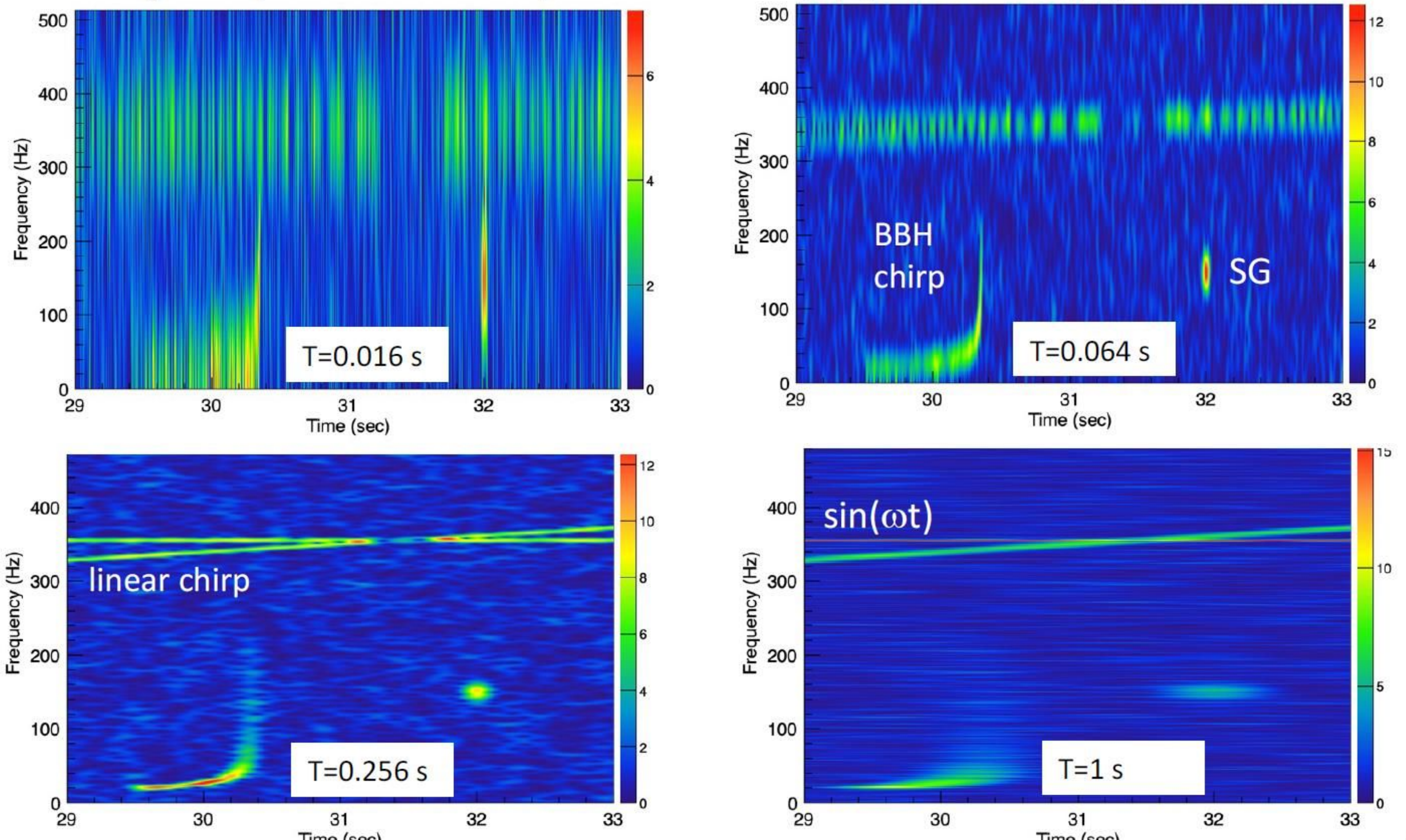


Wavescan

Time-Frequency Distribution $P(\omega, t) = |\hat{x}(t)|^2$

Short Time Fourier Transform: $\hat{x}(t,\omega) = \int_{-\infty}^{\infty} x(\tau) w(\tau - t) e^{-i\omega\tau}\, d\tau$

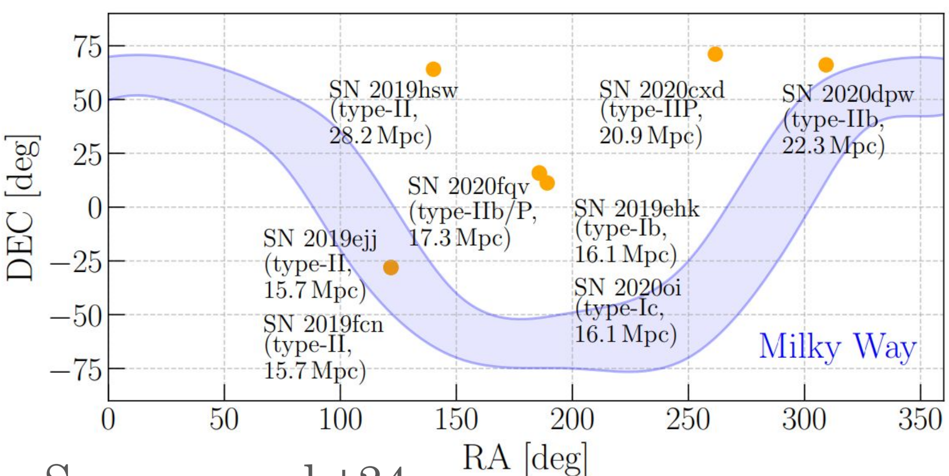
Which window w(t) is optimal? – The answer depends of the type of the signal we try to resolve
More general question: what is the optimal distribution $\boldsymbol{P}(\boldsymbol{\omega}, \boldsymbol{t})$ of the time-varying spectrum?



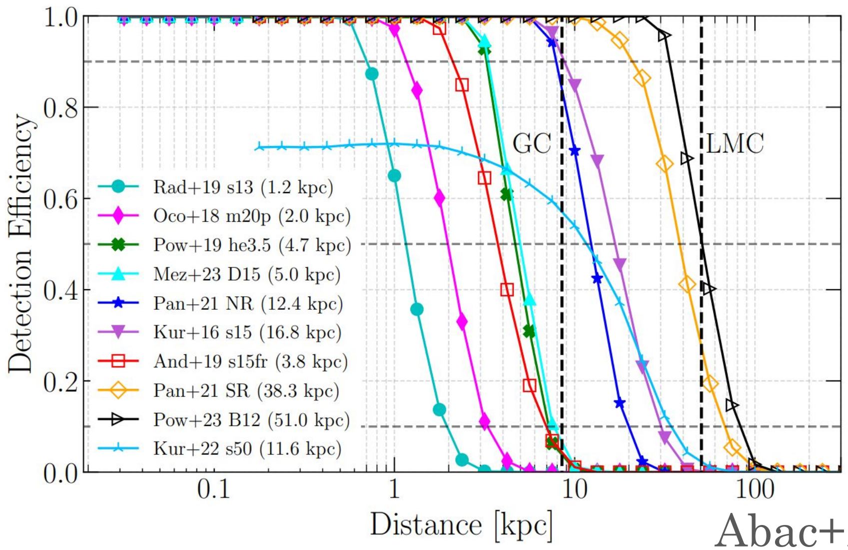
S. Klimenko, APS, April 2022 3

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 (my main PhD thesis result)
- O3 search (Szczepanczyk+24, 2305.16146):
  - We could not beat previous 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

O4 cWB low-latency searches

- The cWB searches: cWB-AllSky (generic) and cWB-BBH
- Analysis:
  - LH: searches, significance
  - LHV: sky map follow-up

cWB-AllSky (generic)

- cWB-XP and cWB-2G
- Public alert for GW bursts: "fluence" (~luminosity), peak frequency, duration
- Only one event so far S200114f (O3) - classified as noise offline

cWB-BBH search

- cWB-BBH events are treated as CBC (RODA: M2200164)
- 3 events so far
- **It's capable to detect "vanilla" and special/exceptional compact binaries**
- Complementing matched filtering
- It detects around **80%** of BBHs identified by matched filtering searches (HL network)