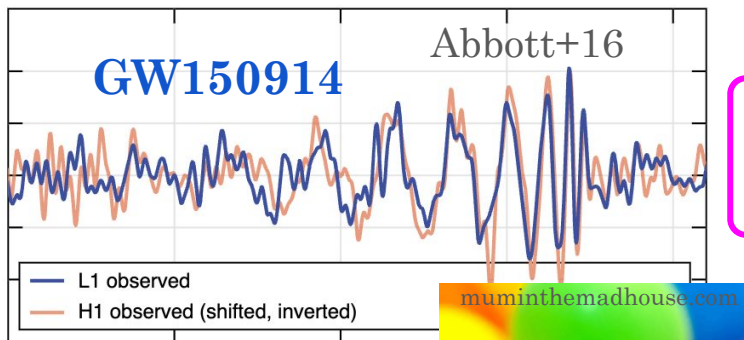


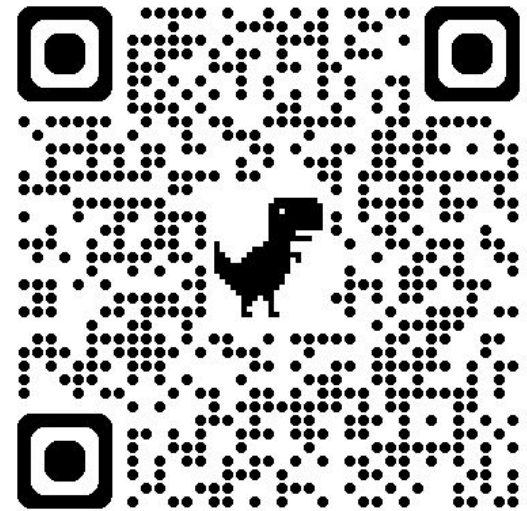
# The quest to detect exceptional gravitational-wave sources

Marek Szczepańczyk

Department of Physics, University of Warsaw



Main theme:  
what's next?



Slides:

[fuw.edu.pl/~mszczepancyk/news.html](http://fuw.edu.pl/~mszczepancyk/news.html)

Astrophysics Seminar Series  
University of Melbourne, 06.05.2026

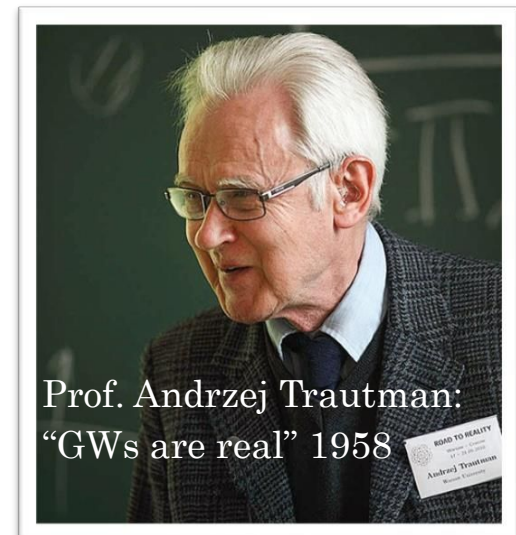
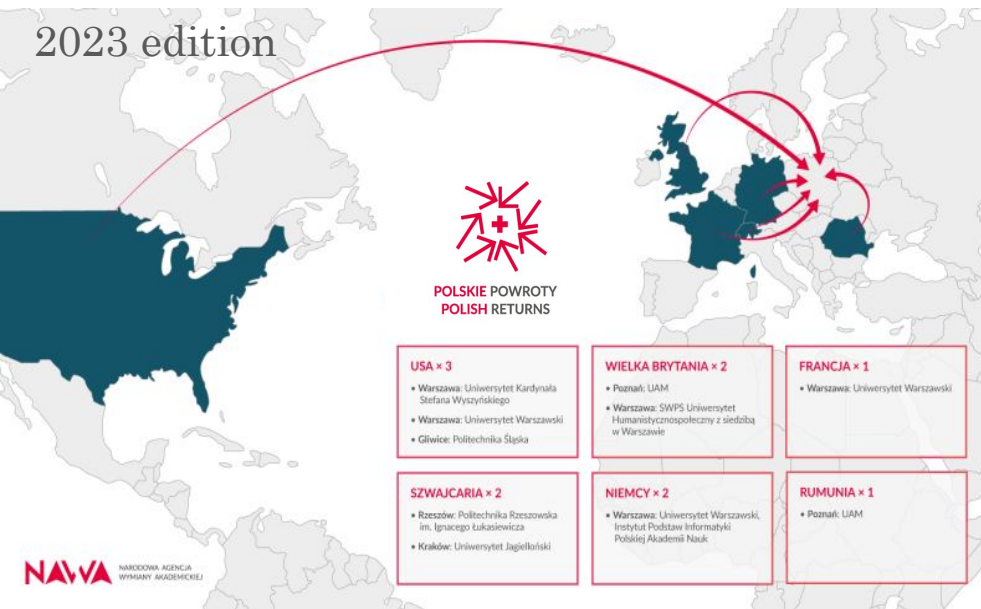
# Return to Poland

- 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/~mszczepancyk/>

## 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



# Polgraw

- Currently 19 members. Group leader: prof. Bulik
  - <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)
  - First database for globular clusters (prof. Askar et al)
- Recent and future GW events:
  - Sep 2019 - LVK Meeting
  - Nov 2024 - 3rd ET Annual Meeting
  - Jul 2025 - IGWN Symposium on supernovae (2nd part of this talk)
  - Possibly in 2027 - LVK/IGWN Meeting



3rd ET Annual Meeting LOC



# Outline

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

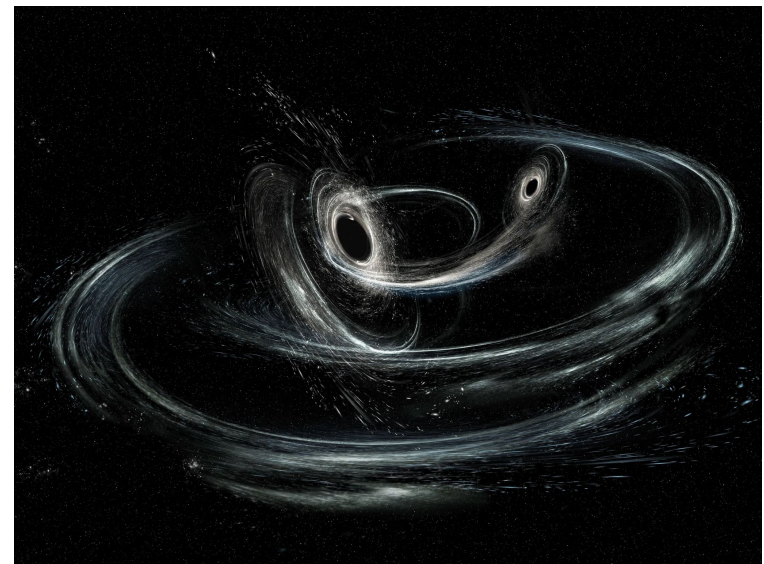
# Model-independent searches

# 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!** (new source populations, multi-messenger sources, new phenomena)

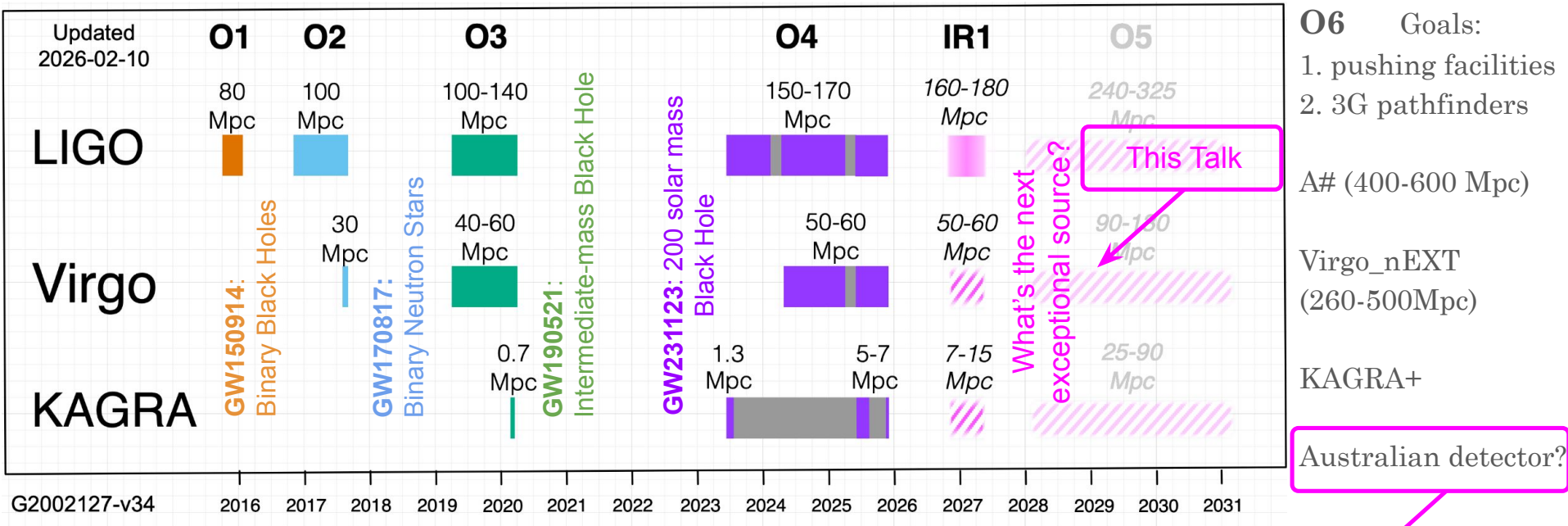


AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE

# Observing Timeline

Past 10 years

Future 10 years



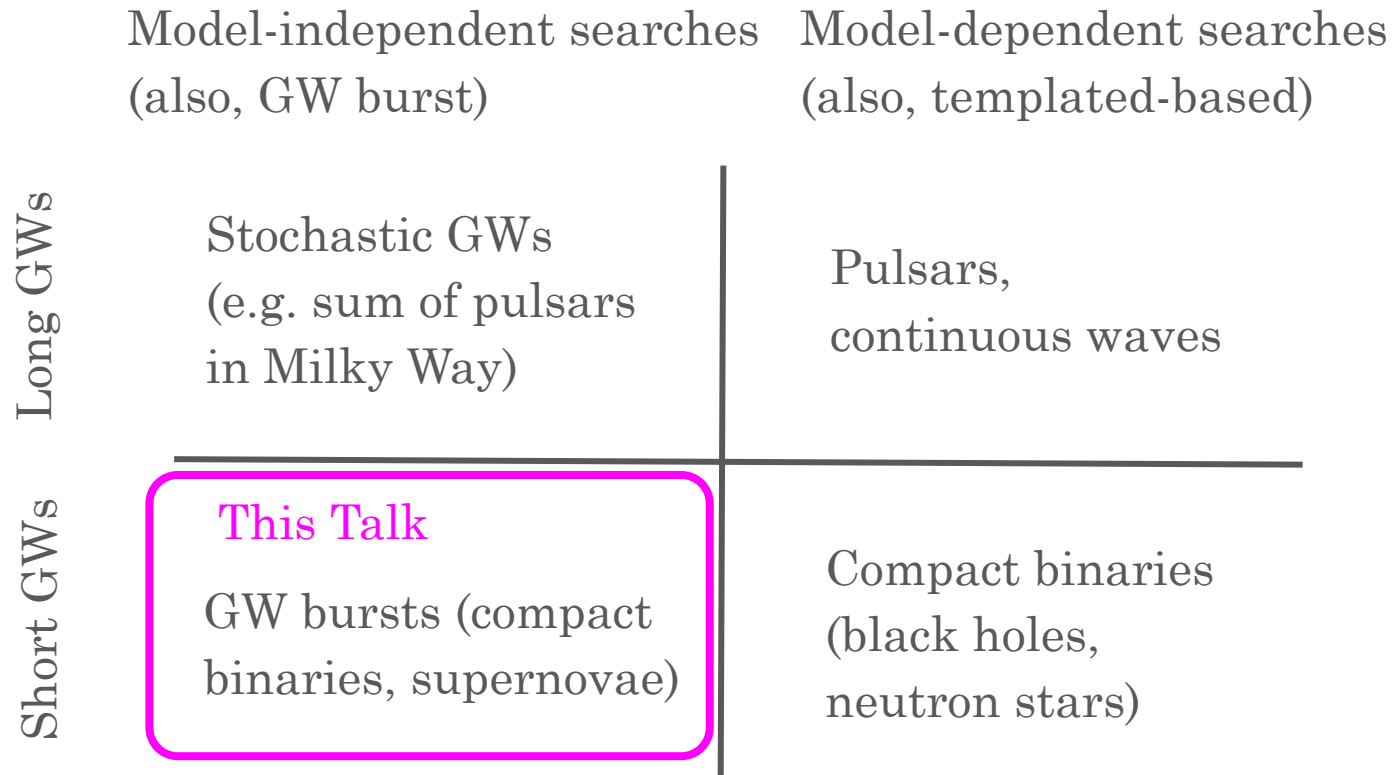
- O4: 24 months total, until 18 Nov 2025
- LIGO: up to 180 Mpc, around 160 Mpc
- Virgo: around 55 Mpc
- KAGRA: not yet observing, reached 7 Mpc

Observing news:

<https://observing.docs.ligo.org/plan/>

Part of my current visit:  
supporting science case

# GW Sources and Searches



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

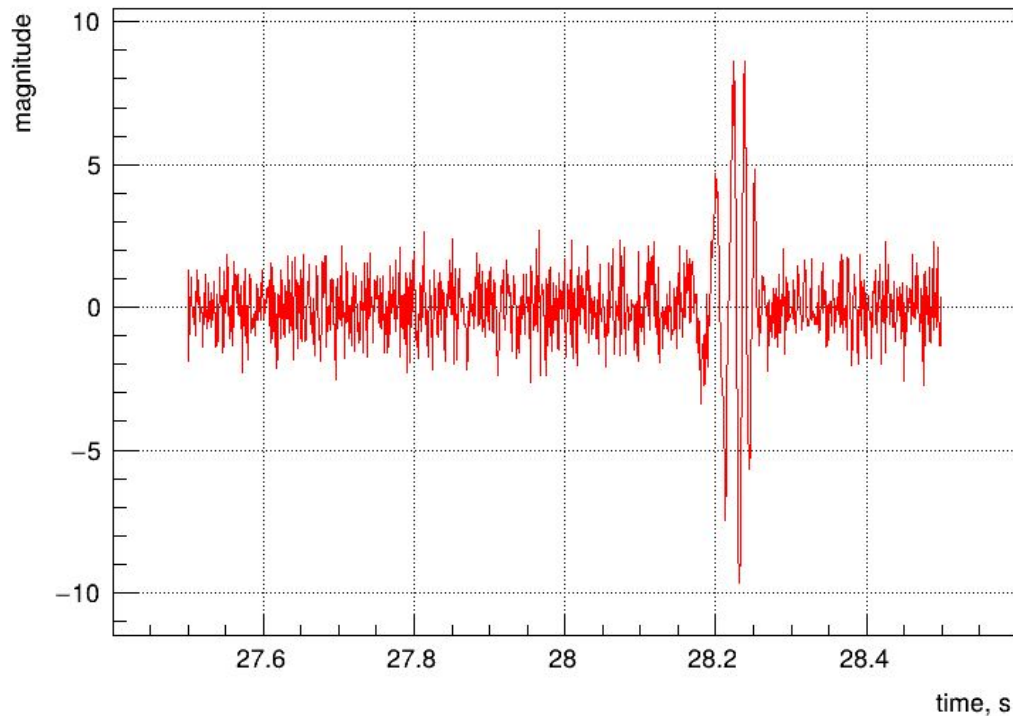
Complementary searches

Candidate	Inst.	cWB-BBH			GstLAL			MBTA			PyCBC		
		FAR ( $\text{yr}^{-1}$ )	SNR	$p_{\text{astro}}$	FAR ( $\text{yr}^{-1}$ )	SNR	$p_{\text{astro}}$	FAR ( $\text{yr}^{-1}$ )	SNR	$p_{\text{astro}}$	FAR ( $\text{yr}^{-1}$ )	SNR	$p_{\text{astro}}$
Abbott et al 2025, GWTC-4													

# GW Bursts

**Bursts** – short-duration transients. Examples:

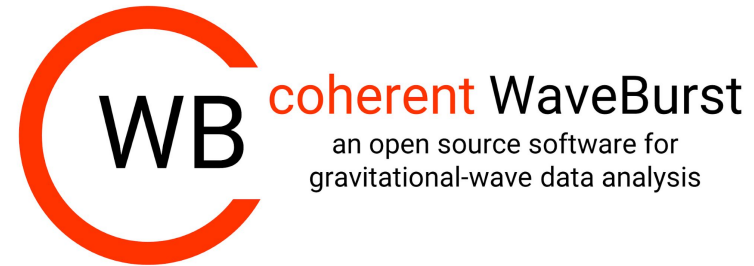
- Electromagnetic: gamma ray burst, fast radio burst, optical, X-ray, etc.
- Neutrino bursts
- Cosmic rays
- **GW Bursts** ← **how to search for them?**



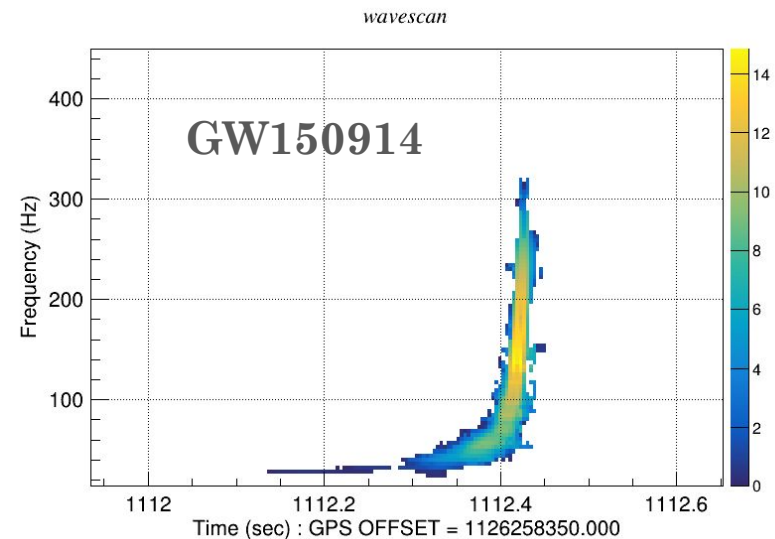
Example of binary  
black hole in the data,  
signal-to-noise ratio of  
around 30  
(very strong)

# Model-independent searches

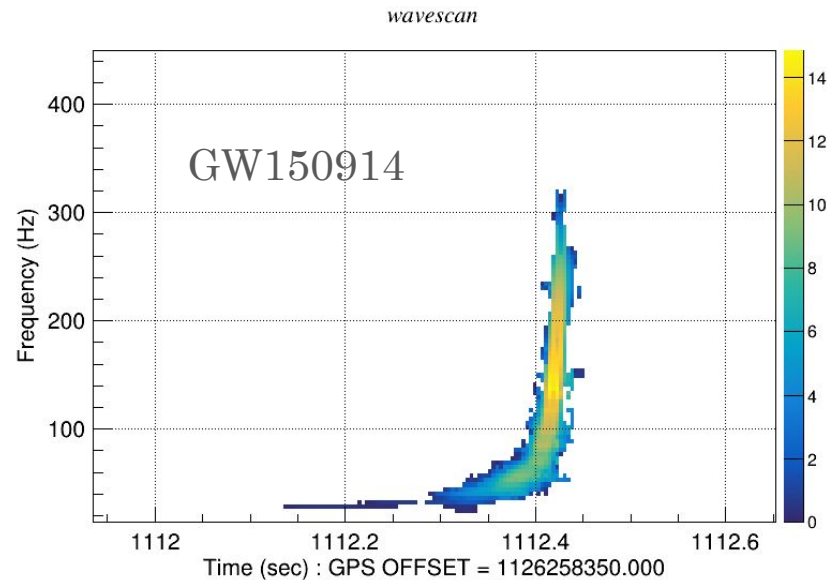
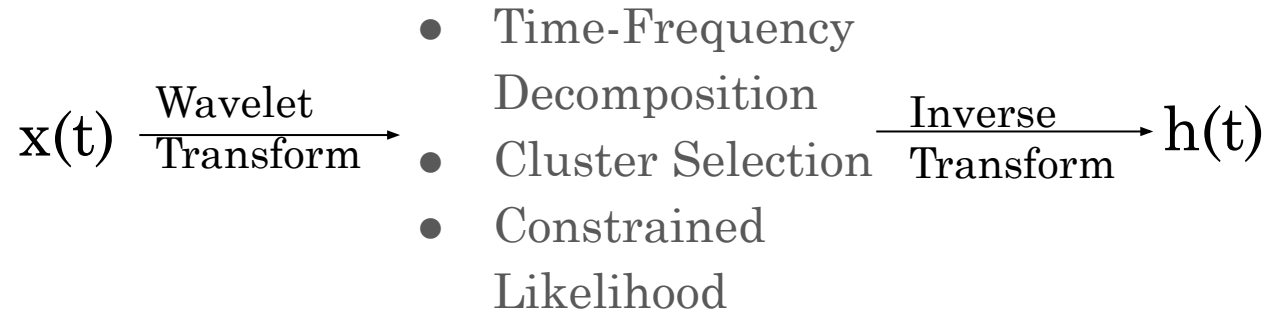
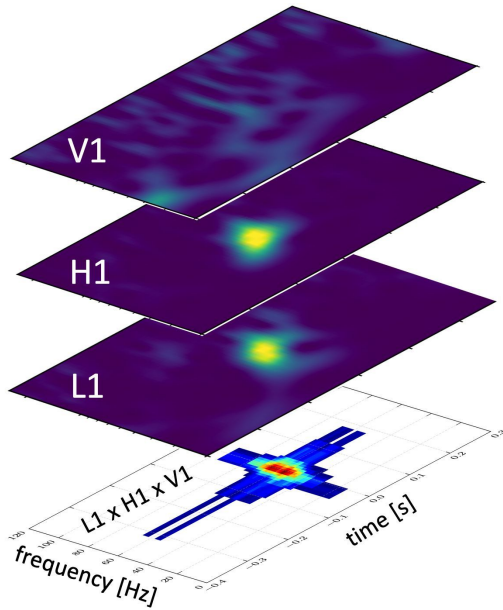
- **Coherent WaveBurst** (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
- cWB may use **minimal assumptions**, for example growing frequency over time in case of binaries
- **Complementing template-based searches**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



<https://gwburst.gitlab.io/>



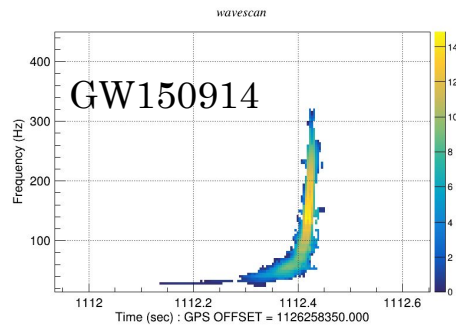
# coherent WaveBurst (cWB)



# Model-independent searches classification

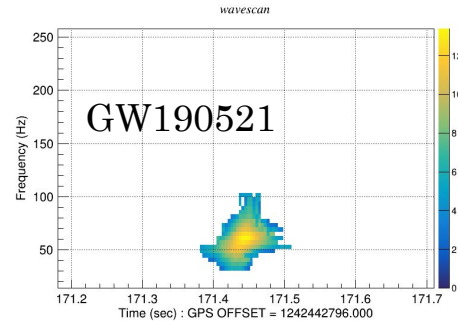
## Compact binary searches (minimally modeled)

Binary black holes  
Binary neutron stars  
Black hole - neutron star



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

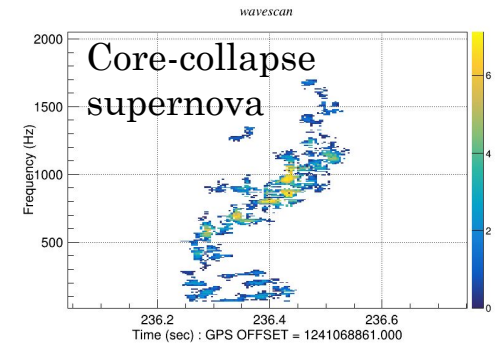
Binaries with eccentric orbits  
Intermediate-mass black holes  
Hyperbolic encounters  
Extreme mass-ratio



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

## Generic searches (unmodeled)

Core-collapse supernovae  
Pulsar glitches  
Cosmic strings  
Unknown



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

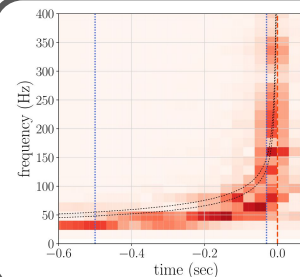
## Low-latency searches



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](#))

# Exceptional Gravitational-Wave Sources

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

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

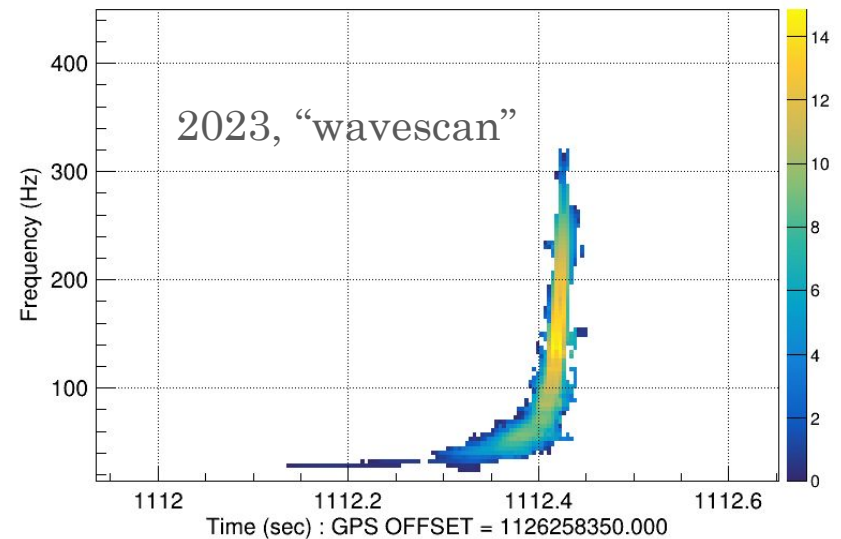
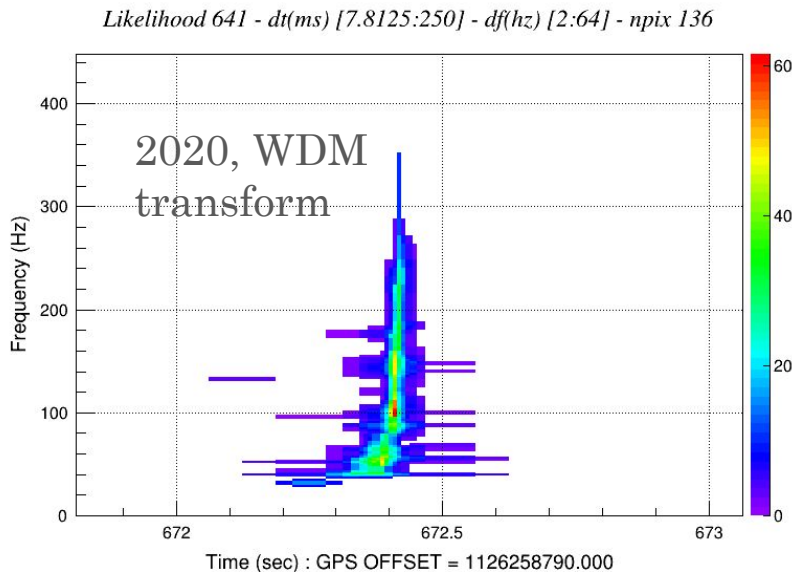
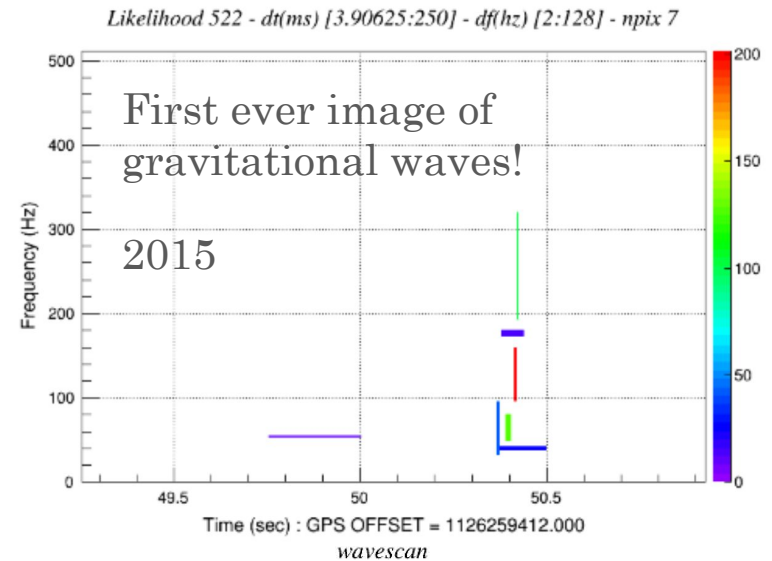
- **New GW source populations:**
  - Compact binaries: **binaries with eccentric orbits**, hyperbolic encounters, head-on collisions, extreme mass ratio, sub-solar mass binaries, **lensed binaries**
  - GW bursts: **core-collapse supernova (CCSN)**, neutron star or pulsar glitches, cosmic strings **High-risk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

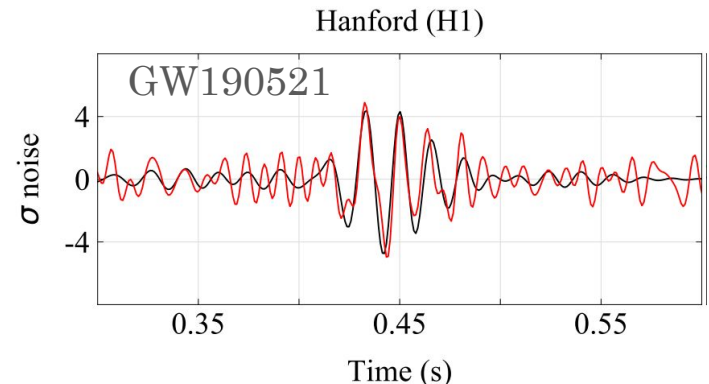
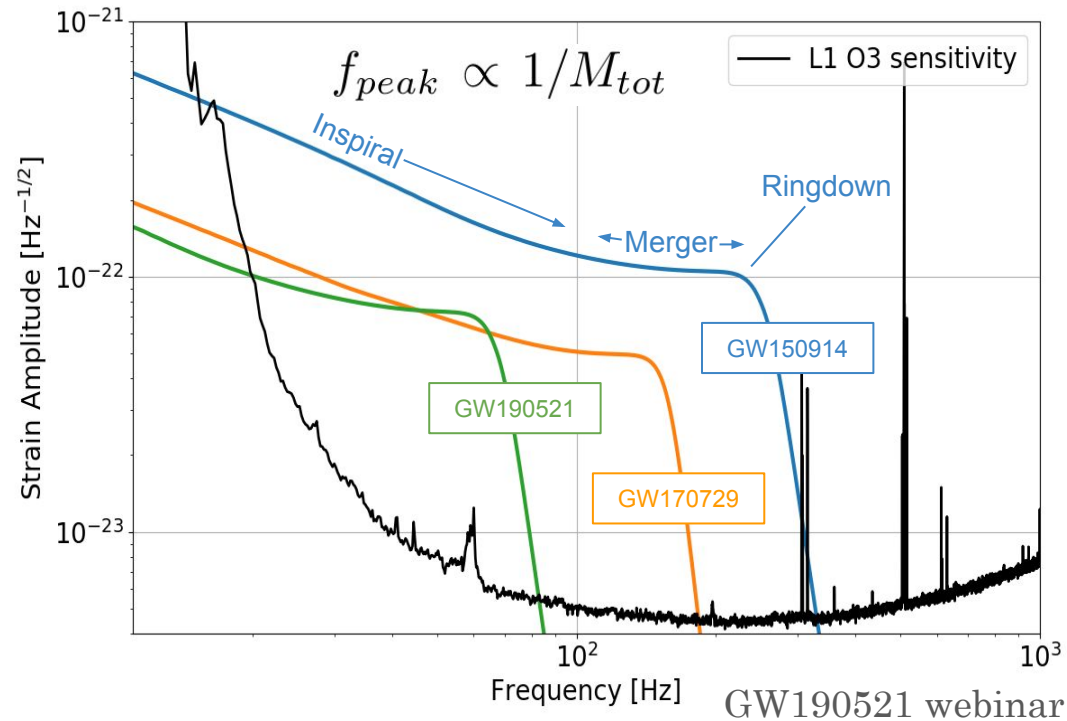
# Stellar-mass black holes, GW150914

- pre-2015: the matched filtering methods were not searching for BBHs above 15 Msun.
- 2023: “wavescan” - high-resolution time-frequency transform



# 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.



# Future: potential GW sources

Potential targets for model-independent low-latency searches:

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

My main purpose of  
visiting Melbourne



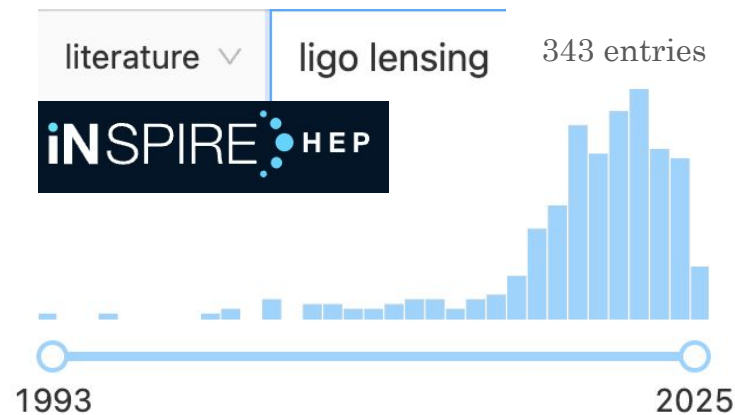
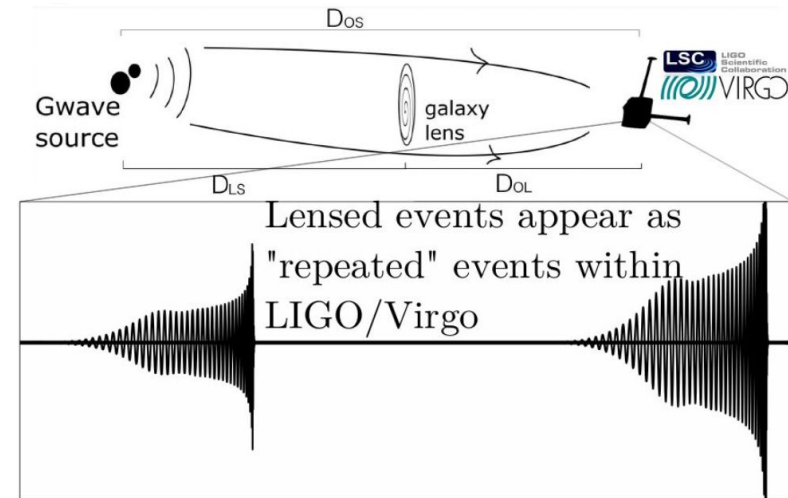
But also:

- Hyperbolic encounters
- Multi-messenger: GWs and GRBs

Eager to discuss options!

# Future: GW lensed binaries

- Similarly to optical lensing: bending of GWs propagation path near a massive object
- **Rate: estimated to be 1 per 1000 GW detections**
- Comparison with electromagnetic wave lensing:
  - Similar to light, GWs can be gravitationally lensed
  - But, very different methodology and science case
- New studies of astrophysics, cosmology and fundamental physics.
- GW lensing: magnification, multiple images
- Growing interest in GW community



# Future: eccentric binaries



“Eccentric” Salvador Dali

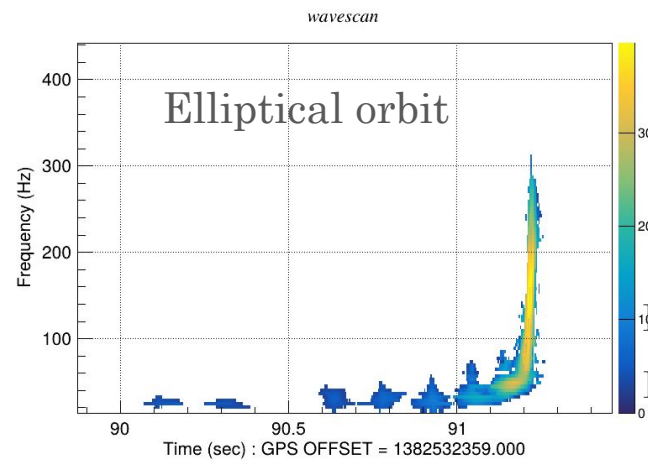
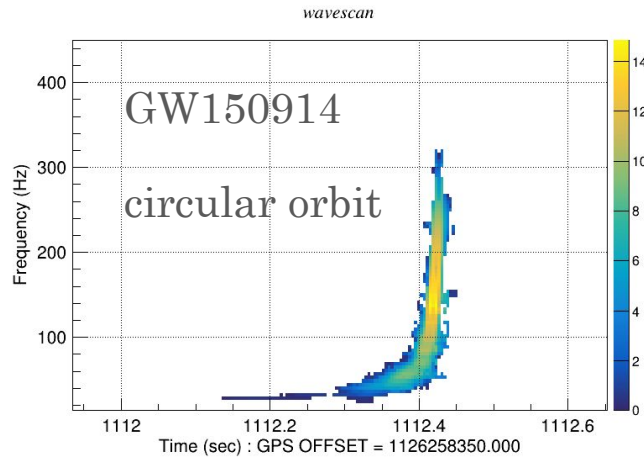
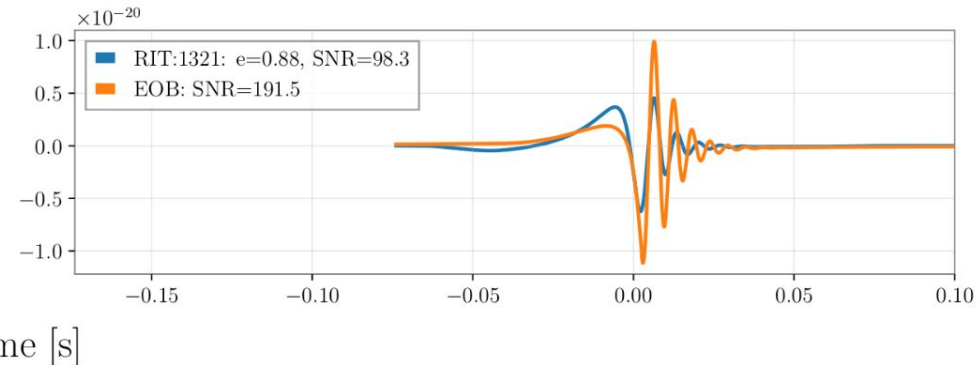
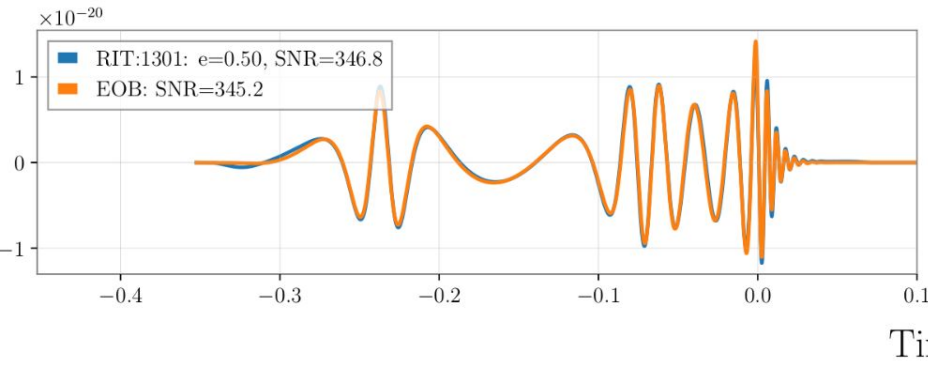


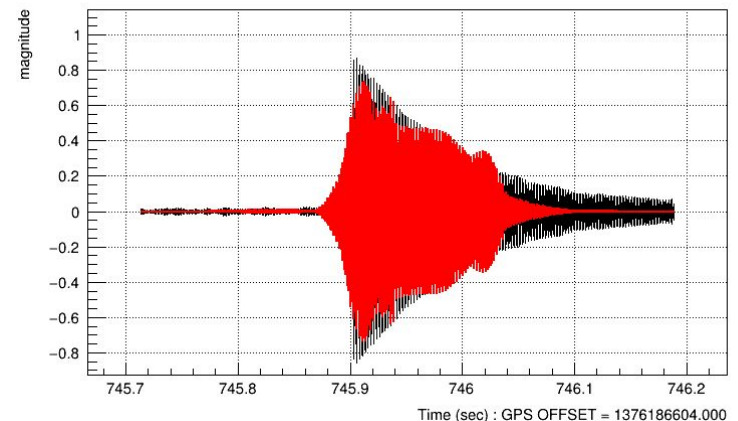
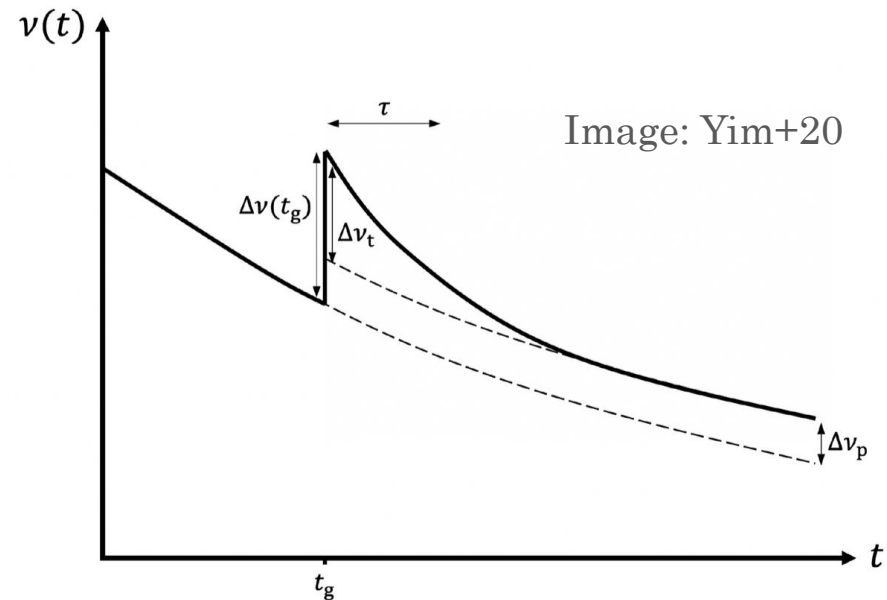
Image:  
Bhaumik

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



# Future: pulsar glitches

- Pulsar glitch: breaking surface crust - rapid change in rotational frequency
- **My main purpose of visiting Melbourne: detectability of pulsar glitches in the context of low-latency searches.**
- Predictions:  $\Delta f_{\text{rot}} = 10^{-5}$  Hz detectable in O5 (Lopez et al 2022)
  - Vela glitch on 29 April 2024:  $\Delta f_{\text{rot}} = 2.6 \times 10^{-5}$  Hz!
- After crust breaking the energy is emitted in GWs: ringdown.



# Future: Core-Collapse Supernova

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

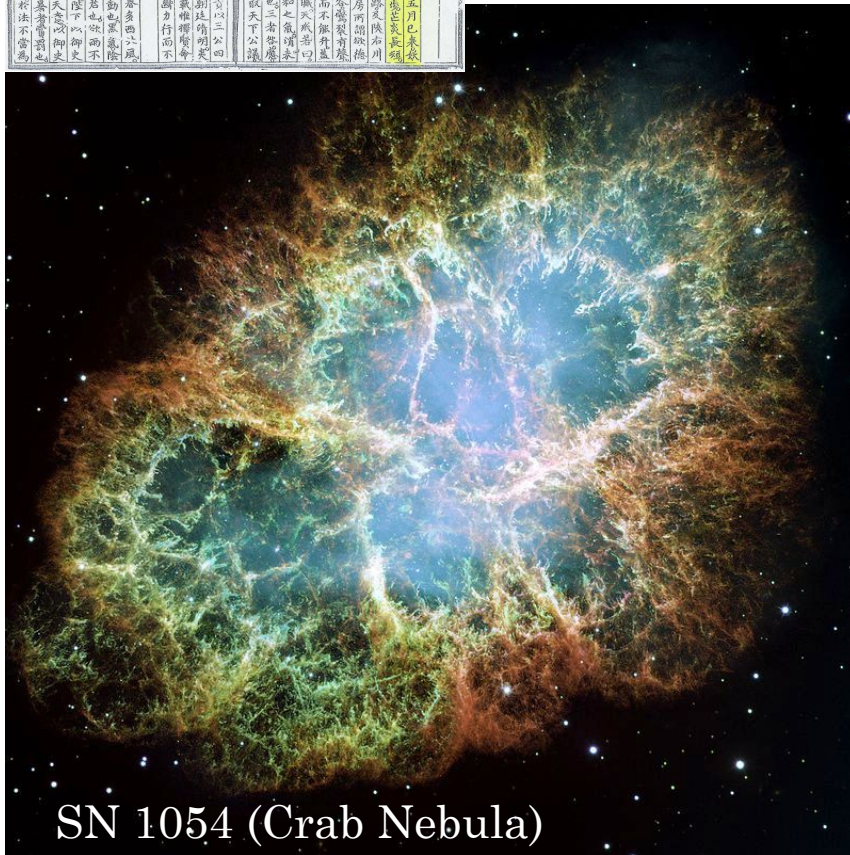
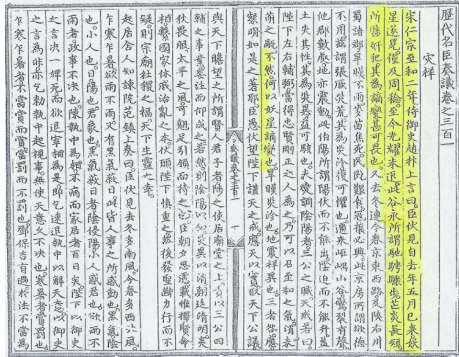
# Core-Collapse Supernova (CCSN)

*Nova on the sky!*

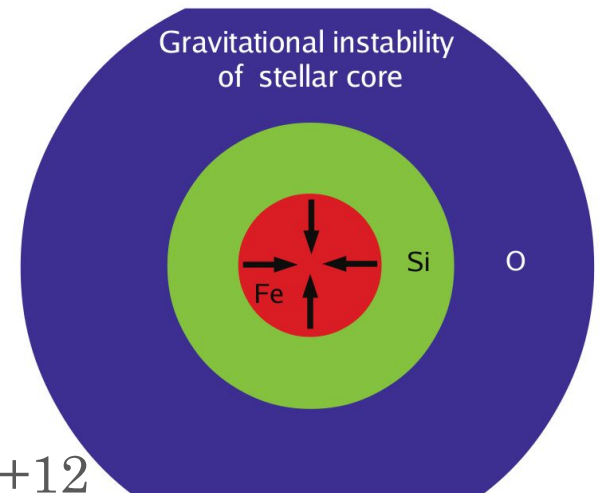
1-2 per century in Milky Way (?)

“Guest star”  
Zhao Bian's memorial to Emperor Renzong

- Burning of a star:  $H \rightarrow He \rightarrow \dots \rightarrow Fe$
- 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



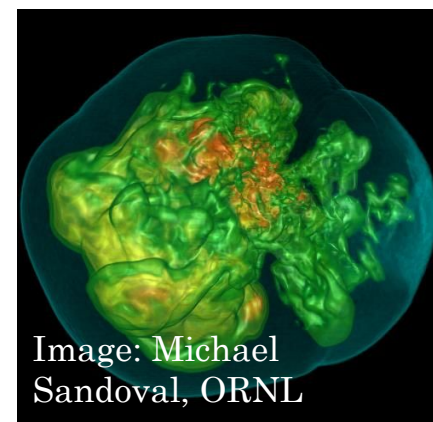
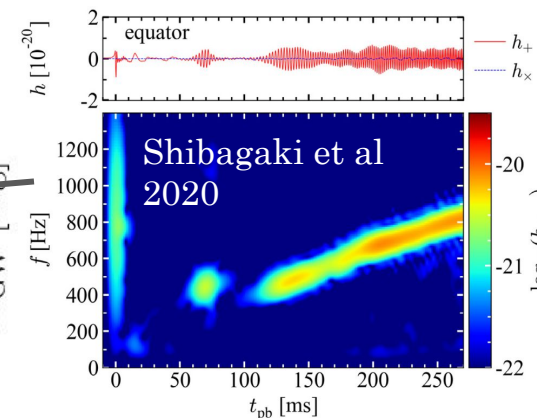
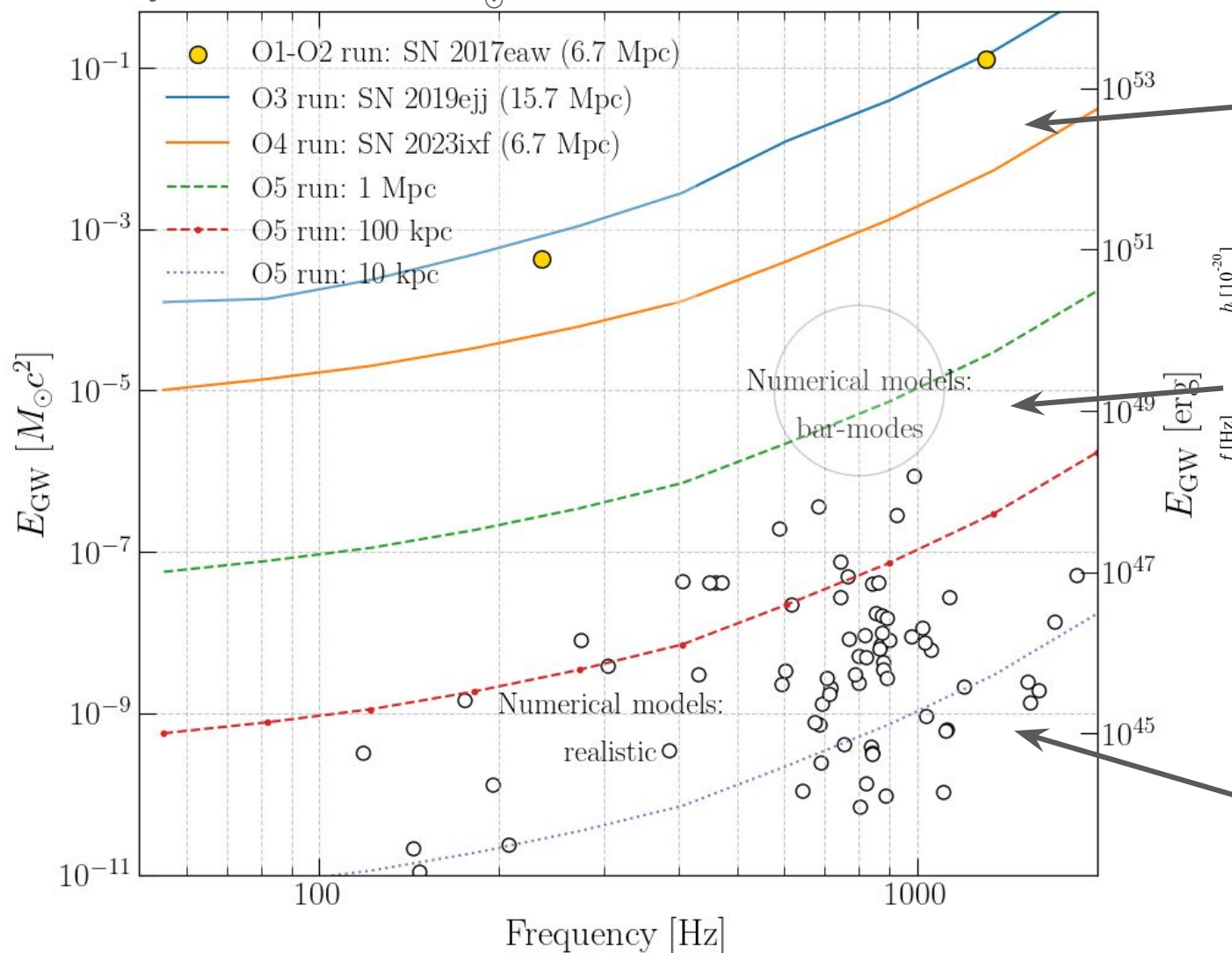
SN 1054 (Crab Nebula)



Janka+12

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

Binary black holes:  $\sim 3 M_{\odot} c^2$



# 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*

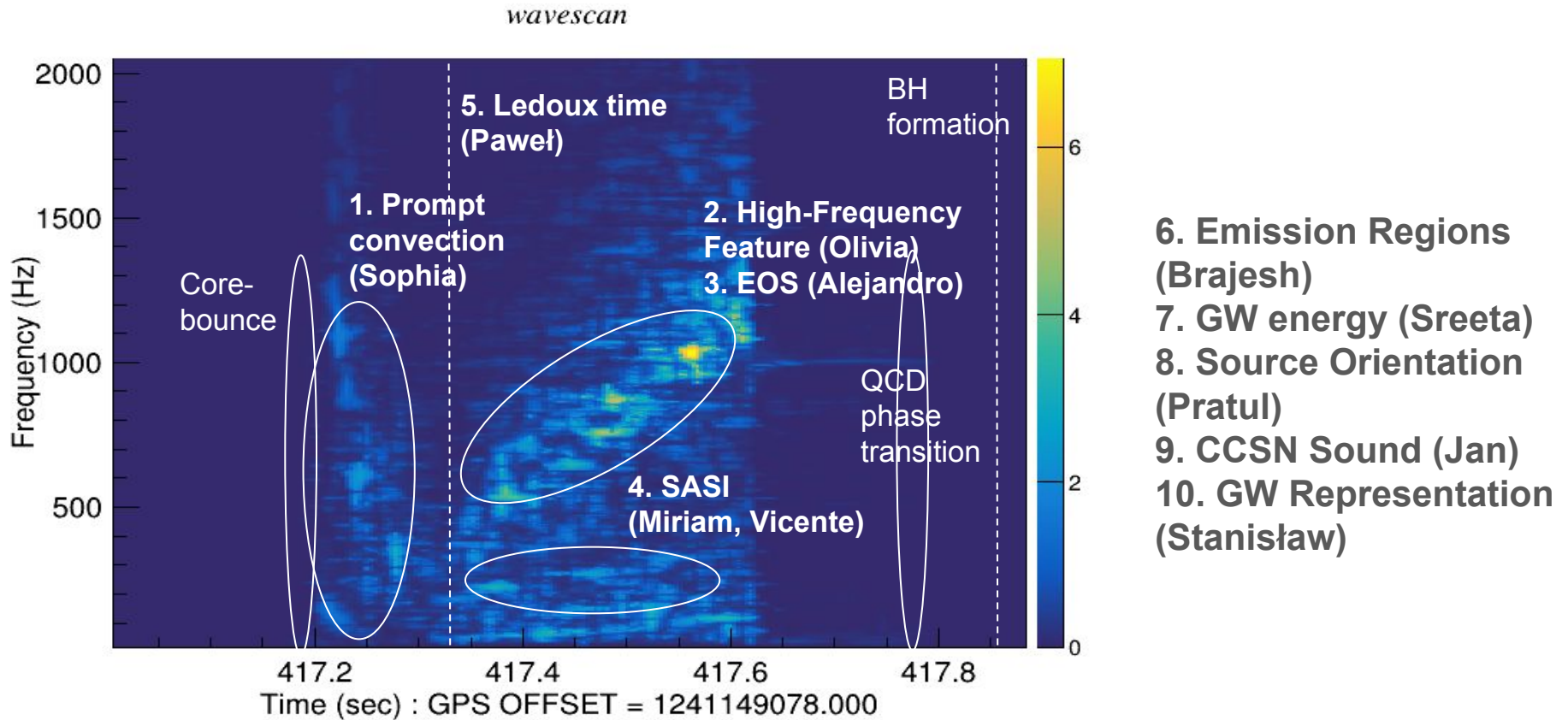
Anthony Mezzacappa, *University of Tennessee Knoxville, United States*

Jade Powell, *Swinburne University of Technology, Australia*

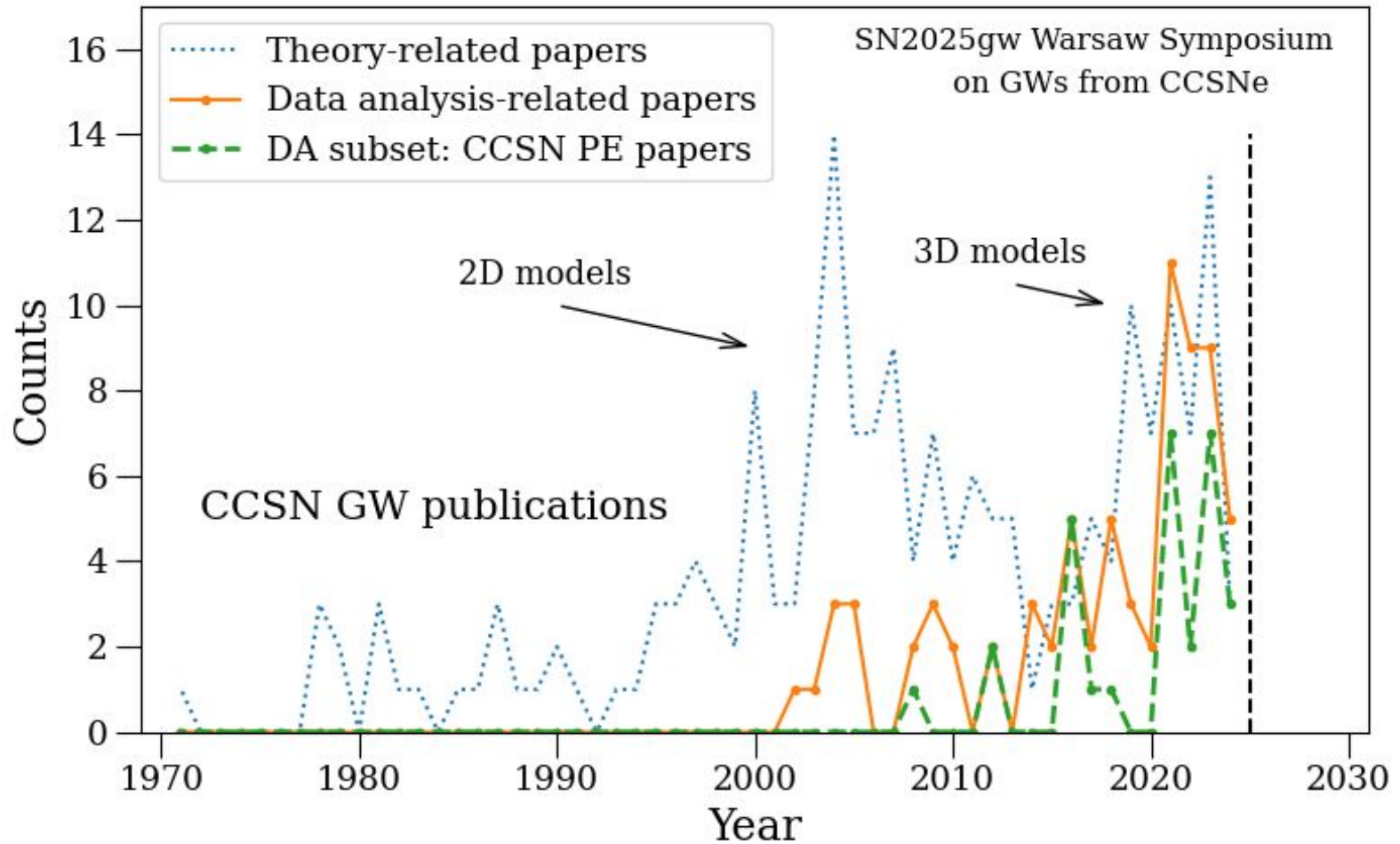
### Scope

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



# SN2025gw: maturity of CCSN models



CCSN GW Literature, by Ewald Mueller:

[https://wwwmpa.mpa-garching.mpg.de/rel\\_hydro/GWlit\\_catalog.shtml](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.

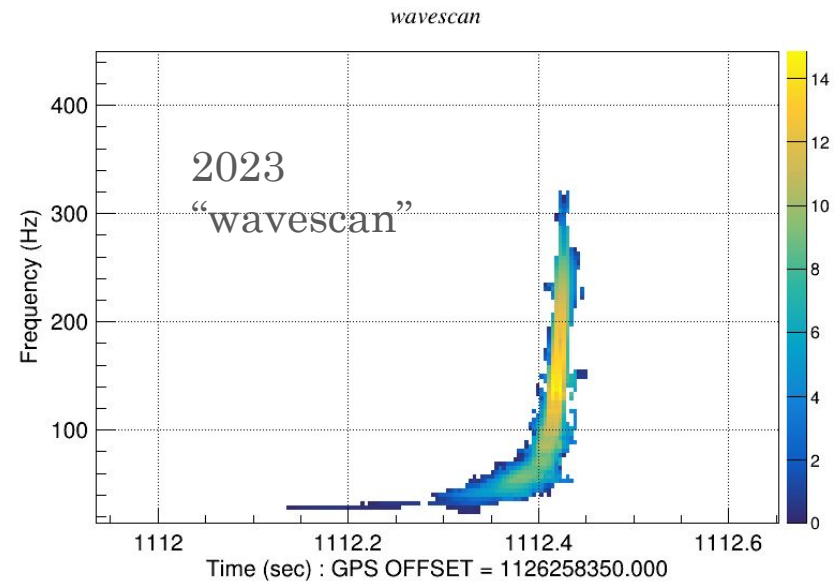
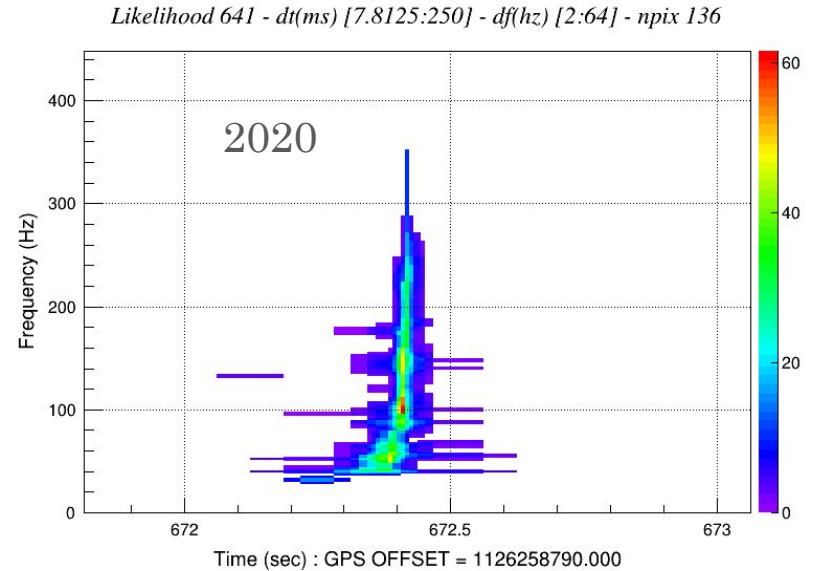
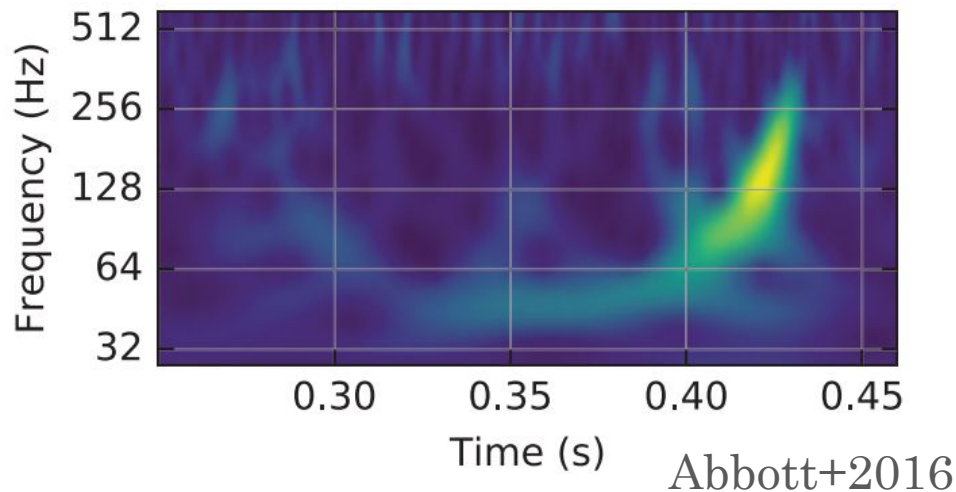
# Summary

- Model-independent searches
  - Complement template-based searches
  - Suitable to discover exceptional GW sources
- Exceptional/special GW sources
  - GW lensing, eccentric binaries, pulsar glitches, CCSN
- Core-Collapse Supernova
  - “Are we ready?”:  
SN2025gw: IGWN Symposium in Warsaw
- “What’s next?” - eager to discuss it, “GW ears” wide open, but we should strive to be prepared as much as possible.

# Extras

# Time-frequency maps (GW150914 example)

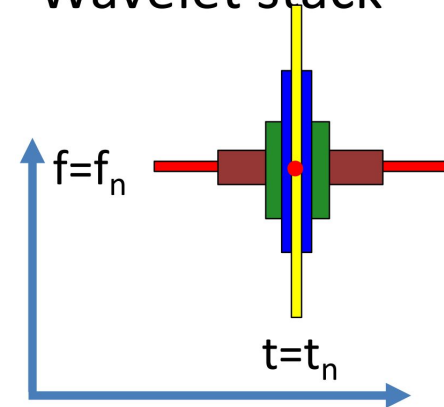
- Challenges:
  - Temporal leakage (time domain)
  - Spectral leakage (frequency domain)
  - Combining resolutions
- Latest developments on high-resolution time-frequency transform and minimizing leakage:  
Klimenko+22 “wavescan” ([2201.01096](https://arxiv.org/abs/2201.01096))



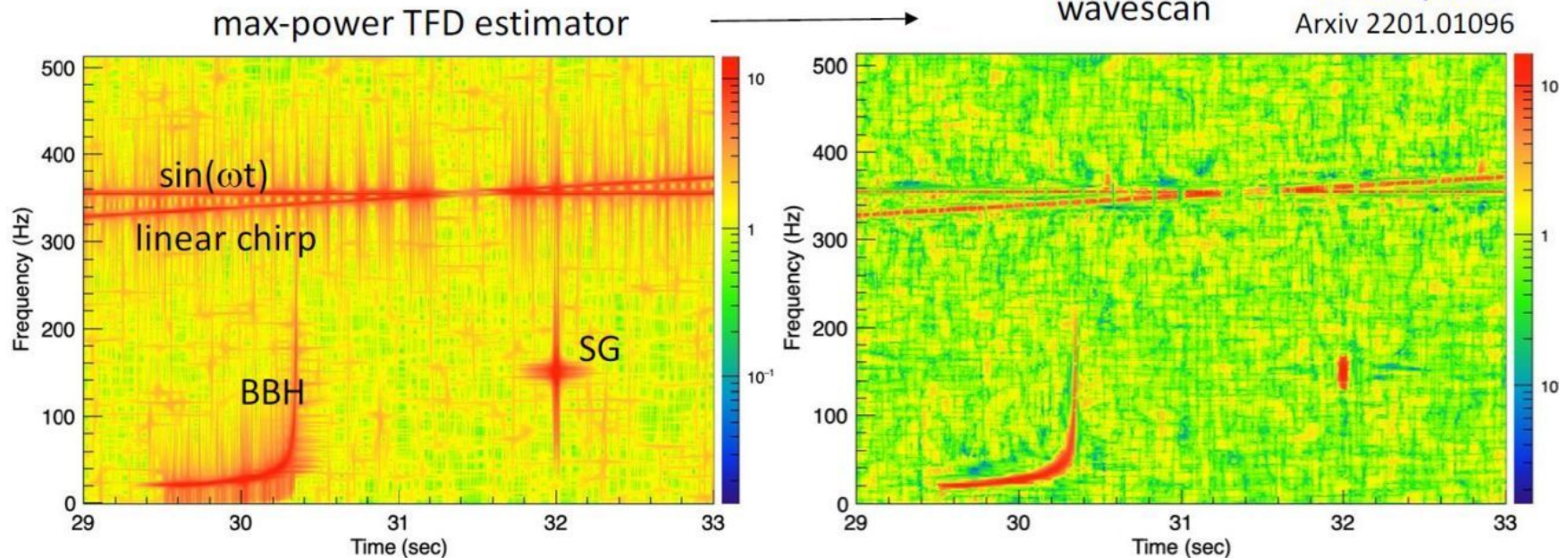
# Wavescan

- Wavescan (Klimenko+22, [2201.01096](https://arxiv.org/abs/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.

## Wavelet stack



Klimenko, 2021  
Arxiv 2201.01096

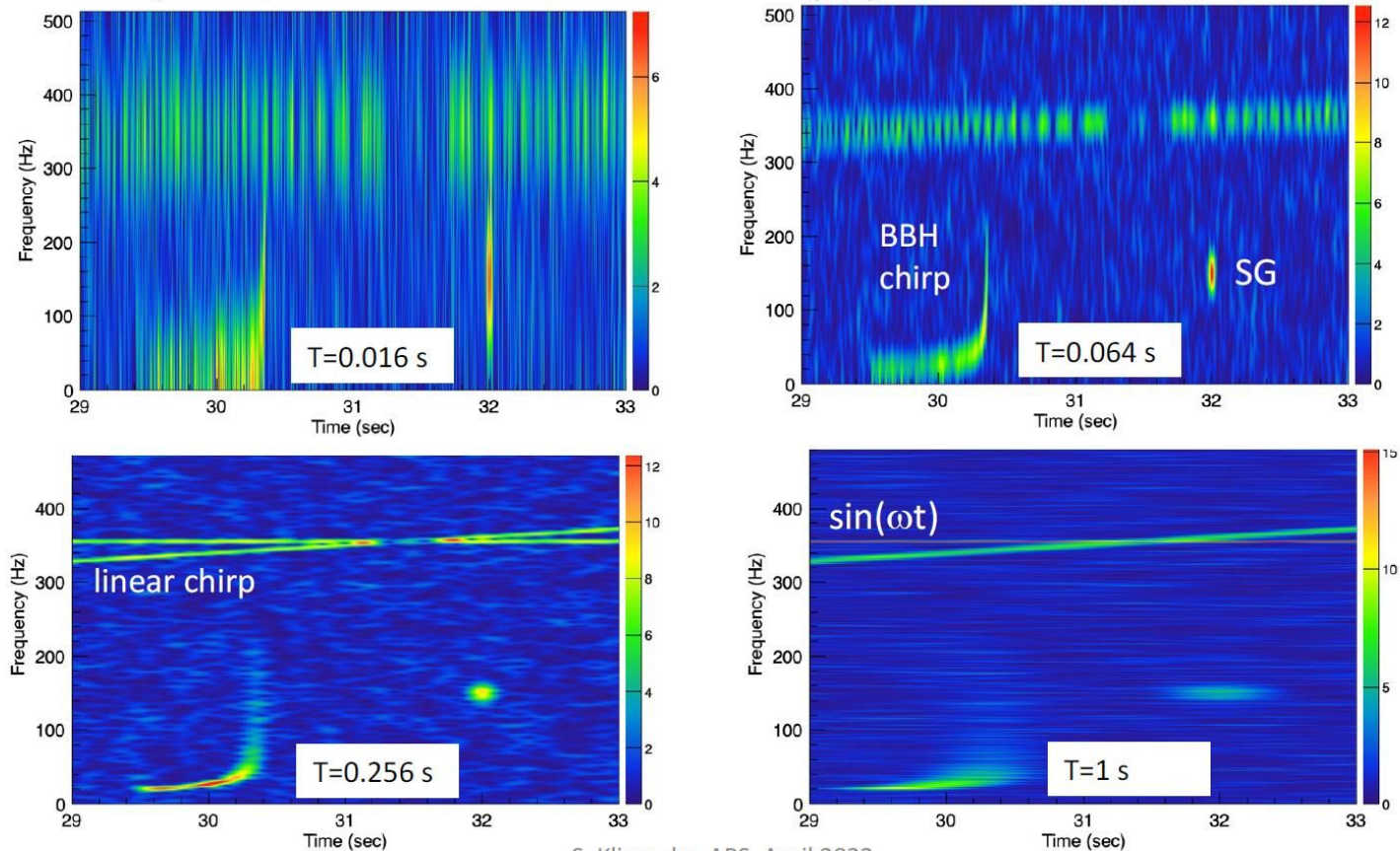


# Wavescan

## 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  $P(\omega, t)$  of the time-varying spectrum?

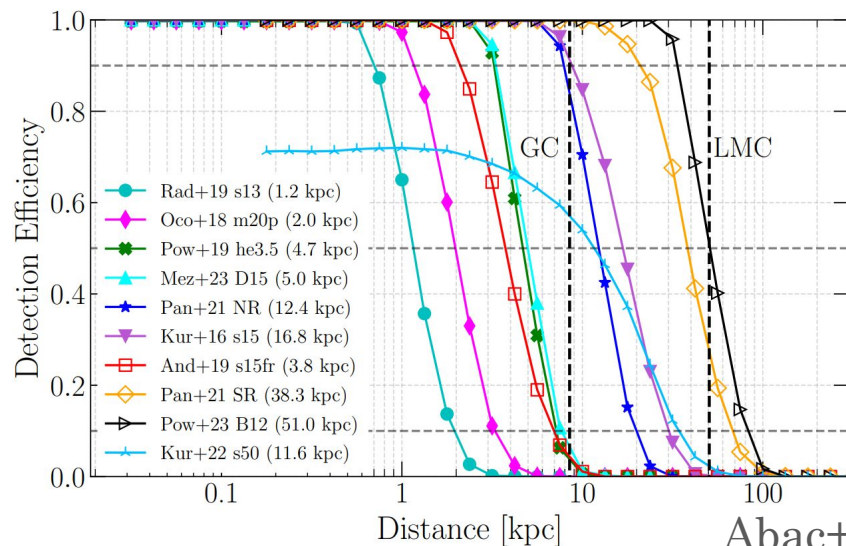
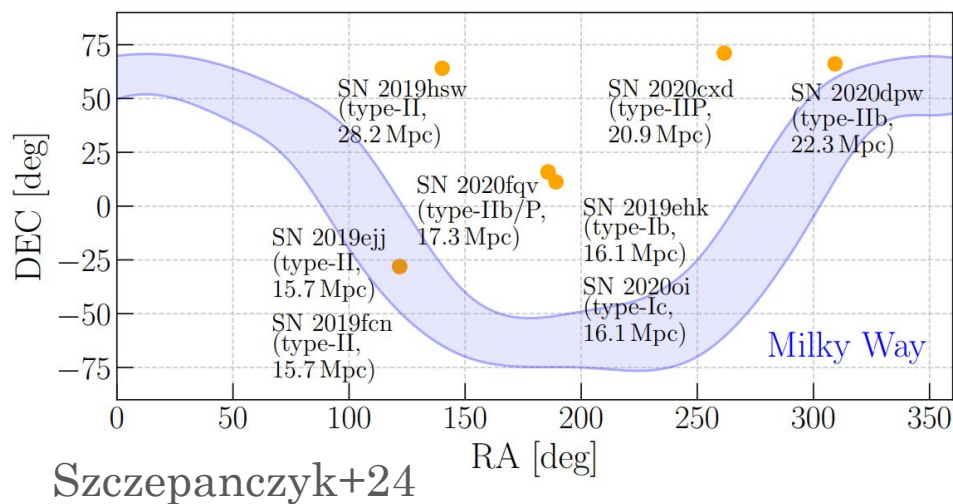


S. Klimenko, APS, April 2022

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



# 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: “fluences” (~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)