The quest to detect (exceptional) gravitational-wave sources

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GRITTS
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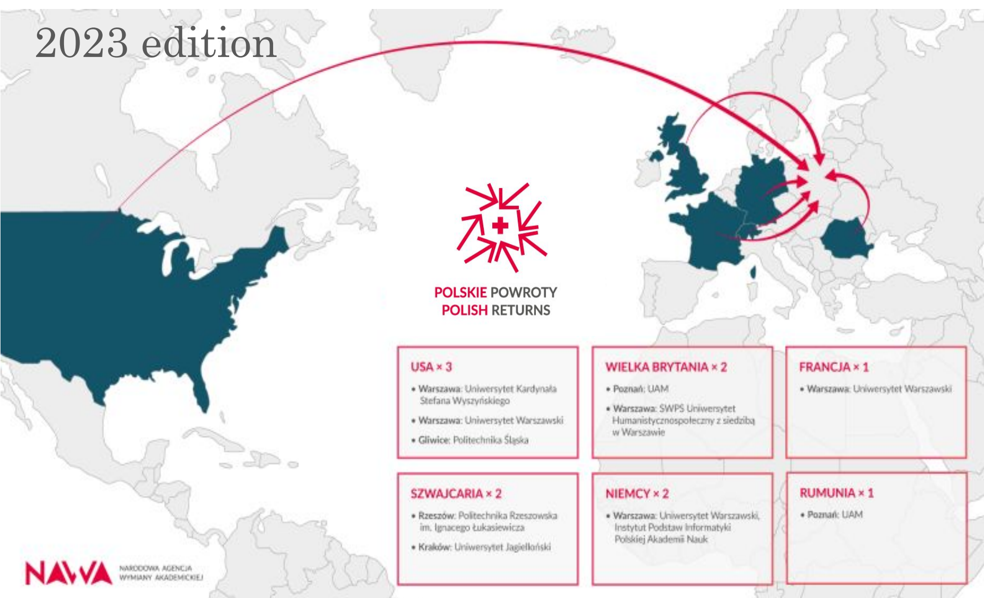
Return to Poland

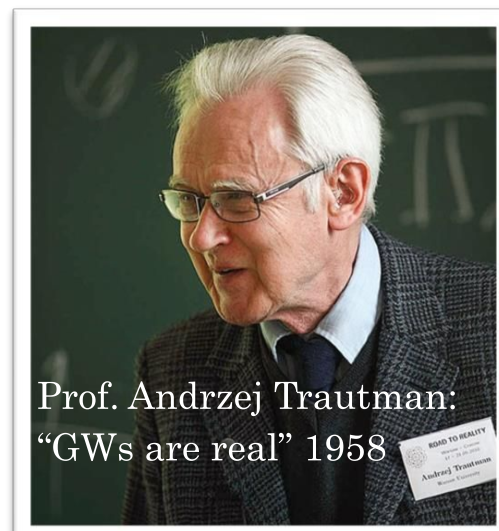
- Ph.D., ~5 years: ERAU (Arizona)
- Postdoc, ~5 years: University of Florida
- Assistant Professor, present: University of Warsaw (permanent position and a Polish Returns grant)

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



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

Outline

- Model-independent searches
  - Exceptional GW sources
  - Coherent WaveBurst
  - Searches
- Core-Collapse Supernova
  - Properties, predictions
  - Optically targeted searches
- LVK workshop announcement

Model-independent searches

Exceptional GW sources

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

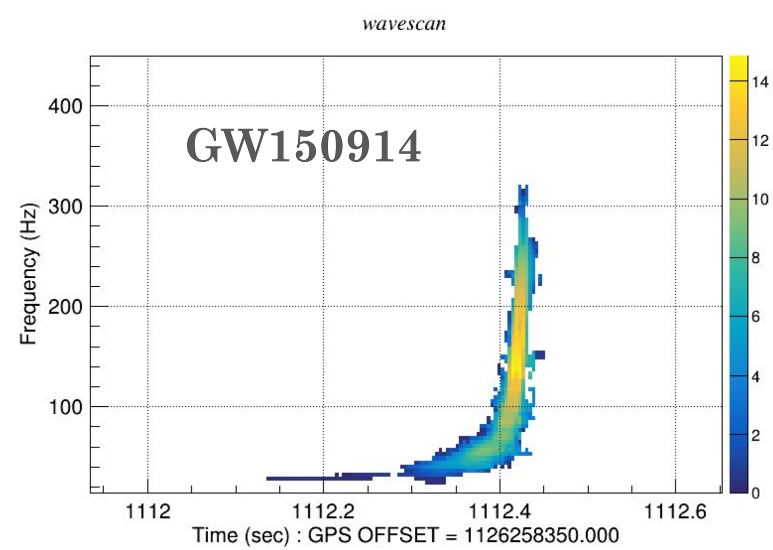
- **New GW source populations**:
  - Compact binaries: binaries with eccentric orbits, hyperbolic encounters, head-on collisions, extreme mass ratio, sub-solar mass binaries
  - GW bursts: core-collapse supernovae, neutron star or pulsar glitches, cosmic strings
- **Multi-messenger GW sources (electromagnetic waves, neutrinos, cosmic rays)**: BNS, NSBH, BNS post-merger
- **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, lensed binaries
  - Beyond GR: GW echo, beyond-quadrupolar GW polarizations,

Model-independent searches

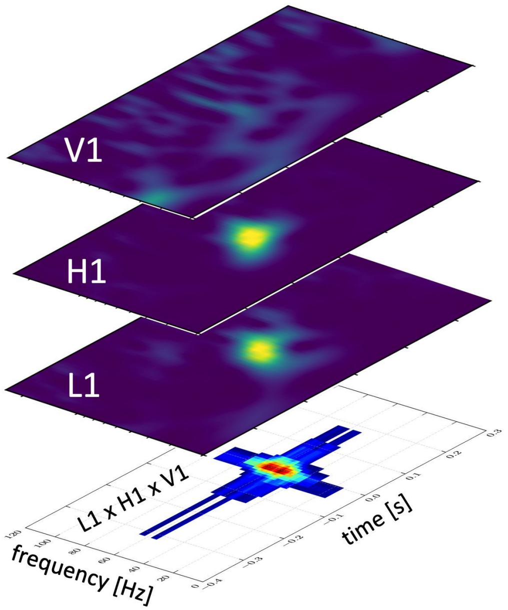
- **Coherent WaveBurst** (cWB, Klimenko+16) is a software designed to detect a wide range of burst transients without prior knowledge of the signal morphology
- cWB uses minimal assumptions, for example growing frequency over time in case of binaries
- **Complementing template-based searches**
- cWB has detected:
  - **GW150914** - the very first GW (PRL 116, 061102)
  - **GW190521** - an intermediate mass binary black hole (PRL 125, 101102)
  - 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/



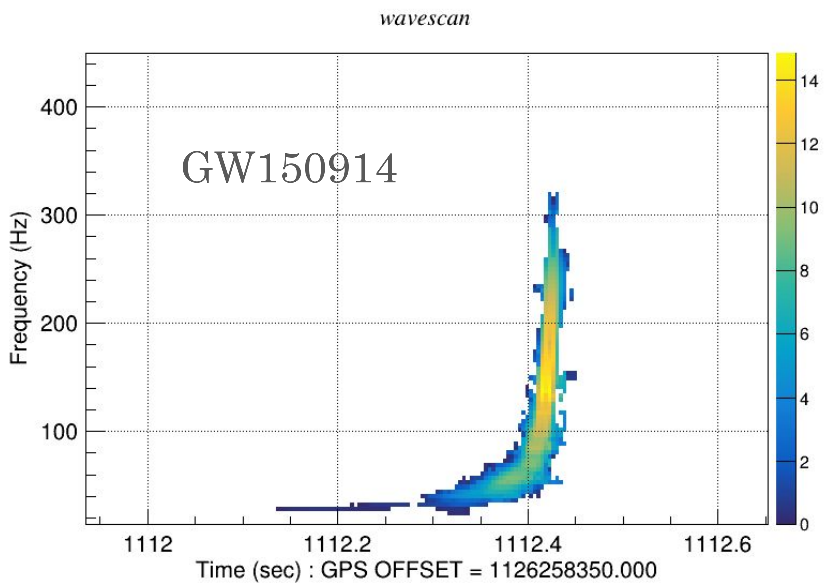
coherent WaveBurst (cWB)



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

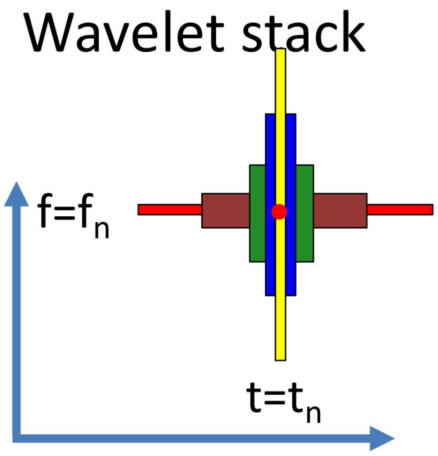
- Time-Frequency Decomposition
- Cluster Selection
- Constrained Likelihood

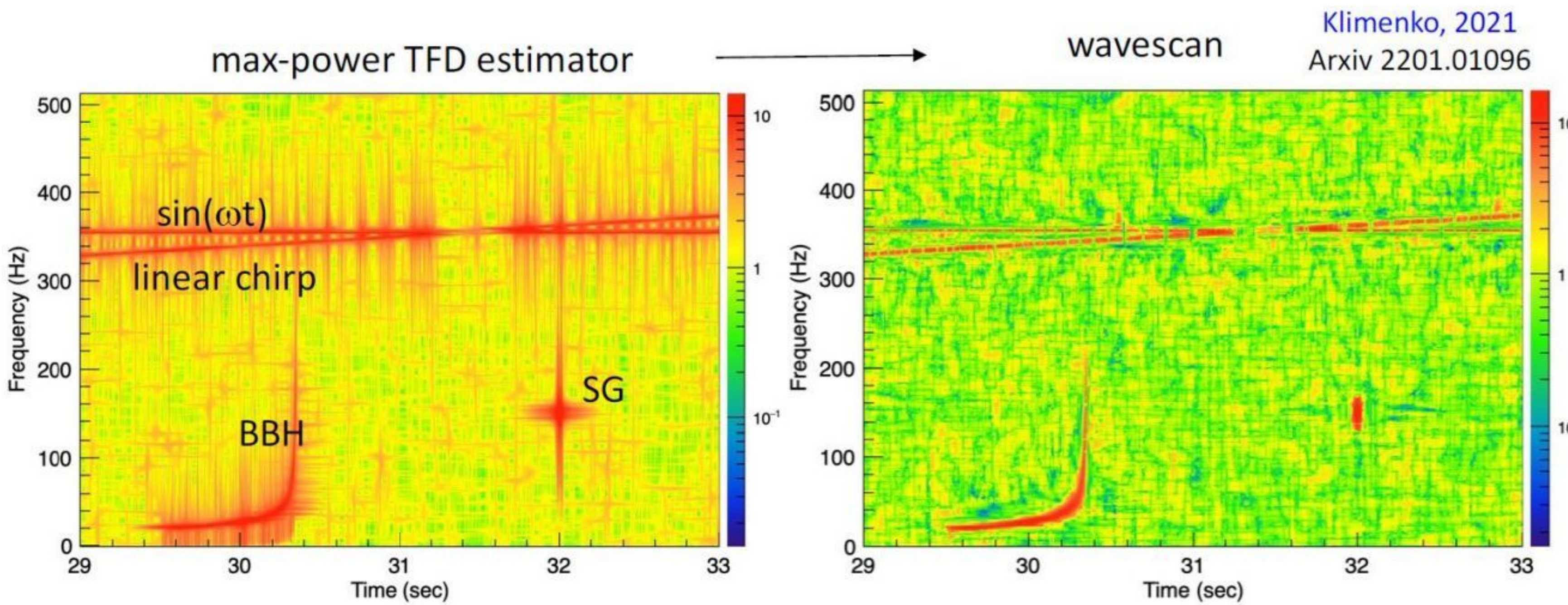
$\xrightarrow[\text{Transform}]{\text{Inverse}}$ h(t)



Wavescan

- Wavescan (Klimenko+22, 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.

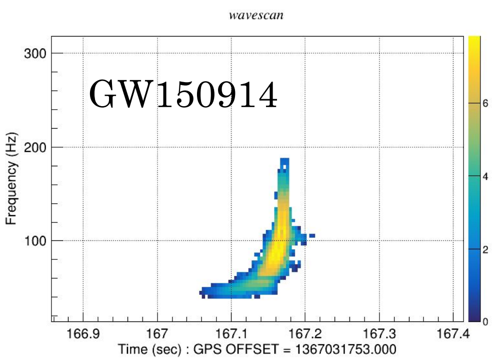




Model-independent searches classification

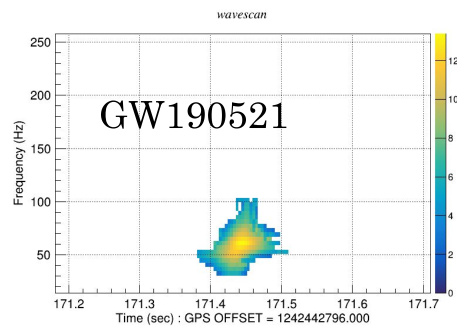
Compact binary searches (minimally modeled)

Binary black holes
Binary neutron stars
Black hole - neutron star



e.g. Mishra+23 (2201.01495)

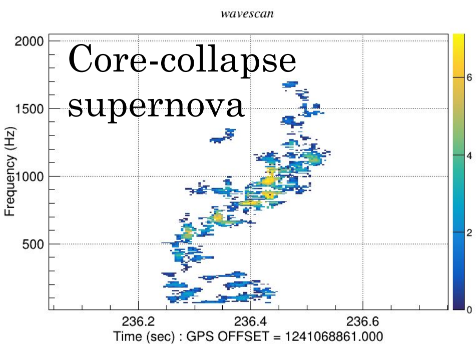
Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



e.g. MS+21 (2009.11336)

Generic searches (unmodeled)

Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



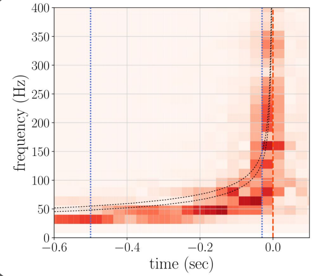
e.g. MS+24 (2305.16146)

Low-latency searches

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

e.g. Chaudhary+24 (2308.04545)

Searches for new phenomena

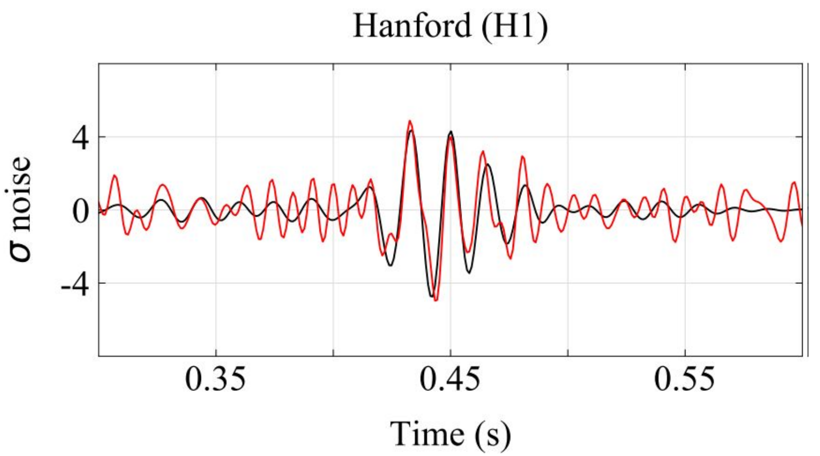


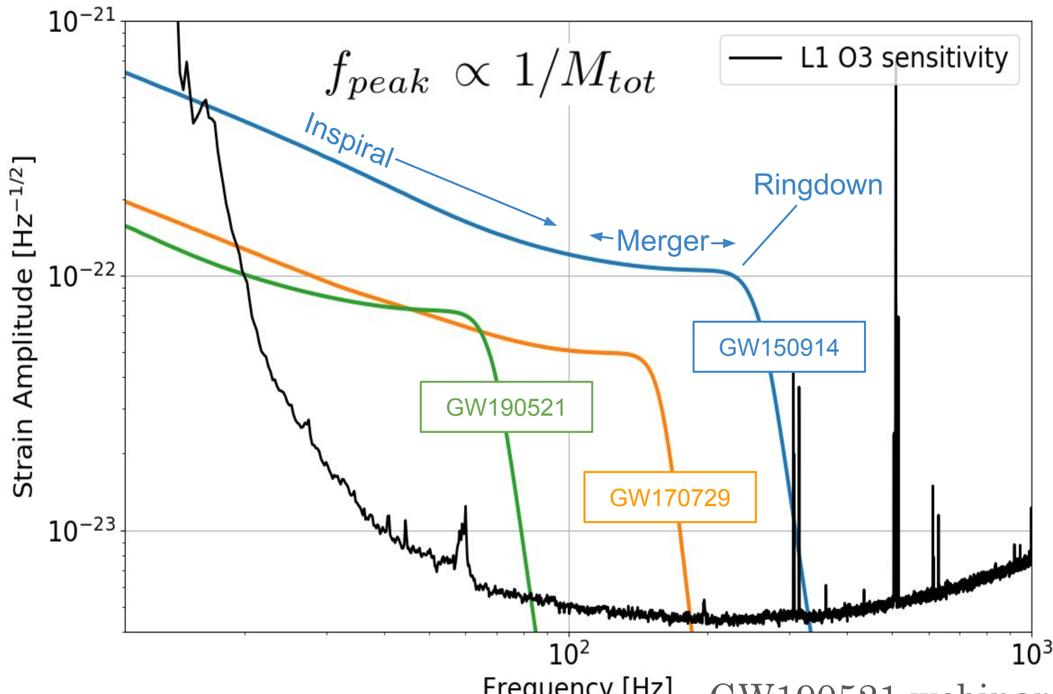
Higher harmonics
GW cross-polarization
Deviations from GR

e.g. Vedovato+22 (2108.13384)

GW190521

- Intermediate-mass black holes (IMBHs) - between stellar mass (100 $M_\odot$) and supermassive (10^5 $M_\odot$). The origin is not yet well understood.
  - Probing pair-instability mass gap (Stars with He mass in (64 $M_\odot$, 135 $M_\odot$)
  - Formation channels
  - Most distant GW sources
- GW190521 - first conclusive evidence of an IMBH.
- No chirping structure
- Detection significance (see MS+21, [2009.11336](2009.11336)):
  - Online: 1 per 28 years
  - Offline: 1 per 4900 years (established by cWB)
  - Challenges: scatter noise, blips

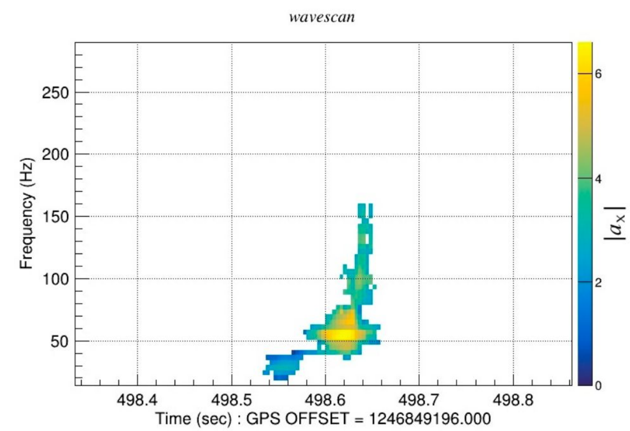


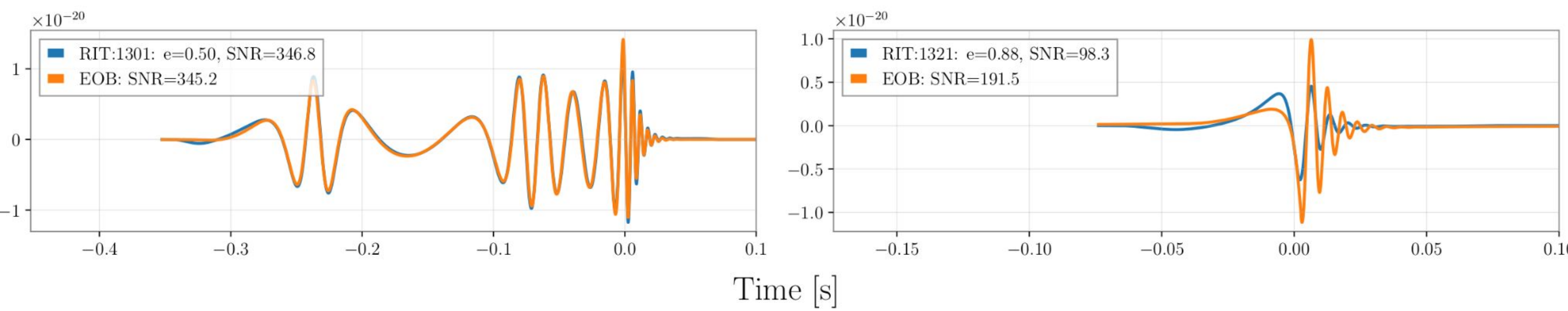


GW190521 webinar

Eccentric binaries

- Eccentric binaries: compact binaries elliptical orbits.
  - Dynamical formation
- Bhaumik et al (MS) 2024 (2410.15192)
  - Comparison between waveform models
  - Sensitivity studies and recommendations
- Mishra et al (MS) 2024 (2410.15191)
  - O3 data reanalysis
  - 3 new GWs: consistent with stellar BHs, one event has large mass-ratio (possible dynamic formation)





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)

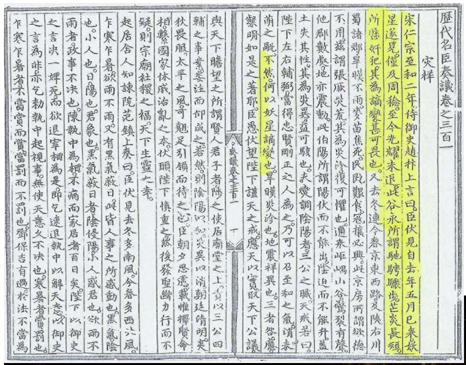
- cWB-XP and cWB-2G
- Public alert for GW bursts: “fluence” (~luminosity), peak frequency, duration
- Only one event so far S200114f (O3) - classified as noise offline

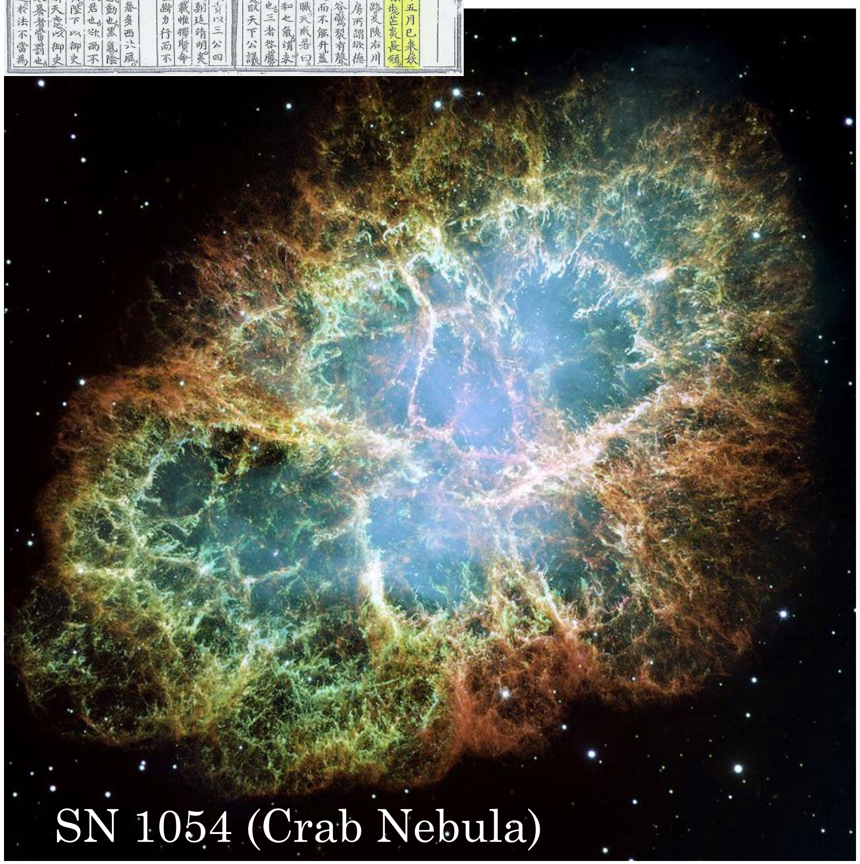
cWB-BBH search

- 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)

Core-Collapse Supernova

Core-Collapse Supernova (CCSN)

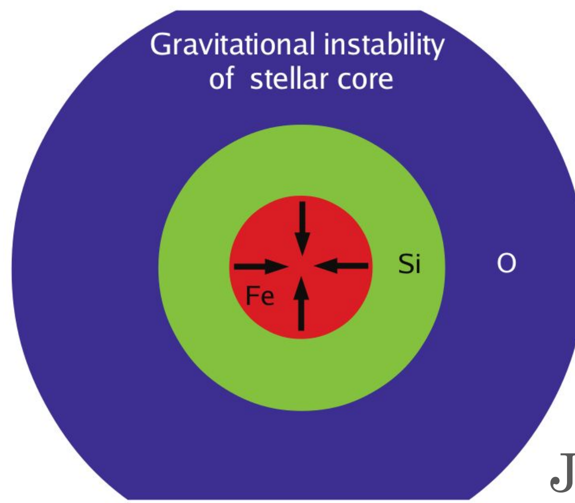




Nova on the sky!
1-2 per century in Milky Way (?)

- 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!

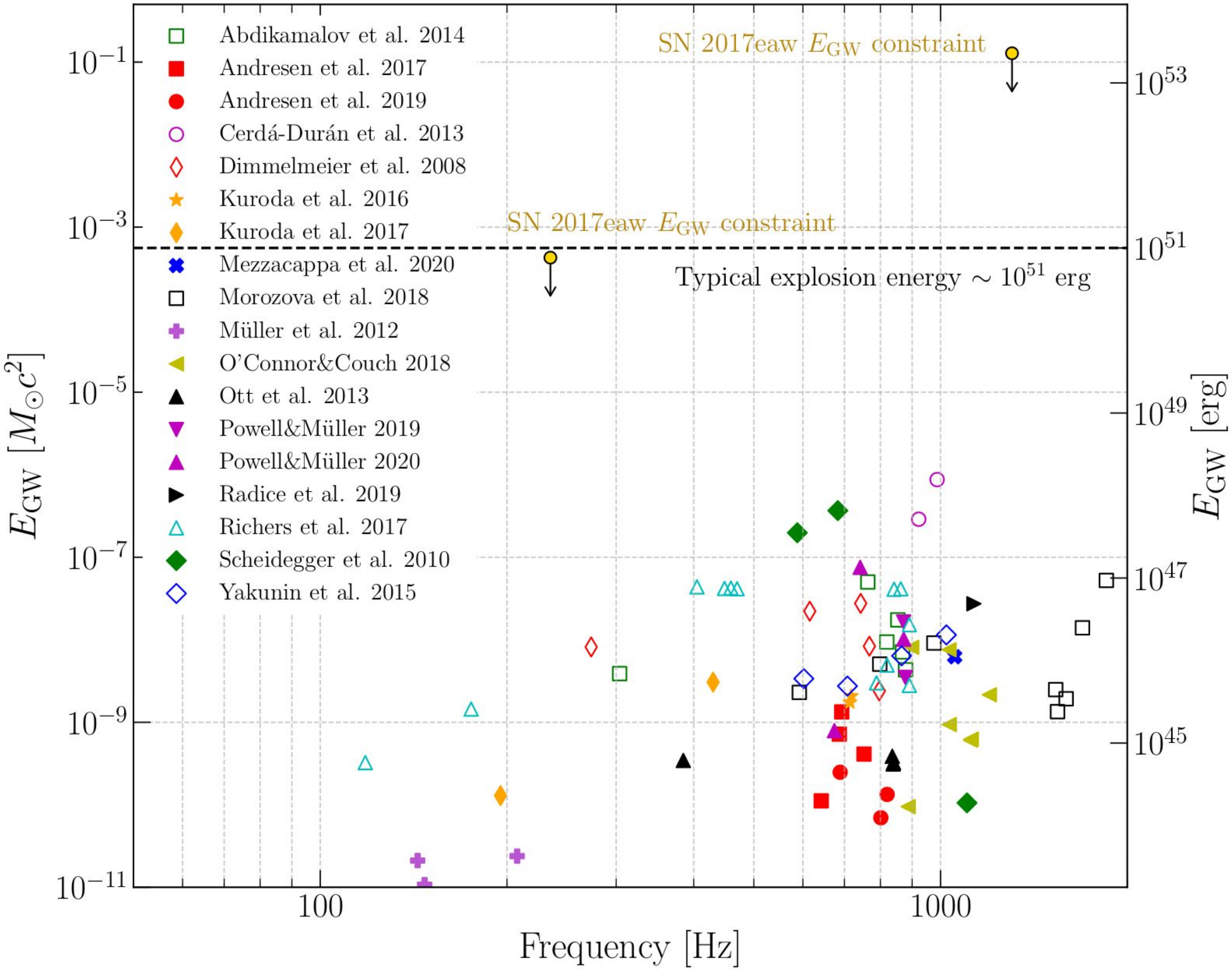
Explosion mechanism(s) is still unknown



Janka+12

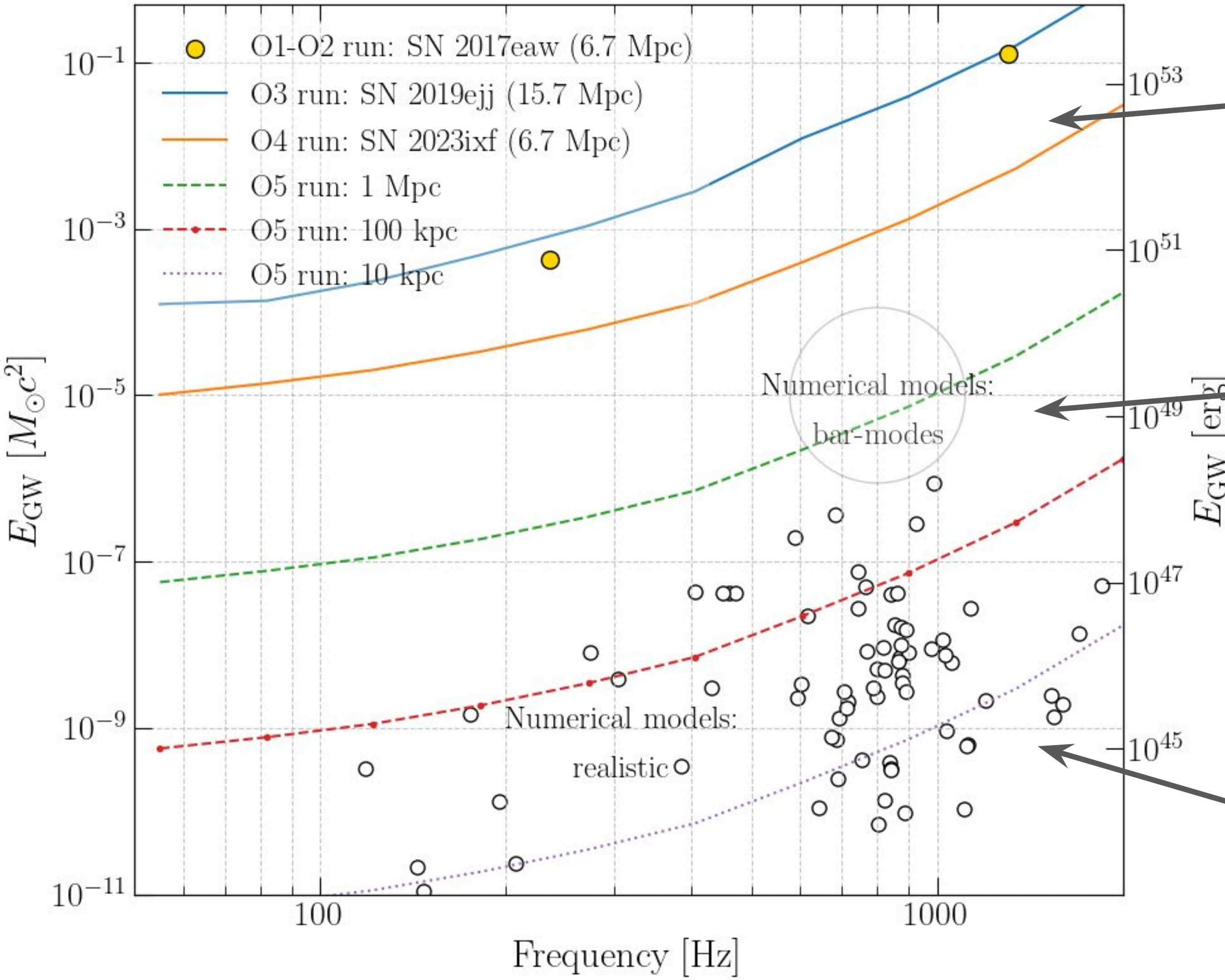
Core-Collapse Supernova Properties

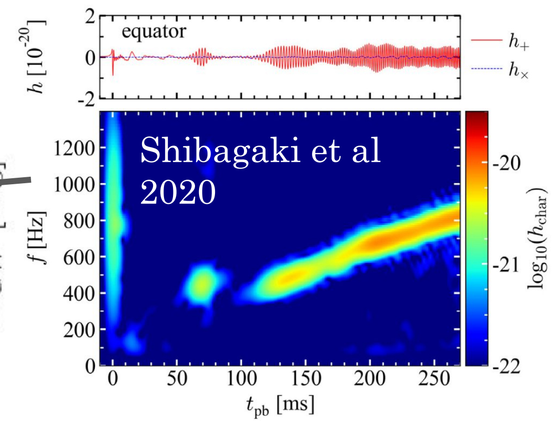
Szczepanczyk et al 2021 (2104.06462)

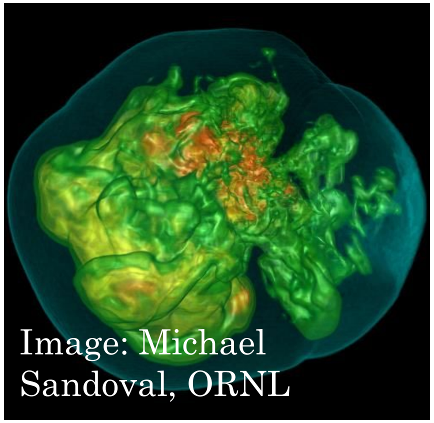


When will we discover GWs?

(realistically: Galactic CCSN)

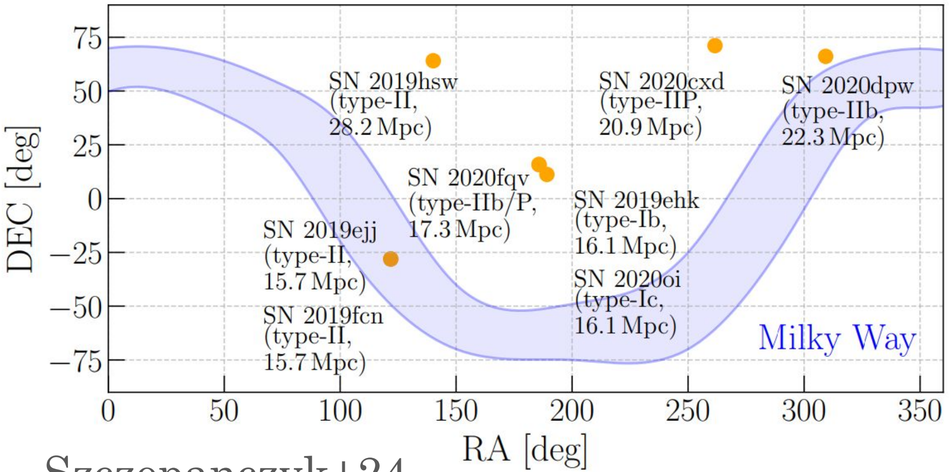




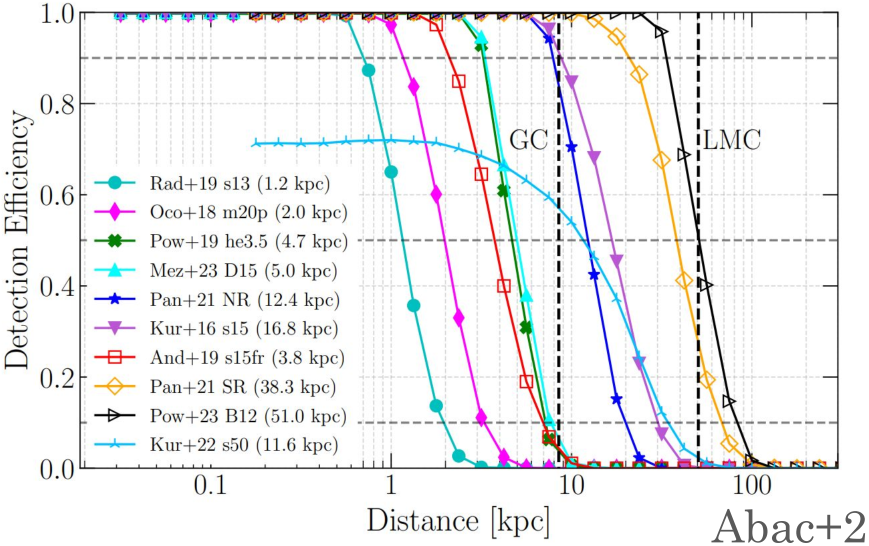


Optically targeted searches

- 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

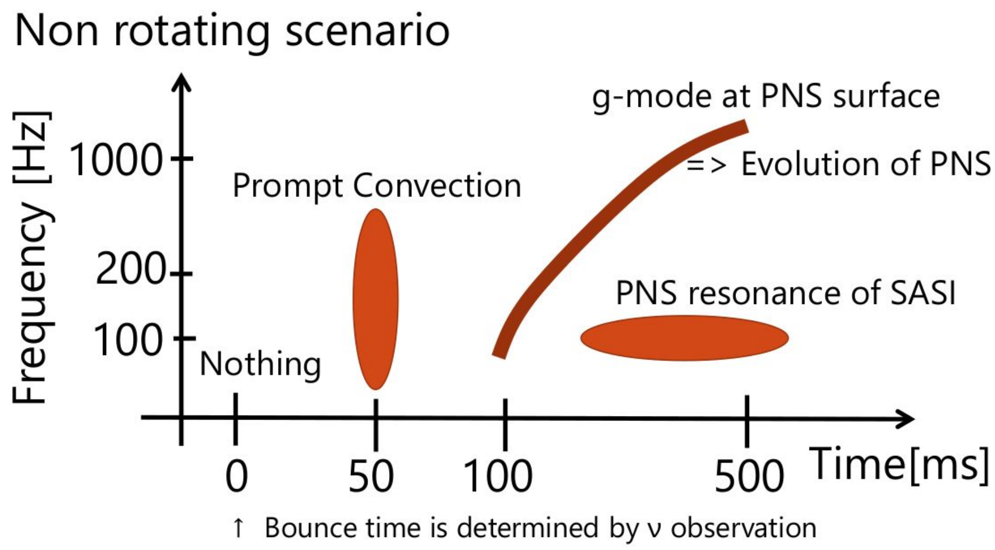


Abac+24

Parameter Estimation

Recently a lot of efforts to extract physical parameters from CCSN. See review in Mezzacappa&Zanolin+24 (2401.11635), examples:

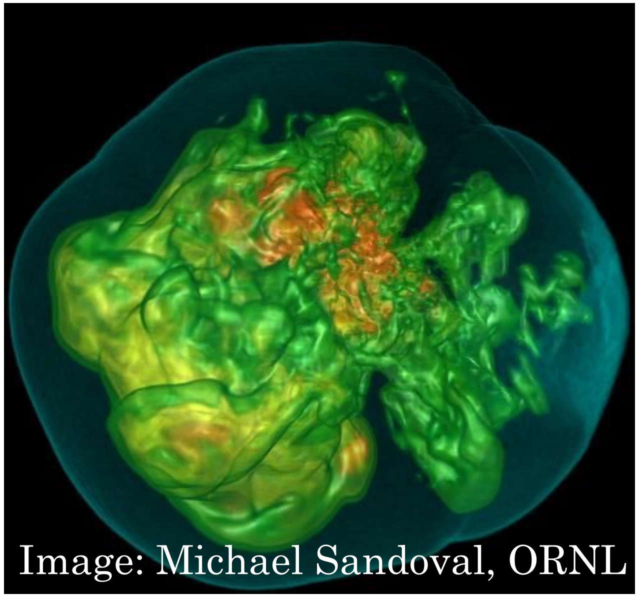
- Proto-neutron star (PNS) evolution: Casallas-Lagos+23 (2304.11498), Bizouard+21 (2012.00846),
- Equation of State: Edwards+21 (2009.07367),
- SN kicks (GW memory): Richardson+21 (2109.01582)
- Standing Accretion Shock Instability: Takeda+21 (2107.05213)
- PNS rotation: Chan+21 (ADS), Hayama+18 (1802.03842)
- Rotation properties: Pastor-Marcos+23 (2308.03456), Villegas+23 (2304.01267)



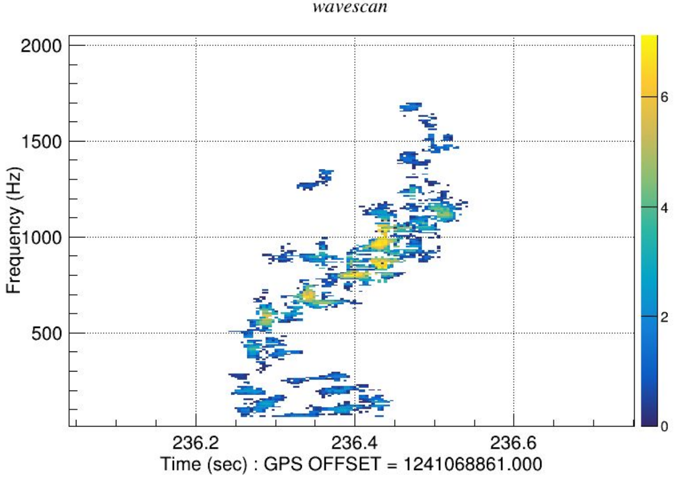
Credit: Takiwaki

LVK and CCSN Theory

Example: Mezzacappa et al 2023



- CCSNe are the most challenging astronomical events to model:
  - All four fundamental forces are important
  - Neutrino transport
  - Computational challenges
- Last joint workshop between LVK and CCSN modelers was at Caltech in 2017
  - Creating Supernova Multimessenger Consortium
- Agenda/webpage: work in progress



LVK workshop:
July 21-23, 2025, in Warsaw

Note: it's right after the GR24/Amaldi16 meeting in Glasgow (July 14-18, 2025)

Summary

- Model-independent searches
  - Preparing for exceptional/special GW sources
  - Complement template-based searches
- Core-Collapse Supernova
  - “Supernova problem”: why do the stars explode?
  - Optically targeted searches: constraining CCSN engine
  - Parameter Estimation - a lot of effort
- Joint workshop between LVK and CCSN modelers:
  July 21-23, 2025 in Warsaw

Slides (and G2500260):
https://www.fuw.edu.pl/~mszczepanczyk/