Search for gravitational waves emitted from core-collapse supernovae

— Past, present and future(maybe?)

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SN2025gw Symposium at Warsaw, Poland

07/22/2025

Image credit: https://www.astrobin.com/5yw3dh/

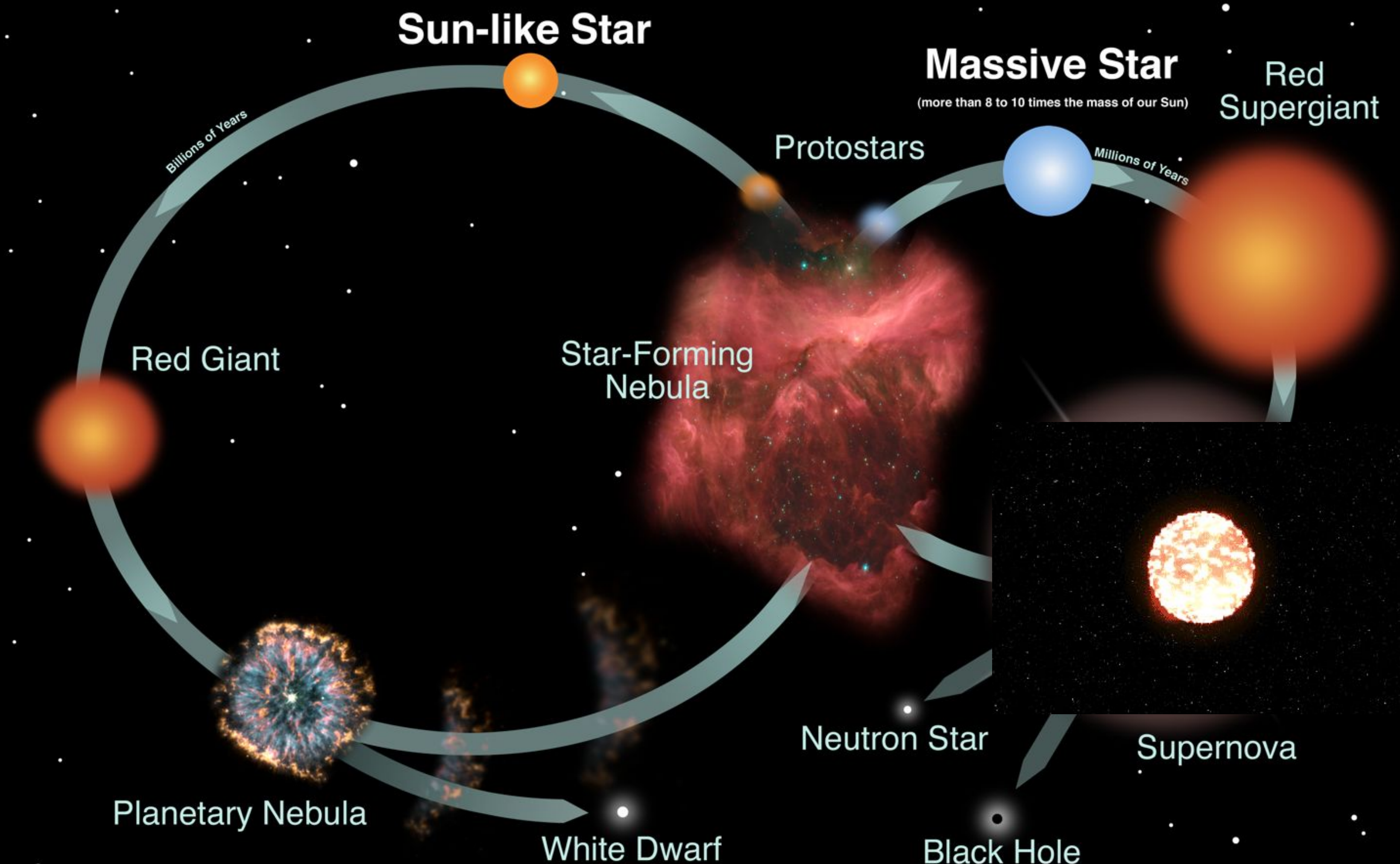
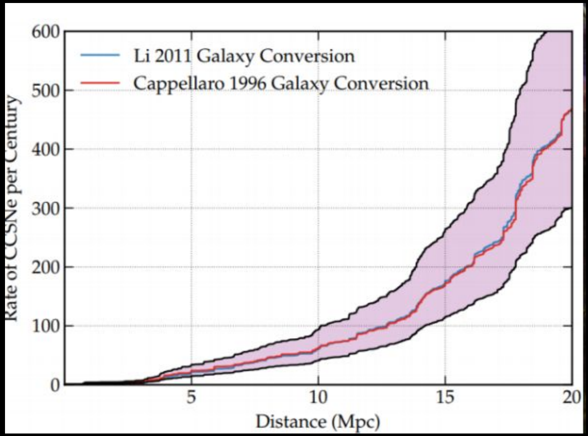


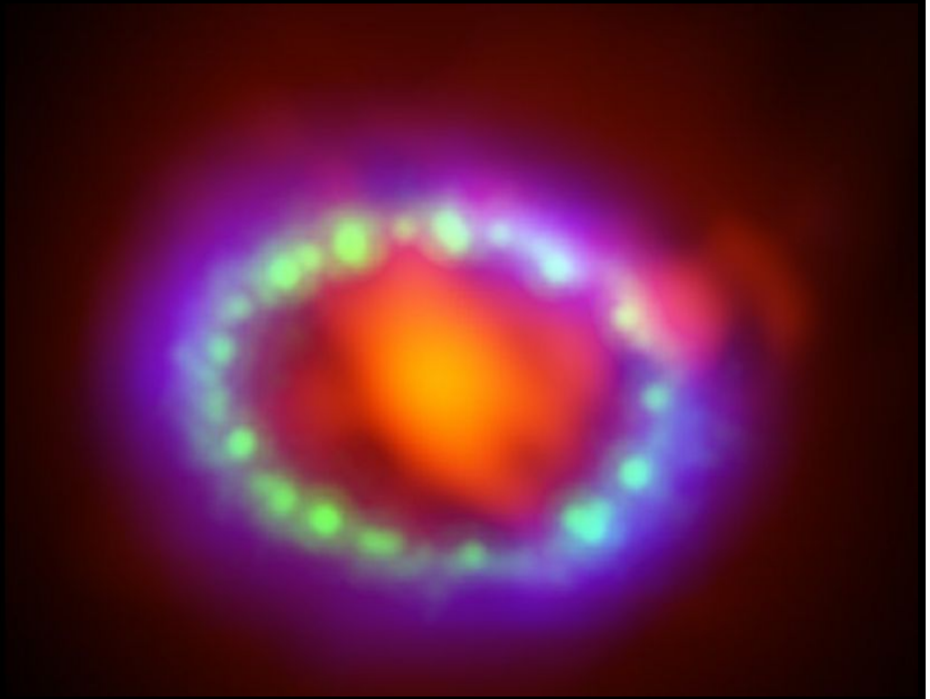
Diagram showing the lifecycles of Sun-like and massive stars. (Credit: NASA and the Night Sky Network)

Core-collapse supernova (CCSN): Rate

- The last supernova known to have occurred in the Milky Way was ~ 300 years ago (Cassiopeia A). Last notable supernova in the vicinity of the Milky Way was in 1987 (SN 1987A).
- 4 supernovae per year up to 20 Mpc, 1- 2 per century in the Milky Way.



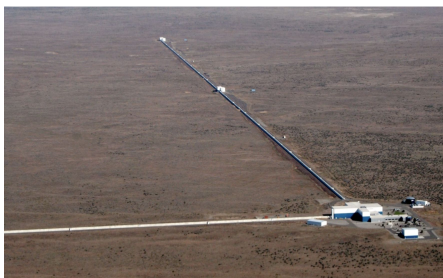
*J. Gill et al,, courtesy of M. Szczepańczyk.*LIGO Document P1500232-v8



Composite of ALMA, Hubble and Chandra data, showing newly formed dust in the center of the remnant and the expanding shock wave.https://en.wikipedia.org/wiki/SN_1987A#/media/File:Composite_image_of_Supernova_1987A.jpg

Gravitational wave (GW) detectors

- First and second Observing runs (O1-O2): 09/12/2015 - 01/19/2016, 11/30/2016 - 08/25/2017.
- Third Observing run (O3): 04/01/2019 - 10/01/2019, 11/01/2019 -03/27/2020.
- Fourth Observing run (O4) is ongoing: starts from 05/24/2023 and ongoing.



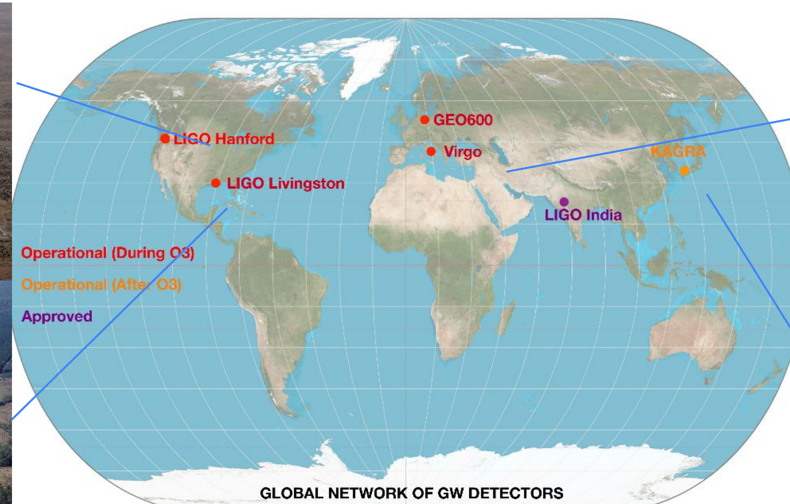


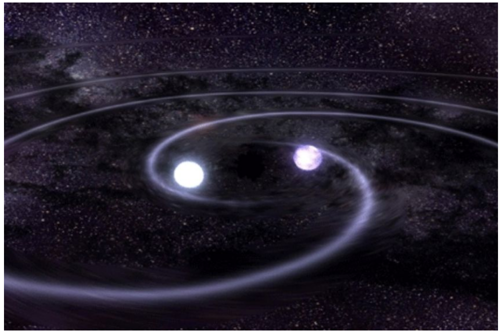
Image credit https://www.ligo.caltech.edu/image/

GW searches: Modeled and unmodeled

Sources: Compact Binary Coalescence (CBC), Burst transient, Continuous Waves, Stochastic

Modeled:

- Used to detect CBC sources
- Known waveforms
- Matched-filter searches
- Low-latency and offline searches



~300 GWs from CBC have been detected

https://www.ligo.org/science/GW-Overview/images/inspiral_image.jpg

Unmodeled - All sky:

- Search for all the time and all the sky.
- Low-latency and offline searches.

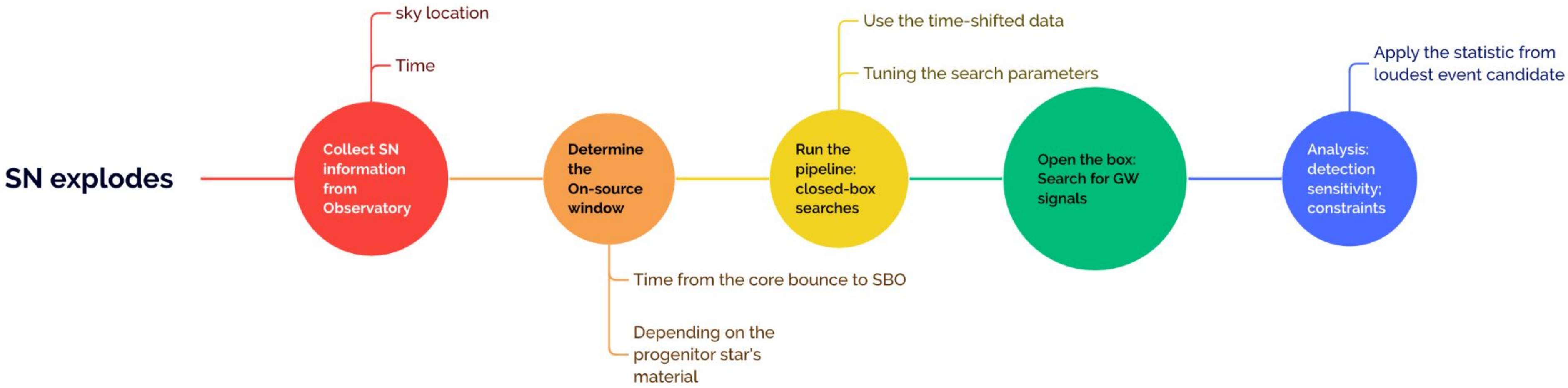
Unmodeled - Targeted:

- Use external triggers from observatories.
- Sky location is constrained
- Search period
- Offline searches

CCSN: An optically triggered search

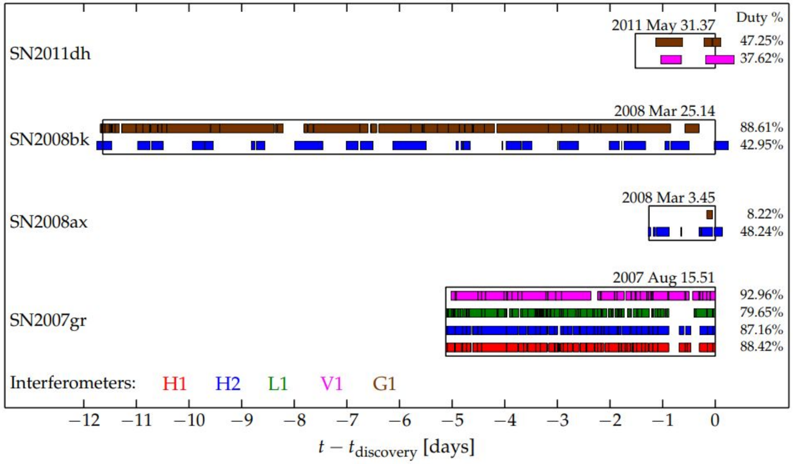
- Triggered search is performed.
- On-source window (OSW):

  The time frame during which a GW event is most likely to be detected.
- Search software: coherent WaveBurst (cWB).

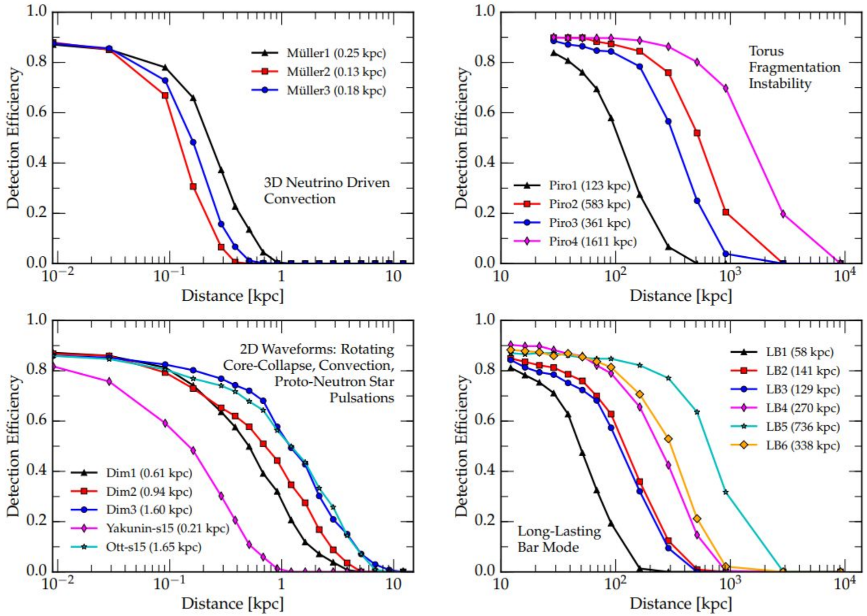


Previous searches: Before O1

- Data: First-generation Initial LIGO, GEO 600 and Virgo (2005-2011).
- Targets: 4 SNe within 15 Mpc.
- The distances out to which we find signals detectable: O(< 1) kpc for simulated waveforms; O(1) Mpc for the more extreme phenomenological models.
- The minimum GW energy corresponding to our sensitivity limits: O(0.1) $M_{\odot}c^2$ at low frequencies to & O(10) $M_{\odot}c^2$ above 1 kHz.

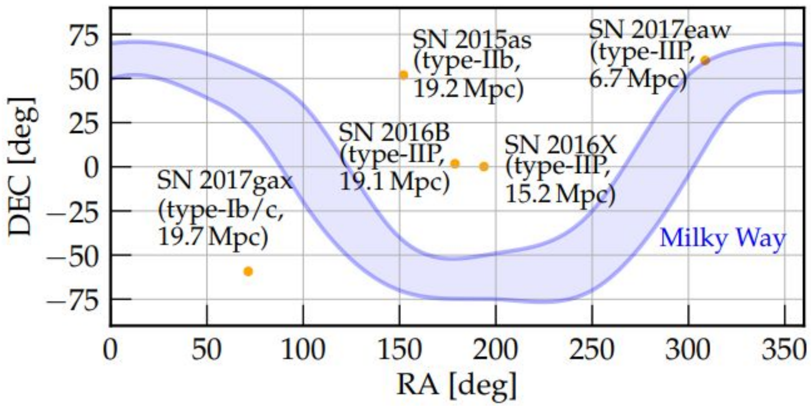


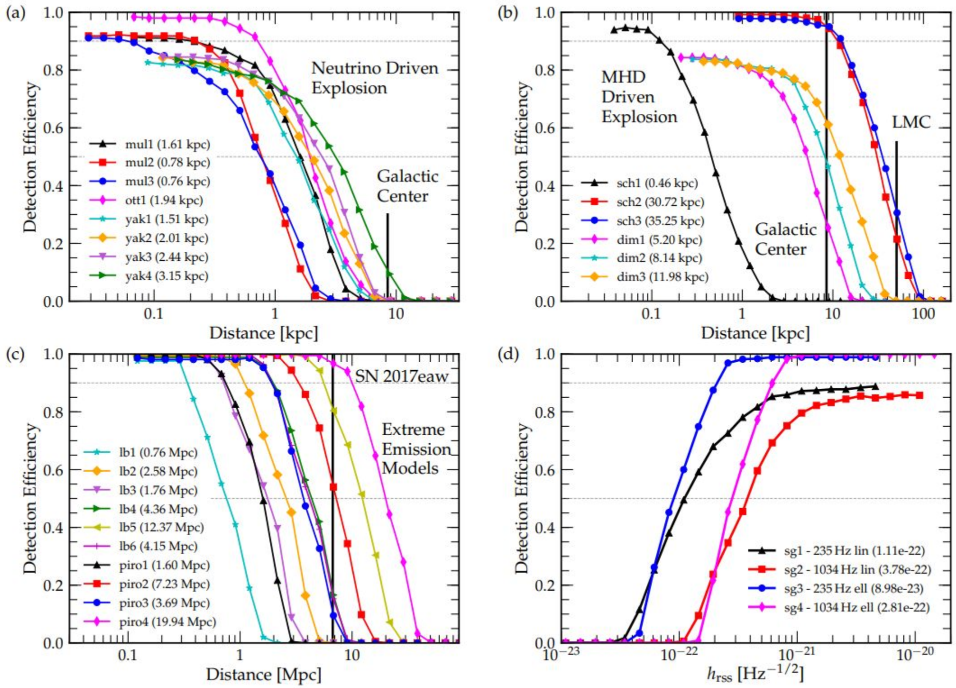
BP Abbott et al, Phys. Rev. D 94, 102001 (2016)



Previous searches: O1O2

- O1O2: search for 5 CCSNe up to 20 Mpc. No GWs were identified.
- Distance @50% detection efficiency: 5 kpc (neutrino-driven explosions), 54 kpc (magneto rotationally-driven explosions); 28 Mpc (extreme emissions)
- Constraints on energy: 4.27×10^{-4} $M_{\odot}c^2$ (235 Hz); 1.28×10^{-4} $M_{\odot}c^2$ (1304 Hz)

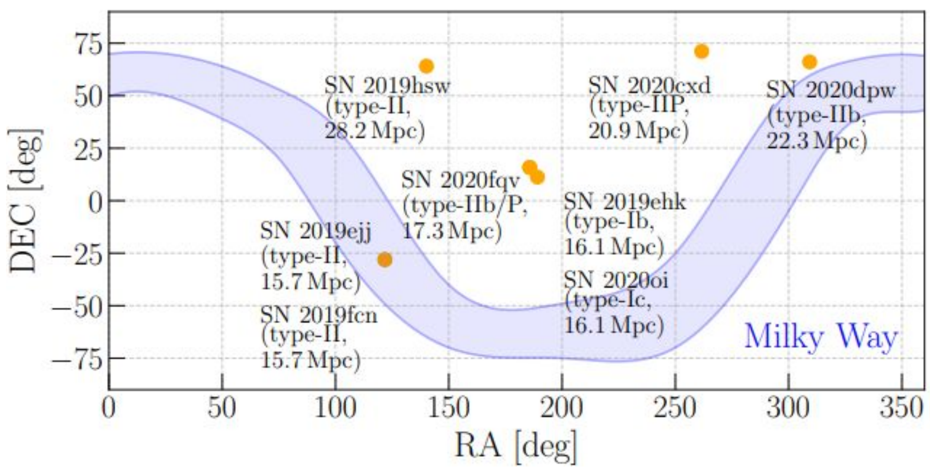


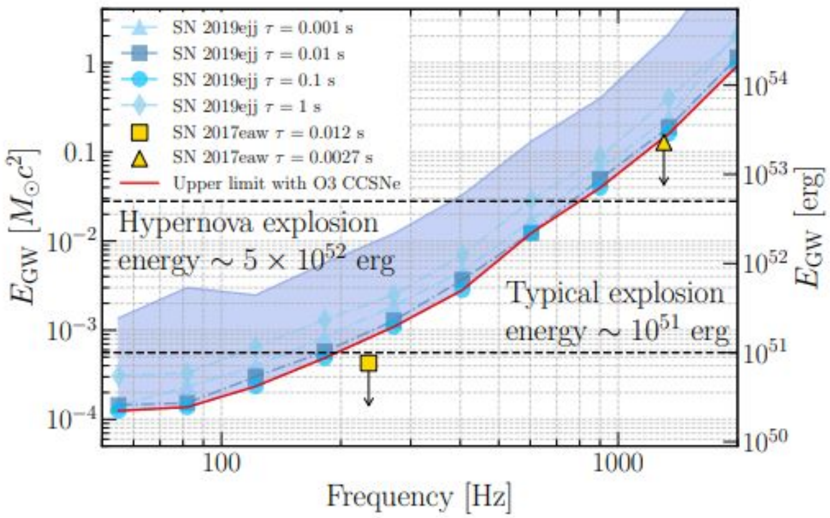


BP Abbott et al, Phys. Rev. D 101, 084002 (2020)

Previous searches: O3

- O3: searches for 8 CCSNe up to 30 Mpc. No GWs were identified.
- Distance @50% detection efficiency: 8.9 kpc (neutrino-driven explosions), 14.65 kpc (magneto rotationally-driven explosions); 53.6 Mpc (Long-lasting bar emissions)
- Constraints on: Energy (10^{-4} M⊙c^2); Luminosity (6×10^{-4} M⊙c^2/s); PNS ellipticity: (3)



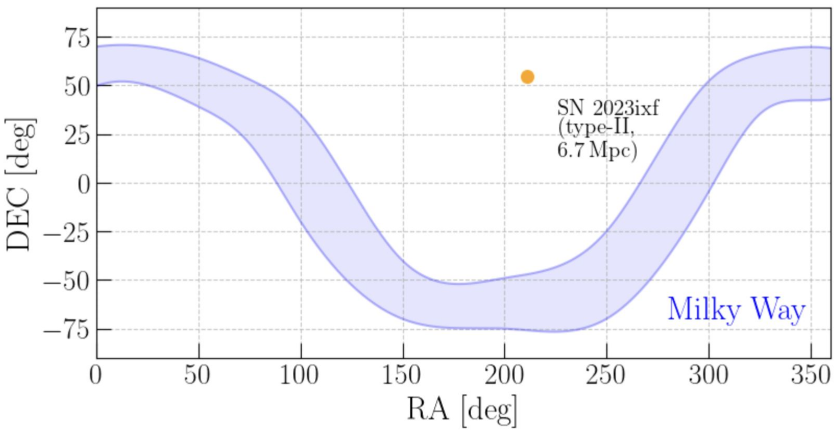


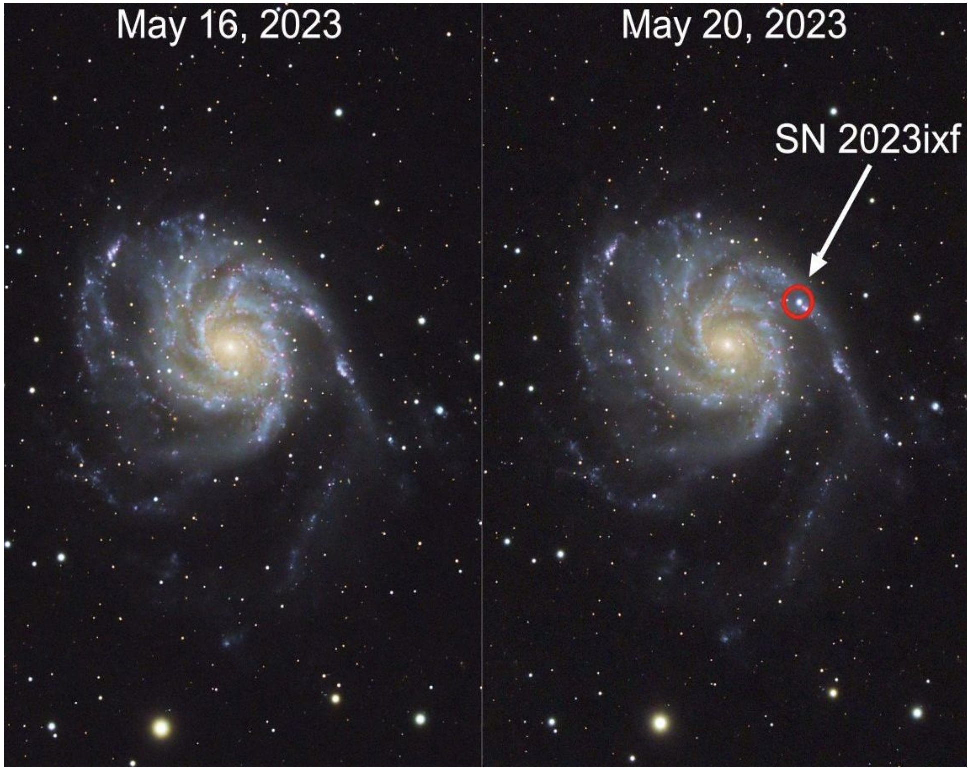
BP Abbott et al, Phys.Rev. D 110.042007 (2024)

Recent search for GWs from SN 2023ixf

SN 2023ixf

- Located in M101, Distance: 6.7 Mpc
- Discovered time: May 19th 2023
- Detector: pre-O4 ER 15th run





Credit Supernova in M101 in 'before and after' images captured by Paul Jacklin

Detector data for SN 2023ixf

On-Source Window: [May 13th 19:49:35 May 18th 19:49:35] UTC 2023

- The first detection is at MJD = 60082.82611, at a CV magnitude of 18.76 ± 0.25
- The time delay between collapse and shock breakout depends on many properties of the progenitor, including its mass.
- The coincident data is ~0.8 days, ~0.68 days after removing the times with poor data quality.

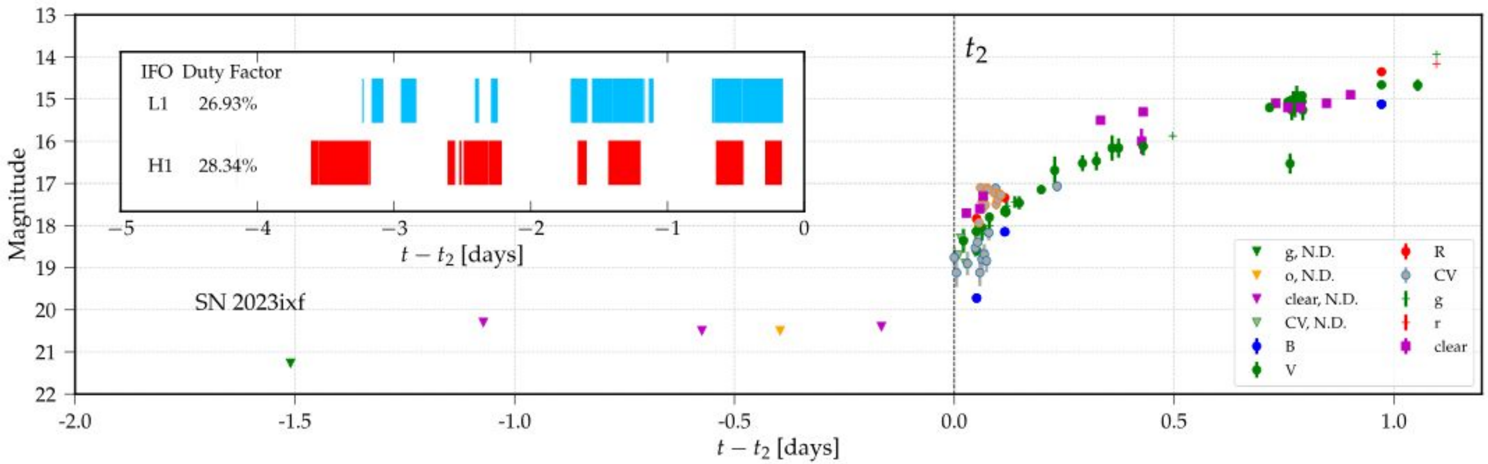
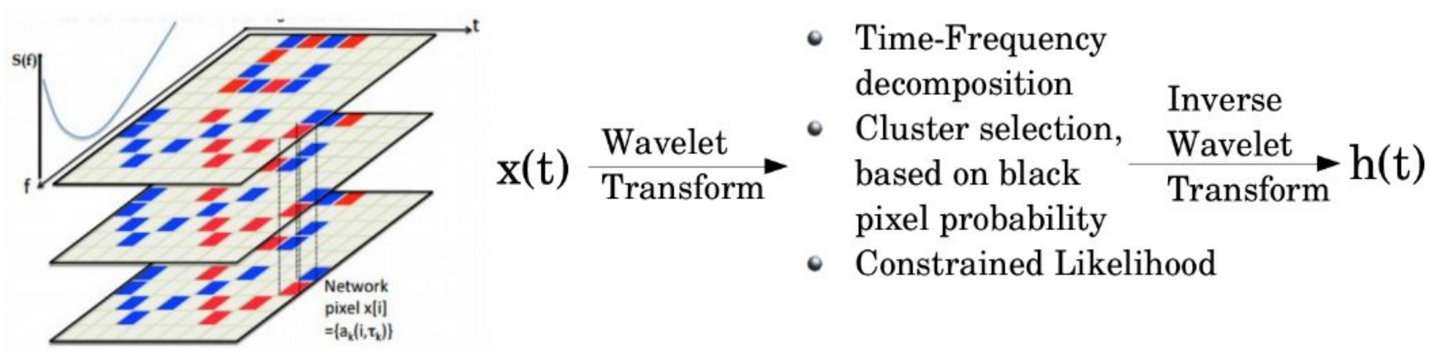


Figure 1. Early evolution of SN 2023ixf covering different photometric bands (B, V, R, g, o) and unfiltered observations (CV, clear); N.D. marks nondetections; inset: duty cycle of LIGO Hanford (H1) and Livingston (L1) detectors within the on-source window described in the text. Photometric data sources: Transient Name Server Astronotes, Astronomical Telegrams, AAVSO, L. A. Sgro et al. (2023), and G. Li et al. (2024).

A. G. Abac et al 2025 ApJ 985 183

Search pipeline: coherent Wave Burst (cWB)

- Used for the detection and reconstruction of unmodeled GW transients since 2003.
- The algorithm identifies GW transients by searching for excess power in spectrograms and reconstructs coherent signals in multiple detectors.
- cWB combines all data from detectors and computed a constrained maximum likelihood analysis.
- Used version: cWB-XP: cross-power statistics is also utilized.

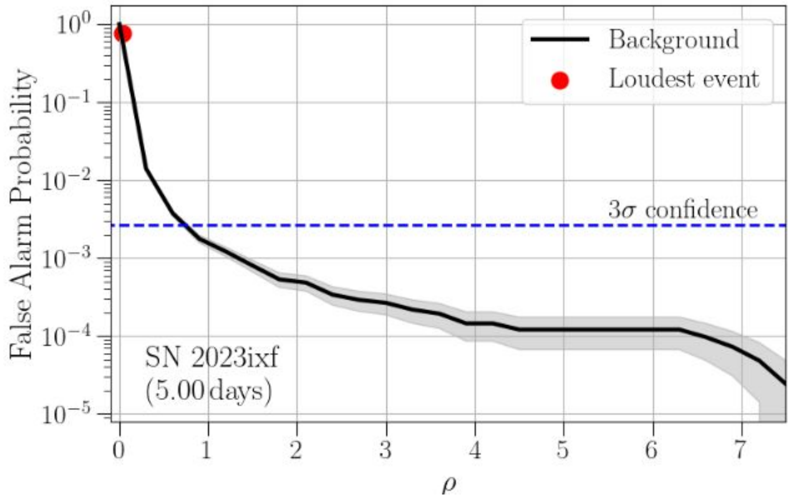


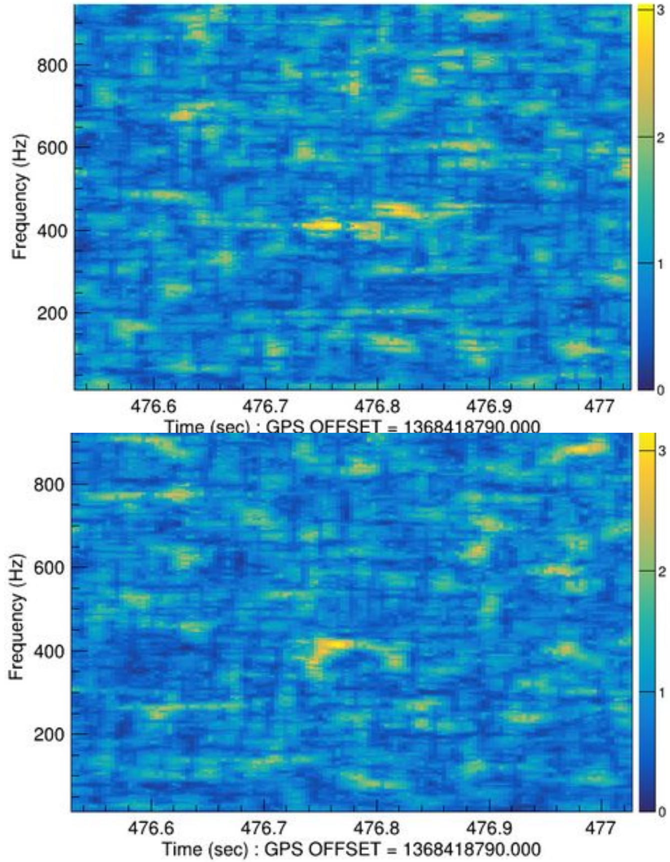
S. Klimenko, et.al, Phys. Rev. D 93, 042004 (2016)

SN 2023ixf open-box search results

- Loudest event: the trigger with the lowest false alarm rate is considered a GW event candidate.
- False alarm rate (FAR) = 2.11 per day.
- False alarm probability (FAP) = 0.75 : a probability of 0.75 that noise alone would produce a trigger of this FAR or lower.

This suggests that this trigger is likely due to noise.





Spectrogram: L1 (top) and H1 (bottom)

Detection distance

- To evaluate the search sensitivity, signal models are randomized the source orientation such that it is uniformly distributed over a sphere.
- Add waveforms to the detector coincident data within the on-source window for the sky location of SN 2023ixf to compute the search detection efficiency.

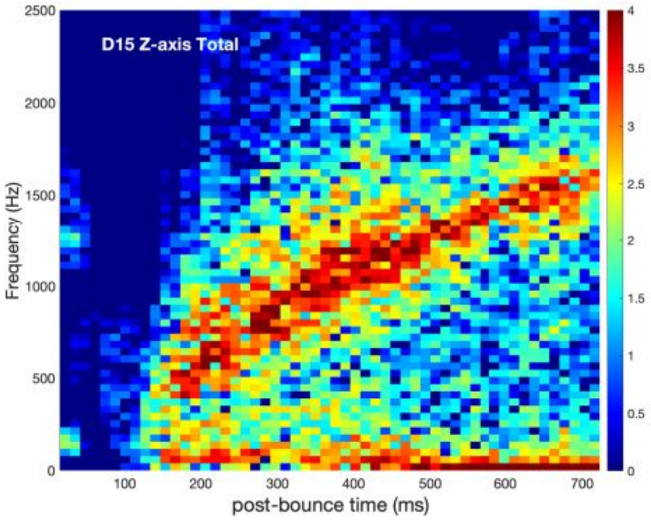
CCSN waveforms (14 models)

- Neutrino Mechanism Waveforms : 8 models from 7 waveform families, M = [3.5, 40] $M_{\odot}$.
- Rapid Rotating Waveforms: 5 models from 4 waveform families. Rotating speed is up to 1 rad/s.
- PNS Phase Transition: 1 model.

Long-lasting bar modes (grid of 40 waveforms):

- Tau [ms]: [1,10,100,1000] ms.
- Frequencies [Hz]:

[55, 82, 122, 182, 272, 405, 604, 900, 1342, 2000].



Mezzacappa, Anthony et al, Phys. Rev. D ***107****, 043008*

Detection distance

Distance of the 90% Detection Efficiency Reached with CCSN Waveform Models for a FAR of 1 Event in 10 Years

Waveform Models		Distance (kpc)
Nonrotating models	Kur+16 s15	**6.9**
	Mez+23 D15	2.9
	Oco+18 m20p	1.0
	Pow+19 s18	5.5
	Pow+19 he3.5	2.8
	Rad+19 s13	0.6
	Rad+19 s25	5.8
	Pan+21 NR	6.6
Rotating models	And+19 s15fr	1.8
	Obe+20 Signal_O	13.4
	Pan+21 SR	18.2
	Pow+20 m39	19.6
	Pow+23 B12	**29.9**
Phase transition model	Kur+22 s50	8.9*

Note. Values in bold represent the farthest distance reached for each family of models. For the model 2D Kur+22 s50, detection efficiency remains lower than 90% whatever the distance because there is only one polarization. We report the 50% detection efficiency instead, which is marked with *.

Distance at which we recover 90% of the added signals for all 14 CCSN models:

- IFAR = 10 years, corresponding to FAP = 1.9×10^{-4}
- At the distance of SN 2023ixf, none of the 14 models from numerical simulations are detected.
- Non-rotating explosions: The distances reach up to 6.9 kpc.
- More extreme models: distance reach up tp 29.9 kpc.

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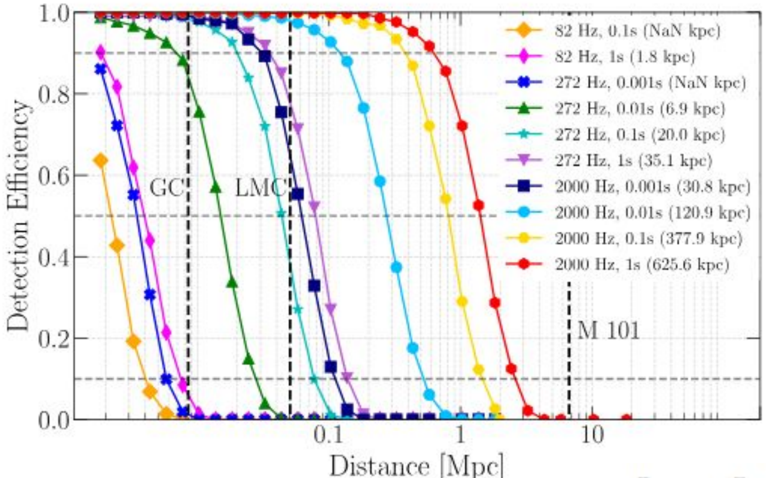
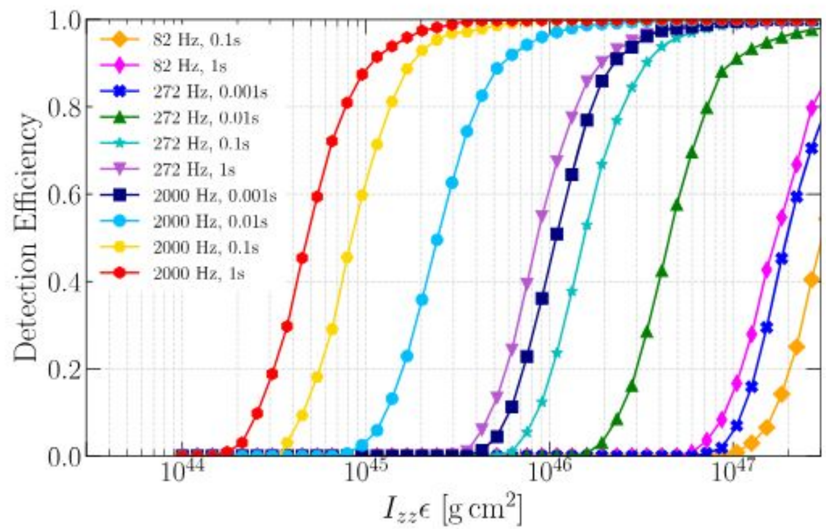
Detection distance

Detection efficiency for long-lasting bar-mode waveforms with frequencies between 82 Hz and 2 kHz and signal durations between 1 ms and 1 s.

- The sensitivity increases with the signals peak frequency and duration.
- We could detect at 90% confidence level a signal lasting 1 s at 2 kHz for $I_{zz}\epsilon \sim 10^{45}$ g cm^2 .
- For lower frequencies, if we assume the canonical value $I_{zz} \sim 10^{45}$ g cm^2 , the source would need to be highly deformed ($\epsilon \gg 1$).





$I_{zz}\epsilon = 0.1 \times 10^{45}$ g cm^2 , $\epsilon \equiv \dfrac{I_{xx} - I_{yy}}{I_{zz}}$.

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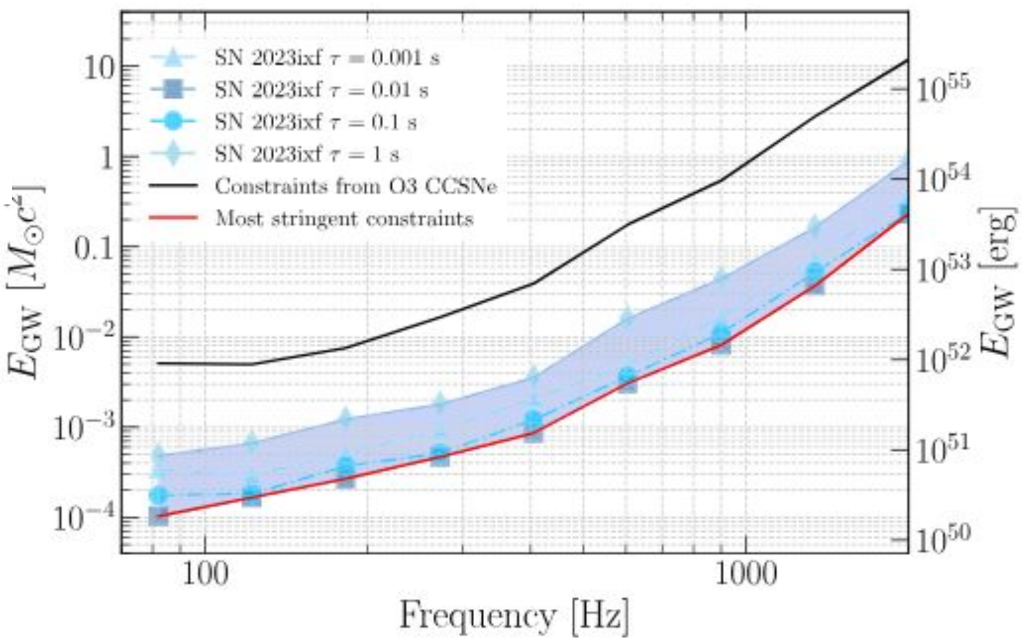
Constraints: Energy

GW energy emission assuming rotating CCSN:

$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G} D^2 f_0^2 \int_{-\infty}^{\infty} [h_+^2(t) + h_\times^2(t)] \quad dt$$
$$= \frac{2}{5}\frac{\pi^2 c^3}{G} \sqrt{\frac{\pi}{2}}\, \tau D^2 f_0^2\, h_0^2$$

f_0: peak frequency, D: distance to the source, h_0 :GW strain squared integral, computed for an optimally oriented source.

- At 82 Hz the most stringent energy constraints are ~1×10^{-4} $M_\odot c^2$.
- The constraints with SN 2023ixf are ~49 times more stringent than for O3 CCSNe over the whole frequency range.



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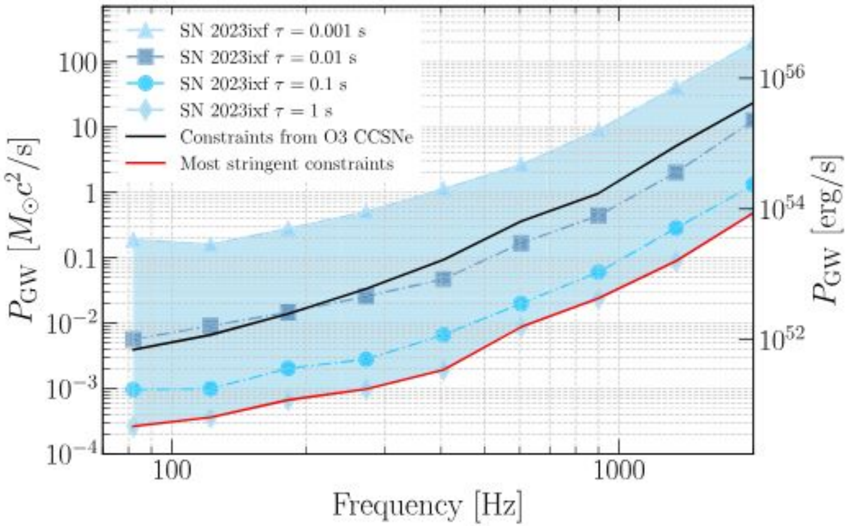
Constraints: Luminosity

GW luminosity: the ratio between the emitted GW energy and the duration of the emission.
We define the duration as the time interval τ_{90} that contains 90% of the energy.

$$P_{\rm GW} = \frac{0.9 E_{\rm GW}}{\tau_{90}}.$$

- The most stringent constraint : 2.6×10^{-4} $M_\odot c^2$ for signals at 82 Hz and 1s long.
- They are a factor of ~36 more stringent than for the O3 CCSNe over the whole frequency range.



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Constraints: Ellipticity

The amplitude of the GW signal emitted by a rotating PNS can be parameterized by its ellipticity and its moment of inertia given by the relation

$$I_{zz}\epsilon = \frac{Dc^4}{G(2\pi f_0)^2}h_0. \qquad \epsilon \equiv \frac{I_{xx} - I_{yy}}{I_{zz}}.$$

- The most stringent constraints are obtained for the signals with τ = 1 s, ranging from 3.6×10^2 at the lowest search frequency to 1.08 at 2 kHz.
- Over the whole frequency range, the constraints given by SN 2023ixf on the ellipticity are ~6.8× more stringent than for O3 CCSNe.

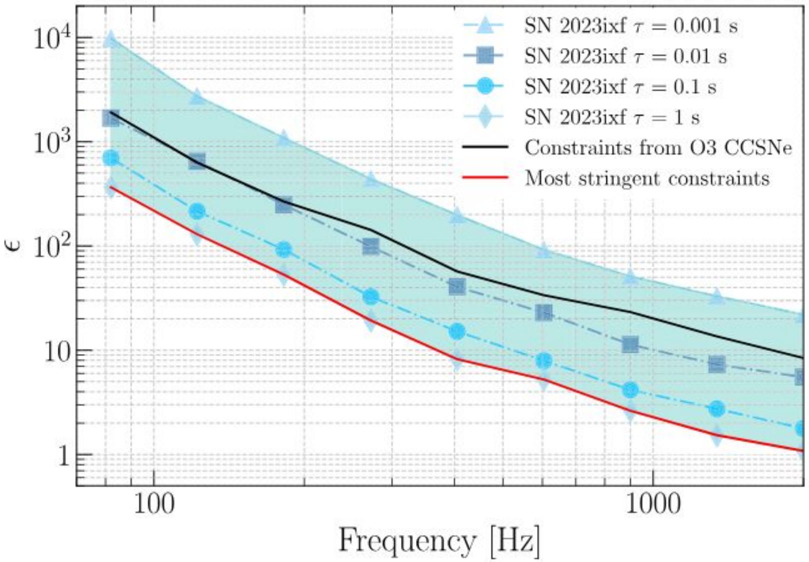
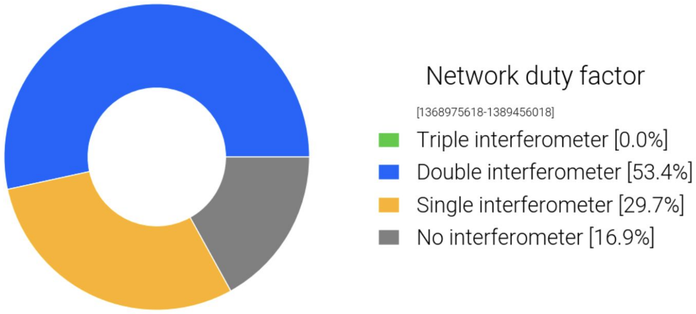


Figure 4. PNS ellipticity as a function of the frequency for bar-mode signals with a detection efficiency of 90% and a FAR of 1 per 10 years. The moment of inertia I_{zz} is fixed to 10^{45} g cm^2. The shaded region contains combined results from all analyzed bar-mode models for SN 2023ixf.

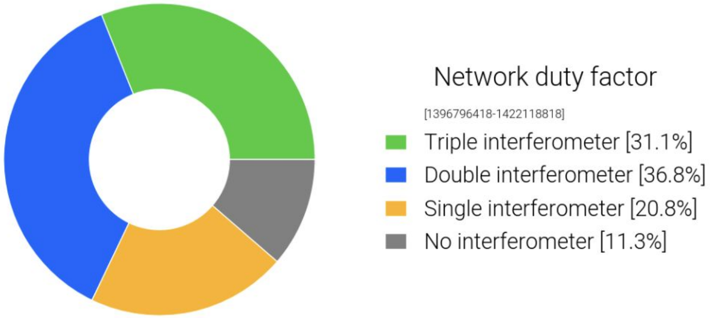
A. G. Abac et al ApJ 985 183 2025

Ongoing and future searches: O4 CCSNe

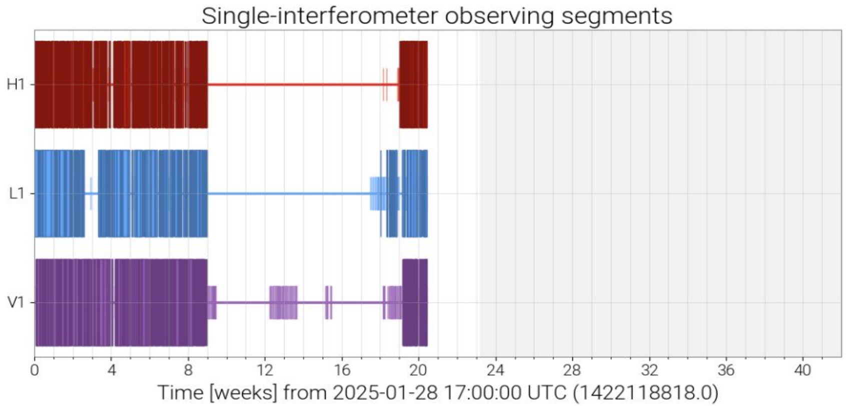
O4a: 2023-05-24 - 2024-01-16



O4b: 2024-04-10- 2025-01-28



O4c: 2025-01-28 - 2025-11-18



Ongoing and future searches: O4 CCSNe

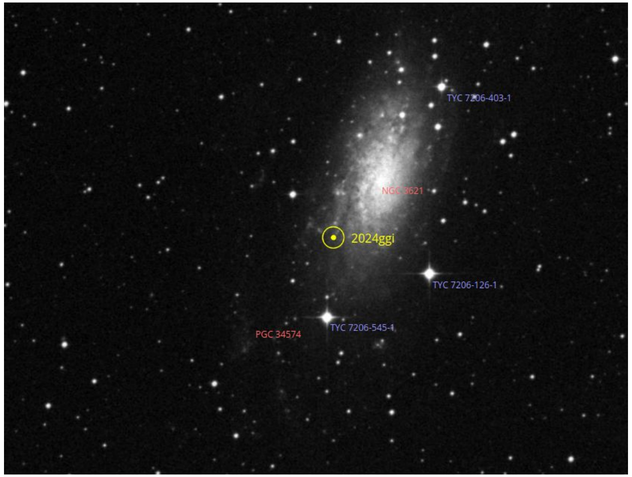
14 CCSNe within 30 Mpc and have enough light curve data:

- 4 from O4a, 8 from O4b.
- 1 from ER16.

Index	SN name	Run	Discovery time	Host Galaxy	Type
1	SN2023mpz	O4a	2023-07-09	GALEXASC	II
2	SN2023rve	O4a	2023-09-08	NGC 1097	II
3	SN2023zcu	O4a	2023-12-08	NGC 2139	II
4	SN2023abdg	O4a	2023-12-24	NGC 7421	II
5	SN2024ggi	ER16	2024-04-11	NGC 3621	II
6	SN2024iss	O4b	2024-05-12	LEDA 1846725	II
7	SN2024jlf	O4b	2024-05-28	NGC 5690	II
8	SN2024phv	O4b	2024-07-10	NGC 3936	II
9	SN2024phz	O4b	2024-07-11	NGC 4330	II
10	SN2024pxg	O4b	2024-07-23	NGC 6221	II
11	SN2024qvh	O4b	2024-08-01	ESO 138-G14	II
12	SN2024abbv	O4b	2024-11-13	UGCA 006	II
13	SN2024abfl	O4b	2024-11-15	NGC 2146	II

SN 2024ggi:

- Distance: 6.7 Mpc
- Host galaxy: NGC 3621
- Discovered time: April 11, 2024
- Detector: pre-O4b ER 16th run



Credit: https://theskylive.com/supernova-2024ggi

Summary

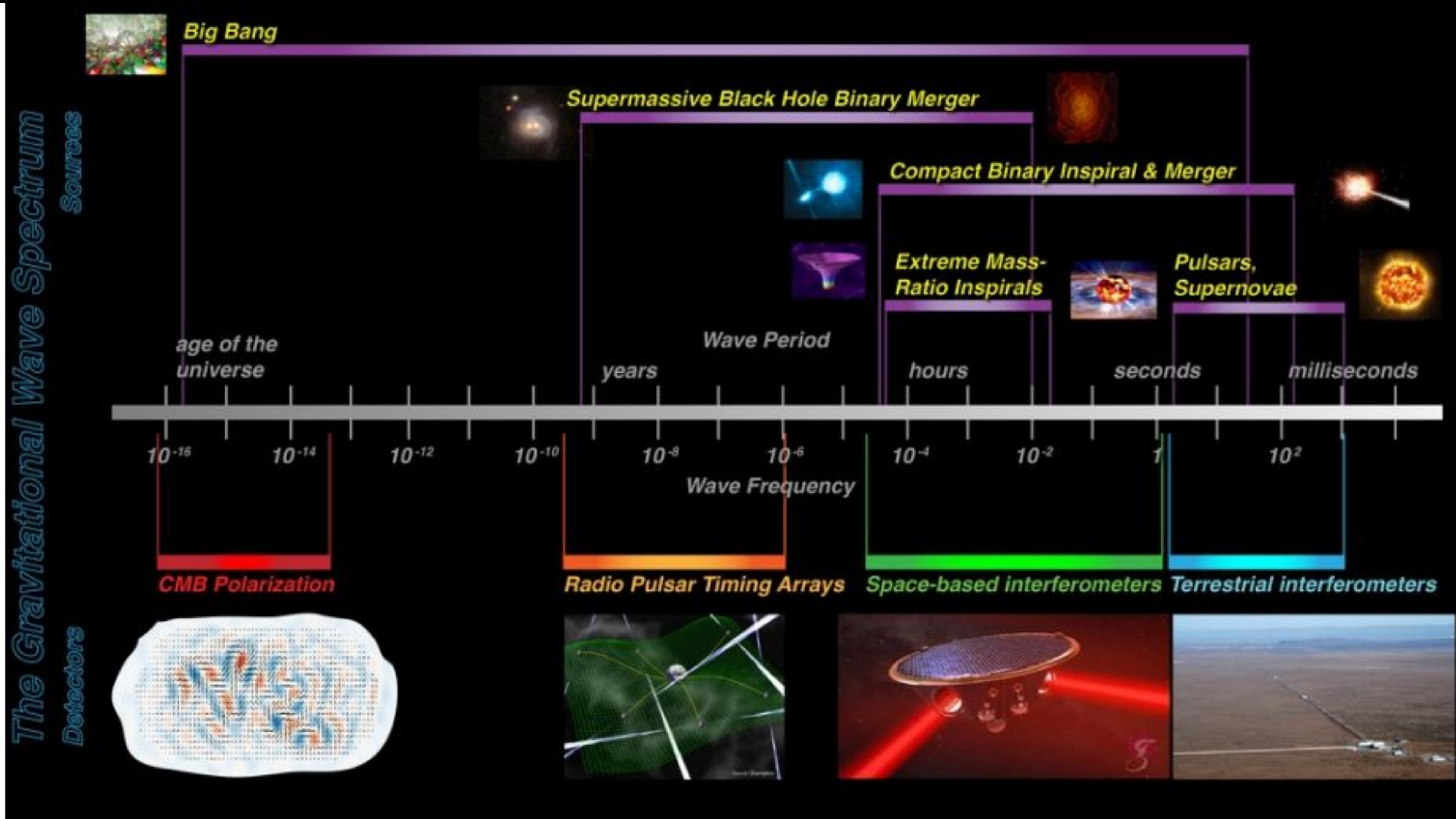
- No GWs from CCSNe were identified so far.
- Detection range can reach up to the galactic center for some waveforms.
- We can set constraints on energy, luminosity ellipticity.
- Expected detection range reaches up to Galactic center in the future runs.

To be continued

- Improve the current searches with ground-based detectors
- New ideas about the searching method
- Provide information for SN modelers from the detection side

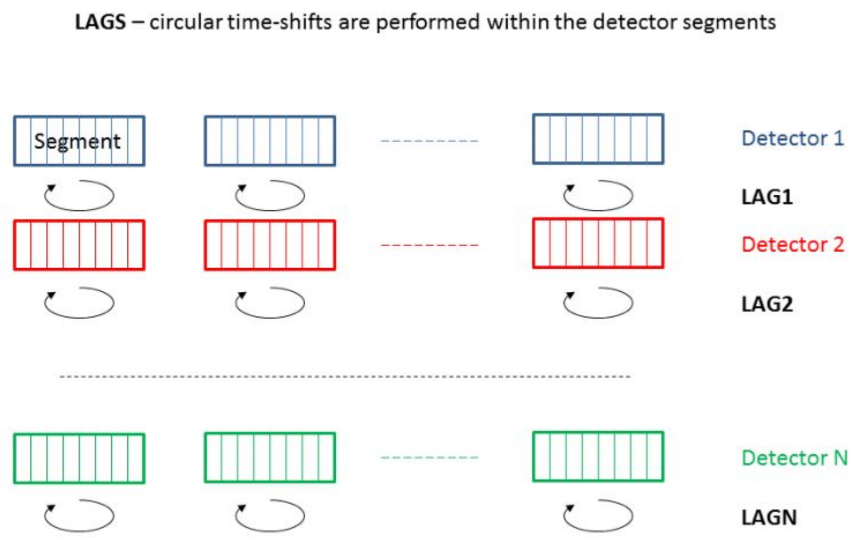
Thank you !

Image credit: https://skyandtelescope.org/online-gallery/supernova-2024ggi-in-ngc3621/


The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
age of the universe
Wave Period
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers

cWB: time shift

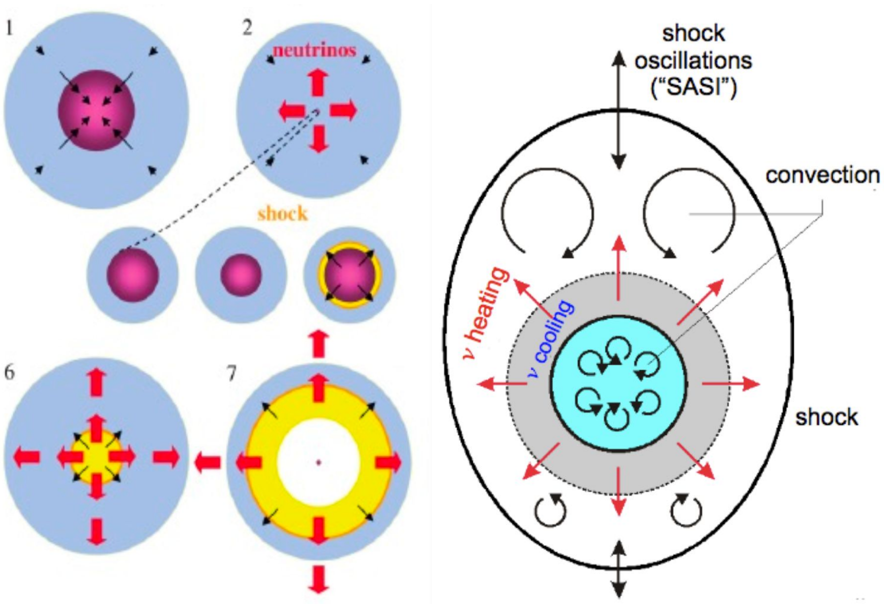
cWB divides the total observation time into time segments,For each segment, a job is sent to the computing cluster: within the job, cWB performs both the time-lagged analyses (i.e. by applying shifts in circular buffers) and the zero-lag analysis at the same time without increasing too much the computational load.



CCSN: Road to explosion

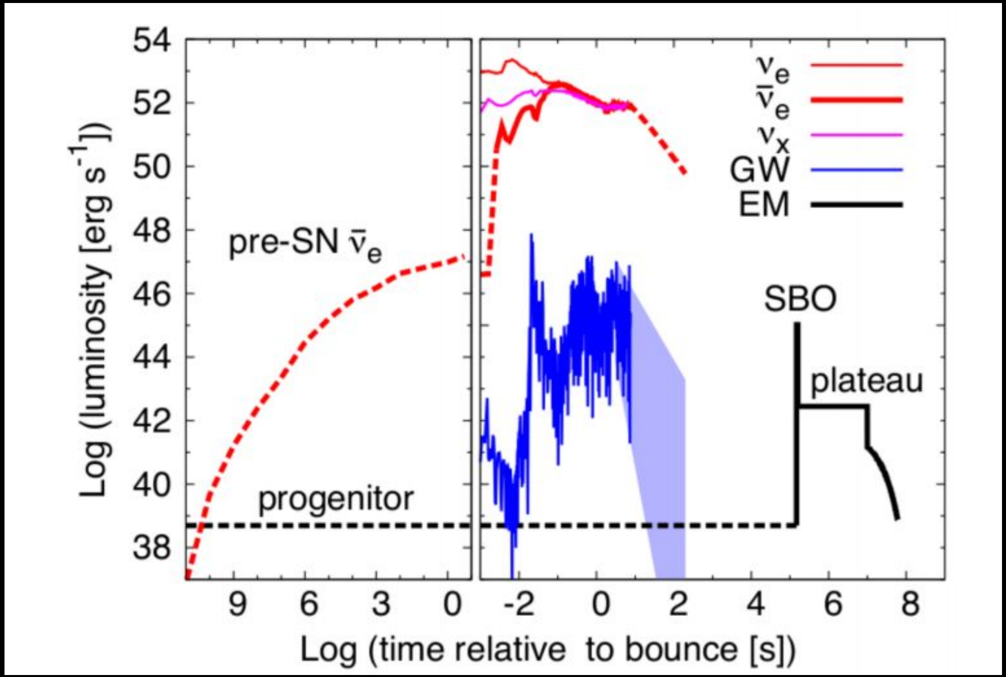
- Core collapse -> nuclear density
- Core bounce -> shock wave launched outwards, robust of neutrinos.
- Shock stalls -> energy is needed to revive the shock and produce a full supernova explosion.
- Neutrino-driven mechanism relies on partial reabsorption of neutrinos emitted from the proton-neutron star (PNS) to revive the shock.
- Heating or gain region develops some tens of ms after bounce
- Convection and SASI helps revive the explosion.
- SASI: Standing accretion shock instability: a hydrodynamical instability of a stalled shock wave formed in supernova cores

$p + e \to n + \nu_e$



Credit: Mezzacappa (2023)

CCSN: Multi-messenger source



- Pre SN: emitting neutrinos in silicon burning.
- Core collapse: neutrinos production
- Core bounce: gravitational waves emission (less than 1s) followed by neutrino flash.
- The shock wave propagates outward
- The moment the shock breaks through the surface, known as Shock Breakout (SBO), marks the point when the supernova becomes optically visible.
- Energy: ~10^{53} erg.

Credit: Ko Nakamura et.al . Monthly Notices of the Royal Astronomical Society, 461(3):3296–3313, 06 2016.