Multi-messenger constraints on core-collapse supernovae in the local Universe (part II)

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In collaboration with:
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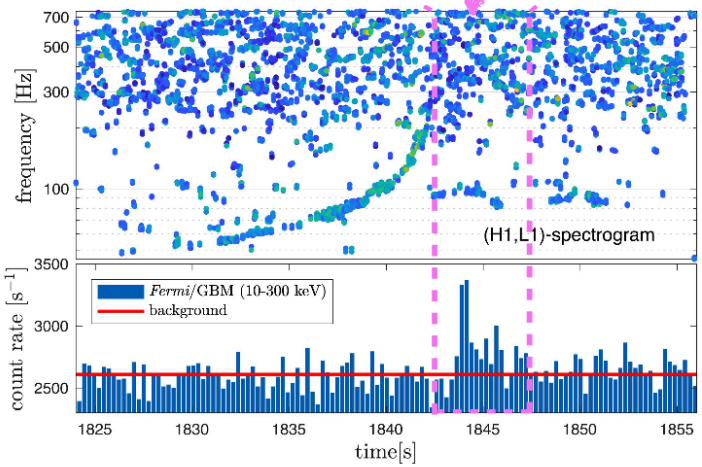
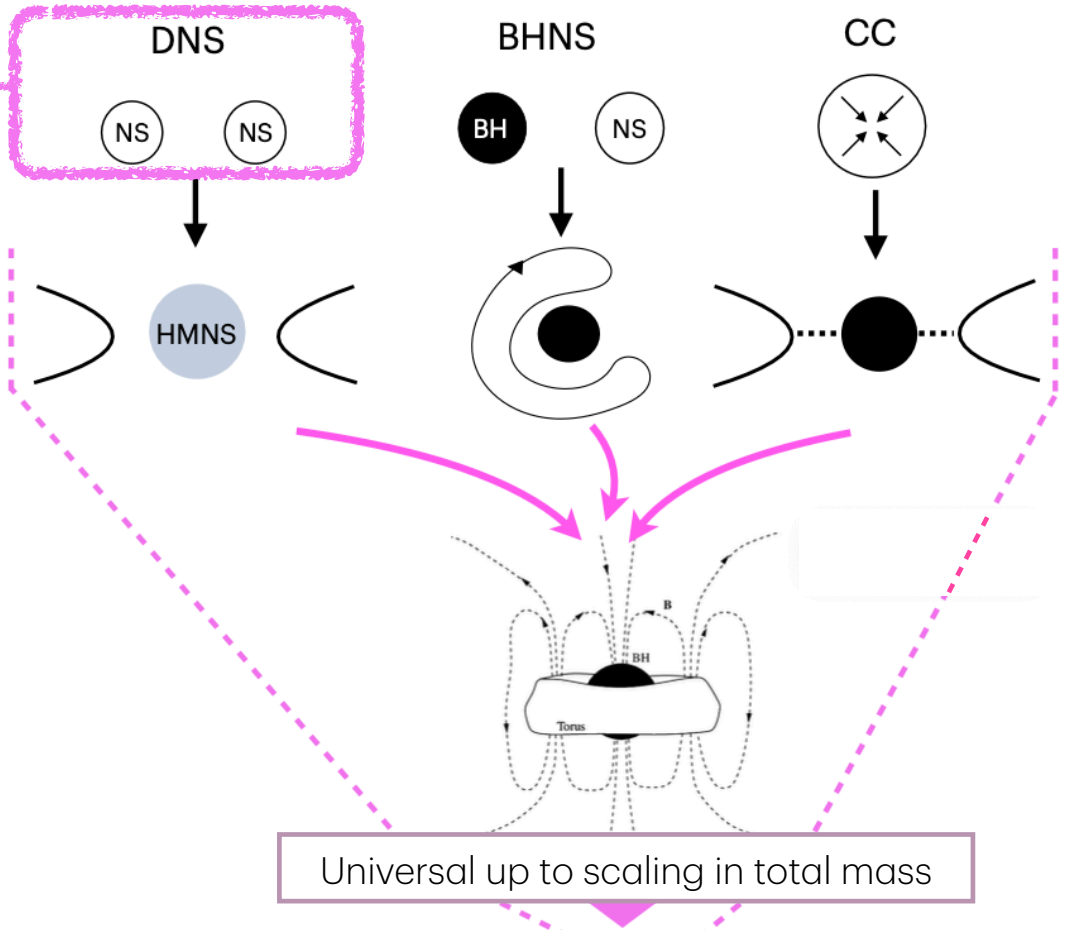
HEAC, Yerevan, 18 June 2026

Universality of Kerr BH central engines





van Putten, Abchouyeh, Della Valle, ApJL, 2024

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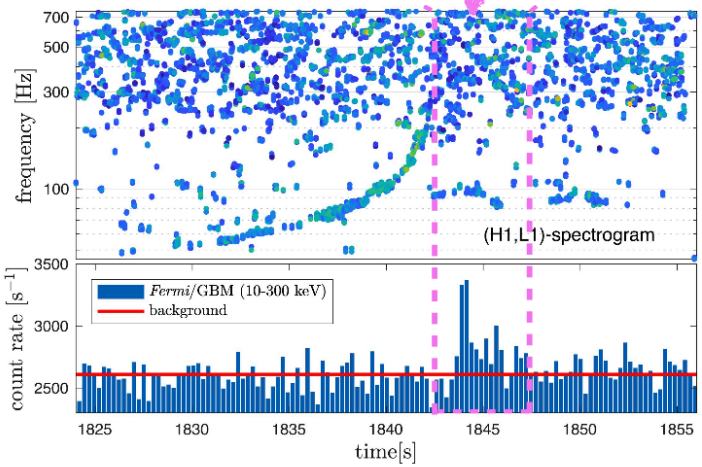
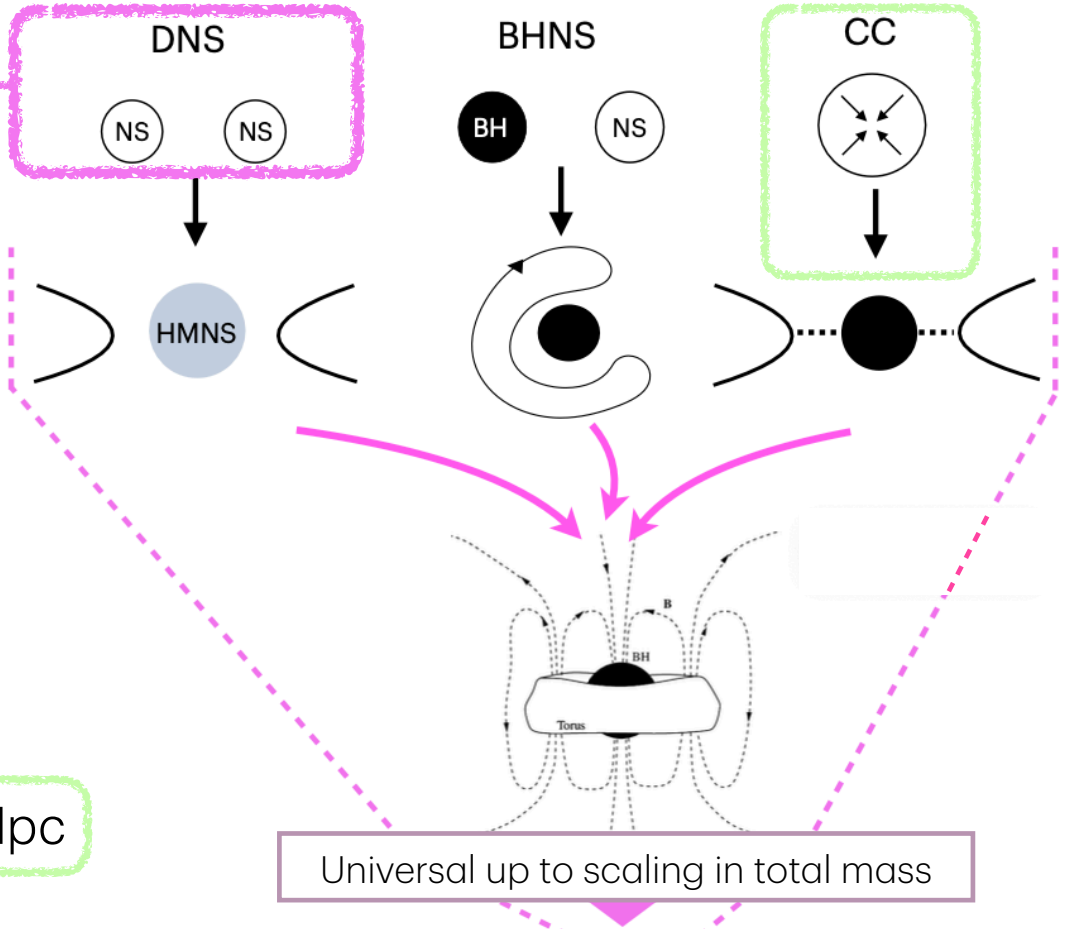
van Putten, Abchouyeh, Della Valle, ApJL, 2024



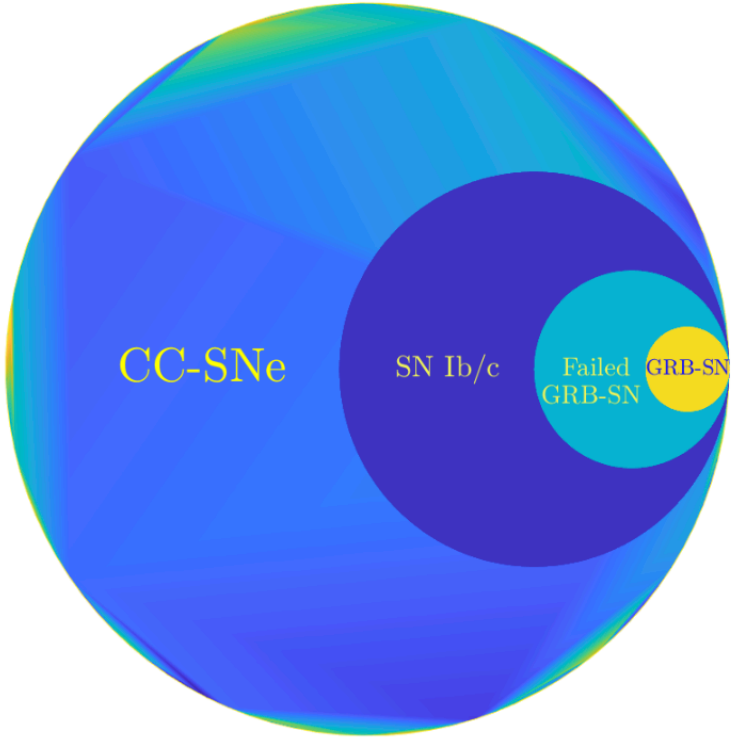
Horizon distance-O4: ~ 160Mpc



Universal up to scaling in total mass

Recent Targets of opportunities

- SN2023ixf type II at ~7Mpc (ER15)
- SN2024ggi type II at ~7Mpc (O4)
- AT2018cow type Ic at ~60Mpc (Post O2)
- SN2020oi type Ic at ~23Mpc (O3)
- SN2020bvc type Ic at ~120Mpc (O3)



Central engine can be constrained either by a detection or an confident non-detection of GW

van Putten, Abchouyeh & Della Valle ApJL (2024)

EM-triggered probes of CC-SNe

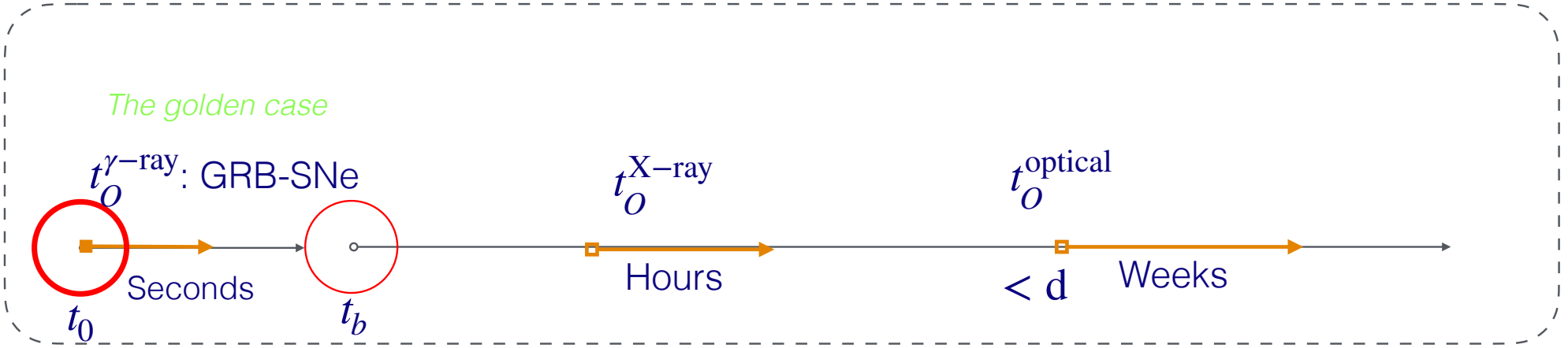
Unlike mergers, GW signal associated with CC-SNe is *unknown, requiring a totally new approach.*

Search in LIGO-Virgo data for GW preceding the EM-trigger

- Search window and delay time?
- Which method to use?
- What to expect from a potential GW candidate associated with CC-SNe?
- Energy thresholds for detection

EM-triggered probes of CC-SNe: Search window

- Delay time relative to shock break-out $\Delta_1 = t_O - t_b$
- Delay time shock-break out relative to time-of-onset t_o



e. g.: EP260321a (GCN 44068)/ Einstein Probe: SN Ic BL O'Conner et al. 2026, arXiv:2606.09992v1

Continuous wide-field observatories (Della Valle et al. 2025, arXiv:2512.18157)

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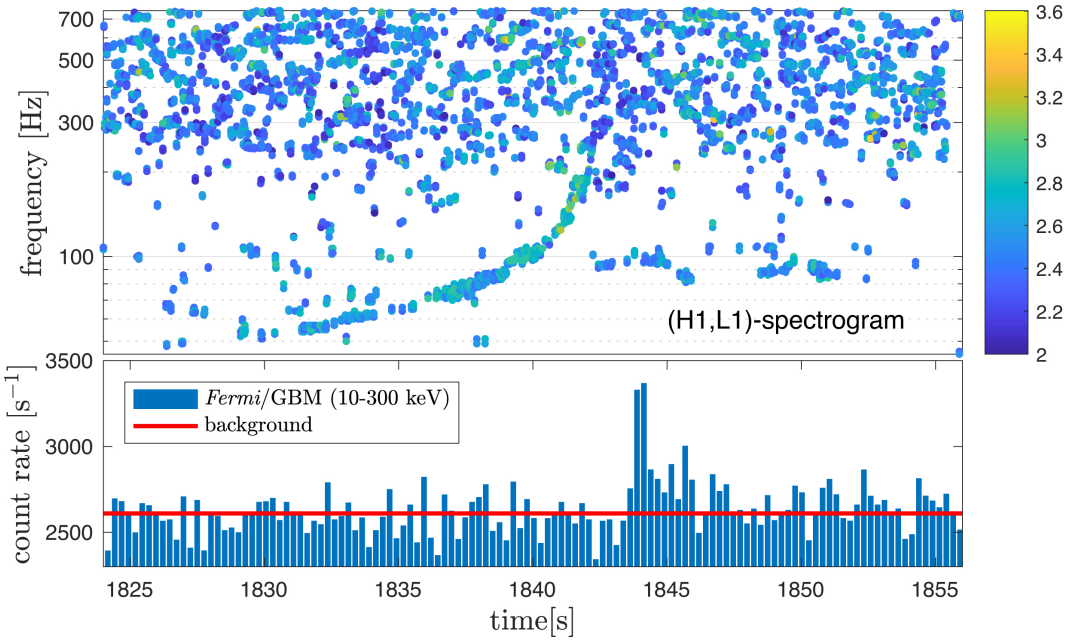
EM-triggered probes of CC-SNe: Method

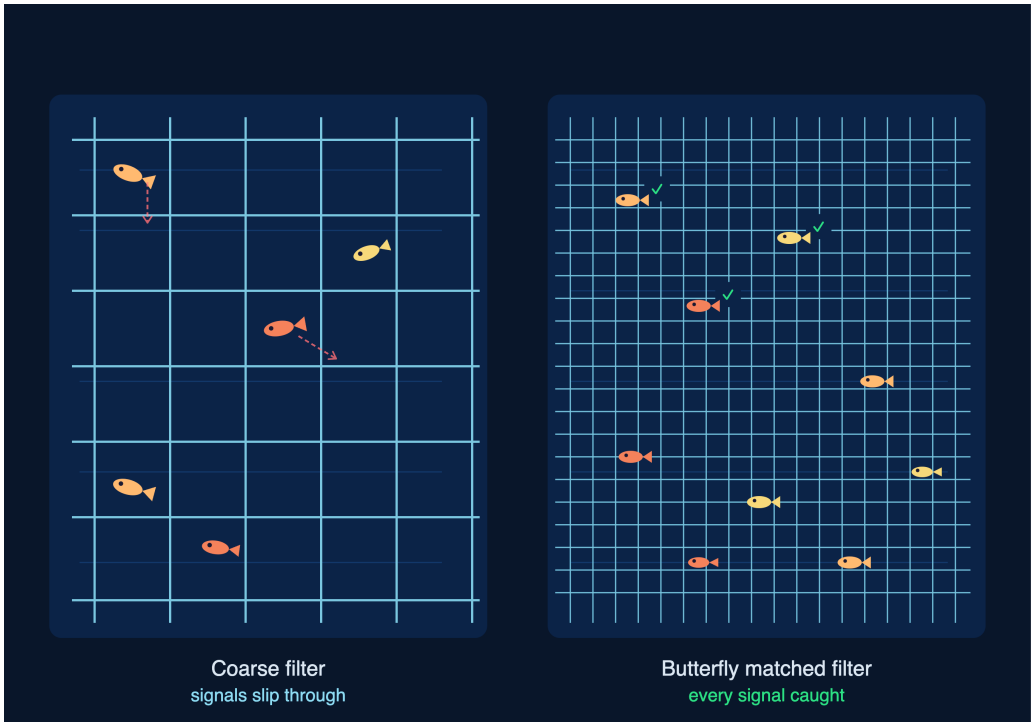
- Model-independent
- Detector limited sensitivity
- No pre-assumptions



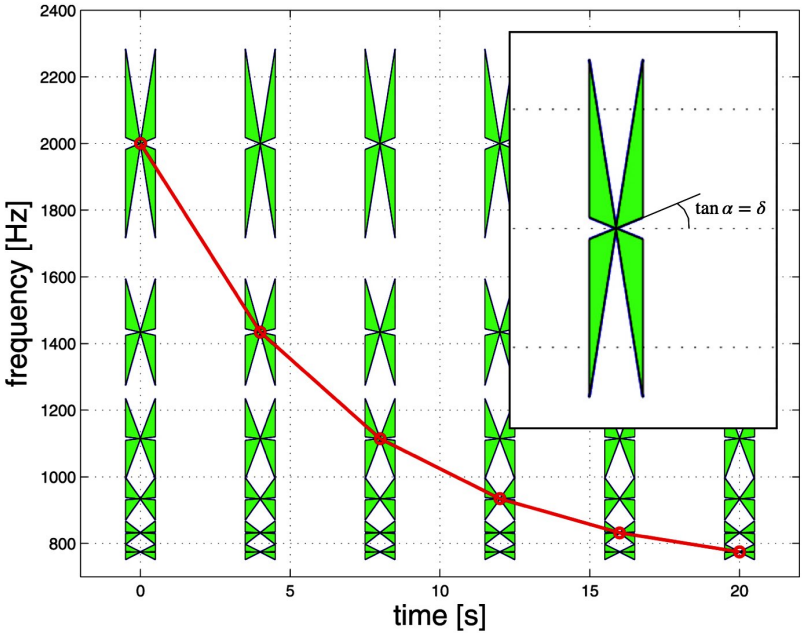
EM-triggered probes of CC-SNe: Method considerations

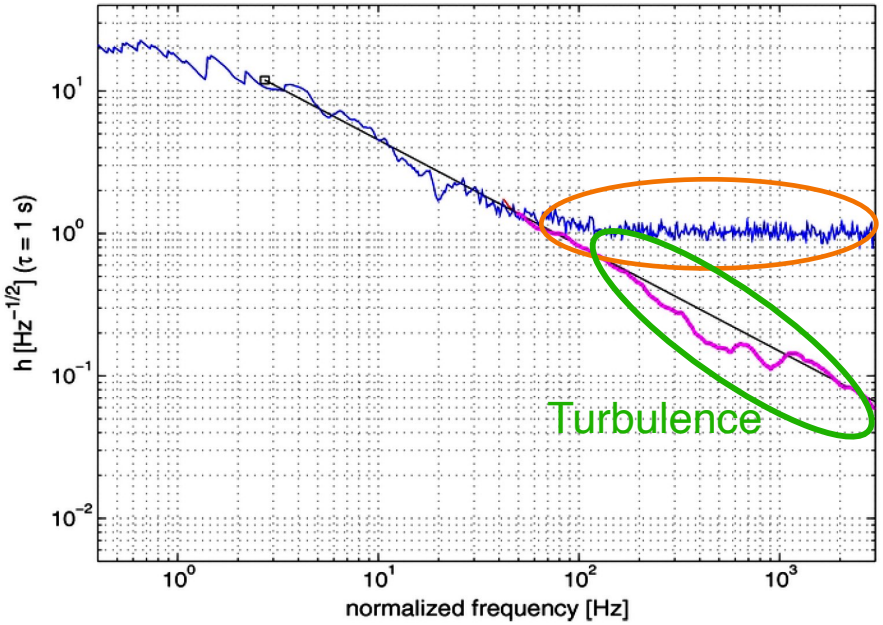
- Template bank size
- Duration of the target signal
- (Non-)linearities

These and other issues need optimization



Method: Butterfly Matched Filtering (BMF)





- An extension to FFT, including frequency and first time derivative of frequency

- Uses a dense symmetric template bank

Van Putten et. al., ApJ, 2014

EM-triggered probes of CC-SNe

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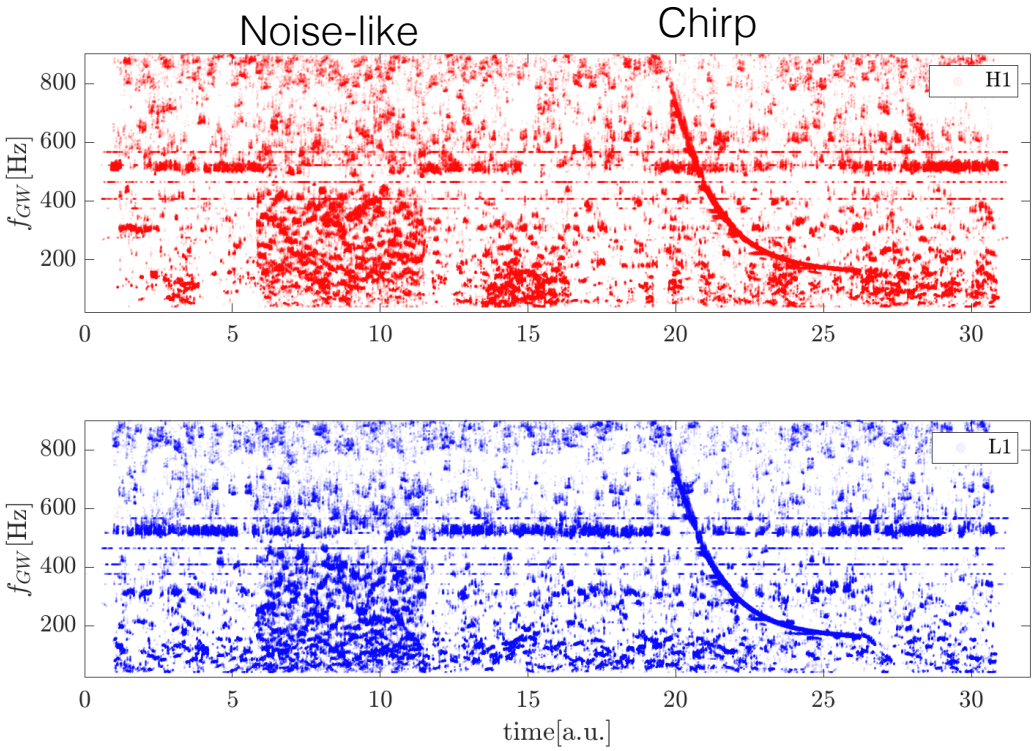
Energy thresholds and Observational expectations



ascending, descending:

$$E_{th,GW}^{chirp} \simeq 10^{-5} M_\odot c^2 \text{ (vs. } 0.035 M_\odot c^2)$$

(hyper-) accretion:

$$E_{th,GW}^{noise-like} = 10^{-2} M_\odot c^2$$

Focus on GW spin-down signal, but our search method is model-independent.

Abchouyeh, van Putten, Della Valle 2026, under review.
Gutiérrez, C. P., Anderson, J. P., Hamuy, M., et al. 2017, ApJ, 850, 89
Maurer, J. I., Mazzali, P. A., Deng, J., et al. 2009, MNRAS, 402, 161
van Putten, Abchouyeh & Della Valle ApJL (2024)

Recent targets of opportunities

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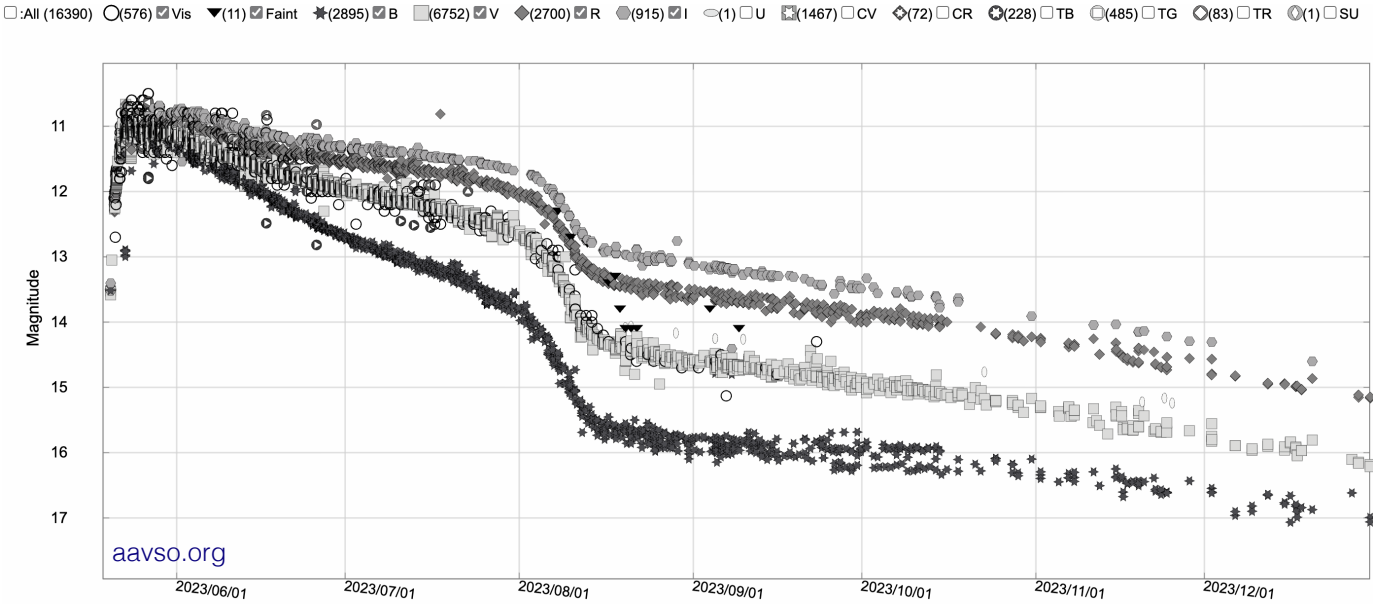

Pajkos, M. A., et al. 2023, ApJ, 959, 21
Zimmerman, E., Chandra Proposal, p. 6690, 2023
Smartt, S. J., ATel11727, 2018
Stroh, M., Chandra Proposal, p. 5774, 2019
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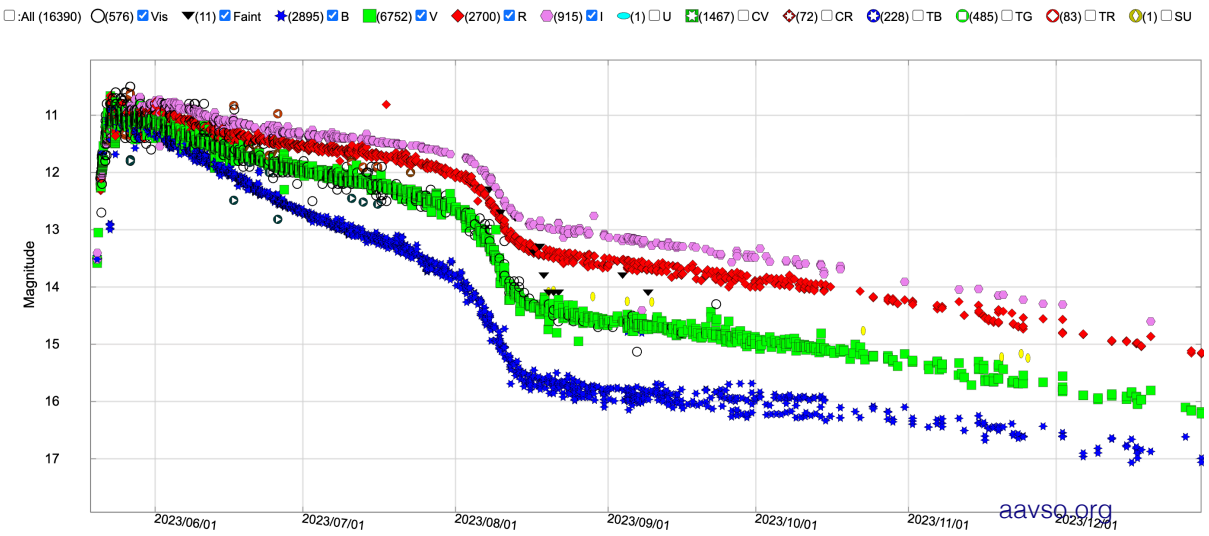
SN 2023ixf



- Observed on: May 19th, 2023
- Distance: 6.8 Mpc
- SN type II
- Progenitor mass from EM: $12M_{\odot} \lesssim M \lesssim 22M_{\odot}$
- Search window: $t_{Obs} - t_0 \sim 1$ day

Pajkos, M. A., et al. 2023, ApJ, 959, 21
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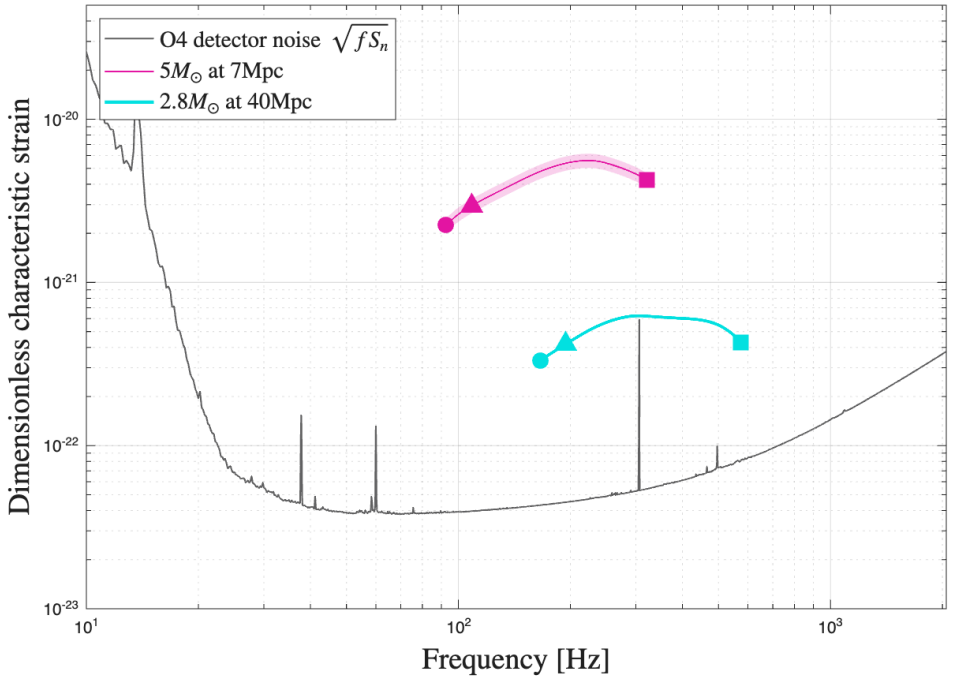
Detectability of descending signal



By mass scaling to GW170817B

Maurice's talk: SNR gain

$$\mathscr{K} = (k_d\times)k_D \times k_n \times k_m \simeq 4.4 \times 7 \sim 30$$

Abchouyeh, van Putten & Della Valle, under review

Data Processing

Within the availability of LIGO data, we did an injection in a search using BMF

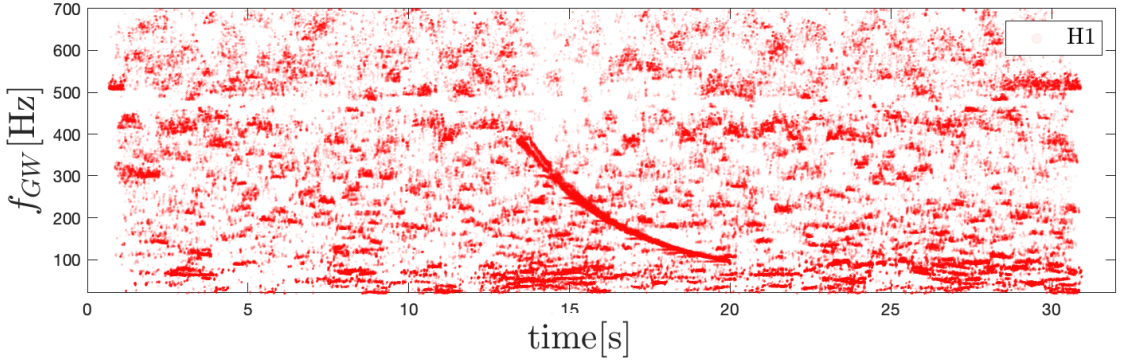
Window size: 32 seconds windows
Sampling rate: 8KHz (after down-sampling)
Search frequency range: 50-1000Hz
Method in use: BMF
Total search duration: 2.5 day window before and after the event

van Putten, Abchouyeh, Della Valle 2025 in preparation.

SN2023ixf: what if powered by a BH central engine?

Injection for the spin-down signal based on the specific case of SN 2023ixf assuming $M \simeq 5M_{\odot}$

Butterfly matched filtering has no bias towards the slope or monotonicity of the signal.



Abchouyeh, van Putten, Della Valle 2026, under review
van Putten, Della Valle, A&A, 2023

SN2023ixf: what if powered by a BH central engine?

The ground rule is essential to follow in this case!

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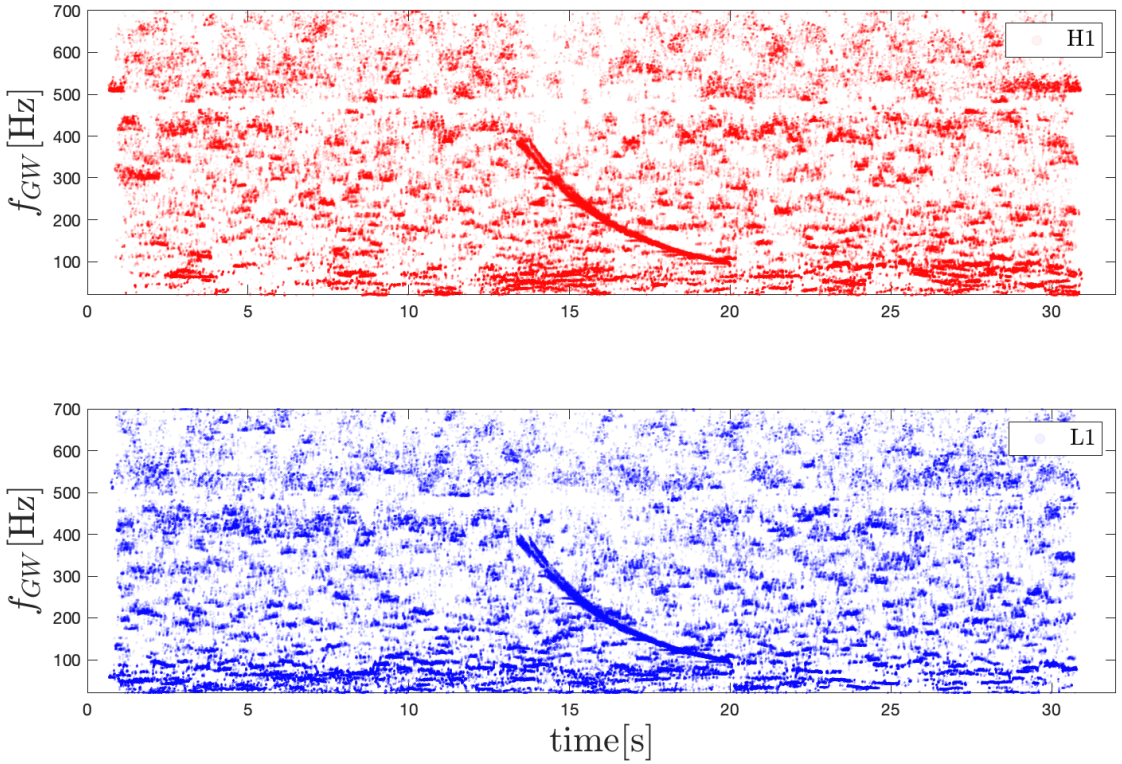

Abchouyeh, van Putten, Della Valle 2026, under review
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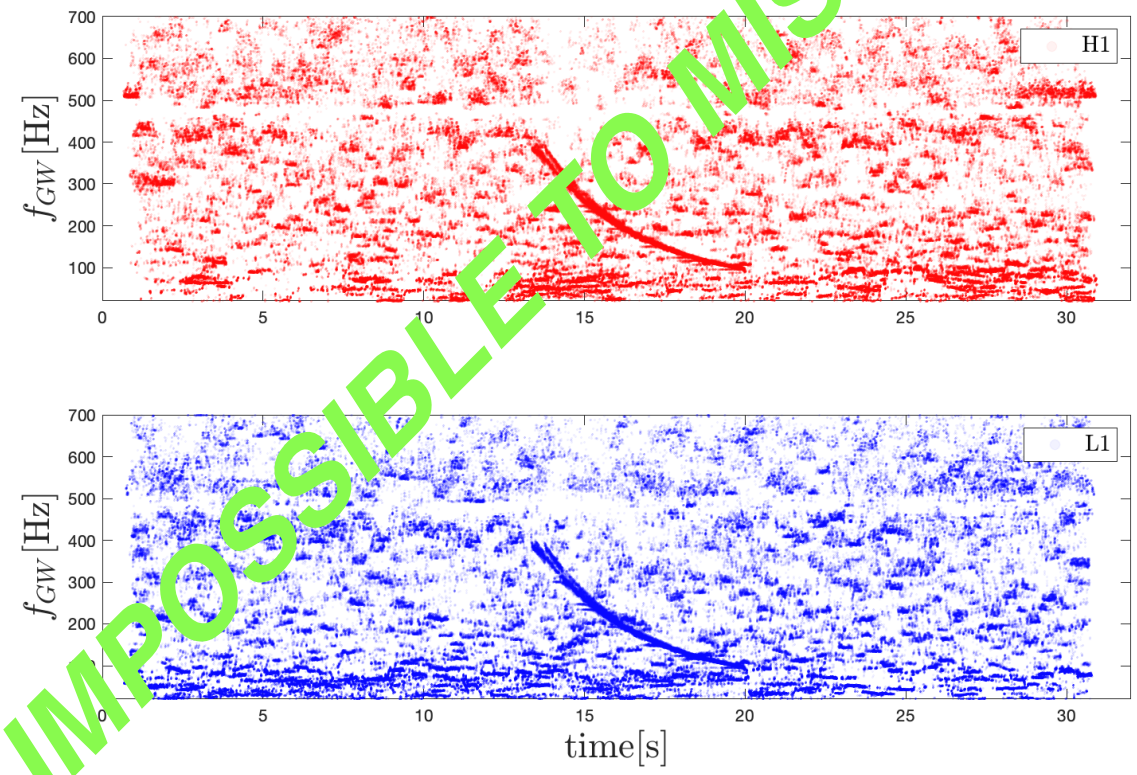


Abchouyeh, van Putten, Della Valle 2026, under review

Search result

In searching the LIGO data 2 days before and half a day after the estimated t_0

No such "impossible to miss" is observed within the available LIGO data.

Then the central engine is an NS?

van Putten, Abchouyeh & Della Valle ApJL (2024)

Black hole central engine?

Spin-powered:

Ruled out due to the non-detection of spin-down chirp

Accretion-powered:

Our $E_{th,GW}^{noise-like} = 10^{-2} M_\odot c^2$ *is insufficient so we go multi-messenger*

$E_k = (1.8 \pm 0.2) \times 10^{51}$erg

$\beta_{ej} = v_{ej}/c \simeq 0.017$

→ $E_w \lesssim 2.4 \times 10^{53}$erg

Consistent with baryon-poor relativistic winds: ***GRB-SNe***

If instead derived from baryon-rich wind →

Possibly over producing ^{56}Ni

Abchouyeh, van Putten & Della Valle, under review
smartt, 2009

The central engine is a black hole?

By these multi-messenger observational constraints,

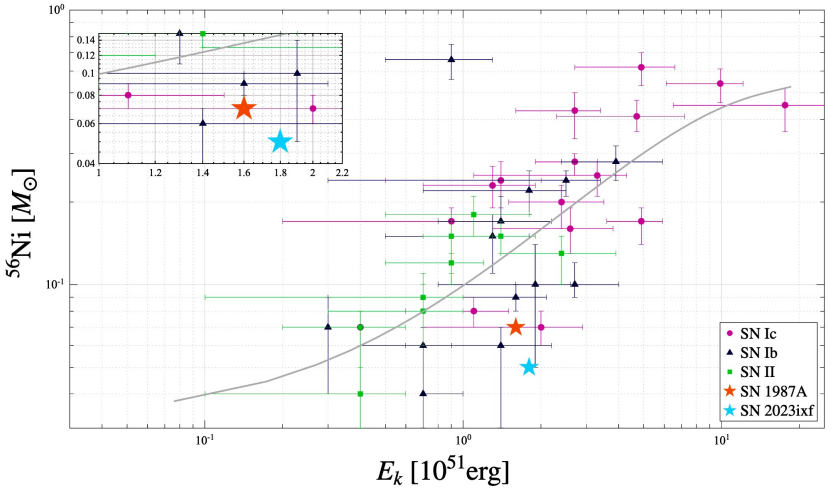
a black hole central engine powering E_k by its spin-energy or by (hyper-)accretion

appears unlikely

Abchouyeh,van Putten & Della Valle, under review
smartt, 2009

….or a neutron star?

- No-detection of GW signal
- Similar E_k and ^{56}Ni with SN 1987A
- Positive correlation^{56}Ni between E_k and ^{56}Ni

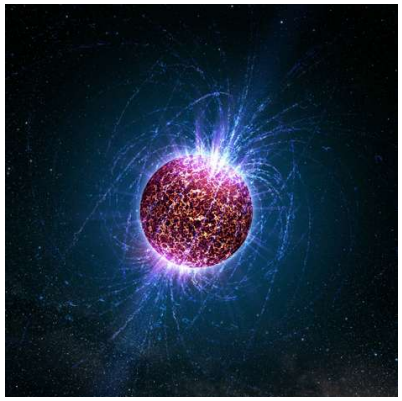


A robust multi-messenger pointer to the central engine of SN 2023ixf to be a

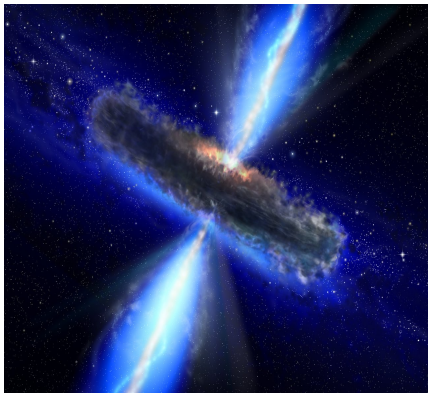
Neutron Star

van Putten, Abchouyeh & Della Valle ApJL (2024)

Take home message



NS: ~1Mpc



BH: 160Mpc

$$\frac{N_{BH}}{N_{NS}} \gtrsim 0.25 \simeq \frac{\text{SN Ib/c}}{\text{CC-SNe}}$$

- *The results of our image-based search show no detection of the "impossible to miss" signal.*
- *Based on GW and EM radiation associated with SN 2023ixf: NS central engine, hence the progenitor mass of* $\lesssim 20 M_{\odot}$.