Progresses on targeted searches for gravitational waves emitted by Core-Collapse Supernovae

Francesco Salemi, Università la “Sapienza” and INFN, Roma, Italia

Gabriele Vedovato, Università di Padova and INFN Padova, Italia

Outline

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- GW detectors and Observing runs
- Optically targeted search for CCSNe in the LIGO-Virgo-KAGRA third observational (O3) run
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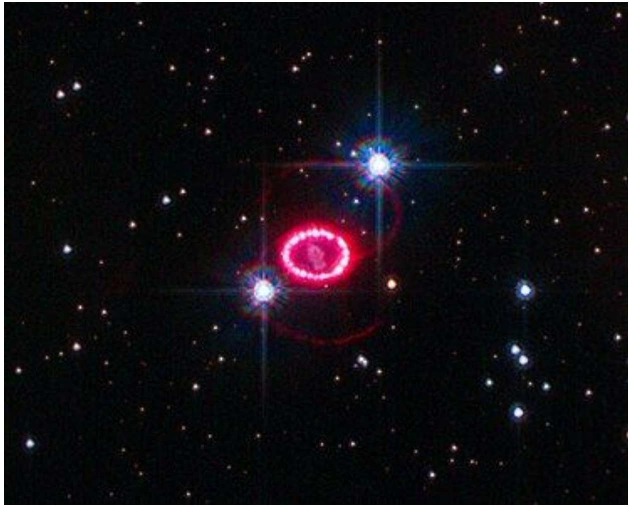
  - CCSNe Numerical simulations
  - Distance ranges
- Progresses on CCSNe targeted searches
  - a ML boosted decision tree model for GW post-production
    - generic training
    - sky features
  - Directional constraint
    - Issues
- Results & comparisons
- Conclusions and future steps

Intro on CCSNe

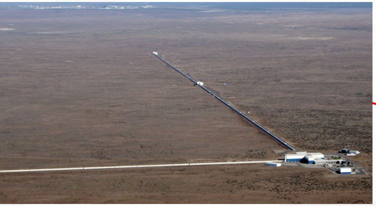
- The CCSNe are the explosions of massive stars at the end of their life, giving birth to neutron stars and black holes.
- The GWs predicted from the CCSN simulations produce relatively weak amplitudes; they can be **detectable only within the Milky Way for Advanced GW detectors.** However, these simulations and the many models of more energetic GW emission have yet to be observationally constrained.
- The need for direct observations to understand **the inner dynamics of the CCSN** explains the urgency and importance of searches for GWs from CCSNe. GWs and neutrinos are indeed ideal probes for this endeavor.
- All known CCSNe are observed in the electromagnetic spectrum. Low-energy neutrinos have been detected only from **SN 1987A** from the **Large Magellanic Cloud (LMC)**.
- The scientific community awaits a multimessenger observation of neutrinos, EM radiation, and GWs from a nearby CCSN.

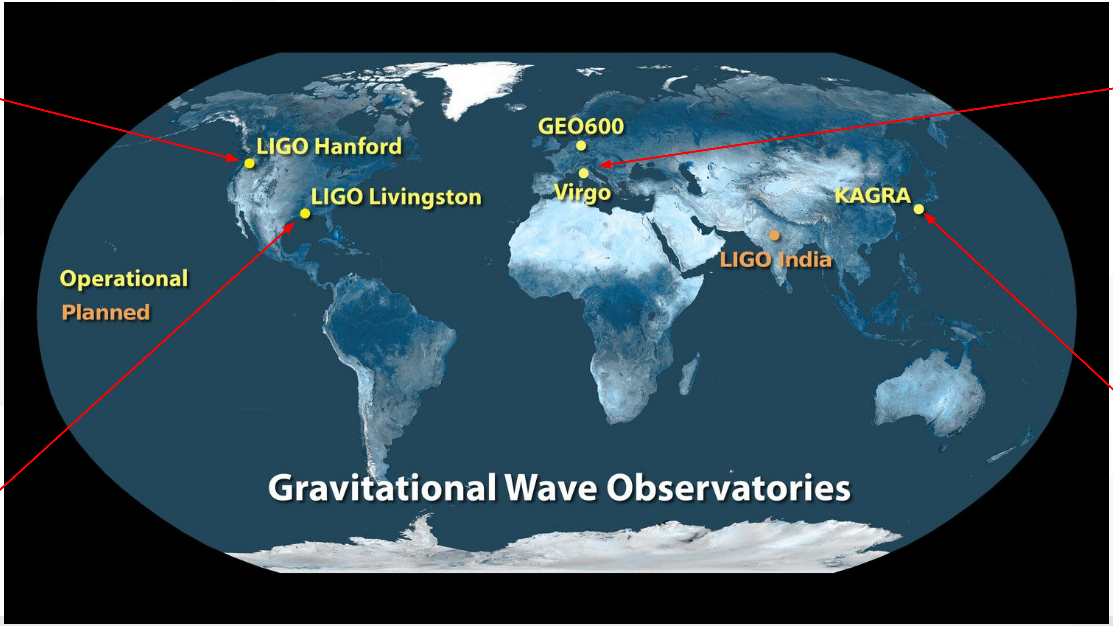


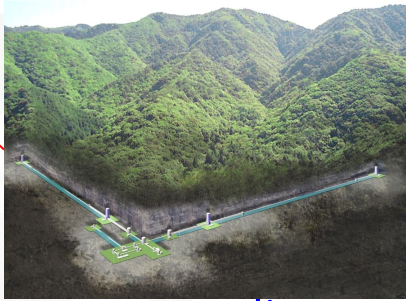
The remnant of SN 1987A from credit

The LIGO-Virgo-KAGRA network of GW detectors

- Third Observing run (O3): April 1st, 2019 to January 10th, 2019, and January 11th, 2019 to March 27th, 2020.
- Fourth Observing run (O4) is ongoing: May 24th, 2023 to January 16th, 2024) and April 10th, 2024 to June 9th, 2025



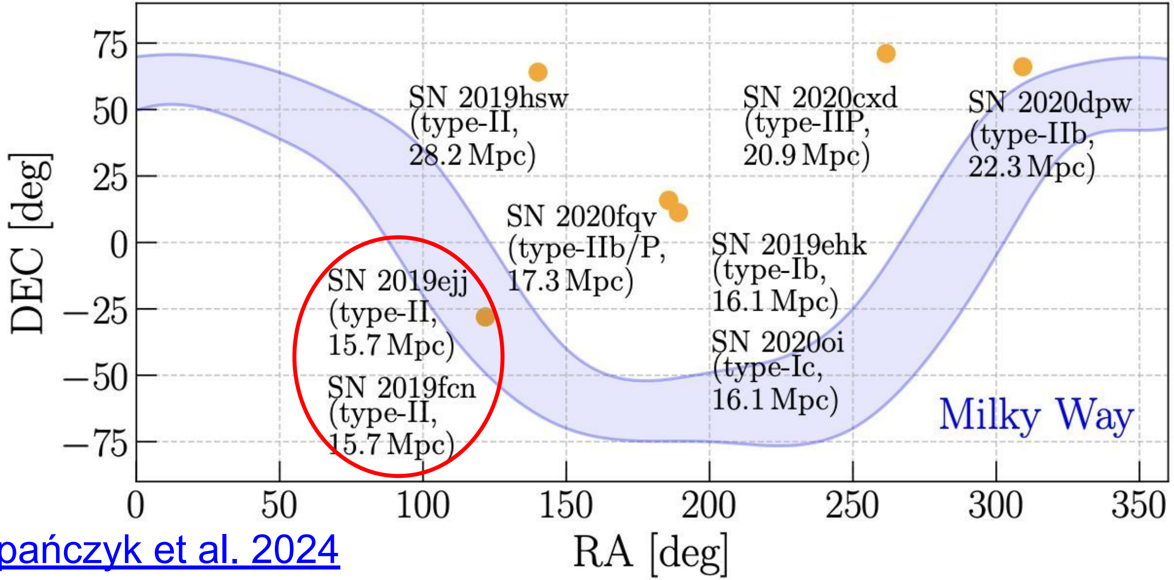




Images credit

Optically targeted search for CCSNe during the O3 run

- Within the **LVK** Collaboration, during the O3 run, 8 SNe were selected (estimated distance < 30 Mpc), for an optically targeted search for GWs from CCSNe.
  - The closest SNe were **SN2019ejj** and SN2019fcn (15.7 Mpc)
- No detections, but various interesting upper limits. Detection range can reach up to the galactic center for some waveforms.
- Results of that search are reported in an **arXiv**: Marek J. **Szczepanczyk et al.**, "*An Optically Targeted Search for Gravitational Waves emitted by Core-Collapse Supernovae during the Third Observing Run of Advanced LIGO and Advanced Virgo*"



M. Szczepańczyk et al. 2024

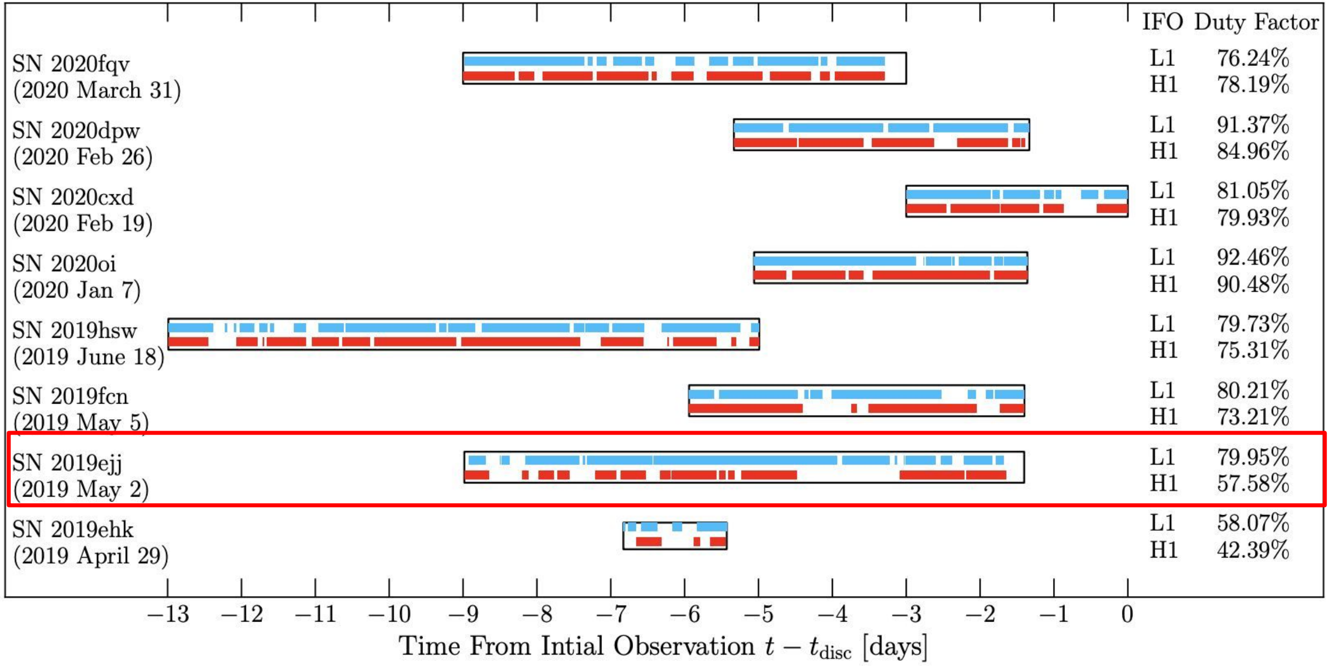
A simple yet robust approach

Marek J. **Szczepanczyk et al.**, “*An Optically Targeted Search for Gravitational Waves emitted by Core-Collapse Supernovae during the Third Observing Run of Advanced LIGO and Advanced Virgo*”

A simple yet robust approach

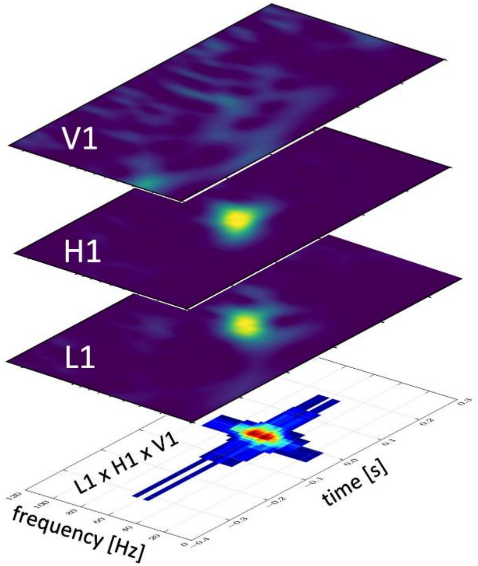
- the L1 and H1 detectors only were used for the search
  - V1 data was less sensitive
  - 3-fold analysis more complex
- Standard search analysis & thresholds
- No directional information was used
  - All-sky search

Data coverage for the O3 CCSNe On Source Windows (OSW) from [M. Szczepańczyk et al. 2024]



Coherent WaveBurst (cWB)

- Coherent WaveBurst (cWB) is an unmodeled GW search algorithm [S. Klimenko et al. 2016, M.Drago et al. 2021].
  - The cWB searches do not use signal models to identify candidate events.
- cWB was used within the LIGO-Virgo-KAGRA (LVK) collaboration to analyze the O3 CCSNe OSWs using data from the advanced ifos **L1**, **H1** and searching for generic GW candidates [M. Szczepańczyk et al. 2024].
- The standard veto method used a priori defined post-production selection cuts on the cWB summary statistics to reduce due to detector noise.
- The development of these selection cuts is complex and time-consuming
- 3-fold network and directional analysis were hard to tune



Excess power in time-frequency domain [GW190521 webinar]

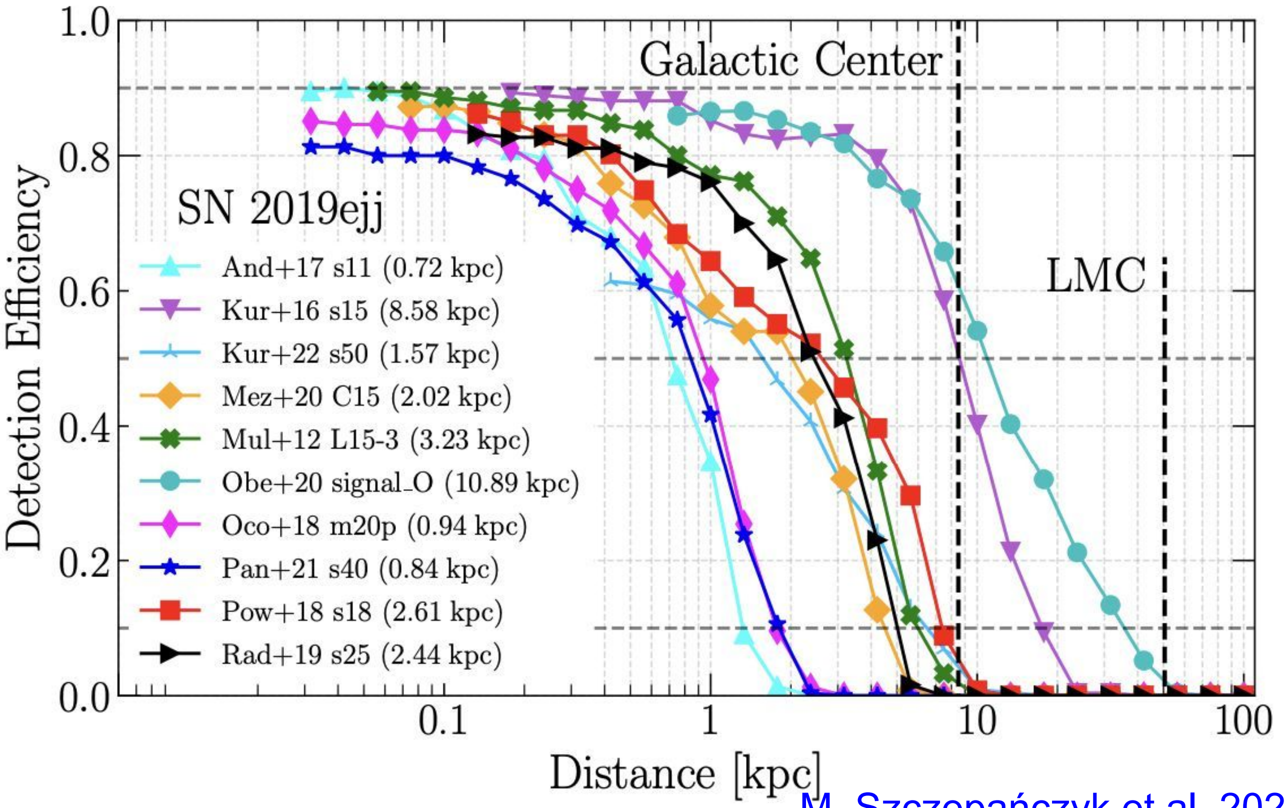
SN2019ejj: CCSNe simulations

In M. Szczepańczyk et al. 2024, the search sensitivity with waveforms calculated also from **14** CCSN simulations:

- neutrino-driven explosion
  - **s11** model, Andresen et al. 2017
  - **s15** model, Kuroda et al. 2016 (relabeled **SFHx**)
  - **C15** (or **C15-3D**) model, Mezzacappa et al. 2020
  - **L15-3** model, Müller et al. 2012
  - **mesa20** (or **m20**) and **mesa20_pert** (or **m20p**) models, O'Connor and Couch 2018
  - **he3.5** (relabeled **s3.5_pns**) and **s18** models, Powell and Müller 2019
  - **s9**, **s13** and **s25** models, Radice et al. 2019
- Magnetorotational explosions
  - **signal_O** (or **3d_signal_O**) Obergaulinger et al. 2020
- The black hole formation
  - **s40** model (relabeled **NR**), Pan et al. 2021
- QCD Phase Transition
  - **s50** Kuroda et al. 2022

SN2019ejj: detection ranges

- The CCSN waveforms were injected into the detector data within the on-source window.
- Detection Efficiency: the fraction of the injected signals that can be detected and pass the selection criteria
- Detection range: the distance @50% detection efficiency
- Loudest event False Alarm Rate threshold: ~ 1 event/day



M. Szczepańczyk et al. 2024

Progresses on targeted searches for GWs from CCSNe

Since O3, a lot of work has been devoted to improving the sensitivity of burst un-modeled searches, both in terms of reducing the minimal “magnitude” of reconstructed events and of robustness.

Main changes on cWB 2G since O3

- Machine learning trained decision tree used for post-processing (2022)
  - Use of directionality features (2023)
- Sub-threshold event reconstruction (2022)
- Enhanced performances for 3-fold networks (2023)

ML-enhanced cWB

+

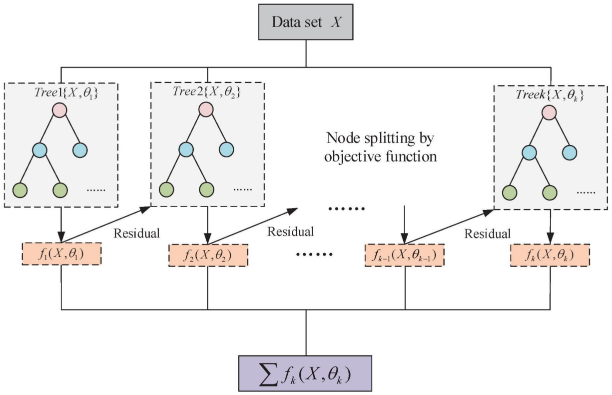
- Enhanced directional analysis (WIP)

Sky-targeted ML-enhanced cWB

- For this case study, we selected **SN2019ejj** and repeated the 2-fold analysis (L1 and H1 only) twice: first in all-sky mode (ML-enhanced cWB), and then in sky targeted mode (Sky-targeted ML-enhanced cWB)

ML-enhanced cWB

- A Machine Learning (ML) method to automate and improve the separation between BBH GW signals and glitches was proposed [T. Mishra et al. 2021].
- cWB maps properties of GW events into summary statistics. A subset of generic summary statistics is used as input features into the ML algorithm XGBoost - a boosted decision-tree based ensemble learning classifier algorithm.
- Unlike template-based searches that find events based on specific signal waveforms, the XGBoost classification is designed to exclude events that are inconsistent with the generic signal features. For example, events that are not coherent in the detector network.
- In this work, we apply a similar methodology to the search for generic GW transients.



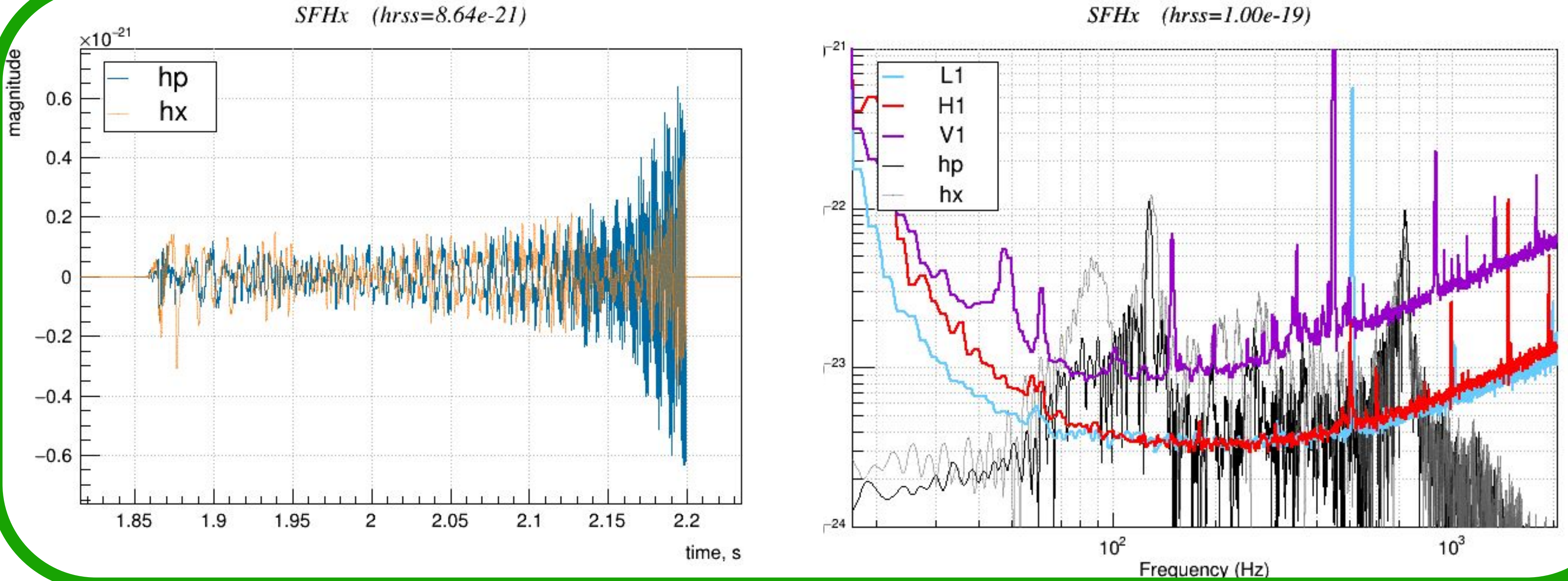
XGBoost flow chart for building an ensemble of trees. [Rui Guo et al. 2020]

cWB searches for GWs from SN2019ejj

- The **SN2019ejj** OSW covers a period of roughly 7.5 days.
    - On that data we performed a 2-fold analysis (L1 and H1 only) with:
        - the **background estimation** on time shifted data (~120 yr of equivalent time); we use 50% of the available background data for training and use the remaining for testing.
        - a GW **signal training set**, i.e., a simulation to be injected on the OSW with a generic distribution of White Noise Bursts (WNBs) from the celestial coordinates of SN2019ejj that populate a wide range of frequencies, bandwidths and durations.
        - a GW **signal testing set**, i.e., a simulation composed of tens of thousands of CCSNe (14 different NR waveforms) to be injected on the OSW at different distances. **Goal**: comparison with results from [M. Szczepańczyk et al. 2024].
    -

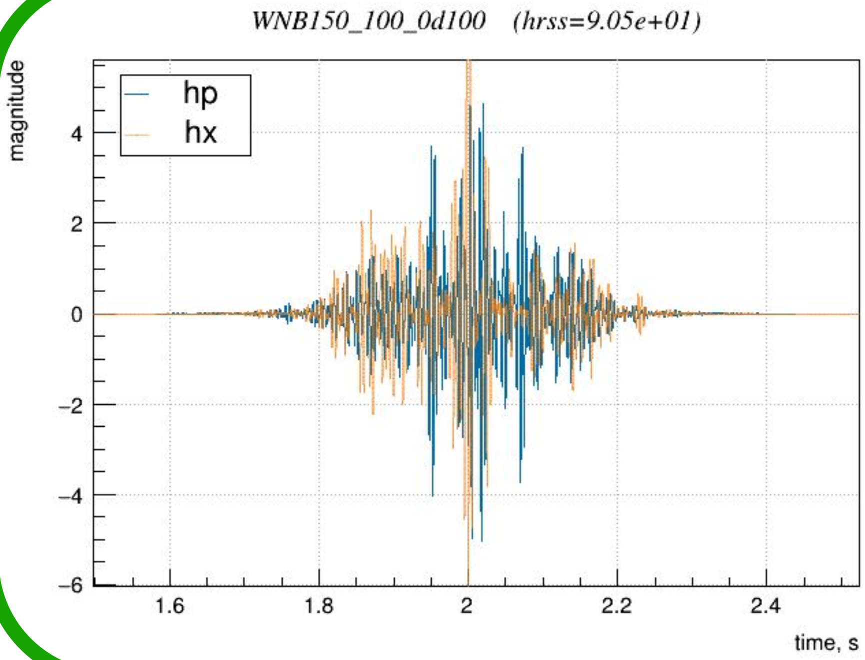
cWB searches for GWs from SN2019ejj: testing set

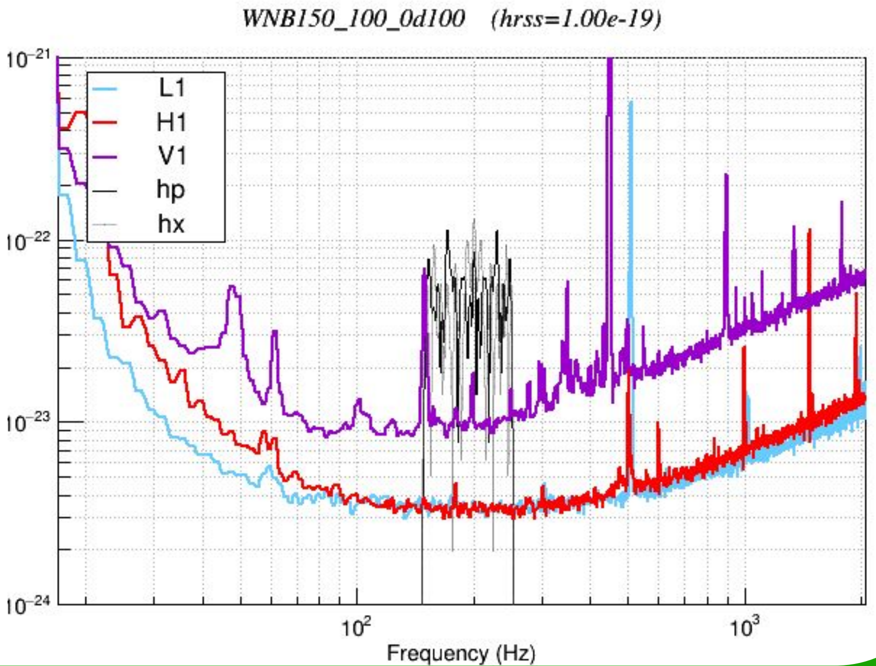
Kuroda et al. 2016 neutrino-driven CCSN model



cWB searches for GWs from SN2019ejj: training set

An example of a WNB with initial frequency at 150 Hz, bandwidth 100 Hz.



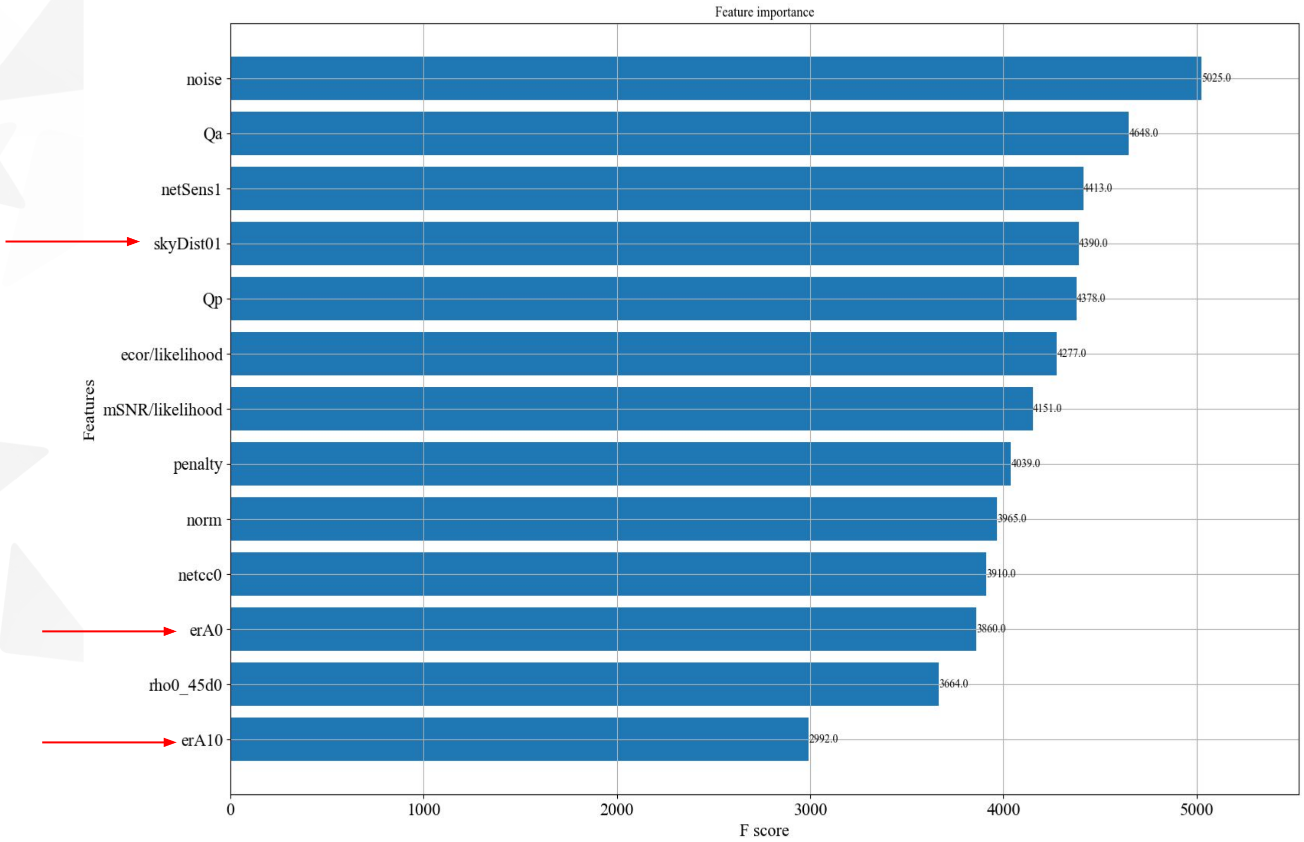


ML-enhanced cWB search for GWs from SN2019ejj

- Since this search for CCSN GW transients should be as "generic" as possible, **training on generic signals is necessary, but not sufficient.** Therefore, we feed XGBoost with just **"generic" features**, i.e., no GW signal characteristics, such as frequency, bandwidth, duration, etc.

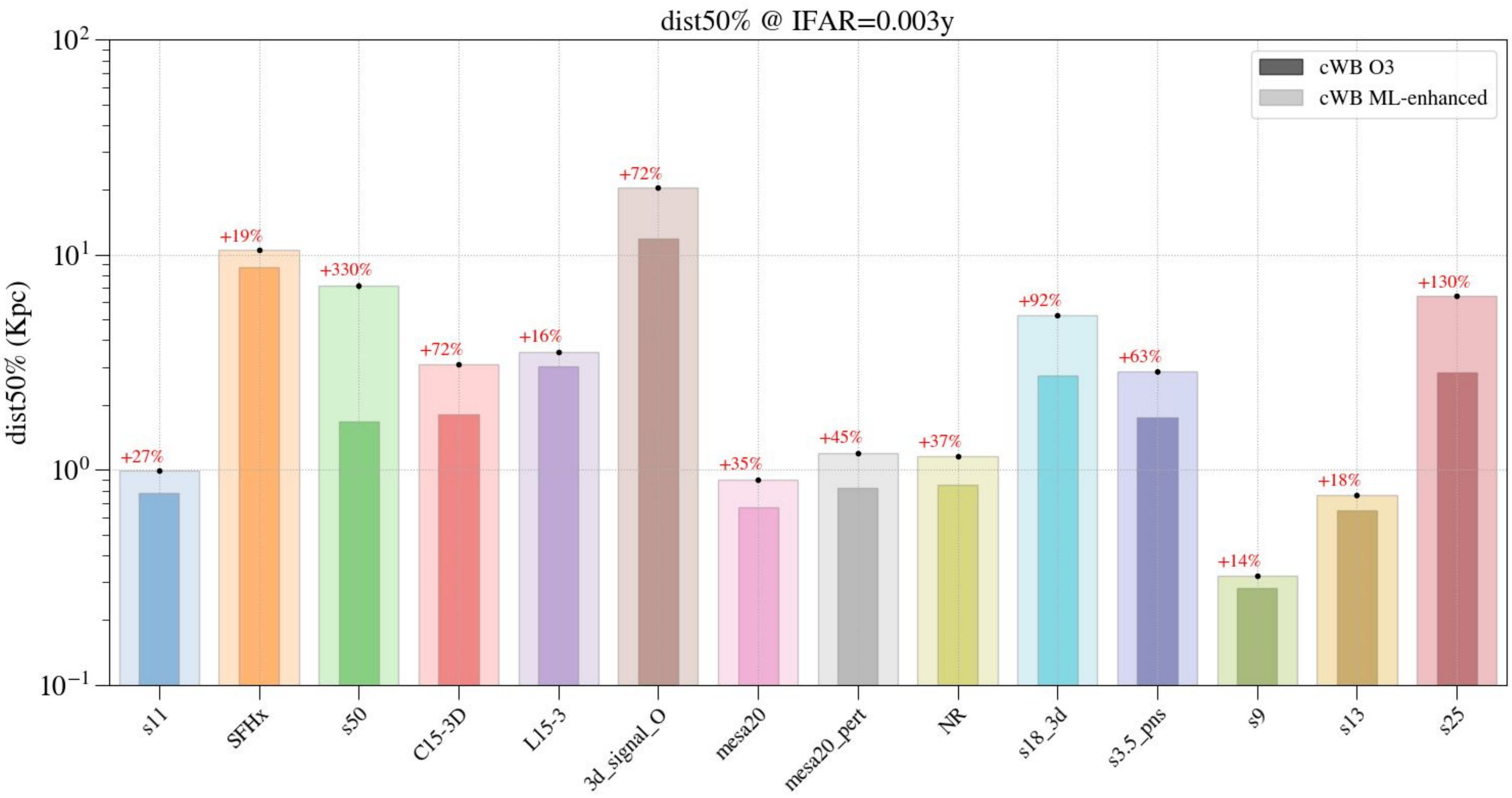
- For this CCSN search, we added 3 extra features to the XGBoost model to further enhance its signal/noise classification accuracy. The 3 extra features are related to the GW point-estimate sky position and to the reconstructed sky error regions (regions in the sky consistent with the GW trigger)

ML-enhanced cWB search: list of features



Results on SN2019ejj - dist50%: cWB ML-enhanced

The dist50% achieved with cWB with standard post-production veto procedure (darker colors) and with ML-enhanced cWB (lighter colors) at iFAR≥ 0.003 years.



Sky-targeted ML-enhanced cWB search

- We implemented and tested a new code to constrain cWB search over the sky in a given direction in celestial coordinates.

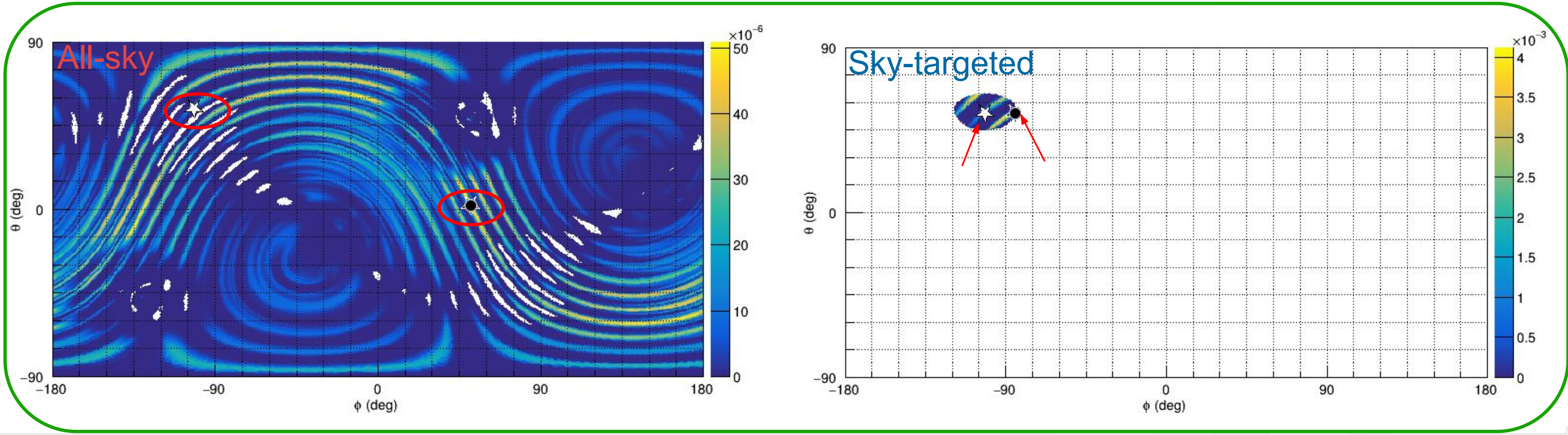
- As a case study for SN2019ejj, we chose (somewhat arbitrarily) to constrain the sky search on **a circle of 10 degrees**, and we kept all other cWB parameters fixed to the previous test.

- As expected, **this sky constraint significantly reduces the background of false positives but also impacts the simulated GW signals**. Moreover, the positive effect of the directional features within the XGBoost model is decreased considerably.

  Overall, the improvement over the all-sky search is relatively marginal in this case. However, careful tuning of cWB parameters may significantly improve the performances of the sky-targeted search. Our next step!

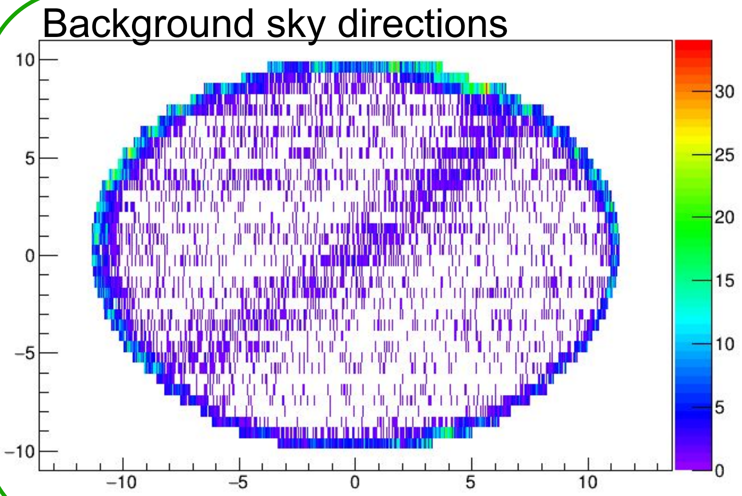
Sky-targeted ML-enhanced cWB search (2)

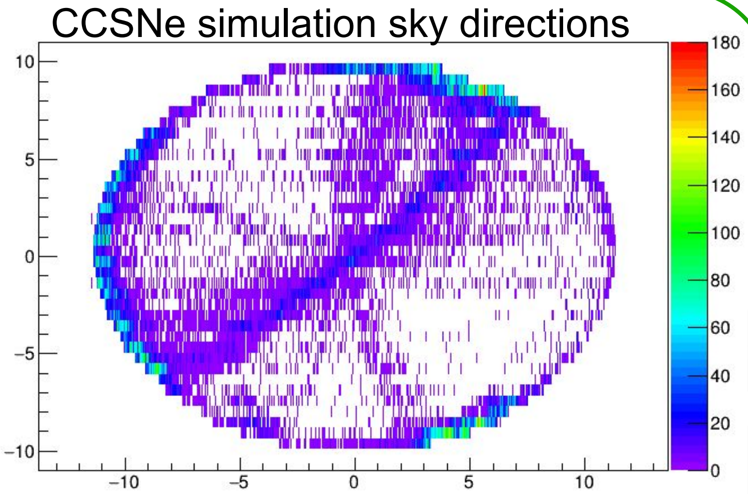
- An example of a sky-probability map for an all-sky search (bottom left) and for a sky-targeted search(bottom right). The sky-targeted search is constrained to a circle of 10 degrees centered on the direction of SN2019ejj (RA = 121.7865, DEC = -28.053239). For both searches, we injected the same weak CCSN signal on the GW data from a direction consistent with the SN2019ejj (white star); the black star shows the cWB reconstructed direction for the all-sky (bottom left), and for the sky-targeted (bottom right).



Sky-targeted ML-enhanced cWB search (3)

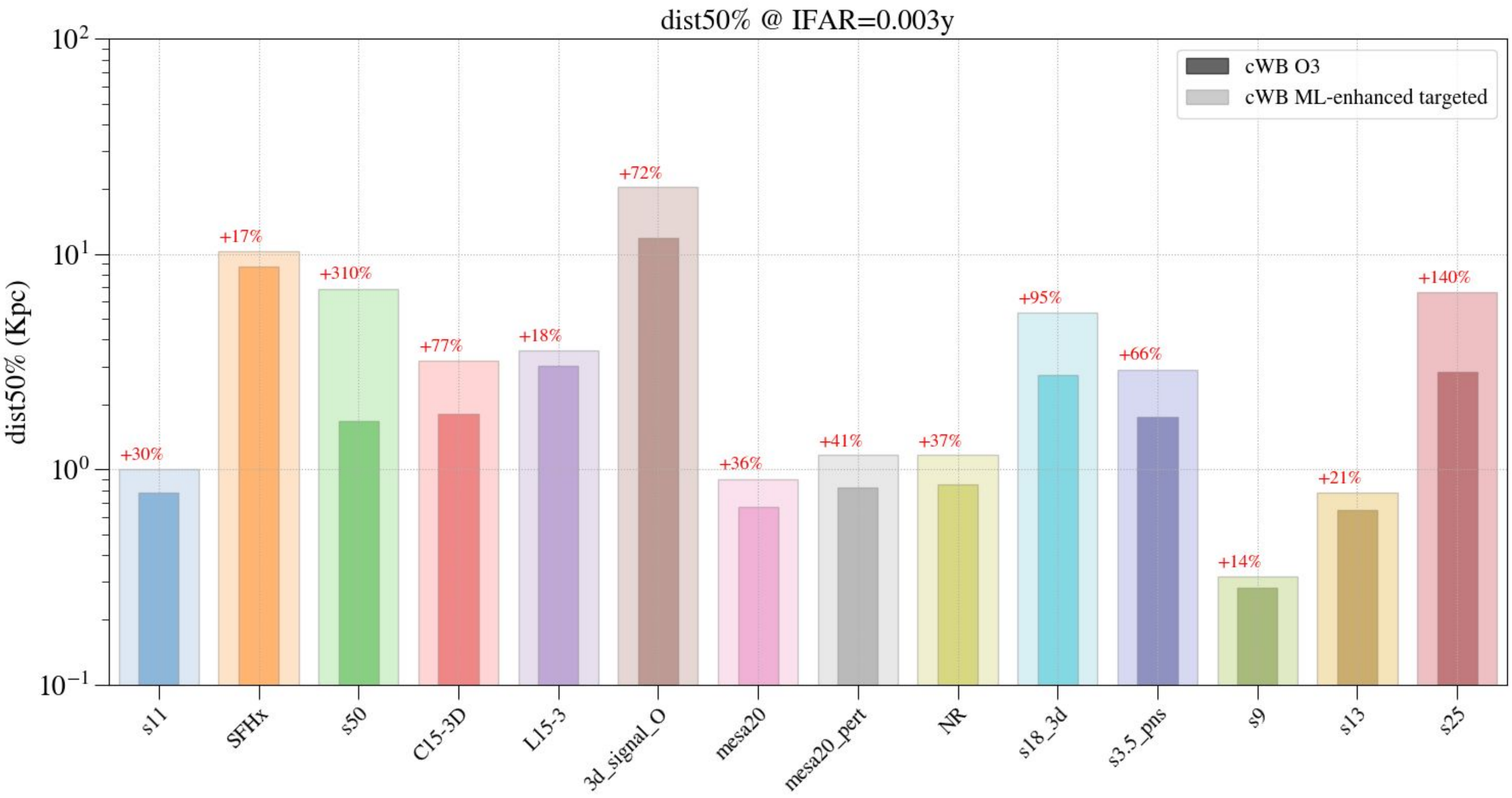
- Color density plot of the reconstructed sky directions for the background of accidentals (bottom left) and the CCSNe simulation(bottom right) at an iFAR>0.003 yrs. The sky-targeted search is reduced to an area of 10 degrees centered on the direction of SN2019ejj (RA = 121.7865, DEC = -28.053239). In both cases, the reconstructed direction usually hits the boundary with no significant difference between the signals and the accidental noises.





Results on SN2019ejj - dist50%: cWB ML-targeted

The dist50% achieved with cWB with standard post-production veto procedure (darker colors) and with ML-enhanced cWB + directional constraint (lighter colors) at iFAR≥ 0.003 years.



Conclusions and future steps

- We underscored the ongoing importance of the targeted searches for GW transients associated with CCSNe, a crucial aspect of our collective research efforts.

- We showed recent progress on the data analysis side, led by adopting an ML-boosted decision tree algorithm in post-processing and using directional features.

- Finally, we presented preliminary results using a sky-targeted GW transient search and discussed its current limits.

- Next steps:
    - a careful tuning of cWB parameters to significantly improve the performances of the sky-targeted search.
    - extension to the 3-fold (Hanford-Livinston-Virgo) network

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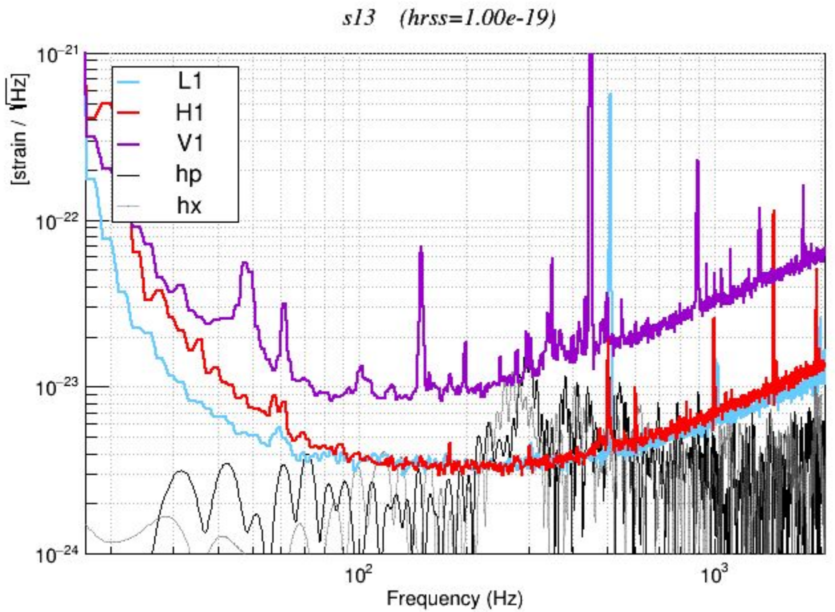
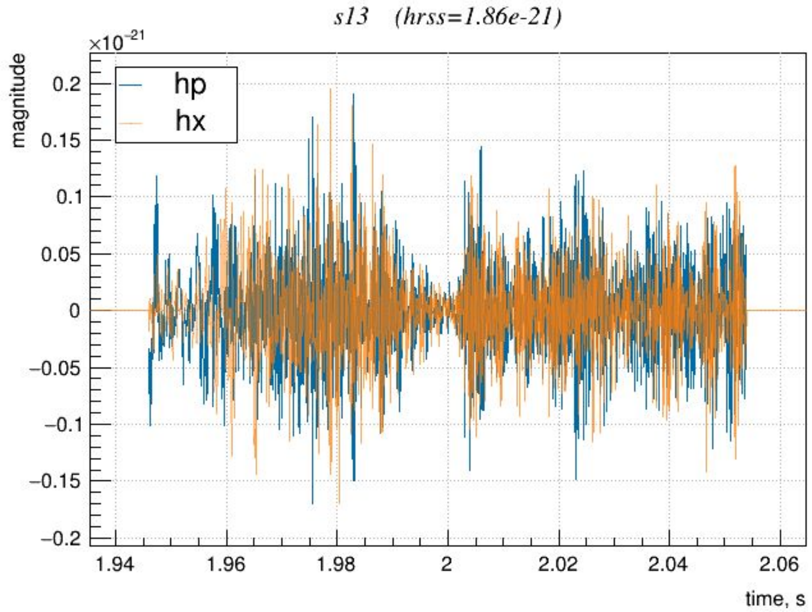
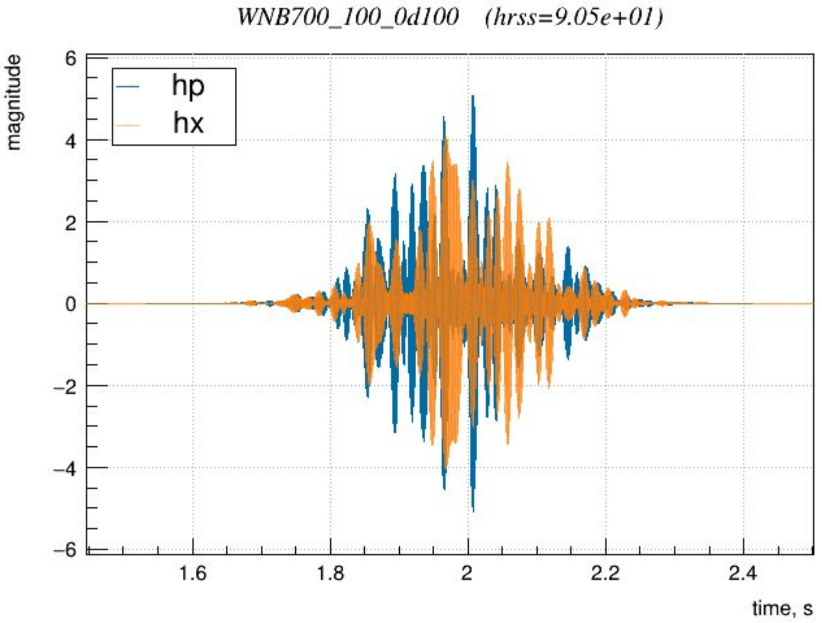
EXTRA SLIDES

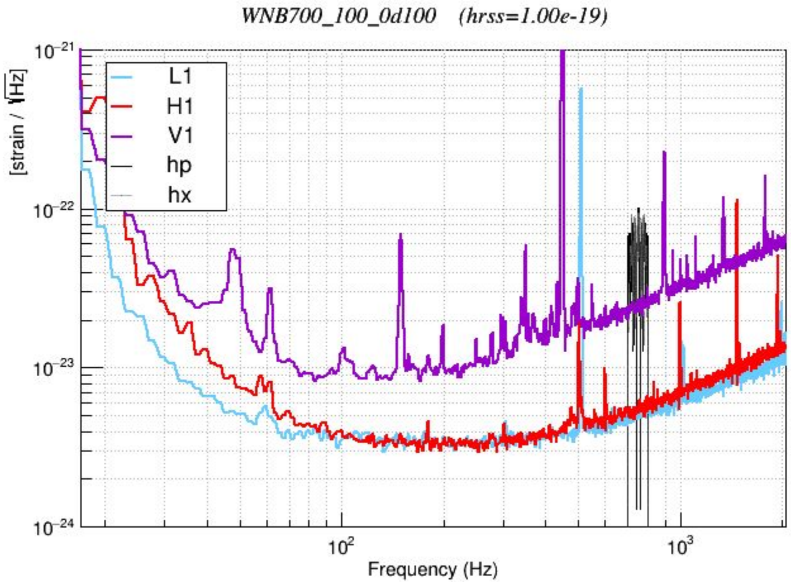
cWB searches for GWs from SN2019ejj





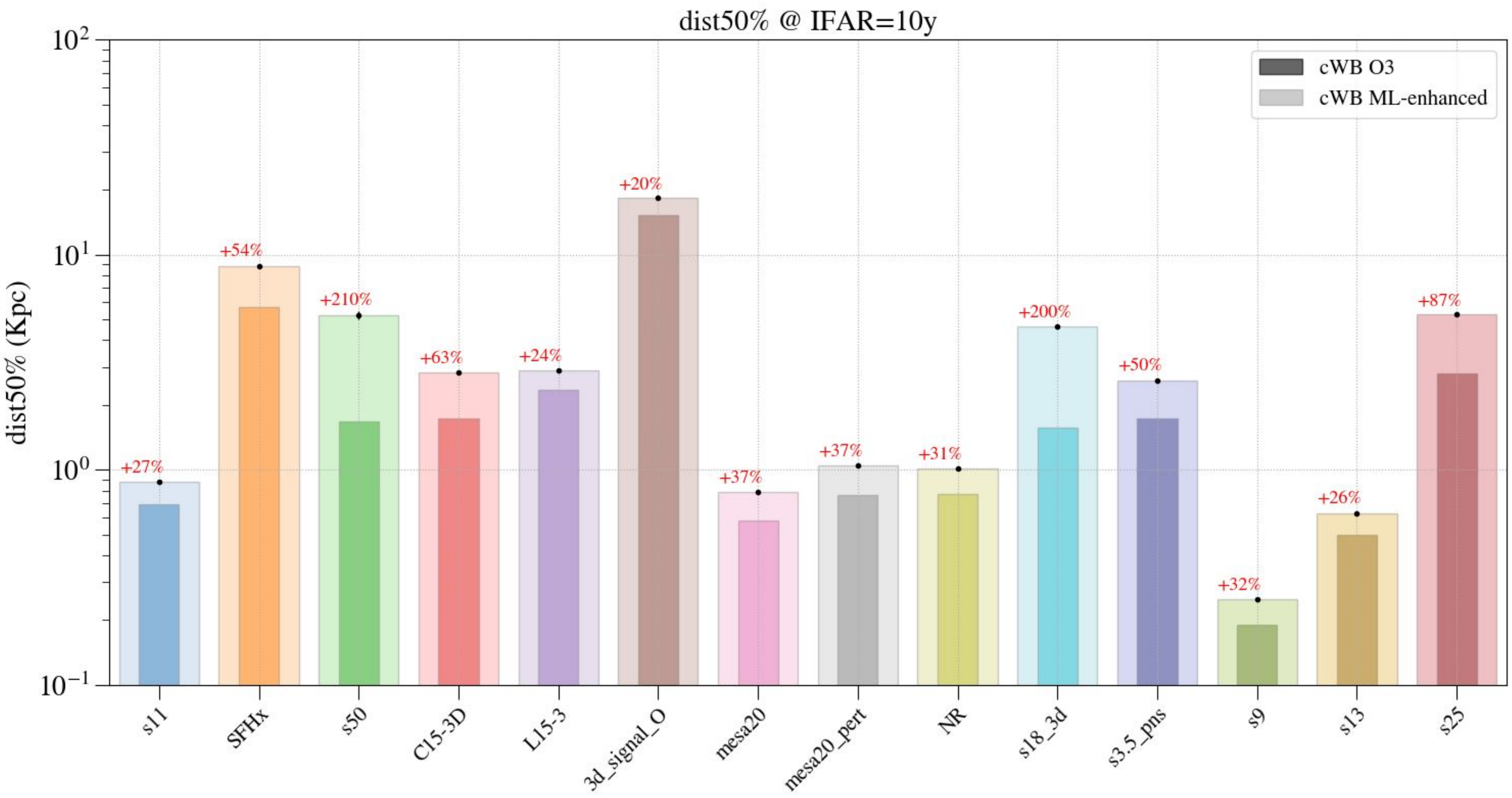
cWB searches for GWs from SN2019ejj





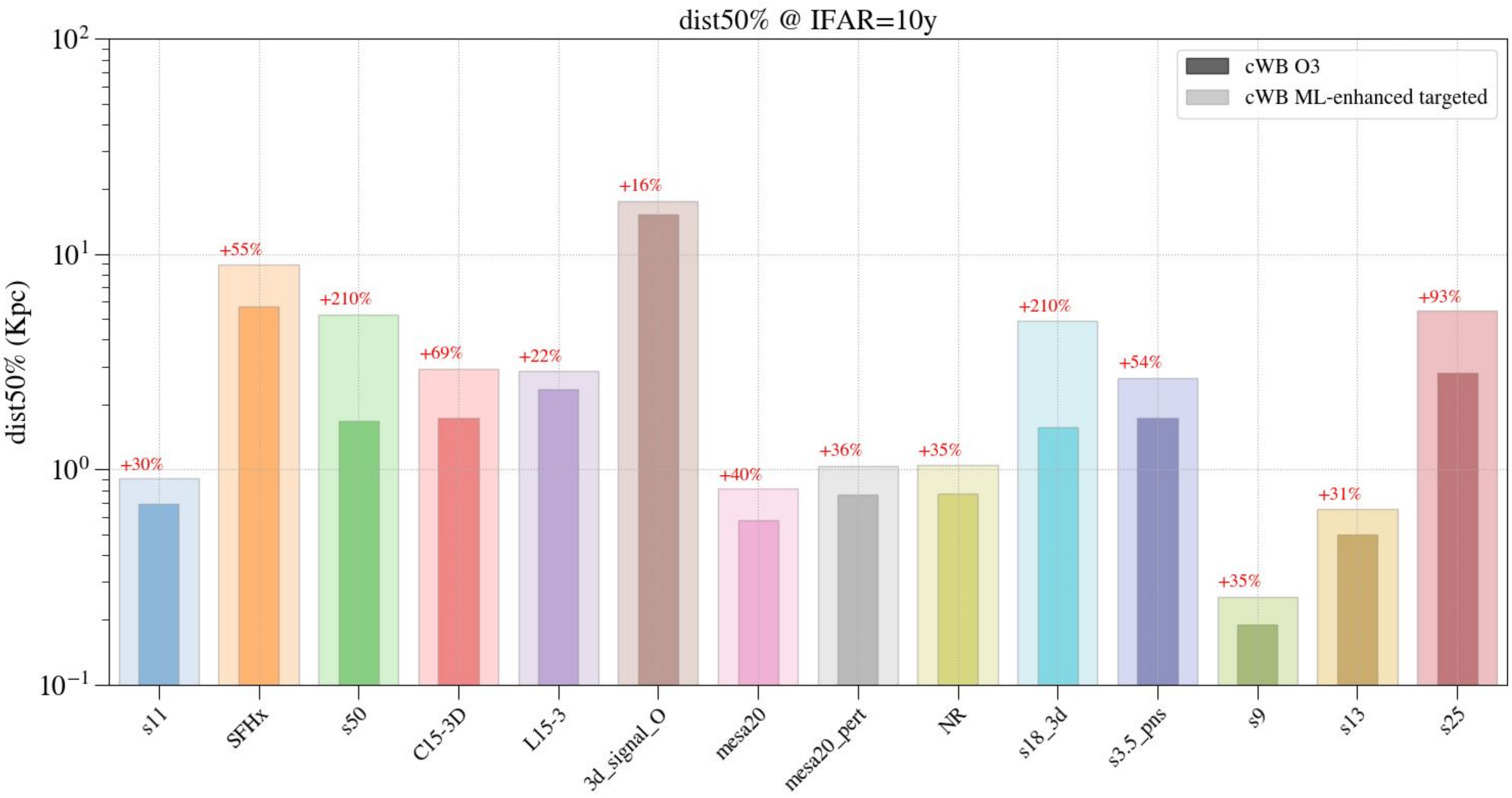
Results on SN2019ejj - dist50%: cWB ML-enhanced

The dist50% achieved with cWB with standard post-production veto procedure (darker colors) and with ML-enhanced cWB (lighter colors) at iFAR≥ 10 years.



Results on SN2019ejj - dist50%: cWB ML-targeted

The dist50% achieved with cWB with standard post-production veto procedure (darker colors) and with ML-enhanced cWB + directional constraint (lighter colors) at iFAR≥ 10 years.



GW transient searches: templated vs burst

- Matched-filter searches
  - Templates are anticipated GR waveforms as a function of (limited) source parameters.
  - searches for Compact Binary Coalescence (CBC) waveforms find template that fits data best
  - confident detection & parameter estimation (PE)
  - need exact source model, may fail, if theory does not match Nature
- Burst searches
  - do not assume accurate source models – **affected by noise**
  - limited PE: waveforms, sky, polarizations
  - can detect the unexpected
  - ...or some collection of detectors glitches