Multi-messenger observations of core-collapse supernovae: Exploiting the standing accretion shock instability

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Outline

SASI with ν and GW

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Motivation

- GW era has begun since 2015
  - First GW detection
  - And many others!
- Supernova explosions are not perfectly modeled in GW like other sources
  - Compact Binary Coalescences where matched filter is the main algorithm
  - Need to search for less stringent pipelines
    (excess power, machine learning)
  - Less sensitive and wide-open to detector noise
- Multi-messenger could be the key?
  - Usually, triggered searches in time and source direction (optical, neutrino)
  - <u>Could we use more information from other messengers?</u>

Abstract

The gravitational wave (GW) and neutrino signals from core-collapse supernovae (CCSNe) are expected to carry pronounced imprints of the standing accretion shock instability (SASI). We investigate whether the correlation between the SASI signatures in the GW and neutrino signals could be exploited to enhance the detection efficiency of GWs. We rely on a benchmark full-scale three-dimensional CCSN simulation with zero-age main sequence mass of 27 $M_\odot$. Two search strategies are explored: 1. the inference of the SASI frequency range and/or time window from the neutrino event rate detectable at the IceCube Neutrino Observatory; 2. the use of the neutrino event rate to build a matched filter template. We find that incorporating information from the SASI modulations of the IceCube neutrino event rate can increase the detection efficiency compared to standard GW excess energy searches up to 30% for nearby CCSNe. However, we do not find significant improvements in the overall GW detection efficiency for CCSNe more distant than 1.5 kpc. We demonstrate that the matched filter approach performs better than the unmodeled search method, which relies on a frequency bandpass inferred from the neutrino signal. The improved detection efficiency provided by our matched filter method calls for additional work to outline the best strategy for the first GW detection from CCSNe.

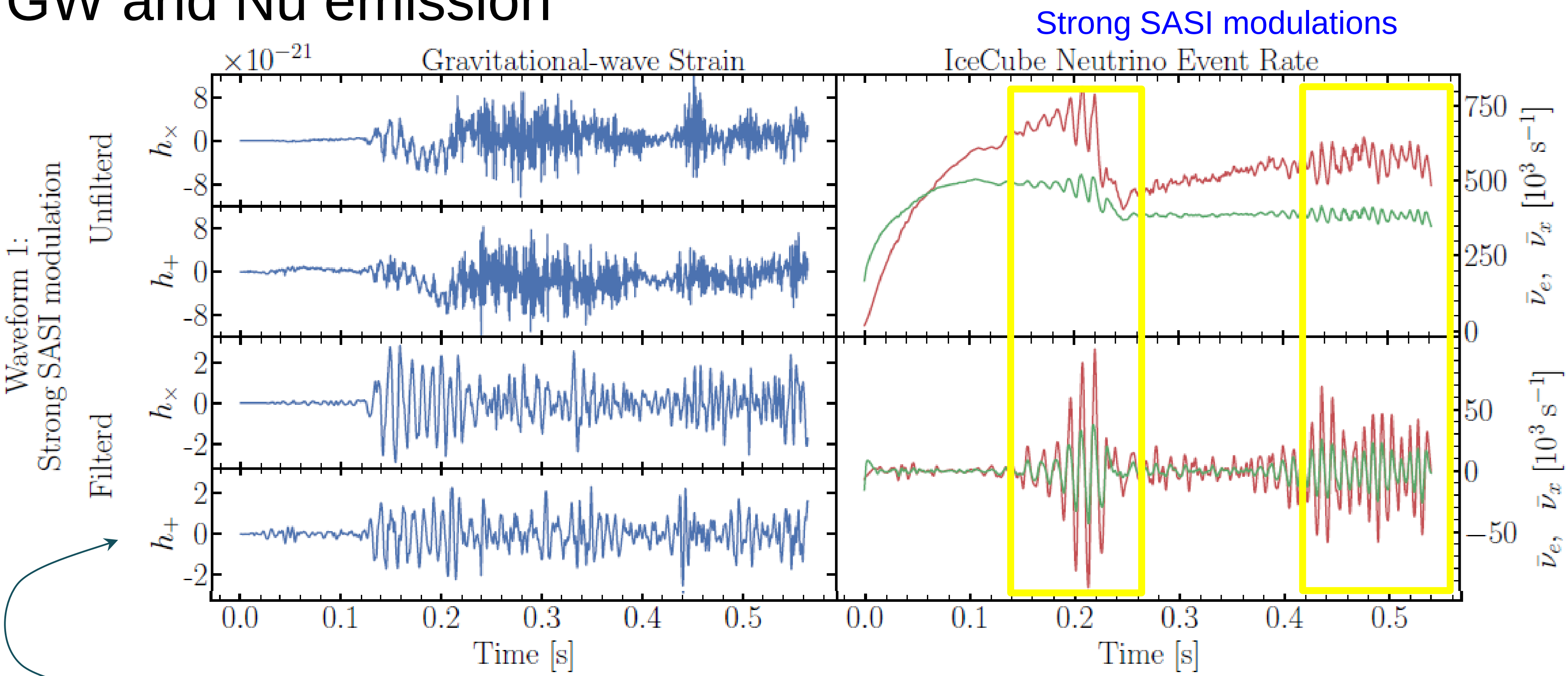
Benchmark SuperNova

SN model is S27 from Astrophys. J. 770, 66 (2013) *

- Progenitor: non-rotating star of solar metallicity with zero-age main sequence mass of 27 M
- simulated until 550 ms post bounce and it exhibits two periods of strong SASI
  - 120-260 ms after bounce
  - 410s after bounce - end of simulation
- SASI components in frequency domain
  - GW: 75 and 250 Hz,
  - Nu: 50 and 120 Hz, peaking around85 Hz
- ν SASI modulations present for all flavors
  - smaller amplitude for the non-electron flavor

* F. Hanke et al, SASI Activity in Three-Dimensional Neutrino-Hydrodynamics Simulations of Supernova Cores, arXiv:1303.6269

GW and Nu emission



Band pass filter of 50-300 Hz

3 cases explored changing observer directionality strong, intermediate and weak SASI modulations

Search methods

Main idea: use SASI ν information to feed GW analysis. Informations:

- time
- time and frequency

Two analyses performed:

- Matched filter
- Excess Power (i.e. cWB)
  - Standard cWB with HL configuration: EP (*)
  - cWB with band-pass filter: EP(f)

*(*) Configuration used in Phys. Rev. D **101**, 084002 (2020)*

Matched filter method

Focus on SASI component in ν detection to build a template for GW

1. Time
2. Time & Frequency

Method	Time [ms]	Frequency [Hz]
$MF(t_1)$	$[120, 260]$	NA
$MF(t_2)$	$[410, 550]$	NA
$MF(t_{1,2})$	$[120, 260]$–$[410, 550]$	NA
$MF(t_1, f)$	$[120, 260]$	$[50, 300]$
$MF(t_2, f)$	$[410, 550]$	$[50, 300]$
$MF(t_{1,2}, f)$	$[120, 260]$–$[410, 550]$	$[50, 300]$

Caveat:

- eventually match only part of GW signal
- different observer directions give different SASI modulations

Advantages:

- Time and Frequency of ν for SASI are very well determined

Flowchart

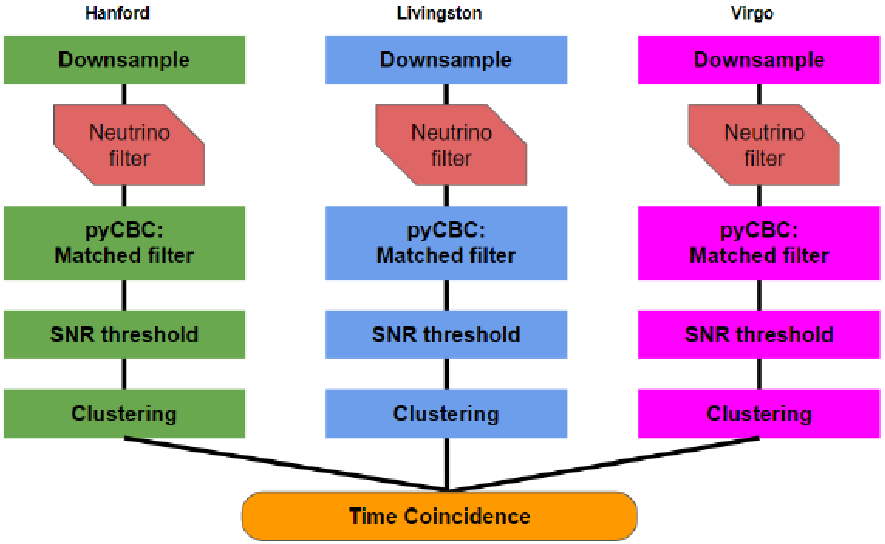


FIG. 2. Flowchart of the novel matched filter pipeline proposed in this paper to search for GWs by relying on the SASI signatures detectable in the neutrino signal.

- Downsampling of the original data to sample rate of 4kHz.
- Applying the pyCBC function filter.matched_filter
- Selecting SNR>SNR_{th}
- Collect consecutive samples if time differs less than Δt_c
- Apply Δt_n coincidence between detectors

Sample rate [Hz]	$SNR_{\rm thr}$	Δt_c [ms]	Δt_n [ms]
4096	3.5	250	300

Results, benchmark distance: 0.5 kpc, FAR=1/1y

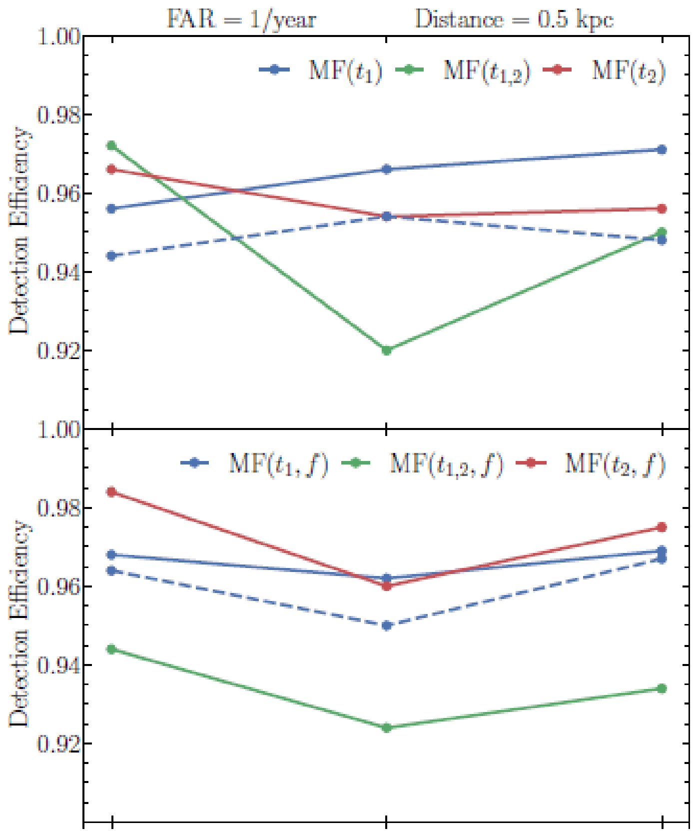
No real GW data used. Considering simulated white noise based on O5 spectral sensitivity (*)

Efficiency: compatible among 5% difference

Using two SASI periods not performing better

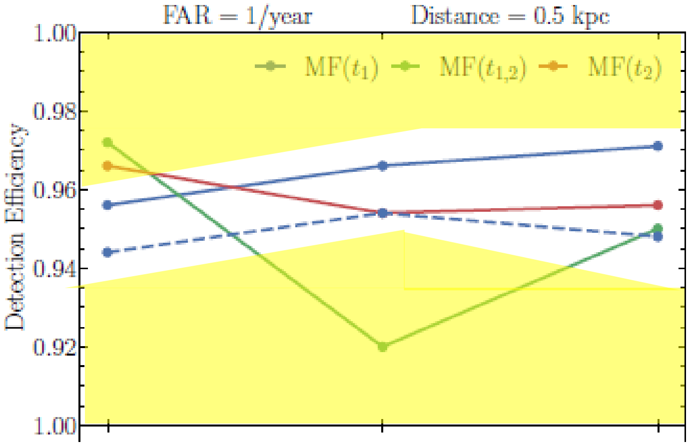
- they do not align
- optimal direction for first SASI is not optimal for second SASI

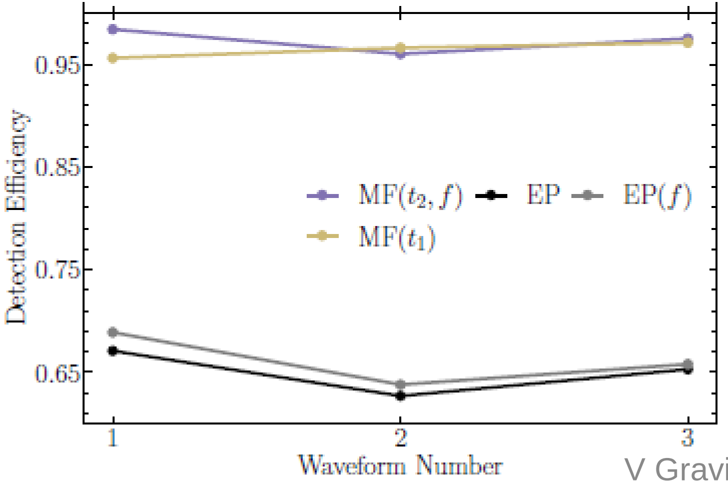
(*) *Living Rev Relativ 23, 3 (2020)*



Results, benchmark distance: 0.5 kpc, FAR=1/1y

- Consider two extreme cases for the neutrino signal
  - absence of flavor conversion (straight line)
  - full flavor conversion (dashed line)
- Effect of full flavor conversion is negligible

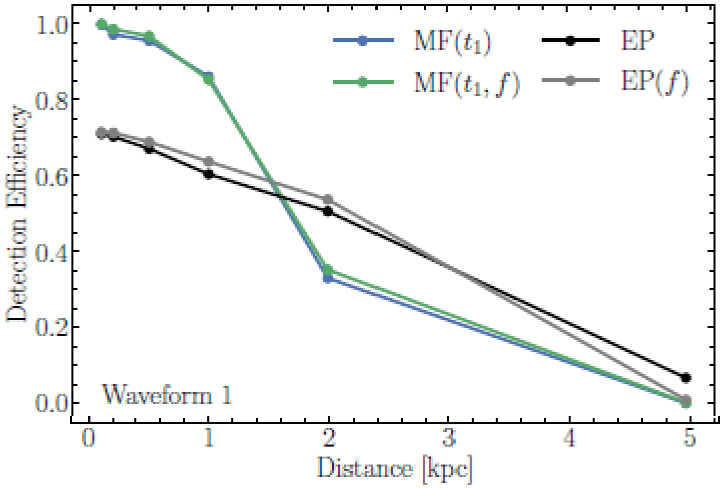


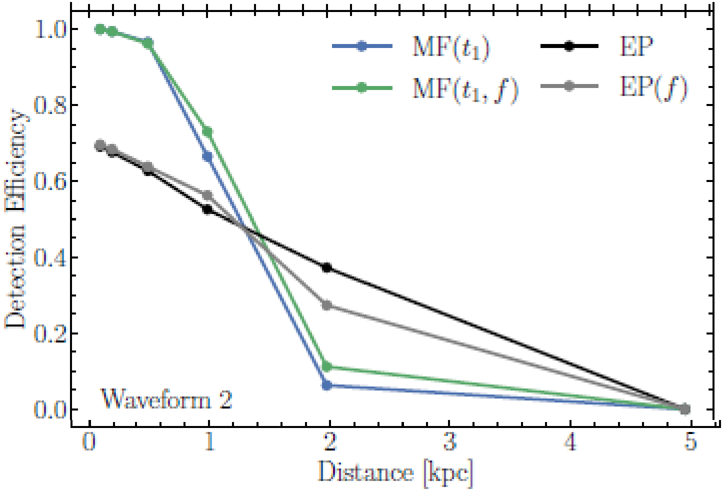


General increase wrt standad excess power (EP), even applying a band-pass (EP(f))

Detection Horizon

At low distance (<1.5 kpc) the matched-filter have better efficiency, but soon we arrive at high distance, EP performs better





Summary

- Matched filter between ν-SASI and GW can increase the detection efficiency, compared to standard EP, by up to 30% for nearby galactic events (closer than 1.5 kpc).
  At distances above 1.5 kpc decrease in the overall detection efficiency

- Combining two distinct SASI episodes is in general a bad strategy and leads to a degradation of the detection efficiency.
  Associated GW signal modulation is not as strong for both periods for any given observer -> decrease of the SNR

- Incorporating ν–frequency band into the EP does not significantly improve the detection sensitivity.
  Reduces the FAR, but decreases the SNR of the GW signal: balance effect

Final remarks and future work

Multimessenger techniques could improved detection horizon. Literature has many examples with many approaches

- Not easy to compare different methods

We investigate the use of SASI signature to specialize GW analysis

- We use a specific CCSN model, should explore more models
  - Expected to improve for models where SASI is more dominant
- Should consider more advanced methods to build the filter templates

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