Memory-triggered supernova neutrino detection

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We demonstrate that observations of the gravitational memory from core collapse supernovae at future deci-Hz interferometers enable time-triggered searches of supernova neutrinos at Mt-scale detectors. Achieving a sensitivity to characteristic strains of at least $\sim 10^{-25}$ at $f \simeq 0.3$ Hz—e.g., by improving the noise of DECIGO by one order of magnitude—will allow robust time triggers for supernovae at distances $D \sim 40$–300 Mpc, resulting in a nearly background-free sample of ~ 3–70 neutrino events per Mt per decade of operation. This sample would bridge the sensitivity gap between rare galactic supernova bursts and the cosmological diffuse supernova neutrino background, allowing detailed studies of the neutrino emission of supernovae in the local Universe.

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I. INTRODUCTION

Neutrinos are major players in the emerging field of multimessenger astronomy. With gravitational waves (GWs) and photons, they have the potential to probe the most extreme astrophysical phenomena in unprecedented detail. Core collapse supernovae (CCSNe) are prime targets of multimessenger observations, where neutrinos dominate the energy output and carry direct information on the extremely dense environment surrounding the collapsed core. The ~ 10 s burst of neutrinos from a supernova will also allow tests of particle physics beyond the Standard Model [1–4].

The detection of an individual supernova neutrino burst is exciting as well as challenging. A statistically significant observation is possible only for supernovae within 1–3 Mpc from Earth [5,6], where collapses are rare, resulting in decades of waiting time. An alternative is to search for the diffuse supernova neutrino background (DSNB), from all the supernovae in the universe [7–10], which has a substantial cosmological component. $\mathcal{O}(10-100)$ DSNB neutrinos could be detected in a decade (see, e.g., [11]), and preliminary data could be available in just a few years [12–17].

Burst and DSNB searches lack sensitivity to the local universe, $r \sim 3$–100 Mpc, where many supernova-rich galaxies are situated. Ideas to overcome this gap typically rely on time-triggers that would allow to identify a single neutrino as signal instead of background. One could use either a neutrino self-trigger—where 2–3 neutrinos observed less than 10 s apart can be attributed to a supernova with high confidence [5,18]—or the time coincidence with the $O(10^2)$ Hz supernova GW signal from interferometers like LIGO-Virgo and its successors [19–21]. Both methods are still limited to a few Mpc distance, except for the most optimistic GW models (see, e.g., [22] and references therein) and futuristic multi-Megaton neutrino detectors [6].[1]

In this paper, we propose a new time-triggered method to detect supernova neutrinos, which is potentially sensitive to supernovae up to ~ 100 Mpc. The time trigger is the observation of the gravitational memory signal caused by the neutrino emission itself. The memory is a non-oscillatory, permanent distortion of the local space time due to the anisotropic emission of matter or energy by a distant source. The memory due to neutrino emission by a supernova at distance r has characteristic strain $h_c \sim 10^{-23}$–$10^{-21}(10\ \mathrm{kpc/r})$ and frequencies in the deci-Hz band, $f \sim 0.1$–3 Hz [23–29]. The memory develops ~ 0.1 s from the start of the neutrino emission, thus being

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[1] Astronomical observations of supernovae cannot serve as time triggers, due to the $\mathcal{O}(1)$ hour uncertainty in the time delay between the neutrino and the electromagnetic signal from the same star.

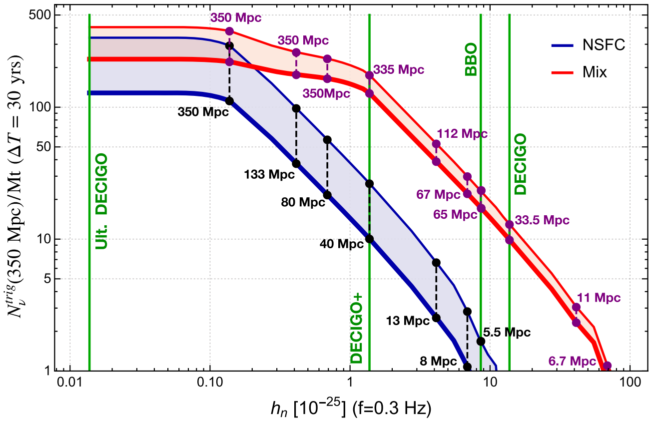

FIG. 1. The number of memory-triggered supernova neutrinos detected at a 1 Mt water Cherenkov detector in 30 years, as a function of the noise of the GW detector at $f = 0.3$ Hz. The vertical lines mark specific experiments considered here. The lower and upper shaded regions refer respectively to a homogeneous population with moderate memory strain and a mixed population where 40% of collapses have stronger memory strain; the shading describes the effect of varying the neutrino spectrum, see Table I. The dots (upper set: NSFC and lower set: BHFC) and legends on the curves give the GW distance of sensitivity [$r_{\mathrm{max}}^{\mathrm{GW}}$, see text below Eq. (2)] corresponding to the noise on their abscissa.

an ideal time-trigger. Next generation powerful deci-Hz GW detectors, like the deci-hertz Interferometer Gravitational wave Observatory (DECIGO) [30–33] and the Big Bang Observer (BBO) [31] will provide robust triggers for supernovae at 10 Mpc and beyond [34]. These would result in a nearly pure sample of ~10–100 supernova neutrino events from the local universe within a few decades; see our summary figure, Fig. 1. Here we illustrate our proposed methodology and its physics potential.

II. FORMALISM

A. Gravitational memory signals

The supernova neutrino memory strain can be expressed as [24,35,36]

$$h_{TT}^{xx} = h(r,t) = \frac{2G}{rc^4}\int_{-\infty}^{t-r/c} dt' L_\nu(t')\alpha(t'). \tag{1}$$

where c is the speed of light, t is the time postbounce and G is the universal gravitational constant. L_ν is the all-flavors neutrino luminosity and $\alpha \sim \mathcal{O}(10^{-3}\text{–}10^{-2})$ is the time-varying anisotropy parameter [25,28].[2] Simulations show

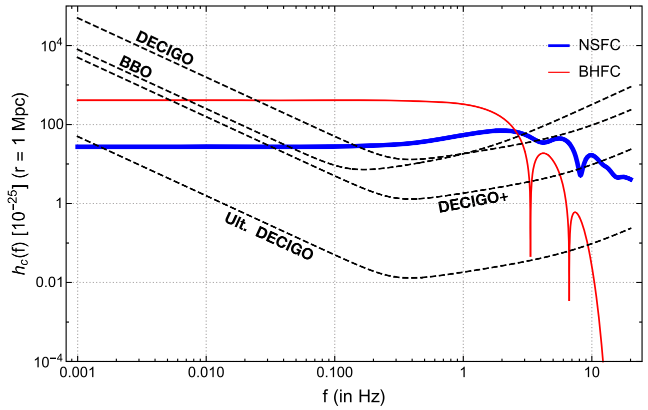

FIG. 2. Solid: the characteristic gravitational memory strain $h_c(f)$ for the NSFC and BHFC models (thin and thick lines, respectively). The distance to the supernova is $r = 1$ Mpc. Dashed: sky-averaged noise curves for representative detectors (see Fig. 1).

that $\alpha(t)$ becomes nonzero within a few ms postcollapse, during the accretion phase, and can change sign multiple times within the first second, as a result of the dynamics of the matter near the collapsed core. The behavior of $\alpha(t)$ at $t > 1$ s, during the cooling phase, is unknown. Following [34], we consider two phenomenological models for the memory: the first, characterized by a weaker and shorter anisotropic phase, is representative of a neutron-star-forming collapse (NSFC); the second has larger and prolonged anisotropy, and could represent a black-hole-forming collapse (BHFC). In both models, $\alpha = 0$ for $t > 1$ s. Maximum values of $rh(r,t) \sim 26.5$ cm and $rh(r,t) \sim 400$ cm are obtained for the two models respectively. In Fig. 2, we show the memory characteristic strain [27], $h_c(r,f) = 2f|\tilde{h}(r,f)|$, where $\tilde{h}(r,f)$ is the Fourier transform of $h(r,t)$. Also shown are the noise curves of deci-Hz detectors, which are given by the quantity $h_n(f) = \Upsilon\sqrt{5fS_n(f)}$ [27], where $S_n(f)$ is the power spectral noise density [37]. We choose $\Upsilon = 1, 10^{-1}, 10^{-3}$; the first and last correspond to DECIGO and its optimal (futuristic) realization, Ultimate DECIGO [30–32]; the middle value represents an hypothetical intermediate case (DECIGO+ from here on).

The detectability of a memory signal is determined by the signal-to-noise (SNR) ratio of the detector,[3] which is defined as [38]

$$\rho^2(r) = \int_{-\infty}^{\infty} d(\log f)\left(\frac{h_c(r,f)}{h_n(f)}\right)^2. \tag{2}$$

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[2] In axisymmetric simulations [24,25], only the + strain may be extracted, and the observer is positioned such that the + strain is maximized.

[3] Here the comparison with published SNR curves has indicative character only; a signal-specific study of the detectability is ultimately needed, and is left for future work.

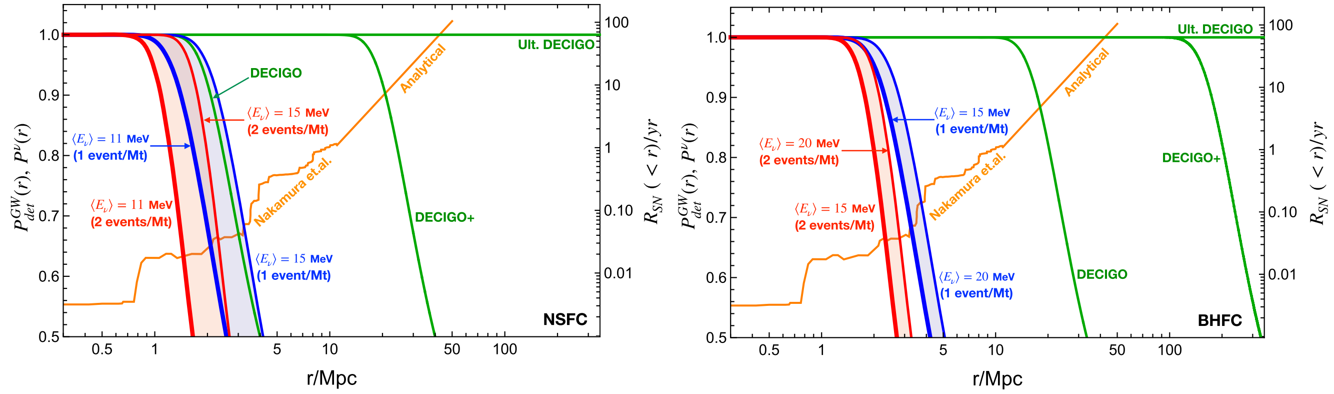

FIG. 3. Detection probabilities for a memory signal, $P_{\rm det}^{\rm GW}(r)$, at three GW detectors of reference, and neutrino detection probabilities, $P^\nu(1,r)$ and $P^\nu(2,r)$ [see Eq. (4)]. Shadings describe the variations with the varying neutrino spectrum, see Table I. The left (right) panel is for NSFC (BHFC). Also shown is the cumulative rate of core collapses (vertical axis on the right). See labels on the curves for details.

We compute the probability of detecting a CCSN memory, $P_{\rm det}^{\rm GW}$, for a fixed false alarm probability $P_{\rm FA}^{\rm GW} = 0.1$. This requires producing receiver operating curves (ROCs) in the plane $P_{\rm det}^{\rm GW} - P_{\rm FA}^{\rm GW}$, which we do following the formalism in [39] for $N = 3$ degrees of freedom (here N is set equal to the number of Gaussian functions used to represent $\alpha(t)$, see [34]).[4] The result is that $P_{\rm det}^{\rm GW}$, at a fixed $P_{\rm FA}^{\rm GW}$, is an increasing function of $\rho(r)$, through which it depends on the distance, r. We define the GW detector distance of sensitivity, $r_{\rm max}^{\rm GW}$ such that $P_{\rm det}^{\rm GW}(r_{\rm max}^{\rm GW}) = 0.5$. $P_{\rm det}^{\rm GW}(r)$ is shown in Fig. 3 for our cases of reference. For DECIGO, and for NSFC and BHFC, respectively, we have $r_{\rm max}^{\rm GW} \simeq 4$ Mpc and $r_{\rm max}^{\rm GW} \simeq 33$ Mpc. We find $r_{\rm max}^{\rm GW} \simeq 40$ Mpc and $r_{\rm max}^{\rm GW} \simeq 335$ Mpc for DECIGO+; for Ultimate DECIGO, $r_{\rm max}^{\rm GW} > 350$ Mpc for both population models.

We note in passing that, in principle, the stochastic effect of the memory signals from cosmological supernovae contributes to the noise in a GW detector, and therefore to $r_{\rm max}^{\rm GW}$. For real-time searches of transient signals at a modern interferometer like LIGO, the noise spectral density is measured over sliding time windows of $\mathcal{O}(10^2)$ s width, leading to a fast identification of seconds-long transients [40]. Due to the high supernova rate ($\dot\rho_{\rm SN} \sim 10^{-4}\ {\rm yr}^{-1}\ {\rm Mpc}^{-3}$ locally, corresponding to $\sim 10^7$ core collapses per year in the visible universe) [41–43], the individual cosmological memory signals combine to constitute a continuum, that is best described by an integral over the cosmic volume. Such integral represents the contribution of supernovae to the fraction of cosmic energy density in GW, $\Omega_{\rm GW}$ (see, e.g., [44–47] for the formalism).

Following Ref. [45], we have estimated the supernova memory contribution to $\Omega_{\rm GW}$, and found that it affects the probability curves in Fig. 3 solely for Ultimate DECIGO, and only for $r \gtrsim 300$ Mpc and for the most optimistic memory model (BHFC curve in Fig. 2, corresponding to a GW spectral energy density $\Omega_{\rm GW} = \mathcal{O}(10^{-17})$). As will be seen in the next section, the triggered neutrino search is limited to $r \lesssim 300$ Mpc by the background at the neutrino detector. Therefore, the stochastic GW noise from supernovae is negligible in the present context, and will not be considered further.

B. Neutrino signals

For neutrino detection, we consider a water Cherenkov experiment, where the main channel of sensitivity is inverse beta decay (IBD), $\bar\nu_e + p \to n + e^+$. For the time-integrated (over $\Delta t = 10$ s) $\bar\nu_e$ flux at Earth, $\Phi(r, E_\nu)$ we use analytical quasi-thermal spectra of the form given in [48]. The average $\bar\nu_e$ energy is varied in an interval motivated by numerical simulations [49–51], in a way to effectively account for neutrino oscillations. The spectrum shape parameter, β, and the total energy in $\bar\nu_e$ are fixed. See Table I for details.

TABLE I. The neutrino flux parameters, from numerical simulations [49–51]. The Ac. ph. and $\bar\nu_e$ columns refer to the all flavor energy in the accretion phase only (which contributes to the memory signal, see text) and to the energy in $\bar\nu_e$ emitted over the time-triggered interval of 10 s. β is related to the second momentum of the spectrum: $\beta = (2\langle E_\nu\rangle^2 - \langle E_\nu^2\rangle)/(\langle E_\nu^2\rangle - \langle E_\nu\rangle^2)$.

	Energy ($\times 10^{53}$ ergs)			$\langle E_\nu\rangle$ (in MeV)	
Model	Ac. ph.	$\bar\nu_e$	β	Lower	Upper
NSFC	1.2	0.5	3	11	15
BHFC	2	0.45	2	15	20

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[4] In Ref. [39], the formalism of $P_{\rm det}$ and $P_{\rm FA}$ are presented in the context of matched filter analysis. In the search for gravitational memory signals, we applied a filter studied in [34], which reasonably reproduce the results from numerical simulations.

The predicted number of events in the detector from a CCSN at distance r is

$$N(r) = \int_{E_\nu^{\rm th}}^{E_\nu^{\rm max}} N_p \eta \sigma(E_\nu) \Phi(r, E_\nu) dE_\nu, \tag{3}$$

where N_p is the number of target protons, $\eta = 0.9$ is the detection efficiency [52–54] and $\sigma(E_\nu)$ is the IBD cross section [55]. We take an energy interval $[E_\nu^{\rm th}, E_\nu^{\rm max}] = [19.3, 50]$ MeV to avoid the spallation background at low energy and the atmospheric neutrino background at high energy [15,53,56]. We find $N(1\ {\rm Mpc}) \simeq 5$–12 and $N(1\ {\rm Mpc}) \simeq 12$–$18$ for NSFC and BHFC respectively, by varying the mean $\bar{\nu}_e$ energy in the intervals given in Table I.

The Poisson probability of observing $N \geq N_{\rm min}$ neutrino events in a detector is

$$P^\nu(N_{\rm min}, r) = \sum_{n=N_{\rm min}}^{\infty} \frac{N^n(r)}{n!} e^{-N(r)}. \tag{4}$$

It is plotted for $N_{\rm min} = 1, 2$ in Fig. 3 for the two models of reference. As expected, $P^\nu(N_{\rm min}, r)$ declines rapidly at $r \gtrsim 3$ Mpc.

III. MEMORY-TRIGGERED NEUTRINO OBSERVATIONS

A. Event rates

To estimate the rate of memory-triggered neutrino events, we model the rate of core collapses as a function of r. For $r \lesssim 11$ Mpc, we use the rates for individual galaxies from [57]. For $r > 11$ Mpc we assume a constant volumetric rate of $R_{\rm SN} = 1.510^{-4}\ {\rm Mpc}^{-3}\ {\rm yr}^{-1}$ (the evolution with redshift is negligible for the distances of interest here). The cumulative rate (total rate of core collapses with $r < D$) is shown in Fig. 3.

The number of memory-triggered neutrino events from all supernovae within a distance D, over a detector running time ΔT can be calculated as a sum over all the galaxies (index $j = 1, 2, \ldots$), at distance $r_j < D$:

$$N_\nu^{\rm trig}(D) = \Delta T \sum_{j, r_j < D} R_j N(r_j) P_{\rm det}^{\rm GW}(r_j), \tag{5}$$

where R_j indicates the supernova rate in the galaxy j. This discrete expression is replaced by a continuum one, involving an integral, for $D > 11$ Mpc, where the cosmological supernova rate is used.

We now discuss the background of the time-triggered neutrino search. The number of supernova memory signals observed in the time ΔT is, $N_{\rm SN}^{\rm trig}(D) = \Delta T \sum_{j, r_j < D} R_j P_{\rm det}^{\rm GW}(r_j)$, and the number of expected background events is $N_{\rm bckg}^{\rm trig}(D) = N_{\rm SN}^{\rm trig}(D) \lambda \Delta t$, where $\lambda \simeq 1313$ events/year is the background rate in the detector [15,53,56]. Note that the background level is reduced by a factor $\epsilon_{\rm bckg=} N_{\rm SN}^{\rm trig}(D) \Delta t / \Delta T$ compared to an untriggered search.[5]

We limit our study to neutrino events [Eq. (5)] from CCSNe in the cosmic volume with $4 < D < 350$ Mpc, thus accounting for the fact that a nearby supernova ($D < 4$ Mpc) is unlikely to occur in three decades time. The upper bound on D is justified because beyond it the total event rate becomes dominated by background. Experimentally, a distance cut can be accomplished in different ways. For NSFC, one can make a selection using estimates of D from astronomy follow ups, which will benefit from the alerts from the memory detection and should have excellent sensitivity to supernovae in the local universe (see, e.g., [59–63] for dedicated projects). In the absence of an optical counterpart (BHFC), a similar (although less efficient) data selection can be performed using minimal input from theoretical models, e.g., to obtain conservative upper limits on the distances of individual observed BHFCs via GW memory signals. In the mature stage of this search, specifically designed data-analysis algorithms—exploiting the correlation of multiple observables—could reduce the level of model-dependency to a minimum.

B. Results

Our main results are in Figs. 4 and 1 for $\Delta T = 30$ yrs and for two scenarios: (i) a supernova population entirely comprised of NSFC; and (ii) a mixed population with 60% NSFC and 40% BHFC. Figure 4 shows $N_\nu^{\rm trig}(D)$ as a function of D. We observe the (expected) trend $N_\nu^{\rm trig}(D) \propto D$ for $D \lesssim r_{\rm max}^{\rm GW}$,[6] with a flattening of the curves at larger D due to the loss of sensitivity of the GW detector. For case (i), time triggers from DECIGO+ will result in $N_\nu^{\rm trig} \sim 10$–30. For Ult. DECIGO, $N_\nu^{\rm trig} \sim 100$–$300$ is expected.[7] For the mixed population [case (ii)], results for Ult. DECIGO change only minimally, due to the different neutrino parameters between NSFC and BHFC. Instead, $N_\nu^{\rm trig}$ increases dramatically, surpassing 100, for DECIGO+, due to the larger distance of sensitivity to BHFC. Indeed, the number of triggered neutrino events from collapses with $30 < D < 350$ Mpc is dominated by BHFC (see also Fig. 3). For this mixed population scenario, even DECIGO could be effective, providing a few triggers of BHFC up to $D \sim 30$ Mpc, resulting in $N_\nu^{\rm trig} \sim 10$. As Fig. 4 shows, in all cases the signal exceeds the background for triggers with $r \lesssim 100$ Mpc. For Ultimate DECIGO,

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[5] The time delay effect due to the nonzero neutrino mass can be neglected; it is estimated to be only a fraction of a second for energies and distances of interest here, see, e.g., [58].

[6] Recall that, in the continuum limit, the number of supernovae scales like D^3 and the flux dilution factor like D^{-2}.

[7] For comparison, our estimated number of CCSNe within 350 Mpc is $N_{\rm SN}^{\rm trig} \sim 1.21 \times 10^6$.

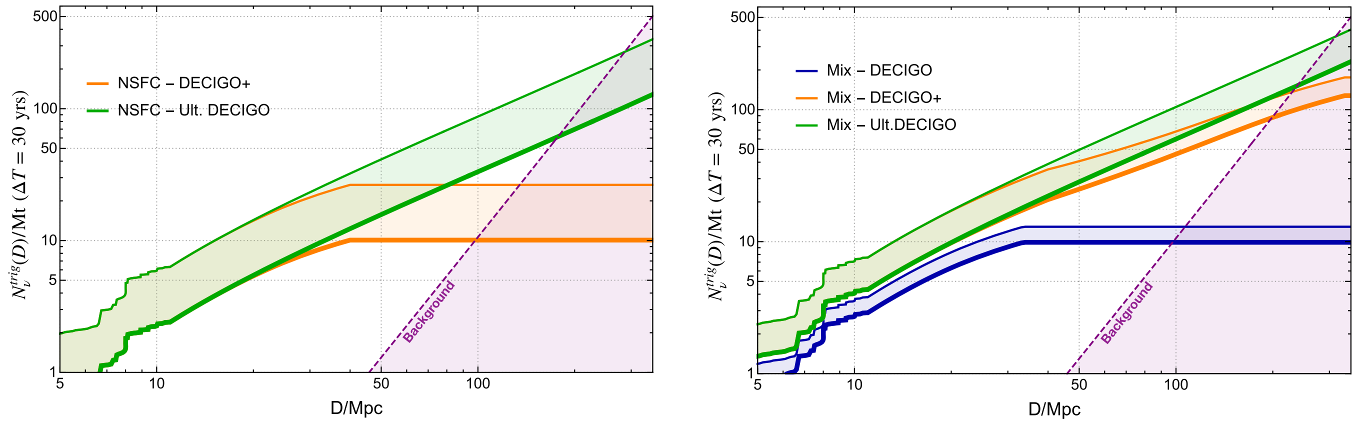

FIG. 4. Number of background events and of memory-triggered neutrino events from collapses at distance $r < D$, as a function of D, for a Mt water Cherenkov detector and 30 years running time. The upper to lower shaded regions are for triggers from Ultimate DECIGO, DECIGO+ and DECIGO (the latter is invisible in the left panel). Shadings describe the effect of varying the neutrino spectrum, see Table I. Left panel: homogeneous NSFC population. Right: mix of 60% NSFC and 40% BHFC.

even for the largest D the signal is comparable to the background, and would cause a statistically significant excess.

Our summary figure, Fig. 1, shows $N_\nu^{\rm trig}(350\ {\rm Mpc})$, as a function of h_n, together with representative values of $r^{\rm GW}_{\rm max}$. Roughly, we find $N_\nu^{\rm trig} \propto 1/h_n$, for $h_n \gtrsim 10^{-26}$, with a flattening at lower values of h_n, due to upper cutoff on D. It appears that, even for the most conservative parameters, a $\mathcal{O}(10)$ noise abatement with respect to DECIGO (i.e., DECIGO+) is sufficient to obtain a signal at a Mt scale detector in ∼20–30 years.

IV. CONCLUSIONS AND DISCUSSION

Summarizing, we have described a new multimessenger approach to core collapse supernovae, where a time-triggered search of supernova neutrinos is enabled by observing the gravitational memory caused by the neutrinos themselves. This scenario could be realized a few decades from now, when powerful deci-Hz interferometers (noise $h_n \lesssim 10^{-25}$) and Mt-scale neutrino detectors start operating. For optimistic parameters, DECIGO and HyperKamiokande (mass $M = 0.260$ Mt) might already achieve a low statistics observation. This approach will also enable joint analyses of neutrino, GW, and light curves of CCSNe in local universe.

Our proposed method will deliver a sample of neutrino events from supernovae in the *local* universe, from which the main neutrino properties—i.e., the (population-averaged) energy spectra and time profiles—will be measured. These can then be compared to the same quantities from (1) SN 1987A, to measure the deviation between SN1987A and an average local supernova (the same exercise can be done for a future nearby supernova burst, if it occurs); (2) the DSNB, to distinguish the contributions to the DSNB by CCSNe in the distant universe and by other transients (e.g., binary mergers). The comparison between cosmological and local contributions to the DSNB will test hypotheses of how the supernova progenitor population evolves with the distance. Even within the local-neutrino sample, one could test the evolution with distance, if the latter is estimated for each supernova using multimessenger observations (e.g., the amplitude of the memory signal and astronomical imaging).

Correlating memory and neutrino data might reveal two distinct populations, like those described here (NSFC and BHFC), which could be statistically separated. For example, events having a relatively large neutrino-memory time separation (bigger than 1 s, as black hole formation typically occur within 1 s, cutting off the neutrino luminosity [64–66]) and(or) followed by electromagnetic (EM) signals of a CCSN could be attributed to NSFC. The possibility to study such subpopulation individually is unique of this local-collapses neutrino sample. Additionally, our method provides a unique chance to jointly analyze neutrino and follow-up EM signals [59,67] from the *same* NSFC. Although only ≈1 event would be detected from a specific NSFC, it can help to determine the time when the core of a NSFC collapses and the shock is formed. Such estimation would be relatively precise, considering that the neutrino burst from a NSFC only lasts for ≈10 s. A supernova EM signal is delayed relative to the neutrinos, by at least the time it takes the shock to propagate through the envelope, typically hours. Measuring this time delay will provide a crucial confirmation and can test the variation of the CCSNe explosion mechanism.

To conclude, we have demonstrated that the interplay between neutrino detectors and sub-Hz GW observatories will open a new path to studying supernova neutrinos. Although several decades may pass before the first results become available, the work of designing the next generation of experiments is well under way, and we hope that our work will contribute to its progress.

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[1] G. Raffelt and D. Seckel, Bounds on Exotic Particle Interactions from SN 1987a, Phys. Rev. Lett. **60**, 1793 (1988).

[2] M. S. Turner, Axions from SN 1987a, Phys. Rev. Lett. **60**, 1797 (1988).

[3] R. Mayle, J. R. Wilson, J. R. Ellis, K. A. Olive, D. N. Schramm, and G. Steigman, Constraints on axions from SN 1987a, Phys. Lett. B **203**, 188 (1988).

[4] J. H. Chang, R. Essig, and S. D. McDermott, Supernova 1987A constraints on sub-GeV dark sectors, millicharged particles, the QCD axion, and an axion-like particle, J. High Energy Phys. 09 (2018) 051.

[5] S. Ando, J. F. Beacom, and H. Yüksel, Detection of Neutrinos from Supernovae in Nearby Galaxies, Phys. Rev. Lett. **95**, 171101 (2005).

[6] M. D. Kistler, H. Yuksel, S. Ando, J. F. Beacom, and Y. Suzuki, Core-collapse astrophysics with a five-megaton neutrino detector, Phys. Rev. D **83**, 123008 (2011).

[7] G. S. Bisnovatyi-Kogan and Z. F. Seidov, Medium-energy neutrinos in the universe, SOVAST **26**, 132 (1982).

[8] L. M. Krauss, S. L. Glashow, and D. N. Schramm, Antineutrinos astronomy and geophysics, Nature (London) **310**, 191 (1984).

[9] J. F. Beacom, The diffuse supernova neutrino background, Annu. Rev. Nucl. Part. Sci. **60**, 439 (2010).

[10] C. Lunardini, Diffuse neutrino flux from supernovae, in *Handbook of Supernovae*, edited by A. W. Alsabti and P. Murdin (Springer International Publishing AG, 2017), p. 1637.

[11] A. De Gouvêa, I. Martinez-Soler, Y. F. Perez-Gonzalez, and M. Sen, Fundamental physics with the diffuse supernova background neutrinos, Phys. Rev. D **102**, 123012 (2020).

[12] J. F. Beacom and M. R. Vagins, GADZOOKS! Anti-Neutrino Spectroscopy with Large Water Cherenkov Detectors, Phys. Rev. Lett. **93**, 171101 (2004).

[13] H. Zhang *et al.* (Super-Kamiokande Collaboration), Supernova relic neutrino search with neutron tagging at Super-Kamiokande-IV, Astropart. Phys. **60**, 41 (2015).

[14] F. An *et al.* (JUNO Collaboration), Neutrino physics with JUNO, J. Phys. G **43**, 030401 (2016).

[15] K. Abe *et al.* (Hyper-Kamiokande Collaboration), Hyper-Kamiokande design report, arXiv:1805.04163.

[16] M. Askins *et al.* (Theia Collaboration), THEIA: An advanced optical neutrino detector, Eur. Phys. J. C **80**, 416 (2020).

[17] B. Abi, R. Acciarri, M. A. Acero, G. Adamov, D. Adams, M. Adinolfi, Z. Ahmad, J. Ahmed, T. Alion, S. A. Monsalve *et al.*, Deep underground neutrino experiment (dune), far detector technical design report, volume ii: Dune physics, arXiv:2002.03005.

[18] S. M. Adams, C. S. Kochanek, J. F. Beacom, M. R. Vagins, and K. Z. Stanek, Observing the next galactic supernova, Astrophys. J. **778**, 164 (2013).

[19] G. Pagliaroli, F. Vissani, E. Coccia, and W. Fulgione, Neutrinos from Supernovae as a Trigger for Gravitational Wave Search, Phys. Rev. Lett. **103**, 031102 (2009).

[20] B. P. Abbott *et al.* (LIGO Scientific, Virgo Collaborations), A first targeted search for gravitational-wave bursts from core-collapse supernovae in data of first-generation laser interferometer detectors, Phys. Rev. D **94**, 102001 (2016).

[21] K. Abe *et al.* (Super-Kamiokande Collaboration), Search for neutrinos in coincidence with gravitational wave events from the LIGO-Virgo O3a Observing Run with the Super-Kamiokande detector, Astrophys. J. **918**, 78 (2021).

[22] M. Szczepanczyk, J. Antelis, M. Benjamin, M. Cavaglia, D. Gondek-Rosinska, T. Hansen, S. Klimenko, M. Morales, C. Moreno, S. Mukherjee *et al.*, Detecting and reconstructing gravitational waves from the next galactic core-collapse supernova in the advanced detector era, Phys. Rev. D **104**, 102002 (2021).

[23] A. Burrows and J. Hayes, Pulsar Recoil and Gravitational Radiation Due to Asymmetrical Stellar Collapse and Explosion, Phys. Rev. Lett. **76**, 352 (1996).

[24] E. Mueller and H. T. Janka, Gravitational radiation from convective instabilities in Type II supernova explosions, AAP **317**, 140 (1997).

[25] K. Kotake, W. Iwakami, N. Ohnishi, and S. Yamada, Ray-tracing analysis of anisotropic neutrino radiation for estimating gravitational waves in core-collapse supernovae, Astrophys. J. **704**, 951 (2009).

[26] E. Muller, H. T. Janka, and A. Wongwathanarat, Parametrized 3D models of neutrino-driven supernova explosions: Neutrino emission asymmetries and gravitational-wave signals, Astron. Astrophys. **537**, A63 (2012).

[27] J.-T. Li, G. M. Fuller, and C. T. Kishimoto, Neutrino burst-generated gravitational radiation from collapsing supermassive stars, Phys. Rev. D **98**, 023002 (2018).

[28] D. Vartanyan and A. Burrows, Gravitational waves from neutrino emission asymmetries in core-collapse supernovae, Astrophys. J. **901**, 108 (2020).

[29] C. Richardson, M. Zanolin, H. Andresen, M. J. Szczepańczyk, K. Gill, and A. Wongwathanarat, Modeling core-collapse supernovae gravitational-wave memory in laser interferometric data, Phys. Rev. D **105**, 103008 (2022).

[30] N. Seto, S. Kawamura, and T. Nakamura, Possibility of Direct Measurement of the Acceleration of the Universe Using 0.1-Hz Band Laser Interferometer Gravitational Wave Antenna in Space, Phys. Rev. Lett. **87**, 221103 (2001).

[31] K. Yagi and N. Seto, Detector configuration of DECIGO/BBO and identification of cosmological neutron-star binaries, Phys. Rev. D **83**, 044011 (2011).

[32] S. Sato *et al.*, The status of DECIGO, J. Phys. Conf. Ser. **840**, 012010 (2017).

[33] S. Kawamura, M. Ando, N. Seto, and e. Sato, Shuichi, Current status of space gravitational wave antenna DECIGO and B-DECIGO, Prog. Theor. Exp. Phys. **2021**, 05A105 (2021).

[34] M. Mukhopadhyay, C. Cardona, and C. Lunardini, The neutrino gravitational memory from a core collapse supernova: Phenomenology and physics potential, J. Cosmol. Astropart. Phys. 07 (2021) 055.

[35] R. Epstein, The generation of gravitational radiation by escaping supernova neutrinos, Astrophys. J. **223**, 1037 (1978).

[36] M. S. Turner, Gravitational radiation from supernova neutrino bursts, Nature (London) **274**, 565 (1978).

[37] B. S. Sathyaprakash and B. F. Schutz, Physics, astrophysics and cosmology with gravitational waves, Living Rev. Relativity **12**, 2 (2009).

[38] C. J. Moore, R. H. Cole, and C. P. L. Berry, Gravitational-wave sensitivity curves, Classical Quantum Gravity **32**, 015014 (2015).

[39] P. Jaranowski and A. Krolak, Data analysis of gravitational wave signals from spinning neutron stars. 3. Detection statistics and computational requirements, Phys. Rev. D **61**, 062001 (2000).

[40] R. Abbott *et al.* (KAGRA, VIRGO, LIGO Scientific Collaborations), All-sky search for long-duration gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run, Phys. Rev. D **104**, 102001 (2021).

[41] P. Madau, M. Della Valle, and N. Panagia, On the evolution of the cosmic supernova rates, Mon. Not. R. Astron. Soc. **297**, L17 (1998).

[42] S. Ando and K. Sato, Relic neutrino background from cosmological supernovae, New J. Phys. **6**, 170 (2004).

[43] F. Daigne, K. A. Olive, E. Vangioni-Flam, J. Silk, and J. Audouze, Cosmic star formation, reionization, and constraints on global chemical evolution, Astrophys. J. **617**, 693 (2004).

[44] E. S. Phinney, A practical theorem on gravitational wave backgrounds, arXiv:astro-ph/0108028.

[45] A. Buonanno, G. Sigl, G. G. Raffelt, H.-T. Janka, and E. Muller, Stochastic gravitational wave background from cosmological supernovae, Phys. Rev. D **72**, 084001 (2005).

[46] K. Crocker, T. Prestegard, V. Mandic, T. Regimbau, K. Olive, and E. Vangioni, Systematic study of the stochastic gravitational-wave background due to stellar core collapse, Phys. Rev. D **95**, 063015 (2017).

[47] B. Finkel, H. Andresen, and V. Mandic, Stochastic gravitational-wave background from stellar core-collapse events, Phys. Rev. D **105**, 063022 (2022).

[48] M. T. Keil, G. G. Raffelt, and H.-T. Janka, Monte Carlo study of supernova neutrino spectra formation, Astrophys. J. **590**, 971 (2003).

[49] T. Sukhbold, T. Ertl, S. E. Woosley, J. M. Brown, and H. T. Janka, Core-collapse supernovae from 9 to 120 solar masses based on neutrino-powered explosions, Astrophys. J. **821**, 38 (2016).

[50] T. Ertl, H. T. Janka, S. E. Woosley, T. Sukhbold, and M. Ugliano, A two-parameter criterion for classifying the explodability of massive stars by the neutrino-driven mechanism, Astrophys. J. **818**, 124 (2016).

[51] D. Kresse, T. Ertl, and H.-T. Janka, Stellar collapse diversity and the diffuse supernova neutrino background, Astrophys. J. **909**, 169 (2021).

[52] K. S. Hirata *et al.*, Observation in the Kamiokande-ii detector of the neutrino burst from supernova sn1987a, Phys. Rev. D **38**, 448 (1988).

[53] K. Abe *et al.*, Letter of intent: The hyper-Kamiokande experiment—detector design and physics potential, arXiv:1109.3262.

[54] K. Kyutoku and K. Kashiyama, Detectability of thermal neutrinos from binary neutron-star mergers and implications for neutrino physics, Phys. Rev. D **97**, 103001 (2018).

[55] A. Strumia and F. Vissani, Precise quasielastic neutrino/nucleon cross-section, Phys. Lett. B **564**, 42 (2003).

[56] H. Kunxian, Ph.D. thesis, Kyoto University, 2015.

[57] K. Nakamura, S. Horiuchi, M. Tanaka, K. Hayama, T. Takiwaki, and K. Kotake, Multimessenger signals of long-term core-collapse supernova simulations: Synergetic observation strategies, Mon. Not. R. Astron. Soc. **461**, 3296 (2016).

[58] A. Burrows, D. Klein, and R. Gandhi, The future of supernova neutrino detection, Phys. Rev. D **45**, 3361 (1992).

[59] C. S. Kochanek *et al.*, The all-sky automated survey for supernovae (ASAS-SN) light curve server v1.0, Publ. Astron. Soc. Pac. **129**, 104502 (2017).

[60] D. Hiramatsu *et al.*, The electron-capture origin of supernova 2018zd, Nat. Astron. **5**, 903 (2021).

[61] S. Valenti *et al.*, The diversity of type II supernova versus the similarity in their progenitors, Mon. Not. R. Astron. Soc. **459**, 3939 (2016).

[62] S. Spiro, A. Pastorello, M. Pumo, L. Zampieri, M. Turatto, S. Smartt, S. Benetti, E. Cappellaro, S. Valenti, I. Agnoletto *et al.*, Low luminosity type ii supernovae–ii. Pointing towards moderate mass precursors, Mon. Not. R. Astron. Soc. **439**, 2873 (2014).

[63] G. Hosseinzadeh *et al.*, Short-lived circumstellar interaction in the low-luminosity type IIP SN 2016bkv, Astrophys. J. **861**, 63 (2018).

[64] S. E. Woosley, A. Heger, and T. A. Weaver, The evolution and explosion of massive stars, Rev. Mod. Phys. **74**, 1015 (2002).

[65] K. Sumiyoshi, S. Yamada, H. Suzuki, and S. Chiba, Neutrino Signals from the Formation of Black Hole: A Probe of Equation of State of Dense Matter, Phys. Rev. Lett. **97**, 091101 (2006).

[66] E. O'Connor and C. D. Ott, Black hole formation in failing core-collapse supernovae, Astrophys. J. **730**, 70 (2011).

[67] LSST Science Collaboration, LSST Science Book, Version 2.0, arXiv:0912.0201.