I study the diffuse flux of electron antineutrinos from stellar collapses with direct black hole formation (failed supernovae). This flux is more energetic than that from successful supernovae, and therefore it might contribute substantially to the total diffuse flux above realistic detection thresholds. The total flux might be considerably higher than previously thought, and approach the sensitivity of SuperKamiokande. For more conservative values of the parameters, the flux from failed supernovae dominates for antineutrino energies above 30-45 MeV, with potential to give an observable spectral distortion at Megaton detectors.

Since stars are distributed in mass as $\phi(M) \propto M^{-2.35}$, one gets that neutron star-forming collapses are a fraction $f_{NS} \simeq 0.78$ of the total. Their neutrino output is roughly equipartitioned between the six species: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ (from here on). At the production site, the flux in each species $w$, differential in energy, can be described as [16]:

$$F_w^0 \sim \frac{(1 + \alpha_w)^{1 + \alpha_c} L_w}{\Gamma(1 + \alpha_w) E_{0w}^{2}} e^{-\frac{E}{E_{0w}}} \frac{E_{0w}}{E}, \quad (2)$$

where $\Gamma(x)$ stands for the Gamma function. Here $\alpha_w$ controls the spectral shape, $L_w$ is the time integrated luminosity and $E_{0w}$ is the average energy. For illustration (fig. 1 dashed lines), here I use the typical values [16]: $E_{0e} = 15$ MeV, $E_{0x} = 18$ MeV, $L_\bar{e} = L_x = 5 \cdot 10^{52}$ ergs, $\alpha_x = 3.5$ and $\alpha_e = 2.5$. After neutrino oscillations in the star (those in the Earth are negligible [3]), the $\bar{\nu}_e$ flux is determined by the survival probability $\bar{p}$:

$$F_\bar{e} = \bar{p} F_\bar{e}^0 + (1 - \bar{p}) F_x^0, \quad \bar{p} = 0 - \cos^2 \theta_{12} \simeq 0 - 0.68. \quad (3)$$

The interval for $\bar{p}$ reflects the possible different oscillation scenarios, depending on the neutrino mass hierarchy, on the still unknown angle $\theta_{13}$ [18] and on the effects of neutrino-neutrino scattering (see e.g., [19] [20]). $\bar{p}$ can change during neutrino emission [21], but always remains in the interval [3], which therefore describes the time averaged probability. To illustrate how results can vary, I consider the extreme values of $\bar{p}$. They can be taken as constant in energy, which is adequate [18] for the experimentally relevant energy range ($E \gtrsim 19.3$ MeV for SuperKamiokande [1]).

While neutron star-forming collapses (NSFCs) have been widely studied, the evolution of higher mass stars is more uncertain. For $M \sim 25-40 M_\odot$ (13% of the total) a weaker explosion should occur, with a black hole formed by fallback [13]. Stars with $M \gtrsim 40 M_\odot$ (a 9% fraction), would instead collapse into a black hole directly. Simulations of such direct black hole-forming collapses (DBHFCs) [17] [18] [19] show an emitted neutrino flux that is more energetic and more luminous than the NSFC case, with especially high luminosity in $\nu_\tau$ and $\bar{\nu}_e$ due to capture of electrons and positrons on nucleons.

There is confidence, in the neutrino astrophysics community, that the diffuse flux (DF) of neutrinos from core collapse supernovae will be detected in the near future. The current upper limit from the 50 kt water tank of SuperKamiokande on diffuse electron antineutrinos, $\phi_{\nu_e}(E > 19.3 \text{ MeV}) < 1.4 - 2 \text{ cm}^{-2} \text{s}^{-1} \text{ at 90\% confidence level}$ [1-2], already approaches theoretical predictions [3]. Within a decade or so, tens to hundreds of events from the diffuse flux will be available from detectors of 0.1-1 Mt mass [4-5], allowing steady progress in the investigation of the physics of core collapse, of the cosmological rate of supernovae and of the properties of the neutrino.

So far, predictions for the DF have considered only the most common scenario: the collapse into a neutron star, with $\sim 3 \cdot 10^{53}$ ergs emitted in neutrinos of average energy $E_0 \sim 9 - 18$ MeV (see Eq. (2)). Recently, detailed studies have appeared [6-7] [8] [9] [10] [11] on the rarer case of direct collapse into a black hole without explosion, i.e., a failed supernova. It was shown that the neutrino emission is somewhat more luminous and decidedly more energetic than for neutron star-forming collapse, due to the rapid contraction of the newly formed protoneutron star preceding the black hole formation. Average energies are $E_0 \sim 20 - 24$ MeV for all neutrino flavors. This suggests that the hotter contribution of black hole-forming collapses to the DF might exceed that of neutron star-forming ones in part of the energy spectrum.

In this letter I study the diffuse flux from failed supernovae, with focus on its the electron antineutrino component, which is relevant for water Cherenkov detectors. The results confirm the intuition that the flux from failed supernovae might be significant and bring the DF even closer to being finally detected.

Core collapse occurs for stars with mass $M \gtrsim 8 M_\odot$ ($M_\odot$ is the mass of the Sun), at an average rate of $R_{cc}(0) \sim 10^{-4}$ Mpc$^{-3}$ yr$^{-1}$ today [12] and of

$$R_{cc}(z) \simeq R_{cc}(0)(1 + z)^{3} \quad (1)$$

(best fit $\beta = 3.28$ [12], up to redshift $z \approx 1$). The rate flattens at larger $z$. For $M \approx 8 - 25 M_\odot$ [13] the collapse leads to an explosion – the observed explosion of $\sim 20 M_\odot$ star Sanduleak into SN1987A [14] supports this – and to the formation of a neutron star.

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1. Arizona State University, Tempe, AZ 85287-1504
2. RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973
A "stiffer" equation of state (EoS) of nuclear matter \[7\] and/or a smaller accretion rate of matter on the protoneutron star \[9\] correspond to more luminous and hotter neutrinos. Here I use the fluxes from DBHFCs as in fig. 5 of ref. \[11\]. They are shown in fig. 1 (solid lines and inserts). These fluxes were obtained for the 40\(M_{\odot}\) progenitor in \[22\] with the stiffer Shen et al. (S) EoS \[23\] (incompressibility \(K = 281\) MeV) and the softer Lattimer-Swesty (LS) one \[24\] (with \(K = 180\) MeV \[11\]). For the different progenitors considered in \[11\] results appear unchanged for the S EoS, while for the LS one the luminosity and average energy may be lower by a factor of two and by 10-20\% respectively. For the energy spectra, I use the same linear interpolation of numerically calculated points as in \[11\], which underestimates the DF in the SuperKamiokande window by about 10-20\%, so my results are conservative. Ref. \[11\] shows that Eq. (3) applies to the DBFC case, with the same extreme values of \(\bar{p}\) being realized for the same oscillation parameters as in the NSFC case.

I calculated the neutrino fluxes from NSFCs and DBHFCs, and the total DF for a schematic two-population scenario, with a fraction \(f_{NS} (f_{BH} = 1 - f_{NS})\) of identical neutrino emitters of the NSFC (DBHFC) type \[31\]. Generalizing the single population formula (e.g., \[25\]) one gets the total diffuse \(\bar{\nu}_e\) flux at Earth, differential in energy and area:

\[
\Phi(E) = \frac{c}{H_0} \int_0^{z_{max}} R_{cc}(z) \left[ f_{NS} F_{\bar{\nu}_e}^{NS}(E(1 + z)) + (1 - f_{NS}) F_{\bar{\nu}_e}^{BH}(E(1 + z)) \right] \frac{dz}{\sqrt{\Omega_m(1 + z)^3 + \Omega_{\Lambda}}}, \tag{4}
\]

where \(\Omega_m = 0.3\) and \(\Omega_{\Lambda} = 0.7\) are the fractions of the cosmic energy density in matter and dark energy; \(c\) is the speed of light and \(H_0\) is the Hubble constant. I took the parameters \(R_{cc}(0) = 10^{-4}\) Mpc\(^{-3}\)yr\(^{-1}\), \(\beta = 3.28\) and \(z_{max} = 4.5\) \[12\] (results depend weakly on \(z_{max}\), at the level of \(\sim 7\%) or less for \(z_{max} \gtrsim 3\) \[25\]). To parametrize the uncertainty in \(f_{NS}\) I take the interval \(f_{NS} = 0.78 - 0.91\), corresponding to a mass 25 - 40 \(M_{\odot}\) as upper limit for neutron star-forming collapse.

Results are shown in fig. 2. The diffuse flux from NSFCs, \(\Phi_{NS}\), is maximum at \(E \sim 5 - 6\) MeV, with an exponential decay at higher energy \[26\]. The contribution from DBHFCs, \(\Phi_{BH}\), has hotter spectrum, and thus is increasingly important at higher energy. Oppositely to \(\Phi_{NS}\), \(\Phi_{BH}\) is larger for minimal permutation \((\bar{p} = 0.68)\) \[11\], because of the high original \(\bar{\nu}_e\) flux. The dependence of the original fluxes on the EoS is evident in \(\Phi_{BH}\).

Fig. 2 shows that \(\Phi_{BH}\) might dominate already at \(E \sim 22\) MeV, implying a strong effect at SuperKamiokande. For the most favorable parameters the total flux above 19.3 MeV more than doubles compared to 100\% NSFCs, (fig. 3), reaching a value \((\Phi \simeq 0.89\) cm\(^{-2}\)s\(^{-1}\)) tantaliz-
ingly close to the current upper limit. The enhancement of the event rate is even larger, thanks to the $\sim E^2$ dependence of the detection cross section. Thus, the DF might be closer to detection than previously thought, within the reach of improved searches at SuperKamiokande.

It is more likely, however, that $\Phi_{BH}$ exceeds $\Phi_{NS}$ only above 30–40 MeV (fig. 2). Its effect would be below the sensitivity of SuperKamiokande – which would therefore place limits on neutrinos from DBHFCs – but might be visible with the 1 Mt planned Cherenkov detectors, where $O(10)$ events are expected in this energy interval for a few years running time. Besides the excess in event rate, which suffers normalization uncertainties, the DBHFC diffuse flux could be visible for the spectral distortion that it produces. The lower threshold ($\sim 11$ MeV) of a liquid scintillator [27] or Gadolinium-loaded water detector [28] could allow to see a break in the energy spectrum at $\sim 20$ MeV, that might escape a pure water detector.

If all parameters conspire to maximally suppress it, $\Phi_{BH}$ might be invisible even for a Mt detector at least in the first few years running time. A negative result would then constrain the parameter space strongly.

To illustrate how results change for a more energetic NSFC flux I have repeated the calculations with $E_{0x} = 22$ MeV; in what follows I discuss how results compare to those in fig. 2. For $\bar{\nu}_e$ fluxes, differences are only minimal relative to fig. 2. This is because the $\bar{\nu}_e$ flux at Earth is dominated by the original $\bar{\nu}_e$ flux, which for the DBHFCs is markedly more energetic than in the NSFC case. For the S EoS $\Phi_{BH}$ exceeds $\Phi_{NS}$ above 22 MeV (38 MeV) for $f_{NS} = 0.78$ ($f_{NS} = 0.91$). Instead, for the LS EoS the two components are comparable at energy of 44 MeV or higher. This slight worsening compared to fig. 2 may make the difference between a positive or negative signal of $\Phi_{BH}$ at an experiment. For $\bar{\nu}_e$ fluxes, the distinctive original $\bar{\nu}_e$ flux from DBHFC does not contribute to the $\bar{\nu}_e$ flux at Earth, and so the main signature of direct black hole formation is lost. One may see a slight excess flux at $E \sim 45 – 50$ MeV only for the S EoS and $f_{NS} = 0.78$.

If the flux excess due to $\Phi_{BH}$ appears only above 30 MeV, it might partially be masked by the invisible muon and atmospheric neutrino backgrounds, which are strong at that energy [1]. I modeled these following [29] and taking a 100% flux excess in the 30-35 MeV bin, relative to a theoretical model or fit to the data with $f_{NS} = 1$. For pure water, where invisible muons dominate, the excess would not be statistically significant in the single bin, but might be distinguishable with a fit of the spec-

![Figure 2](image_url)
trum of events. With the reduced background allowed by Gadolinium, $3\sigma$ significance in the single bin would be achieved with about 12 Mt yr exposure, with a lower exposure needed if a spectral fit is done.

To summarize, the diffuse flux of neutrinos from failed supernovae may be significant, at a level detectable at SuperKamiokande or at M$	ext{t}$ scale detectors. While conclusions are limited by uncertainties, it is hoped that this letter will serve as a motivation for the development of more realistic predictions of the diffuse flux, which would be of great service to the experimental community.

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**FIG. 3:** Left: the largest possible $\bar{\nu}_e$ diffuse flux from direct black hole-forming collapses (solid, thick line), compared to that from neutron star-forming ones (dashed), from fig. [2]. The total flux is shown too (thin). Integrated fluxes above two thresholds are $E > 19.3$ MeV 0.33 0.56 0.89, $E > 11.3$ MeV 1.9 1.5 3.4, respectively.

Right: same figure for inverse beta decay events in water with 2 M$	ext{t}$ yr exposure, with a lower exposure needed if a spectral fit is done.

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[31] the neutrino emission in the case of black hole formation by fallback – for which detailed studies lack – should be qualitatively similar to the neutron star-forming case because the timescale of the black hole formation is expected to exceed that of neutrino emission [19].