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Supernova Neutrinos: Risks and Opportunities

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Are we ready for the next galactic supernova? What would we like to observe and what do we risk to miss? In the hope to trigger a discussion on these questions we have selected three specific topics, namely 1) the time of occurrence of core collapse events in the Milky Way; 2) the expectations and uncertainties; 3) the role of scintillation detectors. We find that 1) the best estimation of the time of occurrence in the Galaxy is about 58 ± 17 yr; 2) plausibly, the uncertainties on the energy distribution amount to many tens of percents and, surely, more than 5%; 3) scintillation detectors have a special potential to detect the non-electronic neutrinos through neutral current reactions.

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What is a core collapse supernova? This question, only apparently naive, evokes in fact completely different ideas in the minds of different professional scientists.

⋆ An astronomer will imagine the impressive visible manifestations, some individual event such as SN1987A and will think of supernova remnants or compact objects.

⋆ An astrophysicist will be concerned with the old problem of understanding the explosion and typically, he/she will apply for appropriate computing resources.

⋆ A nuclear physicist will consider the chain of reactions, the ν-processes, and the axial form factors affecting neutrino interactions in the supernova or in the detector.

⋆ A theorist working in particle physicist will think of flavor transformations, or of potential manifestations of unknown physics, such as the magnetic moment or new oscillations.

⋆ An experimentalist instead will take care of running (or planning) his/her neutrino (or gravity wave) detector, and will wonder what to do while waiting for galactic supernova events.

The hope to obtain a correct picture of core collapse supernovae requires that all these different points of view are considered. Conversely, it is important to understand that if some of these points of view play an exaggerated role or if the pending problems do not receive sufficient attention, our chances will be undermined. However, being in Venice we feel that the point of view of the colleagues who work at the neutrino telescopes is the one that should be given special attention. This choice will lead us to the selection of the material to present and discuss.

1. Next occurence of a supernova

Several operating neutrino telescopes can see neutrinos from a core collapse supernova in the whole Milky Way, but there is no safe of way to predict the occurrence of the next event and we have to rely on statistical approaches. E. g. from the known matter distribution we can infer a typical distance of about 10 ± 5 kpc, with a minor impact on the expectations coming from the uncertain contribution due to the region around the galactic center [1, 2]. The question of the value of the *average time of occurrence* in the Milky Way τ is even more important for neutrino telescopes. It is discussed in the literature, but further contributions by astronomers and astrophysicists would be precious and certainly welcome. Here, we would like to argue in favor of a global approach.

We can estimate this time knowing our galactic type reliably and using the statistics collected in cosmological observations. The results of the analysis of Padova-Asiago group [3, 4] is consistent with the range $\tau = 50 \pm 20$ yr/SN (but see also [5]). This hypothesis renders it interesting to search for an event directly (i. e. by neutrino telescopes) for a period of at least 100 years. This term is long on human time scale and requires not only to be sure of technological reliability of the telescope, but to consider also issues of political, economical and geological stability.

Other useful astronomical facts concerning the Milky Way and its surroundings are,

- no event has been seen in 22 years in LVD [6] (this is conservative: Baksan [7] has claimed 30 yr [7]; accounting for Artyomosk and other detectors, this time increases [4])

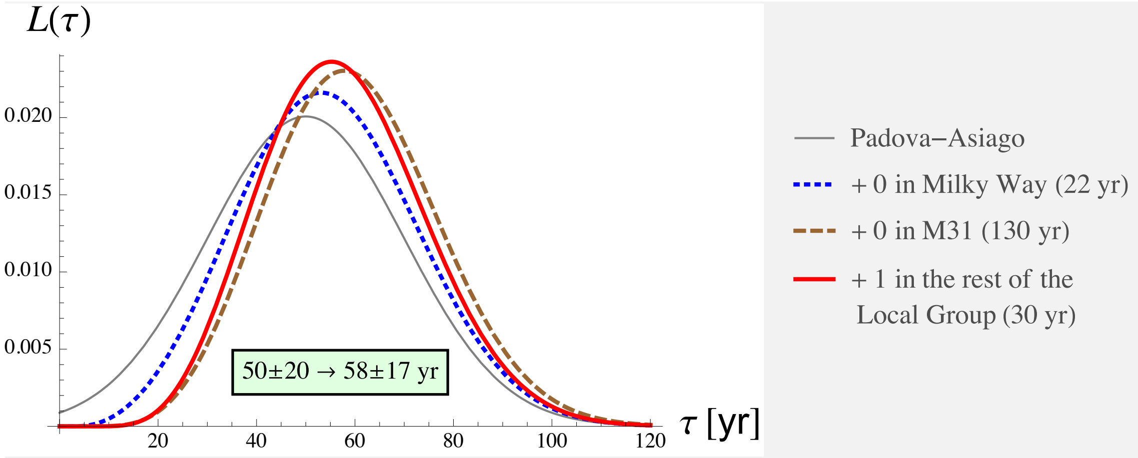

Figure 1: *Likelihoods for the true average time of occurrence of a core collapse supernova in the Milky Way. We show the one based on Padova-Asiago database (thin continuous line, gray) and the ones enhanced to account also for the absence of observations of a neutrino burst in 22 yr (dotted line) also for the absence of a visible supernovae in Andromeda (dashed line) also for the occurrence of SN1987A (thick line, red).*

- no event has been seen since 1885 in Andromeda (M31). We follow [8] and assume to have 3 times less supernovae there; $\tau_{\rm M31} = 3\tau$.
- one supernova has been seen in 30 years in the rest of local group, that we assume to provide as many supernovae as in the Milky Way alone; $\tau_{\rm rest} = \tau$.

We can refine the expectations multiplying the Gaussian likelihood (that describes the Padova-Asiago expectations) by the two Poisson factors $\exp(-\mu)$, with $\mu = 22\text{ yr}/\tau$ or $\mu = 130\text{ yr}/(3\tau)$ corresponding to the two negative facts above, and also by $\mu\exp(-\mu)$ with $\mu = 30\text{ yr}/(\tau)$ to account for SN1987A (occurred neither in the Milky Way nor in M31). The $1\,\sigma$ region changes as follows (see Fig. 1): $\tau = 50\pm 20 \to 58\pm 17$ yr/SN: The additional information, in particular the *absence* of local supernovae does not affect much the estimated theoretical error, but shifts our expectations by about half the size of the uncertainty. Thus, this type of information is beginning to have an impact on the expectations.[1] The rate in the local group is predicted to be $\tau_{\rm local} = 3\tau/7 = 25\pm 7$ yr/SN, but this depends crucially on our hypothesis on $\tau_{\rm rest}$.

2. Expectations and uncertainties

Core collapse supernovae emit neutrinos and antineutrinos of all 3 types with energies up to many tens of MeV. In this energy range, neutrino telescopes can tag 3 classes of events

charged current due to $\bar\nu_{\rm e}$, charged current due to $\nu_{\rm e}$, and neutral current events

[1]The compatibility of the information was tested as follows. If the true value τ is in the range $[0,100\,\text{yr}]$ using only the likelihoods $\exp(-t_{\rm obs}/\tau)$ we get 62 ± 24 yr/SN (LVD) and 67 ± 22 yr/SN (M31). If these 2 likelihoods are combined with the Gaussian likelihood (omitting the information on SN1987A) we obtain 59^{+18}_{-17} yr/SN. If alternatively we use the frequency $f = 1/\tau = 2\pm 0.8$ SN/100 yr treated as a Gaussian variable with $\delta f \equiv \delta\tau/\tau^2$, and we include the factors $\exp(-f\,t_{\rm obs})$, we find $f = 2\pm 0.8 \to 1.5^{+0.9}_{-0.8}$ SN/100 yr. Thus, the indications we obtain seem to be stable.

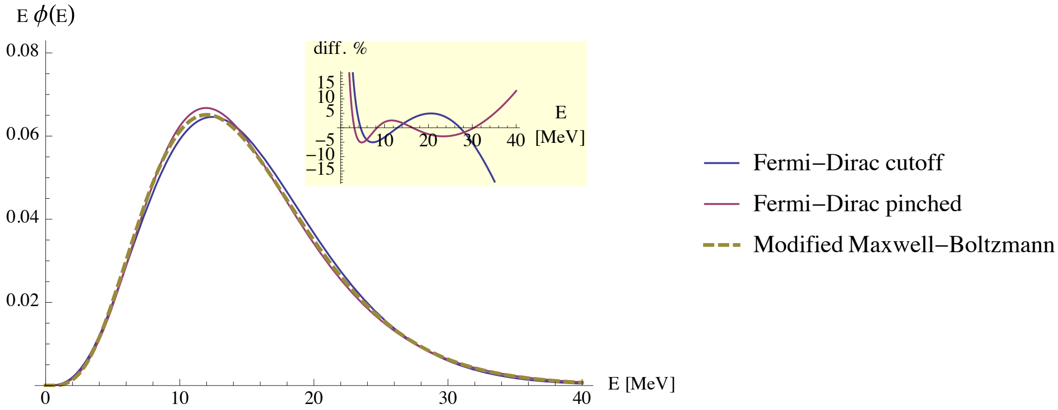

Figure 2: *Comparison of various parameterizations of the function $E\,\phi(E,\xi)$, normalized to unity.*

The classification is not strict as some reactions, such as the elastic scattering on electrons, fall into more classes; there are also reactions, such as the charged current excitation of carbon-12 nuclei, where the electron neutrinos and the electron antineutrinos give similar signals and their separation is demanding. The conventional type of detectors, composed of water or hydrocarbon compounds, have optimal response to electron antineutrinos due to the free proton nuclei, as well-known and consistently seen from the ~ 20 events from SN1987A.

A very important issue for data analysis is an accurate and effective parametric description of the flux. The emission spectra are expected to be *approximatively* thermal. The flux for any species will be,

$$\Phi_i(E) = N_i \times \frac{L_i}{4\pi D^2} \times \phi(E, T_i, \xi_i) \tag{2.1}$$

where $i = \nu_e, \bar{\nu}_e, \nu_x$ denotes the neutrino flavor, L_i is the luminosity (i. e. the emitted power), D the distance, T_i a 'temperature' parameter linked to the average energy and ξ_i describes deviations from a thermal distribution. The normalization N_i is fixed accordingly to these definitions and ν_x denotes any of the 4 non-electronic neutrino or antineutrino species, assumed to all have equal distributions.

In the literature, several parameterizations of the spectral shape have been used, from the oldest to the newest:

$$\phi(E,T,\xi) \propto \begin{cases} \frac{E^2}{1+e^{E/T+\varepsilon(E/T)^2}} & \text{Fermi-Dirac cutoff} \\ \frac{E^2}{1+e^{E/T-\eta}} & \text{Fermi-Dirac pinched} \\ E^\alpha\ e^{-E/T} & \text{Modified Maxwell-Boltzmann} \end{cases} \tag{2.2}$$

As the parameter $\xi = \varepsilon, \eta$ or α increases, the spectra become narrower; this is called 'pinching' and describes the physical fact that the interaction of high-energy neutrinos with matter is more effective and therefore the high-energy flux is depleted. In Fig. 2 we compare the three parameterizations assuming $\langle E \rangle = 12$ MeV and $\delta E = 6$ MeV.[2] Since the right parameterization is not known a priori,

[2]They correspond respectively to the following choices of parameters: $T = 4.8$ MeV and $\varepsilon = 1/22$; $T = 3.4$ MeV and $\eta = 1.7$; $T = 3$ MeV and $\alpha = 3$.

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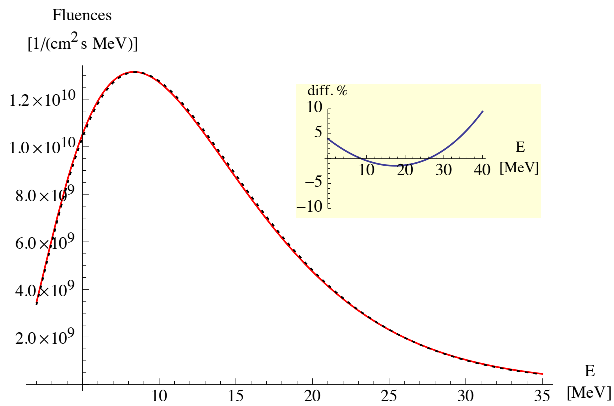

Figure 3: *Electron antineutrino fluences, the first described by Maxwell-Boltzmann distribution (dotted) and the second by the overlap of two Maxwell-Boltzmann distributions (red, continuous), as implied by the simplest description of neutrino oscillations. The two distributions are assumed to have the same integral and the same average energy to allow a comparison. See the text for details and compare with Fig. 2.*

it is dangerous to rely much on statements that depend on $\sim 5\%$ effects on the flux or fluence: see again Fig. 2. Until theory will be able to make more precise statements, we can use these considerations to assess the level of *irreducible uncertainty.*

However, much larger contributions to the spectrum's uncertainty come from the lack of precise knowledge of temperature, luminosity and radiated energy $\mathscr{E}_i = \int L_i(t)dt$. One should allow for several tens of percents variation in the parameters T and L when analyzing the data.[3] Moreover, and even more importantly, the emission will not be constant in time. Finally, it should be repeated that the three parameters we introduced for a given parameterization (i. e. radiated energy, temperature and ξ-parameter) will depend on the species of the neutrino: recall that in the case of SN1987A, all we are sure is that we have seen electron antineutrinos [9].

A question of great interest is the study of the oscillations induced by the measured parameters that describe three-flavor transformations, aka oscillations. Oscillations in a supernova

1. occur if the fluxes of neutrinos of different flavors are different;
2. depend on the type of mass hierarchy due to ordinary matter (MSW) effect [10];
3. are modified through neutral-current self-induced effect [11] by the fluxes themselves (i. e. the physics is likely to be affected by non-linear effects).

Let us discuss these three points. As recalled above the astrophysical uncertainties are large and should be accounted for in conservative analyses of the (true or simulated) data. The second point is well understood. However, the third one is still a matter of scientific debates, thereby contributing to the overall uncertainty [12]. In order to illustrate the size of the expected effect, we plot in Fig. 3 the fluence (i. e. the time integrated flux $F_i = \int \Phi_i(t)dt$) of the electron antineutrinos for normal mass hierarchy including 2) but not 3) and assuming that the muon and tau antineutrinos have a

[3] Theory suggests a comparable amount of energy in any of the 6 species, a hypothesis know as 'equipartition', but deviations cannot be excluded.

temperature 20% higher than the electron antineutrinos. Note that the effect is not much larger than the one discussed in Fig. 2. See [9] for a detailed discussion of the theory and of the comparison with SN1987A.

Which of the models to describe the neutrino flux or fluence is preferable? For each problem at hand we should assess appropriateness, accessibility to use and convenience. A Maxwell-Boltzmann type distribution of the fluence is appropriate for SN1987A or for certain applications as the search for neutrinos from cosmic supernovae (aka, relic supernova neutrinos or diffuse supernova neutrino background). However for the next supernova we will certainly need better and possibly physically meaningful parametric models. There were attempts for such models after SN1987A [13]. We hope that astrophysicists will be able to help the colleagues, who work at the neutrino telescopes, to progress and to be ready.

3. Scientific potential of scintillation telescopes

The great potential of water Cherenkov detectors has been demonstrated by the successful observation of SN1987A. In the case of a galactic supernova, the dataset will increase with the distance squared, $(50\,\text{kpc}/10\,\text{kpc})^2 = 25$ and we will gain at least one order of magnitude thanks to (SuperKamiokande's) detector mass. Moreover, IceCube can monitor the supernova counting rate as a function of time and it is possible that HyperKamiokande will be ready to contribute. Thus, one may ask: Do we need to have other types of detectors to see core collapse supernovae?

In our view, the question is so important that we prefer to leave it as it stands rather than performing a cursory investigation.[4] We prefer to analyze in some detail a specific issue, namely, the physics reach of hydrocarbon based detectors, and in particular those based on the detection of scintillation light. There are several reasons for this choice:

(*i*) these are very stable and, in fact, they are the oldest types of detectors used for the purpose of supernova neutrino detection, as recalled previously;

(*ii*) there are several operating detectors of kton class, including LVD, KamLAND, Borexino, MiniBOONE and Baksan, that worked properly for SN1987A; SNO+ will join soon.

(*iii*) Borexino has demonstrated how to attain amazing standards of radiopurity, thus becoming sensitive to very low energies events: Its present energy threshold is as low as 200 keV;

(*iv*) finally, there are realistic plans of having even bigger scintillation detectors, in particular JUNO, but also the LENA and ANDES projects.

Therefore we specify the question a bit further, asking what is the physics contribution of (large, pure) scintillation telescopes to our understanding of supernova neutrino emission.

The comparison again is with the Cherenkov detectors. In their case, the main signal is from the detection of charged current interactions of electron antineutrino scattering hitting free protons,

[4] Usually one decides *a priori* whether to address some specific physics question or to emphasize which type of detector to consider; evidently the best would be to harmonize these points of view. Also, it should be remarked that one should keep new types of detectors in mind, but also think about how to improve the performances of the conventional ones and exhaustively explore their physics reach.

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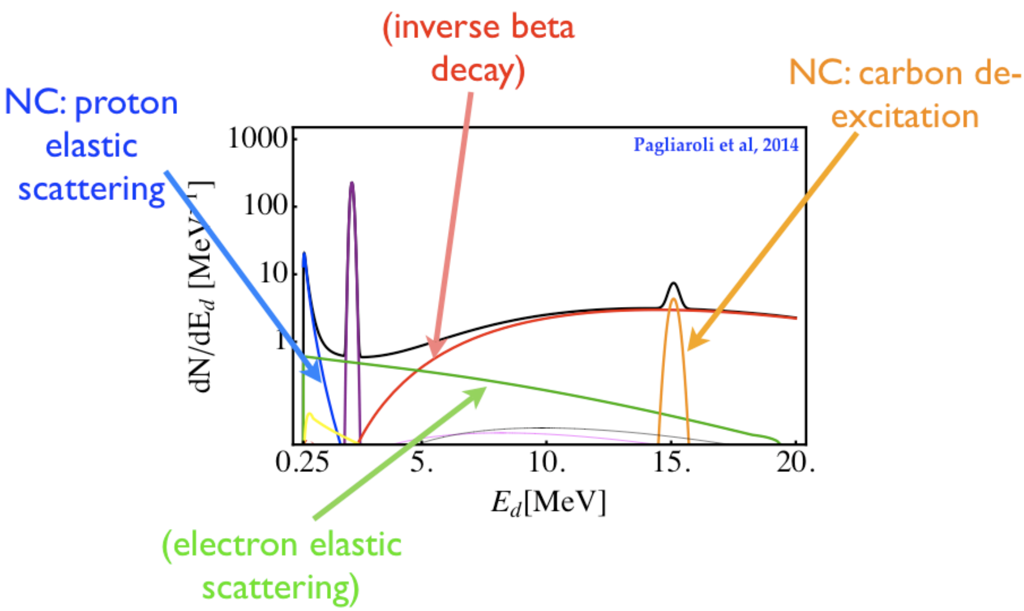

Figure 4: *Expected counting rate in Borexino from a galactic supernova at 10 kpc. The two main neutral current (NC) channels are emphasized. The largest peak (at* ~ 2 *MeV) is due to neutrons, that can be associated to positrons released in the IBD reaction and therefore tagged during data analysis. From [15].*

$\bar{\nu}_{\rm e} + {\rm p} \to {\rm e}^+ + {\rm n}$, also called *inverse beta decay* (IBD) reaction. This reaction depends upon a single species of the emitted neutrinos, out of six. It is difficult to observe the other ones and the neutral current events are quite essential to achieve this goal. One possibility is to see the de-excitation lines of oxygen-16 at 5-10 MeV. These are expected to lead to some 100 events [14] in Super-Kamiokande and from a typical galactic event. However, comparably small scintillator detectors can offer other interesting possibilities, in particular,

1. via the conspicuous gamma line at 15.1 MeV resulting from neutral current excitation of carbon-12, and
2. via the elastic scattering reaction $\nu + {\rm p} \to \nu + {\rm p}$, that produces scattered protons at the lowest detectable energies.

The contribution of these two reactions to the expected energy spectrum of Borexino is shown in Fig. 4, based on Ref. [15]. Note that this is the spectrum before any tagging; in particular, a big deal of neutrons and of positron are associated in time, being due to the IBD reaction.

In order to further illustrate the importance of the neutral current events, we can consider their application to detect (or exclude) the presence of *new* oscillations, happening on cosmic scales and leading to important effects. This is motivated by various models, such as those with mirror matter[5] [16] or equivalently also those with pseudo-Dirac neutrinos [17]. In the case of SN1987A, it can be easily shown that if the new oscillation parameters lie in the wide range

$$10^{-20}\ {\rm eV}^2 < \Delta m^2_{\rm new} < 10^{-12}\ {\rm eV}^2 \tag{3.1}$$

[5] In this kind of models, mirror baryons can account for dark matter.

	$p(H_0)$	$p(H_1)$	$p(H_1)/p(H_0)$
disregarding uncertainties	9.0 %	0.3 %	0.04
including uncertainties	4.2 %	1.8 %	0.42

Table 1: *The 19=8+11 events seen in IMB and Kamiokande-II from SN1987A and above threshold are compared with the number of signal events expected from a conventional emission, defined as the best fit point of SN1987A data analysis and omitting oscillations (H_0) and assuming instead that only half of the neutrinos reached us (H_1), see footnote 7. If we neglect the uncertainties, the new hypothesis H_1 is disfavored, whereas accounting for the uncertainties, the conclusion becomes much weaker.*

we expect that *half* of the neutrinos become undetectable upon reaching the Earth; therefore, we have seen just half of them and we have to assume that the energy radiated is twice as large as deduced by the conventional analyses of the data. If we note that SN1987A data analysis indicates an amount of radiated energy that is in reasonable agreement with the expectations [9], we may conclude that this possibility is disfavored by the observed sample of IBD events. However, when we account for the present theoretical uncertainties[6] it is not possible to make strong statements: see Tab. 1.

Finally an important question is how to measure the electron neutrino component of the supernova neutrino emission. One way is to use the elastic neutrino interactions onto electrons (ES) namely $\nu + \mathrm{e} \to \nu + \mathrm{e}$, that leads to 1/15 - 1/25 of the events and that has *also* a contribution from electron neutrinos. Water Cherenkov detectors will be able to isolate a sample of events due to this reaction, thanks to the possibility to observe the direction of the events. However, as it can be seen from Fig. 4, in the region below 5 MeV there is a significant contribution from elastic scattering on electrons, meaning that scintillation detectors will be able to contribute to this problem as well. For a recent discussion, see [18].

4. Discussion

Observational neutrino astronomy has many important needs that are connected to supernova neutrinos, and in particular to galactic supernova neutrino astronomy. In this talk, we have attempted to argue that the field could progress significantly by joining the efforts of a widened scientific community. We would like to conclude by emphasizing a few special items of this brief but focused discussion.

- The discussions on important issues do not converge yet; conversely, not all relevant issues are actively discussed.

[6]In order to make a quantitative statement on the uncertainties, we assume that [9], $\mathscr{E}_{\rm tot} = (3\pm 0.5)\times 10^{53}$ erg , $f_{\bar\nu_e} = \frac{1}{6}\times(1\pm 0.2)$, $\langle E_{\bar\nu_e}\rangle = 12\pm 2$ MeV, $\alpha_{\bar\nu_e} = 2.5\pm 0.5$ where the key parameter is the total energy radiated in antineutrinos, $\mathscr{E}_{\bar\nu_e} = f_{\bar\nu_e}\times\mathscr{E}_{\rm tot}$. We model oscillations using $P_{\bar\nu_e\to\bar\nu_e} = 0.67$ and supposing that the parameters of the non-electronic neutrinos are $f_x = (1-2f_{\bar\nu_e})/4$, $\langle E_x\rangle = \langle E_{\bar e}\rangle(1.1\pm 0.2)$, $\alpha_x = 2$, where $x = \bar\nu_\mu$ or $= \bar\nu_\tau$; note that $f_x/f_{\bar\nu_e}$ is 1 within a typical 30% range. All quoted ranges are treated as 1 sigma Gaussian ranges in this calculation.

- The question of the expected rate of galactic supernova neutrino events remains a burning one, and the available results are not entirely satisfactory.
- The general picture of supernova neutrino emission seems reliable but the uncertainties are considerable. It would be useful to have reliable predictions with error bars and probably we can improve on that.
- We have argued that (ultra-pure) scintillation detectors can contribute in an important way to the physics that will be investigated by means of supernova neutrinos; in particular, by contributing to our understanding of non-electronic neutrinos.
- One risk is that we observe a signal but we are not ready to understand it; e. g., it would be shocking to realize that our detectors were not sufficient. Surprises are possible but we should avoid wasting a unique opportunity.

To conclude, let us make clear that the words 'risks and opportunities' used in title of this talk should not evoke the risks of a nearby supernova, that are absent; rather, they are meant to recall our responsibility toward the colleagues who patiently run neutrinos observatories. We have emphasized some opportunities with scintillation telescopes but as it is evident to any participant to Neutrino Telescopes, the next galactic supernova will offer us many valuable chances of understanding the physics of gravitational collapse. The main risk is just not to be ready for this epoch-making appointment.

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PoS(NEUTEL2015)008