EPJ Web of Conferences **280**, 05002 (2023) https://doi.org/10.1051/epjconf/202328005002
RICAP-22

Exploiting synergies between neutrino telescopes for the next galactic core-collapse supernova

Meriem Bendahman[1,3], *Anne-Cécile* Buellet[2], *Matteo* Bugli[2], *Joao* Coelho[1], *Alexis* Coleiro[1], *Gwenhaël* de Wasseige[1], *Sonia* El Hedri[1,*], *Thierry* Foglizzo[2], *Davide* Franco[1], *Isabel* Goos[1], *Jérôme* Guilet[2], *Antoine* Kouchner[1], *Yahya* Tayalati[3], *Alessandra* Tonazzo[1], *Cristina* Volpe[1]

[1]Laboratoire Astroparticules et Cosmologie, Université Paris Cité, Paris
[2]CEA Saclay, Department of Astrophysics
[3]Faculty of Sciences, Mohammed V University, Rabat

Abstract. Observing and characterizing the next galactic core-collapse supernova will be a critical step for neutrino experiments. Extracting information about the supernova progenitors and neutrino properties within minutes after an observation will in particular be crucial in order to optimize analysis strategies at other observatories. Moreover, certain classes of progenitors, with strong magnetic fields, could give rise to gamma-ray bursts but have been underinvestigated to date. In this contribution we propose a strategy to combine results from next-generation neutrino experiments, focusing notably on the determination of the progenitor mass and the neutrino mass ordering. Additionally, we investigate the impact of strong magnetic fields on neutrino observations, and demonstrate the detectability of the associated effects in upcoming experiments.

1 Introduction

Observing neutrinos emitted by the next galactic core-collapse supernova (CCSN) would allow a full characterization of its three phases: neutronization, accretion, and cooling. The next generation of neutrino detectors will be uniquely suited to this task: the Hyper-Kamiokande and KM3NeT water Cherenkov (WC) detectors will be sensitive to $\overline{\nu_e}$ while the DUNE and DarkSide-20k liquid argon detectors will be sensitive to ν_e and to the sum of all neutrino flavors, respectively. In this contribution, we will investigate how to use these experiments to uncover novel information about CCSNe and neutrino properties.

2 Combining Water Cherenkov detectors, DUNE, and DarkSide-20k

The time variation of the neutrino rate observed at a given experiment ("light curve") contains crucial information about the CCSN properties and can be obtained less than a minute after the beginning of a supernova. By combining light curves from multiple detectos, alert systems can inform analyses at other observatories. Here, we outline a simple strategy to combine CCSN light curves for detectors sensitive to different neutrino flavors, taking the example of KM3NeT, DUNE, and DarkSide-20k.

*e-mail: elhedri@apc.in2p3.fr

2.1 Multi-detector observables

Existing analyses of CCSN neutrino light curves and spectra are based on supernova simulations. Since accurate three-dimensional (3D) simulations are only available for a limited number of progenitors, over-reliance on simulations could bias our analyses. We therefore elaborated an analysis strategy based on simple assumptions about the flavor complementarity of the neutrino experiments considered, without relying on CCSN simulations. More specifically, we proposed the following two observables:

$$\mathcal{R}(t_{\min}, t_{\max}) = \frac{R_{\mathrm{WC}}(t_{\min}, t_{\max}) + R_{\mathrm{DUNE}}(t_{\min}, t_{\max})}{R_{\mathrm{DS}}(t_{\min}, t_{\max})} \tag{1}$$

$$\mathcal{A}(t_{\min}, t_{\max}) = \frac{R_{\mathrm{WC}}(t_{\min}, t_{\max}) + R_{\mathrm{DUNE}}(t_{\min}, t_{\max}) - R_{\mathrm{DS}}(t_{\min}, t_{\max})}{R_{\mathrm{WC}}(t_{\min}, t_{\max}) + R_{\mathrm{DUNE}}(t_{\min}, t_{\max}) + R_{\mathrm{DS}}(t_{\min}, t_{\max})} \tag{2}$$

where $R_{\mathrm{WC}}, R_{\mathrm{DUNE}}, R_{\mathrm{DS}}(t_{\min}, t_{\max})$ are the neutrino rates observed in the $[t_{\min}, t_{\max}]$ time window at a WC detector, DUNE, and DarkSide-20k, respectively. For a given analysis, the $[t_{\min}, t_{\max}]$ window will be optimized to maximize the search's sensitivity. $\mathcal{R}$ and $\mathcal{A}$ can be interpreted as the ratio and the asymmetry between electronic and non-electronic neutrino flavors. Evaluating the sensitivity of these observables to different supernova parameters will hence allow us to identify which supernova properties warrant a multi-detector study.

2.2 Simple case study with spherically symmetric supernova models

We consider spherically-symmetric supernova simulations from the Garching group [1], which model CCSNe up to the cooling phase, and we assume adiabatic MSW conversions for neutrino flavor transitions. We vary two parameters: the progenitor mass (11 $M_\odot$ vs 27 $M_\odot$), and the neutrino mass ordering. For each configuration we compute $\mathcal{R}$ and $\mathcal{A}$ over different time windows for a supernova occurring at 10 kpc. We choose the fiducial volume of the WC detector to be the one of the KM3NeT experiment, and, for all the detectors considered here, neglect backgrounds and resolution effects. We observe no significant variations of $\mathcal{R}$ and $\mathcal{A}$ with the progenitor mass, with a maximal difference of 1.5σ between the two models. Conversely, as shown in figure 1, the fraction of detected electronic flavors $\mathcal{R}$ in the first 20ms of the supernova is considerably larger in the IMO than in the NMO; measuring $\mathcal{R}$ would in fact allow to determine the neutrino mass ordering at more than 5σ for a galactic supernova. This striking result is explained by the higher ν_e survival probability in the IMO (30%) compared to the NMO (2%) , and should hence hold across a wide range of CCSN models. In the next section, we investigate this result for more realistic supernova models and detector properties.

2.3 Stable observables: from the neutrino mass ordering to new physics

The dependence of $\mathcal{R}$ on the neutrino mass ordering is driven by the variations in the ν_e rates expected at DUNE. Conversely, DarkSide-20k, which treats all flavors equally, provides a reference point to estimate the electron neutrino survival probability independently of the supernova distance. In this section we therefore focus on these two experiments, and use the observable $\mathcal{R}' = R_{\mathrm{DUNE}}/R_{\mathrm{DS}}$ to probe neutrino flavor conversion processes. Specifically, we investigate the variations of $\mathcal{R}'$ with the electron neutrino survival probability p_{ee}, for state-of-the-art 3D supernova models designed by the Garching group [1] with progenitor masses ranging from 15 to 40 $M_\odot$. We also consider realistic detector conditions, using the SNEWPY [2] tool to model detection efficiencies and energy smearing. However, instead of the optimal $[1, 10]$ ms window used in section 2.2, the new simulations constrain us to use a $[11, 20]$ ms window, making our results overpessimistic.

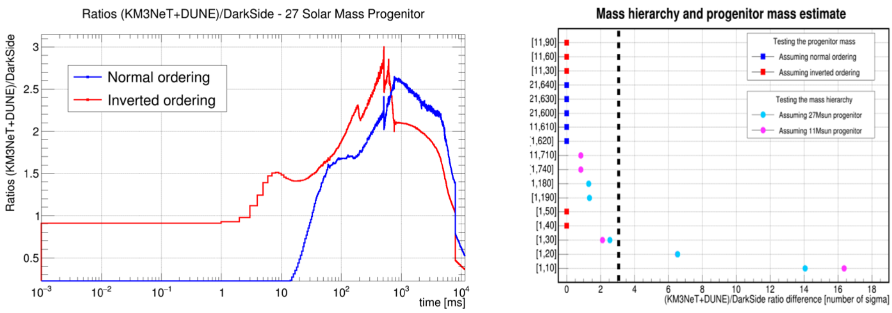

Figure 1. Left: Values of $\mathcal{R}$, computed in 1 ms bins, as a function of time for a 27 $M_\odot$ progenitor. Right: Significances of the differences in $\mathcal{R}$ between models for different time windows.

Figure 2 shows $\mathcal{R}'$ as a function of p_{ee} for the progenitor masses simulated in [1]. The (linear) dependence of $\mathcal{R}'$ in p_{ee} is remarkably stable across models, due to the near-universality of the size of the neutronization peak [3]. While numerous analyses exploiting the size of this peak have been proposed in the literature (see e.g. [3]), a novel aspect of our study is the use of DarkSide-20k to make $\mathcal{R}'$ independent of both the CCSN model and distance. Being exclusively sensitive to neutrino properties, $\mathcal{R}'$ could hence be a unique probe of new physics phenomena. The right panel of figure 2 shows the 1σ absolute uncertainty on the value of p_{ee} obtained from a measurement of $\mathcal{R}'$ as a function of the supernova distance to Earth, for the NMO and the IMO. For a close-by supernova, if the mass ordering is known, a p_{ee} measurement would allow probing new physics scenarios such as neutrino two-body decays, which could modify DUNE's early-time measurements by up to an order of magnitude [4].

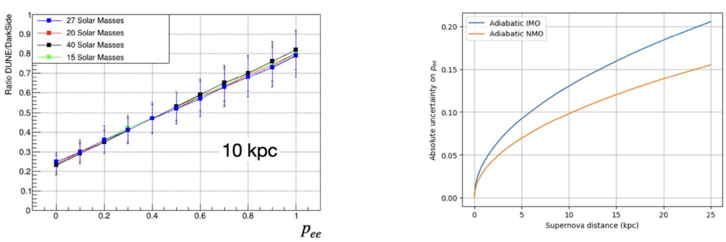

Figure 2. Left: $\mathcal{R}'$ as a function of p_{ee} for a CCSN at 10 kpc. Right: Uncertainty on the measured p_{ee} as a function of the CCSN distance in the NMO and the IMO.

3 Atypical supernovae: progenitor rotation and magnetic fields

Supernova progenitors with strong rotations and magnetic fields can lead to extreme explosions producing long gamma-ray bursts and studying their light curves could therefore advance our understanding of extreme astrophysical phenomena. Here, we investigate the impact of magnetic fields on neutrino emission, using simulations from [5]. These simulations model a $35M_\odot$ fast-rotating progenitor and an initial 10^{12} G magnetic field with different possible radial profiles and angular momenta. A reference model with no magnetic field is also provided. For all magnetic field configurations, we observed a suppression of the neutrino emission rate in the progenitor's equatorial plane during the accretion phase. This suppression is due to the magnetic field transporting angular momentum towards the periphery of the star, thus inhibiting the matter accretion rate perpendicularly to the rotation axis.

The effect of this flux suppression on neutrino observations is shown in figure 3 for the KM3NeT experiment, assuming the full configuration of the ARCA detector and a CCSN occurring at 5 kpc. Here, in spite of accounting for the detector efficiency and the presence of backgrounds, we observe a clear suppression of the neutrino flux for the $\ell = 1$ model in 200-400 ms. Finally, we assess the observability of this suppression by comparing the numbers of expected events in 200-400 ms for the no-magnetic field model and the $\ell = 1$ model, at different detectors. The right panel of figure 3 shows the significance of this flux suppression for KM3NeT, Hyper-Kamiokande, DUNE, and DarkSide-20k. Even at KM3NeT, the effect of magnetic fields is still observable up to the galactic center at 3σ, while other experiments have full galactic sensitivity. This simple study confirms that magnetic fields can leave detectable imprints on neutrino spectra for a wide range of supernovae. An in-depth investigation involving lighter, more representative progenitors, is therefore warranted.

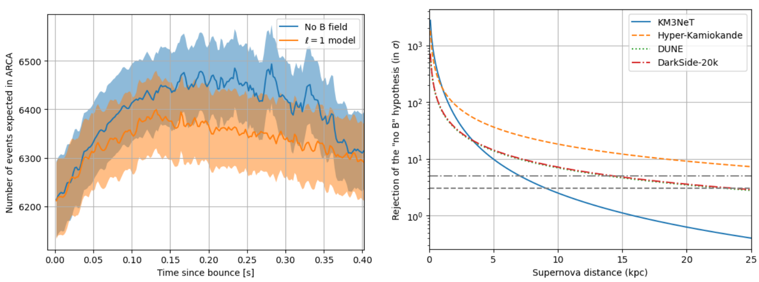

Figure 3. Left: Neutrino rates expected at KM3NeT-ARCA for the rotating progenitors simulated in [5]. Right: Significance of the difference between the "no magnetic field" and the dipolar models as a function of the CCSN distance.

4 Conclusion

In this contribution we presented new approaches to link supernova parameters to neutrino observations. We designed a generic method to identify mechanisms modifying the flavor composition of CCSN neutrinos, and combined experiments to probe new physics phenomena. Furthermore, we showed that the presence of strong magnetic fields could be detected by upcoming neutrino experiments and thus should be targeted by future CCSN analyses.

5 Acknowledgments

LEAK is supported by LabEx UnivEarthS (ANR-10-LABX-0023 and ANR-18-IDEX-0001).

References

[1] https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/archive.html
[2] A. Baxter, *et al.*, J. Open Source Softw. **6**, no.67, 3772 (2021)
[3] M. Kachelriess, *et al*, Phys. Rev. D **71**, 063003 (2005)
[4] A. de Gouvêa, *et al*, Phys. Rev. D **101**, no.4, 043013 (2020)
[5] M. Bugli, *et al*, Mon. Not. Roy. Astron. Soc. **492**, no.1, 58-71 (2020)