

# MSW effects on the time evolution of the supernova neutrino event rates

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The flavor transition mechanisms of supernova neutrinos as they propagate outward from the deep inside of the supernova are yet to be determined. We study the time-evolution patterns of different neutrino flavors in various flavor transition scenarios. With simulation data of supernova neutrinos, we calculate the neutrino event rates at different kinds of detectors for different flavor transition scenarios. Using the calculated event rates of IBD and  $\nu_e$ Ar in corresponding liquid scintillation detectors and liquid argon detectors, we calculate the ratios of two cumulative time distribution up to  $t = 100$  ms in Nakazato's supernova models with 13, 20 and 30  $M_\odot$  progenitor mass. We show that the time evolutions of cumulative ratios are effective in determining whether MSW oscillations really occur for SN neutrinos or not.

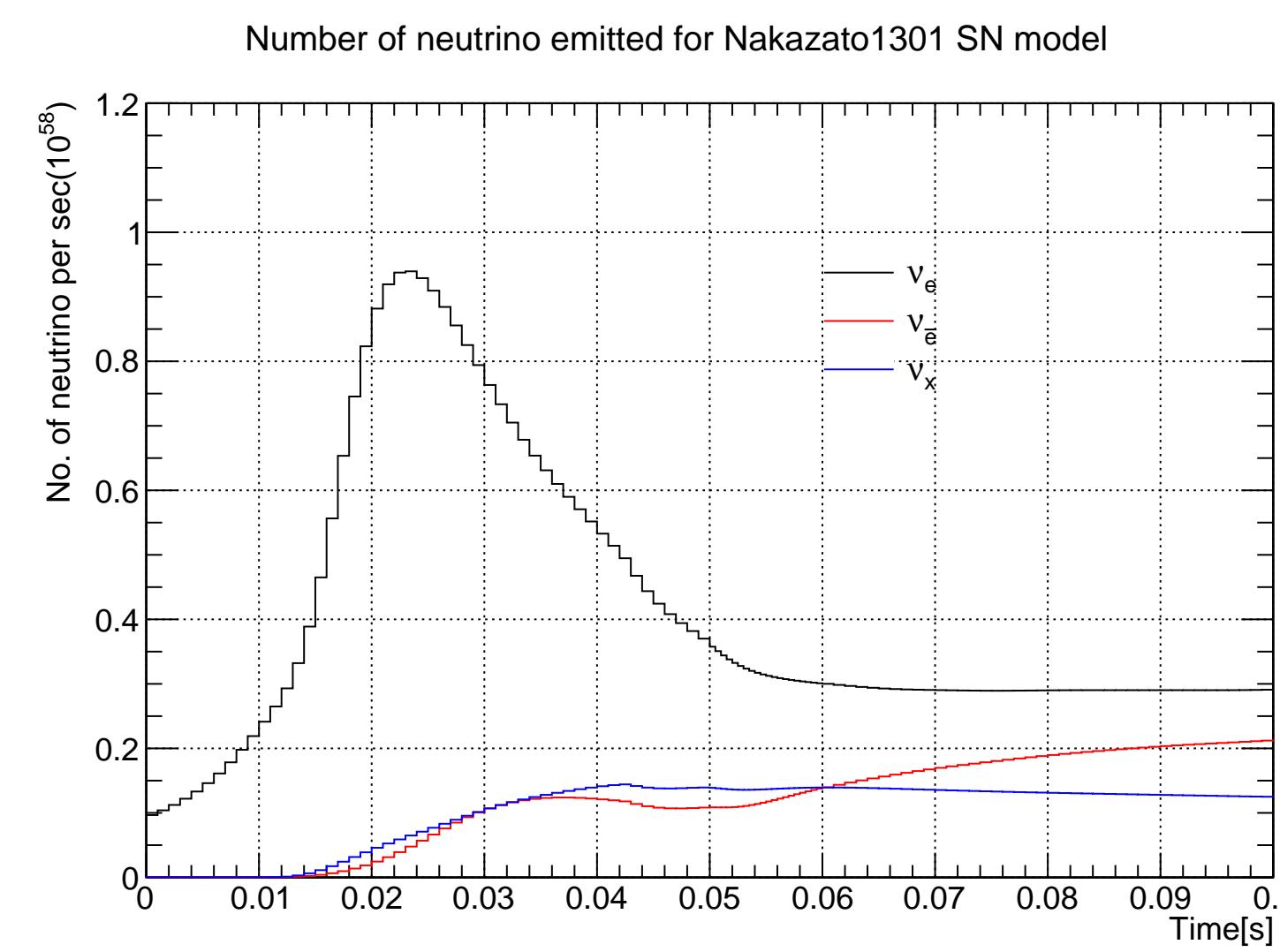
## Detectors Parameters

	JUNO <sup>[1]</sup>	DUNE <sup>[2]</sup>
Materials	Linear Alkyl Benzene	Liquid Argon
Fid. Mass	20 ktons	40 ktons
Targets No.	$N_p \approx 1.45 \times 10^{33}$	$N_{Ar} \approx 6 \times 10^{32}$

A 0.2 MeV proton detection threshold energy is applied for JUNO.

## SN Model

- Nakazato's SN 1301 (13  $M_\odot$ ) simulation<sup>[7]</sup>
- 5 kpc distance



## MSW Effects

MSW neutrino oscillation formula<sup>[3]</sup> :

$$\begin{aligned} F_e &= F_x^0 \\ F_{\bar{e}} &= (1 - \bar{P}_{2e})F_{\bar{e}}^0 + \bar{P}_{2e}F_x^0 \\ F_x &= \frac{1}{4}(F_e^0 + \bar{P}_{2e}F_{\bar{e}}^0 + (3 - \bar{P}_{2e})F_x^0) \end{aligned}$$

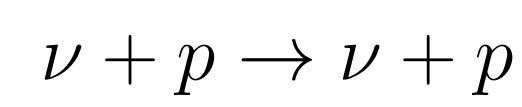
for normal mass ordering (NMO), and

$$\begin{aligned} F_e &= P_{2e}F_{\bar{e}}^0 + (1 - P_{2e})F_x^0 \\ F_{\bar{e}} &= F_{\bar{e}}^0 \\ F_x &= \frac{1}{4}((1 - P_{2e})F_e^0 + F_{\bar{e}}^0 + (2 + P_{2e})F_x^0) \end{aligned}$$

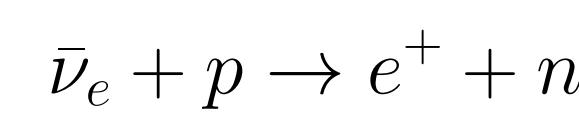
for inverted mass ordering (IMO)

## Reaction Channels

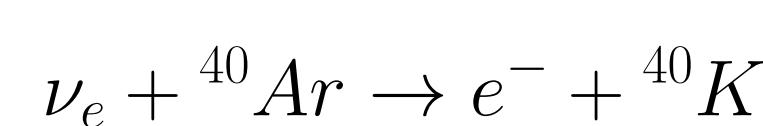
Neutrino Proton Elastic Scattering (pES)<sup>[4]</sup>



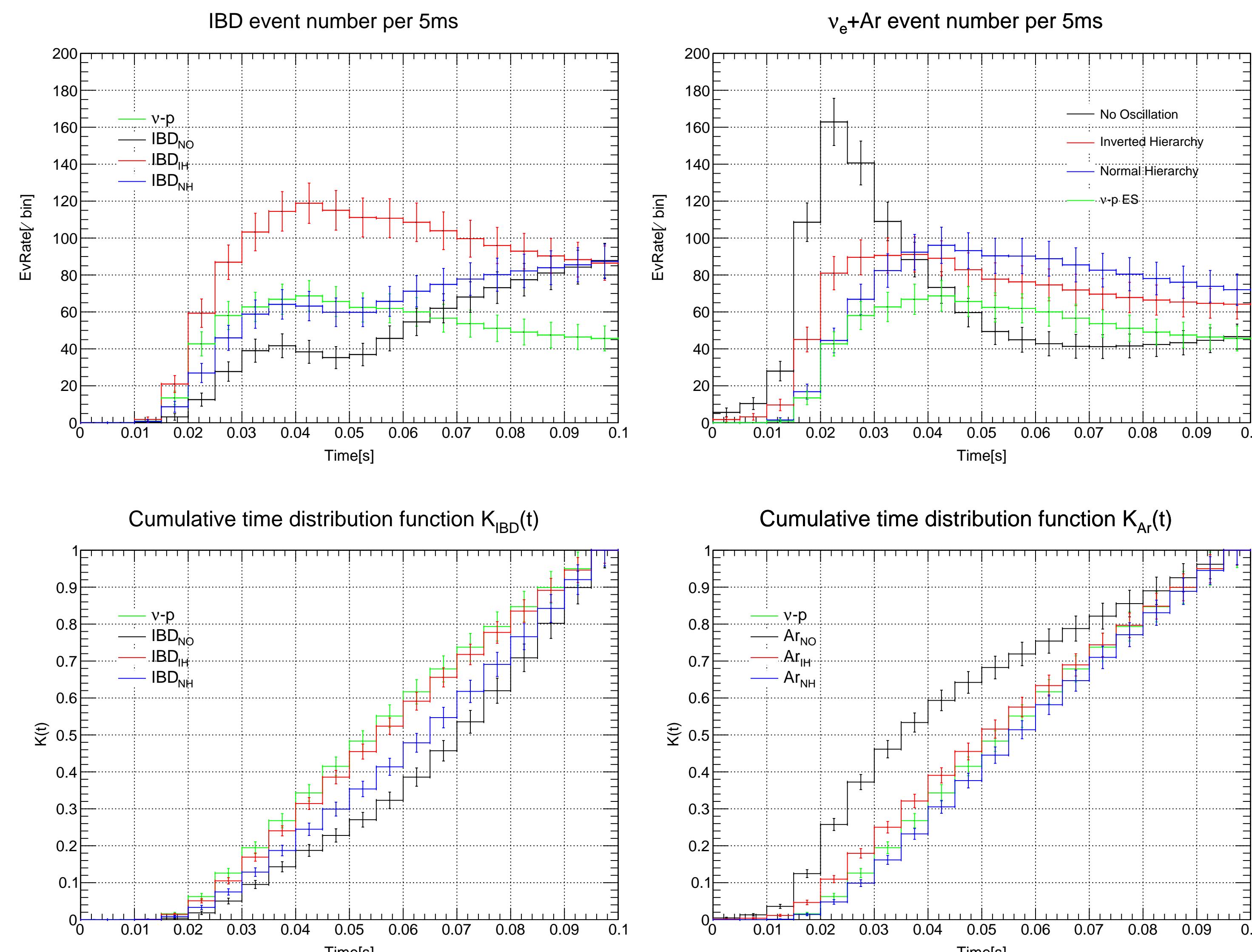
Inverse Beta Decay (IBD)<sup>[5]</sup>



Argon Neutrino Absorption ( $\nu_e$ Ar)<sup>[2]</sup>



## Event Rates and Cumulative Time Distributions

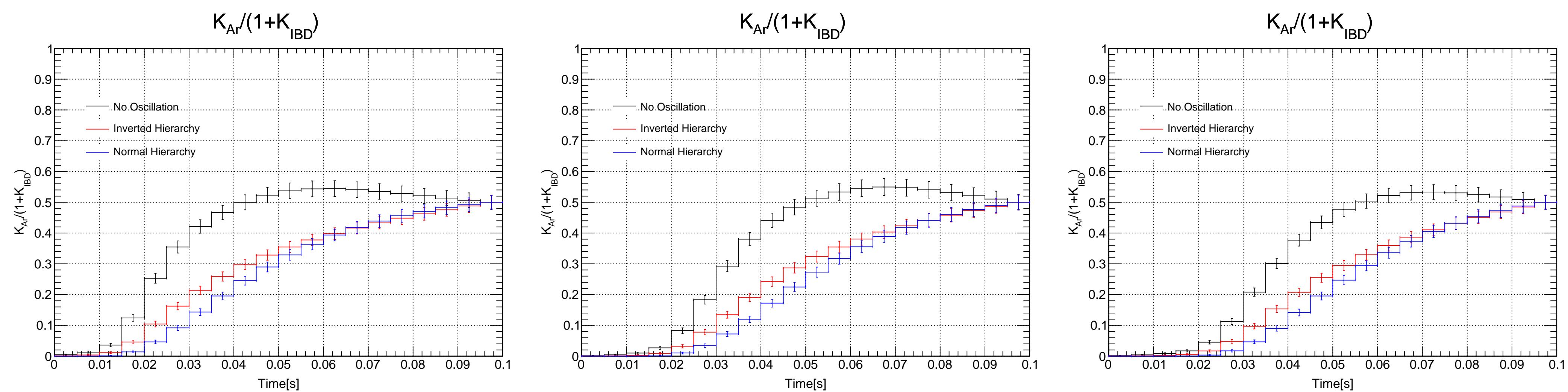


The event rates of IBD, pES and  $\nu_e$ Ar reactions are obtained by convoluting their corresponding reaction cross-section and SN neutrino differential fluxes over energies, they exhibit several shapes in different neutrino mass ordering scenarios.

The definition of cumulative time distribution function is given in following "Definitions" section.

- Non-oscillation scenario has the fastest accumulation rate than the others for  $\nu_e$ Ar event and the slowest rate for IBD event.
- Taking the ratio of two cumulative time distribution can effectively demonstrate the differences between the non-oscillation scenario (black) and the others (blue and red).

## Ratio of Cumulative Time Distributions



The figures above showed the ratio of cumulative distribution for Nakazato's SN models with 13, 20 and 30  $M_\odot$  progenitor mass. One can see that the non-oscillation scenario exhibit a different pattern compared to those of MSW oscillation scenarios in all three SN simulation analysis. We believe that such ratios will be useful for testing the occurrence of MSW oscillations for neutrinos in SNe.

## Definitions

Cumulative Time Distributions<sup>[8]</sup>:

$$K(t_i) \equiv \int_0^{t_i} \frac{dN}{dt} dt / \int_0^{100\text{ms}} \frac{dN}{dt} dt$$

Ratio of Cumulative Time Distributions:

$$K_r(t_i) \equiv K_{\text{Ar}}(t_i) / (1 + K_{\text{IBD}}(t_i))$$

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## Conclusion

JUNO and DUNE can measure IBD and  $\nu_e$ Ar events, respectively. The MSW oscillation effect in SN can be tested by investigating the ratio of cumulative time distributions.

It is observed that, for non-oscillation case, there exists a local maximum in the ratio of cumulative time distribution for  $t$  between 0 to 100 ms with a value greater than 0.5.

## References

- [1] Neutrino Physics with JUNO, J. Phys. G 43 (2016) 030401, arXiv:1507.05613v2 [physics.ins-det]
- [2] DUNE Conceptual Design Report, arXiv:1512.06148v2 [physics.ins-det]
- [3] A. S. Dighe and A. Y. Smirnov, Phys. Rev. D 62, 033007 (2000), arXiv:hep-ph/9907423.
- [4] J. F. Beacom, W. M. Farr, P. Vogel, "Detection of Supernova Neutrinos by Neutrino-Proton Elastic Scattering", Phys. Rev. D66 (2002) 033001
- [5] A. Strumia, F. Vissani, "Precise quasielastic neutrino/nucleon cross section", Phys. Lett. B564:42-54, 2003
- [6] K. C. Lai et al., "Probing Neutrino Mass Hierarchy by Comparing the Charged-Current and Neutral-Current Interaction Rates of Supernova Neutrinos", JCAP 07 (2016) 039
- [7] K. Nakazato et al., "Supernova Neutrino Light Curves and Spectra for Various Progenitor Stars: From Core Collapse to Proto-neutron Star Cooling", Astrophys.J.Supp.205:2,2013
- [8] Tobias Fischer, Lorenz Hudepohl et al., "Probing the neutrino mass hierarchy with the rise time of supernova burst", Phys. Rev. D85 085031