Prospects of neutrino mass ordering with supernova neutrinos in the upcoming long-baseline experiments

based on the paper: arXiv:hep-ph[2304.13303]

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Main objectives

The main objectives of this presentation are:

- To show mass ordering sensitivity of the supernova neutrinos by detailed statistical analysis in two future neutrino experiments: DUNE and T2HK .
- To see the effect of different types of systematics on mass ordering sensitivity.
- To see the effect of energy smearing on mass ordering sensitivity.

Overview

- When a massive star of $M > 8M_\odot$ comes to the end of its life, often the core of the star collapses and explodes with huge energy and luminosity. This is called as core-collapse supernova.
- Neutrinos coming out from core-collapse supernova take 99% of its total gravitational energy after the explosion, where optical photons take only 1%.

Why supernova neutrinos?

- Neutrinos produced in the supernova reach earth before the optical photons: neutrinos from SN1987A come out nearly 2.5 hours prior to photons.
- Help to know about supernova evolution, black hole and neutron star formation.
- Improve the understanding of neutrino physics.

Garching parametrization (ECSN model) *Phys.Rev.Lett. 105, 249901

Remarks

- We have taken Garching electron-capture supernova model (ECSN).
- Flavor dependent primary neutrino spectra can be parametrized by

$$\Phi_\nu(E) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha e^{-(\alpha+1)\frac{E}{\langle E_\nu\rangle}} \tag{1}$$

where α represents the pinching parameter.

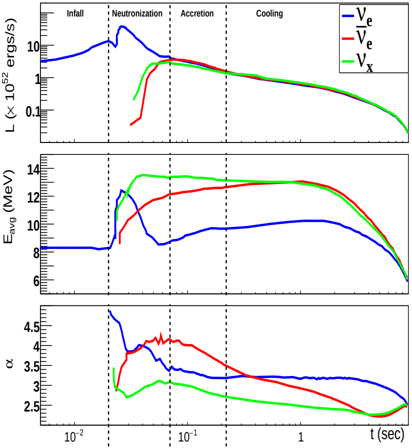
- $\mathcal{N}$ is the normalisation constant expressed as

$$\mathcal{N} = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)} \tag{2}$$

- The neutrino flux (F_ν^0) at neutrinosphere

$$F_\nu^0 = \frac{L_\nu}{\langle E\rangle_\nu}\Phi_\nu(E) \tag{3}$$

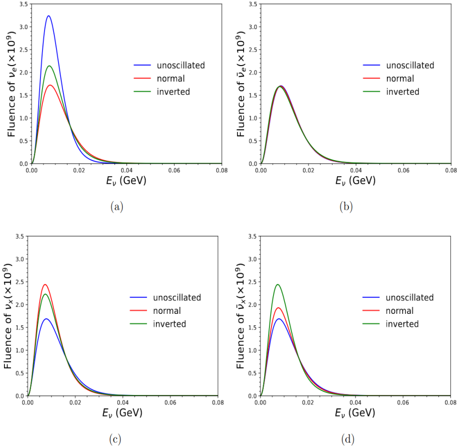
Garching parametrization (ECSN model) *Phys.Rev.Lett. 105, 249901



Three stages of explosion: neutronization, accretion and cooling.

- **Neutronization era** → 0.02 seconds to 50 ms.
- **Accretion** → 50 ms to 0.2 sec
- **Cooling** → 0.2 sec to 9 seconds.

Integrated flux



- Flux expressions in presence of MSW effect,

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x},$$
$$F_{\bar{\nu}_e} = \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\bar{\nu}_x},$$
$$2F_{\nu_x} = (1-p)F^0_{\nu_e} + (1+p)F^0_{\nu_x},$$
$$2F_{\bar{\nu}_x} = (1-\bar{p})F^0_{\bar{\nu}_e} + (1+\bar{p})F^0_{\bar{\nu}_x}$$

Survival probabilities in MSW

Ordering	p	$\bar{p}$
Normal	$\sin^2\theta_{13}$	$\cos^2\theta_{12}\cos^2\theta_{13}$
Inverted	$\sin^2\theta_{12}\cos^2\theta_{13}$	$\sin^2\theta_{13}$

Table: Survival probability expressions of neutrino (p) and antineutrino ($\bar{p}$) fluxes for two cases: normal ordering and inverted ordering.

Simulation details

SNOwGLoBES

- SNOwGLoBES (**S**upernova **N**eutrino **O**bservatories **w**ith **G**eneral **Lo**ng **B**aseline **E**xperiment **S**imulator) is a package for calculating mean event rate for each interaction type.
- Low energy neutrinos (5-55 MeV) are studied with different models.
- Most of the current and future detectors are sensitive to detect $\bar{\nu}_e$ (exception: DUNE, it will detect ν_e).

Experiments and their details

Experiment	DUNE-FD	HK
detector volume	40 kt	374 kt (187×2)
Energy resolution	20%	18%
Baseline	1300 km	295 km

Main channels:

Experiment	Channel-A	Channel-B	Channel-C
DUNE	$\nu_e - ^{40}\mathrm{Ar}$	$\bar{\nu}_e - ^{40}\mathrm{Ar}$	$\nu_e - e$
T2HK	IBD	$\bar{\nu}_e - ^{16}O$	$\nu_e - e$

Table: Different interaction modes for two experiments, DUNE and T2HK

Event spectra

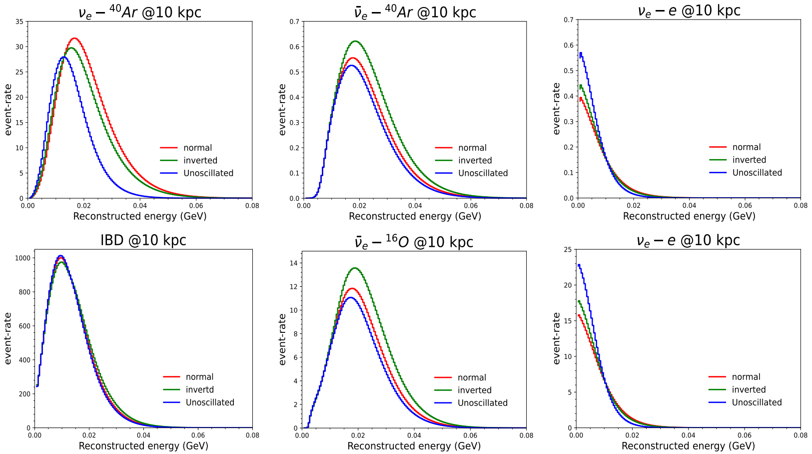


Figure: Event-rates vs reconstructed energy for DUNE and T2HK in three different cases: unoscillated (blue), normal ordering (red) and inverted ordering (green). Upper row: DUNE, lower row: T2HK @10 kpc

χ^2 calculation:

Formula

$$\chi^2_{\text{stat}} = 2\sum_{i=1}^{n}\left[N_i^{\text{test}} - N_i^{\text{true}} - N_i^{\text{true}}\log\left(\frac{\text{N}_\text{i}^{\text{test}}}{\text{N}_\text{i}^{\text{true}}}\right)\right]. \quad (4)$$

Mass-ordering vs supernova distance

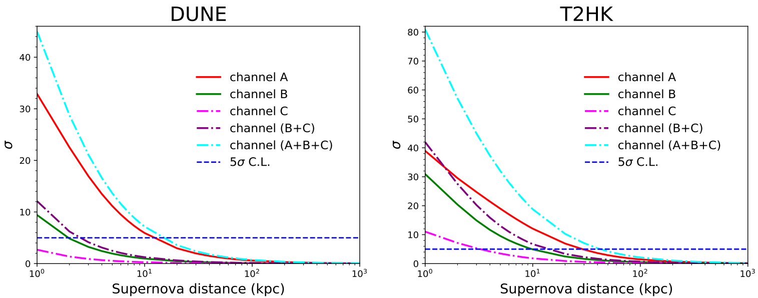


Figure: Neutrino mass ordering sensitivity as a function of supernova distance (in kpc).

Experiment	Channel-A	Channel-B	Channel-C
DUNE	$\nu_e -^{40}$ Ar	$\bar{\nu}_e -^{40}$ Ar	$\nu_e - e$
T2HK	IBD	$\bar{\nu}_e -^{16} O$	$\nu_e - e$

Effect of systematics

- Modified test spectrum in presence of systematics:

$$N_i^{\rm test} \to N_i^{\rm test}[(1+0.05\zeta_1)+0.05\zeta_2(E_i' - \bar{E}')/(E'_{\rm max} - E'_{\rm min})]$$

- ζ_1 is the pull variable responsible for normalisation error.
- ζ_2 is the pull variable responsible for energy calibration errors.
- $E'_{\rm max}$ and $E'_{\rm min}$ are maximum and minimum energy of the event spectrum respectively.
- $\bar{E}' = \frac{1}{2}(E'_{\rm max} + E'_{\rm min})$.
- Chi-square formula in presence of systematics:

$$\chi^2_{\rm stat+sys} = \chi^2_{\rm stat} + \zeta_1^2 + \zeta_2^2\ .$$

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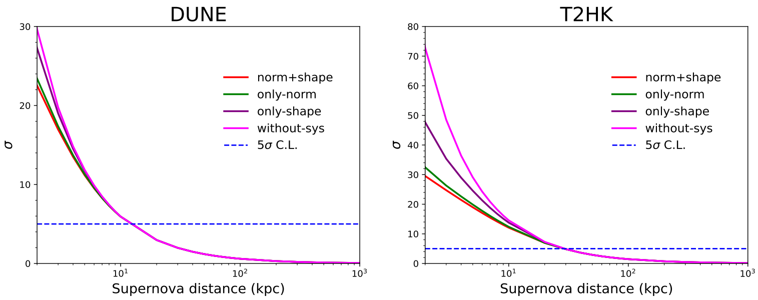

Figure: Left panel: mass ordering sensitivity with respect to supernova distance (in kpc) for DUNE. Right panel: mass ordering sensitivity with respect to supernova distance (in kpc) for T2HK. For each panel, main channel has been considered.

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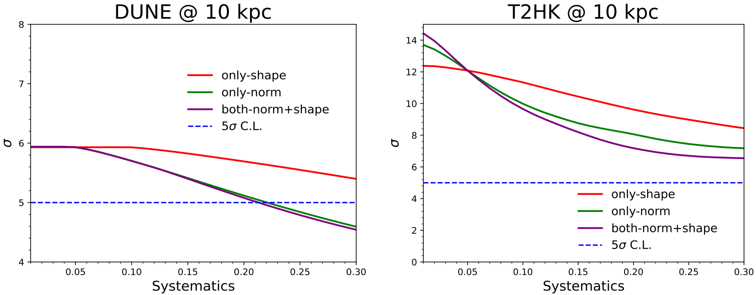

Figure: Mass ordering sensitivity at supernova distance 10 kpc as a function systematic error for channel A of both the experiments.

Effect of energy smearing

What is energy smearing

- Energy of the neutrinos will be reconstructed by measuring the energy and momentum of the outgoing leptons
- In our analysis, we incorporate this effect by the inclusion of energy resolution.
- Because of this energy resolution, the neutrino events will be smeared around its true energy causing a loss of information.
- In the presence of energy smearing, the sensitivity expected to become worse as compared to the sensitivity without energy smearing.

Effect of energy smearing

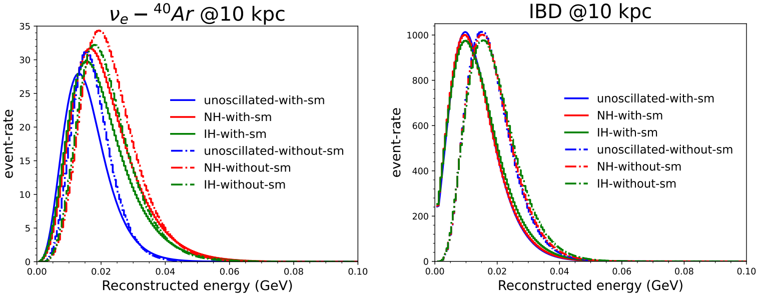

Figure: Event rates vs neutrino energy (in GeV) with and without the energy resolution effect. Left is for DUNE, right is for T2HK.

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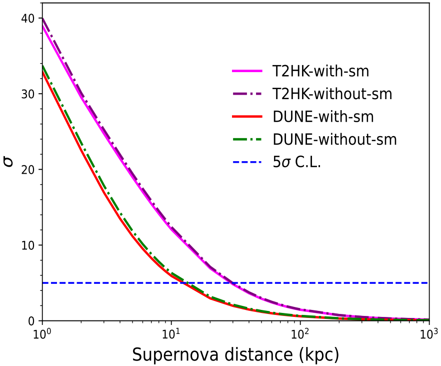


Figure: Mass hierarchy sensitivity as a function of supernova distance (in kpc) for DUNE and T2HK with (solid) and without (dashed-dotted) energy smearing.

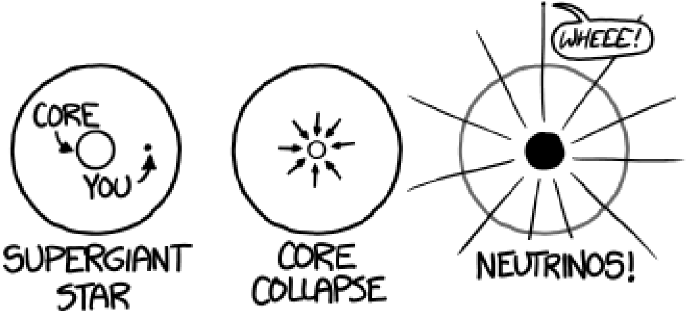
Summary and conclusion

Setup	SD Channel A	SD Channel B	SD Channel C	SD Channel (B+C)	SD Channel (A+B+C)
DUNE	12.4 kpc	1.9 kpc	-	2.5 kpc	15.2 kpc
T2HK	29.1 kpc	9.8 kpc	3.2 kpc	14.2 kpc	42.7 kpc

Table: Supernova distances for which a 5σ mass ordering sensitivity can be achieved. For the table, we have considered the systematic errors for both normalisation and energy calibration.

- For the most optimistic case i.e., we expect that the neutrino mass ordering can be determined at 5 σ C.L., if the supernova explosion occurs at a distance of 42.7 kpc for T2HK and 15.2 kpc for DUNE. This is true if we assume a 5% systematic error in our analysis.
- Among normalisation error and energy calibration error, the deterioration of the sensitivity is mostly dominated by the normalisation error.
- The sensitivity of DUNE and T2HK will be deteriorated to some extent because of the energy smearing which will arise due to the energy reconstruction of the supernova neutrinos.

Thank you for your attention



Backup Slides

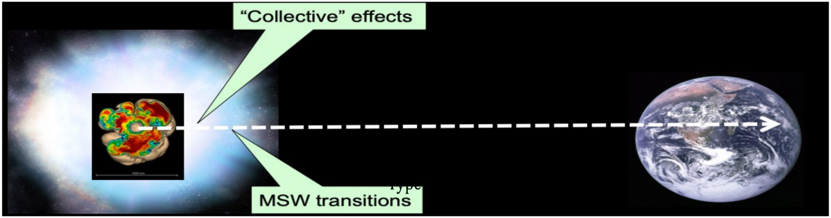
What is Garching model

- A $8.8 M_{\odot}$ electron-capture supernova is simulated in spherical symmetry framework.
- The sperical symmetry framework has been used throughout the supernova evolution to complete deleptonization of the forming neutron star.

Possible backgounds for supernova neutrinos

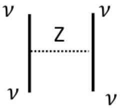
- For Galactic supernova burst, the rate of backgrounds in current and future experiments are very low.
- Background for supernova neutrinos can come from radioactivity, cosmic ray, reactor $\bar{\nu}_e$, solar ν_e etc.
- Even some of the backgrounds can come from low energy atmospheric neutrinos and antineutrinos.
- Fortunately, most of these can be suppressed by taking the detector underground.

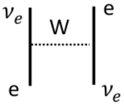
Collective effect



$$H = H_V + H_{\mathrm{coll}} + H_{\mathrm{MSW}} \tag{5}$$

- Collective effects: $\nu \rightarrow \nu$ NC forword scattering
- MSW Transitions: $\nu - e$ CC forward exchange scattering





Why we don't take collective effect

- Collective effects is an active area of research and their effect on neutrino flavour conversions are yet to be understood fully.
- A full multi-angle study of neutrino self-interactions showed that the energy dependent modifications of the spectrum would get smeared out when considering the post-bounce time integrated spectrum and corrections are expected to be small.