Parallel talk for DAE BRNS conference (reg. id: 382)

Probing Neutrino Mass Ordering with Supernova Neutrinos in NOνA with Active-Active vs. Active-Sterile Scenarios

Based on the paper; hep-ph 2412.05213

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Motivation of the work

- To show mass ordering sensitivity of the supernova neutrinos by detailed statistical analysis in currently running neutrino experiment; NOνA .
- To provide a study of **active-active** and **active-sterile** mixing frameworks → **supernova neutrinos can be used to realize the existence of sterile neutrinos.**
- Interactions among active neutrinos → **active-active** framework
  interactions involving sterile neutrinos → **active-sterile** framework.
- To see the effect of different types of systematics on mass ordering sensitivity.
- To see the effect of energy smearing on mass ordering sensitivity.

What is supernova neutrino?

- The core of a massive star with a mass greater than $8M_\odot$, where $M_\odot$ is the mass of the sun, collapses with a tremendous amount of energy and light at the end of its life, producing a “core-collapse supernova”.
- Approximately 99% of this energy is carried away by neutrinos of various types, and their weakly interacting nature provides valuable insights into the supernova explosion mechanism.

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.

Supernova neutrinos to understand sterile neutrino existence

- In this study, we assume that sterile neutrinos are produced during neutrino oscillations occurring in the region between the core and the surface of the supernova.
- In our calculations, we have considered only the Mikheyev-Smirnov-Wolfenstein (MSW) effect.

Garching parametrization (ECSN model)

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

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

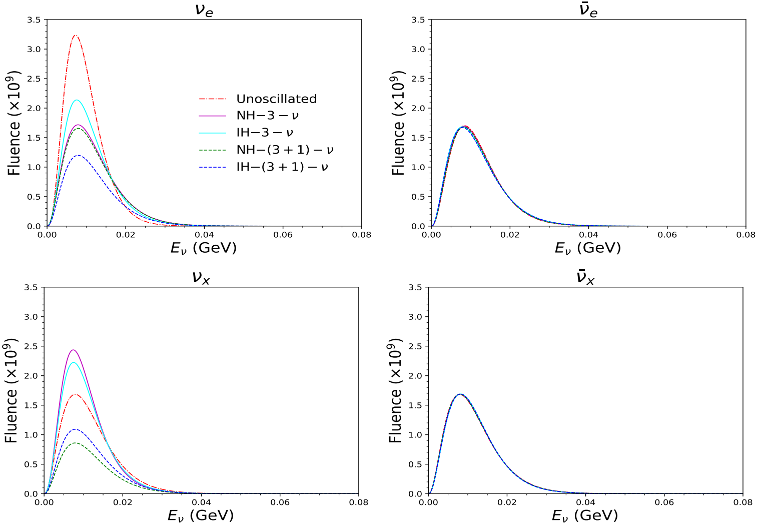
- $\mathcal{N}$ is the normalisation constant with the expression,

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

- The neutrino flux (F_ν^0) at neutrinosphere,

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

Fluences



Fluence (integrated flux over time) as a function of neutrino energy (E_ν) in GeV. Left (right) of upper row is for $\nu_e(\bar{\nu}_e)$ while left (right) of lower panel is for $\nu_x(\bar{\nu}_x)$ flavour. In each panel, color code is given in the legend.

- Flux expressions in active-active scenario,

$$\begin{aligned}
F_{\nu_e} &= pF^0_{\nu_e} + (1-p)F^0_{\nu_x} \\
F_{\bar{\nu}_e} &= \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\bar{\nu}_x} \\
2F_{\nu_x} &= (1-p)F^0_{\nu_e} + (1+p)F^0_{\nu_x} \\
2F_{\bar{\nu}_x} &= (1-\bar{p})F^0_{\bar{\nu}_e} + (1+\bar{p})F^0_{\bar{\nu}_x},
\end{aligned} \tag{4}$$

- Flux expressions in active-sterile framework,

$$\begin{aligned}
F_{\nu_e} &= a_{ee}F^0_{\nu_e} + a_{ex}F^0_{\nu_x} + a_{es}F^0_{\nu_s} \\
F_{\bar{\nu}_e} &= b_{ee}F_{\bar{\nu}^0_e} + b_{ex}F_{\bar{\nu}^0_x} + b_{es}F^0_{\bar{\nu}_s} \\
2F_{\nu_x} &= (a_{\mu e} + a_{\tau e})F^0_{\nu_e} + (a_{\mu x} + a_{\tau x})F^0_{\nu_x} + (a_{\mu s} + a_{\tau s})F^0_{\nu_s} \\
2F_{\bar{\nu}_x} &= (b_{\mu e} + b_{\tau e})F^0_{\bar{\nu}_e} + (b_{\mu x} + b_{\tau x})F^0_{\bar{\nu}_x} + (b_{\mu s} + b_{\tau s})F^0_{\bar{\nu}_s} \\
F_{\nu_s} &= a_{se}F^0_{\nu_e} + a_{sx}F^0_{\nu_x} + a_{ss}F^0_{\nu_s} \\
F_{\bar{\nu}_s} &= b_{se}F^0_{\bar{\nu}_e} + b_{sx}F^0_{\bar{\nu}_x} + b_{ss}F^0_{\bar{\nu}_s},
\end{aligned} \tag{5}$$

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

In active-active neutrino framework, survival probability expressions of neutrino (p) and antineutrino ($\bar{p}$) fluxes for two cases: normal hierarchy (NH) and inverted hierarchy (IH).

Hierarchy	$a_{\alpha e}$	$a_{\alpha x}$	$b_{\alpha e}$	$b_{\alpha x}$
Normal	$\lvert U_{\alpha 4}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2 + \lvert U_{\alpha 2}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2$	$\lvert U_{\alpha 2}\rvert^2 + \lvert U_{\alpha 3}\rvert^2$
Inverted	$\lvert U_{\alpha 4}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2 + \lvert U_{\alpha 3}\rvert^2$	$\lvert U_{\alpha 3}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2 + \lvert U_{\alpha 2}\rvert^2$

In the active-sterile neutrino framework, the expressions for the couplings of neutrinos ($a_{\alpha e}$, $a_{\alpha x}$) and anti-neutrino ($b_{\alpha e}$, $b_{\alpha x}$) are provided for two scenarios: normal hierarchy (NH) and inverted hierarchy (IH).

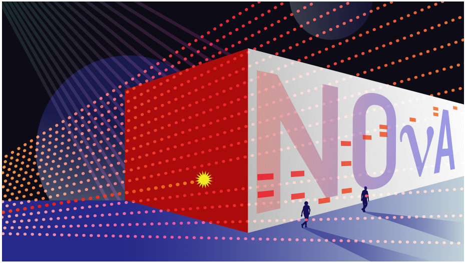
- **Different values of oscillation probabilities in normal and inverted hierarchy scenario → results of non-zero mass hierarchy sensitivity.**

Experimental setup

- NOνA (NuMI Off-axis Appearance) experiment is a currently ongoing long-baseline accelerator neutrino experiment.
- Material of far detector; mainly ^{12}C, fiducial volume → 14 kilotons.

Parameters	Values
θ_{12}	33.41°
θ_{13}	8.58°
θ_{23}	42.20°
θ_{14}	5°
Δm^2_{21}	$7.410 \times 10^{-5}\ eV^2$
Δm^2_{31}	$\pm 2.507 \times 10^{-3}\ eV^2$
Δm^2_{41}	$1\ eV^2$

Neutrino oscillation parameter values used in the study.



Simluation details

- For our simulations, we use the Supernova Neutrino Observatories with GLoBES (SNOwGLoBES) software.
- This tool is specifically designed to study supernova neutrinos. SNOwGLoBES calculates event rates by utilizing input parameters such as neutrino fluxes, cross sections, and detector configurations.
- For calculating mass hierarchy sensitivity, Poisson log-likelihood statistical formula is,

$$\chi^2_{\mathrm{stat}} = 2\sum_{i=1}^{n}\left[N_i^{\mathrm{test}} - N_i^{\mathrm{true}} - N_i^{\mathrm{true}}\log\left(\frac{\mathrm{N}_\mathrm{i}^{\mathrm{test}}}{\mathrm{N}_\mathrm{i}^{\mathrm{true}}}\right)\right], \tag{6}$$

Main channels

Channel	Framework: $3\nu/(3+1)\nu$	Hierarchy	Event Number
Channel (i) (IBD)	3ν	NH	129665
		IH	133128
	$(3+1)\nu$	NH	128679
		IH	132117
Channel (ii) ($\bar{\nu}_e - C^{12}$)	3ν	NH	3856.54
		IH	4411.67
	$(3+1)\nu$	NH	3827.24
		IH	4378.15
Channel (iii) ($\nu_e - C^{12}$)	3ν	NH	3809.95
		IH	2996.25
	$(3+1)\nu$	NH	3767.84
		IH	2713.18
Channel (iv) ($\nu_e - e$)	3ν	NH	1123.14
		IH	1178.39
	$(3+1)\nu$	NH	1095.48
		IH	791.09

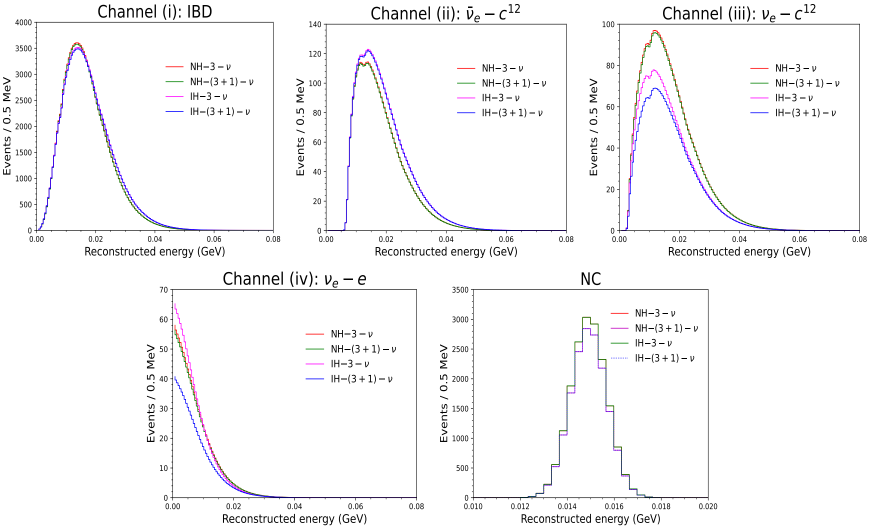
Event numbers for different channels (Channel (i), Channel (ii), Channel (iii), and Channel (iv)) at a supernova distance of 1 kpc. NH (normal hierarchy) and IH (inverted hierarchy) represent the mass hierarchy, while 3ν [$(3+1)\nu$] represents the active-active [active-sterile] neutrino framework.

NC channels

Scenario	NH/IH	$\nu_e - ^{12}C$	$\bar{\nu}_e - ^{12}C$	$\nu_\mu - ^{12}C$	$\bar{\nu}_\mu - ^{12}C$	$\nu_\tau - ^{12}C$	$\bar{\nu}_\tau - ^{12}C$	Total NC
3ν	NH	2274.80	2019.66	1533.19	2242.18	1533.19	2242.18	**11845.21**
	IH	1838.70	2300.71	1751.24	2101.66	1751.24	2101.66	**11845.21**
$(3+1)\nu$	NH	2247.06	2004.31	1180.84	2242.18	1180.84	2242.18	**11097.41**
	IH	1618.02	2283.22	1497.76	2101.66	1497.76	2101.66	**11100.08**

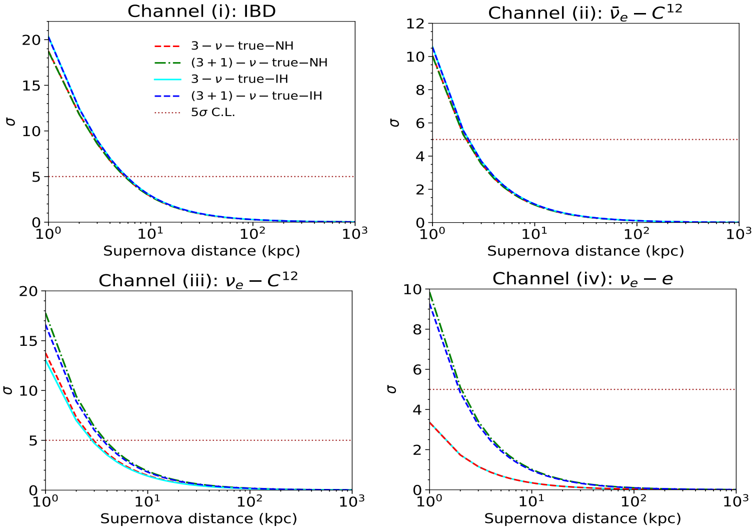
The event rates for six types of neutral current channels at a supernova distance of 1 kpc for different mass hierarchy cases: NH and IH. 3ν [$(3+1)\nu$] represents the active-active [active-sterile] neutrino framework.

Event rates



Event rate in active-active and active-sterile frameworks for five different channels for supernova at a distance of 1 kpc. Color codes are given in the legend. NH (IH) represents the normal (inverted) hierarchy.

Mass hierarchy sensitivity



Mass ordering sensitivity as a function of supernova distance (in kpc). Color code are given in the legends.

Conclusion I

- The primary channel of NOνA can distinguish normal mass hierarchy from inverted mass hierarchy at 5σ confidence level for a supernova explosion occurring at a distance of 5 kpc.
- Observation of the NC channel alone can differentiate between the presence and absence of sterile neutrinos.
- Mass hierarchy sensitivity is more in active-steile framework than active-active scenario.

Effect of systematics

- The test event rate including normalisation and energy calibration error is expressed as

$$N_i^{\text{test}} \to N_i^{\text{test}}[(1+a) + b(E'_i - \bar{E}')/(E'_{\max} - E'_{\min})], \tag{7}$$

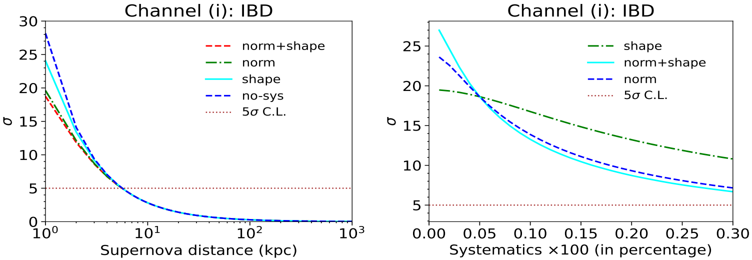
- a, b → the nuisance parameters corresponding to the normalization and energy calibration errors.
- For a 5% systematic error in both types, the nuisance parameters a and b can be expressed in terms of the pull variables p_1 and p_2 as

$$a = 0.05\,p_1, \qquad b = 0.05\,p_2. \tag{8}$$

Finally, in presence of systematics errors, the final expression of sensitivity is,

$$\chi^2_{\text{stat+sys}} = \chi^2_{\text{stat}} + p_1^2 + p_2^2\ . \tag{9}$$

Effect of systematics



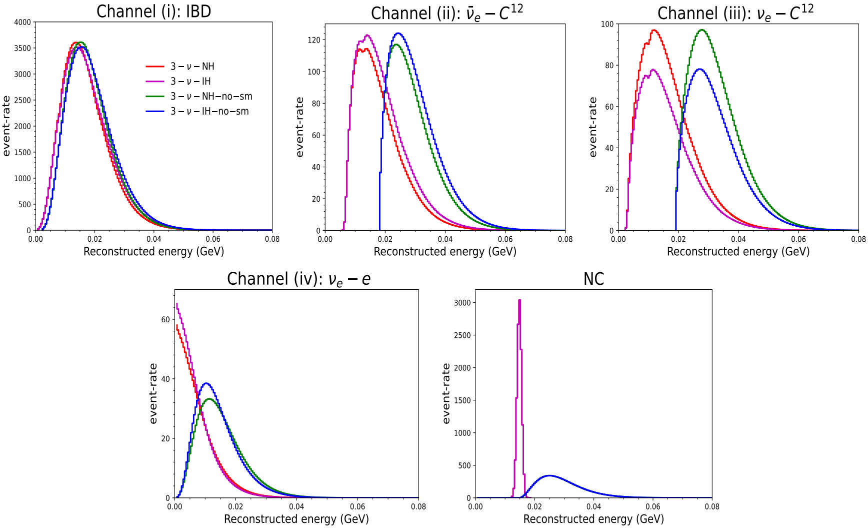
Left : Mass hierarchy sensitivity as a function of supernova distance (in kpc) for main channel in different systematics uncertainty conditions; “norm” (“shape”) stands for normalization (energy calibration) error. Right: mass hierarchy sensitivity with respect to systematic error.

Conclusion II

- Presence of systematic error decreases the mass hierarchy sensitivity.
- Among normalisation error and energy calibration error, the deterioration of the sensitivity is mostly dominated by the normalisation error.
- As systematic uncertainty increases from 0% to 30%, the sensitivity decreases from 25σ to 12σ for the primary IBD channel.

Effect of smearing

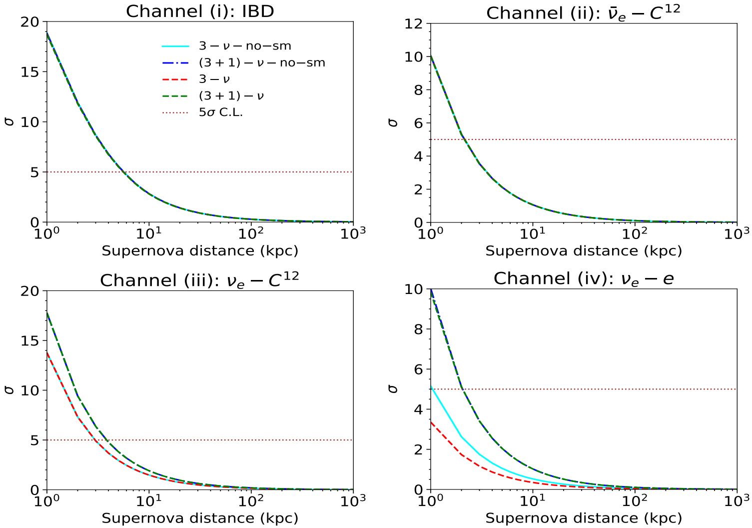
- Energy of the neutrinos will be reconstructed by measuring the energy and momentum of the outgoing leptons.
- In our analysis, we incorporate this effect by the inclusion of energy resolution.
- Because of this energy resolution, the neutrino events will be smeared around its true energy causing a loss of information.



Event rate for active-active framework as a function of neutrino energy (GeV) for all the main channels and NC. Similar nature has been shown for active-sterile scenario also. Here sm [no-sm] refers to the terms with [without] smearing matrix. Color codes are given in the legend of each panel.

Conclusion III

- For channels (i), (ii), and (iii), the event rate spectra remain similar in shape but shift leftward due to energy smearing, as the smearing reduces the reconstructed energy of events.
- For channel (iv), energy smearing modifies the shape of the event rate spectrum.
- For the NC channel, the spectrum becomes more compact with energy smearing, whereas, without smearing, the spectrum is more widely spread.



Mass hierarchy sensitivity as a function of supernova distance (in kpc) with [without] smearing matrix condition for all the channels. Here sm [no-sm] refers to the terms with [without] smearing matrix. Color codes are given in the legend of each panel.

Conclusion

- Work presents a detailed analysis of mass hierarchy sensitivity using supernova neutrinos within the active-active and active-sterile frameworks, focusing on the context of the NOνA experiment.
- The study incorporates the impact of sterile neutrinos on mass hierarchy sensitivity.
- The study shows mass hierarchy sensitivity as a function of supernova distance for both active-active and active-sterile scenarios. Primary channel of NOνA can distinguish normal mass hierarchy from inverted mass hierarchy at 5σ confidence level for a supernova explosion occurring at a distance of 5 kpc.
- Considering NC channel, although active-active scenario is blind on hierarchy conditions, there is a non-zero mass hierarchy sensitivity in active-sterile framework.
- In the presence of energy smearing, the sensitivity expected to become worse as compared to the sensitivity without energy smearing.

Backup Slides

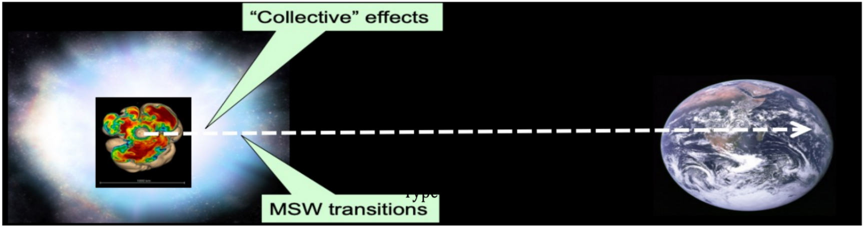
What is Garching model

- $8.8M_{\odot}$ 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

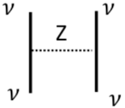
- For Galactic supernova burst, the rate of backgrounds in current and future experiments are very low.
- Background for supernova neutrinos can come from radioactivity, cosmic ray, reactor $\bar{\nu}_e$, solar ν_e etc.
- Even some of the backgrounds can come from low energy atmospheric neutrinos and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

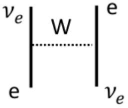
Collective effect



$H = H_V + H_{coll} + H_{MSW}$

- 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.