Triangulation and Neutrino Mass Ordering Determination with SNEWS

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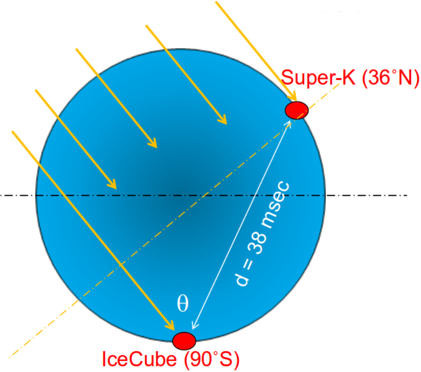
Supernova Triangulation



Delay between the arrival times of the neutrino pulse:

$$\Delta t = \frac{d}{c} \cos\theta$$

- A. Burrows, D. Klein, and R. Gandhi, Phys. Rev. D45, 3361 (1992)
- J. Beacom, P. Vogel, Phys. Rev. D60 (1999)
- VB, Manfred Lindner, Xun-Jie Xu, JCAP 1804 (2018) 025
- N. B. Linzer and K. Scholberg, Phys. Rev. D 100, 103005 (2019)
- A. Coleiro et al., Eur. Phys. J. C 80, 856 (2020)

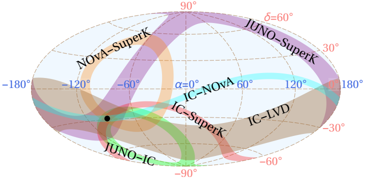
Uncertainties on SN Neutrino Arrival Times

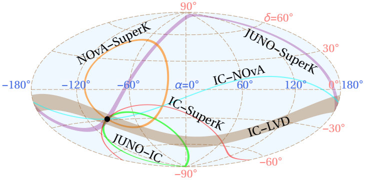
- to determine δt we adopt χ^2 fit: $\chi^2(t_0) = 2\sum_{i=1}^{i_{\max}} \left(\mu_i - n_i + n_i \ln \frac{n_i}{\mu_i}\right)$ $N_\alpha^i(A,\, t_0) = A \int dE \int_{t_i}^{t_i+\Delta t} dt\, \sigma(E)\, \phi_{\nu_\alpha}(\, t - t_0, E)$; fluxes form Garching group
- we include a background $\mu_{\rm bkg}$ – 0.01 events per second for Super-K (rescaled for other experiments according to the fiducial volume)

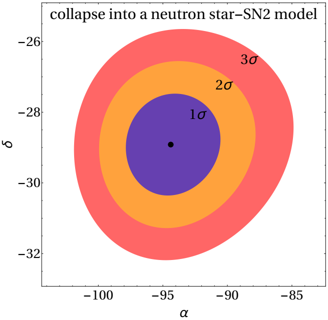
Experiments	major process	target	$N_{\rm total}$	δt	$N_{\rm total}$ (BH)	δt (BH)
Super-Kamiokande [27]	$\overline{\nu}_e + p \to e^+ + n$	32 kt H_2O	7625	0.9 ms	6666	0.14 ms
JUNO [43]	$\overline{\nu}_e + p \to e^+ + n$	20kt C_nH_m	4766	1.2 ms	4166	0.19 ms
RENO50 [60]	$\overline{\nu}_e + p \to e^+ + n$	18kt C_nH_m	4289	1.3 ms	3749	0.21 ms
DUNE [61]	$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$	40 kt LAr	3297	1.5 ms	3084	0.18 ms
NOνA [62]	$\overline{\nu}_e + p \to e^+ + n$	15 kt C_nH_m	3574	1.4 ms	3125	0.24 ms
CJPL [63]	$\overline{\nu}_e + p \to e^+ + n$	3kt H_2O	715	3.8 ms	625	0.97 ms
IceCube [64]	noise excess	H_2O	$\mathcal{O}(10^6)$[65]	1ms	$\mathcal{O}(10^6)$[65]	0.16 ms
ANTARES [66]	noise excess	H_2O	$\mathcal{O}(10^3)$[67]	100ms	$\mathcal{O}(10^3)$[67]	32 ms
Borexino [68]	$\overline{\nu}_e + p \to e^+ + n$	0.3 kt C_nH_m	71.5	16 ms	62.5	5.5 ms
LVD [69]	$\overline{\nu}_e + p \to e^+ + n$	1 kt C_nH_m	238	7.5 ms	208	2.4 ms
XENON1T [70]	coherent scattering	2t X_e	31	27 ms	29	10 ms
DARWIN [57]	coherent scattering	40t X_e	622	1.3 ms	588	0.7 ms

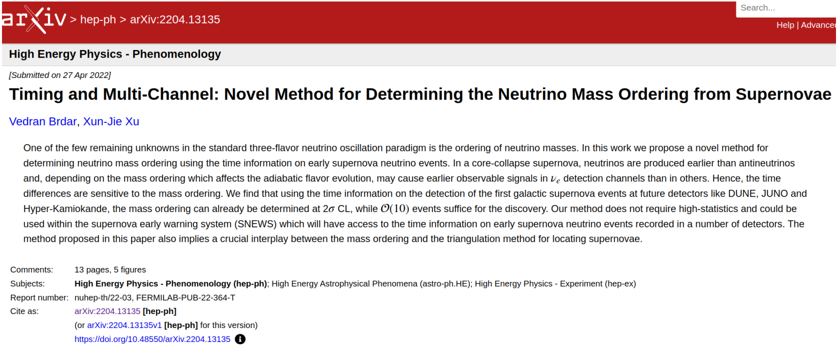
Triangulation Results

- time difference of SN neutrino arrival at two detectors located at $\vec{r}_i$ and $\vec{r}_j$ reads $t_{ij} = (\vec{r}_i - \vec{r}_j) \cdot \vec{n}/c$
- for a pair of detectors $\chi^2_{ij}(\alpha, \delta) = \left(\frac{t_{ij}(\alpha', \delta') - t_{ij}(\alpha, \delta)}{\mathrm{Max}(\delta t_i, \delta t_j)} \right)^2$ and for more than two detectors involved in the analysis $\chi^2_{\mathrm{tot}}(\alpha, \delta) = \sum_{i,j}^{i<j} \chi^2_{ij}(\alpha, \delta)$









arXiv > hep-ph > arXiv:2204.13135

High Energy Physics - Phenomenology

[Submitted on 27 Apr 2022]

Timing and Multi-Channel: Novel Method for Determining the Neutrino Mass Ordering from Supernovae

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One of the few remaining unknowns in the standard three-flavor neutrino oscillation paradigm is the ordering of neutrino masses. In this work we propose a novel method for determining neutrino mass ordering using the time information on early supernova neutrino events. In a core-collapse supernova, neutrinos are produced earlier than antineutrinos and, depending on the mass ordering which affects the adiabatic flavor evolution, may cause earlier observable signals in ν_e detection channels than in others. Hence, the time differences are sensitive to the mass ordering. We find that using the time information on the detection of the first galactic supernova events at future detectors like DUNE, JUNO and Hyper-Kamiokande, the mass ordering can already be determined at 2σ CL, while $\mathcal{O}(10)$ events suffice for the discovery. Our method does not require high-statistics and could be used within the supernova early warning system (SNEWS) which will have access to the time information on early supernova neutrino events recorded in a number of detectors. The method proposed in this paper also implies a crucial interplay between the mass ordering and the triangulation method for locating supernovae.

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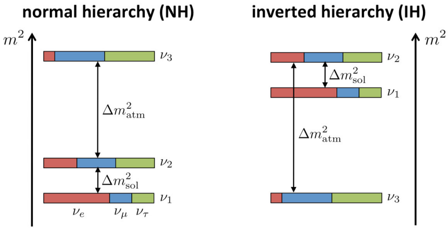


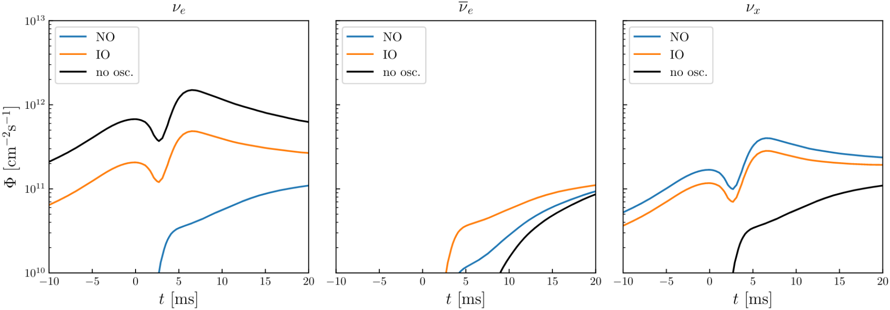
Neutrino Fluxes

Inverted Ordering (IO)

$$\begin{aligned}
\Phi_{\nu_e} &= \Phi^0_{\nu_e} \sin^2\theta_{12} + \Phi^0_{\nu_x} \cos^2\theta_{12}\,, \\
\Phi_{\bar\nu_e} &= \Phi^0_{\nu_x}\,, \\
\Phi_{\nu_x} &= \frac{1}{4}\left(2+\sin^2\theta_{12}\right)\Phi^0_{\nu_x} + \frac{1}{4}\Phi^0_{\bar\nu_e} + \frac{1}{4}\Phi^0_{\nu_e}\cos^2\theta_{12}
\end{aligned}$$

Normal Ordering (NO)

$$\begin{aligned}
\Phi_{\nu_e} &= \Phi^0_{\nu_x}\,, \\
\Phi_{\bar\nu_e} &= \Phi^0_{\bar\nu_e} \cos^2\theta_{12} + \Phi^0_{\nu_x} \sin^2\theta_{12}\,, \\
\Phi_{\nu_x} &= \frac{1}{4}\left(2+\cos^2\theta_{12}\right)\Phi^0_{\nu_x} + \frac{1}{4}\Phi^0_{\nu_e} + \frac{1}{4}\Phi^0_{\bar\nu_e}\sin^2\theta_{12}
\end{aligned}$$



- for DUNE that will be successful in detecting ν_e, more of early produced neutrinos will be detected if the mass ordering is inverted

Event Rates

$$R(t) = N_{\text{target}} \int \Phi(E_\nu, t)\sigma(E_\nu)dE_\nu$$

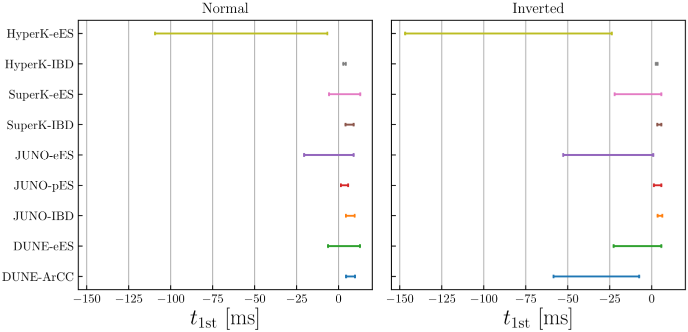
	N ($t < 20$ ms, NO)	N ($t < 20$ ms, IO)	N (total, NO)	N (total, IO)
DUNE-ArCC	11.3	50.9	3285	3097
DUNE-eES	2.99	6.48	311	314
JUNO-IBD	14.2	27.2	6297	6194
JUNO-eES	4.11	8.50	362	369
JUNO-pES	18.8	19.2	3670	3798
SuperK-IBD	17.6	33.8	7830	7701
SuperK-eES	2.95	6.39	307	310
HyperK-IBD	206	395	91517	90011
HyperK-eES	34.5	74.7	3588	3628

- for IO there are many more ArCC events in $t < 20$ ms window meaning that for IO the first event recorded in the detector will occur earlier
- no big difference between IBD event counts in $t < 20$ ms window when comparing NO and IO
- the time difference between the onset of neutrino events at DUNE and at a given IBD detector will be larger for IO

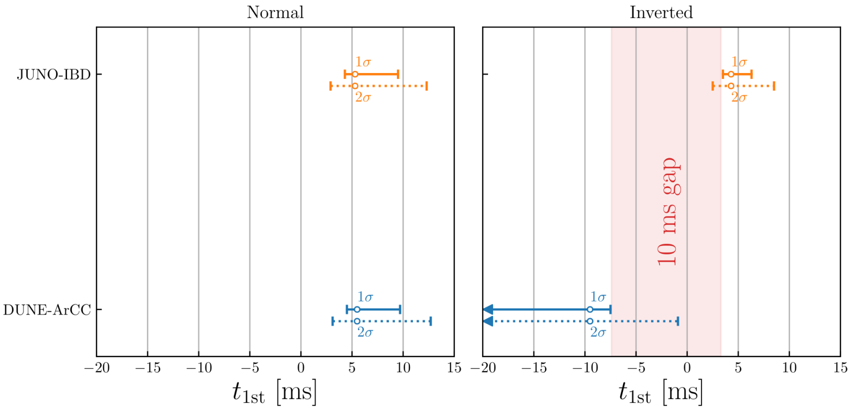
Time Window for the 1st Event Detection

- probability density function for t_{1st}: $p_{\mathrm{1st}}(t_{\mathrm{1st}}) = R(t_{\mathrm{1st}}) \exp\left[-\int_{-\infty}^{t_{\mathrm{1st}}} R(t)dt\right]$
- probability of t_{1st} in $[t_-, t_+]$ equals $1 - \alpha = 0.6827$ for 1σ CL

$$\int_{-\infty}^{t_-} p_{\mathrm{1st}}(t)dt = \int_{t_+}^{\infty} p_{\mathrm{1st}}(t)dt = \frac{\alpha}{2}$$

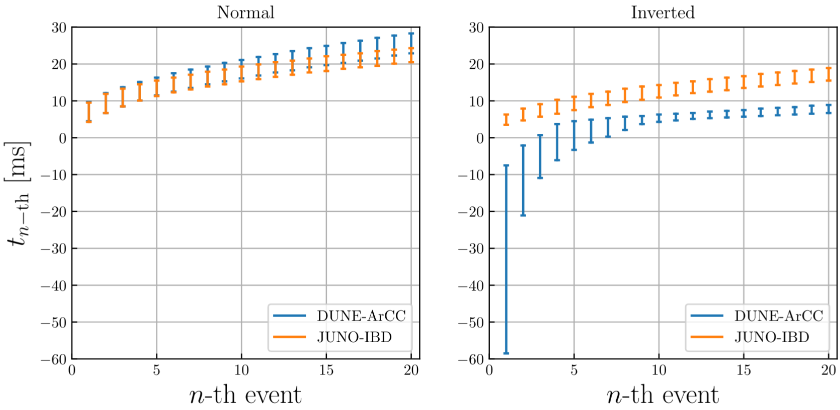


1st Event Detection: DUNE vs JUNO



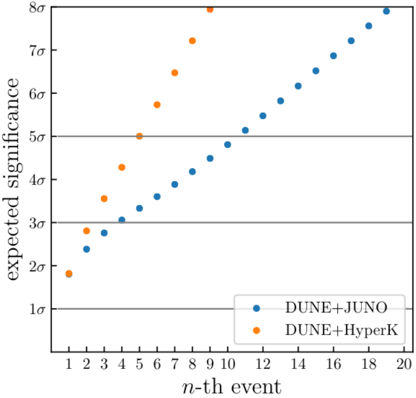
- the time difference between t_{1st} at DUNE and JUNO in the case of IO should be greater than ~ 10 ms

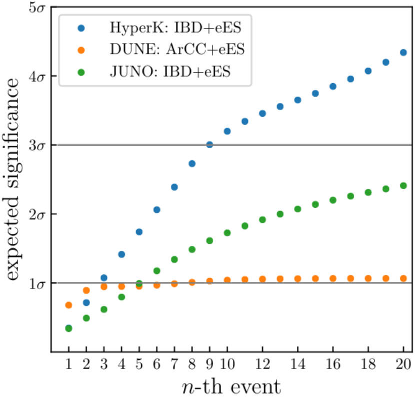
n-th Event Detection: DUNE vs JUNO



- for the first ∼ 20 events, DUNE-ArCC events will appear significantly earlier than JUNO-IBD ones in the IO case

Significance for Neutrino Mass Ordering





- knowing only the timing of the first event 2σ statement can be made
- 5σ with DUNE+Hyper-K (or DUNE+JUNO) requires $\mathcal{O}(10)$ events
- combining $\nu - e$ and $\nu - A$ channel leads to weaker results

Entanglement between Mass Ordering and Triangulation

- the method that guarantees 5σ CL result for the mass ordering involves the usage of event time differences between different detectors
- the measurement of these time differences should be corrected by the propagation time difference arising from different locations of detectors with respect to the SN
- such correction can be $\mathcal{O}(20)$ ms
- strategy: determine SN location $\Longrightarrow$ determine mass ordering
- $\nu - e$ elastic scattering, triangulation and/or optical telescopes
- both SN location and mass ordering can be done with SNEWS!

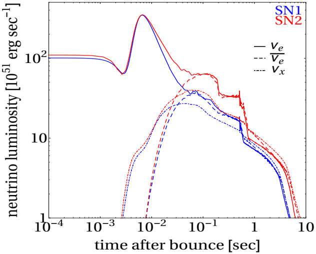
Summary

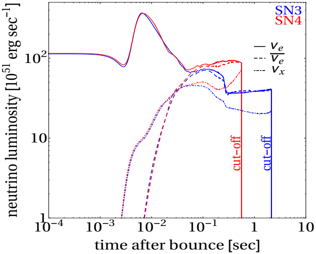
- triangulation is a viable method and can be implemented in SNEWS
- a novel method for determination of neutrino mass ordering using SN neutrinos is proposed
- it requires the time information on the first couple of SN events in several upcoming large detectors
- for IO, there is a large time difference between the onset of SN events in DUNE and JUNO/Hyper-Kamiokande
- $\mathcal{O}(10)$ events is enough for a 5σ result
- this method can be incorporated in SNEWS

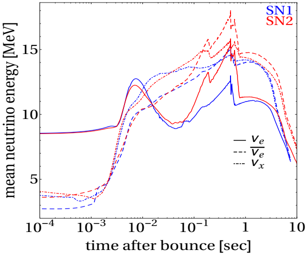
BACKUP SLIDES

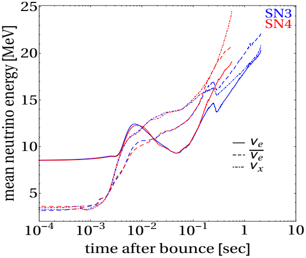
Neutrino Luminosities and Mean Energies

- SN1, SN2 collapse into a neutron star ; SN3, SN4 black hole collapse









Results Using Princeton Group Fluxes