Flavour Oscillations of the Supernova Neutrinos

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ESS neutrino Super Beam plus

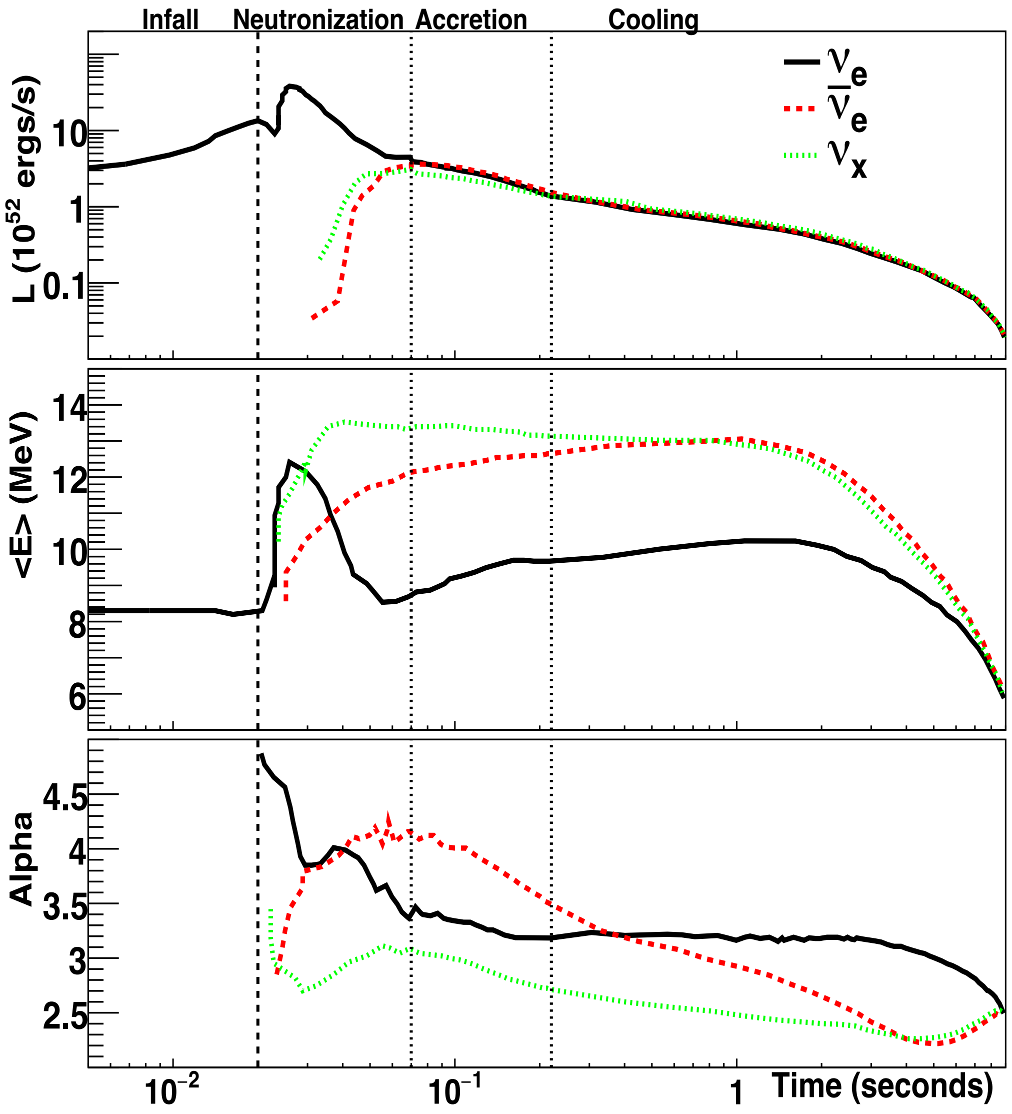
Core Collapse Supernova

- When a star > 8 $M_{\odot}$ comes to the end of its life, often the core of the star collapses and it explodes with huge energy and luminosity.
- Neutrinos of different flavours are produced in the energy range around few tens of MeV
- Till now we are only able to detect neutrinos from SN1987A supernova occurred at a distance of 50 kpc from Earth
- Only 24 events are detected by:

(i) water Cherenkov Kamiokande II,
(ii) water Cherenkov Irvine-Michigan-Brookhaven (IMB)
(iii) scintillator Baskan

Tarantula Nebula in the Large Magellanic Cloud. Supernova 1987A visible as the very bright star

Neutrino Production in a Supernova



Neutrinos are produced in three stages

- Neutronization or the breakout: In the first tens-of-milliseconds of the collapse, ν_e is produced from the electron capture i.e.,

$$e^- + p \rightarrow \nu_\mathrm{e} + n$$

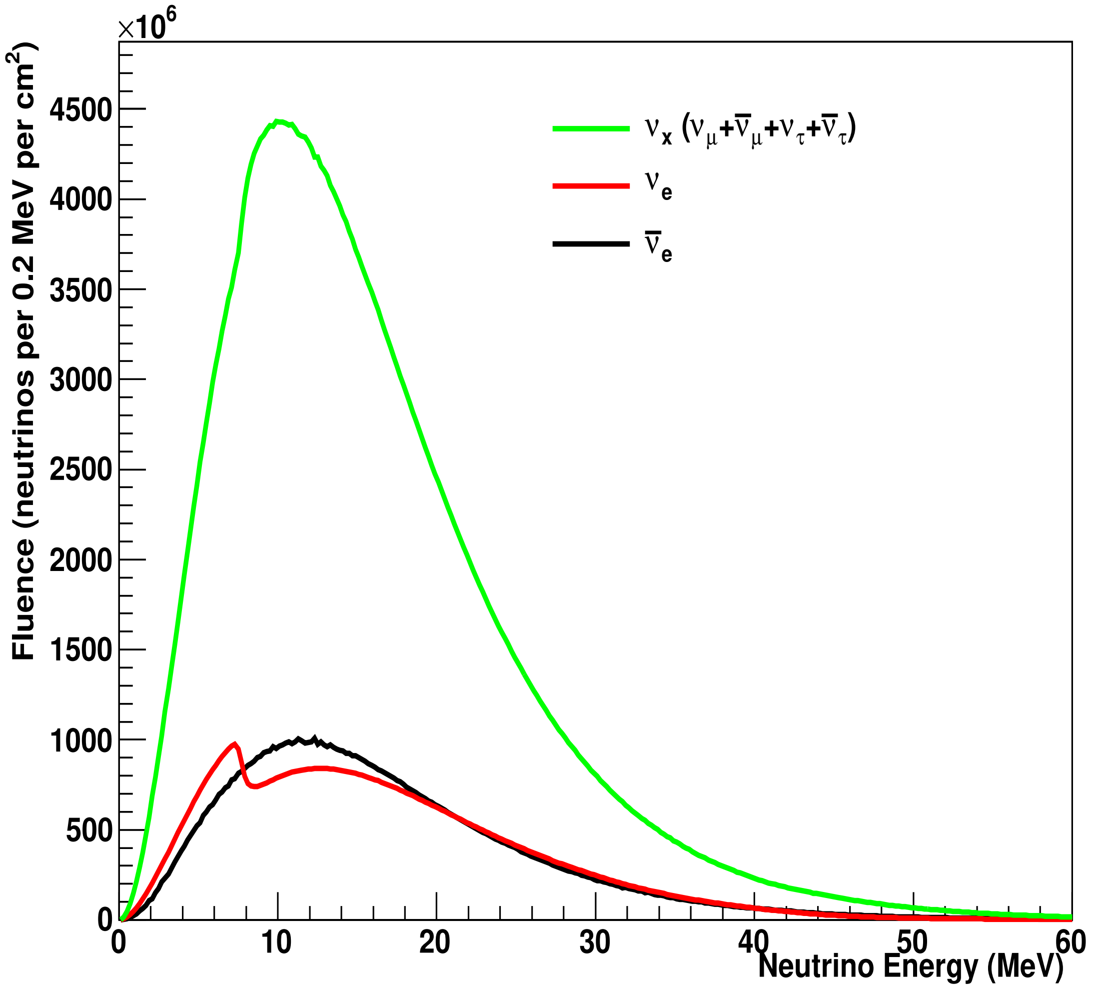
- Accretion phase: Lasts tens to hundred of milliseconds long. Production of ν_e dominates.

- Cooling phase: Lasts few tens of second. Dominated by $\nu\bar{\nu}$ pair

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle, \text{ x} = \mu, \tau$$

B. Abi et al. [DUNE], Eur. Phys. J. C 81 (2021), 423

Neutrino Flux



$$\Phi = N\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

N = Normalization constant related to lumonosity
α = Pinching parameter related to supressed tails

N and α are Model Dependent: Figure is for GKVM Model

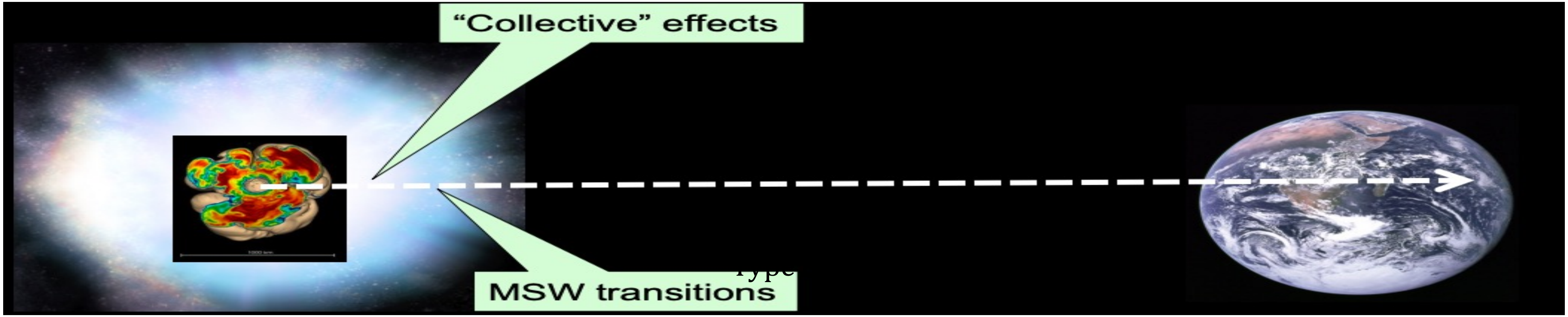
- Evolves the neutrino wavefunctions up to a radius using supernova density profiles at different times during the supernova explosion

- Neutrinos will go through multiple matter resonance areas.

Many other models are available

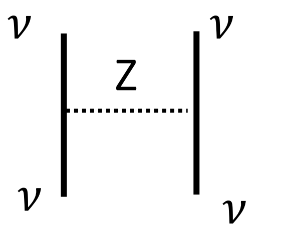
B. Abi et al. [DUNE], Eur. Phys. J. C 81 (2021), 423, K. Scholberg, Ann. Rev. Nucl. Part. Sci. 62 (2012), 81-103

Flavour Oscillations Inside Supernova

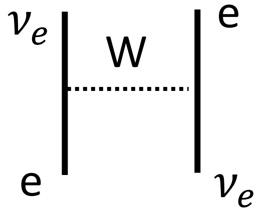


$$H = H_{vac} + H_{coll} + H_{MSW}$$

New Effect



Collective Effects: $\nu - \nu$ neutral current forward scattering



MSW Transitions: $\nu - $ e charged current forward exchange scattering

Collective Effects

Depends on neutrino mass ordering

Ordering	p_{coll}	$\overline{p_{coll}}$
Normal	1	1
Inverted	p_s = 1 if E < 8 MeV = 0 otherwise	0

For normal ordering: No effect

For inverted ordering: $\bar{\nu}_e \rightarrow \bar{\nu}_x$ for all E
$\nu_e \rightarrow \nu_x$ for E > 8 MeV

$$F_{\nu_e}^{c} = p_{coll}\, F_{\nu_e}^{0} + (1 - p_{coll})\, F_{\nu_x}^{0}$$

$$2\, F_{\nu_x}^{c} = (1 - p_{coll})\, F_{\nu_e}^{0} + (1 + p_{coll})\, F_{\nu_x}^{0}$$

F^0 = Intial flux
F^c = Flux after collective effect
p_{coll} = Survival probability due to collective effect

Collective effects can also alter the flavour oscillations in other non-trivial ways: active research topic

S.H. Chiu, C.C. Huang and K.C. Lai, PTEP (2015), 063B01

MSW Transitions

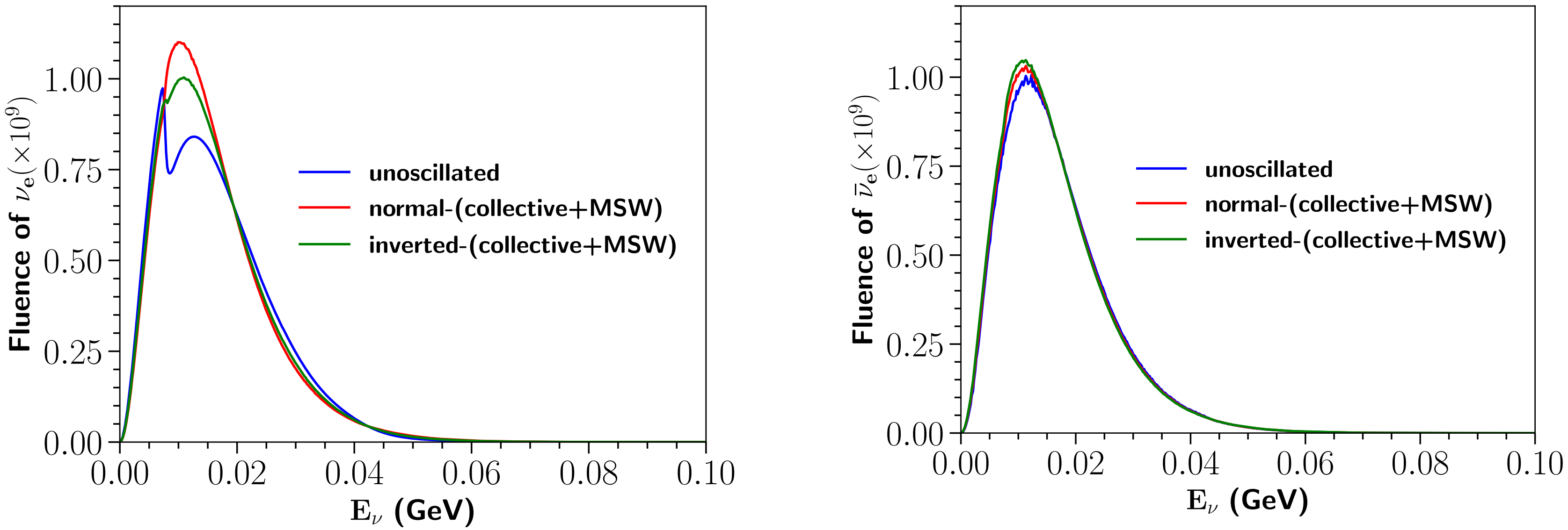
Also Depends on neutrino mass ordering

F_{ν_e} = p $F^c_{\nu_e}$ + (1 - p) $F^c_{\nu_x}$

2 F_{ν_x} = (1 - p) $F^c_{\nu_e}$ + (1 + p) $F^c_{\nu_x}$

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

F = Flux after colective effect + MSW transition,
F^c = Flux after collective effect
p = Survival probability due to MSW transition



A.S. Dighe and A.Y. Smirnov, Phys. Rev. D 62(2000), 033007, P. Panda, M. Ghosh and R. Mohanta, arXiv:2304.13303

Detection of the Supernova Neutrinos

For water cherenkov detectors (T2HK, ESSnuSB)

$\bar{\nu_e} + p \rightarrow n + e^+$ (A)

$\bar{\nu_e}$ + $O^{16} \rightarrow e^+$ + N^{16} (B)

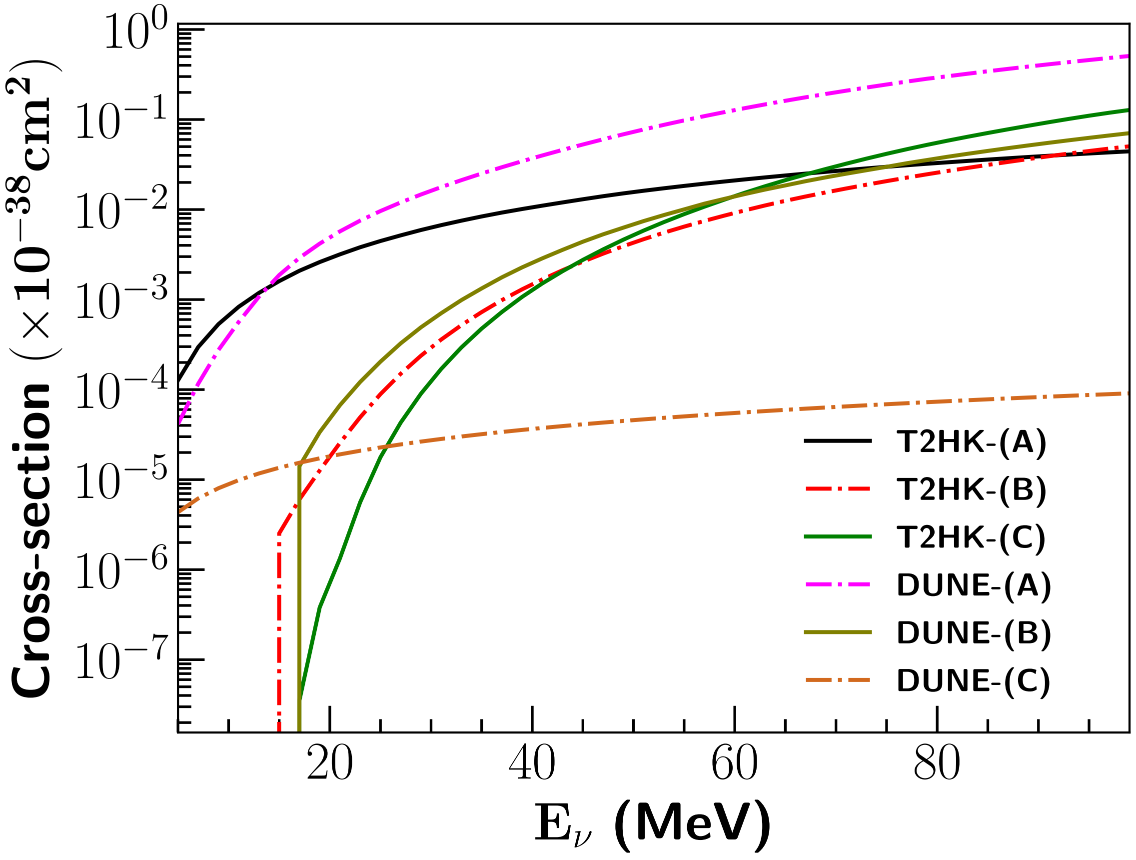
ν_e + $O^{16} \rightarrow e^-$ + F^{16} (C)

For liquid argon detectors (DUNE)

$\nu_e + Ar^{40} \rightarrow e^-$ + K^{40} (A)

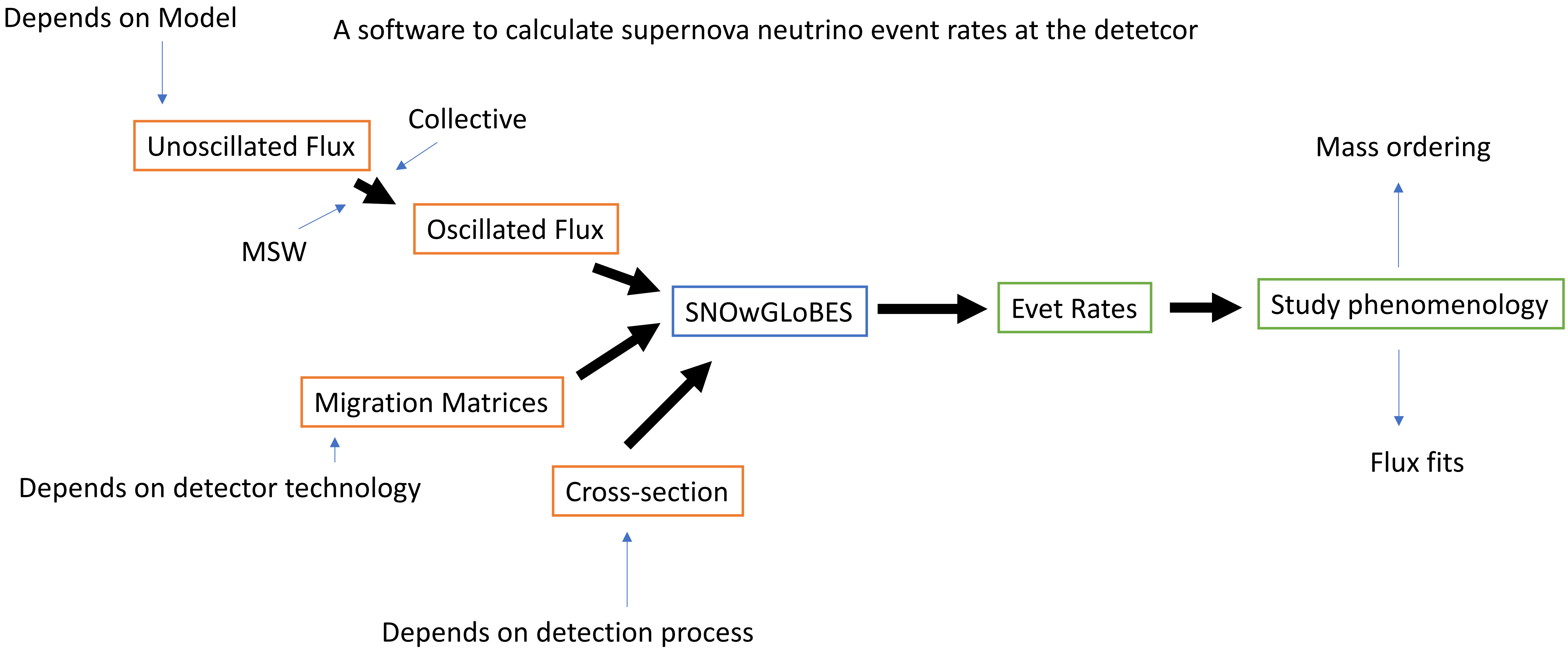
$\bar{\nu_e}$ + $Ar^{40} \rightarrow e^+$ + Cl^{40} (B)

$\nu_e + e^- \rightarrow e^- + \nu_e$ (C)



SNOwGLoBES

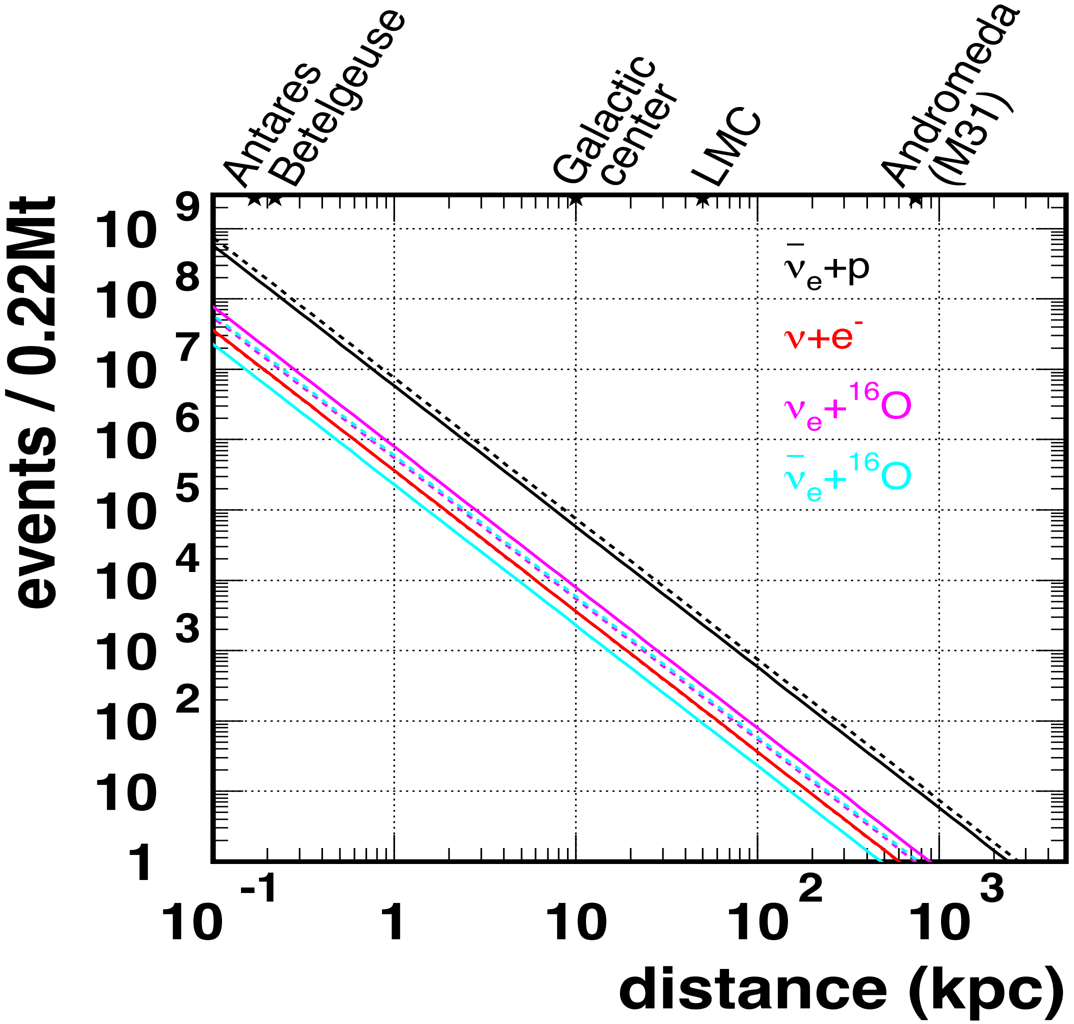
A software to calculate supernova neutrino event rates at the detetcor

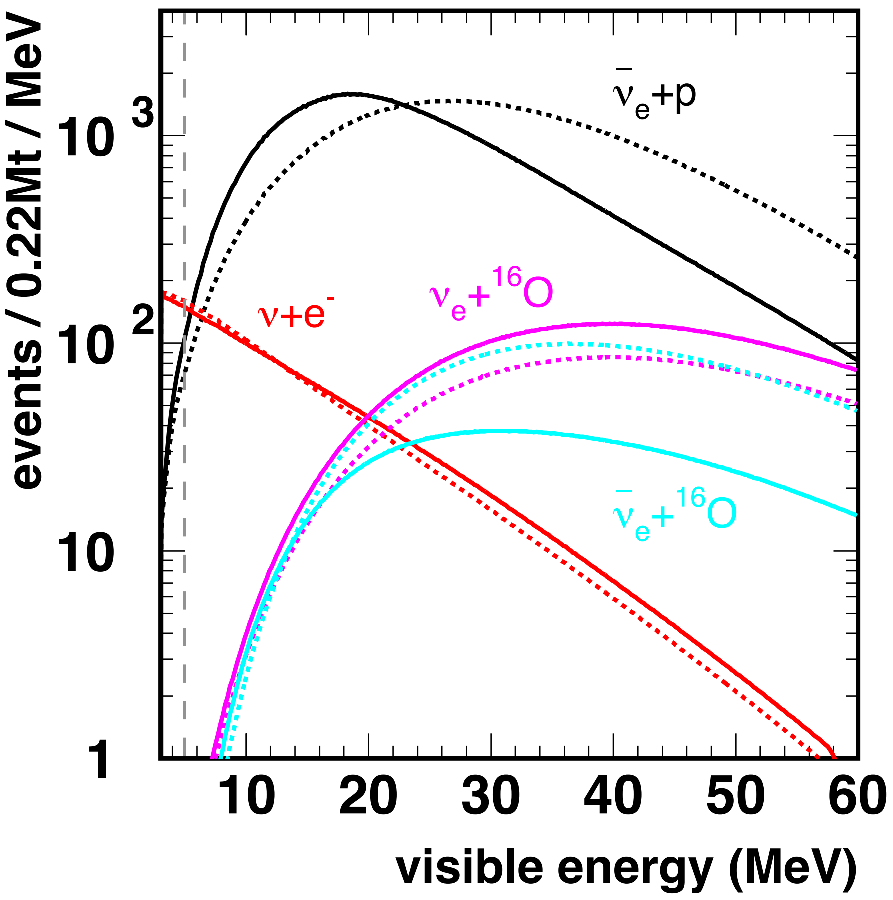


http://www.phy.duke.edu/ schol/snowglobes, “Github,” (2021).

Supernova study by Hyper-K collaboration

- They study the first 500 ms of the neutrino burst (accretion phase)

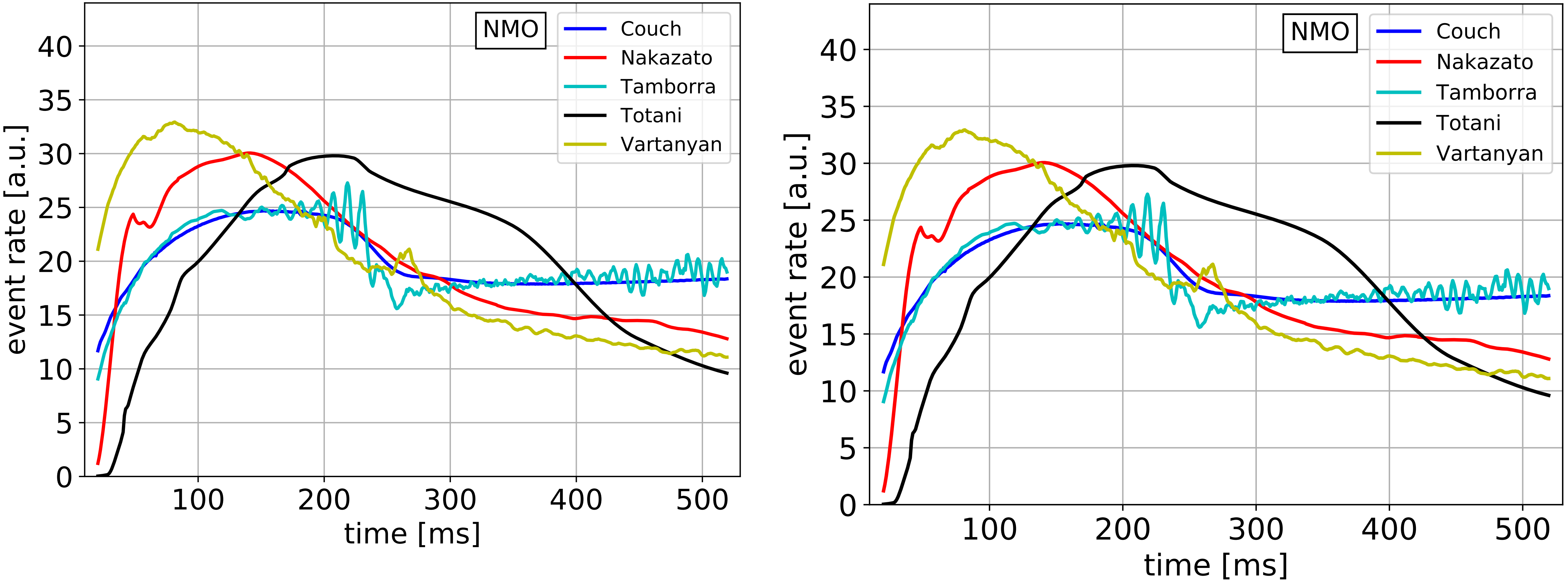




K. Abe et al. [Hyper-Kamiokande],Astrophys. J. 916 (2021), 15

Supernova study by Hyper-K collaboration

- They study response to five different supernova models.

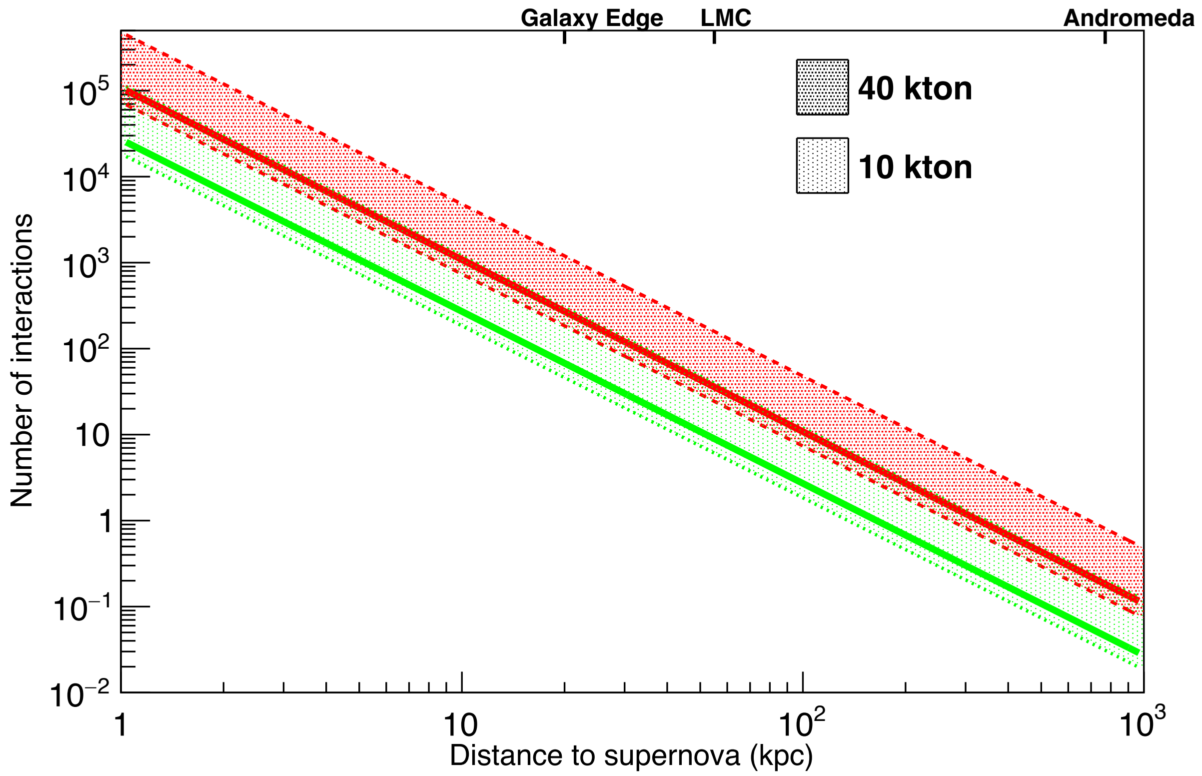


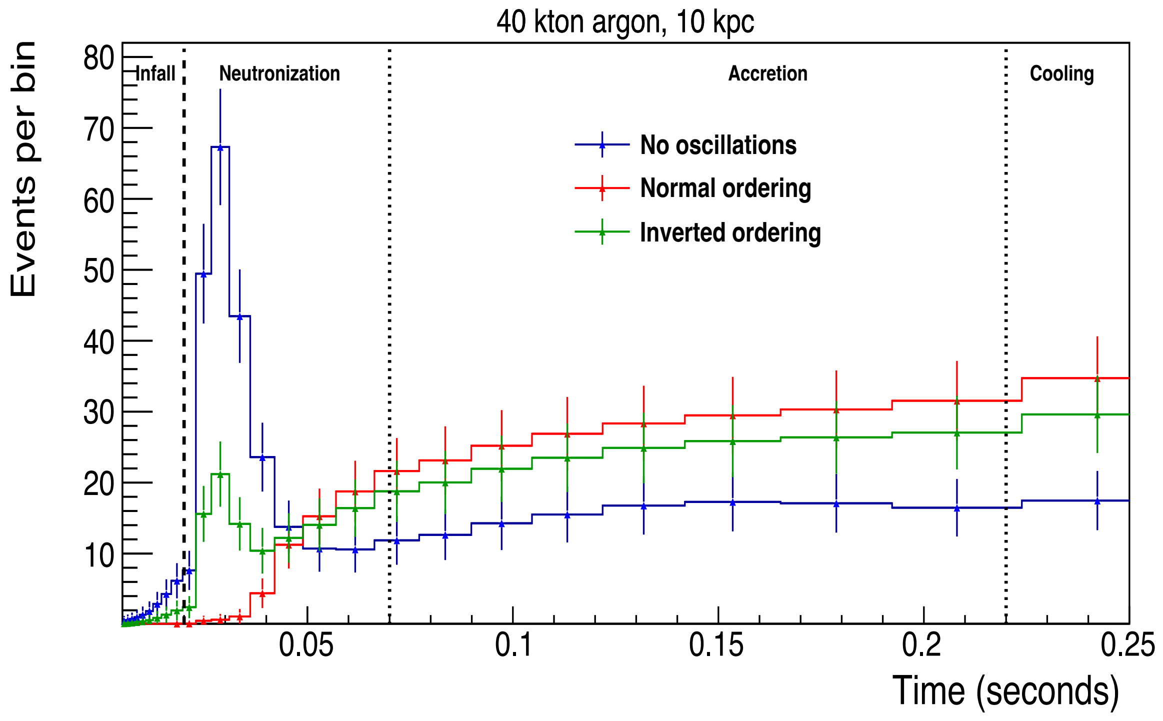
Only MSW transitions

K. Abe et al. [Hyper-Kamiokande], Astrophys. J. 916 (2021), 15

Supernova study by DUNE collaboration

- They study Garching model with SNOwGLoBES





Only MSW transitions

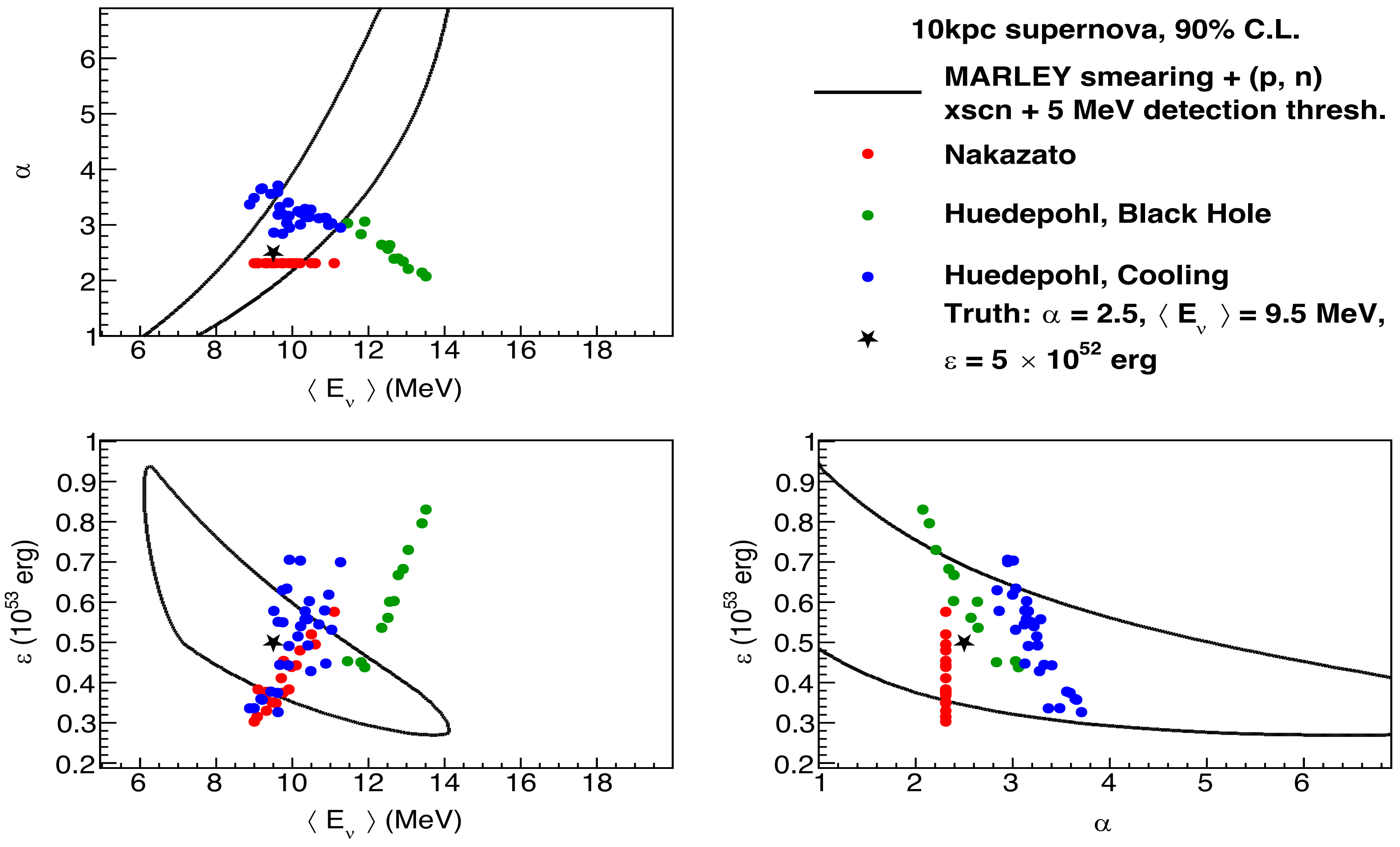
B. Abi et al. [DUNE], Eur. Phys. J. C 81 (2021), 423

Supernova study by DUNE collaboration

- They fitted the flux parameters

$$\Phi = N\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

$\varepsilon =$ Total binding energy release $\propto N$



B. Abi et al. [DUNE], Eur. Phys. J. C 81 (2021), 423

Our Work

Capability of DUNE and T2HK to determine neutrino mass ordering

(i) Considered GKVM flux model
(ii) Considering both collective effecs and MSW transitions
(iii) Defined a $\chi2$ formula:

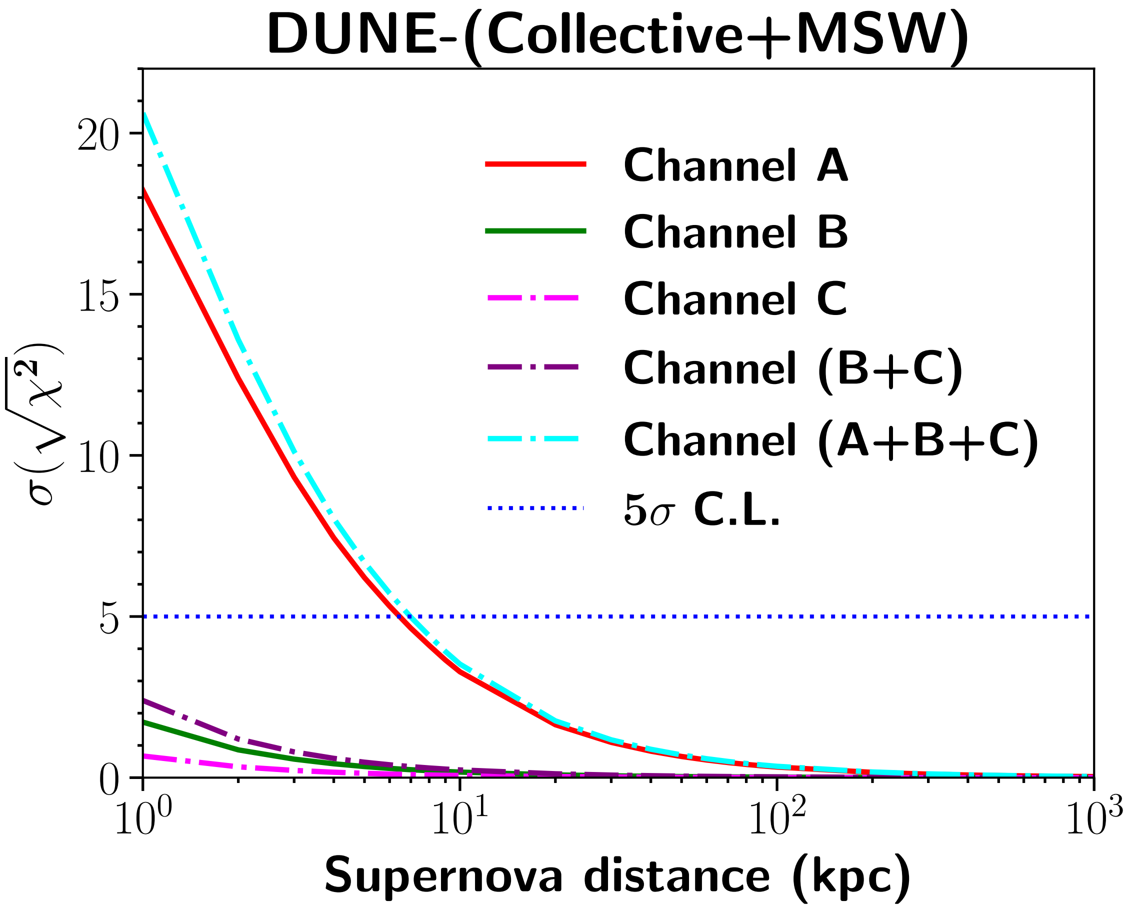
$$\chi2 = 2 \sum_{i=1}^{n} \left[N_i^{test} - N_i^{true} - N_i^{true}\, ln\left(\frac{N_i^{test}}{N_i^{true}}\right)\right]$$

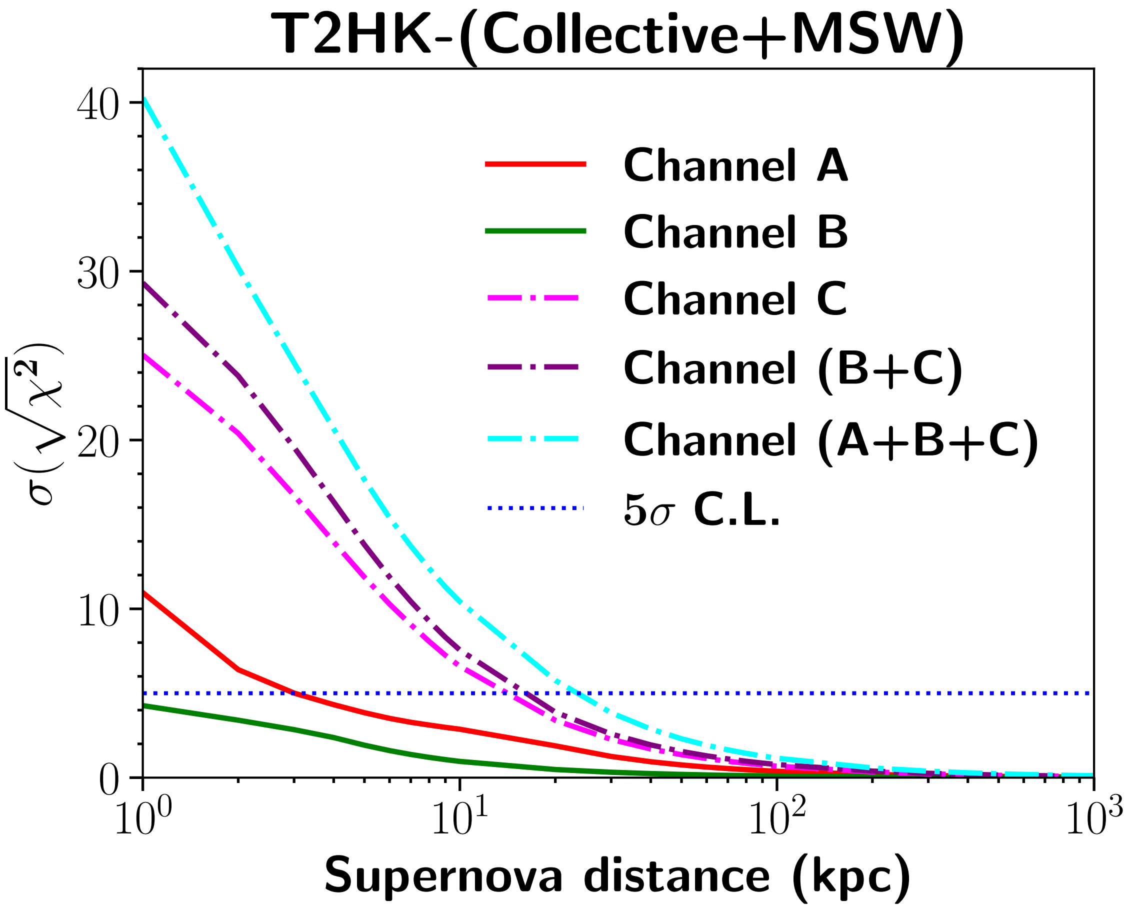
i = number of energy bins, N_i^{true} = Normal ordering, N_i^{test} = Inverted ordering

(iv) Considered a 5% overall normalization error for systematics
(v) Plotted $\chi2$ as a function of supernova distance

Mass ordering sensitivity: 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	$\bar{\nu}_e - ^{16}O$	$\nu_e - ^{16}O$

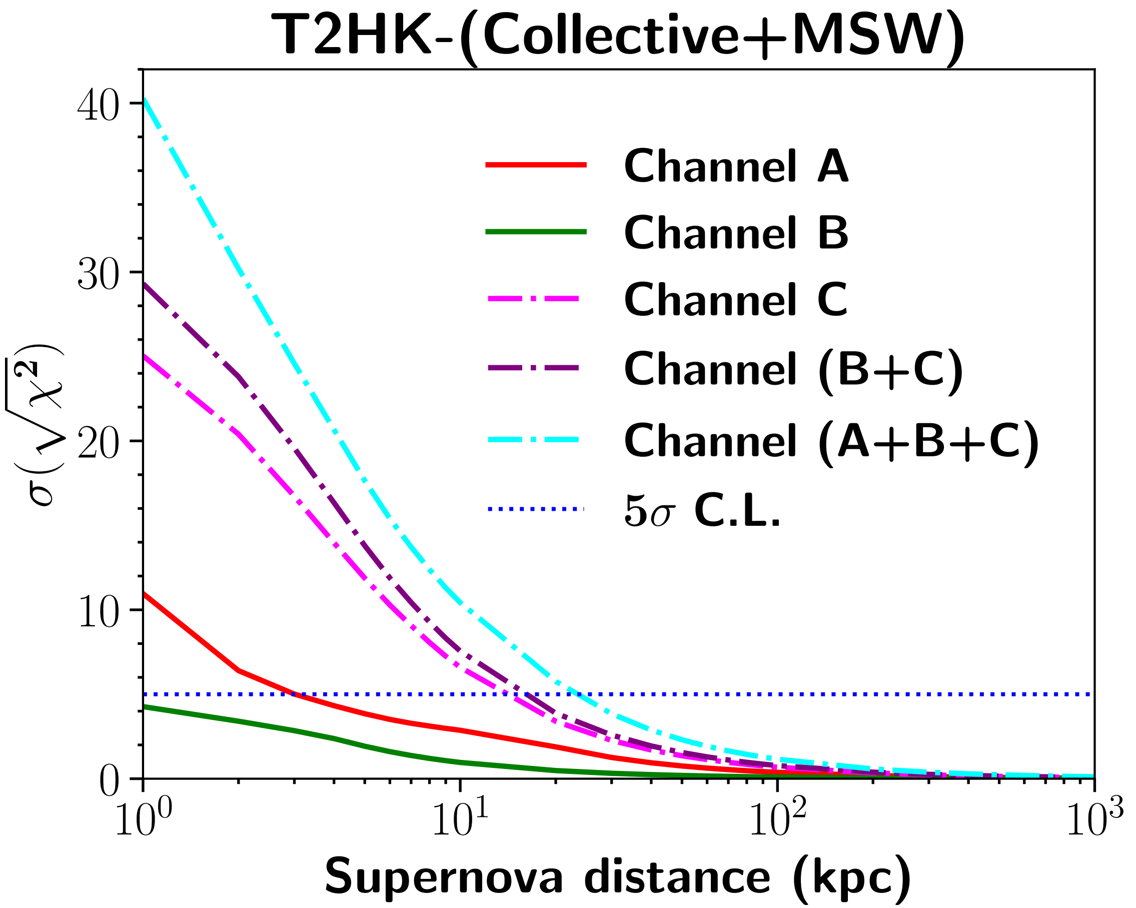


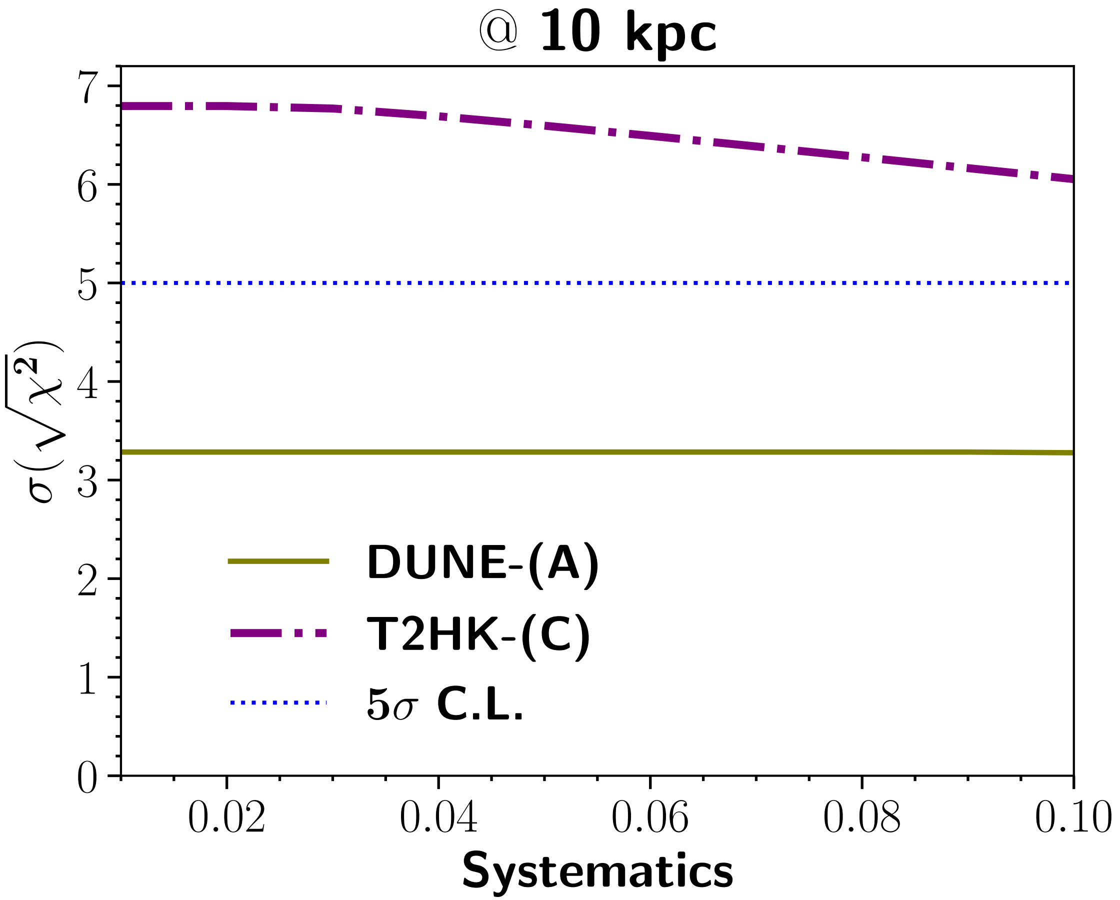


P. Panda, M. Ghosh and R. Mohanta, arXiv:2304.13303

Mass ordering sensitivity: Systematics

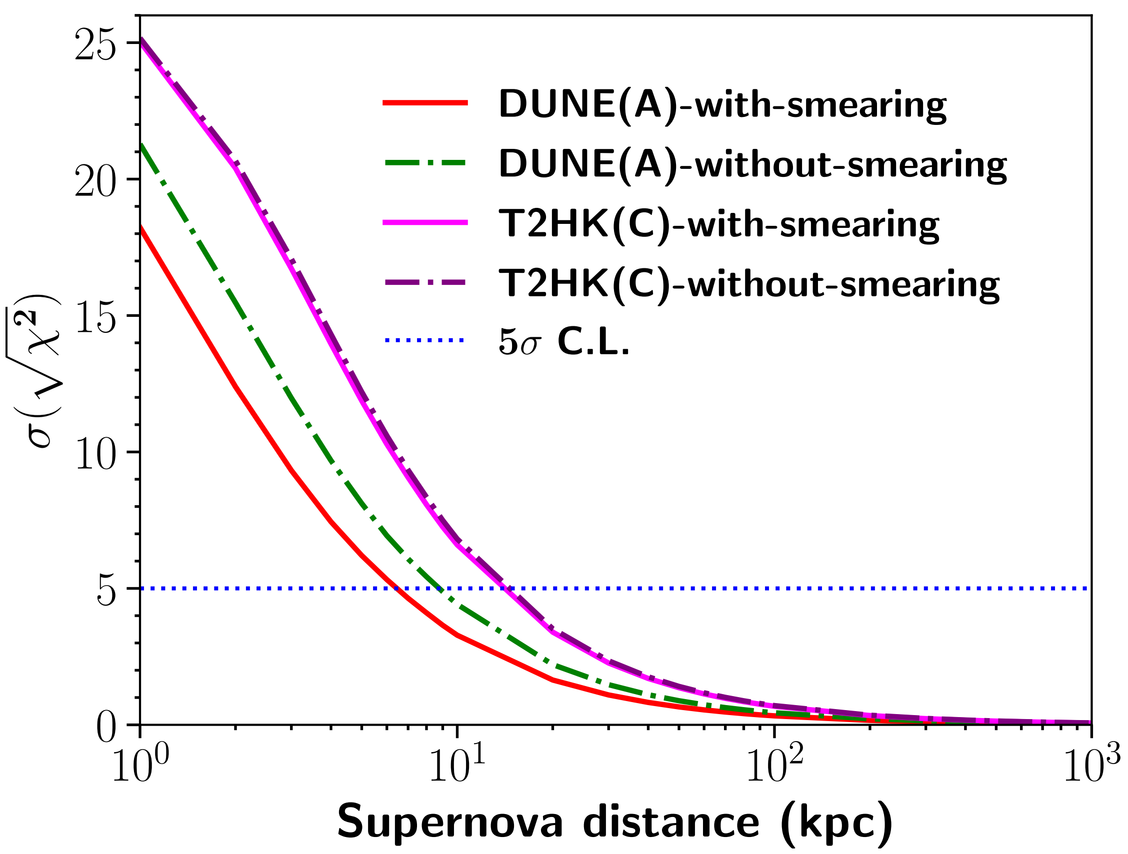
Experiment	Channel-A	Channel-B	Channel-C
DUNE	$\nu_e - ^{40}\mathrm{Ar}$	$\bar{\nu}_e - ^{40}\mathrm{Ar}$	$\nu_e - e$
T2HK	IBD	$\bar{\nu}_e - ^{16}O$	$\nu_e - ^{16}O$





P. Panda, M. Ghosh and R. Mohanta, arXiv:2304.13303

Mass ordering sensitivity: Smearing



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

P. Panda, M. Ghosh and R. Mohanta, arXiv:2304.13303

Plans for ESSnuSB

- Prepare migration matrices relevent to supernova energies (can assume Gaussian smearing for preliminary analysis)
- Calculate event rates at ESSnuSB FD for relevant channles
- Study different physics scenarios

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Thank You