Sensitivity study of next generation neutrino detectors to supernova neutrinos with varied flux models

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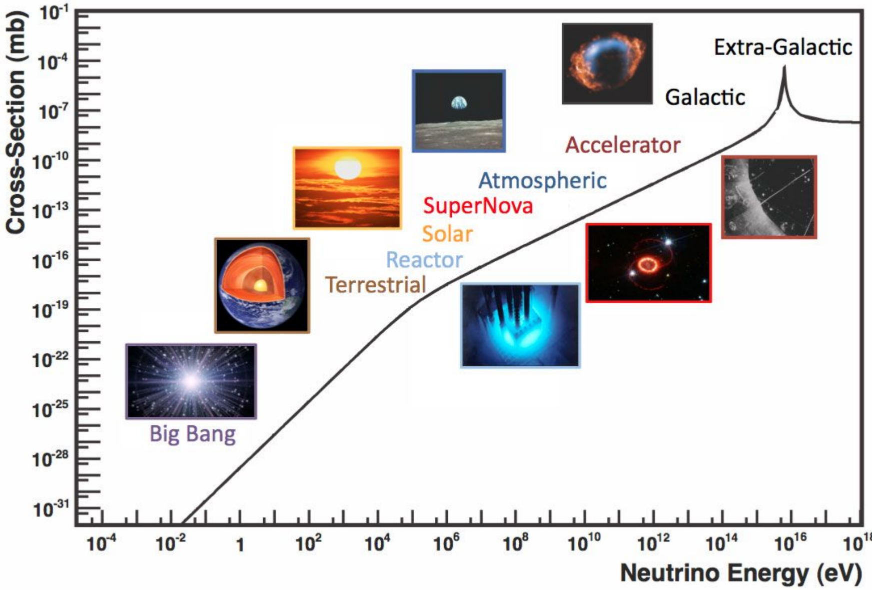
Overview

- Introduction
- Motivation
- Core-collapse mechanism
- Detection
- Detectors
  - Flux models
  - Event Rates
  - Sensitivity plots
- Conclusion and summary

Introduction

- Standard model classifies the fundamental particles and describe the three of four known fundamental forces
- It leaves some physical phenomena unexplained
- It does not fully explain baryon asymmetry, general relativity, dark energy or dark matter
- It also does not incorporate neutrino oscillations and their non-zero masses
- Used as a basis for building more exotic models to explain experimental results, such as the existence of dark matter and neutrino oscillations



Motivation

- Neutrinos typically pass through normal matter unimpeded and undetected
- Today, scientists are trying to determine the neutrino mass, how it interacts with matter, and whether the neutrino is its own antiparticle (a particle with the same mass but opposite electric or magnetic properties) or not
- One such type of neutrinos that can be studied are **Supernova Neutrinos**
- Generated by the collapse of the core of massive stars and for a few seconds following the collapse, neutrinos of all types are produced
- Can provide early alarm to astronomers to prepare the telescope to capture light from the supernova and offer an opportunity to examine neutrino flavor mixing under high-density conditions

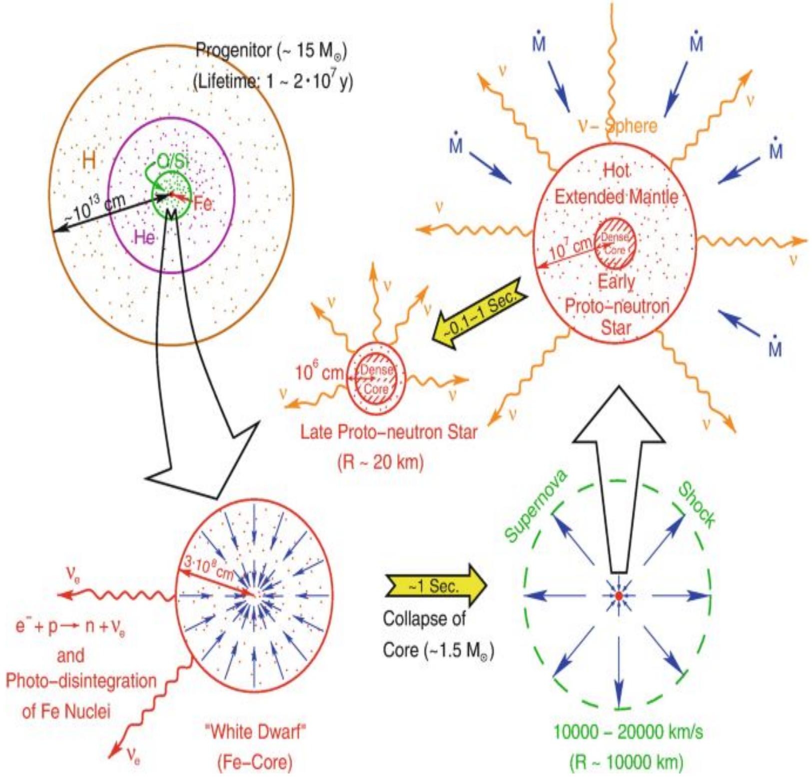
How these particles are produced ?

- Star at the end of its life ⇨ Onion like structure ⇨ ^{56}Fe core (no more fusion/ heat production)

- Core contracts ⇨ Temperature ↑ ⇨ photodissociation of Fe(absorbs) and electron capture rxn

- Pressure and no. of electron ↓ ⇨ Onset of core collapse

- Gravitational energy released in the form of neutrinos



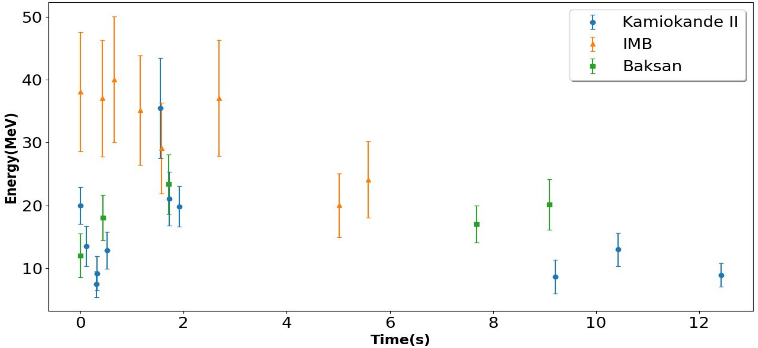
How to detect ?

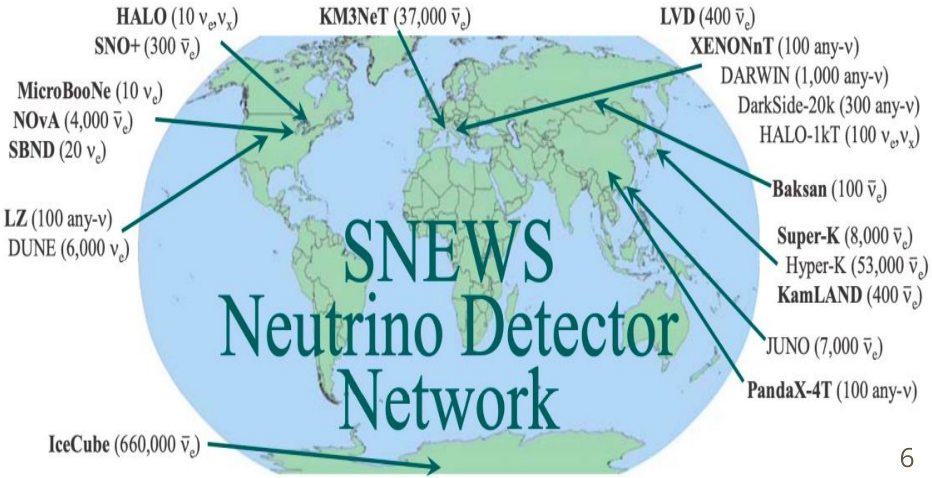
- Almost all methods involve the inverse beta decay reaction for the detection of neutrinos. The reaction is a charged current weak interaction,

$$\text{Anti-}\nu_e + p \longrightarrow n + e^+$$

- With current detector sensitivities, it is expected that thousands of neutrino events would be observed

- So the next generation of underground experiments, like Hyper-Kamiokande, are designed to be sensitive to neutrinos from, as far as Andromeda or beyond.

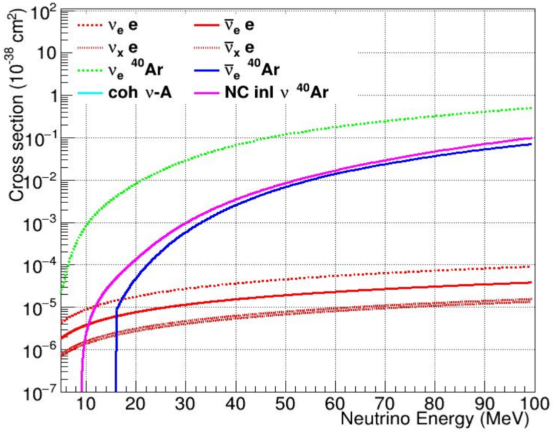




Detectors

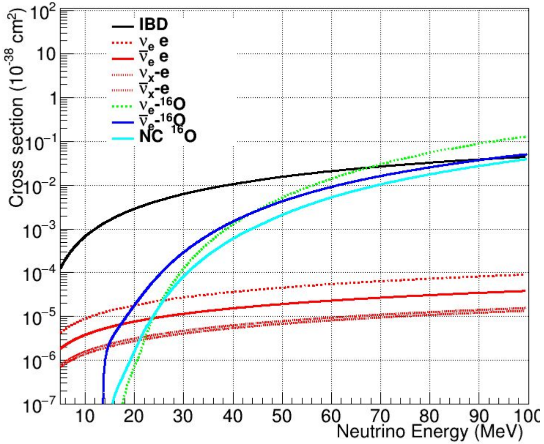
DUNE

- A 40 kt (fiducial mass) LArTPC detector
- Liquid argon has a particular sensitivity to the ν_e component of a supernova neutrino burst, via the dominant interaction, CC absorption of ν_e on ^{40}Ar
- Complimentary to other detectors with sensitivity towards anti-ν_e.



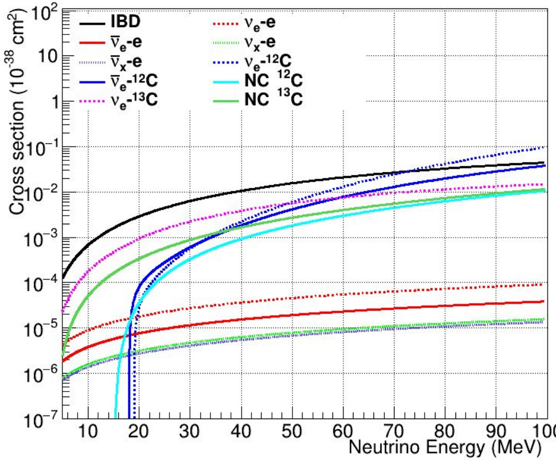
Hyper-K

- It is similar to the Super-K detector, with an enlarged volume of 260 kt of pure water
- Supernova neutrinos are mainly detected through the inverse beta decay channel



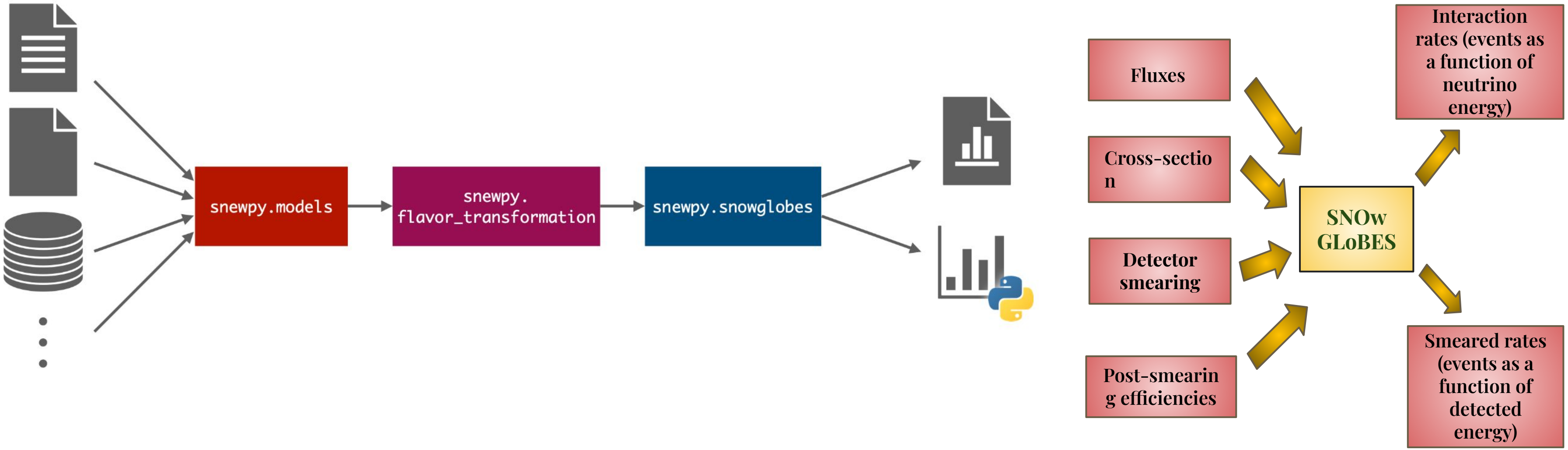
JUNO

- The central detector is a 20 kt liquid organic scintillation (LS) detector with a goal to reach a rather low detection energy threshold of 0.2 MeV
- Supernova detection is one of the major purposes for JUNO



SNEWPY

SNEWPY* is a Python package providing a simple and unified interface to hundreds of supernova simulations. It also offers a large library of flavor transformations that relate neutrino fluxes produced in the supernova to those reaching a detector on Earth. Also has a Python interface to SNOwGLoBES which lets you estimate and plot event rates in many different neutrino detectors.



*SNEWPY: A Data Pipeline from Supernova Simulations to Neutrino Signals, https://doi.org/10.48550/arXiv.2109.08188

Models

Nakazato 2013*

- Successor to “Livermore” model
- One dimensional simulation was performed from start to 20s in two stages.

Supernova Neutrino Light Curves and Spectra for Various Progenitor Stars: From Core Collapse to Proto-neutron Star Cooling,
K. Nakazato, K. Sumiyoshi, H. Suzuki, T. Totani, H. Umeda, and S.
Yamada, [Astrophys. J. Supp. 205 (2013)2](http://dx.doi.org/10.1088/0067-0049/205/1/2), [arXiv:1210.6841](http://arxiv.org/abs/1210.6841).

Tamborra 2014*

- 3D simulation with sophisticated neutrino transport
- Signal depends on direction of observer relative to progenitor

*Data from I. Tamborra, G. Raffelt, F. Hanke, H.-T. Janka, and B. Mueller *Neutrino emission characteristics and detection opportunities based on three-dimensional supernova simulations*, [Phys. Rev. D 90:045032, 2014](https://arxiv.org/abs/1406.0

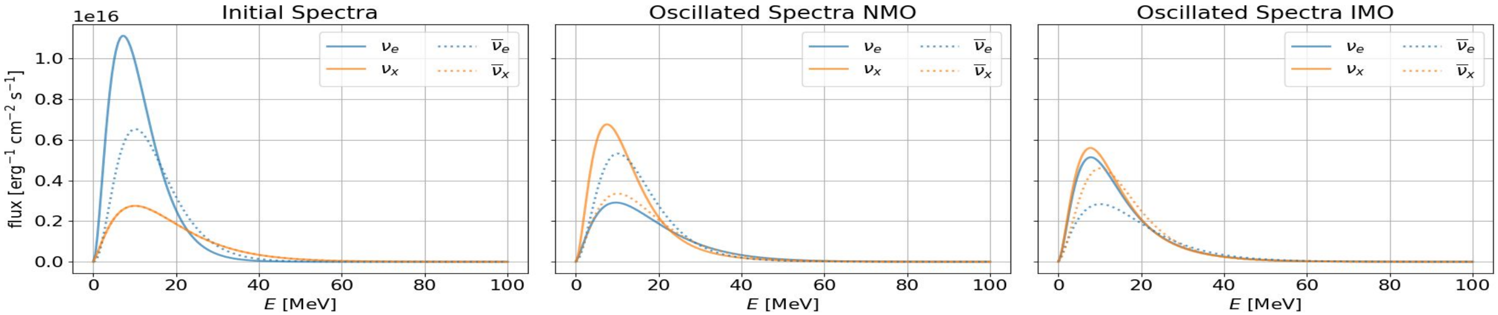
Bollig 2016*

- Spherically symmetric 1D model
- It uses Lattimer and Swesty equation of state

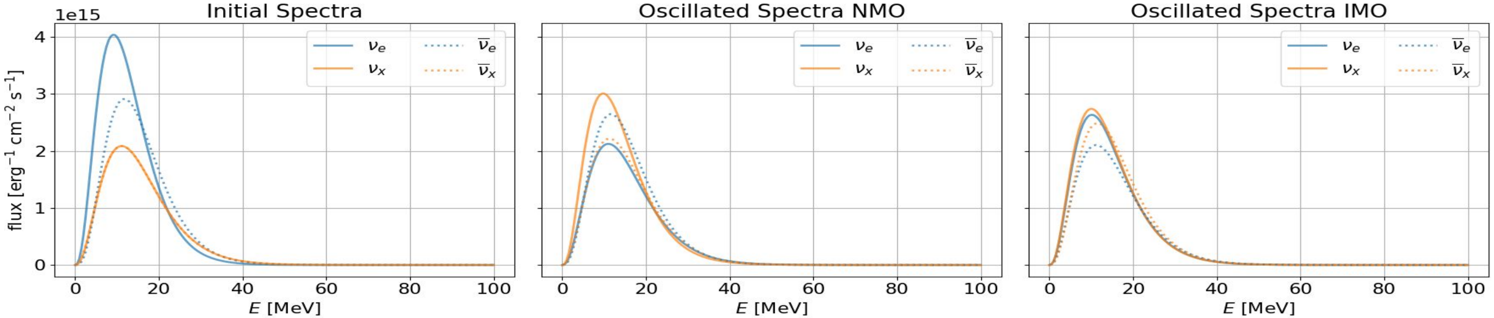
*Mirizzi et al. Rivista del Nuovo Cimento Vol 39 N. 1-2 (2016)
doi:10.1393/ncr/i2016-10120-8
arXiv:1508.00785

Spectra of Flux models

Nakazato



Tamborra



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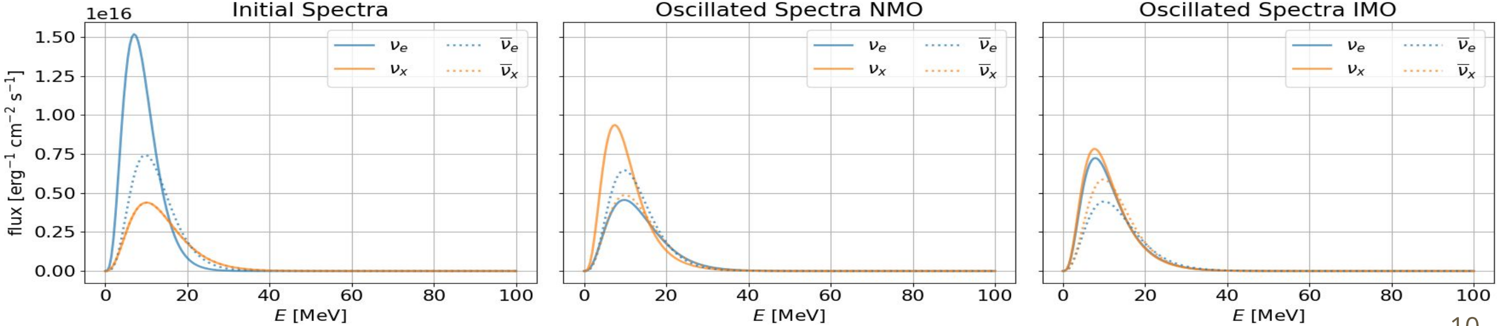
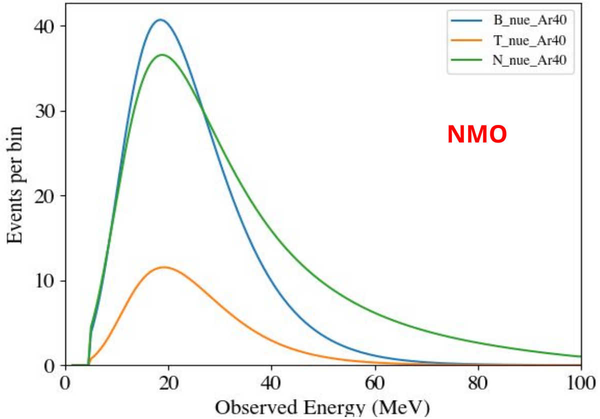
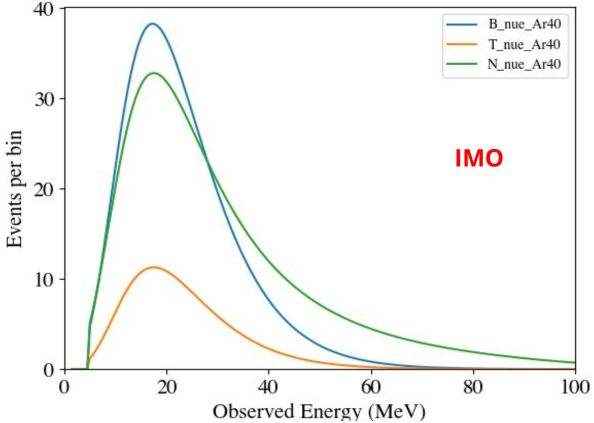


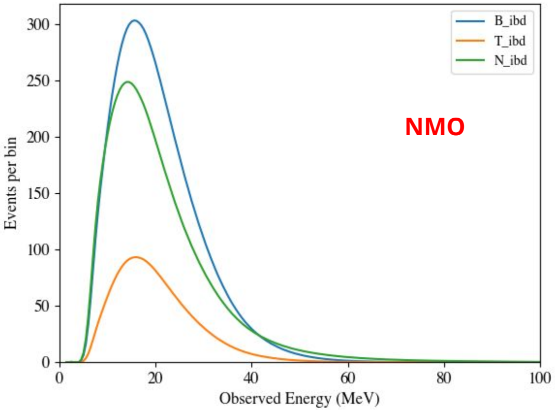
Event rates

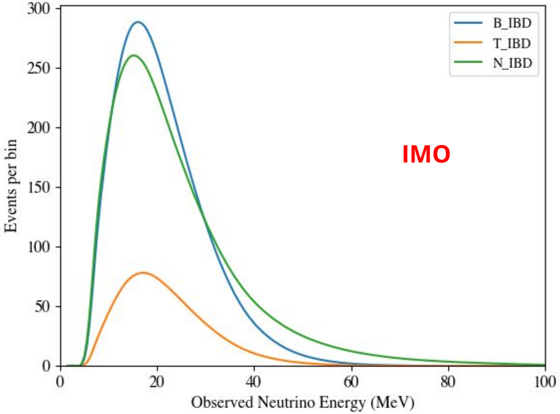
DUNE



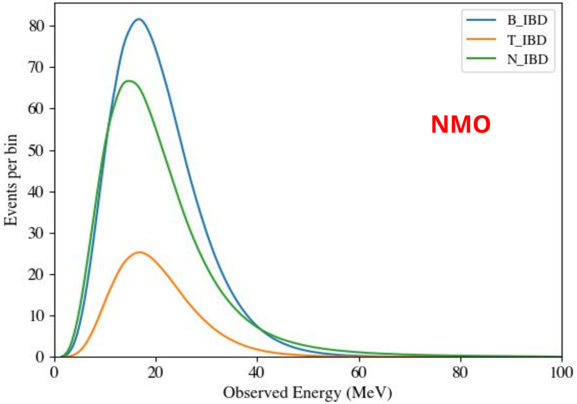


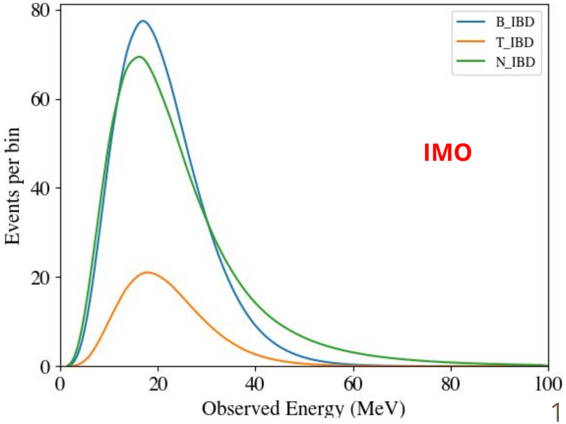
Hyper-k





JUNO





χ^2 analysis (statistical)

- χ^2 is calculated using the poisson formula as events are less:

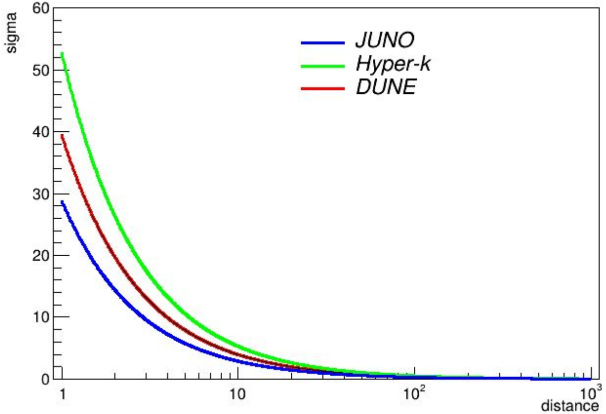
$$\chi^2_{stat} = 2\sum_{i=1}^{n}\left[N_i^{IMO} - N_i^{NMO} - N_i^{NMO} log(\frac{N_i^{IMO}}{N_i^{NMO}})\right]$$

- Event rate follows the inverse square law for its dependency on the distance of supernova from earth.

$$\text{Event Rate} \propto \quad 1 / (\text{distance})^2$$

- Also sigma(σ) is square root of χ^2 which gives us the sensitivity of detectors to the mass ordering w.r.t distance.

Sensitivity comparison plots for different models



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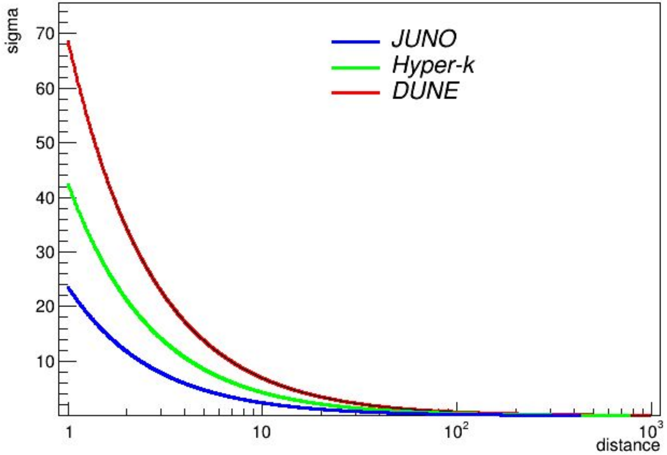
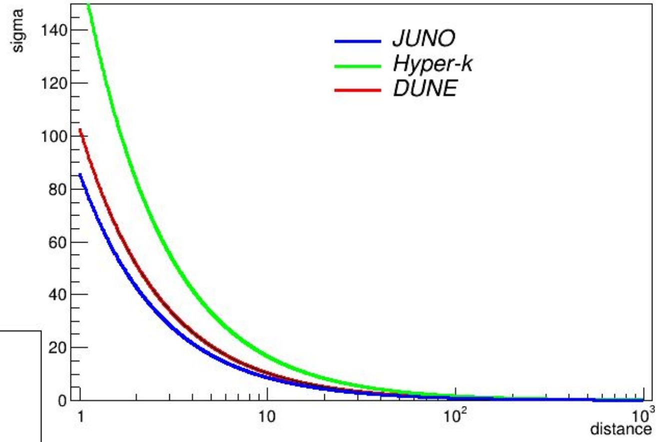
Tamborra





Nakazato

Conclusion and summary

- Neutrinos being least interactive help point towards supernova
- Provide ability to observe supernovae hours or days before visual detection
- Being sensitive to mass hierarchy, they will help in finding the true nature whether they are normal mass ordered or inverse
- Sensitivity diminishes with increased distance; to go beyond we would need bigger detectors.

THANK YOU FOR LISTENING

Back up

Msw effect

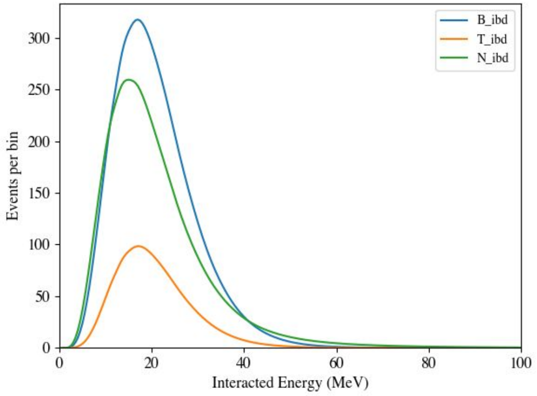
- Matter oscillation effects (known as Mikheyev-Smirnov-Wolfenstein effects), where neutrinos experience matter potential given by

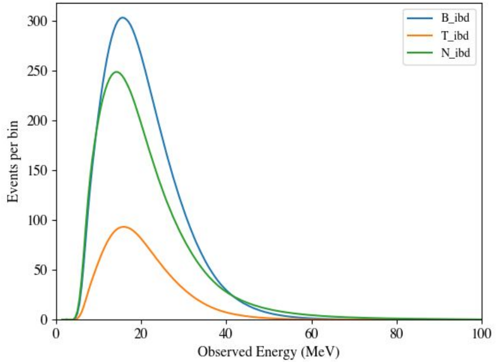
$$\lambda = \sqrt{2}G_f\, n_e(r)$$

  G_f and n_e being fermi constant and electron density respectively.
- Spectra influenced by mass and oscillation parameters, such as θ_{13} and the mass hierarchy.
- Adiabatic case: Rate of change in the matter density is slow relative to the neutrino oscillation frequency
- Non-Adiabatic case: when the matter density changes too quickly for the neutrino to stay in a single flavor state

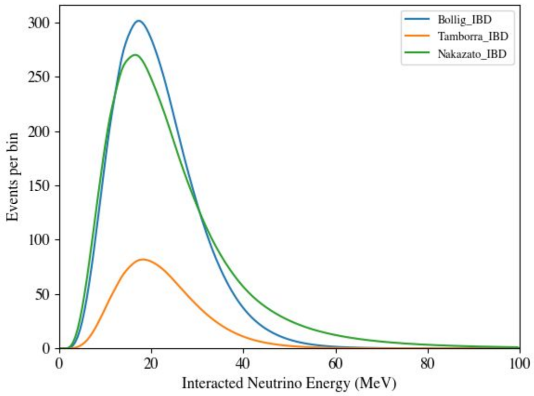
Hyper-k

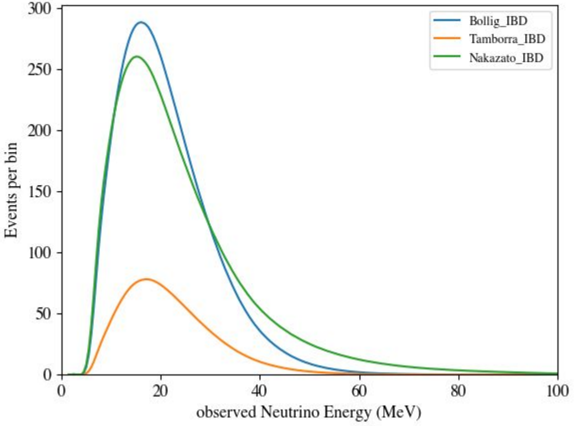
Adiabatic_NMO



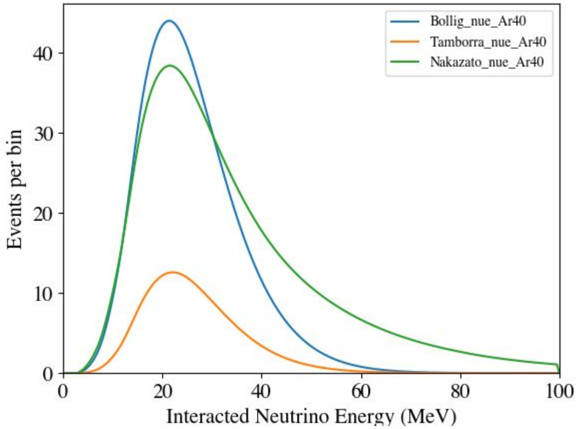


Adiabatic_IMO

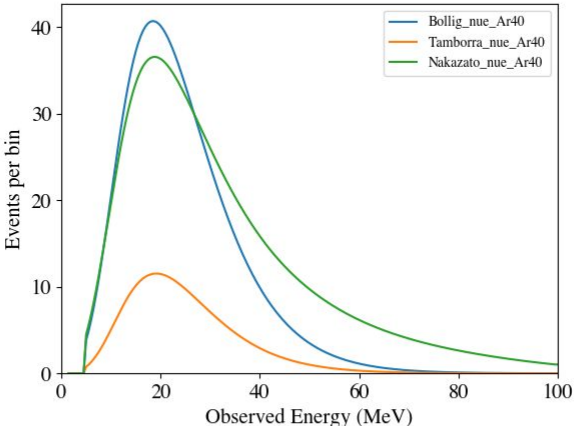


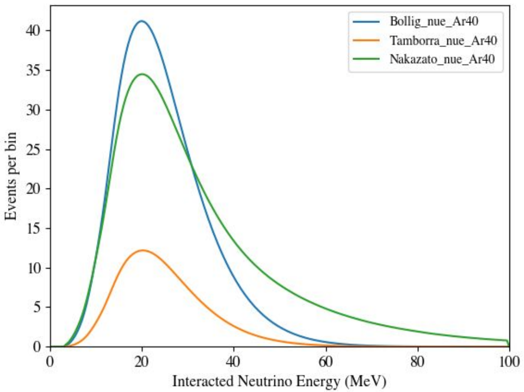


DUNE

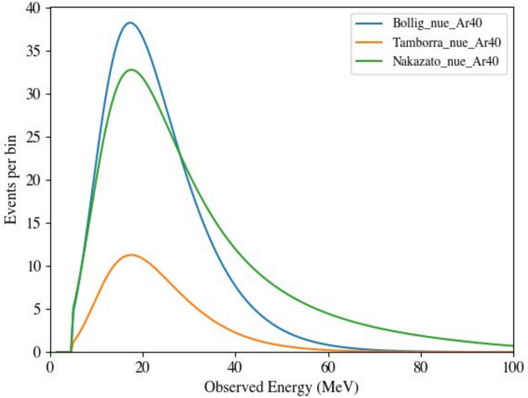


Adiabatic_NMO

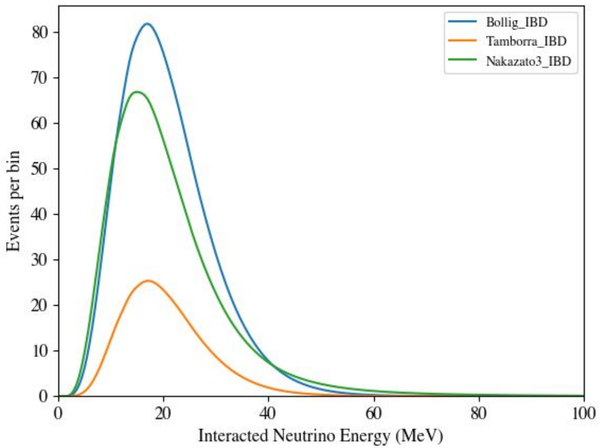




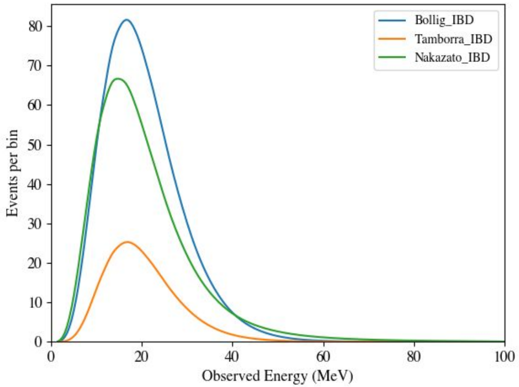
Adiabatic_IMO

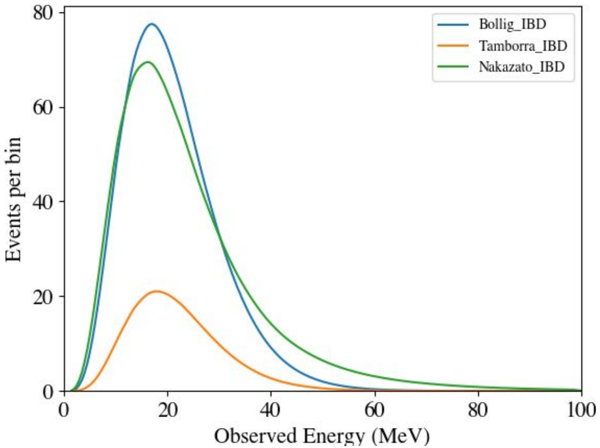


JUNO



Adiabatic_NMO





Adiabatic_IMO