HyperK physics Workshop at Donostia International Physics Center (DIPC)

Neutrino Mass Ordering with Supernovae

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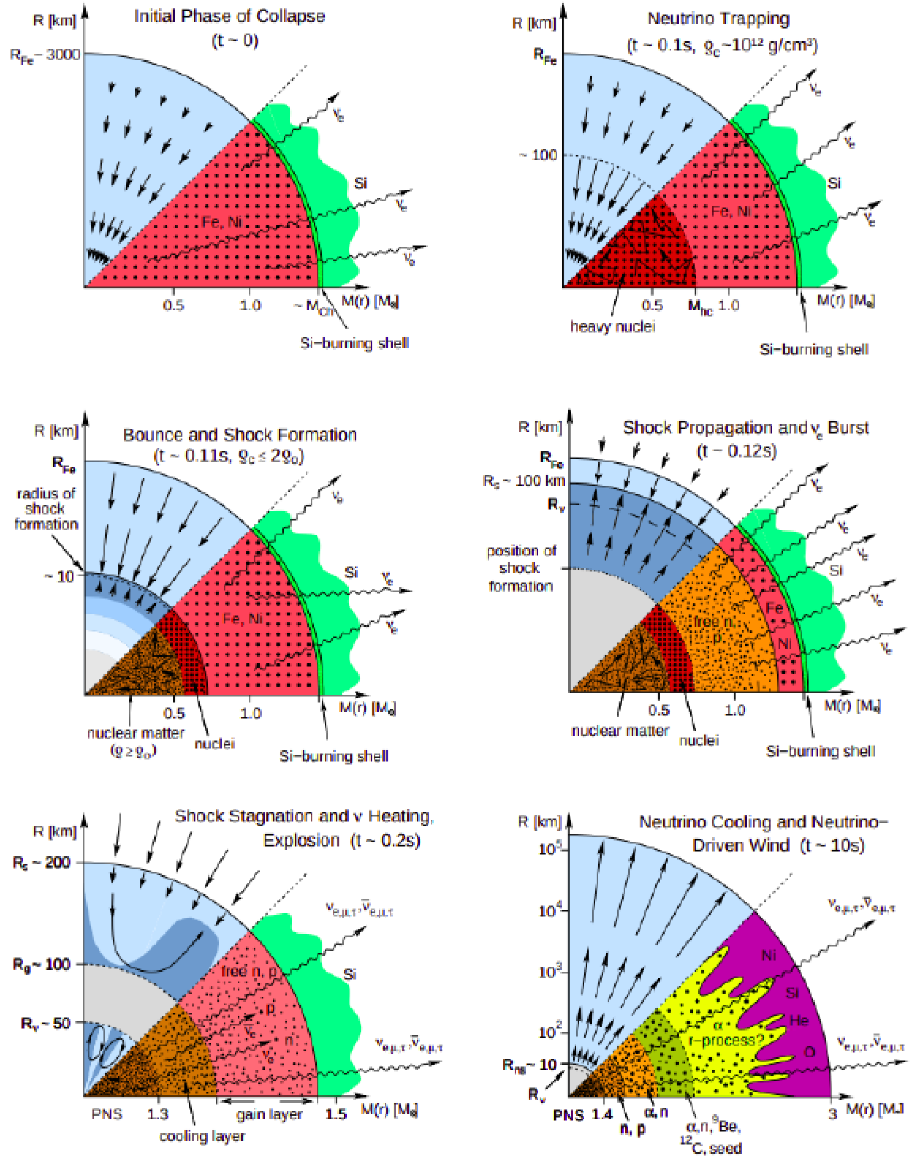
Introduction

- Neutrinos are elementary particles of the Standard Model. Weakly interacting particles with no charge.
- They were predicted to be massless, but in fact they are not; neutrino oscillation evidence.
- They are produce in a wide range of sources: among them, supernovae → core-collapse supernovae (CCSNe).
- Stars are stable due to the balance of forces. Onion-like structure since they produce heavy elements in their interior.
- Once Fe is reached, gravity is not countered by pressure any more. The star collapses.
- CCSNe are the fate of most of massive stars.
- CCSN event rate in a region with radius of 10kpc → 2-3 per century.
- CCSN eject 10^{53}erg of energy, ~99% of it in form of neutrinos and produce $\sim 10^{58}$ neutrinos.

H.-Thomas Janka et al., Theory of Core-Collapse Supernovae, February 5, 2008



Neutrinos are of crucial importance to study these cataclysmic explosions.

Throughout the explosion mechanism as it is understood up to date, neutrino emission would take place at three different stages: *burst of electron neutrinos*, *post-bounce accretion phase* and *neutrino cooling of the proto neutron star phase*.

Neutrino Oscillations

- Flavour eigenstates of neutrinos can be described as a superposition of mass eigenstates.

- Since mass eigenstates propagate as plane waves, when we detect a neutrino some time *t* after their production, there is a probability of observing a different flavour than the one produced → Neutrinos oscillate!

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle \quad \text{with } \alpha = e, \mu, \tau \text{ and } i = 1,2,3$$

$$|\nu_i(t)\rangle = |\nu_i(0)\rangle \cdot e^{E_i t - \vec{p_i}\vec{x}}$$

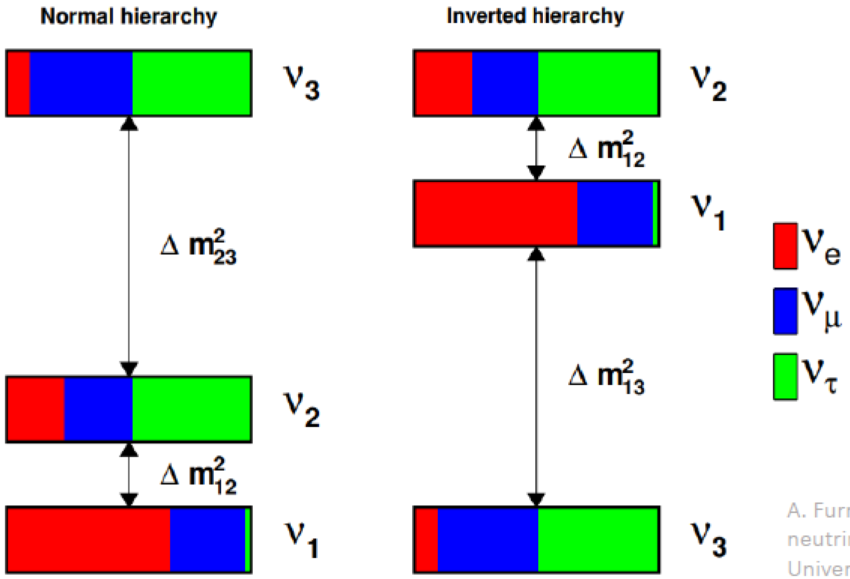
$$P(\alpha \to \beta) = sin^2 2\theta sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- A flavour oscillation implies a change in mass.
- Hence, the observation of neutrino oscillations implies that they have mass.

Neutrino Mass Hierarchy (MH)

- From the detailed study of solar neutrinos without any limitations we can define ν_2 heavier than ν_1.

- Then remains the question of whether ν_3 is the heaviest or the lightest, leading to two possible situations: *normal mass hierarchy* (NH) or *inverted mass hierarchy* (IH).

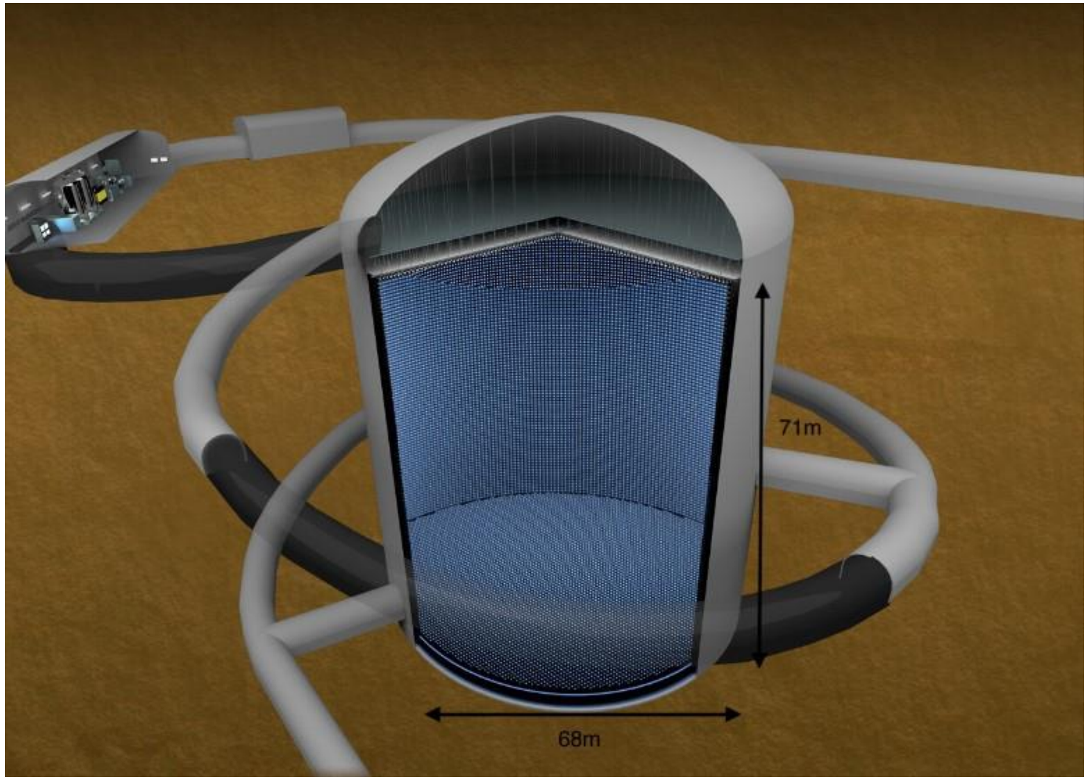


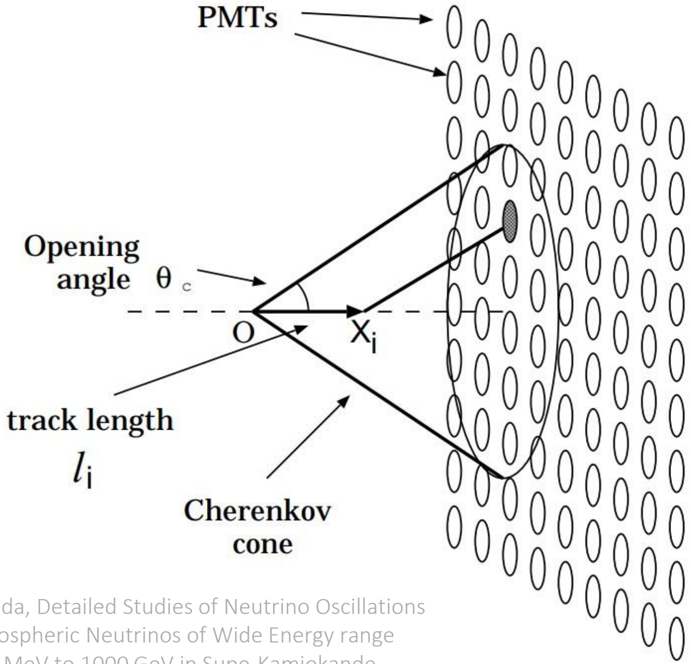
A. Furmanski, Charged-current Quasi-elastic-like neutrino interactions at the T2K experiment, PhD Thesis, University of Warwick, August 2015

[ハイパーカミオカンデ ホームページ | ハイパーカミオカンデ (u-tokyo.ac.jp)]

Hyper-Kamiokande

- Next generation water Cherenkov detector. Planned to be operational in 2027.
- It will have a mass roughly about one order of magnitude larger than its predecessor.





Jun Kameda, Detailed Studies of Neutrino Oscillations with Atmospheric Neutrinos of Wide Energy range from 100 MeV to 1000 GeV in Supe-Kamiokande, Doctor Thesis, September 2002, University of Tokyo.

- When a charged particle travels in a dielectric medium with $n > 1$, some of its energy is converted into light: this light is known as Cherenkov radiation.
- These photons describes the shape of a cone → ring pattern in the walls.
- Detected with photomultipliers (PMTs): PMT hit, then vertex reconstruction.

Relevant interaction channels in HyperK

- Inverse beta decay (IBD) - $\bar{\nu}_e + p \rightarrow n + e^+$

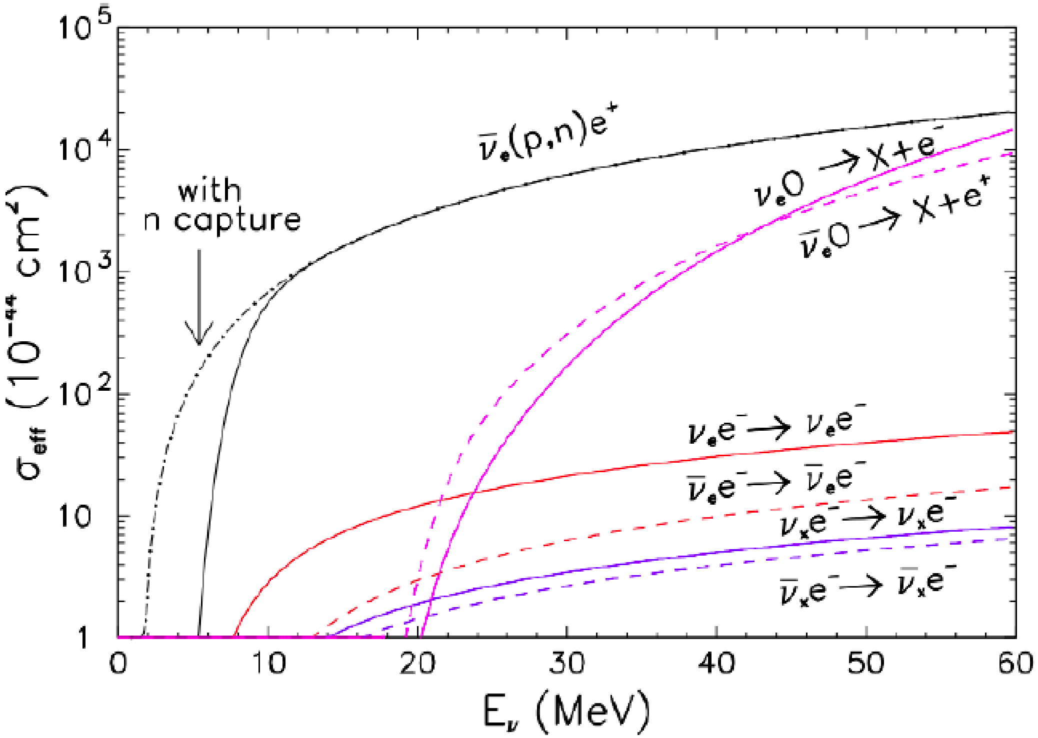
  Dominant interaction channel in Hyper-Kamiokande, from which we can only detect electron antineutrinos.

  Low energy threshold and high cross section + large number of protons in the ultra-pure water of HyperK.

- Electron scattering (ES) - $\nu + e^- \rightarrow \nu + e^-$

  Subdominant channel in HyperK. ν here represents all neutrino flavours, thus through ES we can detect all flavours.

  Important feature! Angular distribution is strongly peaked into the forward direction.



G.L.Fogli, E.Lisi, A.Mirizzi, D.Montanino, Probing supernova shock waves and neutrino flavor transitions in next-generation water-Cherenkov detectors, March 10, 2005.

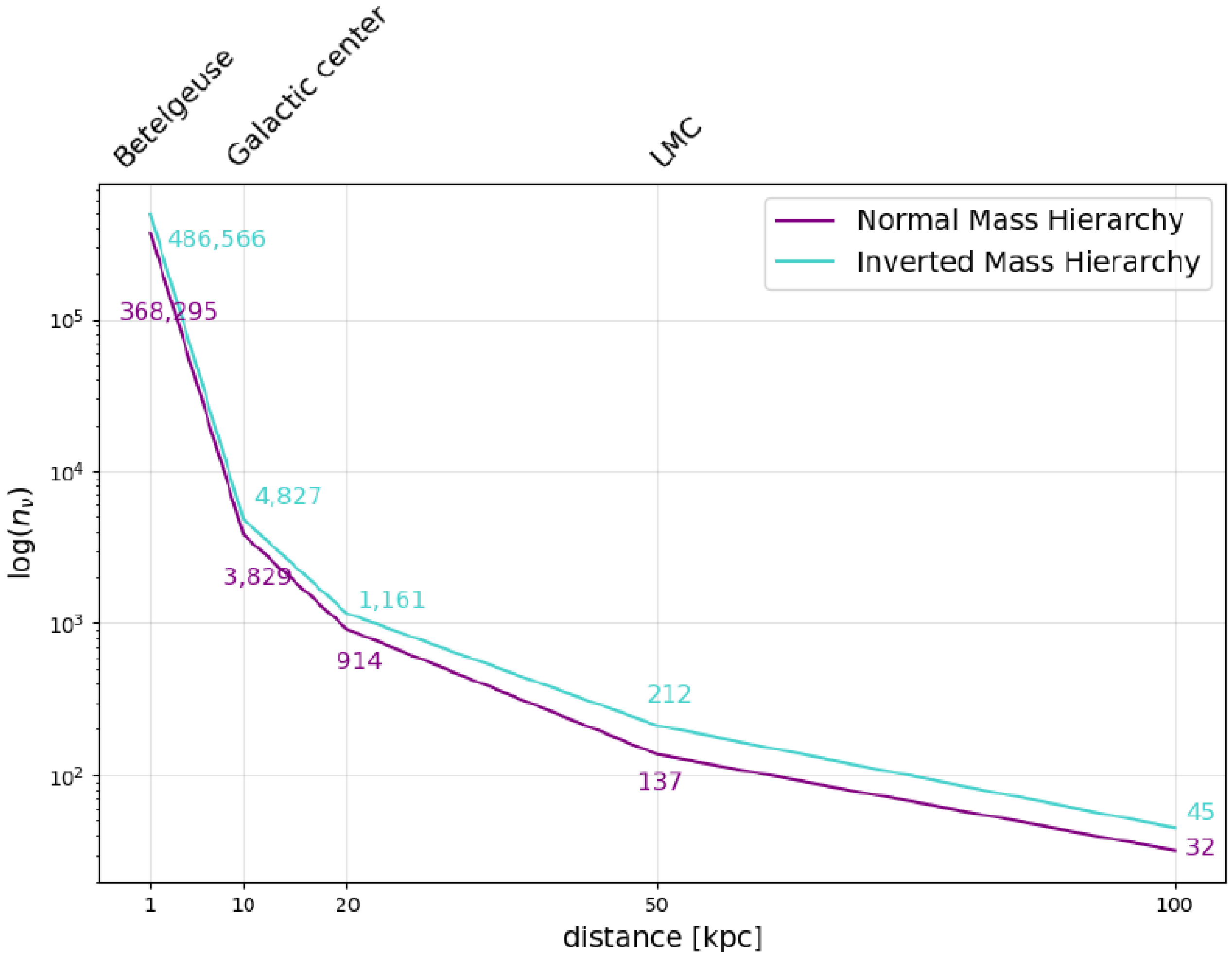
- Charge-current interaction on oxygen nuclei (O16e) – $\nu_e + {}^{16}O \rightarrow e^- + X, \quad \bar{\nu}_e + {}^{16}O \rightarrow e^+ + X$

  Subdominant channel in HyperK. High energy thresholds for both reactions.

  Only electron neutrinos and antineutrinos.

  Sensitive proof of the high energy tail of neutrino flux coming from SN.

Simulations



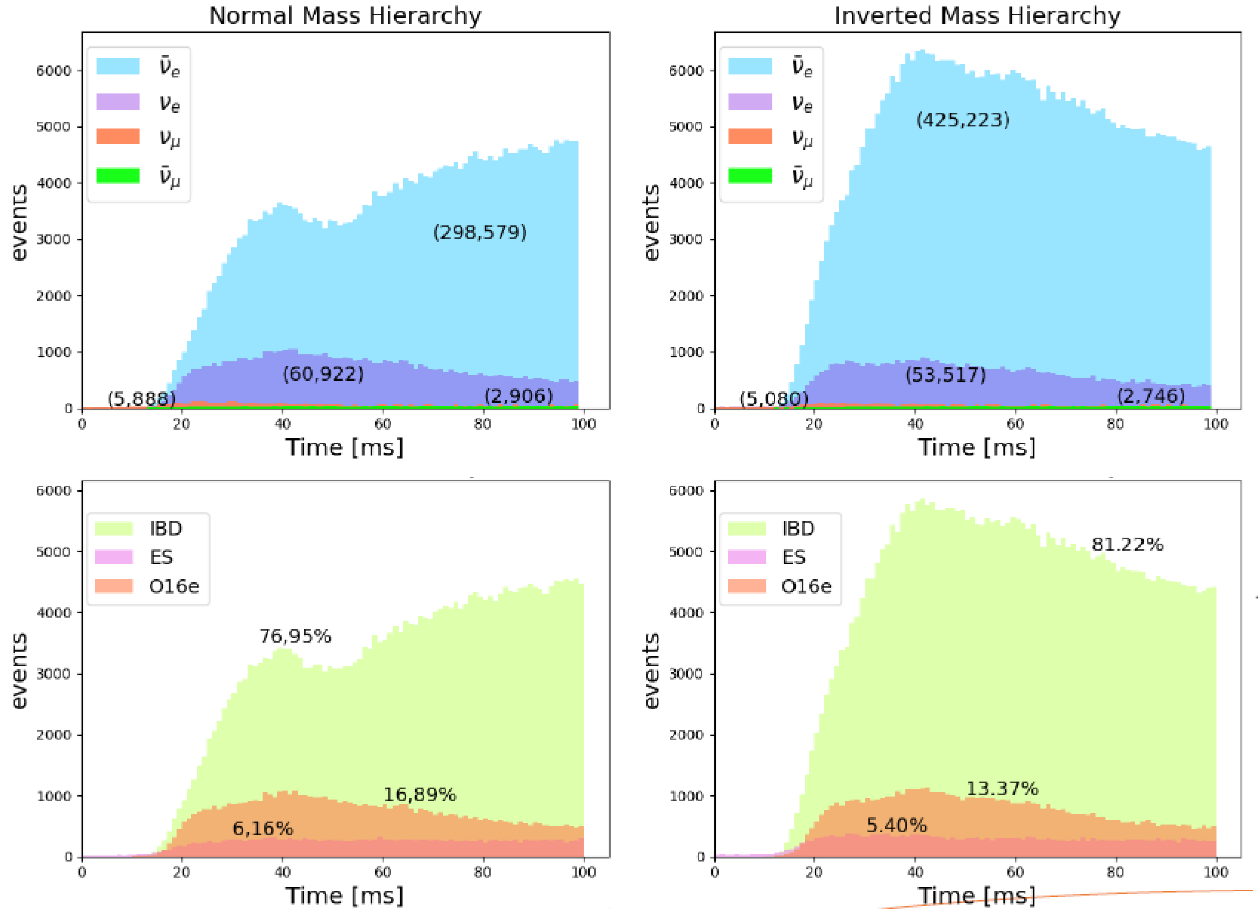
MC data
↓
no detector effects are considered!

sntools → Monte Carlo (MC) event generator for neutrinos from supernovae

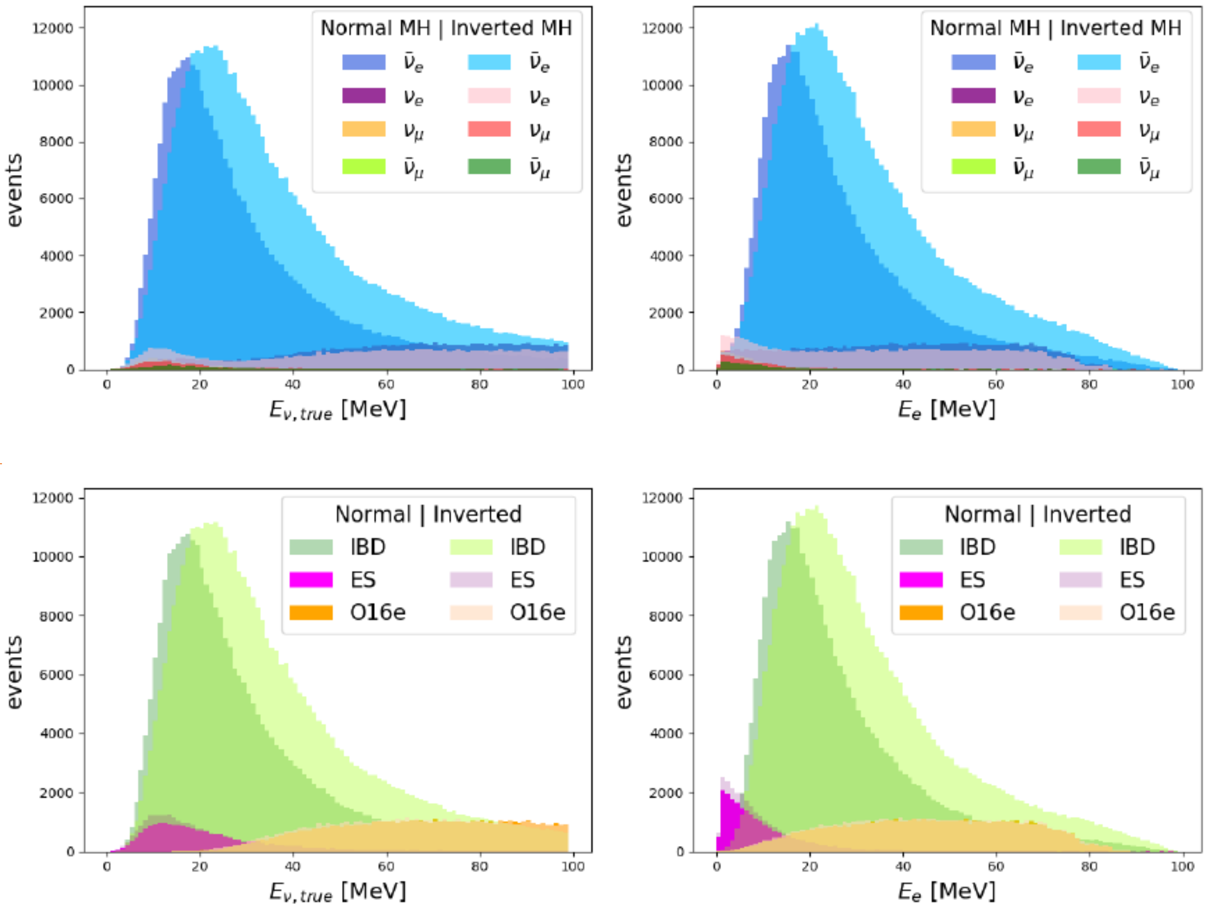
We used the Nakazato model for a $13M_\odot$ progenitor star and time interval of [0-100]ms, setting the 0 at the point when the core bounces i.e., phase 3 of the explosion mechanism of CCSN.

We created 2 data sets –reference files-, one with NH and the other IH.

Distance references: Betelgeuse at 0.2kpc, center of the Milky Way at 8.5kpc and Large Magellanic Cloud at 50kpc



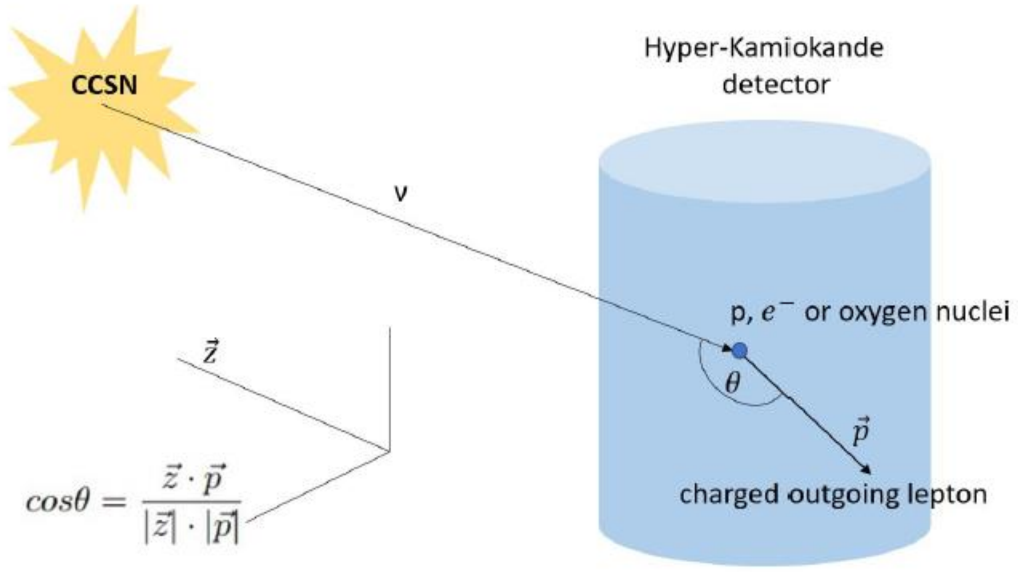
- The simulations reflect the previous mentioned phases of the CCSN explosion mechanism.
- Also MC events of neutrino flavours agree with the interaction processes.

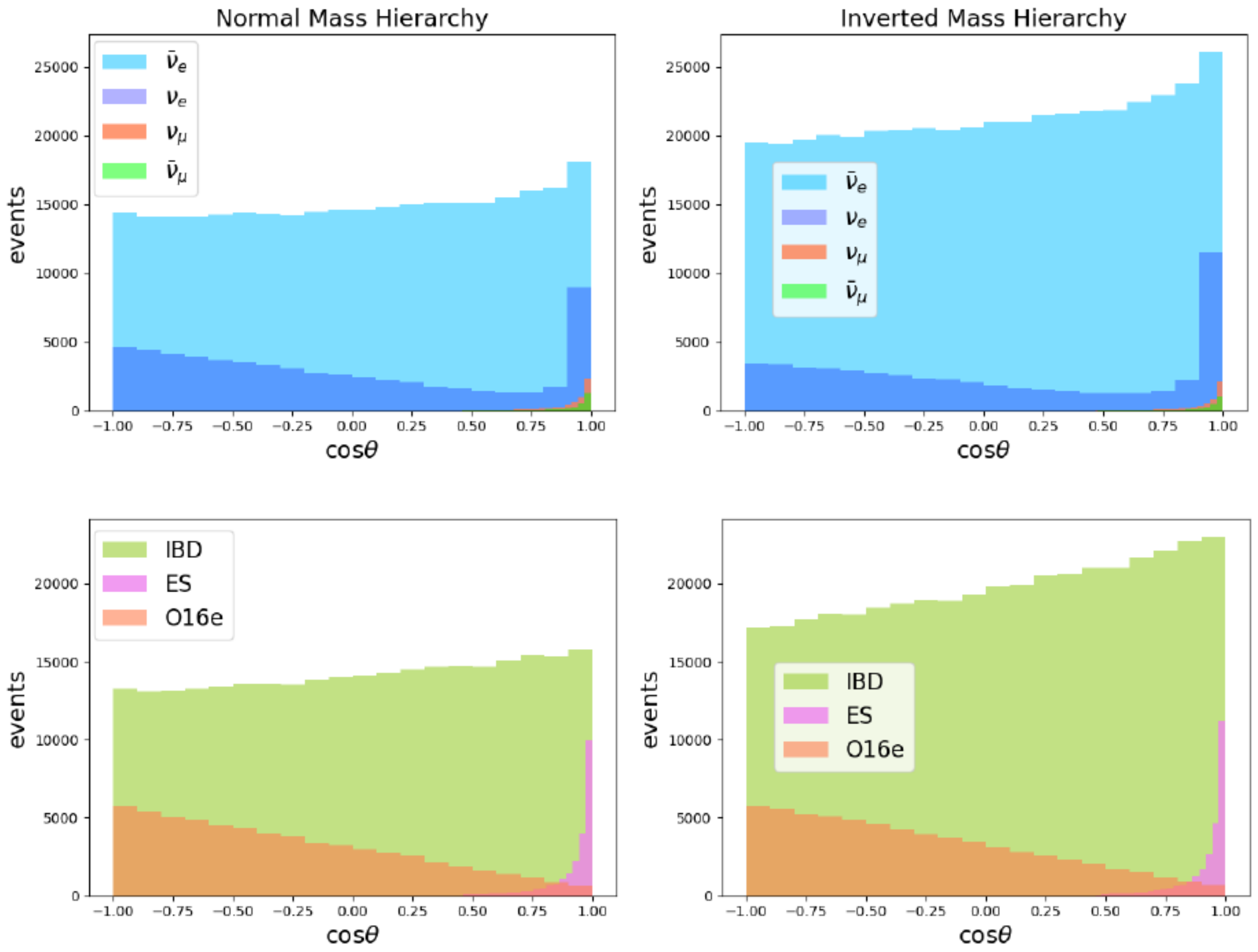


- Energy of the incoming neutrino: $E_{\nu,true}$.
- Detected energy of the outgoing leptons which are produced when neutrinos interact with particles in the water that fills the tank: E_e.

MH discrimination method

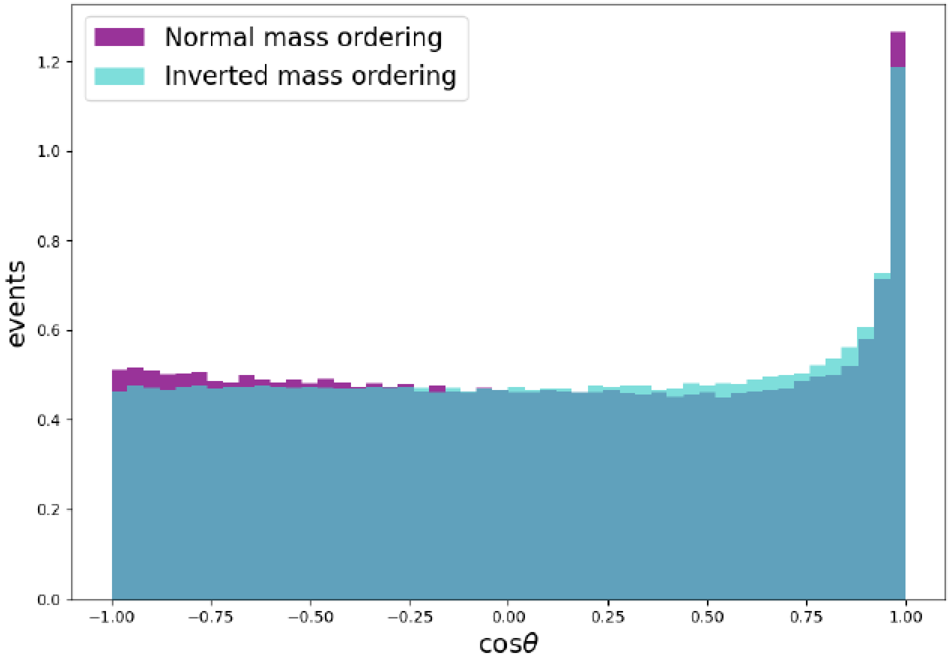
- MH changes the flavour composition of the SN neutrino flux.
- This changes the fraction of each interaction channel since different processes are sensitive to different ν flavours.
- Which changes the observed angular distribution.

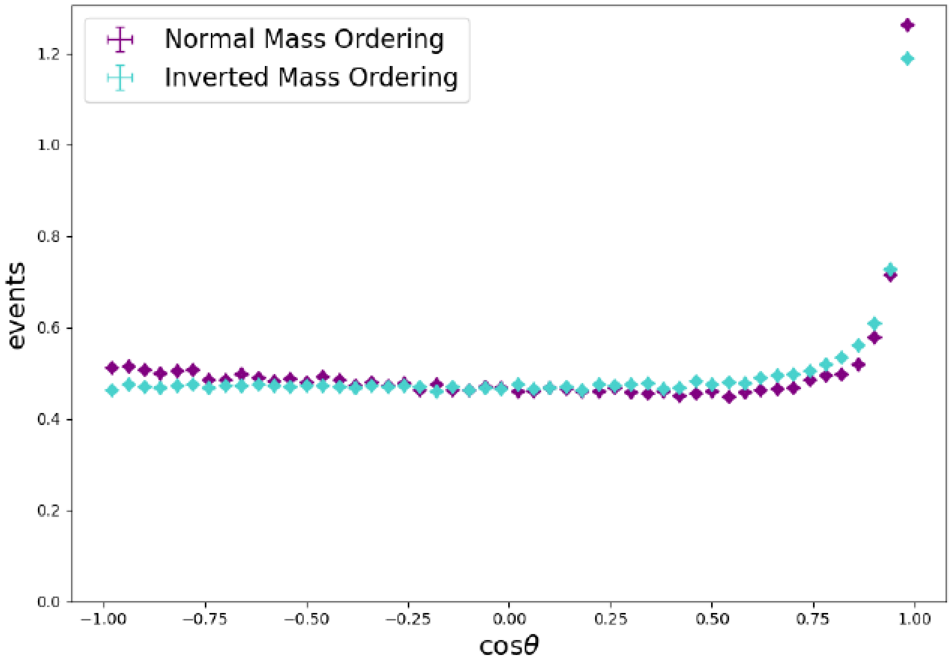




Analysis strategy

The key point is to check the shape of the distributions independently of the number of events





$$ratioNH \equiv N = \frac{N_1}{N_2}, \quad ratioIH \equiv N' = \frac{N_3}{N_4}$$

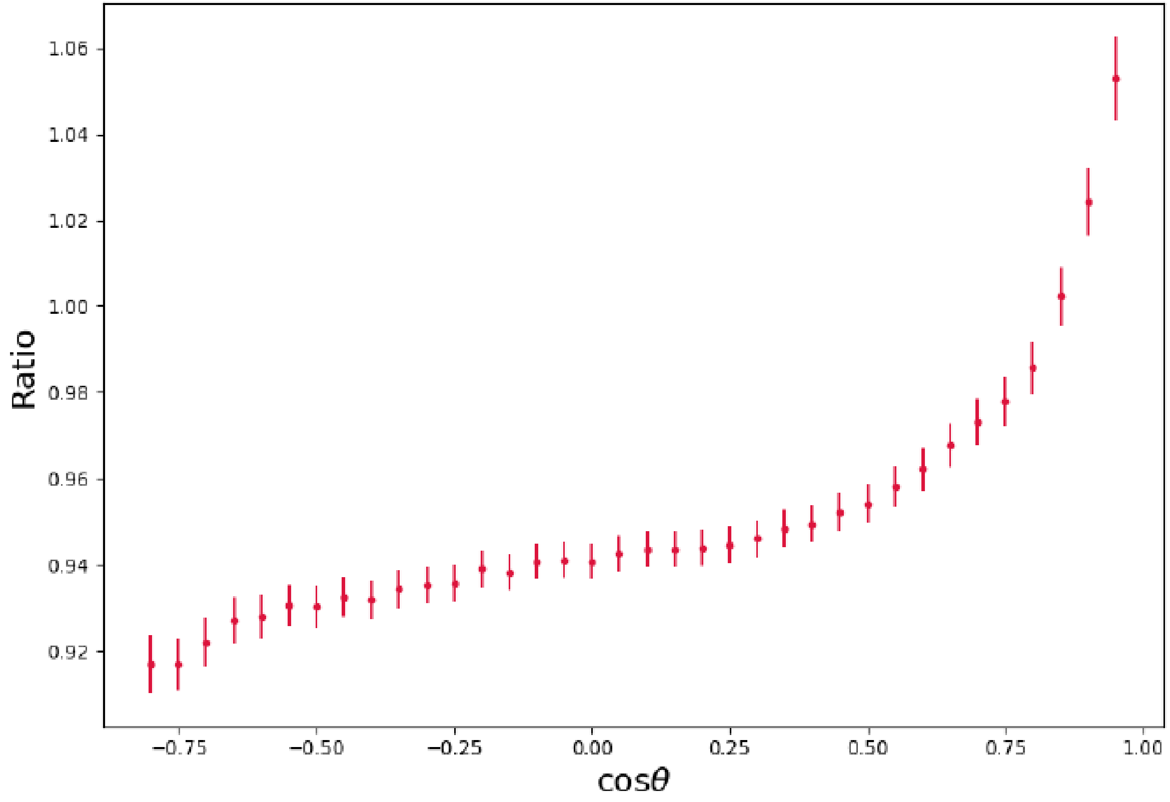
$$\sigma_{ratioNH} \equiv \sigma_N = \sqrt{\left|\frac{\partial}{\partial N_1}\left(\frac{N_1}{N_2}\right) \cdot \sigma_{N_1}\right|^2 + \left|\frac{\partial}{\partial N_2}\left(\frac{N_1}{N_2}\right) \cdot \sigma_{N_2}\right|^2} = \sqrt{\frac{N_1(N_2+N_1)}{N_2^3}},$$

$$\sigma_{ratioIH} \equiv \sigma_{N'} = \sqrt{\left|\frac{\partial}{\partial N_3}\left(\frac{N_3}{N_4}\right) \cdot \sigma_{N_3}\right|^2 + \left|\frac{\partial}{\partial N_4}\left(\frac{N_3}{N_4}\right) \cdot \sigma_{N_4}\right|^2} = \sqrt{\frac{N_3(N_4+N_3)}{N_4^3}}.$$

$$Ratio = \frac{ratioNH}{ratioIH} \equiv \frac{N}{N'}$$

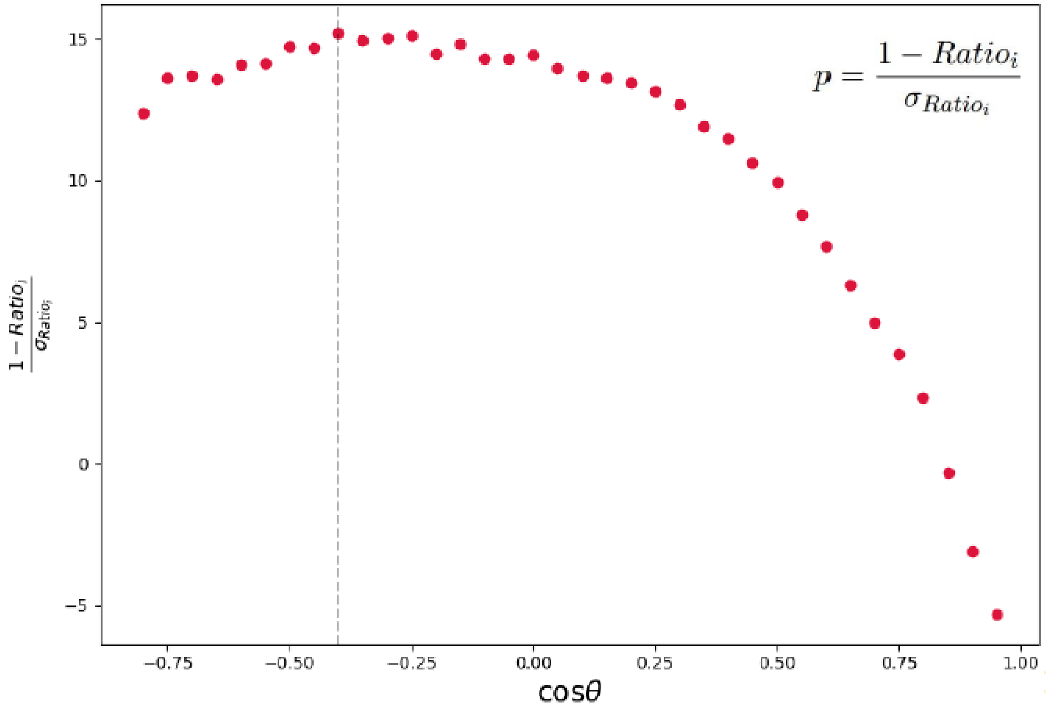
$$\sigma_{Ratio} = \sqrt{\left|\frac{\partial}{\partial N}\left(\frac{N}{N'}\right)\cdot\sigma_N\right|^2 + \left|\frac{\partial}{\partial N'}\left(\frac{N}{N'}\right)\cdot\sigma_{N'}\right|^2} = \sqrt{\left(\frac{1}{N'}\cdot\sigma_N\right)^2 + \left|\frac{-N}{N'^2}\cdot\sigma_{N'}\right|^2}$$

MC data
↓
no detector effects are considered!



Ratio optimized at -0.40 with 15.2σ

Pull distribution



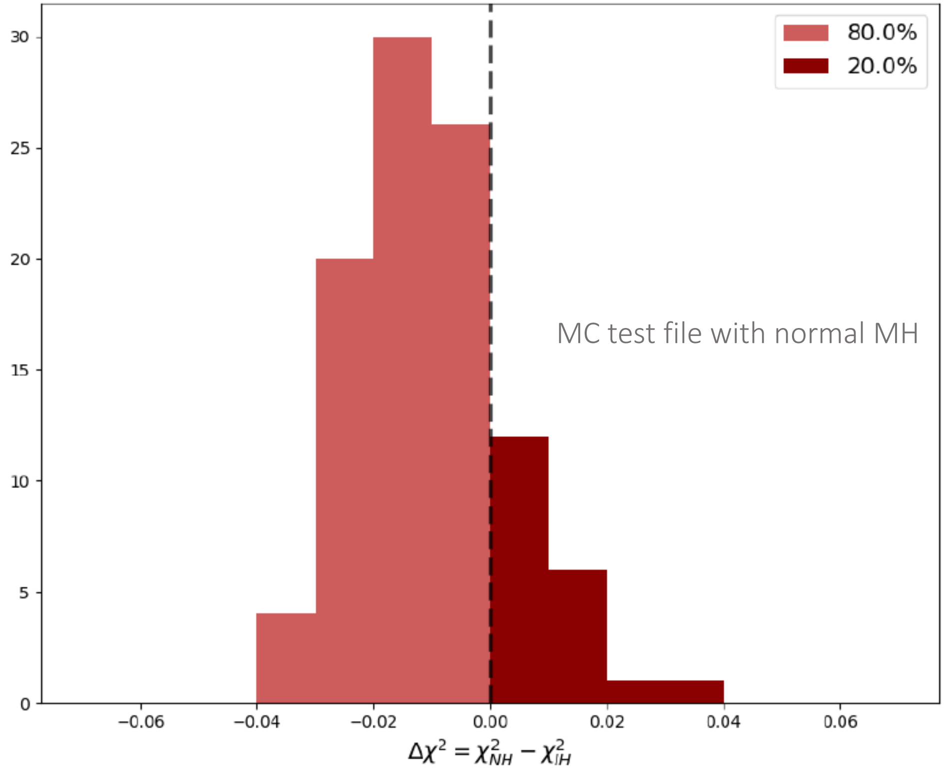
Analysis & Results

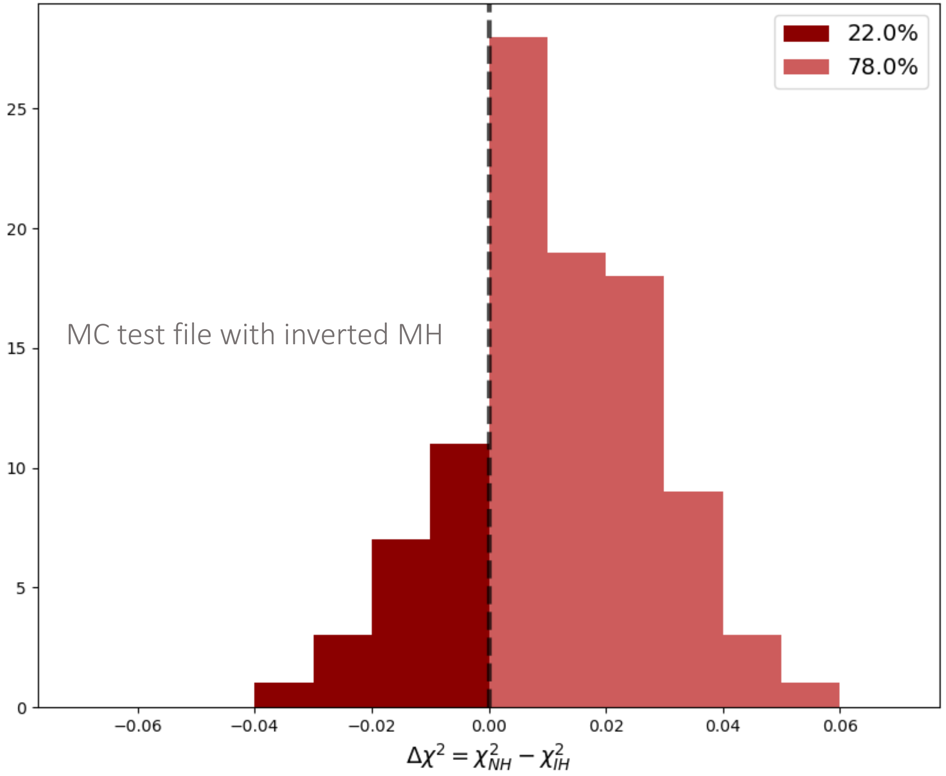
- We develop a likelihood method using $\chi^2 = \frac{(E_i - O_i)^2}{E_i}$
- Method applied to *N=100* experiments from the same test file of 300,000 events.
- We need statistically independent events → *n=3,000* events per experiment.

Equivalent to detecting a SN ν burst from a SN 10kpc away from Earth.

By counting the fraction of the $\Delta\chi^2$ values that we have on the left and on the right side of 0, we can estimate how many times the observation has normal or inverted MH.

$$\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH}$$

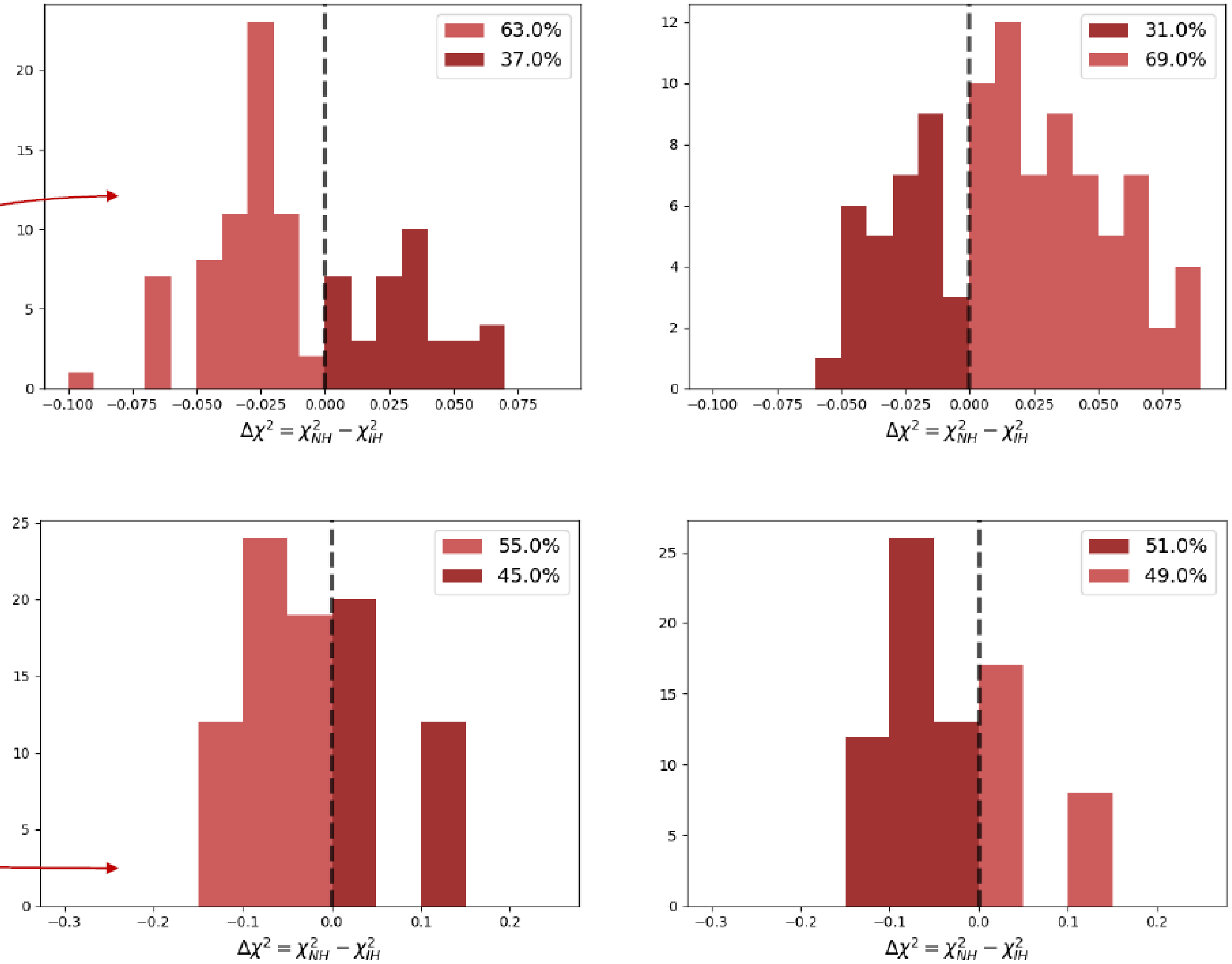




Distance dependency study

MH discrimination method applied for *N=100* experiments of *n=300* events each → 50kpc

MH discrimination method applied for *N=100* experiments of *n=30* events each → 100kpc

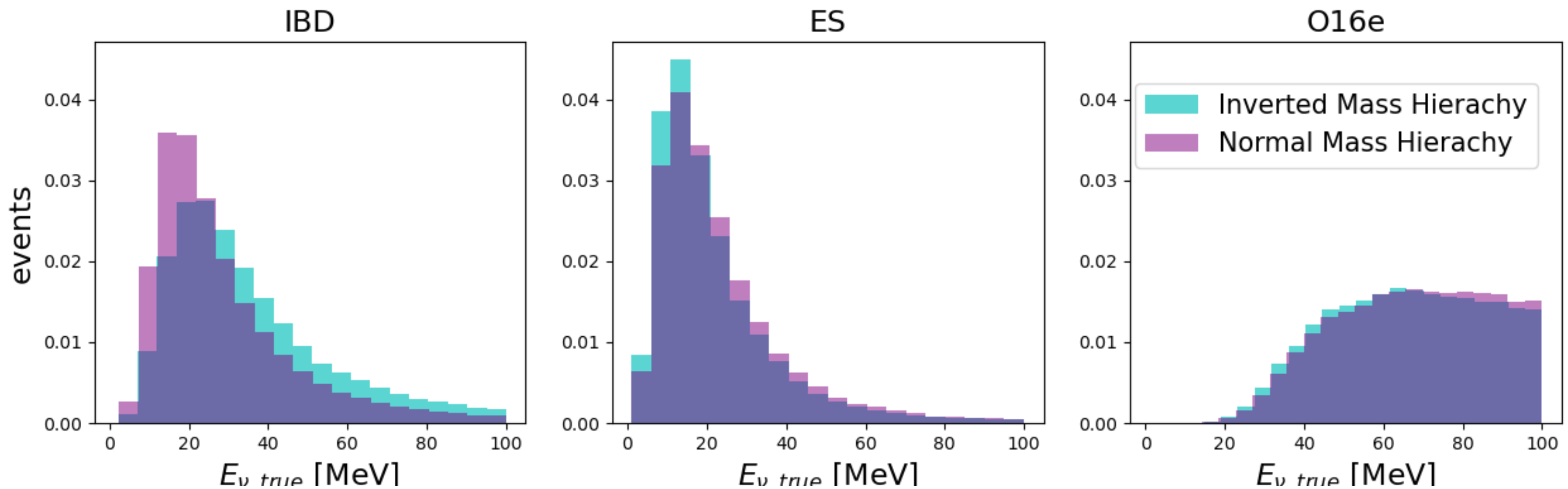


Conclusions & overlook

- From the first analysis, we confirmed that the MC simulated data agrees with theory.
- If a SN occurs at a fiducial distance of 10kpc and we have the capability of detecting 10^3 neutrinos, we could apply our method and discriminate the neutrino MH with ~80% probability.
- Sensitivity is very low even assuming MC data with no detector effects considered. Not satisfactory results.
- At 50kpc, we have a probability of ~60%, and at 100kpc, our method is not conclusive.
- Supernova every 25 years. The sensitivity for a SN at 10kpc is very limited, so this is a very basic analysis.

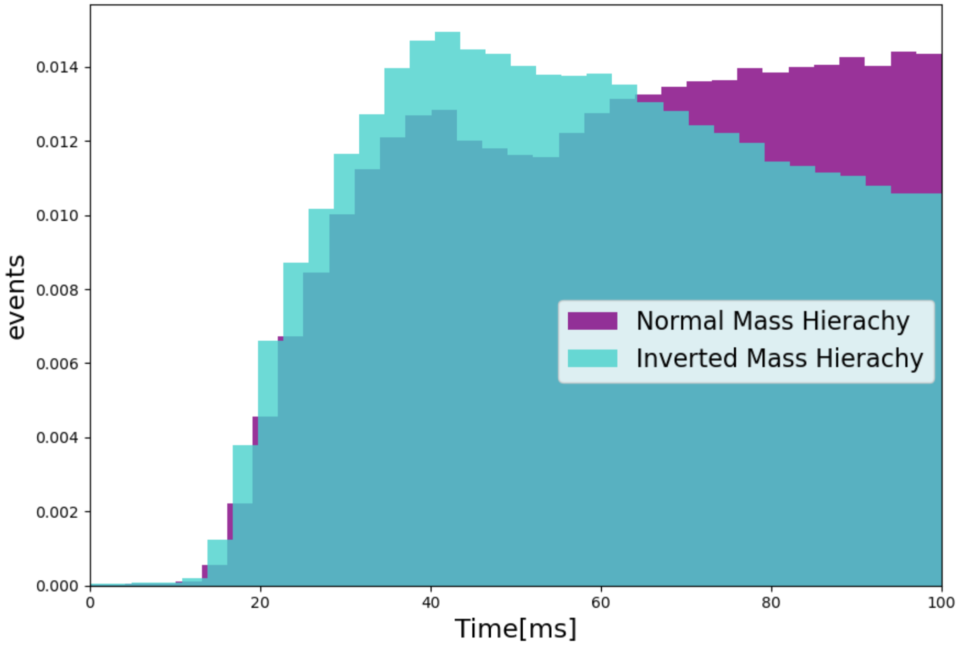
Results neither satisfactory nor decisive.

→ Starting point for future enhanced analysis (e.g. with more sophisticated shape analysis of the data).



Energy shape analysis

Time shape analysis



Bin-by-bin analysis

For the i-th bin, you calculate $\chi_i{}^2$, and then

$$\chi^2 = \sum_i \chi_i{}^2$$

This way, you should have much more sensitivity, basically because you have a *shape information*, whereas in the ratio method developed in this work, you have all the information projected into a single parameter: the ratio.

THE END

Thank you for your attention