SNB/LE Physics Working Group meeting

MH Study Updates

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Introduction

- The neutronization burst counts are expected to be an intrinsically robust signature of mass hierarchy (mass ordering), as there any collective effects are not expected at that early time.

- However, the MH discrimination using the neutronization burst looks to be model dependent.

- We are analyzing 4 SN neutrino databases with different neutrino signatures, searching for MH discriminators

Introduction

SN neutrino databases (different solar masses, metallicities, shock revival times, time scales, etc):

- Garching: 1 model
- Wallace, Burrows & Dolence: 5 models
- Nakazato: 24 models
- Huedepohl: 113 models

Introduction

Strategies used:

- Sum of events in the neutronization burst

- Ratio of events from different interaction channels

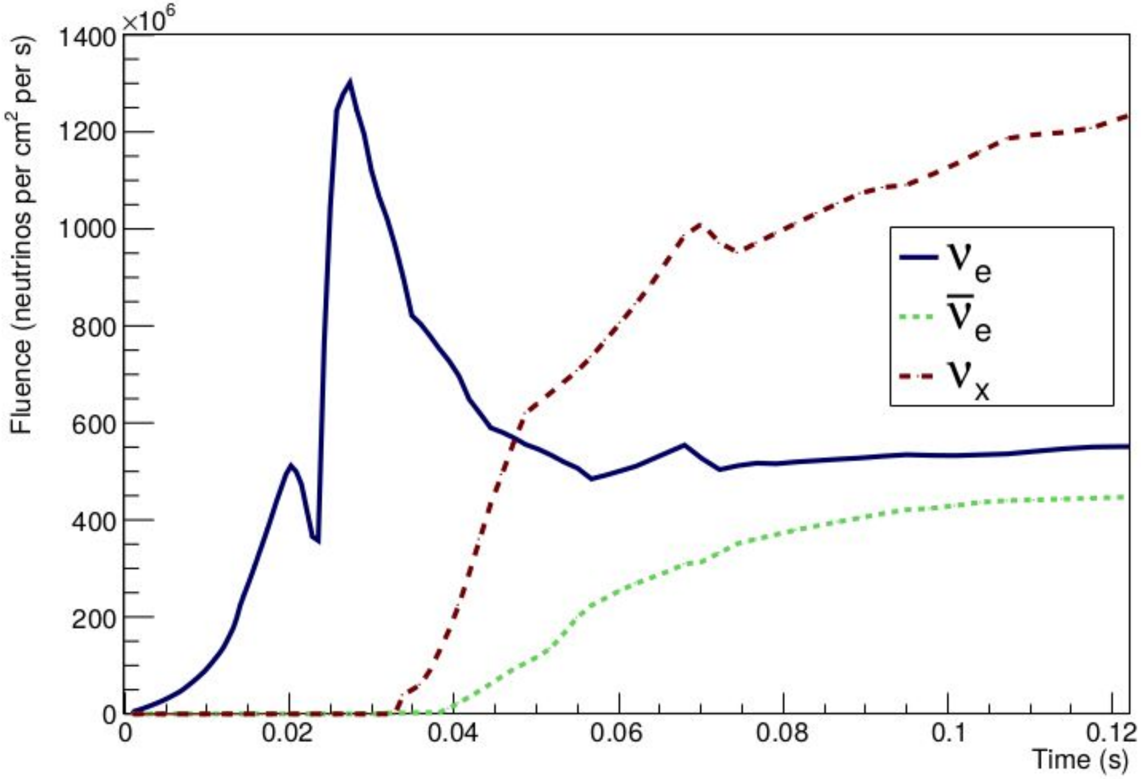
- Antineutrinos in water and scintillator

- ΔChi^2 analysis for NH and IH with a fit considering a pinched-thermal flux

SN model databases - Garching

Garching group SN model:

- Electron capture supernova
- 8.8 solar masses
- 10 kpc
- Time interval: 10 s
- Fluence units (ν/cm^2)



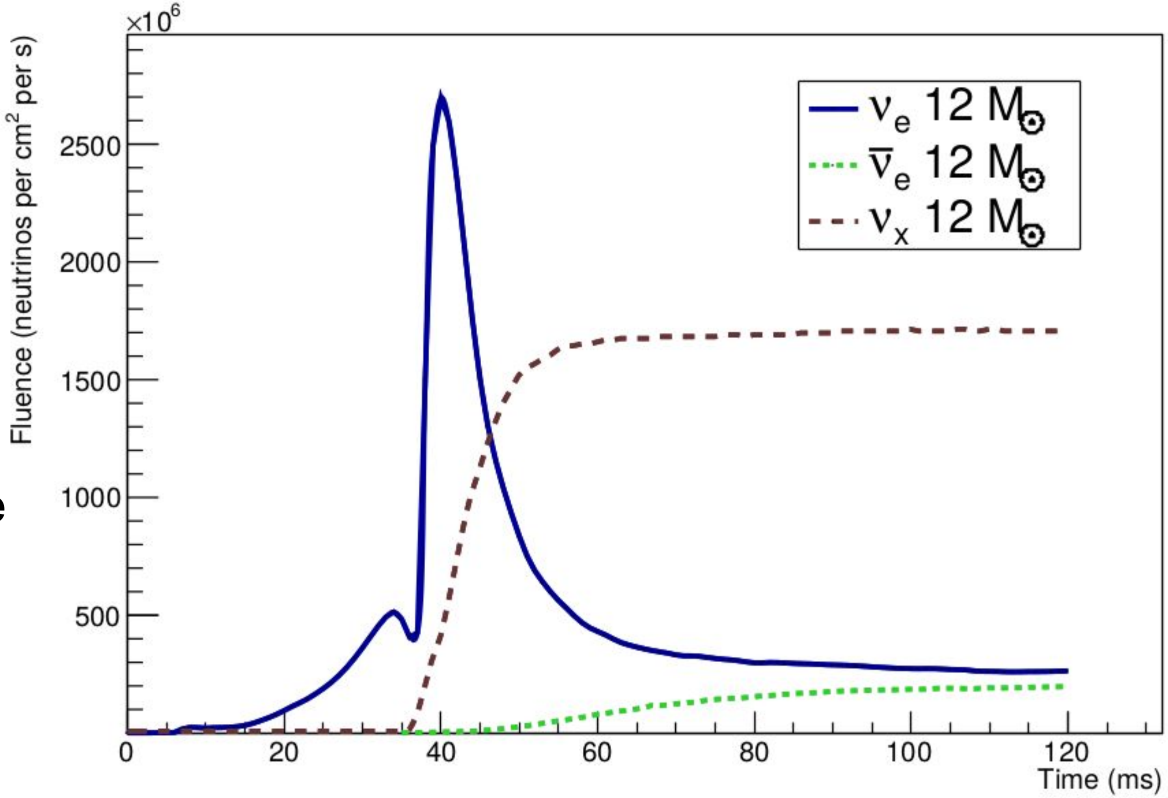
Hüdepohl, L., et al. ”Neutrino signal of electron-capture supernovae from core collapse to cooling.” Physical Review Letters 104.25 (2010): 251101.

SN model databases - Wallace, Burrows & Dolence

Progenitor models: 12, 15, 15 Shen nuclear EOS, 20, and 25 solar masses

D = 10 kpc

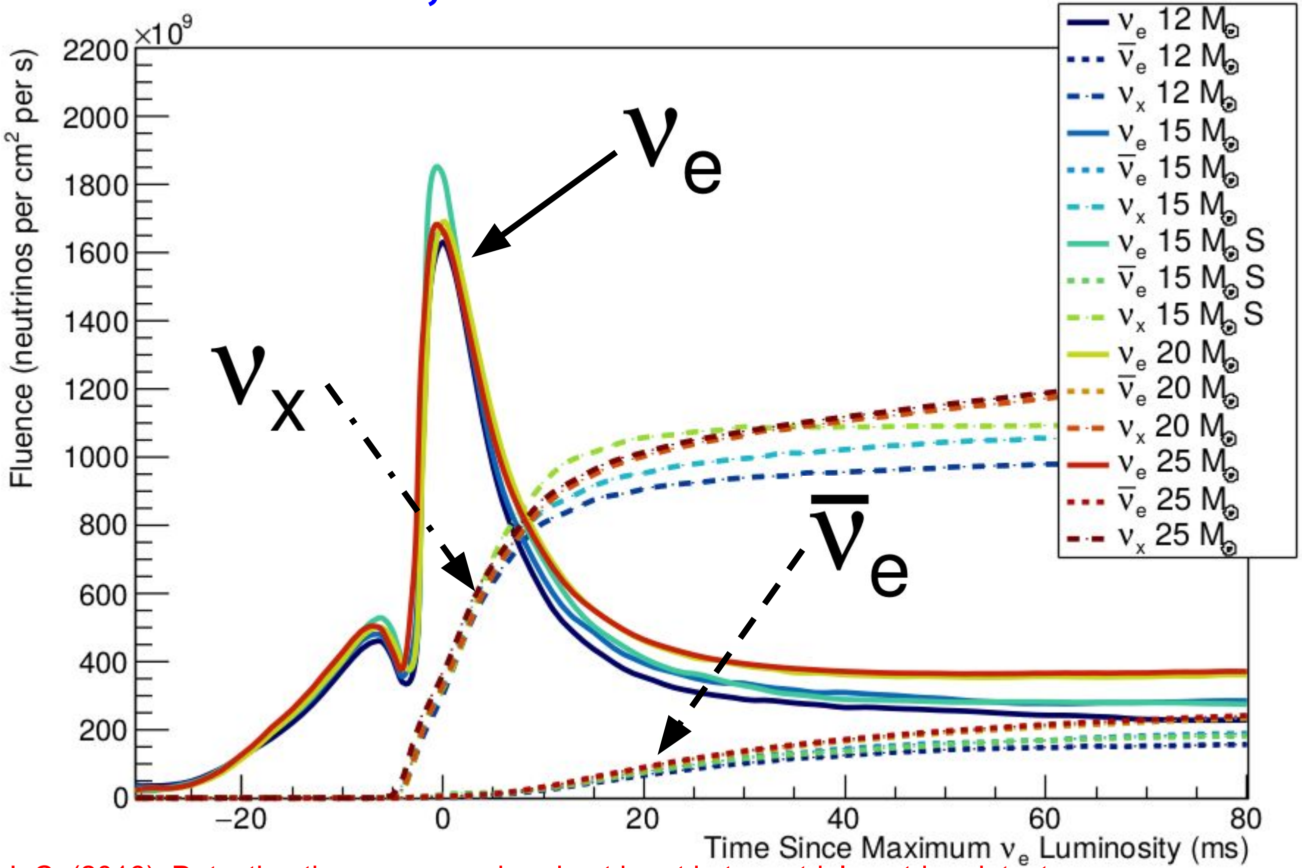
Energy luminosity (10^{51} erg/s/MeV) for each time slice (-40 ms to 80 ms, 0 = L_{max}) in 40 energy bins for ν_e, $\overline{\nu}_e$ and ν_x



Wallace, J., Burrows, A., & Dolence, J. C. (2016). Detecting the supernova breakout burst in terrestrial neutrino detectors. *The Astrophysical Journal*, *817*(2), 182.

SN model databases - Wallace, Burrows & Dolence

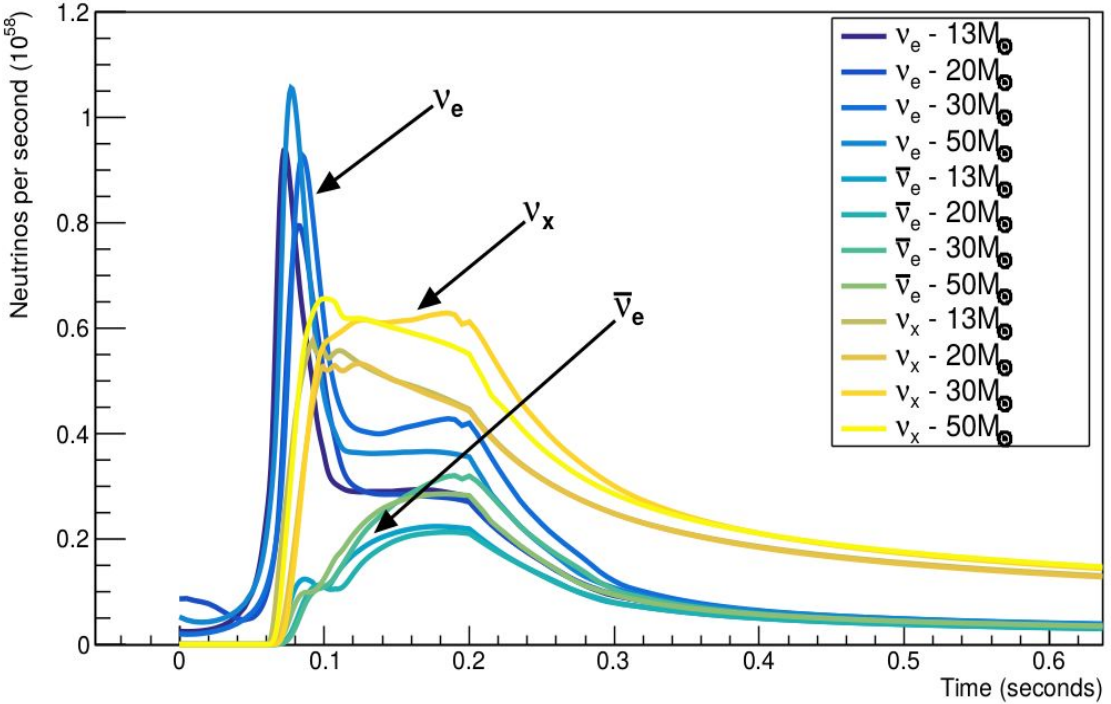
Same neutronization burst characteristics for all progenitor masses



Wallace, J., Burrows, A., & Dolence, J. C. (2016). Detecting the supernova breakout burst in terrestrial neutrino detectors. *The Astrophysical Journal*, *817*(2), 182.

SN model databases - Nakazato

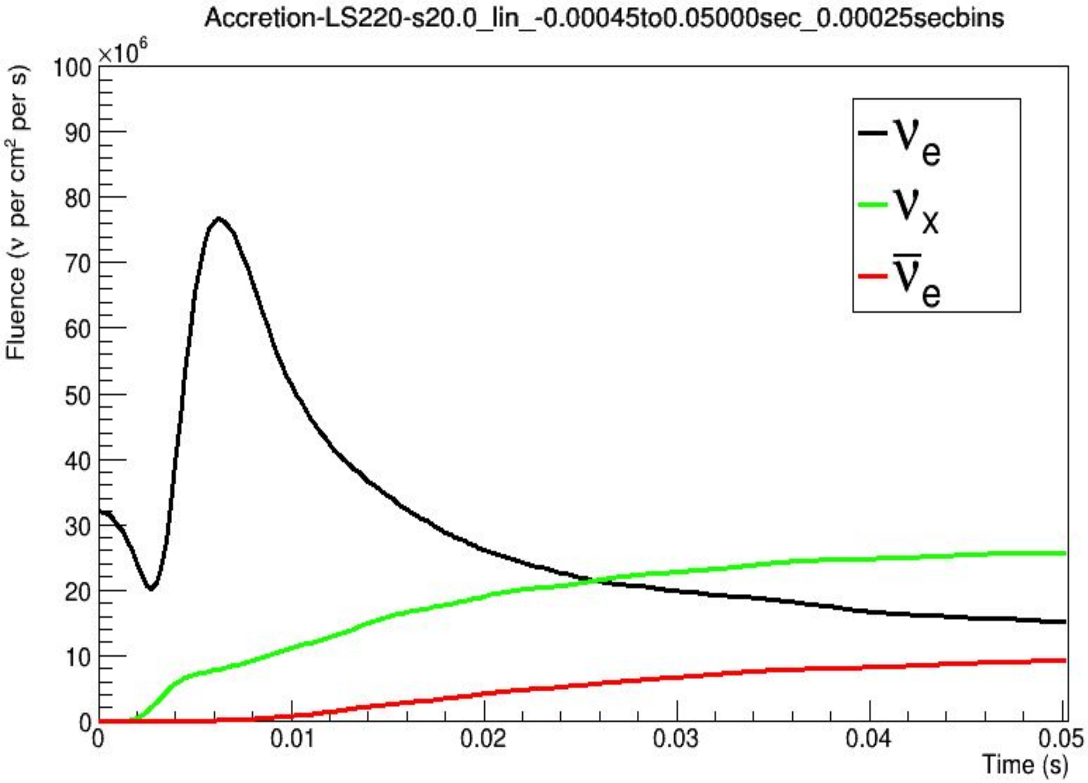
- Progenitor models: 13, 20, 30, and 50 solar masses
- Metallicity: 0.02 and 0.004
- Shock revival time: 100, 200, and 300 ms
- Time: 0 to 20 s
- Database available in: http://asphwww.ph.noda.tus.ac.jp/snn/



Nakazato et al., Astrophys. J. Supp. 205 (2013) 2, arXiv:1210.6841 [astro-ph.HE]

SN model databases - Huedepohl

- Models: Shen EOS, LS180, and LS220
- Progenitor masses: 11.2, 12, 13.8, 15, 17.6, 17.8, 20, 20.6, 25, 27, 35, 36, and 40 solar masses
- Accretion, Black Hole formation, and Cooling phases



Huedepohl, L. (2014), Neutrinos from the Formation, Cooling and Black Hole Collapse of Neutron Stars, PhD. Thesis, Technische Universitat Muenchen. http://wwwmpa.mpa-garching.mpg.de/ccsnarchive/data/Huedepohl2014_phd_thesis/

SN model databases - Huedepohl

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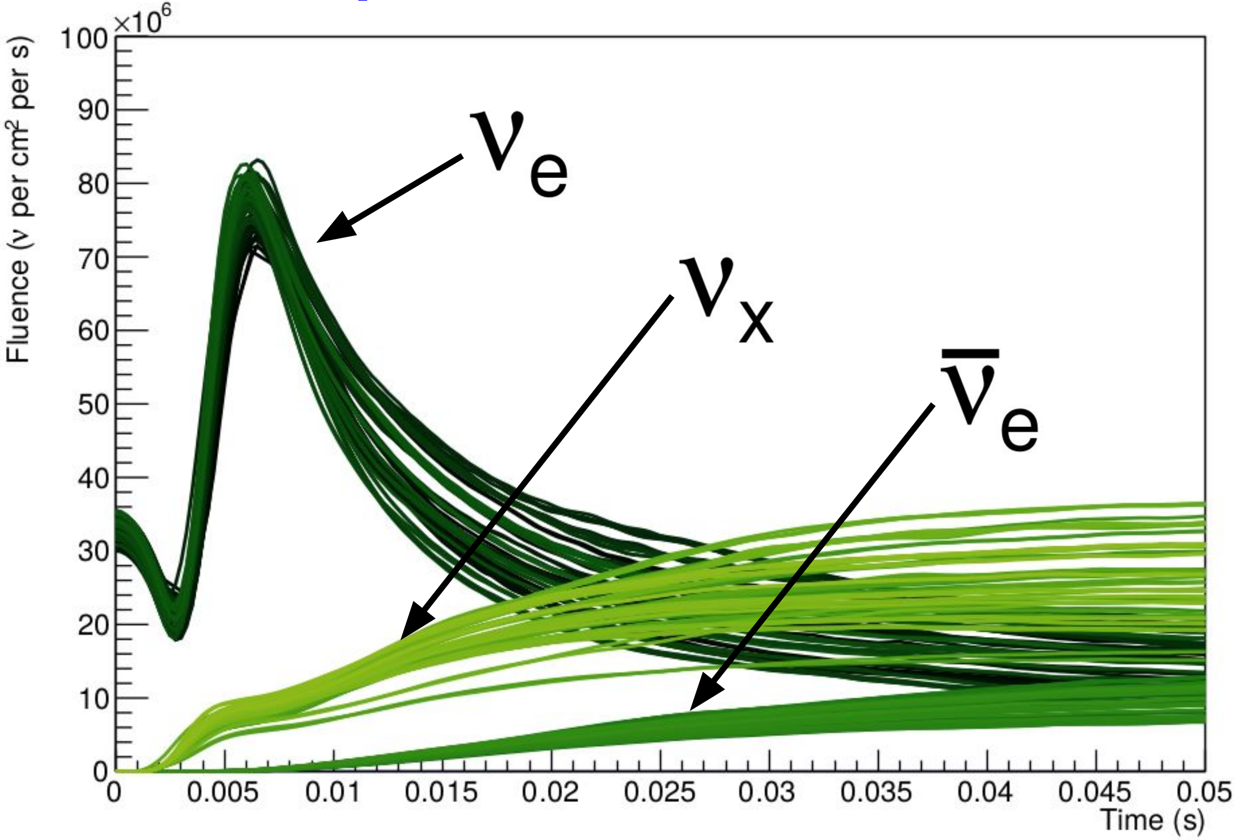


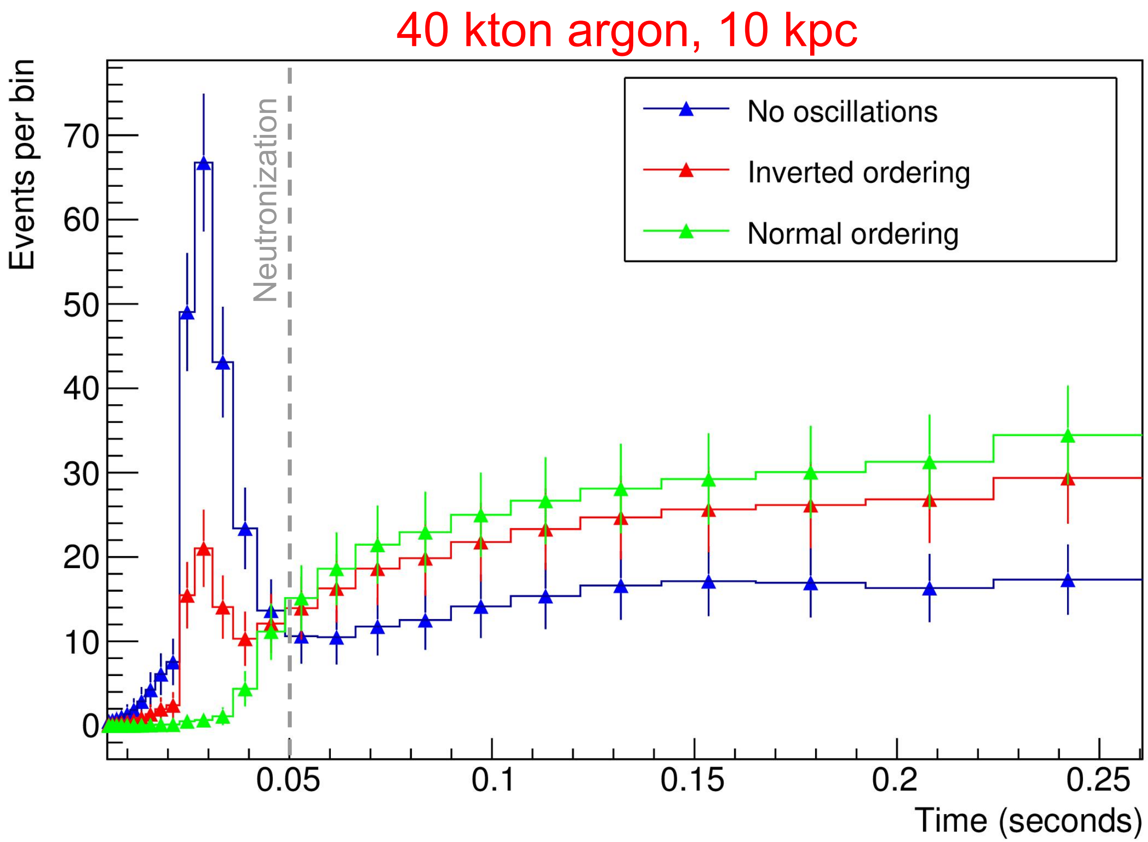
Huedepohl, L. (2014), Neutrinos from the Formation, Cooling and Black Hole Collapse of Neutron Stars, PhD. Thesis, Technische Universitat Muenchen. http://wwwmpa.mpa-garching.mpg.de/ccsnarchive/data/Huedepohl2014_phd_thesis/

MH discrimination - Neutronization burst events

Neutronization burst: valuable information for MH estimation.

- Normal Hierarchy: burst is very suppressed;
- Inverted Hierarchy: burst is suppressed, but still visible;

"Method of opportunity"



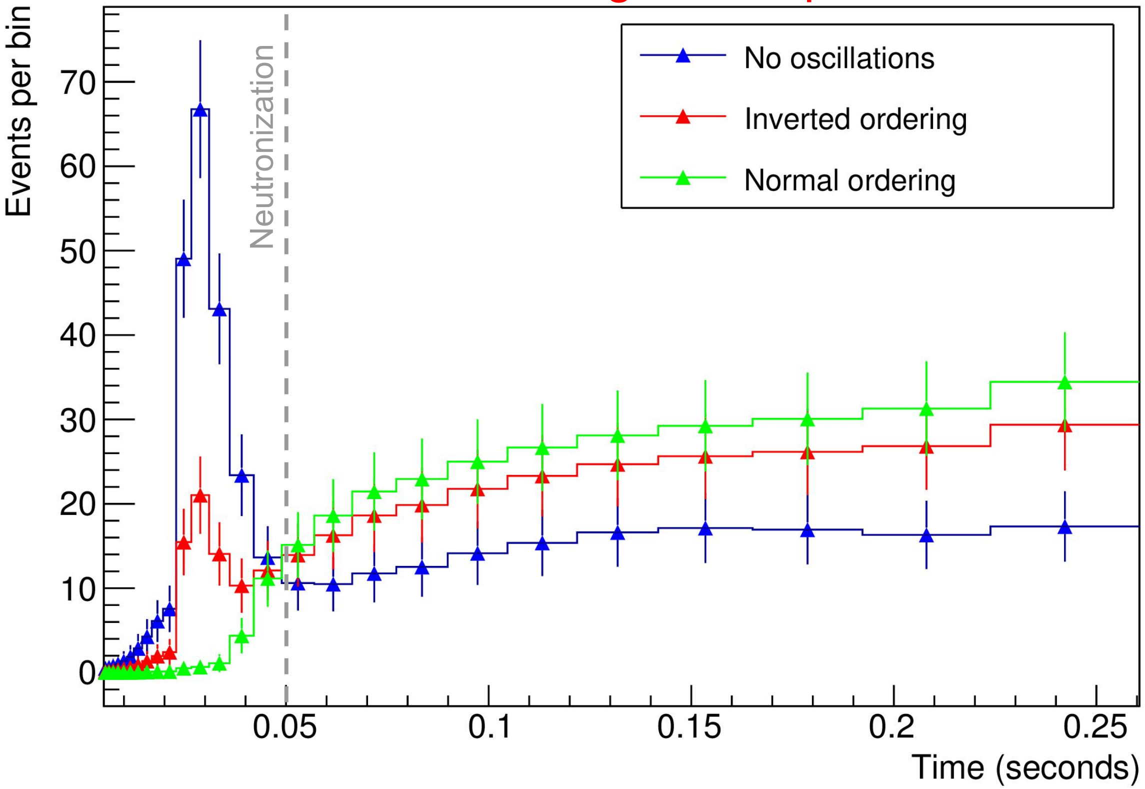
Neutronization burst events - Garching

MH discrimination method

- SN model: Garching group

- Integration of events in the neutronization time window (t < 50ms)

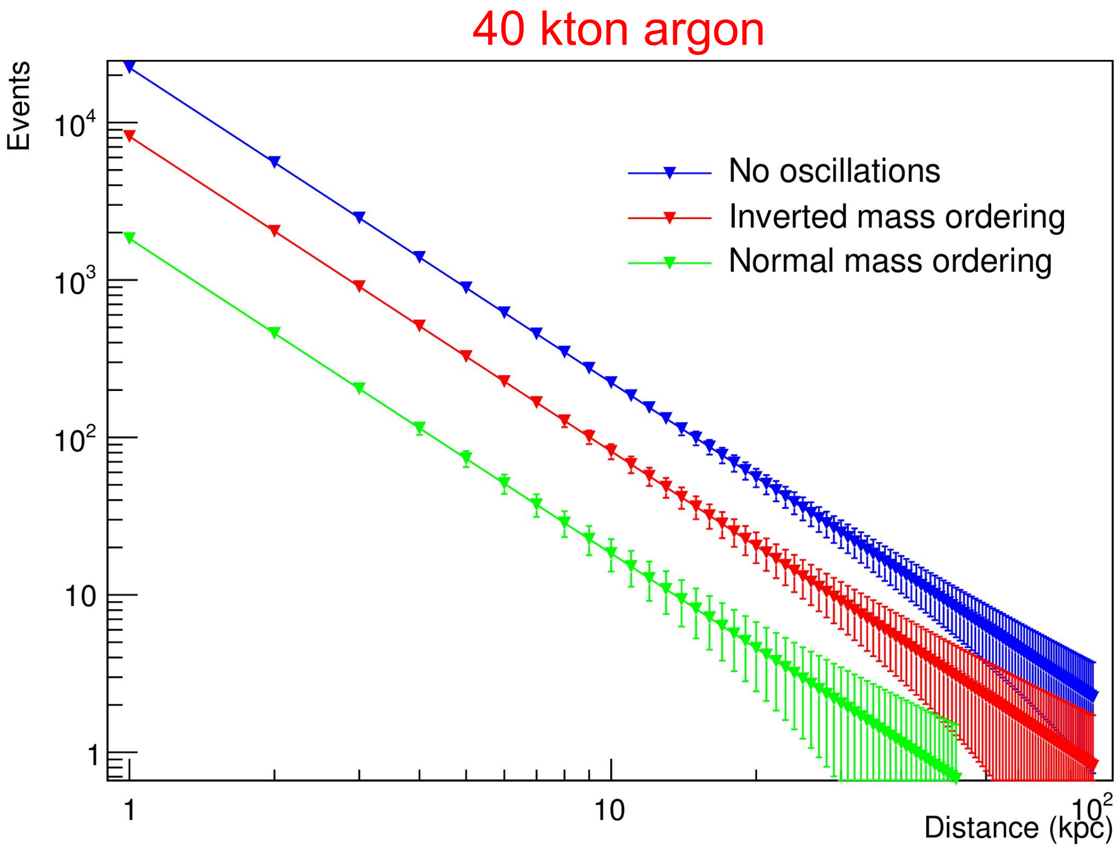
40 kton argon, 10 kpc



Hüdepohl, L., et al. "Neutrino signal of electron-capture supernovae from core collapse to cooling." Physical Review Letters 104.25 (2010): 251101.

Neutronization burst events - Garching

- Number of events is inversely proportional to D^2
- D from 1 to 100 kpc
- Good separation for different MH
- Distance dependent



Neutronization burst events - Garching

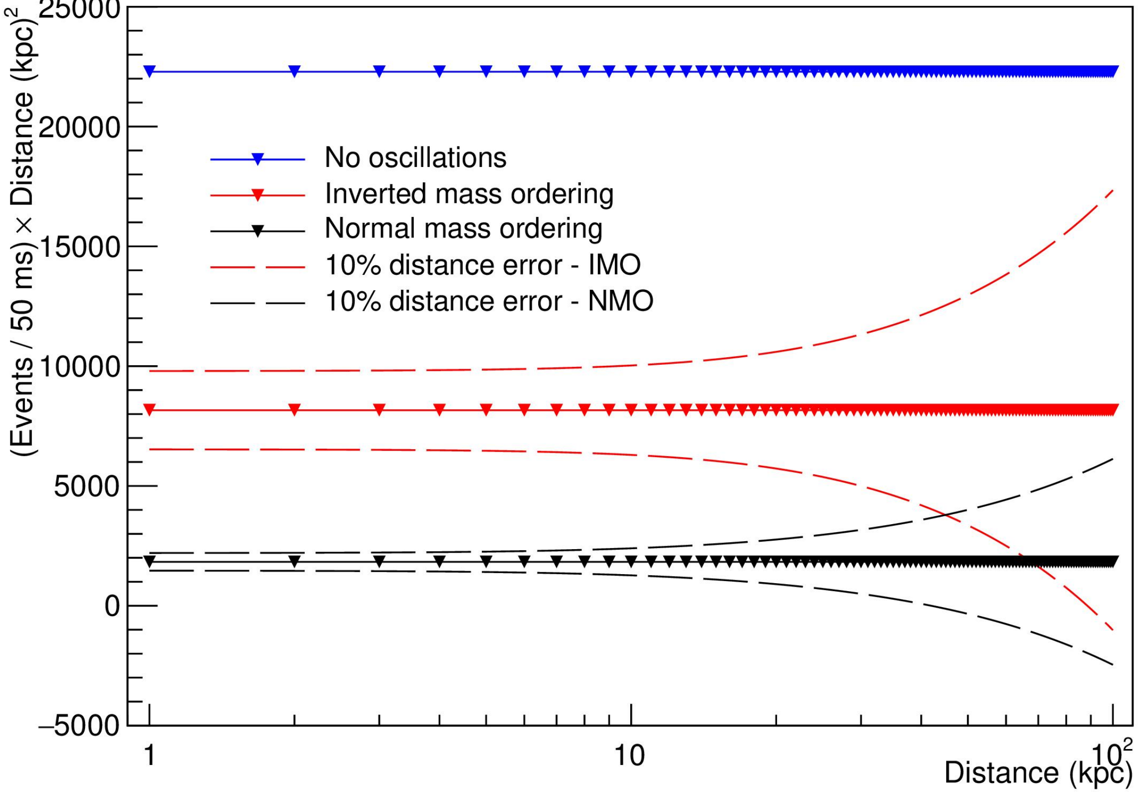
Results

Sum of events in neutronization * D^2

Distance uncertainty - 10%

Method seems promising for MH separation

40 kton argon, σ_D = 10%



Neutronization burst events - Garching

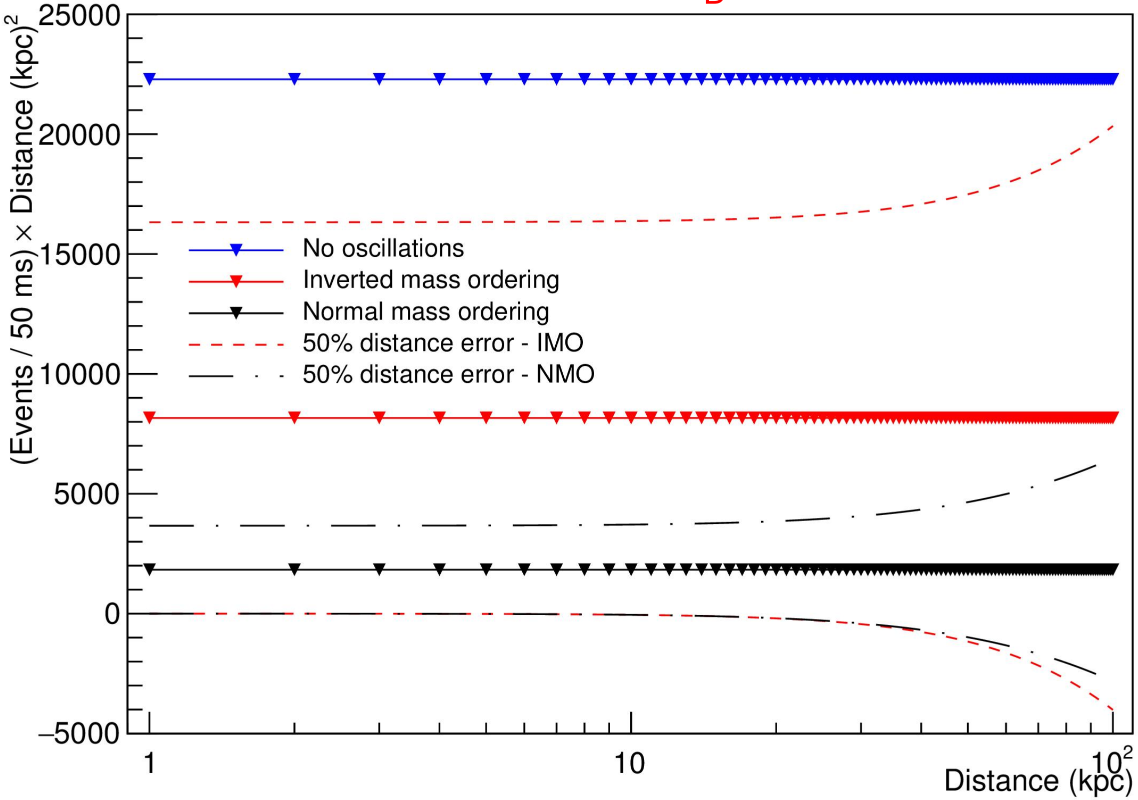
Results

Sum of events in neutronization * D^2

Distance uncertainty - 50%

For big uncertainties in distance estimation, we can't estimate the MH for any SN distances

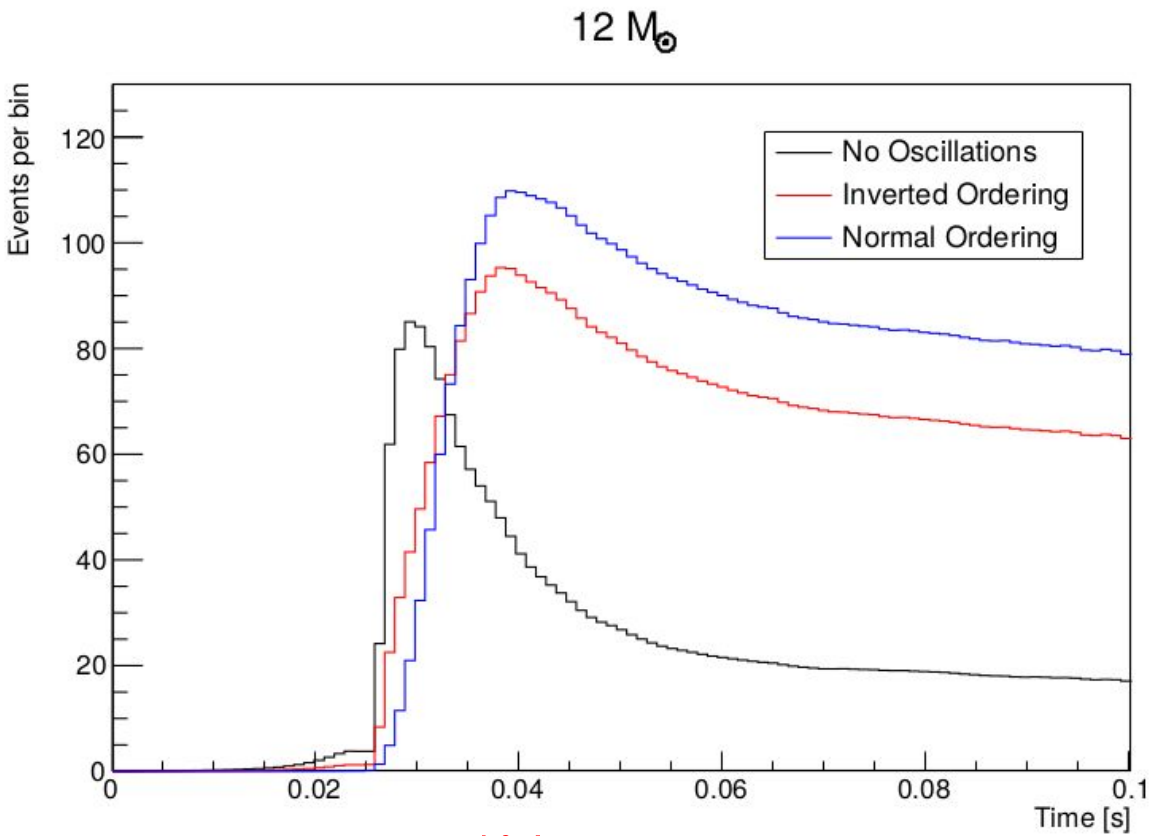
40 kton argon, σ_D = 50%



Neutronization burst events - Wallace, Burrows & Dolence

Model comparison

After run SNOwGLoBES using Wallace, Burrows & Dolence models, the events in neutronization burst doesn't look the best MH discriminator.

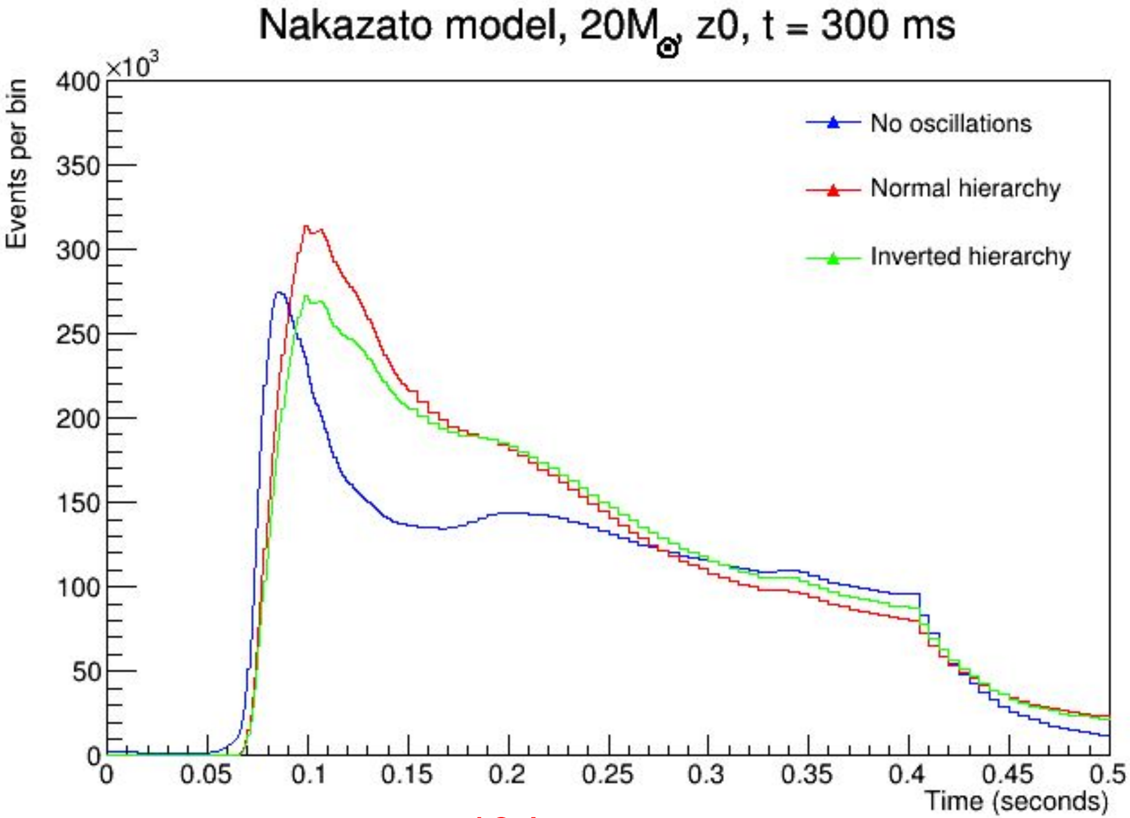


40 kton argon

Neutronization burst events - Nakazato

Model comparison

For Nakazato database the neutronization burst counts can't be used in a simple way. NH and IH events have similar event counts.

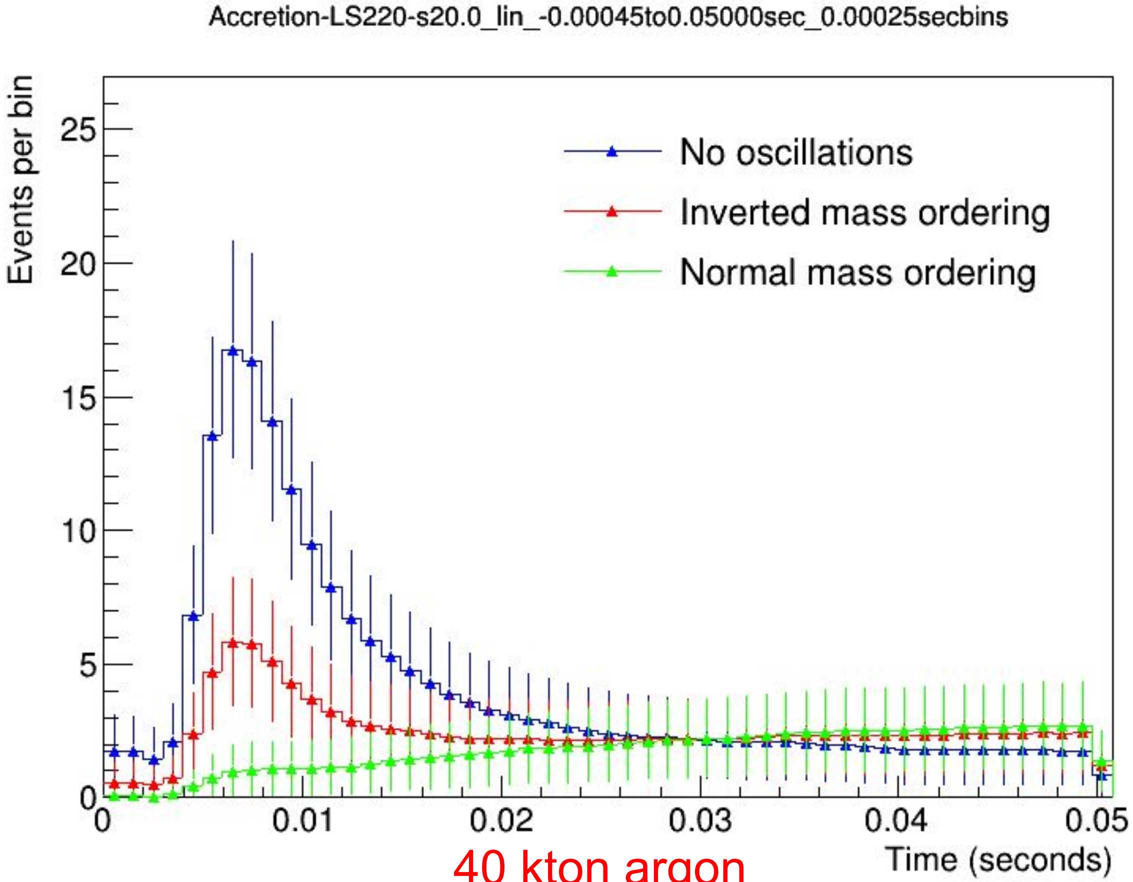


40 kton argon

Neutronization burst events - Huedepohl

Model comparison

Huedepohl database has the same behavior as the Garching database (same research group).



40 kton argon

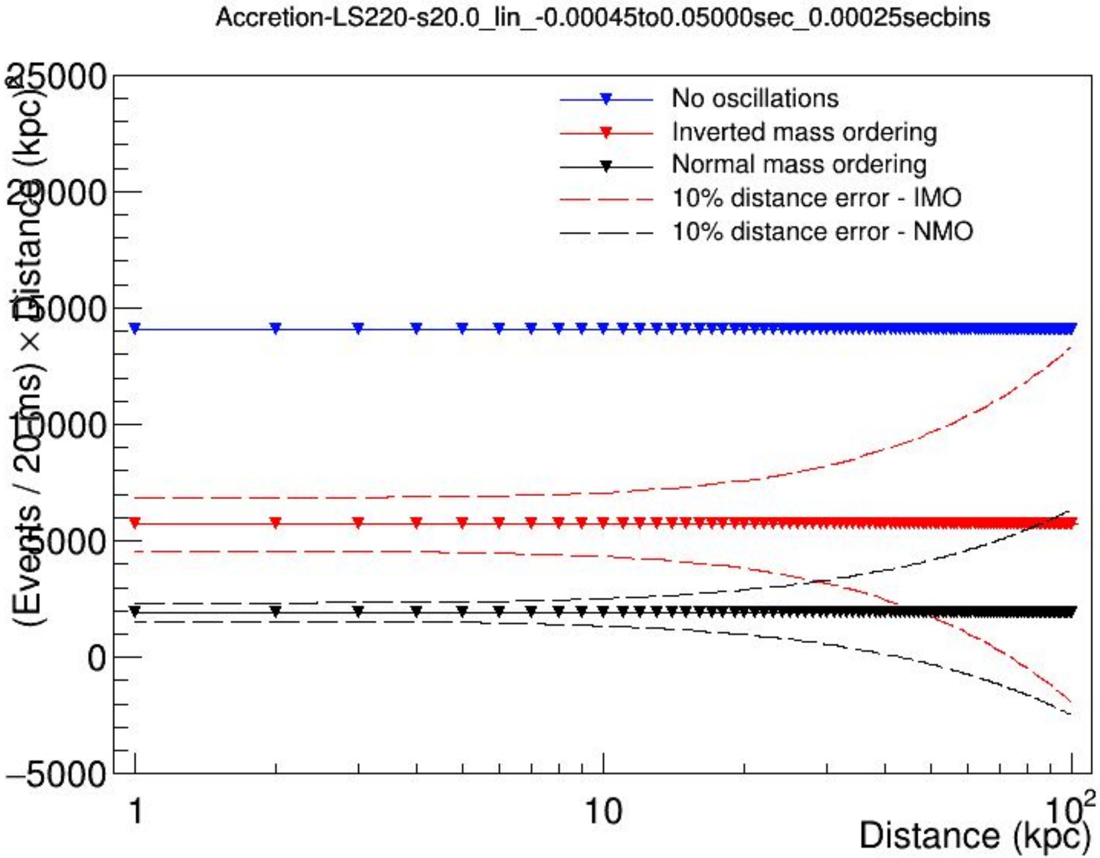
Neutronization burst events - Huedepohl

Results

Distance uncertainty - 10%

The method can be used in the same way as for Garching database

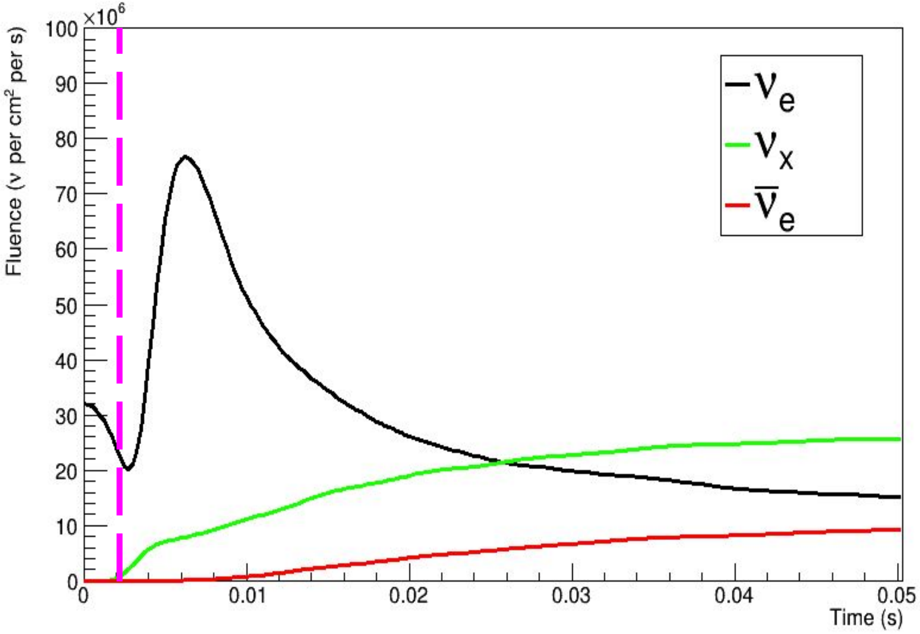
40 kton argon, σ_D = 10%



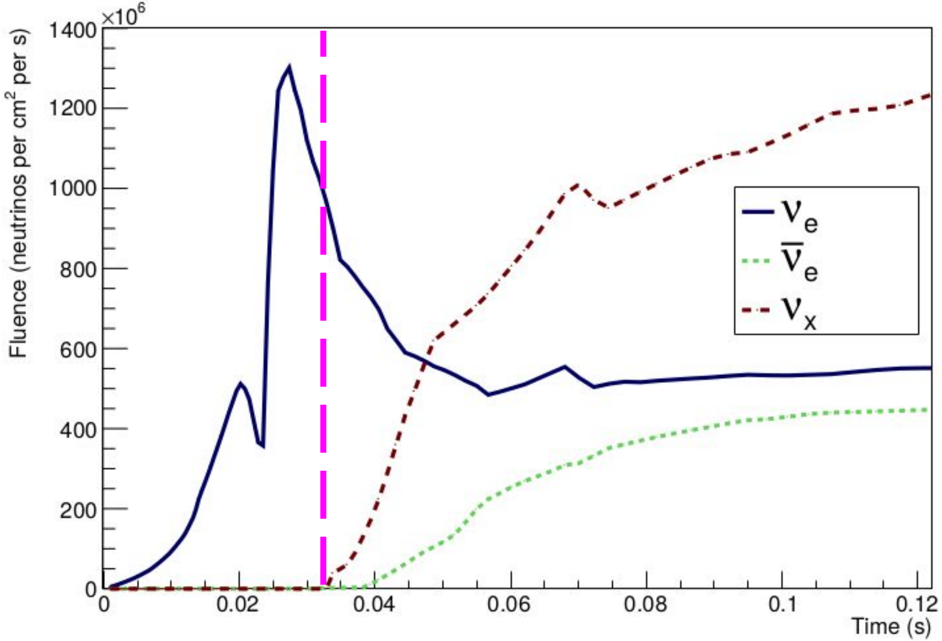
Flux differences

$$F_{\nu_e} = F^0_{\nu_x} \quad \text{(NMO)}$$
$$F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x} \quad \text{(IMO)}$$

Huedepohl



Garching

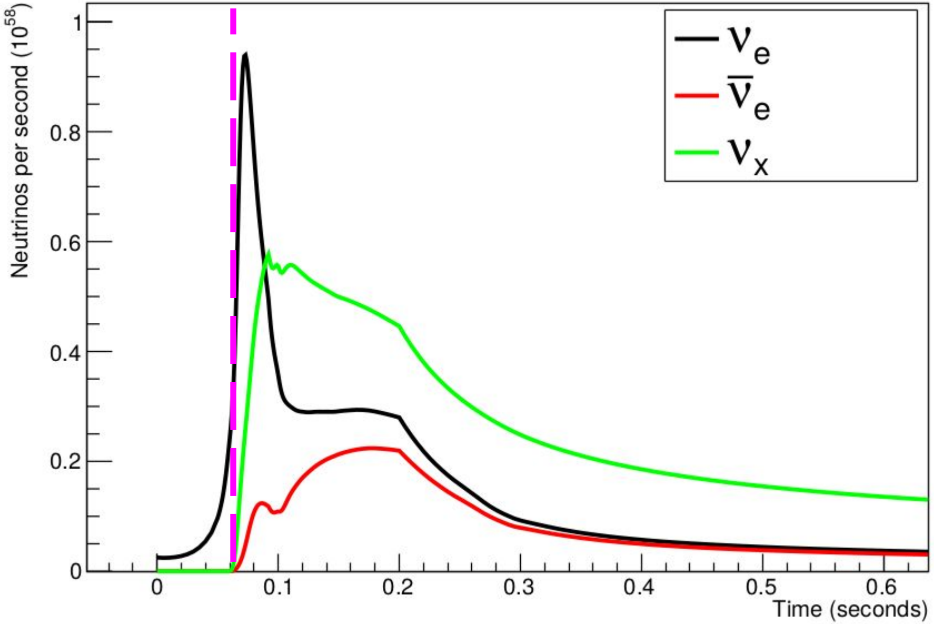


For Huedepohl and Garching, ν_x has a significant number of events after the neutronization burst.

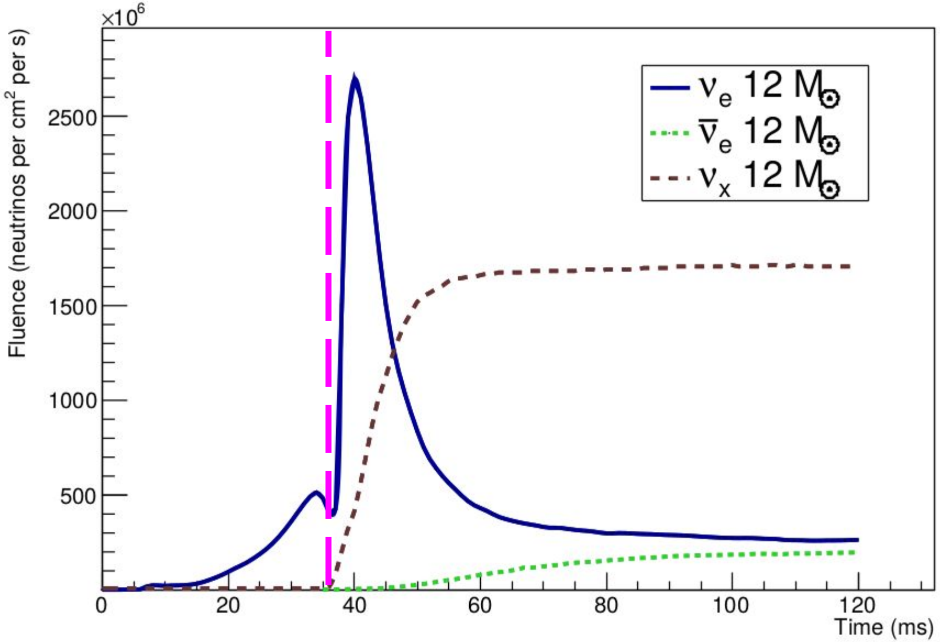
Flux differences

$$F_{\nu_e} = F^0_{\nu_x} \qquad \text{(NMO)}$$
$$F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x} \qquad \text{(IMO)}$$

Nakazato



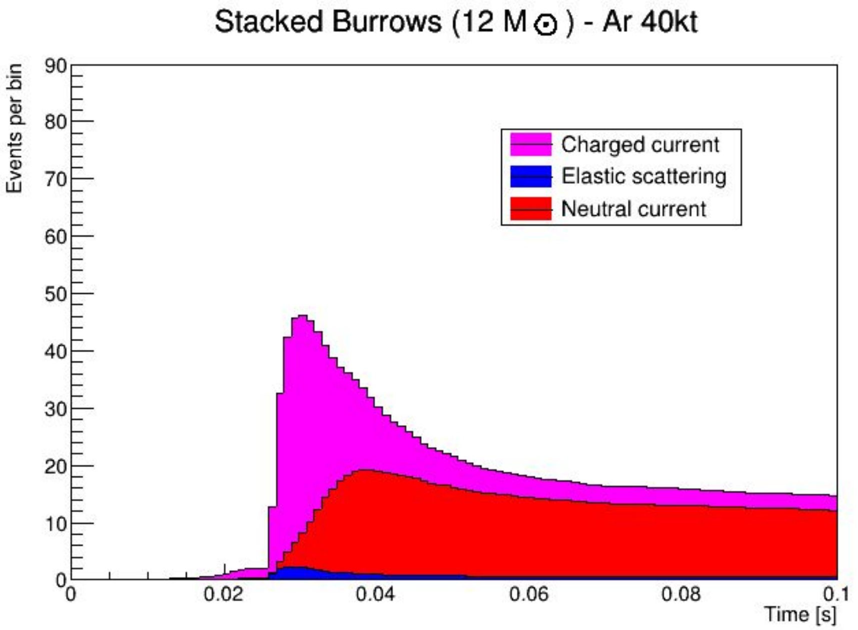
Wallace, Burrows & Dolence

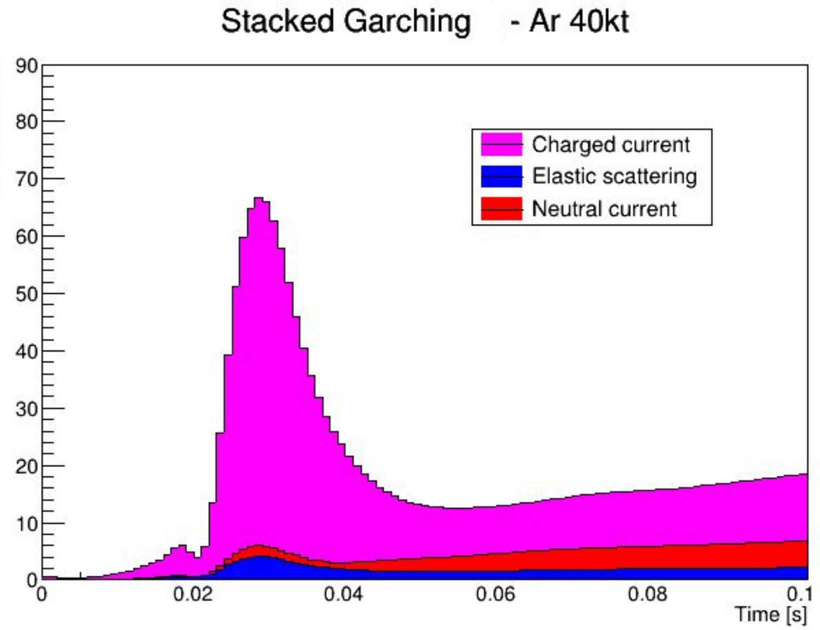


In Nakazato and Wallace, Burrows & Dolence model, ν_x start to rise before the neutronization burst, with a significant amount in the burst times.

MH discrimination - Ratio of different interaction channel events

- ➔ We are searching for another MH discriminants valid for both models.
  - ◆ Ratios of events in different interaction channels (NC/CC or ES/CC);

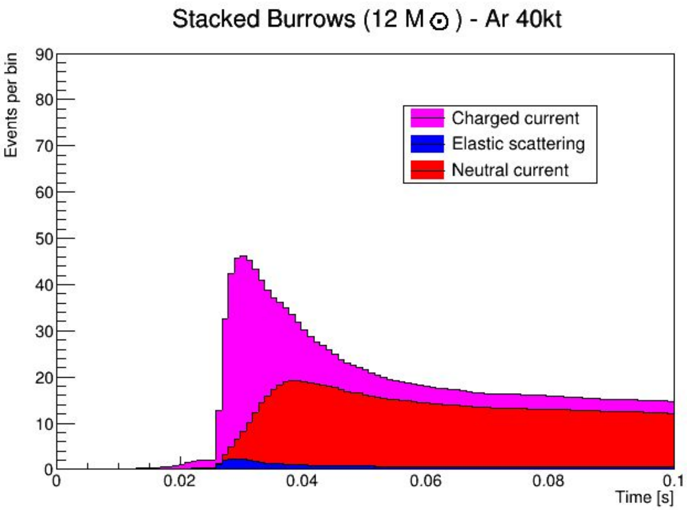


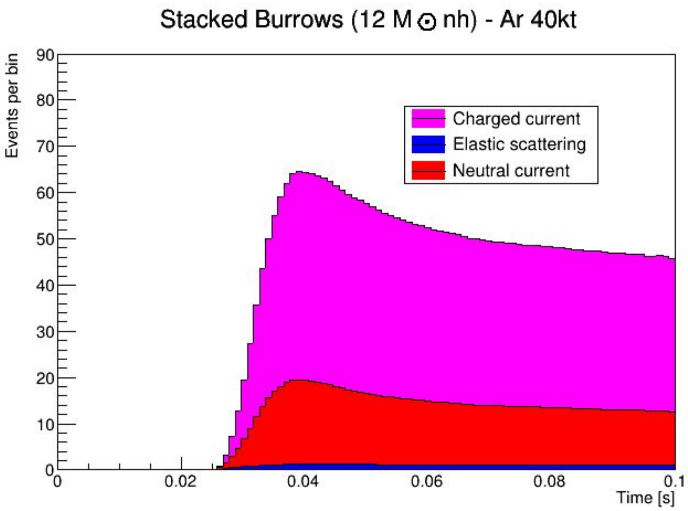


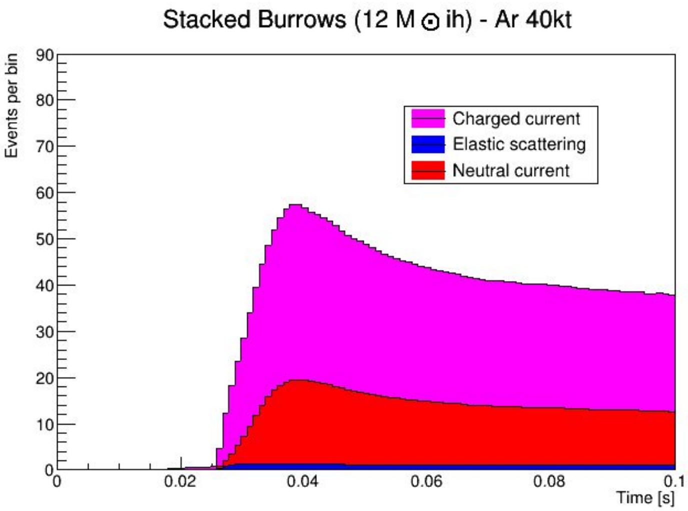
Interaction channels ratio

Wallace, Burrows & Dolence

Events in NC and ES channels doesn't change significantly for any MH case







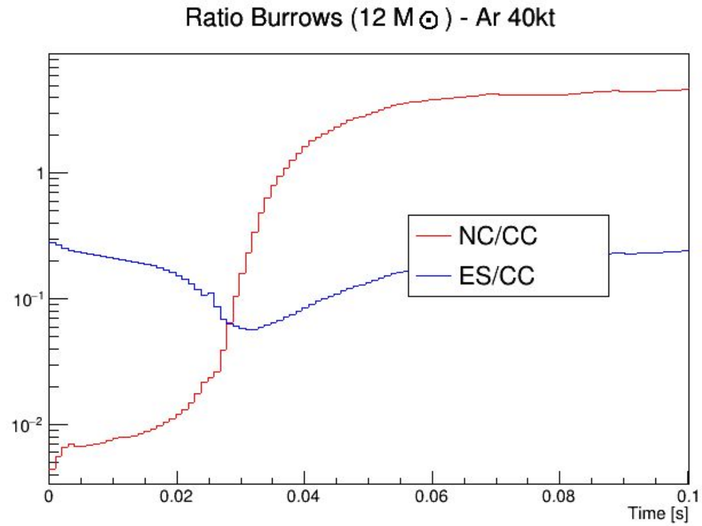
Interaction channels ratio

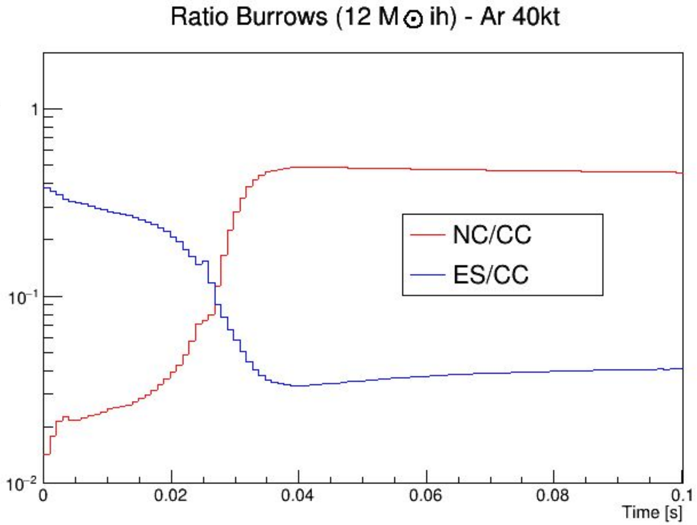
Wallace, Burrows & Dolence

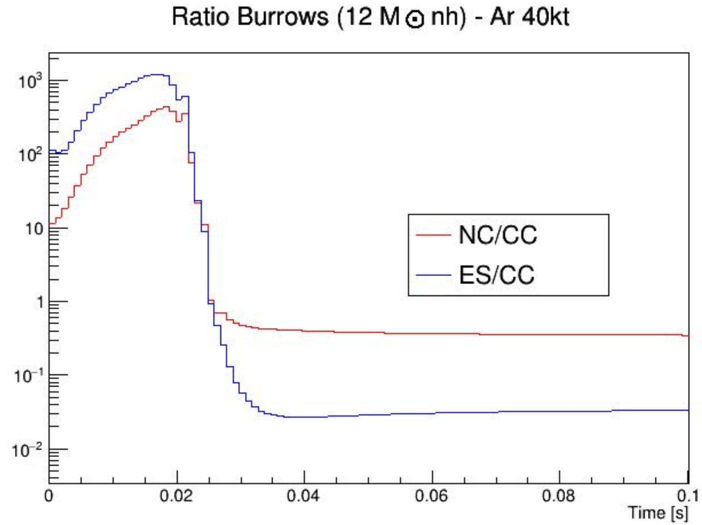
NC/CC event ratios:

IH - start low and finish high

NH - start high and finish low







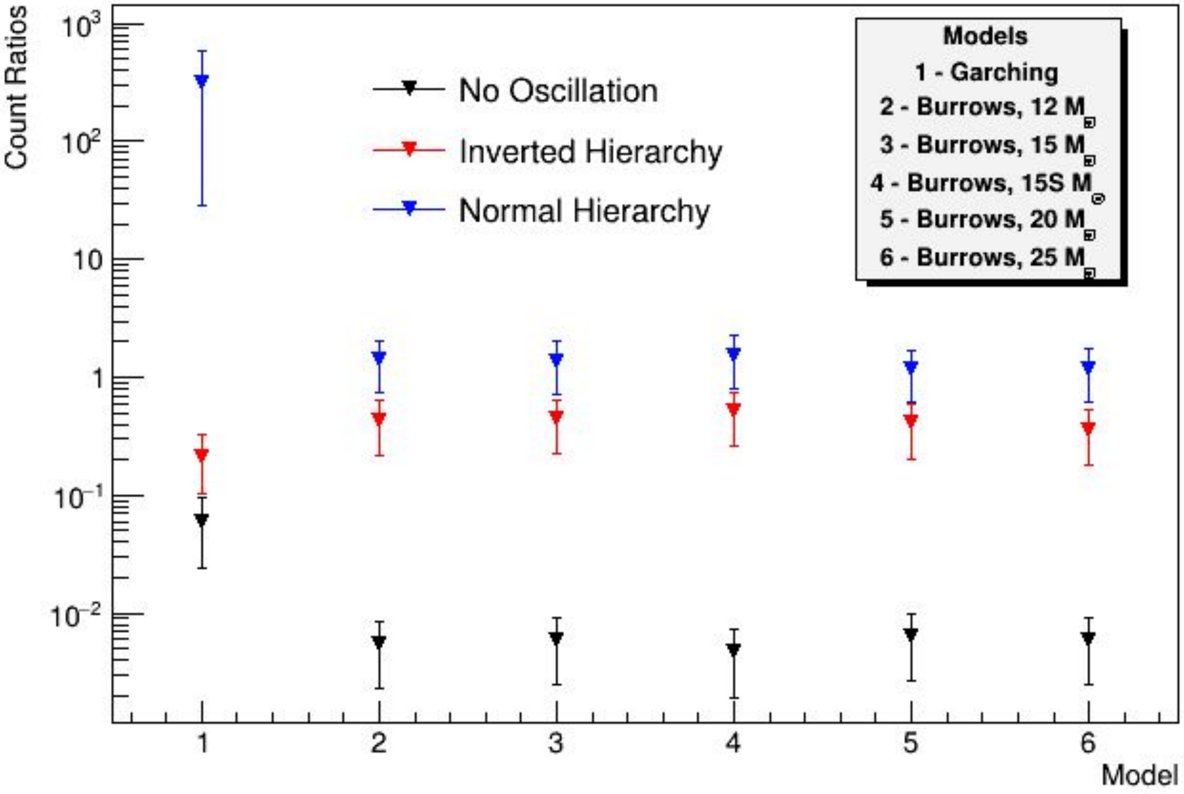
Interaction channels ratio

- Ratio of mean event ratios in 2 time windows;
- T1 from the first event time with 6ms width.
- T2 from end of T1 to 70 ms width

NO: ratio > 1 IO: ratio < 1

Error bars propagated from statistical errors in event histograms

This method doesn't work for Nakazato database



MH discrimination - Pinched-thermal flux ΔChi^2 analysis

Assuming that in a given time slice the SN neutrino flux can be described by a pinched-thermal form

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

we can expect that for different hierarchies the spectrum will fit in different ways with the pinched-thermal form, providing different Chi^2 values (method proposed by Kate).

- Find the best-fit parameters and the Chi^2 (using the Erin's method - DUNE-doc-14068-v4) for each hierarchy, calculating a ΔChi^2 between IH and NH for different databases.

Conclusions

- There is significant model variation

- Some methods can discriminate MH for some models

- If we have a "Garching" or "Huedepohl" shaped SN signal, just the neutronization burst counts will be enough to MH discrimination, however, if we have a "Burrows" or "Nakazato" shaped SN signal, a more sophisticated method is necessary

- We still need to implement the Kate's ΔChi^2 method

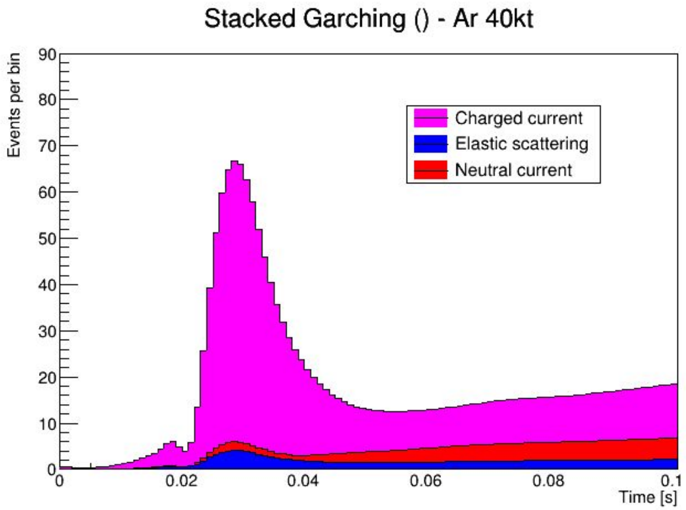
Thanks!

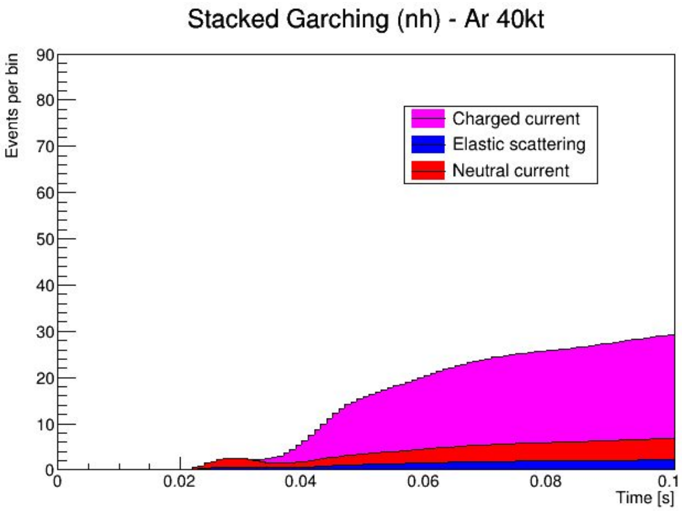
Backup slides

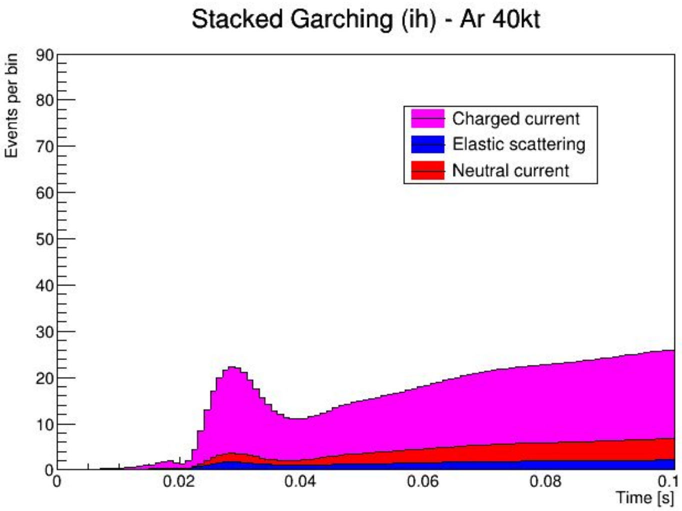
Interaction channels ratio

Garching model

Events in NC and ES channels doesn't change significantly for any MH case







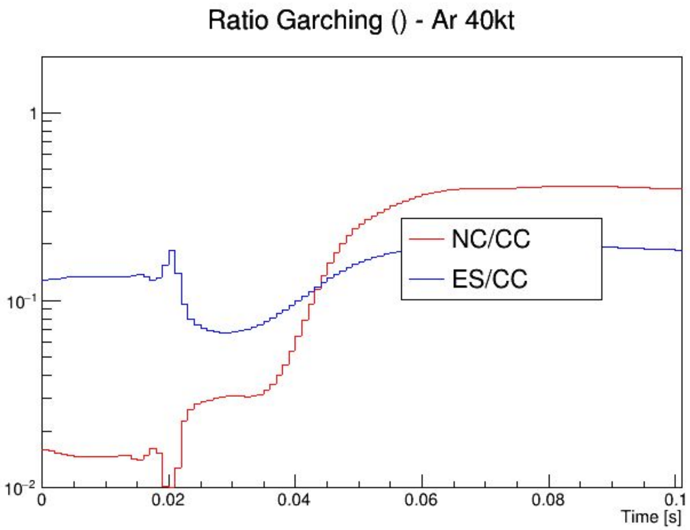
Interaction channels ratio

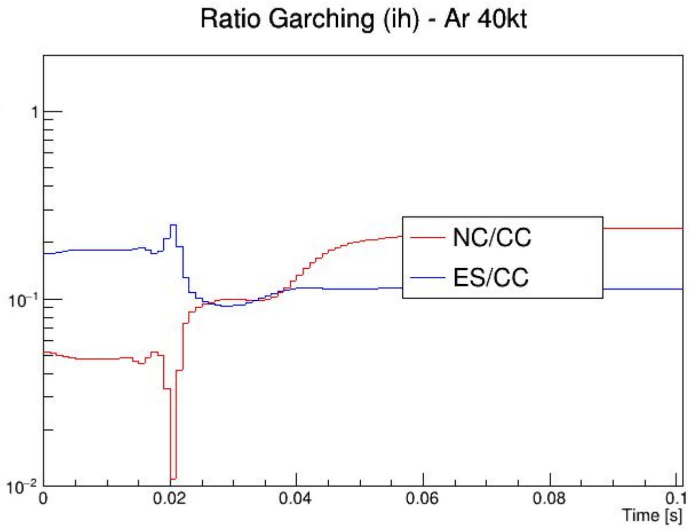
Garching model

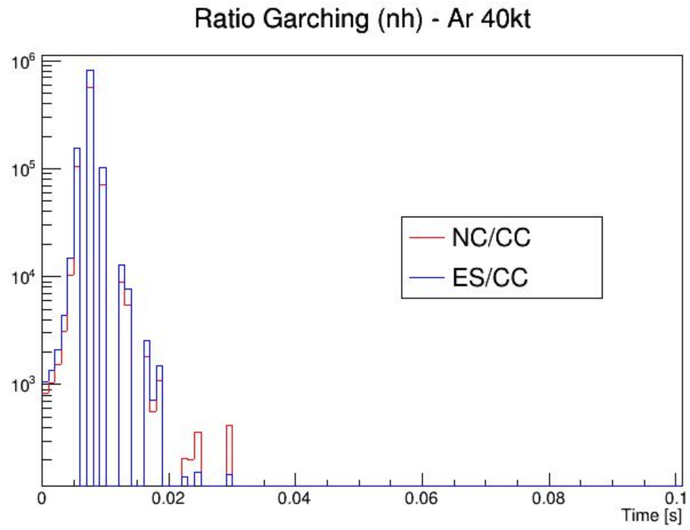
NC/CC event ratios:

IH - start low and finish high

NH - start high and finish low







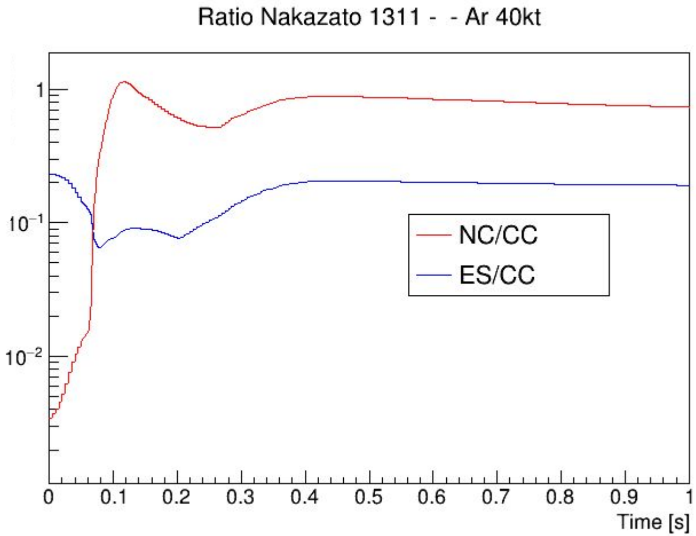
Interaction channels ratio

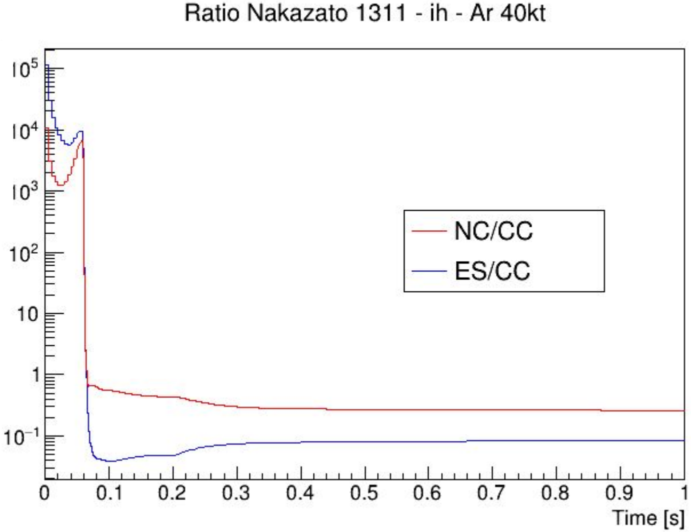
Nakazato database

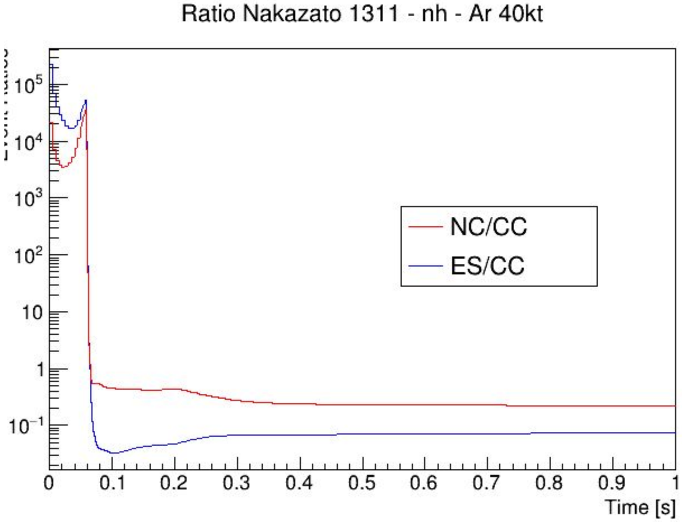
NC/CC event ratios:

IH - start low and finish high

NH - start high and finish low



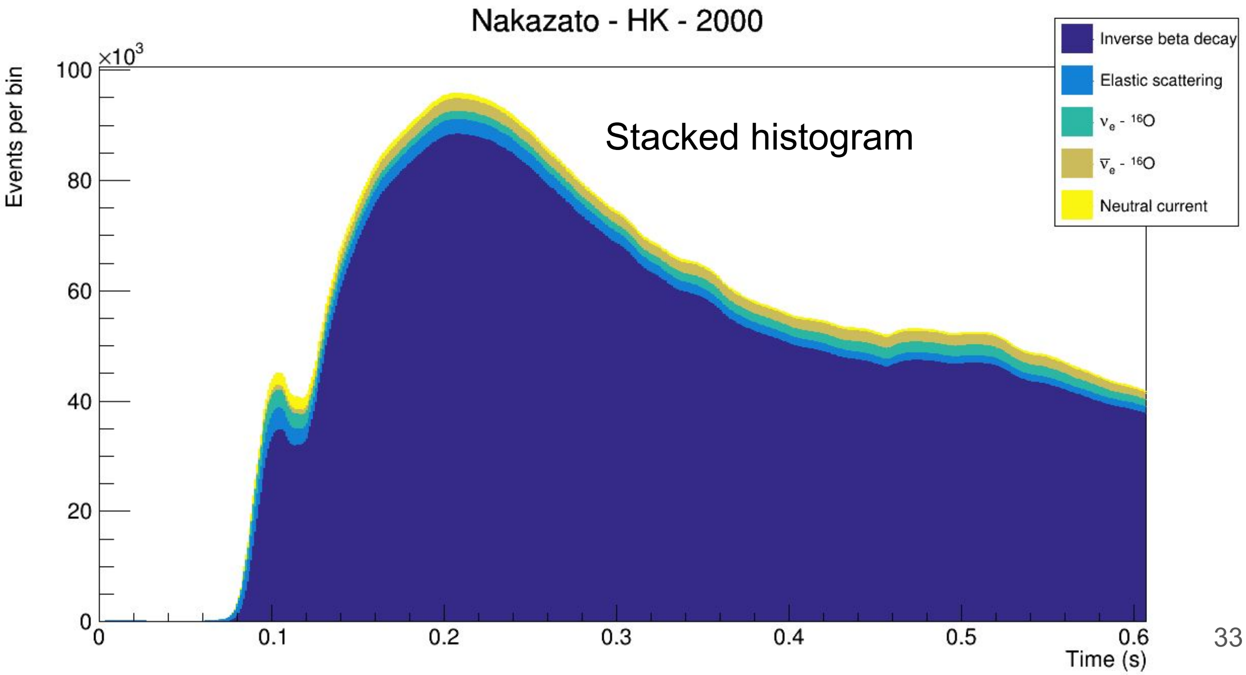




MH discrimination - $\bar{\nu}_e$ in water and scintillator detectors

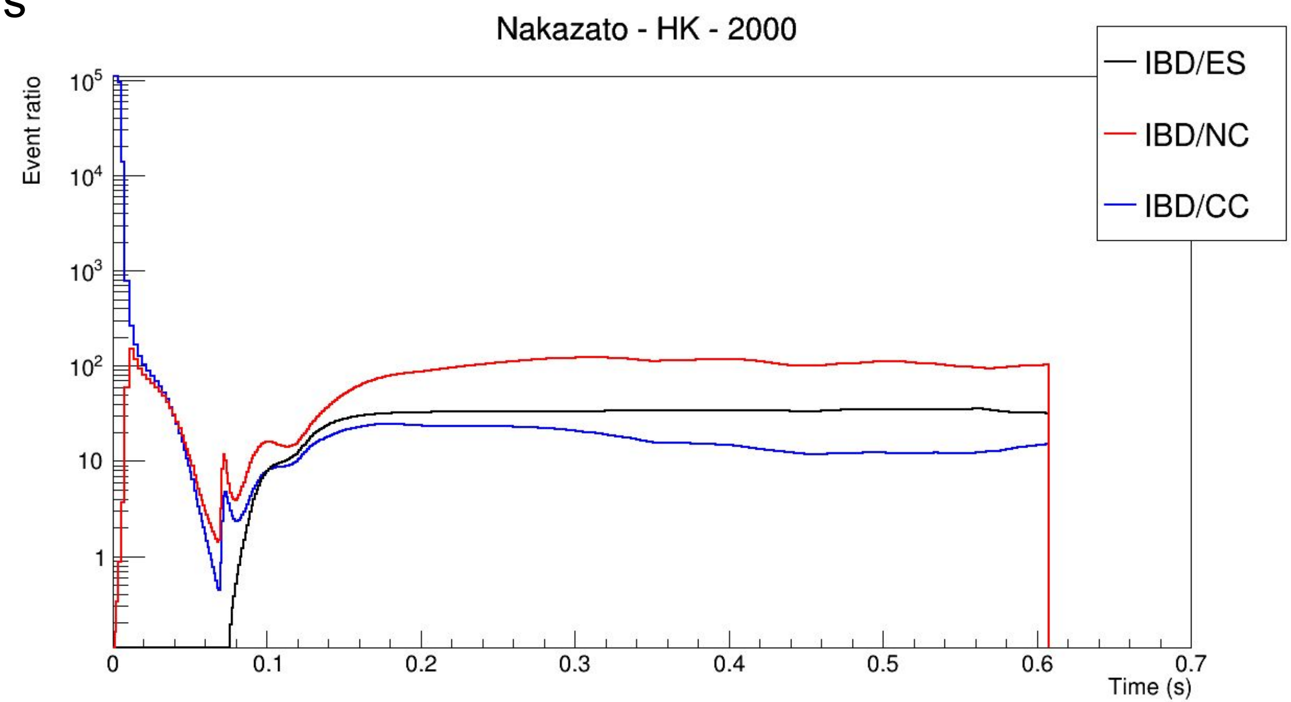
Ratio of events in different interaction channels in water and scintillator detectors:

- Inverse beta decay
- Charged current
- Elastic scattering
- Neutral current



MH discrimination - $\bar{\nu}_e$ in water and scintillator detectors

Ratio of events in different interaction channels in water and scintillator detectors



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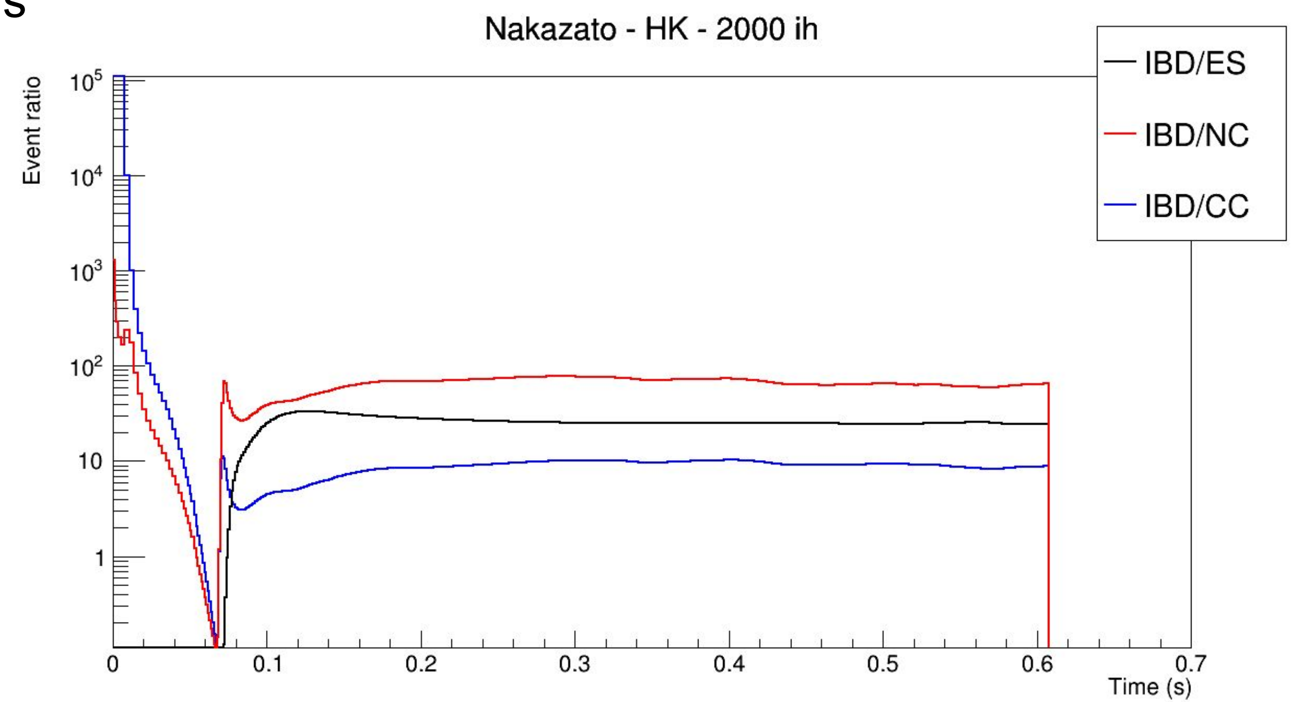
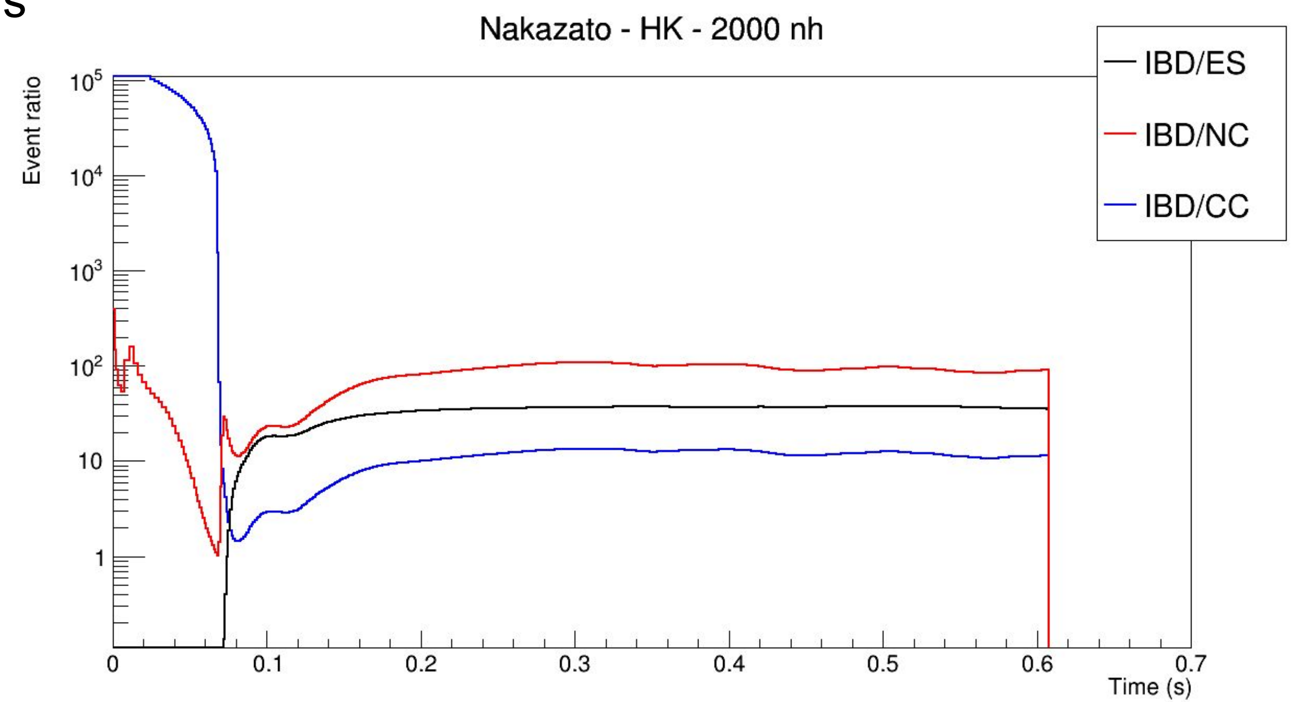


MH discrimination - $\bar{\nu}_e$ in water and scintillator detectors

Ratio of events in different interaction channels in water and scintillator detectors



MH discrimination - $\bar{\nu}_e$ in water and scintillator detectors

This method has the potential to work with the Nakazato database, however, it doesn't work for Wallace, Burrows & Dolence, Garching, and Huedepohl databases.

Due to the differences in the models, we need a more sophisticated method, model-independent, to discriminate the mass hierarchy using the neutronization burst information.