DETERMINING NEUTRINO MASS HIERARCHY BY COMPARING CHARGED AND NEUTRAL CURRENT INTERACTION RATES OF SUPERNOVA NEUTRINOS

G.-L. Lin

Based upon work done with K.-C. Lai, F.-F. Lee, F.-S. Lee, T.-C. Liu and Y. Yang, arXiv: 1603.00692 [hep-ph], to appear in JCAP

OUTLINE:

- Introduction
- Supernova (SN) neutrino fluence and flavour transitions in SN, Supernova neutrino fluence on Earth
- Detection channels of supernova neutrinos in liquid scintillator detectors: **inverse beta decay, neutrino-proton elastic scattering**, neutrino-electron elastic scattering, and neutrino interactions with carbon nuclei
- Resolving neutrino mass hierarchy
- Summary

INTRODUCTION

- Neutrino mass hierarchy is still a unanswered question in particle physics.
- Proposals to resolve neutrino mass hierarchy include the ***precision studies of reactor neutrinos, multi-detector accelerator experiments at different baselines, Earth matter effect on SN neutrino signal, rise time of SN electron-neutrino light curve, electron-neutrino (anti-neutrino) light curves on the early accretion phase, and the detection of atmospheric neutrinos.***
- Here we will focus on neutrino source from galactic supernovae and compare the signature of neutrino charged current and neutral current interaction rates.

PROPOSALS FOR RESOLVING NEUTRINO MASS HIERARCHY

Reactor neutrino experiments:

S.T. Petcov, M. Piai, Phys. Lett. B **533**, 94 (2002), arXiv:hep-ph/0112074.

S. F. Ge, K. Hagiwara, N. Okamura and Y. Takaesu, JHEP **1305**, 131 (2013), arXiv:1210.8141.

Yu-Feng Li, Jun Cao, Yifang Wang, and Liang Zhan, Phys. Rev. D **88**, 013008 (2013), arXiv:1303.6733.

F. Capozzi, E. Lisi, and A. Marrone, Phys. Rev. D **89**, 013001 (2014), arXiv:1309.1638.

JUNO experiment

Detection of atmospheric neutrinos

W. Winter, Phys. Rev. D **88**, 013013 (2013), arXiv:1305.1419.

IceCube-PINGU experiment

Earth matter effect on SN neutrino signal

C. Lunardini and A. Yu Smirnov, J. Cosm. Astropart. Phys. **06**, 009 (2003), arXiv:hep-ph/0302033.

B. Dasgupta, A. Dighe, A. Mirizzi, Phys. Rev. Lett. **101** 171801 (2008), arXiv:08021481.

Rise time of SN electron-neutrino light curve

P. D. Serpico, S. Chakraborty, T. Fischer et al., Phys. Rev. D **85**, 085031 (2012), arXiv:1111.4483.

SUPERNOVA NEUTRINO FLUENCE

Parametrisation by Keil et al.

M. T. Keil, G. G. Raffelt, and H.-T. Janka, Astrophys. J. **590**, 971 (2003), arXiv:astro-ph/0208035.

$$F^0_\alpha(E) = \frac{\Phi_\alpha}{< E_\alpha >} \frac{(1+\eta_\alpha)^{(1+\eta_\alpha)}}{\Gamma(1+\eta_\alpha)} \left(\frac{E}{< E_\alpha >}\right)^{\eta_\alpha} \exp\left[-(\eta_\alpha+1)\frac{E}{< E_\alpha >}\right]$$

Φ_α *time-integrated flux of flavour* α

$< E_\alpha >$ *average energy of neutrinos of flavour* α

Fluence on Earth: assuming no oscillations

$$F_\alpha = \frac{F^0_\alpha}{4\pi d^2} = \frac{2.35\times 10^{13}}{\mathrm{cm}^2\mathrm{MeV}} \frac{\mathcal{E}_\alpha}{d^2} \frac{E^3}{< E_\alpha >^5} \exp\left(-\frac{4E}{< E_\alpha >}\right)$$

with $\mathcal{E}_\alpha$ in units of 10^{52} erg, d in 10 kpc, and energies in MeV.

We choose $< E_{\nu_e} >= 12$ MeV, $< E_{\bar{\nu}_e} >= 15$ MeV, and $< E_{\nu_x} >= 18$ MeV

NEUTRINO FLAVOUR TRANSITION INSIDE SN

Collective neutrino oscillation due to coherent nu-nu forward scattering in the deep region of the core

$$\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x \ (x = \mu, \ \tau)$$

B. Dasgupta, A. Dighe, G. G. Raffelt and A. Y. Smirnov, Phys. Rev. Lett. **103**, 051105 (2009), arXiv:0904.3542.

B. Dasgupta, G. G. Raffelt and I. Tamborra, Phys. Rev. D **81**, 073004 (2010), arXiv:1001.5396.

A. Esteban-Pretel, S. Pastor, R. Tomas, G. G. Raffelt and G. Sigl, Phys. Rev. D **76**, 125018 (2007), arXiv:0706.2498.

G. G. Raffelt and A. Y. Smirnov, Phys. Rev. D **76**, 081301 (2007), Phys. Rev. D **77**, 029903 (2008), arXiv:0705.1830.

S. Hannestad, G. G. Raffelt, G. Sigl and Y. Y. Y. Wong, Phys. Rev. D **74**, 105010 (2006), Phys. Rev. D **76**, 029901 (2007), astro-ph/0608695.

B. Dasgupta and A. Dighe, Phys. Rev. D **77**, 113002 (2008), arXiv:0712.3798.

S. Choubey, B. Dasgupta, A. Dighe and A. Mirizzi, arXiv:1008.0308.

H. Duan, G. M. Fuller and Y. Z. Qian, Phys. Rev. D **74**, 123004 (2006), arXiv:astro-ph/0511275

A. Mirizzi and R. Tomas, Phys. Rev. D **84**, 033013 (2011), arXiv:1012.1339.

NEUTRINO FLAVOUR TRANSITION INSIDE SN

MSW effect

L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).

S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985) [Yad. Fiz. **42**, 1441 (1985)].

Normal hierarchy

$$F_e = F_x^0, \qquad x \equiv \mu, \tau, \bar{\mu}, \bar{\tau}$$

$$\bar{P}_{2e} = \sin^2\theta_{12}$$

$$F_{\bar{e}} = (1-\bar{P}_{2e})F_{\bar{e}}^0 + \bar{P}_{2e}F_{\bar{x}}^0,$$

$$4F_x = F_e^0 + F_{\bar{e}}^0 + 4F_x^0 - F_e - F_{\bar{e}} = F_e^0 + \bar{P}_{2e}F_{\bar{e}}^0 + (3-\bar{P}_{2e})F_x^0,$$

Inverted hierarchy

$$F_e = P_{2e}F_e^0 + (1-P_{2e})F_x^0,$$

$$P_{2e} = \sin^2\theta_{12} + f_{\mathrm{reg}}$$

Earth matter effect

$$F_{\bar{e}} = F_{\bar{x}}^0,$$

$$4F_x = F_e^0 + F_{\bar{e}}^0 + 4F_x^0 - F_e - F_{\bar{e}} = (1-P_{2e})F_e^0 + F_{\bar{e}}^0 + (2+P_{2e})F_x^0$$

DETECTION CHANNELS IN LIQUID SCINTILLATOR DETECTOR

Inverse beta decay (IBD):

$$\bar{\nu}_e + p \to n + e^+$$

positron annihilates with electron to produce prompt signal,

while neutron is captured by hydrogen to produce delayed signal

Neutrino-proton elastic scattering

$$\nu + p \to \nu + p$$

Neutrino-electron scattering

$$\nu + e^- \to \nu + e^-$$

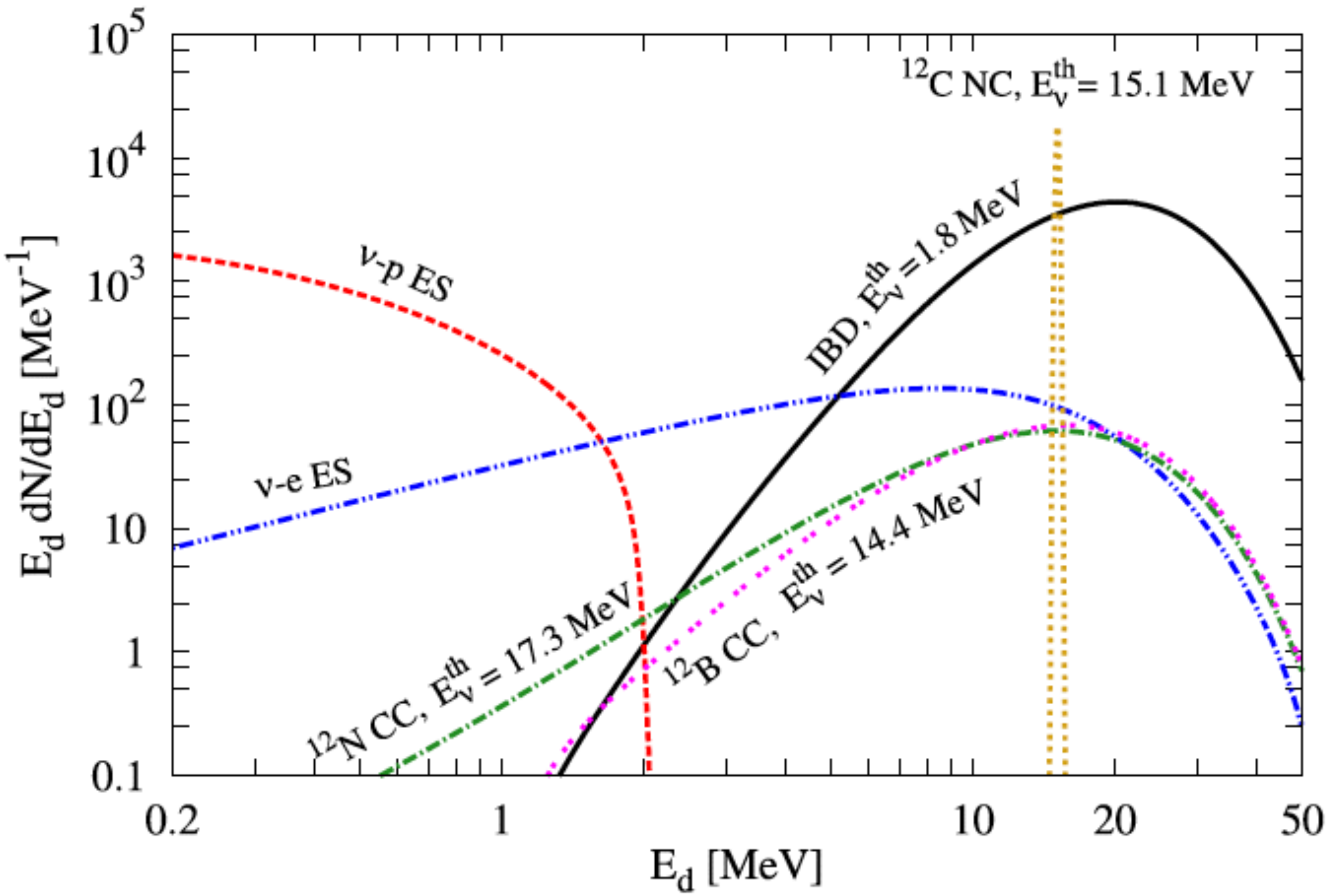
Neutrino-carbon scattering, NC

$$\nu +^{12} C \to \nu +^{12} C^*$$

Neutrino-carbon scattering, CC

$$\nu_e +^{12} C \to e^- +^{12} N \qquad \bar{\nu}_e +^{12} C \to e^+ +^{12} B$$

OVERVIEW OF SN EVENTS FROM DIFFERENT CHANNELS



Prompt spectra

SN at 10 kpc with energy of 10^{53} erg. Neutrino average energy is chosen as

$\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\overline{\nu}_e} \rangle = 14$ MeV and $\langle E_{\nu_x} \rangle = 16$ MeV.

F. An *et al*. [JUNO Collaboration], J. Phys. G 43, no. 3, 030401 (2016)

INTERACTION SPECTRA OF IBD AND NC EVENTS

$$\left(\frac{dN}{dE_\nu}\right)_{\rm IBD} = N_p \cdot \frac{dF_{\bar{e}}}{dE_\nu} \cdot \sigma_{\rm IBD}(E_\nu), \qquad F_{\rm tot} \equiv F_e + F_{\bar{e}} + 4F_x$$

$$\left(\frac{dN}{dE_\nu}\right)_{\rm NC} = N_p \cdot \int_0^{T_{\rm max}} \frac{dF_{\rm tot}}{dE_\nu} \frac{d\sigma_{\nu p}(E_\nu)}{dT} dT$$

For IBD events: $E_d = E_\nu - 0.8\,\mathrm{MeV}$

For NC events, it is highly no-trivial to reconstruct interaction spectra but can be done.

B. Dasgupta and J. F. Beacom, Phys. Rev. D **83**, 113006(2011)

PROTON RECOIL AND QUENCHING

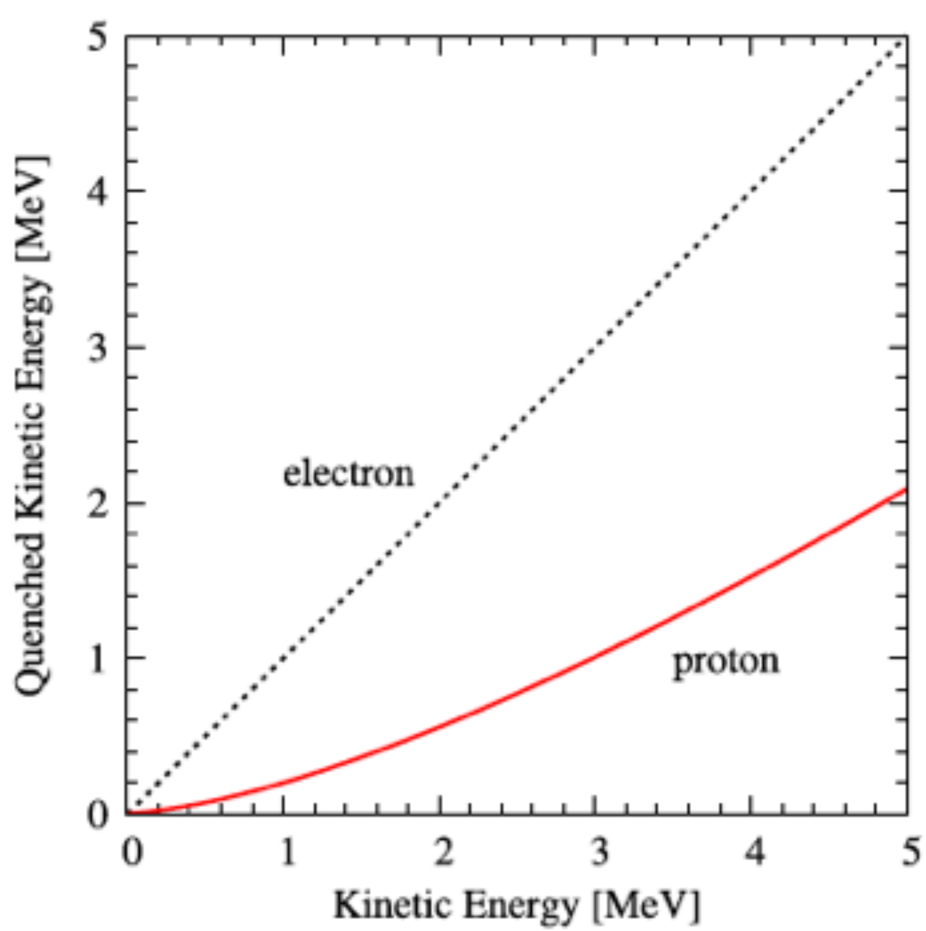
$\nu + p \to \nu + p$ *Let T be the proton recoil kinetic energy.*

To produce a proton with recoil kinetic energy T,

the minimal energy for neutrino is $E_{\nu,\mathrm{min}} = \sqrt{m_p T/2}$

$E_\nu \longrightarrow 0 \leq T \leq 2E_\nu^2/m_p$

The proton is detected with an electron-equivalent quenched energy T' < T



The light output of a recoiled proton in a LAB-based liquid scintillator detector with the Birk's constant $k_B = 0.0098\ \mathrm{cm\ MeV^{-1}}$

BACKGROUNDS AND RECONSTRUCTION

The irreducible backgrounds come from radioactivities in the scintillator and surroundings: β *decays of* ^{14}C *produce a high rate of electrons below 0.2 MeV. So we perform the analysis for T'>0.2 MeV.*

The detected event spectrum is related to the neutrino fluence by

$$\frac{dN}{dT'} = \frac{N_p}{dT'/dT} \int_{E_{\nu,\min}}^{\infty} dE_\nu \frac{dF_{\rm tot}}{dE_\nu} \frac{d\sigma}{dT}(E_\nu)$$

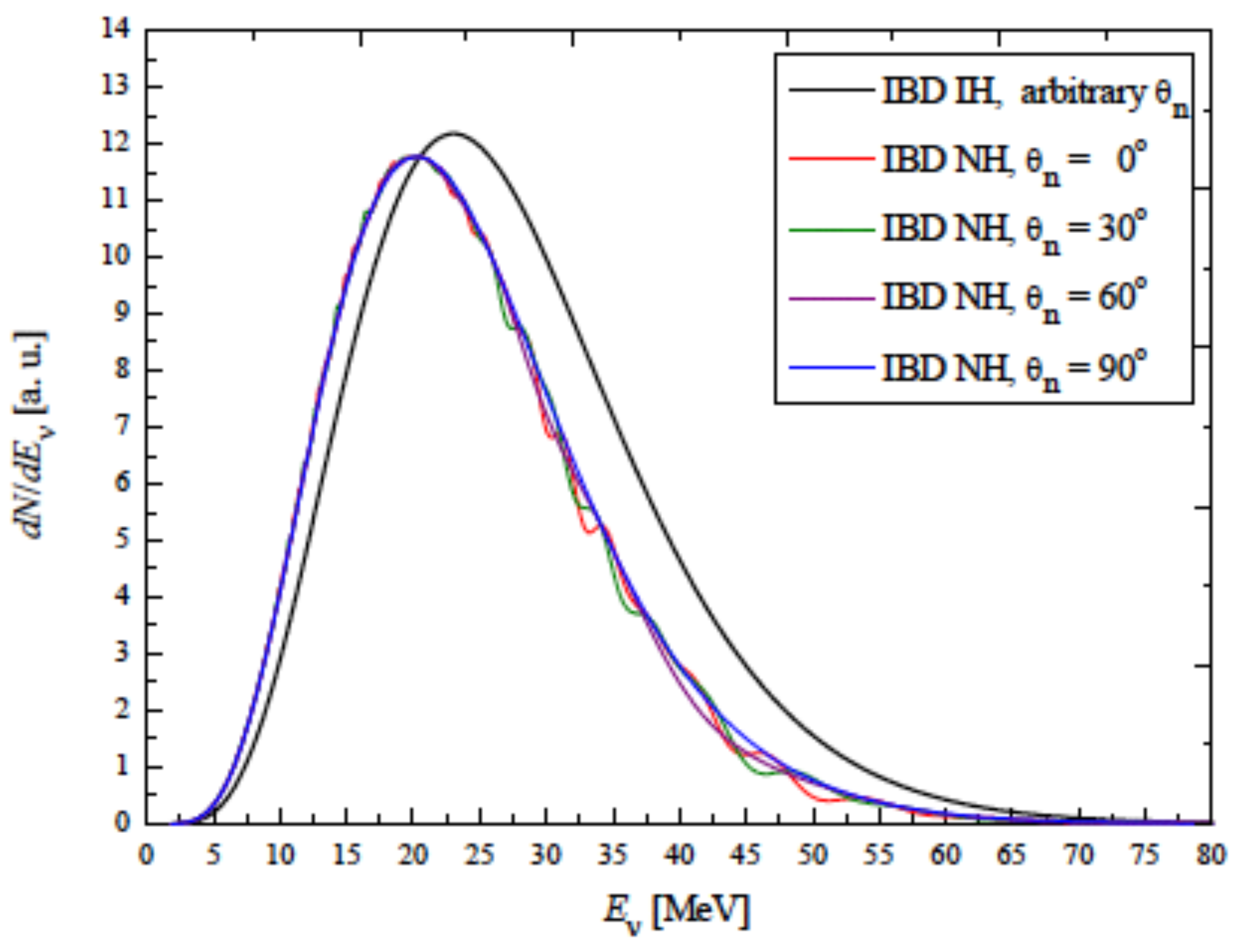
The technique of reconstructing the fluence from the detected event spectrum has been demonstrated in

B. Dasgupta and J. F. Beacom, Phys. Rev. D **83**, 113006(2011)

Once again

$$\left(\frac{dN}{dE_\nu}\right)_{\rm NC} = N_p \cdot \int_0^{T_{\max}} \frac{dF_{\rm tot}}{dE_\nu} \frac{d\sigma_{\nu p}(E_\nu)}{dT} dT$$

THE INTERACTION SPECTRA



Normal ordering

$$F_e = F_x^0,$$

$$F_{\bar{e}} = (1 - \bar{P}_{2e}) F_{\bar{e}}^0 + \bar{P}_{2e} F_{\bar{x}}^0,$$

Inverted ordering

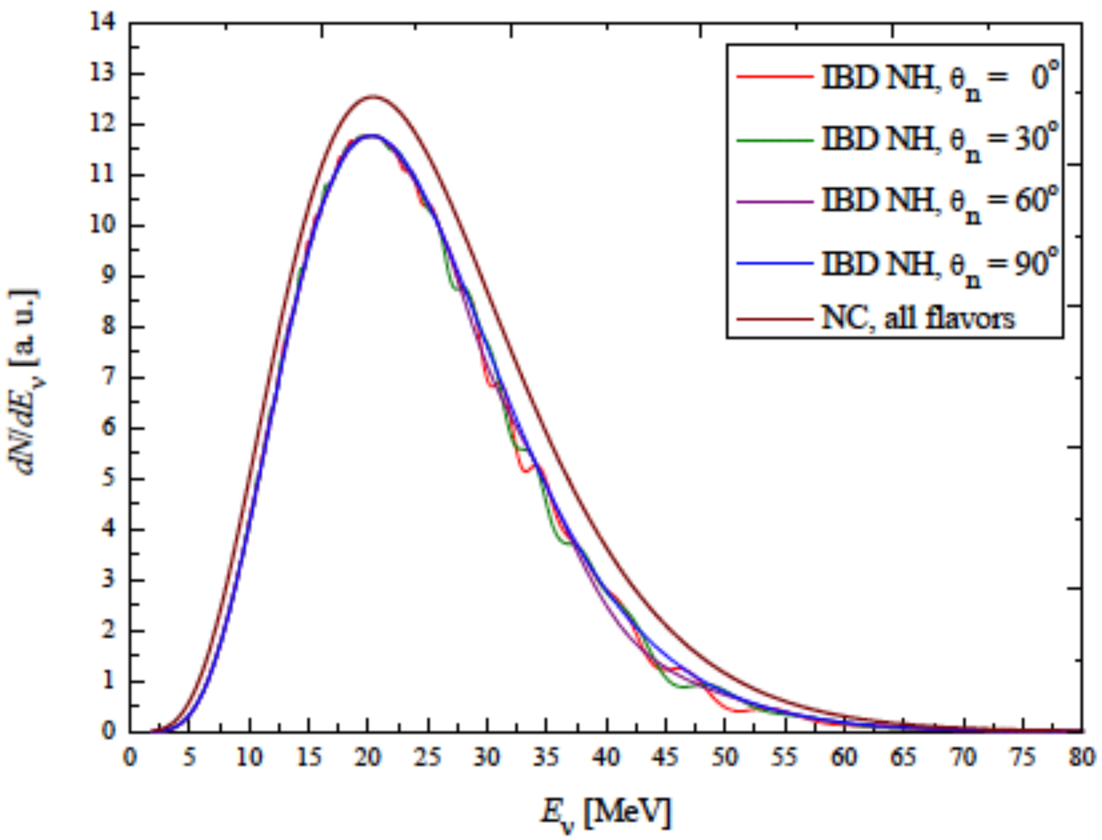
$$F_e = P_{2e} F_e^0 + (1 - P_{2e}) F_x^0,$$

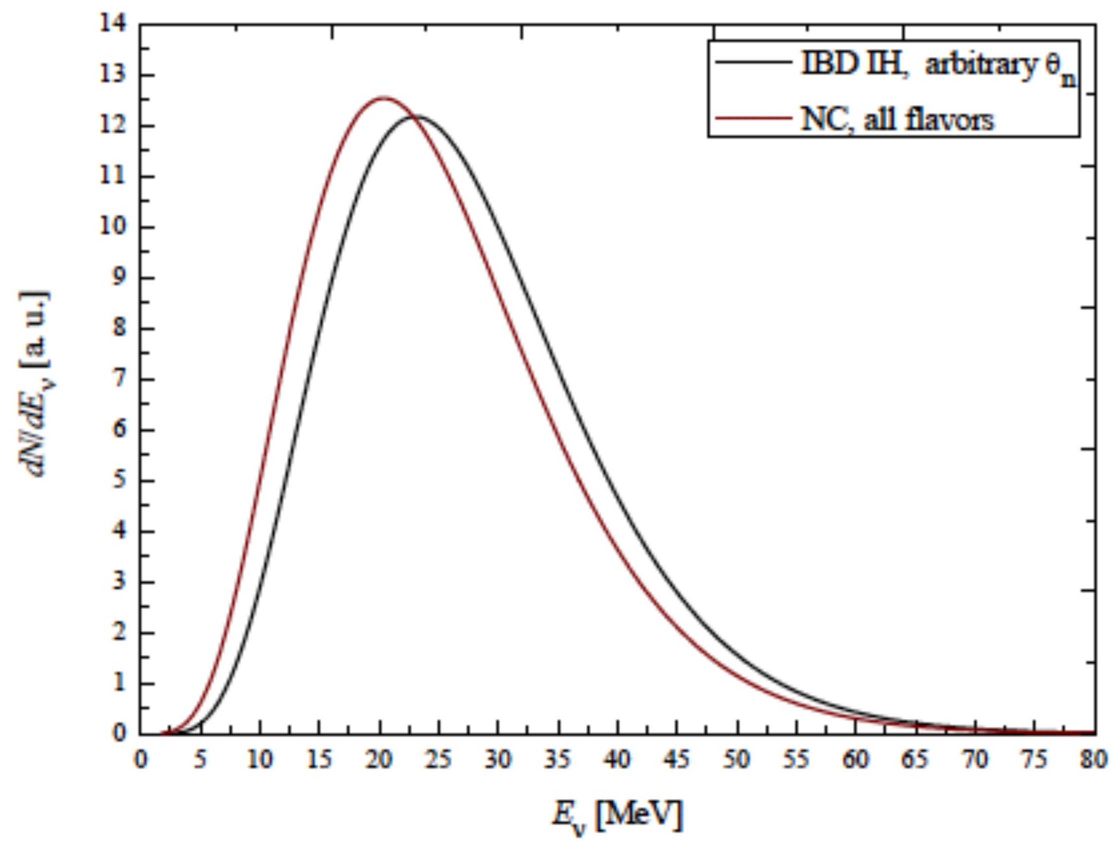
$$F_{\bar{e}} = F_{\bar{x}}^0,$$

The IBD interaction spectra for different nadir angles of supernova neutrinos. Results for both mass orderings are shown. Earth matter effects are not significant. Crossover at around 20 MeV

$< E_{\nu_e} >= 12$ MeV, $< E_{\bar{\nu}_e} >= 15$ MeV, and $< E_{\nu_x} >= 18$ MeV

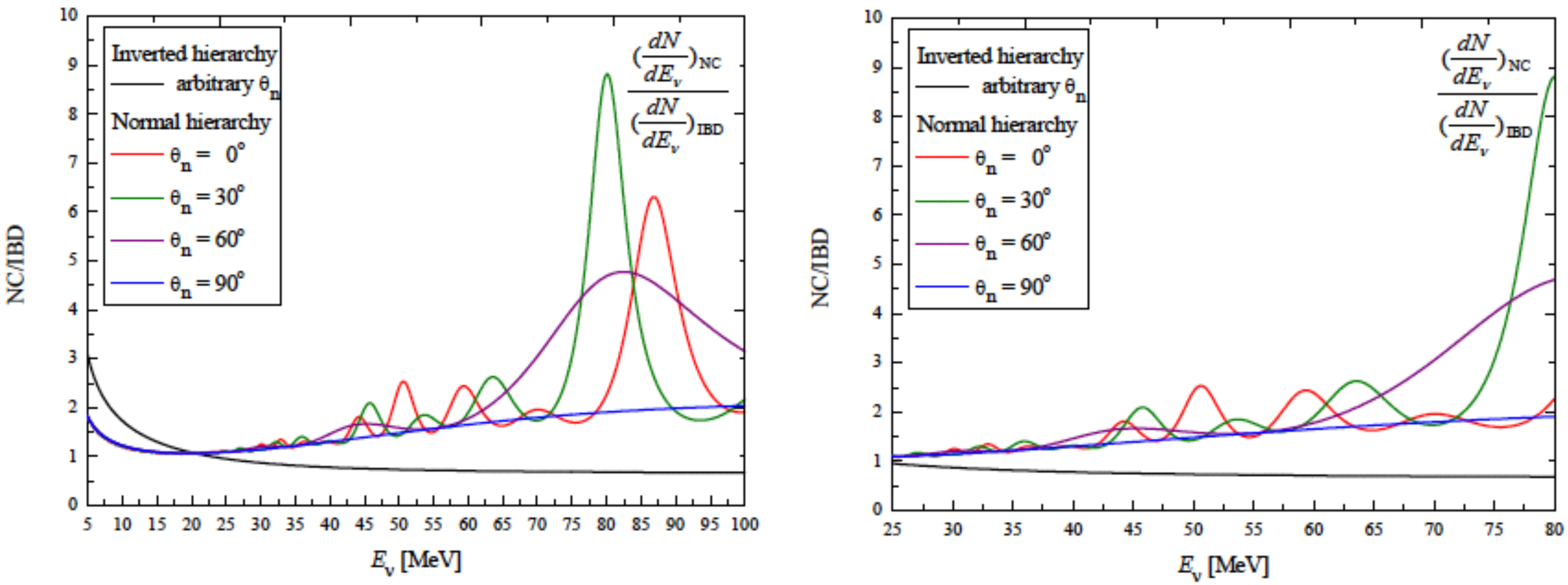
THE INTERACTION SPECTRA





NC interaction spectra are independent of neutrino mass ordering, since NC interaction measures the total neutrino fluence, which is not affected by neutrino flavor transition. On the right panel, the crossover energy is about 25 MeV.

RATIO OF INTERACTION SPECTRA



The right panel focuses on $25 \text{ MeV} \leq E_\nu \leq 80 \text{ MeV}$

One can see a clear separation between NH and IH in this energy range

The background issue for NC also flavors the selection $E_\nu \geq 25 \text{ MeV}$

EVENT SELECTION FOR NC INTERACTION

We focus on T'> 0.2 MeV. The proton recoil energy T corresponding to T'=0.2 MeV varies over different scintillation liquids (with different Birk's constant). Once T is determined, the minimum neutrino energy which generates such a recoil is $E_{\nu,\mathrm{min}} = \sqrt{m_p T/2}$.

	Mass [kton]	N_p [10^{31}]	k_B [cm/MeV]	Measured Event $T' > 0.2$ MeV	T [MeV]	$E_{\nu,\mathrm{min}}$ [MeV]
Borexino	0.278	1.7	0.010	27	1.00	21.67
KamLAND	0.697	5.9	0.010	66	1.33	25.01
SNO+	0.800	5.9	0.0073	111	0.86	20.11
JUNO	20	144	0.00759	2490	0.93	20.84
LENA	44	325	0.010	5060	1.02	21.82

$\longleftarrow \quad E_{\nu,\mathrm{min}} = \sqrt{m_p T/2}$

NC events expected for various liquid scintillation detectors

THE VARIABLE FOR DISCRIMINATING THE NEUTRINO MASS ORDERING

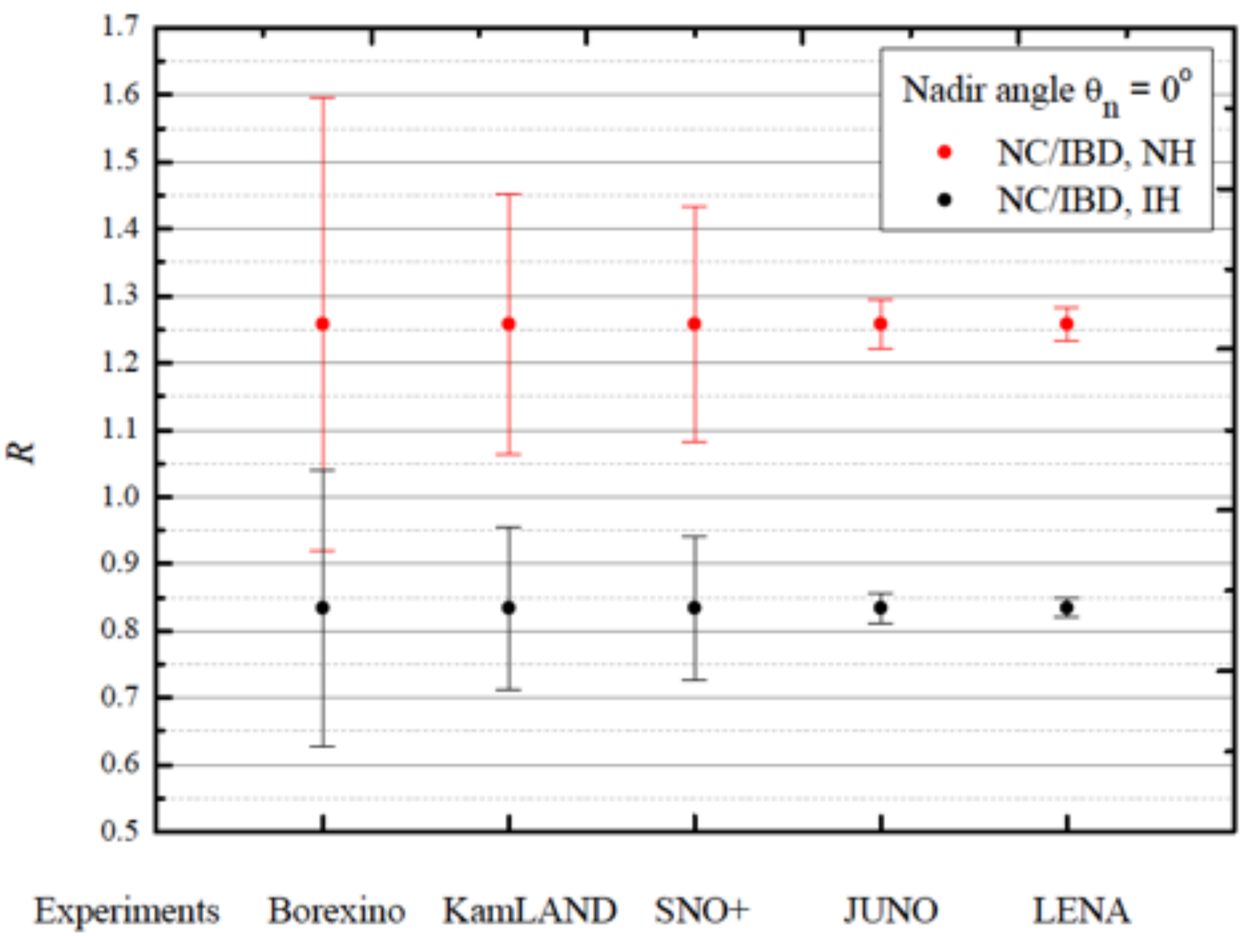
$$R = \frac{\int_{E_{\nu,\rm s}}^{\infty} \left(\frac{dN}{dE}\right)_{\rm NC} dE}{\int_{E_{\nu,\rm s}}^{\infty} \left(\frac{dN}{dE}\right)_{\rm IBD} dE}$$

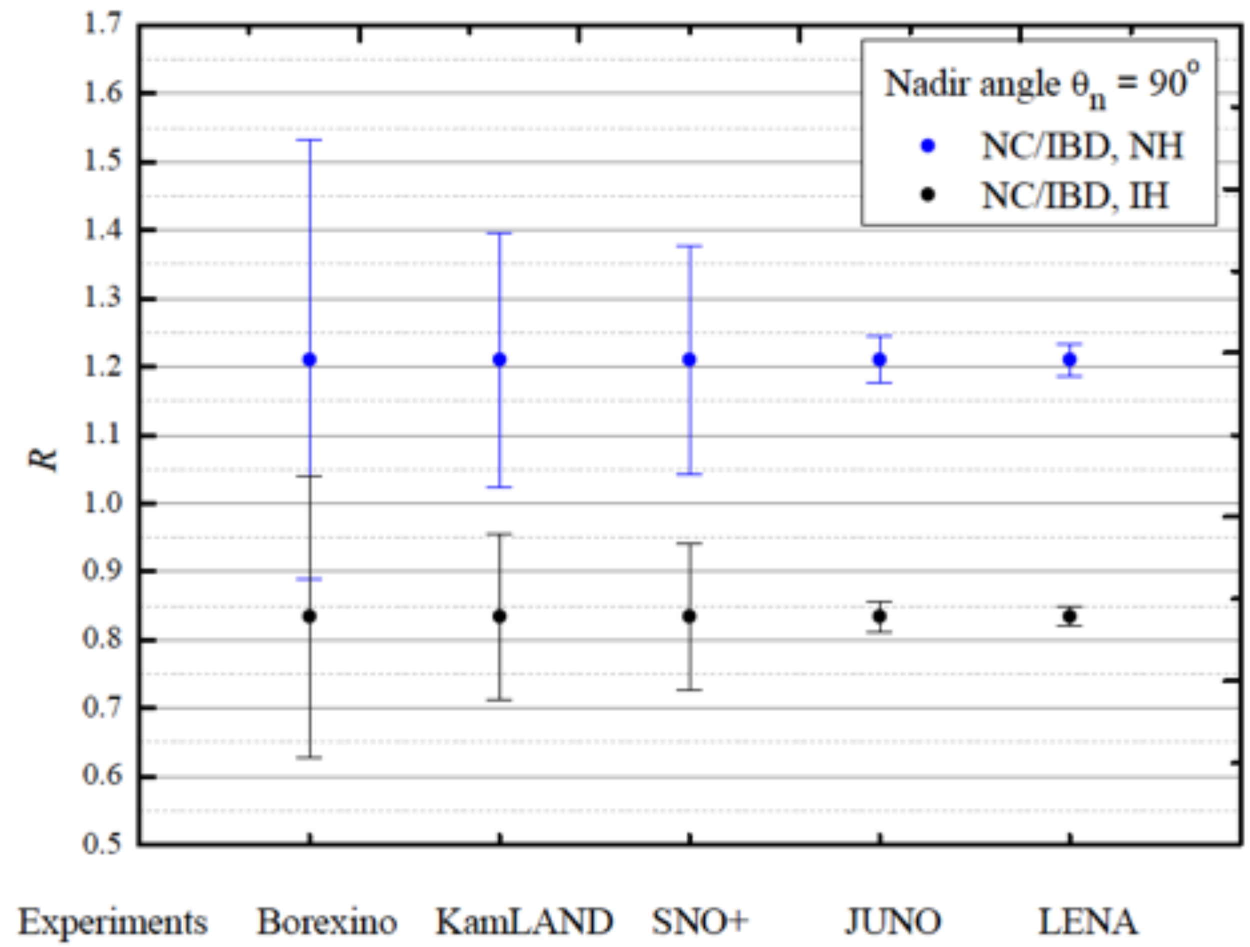
$E_{\nu,s}$ ***the selected energy threshold***

	NC	IBD			R			$\sigma_{\rm R}[10^{-2}]$		
		IH	NH 0°	NH 90°	IH	NH 0°	NH 90°	IH	NH 0°	NH 90°
Borexino	40	48	32	33	0.83	1.25	1.21	20.0	32.7	31.5
KamLAND	141	169	112	116	0.83	1.26	1.22	12.1	19.5	18.7
SNO+	141	167	111	115	0.84	1.27	1.23	10.3	17.1	16.3
JUNO	3413	4092	2713	2821	0.83	1.26	1.21	2.12	3.49	3.33
LENA	7677	9204	6104	6345	0.83	1.26	1.21	1.46	2.39	2.28

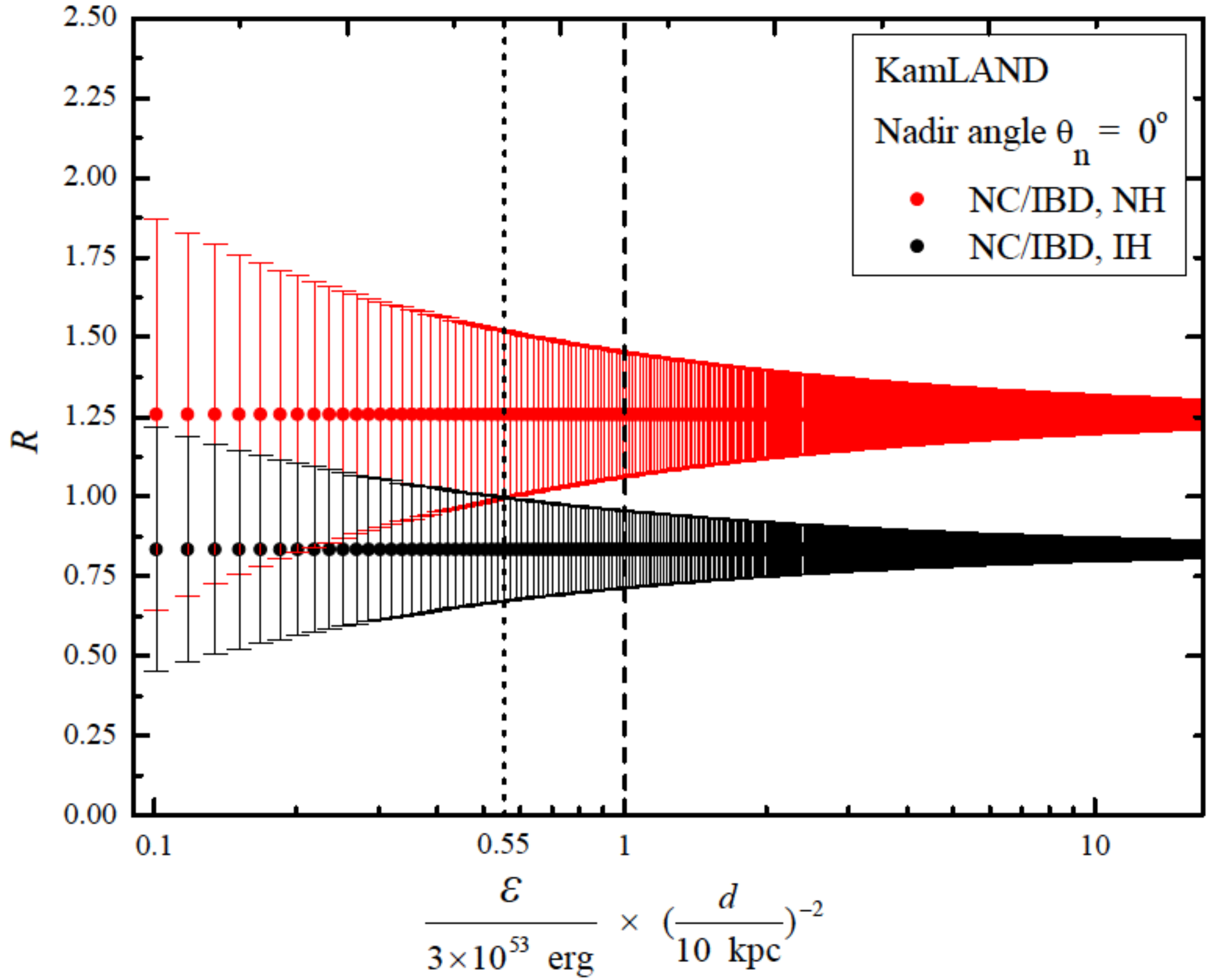
$$\varepsilon = 3 \times 10^{53}\ \text{erg}, d = 10\ \text{kpc}$$

R VALUE AND ITS STATISTICAL UNCERTAINTY FOR EACH SCINTILLATION DETECTOR

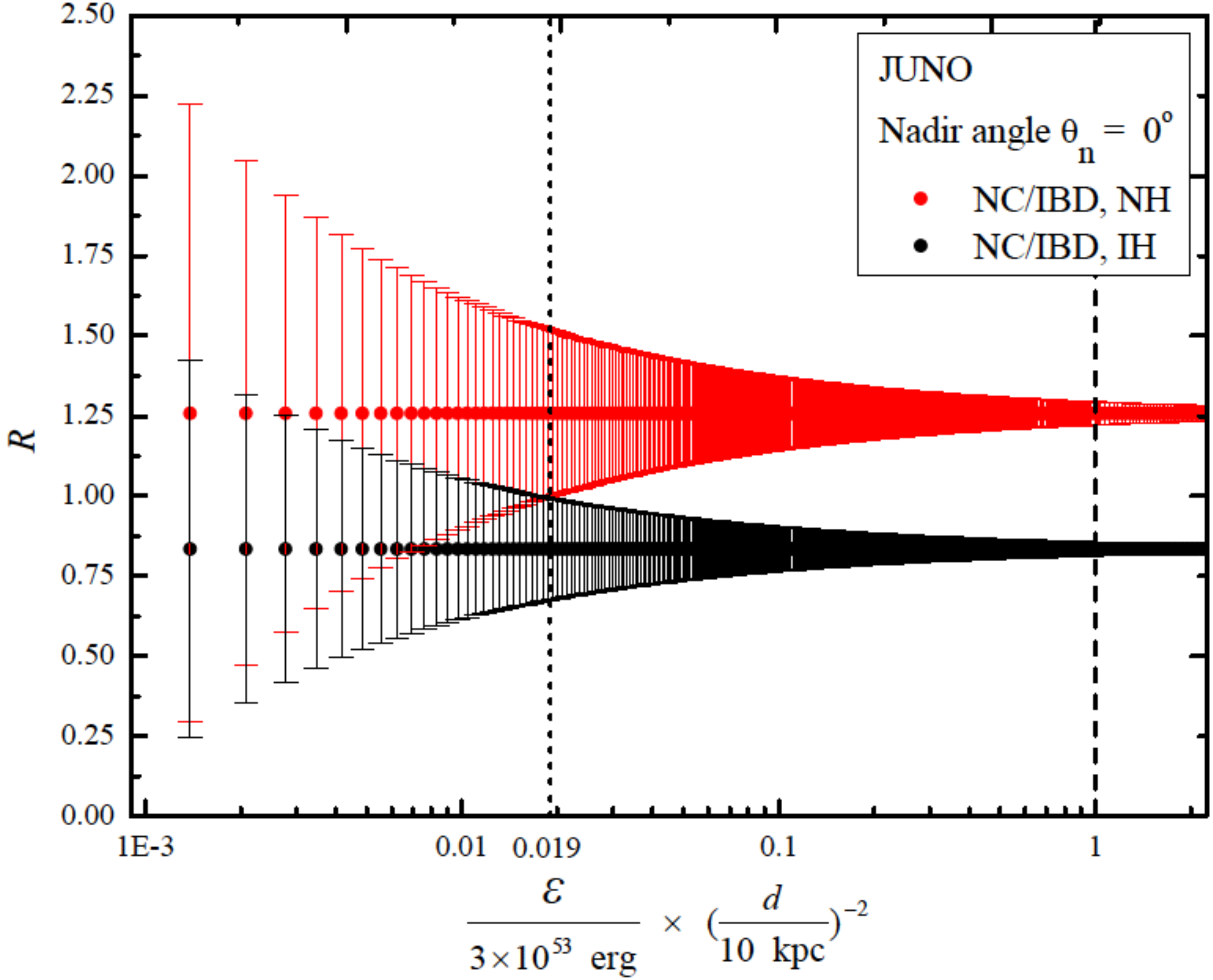




KamLAND detection with varied total energy and distance



JUNO detection with varied total energy and distance



SUMMARY AND OUTLOOK

- We have presented a method of identifying neutrino mass hierarchy from the detection of SN neutrinos with liquid scintillator detector.
- The IBD and NC interaction spectra can be obtained from IBD event spectrum (sensitive to electron anti-neutrino only) and NC event spectrum for all flavors.
- The IBD interaction spectrum is affected by neutrino flavor transition. It is therefore sensitive to neutrino flavor transition.The NC interaction spectrum is not affected by neutrino flavor transition, but it is useful to provide a normalization for the total neutrino fluence from SN.

SUMMARY AND OUTLOOK

- We propose the discriminator *R*, which is the ratio of NC events to IBD events for E_ν greater than 25 MeV. Such a cut is used to avoid backgrounds to NC events.
- We have so far considered only statistical uncertainties in our analysis. We are currently considering systematic uncertainties-such as the above energy cut, the uncertainty in reconstructing the NC interaction spectrum and the backgrounds to IBD and NC events.