Neutrino mass and mass ordering from supernova neutrinos

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MITP Workshop "Supernova Neutrino Observations: What can we learn and do?",

9-13 October 2017, Mainz

Motivation

I will continue on the discussion for the large liquid scintillation detector, e.g., JUNO

(1) Best energy resolution: energy spectrum

(2) Low threshold: IBD as well as nu-p/nu-e channels

(3) Multi-flavor detection: all three flavors

Absolute mass: time-of-flight effect

Mass ordering: MSW

Both studies need a better description on the energy and time distribution of supernova neutrinos

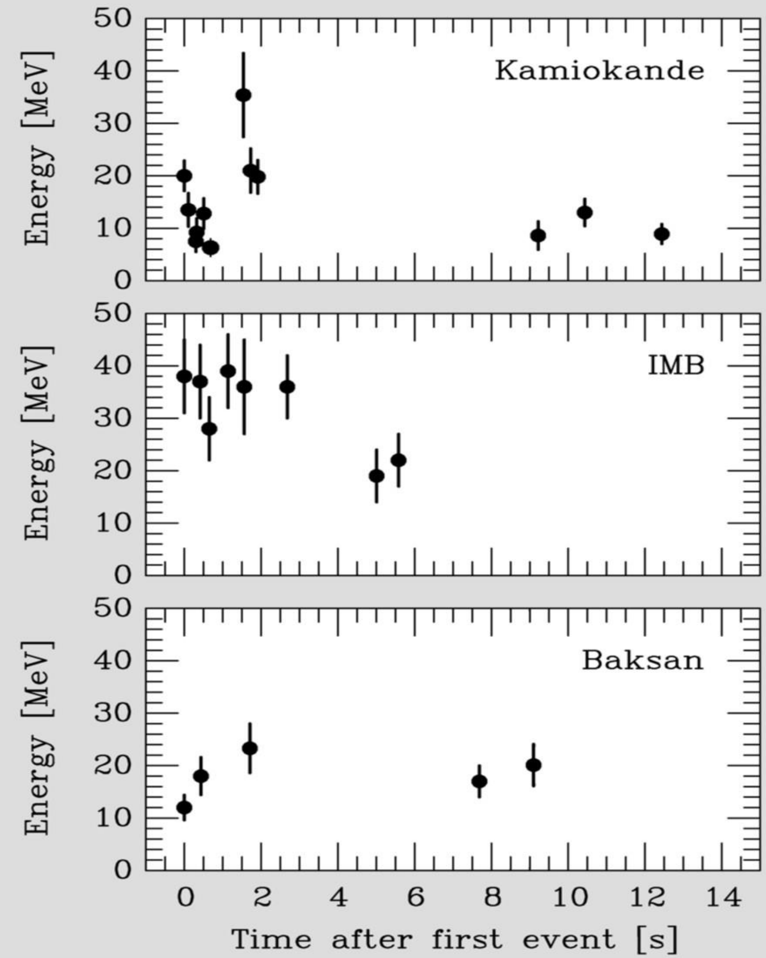
Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):
- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

Irvine-Michigan-Brookhaven (US):
- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

Baksan LST (Soviet Union):
- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier

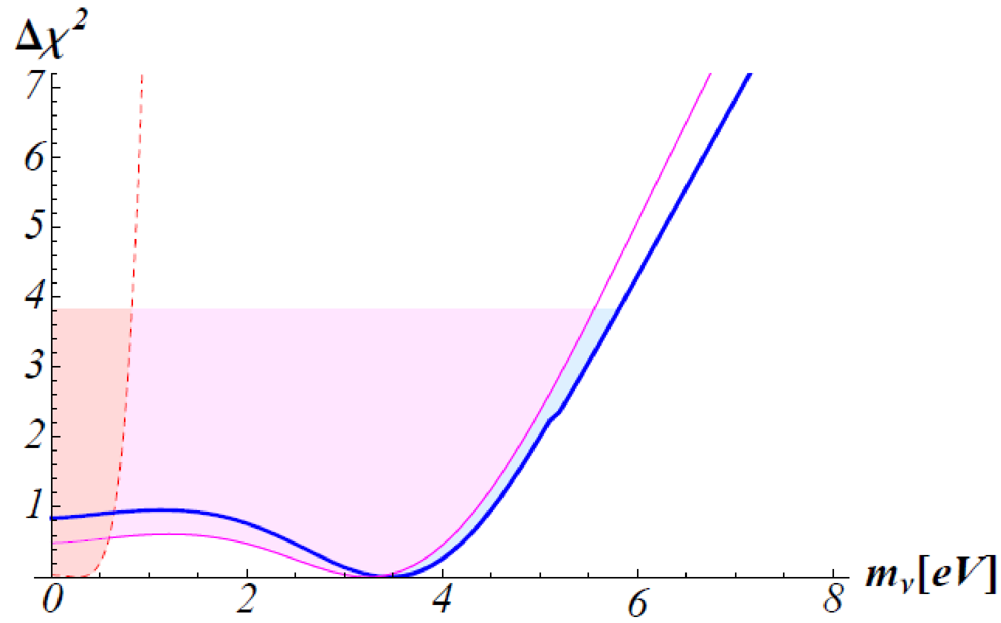


Limit from SN1987A

$$\Delta t(m_\nu, E_\nu) \simeq 5.14\ \mathrm{ms}\ \left(\frac{m_\nu}{\mathrm{eV}}\right)^2 \left(\frac{E_\nu}{10\ \mathrm{MeV}}\right)^{-2} \frac{D}{10\ \mathrm{kpc}}$$

SN1987A limits: around 6 eV@ 95 C.L.

By Loredo and Lamb, and many other scientists

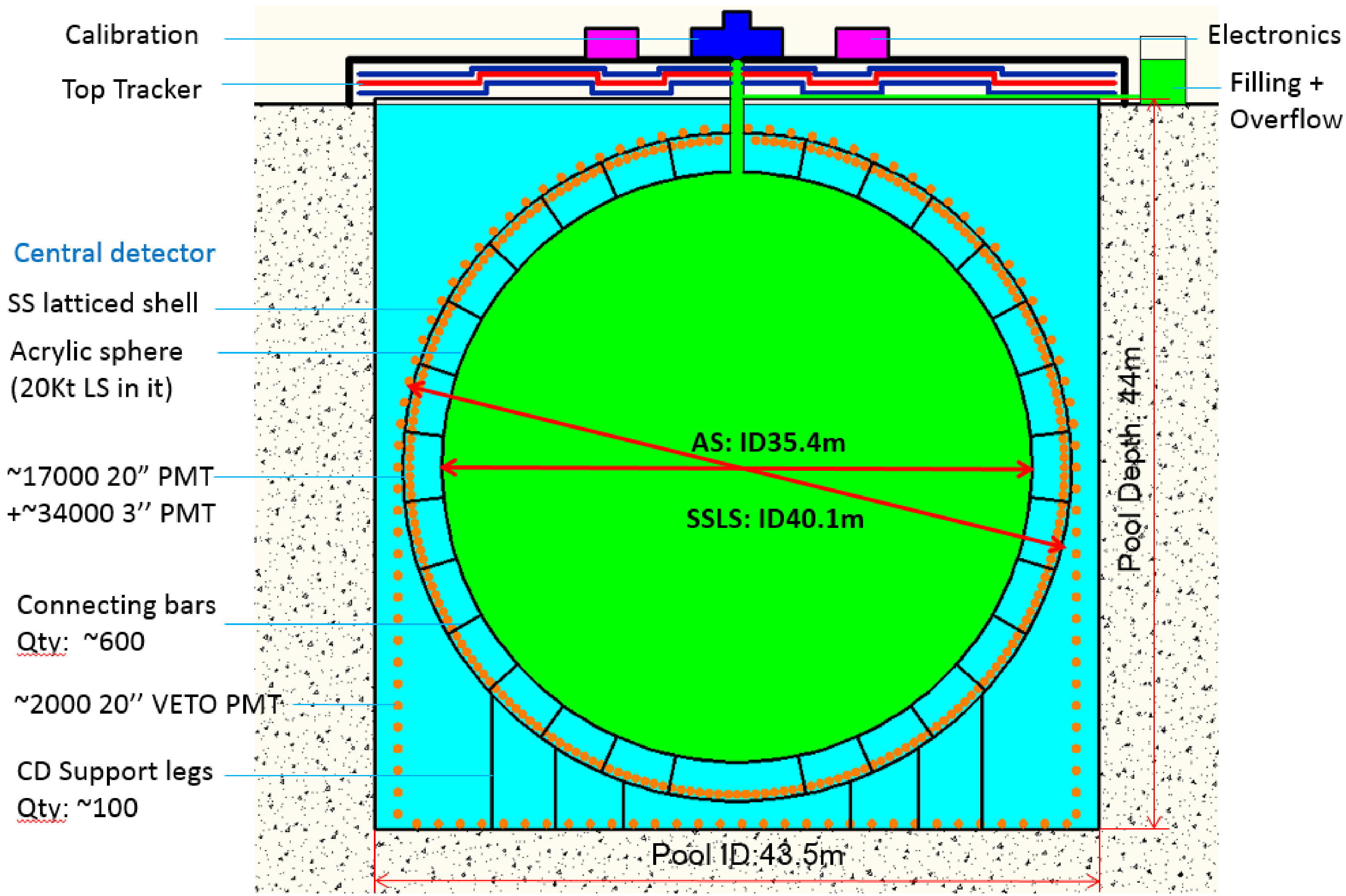


One analysis taken from Pagliaroli,Rossi-Torres, Vissani Astropart. Phys. 33 (2010) 287-291

Using an un-binned likelihood method with a prior description of the supernova neutrino fluxes.

5.8 eV @ 95 C.L.

Large and precision Liquid Scintillator detector



AS: Acrylic sphere; SSLS: stainless steel latticed shell

JUNO Collaboration, JPG 2016

Neutrino observation at JUNO

Lu, YFL, Zhou, PRD 2016

Channel	Type		Number of SN Neutrino Events at JUNO: No Oscillations	Normal Ordering	Inverted Ordering
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES		314	316	316
		ν_e	157	159	158
		$\overline{\nu}_e$	61	61	62
		ν_x	96	96	96
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC		43	134	106
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC		86	98	126
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC		352	352	352
		ν_e	27	76	61
		$\overline{\nu}_e$	43	50	65
		ν_x	282	226	226

A flux model based on SN1987A

- A simple parameterized model focusing on antineutrino emission in accretion phase and cooling phase is used in our work. ***A.Ianni et al., PRD, 2009***
- Accretion phase: $\bar{\nu}_e$ only $(e^+ + n \rightarrow \bar{\nu}_e + p)$.
  - Parameters: M_a, T_a, τ_a
- Cooling phase: all flavors. Spectrum of each flavor is thermal equilibrium spectrum.
  - Parameters: R_c, T_c, τ_c
- An interpolate function is used to smoothly connect the two phases.
- Other Parameters: flux rising time τ_r and burst start time t_s.

Likelihood

- Given the SN neutrino flux, we can calculate the IBD event rate $R(t, E_e)$.

$$R(t, E_e) = N_p \Phi_{\overline{\nu}_e}(t, E_\nu)\sigma_{\mathrm{IBD}}(E_\nu)\eta(E_e)$$

- We want to use the information of every event, so the likelihood function is written as

$$\mathcal{L} = e^{-\int_0^T R(t)\mathrm{d}t} \prod_{i=1}^{N} \int_{E_{\mathrm{th}}}^{\infty} R(t_i', E_e) G(E_e + m_e, E_i; \delta E_i) \mathrm{d}E_e \ ,$$

where $t_i' = t_i - \Delta t(m_\nu, E_\nu^i) - t_{\mathrm{s}}$ stands for the real time when the corresponding neutrino is emitted, G is the energy smear function.

Data distribution

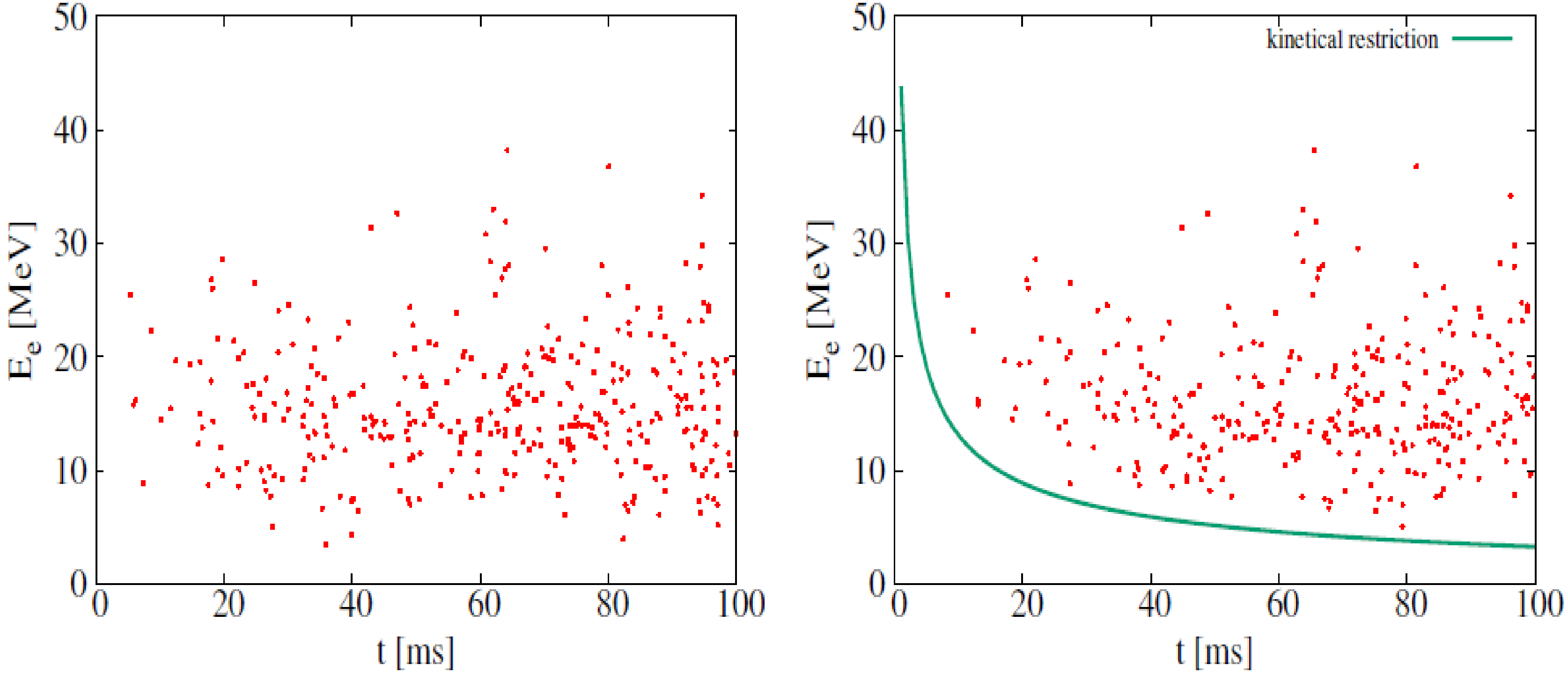
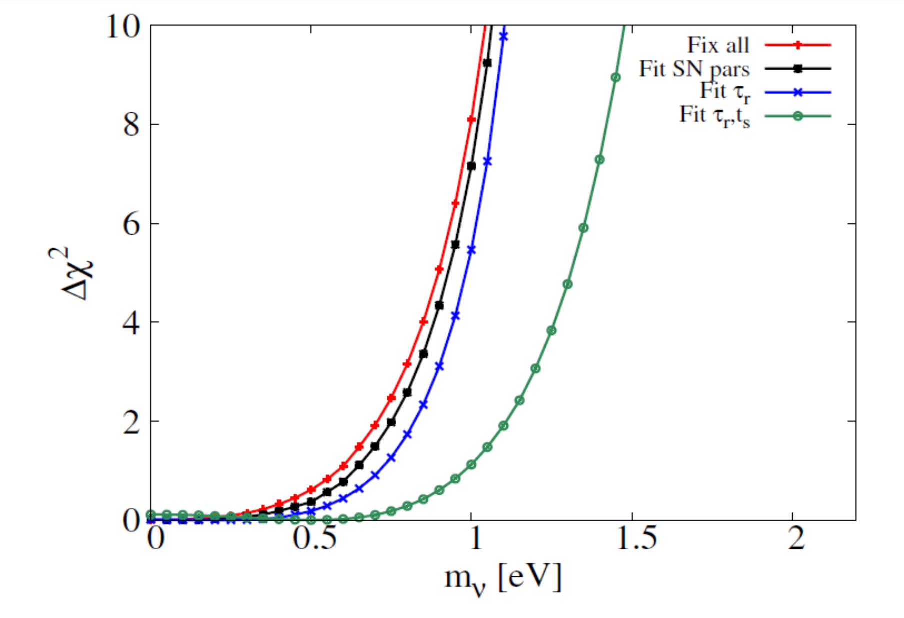
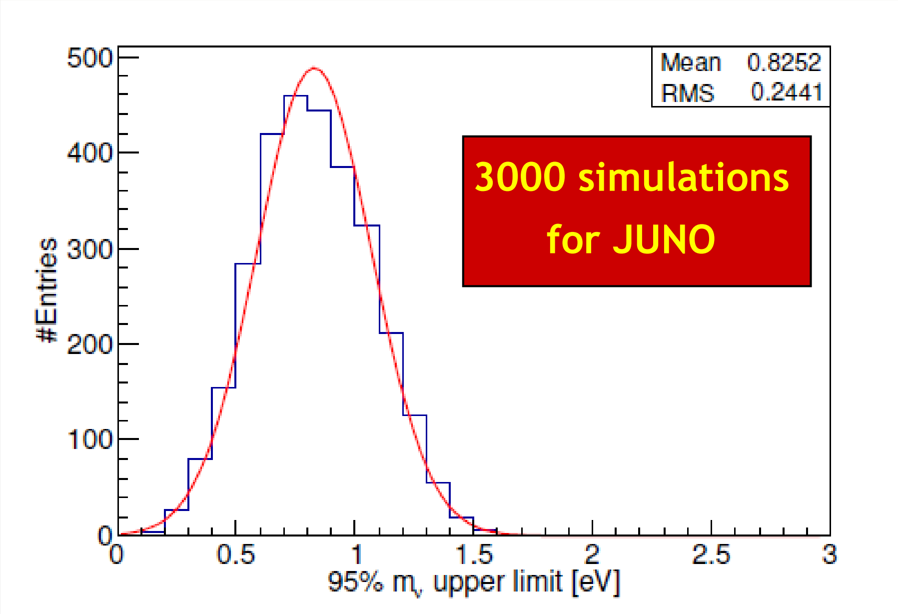


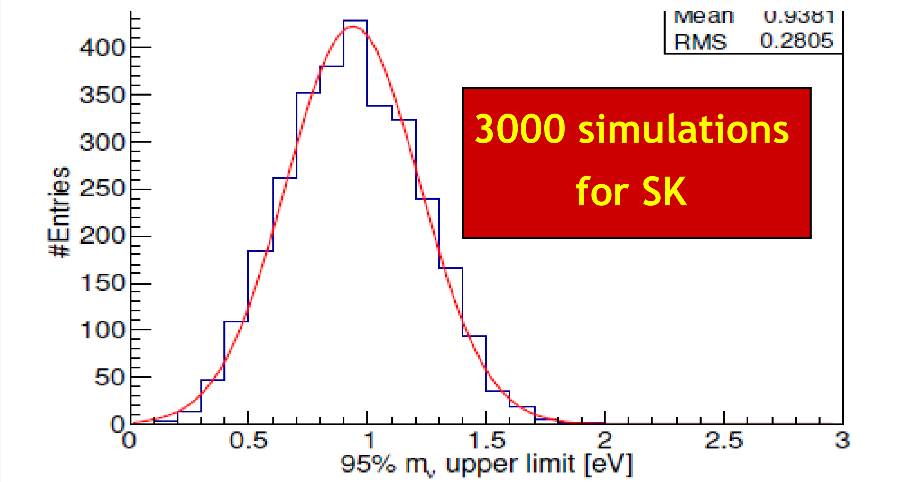
Figure: Example of time delay of SN neutrinos for a 10 kpc away SN. Left: $m_\nu = 0$. Right: $m_\nu = 2$ eV.

Statistical/Systematic uncertainties





Lu, Cao, Li, Zhou, JCAP, 2015

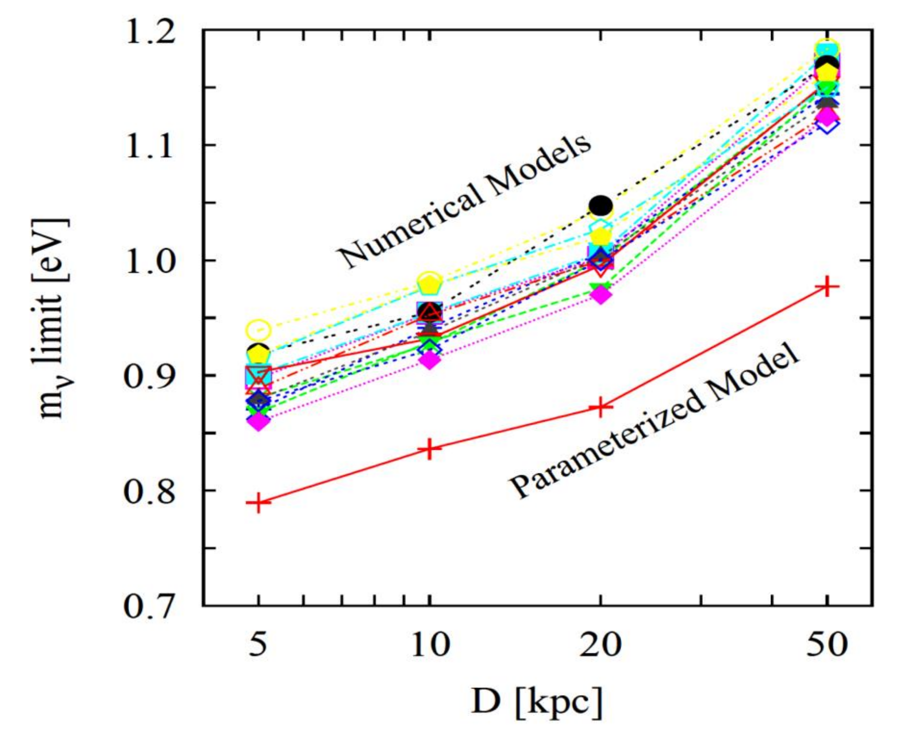


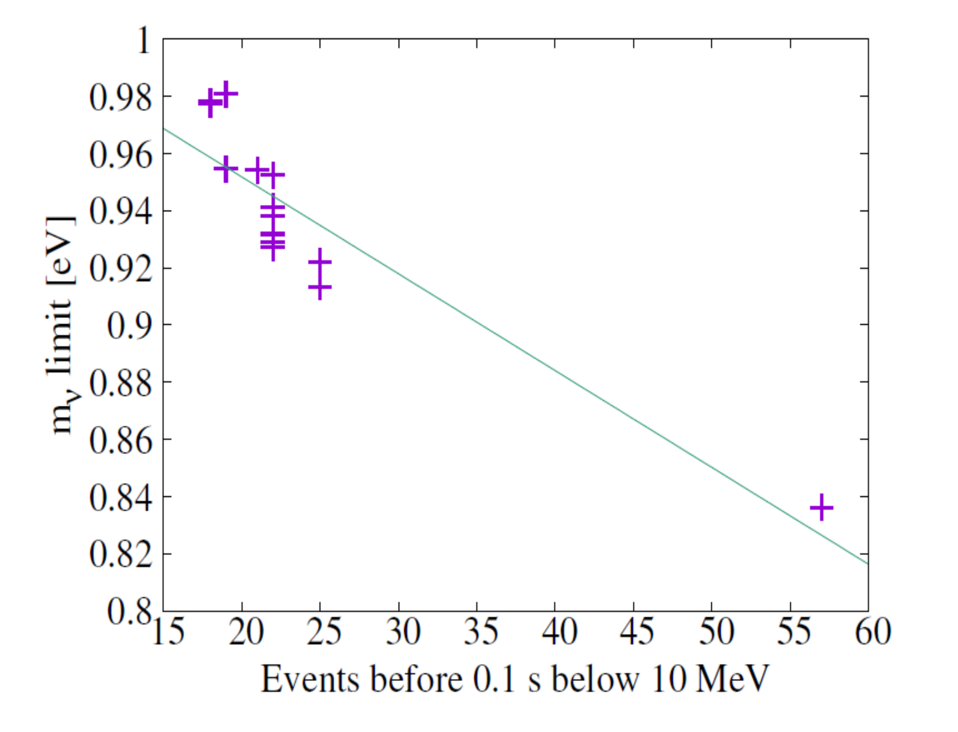
(1) Include the MSW effect for NH.

(2)Among different systematics, the starting time affects most.

(3) For the difference between JUNO and SK, the threshold is the main reason (compared to resolution).

Distance and Model Variations



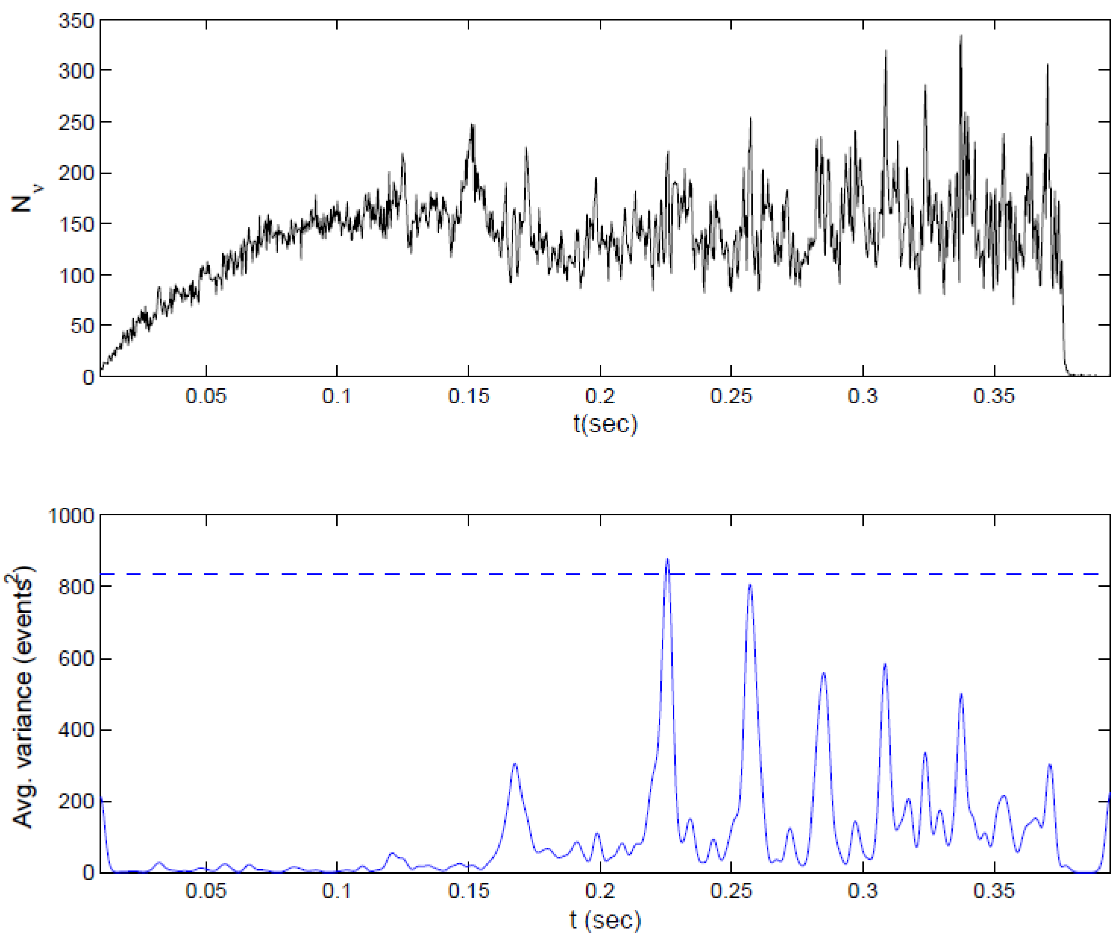


(1) For a large number of numerical models, the sensitivities are better than 1 eV @ 95 C.L. for 10 kpc.

(2) Early low energy events are most important for the time-of-flight measurements.

Fine-scale time structures in the wavelet analysis

J.Ellis, H.T.Janka et al., PRD, 2012



(1) Using the 2-d simulation data and the wavelet analysis technique

(2) Ice-Cube or a water Cerenkov low-energy detector at 10 kpc (@95C.L.):

$$\boxed{m_\nu < 0.14 \text{ eV}.}$$

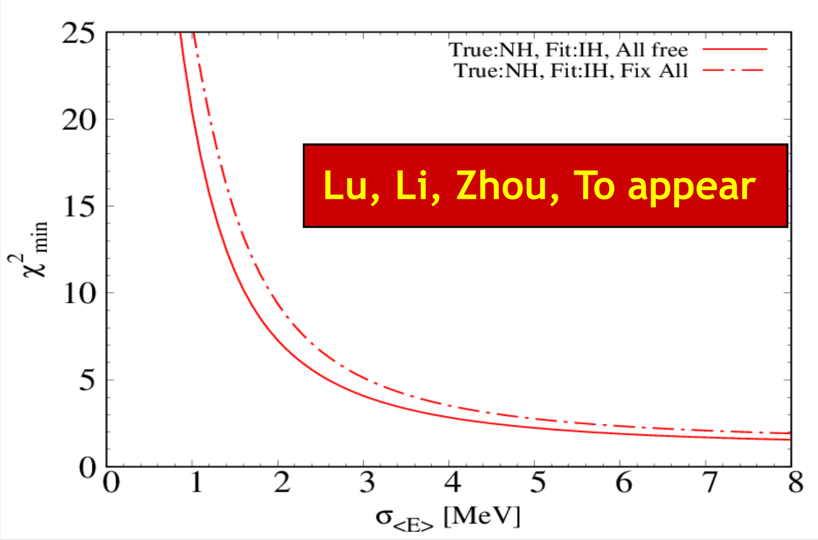
Mass ordering via MSW effects

Using the integrated energy spectrum

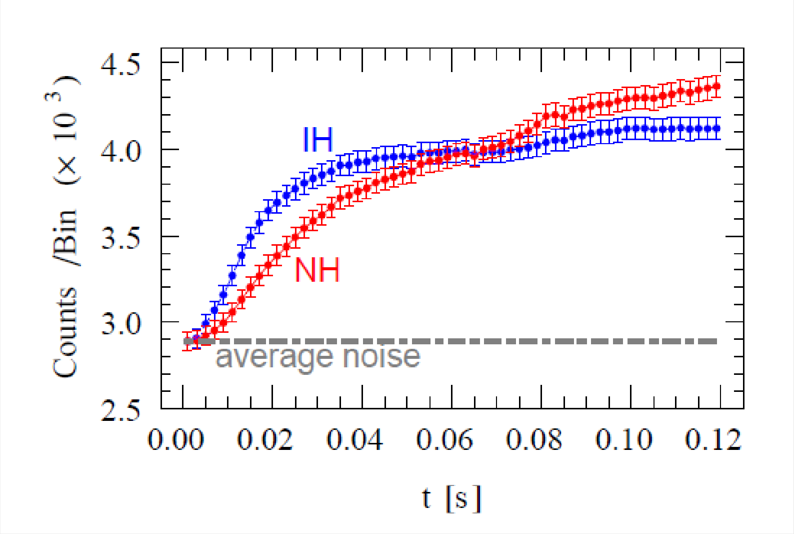
Using the facts of the average energy hierarchies:

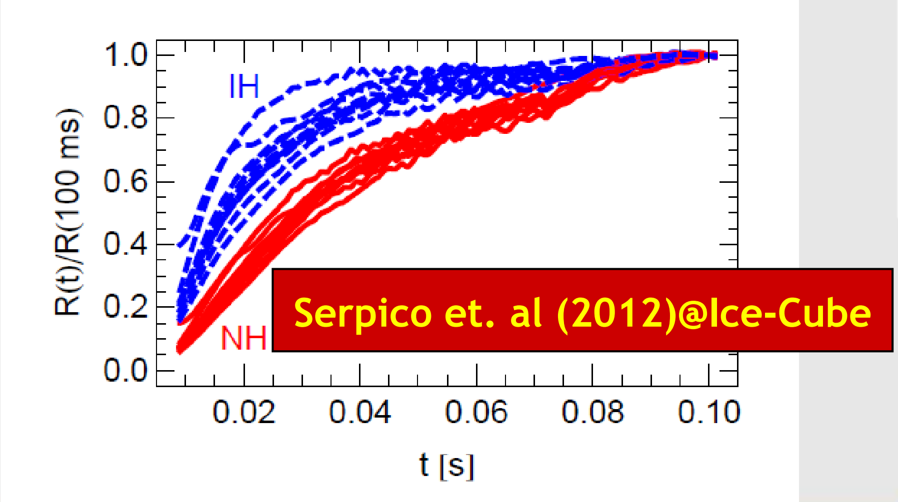
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Taking the advantage of multi-flavor measurement in LS detectors (all six channels@JUNO)



Using the time distribution





Concluding remarks

(a) The neutrino mass and mass ordering would be measured with beta decay and oscillation experiments (accelerator, reactor, atmospheric neutrinos).

(b) The studies of sensitivity are intended to show their quantitative effects on the future measurements.

(c) Good sensitivity needs a better understanding of the initial supernova neutrino fluxes.

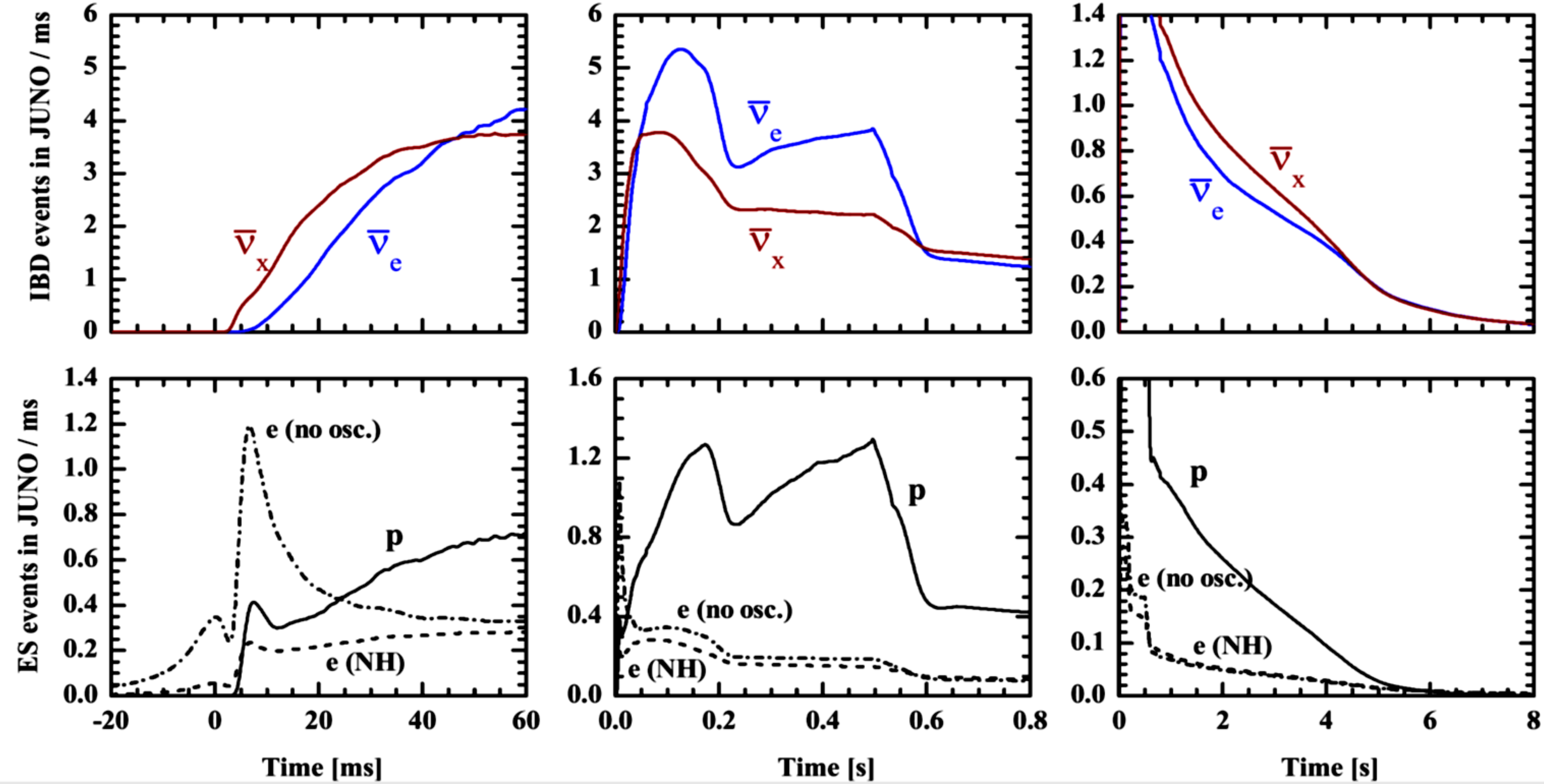
(d) These two effects (initial flux and mass/mass ordering) are coupled from the point of view of measurements.

Welcome to the JUNO site
@Jiangmen

Thank you

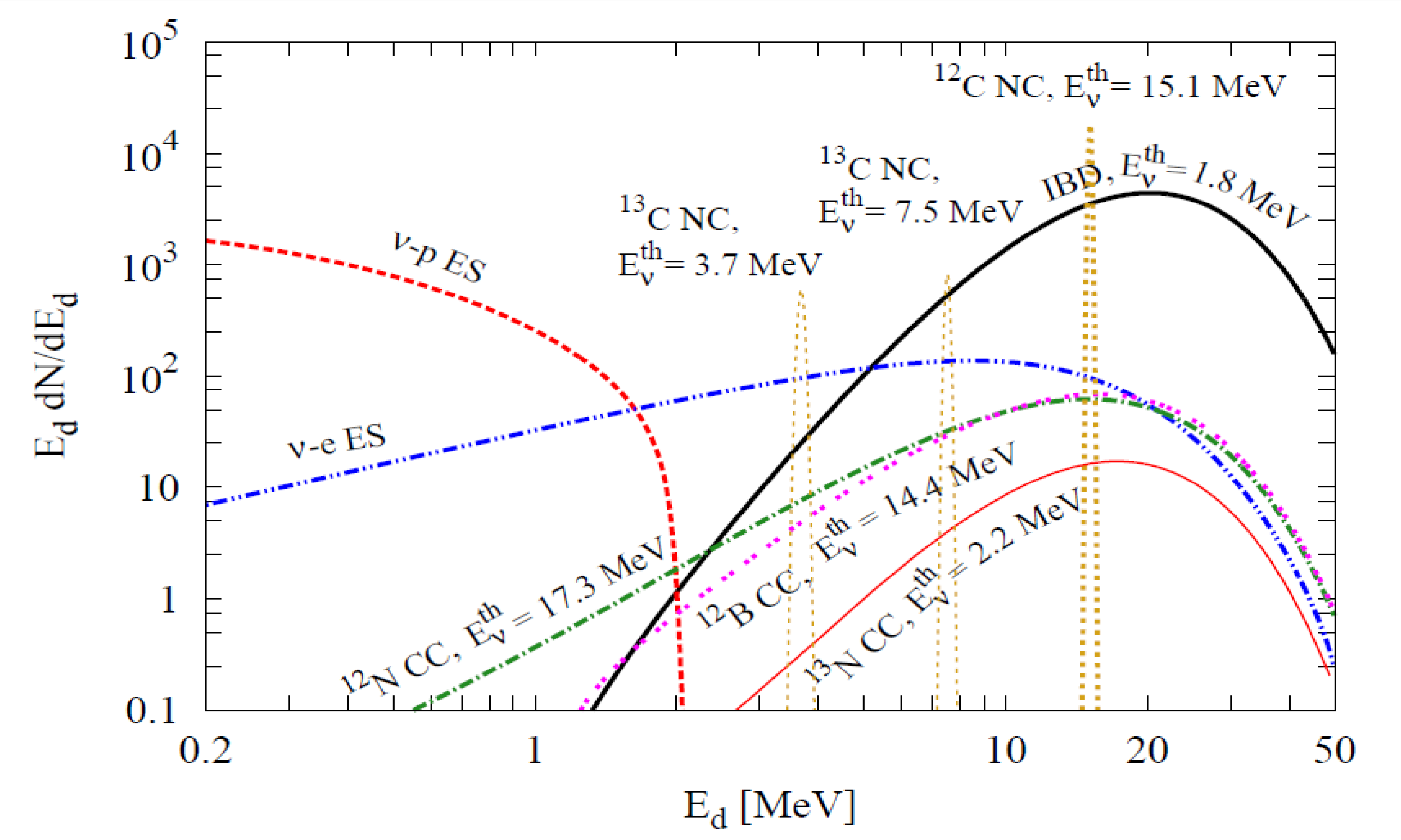
Backup

Time distribution (IBD & ES events)



w/o oscillation or **with largest transition** between ν_e($\bar{\nu}_e$) and ν_x

Neutrino energy distribution



Lu, YFL, Zhou, PRD 2016

See also Lujan-Peschard, Pagliaroli, Vissani, 2014

1) IBD events dominate at the high energy range
2) nu-p ES channel dominates at low energies
3) coincidence events vs. singles events
4) e. vs. p discrimination: Pulse shape discrimination

Detection of SN $\bar{\nu}_e$

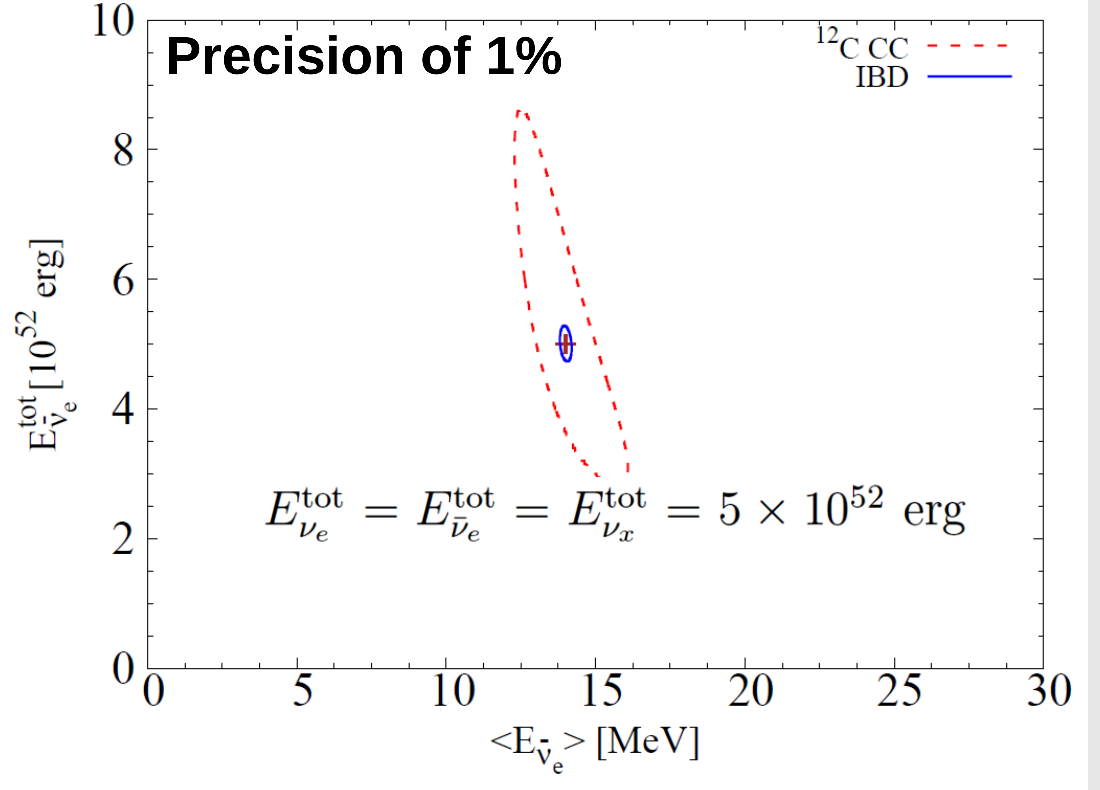
Mostly Inverse beta decay (IBD) $\bar{\nu}_e + \mathrm{p} \longrightarrow n + e^+$

Spectra $$F_\alpha^0(E) = \frac{1}{4\pi D^2}\frac{E_\alpha^{\rm tot}}{\langle E_\alpha\rangle}\frac{(1+\gamma_\alpha)^{1+\gamma_\alpha}}{\Gamma(1+\gamma_\alpha)}\left(\frac{E}{\langle E_\alpha\rangle}\right)^{\gamma_\alpha}\exp\left[-(1+\gamma_\alpha)\frac{E}{\langle E_\alpha\rangle}\right]$$

(1) ~5000 IBD events, golden channel for SN neutrino observations

(2) Coincidence of prompt and delayed signals: least background

(3) good reconstruction of the neutrino energy

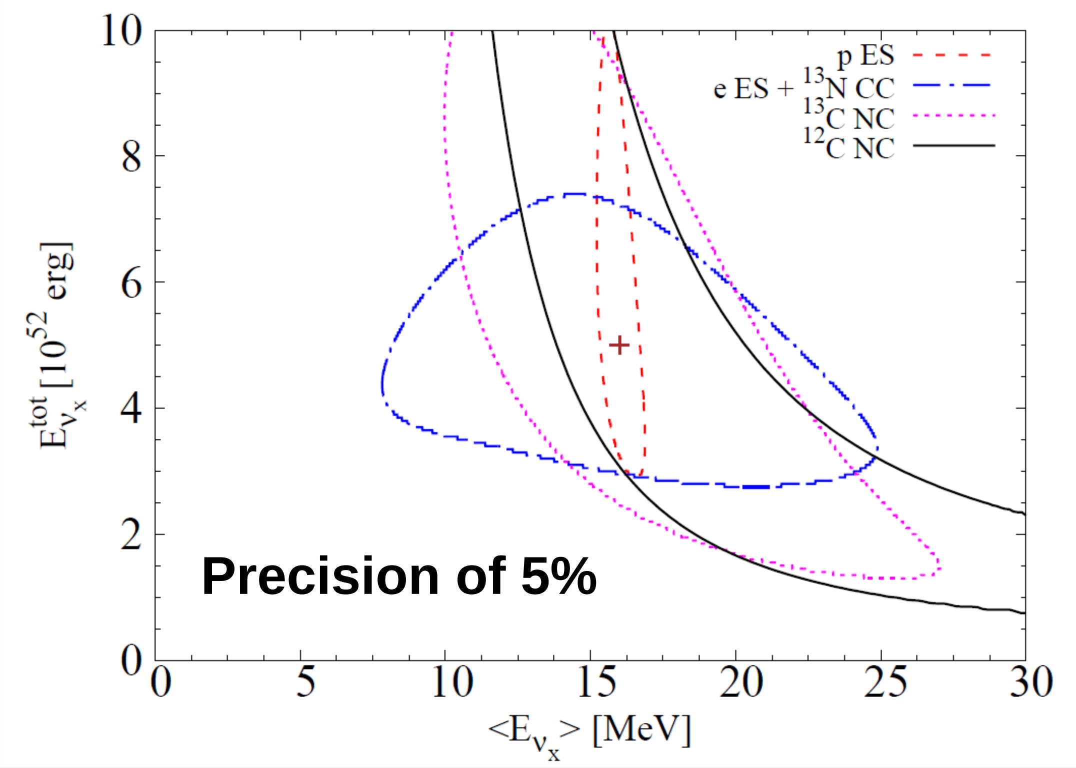


Lu, YFL, Zhou, PRD 2016

Detection of SN ν_x

(1) nu-p scattering (pES) events: quenched proton
(2) nu-^{12}C NC events: 15.11 MeV γ
(3) nu-electron scattering (eES) events: recoiled electron

- ~2000 pES events
- Low threshold **(0.2 MeV)**
- reconstruction of neutrino energy spectrum: **high-energy tail**



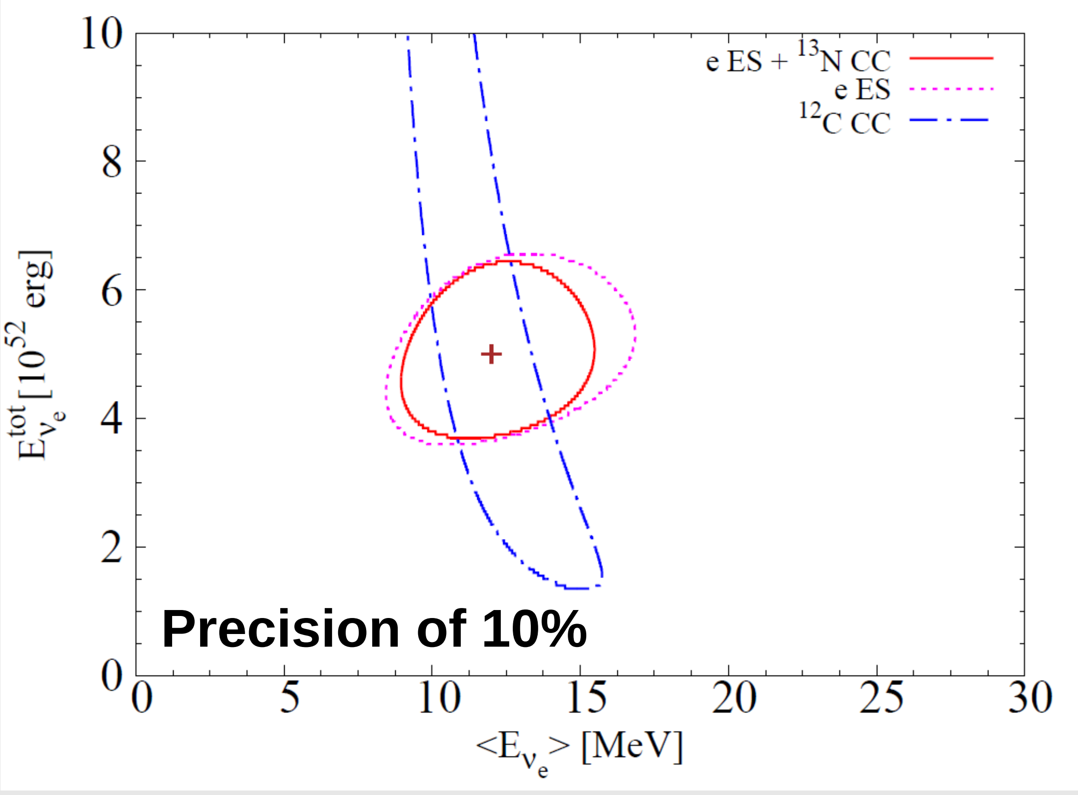
Lu, YFL, Zhou, PRD 2016

Detection of SN ν_e at JUNO

(1) nu-electron scattering events: recoiled electrons

(2) nu-^{12}C CC events: coincidence with decayed ^{12}N

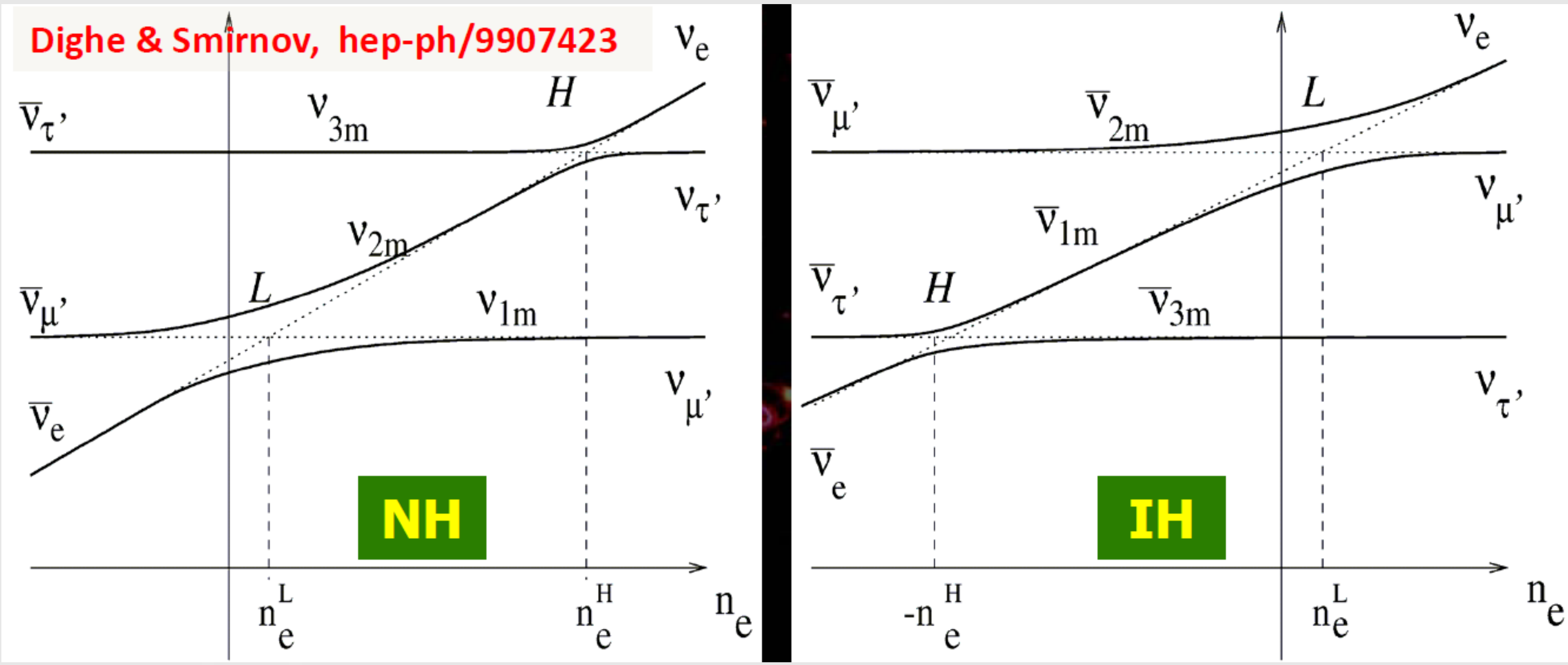
- ~300 eES events
- ~300 ^{12}C CC events
- Background events: from IBD in-efficiency
- electron v.s. proton: pulse shape discrimination (PSD)



Lu, YFL, Zhou, PRD 2016

MSW effects: neutrino flavor conversion

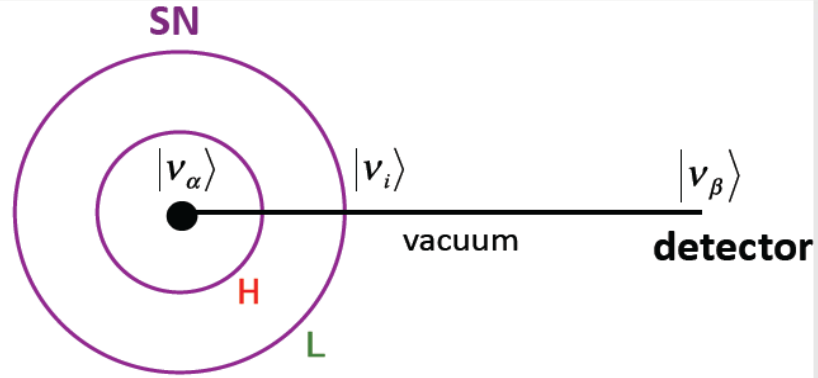
MSW effect: caused by changing matter density, not by "oscillation"



For normal MH, both the High and Low resonance happen in the neutrino sector.

For inverted MH, Low resonance in the neutrino sector and High resonance in the antineutrino sector.

Survival and transition probabilities



$$\phi_{\nu_e} = \phi^0_{\nu_e} P_{ee} + \phi^0_{\nu_x}(1 - P_{ee})$$
$$\phi_{\bar\nu_e} = \phi^0_{\bar\nu_e} P_{\bar e\bar e} + \phi^0_{\bar\nu_x}(1 - P_{\bar e\bar e})$$
$$\phi_{\nu_\mu} + \phi_{\nu_\tau} = \phi^0_{\nu_e}(1 - P_{ee}) + \phi^0_{\nu_x}(1 + P_{ee})$$
$$\phi_{\bar\nu_\mu} + \phi_{\bar\nu_\tau} = \phi^0_{\bar\nu_e}(1 - P_{\bar e\bar e}) + \phi^0_{\nu_x}(1 + P_{\bar e\bar e})$$