Supernova Neutrinos in Large Liquid Scintillator detectors

Yu-Feng LI

liyufeng@ihep.ac.cn

Institute of High Energy Physics, Beijing

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Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):

- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

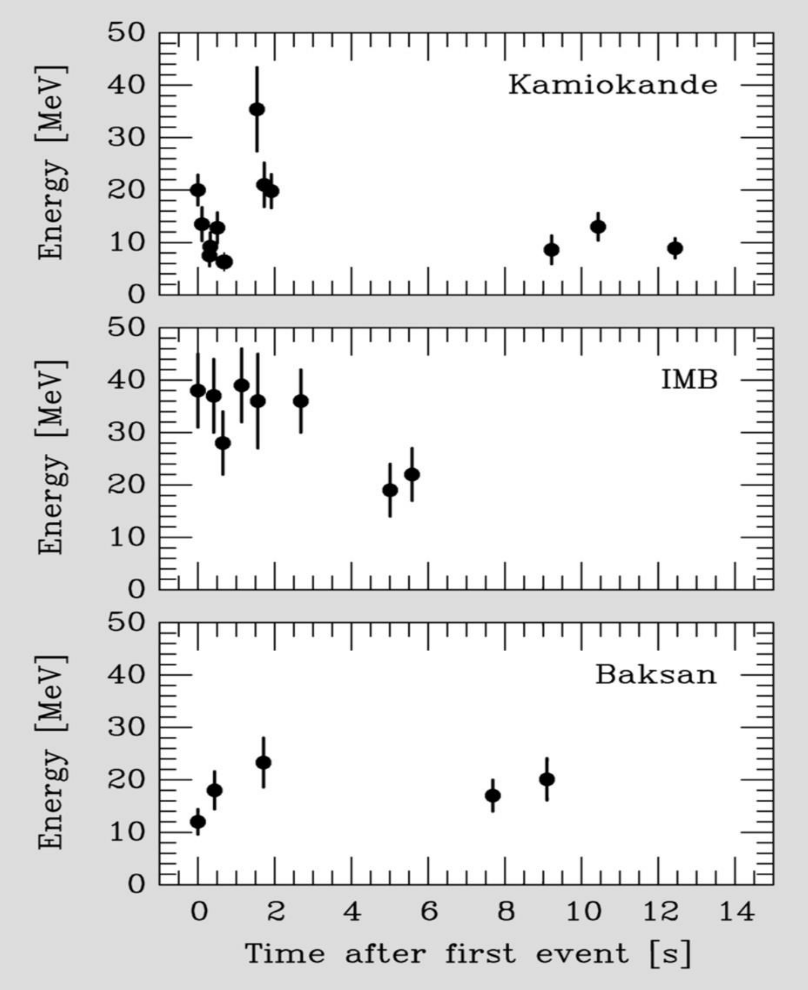
Irvine-Michigan-Brookhaven (US):

- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

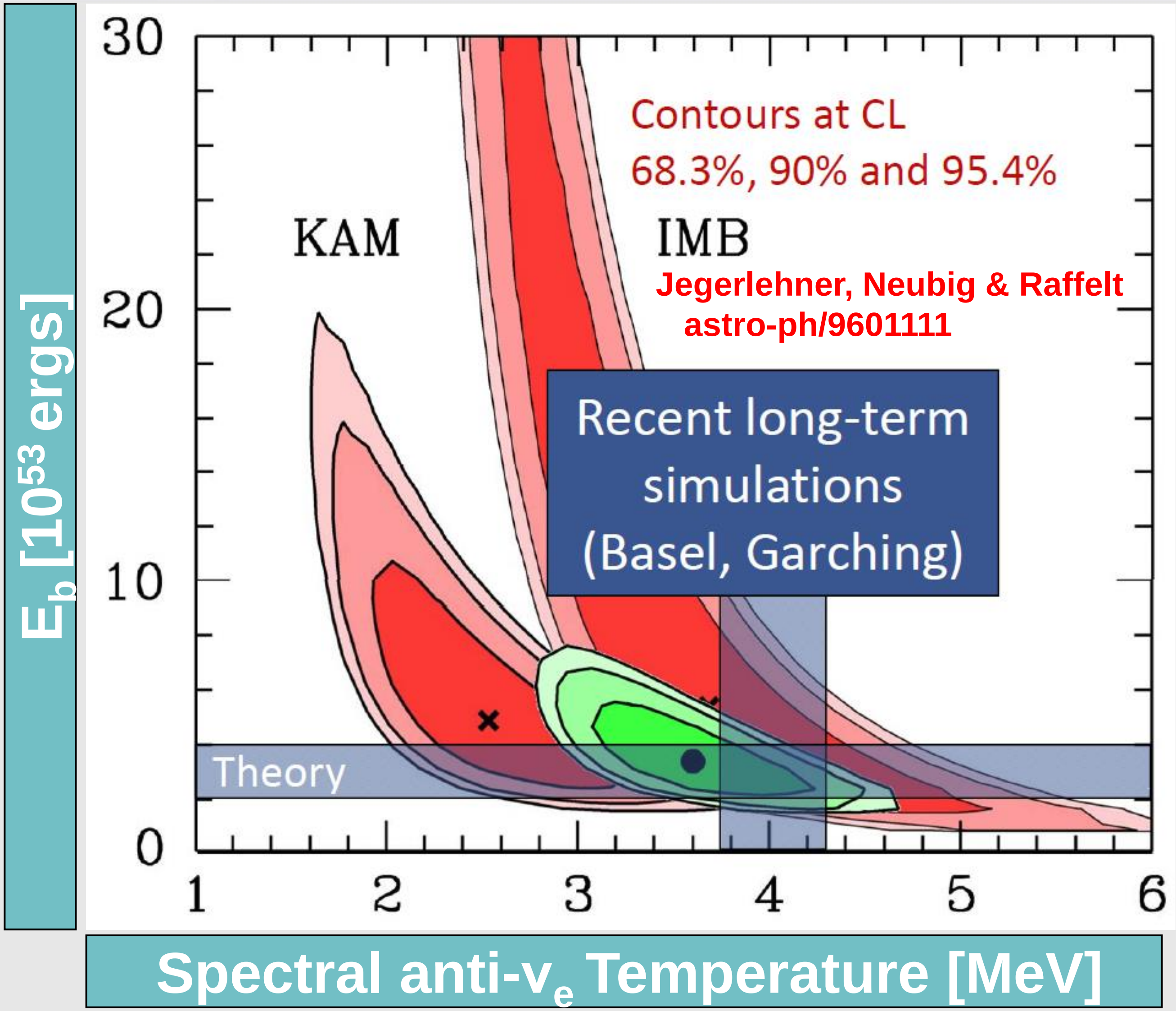
Baksan LST (Soviet Union):

- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



Supernova Neutrinos: SN 1987A



Jegerlehner, Neubig & Raffelt
astro-ph/9601111

Recent long-term simulations (Basel, Garching)

Assumptions:
- Thermal spectrum
- Equipartition

Conclusions:
- Collapse with nus
- Average Energy
- Duration

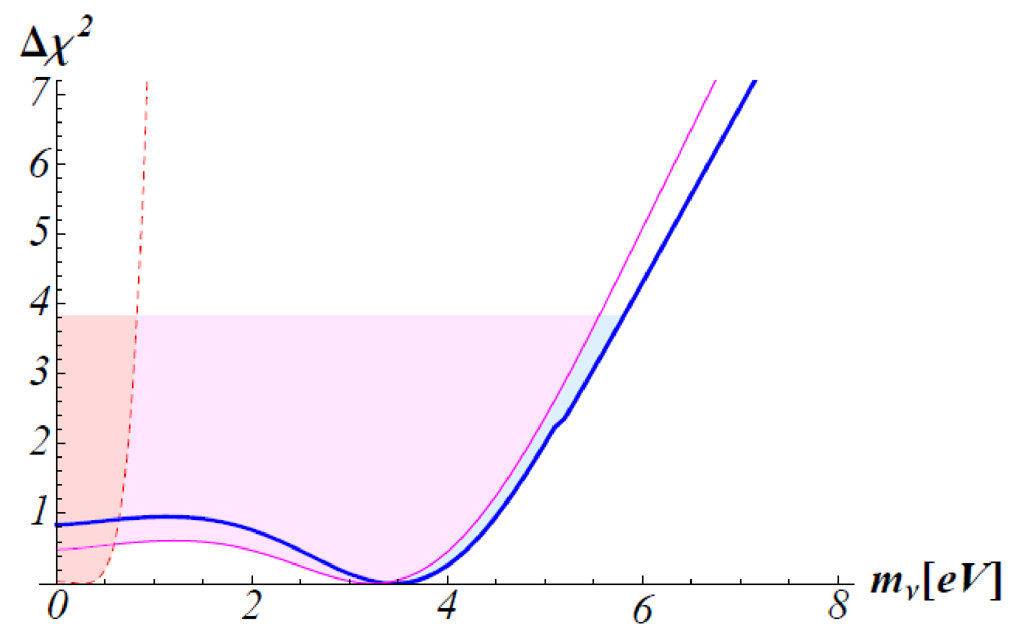
Lessons:
- once for a lifetime
- Don’t miss the Next Galactic SN

Neutrino mass limit: SN 1987A

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

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

By Loredo and Lamb, and many other researches



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

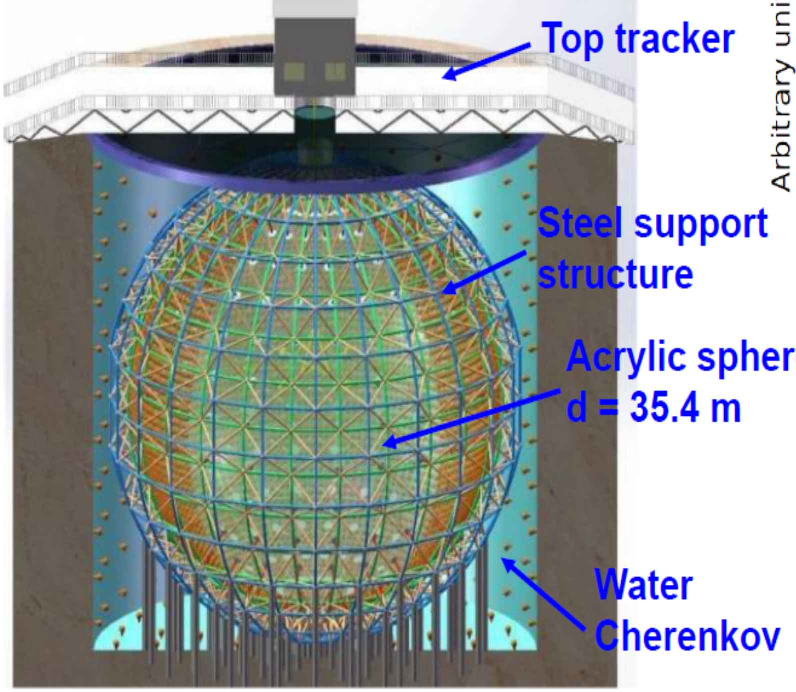
Using an un-binned likelihood method with a prior description of the supernova neutrino fluxes.

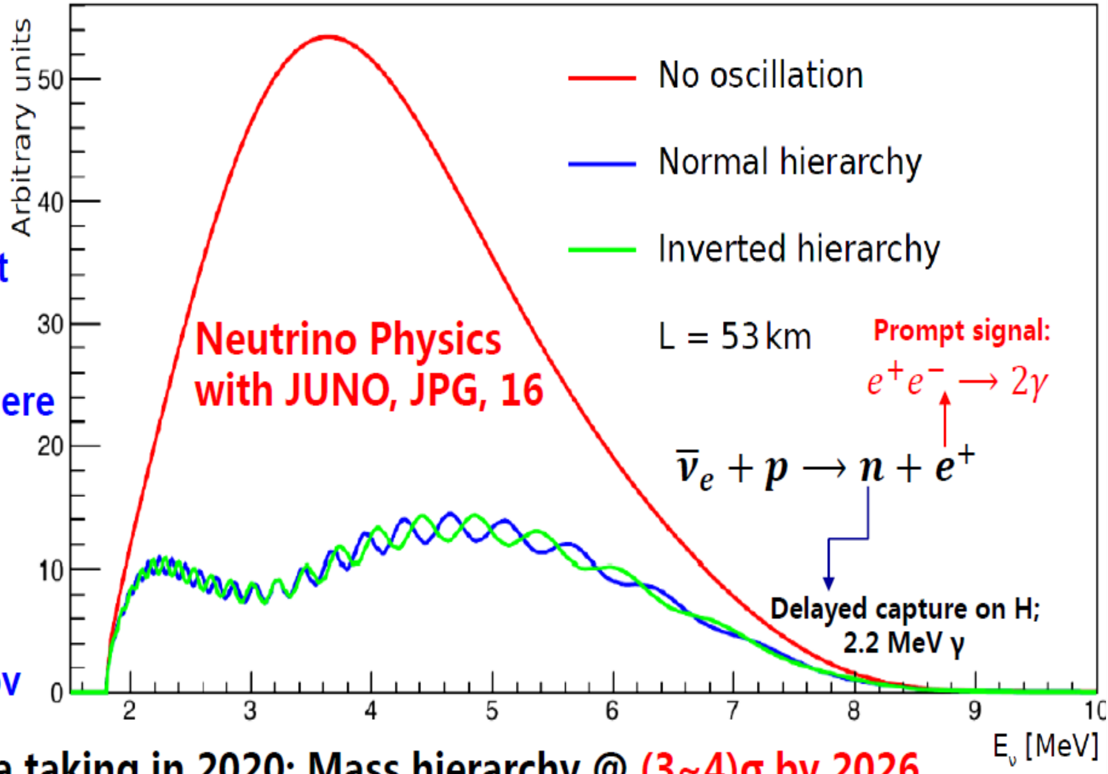
5.8 eV @ 95 C.L.

Large and precision Liquid Scintillator detector

See the talk by Gioacchino

Jiangmen Underground Neutrino Observatory





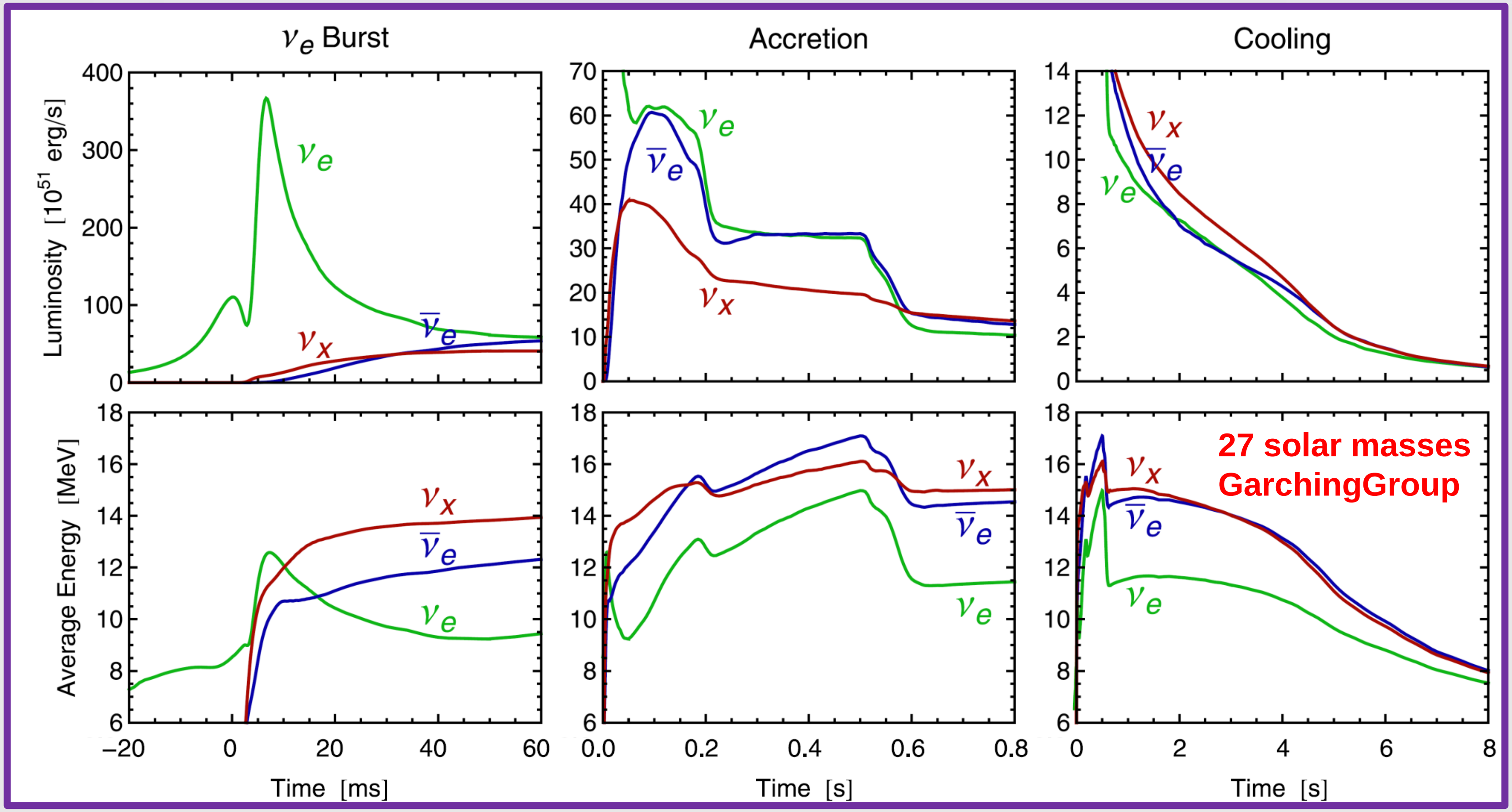
Neutrino Physics with JUNO, JPG, 16

- 20 kiloton LS detector
- 3% energy resolution@ 1 MeV
- 700 m underground
- 18,000 20" +25,000 3" PMTs
- 53 km to the NPPs

Data taking in 2020; Mass hierarchy @ (3~4)σ by 2026

	KamLAND	Borexino	JUNO
LS mass	1 kt	0.3 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

SN neutrino bursts from simulation



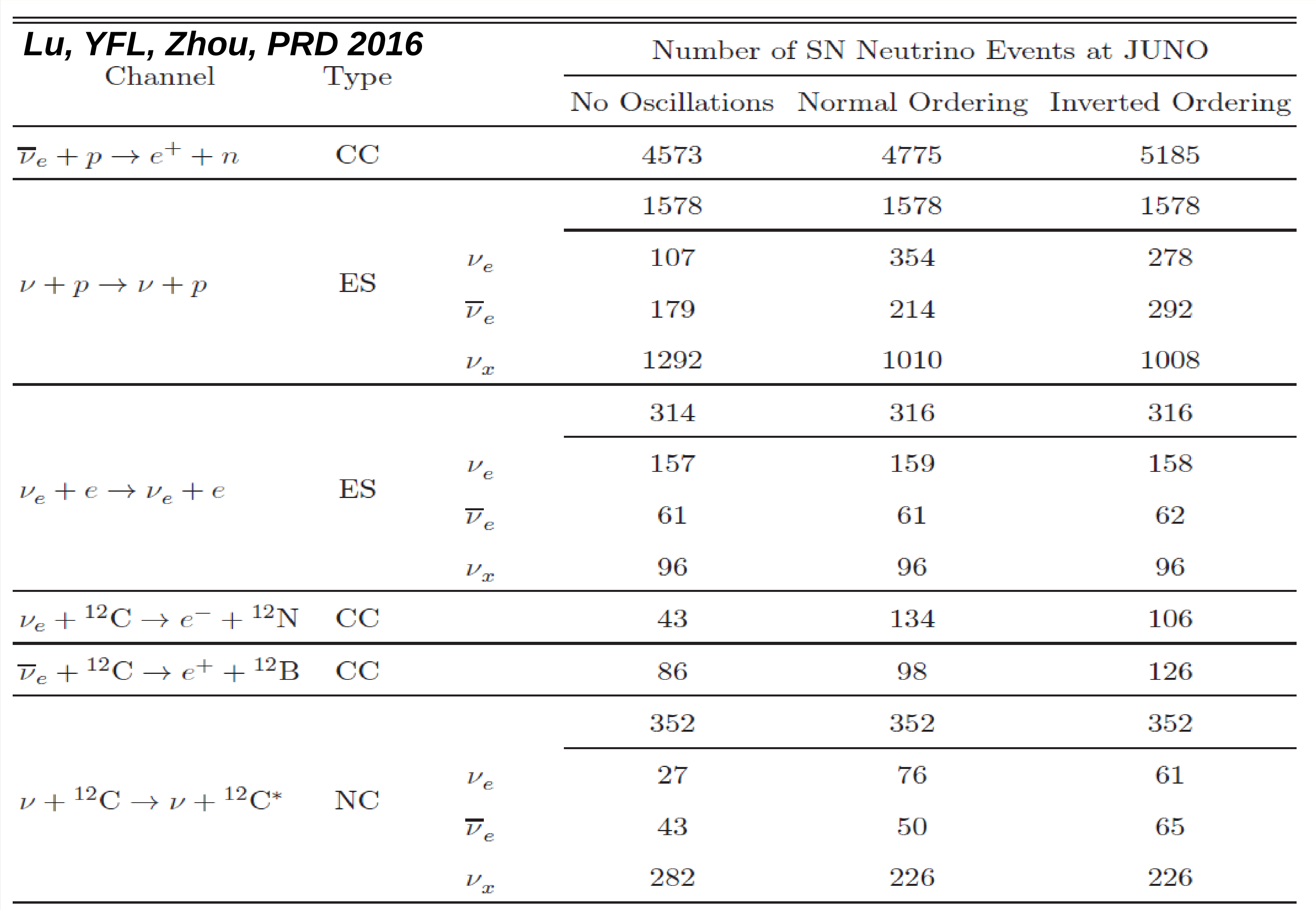
Shock breakout

$$e^- + p \to n + \nu_e$$

Shock stalls ~150 km
Neutrinos powered by infalling matter

Cooling on the neutrino diffusion time scale

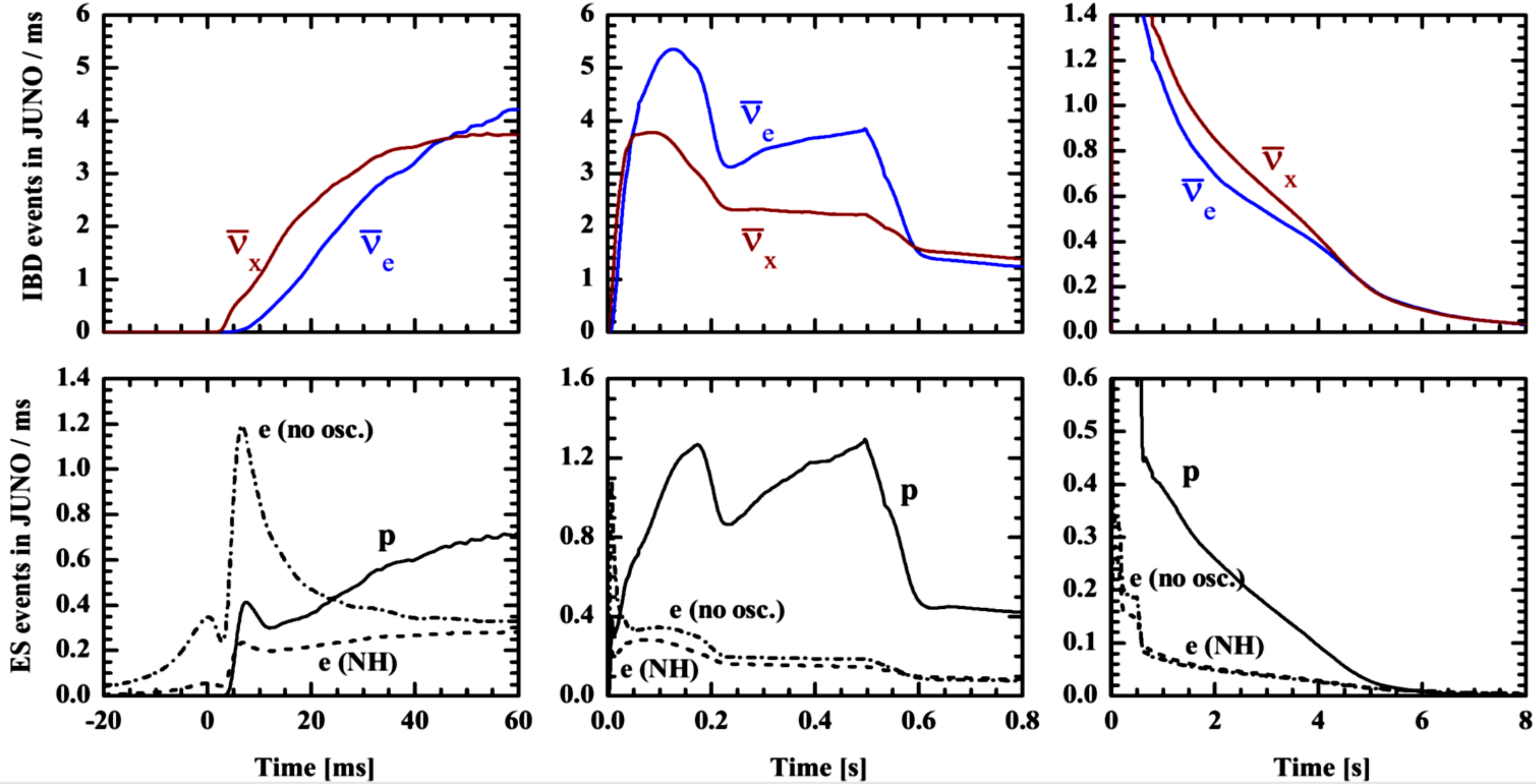
Neutrino observation at JUNO (@ 10 kpc)



Lu, YFL, Zhou, PRD 2016

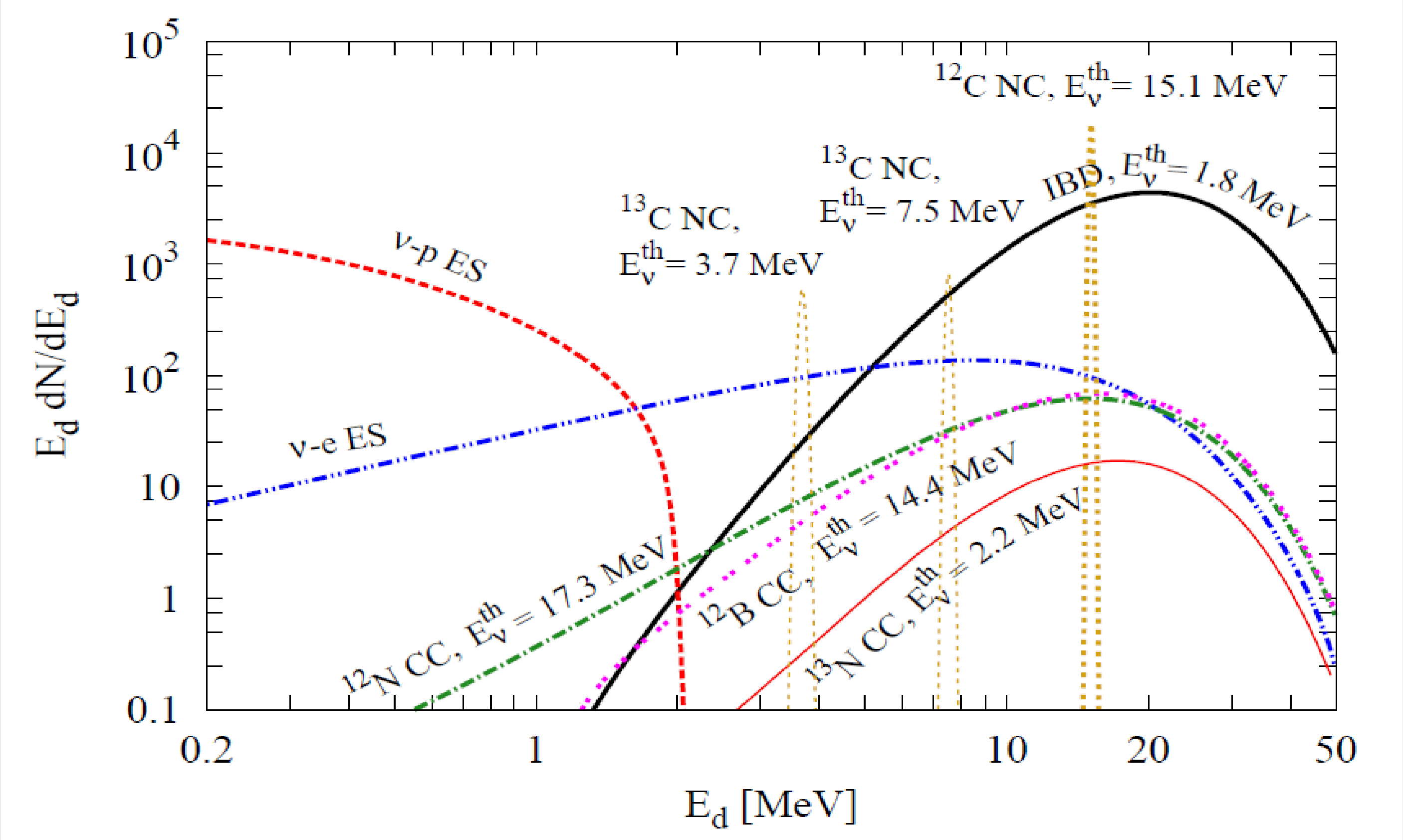
Channel	Type		Number of SN Neutrino Events at JUNO		
			No Oscillations	Normal Ordering	Inverted Ordering
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES		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

Time distribution (IBD & ES events)



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

Neutrino energy distribution

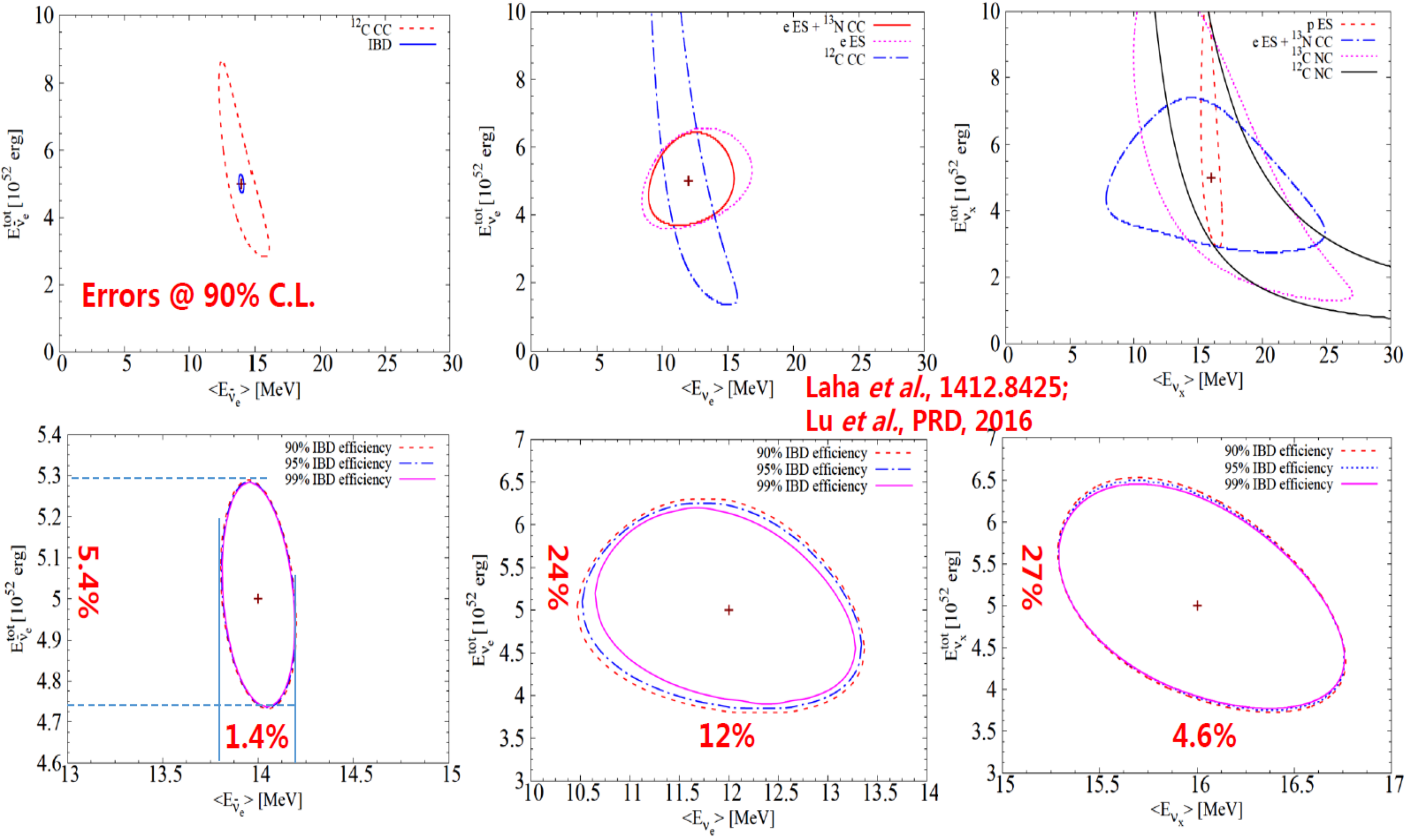


Lu, YFL, Zhou, PRD 2016

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

A global analysis of three flavors



Errors @ 90% C.L.

5.4%

1.4%

24%

12%

27%

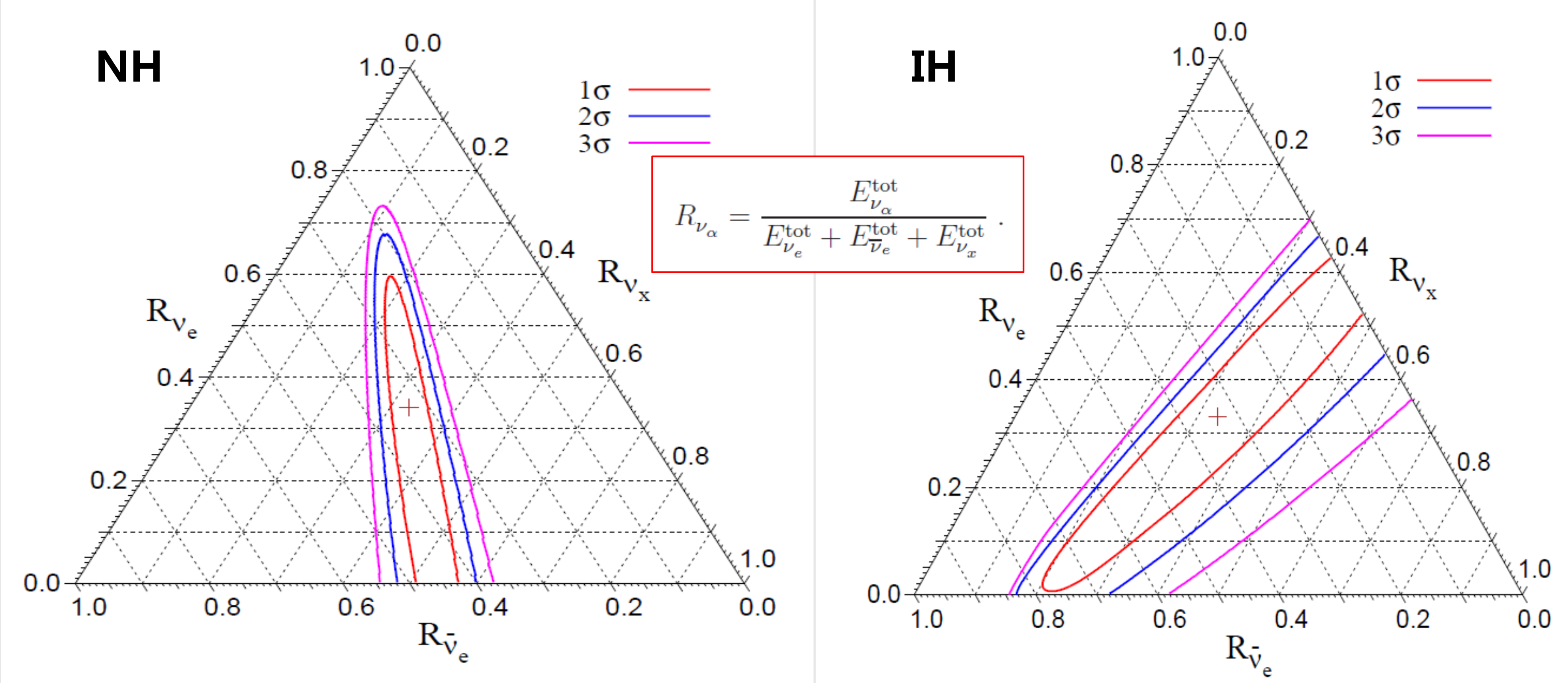
4.6%

Laha *et al.*, 1412.8425;
Lu *et al.*, PRD, 2016

Test of the energy equipartition

A fundamental assumption in SN physics
Not guaranteed in simulation

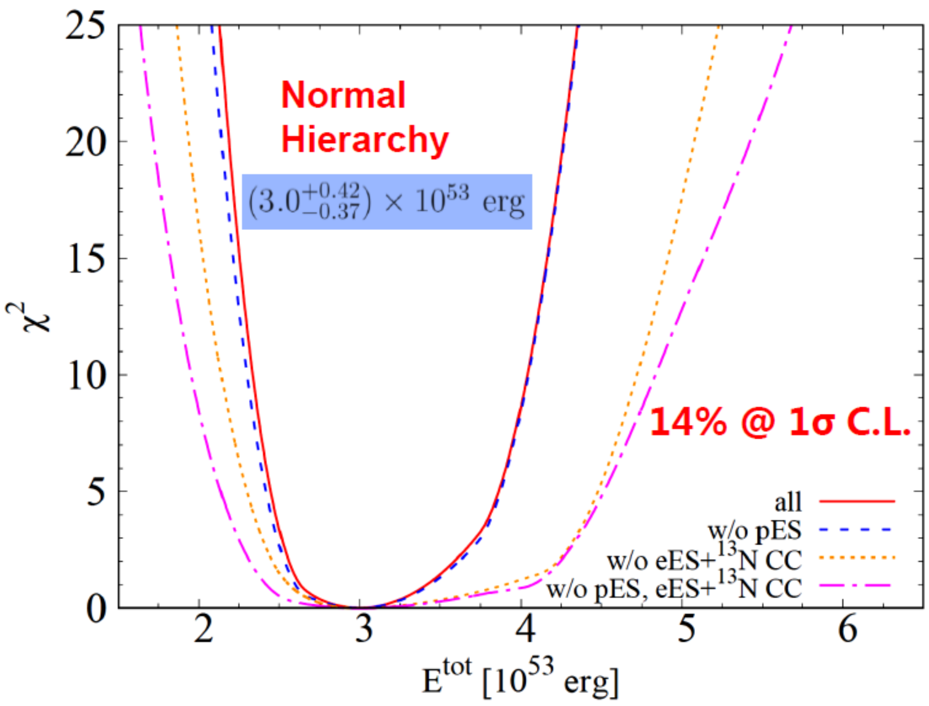
Lu, YFL, Zhou, PRD 2016



$$R_{\nu_\alpha} = \frac{E^{\rm tot}_{\nu_\alpha}}{E^{\rm tot}_{\nu_e} + E^{\rm tot}_{\overline{\nu}_e} + E^{\rm tot}_{\nu_x}} \,.$$

(1) Assuming standard MSW effects
(2) marginalization of three average energies and E_tot.

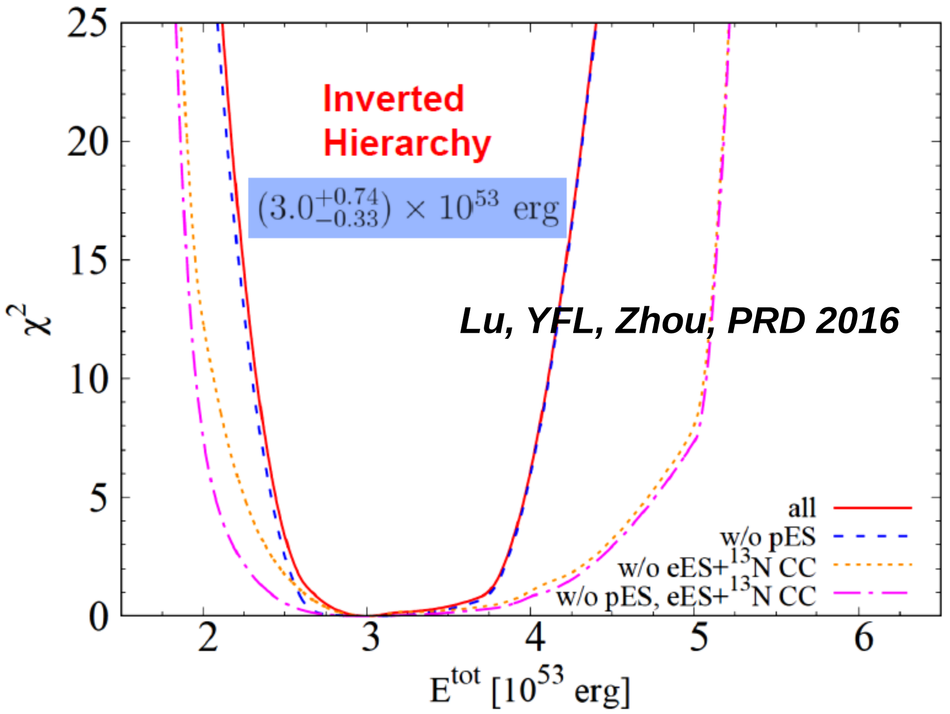
Total gravitational binding energy



Normal Hierarchy

$(3.0^{+0.42}_{-0.37}) \times 10^{53}$ erg

14% @ 1σ C.L.



Inverted Hierarchy

$(3.0^{+0.74}_{-0.33}) \times 10^{53}$ erg

Lu, YFL, Zhou, PRD 2016

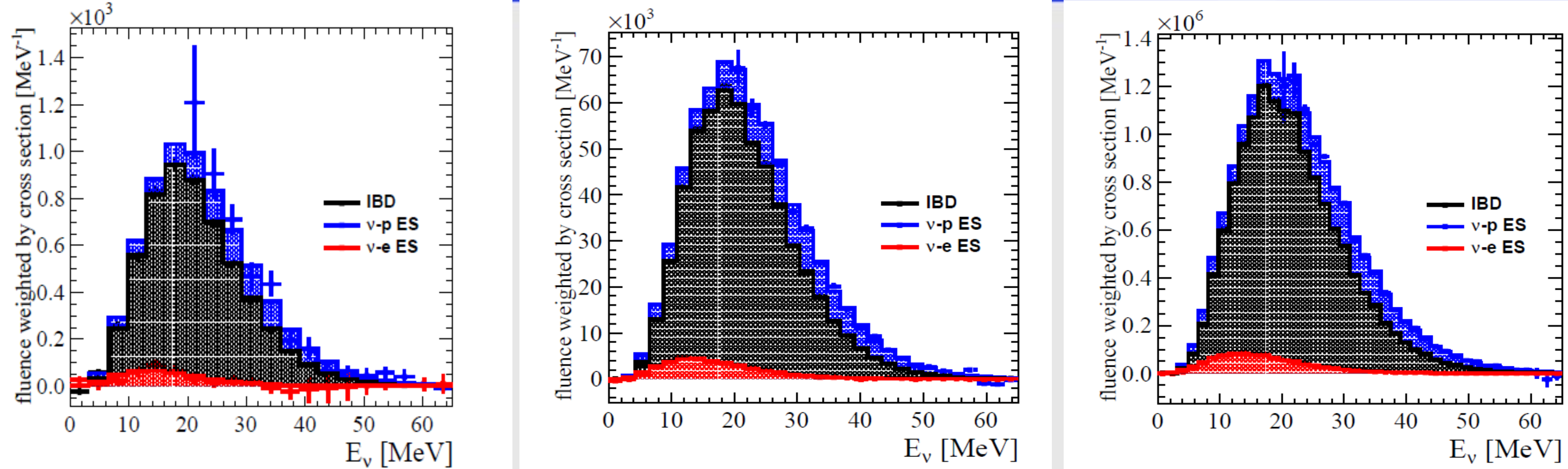
(1) Including only the MSW effects, and fixing the spectral indices at γ=3

(2)Conservatively assuming the uncertainties of 20% for the ν-p and ν-C cross sections (how large in the future?)

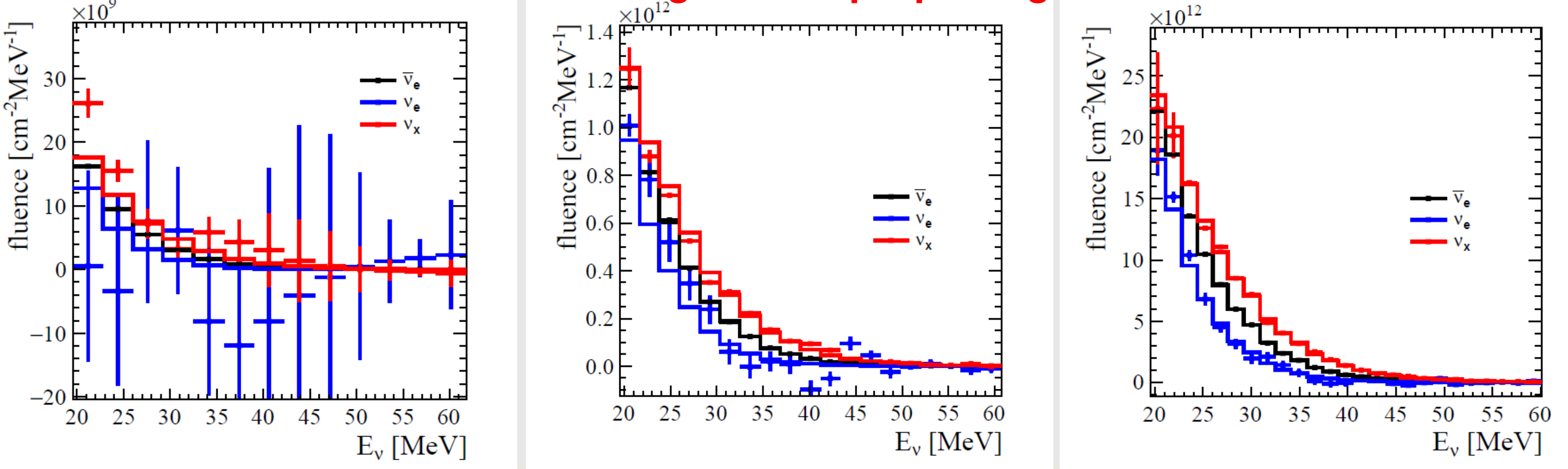
(3) Possible to relax the constraint on the spectral index (important for <E>, not for E_{tot}?). *See also 1708.00760 by Rosso, Vissani and Volpe for SuperKamiokande*

Reconstruction without parametrization

Li, YFL, Wen, Zhou, 17, to appear



One trial using SVD w. proper regularizations



Neutrino mass: time of flight measurements

Time delay:

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

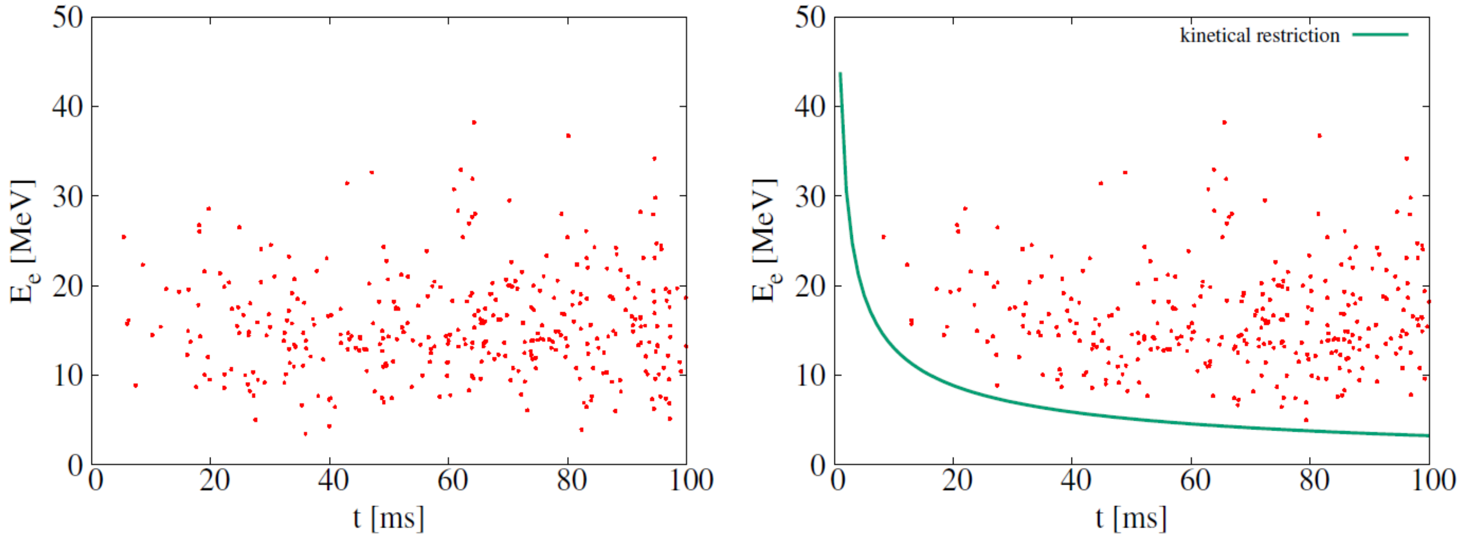


Figure: Example of time delay of SN neutrinos for a 10 kpc away SN. Left: $m_\nu = 0$. Right: $m_\nu = 2$ eV.

Method:

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

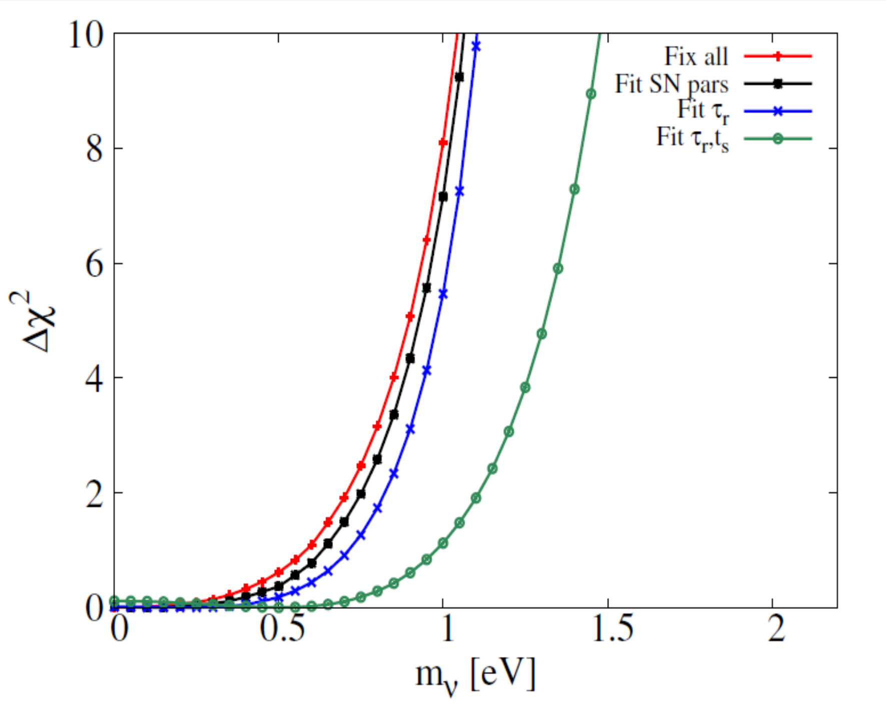
Statistical and Systematic uncertainties

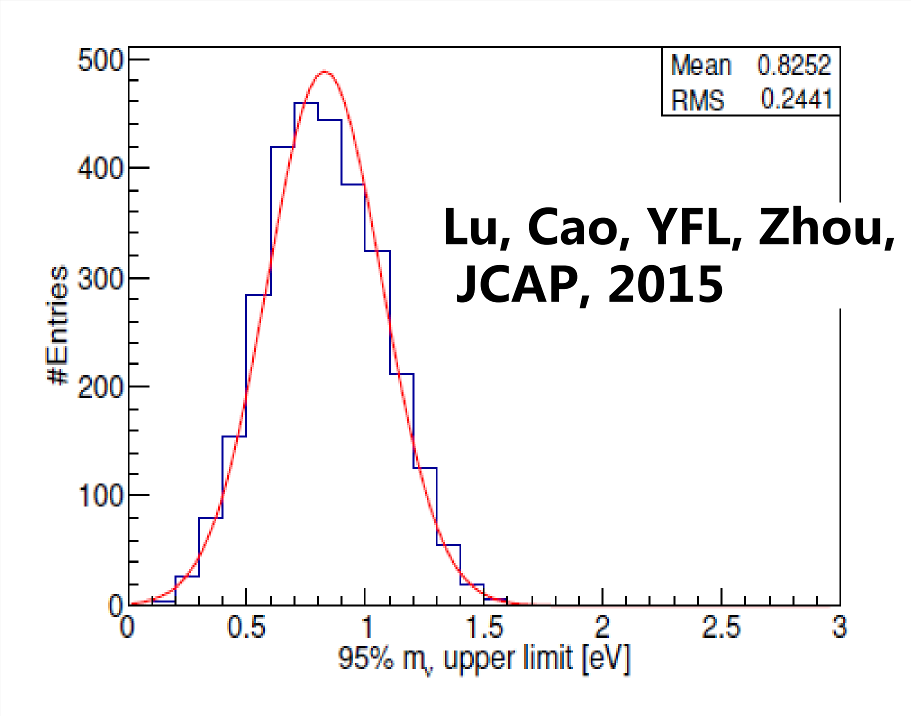
Using a parametrized model from SN1987A observation.

(parametrized model from 0810.0466)

(1) In one trial, to study the model parameter effects.

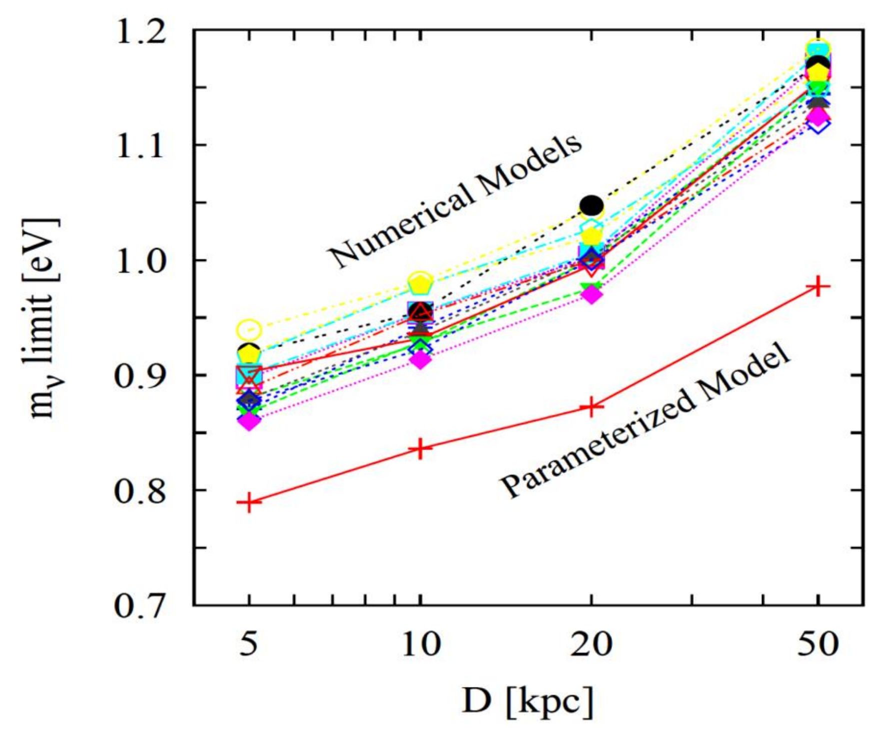
(2) With 3000 simulations, to show the fluctuation.

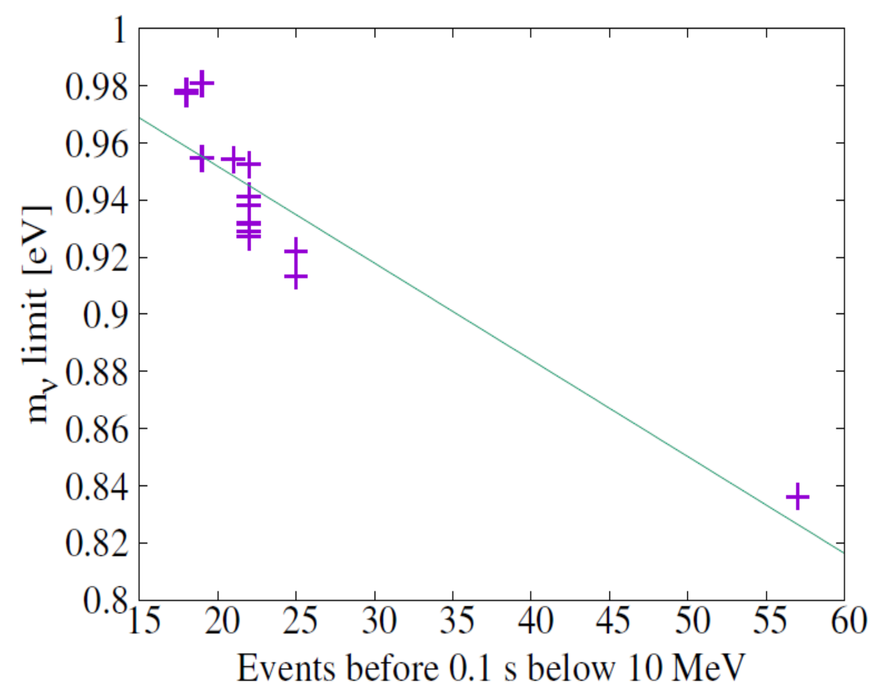




Lu, Cao, YFL, Zhou, JCAP, 2015

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.

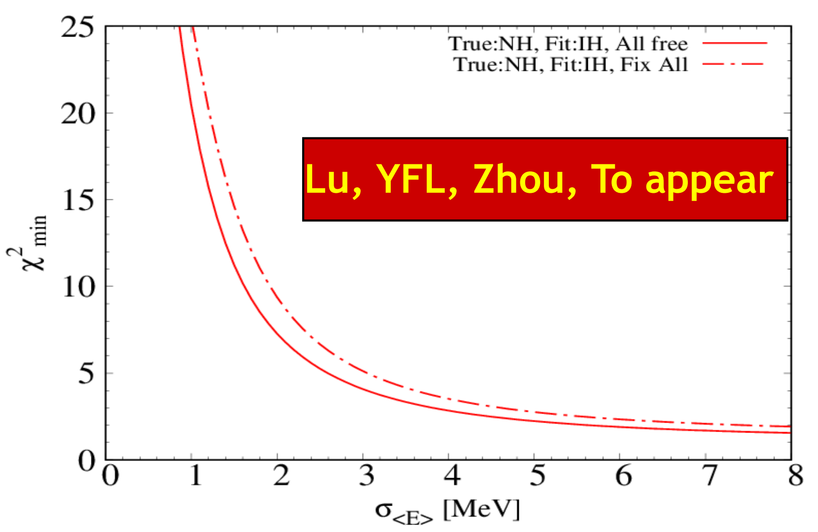
Mass ordering: MSW effects

Using the integrated energy spectrum

Using the facts of the average energy hierarchies:

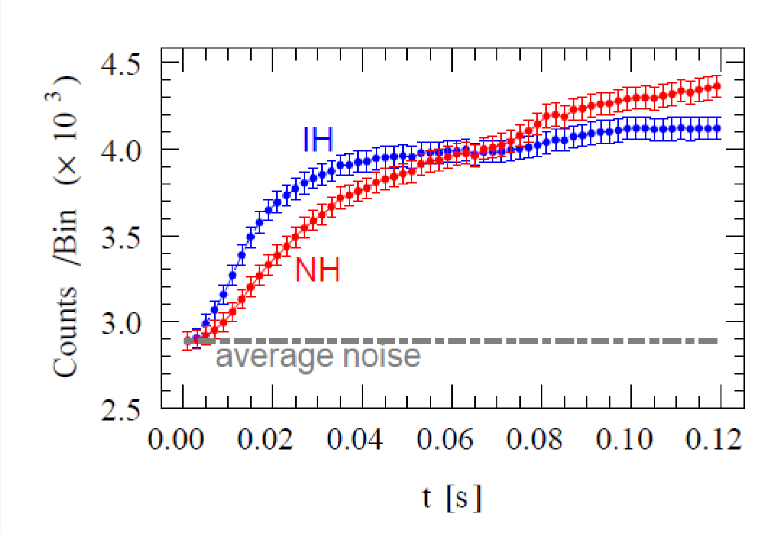
$$\langle E_{\nu_e}\rangle < \langle E_{\bar{\nu}_e}\rangle < \langle E_{\nu_x}\rangle$$

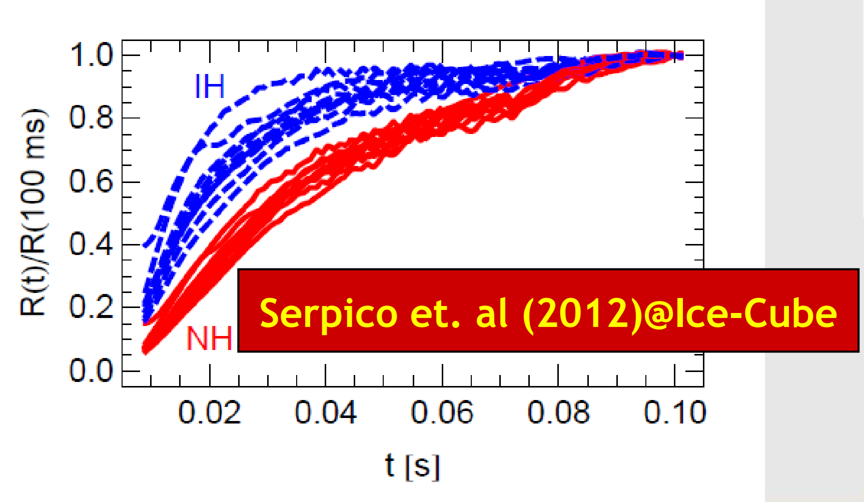
Taking the advantage of multi-flavor measurement in LS detectors (all six channels@JUNO)



Lu, YFL, Zhou, To appear

Using the time distribution





Serpico et. al (2012)@Ice-Cube

Concluding remarks

(a) Neutrinos from next nearby supernova cannot be missed (a once-in-a-lifetime opportunity!)

(b)10^4 neutrino events @ future LS detectors (JUNO) for a typical galactic SN; to reconstruct neutrino spectra, improve neutrino mass bound, probe neutrino mass ordering, etc.

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

the JUNO site@Jiangmen

Thank you

Backup

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 $(e^+ + n \to \bar{\nu}_e + p)$.
    - 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 $R(t, E_e)$.

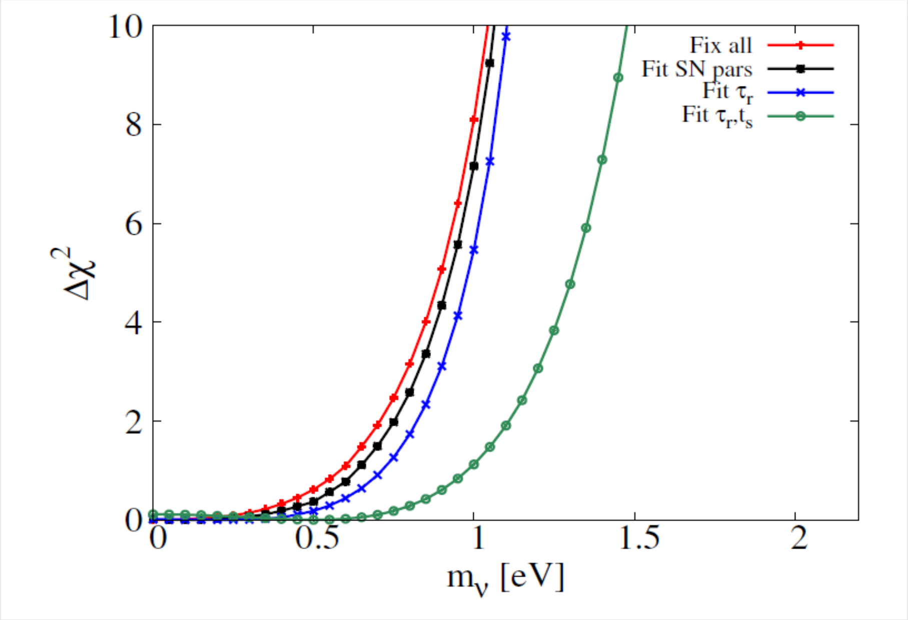
$$R(t, E_e) = N_p \Phi_{\overline{\nu}_e}(t, E_\nu) \sigma_{\rm IBD}(E_\nu) \eta(E_e)$$

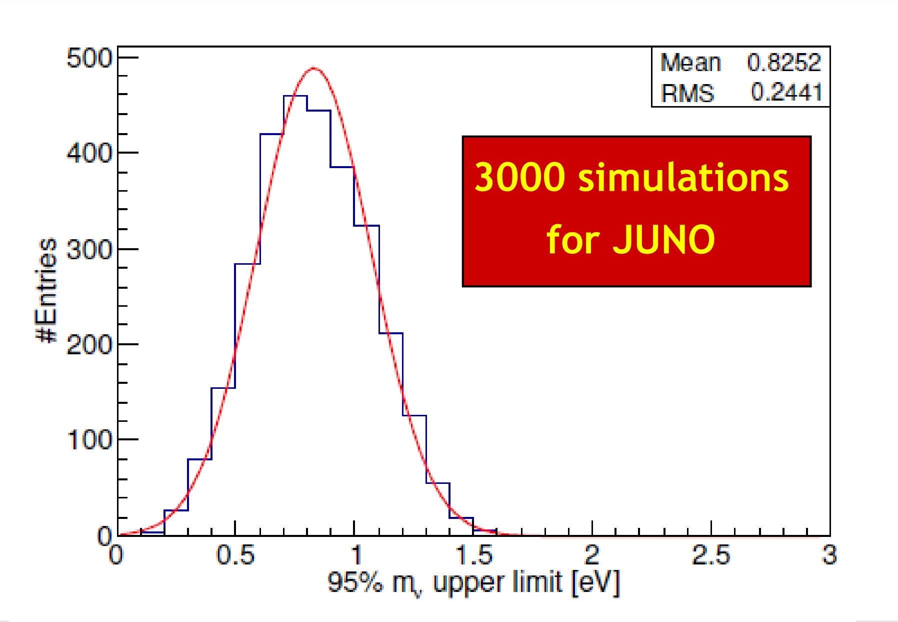
- We want to use the information of every event, so the likelihood function is written as

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

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

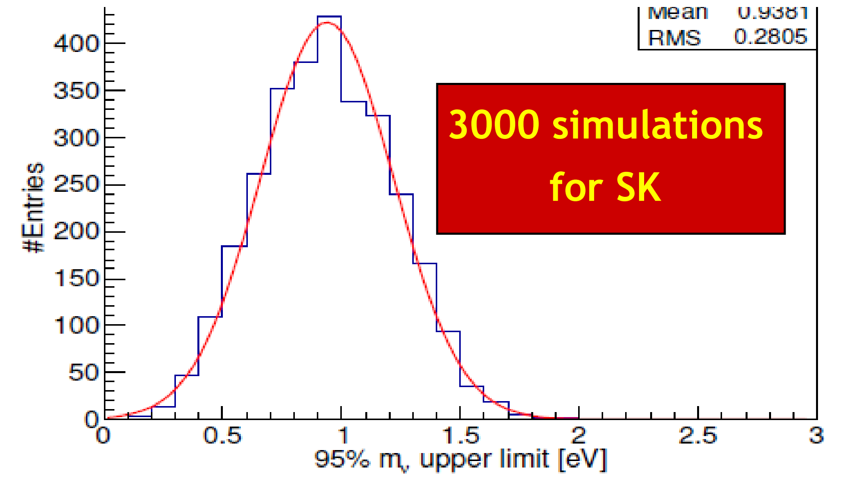
Statistical/Systematic uncertainties





3000 simulations for JUNO

Lu, Cao, Li, Zhou, JCAP, 2015



3000 simulations for SK

(1) Include the MSW effect for NH.

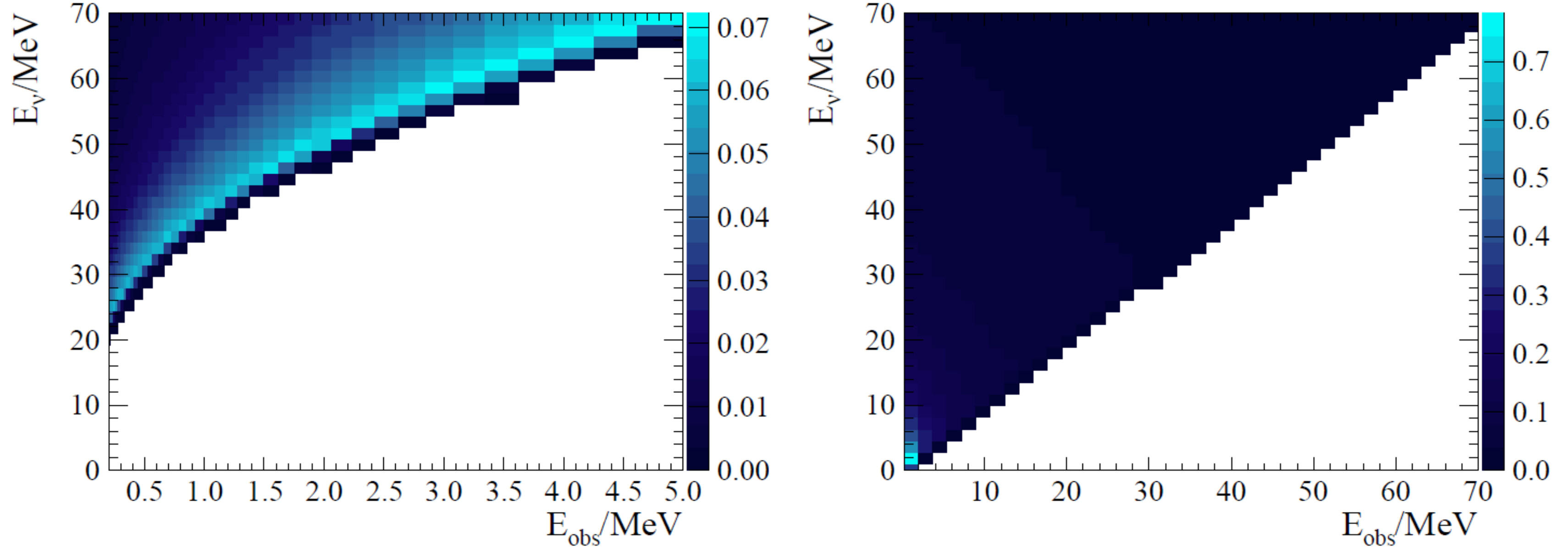
(2)Among different systematics, the starting time affects most.

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

Keil-Raffelt-Janka (KRJ) parametrization

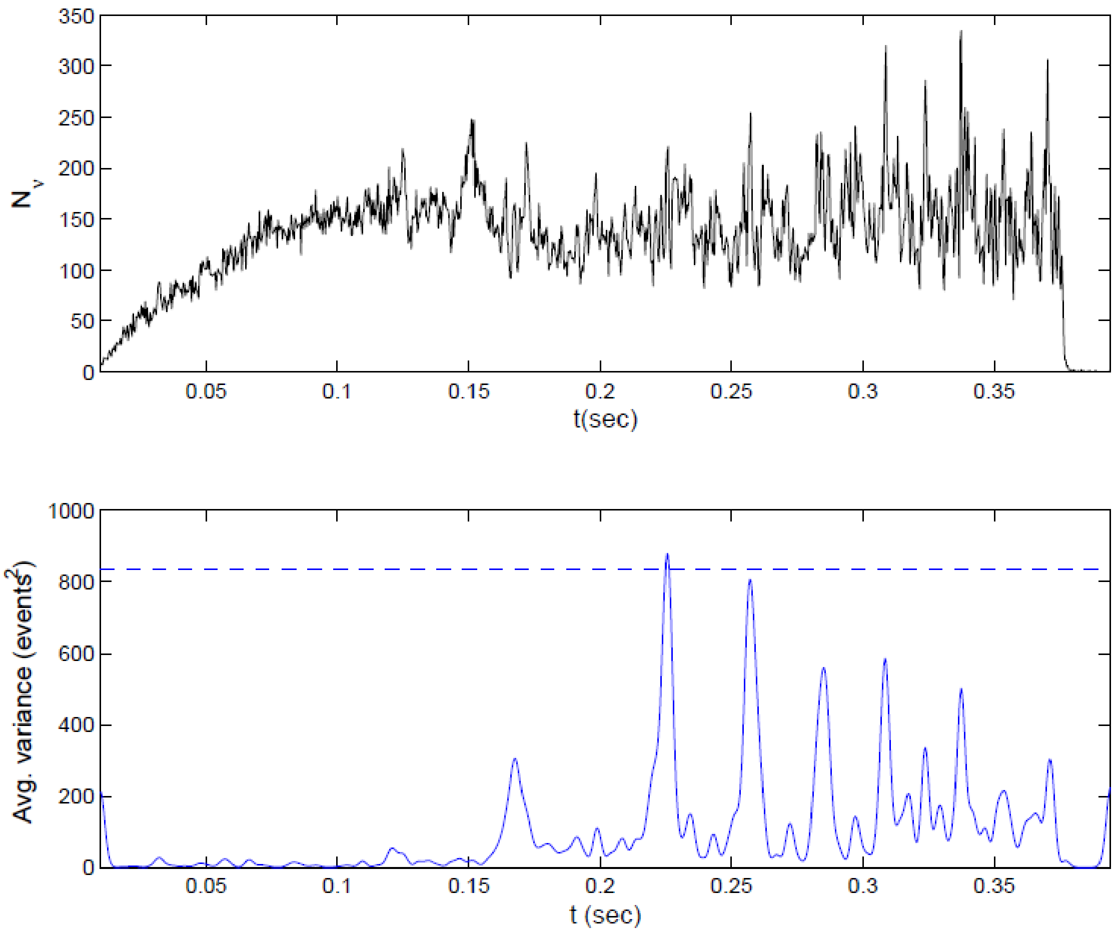
$$\frac{\mathrm{d}F_\alpha}{\mathrm{d}E_\alpha} = \frac{3.5\times 10^{13}}{\mathrm{cm}^2\ \mathrm{MeV}} \cdot \frac{1}{4\pi D^2}\frac{\varepsilon_\alpha}{\langle E_\alpha\rangle}\frac{E_\alpha^{\gamma_\alpha}}{\Gamma(1+\gamma_\alpha)}\left(\frac{1+\gamma_\alpha}{\langle E_\alpha\rangle}\right)^{1+\gamma_\alpha}\exp\left[-(1+\gamma_\alpha)\frac{E_\alpha}{\langle E_\alpha\rangle}\right],$$

Detector response for nu-p and nu-e channels



Fine-scale time structures in the wavelet analysis

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



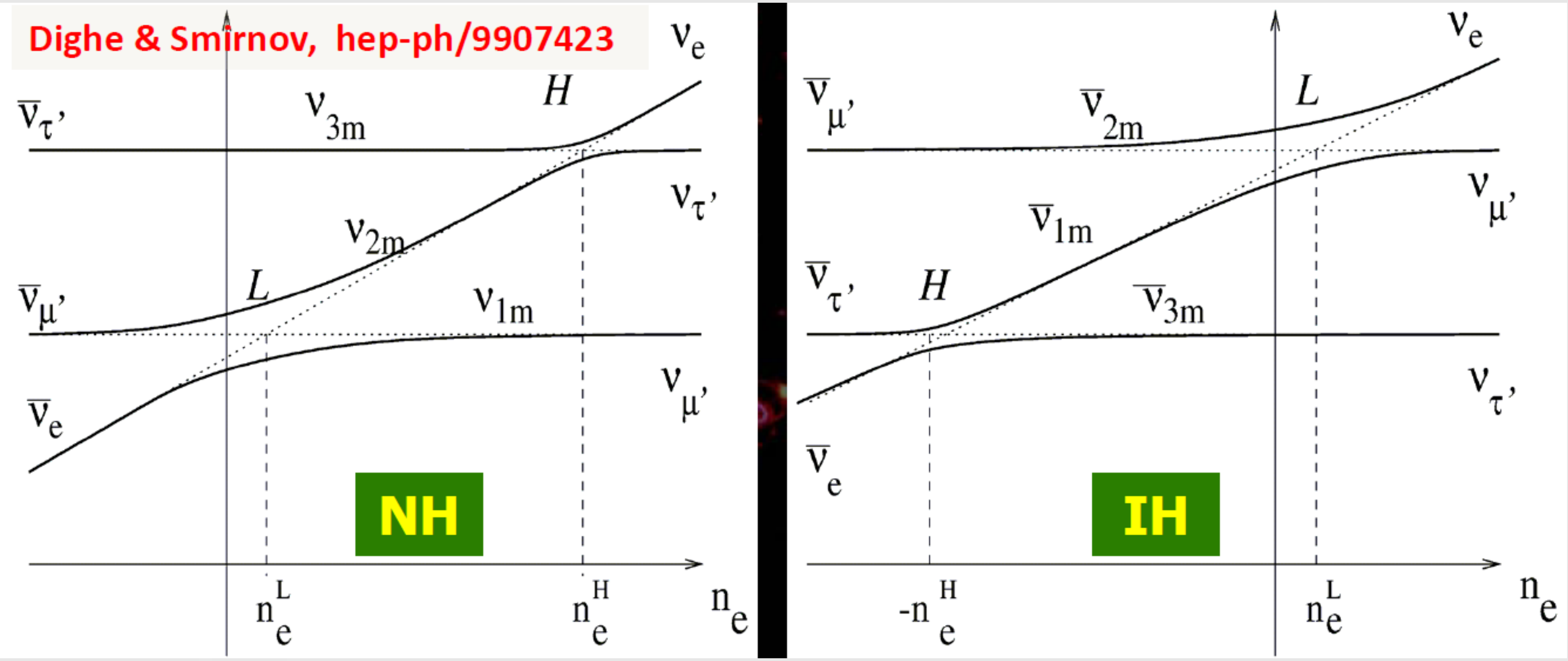
(1) Using the 2-d simulation data and the wavelet analysis technique

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

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

MSW effects: neutrino flavor conversion

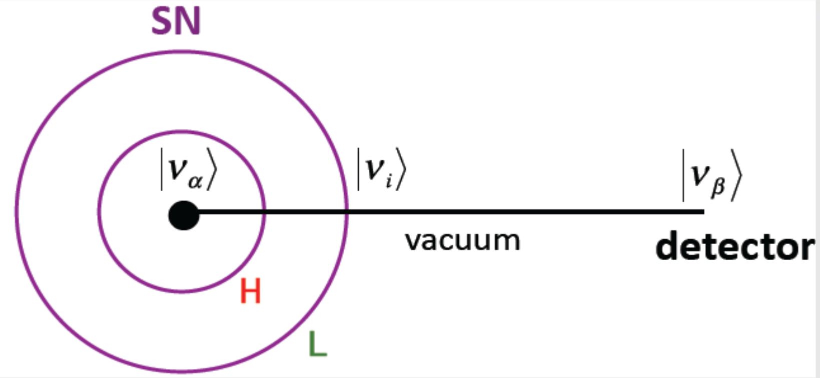
MSW effect: caused by changing matter density, not by "oscillation"


Dighe & Smirnov, hep-ph/9907423

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



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