Prospects for Supernova Neutrino Detection

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The 8th Workshop on Flavor Symmetries , TDLI (Shanghai) & USTC (Hefei)
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Neutrinos: Particle Physics and Astrophysics

Intrinsic Properties of Massive Neutrinos: Portal to NP beyond the SM

- Neutrino mass ordering
- Precision measurements
- Leptonic CP violation/CP phases
- Majorana vs. Dirac neutrinos

→

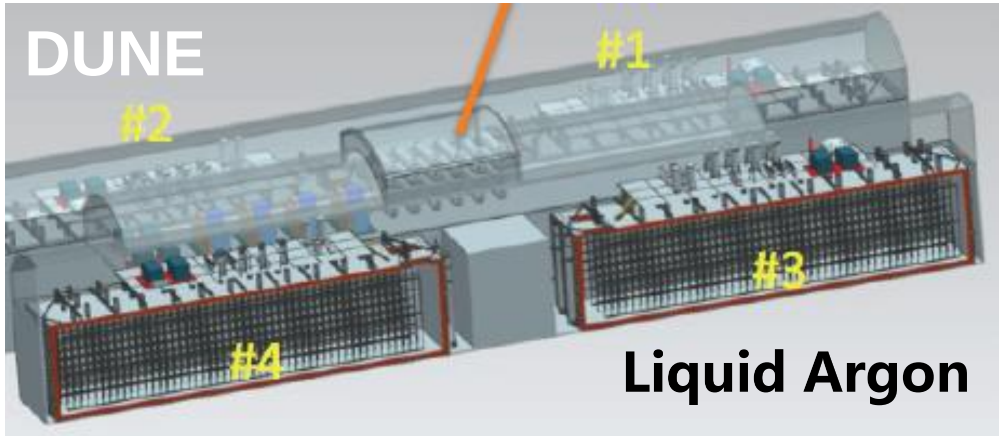
- Origin of neutrino masses
- Dynamics for flavor mixing
- Mechanism for CP violation

→

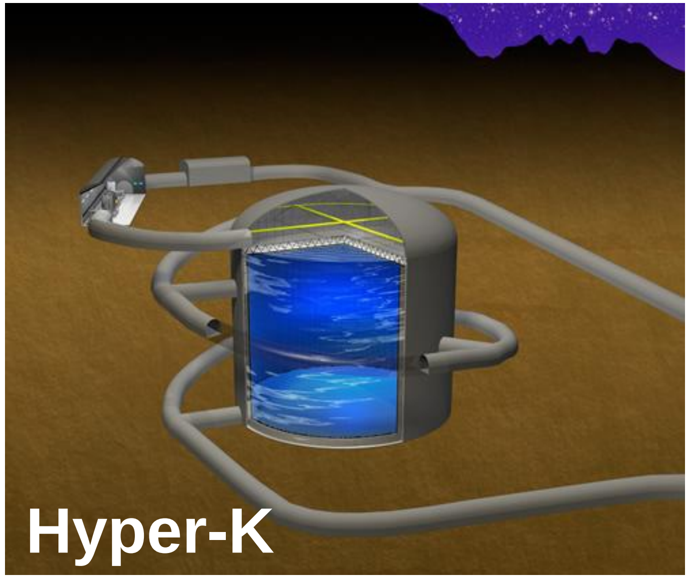
New Physics

Neutrinos as a Cosmic Messenger

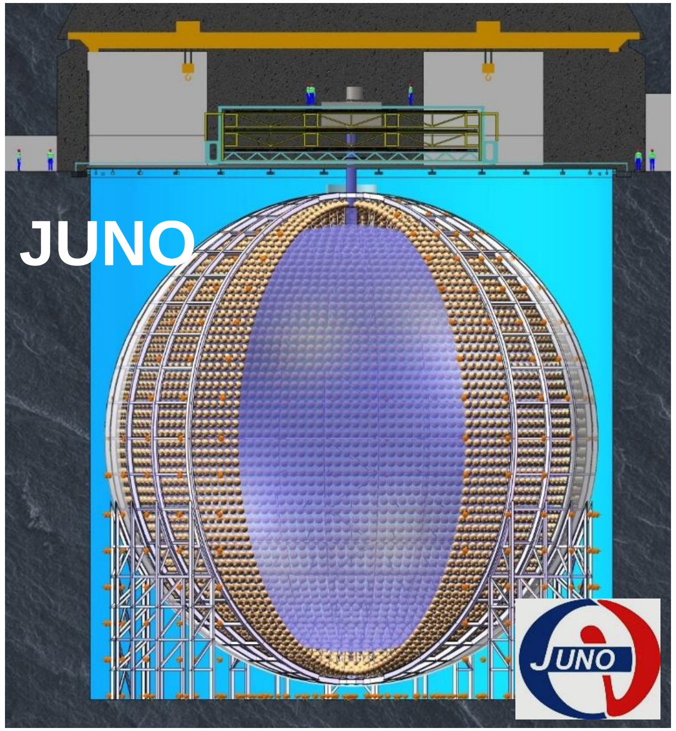
- Core-collapse supernovae
- Origin of high-energy cosmic rays
- Gamma rays & gravitational waves
- CνB & Matter-antimatter asymmetry



Water Cherenkov



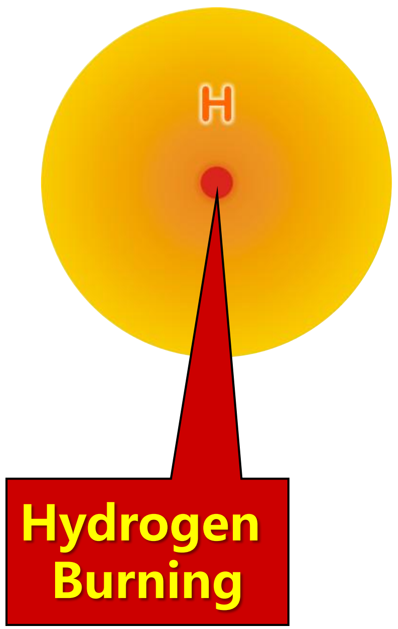
Liquid Scintillator



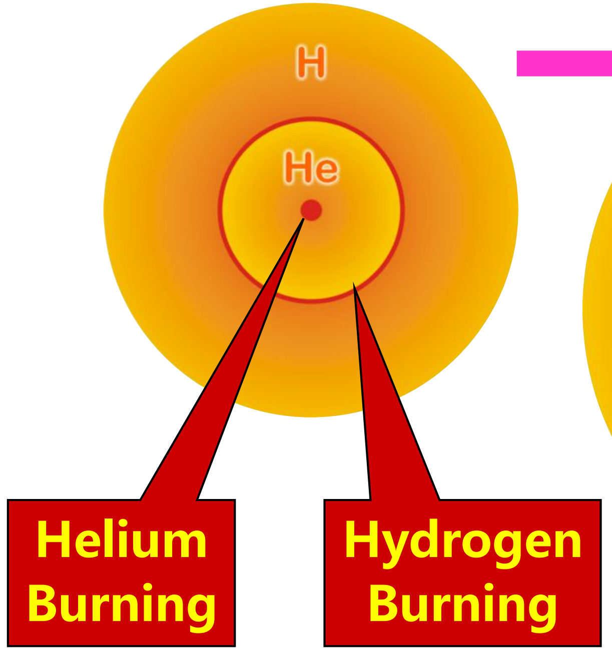
Multi-purpose Detectors

Part A: Neutrinos from Core-Collapse Supernovae

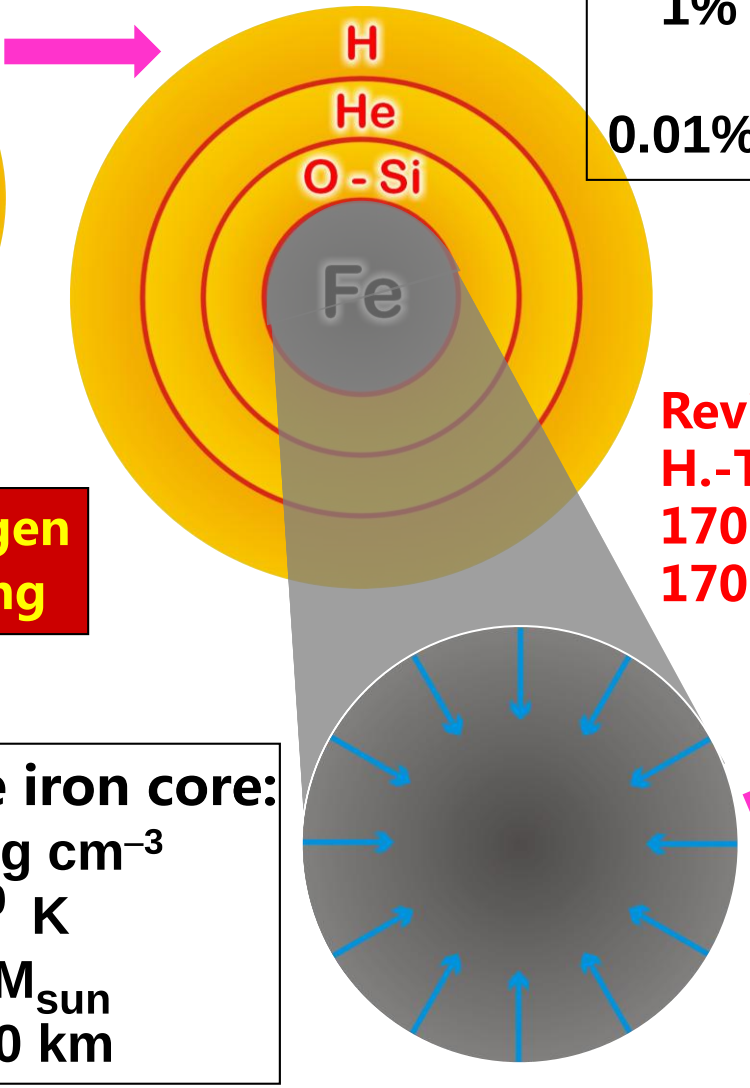
Main-sequence star



Helium-burning star



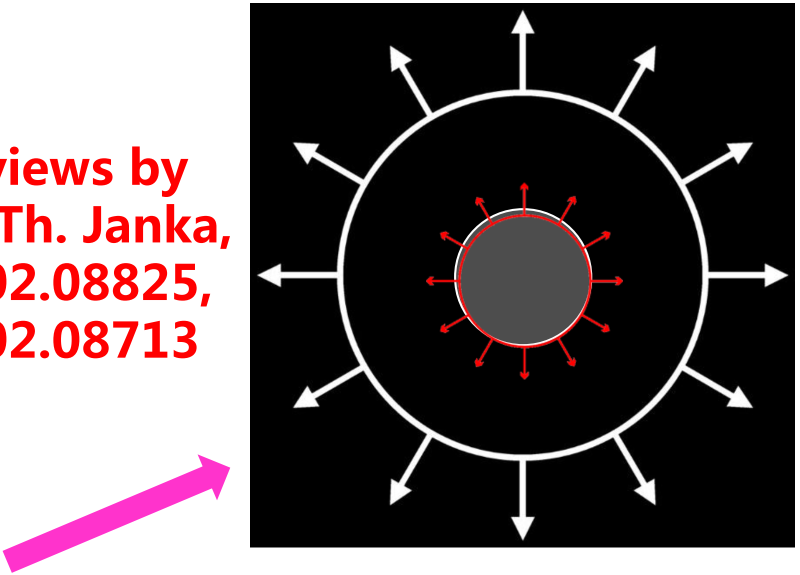
© G. Raffelt



Grav. binding energy $E_b \approx 3 \times 10^{53}$ erg

99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

Reviews by H.-Th. Janka, 1702.08825, 1702.08713



Proto-Neutron star:

$\rho \sim \rho_{\rm nuc} = 3 \times 10^{14}$ g cm^{-3}

$T \sim 30$ MeV

0. > 8 Solar Masses
1. Collapse⟶Bounce
2. Shock wave halted
3. ν energy deposited
4. Final SN explosion

Degenerate iron core:

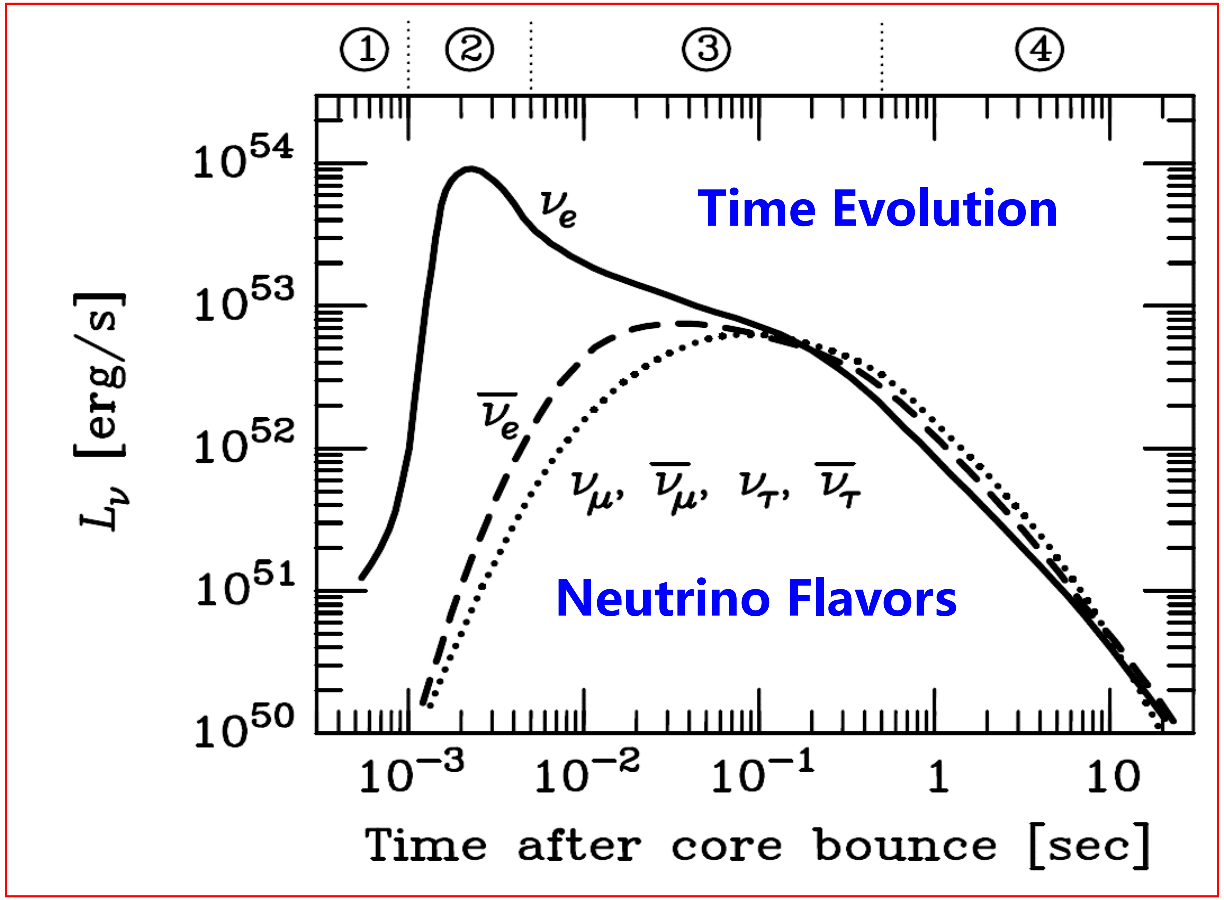
$\rho \approx 10^{9}$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{\rm Fe} \approx 1.5\ M_{\rm sun}$

$R_{\rm Fe} \approx 8000$ km

Part A: Neutrinos from Core-Collapse Supernovae

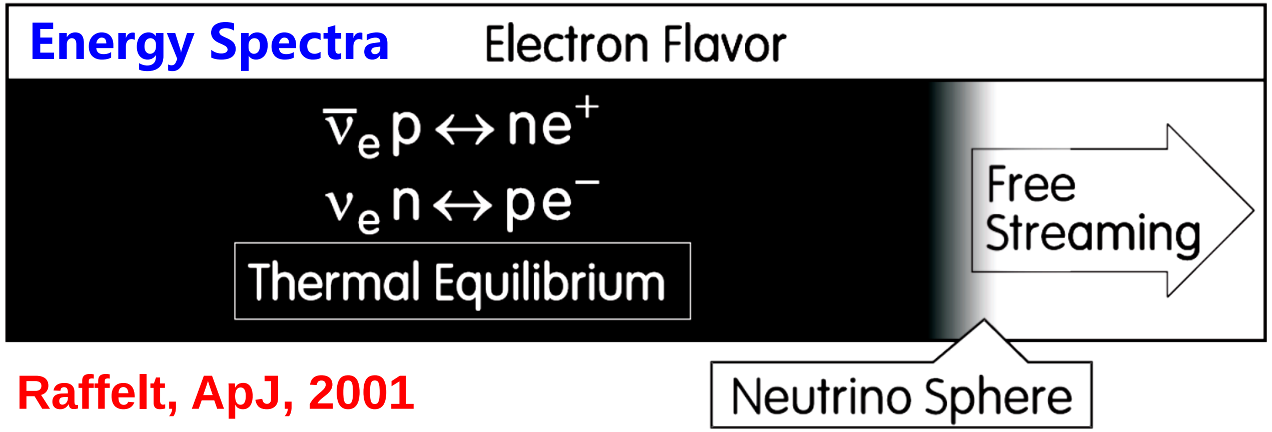


① **Collapse:** ν_e production via $e^- + p \longrightarrow \nu_e + n$

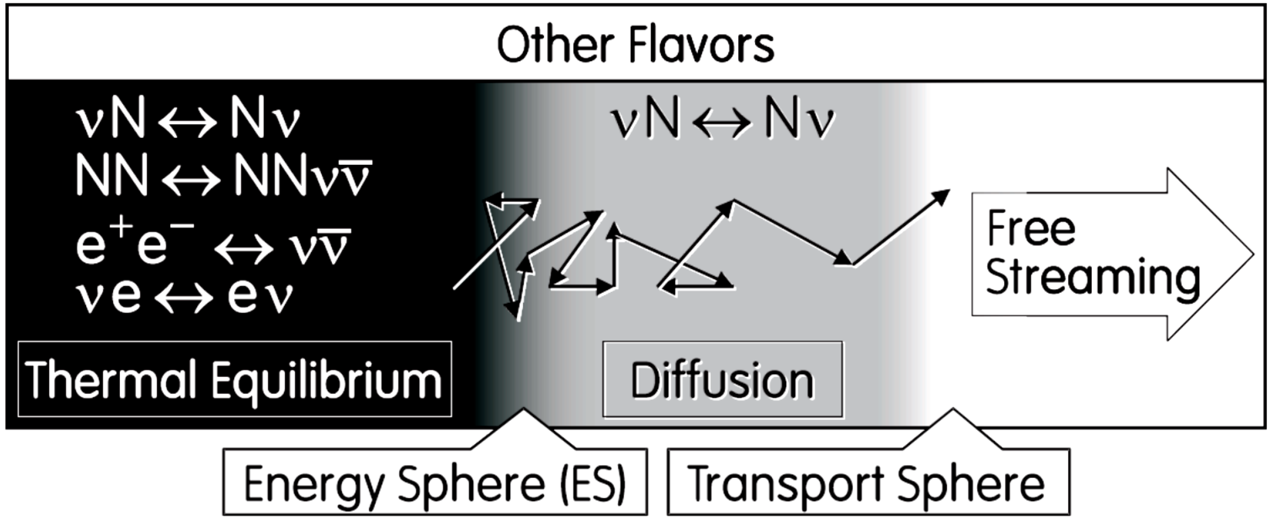
② **Neutronization ν_e burst:**
disintegration of heavy nuclei, capture on free p's, shock passing through ν-sphere

③ **Accretion:** reduction of $\mu_{\nu_e} \longrightarrow$ neutrino pairs

④ **Cooling:** (anti)neutrinos of three flavors



Raffelt, ApJ, 2001



- **Neutrinos are close to thermal equilibrium**
- **Different flavors decouple at different radii**
- **SN neutrino fluxes are time dependent**
- **Keil-Raffelt-Janka (2003):** $F(E) \propto E^{\alpha}\, e^{-(\alpha+1)E/\overline{E}}$

Part A: Neutrinos from Core-Collapse Supernovae

Parametrizations of Neutrino Spectra

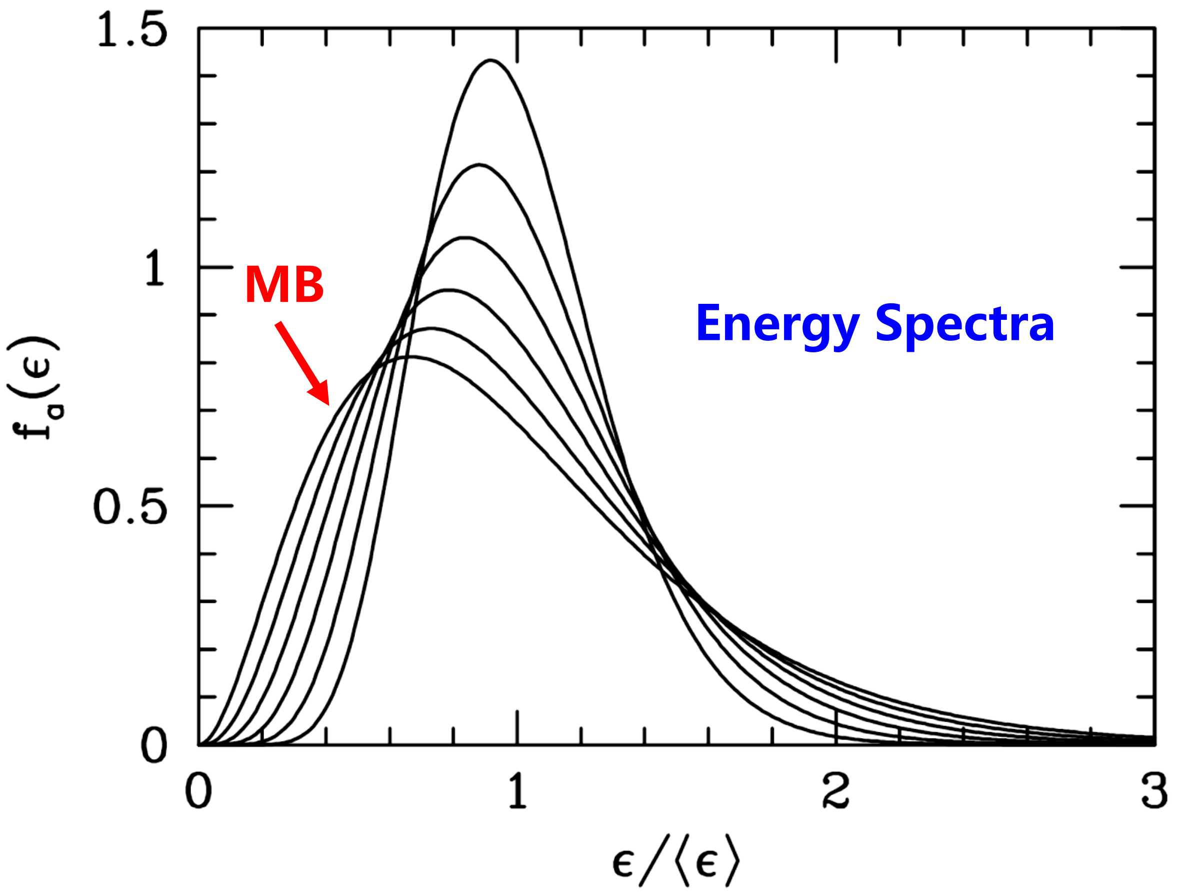
Keil, Raffelt & Janka, astro-ph/0208035

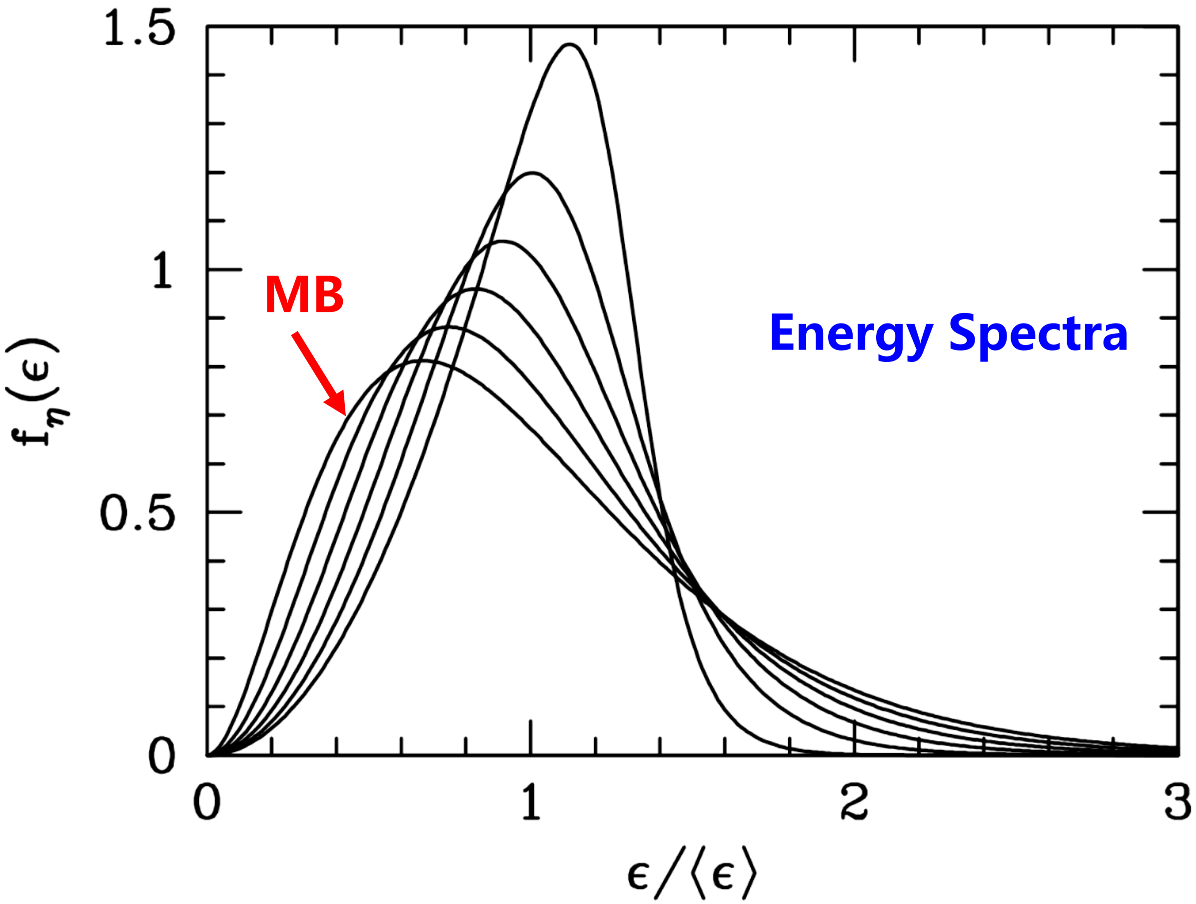
Modified Maxwell-Boltzmann Distribution

$$f_\alpha(\epsilon) = \left(\frac{\epsilon}{\bar{\epsilon}}\right)^\alpha \mathrm{e}^{-(\alpha+1)\epsilon/\bar{\epsilon}}$$

Fermi-Dirac Distribution

$$f_\eta(\epsilon) = \frac{\epsilon^2}{1+\exp\left(\frac{\epsilon}{T}-\eta\right)}$$



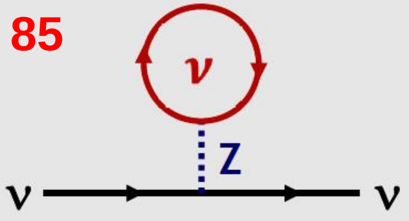


Part A: Neutrinos from Core-Collapse Supernovae

Flavor Conversions of Supernova Neutrinos

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Wolfenstein, 78
Mikheyev & Smirnov, 85
Pantaleone, 92



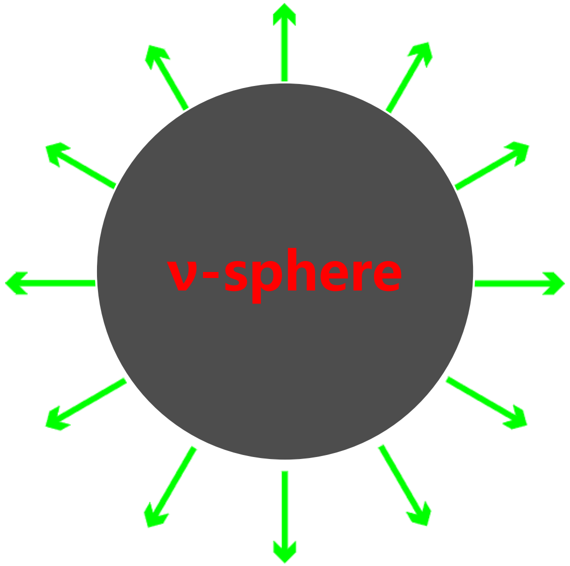
Effective mixing Hamiltonian

$$H = \frac{M^2}{2E} + \sqrt{2}G_F\begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2}\end{pmatrix} + \sqrt{2}G_F\begin{pmatrix} N_{\nu_e} & N_{\langle\nu_e|\nu_\mu\rangle} \\ N_{\langle\nu_\mu|\nu_e\rangle} & N_{\nu_\mu}\end{pmatrix}$$

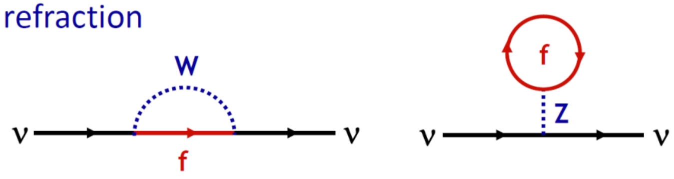
Mass Term | **MSW Effects** | **Collective Oscillations**

Extremely dense matter

- ☐ Frequent interactions
- ☐ No flavor conversion



Neutrinos in a medium suffer flavor-dependent refraction



$$V_{\mathrm{weak}} = \sqrt{2}G_F \times \begin{cases} N_e - N_n/2 & \text{for } \nu_e \\ -N_n/2 & \text{for } \nu_\mu \end{cases}$$

Typical density of Earth: 5 g/cm^3

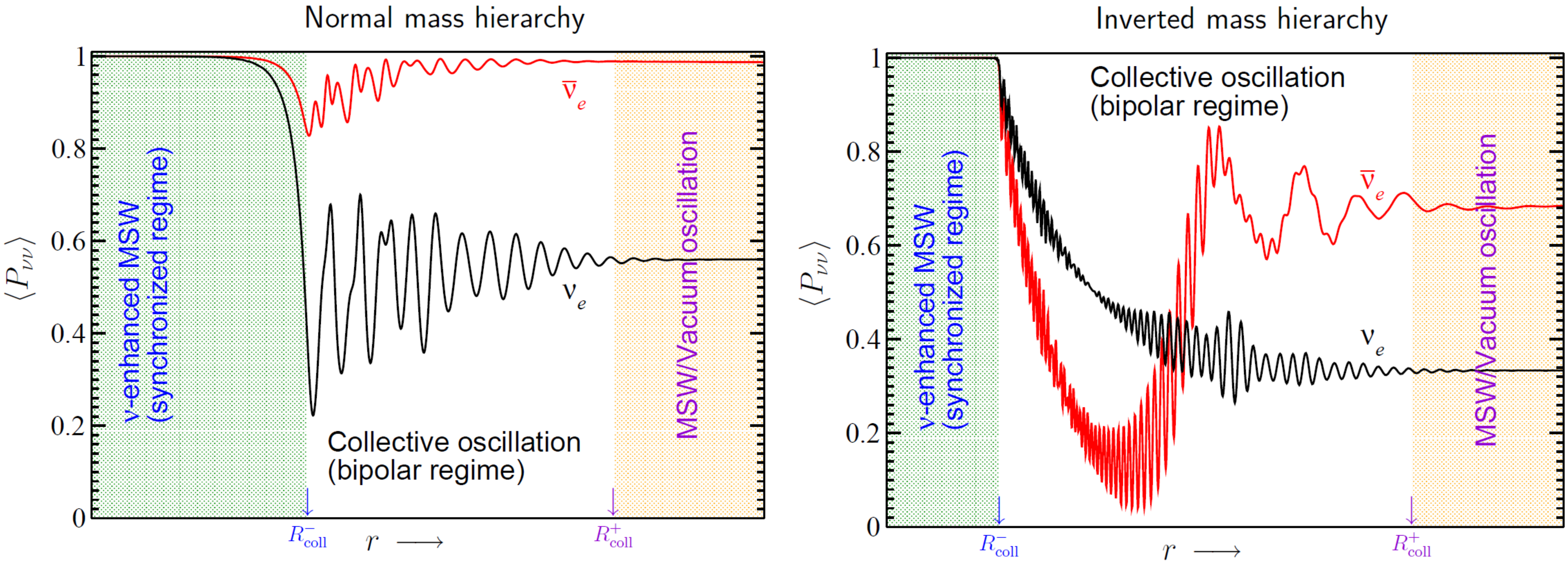
$$\Delta V_{\mathrm{weak}} \approx 2 \times 10^{-13}\ \mathrm{eV} = 0.2\ \mathrm{peV}$$

Picture of SN neutrino flavor conversions

- No flavor changes within ν-sphere (???)
- Above ν-sphere: slow collective oscillations
- In the envelope: the MSW matter effects

Part A: Neutrinos from Core-Collapse Supernovae

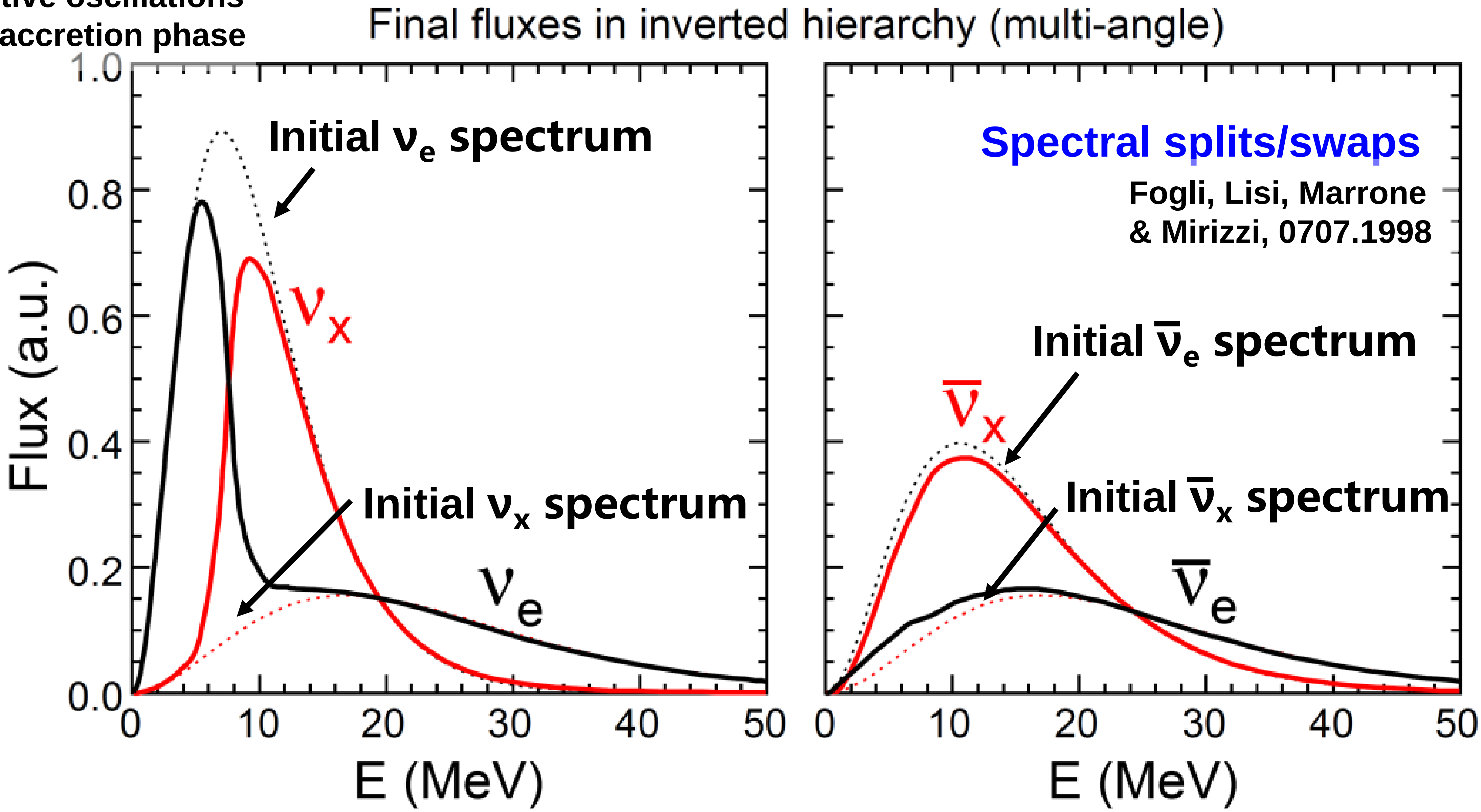
Seminal works: Duan, Fuller & Qian, astro-ph/0511275; Duan, Fuller, Carlson & Qian, astro-ph/0606616



Recent reviews on collective neutrino oscillations: Duan, Fuller & Qian, 1011.2799; Mirizzi et al., 1508.00785; Chakraborty, Hansen, Izaguirre & Raffelt, 1602.0276

Part A: Neutrinos from Core-Collapse Supernovae

Collective oscillations in the accretion phase

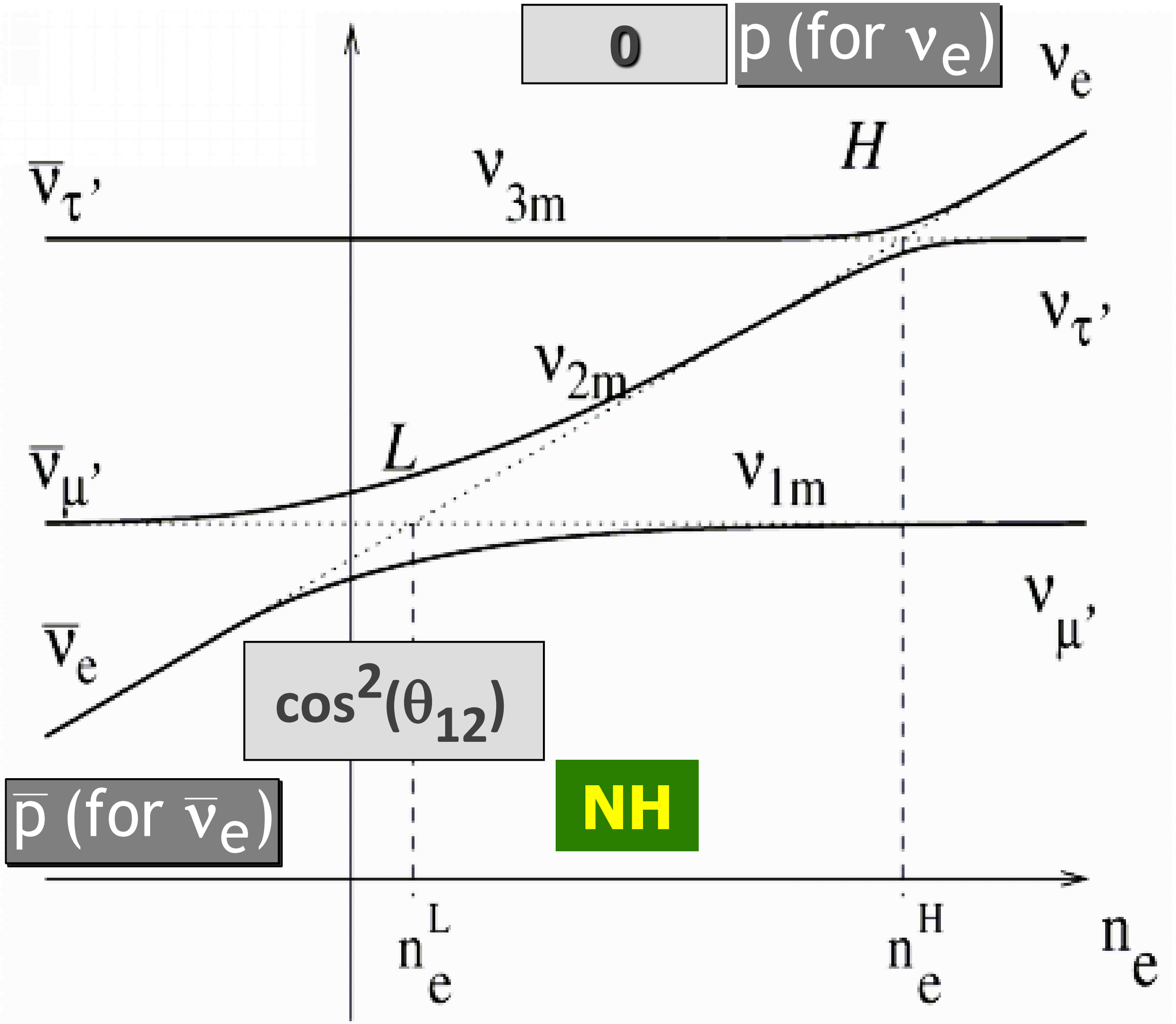


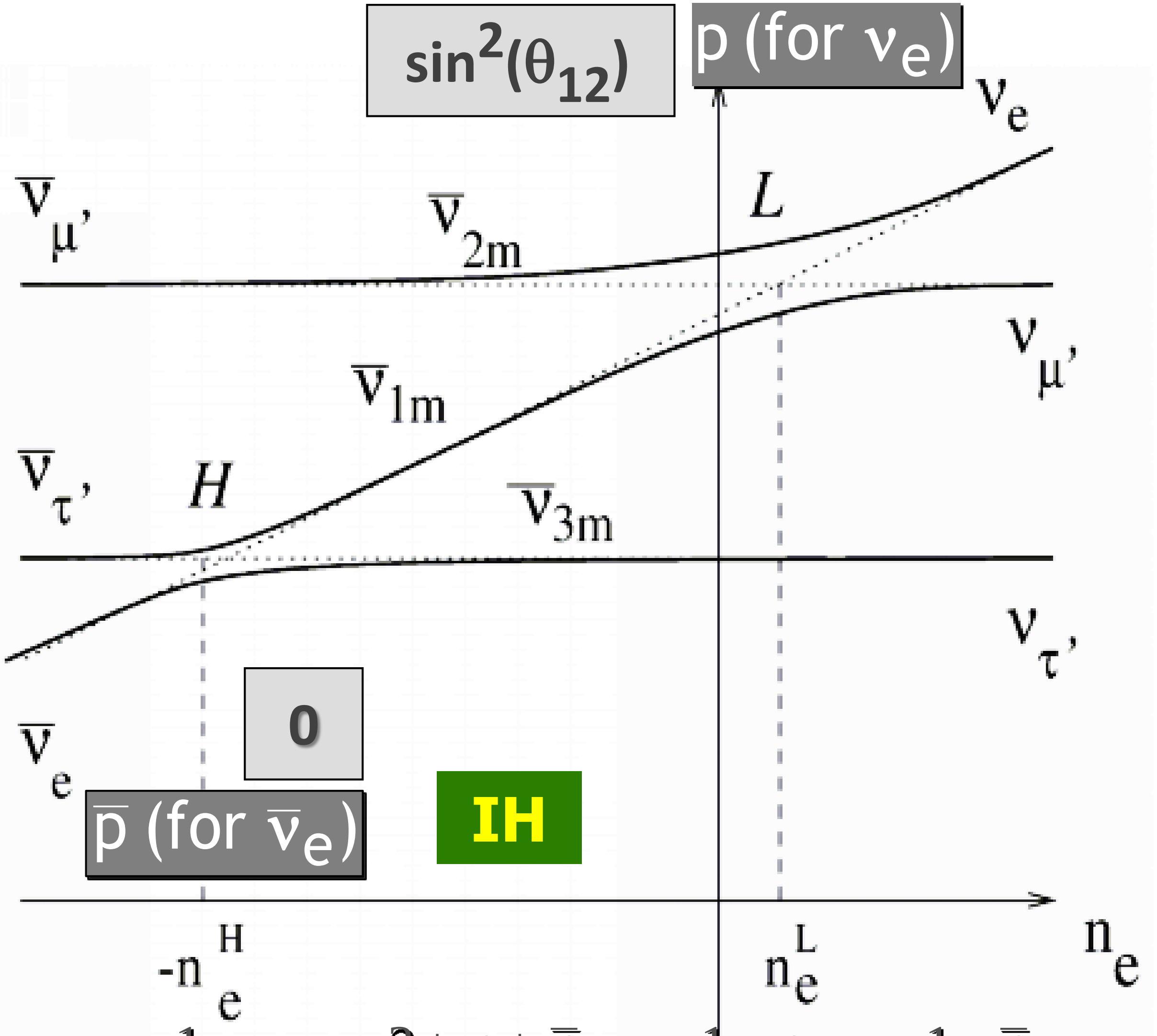
Fogli, Lisi, Marrone & Mirizzi, 0707.1998

Part A: Neutrinos from Core-Collapse Supernovae

MSW matter effects on neutrino flavor conversions

Dighe & Smirnov, hep-ph/9907423



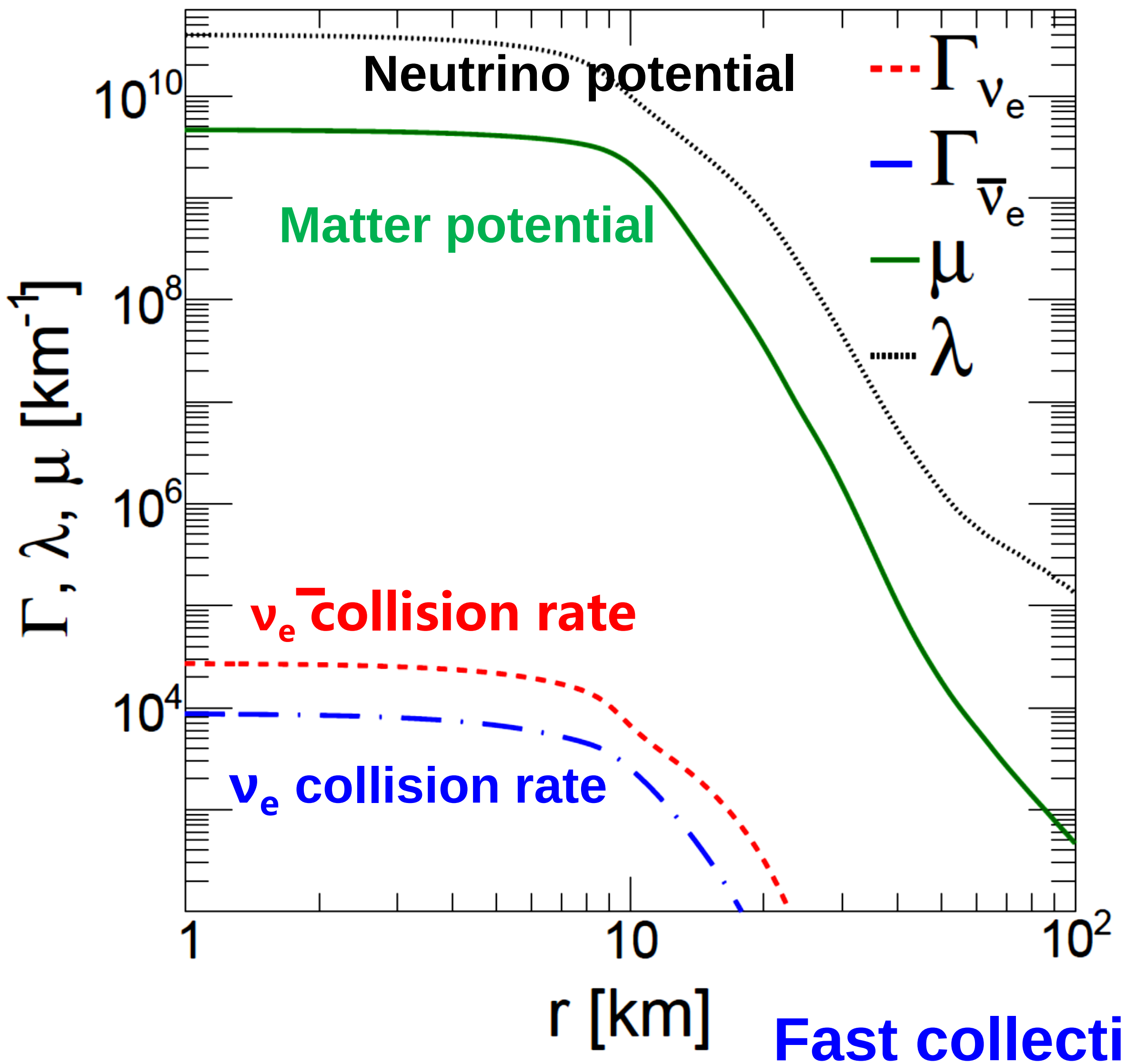


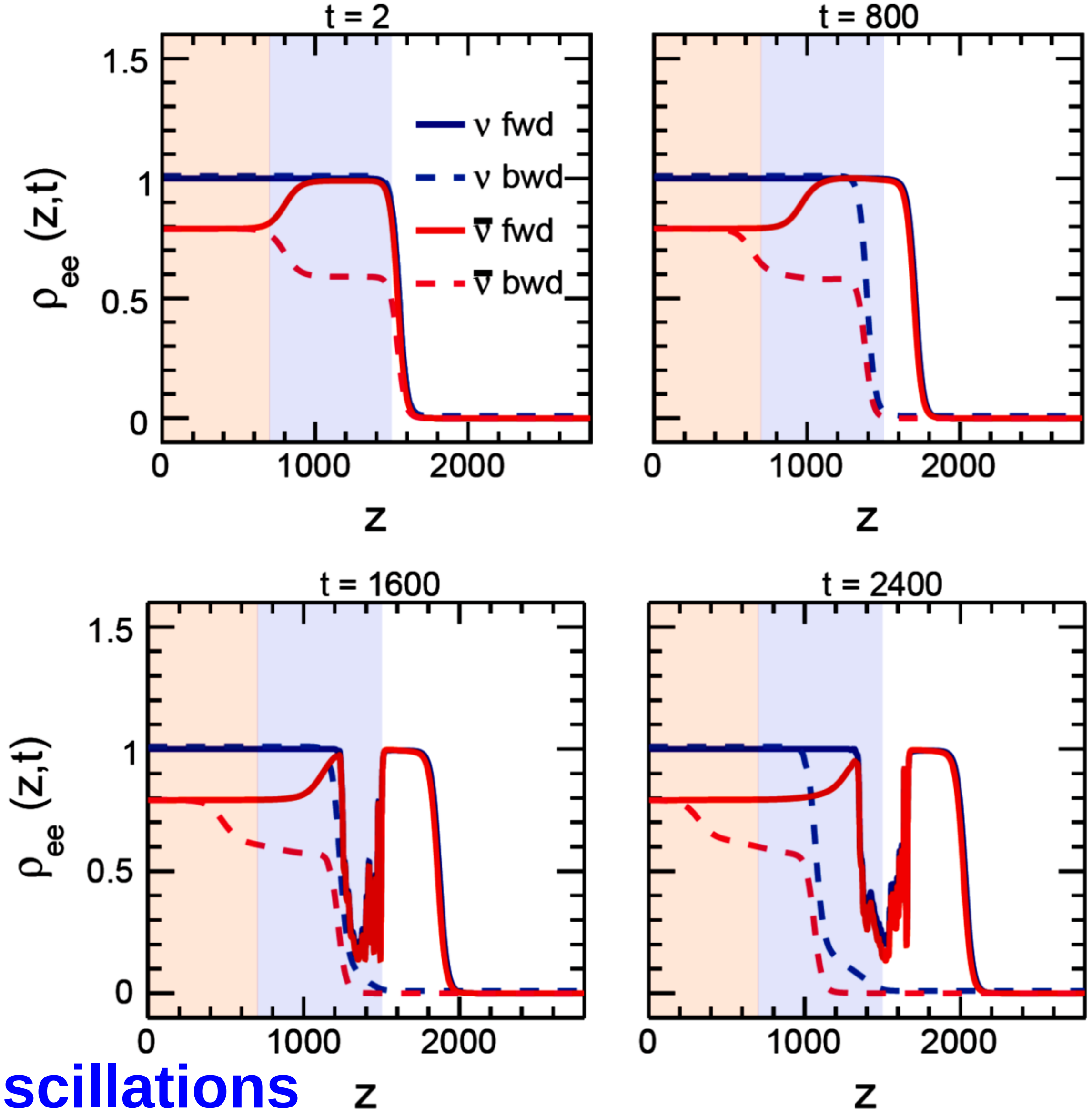
$F_e = p F_e^0 + (1-p) F_x^0$ $\quad$ $F_{\bar e} = \bar p F_{\bar e}^0 + (1-\bar p) F_x^0$

$$\frac{1}{4}\sum F_x = \frac{2+p+\bar p}{4} F_x^0 + \frac{1-p}{4} F_e^0 + \frac{1-\bar p}{4} F_{\bar e}^0$$

Part A: Neutrinos from Core-Collapse Supernovae

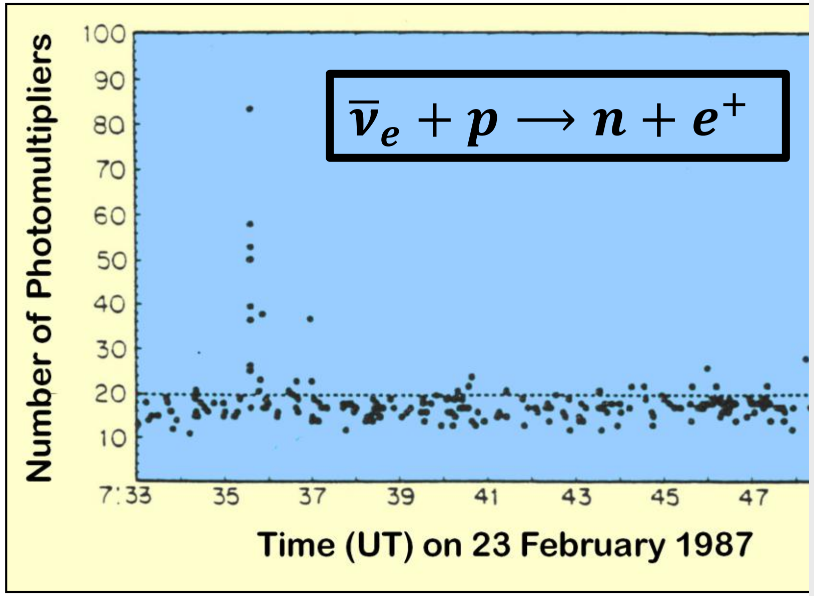
Tamborra *et al.*,1702.00060 (11 solar masses) **Flavor equilibrium??** **Capozzi *et al.*, 1808.06618**



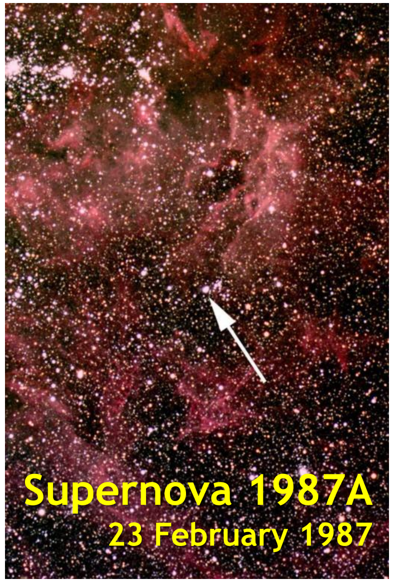


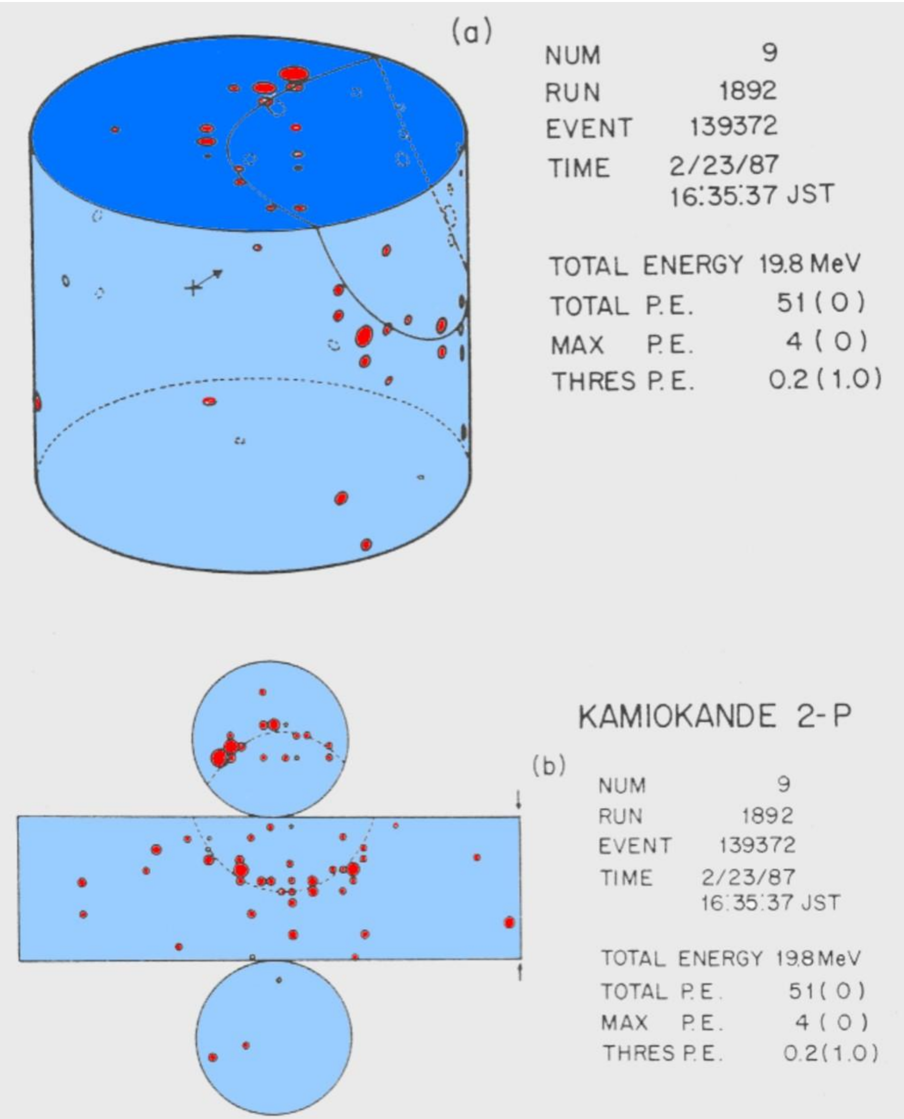
Fast collective oscillations

Part B: Detection of Supernova Neutrinos - SN 1987A



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

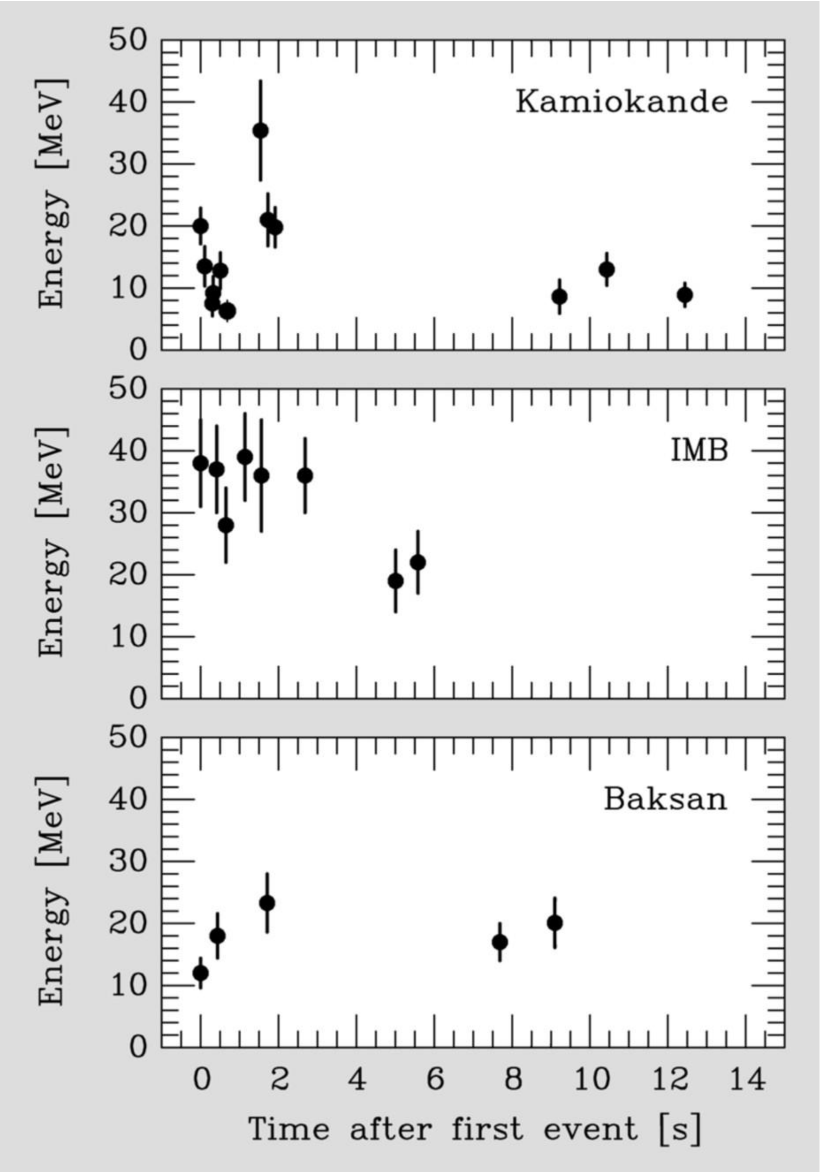

Supernova 1987A
23 February 1987



NUM 9
RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51 (0)
MAX P.E. 4 (0)
THRES P.E. 0.2 (1.0)

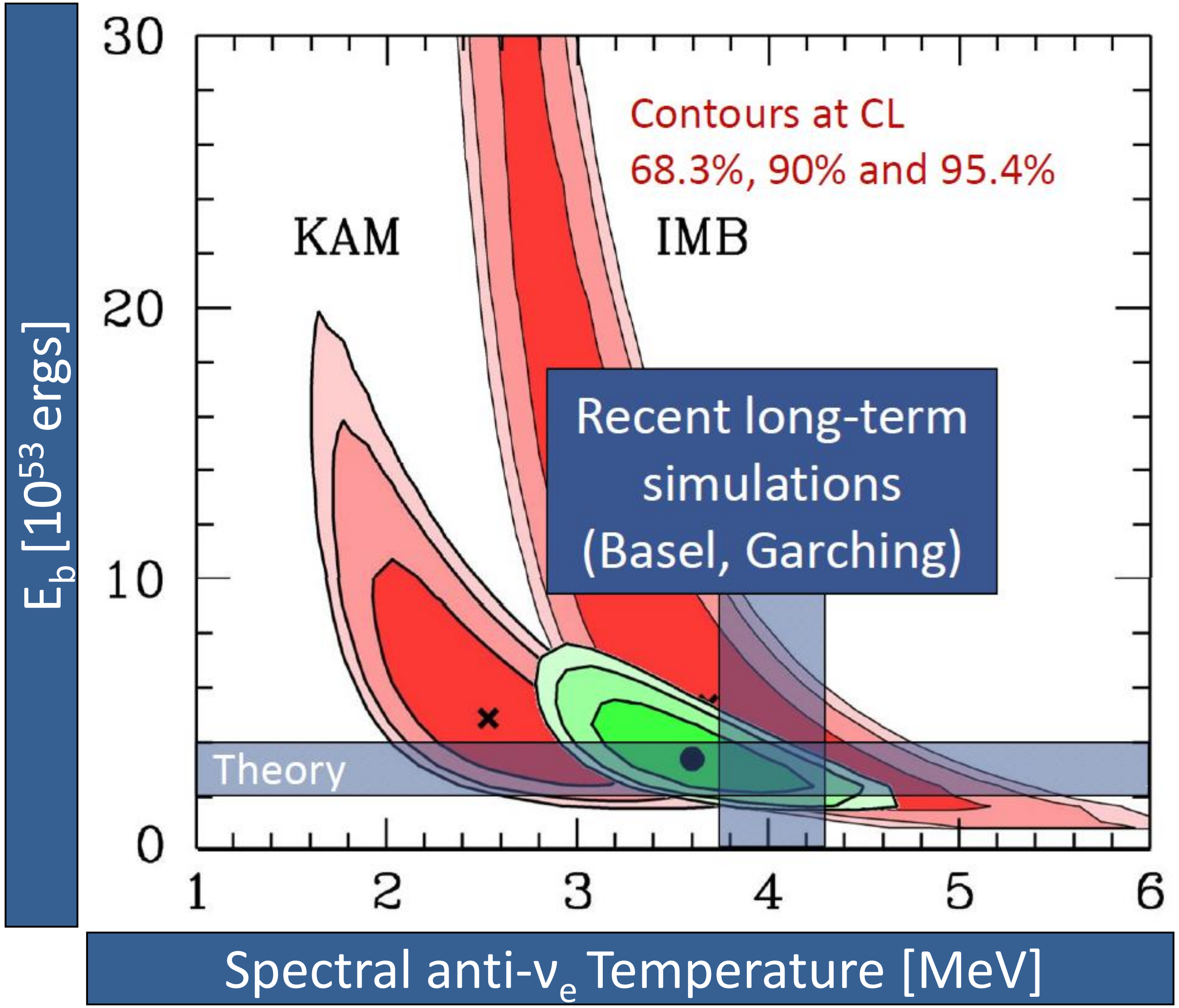
Hirata et al., PRD 38 (1988) 448



SN 1987A: Hirata et al., PRL 58 (1987) 1490; Bionta et al., PRL 58 (1987) 1494; Alekseev et al., PLB 205 (1988) 209

Part B: Detection of Supernova Neutrinos - SN 1987A

Jegerlehner, Neubig & Raffelt, astro-ph/9601111



Assumptions:

☐ Thermal neutrino spectra
☐ Energy equipartition

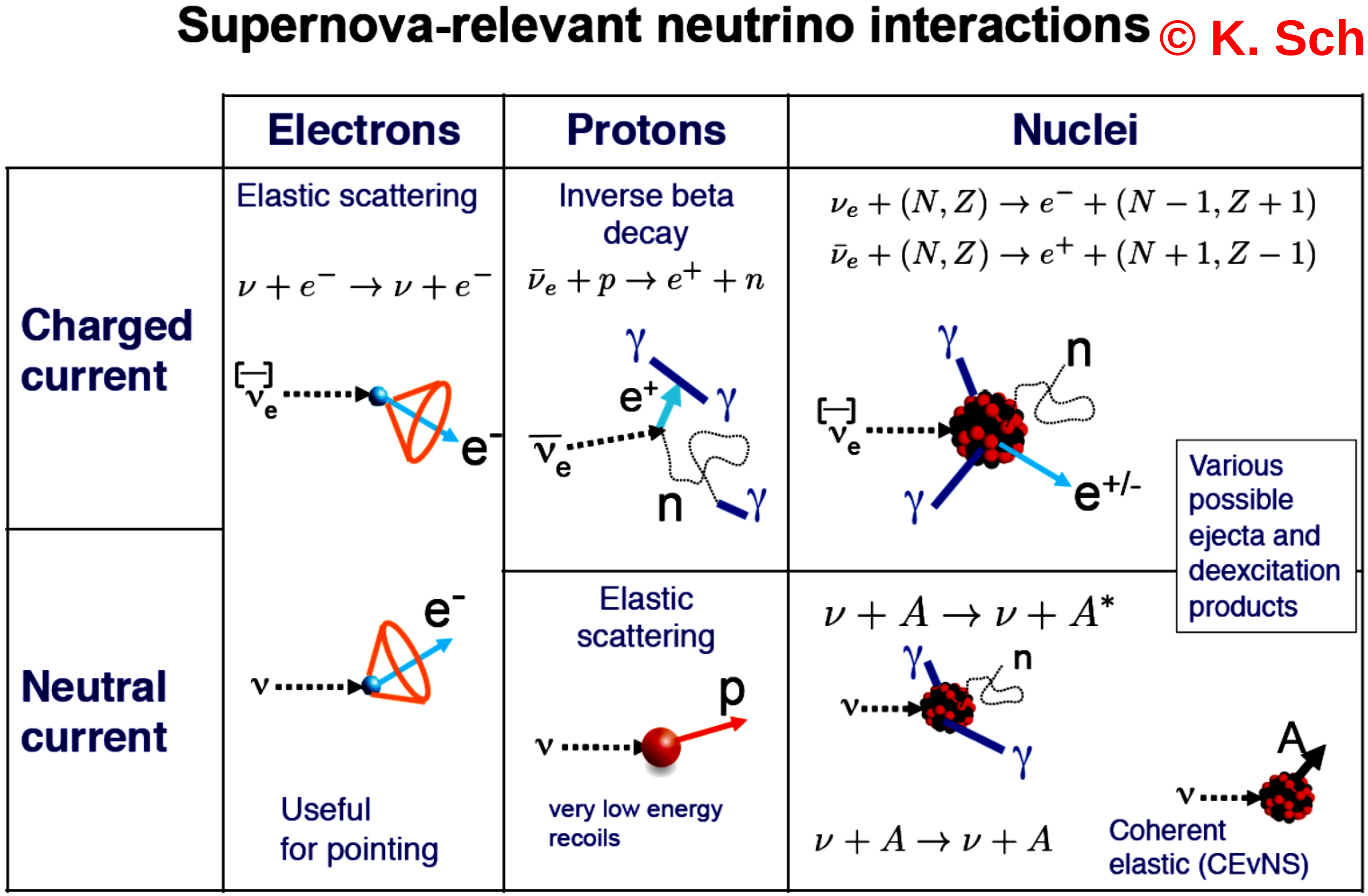
Conclusions:

■ Gravitational core-collapse
■ Expected average energies
■ Expected signal duration

Problems:

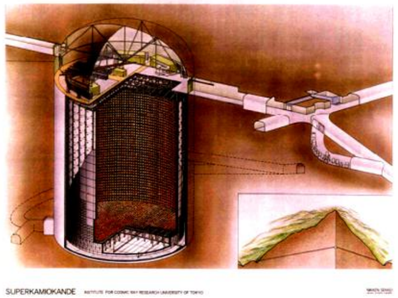
☐ Only twenty-four events
☐ Only observed once

Part B: Detection of Supernova Neutrinos - Prospects



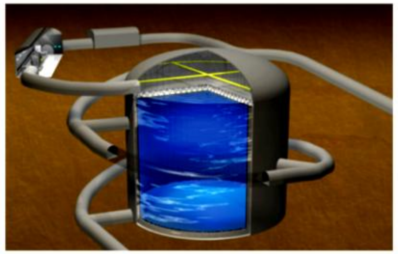
Supernova-relevant neutrino interactions © K. Scholberg

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$	$\nu_e + (N,Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \to e^+ + (N+1, Z-1)$ Various possible ejecta and deexcitation products
Neutral current	Useful for pointing	Elastic scattering very low energy recoils	$\nu + A \to \nu + A^*$ $\nu + A \to \nu + A$ Coherent elastic (CEvNS)



Super-Kamiokande

Mozumi, Japan
22.5 kton fid. volume (32 kton total)
~5-10K events @ 10 kpc
(mostly anti-ν_e)
~5° pointing @ 10 kpc
Future: SK-Gd



Hyper-Kamiokande

- staged 2-module, 374-kton fid. water Cherenkov detector
- 1 module: 40% PMT coverage w/double efficiency

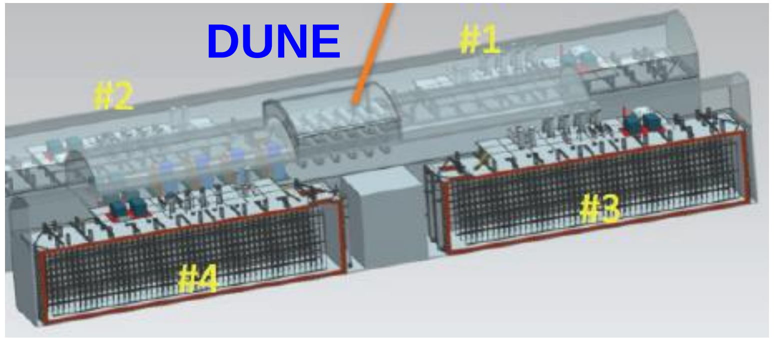
HALO

$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^-$ CC
↘ 1n, 2n emission

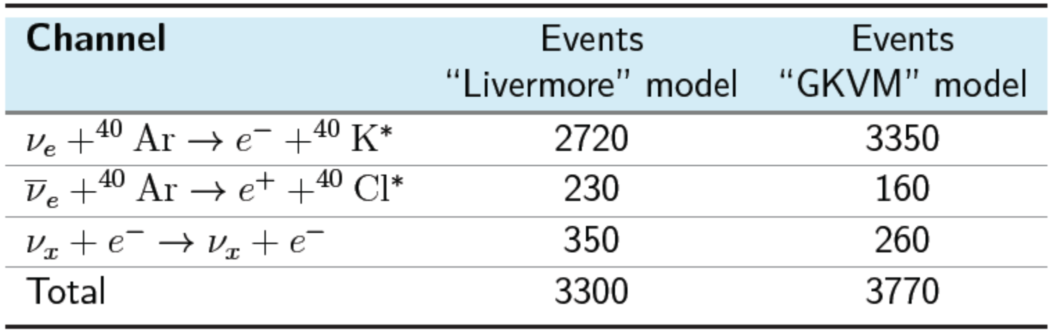
$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x$ NC
↘ 1n, 2n, γ emission

Relative 1n/2n rates sharply dependent on neutrino energy ⇒ spectral sensitivity

SNO ^{3}He counters + 79 t Pb
1~ 40 events @ 10 kpc



DUNE

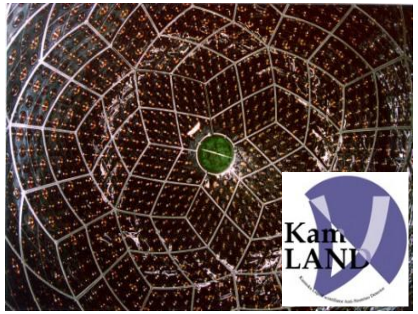


Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	2720	3350
$\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

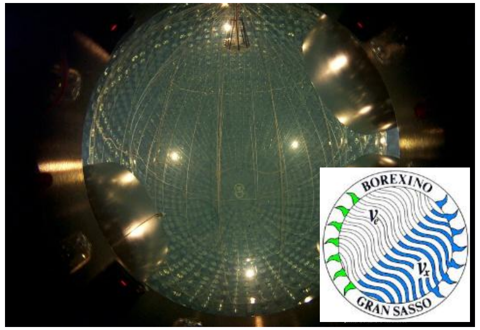
- **Water-Cherenkov: SK, HK**
- **LArTPC: ICARUS, DUNE**
- **Scintillator: NOvA, JUNO**

Part B: Detection of Supernova Neutrinos - JUNO

LVD, 1 kt

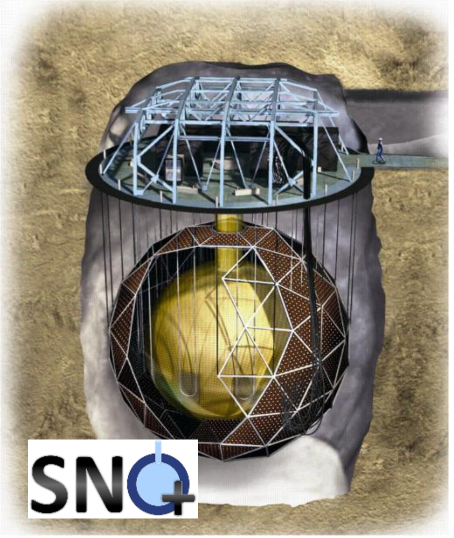


KamLAND, 1 kt

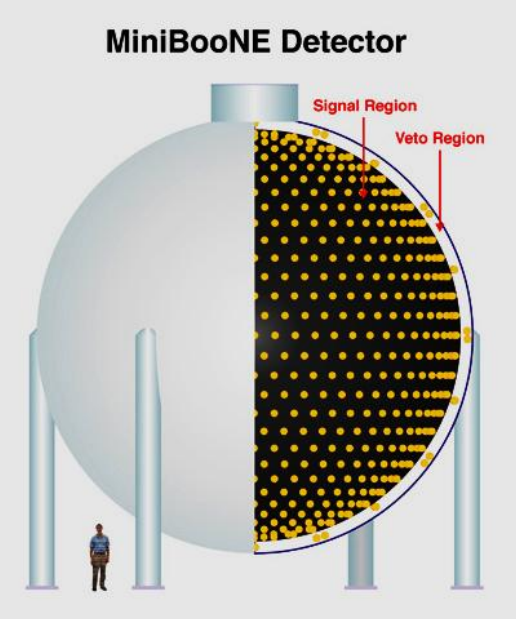


Borexino, 0.3 kt

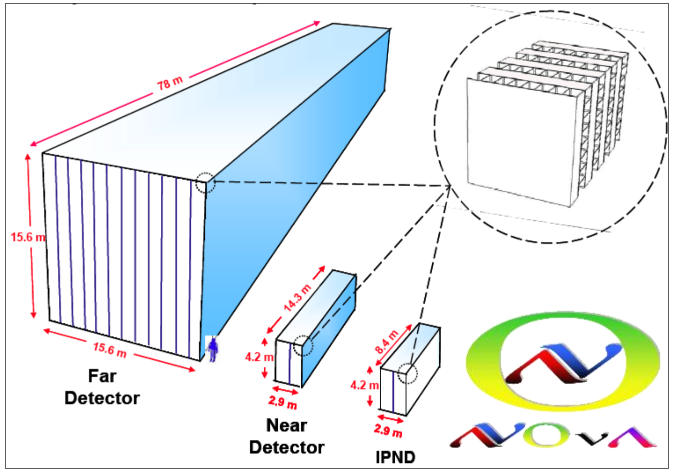
Daya Bay, 0.16 kt



SNO+, 1 kt



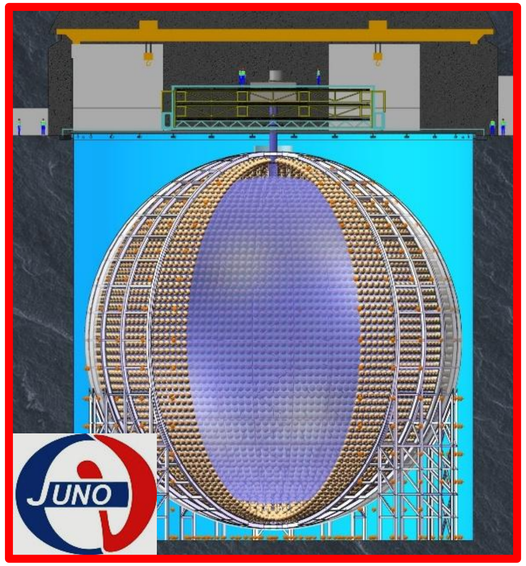
MiniBooNE, 0.7 kt



NOvA, 15 kt

Baksan, 0.33 kt

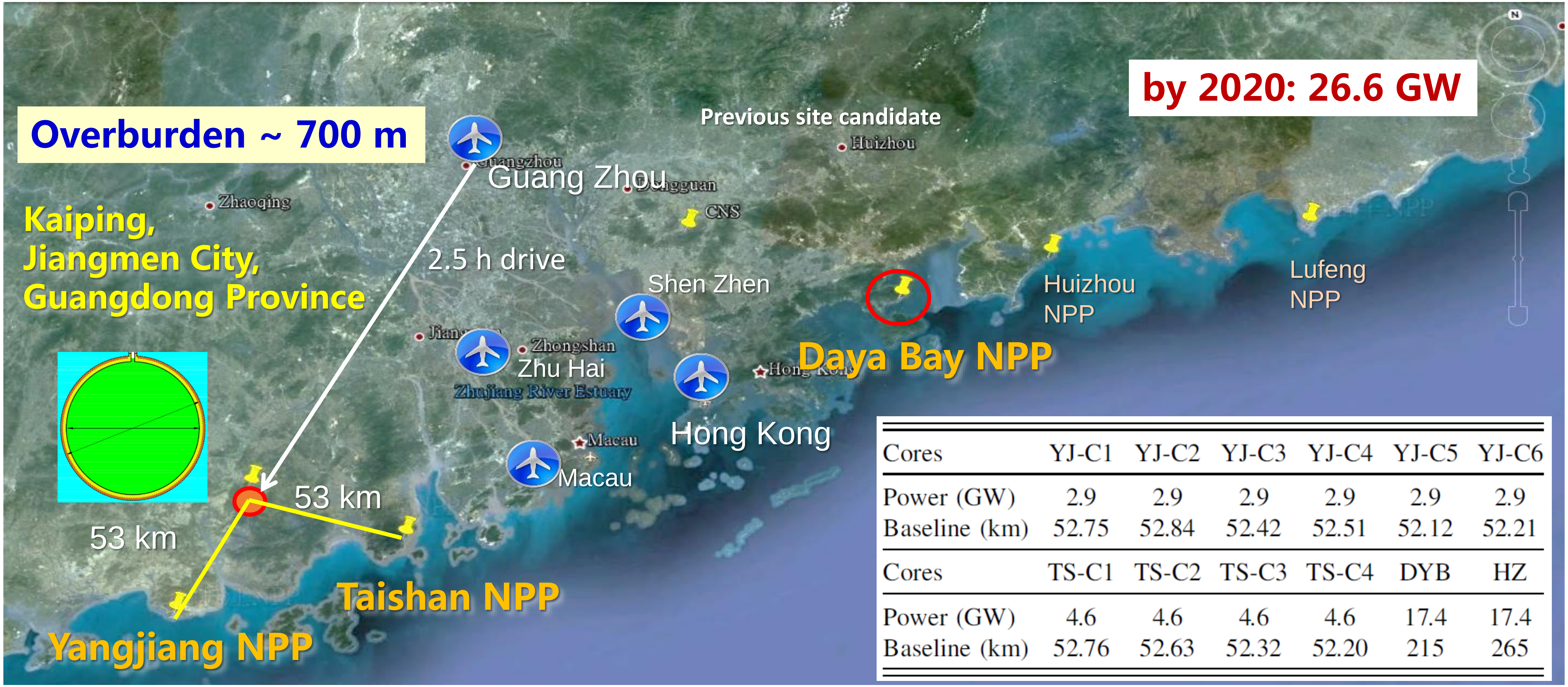
LENA, 50 kt



JUNO, 20 kt

Part B: Detection of Supernova Neutrinos - JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



by 2020: 26.6 GW

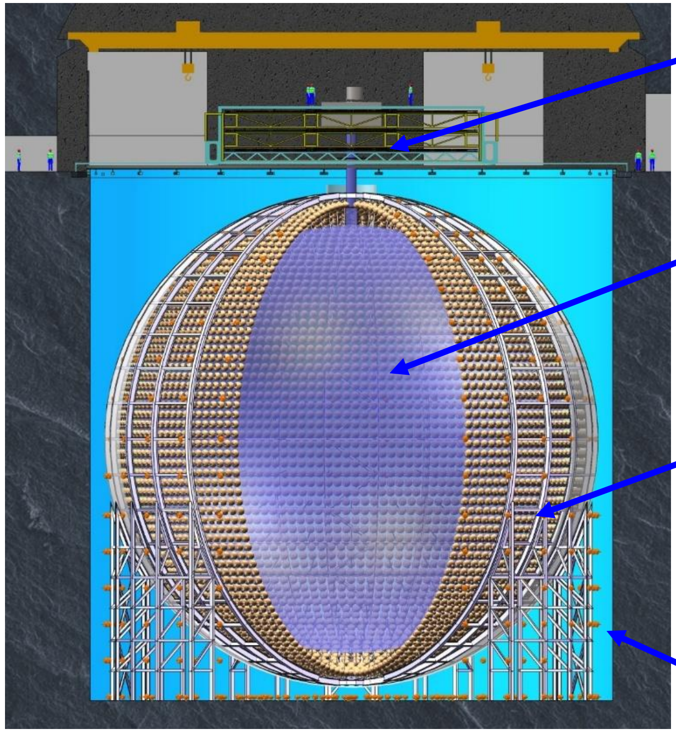
Overburden ~ 700 m

**Kaiping,
Jiangmen City,
Guangdong Province**

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Part B: Detection of Supernova Neutrinos - JUNO

Jiangmen Underground Neutrino Observatory

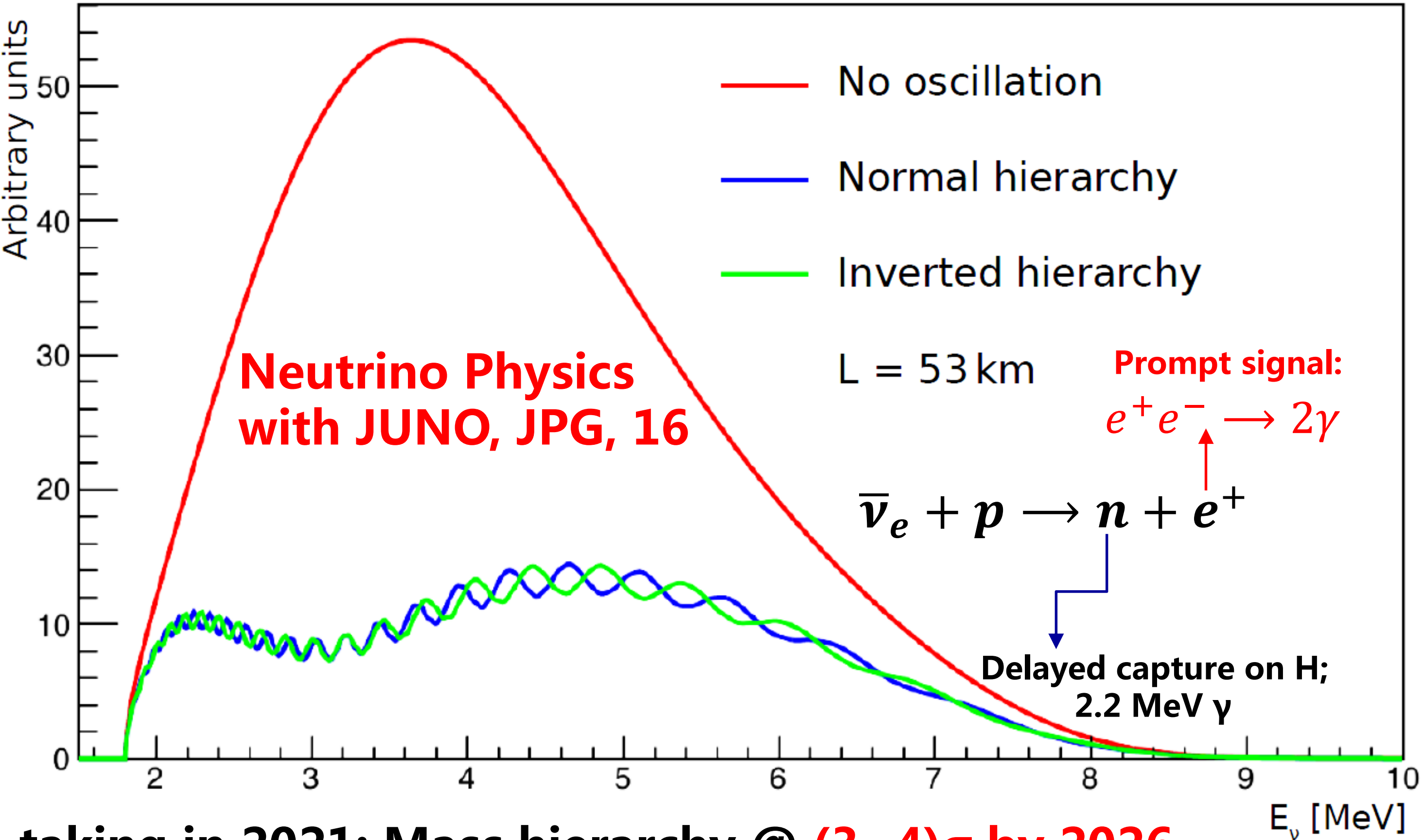


Top tracker

Acrylic sphere
d = 35.4 m

Steel support structure

Water Cherenkov



Neutrino Physics with JUNO, JPG, 16

Prompt signal:

$e^+e^- \longrightarrow 2\gamma$

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

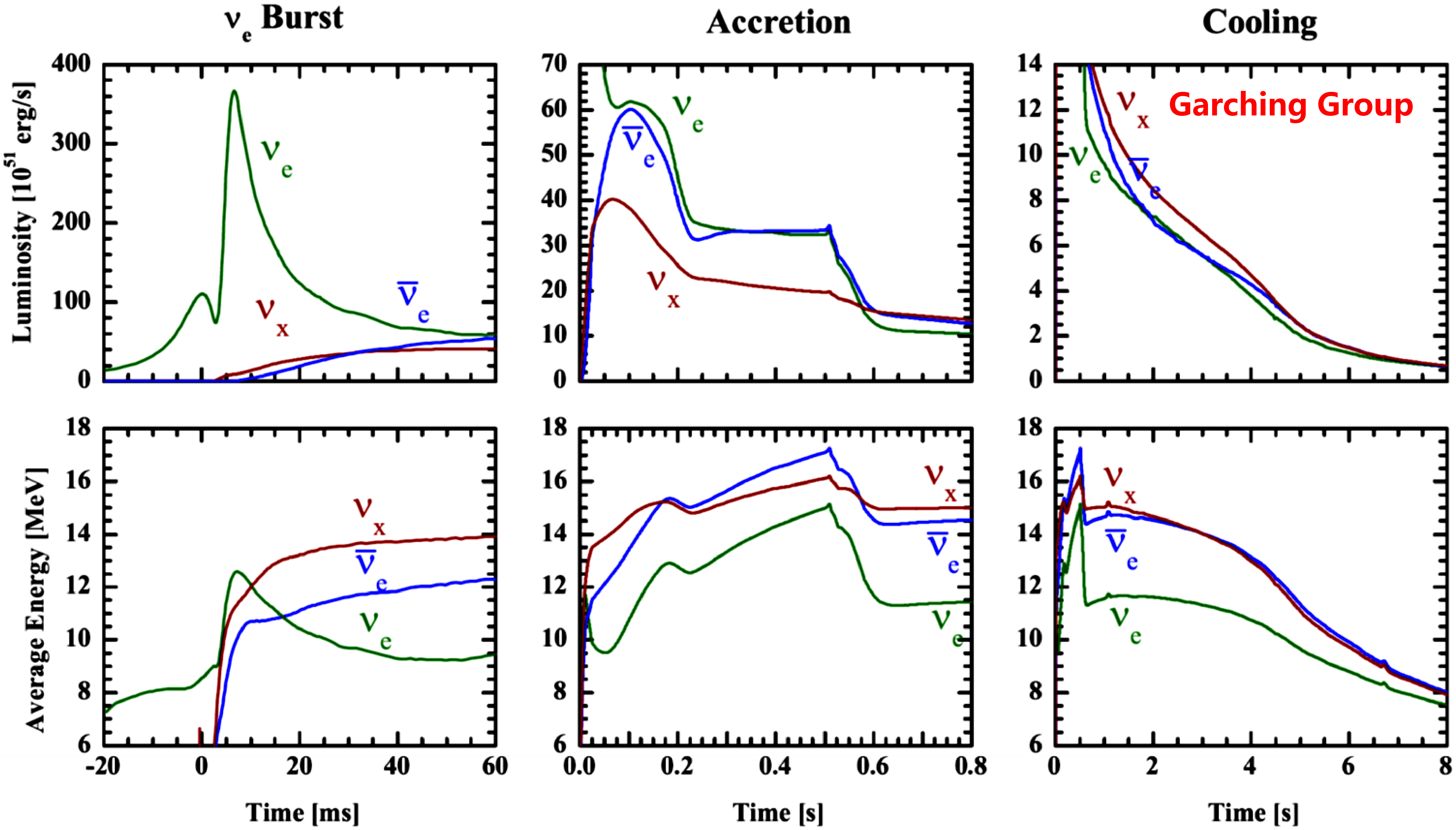
Delayed capture on H;
2.2 MeV γ

Data taking in 2021; Mass hierarchy @ (3~4)σ by 2026

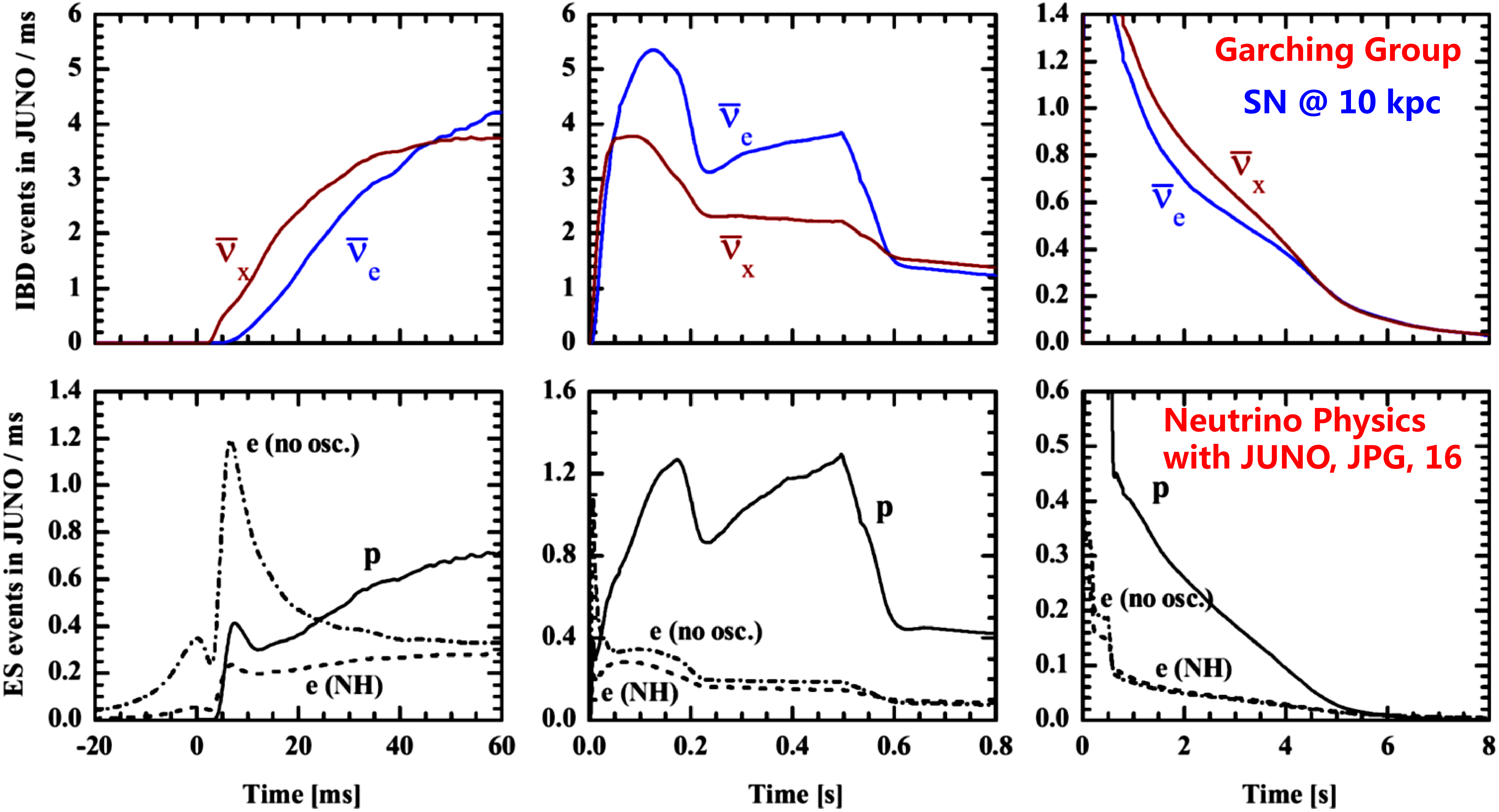
- 20 kiloton LS detector
- 3% energy resolution@ 1 MeV
- 700 m underground
- 18,000 20” +25,000 3” PMTs
- 53 km to the NPPs

	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

Part B: Detection of Supernova Neutrinos - JUNO



Part B: Detection of Supernova Neutrinos - JUNO



Garching Group

SN @ 10 kpc

Neutrino Physics with JUNO, JPG, 16

Part B: Detection of Supernova Neutrinos - JUNO

Reaction channel	Interaction type	Sensitive to
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	$\overline{\nu}_e$
$\nu + p \rightarrow \nu + p$	NC	ν_x
$\nu + e^- \rightarrow \nu + e^-$	CC+NC	ν_e
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$ (14.39 MeV, 20 ms)	CC	$\overline{\nu}_e$
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$ (17.34 MeV, 11 ms)	CC	ν_e
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	ν_x

- **Elastic ν-p scattering important**
- **Advantage of LS: low threshold**

Beacom, Farr, Vogel, PRD, 02;
Dasgupta, Beacom, PRD, 11

Natural abundance of ${}^{13}\mathrm{C}$ is about 1.1%

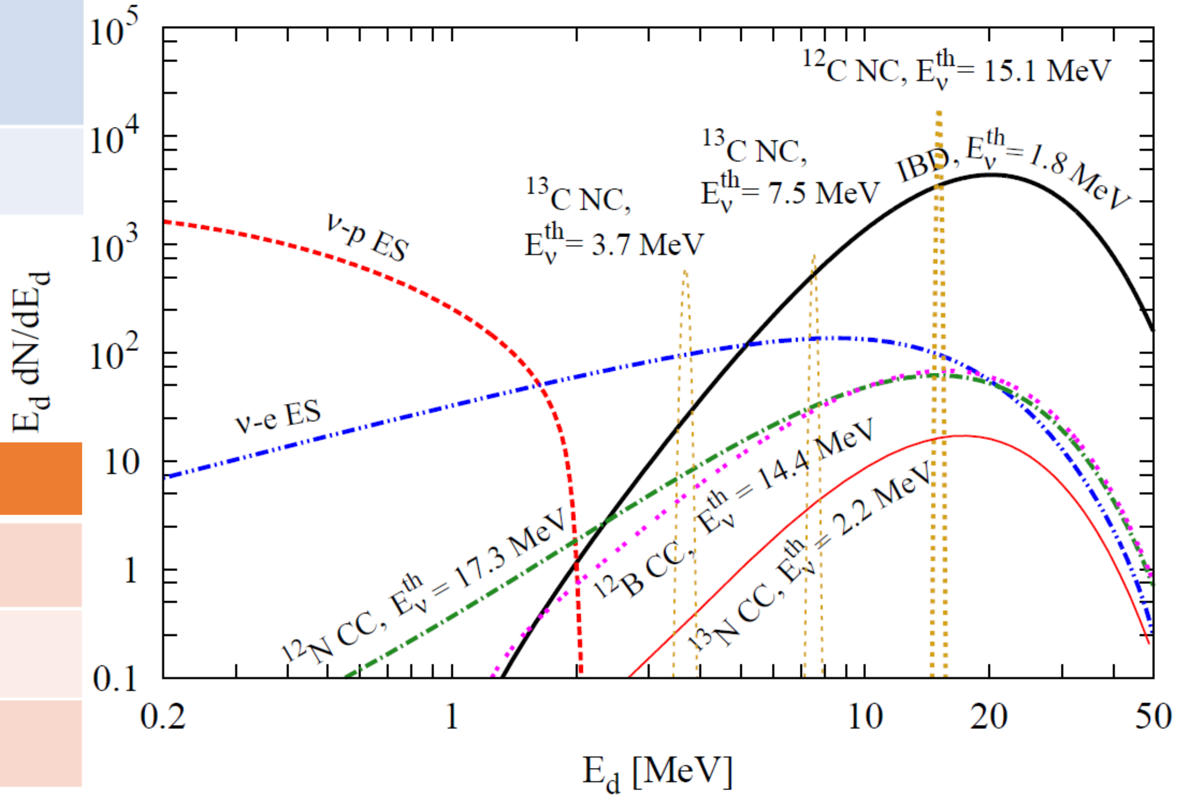
Fukugita *et al.*, PLB, 90; Suzuki *et al.*, PRD, 12

Reaction channel	Interaction type	Sensitive to
$\overline{\nu}_e + {}^{13}\mathrm{C} \rightarrow e^+ + {}^{13}\mathrm{B}$	CC	$\overline{\nu}_e$
$\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}$	CC	ν_e
$\nu + {}^{13}\mathrm{C} \rightarrow \nu + {}^{13}\mathrm{C}^*$	NC	ν_x

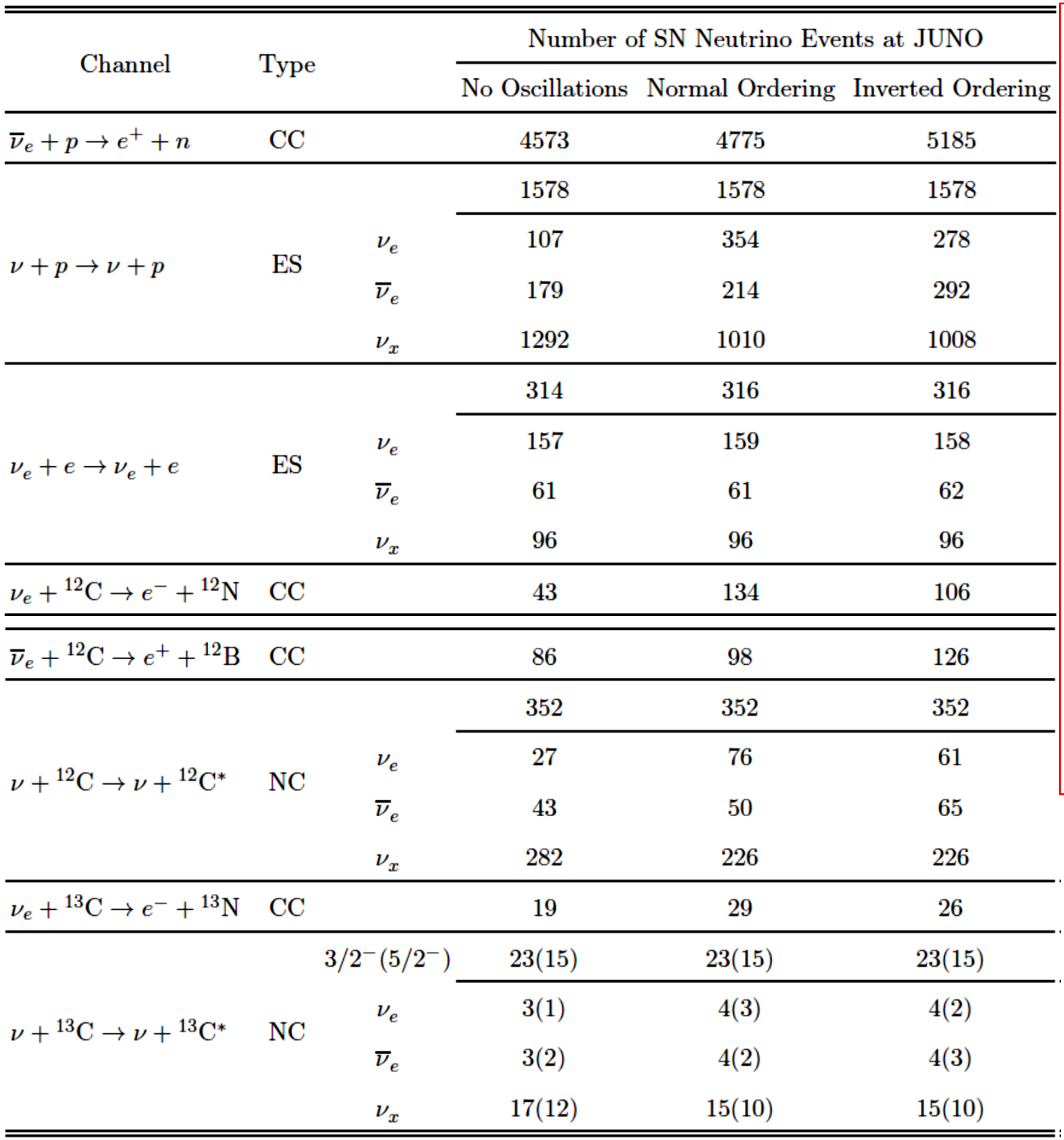
Event spectra @ JUNO

Lu, Li, Zhou, PRD, 16

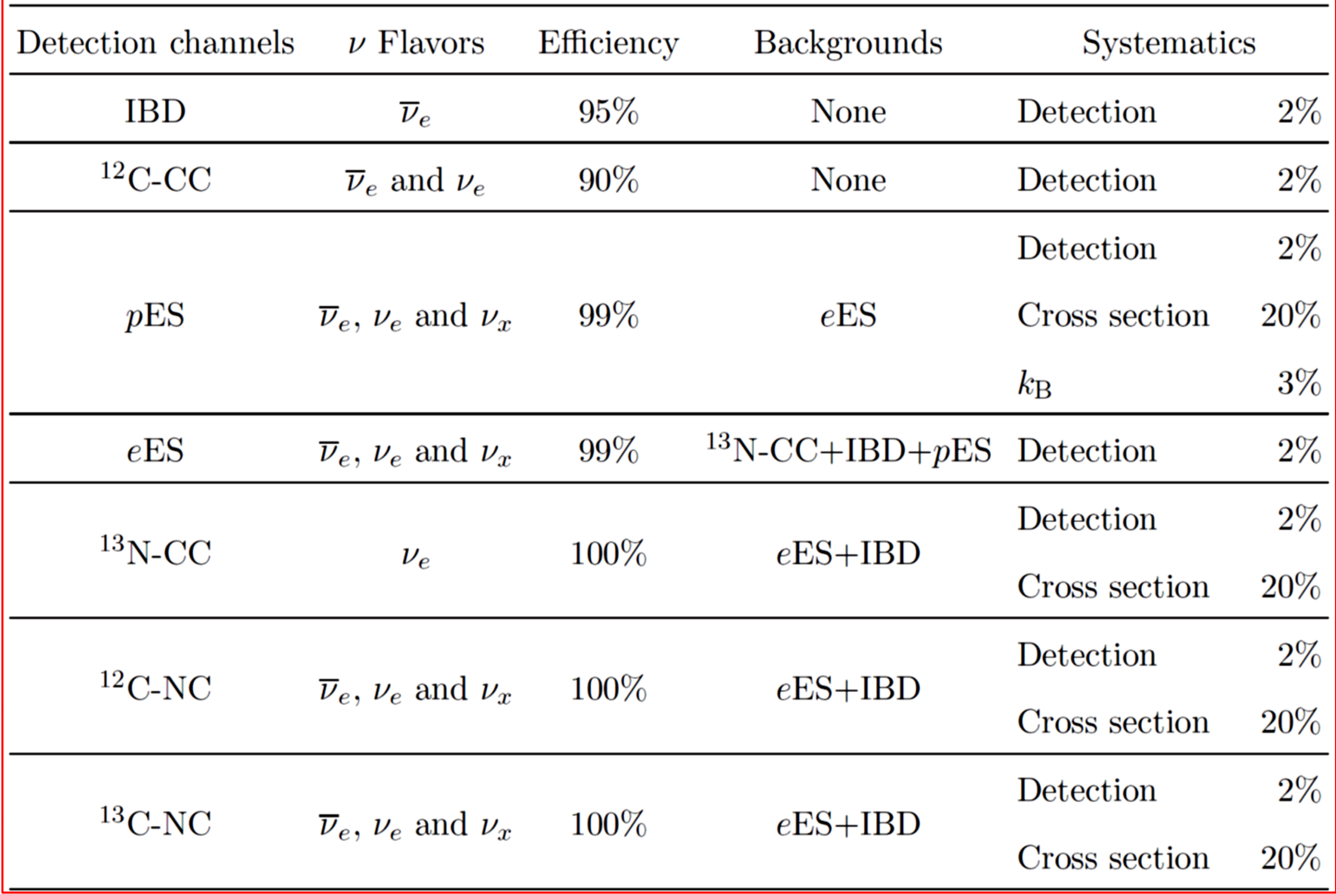
KRJ-para. with (12, 14, 16) MeV



Part B: Detection of Supernova Neutrinos - JUNO



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
$\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}$	CC		19	29	26
$\nu + {}^{13}\mathrm{C} \to \nu + {}^{13}\mathrm{C}^*$	NC	$3/2^-(5/2^-)$	23(15)	23(15)	23(15)
		ν_e	3(1)	4(3)	4(2)
		$\overline{\nu}_e$	3(2)	4(2)	4(3)
		ν_x	17(12)	15(10)	15(10)

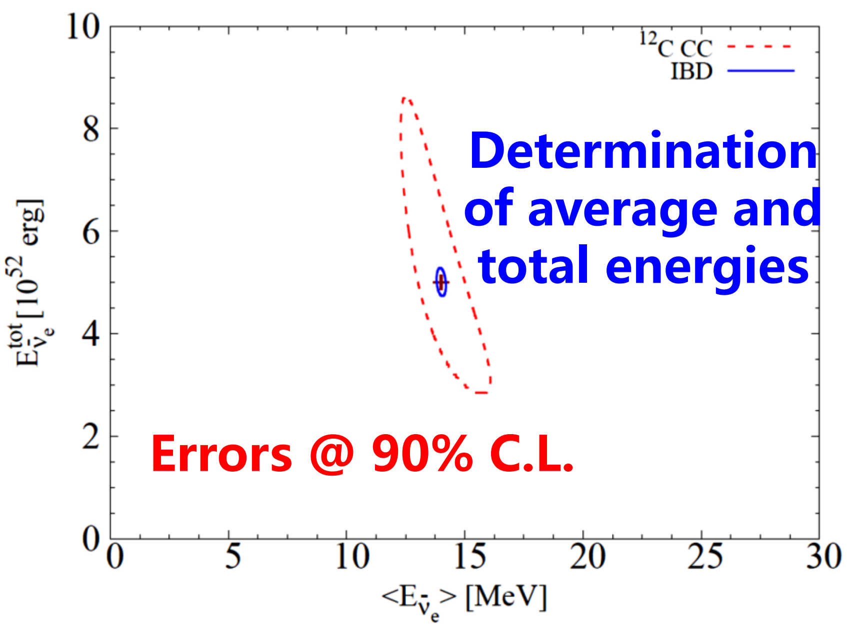


Detection channels	ν Flavors	Efficiency	Backgrounds	Systematics	
IBD	$\overline{\nu}_e$	95%	None	Detection	2%
^{12}C-CC	$\overline{\nu}_e$ and ν_e	90%	None	Detection	2%
pES	$\overline{\nu}_e$, ν_e and ν_x	99%	eES	Detection	2%
				Cross section	20%
				k_B	3%
eES	$\overline{\nu}_e$, ν_e and ν_x	99%	^{13}N-CC+IBD+pES	Detection	2%
^{13}N-CC	ν_e	100%	eES+IBD	Detection	2%
				Cross section	20%
^{12}C-NC	$\overline{\nu}_e$, ν_e and ν_x	100%	eES+IBD	Detection	2%
				Cross section	20%
^{13}C-NC	$\overline{\nu}_e$, ν_e and ν_x	100%	eES+IBD	Detection	2%
				Cross section	20%

- **IBD for $\overline{\nu}_e$ + sub-leading effects from ^{12}C CC**
- **Elastic ν-e scattering for ν_e + ^{12}C CC**
- **Elastic ν-p scattering for ν_x + eES**
- **A global analysis of all reaction channels?**

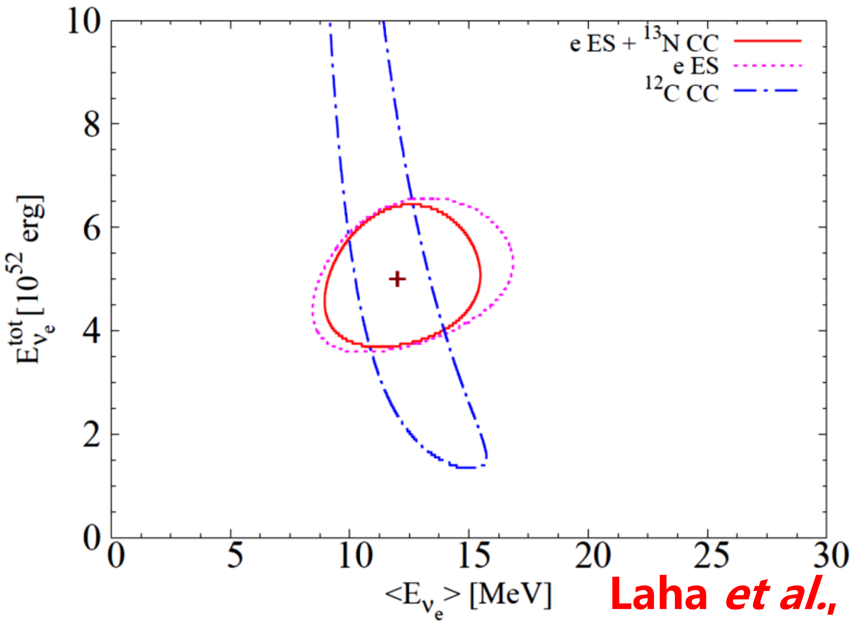
Laha *et al.*, 1412.8425; Lu *et al.*, PRD, 2016

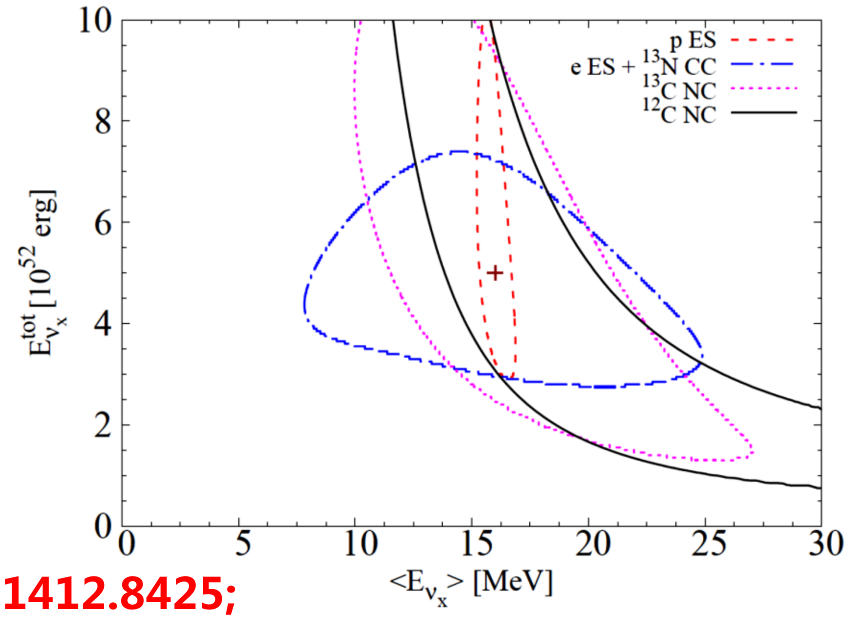
Part B: Detection of Supernova Neutrinos - JUNO



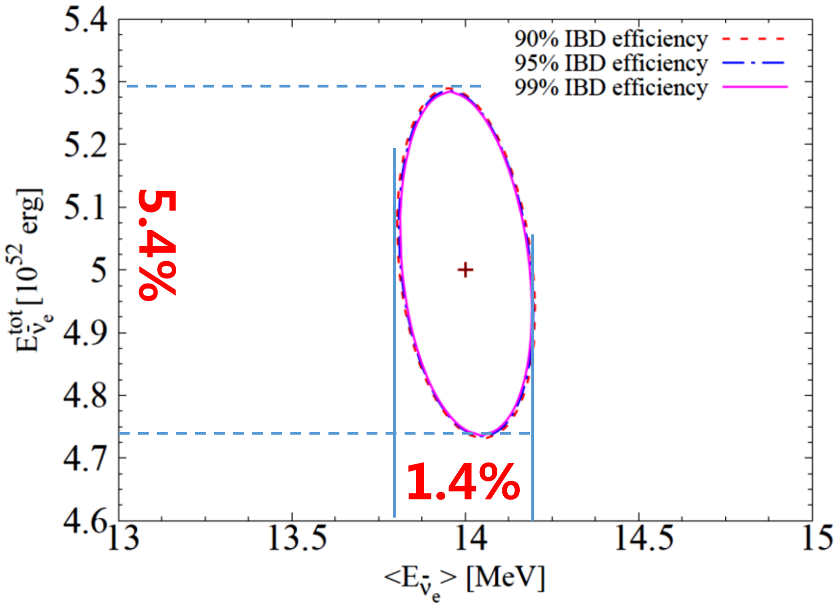
Determination of average and total energies

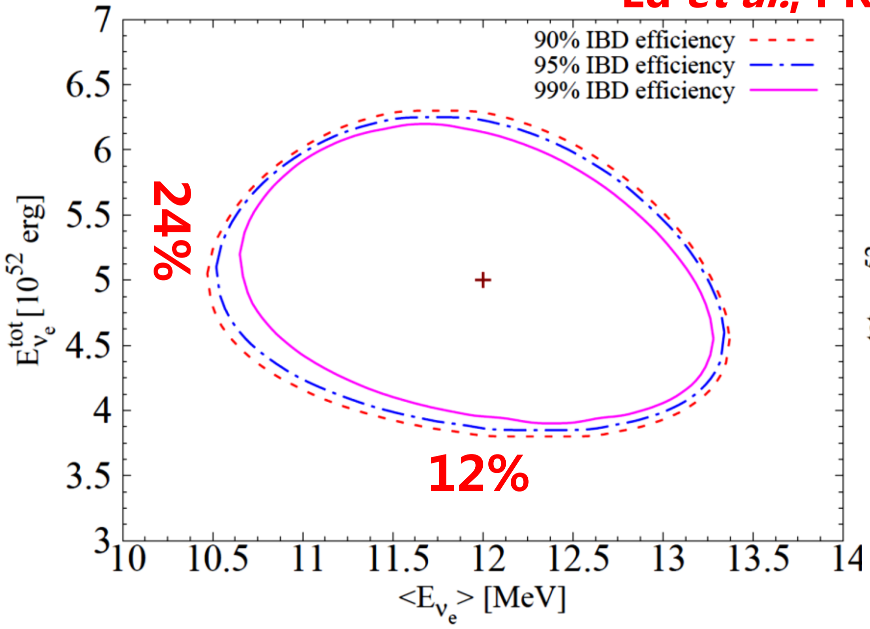
Errors @ 90% C.L.

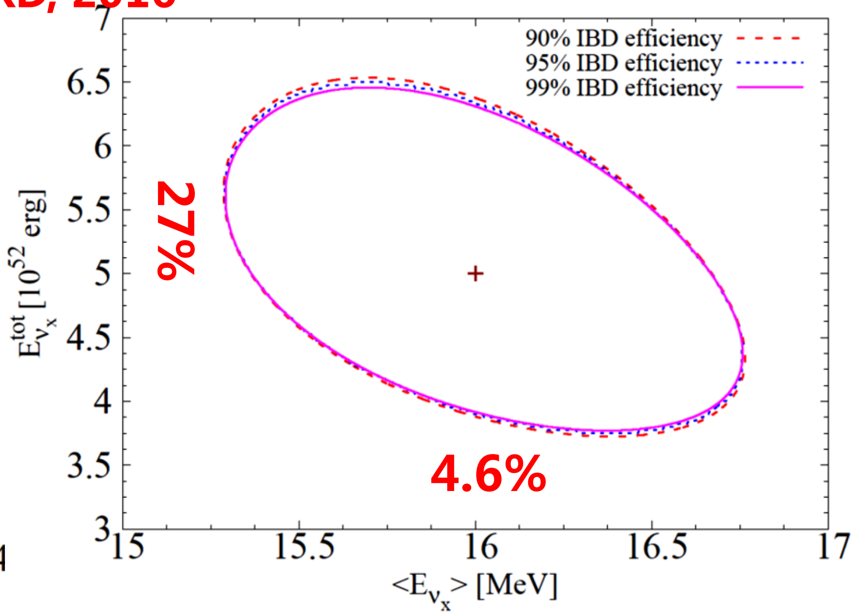




Laha *et al.*, 1412.8425;
Lu *et al.*, PRD, 2016



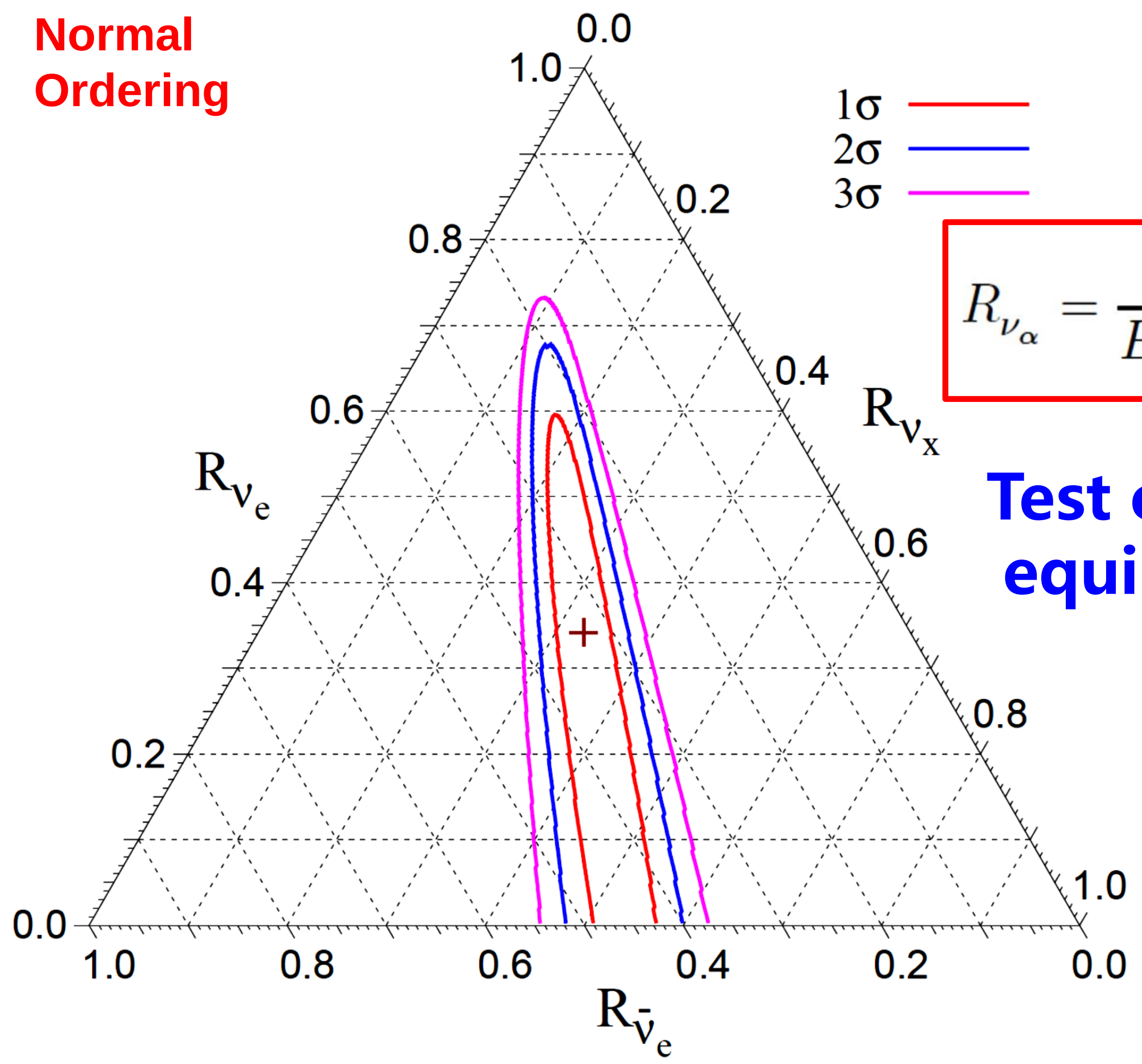




Part B: Detection of Supernova Neutrinos - JUNO

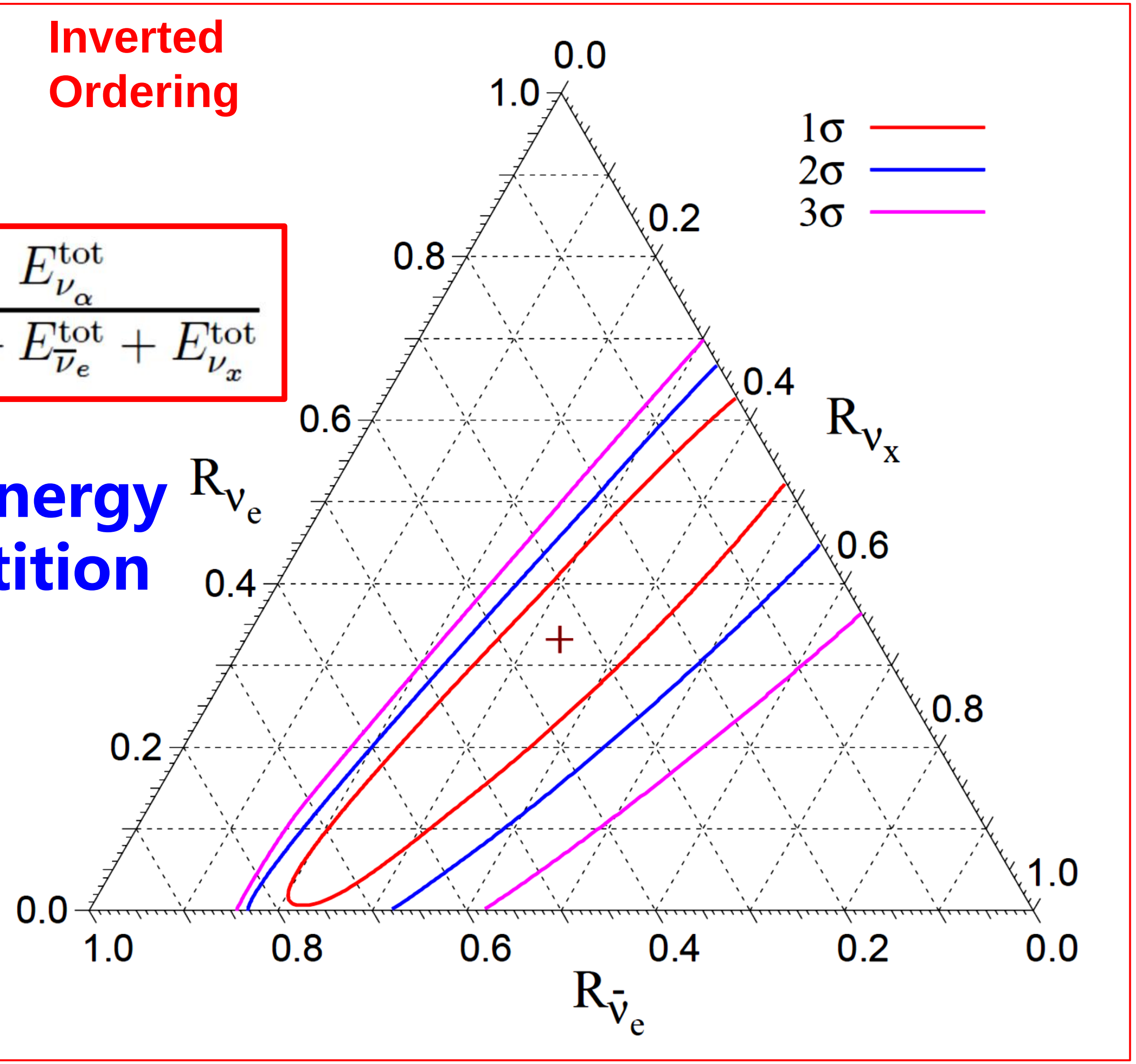
Including only the Mikheyev-Smirnov-Wolfenstein (MSW) matter effects

Lu, Li, Zhou, PRD, 2016



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

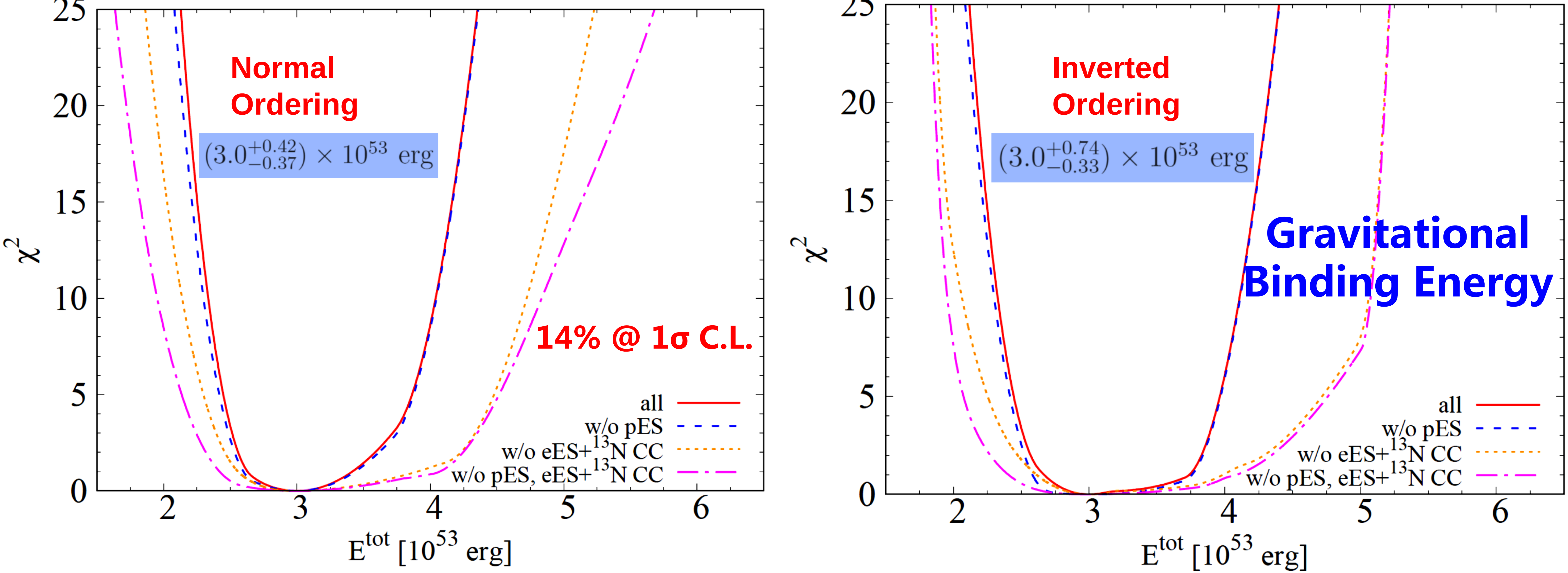
Test of energy equipartition



Part B: Detection of Supernova Neutrinos - JUNO

Including only the MSW effects in the SN, and fixing the spectral indices at α =3

Lu, Li, Zhou, PRD, 2016; Gallo Rosso, Vissani, Volpe, JCAP, 2017



Normal Ordering

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

14% @ 1σ C.L.

Inverted Ordering

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

Gravitational Binding Energy

- **Conservatively assuming an uncertainty of 20% for the ν-p cross section (low as a few%)**
- **Possible to relax the constraint on the spectral index (important for <E>, but not for E_{tot})**

Part C: Reconstruction of Neutrino Spectra with JUNO

Inverse Beta Decay (IBD) $\overline{\nu}_e + p \rightarrow e^+ + n$

Strategy for reconstruction

X-section: $\sigma_{\rm IBD}(E_{e^+}) = 9.52 \times 10^{-44}\ {\rm cm}^2 \left(\frac{E_{e^+}p_{e^+}}{\rm MeV^2}\right)$

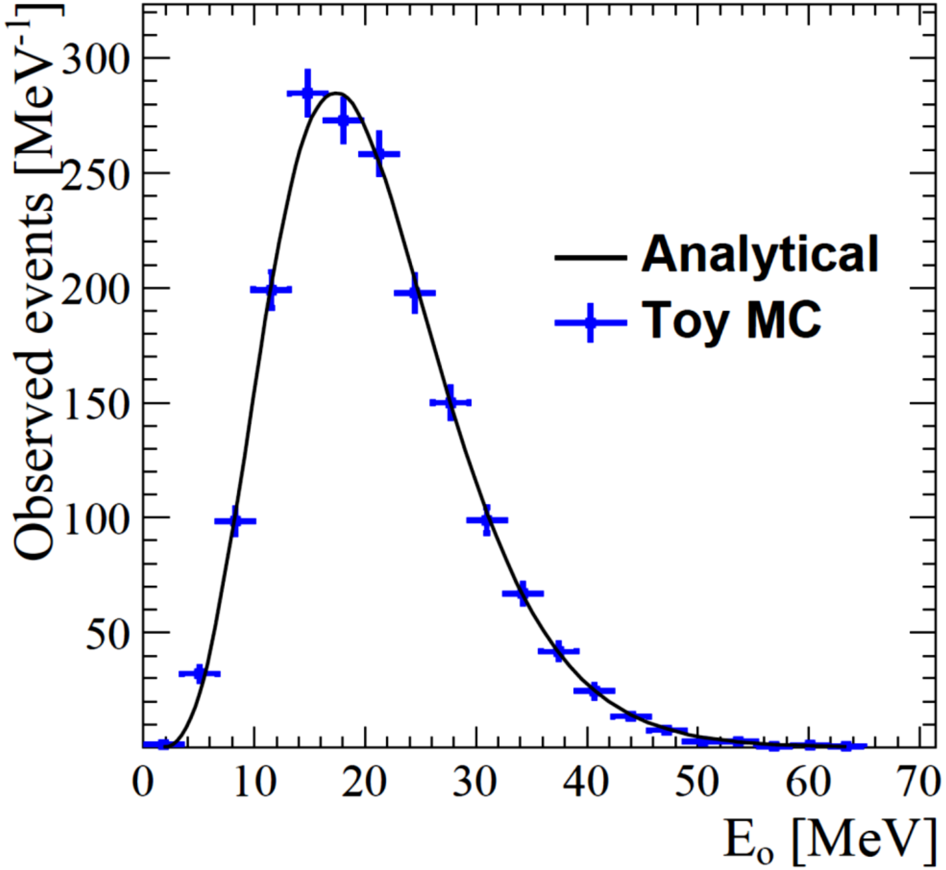
Energy relation: $E_{e^+} \approx E_{\overline{\nu}_e} - \Delta_{np}$

Event rate: $\frac{{\rm d}N_{\rm IBD}}{{\rm d}E_{\rm o}} = N_{\rm p} \int_{E^{\rm th}_{\overline{\nu}_e}}^{\infty} \sigma_{\rm IBD}(E_{\overline{\nu}_e}) \cdot \frac{{\rm d}F_{\overline{\nu}_e}}{{\rm d}E_{\overline{\nu}_e}} \cdot \mathcal{G}(E_{\rm o}; E_{\rm v}, \delta_E)\ {\rm d}E_{\overline{\nu}_e}$

Event spectrum bin: $[E'_0, E'_1], [E'_1, E'_2], \cdots, [E'_{N-1}, E'_N]$

Neutrino energy bin: $[E_{i-1}, E_i]$ $\quad \overline{E}_i = \overline{E}'_i + 0.782\ {\rm MeV}$

$$\boxed{f_i = \left.\frac{{\rm d}F_{\overline{\nu}_e}}{{\rm d}E_{\overline{\nu}_e}}\right|_{\overline{E}_i} \simeq \frac{1}{N_p \sigma(\overline{E}_i)} \cdot \frac{n_i}{\Delta E'_i}}$$



Reconstruct the electron-antineutrino spectrum bin by bin

Part C: Reconstruction of Neutrino Spectra with JUNO

Elastic ν-p Scattering (pES) $\nu + p \rightarrow \nu + p$

Strategy for reconstruction

X-section:

$$\frac{\mathrm{d}\sigma_{\nu p}(E_\nu)}{\mathrm{d}T_\mathrm{p}} \approx 4.83 \times 10^{-42}\ \mathrm{cm}^2\ \mathrm{MeV}^{-1} \left[1 + 466 \left(\frac{T_\mathrm{p}}{\mathrm{MeV}}\right) \cdot \left(\frac{\mathrm{MeV}}{E_\nu}\right)^2\right]$$

Sensitive to all flavors

Energy quenching:

$$T'_\mathrm{p}(T_\mathrm{p}) \approx \int_0^{T_\mathrm{p}} \frac{\mathrm{d}E}{1 + k_\mathrm{B}\langle \mathrm{d}E/\mathrm{d}x\rangle}$$

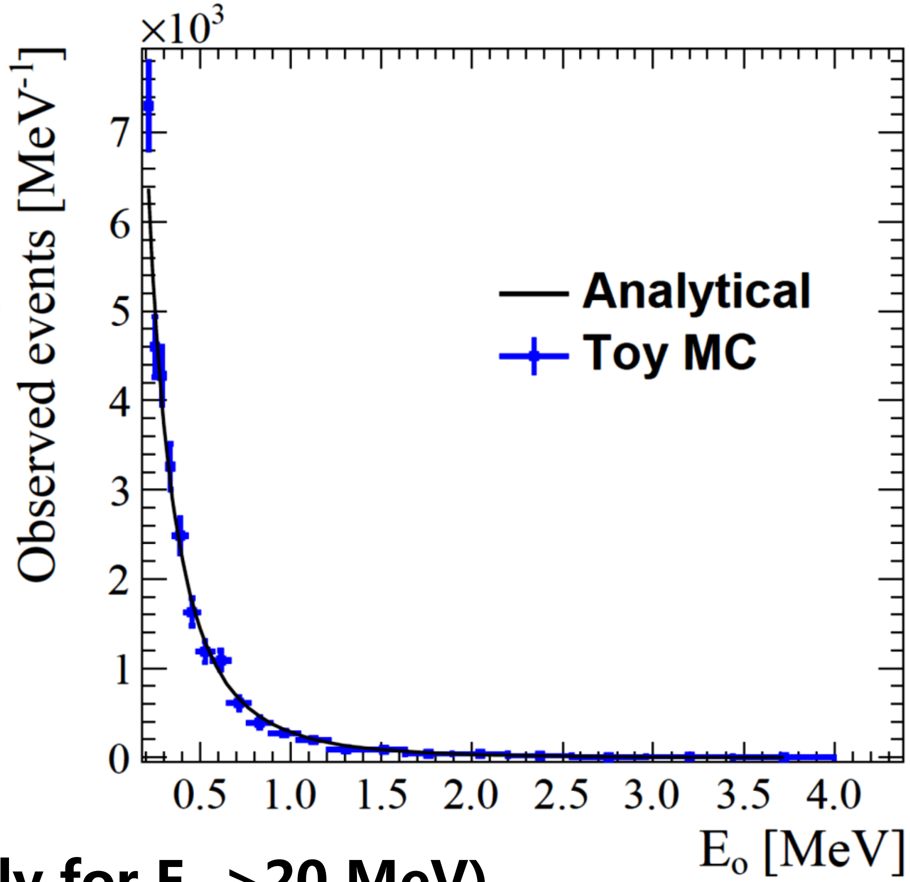
Event spectrum:

$$\frac{\mathrm{d}N_{\nu p}}{\mathrm{d}T'_\mathrm{p}} = N_\mathrm{p} \sum_\alpha \frac{\mathrm{d}T_\mathrm{p}}{\mathrm{d}T'_\mathrm{p}} \int_{E_\alpha^\mathrm{min}}^{\infty} \frac{\mathrm{d}F_\alpha}{\mathrm{d}E_\alpha} \cdot \frac{\mathrm{d}\sigma_{\nu p}(E_\alpha)}{\mathrm{d}T_\mathrm{p}} \mathrm{d}E_\alpha$$

Energy threshold:

$$E_\alpha^\mathrm{min} = (T_\mathrm{p} m_p/2)^{1/2}$$

$$\boxed{\frac{n_i}{\Delta T'_i} \simeq \sum_{j \in \{\overline{E}_j \geq E^i_\mathrm{min}\}} 4N_\mathrm{p} \cdot \left.\frac{\mathrm{d}T}{\mathrm{d}T'}\right|_{\overline{T}'_i} \cdot f_j \Delta E_j \cdot \left.\frac{\mathrm{d}\sigma_{\nu p}(\overline{E}_j)}{\mathrm{d}T_\mathrm{p}}\right|_{\overline{T}_i} \equiv \sum_j f_j K_{ij}}$$



Reconstruct the ν_x spectrum solving the above equation (only for E_ν >20 MeV)

Part C: Reconstruction of Neutrino Spectra with JUNO

Elastic ν-e Scattering (eES) $\nu + e^- \rightarrow \nu + e^-$

Strategy for reconstruction

Event spectrum:

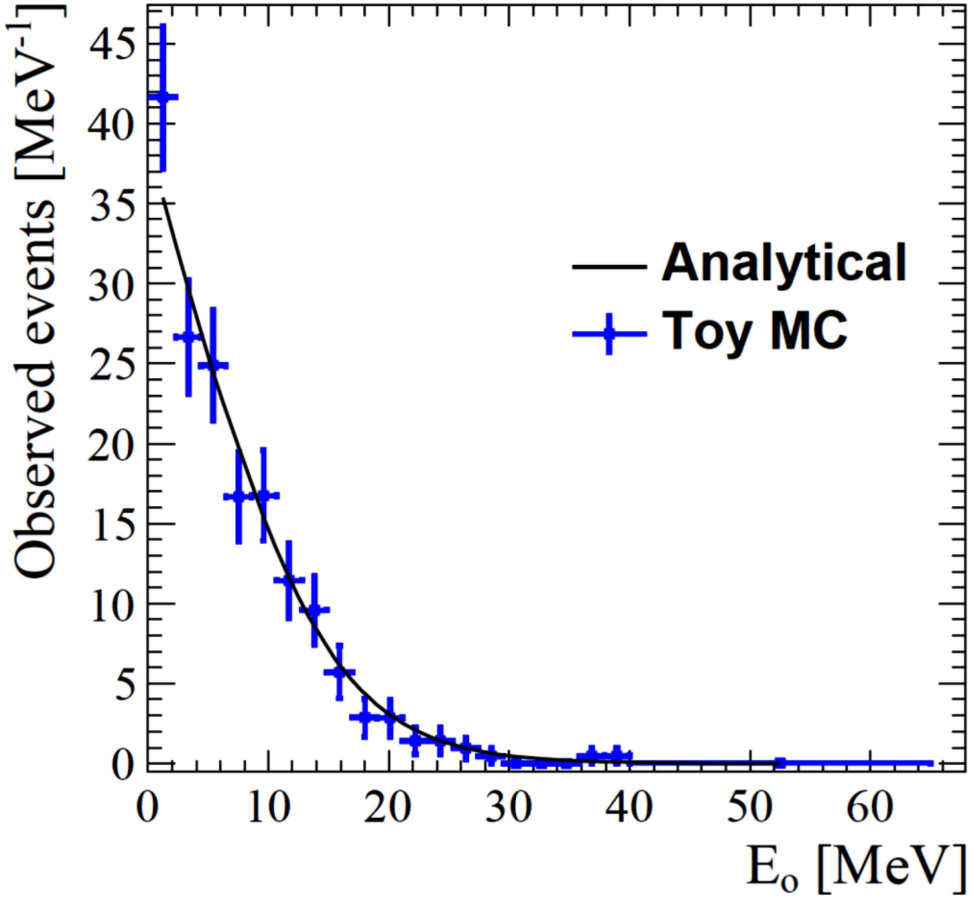
$$\frac{\mathrm{d}N_{\nu e}}{\mathrm{d}E_\mathrm{o}} = N_\mathrm{e} \sum_\alpha \int_0^\infty \mathrm{d}T_\mathrm{e} \cdot \mathcal{G}(E_\mathrm{o}; T_\mathrm{e}, \delta_E) \int_{E_\alpha^\mathrm{min}}^\infty \frac{\mathrm{d}F_\alpha}{\mathrm{d}E_\alpha} \cdot \frac{\mathrm{d}\sigma_{\nu e}(E_\alpha)}{\mathrm{d}T_e} \, \mathrm{d}E_\alpha$$

mainly sensitive to ν_e flavor

Energy threshold:

$$E^i_\mathrm{min} = \overline{T}_i/2 + \sqrt{\overline{T}_i(\overline{T}_i + 2m_e)}/2$$

$$\boxed{\frac{n_i}{\Delta T_i} \simeq \sum_{j \in \{\overline{E}_j \geq E^i_\mathrm{min}\}} N_\mathrm{e} \cdot f_j \Delta E_j \cdot \left.\frac{\mathrm{d}\sigma_{\nu e}(\overline{E}_j)}{\mathrm{d}T_\mathrm{e}}\right|_{\overline{T}_i}}$$



Reconstruct the ν_e spectrum (due to a larger X-section)

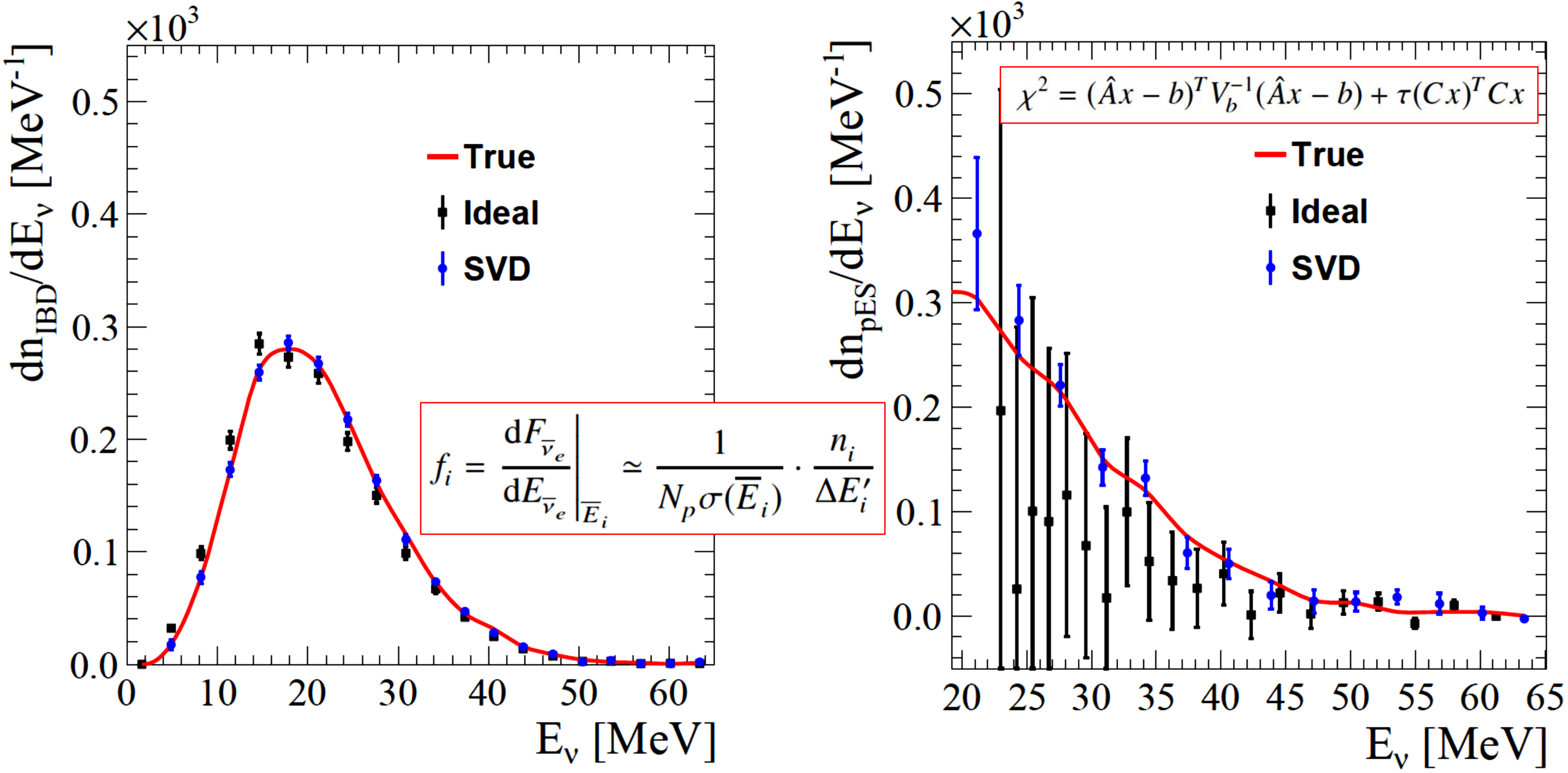
Summary

- **No neutrino spectral information needed**
- **Based on the observed event spectra**
- **Multi-flavor contributions to ePS & pES**

Part C: Reconstruction of Neutrino Spectra with JUNO

Dasgupta, Beacom, PRD, 11

Li^2, Wang, Wen, Zhou, PRD, 18

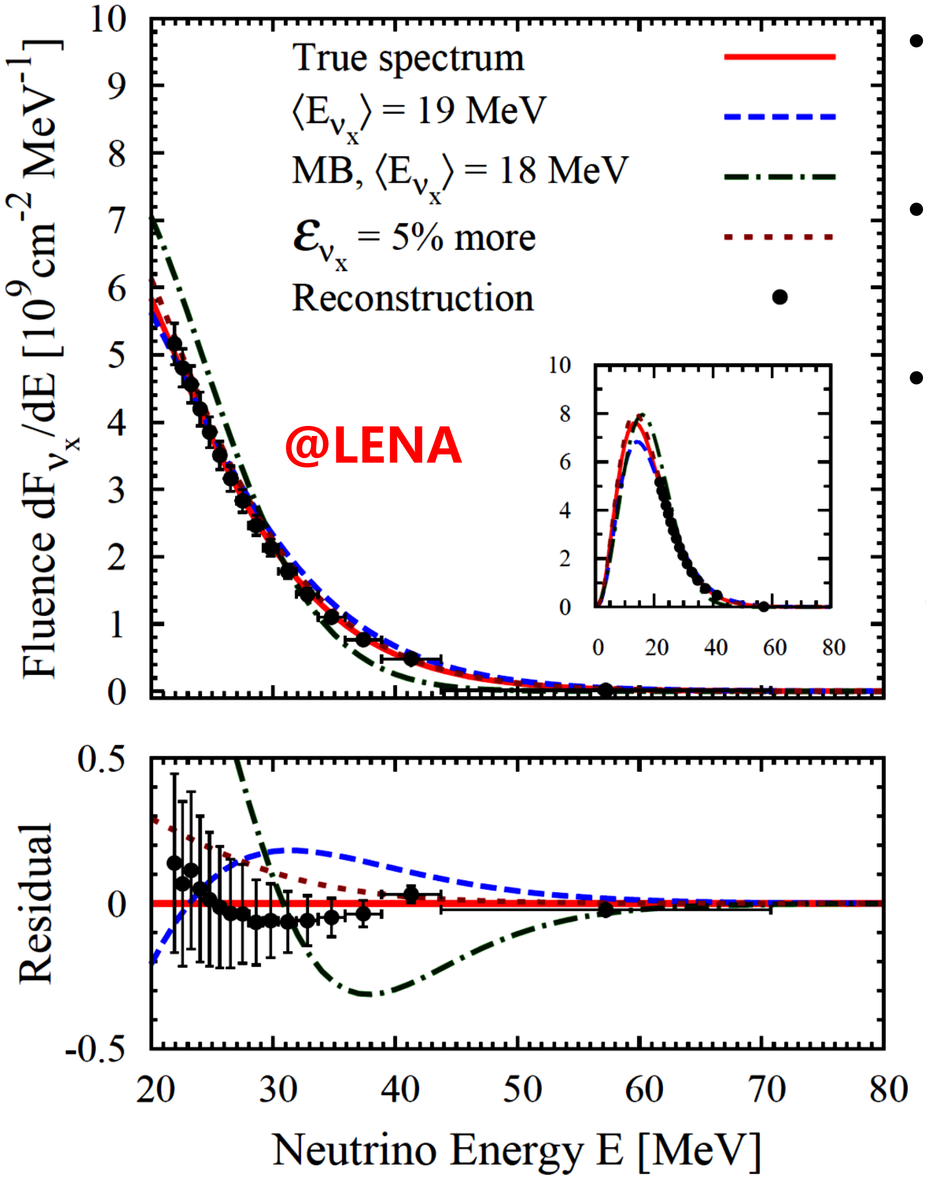


$$f_i = \left.\frac{\mathrm{d}F_{\overline{\nu}_e}}{\mathrm{d}E_{\overline{\nu}_e}}\right|_{\overline{E}_i} \simeq \frac{1}{N_p \sigma(\overline{E}_i)} \cdot \frac{n_i}{\Delta E_i'}$$

$$\chi^2 = (\hat{A}x - b)^T V_b^{-1} (\hat{A}x - b) + \tau (Cx)^T Cx$$

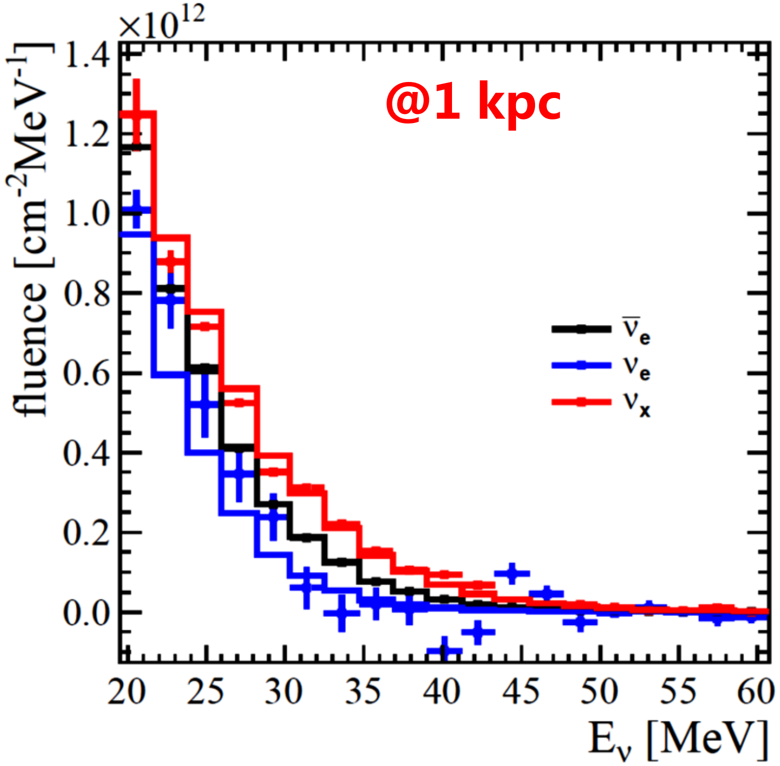
Part C: Reconstruction of Neutrino Spectra with JUNO

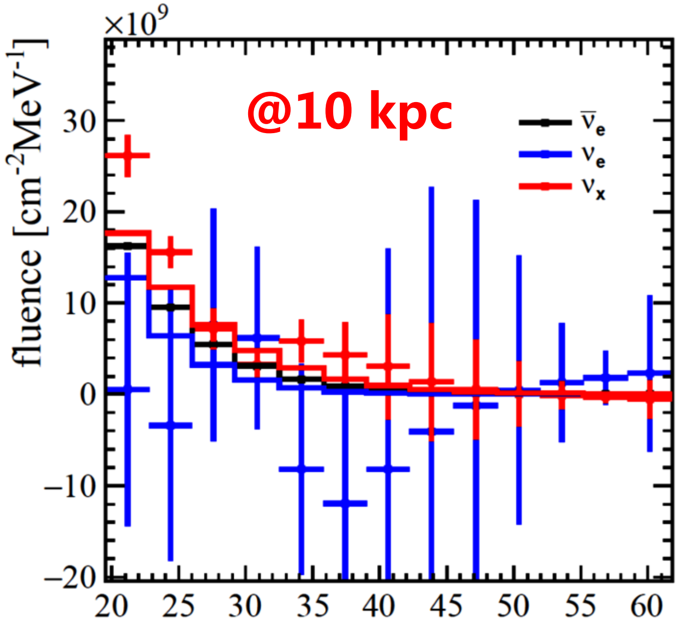
Dasgupta, Beacom, PRD, 11

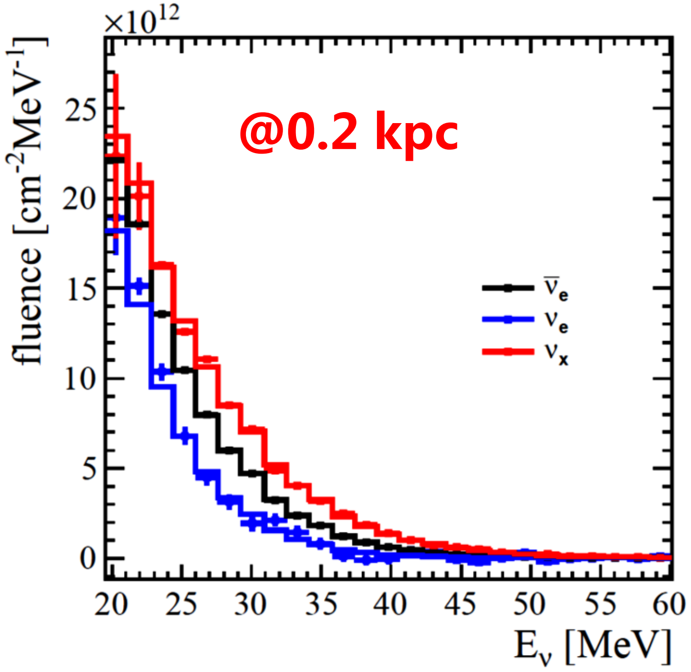


Li², Wang, Wen, Zhou, PRD, 18

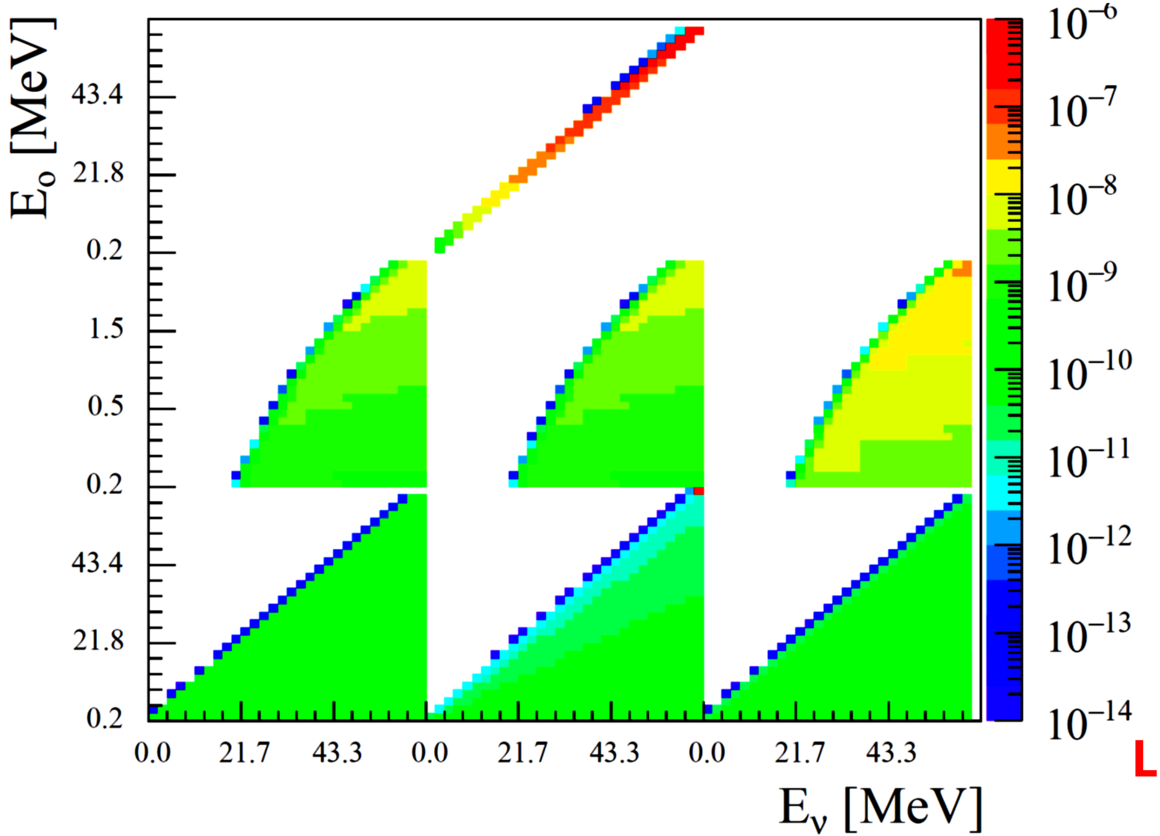
- Reconstruct all SN spectra in a single LS detector (JUNO)
- Full consideration of detector response (e.g., E resolution)
- SVD w. proper regularizations





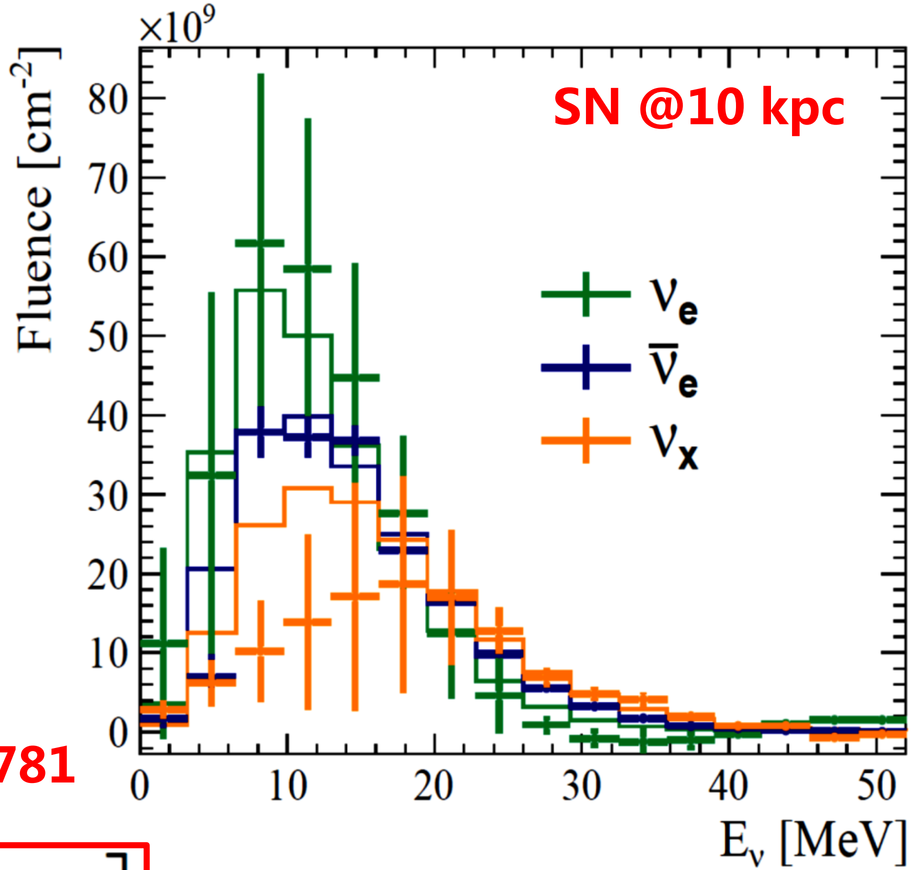


Part C: Reconstruction of Neutrino Spectra with JUNO



Overall detector response matrix

Li *et al.*, 1903.04781



$$\begin{bmatrix} N_{\mathrm{p}}\boldsymbol{D}_{\mathrm{IBD}}\boldsymbol{\sigma}^{\mathrm{IBD}}_{\nu_e} & N_{\mathrm{p}}\boldsymbol{D}_{\mathrm{IBD}}\boldsymbol{\sigma}^{\mathrm{IBD}}_{\overline{\nu}_e} & N_{\mathrm{p}}\boldsymbol{D}_{\mathrm{IBD}}\sum\boldsymbol{\sigma}^{\mathrm{IBD}}_{\nu_x} \\ N_{\mathrm{p}}\boldsymbol{D}_{p\mathrm{ES}}\boldsymbol{\sigma}^{p\mathrm{ES}}_{\nu_e} & N_{\mathrm{p}}\boldsymbol{D}_{p\mathrm{ES}}\boldsymbol{\sigma}^{p\mathrm{ES}}_{\overline{\nu}_e} & N_{\mathrm{p}}\boldsymbol{D}_{p\mathrm{ES}}\sum\boldsymbol{\sigma}^{p\mathrm{ES}}_{\nu_x} \\ N_{\mathrm{e}}\boldsymbol{D}_{e\mathrm{ES}}\boldsymbol{\sigma}^{e\mathrm{ES}}_{\nu_e} & N_{\mathrm{e}}\boldsymbol{D}_{e\mathrm{ES}}\boldsymbol{\sigma}^{e\mathrm{ES}}_{\overline{\nu}_e} & N_{\mathrm{e}}\boldsymbol{D}_{e\mathrm{ES}}\sum\boldsymbol{\sigma}^{e\mathrm{ES}}_{\nu_x} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{F}_{\nu_e} \\ \boldsymbol{F}_{\overline{\nu}_e} \\ \boldsymbol{F}_{\nu_x} \end{bmatrix} = \begin{bmatrix} \boldsymbol{S}_{\mathrm{IBD}} \\ \boldsymbol{S}_{p\mathrm{ES}} \\ \boldsymbol{S}_{e\mathrm{ES}} \end{bmatrix}$$

Event spectra

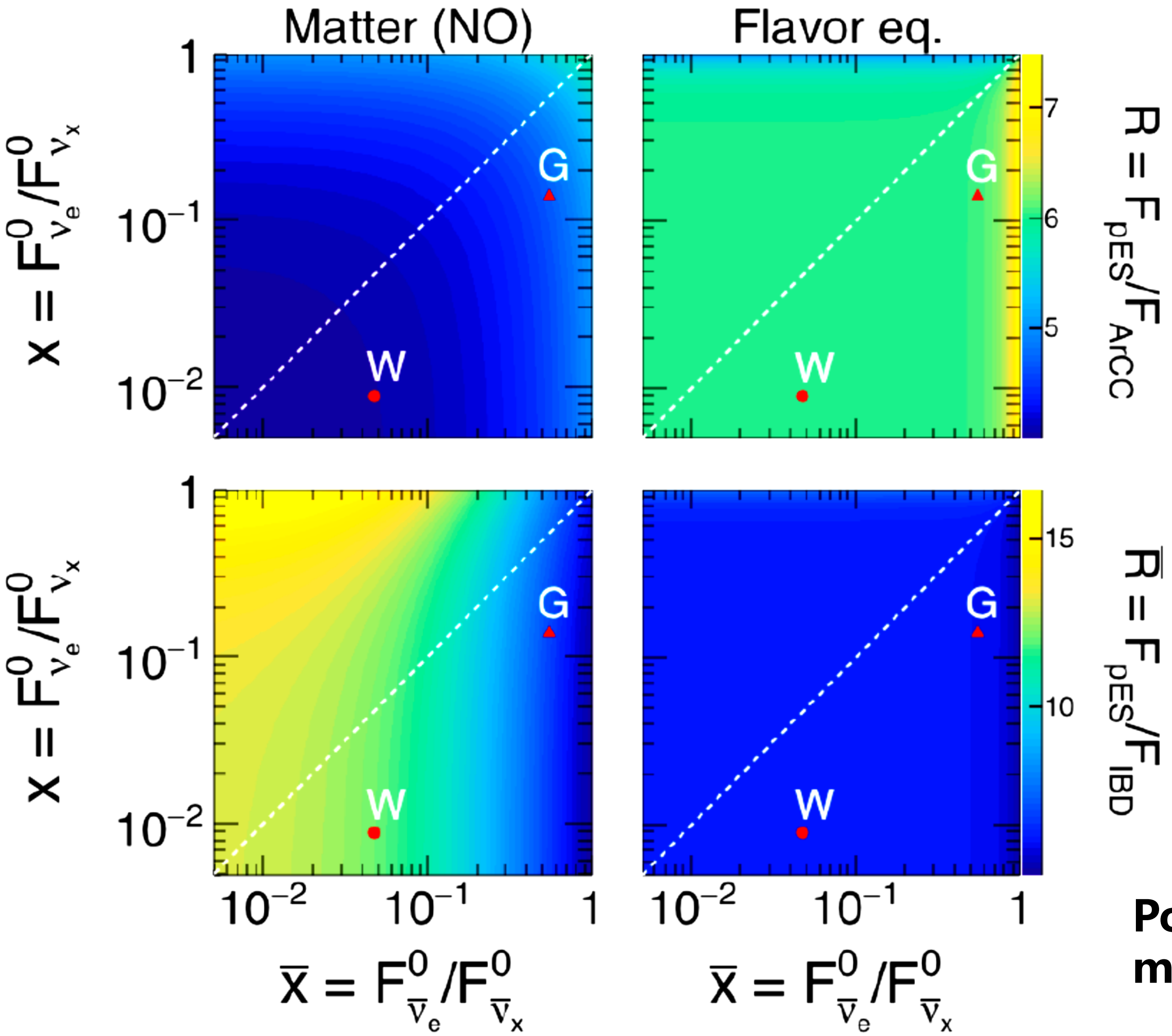
$$\boldsymbol{S}_{\mathrm{c}} = \begin{bmatrix} \boldsymbol{S}_{\mathrm{IBD}} \\ \boldsymbol{S}_{p\mathrm{ES}} \\ \boldsymbol{S}_{e\mathrm{ES}} \end{bmatrix}$$

Energy spectra

$$\boldsymbol{F}_{\mathrm{c}} = \begin{bmatrix} \boldsymbol{F}_{\nu_e} \\ \boldsymbol{F}_{\overline{\nu}_e} \\ \boldsymbol{F}_{\nu_x} \end{bmatrix}$$

Part C: Reconstruction via JUNO, Hyper-K and DUNE

Capozzi, Dasgupta, Mirizzi, PRD, 2018



Diagnosing the neutrino flavor equilibration

$$R = \frac{F_{\rm pES}}{F_{\rm ArCC}} = \frac{4 + x + \bar{x}}{P_{ee}x + (1 - P_{ee})} = \begin{cases} \frac{4}{1-P_{ee}} & x, \bar{x} \ll 1 \\ \frac{4+\bar{x}}{1-P_{ee}} & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}$$

$$\bar{R} = \frac{F_{\rm pES}}{F_{\rm IBD}} = \frac{4 + x + \bar{x}}{\bar{P}_{ee}\bar{x} + (1 - \bar{P}_{ee})} = \begin{cases} \frac{4}{1-\bar{P}_{ee}} & x, \bar{x} \ll 1 \\ \frac{4+\bar{x}}{\bar{P}_{ee}\bar{x}+1-\bar{P}_{ee}} & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}$$

Scenario	Mass Ordering	P_{ee}	$\bar{P}_{ee}$
ME	NO	0	$\cos^2\theta_{12} \simeq 0.7$
ME	IO	$\sin^2\theta_{12} \simeq 0.3$	0
FE	either	$1/3 \simeq 0.33$	$1/3 \simeq 0.33$

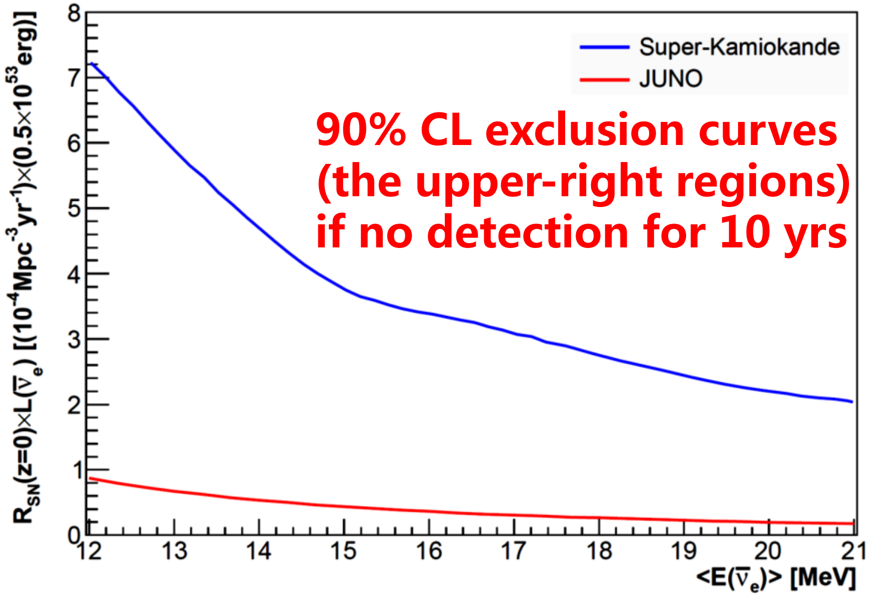
Possible to discriminate between the scenarios of matter effect (ME-NO) and flavor equilibration

Summary & Outlook

- **JUNO will provide a unique opportunity to detect SN ν_x neutrinos via pES, important for a lot of physics studies (independent of flavor conversions, total energy release, etc.)**
- **Give the priority to DSNB, a guaranteed source of SN neutrinos. We have the SK with Gd doping, and JUNO (available within 2 years) also has a very good chance.**

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$2.3\,\sigma$	$2.5\,\sigma$	$2.0\,\sigma$	$2.3\,\sigma$
15 MeV	$3.5\,\sigma$	$3.7\,\sigma$	$3.2\,\sigma$	$3.3\,\sigma$
18 MeV	$4.6\,\sigma$	$4.8\,\sigma$	$4.1\,\sigma$	$4.3\,\sigma$
21 MeV	$5.5\,\sigma$	$5.8\,\sigma$	$4.9\,\sigma$	$5.1\,\sigma$

- Observation window: 11 MeV < E_ν < 30 MeV
- PSD techniques for NC atmospheric ν
- Fast neutrons: r < 16.8 m (equiv. 17 kt mass)



90% CL exclusion curves
(the upper-right regions)
if no detection for 10 yrs

- **Fine with detectors, which take SN neutrino detection as a second physics goal. For JUNO, neutrino mass ordering fixed within 6 yrs, precision measurements <1% within 3yrs. Then, what we should do with JUNO? (Neutrinoless double-beta decays)**
- **Dark matter detectors probe SN neutrinos! (Lang et al., PRD, 2016)**

Thanks!