Full-flavor reconstruction of supernova neutrino energy spectra

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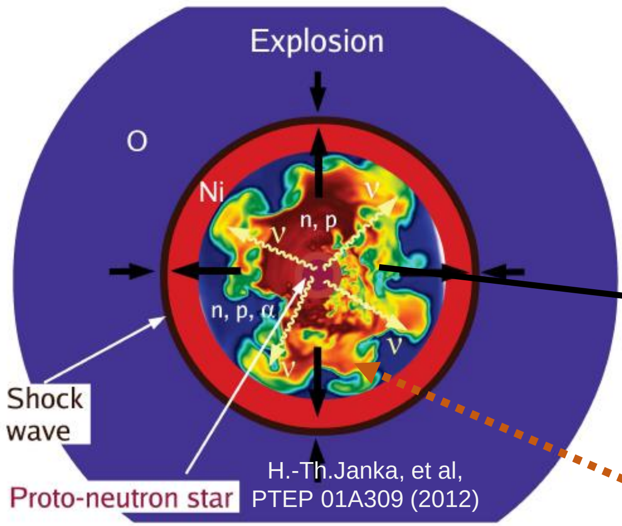
arXiv:1712.06985 **arXiv:1903.04781**

Motivation



Fast/Slow collective oscillation,
MSW effect, Interstellar decoherence,
Regeneration at earth
…

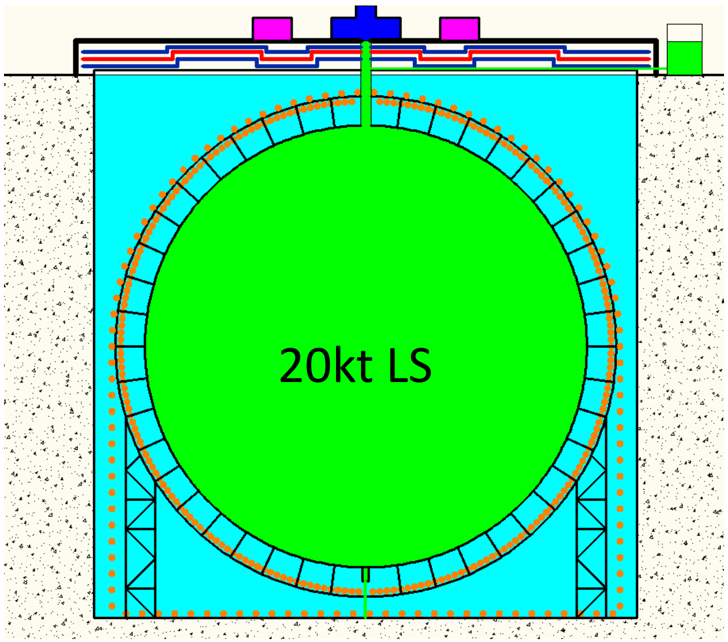
Flavor conversions ?

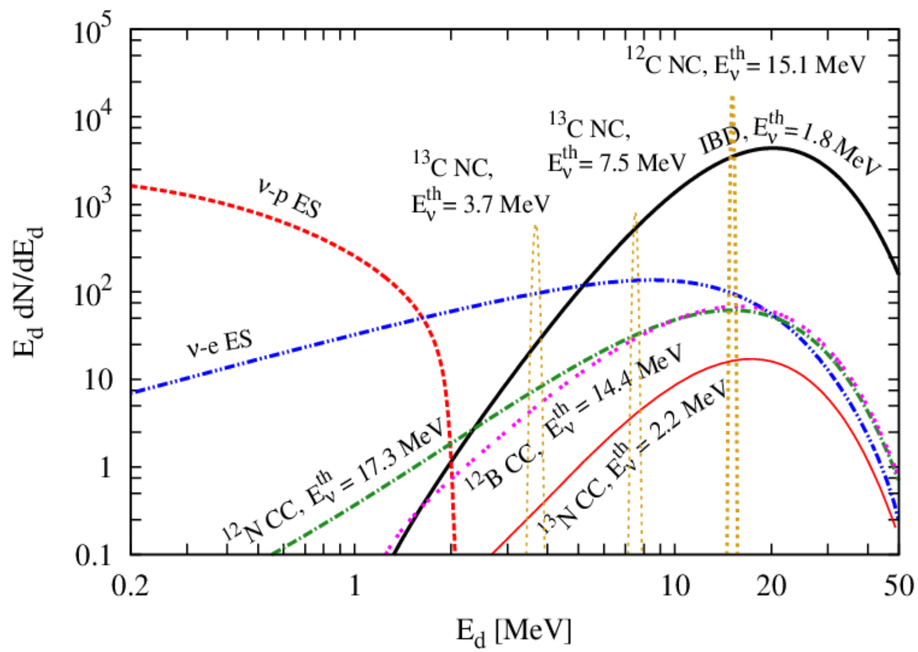
Goal

Reconstruct the energy spectra of each flavor neutrinos from SN

Detected spectra in one or several detectors on the earth

Detection of SN neutrinos in JUNO





- Low energy threshold ~0.2MeV in JUNO LS and full flavor information recorded
- IBD events dominate the high energy range, the golden channel
- ν-p ES events dominate the low energy range

Outline

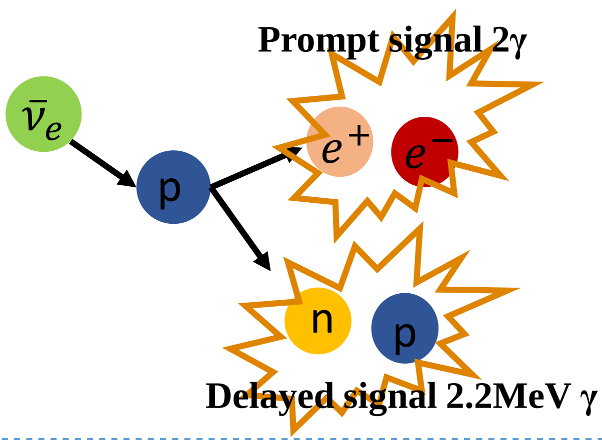
- The separated approach
  - Beacom, Farr, Vogel (2003),
  - Dasgupta and Beacom (2011),
  - Li, Li, Wang, Wen, Zhou (2017)
- The combined approach
  - Li, Huang, Li, Wen, Zhou (2019)
- Summary

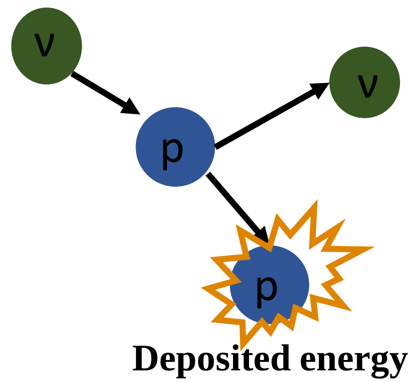
The separated approach

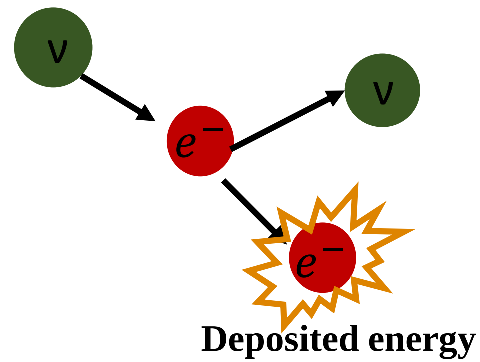
Detected spectra->Unfolded spectra of each channel->Separated flavor spectra

Detection channels in LS

(IBD) $\overline{\nu}_e + p \rightarrow e^+ + n$ (pES) $\nu + p \rightarrow \nu + p$ (eES) $\nu + e \rightarrow \nu + e$







$$\frac{dN_{IBD}}{dE_o} = N_p \int_{E_{min}}^{\infty} dE_{\overline{\nu}_e} \frac{dF_{\overline{\nu}_e}}{dE_{\overline{\nu}_e}} \sigma_{IBD}(E_{\overline{\nu}_e}) G(E_o; E_\nu, \delta_E)$$

Only for $\overline{\nu}_e$

$$\frac{dN_{pES}}{dE_o} = N_p \sum_{\alpha} \int_0^{\infty} dT_q \cdot G(E_o; T_q, \delta_E) \int_{E_\alpha}^{\infty} \frac{dF_\alpha}{dE_\alpha} \cdot \frac{d\sigma_{\nu p}}{dT_p} dE_\alpha$$

For **all flavor** neutrinos

$$\frac{dN_{eES}}{dE_o} = N_e \sum_{\alpha} \int_0^{\infty} dT \cdot G(E_o; T, \delta_E) \int_{E_\alpha}^{\infty} \frac{dF_\alpha}{dE_\alpha} \cdot \frac{d\sigma_{\alpha e}}{dT_e} dE_\alpha$$

Detected spectra —Unfolding→ **True spectra of different channels** —Separation→ **Energy spectra for each flavor**

Unfolding of observed spectra

$$\frac{dN_{pES}}{dE_o} = N_p \sum_\alpha \int_0^\infty dT_q \cdot G(E_o; T_q, \delta_E) \int_{E_\alpha}^\infty \frac{dF_\alpha}{dE_\alpha} \cdot \frac{d\sigma_{\nu p}}{dT_p} dE_\alpha$$

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

No flavor conversion considered

SN neutrino E_ν

Cross section

Recoiled proton energy T_P

Quenching effect

Visible energy T_q

Energy resolution

Observed energy E_o

Unfolding

Neutrino detection in LS

Unfolding belongs to the linear inverse problem:

$$Ax = b \;\rightarrow x = A^{-1}b$$

- Usually direct inverse result has large fluctuations and is unstable.
- Regularization: SVD unfolding method

For IBD channel

$$N_p \cdot \boldsymbol{D}_{IBD} \cdot \boldsymbol{\sigma}_{\overline{\nu}_e}^{IBD} \cdot \boldsymbol{F}_{\overline{\nu}_e} = \boldsymbol{S}_{IBD}$$

Detector effects $E_o \leftarrow T_f$

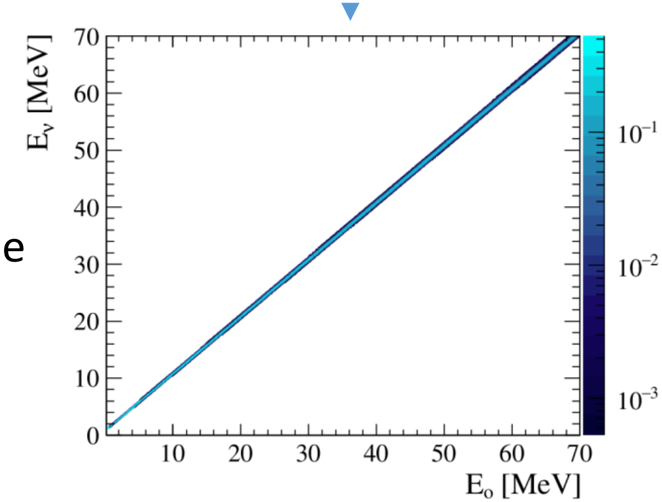
Cross section $T_f \leftarrow E_\nu$

Weighted SN neutrino spectra E_ν

Observed spectra E_o

$$\begin{bmatrix} D_{11}^{IBD} & \cdots & D_{1n_\nu}^{IBD} \\ \vdots & \ddots & \\ D_{n_o1}^{IBD} & \cdots & D_{n_on_\nu}^{IBD} \end{bmatrix} \cdot \begin{bmatrix} \sigma_{11}^{\overline{\nu}_e}/\sigma_1 & \cdots & \sigma_{1n_\nu}^{\overline{\nu}_e}/\sigma_{n_\nu} \\ \vdots & \ddots & \\ \sigma_{n_V}^{\overline{\nu}_e}/\sigma_1 & \cdots & \sigma_{n_Vn_\nu}^{\overline{\nu}_e}/\sigma_{n_\nu} \end{bmatrix} \cdot \begin{bmatrix} N_p\sigma_1 F_{11}^{\overline{\nu}_e} \\ \vdots \\ N_p\sigma_{n_\nu} F_{1n_\nu}^{\overline{\nu}_e} \end{bmatrix} = \begin{bmatrix} S_{11}^{IBD} \\ \vdots \\ S_{1n_o}^{IBD} \end{bmatrix}$$

Response Matrix



$$\boldsymbol{R}_{IBD} \cdot \widehat{\boldsymbol{F}}_{\overline{\nu}_e}^{IBD} = \boldsymbol{S}_{IBD}$$

IBD

For ES channel

$$N_{p(e)} \cdot \boldsymbol{D}_{p(e)ES} \cdot \sum \boldsymbol{\sigma}_{\alpha}^{p(e)ES} \cdot \boldsymbol{F}_{\alpha} = \boldsymbol{S}_{p(e)ES}$$

Detector effects $E_o \leftarrow T_f$

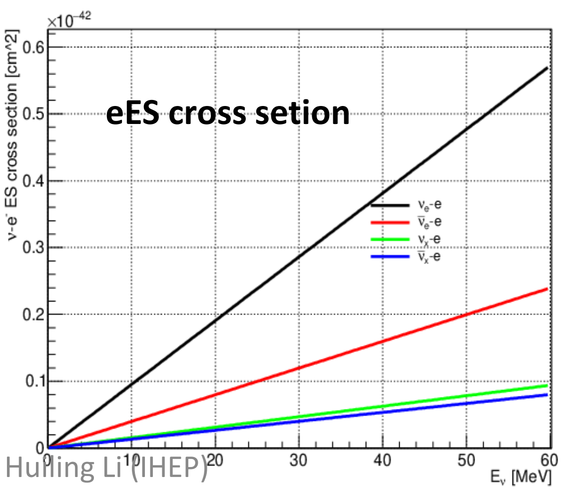
Cross section $T_f \leftarrow E_\nu$

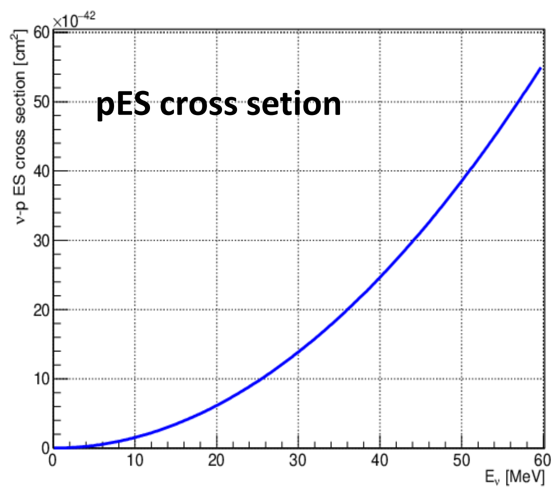
Weighted SN neutrino spectra E_ν

Observed spectra E_o

$$\begin{bmatrix} D_{11}^{ES} & \cdots & D_{1n_\nu}^{ES} \\ \vdots & \ddots & \\ D_{n_o1}^{ES} & \cdots & D_{n_on_\nu}^{ES} \end{bmatrix} \cdot \sum_{\alpha} \begin{bmatrix} \sigma_{11}^{\alpha}/\sigma_1 & \cdots & \sigma_{1n_\nu}^{\alpha}/\sigma_{n_\nu} \\ \vdots & \ddots & \\ \sigma_{n_\nu}^{\alpha}/\sigma_1 & \cdots & \sigma_{n_\nu n_\nu}^{\alpha}/\sigma_{n_\nu} \end{bmatrix} \cdot \begin{bmatrix} N\sigma_1 F_{11}^{\alpha} \\ \vdots \\ N\sigma_{n_\nu} F_{1n_\nu}^{\alpha} \end{bmatrix} = \begin{bmatrix} S_{11}^{ES} \\ \vdots \\ S_{1n_o}^{ES} \end{bmatrix}$$

If the cross section for different flavors are approximately equal.





This this true for pES but not eES.

For ES channel

$$N_{p(e)} \cdot \boldsymbol{D}_{p(e)ES} \cdot \sum \boldsymbol{\sigma}_{\alpha}^{p(e)ES} \cdot \boldsymbol{F}_{\alpha} = \boldsymbol{S}_{p(e)ES}$$

Detector effects $E_o \leftarrow T_f$

Cross section $T_f \leftarrow E_\nu$

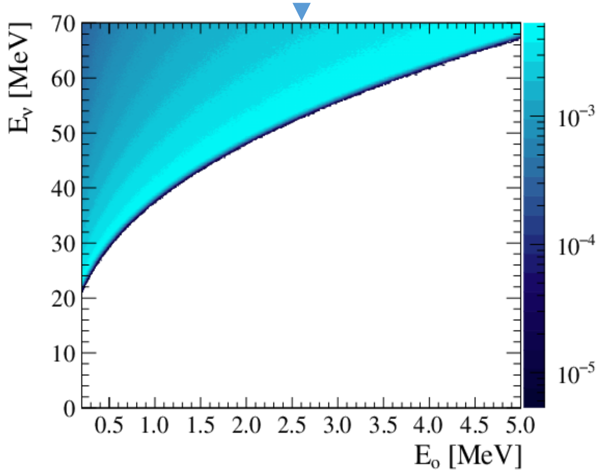
Weighted SN neutrino spectra E_ν

Observed spectra E_o

$$\begin{bmatrix} D_{11}^{ES} & \cdots & D_{1n_\nu}^{ES} \\ \vdots & \ddots & \\ D_{n_o 1}^{ES} & \cdots & D_{n_o n_\nu}^{ES} \end{bmatrix} \cdot \sum_{\alpha} \begin{bmatrix} \sigma_{11}^{\alpha}/\sigma_1 & \cdots & \sigma_{1n_\nu}^{\alpha}/\sigma_{n_\nu} \\ \vdots & \ddots & \\ \sigma_{n_V}^{\alpha}/\sigma_1 & \cdots & \sigma_{n_V n_\nu}^{\alpha}/\sigma_{n_\nu} \end{bmatrix} \cdot \begin{bmatrix} N\sigma_1 F_{11}^{\alpha} \\ \vdots \\ N\sigma_{n_\nu} F_{1n_\nu}^{\alpha} \end{bmatrix} = \begin{bmatrix} S_{11}^{ES} \\ \vdots \\ S_{1n_o}^{ES} \end{bmatrix}$$

After extract the sum sign

Response Matrix



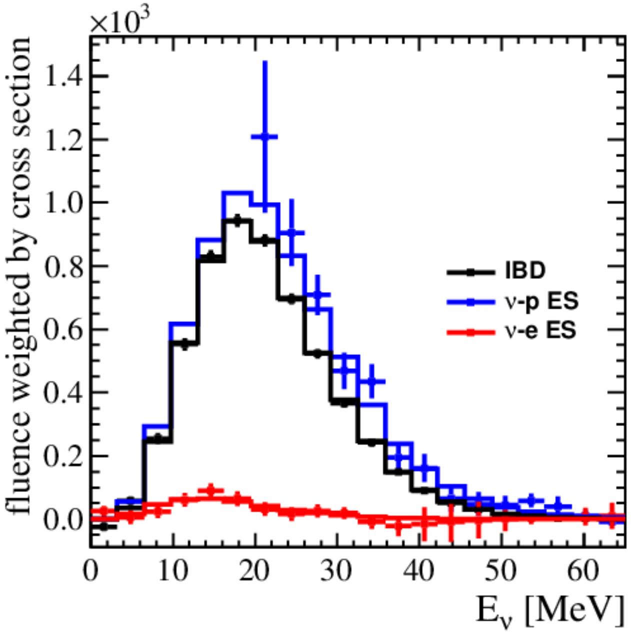
$$\boldsymbol{R}_{ES} \cdot \sum \widehat{\boldsymbol{F}}_{\alpha}^{ES} = \boldsymbol{S}_{ES}$$

Approximation

pES

eES

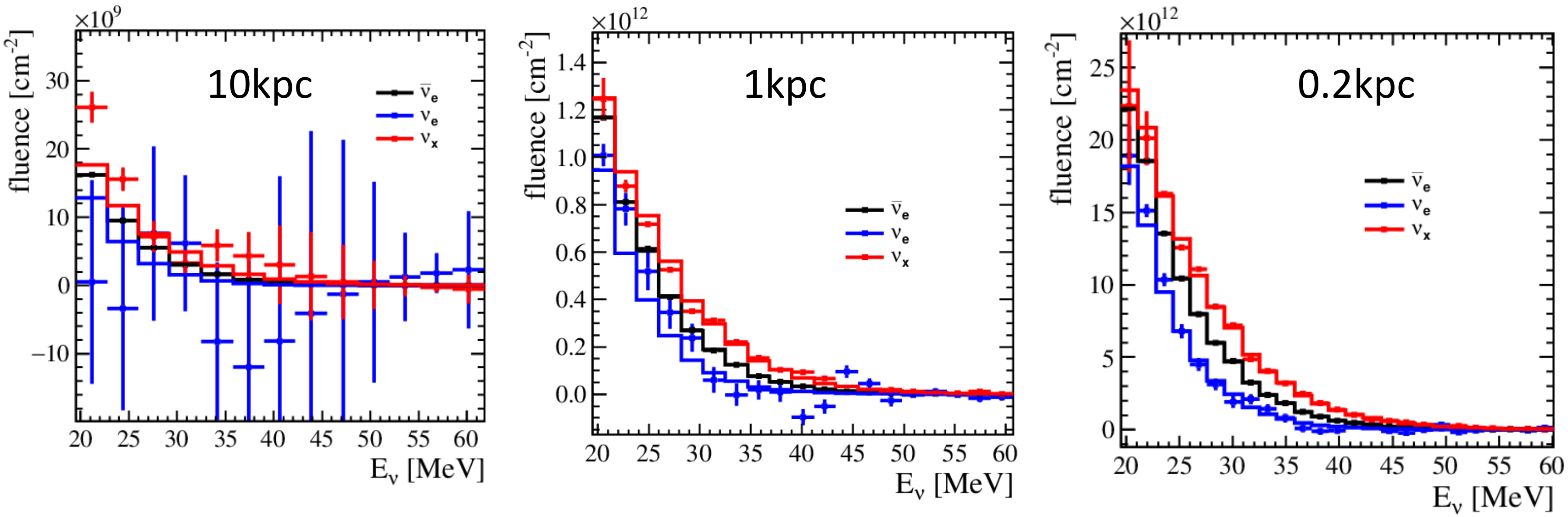
Unfolded results



SN@10kpc
3% energy resolution
0.2MeV detected energy threshold

$$n_{IBD}(E_\nu^i) = N_p \sigma_{IBD}(E_\nu^i) F_{\overline{\nu}_e}(E_\nu^i)$$
$$n_{pES}(E_\nu^i) = N_p\left[\sigma_{\nu_e p}(E_\nu^i) F_{\nu_e}(E_\nu^i) + \sigma_{\overline{\nu}_e p}(E_\nu^i) F_{\overline{\nu}_e}(E_\nu^i) + 4\sigma_{\nu_x p}(E_\nu^i) F_{\nu_x}(E_\nu^i)\right]$$
$$n_{eES}(E_\nu^i) = N_e\left[\sigma_{\nu_e e}(E_\nu^i) F_{\nu_e}(E_\nu^i) + \sigma_{\overline{\nu}_e e}(E_\nu^i) F_{\overline{\nu}_e}(E_\nu^i) + 4\sigma_{\nu_x e}(E_\nu^i) F_{\nu_x}(E_\nu^i)\right]$$

Separation of different flavor spectra



It is possible to reconstruct energy spectra for each flavor of SN neutrinos in JUNO LS detector.

- More accurately treatment with eES?
- Combine with other experiment data?
- SN neutrinos with flavor conversions?

The combined approach

The combined approach

Directly extract spectra for each flavor of SN neutrinos

The combined approach

Cross section && Detector effects

SN neutrinos spectra

Observed spectra

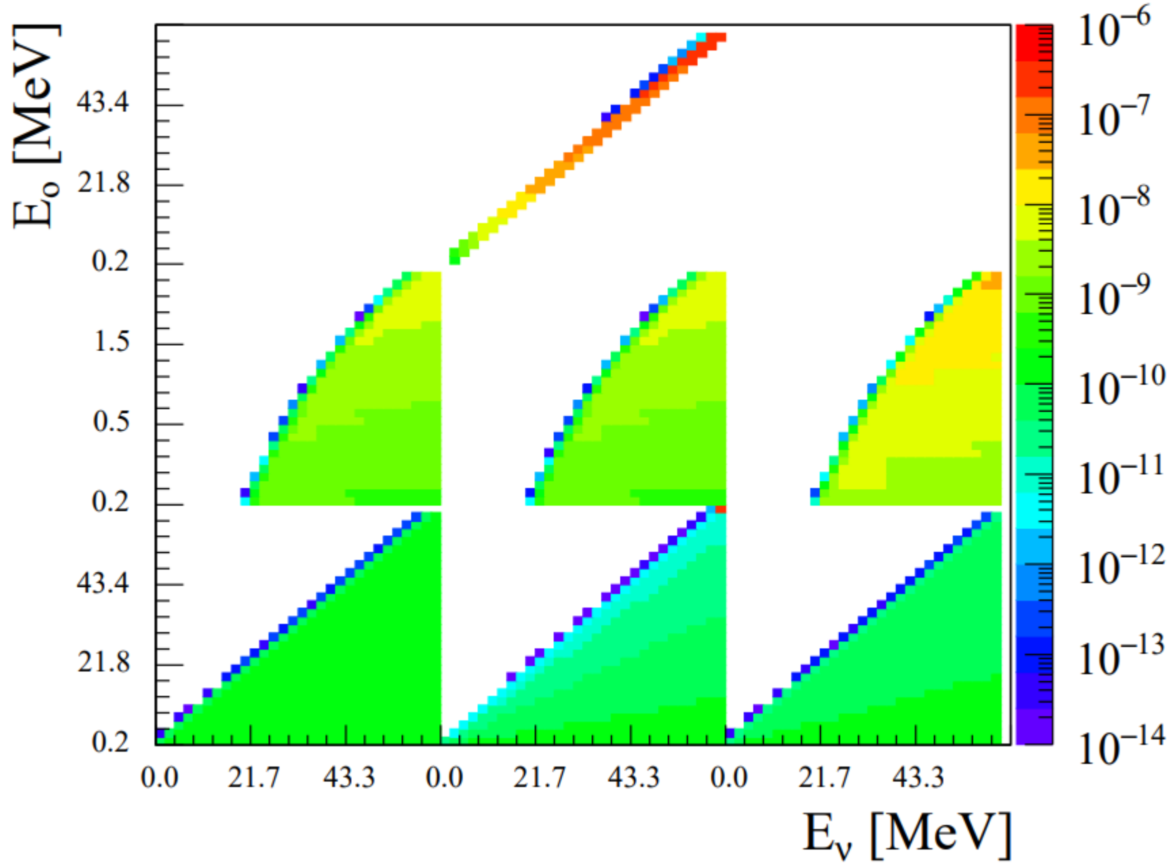
$$\begin{bmatrix} N_\mathrm{p}\boldsymbol{D}_\mathrm{IBD}\boldsymbol{\sigma}^\mathrm{IBD}_{\nu_e} & N_\mathrm{p}\boldsymbol{D}_\mathrm{IBD}\boldsymbol{\sigma}^\mathrm{IBD}_{\overline{\nu}_e} & N_\mathrm{p}\boldsymbol{D}_\mathrm{IBD}\sum\boldsymbol{\sigma}^\mathrm{IBD}_{\nu_x} \\ N_\mathrm{p}\boldsymbol{D}_{p\mathrm{ES}}\boldsymbol{\sigma}^{p\mathrm{ES}}_{\nu_e}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

Model independent response matrix

It can be easily appended to other type detectors, i.e. WC and LAr-TPC.

Detected spectra of different channels —unfold→ Energy spectra of different flavor neutrinos

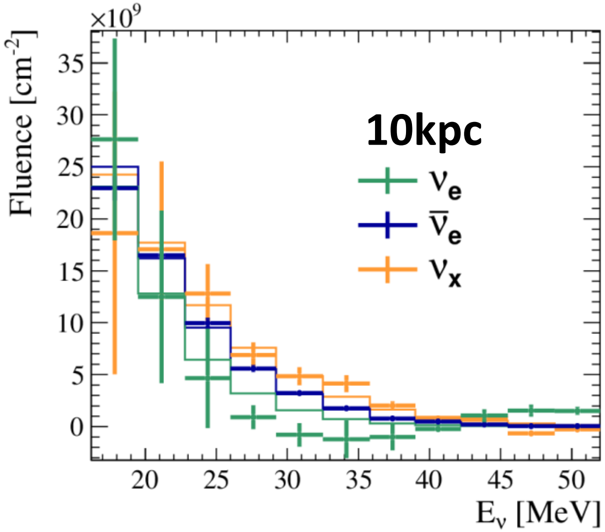
Response Matrix flat model

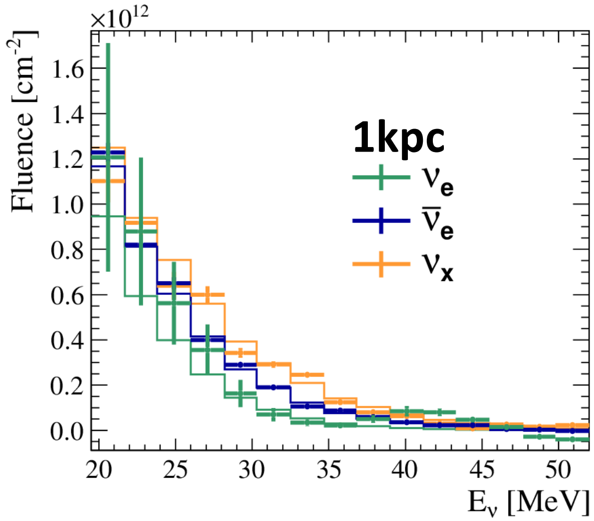


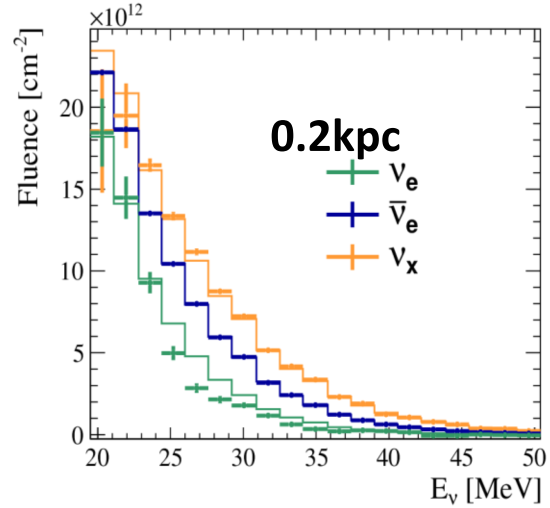
Flat model, 0.2 billion events
0.2MeV energy threshold,
3% energy resolution

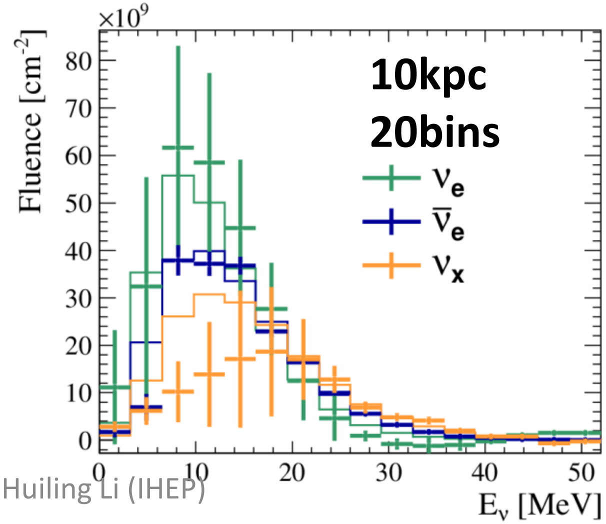
Reconstructed spectra

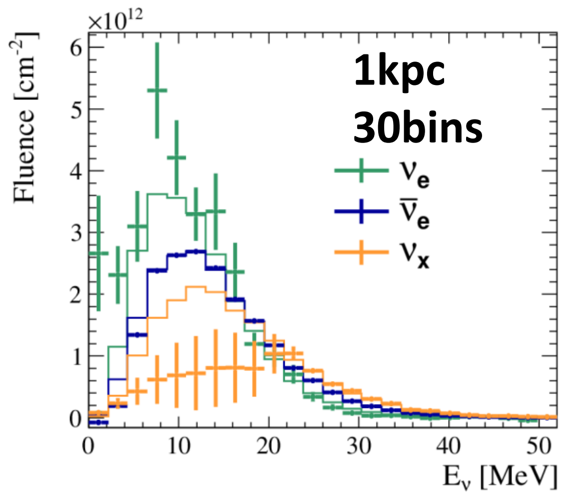
0.2MeV, 3% energy resolution ,analytical model

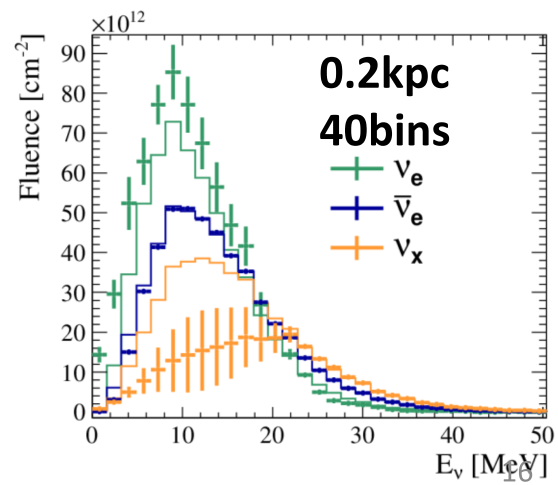




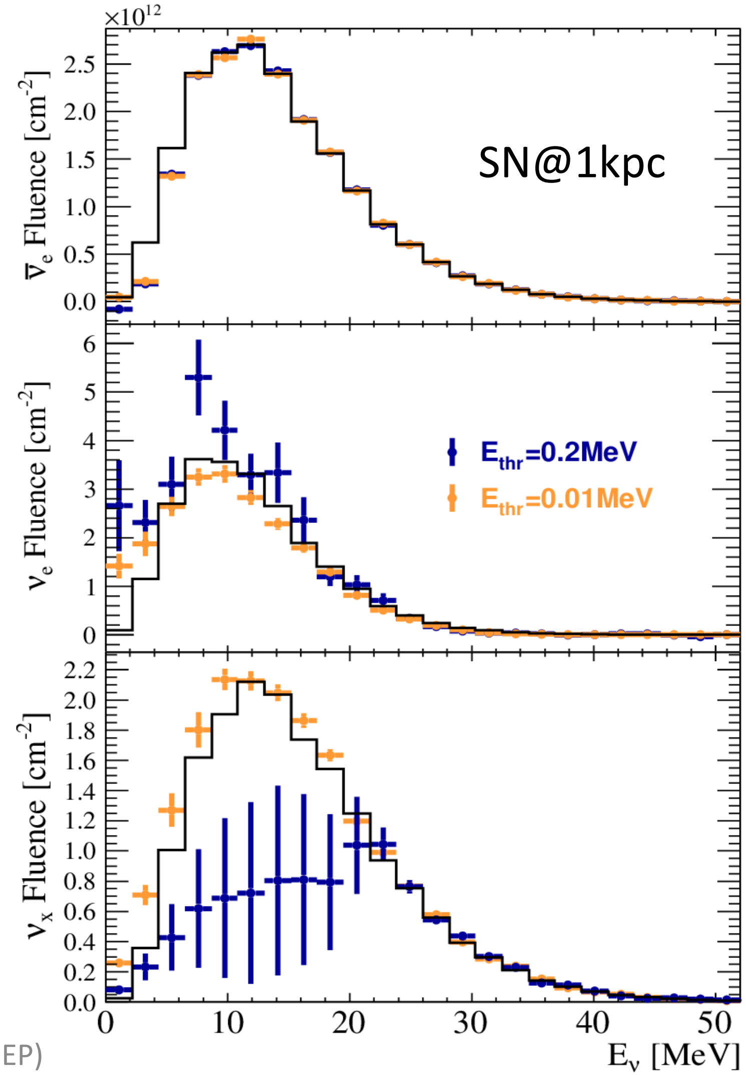








The impact of energy threshold



- A lower energy threshold can give more information about ν_x and ν_e spectra.
- There is a strategy in progress in JUNO to record all the information even the hits information below 0.2MeV, reserving space for new physics in the future.

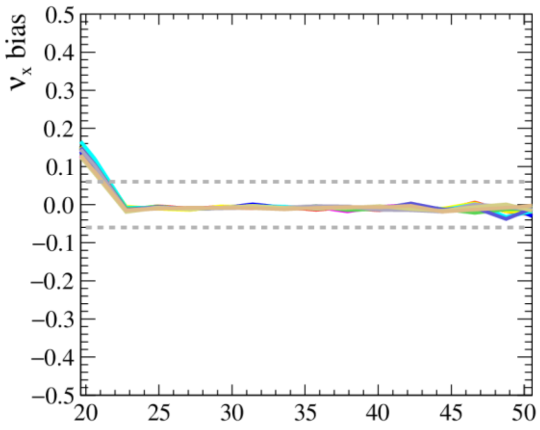
Check of Model independence

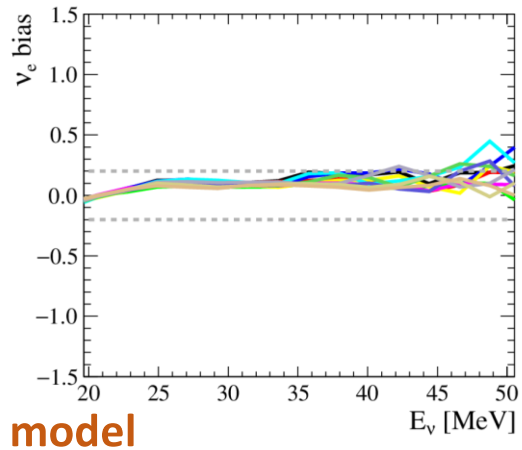
12 Japan models, SN@1kpc

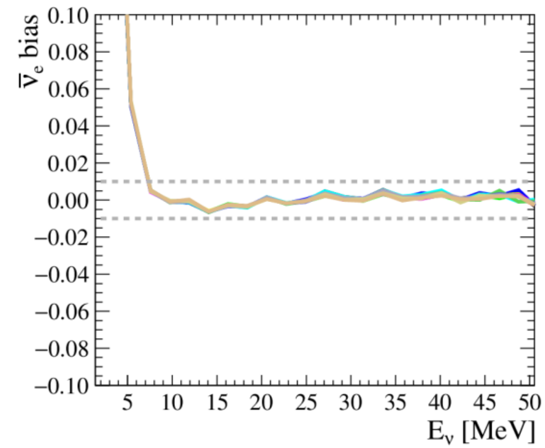
Nakazato et.al, http://asphwww.ph.noda.tus.ac.jp/snn/

$$\text{Averaged Bias} = \frac{1}{N}\sum_{k=1}^{N}\left[\frac{n_k^{\text{true}}(E_\nu^i) - n_k^{\text{reconstructed}}(E_\nu^i)}{n_k^{\text{true}}(E_\nu^i)}\right]$$

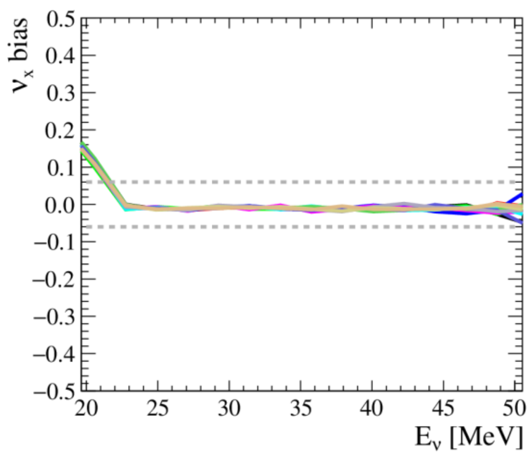
Response matrix from **Flat model**

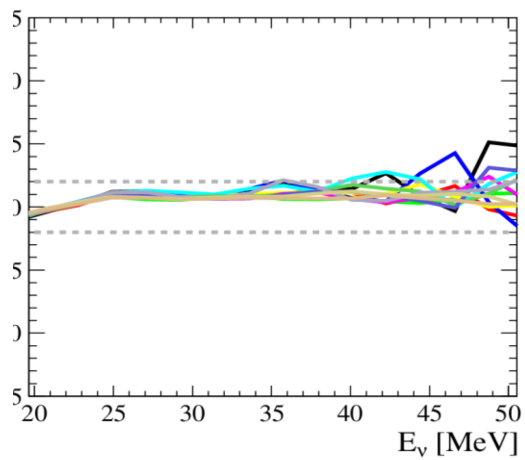


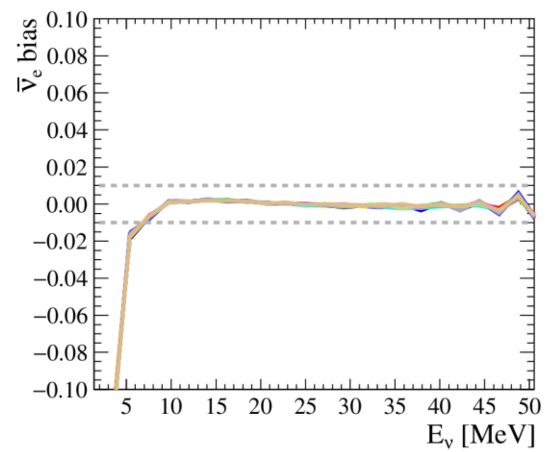




Response matrix from **each model**





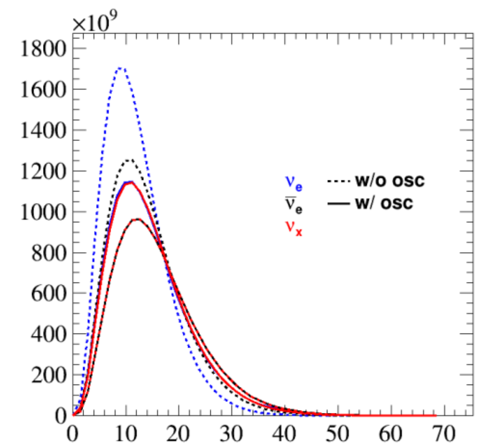


Flavor conversion from MSW effects

F_{ν_x}, $F^0_{\nu_x}$ is the flux for one flavor neutrino of μ , τ neutrinos and their antiparticles

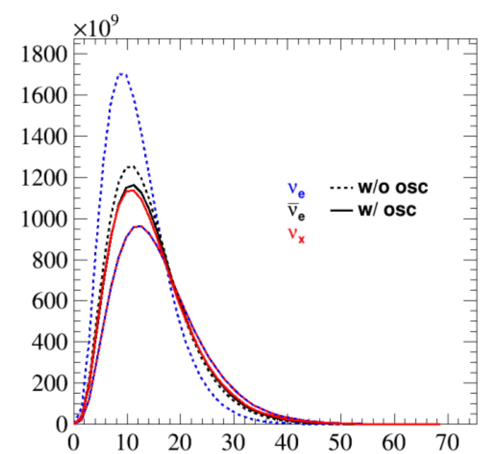
Normal hierarchy

$$\begin{bmatrix} F_{\nu_e} \\ F_{\bar{\nu}_e} \\ F_{\nu_x} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & cos^2\theta_{12} & sin^2\theta_{12} \\ \frac{1}{4} & \frac{1}{4} sin^2\theta_{12} & \frac{1}{4}(2 + cos^2\theta_{12}) \end{bmatrix} \begin{bmatrix} F^0_{\nu_e} \\ F^0_{\bar{\nu}_e} \\ F^0_{\nu_x} \end{bmatrix}$$



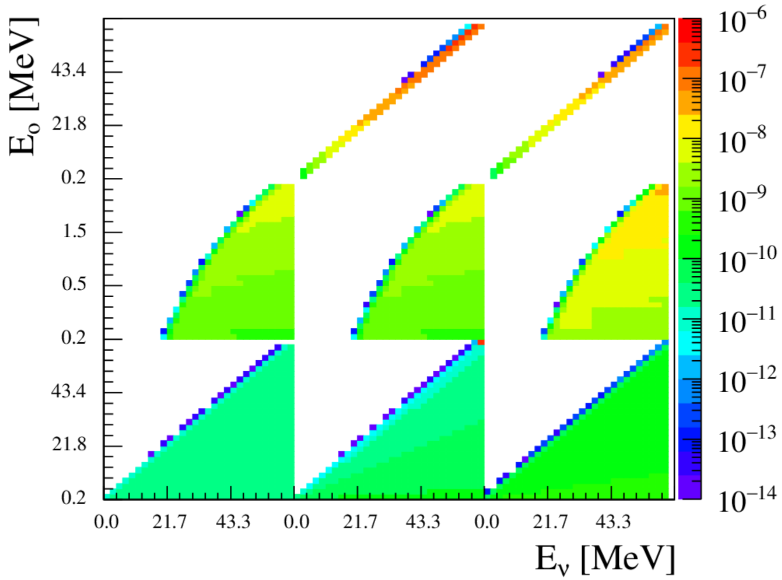
Inverted hierarchy

$$\begin{bmatrix} F_{\nu_e} \\ F_{\bar{\nu}_e} \\ F_{\nu_x} \end{bmatrix} = \begin{bmatrix} sin^2\theta_{12} & 0 & cos^2\theta_{12} \\ 0 & 0 & 1 \\ \frac{1}{4} cos^2\theta_{12} & \frac{1}{4} & \frac{1}{4}(2 + sin^2\theta_{12}) \end{bmatrix} \begin{bmatrix} F^0_{\nu_e} \\ F^0_{\bar{\nu}_e} \\ F^0_{\nu_x} \end{bmatrix}$$

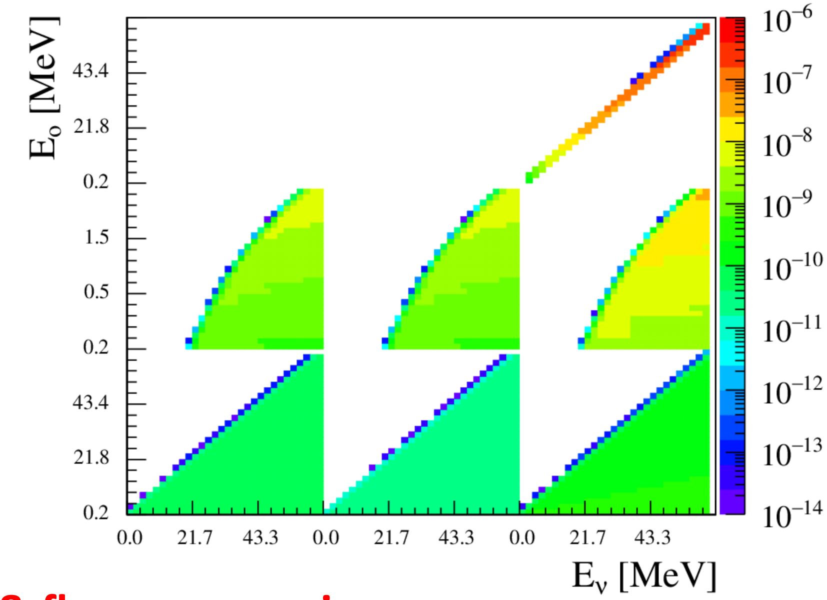


With flavor conversion

Normal hierarchy



Inverted hierarchy



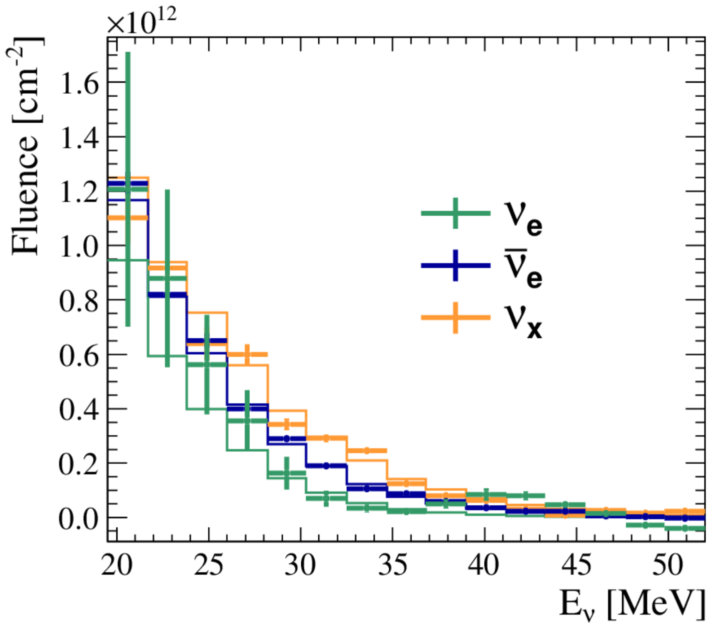
Response matrix && flavor conversion

$$R \cdot C \cdot F = S$$

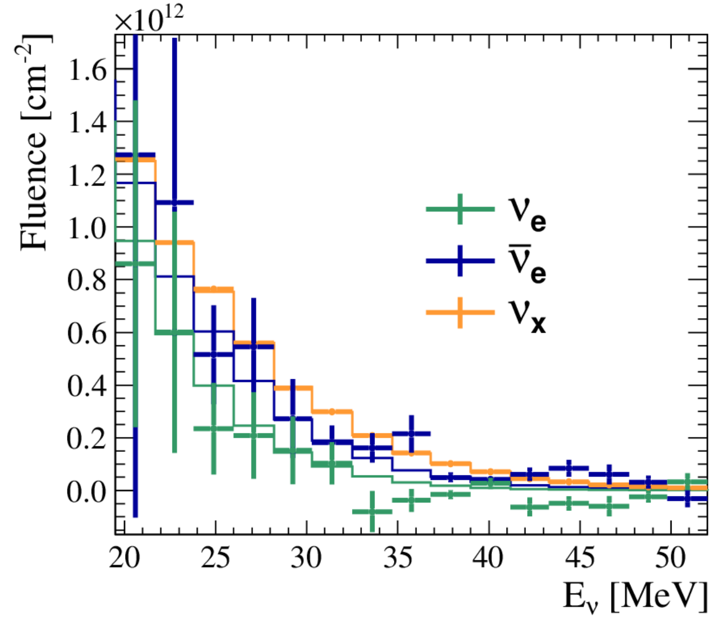
The original fluence

SN@1kpc

Normal hierarchy



Inverted hierarchy



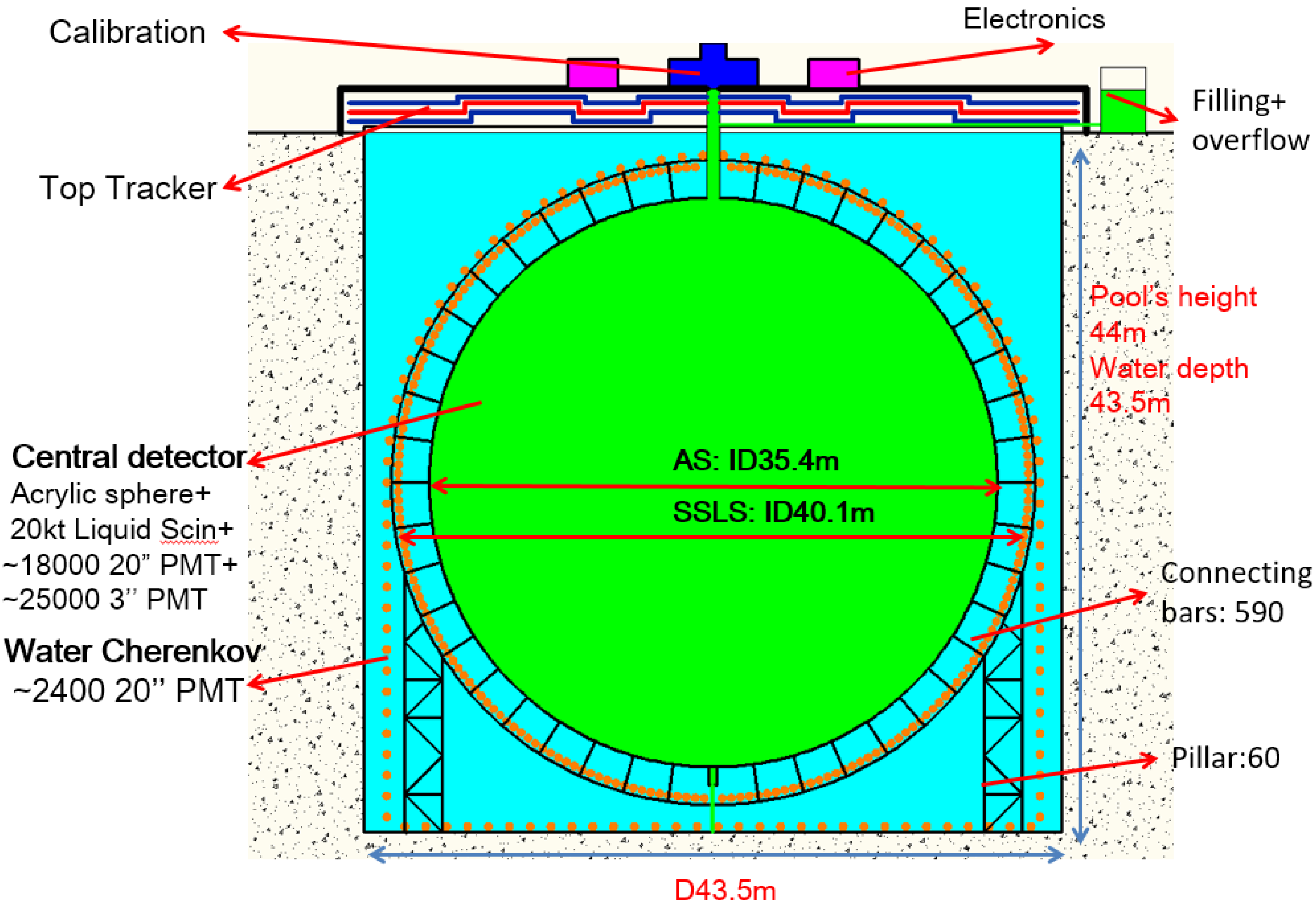
The original fluence from the core of the SN can be partially extracted.
This method is useful to check the models of neutrino oscillation.

Summary

- The combined approach is model independent and robust. It is possible to reconstruct full flavor energy spectra of SN neutrinos in one large LS detector.
- For more complicated scenarios with neutrino oscillations, the combined method is still useful to test models of neutrinos oscillations.
- The combined approach can easily include other type of detectors, e.g. WC (Super-K) and LAr-TPC (DUNE), to do a global analysis. It can also be used to reconstruct the spectra of solar neutrinos and ultrahigh-energy cosmic neutrinos when a large statistics in the multi-avor detection is accumulated.

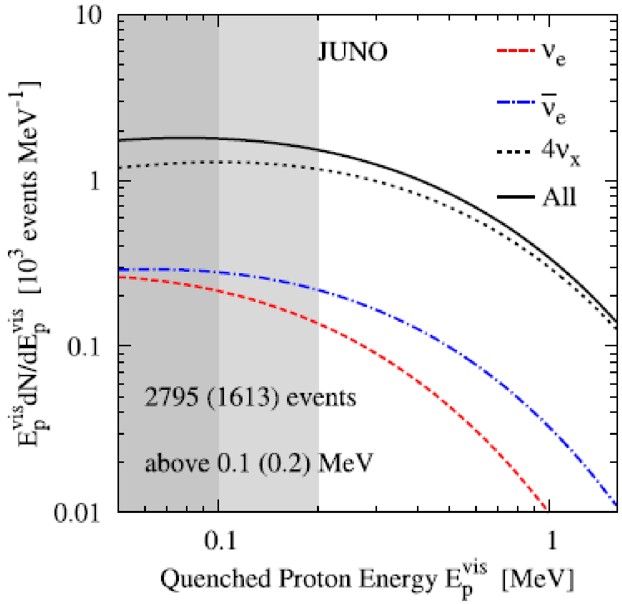
Backup

JUNO detector



AS: Acrylic sphere; SSLS: stainless steel latticed shell

Reconstruction of SN neutrino spectra



SN@10kpc, ν_x for non-electron neutrinos

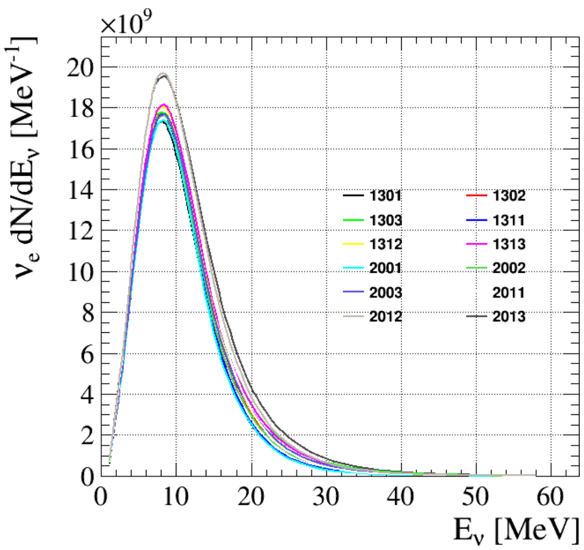
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

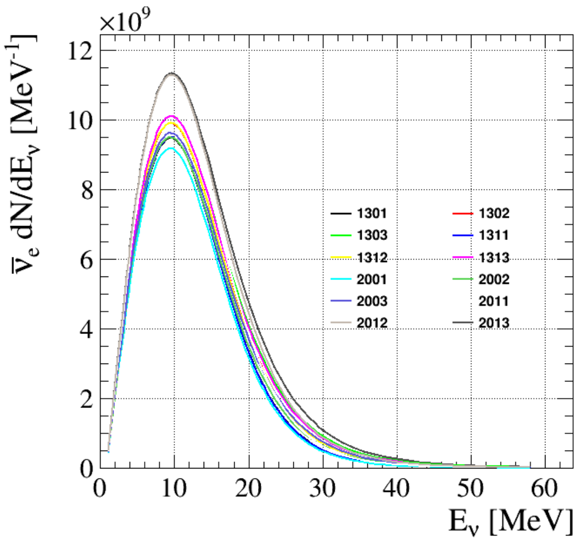
Li, Li, Wang, Wen, Zhou (2017)

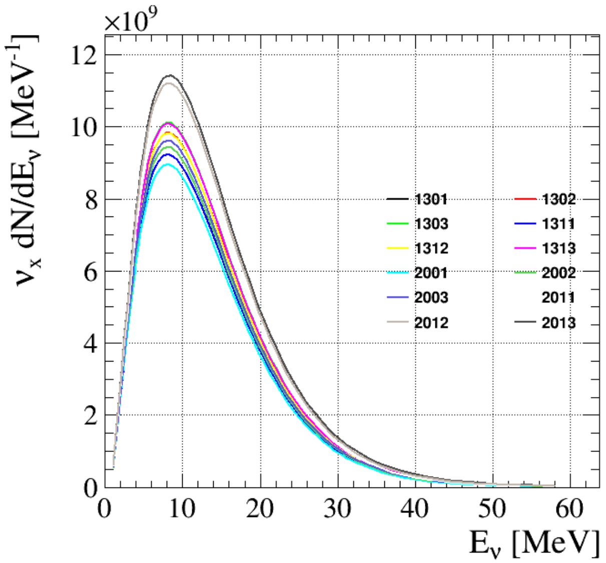
Parameterization fluence

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

Japan models, neutrinos before detector







SVD unfolding method

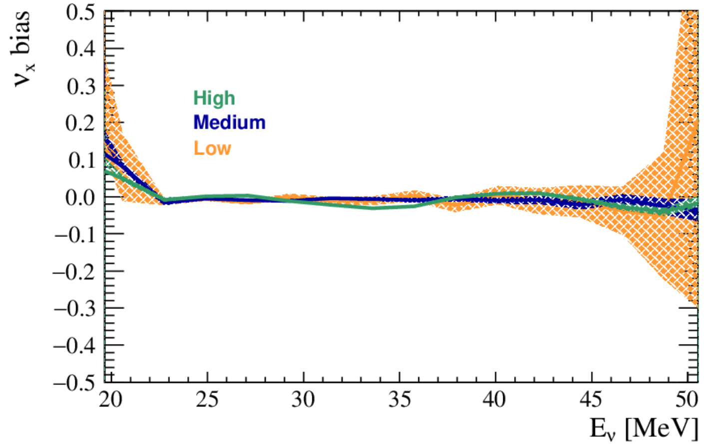
SVD unfolding method is to minimize the following chi-square equation to extract the true distribution:

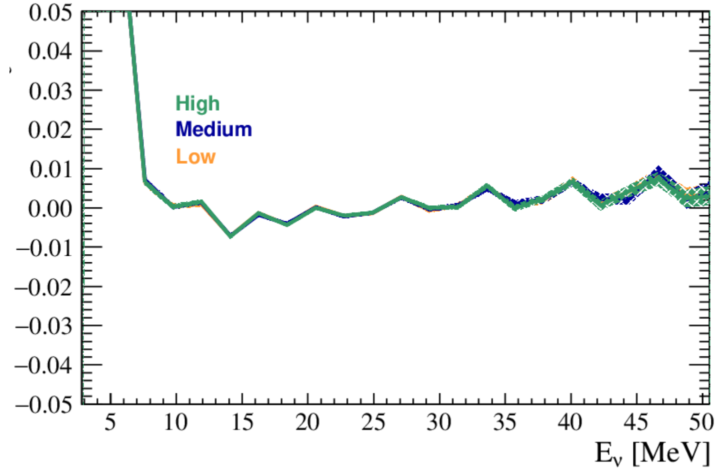
$$\chi^2 = (\tilde{A}w - \tilde{b})^T(\tilde{A}w - \tilde{b}) + \tau(Cw)^T(Cw)$$

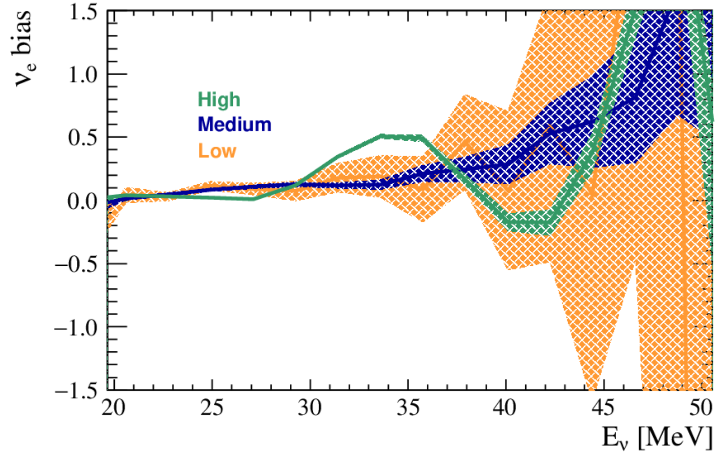
- $\tilde{A}$: **Response matrix**
- $\tilde{b}$: **Observed spectrum**
- w: $w_j = x_j/x_j^{ini}$, x_j^{ini} **is defined by the user**
- τ: **Regularization parameter** $\tau = s_k^2$
- $\tau(Cw)^T(Cw)$: **Penalty term**
- C: **Second derivative（curvature）**

SVD is used to calculate the inverse of a matrix.
Without the penalty term, the intrinsic operation of the unfolding procedure is still a linear inverse problem.

Regularization parameters







In this work, we choose a medium regularization parameter in the unfolding process.