Core-collapse Supernova Neutrino Detection at JUNO

Xin Huang (黄鑫) on behalf of JUNO

Tuesday, May 9, 2023

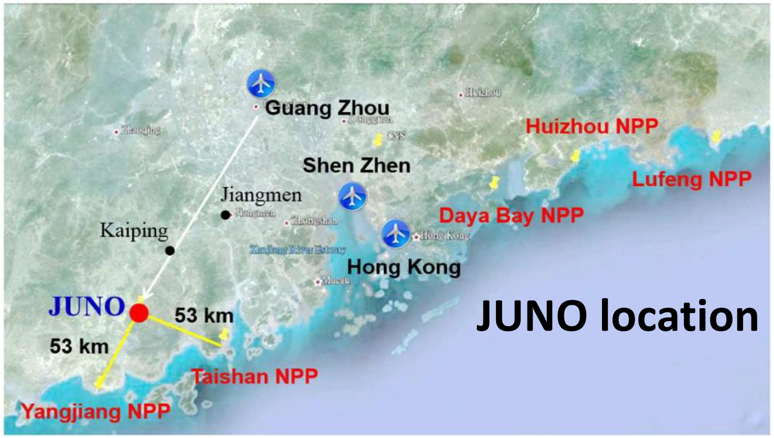
Outline

- JUNO experiment
- CCSN monitor system
- Energy spectra reconstruction
- Summary

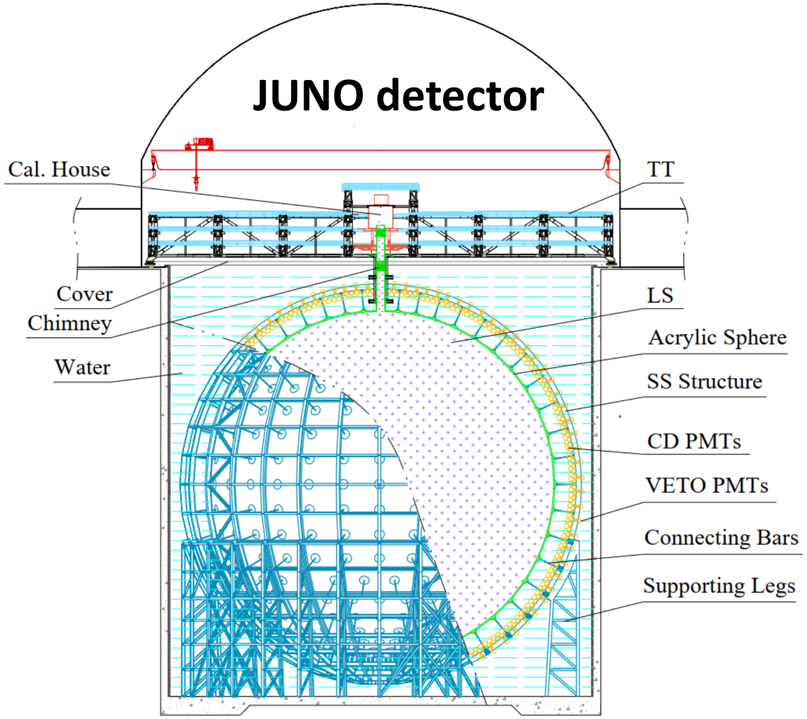
Introduction

JUNO experiment

- **JUNO detector:**
  - 20 kton LS
  - 30 kton water
  - 3% energy resolution @1MeV
  - ~17612 20-inch PMTs
  - ~25600 3-inch PMTs



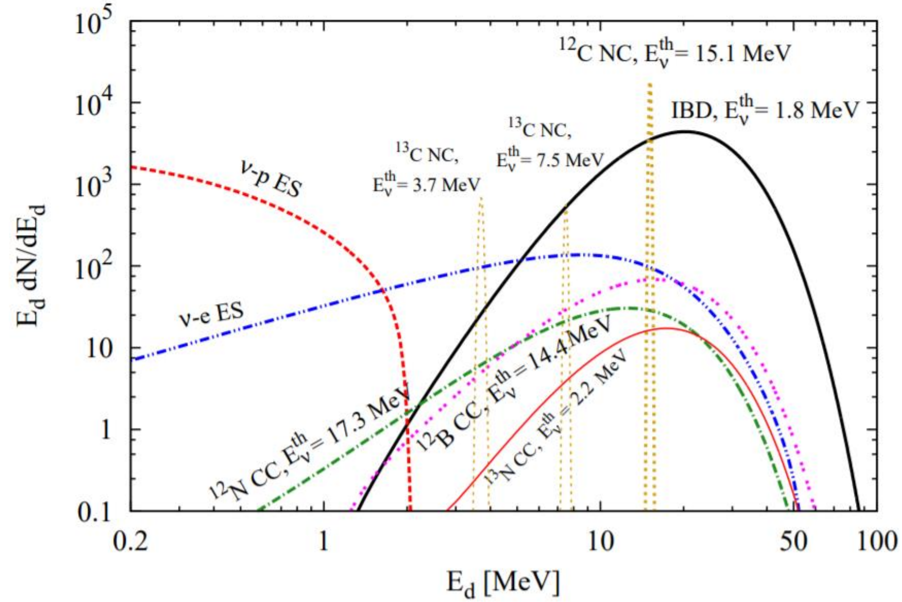
- **Multipurpose:**
  - Neutrino mass ordering
  - Precision measurement of oscillation parameters
  - **Supernova neutrino**
  - Solar neutrino, DSNB, geo-neutrino, …



Ref: JUNO Physics and Detector, PPNP 123 (2022), 103927

CCSN detection at JUNO

JUNO can detect all flavors of neutrinos via several interactions



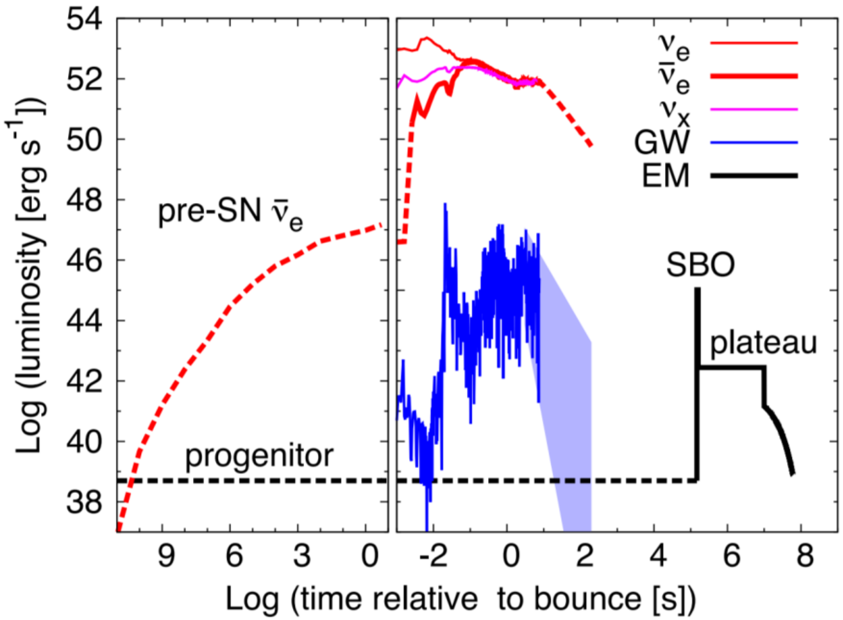
Channel	Interaction	Detection signal	Statistics@10kpc
IBD	$\bar{\nu}_e + p \rightarrow e^+ + n$	Prompt and delayed (220 μs)	~5000
pES	$p + \nu \rightarrow p + \nu$	Single p-like (small energy)	~2000
eES	$e^- + \nu \rightarrow e^- + \nu$	Single e-like	~300
C12	$C12 + \nu \rightarrow \nu + C12*$	Single e-like (E~15.1 MeV)	~300
N12	$\nu_e + C12 \rightarrow e^- + N12$ $N12 \rightarrow \nu_e + e^+ + C12$	Prompt and delayed (11 ms)	~100
B12	$\bar{\nu}_e + C12 \rightarrow e^+ + B12$ $B12 \rightarrow \bar{\nu}_e + e^- + C12$	Prompt and delayed (20 ms)	~100

Ref: JUNO Physics and Detector, PPNP 123 (2022), 103927

CCSN monitoring system

Neutrinos as CCSN early warning

- Messengers of core-collapse supernova
  - Electromagnetic signals
  - Gravitational waves
  - **Neutrinos**
- Neutrino: early warning of CCSN
  - pre-supernova (pre-SN) neutrino:
    - Days before core-collapse
    - $\langle E \rangle < 2\ MeV$
  - Supernova (SN) neutrino:
    - $\sim O(10\ s)$
    - $\langle E \rangle \sim O(10\ MeV)$



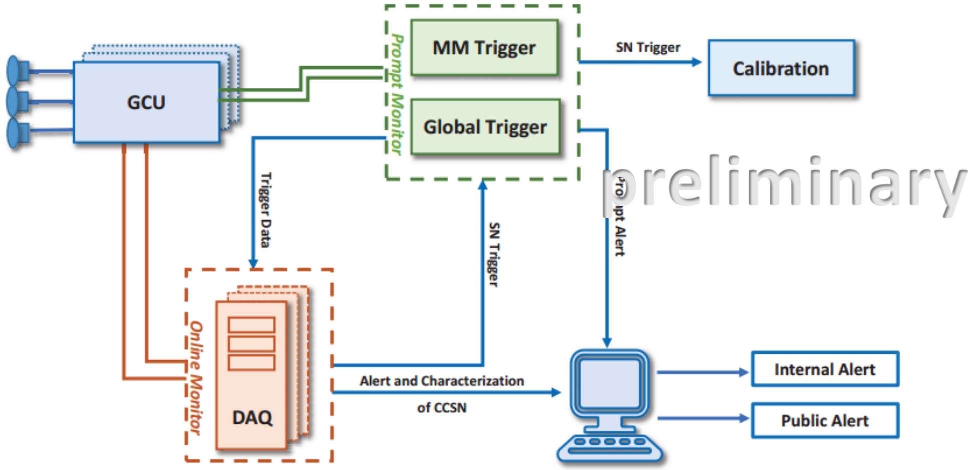
- Pointing using neutrino:
  - Neutrino interaction, such as eES and IBD
  - Triangulation

Ref: K.~Nakamura et al, Mon.Not.Roy.Astron.Soc. 461 (2016) 3, 3296-3313

Design of CCSN monitor system

Three monitoring systems to give CCSN alert:

- ➢ Prompt monitor
  - On global trigger
  - On dedicated Multi-messenger (MM) trigger system
- ➢ Online monitor



Prompt monitor on global trigger board:

- ➢ Embedded in Global trigger board
- ➢ Intend for core-collapse supernova neutrino

DAQ Online monitor:

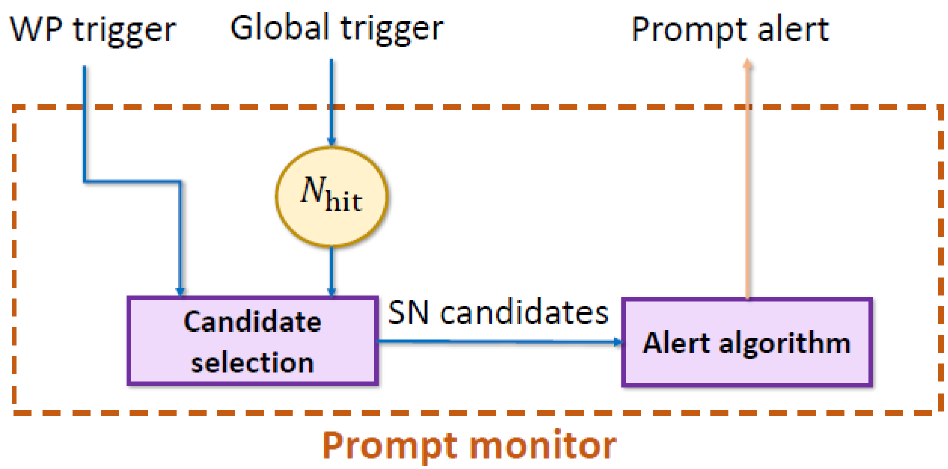
- ➢ Use trigger-less T/Q
- ➢ Perform fast reconstruction

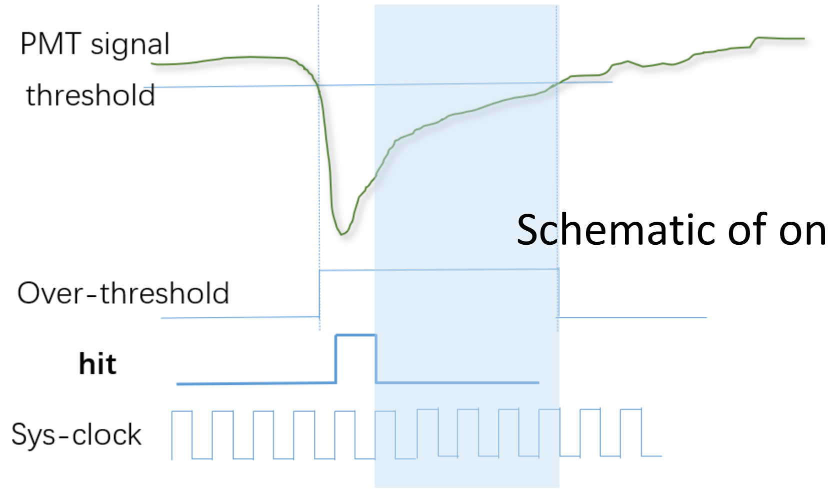
How to find an alert:

- ➢ Select SN/pre-SN candidates
- ➢ Find the sudden increase of event rate

Design of prompt monitor

- Embedded in global trigger board
- Event selection:
  - Select SN signals based on N_{hit}
  - Muon veto based on WP trigger to suppress background
- N_{hit} definition: number of PMTs being fired within some time interval (~1 μs)



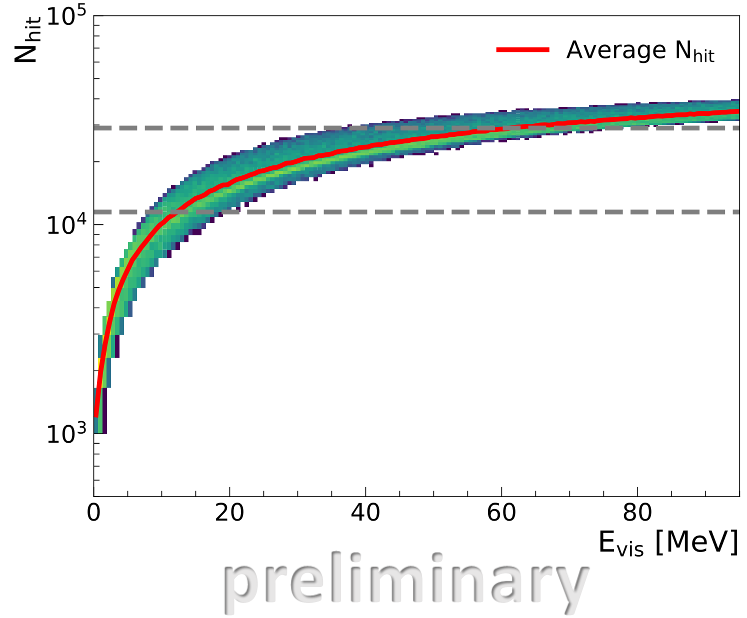


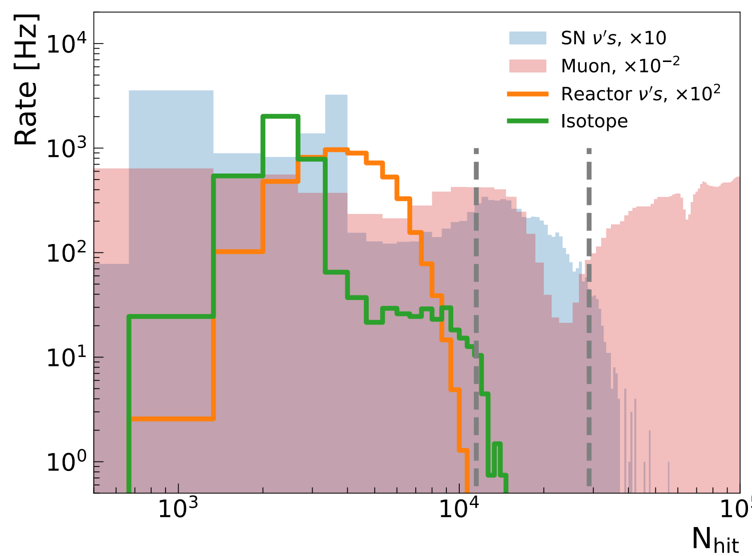
Schematic of one "hit"

Event selection and background

Prompt monitor

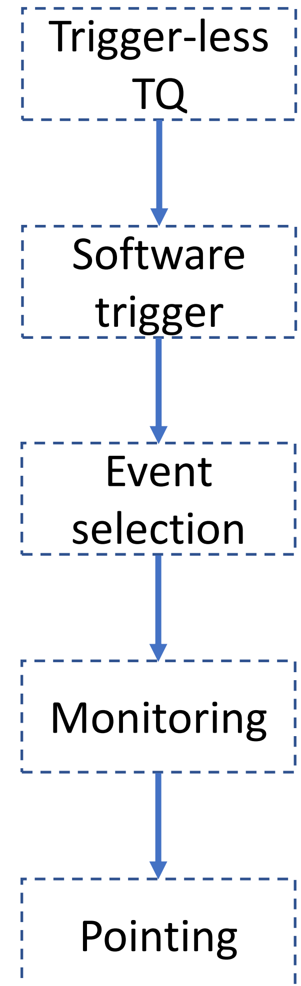
- Select SN candidates
  - No reconstruction info
  - $N_{hit} \in (N_{low}, N_{high})$
  - Energy at $N_{low} \sim 8 MeV$
  - Energy at $N_{high} \sim 40 MeV$
- Dominant background:
  - Cosmogenic isotopes, e.g. B12, B8, …
  - Rate: ~209/day





Design of online monitor

- Use trigger-less T/Q as input
- Use software trigger to build events
  - Perform at DAQ
  - Have lower energy threshold compared with global trigger
- Perform event reconstruction to extract energy, vertex, …
- Select IBD events
  - Different criteria for SN and pre-SN
  - Monitor them separately
- Fast characterization after CCSN alert:
  - Pointing, light curve, etc.

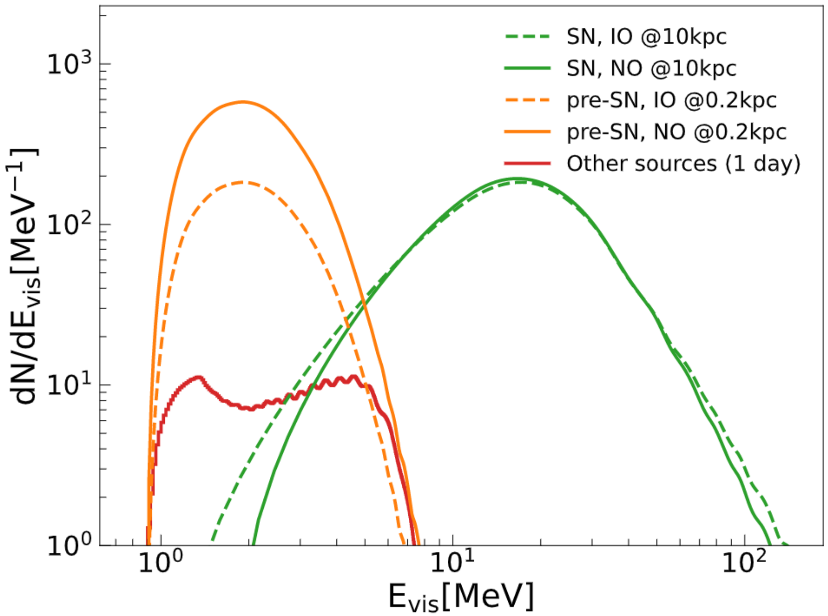


Event selection and background

Online monitor

- ➢ With reconstruction info, select IBD-like candidates
- ➢ SN IBD:
  - ➢ Background: reactor neutrino, Li9/He8, …
  - ➢ Background rate: 127/day
- ➢ Pre-SN IBD:
  - Background: reactor neutrino, …
  - Background rate: 21/day

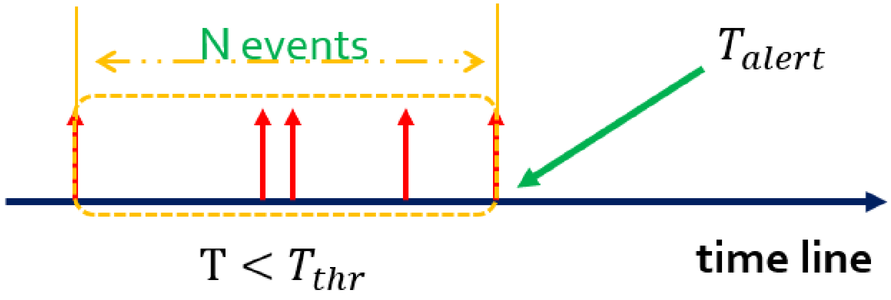
preliminary



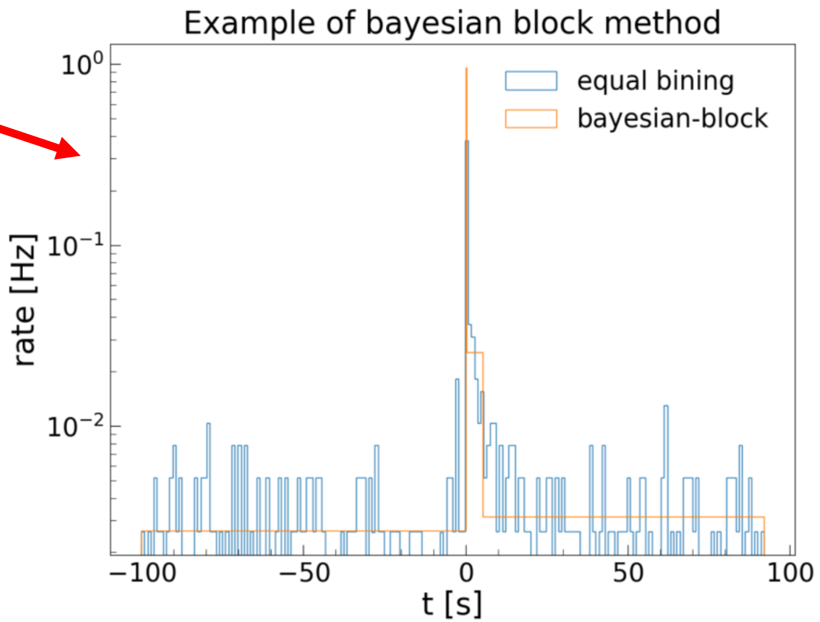
Visible energy of IBDs from pre-SN (Patton model), SN (Nakazato model) and other sources

Performance

- False alert rate (FAR):
  - Determined by:
    - Background rate
    - Alert algorithm
    - Alert algorithm parameters
  - 1/month in the following
- Alert efficiency
- Alert distance:
  - The distance at which alert efficiency is 50%
- Alert time

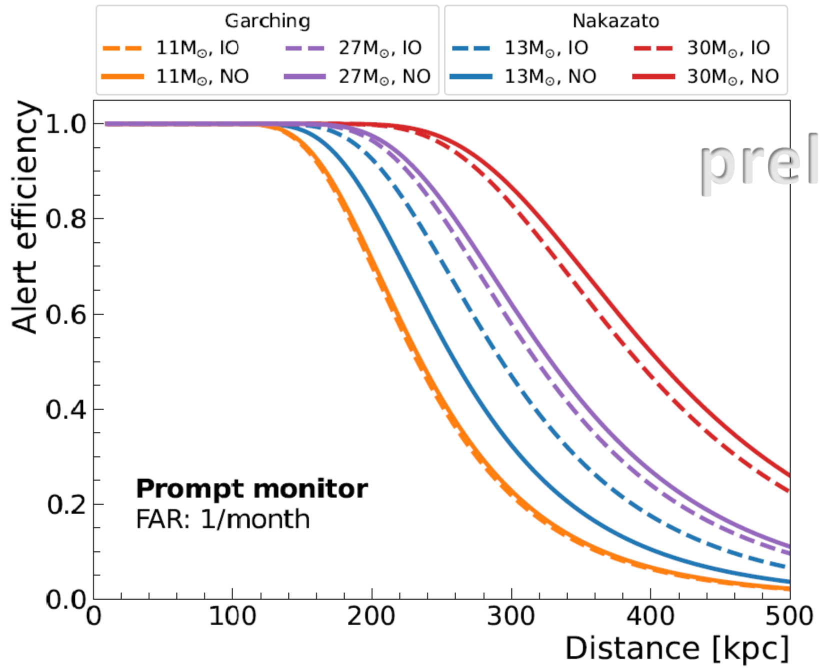


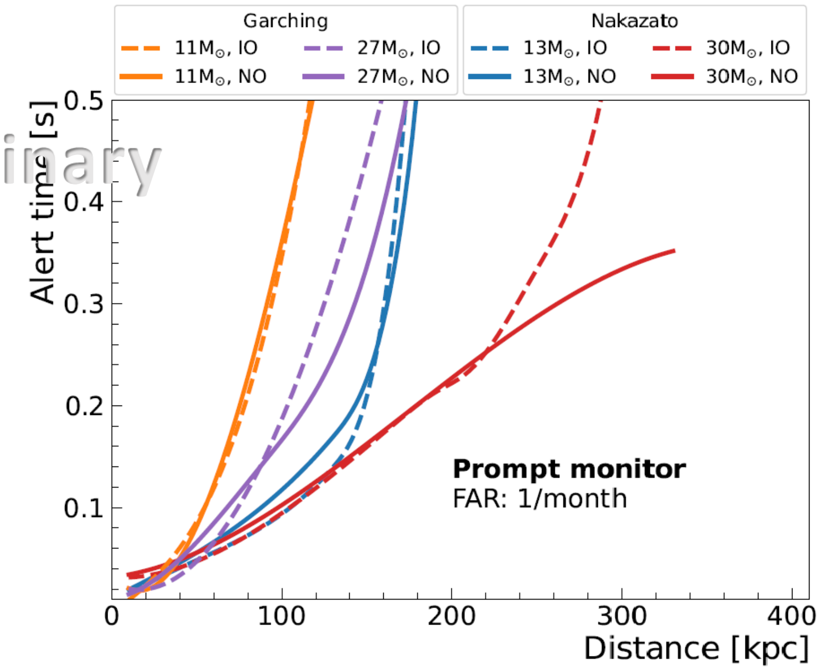
Sliding event method



Bayesian blocks method

Performance—prompt monitor



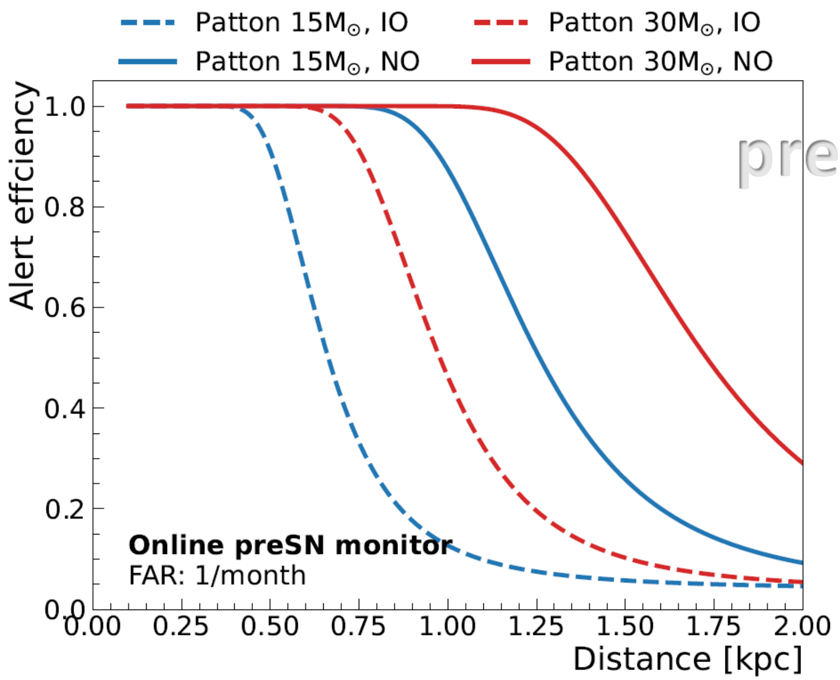


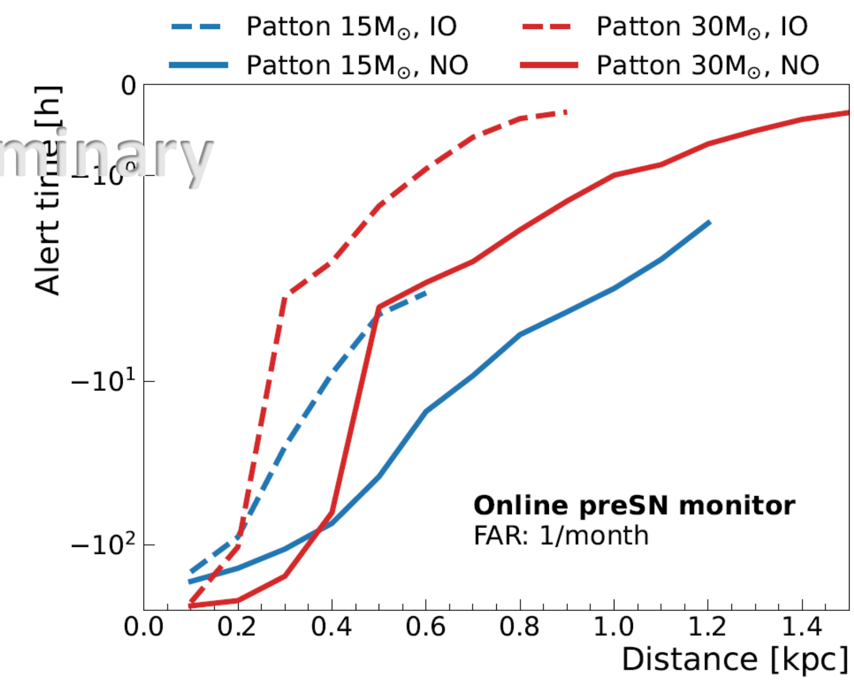
- Alert distance: **230~400 kpc**
- Alert time @10 kpc: **10~30 ms**
- Cover Milky Way, LMC and SMC with 100% efficiency

Nakazato/Garching	13/11 $M_{\odot}$, NO	13/11 $M_{\odot}$, IO	30/27 $M_{\odot}$, NO	30/27 $M_{\odot}$, IO
Distance [kpc]	260/235	294/233	408/328	393/318
Time @10kpc [ms]	18.8/14.4	15.4/12.5	30.8/13.7	30.3/12.3

Performance—online monitor

Use pre-SN monitor as example



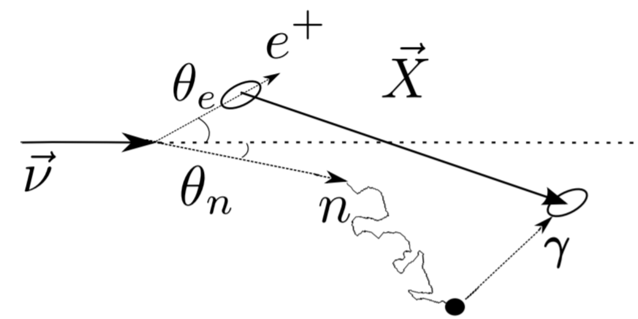


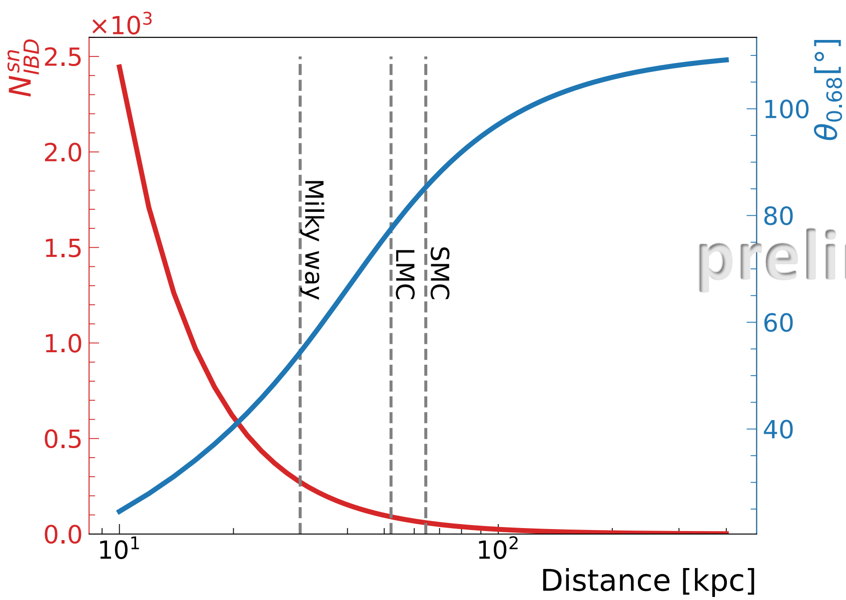
- Alert distance: **0.6~1.7 kpc**
- Alert time @0.2 kpc: **>~100hr earlier**
- Cover Betelgeuse with 100% efficiency

Patton	$15M_\odot$, NO	$15M_\odot$, IO	$30M_\odot$, NO	$30M_\odot$, IO
Distance [kpc]	1.26	0.66	1.73	0.98
Time @0.2kpc [hr]	-139	-90	-219	-103

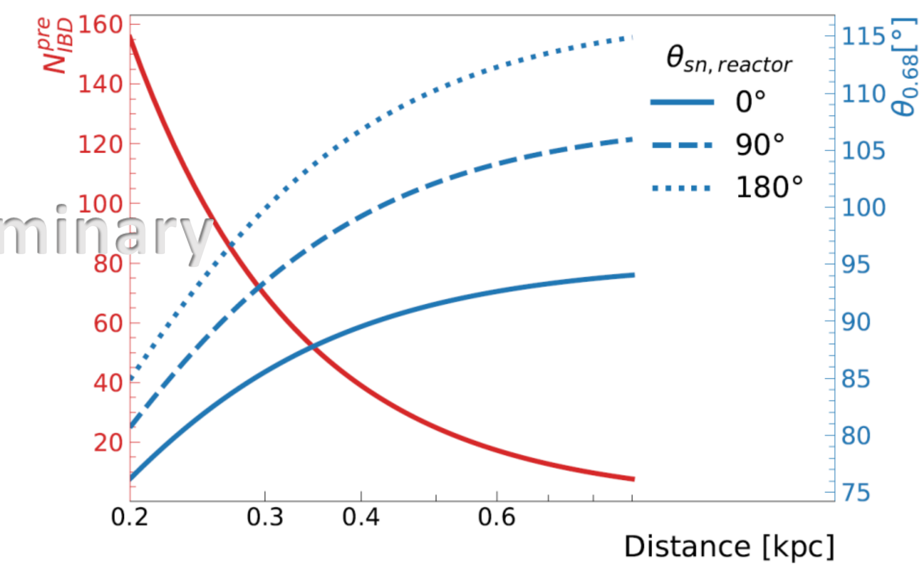
Performance—CCSN pointing

- CCSN pointing using IBD events:
  - $\vec{d}_\nu = \frac{1}{N}\sum_{i=1}^{N}\vec{X}_{pn}^{i}$
- SN@10 kpc: ~25°
- Pre-SN@0.2 kpc: ~80°





preliminary



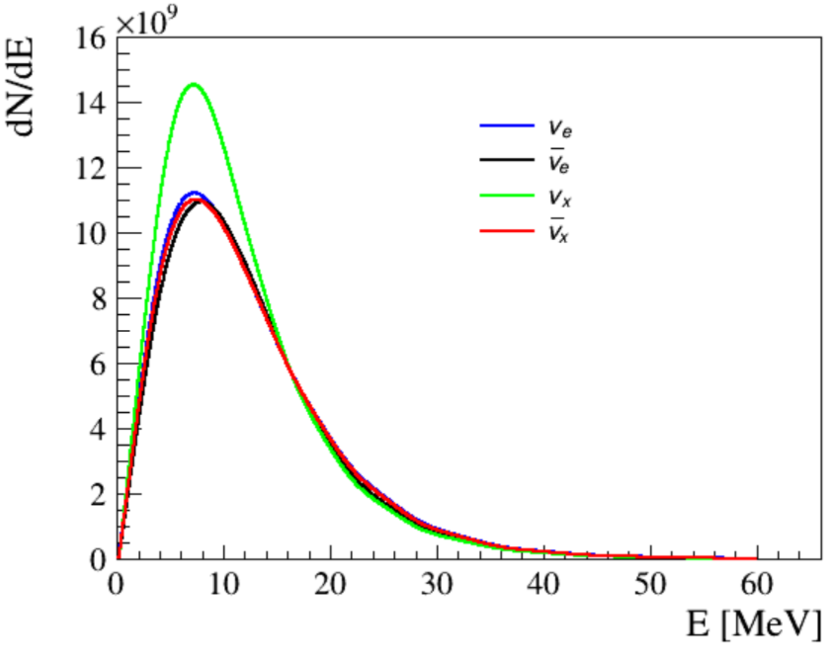
Using 13 $M_\odot$ Nakazato model and 15 $M_\odot$ Patton model as example

Neutrino spectra reconstruction

Extract neutrino energy spectra

Neutrino interactions:

- IBD:
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - $E_{vis} = E_\nu - (m_n - m_p) + m_e$
- pES:
  - $p + \nu \rightarrow p + \nu$
  - $E_k = \frac{E_\nu}{1+m_p/[(1-cos\theta)E_\nu]} < \frac{2E_\nu^2}{m_p}$
- eES:
  - $e^- + \nu \rightarrow e^- + \nu$
  - $E_k = \frac{E_\nu}{1+m_e/[(1-cos\theta)E_\nu]} < E_\nu$
- Combining all three channels can provide full flavor info



Neutrino flux using Nakazato model with 20 $M_\odot$

The unfolding problem

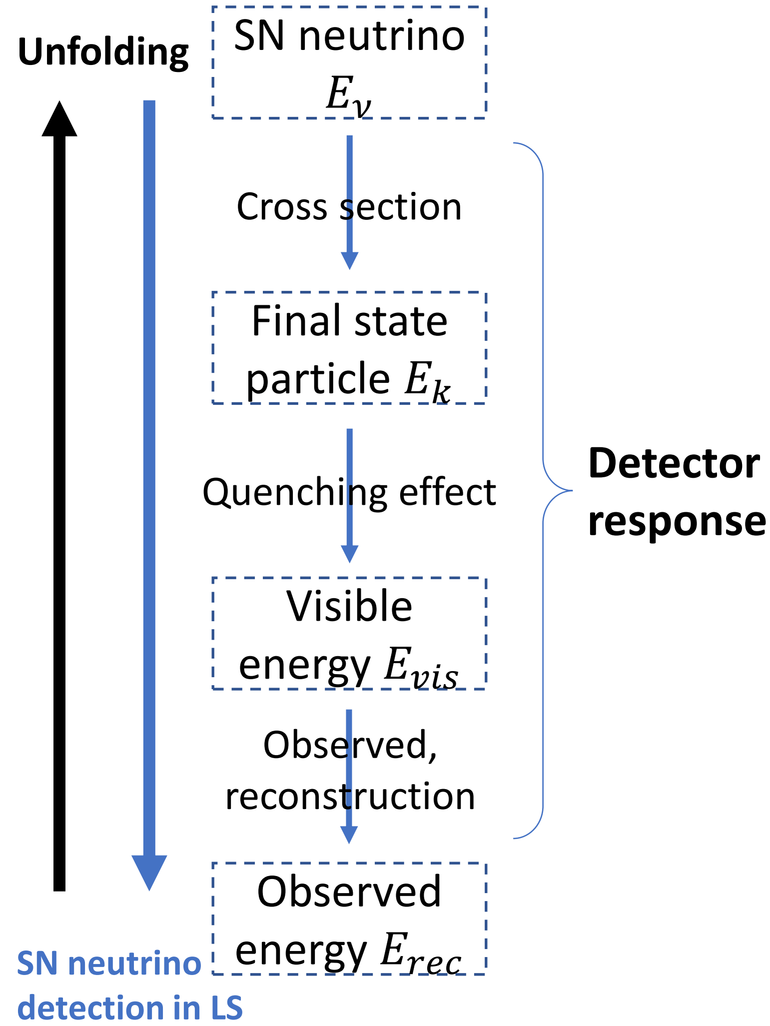
E_ν vs. E_{rec}

- Neutrino spectra: F
- Reconstructed spectra: S
- Detector response: A
- The relationship can be modeled by: $AF = S$

$$\begin{matrix}\text{IBD}\\ \text{pES}\\ \text{eES}\end{matrix}\quad \begin{bmatrix} N_{\rm p}\boldsymbol{D}_{\rm IBD}\boldsymbol{\sigma}^{\rm IBD}_{\nu_e} & N_{\rm p}\boldsymbol{D}_{\rm IBD}\boldsymbol{\sigma}^{\rm IBD}_{\bar\nu_e} & N_{\rm p}\boldsymbol{D}_{\rm IBD}\sum\boldsymbol{\sigma}^{\rm IBD}_{\nu_x} \\ N_{\rm p}\boldsymbol{D}_{p\rm ES}\boldsymbol{\sigma}^{p\rm ES}_{\nu_e} & N_{\rm p}\boldsymbol{D}_{p\rm ES}\boldsymbol{\sigma}^{p\rm ES}_{\bar\nu_e} & N_{\rm p}\boldsymbol{D}_{p\rm ES}\sum\boldsymbol{\sigma}^{p\rm ES}_{\nu_x} \\ N_{\rm e}\boldsymbol{D}_{e\rm ES}\boldsymbol{\sigma}^{e\rm ES}_{\nu_e} & N_{\rm e}\boldsymbol{D}_{e\rm ES}\boldsymbol{\sigma}^{e\rm ES}_{\bar\nu_e} & N_{\rm e}\boldsymbol{D}_{e\rm ES}\sum\boldsymbol{\sigma}^{e\rm ES}_{\nu_x} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{F}_{\nu_e} \\ \boldsymbol{F}_{\bar\nu_e} \\ \boldsymbol{F}_{\nu_x} \end{bmatrix} = \begin{bmatrix} \boldsymbol{S}_{\rm IBD} \\ \boldsymbol{S}_{p\rm ES} \\ \boldsymbol{S}_{e\rm ES} \end{bmatrix}$$

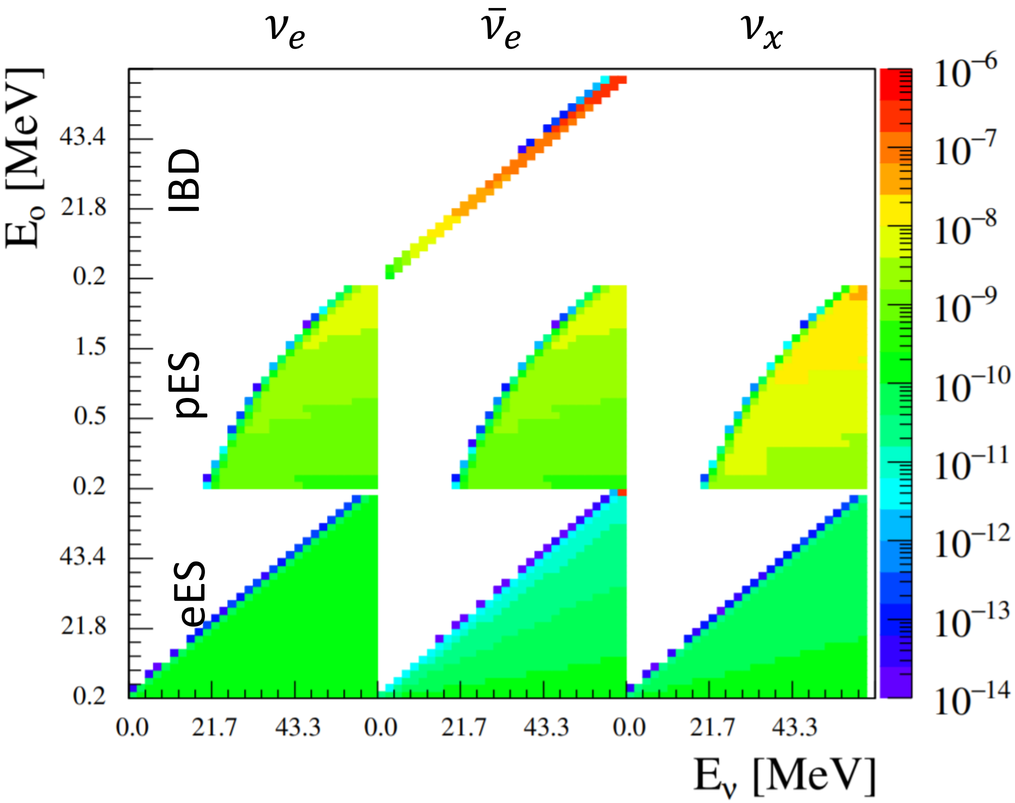
Unfolding

- Due to statistical fluctuation, direct inversion will not get physical results
- Unfolding technique:
  - SVD method
  - Bayesian method



Detector response

- IBD channel:
  - Diagonal matrix
  - In reality, there may be off diagonal elements due to energy leakage
- pES channel:
  - E_{rec} is largely suppressed
  - Cut off due to energy threshold
- eES channel:
  - Lower Triangular Matrix



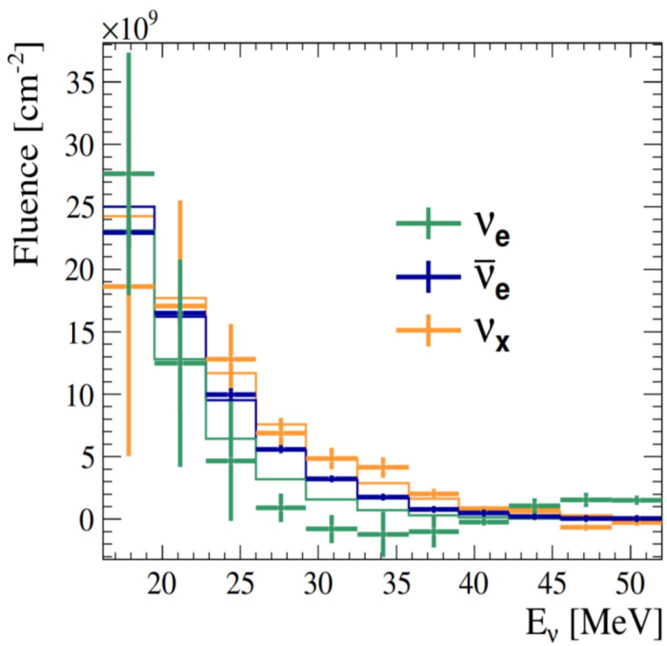
The response matrix combining three interaction channels

Ref: Li, Hui-Ling, et al. Physical Review D 99.12 (2019): 123009.

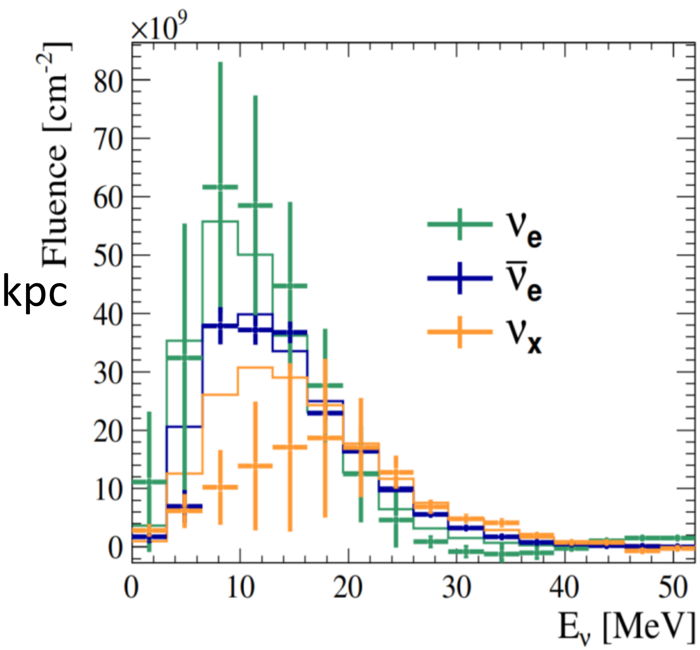
Reconstruction result

The reconstruction of detected energy spectra of all flavors

- ➢Use toy MC samples
- ➢Suppose the actual interaction channel is known
- ➢Due to energy threshold, large bias at $E_\nu < 20MeV$



CCSN @10kpc



Ref: Li, Hui-Ling, et al. Physical Review D 99.12 (2019): 123009.

Summary

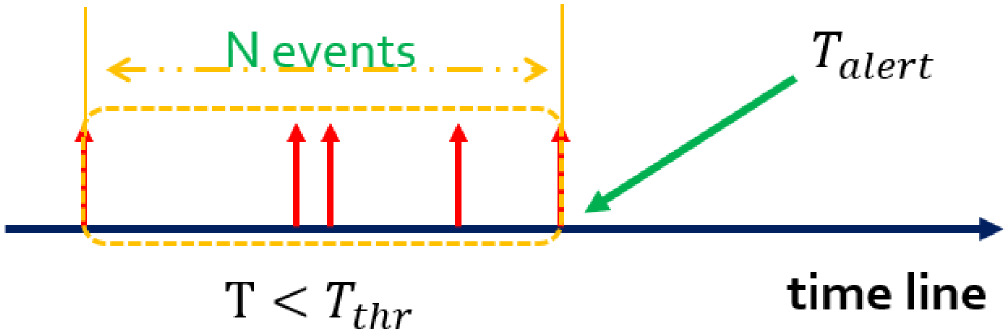
- JUNO advantage in CCSN detection
  - Large detector and excellent energy resolution
  - Multi channel detection, especially the pES channel
- CCSN monitor
  - Contribute to the multi-messenger detection
  - Monitor pre-SN
  - CCSN pointing
- Energy spectra reconstruction:
  - Reconstruct the full flavor neutrino energy spectra
  - CCSN burst mechanism
  - Neutrino flavor conversion

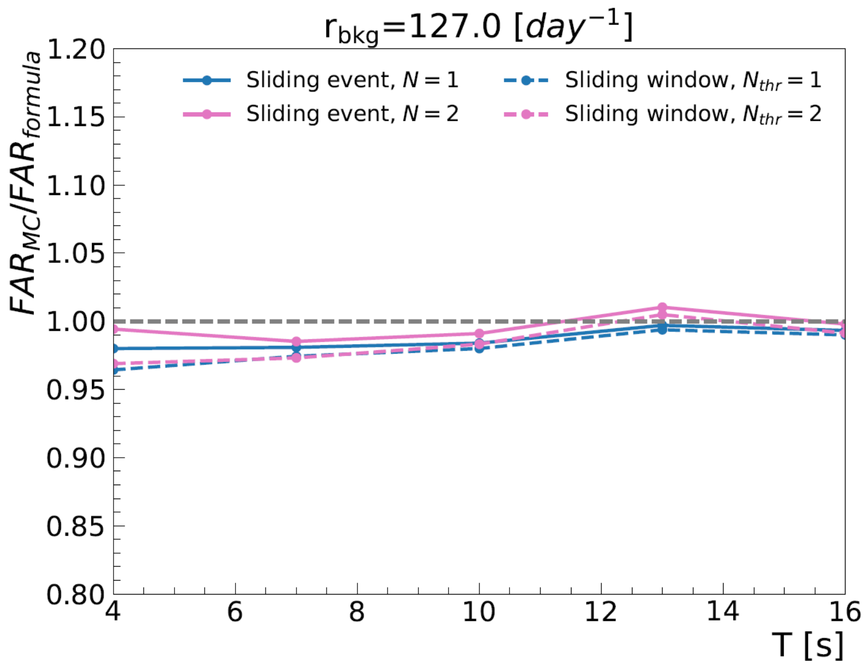
Back up

Alert algorithms—sliding event

- Choose the N latest candidates
- Calculate the time interval of them T
- Compare with a predefined threshold T_{thr} to give the alert
- False alert rate:

$$FAR = \frac{1}{1+\sum_{n=1}^{N_{thr}-1} p_n(T)} r e^{-rT} \sum_{n>N_{thr}-1} \frac{(rT)^n}{n!}$$

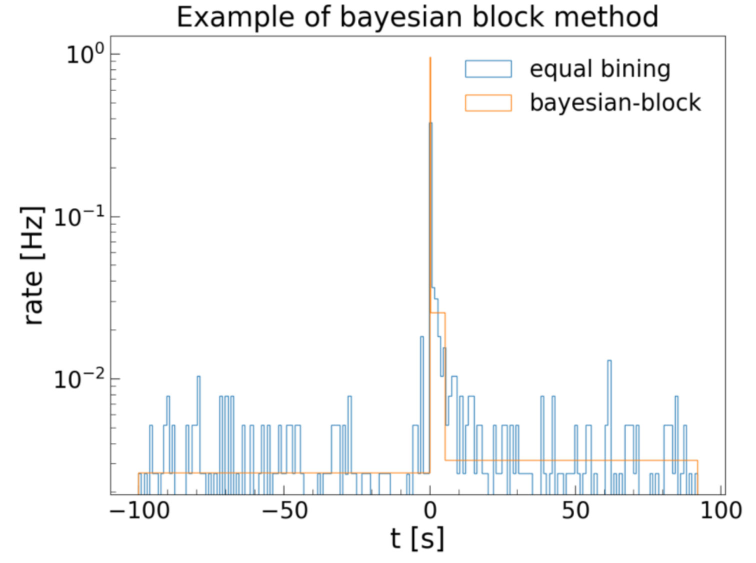


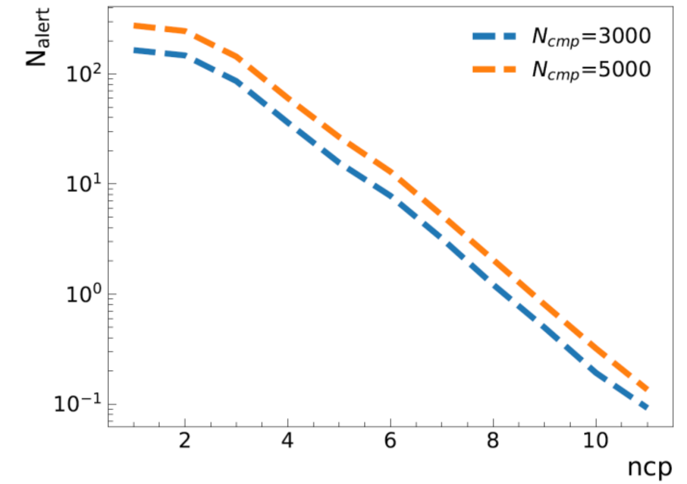


Alert algorithms—Bayesian block

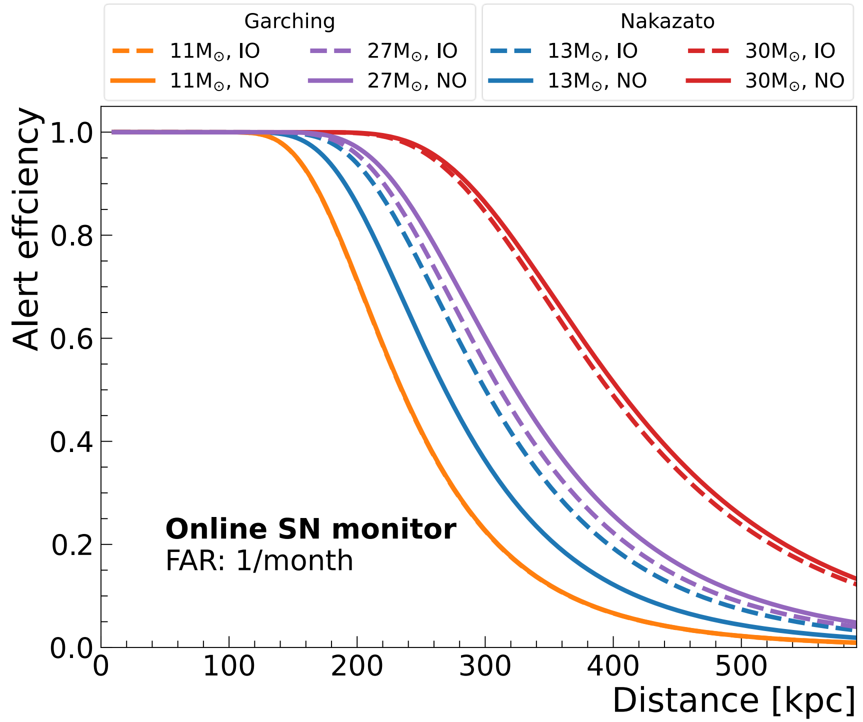
- Choose the N latest candidates
- Use Bayesian block algorithm to divide time line into blocks
- Give the alert when:
  - More than 1 blocks
  - The event rate between adjacent blocks increase
- False alert rate extracted by toy MC

$$FAR = \frac{N_{cmp} f(ncp)}{T} = \frac{r_{bkg} T f(ncp)}{T} = r_{bkg} f(ncp)$$





Online SN monitor results



Nakazato	**$13M_\odot$, NO**	**$13M_\odot$, IO**	**$30M_\odot$, NO**	**$30M_\odot$, IO**
Distance [kpc]	271	303	406	398

Garching	**$11M_\odot$, NO**	**$11M_\odot$, IO**	**$27M_\odot$, NO**	**$27M_\odot$, IO**
Distance [kpc]	238	238	327	314

Summary of Alert distance and time

Prompt monitor

Nakazato	$13M_\odot$, NO	$13M_\odot$, IO	$30M_\odot$, NO	$30M_\odot$, IO
Distance [kpc]	260	294	408	393
Time @10kpc [ms]	18.8	15.4	30.8	30.3

Garching	$11M_\odot$, NO	$11M_\odot$, IO	$27M_\odot$, NO	$27M_\odot$, IO
Distance [kpc]	235	233	328	318
Time @10kpc [ms]	14.4	12.5	13.7	12.3

Online SN monitor

Nakazato	$13M_\odot$, NO	$13M_\odot$, IO	$30M_\odot$, NO	$30M_\odot$, IO
Distance [kpc]	271	303	406	398

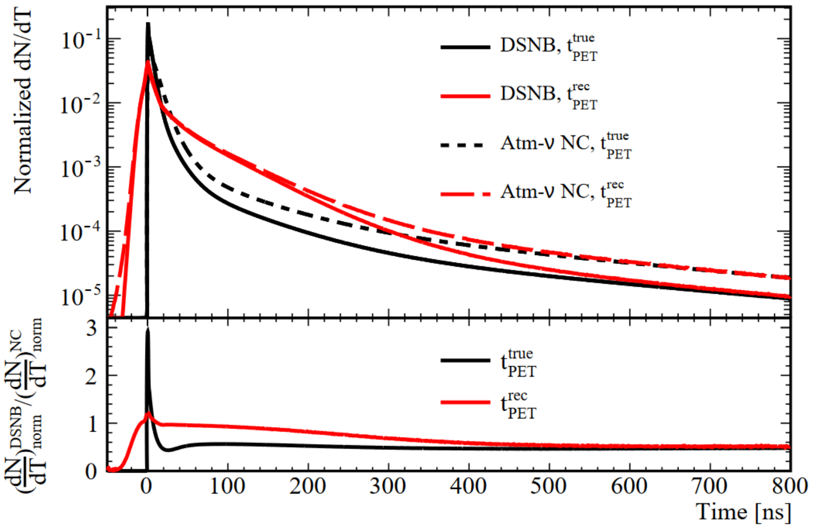
Garching	$11M_\odot$, NO	$11M_\odot$, IO	$27M_\odot$, NO	$27M_\odot$, IO
Distance [kpc]	238	238	327	314

Online pre-SN monitor

Patton	$15M_\odot$, NO	$15M_\odot$, IO	$30M_\odot$, NO	$30M_\odot$, IO
Distance [kpc]	1.26	0.66	1.73	0.98
Time @0.2kpc [hr]	-139	-90	-219	-103

Channel discrimination

- IBD and C12 CC interactions:
  - prompt and delayed coincidence
- pES and eES:
  - Distinguish by utilizing the difference in luminescence time of LS
- Unphysical events:
  - Due to PMT after pulse
  - Characteristics: Small E_{rec}; small R_{rec}; correlated to previous event
- Event pile up: under studying



Selection strategy:

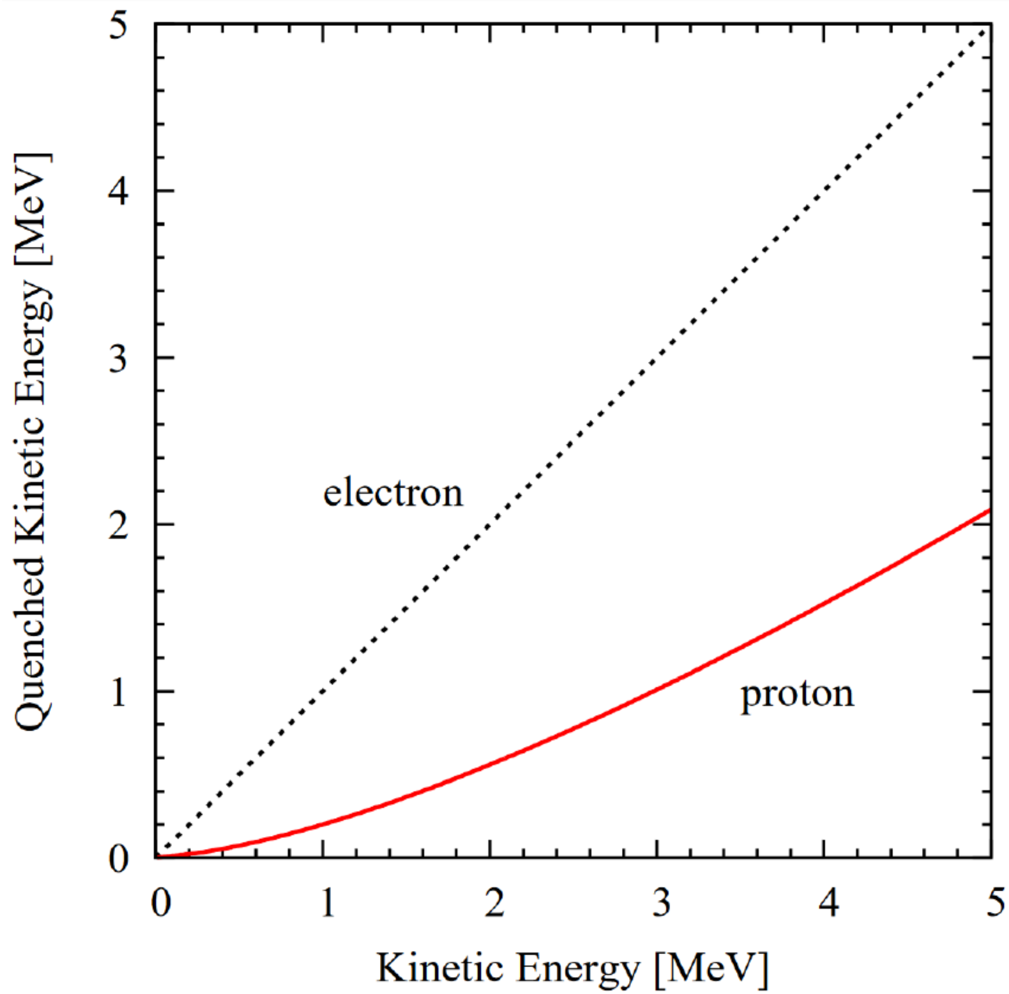
- Remove unphysical events (after pulse triggers)
- Select IBD and CC interactions
- Use PSD to distinguish pES and eES
- Fit and extract C12 channel

Ref: JUNO collaboration, JCAP, 2022, 2022(10): 033.

Quenching

- asd

Quenching effect



Prove of AF=S

$$\frac{\mathrm{d}n^c(E_{rec})}{\mathrm{d}E_{rec}} = \sum_f \int \left(\int N_t R^c(E_{rec}, E_{dep}) \frac{\mathrm{d}\sigma_f^c(E_{dep}, E_\nu)}{\mathrm{d}E_{dep}} \mathrm{d}E_{dep} \right) \frac{\mathrm{d}F^f(E_\nu)}{\mathrm{d}E_\nu} \mathrm{d}E_\nu$$

$$= \sum_f \int g_f^c(E_{rec}, E_\nu) \frac{\mathrm{d}F^f(E_\nu)}{\mathrm{d}E_\nu} \mathrm{d}E_\nu$$

其中

$$g_f^c(E_{rec}, E_\nu) = \int N_t R^c(E_{rec}, E_{dep}) \frac{\mathrm{d}\sigma_f^c(E_{dep}, E_\nu)}{\mathrm{d}E_{dep}} \mathrm{d}E_{dep}$$

$$F_j^f = \int_{bin\, j} \frac{\mathrm{d}F^f(E_\nu)}{\mathrm{d}E_\nu} \mathrm{d}E_\nu$$

$$S_i^c = \int_{bin\, i} \frac{\mathrm{d}n^c(E_{rec})}{\mathrm{d}E_{rec}} \mathrm{d}E_{rec}$$

$$S_i^c = \sum_f \int_{bin\, i} \int g_f^c(E_{rec}, E_\nu) \frac{\mathrm{d}F^f(E_\nu)}{\mathrm{d}E_\nu} \mathrm{d}E_\nu \mathrm{d}E_{rec}$$

$$= \sum_{f,j} \int_{bin\, i} \int_{bin\, j} g_f^c(E_{rec}, E_\nu) \frac{\mathrm{d}F^f(E_\nu)}{\mathrm{d}E_\nu} \mathrm{d}E_\nu \mathrm{d}E_{rec}$$

$$= \sum_{f,j} \int_{bin\, j} \left(\int_{bin\, i} g_f^c(E_{rec}, E_\nu) \mathrm{d}E_{rec} \right) \frac{\mathrm{d}F^f(E_\nu)}{\mathrm{d}E_\nu} \mathrm{d}E_\nu$$

$$R_{f\, ij}^c = \int_{bin\, i} g_f^c(E_{rec}, E_{\nu\, j}) \mathrm{d}E_{rec}$$

$$S_i^c = \sum_{f,j} R_{f\, ij}^c F_j^f$$