Core-collapse Supernova Neutrino Detection at JUNO

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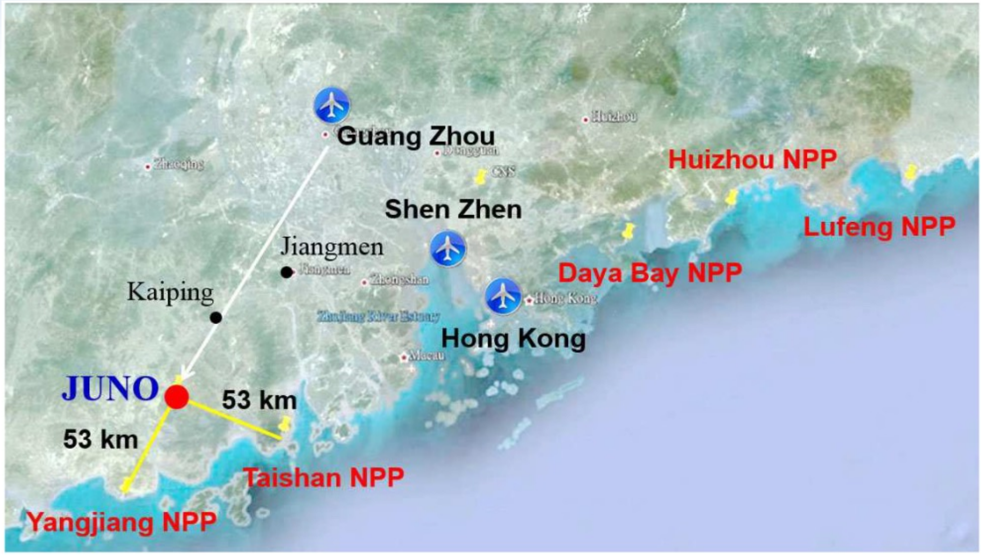
Outline

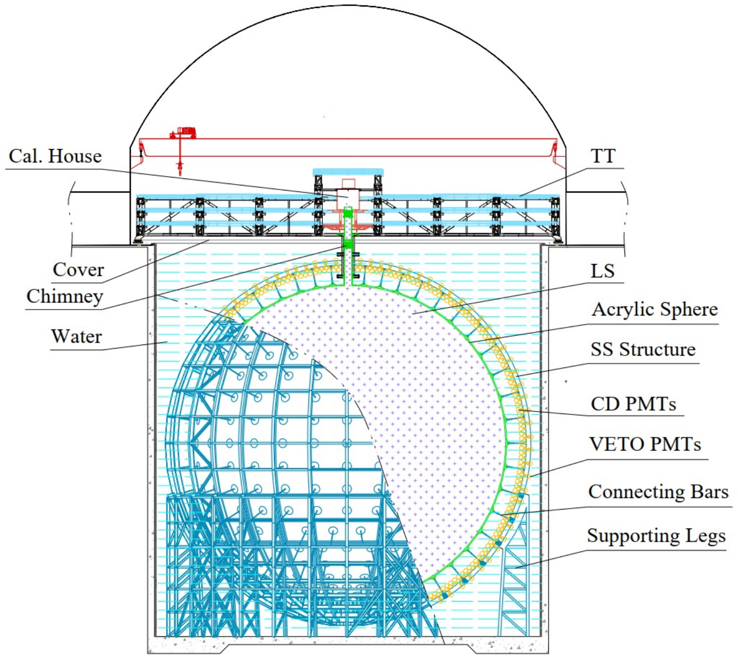
- Introduction to JUNO experiment
- Core-Collapse SuperNova (CCSN) neutrino
- CCSN monitor system
- Energy spectra reconstruction of CCSN neutrinos
- Summary

JUNO experiment



JUNO detector:

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



JUNO detector

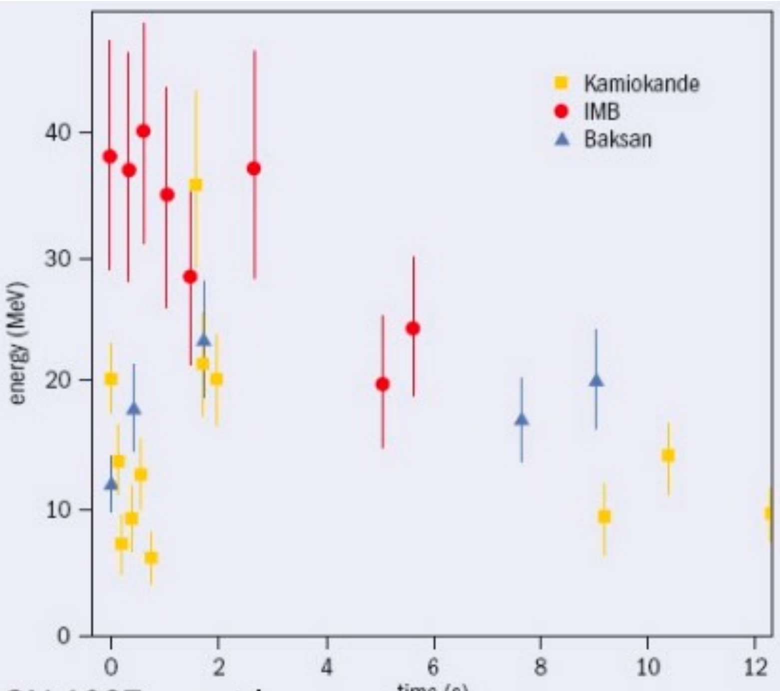
Multipurpose:

- Neutrino mass ordering
- Precision measurement of oscillation parameters
- **Supernova neutrino**
- Solar neutrino, atmospheric neutrinos, DSNB, geo-neutrino, nucleon decay…

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

Neutrinos from CCSN


Crab nebula (SN remnant)



SN 1987a neutrinos

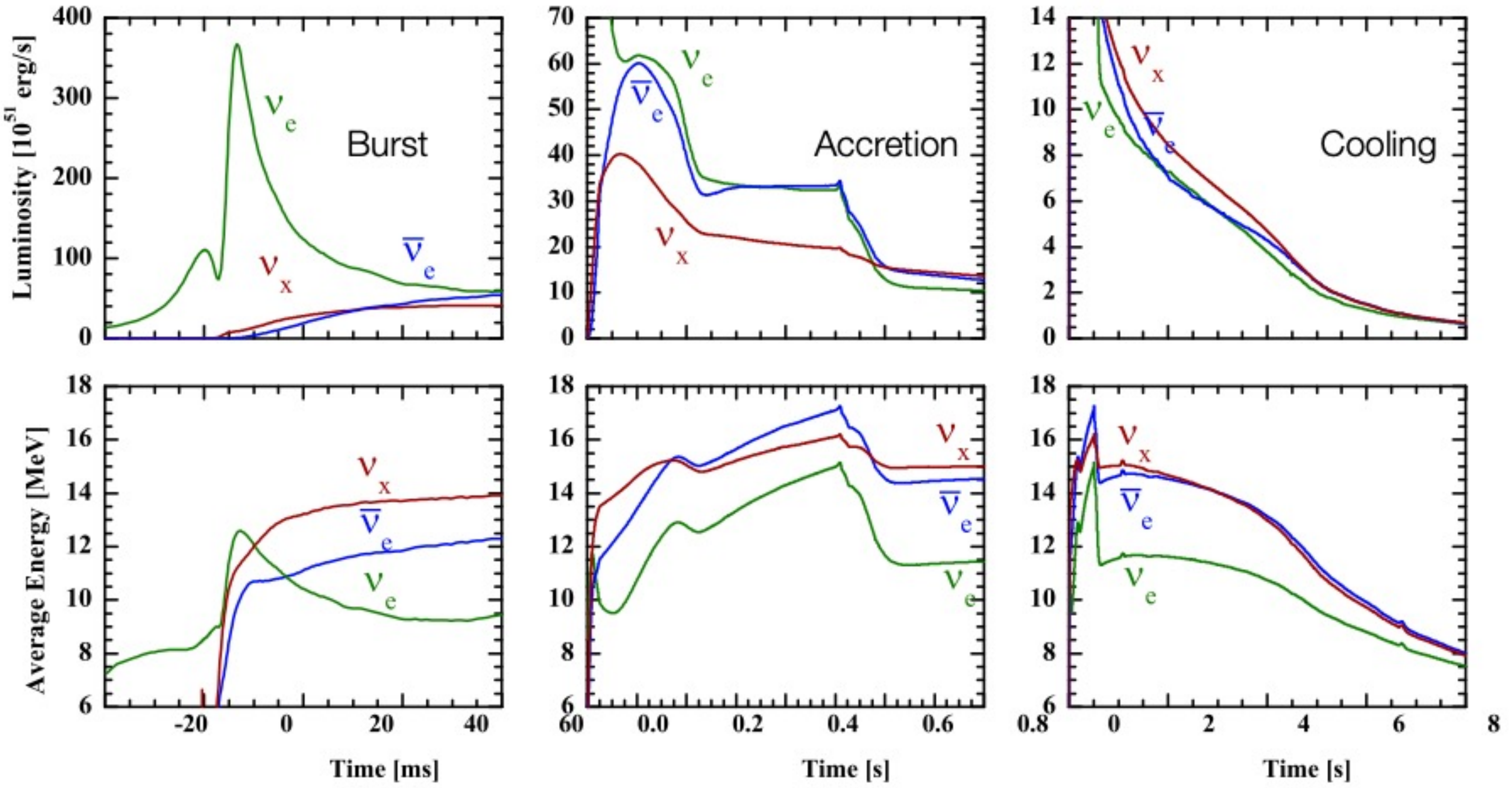

SN 1987A

Only observed SN neutrinos
~25 neutrinos in SN 1987 A

- ~ 1-3 supernovae in our galaxy per century.
- 99% of the energy goes to neutrinos.
- Explosion time scale ~ 10 s

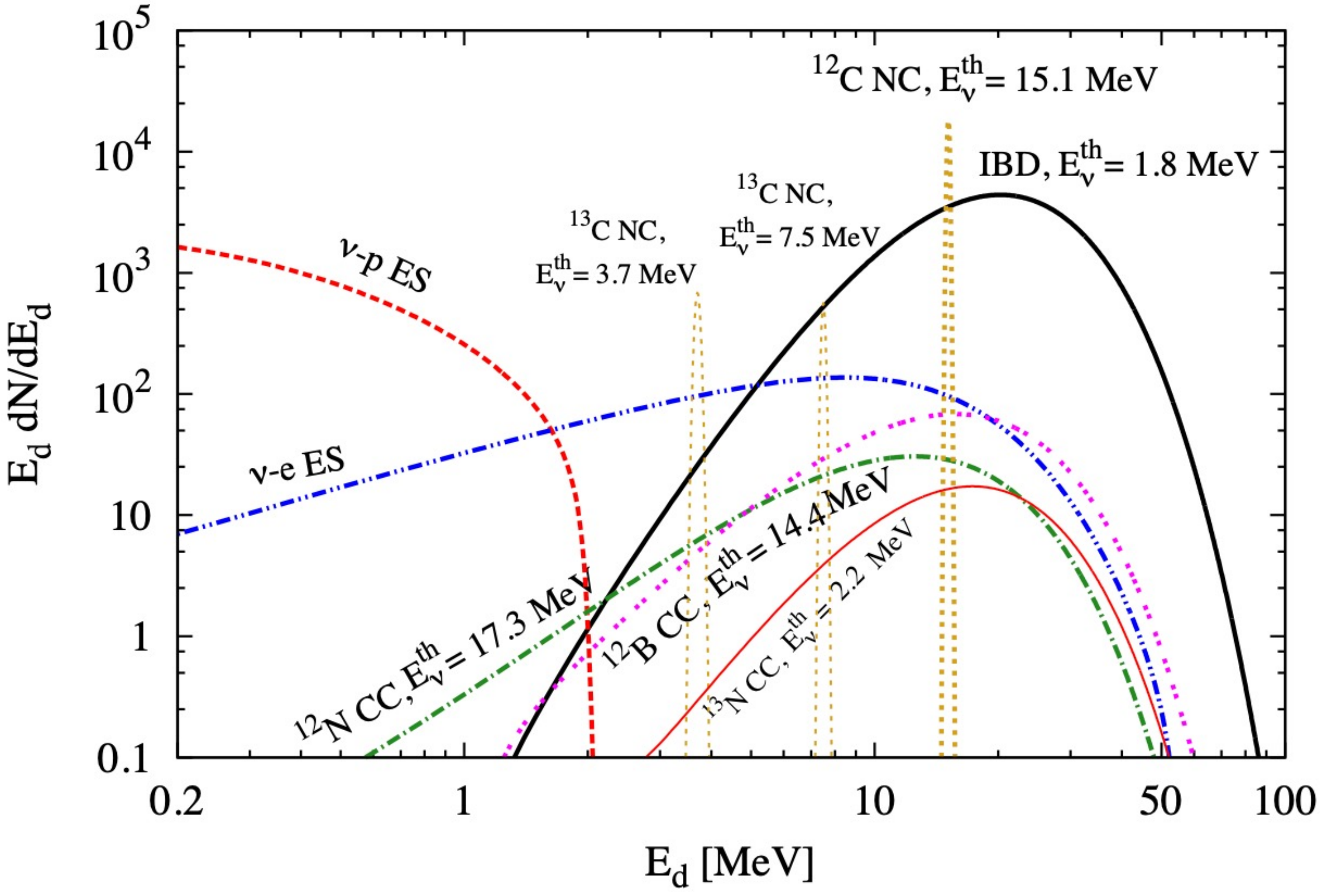
- JUNO with Low energy threshold, high energy resolution and large target mass -> provides large statistics for observing the next SN

Neutrinos from CCSN



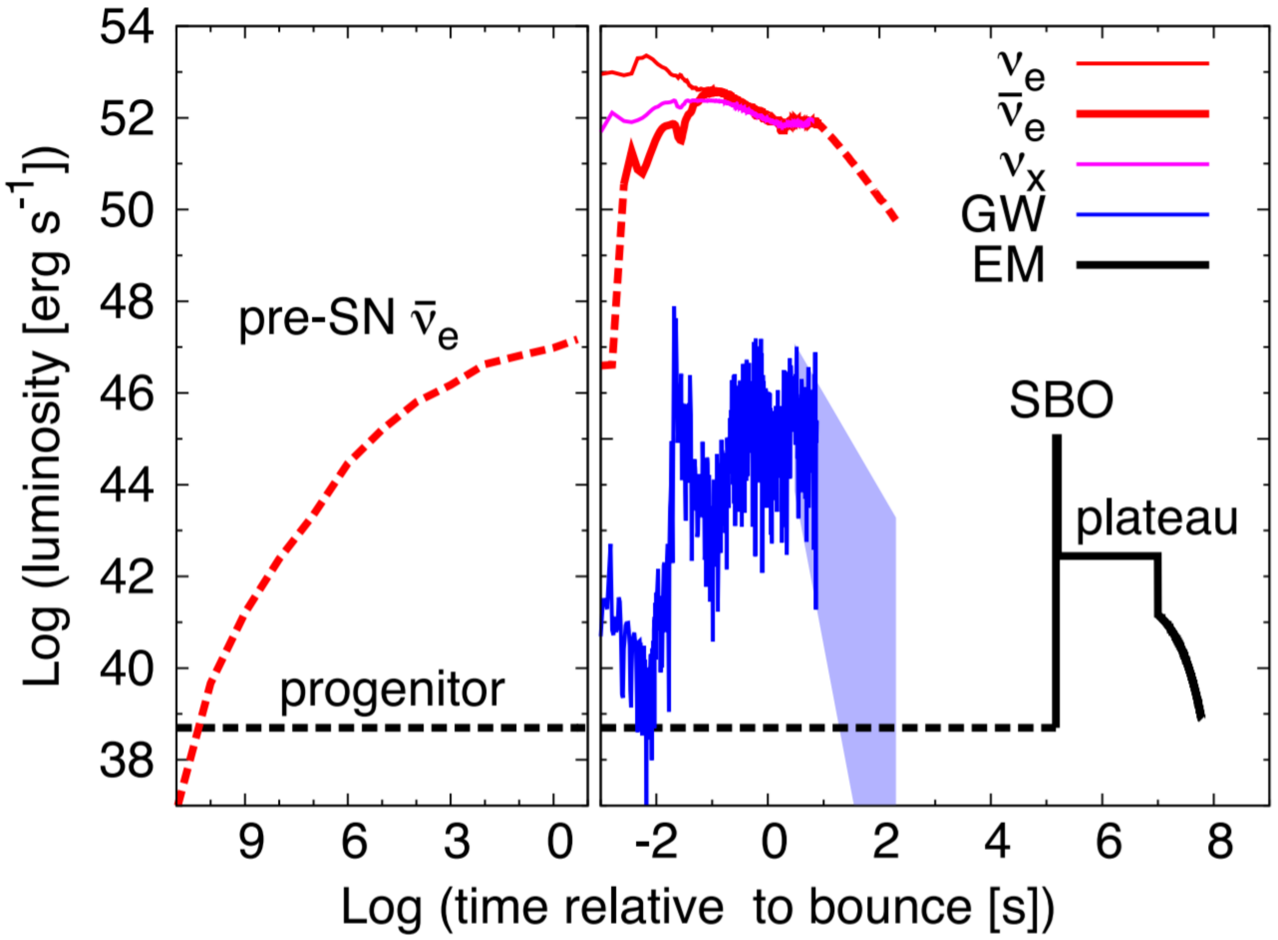
- Luminosity and energy distributions during the three SN phases: burst, accretion and cooling. Depend on the SN model assumptions.
- Mean Energy is around 15 MeV. Energy range: 0-100 MeV.
- 10 s with most of events in the 1st second.

Interactions of CCSN in JUNO



- Details of the SN neutrino spectra are still unknown. JUNO can reconstruct the energy spectra by a high-statistics observation of supernova neutrinos of different flavours.
- This will be helpful in understanding of SN neutrino production, flavour conversion and explosion mechanism.

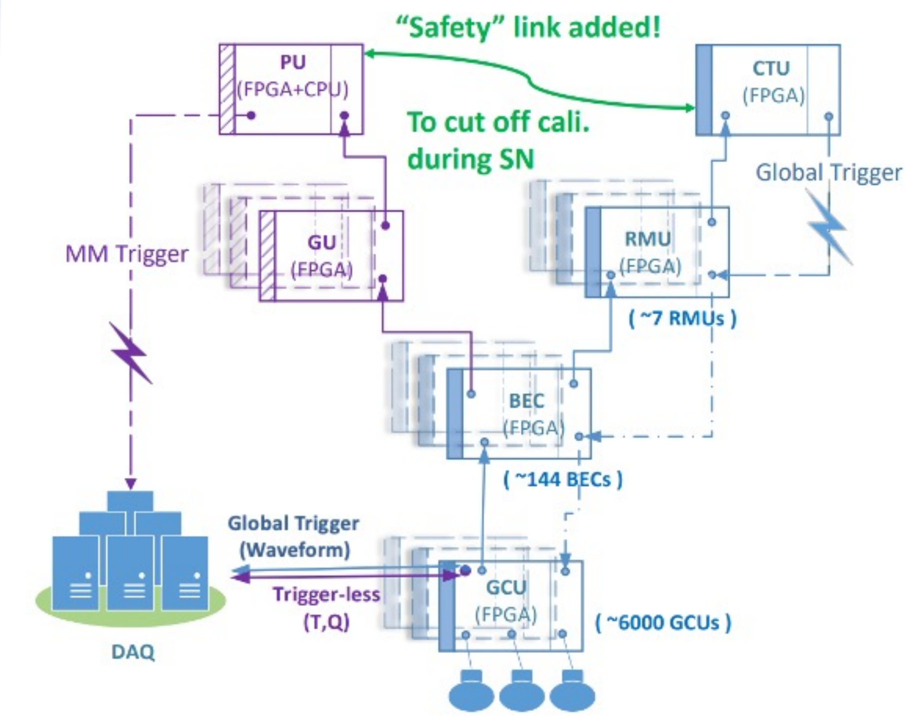
Neutrinos as CCSN early warning

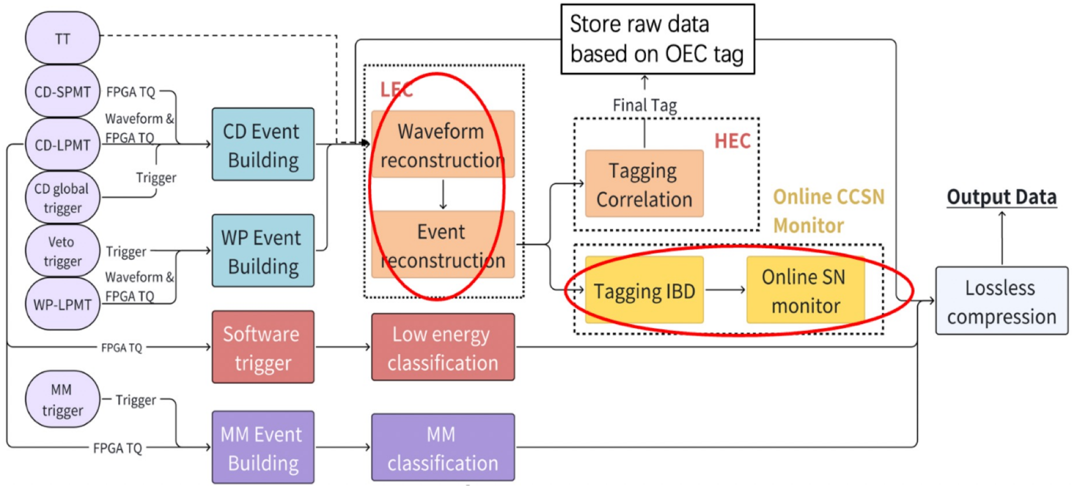


- Messengers of core-collapse supernova
  - Electromagnetic signals
  - Gravitational waves
  - **Neutrinos**
- Neutrino: early warning of CCSN
  - pre-supernova (pre-SN) neutrino:
    - Days before core-collapse
    - $\langle E \rangle < 2\ MeV$
  - Supernova (SN) neutrino:
    - $\sim O(10\ s)$
 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

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

CCSN monitor system

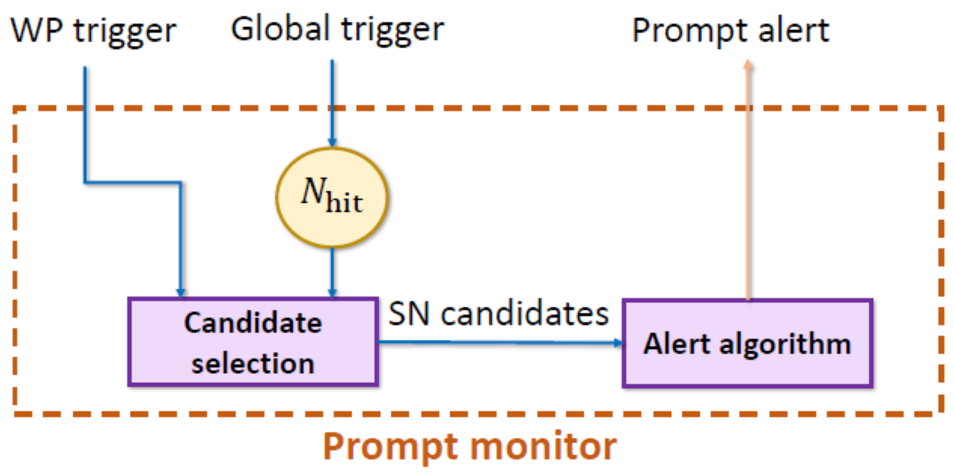


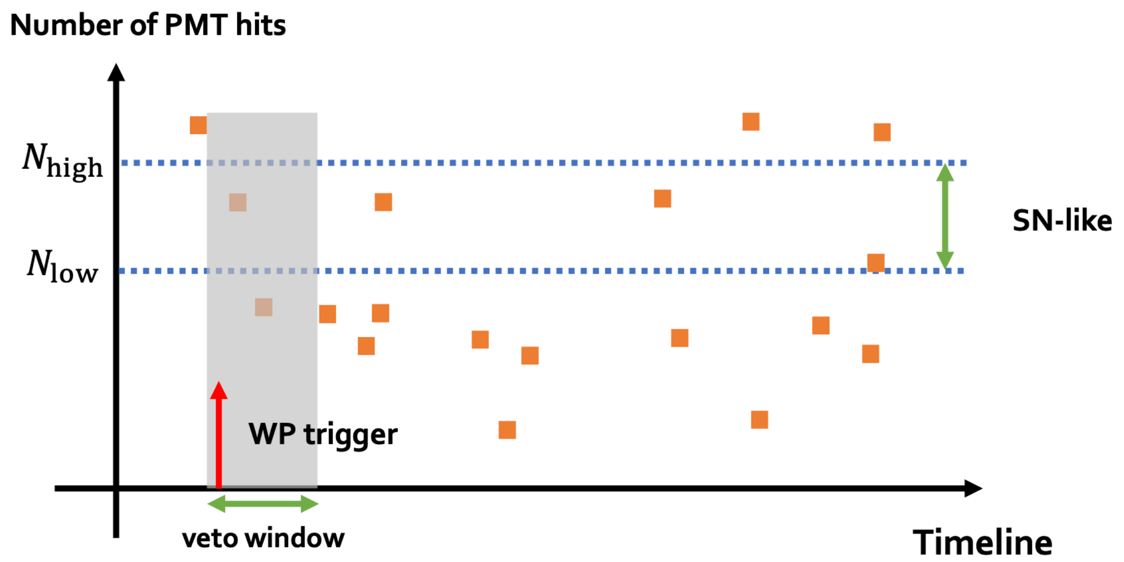


Monitoring systems to give CCSN alert:

- Prompt monitor
  - give fast alert for SN, runs on CTU.
  - Number of PMTs hit & WP trigger info.
- On dedicated Multi-messenger (MM) trigger system
- Online monitor
  - Runs on DAQ .
  - Use IBD candidates selected from the fast event reconstruction

Prompt monitor

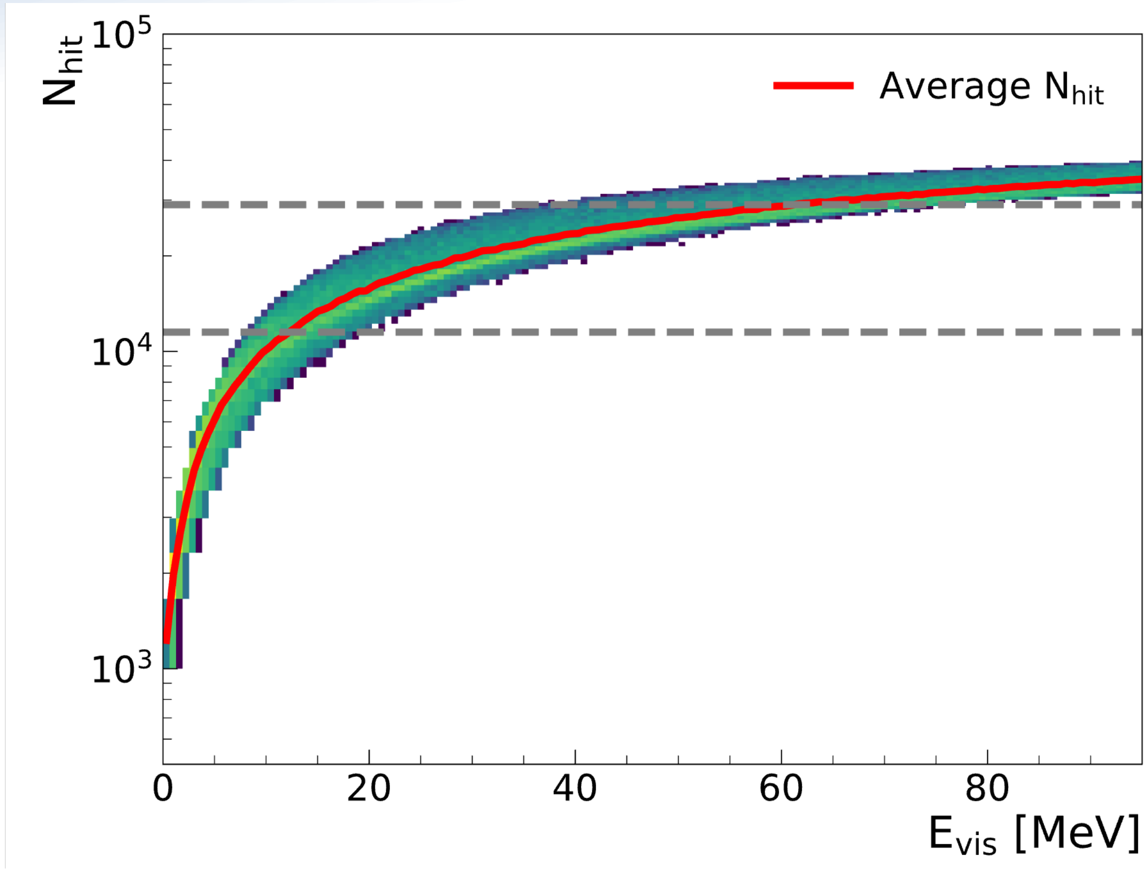


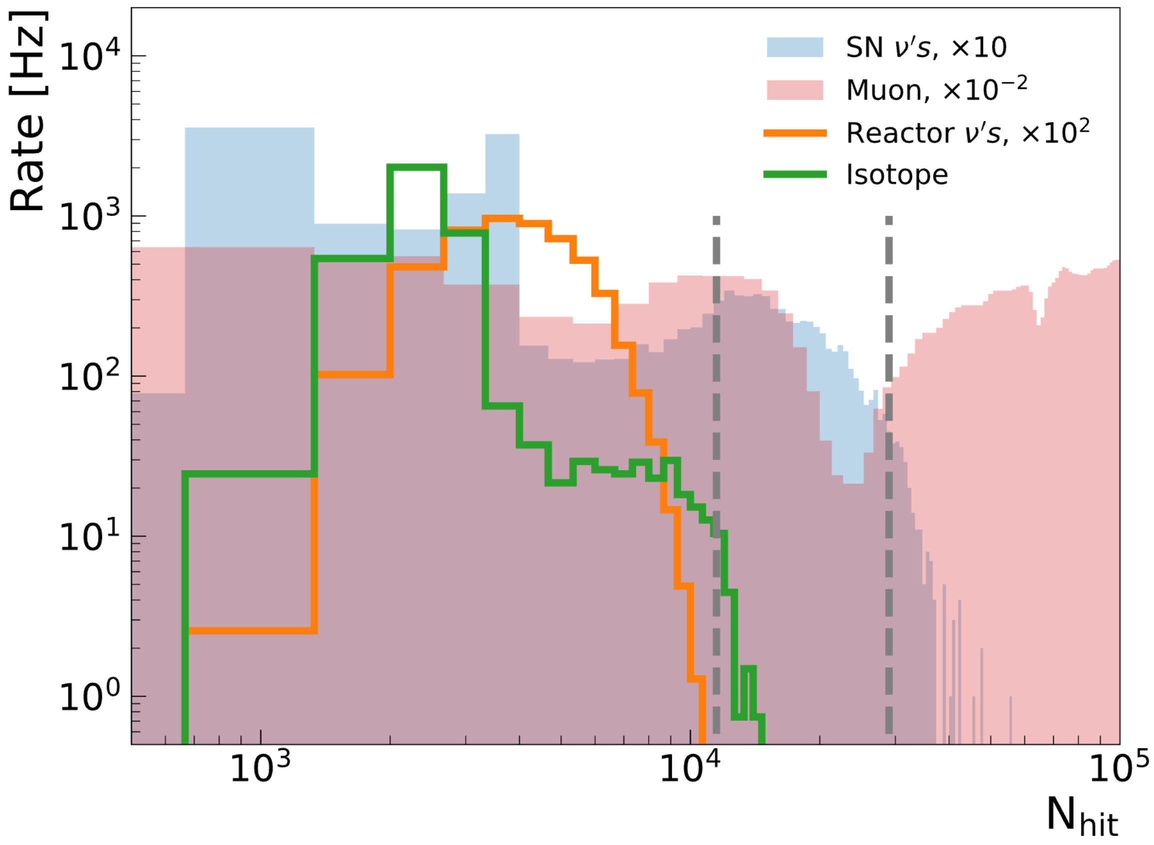


- Event selection:
  - Select SN signals based on N_{hit}
  - Muon veto based on WP trigger to suppress background

- N_{hit} definition: number of PMTs being fired within some time interval (~1 μs)

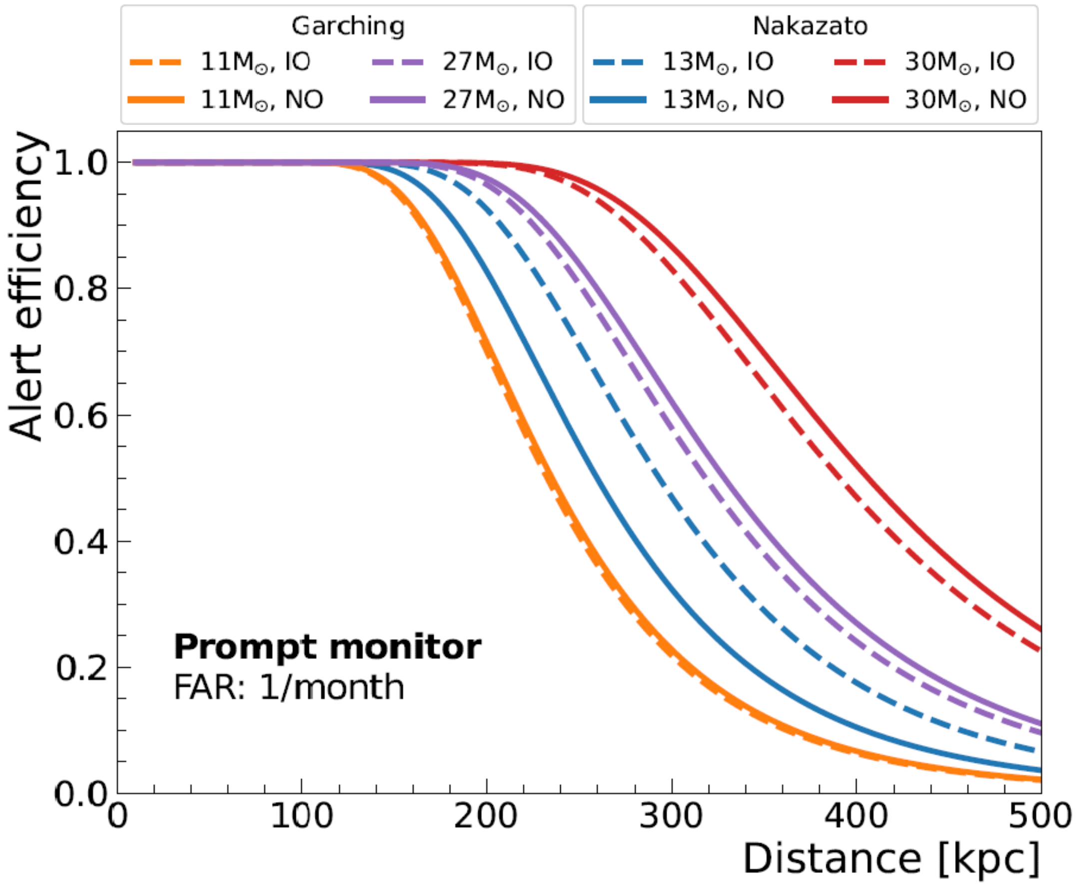
Prompt monitor

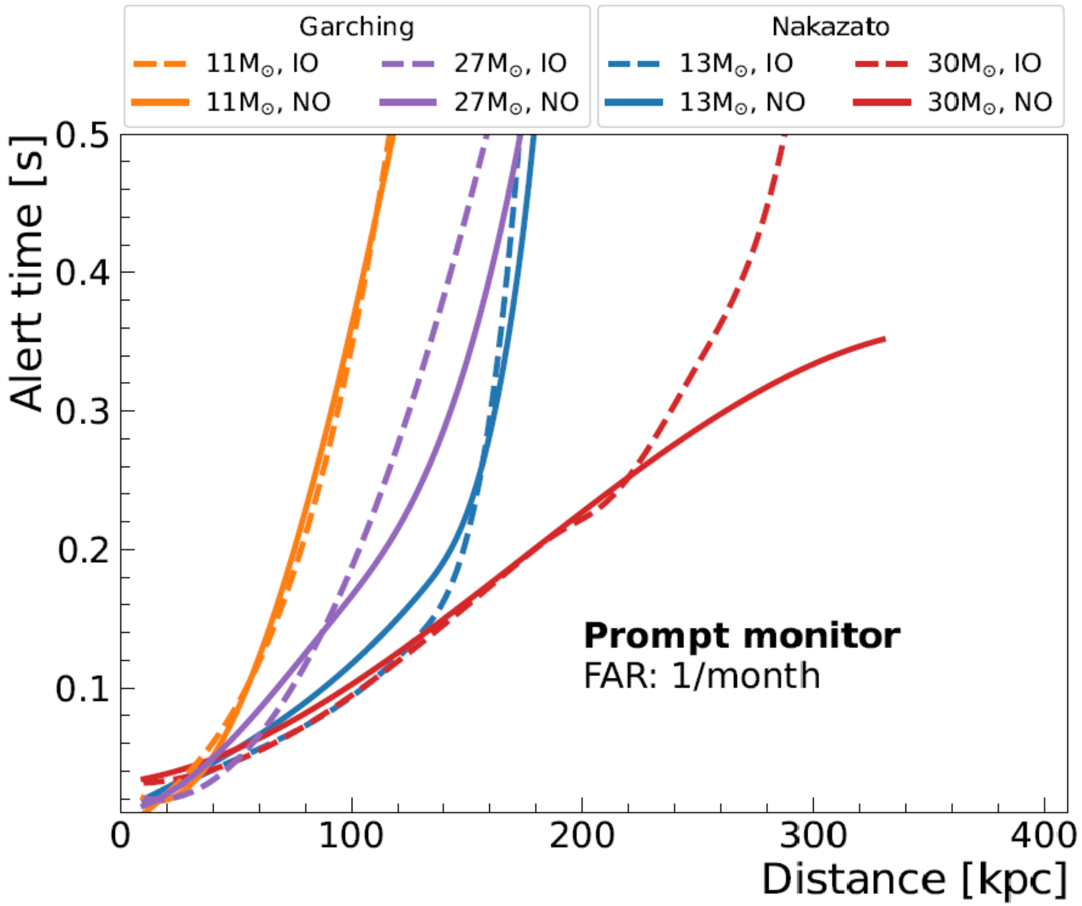




- Select SN candidates
  - No reconstruction info
  - $N_{hit} \in (N_{low}, N_{high})$
  - Energy at $N_{low} \sim 8 MeV$
  - Energy at $N_{high} \sim 40 MeV$
- Dominant background
  - Cosmogenic isotopes
  - Rate: ~209/day

Performance—prompt monitor

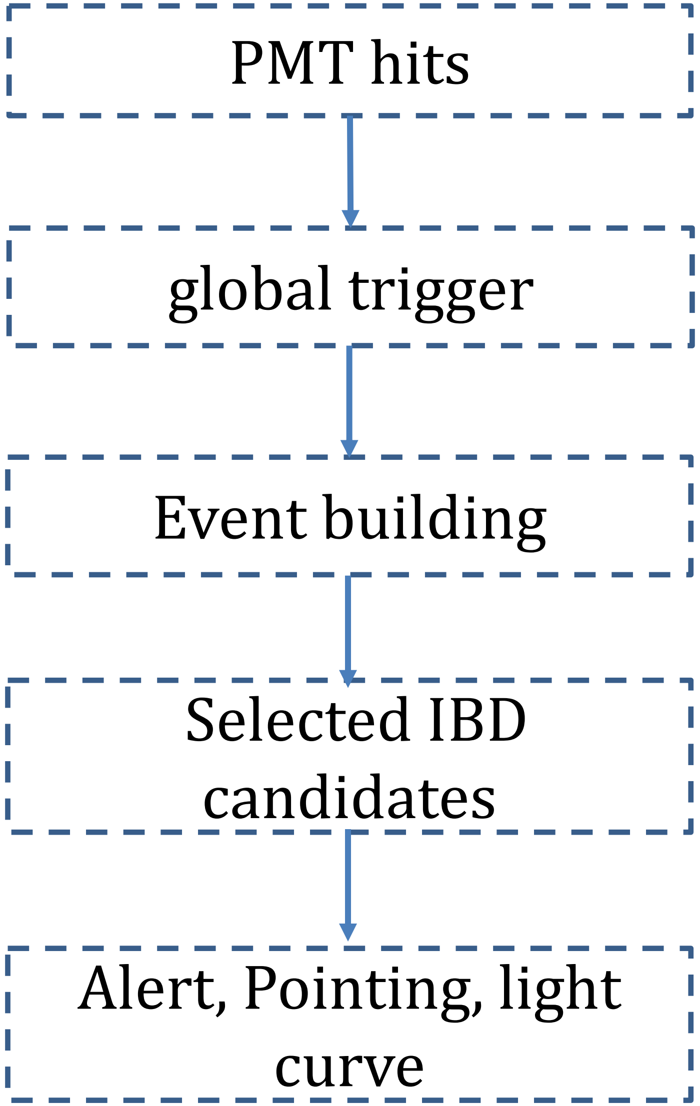




Alert distance: **230~400 kpc**

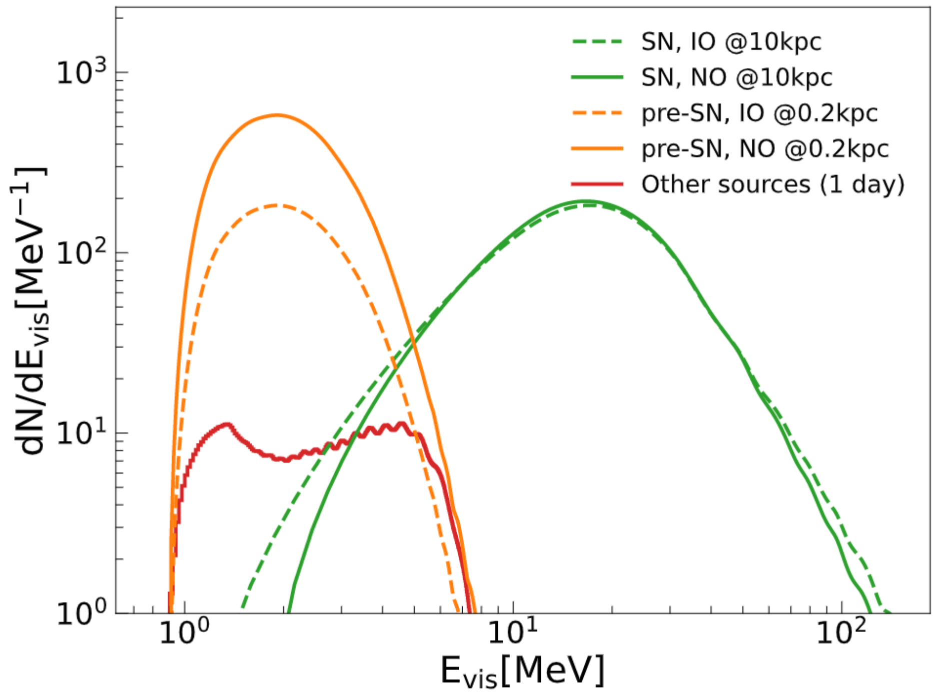
Alert time @10 kpc: **10~30 ms**

Online monitor

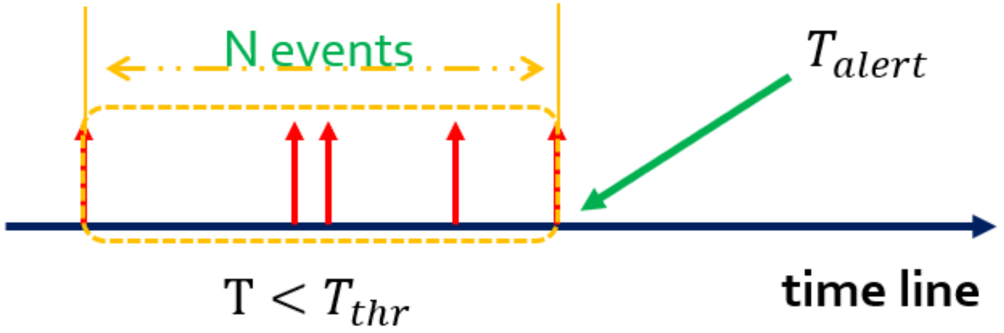


- Use global trigger events on DAQ.
- Perform event reconstruction to extract energy, vertex, …
- Select IBD events
  - Different criteria for SN and pre-SN
  - Monitor them separately
- Fast characterization after CCSN alert:
  - Pointing, light curve, etc.

Online monitor



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

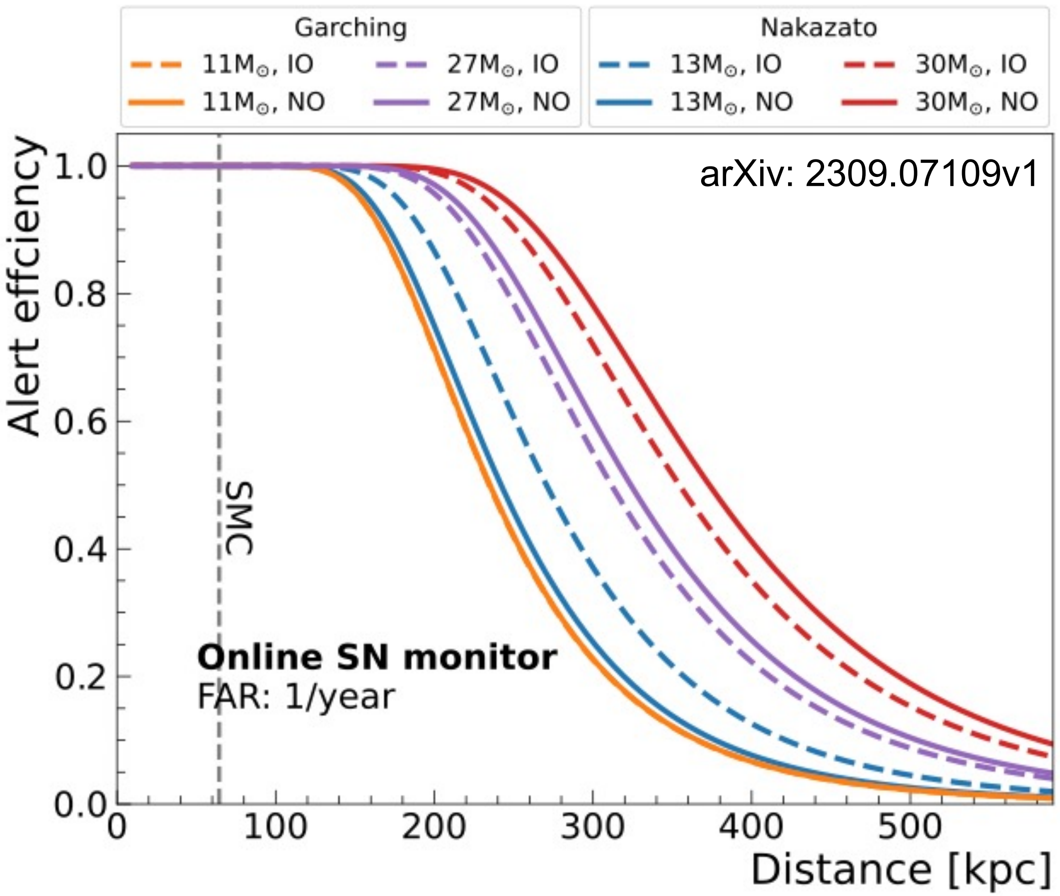


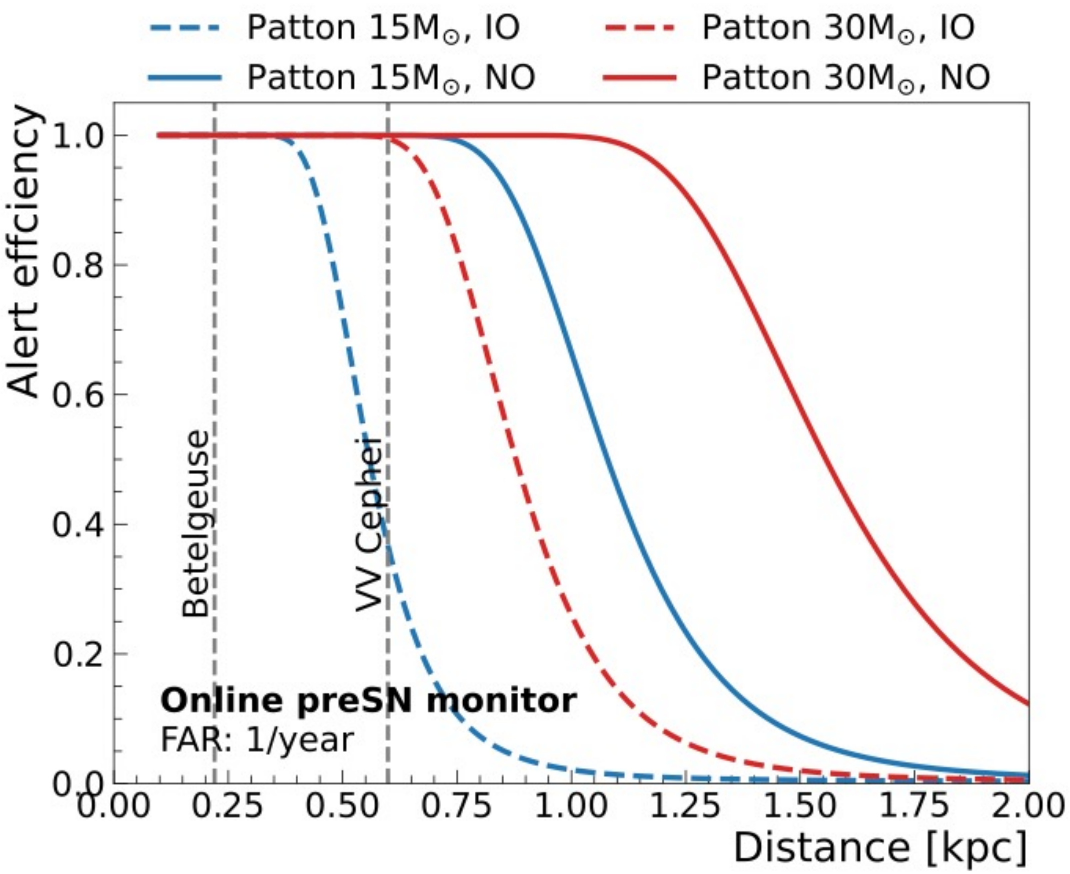
Alert method

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

Online monitor—Alert performance

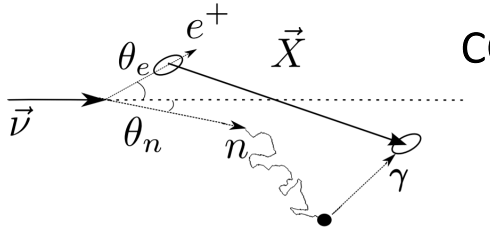




- 100% alert efficiency for SMC.
- Alert Distance (where the alert efficiency reaches 50%) reaches: 230~350 kpc
- Alert Time: 15~30 ms

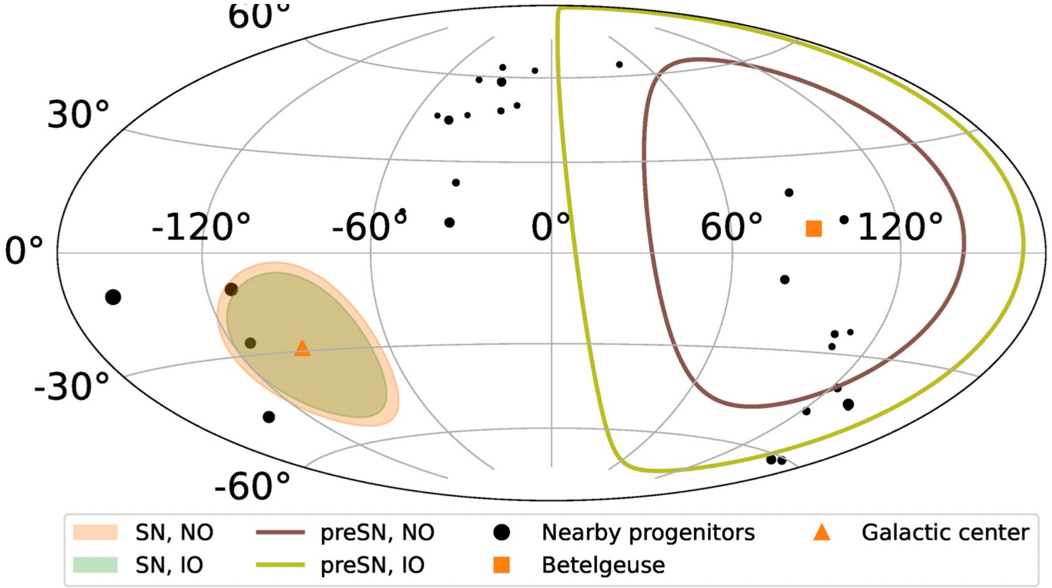
- 100% alert efficiency for Betelgeuse .
- Alert Distance reaches: 0.6~1.6 kpc
- Alert Time: 3~120 hours before SN explosion

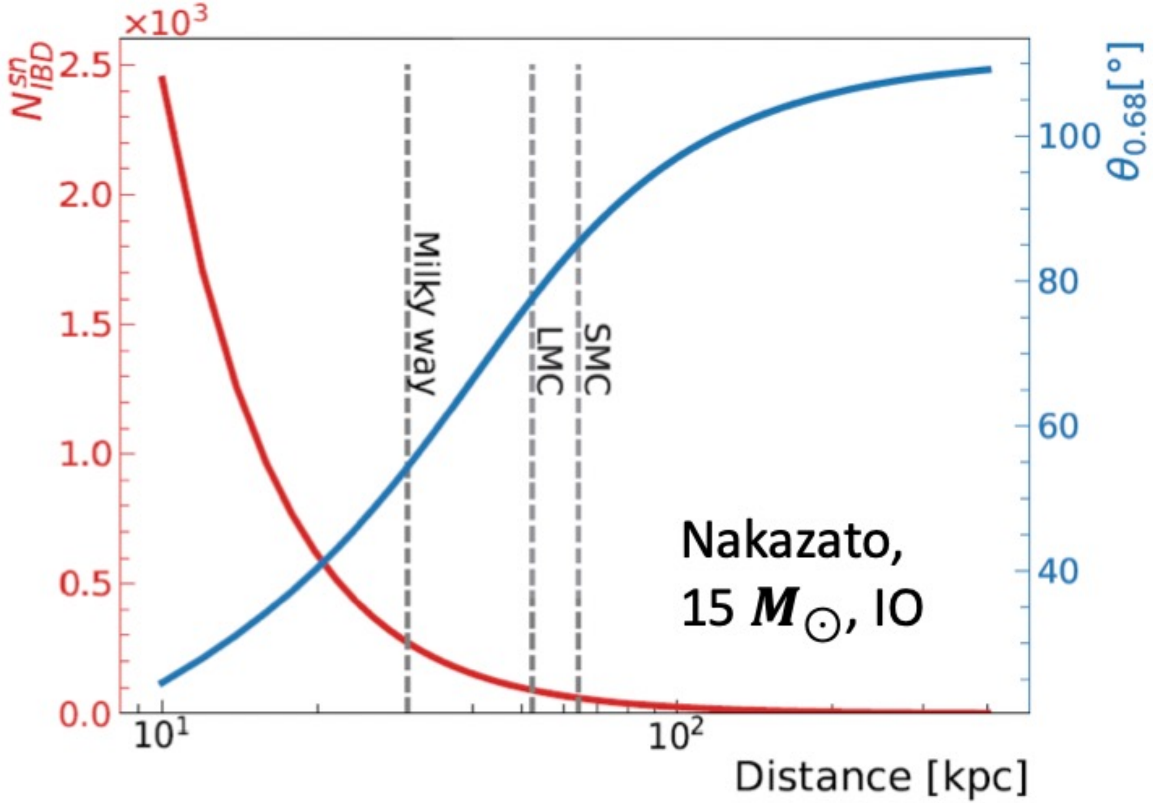
Online monitor—Pointing Performance



CCSN pointing using IBD events:

– $\vec{d}_\nu = \frac{1}{N}\sum_{i=1}^{N} \vec{X}_{pn}^{i}$

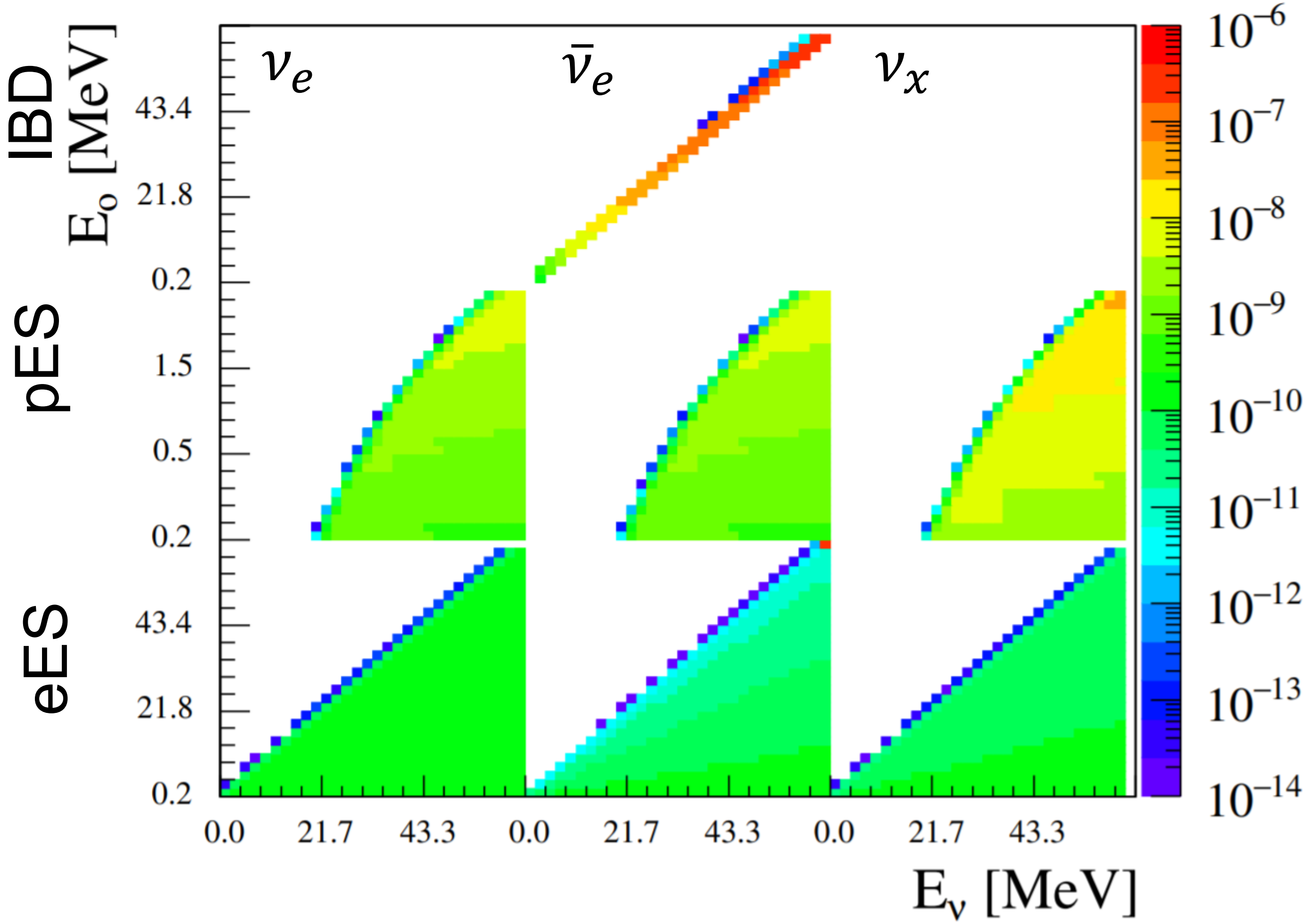




- Guide the telescopes to catch the early light of the CCSN by focusing on the targeted sky area.
- For a Betelgeuse-like star, the pointing ability is about 56° (81°) in the NO (IO) case, 15 $M_\odot$ Patton model.
- For a typical CCSN at 10 kpc, the pointing ability is about 26° (23°) in the NO (IO) case, 13 $M_\odot$ Nakazato model.

Detector response

- IBD channel:
  - Diagonal matrix
- pES channel:
  - E_{rec} is largely suppressed
  - Cut off due to energy threshold
- eES channel:
  - Lower Triangular Matrix



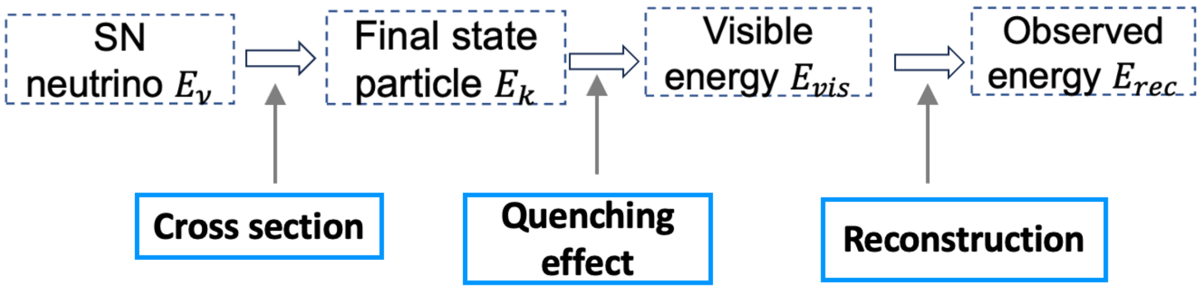
The response matrix combining three interaction channels

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

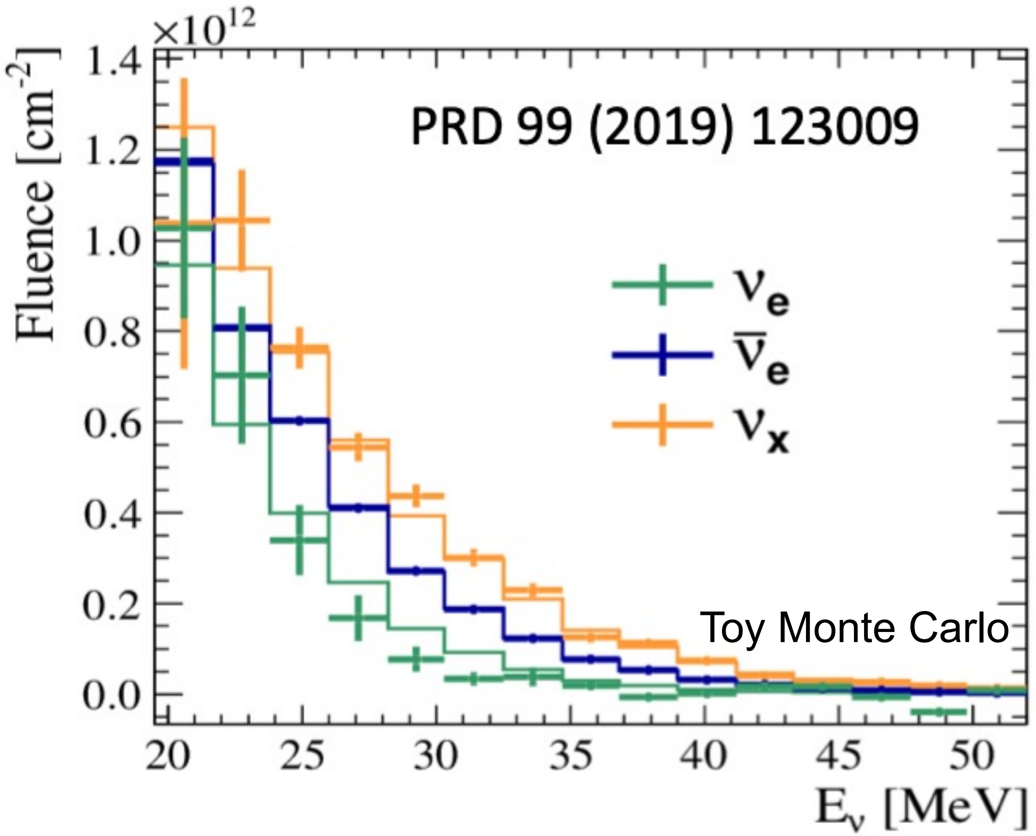
Reconstruction of the CCSN Spectra

The relationship between detector response, neutrino flux and observed spectra can be described by linear equation $AF = S$

$$
\begin{array}{c} \\ \text{IBD} \\ \text{pES} \\ \text{eES} \end{array}
\begin{array}{c}
\begin{array}{ccc} \quad\boldsymbol{\nu_e} \quad & \quad \boldsymbol{\bar{\nu}_e} \quad & \quad \boldsymbol{\nu_x} \end{array} \\
\begin{bmatrix}
N_p \boldsymbol{D}_{\mathrm{IBD}} \boldsymbol{\sigma}^{\mathrm{IBD}}_{\nu_e} & N_p \boldsymbol{D}_{\mathrm{IBD}} \boldsymbol{\sigma}^{\mathrm{IBD}}_{\bar{\nu}_e} & N_p \boldsymbol{D}_{\mathrm{IBD}} \sum \boldsymbol{\sigma}^{\mathrm{IBD}}_{\nu_x} \\
N_p \boldsymbol{D}_{p\mathrm{ES}} \boldsymbol{\sigma}^{p\mathrm{ES}}_{\nu_e} & N_p \boldsymbol{D}_{p\mathrm{ES}} \boldsymbol{\sigma}^{p\mathrm{ES}}_{\bar{\nu}_e} & N_p \boldsymbol{D}_{p\mathrm{ES}} \sum \boldsymbol{\sigma}^{p\mathrm{ES}}_{\nu_x} \\
N_e \boldsymbol{D}_{e\mathrm{ES}} \boldsymbol{\sigma}^{e\mathrm{ES}}_{\nu_e} & N_e \boldsymbol{D}_{e\mathrm{ES}} \boldsymbol{\sigma}^{e\mathrm{ES}}_{\bar{\nu}_e} & N_e \boldsymbol{D}_{e\mathrm{ES}} \sum \boldsymbol{\sigma}^{e\mathrm{ES}}_{\nu_x}
\end{bmatrix}
\end{array}
\cdot
\begin{bmatrix} \boldsymbol{F}_{\nu_e} \\ \boldsymbol{F}_{\bar{\nu}_e} \\ \boldsymbol{F}_{\nu_x} \end{bmatrix}
=
\begin{bmatrix} \boldsymbol{S}_{\mathrm{IBD}} \\ \boldsymbol{S}_{p\mathrm{ES}} \\ \boldsymbol{S}_{e\mathrm{ES}} \end{bmatrix}
$$



- Unfolding algorithm: Singular Value Decomposition (SVD), Bayesian.



- Allow reconstruction of the energy spectra of $\nu_e, \bar{\nu}_e$ and ν_x through the unfolding approach.
- Used for further physics and astrophysics studies
- Full chain Monte Carlo reconstruction results will come soon.

Summary

- JUNO advantage in CCSN detection
  - Large detector and excellent energy resolution
  - Multi channel detection, especially the pES channel
- CCSN monitor
  - Alert method
  - Alert performance
  - CCSN pointing
- Energy spectra reconstruction:
  - Reconstruct the full flavor neutrino energy spectra
  - CCSN burst mechanism
  - Neutrino flavor conversion