Core-Collapse Supernova Neutrino Observation in JUNO

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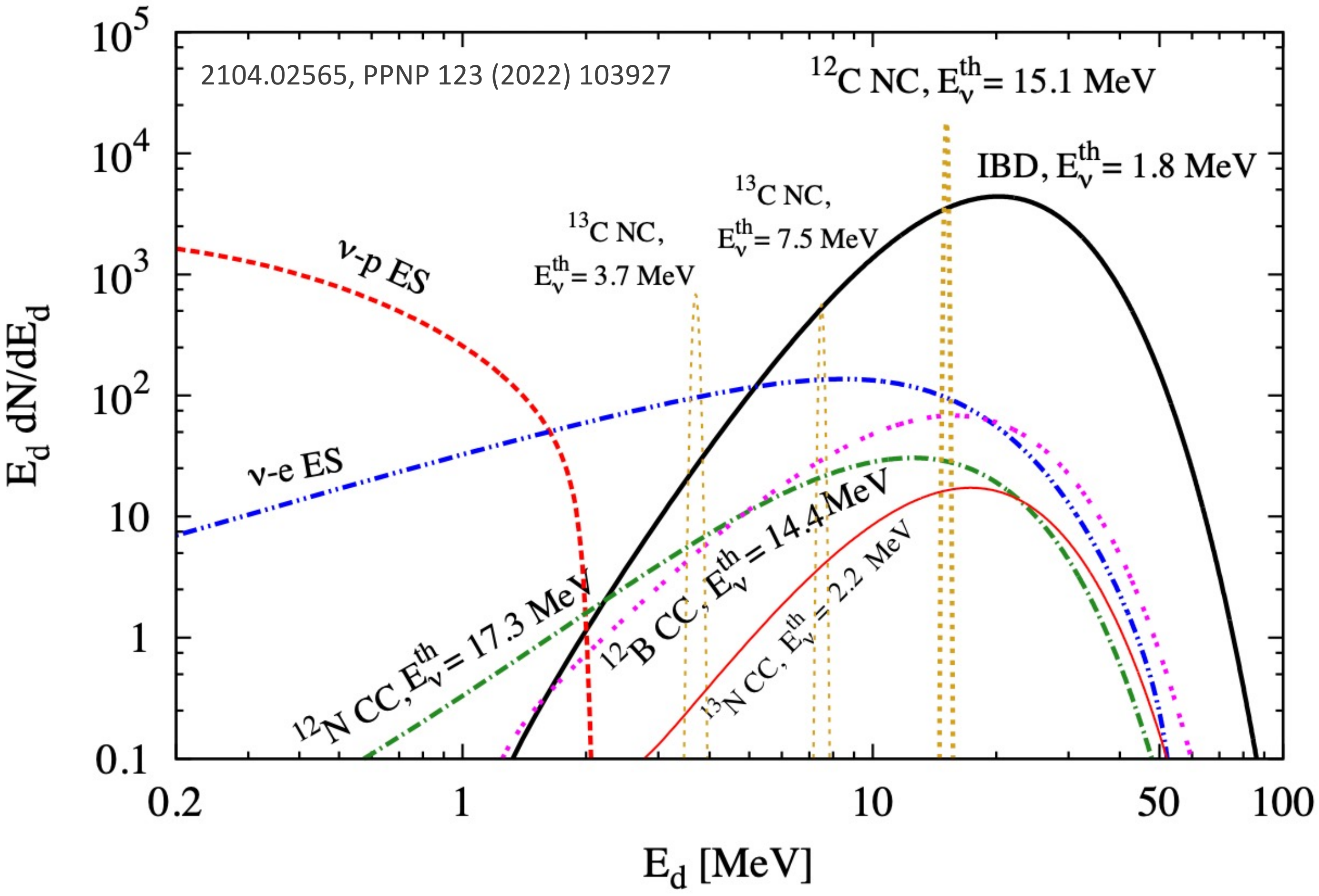
Core-Collapse SuperNova (CCSN) Detection in JUNO



- At 10 kpc, ~5000 IBD, ~2000 pES, ~300 eES can be observed.

Supernova Neutrinos

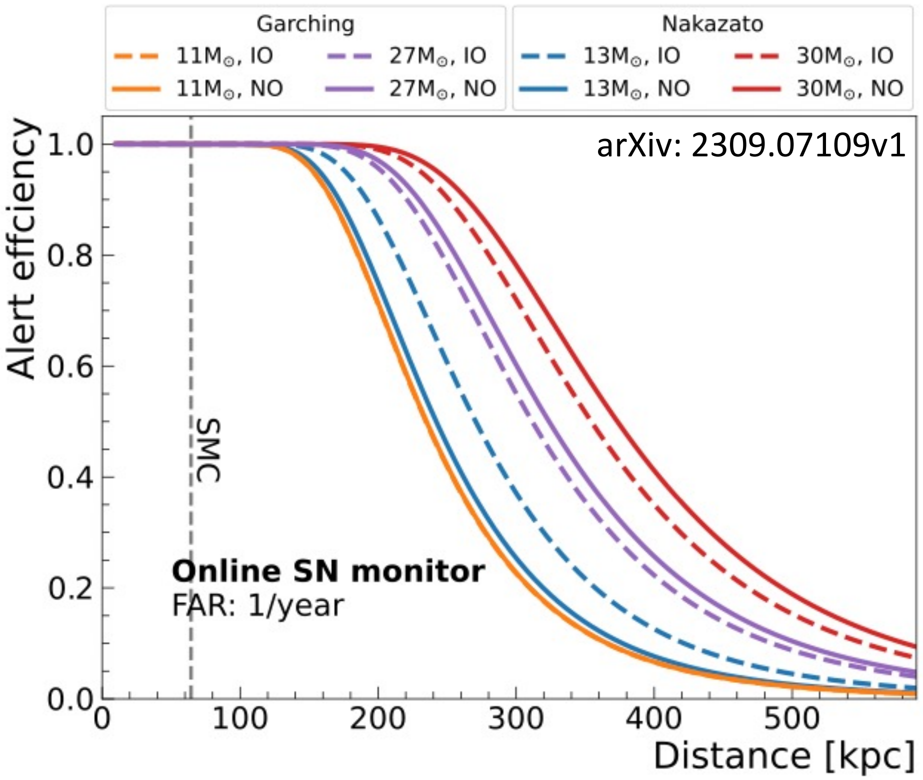
- ~ 1-3 supernovae in our galaxy per century. Release 99% of energy in form of neutrinos.
- Provide precious information about the explosion mechanism and intrinsic properties of neutrinos themselves.
- Time scale ~ 10 s.

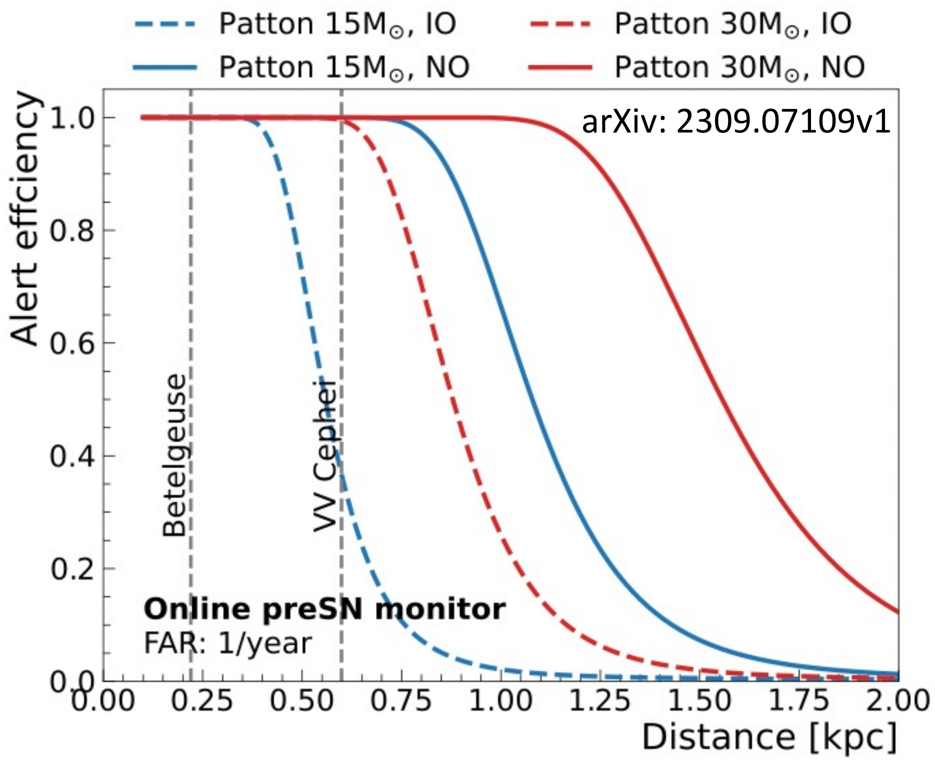
CCSN Detection Potentials of JUNO

- Real-time monitoring for the next CCSN.
- Model-independent reconstruction of $\nu_e, \bar{\nu}_e$ and ν_x spectra for astrophysics study.
- Absolute neutrino masses.

Monitoring System—Alert performance

- Supernova Detection Systems in JUNO
  - Prompt monitor: give fast alert for SN, runs on FPGAs.
  - Online monitor: pre-SN and SN, reconstructed information, DAQ stage
  - Dedicated Multi-Messenger Trigger System (on the way).
- Take the Online monitor as an example

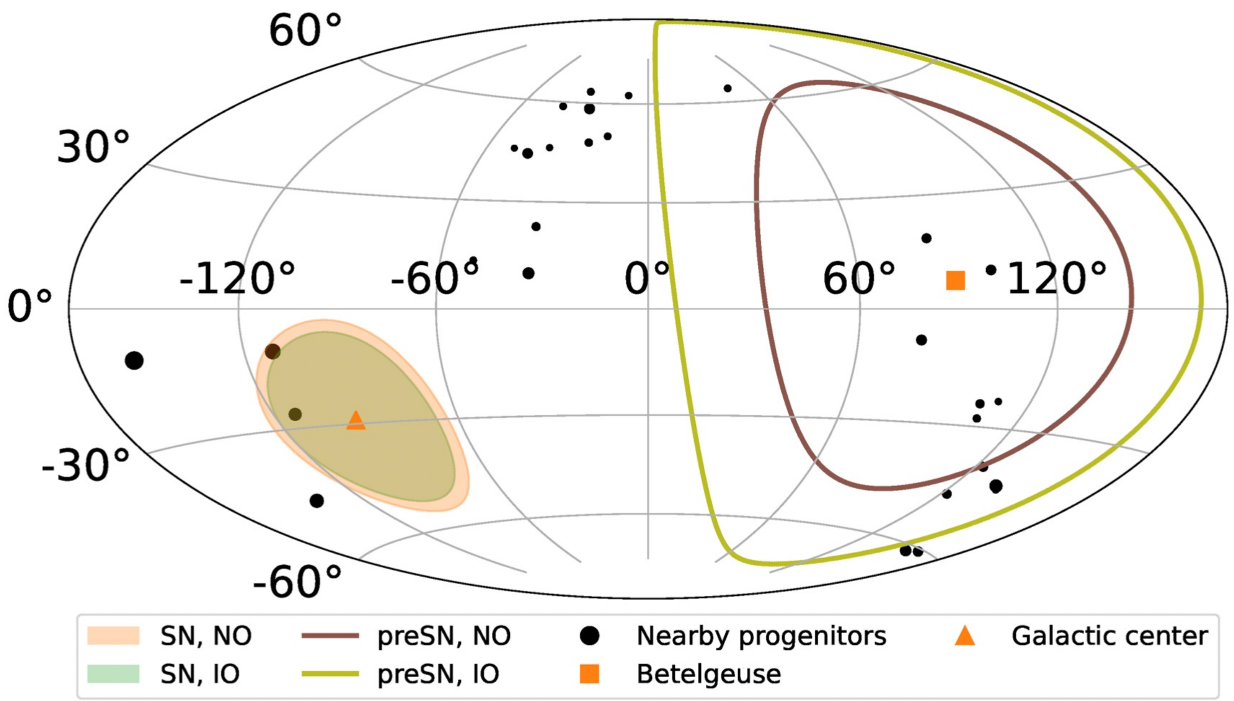




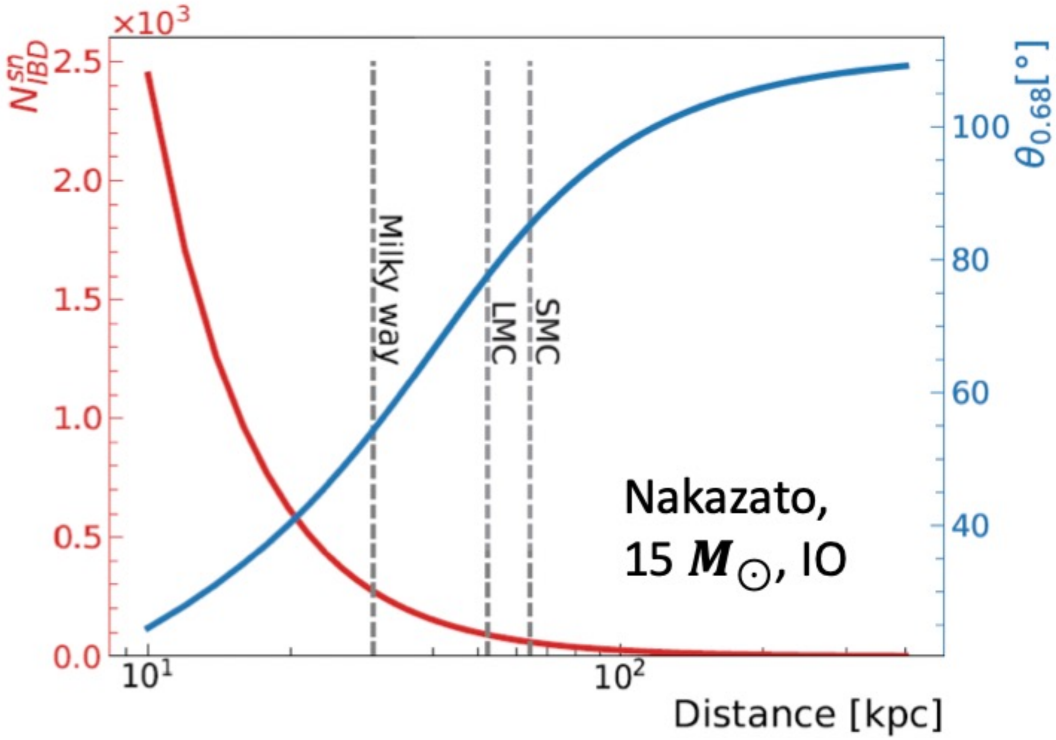
- 100% alert efficiency for SMC.
- Alert Distance (where the alert efficiency reaches 50%) reaches: 230~350 kpc
- Alert Time: 15~30 ms

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

Monitoring System—Pointing Performance



arXiv: 2309.07109v1



- Guide the telescopes to catch the early light of the CCSN by focusing on the targeted sky area.
- For a Betelgeuse-like (0.2 kpc) star, the pointing ability is about 56° (81°) in the NO (IO) case, 15 $M_\odot$ Patton model, with pre-SN.
- For a typical CCSN at 10 kpc, the pointing ability is about 26° (23°) in the NO (IO) case, 13 $M_\odot$ Nakazato model.

Reconstruction of the CCSN Spectra

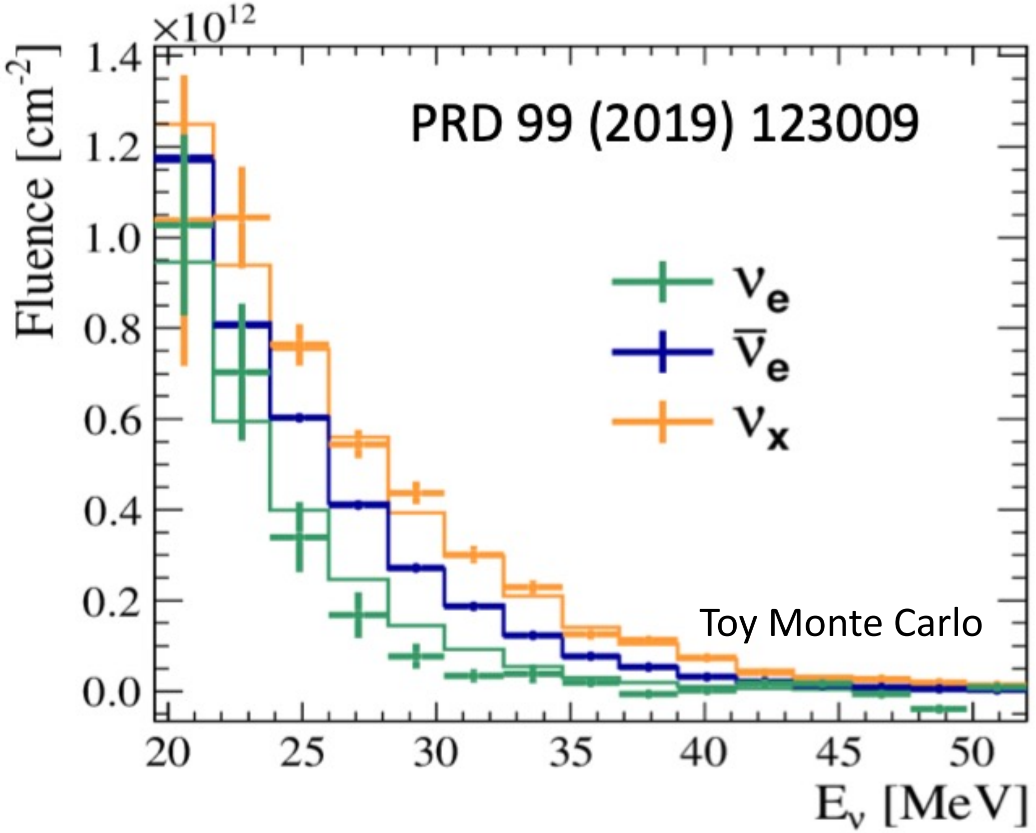
The relationship between detector response, neutrino flux and observed spectra can be described by linear equation $AF = S$

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

SN neutrino E_ν ⇒ Final state particle E_k ⇒ Visible energy E_{vis} ⇒ Observed energy E_{rec}

Cross section **Quenching effect** **Reconstruction**

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



- Allow model-independent 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 uses a large detector with excellent energy resolution, has a good performance in CCSN detection.
- Excellent CCSN monitoring performance
  - The design of Prompt and online monitoring systems are ready.
  - The direction reconstruction of CCSN has a good level of accuracy.
- Energy spectra reconstruction
  - Reconstruct the full flavour neutrino energy spectra
  - Used for further physics and astrophysics studies
  - Full chain monte Carlo reconstruction results to come soon.

Backup

	Model	Mass $[M_\odot]$	Mass ordering	r_{bkg} $[day^{-1}]$	N_{IBD}	N_{sel}	Alert distance [kpc]		Alert time	
							FAR<1/month	FAR<1/year	FAR<1/month	FAR<1/year
SN	Garching	11	NO	39 (83)	1675	1414 (1204)	230 (220)	230 (190)	(16 ms)	(17 ms)
			IO		1676	1413 (1228)	230 (220)	230 (200)	(13 ms)	(14 ms)
		27	NO		3132	2651 (2466)	320 (310)	320 (280)	(15 ms)	(16 ms)
			IO		2958	2502 (2366)	310 (300)	310 (270)	(13 ms)	(13 ms)
	Nakazato	13	NO		2326	1934 (1698)	270 (240)	240 (200)	(20 ms)	(21 ms)
			IO		2827	2365 (2190)	300 (280)	270 (240)	(16 ms)	(17 ms)
		30	NO		5074	4098 (4217)	400 (390)	370 (350)	(31 ms)	(31 ms)
			IO		4972	4131 (4145)	390 (370)	350 (330)	(31 ms)	(31 ms)
pre-SN	Patton	15	NO	21	659	556	1.3	1.1	-140 h	-120 h
			IO		196	156	0.7	0.6	-90 h	-30 h
		30	NO		1176	930	1.7	1.6	-220 h	-180 h
			IO		379	302	1.0	0.9	-100 h	-3 h

Summary of the background rate (rbkg), expected number of signals (NIBD) and selected candidates (Nsel), alert distance and alert time for different models.