SuperNova Early Warning System
SNEWS 2.0 Workshop

Supernova Neutrino Observation in the JUNO Experiment

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On behalf of the JUNO collaboration

Institute of High Energy Physics

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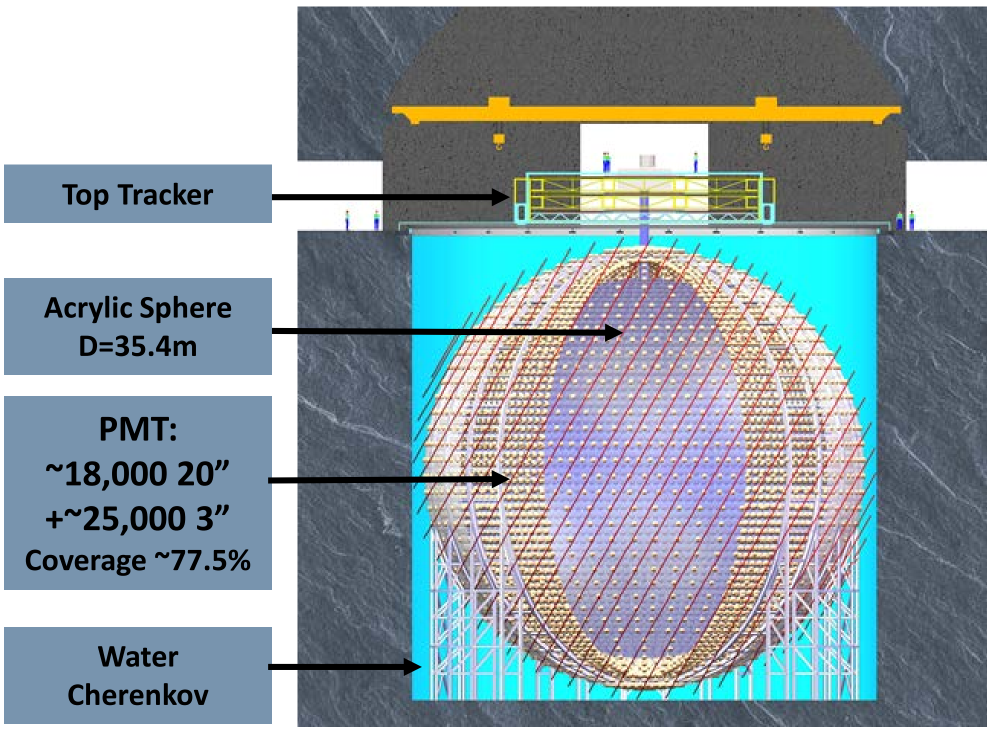
The JUNO Experiment

Jiangmen **U**nderground **N**eutrino **O**bservatory



Multipurpose neutrino experiment

- 700m underground
- 20 kiloton LS detector
- 3% energy resolution @ 1MeV
- Operation in 2021
- Physics:
  - Neutrino mass hierarchy
  - Precise neutrino oscillation parameters
  - Supernova neutrinos & DSNB
  - Solar neutrinos
  - Atmospheric neutrinos
  - Geoneutrinos
  - Proton decay and exotics

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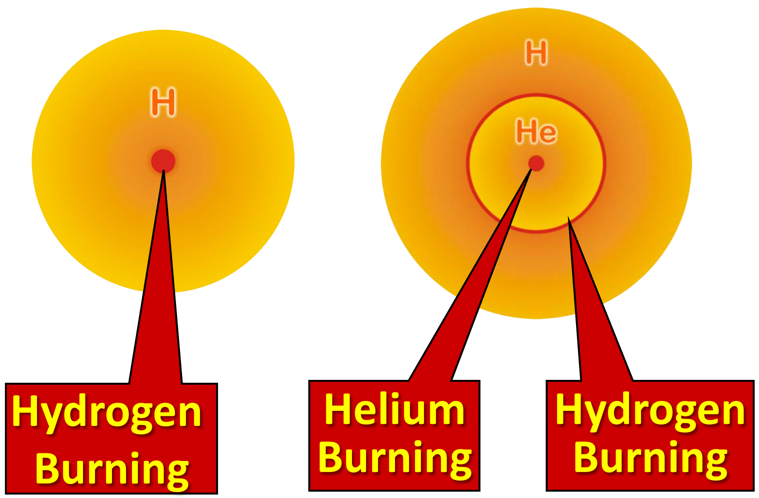
JUNO Location

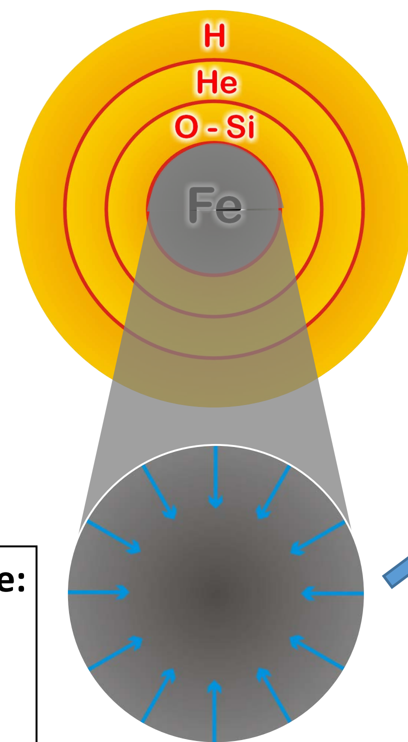
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

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

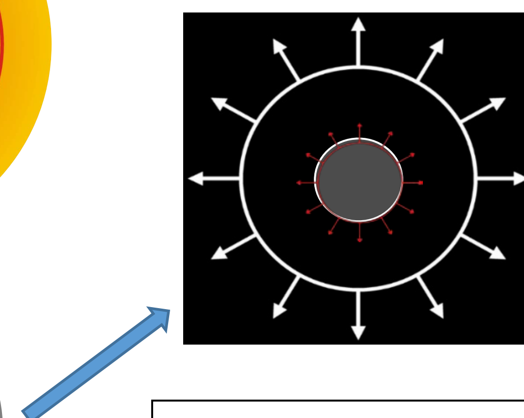
Supernova Burst Neutrinos

Main-sequence star   Helium-burning star   *From 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



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

Degenerate iron core:
$\rho \approx 10^9$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 8000$ km

Proto-Neutron star:
$\rho \sim \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}
$T \sim 30$ MeV

SN Neutrinos at JUNO

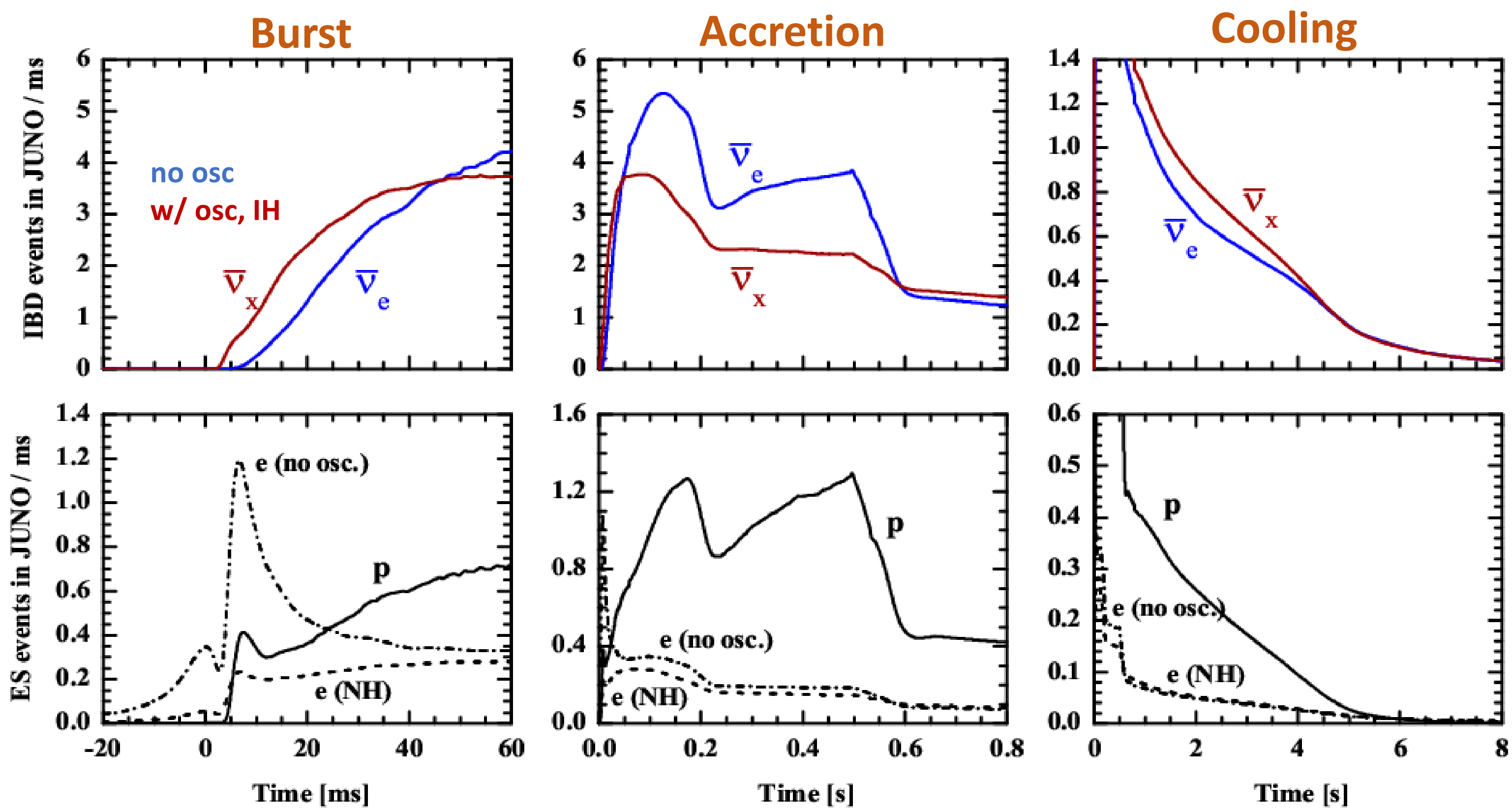
SN@10kpc, 20kt LS

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

F. An et al, Neutrino Physics with JUNO, 2016

- Real-time measurement of three-phase ν signals
- Distinguish between different ν flavors
- Reconstruct ν energies and luminosities
- Almost background free due to time information

SN Neutrino Time Distribution



F. An et al, Neutrino Physics with JUNO, 2016

SN@10kpc, w/ 1D simulations from Garching group

- **Real-time** detection and SN trigger for astronomical communities, e.g. **SNEWS**
- **Background almost free** with SN burst neutrinos ~10s
- **Prompt on-line SN trigger** is feasible

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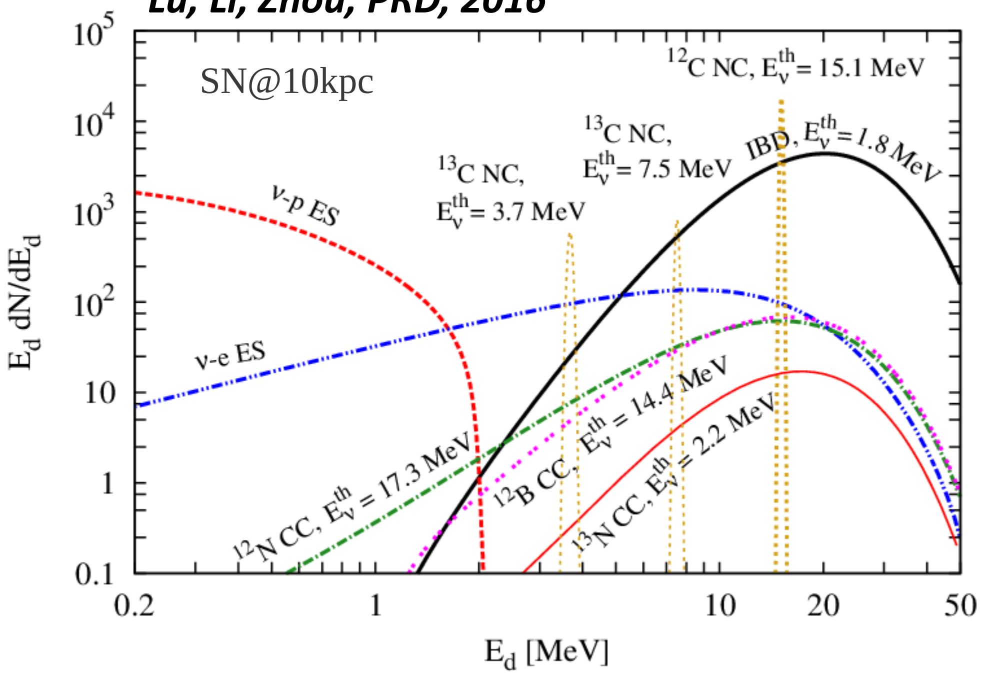
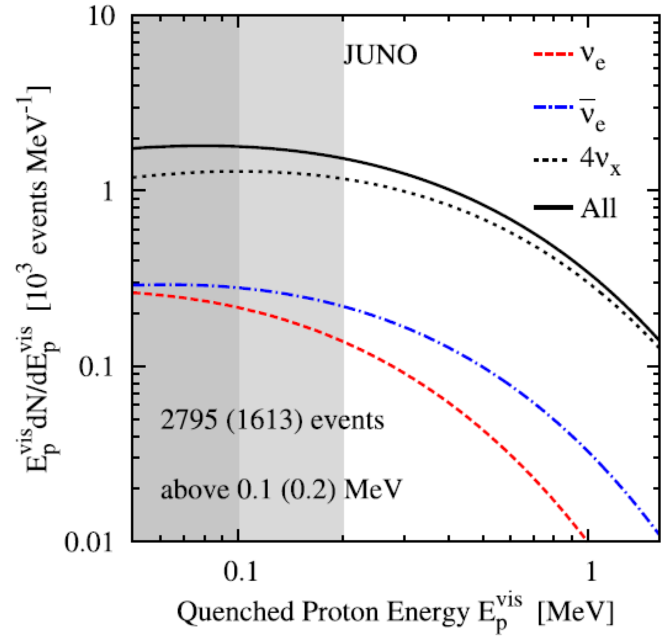
SN Neutrino Energy Spectra

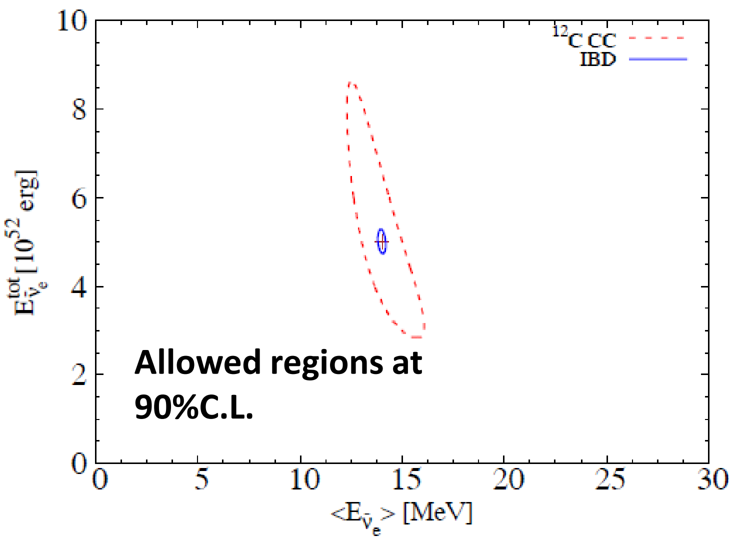
Lu, Li, Zhou, PRD, 2016

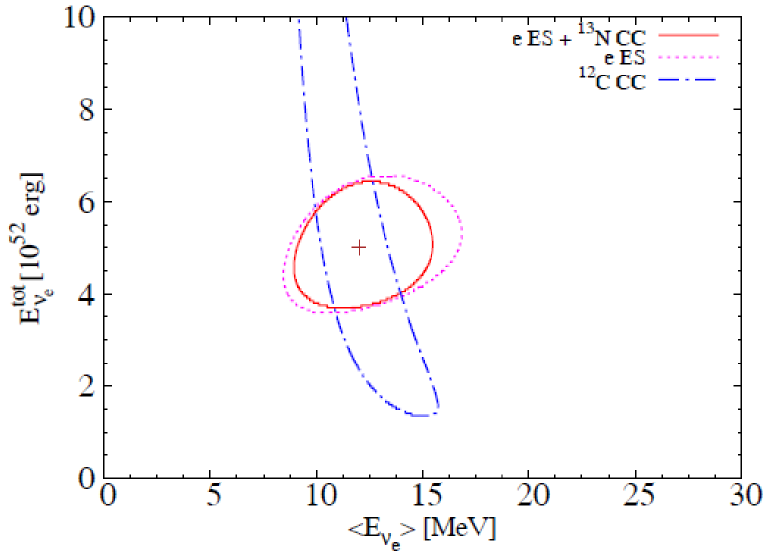


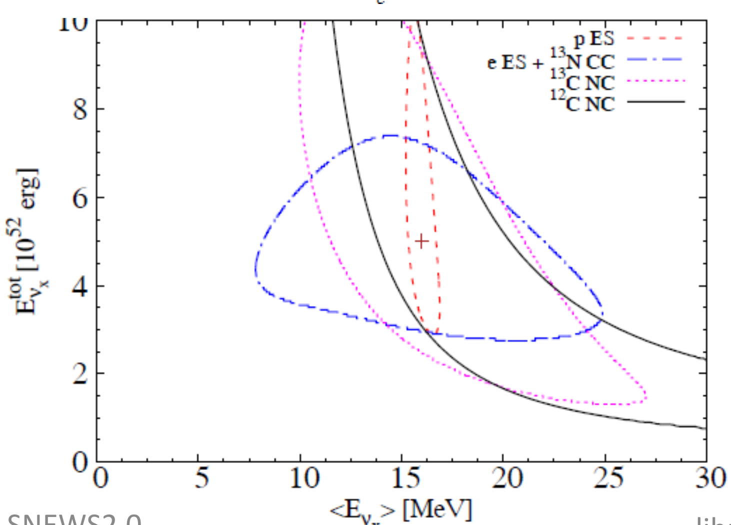


- **Full flavor** detection and **low threshold energy** ~0.2MeV in LS
- Coincidence events vs Singles events
- Unique opportunity to detect **ν_x via pES**
- **PSD method** to distinguish events from eES and pES

Different Neutrino Flavors







Lu, Li, Zhou, PRD, 2016

The reconstructed precision of the average energy of SN neutrinos:

- $\bar{\nu}_e$ 1.4%
- ν_x 5.2%
- ν_e 12%

Reconstruction of SN Neutrino Spectra

Li, Li, Wang, Wen, Zhou, PRD, 2018
Li, Huang, Li, Wen, Zhou, PRD, 2019

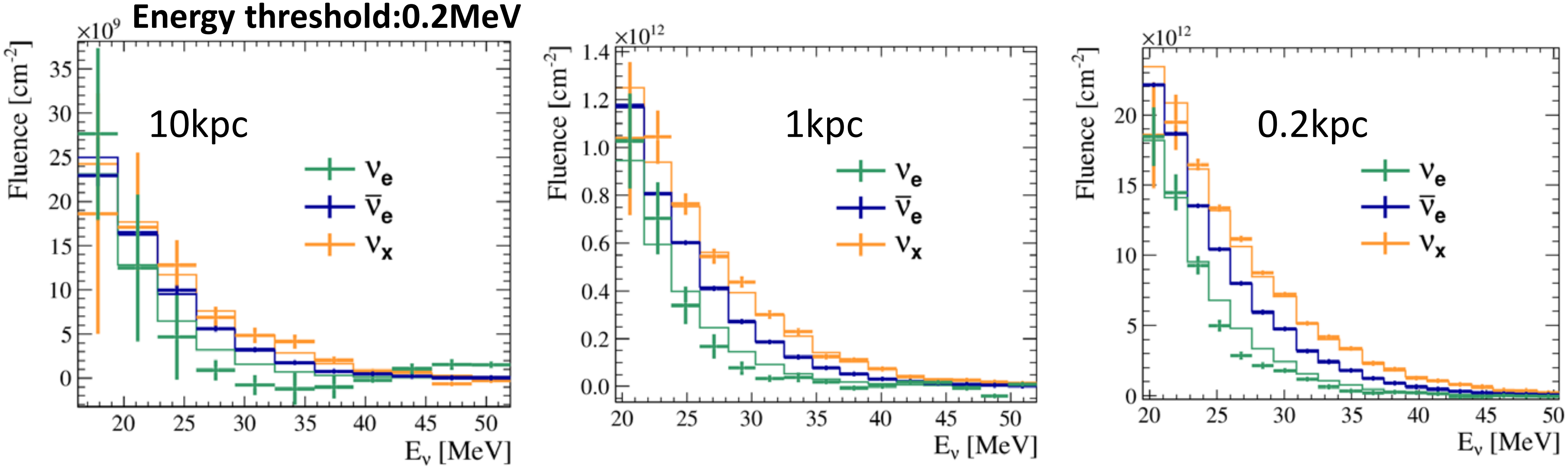
Cross section && Detector effects | SN neutrinos spectra | Observed spectra

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

Full flavor SN neutrino energy spectra reconstruction in JUNO detector

- model independent
- ν_x spectra reconstructed via pES
- promising for global analysis with all channels and other WC, Lar-TPC, et.al detectors.

Energy threshold:0.2MeV



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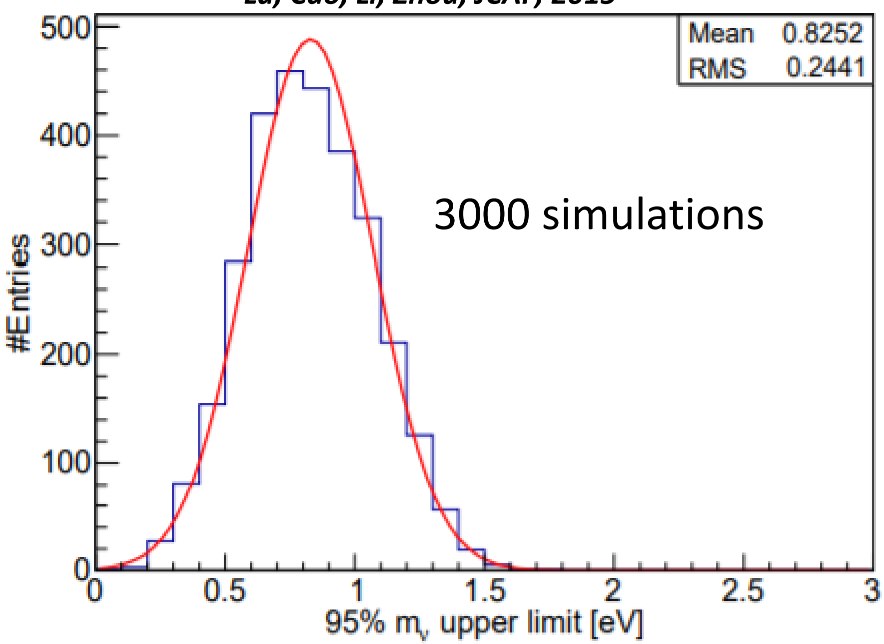
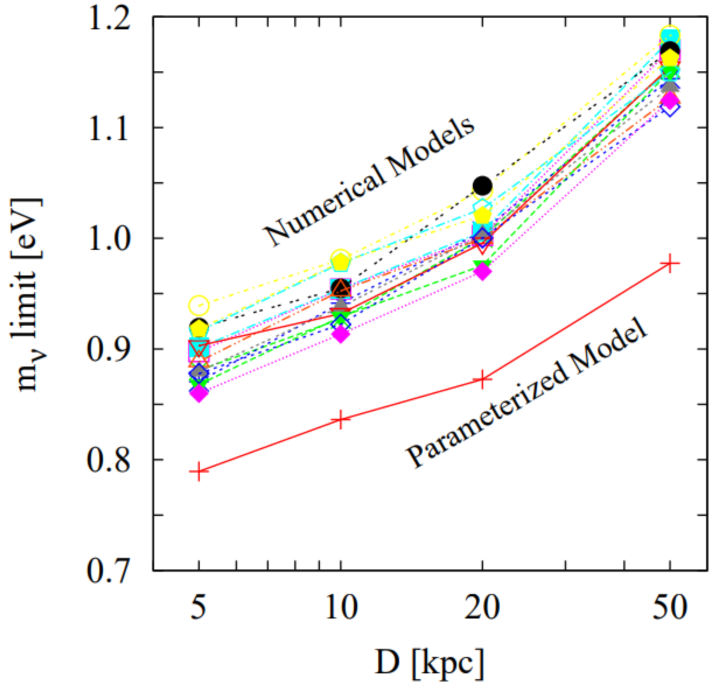
Bound on Neutrino Mass

Time delay of massive neutrinos: $\Delta t(m_\nu, E_\nu) \simeq 5.14 \text{ ms} \left(\frac{m_\nu}{\text{eV}}\right)^2 \left(\frac{10 \text{ MeV}}{E_\nu}\right)^2 \frac{D}{10 \text{ kpc}}$

Lu, Cao, Li, Zhou, JCAP, 2015





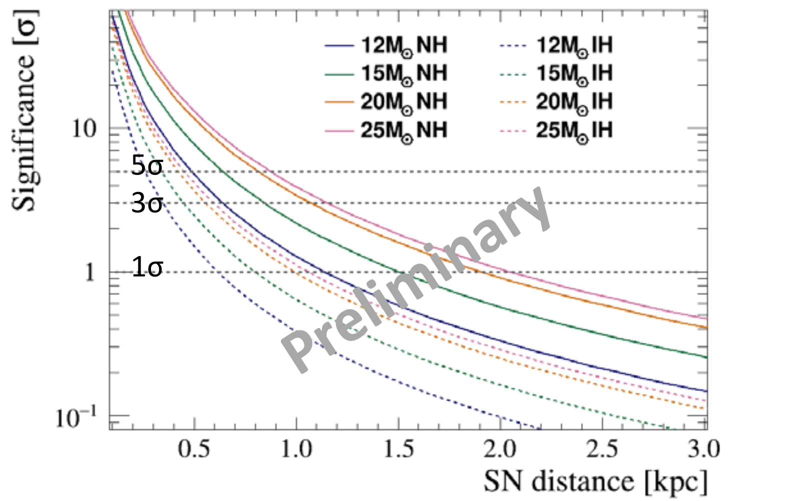
- Global efforts from neutrino experiments to better determine **the bounce time**, and provide an input for the gravitational wave detection

Pre-Supernova Neutrinos

- IBD background with reactor on in JUNO: 18/day
- Pre-SN neutrinos within 48 hr time window
- 0.9< E_p <3.5 MeV

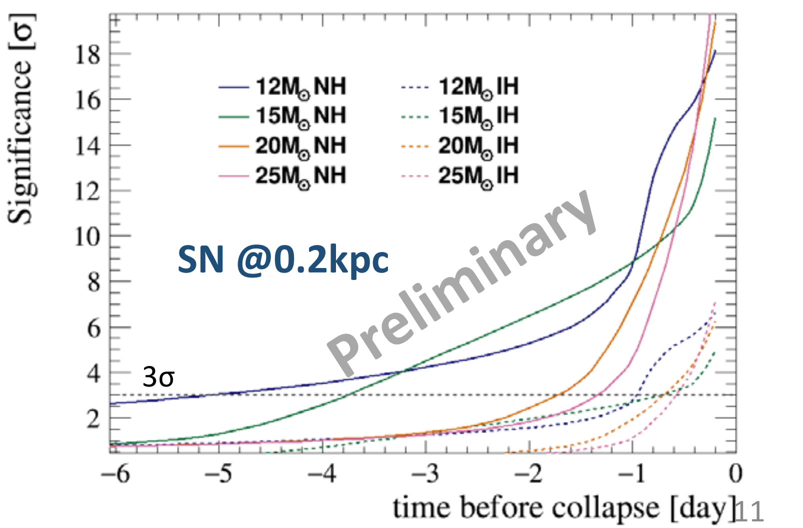
0.2kpc IBD	$[0.9 < E_p < 3.5]$ MeV		
	w/o oscillation	NH	IH
$12M_{\odot}$	371	286	83
$15M_{\odot}$	649	498	140
$20M_{\odot}$	1052	803	216
$25M_{\odot}$	1215	928	248

Thanks for the pre-SN neutrino models from Guo, Qian and Heger!



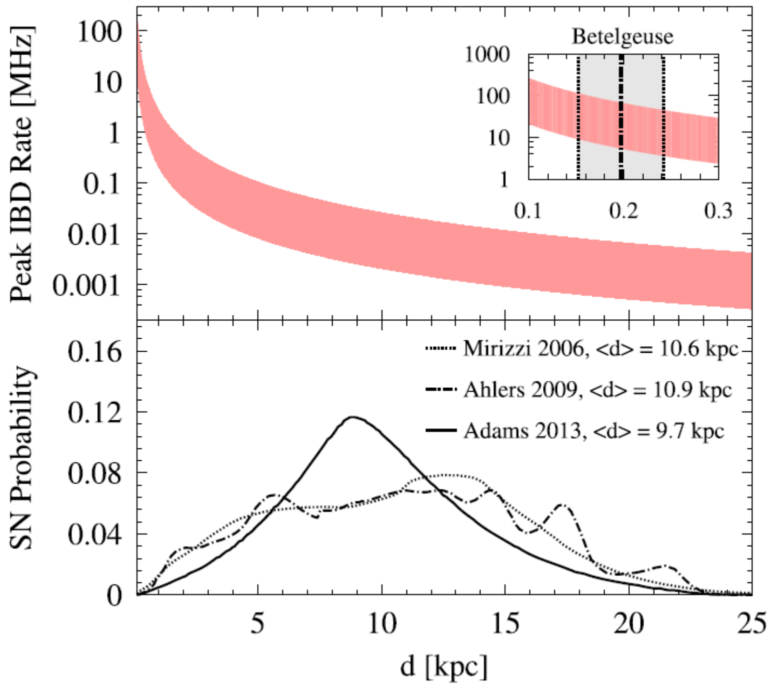
Pre-SN significance:

- Furthest alert (before 48 hours):
  - 3σ for $25M_{\odot}$ NH at 1.16kpc
- Earliest alert at 0.2kpc:
  - $12M_{\odot}$ NH for 5 days, $25M_{\odot}$ IH for 13 hr



Pre-SN alert for nearby SNe

Potentials for Multi-messengers



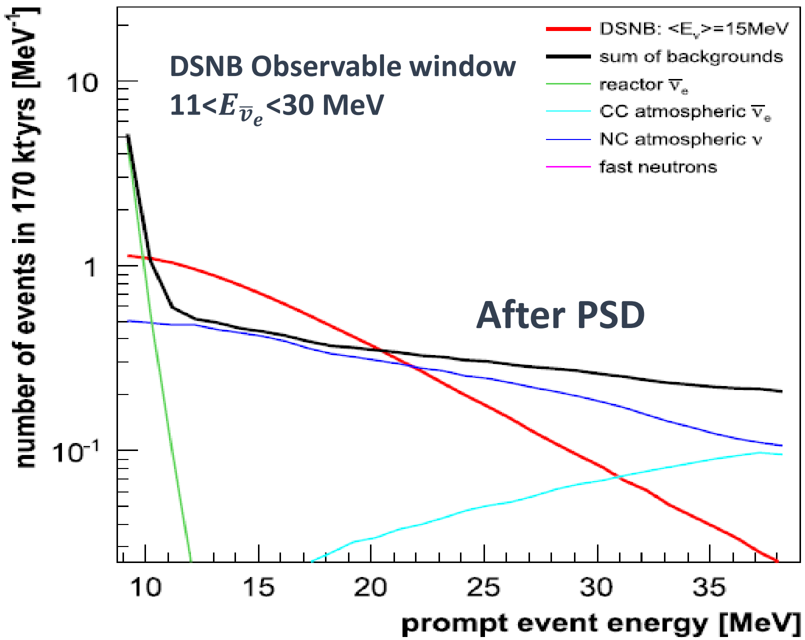
Lu, Li, Zhou, PRD, 2016

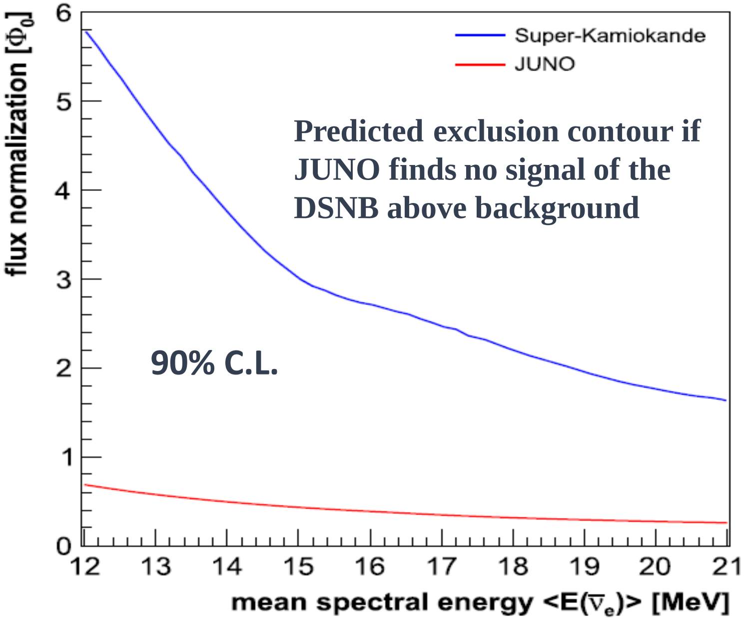
A comprehensive trigger and DAQ strategy is under progress to maximize the potentials on multi-messengers:

- Pre-SN neutrino alert (**Nearby SNe**)
- SN burst neutrino trigger (**Typical**)
- Low-threshold trigger system (**<0.2 MeV**)
  - **Please find Donglian's poster**

Diffused Supernova Neutrino Background

F. An et al, Neutrino Physics with JUNO, 2016





- DSNB: Approx. **10 core collapse/sec** in the visible universe, **3 events/year** in JUNO
- Provide information of star formation rate, ν emission from average **CCSNe** and **BHs**..
- **PSD** to suppress background, mainly **atmospheric NC neutrinos**
- **Detection significance~3σ** after 10 years of data taking in JUNO, with $\langle E_{\bar{\nu}_e} \rangle$~15MeV

Summary & Outlook

- A high statistics and accurate detection is prospected in JUNO for the next galactic SN.
- JUNO can register full flavor SN neutrinos and provide a unique opportunity to detect SN ν_x.
- JUNO has a good chance to detect DSNB, a guaranteed source of SN neutrinos.
- A comprehensive trigger and DAQ strategy for pre-SN neutrinos, SN burst neutrinos as well as low energy events are under progress. JUNO is prepared to contribute to the astronomical communities, e.g. SNEWS.

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Backup

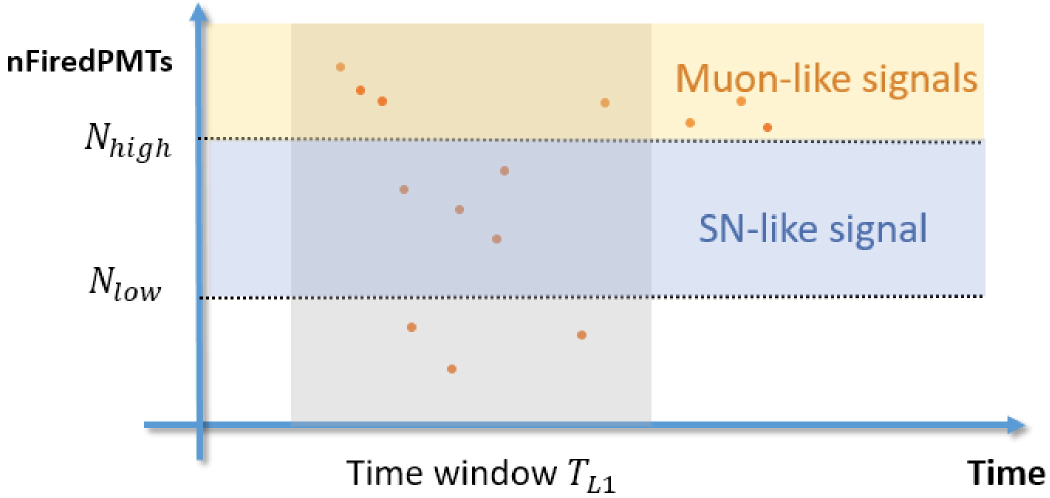
SN neutrinos at JUNO

Lu, Li, Zhou, PRD, 2016

Channel	Type		No Oscillations	Normal Ordering	Inverted Ordering
			Number of SN Neutrino Events at JUNO		
$\overline{\nu}_e + p \to e^+ + n$	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)

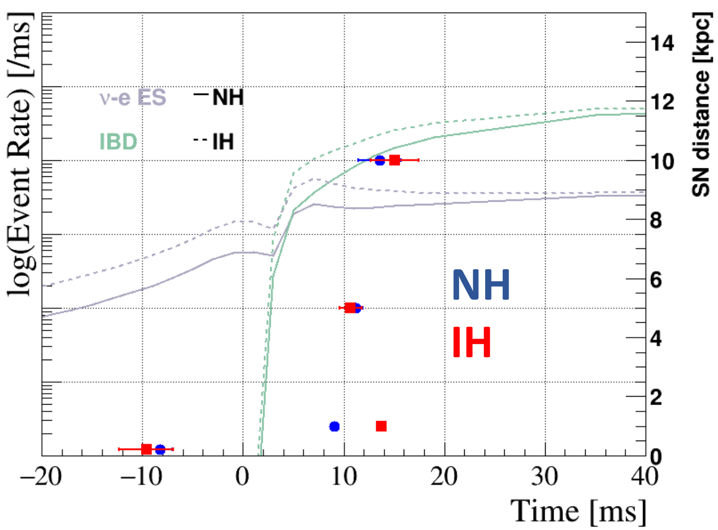
Detection channels	ν Flavors	Efficiency	Backgrounds	Systematics	
IBD	$\overline{\nu}_e$	95%	None	Detection	2%
^{12}C-CC	$\overline{\nu}_e$ and ν_e	90%	None	Detection	2%
pES	$\overline{\nu}_e$, ν_e and ν_x	99%	eES	Detection	2%
				Cross section	20%
				k_{B}	3%
eES	$\overline{\nu}_e$, ν_e and ν_x	99%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

SN trigger (preliminary)



SN trigger strategy:
with number of fired LPMTs of CD and its timestamp

SN trigger time:
Only 10 tests for each SN distance
With 25 $M_{\odot}$ model from Garching group

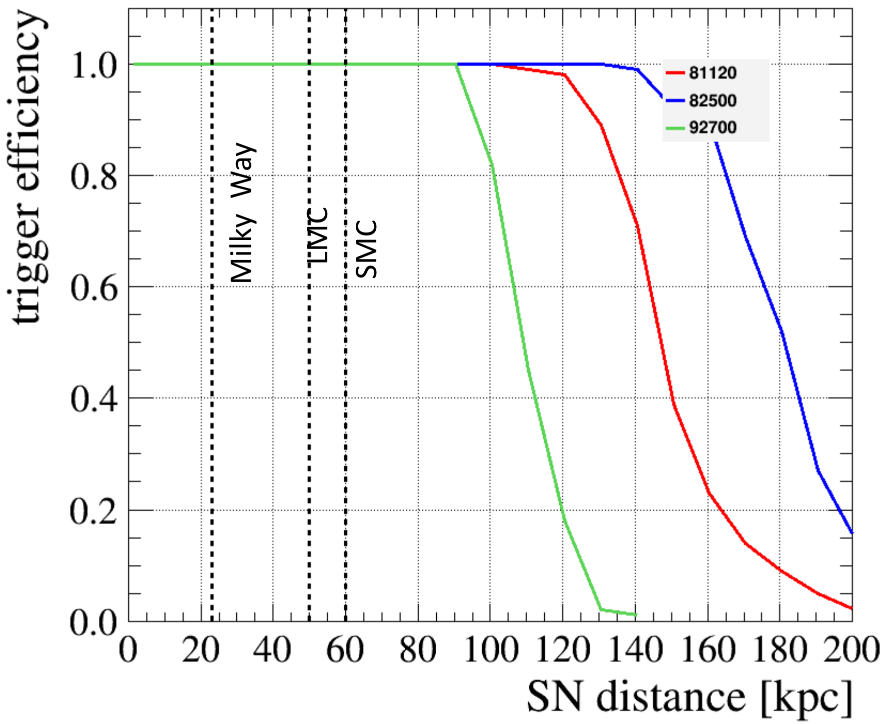


SN trigger efficiency(preliminary)

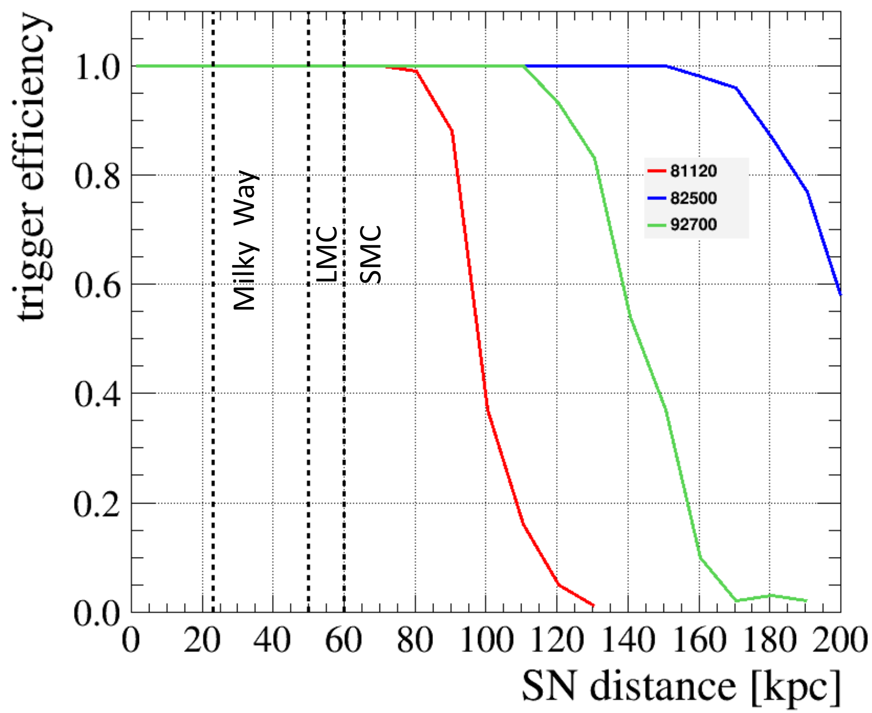
With 2GB buffer for every three PMTs of CD detector, JUNO can still record the basic hit information even for very near SNe.

[T_{L1}=100ms, N_{sn}=4, N_u=7],
No background muon and veto time considered
No pile-up effect for near SN considered

Small Magellanic Cloud (SMC):60kpc
Large Magellanic Cloud (LMC):50kpc
Milky Way: 23kpc



NH



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