Exploring the Potential for Astrophysical Neutrino Detection at JUNO

Jie Cheng
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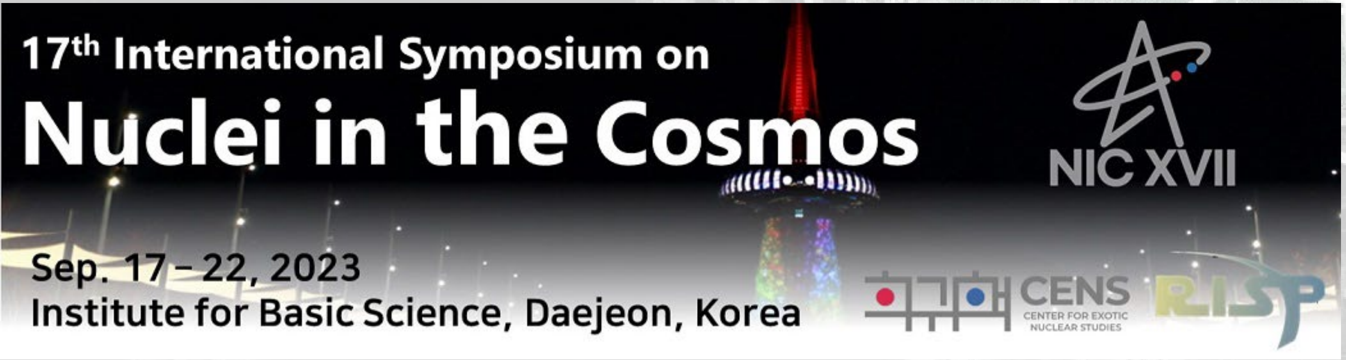
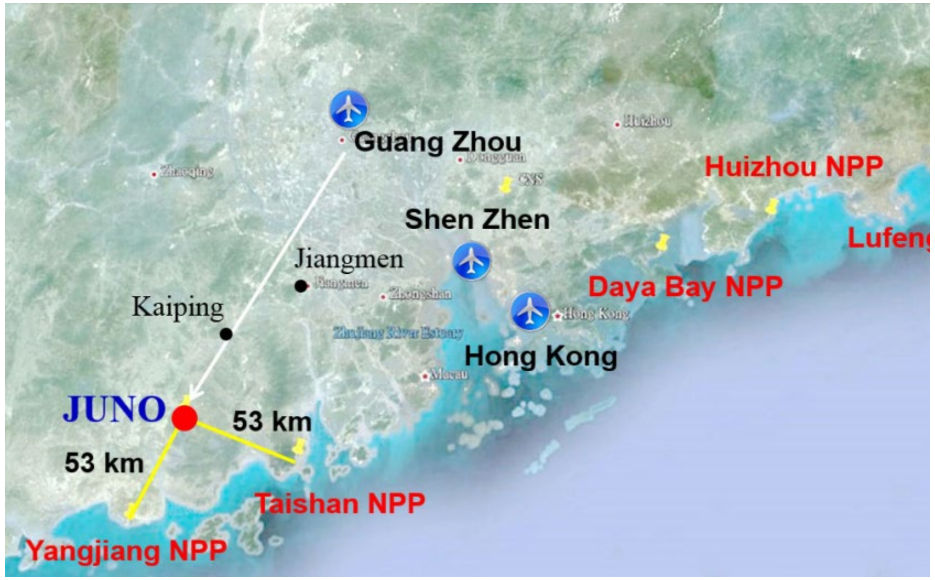
on behalf of the JUNO collaboration
2023/09/18

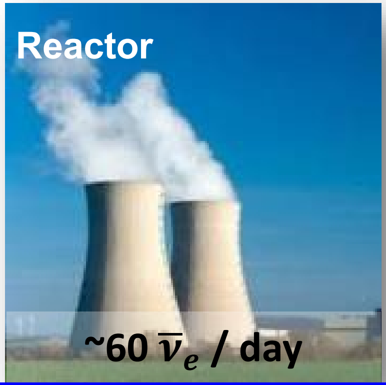


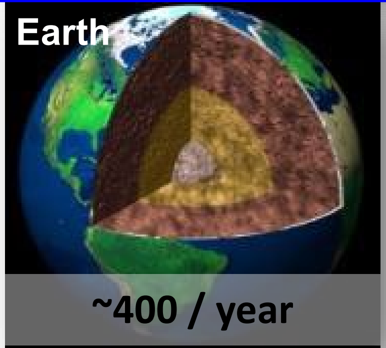
chengjie@ncepu.edu.cn

Jiangmen Underground Neutrino Observatory (JUNO)



- Multi-purpose neutrino experiment





New physics
e.g., proton
decay

- **This talk**

Detection of solar, supernova neutrinos

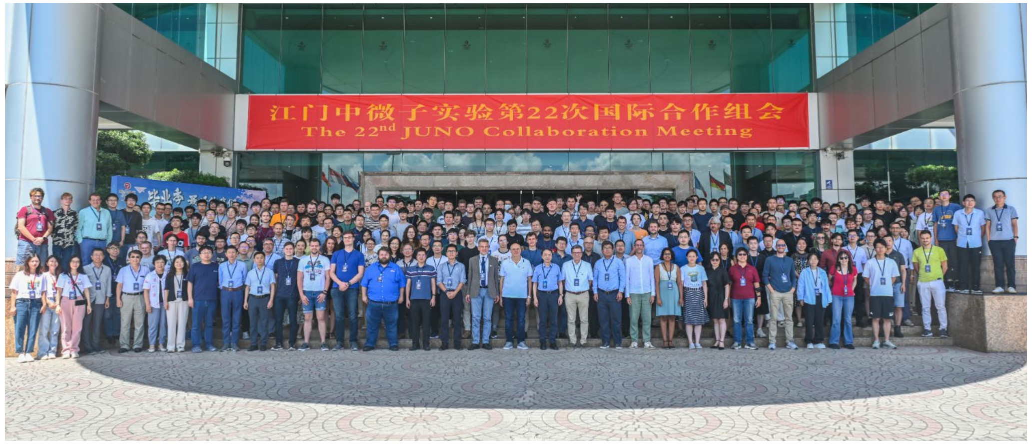
JUNO Collaboration

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Pakistan	PINSTECH (PAEC)
China	CIAE	China	CUG-Beijing	Russia	INR Moscow
China	DGUT	China	ECUT-Nanchang City	Russia	JINR
China	Guangxi U.	China	CDUT-Chengdu	Russia	MSU
China	Harbin Institute of Technology	Czech	Charles U.	Slovakia	FMPICU
China	IHEP	Finland	University of Jyvaskyla	Taiwan-China	National Chiao-Tung U.
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National United U.
China	Nanjing U.	France	CPPM Marseille	Thailand	NARIT
China	Nankai U.	France	IPHC Strasbourg	Thailand	PPRLCU
China	NCEPU	France	Subatech Nantes	Thailand	SUT
China	Pekin U.	Germany	RWTH Aachen U.	U.K.	U. Warwick
China	Shandong U.	Germany	TUM	USA	UMD-G
China	Shanghai JT U.	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Beijing	Germany	FZJ-IKP		

+Observers: University of Liverpool

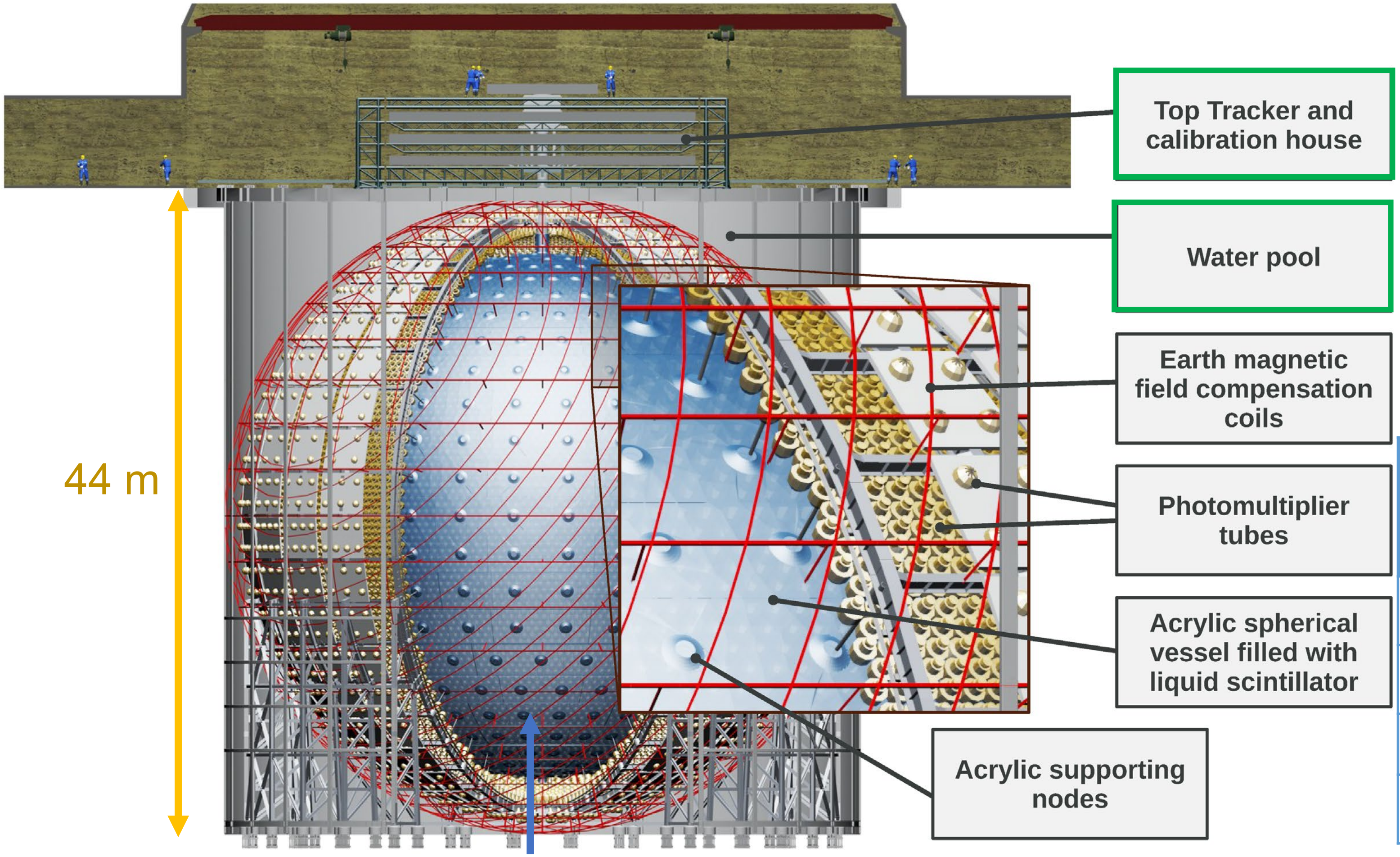
= 74 institutes

(~670 collaborators)



22nd JUNO collaboration meeting, July 24-28, 2023, Kaiping, China

JUNO Detector



Central Detector
20 kton Liquid Scintillator (LS)

Central detector

- 17612 20'' PMTs & 25600 3'' PMTs
- Acrylic Vessel diameter 35.4 m

Veto detector

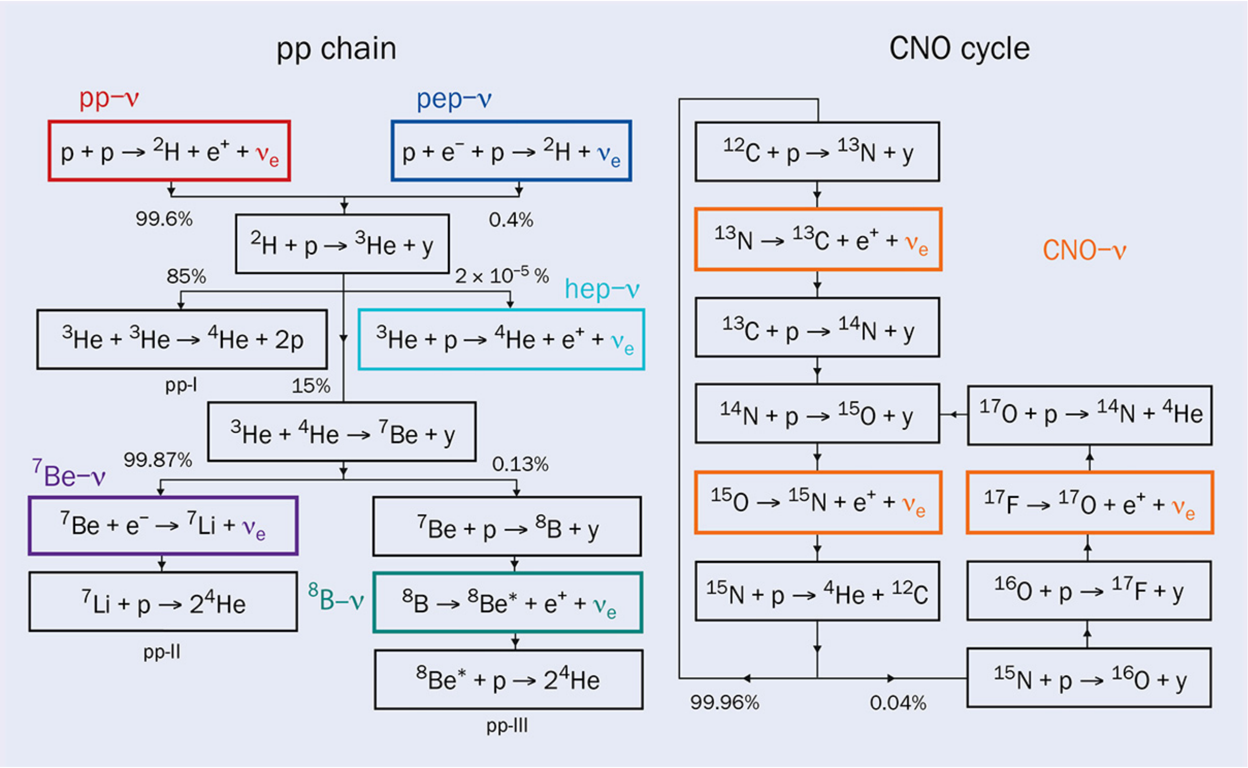
- Top tracker
- **35 kton ultra pure water**
- 2400 20'' PMTs

	Target mass	PMT Coverage	Energy resolution @ 1 MeV	Light yield [PE/MeV]
Daya Bay	20 ton (x8)	12%	8%	160
Borexino	300 ton	34%	5%	500
KamLAND	1 kton	34%	6%	250
JUNO	20 kton	78%	3%	>1300

- **Low energy threshold: ~0.2 MeV**
- **Low radioactivity background level**

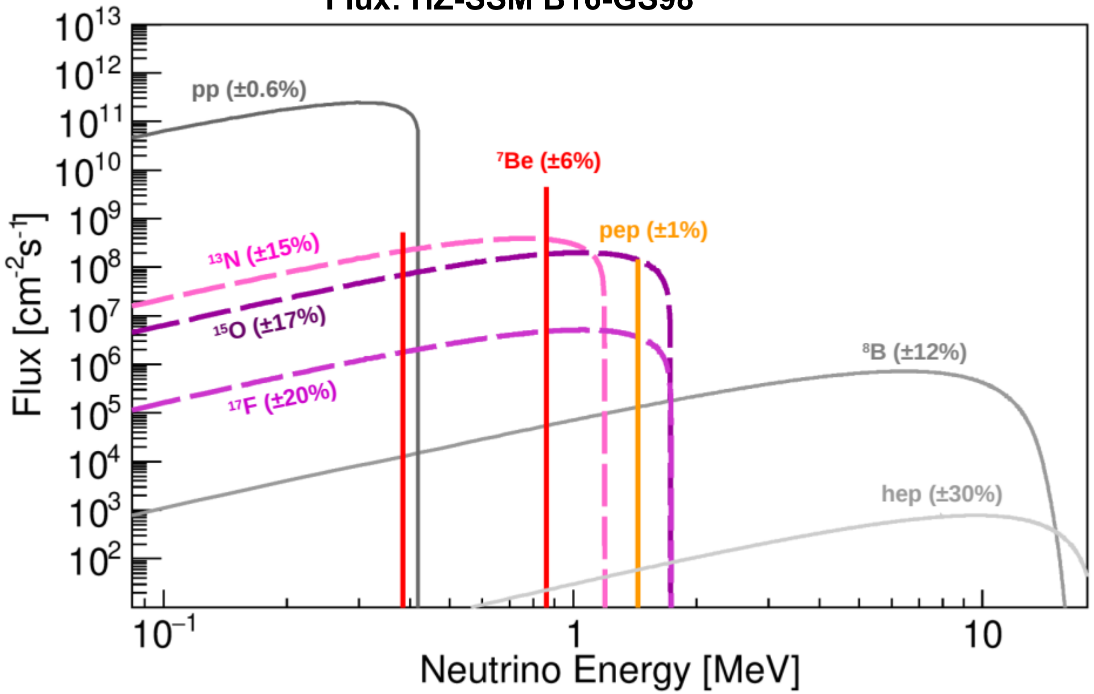
Solar Neutrinos

- ν_e produced by nuclear reactions inside the Sun ➔ unique messenger
- Define neutrino "species" using the origin reaction
- Insights on open questions
  - Sun metallicity: Z>2 element composition (two models, low-metallicity LZ and high-metallicity HZ)
  - Measure and cross validate Δm^2_{21} with solar neutrinos and reactor antineutrinos



https://cerncourier.com/a/how-the-sun-and-stars-shine/

Spectral shapes: http://www.sns.ias.edu/~jnb/
Flux: HZ-SSM B16-GS98



Detection of ^{7}Be, pep and CNO Solar Neutrinos at JUNO

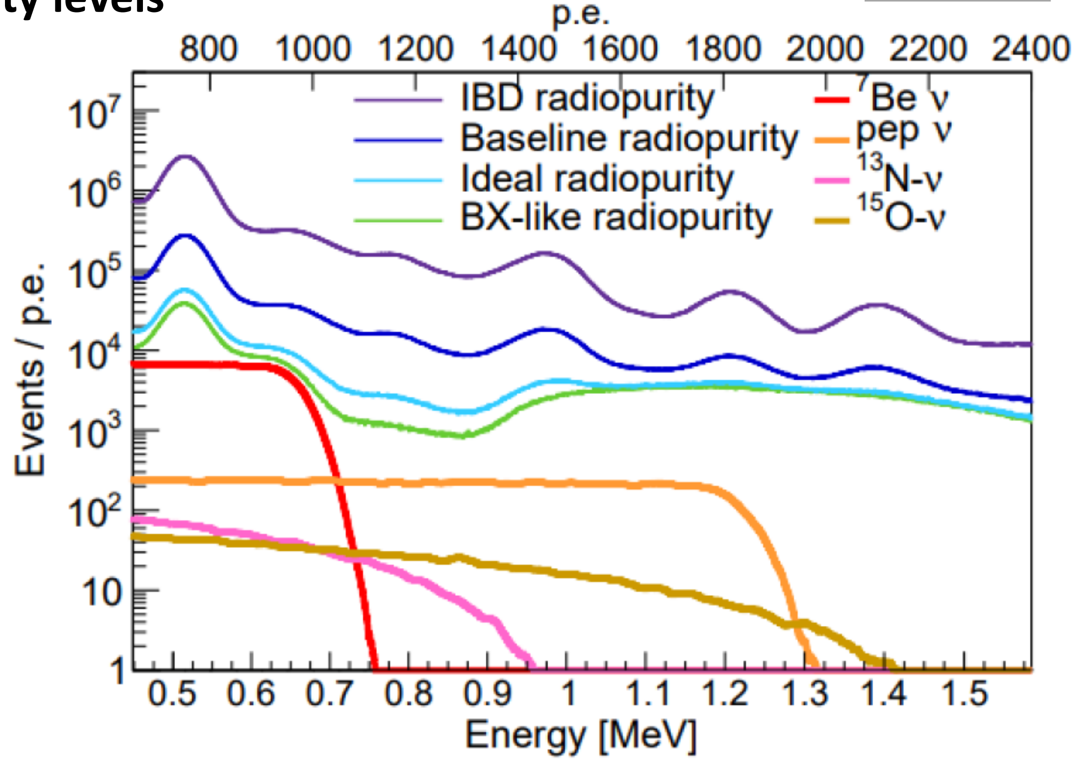
- ^{7}Be, pep, CNO solar neutrino
  - ✓ Primary detection channel: ν-e elastic scattering (ES)
  - ✓ Observe window: [0.46, 1.6] MeV
  - ✓ Highly dependent on the background level radioactivity levels in the LS
    - ❄ Comprehensive studies under different radioactivity levels

$$\nu_x + e \rightarrow \nu_x + e$$

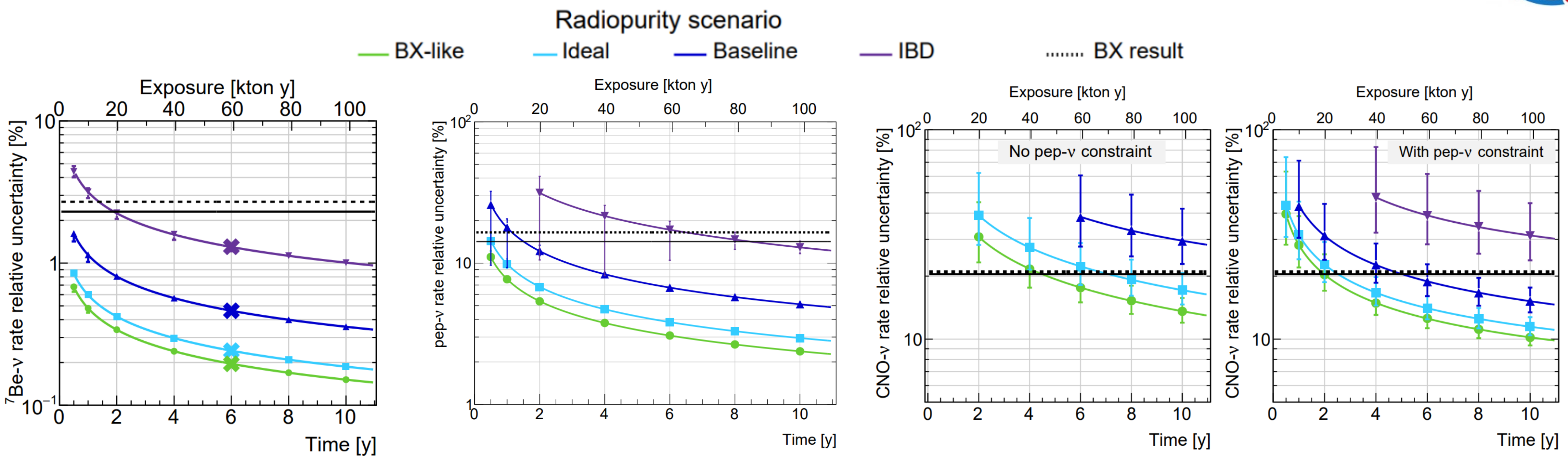
Radio-purity Scenario		^{40}K	^{85}Kr	^{232}Th-chain	^{238}U-chain	^{210}Pb/ ^{210}Bi	^{210}Po
IBD	$c\ [\frac{g}{g}]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R\ [\frac{cpd}{kt}]$	2289	5000	3508	15047	12031	12211
Baseline	$c\ [\frac{g}{g}]$	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	229	500	351	1505	1203	1221
Ideal	$c\ [\frac{g}{g}]$	1×10^{-18}	-	1×10^{-17}	1×10^{-17}	1×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	23	100	35	150	241	244
Borexino	$c\ [\frac{g}{g}]$	-	-	$<5.7\times10^{-19}$	$<9.4\times10^{-20}$	-	-
	$R\ [\frac{cpd}{kt}]$	4.2	100	1.4	2	115	446.9

NOTE: Contribution from pileup and reactor neutrinos found negligible in the ROI

arXiv: 2303.03910



JUNO sensitivity to ^{7}Be, pep and CNO Solar Neutrinos



arXiv: 2303.03910

	^{7}Be	pep	CNO	
			w/ pep-v constraint	w/o pep-v constraint
Borexino	2.7%[1]	17%[1]	-12%, +30%[2]	
6 years data	0.25%-0.5%	4%-7%	20%-40%	15%-18%
10 years data	0.2%-0.35%	3%-5%	16%-30%	12%-16%

[1] Nature 562 (2018) 505
[2] Phys. Rev. Lett. 129 (2022) 252701

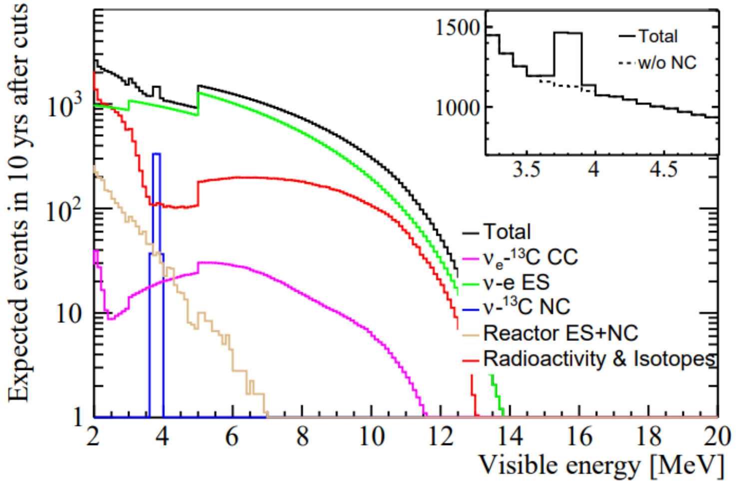
- Precision level refers to ideal-baseline radiopurity scenario

Detection of ^{8}B Solar Neutrinos at JUNO

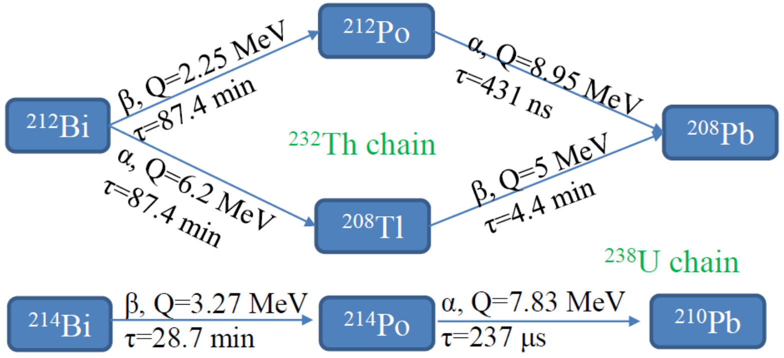
- **^{8}B solar neutrino detection**

arXiv:2210.08437

Channels		Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	after cuts
			Correlated		
CC	$\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + {}^{13}\mathrm{N}$ decay	3929	647
NC	$\nu_x + {}^{13}\mathrm{C} \to \nu_x + {}^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \to \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4
			Single		



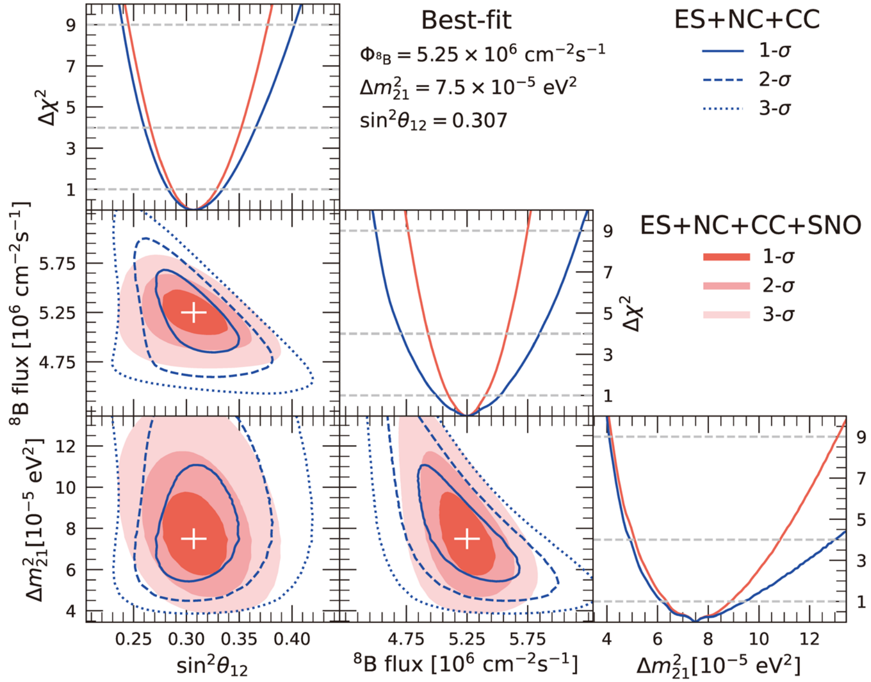
- ✓ **Observe window: [2, 16] MeV**
- ✓ **Dominant backgrounds:**
  - **1. Radioactivity background in LS: U/Th decay chain**
    - ❄ **α: quenching energy in LS < 2 MeV**
    - ❄ **β/γ: reduction by cascade decay feature and pulse shape discrimination method**
  - **2. Cosmogenic isotope background**
    - ❄ **Muon veto**
    - ❄ **Three-Fold-Coincidence (TFC) algorithm**

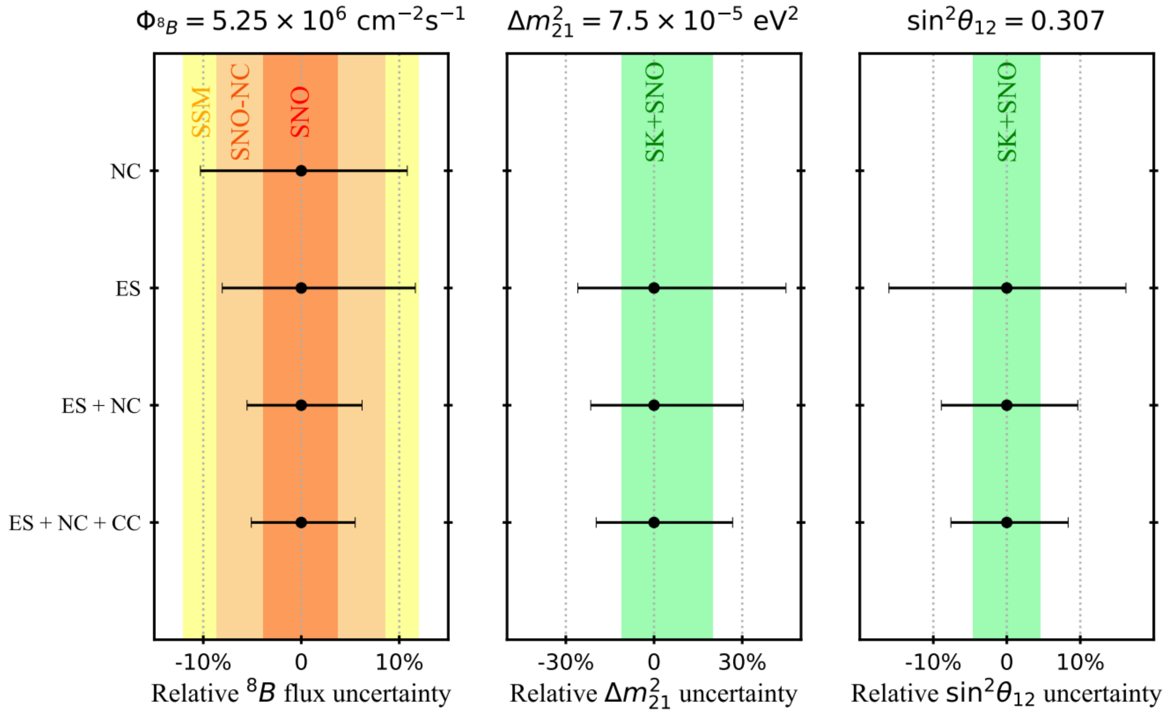


JUNO Sensitivity to ^{8}B Solar Neutrinos

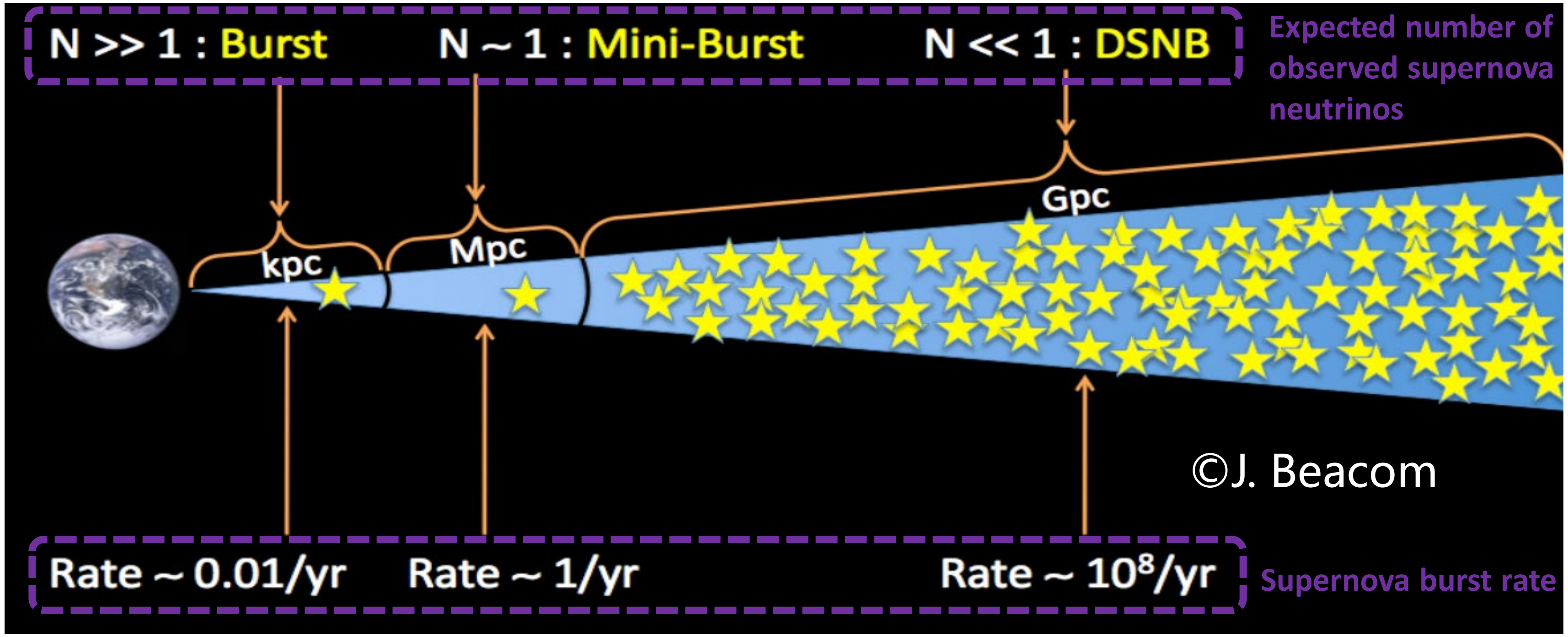
- ~0.2 kt ^{13}C in JUNO LS → enable observation of **^{8}B solar neutrino** CC and NC interactions on ^{13}C for the first time
- Using the joint analysis of ES, CC and NC channels
  - ✓ Model independent measurement of ^{8}B solar neutrino flux (5%) and oscillation parameters $\sin^2\theta_{12}$ (8%), Δm^2_{21} (20%) @ 10 years
  - ✓ Combining with SNO data, the accuracy of ^{8}B flux is 3% @ 10 years

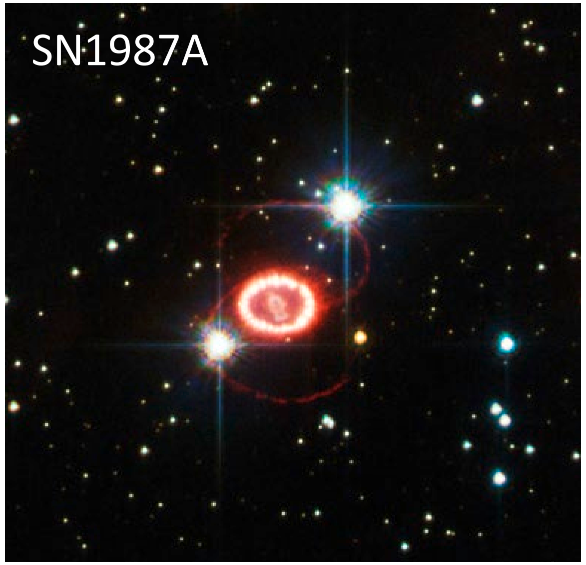
arXiv:2210.08437





Neutrinos from Supernova





- ✓ **only neutrinos produced by SN1987A have been observed**
- ✓ **DSNB is yet to be discovered**

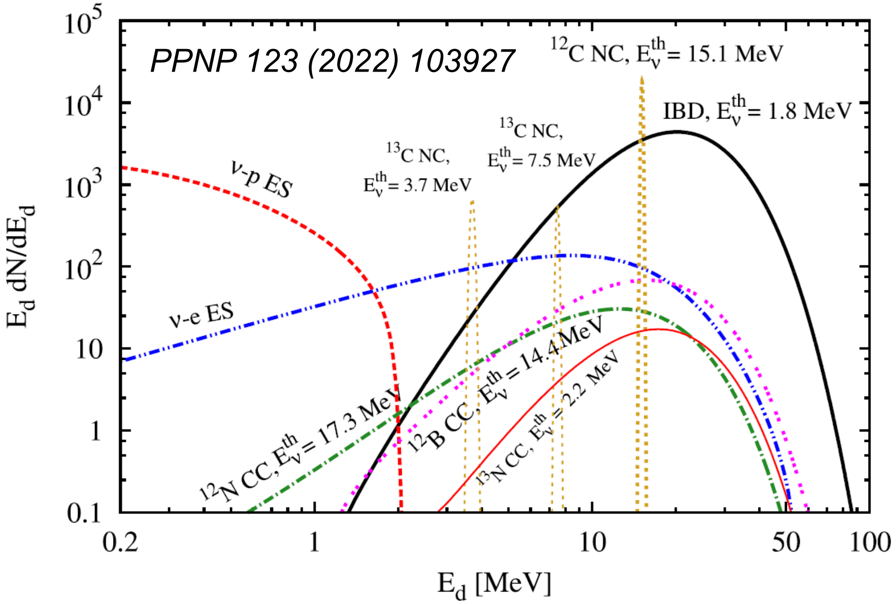
- **Supernova neutrinos**: studying the fate of stars, the evolution of the cosmos, element nucleosynthesis, and the nature of neutrinos, etc.
- Two complementary methods:
  - **Neutrinos from core-collapse supernova (CCSN) bursts** within or near the Milky Way
    - High statistics 😃, almost no background 😃, rare Galactic SNe rate (2-3 / century) 😟
  - **Diffuse supernova neutrino background (DSNB)**: **neutrinos** from supernovae that have either exploded successfully or failed to explode in the cosmos 😃, low event rate (e.g., ~2-4 IBD events / year @ JUNO) 😟

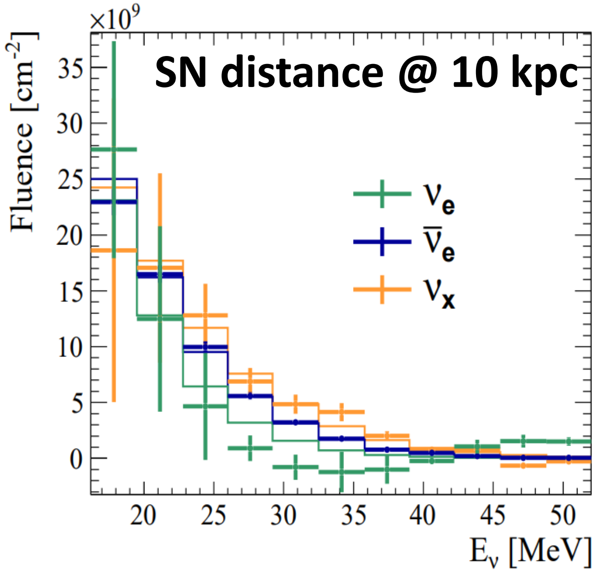
Core-collapse Supernova Neutrinos in JUNO

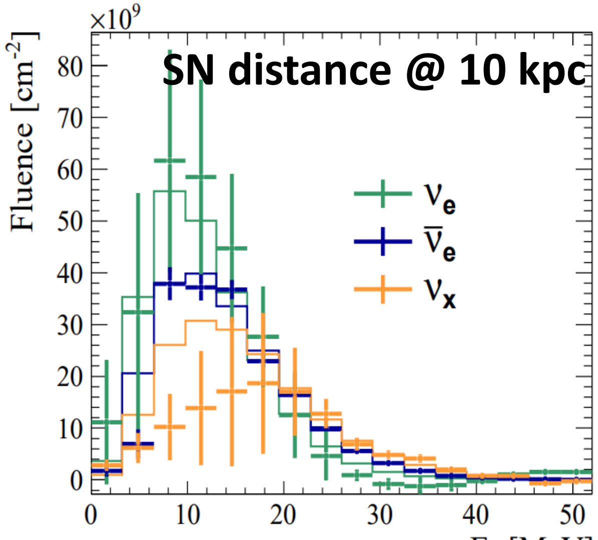
CCSN @ 10 kpc in JUNO *[J. Phys. G43:030401 (2016)]*

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

Expected CCSN neutrino energy spectra
SN distance @ 10 kpc







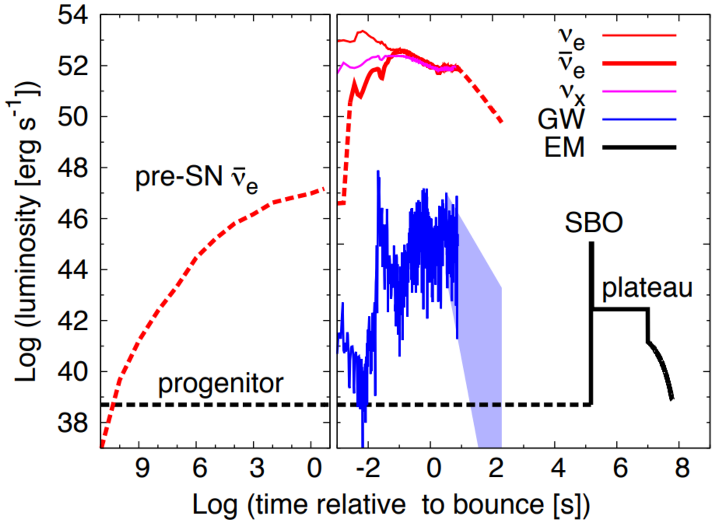
PRD 99 (2019) 12309

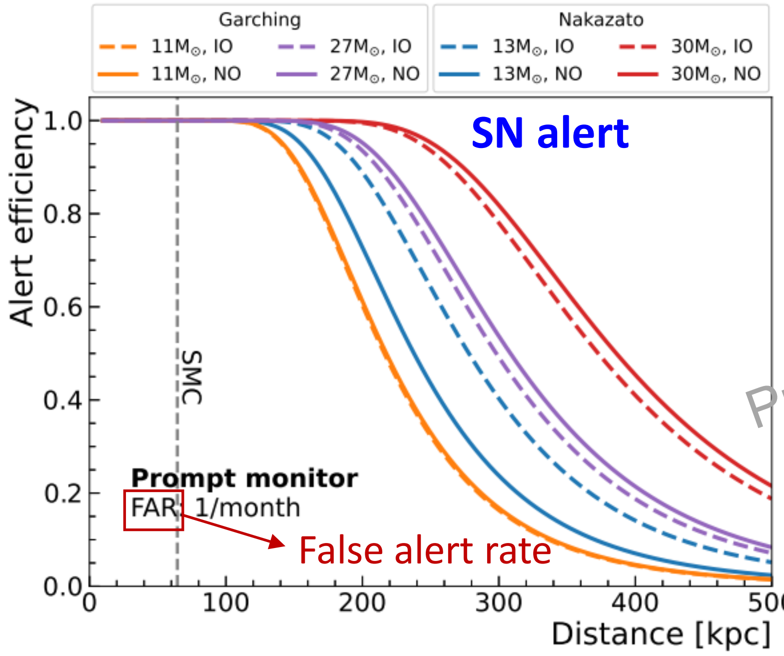
- **JUNO can detect all flavors of neutrinos**
- **Model-independent reconstruction of energy spectra of $\overline{\nu}_e$, ν_e, ν_x via unfolding approach**
  - **→ Allow for further physics and astrophysics studies!**

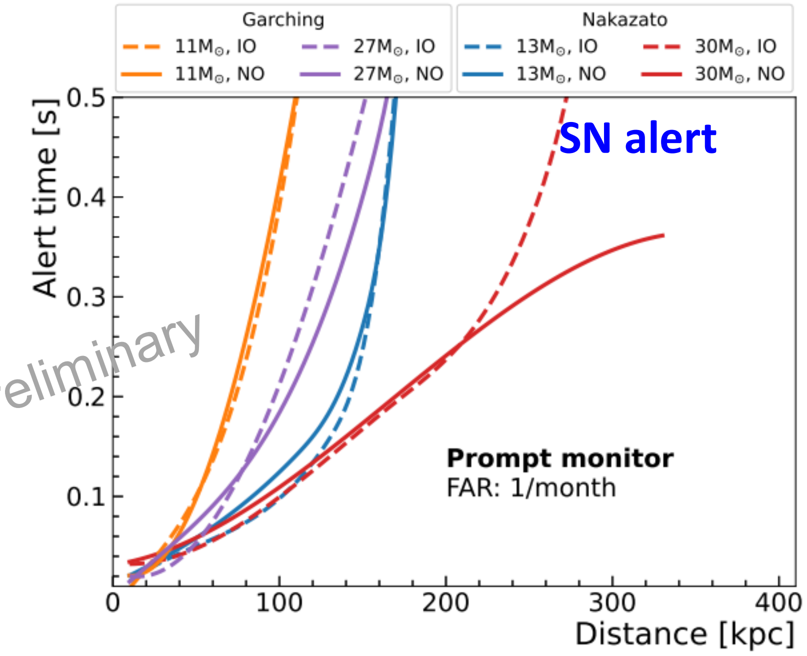
CCSN Monitoring System in JUNO

- Multi-messengers of core-collapse supernova: electromagnetic signals, gravitational waves, **neutrinos**
- **Neutrino** → early warning

Mon. Not. Roy. Astron. Soc. 461 (2016) 3







- **Pre-supernova (pre-SN) neutrino:**
  - Days before core-collapse
- **Supernova (SN) neutrino**
  - ~ $\mathcal{O}$(10 s)

- SN prompt monitor
  - ✓ Alert distance: 240 ~ 400 kpc with 50% alert efficiency
  - ✓ Alert time @ 10 kpc: 10 ~ 30 ms
- Pre-SN monitor
  - ✓ Alert distance: 0.6 ~ 1.7 kpc with 50% alert efficiency
  - ✓ Alert time @ 0.2 kpc: > ~ 100 hr earlier

A dedicated Multi-Messenger Trigger System is on the way

Diffuse Supernova Neutrino Background (DSNB)

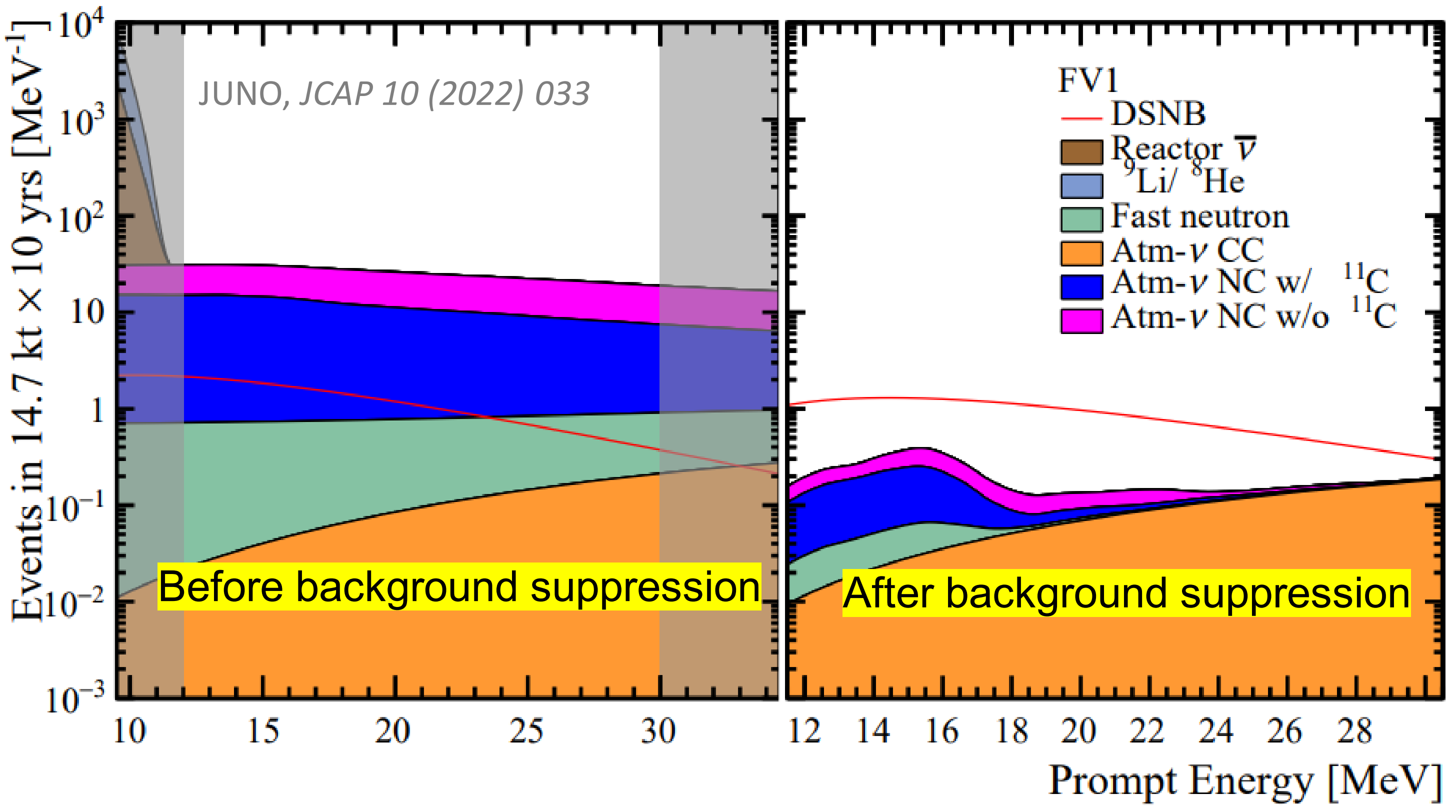
- **DSNB: 2-4 events in JUNO per year**
  - ✓ Not detected yet

Three key (uncertain) parameters in DSNB flux:

- Supernova (SN) rate ($R_{SN}(0)$)
- Average energy of SN neutrinos ($\langle E_\nu \rangle$)
- Fraction of black hole (f_{BH})

- Dominant background (above 12 MeV):
  - ✓ Atm-ν NC interactions

- Highlights on background suppression
  - ✓ Muon veto
  - ✓ Pulse shape discrimination (PSD) technique
  - ✓ Triple coincidence (^{11}C delayed decay)



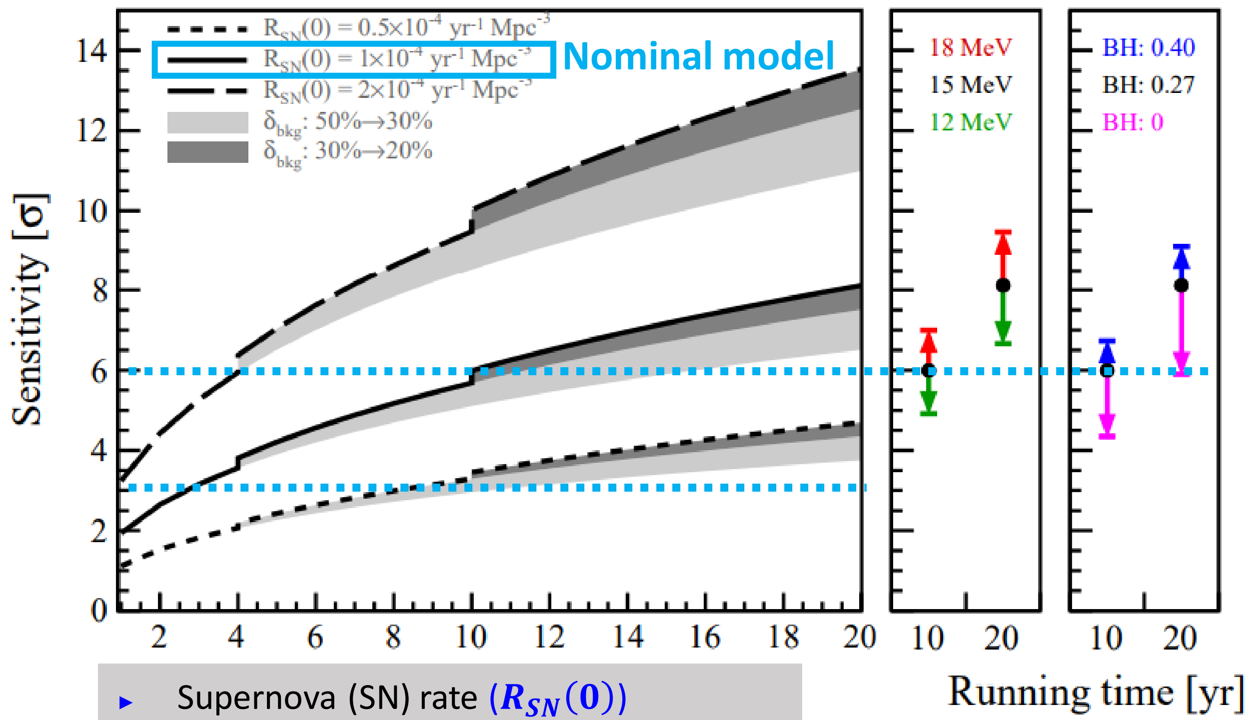
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)* :

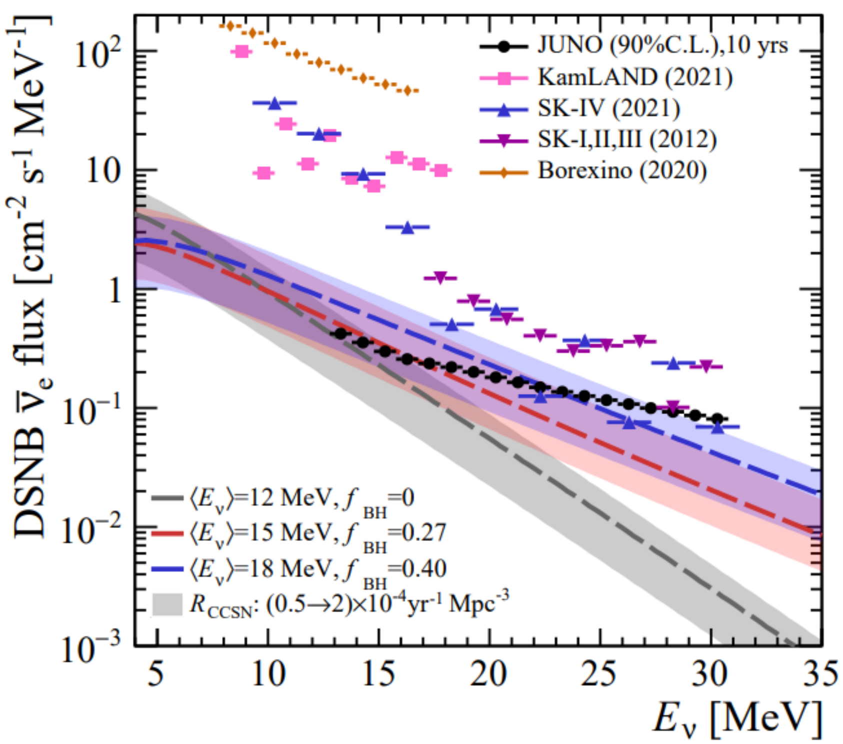
- ✓ **Background evaluation:** 0.7 per year → 0.54 per year
- ✓ **PSD:** signal efficiency 50%→80% (1% residual background)
- ✓ **Realistic DSNB signal model:** non-zero fraction of failed Supernova

➡ **Signal/Background ratio improved from 2 to 3.5**

DSNB Sensitivity

JUNO, *JCAP 10 (2022) 033*



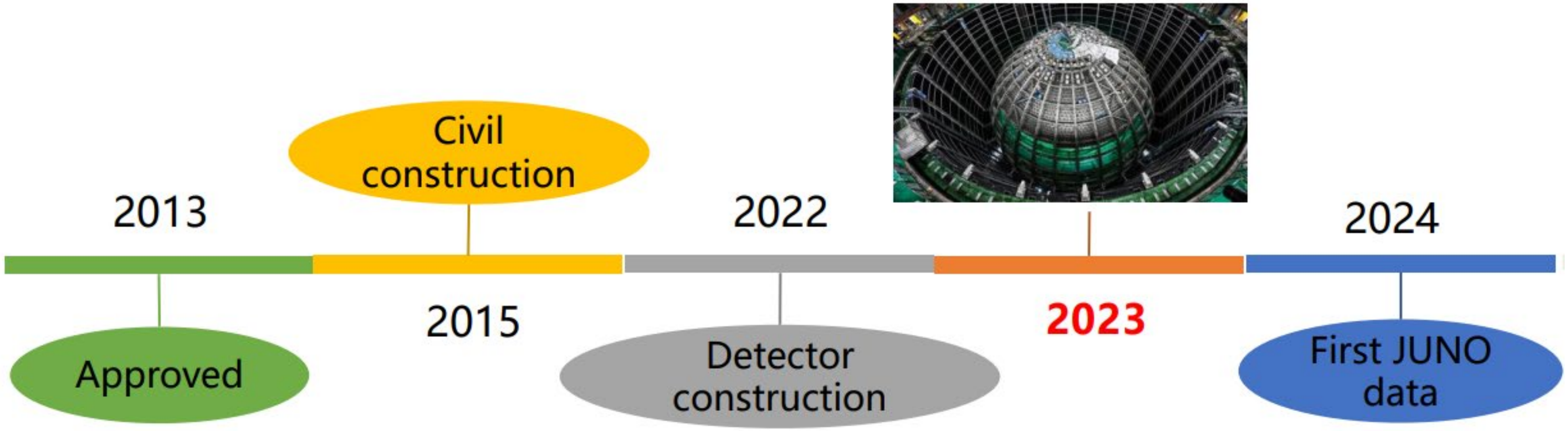


- Supernova (SN) rate **($R_{SN}(0)$)**
- Average energy of SN neutrinos **($\langle E_\nu \rangle$)**
- Fraction of black hole **(f_{BH})**

- **If no positive observation, JUNO can set the world-leading best limits of DSNB flux**
- **With the nominal model (black solid curve (left plot)): 3σ (3 yrs) and 6σ (10 yrs)**

Summary and Prospects

Physics	Sensitivity
Solar Neutrino	Measure ^{7}Be, pep, CNO simultaneously, measure ^{8}B flux independently
Supernova Burst (10 kpc)	~7300 of all-flavor neutrinos
DSNB	3σ in 3 yrs



backup

Central Detector: Liquid Scintillator (LS)

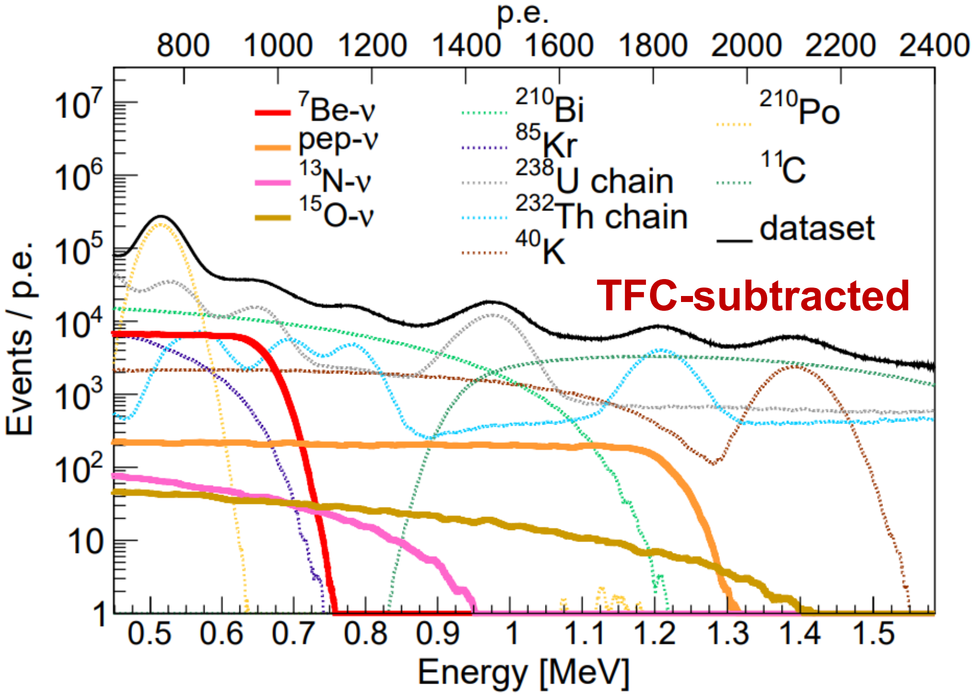
- ➢ **20 kt liquid scintillator: LAB based, PPO as fluorescence, bis-MSB as wavelength shifter**
- ✓ 20 m attenuation length at 430 nm
- ✓ required radioactivity 10^{-15} g/g for reactor and 10^{-17} g/g for solar
- ✓ full system commissioning started in April 2023

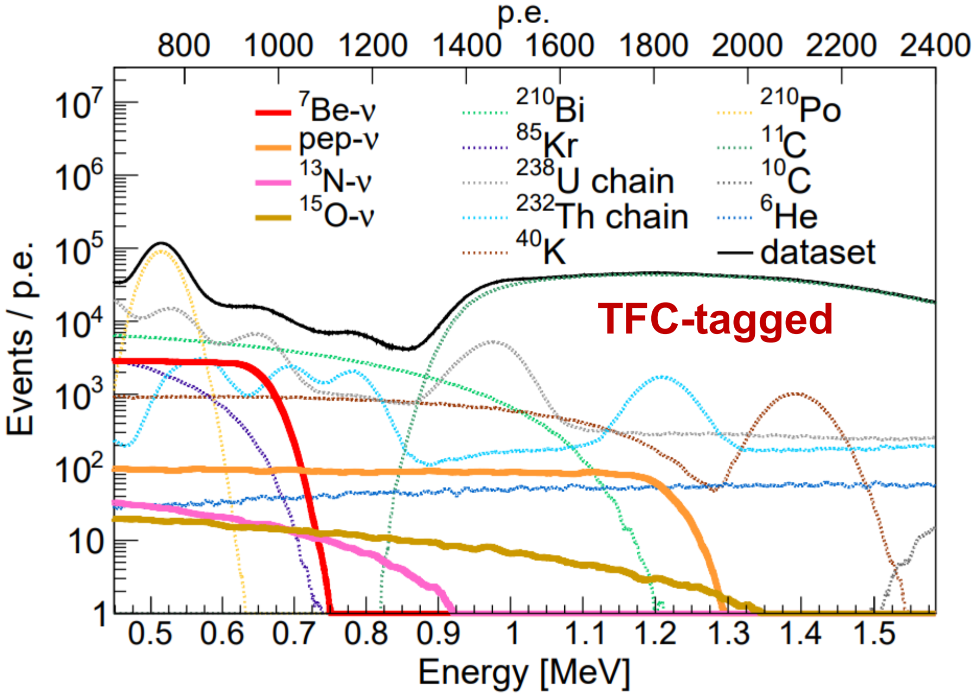
*OSIRIS: Online Scintillator Internal Radioactivity Investigation System

Detection of ^{7}Be, pep and CNO Solar Neutrinos at JUNO

- **^{7}Be, pep, CNO solar neutrino**
  - ✓ **Primary detection channel: ν-e elastic scattering (ES)**
  - ✓ **Observe window: [0.46, 1.6] MeV**
  - ✓ **Highly dependent on the background level**
    - **2. Cosmogenic long lifetime isotopes, ^{11}C, ^{10}C and ^{6}He background**
    - ❄ **Three-Fold-Coincidence (TFC) algorithm**

$$\nu_x + e \rightarrow \nu_x + e$$





- Two complementary data sets
- Simultaneously fitted in the fitter

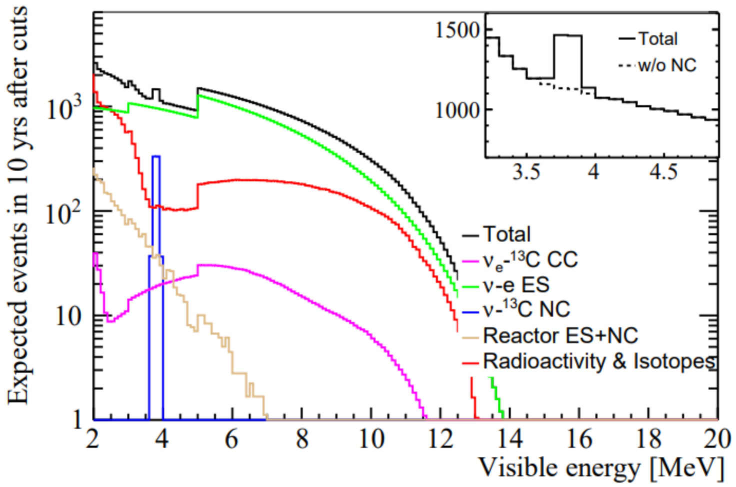
arXiv: 2303.03910

JUNO ^{8}B solar ν measurements

^{8}B solar neutrino detection

[arXiv:2210.08437]

Channels		Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers after cuts
CC	$\nu_e + ^{13}\mathrm{C} \to e^- + ^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + ^{13}$N decay	3929	647
NC	$\nu_x + ^{13}\mathrm{C} \to \nu_x + ^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \to \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4



- Cross-section of interactions between neutrinos and carbon [Phys. Rev. C 86, 015502 (2012), J. Phys. G 46, 075103 (2019)]
- Uncertainties from interaction cross-section are considered

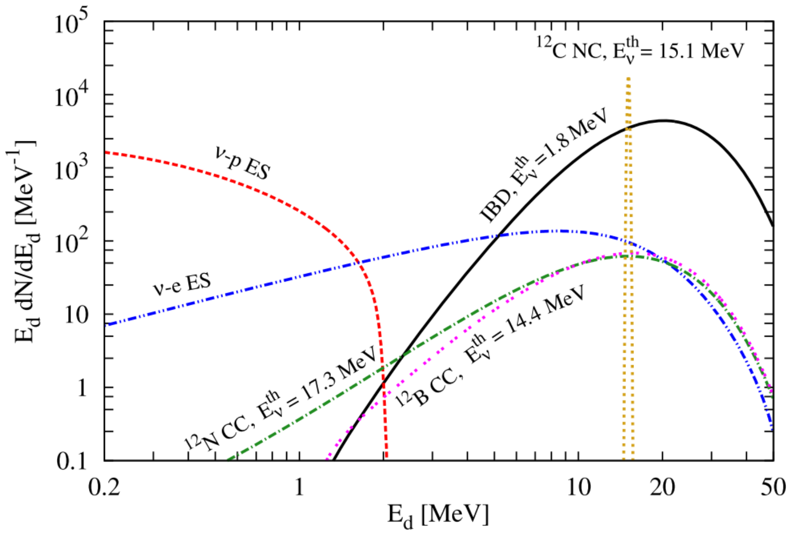
Sys.	Description for the pull term	Uncertainty
$\varepsilon_X^{\mathrm{ES}}$, $\varepsilon_X^{\mathrm{NC}}$, $\varepsilon_X^{\mathrm{CC}}$	Cross section for the CC, NC, ES channels	1%, 1%, 0.5%
$\varepsilon_{\mathrm{eff}}^{\mathrm{C}}$, $\varepsilon_{\mathrm{eff}}^{\mathrm{S}}$	Detector efficiency	2% [27]
$\varepsilon_{\mathrm{B}}^{k_\mathrm{C}}$, $\varepsilon_{\mathrm{B}}^{k_\mathrm{S}}$	Rate for the k_C-th or k_S-th background component	1%-10%, same as Ref. [27]
ε_s	^{8}B neutrino energy spectrum	Refs. [30, 31]

- Under these conditions, and combined with SNO, the accuracy of ^{8}B flux is 3% @ 10 years
- If the cross-section uncertainty becomes 10%, ^{8}B flux is 6%

JUNO supernova neutrino (burst)

SN @ 10 kpc in JUNO **[J. Phys. G43:030401 (2016)]**

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
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	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
$\overline{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2



- Cross-section of interactions between neutrinos and carbon

  [Phys. Lett. B 212, 139 (1988)]
- Neutrino-^{12}C interactions are an important part for supernova neutrino energy reconstruction
- Few and old measurements (e.g., LSND), need more precise predictions and measurements