



Non-oscillation Physics at JUNO

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On behalf of the JUNO collaboration

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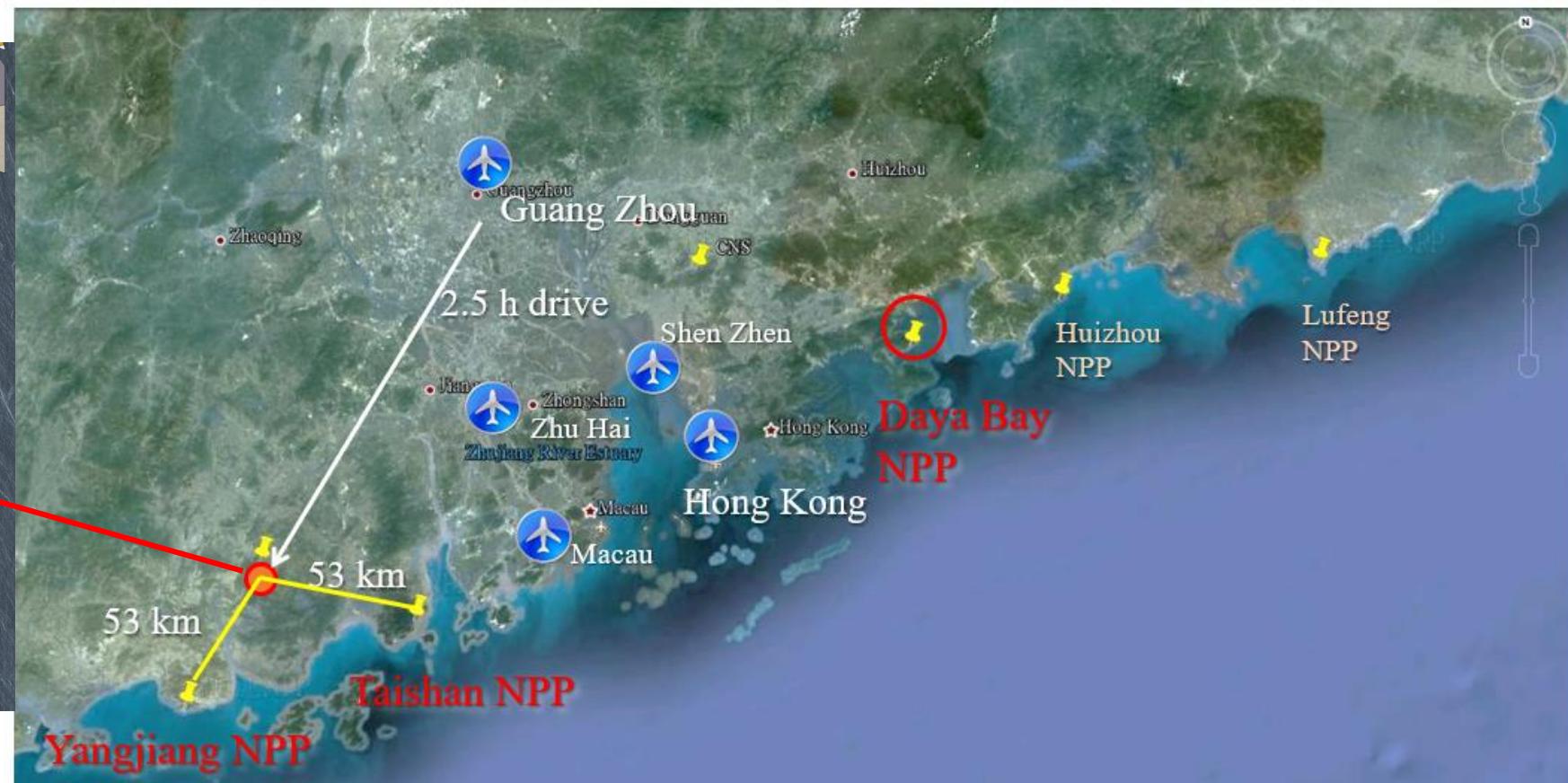
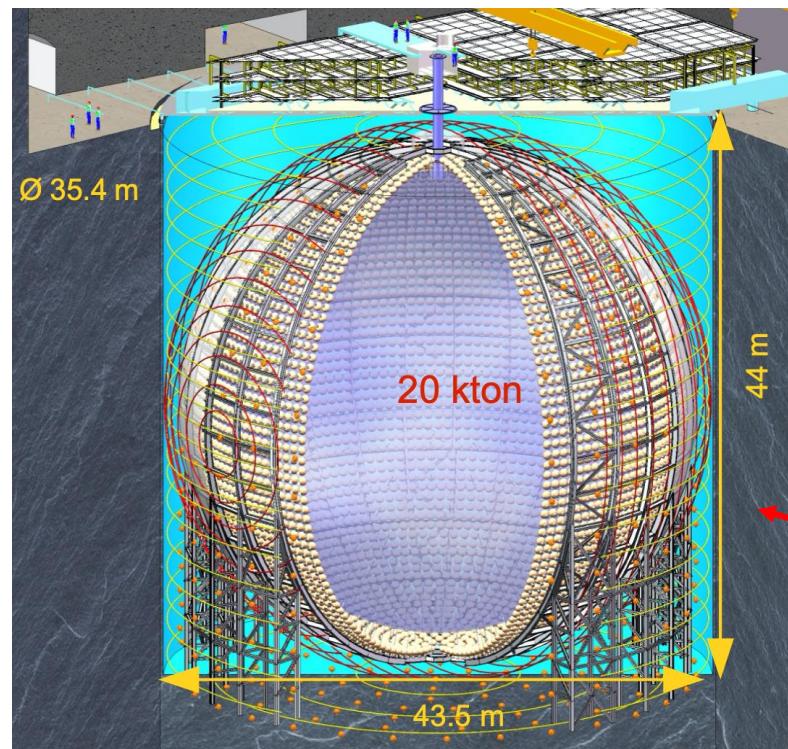
Photo by Y.X. Liu



XVIII
International Conference
on Topics in Astroparticle
and Underground
Physics 2023

28.08. – 01.09.2023
University of Vienna

JUNO Overview



Largest ever LS detector

- 20 kton LS
- 78% photo-coverage
- Low radioactivity background

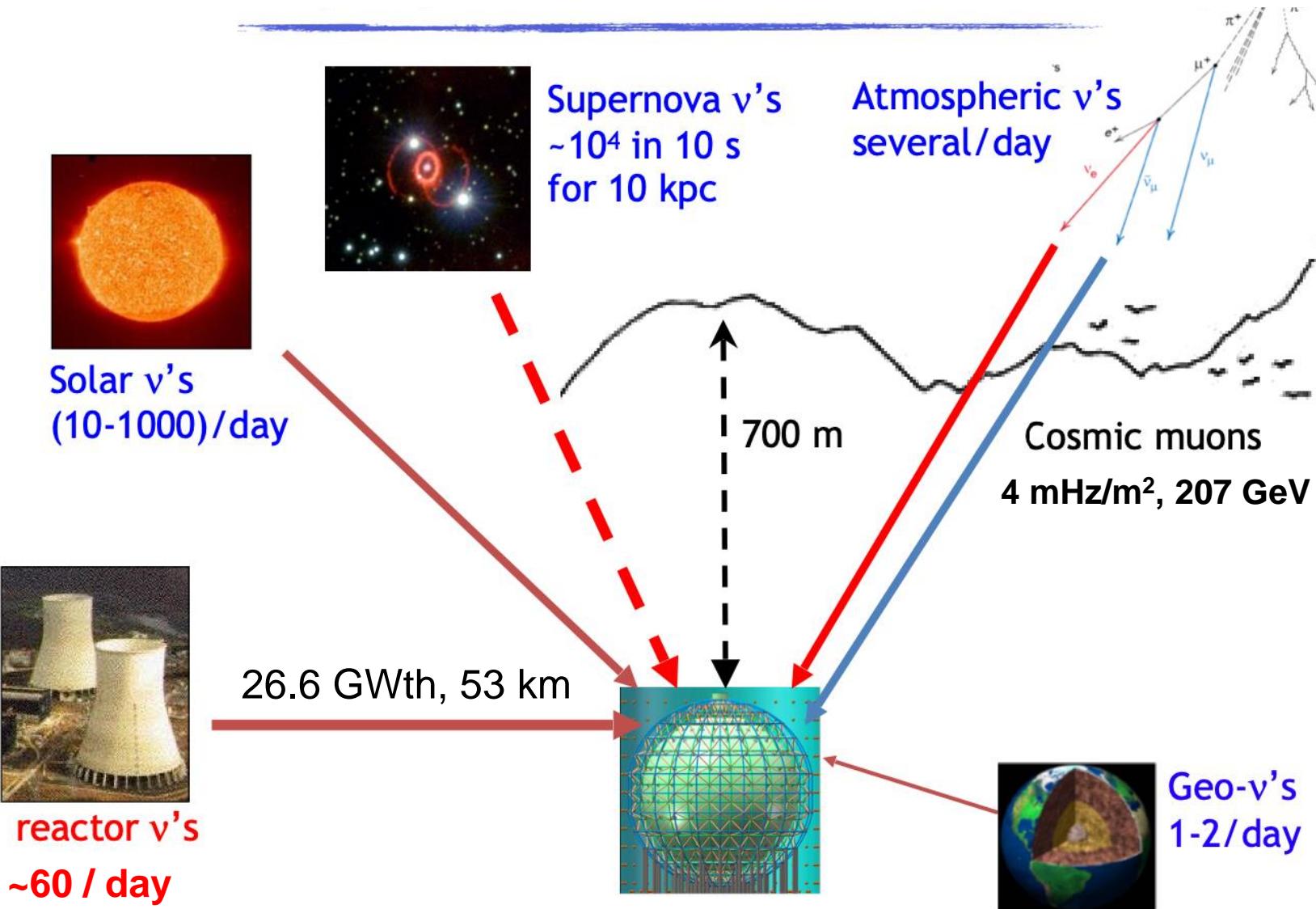
Talk by Cong Guo, JUNO detector design and status
Talk by Jie Zhao, Strategies of radon and cleanliness control in underground environment at JUNO

Jiangmen Underground Neutrino Observatory (JUNO)

- Location optimized for neutrino mass ordering with reactor- ν
- 700m rock overburden to suppress muon flux
- Expected to finish detector construction in 2023



A Multipurpose Neutrino Observatory



Primary physics goal

- NMO with reactor ν
- Precision meas. of osc. parameters

Talk by Rebin Karaparambil
Neutrino oscillation physics at JUNO

Rich program of non-oscillation physics:

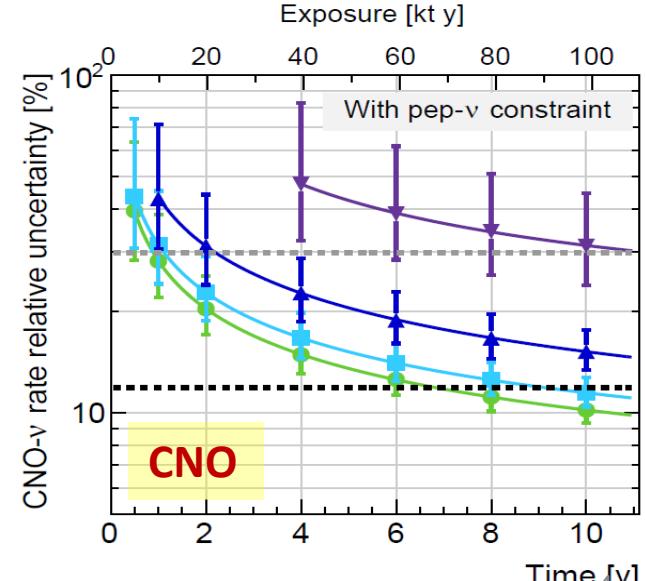
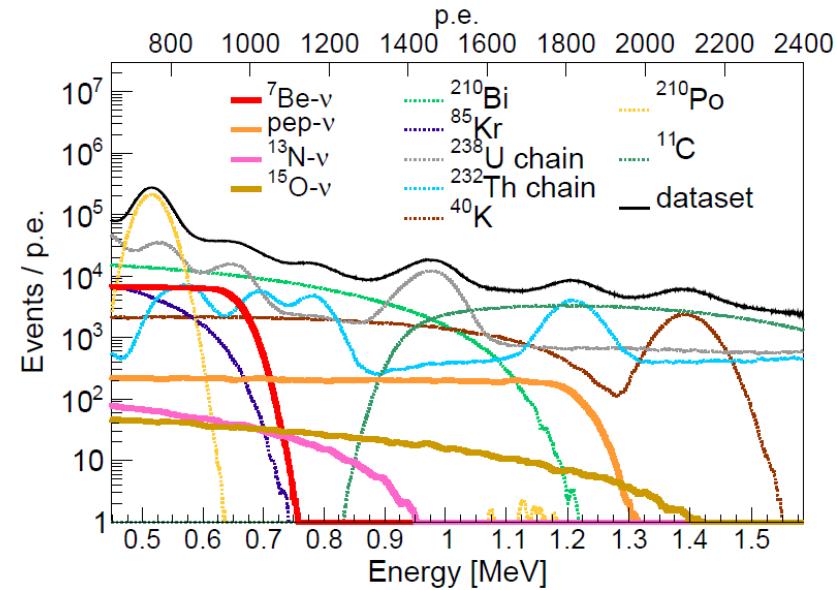
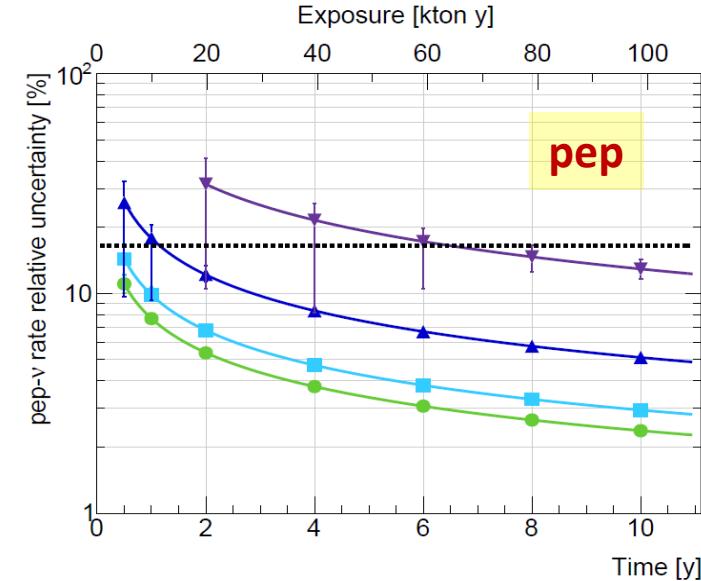
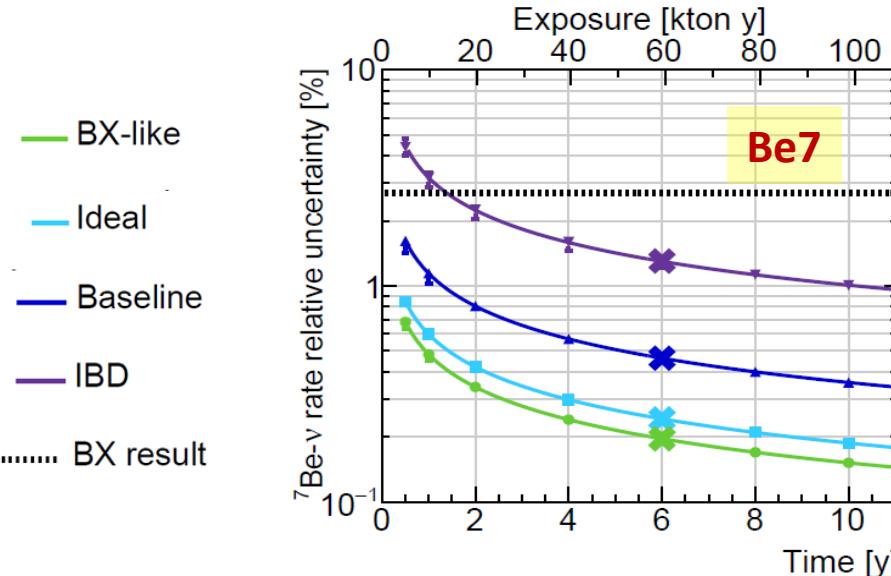
- Solar ν
- Supernova ν
- Atmospheric ν
- Geo- ν
- Nucleon decays
- Indirect DM search
- ...

In this talk!

Solar neutrinos (${}^7\text{Be}$, pep, CNO)



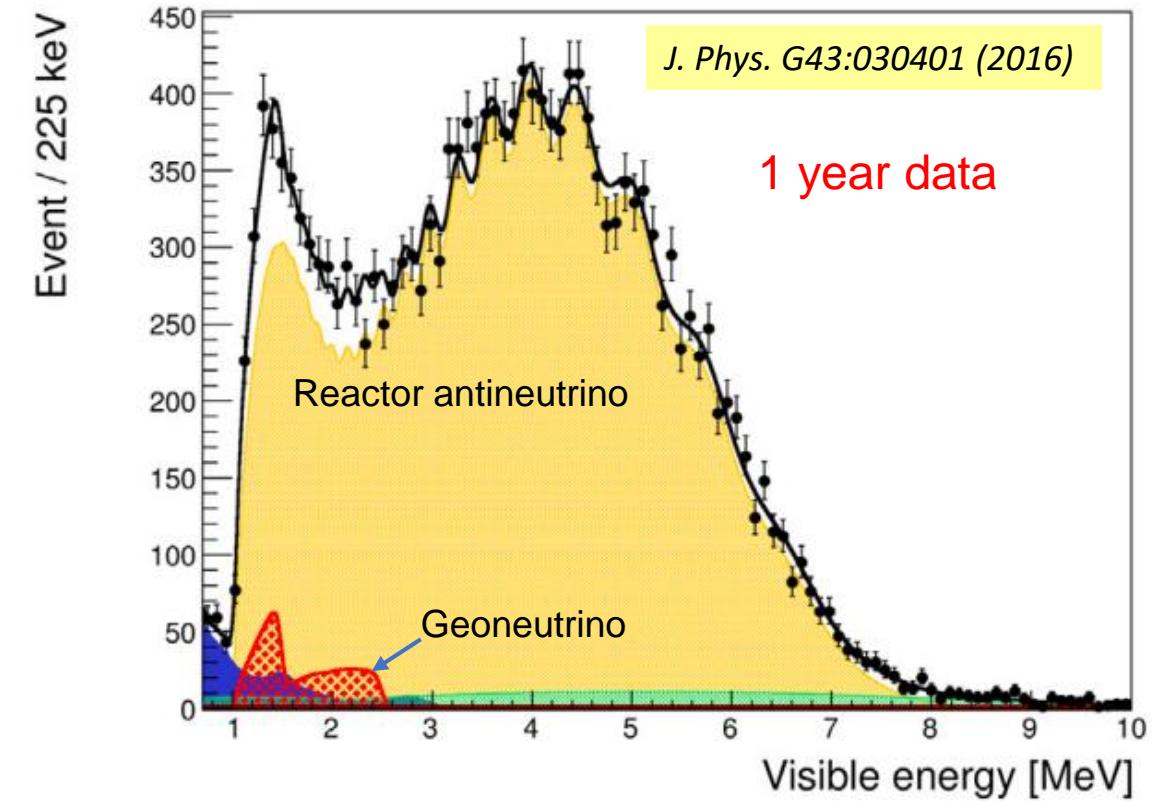
- Sensitivity to *intermediate energy* solar neutrinos in different radiopurity scenarios
 - IBD: min. requirement for MH determination, $\text{U/Th } 10^{-15} \text{ g/g}$
 - Baseline $\rightarrow \text{U/Th } 10^{-16} \text{ g/g}$, Ideal $\rightarrow \text{U/Th } 10^{-17} \text{ g/g}$
- ${}^7\text{Be}$ and pep
 - Can improve against Borexino in a few years of data taking in all radiopurity scenarios
- CNO
 - Can improve against Borexino except the worst scenario
 - Can reach 10%



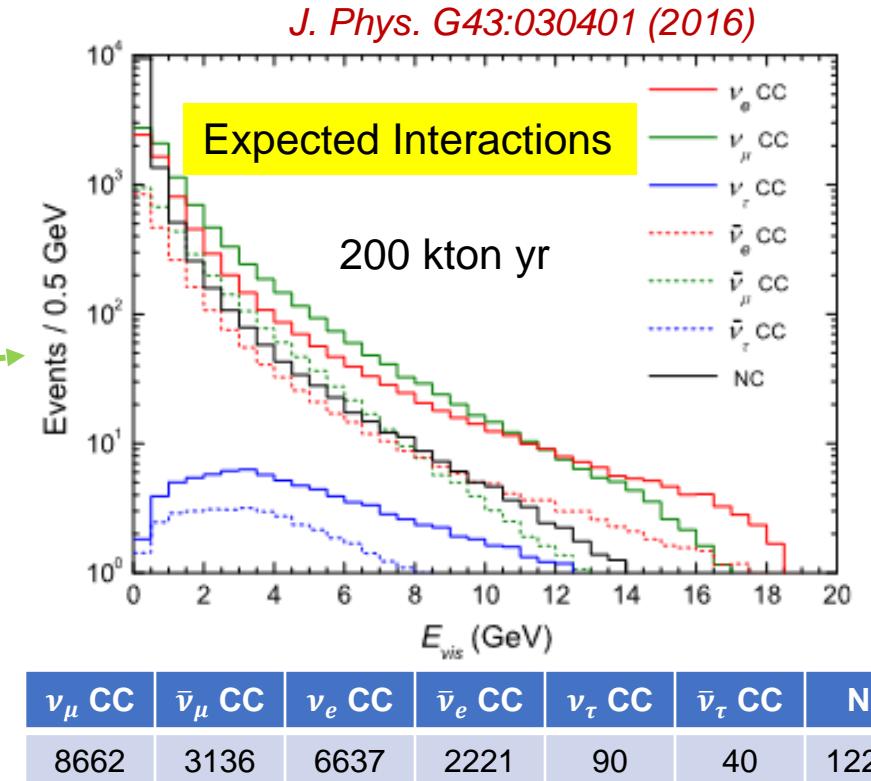
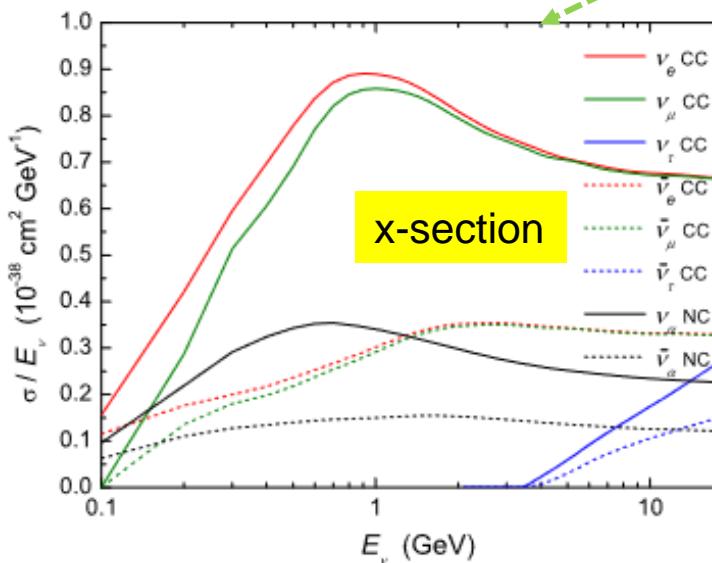
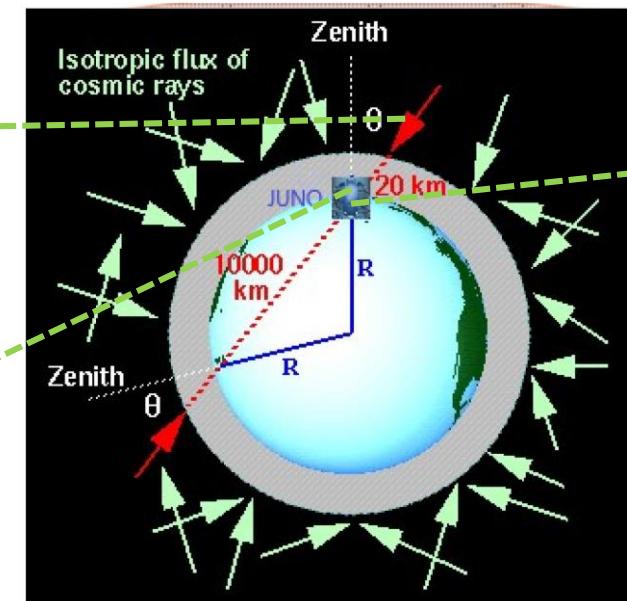
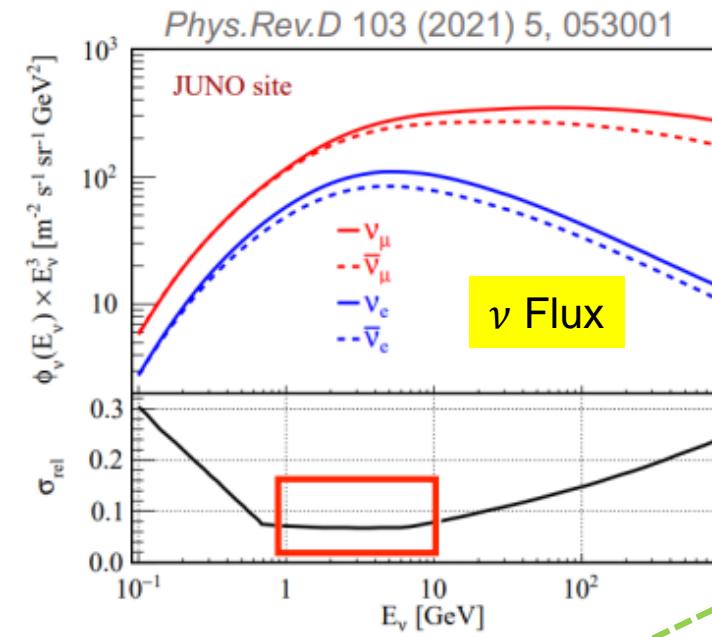
Geo-neutrinos



- $\bar{\nu}_e$ from ^{238}U and ^{232}Th decay chains in earth
- Probe the inner structure of the Earth by U/Th decays in the crust and mantle
- Huge statistics expected at JUNO
 - Signal in JUNO (CRUST1.0): $39.7+6.5-5.2$ TNU (**~400 geo- ν per year**), 5% meas. in 10 years
 - Stats in 1 yr comparable to total amount already measured by Borexino and KamLAND
- With new Local Refined Crust model (*PEPI*, [299 \(2020\) 106409](#)) \rightarrow **~30% more geo- ν**
 - updated sensitivity being evaluated
 - mantle discovery potential ongoing



Atmospheric neutrinos



- ~10 atm-ν interactions per day in JUNO
- Good potential to reconstruct atm-ν in large homogenous LS detector
 - ✓ Large photo-coverage → μ vs e
 - ✓ Hadronic information visible → better E/θ rec for ν (than l^\pm)
 - ✓ Excellent neutron tagging → ν vs ν̄
 - ✓ Final state isotopes identifiable → measure exclusive channels

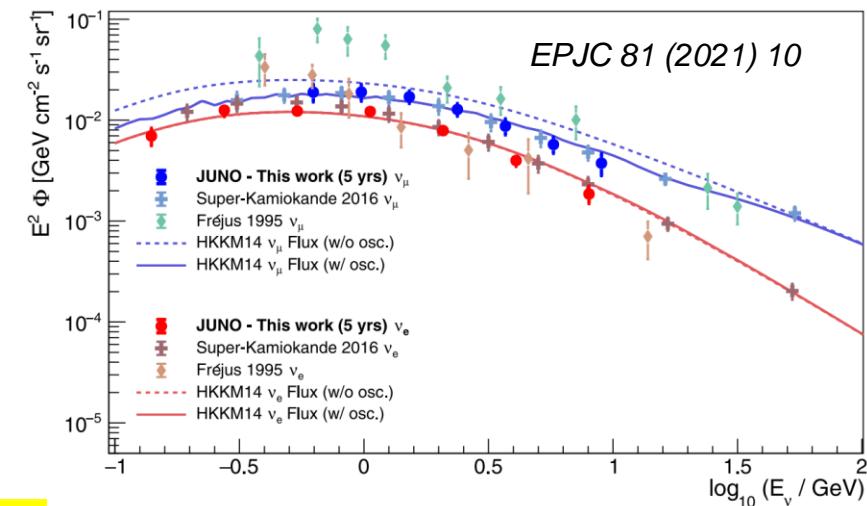


Atmospheric neutrino programs at JUNO

Physics related to atm- ν

- NMO through MSW (not covered here)
- Low energy flux measurement
- Measurement of NC/CC interactions
 - Background for many analyses above the reactor- ν energies: DSNB, proton decay, indirect DM ...
- Search for ν_τ in LS detector
- ...

Poster by Zhenning Qu
Atmospheric Tau Neutrino Search at JUNO



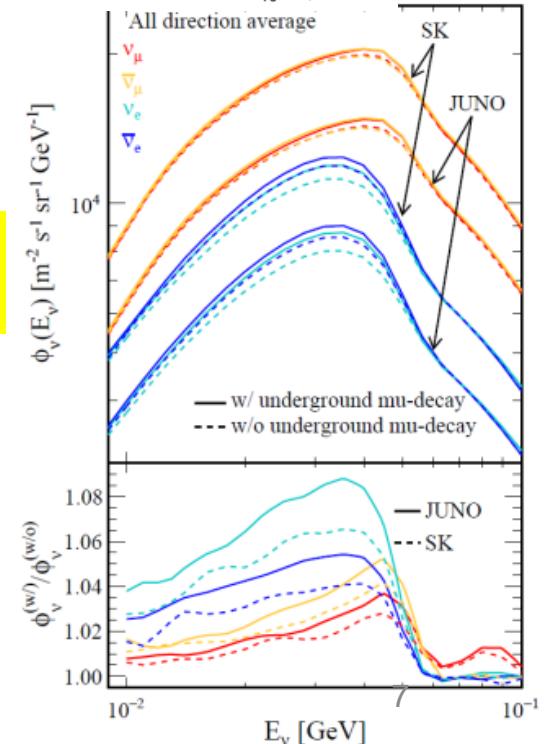
Flux calculation

- 3D flux
- On-going improvement at < 100 MeV
 - Muon propagation inside the earth and local info

J. Cheng
@WANP2022

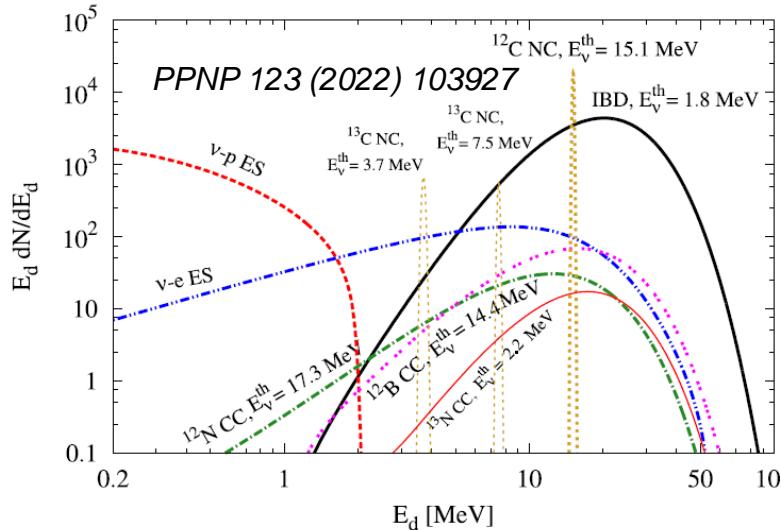
Evaluation of Interaction models

- GENIE/NuWro/Gibuu/Neut
- Model variations as one source of uncertainties
- Seek unique features in LS with atm- ν for *in-situ* measurements

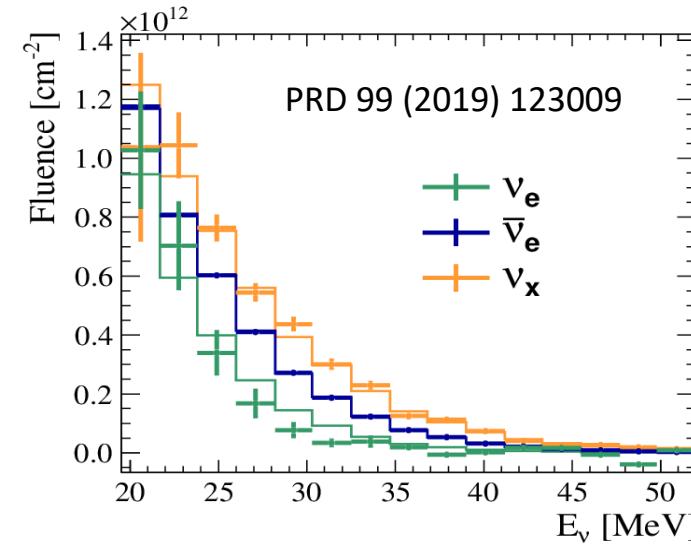




Multi-channel detection, all flavors of CCSN:



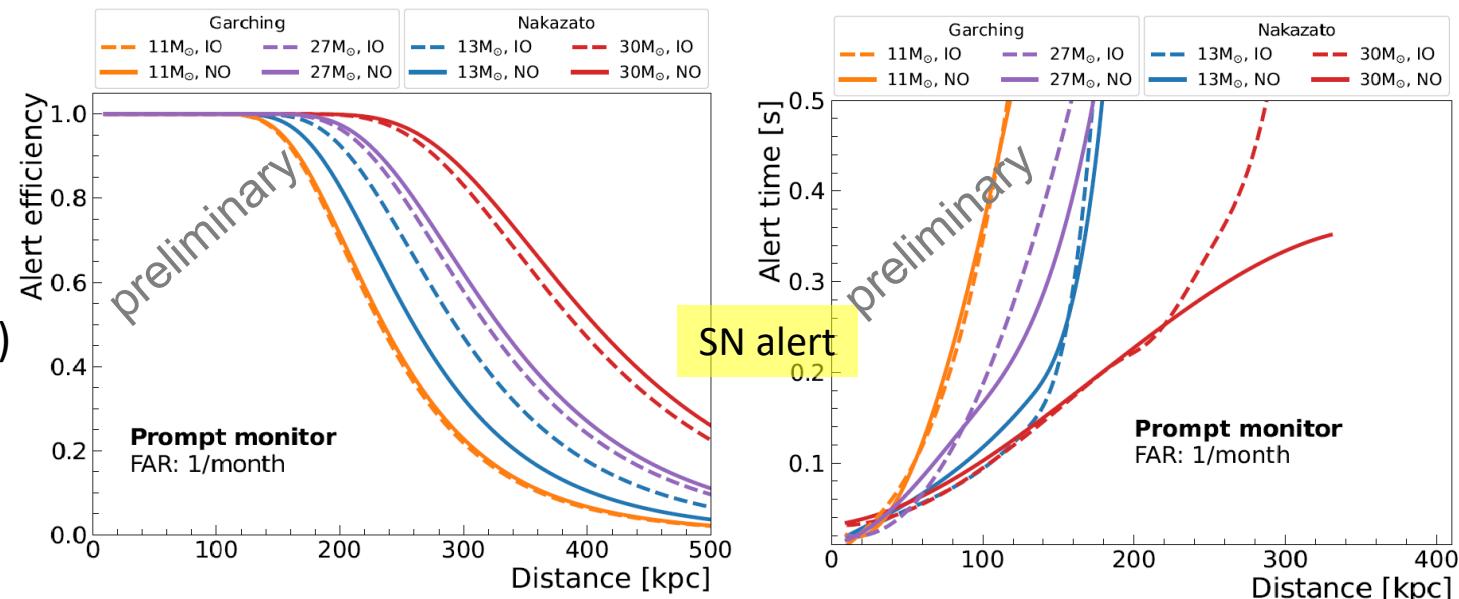
channel	# of events
IBD	5000
eES	300
pES	2000
¹² C CC	200
¹² C NC	300
@10 kpc	



Model-independent reconstruction of the energy spectra of $\bar{\nu}_e$, ν_e , ν_x via unfolding approach
 → Allow for further physics and astrophysics studies!

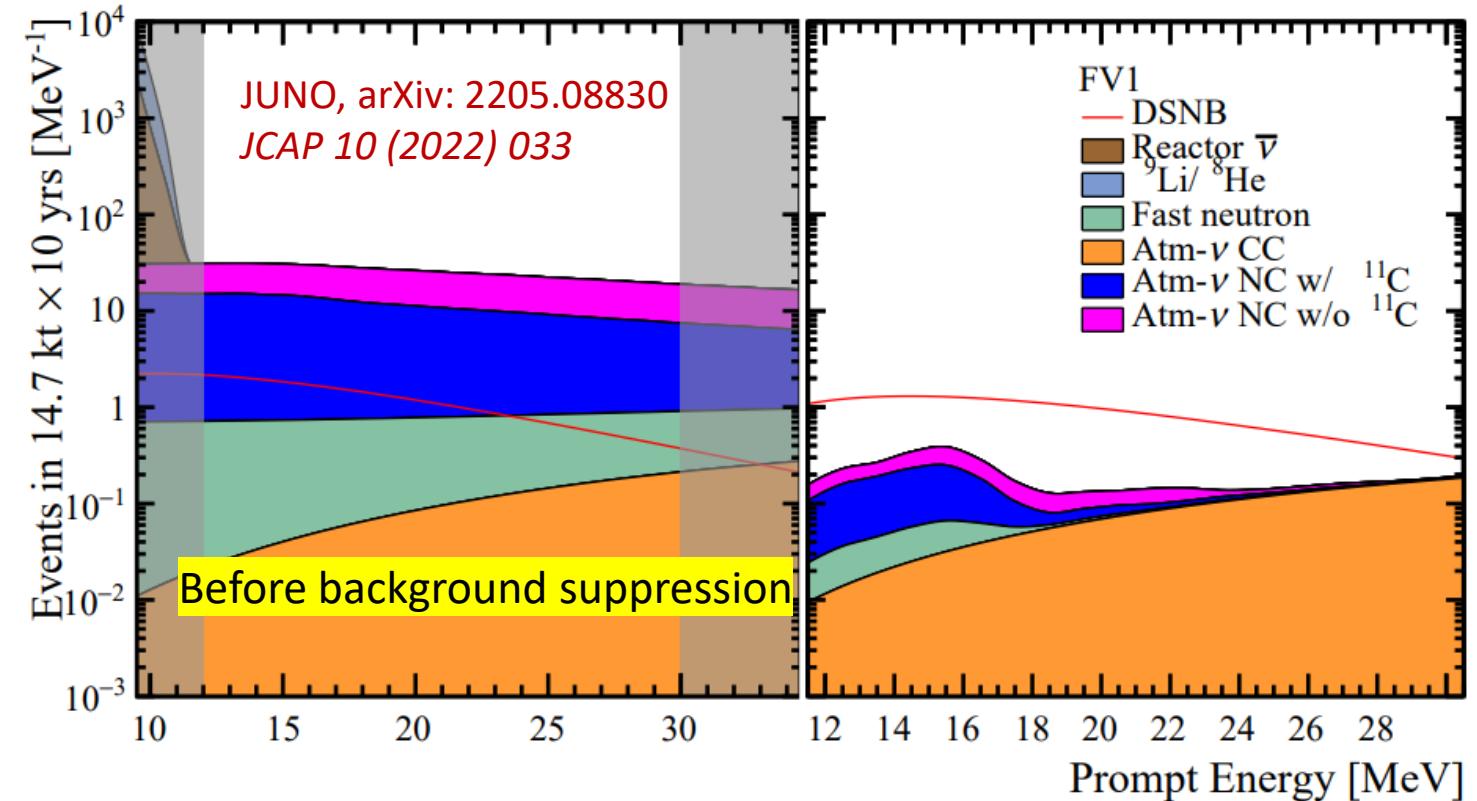
- Excellent capability of early warning
- CCSN: reach 240 ~ 400 kpc w/ 50% prob., alert in 10 ~ 30 ms
- pre-SN: reach 0.6 ~ 1.7 kpc w/ 50% prob., >100 hr in advance for Betelgeuse (<0.2 kpc)

A dedicated Multi-Messenger Trigger System is on the way



DSNB

- DSNB: 2-4 events in JUNO per year**
 - 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
 - x20 larger than signal
- Highlights on background suppression
 - Muon veto
 - Pulse shape discrimination (PSD)
 - Triple coincidence (^{11}C delayed decay)



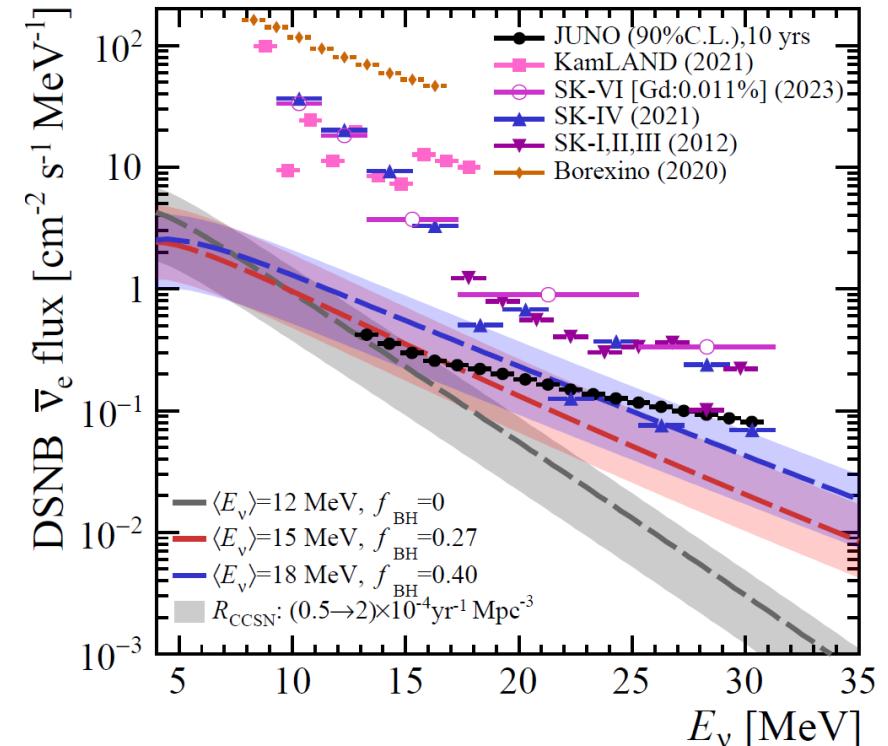
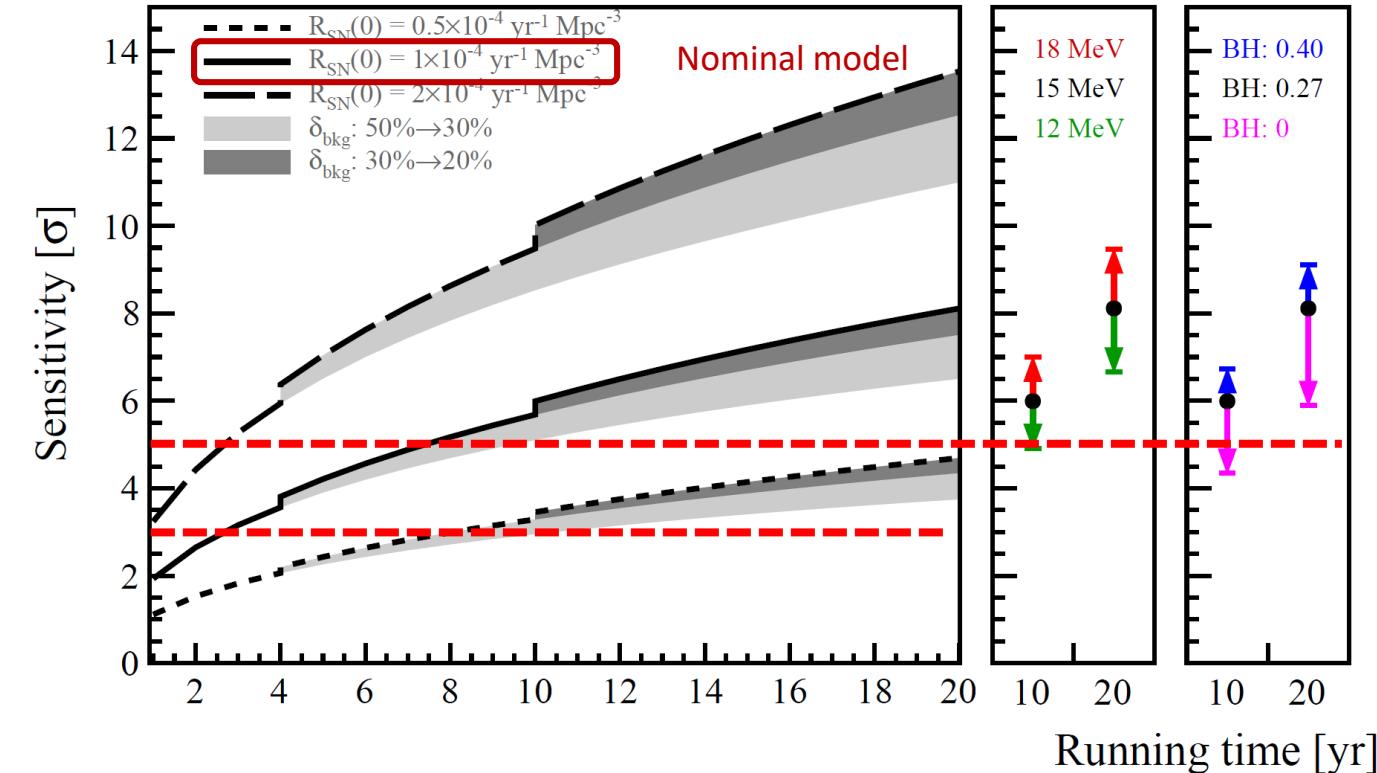
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)*:

- ✓ **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**

→ S/B improved from **2 to 3.5**

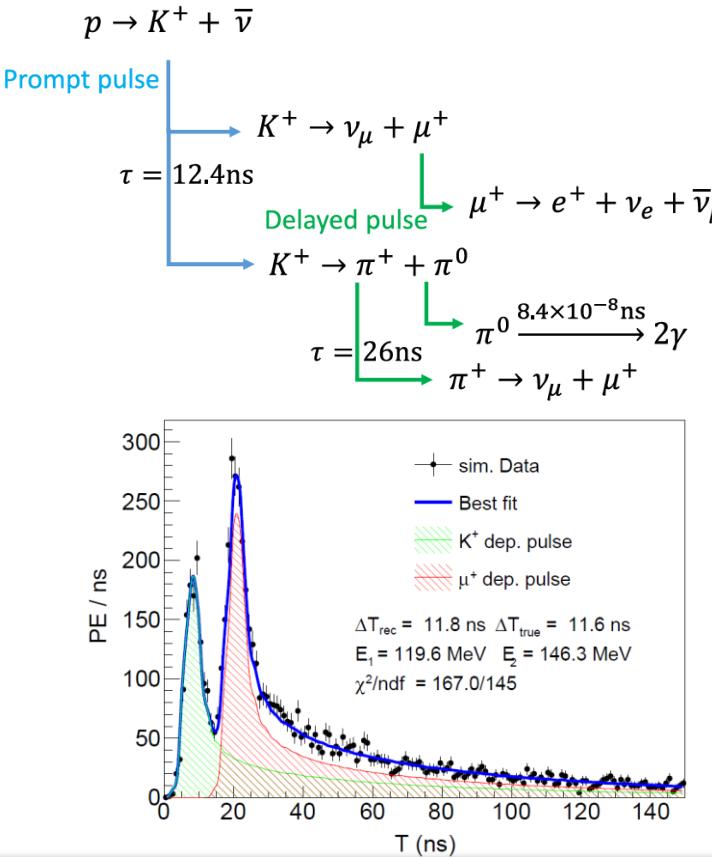


arXiv: 2205.08830, JCAP 10 (2022) 033



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

Nucleon decay



- **Signature:** three-fold coincidence
- **Dominant background**
 - Atm- ν interactions
- Disentangle pile-up of signals with 3-inch PMTs
- Multiplicity, spatial distribution of Michel e- and neutrons in the FSI
- **Expect sensitivity:** 9.6×10^{33} years (90% C.L.) for 200 kton*yrs exposure

Talk by Ulrike Fahrendholz
Kaon Quenching Studies to Improve JUNO's Sensitivity to Proton Decay

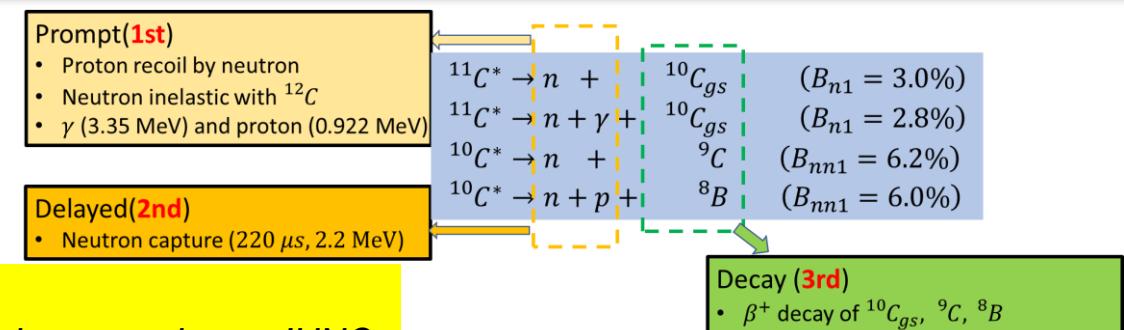
[arXiv:2212.08502](https://arxiv.org/abs/2212.08502),
accepted by CPC

Super-K (2014): $>5.9 \times 10^{33}$ yrs @ 260 kton·yr

Triple-coincidence signatures from excited

- $^{11}\text{C}^*$ (n -decay)
- $^{10}\text{C}^*$ (nn -decay)

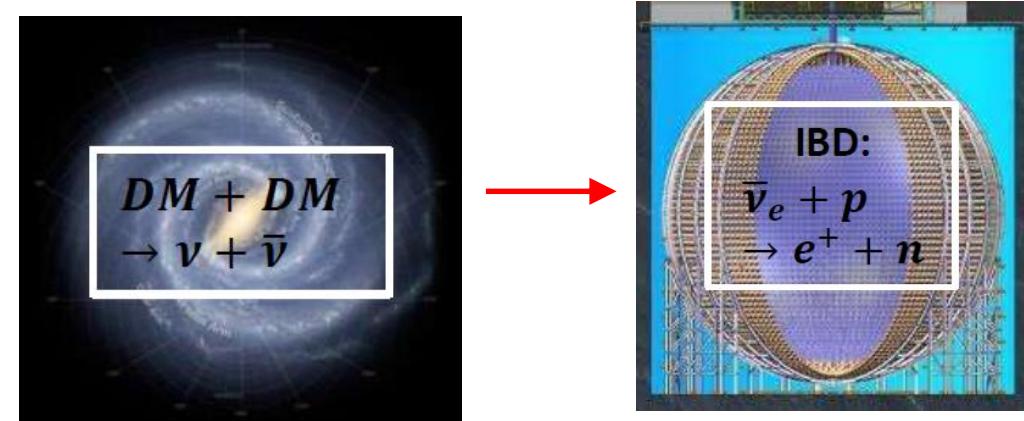
after **Invisible decay of bounded neutron(s) in ^{12}C**



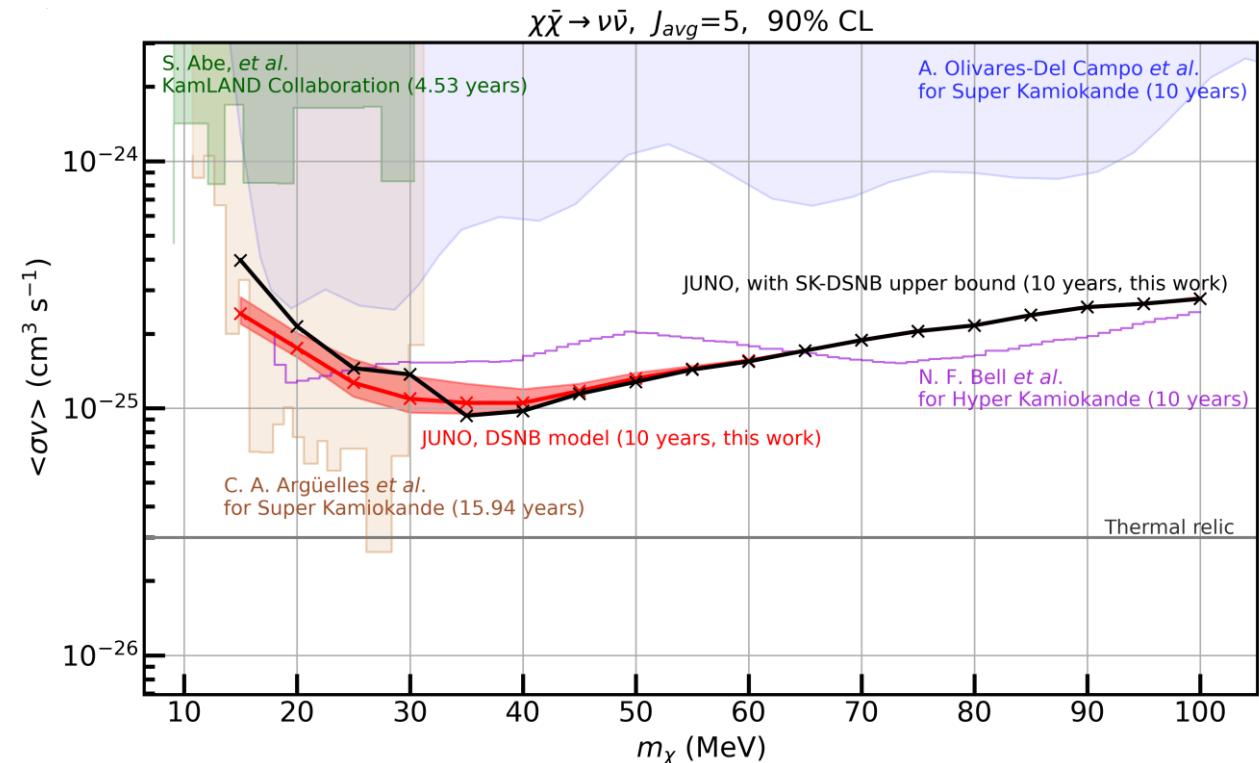
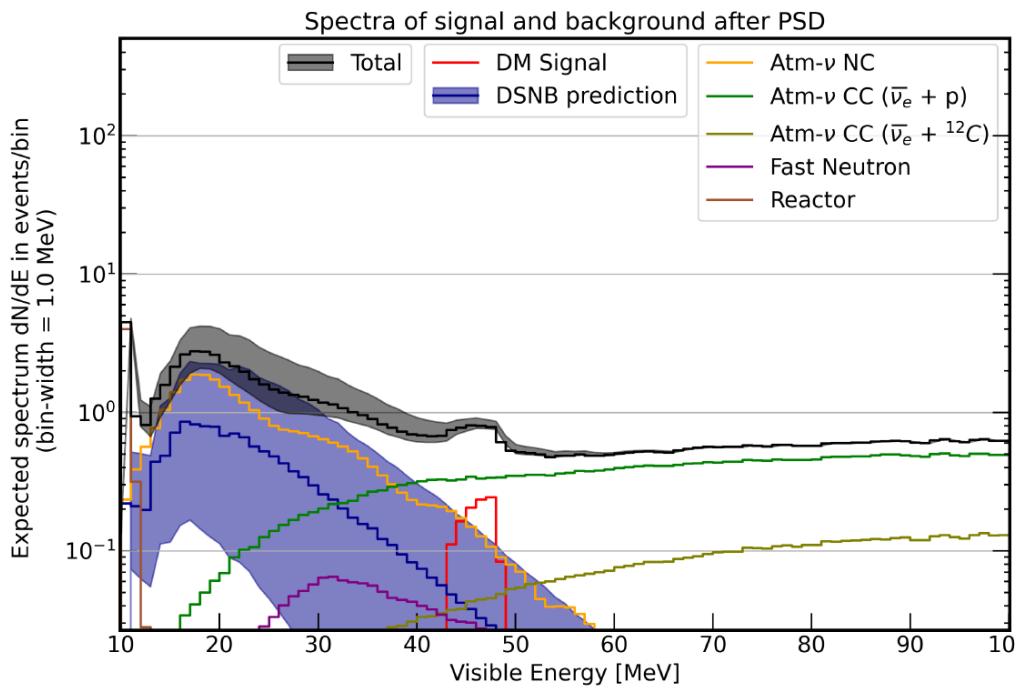
Talk by Cailian Jiang
Sensitivity to neutron invisible decay modes at JUNO



Indirect dark matter search



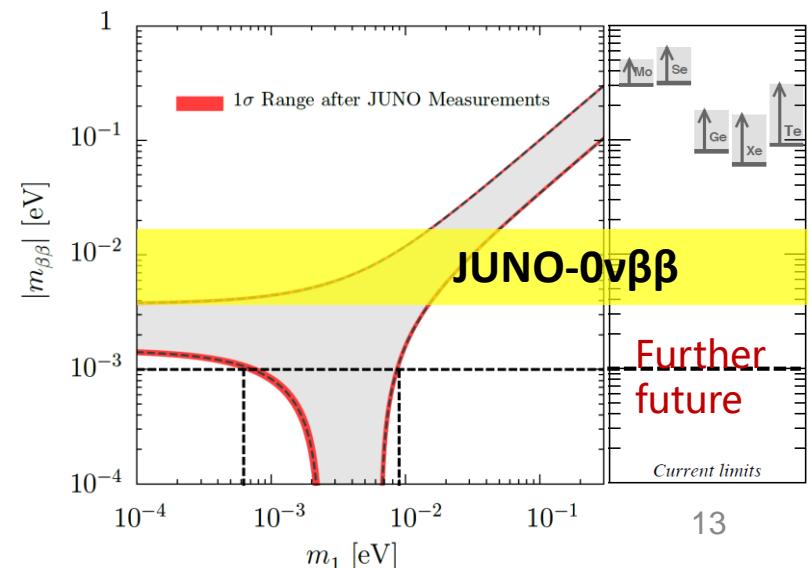
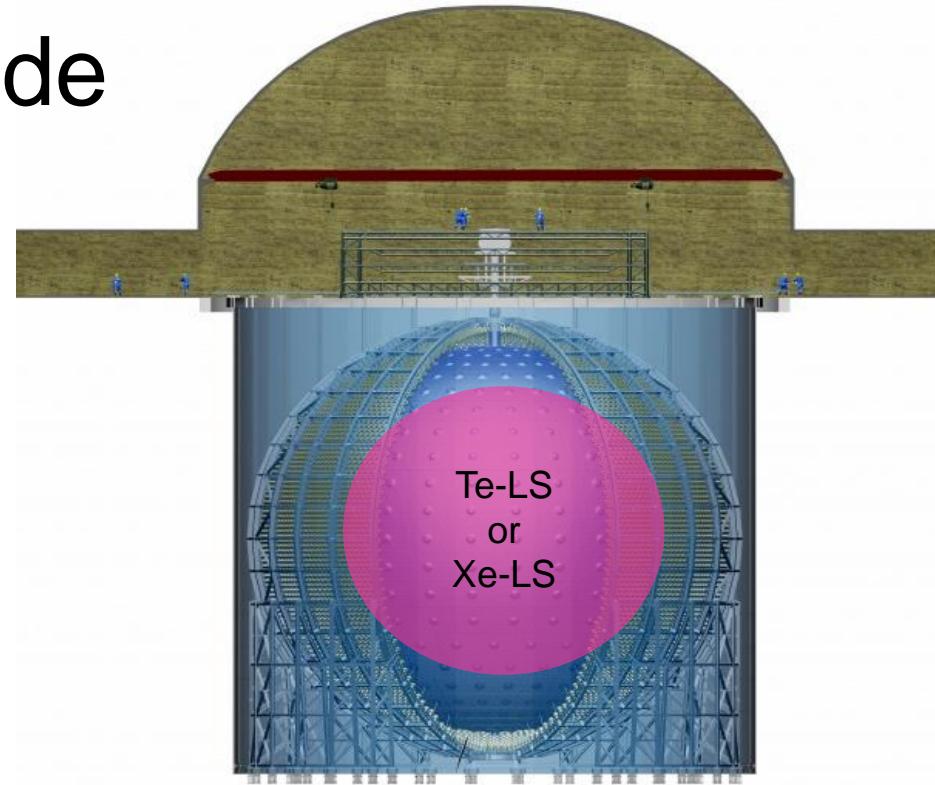
- DM annihilation into neutrinos in the Milky Way
- DM masses: **15 - 100 MeV**
- Detection channel in JUNO: Inverse Beta Decay
- Backgrounds: **atm-v NC/CC, DSNB**, fast neutron, reactor
 - PSD technique to suppress atm-v NC and fast neutron





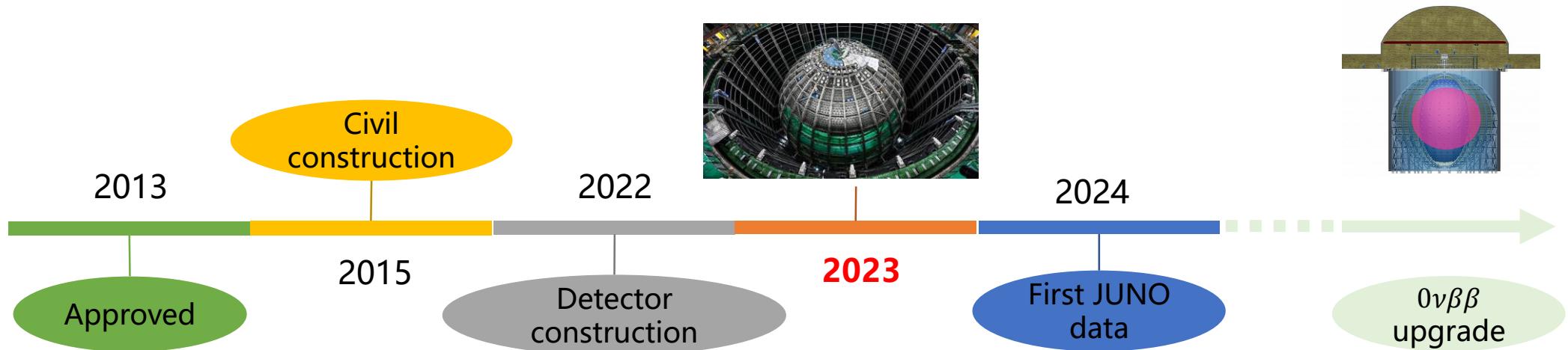
JUNO- $0\nu\beta\beta$ upgrade

- JUNO offers a unique opportunity to search for $0\nu\beta\beta$ after completion of mass ordering measurements (~2030)
 - Large target mass: 20 kton LS → **100-ton scale isotope loading** (e.g., Tellurium / Xenon)
 - Low background
 - Energy resolution < 3% @ 1 MeV
 - → Potential to explore normal mass ordering parameter space of Majorana neutrino mass (Xe-loading as an example) **CPC 41 (2017) 053001**
- Critical R&D in progress
 - Te loaded LS requirements: high light yield, transparency, solubility and stability
 - Staged progress **NIM A 1049 (2023) 168111**
 - Background rejection (^8B solar neutrinos, Te/Xe muon-spallation products)



Summary

Physics	Sensitivity
Supernova Burst (10 kpc)	~7300 of all-flavor neutrinos
DSNB	3 σ in 3 yrs
Solar Neutrino	Measure ^7Be , pep, CNO simultaneously, measure ^8B flux independently
Nucleon Decays ($p \rightarrow \bar{\nu}K^+$)	9.6×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs



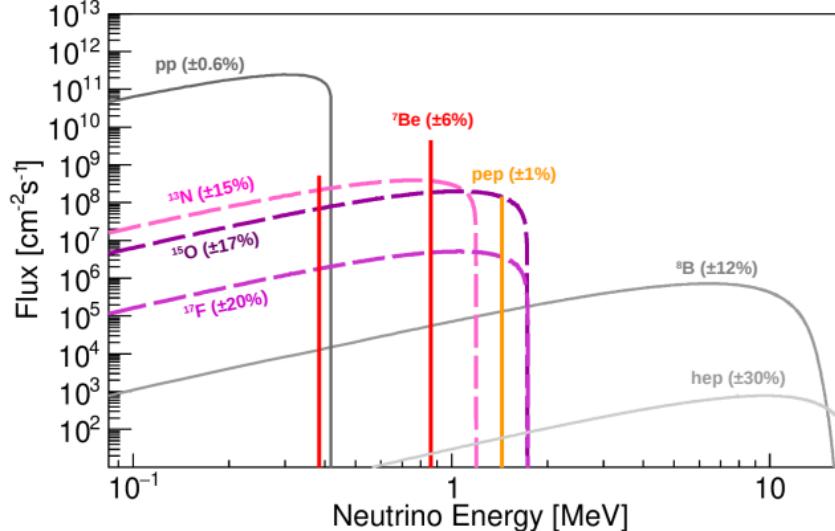
Stay tuned!



Backup



Solar neutrinos



	Solar ν	${}^7\text{Be}$	pep	CNO	
HZ- SSM	$\Phi [10^8 \text{ cm}^{-2} \text{ s}^{-1}]$	$49.3(1 \pm 0.06)$	$1.44(1 \pm 0.009)$	$4.88(1 \pm 0.11)$	
	$R [\text{cpd/kton}]$	489 ± 29	28.0 ± 0.4	50.3 ± 8.0	
	$R^{\text{ROI}} [\text{cpd/kton}]$	142.5 ± 8.3	17.1 ± 0.2	16.6 ± 2.6	
LZ- SSM	$\Phi [10^8 \text{ cm}^{-2} \text{ s}^{-1}]$	$45.0(1 \pm 0.06)$	$1.46(1 \pm 0.009)$	$3.51(1 \pm 0.10)$	
	$R [\text{cpd/kton}]$	447 ± 26	28.4 ± 0.4	36.0 ± 5.3	
	$R^{\text{ROI}} [\text{cpd/kton}]$	130.0 ± 7.5	17.3 ± 0.2	11.9 ± 1.8	
Borexino results	$\Phi [10^8 \text{ cm}^{-2} \text{ s}^{-1}]$	$49.9 \pm 1.1^{+0.6}_{-0.8}$	$1.27 \pm 0.19^{+0.08}_{-0.12} (\text{LZ})$ $1.39 \pm 0.19^{+0.08}_{-0.13} (\text{HZ})$	$6.6^{+2.0}_{-0.9}$	

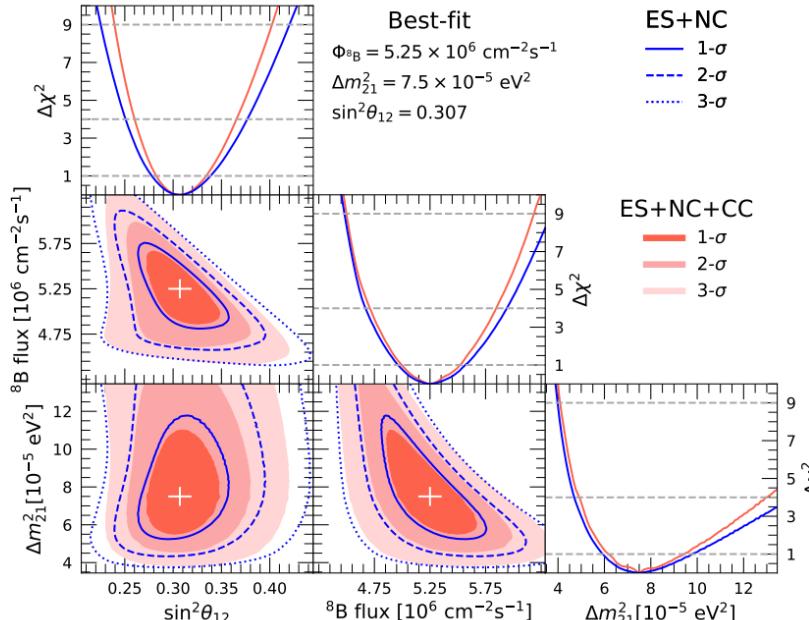
Radio-purity Scenario		${}^{40}\text{K}$	${}^{85}\text{Kr}$	${}^{232}\text{Th-chain}$	${}^{238}\text{U-chain}$	${}^{210}\text{Pb}/{}^{210}\text{Bi}$	${}^{210}\text{Po}$
IBD	$c [\frac{\text{g}}{\text{g}}]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R [\frac{\text{cpd}}{\text{kt}}]$	2289	5000	3508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

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



Model independent solar ${}^8\text{B}$ flux measurement

- Model independent measurement of ${}^8\text{B}$ - ν flux ($\sim 5\%$) and solar oscillation parameters
- Detection channel
 - NC, CC: ${}^8\text{B}$ - ν + ${}^{13}\text{C}$
 - ES: ${}^8\text{B}$ - ν + e



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

