Prospects of JUNO

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on behalf of the JUNO collaboration

2024/09/16

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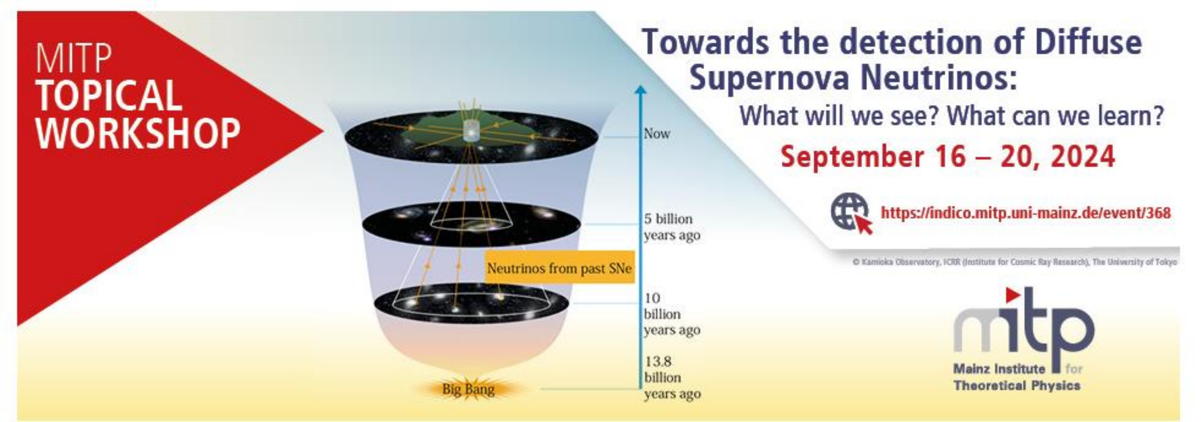

MITP
TOPICAL
WORKSHOP

Towards the detection of Diffuse Supernova Neutrinos:
What will we see? What can we learn?
September 16 – 20, 2024

https://indico.mitp.uni-mainz.de/event/368

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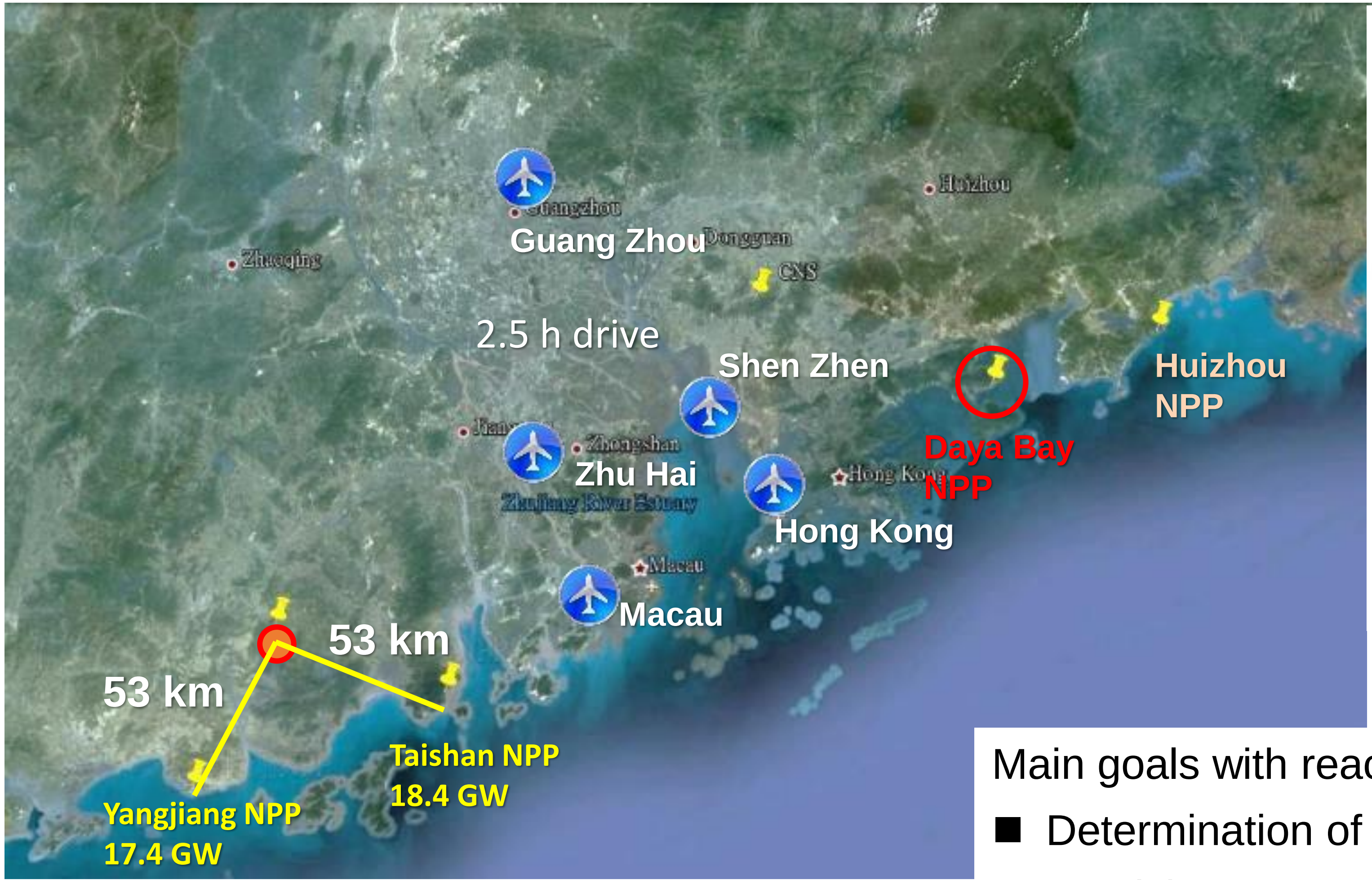
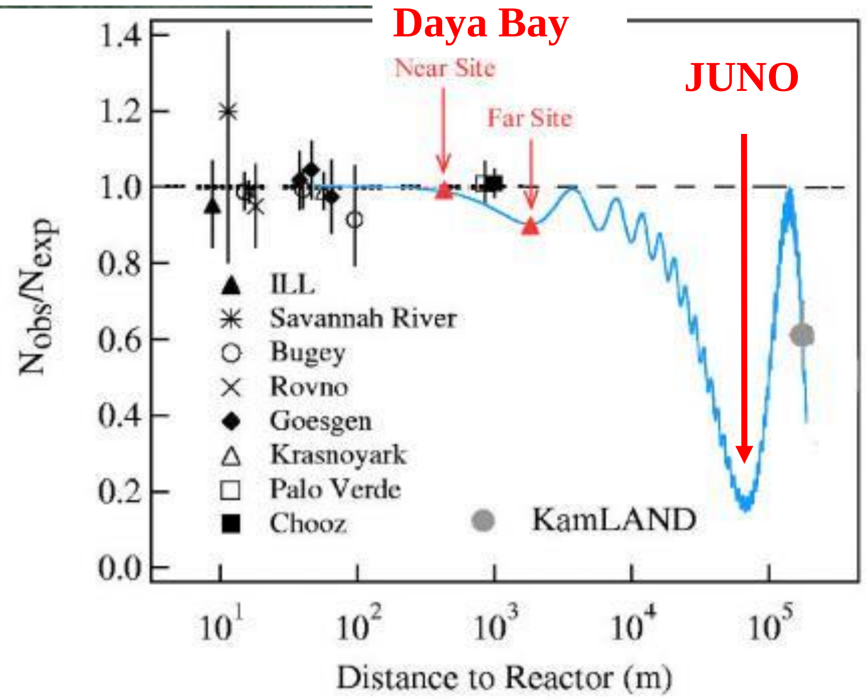
Mainz Institute for Theoretical Physics

JUNO Experiment

- **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a multi-purpose neutrino experiment currently under construction in South China.





L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Main goals with reactor antineutrino oscillations

- Determination of the Neutrino Mass Ordering (NMO)
- Precision measurement of neutrino oscillation parameters

JUNO Experiment

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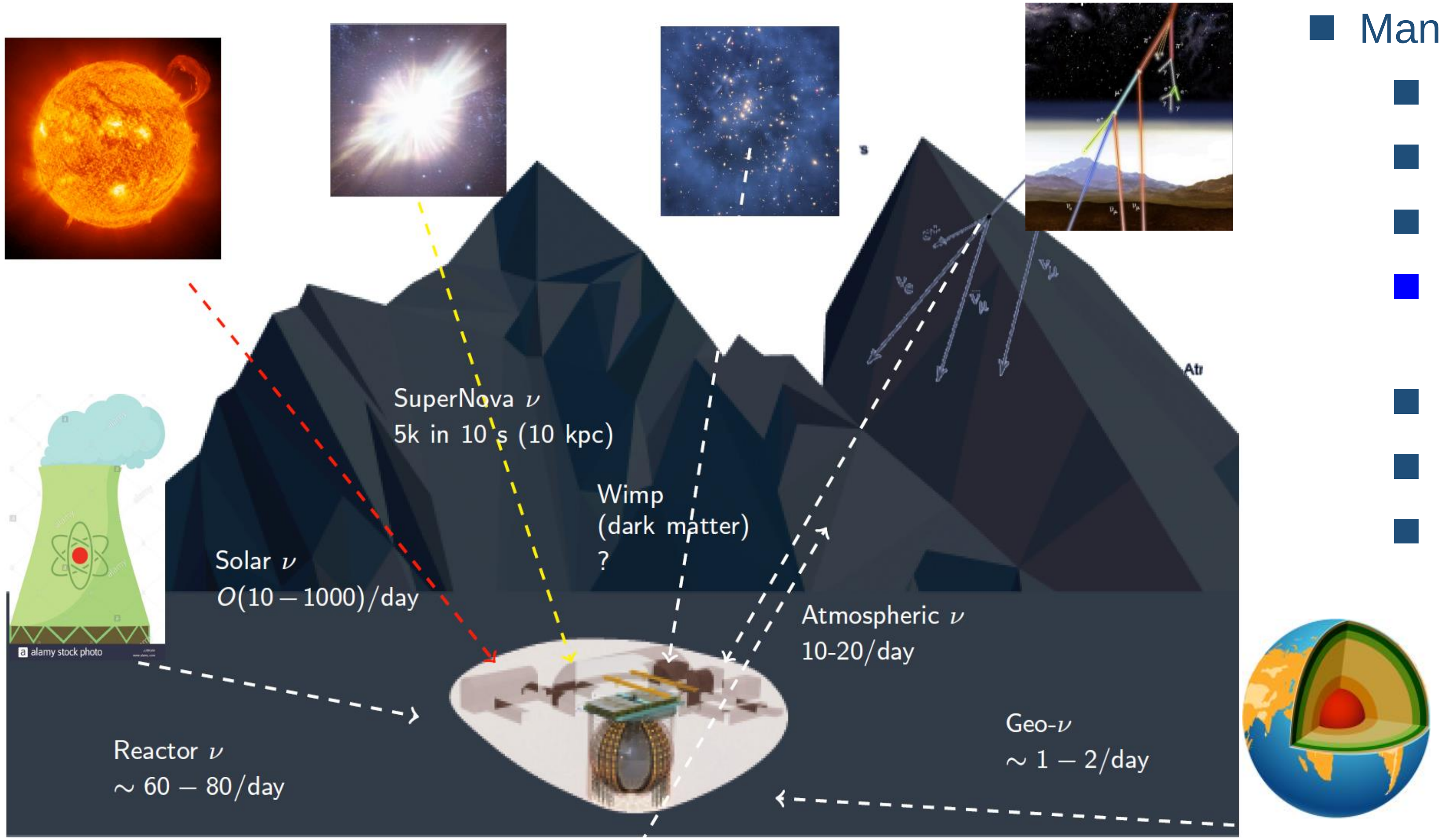
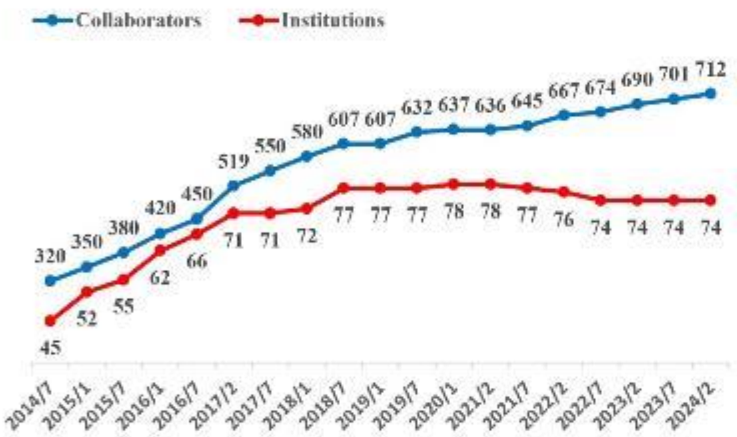


- Many other physics programs
  - Solar neutrinos
  - Atmospheric neutrinos
  - Supernova burst neutrinos
  - Diffuse supernova neutrino background (This talk)
  - Geo-neutrinos
  - Exotic neutrinos
  - Nucleon decay

JUNO Collaboration

- **Collaboration established in 2014**
- **Now more than 700 collaborators from 74 institutions**

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Tsinghua U.	Germany	U. Tuebingen
Belgium	Universite libre de Bruxelles	China	UCAS	Italy	INFN Catania
Brazil	PUC	China	USTC	Italy	INFN di Frascati
Brazil	UEL	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. Liverpool
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	GSI	USA	UC Irvine
China	SYSU	Germany	U. Mainz		



The 24th JUNO collaboration meeting

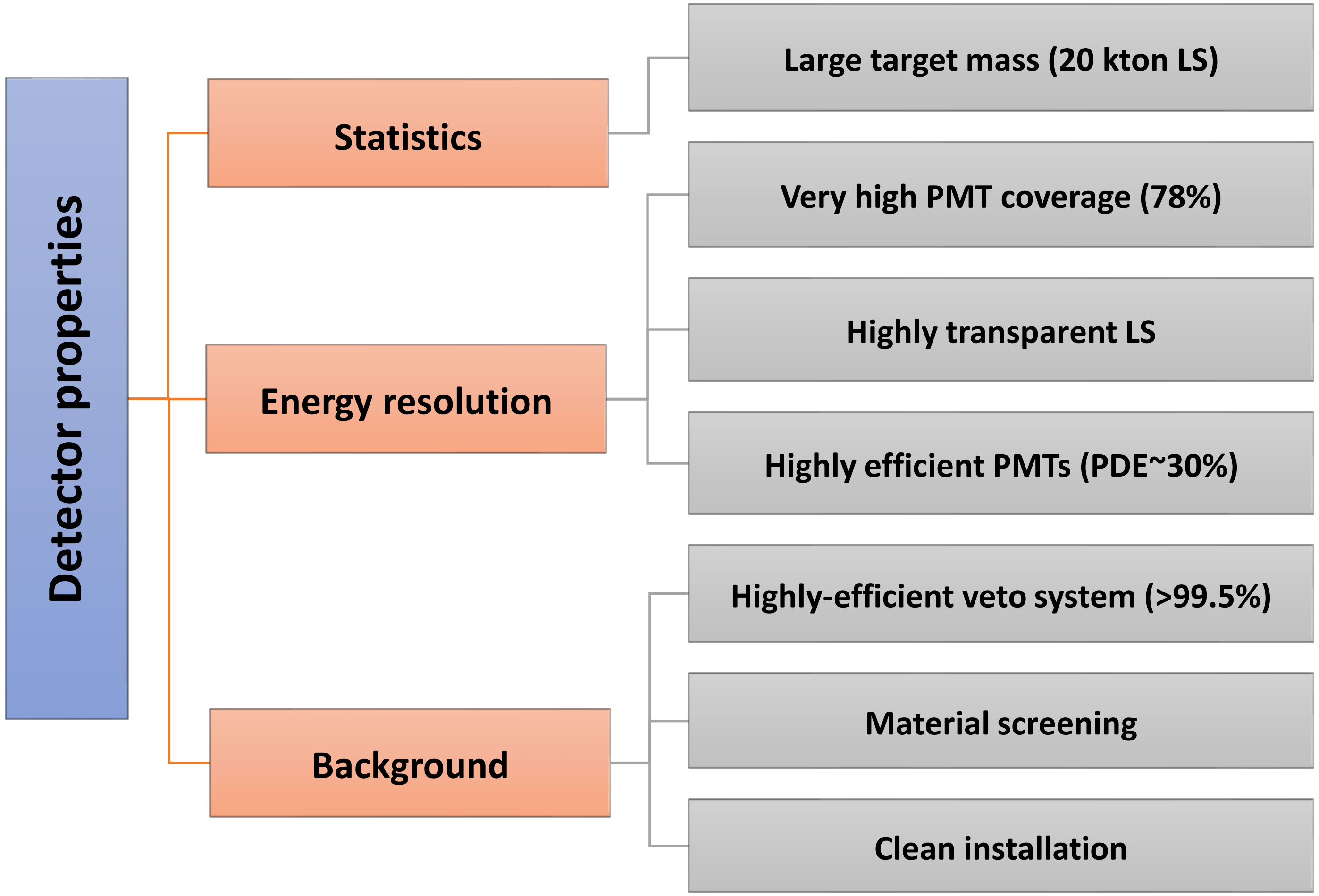
JUNO Site


Vertical Shaft: 564 m
Overburden ~650 m
(1800 m.w.e)
Slope tunnel: 1266 m
Civil construction finished in 2021/12

JUNO Detector Requirements

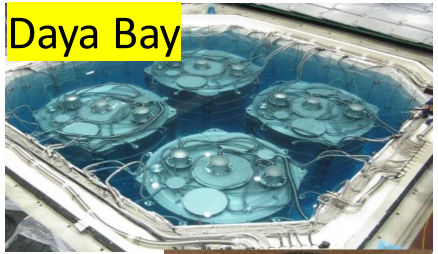
Main requirements:

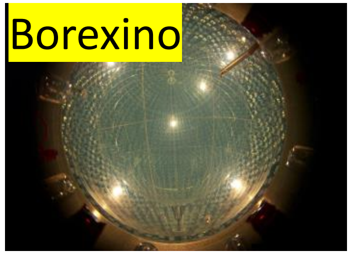
➔ **Unprecedented liquid scintillator (LS) neutrino experiment**



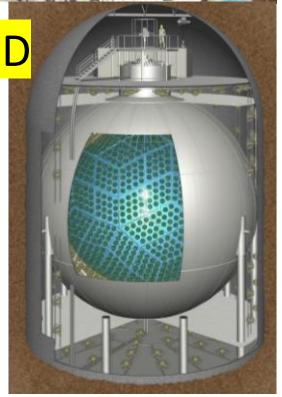
- **Detector properties**
  - **Statistics**
    - Large target mass (20 kton LS)
  - **Energy resolution**
    - Very high PMT coverage (78%)
    - Highly transparent LS
    - Highly efficient PMTs (PDE~30%)
  - **Background**
    - Highly-efficient veto system (>99.5%)
    - Material screening
    - Clean installation

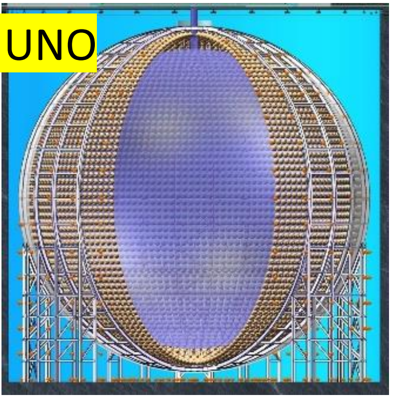
	Target mass	PMT Coverage	Energy resolution @ 1 MeV	Light yield [PE/MeV]
Daya Bay	20 ton (x8)	12%	8%	160
Borexino	300 ton	34%	5%	500
KamLAND	1 kton	34%	6%	250
JUNO	20 kton	78%	3%	>1300


Daya Bay

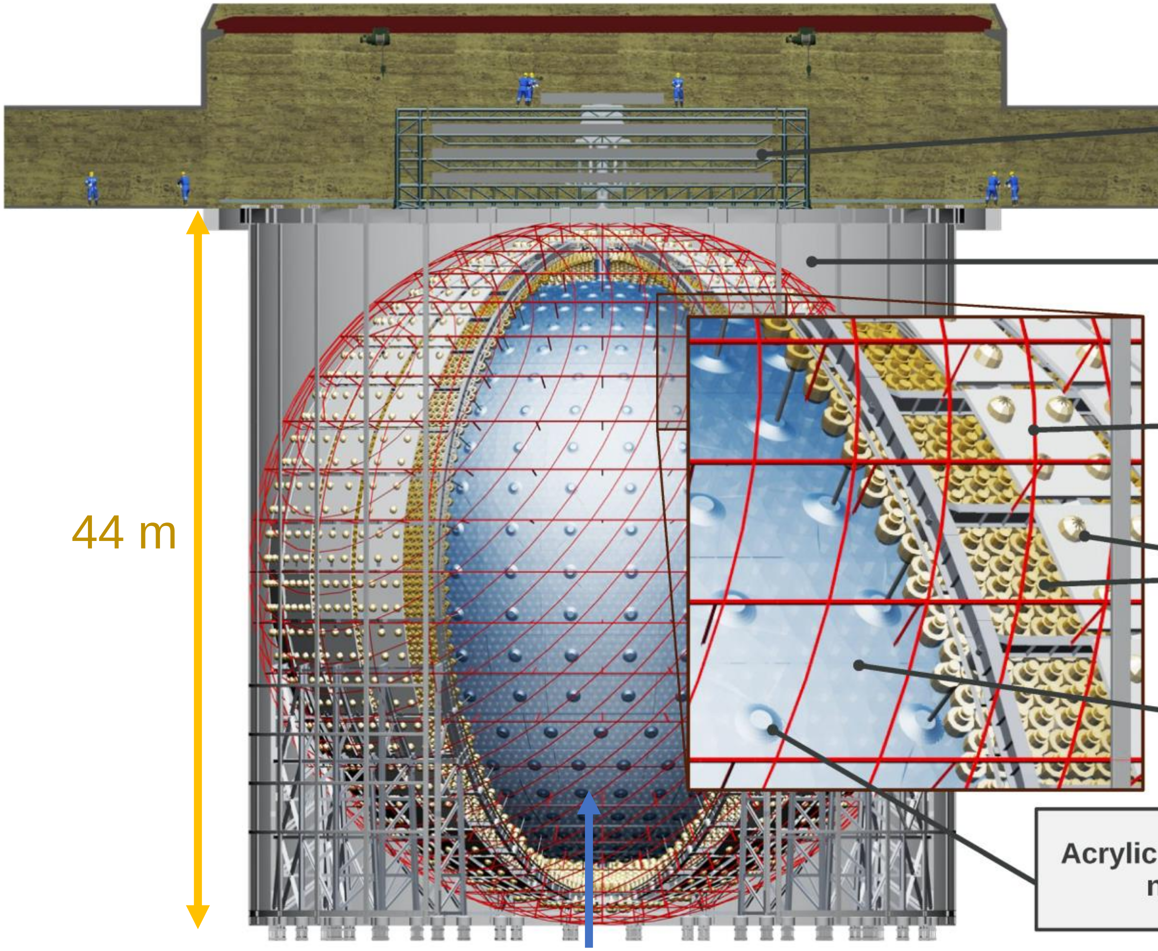

Borexino

KamLAND




JUNO

JUNO Detector



44 m

Top Tracker and calibration house

Water pool

Earth magnetic field compensation coils

Photomultiplier tubes

Acrylic spherical vessel filled with liquid scintillator

Acrylic supporting nodes

Central Detector
20 kton LS

Central detector

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

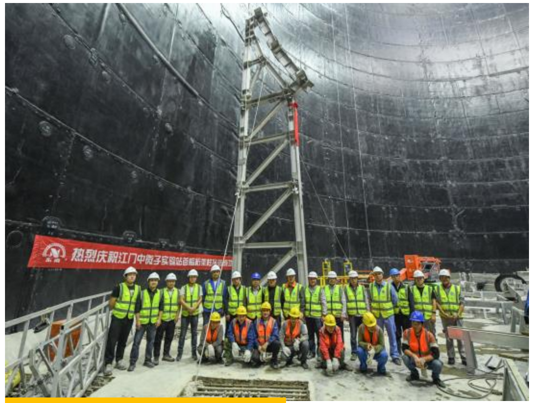
Veto detector

- Top tracker
- 35 kt ultra pure water
- 2400 20'' PMTs

Central Detector: Stainless Steel Structure

arXiv: 2311.17314 (2023)

- A D=40.1 m stainless steel structure supports the acrylic vessel via 590 connecting bars.

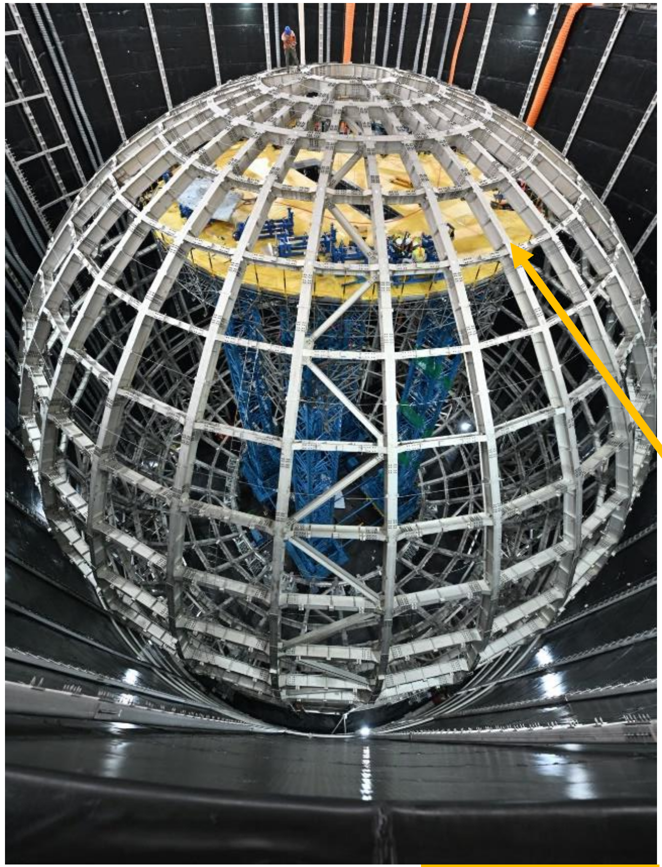


Jan. 21st , 2022

Mar. 8th, 2022

April 28th, 2022

May 27th, 2022



July 1st , 2022

- ✓ **Assembly precision: < 3 mm for each grid**
- ✓ **Natural radioactivity level < 1ppb**

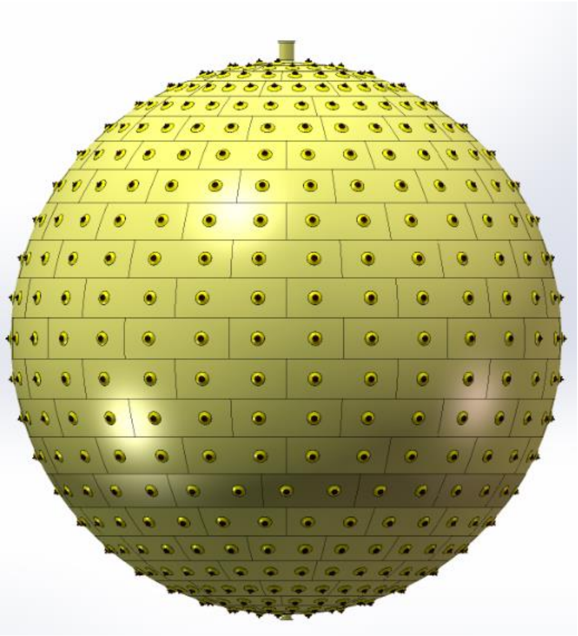
The platform for installing the acrylic vessel.

Central Detector: Acrylic Vessel

arXiv: 2311.17314 (2023)

Contains 20 kton of LS:

- ✓ 263 Acrylic panels: ~8m x 3m x 12 cm
- ✓ Inner diameter: ~35.40 m
- ✓ Light transparency > 96%
- ✓ Radiopurity: U/Th/K < 1 ppt



Pre-assembly at Donchamp

Acrylic panel: polished, cleaned, covered by PE film

Connection bar installation

Acrylic assembly: ongoing (Jul. 2022- now)

Muon Veto System

- **~650 m rock overburden (1800 m.w.e.) → R_μ = 4 Hz in LS, $< E_\mu >$ = 207 GeV**

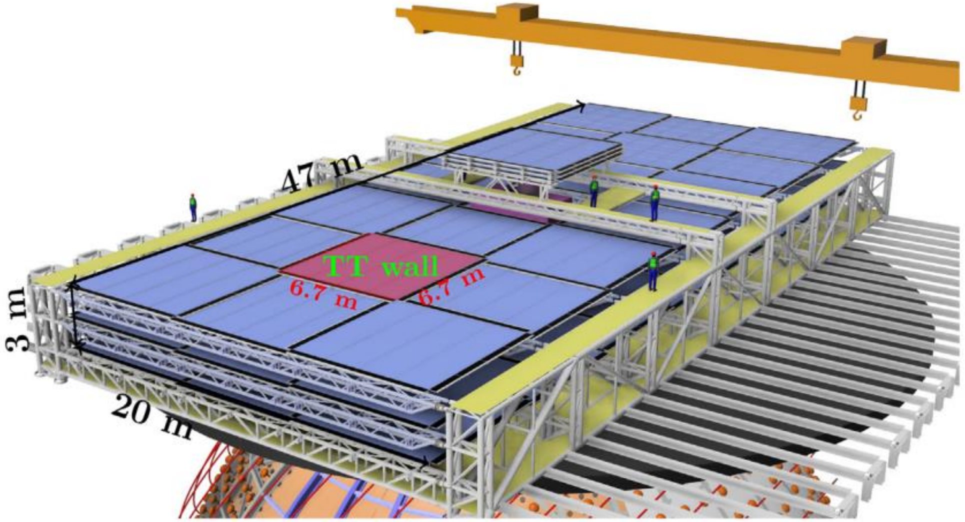
✓ **About 127 ^{9}Li and 40 ^{8}He isotopes, but 57 reactor neutrinos per day**

Ultrapure water system

35 kton of ultrapure water serving as passive shield and water Cherenkov detector.

- ✓ 2400 20-inch PMTs, detection efficiency of cosmic muons larger than 99.5%

NIMA 1057 (2023) 168680



Plastic scintillator from the OPERA

- ✓ About 50% coverage on the top, three layers to reduce accidental coincidence
- ✓ All scintillator panels arrived on site in 2019

✓ **One effective veto strategy keeps 47.1 reactor neutrinos but only 0.8 residual Li9/He8 background**

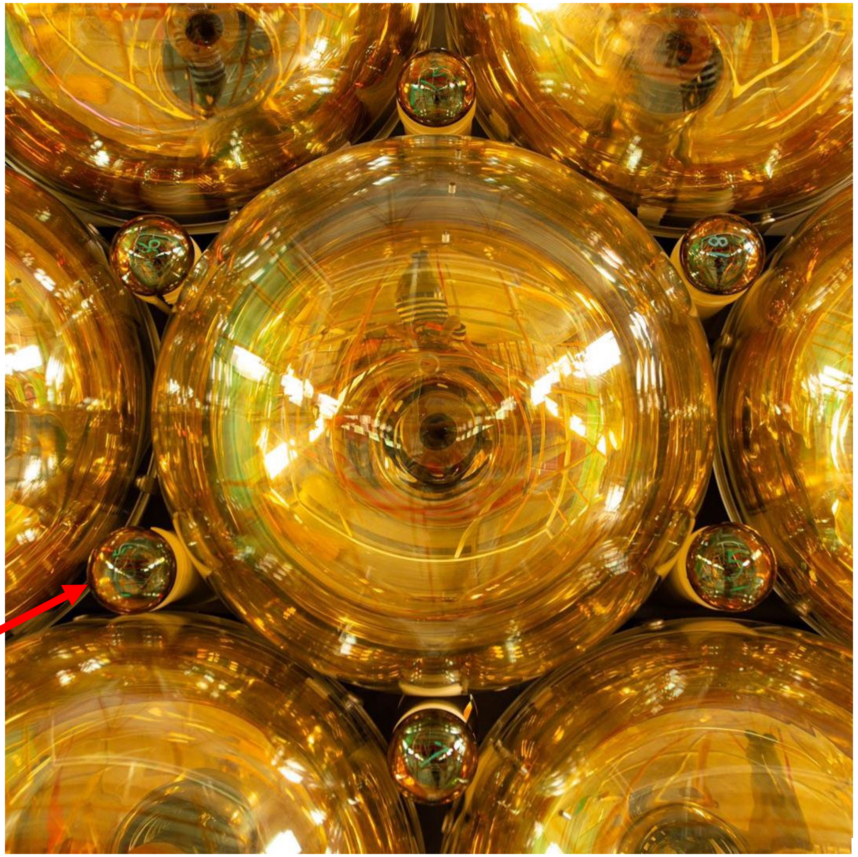
Liquid Scintillator (LS)

- **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 neutrinos and 10^{-17} g/g for solar neutrinos
- ✓ full system commissioning started in April 2023

*OSIRIS: Online Scintillator Internal Radioactivity Investigation System

Photomultiplier Tubes (PMTs)

- **Synergetic 20-inch (L) and 3-inch (S) PMT systems to ensure energy resolution and control systematics**
- ✓ **All PMTs produced, tested, and instrumented with waterproof potting.**
- ✓ **More than 7000 LPMTs and 9000 SPMTs installed and tested OK!**


SPMT

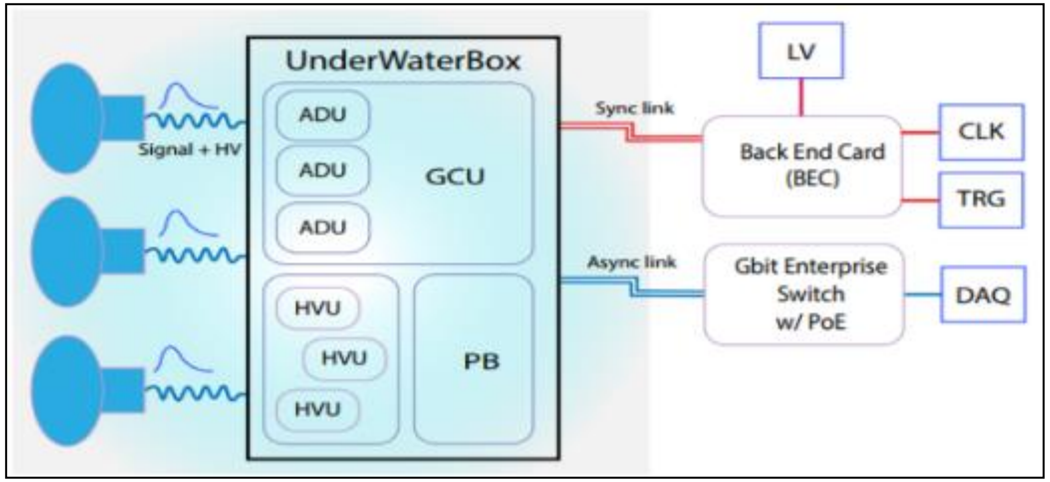
		LPMT (20-inch)		**SPMT (3-inch)**
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		Eur. Phys. J. C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

12.6k NNVT PMTs with the highest PDE are selected for light collection from LS and the rest are used in the Water Cherenkov detector.

Electronics

- ➢ **Underwater electronics to improve signal-to-noise ratio for better energy resolution**

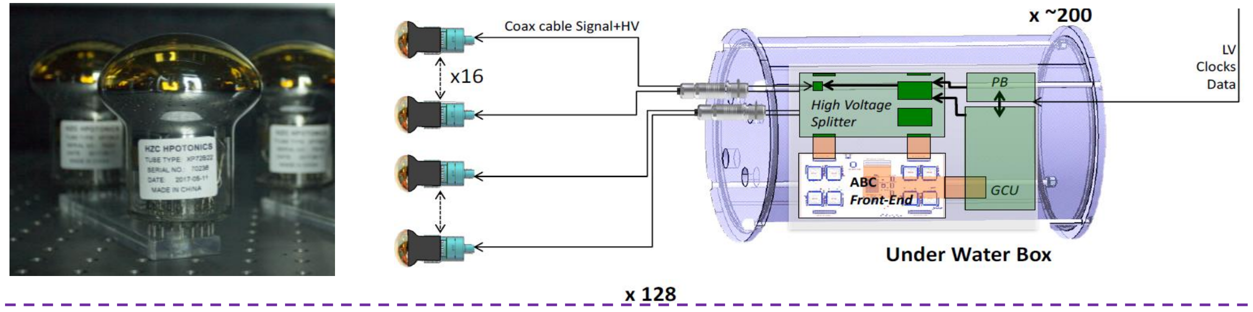
- **LPMT electronics: 20012 channels**
  - ➔Dynamic range: 1- 4000 PE
  - ➔Noise: <10% @1 PE
  - ➔Resolution: <10%@1 PE, <1%@100 PE
- 1 GHz FADC (14 bit) in an underwater box (3 ch./box), connected to PMTs by water proof connectors
- **Failure rate: < 0.5% in 6 years**

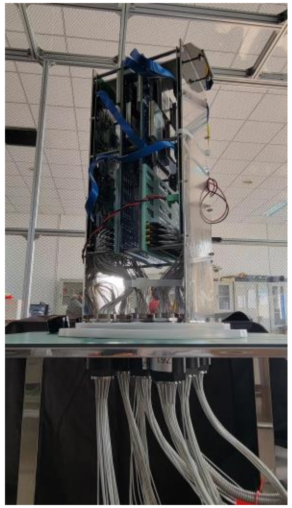


Electronics assembly and tests done➔ Installation is ongoing

- **SPMT electronics: 25600 channels**
- 200 underwater boxes, each for 128 PMTs read by ASIC Battery Cards (ABC), each with 8 CatiROC chips
- Only time/charge readout

System overview: 200 boxes × 128 PMTs

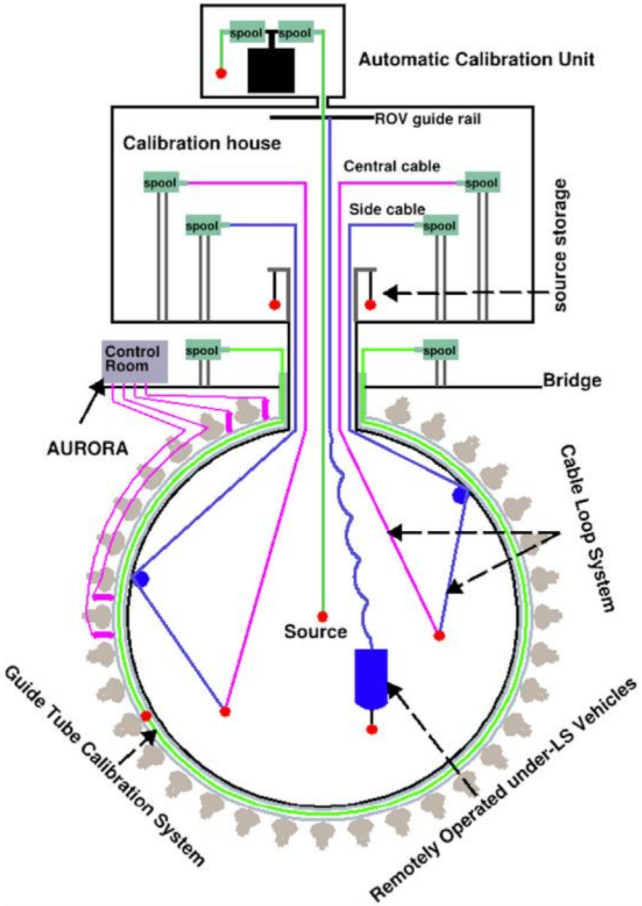


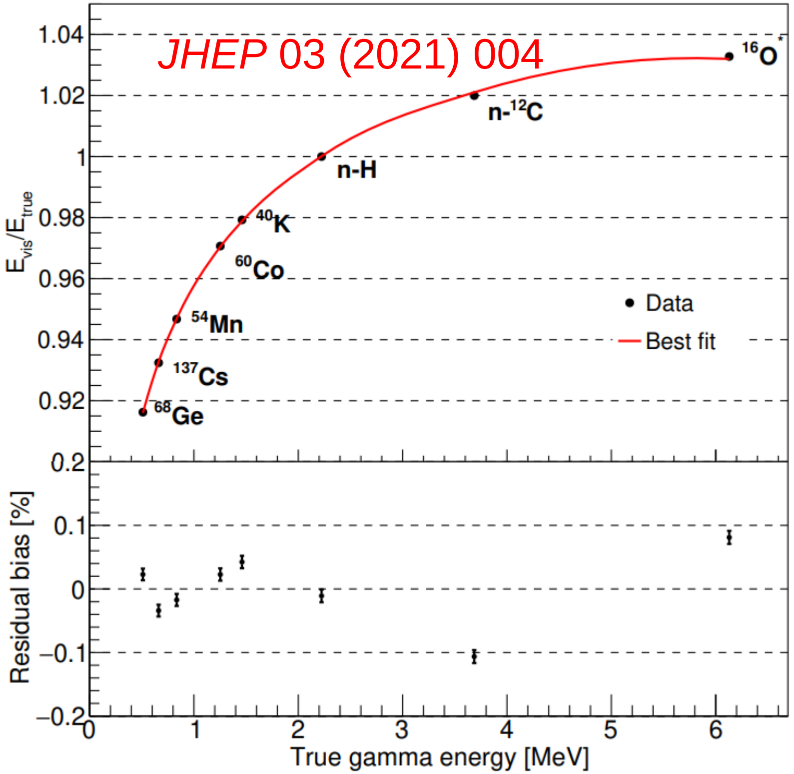


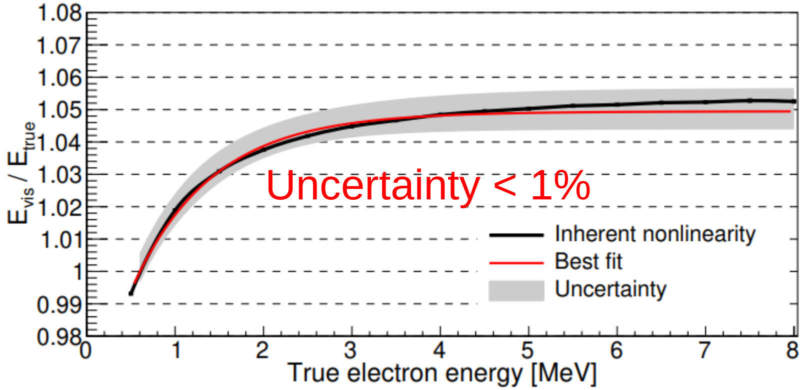
Calibration

- ➢ **1D,2D,3D scan systems with multiple calibration sources**
- ✓ **Calibrate energy scale to better than 1% using gamma peaks and cosmogenic ^{12}B beta spectrum**

All system ready for installation




JHEP 03 (2021) 004


Uncertainty < 1%

Radiopurity Control

JHEP 11 (2021) 102

Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
Acrylic	3.61	**-3.2**	10 ppt ➔ 1 ppt
Metal in node	0.087	**+1.0**	Copper ➔ SS
PMT glass	0.33	**+2.47**	Schott ➔ NNVT/Ham
Rock	0.98	**-0.85**	3.2 m ➔ 4 m
Radon in water	1.31	**-1.25**	200 mBq/m^3 ➔ 10 mBq/m^3
Other	0	**+0.52**	Add PMT readout, calibration sys.
Total	8.5	**-1.3**	

- Reduced by 15% compared to the design.
- **Good enough for reactor neutrinos**

Radiopurity control on raw material:

- ✓ Careful material screening
- ✓ Meticulous Monte Carlo Simulation
- ✓ Accurate detector production handling

Liquid Scintillator Filling

- ✓ Recirculation is impossible at JUNO due to its large size
- → Target radiopurity needs to be obtained from the beginning
- ✓ **Strategies:**

1. **Leakage** (single component < 10^{-6} mbar·L/s)
2. **Cleaning vessel** before filling
3. **Clean environment**
4. **Surface treatment of the acrylic vessel**
5. **LS filling strategy**

Expected Performance

- Background in LS can reach U/Th/K < 10^{-15} g/g for reactor ν, 10^{-17} g/g is feasible for solar ν and future 0νββ decays
- From measured PMT, LS and acrylic properties, the energy resolution will be < 3%@1 MeV, based on full simulation, calibration and reconstruction

Changes	Light yield in detector center [PEs/MeV]		Energy resolution @ 1 MeV	Reference
Design	1345		3.0%	JHEP03 (2021) 004
20-inch PMT PDE (27%→30.1%)	↑ 11%	1665	2.9%	EPJC 82 (2022) 12, 1168
New Center Detector geometries	↑ 3%			-
More realistic optical model	↑ 8%			EPJC 82 329 (2022)

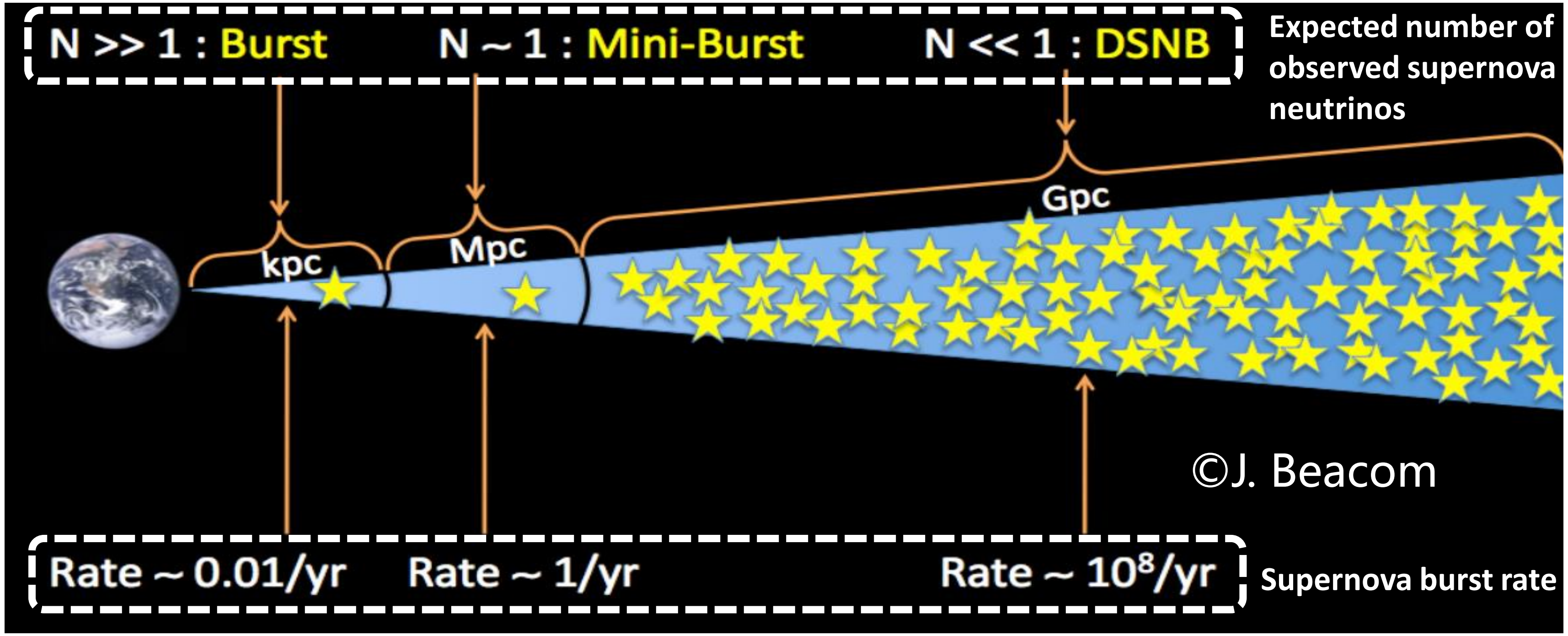
$$\frac{\sigma}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{\boldsymbol{a}}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + \boldsymbol{b}^2 + \left(\frac{\boldsymbol{c}}{E_{\mathrm{vis}}}\right)^2}$$

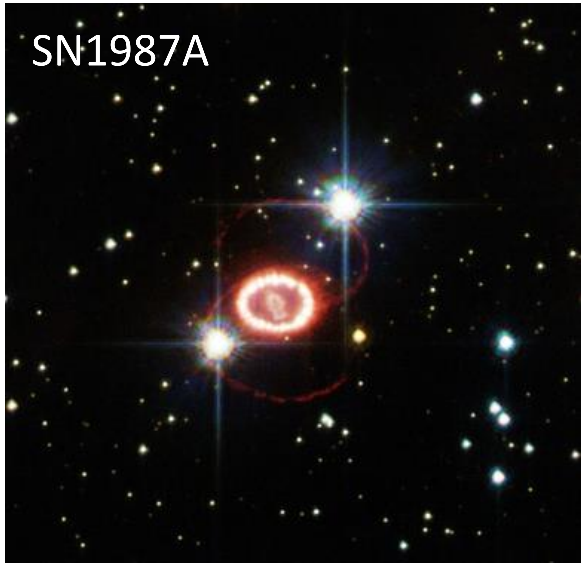
- **Photon statistics**

- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity
- **Detector uniformity and reconstruction**

- **Annihilation-induced γ's**
- **Dark noise**

Neutrinos from Supernova

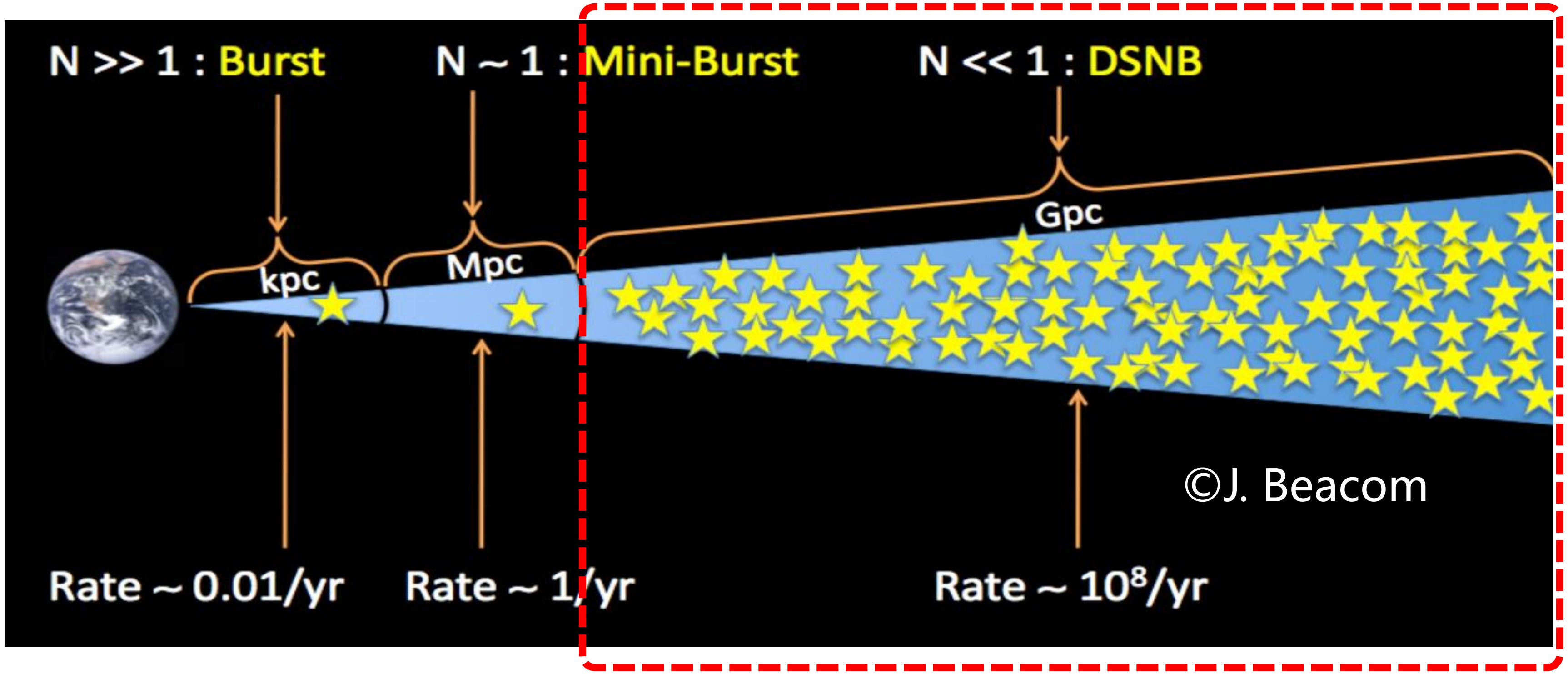




✓ **only neutrinos produced by SN1987A have been observed**

- **Supernova neutrinos**: studying the fate of stars, the evolution of the cosmos, element nucleosynthesis, 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 (1-3 / 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) 😟

Prospect on Detecting DSNB



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- ✓ **DSNB is yet to be observed**
- ✓ **Expected to achieve the first observation using large LS and Water detectors**

- holds the important information on the average core-collapse SN neutrino spectrum, the cosmic star-formation rate and the fraction of failed black-hole forming SNe.
- The probability of detecting the DSNB relies on
  - The size of detector (**JUNO**, SuperK-Gd, Hyper-K, DUNE, THEIA)
  - Background suppression

DSNB Signal Prediction

- **DSNB flux**

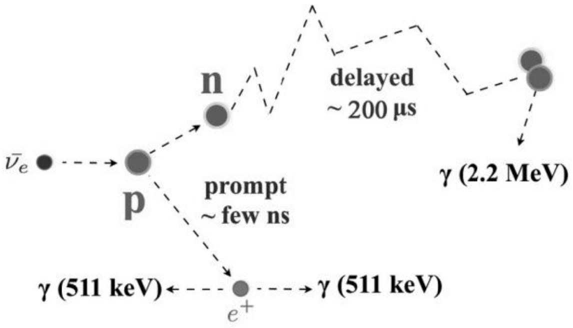
Average SN neutrino spectrum, including failed and successful SNe

$$\frac{d\phi}{dE_\nu} = \int_0^5 \boxed{R_{\mathrm{SN}}(z)} \boxed{\frac{dN\left(E'_\nu\right)}{dE'_\nu}} \boxed{(1+z)\left|\frac{cdt}{dz}\right| dz}$$

Core-collapse supernova rate at the red-shift z

Dependent on cosmic evolution

- **DSNB primary detection via inverse beta decay (IBD)**



JUNO: neutron captured on H

2-4 DSNB IBD events per year

- **DSNB prompt energy spectrum:**

Jacobian factor

Measured →
$$\frac{dS(E_{\mathrm{prompt}})}{dE_{\mathrm{prompt}}} = \boxed{N_p \times \sigma(E_\nu)} \times \boxed{J(E_\nu)} \times \frac{d\phi}{dE}(E_\nu)$$
→ DSNB flux

Detector capabilities

DSNB Signal Prediction

- **DSNB flux**

Average SN neutrino spectrum, including failed and successful SNe

$$\frac{d\phi}{dE_\nu} = \int_0^5 \boxed{R_{\rm SN}(z)} \boxed{\frac{dN(E'_\nu)}{dE'_\nu}} \boxed{(1+z)\left|\frac{cdt}{dz}\right| dz}$$

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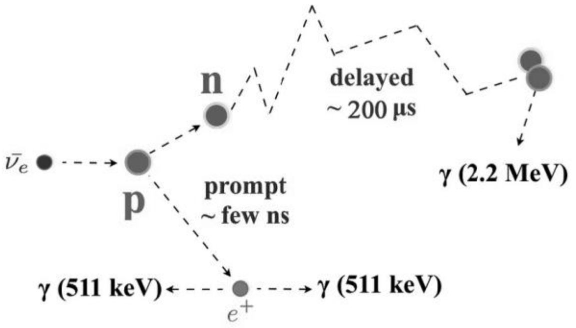

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$$\text{Measured} \rightarrow \frac{dS(E_{\rm prompt})}{dE_{\rm prompt}} = \boxed{N_p \times \sigma(E_\nu)} \times \boxed{J(E_\nu)} \times \frac{d\phi}{dE}(E_\nu) \rightarrow \text{DSNB flux}$$

Detector capabilities

There Key (unknown) parameters:

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

⇩

- **A reference set :**
  - $\langle E_\nu \rangle = 15\ \mathrm{MeV}$
  - $f_{BH} = 0.27$
  - $R_{SN}(0) = 1.0 \times 10^{-4} \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}$

⇩

Scan of a broader parameter region for sensitivity study

DSNB Signal Prediction

- **DSNB flux**

Average SN neutrino spectrum, including failed and successful SNe

$$\frac{d\phi}{dE_\nu} = \int_0^5 \boxed{R_{\rm SN}(z)}\,\boxed{\frac{dN(E'_\nu)}{dE'_\nu}}\,\boxed{(1+z)\left|\frac{cdt}{dz}\right| dz}$$

Core-collapse supernova rate at the red-shift z

Dependent on cosmic evolution

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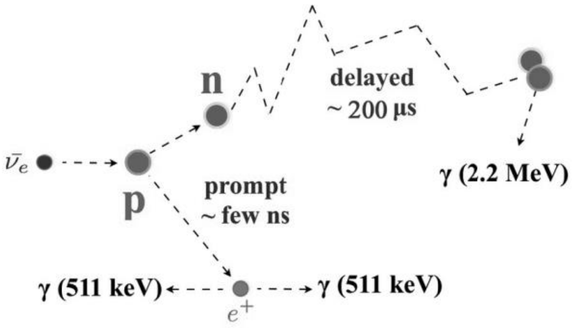

JUNO: neutron captured on H

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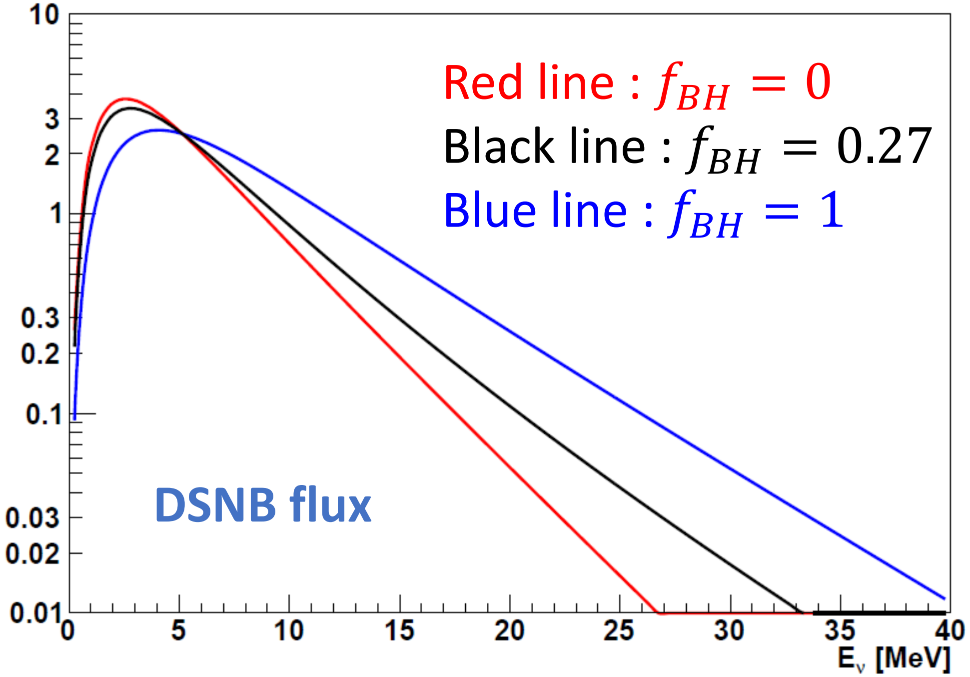


- **DSNB prompt energy spectrum:**

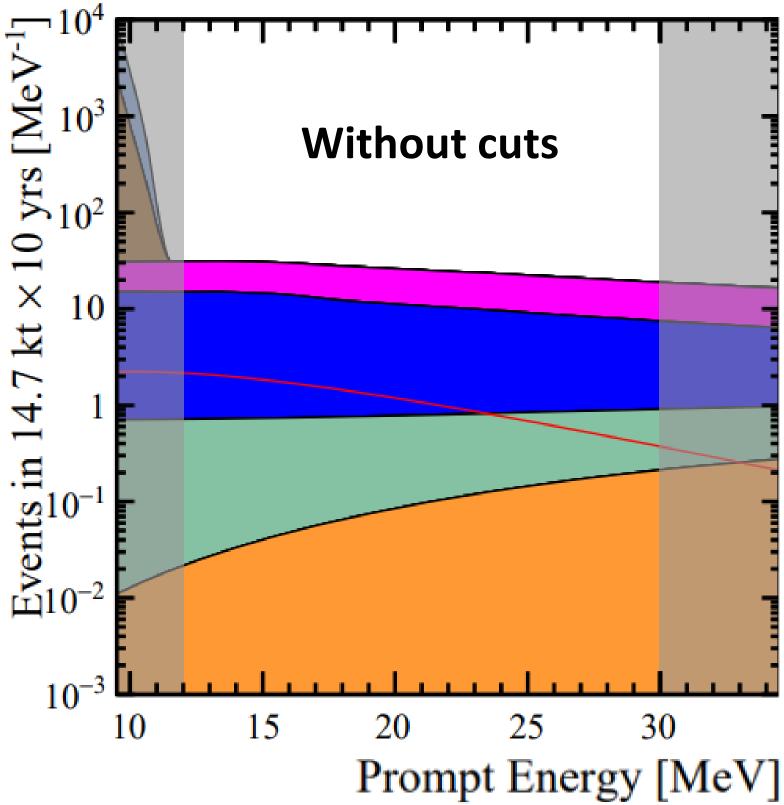
Jacobian factor

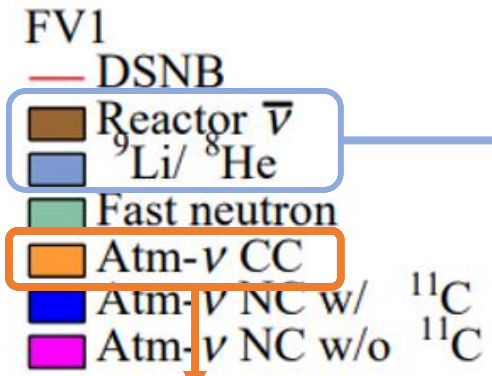
$$\text{Measured} \longrightarrow \frac{dS(E_{\rm prompt})}{dE_{\rm prompt}} = \boxed{N_p \times \sigma(E_\nu)} \times \boxed{J(E_\nu)} \times \frac{d\phi}{dE}(E_\nu) \longrightarrow \text{DSNB flux}$$

Detector capabilities

DSNB Observation Window

JUNO, *JCAP 10 (2022) 033*



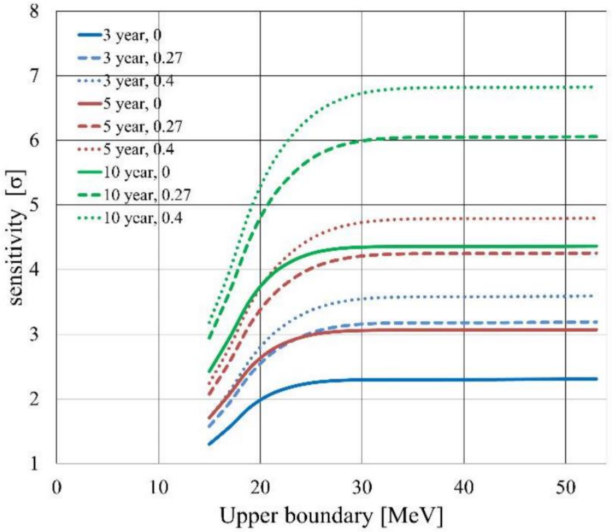


Low energy range (< 12 MeV):

- ▶ Main background: reactor $\bar{\nu}_e$ and cosmogenic ^{9}Li/^{8}He isotope
- ▶ lower limit of the DSNB observation window is set at 12 MeV, so these two backgrounds can be ignored.

High energy range (> 30 MeV):

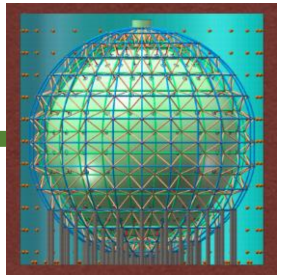
- ▶ Event rate of atm-ν charged current (CC) $\bar{\nu}_e$ IBD increases with energy➔ upper the observation of DSNB
- ▶ Studying impact of the different upper limits on the sensitivity to DSNB➔ upper limit: 30 MeV



- DSNB observation window [12, 30] MeV, **main residual backgrounds:**
  - **Fast neutron background**
  - **Atmospheric neutrino neutral current (NC) background**

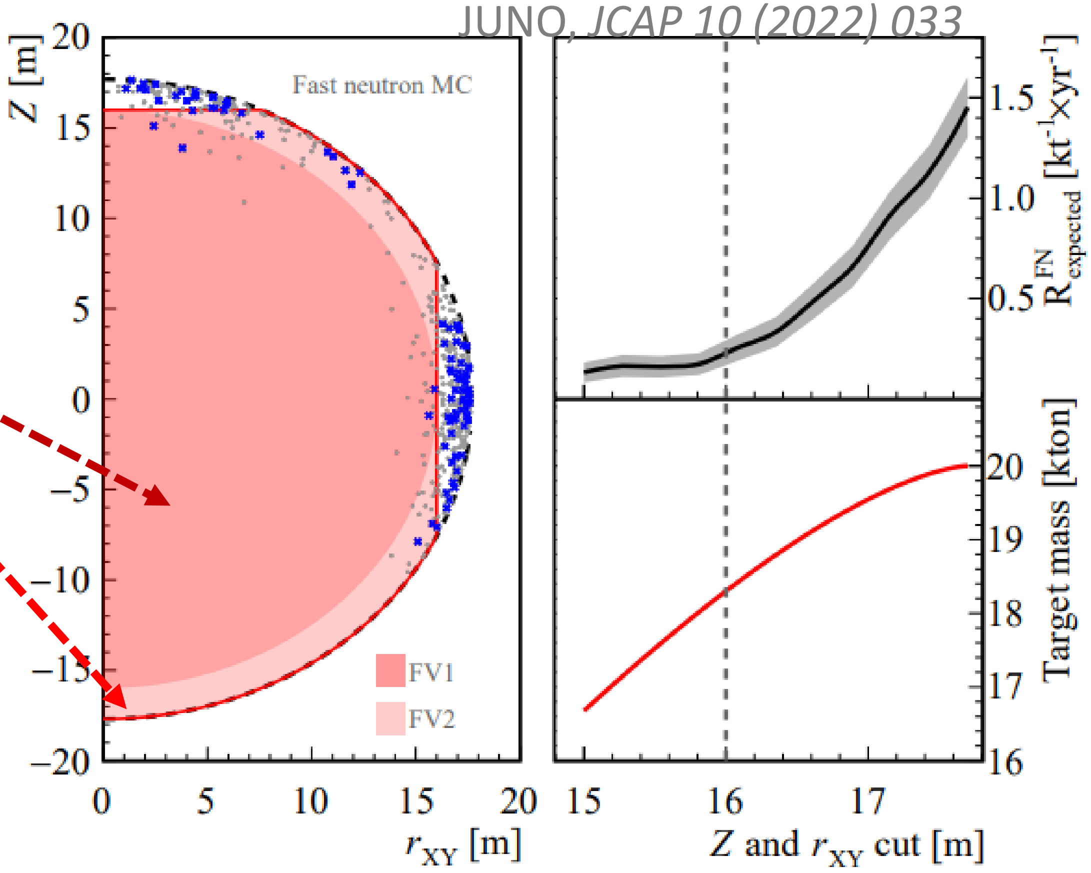
Fast Neutron Background

- **Detection efficiencies of cosmic muons in JUNO LS and Water detectors: ~100% and 99.5%, respectively**
- **Fast neutrons:** from muons that only pass through the rock surrounding the detector
  - Because of water shielding, most of fast neutrons distributed at equator and top of the LS
  - approximately flat visible energy spectrum



Use fiducial volume cut to remove most of fast neutron backgrounds

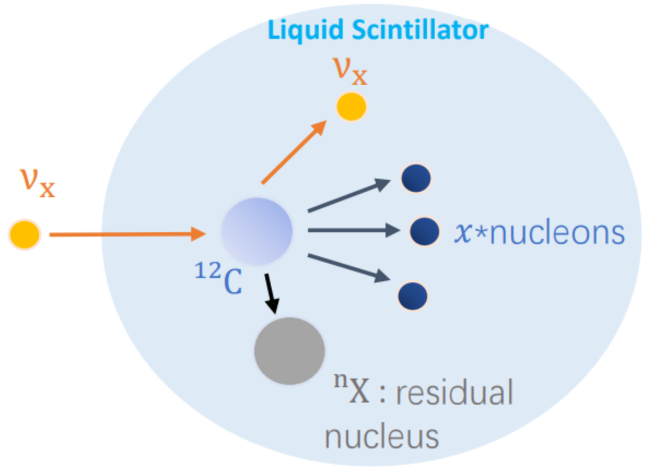
- Two fiducial volumes: **FV1** and **FV2**
- FV1 (inner region): R≡ $\sqrt{X^2+Y^2+Z^2}$<16m (14.7 kt)
- FV2 (outer region): R>16m, Z and $r_{XY}=\sqrt{X^2+Y^2}<$ 16m (3.6 kt)
- Background suppression strategies are different in FV1 and FV2

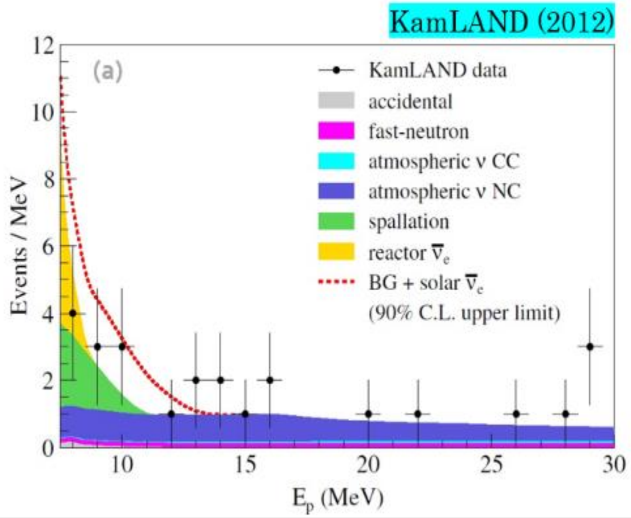


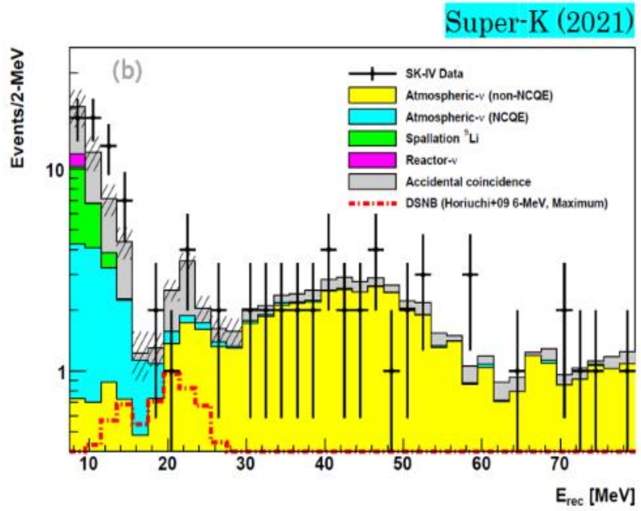
JUNO, *JCAP 10 (2022) 033*

Atm-ν NC Background

- ☐ **NC interactions of atm. neutrino with ^{12}C in LS: the most significant background source in the DSNB study**

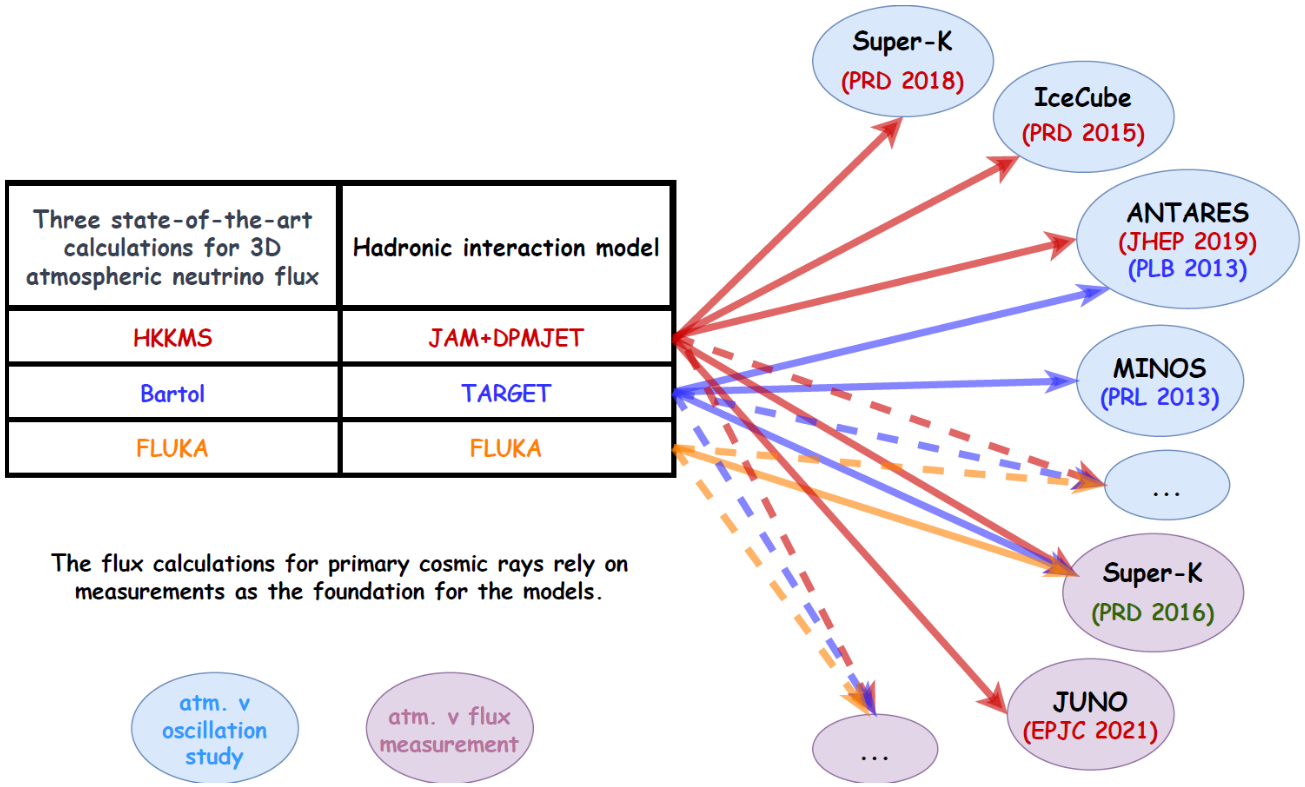






Analysis work	Highlights	reference
Flux calculation	Optimization of low energy range, based on Honda flux calculation	Paper in preparation
Model prediction	ν-^{12}C interaction (GENIE, NuWro) + residual nucleus deexcitation (TALYS)	Phys. Rev. D 103 (2021) 5, 053001 arXiv 2404.07429
Uncertainty estimation	*in-situ* measurement (~15% @ 10 yrs JUNO data)	Phys. Rev. D 103 (2021) 5, 053002
Background suppression	Pulse shape discrimination (PSD) & triple coincidence (TC) cut (^{11}C delayed decay)	Eur. Phys. J. C 84 (2024) 5, 482

Atm-ν Flux



Three state-of-the-art calculations for 3D atmospheric neutrino flux	Hadronic interaction model
HKKMS	JAM+DPMJET
Bartol	TARGET
FLUKA	FLUKA

Super-K (PRD 2018)

IceCube (PRD 2015)

ANTARES (JHEP 2019) (PLB 2013)

MINOS (PRL 2013)

…

Super-K (PRD 2016)

JUNO (EPJC 2021)

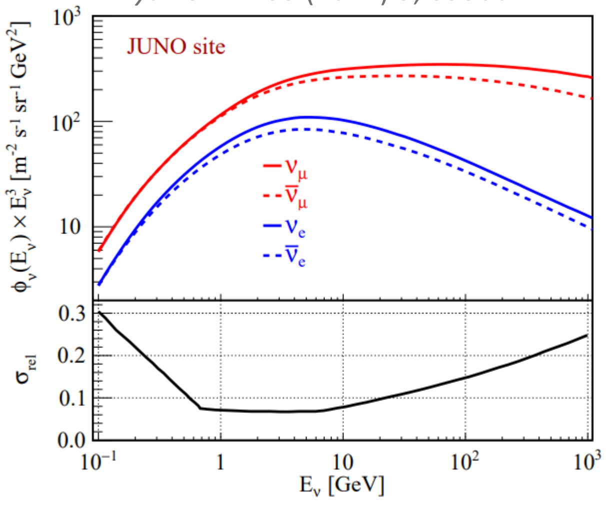
…

The flux calculations for primary cosmic rays rely on measurements as the foundation for the models.

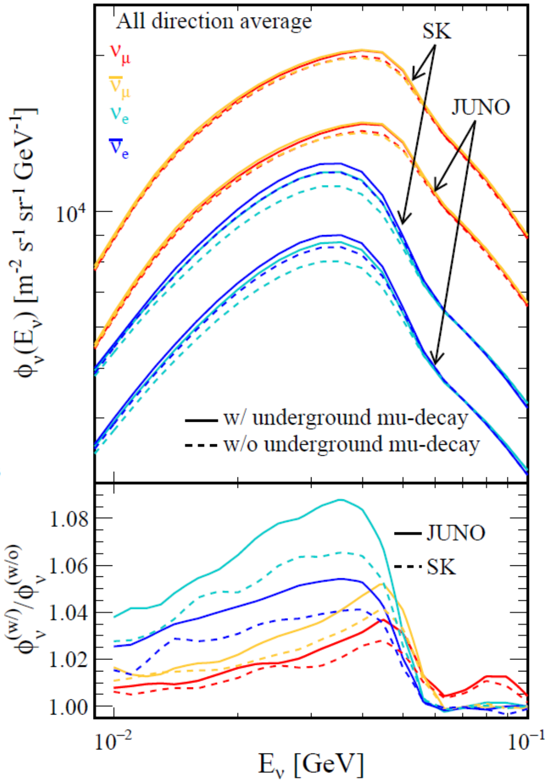
atm. ν oscillation study

atm. ν flux measurement

Phys.Rev.D 103 (2021) 5, 053001



Curtesy of the Honda Group



Jie Cheng@WANP2022

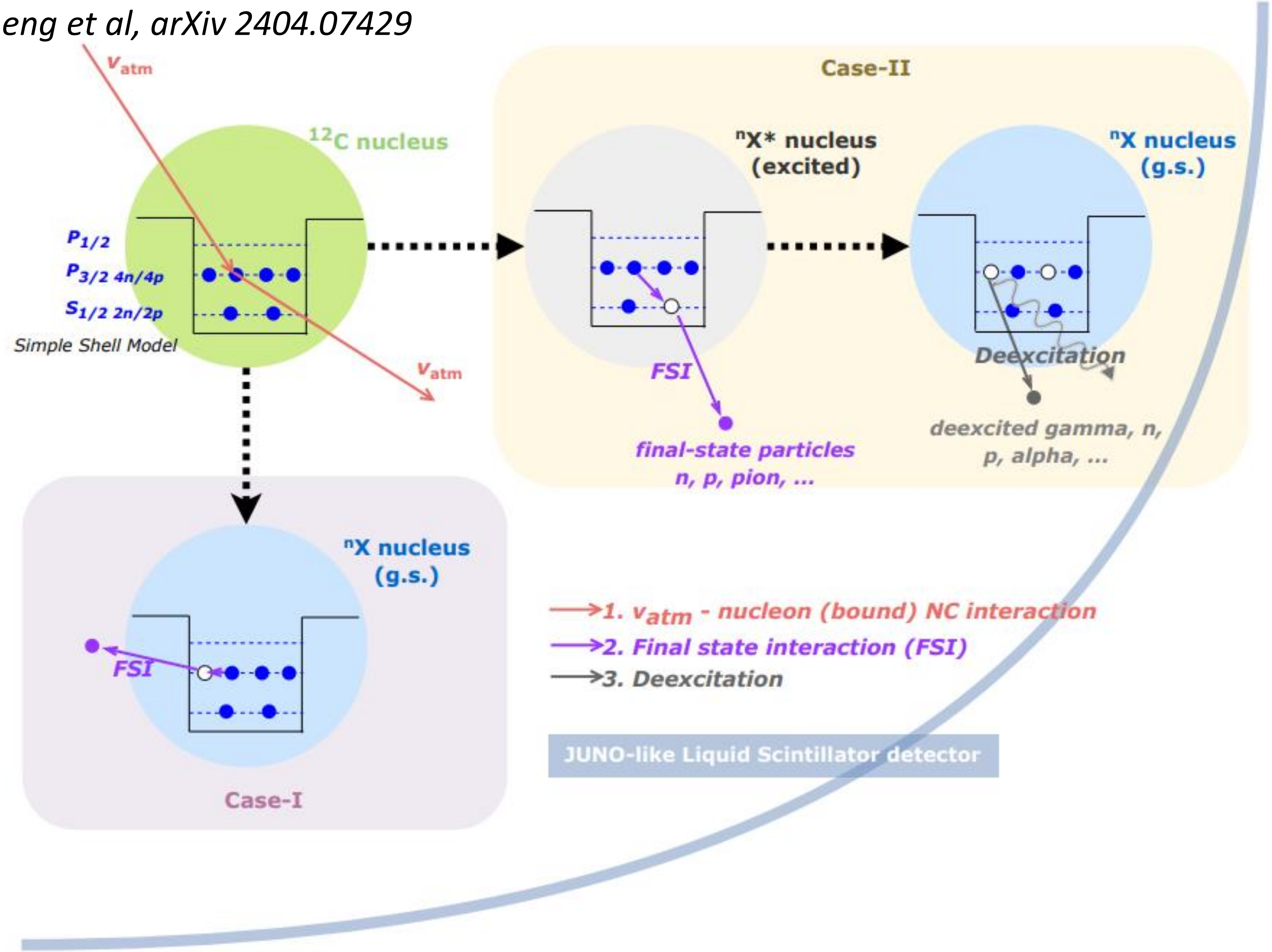
Sato Kazufumi@Neutrino2022

- **HKKMS atmospheric neutrino flux model for JUNO**
- **Flux calculation developed from 10 MeV to 100 GeV**

Methodology for Atm-ν and ^{12}C Interaction Prediction

Cheng et al, Phys. Rev. D 103. 05001 (2021)

Cheng et al, arXiv 2404.07429



Methodology for Atm-ν and ^{12}C Interaction Prediction

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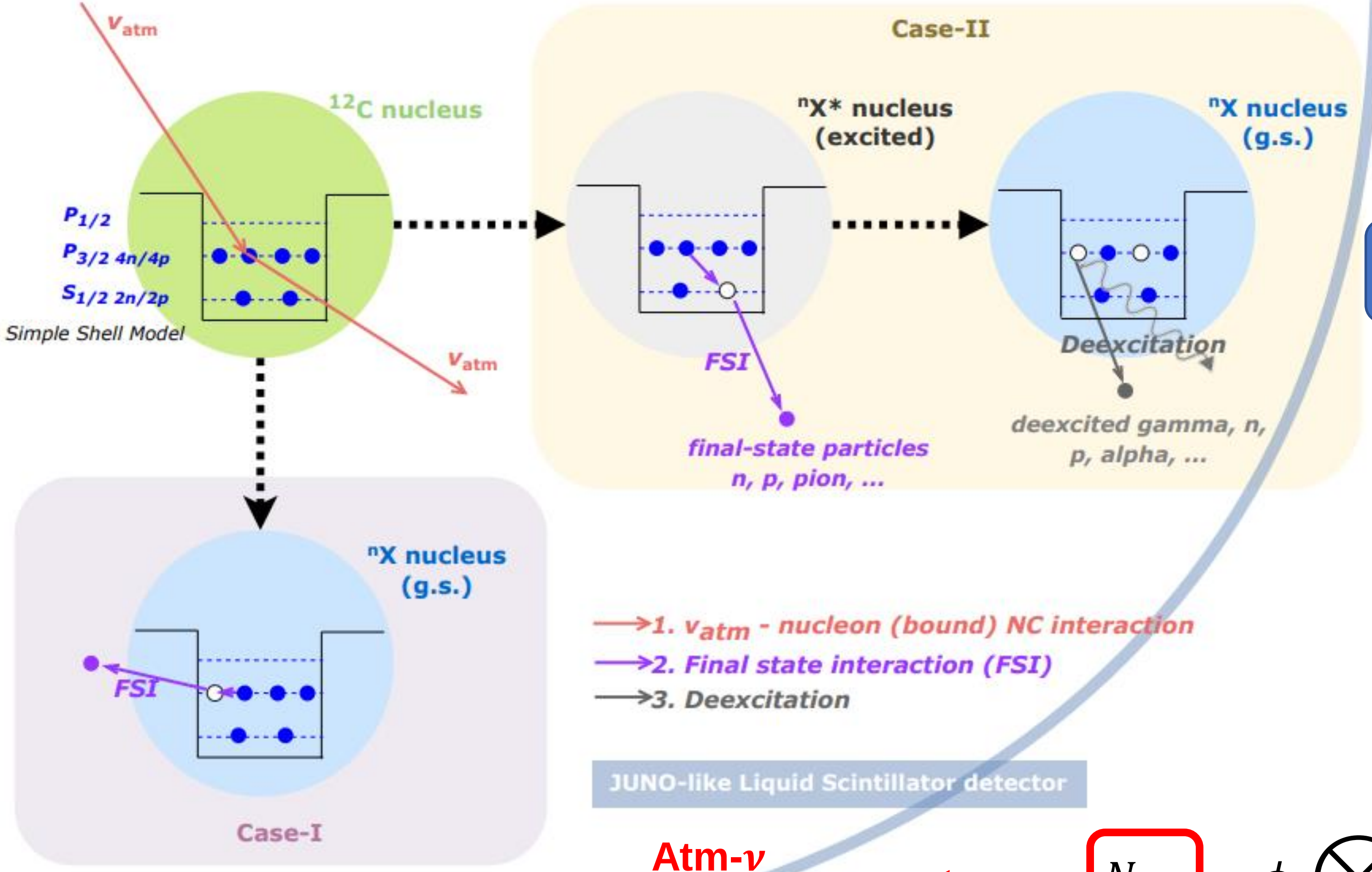
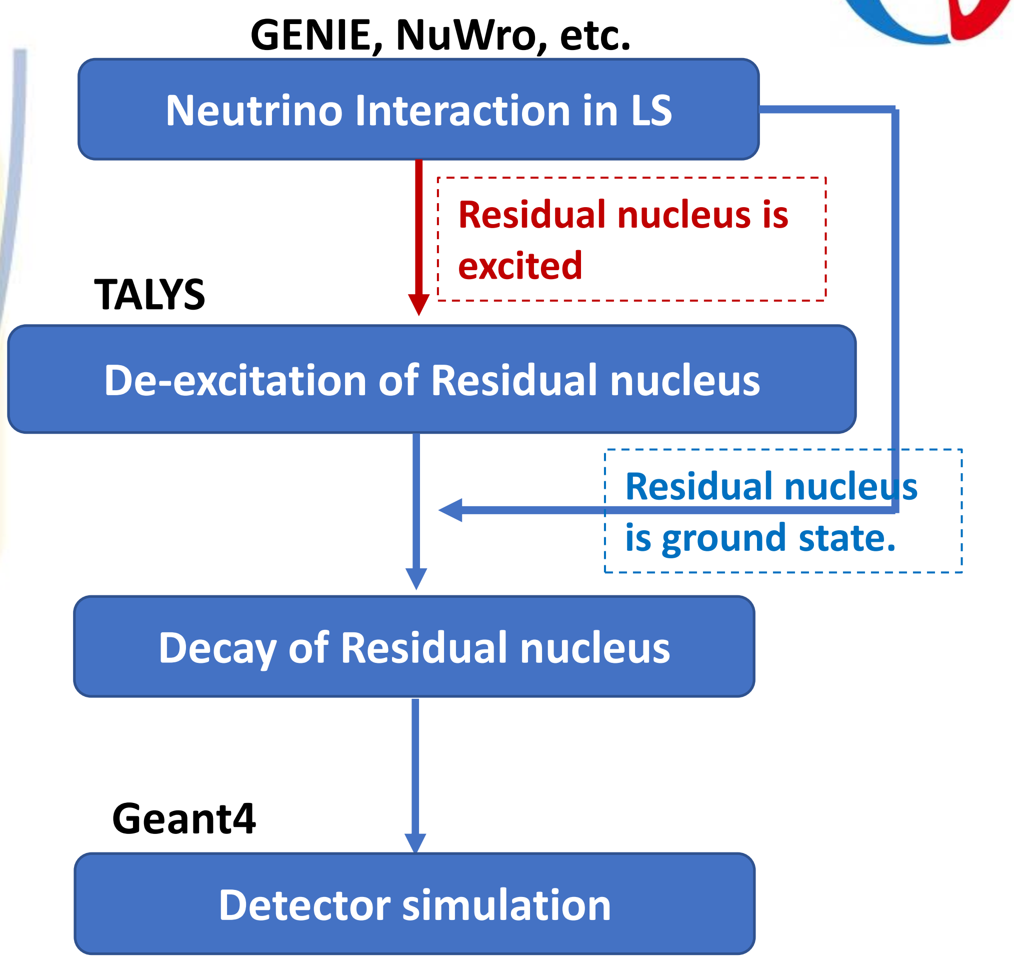




GENIE, NuWro, etc.

Neutrino Interaction in LS

Residual nucleus is excited

TALYS

De-excitation of Residual nucleus

Residual nucleus is ground state.

Decay of Residual nucleus

Geant4

Detector simulation

Atm-ν measurement

$$\boxed{N_{det}} = \phi \otimes P \otimes \sigma \otimes \epsilon$$

Neutrino flux

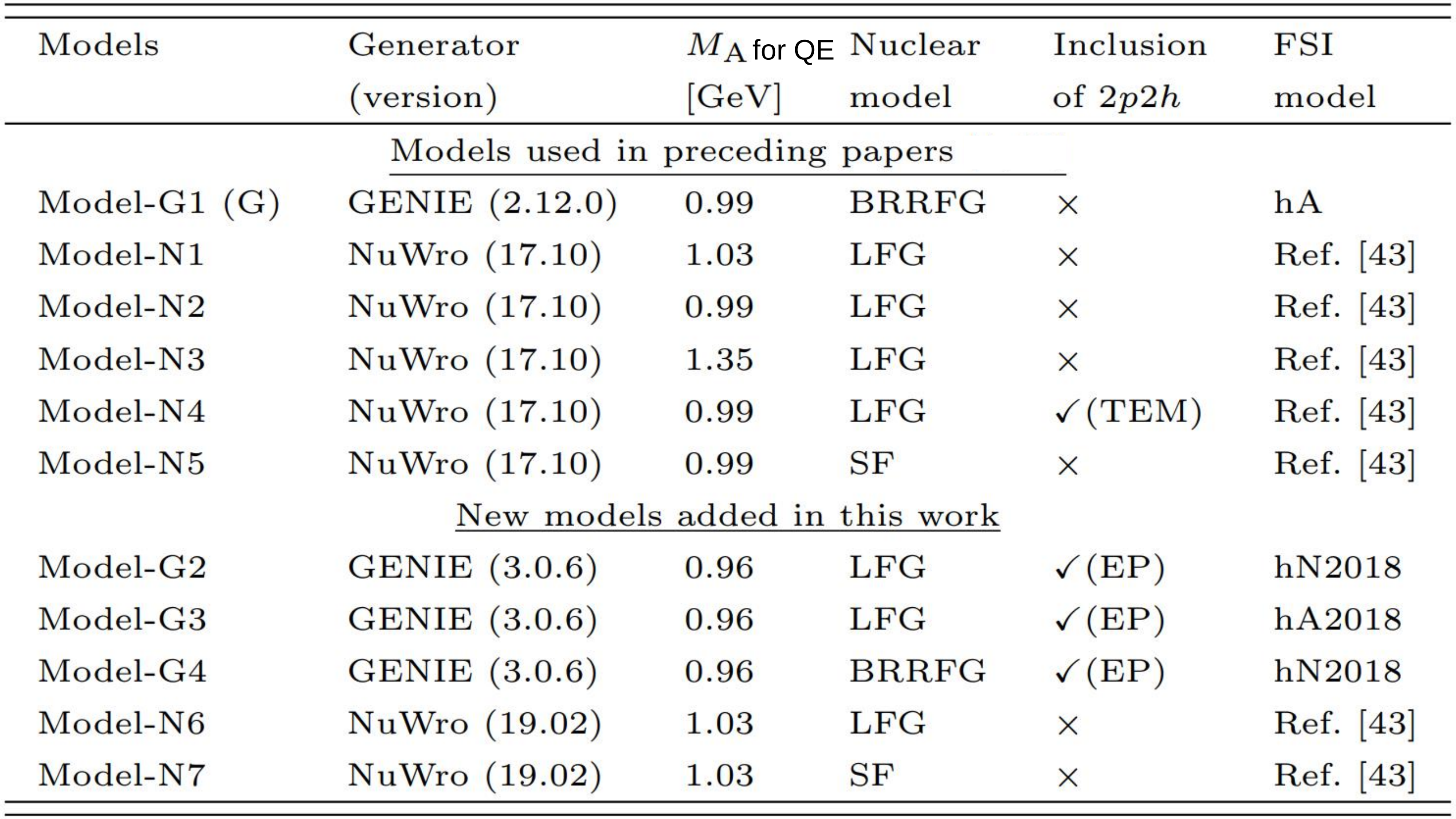
Oscillation probability

Cross section of $\nu_x + {}^{12}$C

Detector efficiency

Neutrino Generator Models

Summary of the main features of models used in early and recent stages



Models	Generator (version)	M_A for QE [GeV]	Nuclear model	Inclusion of $2p2h$	FSI model
		Models used in preceding papers			
Model-G1 (G)	GENIE (2.12.0)	0.99	BRRFG	×	hA
Model-N1	NuWro (17.10)	1.03	LFG	×	Ref. [43]
Model-N2	NuWro (17.10)	0.99	LFG	×	Ref. [43]
Model-N3	NuWro (17.10)	1.35	LFG	×	Ref. [43]
Model-N4	NuWro (17.10)	0.99	LFG	✓(TEM)	Ref. [43]
Model-N5	NuWro (17.10)	0.99	SF	×	Ref. [43]
		New models added in this work			
Model-G2	GENIE (3.0.6)	0.96	LFG	✓(EP)	hN2018
Model-G3	GENIE (3.0.6)	0.96	LFG	✓(EP)	hA2018
Model-G4	GENIE (3.0.6)	0.96	BRRFG	✓(EP)	hN2018
Model-N6	NuWro (19.02)	1.03	LFG	×	Ref. [43]
Model-N7	NuWro (19.02)	1.03	SF	×	Ref. [43]

BRRFG: relativistic Fermi gas model with "Bodek-Ritchie" modifications

LFG: local Fermi gas model

SF: spectral function

0.99 GeV: deuterium measurements

1.35 GeV: MiniBooNE neutrino QE data

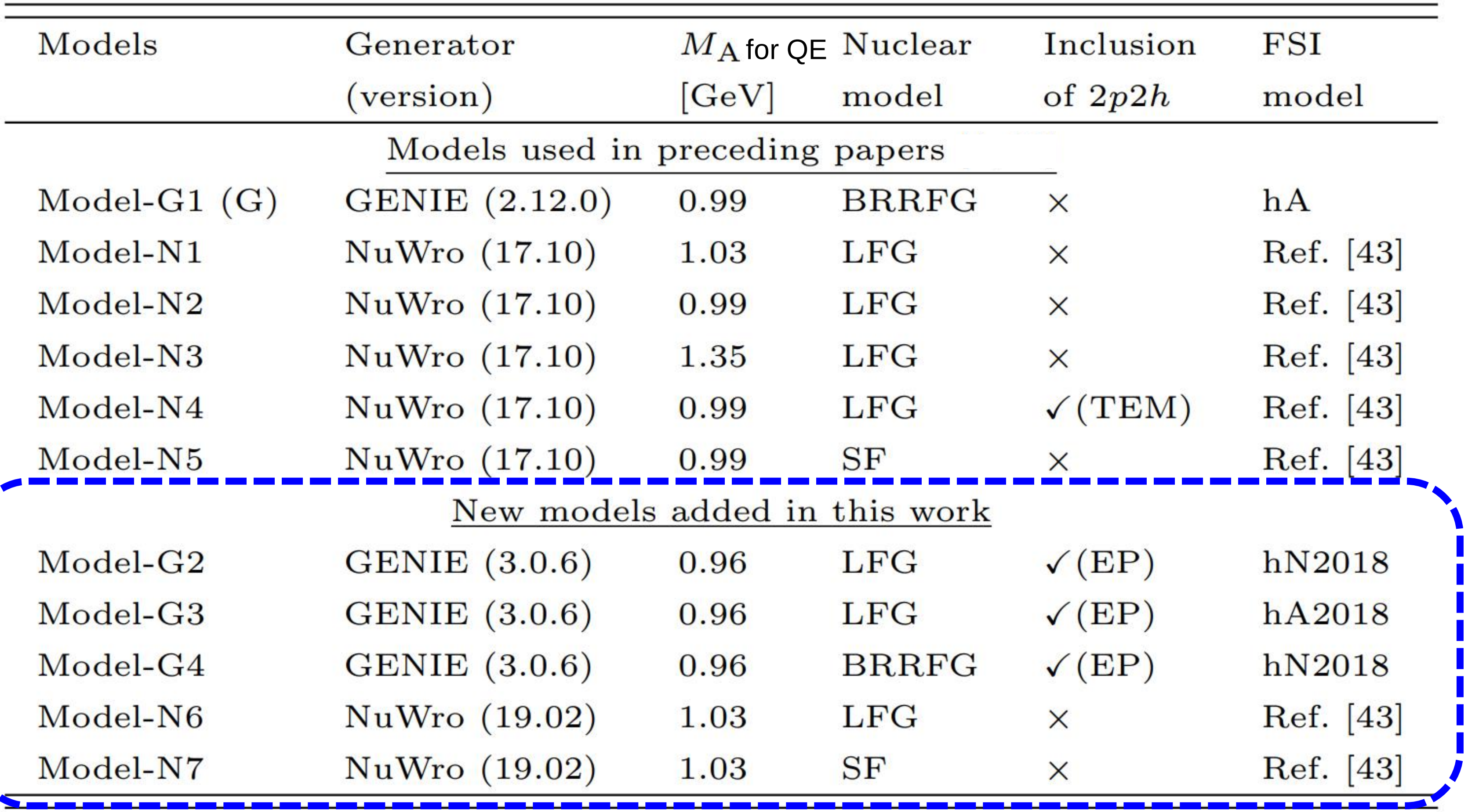
TEM: Transverse Enhancement model for *2p2h*

EP: Empirical model for *2p2h*

Ref.[43]: Phys. Rev. D 79, 053003 (2009)

Neutrino Generator Models

Summary of the main features of models used in early and recent stages



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Model-N6	NuWro (19.02)	1.03	LFG	×	Ref. [43]
Model-N7	NuWro (19.02)	1.03	SF	×	Ref. [43]

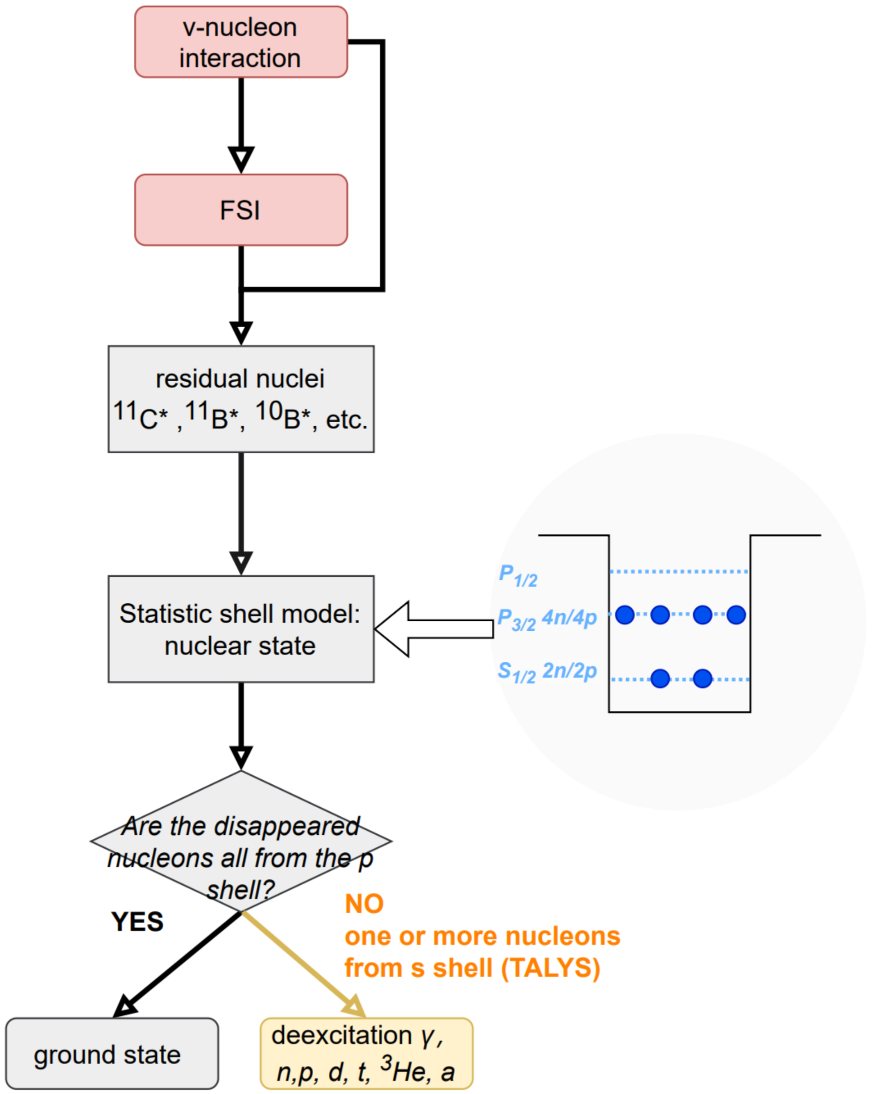
Validated with MINERvA data

https://zenodo.org/records/6774990

- Investigate the impact of different generators, nuclear model, FSI models on the prediction

- All processes are included, new models primarily focus on variations related to QE and do not fully explore variations related to RES, COH, and DIS
- Plan to include GiBUU and NEUT in our calculation

TALYS-based Deexcitation Model of Residual Nucleus



ν-nucleon interaction

FSI

residual nuclei $^{11}C^*$, $^{11}B^*$, $^{10}B^*$, etc.

Statistic shell model: nuclear state

Are the disappeared nucleons all from the p shell?

YES

NO
one or more nucleons from s shell (TALYS)

ground state

deexcitation γ, n,p, d, t, ^{3}He, a

1. Simple shell model → Status of the residual nuclei

Phys. Rev. D 67 (2003) 076007

- All residual nuclei with A>5 have been considered
- Go beyond simple shell model
  - ✓ considering the correlation between P shell ($P_{1/2}$ and $P_{3/2}$)
  - ✓ will be adopted in our calculation

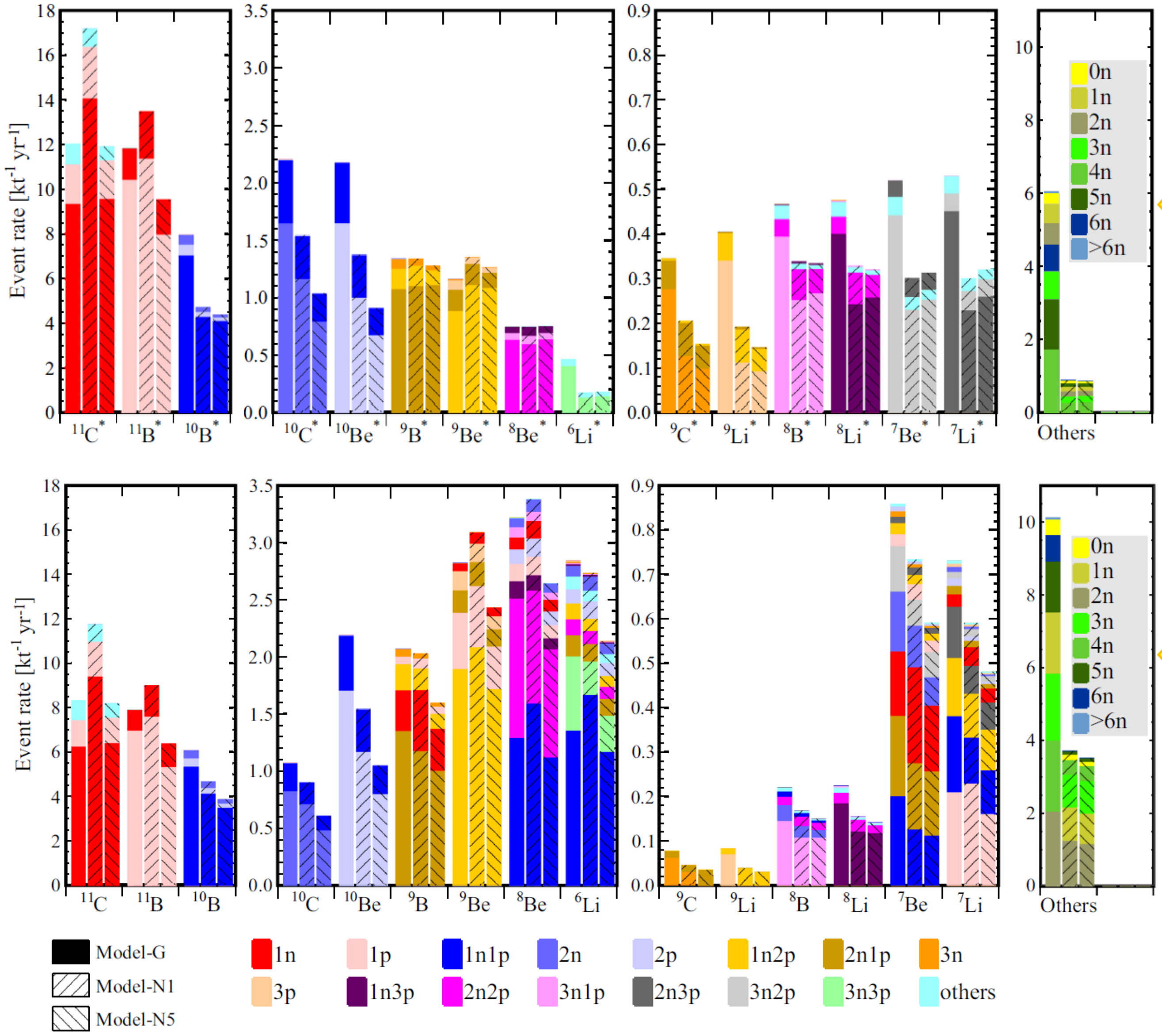
2. TALYS → Simulate residual nucleus at certain high excited energy

Reaction channels	Fraction [%]
$^{11}C^* \to \gamma +$ (E^*= 23 MeV : 1/3)	
$p + d + {}^8Be$	20
$p + \alpha + {}^6Li$	20
$p + {}^{10}B$	17
$2p + {}^9Be$	14
$d + {}^9B$	11
$n + {}^{10}C$	5
$n + p + {}^9B$	5
$\alpha + {}^7Be$	4
${}^3He + {}^8Be$	3
others	1

Reaction channels	Fraction [%]
$^{11}B^* \to \gamma +$ (E^*= 23 MeV : 1/3)	
$n + {}^{10}B$	23
$n + \alpha + {}^6Li$	17
$n + d + {}^8Be$	15
$d + {}^9Be$	14
$n + p + {}^9Be$	11
$p + {}^{10}Be$	8
$\alpha + {}^7Li$	6
$t + {}^8Be$	4
$2n + {}^9B$	2
others	<1

Impact of Deexcitation on Final-state Production

Cheng et al, Phys. Rev. D 103. 05001 (2021)



Before deexcitation, ^{11}C, ^{11}B, ^{10}B **dominated**

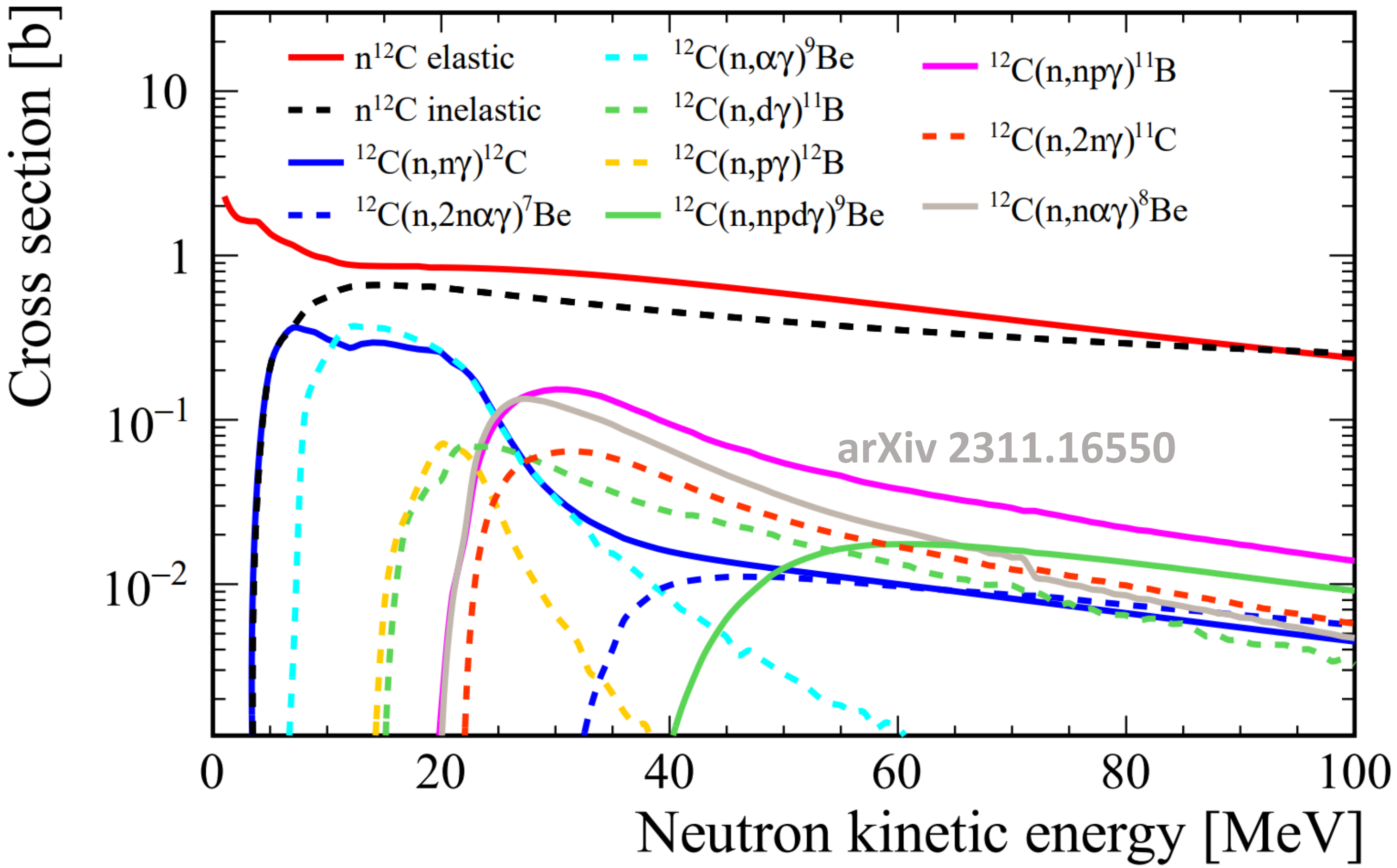
After deexcitation , ^{11}C, ^{11}B, ^{10}B **reduced, with more lighter nuclei**

Exclusive final-state information, such as the neutron multiplicity, the charge pion multiplicity, the unstable nuclei, is important for tagging and reducing the background

Geant4-based Detector Simulation

- ☐ **GEANT4 (4.10.p02)➔ simulate the propagation of final-state particles in LS**
- ☐ **Hadronic models: QGSP_BERT_HP**
- ☐ **Considering decay processes of unstable isotopes after deexcitation stage in detector simulation**
  - **➔ Important for *in-situ* measurement**
- ☐ **Secondary interactions (SI): final-state particles produced by a primary interaction, subsequently interact within the LS**
- ☐ **Neutron tagging takes place after the SI**

Tagged neutrons ≠ final-state neutrons

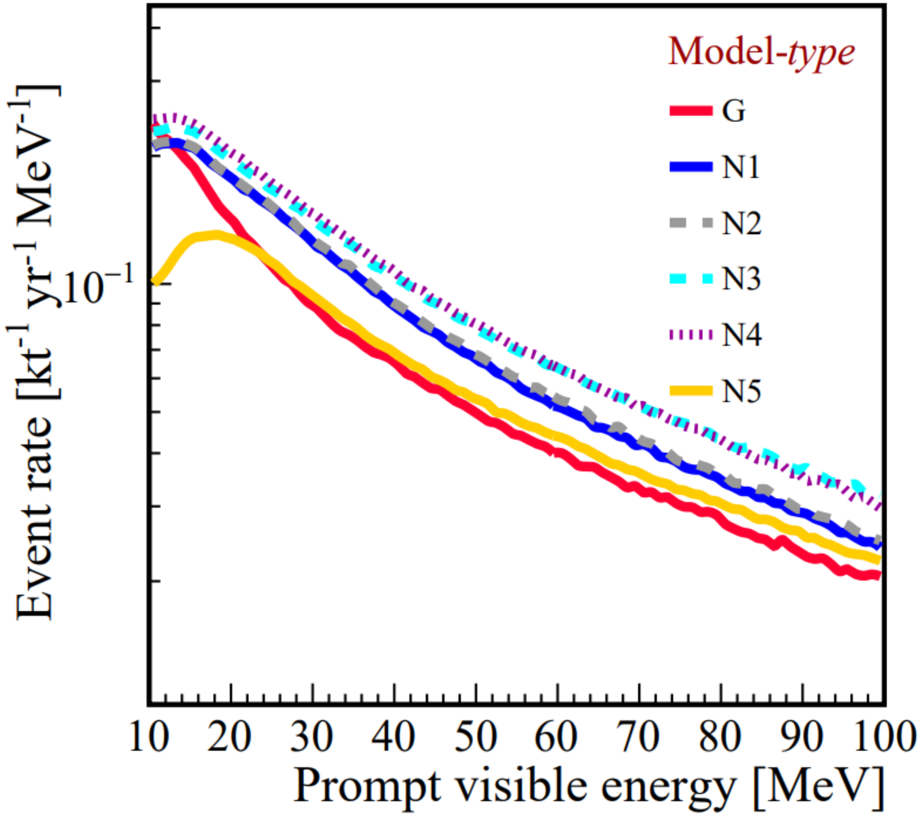


arXiv 2311.16550

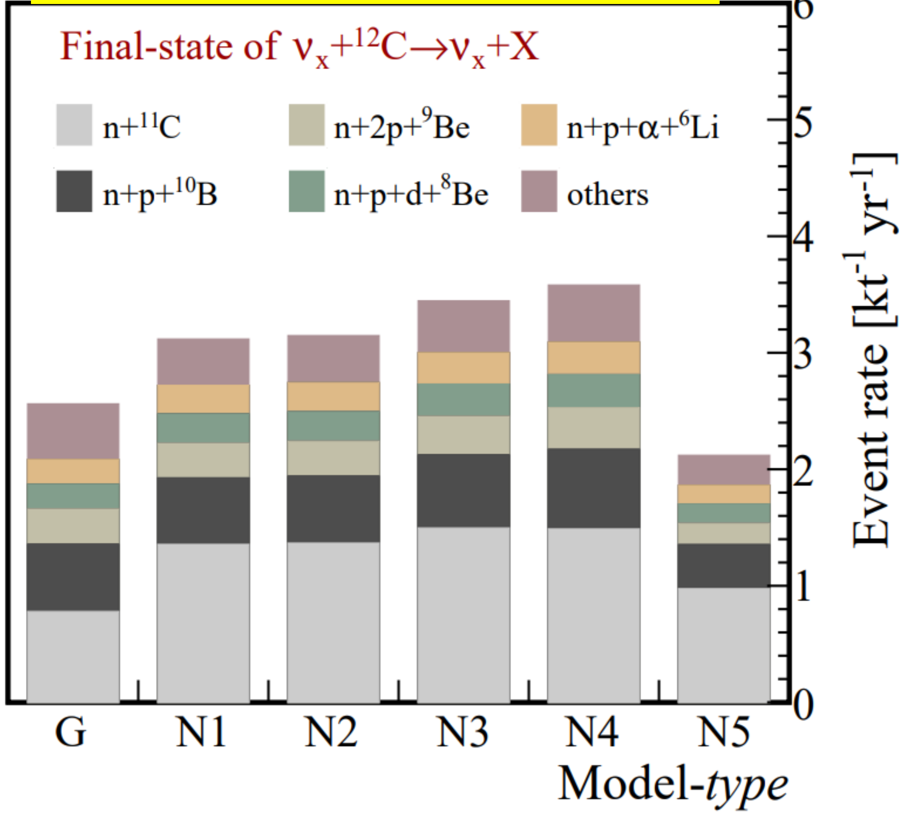
Extracted from the results of TALYS

IBD-like NC Background

JUNO, *JCAP 10 (2022) 033*



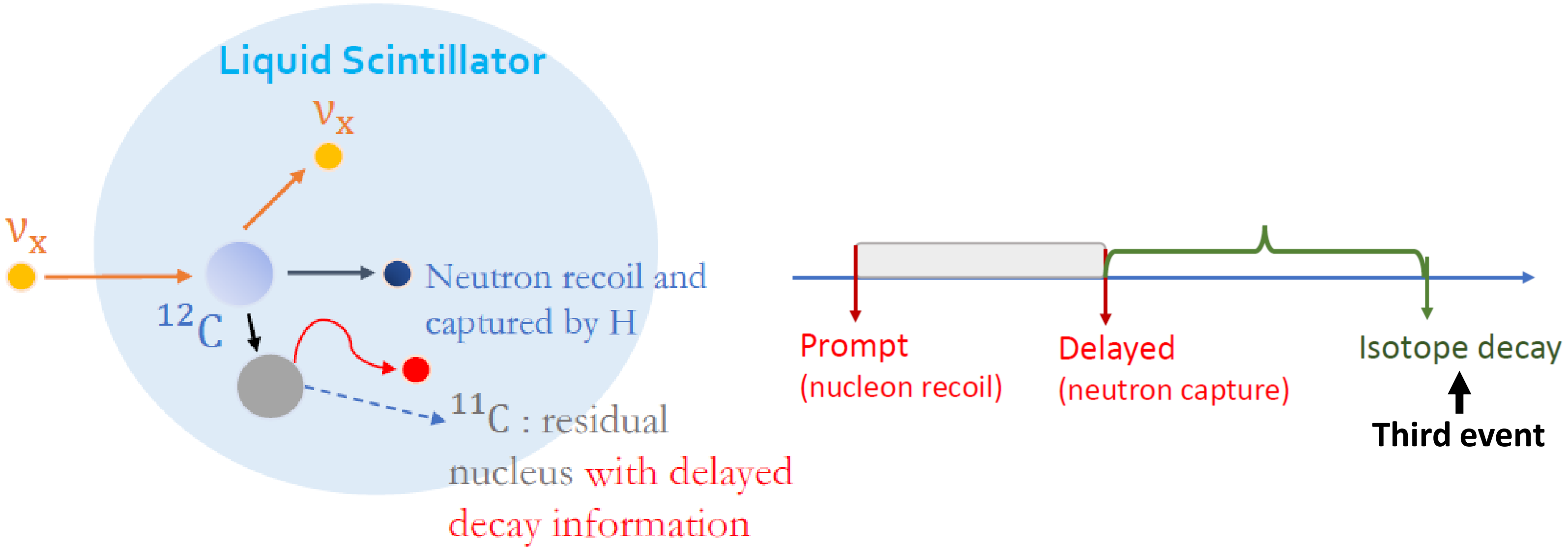
Dominant channels in [12, 30] MeV



- **Energy spectra of IBD-like events.** Average of six model calculations as the prediction and combination of the flux uncertainty and model variations as the total uncertainty → (3.0 ± 0.5) kt^{-1} yr^{-1} within [12, 30] MeV
- **Exclusive final-state information of these IBD-like events**
  - **Important for *in situ* measurement, PSD and TC cut**

In situ Measurement

Phys. Rev. D 103 (2021) 5, 053002



Liquid Scintillator

ν_x

ν_x

^{12}C

Neutron recoil and captured by H

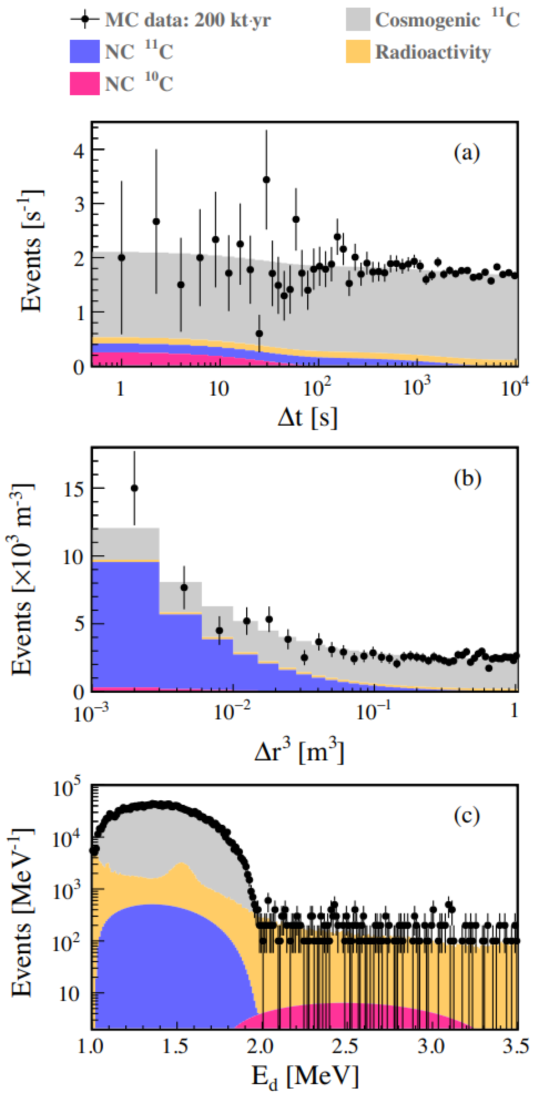
^{11}C : residual nucleus with delayed decay information

Prompt
(nucleon recoil)

Delayed
(neutron capture)

Isotope decay

Third event



- Model variations

  ➔ ~20%

- Dominant channel:

  $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + n + {}^{11}\mathrm{C}$ (triple-coincident signature)

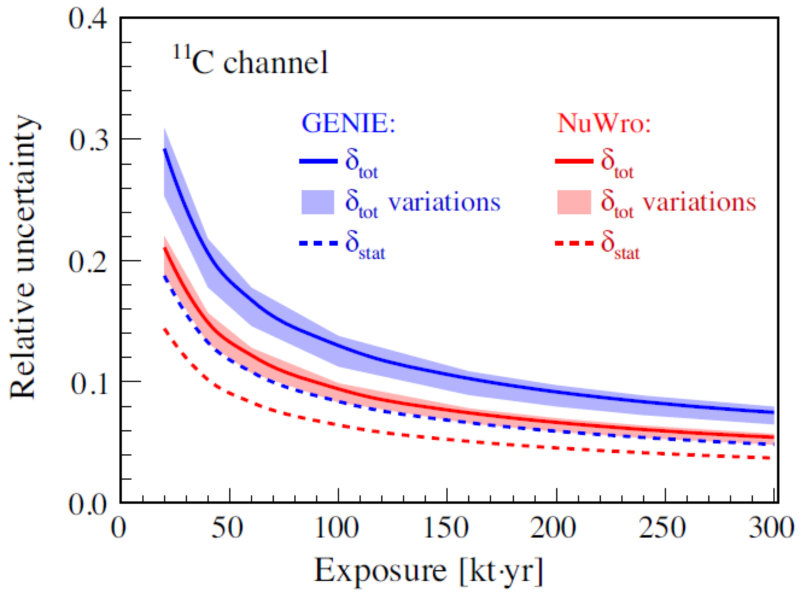
- A maximum-likelihood method ➔ a combine fit to the time interval between the prompt and third events (a), cubic distance between the prompt and third events (b), and energy of the third event (c)

  ➔ A systematic study on the measurement of the NC background and evaluation of the associated uncertainties

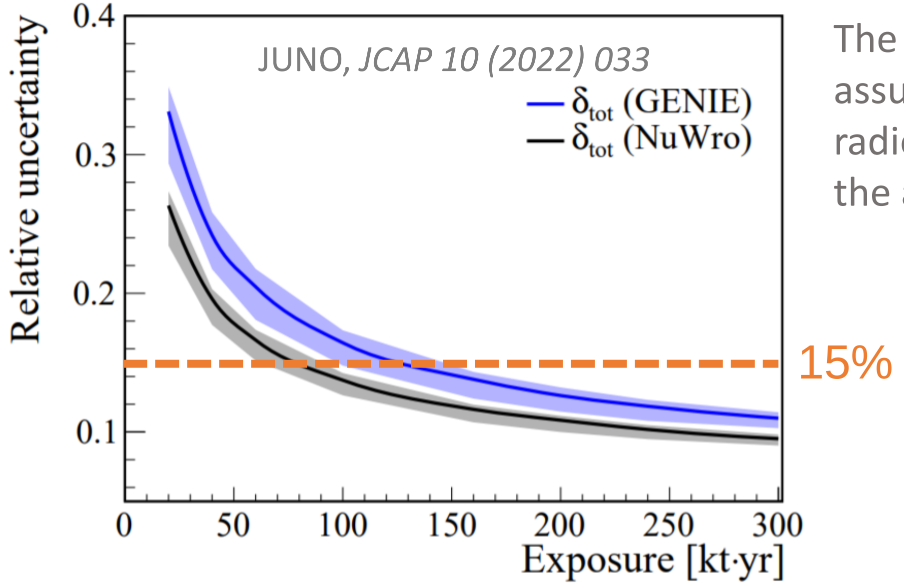
Uncertainty Estimation via *In situ* Measurement

Phys. Rev. D 103 (2021) 5, 053002

- The uncertainty for the NC background for DSNB is evaluated
- Future JUNO will be able to make a unique contribution to the worldwide dataset to improve the prediction of NC interaction on ^{12}C



Reproduce NC background uncertainty from the summary in Phys.Rev.D 103 (2021) 5, 053002



The bands are obtained by assuming different levels of natural radioactivity and cosmogenic ^{11}C in the accidental background

Exposure	1-3 years	4-9 years	10-20 years
NC background uncertainty	35%	25%	15%

- Within 10 years JUNO data, NC background rate can be constrained on 15% level

Pulse Shape Discrimination (PSD)

- The S/B ratio in DSNB study is about 0.05 without cuts
- Pulse shape discrimination (PSD): a powerful tool to significantly suppress atmospheric NC backgrounds and fast neutron backgrounds
  - → Because the component of the prompt signal: different

- In LS, fluorescence time profile: characterized by typical decay time constants
- Probability of photon emission time: weighted sums of exponential functions of several components
- Time profiles of different kinds of particles: different
  - → Foundation of the PSD technique

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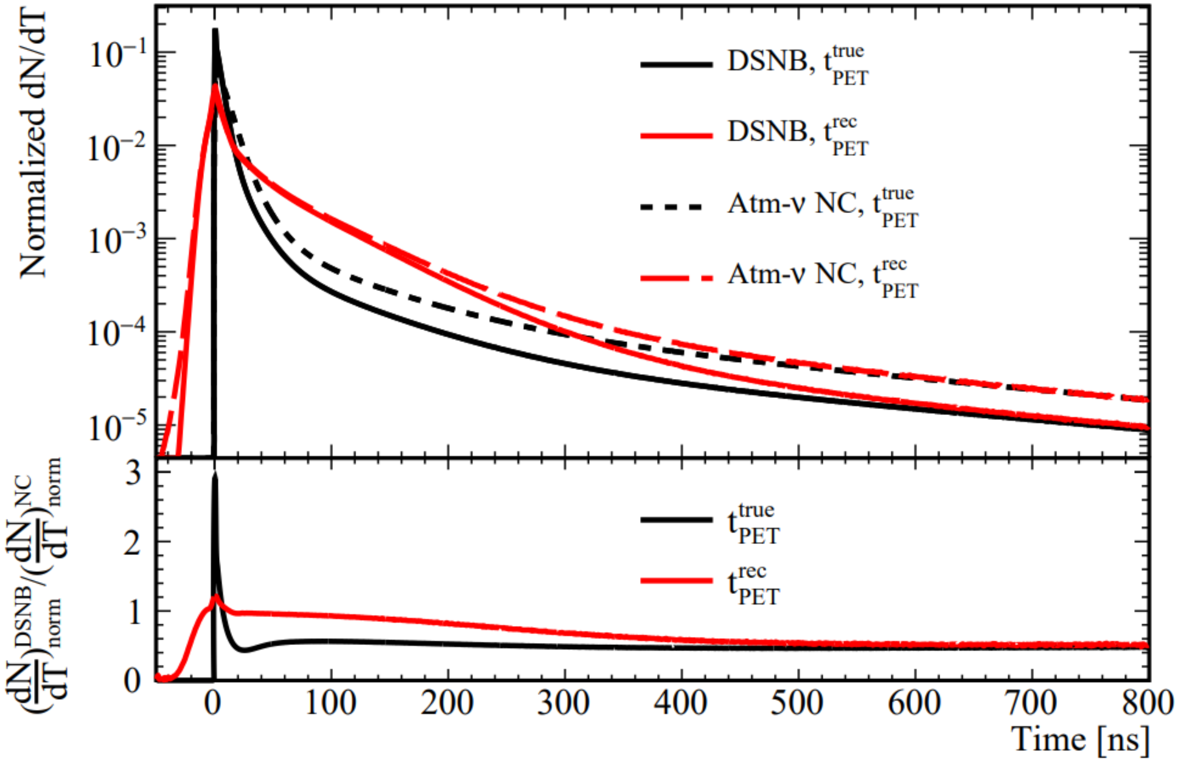
Averaged photon emission time (PET)



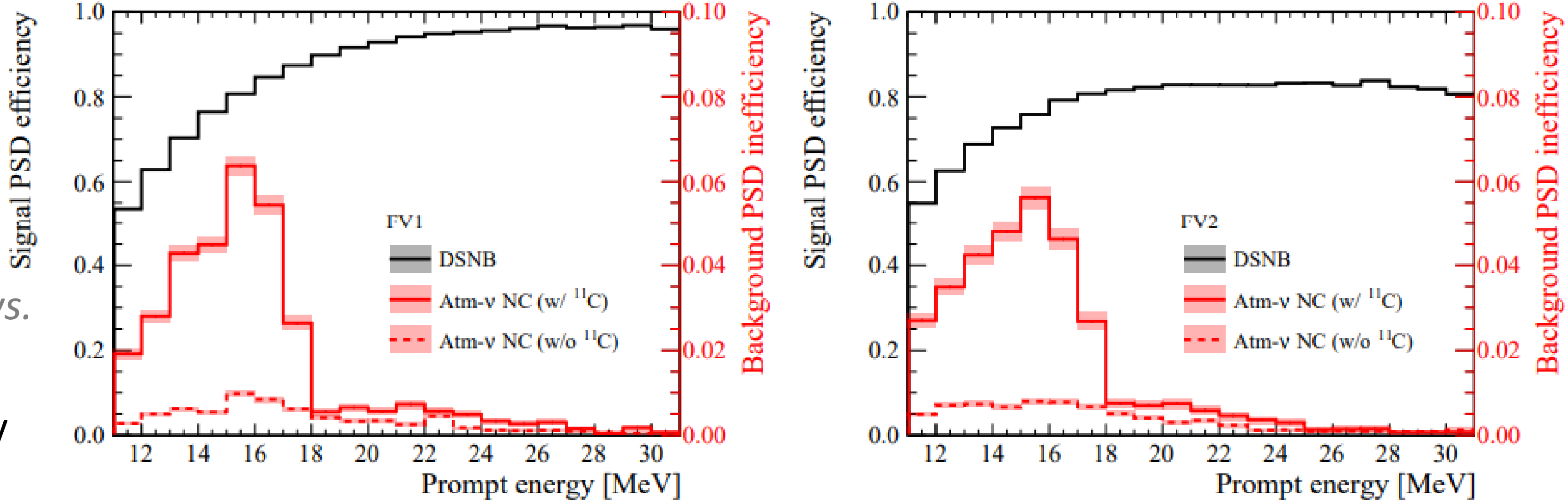
PSD Efficiency & Uncertainty Estimation

JUNO, *JCAP 10 (2022) 033*

- BDT (baseline) and neural network (alternative) based methods are developed (instead of simple tail-to-total method)

- ✓ The PSD efficiency for DSNB @ 1% bkg residual
  - ✓ 84% (FV1)
  - ✓ 77% (FV2)
- ✓ Compared to 50% DSNB PSD efficiency in 2016 analysis [*J. Phys. G43:030401(2016)*]
- ✓ Energy dependent PSD efficiency is used for the first time

Energy-dependent PSD efficiency: optimized



PSD uncertainty estimation via possible similar data samples

- **Spallation neutrons**
- **Neutron calibration sources for the low energy range**
- **The muon capture and Michael electrons**

Exposure	**1-3 years**	**4-9 years**	**10-20 years**
PSD cut uncertainty	30%	20%	10%

More details for PSD study, refers to Xiaojie's talk

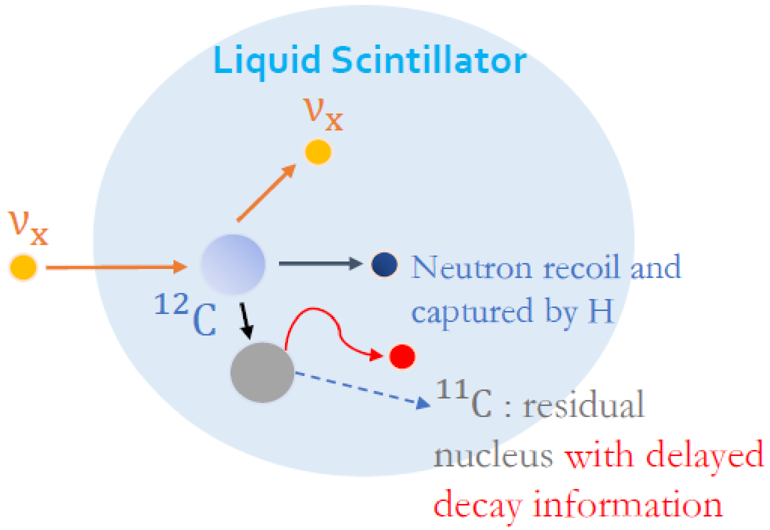
Triple-coincidence (TC) Cut

- **TC cut**

⇨ Relies on the three-fold signature of the ^{11}C NC channel

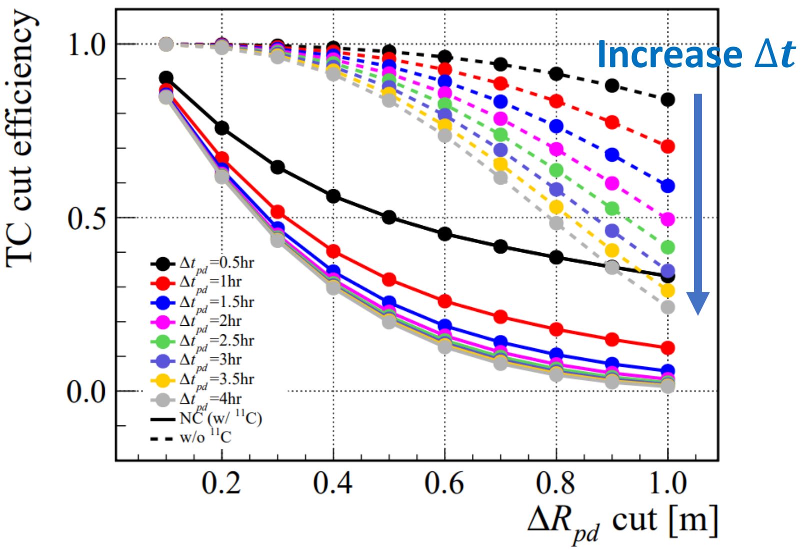
- Prompt signal: a fast neutron recoil
- Delayed signal: neutron captured on hydrogen
- Delayed decay signal from unstable ^{11}C nucleus

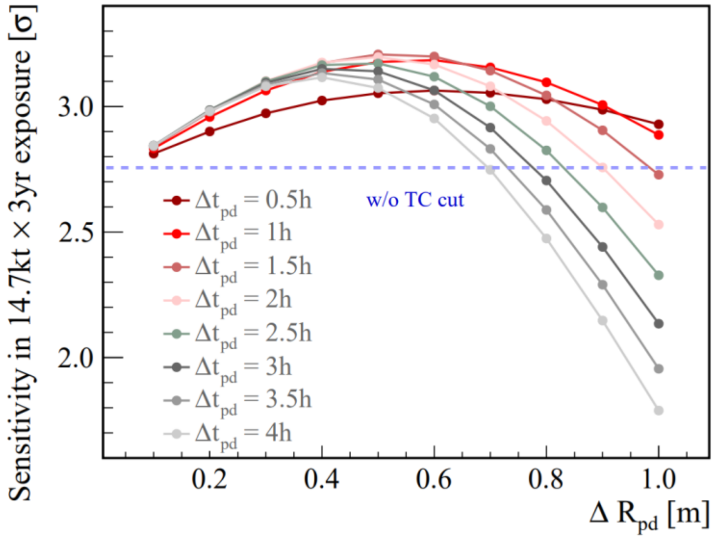
⇨ Apply time and distance ΔR_{pd} cuts between the third delayed signal and the prompt one



- ▶ Accidental background (mimicking a third signal)
  - ✓ cosmogenic ^{11}C
  - ✓ natural radioactivity

  Due to high level of natural radioactivity background in FV2, TC cut cannot be applied
- ▶ Study impact of the different TC cuts on sensitivity to DSNB ➔ select optimal cut setting





Final Rates and Spectra of Signal and Backgrounds

Rate (/(10 yrs))		w/o cuts	w/ cuts
FV1	dsnb	20.8	15.6
	bkg	459.4	3.5
	S/B	0.05	4.5
FV2	dsnb	5.0	3.6
	bkg	136.5	1.9
	S/B	0.04	2.0

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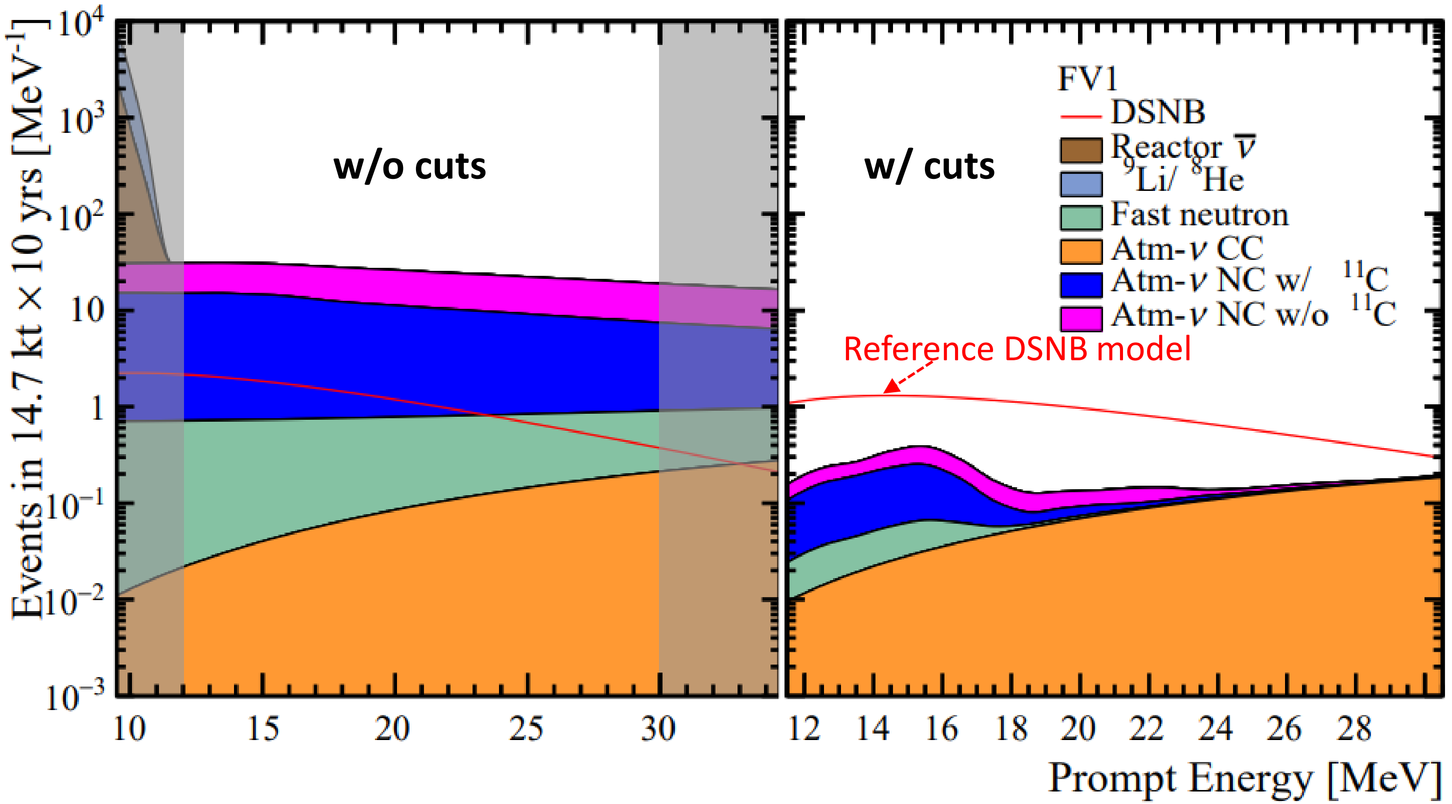


- Highlights on background suppression
  - ✓ Muon veto
  - ✓ PSD technique
  - ✓ TC (^{11}C delayed decay)

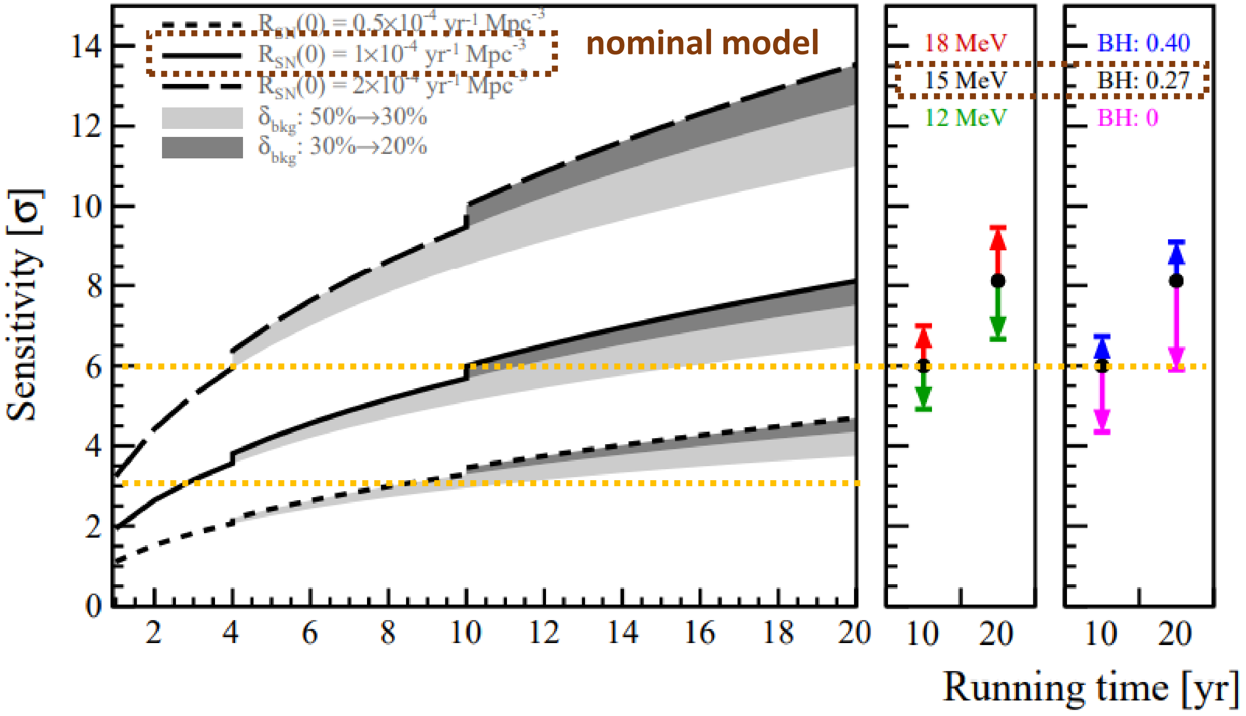
Improvements compared to 2016 analysis *J. Phys. G43:030401(2016)* :

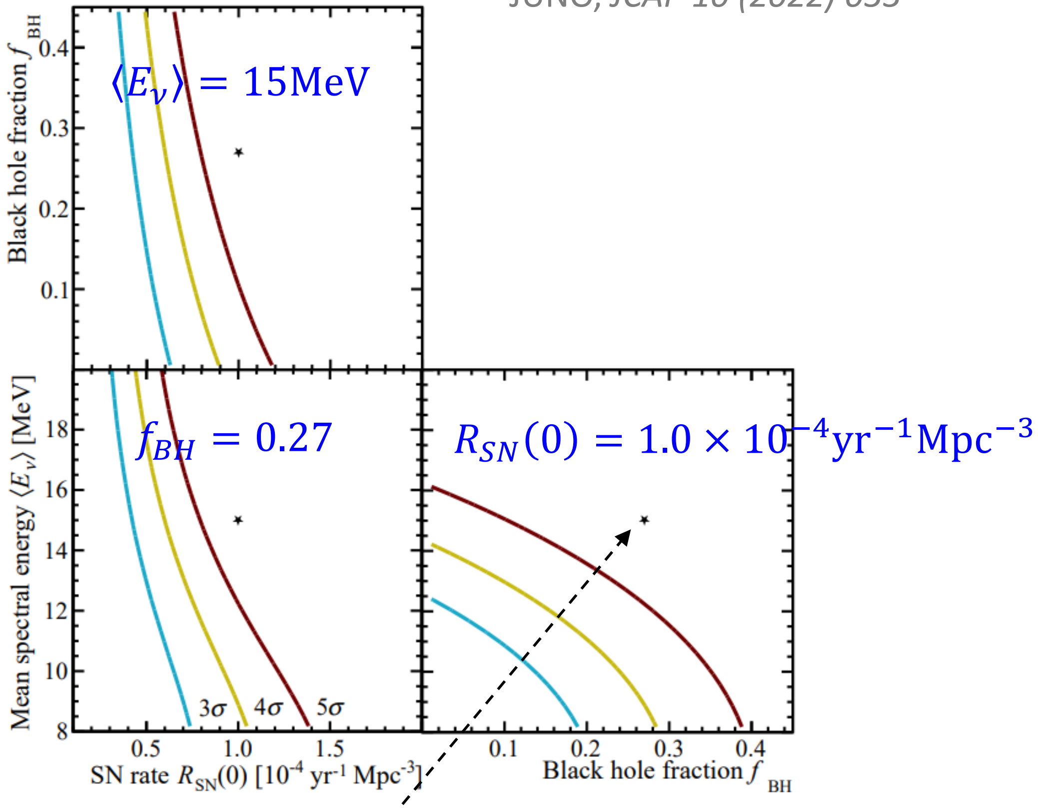
- ✓ **Background evaluation:** 0.7 per year → 0.54 per year
- ✓ **PSD:** signal efficiency 50%→80% (1% residual background)
- ✓ **Realistic DSNB signal model:** non-zero fraction of failed Supernova

➡ S/B improved from 2 to 3.5

Model Dependent DSNB Sensitivity

JUNO, *JCAP 10 (2022) 033*





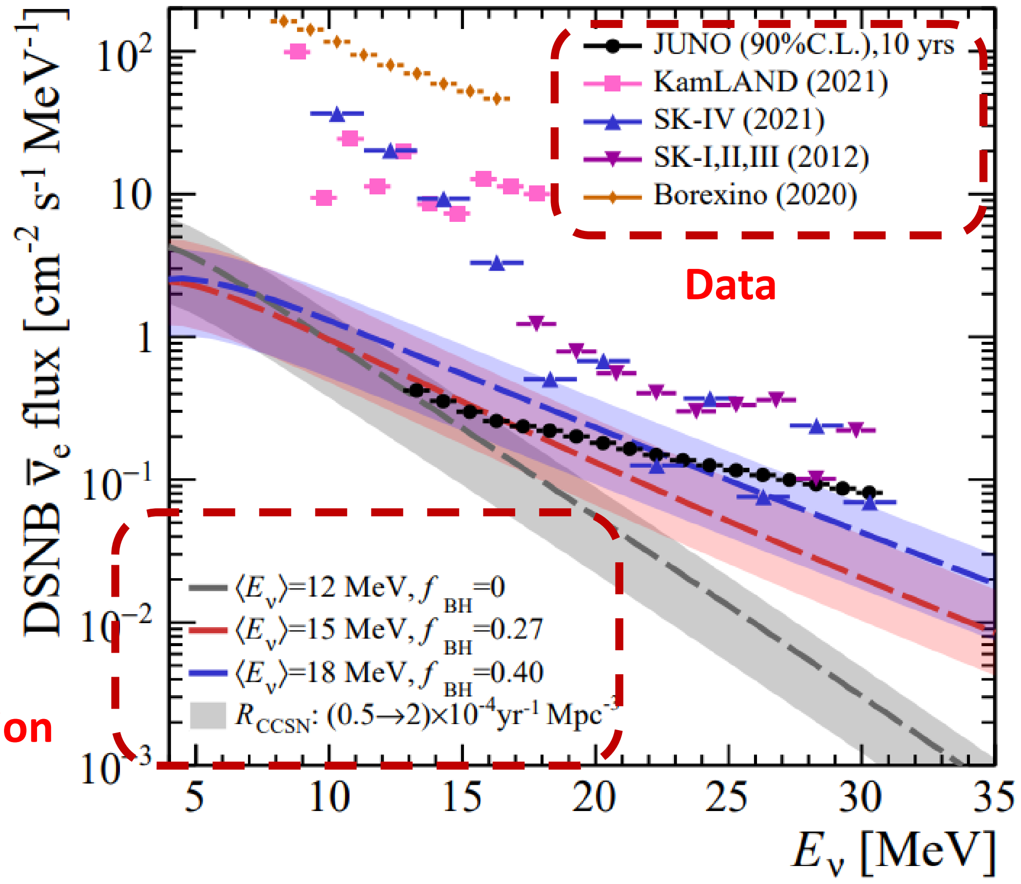
- $\boldsymbol{\delta_{bkg}}$: combination of NC background uncertainty (estimated from in situ measurement) and PSD uncertainty (using spallation neutron sample) as a function of the exposure
- With the nominal model (black solid curve): 3σ (3yrs) and 6σ (10yrs)

⇨ DSNB sensitivity as a functions of three model parameters with 10 years of JUNO data

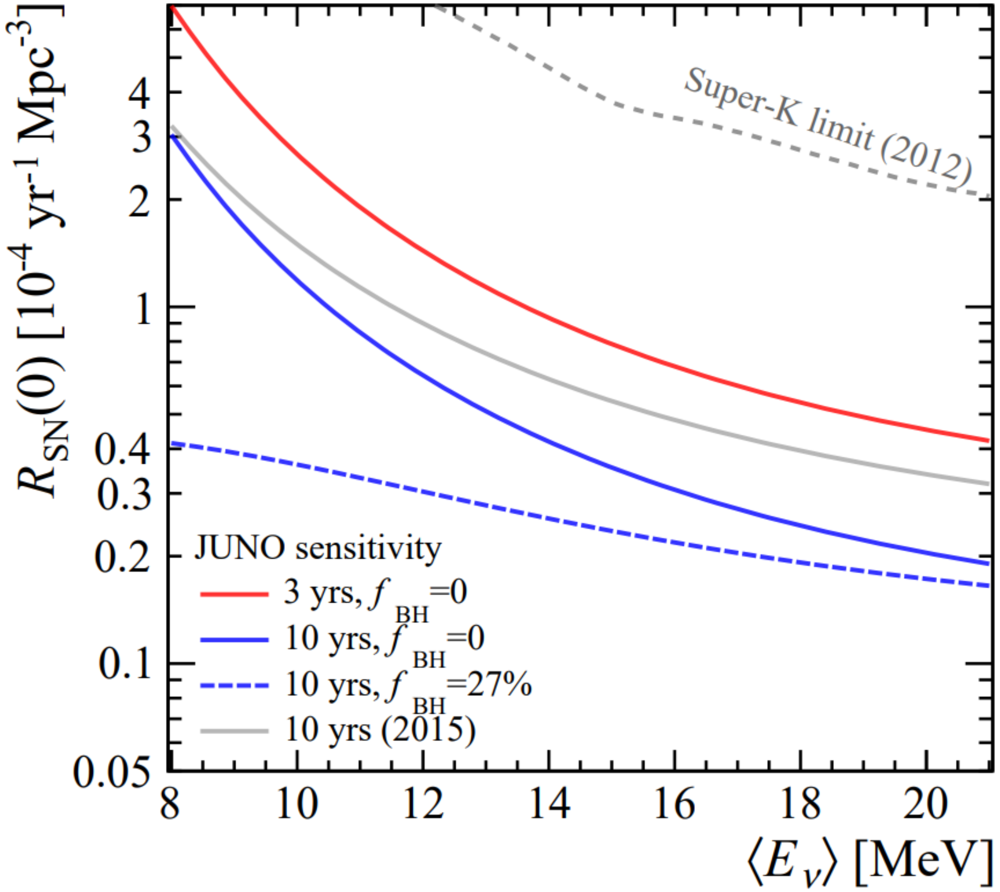
- The black stars show the locations of nominal model: better than 5-σ discovery potential

DSNB Sensitivity: Exclusion Limits

JUNO, *JCAP 10 (2022) 033*



Model prediction



► **If no positive observation, JUNO can set the world-leading best limits of DSNB flux**

Improvement compare to JUNO (2015)

1. **Background evaluation and PSD improvement**
2. **Realistic DSNB signal model**

Summary and Prospects

- JUNO is designed to measure the Neutrino Mass Ordering via reactor neutrinos, is also sensitivity to many other neutrino sources (including solar neutrinos, atmospheric neutrinos, supernova neutrinos, geo-neutrinos)

  20 kton LS, 3% @ 1 MeV energy resolution, advance detector technology

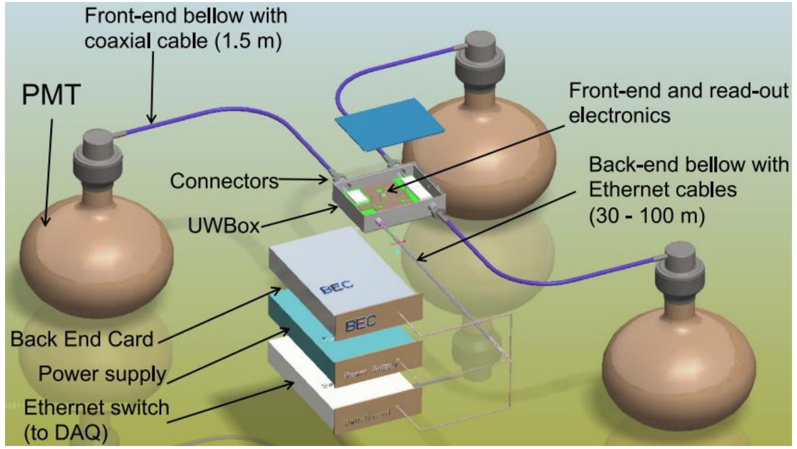
- The Construction is proceeding well: first data in 2025
- Promising prospects for detecting the DSNB
  - For the nominal model of DSNB, the DSNB discovery potential can be achieved 3σ (3yrs) and 6σ (10yrs)
  - Significantly improve the limits of the DSNB parameter space

Thank you!

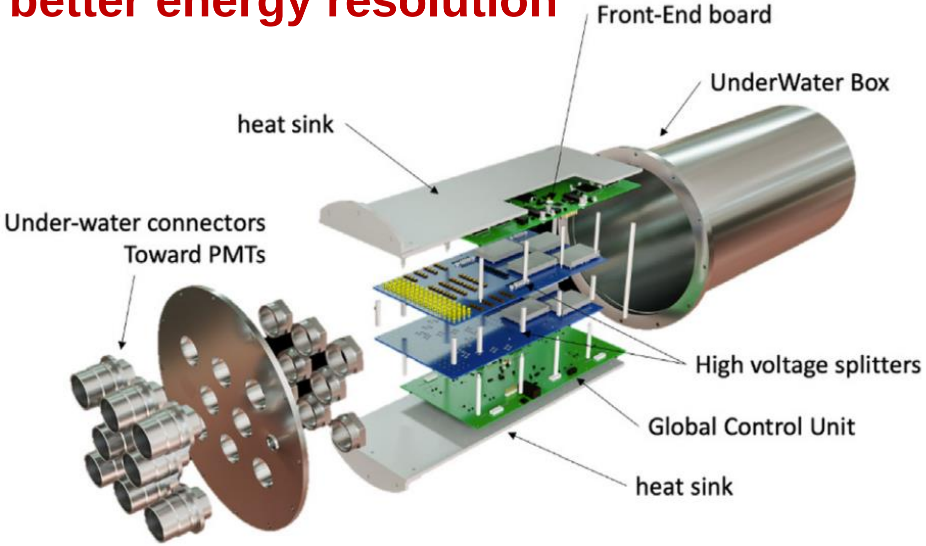
backup

Electronics

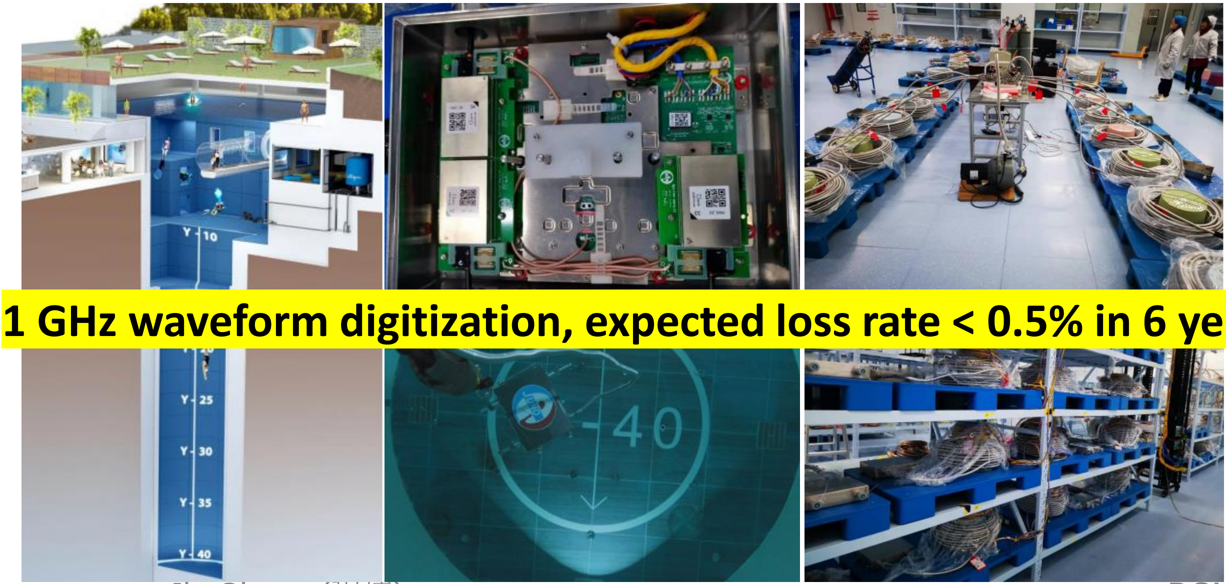
- **Underwater electronics to improve signal-to-noise ratio for better energy resolution**



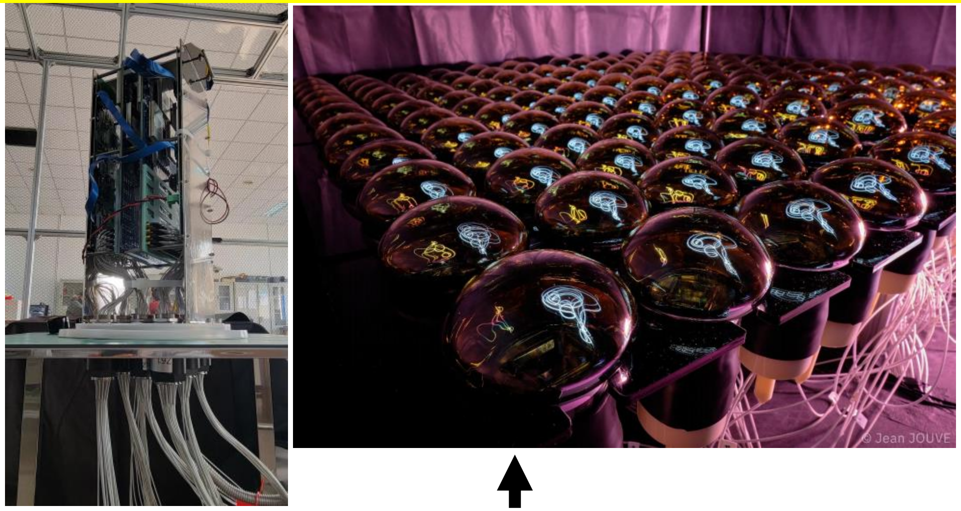
3 20-inch PMTs connected to one underwater box



128 3-inch PMTs connected to one underwater box



1 GHz waveform digitization, expected loss rate < 0.5% in 6 years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Electronics assembly and tests done