

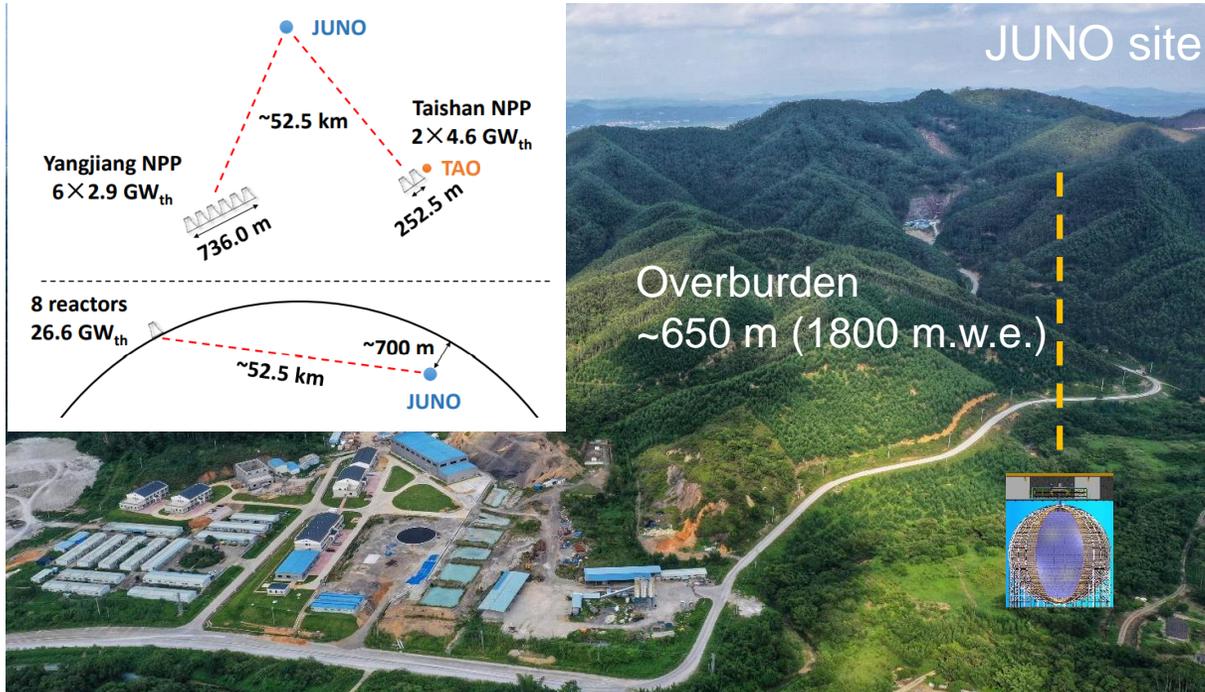
JUNO's Physics Prospects

Jie Cheng

North China Electric Power University
on behalf of the JUNO collaboration

2022/07/08

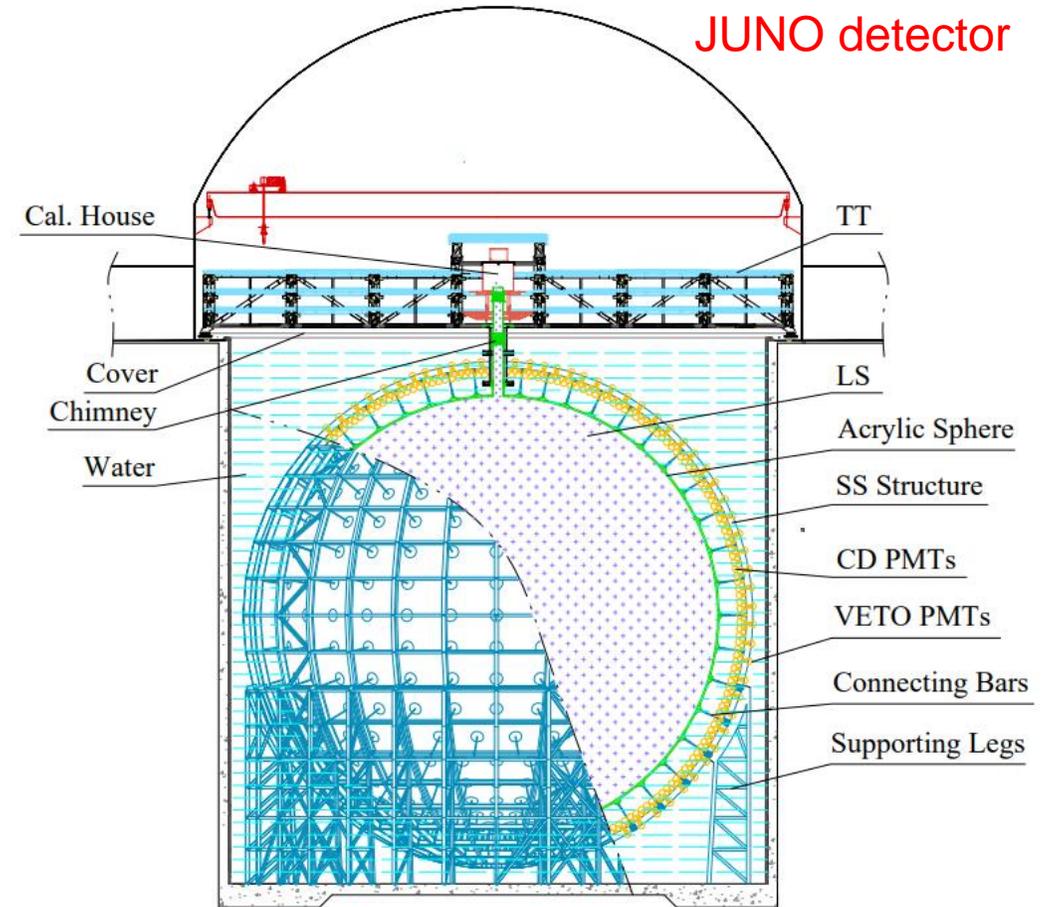
Jiangmen Underground Neutrino Observatory (JUNO)



20 kt LS (large target)
3% energy resolution @ 1 MeV

Civil construction finished in 2021/12
Detector assembly and installation

- in progress
- to be completed by 2023



For more details on the detector's progress, please refer to Alessandra Carlotta Re's talk
"The JUNO detector: design concept and status"

JUNO Collaboration

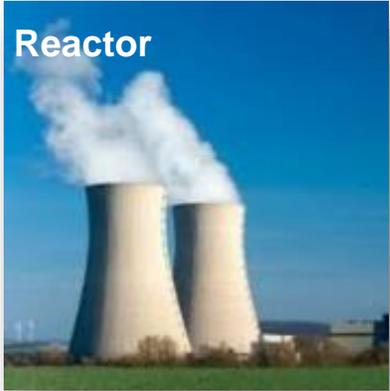


Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC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

= 76 institutes

(over 650 collaborators)

Abundant Physics with JUNO



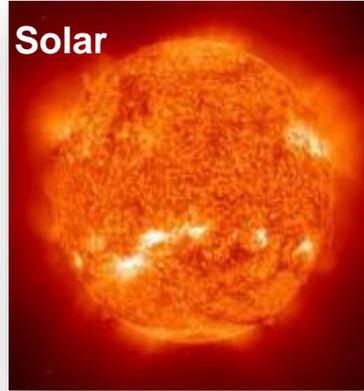
Reactor

~60 $\bar{\nu}_e$ per day



Atmosphere

Hundreds per year



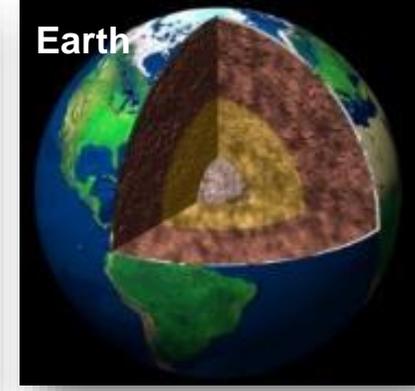
Solar

Hundreds per year for ^8B



Supernova

Supernova burst:
~7300 at 10 kpc
DSNB: 2-4 $\bar{\nu}_e$ per year



Earth

~400 per year

+
New physics

Neutrino oscillation & properties

Neutrinos as probes

- Many improvements of the JUNO physics topics compared to the JUNO physics book (J. Phys. G43:030401 (2016))
- For topics that are not presented here, please refer to [PPNP 123 \(2022\) 103927](#)

Reactor $\bar{\nu}_e$ Oscillation and Detection

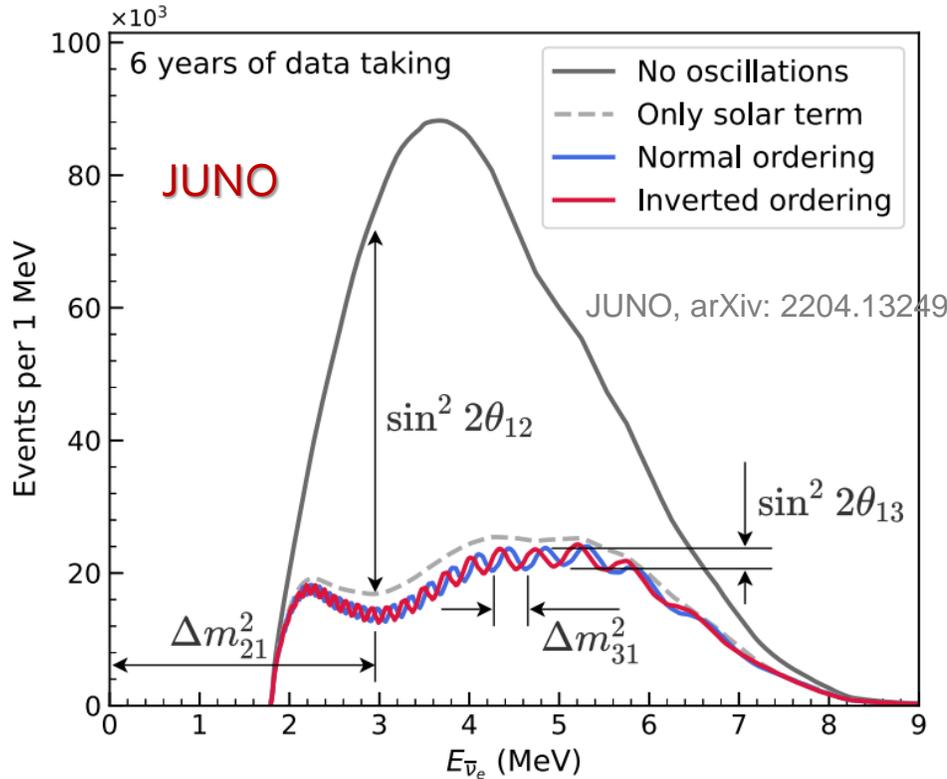
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}(\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21},$$

(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)

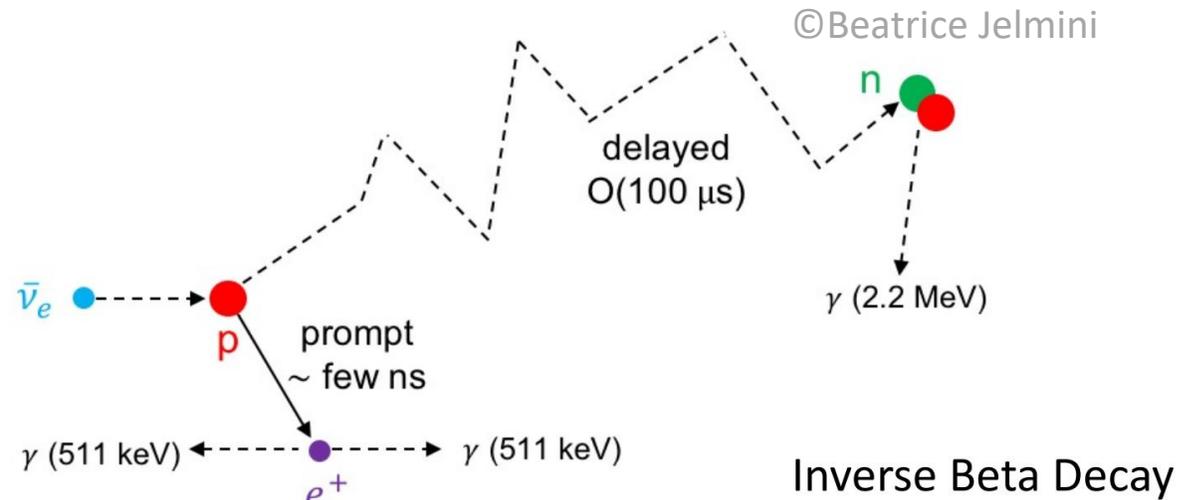
$$\Delta_{ij} \equiv \Delta m_{ij}^2 L / (4E)$$

The baseline of ~52.5km for JUNO

- ▶ optimized for the sensitivity to neutrino mass ordering



Detection via inverse beta decay (IBD):



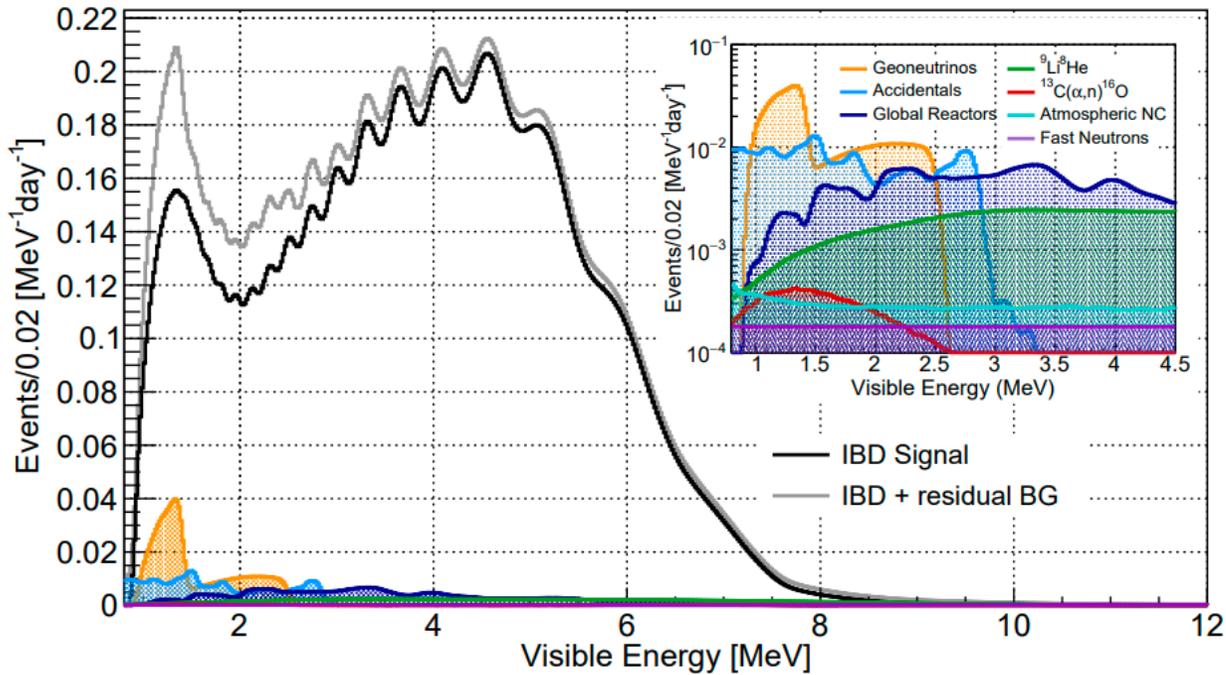
- The double coincidence → suppression of background

- Good knowledge of spectral shape is important for physics goals

Expected Reactor $\bar{\nu}_e$'s Signal and Background



JUNO, arXiv: 2204.13249



Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → 47	-	-
Geo- ν 's	1.1 → 1.2	30%	5%
Accidental signals	0.9 → 0.8	1%	negligible
Fast-n	0.1	100%	20%
${}^9\text{Li}/{}^8\text{He}$	1.6 → 0.8	20%	10%
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	0.05	50%	50%
Global reactors	0 → 1.0	2%	5%
Atmospheric ν 's	0 → 0.16	50%	50%

JUNO physics book (*J. Phys. G43:030401(2016)*) → **this update**

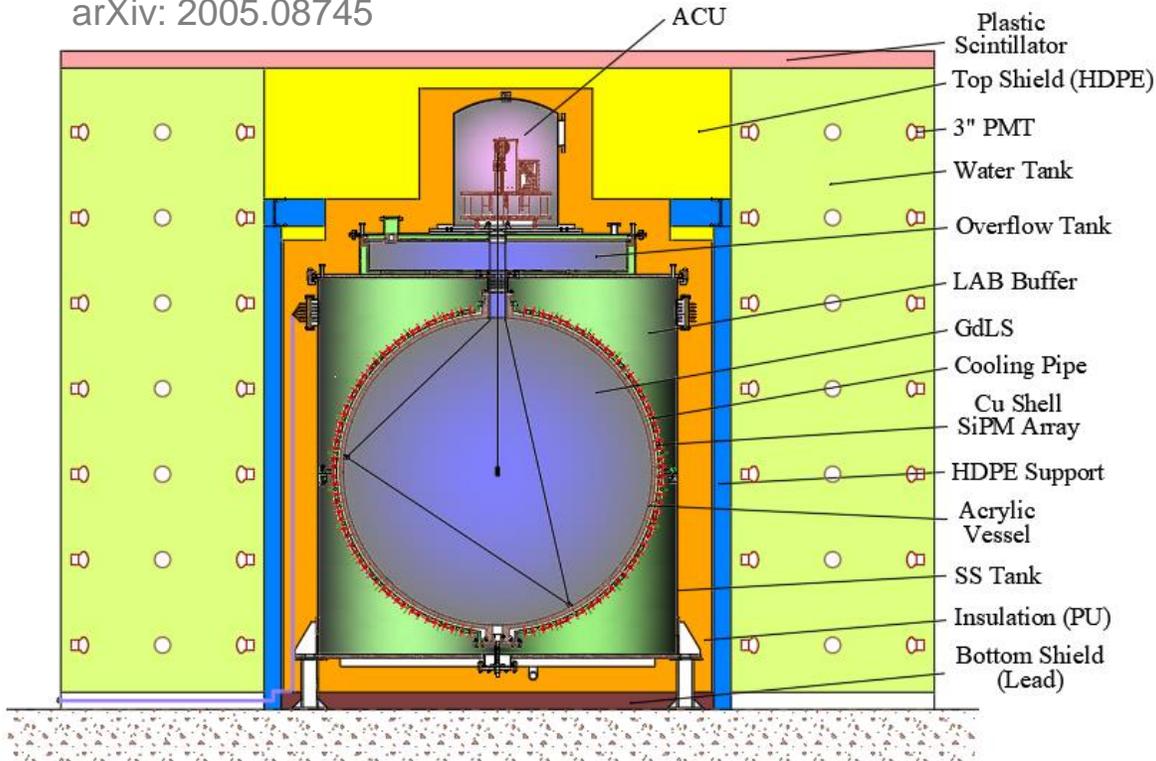
Updates for the spectra and rates since JUNO (2016)

- ☹️ 2 fewer reactor cores in Taishan
- ☹️ Better muon veto strategy
- ☹️ Improved energy resolution
- ☹️ Signal and backgrounds now assessed with full JUNO simulation
- ☹️ Final knowledge of JUNO site and overburden
- ☹️ Lower radioactivity background based on latest measurements on material radiopurities

Taishan Antineutrino Observatory (TAO)



arXiv: 2005.08745

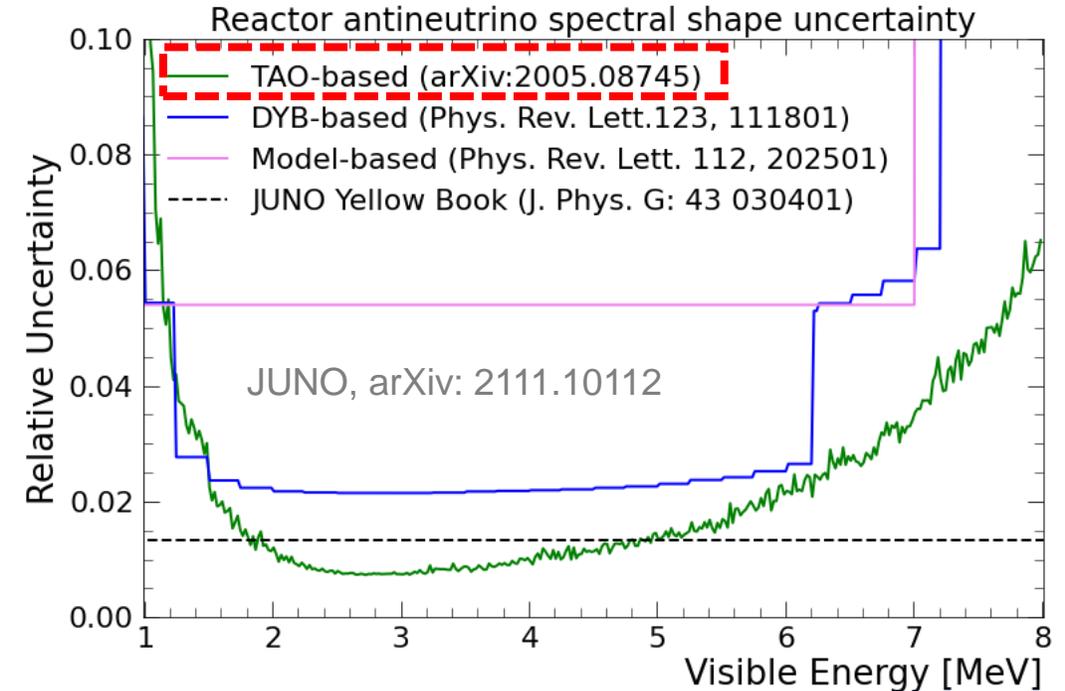


JUNO-TAO detector (2.8-ton GdLS)

- 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ SiPM: achieve high light yield with ~94% coverage
- ✓ Gd-LS works at -50°C: lower the dark noise of SiPM

- Precisely measure the unoscillated reactor $\bar{\nu}_e$ spectrum

→ good understanding of the shape uncertainty



Shape uncertainty close to the assumption in the JUNO physics book *J. Phys. G43:030401(2016)*

→ model-independent combined analysis with JUNO

- Also search for sterile neutrinos and measure spectra of dominant isotopes

Improvement of Energy Resolution



Changes	Light yield in detector center [PEs/MeV]	Energy resolution @ 1 MeV	Reference
Previous estimation	1345	3.0%	JHEP03 (2021) 004
20-inch PMT PDE (27%→30.1%)	↑ 11%	2.9%	arXiv: 2205.08629
New Center Detector geometries	↑ 3%		-
More realistic optical model	↑ 8%		EPJC 82 329 (2022)

e^+ energy resolution is understood:

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

• **Photon statistics**

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

- **Scintillation quenching effect**

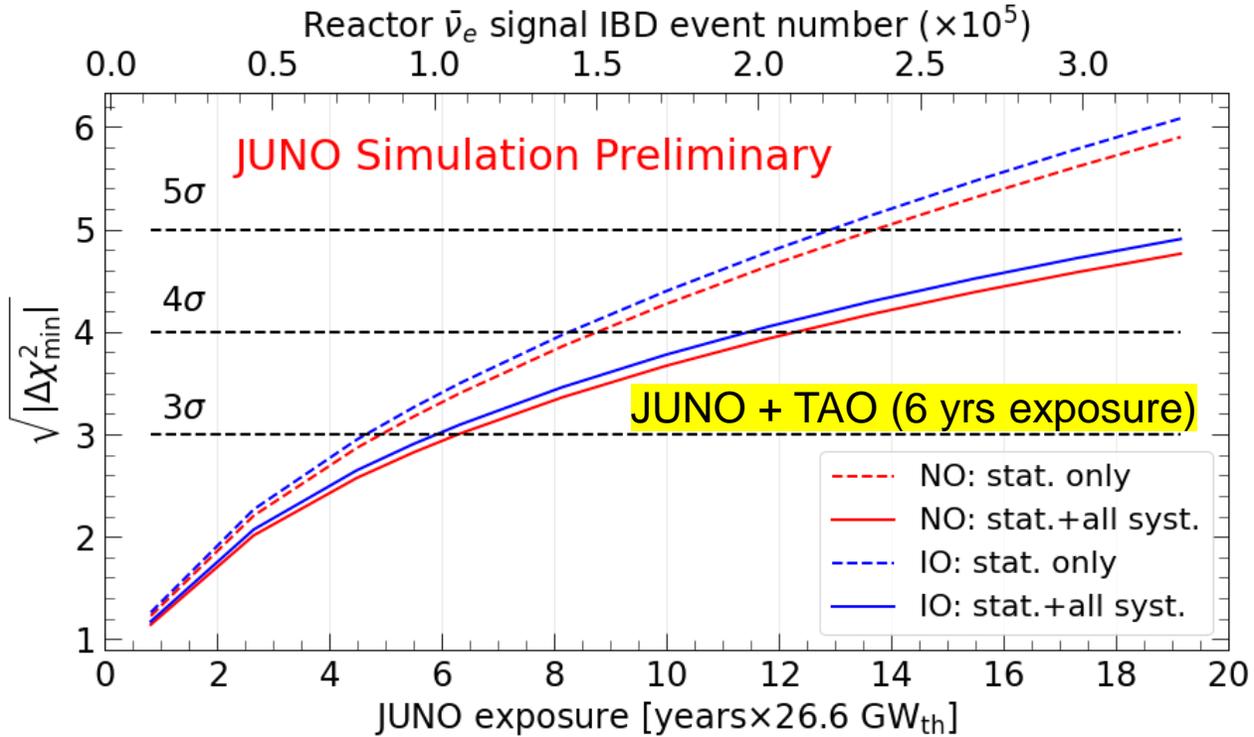
- LS Birks constant from table-top measurements

- **Cherenkov radiation**

- Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity

- **Detector uniformity and reconstruction**

Neutrino Mass Ordering (NMO)



Updates since JUNO (2016):

	JUNO (2016)	Now (2022)
Thermal Power	35.8 GW _{th}	26.6 GW _{th} (26%↓)
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (11%↑)
Signal rate	60 /day	47.1 /day (22%↓)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3% @ 1 MeV	2.9% @ 1 MeV (3%↑)
Shape uncertainty	1%	TAO-based model
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

❑ **Reactor only: 3σ @ ~6 yrs × 26.6 GW_{th} exposure**

❑ Combined reactor + atmospheric neutrino analysis is **in progress**: further improve the NMO sensitivity

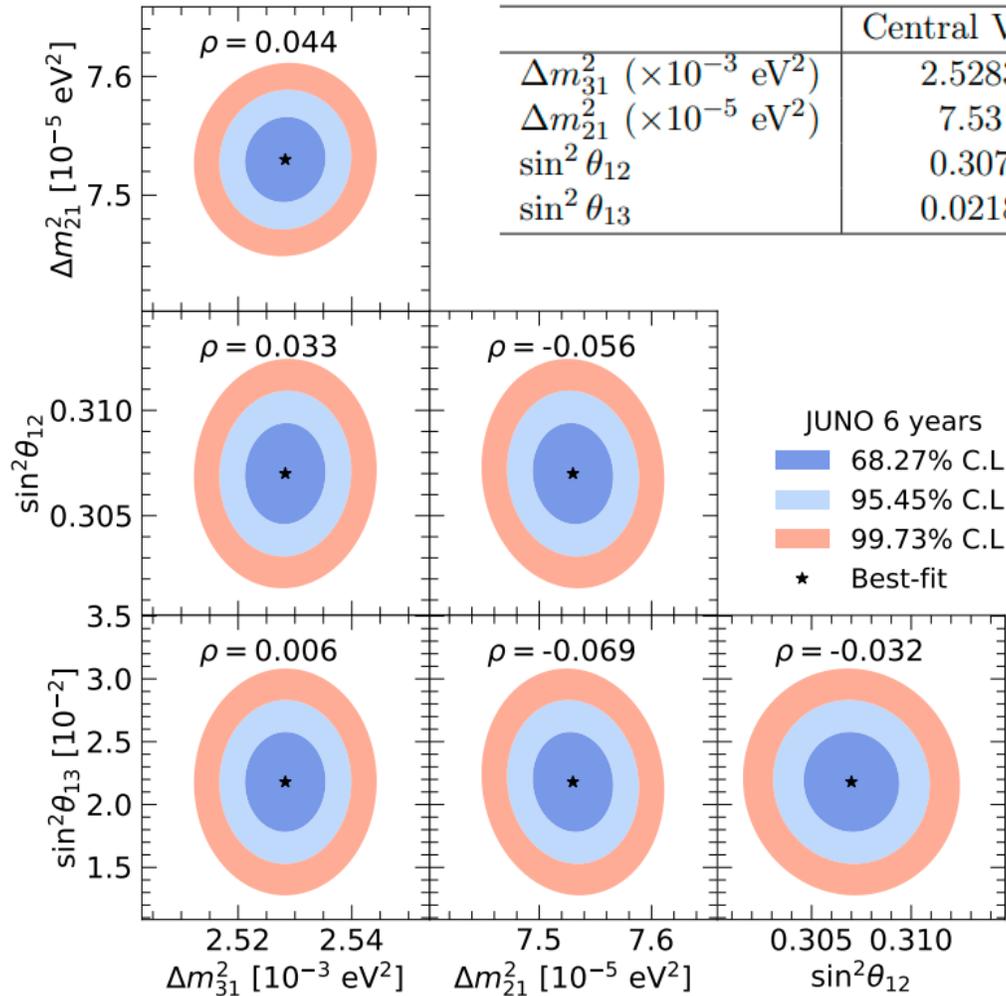
Poster #848 by Jinnan Zhang

Precision Measurement of Oscillation Parameters

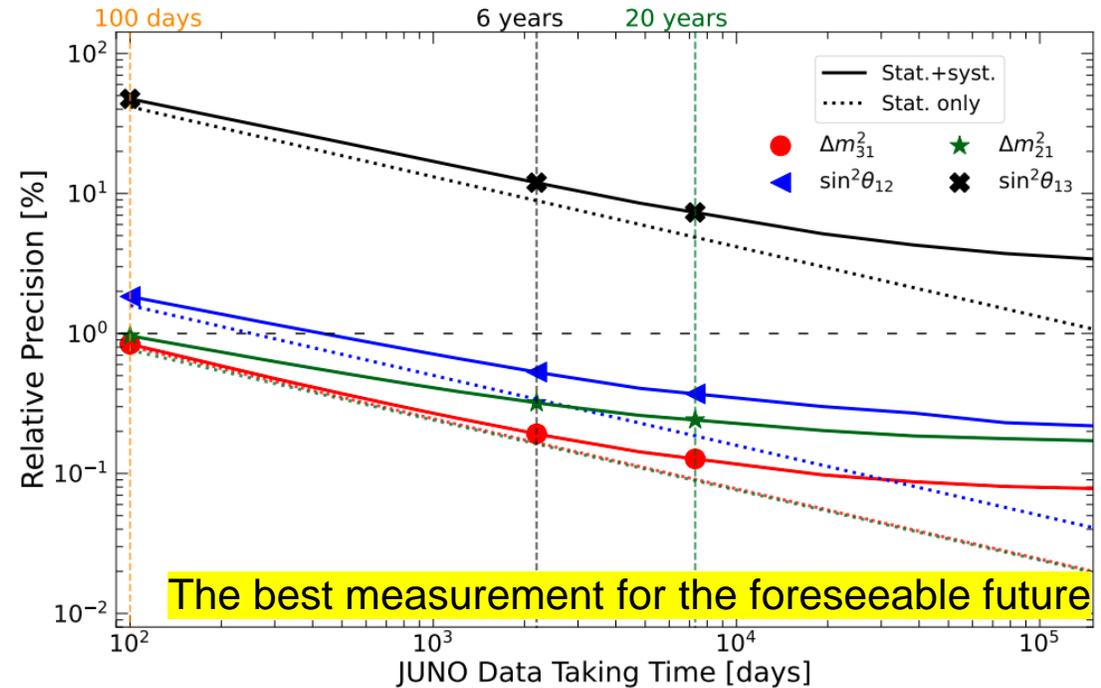


JUNO, arXiv: 2204.13249

Precision of $\sin^2\theta_{12}$, Δm_{21}^2 , $|\Delta m_{31}^2| < 0.5\%$ in 6 yrs



	Central Value	PDG2020	100 days	6 years	20 years
Δm_{31}^2 ($\times 10^{-3}$ eV ²)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm_{21}^2 ($\times 10^{-5}$ eV ²)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)



Diffuse Supernova Neutrino Background (DSNB)



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

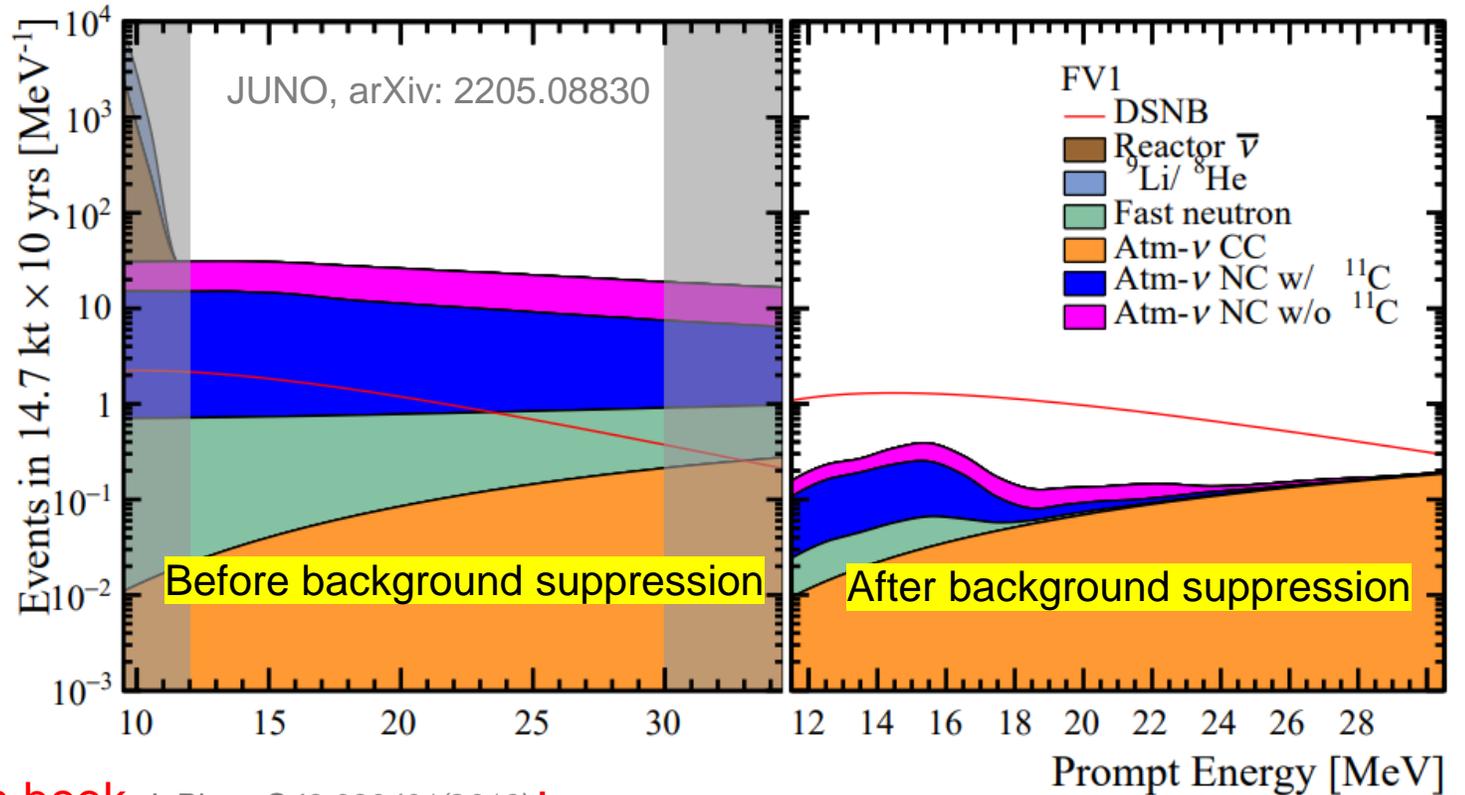
Holding:

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

- 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)* :

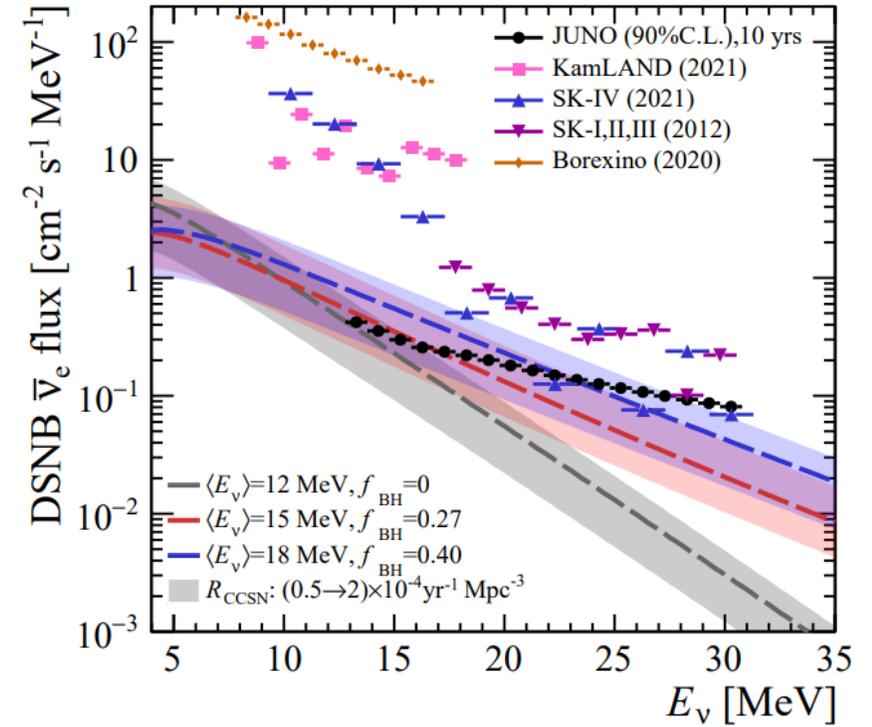
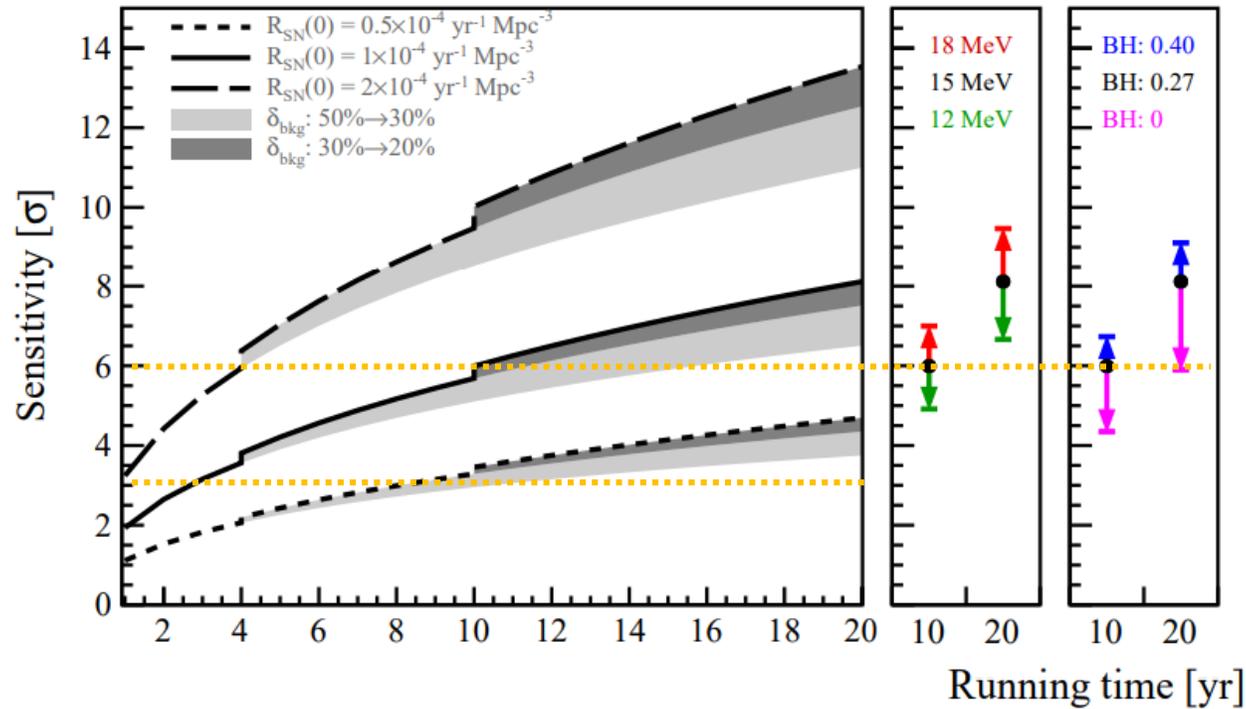
- ✓ **Background evaluation:** 0.7 per year \rightarrow 0.54 per year
- ✓ **PSD:** signal efficiency 50% \rightarrow 80% (1% residual background)
- ✓ **Realistic DSNB signal model:** non-zero fraction of failed Supernova

➔ S/B improved from 2 to 3.5

Poster #574 by Yiyu Zhang

DSNB Sensitivity

JUNO, arXiv: 2205.08830



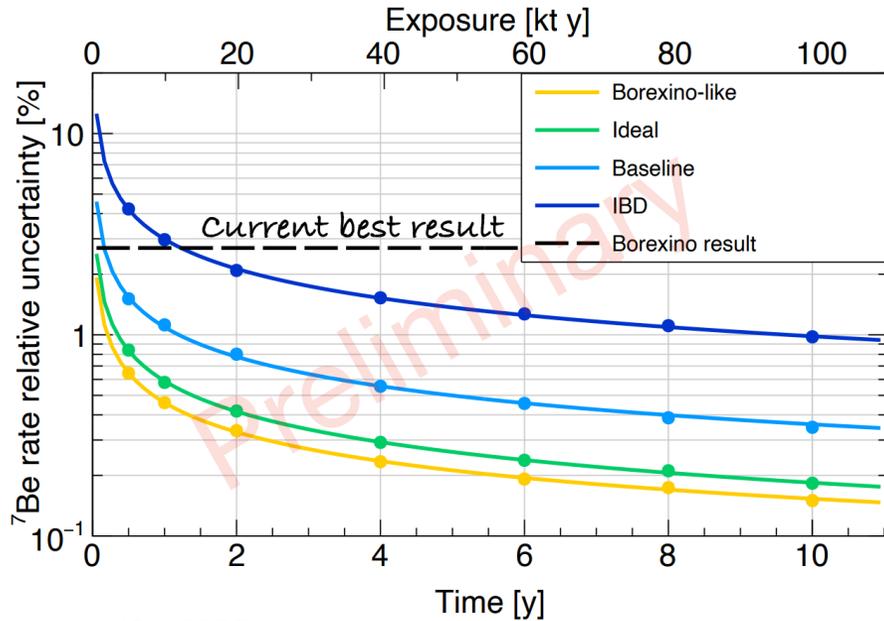
- ▶ If no positive observation, JUNO can set the world-leading best limits of DSNB flux
- ▶ With the nominal model (black solid curve (left plot)): 3σ (3yrs) and 6σ (10yrs)

^7Be , pep and CNO Solar Neutrino

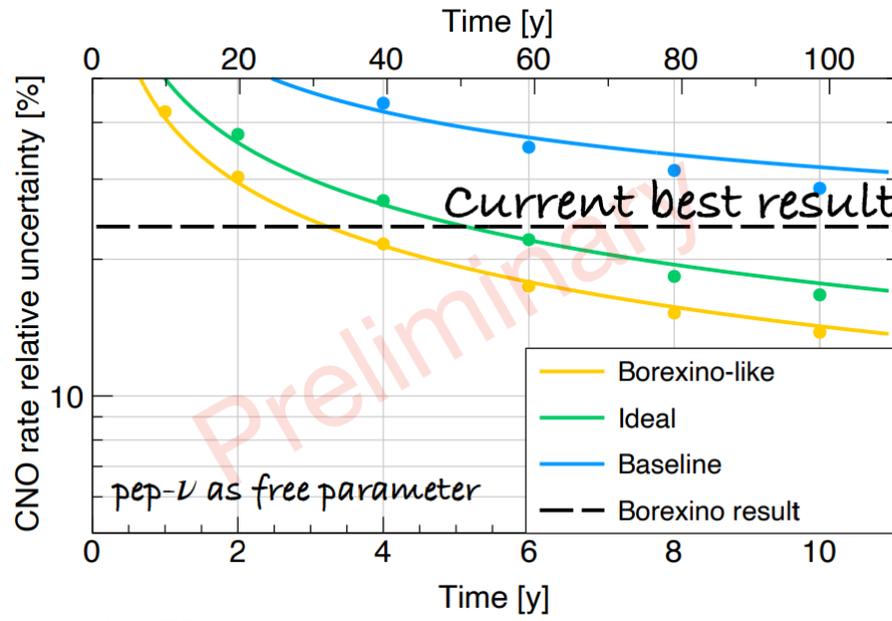
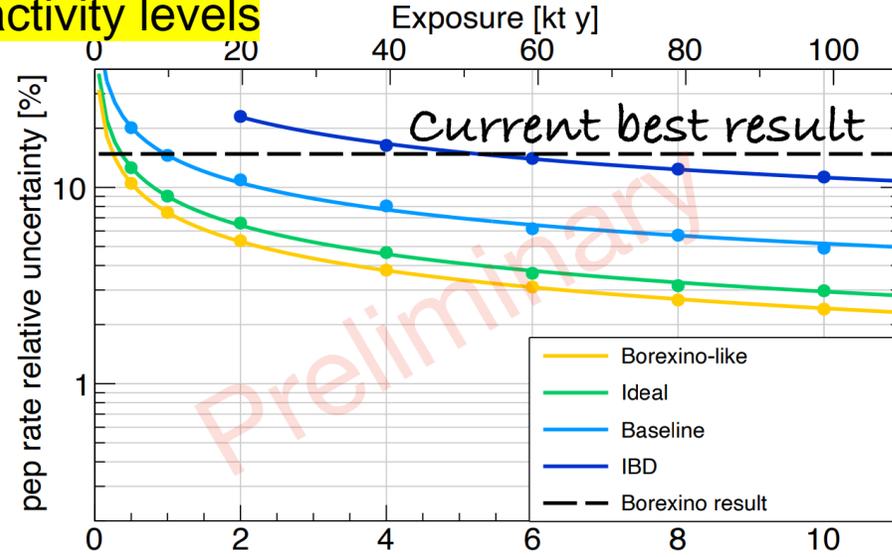
Comprehensive studies under different radioactivity levels

Radio-purity Scenario		^{40}K	^{85}Kr	$^{232}\text{Th-chain}$	$^{238}\text{U-chain}$	$^{210}\text{Pb}/^{210}\text{Bi}$	^{210}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



Jie Cheng



ICHEP 2022

- ▶ $E_{\text{vis}} < 2 \text{ MeV}$
- ▶ Measure simultaneously ^7Be , pep, and CNO solar neutrinos
- ▶ Compared to the current best result: expected uncertainty on ^7Be , pep neutrinos will significantly improve
- ✓ depends on the final radioactivity level

Model-independent Measurement of ^8B Solar Neutrino



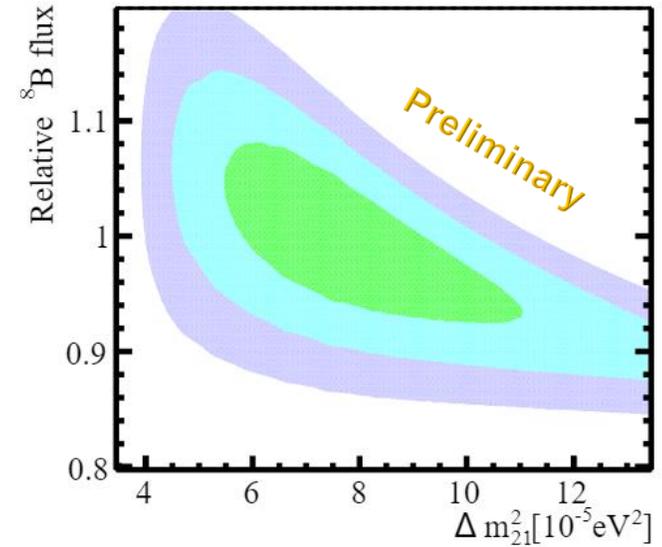
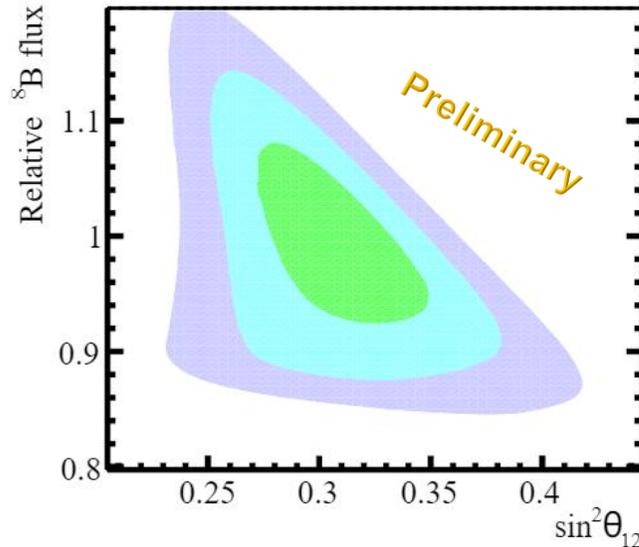
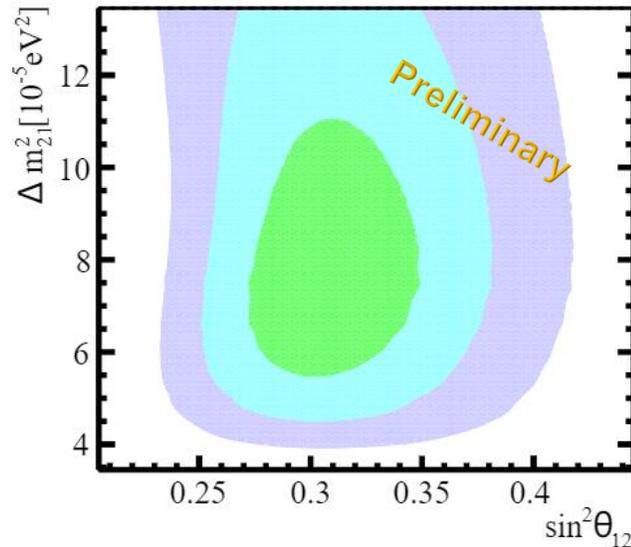
	Channels	Threshold [MeV]	Signal	Event numbers	
				[200 kt×yrs]	after cuts
CC	$\nu_e + ^{13}\text{C} \rightarrow e^- + ^{13}\text{N} (\frac{1}{2}^-; \text{gnd})$	2.2 MeV	$e^- + ^{13}\text{N}$ decay	3929	647
NC	$\nu_x + ^{13}\text{C} \rightarrow \nu_x + ^{13}\text{C} (\frac{3}{2}^-; 3.685 \text{ MeV})$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

→ **Correlated**
} **Single**

- ~ 0.2 kt ^{13}C in JUNO LS \rightarrow enable observation of ^8B solar neutrino CC and NC interactions on ^{13}C for the first time
- **Model independent** measurement of ^8B solar neutrino flux (5%) and oscillation parameters $\sin^2\theta_{12}$, Δm_{21}^2

Joint analysis of the spectra from ES+NC+CC

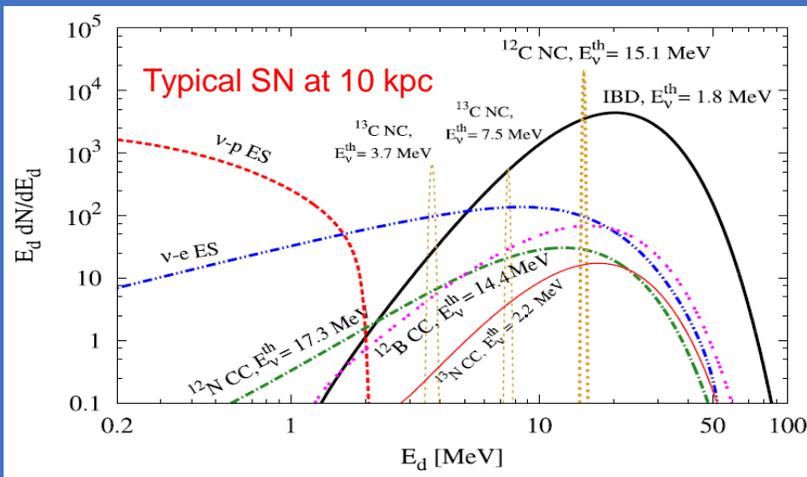
Paper in preparation



Other Topics with JUNO



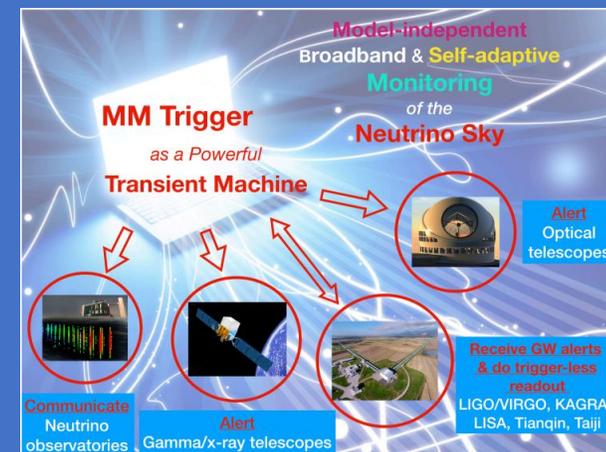
Neutrinos from Supernova Burst



Detect all flavors
@ 10 kpc:
~7300 supernova
neutrinos

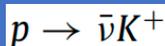
Multi-messenger Astrophysics

- Lower the energy threshold of the detector down to O(10) keV
- Realtime monitoring of the MeV transient neutrino sky

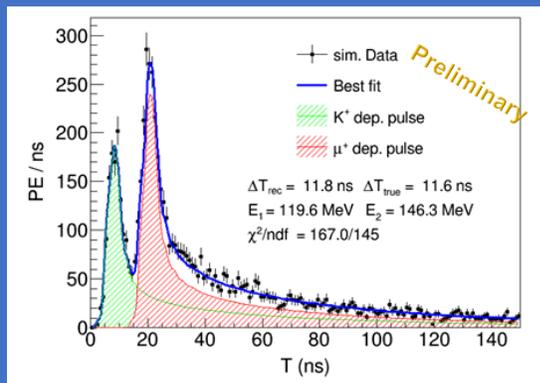
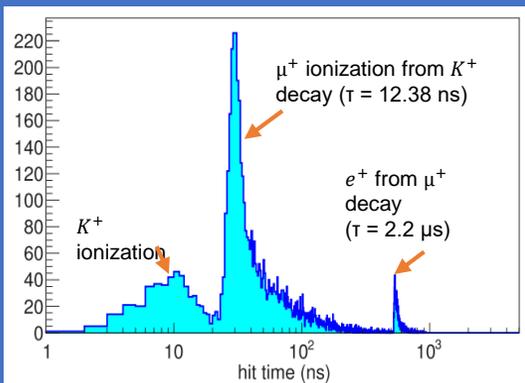


Nucleon Decays

Poster #396 by Yuhang Guo

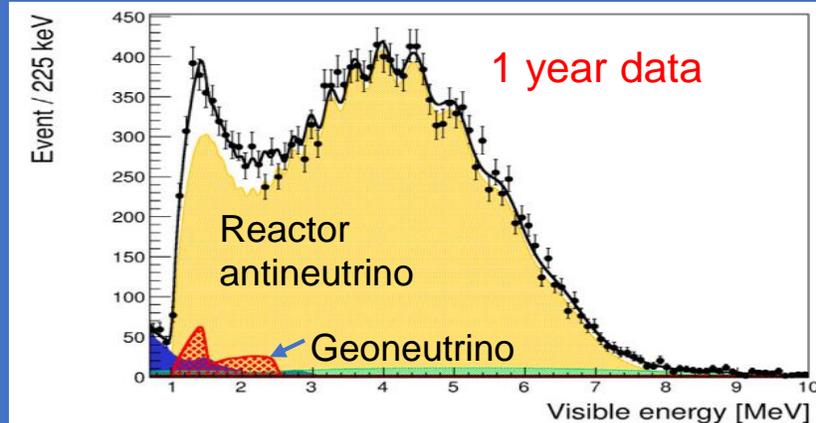


Signature: three-fold time coincidence



Expect sensitivity: 8.3×10^{33} years (90% C.L.) for 10 years

Neutrinos from Earth

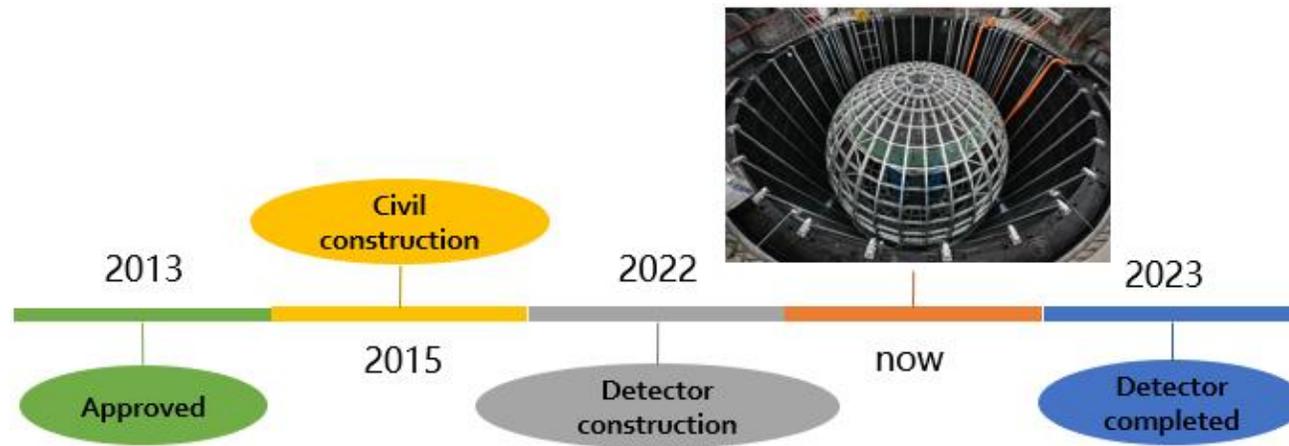


- $\bar{\nu}_e$ from ^{238}U and ^{232}Th decay chains in earth
- Signal in JUNO: $39.7^{+6.5}_{-5.2}$ TNU (~400 geoneutrinos per year)
- 5% measurement in 10 years.

Summary and Prospects



Physics	Sensitivity
Neutrino Mass Ordering	3σ ($\sim 1\sigma$) in 6 yrs by reactor (atmospheric) neutrinos
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm_{21}^2 , $ \Delta m_{31}^2 < 0.5\%$ in 6 yrs
Supernova Burst (10 kpc)	~ 7300 of all-flavor neutrinos
DSNB	3σ in 3 yrs
Solar Neutrino	Measure ${}^7\text{Be}$, pep, CNO simultaneously, measure ${}^8\text{B}$ flux independently
Nucleon Decays ($p \rightarrow \bar{\nu}K^+$)	8.3×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~ 400 per year, 5% measurement in 10 yrs



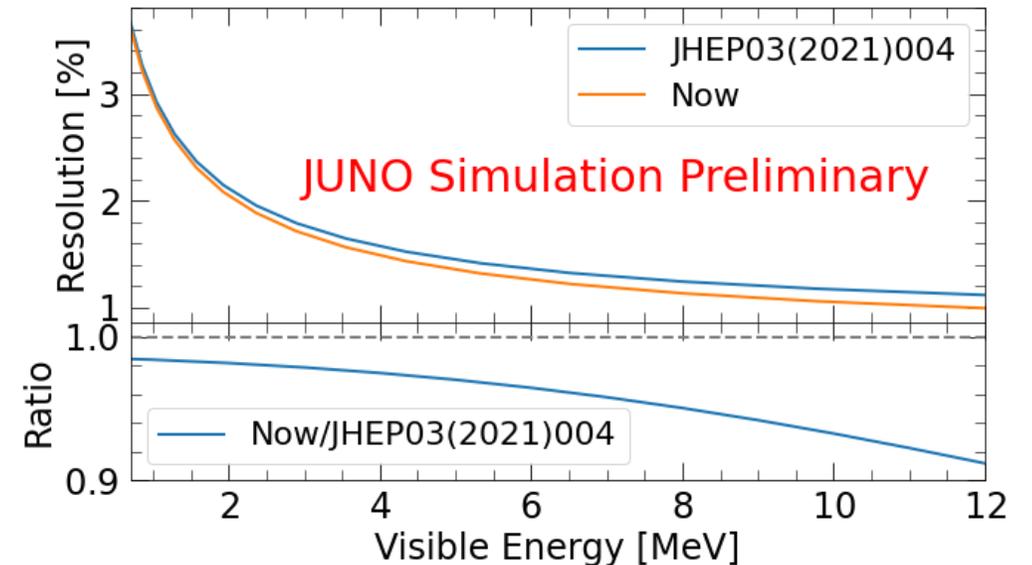
backup

Improvement of Energy Resolution

- **Updates** of energy resolution compared to **JHEP03 (2021) 004**
- **Better understanding** of the e^+ energy resolution

	Light yield in detector center [PEs/MeV]	Energy resolution @ 1MeV
JHEP03 (2021) 004	1345	3.0%
20-inch PMT PDE (27%→30.1%) (arXiv: 2205.08629)	1497 (↑ 11%)	-
New Center Detector geometries (neutrino2022 poster #184)	1537 (↑ 3%)	-
More realistic optical model (EPJC 82 329 (2022))	1665 (↑ 8%)	-
Now	1665	2.9%

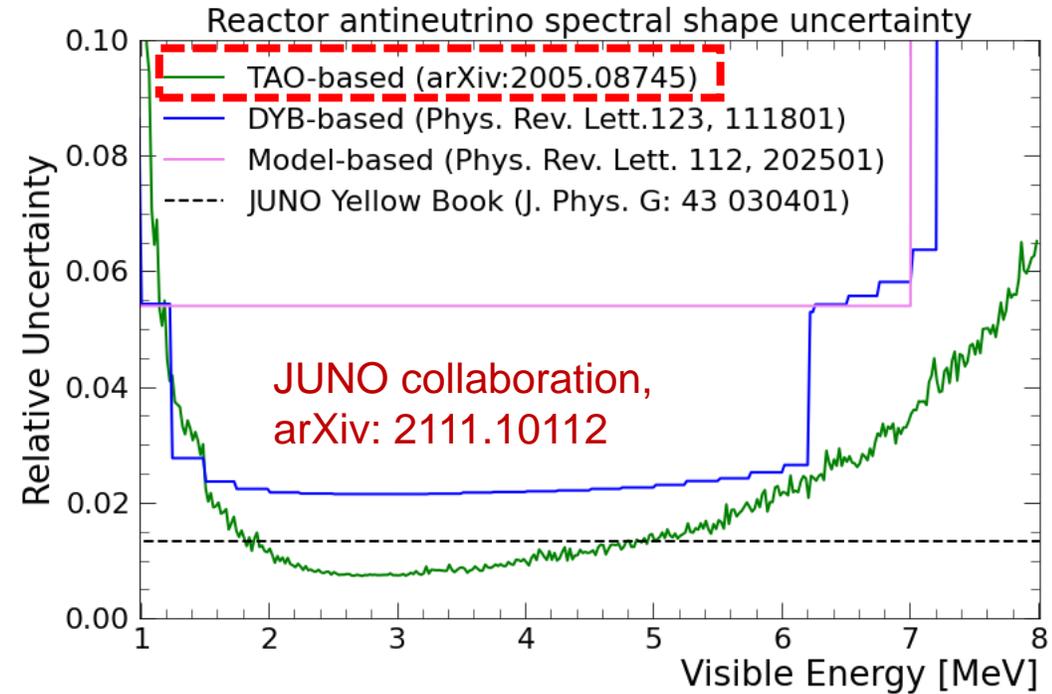
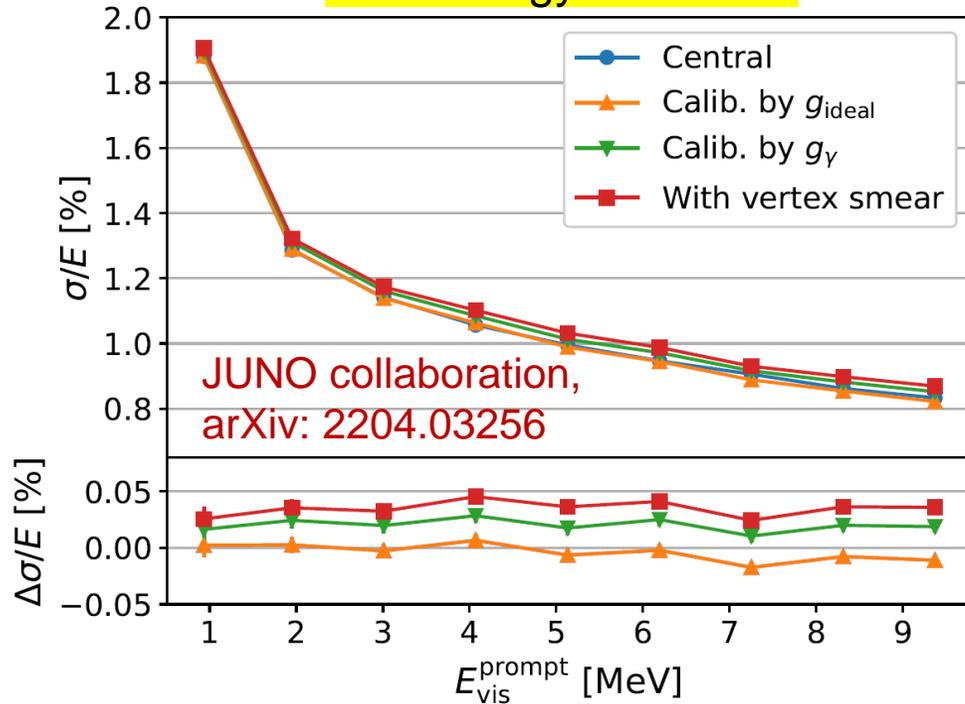
$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}$$



Reference Reactor $\bar{\nu}_e$ Spectrum from TAO

- With the excellent energy resolution, precisely measure the unoscillated reactor $\bar{\nu}_e$ spectrum (reference spectrum for JUNO) → good understanding of the shape uncertainty

TAO energy resolution



Unprecedented energy resolution < 2% @ 1 MeV

- ~94% coverage of SiPM → ~50% photon detector efficiency
- 1.8 m inner diameter of target → small absorption of scintillation
- GdLS works at -50°C → increase the photon yield

Shape uncertainty close to the assumption in the JUNO physics book (2016)

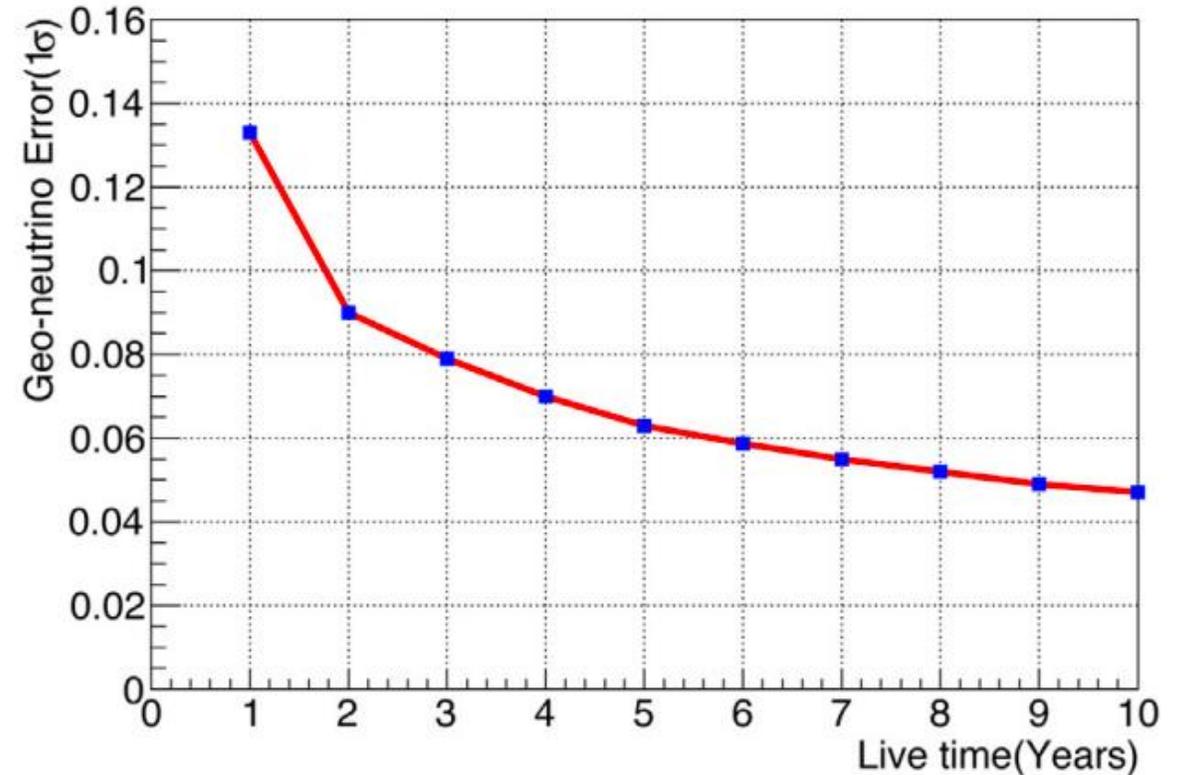
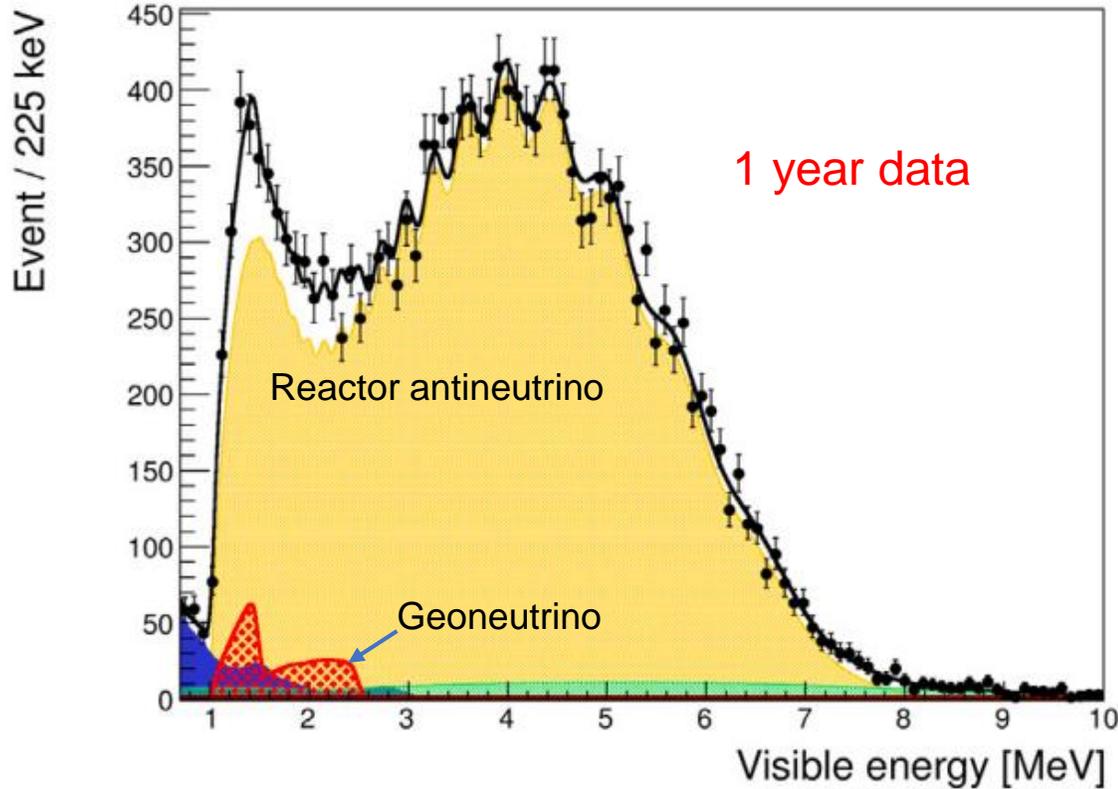
DSNB: Signal and Background Budget

- Diffuse supernova neutrino background (DSNB)
 - Not detected yet
 - Associated to cosmological SN rate ($R_{SN}(\mathbf{0})$), the average energy of SN neutrinos ($\langle E_\nu \rangle$), the fraction of failed black-hole-forming SNe (f_{BH})
 - Detection via IBD
- Dominant background (above 12 MeV): Atmospheric neutrino NC interactions

Analysis	Highlights	Method Reference
Prediction	ν -N interactions (GENIE, NuWro) + TALYS (de-excitation)	Phys.Rev.D 103 (2021) 5, 053001
Uncertainty	Future <i>in situ</i> meas. (~15% after ten years)	Phys.Rev.D 103 (2021) 5, 053002
Discrimination	PSD technique & Triple coincidence (^{11}C delayed decay)	Paper in preparation

Neutrinos from earth

$\bar{\nu}_e$ from ^{238}U and ^{232}Th decay chains in earth



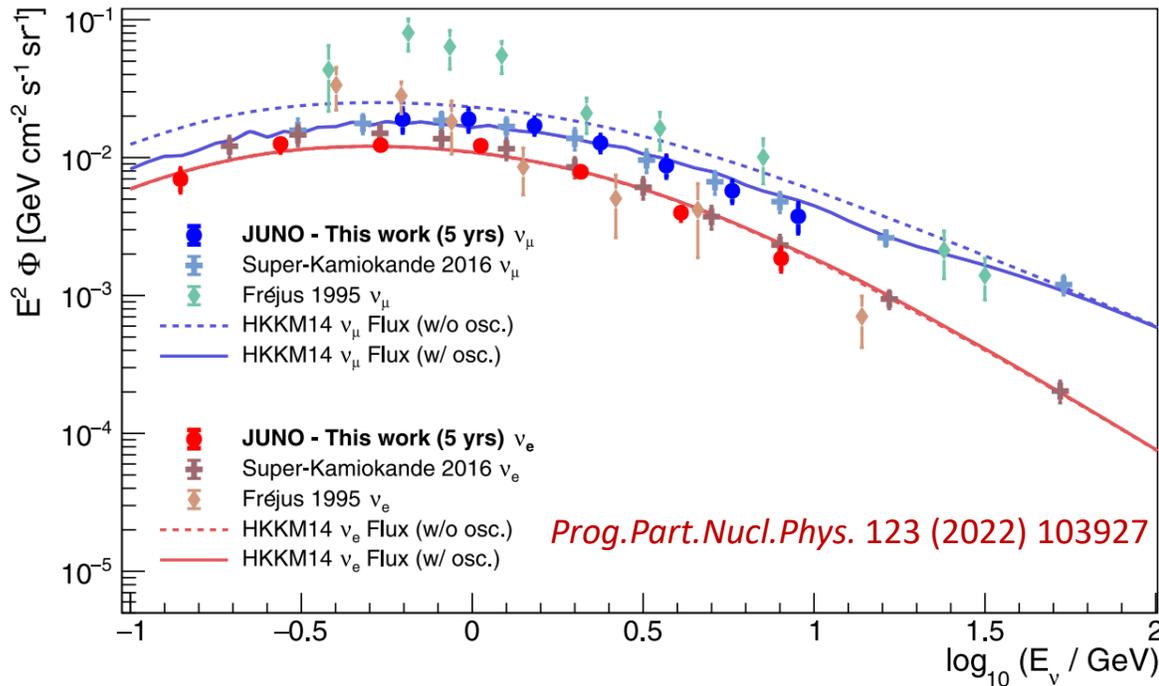
Signal in JUNO: $39.7 +6.5 -5.2$ TNU (~ 400 geoneutrinos per year), 5% measurement in 10 years.

JUNO can observe as much geo- ν as Borexino and KamLAND for the whole time combined in 1 yr.

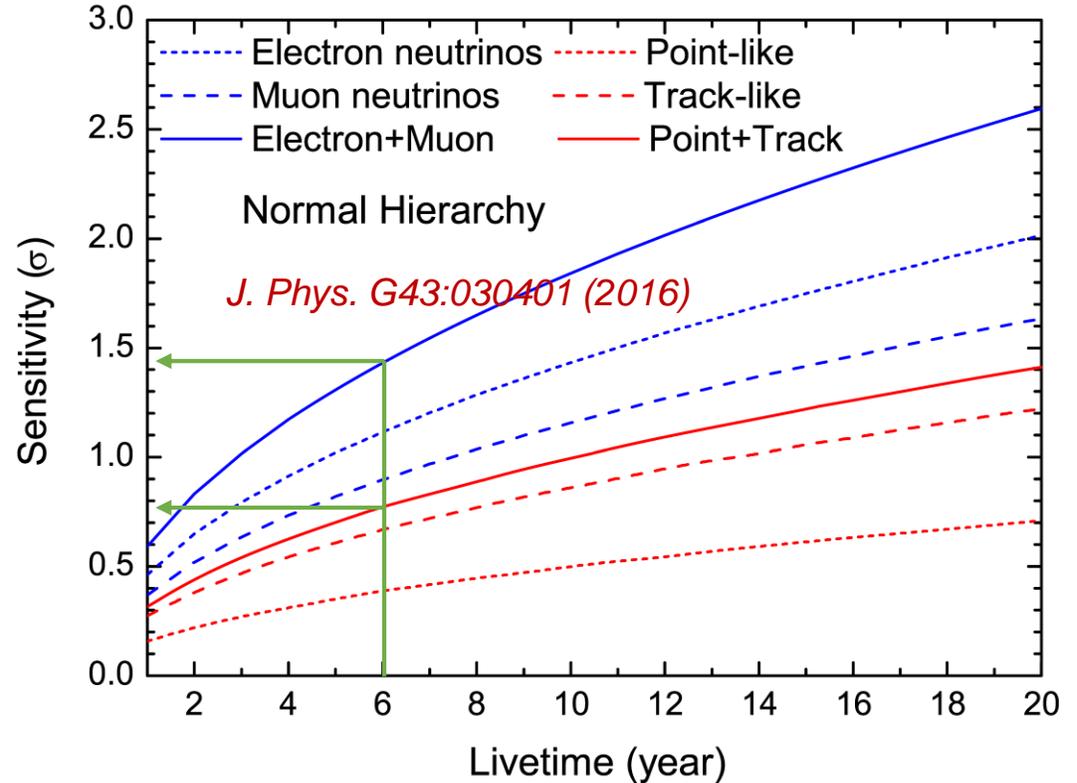
Atmospheric neutrino

MSW effect \rightarrow Neutrino Mass Ordering (NMO) \rightarrow Independent measurement from reactor antineutrino

Critical techniques: energy and angular resolutions, flavor identifications



ν_e/ν_μ discrimination thanks to PMT hit pattern



JUNO sensitivity on NMO: 0.7~1.4 σ (atmospheric only) @ ~6 yrs exposure

Combined analysis of reactor antineutrino and atmospheric neutrinos on NMO are in progress.