Status of the JUNO experiment

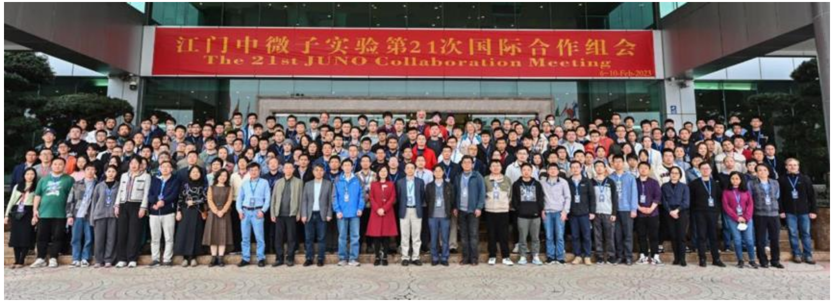
Steven Calvez on behalf of the JUNO collaboration
IRN Neutrino June 2023
June 20th 2023

The JUNO collaboration

- 76 institutes, 18 countries

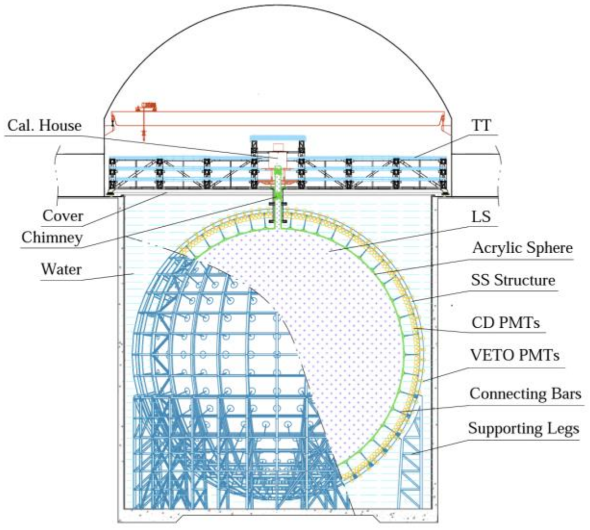
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	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		

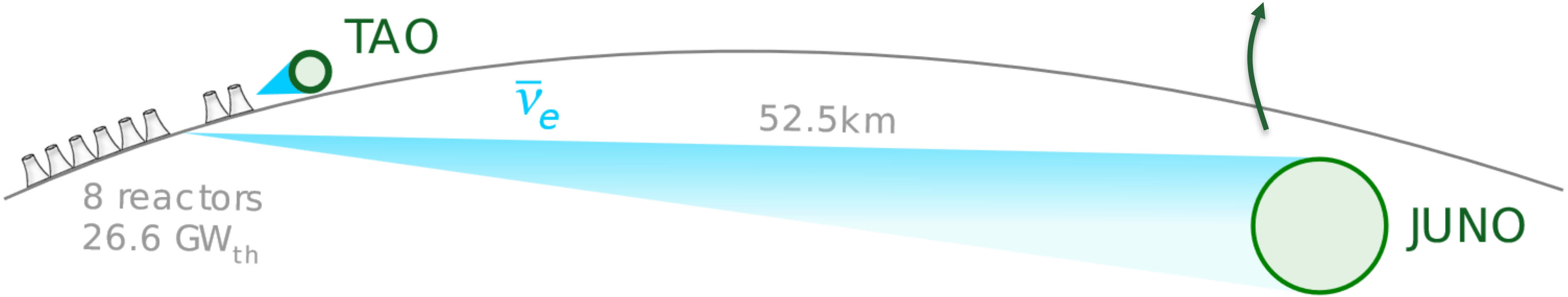
- >650 collaborators



Jiangmen Underground Neutrino Observatory

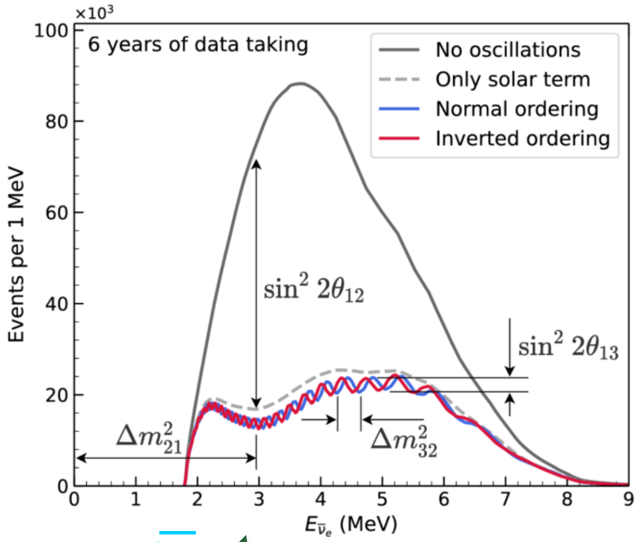
- **JUNO** is a **20-kton Liquid Scintillator** neutrino observatory located in Southern China.

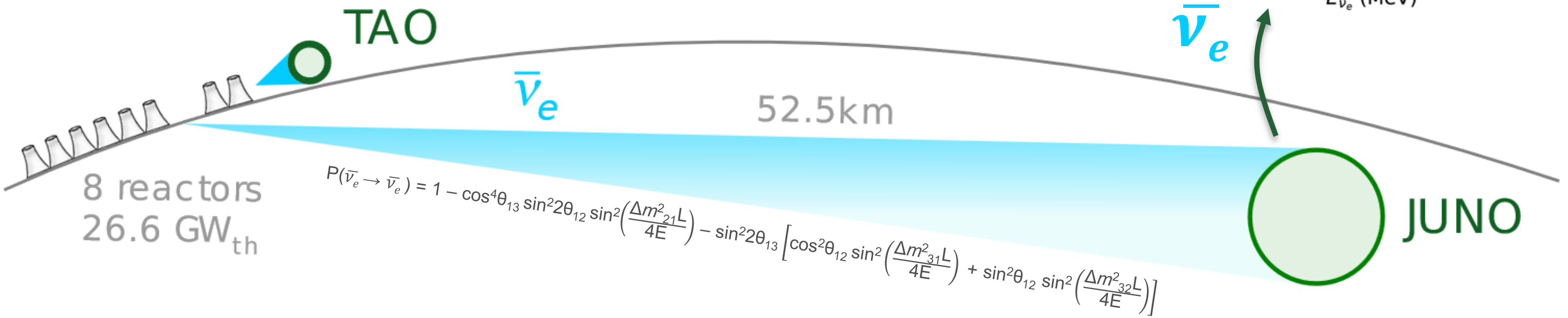




Jiangmen Underground Neutrino Observatory

- **JUNO** is a **20-kton Liquid Scintillator** neutrino observatory located in Southern China.
- JUNO studies **reactor electron antineutrino oscillations** over a medium baseline to:
  - Determine the **neutrino mass ordering**: 3σ in 6 years.
  - Measure $\boldsymbol{\Delta m^2_{31}}$, $\boldsymbol{\Delta m^2_{21}}$, and $\boldsymbol{\sin^2 2\theta_{12}}$ with sub-percent precision.



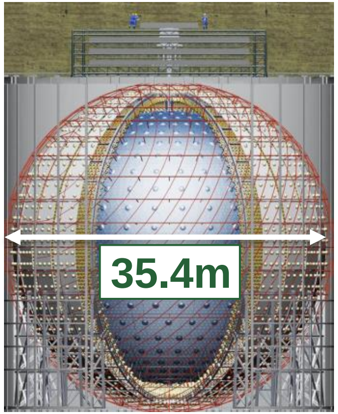


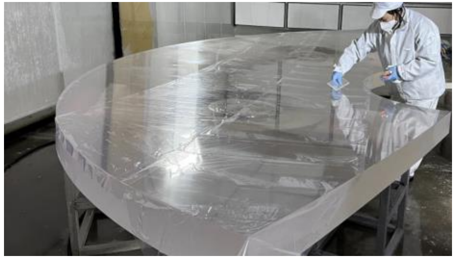
JUNO key experimental features

- **Large statistics**
  - 20-kton Liquid Scintillator (LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- **Energy resolution: 3% @ 1MeV**
  - High photon yield, highly transparent LS
  - Very high PMTs coverage (78 %)
  - High PMT efficiency (30%)
- **Low background**
  - 650m or 1800 m.w.e overburden
  - Efficient veto system (>99.5%)
  - Material screening, clean environment
- **Precise knowledge of reactor spectra**
  - Satellite detector TAO

JUNO key experimental features

- Large statistics
  - **20-kton Liquid Scintillator (LS)**
  - Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution: 3% @ 1MeV
  - **High photon yield, highly transparent LS**
  - Very high PMTs coverage (78 %)
  - High PMT efficiency (30%)
- Low background
  - 650m or 1800 m.w.e overburden
  - Efficient veto system (>99.5%)
  - **Material screening, clean environment**
- Precise knowledge of reactor spectra
  - Satellite detector TAO



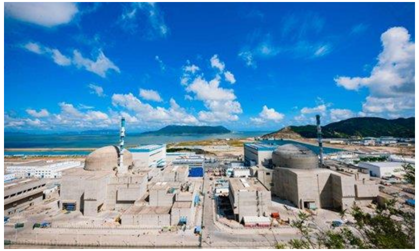


- **20kton LS**: LAB + 2.5g/L PPO + 3 mg/L bis-MSB
- **Osiris**: measures radiopurity of LS.

JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - o **Powerful nuclear reactors (26.6 GW_{th})**
- Energy resolution: 3% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - o Very high PMTs coverage (78 %)
  - o High PMT efficiency (30%)
- Low background
  - o 650m or 1800 m.w.e overburden
  - o Efficient veto system (>99.5%)
  - ✓ Material screening, clean environment
- Precise knowledge of reactor spectra
  - o Satellite detector TAO

Taishan



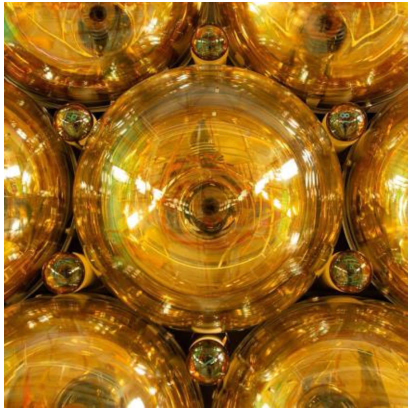
Yangjiang

- Two nuclear power plants
- 8 reactor cores
- **26.6 GW_{th}**

Reactor	Power (GW_{th})	Baseline (km)	IBD Rate (day^{-1})	Relative Flux (%)
Taishan	9.2	52.71	15.1	32.1
Core 1	4.6	52.77	7.5	16.0
Core 2	4.6	52.64	7.6	16.1
Yangjiang	17.4	52.46	29.0	61.5
Core 1	2.9	52.74	4.8	10.1
Core 2	2.9	52.82	4.7	10.1
Core 3	2.9	52.41	4.8	10.3
Core 4	2.9	52.49	4.8	10.2
Core 5	2.9	52.11	4.9	10.4
Core 6	2.9	52.19	4.9	10.4
Daya Bay	17.4	215	3.0	6.4

JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - ✓ Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution: 3% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ○ **Very high PMTs coverage (78 %)**
  - ○ **High PMT efficiency (30%)**
- Low background
  - ○ 650m or 1800 m.w.e overburden
  - ○ Efficient veto system (>99.5%)
  - ✓ Material screening, clean environment
- Precise knowledge of reactor spectra
  - ○ Satellite detector TAO



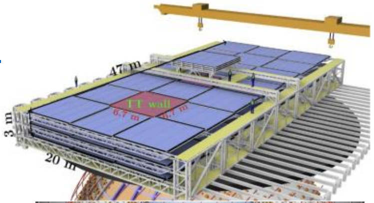
- 17,512 **20” PMTs** + 25,600 **3” PMTs**

		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		arXiv: 2205.08629		NIM.A 1005 (2021) 165347

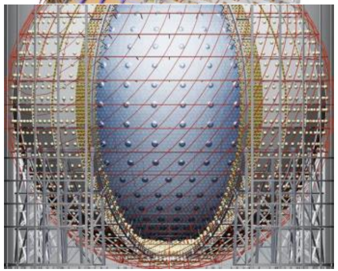
JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - ✓ Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution: 3% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ✓ Very high PMTs coverage (78 %)
  - ✓ High PMT efficiency (30%)
- Low background
  - ○ **650m or 1800 m.w.e overburden**
  - ○ **Efficient veto system (>99.5%)**
  - ✓ Material screening, clean environment
- Precise knowledge of reactor spectra
  - ○ Satellite detector TAO

- **650m overburden**: 4Hz of cosmic muons in LS
- **Top Tracker**: arXiv:2303.05172
  - ○ Opera plastic scintillator



- **Outer Cherenkov Detector**:
  - ○ 35 kton ultrapure water
  - ○ 2400 20” PMTs



- **Veto strategy** :

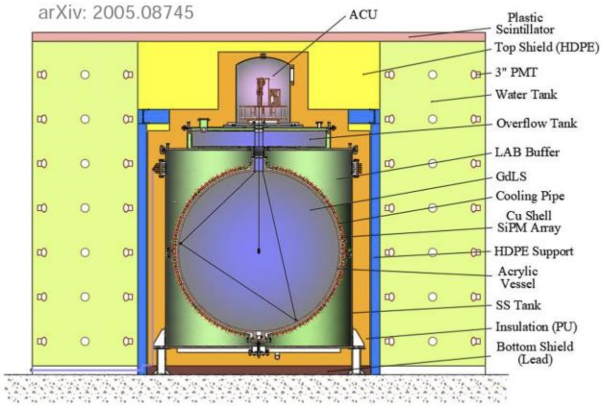
57 reactor $\bar{\nu}_e$ + 127 ^{9}Li + 40 ^{8}He events/day

⬇

47 reactor $\bar{\nu}_e$ + 0.8 ^{9}Li/^{8}He events/day

JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - ✓ Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution: 3% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ✓ Very high PMTs coverage (78 %)
  - ✓ High PMT efficiency (30%)
- Low background
  - ✓ 650m or 1800 m.w.e overburden
  - ✓ Efficient veto system (>99.5%)
  - ✓ Material screening, clean environment
- Precise knowledge of reactor spectra
  - ✓ **Satellite detector TAO**



- **TAO** can perform a precise measurement of **reactor $\bar{\nu}_e$ spectrum**:
  - 30m from reactor → 30 times JUNO event rate
  - 2.8 ton Gd-LS, 1 ton fiducial volume
  - 4500 PEs/MeV
  - SiPM: 94% coverage with 50% PDE
  - ➢ Energy resolution <2% @ 1 MeV
  - ➢ Sub-percent shape uncertainty

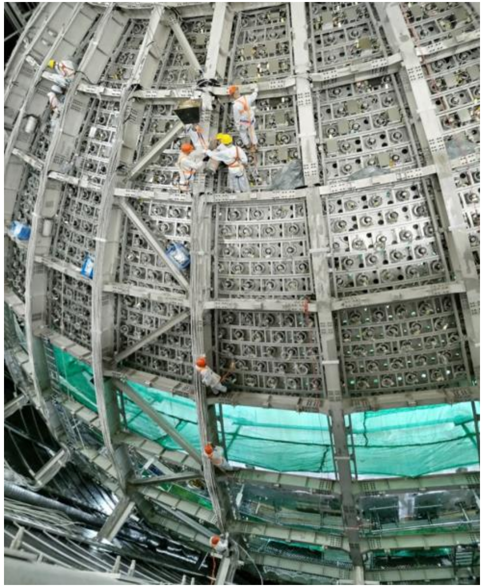
Updates on JUNO construction

- **Support Structure** completed.

- 43% of **Acrylic Vessel** installed.

- All PMTs produced and tested.
  - 4000 20” PMTs **installed**.
  - 3100 3” PMTs **installed**.

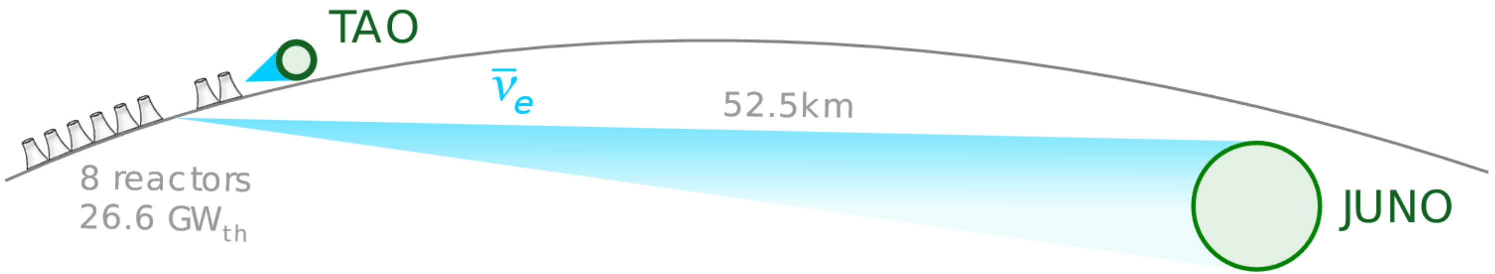
- **Detector completion** expected by **end 2023**.



June 2023

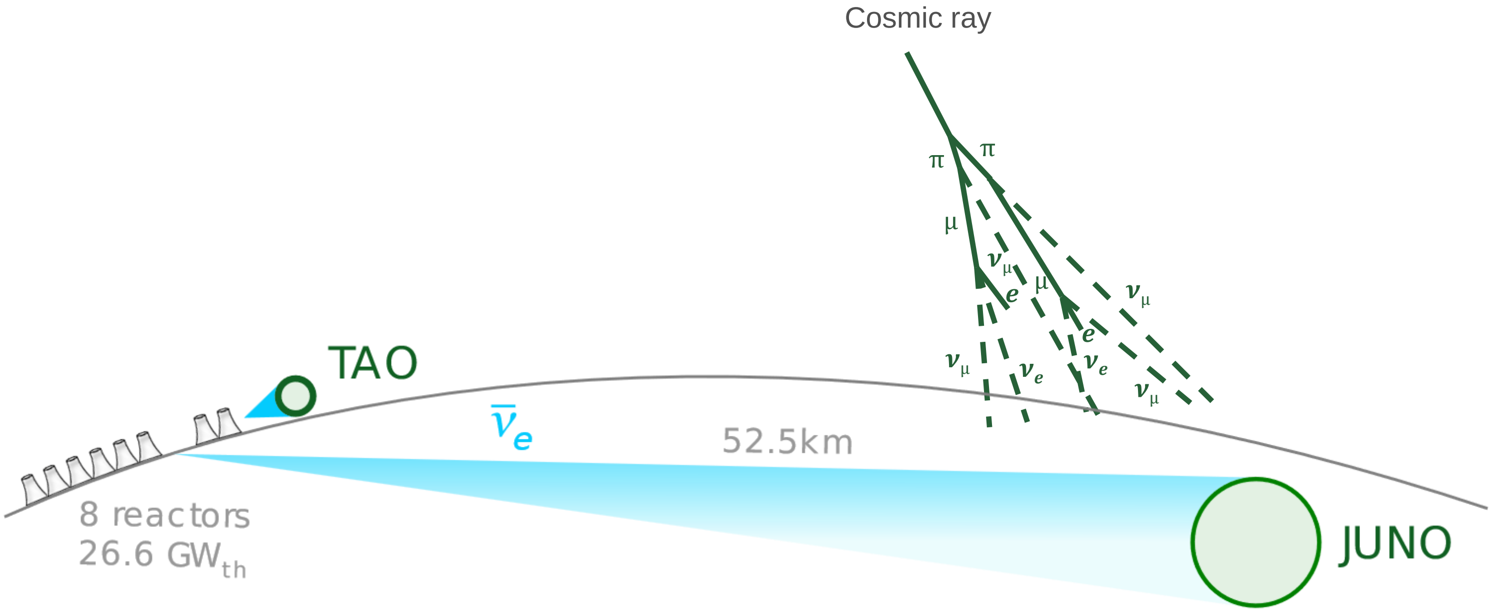
Neutrino landscape in JUNO

- **JUNO's design** also enables a **rich physics program**.



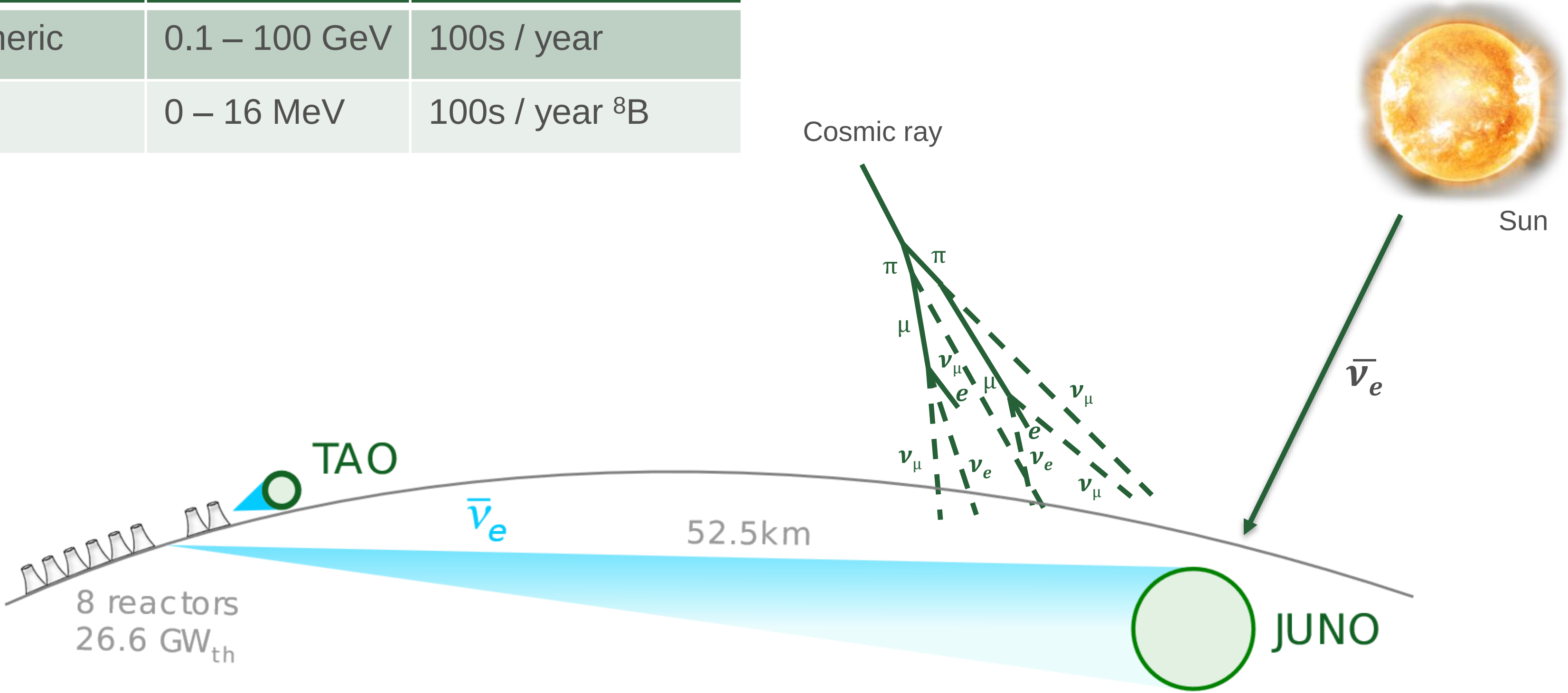
Neutrino landscape in JUNO

Neutrinos	Energy range	Rate in JUNO
Atmospheric	0.1 – 100 GeV	100s / year



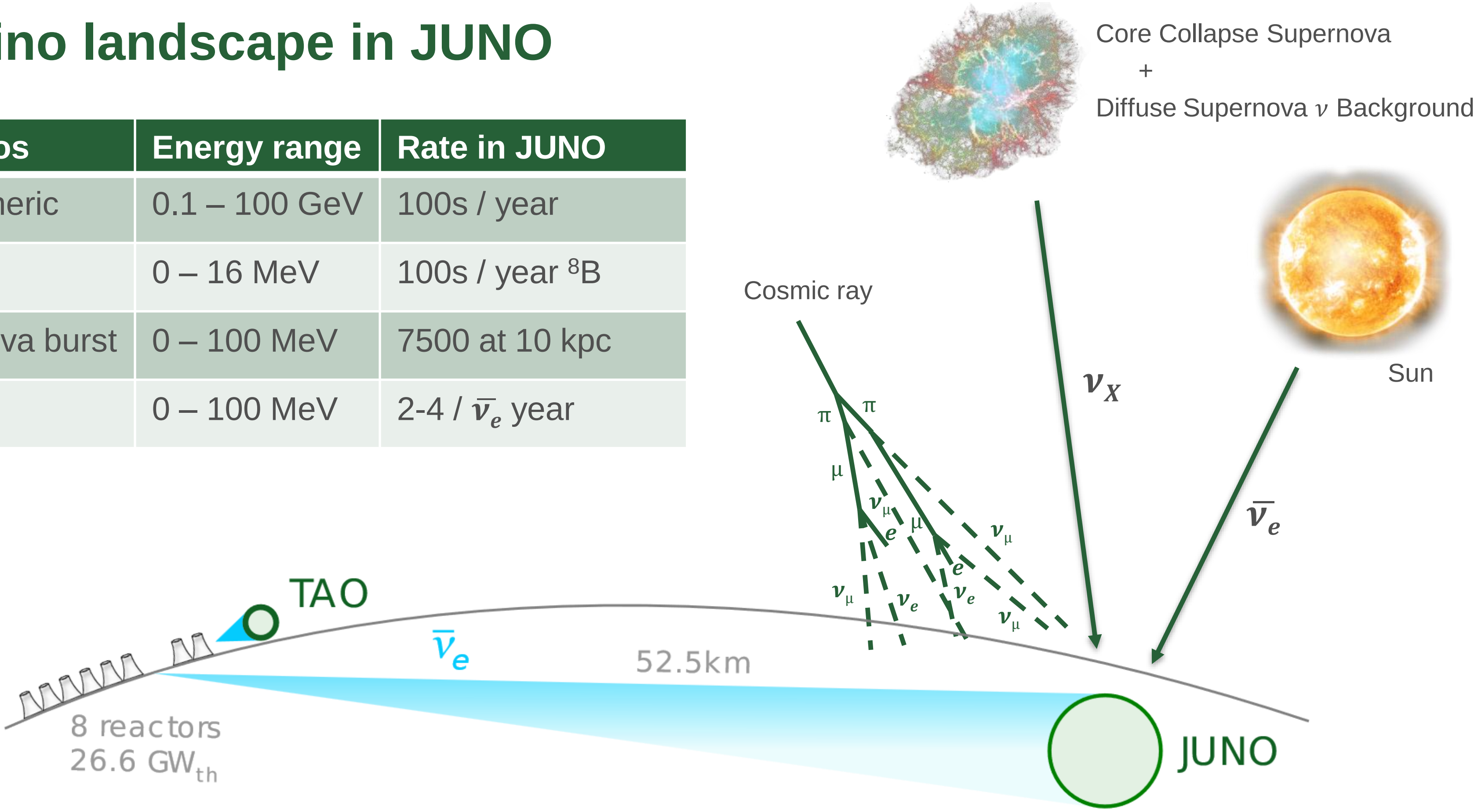
Neutrino landscape in JUNO

Neutrinos	Energy range	Rate in JUNO
Atmospheric	0.1 – 100 GeV	100s / year
Solar	0 – 16 MeV	100s / year ^8B



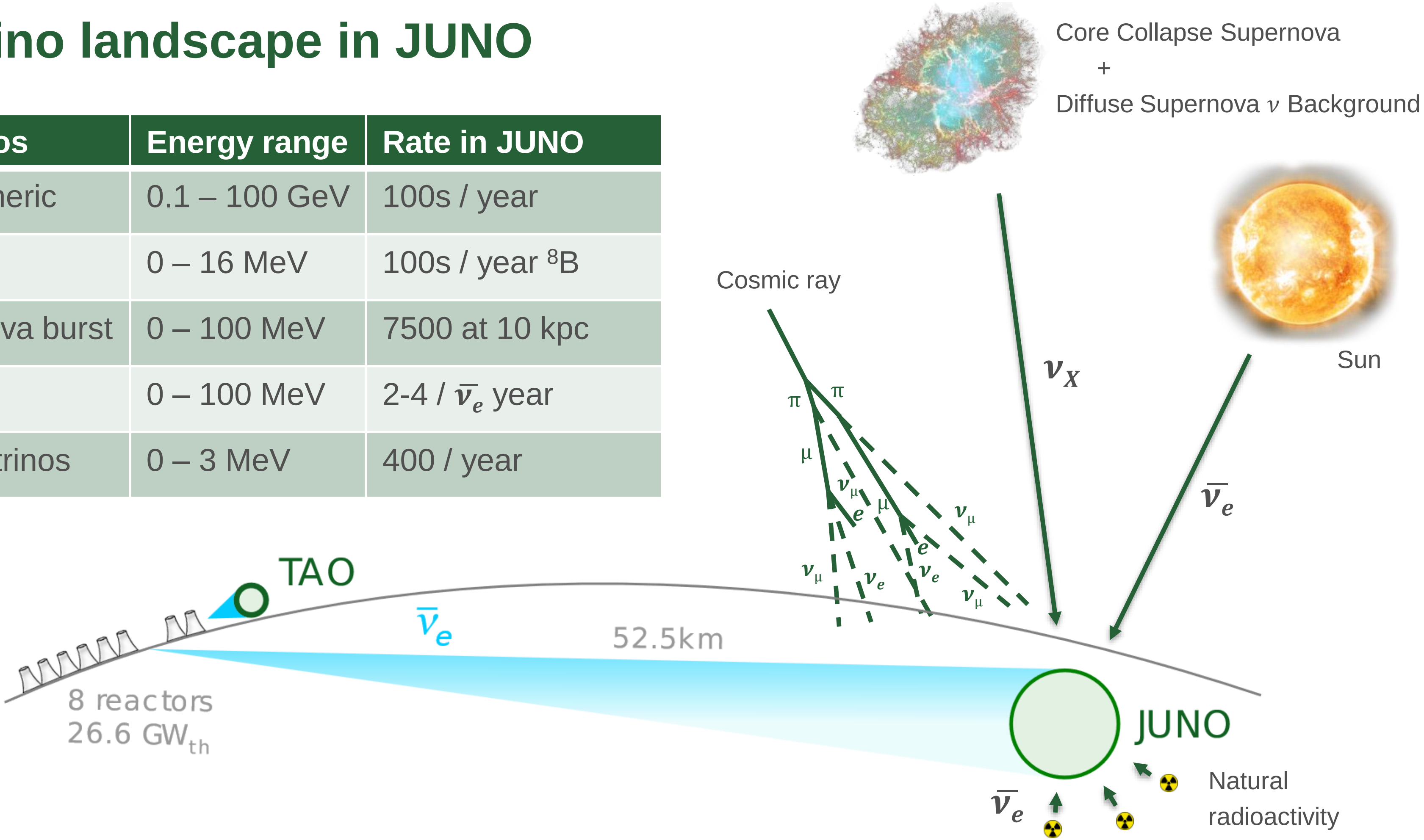
Neutrino landscape in JUNO

Neutrinos	Energy range	Rate in JUNO
Atmospheric	0.1 – 100 GeV	100s / year
Solar	0 – 16 MeV	100s / year ^{8}B
Supernova burst	0 – 100 MeV	7500 at 10 kpc
DSNB	0 – 100 MeV	2-4 / $\bar{\nu}_e$ year



Neutrino landscape in JUNO

Neutrinos	Energy range	Rate in JUNO
Atmospheric	0.1 – 100 GeV	100s / year
Solar	0 – 16 MeV	100s / year ^8B
Supernova burst	0 – 100 MeV	7500 at 10 kpc
DSNB	0 – 100 MeV	2-4 / $\bar{\nu}_e$ year
Geoneutrinos	0 – 3 MeV	400 / year



Solar neutrinos

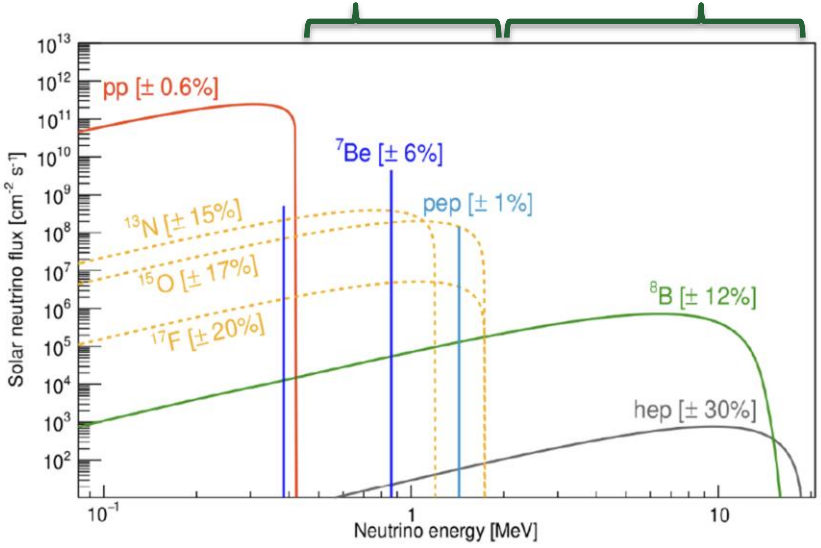
- **JUNO** sensitive to both **high** and **intermediate energy** solar neutrinos.

JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos

arXiv:2303.03910

Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program

arXiv:2210.08437

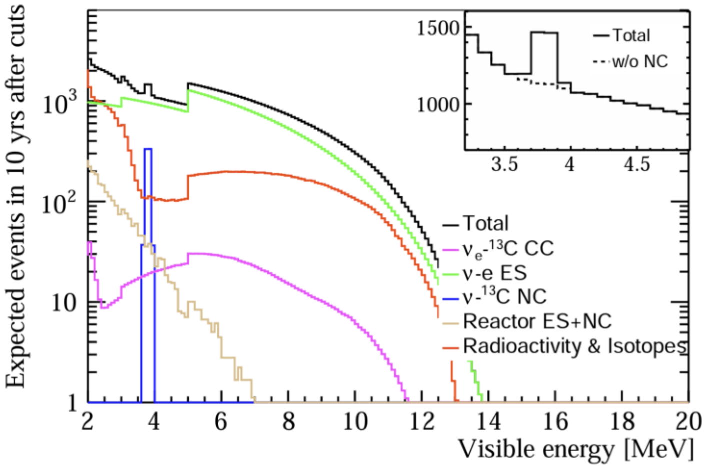


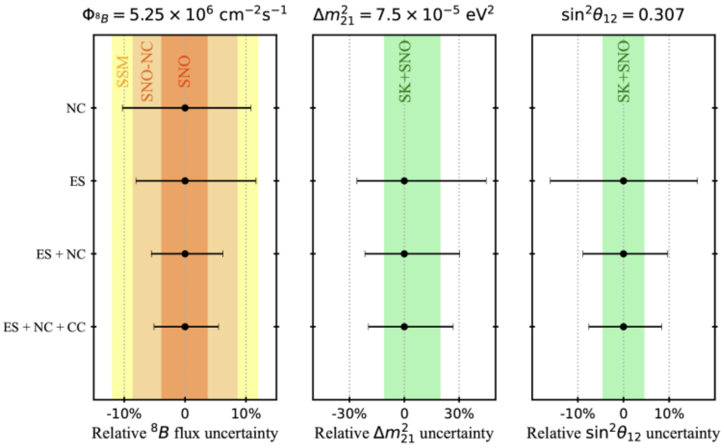
arXiv:2210.08437

High energy solar neutrinos

- Model independent detection of **^{8}B neutrinos** via three interaction channels **CC, NC** and **ES**:
  - 5% uncertainty on **^{8}B neutrino flux**
  - 20% uncertainty on **Δm^2_{21}**
  - 8% uncertainty on **$\sin^2\theta_{12}$**

Channels		Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	after cuts
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

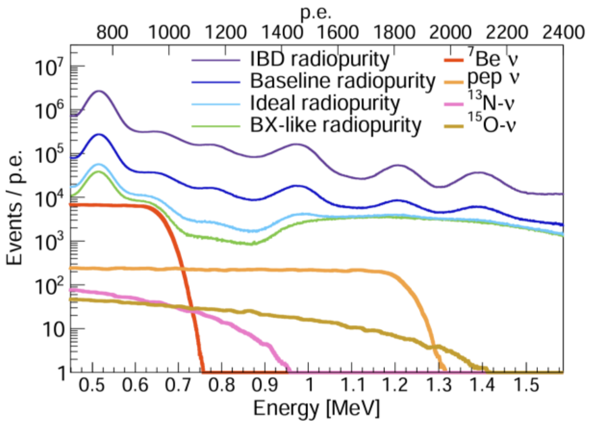




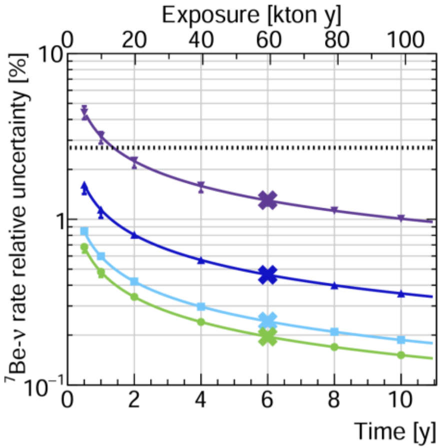
arXiv:2303.03910

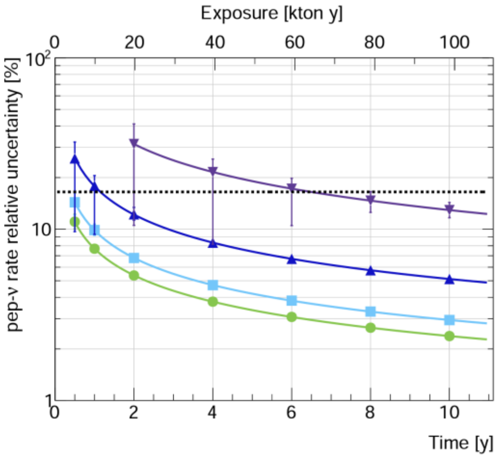
Intermediate energy solar neutrinos

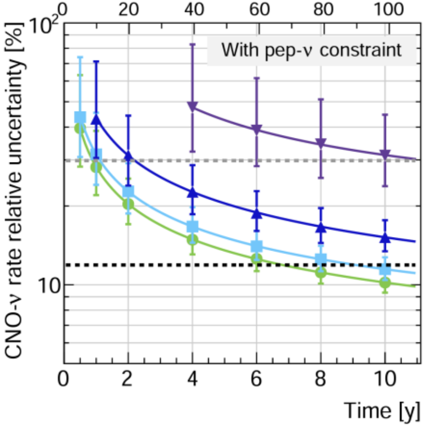
- Possible thanks to **radiopurity** efforts.
- **World leading constraints** after a few years.
- Day/Night asymmetry sensitivity <1%.



Radiopurity scenario: BX-like Ideal Baseline IBD

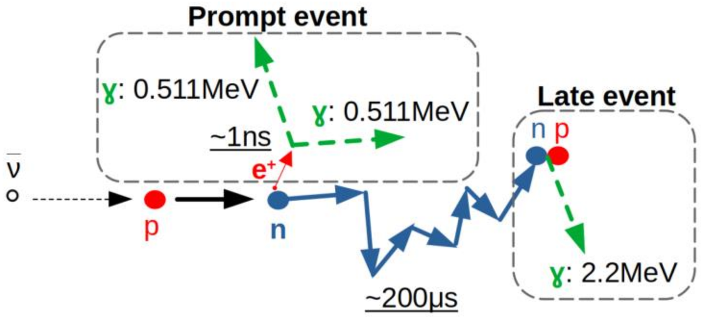


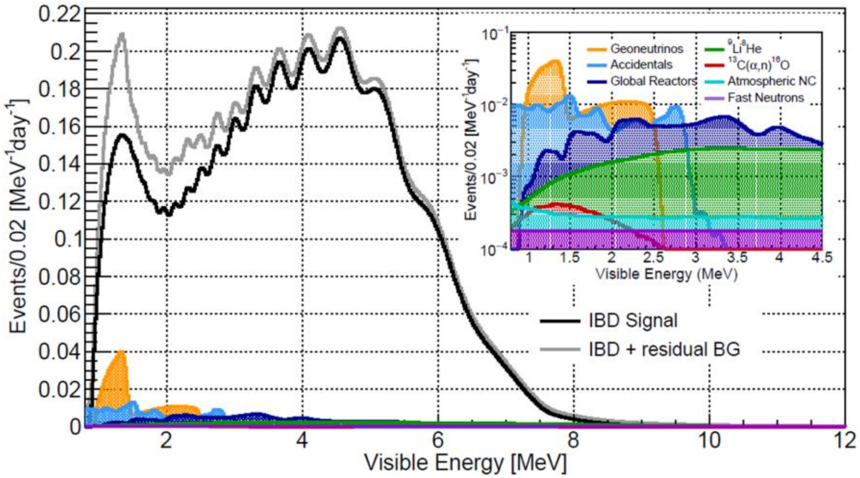




Reactor neutrino oscillations

- **47 IBD per day** expected:
  - Prompt + delayed signals to strongly suppress backgrounds.
  - 7% backgrounds, mostly below 3MeV.
  - ~10^5 IBD candidates in 6 years.

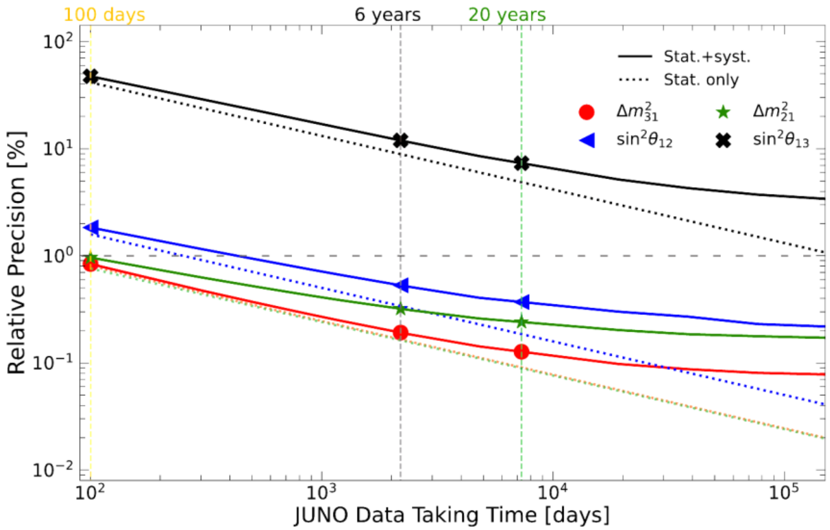




Precision measurement of neutrino oscillations parameters

- “Sub-percent Precision Measurement of Neutrino Oscillation Parameters withJUNO” arXiv:2204.13249

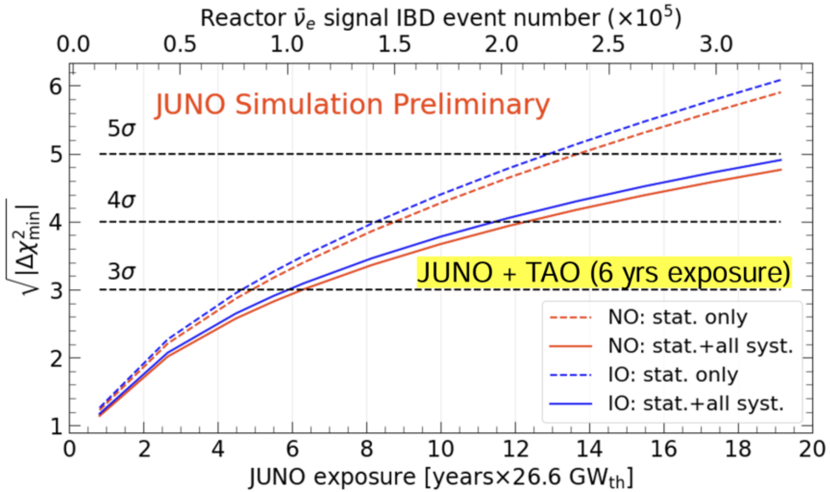
- An order of magnitude improvement over current knowledge of **Δm^2_{31}, Δm^2_{21}**, and **$\sin^2\theta_{12}$.**



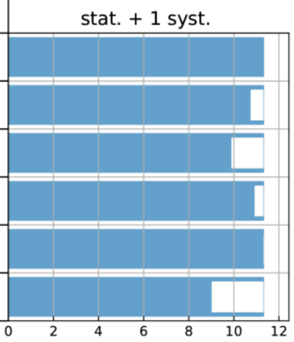
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (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%)

Determination of the neutrino mass ordering

- NMO paper in preparation.
- JUNO reactor neutrino oscillation analysis alone provides a **3σ sensitivity** to **NMO** in **6 years**!
- Combination with **atmospheric neutrino analysis** in progress.



6 years	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



JUNO Simulation Preliminary

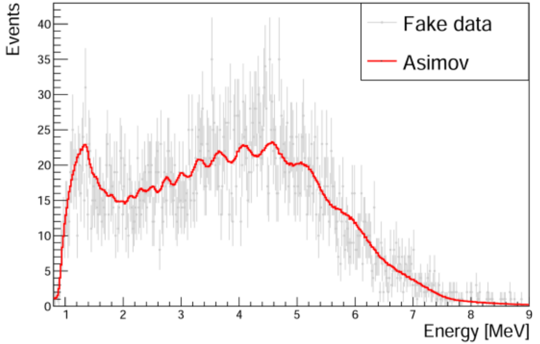
Reactor neutrino analysis at Subatech

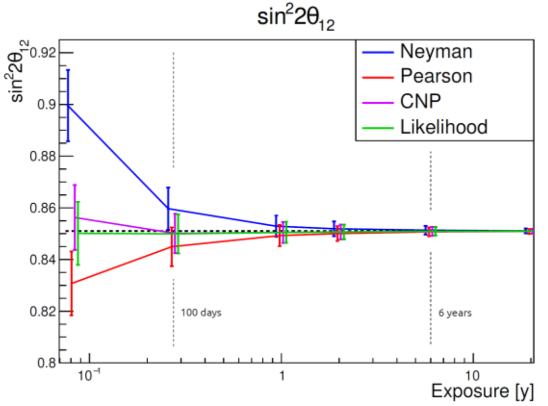
- Development of **analysis framework AveNu_e**.

- **Sensitivity studies** for JUNO:
  - Data taking in 2024.
  - Until now, only Asimov sensitivities.
  - Development of **statistically realistic framework**: median sensitivity vs Asimov, biases, statistical coverage, pulls, etc…

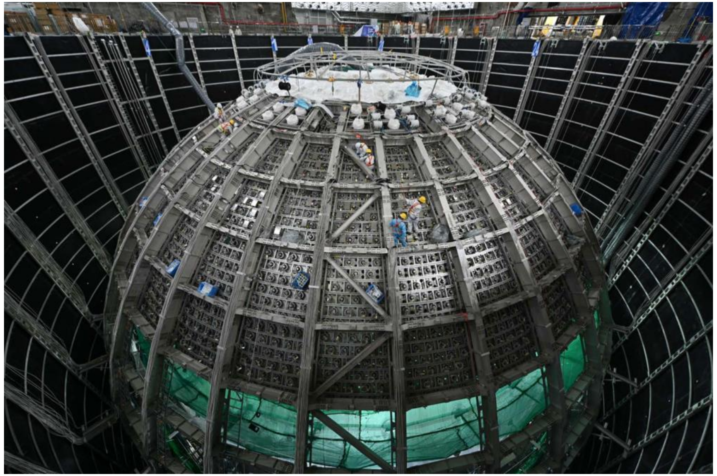
- Preparation for a **100-day measurement**: statistical challenges being identified and addressed.

- Improve **JUNO NMO sensitivity** using **NOvA** and **T2K** results.





Conclusions



- **JUNO detector construction** underway: **first data** next year!
- Multipurpose 20-kton Liquid Scintillator neutrino observatory with a **rich physics program**.

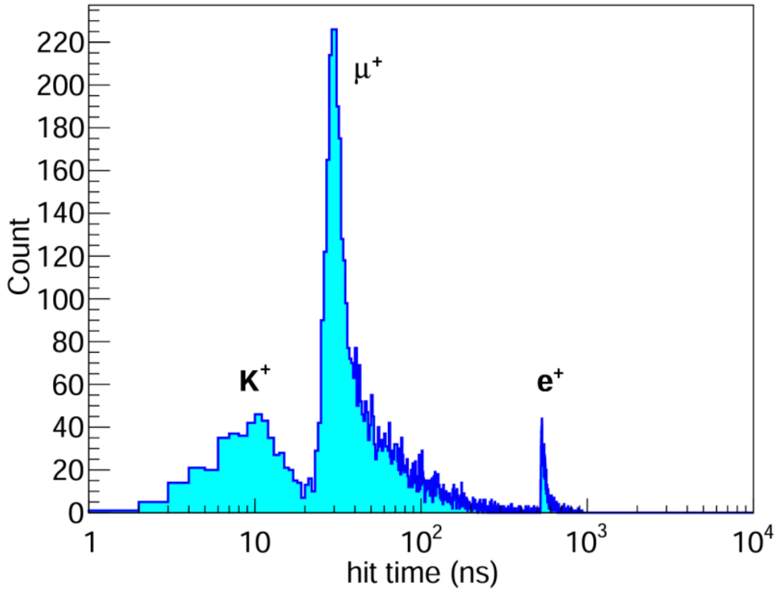
➢ JUNO will measure Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ with unprecedented accuracy <0.5%.

➢ JUNO will determine the **Neutrino Mass Ordering** at **3σ significance in 6 years.**

Backup

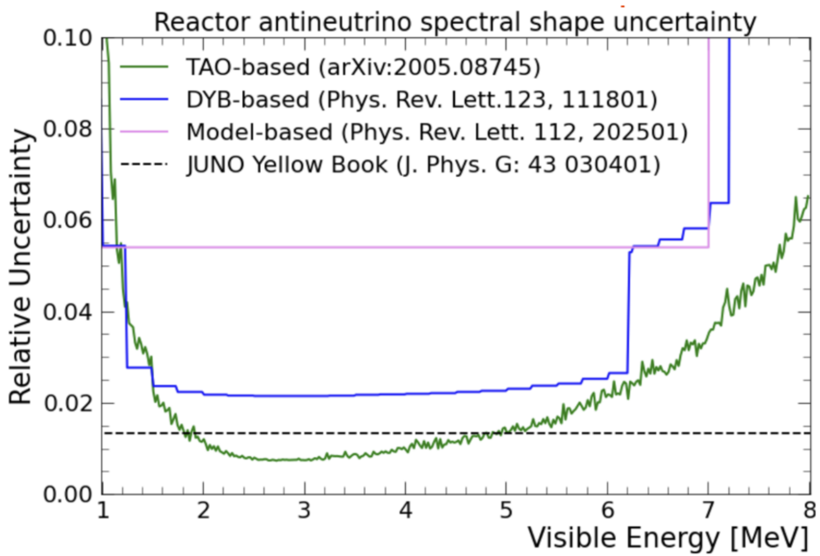
Proton decay

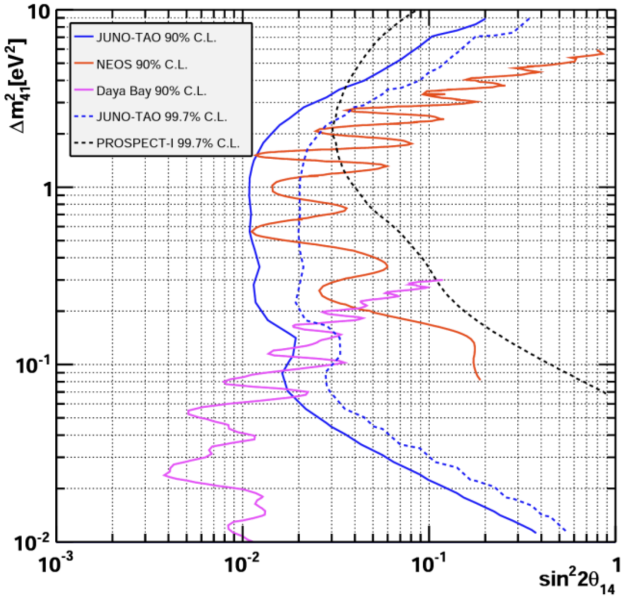
- **$p \rightarrow \bar{\nu}\ K^+$** : three-fold coincidence to detect proton decay with high efficiency (36.9%).
- Good energy resolution helps reduce the backgrounds: less than 0.2 events after 10 years.
- Competitive limit on **proton lifetime** of **9.6×10^{33} years** for 200 kton-year exposure.
- More details in arXiv:2212.08502 .



TAO

- **Sub-percent precision** on reactor neutrino **spectrum shape**.
- **TAO** can search for **sterile neutrinos**.





Precision measurement

- **Statistical** and **systematic uncertainties** for **6 years**.

Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

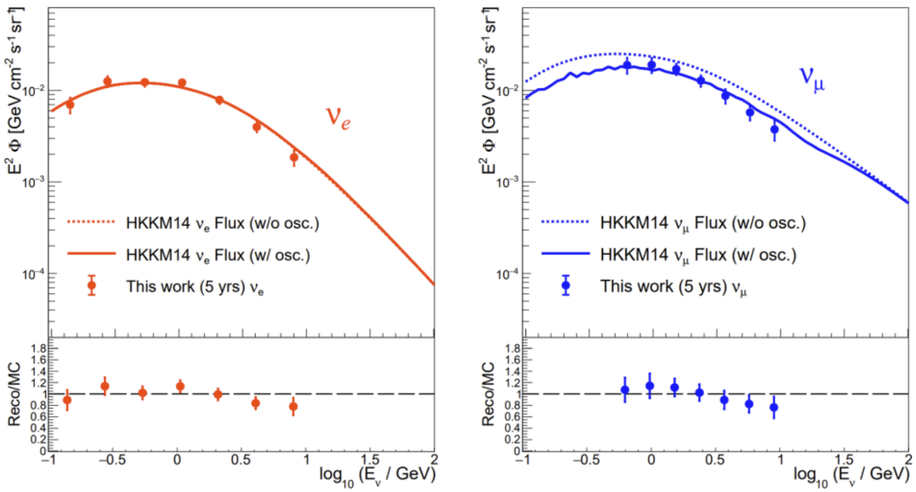
Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32

$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52

$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11

Atmospheric neutrinos

- Detect and discriminate **ν_e and ν_μ CC interactions** through **event time profile**.
- Sensitivity to **NMO** through **matter effects**: **0.7-1.4σ** in 6 years.
- Can be combined with **reactor NMO analysis**.



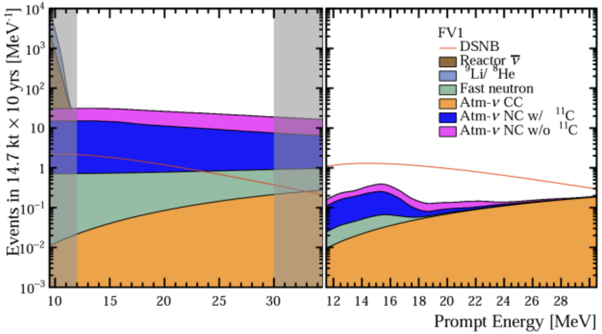
Core collapse supernova neutrinos

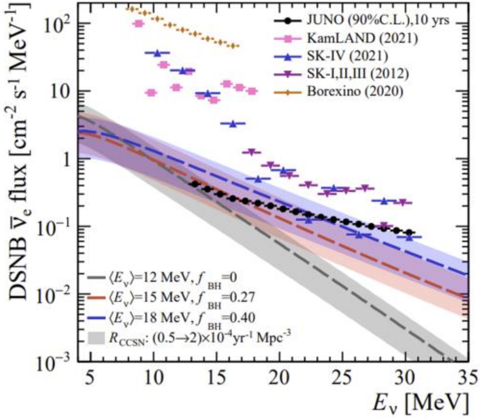
- Core collapse supernova neutrinos detection channels :

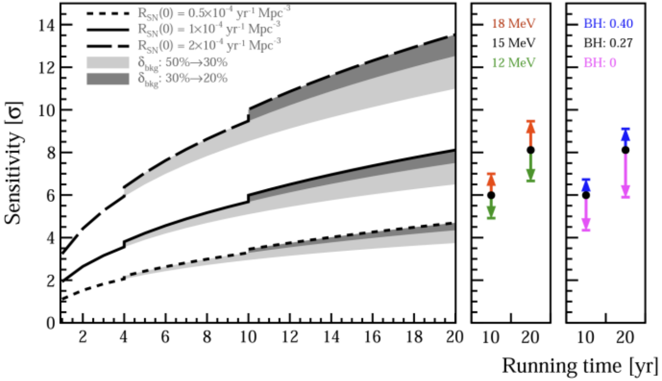
Process	Num. Events (E_{thr} = 0.2MeV)
IBD | $\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
pES | $\nu + p \rightarrow \nu + p$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~2000
eES | $\nu + e \rightarrow \nu + e$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~400
CC | $\overset{(-)}{\nu}_e +^{12}C \rightarrow e^{-(+)} +^{12}N(^{12}B)$	~200
NC | $\nu +^{12}C \rightarrow \nu +^{12}C^*$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$ $\rightarrow \gamma(15.11\text{MeV})$	~300

DSNB

- **DSNB** 2-4 per year (w/o PSD)
- **3σ discovery** potential in **3 years** (reference model).



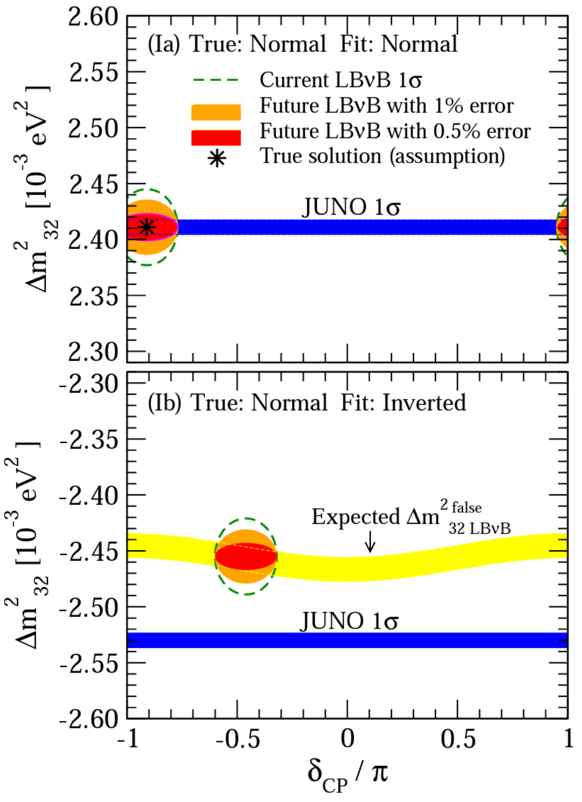




Geoneutrinos

- **Geoneutrinos**: 400 $\bar{\nu}_e$ per year (0-3MeV)
  - More than Borexino and KamLAND combined in 1 year. To date, Borexino + KamLAND = ~200 events.
- Decay of radionuclides (U/Th/K) within the Earth.
- Measure U and Th abundances, **U/Th ratio** in crust and mantle **: 30% uncertainty in 10 years**.
- **Probes** : Earth's formation, Mantle convection, Plate tectonics,Earth's magnetic field production

Synergy between JUNO and NOvA+T2K



- A **5σ determination of NMO** is possible by combining **JUNO** and **NOvA+T2K's results**.

- See arXiv:2008.11280