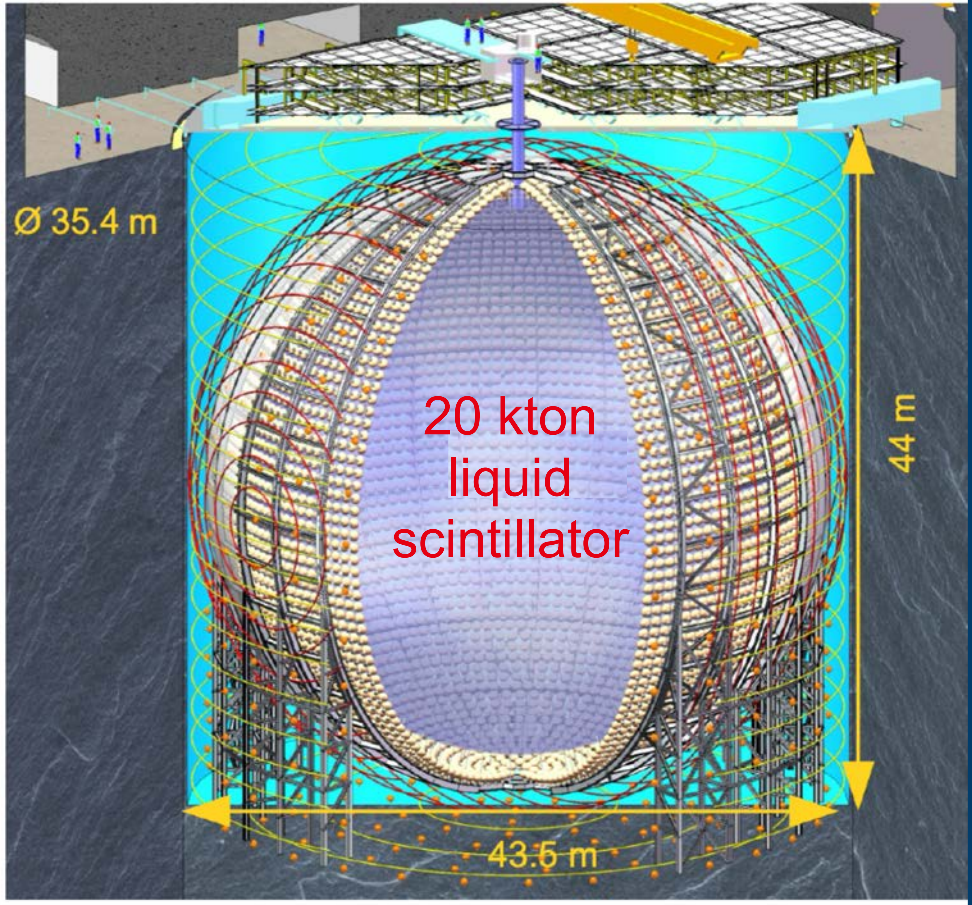
JUNO STATUS

LIVIA LUDHOVA

ON BEHALF OF THE JUNO COLLABORATION

IKP-2, FORSCHUNGSZENTRUM JÜLICH

AND RWTH AACHEN UNIVERSITY, GERMANY



AUGUST 1ST, 2022

INVITED PLENARY TALK

23rd International Workshop on Neutrinos from Accelerators (NUFACT 2022)

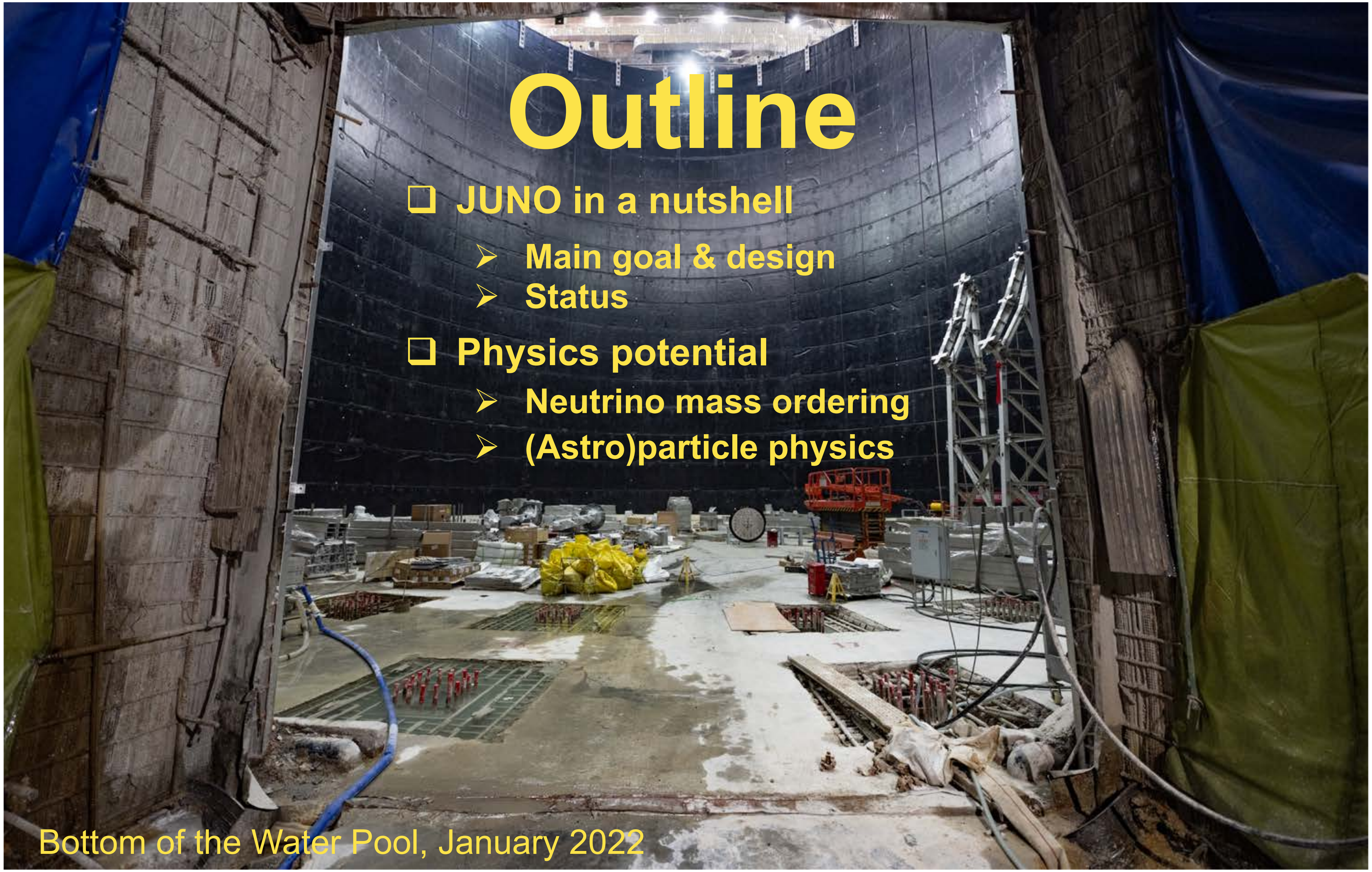
Mitglied der Helmholtz-Gemeinschaft

RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum

Outline

- ❑ **JUNO in a nutshell**
  - ➢ Main goal & design
  - ➢ Status
- ❑ **Physics potential**
  - ➢ Neutrino mass ordering
  - ➢ (Astro)particle physics



Bottom of the Water Pool, January 2022

Jiangmen Underground Neutrino Observatory

The first multi-kton liquid scintillator (LS) detector ever built.

Construction in south China to be completed by the end of 2023.
Neutrino Mass Ordering (NMO) - 3σ in ~6 years.
Many other goals: neutrino properties, astrophysics, and rare processes.

Train in the slope tunnel, Jan 24, 2022

JUNO COLLABORATION

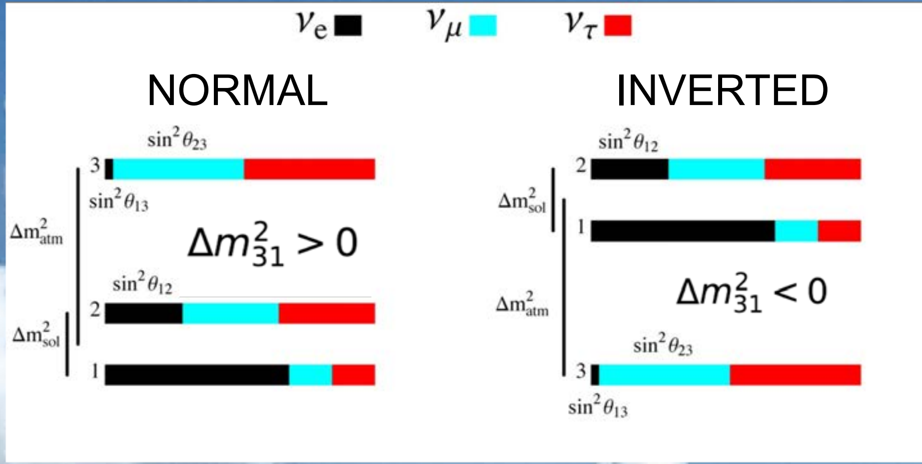
JUNO Collaboration

- established in 2014
- 76 institutions
- 694 collaborators

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		

Main goal: Neutrino Mass Ordering with the strongest human-made neutrino source

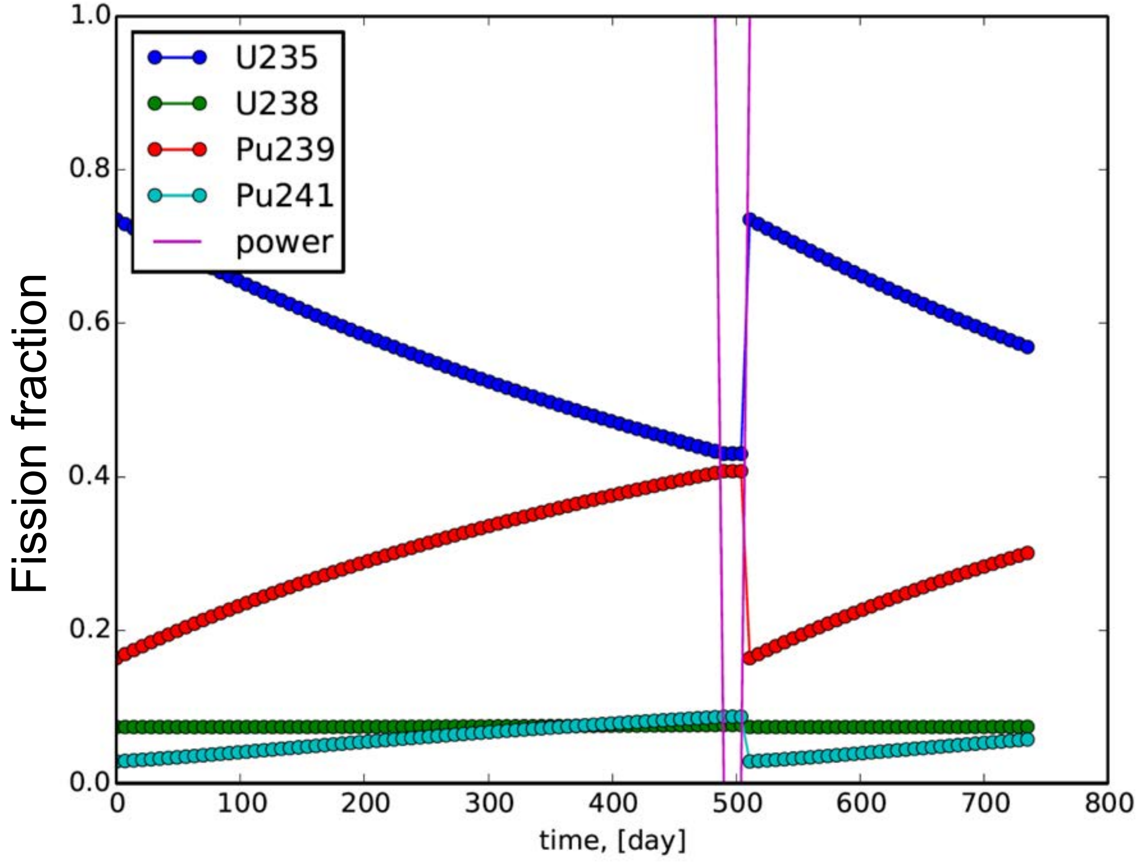
Neutrino Mass Ordering (NMO)

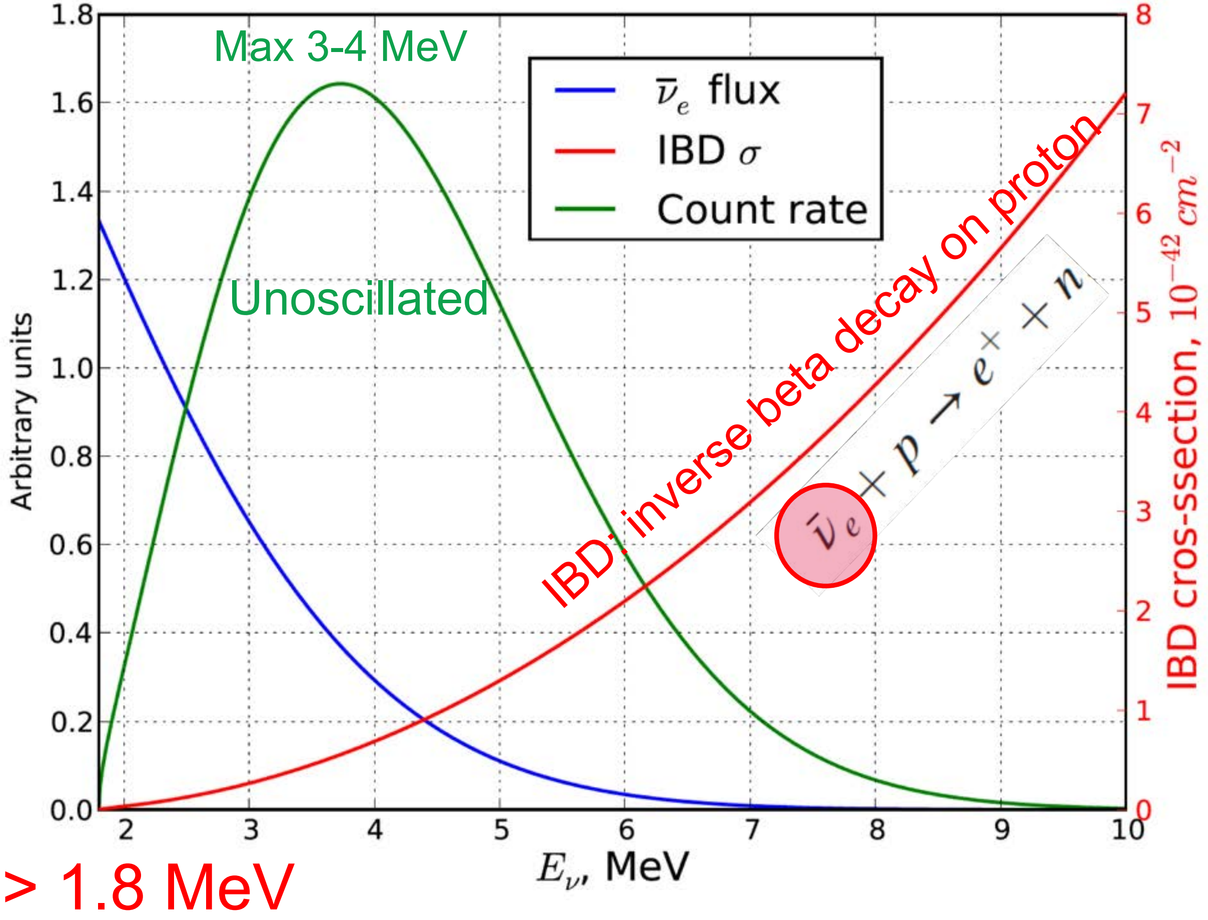


https://news.fnal.gov/2015/10/neutrino-mixings-masses/

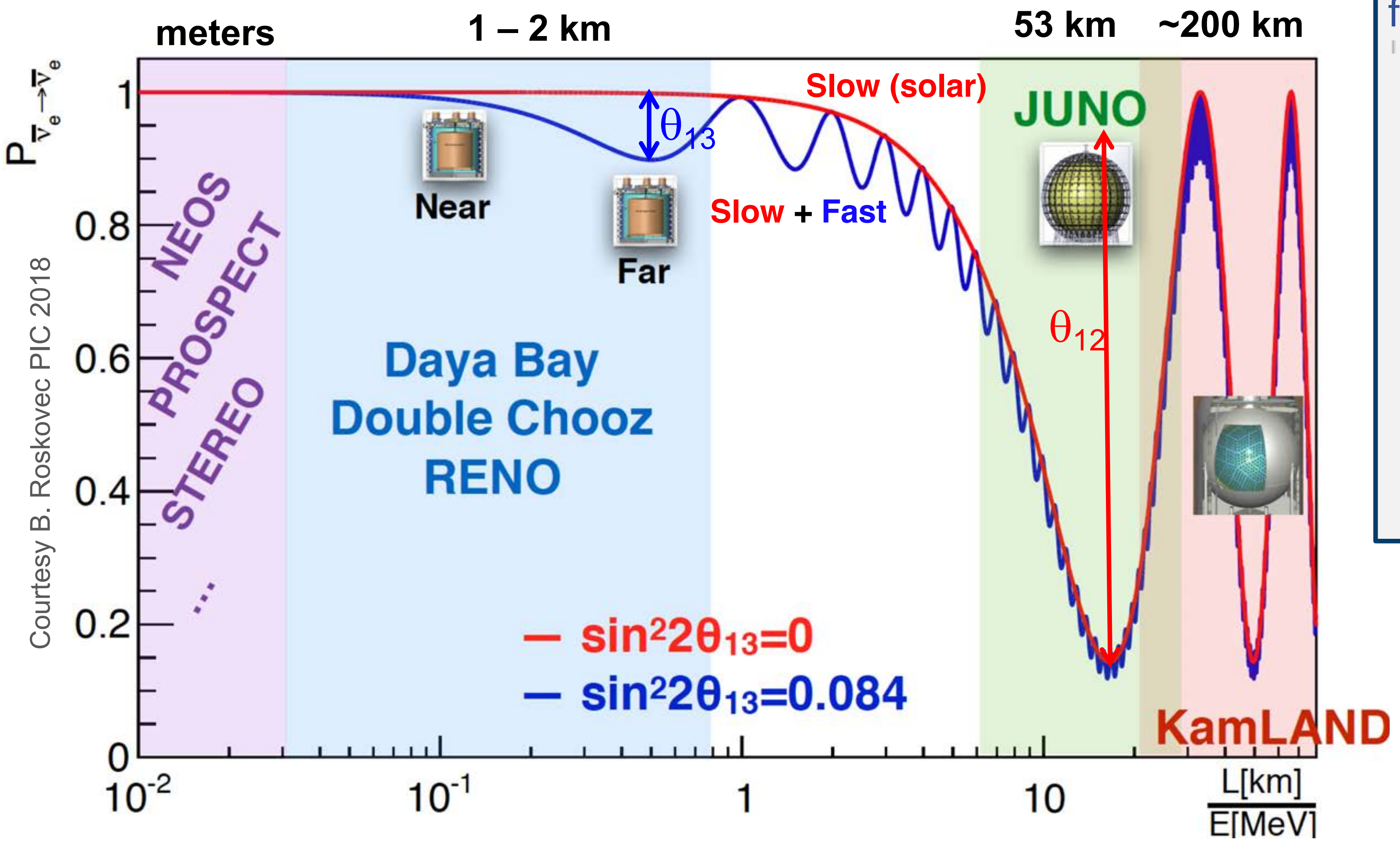
A typical nuclear reactor emits every second about 10^{20} electron flavour antineutrinos (E > 1.8 MeV = detectable with present day technology)

REACTOR ANTINENUTRINO SPECTRUM AND FUEL CYCLE





JUNO AMONG REACTOR NEUTRINO EXPERIMENTS AT DIFFERENT BASELINES



Electron survival probability for reactor antineutrinos

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

Slow (solar)

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Fast (atm.)

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

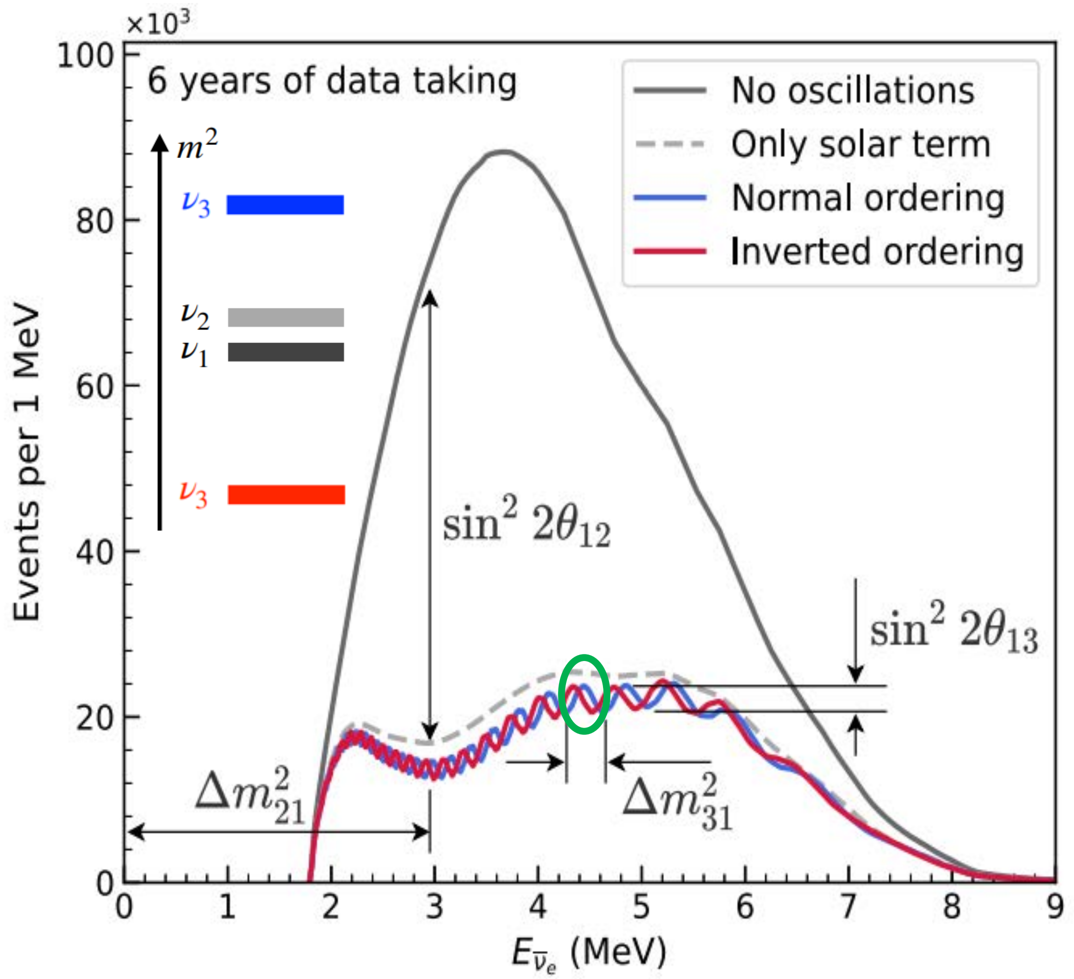
Normal ordering: $\Delta m^2_{31} > 0$

Inverted ordering: $\Delta m^2_{31} < 0$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

- 53 km baseline used only by JUNO .
- Fast oscillation pattern of reactor antineutrinos at 53 km baseline.
- **Dependent on NMO (sign of $\Delta m^2_{31/2}$)**
- **Independent from δ_{CP} and θ_{23}.**

REACTOR ANTINEUTRINO SPECTRUM @ JUNO



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

- Method for the **Neutrino Mass Ordering** with reactors antineutrinos suggested by Petcov and Piai, PLB 553 (2002) 94.
- **Complementarity** to the method based on matter effects on long baseline oscillations of atmospheric and accelerator neutrinos that depend also on δ_{CP} and θ_{23}.
- High sensitivity to the **oscillation parameters**
  - solar mixing angle θ_{12}
  - solar mass splitting Δm^2_{21}
  - atmospheric mass splitting Δm^2_{31}

JUNO PHYSICS CHALLENGES

(more details by Michele Montuschi on Friday's plenary talk)

- Resolving signature wiggles of the fast oscillation in the energy spectrum
  - excellent **energy resolution ~3% @ 1 MeV**
  - better than **1% understanding of the intrinsically non-linear energy scale of the liquid scintillator (LS)**
  - **possible micro-structures in the reactor spectrum under control** (PRL 114 (2015) 012502)
- Large antineutrino statistics O(100k) @ 53 km baseline: **powerful reactors (26.6 GW_{th}) & large mass (20 kton)**
- **Backgrounds:**
  - cosmogenic background: rock overburden of 650 m
  - radio-purity of all materials: < 10^{-15} / 10^{-17} g of U/Th /g of LS for NMO/solar physics (JHEP 11 (2021) 102)
- **Time stability** over several years

Stochastic terms in the energy resolution (photon statistics)

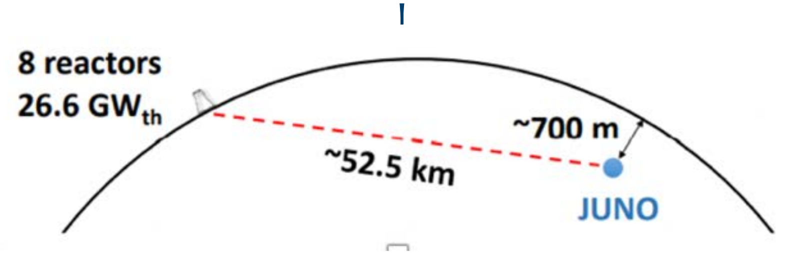
- **High light yield (LY ~ 10^4 photons/MeV)**
- **LS transparency: λ_{att} > 20 m @ 430 nm**
- **PMT geometrical coverage: 78%**
- **PMT collection efficiency x quantum efficiency: ~30%**

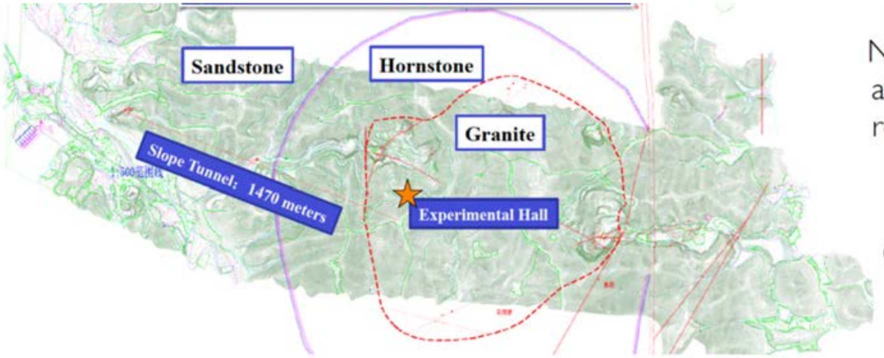
Systematic effects in the energy scale/spectra

- **Calibration** (JHEP 03 (2021) 004 and **Davide Basilico talk in WG 6**)
  - ✓ $\alpha/\beta/\gamma$ sources, light pulses, UV-laser
  - ✓ 5 complementary systems
- **Double calorimetry concept**
  - ✓ large 20" and small 3" PMTs
- **TAO** – Taishan Antineutrino Observatory with an excellent energy resolution <2% (stat) @ 1MeV (arXiv:2005.08745, 2020)

JUNO EXPERIMENTAL SITE IN SOUTH CHINA

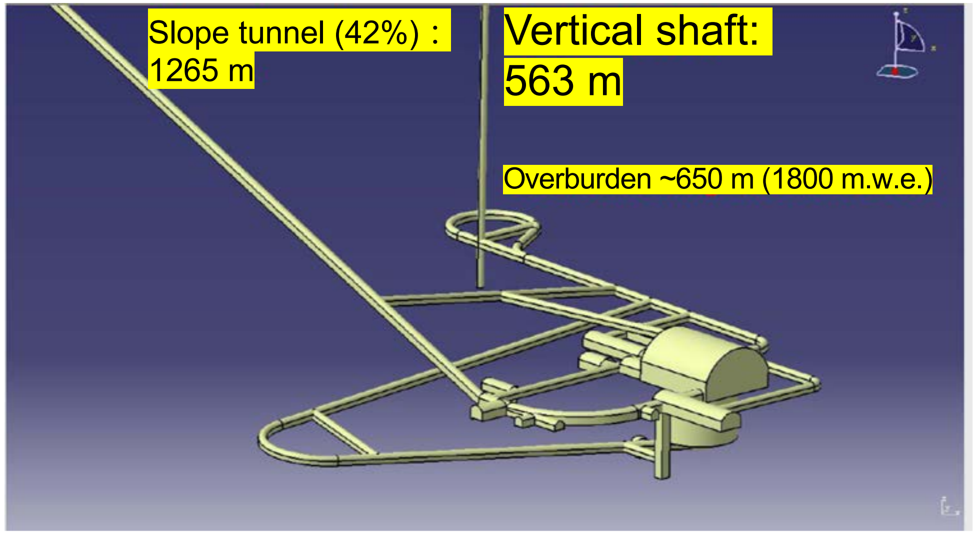
	Yangjian						Taishan			
Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265





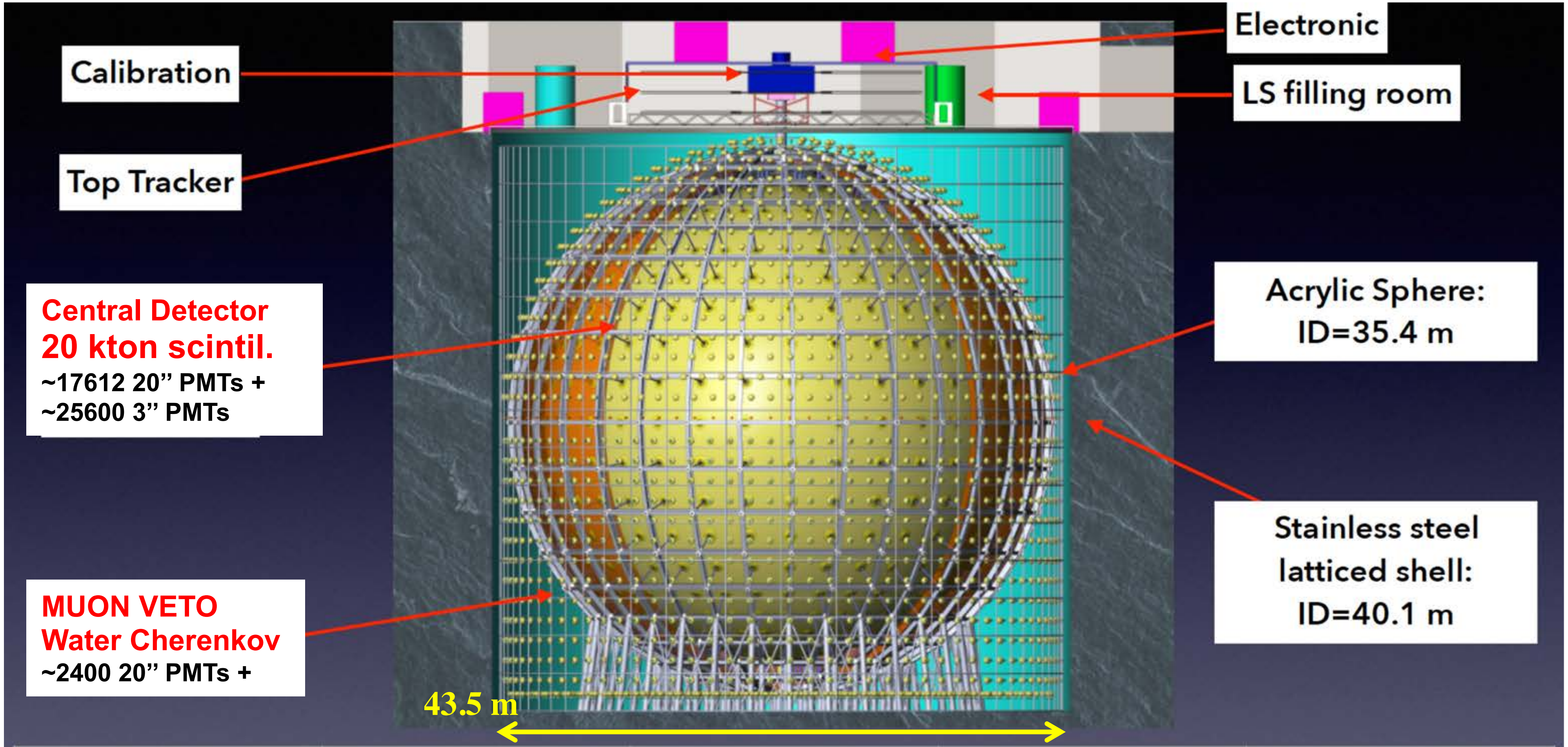
Nice granite structure at right distance from reactors (very lucky!)

Jiangmen City
Guandong province



CIVIL CONSTRUCTION FINISHED IN DECEMBER 2021

JUNO DETECTOR



Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	8x 20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	78%
Energy resolution	8.5% / √E MeV	~5%/√E MeV	~6%/√E MeV	~3%/√E MeV
Eff. Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	>1345 p.e./MeV

JÜLICH
Forschungszentrum

CONSTRUCTION HIGHLIGHTS

Installation platform finished (May 2022)

Support structure finished (June 2022)

CONSTRUCTION HIGHLIGHTS

(more details by Michele Montuschi on Friday‘s plenary talk)

Distillation & LS mixing plant in ground hall

Installation of acrylic panels started

Large PMTs are potted and tested

OSIRIS - LS monitor – under installation

Electronics assembled

<u>Key steps ahead:</u>

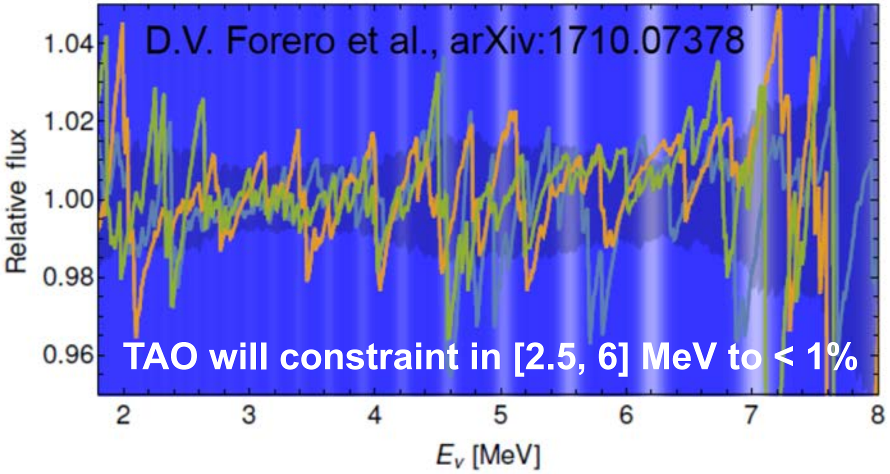
- Acrylic vessel installation
- PMT installation
- Completion of the LS purification plants
- 6 months of LS filling (water replacement)

JUNO-TAO – TAISHAN ANTINEUTRINO OBSERVATORY

Satellite detector of JUNO

2.8 ton Gd-loaded liquid scintillator detector at -50℃ at ~30 m baseline from the Taishan-1 reactor core (4.6 GW_{th}):

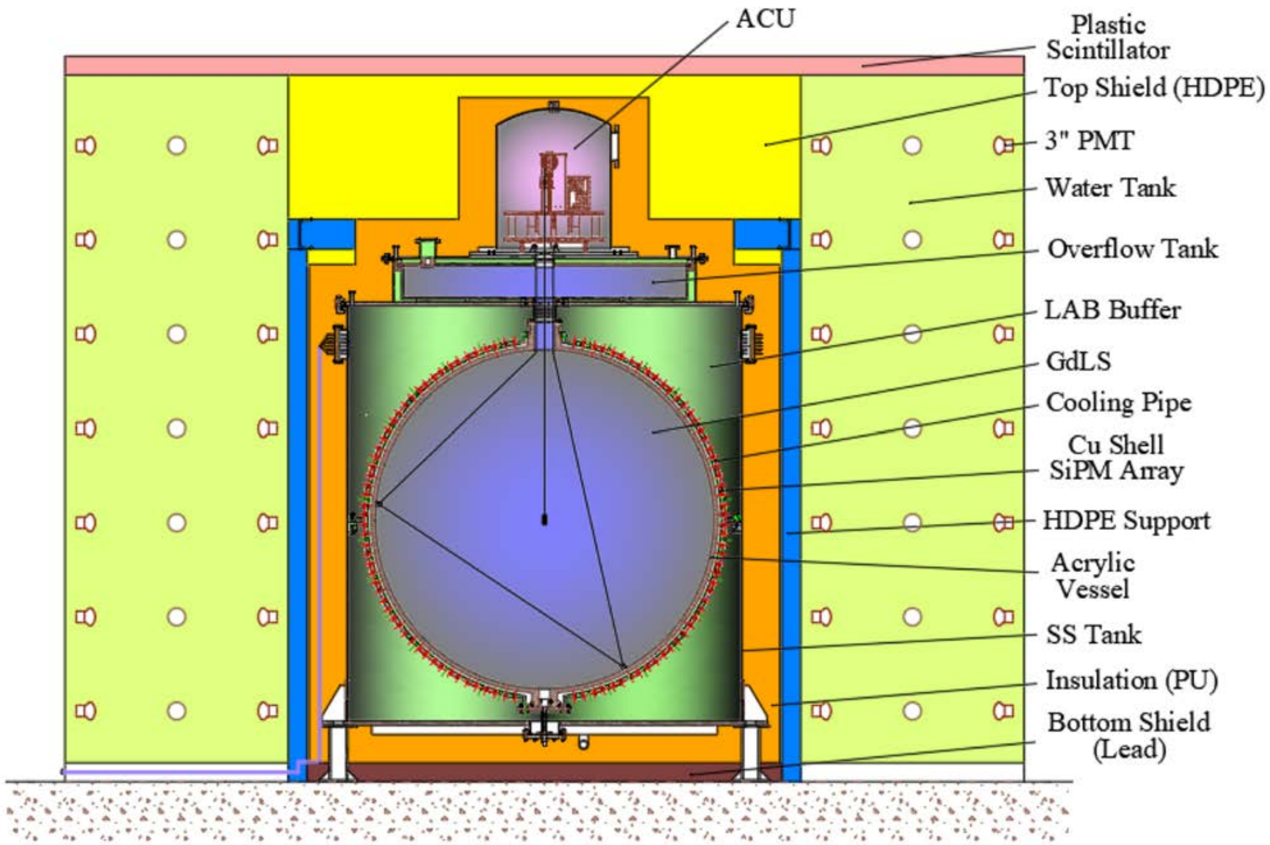
- **Reference spectrum for JUNO**
- Benchmark for nuclear databases
- Isotopic yields & spectra
- Search for sterile neutrino in 10^{-1} eV^2 < Δm^2_{41} < 10 eV^2



Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)

CDR: arXiv: 2005.08745

Calibration strategy: *arXiv: 2204.03256*

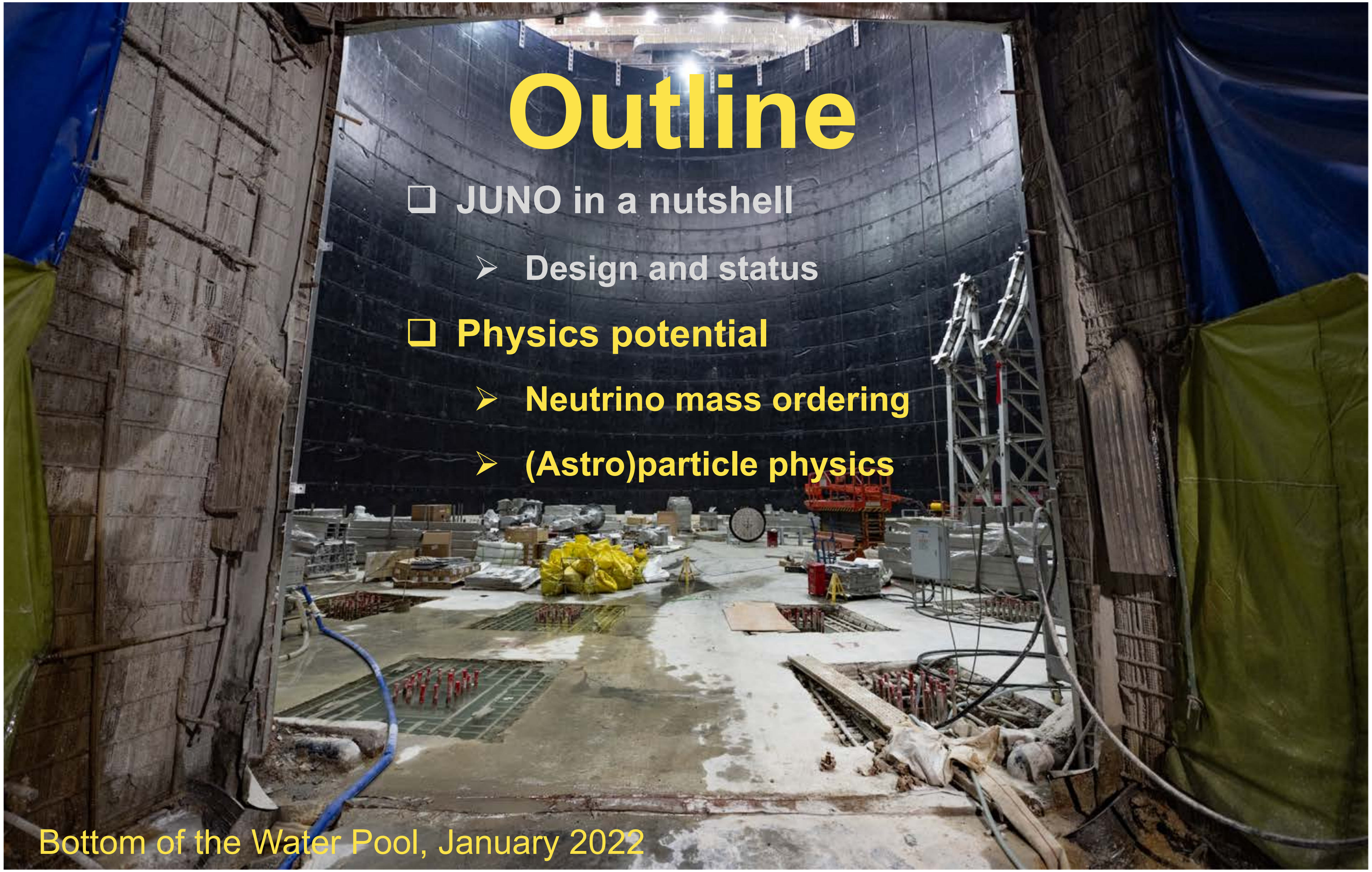


~10 m^2 SiPM (>94% coverage) with 50% photon detection efficiency operated at -50 °C → 4500 p.e./MeV & energy resolution < 2% @ 1 MeV

1:1 Prototype will be completed soon at IHEP, China

Outline

- ❑ JUNO in a nutshell
  - ➢ Design and status
- ❑ Physics potential
  - ➢ Neutrino mass ordering
  - ➢ (Astro)particle physics



Bottom of the Water Pool, January 2022

A MULTI-PURPOSE OBSERVATORY

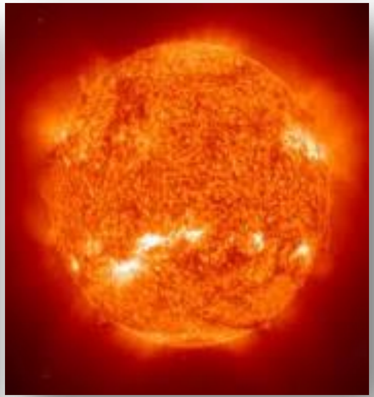
Reactor anti-ν

~60 / day

Atmospheric ν

Several / day

Solar ν



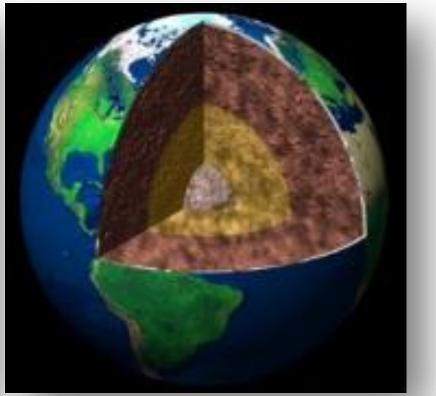
^{8}B: ~50/day
CNO: ~1000/day
^{7}Be: ~10000/day

Supernovae (SN) ν

Core Collapse SN @ 10 kpc: thousands in few sec.

Diffuse SN signal: few / year

Geoneutrinos



~400 / year

\+

New physics

Proton decay

Neutrino magnetic moment

Sterile neutrinos

Non-standard interactions

Lorentz invariance violation

Others

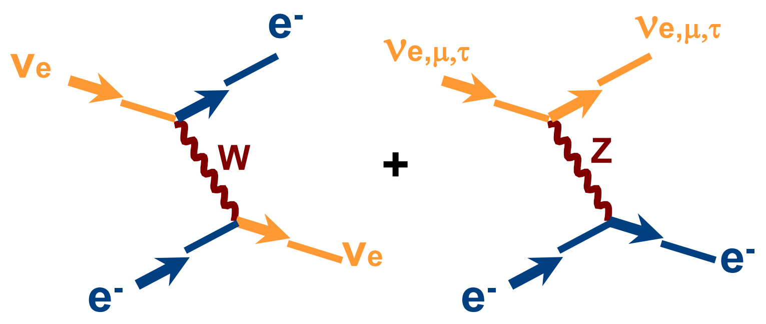
Neutrino oscillation & properties

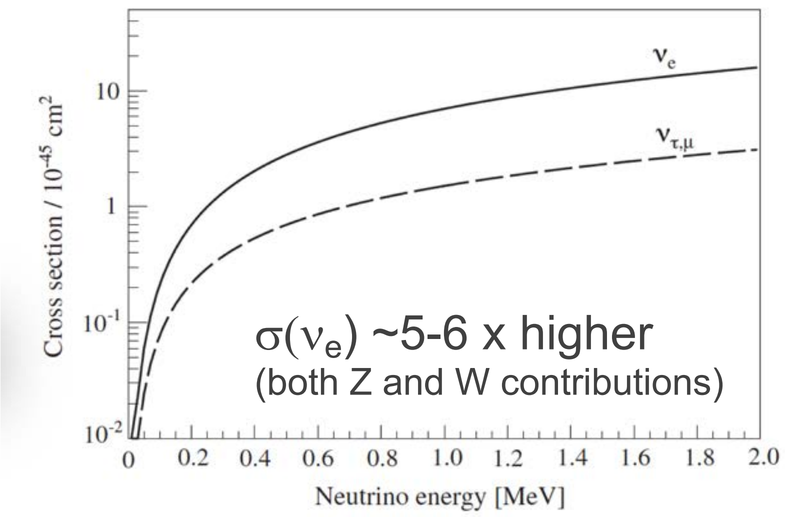
Neutrinos as a probe

MeV (ANTI-)NEUTRINO DETECTION WITH LIQUID SCINTILLATORS

Neutrino detection: SINGLES

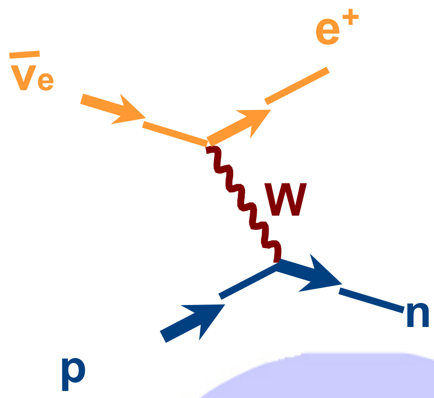
- Elastic scattering (ES) off electrons
- No threshold
- All flavours
- σ@ few MeV: ~10^{-44} cm^2





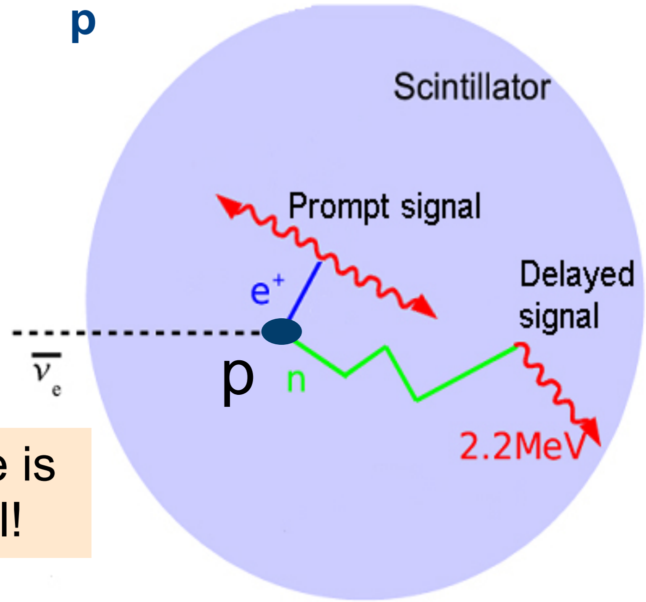
Antineutrino detection: Coincidences (BGR suppression)

- Inverse beta decay (IBD)
- Charge current, e-flavor only



Energy threshold = 1.8 MeV
Electron flavor only
σ@ few MeV: ~10^{-42} cm^2
(~100 x more than scattering)

$$E_{prompt} = E_{visible}$$
$$= T_{e+} + 2 \times 511 \text{ keV}$$
$$\sim E_{antinu} - 0.784 \text{ MeV}$$



Prompt + delayed space & time coincidence is an exceptional background suppressing tool!

UPDATED JUNO SENSITIVITY TO NEUTRINO MASS ORDERING

JUNO original estimate → NEW update presented at NEUTRINO 2022

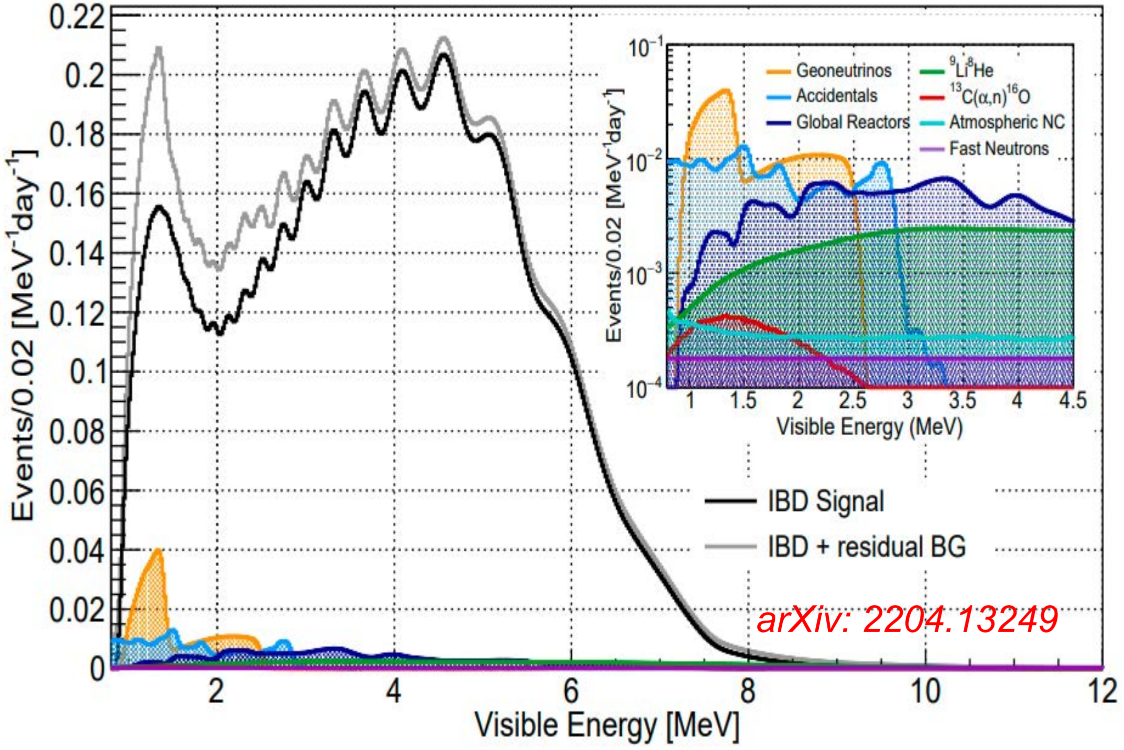
J. Phys. G 43:030401 (2016)

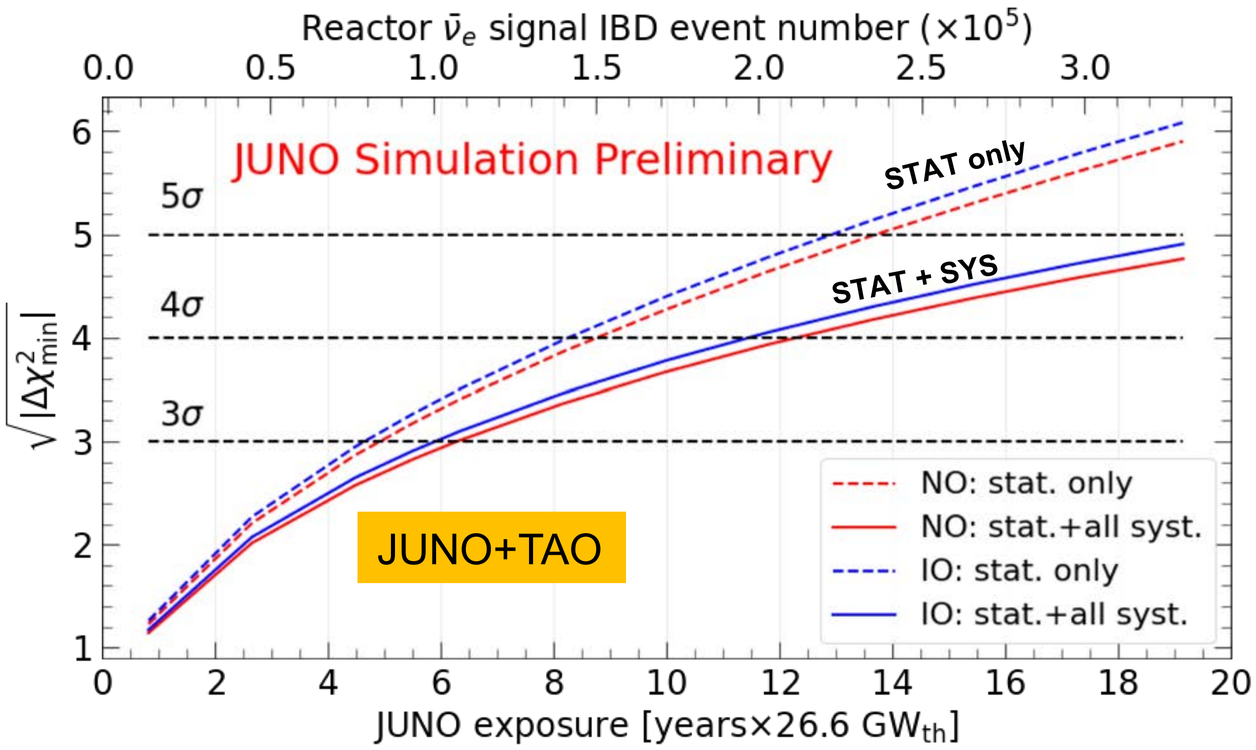
@NUFACT 2022: see parallel talk of Jinnan Zhang at WG1

1) Only Taishan 1 and 2 cores will be built in a near term instead of original 4 cores
2) JUNO experimental hall ~60 m shallower -> 30% higher flux of cosmic muons

1) Improved **energy resolution** (from 3.0 to 2.9% @ 1 MeV)
   - Results of the PMT testing (increased photon detection efficiency 27-> 30%, arXiv: 2205.08629)
   - New PMT Optical Model (EPJC 82 (2022) 329)
   - New Central Detector Geometries
2) Improved reactor spectral shape uncertainty: **combined analysis with TAO**
3) Improved **muon veto strategy** – exposure fraction from 83 to 91.6%
4) Updated values on the **expected backgrounds** and radiopurity of the construction material
5) New modelling of the **liquid scintillator properties** and its non-linearity (exploiting Daya Bay experience)

JUNO SENSITIVITY TO NEUTRINO MASS ORDERING



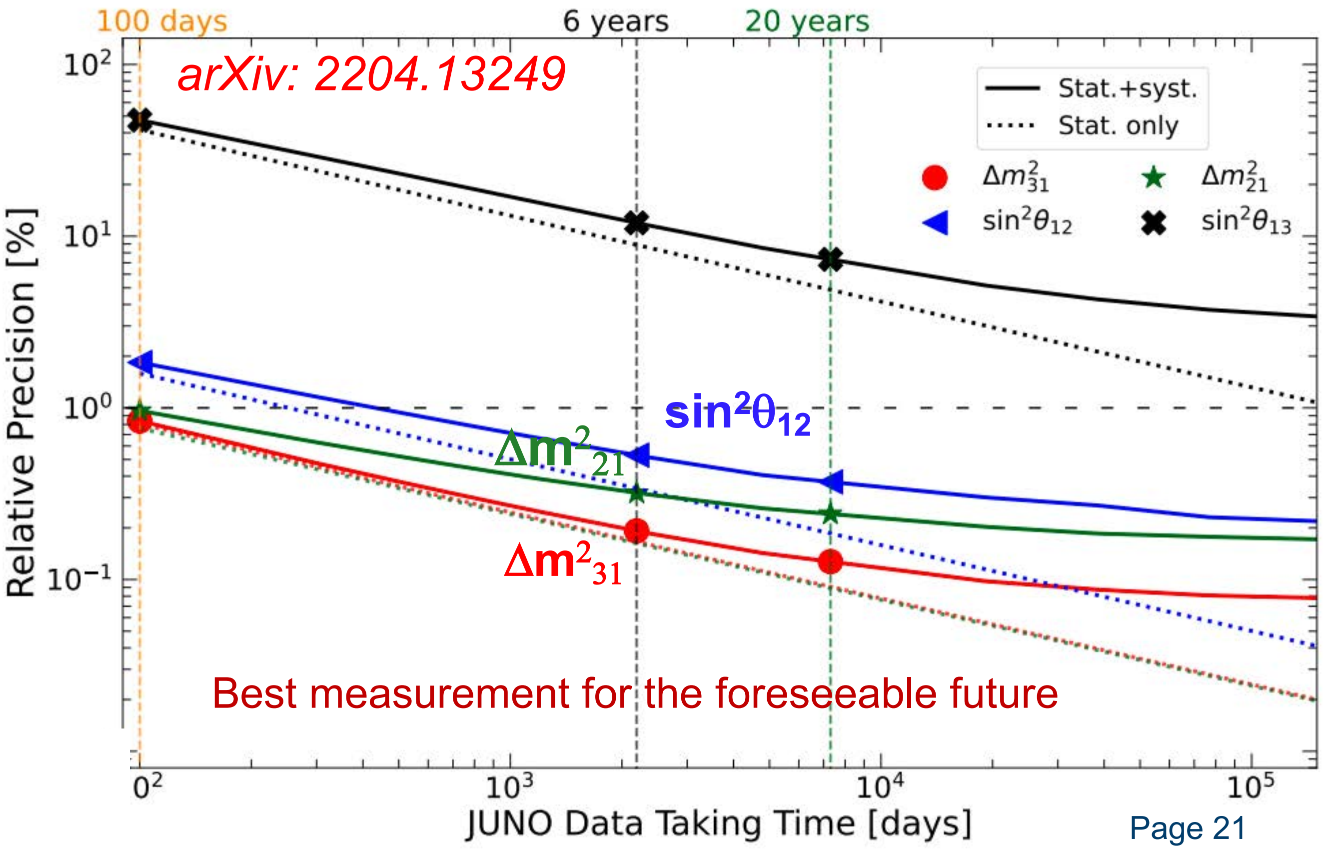


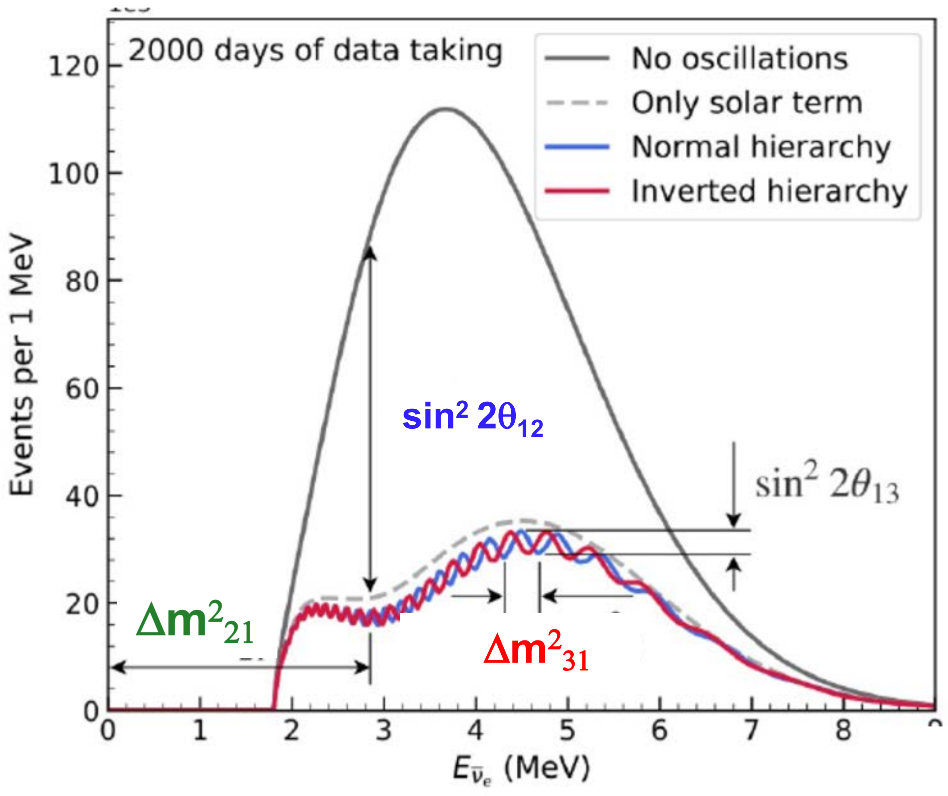
JUNO sensitivity on neutrino mass ordering: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

Estimation of combined sensitivity with reactor + atmospheric neutrino analysis under preparation

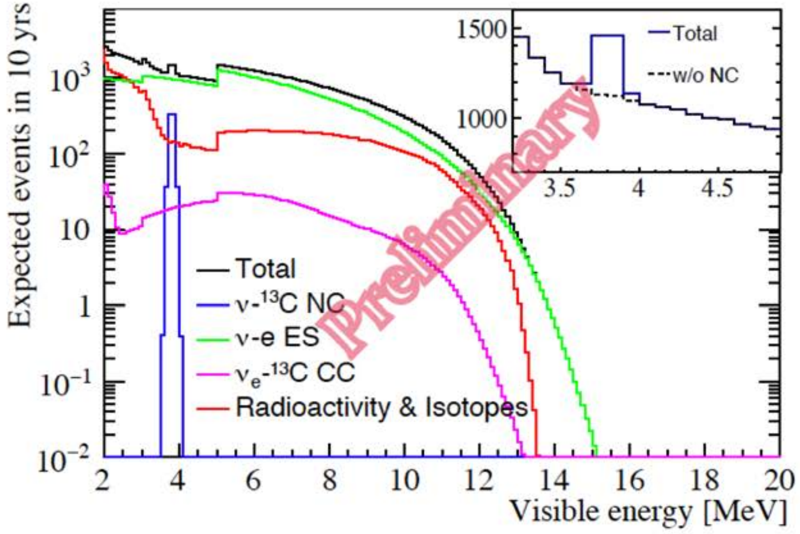
JUNO SENSITIVITY TO OSCILLATION PARAMETERS

- Precision of $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31} **< 0.5% in 6 years** using reactor neutrinos (arXiv: 2204.13249)
- Measurement of $\sin^2\theta_{12}$($^{+9\%}$ / $_{-8\%}$) and Δm^2_{21} ($^{+27\%}$ / $_{-17\%}$) also with ^{8}B solar neutrinos (next slide)
- Unique: solar neutrino oscillation parameters with neutrinos and antineutrinos in one detector

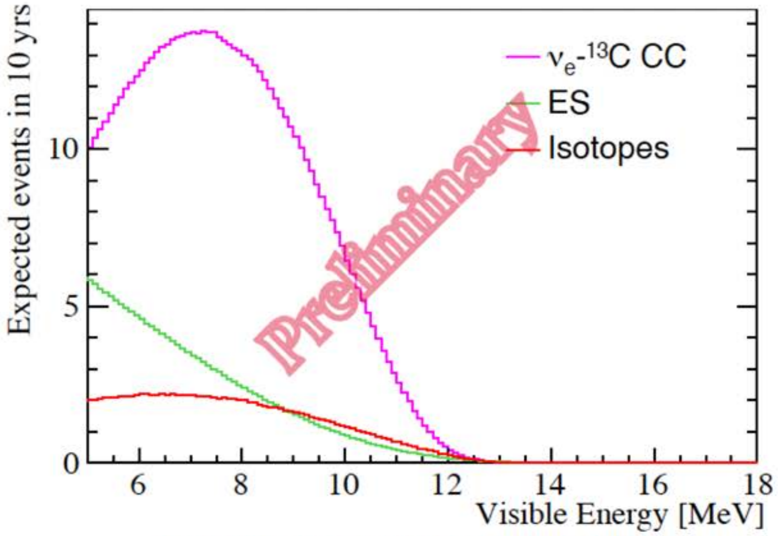




MODEL INDEPENDENT MEASUREMENT OF ^{8}B SOLAR NEUTRINOS



Single visible signal channel



Prompt signal of the prompt-delayed pair signal channel

ES: Chinese Phys. C 45 (2021) 1
ES+NC+CC: paper under preparation

Expected precision in 10 years:

^{8}B flux: 5% JUNO

3% JUNO + SNO

$\sin^2\theta_{12}$: +9% / -8%

Δm^2_{21}: +27% / -17%

Unprecedented 2 MeV threshold for ES

~200 ton ^{13}C in JUNO LS → observation of **^{8}B solar neutrinos via CC and NC interactions** on ^{13}C

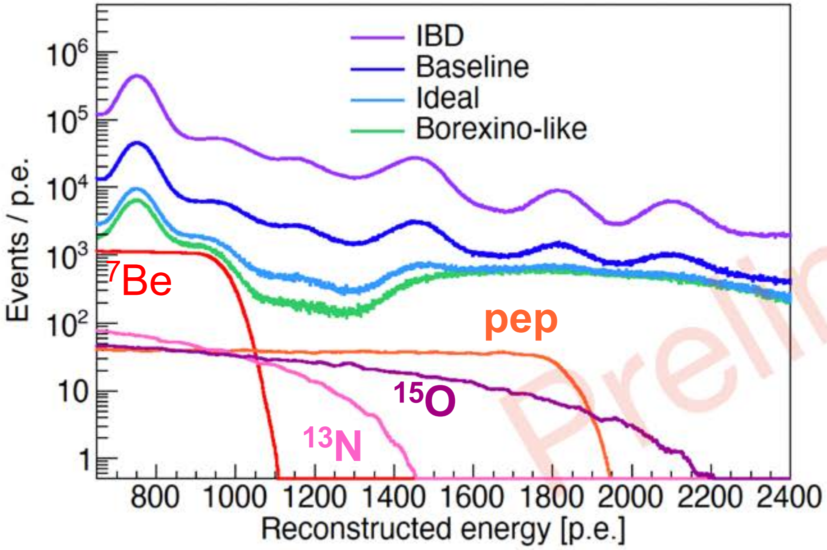
	Channels	Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers after cuts
CC	$\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}\,(\frac{1}{2}^-; \mathrm{gnd})$	2.2 MeV	$e^- + {}^{13}$N decay	3929	647
NC	$\nu_x + {}^{13}\mathrm{C} \rightarrow \nu_x + {}^{13}\mathrm{C}\,(\frac{3}{2}^-; 3.685\,\mathrm{MeV})$	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 events (CC)

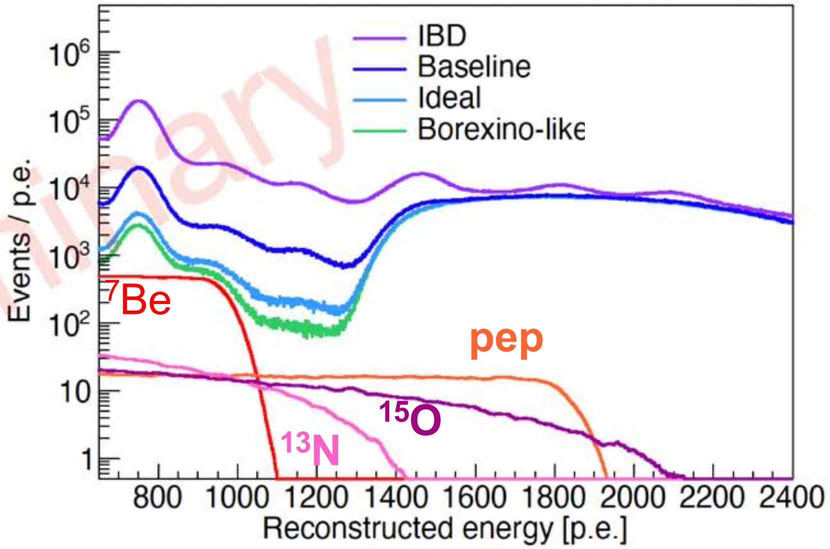
Singles event (NC, ES)

JUNO SENSITIVITY TO ^{7}Be, pep, CNO SOLAR NEUTRINOS

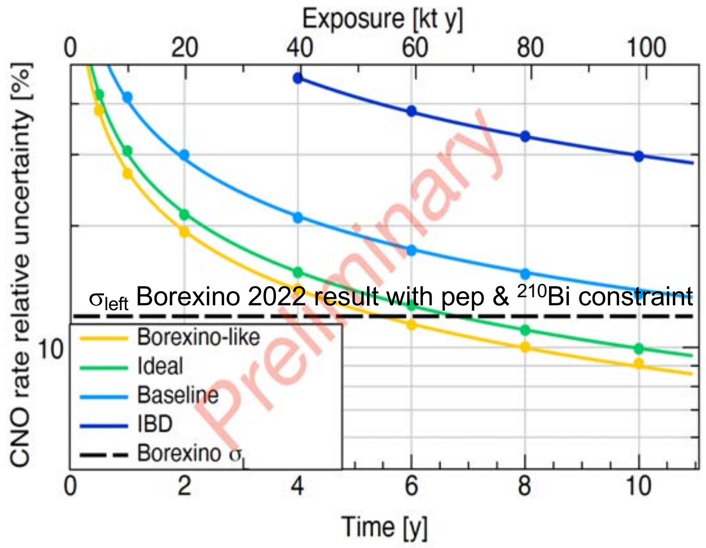
70% exposure of 1 year
cosmogenic ^{11}C suppressed to 10%



30% exposure of 1 year
90% of cosmogenic ^{11}C tagged



CNO precision with the *pep* constraint

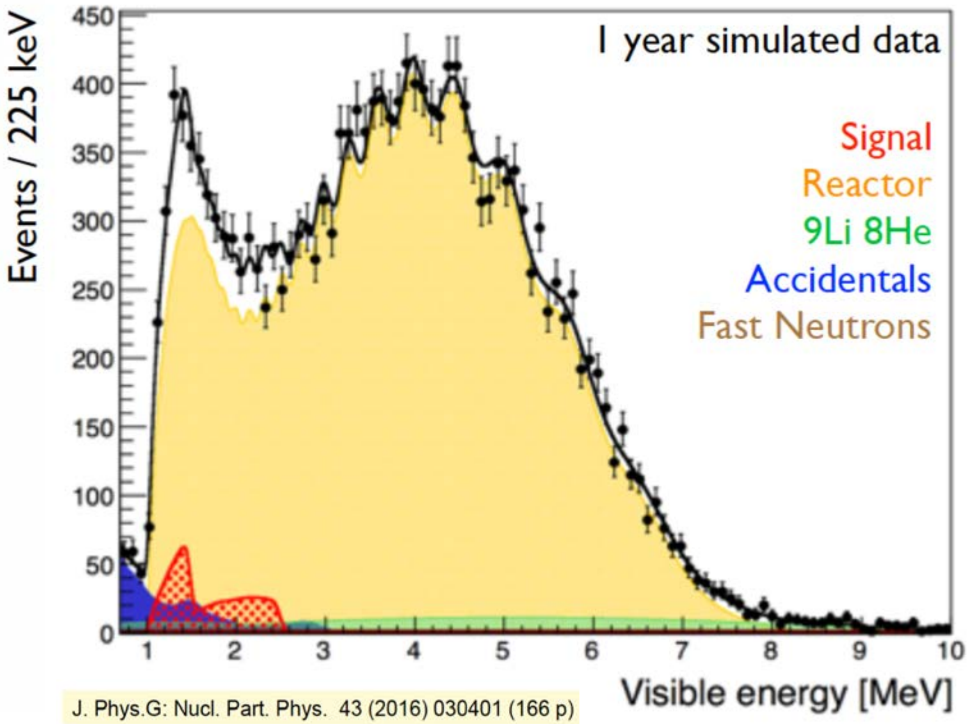


- Several radio-purity scenarios: from the Borexino level up to the "IBD" one (minimum required for the NMO)
- JUNO has potential to improve the precision of the existing Borexino measurements
  - **^{7}Be: in 1-2 years time < 2.7% (current Borexino precision) for all radiopurity scenarios**
  - **pep: in 1-2 years time < 17% (current Borexino precision), only in IBD scenario after more than 6 years**
  - **CNO:** constraining pep rate is crucial, precision of 20% possible in 2 to 4 years (except for the IBD scenario)
    - constraint of ^{210}Bi radioactive background not needed (applied in Borexino analysis *arXiv:2205.15975*)
    - Independent measurement of ^{13}N and ^{15}O might be possible for the first time
- Collaboration paper under preparation

GEONEUTRINOS IN JUNO

Geoneutrinos from ^{238}U and ^{232}Th chains:
400 IBDs /year

Current world sample (KamLAND + Borexino) ~230 geoneutrino events!



J. Phys.G: Nucl. Part. Phys. 43 (2016) 030401 (166 p)

Motivation:
- ✓ Earth radiogenic heat, especially from the Earth's mantle
- ✓ U/Th ratio and insight about the Earth formation

Big advantage:
- ✓ Large volume and thus high IBD statistics!

Main limitations:
- ✓ Large reactor neutrino background;
- ✓ Relatively shallow depth – cosmogenic background;

Critical:
- ✓ Keep other backgrounds (^{210}Po contamination!) under control;

- Current (KamLAND and Borexino) precision on measured geoneutrino flux is ~16-18%
- JUNO can reach precision of the current experiment in about a year
- JUNO will be sensitive to U/Th ratio
- **Geological study of the local crust** important in order to separate the mantle contribution and it is ongoing

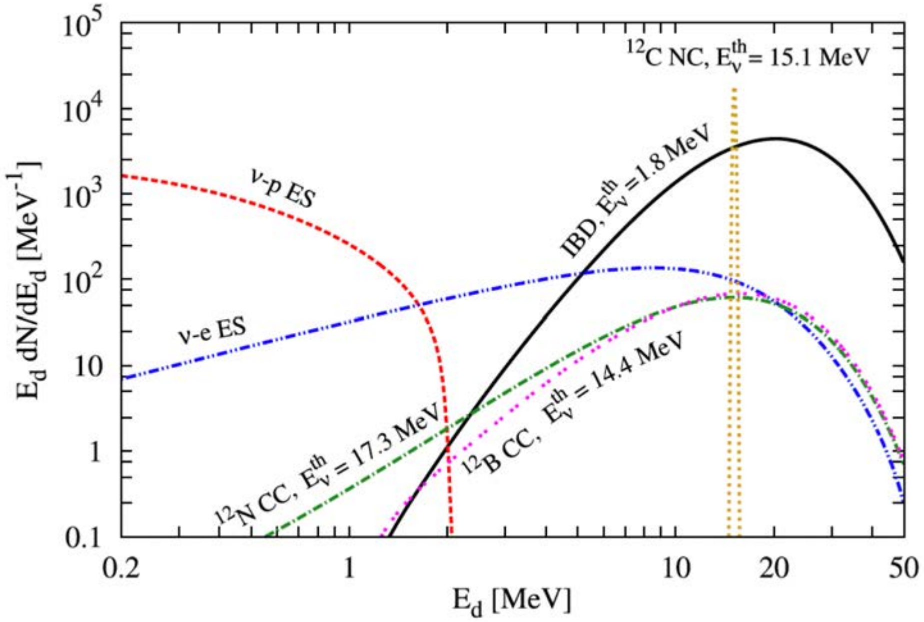
R. Han *et al.*, Chin.Phys. **C 40** (2016) 033003

M. Reguzzoni *et al.*J. Geophys. Res. Solid Earth **124** (2019) 4231

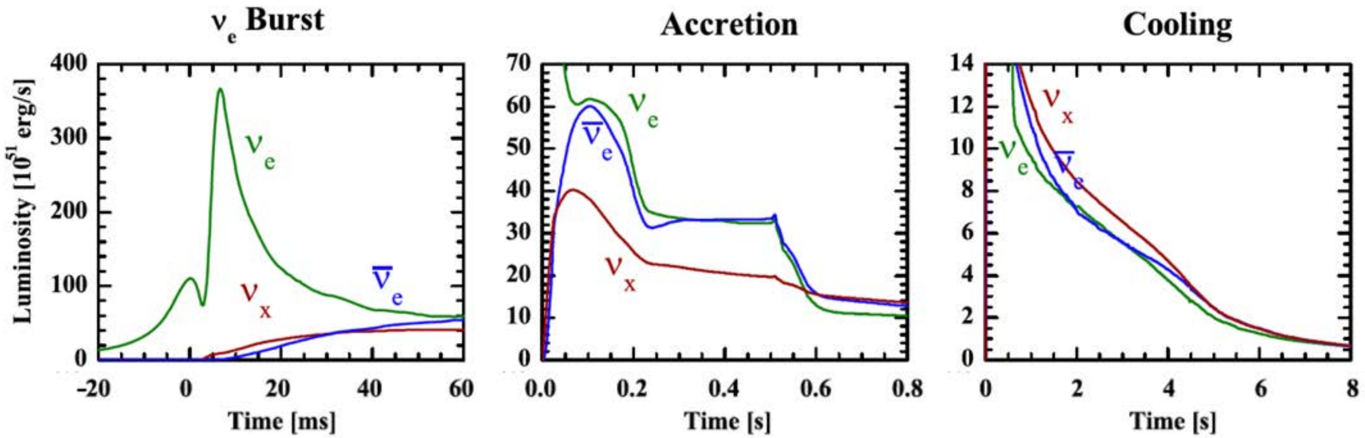
R. Gao *et al.*, Phys. Earth Planet. Inter. **299** (2020) 106409

SUPERNOVAE (SN)

- Core-collapse SN emits 99% of the energy via neutrinos
- SN rate: ~3 per century
- Determination of flavour content, energy spectrum, time evolution of the signal
- 200 keV threshold



Expected signal from a CCSN @ 10 kpc



J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401

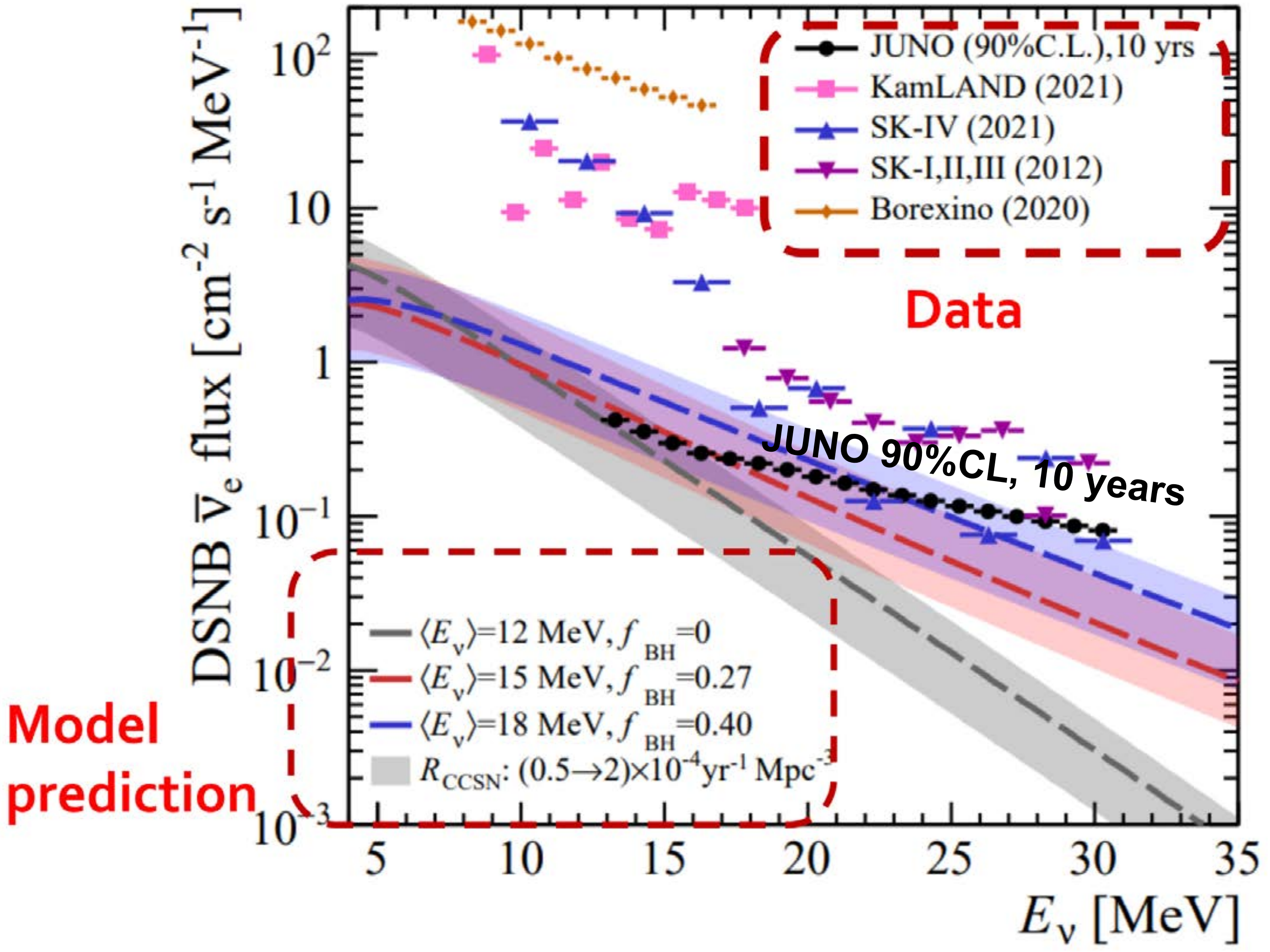
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$ (IBD)	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \rightarrow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

arXiv: 2205.08830

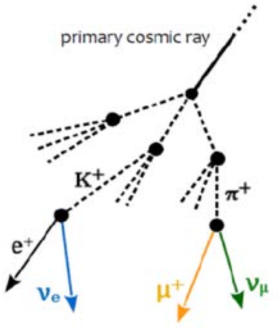
DIFFUSE SUPERNOVAE ~~BACKGROUND~~ SIGNAL (DSNB)

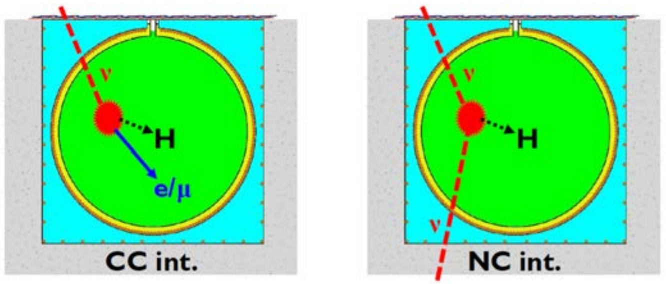
- Integrated neutrino flux from the past SN in the visible Universe
- ~10 core collapse SN/s in the visible Universe
- Info about the star formation rate
- Expected signal: few IBD events / year
- Main background:
  - ✓ reactor anti-ν → go above 10 MeV
  - ✓ NC atmospheric ν - pulse shape discrimination (eff 50% → 80%),

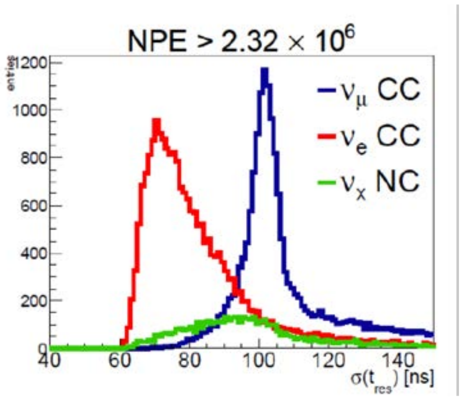
JUNO DSNB discovery potential:
3σ in 3 years with nominal models



ATMOSPHERIC NEUTRINOS

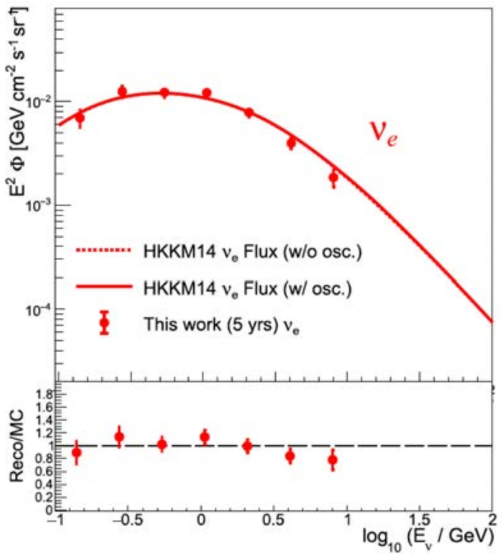


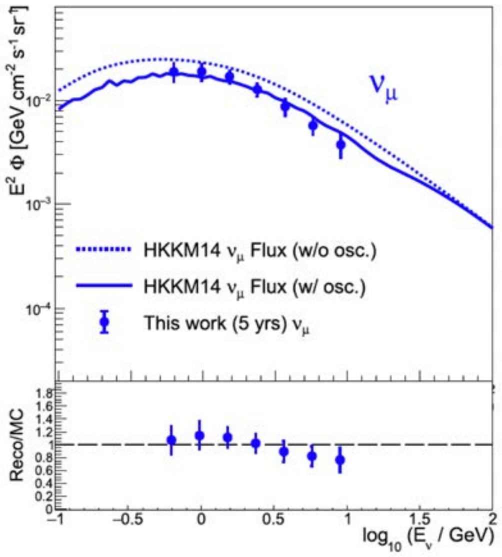




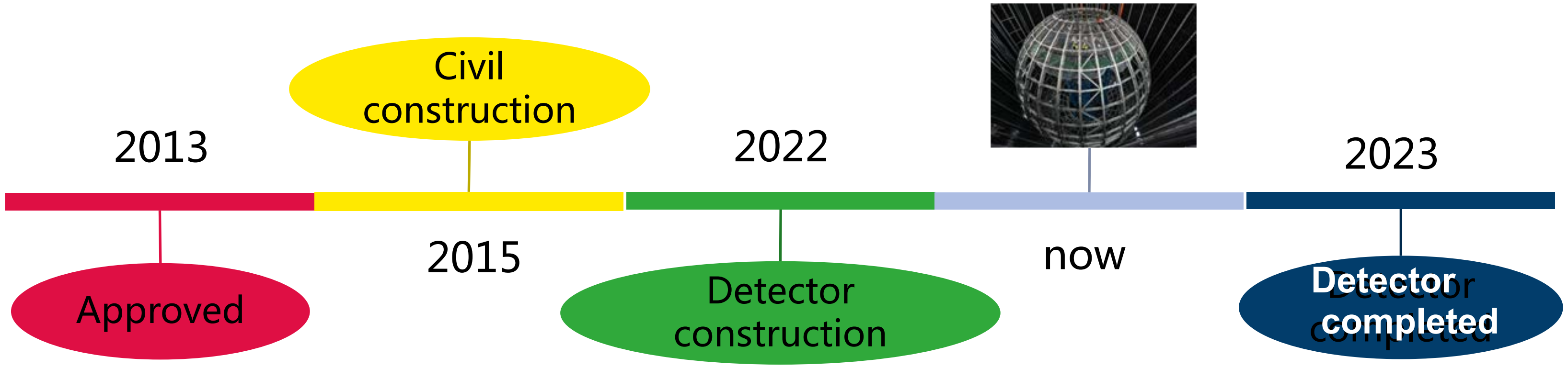
Eur. Phys. J. C 81 (2021) 887

- First measurement with LS: can play a major role in GeV range, possibly pushing to MeV region (rare events background)
- CC and NC interactions
- Analysis focus on fully contained CC events
  - ✓ Muon/electron flavour discrimination based on hit-time
  - ✓ ν_e and ν_μ energy spectra: 25% precision after 5 years
  - ✓ θ_{23} with 6 degree precision
- **Complementary sensitivity to neutrino mass-hierarchy** via matter effects – possible improvement of the sensitivity via a combined analysis under study
  - ✓ reconstruction of the energy and direction
- Proton spectrum from atmospheric neutrinos has large uncertainties at low energies – data for model improvements





OUTLOOK AND TIMELINE



JUNO sensitivity on **neutrino mass ordering (NMO)**: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

Many other goals:

- precision measurement of θ_{12}, Δm^2_{21}, Δm^2_{31}
- **solar neutrinos:** ^8B model independent measurement + precision ^7Be, pep, and CNO
- **geoneutrinos** and Th/U ratio in the measured signal
- **core collapse SN** in many channels
- discovery potential for **DSNB**
- **atmospheric neutrinos** down to MeV region and additional handle on NMO

READS

Thank you! *... and stay tuned*

Overview:

A. Abusleme et al., JUNO physics and detector, *Progress in Particle and Nuclear Physics* Available online 03 December 2021, 103927.
F. An et al., Neutrino physics with JUNO, *J. Phys. G: Nucl. Part. Phys.* 43 (2016) 030401

Detectors:

A. Abusleme et al., Mass Testing and Characterization of 20-inch PMTs for JUNO, arXiv:2205.08629 (2022).
Y. Wang et al., A new optical model for photomultiplier tubes, EPJC 82 (2022) 329.
A. Abusleme et al., The Design and Sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS, *Eur. Phys. J. C* 81 (2021) 973.
A. Abusleme et al., TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution, arXiv:2005.08745 (2020), to be submitted to *Journal of High Energy Physics*.
A. Abusleme et al., Radioactivity control strategy for the JUNO detector, *JHEP11* (2021) 102.
A. Abusleme et al., Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector, *NIM A*, 988 (2020) 164823.
A. Abusleme et al., Calibration strategy of the JUNO experiment, *J. High En. Phys.* 3 (2021) 4.

Physics reach:

A. Abusleme et al., Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO, arXiv:2205.08830 (2022).
A. Abusleme et al., Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO, arXiv:2204.13249 (2022).
A. Abusleme et al., Damping signatures at JUNO, a medium-baseline reactor neutrino oscillation experiment, *J. High En. Phys. 62 (2022) 82*.
A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, *Eur. Phys. J. C* 81 (2021) 887.
A. Abusleme et al., Feasibility and physics potential of detecting 8B solar neutrinos at JUNO, *Chinese Physics C* 45 (2021) 1.
R. Han et al., Potential of geo-neutrino measurements at JUNO, *Chinese Physics C* 40,3 (2016) 033003.

Backup slides

MUON VETO DETECTOR (WATER CHERENKOV)

~650 m rock overburden (1800 m.w.e.) → R_μ = 4 Bq in the liquid scintillator, $< E_\mu >$ = 207 GeV

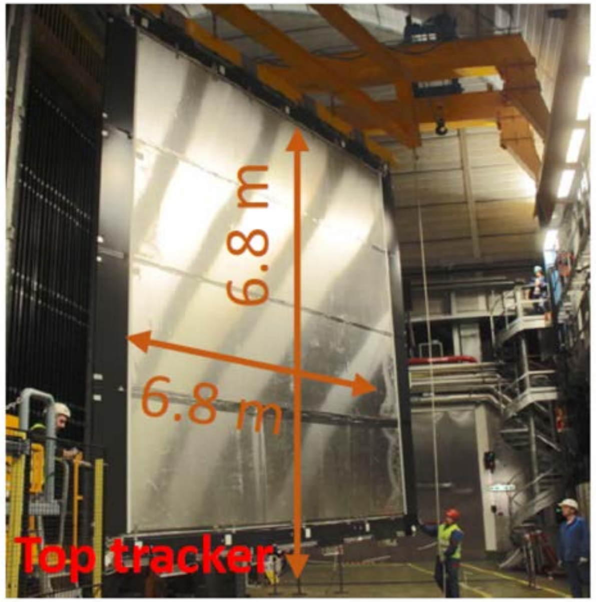
35 kton of ultrapure water serving as a passive shield and muon water Cherenkov detector.

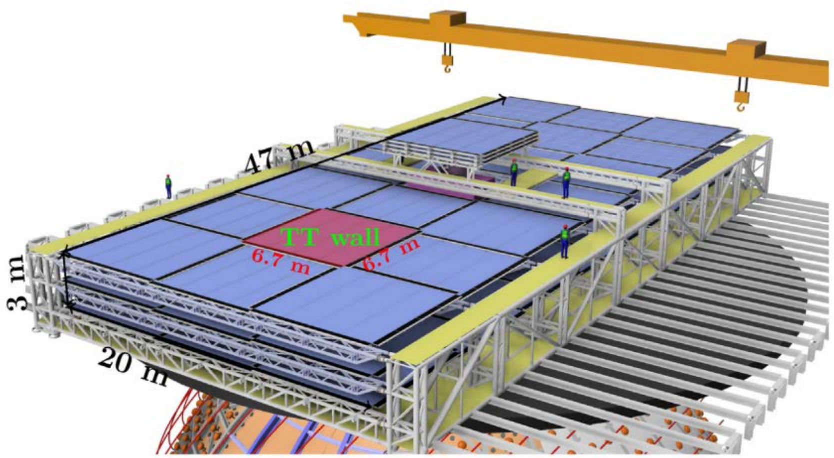
- ✓ 2400 20-inch MCP PMTs, detection efficiency of cosmic muons larger than 99.5%
- ✓ Keep the temperature uniformity stable at 21℃ ± 1℃
- ✓ Quality: ^{222}Rn < 10 mBq/m^3, attenuation length 30~40 m

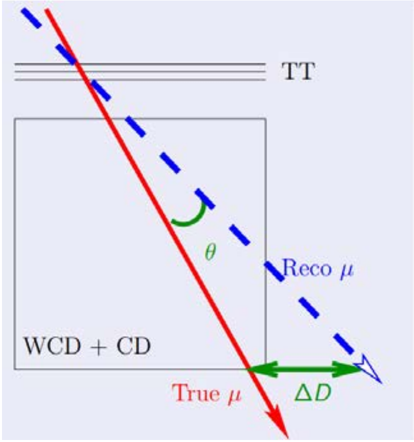
Muon reconstruction in JUNO:

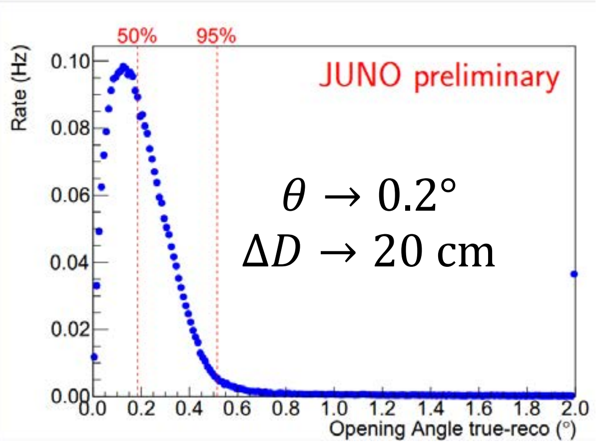
- 2018 JINST 13 T03003
- Radiation Detection Thechnology and Methods 2 (2018) 13

VETO DETECTOR (TOP TRACKER)







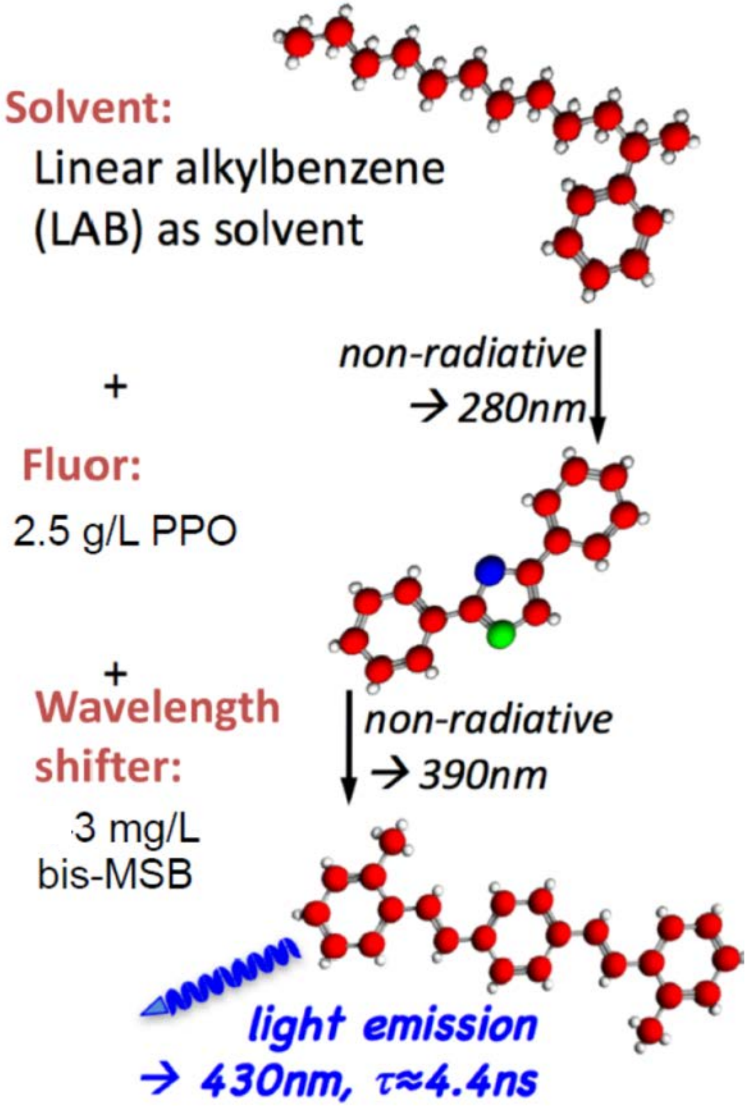


Plastic scintillator from the OPERA experiment

- ✓ About 50% coverage on the top, three layers to reduce accidental coincidence
- ✓ All scintillator panels arrived on site in 2019
- ✓ Provide control muon samples to validate the track reconstruction and to study cosmogenic background

LIQUID SCINTILLATOR (LS)

High light yield: ~10^4 ph/MeV



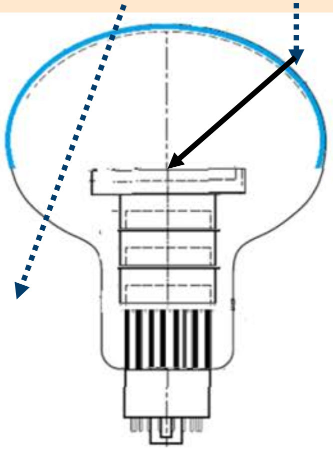
- Low radioactivity requirements
  - $< 10^{-15}$ g/g U/Th for IBDs
  - $< 10^{-17}$ g/g U/Th for solar neutrinos
- Purification systems using the Borexino know-how (Al_2O_3 filtration column, water extraction, N_2 stripping)
- Attenuation length achieved $\lambda_{att} > 20$ m at 430 nm

NIM A 908 (2021) 164823

TWO TYPES OF LARGE 20'' PMTS

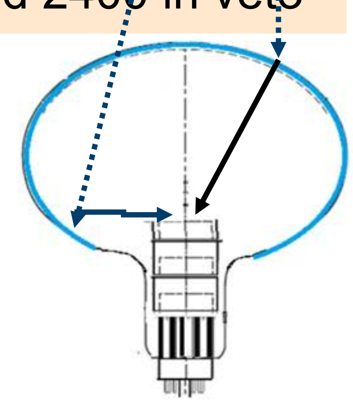
Dynode Hamamatsu

5000 in CD

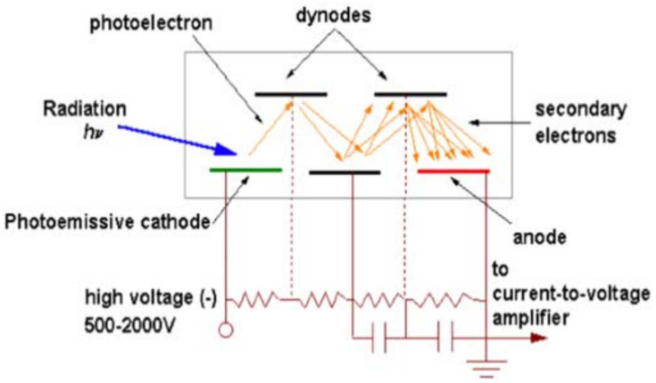


MCP (multichannel-plate) NNVT

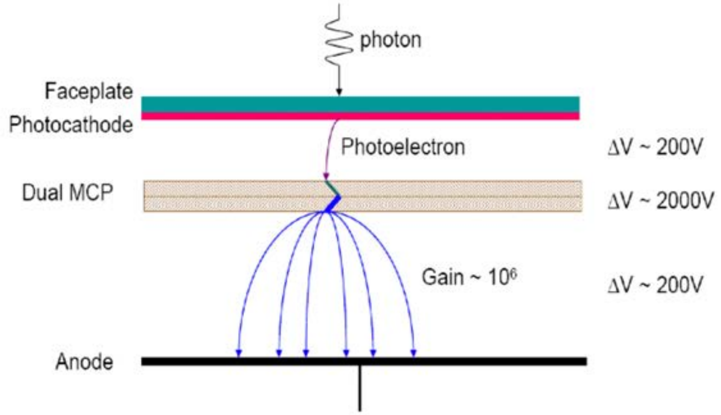
12612 in CD and 2400 in veto

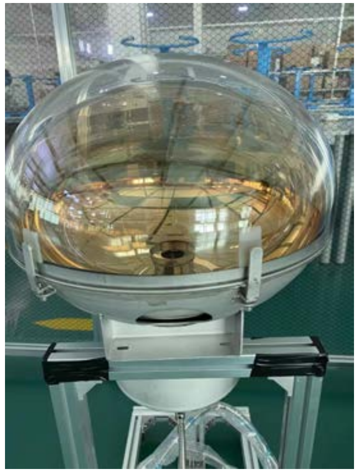


TRANSMISSION ONLY



TRANSMISSION + REFLECTION





Acrylic cover

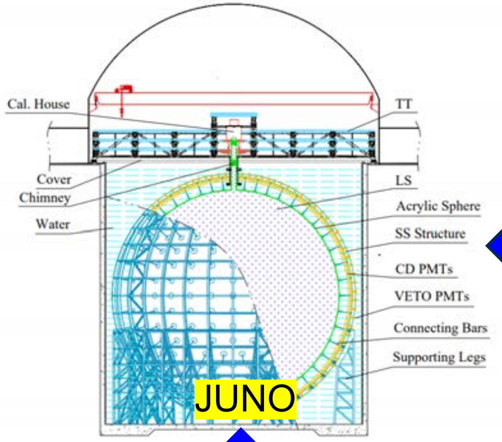
Stainless Steel cover

LIQUID SCINTILLATOR PLANTS ON SITE

All the liquid-scintillator related systems will be assembled until this summer.

SS pipes to underground

15%



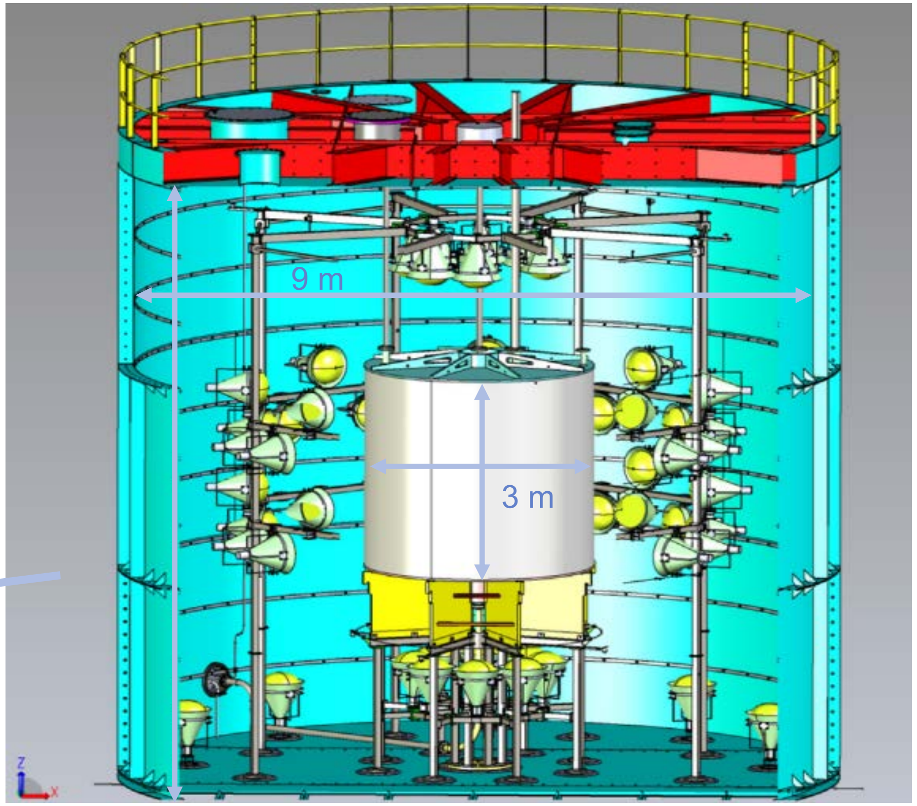
85%

ONLINE SCINTILLATOR INTERNAL RADIOACTIVITY INVESTIGATION SYSTEM (OSIRIS)

A 20-t detector to monitor radiopurity of LS before and during filling to the central detector

- ✓ Few days: U/Th (Bi-Po) ~ 1 × 10^{-15} g/g (reactor baseline case)
- ✓ 2~3 weeks: U/Th (Bi-Po) ~ 1 × 10^{-17} g/g (solar ideal case)
- ✓ Other radiopurity can also be measured: ^{14}C, ^{210}Po and ^{85}Kr

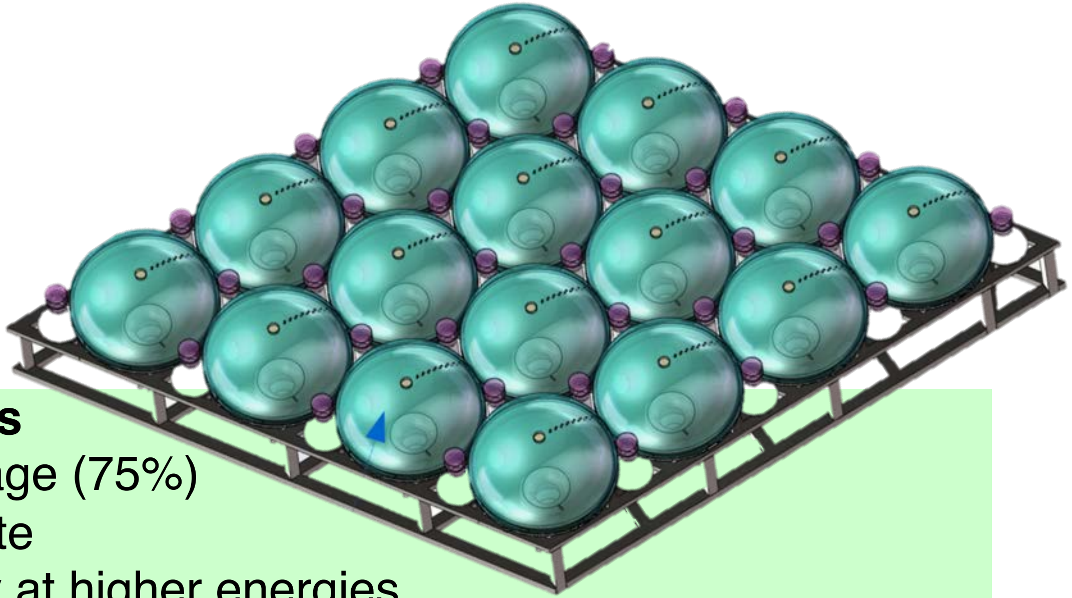
Eur.Phys.J.C 81 (2021) 11, 973



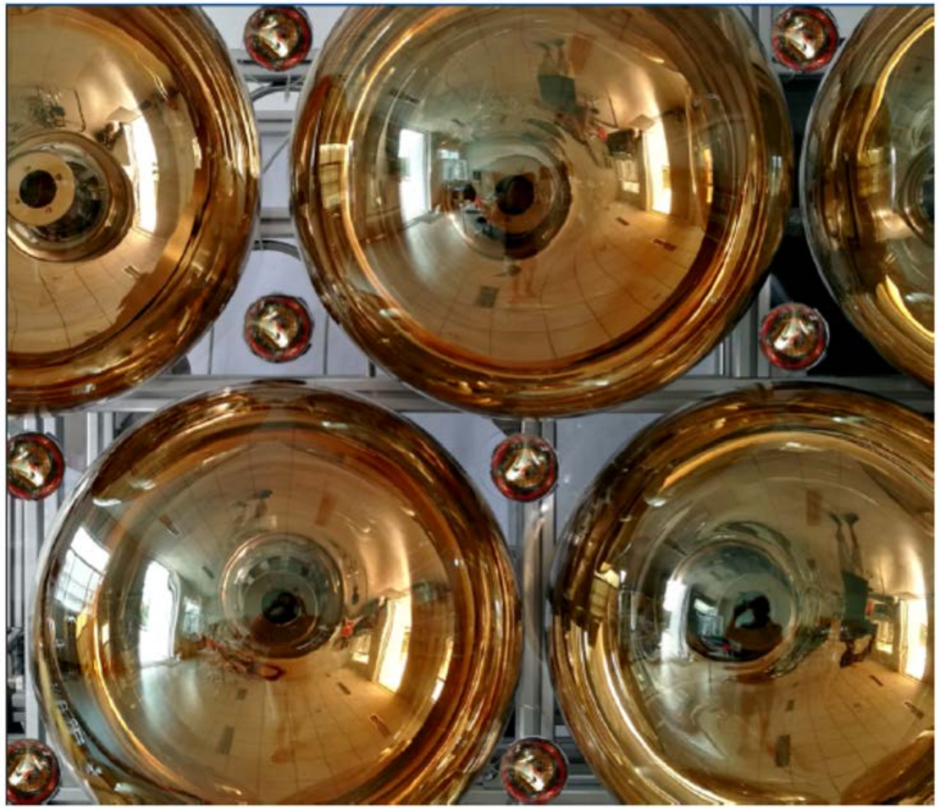
Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator): *arXiv: 2109.10782*

- ✓ A precision measurement of the flux of solar *pp* neutrinos on the few-percent level

DOUBLE CALORIMETRY: 20” AND 3” PMTs



Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm**



20-inch and 3-inch PMTs interleaving

Large 20-inch PMTs

- large coverage (75%)
- high dark rate
- non-linearity at higher energies
- waveforms -> multiple hits with charge

Small 3-inch PMTs

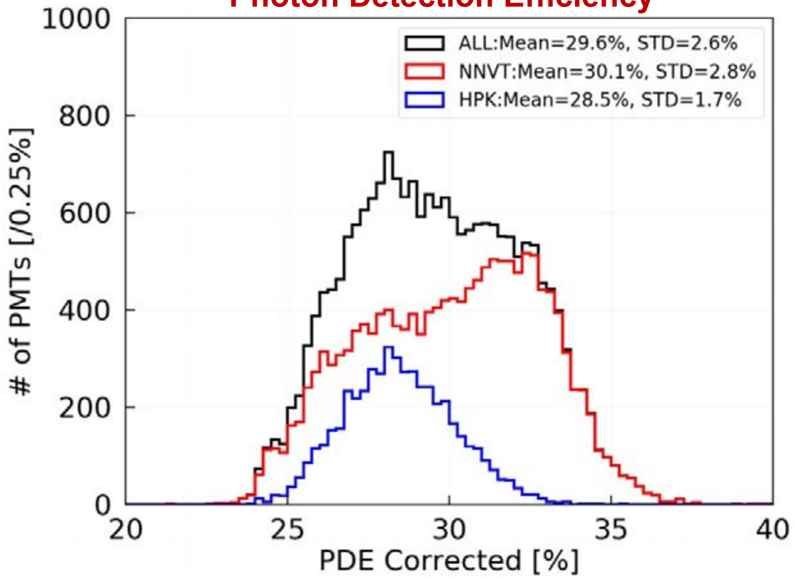
- small coverage (3%)
- small dark rate, smaller non-linearity
- photon counting (no waveform)
- higher effective dynamic range

Importance

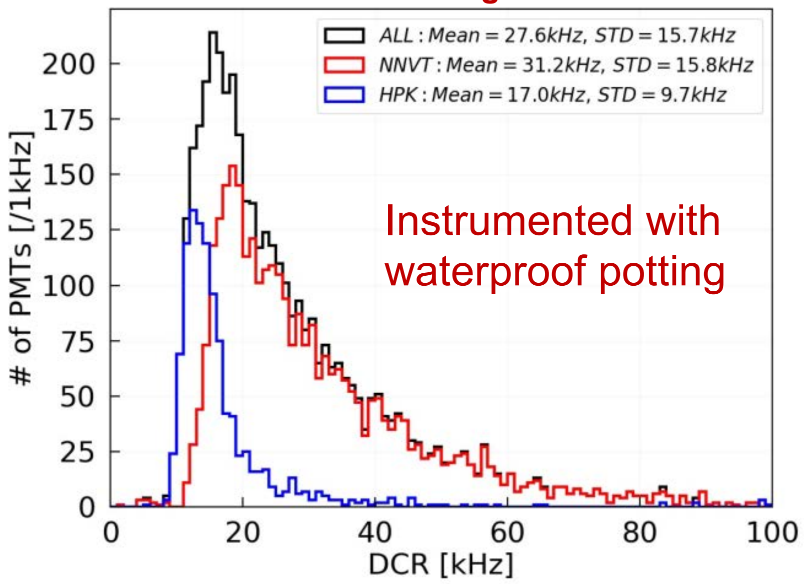
- muon detection
- supernovae
- **reduce systematics using the 2 independent systems**
- solar oscillation parameters also with small-PMTs-only

PMT TESTING AND PERFORMANCE

Photon Detection Efficiency



Dark Counting Rate



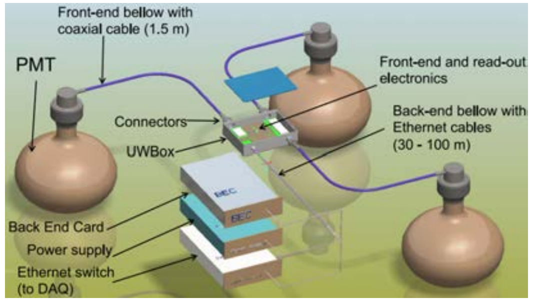
All PMTs are produced, tested, and instrumented with waterproof potting

		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 [kBq]	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

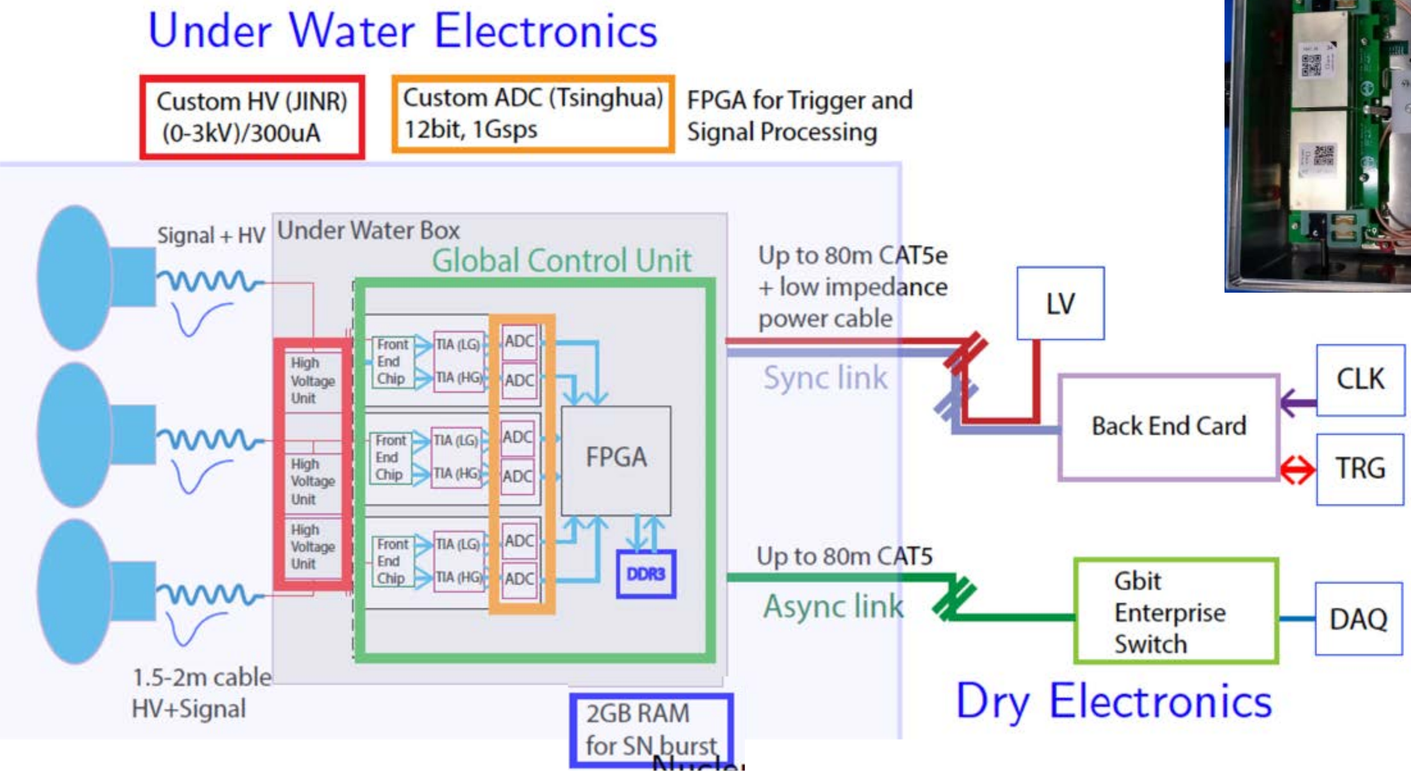
12612 NNVT PMTs with the highest PDE are selected for the CD

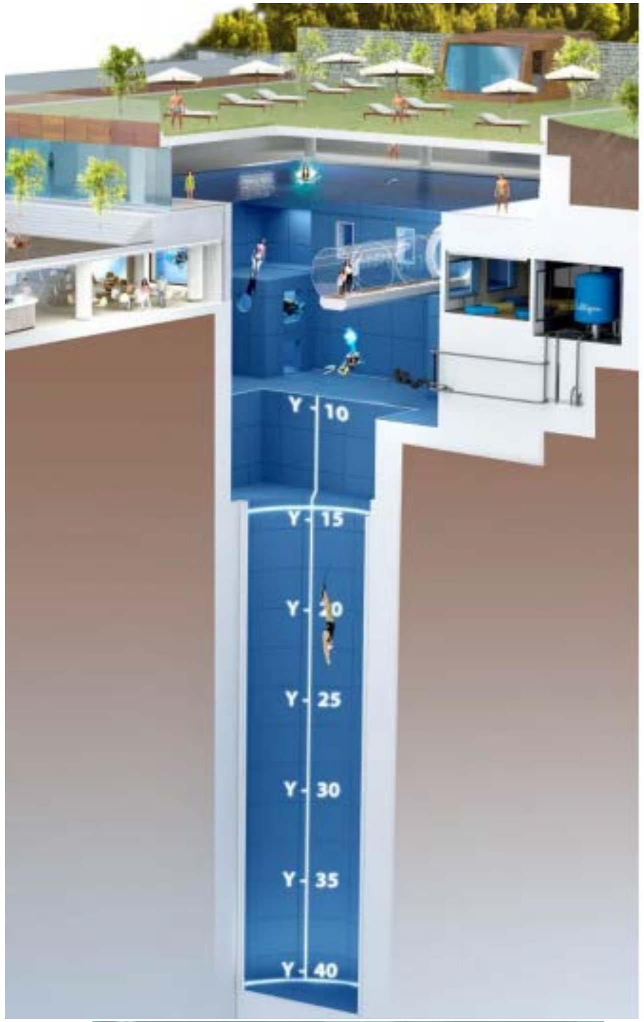
JÜLICH Forschungszentrum

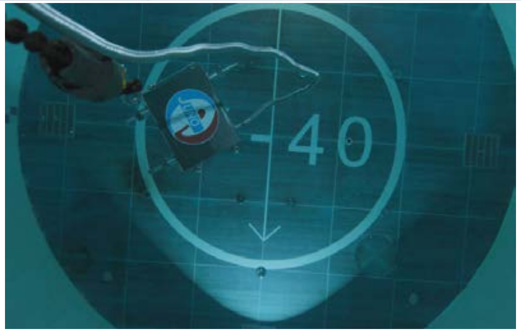
LARGE 20" PMTS ELECTRONICS



- waveforms sampled at 1GHz with high resolution (12-14 bits) ADC
- high-reliability (no access after installation)
- high precision
- large dynamic range
- stand high rates for short times (Supernovae)



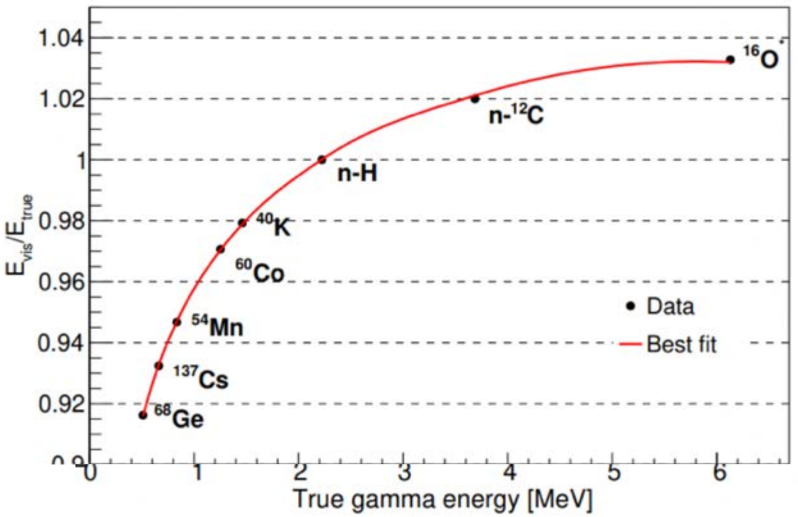




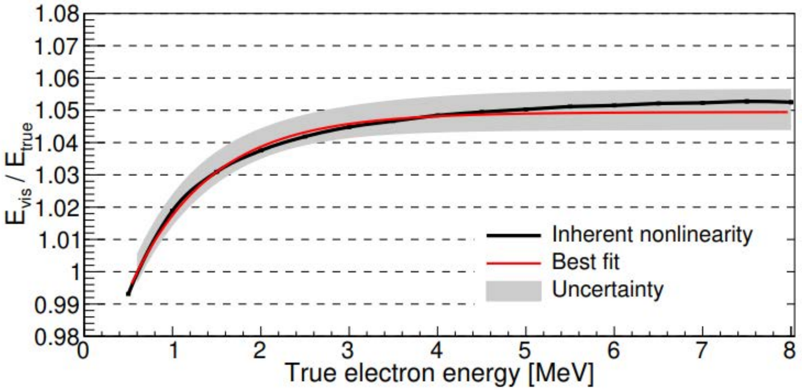
CALIBRATION SYSTEM

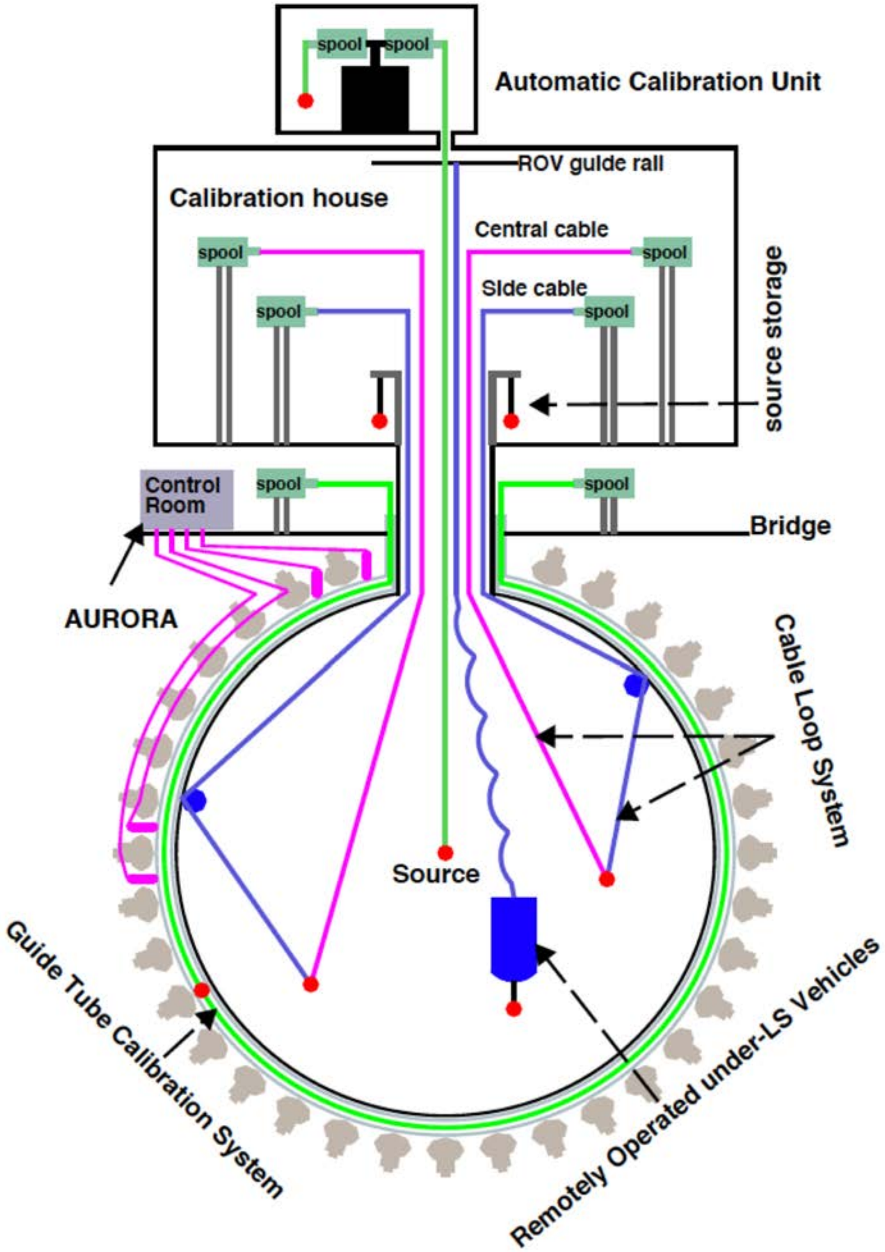
- requirements: 3% energy resolution at 1 MeV and 1% energy scale uncertainty
- Different tools deployed for detector calibration
  - 1D: Automatic Calibration Unit (ACU)
  - 2D: Cable Loop System (CLS) and Guide Tube Calibration System (GTCS)
  - 3D: Remotely Operated Vehicle (ROV)
  - Auxiliary systems: Calibration house, Ultrasonic Sensor System (USS), CCD and A Unit for Researching Online the LSc tRAnsparency (AURORA)

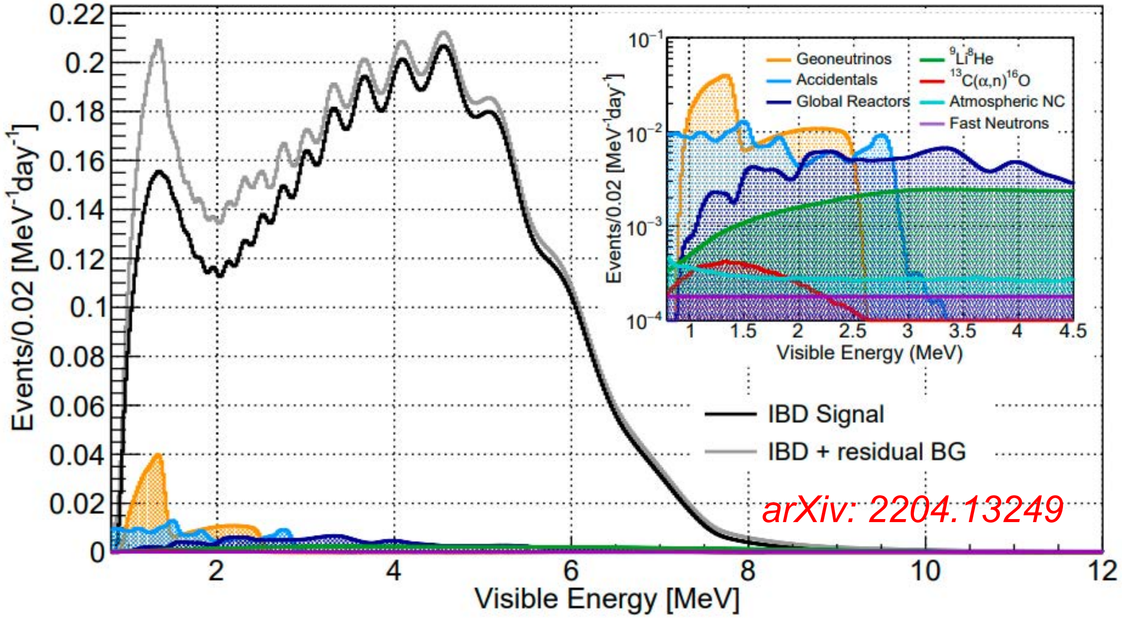
JHEP 03 (2021) 004

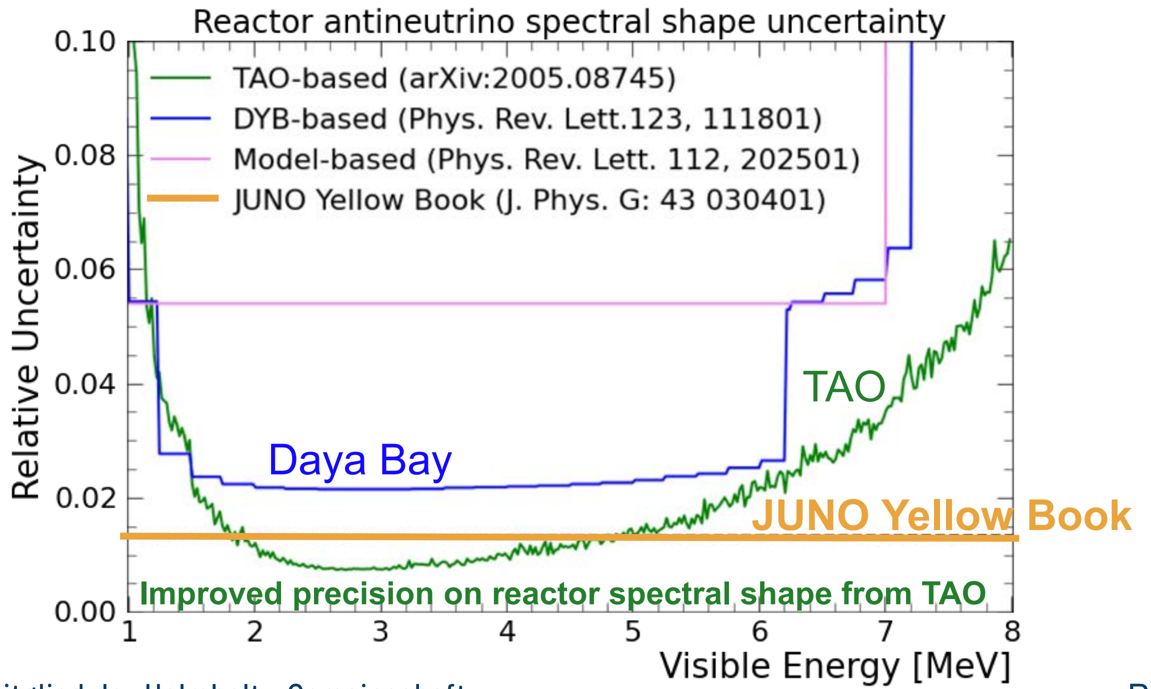


Uncertainty < 1%









UPDATED REACTOR SIGNAL AND IBD-LIKE BACKGROUND SPECTRA

NEW FROM NEUTRINO 2022

J. Phys. G 43:030401 (2016)

Design in Physics book → **this update**

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

IMPROVEMENTS ON THE ENERGY RESOLUTION

Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	*JHEP03 (2021) 004*
Photon Detection Efficiency (27%→30%)	+11%↑	**2.9% @ 1MeV** (Poster #519 at Neutrino)	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		Poster #184 at Neutrino
New PMT Optical Model	+8%↑		*EPJC 82 329 (2022)* Poster #815 at Neutrino

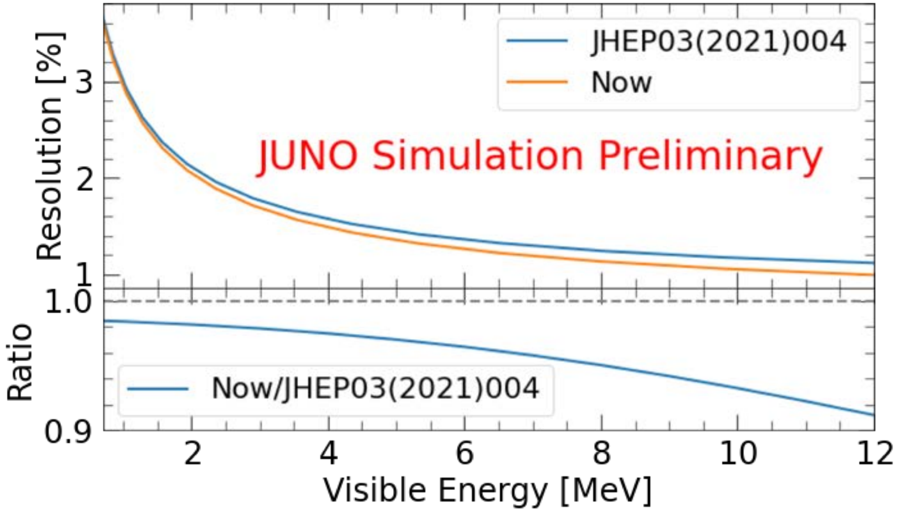
Positron energy resolution is modelled as:

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

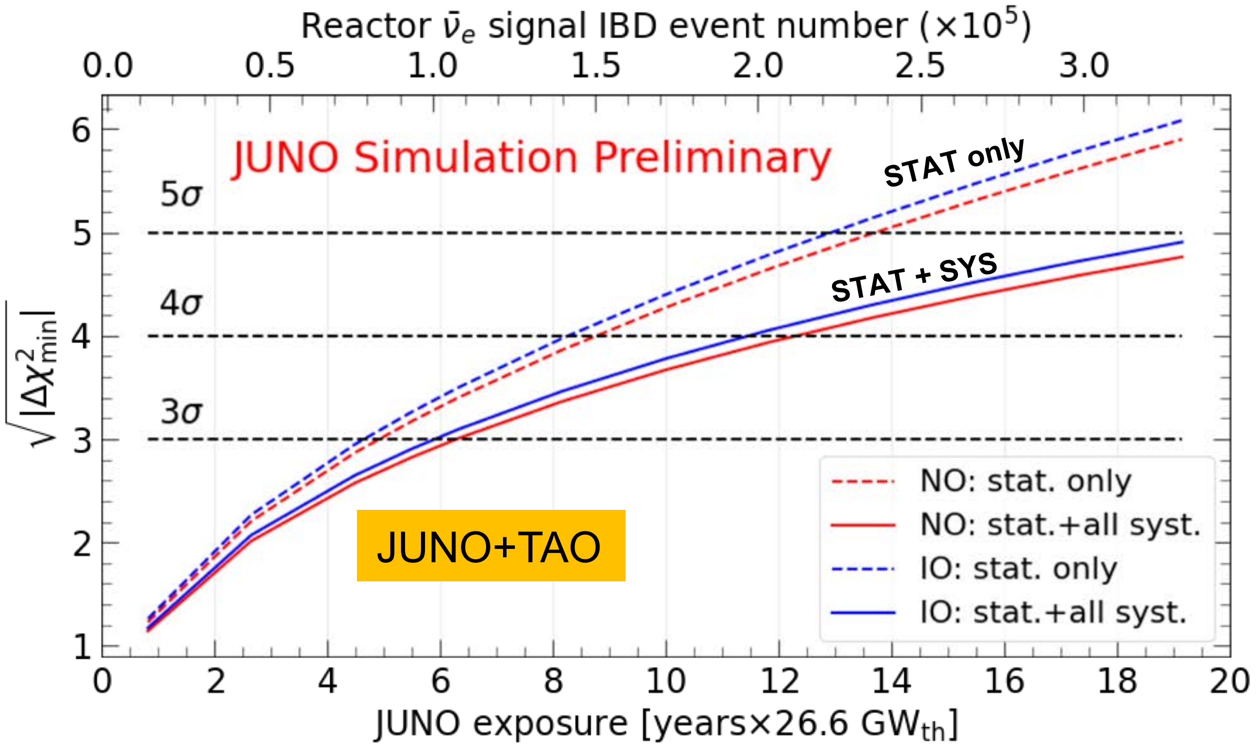
- **Photon statistics**

- **Annihilation-induced γs**
- **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**



JUNO SENSITIVITY TO NEUTRINO MASS ORDERING



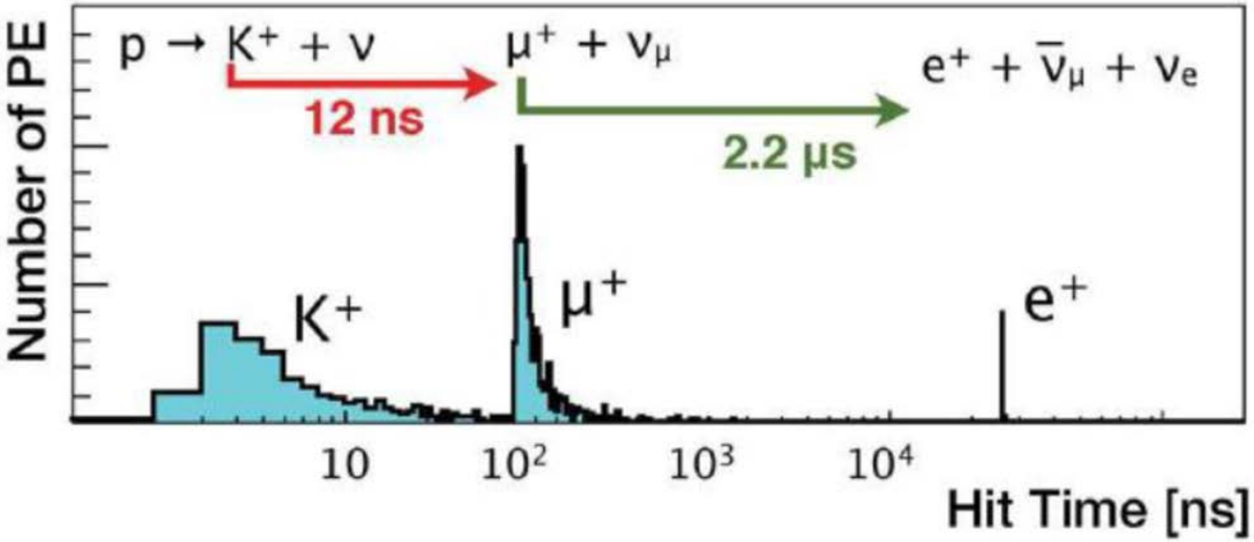
	JUNO Yellow Book (J. Phys. G 43:030401 (2016))	Neutrino 2022
Thermal Power	36 GW_{th}	**26.6 GW_{th} (26%↓)**
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	**4 Hz (33%↑)**
Muon veto efficiency	83%	**91.6% (8.6%↑)**
Signal rate	60 /day	**47.1 /day (22%↓)**
Backgrounds	3.75 /day	**4.11 /day (10%↑)**
Energy resolution	3% @ 1 MeV	**2.9% @ 1 MeV (3%↑)**
Shape uncertainty	1.34% for 20 keV bin	**JUNO + TAO**
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~6 yrs × 26.6 GW_{th}

JUNO sensitivity on neutrino mass ordering: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

Estimation of combined sensitivity with reactor + atmospheric neutrino analysis under preparation

PROTON DECAY

Tripple signal



- Possible decay channels:
  $p \to \pi^0 + e^+$ (GUT flavored)
  $p \to K^+ + \nu$ (SUSY flavored)
- current best limits set by Super-Kamiokande in $p \to \pi^0 + e^+$ and $p \to \pi^0 \mu^+$
  (K. Abe *et al.*, Phys. Rev. D 95 (2017) 012004)
- JUNO has potentials in the other channel, by detecting K^+ in LS
- signals can be separated from background thanks to a triple coincidence signal
- JUNO will reach a sensitivity of about 8×10^{33} years with 10 year exposure