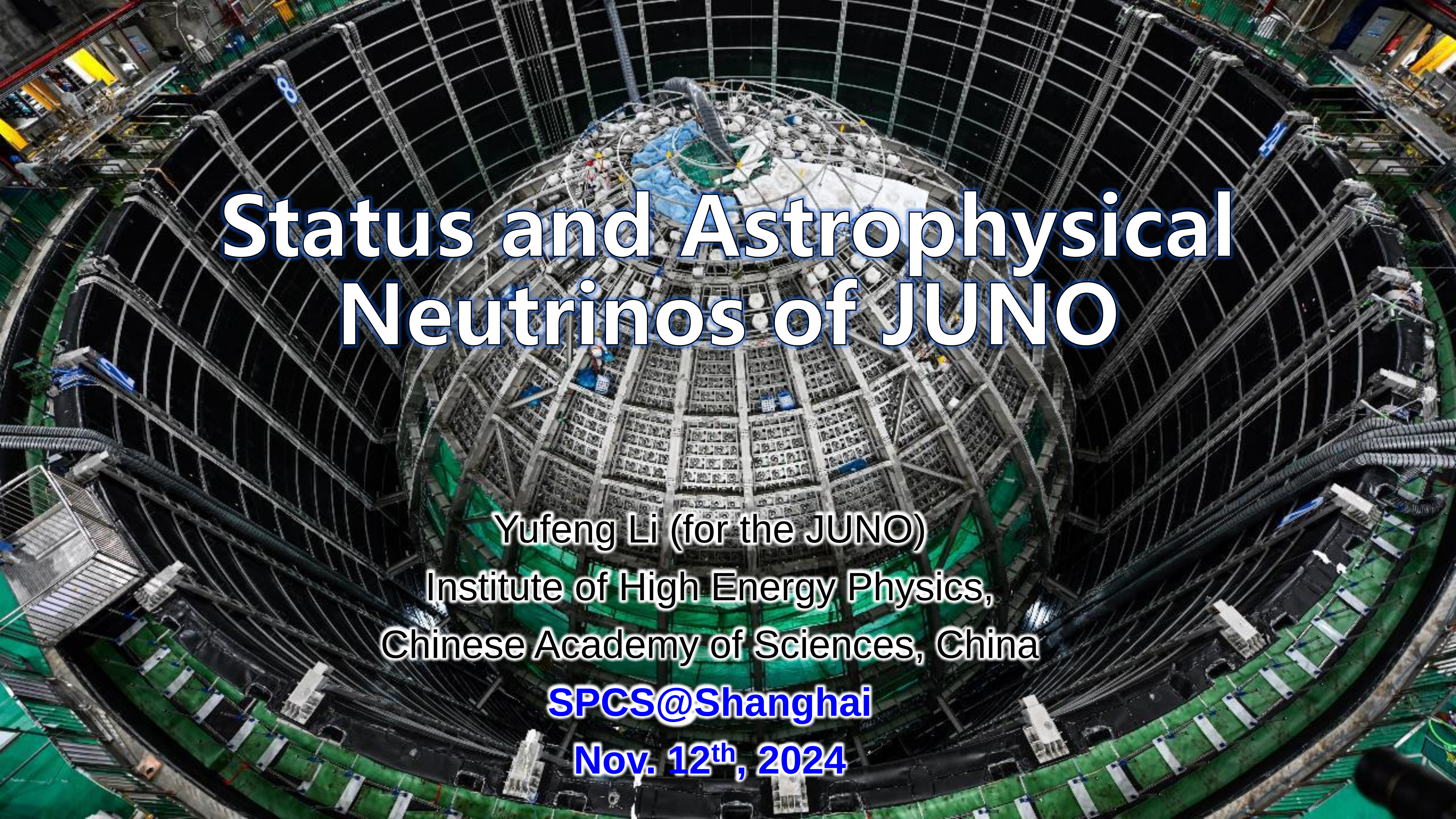


Status and Astrophysical Neutrinos of JUNO

Yufeng Li (for the JUNO)

Institute of High Energy Physics,

Chinese Academy of Sciences, China

SPCS@Shanghai

Nov. 12th, 2024

Jiangmen Underground Neutrino Observatory

Jiangmen Underground Neutrino Observatory (JUNO)

JUNO Physics and Detector, arXiv:2104.02565

Approved in Feb. 2013. Ground-breaking in 2015. Construction to be completed in 2024.

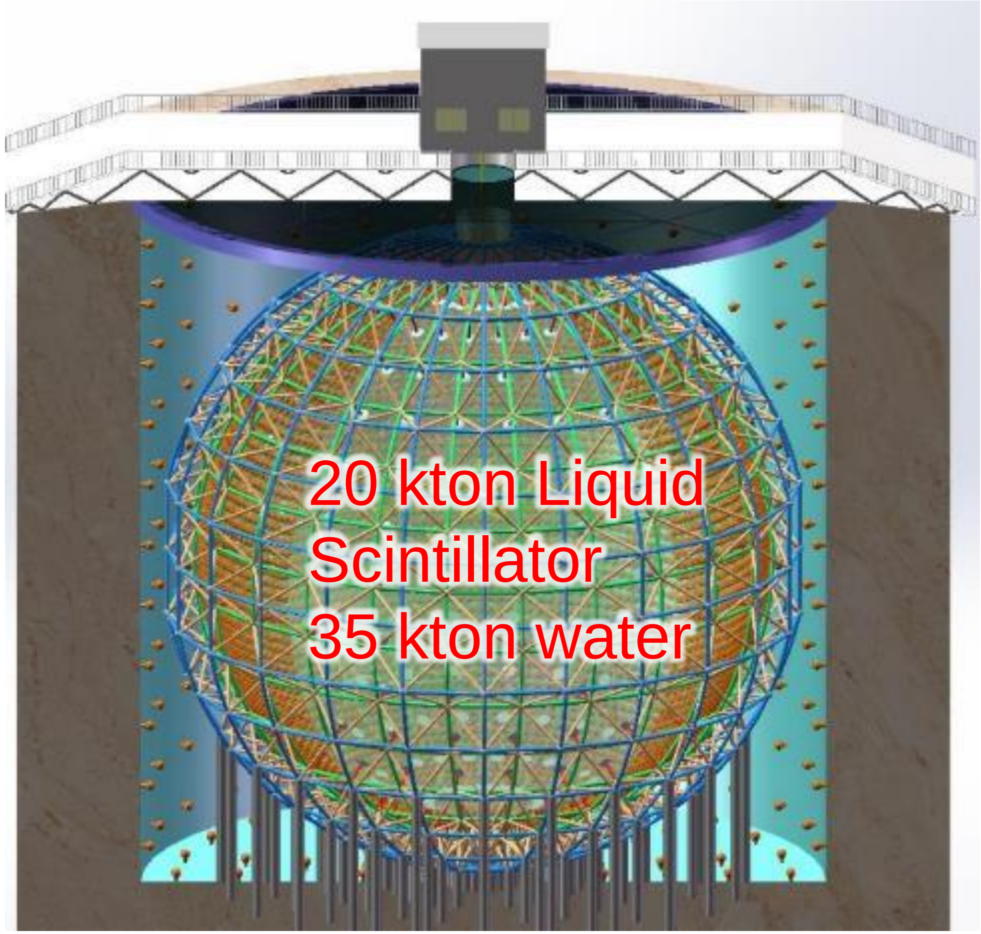
A multiple-purpose neutrino experiment with rich physics programs:

- **Reactor ν:** Oscillation, spectrum
- **Atmospheric ν**
- **Solar ν**
- **CCSN**
- **DSNB** (aka supernova relic ν)
- **Dark matter**
- **geo-νs**
- **Nucleon decay**
- **0νββ potential (future upgrade)**

Acrylic Sphere:
ID: 35.4m
Thickness:12cm

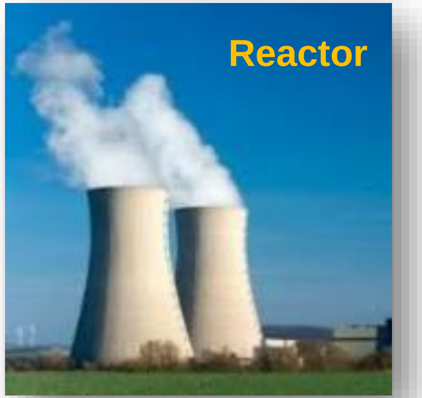
SS Lattice:
ID: 40.1m
OD: 41.1m
17612 20-in PMTs
25600 3-in PMTs

Water pool:
ID: 43.5m
Height: 44m
Depth: 43.5m
2400 20-in PMTs



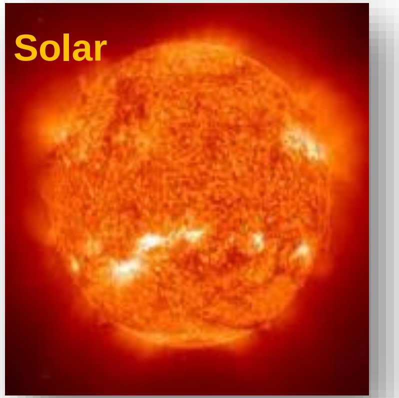
A multi-purpose observatory

Mass Ordering



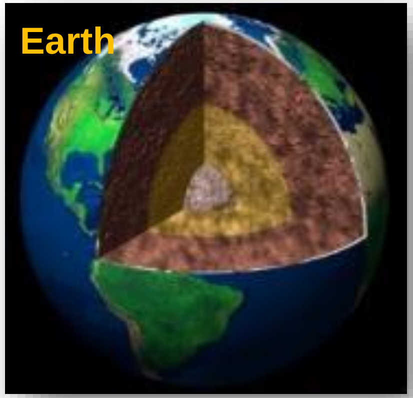
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

JUNO Location

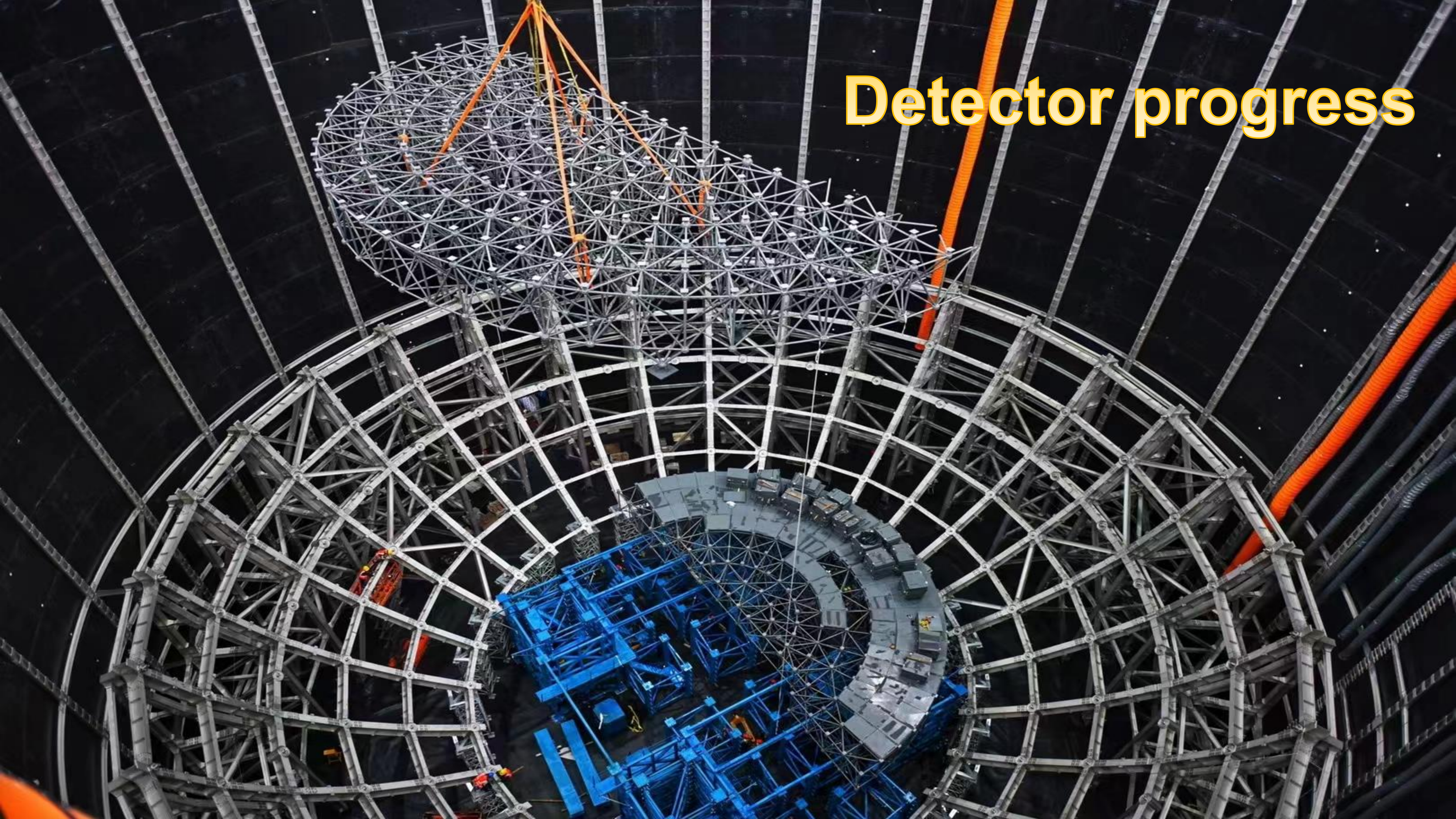
JUNO Collaboration

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		

= 74 institutes

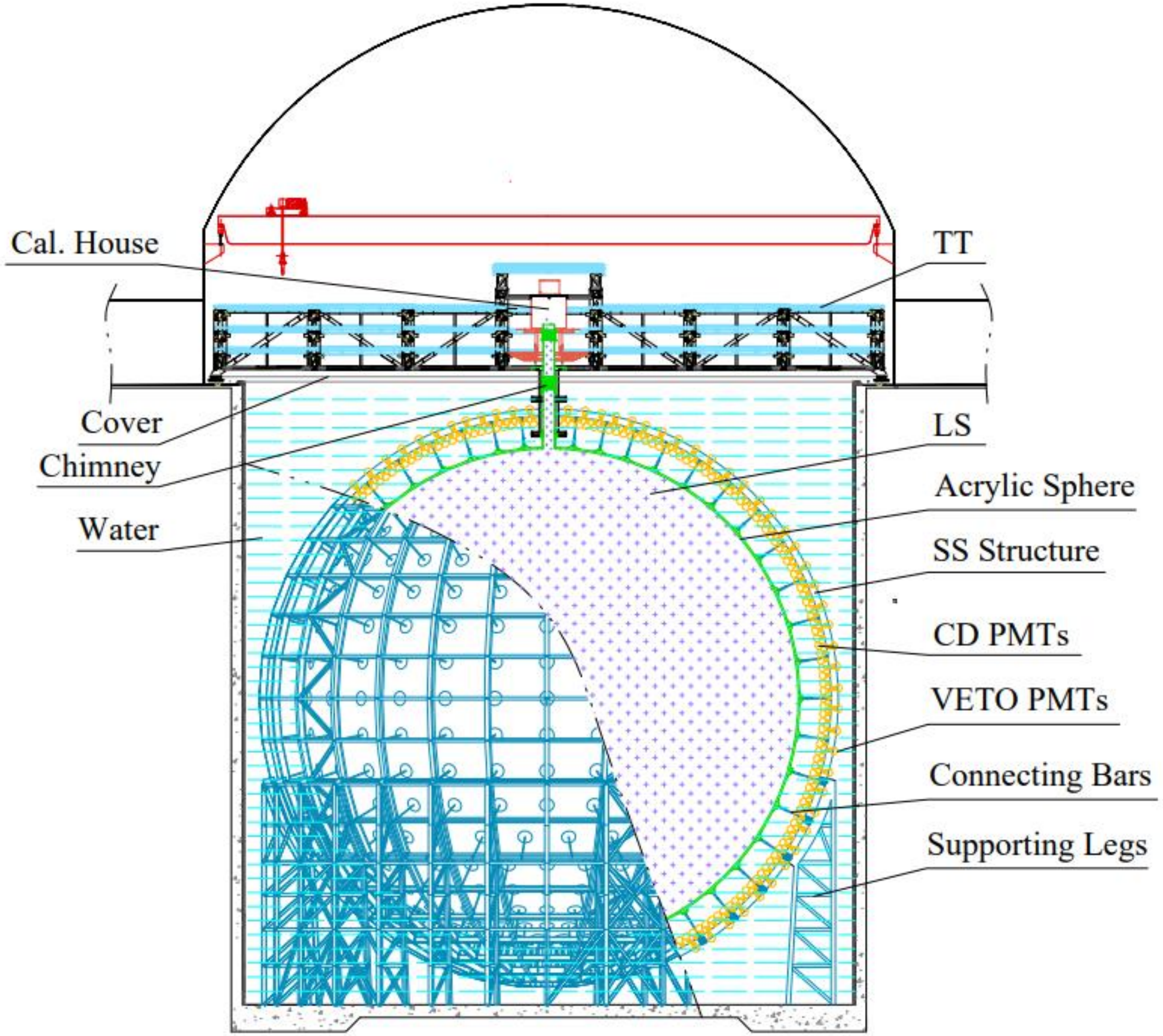
> 700 collaborators

Detector progress



Detector construction status

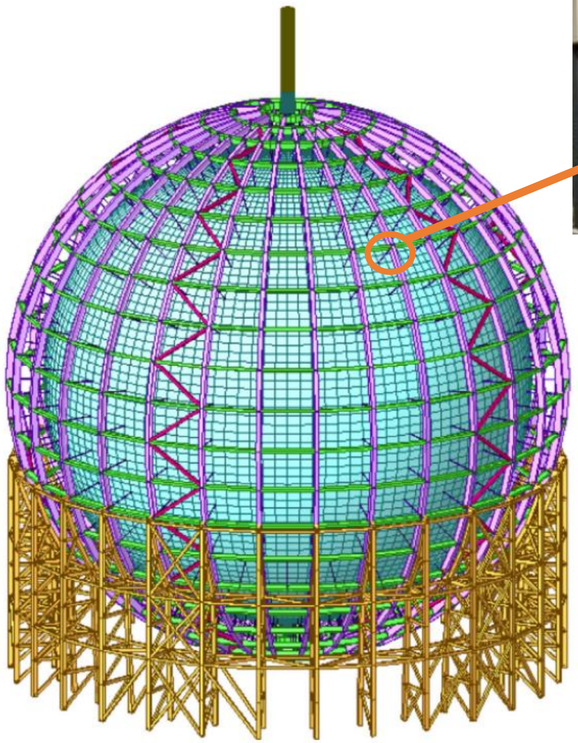
- **Acrylic panels**
  - All the panels installed
  - Whole sphere is finished (Oct. 2024)
- **Stainless Steel structure**
  - Finished in June 2022
- **20012 20'' PMTs + 25600 3'' PMTs**
  - Production and performance test done
  - 95% LPMTs and SPMTs installed
- **Liquid scintillator (20 kt)**
  - Purification plants finished onsite construction
  - Under commissioning now

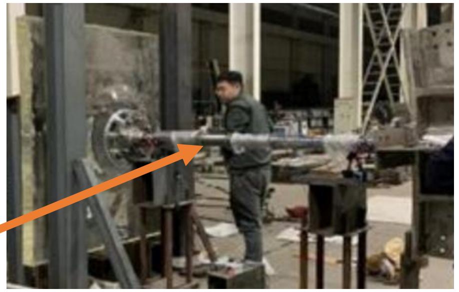


Central detector (SS structure)

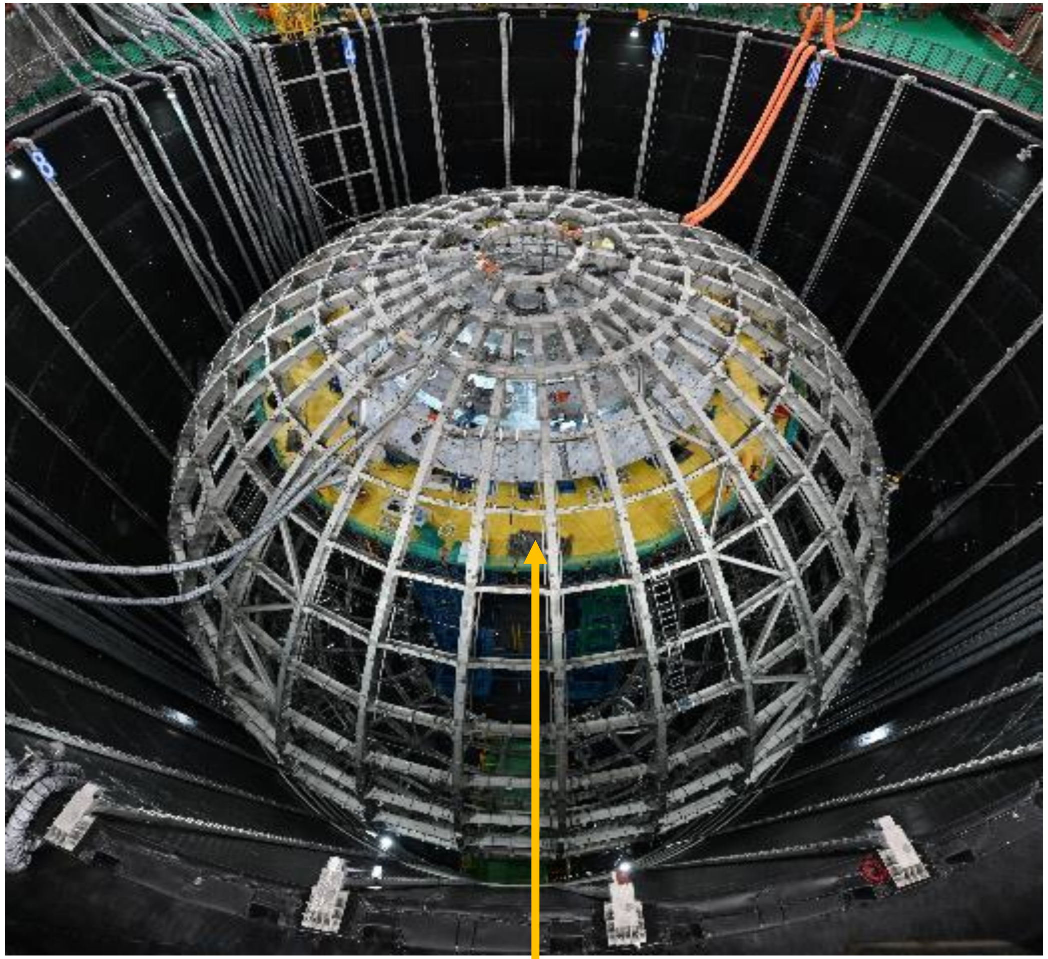
Acrylic vessel is supported by D = 40.1 m stainless steel structure via 590 Connecting Bars

Assembly precision: < 3 mm for each grid





The SS structure has been finished in June 2022



The platform to install the acrylic vessel

Central detector (acrylic vessel)

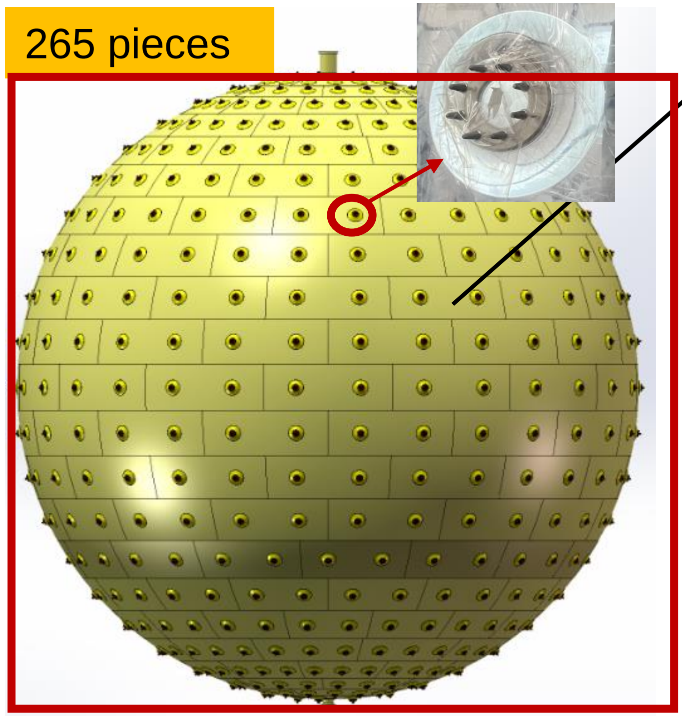
LS container:

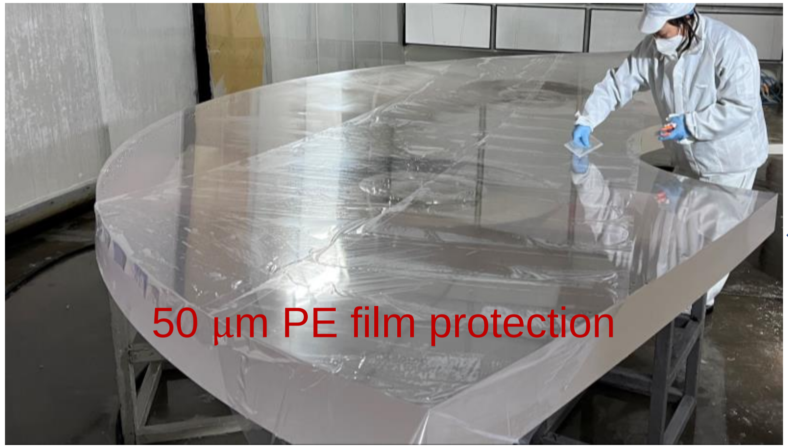
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ water

Radiopurity: U/Th/K < 1 ppt





Central detector (acrylic vessel)

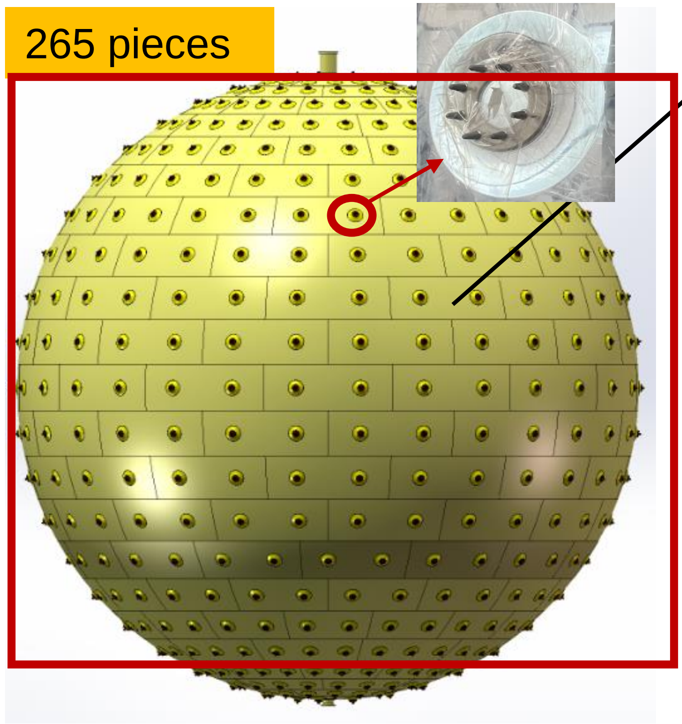
LS container:

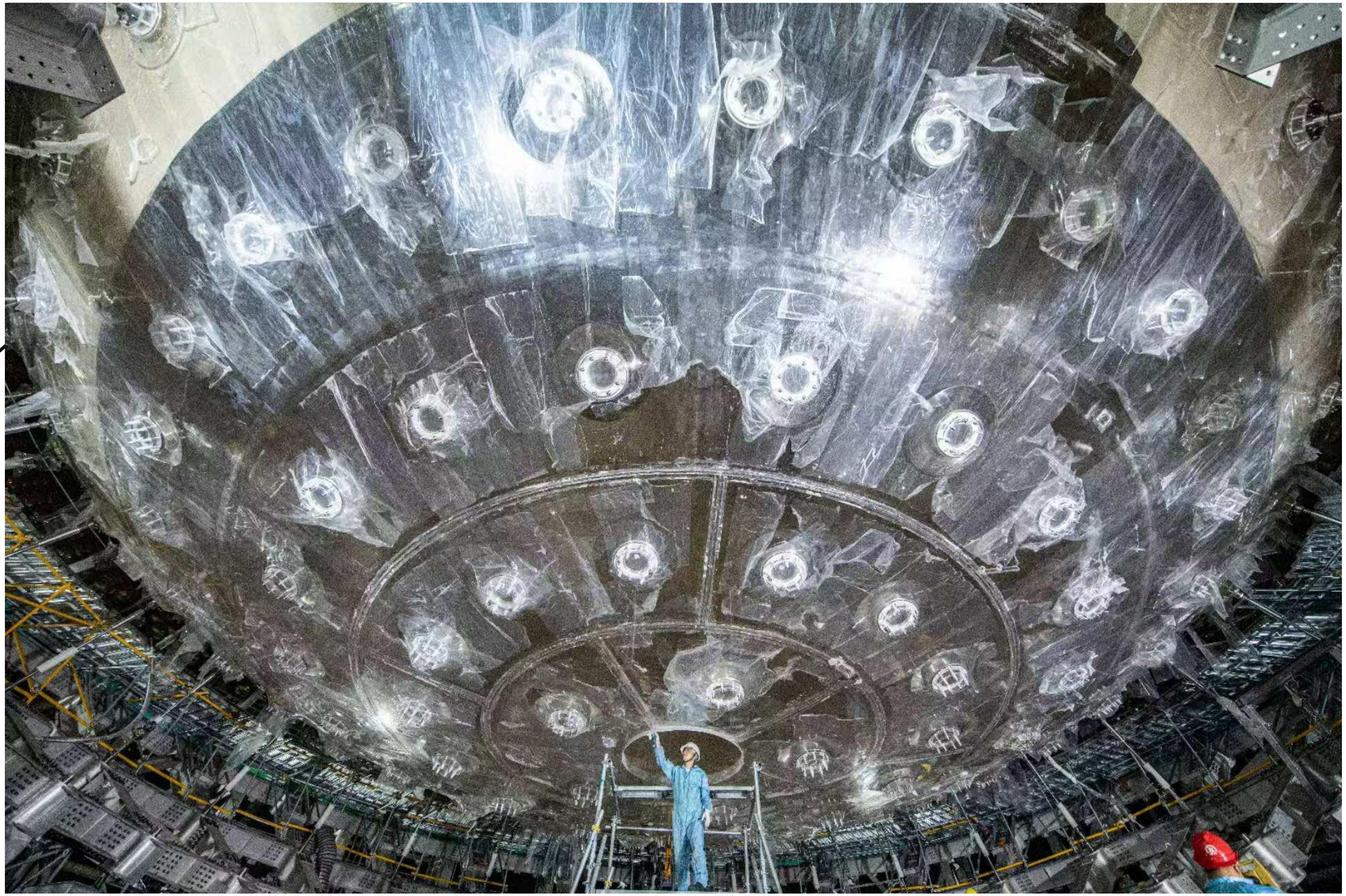
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ water

Radiopurity: U/Th/K < 1 ppt

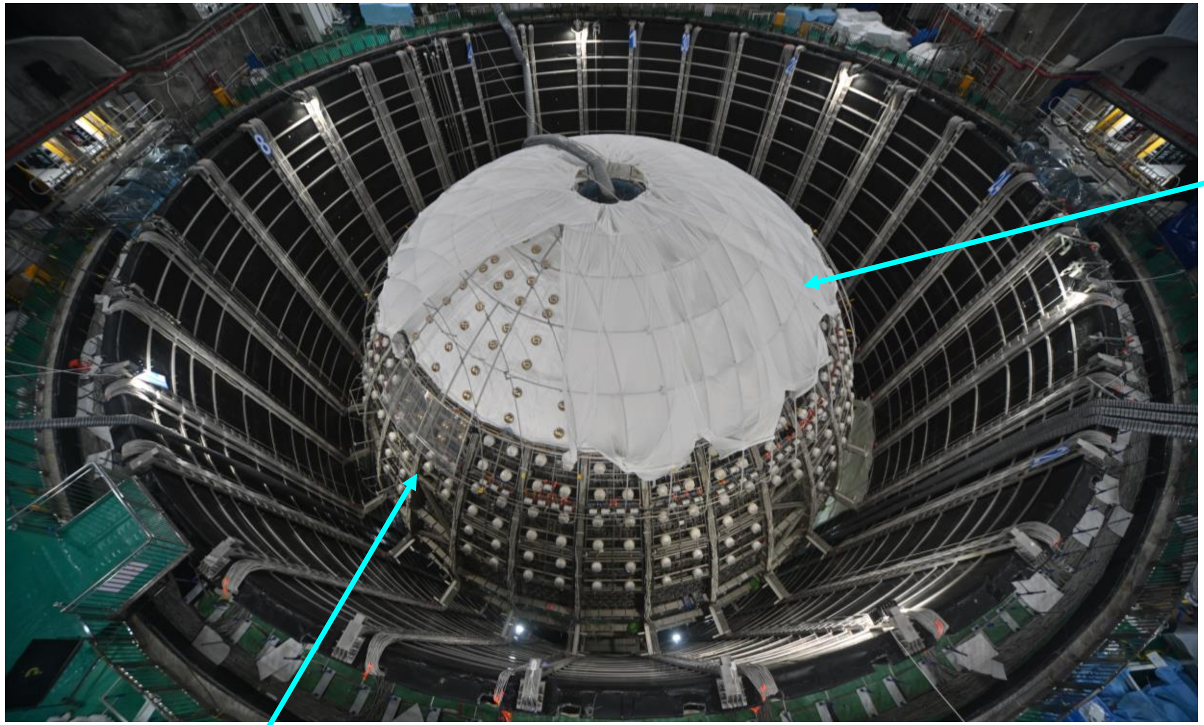




Just finished (Oct. 2024) !

Veto detector (Water Cherenkov)

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



Earth magnetic shielding coils

88% of veto PMTs installed

Ultra Pure Water system

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

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

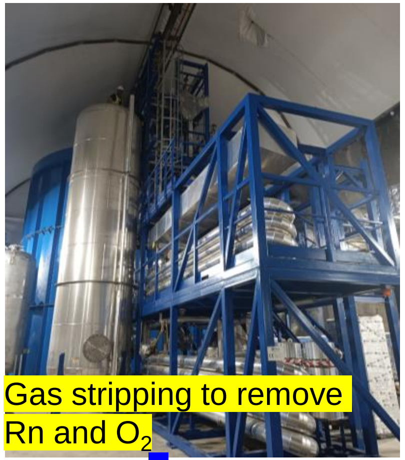
Liquid scintillator (20 kton)

NIM.A 908 (2021) 164823

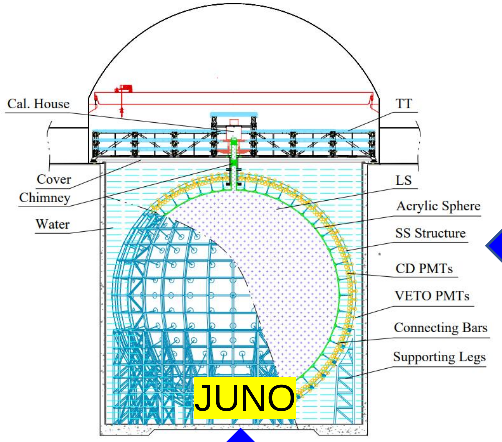
Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

All LS related systems finished assembly, joint commissioning ongoing

SS pipes to underground



15%



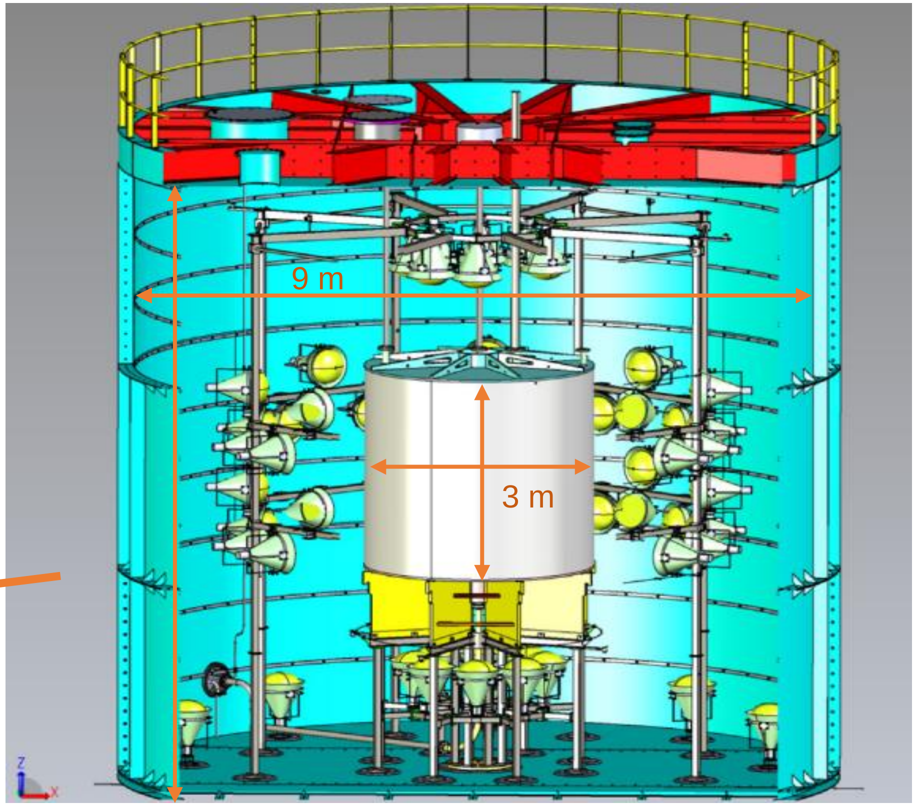
85%

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

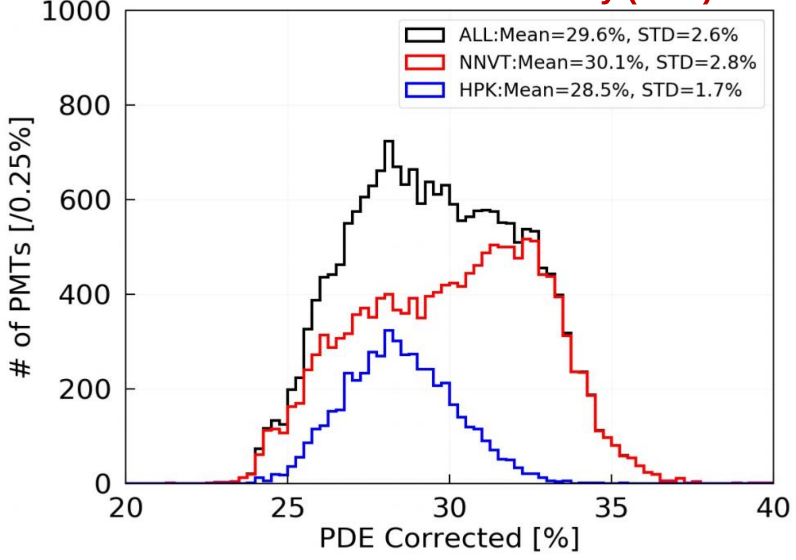


Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator): *arXiv: 2109.10782*

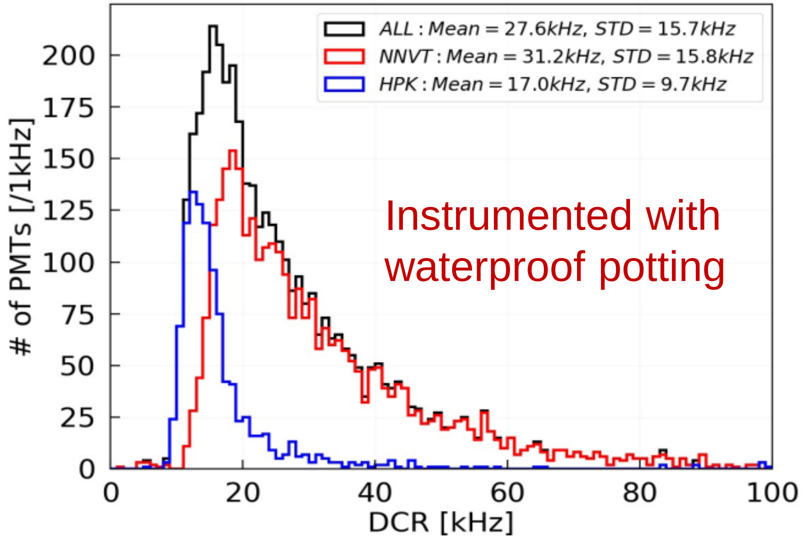
- ✓ A precision measurement of the flux of solar *pp* neutrinos on the few-percent level

Photomultiplier Tubes

Photon Detection Efficiency (PDE)



Dark Counting Rate



All PMTs 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 [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

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

Photomultiplier Tubes

Synergetic 20-inch and 3-inch PMT systems to ensure energy resolution and charge linearity

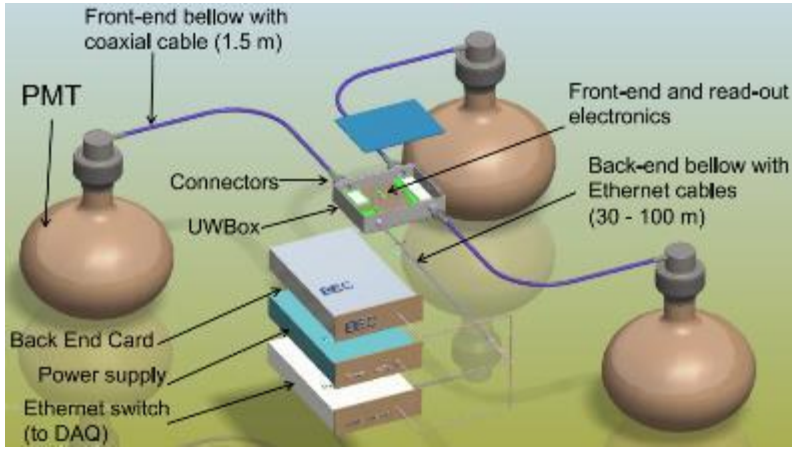
Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm** **w/ protection cover** (JINST 18 (2023) 02, P02013)

Eur.Phys.J.C 82 (2022) 12

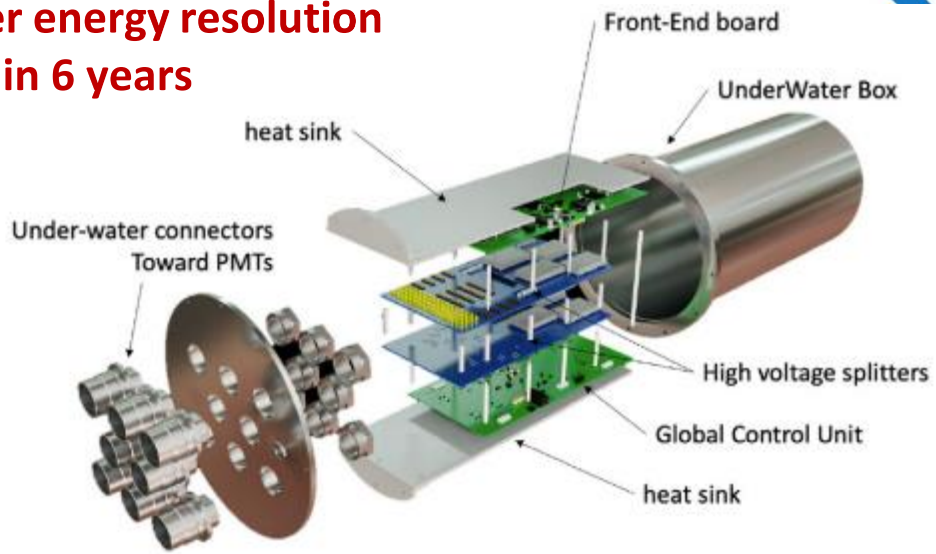
Electronics

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

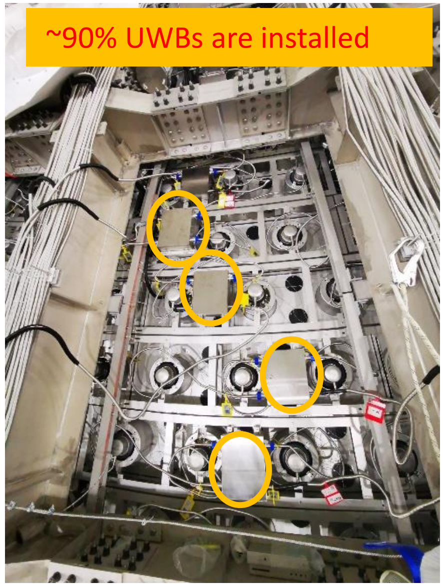
1 GHz waveform digitization, expected loss rate < 0.5% in 6 years

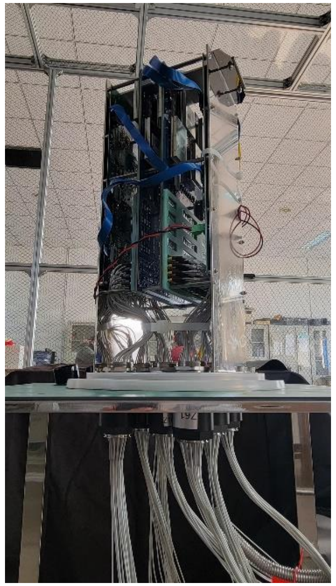


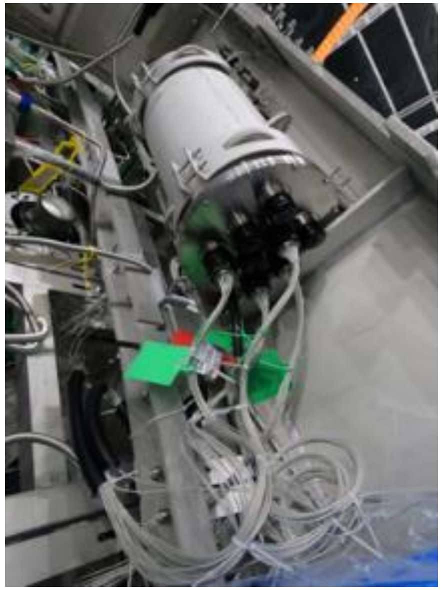
3 20-inch PMTs connected to one underwater box (UWB)



128 3-inch PMTs connected to one underwater box



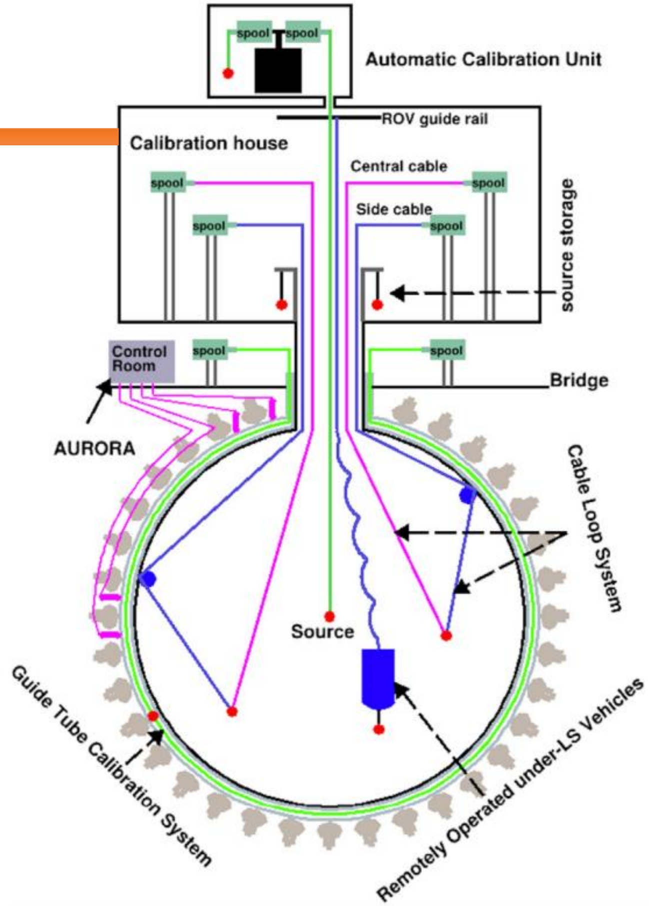




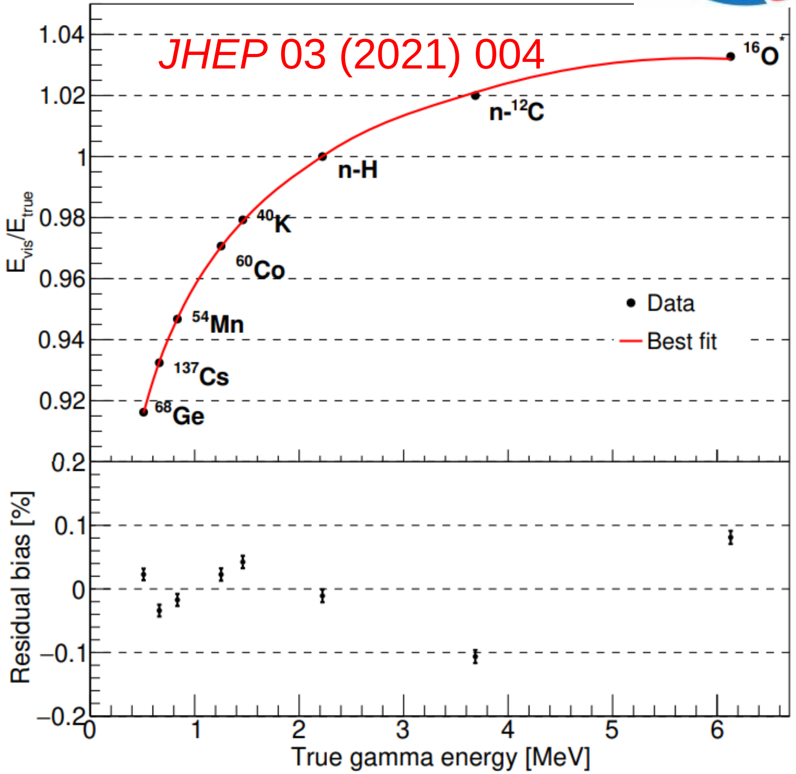
Calibration

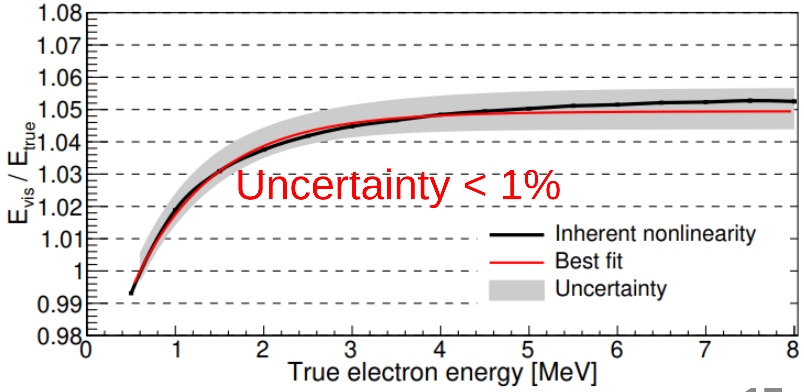
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Installation in progress



Shadowing effect uncertainty from Teflon capsule of radioactive sources: < 0.15%





Reactor Neutrinos

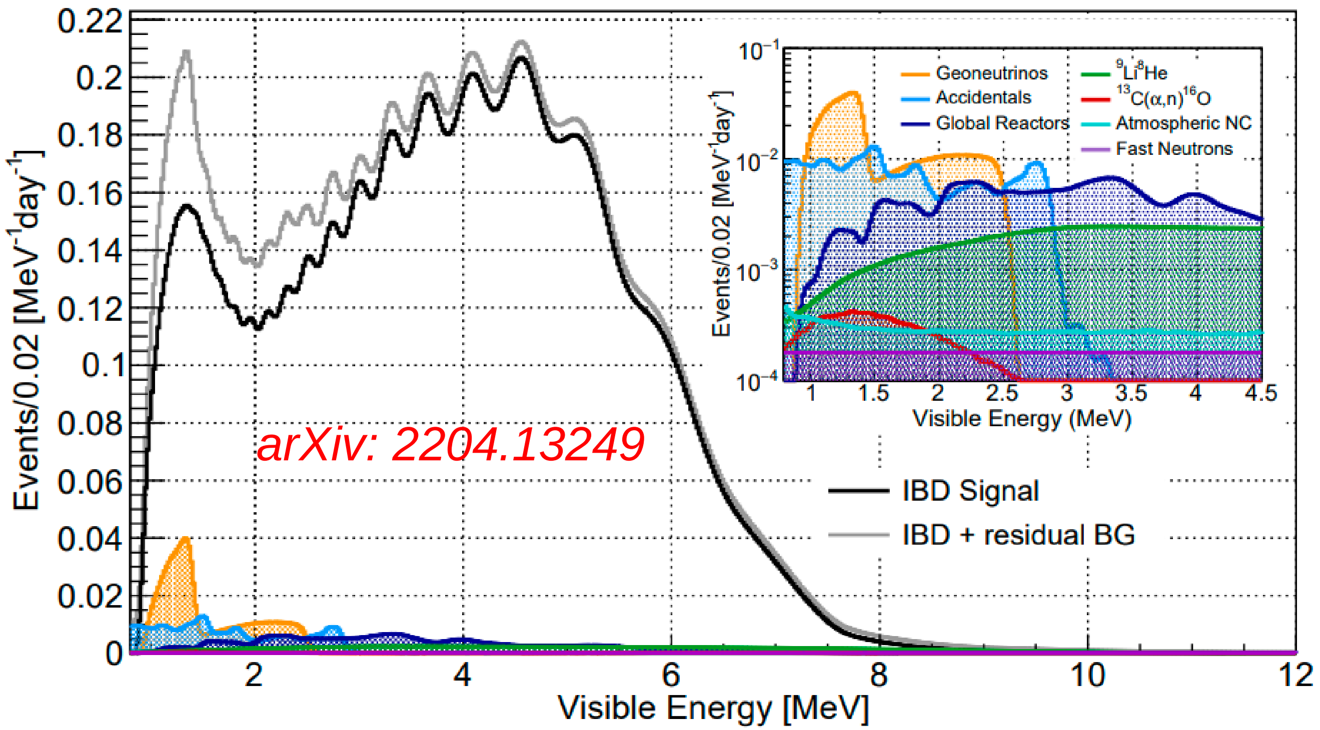
Reactor Antineutrino Oscillation & Detection

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

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

Inverse beta decay reaction

$$\bar{\nu}_e + p \to e^+ + n$$



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}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%**

JUNO physics book *(J. Phys. G43:030401(2016))* ➔ **updated values**

- ☹ 2 fewer reactor cores in Taishan
- ☺ Better muon veto strategy
- ☺ Improved energy resolution: 3.0% @1MeV ➔ 2.9% @1MeV
- ☺ Signal and backgrounds now assessed with full JUNO simulation
- ☹ Slight less overburden
- ☺ Lower radioactivity background based on latest measurements on material radiopurities

Energy resolution

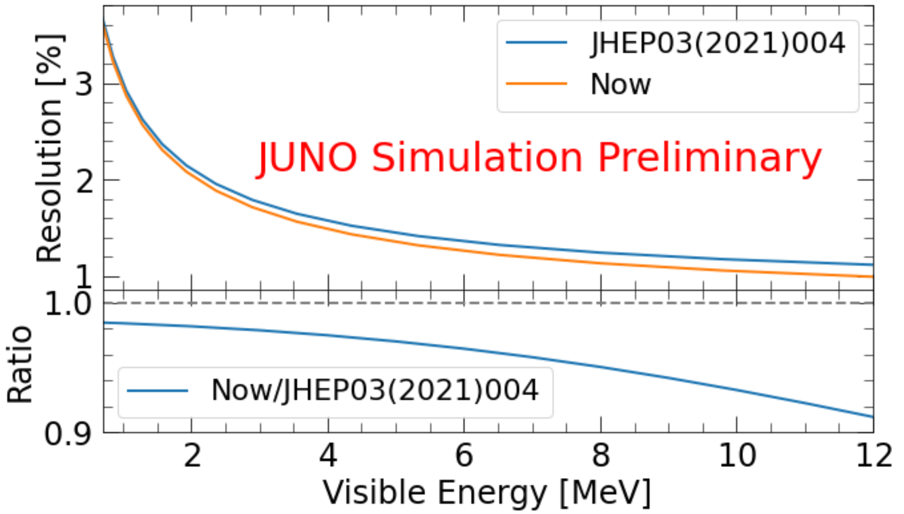
arXiv: 2405.17860

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**	arXiv: 2205.08629
New Central Detector Geometries	**+3%↑**		
New PMT Optical Model	**+8%↑**		EPJC 82 329 (2022)

Positron energy resolution is understood:

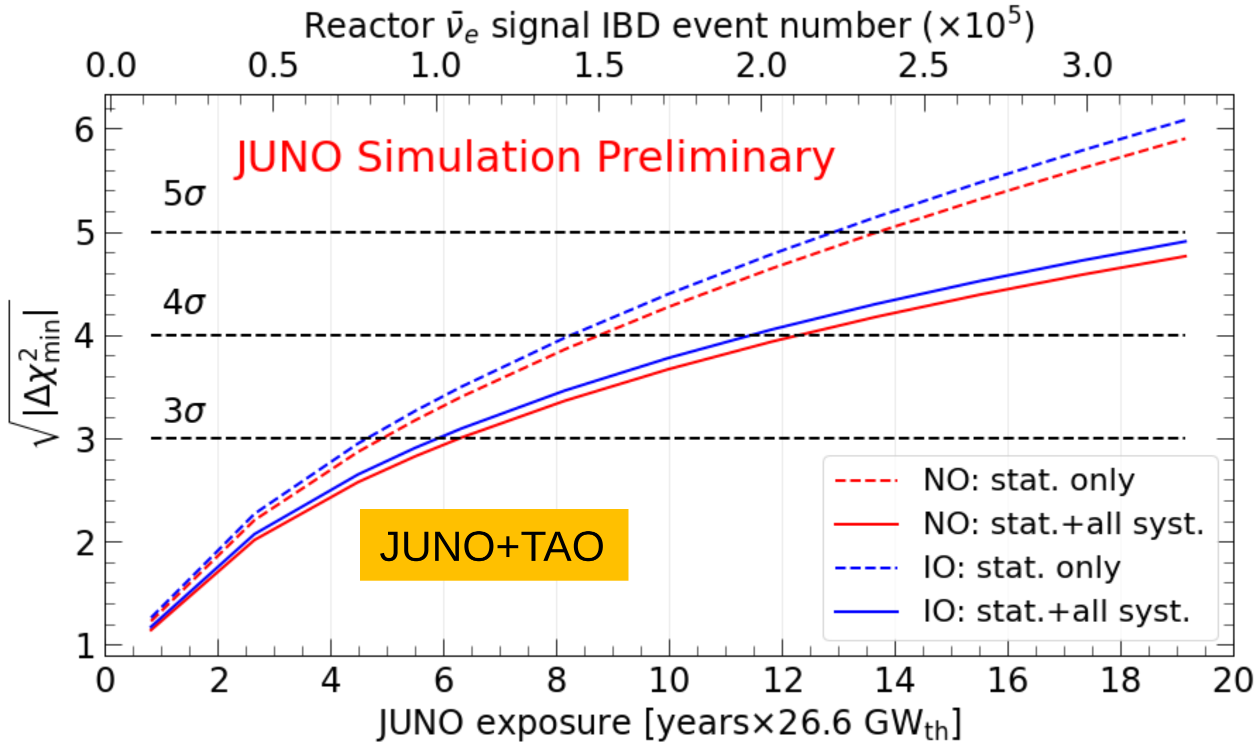
$$\frac{\sigma}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

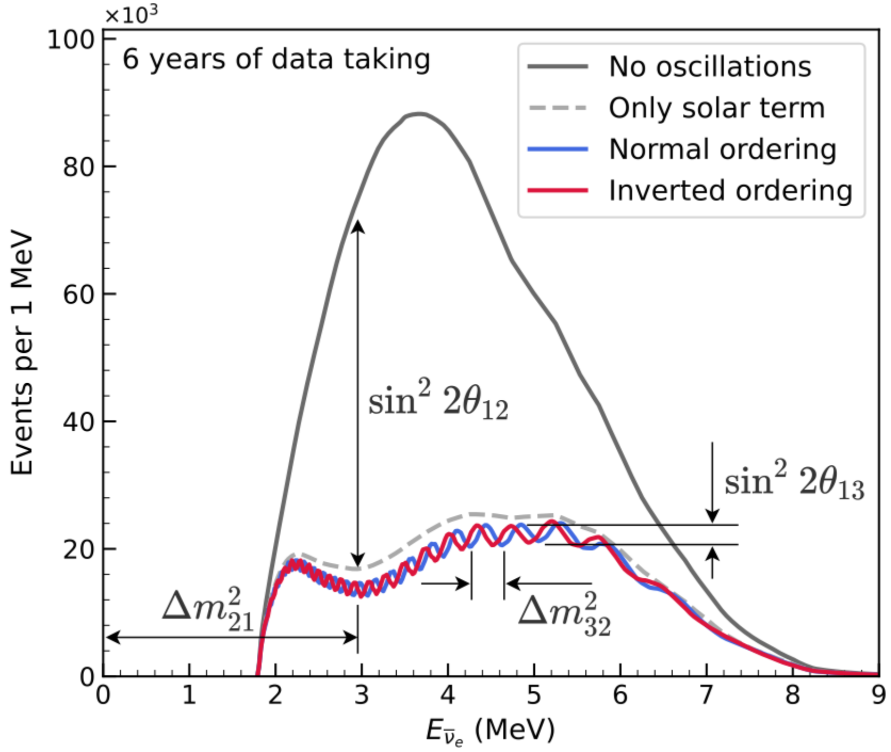
- **Photon statistics**
- **Annihilation-induced γs**
- **Dark noise**
- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity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



Neutrino Mass Ordering

arXiv: 2405.18008





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

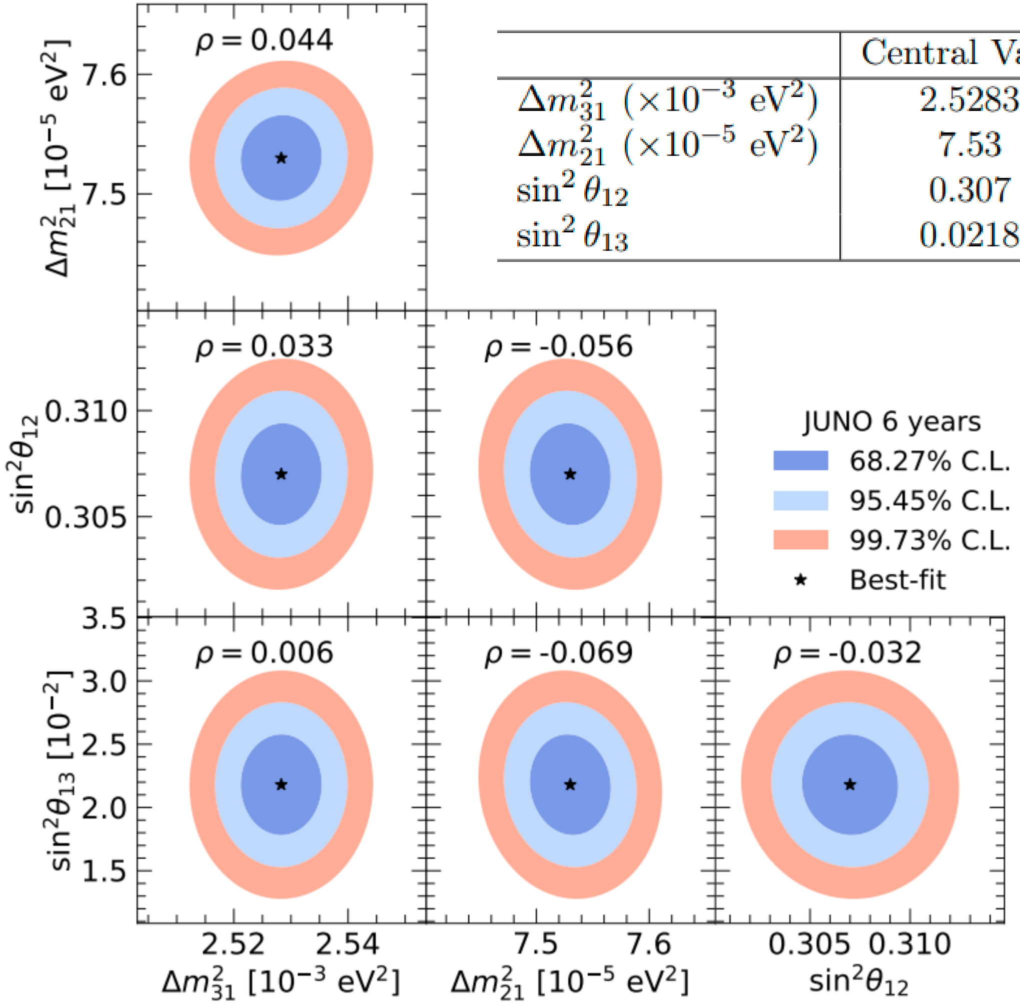
Combined reactor + atmospheric neutrino analysis is in progress: further improve the NMO sensitivity

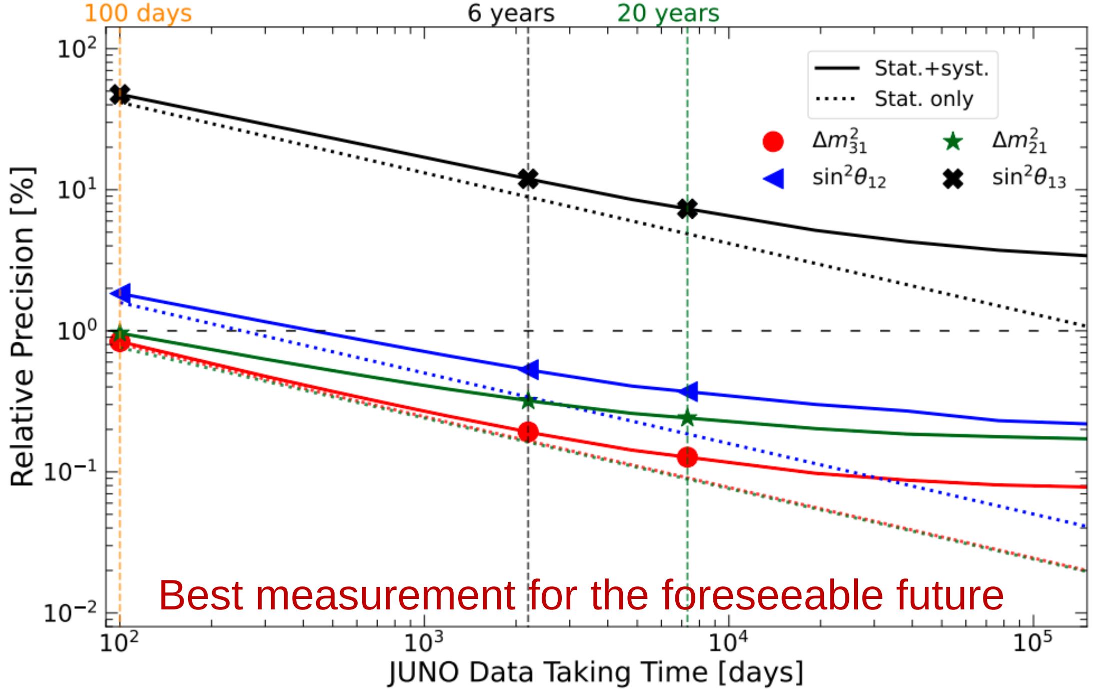
Neutrino oscillation parameters

arXiv:2204.13249, Chin. Phys. C 46 (2022) 123001

Precision of $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ < 0.5% in 6 yrs

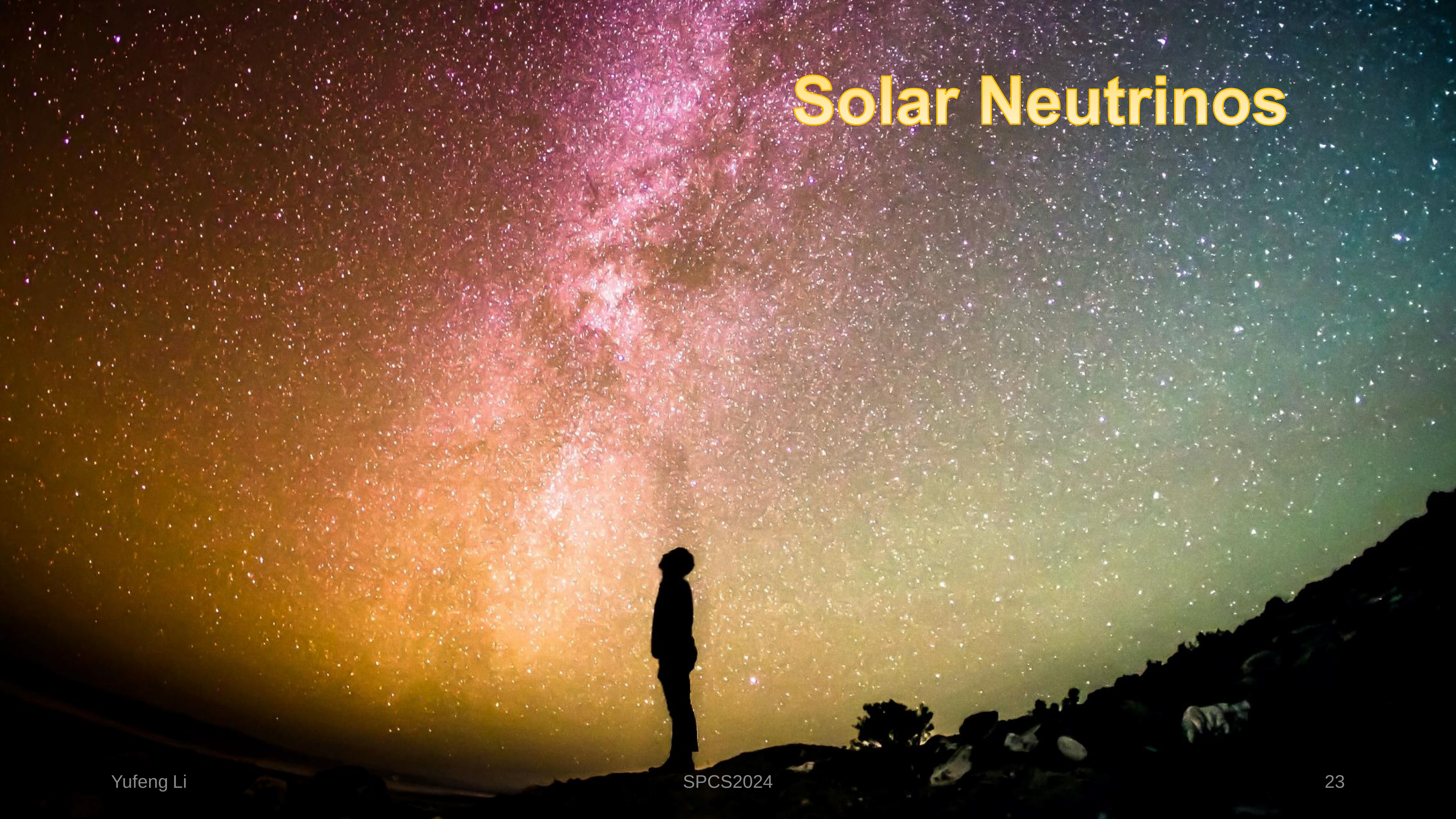
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 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%)





The improvement in precision over existing constraints will be about one order of magnitude

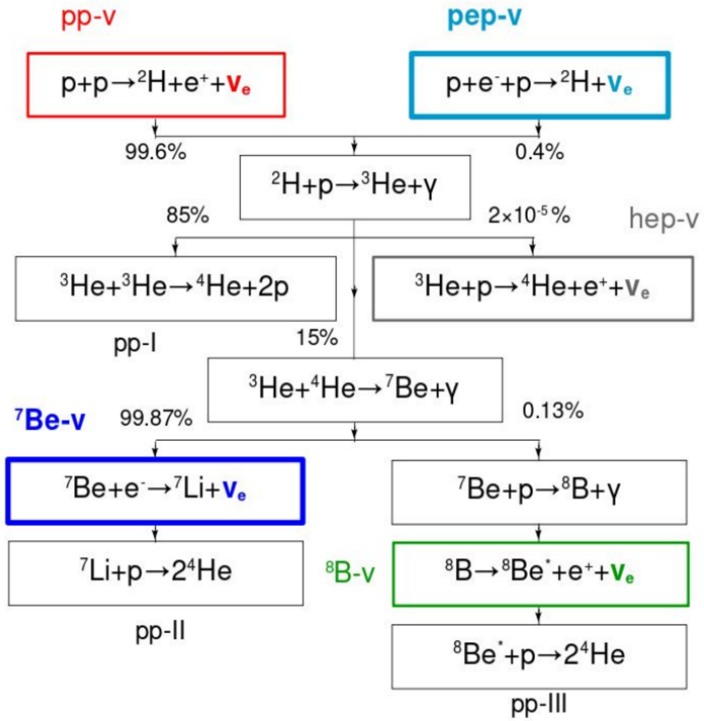
Solar Neutrinos



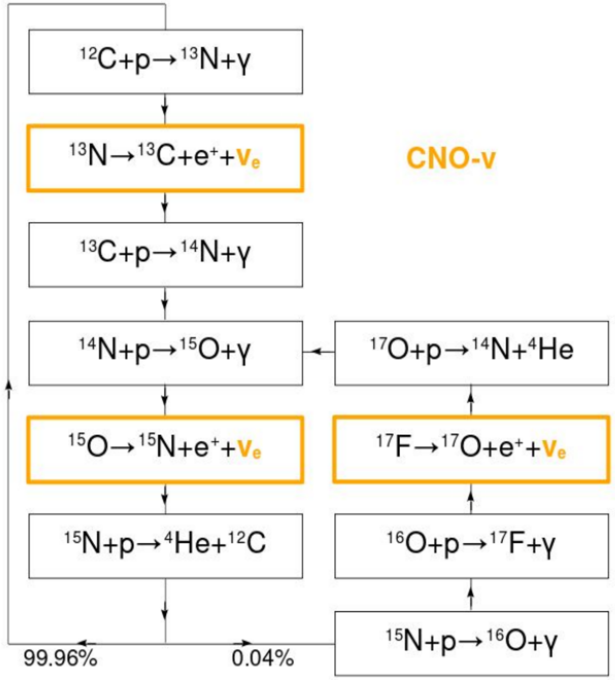
Solar neutrinos

Produced in the core of the Sun through **fusion reactions**:

pp chain

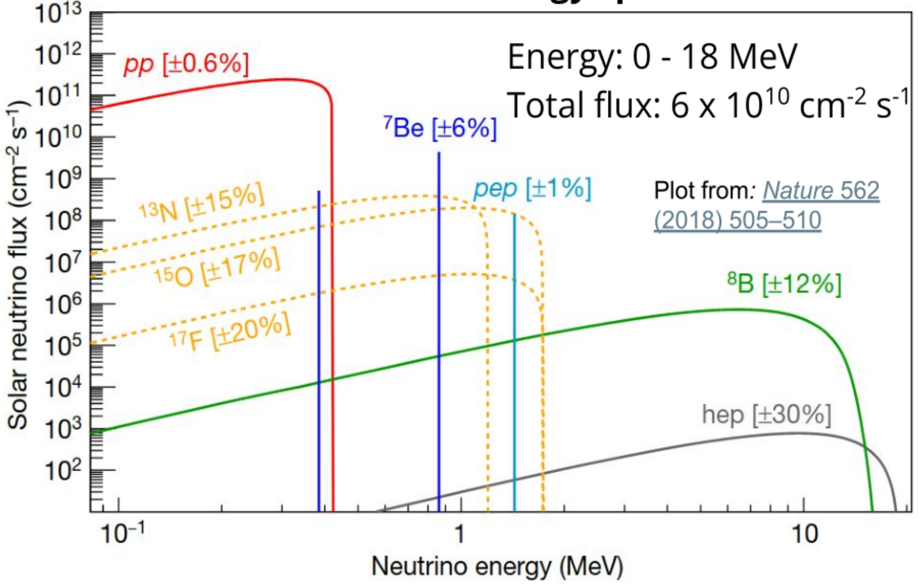


CNO cycle



The ***pp* chain** accounts for **99%** of the total **solar luminosity**
The CNO cycle becomes dominant in heavier stars

Solar neutrinos energy spectrum



Solar neutrinos are helpful to **probe**:

- Physical **quantities** of the **Sun** (i.e. luminosity, metallicity)
- **Neutrino properties**:
  - θ_{12} and Δm^2_{21}
  - Matter effects on neutrino oscillations

JUNO: Feasibility (low energy part)

J. Cos. Astro. Phys. 10 (2023)

Solar neutrinos with energy **< 2 MeV** (^{7}Be, *pep* and CNO) can be detected only through elastic scattering (**ES**) with LS **electrons:**

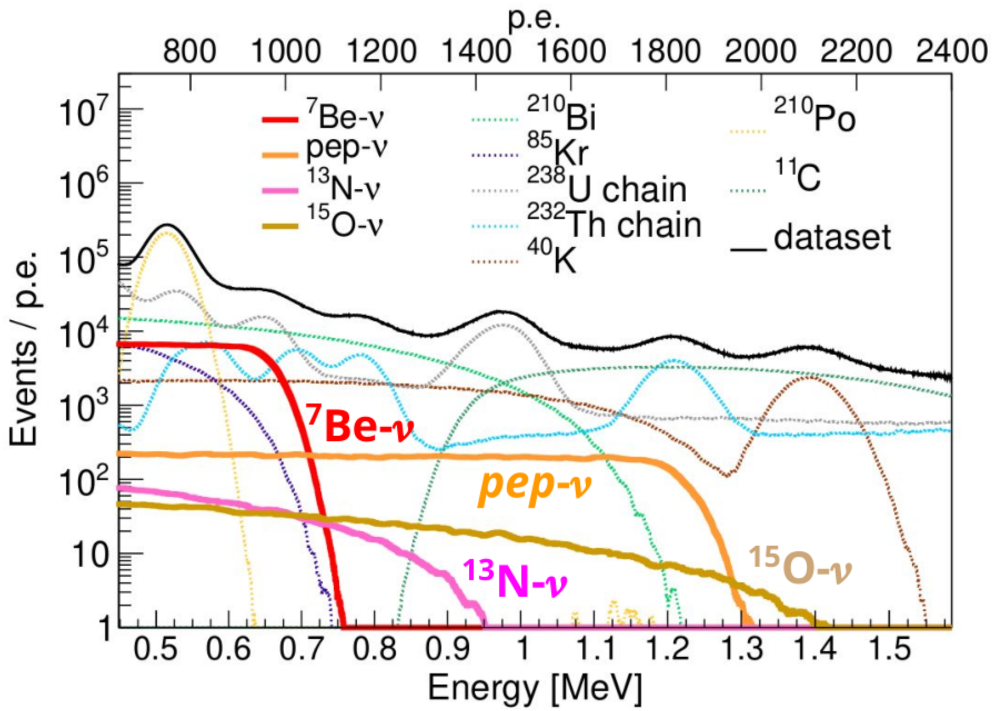
$$\textbf{ES:} \quad \nu_x + e^- \rightarrow \nu_x + e^- \qquad x = e, \mu, \tau$$

BACKGROUNDS

- **External backgrounds**: negligible with fiducial volume cut
- **Cosmogenic backgrounds**: ^{11}C dominated, tagging with Three-Fold coincidence algorithm Eur. Phys. Journal C 81 (2021) 1075
- **Internal backgrounds**: will drive the sensitivity to solar neutrinos, different concentration scenarios studied:

Very low	Borexino phase-III
Low	10 x Very Low
Medium	10 x Low
High	Minimum requirement for NMO studies

6 years, Medium radiopurity scenario

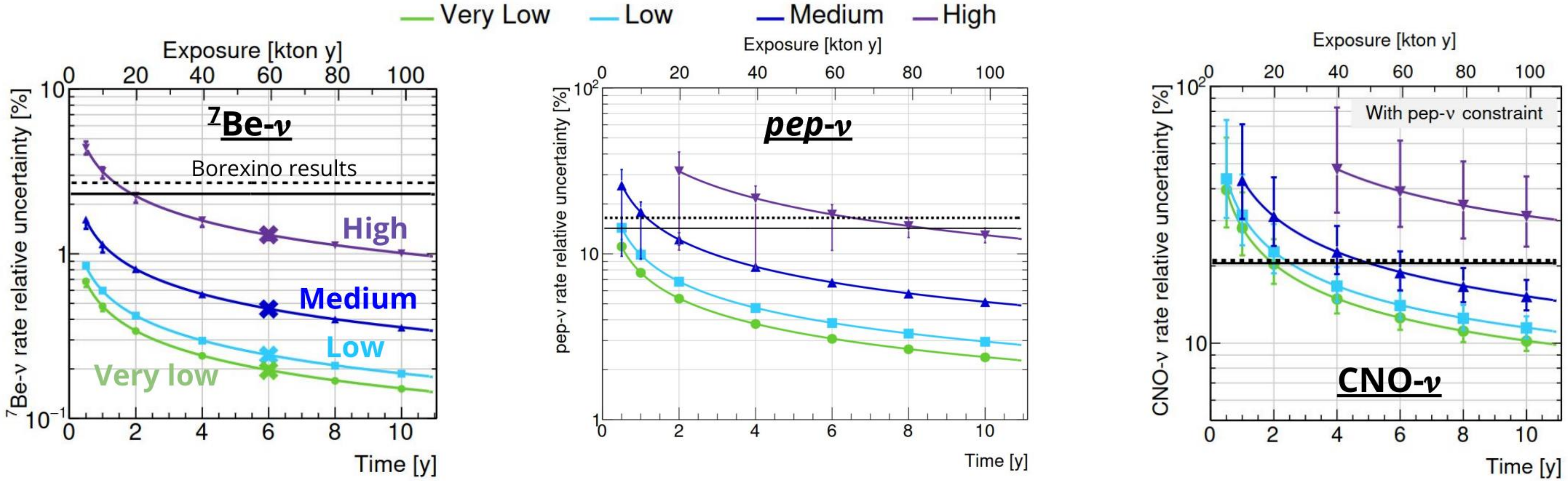


Solar neutrinos contribution can be extracted thanks to the **different spectral shapes** of the species.

JUNO: Feasibility (low energy part)

[J. Cos. Astro. Phys. 10 (2023) 022](#)

Internal backgrounds scenarios



JUNO can provide the **most precise measurements** within:

~2 years

~2 years, **apart** from **High** radiopurity scenario

~6 years, **apart** from **High** radiopurity scenario

No constraint on ^{210}Bi needed

Separation of ^{13}**N-ν** and ^{15}**O-ν** possible with **good radiopurity**

JUNO: Feasibility (high energy ^{8}B)

Chin. Phys. C 45 023004 (
Ap. J. 965 (2024) 122

Interaction channels of ^{8}B-ν:

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

- No threshold
- All flavours & $\sigma(\nu_{\mu,\tau}) / \sigma(\nu_e) = 1/6$
- Single events - continuous spectrum

CC: $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$

- $E_{thr} = 2.2$ MeV
- Possible only with ν_e
- Prompt: e^-; Delayed: ^{13}N decay

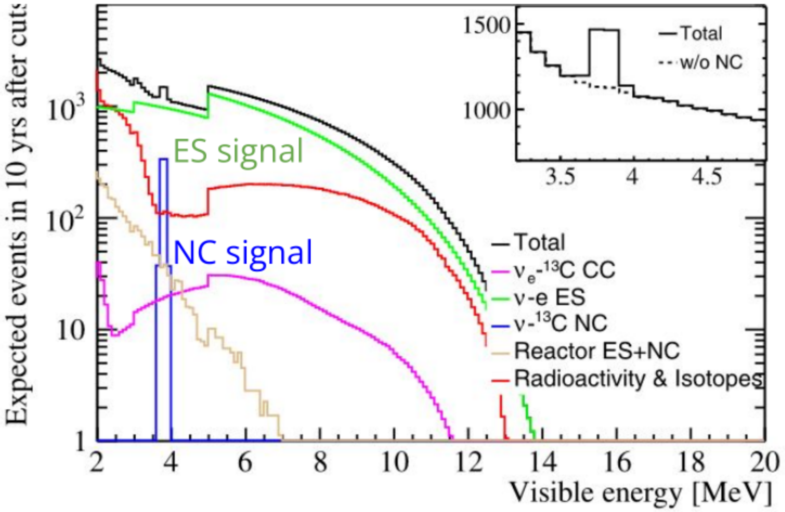
NC: $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}C^*$

- $E_{thr} = 3.685$ MeV
- All flavors & equal σ
- Single events - monochromatic γ

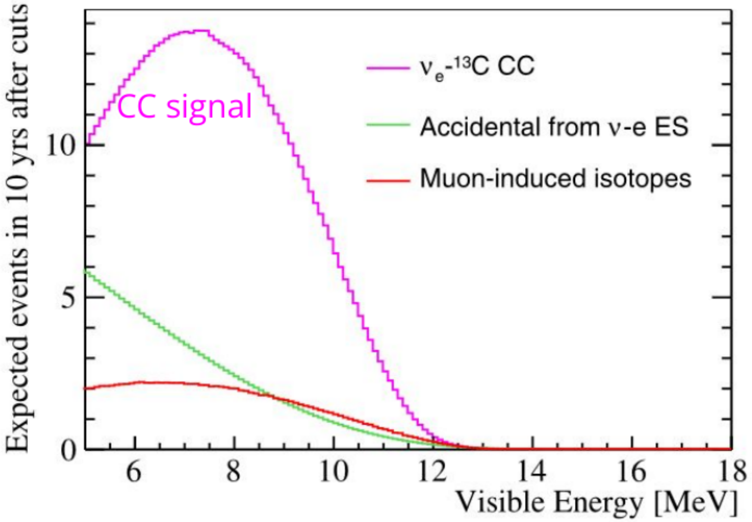
Backgrounds:

- **Externals**: can be neglected after FV cuts
- **Internals**: unstable nuclei in ^{232}Th and ^{238}U chains with high Q values
- **Cosmogenics**: can be reduced after Three-Fold Coincidences cuts
- **Accidental** coincidences (specific for CC)

10 years, single events after cuts



10 years, correlated prompt events after cuts



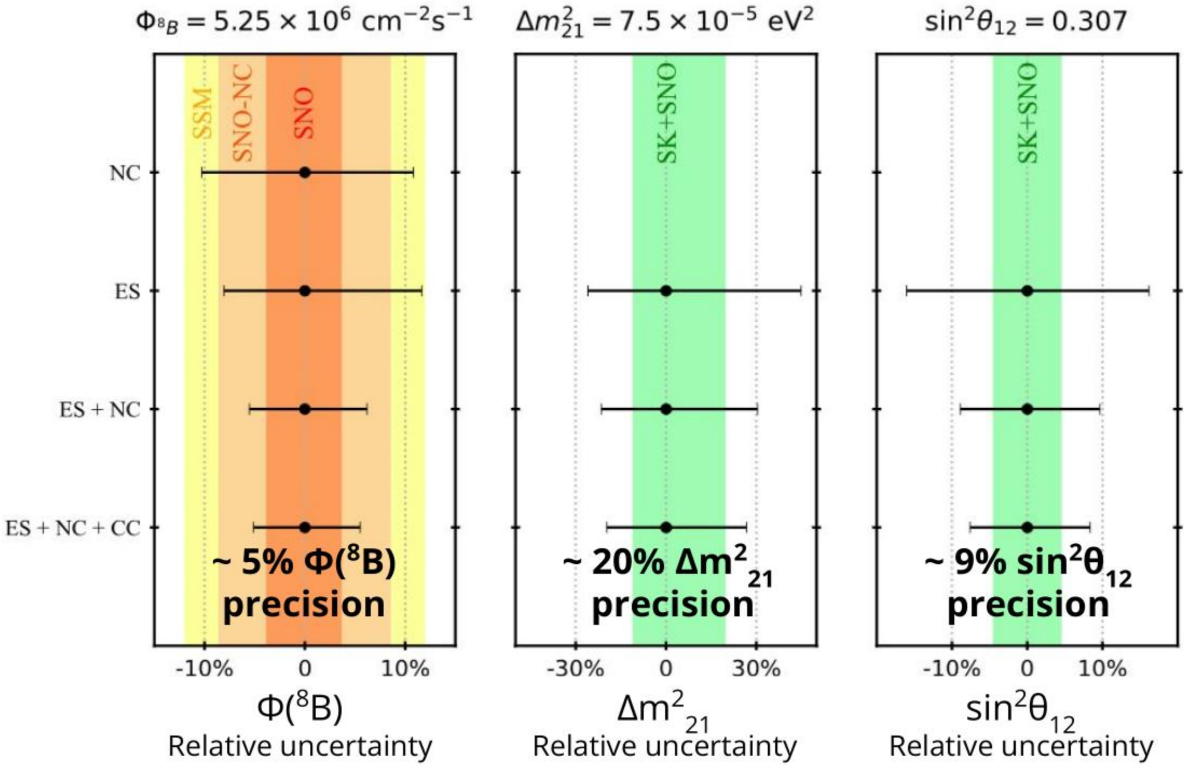
Neutrinos from Sun (B8)

CC & ES: their event **rate** depends on the neutrino flux and on the ν_e **survival probability** model
NC: it will allow a **model independent measurement** of **Φ(^{8}B)**, first after SNO

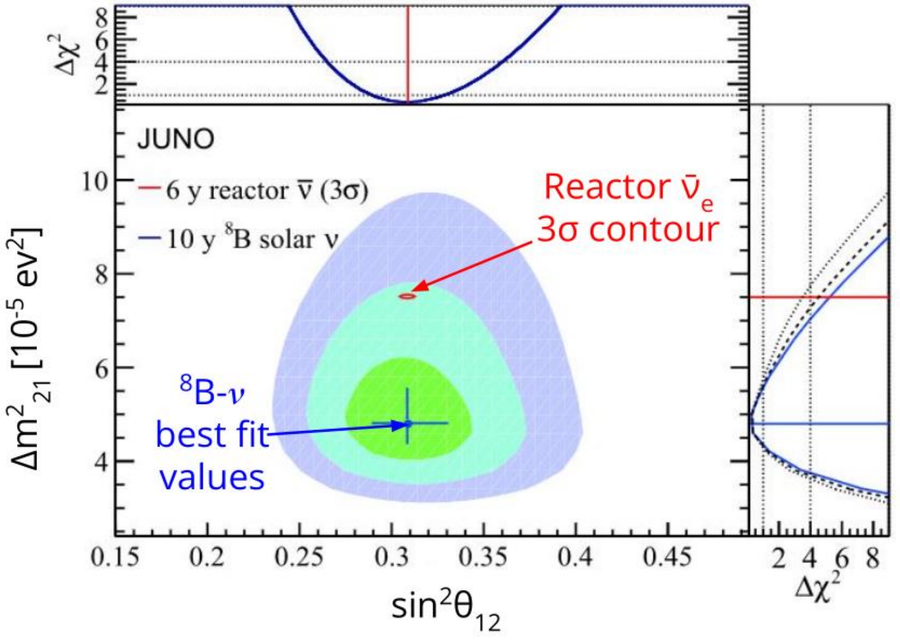
→ **Simultaneous measurement** of **Φ(^{8}B), Δm^2_{21}, and $\sin^2\theta_{12}$**

Chin. Phys. C 45 023004 (2021) 1
Ap. J. 965 (2024) 122

JUNO results with 10 years of data-taking



Δm^2_{21} and **$\sin^2\theta_{12}$** with **^{8}B-ν & reactor $\bar{\nu}_e$**

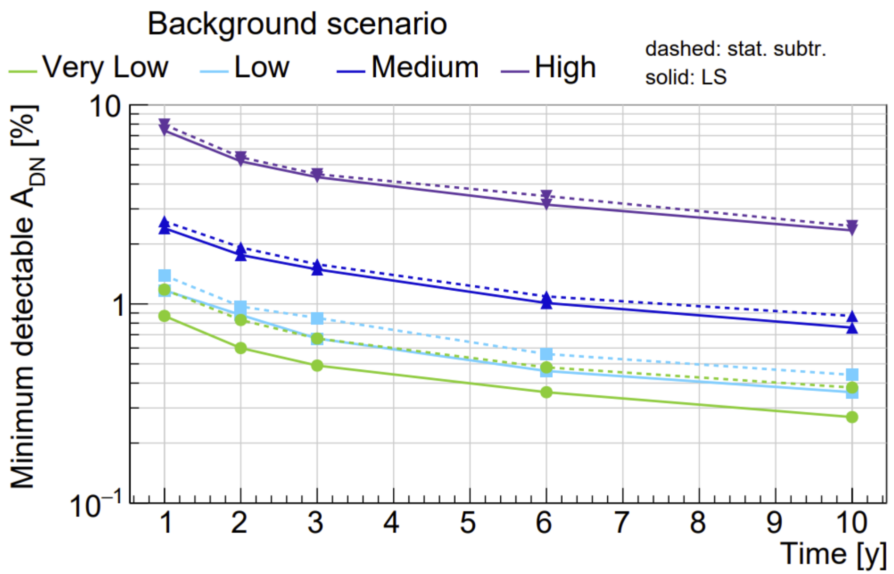


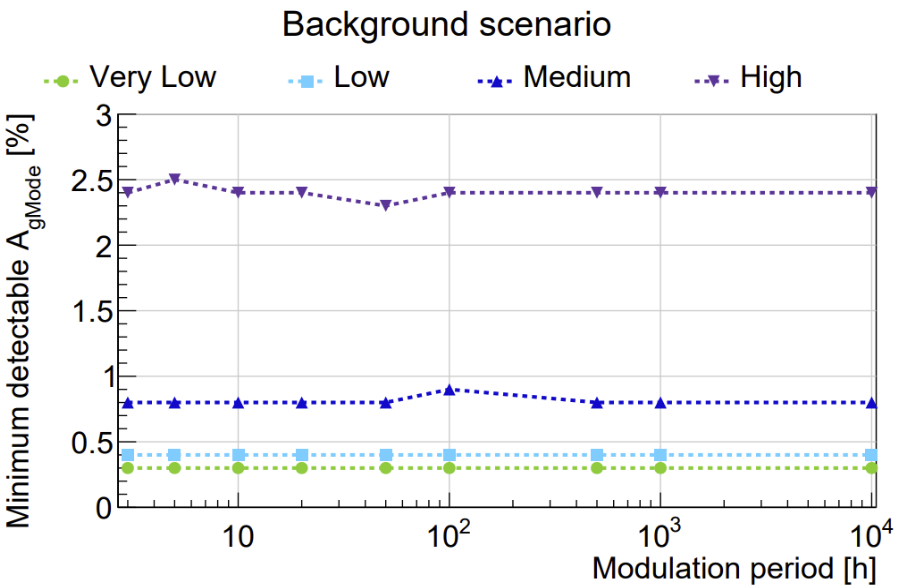
Potential to search for possible discrepancies

Periodic modulations of Solar neutrinos

Periodic modulations of Solar neutrinos

- Seasonal modulation
  - Vacuum oscillation
  - Eccentricity of the Earth's orbit
- Day-Night Asymmetries
  - Earth matter effects
- Solar gravity modes (or g modes)
  - oscillations of the solar interior

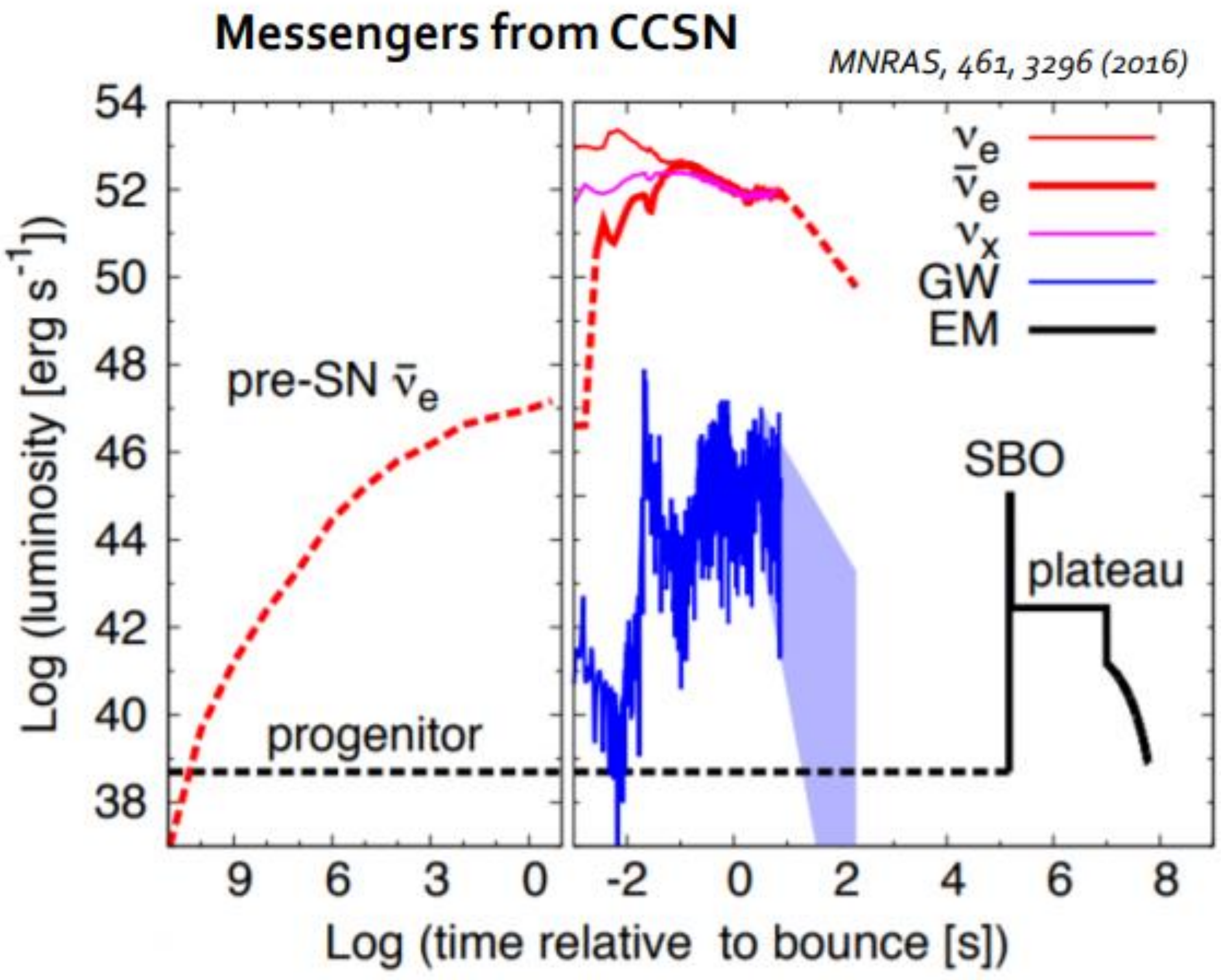




JUNO, arxiv:2303.03910, JCAP 10 (2023) 022

Supernova Neutrinos

Multi-messenger Signals



Large liquid scintillator detectors, like JUNO, has great potential on detecting both pre-SN and SN ν's

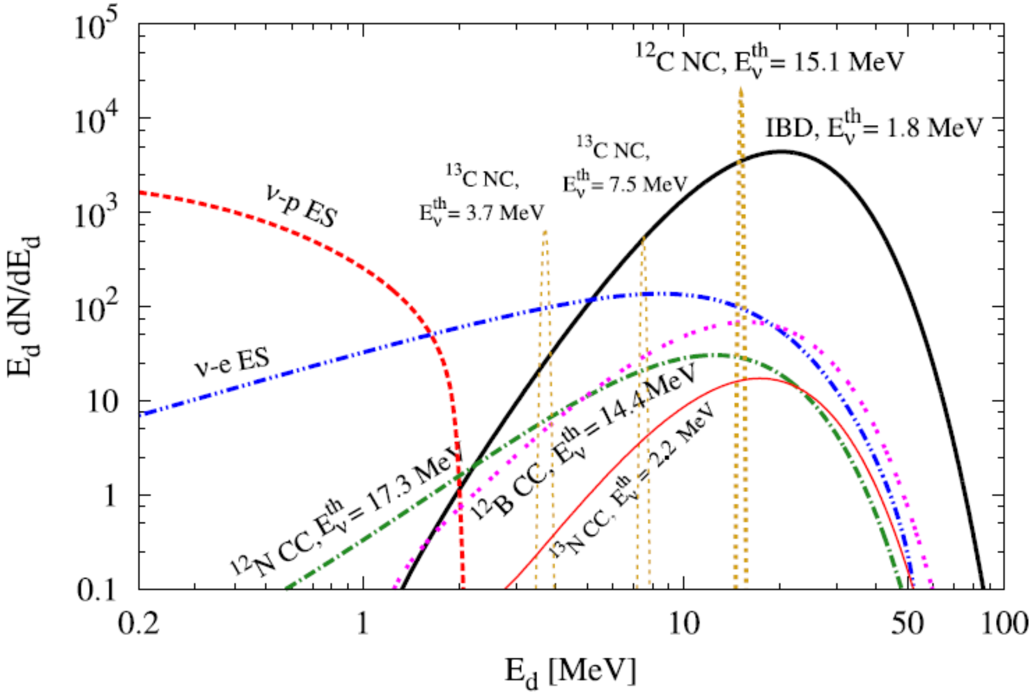
- **Pre-SN neutrinos**
  - **~MeV** neutrinos, much lower luminosity than SN burst neutrino
  - visible ~**days** before core collapse for **nearby** galactic progenitors
- **SN burst neutrinos**
  - **Few tens of MeV** neutrinos, last for ~**10s** with burst, accretion and cooling stages
  - Background almost **free** for SN burst neutrinos

CCSN potential at JUNO

Multi-channel detection, all flavors

5000 IBD, 300 eES, 2000 pES,
200 ^{12}C CC, 300 ^{12}C NC @10 kpc

- Early warning
- CCSN Characteristics
  - Time evolution & Energy spectra
  - Total energy, luminosity ...
- Neutrino properties
  - Mass ordering
  - Absolute mass
  - New physics

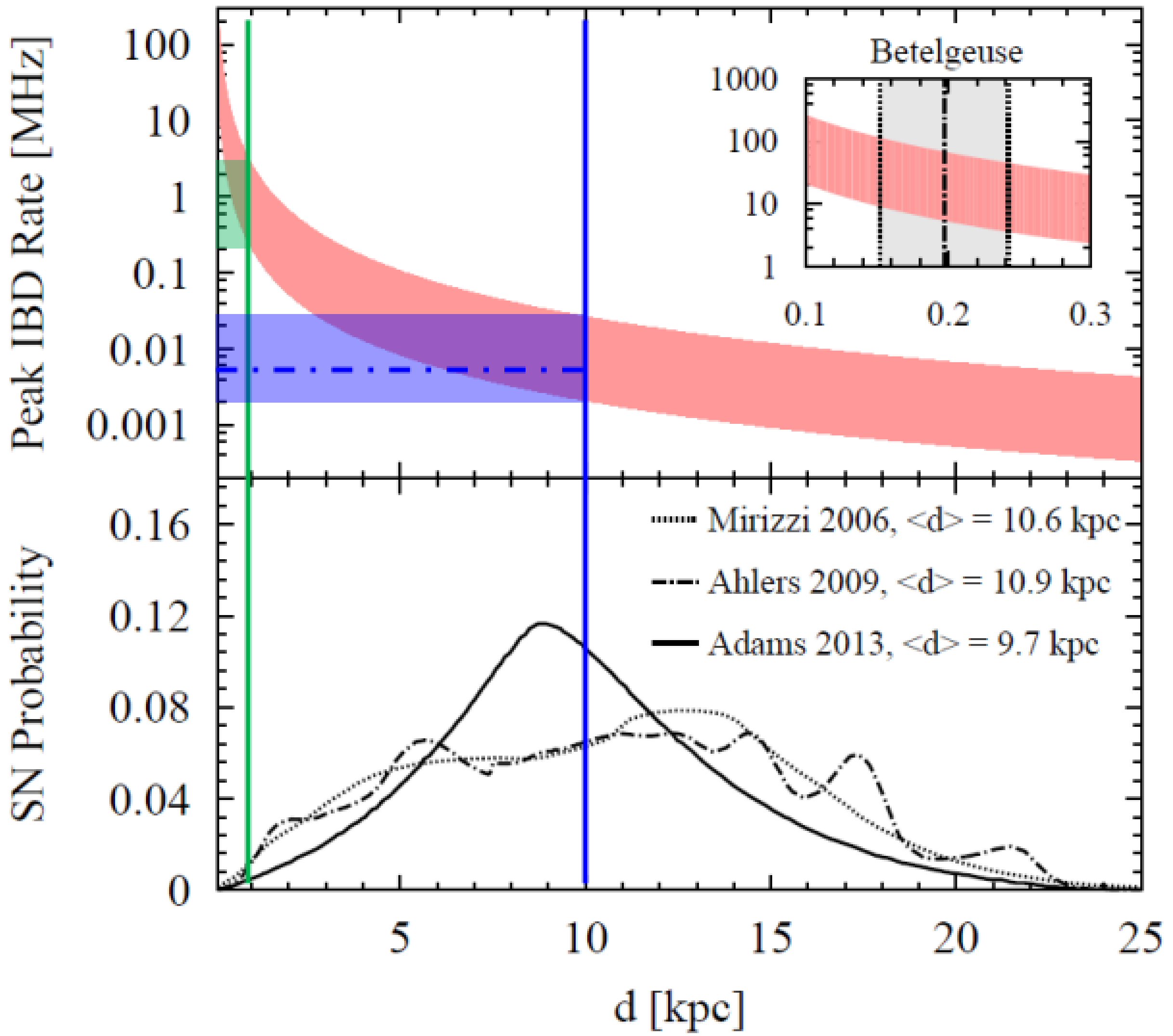


Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2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

Early Warning

- Prompt and Online monitor systems designed for **SN Early Warning**
  - Non-stop, continuous monitoring even from the LS filling period
  - Not affected by any Run Modes (physics, calibration, diagnostic, etc)

- DAQ design can fulfil the requirements on SN data taking
  - **For >0.2 kpc CCSN: No (T, Q) data loss**
  - For <0.2 kpc CCSN: acquire maxi. data as we can
  - For each PMT channel, real-time waveform processing at FPGA to extract (T, Q)

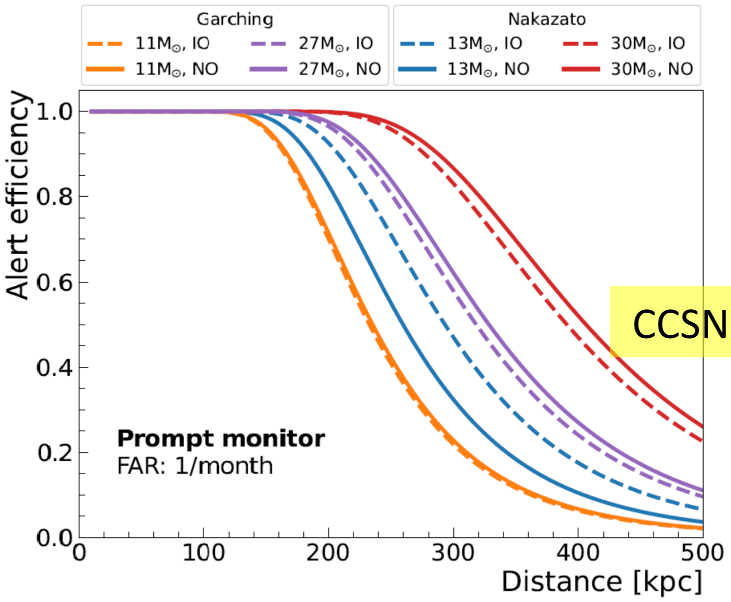


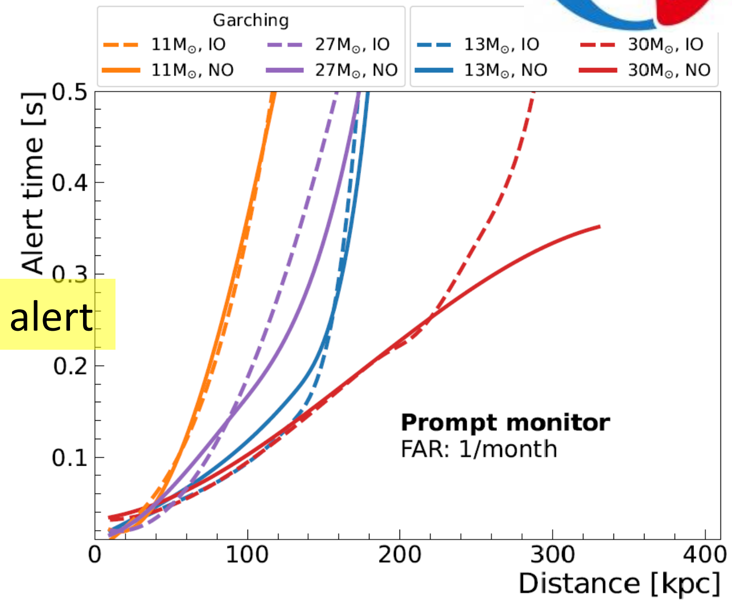
Alert Capability

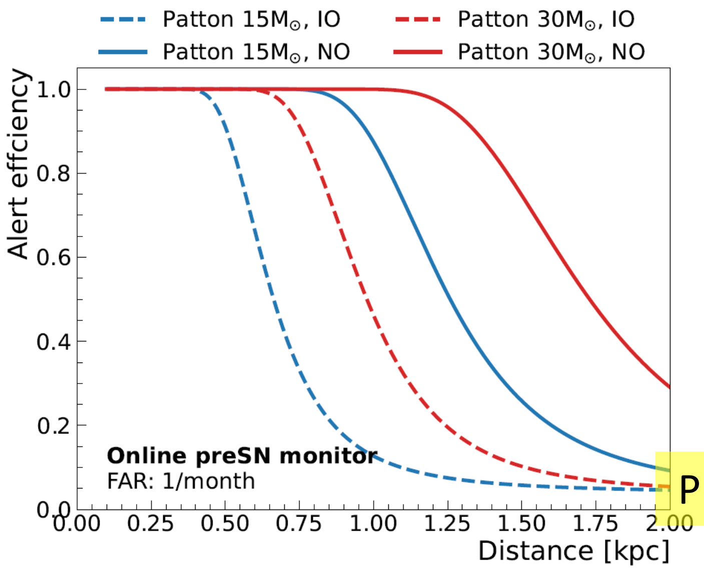
- Excellent capability of early warning
- **CCSN**
  - reach 240 ~ 400 kpc w/ **50% prob**.
  - alert in 10 ~ 30 ms
- **pre-SN:**
  - reach 0.6 ~ 1.7 kpc w/ **50% prob.**
  - >~ 100 hr in advance if 0.2 kpc

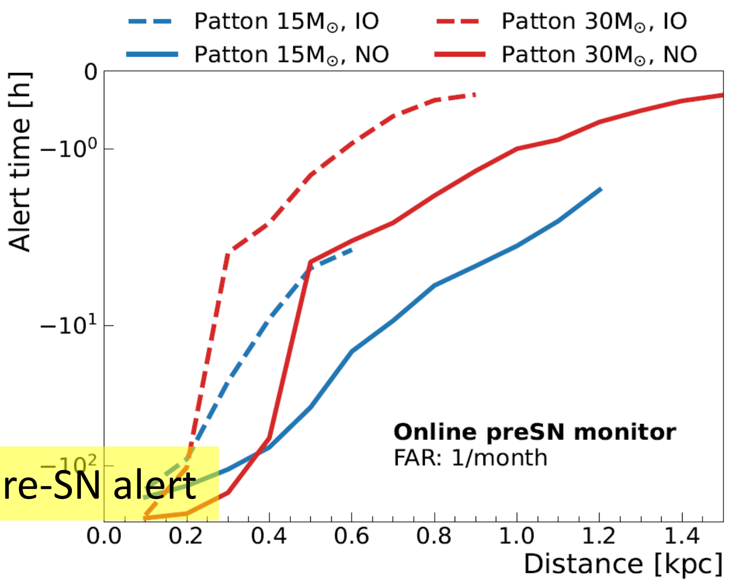
JUNO, JCAP 01 (2024) 057 arXiv: 2309.07109 [hep-ex]

A dedicated Multi-Messenger Trigger System (low threshold) is on the way!





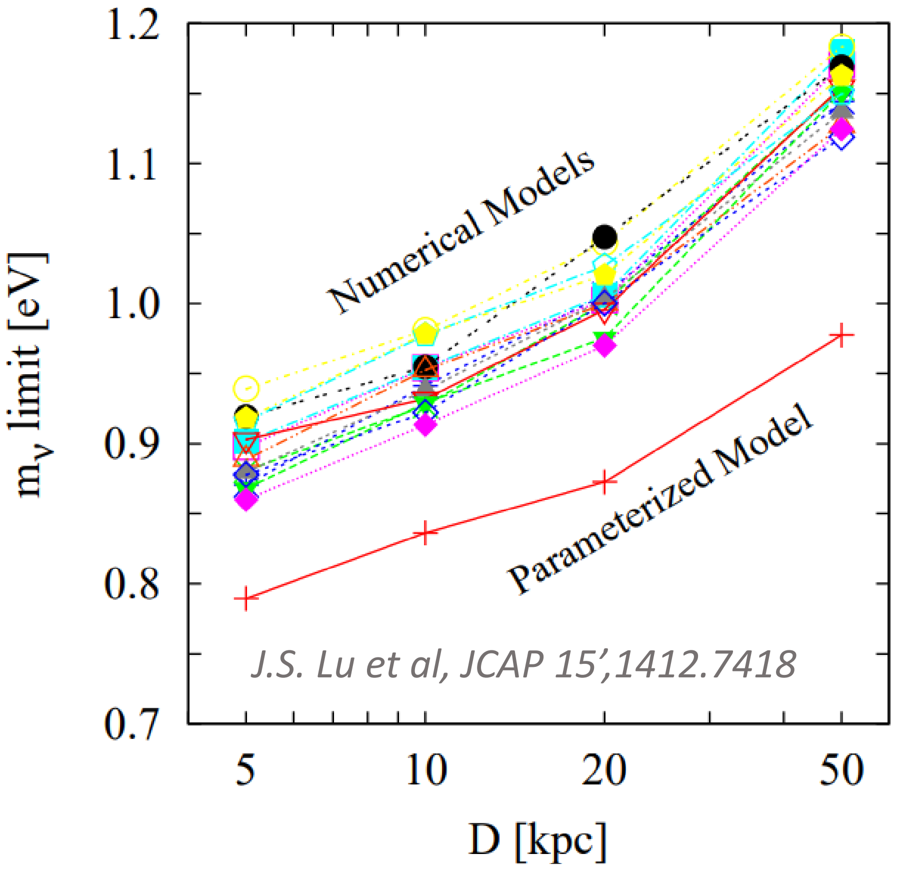




Particle and Astro Physics

Time delay of massive neutrinos:

$$\Delta t(m_\nu, E_\nu) \simeq 5.14 \text{ ms} \left(\frac{m_\nu}{\text{eV}}\right)^2 \left(\frac{10 \text{ MeV}}{E_\nu}\right)^2 \frac{D}{10 \text{ kpc}}$$



- Full flavor SN neutrino energy and time spectra reconstruction
- CCSN explosion mechanism
- Flavor conversion:

  MSW effects

  Fast and slow collective oscillations
- Neutrino mass and ordering:

  Spectral comparison

  Time profile
- New particle and new physics:

→ Rich program to be explored!

Diffuse Supernova Neutrino Background (DSNB)

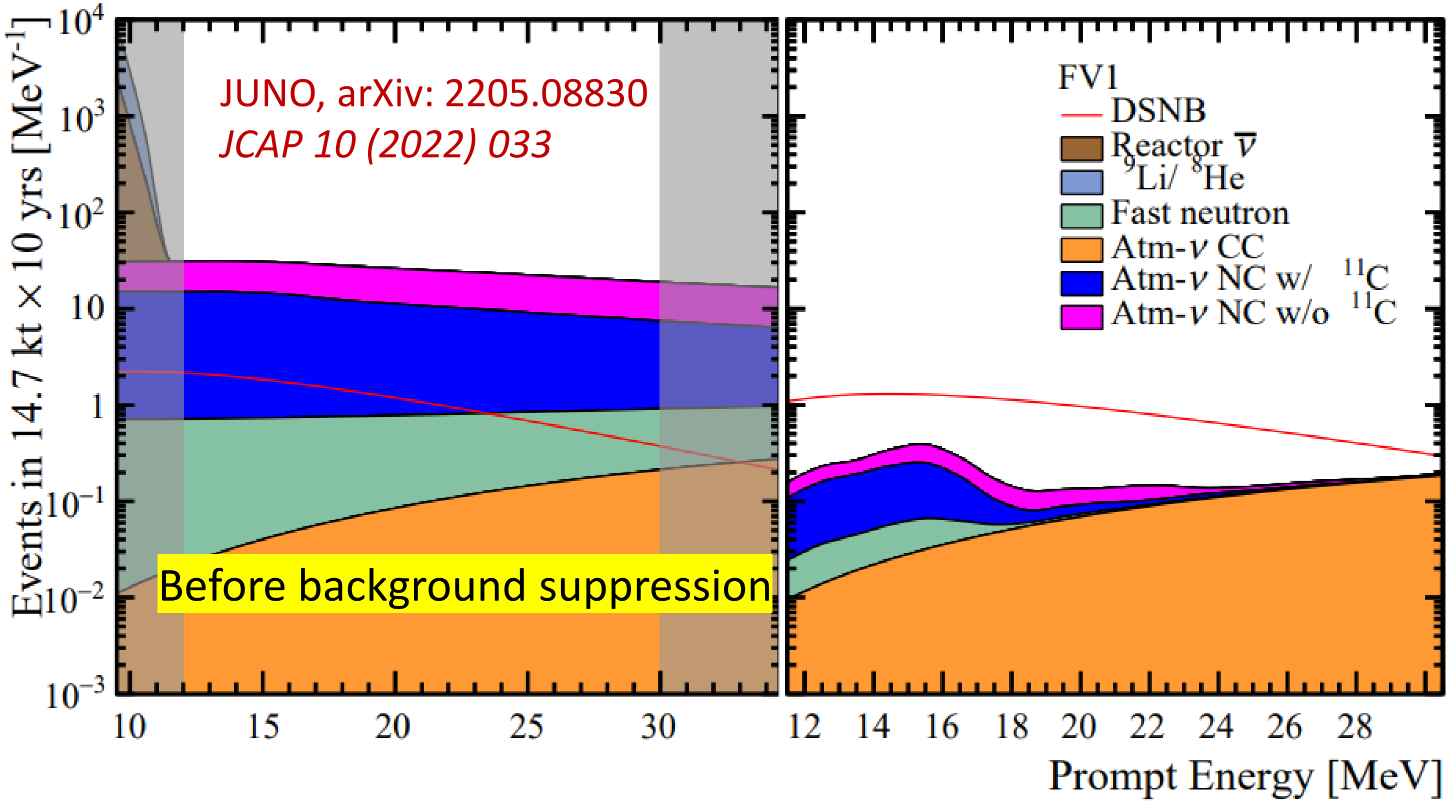
- **DSNB: 2-4 events in JUNO per year**
  - ✓ **Not detected yet**

Holding:

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

- 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)



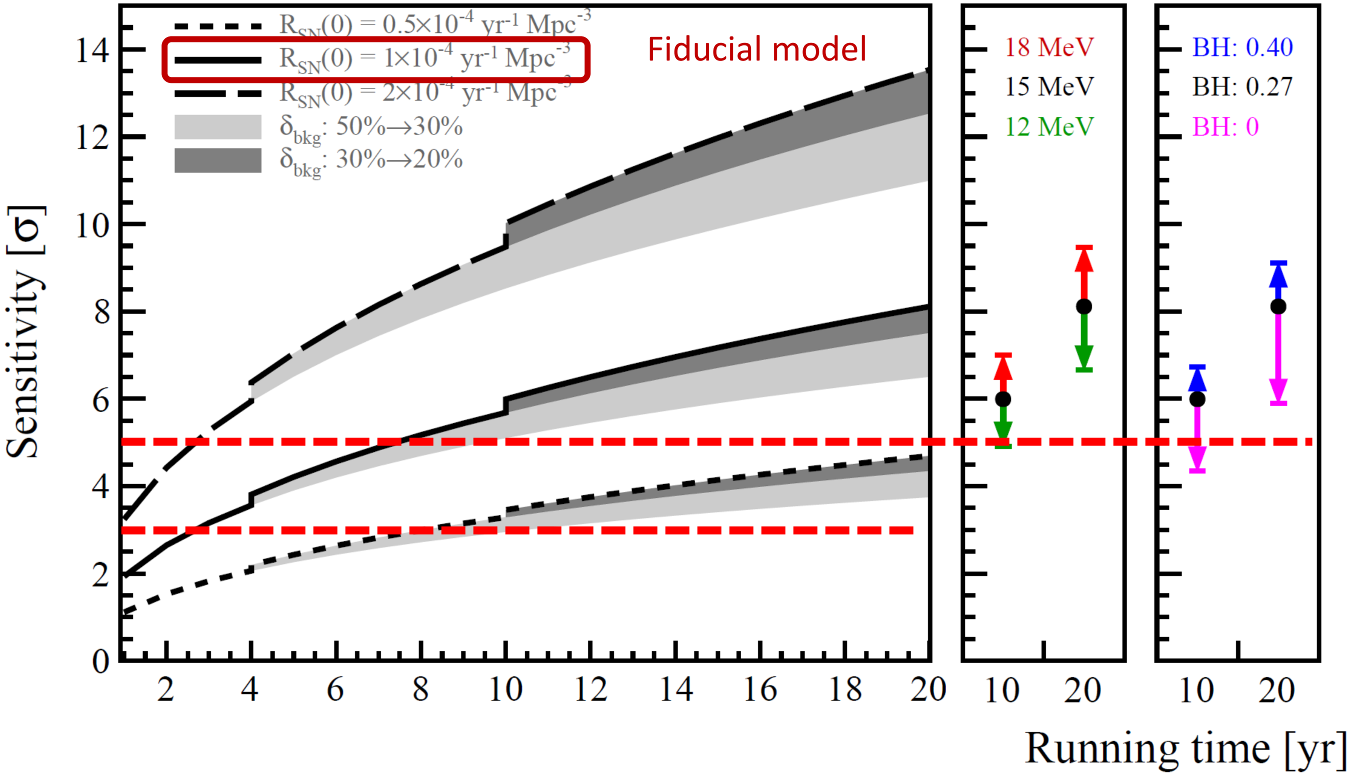
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)* :

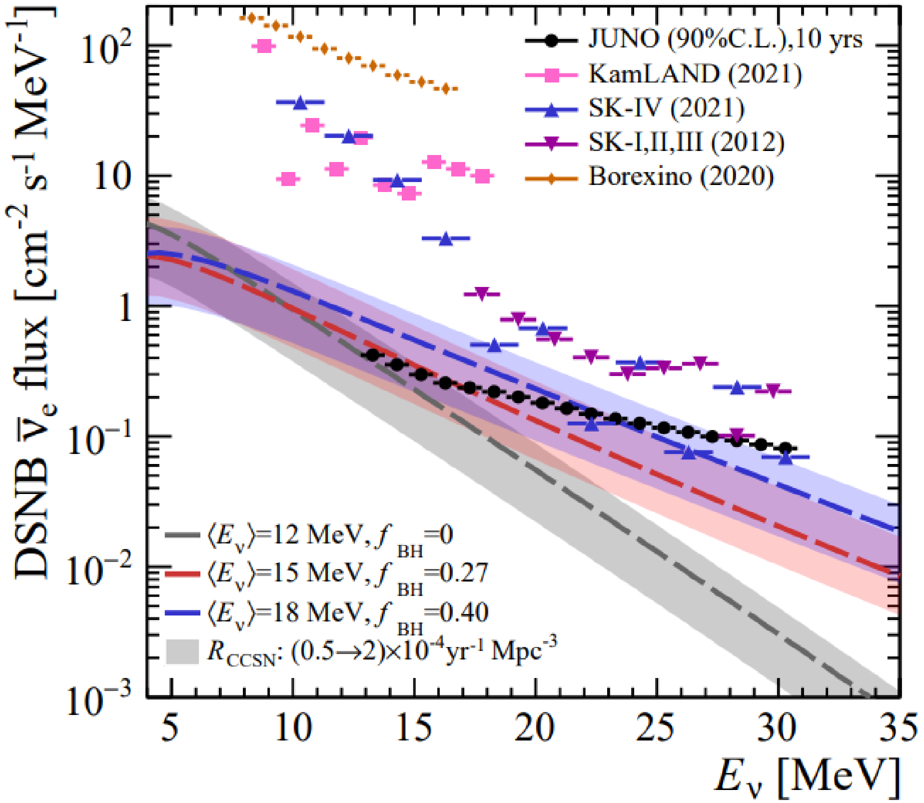
- ✓ **Background evaluation:** 0.7 per year → **0.54** per year
- ✓ **PSD:** signal efficiency 50% → **80%** (1% residual background)
- ✓ **Realistic DSNB signal model: non-zero fraction of failed Supernova**

→ S/B improved from **2 to 3.5**

Diffuse Supernova Neutrino Background (DSNB)

arXiv: 2205.08830, JCAP 10 (2022) 033

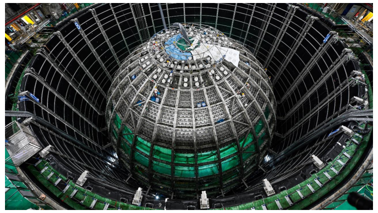




- **If no positive observation, JUNO can set the world-leading best limits of DSNB flux**
- **With the nominal model (black solid curve (left plot)): 3σ (3 yrs) and 6σ (10 yrs)**

Outlook

Physics	Sensitivity
Neutrino Mass Ordering	3σ in 6 yrs by reactor neutrinos. *Atmospheric ν sensitivity to be improved*
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{31}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~7300 of all-flavor neutrinos
DSNB	3σ in 3 yrs
Solar Neutrinos	Measure ^{7}Be, pep, CNO simultaneously, measure ^{8}B flux independently
Nucleon Decays ($p \to \bar{\nu} K^+$)	9.6×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs



2013 – Approved

2015 – Civil construction

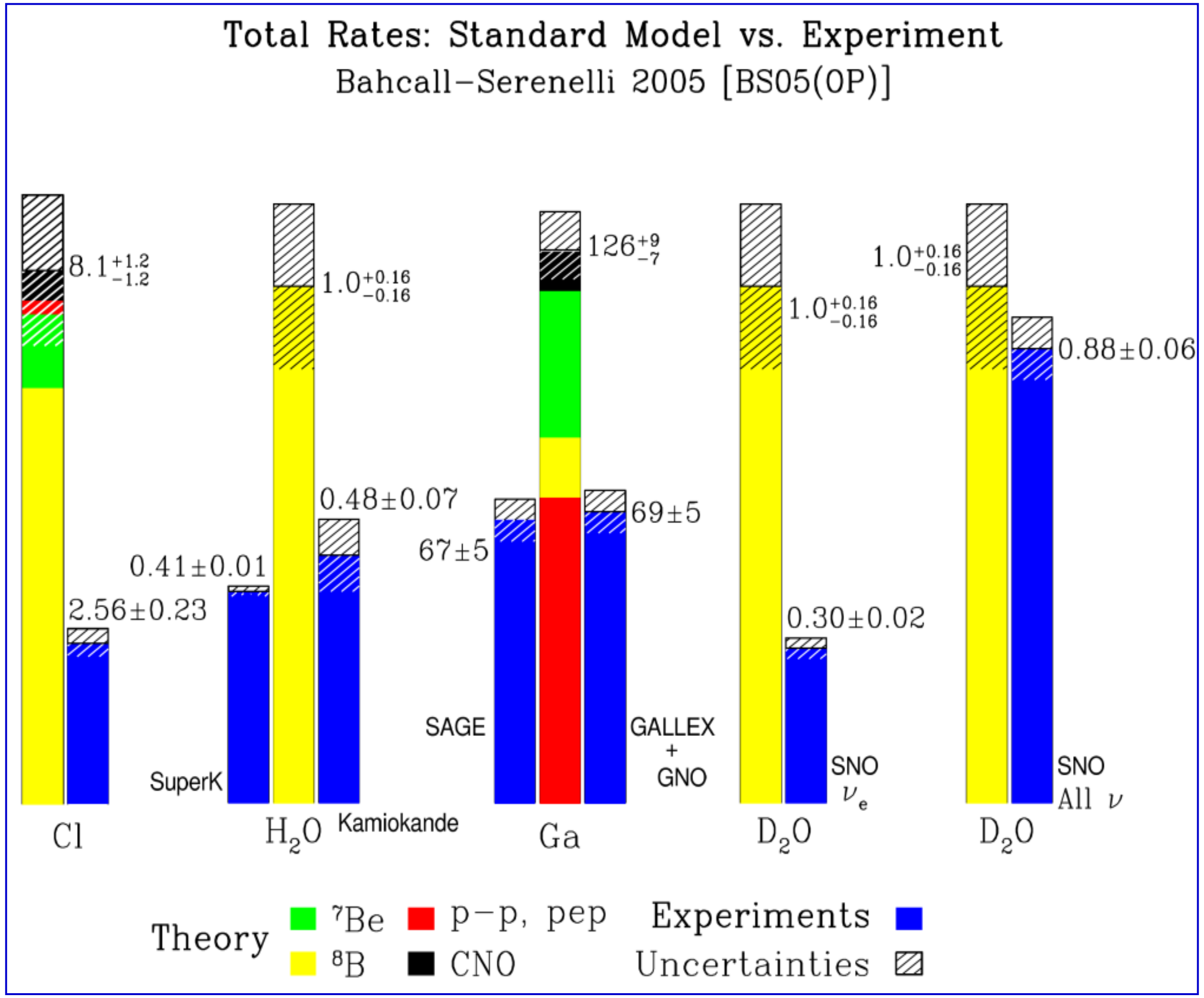
2022-2023 – Detector construction

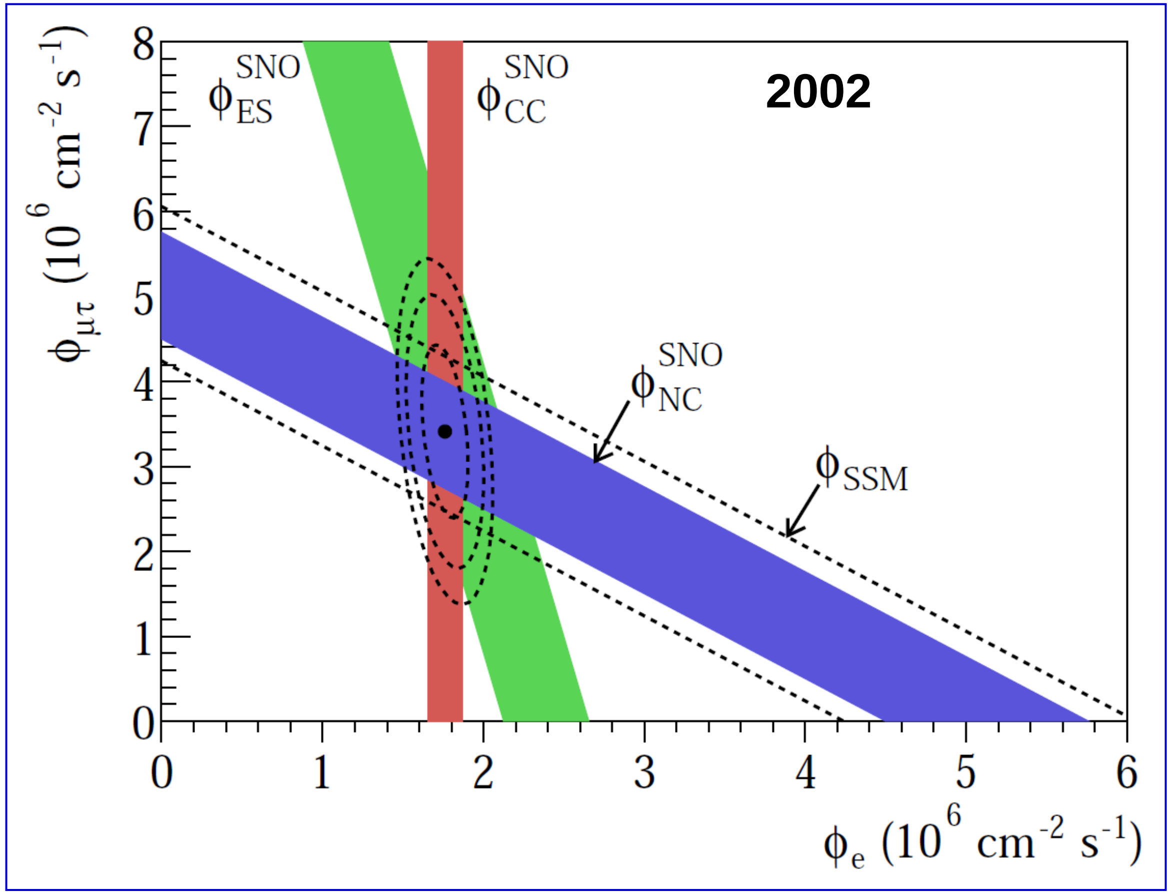
2024

2025 – First JUNO data

Back up

Neutrinos from Sun



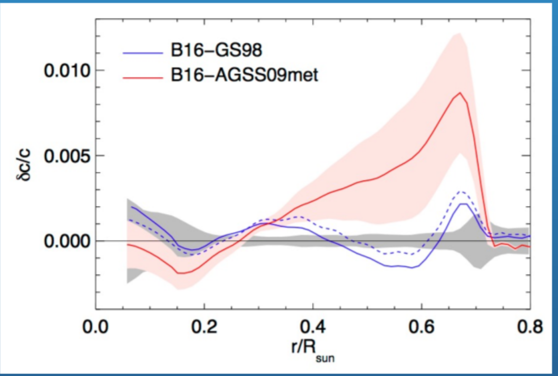


- **Proved Standard Solar Model !**
- **Proved neutrino flavor oscillations !**

After SNO:
Precision spectroscopy for solar physics

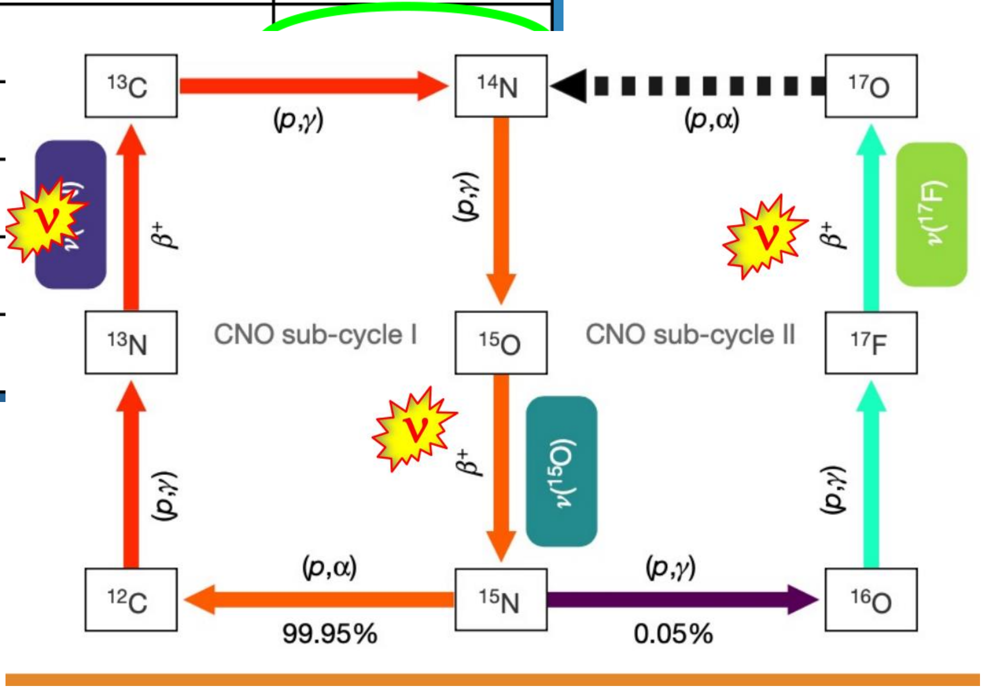
Metallicity puzzle
(abundance of elements Z>2)

23% difference on Z/X



(1) SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (**2017**) 202 + Grevesse et al.,Space Sci.Rev. (**1998**)85
(2) SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli ert al., Astr. J. 743,(2011)24
J. Bahcall et al Phys.Rev.D53:4202-4210,1996

	FLUX	Dependence on T	SSM-HZ(1)	SSM-LZ(2)	DIFF. (HZ-LZ)/HZ
pp chain	pp (10^{10} cm^{-2} s^{-1})	$T^{-0.9}$	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pp chain	pep (10^{8} cm^{-2} s^{-1})	$T^{-1.4}$	1.44(1±0.01)	1.46(1±0.009)	-1.4%
pp chain	^{7}Be (10^{9} cm^{-2} s^{-1})	T^{11}	4.94(1±0.06)		
pp chain	^{8}B (10^{6} cm^{-2} s^{-1})	T^{24}	5.46(1±0.12)		
CNO	^{13}N (10^{8} cm^{-2} s^{-1})	T^{19}	2.78(1±0.15)		
CNO	^{15}O (10^{8} cm^{-2} s^{-1})	T^{20}	2.05(1±0.17)		
CNO	^{17}F(10^{6} cm^{-2} s^{-1})	T^{23}	5.29(1±0.20)		

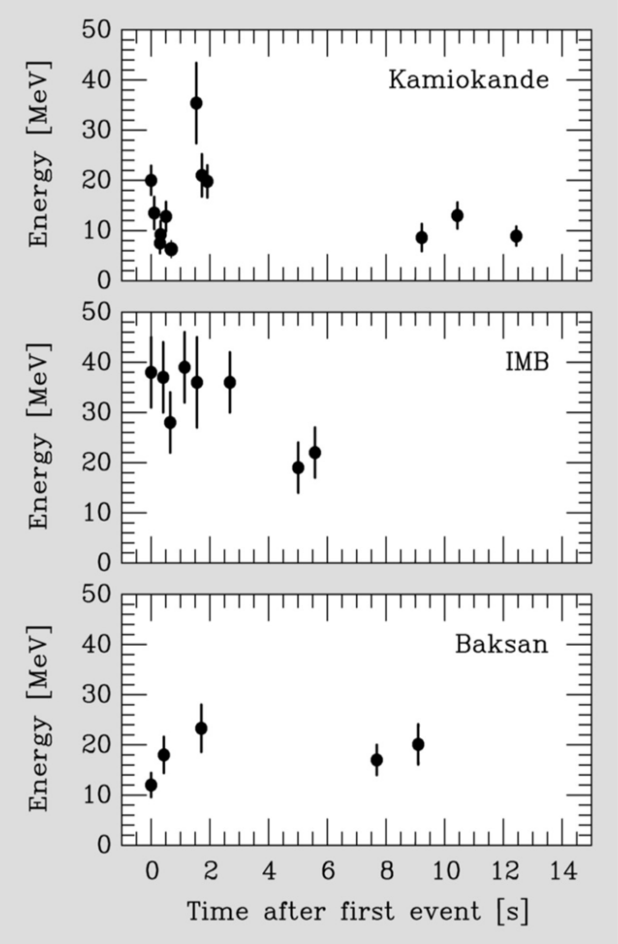


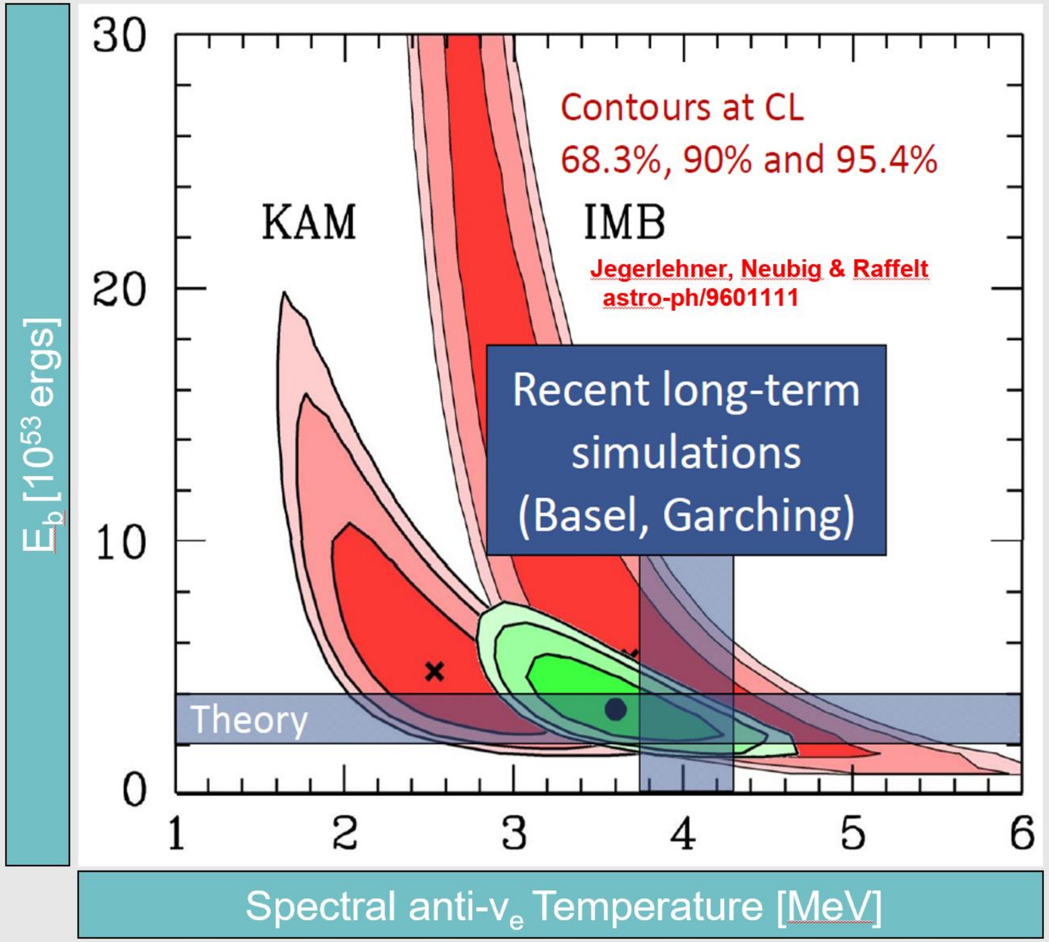
- ✓Understand the high/Low metallicity solar model controversy
- ✓Understand the role of CNO cycle (if any)

Borexino

Solar neutrinos	Rate (Counts/day/100t)	Uncertainty	Flux* (neutrinos/cm²/sec)	SSM predictions** (neutrinos/cm²/sec)
pp	$134 \pm 10^{+6}_{-10}$	9.5%	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1 \pm 0.006) \times 10^{10}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	17%	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1 \pm 0.01) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	17%	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1 \pm 0.01) \times 10^{8}$ (LZ)
7Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	2.7%	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1 \pm 0.06) \times 10^{9}$ (LZ)
8B	$0.223^{+0.015+0.006}_{-0.016-0.006}$	7.6%	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1 \pm 0.12) \times 10^{6}$ (LZ)
CNO	$6.7^{+1.2+0.3}_{-0.7-0.4}$	+30% -12%	$(6.7^{+1.2+0.3}_{-0.8-0.4}) \times 10^{8}$	$4.88(1 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1 \pm 0.10) \times 10^{8}$ (LZ)

SN1987A





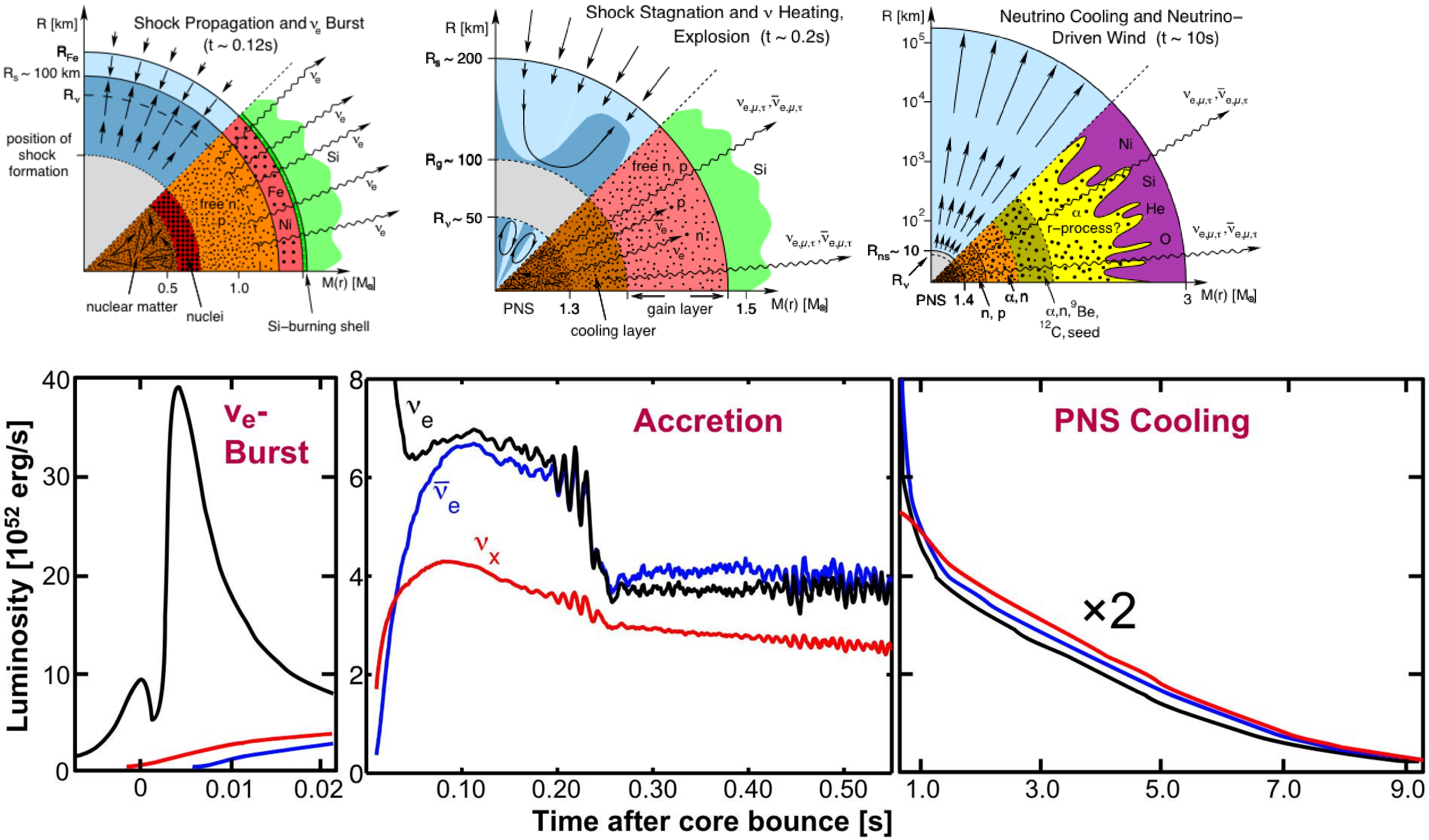
Assumptions:
- Thermal
- Equipart.

Conclusions:
- Collapse
- Ave.Ener.
- Duration

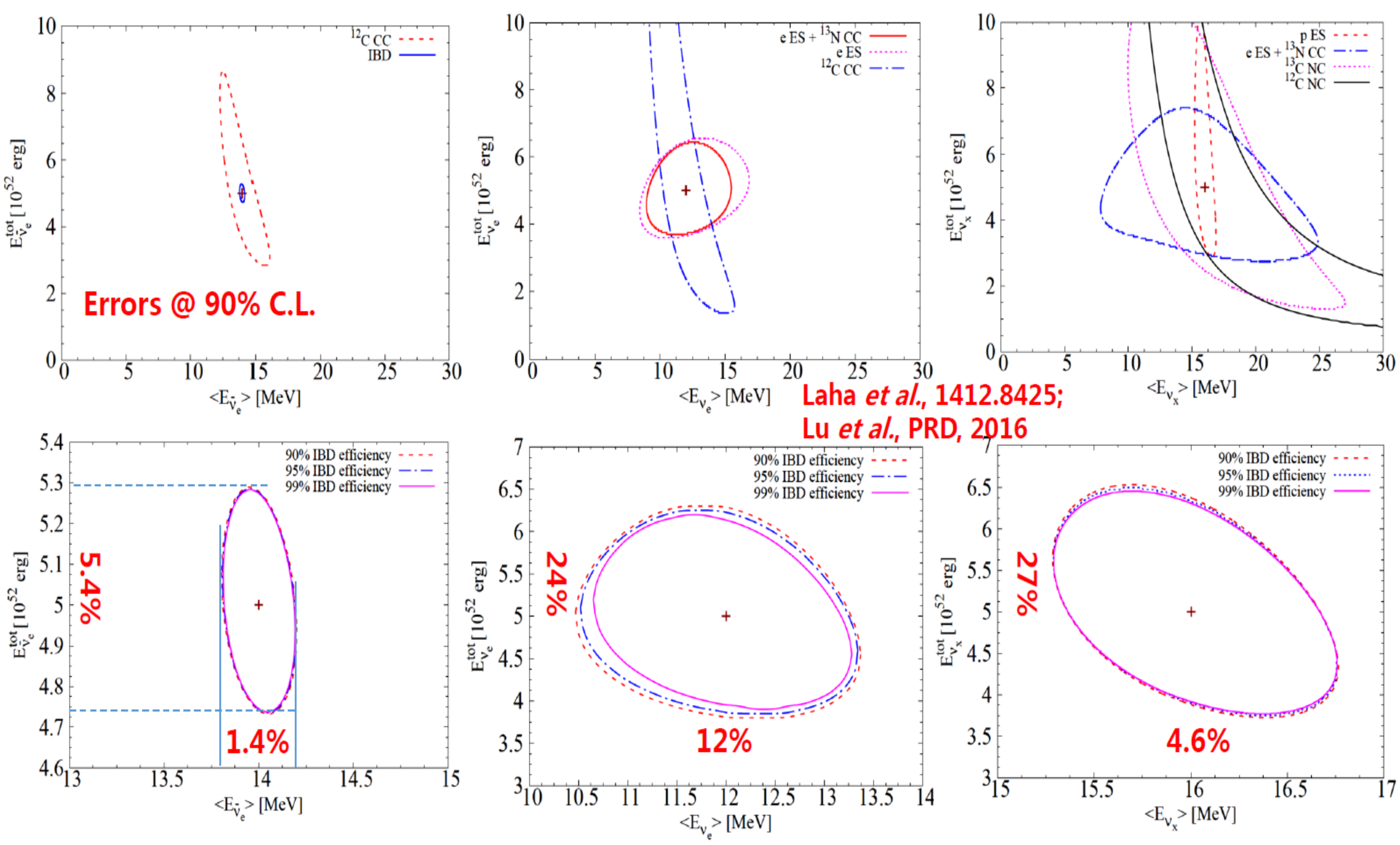
Problems:
- 24 events
- by chance

Supernova Neutrino Emission

H. T. Janka, et al., “Theory of core-collapse supernovae”



CCSN Characteristics **@10kpc**



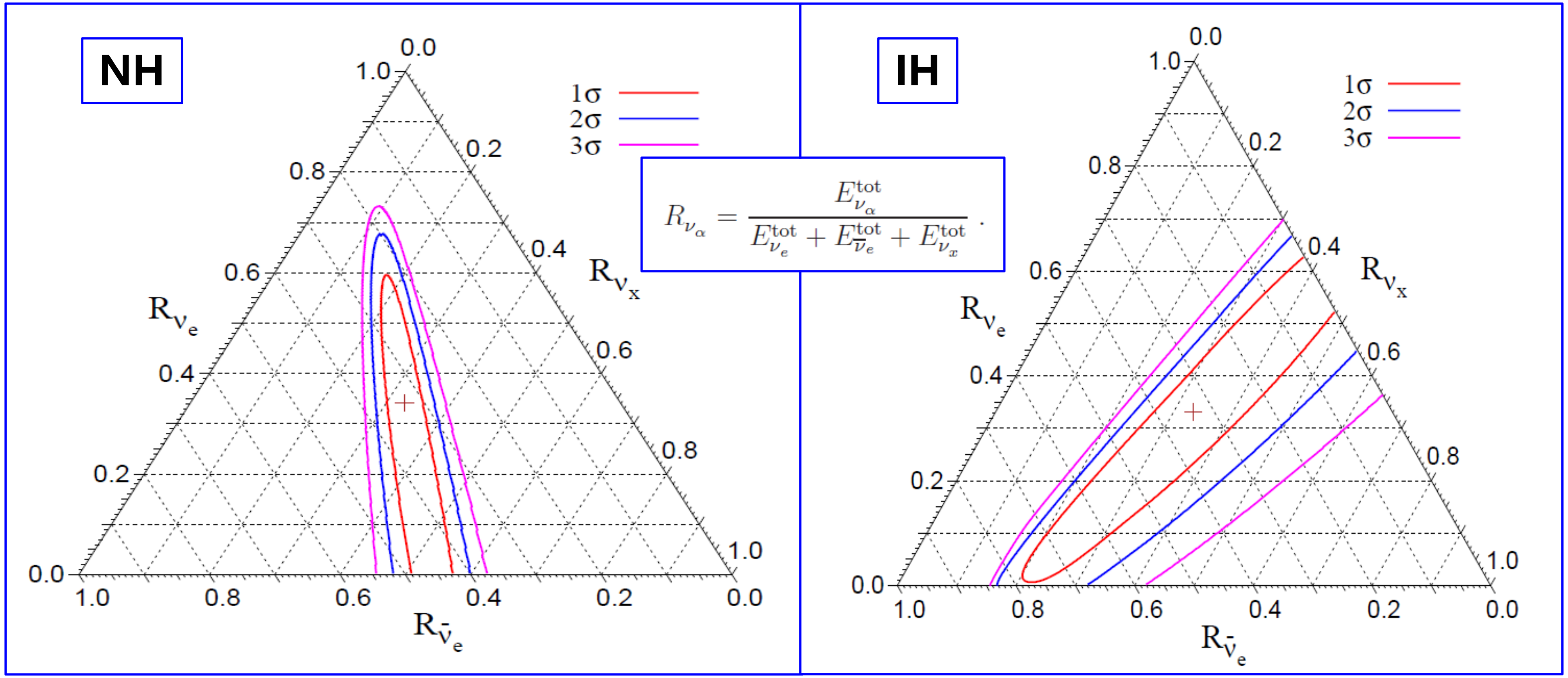
Lu, YFL, Zhou, PRD 2016

CCSN Characteristics **@10kpc**

The energy equipartition is a fundamental concept in SN physics →

How to test it experimentally ? → **5%-10%**

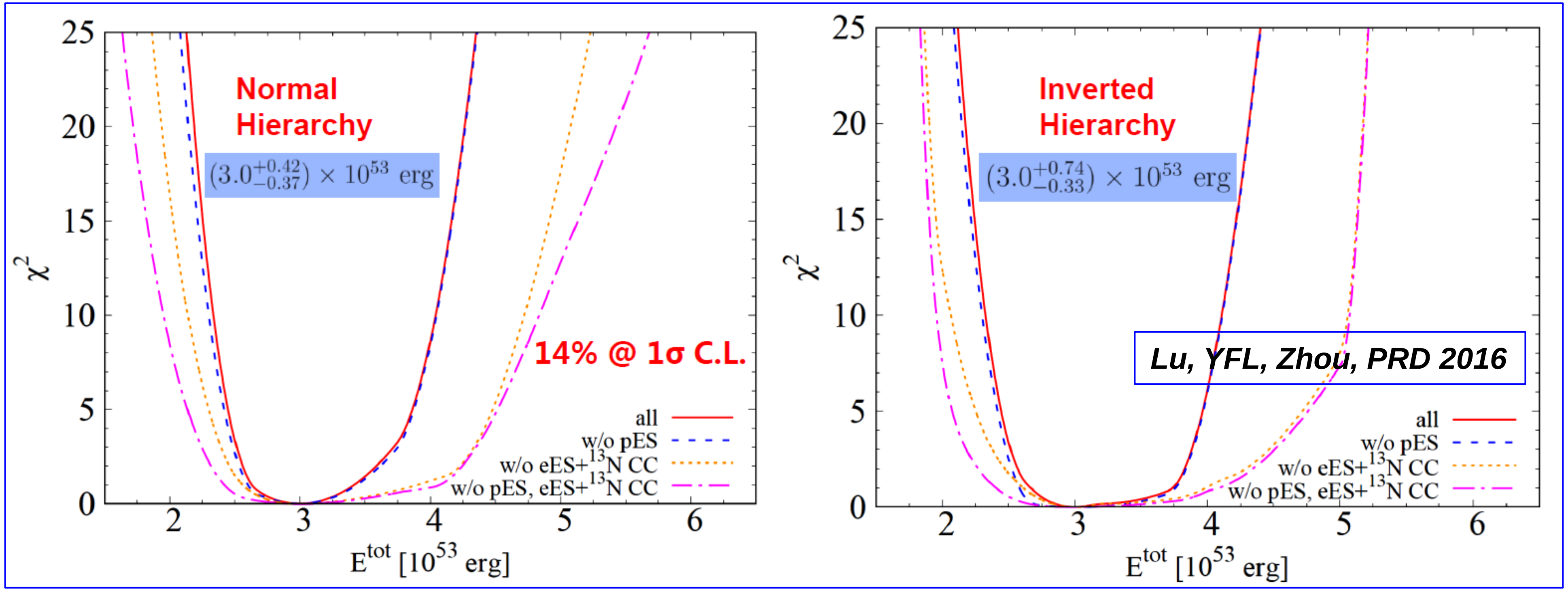
JUNO is unique because of its multi-channel detection capability



$$R_{\nu_\alpha} = \frac{E^{\rm tot}_{\nu_\alpha}}{E^{\rm tot}_{\nu_e} + E^{\rm tot}_{\overline{\nu}_e} + E^{\rm tot}_{\nu_x}} .$$

Lu, YFL, Zhou, PRD 2016

CCSN Characteristics **@10kpc**



Measurement of the total gravitational binding energy→

A direct test of neutrino-driven CCSN mechanism → at 10% level

JUNO is unique because of its multi-channel detection capability

Spectral reconstruction

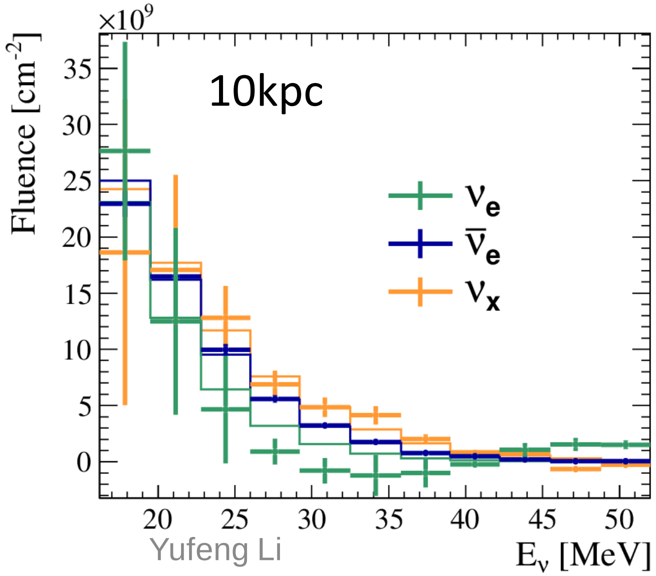
Cross section && Detector effects | SN neutrinos spectra | Observed spectra

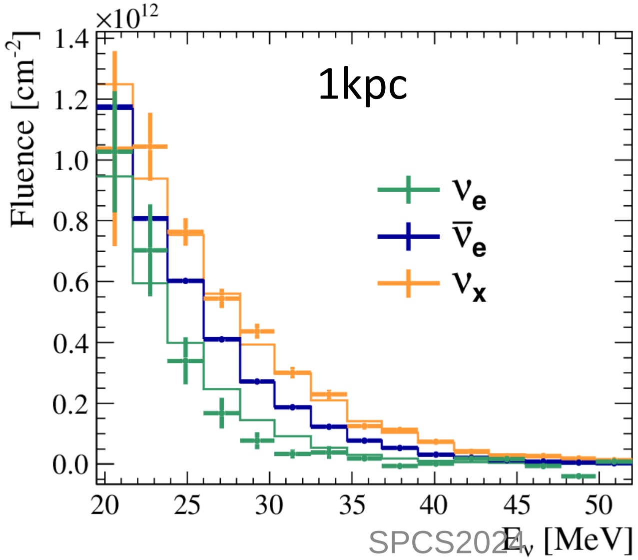
$$
\begin{bmatrix}
N_{\rm p} D_{\rm IBD} \sigma_{\nu_e}^{\rm IBD} & N_{\rm p} D_{\rm IBD} \sigma_{\bar{\nu}_e}^{\rm IBD} & N_{\rm p} D_{\rm IBD} \sum \sigma_{\nu_x}^{\rm IBD} \\
N_{\rm p} D_{\rm pES} \sigma_{\nu_e}^{\rm pES} & N_{\rm p} D_{\rm pES} \sigma_{\bar{\nu}_e}^{\rm pES} & N_{\rm p} D_{\rm pES} \sum \sigma_{\nu_x}^{\rm pES} \\
N_{\rm e} D_{\rm eES} \sigma_{\nu_e}^{\rm eES} & N_{\rm e} D_{\rm eES} \sigma_{\bar{\nu}_e}^{\rm eES} & N_{\rm e} D_{\rm eES} \sum \sigma_{\nu_x}^{\rm eES}
\end{bmatrix}
\cdot
\begin{bmatrix} F_{\nu_e} \\ F_{\bar{\nu}_e} \\ F_{\nu_x} \end{bmatrix}
=
\begin{bmatrix} S_{\rm IBD} \\ S_{\rm pES} \\ S_{\rm eES} \end{bmatrix}
$$

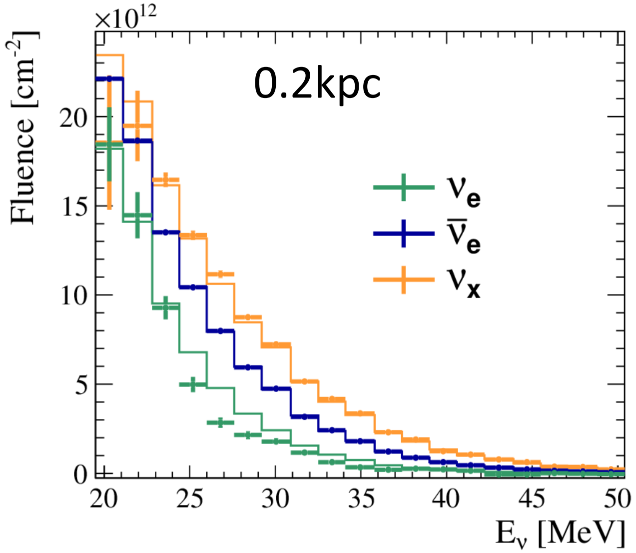
Full flavor SN neutrino energy spectra reconstruction in JUNO detector

- Model independent
- ν_x spectra reconstructed via pES
- promising for global analysis with all channels and other WC, Lar-TPC, et.al detectors.

Li, Li, Wang, Wen, Zhou, PRD, 2018
Li, Huang, Li, Wen, Zhou, PRD, 2019







Energy threshold: < 0.2 MeV

Neutrinos from the Earth

Geoneutrinos: (anti)neutrinos from the decay of long-lived particles

Abundance of the radioactive elements

Radiogenic heat

Accessible via anti-ν_e measurement

$$^{238}_{92}\mathrm{U} \rightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} \rightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$

$$^{232}_{90}\mathrm{Th} \rightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}$$

Prediction

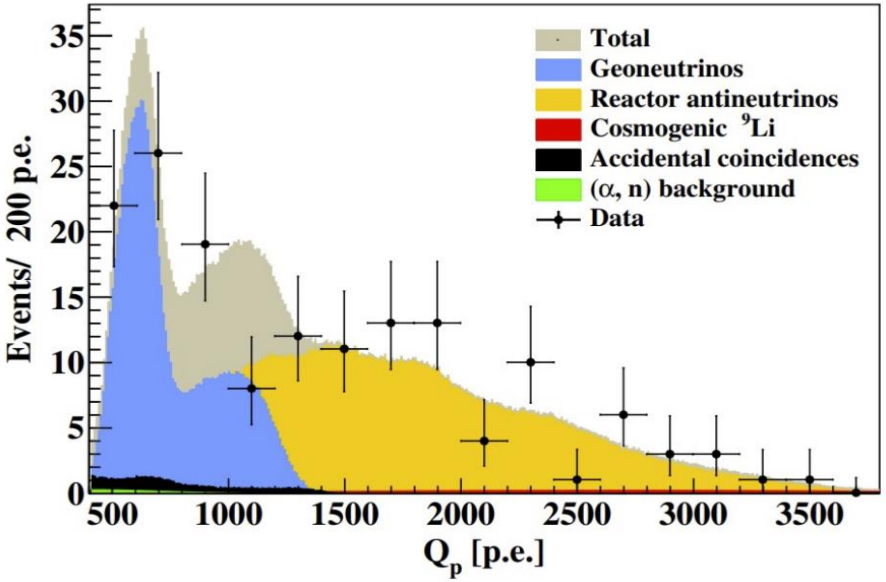
Interpretation

Geoneutrino flux

Neutrinos from the Earth

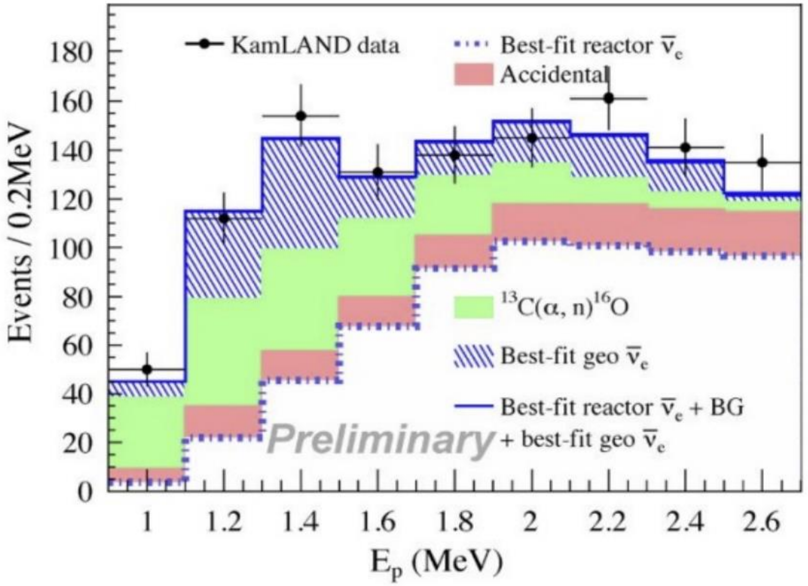
Borexino (2020) Phys. Rev. D 101, 012009

- Located in Gran Sasso, Italy
- Liquid Scintillator ~ 0.3 kton
- In 10 years ~ 50 geoneutrinos
- Precision ~ 17%
- Favors **high** U and Th abundances BSE models



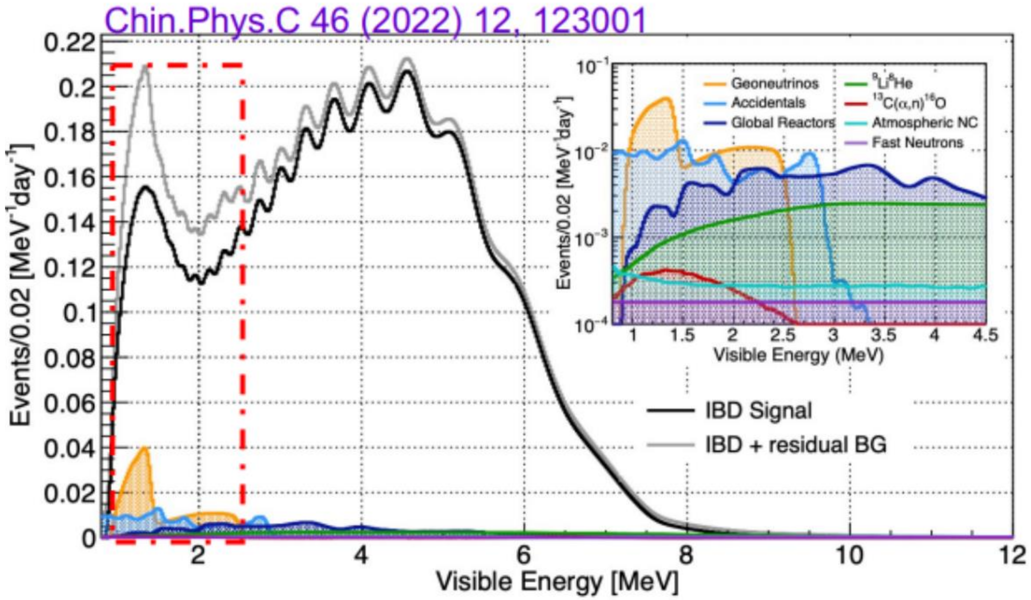
KamLAND (2022) Phys. Rev. C, 80, 015807

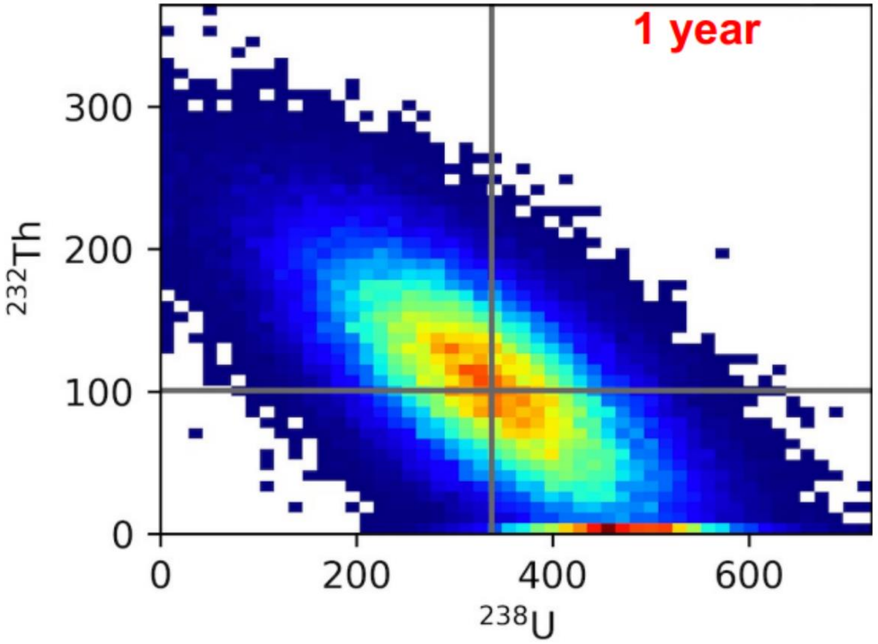
- Located in Hida, Gifu, Japan
- Liquid Scintillator 1 kton
- In almost 18 years ~ 170 geoneutrinos
- Precision ~ 15%
- Favors **medium** U and Th abundances BSE models



- JUNO will collect more geo-neutrino events than all the other experiments with 1 year data !

Neutrinos from the Earth





- JUNO will collect the highest geoneutrino statistics

  More geoneutrino events than all the other experiments with 1 year data

- Precise measurement of total geoneutrino flux:
  - Borexino ~17% precision (10 years)
  - KamLAND ~15% precision (18 years)
  - **JUNO ~ 22% precision (1 year) and ~ 8% precision (10 years)**

  ➡ JUNO will provide the World’s most precise measurements

- JUNO can measure U and Th individual contributions with high statistical significance

Nucleon decay (GUTs)