JUNO Status & Prospects

Liangjian Wen (IHEP)

Seminar @ USTC MPHY

2023.06.30

Neutrinos

Neutrino Properties

$$\frac{\tau}{m} > 7 \times 10^9 \text{ s/eV} \xrightarrow{m \approx 0.1 \text{ eV}} \tau > 20 \text{ yr}$$

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 1.1$ eV, CL = 90% (tritium decay)

Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)

Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)

Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)

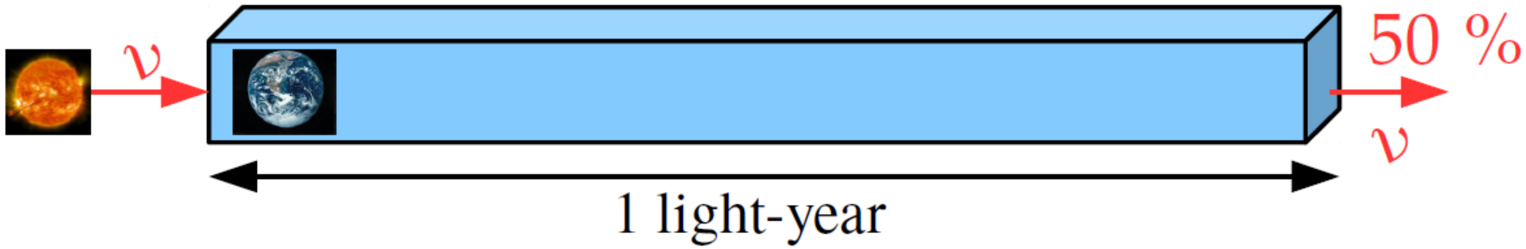
Magnetic moment $\mu < 0.28 \times 10^{-10}\ \mu_B$, CL = 90% (solar + radiochemical)

PDG2020（粒子数据组） (https://pdg.lbl.gov/)

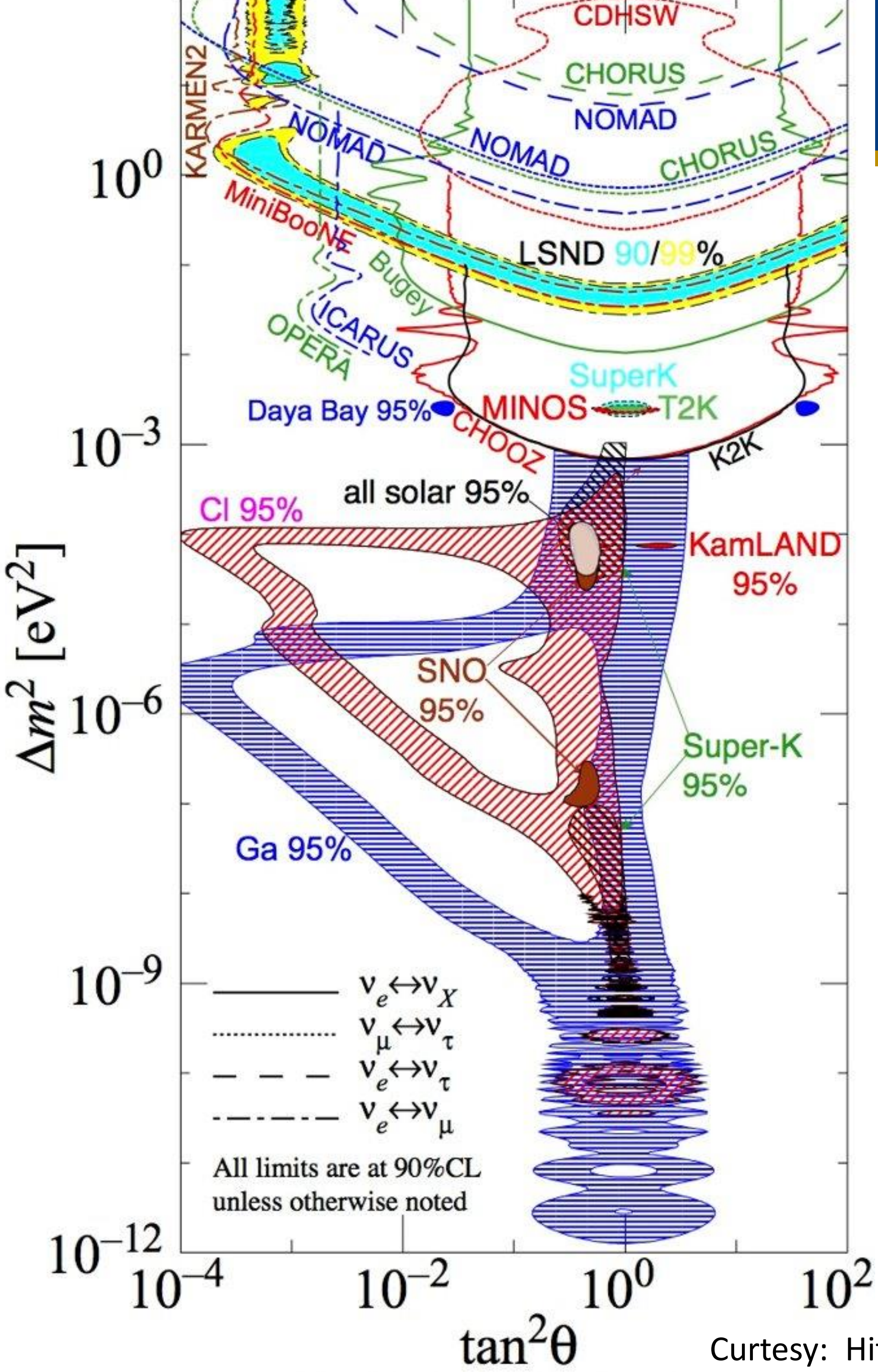
- **Massive, but tiny mass**
  - Beyond Standard Model
  - Absolute mass unknown
  - Mass origin unknown
- The only neutral fermion
  - Possibly to have Majorana nature

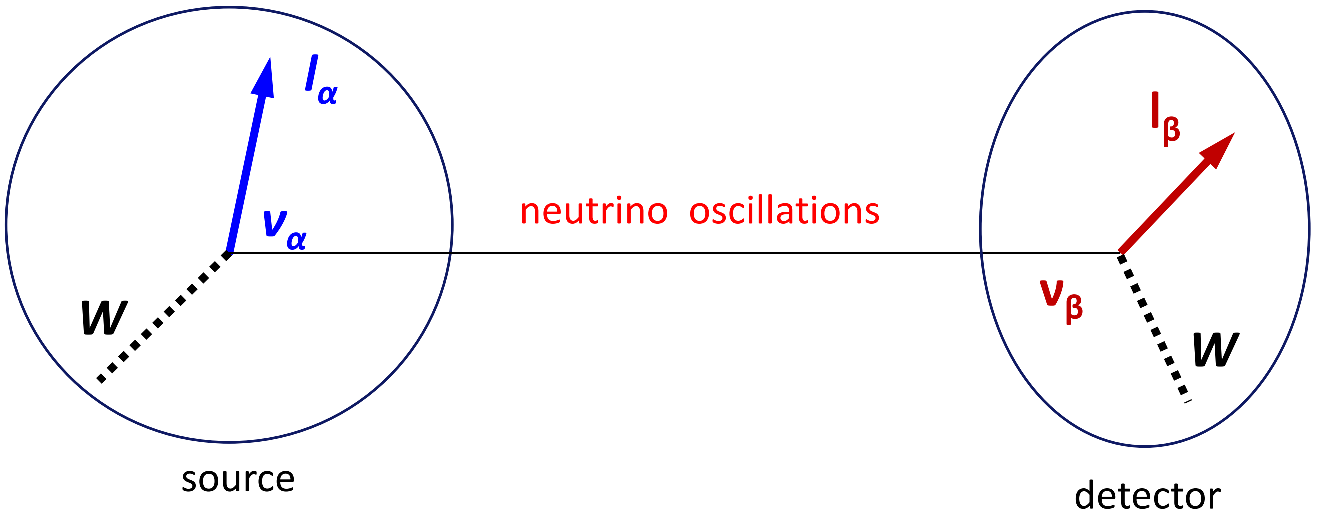
Hard to detect

Many unknows



Neutrino Oscillation Experiments

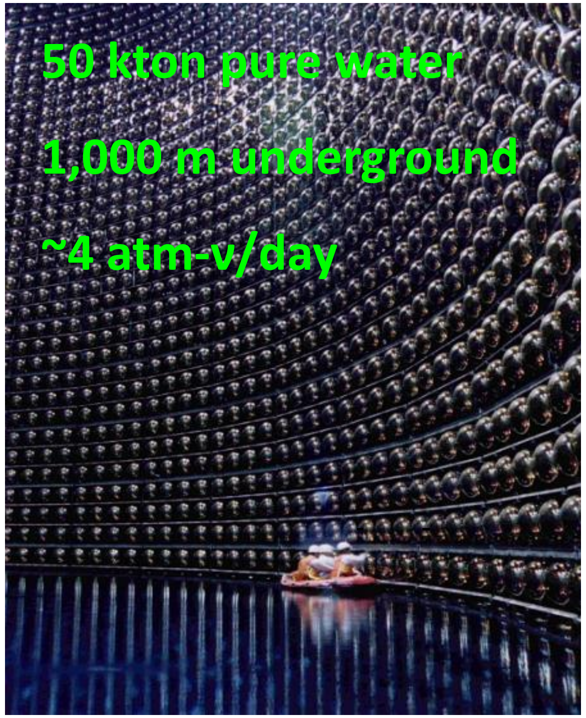




- ν prod. & detection: $W^\pm$ weak interaction → identify *flavor*
- ν propagation: *mass eigenstates (!= flavor eigenstates)*
- Experimental searches for ν oscillations
  - > 50 years
  - > 30 experiments
  - > Phase space over tens of orders of magnitude

Curtesy: Hitoshi Murayama

Discovery of Neutrino Oscillations

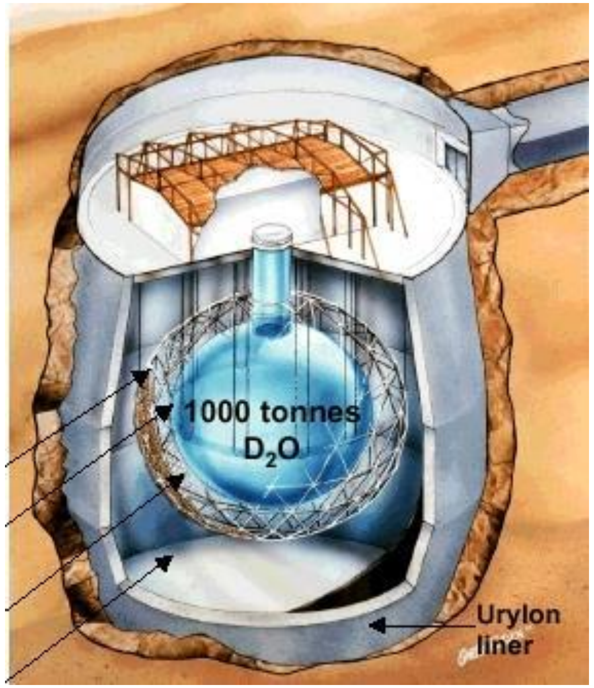


Atmospheric ν Oscillation discovered

@ Super-K, 1998

Solar ν Oscillation discovered

@ SNO, 2001

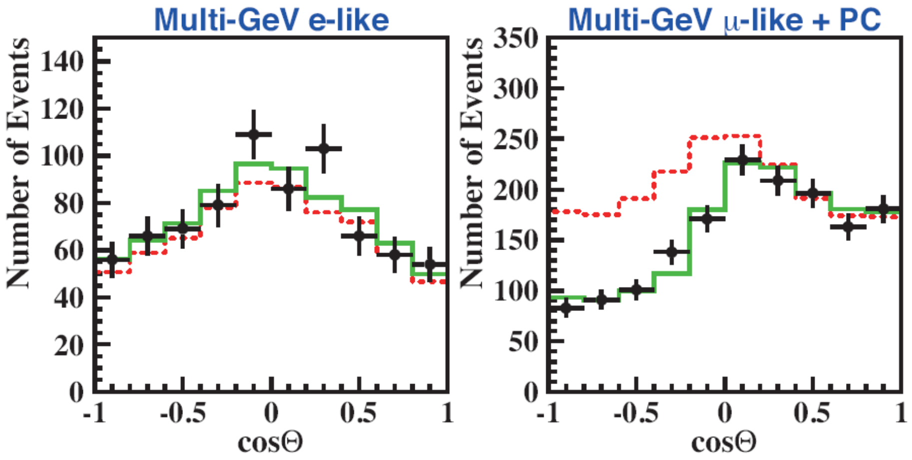


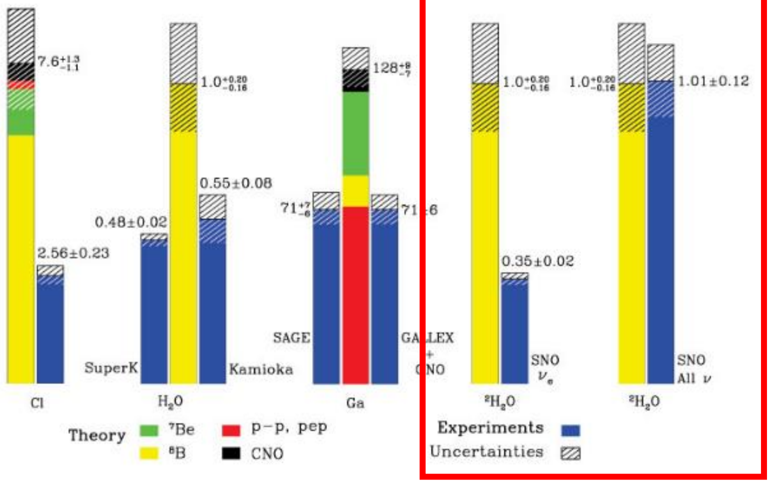
Reactor ν oscillation @ KamLAND, 2002

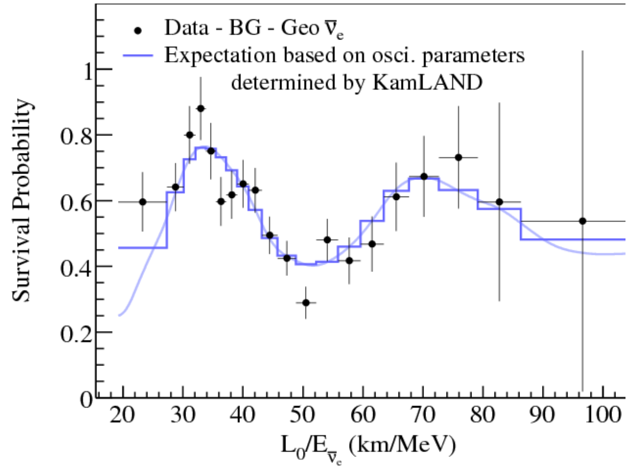
confirmed solar ν oscillation

Accelerator ν oscillation @ K2K, 2003

confirmed atmospheric ν oscillation



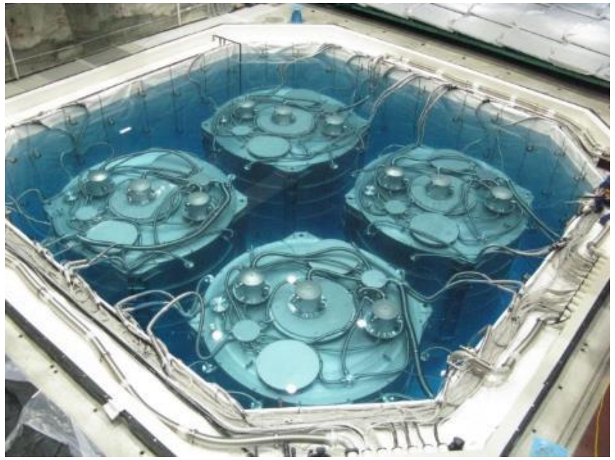


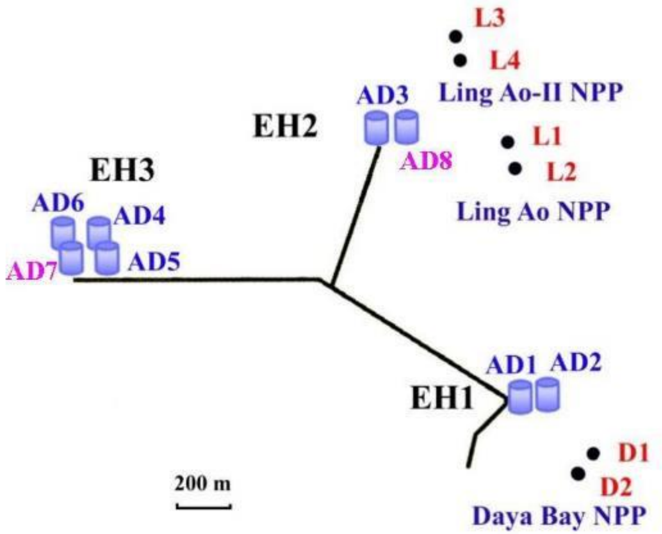


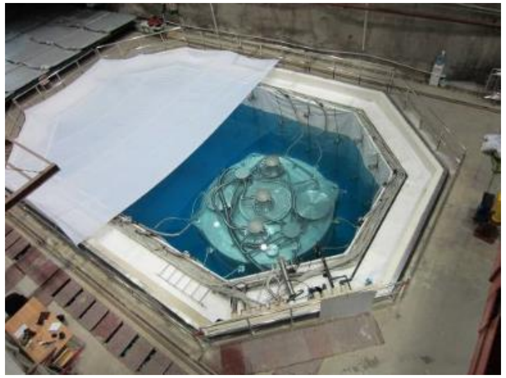
Daya Bay experiment

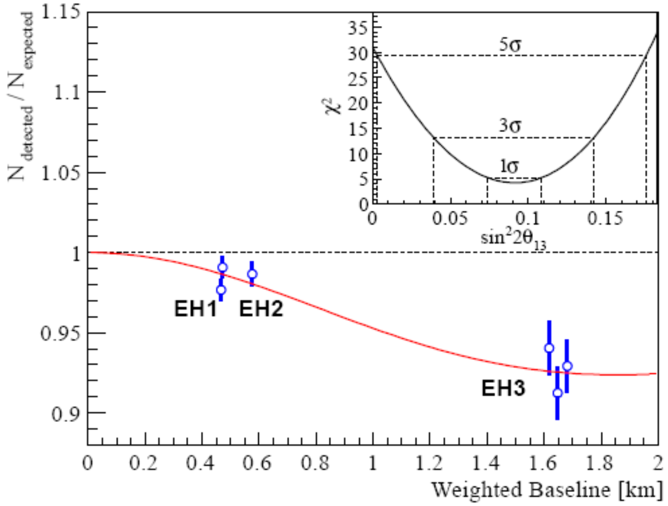
Proposed in 2003, construction completed in 2012.

Observed a new mode of $\overline{\nu}_e$ oscillation ➔ non-zero θ_{13}









2016年度国家自然科学一等奖

2016年度基础物理学突破奖

等十多个国内外奖项

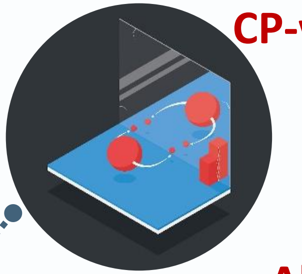
- $\sin^2 2\theta_{13}$~ 0.092, much larger than early expectation 0.01~0.03 ➔ Opened the gate to determine mass ordering and leptonic CP-violation

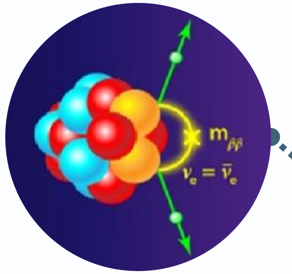
Problems with neutrinos

Particle Physics relevant

Mass ordering

Leptonic CP-violation



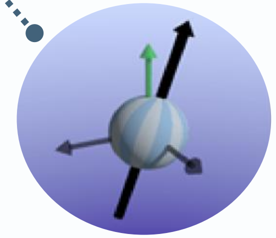


$\nu = \bar{\nu}$?

Absolute mass

Fundamental Properties of ν

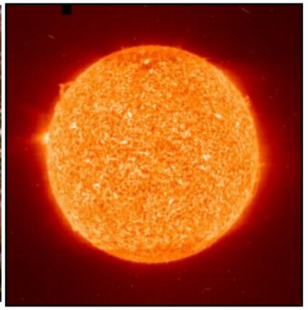
θ_{13} oscillation



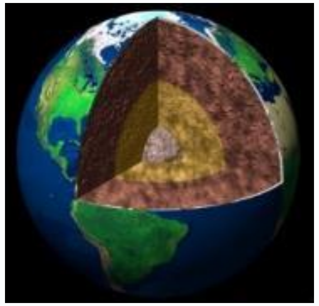
Magnetic moment

Astro-physics, Cosmology relevant

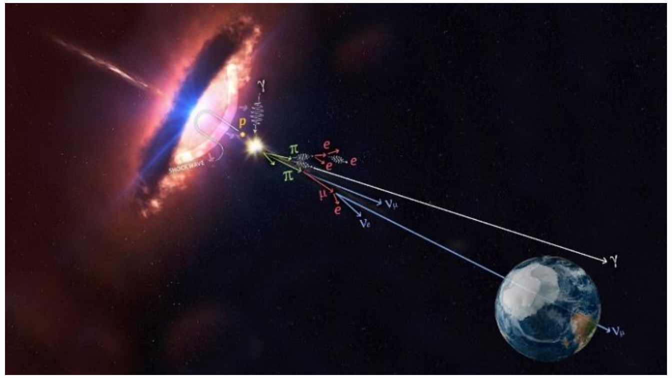
Supernova ν
(mechanism, relic)



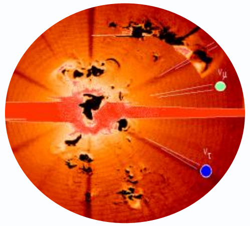
Solar ν
(Metallicity)



Geo ν
(geo phys, geo chem)



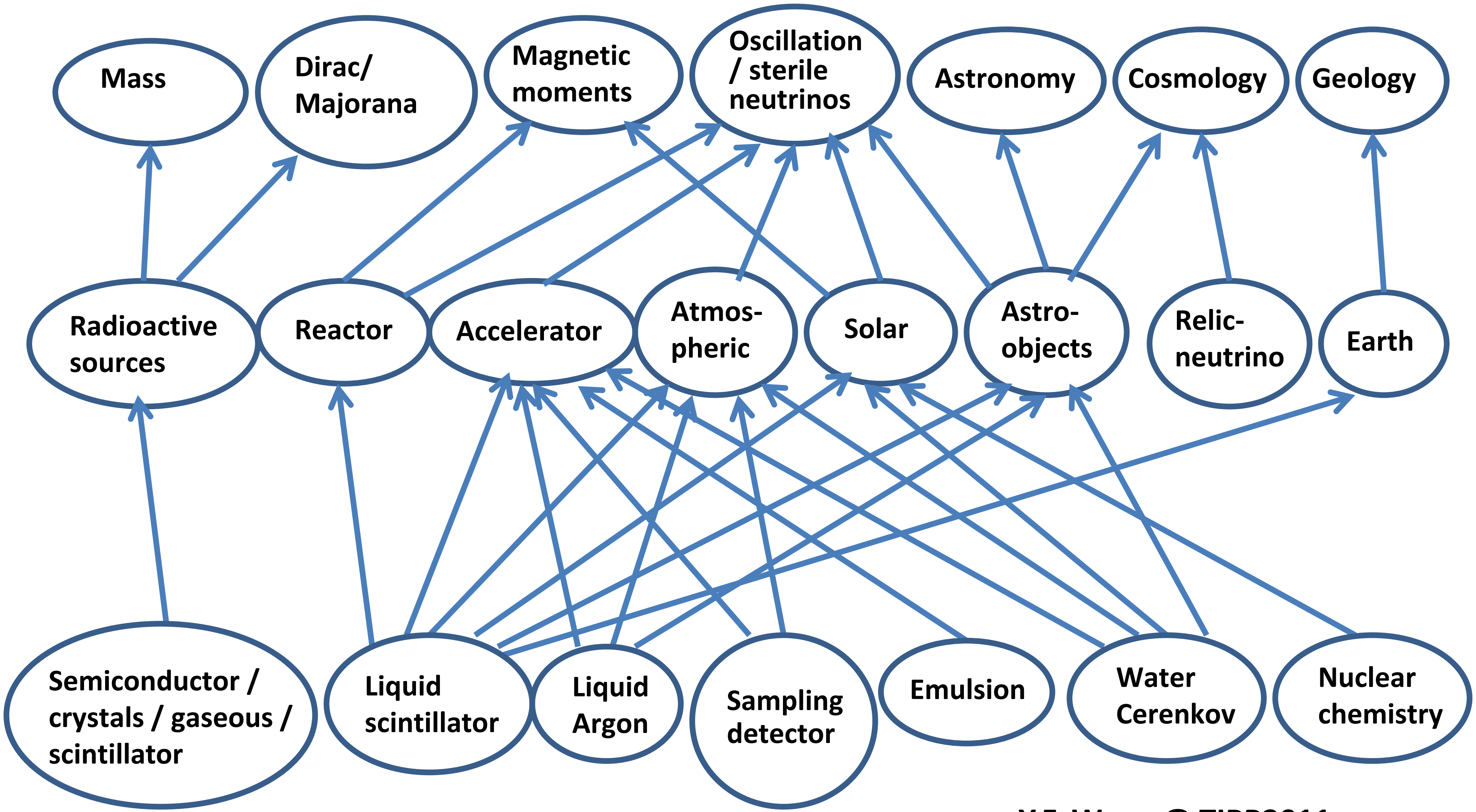
Big-Bang ν



ν from extreme astronomical phenomena?
(NS merger, GAN, γ burst, …)

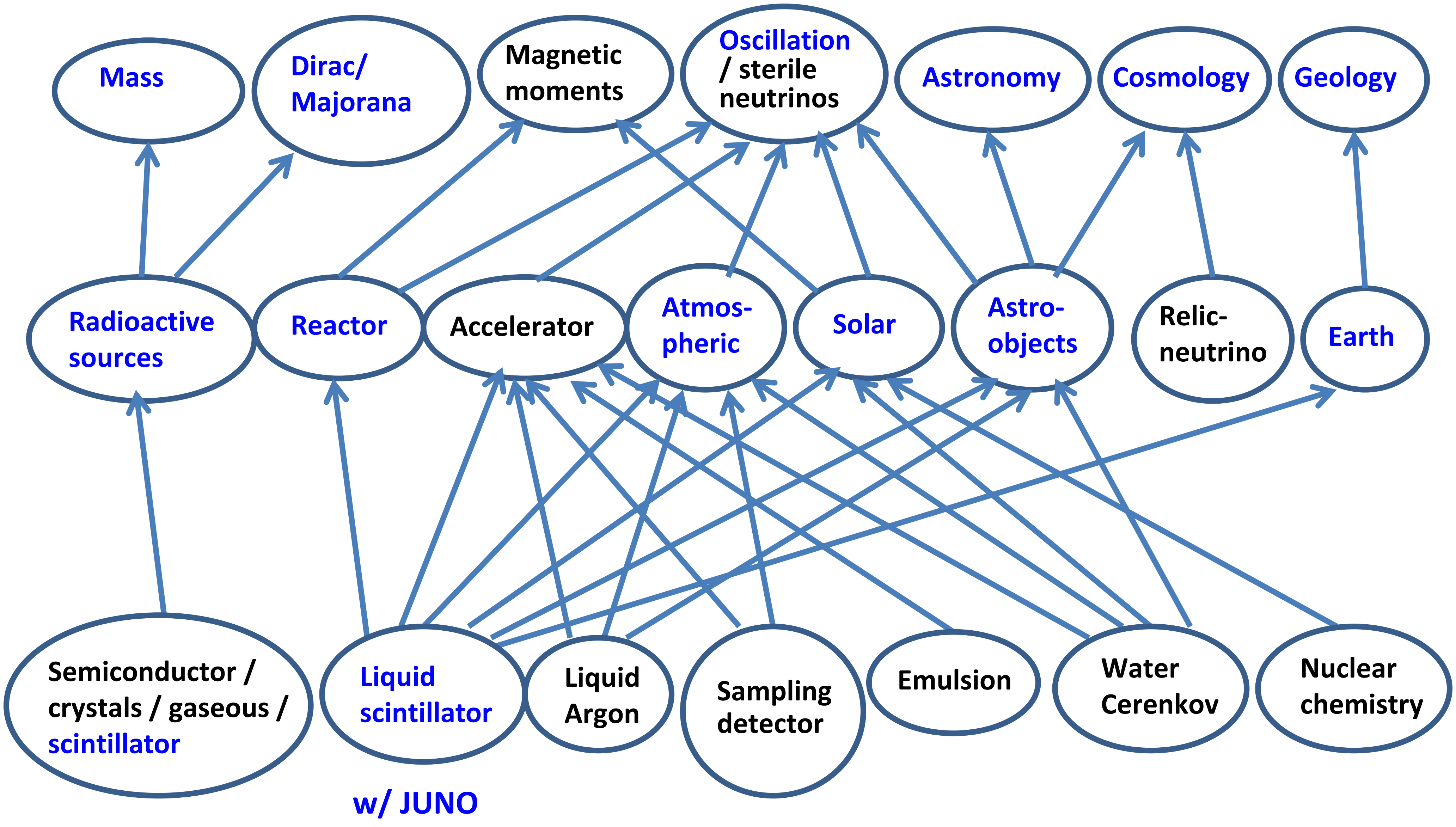
Origin of cosmic rays?

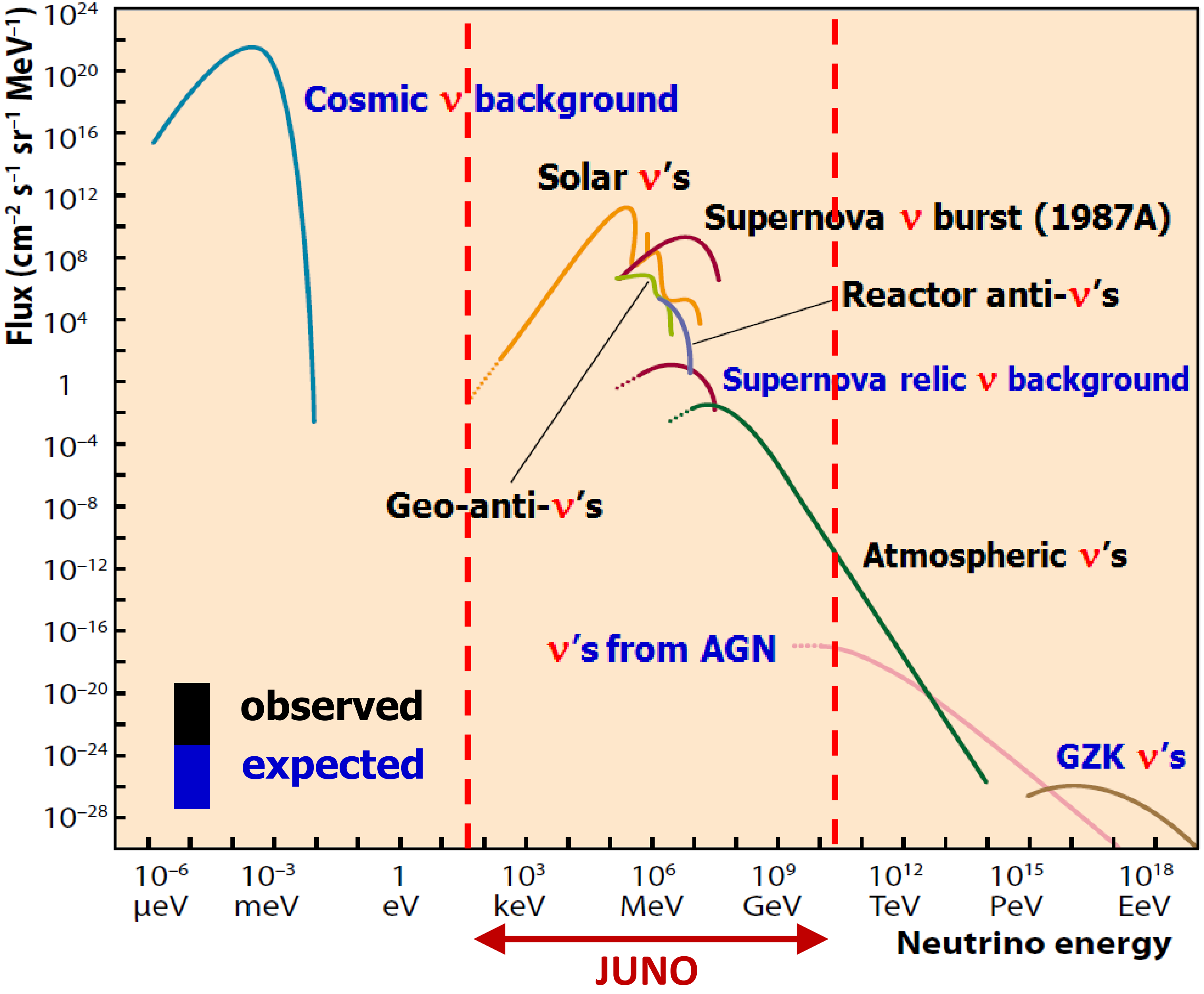
Problems vs. Technologies



Y.F. Wang @ TIPP2011

Problems vs. Technologies





Topics for this talk

Status of JUNO Detector Construction

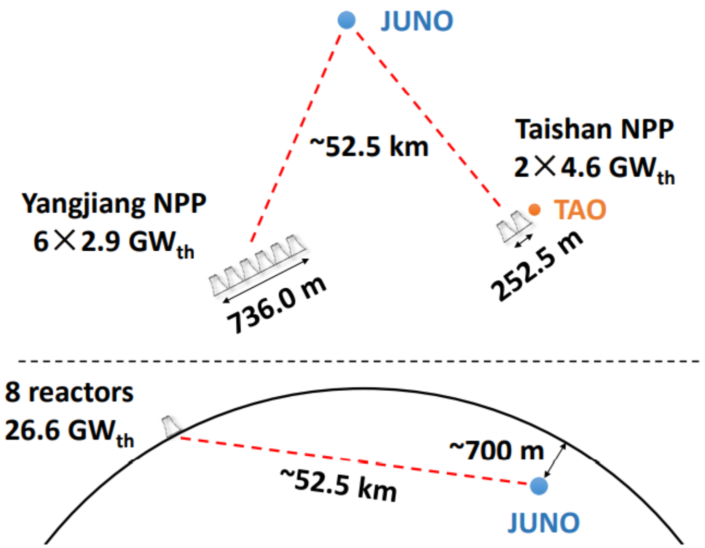
JUNO Physics Prospects

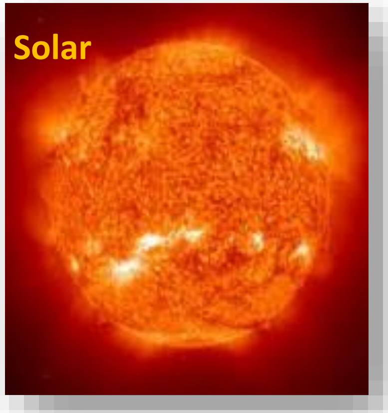
- Reactor ν: Oscillation, spectrum
- Atmospheric ν
- Solar ν
- CCSN
- DSNB (aka supernova relic ν)
- geo-ν
- Nucleon decay
- 0νββ potential

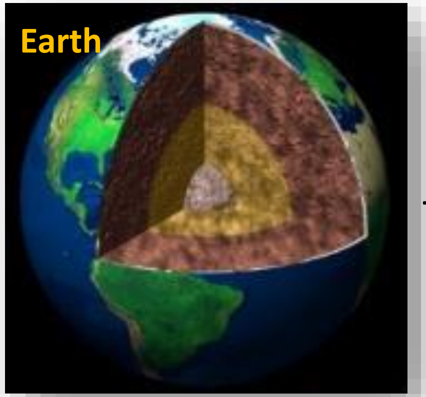
Jiangmen Underground Neutrino Observatory

A multi-purpose observatory

- Physics goals: neutrino mass ordering **(~4σ)**, precision measurement of neutrino mixing parameters **(<<1%)**, supernova ν, geo-ν, solar ν, nucleon decay, etc
- Future upgrade (2030s) : searching for 0νββ
- Detector construction completed in 2023







\+ New physics

~60 IBDs per day | Several per day | Hundreds per day | ~5000 IBDs for CCSN @10 kpc | Several IBDs per day

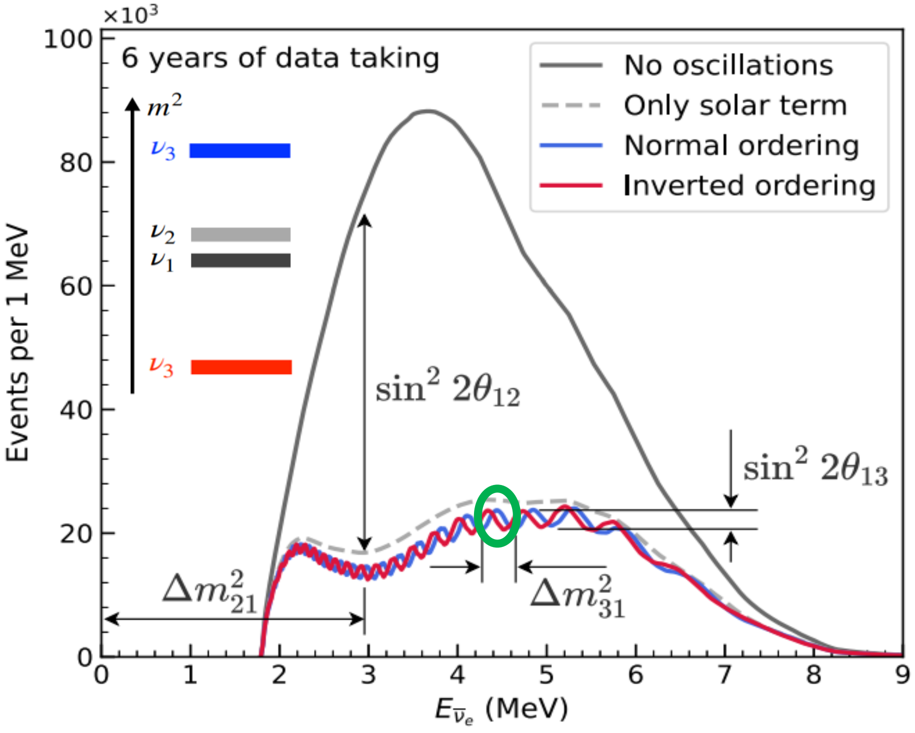
Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay
CCSN: core-collapse supernova

Requirement for rich physics program

Example: Precision Neutrino Oscillation Measurements



Detector properties

- **Statistics**
  - Large target mass (20 kton LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- **Energy resolution**
  - Very high PMT coverage (78%)
  - Highly transparent LS
  - Highly efficient PMTs (PDE~30%)
- **Shape uncertainty**
  - Satellite detector (TAO)
- **Background**
  - Good overburden (~650 m)
  - Highly-efficient veto system (>99.5%)
  - Material screening
  - Clean installation

For solar neutrinos: tighter requirements on Liquid Scintillator (LS) radiopurity by 1~2 orders of magnitude.

Highlights of JUNO detectors

中心探测器

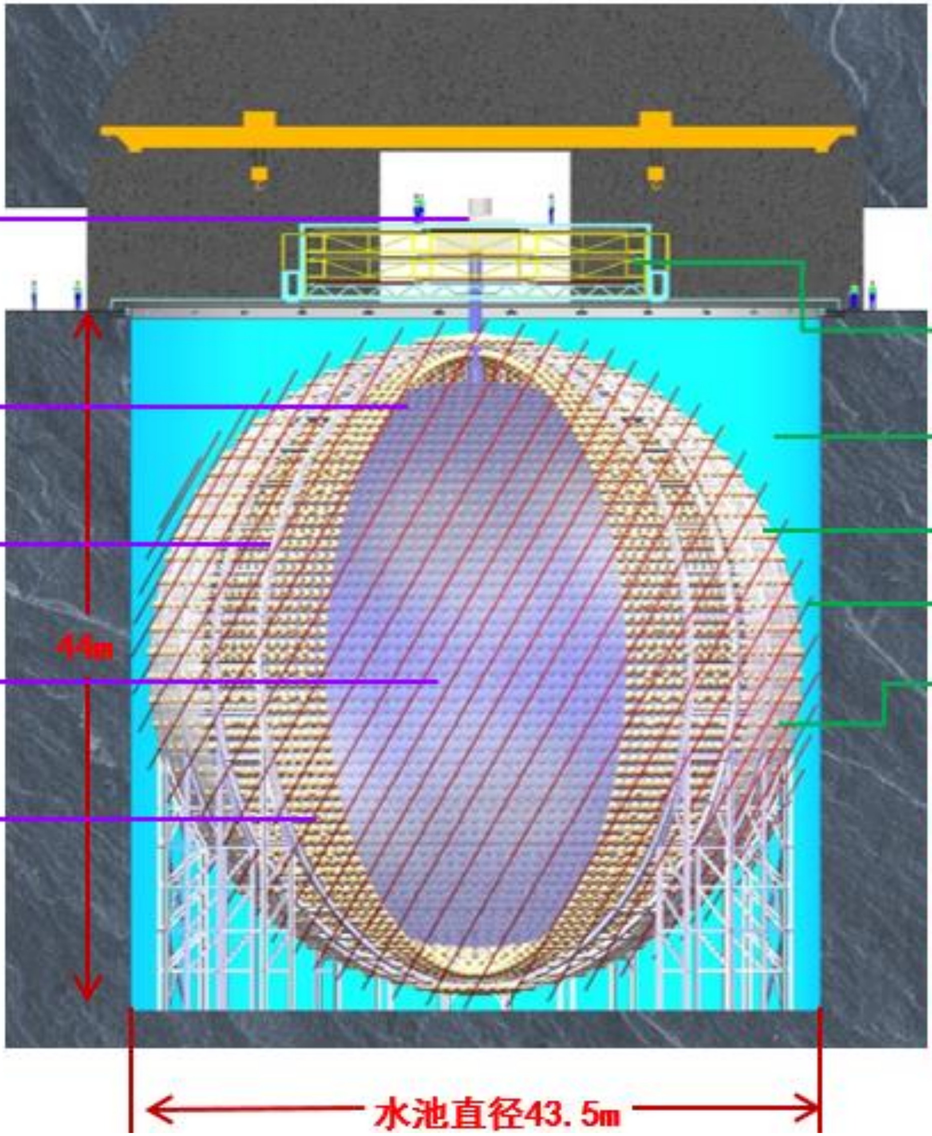
刻度系统

(世界上最大)
Φ35.4m 有机玻璃球

Φ41.1m 不锈钢网架

(透明度最好)
2万吨液闪（A_L>20m）

(国产PMT探测效率世界最高)
17612个20吋PMTs
25600个3吋PMTs
（总光学覆盖率：77.9%）



反符合探测器

Moun径迹探测器

3.5万吨高纯水（A_L>40m）

Tyvek遮光膜

地磁屏蔽线圈

2400个20吋 PMTs

- 世界上最大的液体闪烁探测器
  - KamLAND x 20, Borexino x 40
- 性能最好
  - 光产额 Borexino x 2, KamLAND x 5

科学的发现首先需要技术的领先

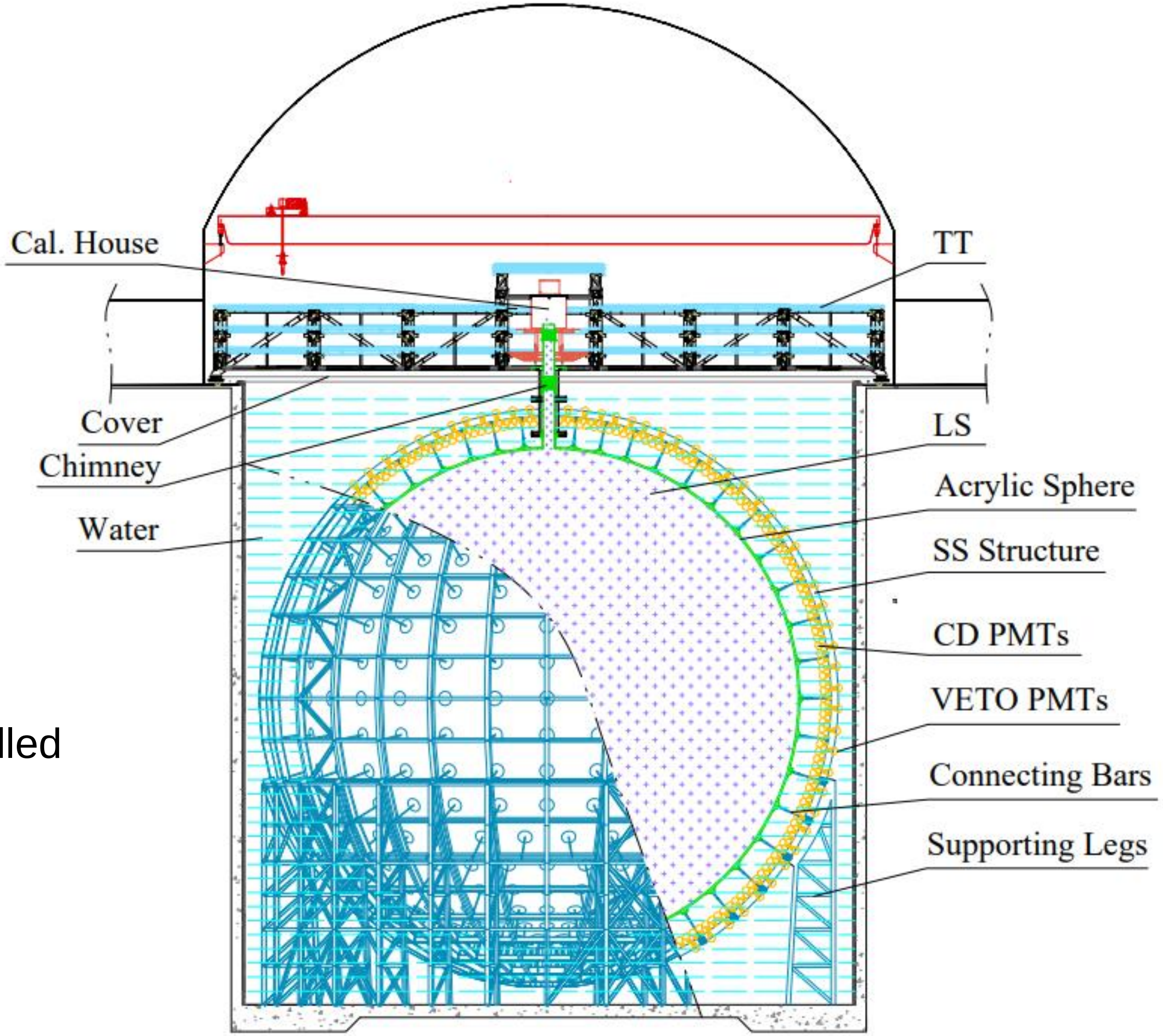
- **13层大楼的规模，毫米的精度**
- **化工规模，超过半导体要求的纯度**
- **普通的商业电子器件，航天的可靠性**
- **几万立方规模，单光子的灵敏**
- **灰尘总量< 0.01 克/2万吨**
- **总空气残留量 < 1 m^3**

JUNO Physics and Detector,
arXiv:2104.02565

Detector progress

Detector Construction Status

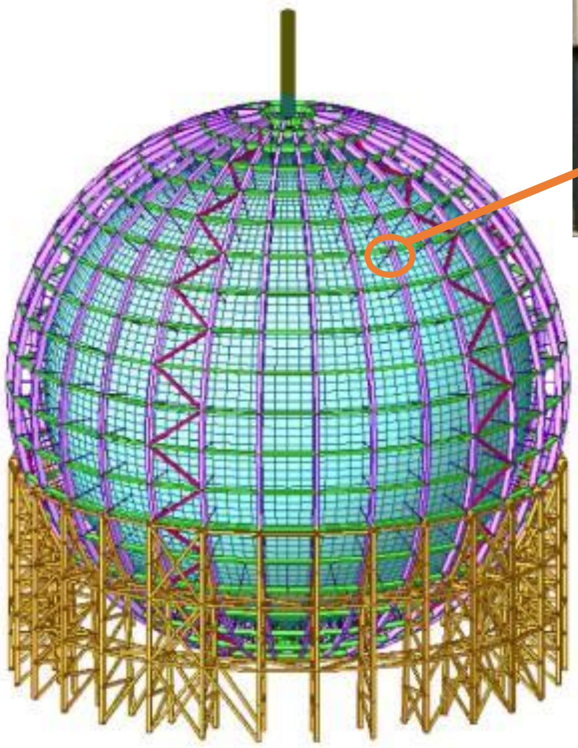
- **Acrylic panels**
  - All the panels are ready for shipping
  - About half sphere is finished
- **Stainless Steel structure**
  - Finished in June 2022
- **20012 20'' PMTs + 25600 3'' PMTs**
  - Production and performance test done
  - ~4800 LPMT and ~4400 SPMT have been installed
- **Liquid scintillator**
  - Purification plants finished onsite construction
  - Under commissioning now



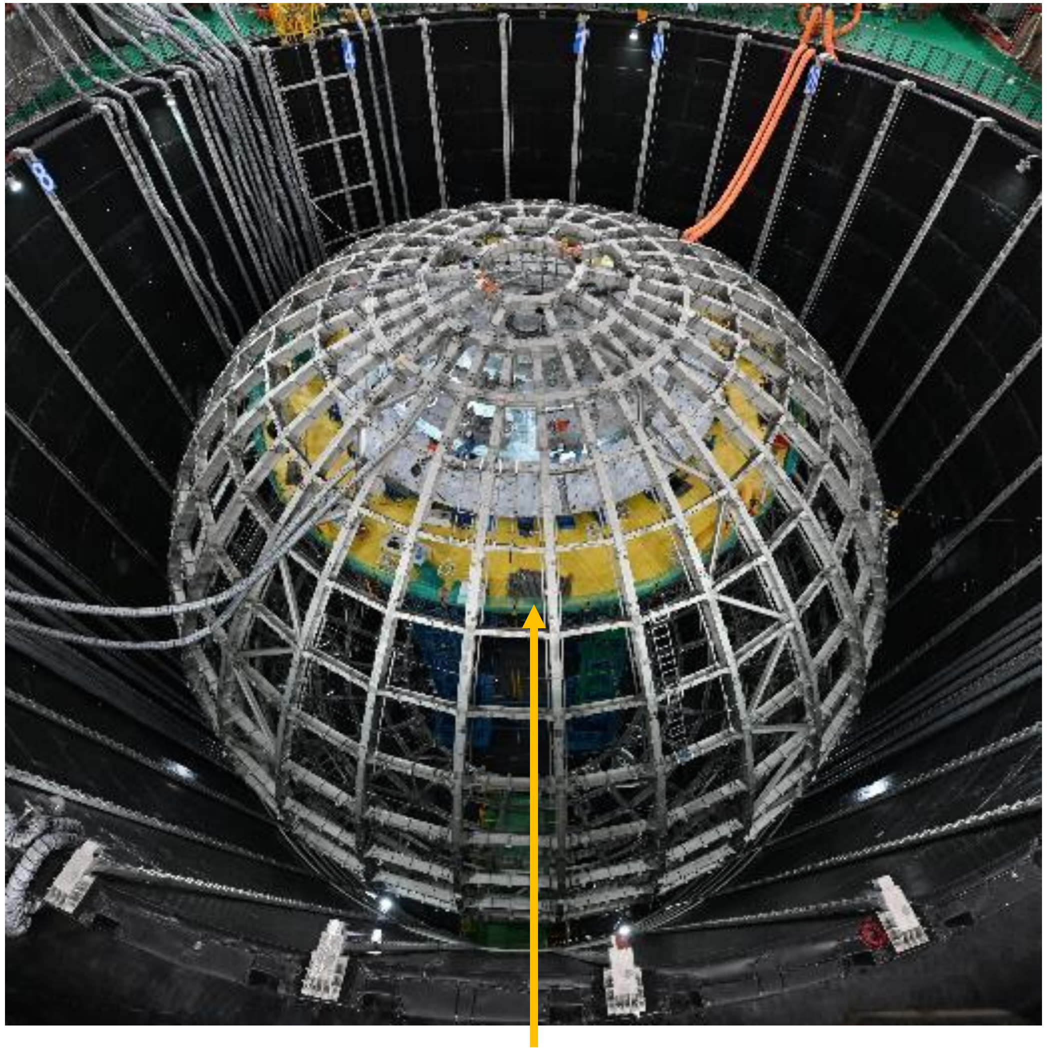
Central Detector (SS structure)

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

Assembly precision: < 3 mm for each grid



- **研发了不锈钢表面粗化技术➔不锈钢表面抗滑移系数由普通的0.2提高至0.5以上**
- **发明高强不锈钢短尾环槽铆钉(专利+国标) ➔ 首次用于不锈钢钢结构领域（抗螺纹咬死，一致性可靠性高），实现创新性全螺栓(12万套)不锈钢结构，避免现场焊接减少变形，**
- **结构整体变形~20 mm，球心偏差(-2, 6, -11) mm ➔ 建筑结构达到机械结构精度，以实现PMT间距3 mm**
- **不锈钢和焊料实现极低放射性本底（<1 ppb）**



The platform to install the acrylic vessel

By 刘悦湘

Central Detector (Acrylic Vessel)

LS container:

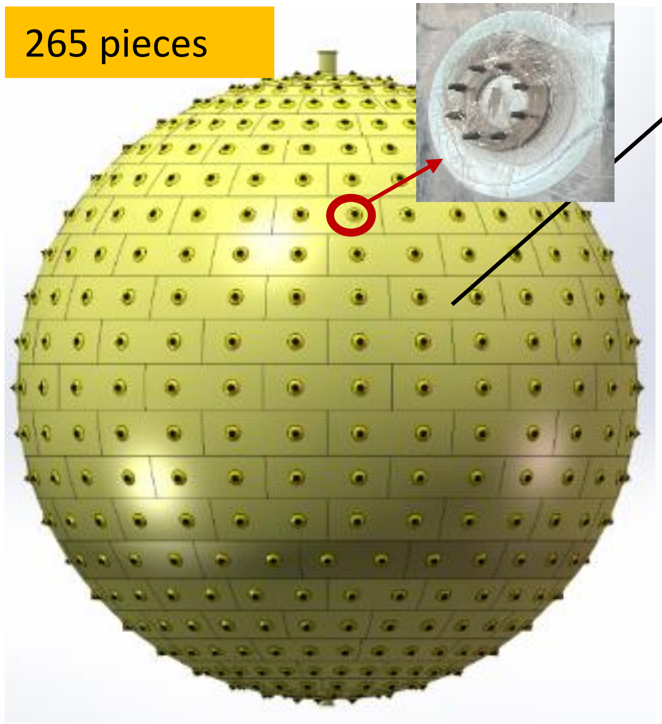
Inner diameter: 35.40±0.04 m

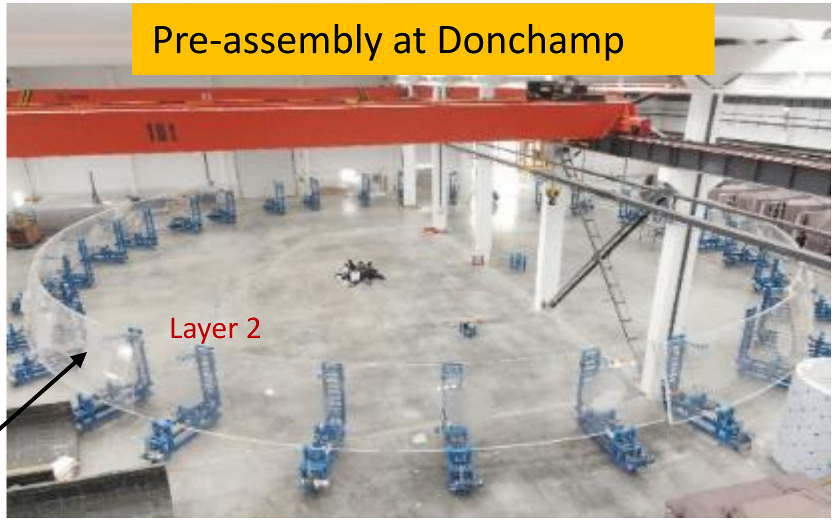
Thickness: 124±4 mm

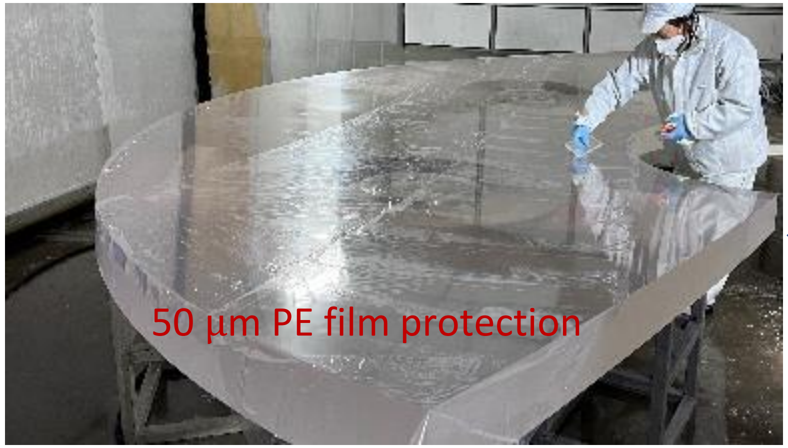
Light transparency > 96% @ LS

Radiopurity: U/Th/K < 1 ppt

265 pieces





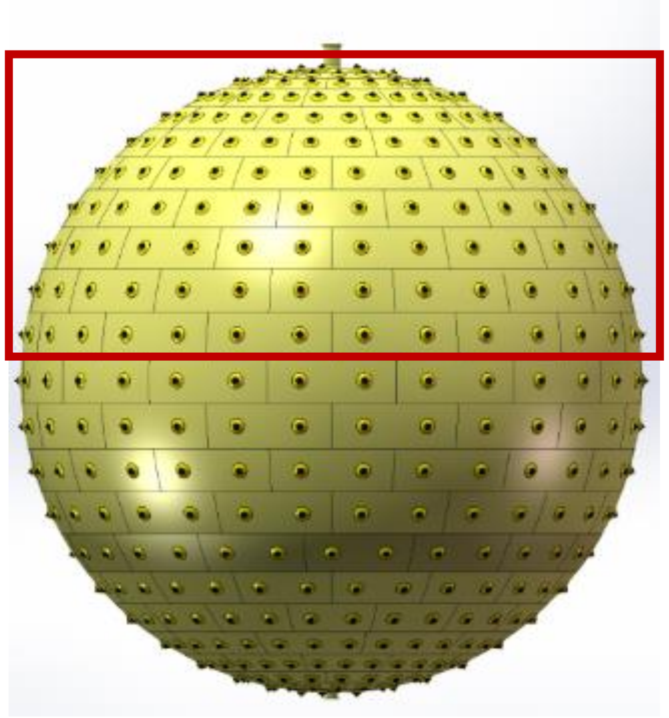


Similar surface treatments will be done on bonding area at JUNO site

Central Detector (Acrylic Vessel)

Acrylic surface is protected with film after cleaning to avoid radon daughters and dust deposition

Outer surface: PE film → remove later
Inner surface: PE film → paper film



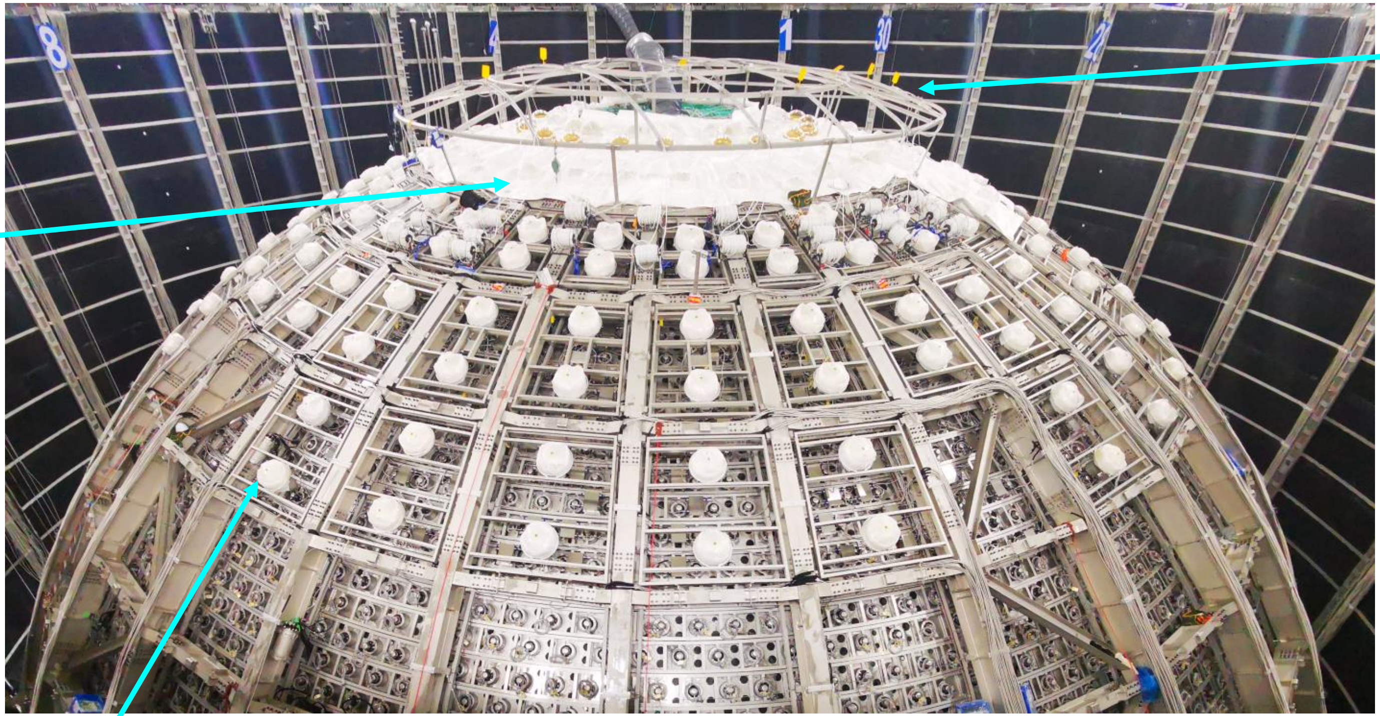
About half acrylic sphere was finished

Veto Detector (water Cherenkov)

Earth magnetic shielding coils installation:

7 coils installed (32 coils in total)

Tyvek reflective film installation started



250 veto PMTs installed(~10% of PMT)

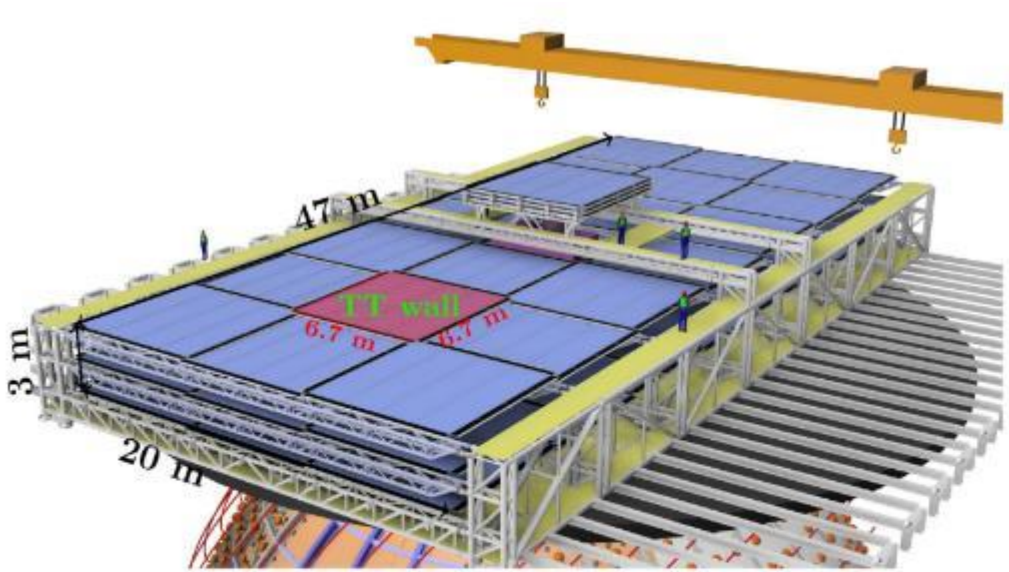
Water system almost ready for commissioning

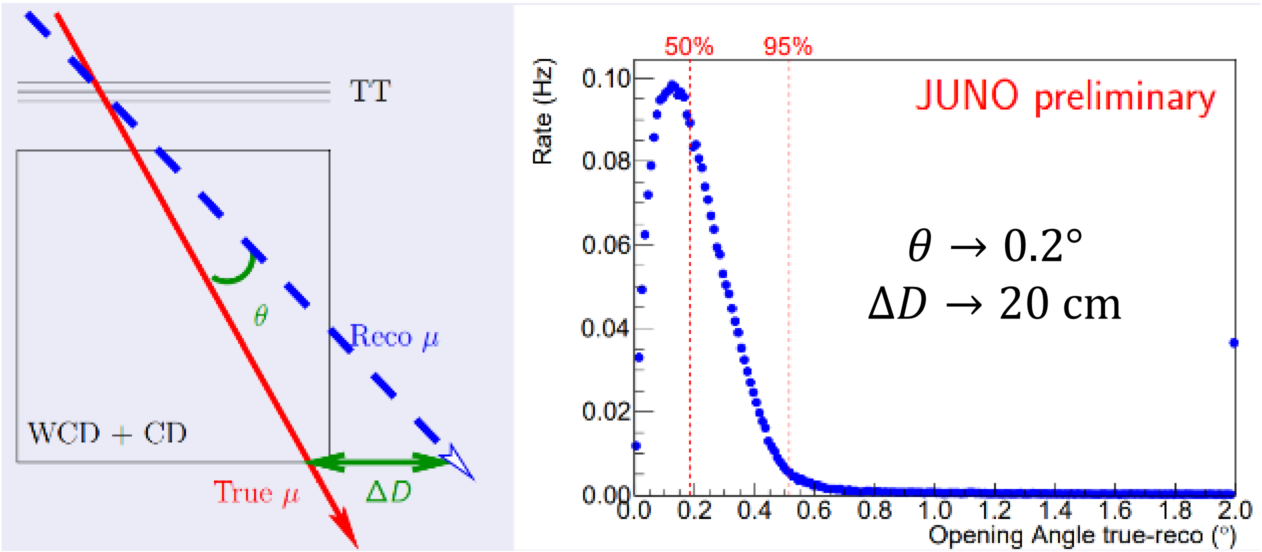
35 kton of ultrapure water serving as passive shield and water Cherenkov detector.

- 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

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

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 study cosmogenic backgrounds

Status:

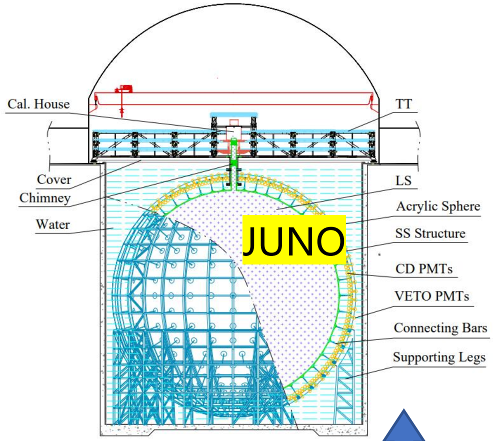
- The TT scintillator detector is onsite.
- The TT support bridge is ready for production.

Liquid Scintillator Purification

	江门实验（2万吨）	对比大亚湾（200吨）
U/Th含量	10^{-17} g/g	低1000倍以上
透明度	>20 m	提高>30%

- **极低本底挑战：**
  - 日本KamLAND 1000吨，意大利Borexino 500吨，加拿大SNO+ 1000吨，第一次灌装都未达标，重新进行了纯化
  - 液闪纯化、有机玻璃板表面处理、探测器和环境的洁净、灌装方案

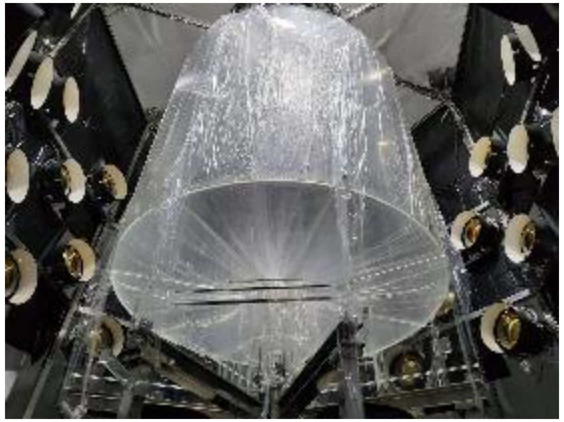
单系统调试部分完成，准备全系统联调



Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

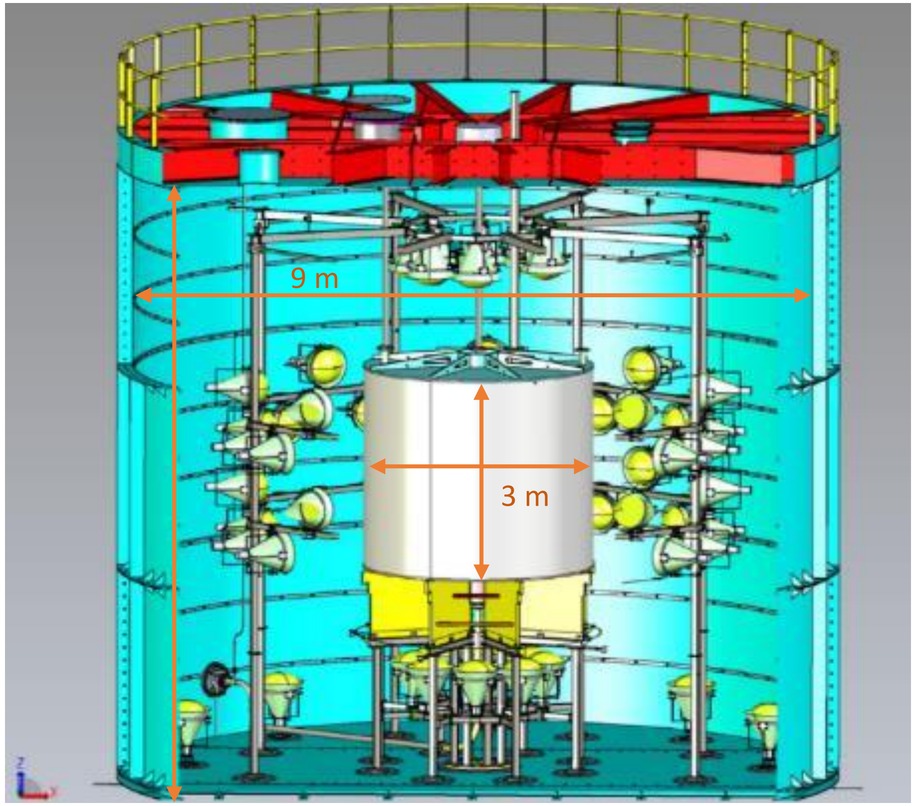
A 20-t detector to monitor radiopurity of LS before and during filling to the central detector

- 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



Expect to start commissioning in July.

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

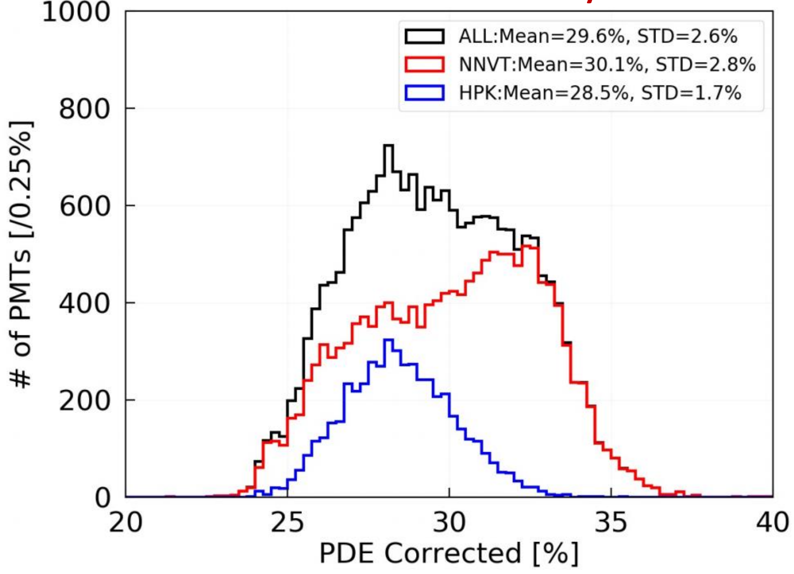


Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator): *arXiv: 2109.10782*

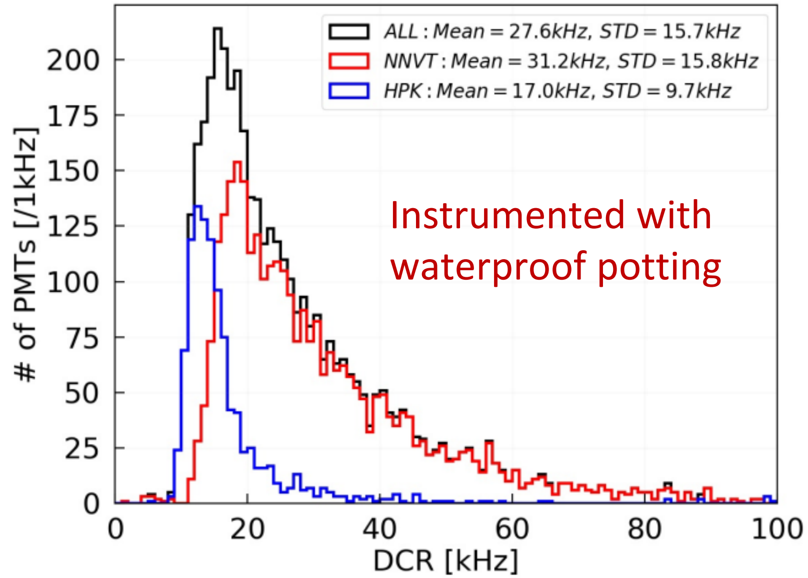
✓ A precision measurement of the flux of solar *pp* neutrinos on the few-percent level

Photomultiplier Tubes

Photon Detection Efficiency



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)

~4800 LPMT and ~4400 SPMT have been installed

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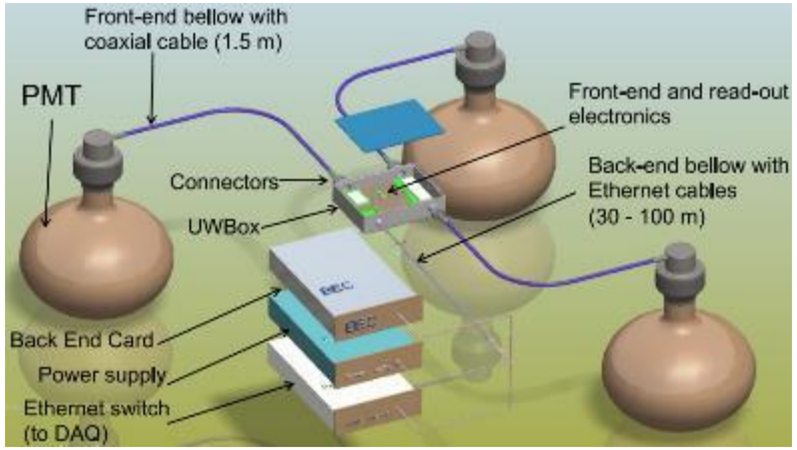
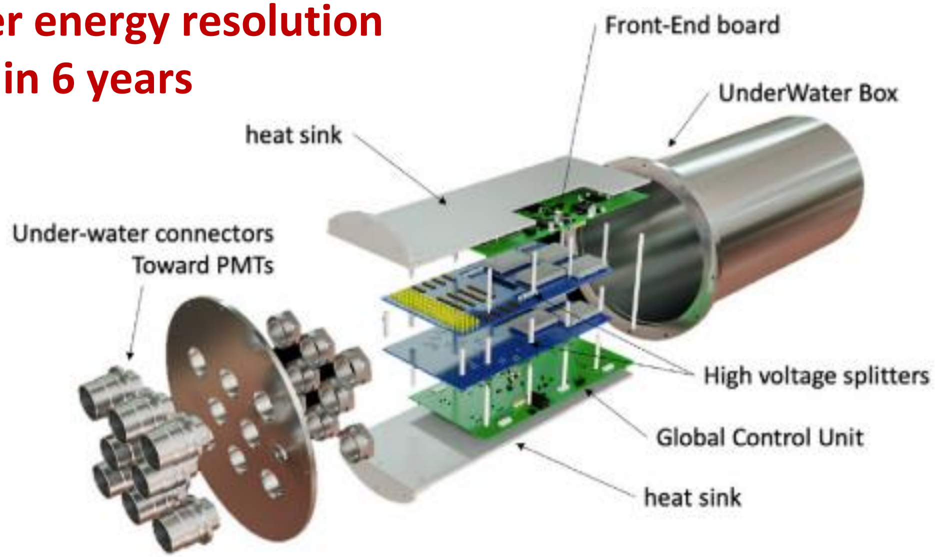
Electronics

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

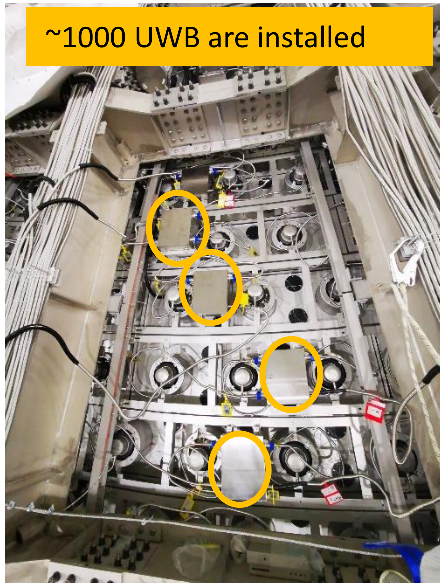
1 GHz waveform digitization, expected loss rate < 0.5% in 6 years

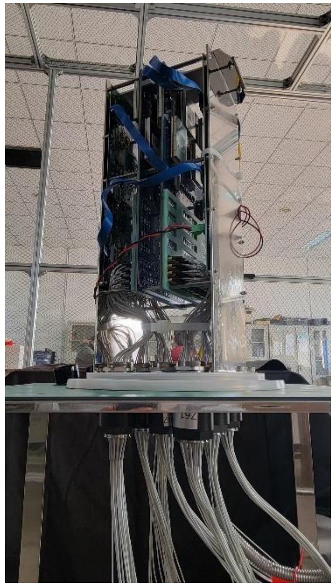




3 20-inch PMTs connected to one underwater box

128 3-inch PMTs connected to one underwater box

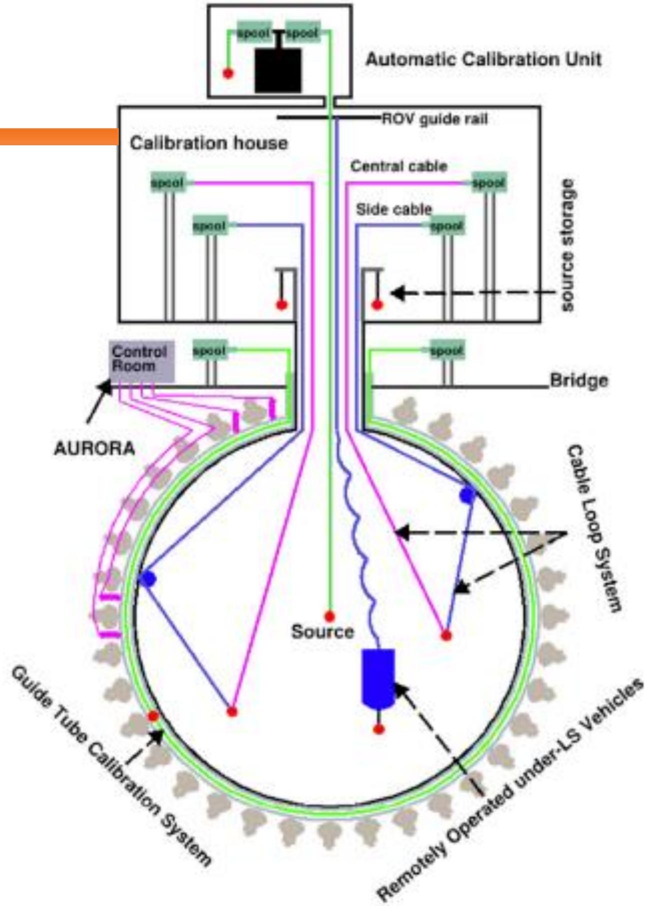




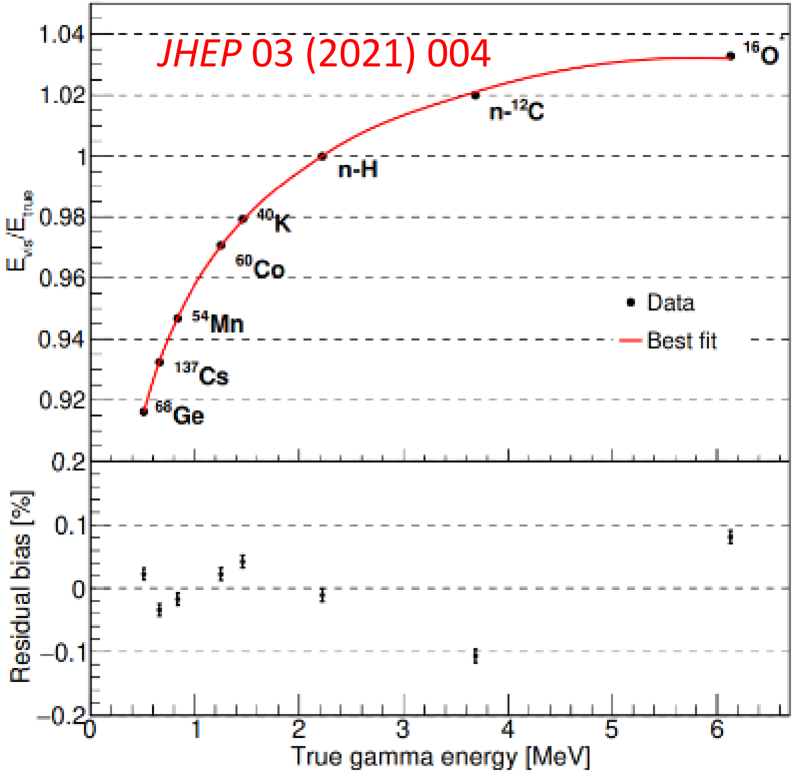
Calibration

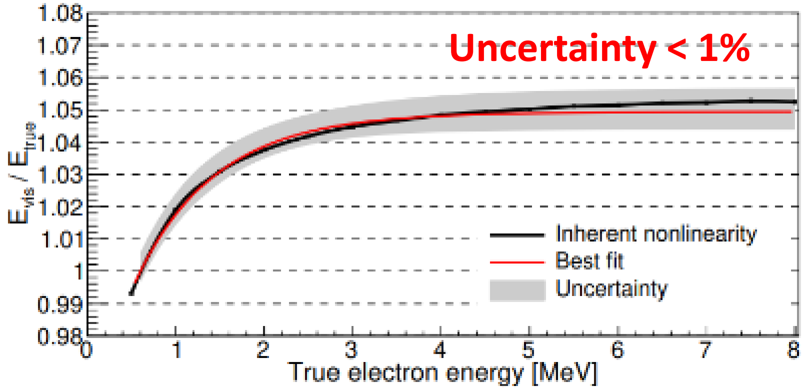
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Cable system finished prototype test



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





Radiopurity Control

Reduced by 15% compared to the design. Ref: *JHEP* 11 (2021) 102

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

Radiopurity control on raw material:

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

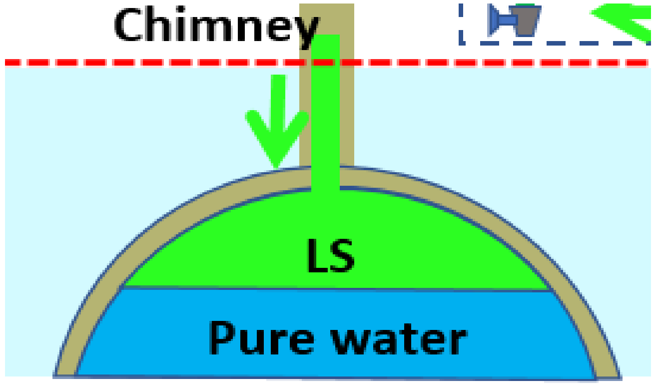
Liquid Scintillator Filling

- Recirculation is impossible at JUNO due to its large size

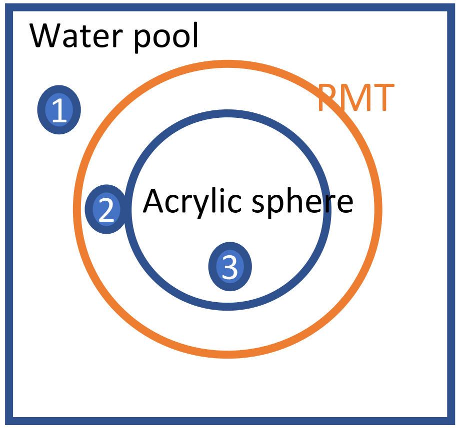
→ Target radiopurity need to be obtained from the beginning

Strategies:

1. **Leakage** (single component < 10^{-6} mbar·L/s)
2. **Cleaning vessel** before filling
3. **Clean environment**
4. **Water/LS filling**



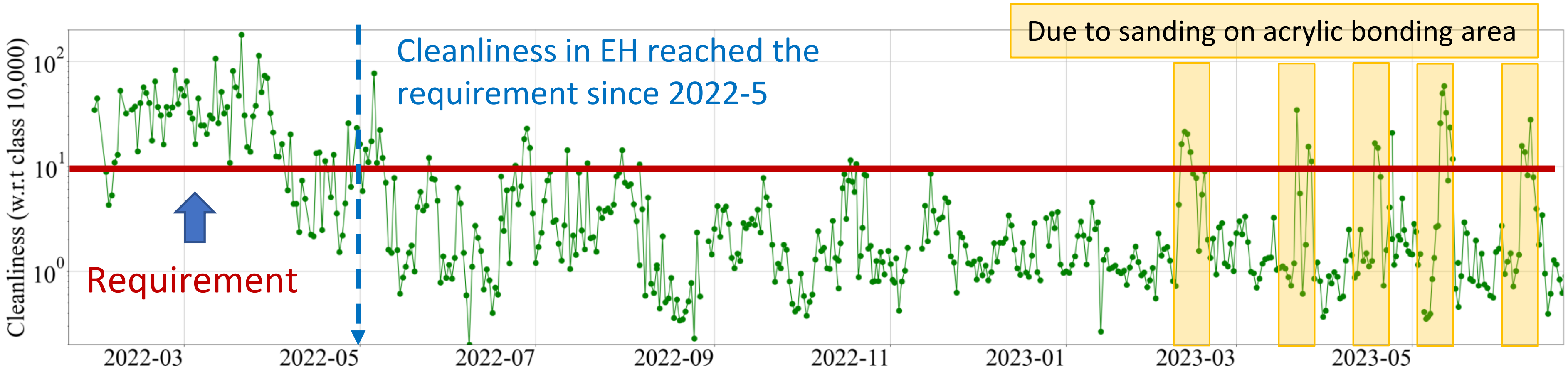
Radiopurity Control: environmental cleanliness



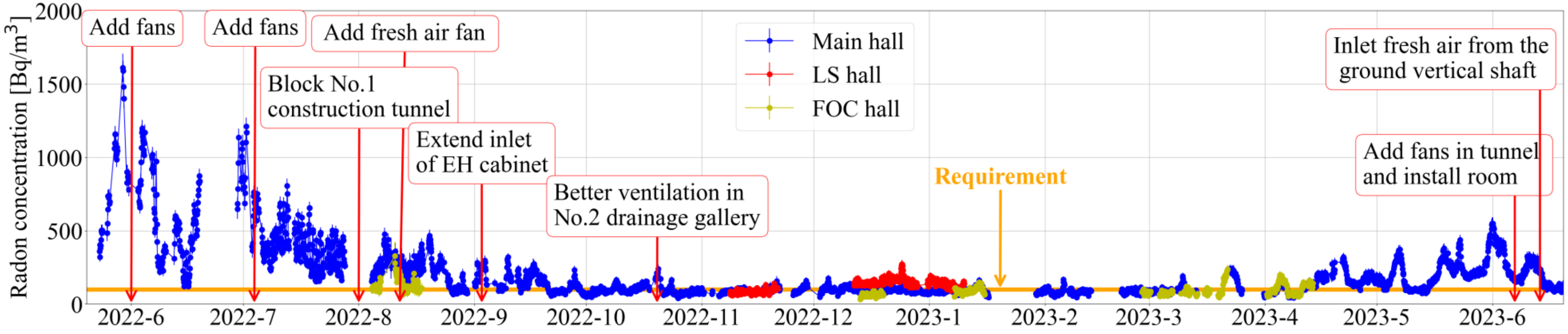
Region	Level
1	Class 100,000
2	Class 10,000
3	Class 1000

Temperature: 21℃±1℃
Radon in air: 100 Bq/m^3

Acceptable dust in 20 kt LS: < 10 mg!



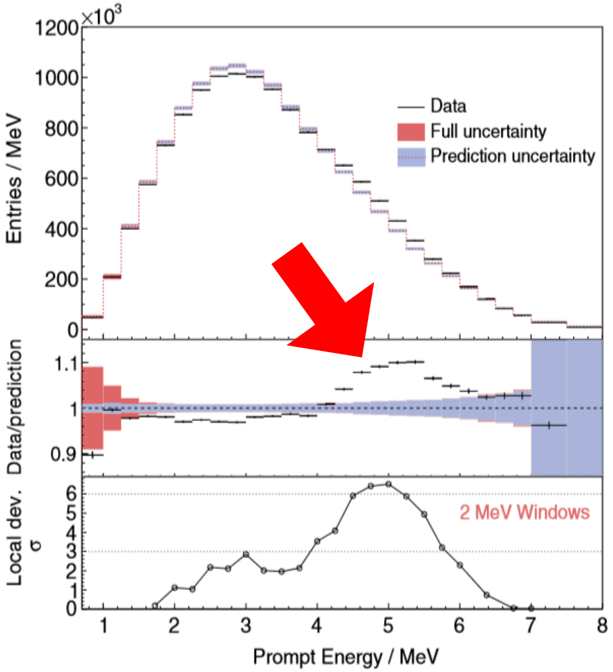
- Cleanliness Class calculation: total dust volume divide Class 10,000 particles volume



With great efforts on onsite cleanliness control and ventilation optimization, both the radon and the cleanliness in the hall reached our requirement

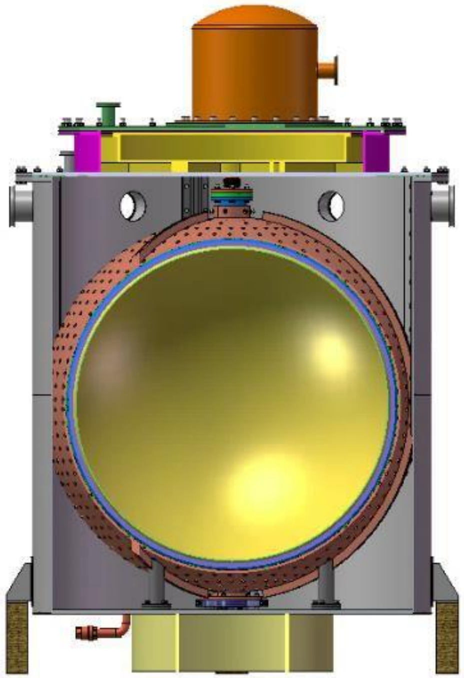
反应堆中微子能谱反常、反应堆监测

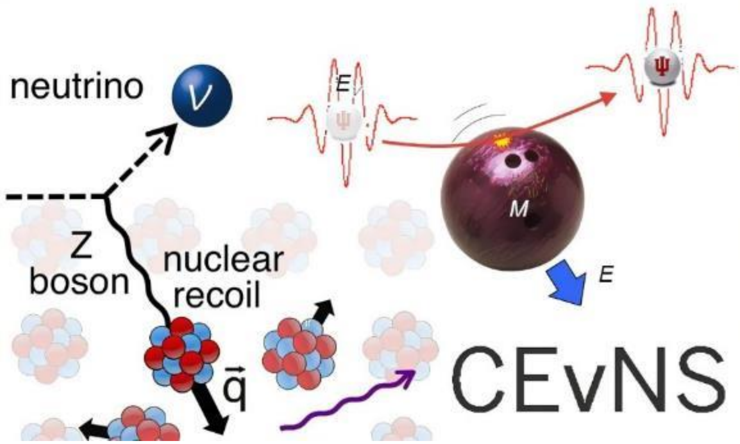
- 2016年大亚湾实验发现反应堆中微子**事例率低于理论预期6%，能谱在5MeV处超出10%**（中国核学会2015-2017年度中国十大核科技进展，科技日报头版报道）
  - ⇨ 理论模型不准确，需要进行精确测量；**核数据库**不够准确，成为核数据专家的研究热点
  - ⇨ 2019年，国际原子能机构核数据中心讨论利用中微子研究核数据问题 → 台山中微子实验
- 2017年美国COHERENT组首次观测到中微子相干散射，入选当年《科学》十大科学突破。但反应堆中微子相干散射探测的技术难度高，迄今尚未观测到。有望实现**中微子探测器小型化**。



距反应堆30米处建立实验室：

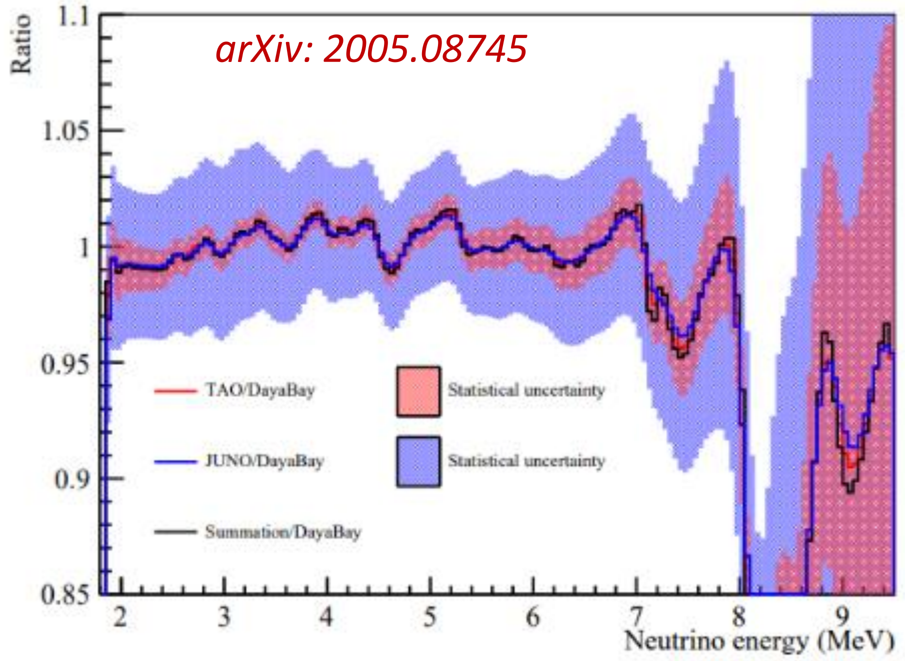
- 高精度测量反应堆中微子能谱（台山中微子实验，2023年运行）
- 研发小型化中微子探测器，用于反应堆监测



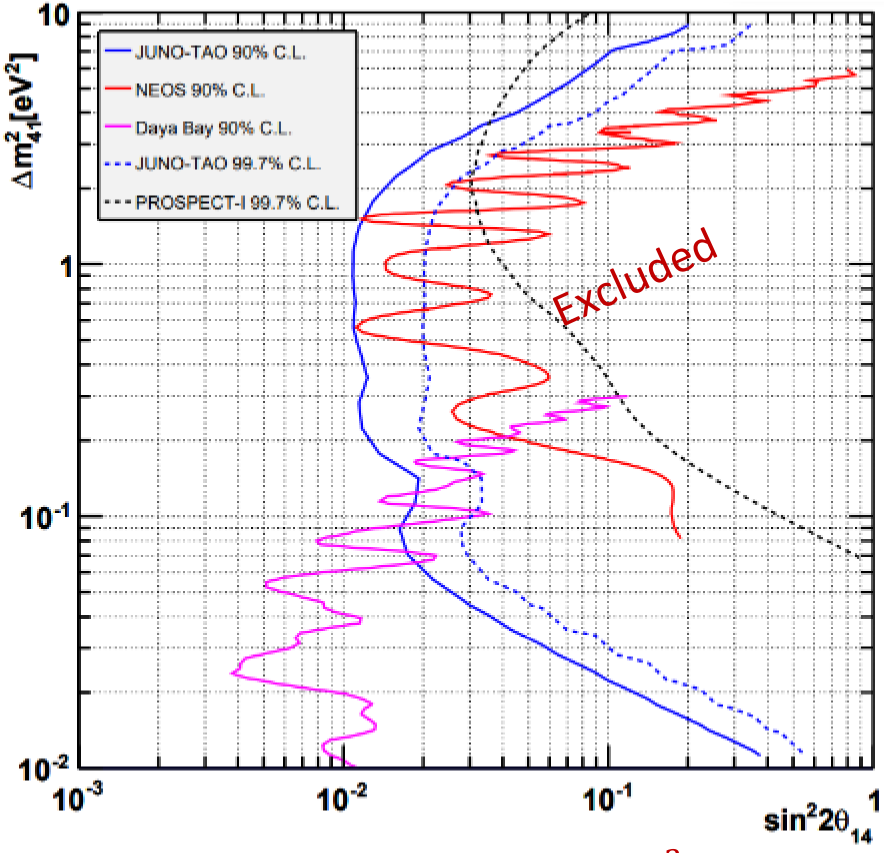


Taishan Antineutrino Observatory (TAO)

- Measure the reactor antineutrino spectrum (fine structure) with unprecedented energy resolution
- Provide a reference spectrum for JUNO, other experiments, and nuclear databases
- Search for light sterile neutrinos
- Make improved measurements of isotopic yields & spectra



Constrain the fine structure in [2.5,6] MeV to < 1%



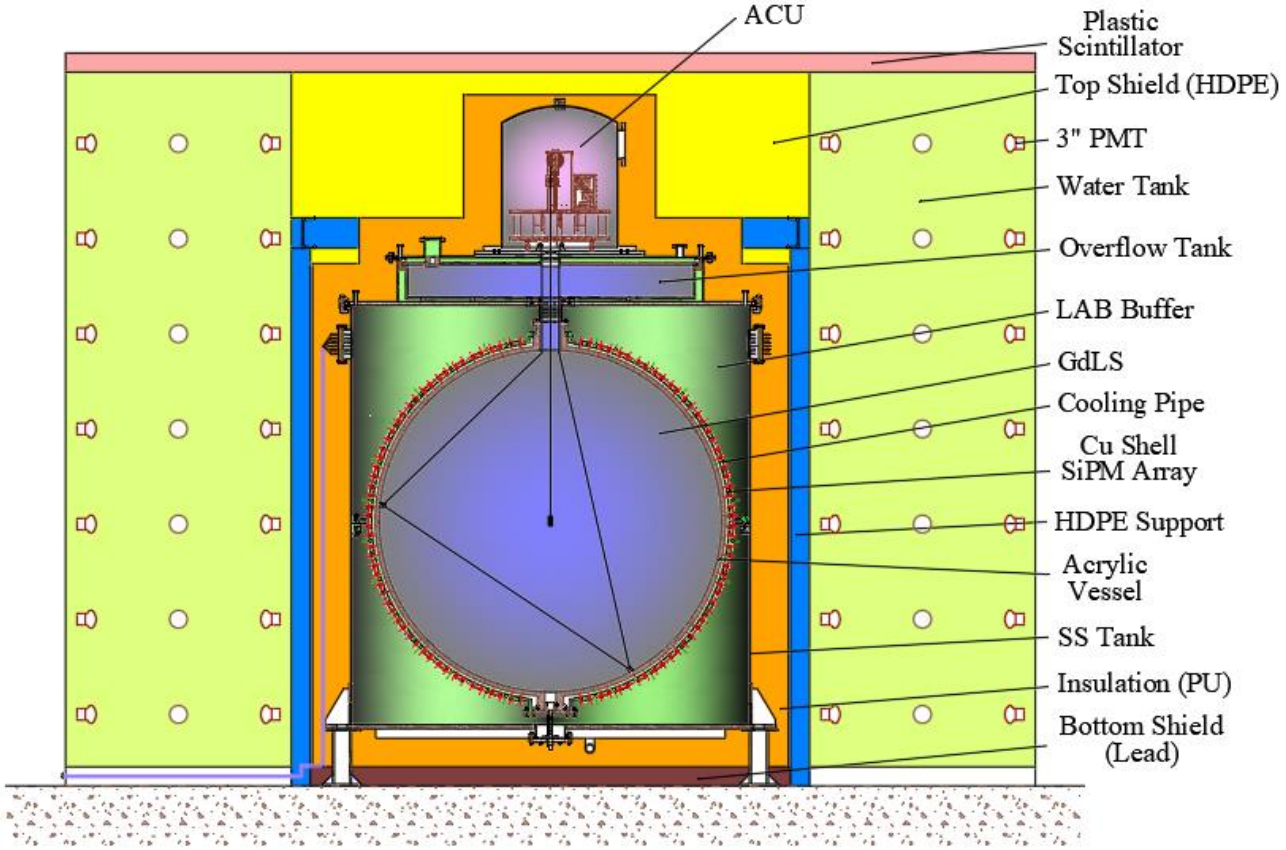
TAO sensitive in region 10^{-2} eV^2 < Δm_{41}^2 < 10eV^2

Taishan Antineutrino Observatory (TAO)

- **Innovative design of low-temperature LS + state-of-the-art SiPM**

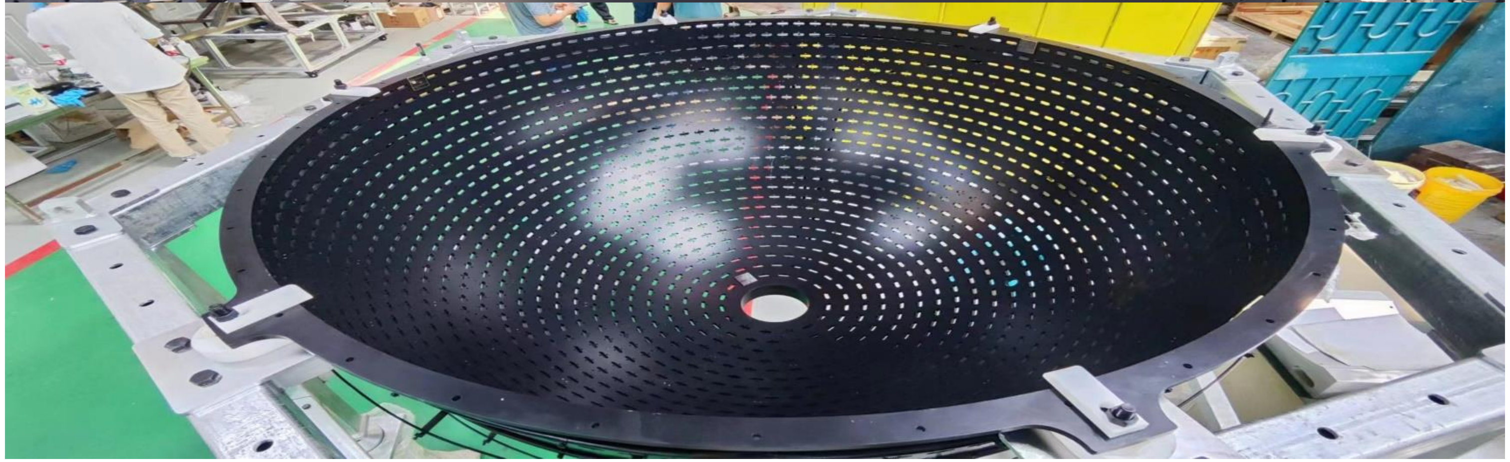
  → unprecedented energy resolution (≤ 2%@1MeV)

Detector Concept Design (arXiv: 2005.08745)	
Gd-LS	2.8 ton
Baseline	~30 m
Reactor Thermal Power	4.6 GW
Light Collection	SiPM
Photon Detection Efficiency	≥ 50%
Working Temperature	-50 ℃
Dark Count Rate [Hz/mm^2]	< 100
Coverage	~94%
Detected Light Level [PE/MeV]	4500
Energy resolution	< 2% @ 1 MeV



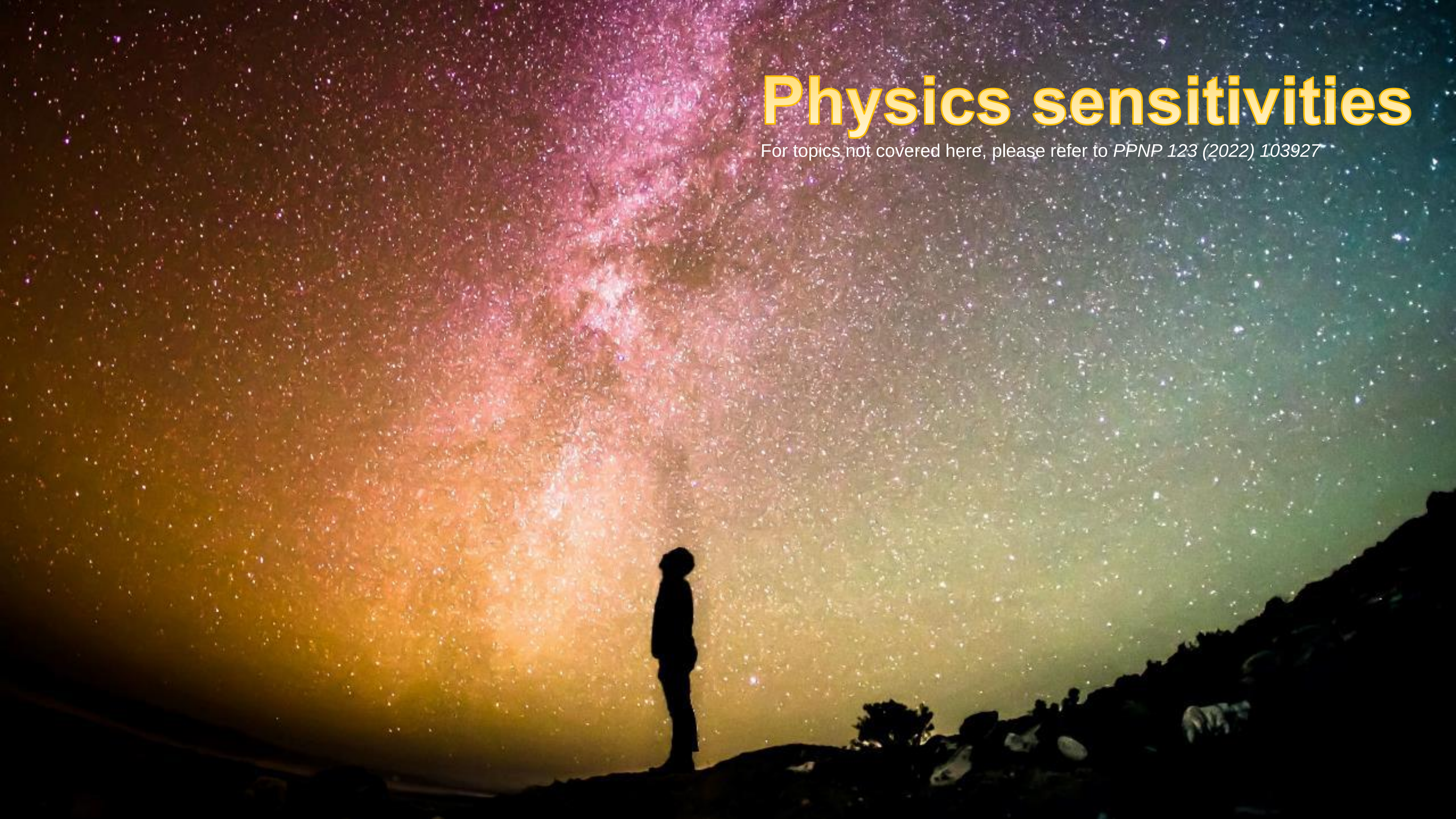
Taishan Antineutrino Observatory (TAO)

- **Key mechanical structures manufactured → building 1:1 prototype @IHEP → final installation @Taishan by end of year → data-taking by 2024**

Physics sensitivities

For topics not covered here, please refer to *PPNP 123 (2022) 103927*



Reactor Antineutrino Oscillation

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$ ← 江门主导项

$$- \frac{1}{2} \underline{\sin^2 2\theta_{13}} \left[\sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \frac{\Delta m^2_{32} L}{4E} \right]$$ ← 大亚湾主导项

$$- \frac{1}{2} \cos 2\theta_{12} \underline{\sin^2 2\theta_{13}} \sin \frac{\Delta m^2_{21} L}{4E} \sin \frac{(\Delta m^2_{31} + \Delta m^2_{32}) L}{4E}$$ ← 干涉

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

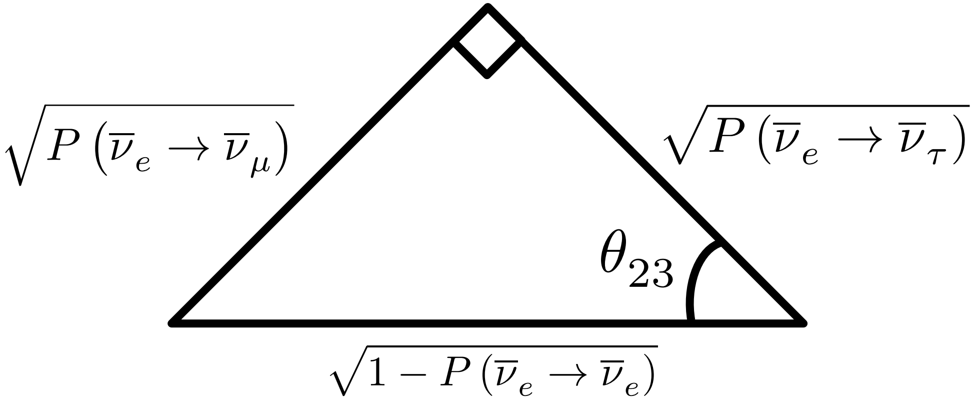
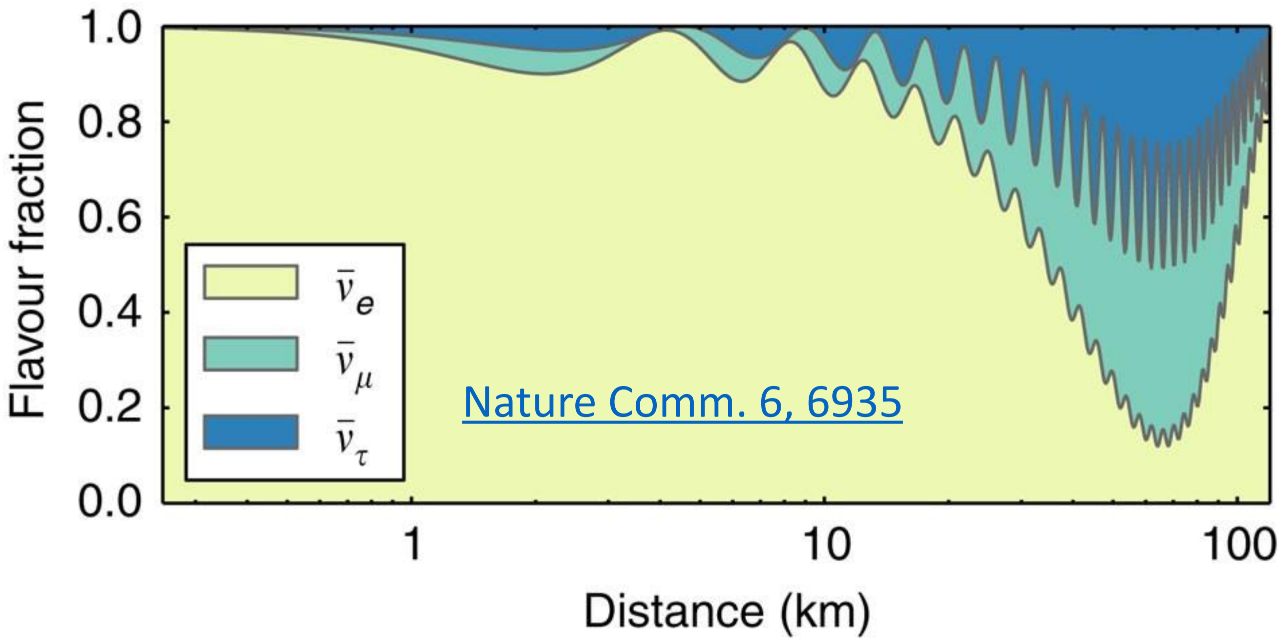


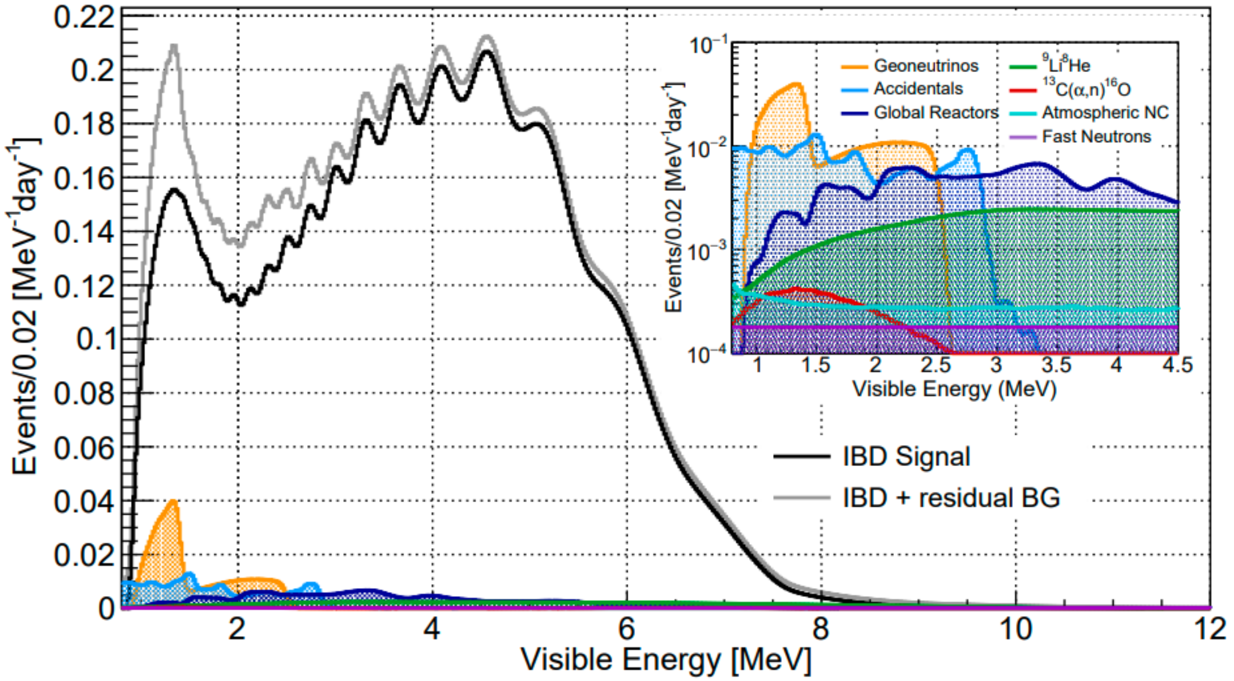
Illustration: Daya Bay Conversion Probability

Curtesy: Jihong Huang, Zhi-zhong Xing



Reactor Antineutrino Oscillation & Detection

JUNO, arXiv: 2204.13249



Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 ➔ 47	-	-
Geo-ν's	1.1 ➔ 1.2	30%	5%
Accidental signals	0.9 ➔ 0.8	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 ➔ 0.8	20%	10%
^{13}C (α, 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 ana.**

Updates for the spectra and rates since JUNO (2016)

- ☹ 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

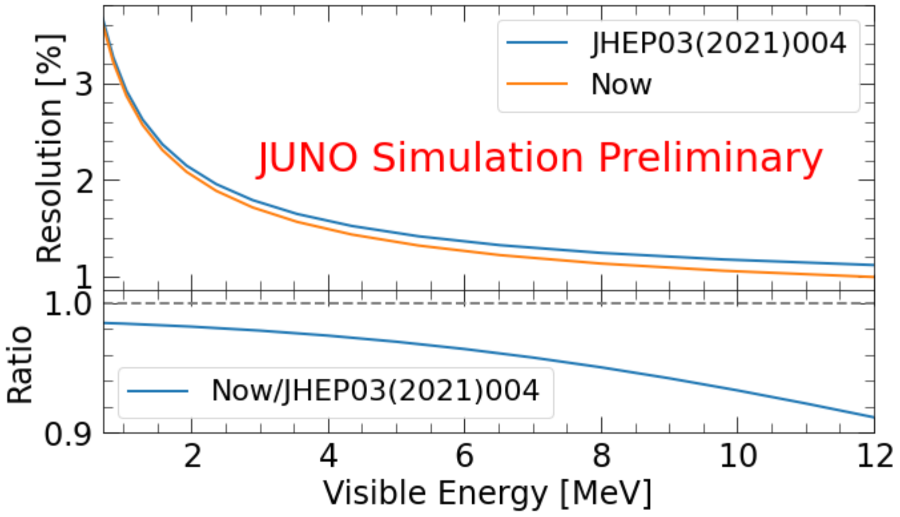
Energy Resolution

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)

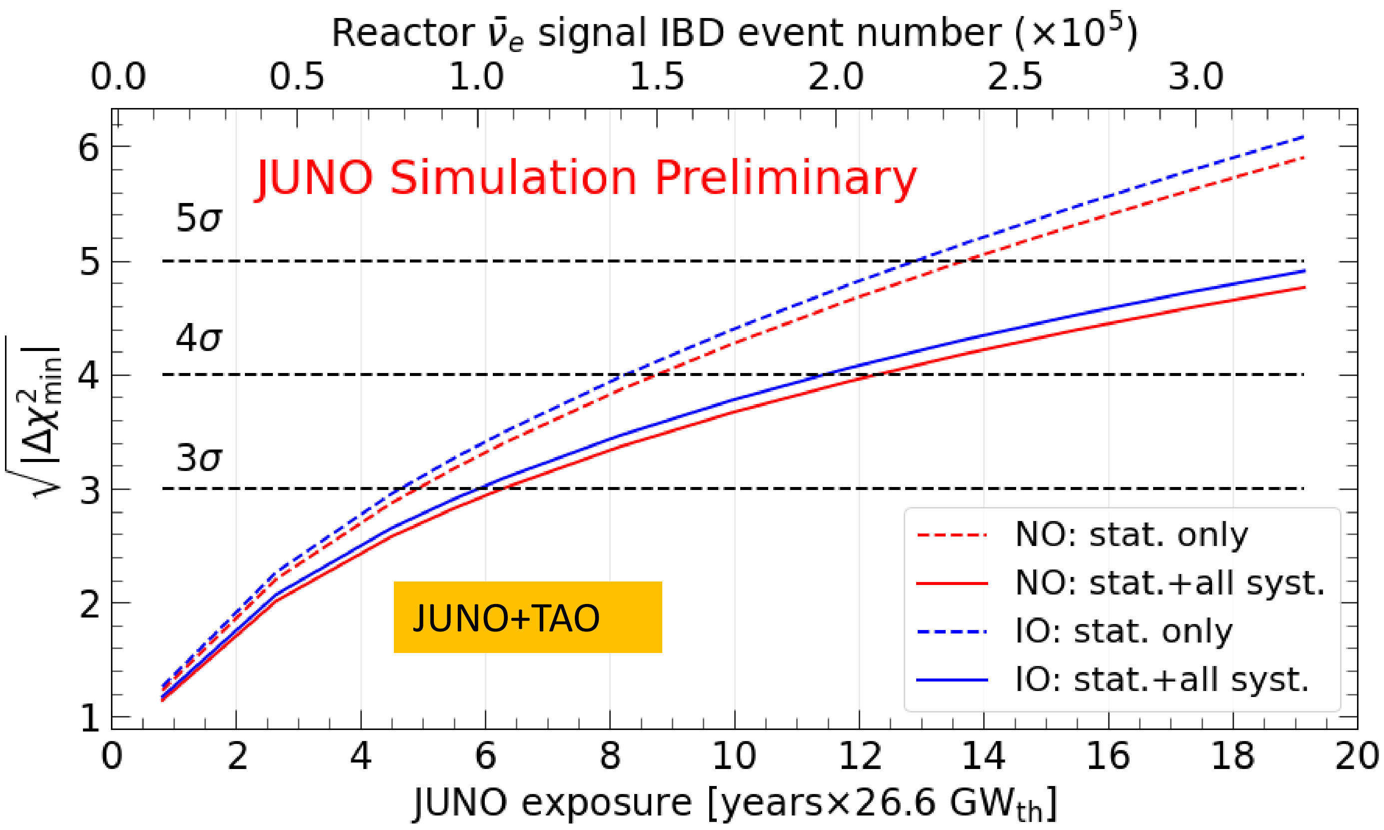
Positron energy resolution is understood:

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

- **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**



Neutrino Mass Ordering



	Design *	Now (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% (**11%↑**)
Signal rate	60 /day	47.1 /day (**22%↓**)
Backgrounds	3.75 /day	4.11 /day (**10%↑**)
Energy resolution	3% @ 1 MeV	2.9% @ 1 MeV (**3%↑**)
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sens. exposure	**< 6 yrs × 35.8 GW$_{th}$**	**~ 6 yrs × 26.6 GW$_{th}$**

* J. Phys. G 43:030401 (2016)

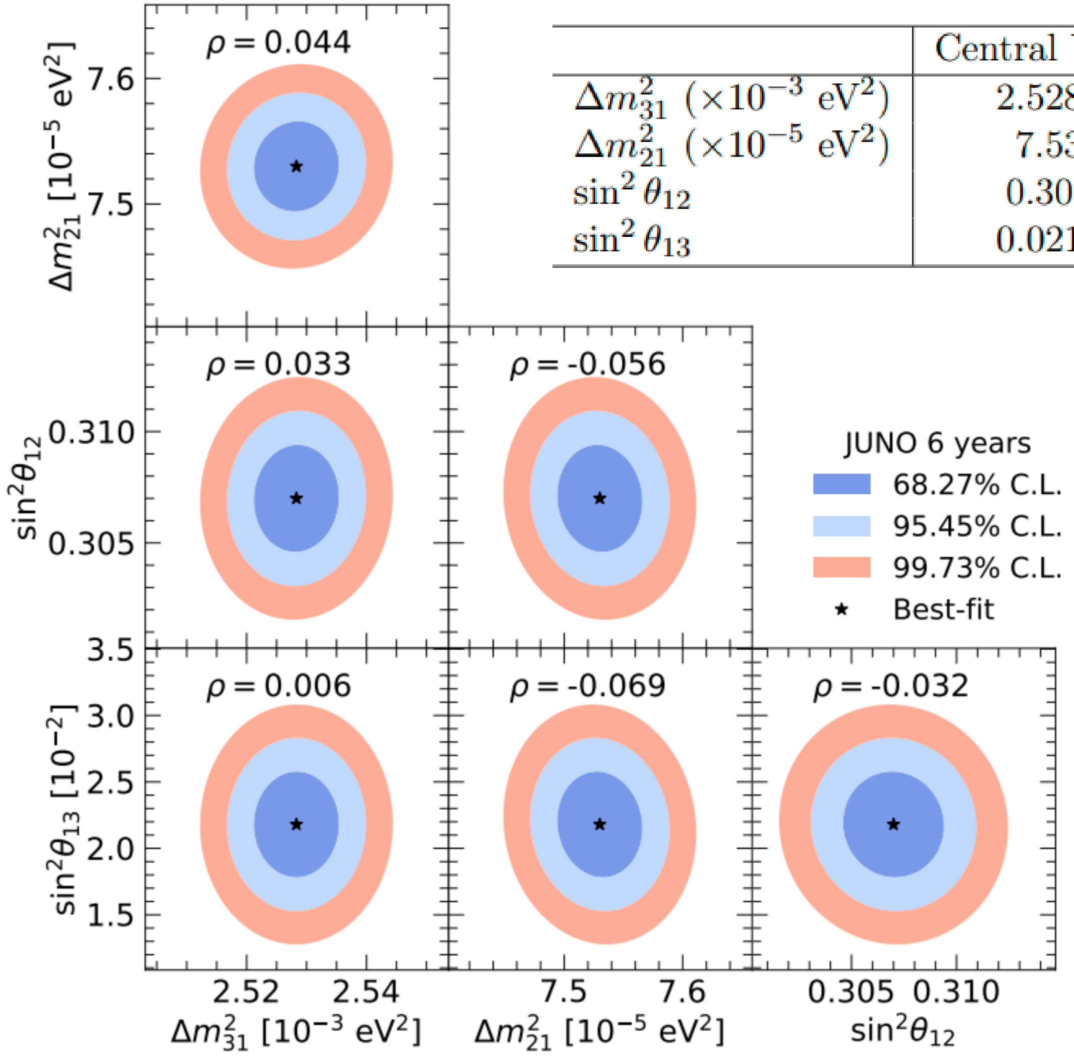
- JUNO NMO median sensitivity: **3σ (reactors only) @ ~6 yrs * 26.6 GW$_{th}$ exposure**
- Combined reactor + atmospheric neutrino analysis is in progress: further improve the NMO sensitivity

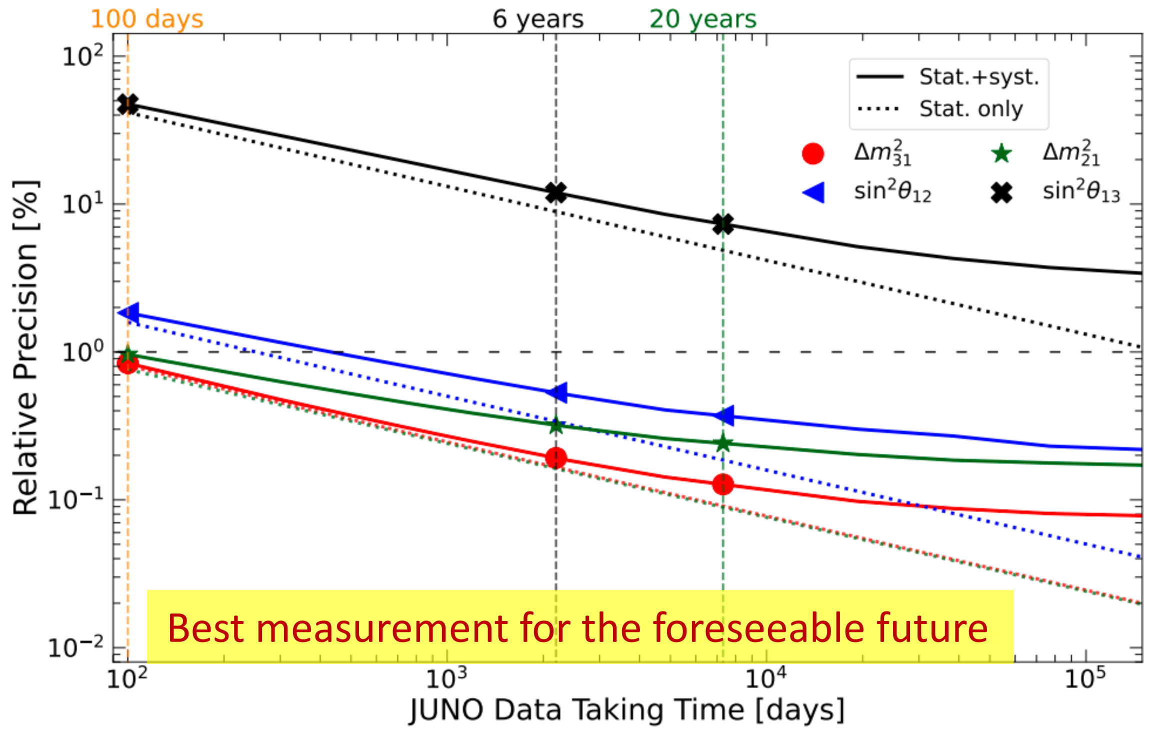
Neutrino oscillation parameters w/ reactors

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

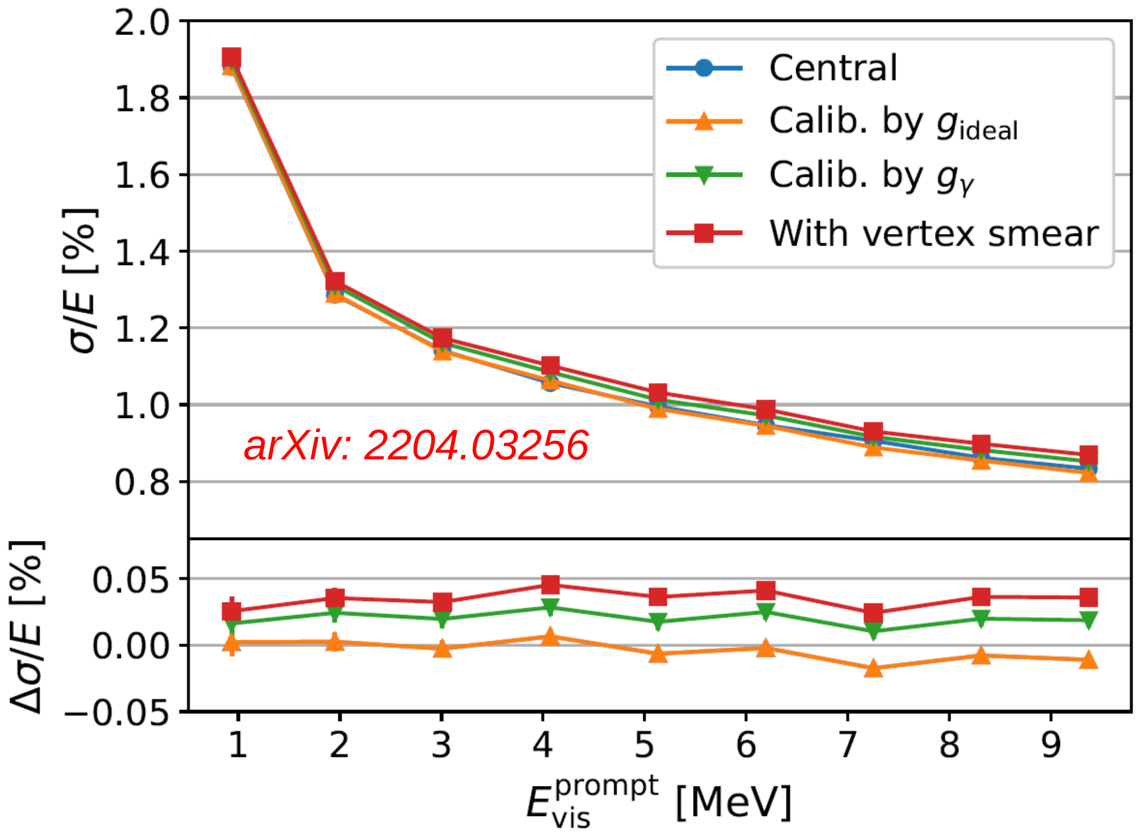
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (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%)

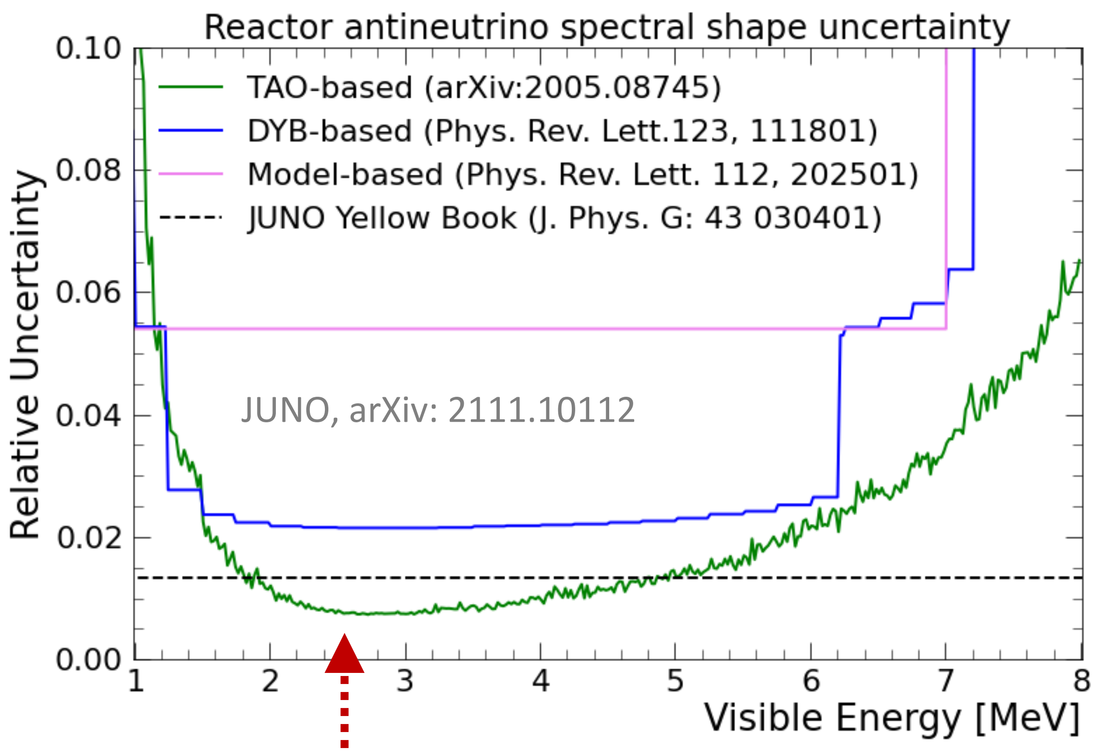




The improvement in precision over existing constraints will be about one order of magnitude

Reactor Antineutrino Spectrum from TAO





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

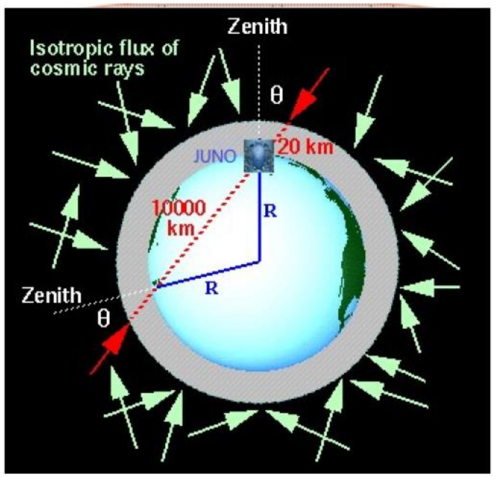
- Precisely measure the unoscillated reactor $\bar{\nu}_e$ spectrum

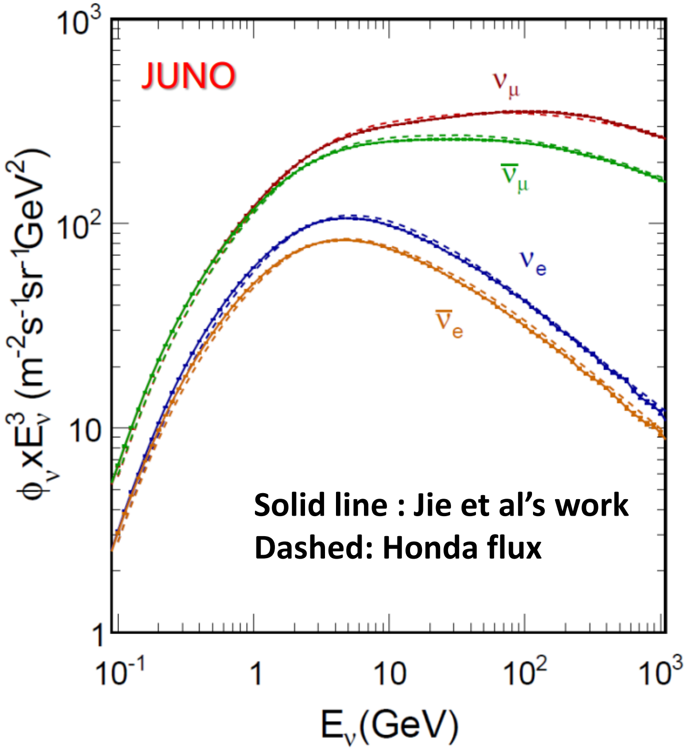
➔ good understanding of the shape uncertainty

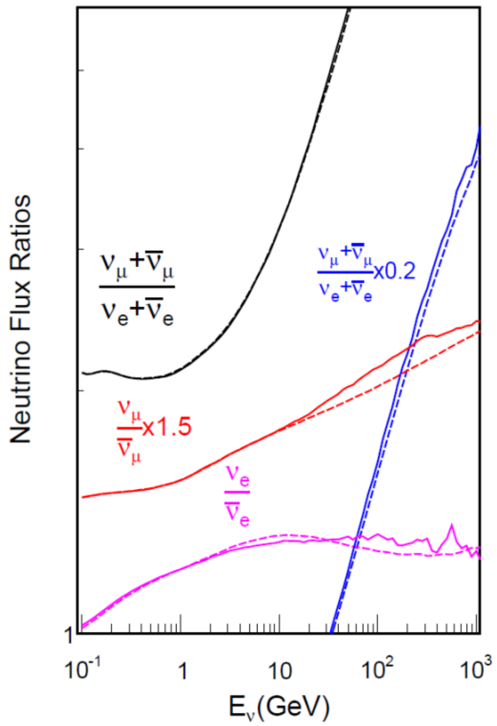
➔ model-independent combined analysis with JUNO

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

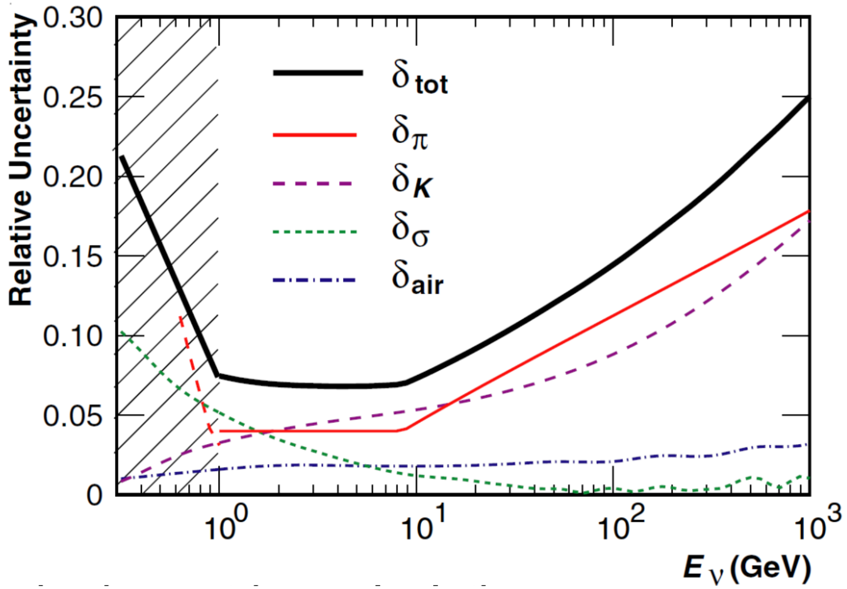
Atmospheric Neutrinos







PHYSICAL REVIEW D **75,** 043006 (2007)



3D atm-ν flux calculation based on:

- Primary cosmic ray flux
- Rigidity cut, depends on geomagnetic field and rigidity of cosmic ray particle
- Hadronic interaction model, air profile and meson-muon decay

Evaluation of GeV ν interaction models

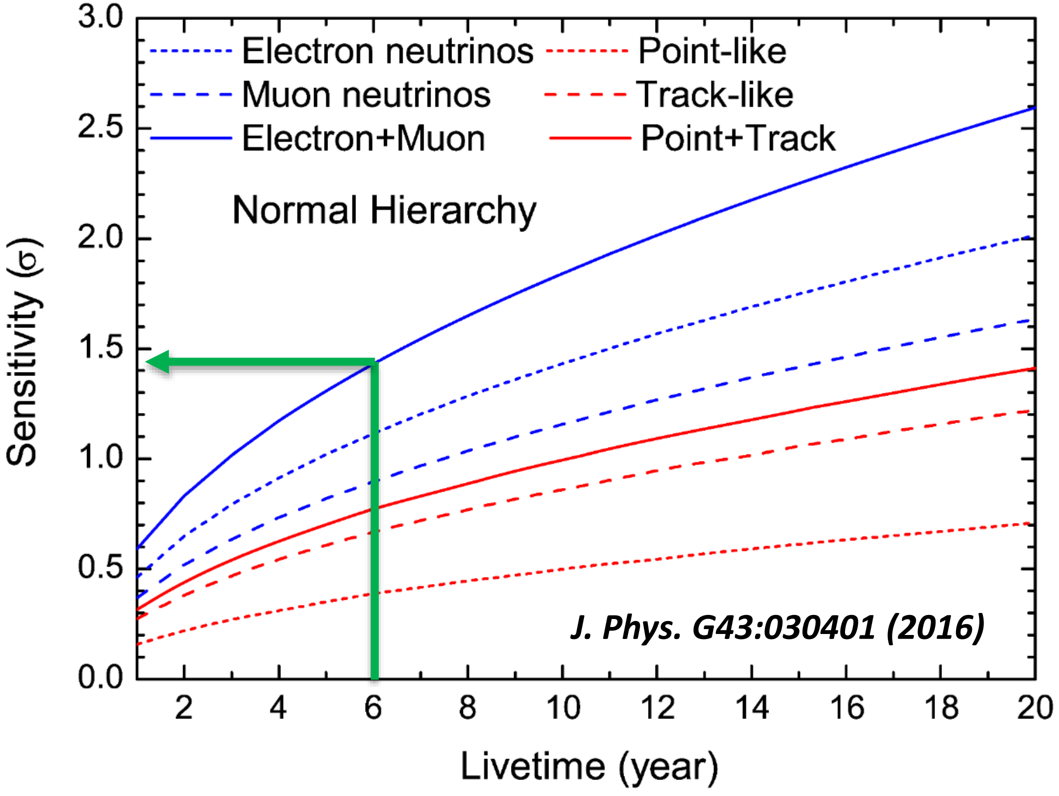
- GENIE, GiBUU, NuWro, etc

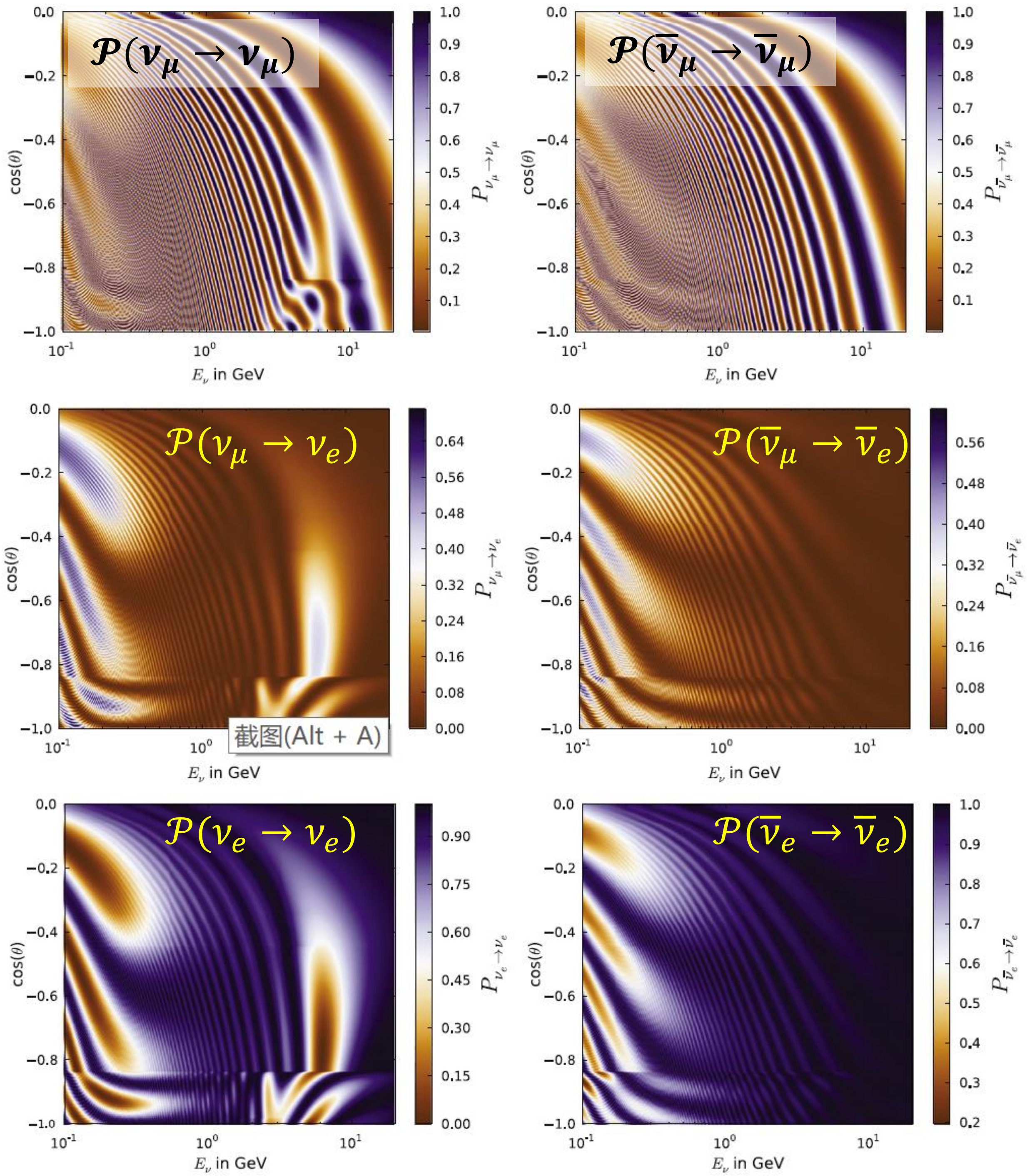
On-going improvement at <100 MeV:

- Propagation of muon inside the earth
- Local info: mountain profile, atmospheric density, geomagnetic field

Atmospheric Neutrinos

MSW effect of atmospheric ν →
synergy on NMO determination with reactor ν



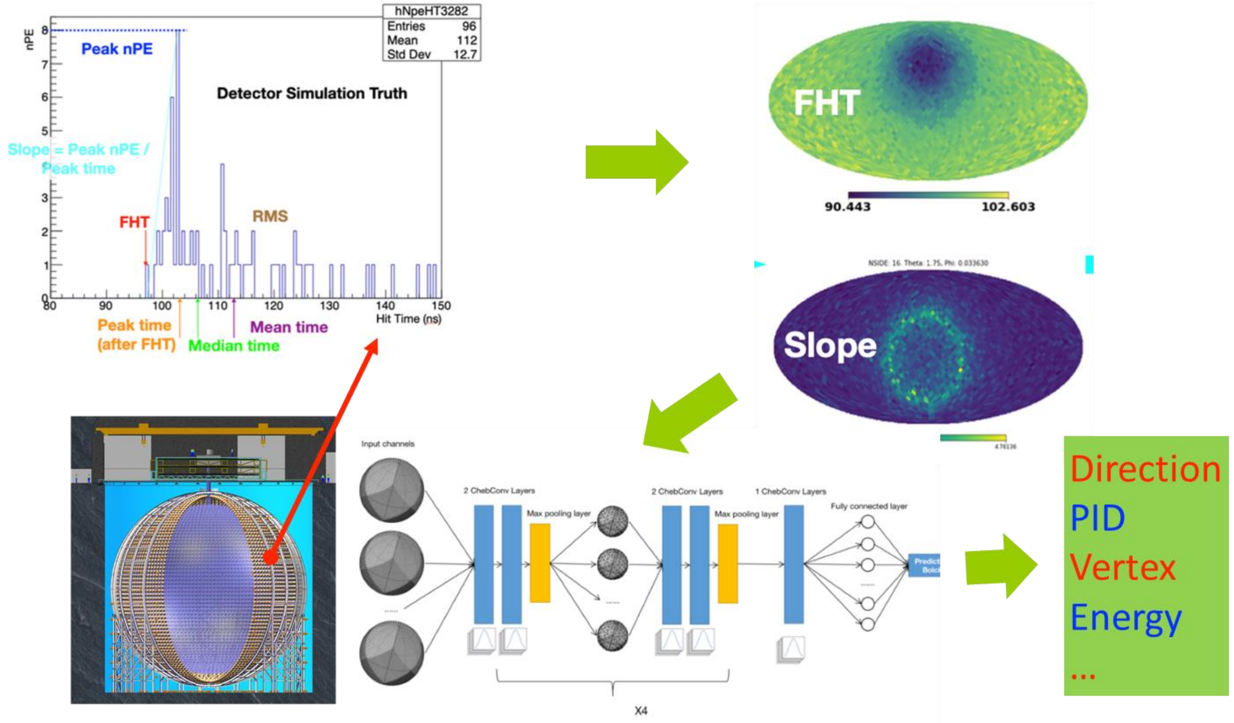


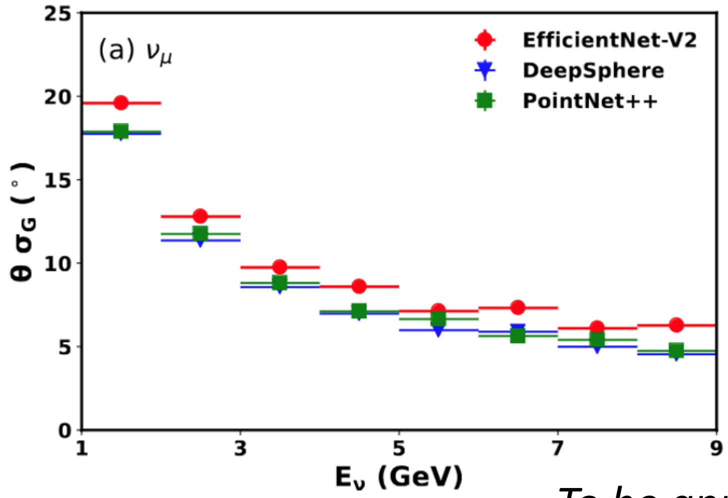
Conservative 6 yrs sensitivity on NMO:

0.8~1.4 σ (atmospheric only)

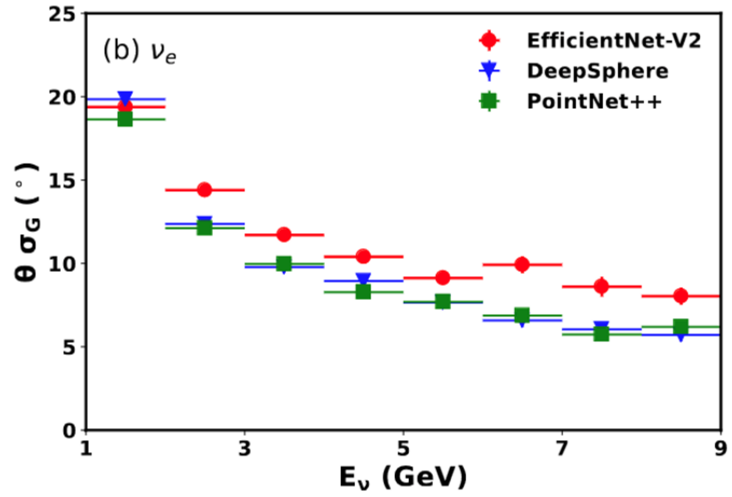
Atmospheric Neutrinos

- **Very promising reconstruction technique (ML based) under development to extract directionality, energy, flavor identification of atmospheric ν's**



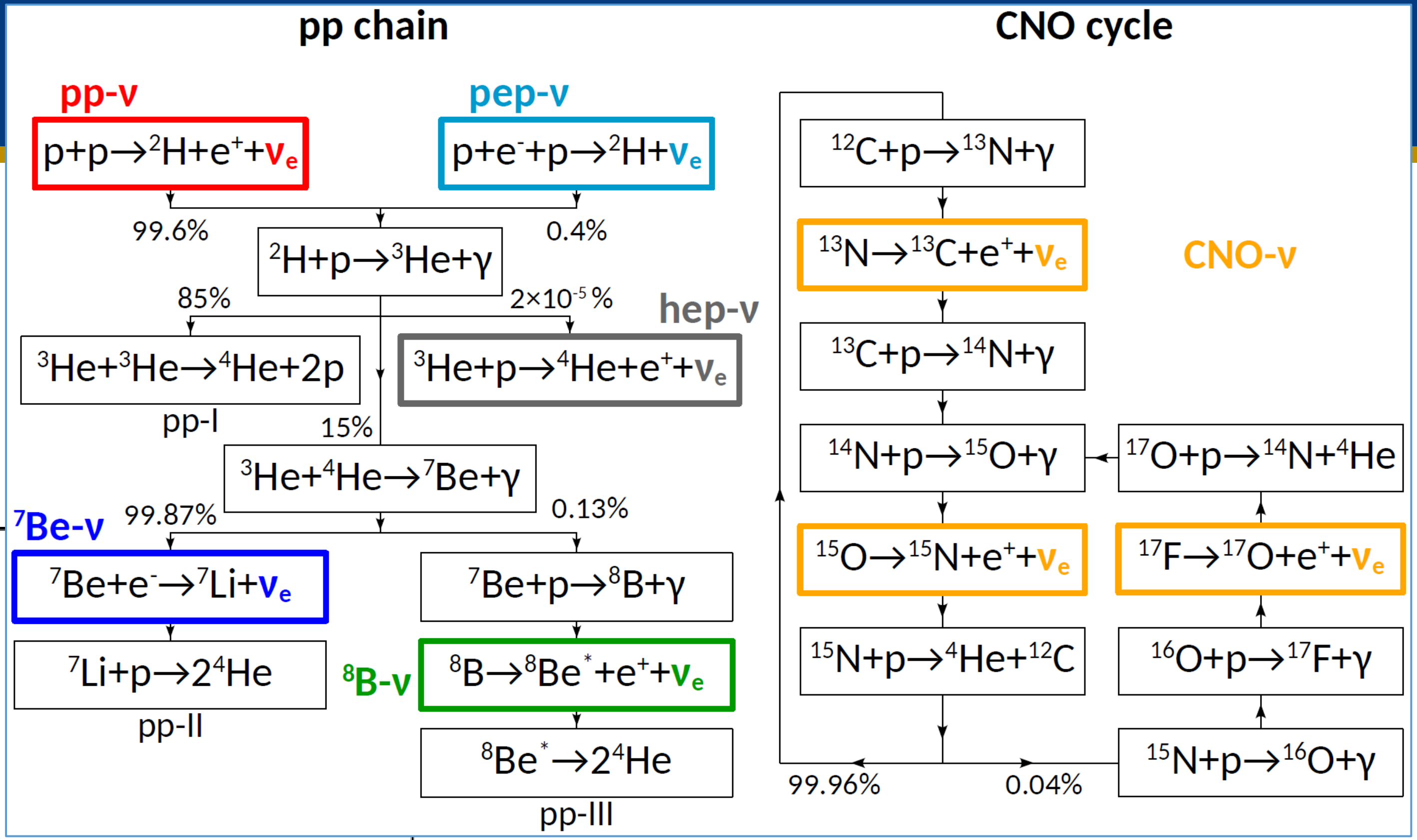


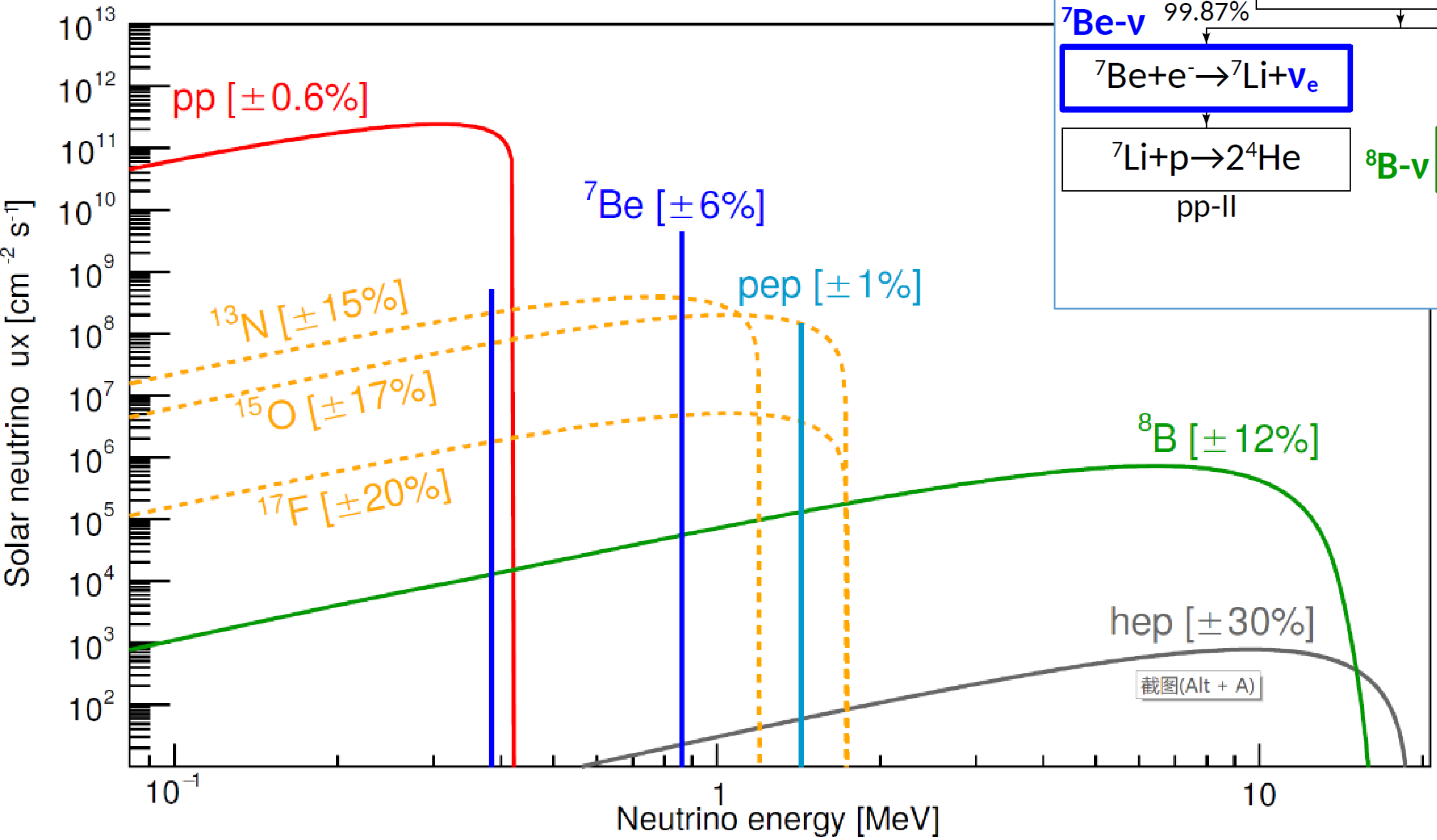
To be appeared



➔ Significant enhancement on NMO sensitivity from atm-ν, stay tuned

Solar neutrinos



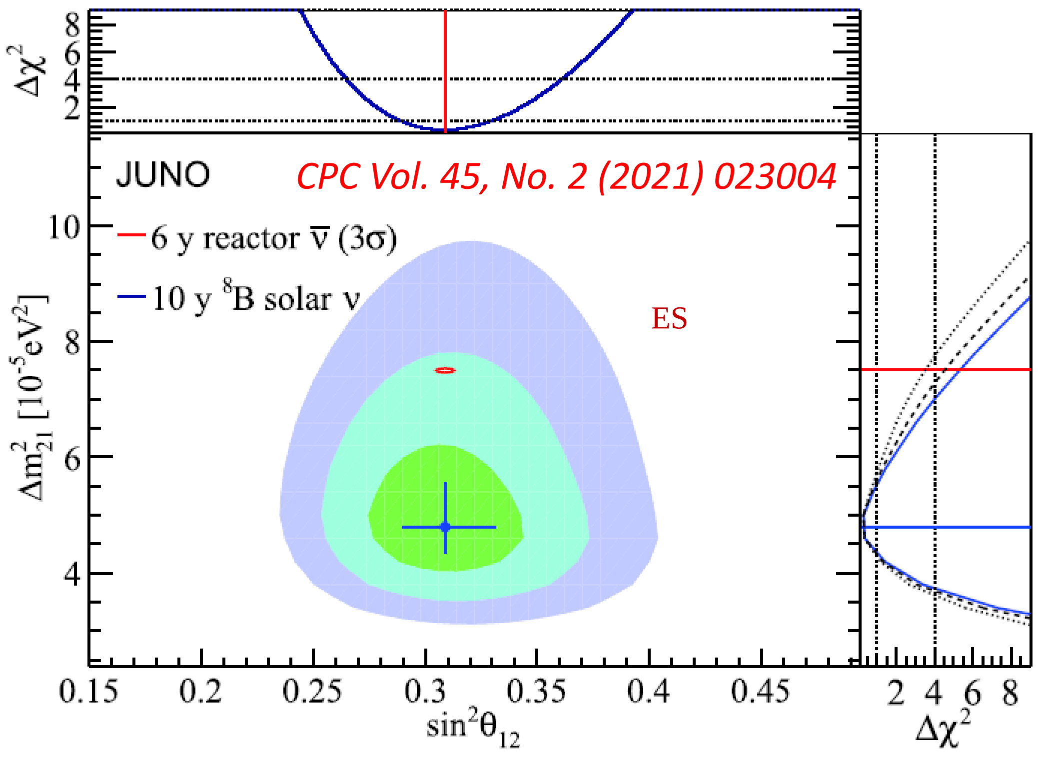


Refs：2111.07586,
https://www.iupapneutrinopanel.org/

Solar neutrinos (^8B)

Low visible energy threshold: E_{th} ~ 2 MeV
Day-Night-Asy precision: 0.9% in 10 yr

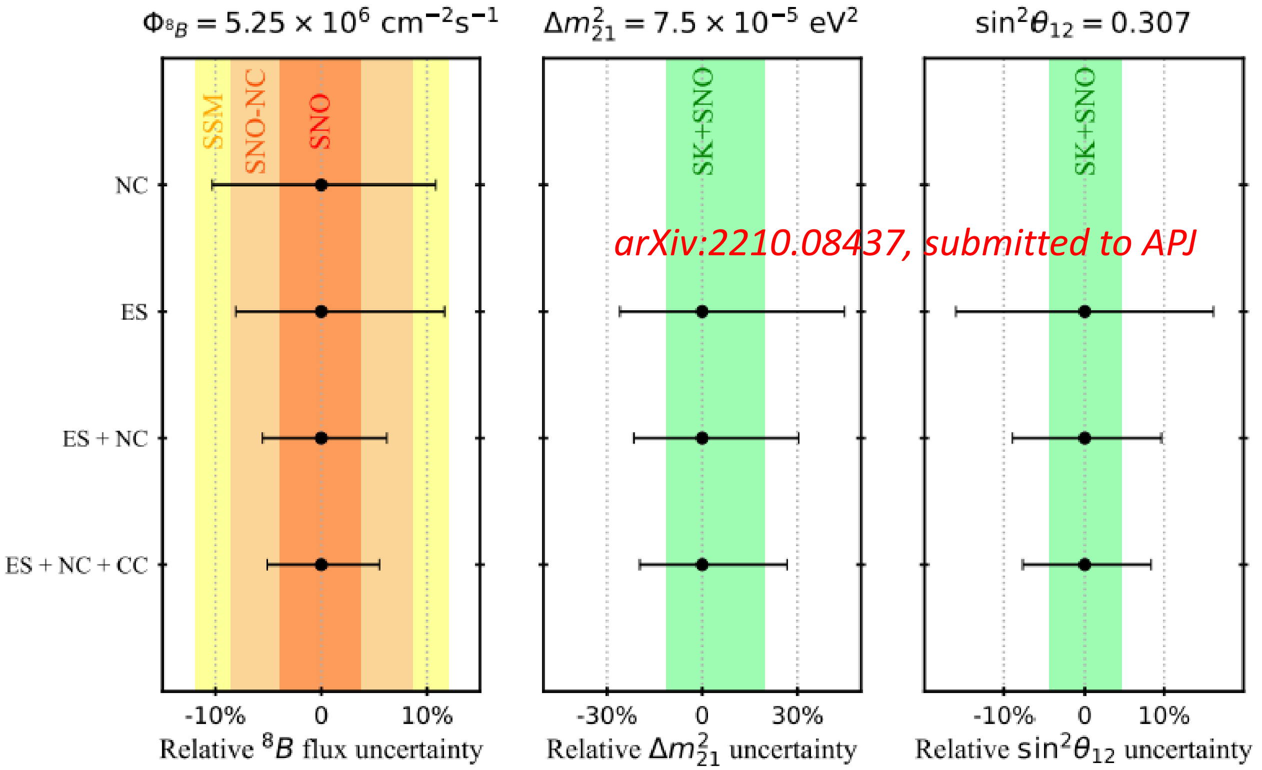
Solar & reactor measurement in Δm^2_{21} with one single detector



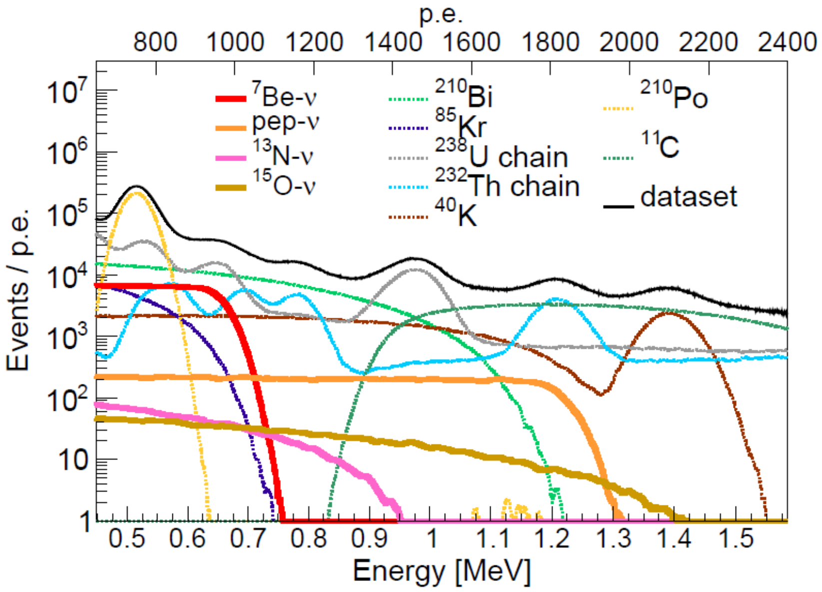
Model independent measurement of ^8B-ν flux (~5%) and oscillation parameters

Correlated: CC
Single: NC, ES

	Channels	Threshold [MeV]	Signal
CC	$\nu_e + ^{13}C \to e^- + ^{13}N\,(\frac{1}{2}^-; \text{gnd})$	2.2 MeV	$e^- + ^{13}N$ decay
NC	$\nu_x + ^{13}C \to \nu_x + ^{13}C\,(\frac{3}{2}^-; 3.685\,\text{MeV})$	3.685 MeV	γ
ES	$\nu_x + e \to \nu_x + e$	0	e^-

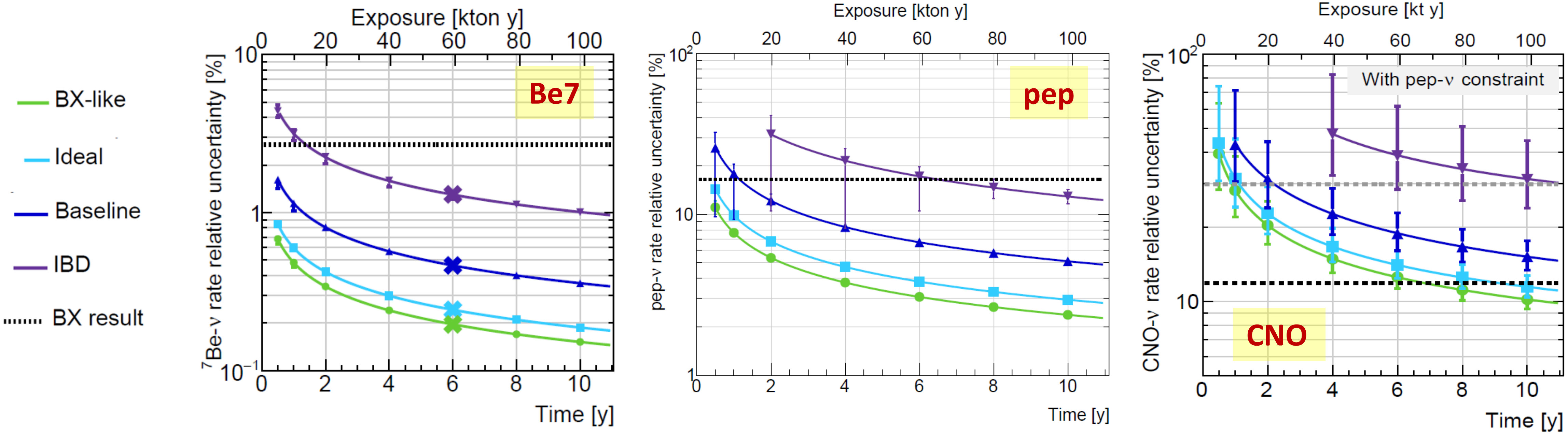


Solar neutrinos (^{7}Be, pep and CNO)



- In Intermediate-E region, sensitivity to **Be7, pep and CNO** depends on LS radio-purity
- Compared to the current best measurement: the projected uncertainty on ^{7}Be, pep neutrinos will significantly improve

arxiv:2303.03910, submitted to JCAP



Diffused Supernova Neutrino Background (DSNB)

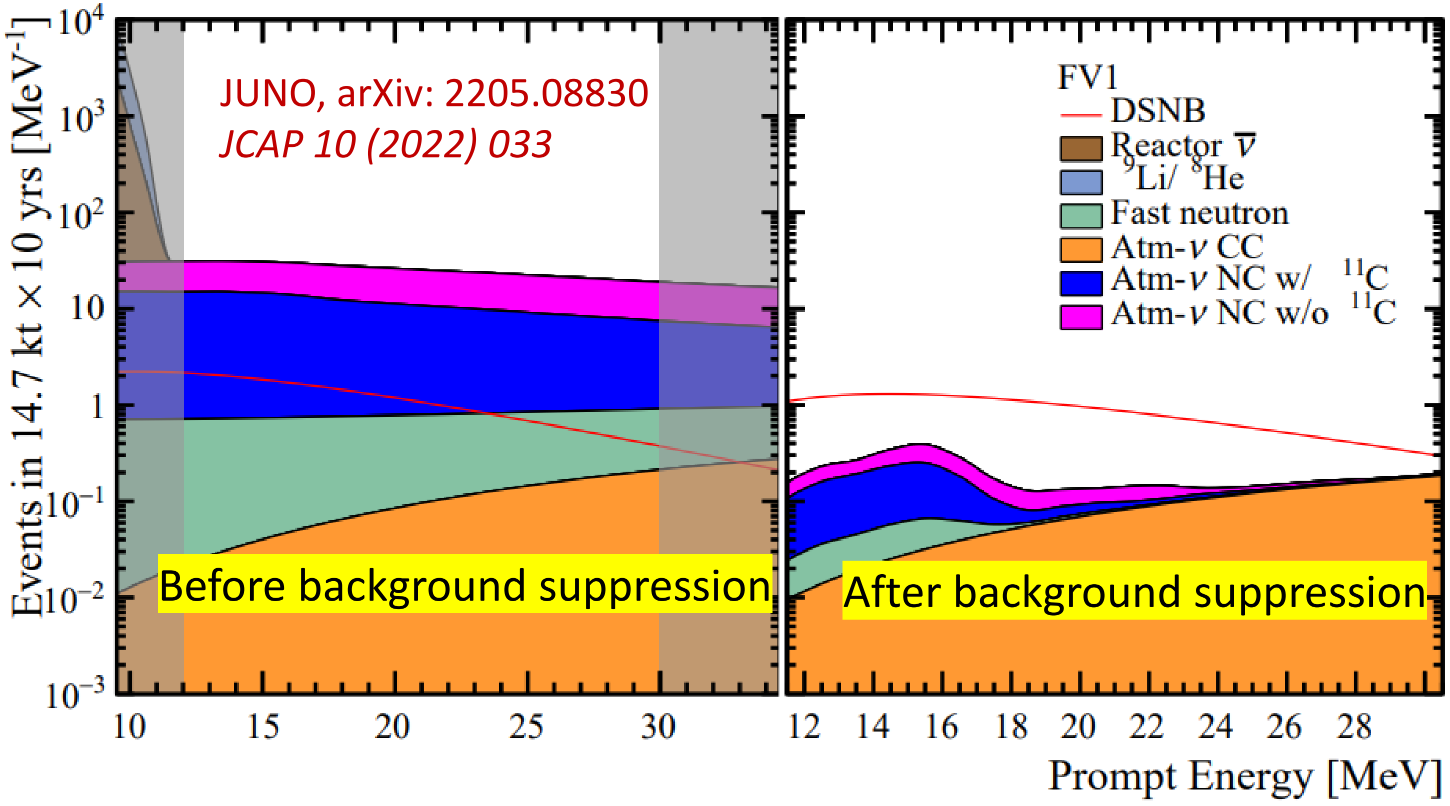
- **DSNB: 2-4 events in JUNO per year**
  - ✓ **Not detected yet**

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)



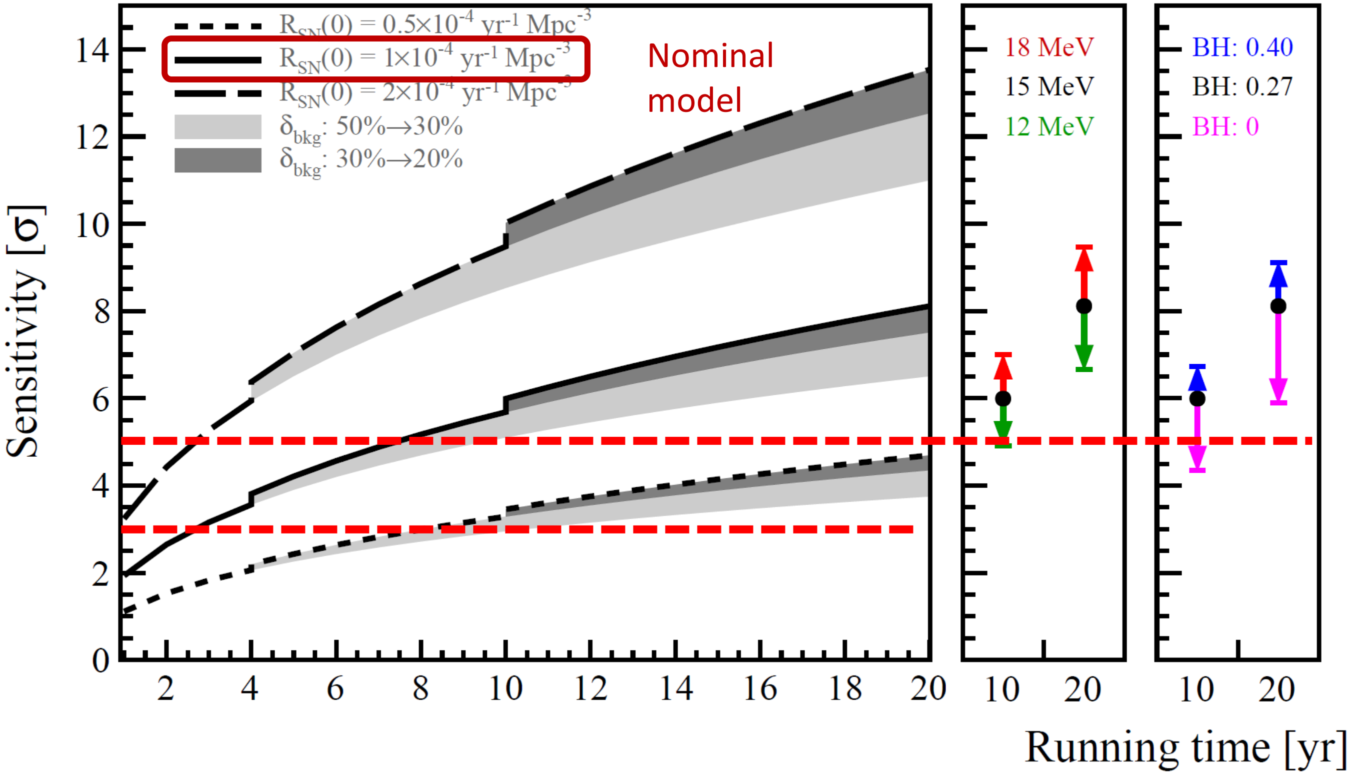
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)* :

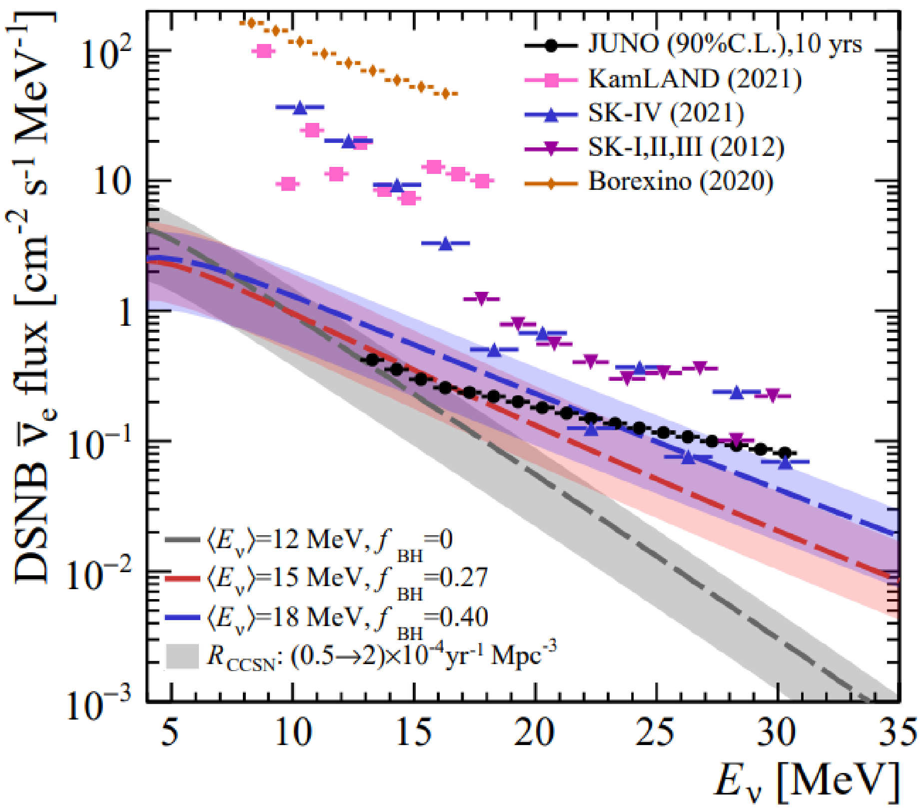
- ✓ **Background evaluation:** 0.7 per year → **0.54** per year
- ✓ **PSD:** signal efficiency 50% → **80%** (1% residual background)
- ✓ **Realistic DSNB signal model: non-zero fraction of failed Supernova**

→ S/B improved from **2 to 3.5**

Diffused Supernova Neutrino Background (DSNB)

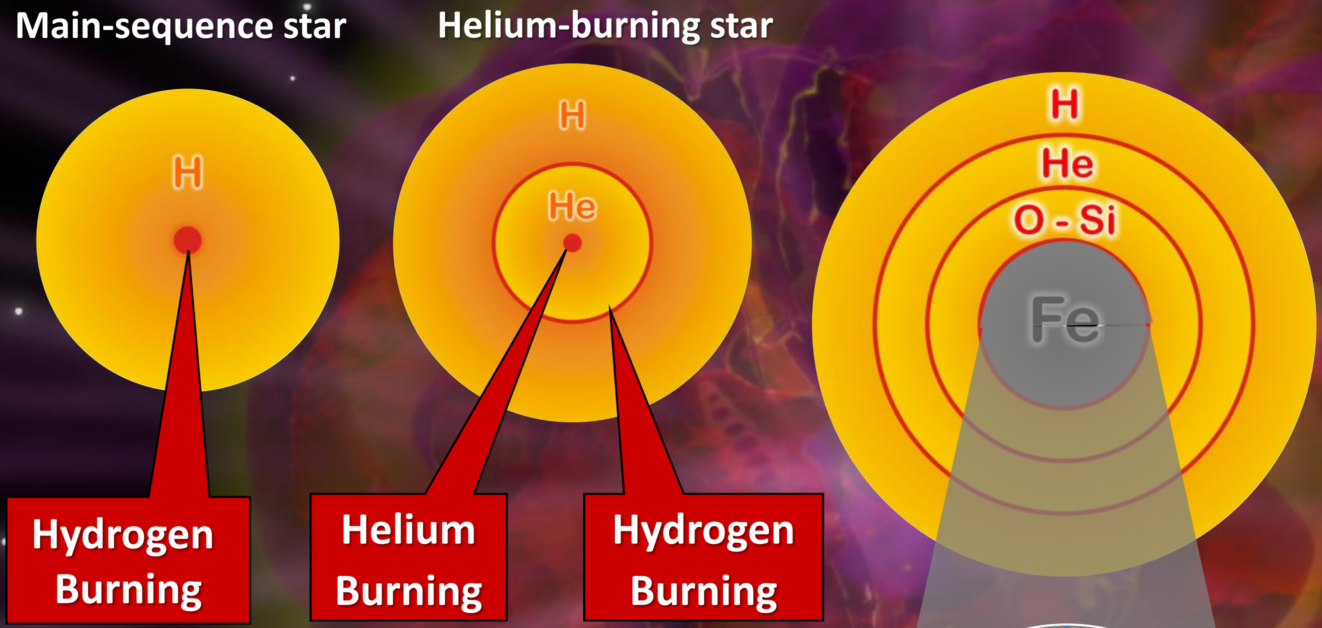
arXiv: 2205.08830, JCAP 10 (2022) 033





- **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)**

Core-Collapse Supernova Neutrinos



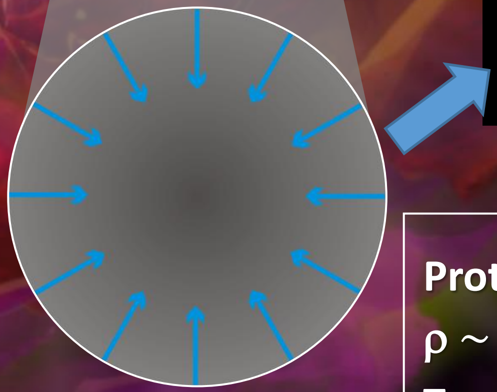
© Raffelt

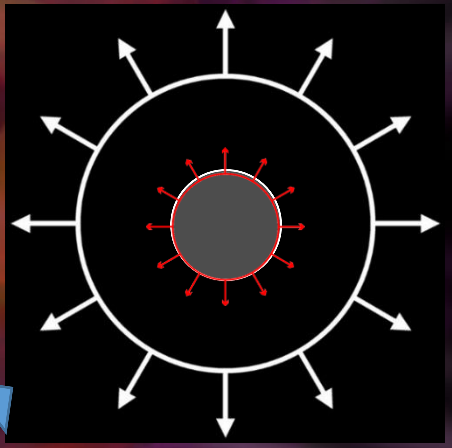
Grav. binding energy $E_b \approx 3 \times 10^{53}$ erg

99% Neutrinos

1% Kinetic energy of explosion
(1% of this into cosmic rays)

0.01% Photons, outshine host galaxy





1. > 8 Solar Masses
2. Collapse→Bounce
3. Shock wave halted
4. ν energy deposited
5. Final SN explosion

Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Proto-Neutron star:

$\rho \sim \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

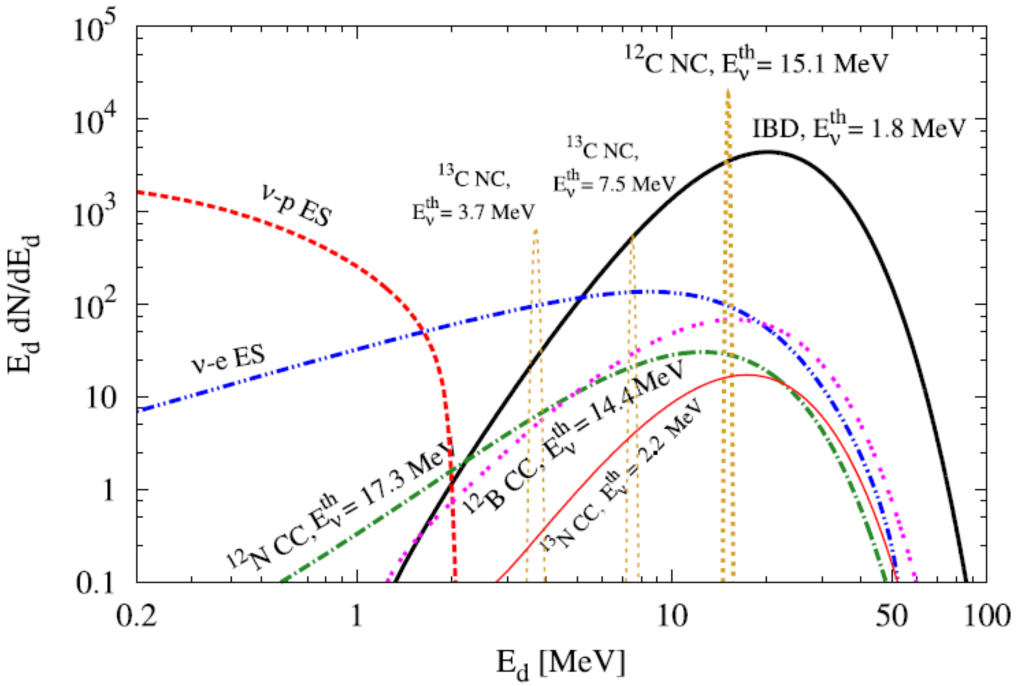
$T \sim 30$ MeV

Figure courtesy: Kei Kotake

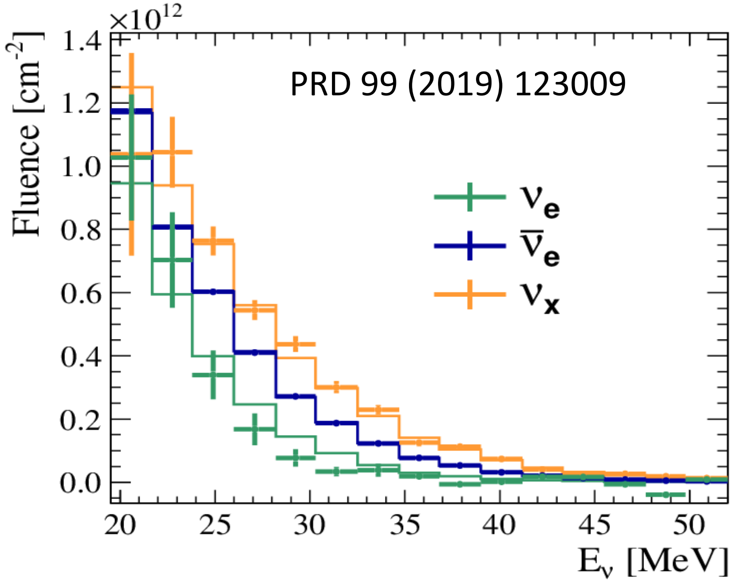
Core-collapse Supernova Neutrinos (CCSN)

Multi-channel detection, all flavors of CCSN:

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

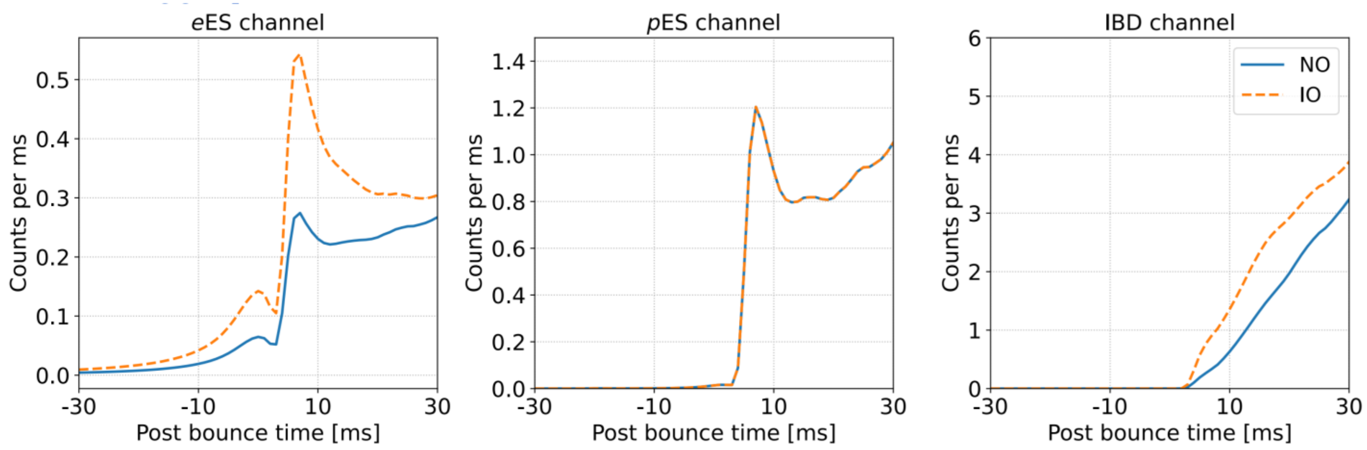


Allow model-independent reconstruction of the energy spectra of $\bar{\nu}_e, \nu_e, \nu_x$ via unfolding approach ➔



Potential on NMO

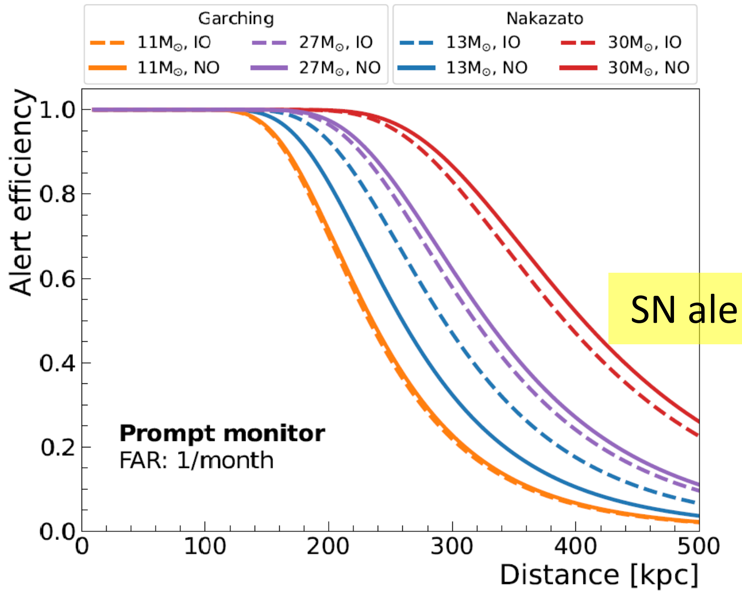
- pES channel is not sensitive to NMO, but it is helpful to “fix” the correct bounce time.
- Important effects: Model dependency and Threshold
- 10 kpc, 0.1 MeV baseline sensitivity: ~2σ (IO & NO)



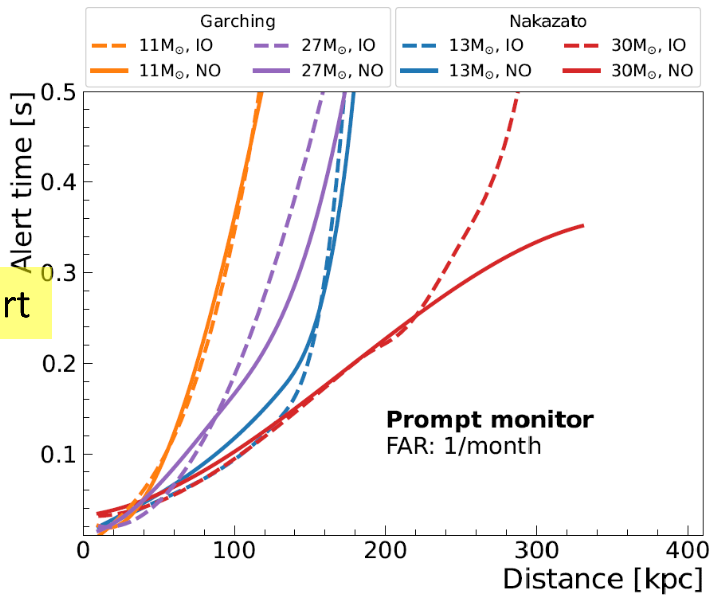
Garching group, 1D simulation, LS220 EoS , 27 solar mass

Core-collapse Supernova Neutrinos (CCSN)

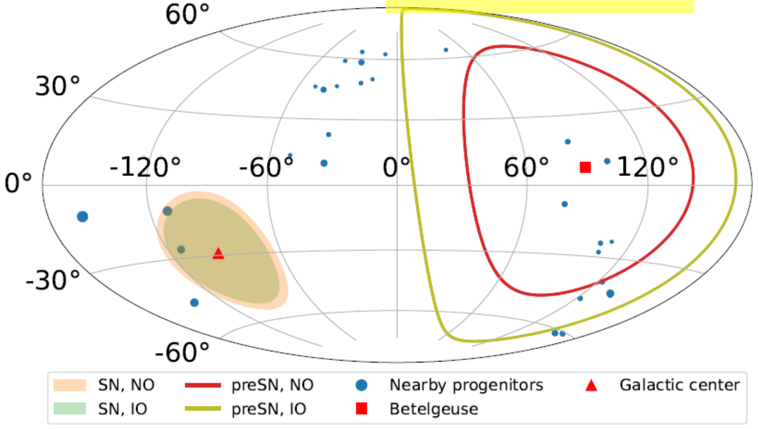
- Excellent capability of early warning
- CCSN
  - reach 240 ~ 400 kpc w/ 50% prob.
  - alert in 10 ~ 30 ms
- pre-SN:
  - reach 0.6 ~ 1.7 kpc w/ 50% prob.
  - >~ 100 hr in advance if 0.2 kpc

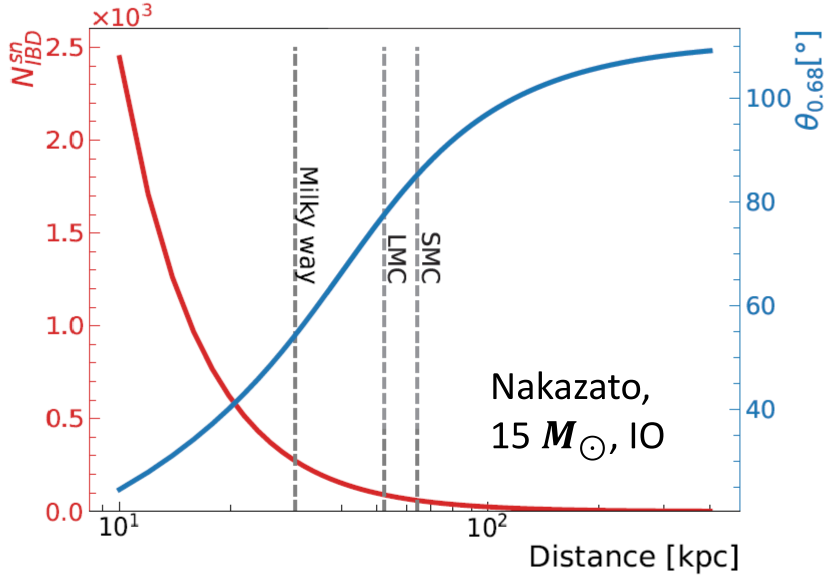


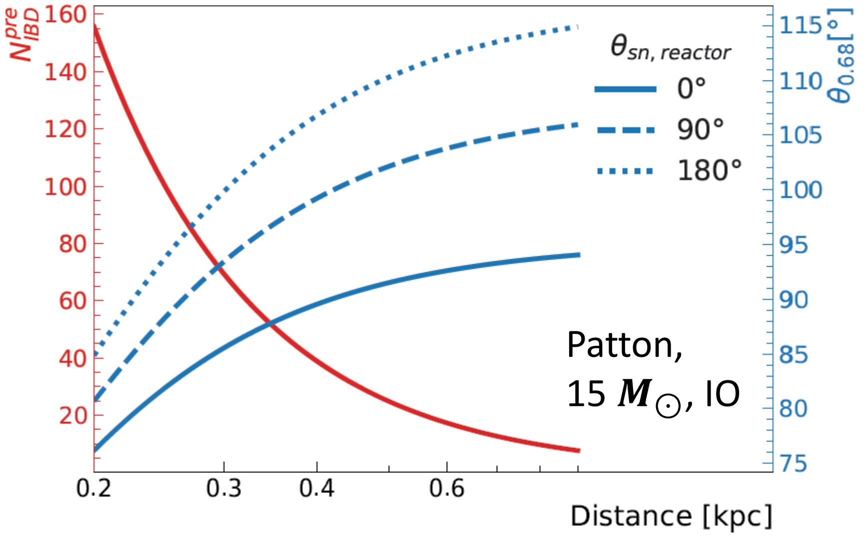
SN alert



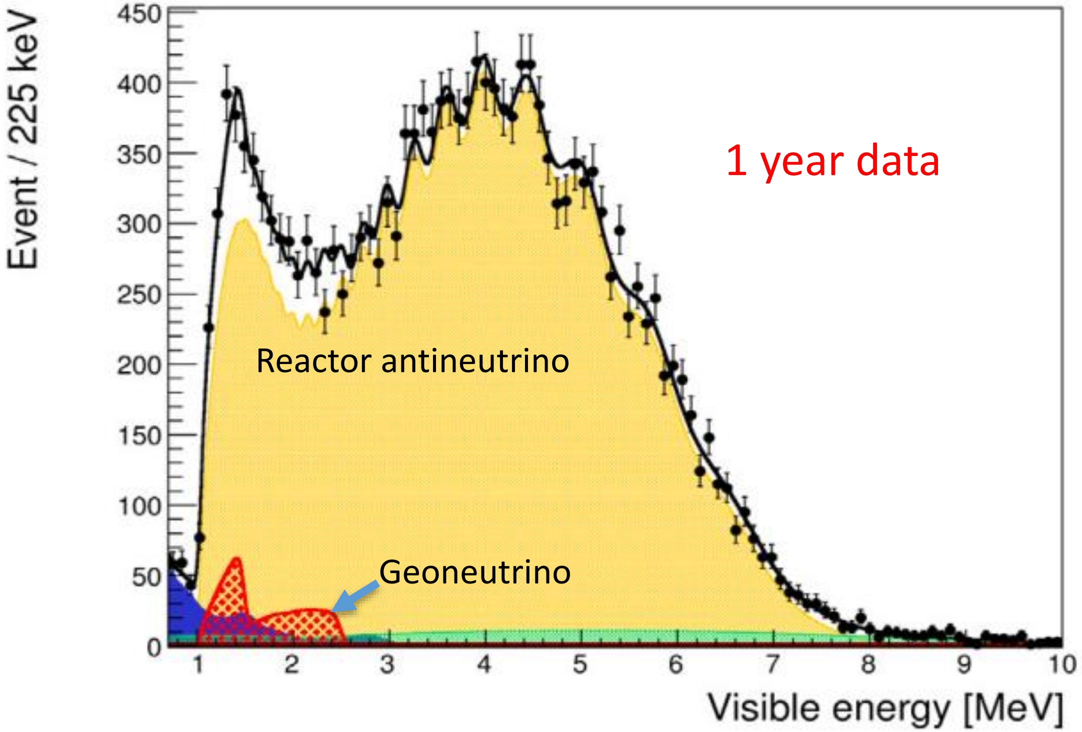
CCSN Pointing

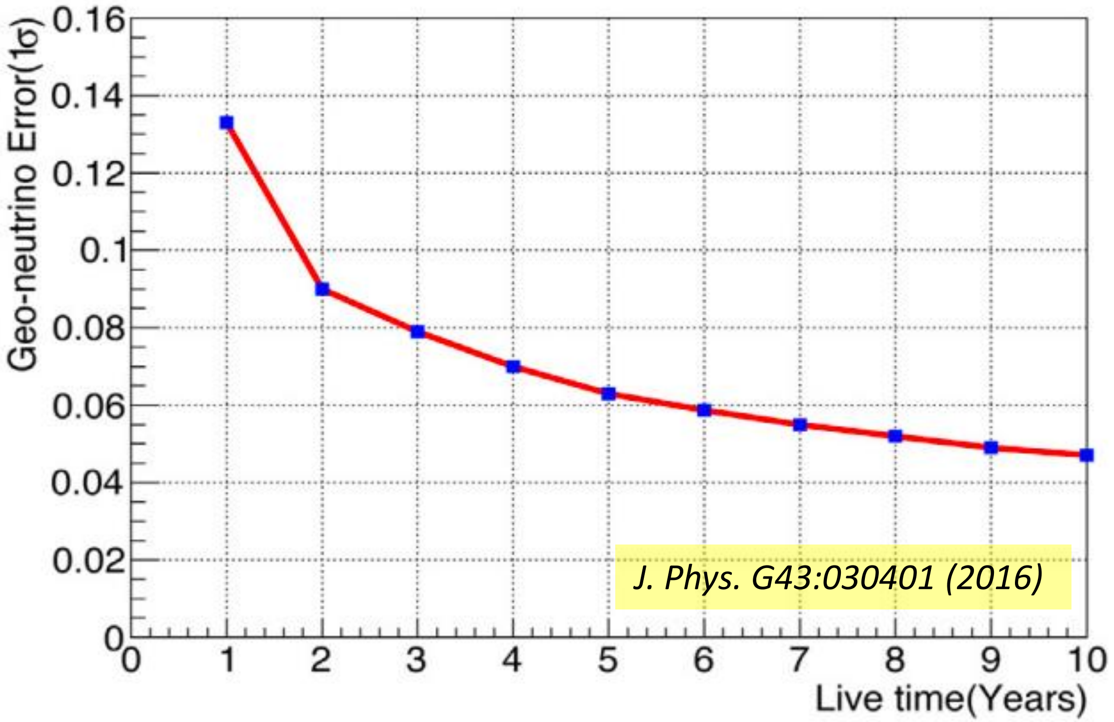






Geo-neutrinos





Signal in JUNO (based on GLOBAL model): **~400 geoneutrinos per year, 5% measurement in 10 years.**

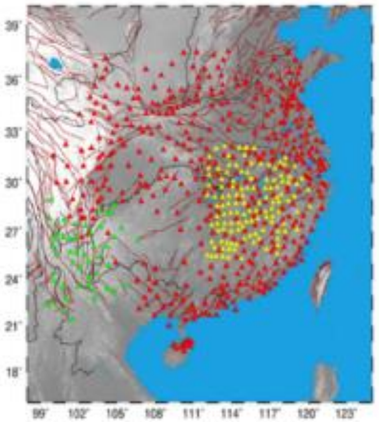
In 1 yr, JUNO can observe as much geo-ν as Borexino and KamLAND for the whole time combined.

With new Local Refined Crust model, the geo-ν signal is ~30% larger, updated sensitivity is on-going.

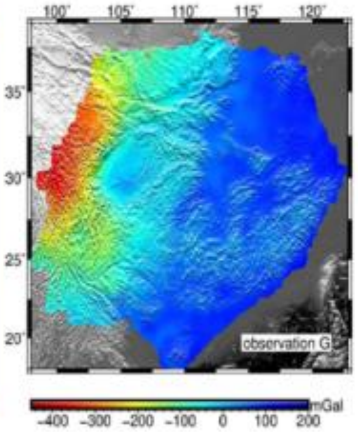
Local Refined Crust model for Geo-ν -- multi-disciplinary

With new Local Refined Crust model, the geo-ν signal is ~30% larger, updated sensitivity is on-going.

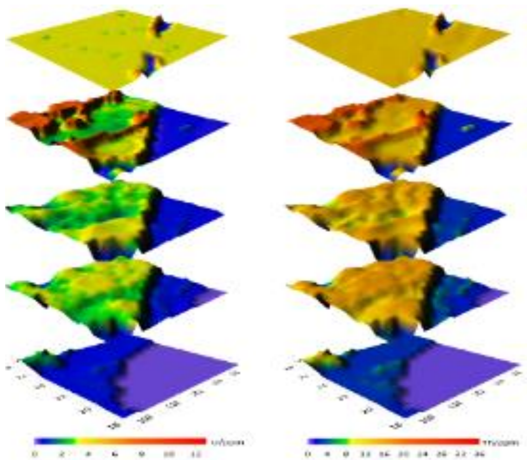
$$S_{EXP} = S_{LOC} + S_{ROL} + S_{Mantle}$$



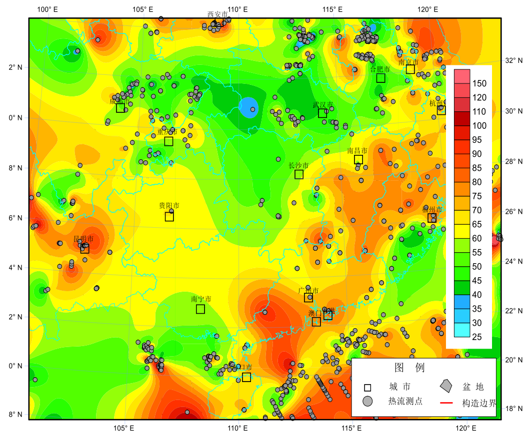
Seismic data &



Gravity data



3-D U/Th abundance distri.

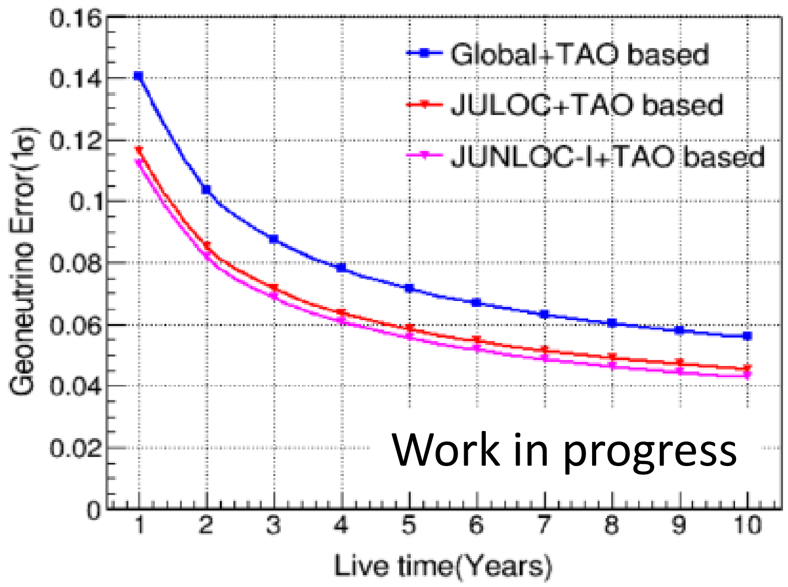


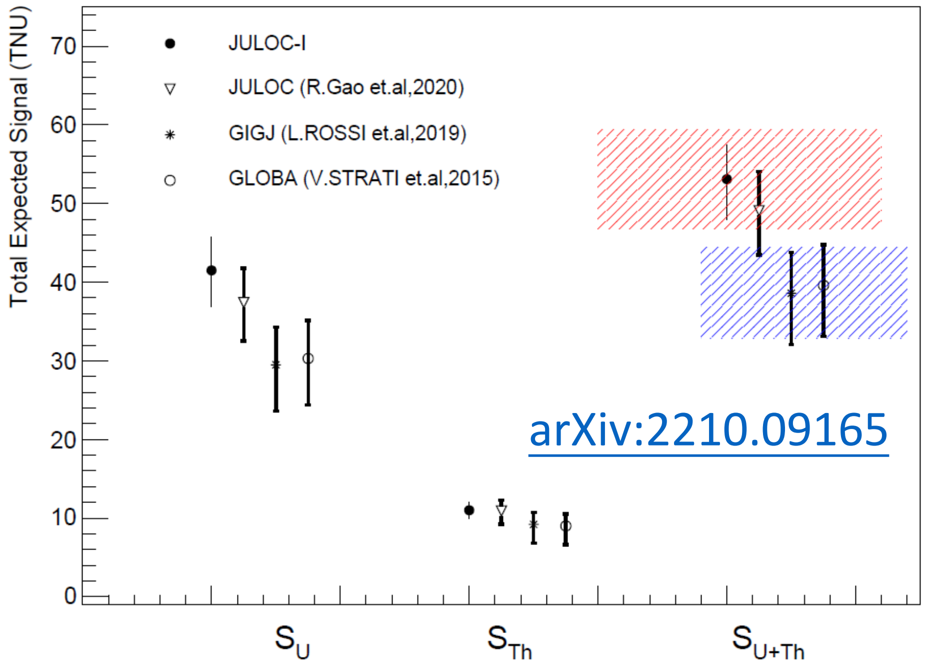
geothermal data

W/ the ewn JUNLOC-I model, precision on crust geo-ν flux：

1 yr： 14% → 11%

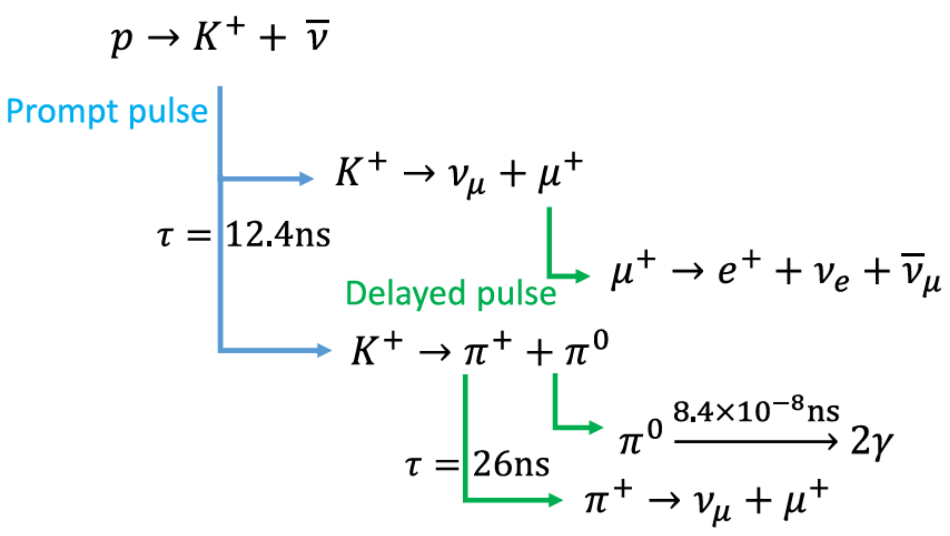
10 yr： 6% → 4%





arXiv:2210.09165

Nucleon Decay



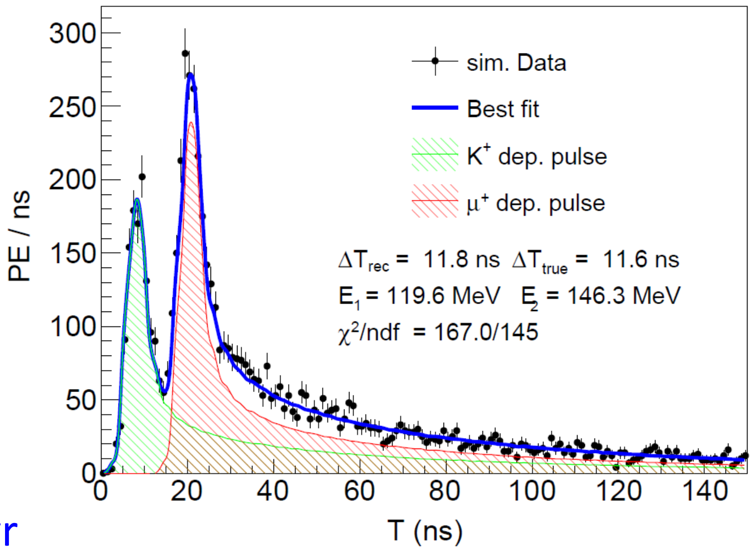
- Signature: three-fold coincidence
- Dominant background: atmospheric neutrino interactions

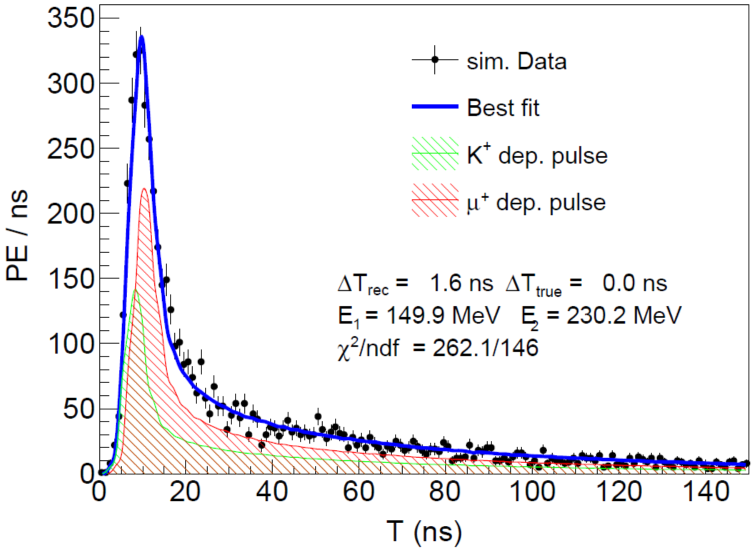
Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \to \nu + n$ $\nu + p \to \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \to n + l^+$ $\nu_l + n \to p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \to l^- + p + \pi^+$ $\nu + p \to \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \to l^- + \Lambda + K^+$ $\nu_l + p \to l^- + p + K^+$	Double Pulse

- Disentangle pile-up of signals with 3-inch PMTs
- Multiplicity, spatial distribution of Michel e- and neutrons in the FSI

- **Expect sensitivity:** 9.6×10^{33} years (90% C.L.) for 200 kton*yrs exposure

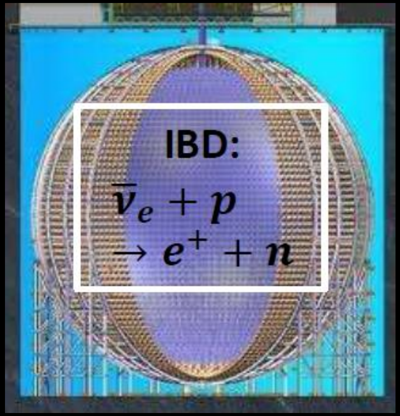
Super-K (2014): >5.9 × 10^{33} yrs @ 260 kton·yr



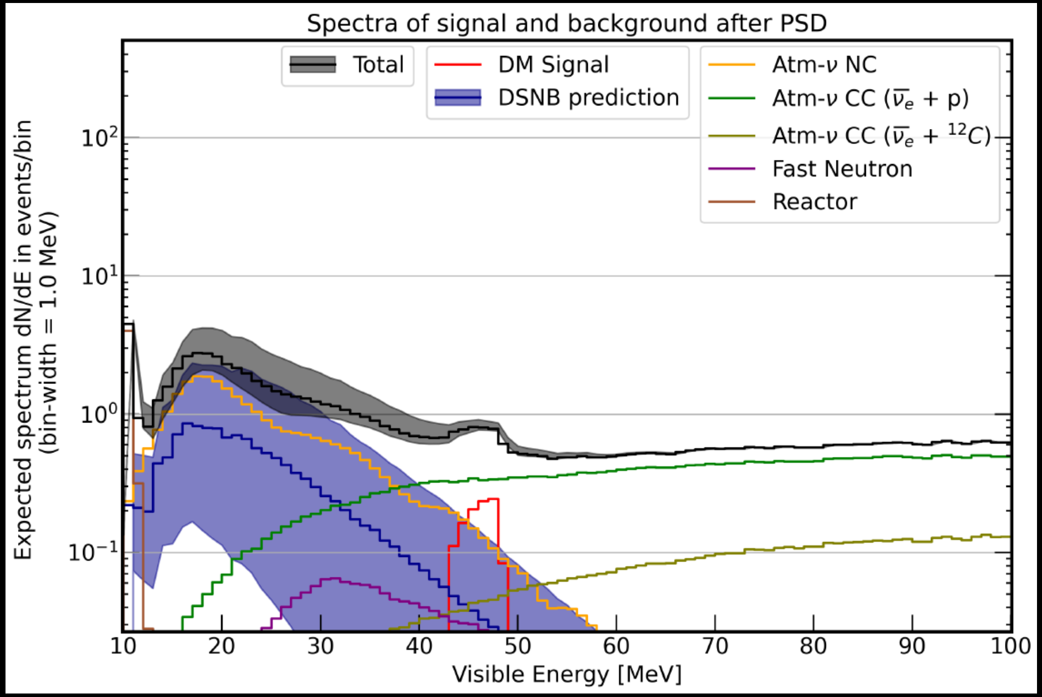


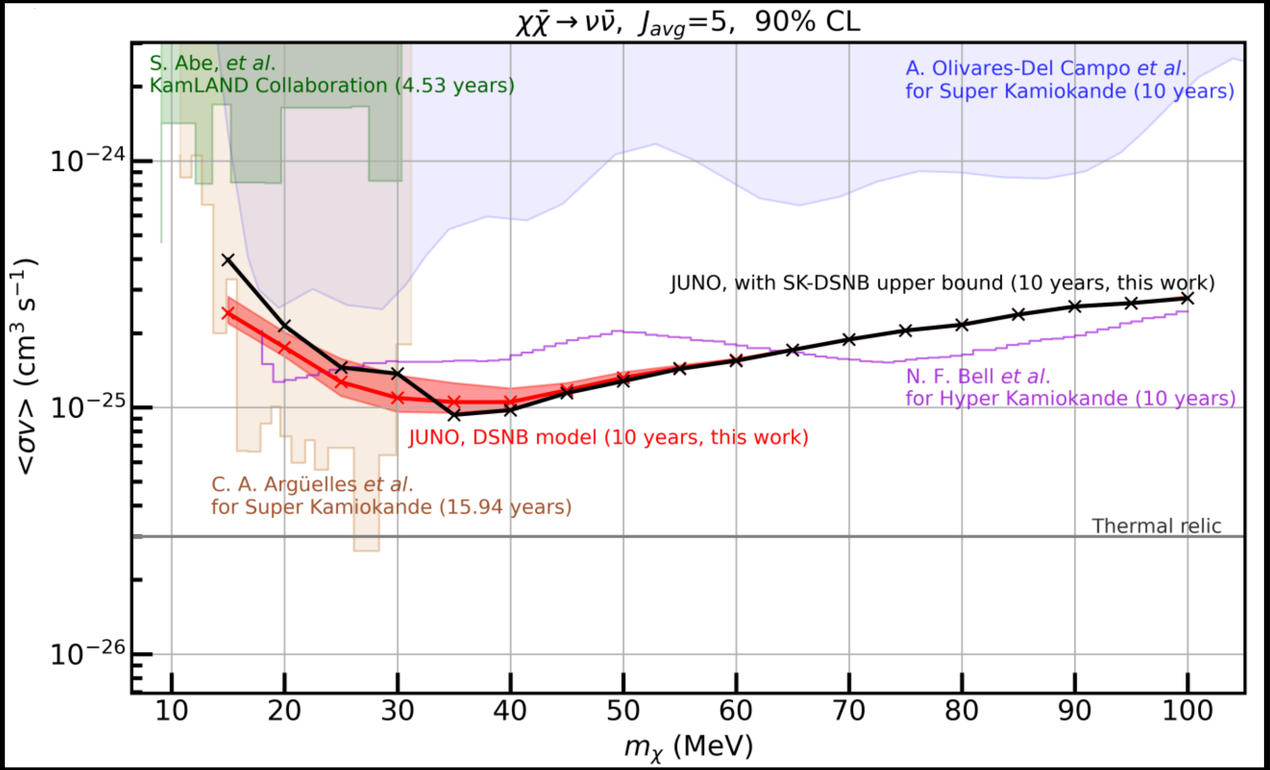
arXiv:2212.08502, submitted to CPC

Indirect Dark Matter Search



- DM annihilation into neutrinos in the Milky Way
- DM masses: 10 - 100 MeV
- Detection channel in JUNO: IBD
- Backgrounds: DSNB, atm-ν NC/CC (dominant), fast neutron, reactor
  - PSD technique to suppress atm-ν NC and fast neutron





arXiv:2306.09567

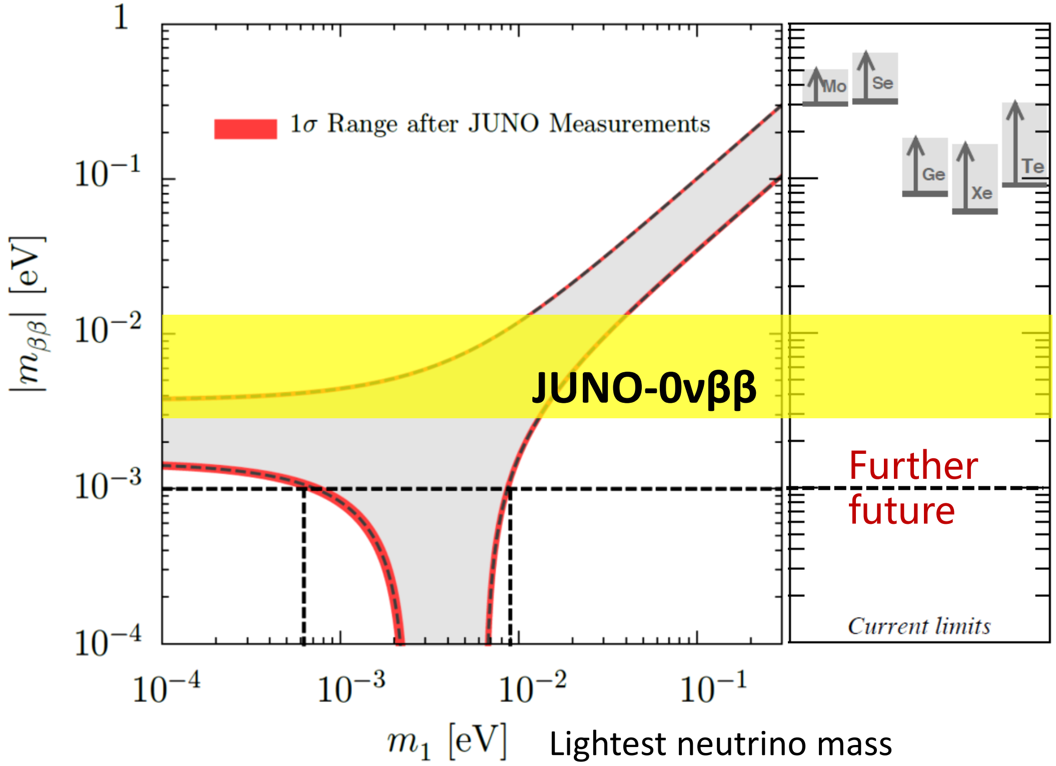
JUNO-0νββ: towards the meV sensitivity

If reaching 1 meV sensitivity of $|m_{\beta\beta}|$

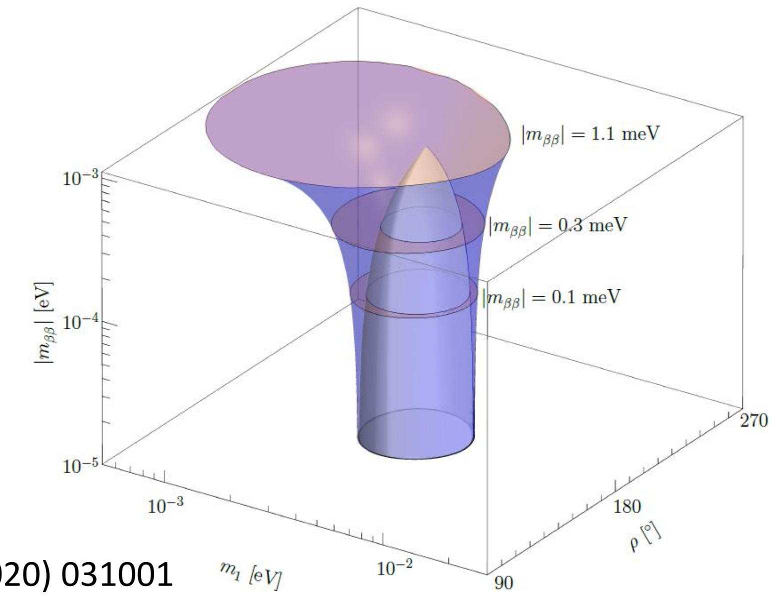
- **Precise determination of the lightest neutrino mass**

$$m_1 \in [0.7, 8]\ \text{meV}$$

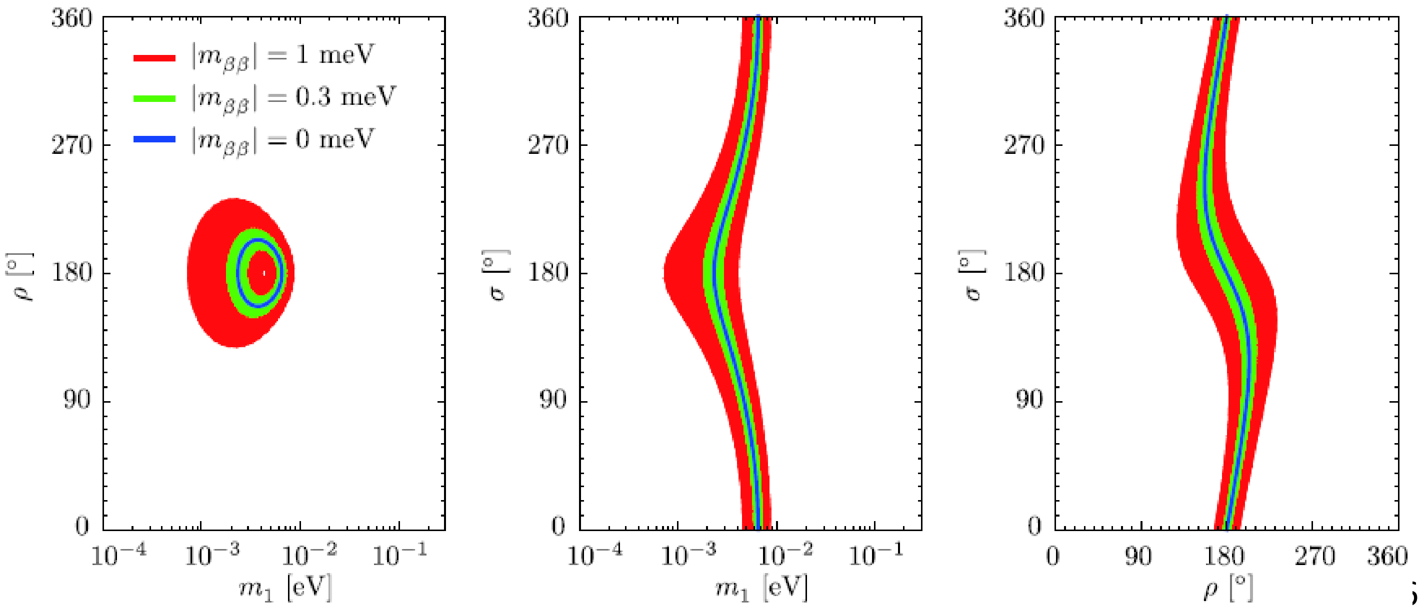
- **Constrain (m_1, ρ, σ) to a very small parameter space**



Lightest neutrino mass



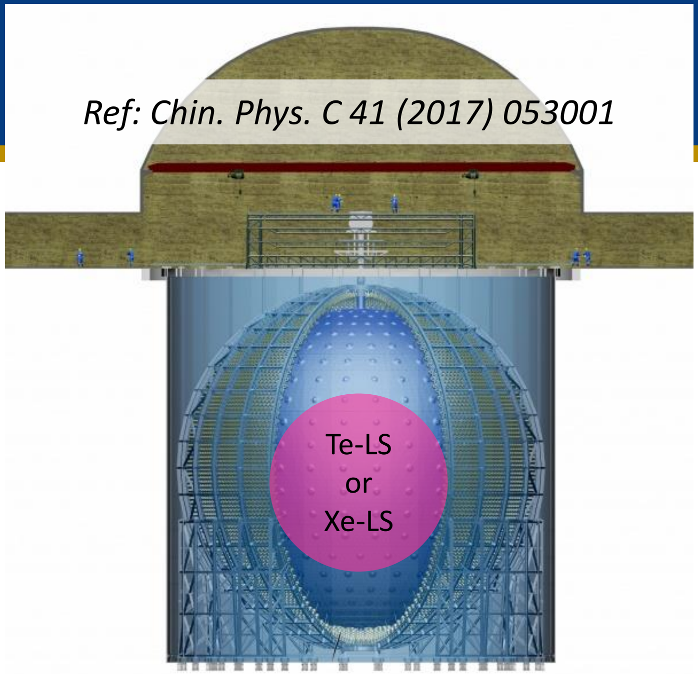
Chin. Phys. C 44 (2020) 031001



JUNO's potential on 0νββ searches

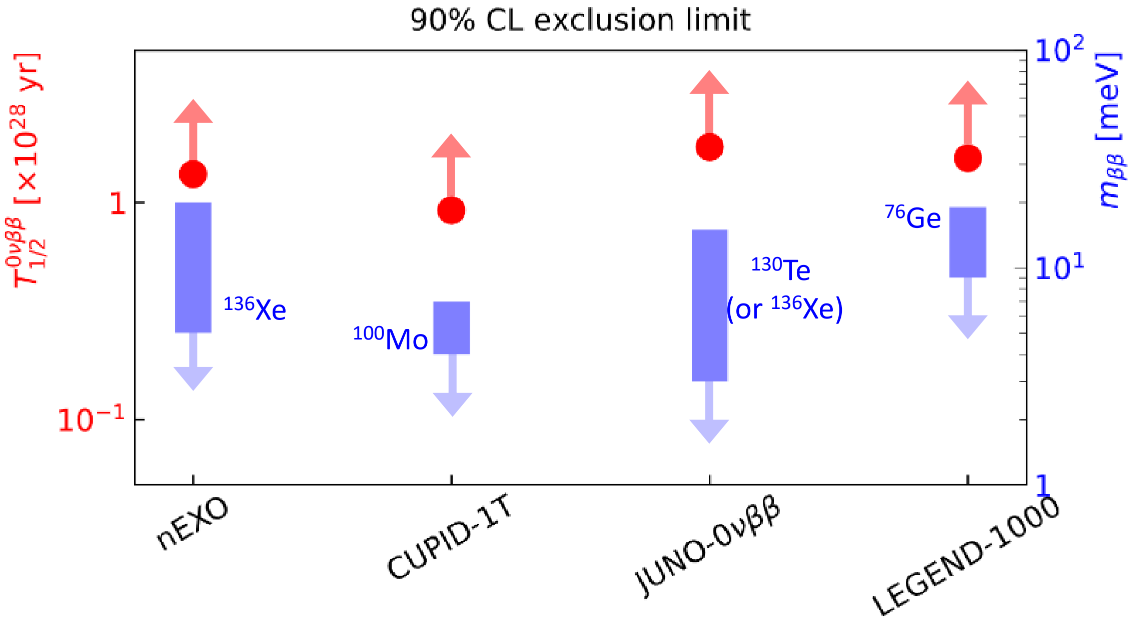
- JUNO offers an unique opportunity to search for 0νββ after completion of mass ordering measurements (~2030)
  - Large target mass: 20 kton LS → **100-ton scale isotope loading** (e.g., Tellurium, no enrichment, cost effective)
  - Low background
  - Energy resolution < 3% @ 1 MeV

  ➔ Potential to explore normal mass ordering parameter space of Majorana neutrino mass.



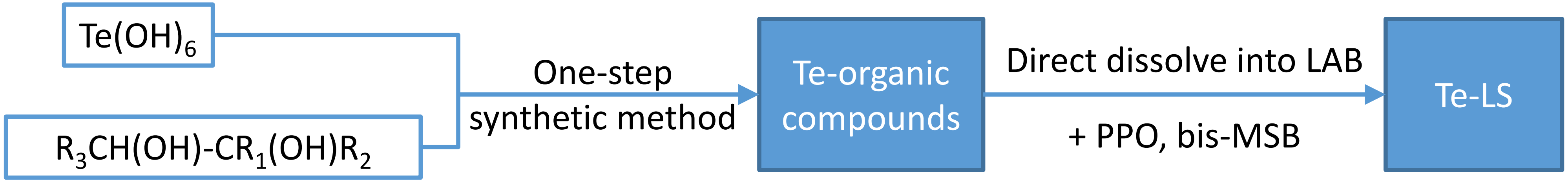
Concept of the experiment

- Critical R&D in progress
  - **Te-loaded LS** (requirements: high light yield, transparency and solubility and stability)
  - **Background rejection** (^{8}B solar neutrinos, Te muon-spallation products)

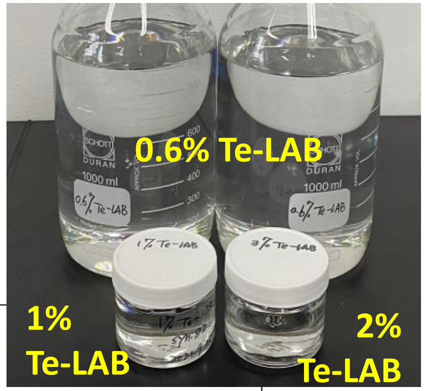


JUNO Recipe of Te-LS

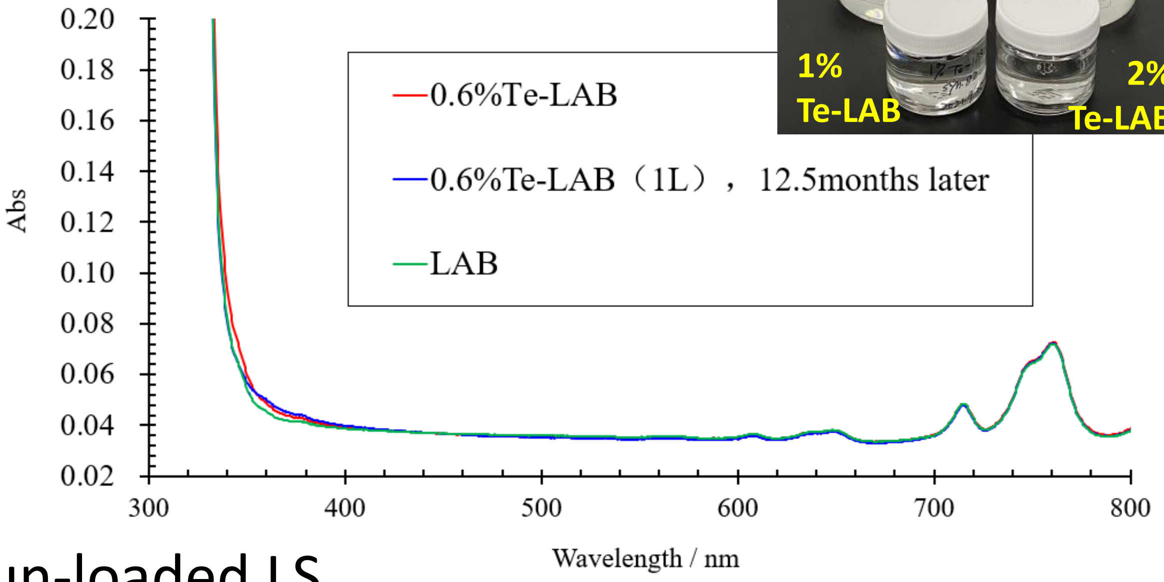
A promising recipe under R&D



- Promising one-step synthetic method, capability of Te loading in LAB: > 3%
  - Good stability, transparency and solubility of Te-compounds
  - Quick, convenient and applicable for most diols



- Current characteristics w/ 0.6% Te-loading
  - Good UV-Vis spectra for Te-LAB
    - NO visible difference (Δ_{ABS}<0.002 for λ>370 nm) compared to the purified LAB (A.L. > 20m)
    - NO degradation after 6 months
  - Light yield to-be-improved: 60%~70% w.r.t un-loaded LS



Summary

- JUNO detector construction/installation in full speed
- Expect JUNO data in 2024, exciting moment!
- JUNO has good physics potential on various topics. Close collaboration between theorists and experimentalists will further advance JUNO

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 Neutrino	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

Thanks!