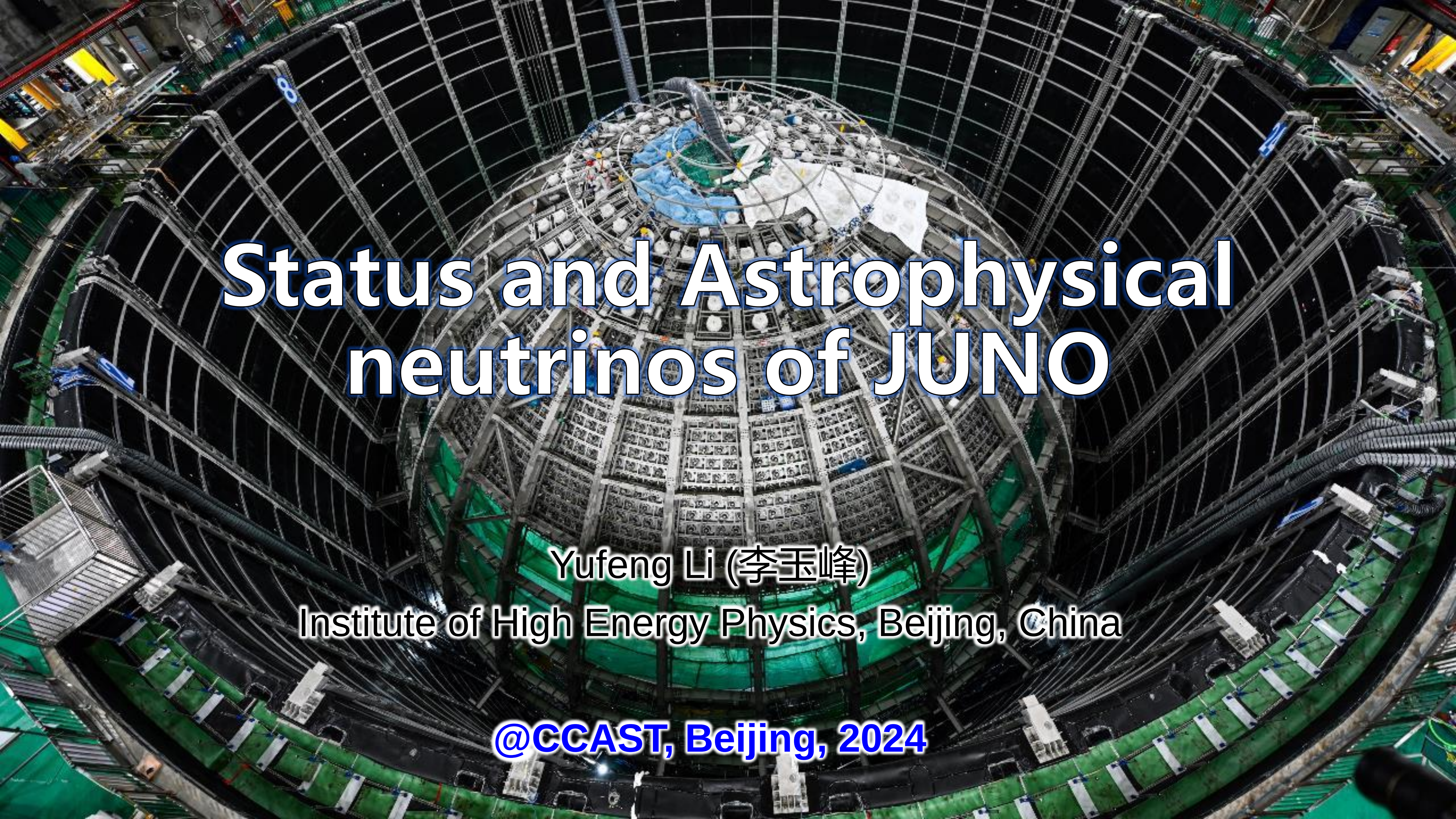

Status and Astrophysical neutrinos of JUNO

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@CCAST, Beijing, 2024

Jiangmen Underground Neutrino Observatory

Jiangmen Underground Neutrino Observatory (JUNO)

Approved in Feb. 2013. Ground-breaking in 2015. Construction to be completed in 2023.

A multiple-purpose neutrino experiment with rich physics programs:

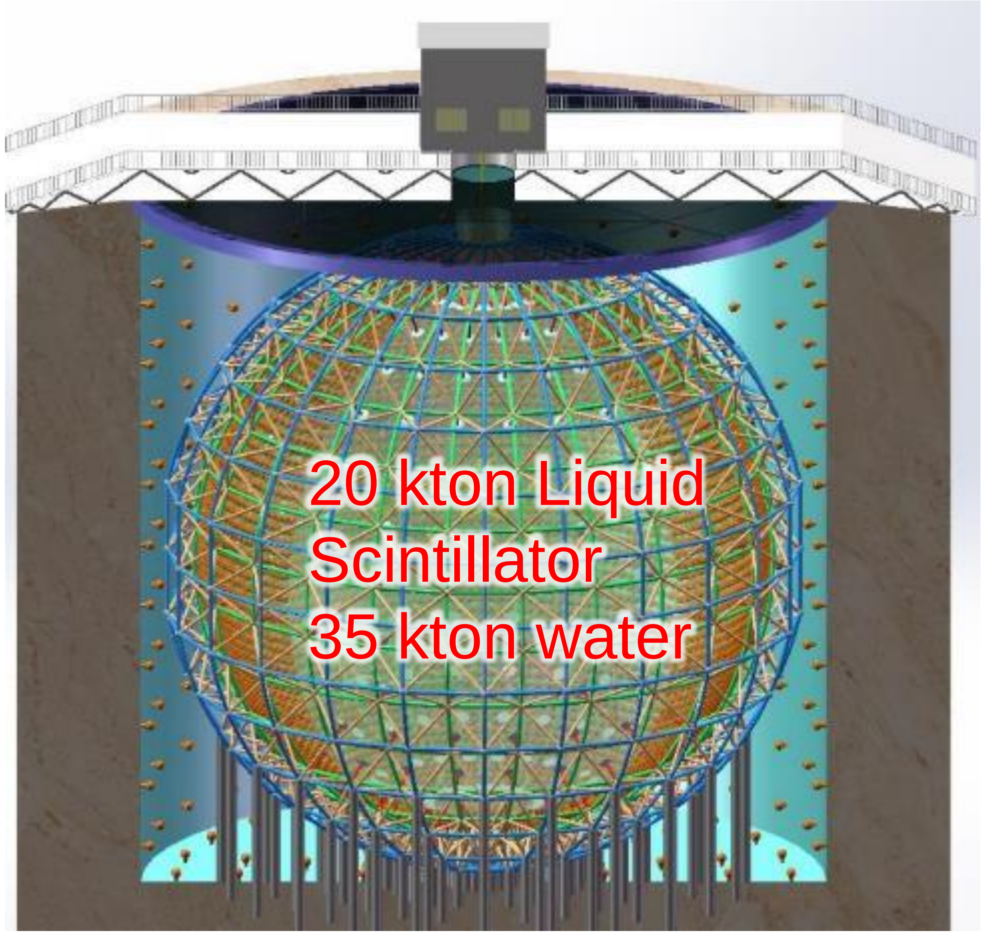
- **Reactor ν:** Oscillation, spectrum
- **Atmospheric ν**
- **Solar ν**
- **CCSN**
- **DSNB** (aka supernova relic ν)
- **Dark matter**
- **geo-νs**
- **Nucleon decay**
- **0νββ potential**

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

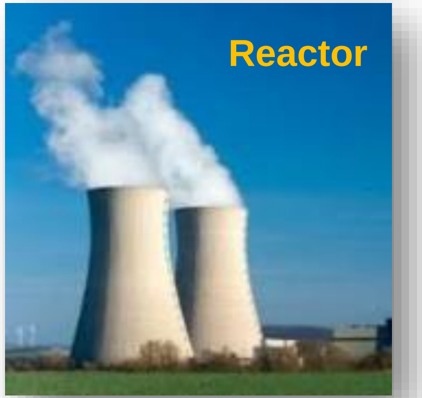
JUNO Physics and Detector, arXiv:2104.02565



Jiangmen Underground Neutrino Observatory

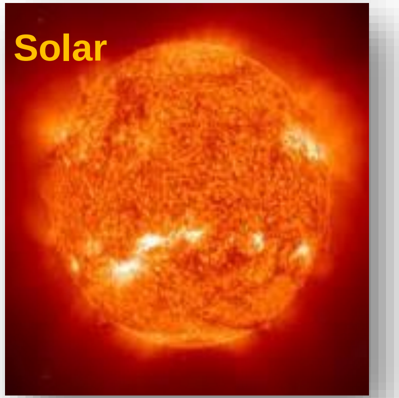
A multi-purpose observatory

Mass Ordering



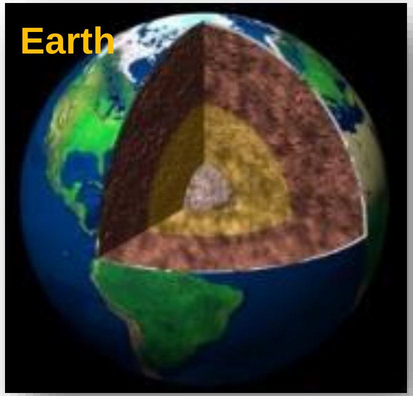
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

\+ New physics

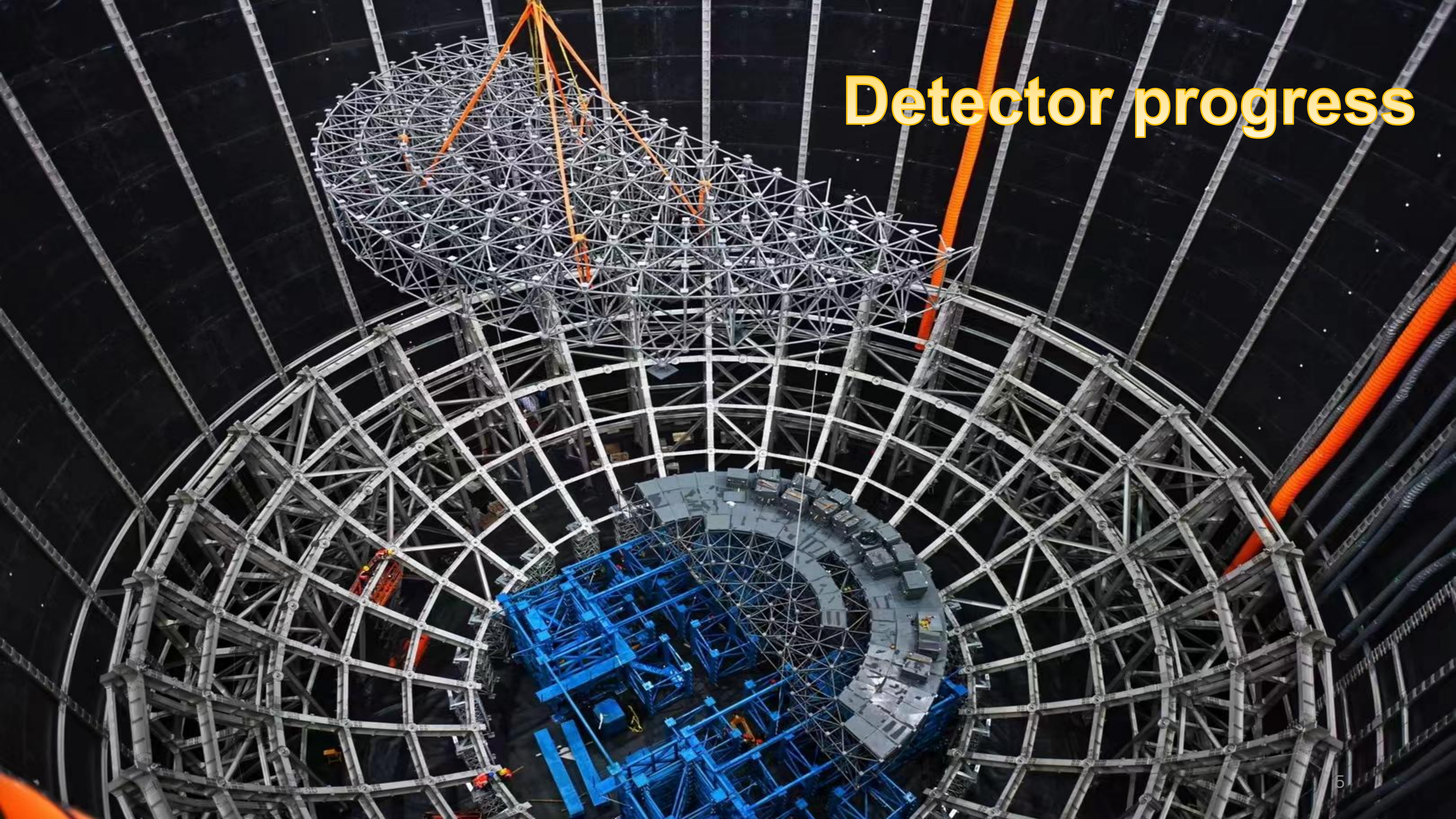
Neutrino oscillation & properties

Neutrinos as a probe

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

CCSN: core-collapse supernova

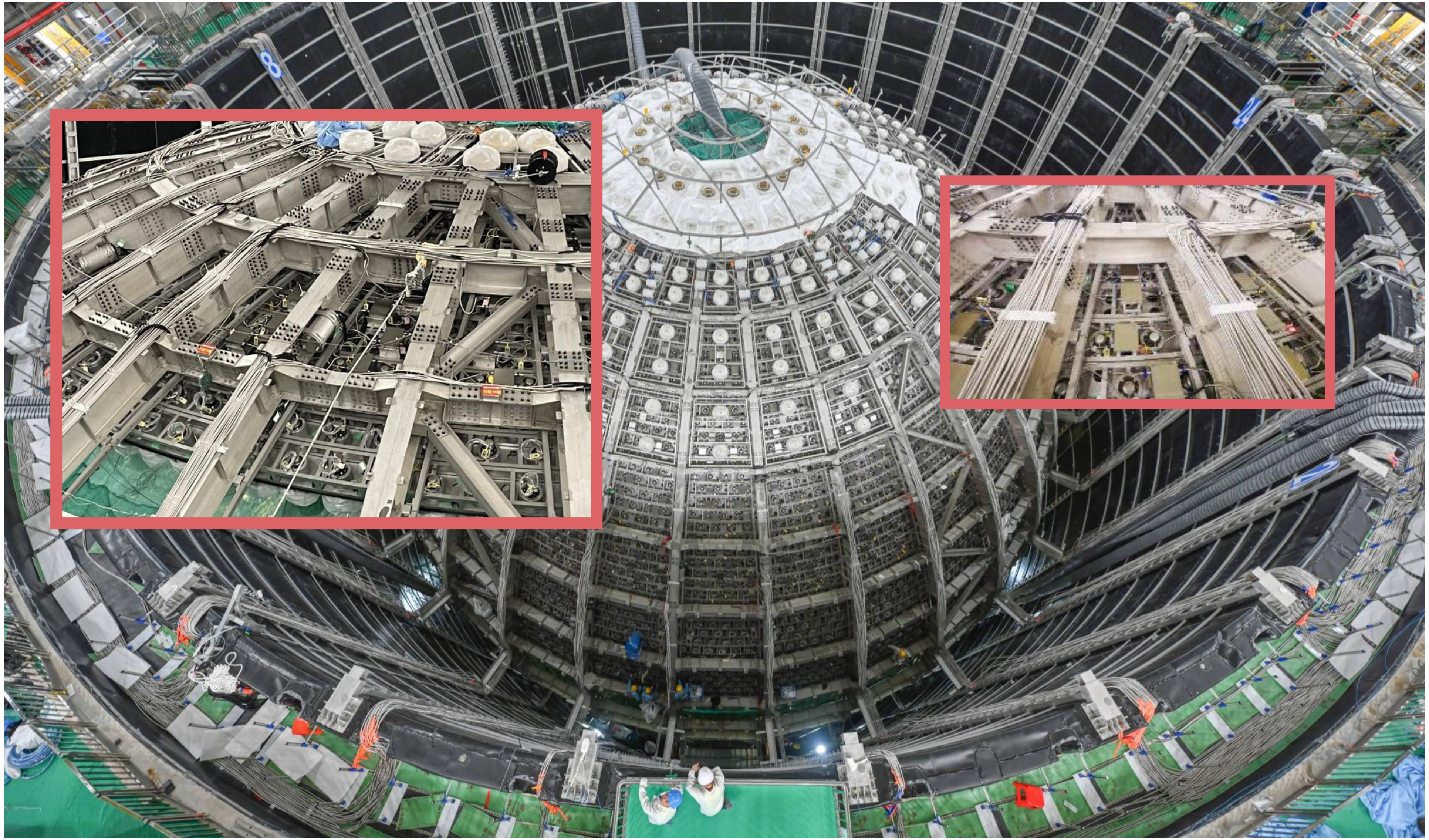
Detector progress



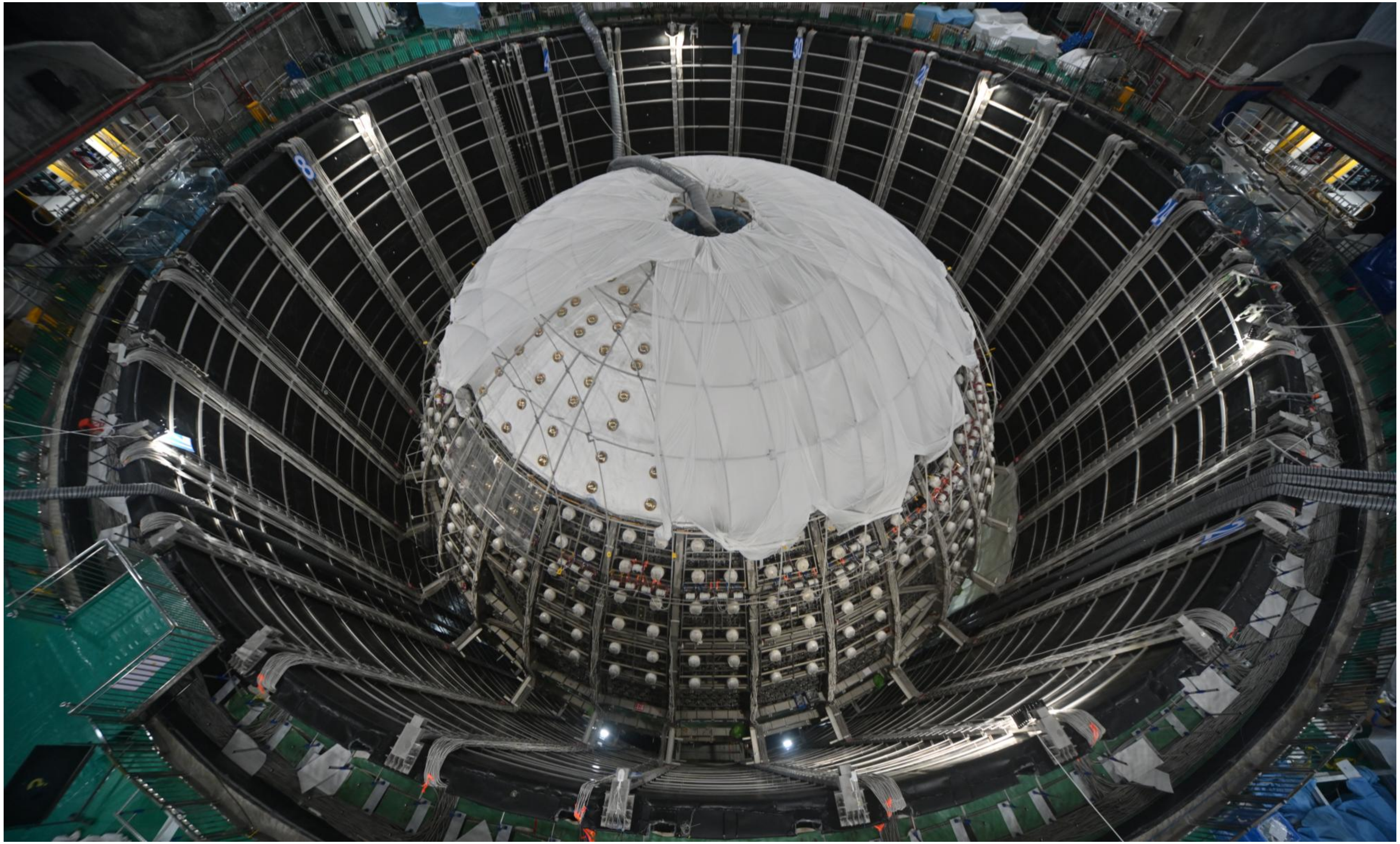
Overview of Installation Process

Bird’s Eye View of the Detector

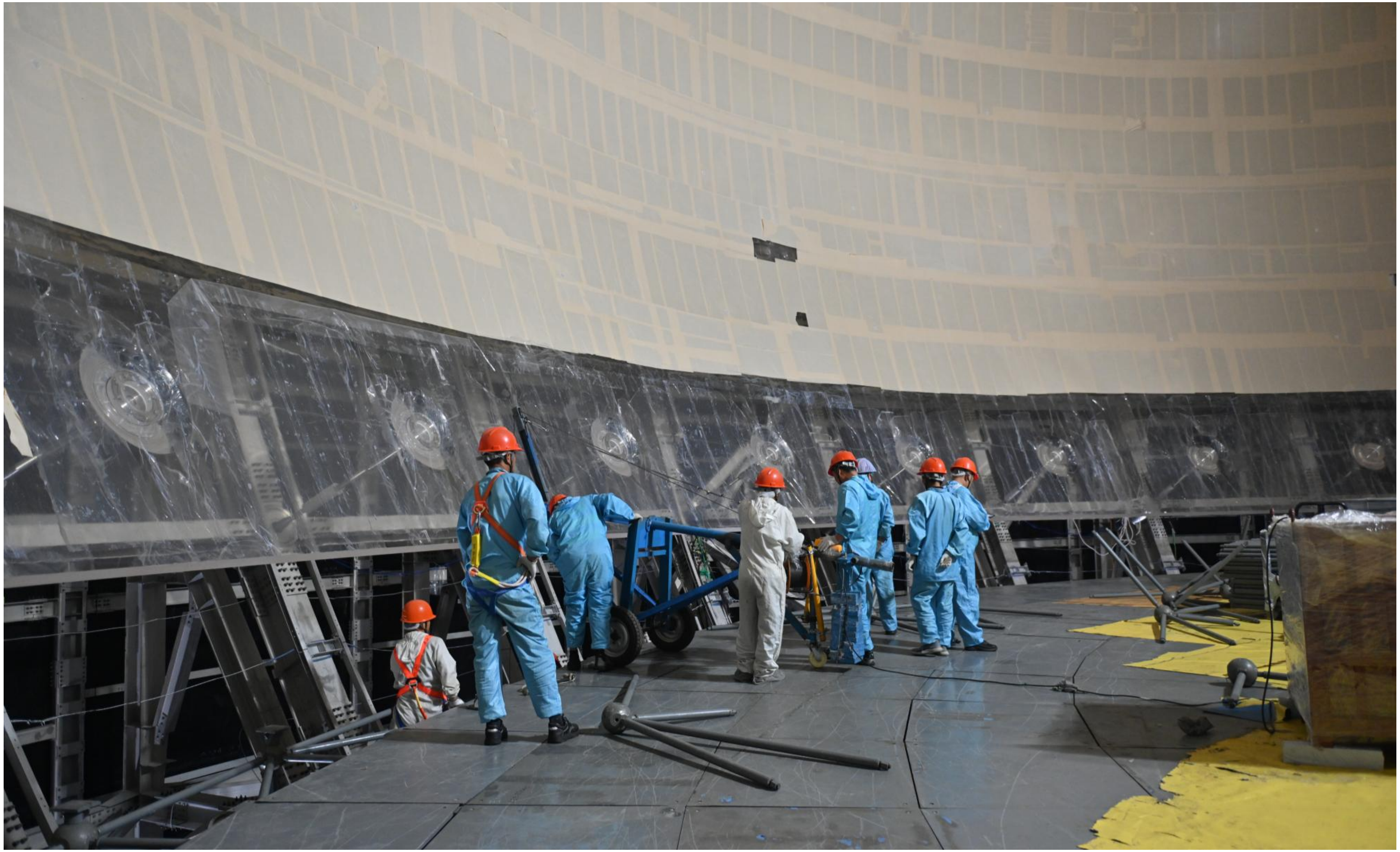
Bird’s Eye View of the Detector



Bird's Eye View of the Detector



Inside the Acrylic Sphere

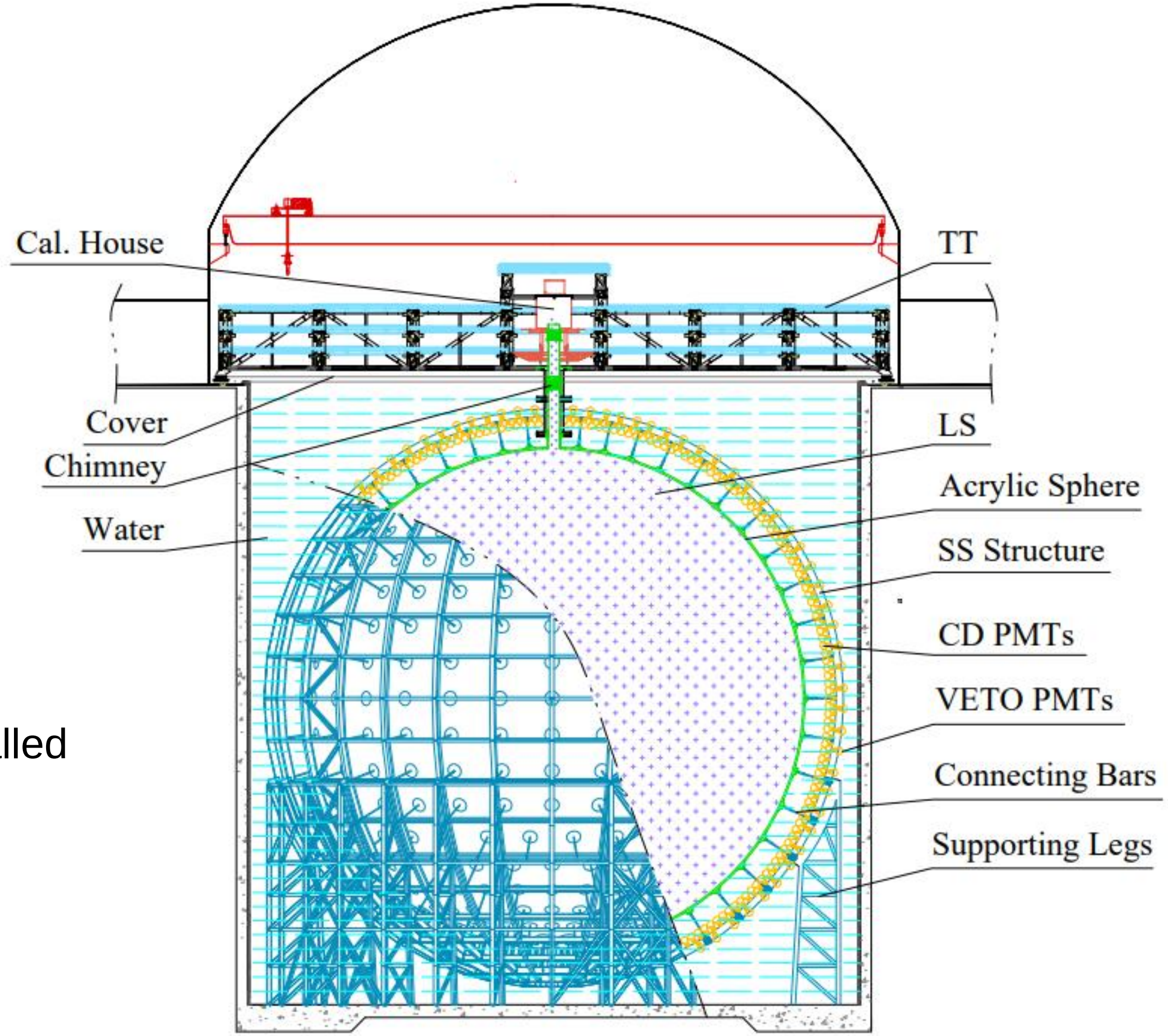


Inside the Acrylic Sphere

Between the Acrylic and the PMTs

Detector construction status

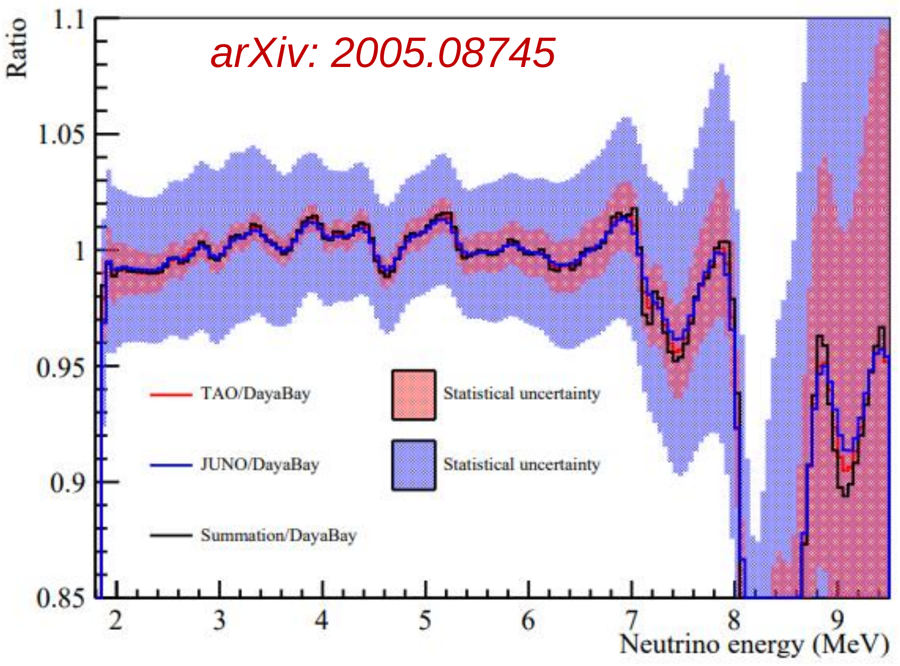
- **Acrylic panels**
  - All the panels are ready for shipping
  - More than half sphere is finished
- **Stainless Steel structure**
  - Finished in June 2022
- **20012 20'' PMTs + 25600 3'' PMTs**
  - Production and performance test done
  - ~7000 LPMT and ~9000 SPMT have been installed
- **Liquid scintillator (20 kt)**
  - Purification plants finished onsite construction
  - Under commissioning now



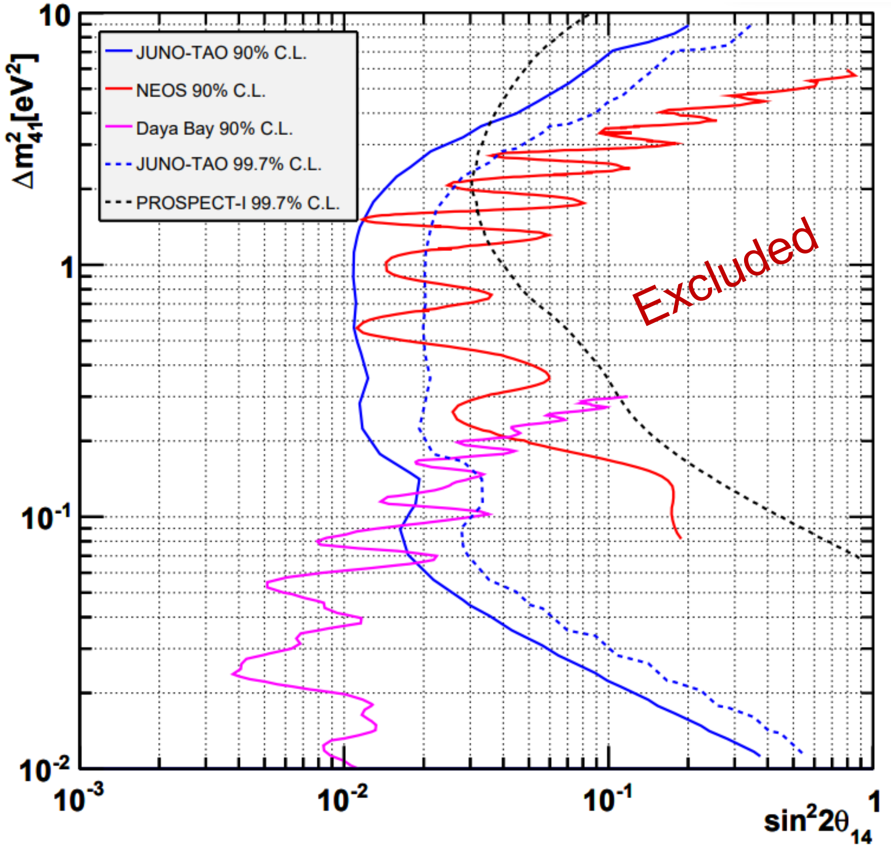
Taishan Antineutrino Observatory (TAO)

Goals:

1. Measure the reactor antineutrino spectrum with unprecedented energy resolution and see its fine structure for the first time.
2. Provide a reference spectrum for JUNO, other experiments, and nuclear databases
3. Search for light sterile neutrinos
4. Make improved measurements of isotopic yields & spectra



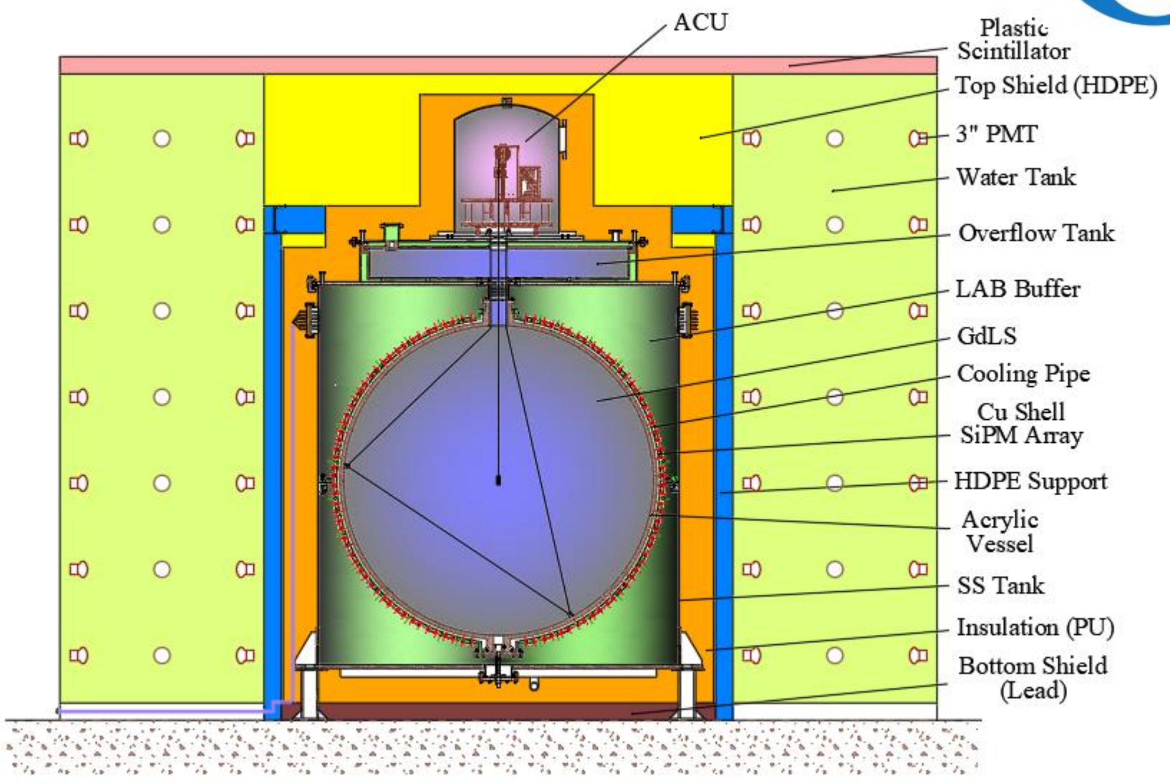
Constrain the fine structure in [2.5,6] MeV to < 1%

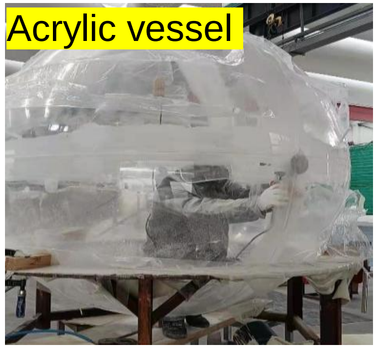


TAO sensitive in region 10^{-2} eV^2 < Δm^2_{41} < 10eV^2

Taishan Antineutrino Observatory (TAO)

2.8 ton GdLS detector	*arXiv: 2005.08745*
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



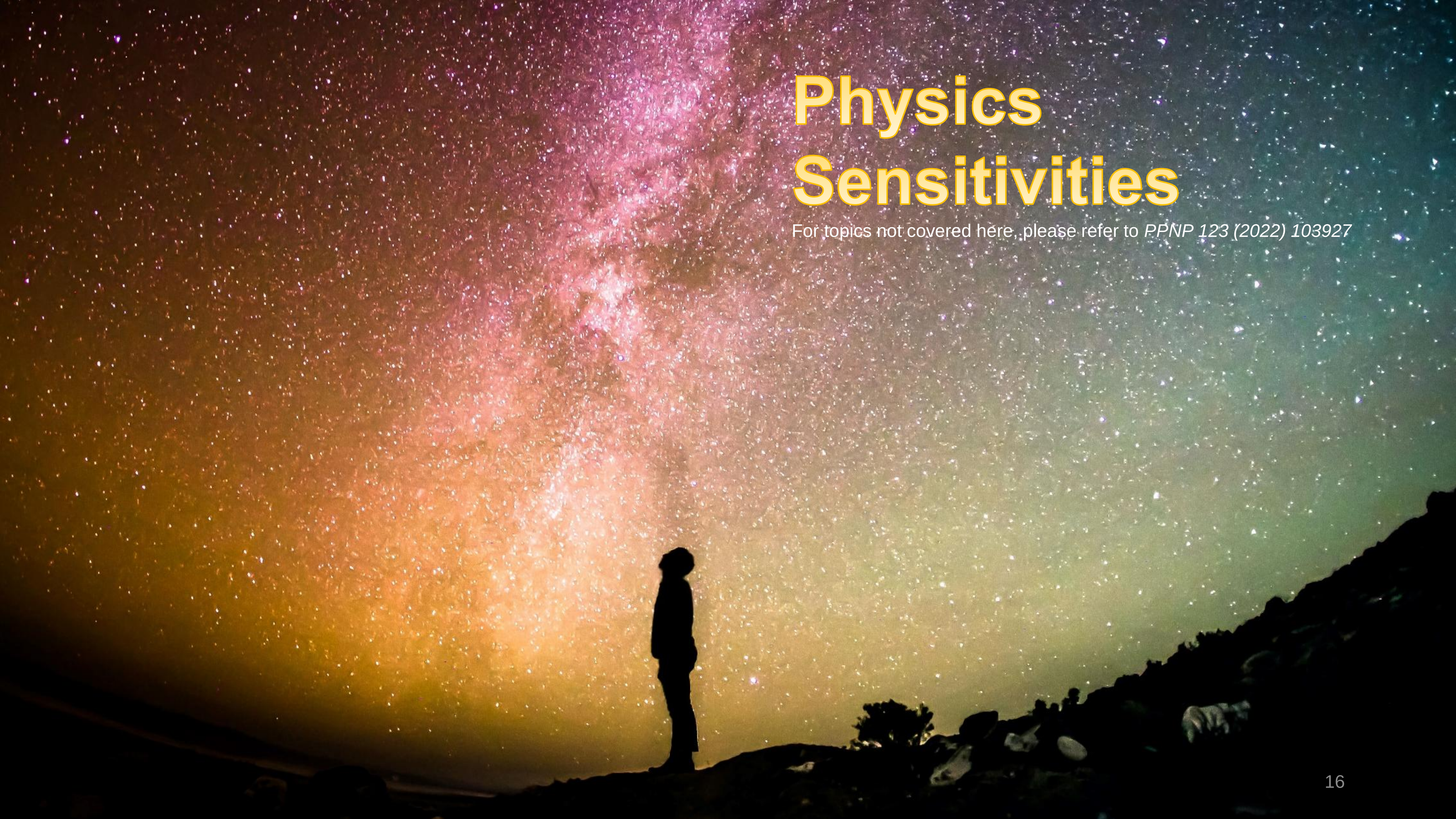


- ✓ SiPM is used to achieve high light yield with ~94% coverage
  → 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ Gd-LS works at -50℃ to lower the dark noise of SiPM

- ➢ **1:1 Prototype ongoing at IHEP**
- ➢ **Data-taking by 2024**

Physics Sensitivities

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



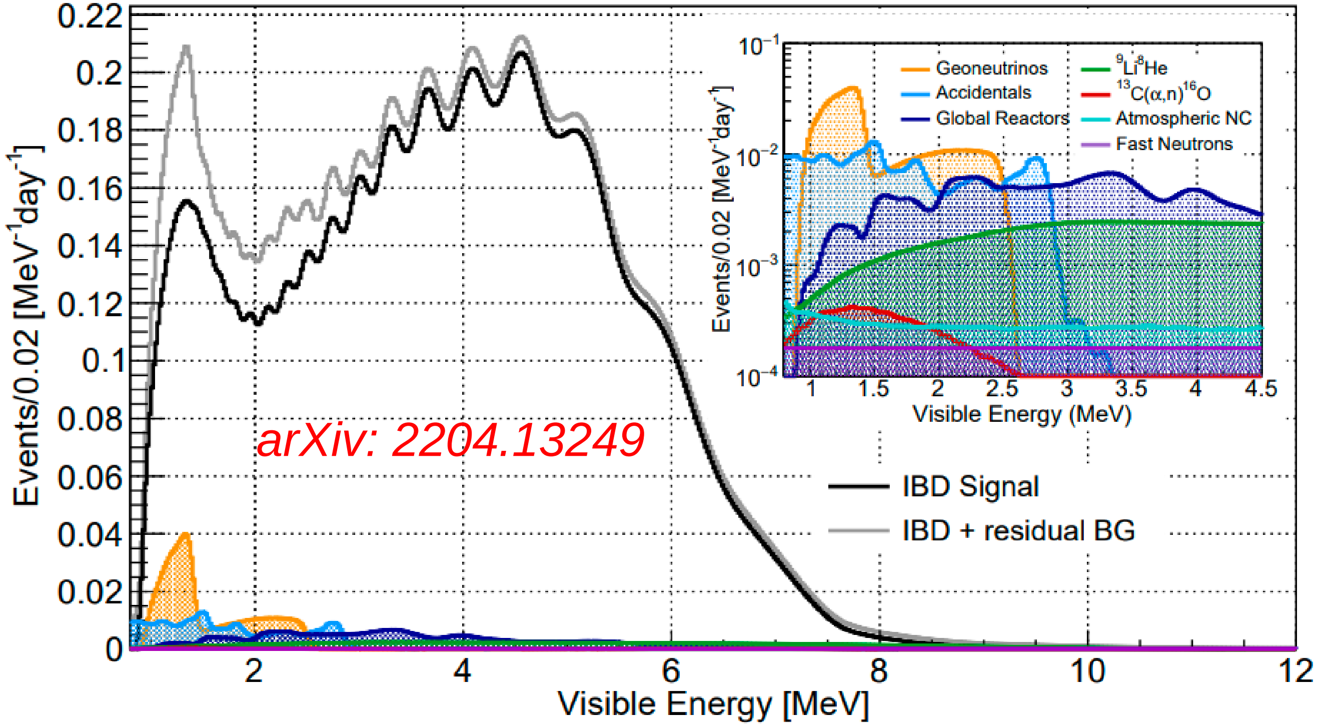
Reactor Antineutrino Oscillation & Detection

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

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

Inverse beta decay reaction

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



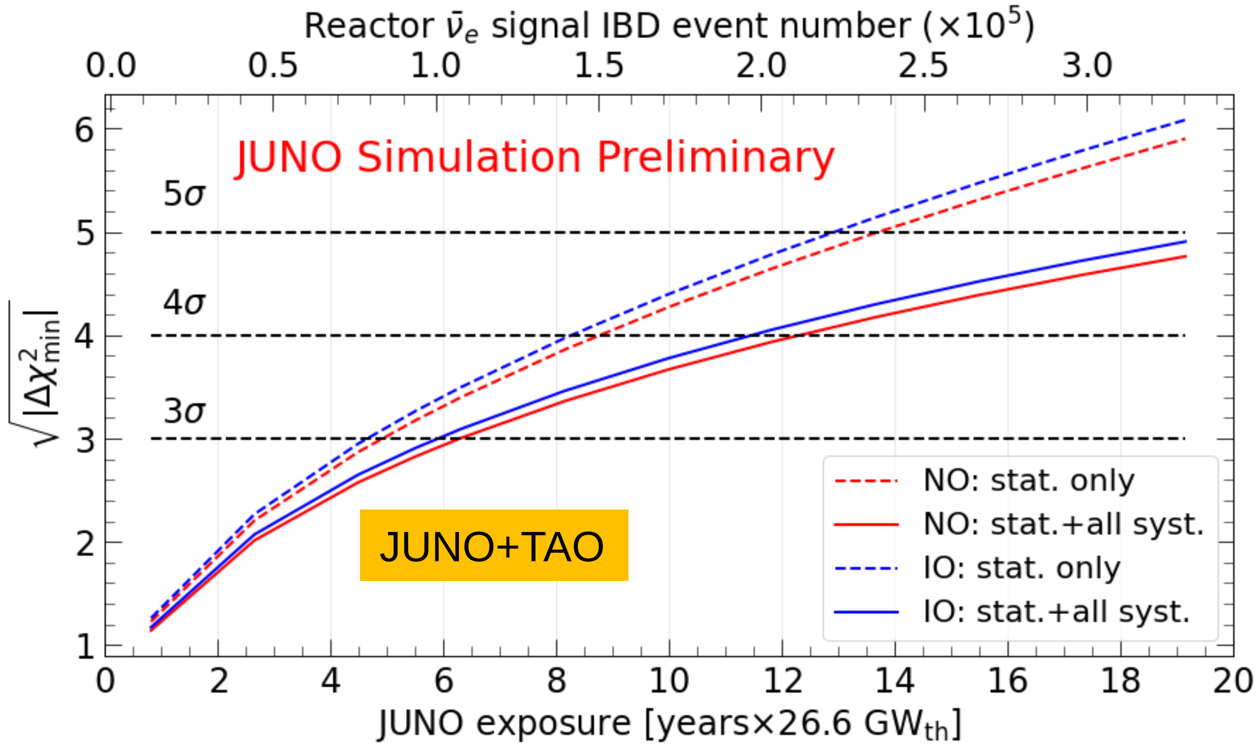
Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 ➔ **47**	-	-
Geo-ν's	1.1 ➔ **1.2**	30%	5%
Accidental signals	0.9 ➔ **0.8**	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 ➔ **0.8**	20%	10%
^{13}C(α, n) ^{16}O	0.05	50%	50%
Global reactors	0 ➔ **1.0**	**2%**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

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

Neutrino Mass Ordering



	Design (J. Phys. G 43:030401 (2016))	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%	**93% (12%↑)**
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 sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

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

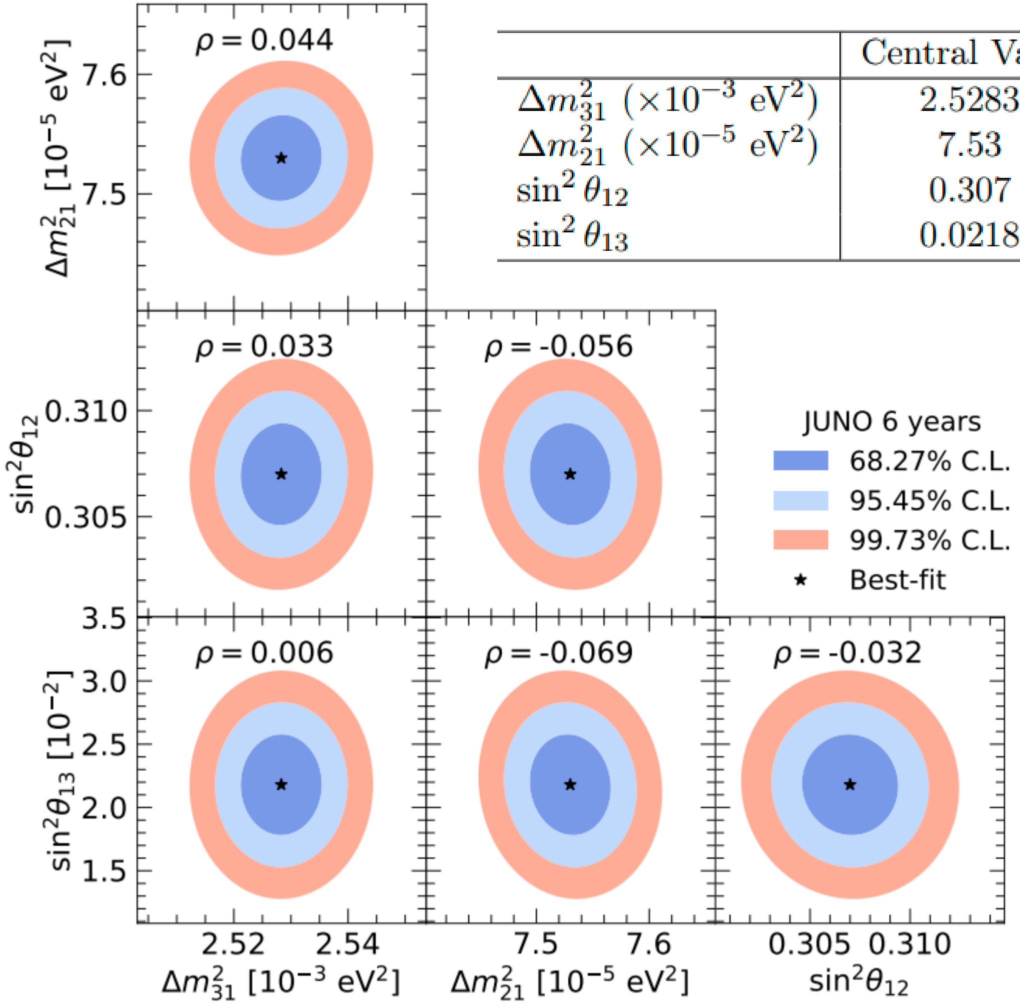
Combined reactor + atmospheric neutrino analysis is in progress: further improve the NMO sensitivity

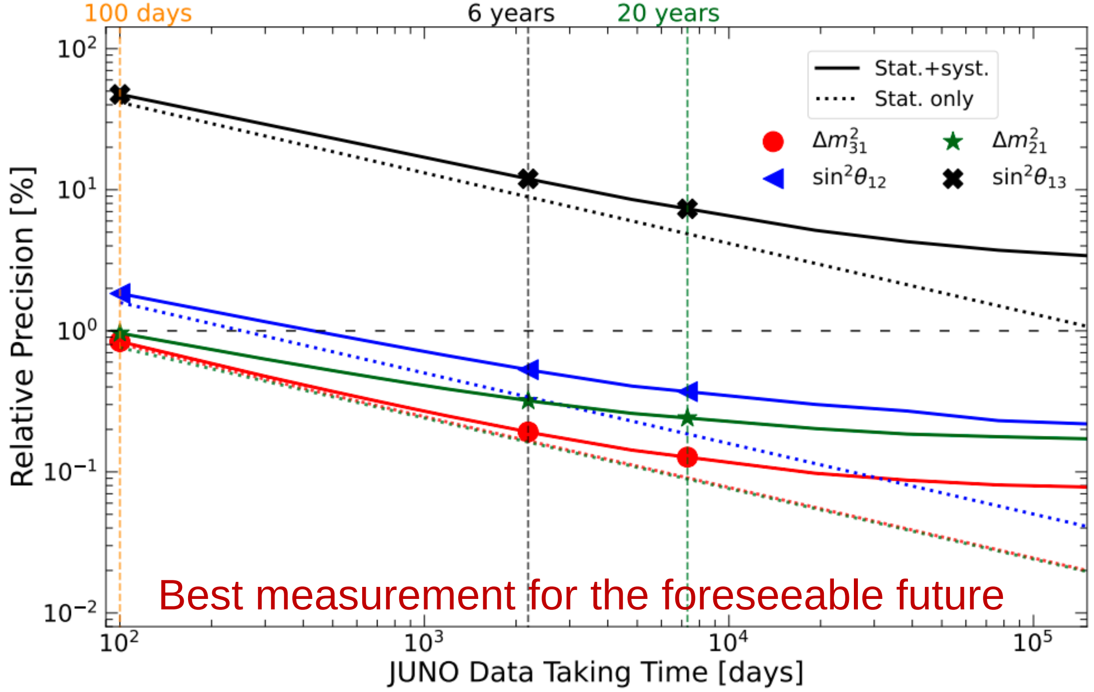
Neutrino oscillation parameters

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

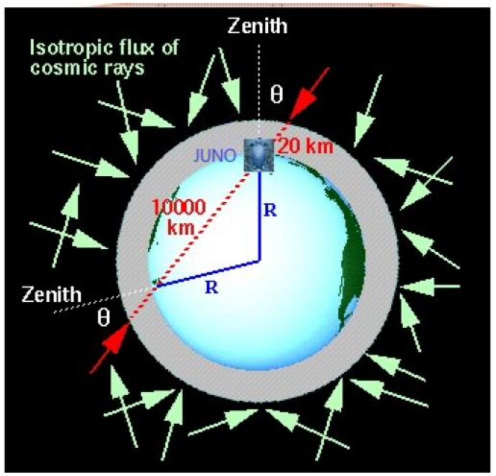
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016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

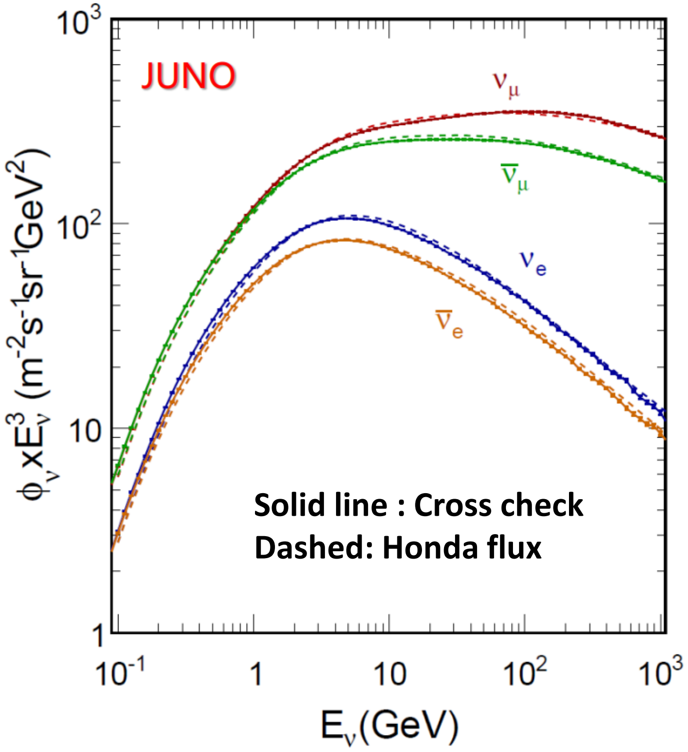


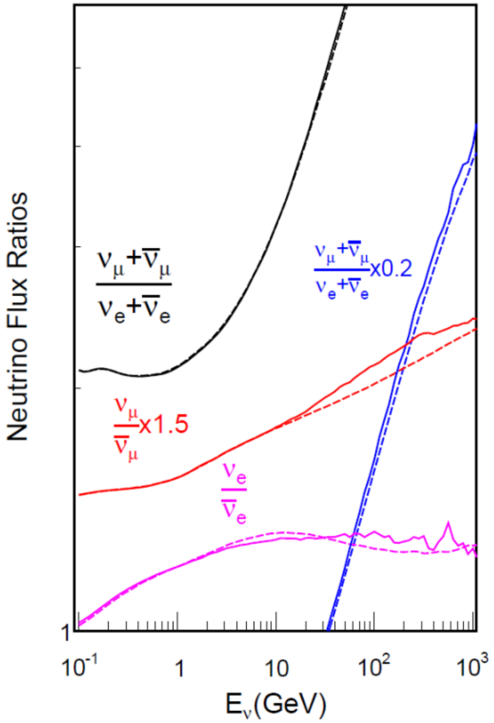


The improvement in precision over existing constraints will be about one order of magnitude

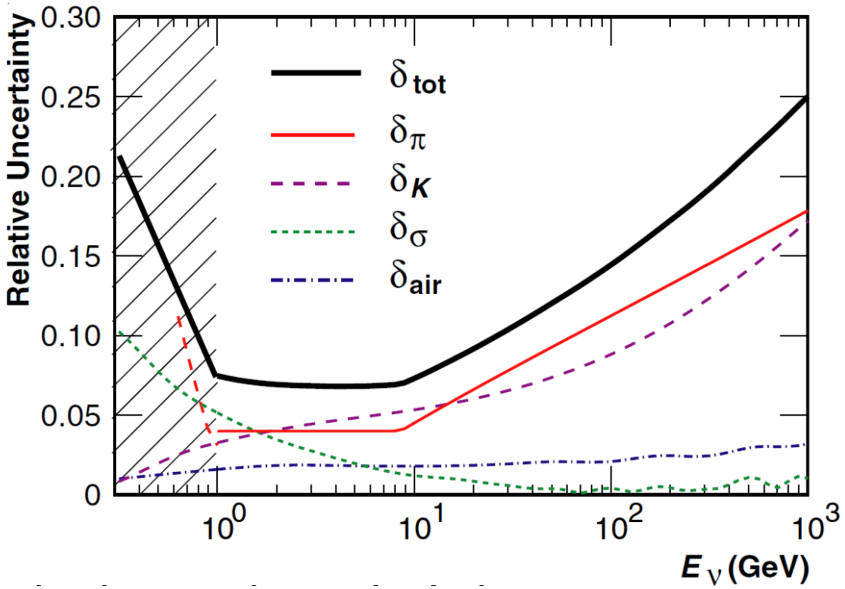
Atmospheric Neutrinos







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, NEUT

Energy/direction reconstruction, PID

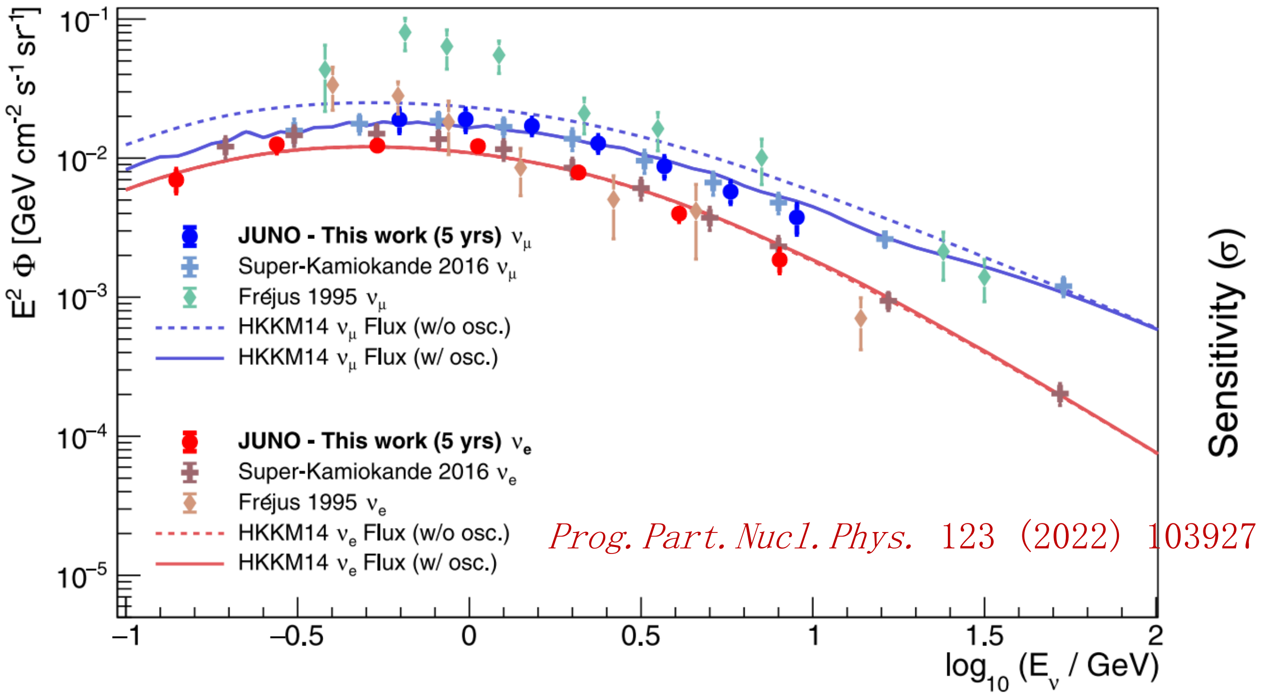
Physics potentials

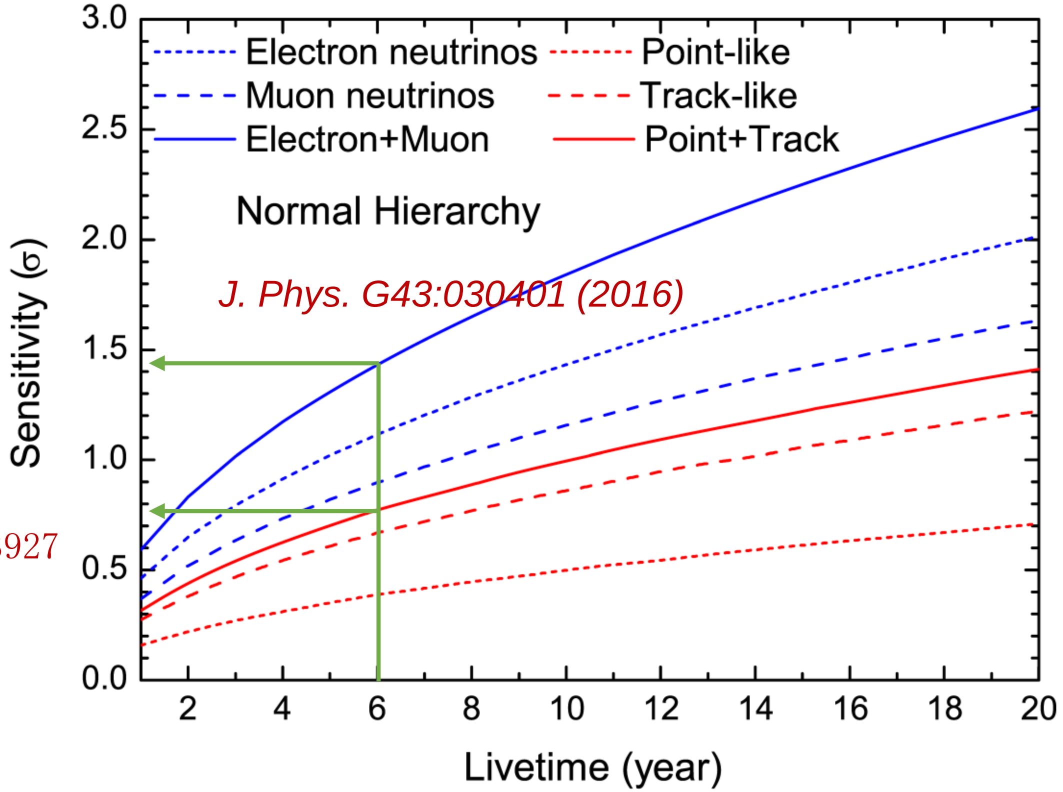
Atmospheric neutrinos

Precision measurement of low energy atmospheric neutrino fluxes

MSW effect → Neutrino Mass Ordering (NMO) → Independent measurement from reactor antineutrinos

Critical techniques: **energy and angular resolutions, flavor and $\nu/\bar{\nu}$ identifications**





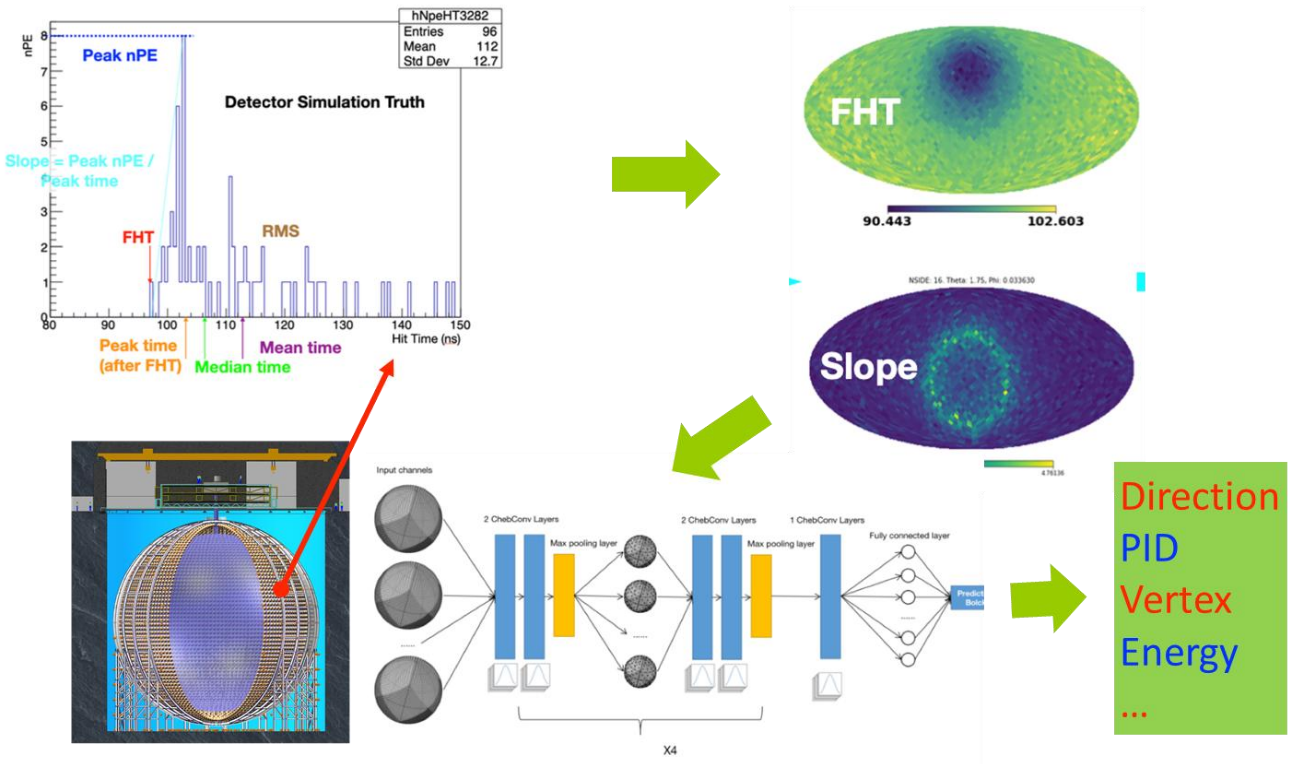
ν_e/ν_μ discrimination thanks to PMT hit pattern

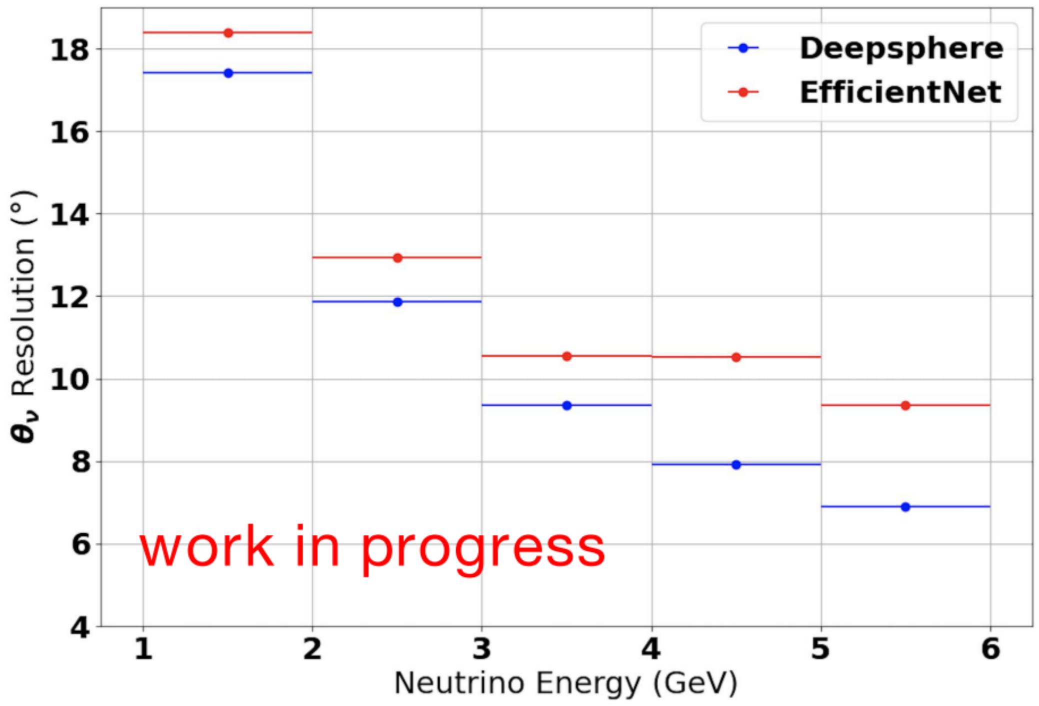
JUNO sensitivity on NMO: **0.7~1.4 σ (atmospheric only) @ ~6 yrs exposure**

Updated sensitivity based on ML-based reconstruction and PID performance

Atmospheric neutrinos

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

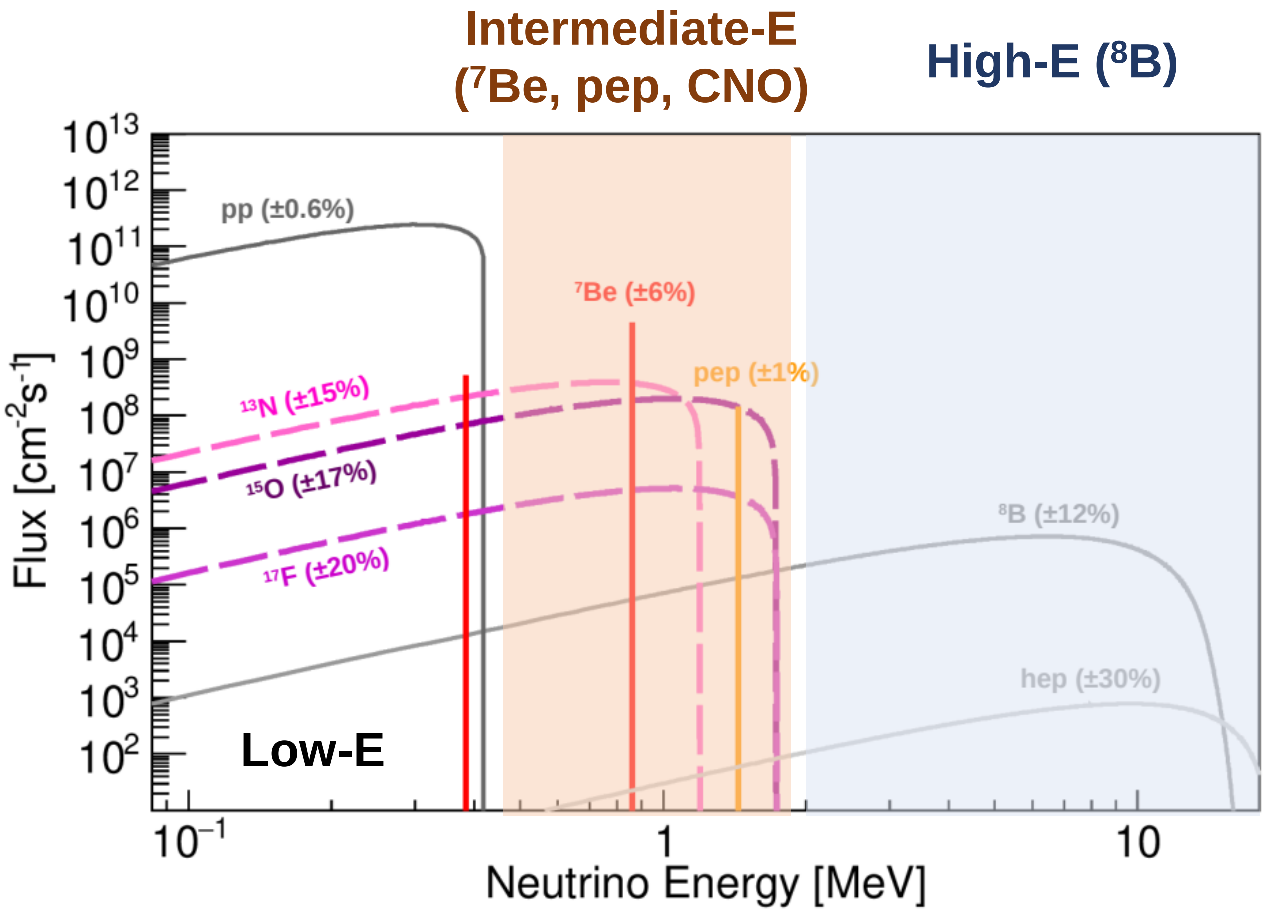




[1] DOI: 10.5281/zenodo.6769313. [2] DOI: 10.5281/zenodo.6782362. [3] DOI: 10.5281/zenodo.6804861.

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

Neutrinos from Sun



- JUNO has strong capability of simultaneously detecting B8 (2006.11760) and Be7, pep and CNO solar neutrinos (2303.03910)

- Physics topics
  - Independent θ_{12}, Δm^2_{21}
  - Periodic modulations (Day-Night Asymmetry)
  - Flux measurement

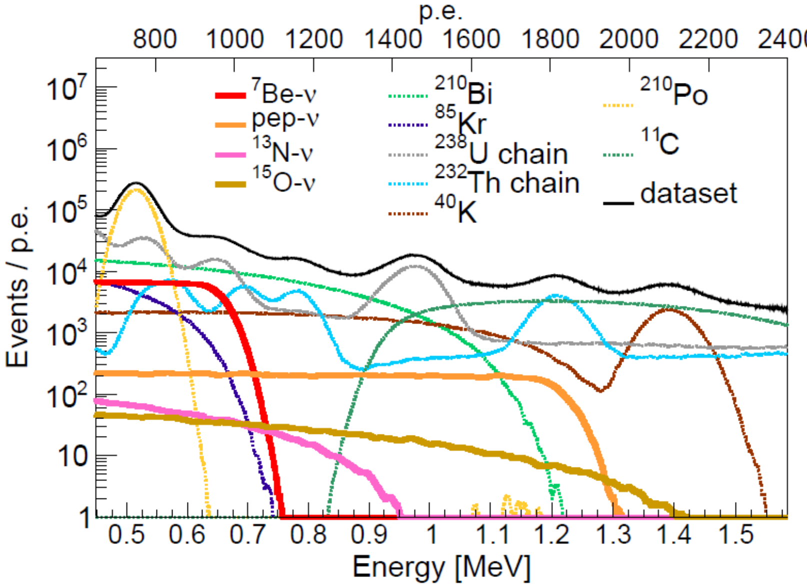
- Background rejection is the key
  - Good LS internal radio-purity (10^{-17} g/g)
  - Excellent muon veto to remove long-lived cosmogenic isotopes

Neutrinos from Sun (Be7, pep and CNO)

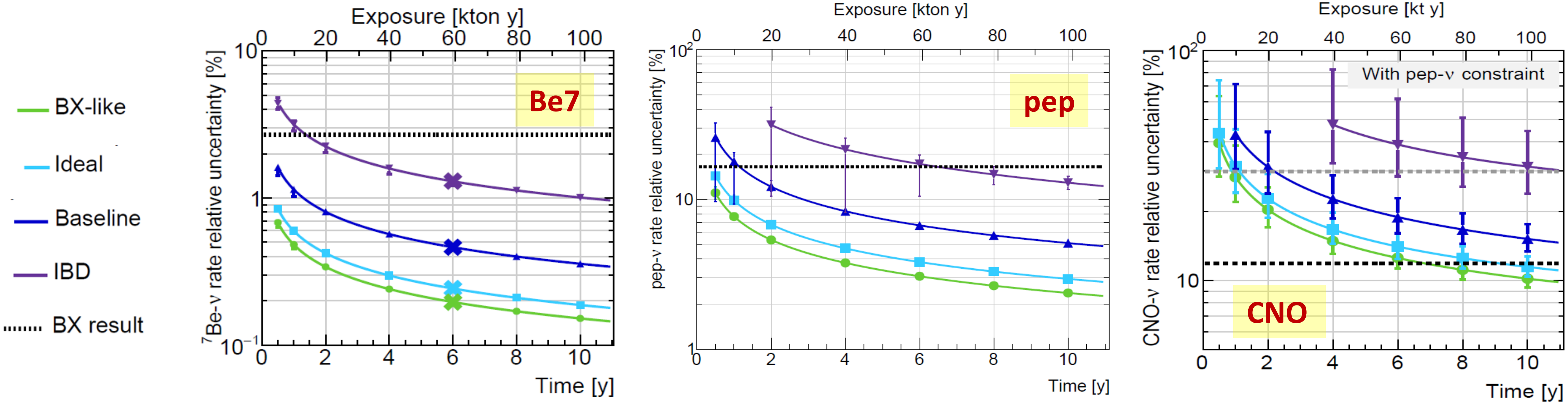
Radio-purity Scenario		^{40}K	^{85}Kr	^{232}Th-chain	^{238}U-chain	^{210}Pb/ ^{210}Bi	^{210}Po
IBD	$c\ [\frac{g}{g}]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R\ [\frac{cpd}{kt}]$	2289	5000	3508	15047	12031	12211
Baseline	$c\ [\frac{g}{g}]$	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	229	500	351	1505	1203	1221
Ideal	$c\ [\frac{g}{g}]$	1×10^{-18}	-	1×10^{-17}	1×10^{-17}	1×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	23	100	35	150	241	244
Borexino	$c\ [\frac{g}{g}]$	-	-	$<5.7\times10^{-19}$	$<9.4\times10^{-20}$	-	-
	$R\ [\frac{cpd}{kt}]$	4.2	100	1.4	2	115	446.9

NOTE: Contribution from pileup and reactor neutrinos found negligible in the ROI

No detector systematics is included



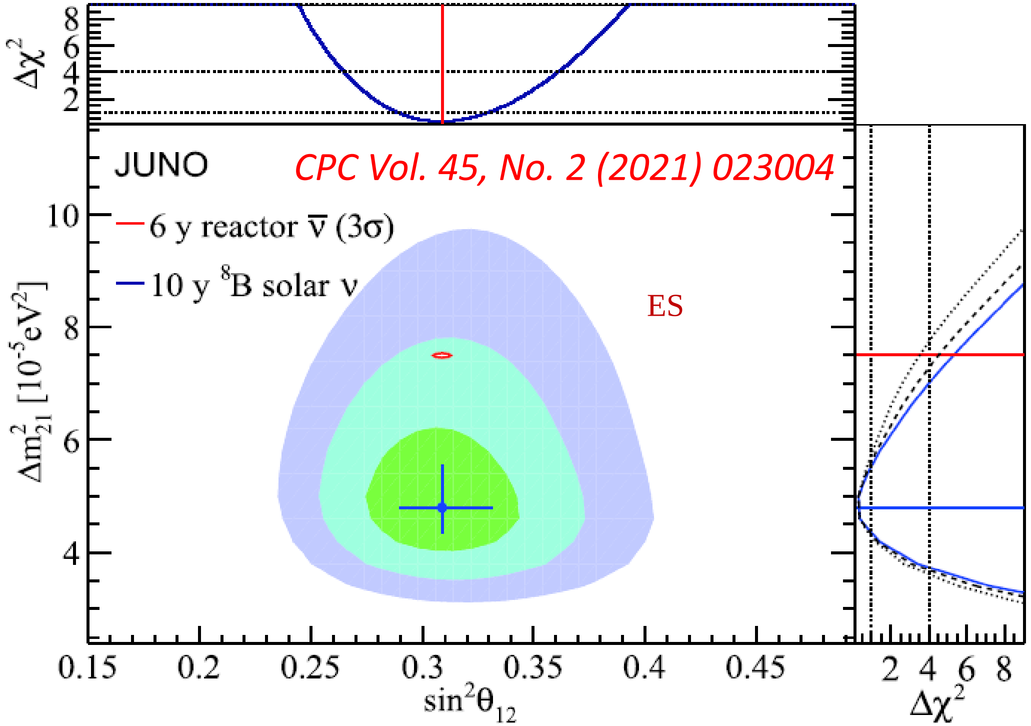
arxiv:2303.03910, JCAP 10 (2023) 022



Neutrinos from Sun (B8)

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

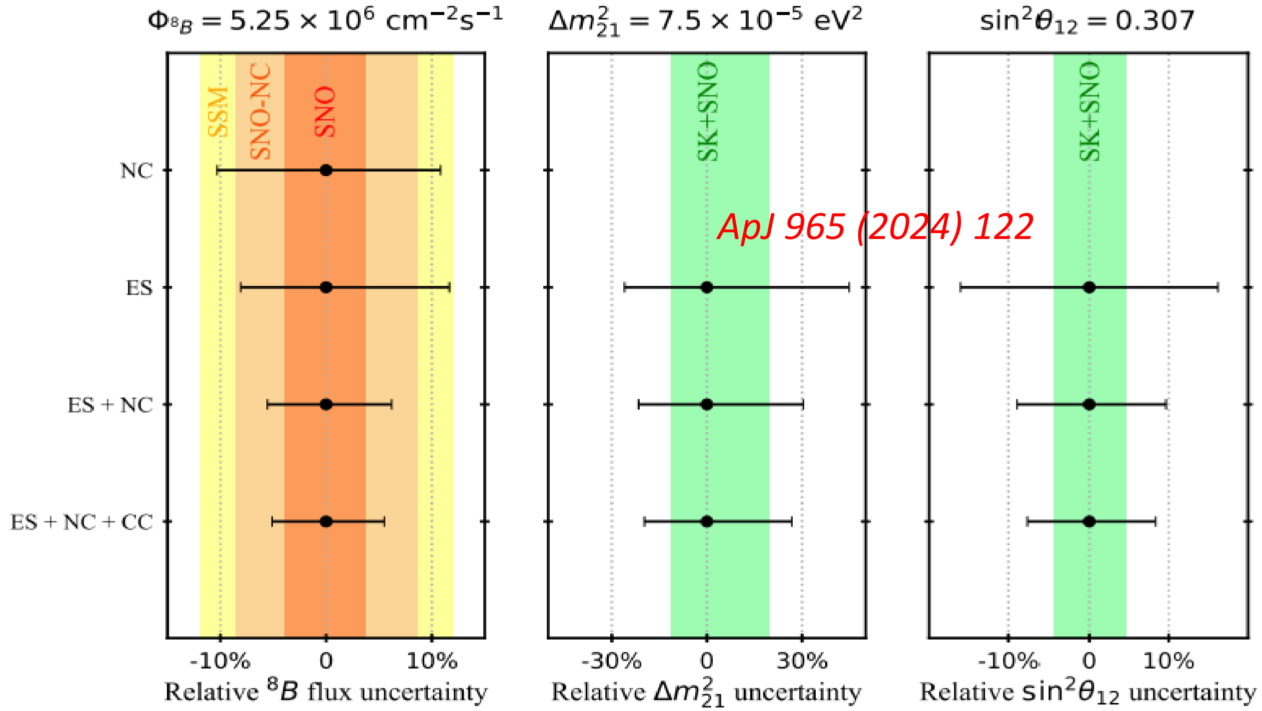
Solar & reactor measurement in Δm^2_{21} with one single detector



Model independent measurement of ^{8}B-ν flux (~5%) and solar 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^-

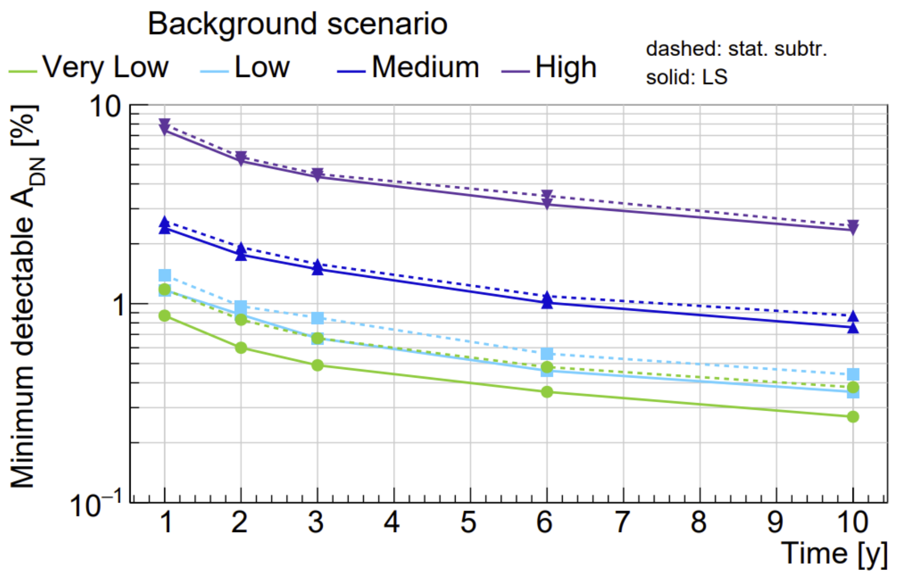


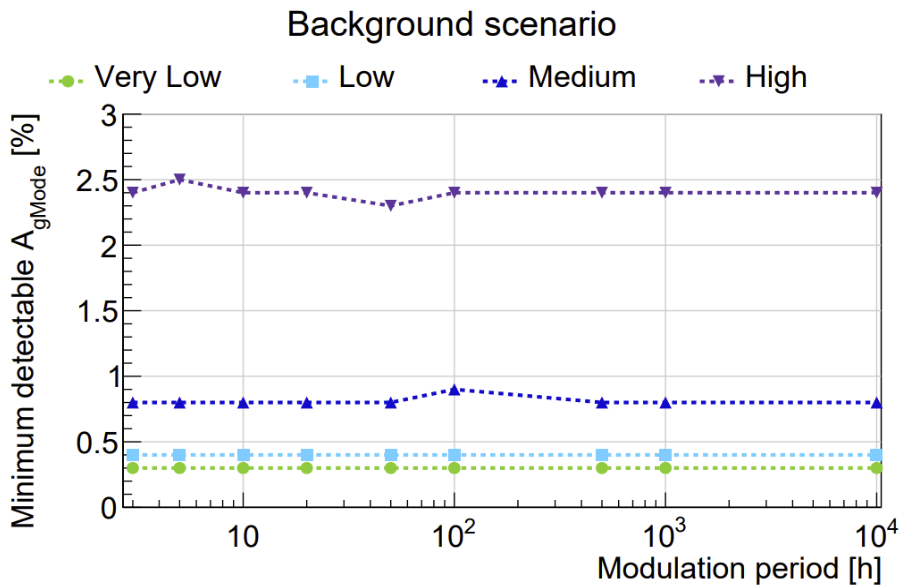
Periodic modulations of Solar neutrinos

Periodic modulations of Solar neutrinos

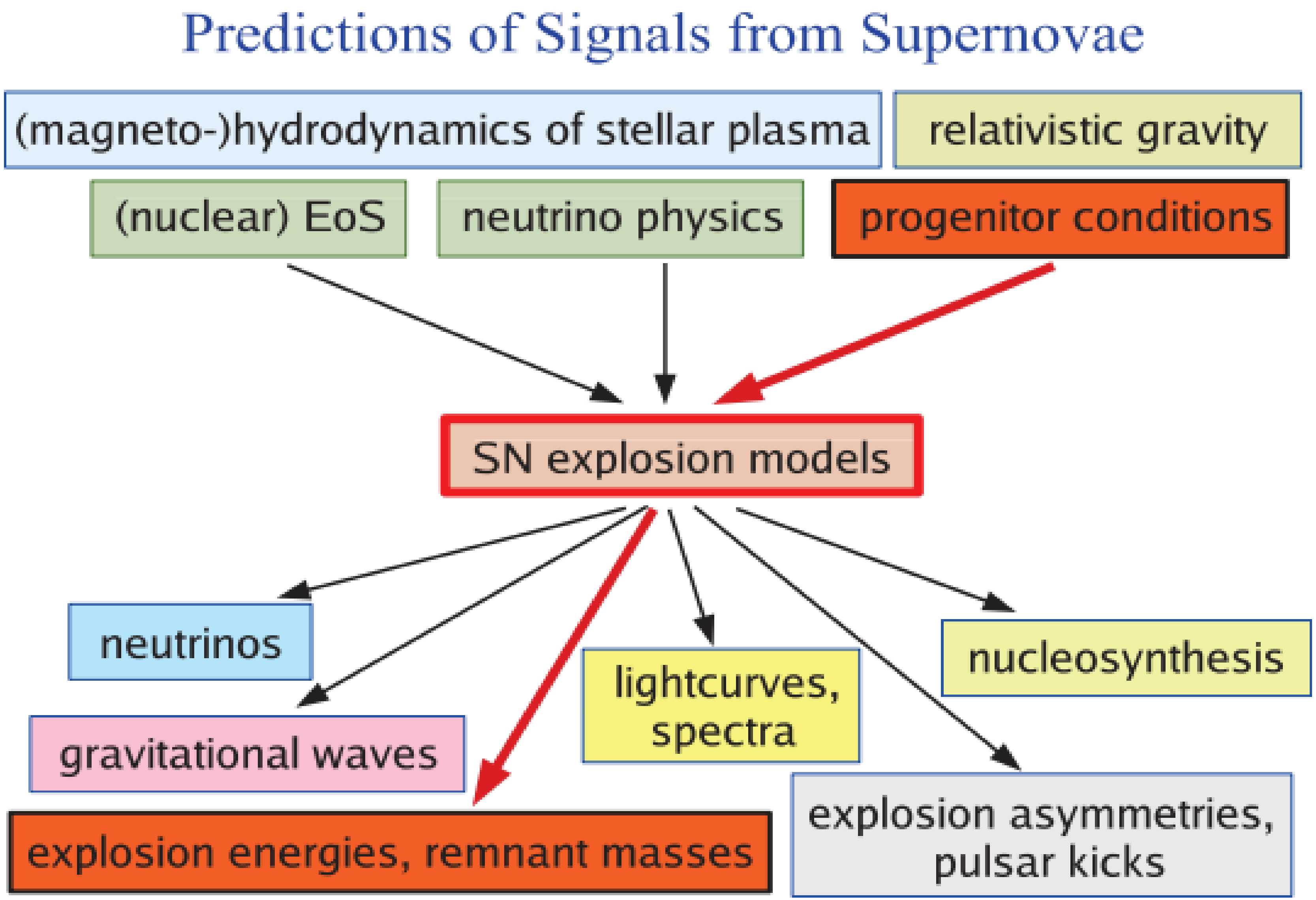
- Seasonal modulation
  - Vacuum oscillation
  - Eccentricity of the Earth's orbit
- Day-Night Asymmetries
  - Earth matter effects
- Solar gravity modes (or g modes)
  - oscillations of the solar interior

arxiv:2303.03910, JCAP 10 (2023) 022



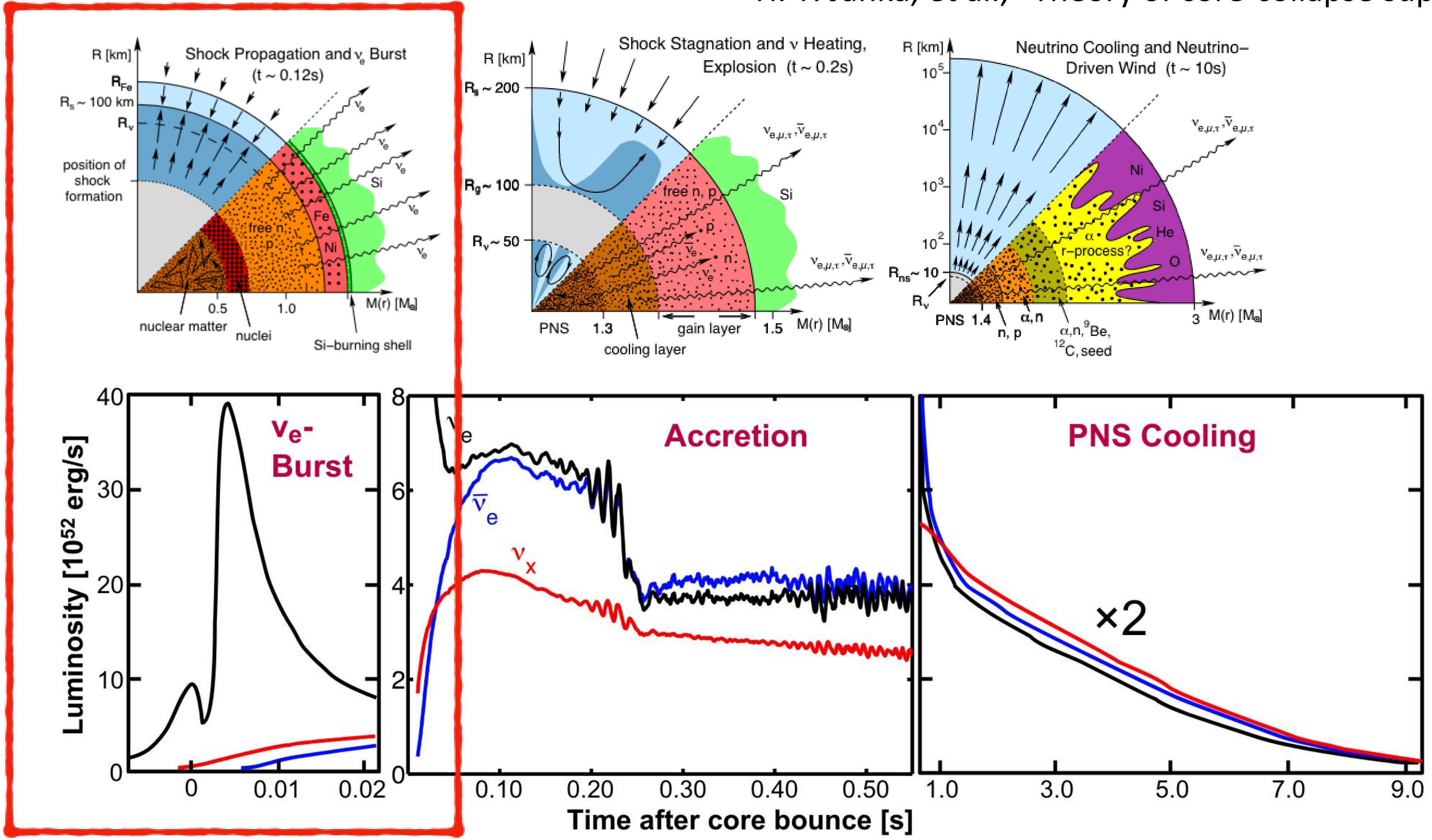


Supernova Explosion



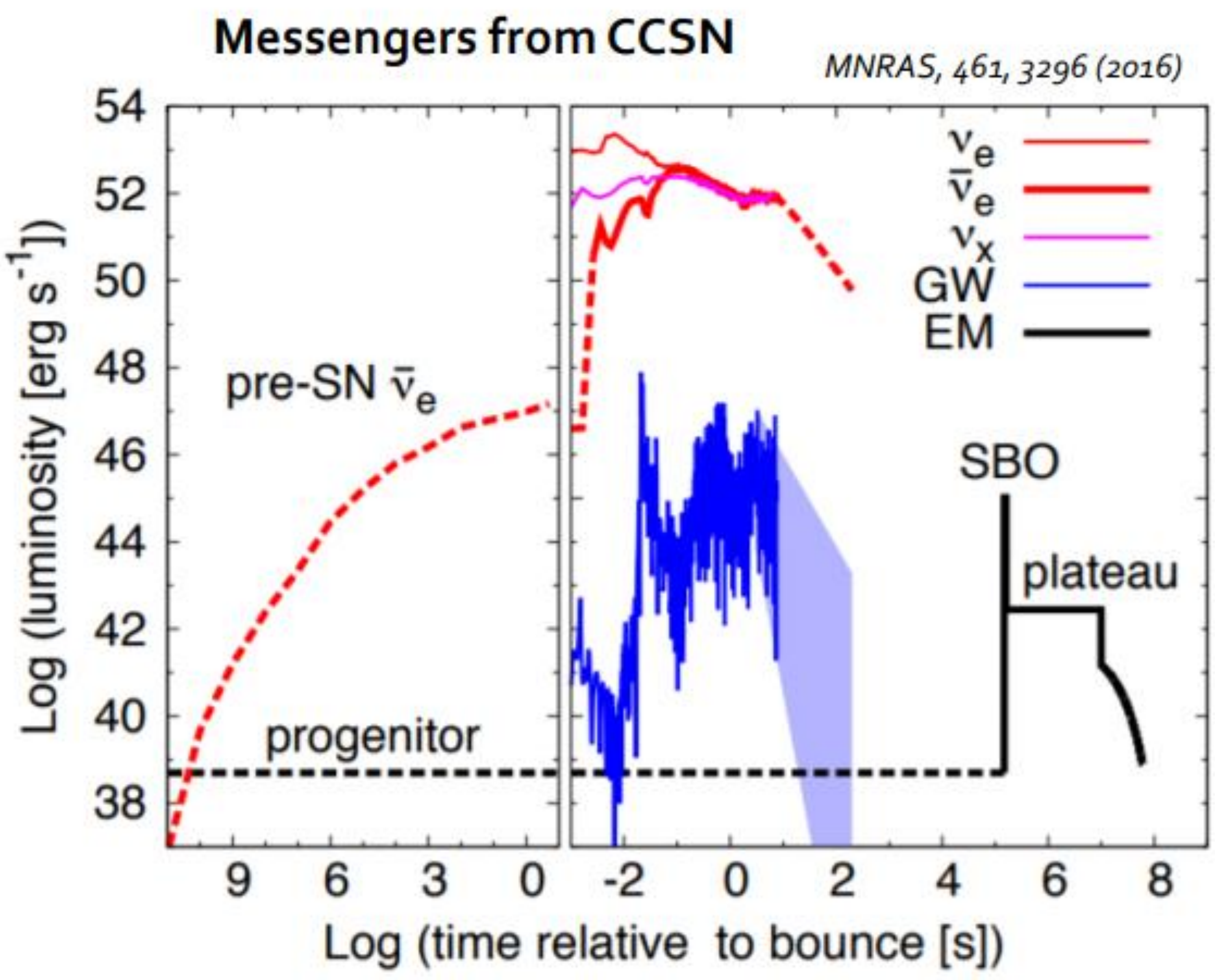
Supernova Neutrino Emission

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



Well-understood, regarded as a “standard candle”

Multi-messenger Signals



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

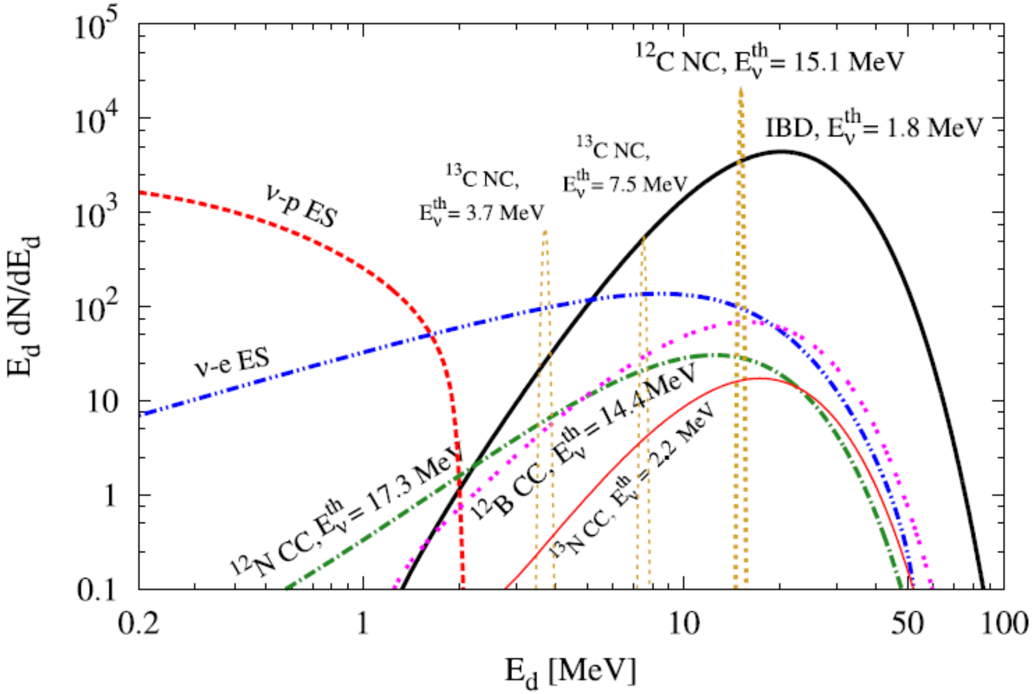
- **Pre-SN neutrinos**
  - **~MeV** neutrinos, much lower luminosity than SN burst neutrino
  - visible **~days** before core collapse for **nearby** galactic progenitors
- **SN burst neutrinos**
  - **Few tens of MeV** neutrinos, last for **~10s** with burst, accretion and cooling stages
  - Background 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, luminorsity,
- Neutrino properties
  - Mass ordering
  - Absolute mass
  - New physics

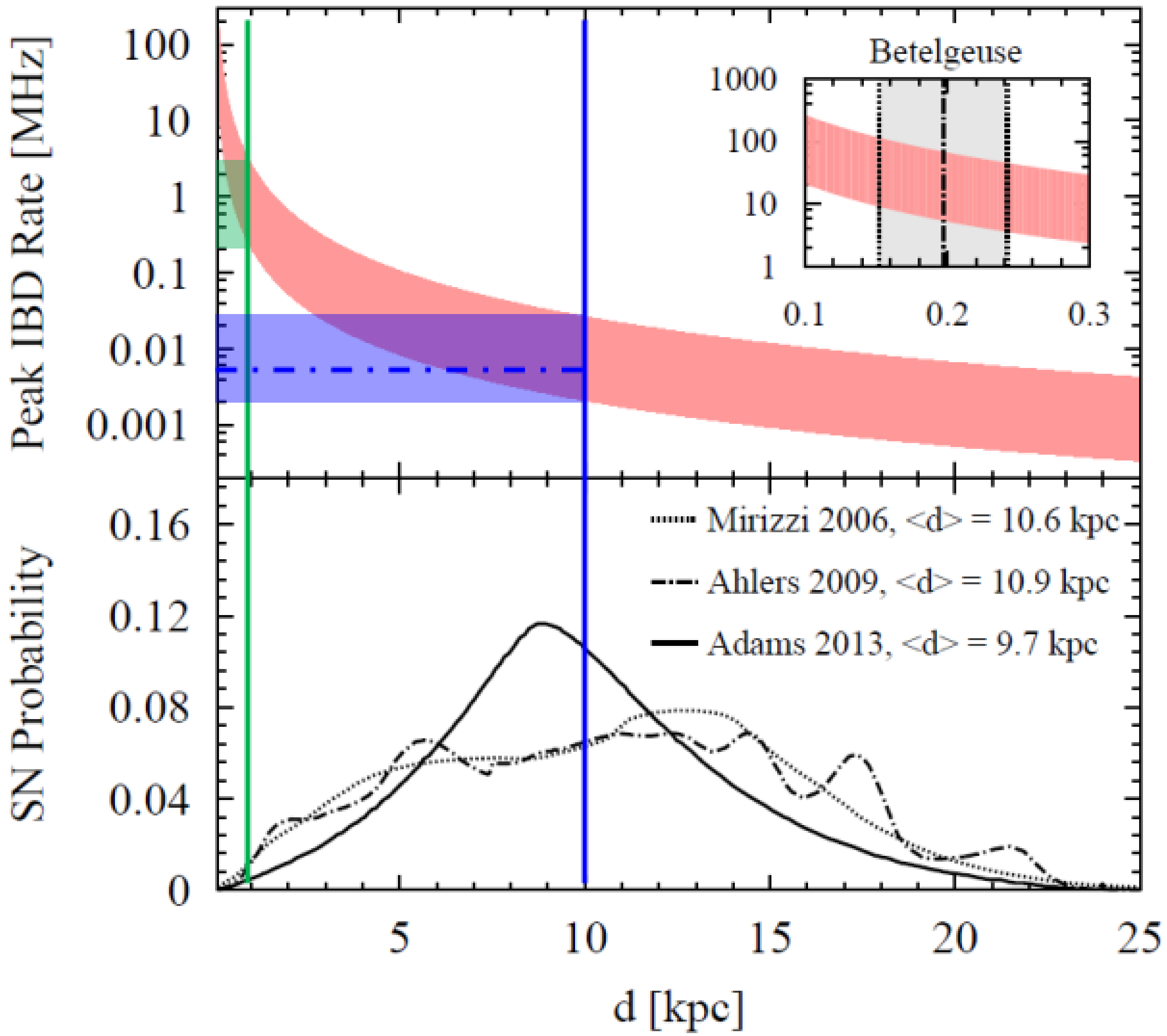


Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	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)

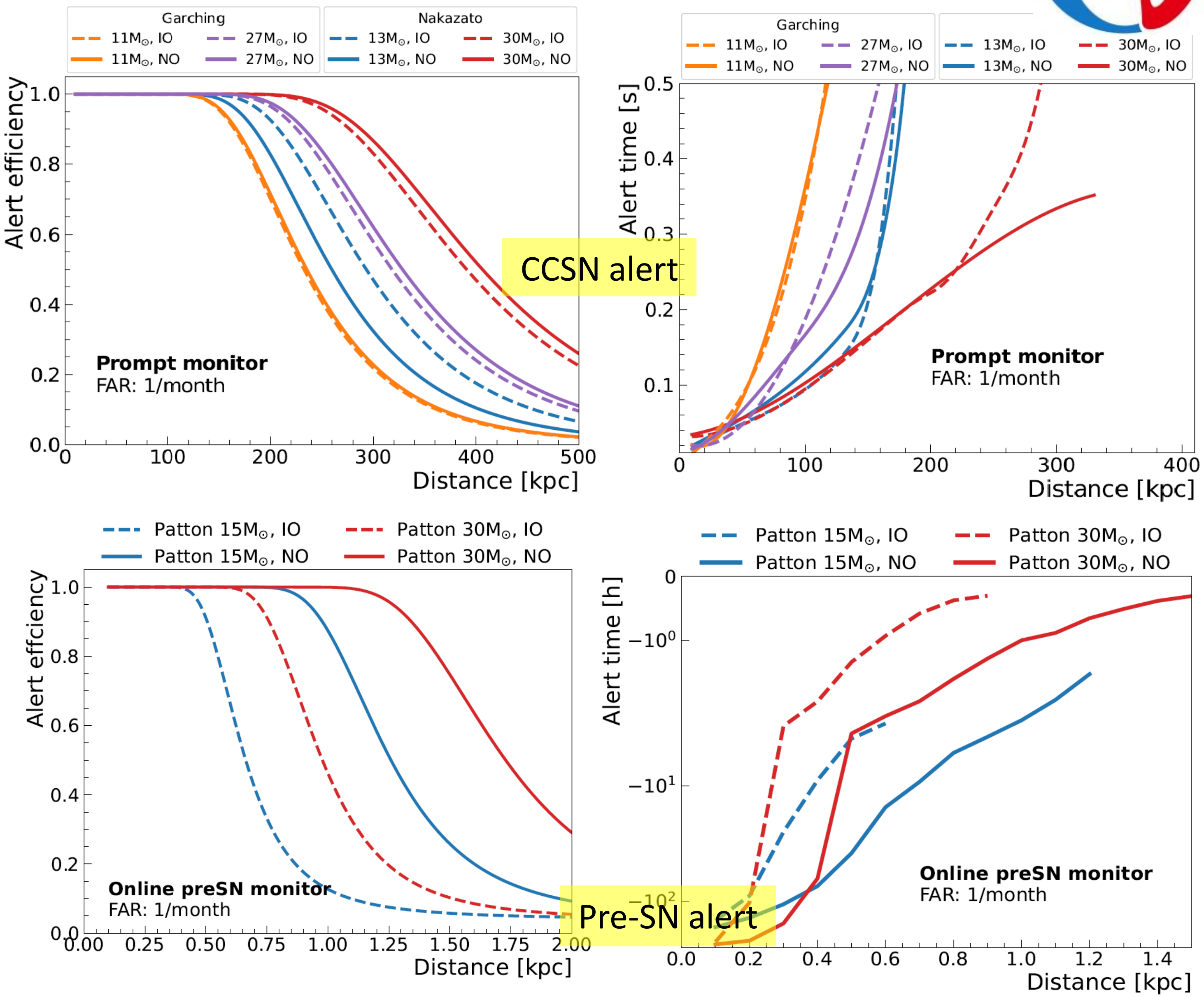
- DAQ design can fulfil the requirements on SN data taking
  - **For >1kpc CCSN: No data loss**
  - For <1kpc CCSN: acquire maxi. data as we can
  - For each PMT channel, real-time waveform processing at FPGA to extract (T, Q)



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

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



Spectral reconstruction

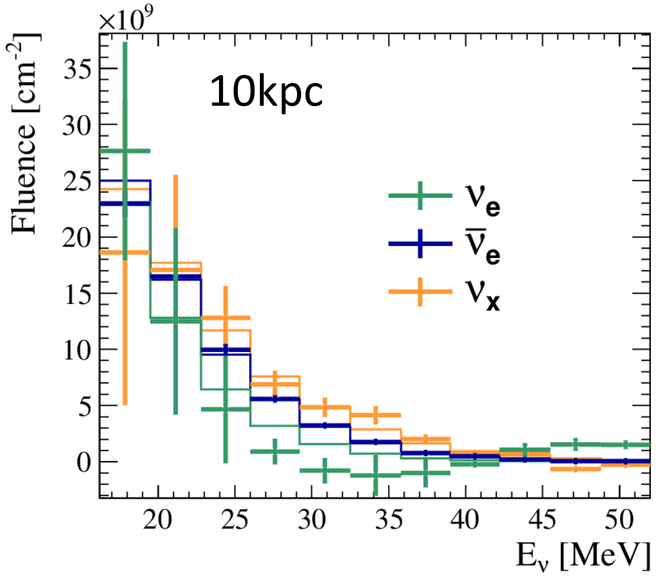
Cross section && Detector effects | SN neutrinos spectra | Observed spectra

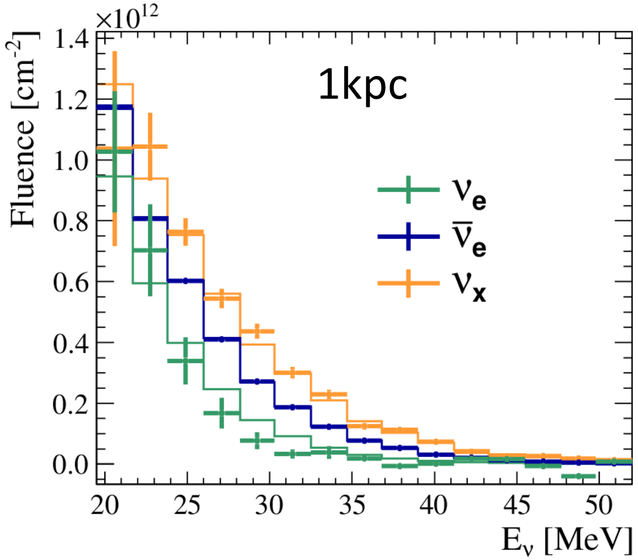
$$\begin{bmatrix} N_p D_{IBD}\sigma^{IBD}_{\nu_e} & N_p D_{IBD}\sigma^{IBD}_{\bar{\nu}_e} & N_p D_{IBD}\sum\sigma^{IBD}_{\nu_x} \\ N_p D_{pES}\sigma^{pES}_{\nu_e} & N_p D_{pES}\sigma^{pES}_{\bar{\nu}_e} & N_p D_{pES}\sum\sigma^{pES}_{\nu_x} \\ N_e D_{eES}\sigma^{eES}_{\nu_e} & N_e D_{eES}\sigma^{eES}_{\bar{\nu}_e} & N_e D_{eES}\sum\sigma^{eES}_{\nu_x} \end{bmatrix} \cdot \begin{bmatrix} F_{\nu_e} \\ F_{\bar{\nu}_e} \\ F_{\nu_x} \end{bmatrix} = \begin{bmatrix} S_{IBD} \\ S_{pES} \\ S_{eES} \end{bmatrix}$$

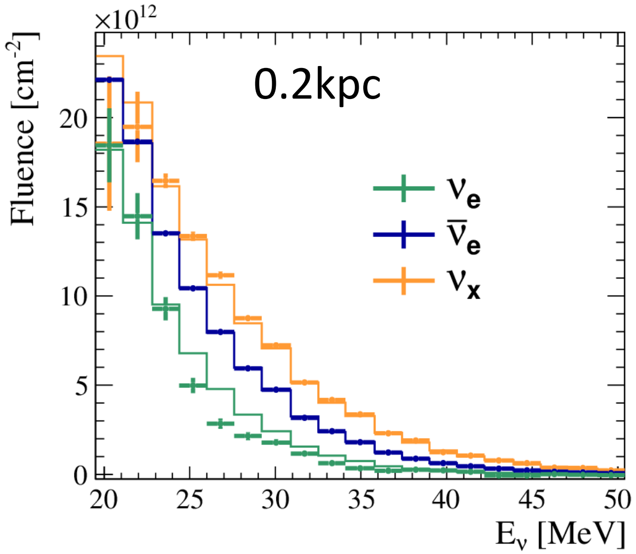
Full flavor SN neutrino energy spectra reconstruction in JUNO detector

- 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





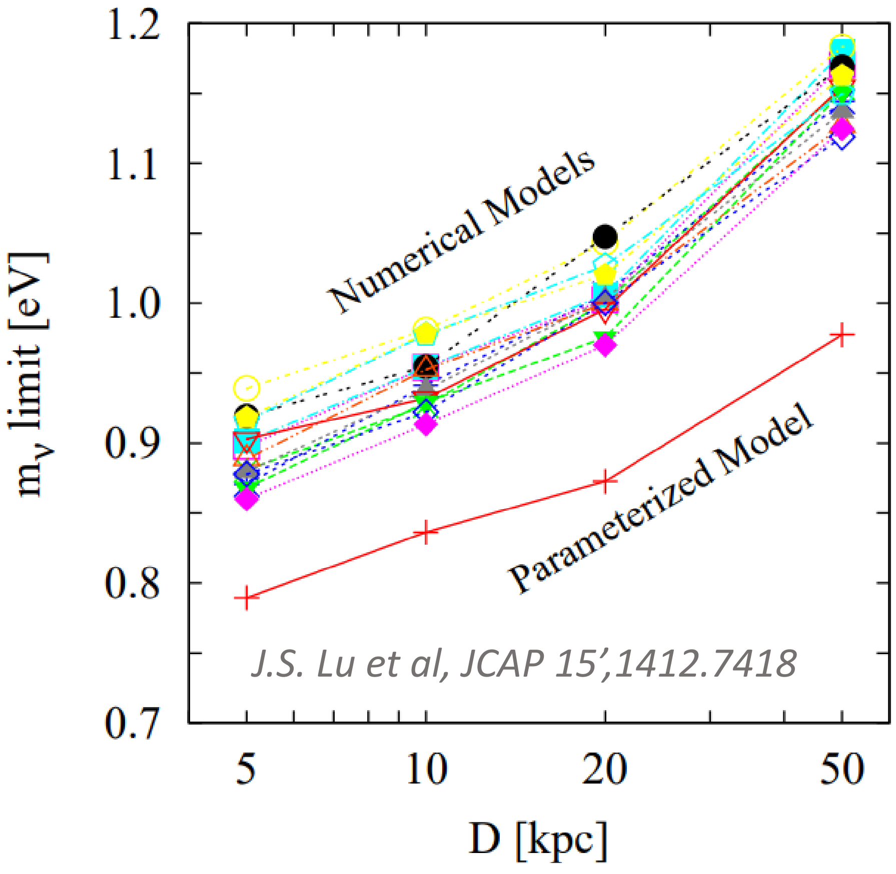


Energy threshold: < 0.2 MeV

Particle Physics

Time delay of massive neutrinos:

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



- Flavor conversion

  MSW effects

  Fast and slow collective oscillations
- Neutrino mass ordering:

  Spectral comparison

  Time profile
- New particle and new physics

  Axion (ALP)

  keV sterile neutrinos

  Dipole portal

  … … …

→ Rich program to be explored!

Diffuse Supernova Neutrino Background (DSNB)

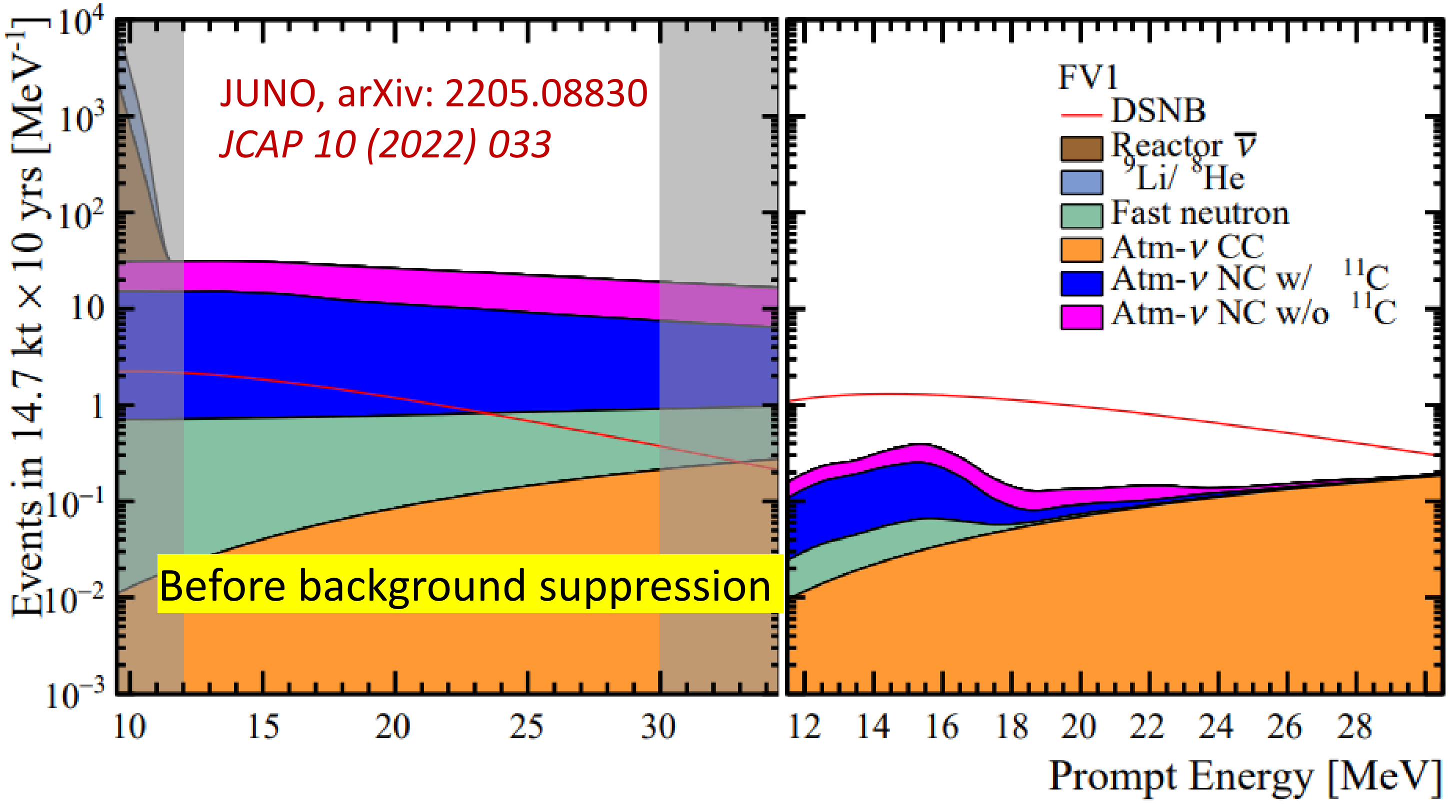
- **DSNB: 2-4 events in JUNO per year**
  - ✓ **Not detected yet**

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)



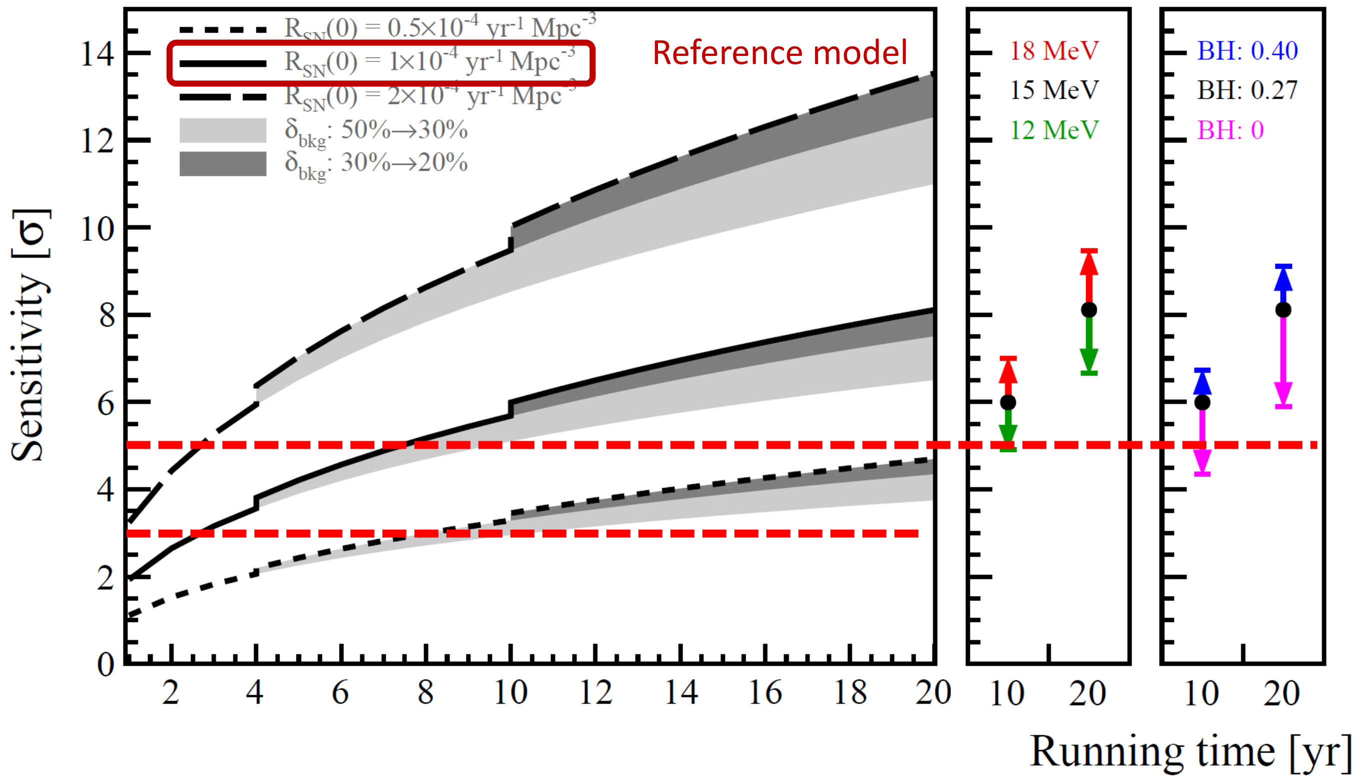
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)* **:**

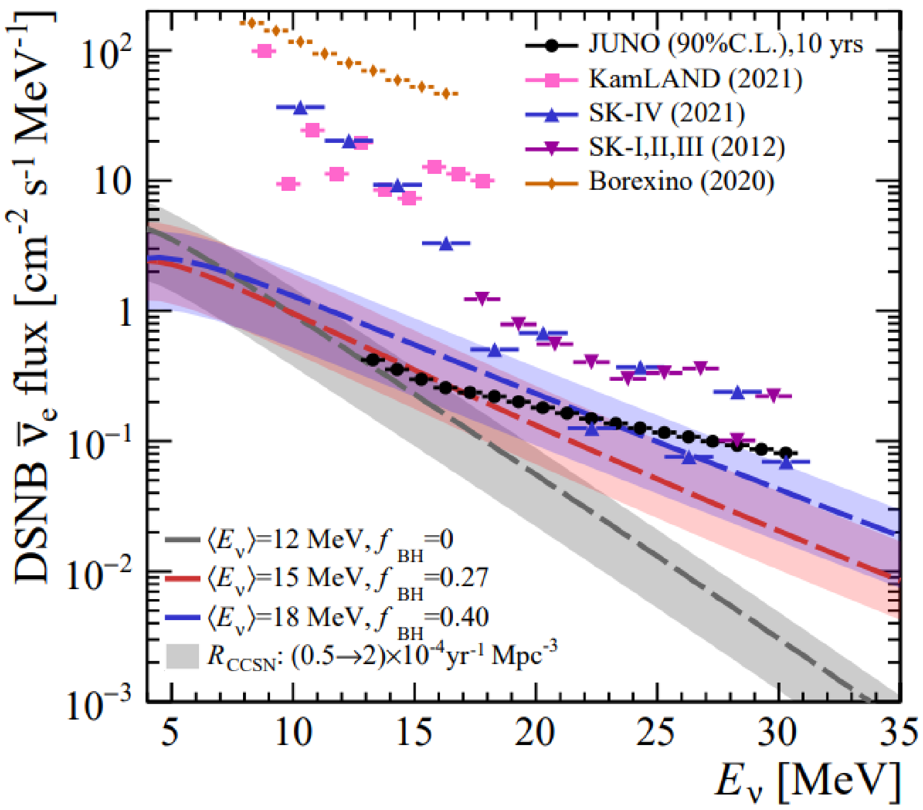
- ✓ **Background evaluation:** 0.7 per year → **0.54** per year
- ✓ **PSD:** signal efficiency 50% → **80%** (1% residual background)
- ✓ **Realistic DSNB signal model: non-zero fraction of failed Supernova**

➡ S/B improved from **2 to 3.5**

Diffuse Supernova Neutrino Background (DSNB)

arXiv: 2205.08830, JCAP 10 (2022) 033





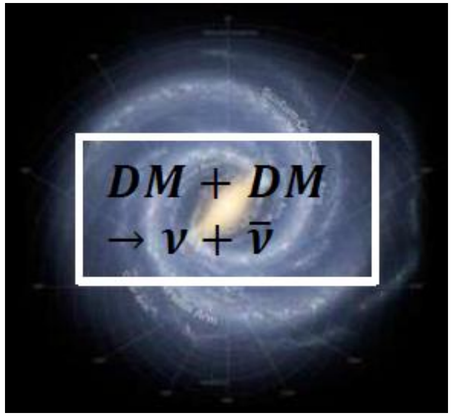
- **If no positive observation, JUNO can set the world-leading best limits of DSNB flux**
- **With the nominal model (black solid curve (left plot)): 3σ (3 yrs) and 6σ (10 yrs)**

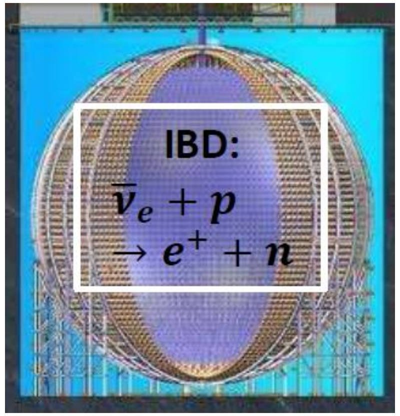
Indirect Dark Matter Search

- Neutrinos (other “invisible particles”) from Dark Matter
  - Dark Matter captures in the solar core, Earth, Milky Way
  - Neutrinos from Dark Matter annihilation or decays
  - See JUNO Yellow Book, & W.L Guo, JCAP 01 (2016) 039

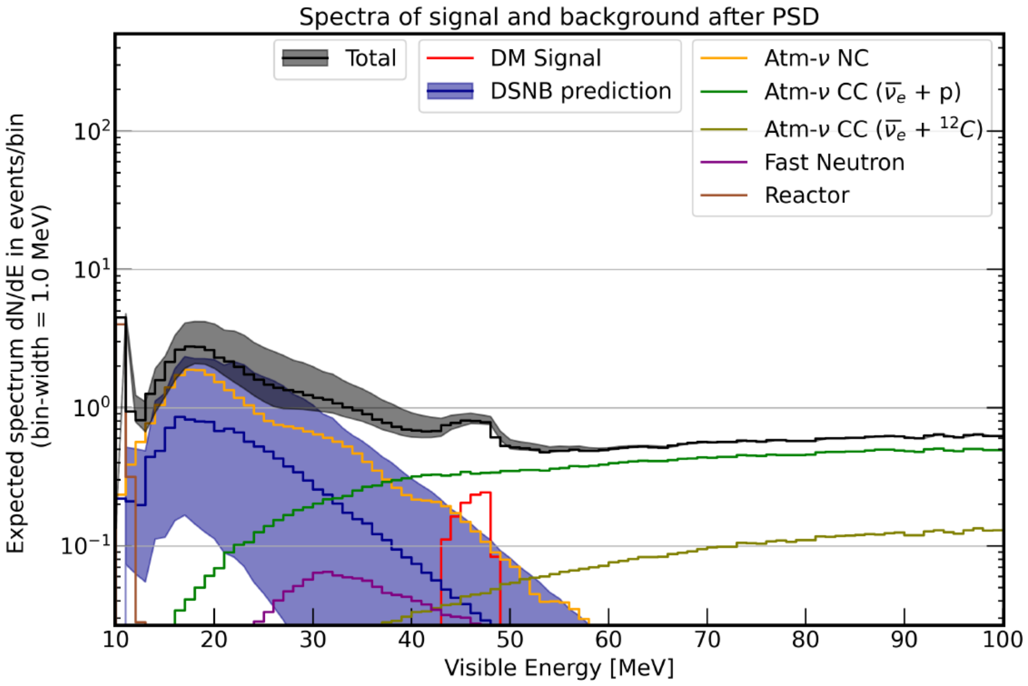
- Boosted dark matter, new particles produced in the atmosphere
  - many new ideas

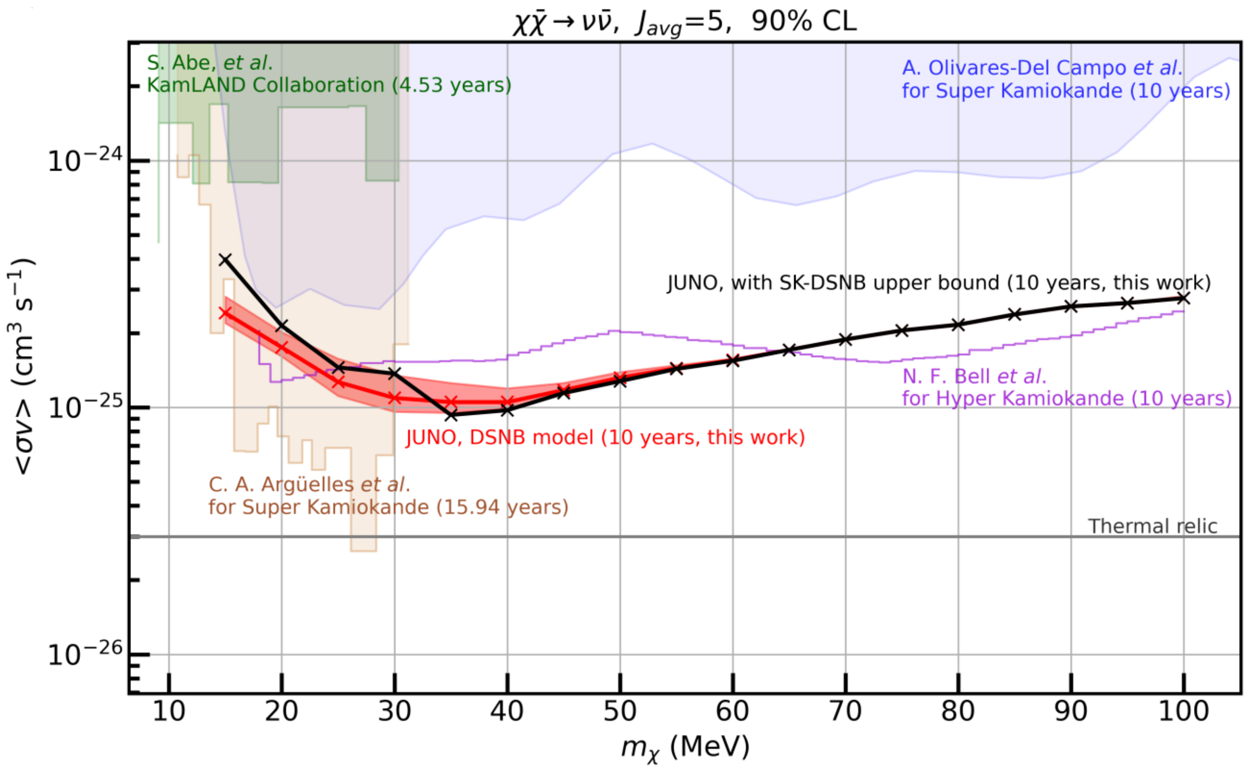
Indirect Dark Matter Search





- 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

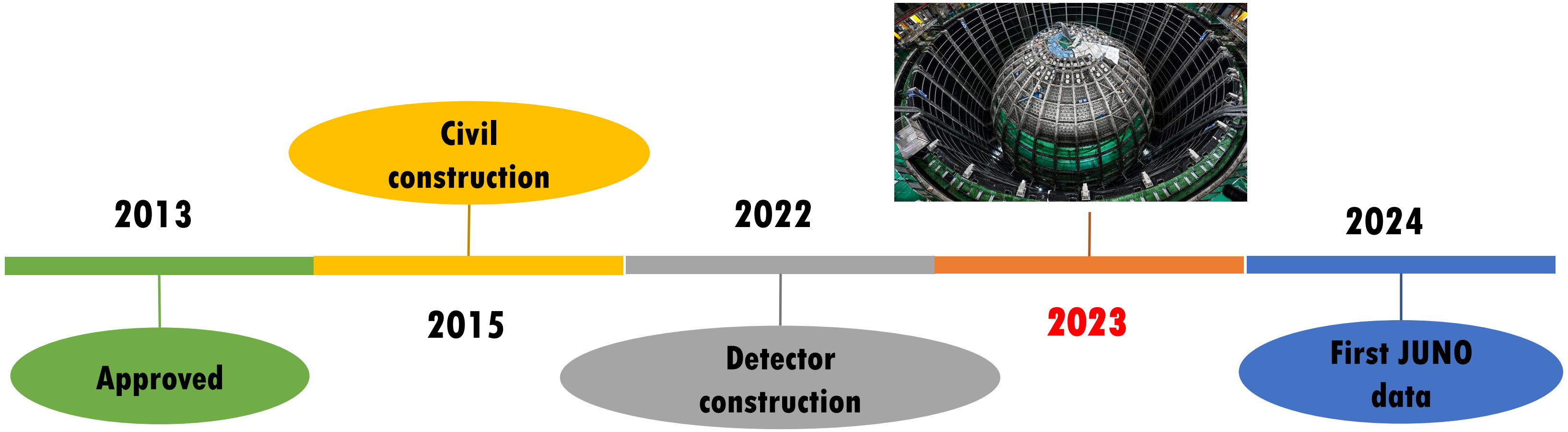




arXiv:2306.09567 [hep-ex]

Outlook

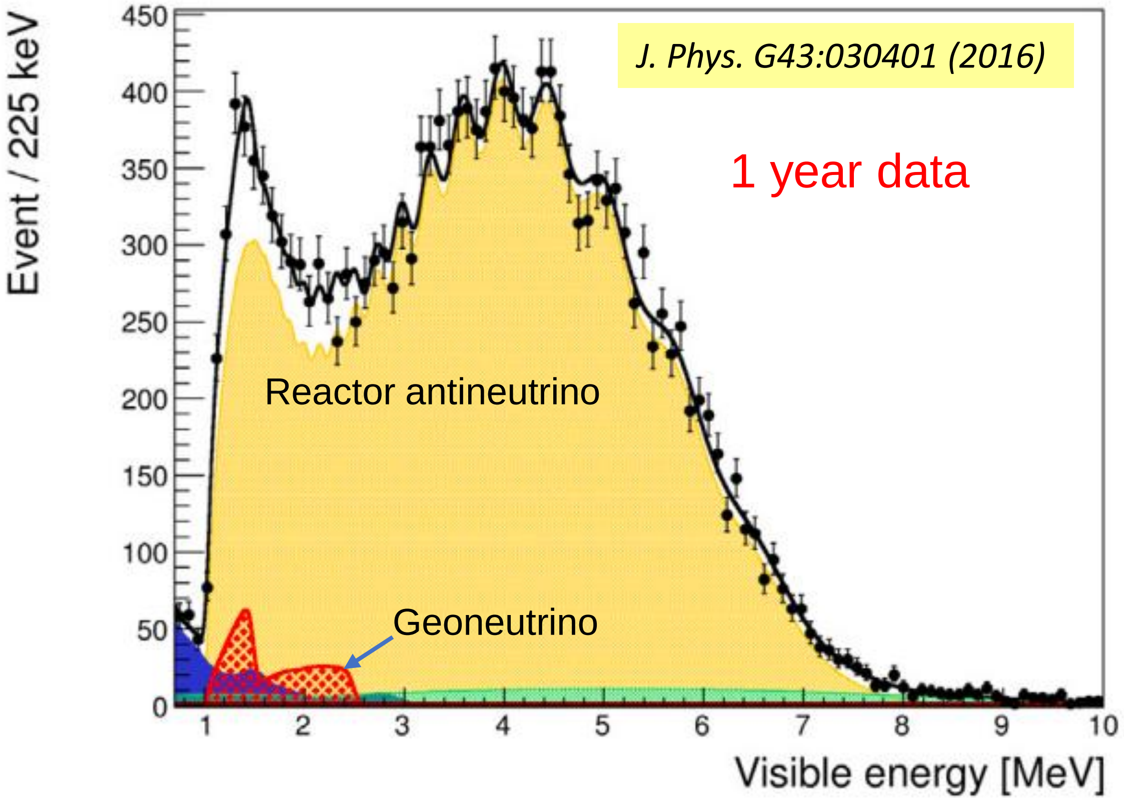
Physics	Sensitivity
Neutrino Mass Ordering	3σ in 6 yrs by reactor neutrinos. *Atmospheric ν sensitivity to be improved*
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{31}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~7300 of all-flavor neutrinos
DSNB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

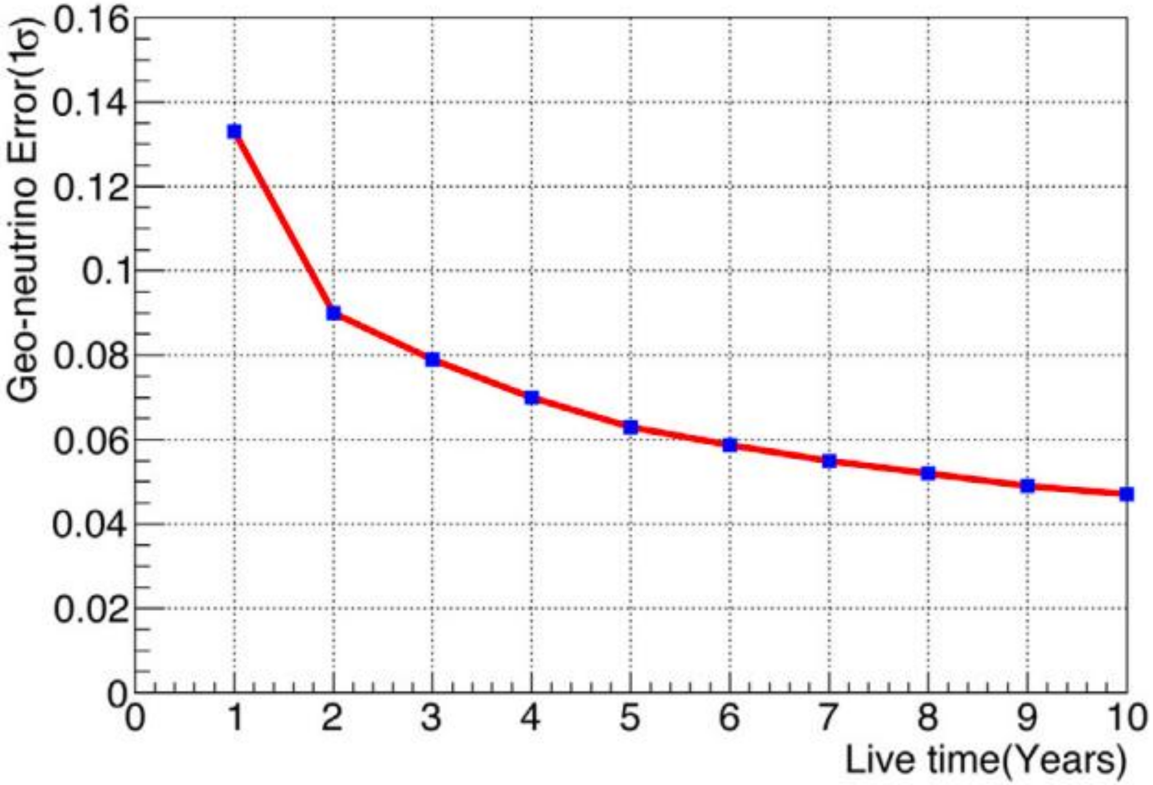


Back up

Neutrinos from earth

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



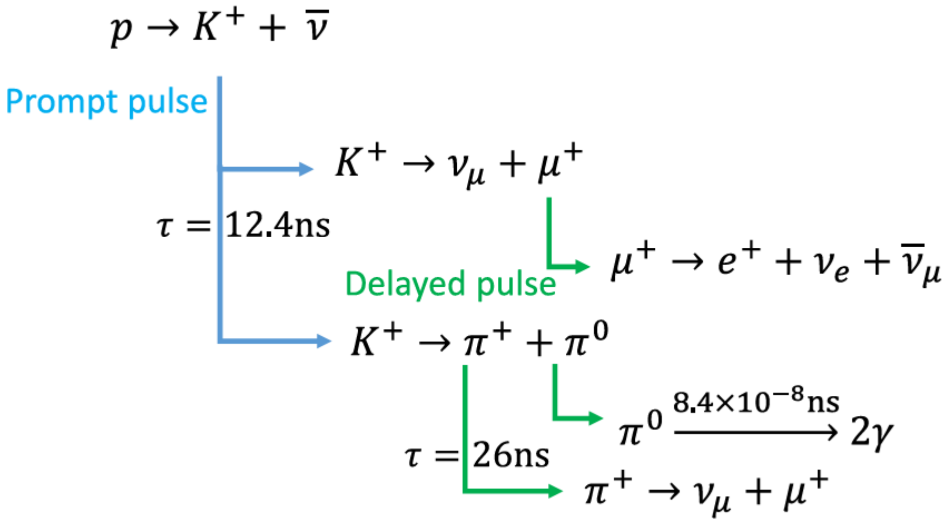


Signal in JUNO (CRUST1.0): 39.7 +6.5 −5.2 TNU (~400 geo-νs per year), 5% measurement in 10 years.

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

With new Local Refined Crust model (*PEPI*, 299 (2020) 106409), the geo-ν signal is ~30% larger, updated sensitivity is on-going.

Nucleon decays



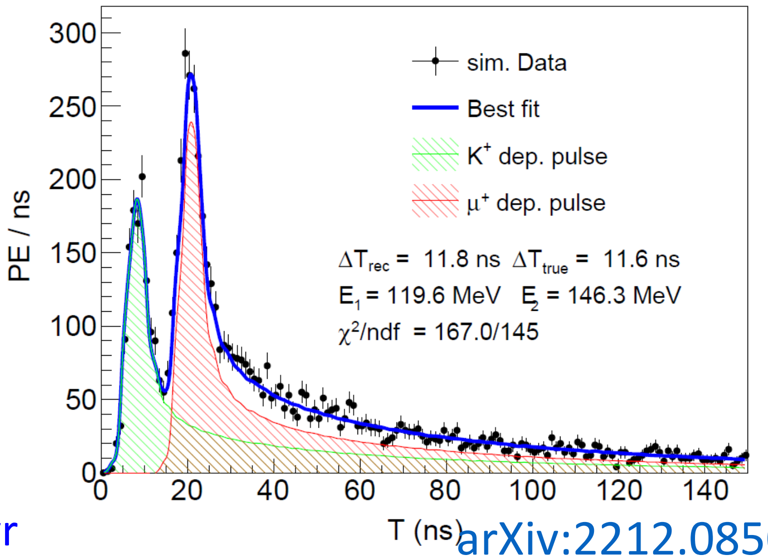
- **Signature:** three-fold coincidence
- **Dominant background:** atmospheric neutrino interactions

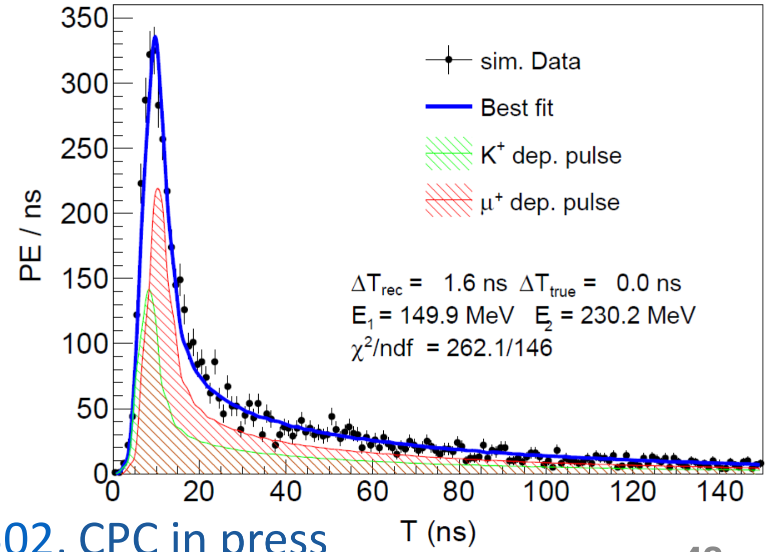
Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \rightarrow \nu + n$ $\nu + p \rightarrow \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \rightarrow n + l^+$ $\nu_l + n \rightarrow p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \rightarrow l^- + p + \pi^+$ $\nu + p \rightarrow \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \rightarrow l^- + \Lambda + K^+$ $\nu_l + p \rightarrow l^- + p + K^+$	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): $>5.9 \times 10^{33}$ yrs @ 260 kton·yr

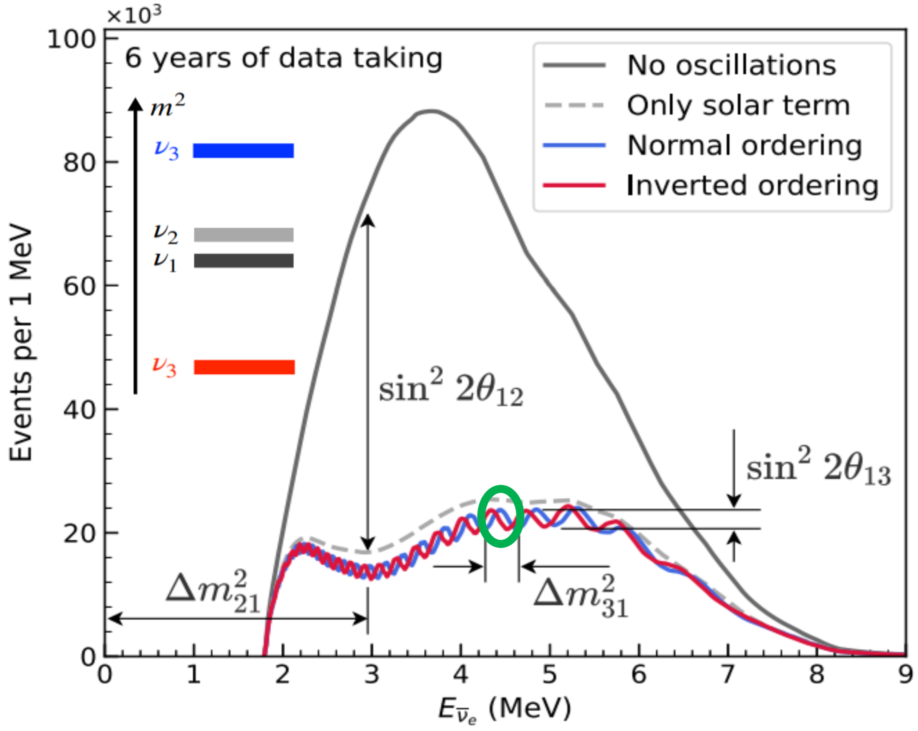




arXiv:2212.08502, CPC in press

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.

Update of energy resolution

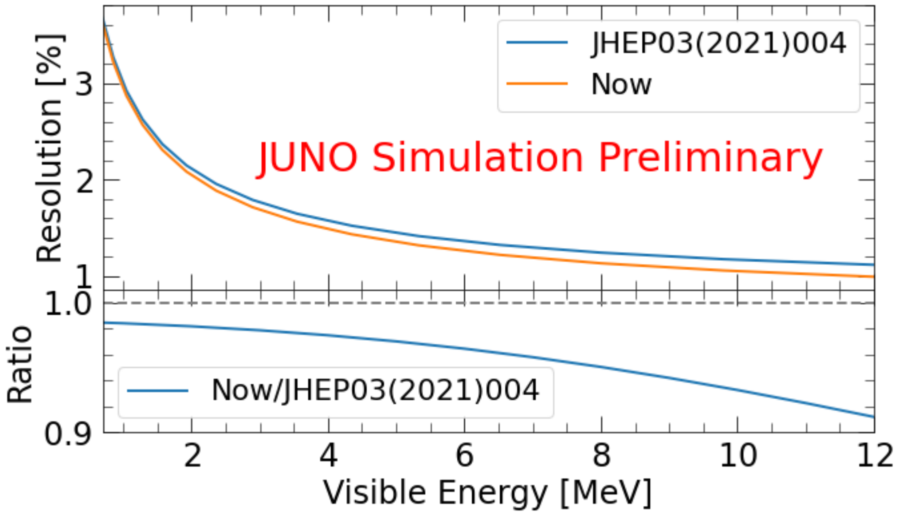
Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	JHEP03(2021)004
Photon Detection Efficiency (**27%→30%**)	**+11%↑**	**2.9% @ 1MeV**	arXiv: 2205.08629
New Central Detector Geometries	**+3%↑**		
New PMT Optical Model	**+8%↑**		EPJC 82 329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

- **Annihilation-induced γs**
- **Dark noise**



Positron energy resolution

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

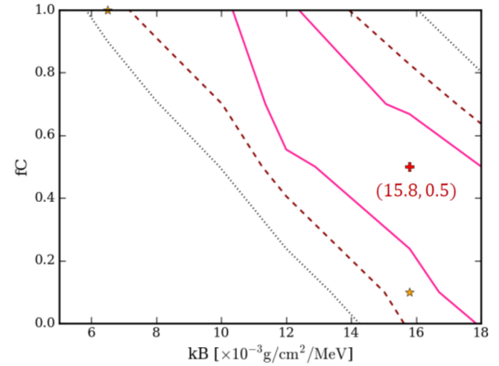
Photon statistics

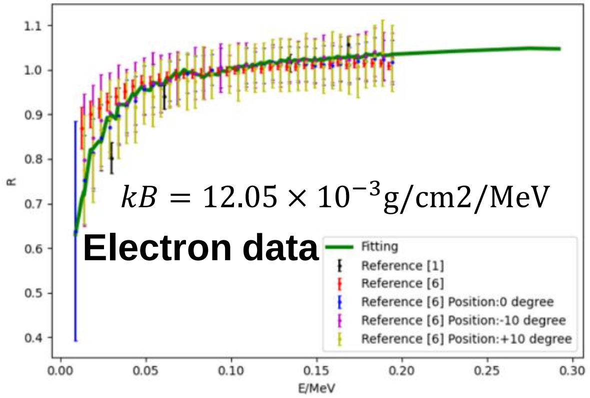
- **Annihilation-induced γs**
- **Dark noise**

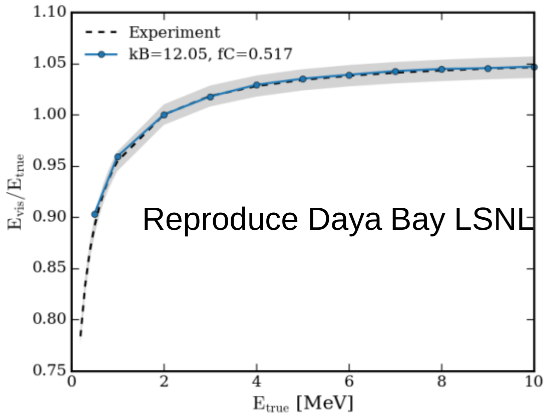
- **Scintillation quenching effect**
  - LS Birks constant **(kB)**
- **Cherenkov radiation**
  - LS refractive index
  - LS re-emission probability
  - Cherenkov yield scale factor **(fC)**
- **Detector uniformity and reconstruction**

- **kB** & **fC** are key parameters to predict energy resolution

- **Firstly attempt to constrain kB & fC with Daya Bay LS non-linearity**
  - Strong correlation between kB and fC
- **Solved by combining a series of table-top measurements on scintillation quenching effect**
  - kB of LS is determined to be $12.05 \times 10^{-3}\mathrm{g/cm2/MeV}$
- **Re-constrain fC with Daya Bay LS non-linearity**
  - fC is determined to be 0.517



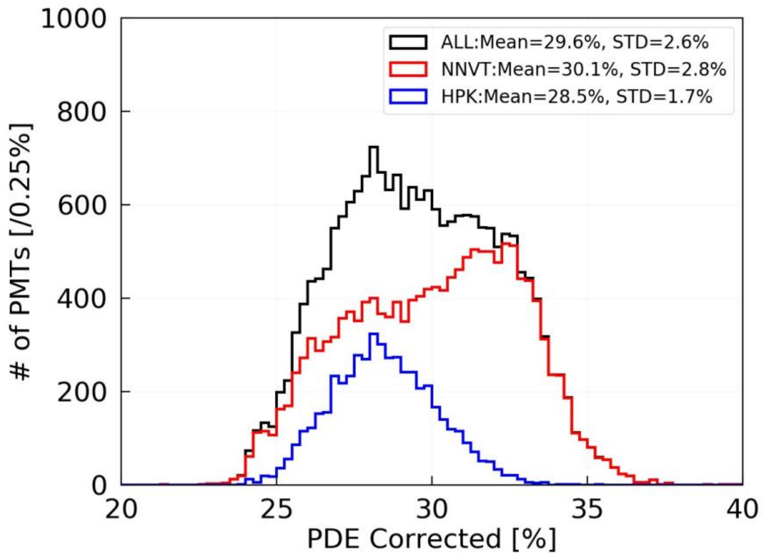




Light yield evolution

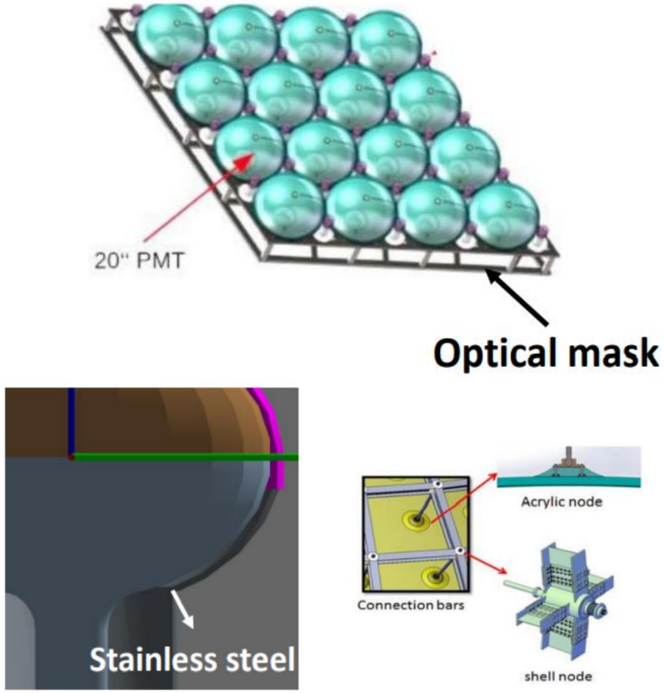
PMT PDE

- Averaged PDE:27.0%→30.1%
- 27.0% is based on the original requirement of **QE~30%, CE~90%**
- 30.1% is the selected mean PDE, from **PMT mass testing system**



arXiv:2205.08629

New Geometries

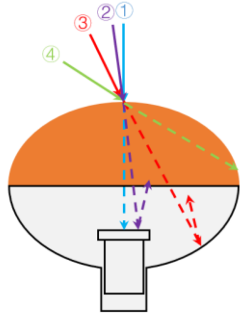


- **Reflections** on them are taken into consideration
- Yield 2.7% more photons

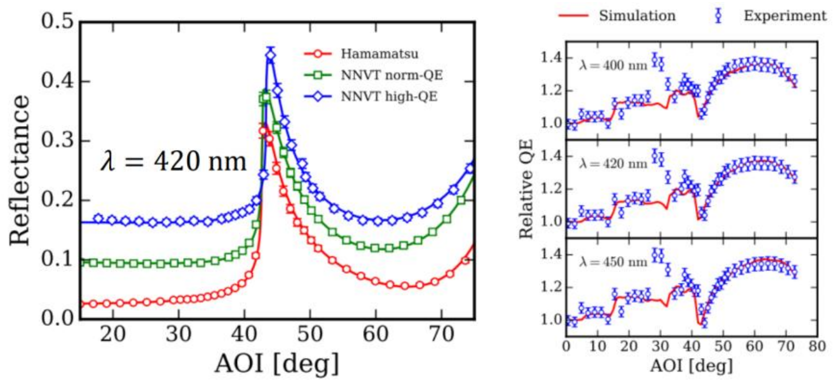
New PMT Optical Model

Optical Processes in PMT

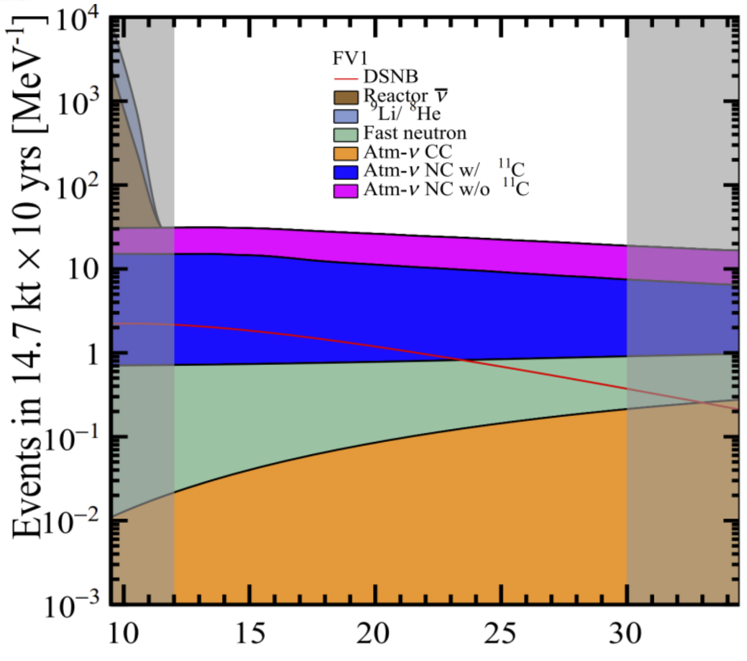
- Reflection on photocathode
- PDE angular response
- Multiple reflections inside PMT



- ◆ Multilayer thin film theory
- ◆ Experimental tests
- ◆ GEANT4 simulation

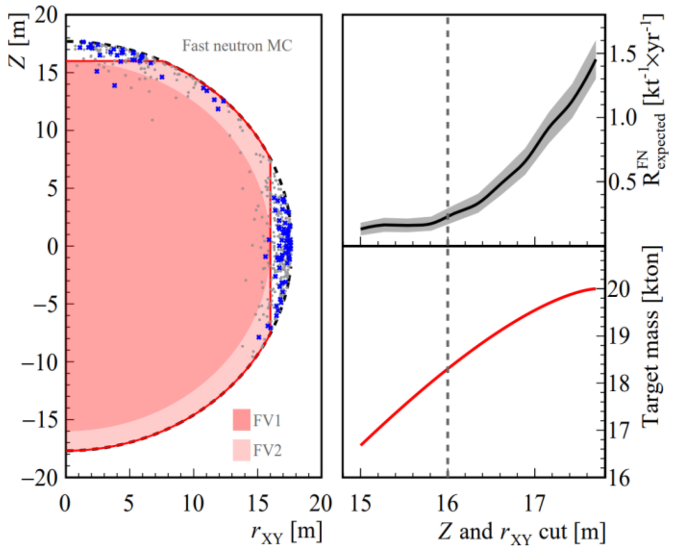


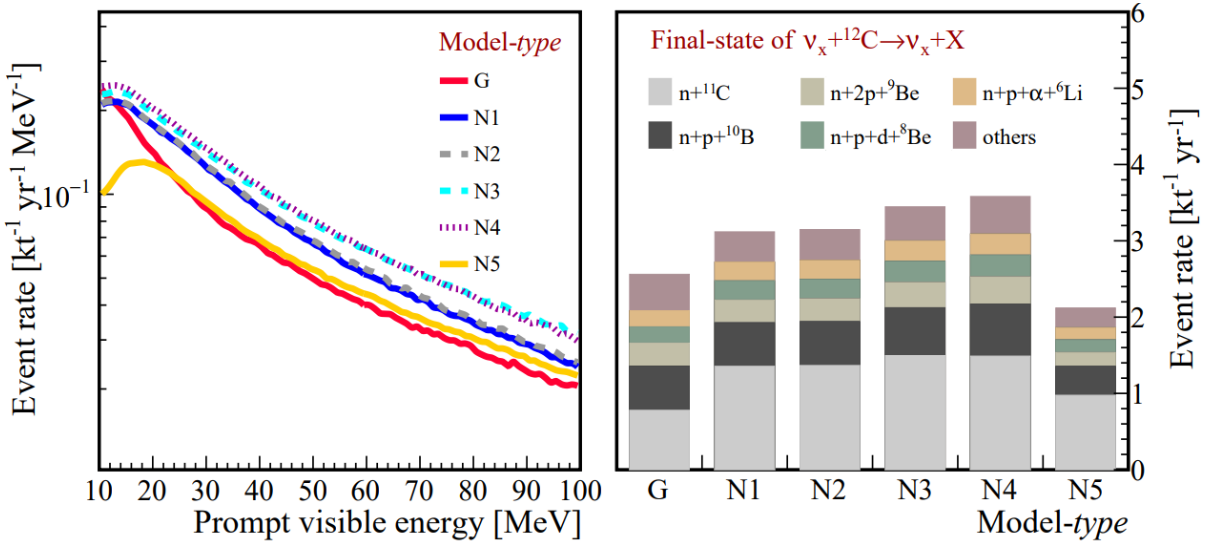
Diffuse Supernova Neutrino Background



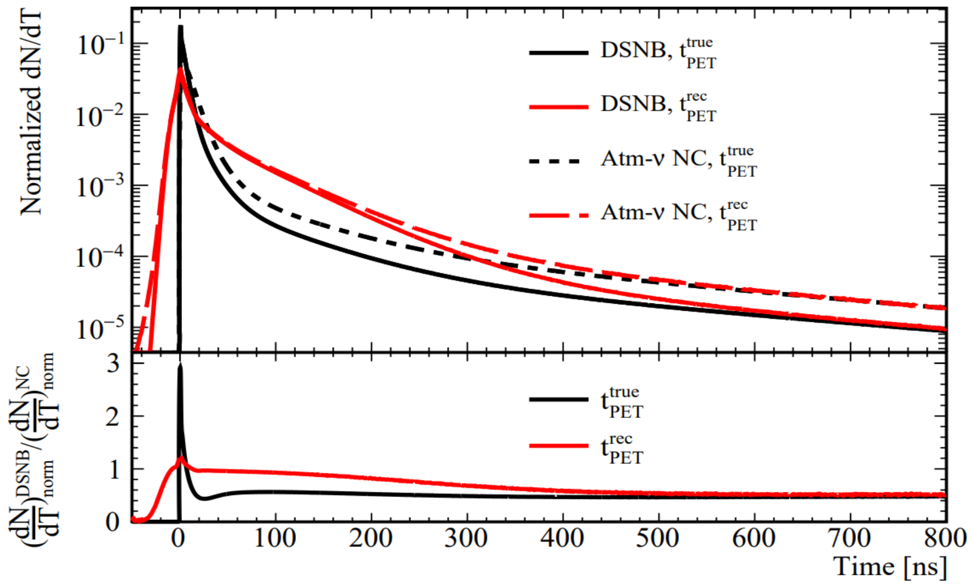
Major backgrounds (above 12 MeV):

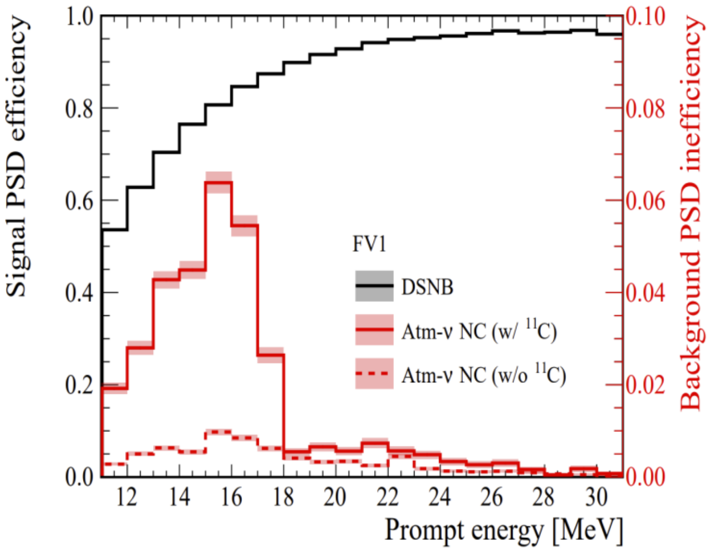
- Fast neutron ➔ Two fiducial volumes
- Atmospheric neutrino CC interactions (intrinsic IBDs)
- Atmospheric neutrino NC interactions
  - Prediction ➔ ν-N interactions (GENIE, NuWro) + TALYS (de-excitation)
    method Ref: Phys.Rev.D 103 (2021) 5, 053001
  - Uncertainty ➔ Future *in situ* meas. (~15% after ten years)
    method Ref: Phys.Rev.D 103 (2021) 5, 053002
  - Discrimination ➔ PSD technique & Triple coincidence (^{11}C delayed decay)

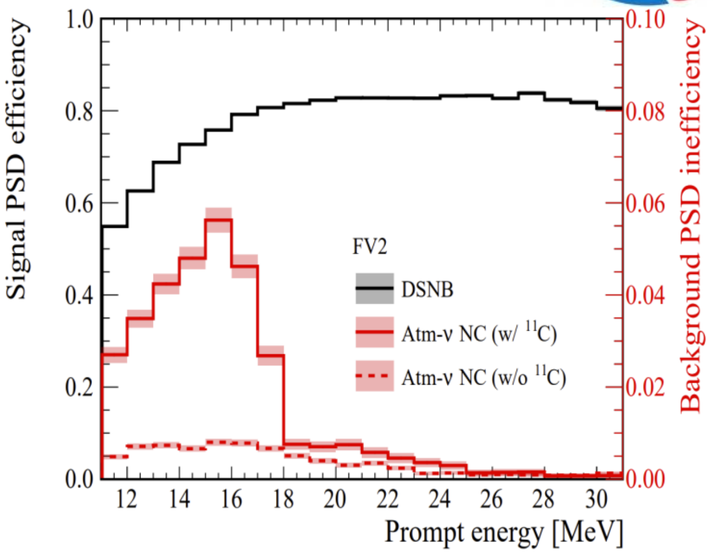




Diffuse Supernova Neutrino Background







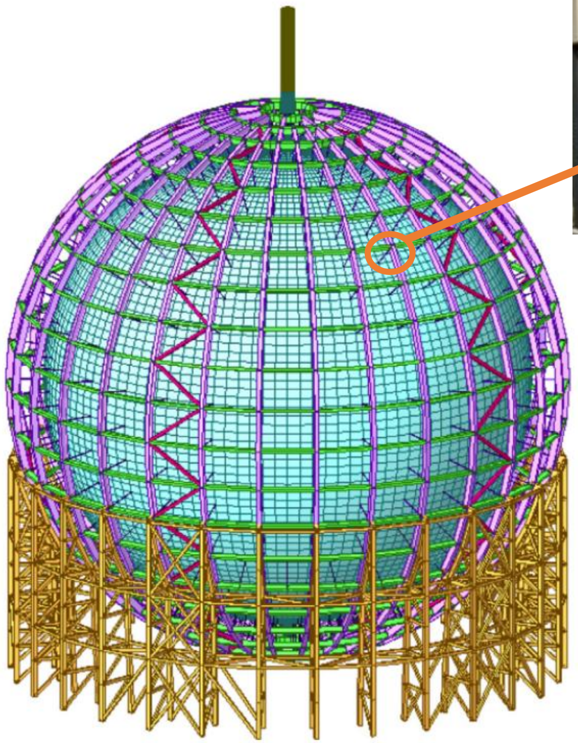
- Different time profiles of signal and background lay the foundation of pulse shape discrimination
- Machine-learning based PSD analysis
  - TMVA (baseline), Scikit-learn (cross check)

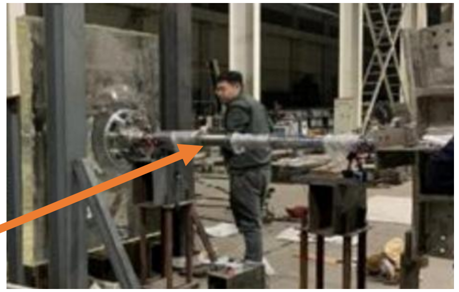
> - Final PSD efficiency at 1% residual background
>   - FV1 (84%), FV2 (77%) versus 50% in JUNO (2015)
> - Energy dependent feature of PSD in DSNB analysis (first time found in LS detectors)
>   - Energetic neutron below 18 MeV in LS: the inelastic reaction channel of ^{12}C with gamma production becomes dominate

Central detector (SS structure)

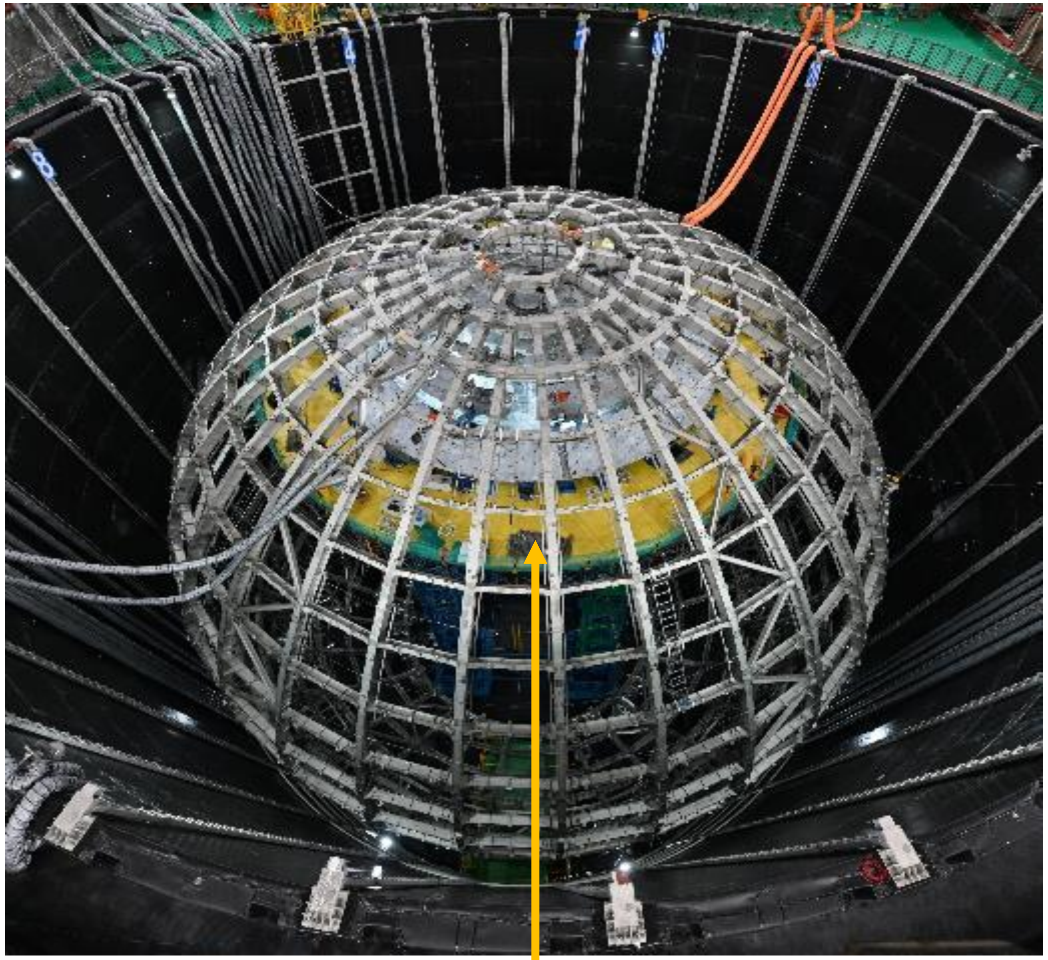
Acrylic vessel is supported by D = 40.1 m stainless steel structure via 590 Connecting Bars

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)

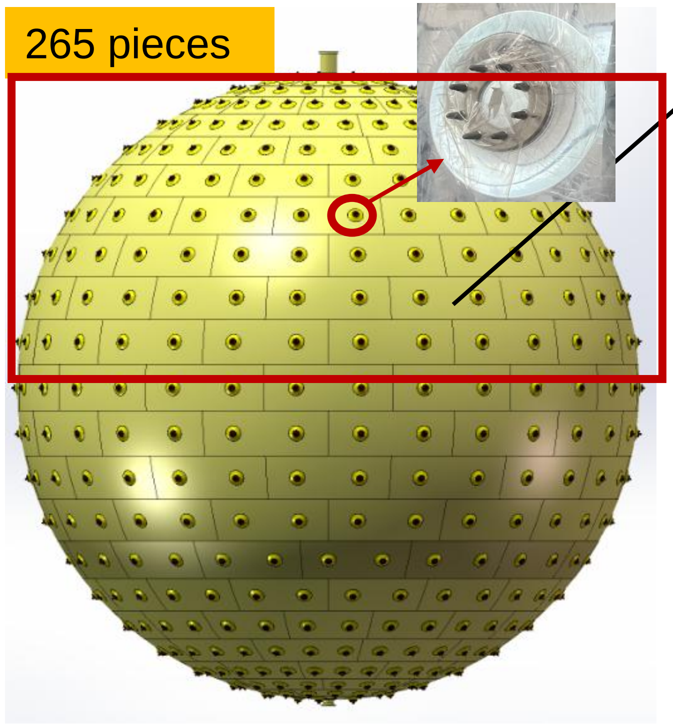
LS container:

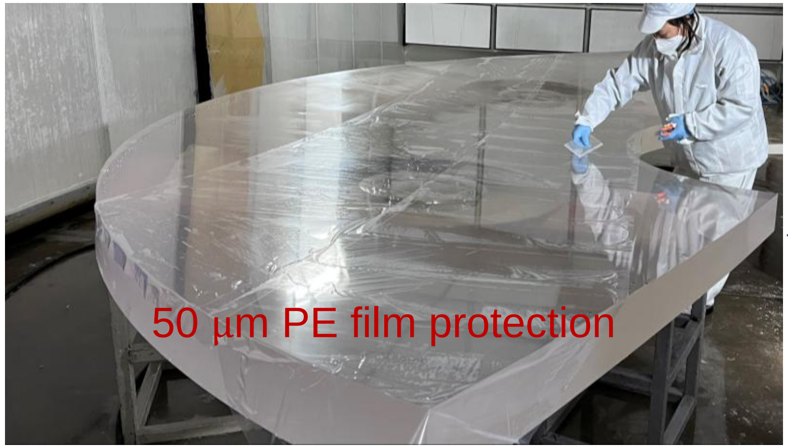
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ water

Radiopurity: U/Th/K < 1 ppt





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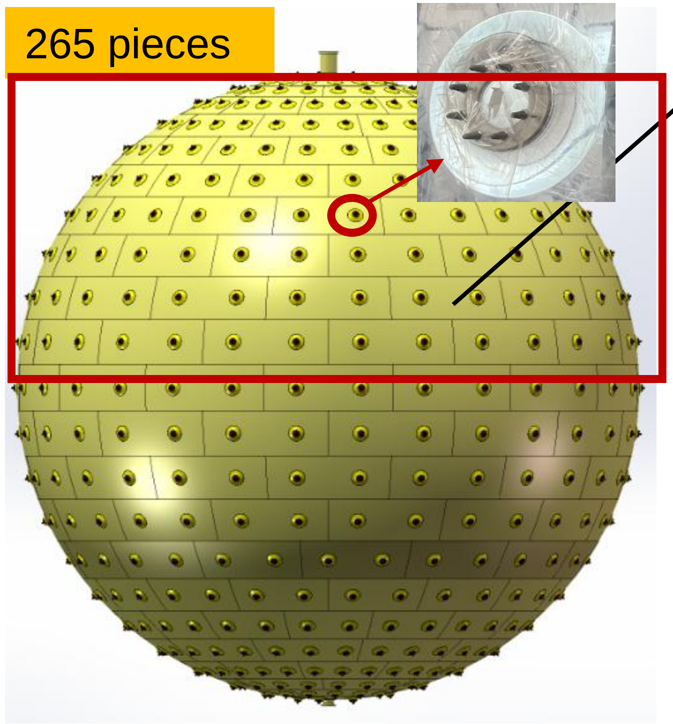
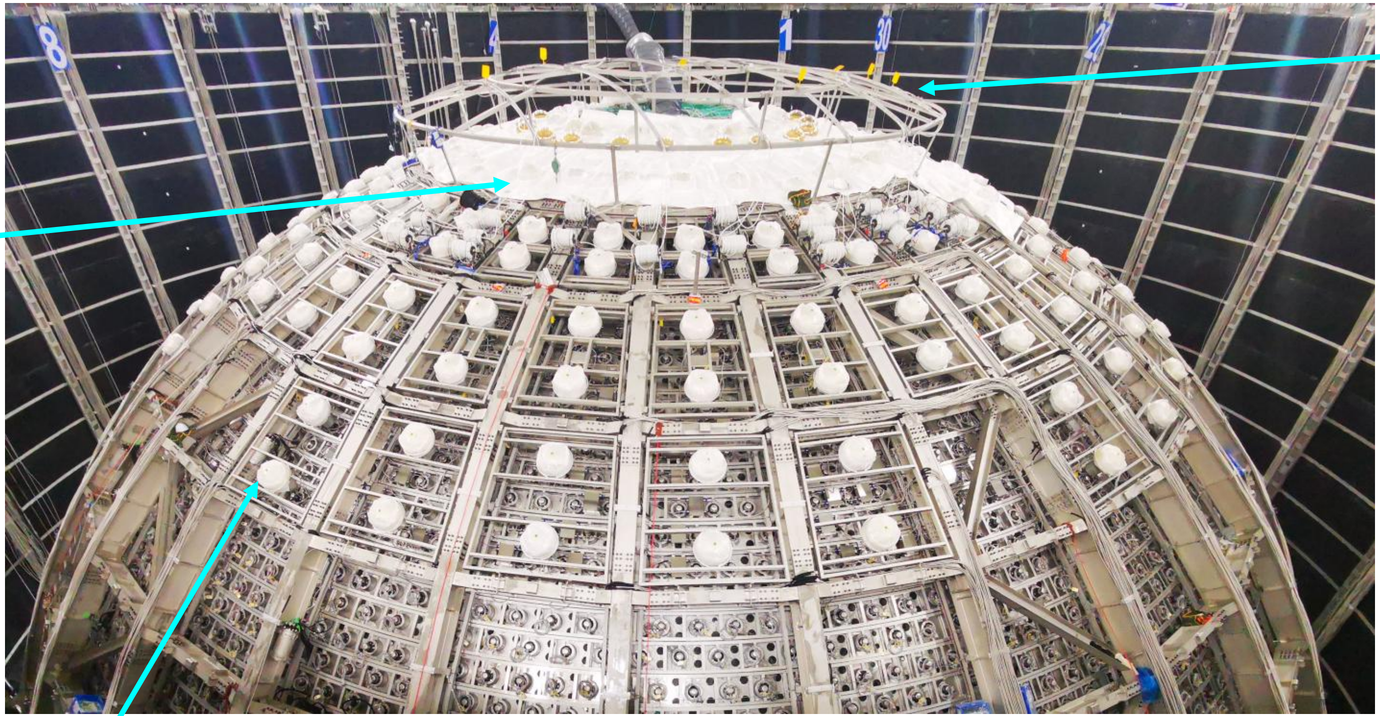


More than half acrylic sphere was finished!

Veto detector (Water Cherenkov)

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

Tyvek reflective film installation started



Earth magnetic shielding coils installation: 6 coils installed (32 coils in total)

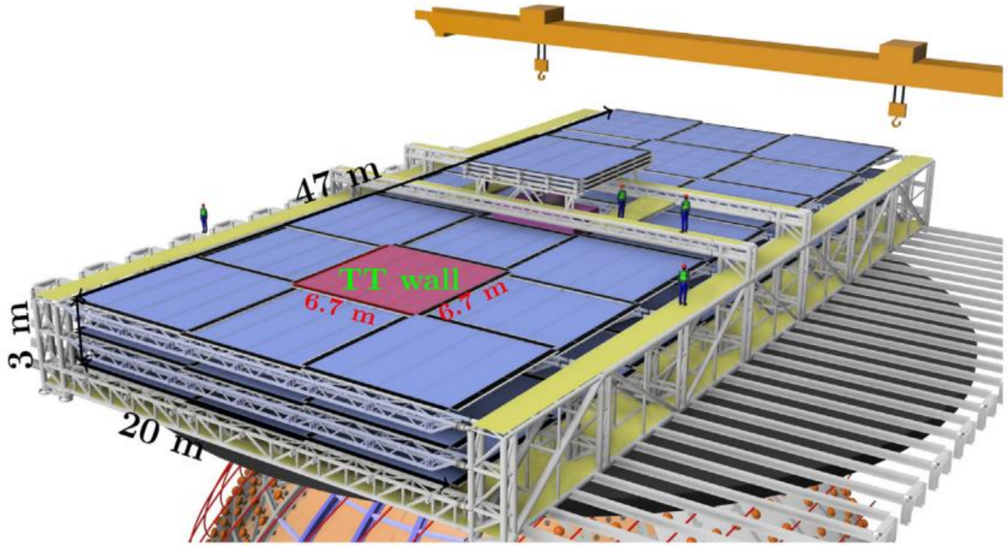
200 veto PMTs installed (~10% of PMT)

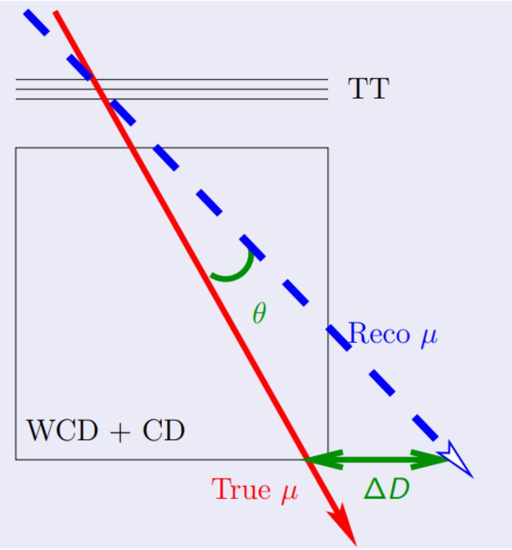
Water system almost ready for commissioning

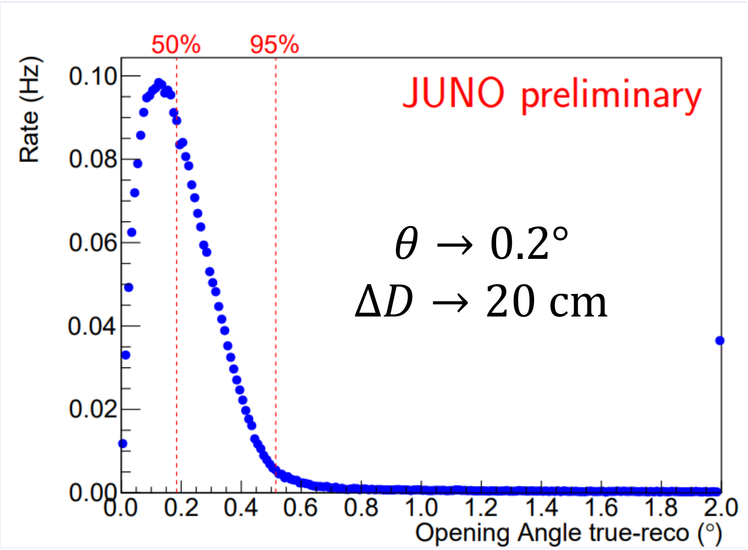
35 kton of ultrapure water serving as passive shield and water Cherenkov detector.

- ✓ 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

Veto detector (Top Tracker)







Plastic scintillator from the OPERA experiment *(NIM.A 1057 (2023) 168680)*

- 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 (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.


5000 m³ LAB tank


Al_2O_3 to improve transparency

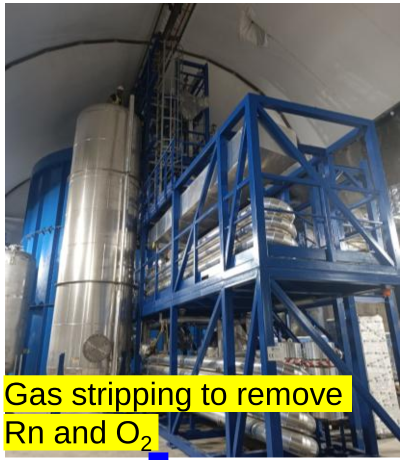

Distillation to remove radioactive impurities


Add 2.5 g/L PPO and 3 mg/L bis-MSB

SS pipes to underground

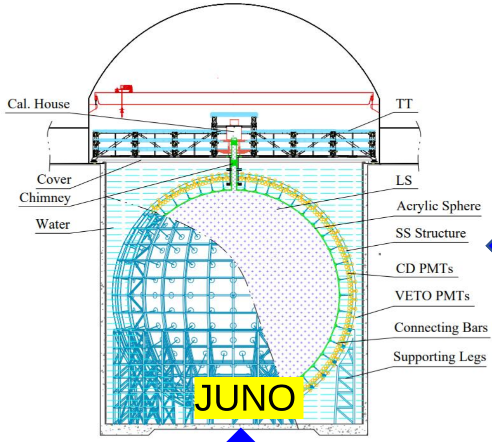
All LS related systems finished assembly, commissioning ongoing


Water extraction to remove radioactive impurities


Gas stripping to remove Rn and O_2

15%


OSIRIS for LS qualification



JUNO

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

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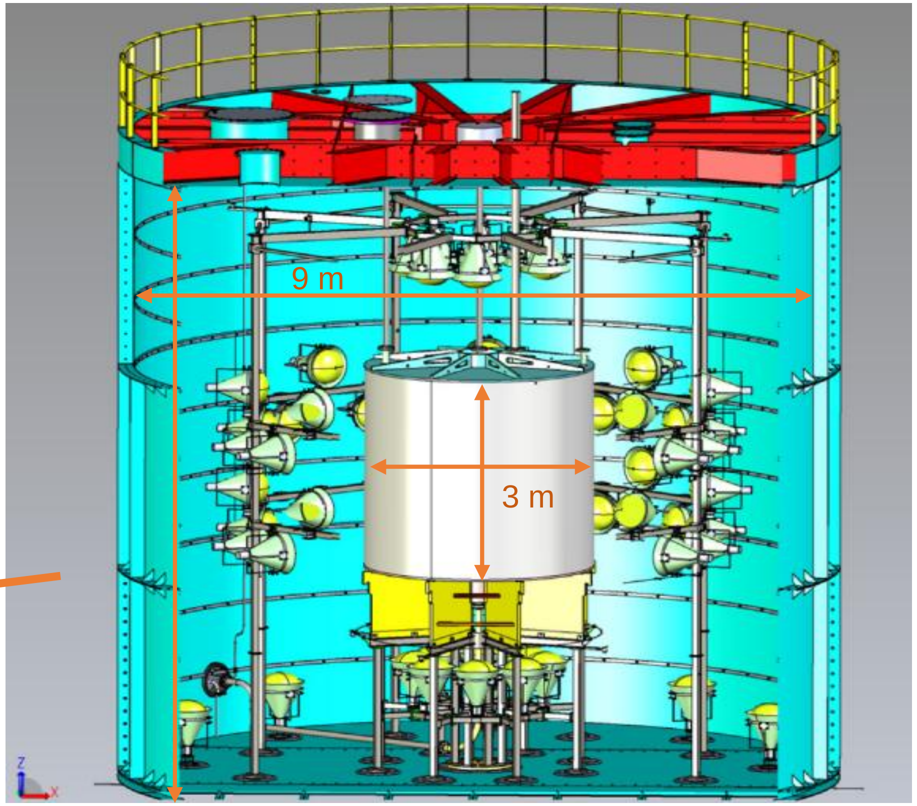
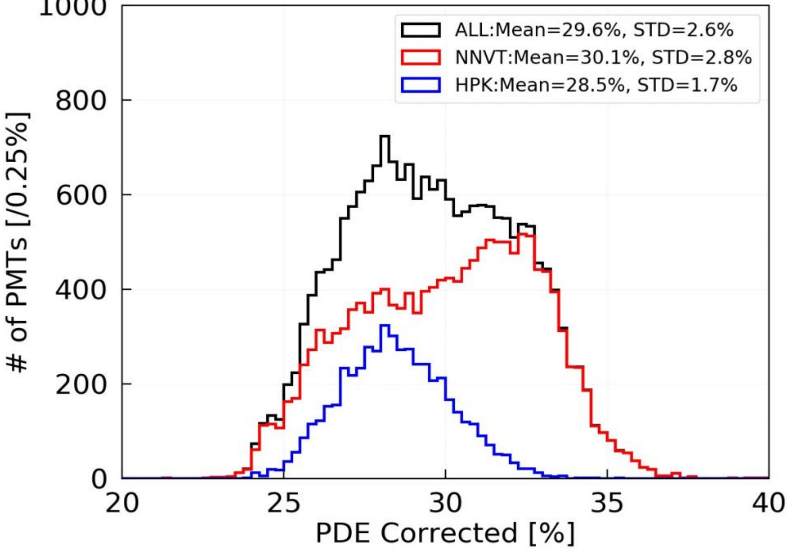


Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator): *arXiv: 2109.10782*

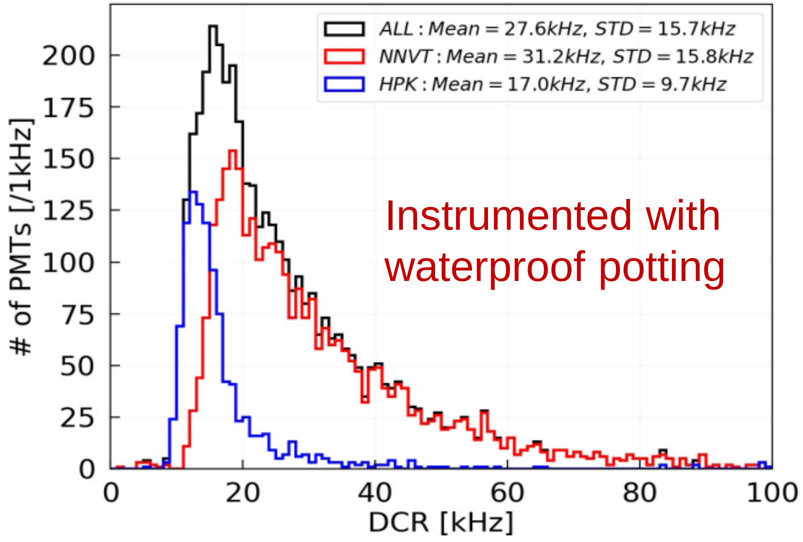
- ✓ A precision measurement of the flux of solar *pp* neutrinos on the few-percent level

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

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

Clearance between PMTs: 3 mm →

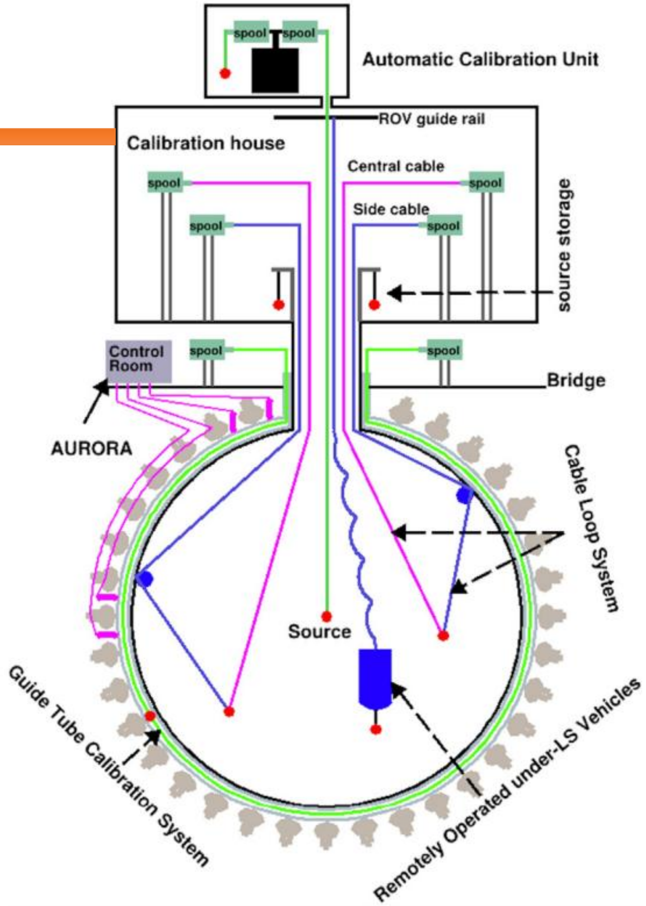
Assembly precision: < 1 mm

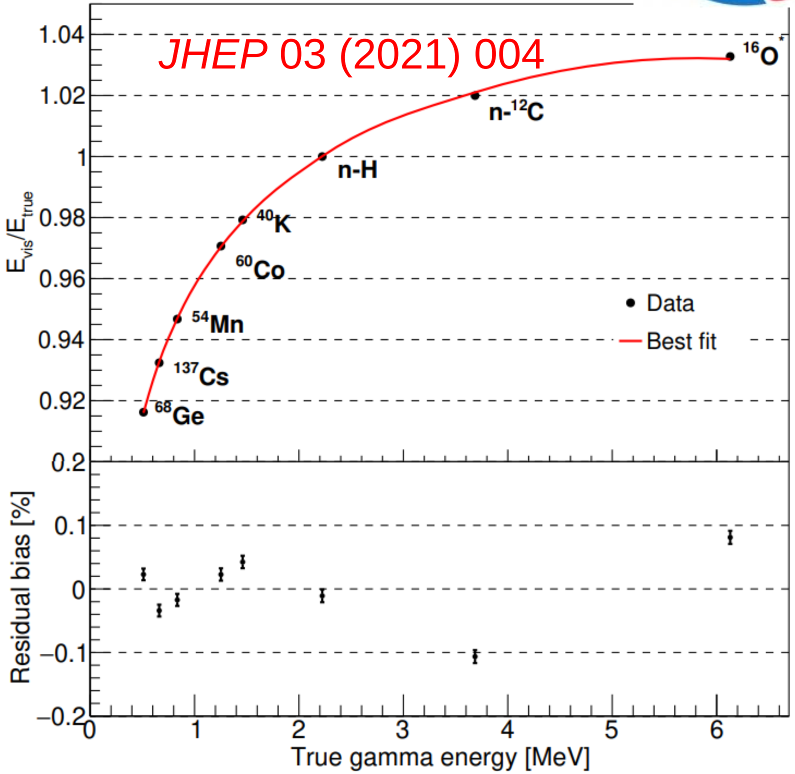
w/ protection cover (JINST 18 (2023) 02, P02013)

~5800 (CD) + ~200 (veto) LPMT and ~6000 SPMT have been installed

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%