Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI PADOVA

The JUNO experiment: status and physics potential

Neutrino Oscillation Workshop 2024 @ Otranto

Andrea Serafini
on behalf of the JUNO collaboration
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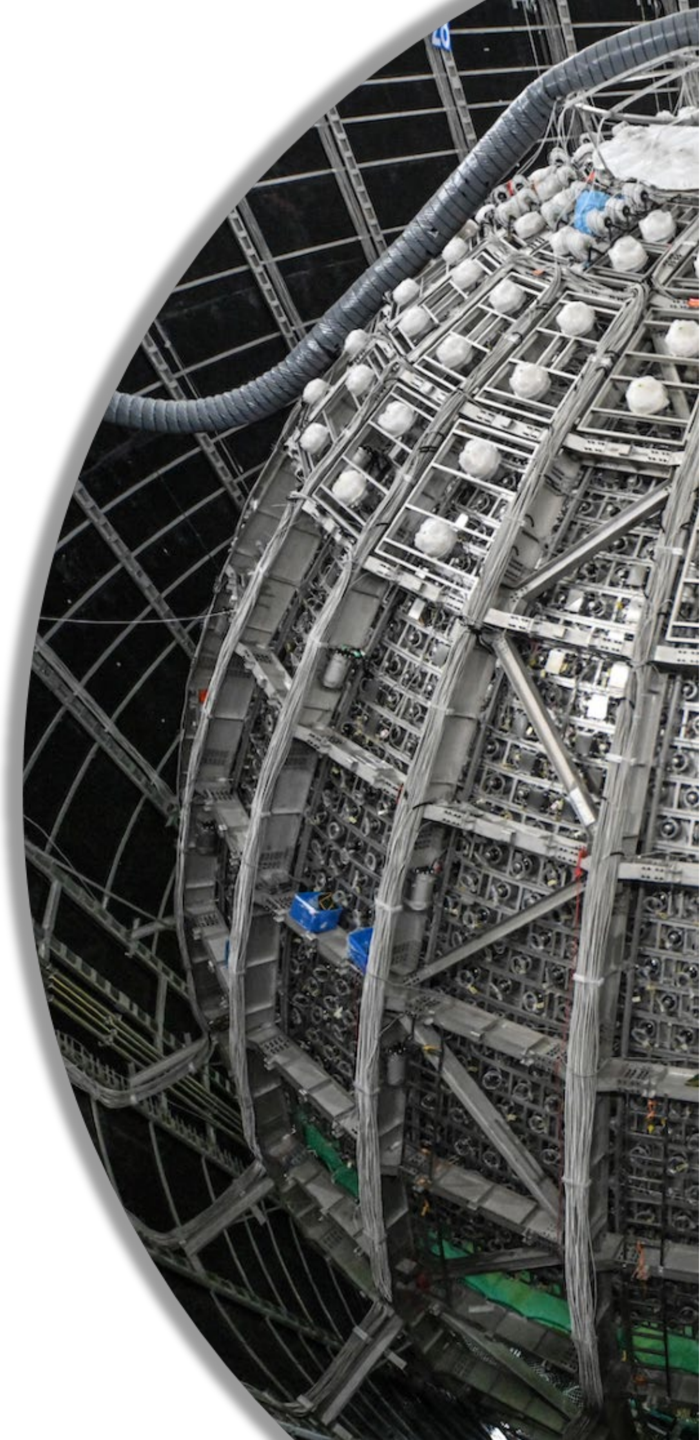

Where are we now?

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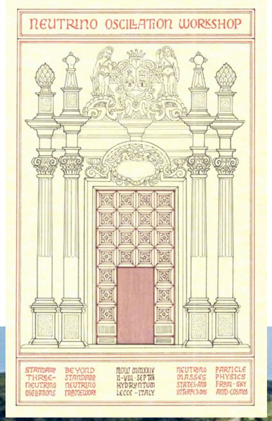
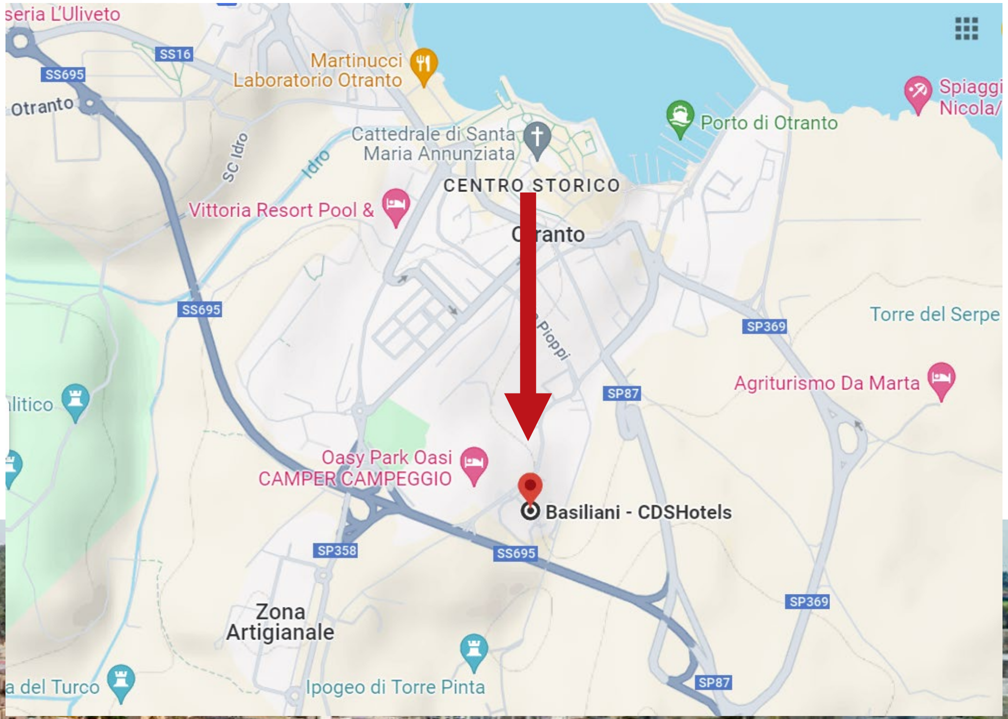


NOW 2024 conference
Basiliani SPA Hotel
Otranto (Lecce, Italy)



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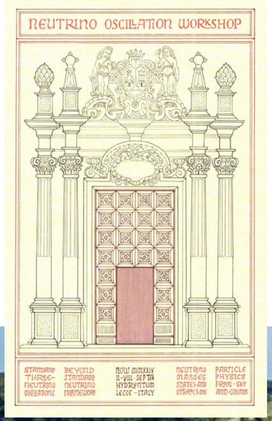

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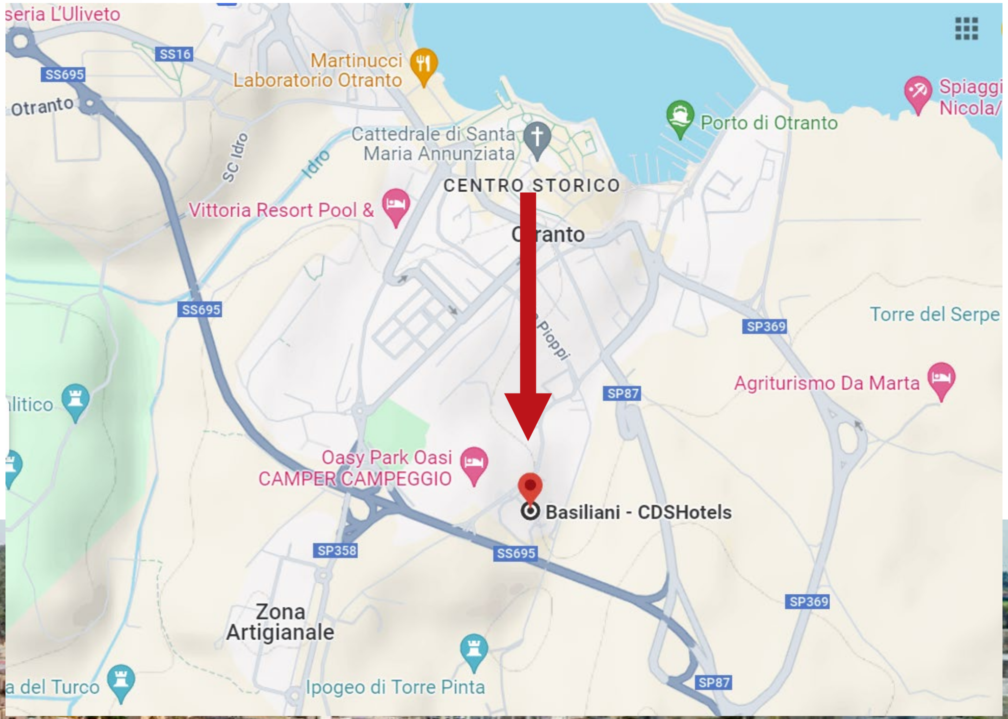


Just kidding!
Let me be more specific…

Where are we now? (in the neutrino field)

Eligio Lisi [slides](#) @ Neutrino 2024

Five pillars have been raised and will be further refined: δm^2, $|\Delta m^2|$, θ_{12}, θ_{13}, θ_{23}

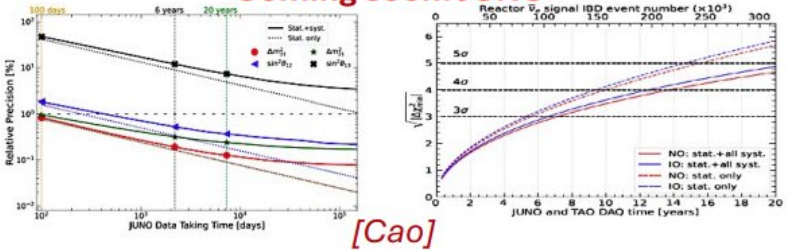
(θ_{23} still a bit unstable, consolidation will take some time...)

Two more pillars are under construction: **mass ordering, CP phase**

... and exciting plans + guaranteed results for decades!

Both precision and discovery frontiers

Coming soon: JUNO



[Cao]

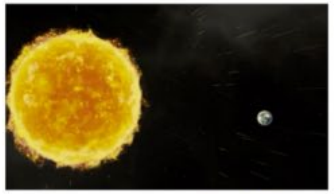
Expt frontiers with strong impact on theory/pheno

[Tortola, global analysis]
[Soler, Brunner, Yanez, atmos. analysis]
[Ding, flavor symmetries]
[Worcester, LBL pheno]
[Menendez, Guenette, $0\nu\beta\beta$ pheno]
[Maneira, solar ν]
[Expt. talks...]

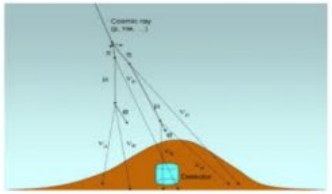
Each pillar supported by ≥2 classes of expts
→ Learn from ≥2 datasets via joint/global analyses

[Tortola]

Solar sector: θ_{12}, θ_{13}, Δm^2_{21}

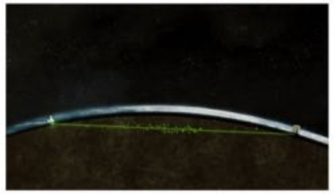


Atmospheric sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



Reactor sector: θ_{13}, Δm^2_{31}

Accelerator sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



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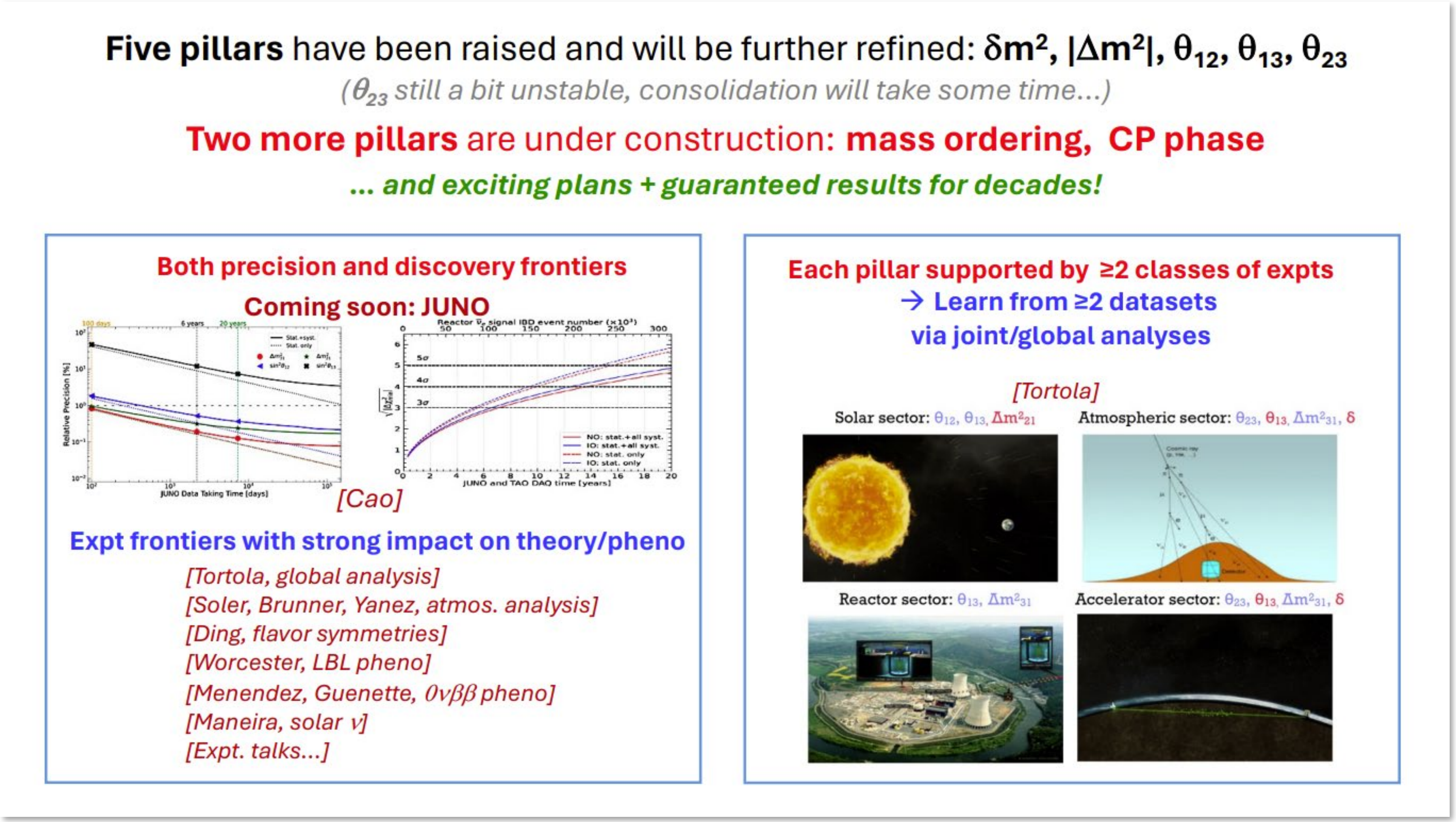

Pillars in ν physics

MO δ_{CP}

θ_{13} θ_{23}

θ_{12}

δm^2

Δm^2

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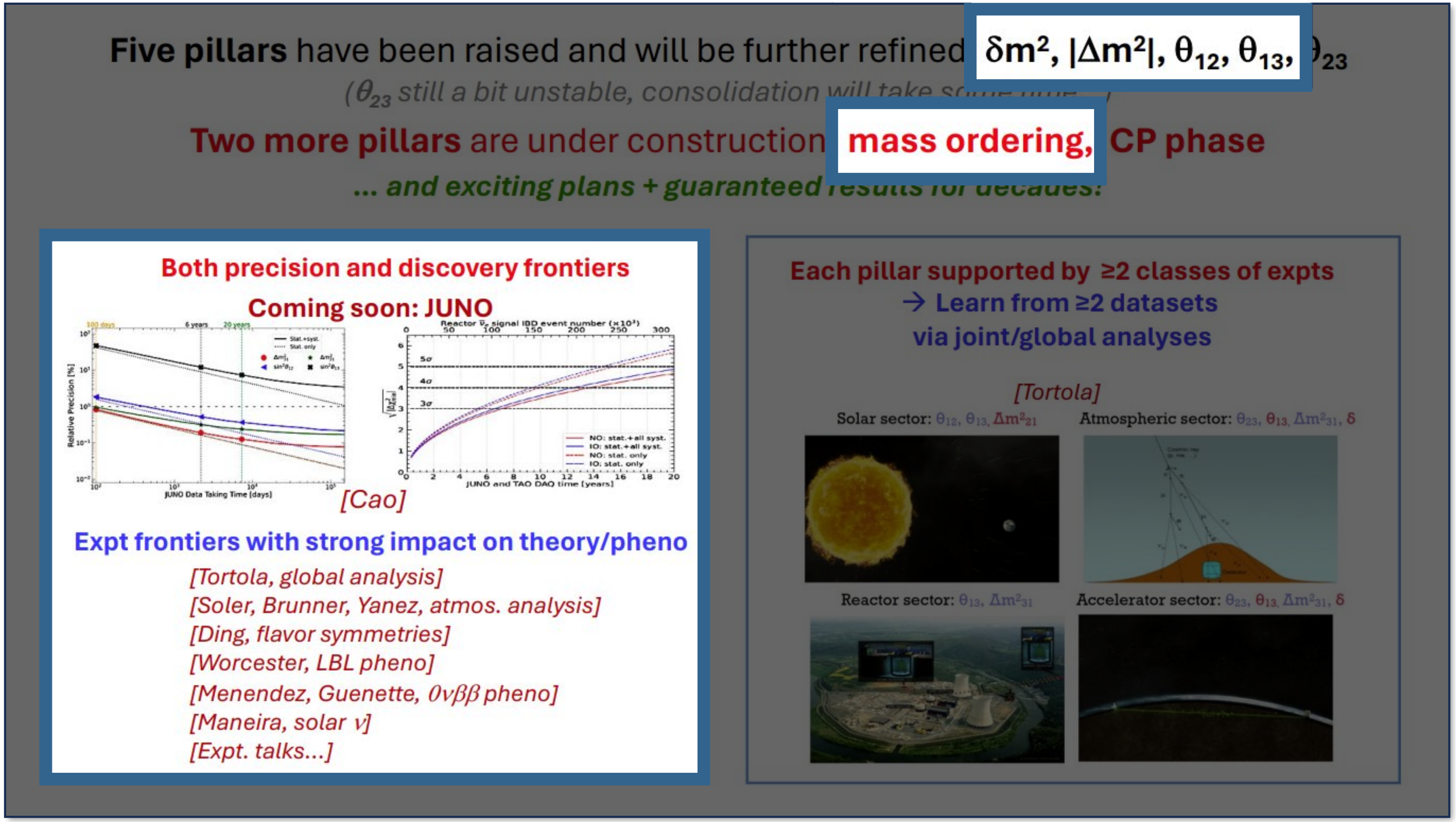
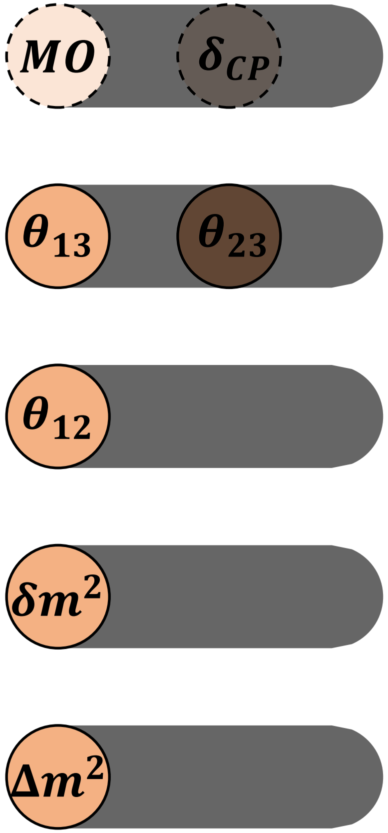
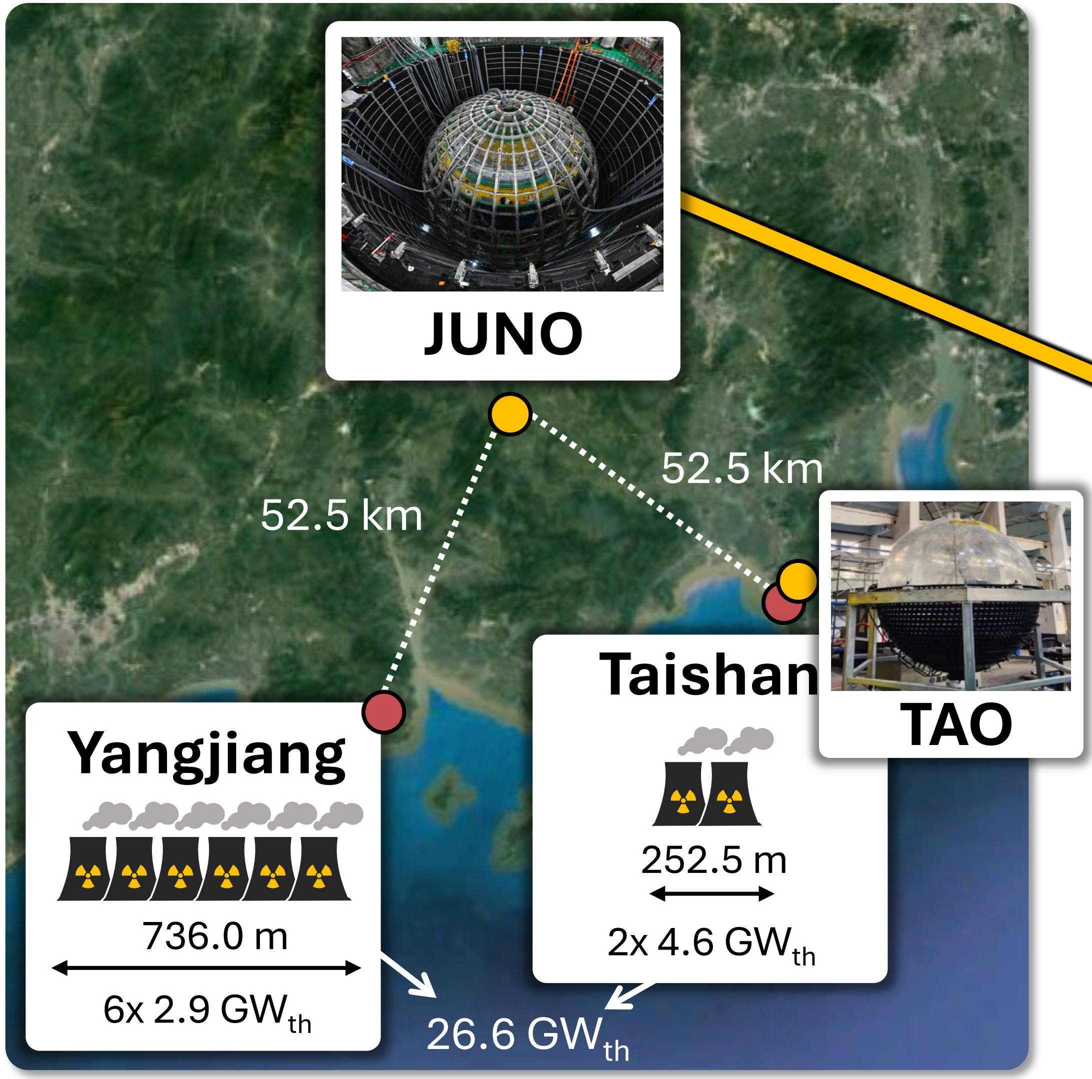


Pillars in ν physics
(from JUNO PoV)

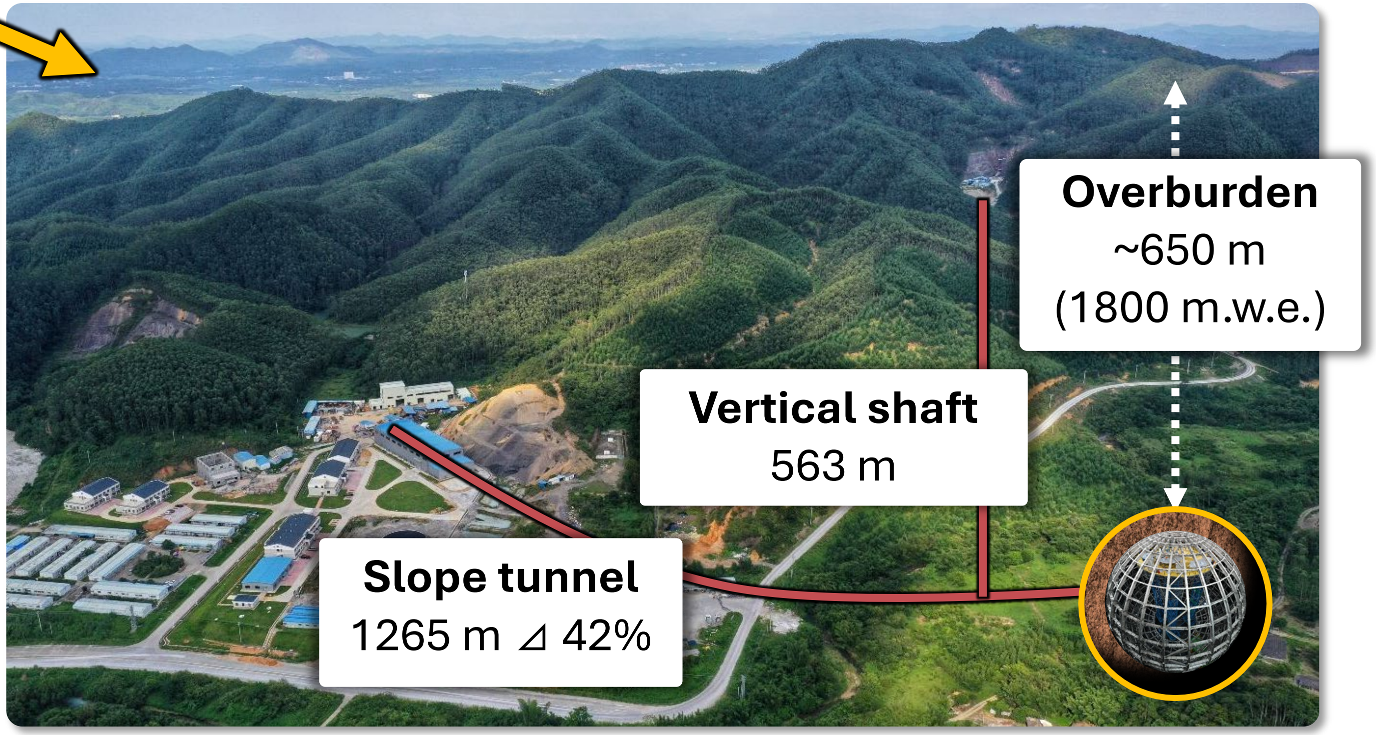


The Jiangmen Underground Neutrino Observatory



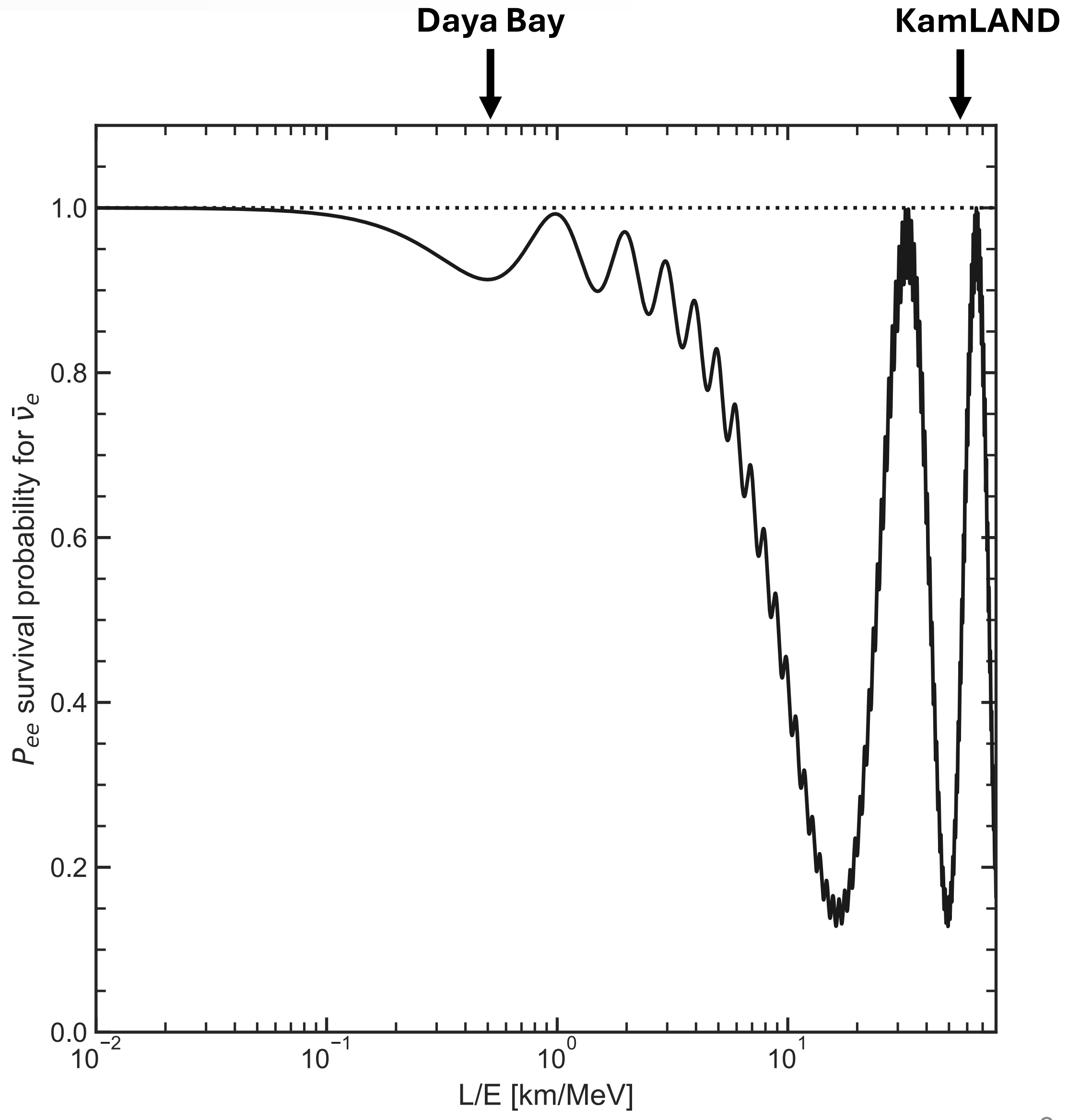
JUNO is a **20 kton** multi-purpose underground **liquid scintillator** detector currently under construction.

It sits at a baseline of about **52.5 km** from eight **nuclear reactors** in the Guangdong Province of South China.



JUNO oscillation physics in a nutshell

JUNO recipe: $\bar{\nu}_e$ from reactors **as source**, oscillated $\bar{\nu}_e$ **detected** via Inverse Beta Decay (IBD) → sensitive to $\mathbf{P_{ee}}$



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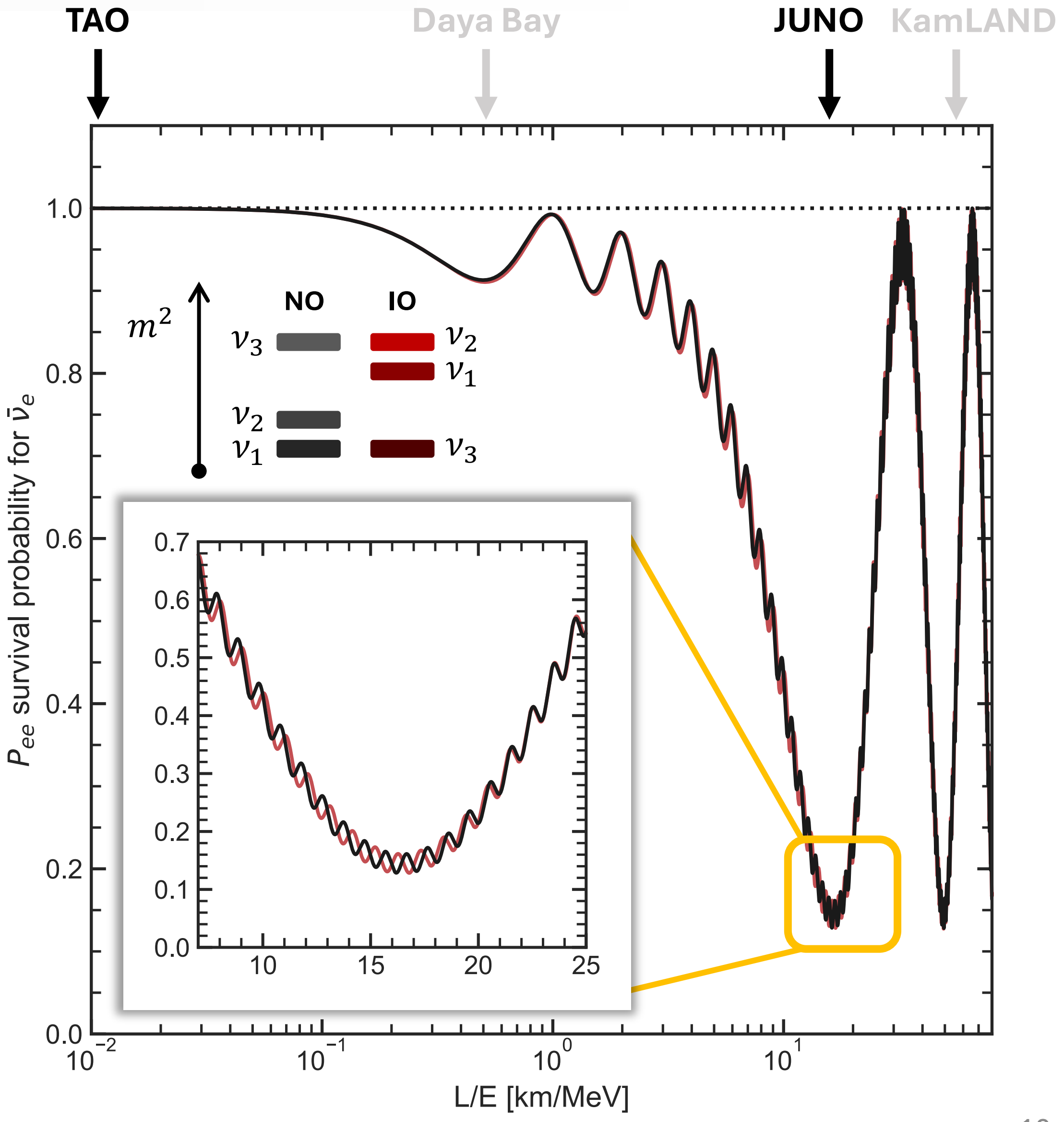
Neutrino Mass Ordering (NMO)

NMO sensitivity manifests as an energy dependent phase

→ **JUNO** sits at the **baseline maximizing NMO sensitivity**



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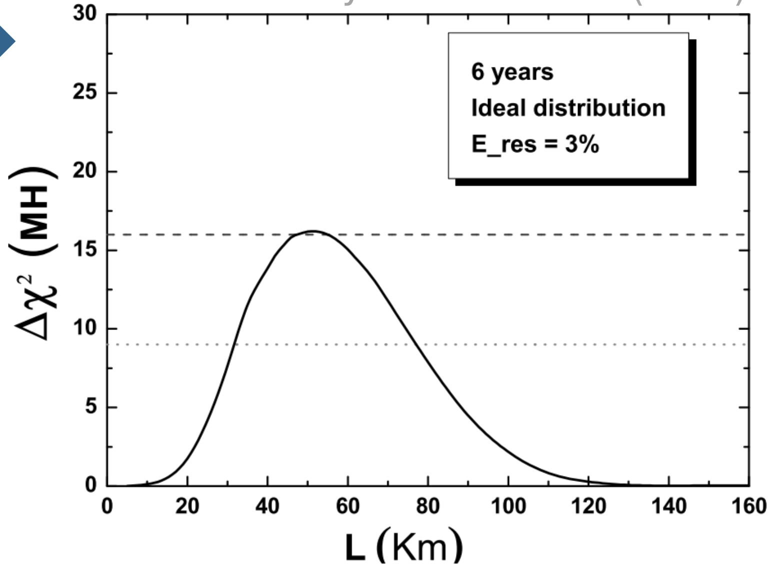
J.Phys .G43 030401 (2016)



For the energy range of the **JUNO spectrum:**
→ **baseline** L of **52.5 km***

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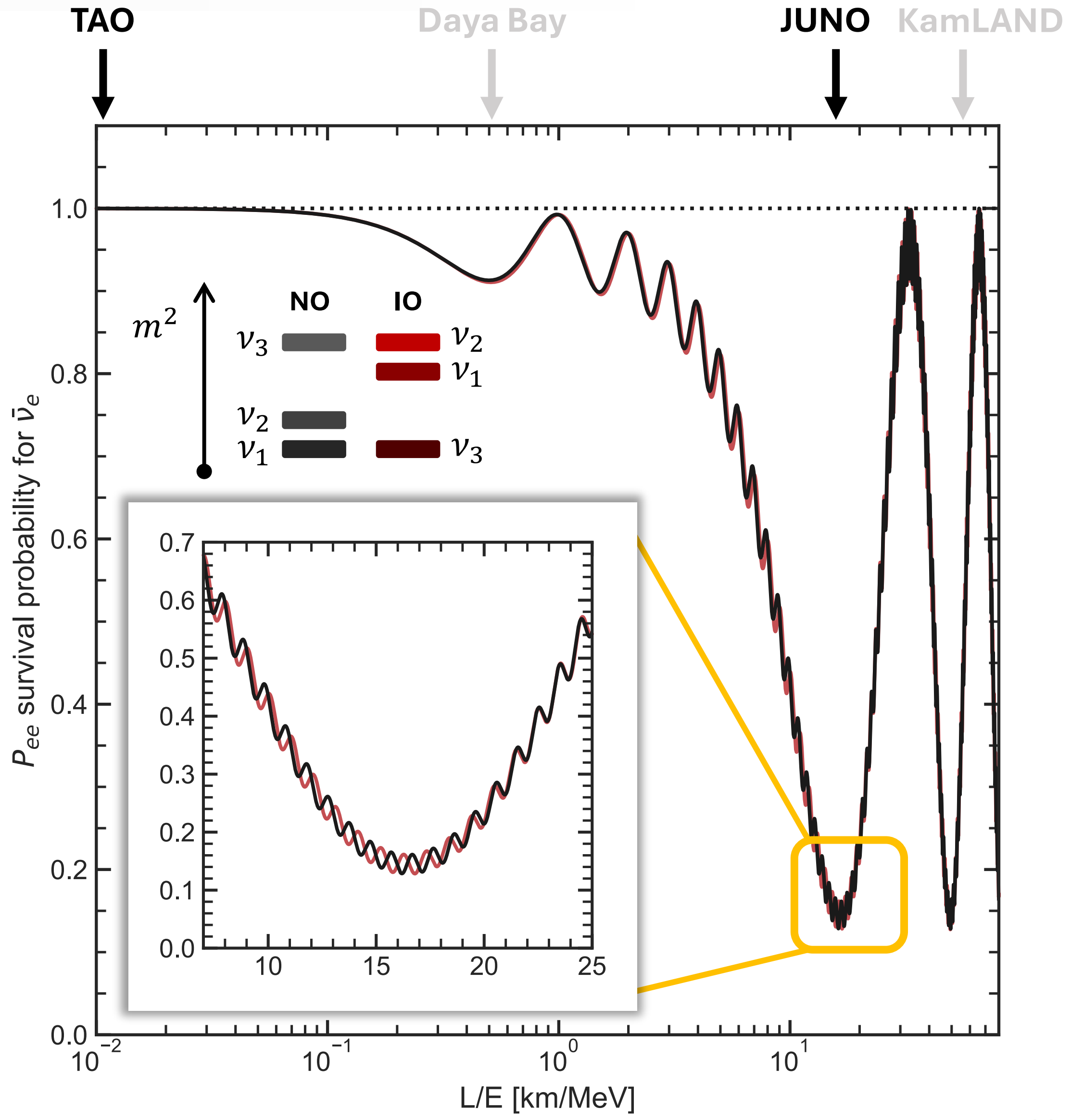

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$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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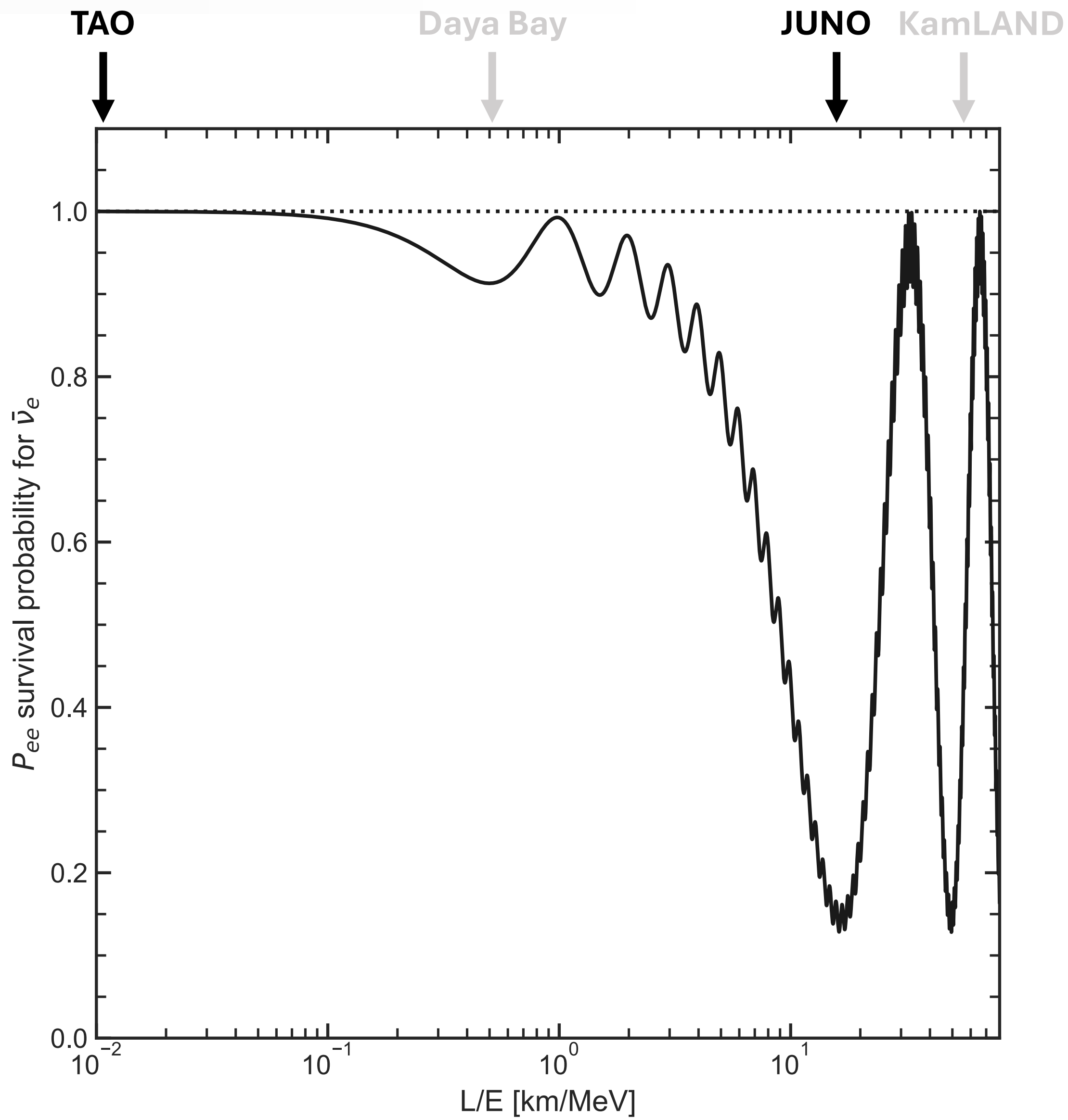
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

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

→ probability does **not depend on $\boldsymbol{\delta_{CP}}$ and $\boldsymbol{\theta_{23}}$**

→ **JUNO** is **sensitive to $\boldsymbol{\Delta m_{21}^2, \theta_{12}, \Delta m_{31}^2}$** and $\boldsymbol{\theta_{13}}$



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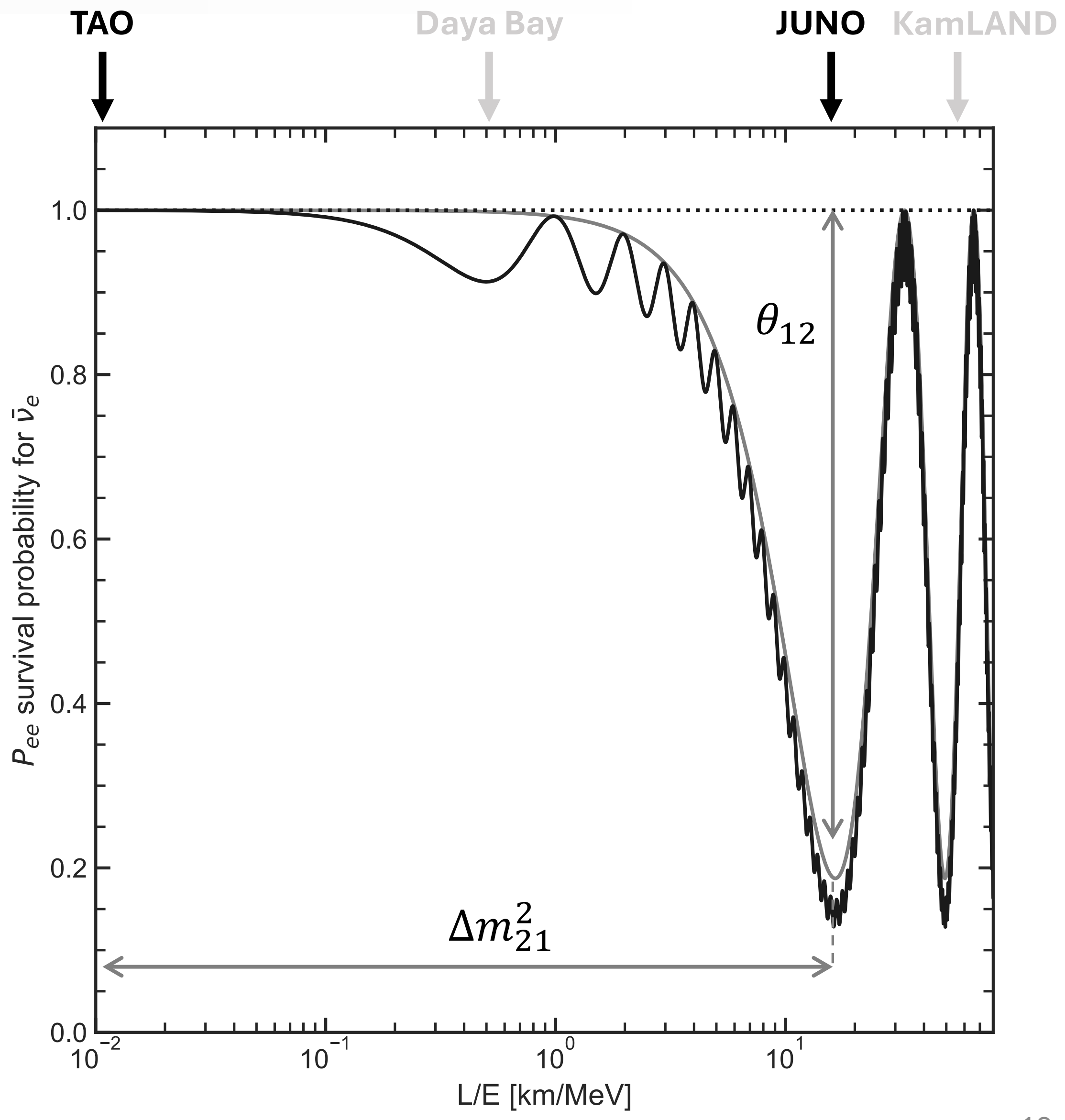

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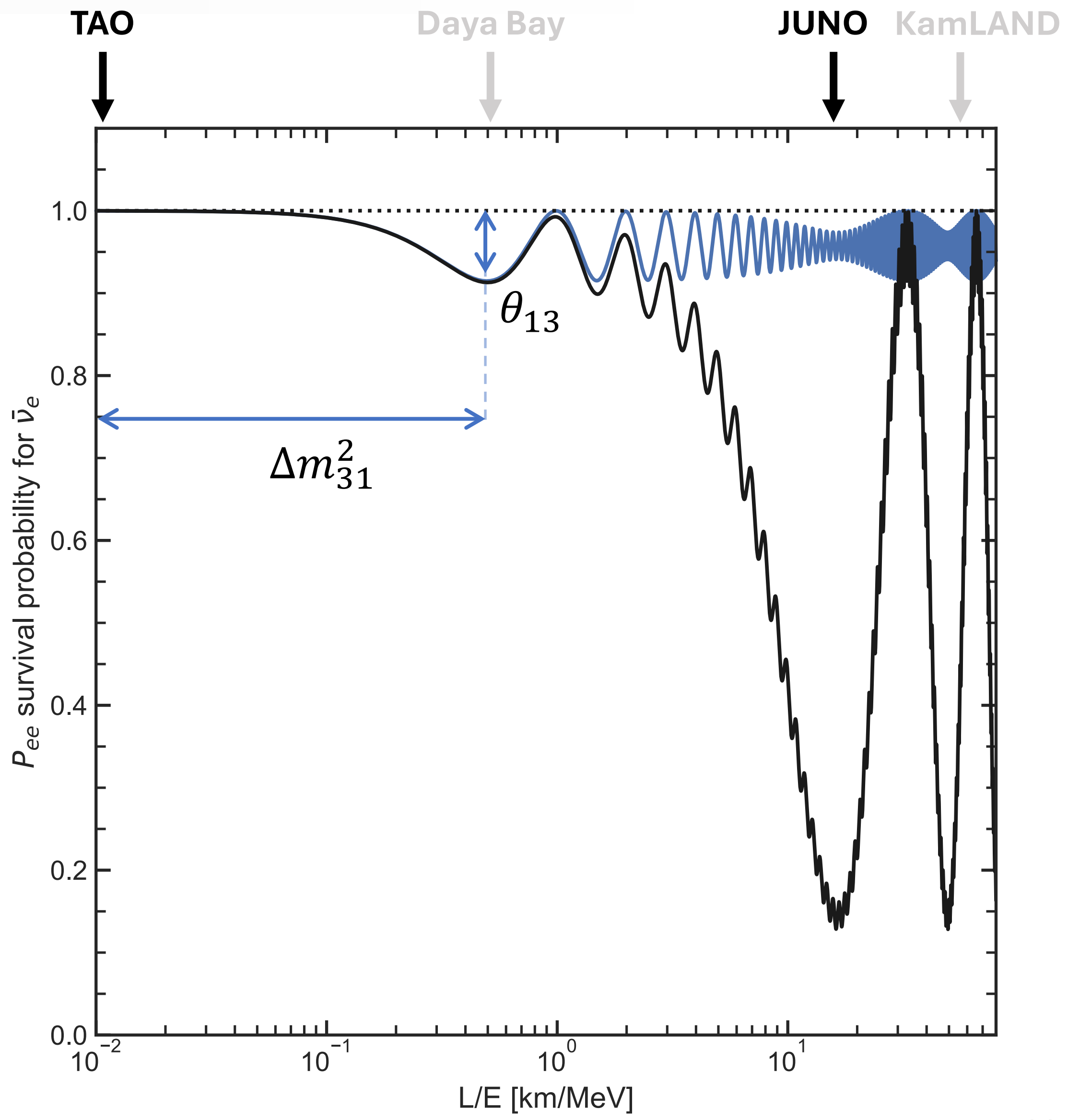

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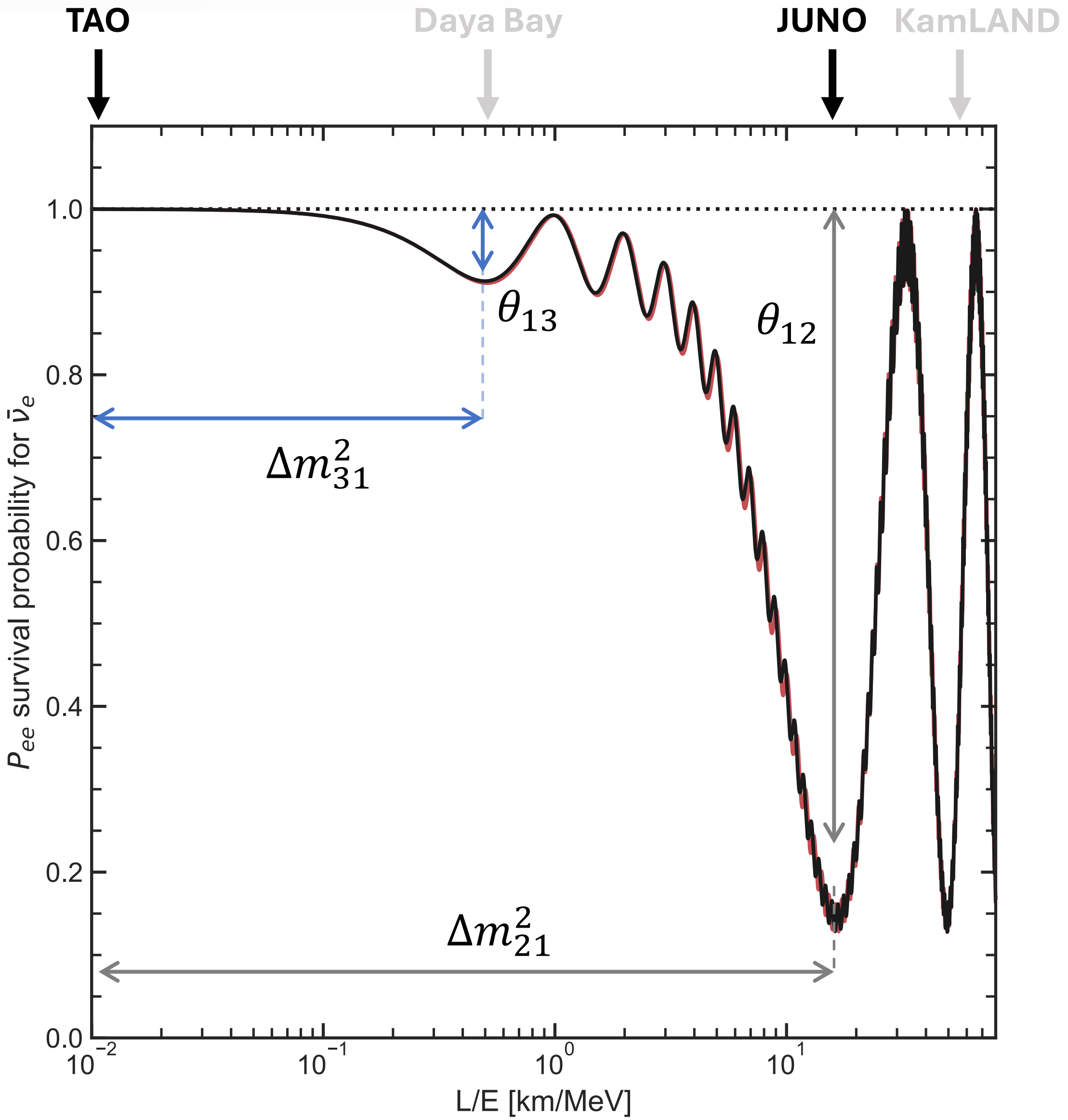


Main ingredients for the JUNO NMO recipe

High energy resolution (goal <3% @ 1MeV)

→ high light yield ~1600 PE/MeV
→ good photocoverage 78%
→ high performances electronics 1 GHz FADC, noise <10% @1 PE

A lot of light

High precision measurement

→ high statistics (large target mass) 20 kton → ~60 IBD evts/day *
→ long exposure (reliable electronics) <0.5% failure/6 years
→ low background (overburden + radiopurity + veto) ~ 4 bkg evts/day

A lot of events

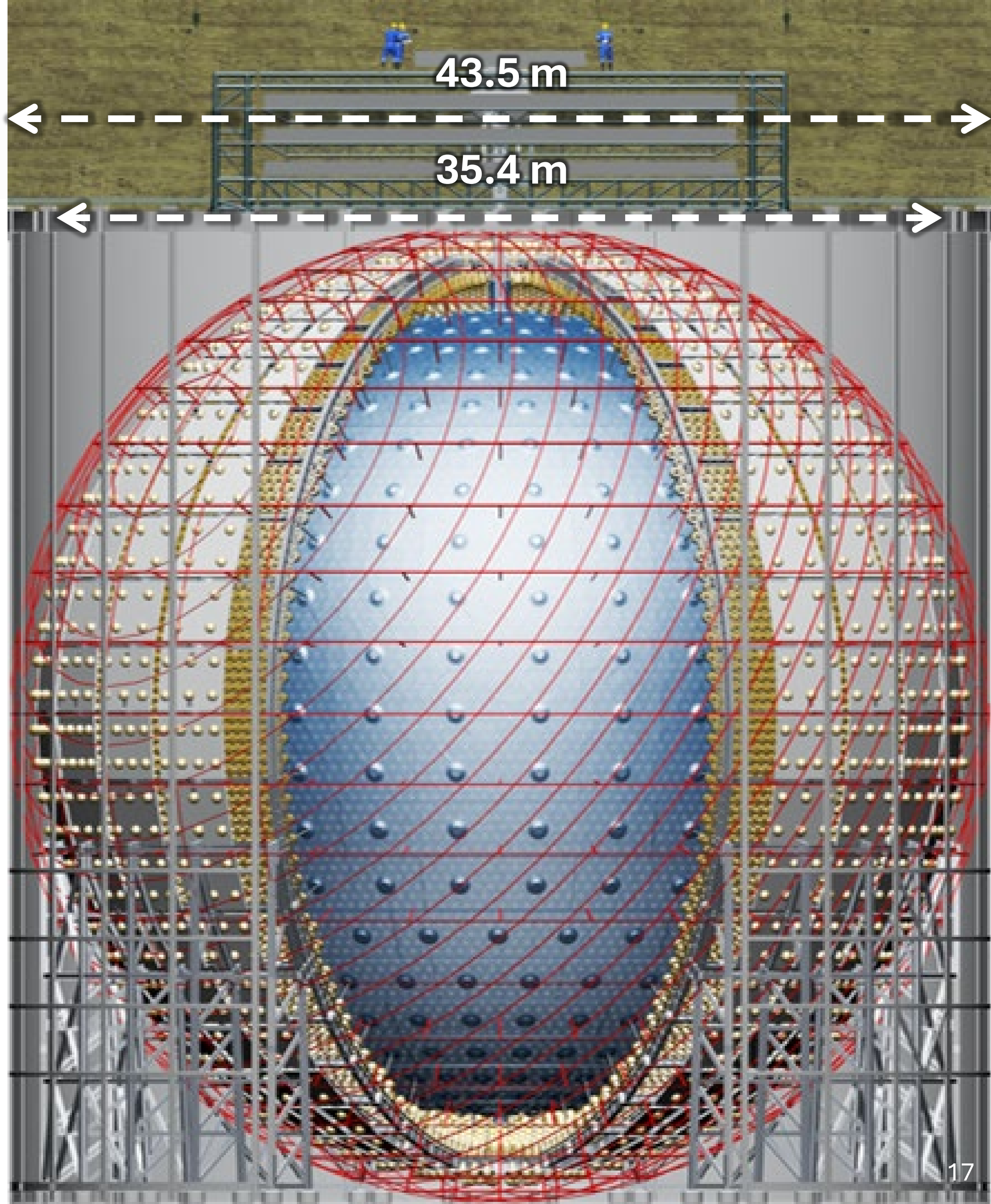
High accuracy

→ energy scale systematics (calibrations) < 1% uncertainty on energy scale
→ understanding of reference spectrum (TAO) < 2% shape uncertainty

Know our detector

*before efficiency cuts

The JUNO detector



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Central detector (CD) arXiv: 2311.17314 (2023)

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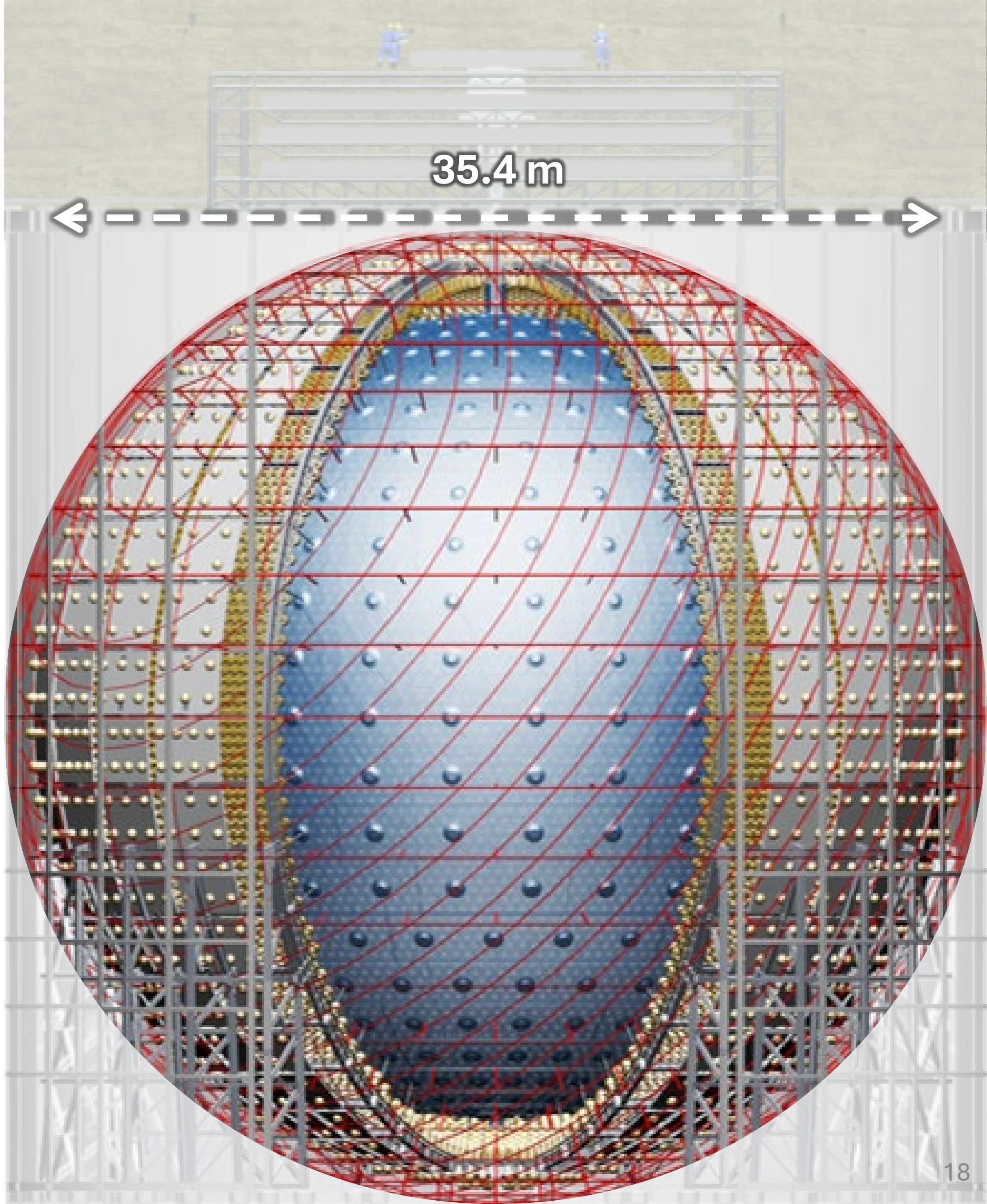

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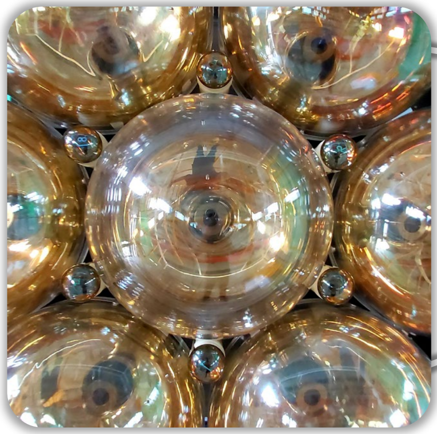

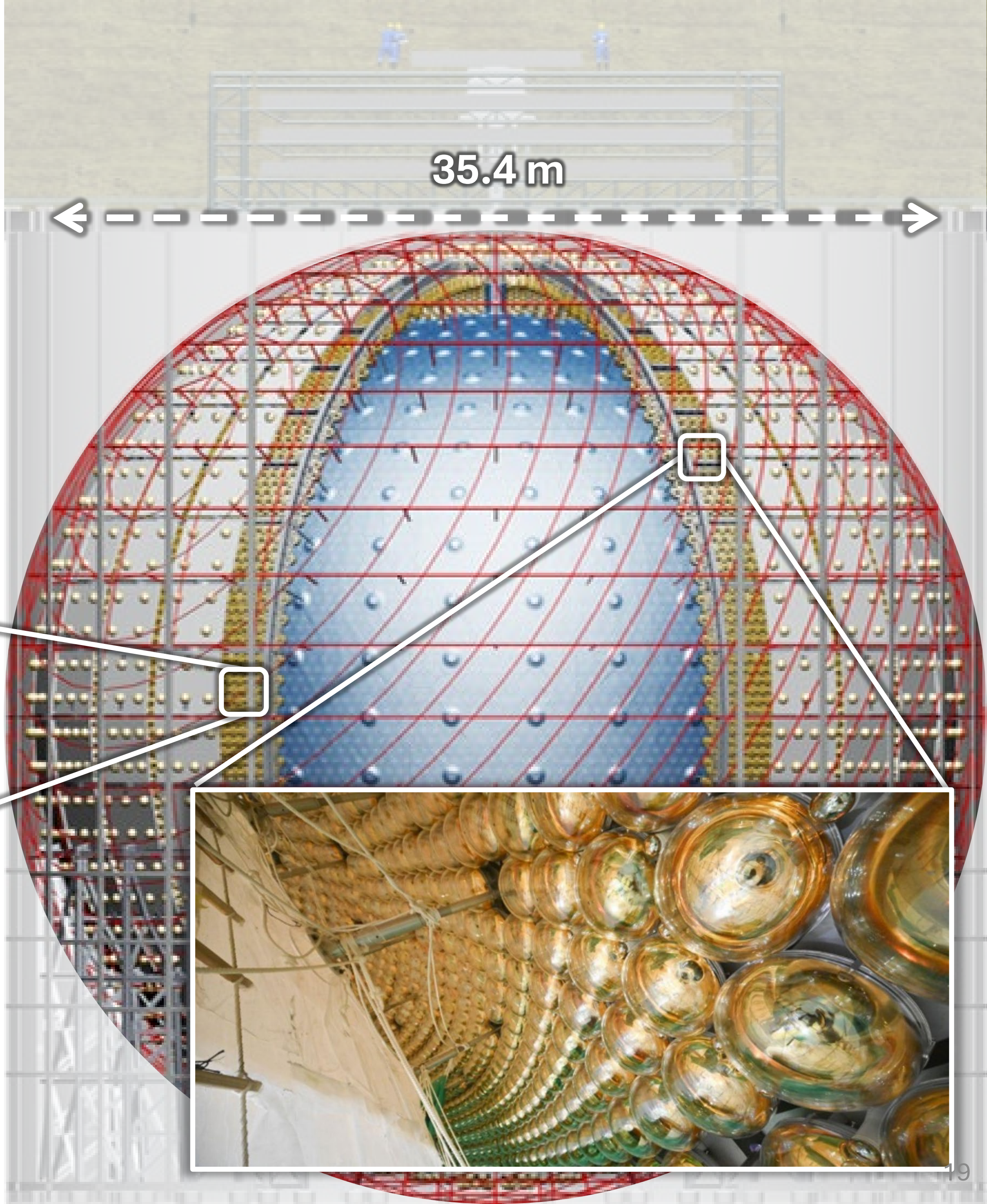

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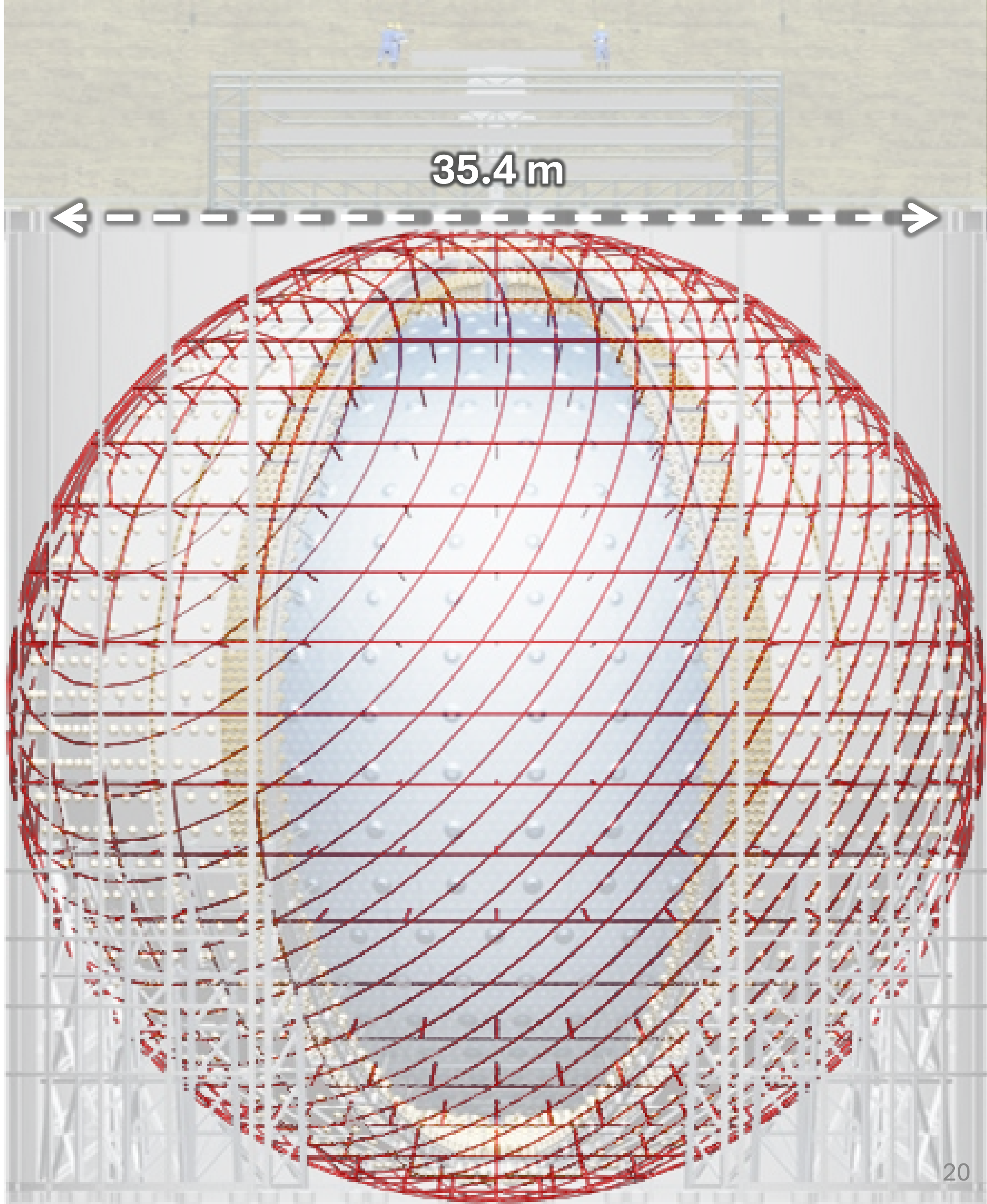
→ **Predicted 2.95% resolution @ 1 MeV** arXiv 2405.17860



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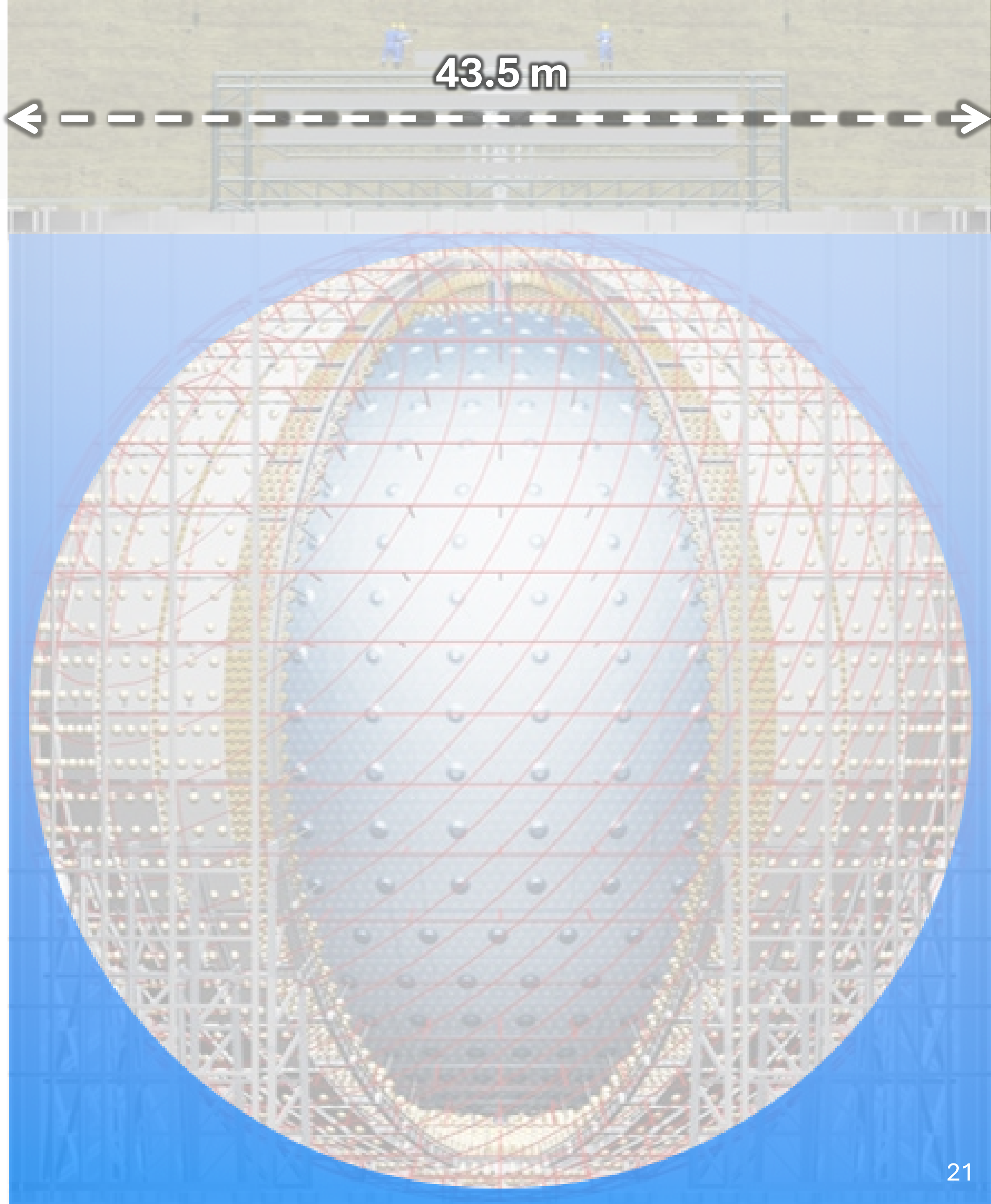

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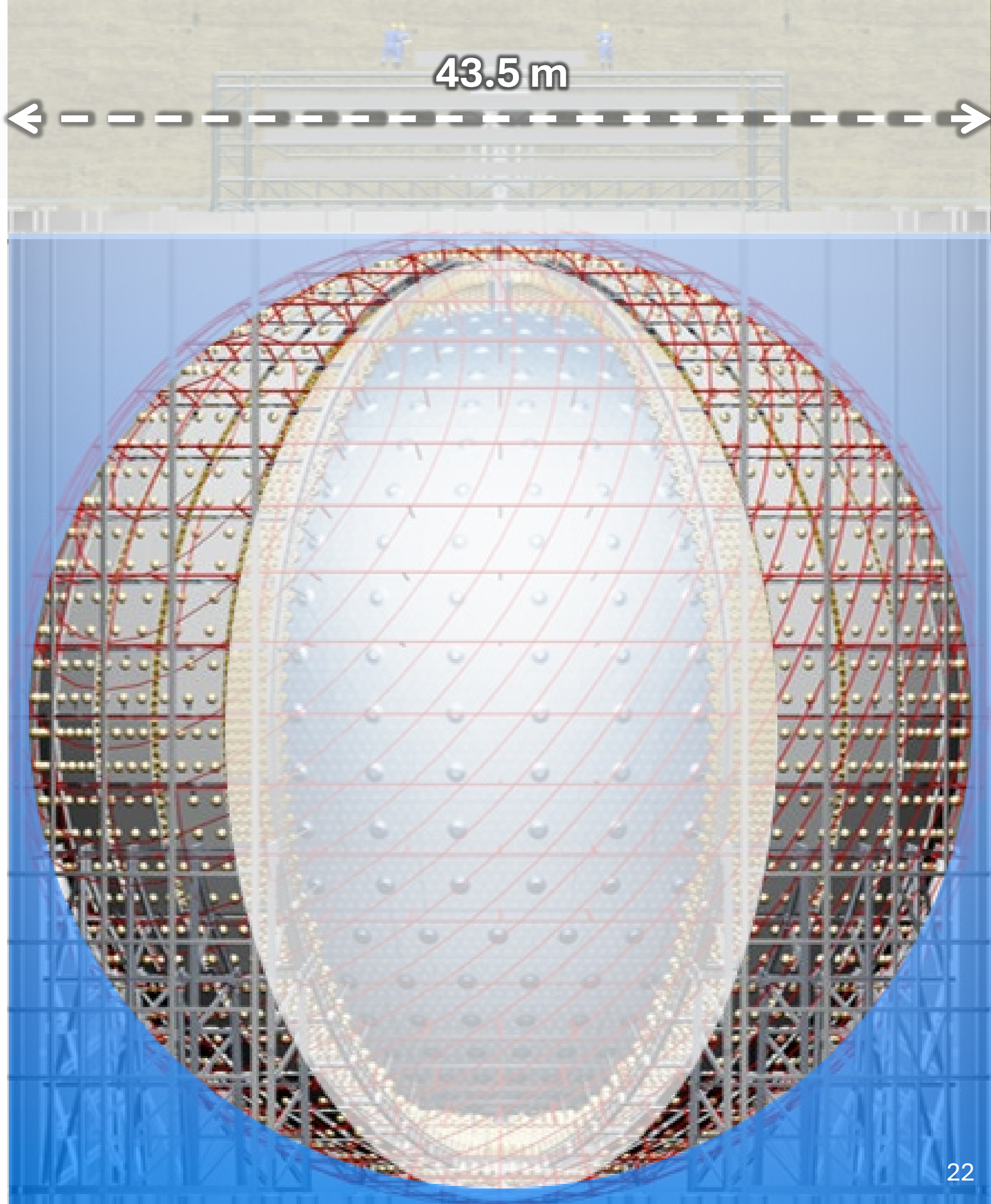

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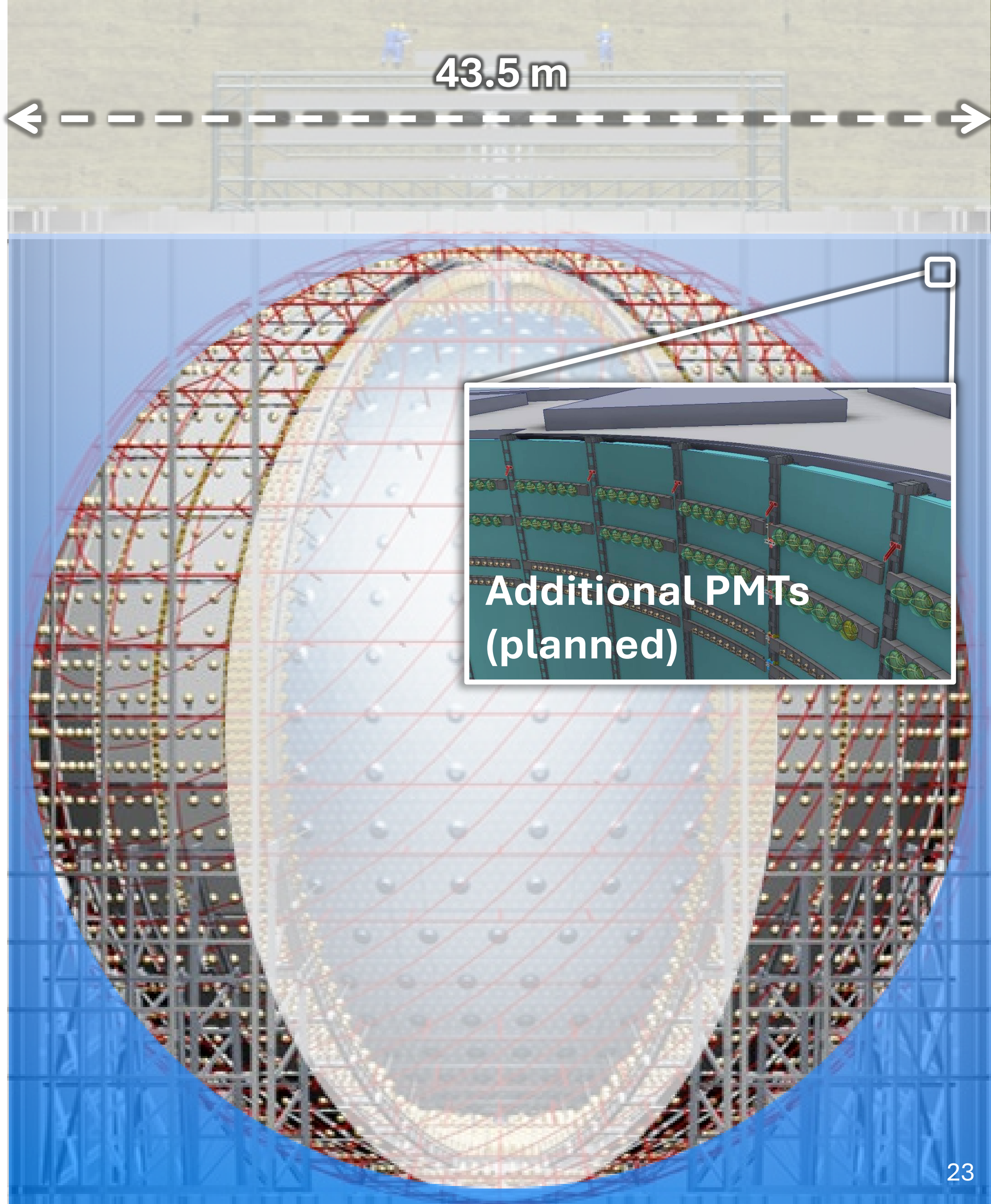

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Top Tracker (TT)
NIMA 1057 168680 (2023)

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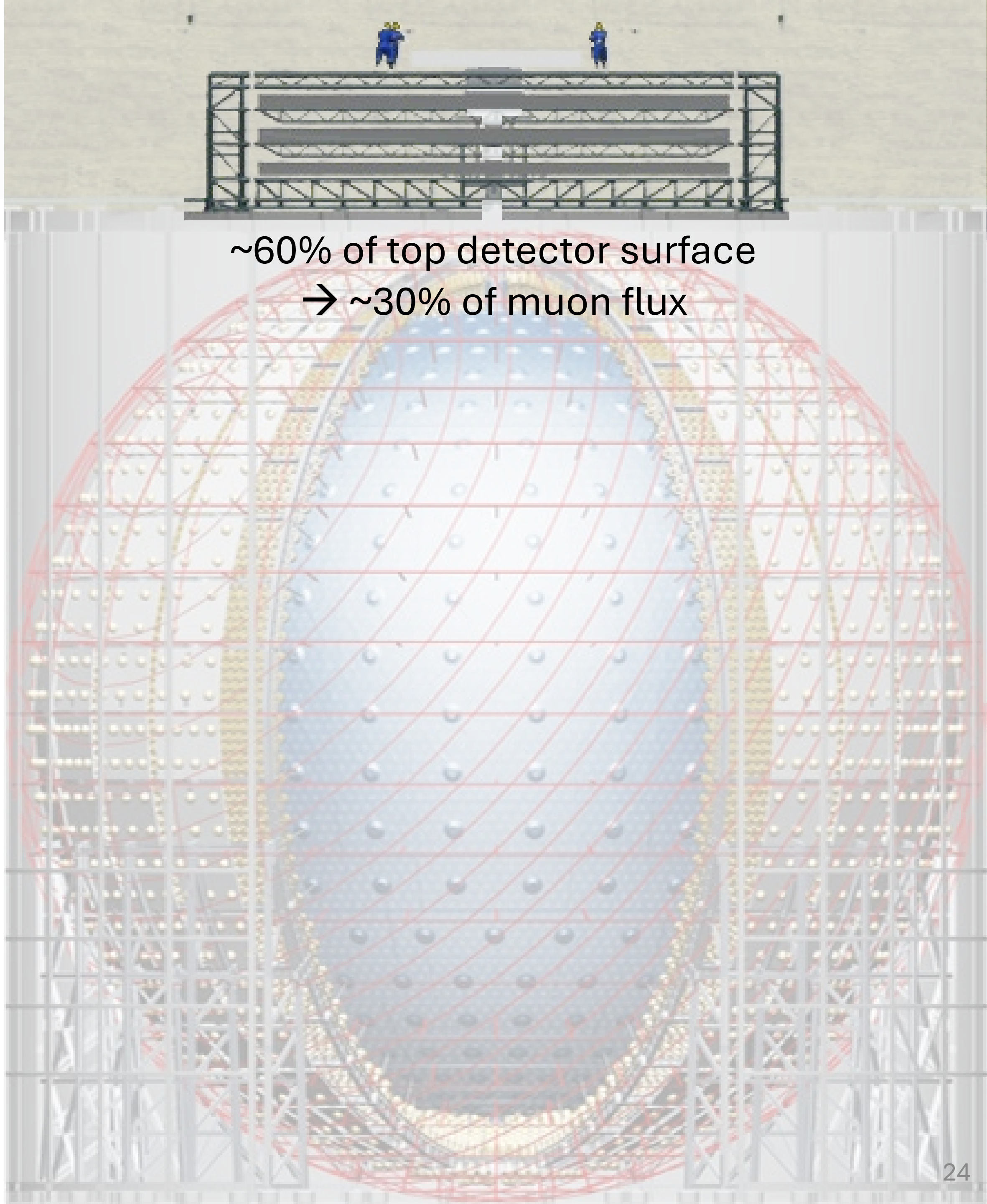

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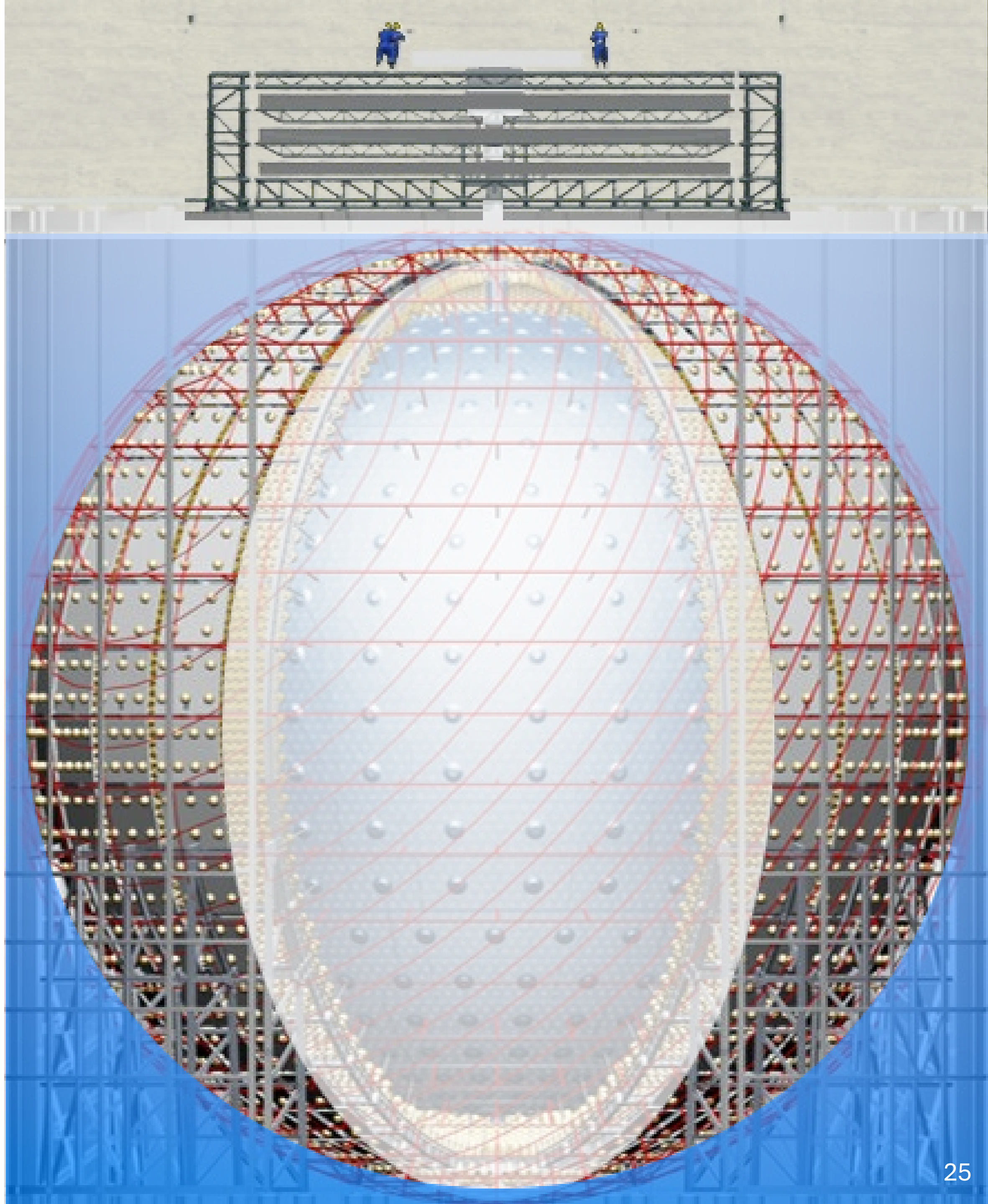

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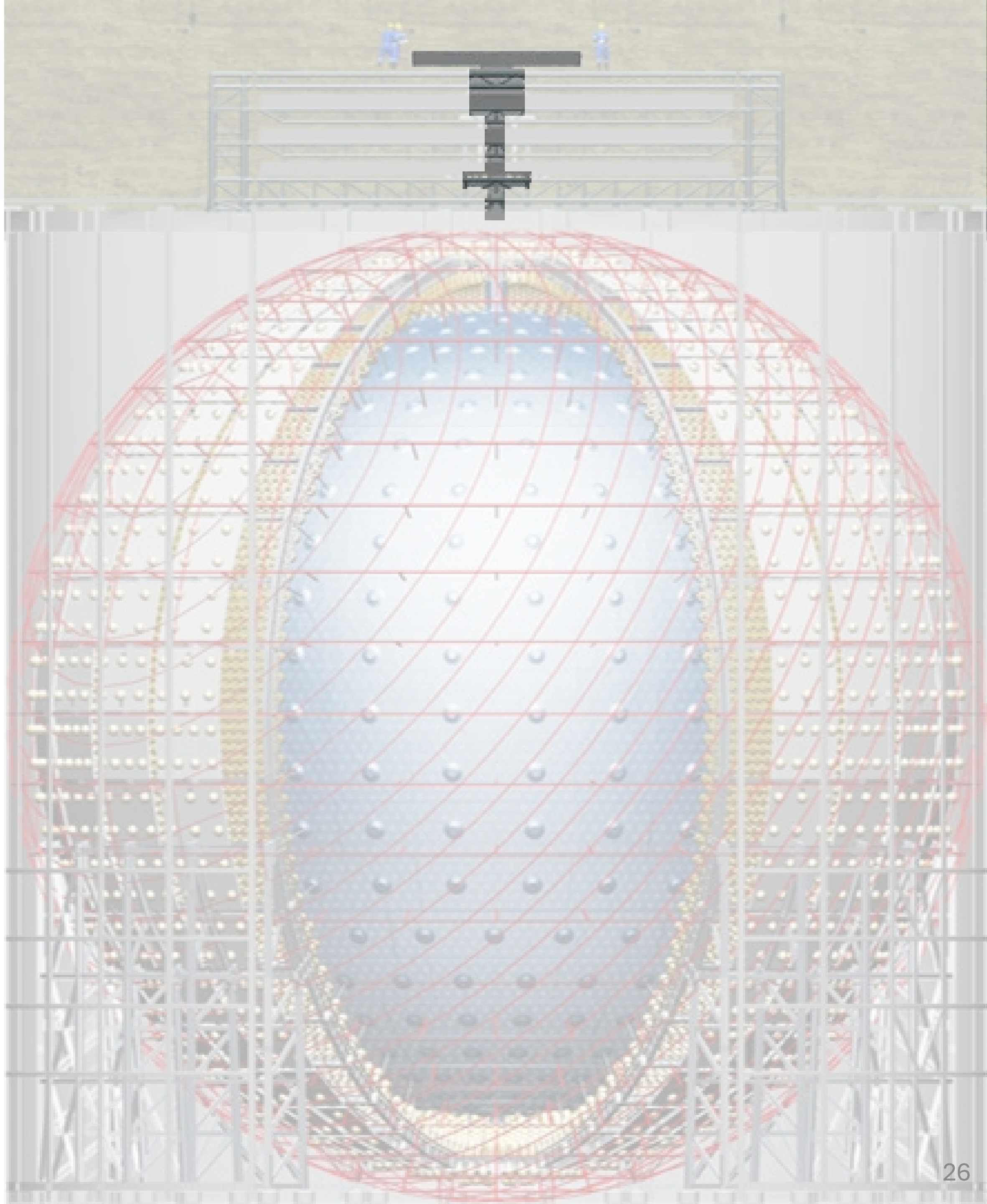
Calibration system
JHEP 03 (2021) 004

- >6 sources + laser + **calibration system**



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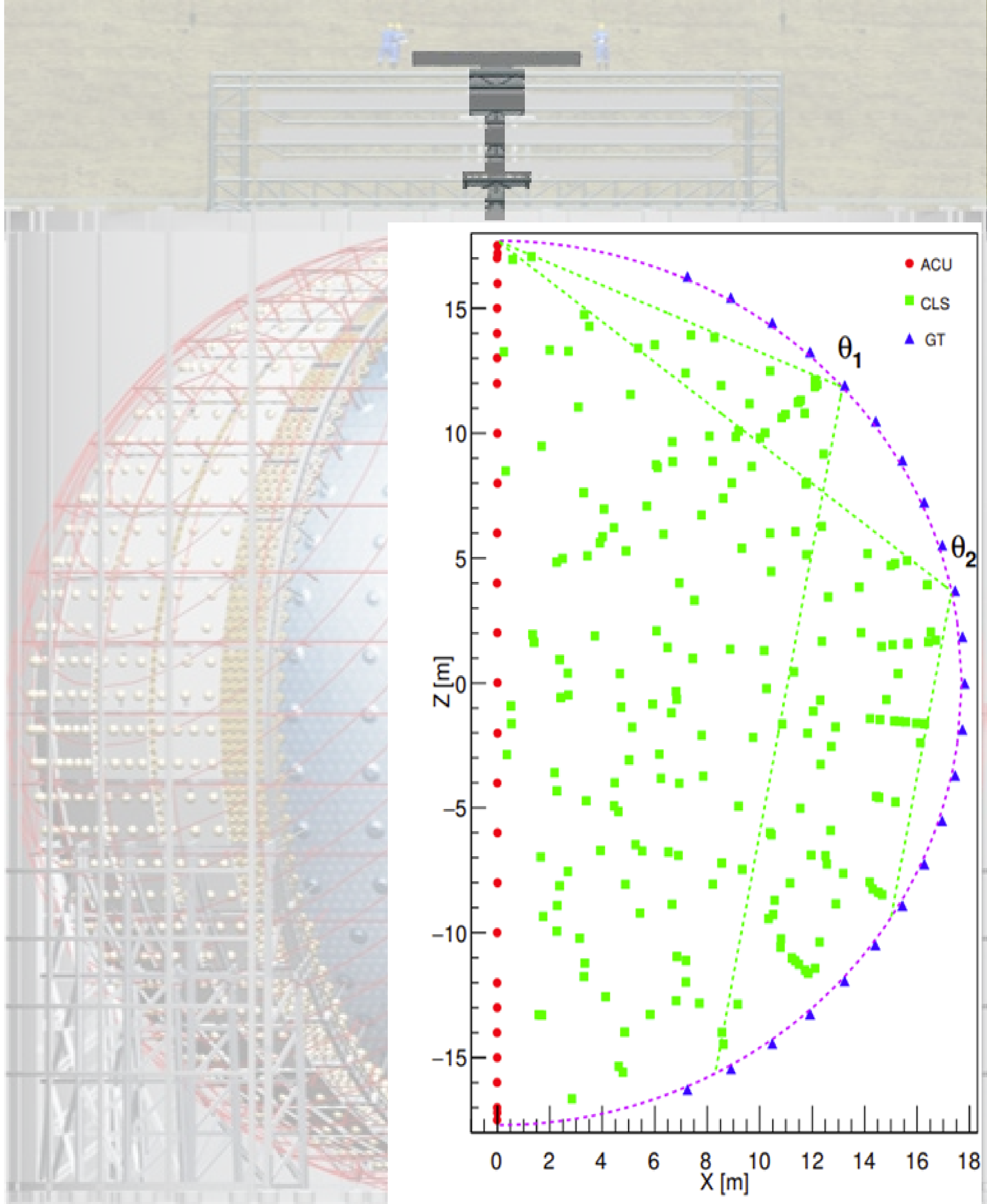
  → energy-scale **systematics below 1%**

*before efficiency cuts



The JUNO detector

Central detector (CD) arXiv: 2311.17314 (2023)

- **20 kton** of **LAB** scintillator → ~60 IBD evts/day *
- **17612** 20” **L-PMTs** and **25600** 3” **S-PMTs:**
  → **78%** photocoverage, ~1600 PE/MeV → high resolution
  → dual calorimetry L-PMTs / S-PMTs → self calibration
- Earth’s magnetic field **compensation coils**

→ **Predicted 2.95% resolution @ 1 MeV** arXiv 2405.17860

Instrumented Water Pool (WP)

- **35 kton** of high pure **water as shield**
- **2400** 20” **L-PMTs** for **active veto**

Top Tracker (TT) NIMA 1057 168680 (2023)

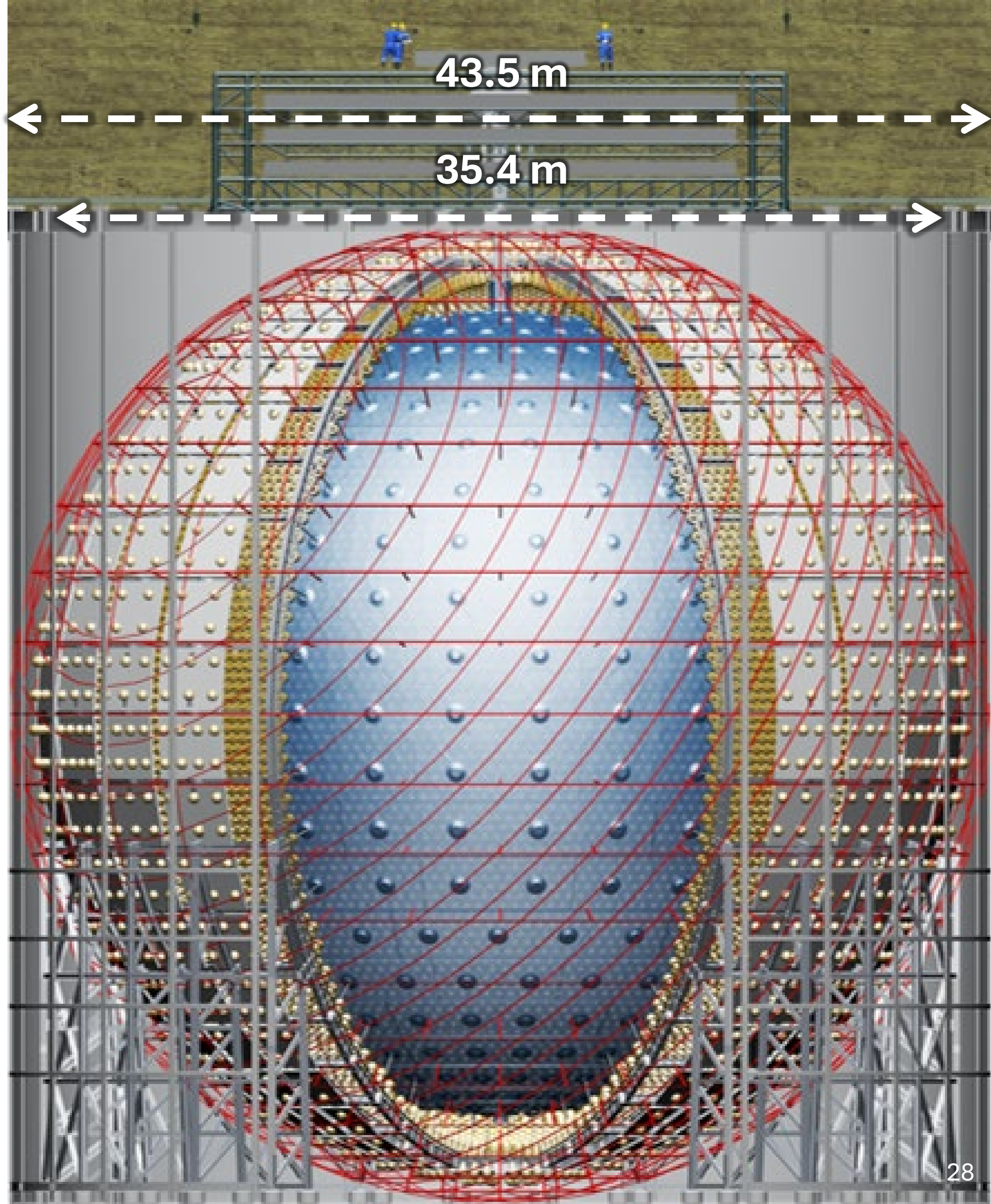
- **3× plastic** scintillator **layers** (coverage ~30% of muons)

→ CD+WP+TT **muon veto strategy** → **92% efficiency**

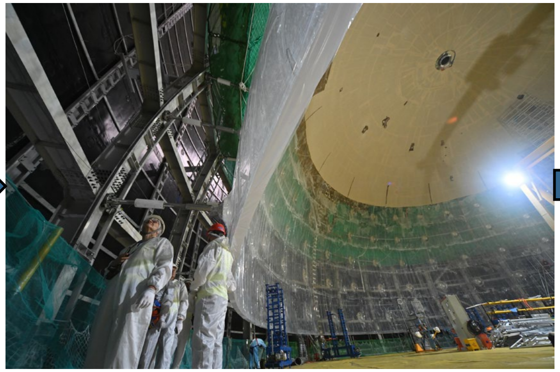
Calibration system JHEP 03 (2021) 004

- >6 sources + laser + **calibration system**
  → energy-scale **systematics below 1%**

*before efficiency cuts



The Central Detector status



✓ Stainless **Steel (SS) structure completed** (except bottom 4 layers, waiting for acrylic)

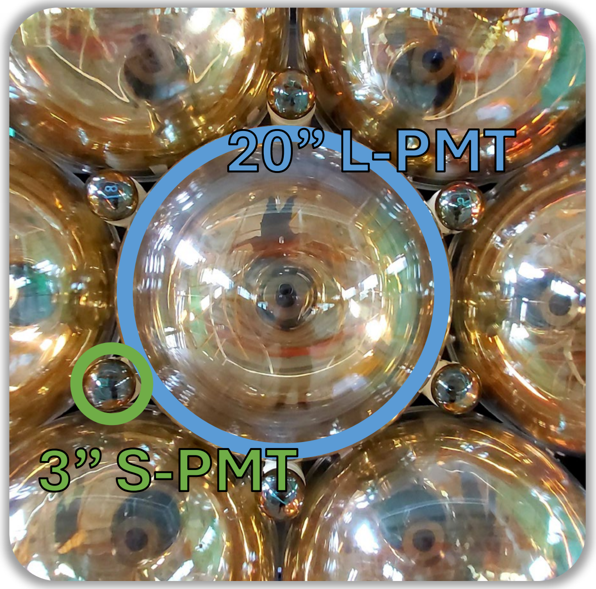
✓ **Acrylic** panel **production completed**

- **<1 ppt U/Th/K** contamination in production
- **high transparency** reached **(>96%)**
  low surface contamin. (<5 ppt U/Th in 50 μm)

~ **Acrylic vessel construction on-going**

- **17/23 layers** finished

The Photo Multiplier Tubes status



JUNO employs a combination of 20” L-PMTs and 3” S-PMTs
→ **calibrate** charge **non-linearity systematics**

NIM.A 1005 165347 (2021)
Eur.Phys.J.C 82 12, 1168 (2022)

✓ All **PMTs** tested and **characterized:**

Dimension	Type	Number	Phot. Det. Eff.	Dark Noise	Transit time spread (1σ)
20” L-PMT	MCP-PMT (NNVT)	15,012	**30.1%**	31.2 kHz	7.0 ns
	Dynode PMT(Hamamatsu)	5,000	**28.5%**	17.0 kHz	1.3 ns
3” S-PMT	Dynode PMT (HZC XP72B22)	25,600	**24.9%**	0.5 kHz	1.6 ns

✓ All PMTs installed in **waterproof potting** (failure rate <0.5% / 6 years)

✓ **Implosion protection system** (acrylic top + steel bottom) **developed** and **produced**
JINST 18,P02013 (2023)

~ PMTs **under installation and testing** following central detector commissioning

The liquid scintillator purification status

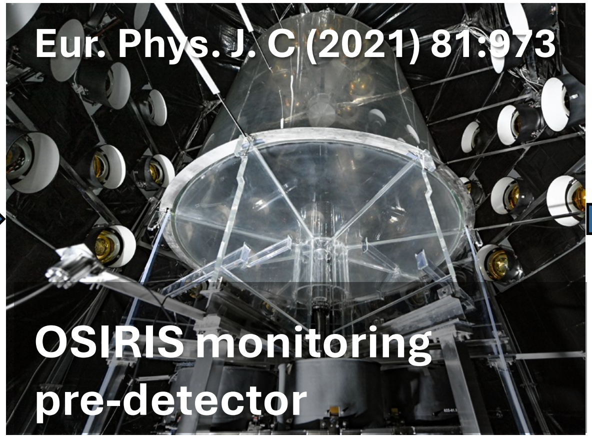
JUNO liquid scintillator **cocktail: LAB** + 2.5 g/L **PPO** + 3 mg/L **bis-MSB**. Aiming at:

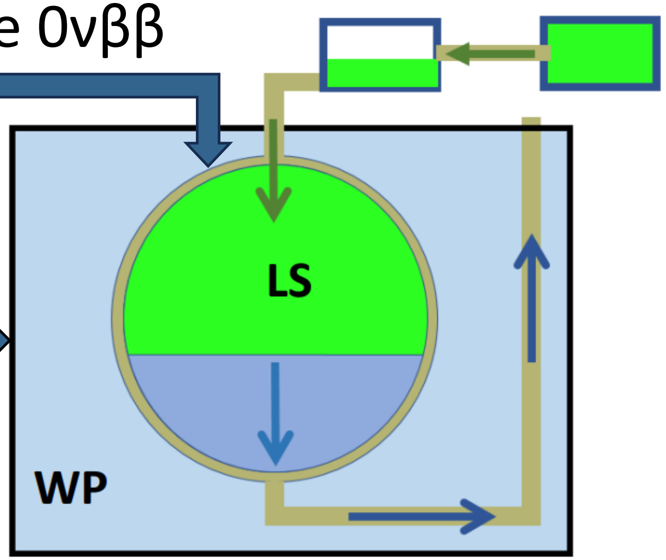
→ Attenuation length: LAB > 24m, LS > 20 m

→ U/Th for NMO **< 10^{-15} g/g**, aiming at 10^{-17} g/g for solar and future 0νββ

85%

15%





- ✓ Liquid scintillation **purification plant completed** and **commissioned**
- ✓ All 60 ton **PPO delivered** (U/Th <0.1 ppt), **Bis-MSB almost complete** (U/Th <5 ppt)
- ✓ OSIRIS radiopurity monitoring **pre-detector** (20ton LS) ready, **up and running**
- ~ **Filling plan developed**, waiting for detector construction

The liquid scintillator purification s

JUNO liquid scintillator **cocktail: LAB** + 2.5 g/L **PPO** + 3 mg/L **bis-**

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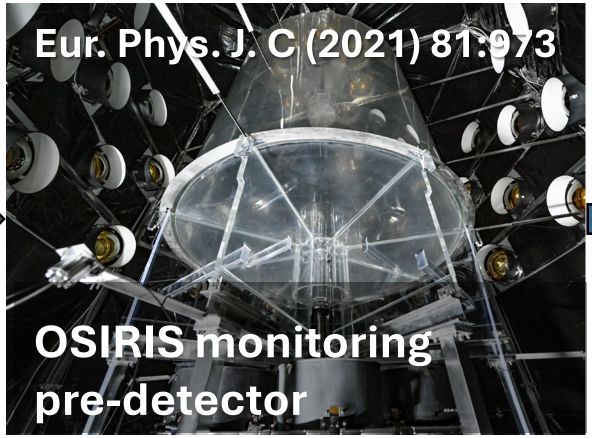
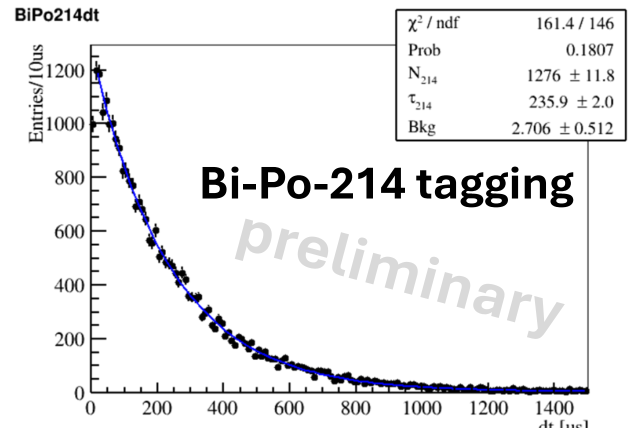
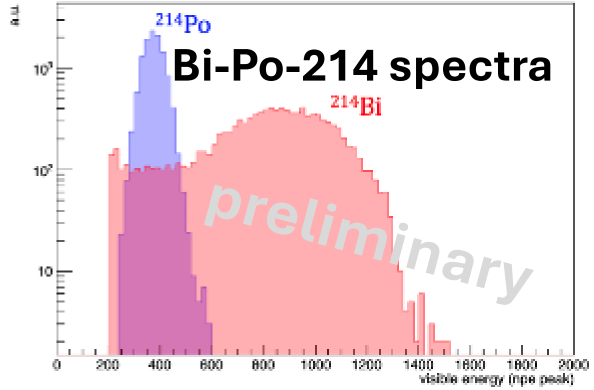
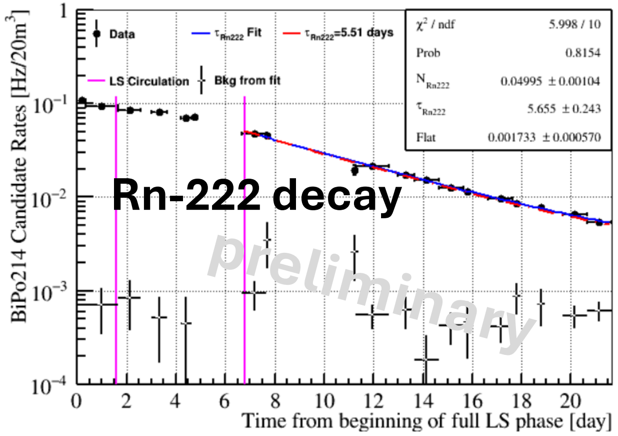








- ✓ Liquid scintillation **purification plant completed** and **comm**
- ✓ All 60 ton **PPO delivered** (U/Th <0.1 ppt), **Bis-MSB almost co**
- ✓ OSIRIS radiopurity monitoring **pre-detector** (20ton LS) ready
- ~ **Filling plan developed**, waiting for detector construction

The JUNO-TAO detector status

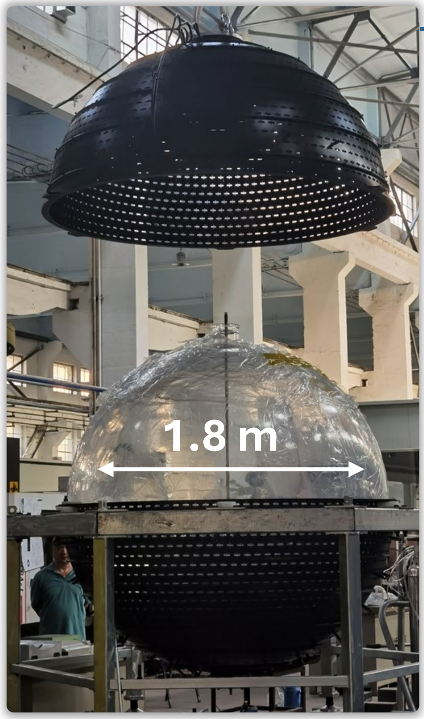
Accurate and **precise reference spectrum → boost** JUNO in **parameters** and **NMO**

- Conversion and ab-initio **reactor** spectrum **models** affected by **large uncertainties**
- **Models/data** (e.g. Daya Bay) **inconsistent**, current data has **low** energy **resolution**

→ **Taishan Antineutrino Observatory** (TAO) arXiv:2005.08745 (2020)

~44 m

Taishan core

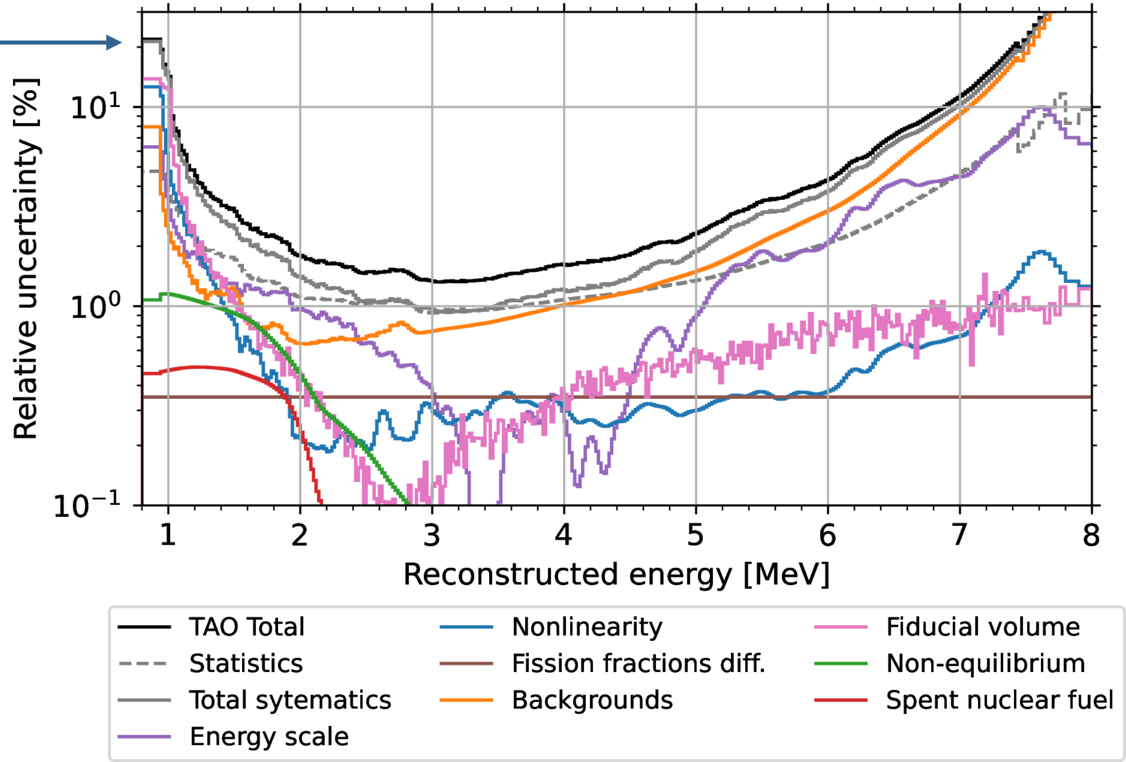


TAO

TAO main features:

- **2.8 ton** of LS with Gd
- **~10 m² (94%)** of **SiPM** working at **-50° C**
  → dark noise to <100 Hz/mm²
- **<2%** / $\sqrt{E\ [MeV]}$
- **~1000 IBD evts/day ***

*after efficiency cuts



Lower uncertainty

The JUNO-TAO detector status

Accurate and **precise reference spectrum** → **boost** JUNO in **parameters** and **NMO**

- Conversion and ab-initio **reactor** spectrum **models** affected by **large uncertainties**
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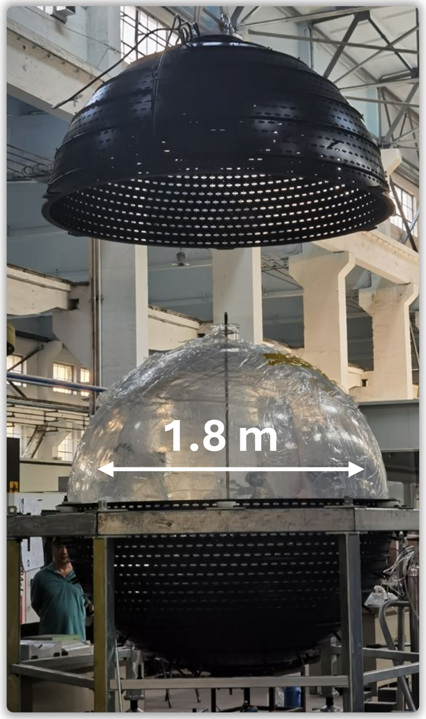
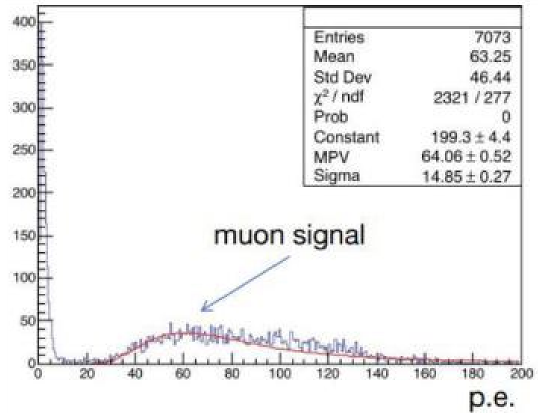


TAO

✓ **Detector assembled at IHEP:** ~100 SiPM tiles/readout (out of 4100 in total)

✓ **Readout, temperature** uniformity and **stability tested.**



~ **Disassembling**, to be re-installed in the Taishan Nuclear Power Plant in 2024

The JUNO physics program

Check out all JUNO contributions at NOW 2024:

155. JUNO sensitivity to mass ordering and mixing parameters
Vanessa Cerrone (Istituto Nazionale di Fisica Nucleare)
04/09/2024, 16:00
Session I (parallel) - Sta...

192. JUNO potential for SN, solar and atmospheric neutrinos
Marco Malabarba (Istituto Nazionale di Fisica Nucleare)
07/09/2024, 18:10
Session IV (parallel) Par...

170. Nucleon decays at JUNO
Wan-lei Guo (Institute of High Energy Physics, Chinese Academy of Sciences)
06/09/2024, 18:50
Session II (parallel) Beyo...

159. Geoneutrino physics at JUNO
Fernanda Rodrigues (Institute of High Energy Physics, Beijing, China)
04/09/2024, 17:50
Session I (parallel) - Sta...

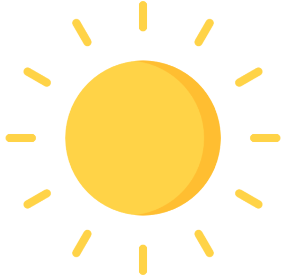
Reactor

~60/day

Atmosphere

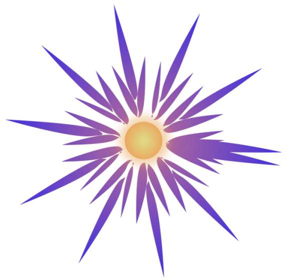
>100/year

Sun



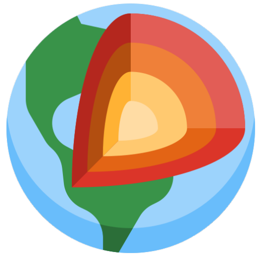
>100/day

Supernovae



~10^4/10 s @ 10kpc

Earth



~400/year

More!! (BSM)

Neutrino oscillation properties (Reactor, Atmosphere, Sun)

Neutrinos as a probe (Sun, Supernovae, Earth)

The JUNO physics program

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Session I (parallel) - Sta...

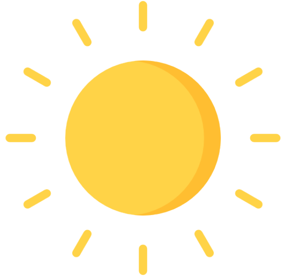
Reactor

~50/day

Atmosphere

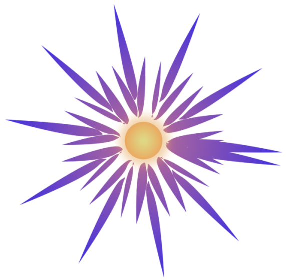
>100/year

Sun



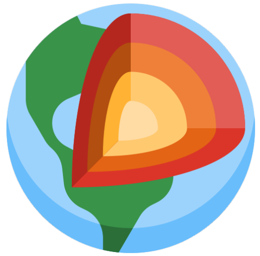
>100/day

Supernovae



~10^4/10 s @ 10kpc

Earth



~400/year

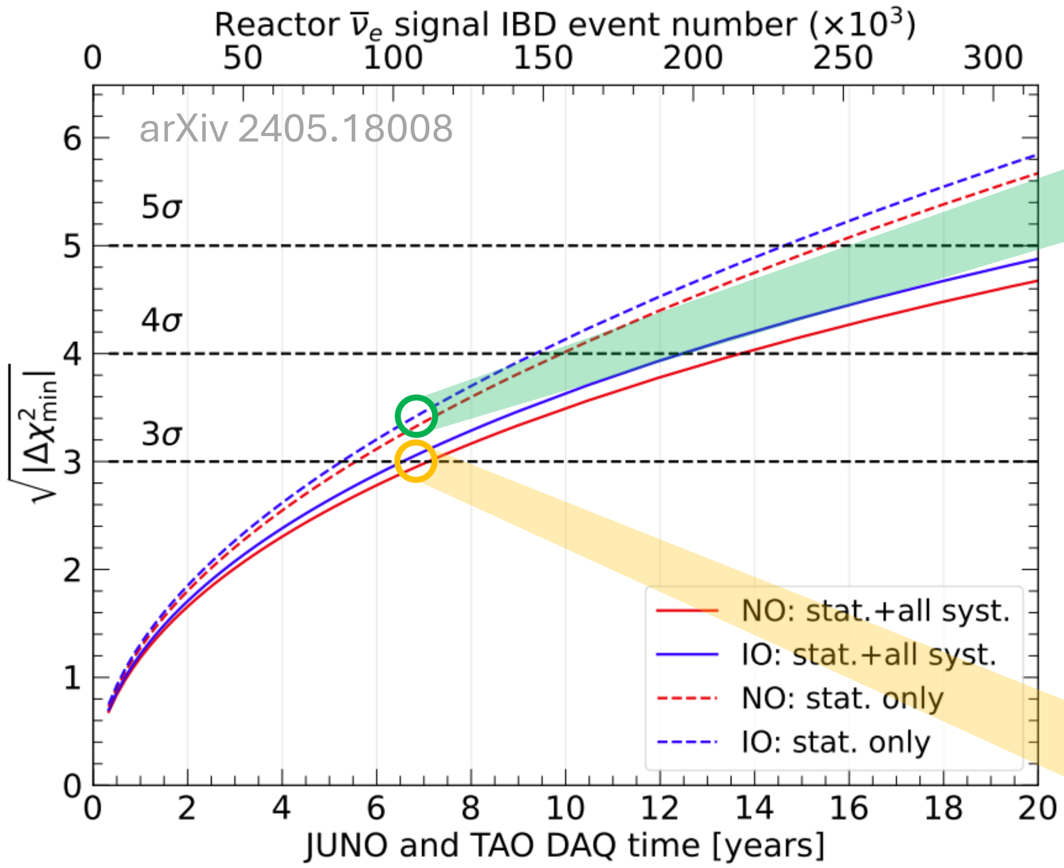
More!! (BSM)

Neutrino oscillation properties

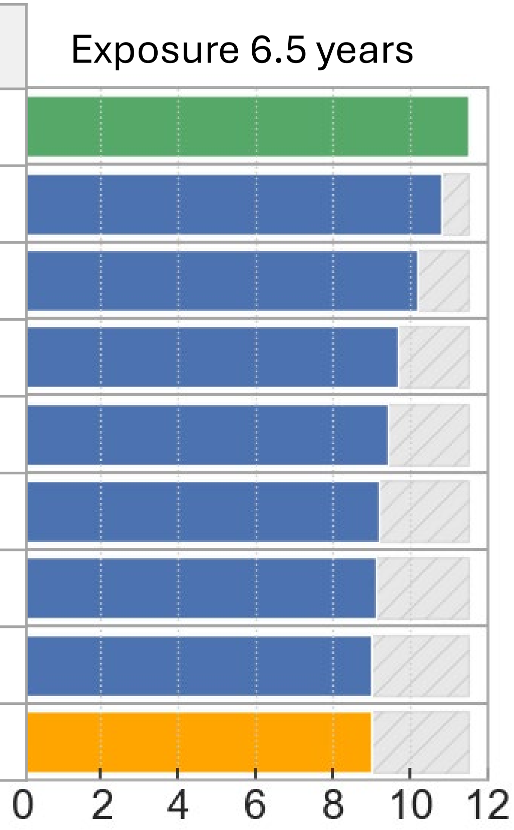
Neutrinos as a probe

Determination of Neutrino Mass Ordering (NMO)

JUNO **NMO sensitivity: 3σ** (**reactors only**) in **6.5 y** (with 26.6 GW_{th}) → 7.1 y with 11/12 reactor duty factor



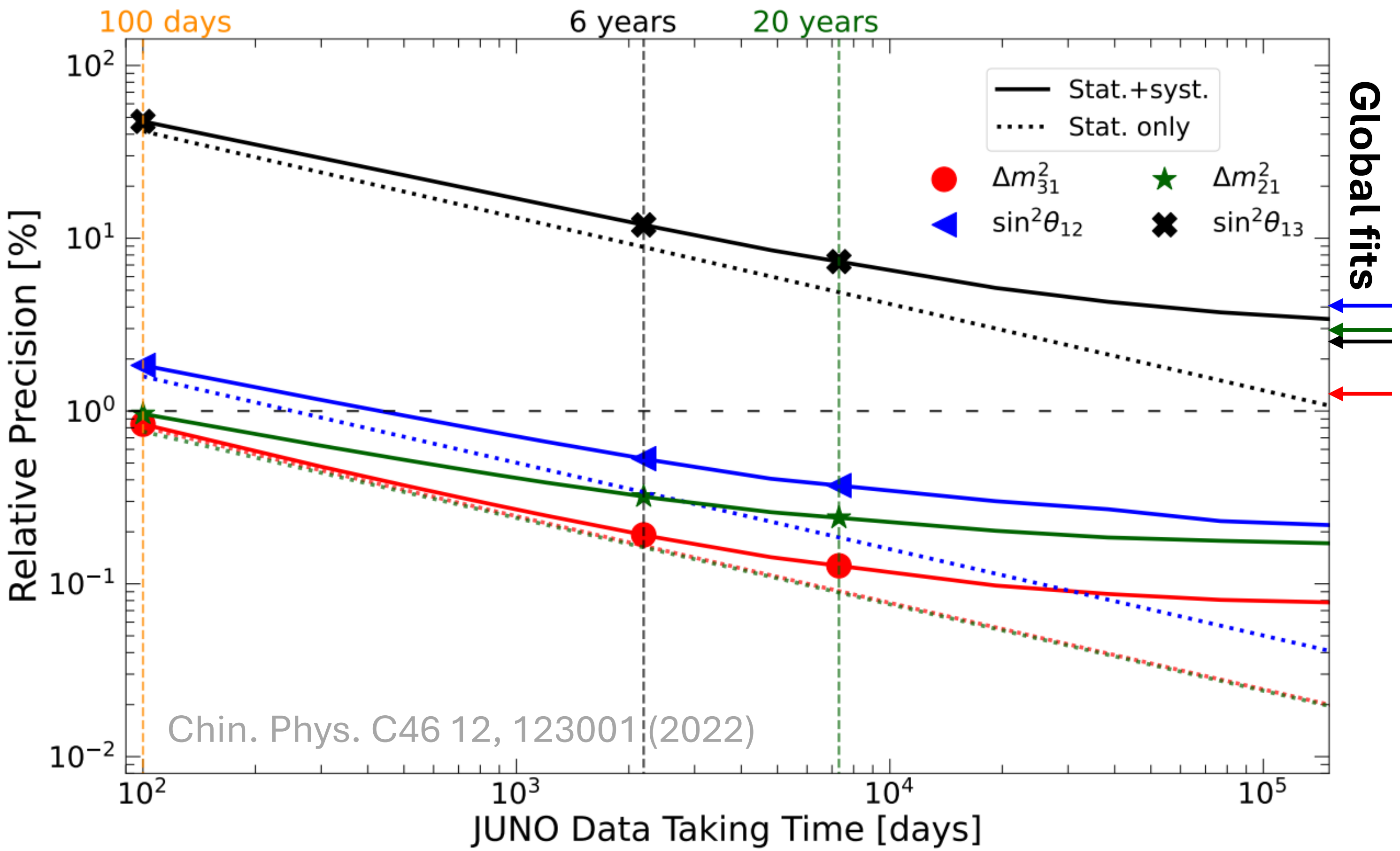
Uncertainty	$\lvert\Delta\chi^2_{min}\rvert$
Statistics (JUNO+TAO)	**11.5**
+ reactor and response	−0.7
+ TAO unc.	−0.6
+ JUNO geoneutrinos	−0.5
+ JUNO world reactors	−0.3
+ JUNO accidentals	−0.2
+ JUNO $^{9}Li/^{8}He$	−0.1
+ JUNO other bkg.	−0.05
Full systematics	**9.0**



- Combination **reactor + atmospheric** neutrino analysis **ongoing** → further **improve NMO** sensitivity
- Combination with **external** $\boldsymbol{\Delta m^2_{31}}$ long baseline experiments constraint → **enhanced NMO sensitivity**

Subpercent precision on oscillation parameters

Huge **leap** in **precision** for mass splittings and θ_{12}
→ **synergies** in the neutrino field!



- In **<2 years** θ_{12}, Δm^2_{21}, Δm^2_{31} precision
  → **unprecedented <1%** level
- **In 6 years** θ_{12}, Δm^2_{21}, Δm^2_{31} precision
  → **0.5%**, **0.3%** and **0.2%**

	PDG 2024	Global fits	JUNO 6 years
$\sin^2\theta_{13}$	3.2%	2.6%	12%
$\sin^2\theta_{12}$	4.2%	3.9%	**0.5%**
Δm^2_{21}	2.4%	2.8%	**0.3%**
Δm^2_{31}	1.1%	1.1%	**0.2%**

Atmospheric neutrinos and synergy with NMO

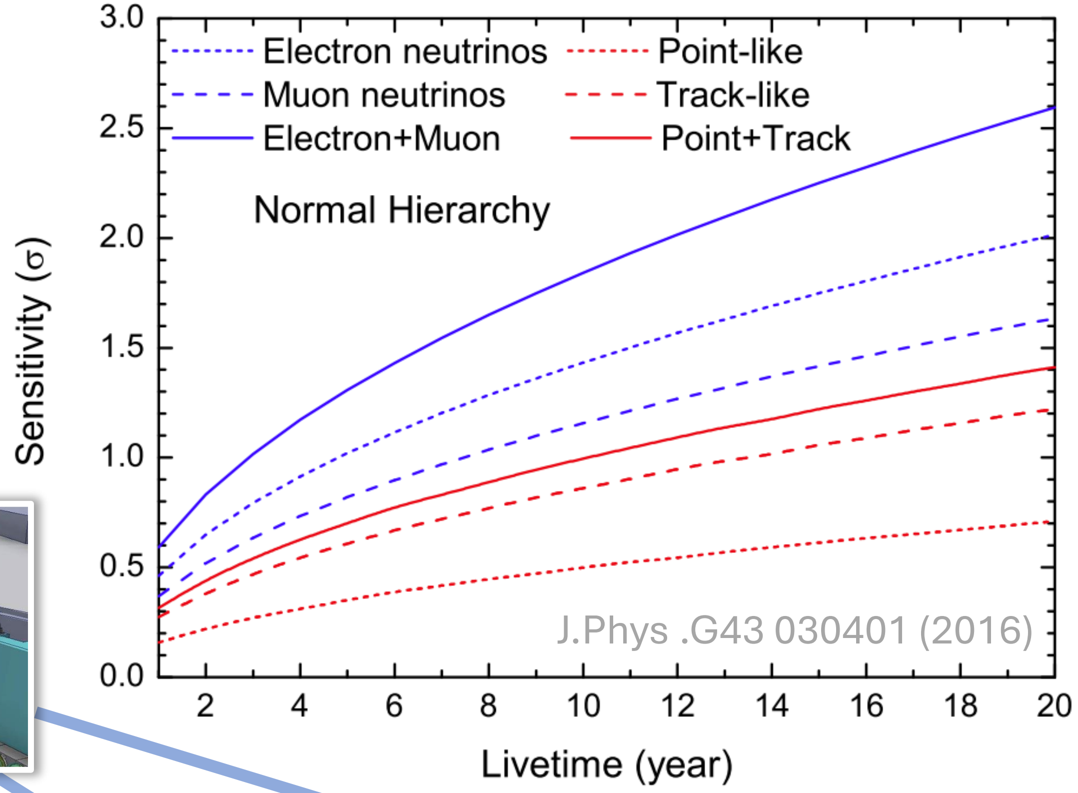
JUNO **first experiment** to study **atmospheric** neutrino oscillation with **liquid scintillator**:

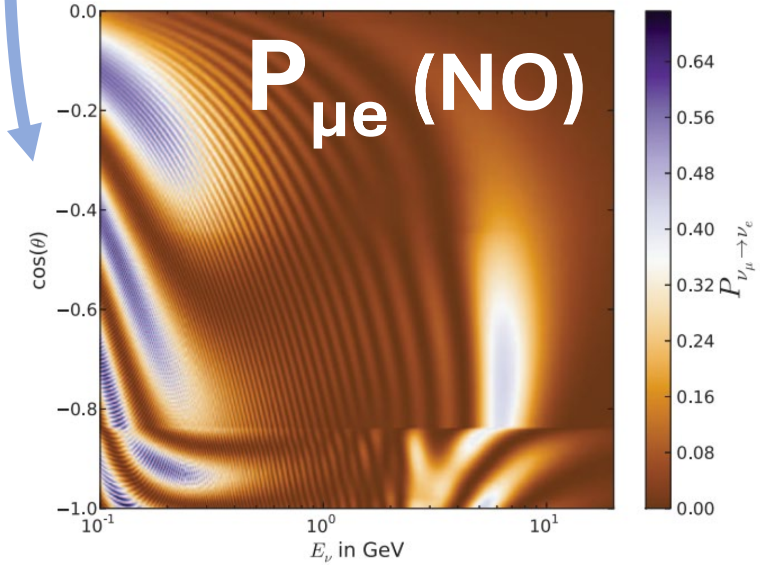
NMO via **matter effects** requirements:

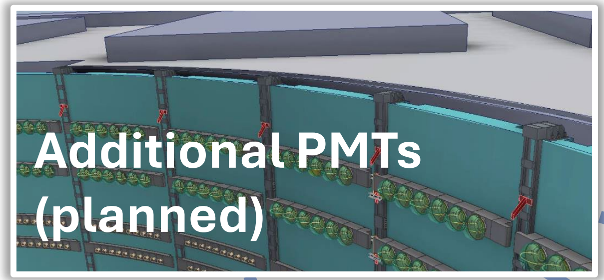
→ Good **flavor separation** (traditional + ML)

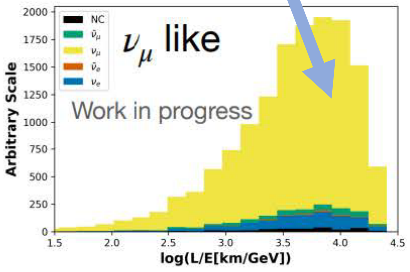
→ Good track reconstruction

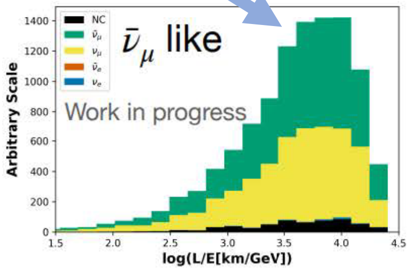
Expected > 3σ in 6 years combined with reactor

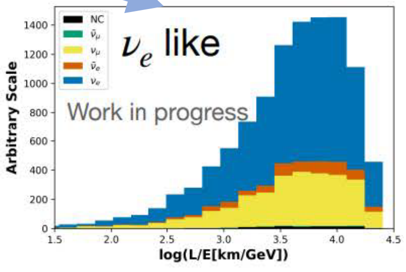


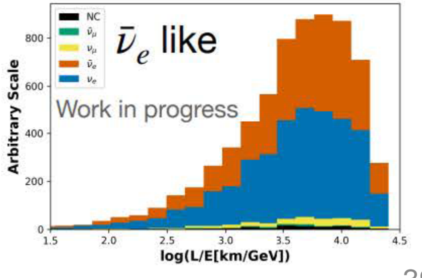












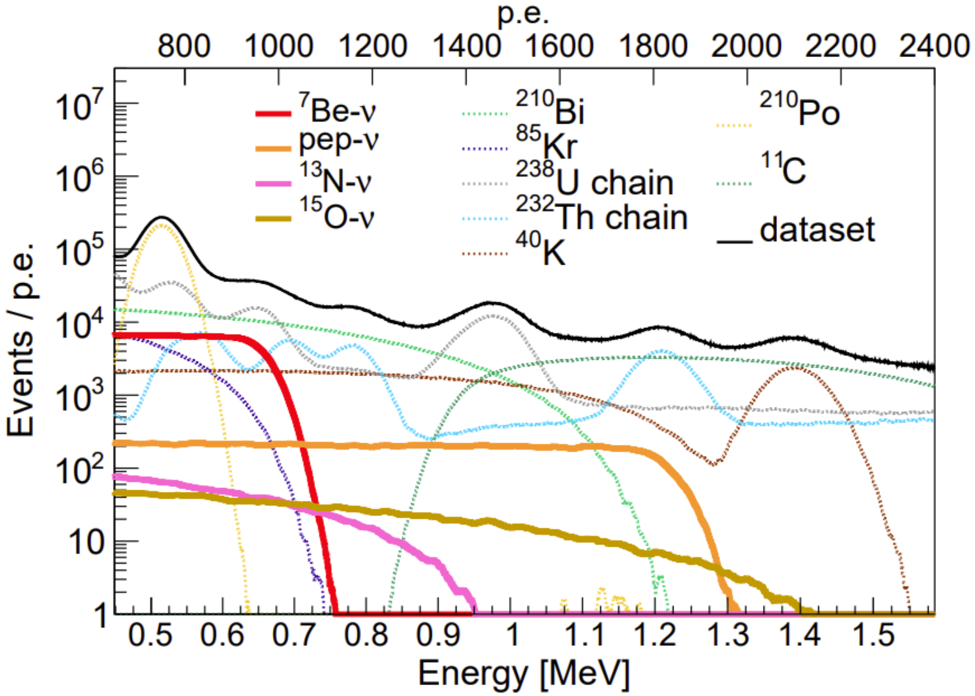
Solar neutrinos in JUNO

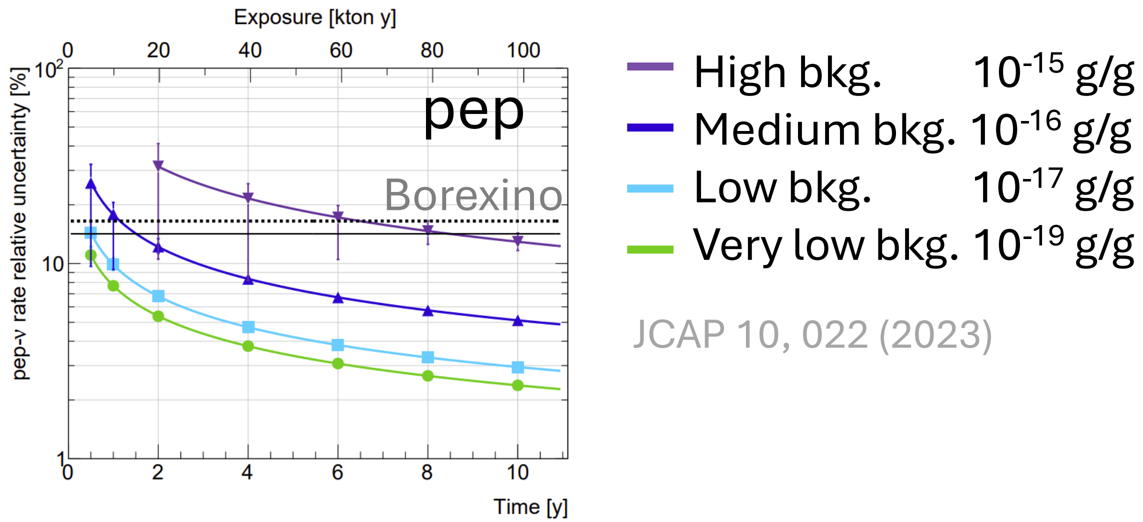
JUNO **is** an **excellent solar neutrino detector** via elastic scattering.

Improve current measurements: (with bkg <= 10^{-16} g/g)

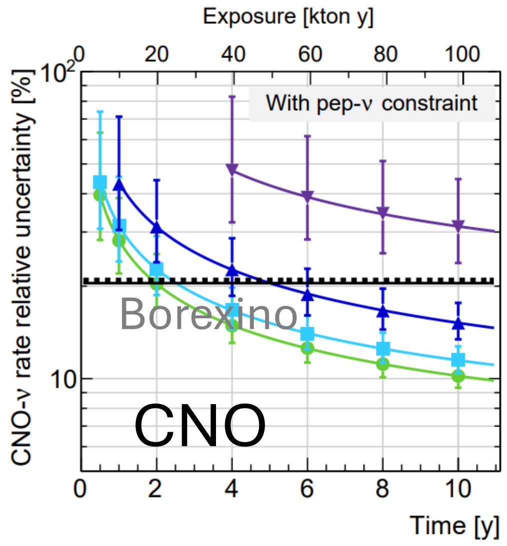
→ ***pep*** and **^{7}Be** better than Borexino in **~2y**

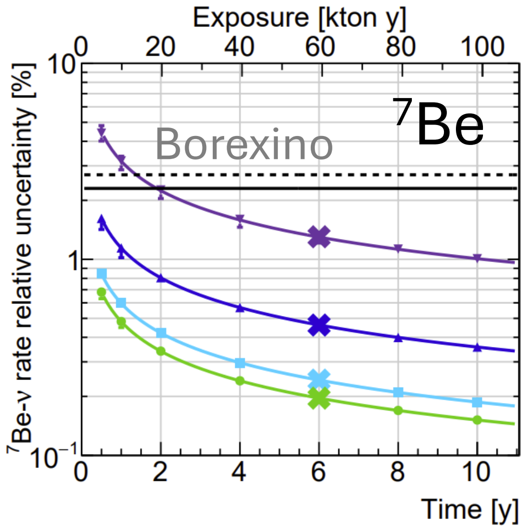
→ **CNO** better than Borexino in **~6y** (with **no constraint on ^{210}Bi**)





JCAP 10, 022 (2023)



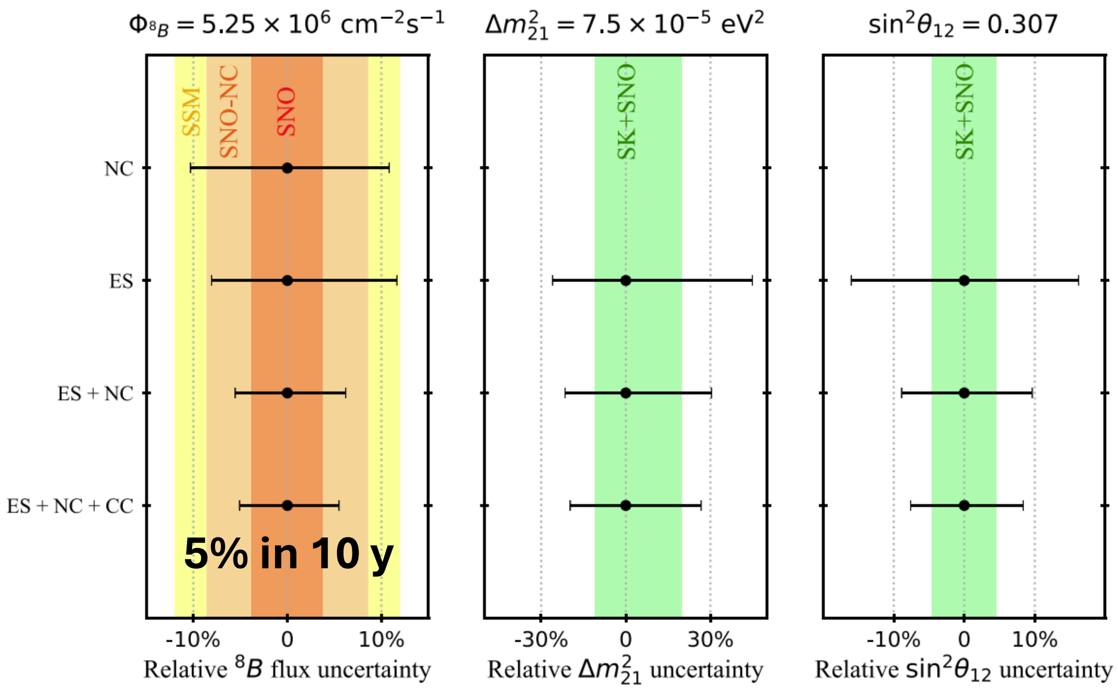


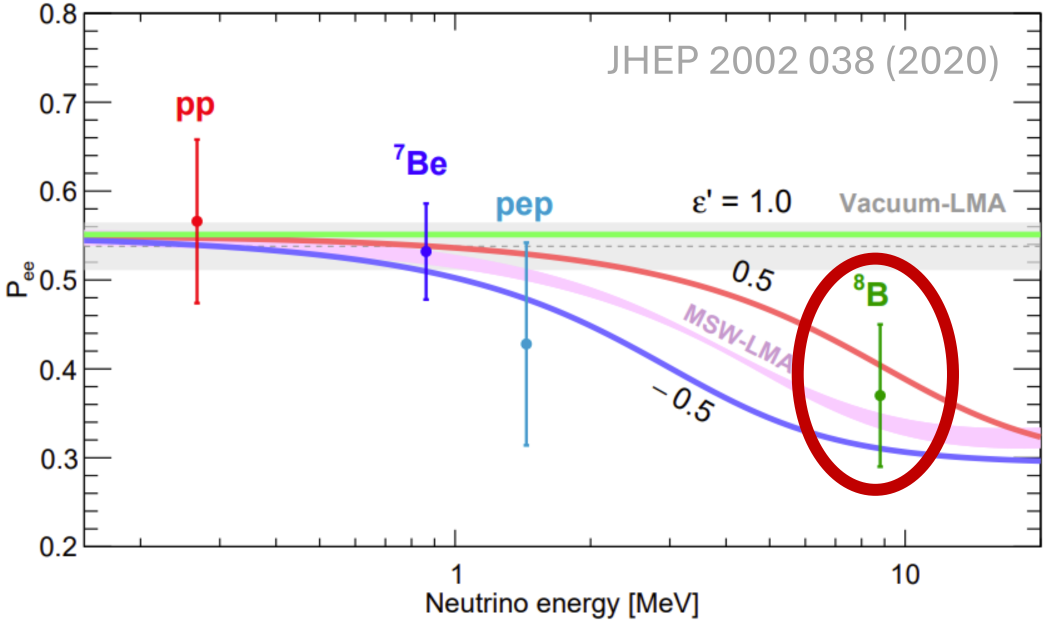
Solar neutrinos from ^{8}B

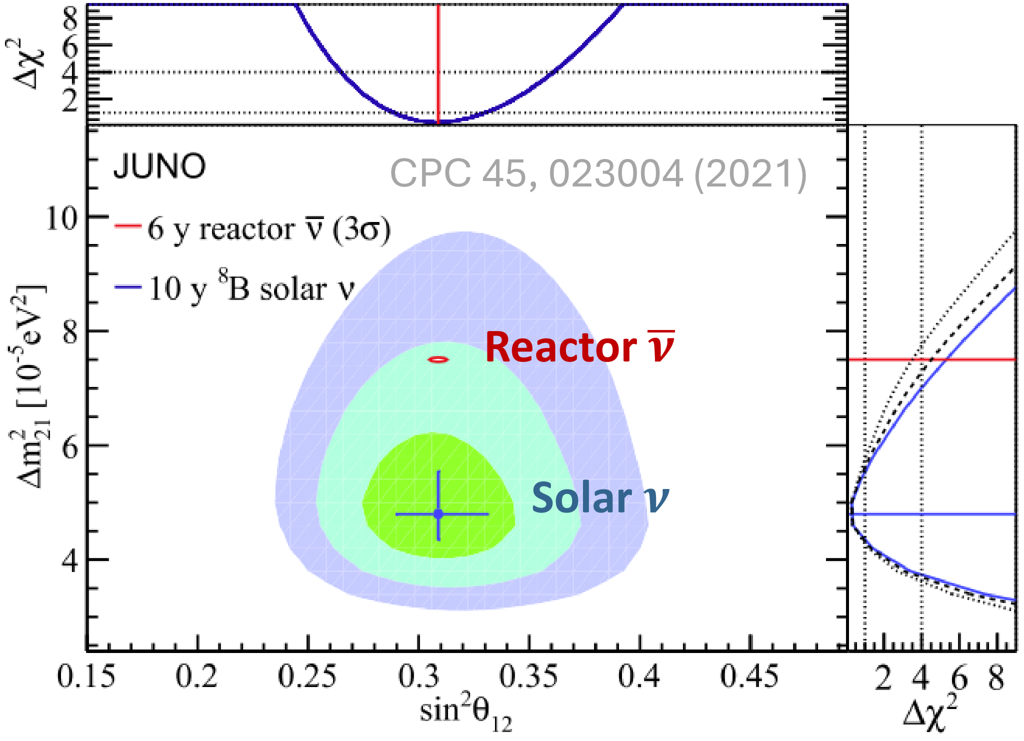
JUNO capable to **detect ^{8}B** in a **model independent** way: Astrophys. J. 965.2: 122 (2024)

→ **combination** of **CC+NC** on ^{13}C **+ES**

→ **independent** measurement of $\theta_{12}, \Delta m^2_{21}$







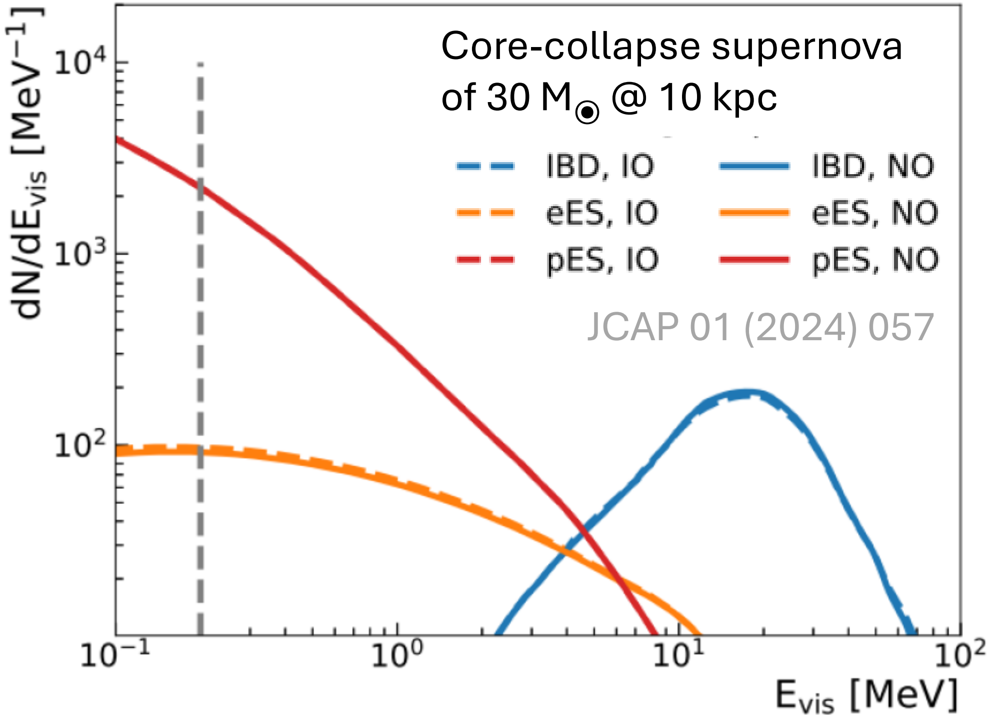
Supernovae and diffuse supernovae background

A **supernovae** observer:

→ **sensitive** to **all flavors** with CC + ES

→ perfect for **multi-messenger**

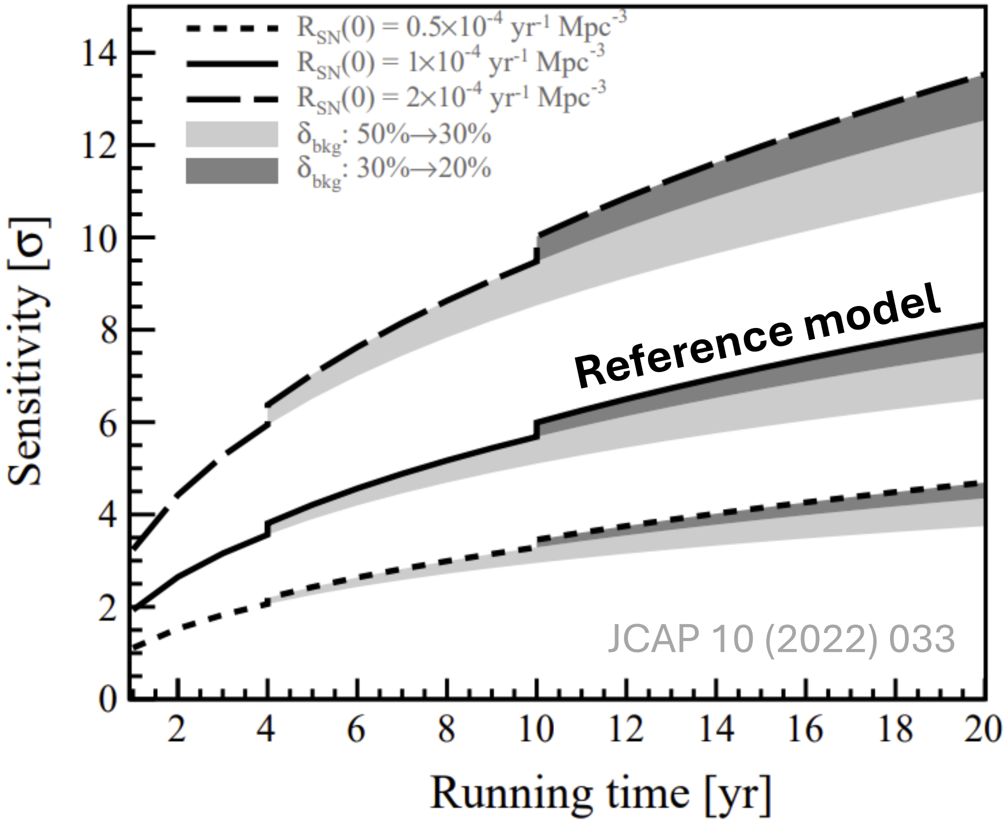
- **pre-supernova** (~hours) neutrinos → **alert!**
- **supernova explosion** (~10^1 seconds) → **telescope**



Discovering **diffuse supernovae bkg.:**

→ **pulse shape** discr. for **S/B ratio** 2→**3.5**

→ **3σ** (>5σ) **in 3y** (10y) with reference model



Geoneutrinos

	Preliminary expected sensitivity [%]				
	Th/U fixed	Th/U free			
Time	U+Th	U	Th	U+Th	U/Th
1y	~22	-	-	-	-
6y	~10	~35	~40	~18	~70
10y	~8	~30	~35	~15	~55

Geoneutrinos provide precious information about our **planet composition** and **formation.**

JUNO will have:

→ **400 evts/year** largest detection rate for geoneutrinos

→ unprecedented precision ~8% in 10y

→ study under active development!

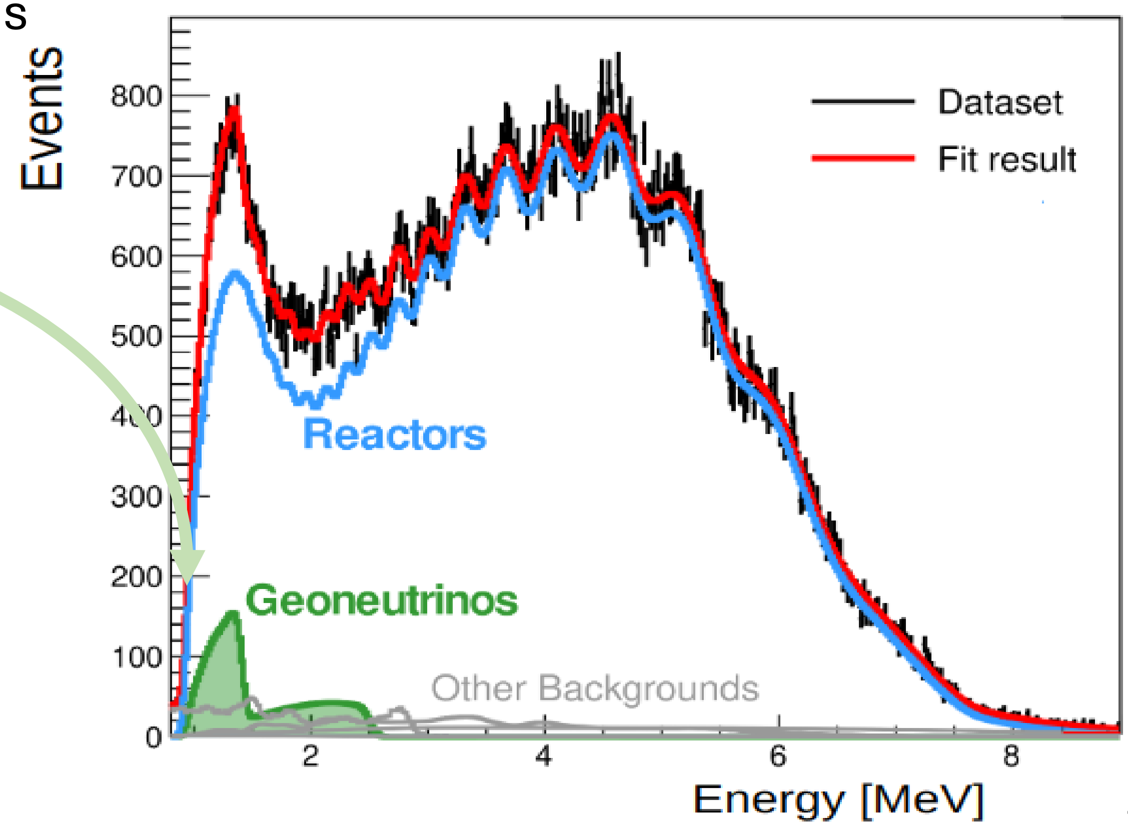
$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7\ MeV$

$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8\ MeV$

~~$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e + 1.32\ MeV$~~

Below threshold for IBD

Heat



Nucleon decay searches

JUNO has competitive **sensitivity** to **nucleon decay** searches **exploiting:**

1. **proton decay:** $p \to \bar{\nu} K^+$ (>9.6 × 10^{33} y)
2. **neutron decay:** $n \to inv$ (>5.0 × 10^{31} y)

   $nn \to inv$ (>1.4 × 10^{32} y)

90% CL in 10 years of data taking (200 ton yr)

→ signal **signature**: 3-fold **time coincidence:**

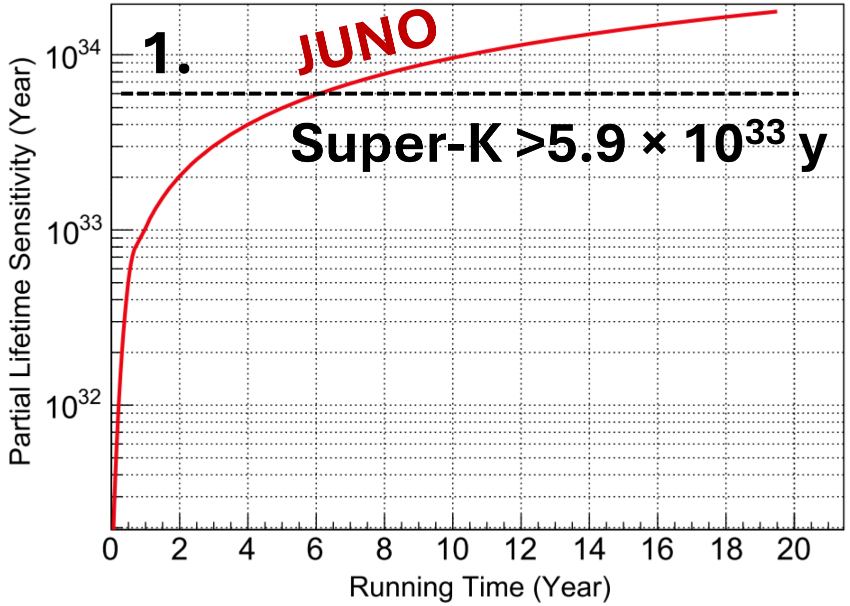
1. **proton decay:** $K^+ \to \mu^+ \to e^+$
2. **neutron decay:** $^{11}C^* \to n + {}^{10}C(\beta^+)$

   $^{11}C^* \to n + \gamma + {}^{10}C(\beta^+)$

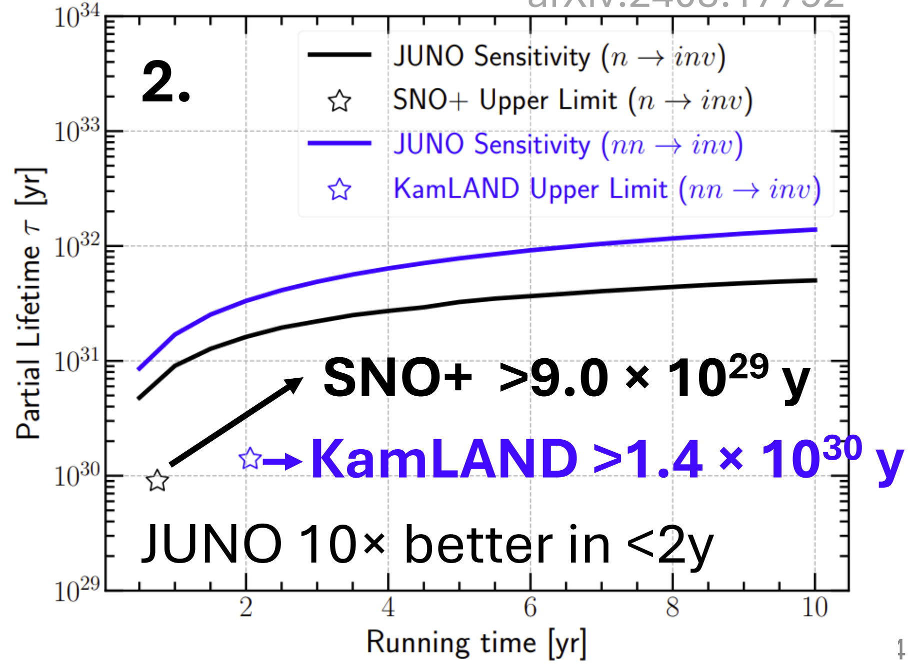
   $^{10}C^* \to n + {}^{9}C(\beta^+)$

   $^{10}C^* \to n + p + {}^{8}B(\beta^+\alpha)$

CPC 47, 113002 (2023)



arXiv:2405.17792



Conclusions

JUNO will be the **largest liquid scintillator** detector ever built (**20 kton** of liquid scintillator)

→ **construction** is **on-going**

→ start of **data taking** foreseen in **2025**

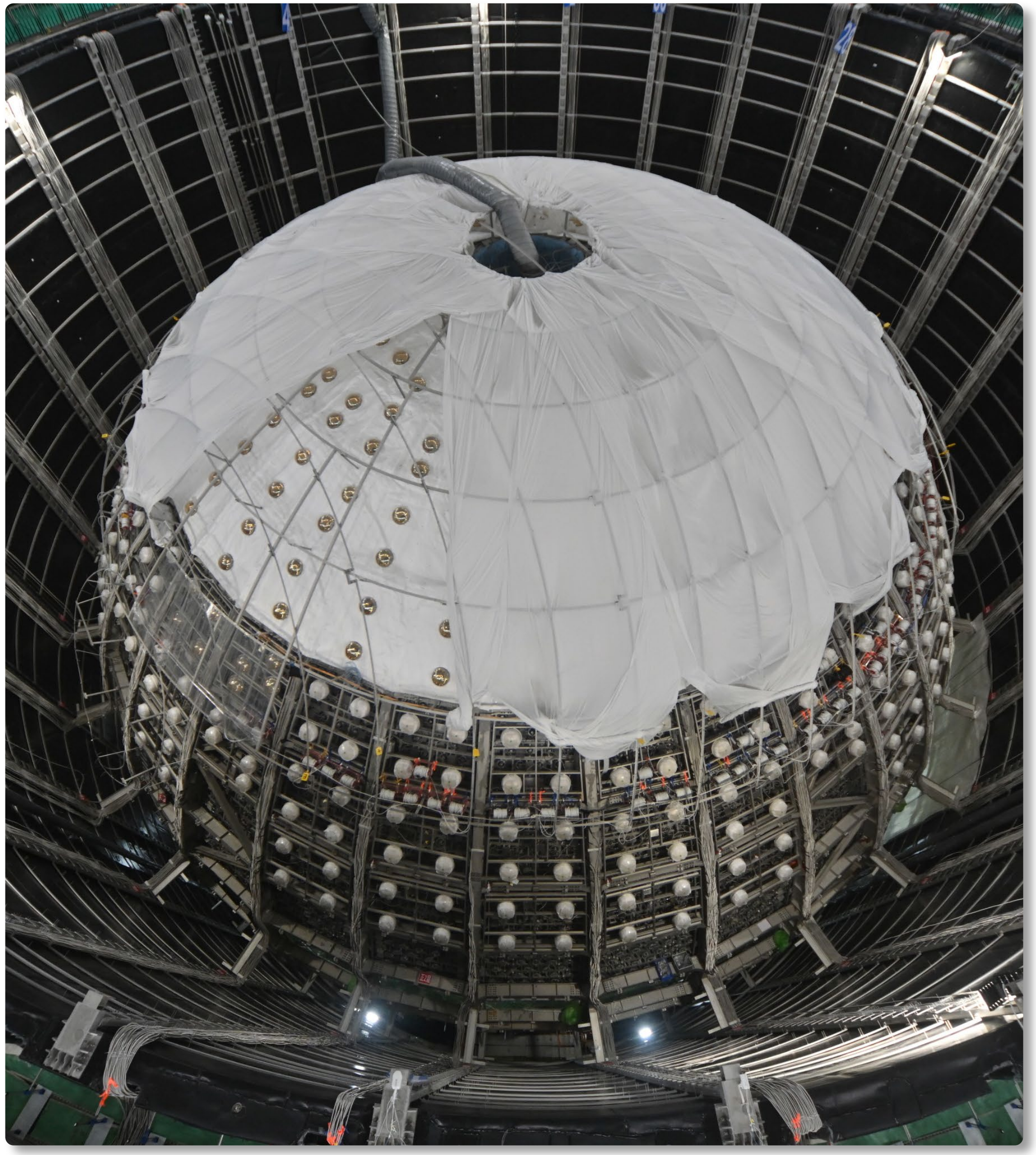
We aim high:

→ **NMO** determination at **3σ** in 6.5 y × 26.6 GW_{th}

→ World-leading **<1% precision** in $\boldsymbol{\theta_{12}, \Delta m^2_{21}}$ and $\boldsymbol{\Delta m^2_{31}}$ in <2y

→ **Synergies** and **discoveries** from **other neutrino sources** (solar, geo, atmospheric, supernovae) and more (proton decay)!

Check out our parallel talks at NOW 2024!



Thank you!

Since 2014, >700 collaborators from 74 institutions in 17 countries/regions