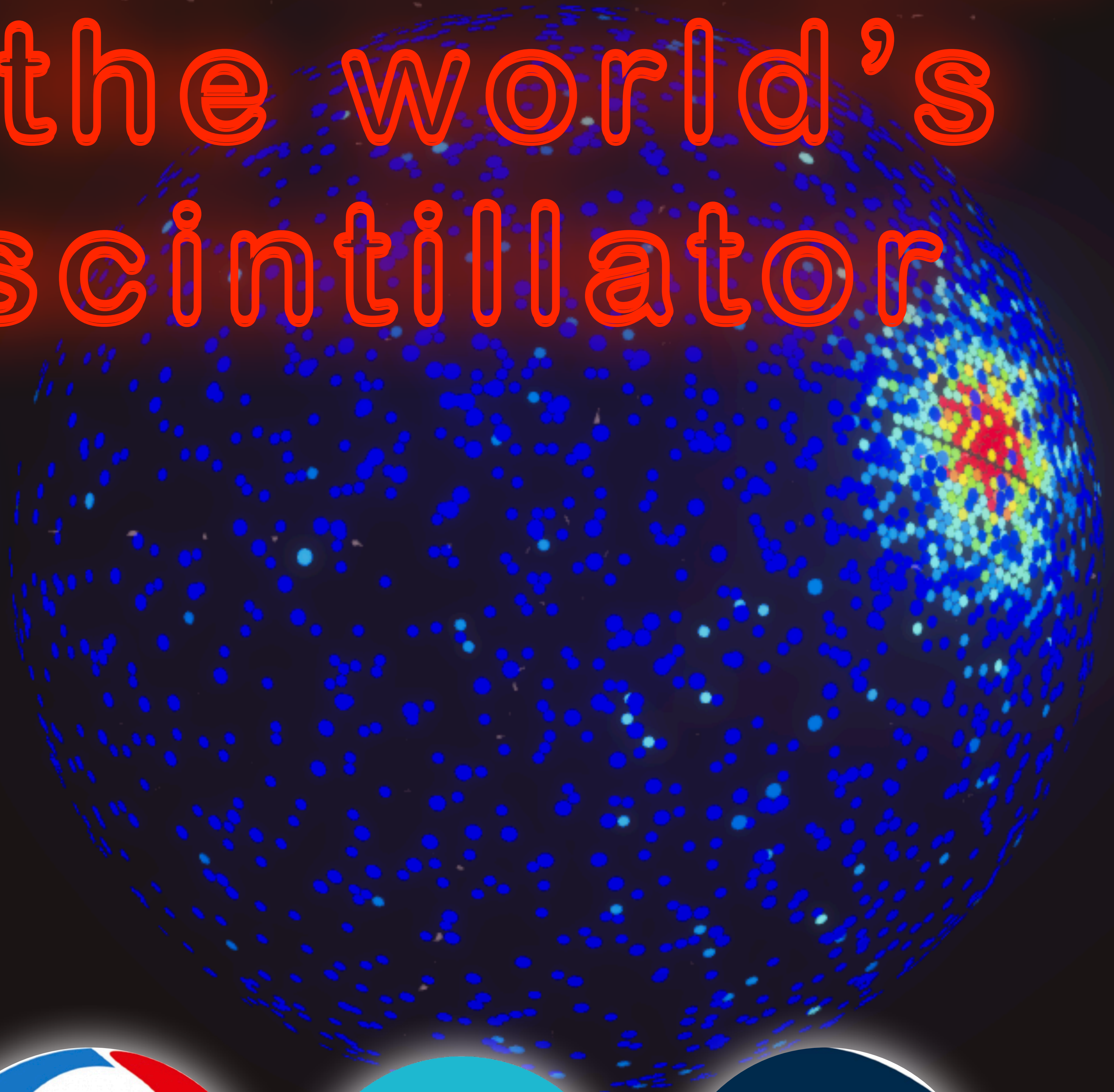
Exploring the neutrino mass hierarchy with the world's largest liquid scintillator

The JUNO experiment



Loïc-René Labit | IPHC Seminar 08/03/2024

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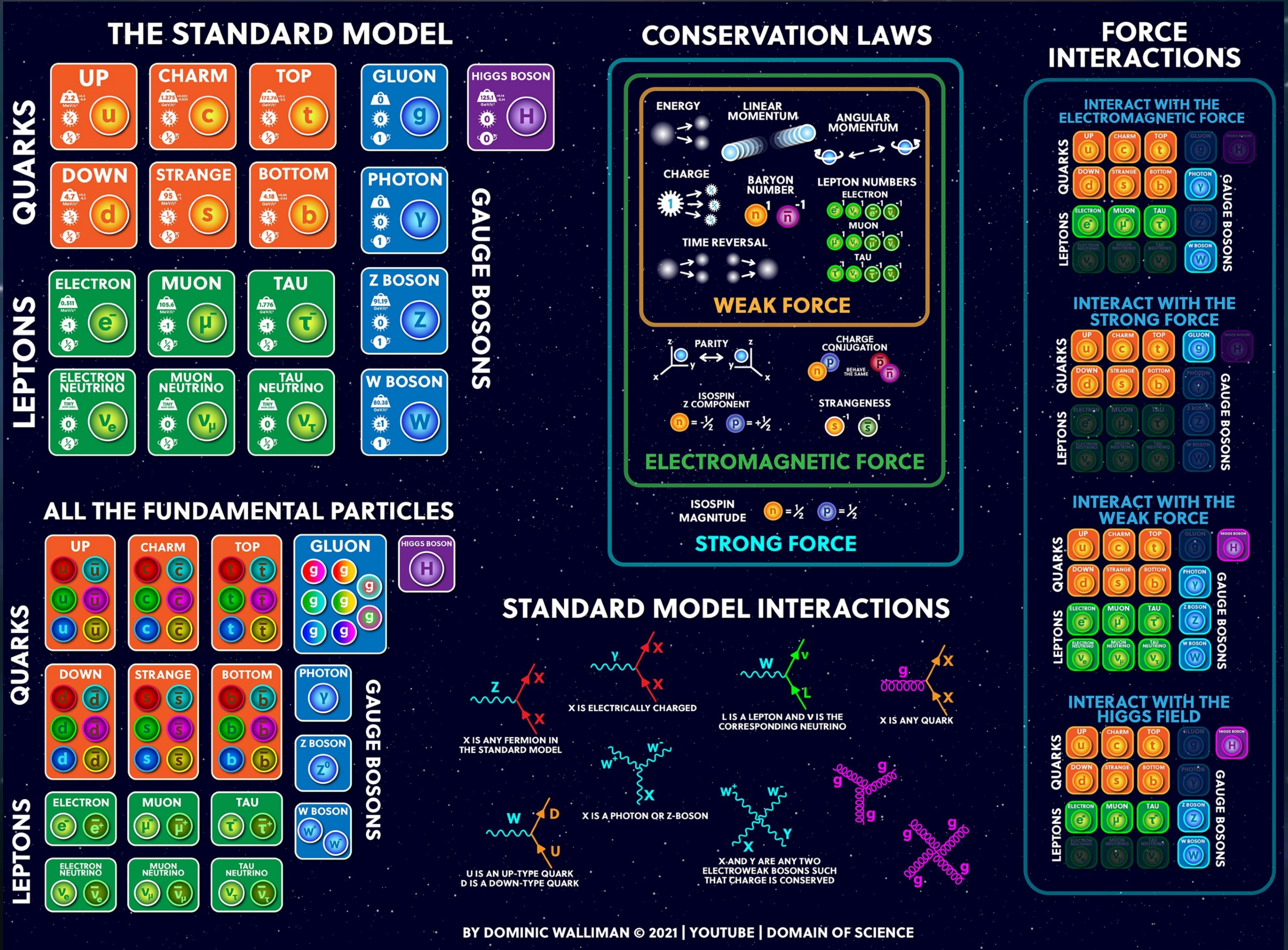
  - Neutrino Mass ordering determination
  - Precision measurement of oscillation parameters
  - Other physics goal

Neutrinos in the Standard Model

- Neutrinos in the SM:
  - No electric charge
    → no electromagnetic interaction
  - No colour charge
    → no strong interaction
  - Only weak interaction
    →neutrinos are left handed
    antineutrinos are right handed
    → tiny cross-section of interaction
    ($\sigma_{IBD} \sim 10^{-43}$ cm^{-2})
  - In principle, neutrinos are massless
- Neutrinos beyond the Standard Model:
  - Experimental evidence for neutrino oscillation (2015's Nobel prize)
    → requires a massive neutrinos



Neutrino oscillation

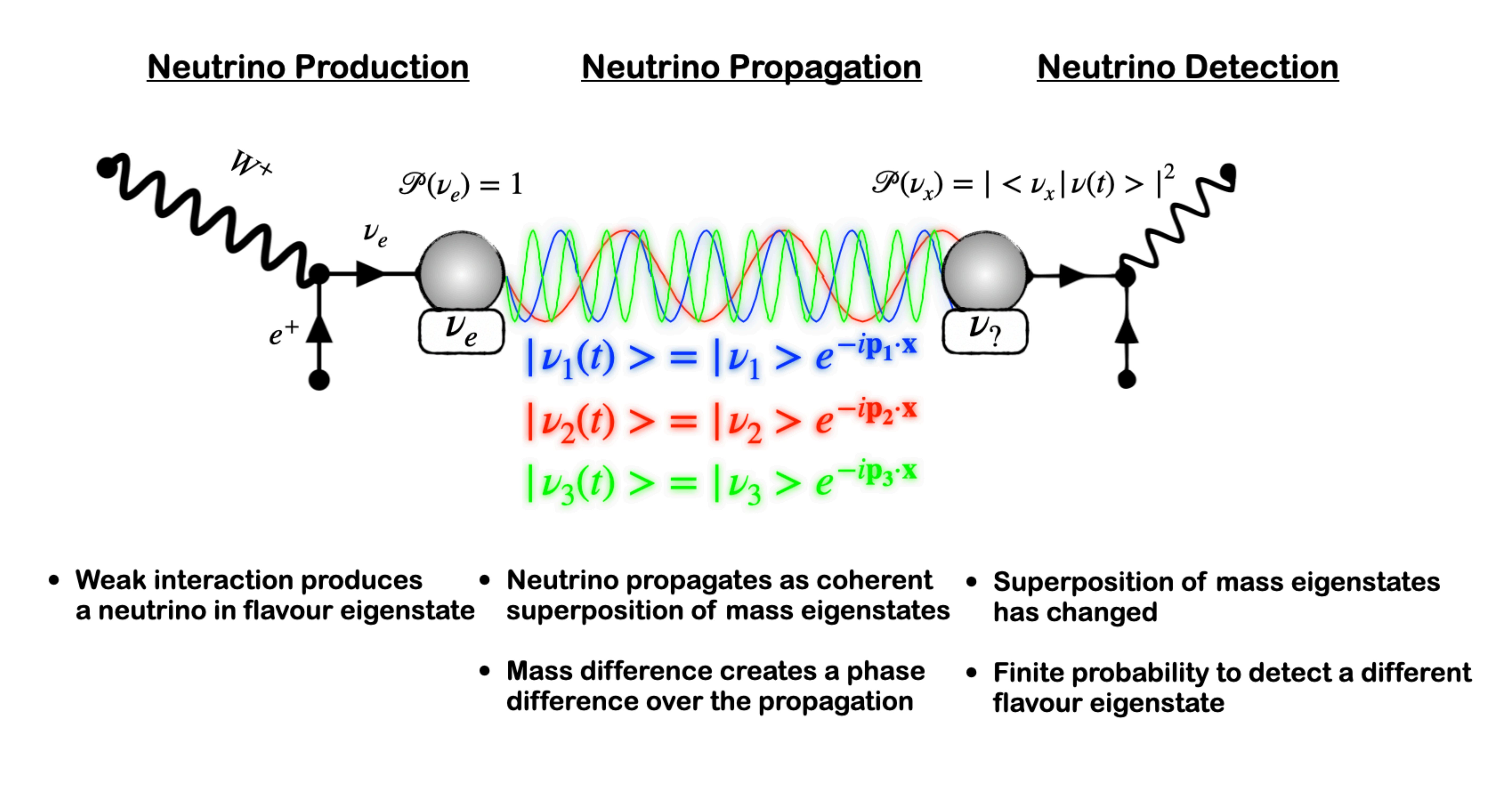
- Interaction (or flavour) eigenstates (ν_e, ν_μ, ν_τ) do not match propagation (or mass) eigenstates (ν_1, ν_2, ν_3)

- Relation between flavour and mass eigenstates given by Pontecorvo-Maki-Nakagawa-Sakata matrix U_{PMNS}

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U_{PMNS} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix} \times \begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha} & 0 & 0\\ 0 & e^{i\beta} & 0\\ 0 & 0 & 1\end{bmatrix}$$

with $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, δ CP-violation phase, α, β Majorana phases (no effect in oscillation)



- Probability to measure a neutrino with flavour β when produced with flavour α is

$$\mathscr{P}_{\nu_\alpha\to\nu_\beta}(L,E) = \sum_k \sum_j U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m^2_{kj}}{2E}\cdot L}$$

It is characterised by 3 mixing angle $\theta_{12}, \theta_{13}, \theta_{23}$ and 2 mass splitting $\Delta m^2_{12}, \Delta m^2_{31}$

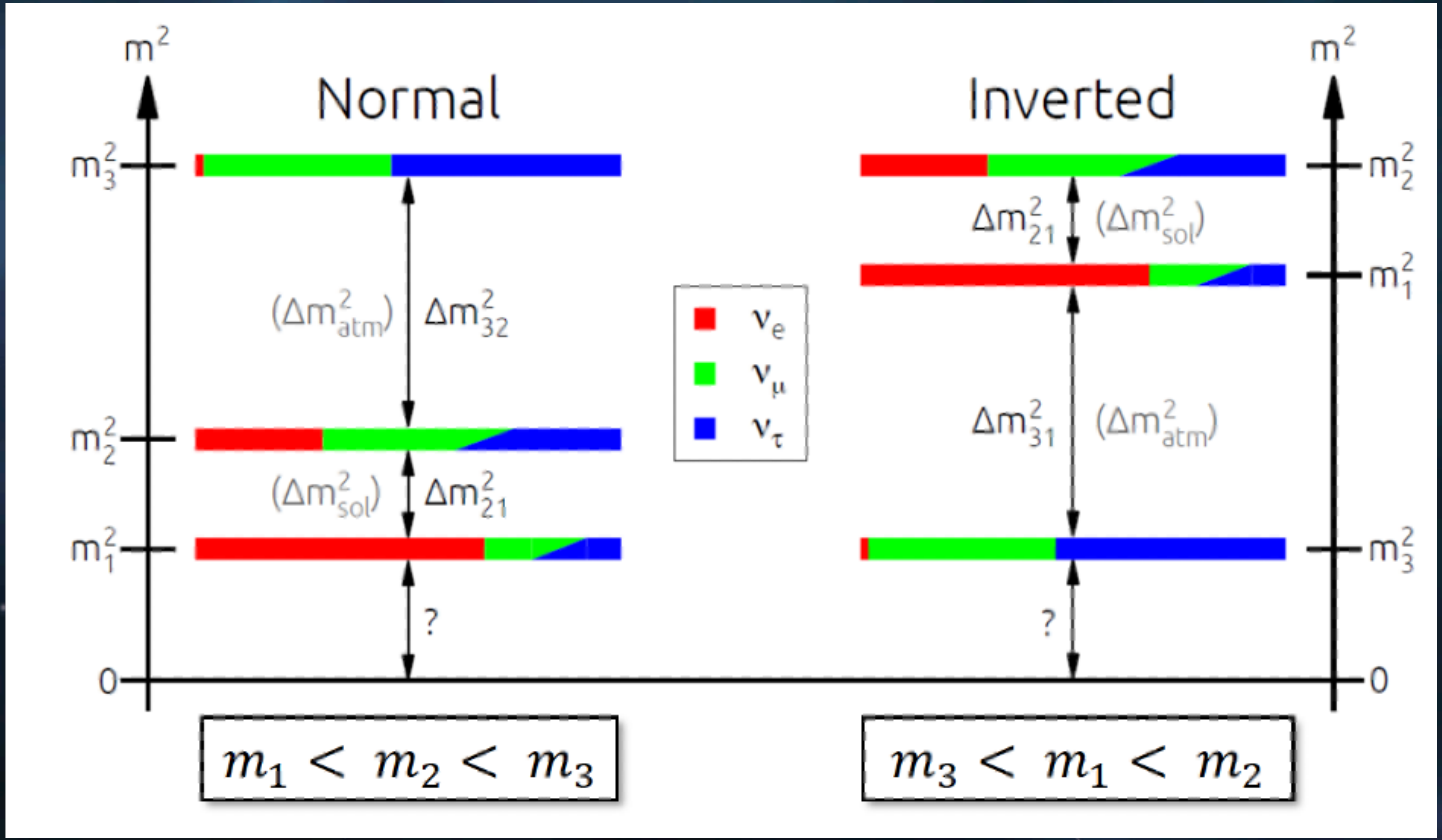
- δ and α, β are unknown

What to do in neutrino physics ?

- Neutrino as a probe to study:
  - The earth, the sun, the supernova, the Universe →still in its infancy ⇒ JUNO can help
- Open questions in neutrino physics:
  - Are there non standard interactions ?
  - How many neutrinos are there ? (Sterile neutrino states ?) ⇒ JUNO can help
  - Are neutrinos their own antiparticle (Dirac or Majorana fermion) ⇒ JUNO can help (in the future)
  - What is the absolute mass scale ?
  - Neutrino mass hierarchy: is it normal or inverted ? ⇒ JUNO can tell

Neutrino Mass Ordering

- Sign of Δm^2_{21} known
- Sign of Δm^2_{31} unknown
  $\rightarrow$ 2 possible mass ordering
- How to determine NMO ?
  - With matter effect
  - With reactor neutrino



Mass ordering with matter effect

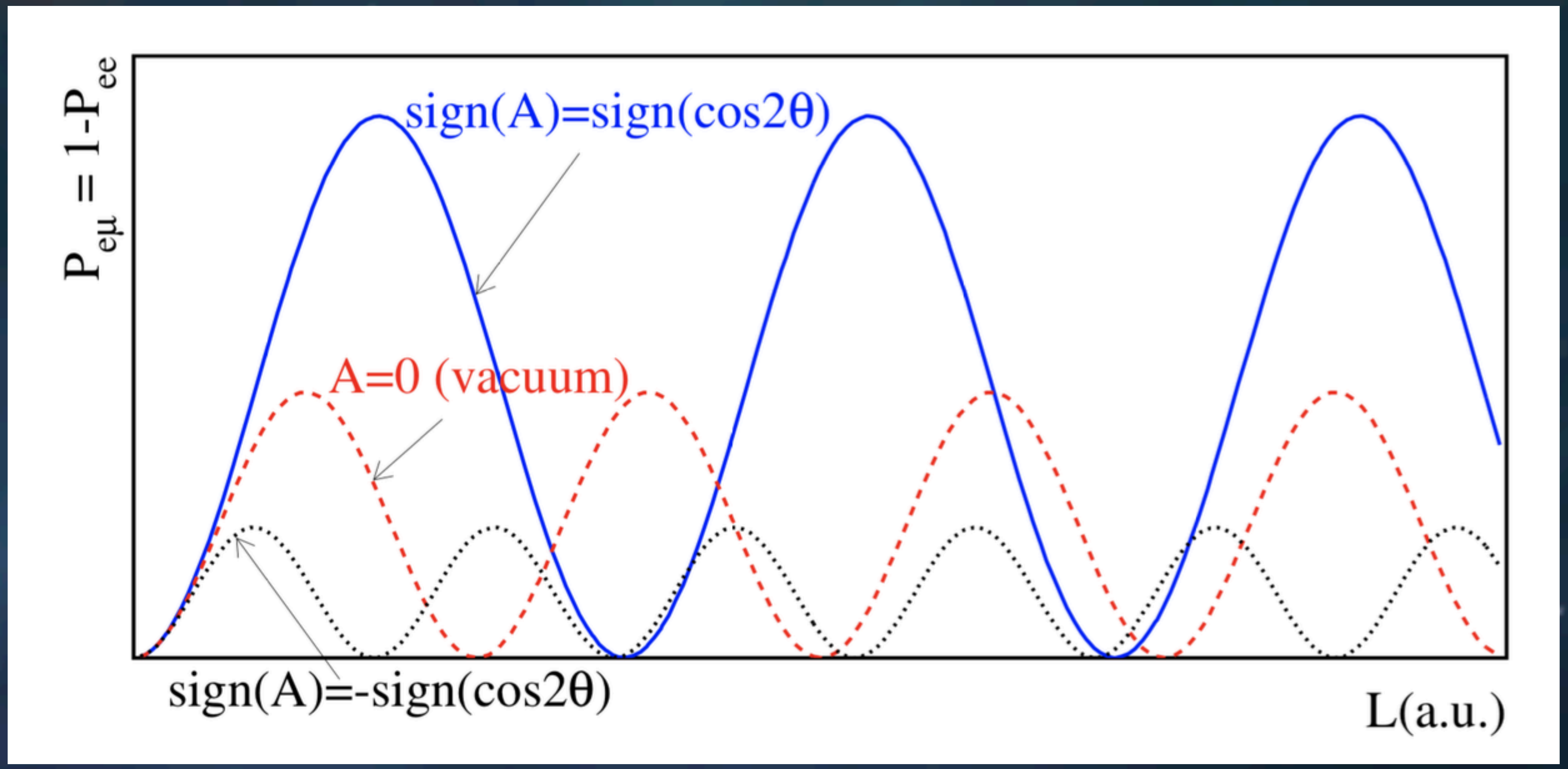
- When neutrinos travel through matter: additional potentials induced by neutral and charged current in matter
- Effective oscillation parameters given by:

$$\sin 2\theta_{MSW} = \frac{\sin 2\theta}{\sqrt{(A - \cos 2\theta) + \sin^2 2\theta}}$$

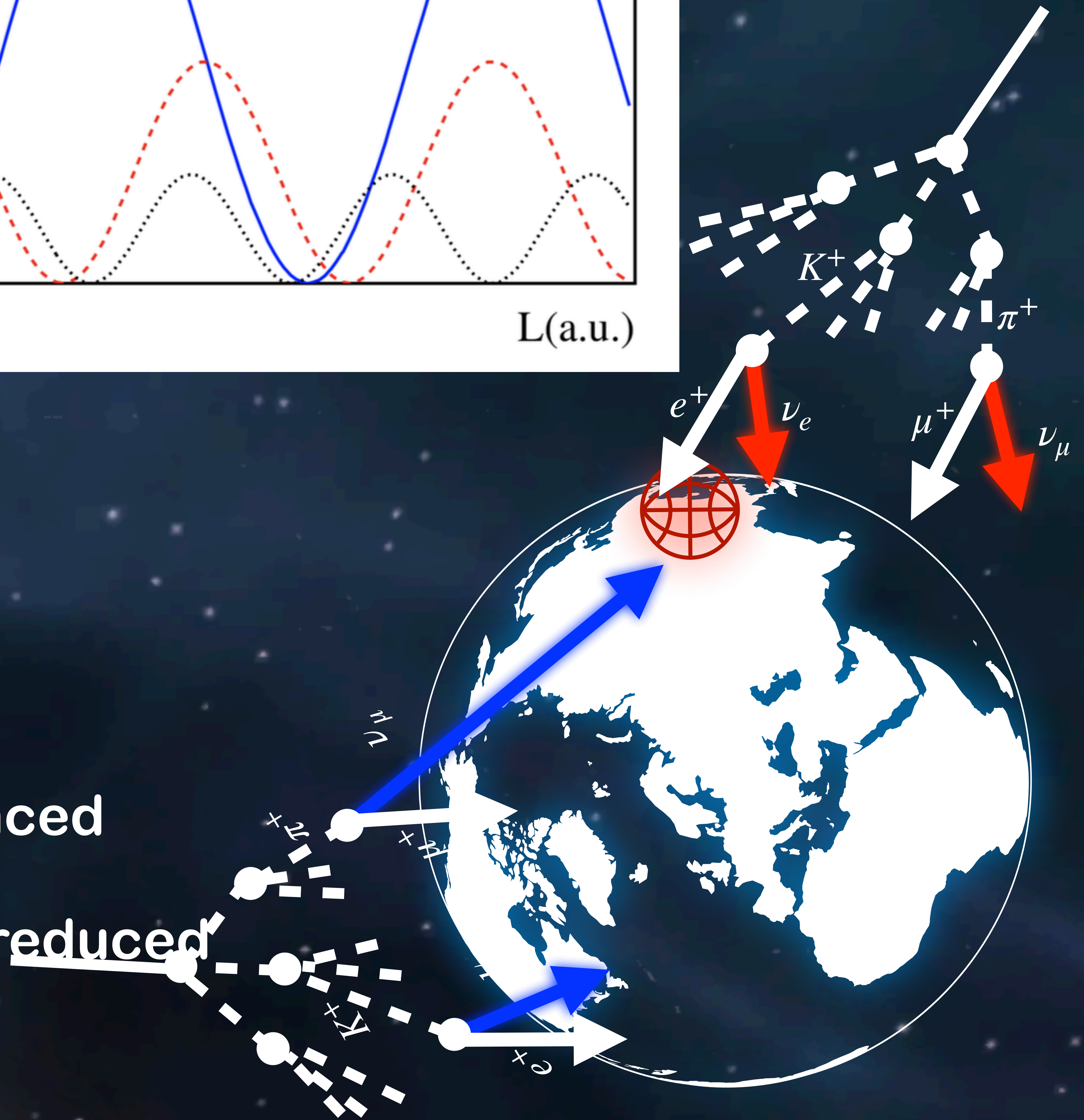
$$\Delta m^2_{MSW} = \Delta m^2 \sqrt{(A - cos2\theta)^2 + \sin^2 2\theta}$$

with $A = \pm 2\sqrt{2} G_F N_e E / \Delta m^2$

+ for ν - for $\bar{\nu}$



- Oscillation probability is modified by matter effect:
  - If A and $\cos 2\theta$ have same sign → oscillation probability enhanced
  - If A and $\cos 2\theta$ have opposite sign → oscillation probability is reduced
  - Sign of A depends on the sign of Δm^2 and if ν or $\bar{\nu}$



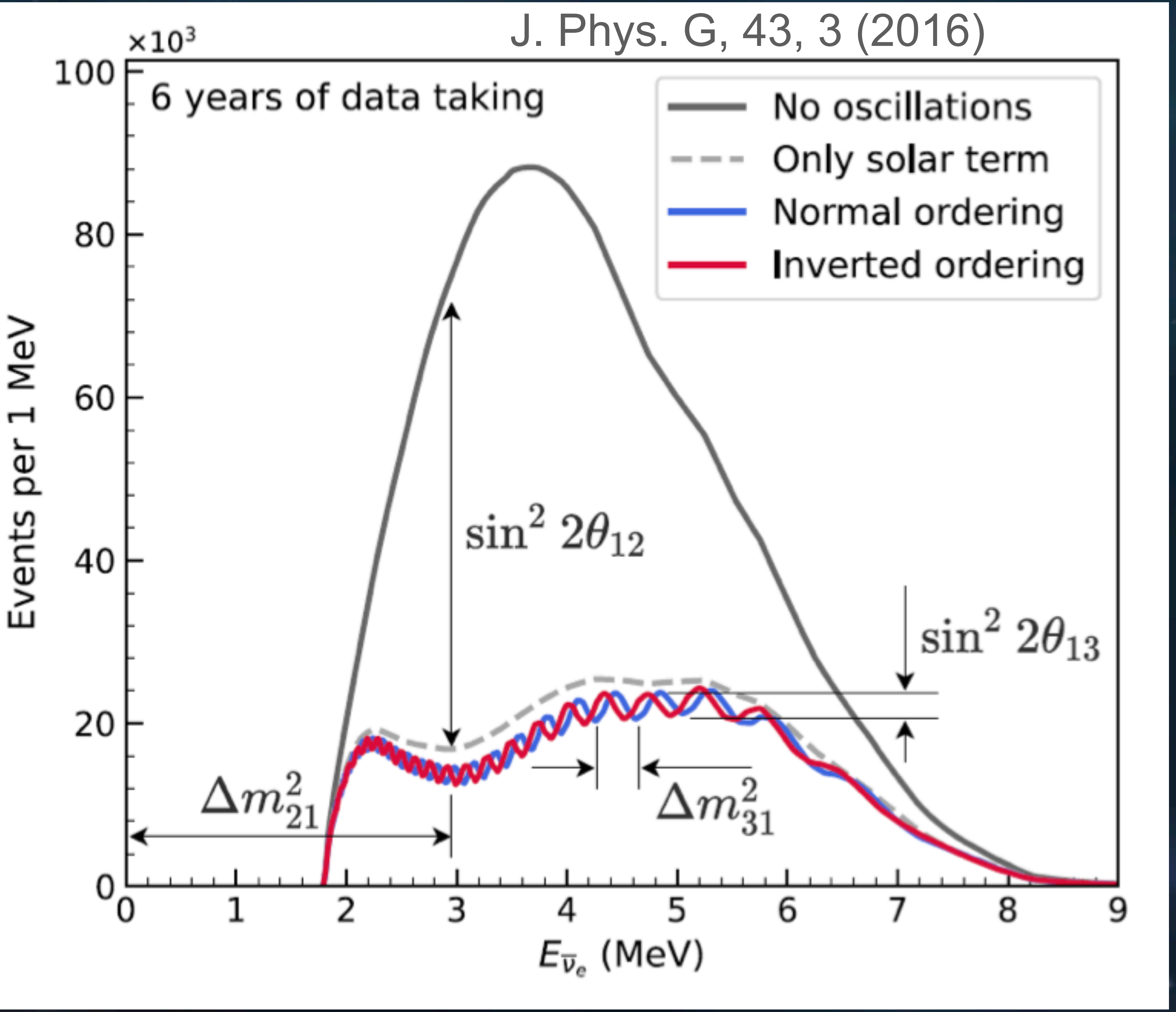
Mass ordering with reactor neutrino

- **Survival probability given by :**

$$\mathscr{P}(\overline{\nu_e} \to \overline{\nu_e}) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}\times L}{4E_\nu}\right) - \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}\times L}{4E_\nu}\right)$$
$$-\sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{21}\times L}{4E_\nu}\right)\cos\left(\frac{2|\Delta m^2_{31}|\times L}{4E_\nu}\right)$$
$$\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin\left(\frac{2\Delta m^2_{21}\times L}{4E_\nu}\right)\sin\left(\frac{2|\Delta m^2_{31}|\times L}{4E_\nu}\right)$$

- **Needs a very good energy resolution and understanding of the energy response**

- **Strategy employed solely by JUNO**



JUNO's essential features

- To resolve mass hierarchy's signature in the oscillated spectrum:

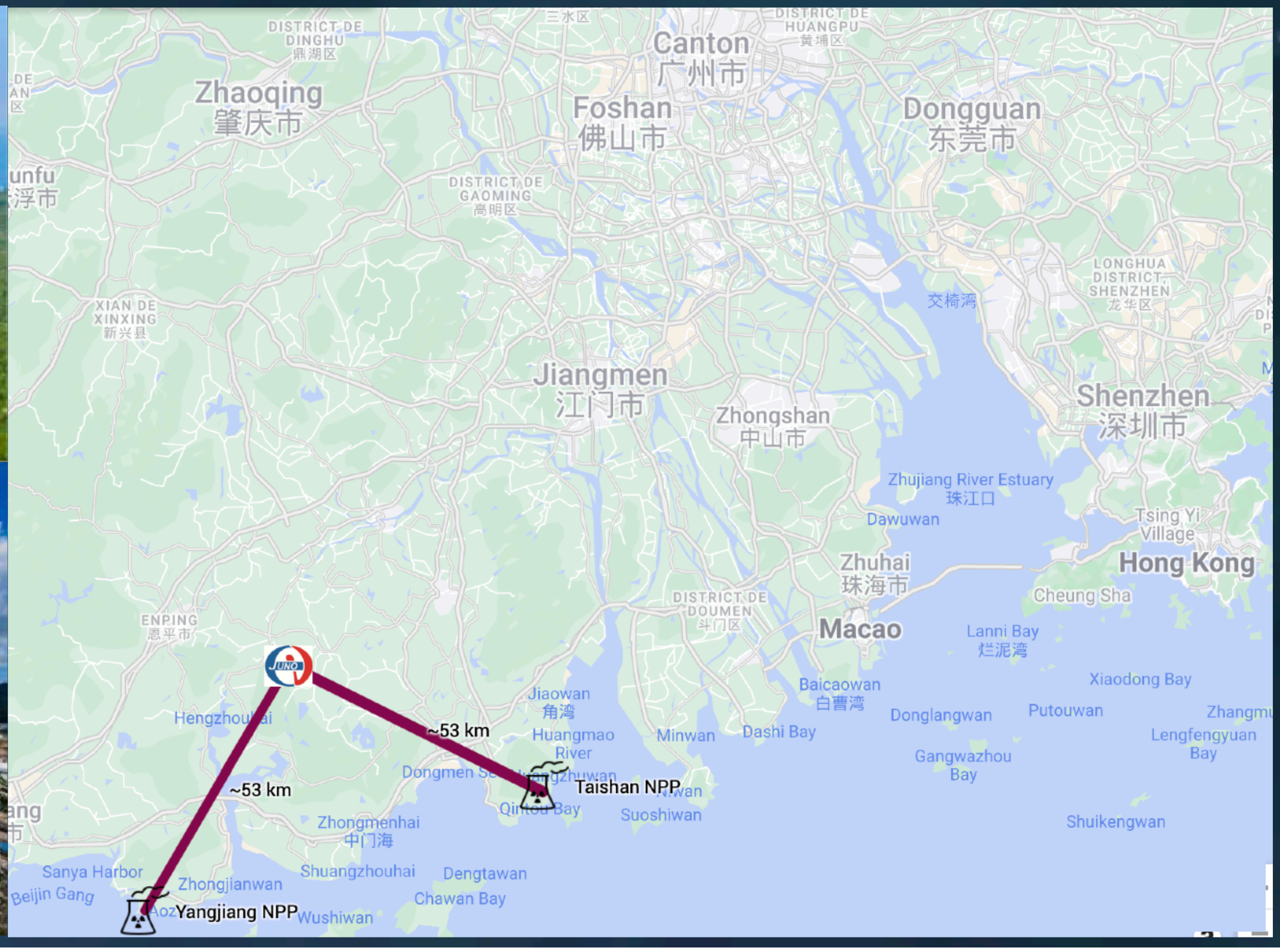
- [ ] Optimised baseline
- [ ] Energy resolution of 3% at 1 MeV
- [ ] Excellent understanding of the energy scale non-linearity
- [ ] Precise knowledge of the antineutrino reactor spectrum
- [ ] Large statistics
- [ ] Low background

JUNO site

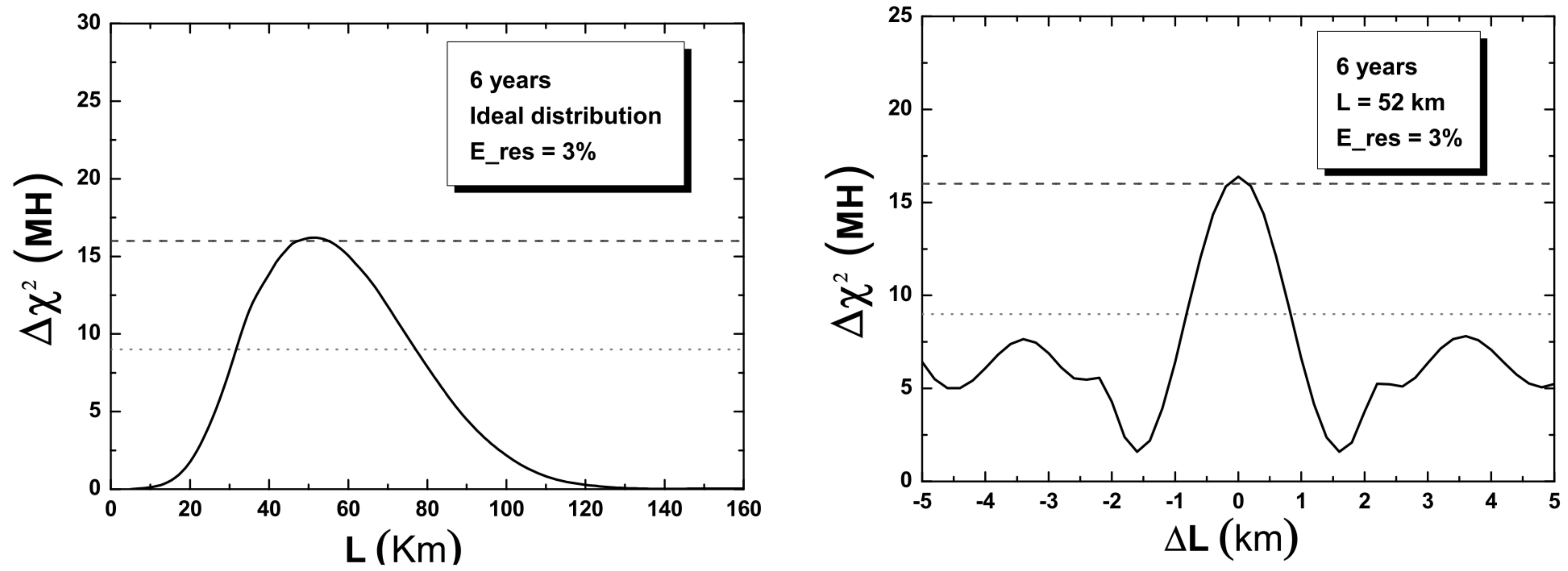
☑ Optimised baseline

- ~52.5 km from Taishan and Yangjiang NPP as to optimise discrimination between normal and inverted ordering

- Baseline spread between nuclear cores $\lesssim$ 0.7 km to optimise discrimination between orderings



Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64



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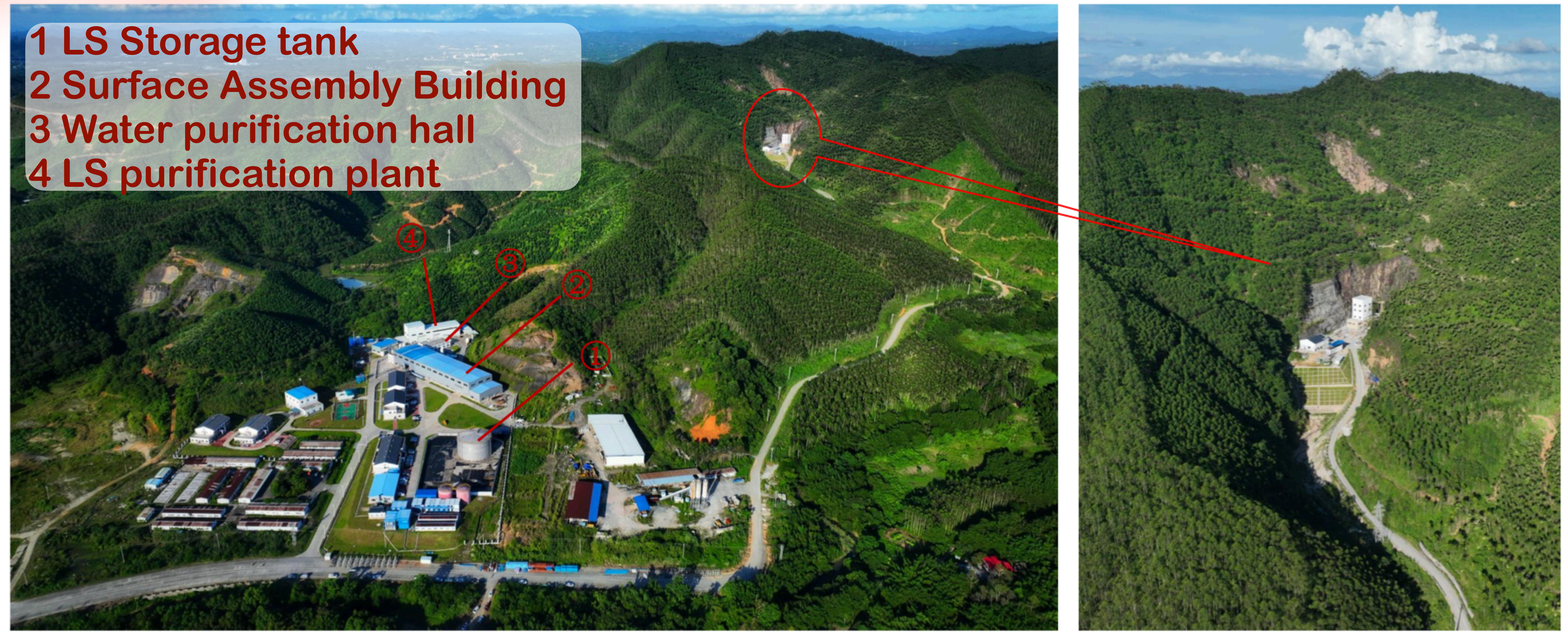
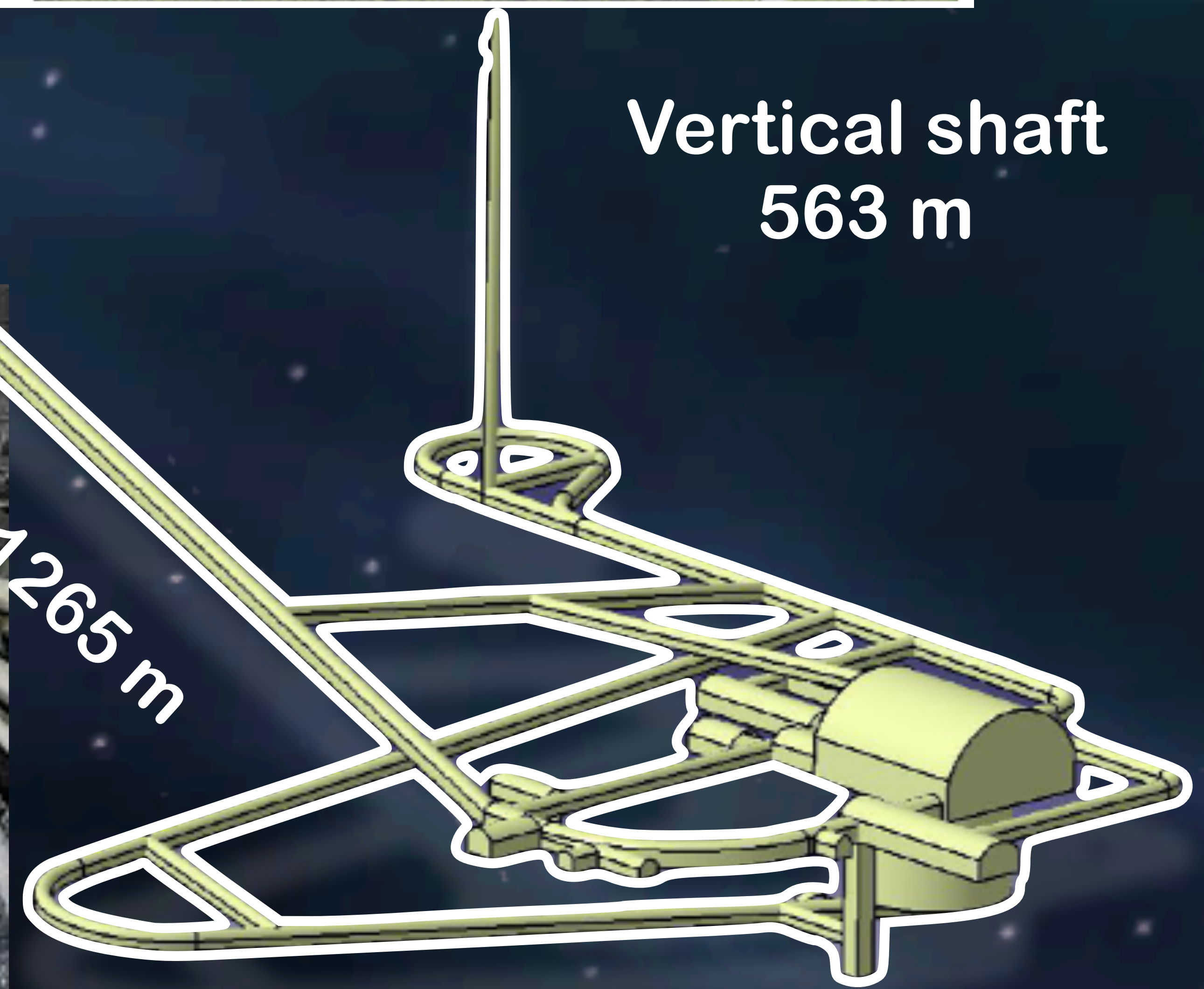
$$\Delta\chi^2_{\rm MH} = |\chi^2_{\rm min}({\rm N}) - \chi^2_{\rm min}({\rm I})|$$

JUNO site

☑ Low background



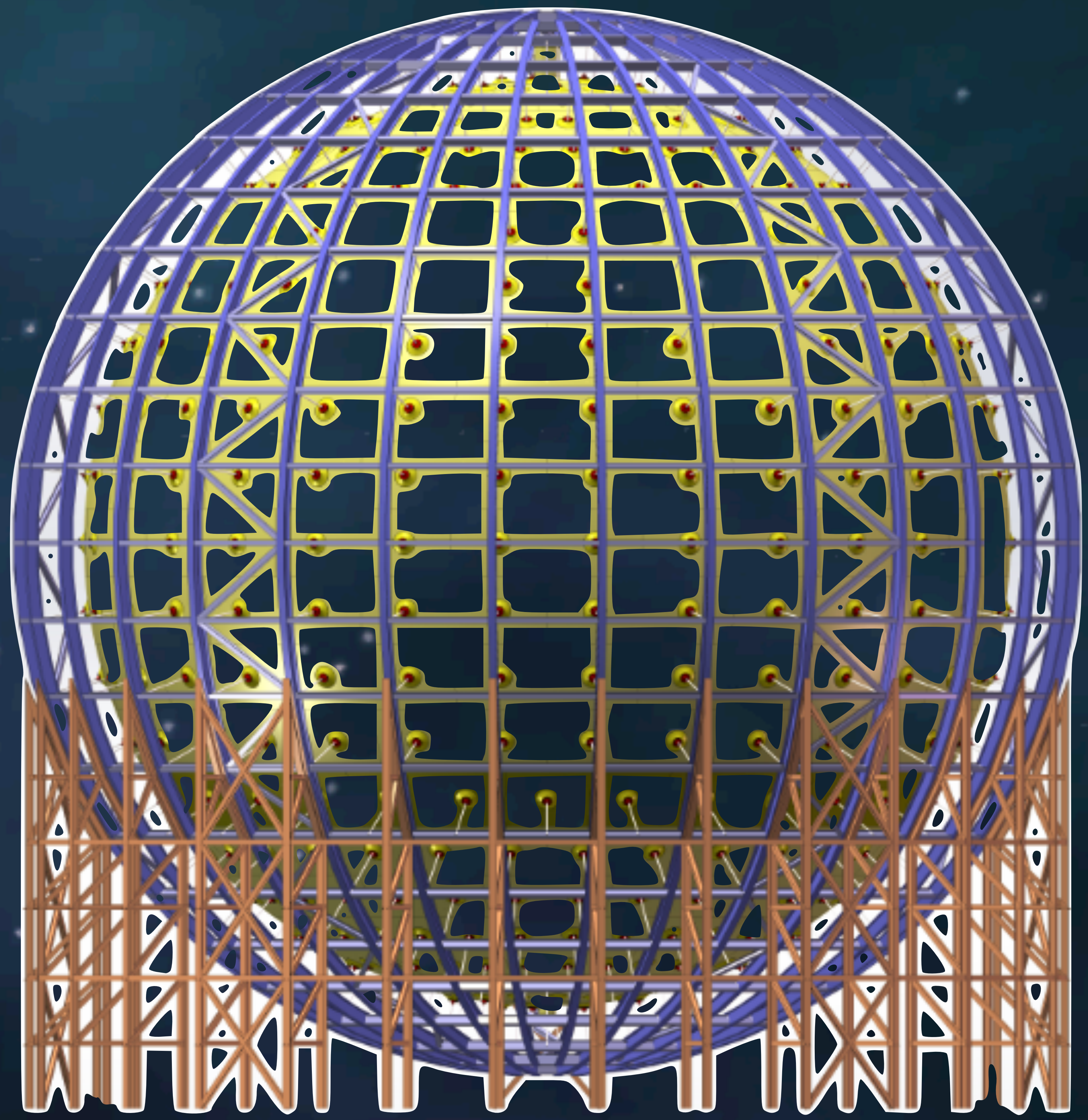
- Underground detector: 650 m overburden
  1800 m.w.e → ~4 Hz of muons in LS



Detector design: Central Detector

- ☑ Large statistics
- ☑ Energy resolution of 3% at 1 MeV

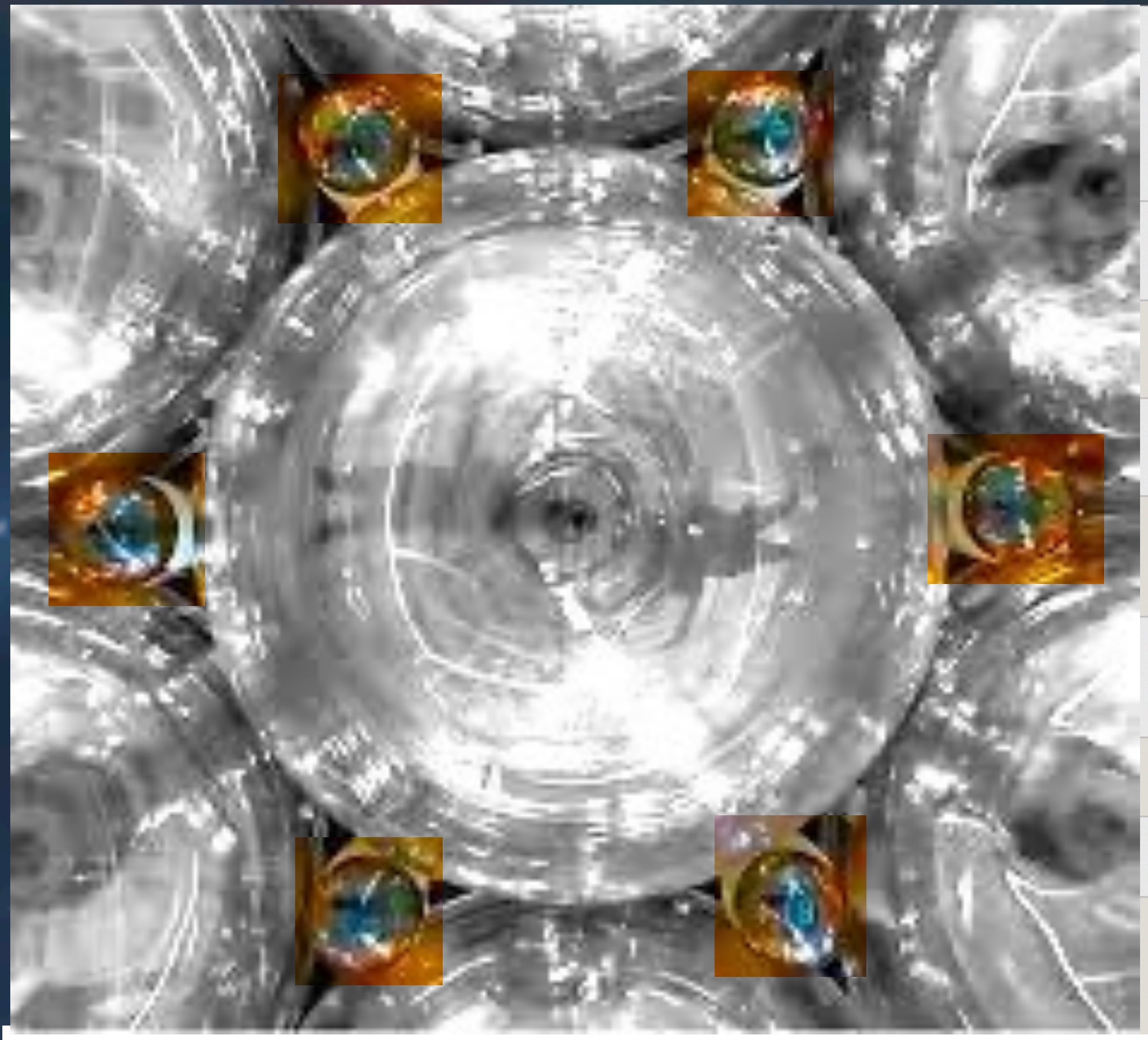
- The world's largest liquid scintillator experiment:
  - 35.4 m diameter acrylic sphere
  - 20 kilotons of liquid scintillator :
    LAB + 2.5 g/L PPO + 3 mg/L bis-MSB
    High photon yield: 10000±10% photons/MeV
    Very transparent: attenuation length ~25m
  - 17 612 20-inch PMTs (LPMT) and 25 600 3-inch PMTs (SPMT) in water buffer
    High optical coverage: 75% LPMT + 3% SPMT
    High PMT quantum efficiency: ~30%



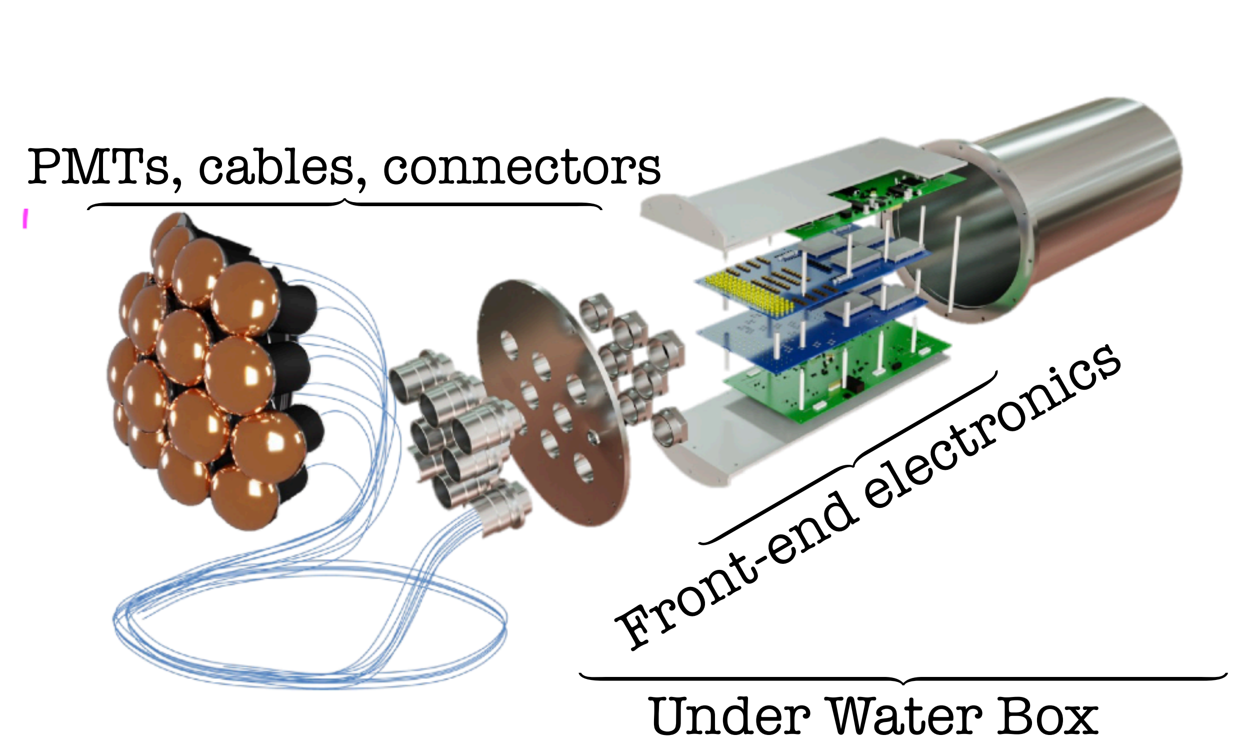
Detector design: Large and Small PMT

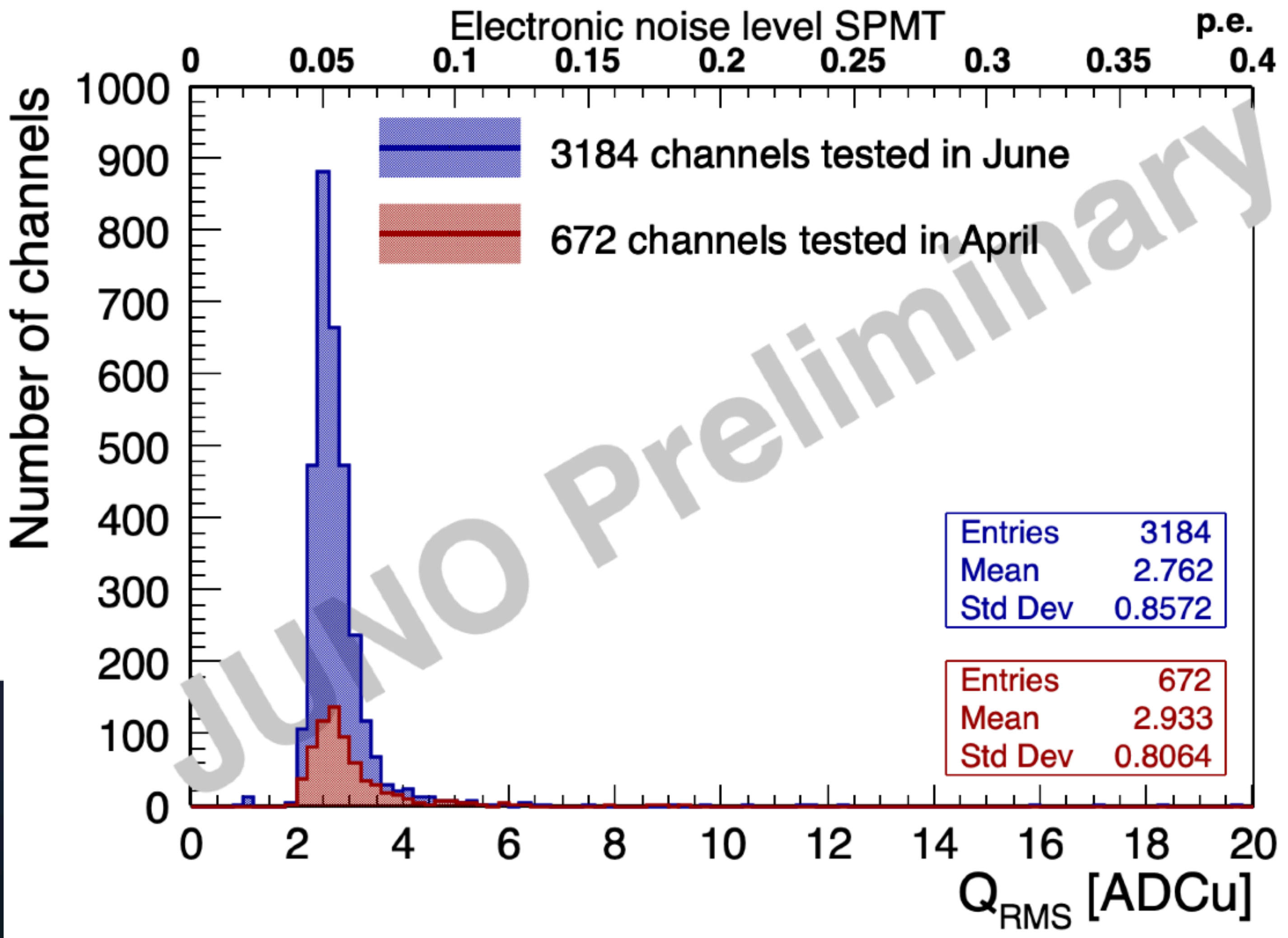
☑ Excellent understanding of the energy scale non-linearity

- 2 types of PMT:
  → LPMT to collect maximum of photon to have excellent energy resolution but non-linearity for large signals
  →SPMT collect few photons but excellent time spread
  Operate in single photo-electron regime: use to constrain LPMT non-linearity
- IN2P3 very involved in the SPMT subdetector
  - Development of Front-end electronics hardware and firmware
  - Myself L3 Co-manager of SPMT commissioning
    Some of my contributions:
    → Test and validation of the Front-end card firmware according to physics goals
    → Coordination of the analysis of commissioning runs

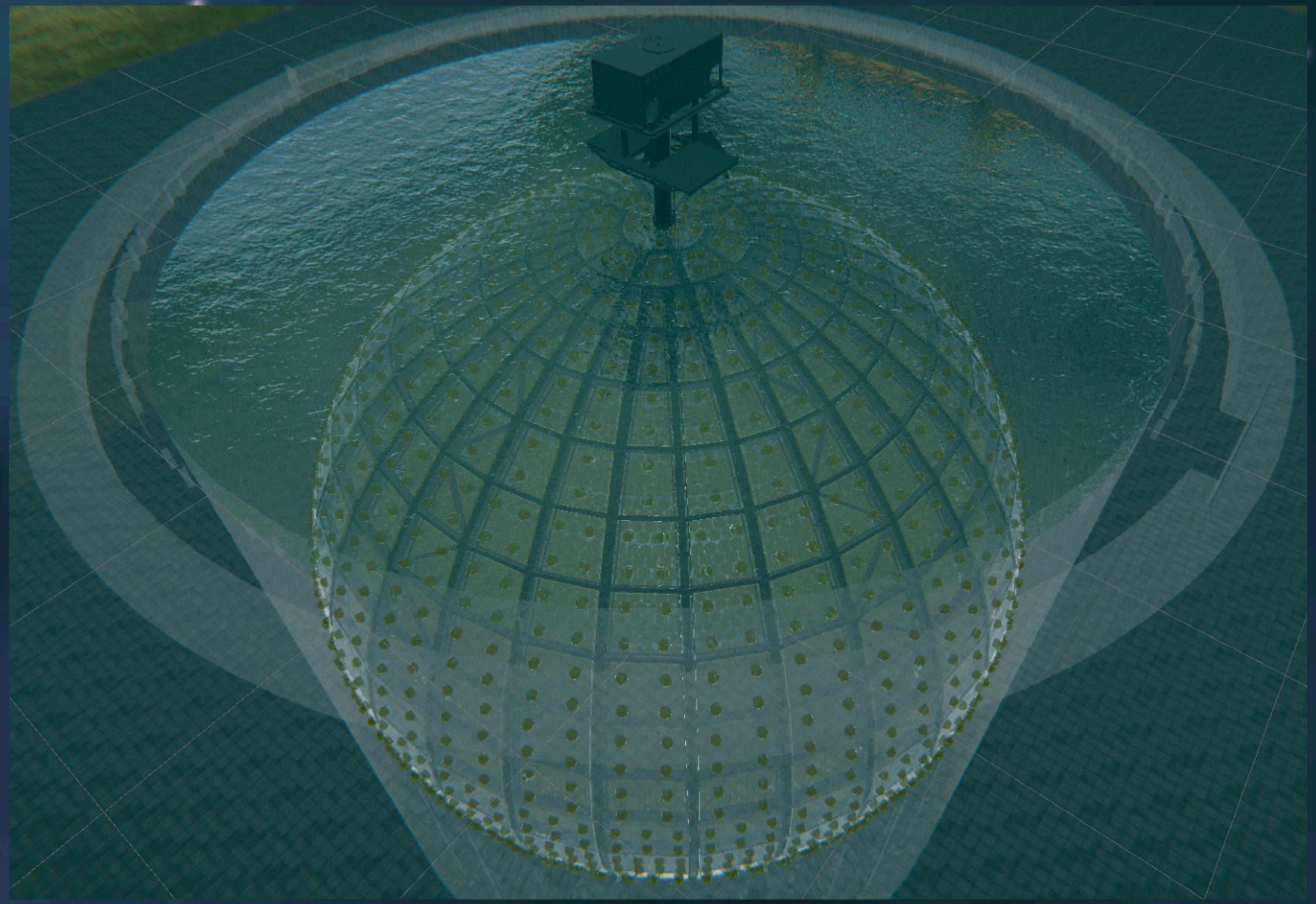


	LPMT		SPMT
	Hamamatsu	NNVT	HZC
Quantity	5000	15012	25600
Technology	Dynode	MCP	Dynode
Photo-detection efficiency	28.5 %	30.1 %	25 %
Mean dark noise [kCounts/s]	17.0	31.2	0.5
Transit Time Spread [ns]	1.3	7.0	1.5
Photo-electron regime	[0,100] PE		[0,2] PE
Coverage	75 %		3 %
Reference	arXiv: 2205.08629		NIM.A 1005 (2021) 165347





Detector design: Water Cherenkov Detector



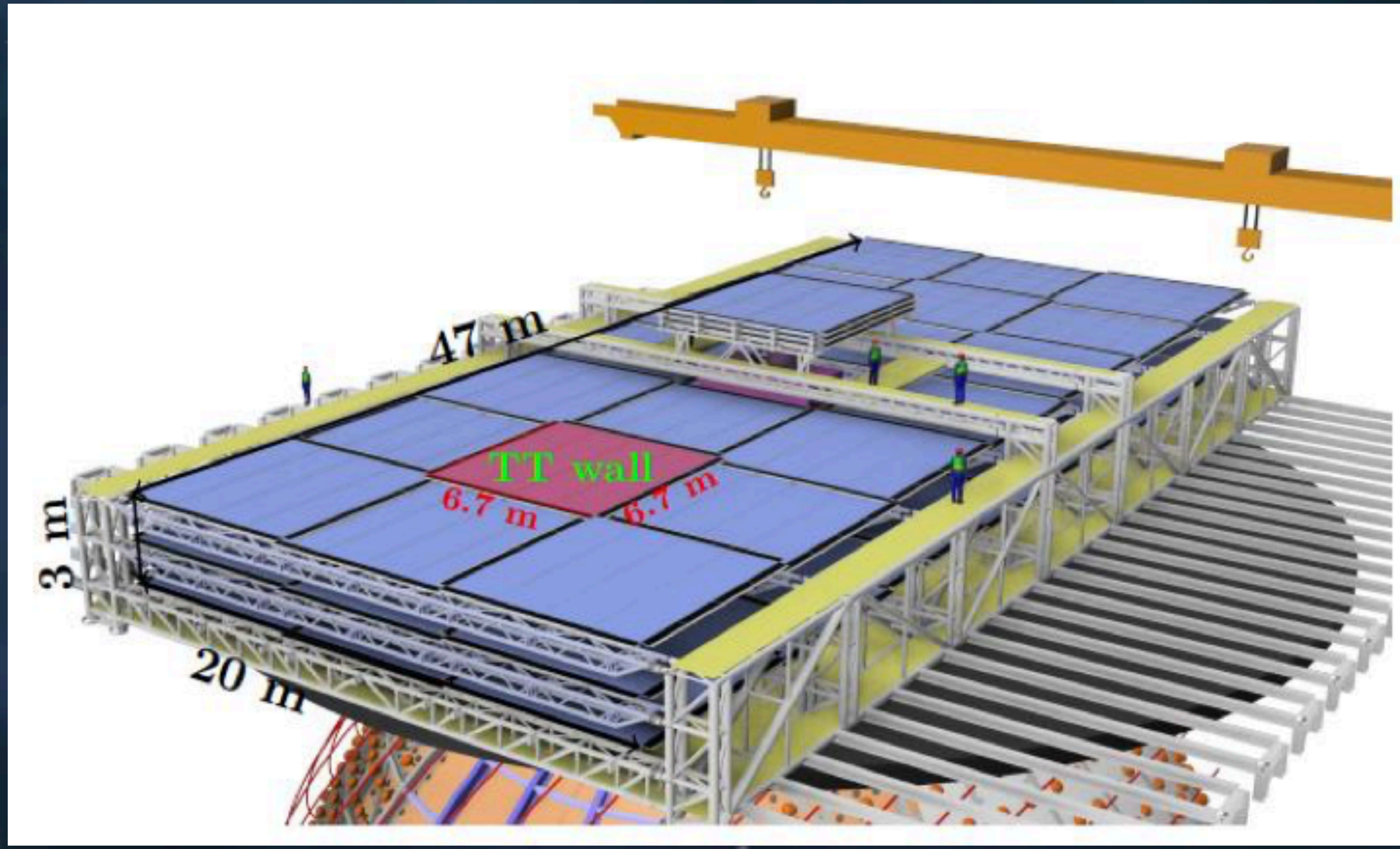
☑ Low background

- 43.5 x 44 m cylinder:
  - Filled with 35 kilotons of ultra pure water seen by 2400 LPMT
  - Passive shielding against natural radioactivity from surrounding rock and fast neutrons from cosmic muons
  - Muon detection efficiency of 99.5 %

Detector design: Top Tracker

☑ Low background

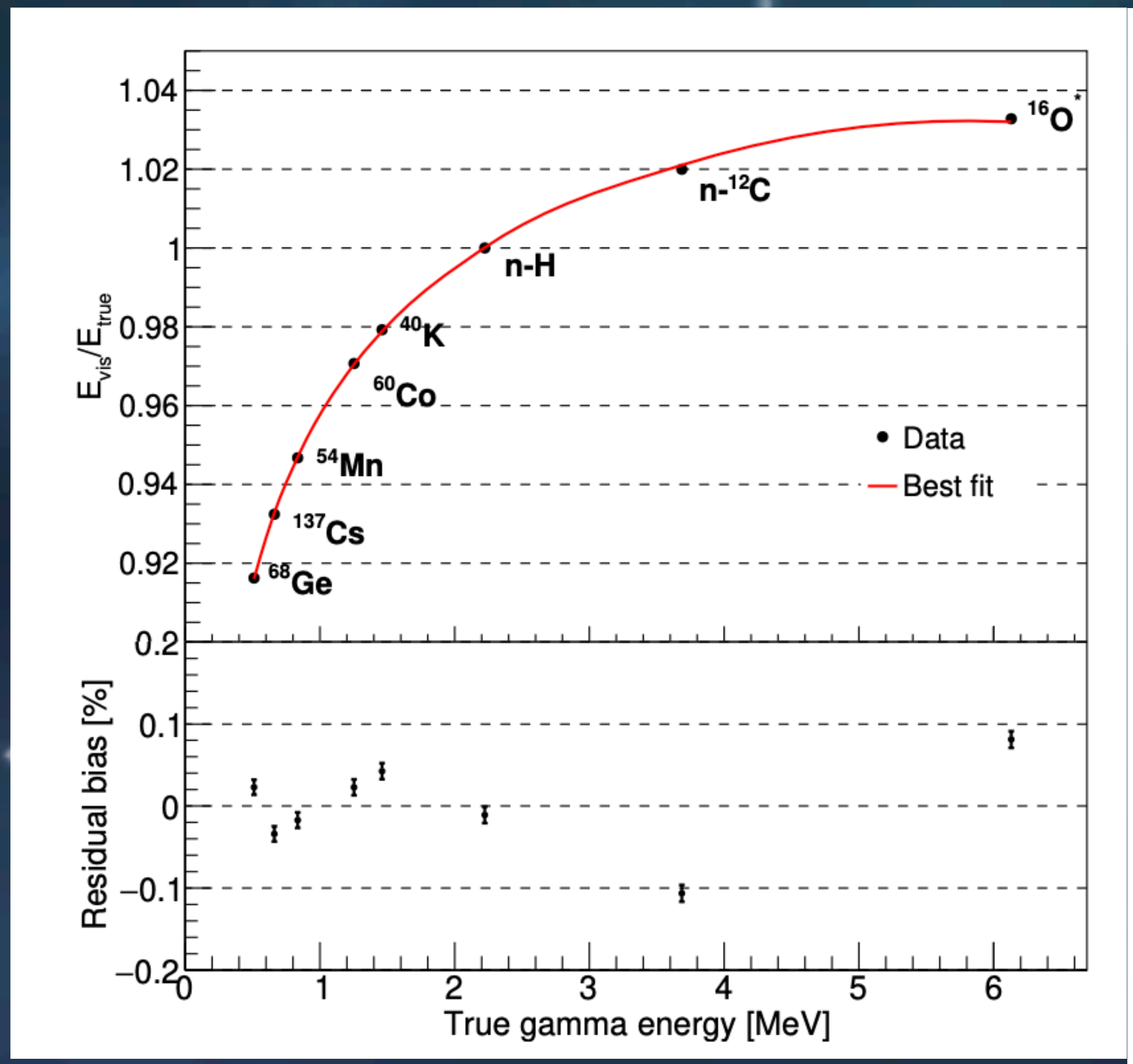
- 3 layers of plastic scintillator refurbished from OPERA Target Tracker
- 50 % coverage on the top
- 2.6 x 2.6 cm^2 granularity
- Muon track angular resolution of 0.2°
- Provide muon control sample to validate track reconstruction and study cosmogenic background

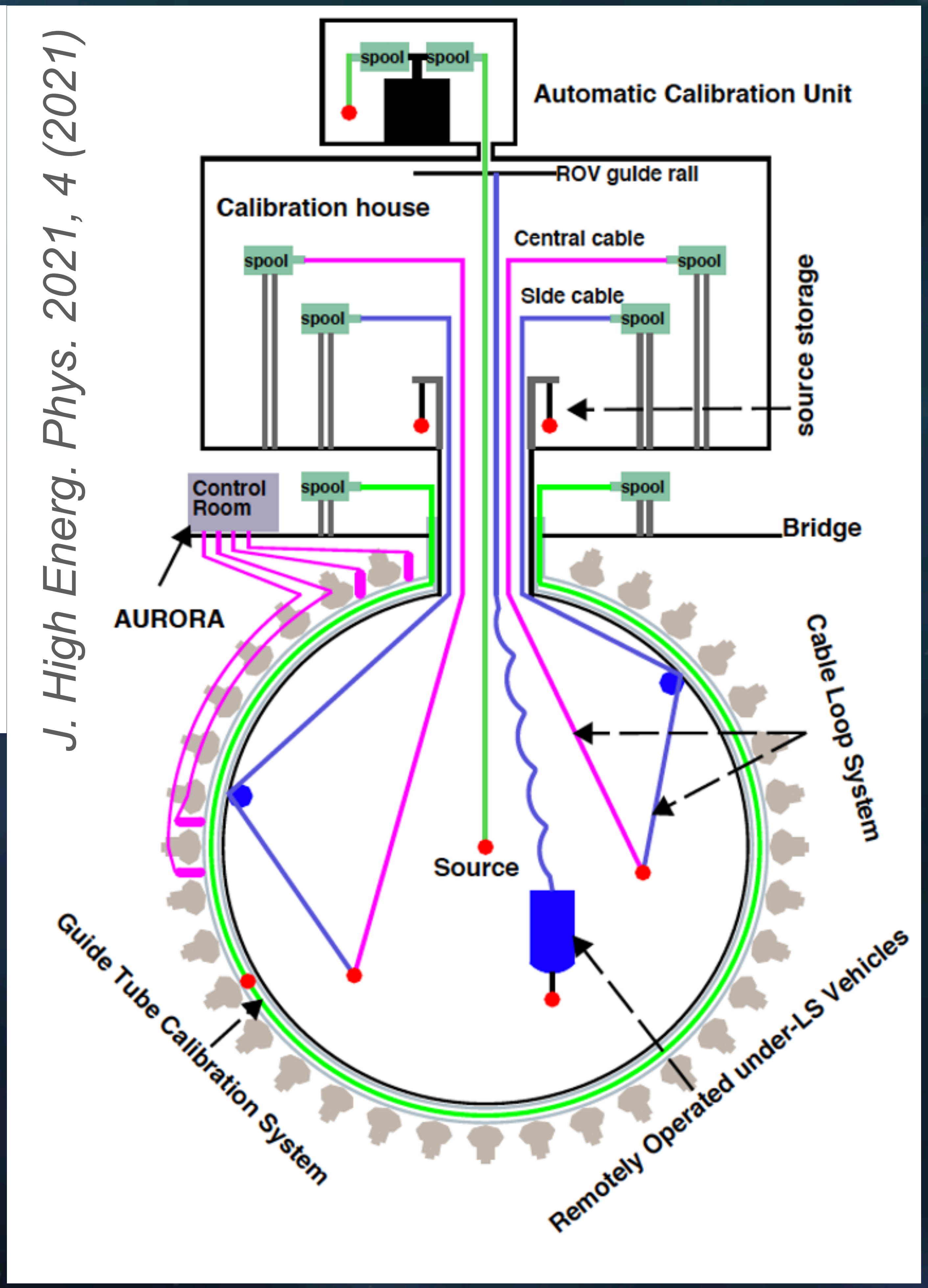


Detector design: Calibration system

- ☑ Energy resolution of 3% at 1 MeV
- ☑ Excellent understanding of the energy scale non-linearity

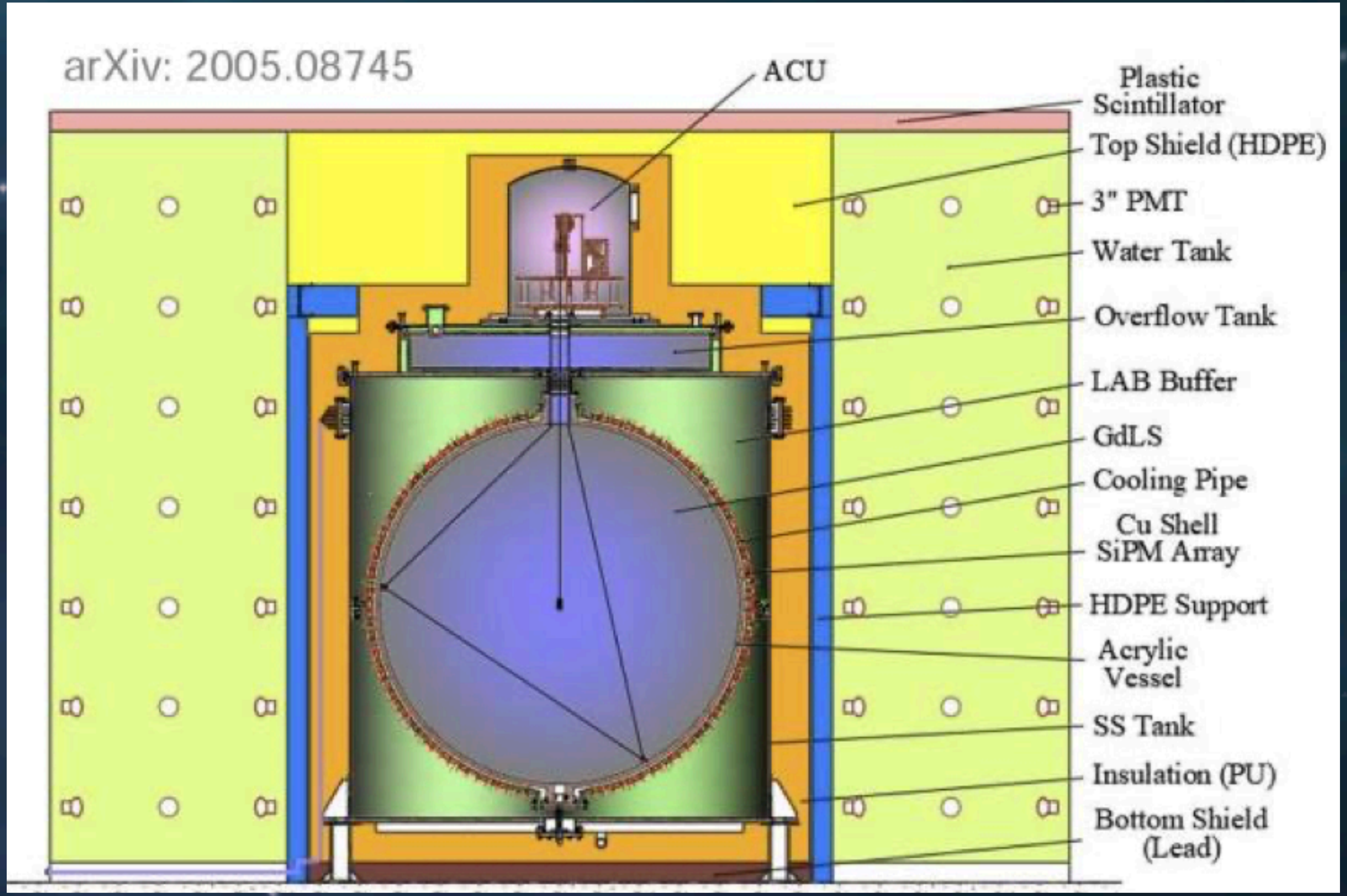
- Various calibration system:
  - 1D: Automatic Calibration Unit (ACU)
  - 2D: Cable Loop System
    Guide Tube Calibration system
  - 3D: Remotely Operated Vehicle
  - Additional system:
    A Unit for Researching Online the LS tRAnsparency (AURORA)





Taishan Antineutrino Observatory

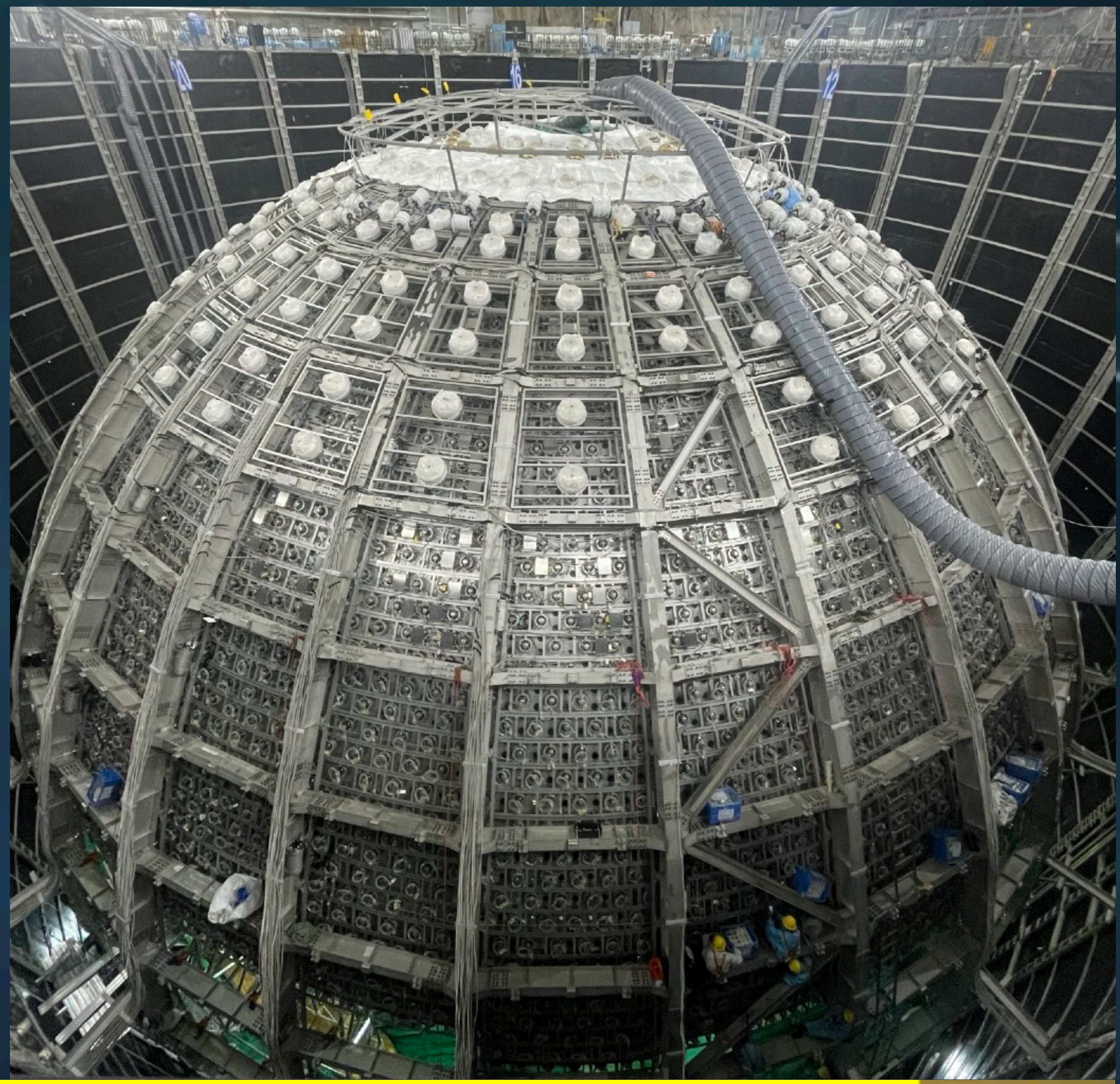
☑ Precise knowledge of the antineutrino reactor spectrum

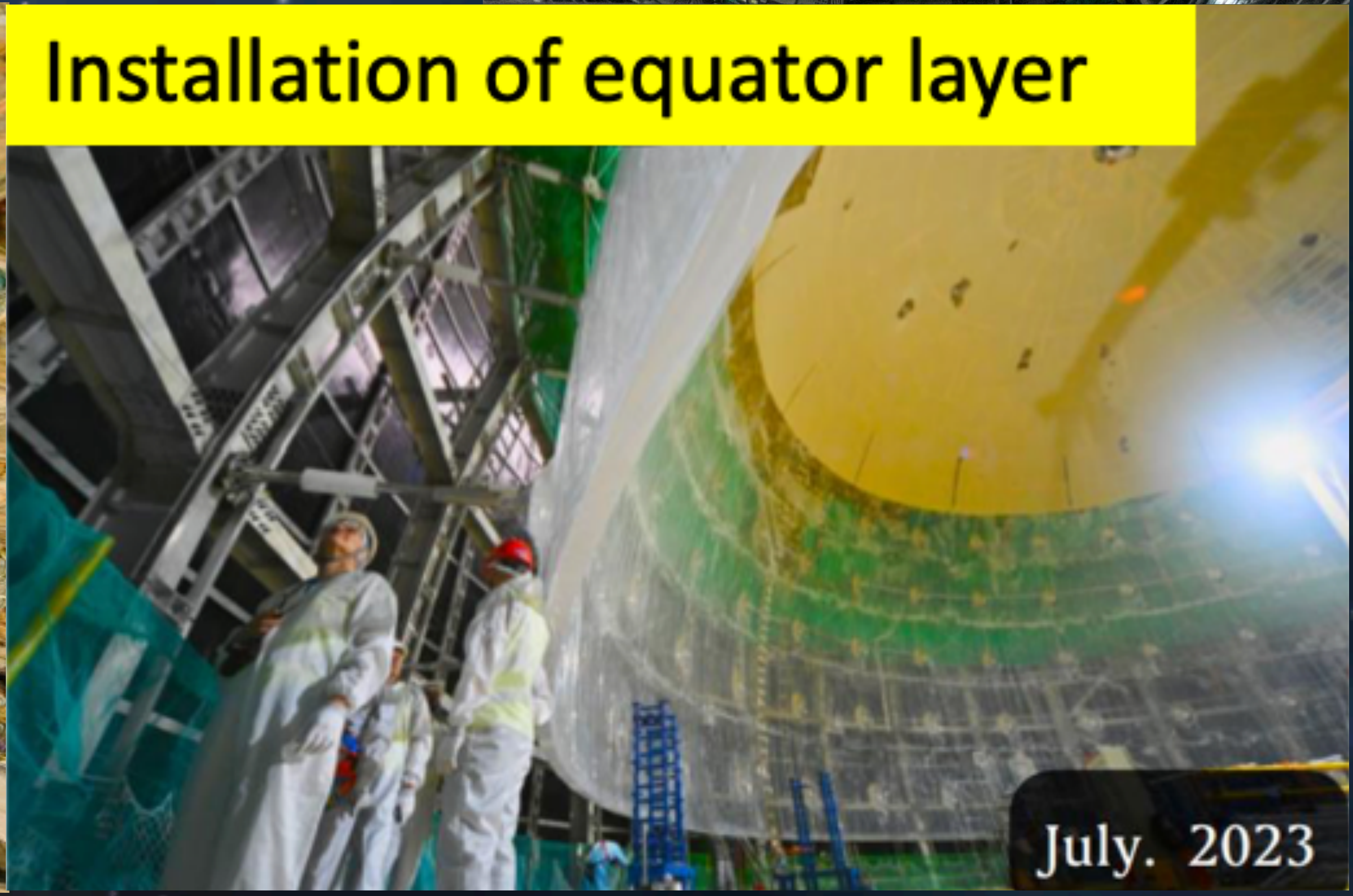


- TAO: satellite detector of JUNO
- 30 m from one of Taishan's reactor: high rate of non-oscillated neutrino
- 2.8 tons of Gd-doped liquid scintillator (1 ton fiducial volume)
- High collected photon yield: 4500 pe/MeV
  → 94% coverage and 50% photo-detection efficiency of SiPM
  → Very good energy resolution ~2% at 1 MeV
- Precise measurement of reactor antineutrino spectrum
  → identify some fine structure in the spectrum

Installation status

- Stainless steel structure completed
- Acrylic vessel up to the equator
- Top hemisphere almost completely instrumented

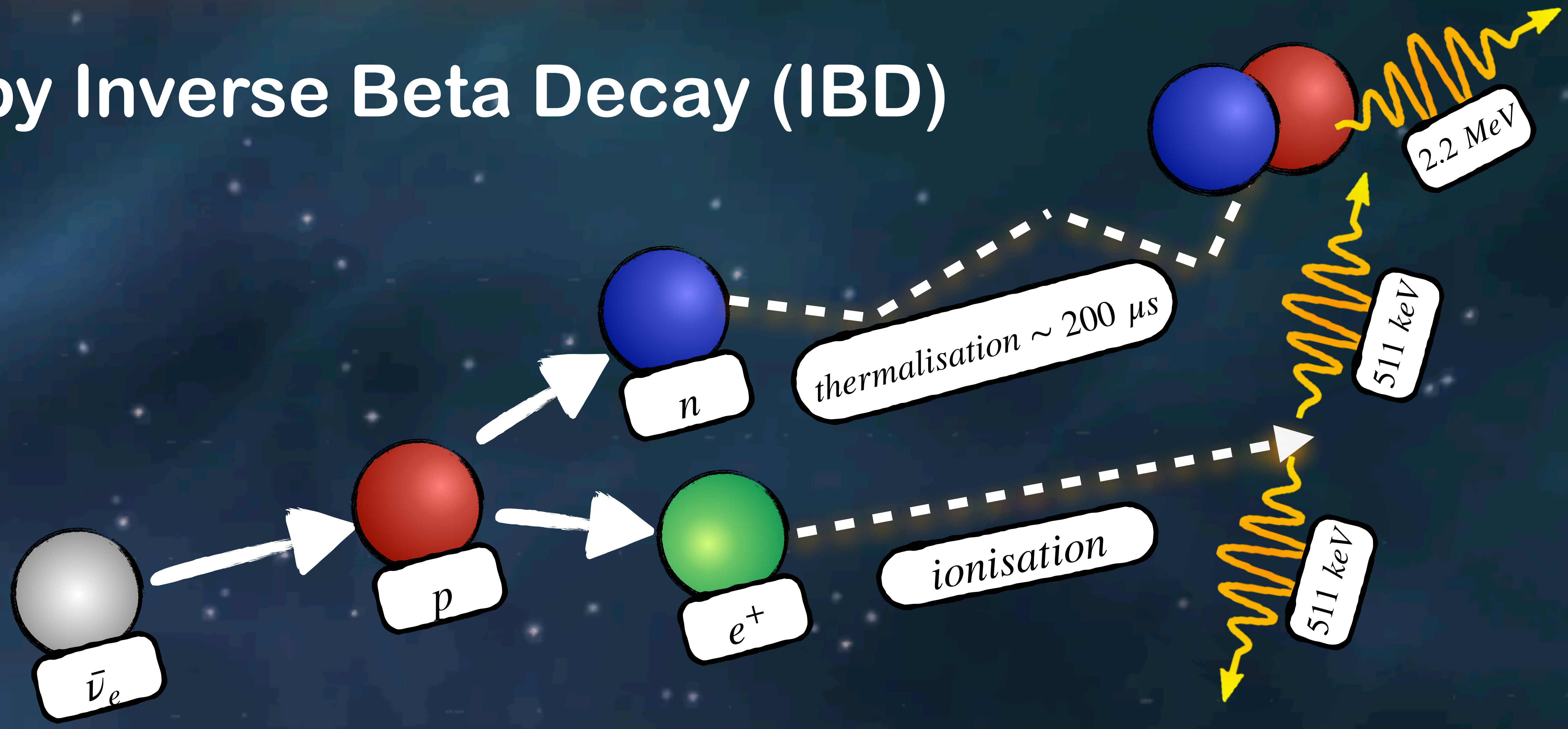




Neutrino detection

- Reactor antineutrinos are observed by Inverse Beta Decay (IBD) resulting in a two fold signal:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$e^+ + e^- \rightarrow \gamma + \gamma \text{ (prompt)}$$
$$n + p \rightarrow d + \gamma \text{ (delayed)}$$



  - Prompt signal: positron ionisation and annihilation with medium electron
  - Delayed signal: neutron capture on hydrogen giving a 2.2 MeV γ

- Energy threshold for the IBD process is: $E(\bar{\nu}_e) > 1.8\ MeV$
- The neutrino energy is given by: $E_{vis} = E(e^+) = E(\bar{\nu}_e) - 0.8$ MeV

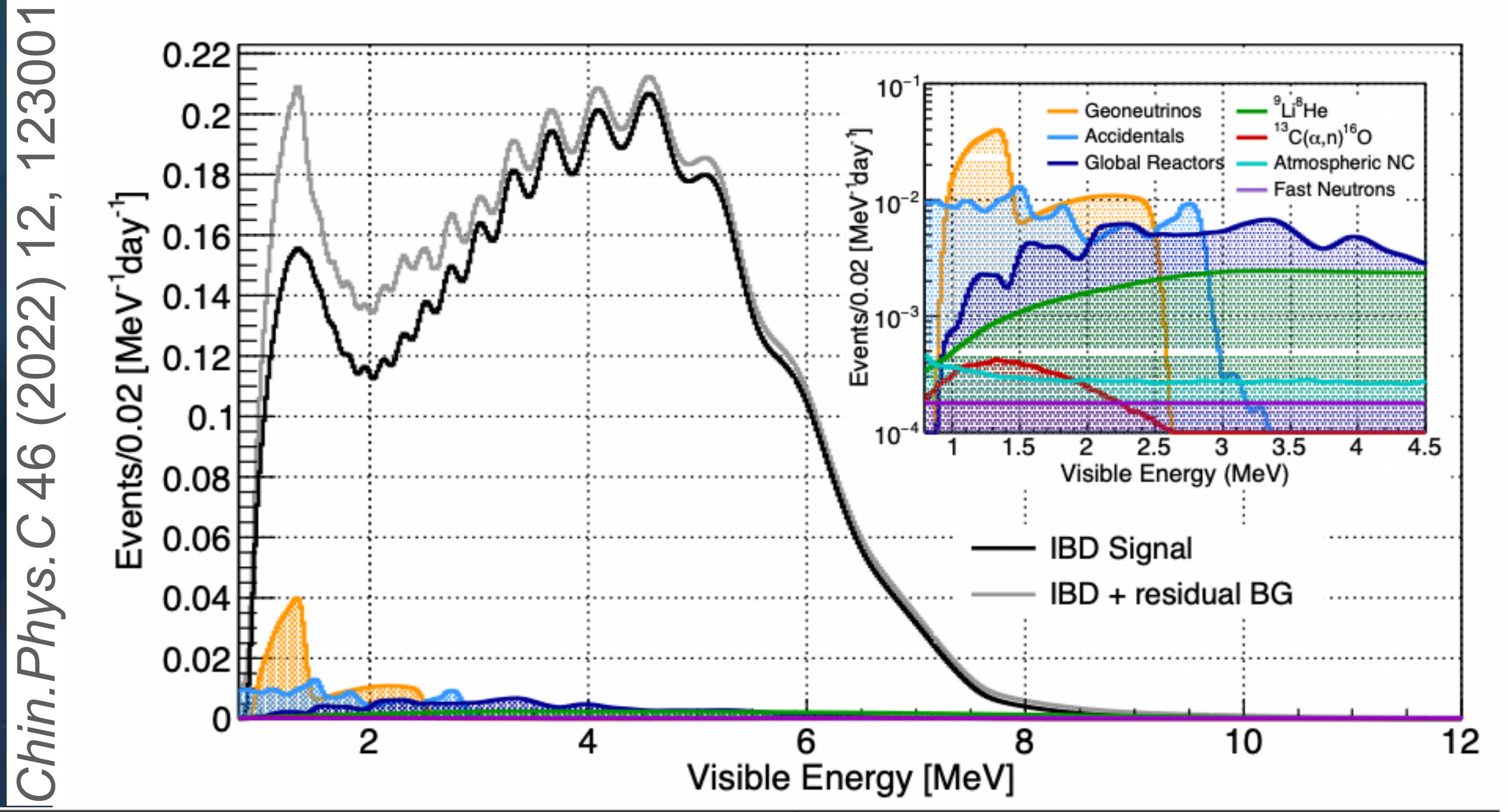
Neutrino signal and background

- Visible energy spectrum from oscillated reactor $\overline{\nu_e}$

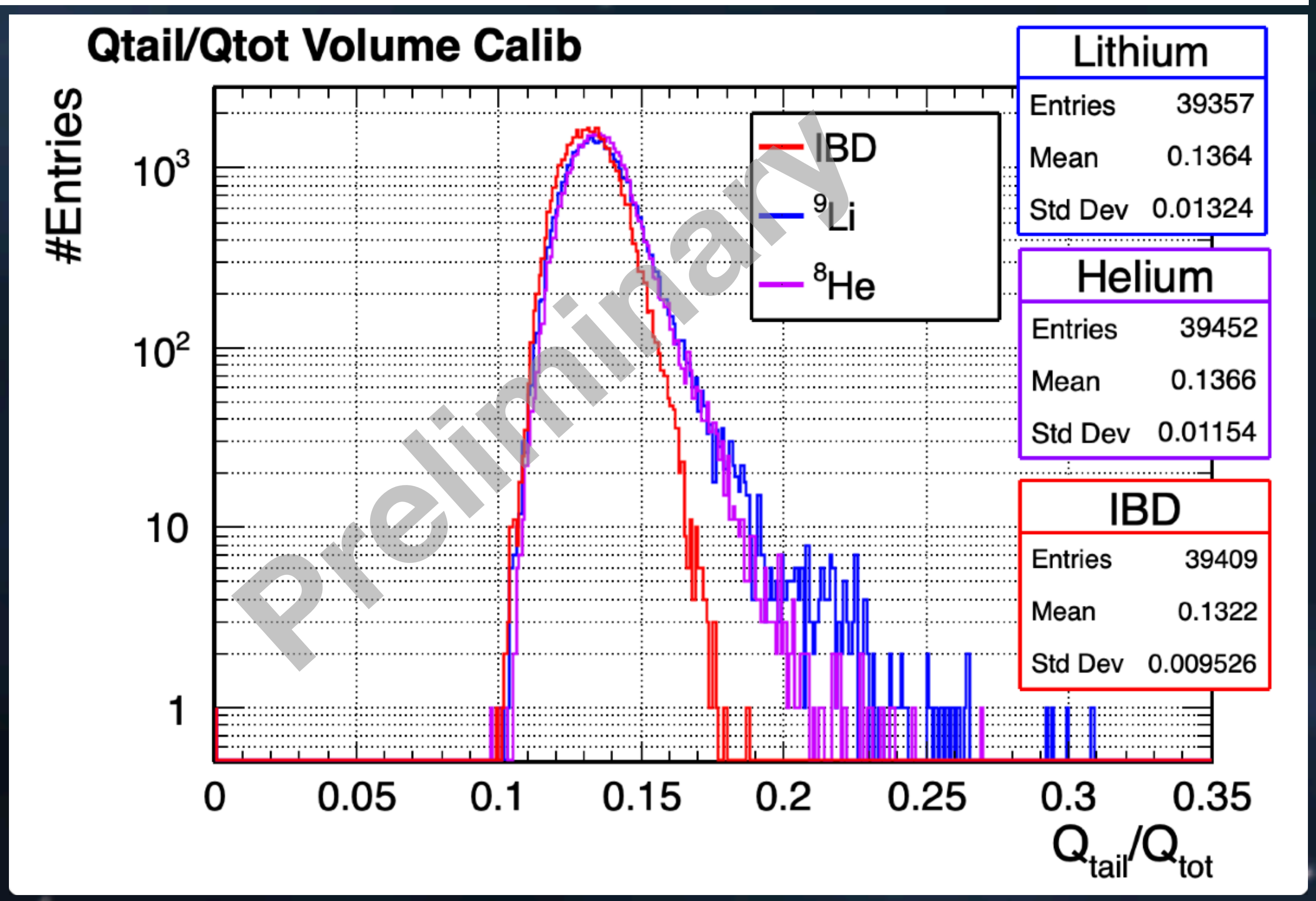
- Selection cuts:
  - Energy threshold: $E_{vis} > 0.7\ MeV$
  - Fiducial volume: $R < 17.2\ m$
  - Time correlation: $\Delta t_{p-d} < 1\ ms$
  - Spatial correlation: $\Delta \vec{R}_{p-d} < 1.5\ m$
  - Muon veto (temporal ⊕ spatial)

- After selection: ~47 signal events/day and ~4 background events/day

- Personal contribution on cosmogenic background ^{9}Li and ^{8}He:
  Study of the pulse shape discrimination of those isotopes
  → discrimination power is small but possible to obtain pure sample to tune the veto strategy

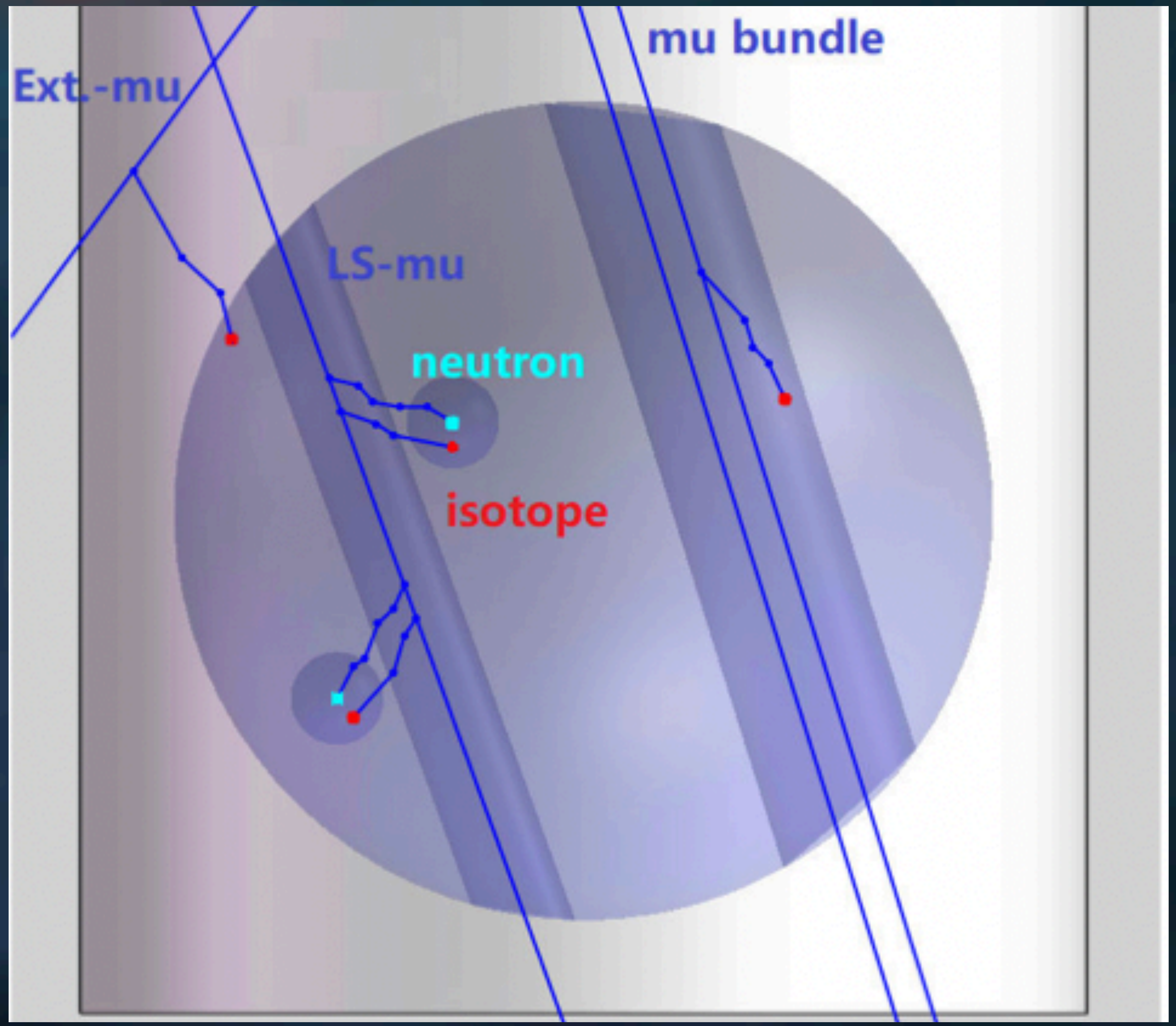


Selection	IBD efficiency [%]	Rate [day^{-1}]						
		IBD	Geo-ν	Accidentals	Cosmogenics	Fast n	$^{13}C(\alpha,n)^{16}O$	World reactors
No cuts	100	57.4	1.5	5.7×10^4	84	-	-	-
All cuts	82.2	47.1	1.2	0.8	0.8	0.1	0.05	1



Muon veto strategy

- 1ms veto on whole FV applied after μ passing through WCD or CD
  ⇒suppress spallation neutrons and short lived radioisotopes
- For well reconstructed single μ tracks in CD:
  - a 600ms, 400ms, 100ms veto applied on a 1m, 2m, 4m cylindrical volume around the muon track
- For muon bundle tracks (closer than 3m and parallel tracks)
  - single track reconstructed with larger dispersion
  - veto applied with cylinder radius enlarged according to the track dispersion
- For events with no track reconstructed
  - Occurs when more than 2 muons pass through the CD
  - 500ms veto over FV
- 1.2s veto on a 3m radius sphere around neutron capture events
- Muon veto strategy has an IBD selection efficiency of 91.6% while removing 98.8% of cosmogenic background



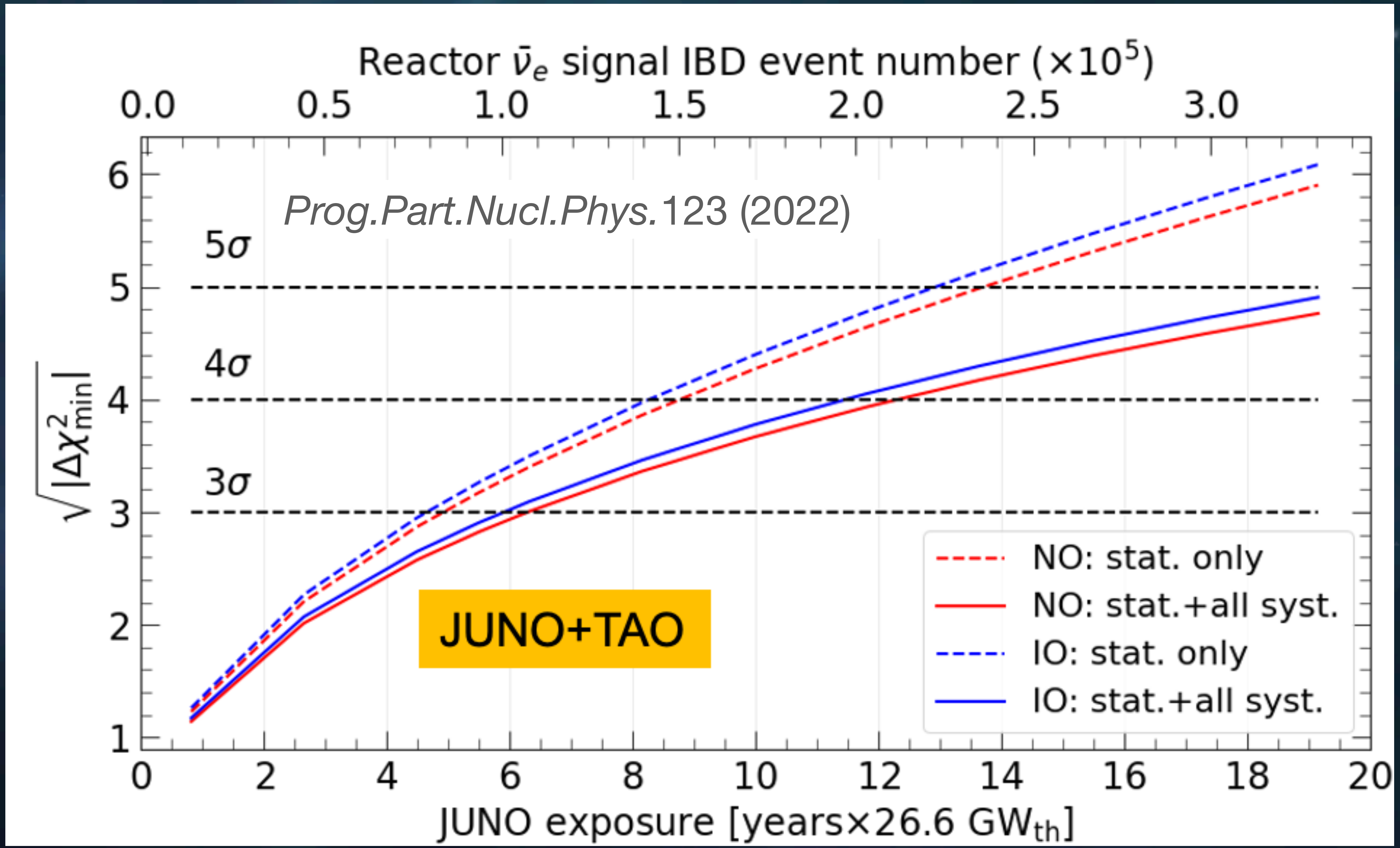
Muon multiplicity	Proportion [%]
1	91.9
2 (track separation > 3 m)	5.5
2 (track separation < 3 m)	0.6
≥ 3	2.0

JUNO's physics prospect

- Primary goal:
  - Determination of the Neutrino Mass Ordering
  - Precision measurement of the oscillation parameters
- Additional physics goal:
  - Solar neutrinos
  - Geoneutrinos
  - Supernovae detection
  - Diffuse supernova neutrino background
  - Atmospheric neutrino
  - Proton decay
  - $0\nu\beta\beta$ search

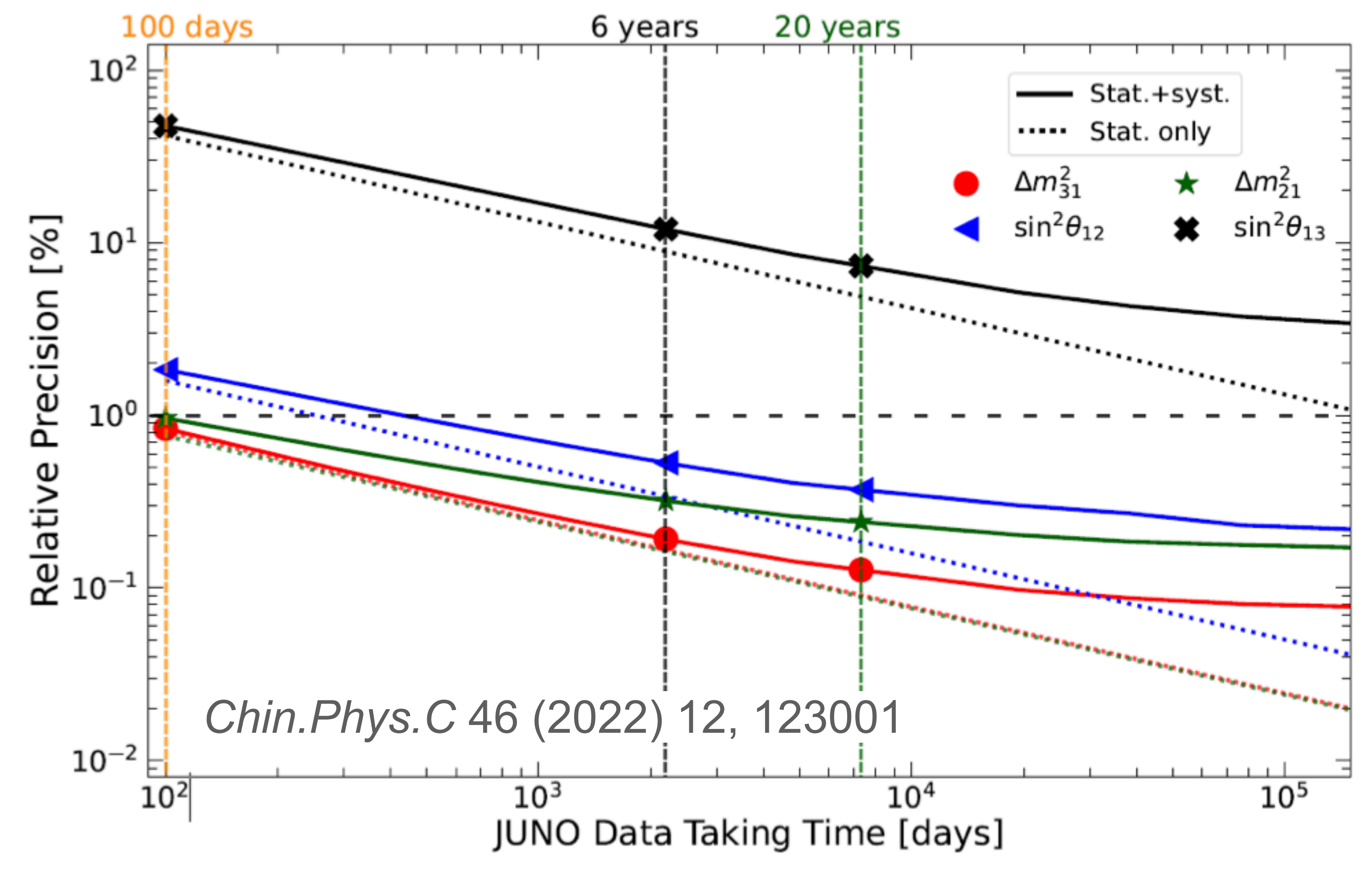
NMO sensitivity

- Main goal is to determine Neutrino Mass Ordering (normal or inverted) at 3σ level
- Combination of JUNO and TAO for spectrum shape
- 3σ sensitivity after 6 years of data taking
- Possibility to gain a bit of sensitivity by combining with atmospheric neutrino → ongoing analysis



Precision measurement of oscillation parameters

- First simultaneous detection of Δm^2_{12} and Δm^2_{13}
- Subpercent precision for 3 oscillation parameters before 6 years of data taking



	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%)

Solar neutrinos (8B,7Be, pep, CNO)

- Large statistic from ^{8}B solar neutrinos: 60 000 events for 10 yr
  → day-night asymmetry at 0.9%
  → Possible to constrain Δm^2_{21} and $\sin^2 2\theta_{12}$ also from solar neutrinos
- Sensitivity to intermediate solar neutrinos energy for different radiopurity scenarii:
  - IBD: minimal requirement for NMO determination → U/Th 10^{-15}g/g
  - Baseline: → U/Th 10^{-16}g/g
  - Ideal: → U/Th 10^{-17}g/g
- ^{7}Be and pep→ Improve Borexino's measurement in few years in all radiopurity scenarii
- CNO → Improve Borexino's measurement except in worst scenario

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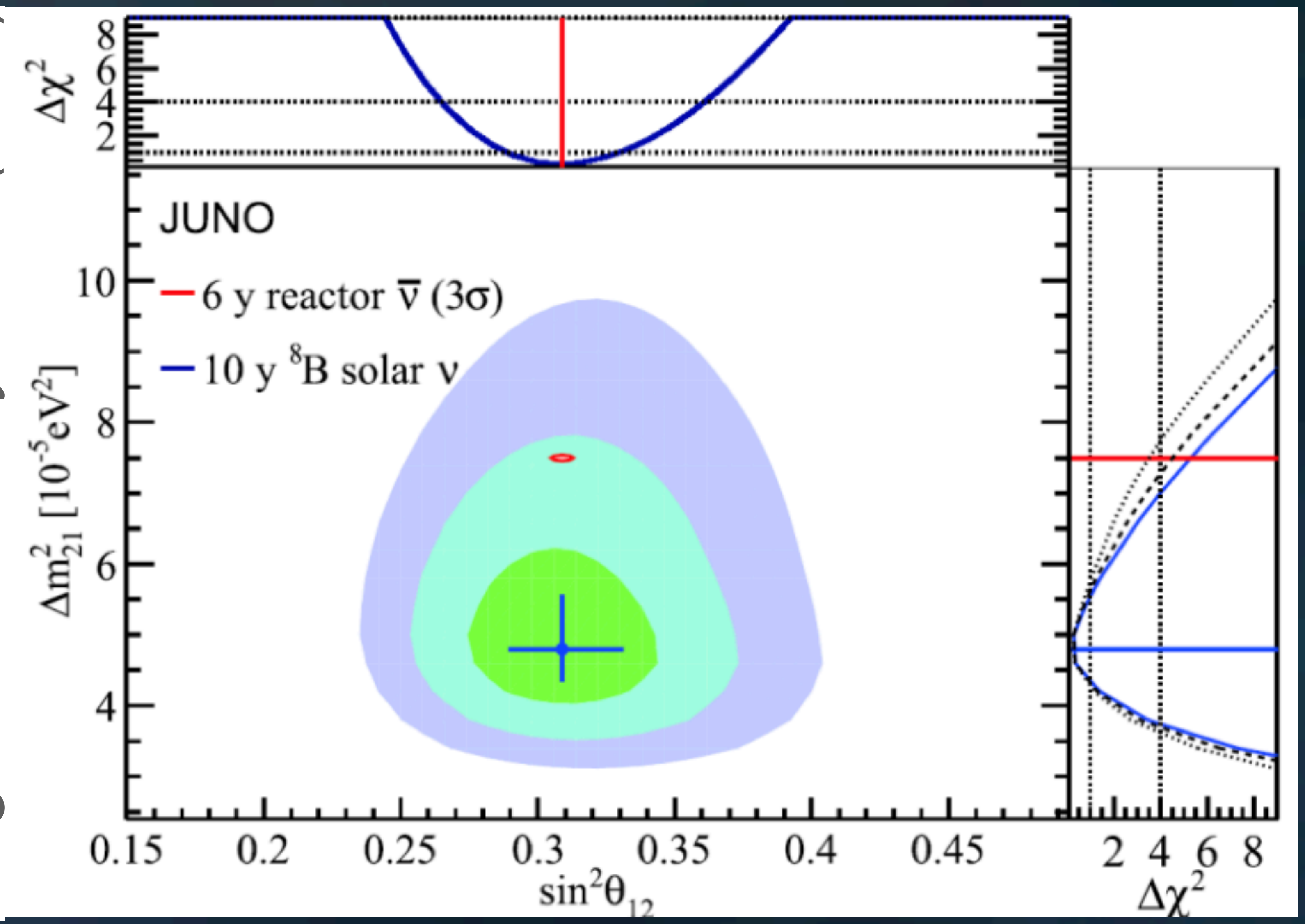

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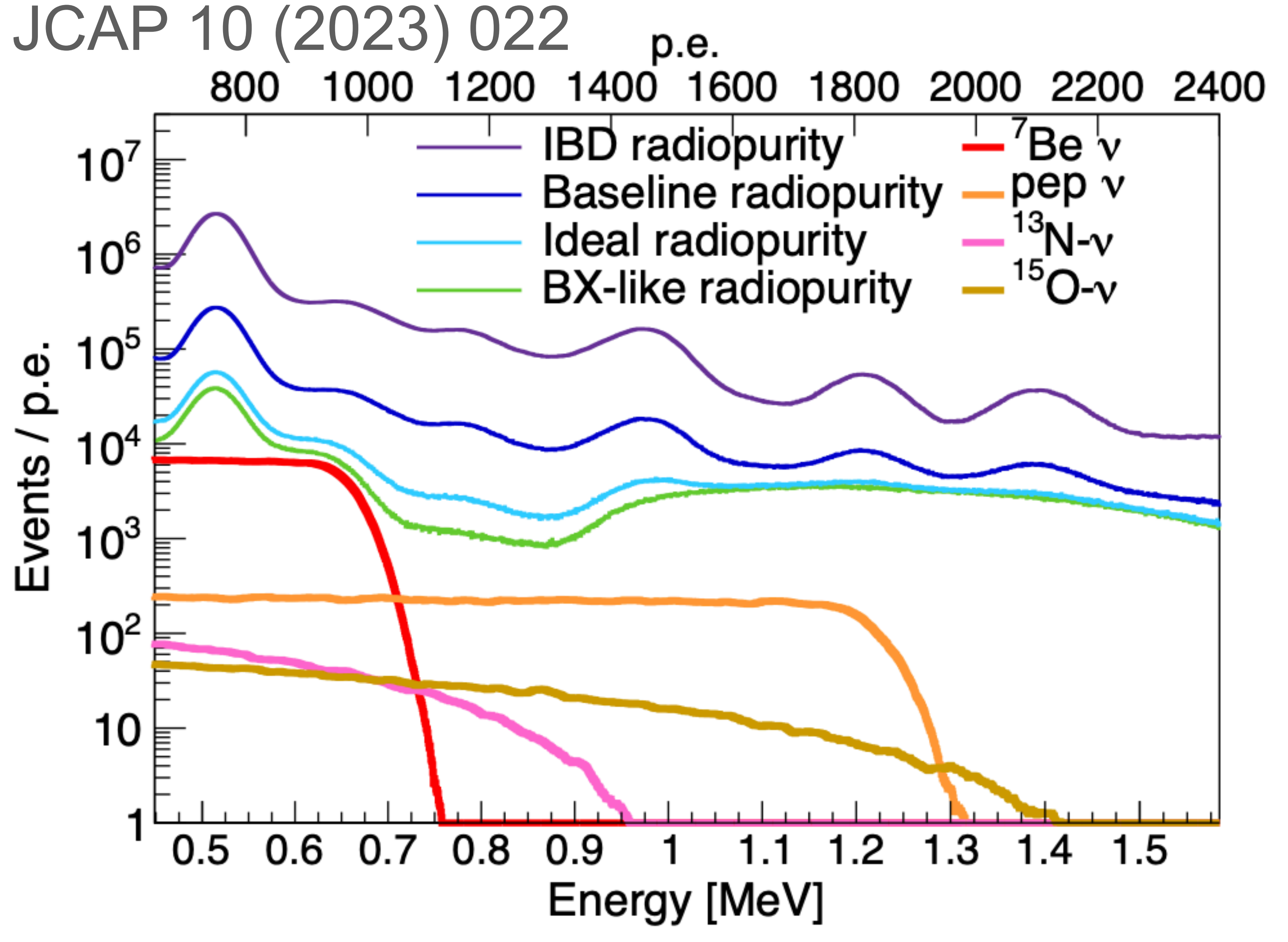
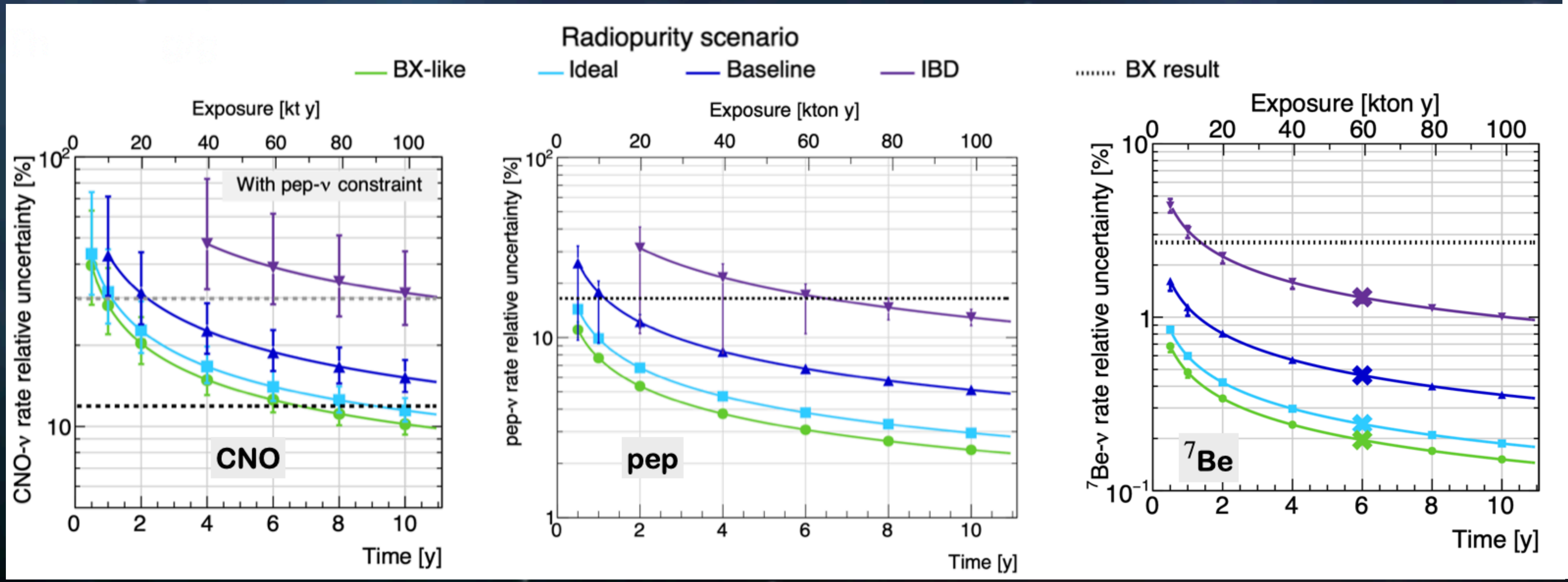
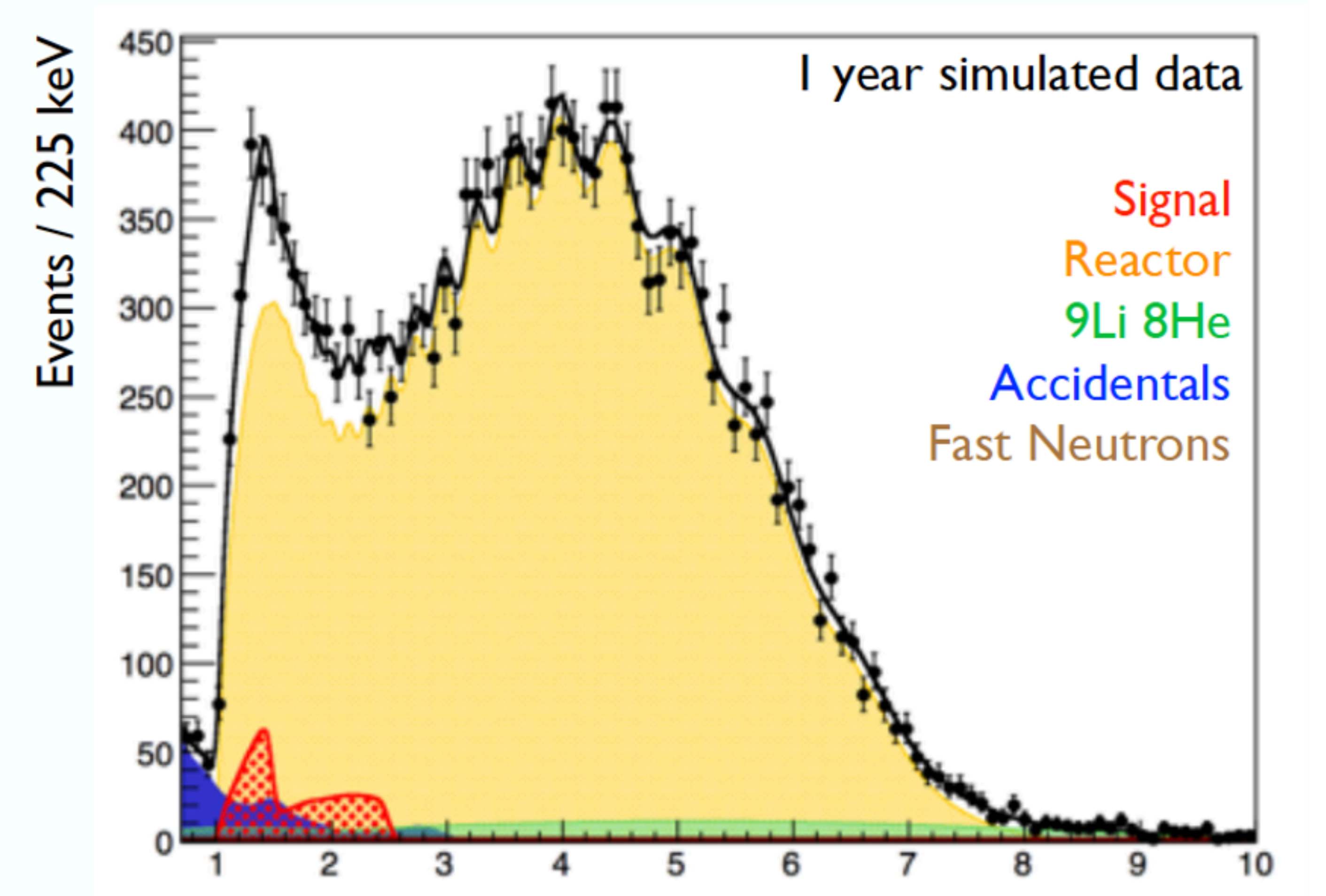




Geoneutrinos measurement

- Geoneutrinos from ^{238}U and ^{232}Th chains → ~400 /year ⇒ 2 times current world sample (KamLAND + Borexino ~200)
- Current rate uncertainty:
  18% for neutrino emitted in the crust
  100% for mantle neutrinos
- Local geological studies ongoing to constrain crustal contribution → derive mantle contribution
- Measure Th/U ratio in crust and mantle to understand their contribution to terrestrial heat production



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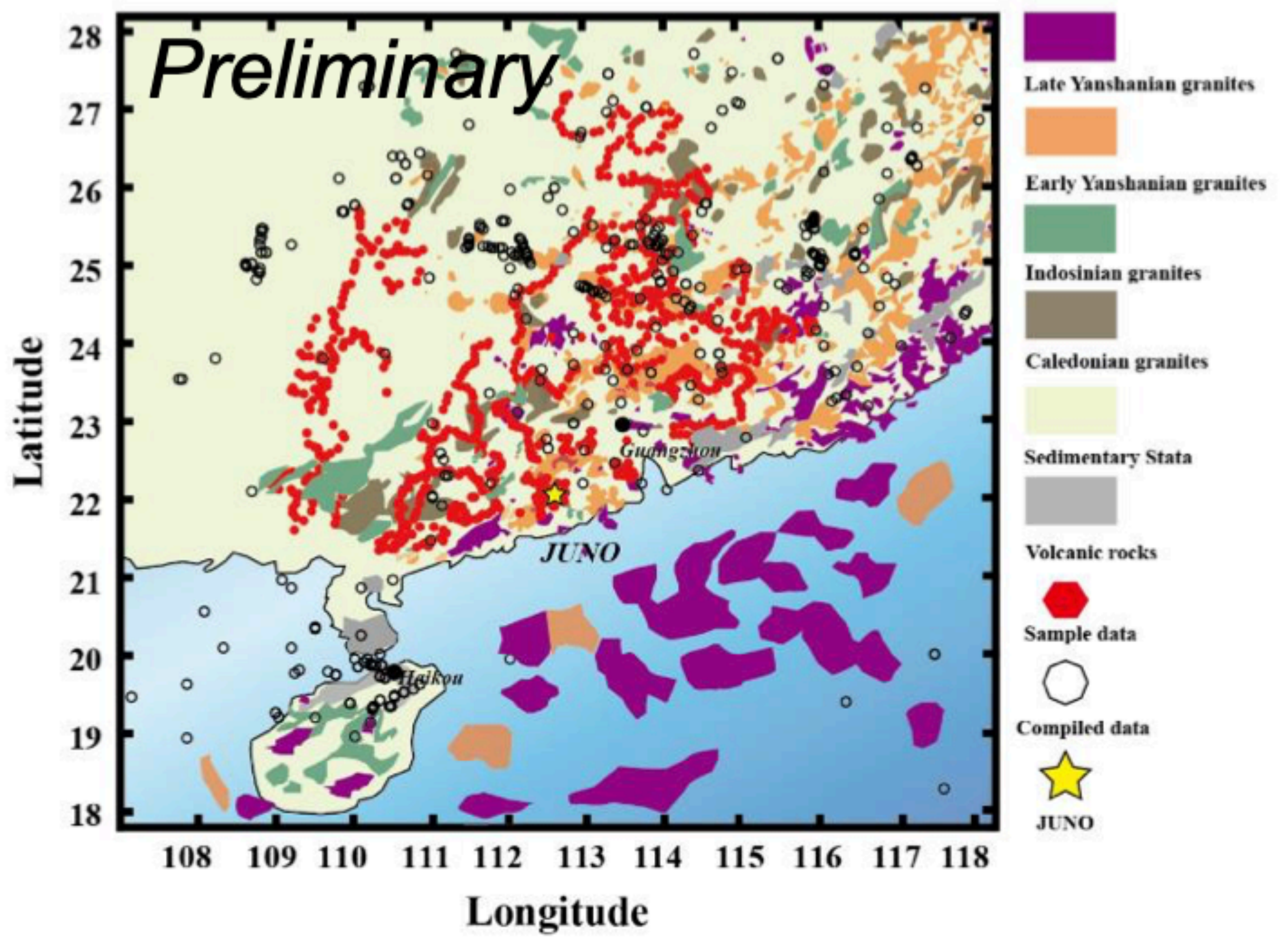
1002 rock samples around JUNO



Supernovae detection

- Core-Collapse Supernova (CCSN) release 99% of its energy by neutrino and antineutrino emission
- CCSN rate: 1.63 ± 0.46 CCSN/century (New Astronomy Vol. 83, 101498)
- Main goals:
  - Flavour content, time evolution of flux and energy spectrum
  - Constrain of absolute neutrino mass
  - Study of star physics: late-stage stellar evolution, SN hydrodynamic models
- Alert efficiency of 100 % up to distance > 100 kpc in various SN model and conditions
- Personal contribution: Study of the SPMT sub detector acceptance to close supernovae $\rightarrow$ decision on final data format

Type	Process	Nb of evts @10 kpc
CC (IBD)	$\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
eES	$\nu + e \rightarrow \nu + e$	~300
pES	$\nu + p \rightarrow \nu + p$	~2000
NC	$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	~300
CC	$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	~200

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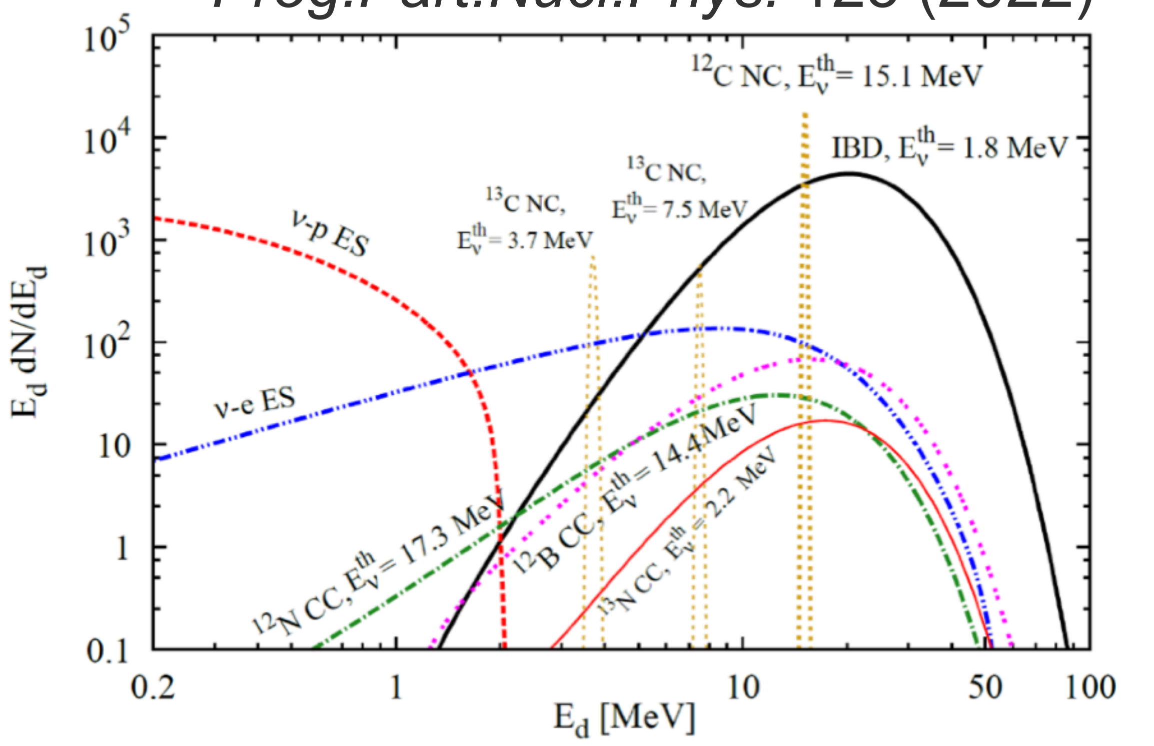

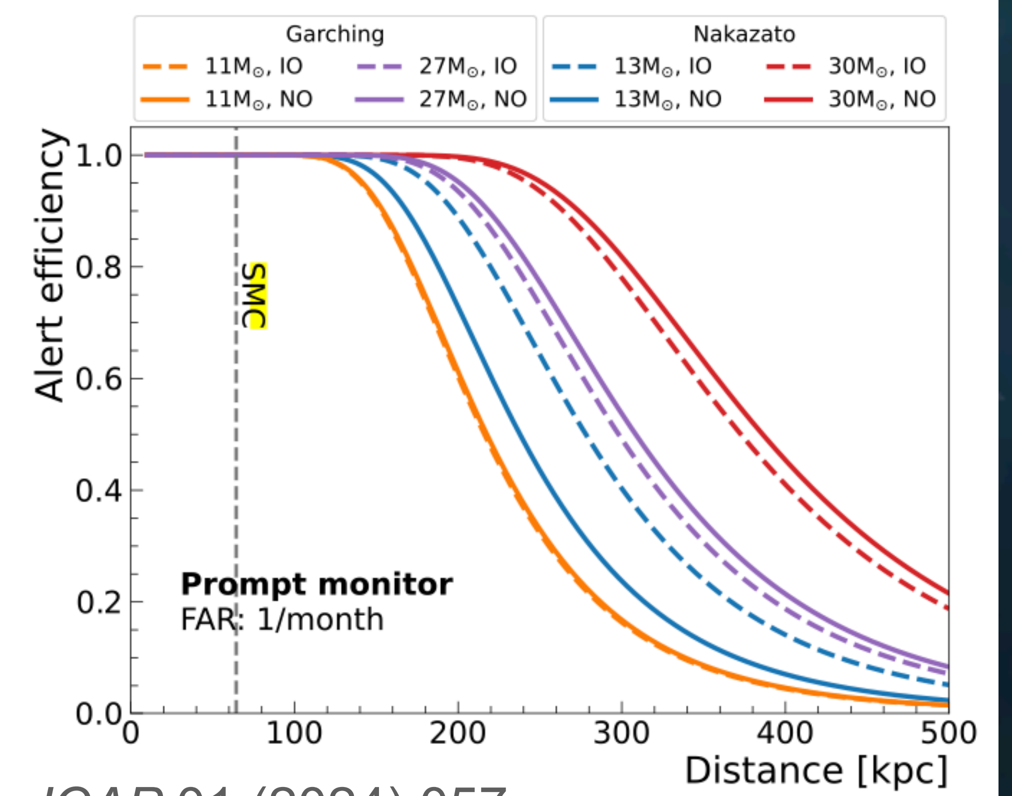

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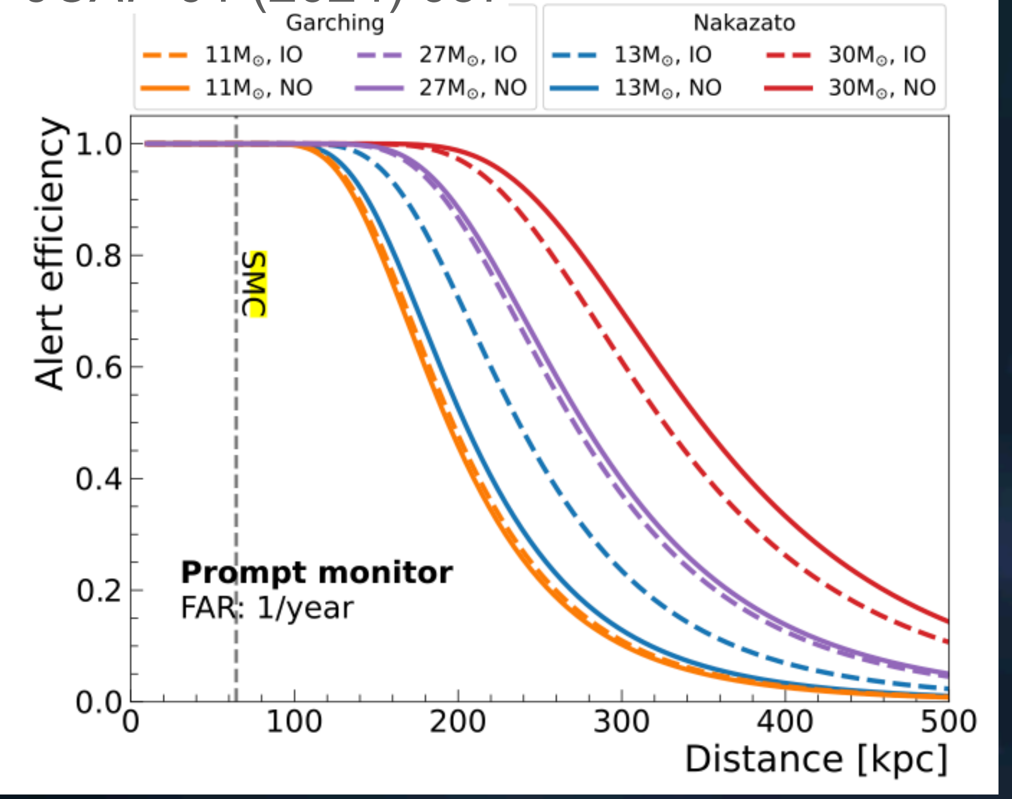
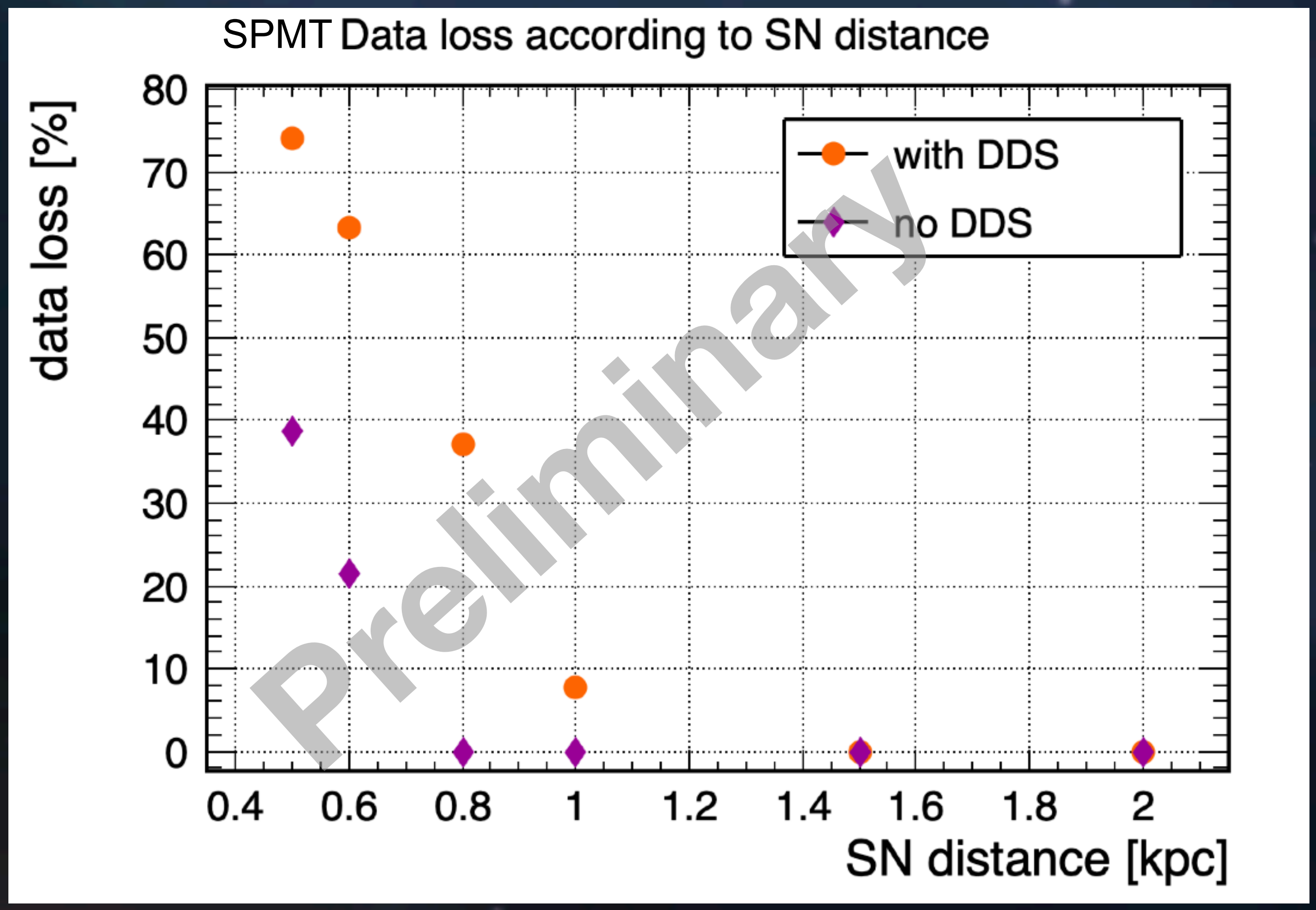
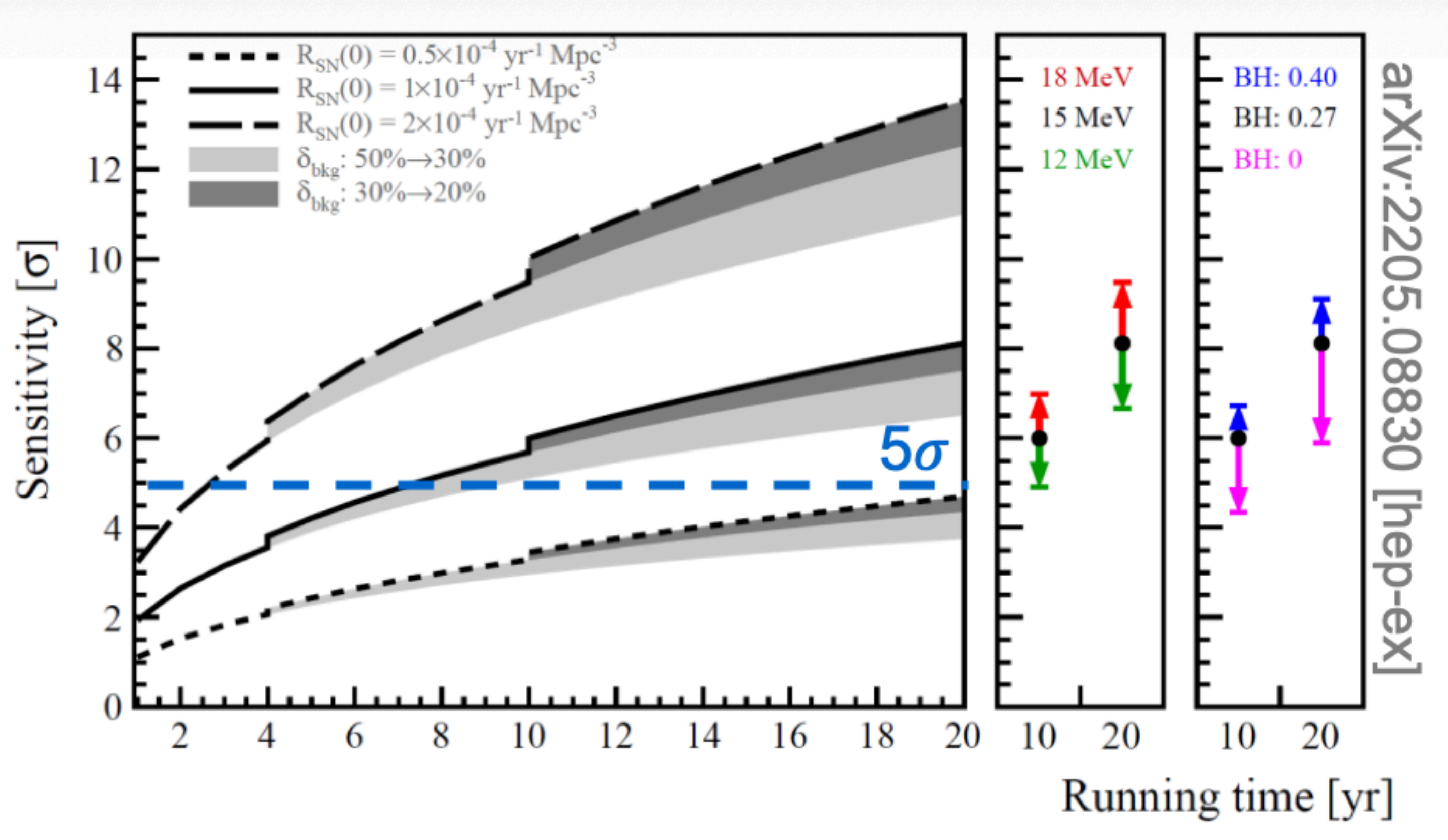
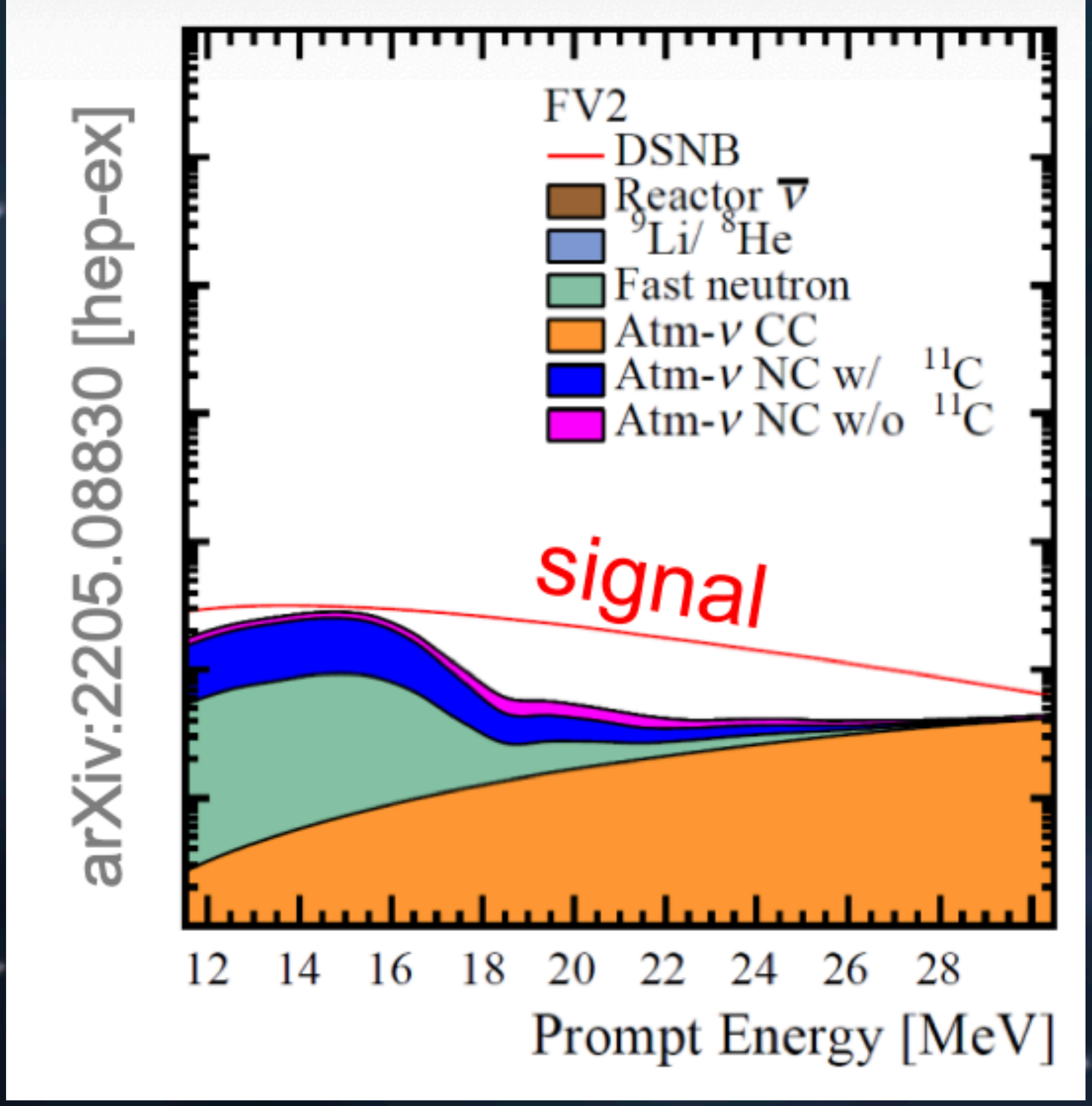




Diffuse supernovae neutrino background

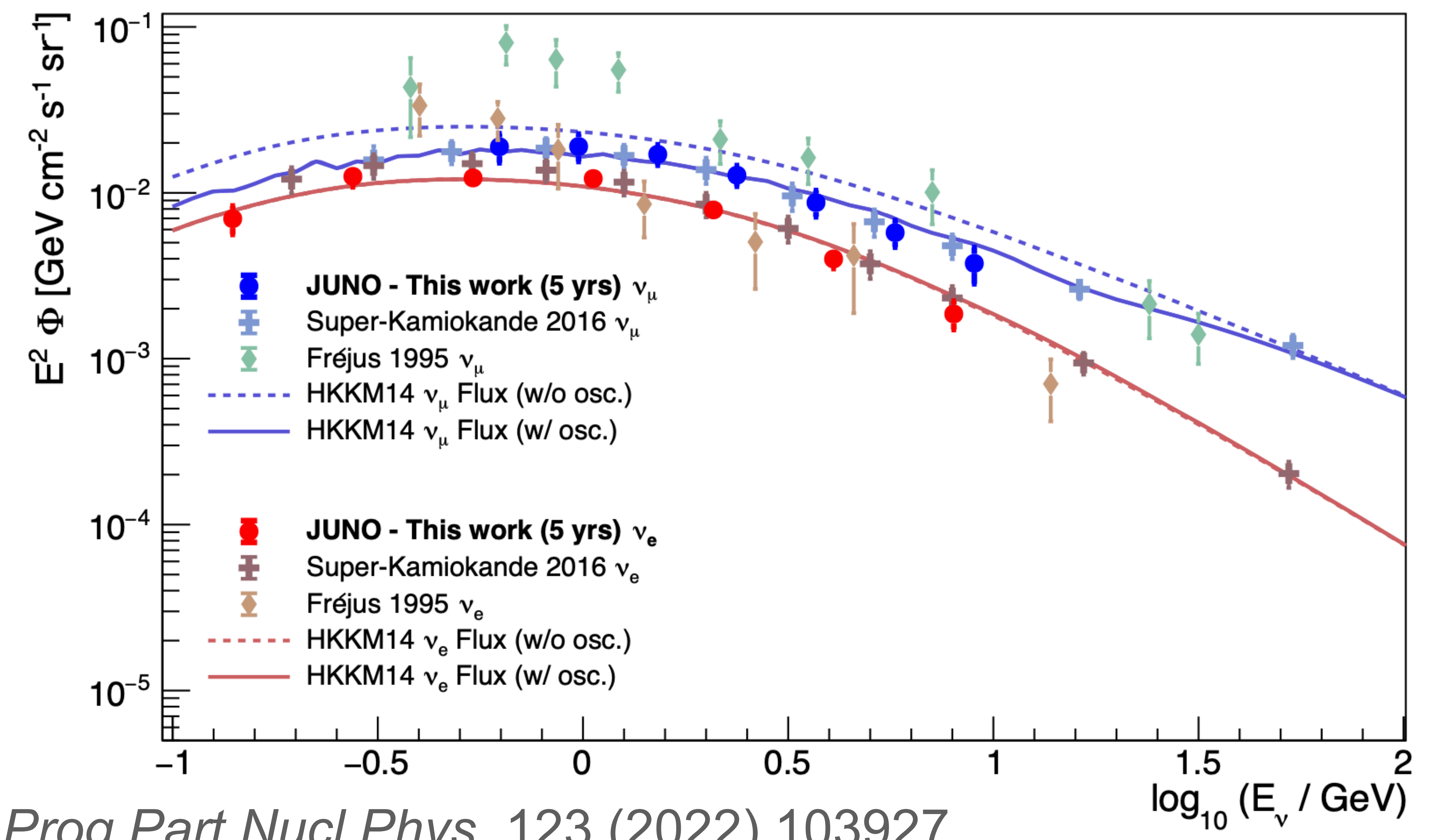
- Diffuse Supernova Neutrino Background (DSNB): neutrino signal integrated from all SN in the Universe
- Provide information on the average CCSN neutrino spectrum and history of supernova explosions throughout the universe
- Never observed before -> JUNO one of the best candidate to observe DSNB for the 1st time
- Challenging :
  - DSNB's IBD signal constrained by reactor's IBD at E < 10 MeV
  - Constrained by atmospheric neutrinos at higher energy
  - Optimal window [12-30] MeV with 2-4 events/year expected
  - 5σ sensitivity to DSNB signal in ~10 years





Atmospheric neutrinos

- JUNO able to measure atmospheric neutrino spectrum
  - Uncertainties between 10 % and 25 % with 5 years of data
- Sensitivity to NMO by matter effect ~1.8σ with 10 years of data
- Ongoing analysis to combine atmospherics and reactors



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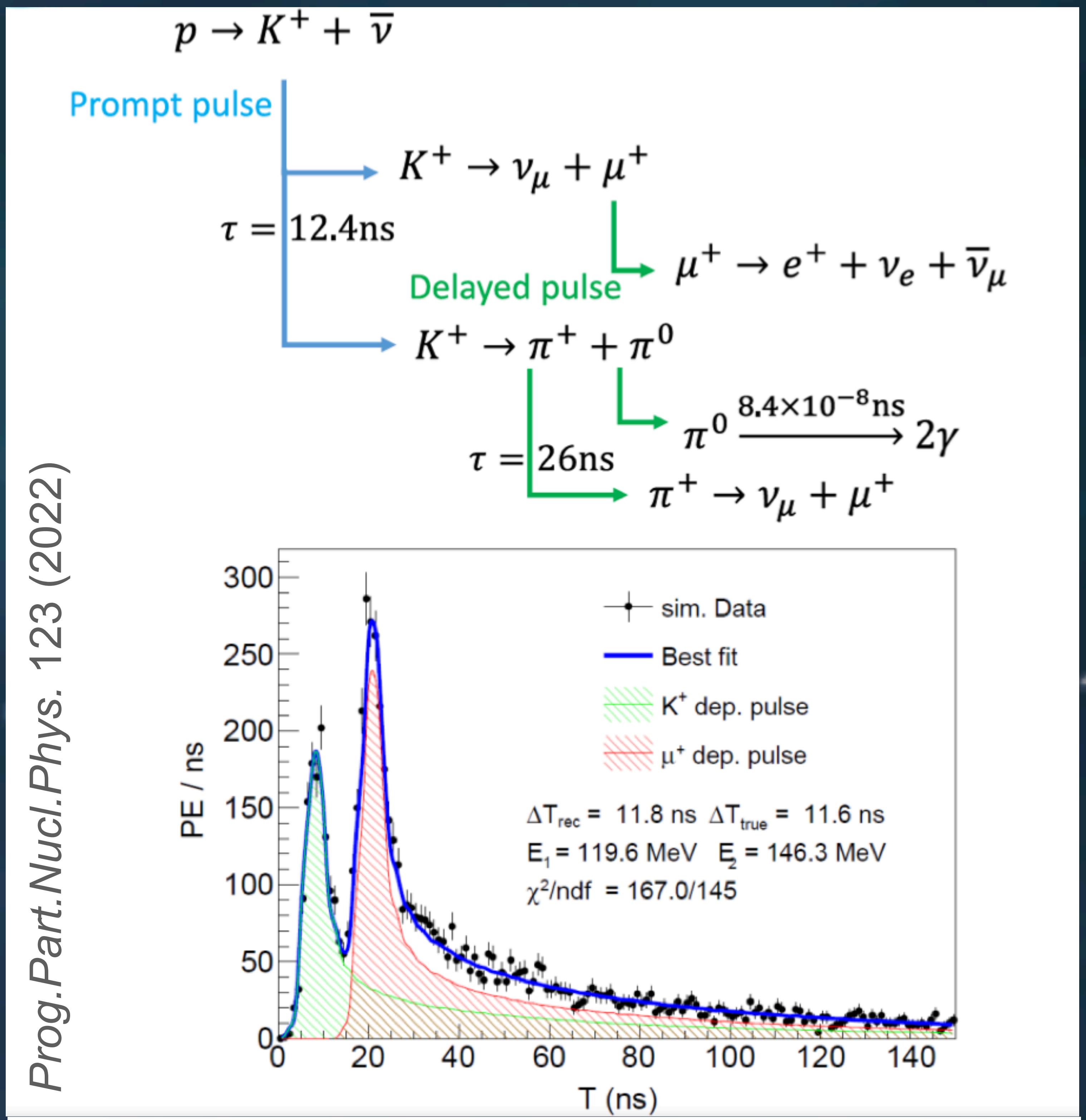
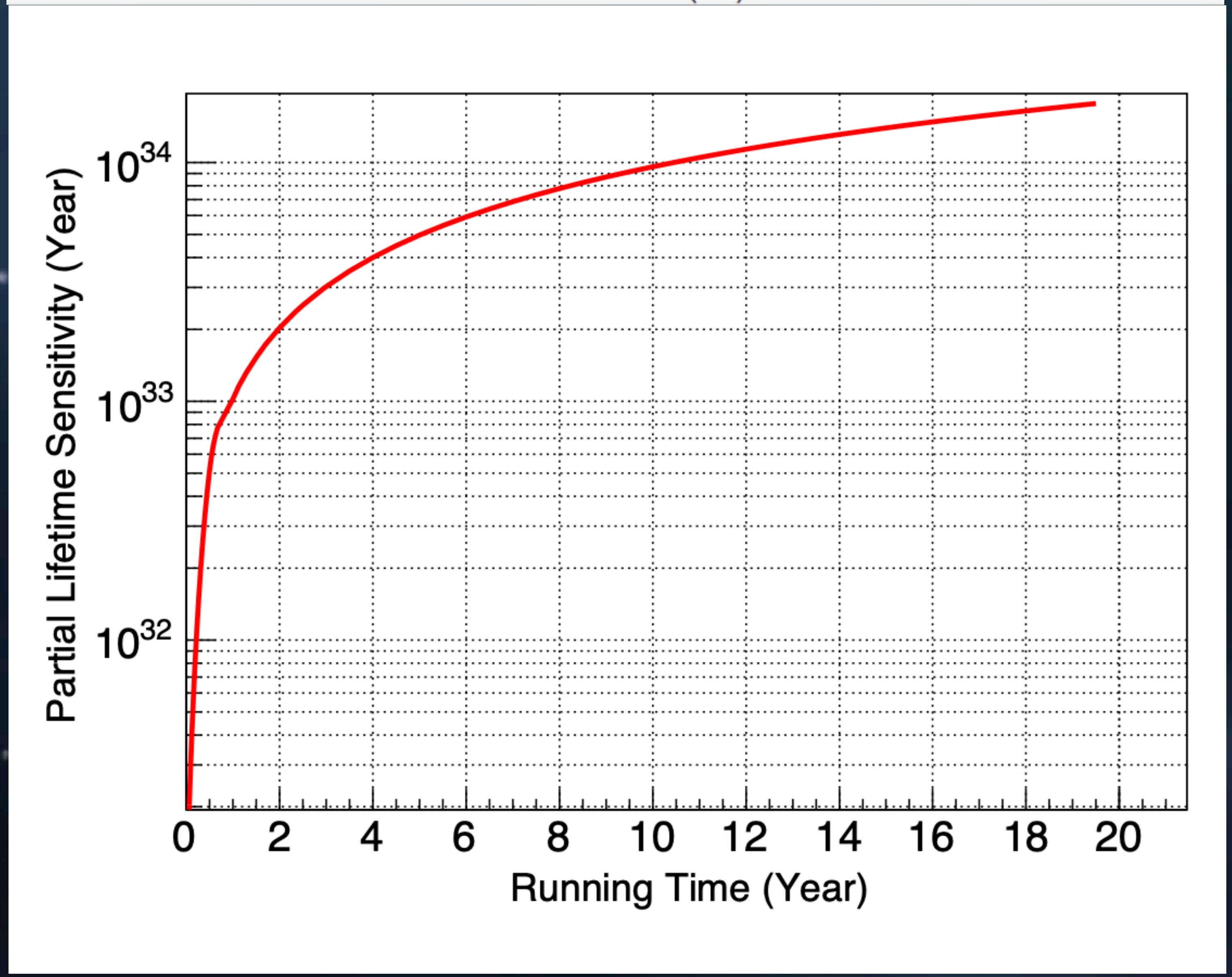
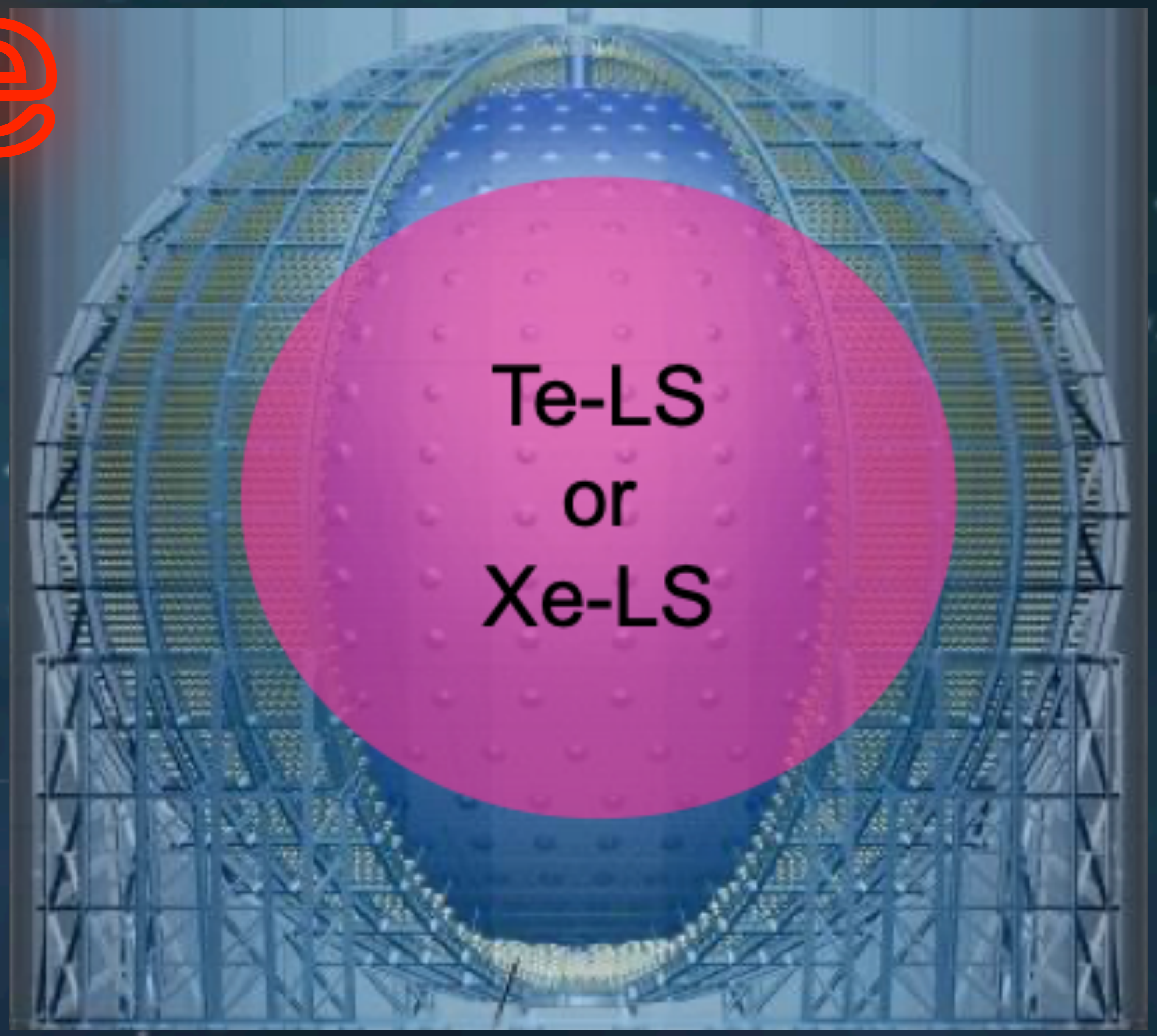
Proton decay



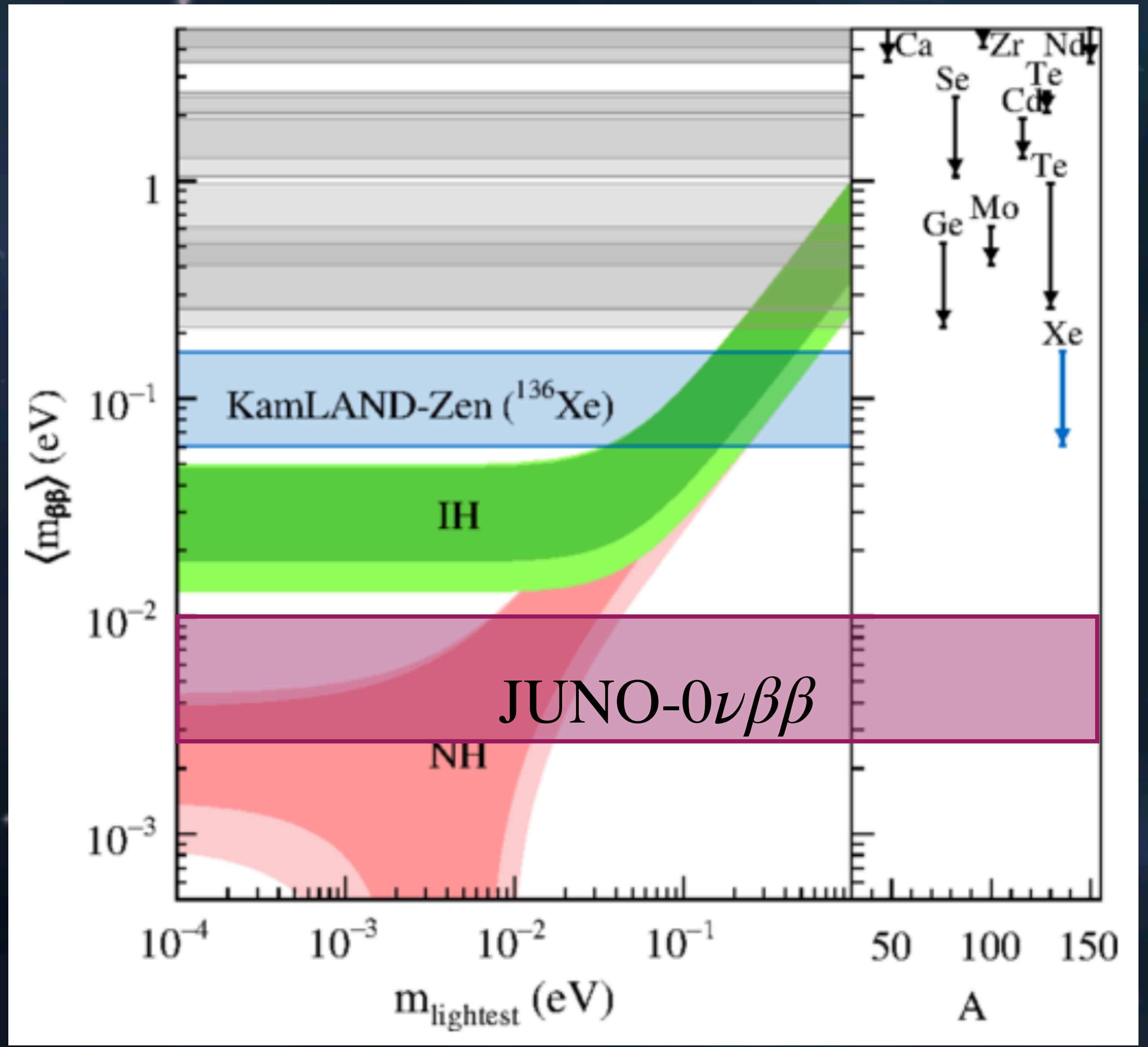


- Signature: 3 fold coincidence
- Disentangle pile up with excellent timing of SPMT
- Expected sensitivity : 9.6×10^{33} years (90% CL) after 10 years

JUNO-0νββ upgrade



- After completion of NMO (>2030):
  100-ton scale isotope loading (Tellurium, Xenon)
- Sensitivity to parameter space of Majorana neutrino in normal ordering
- Lot of R&D:
  → Loaded LS requirement: high light yield, transparency, radio purity



Conclusion

- The JUNO experiment is a technical challenge
  → largest liquid scintillator ever built !
- The primary goal is the Neutrino Mass ordering determination in 6 years of data taking
- Rich physics program: Precision measurement, CCSN, DSNB, Solar, Geo, atmospherics, proton decay and $0\nu\beta\beta$
- Stay tuned for a lot of physics results !