Experimental neutrino physics in Finland

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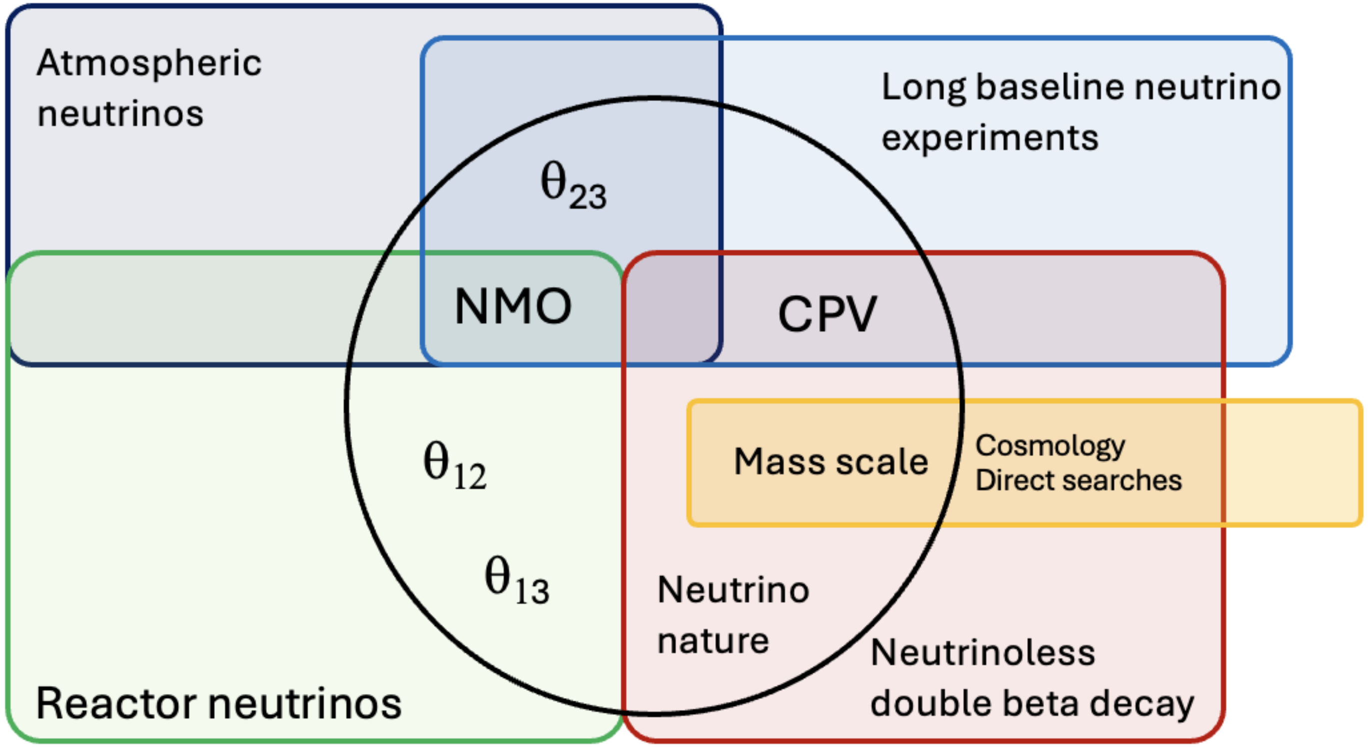
Particle Physics Days 27.-28.11.2024, Lammi

What we want to know



- Three mixing angles (θ_{ij})
- Neutrino mass ordering (NMO)
- CP-violation phase (CPV)

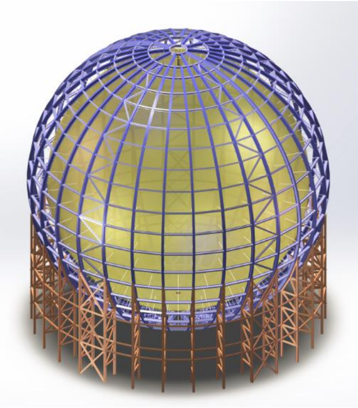
  => oscillation experiments

- Neutrino absolute mass
  => beta decays
  => constraints from cosmological measurements

- Nature: Dirac vs. Majorana
  => double beta decay

+ using neutrinos as messengers: Earth, Sun, stars, other sources…

Jianmen Underground Neutrino Observatory



Main goal: Neutrino mass ordering (>3σ)
Additional goals: solar, supernova, atmospheric, geo neutrinos, proton decay (P2: double beta)

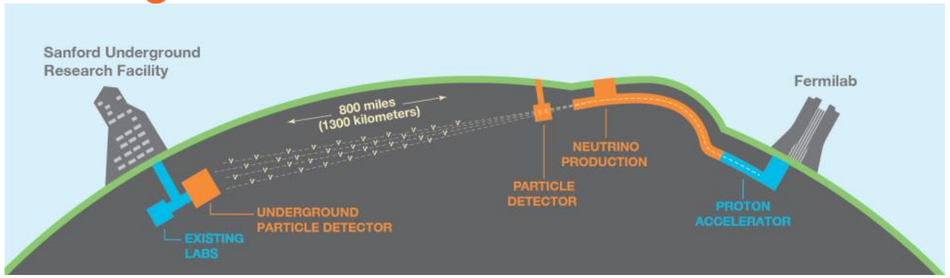
Host: China (IHEP)
Source: 2x reactor complexes 53 km away providing high flux of electron antineutrinos with 0-10 MeV
Detectors:

- 20 kton spherical liquid scintillator, ~17k + 32k photomultipliers.
- Near detector JUNO-TAO, **Radiopurity detector OSIRIS**

Status: Central Detector under instrumentation. Filling of Central detector 15th of Decemeber 2024.

Collaboration: ~700 collaborators, 71 institutes, 17 countries (mainly China, Italy, France, Germany)

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Main goal: Neutrino mass ordering (5σ)
and CP violation (>3σ)
Additional: supernova, atmospheric, proton decay

Host: US, Fermilab + SURF
Source: 1.2 MW neutrino beam 1-10 GeV muon (anti)neutrinos
Detectors: Far: 2 (4) x 10 kton liquid Argon Time projection chambers. Near: multi-technique.

Status: Excavation started**,** starts with 2 modules, Beam upgrade(?), First data expected 2029 (2031).
Collaboration: ~1400 collaborators, ~200 institutes, ~30 countries

Research Fellow project 2024-2028

Suomen Akatemia
Finlands Akademi
Research Council of Finland

Liquid scintillator technique

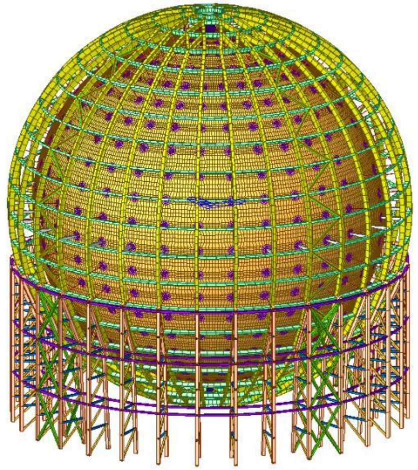
Neutrino Mass Ordering with **JUNO**
Screening of JUNOs target material with **OSIRIS**

JUNO's RUN2: **neutrinoless double beta decay**

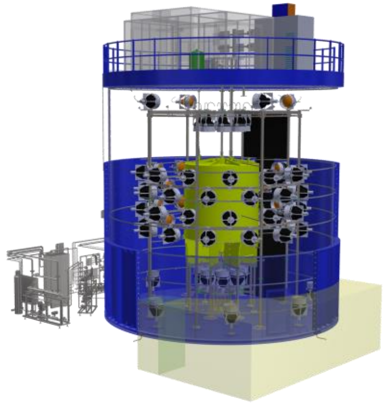
OSIRIS upgrade to R&D test bed
Slow Scintillator development and characterization

Proof-of-concept experiment for **beta spectral shapes and effective g_A**

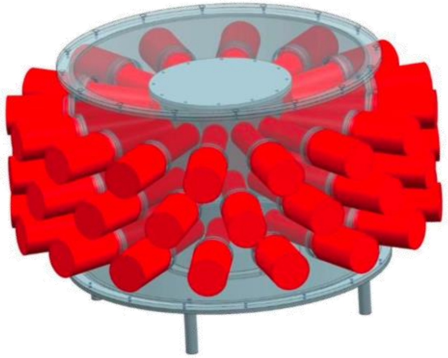
JUNO: ~20 000 tons



OSIRIS: ~20 tons



Lavatrice: 20 litres



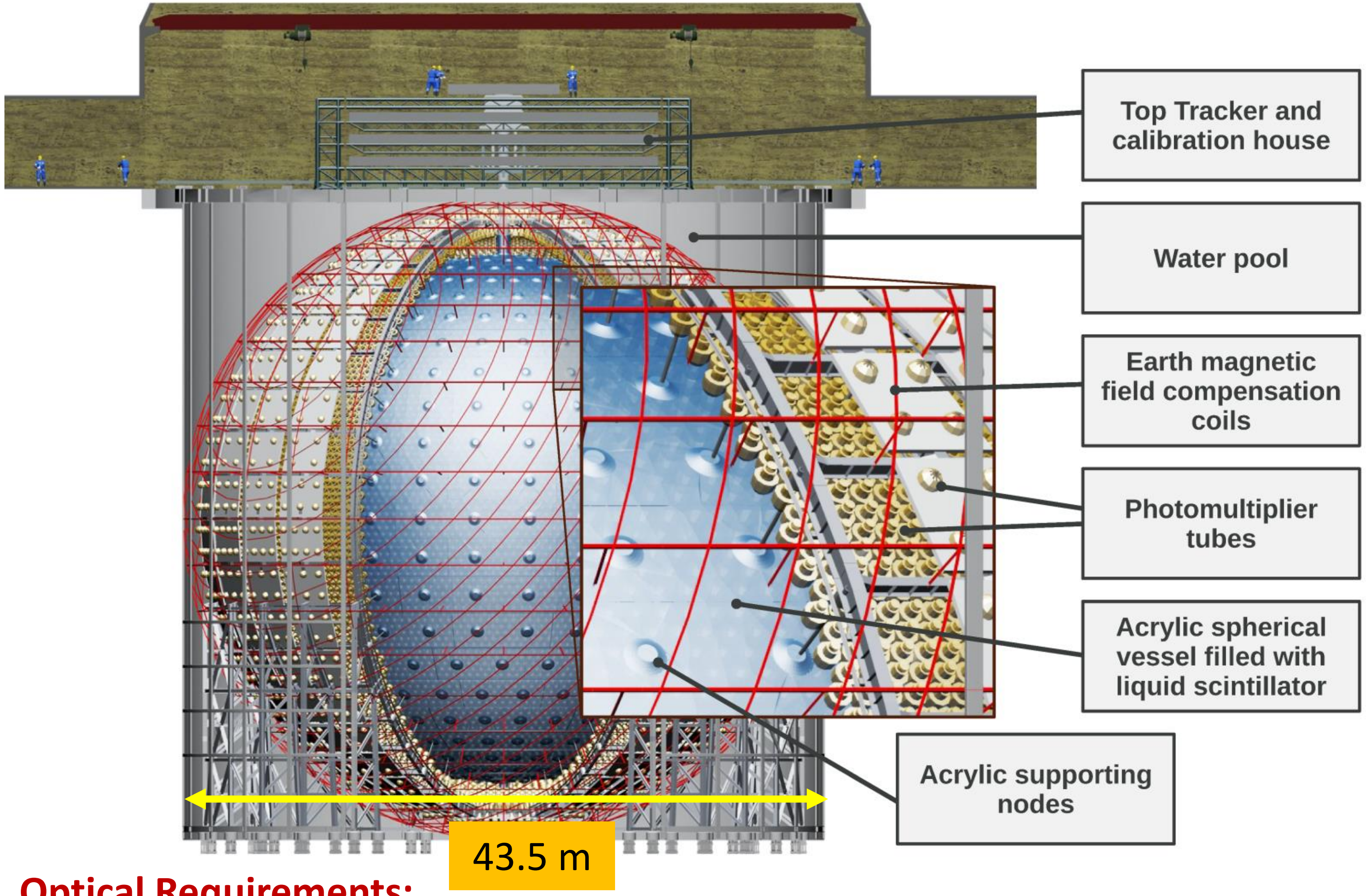
Betashape: ~1 desilitre

Jiangmen Underground Neutrino Observatory (JUNO)

Multi-purpose experiment but with a main focus:
Measurement of the Neutrino Mass Ordering using reactor anti-electron neutrinos

JUNO Detector

- Target
  - Spherical acrylic vessel
  - 20 kton of LAB-based liquid scintillator
  - High transparency
  - High radiopurity
- Light detection
  - ~17 000 20-inch PMTs
  - ~26 000 small PMTs
  - < 3% energy resolution
- 700m underground
- Biggest LSc detector in the world
- Under construction in China



Optical Requirements:

Light output: **~10.000 Photons / MeV → ~1200 p.e**

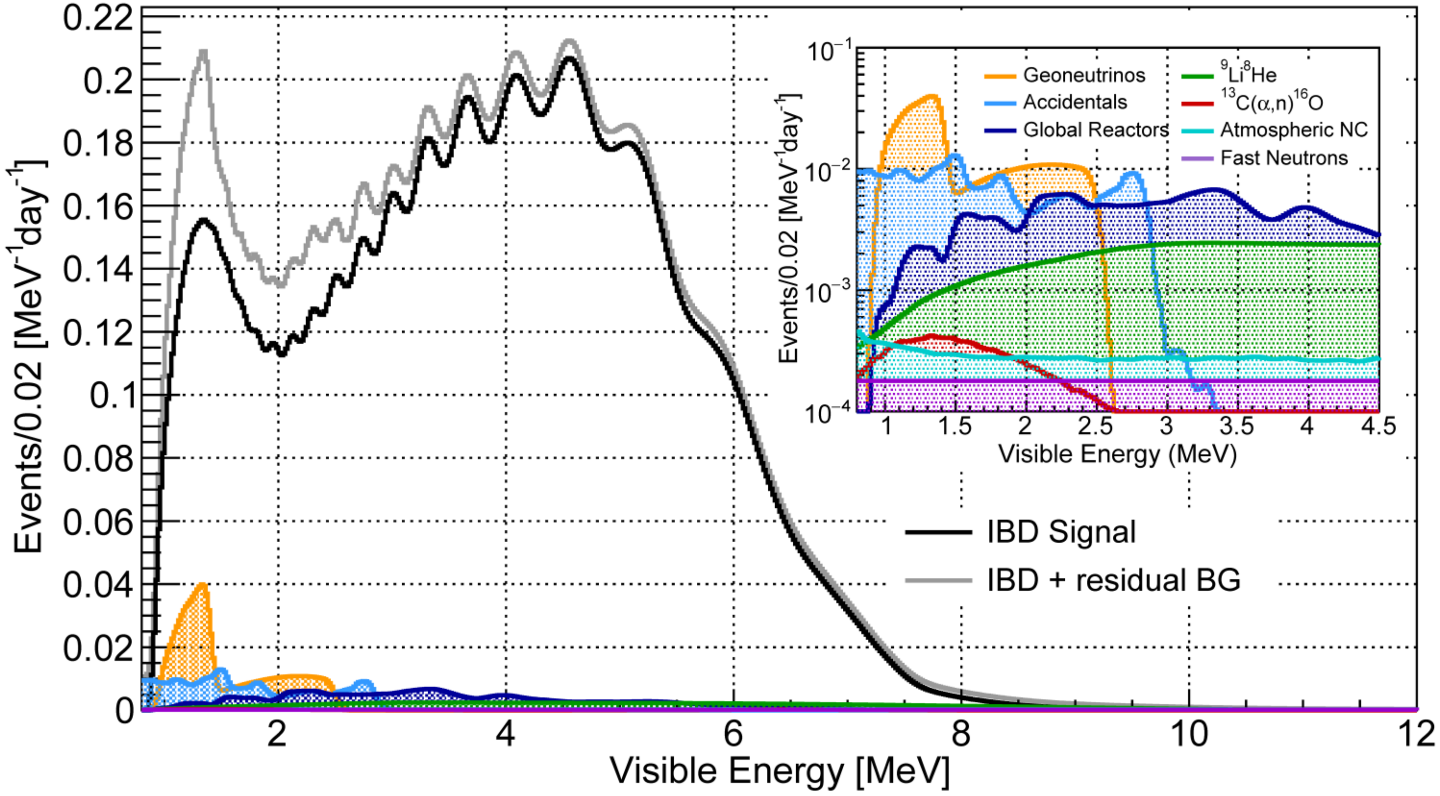
Attenuation length: **> 20 m @ 430 nm**

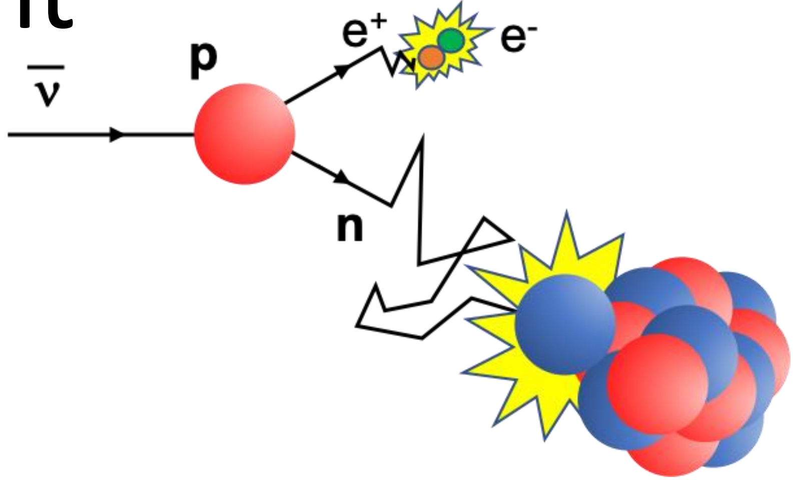
Required Radiopurity:

Reactor neutrinos: **^{238}U / ^{232}Th < 10^{-15} g/g, ^{40}K < 10^{-16} g/g**

Solar neutrinos: **^{238}U / ^{232}Th < 10^{-17} g/g, ^{40}K < 10^{-18} g/g, ^{14}C < 10^{-18} g/g**

Reactor neutrino measurement





Rate [/day]	JUNO	TAO
Reactor IBD signal	**47**	**2000**
Geo-ν's	**1.2**	**-**
Accidental signals	**0.8**	**155**
Fast-n	**0.1**	**92**
^{9}Li/ ^{8}He	**0.8**	**54**
^{13}C(α , n) ^{16}O	**0.05**	**-**
Global reactors	**1.0**	**-**
Atmospheric ν's	**0.16**	**-**

JUNO Collaboration:
Sub-percent precision measurement of neutrino oscillation parameters with JUNO *Chin.Phys.C* 46 (2022) 12, 123001

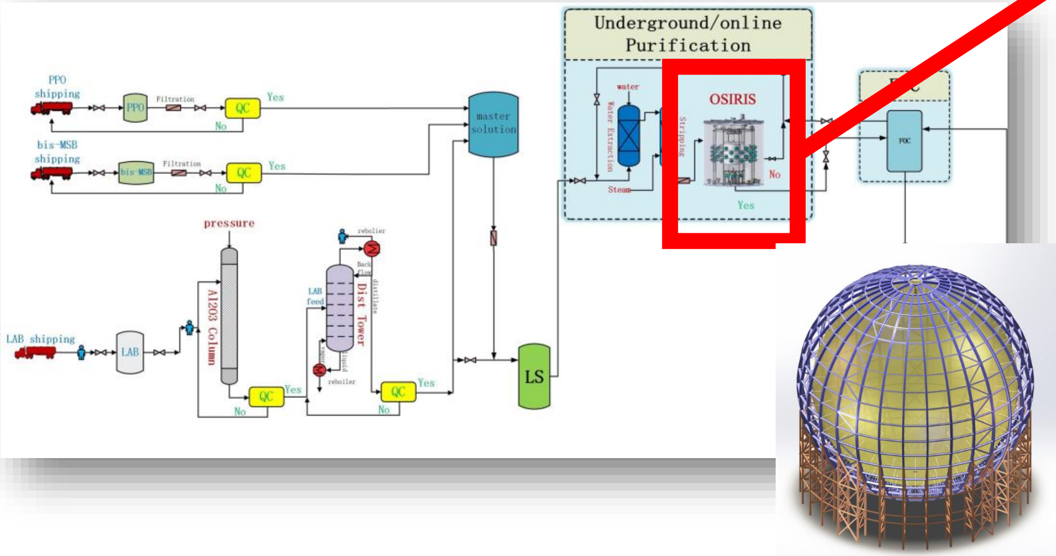
Online Scintillator Internal Radioactivity Investigation System

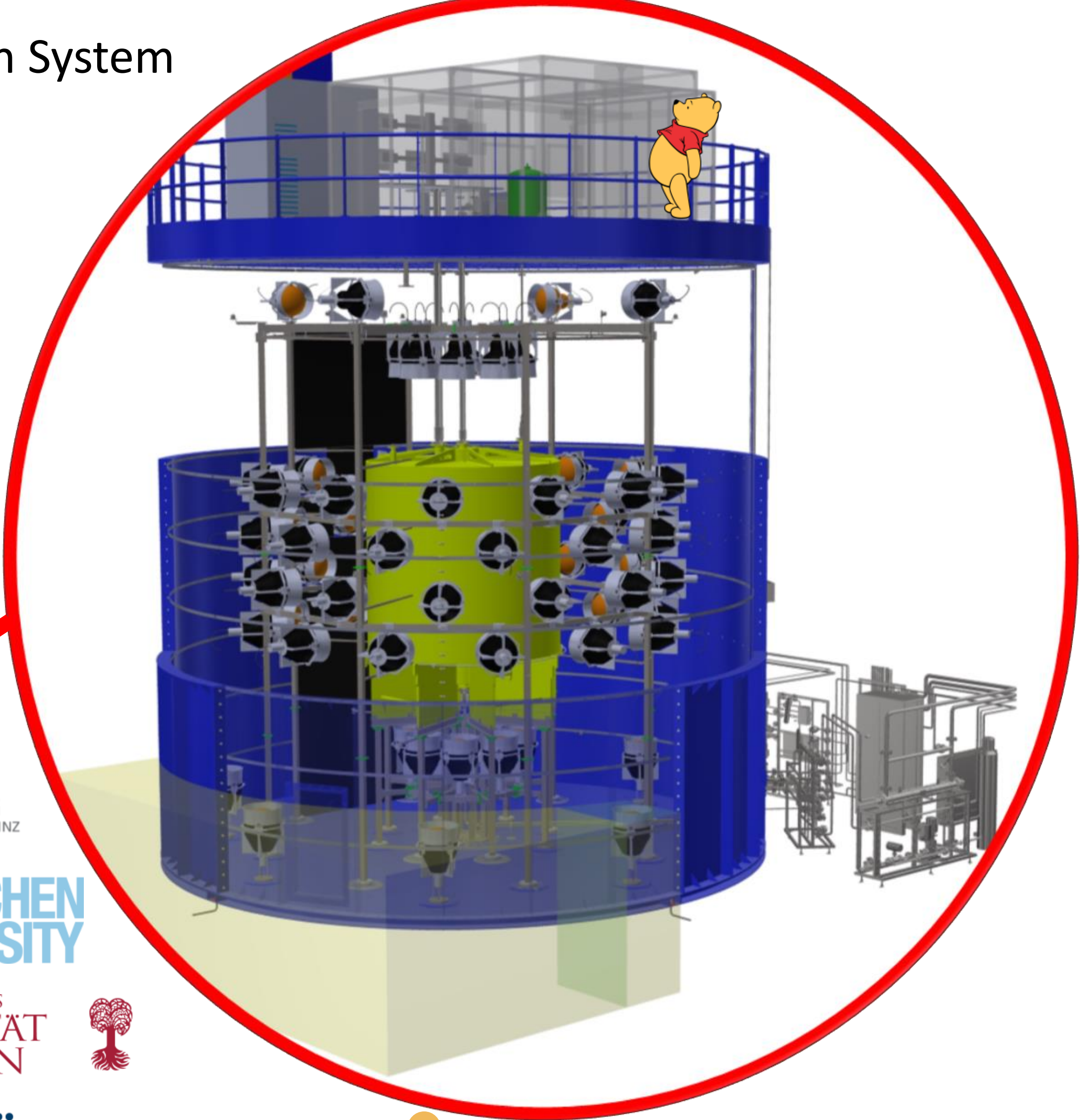
OSIRIS

The **OSIRIS** detector is a subsystem of the liquid scintillator filling chain of the **JUNO neutrino experiment** and its purpose is

- ✓ ***To validate the radiopurity of the scintillator***
- ✓ ***To assure that all components of the JUNO scintillator system work to specifications and***
- ✓ ***To verify that only neutrino-grade scintillator is filled into the JUNO Central Detector.***

The aspired radiopurity level of **10^{-15} to 10^{-17} g/g** (reactor to solar) of **^{238}U and ^{232}Th** requires a large (~20 m^3) detection volume and ultralow background levels.





JOHANNES GUTENBERG UNIVERSITÄT MAINZ

RWTH AACHEN UNIVERSITY

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

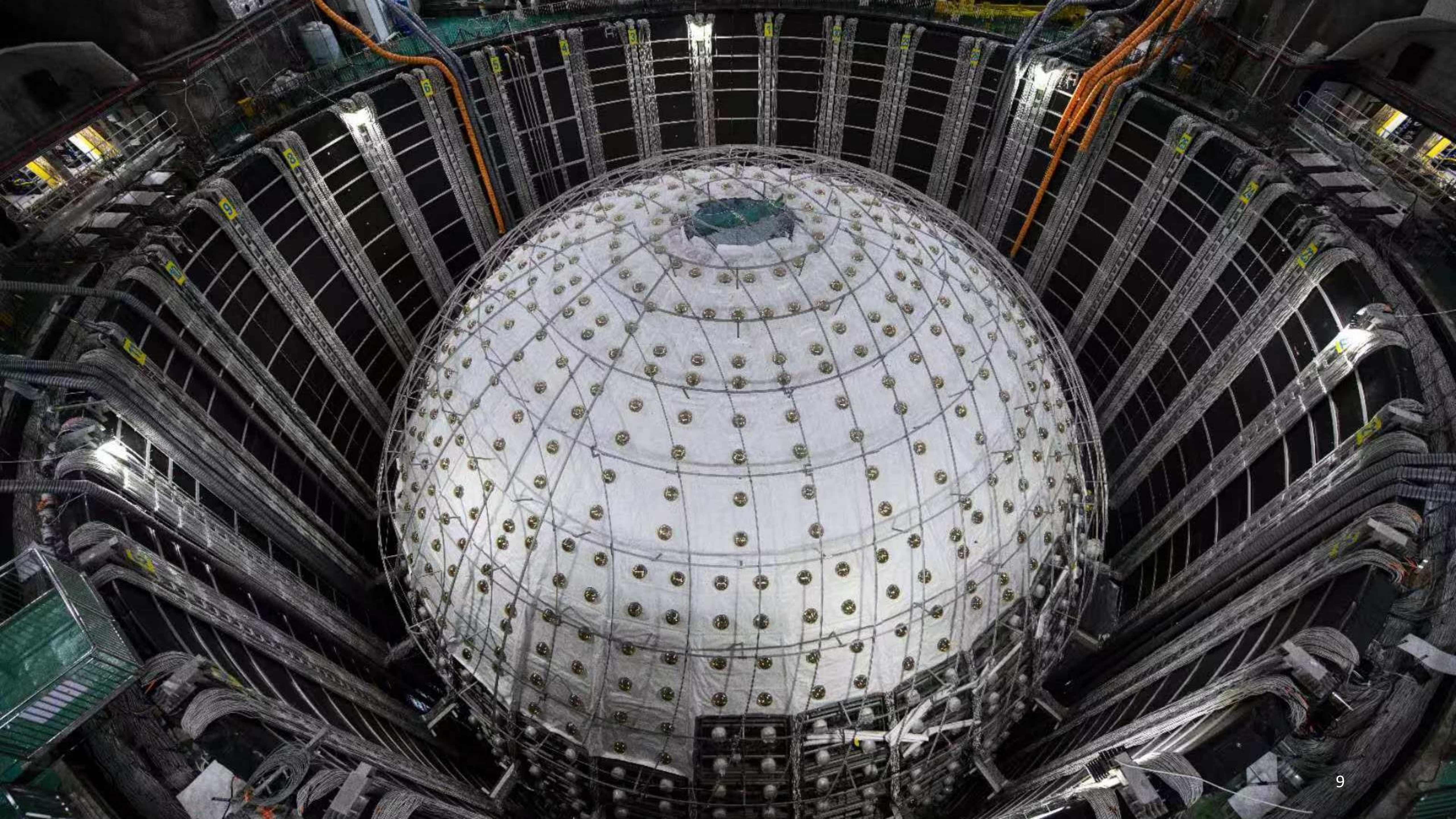
JÜLICH Forschungszentrum

GSI

Technische Universität München

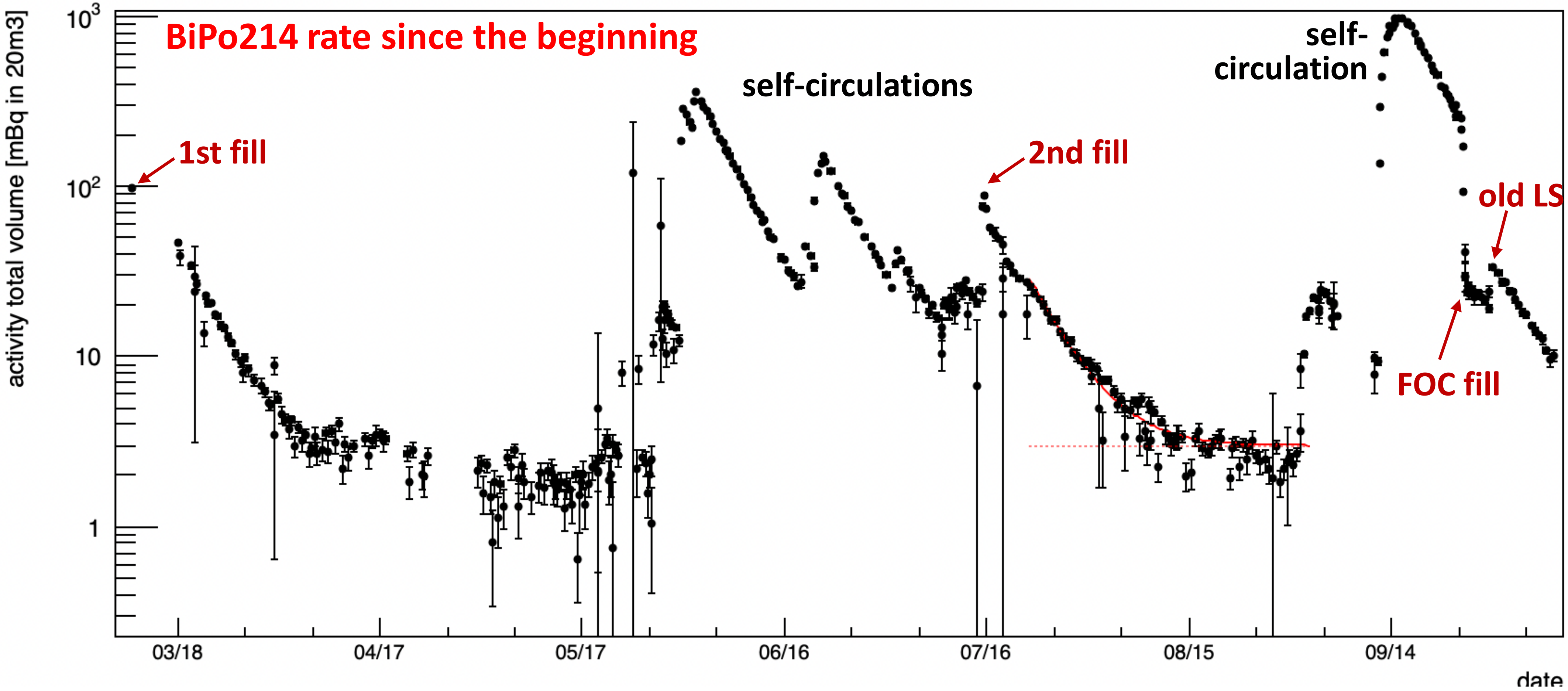
Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ




May ‘22

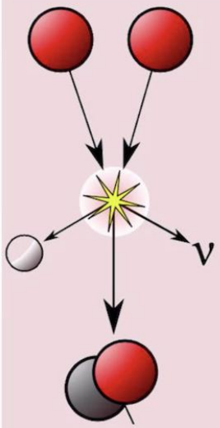
Data taking journey so far with OSIRIS



FOC filling was the lowest in **initial Rn-222** level that we have achieved so far, ~25 mBq in total volume

OSIRIS: After JUNO filling

After JUNO filling, purification infrastructure including OSIRIS will become available

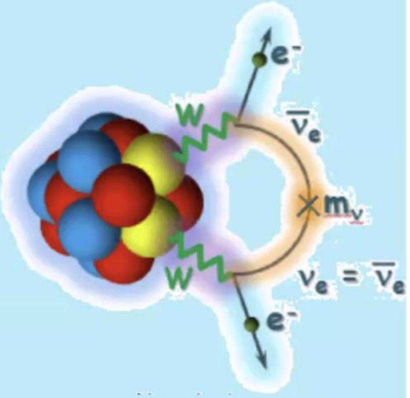


Precision measurement of solar pp neutrinos

- improve Borexino measurement (10%) to 3% level or better
  → θ_{12} for ν_e, for 1% accuracy: hadronic axions, hidden photons
- OSIRIS Upgrade could achieve
  - low ^{14}C scintillator
  - better energy resolution than OSIRIS (and maybe JUNO)
  - slow scintillator for integrated directionality (CID)

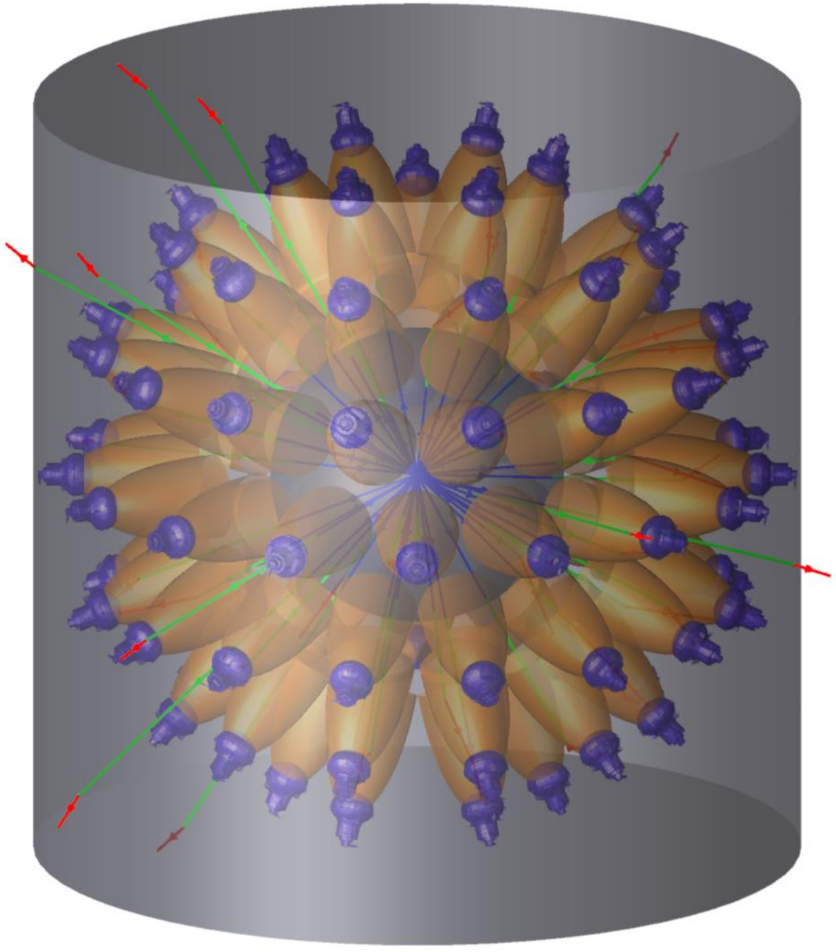
Demonstrator for neutrino-less double-beta decay (0ν2β)

- test Te/Xe-loaded scintillators for JUNO-ββ phase
- develop new background discrimination techniques essential for JUNO sensitivity, e.g. **particle ID based on Cherenkov/scintillation ratio**
- **very sensitive $2\beta^+$ decay measurements (10^{24-25} yrs)** with ^{78}Kr/^{124}Xe-loaded slow scintillators



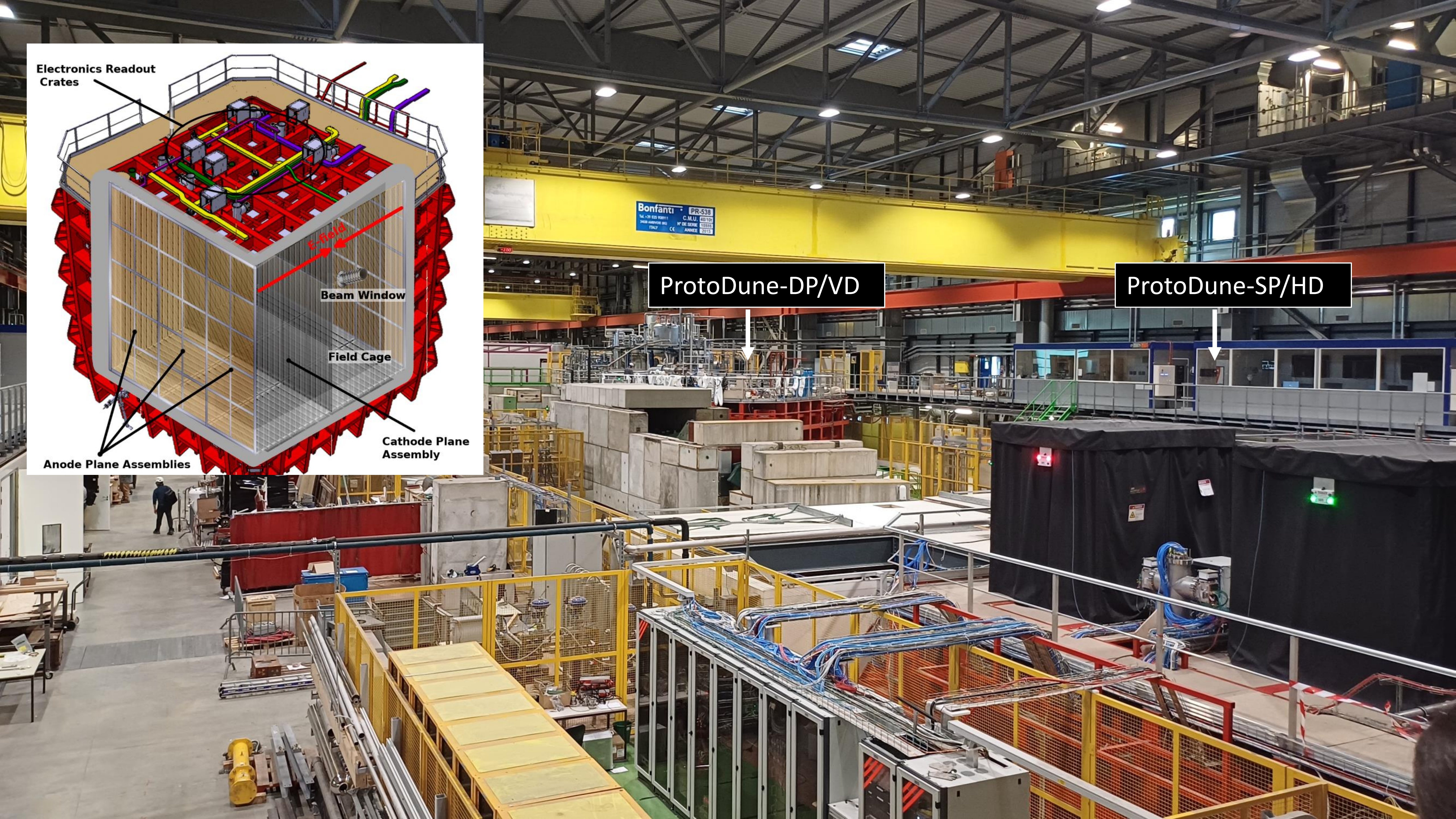
Foreseen upgrade:

- Rearranging PMTs
- Attaching light collector cones
- Adding external shielding against γ's



Long baseline neutrinos

- Represents an effort of CERN to foster fundamental research in the field of Neutrino Accelerator Physics as decided by CERN Council in framework of the 2013 European Strategy.
- Experimental Hall North 1 (EHN1) at Prevessin site: cryogenics, magnets, beamlines H2, H4 protons SPS 10-400 GeV/c, secondary mixed hadrons
- Focus in detector development:
  - DUNE prototyping: ProtoDUNE-SinglePhase (NP04), **ProtoDune-DualPhase (NP02)**
  - T2K near detector (NP07)
  - Prototyping for ENUBET and NuTag collaborations
- Filling and beam to protoDUNEs 2024-2025
- JYU contribution declined since the beginning of 2019. Reactivating.


Electronics Readout Crates
E-field
Beam Window
Field Cage
Cathode Plane Assembly
Anode Plane Assemblies
Bonfanti
PR-538
ProtoDune-DP/VD
ProtoDune-SP/HD

Other closely related activities

- OSIRIS Upgrade planning
  - Standalone test bed for double beta decays (JUNO-II)
- LS technology development
  - Characterisation of slow LS, Cerenkov/Scintillation separation.
  - Improved particle idenfication, directionality, background discrimination
  - Results included to OSIRS-upgrade sensitivity studies and THEIA@DUNE
- Measurement of deta decay spectral shapes
  - Important for all low energy rare-event search (dark Matter, double beta, neutrino) in understanding the radioactive backrgound.

Summary

- Within Finland the current main activity is JUNO. Operational within one year. Main contribution through OSIRIS radiopurity screening
- ProtoDUNE activities at CERN Neutrino Platform has been on hold. Definitely room for improvement. (C/S)hould be reactivated.
- Other indirect nuclear physics and R&D activities: Liquid scintillator R&D, background measurements.

- + theoretical studies: neutrino phenomenology, nuclear physics.

Backups

Schedule

V.6.6

V.6.4 established in July 2024

		Start	End	Condition
1	Underground lab construction	2015.1.1	2021.11.25	
2	Water pool cleaning and CD construction preparation	2021.11.26	2021.12.10	1
3	Acrylic construction/bottom acrylic chimney	2021.12.11	2024.9.30	2
4	CD bottom 4 layers steel structure	2024.10.1	2024.10.15	3
5	CD & VETO PMT installation	2022.10.1	2024.11.15	4
6	CD dust settlement, water washing and film removal	2024.10.1	2024.10.15	3,7
7	TT bridge installation	2024.8.1	2024.9.30	
8	CD top chimney installation	2024.10.16	2024.10.20	6,7
9	pole PMT installation/Calib. House (sealed with chimney)	2024.10.16	2024.11.15	7,8
10	pool cleaning, bottom instrumentation, concrete door construction, cover installation	2024.10.16	2024.11.30	3,4,9
11	VETO & CD water filling	2024.12.1	2025.1.31	10
12	LS filling/water exchange	2025.2.1	2025.7.31	11
13	TT module installation/commissioning	2024.12.1	2025.7.30	10
14	TAO installation	2024.8.1	2025.7.30	
15	Test run	2025.8.1		

Filling of the big detector starts in December

We plan to start the water filling on Dec. 15

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From neutrino mixing to oscillation

Flavor states — PMNS matrix — Mass states

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Notation: $s_{12} = \sin(\theta_{12})$, $c_{12} = \cos(\theta_{12})$

Probability to observe ν_α as ν_β after distance L

$$\begin{aligned} P_{\nu_\alpha \to \nu_\beta}(t) &= |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 \\ &= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \\ &\quad + 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right), \end{aligned}$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$

Parameters

- Three mixing angles
- Two mass-squared splittings
- CP-violation phase δ
- (Two Majorana phases α_i)

The Neutrino Mass Ordering with Reactor ν's

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2 \Delta m^2_{21} \frac{L}{4E} - sin^2 2\theta_{13} \left(cos^2\theta_{12} sin^2 \Delta m^2_{31} \frac{L}{4E} + sin^2\theta_{12} sin^2 \Delta m^2_{32} \frac{L}{4E} \right)$$

$$\approx 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2 \Delta m^2_{21} \frac{L}{4E} - sin^2\theta_{13} sin^2 \Delta m^2_{ee} \frac{L}{4E} \quad for \quad \Delta m^2_{12} \ll \Delta m^2_{32}$$

Δm^2_{ee}
effective ν-mass-squared difference
(beat frequency)

With:

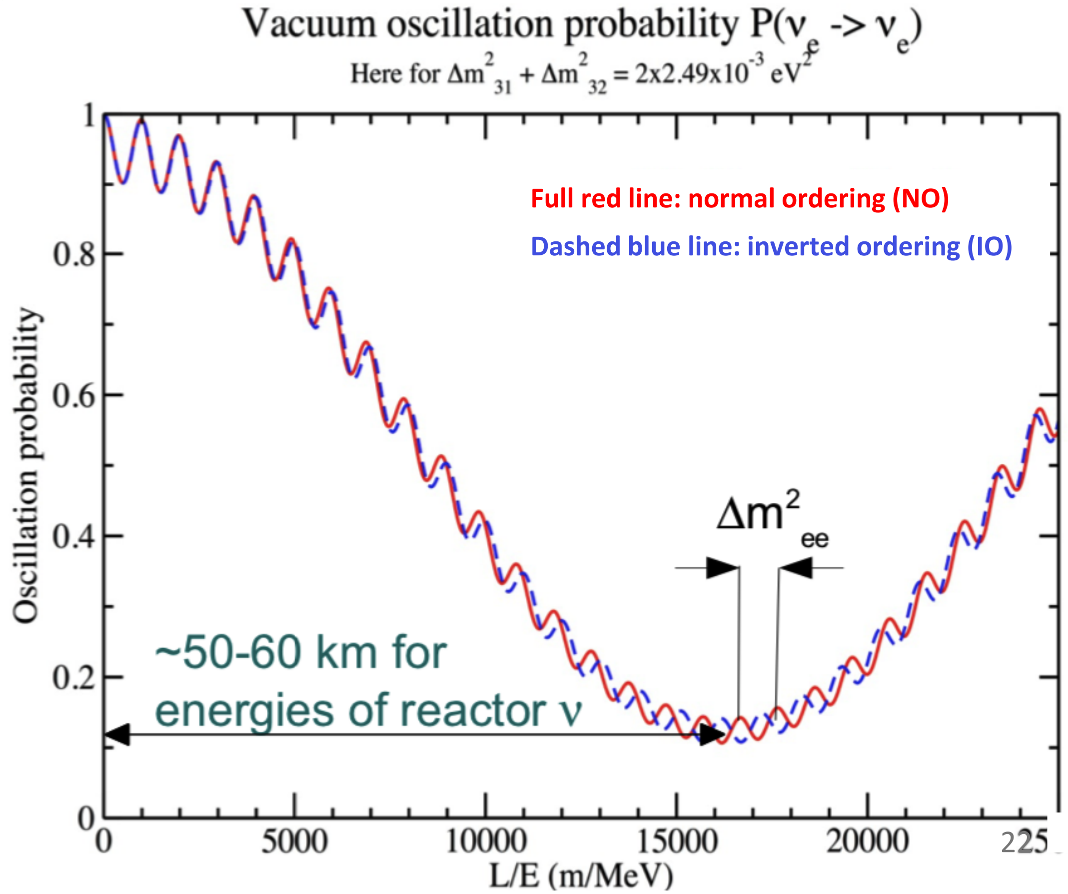
$\Delta m^2_{12} \ll \Delta m^2_{32}$

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

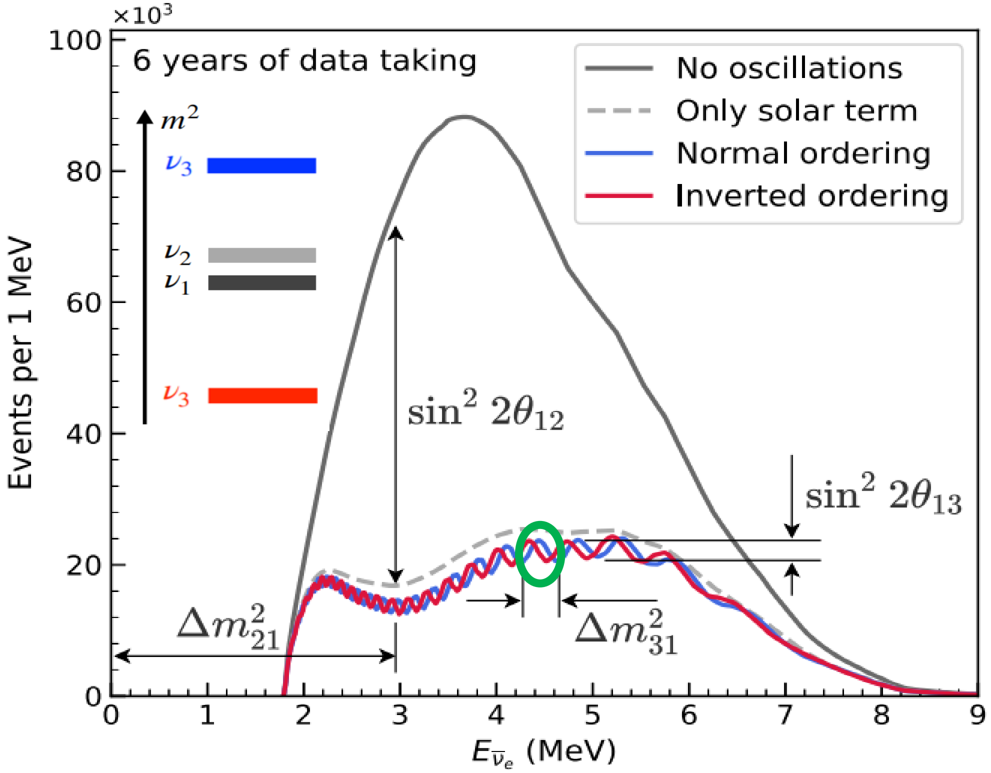
NO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

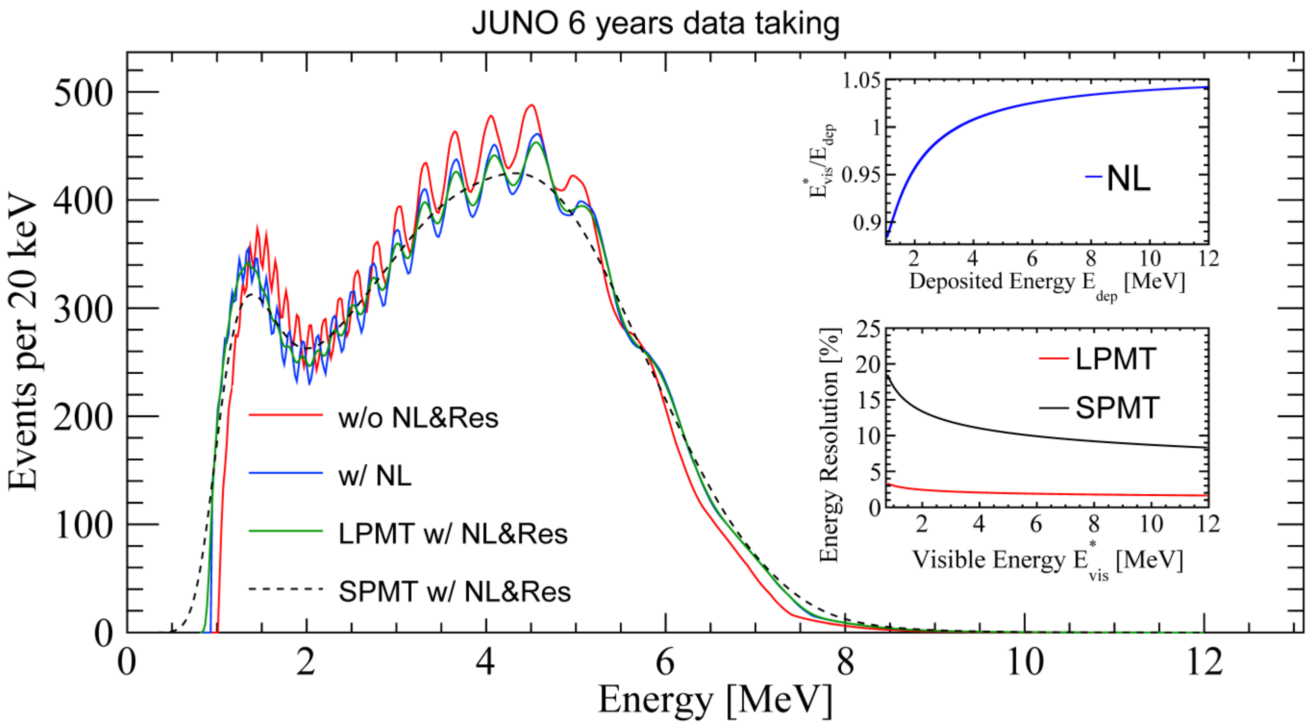
IO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

Different beat frequency Δm^2_{ee} for both orderings!



Precision measurement of mixing parameters





Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|/|\Delta m^2_{32}|$ < 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%)

Sensitivity for NMO determination