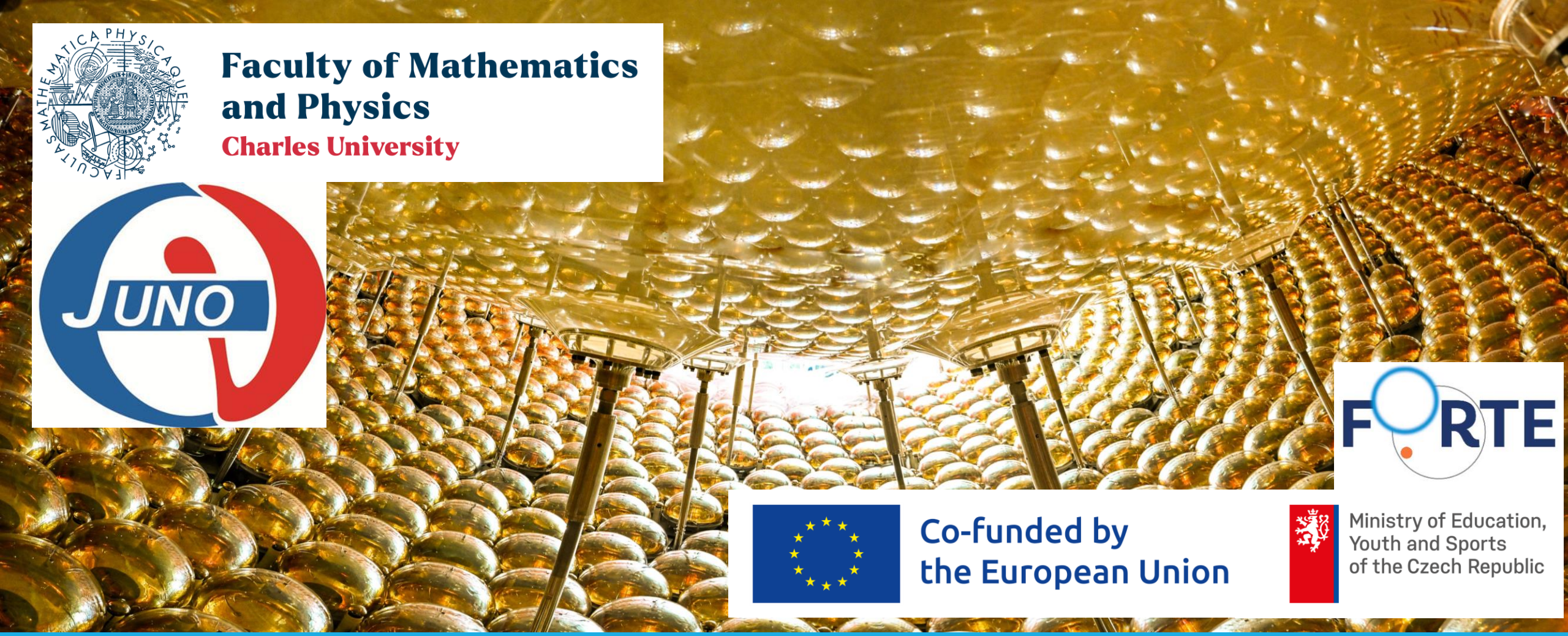


Faculty of Mathematics and Physics
Charles University

JUNO

FORTE

Co-funded by the European Union

Ministry of Education, Youth and Sports of the Czech Republic

# Determination of the energy response of the JUNO detector

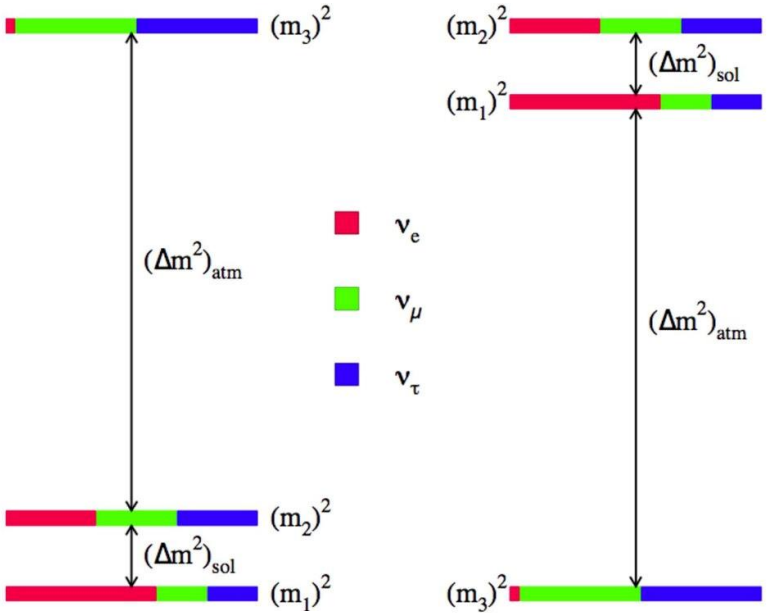
Tomáš Těj on behalf of the JUNO collaboration

# Neutrino oscillation

- Described by $U_{PMNS}$ matrix
- Mass ordering?

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,\mathrm{e}^{-\mathrm{i}\,\delta} \\ 0 & 1 & 0 \\ -s_{13}\,\mathrm{e}^{\mathrm{i}\,\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$



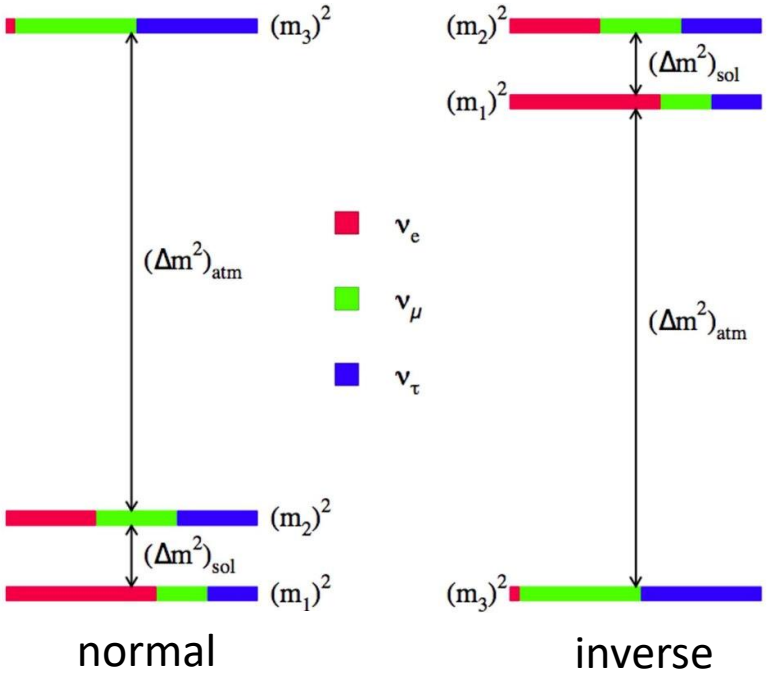

normal inverse

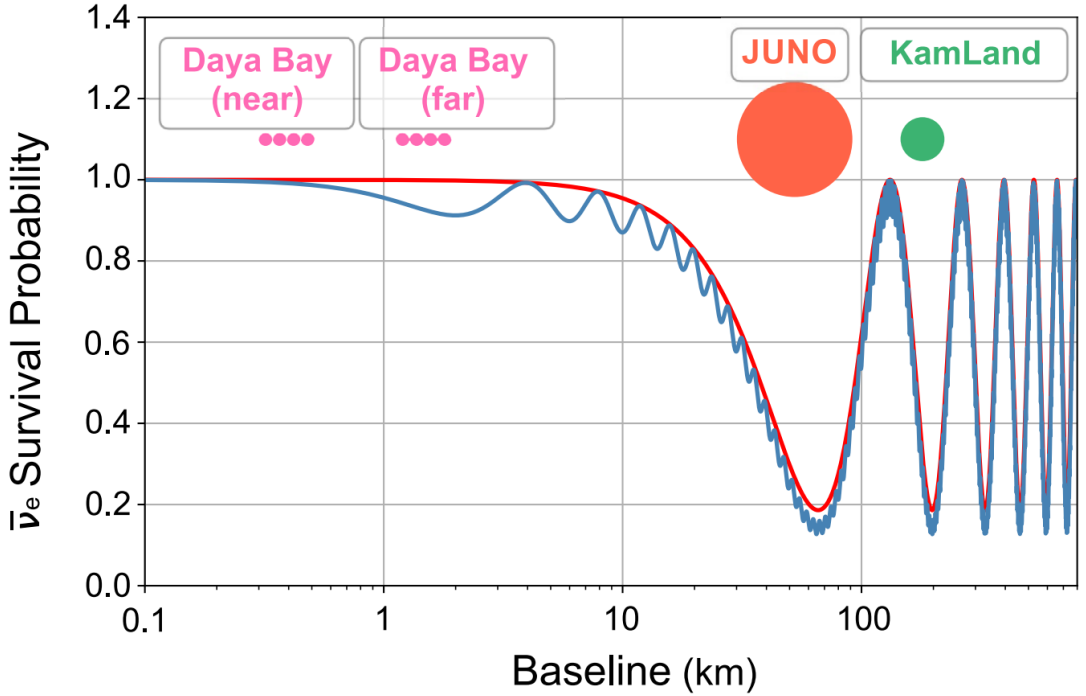
$$P_{ee}(L,E) = 1 - \sin^2(2\theta_{12})c_{13}^4 \sin^2\left(\frac{|m_2^2 - m_1^2|}{4}\frac{L}{E}\right) - \sin^2(2\theta_{13})\left[c_{12}^2 \sin^2\left(\frac{|m_3^2 - m_1^2|}{4}\frac{L}{E}\right) + s_{12}^2 \sin^2\left(\frac{|m_3^2 - m_2^2|}{4}\frac{L}{E}\right)\right]$$

# Neutrino oscillation

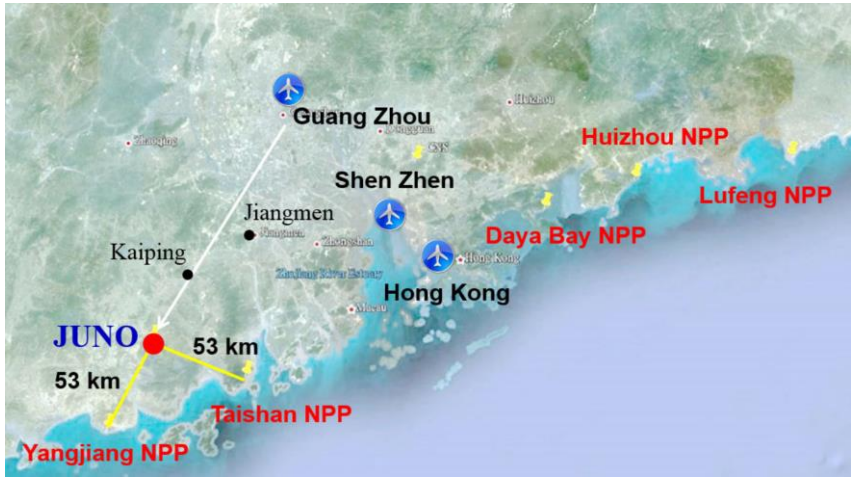
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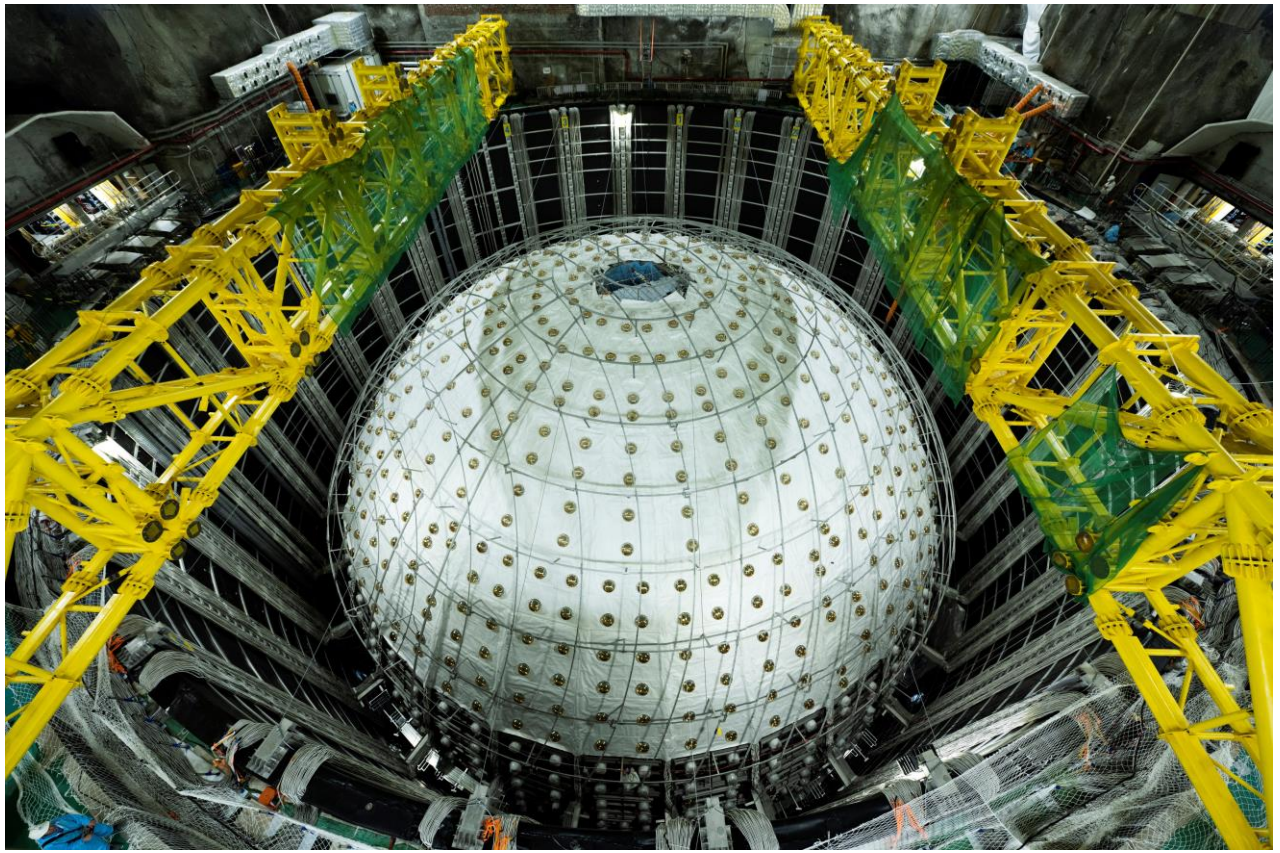


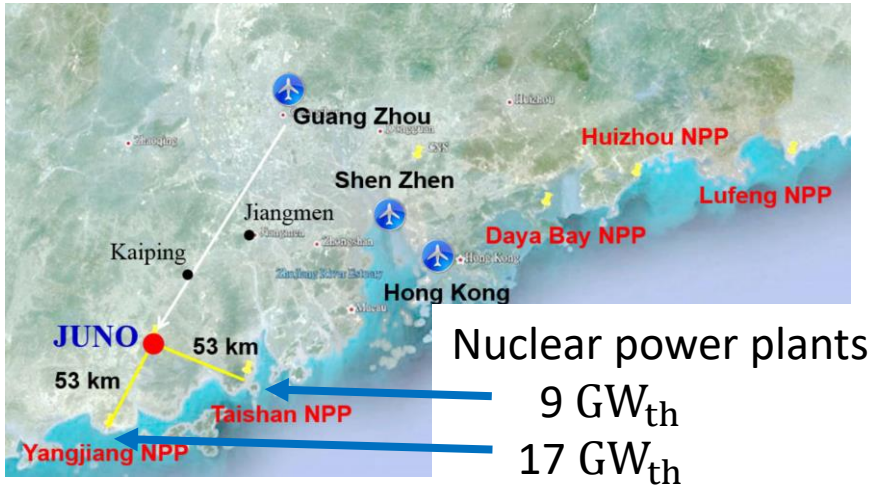
# Jiangmen Underground Neutrino Observatory





# Jiangmen Underground Neutrino Observatory

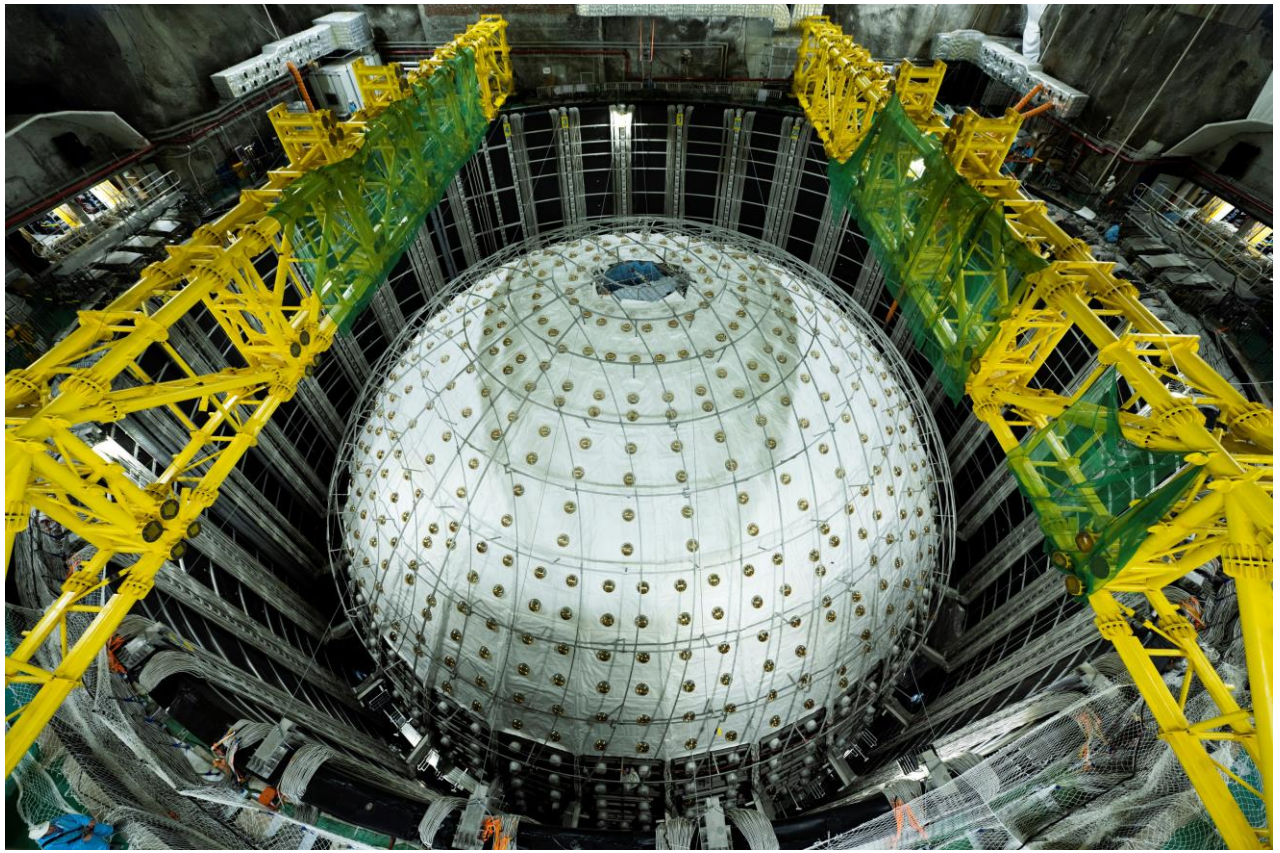



Nuclear power plants

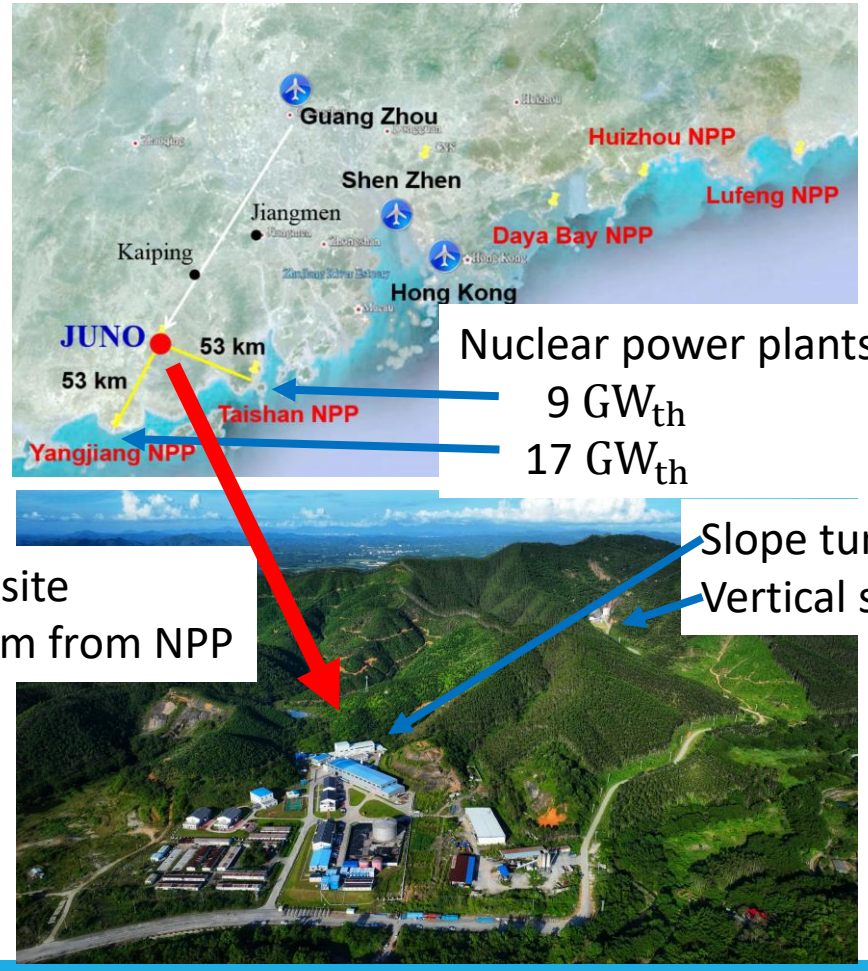
9 $GW_{th}$

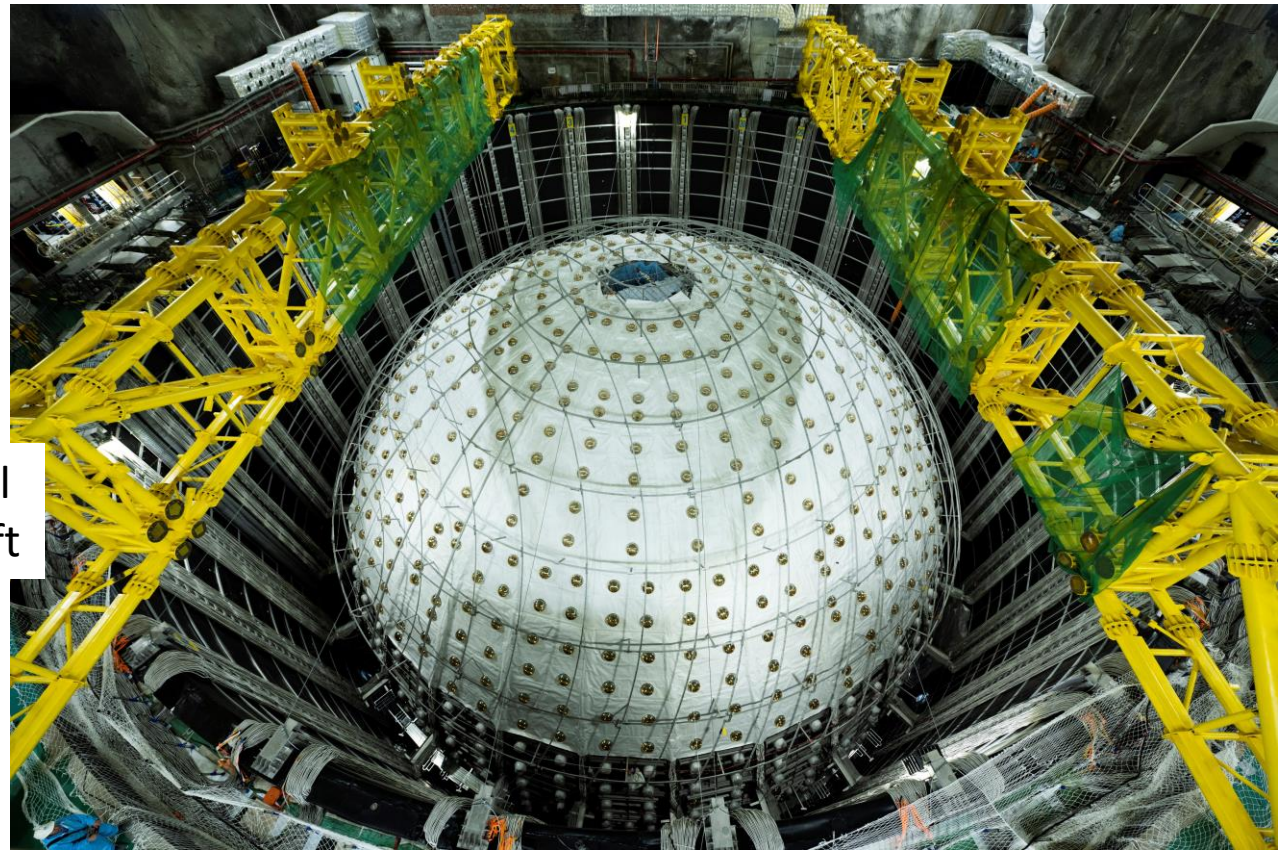
17 $GW_{th}$



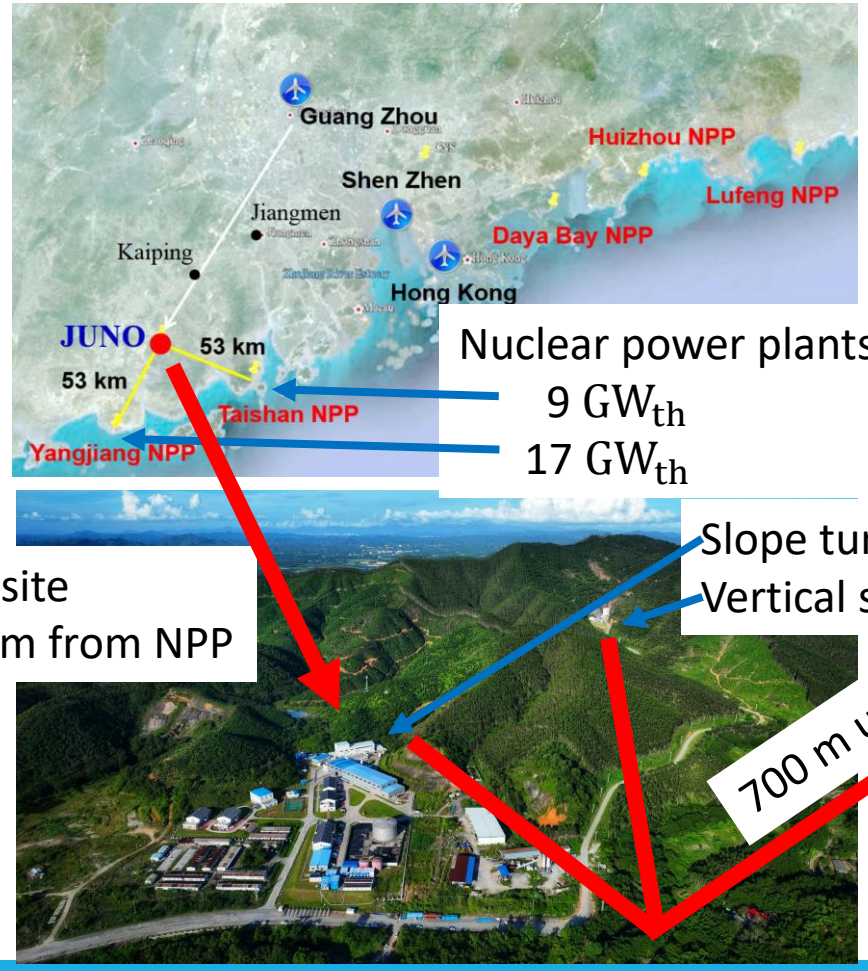


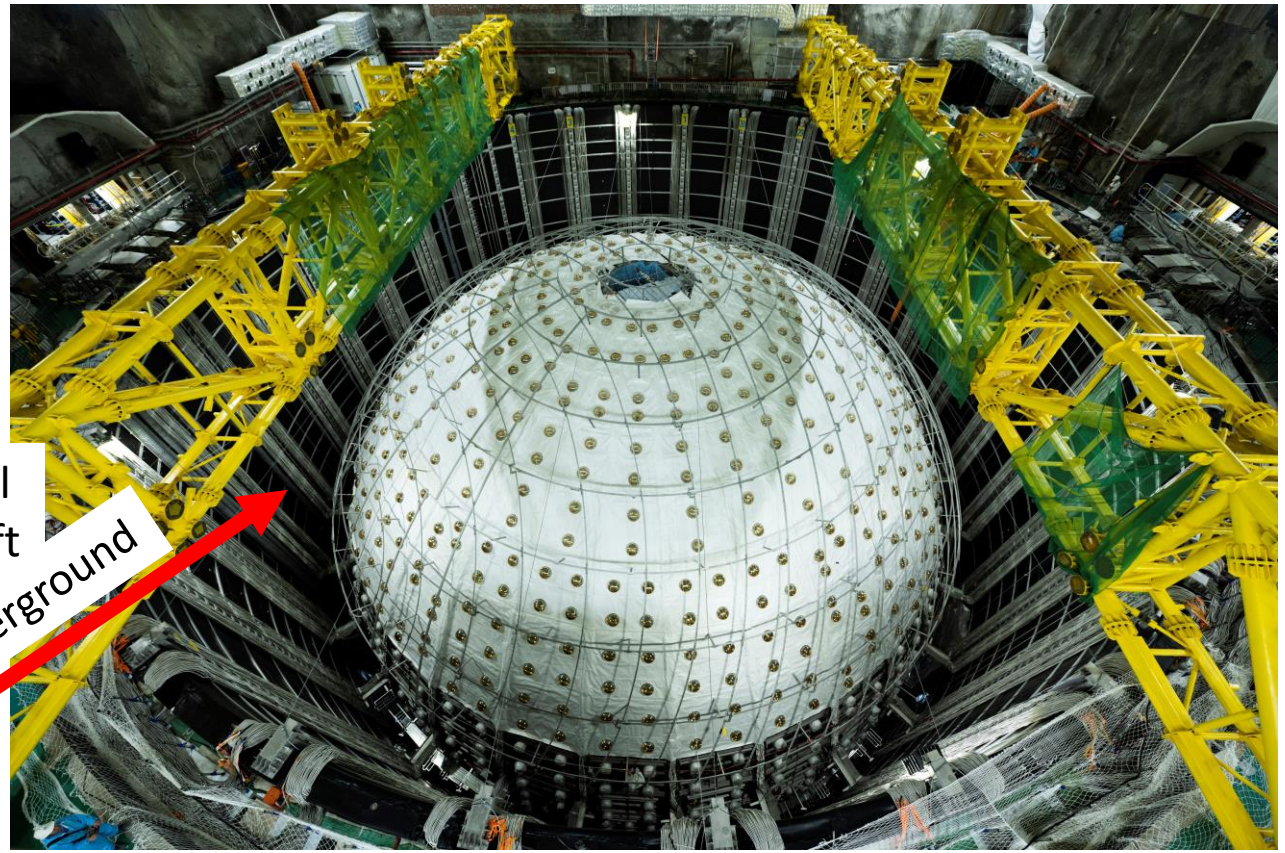
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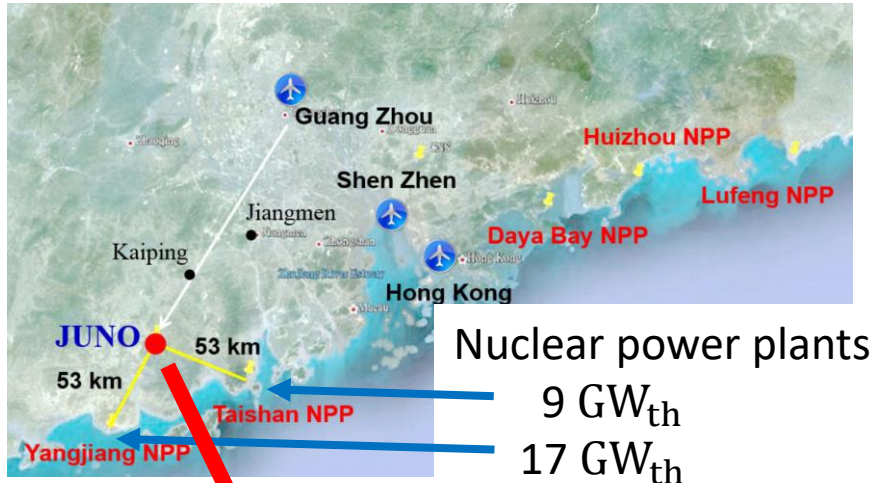



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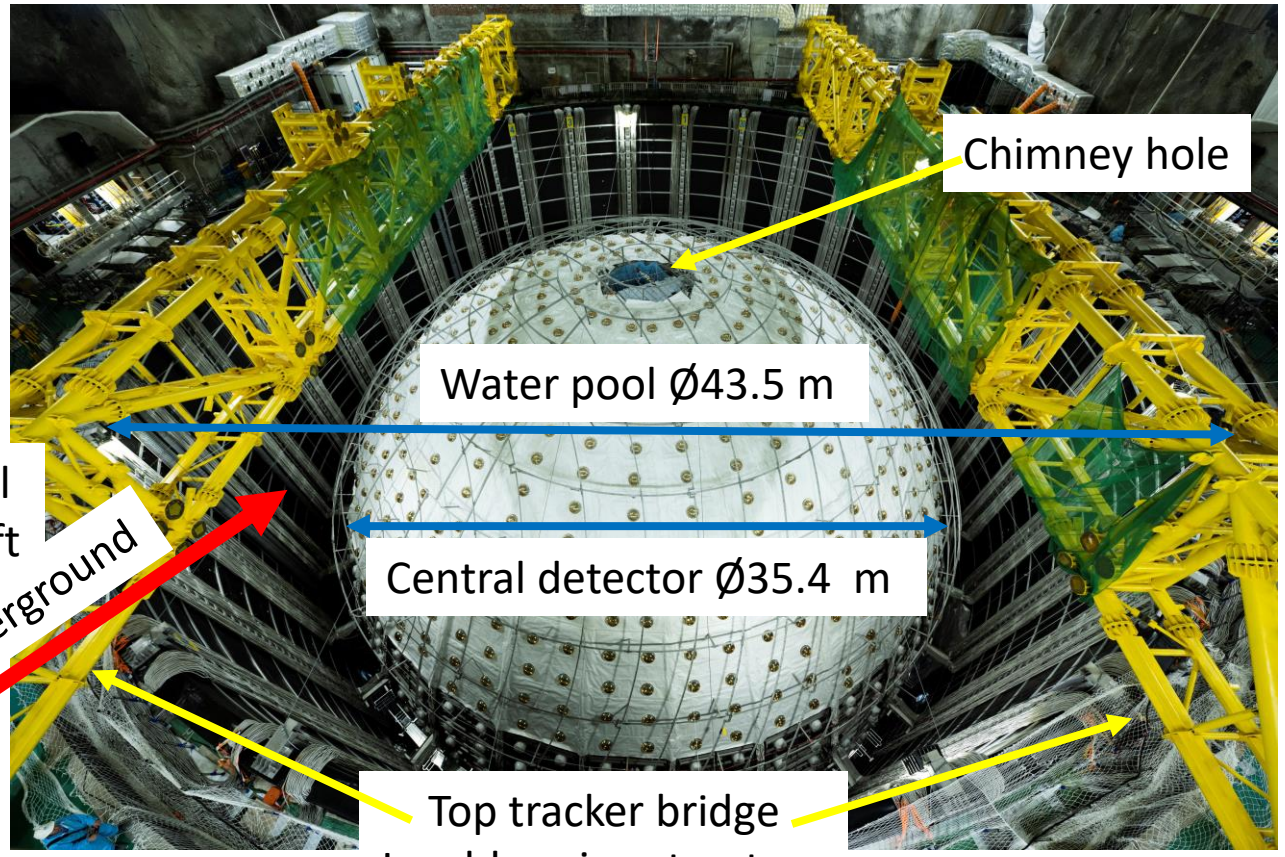

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9 $GW_{th}$
17 $GW_{th}$



JUNO site
52.5 km from NPP

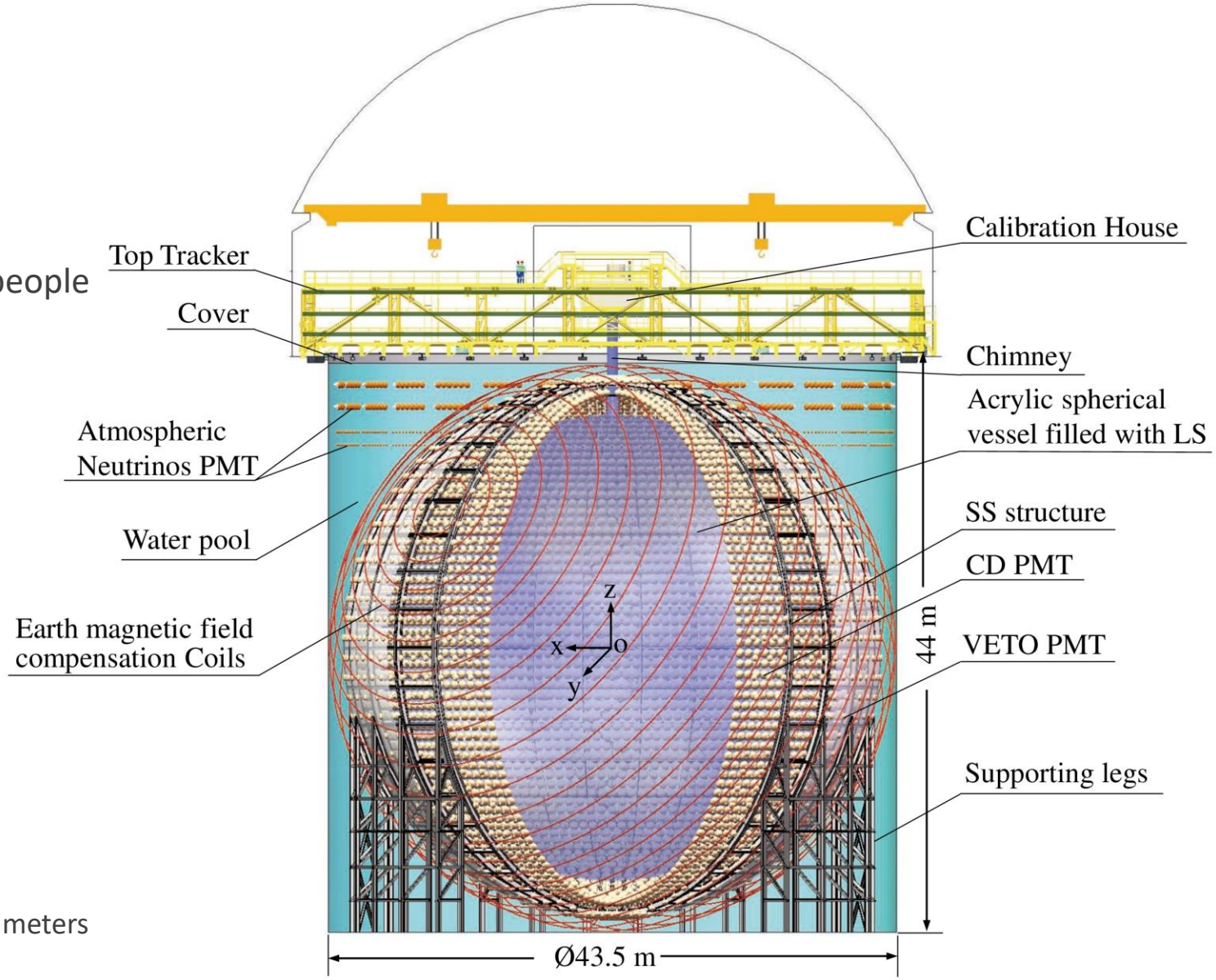
Slope tunnel
Vertical shaft

700 m underground



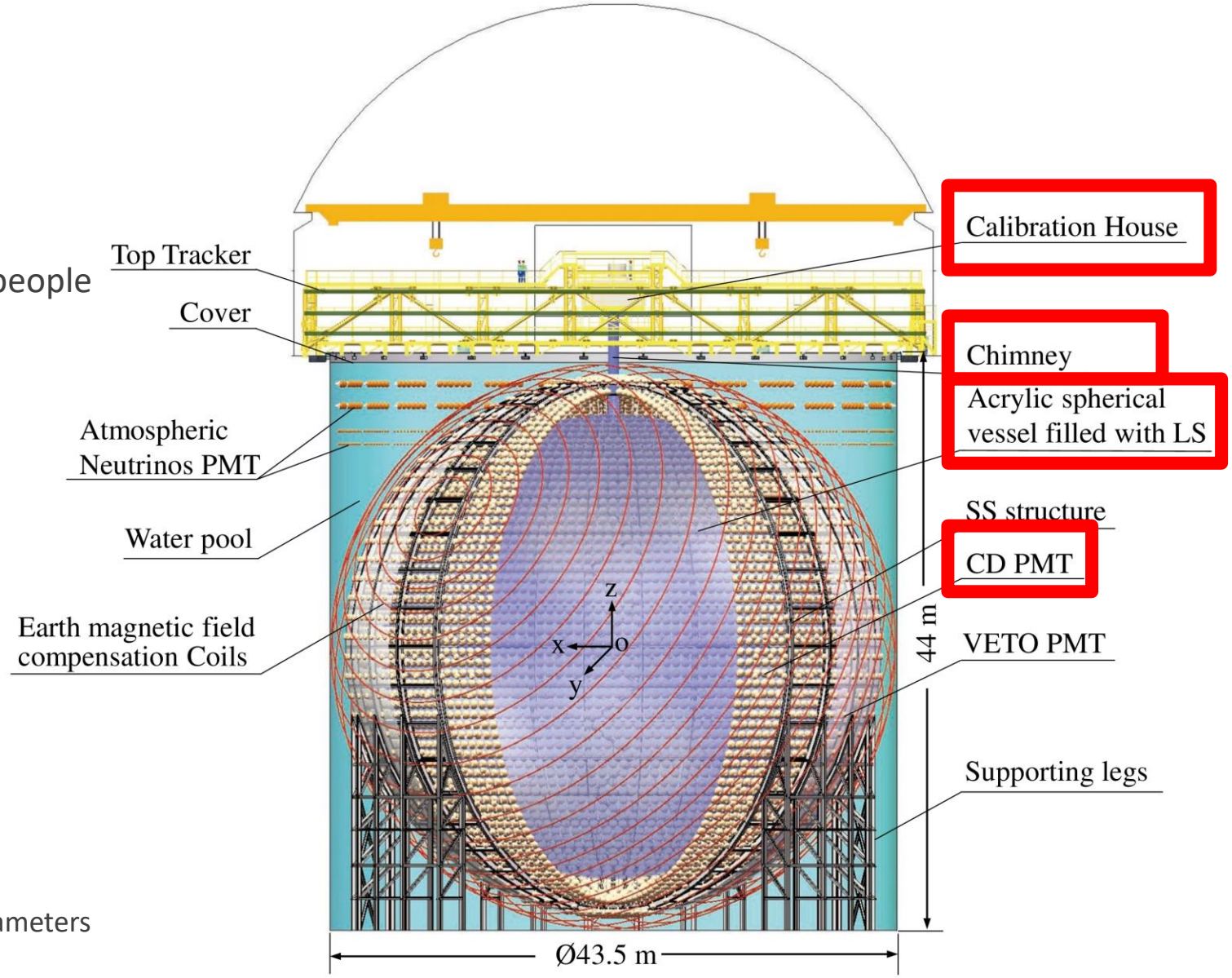
# JUNO

- Collaboration of ~70 institutions, ~700 people
- 700 m underground
- 35.4 m diameter of the acrylic sphere
- 20 kton liquid scintillator
- 17 596 20-inch PMTs
- 25 587 3-inch PMTs
- Veto and calibration systems
- 2 nuclear power plants 53 km away
  - Current overall thermal power 27 $GW_{th}$
- Other subsystems
  - JUNO Tao (near detector)
  - OSIRIS
- Example of its goals
  - Neutrino mass hierarchy
  - Precise measurement of the oscillation parameters



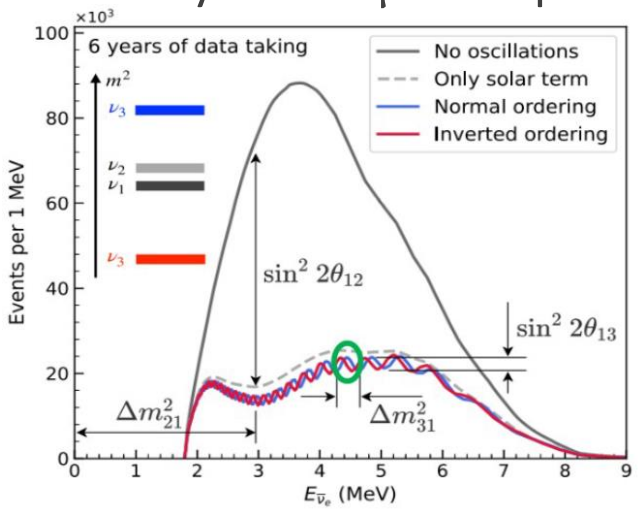
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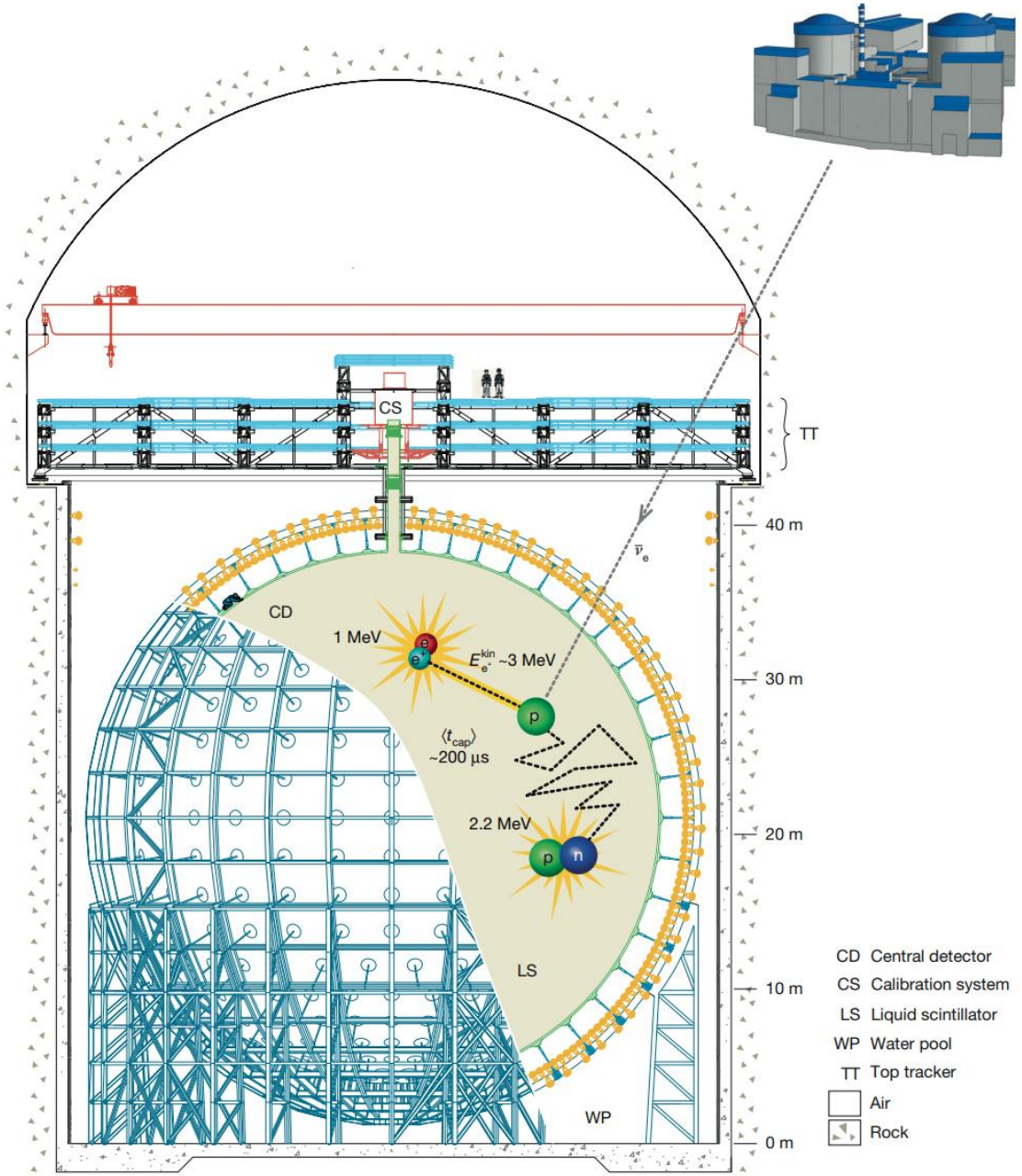
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# JUNO

- An antineutrino is caught by inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$
- The positron slows down and disperses its energy into the scintillator and annihilates with an electron
- The neutron with delay of 200 μs is captured by a proton



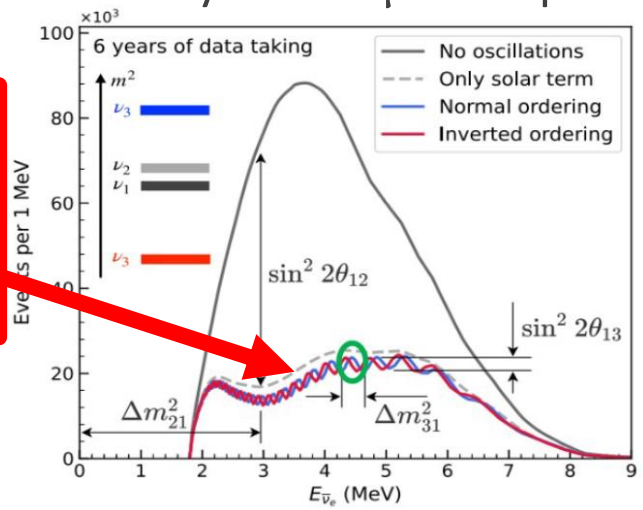



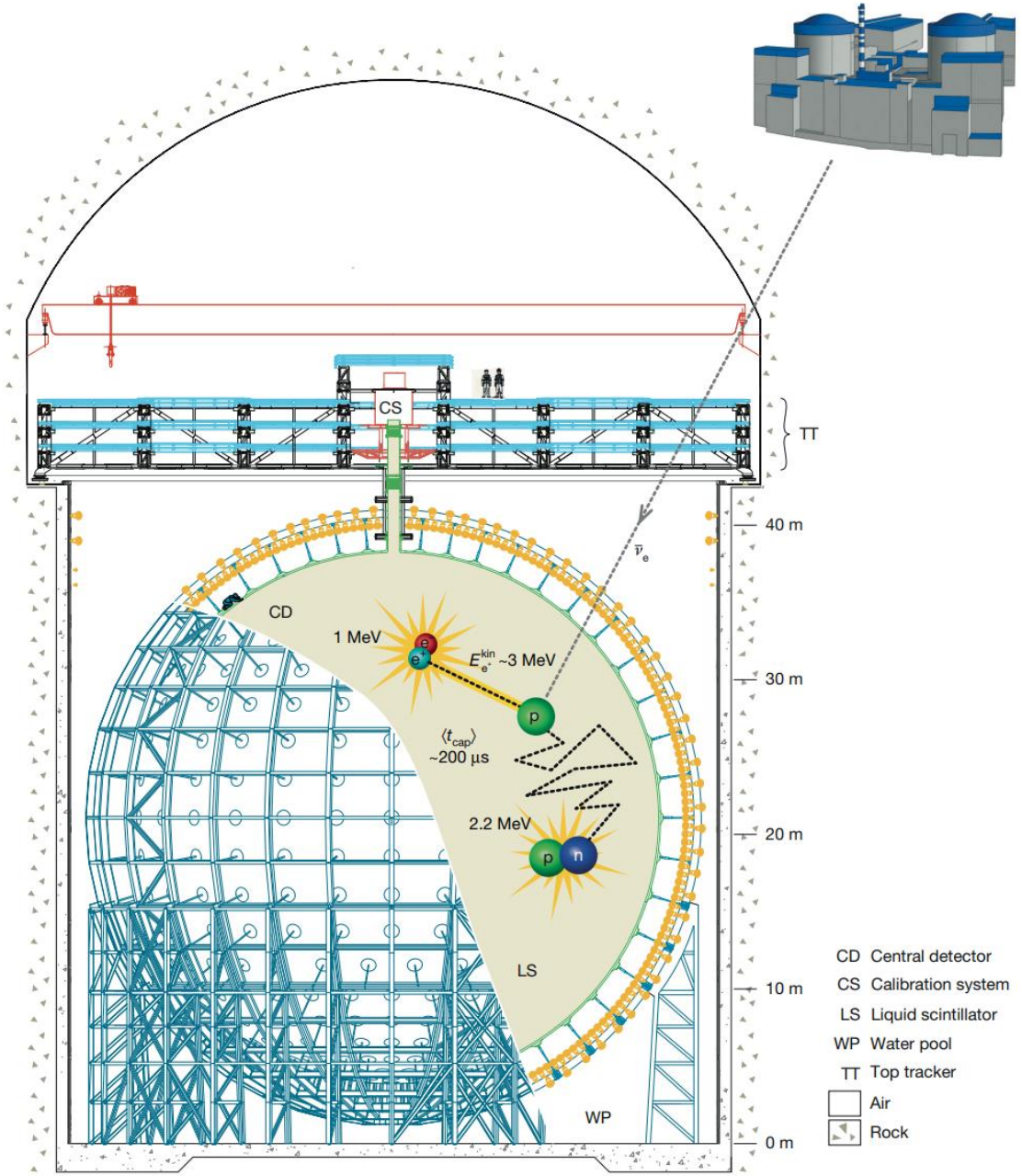
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We need a great energy resolution to distinguish between normal and inverted ordering

design: $\frac{3\%}{\sqrt{E[\mathrm{MeV}]}}$

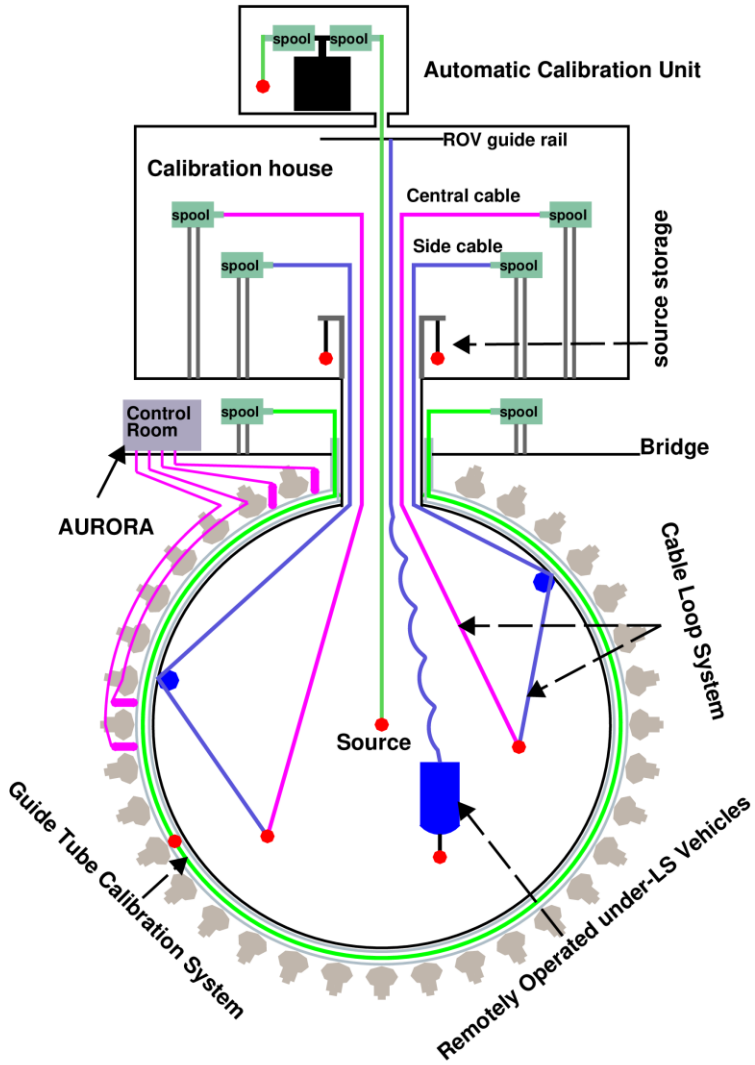


# Calibration

- 1D: $^{137}$Cs, $^{54}$Mn, $^{40}$K, $^{68}$Ge, $^{60}$Co, Am-C, Am-Be, sensors, laser
- 2D: Am-C, $^{68}$Ge, $^{137}$Cs
- 3D: cosmogenic background

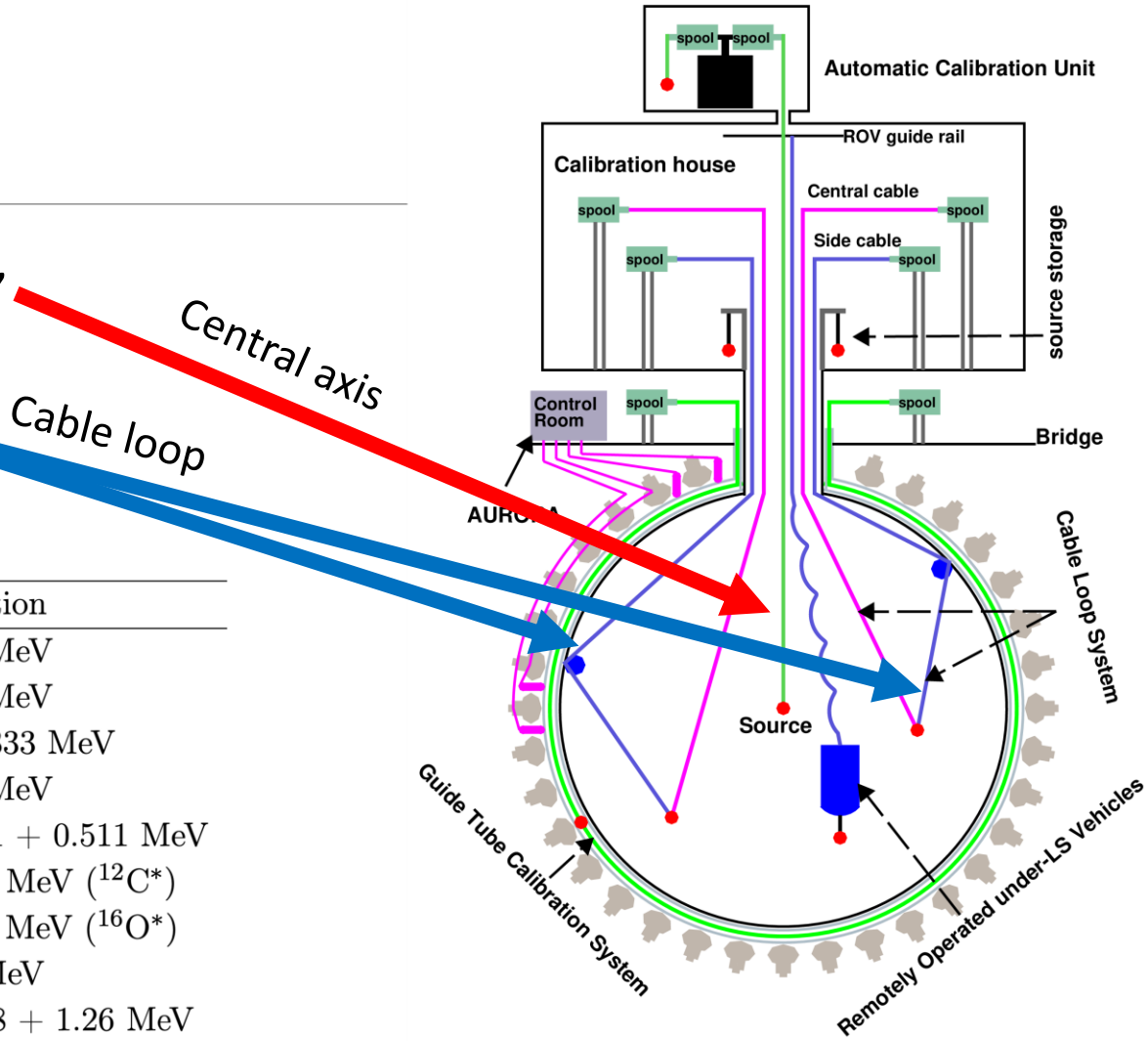
| Sources/Processes | Type | Radiation |
|---|---|---|
| $^{137}$Cs | $\gamma$ | 0.662 MeV |
| $^{54}$Mn | $\gamma$ | 0.835 MeV |
| $^{60}$Co | $\gamma$ | 1.173 + 1.333 MeV |
| $^{40}$K | $\gamma$ | 1.461 MeV |
| $^{68}$Ge | $e^+$ | annihilation 0.511 + 0.511 MeV |
| $^{241}$Am-Be | n, $\gamma$ | neutron + 4.43 MeV ($^{12}$C*) |
| $^{241}$Am-$^{13}$C | n, $\gamma$ | neutron + 6.13 MeV ($^{16}$O*) |
| (n,$\gamma$)p | $\gamma$ | 2.22 MeV |
| (n,$\gamma$)$^{12}$C | $\gamma$ | 4.94 MeV or 3.68 + 1.26 MeV |



# Calibration

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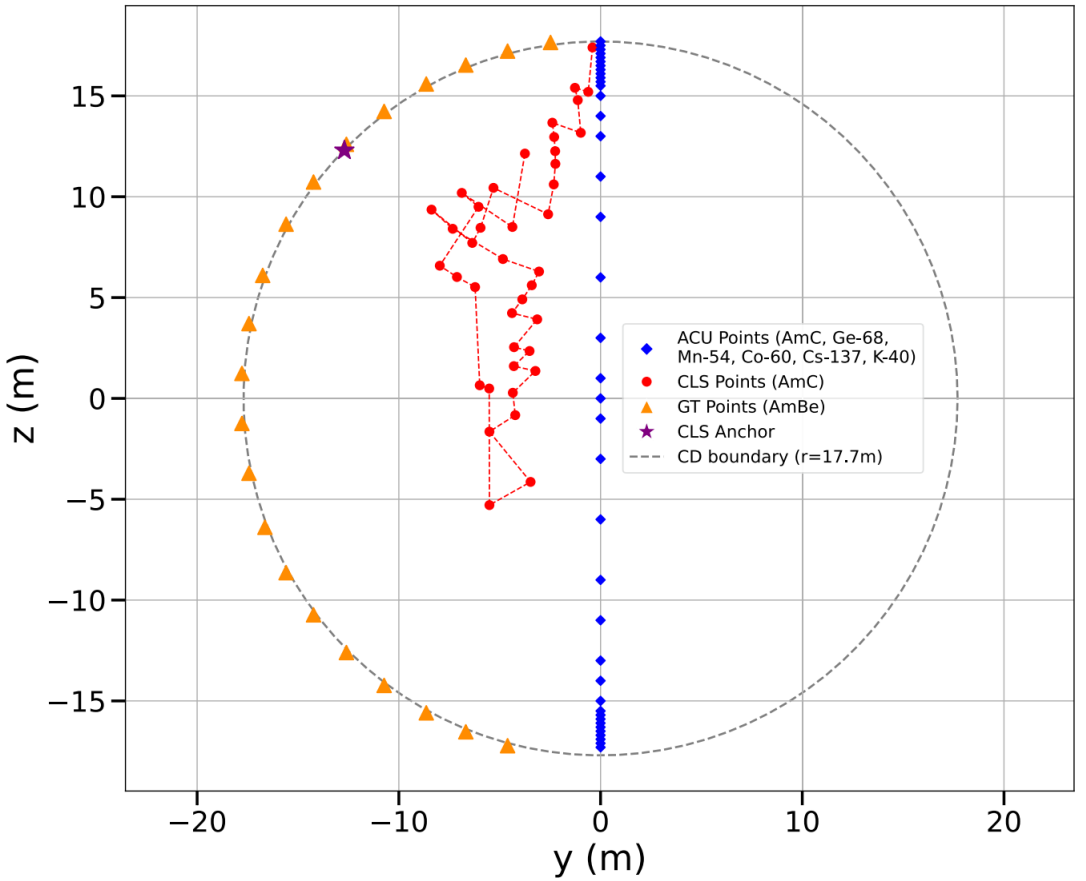
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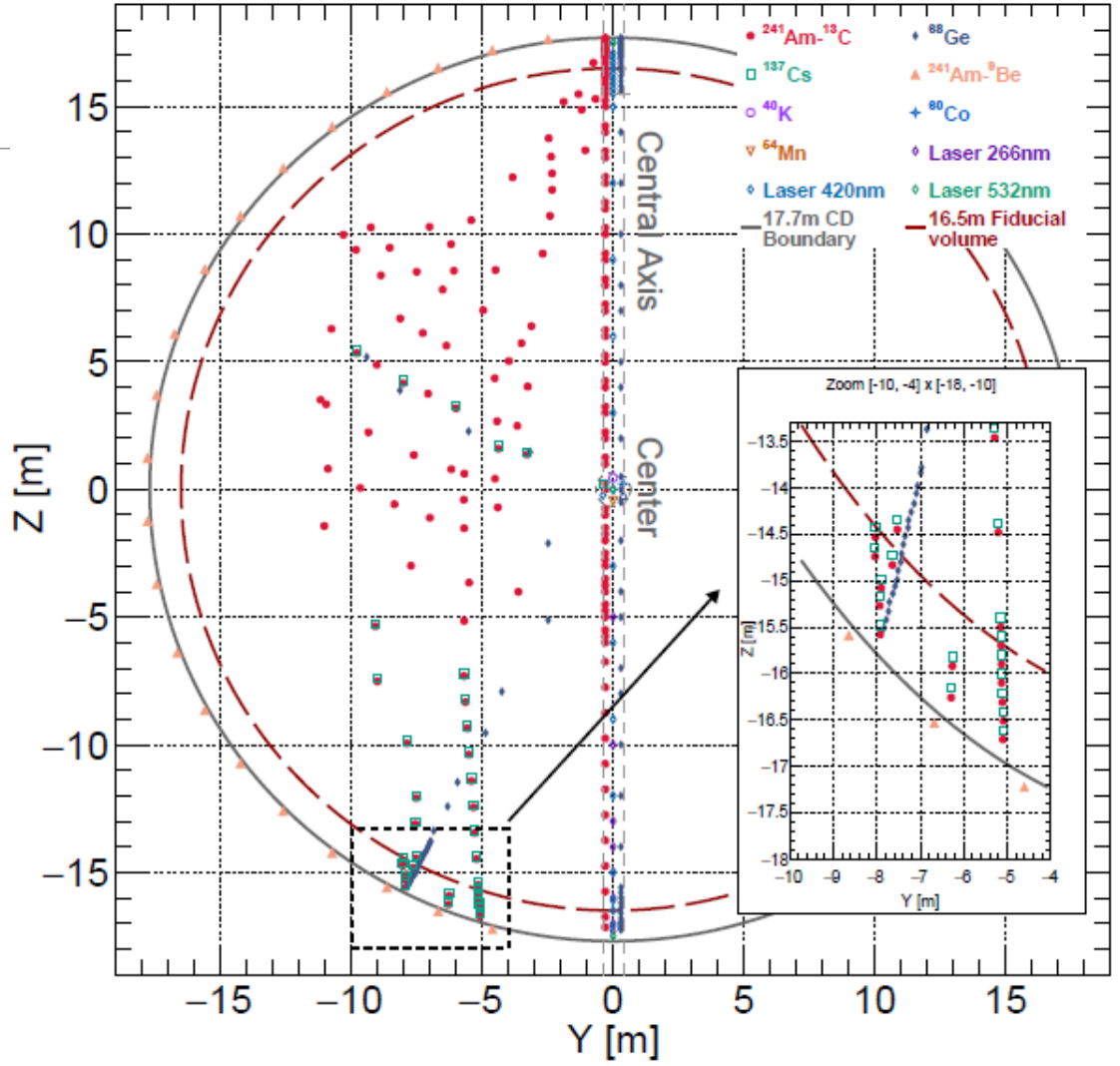



Chinese Phys. C 50 (2026)

# Calibration

- 1D: $^{137}$Cs, $^{54}$Mn, $^{40}$K, $^{68}$Ge, $^{60}$Co, Am-C, Am-Be, sensors, laser
- 2D: Am-C, $^{68}$Ge, $^{137}$Cs
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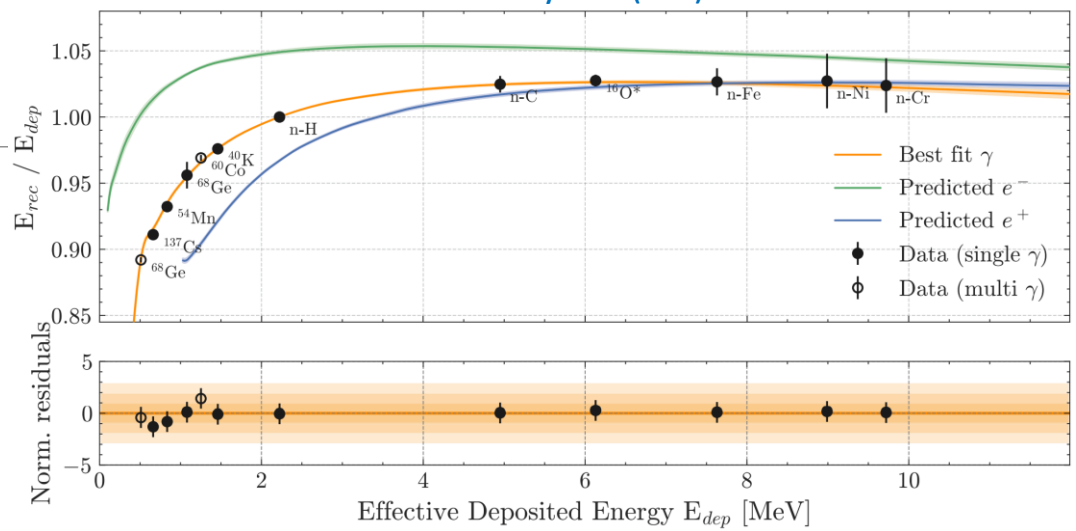
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# Energy nonlinearity

- Nonlinearity is particle dependent
- Main sources:
  - Birk's quenching
  - Cherenkov light
- Measured by calibration sources at the center

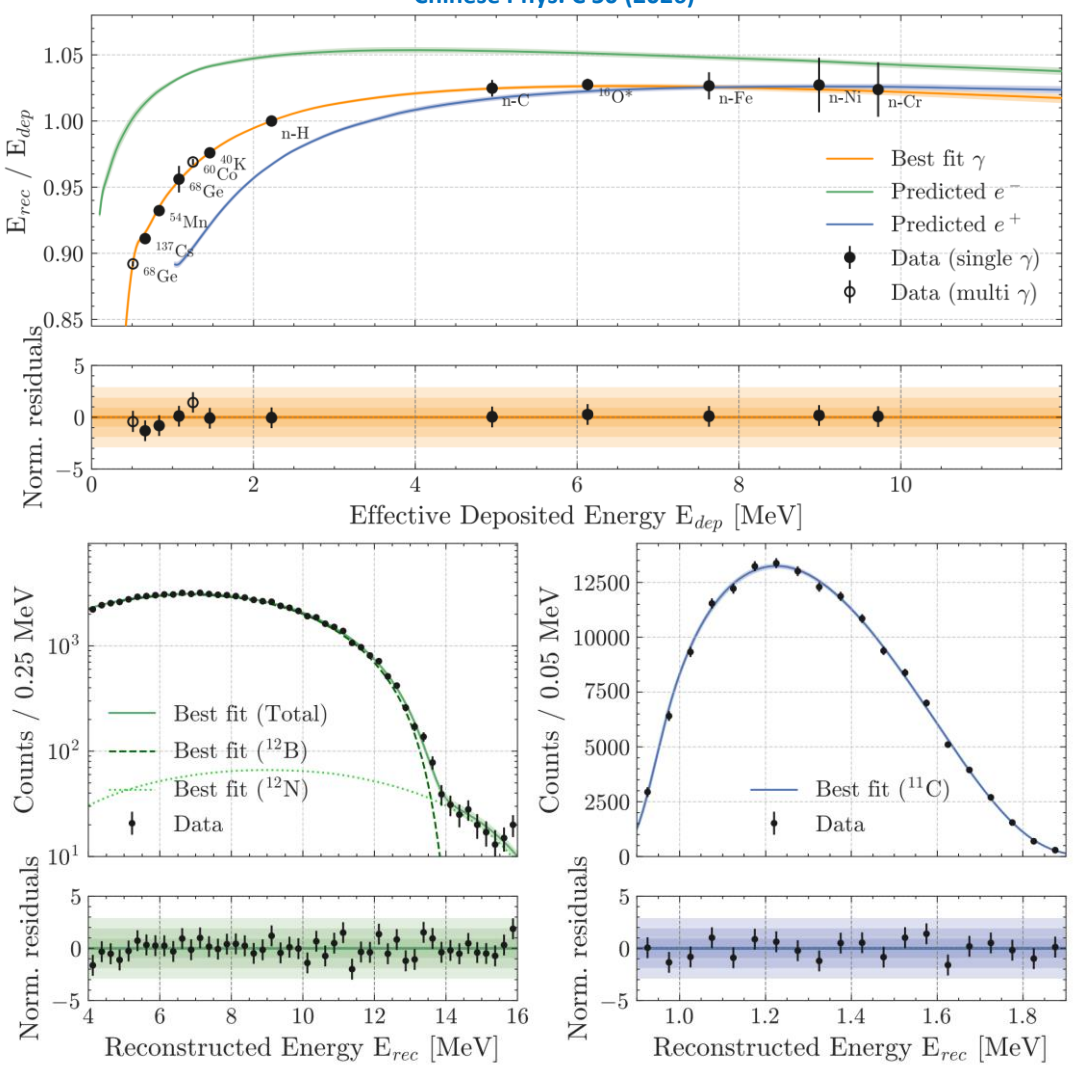
Chinese Phys. C 50 (2026)



# Energy nonlinearity

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- Measured by calibration sources at the center
- Constrained by cosmogenic isotopes

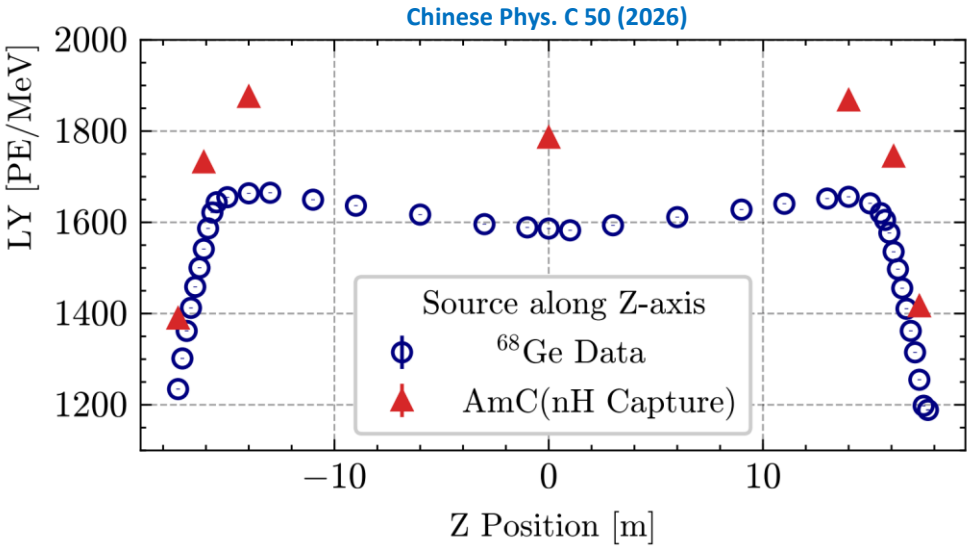
Chinese Phys. C 50 (2026)

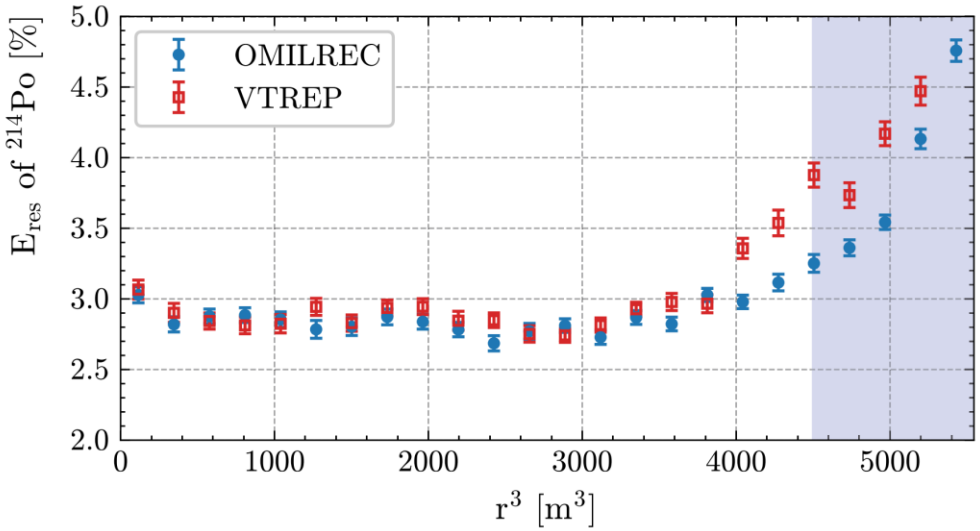


Signal nonuniformity
Preliminary

# Energy nonuniformity

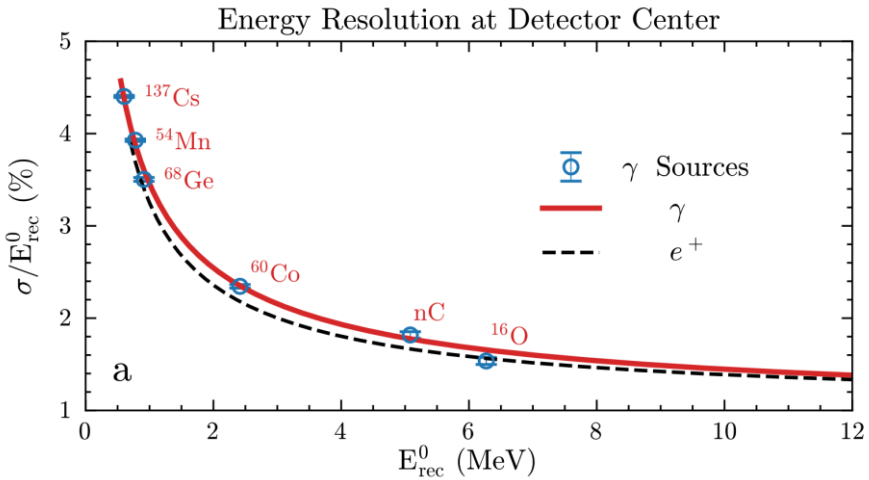
- The signal differs based on where it is created
- Light yield:
  - ~1600 PE/MeV for $^{68}$Ge
  - ~1785 PE/MeV for neutrons
- Energy resolution
  - ~3.5% for $^{68}$Ge $2 \times 0.511$ MeV at the center
  - ~2.9% for $^{214}$Po for $\alpha$ at 0.93 MeV

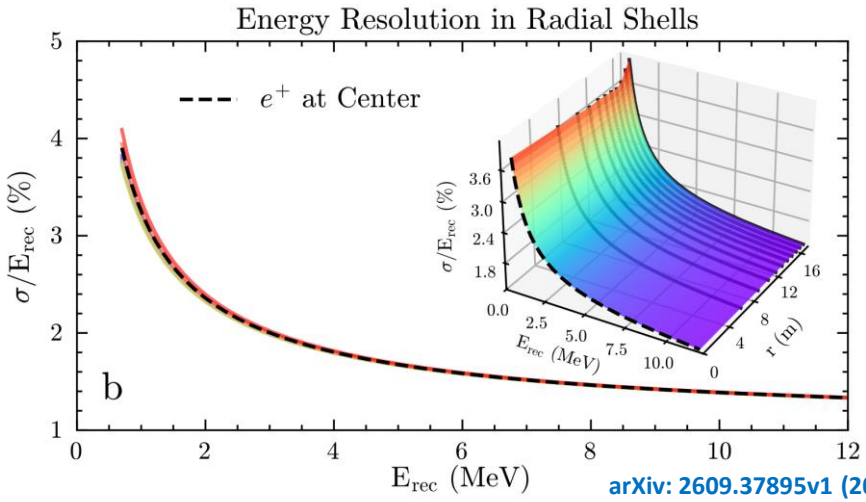


# Energy resolution model

- Energy resolution depends on
  - Particle type
  - Energy
  - Position
- R-dependent resolution model by using
  - $\alpha$ and $\gamma$ calibration sources
  - Geant4 simulation



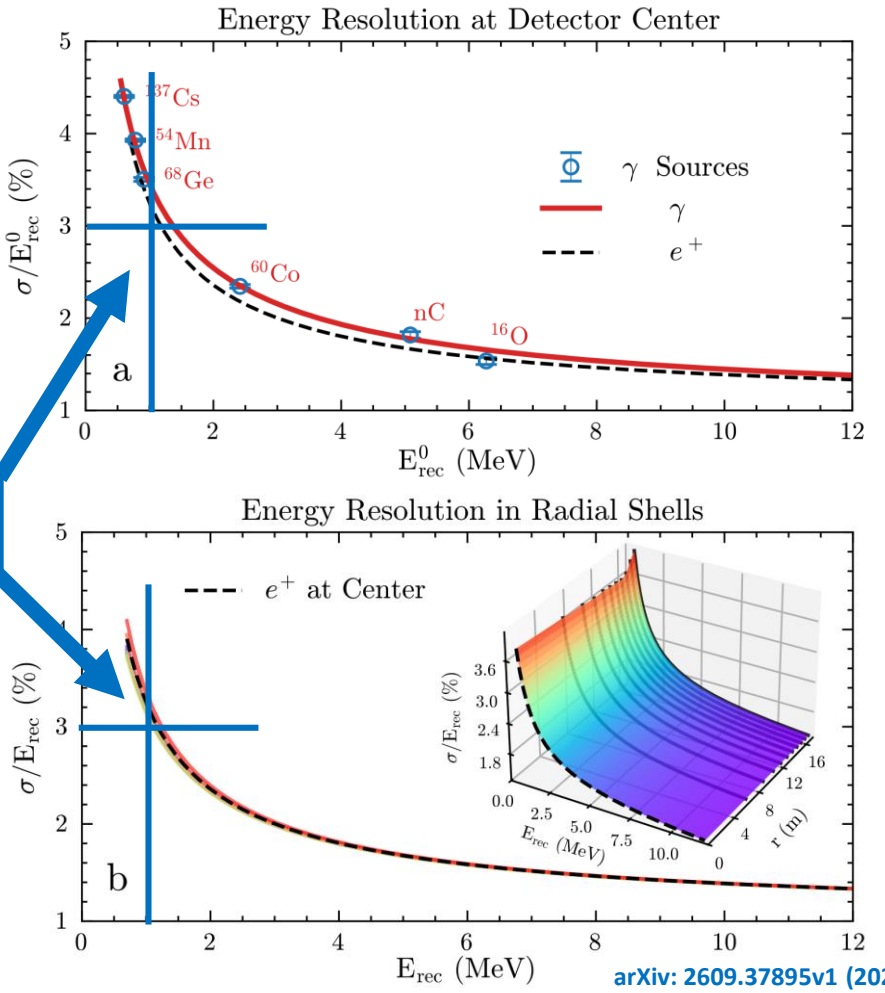




arXiv: 2609.37895v1 (2026)

# Energy resolution model

- Energy resolution depends on
  - Particle type
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- R-dependent resolution model by using
  - $\alpha$ and $\gamma$ calibration sources
  - Geant4 simulation
- We are close to the design (goal) energy resolution

design: $\frac{3\%}{\sqrt{E[\mathrm{MeV}]}}$

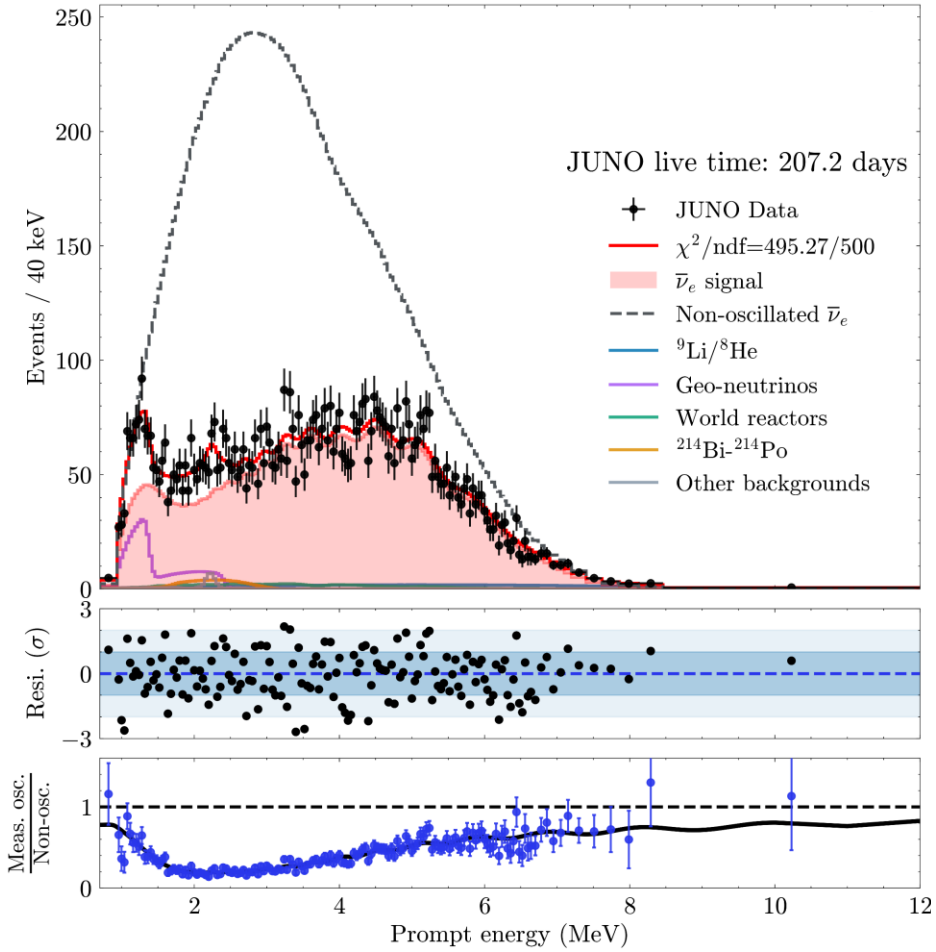



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# Are we able to observe $\Delta m^2_{3l}$ oscillations?

- Taking data since August 2025

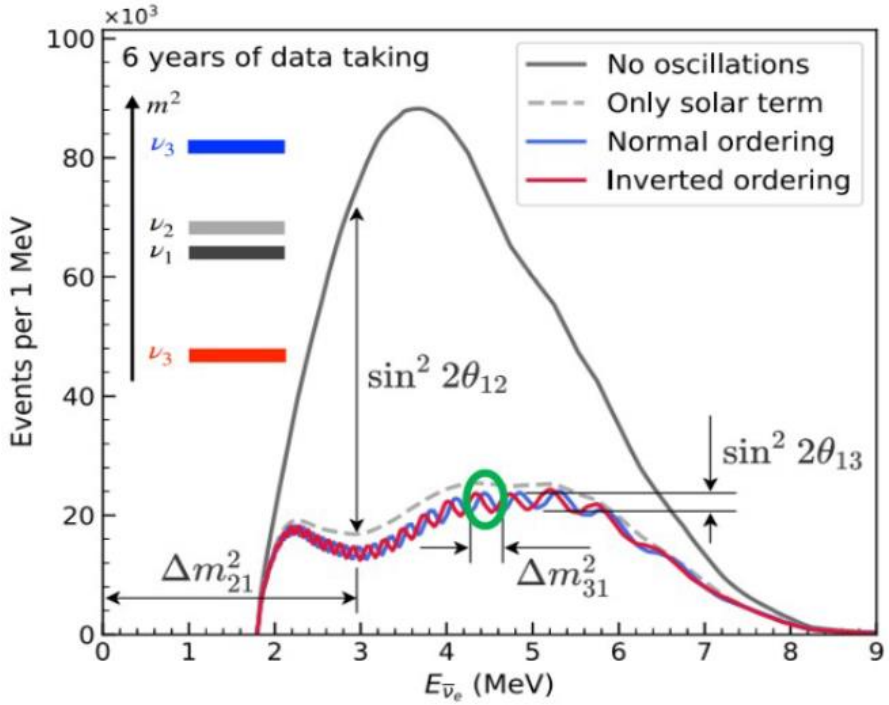
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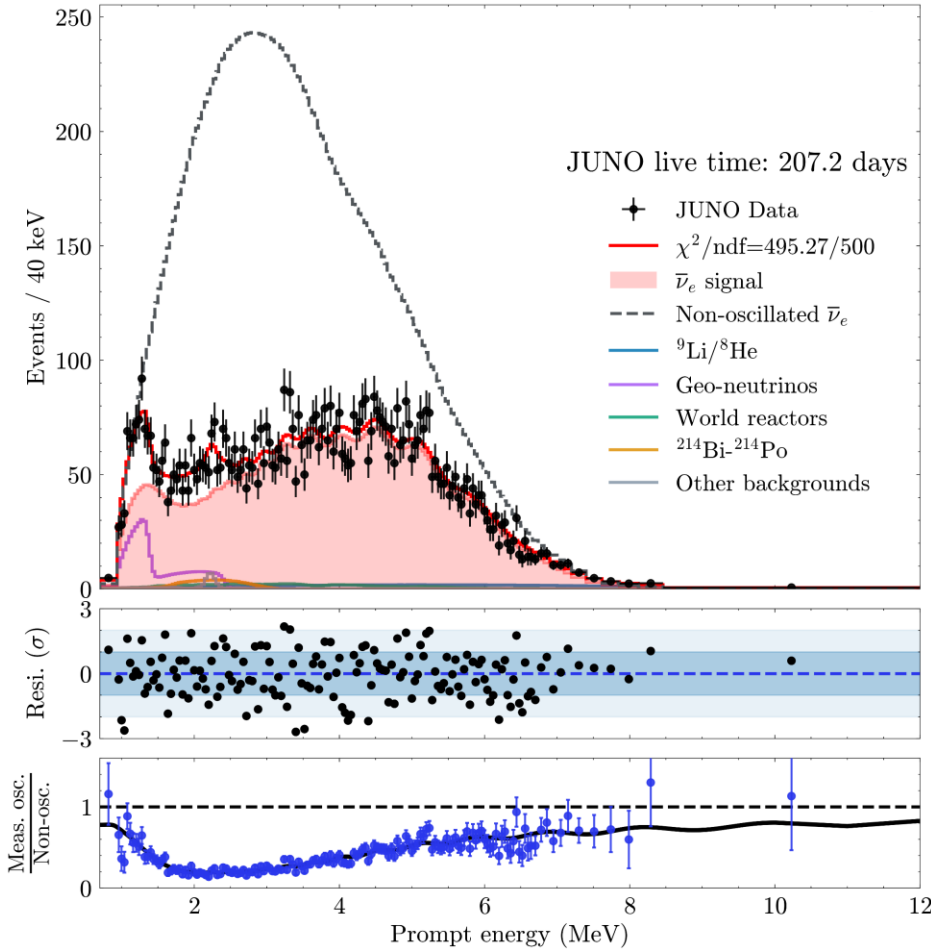

| Antineutrinos ($\overline{\nu}_e$) Candidates Summary | | |
|---|---|---|
| DAQ live time (days) | 207.2 | |
| $\overline{\nu}_e$ candidates | 8294 | |
| **Selection Efficiencies** (%) | $\varepsilon$ | $\sigma_{rel}$ |
| Fiducial volume | 87.12% | 0.96% |
| PMT flasher rejection | > 99.9% | Negligible |
| $\mu$ veto | 93.67% | 0.02% |
| Multiplicity cut | 95.94% | negligible |
| Prompt-delayed coinc. | 95.50% | 0.32% |
| Correlated discriminator | 98.99% | 0.15% |
| Total efficiency ($\varepsilon_{tot}$) | 74.01% | 1.02% |
| **$\overline{\nu}_e$ signal (cpd)** | | |
| w/o $\varepsilon_{tot}$ corrected | $36.02 \pm 0.62$ | |
| w/ $\varepsilon_{tot}$ corrected | $48.67 \pm 1.08$ | |
| **Backgrounds (cpd)** | Pre-fit | Best-fit |
| $^9$Li/$^8$He | $1.05 \pm 0.27$ | $1.41 \pm 0.26$ |
| Geoneutrinos | Free | 2.12 |
| World reactors | $0.92 \pm 0.09$ | $0.92 \pm 0.09$ |
| $^{214}$Bi-$^{214}$Po | $0.42 \pm 0.31$ | $0.57 \pm 0.34$ |
| $^{13}$C($\alpha$, n)$^{16}$O | $0.05 \pm 0.02$ | $0.05 \pm 0.02$ |
| Fast neutrons | $0.02 \pm 0.02$ | $0.02 \pm 0.02$ |
| Double neutrons | $0.10 \pm 0.10$ | $0.13 \pm 0.10$ |
| Atmospheric neutrinos | $0.09 \pm 0.04$ | $0.11 \pm 0.05$ |
| Accidentals | $0.07 \pm 0.01$ | $0.07 \pm 0.01$ |

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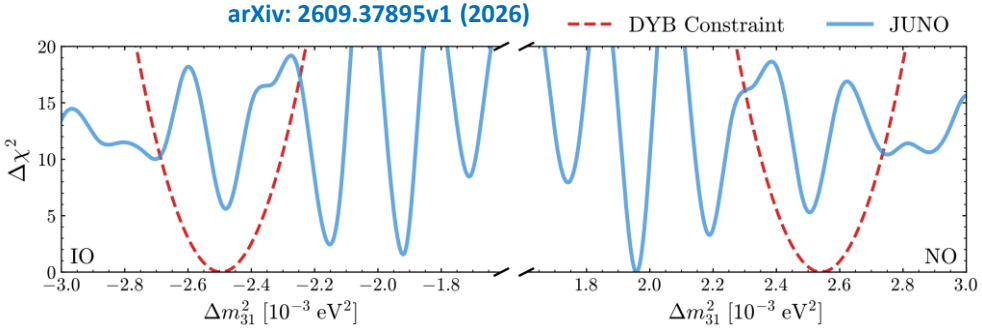



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| $\mu$ veto | 93.67% | 0.02% |
| Multiplicity cut | 95.94% | negligible |
| Prompt-delayed coinc. | 95.50% | 0.32% |
| Correlated discriminator | 98.99% | 0.15% |
| Total efficiency ($\varepsilon_{tot}$) | 74.01% | 1.02% |
| **$\bar{\nu}_e$ signal (cpd)** | | |
| w/o $\varepsilon_{tot}$ corrected | $36.02 \pm 0.62$ | |
| w/ $\varepsilon_{tot}$ corrected | $48.67 \pm 1.08$ | |
| **Backgrounds (cpd)** | Pre-fit | Best-fit |
| $^9$Li/$^8$He | $1.05 \pm 0.27$ | $1.41 \pm 0.26$ |
| Geoneutrinos | Free | 2.12 |
| World reactors | $0.92 \pm 0.09$ | $0.92 \pm 0.09$ |
| $^{214}$Bi-$^{214}$Po | $0.42 \pm 0.31$ | $0.57 \pm 0.34$ |
| $^{13}$C($\alpha$, n)$^{16}$O | $0.05 \pm 0.02$ | $0.05 \pm 0.02$ |
| Fast neutrons | $0.02 \pm 0.02$ | $0.02 \pm 0.02$ |
| Double neutrons | $0.10 \pm 0.10$ | $0.13 \pm 0.10$ |
| Atmospheric neutrinos | $0.09 \pm 0.04$ | $0.11 \pm 0.05$ |
| Accidentals | $0.07 \pm 0.01$ | $0.07 \pm 0.01$ |

# Are we able to observe $\Delta m^2_{3l}$ oscillations?

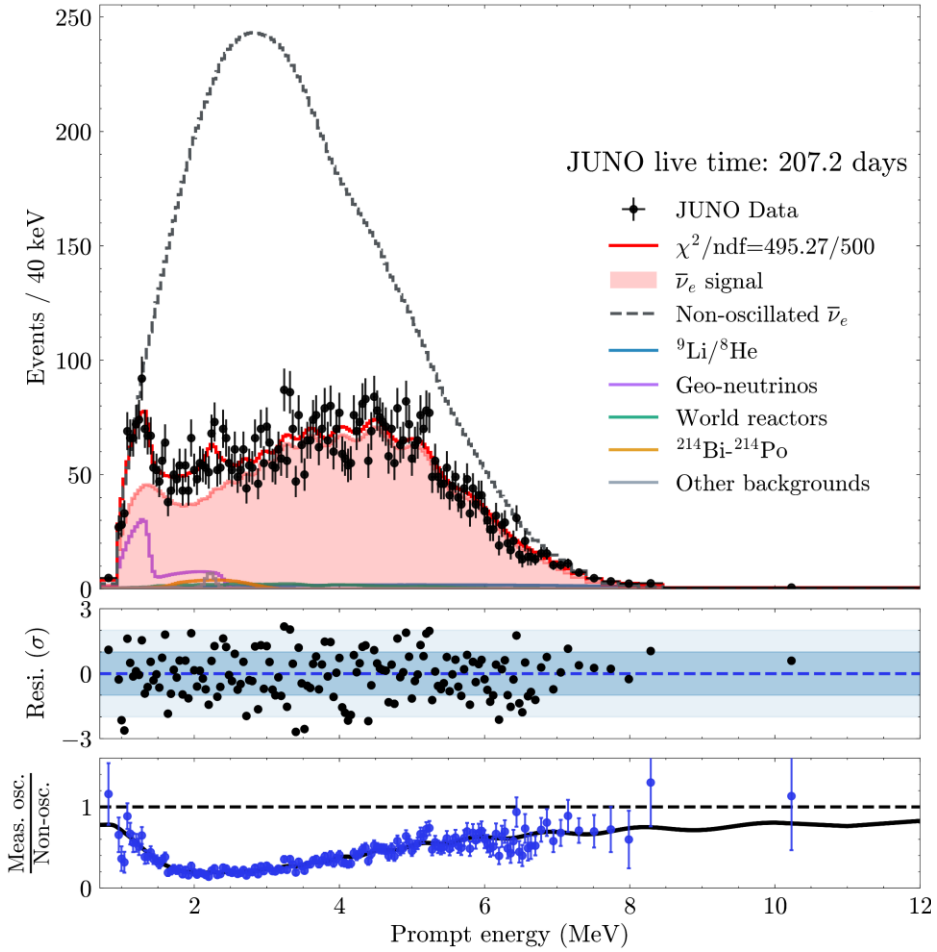
- Taking data since August 2025
- We observe effects of the $\Delta m^2_{3l}$ oscillations.

arXiv: 2609.37895v1 (2026)




$\chi^2$ analysis of the $\Delta m^2_{31}$

arXiv: 2609.37895v1 (2026)




| Antineutrinos ($\overline{\nu}_e$) Candidates Summary | | |
|---|---|---|
| DAQ live time (days) | 207.2 | |
| $\overline{\nu}_e$ candidates | 8294 | |
| **Selection Efficiencies** (%) | $\varepsilon$ | $\sigma_{rel}$ |
| Fiducial volume | 87.12% | 0.96% |
| PMT flasher rejection | > 99.9% | Negligible |
| $\mu$ veto | 93.67% | 0.02% |
| Multiplicity cut | 95.94% | negligible |
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| Atmospheric neutrinos | $0.09 \pm 0.04$ | $0.11 \pm 0.05$ |
| Accidentals | $0.07 \pm 0.01$ | $0.07 \pm 0.01$ |

# Conclusion

- JUNO takes data since August 2025
- JUNO's resolution design (goal): $\frac{3\%}{\sqrt{E[\mathrm{MeV}]}}$
- Multiple ways of calibration
- Created nonlinearity and nonuniformity model
- Current energy resolution has not reached JUNO's design (goal) yet, but it is close.
- We observe effects of the $\Delta m^2_{3l}$ oscillations.

