Parametrisation of Neutrino Mixing

U is a unitary matrix

$3 \times 3 = 9$ complex parameters

$\Downarrow$ unitary conditions

\+

arguments to rotate phase away

PMNS-Matrix (compare to CKM matrix)

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

4 Parameters (Dirac Neutrinos $\nu \neq \bar{\nu}$): 3 mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ ✓measured

1 phase δ (CP-violating) still unknown

2 neutrino mixing ↓ ( ) · ( ) · ( )

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric } \nu_\mu \text{ \& } \nu_\mu\text{-beams}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor } \bar{\nu}_e \text{, } \nu_\mu\text{-beams, maybe: atmospheric } \nu_\mu} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu_e \text{ \& reactor } \bar{\nu}_e} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{23} = \cos\theta_{23}$

$s_{23} = \sin\theta_{23}$

and so on

$\theta_{23} \approx 45°$

Parametrisation of Neutrino Mixing

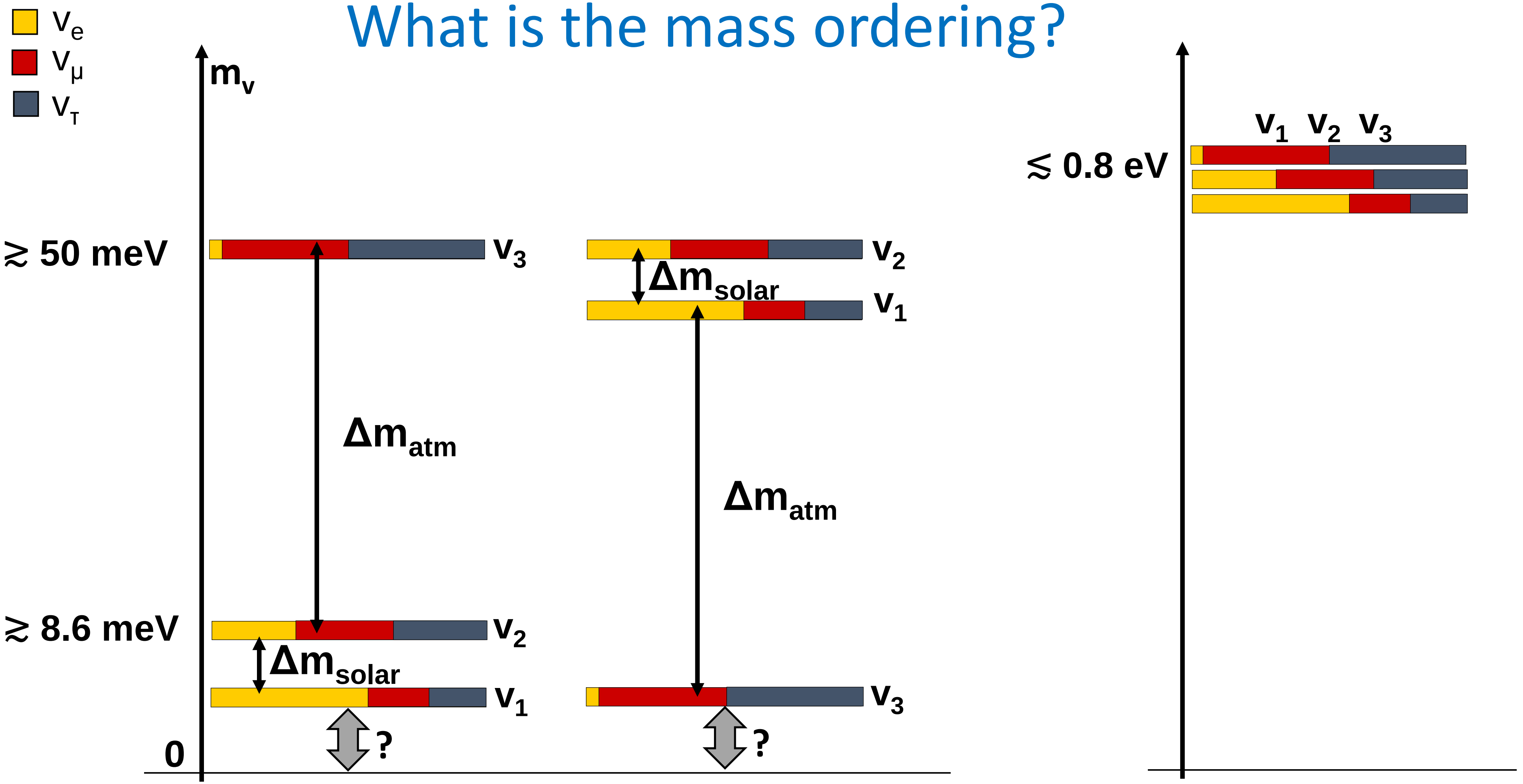
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\alpha_1} & s_{13}e^{-i\delta}e^{i\alpha_2} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & [c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & s_{23}c_{13}e^{i\alpha_2} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & [-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & c_{23}c_{13}e^{i\alpha_2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

c_{12} stands for $\cos\vartheta_{12}$, s_{12} stands for $\sin\vartheta_{12}$ etc.,
δ is the Dirac CP-phase
and
only if neutrinos are Majorana particles:
two more CP-violating phases: $\alpha_{1,2}$ (Majorana CP-phases)

What we about neutrino masses:

$\Delta m^2_{solar} \approx 8 \cdot 10^{-5} eV^2, \quad \Delta m^2_{atm} \approx 2.5 \cdot 10^{-3} eV^2$

What is the mass ordering?

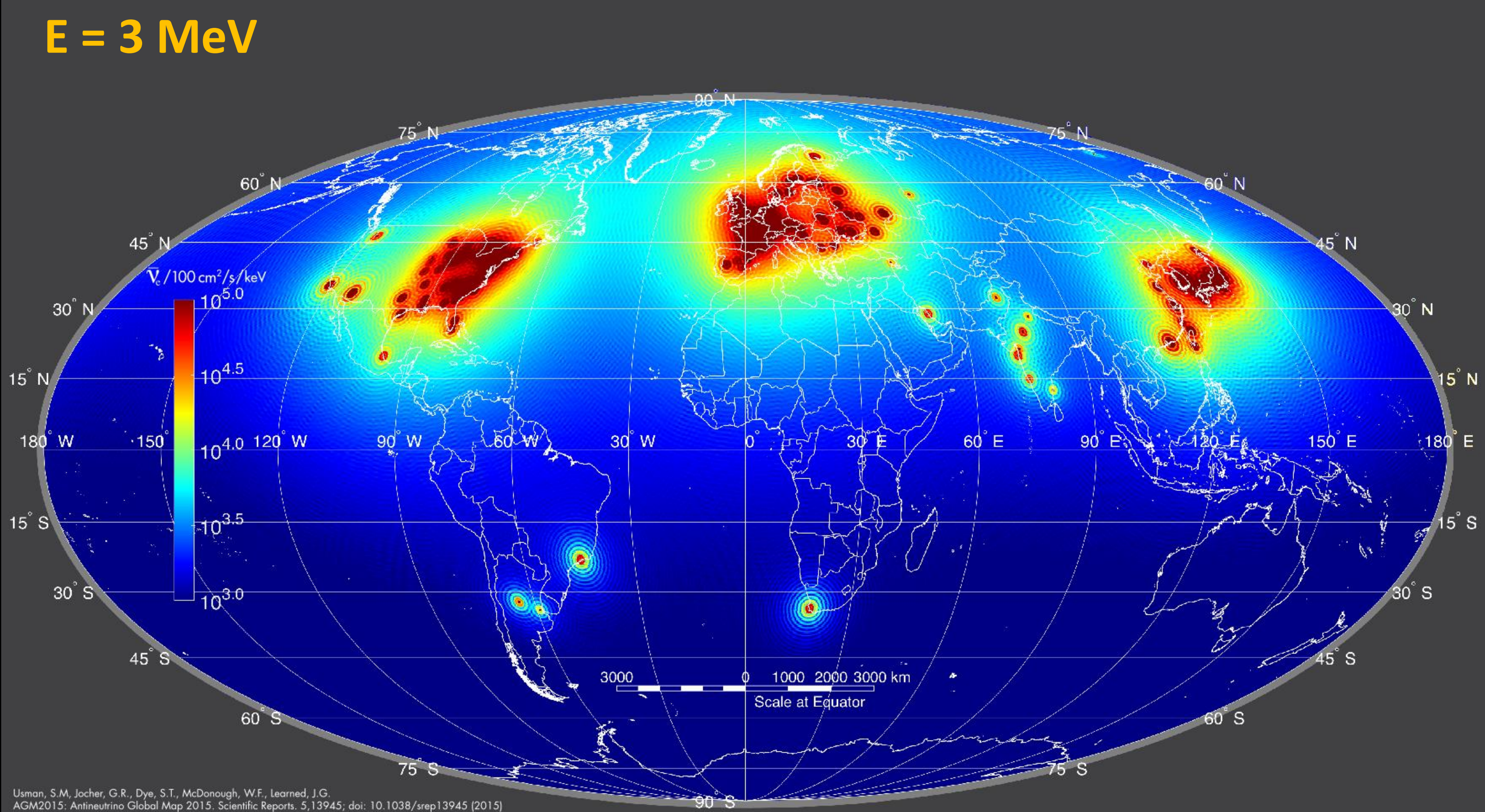


Normal mass ordering

Inverted mass ordering

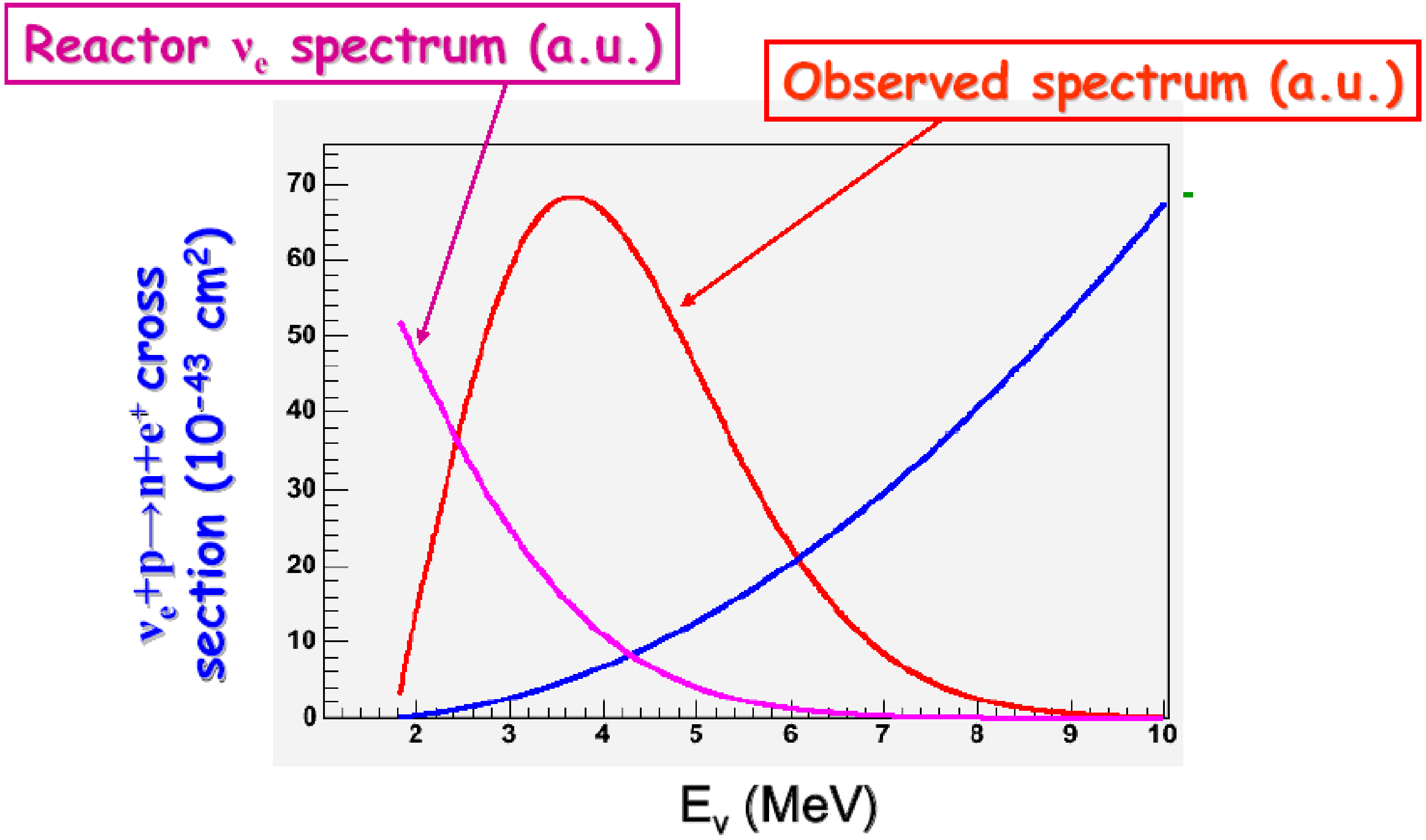
quasi - degenerated

$\bar{\nu}_e$- flux from nuclear reactors



Usman, S.M, Jocher, G.R., Dye, S.T., McDonough, W.F., Learned, J.G.
AGM2015: Antineutrino Global Map 2015. Scientific Reports. 5,13945; doi: 10.1038/srep13945 (2015)

Antineutrino Global Map 2015, Sci.Rep.5 (2015) 13945



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

prompt signal
$E_\nu - 0.77\,\mathrm{MeV}$

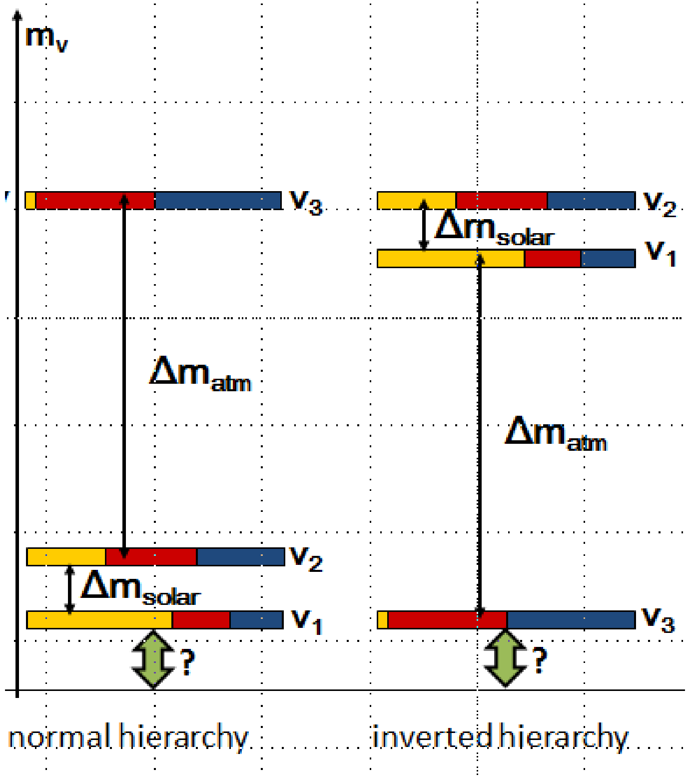
delayed signal

Determination of Mass Hierarchy in a Reactor Neutrino Experiment

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

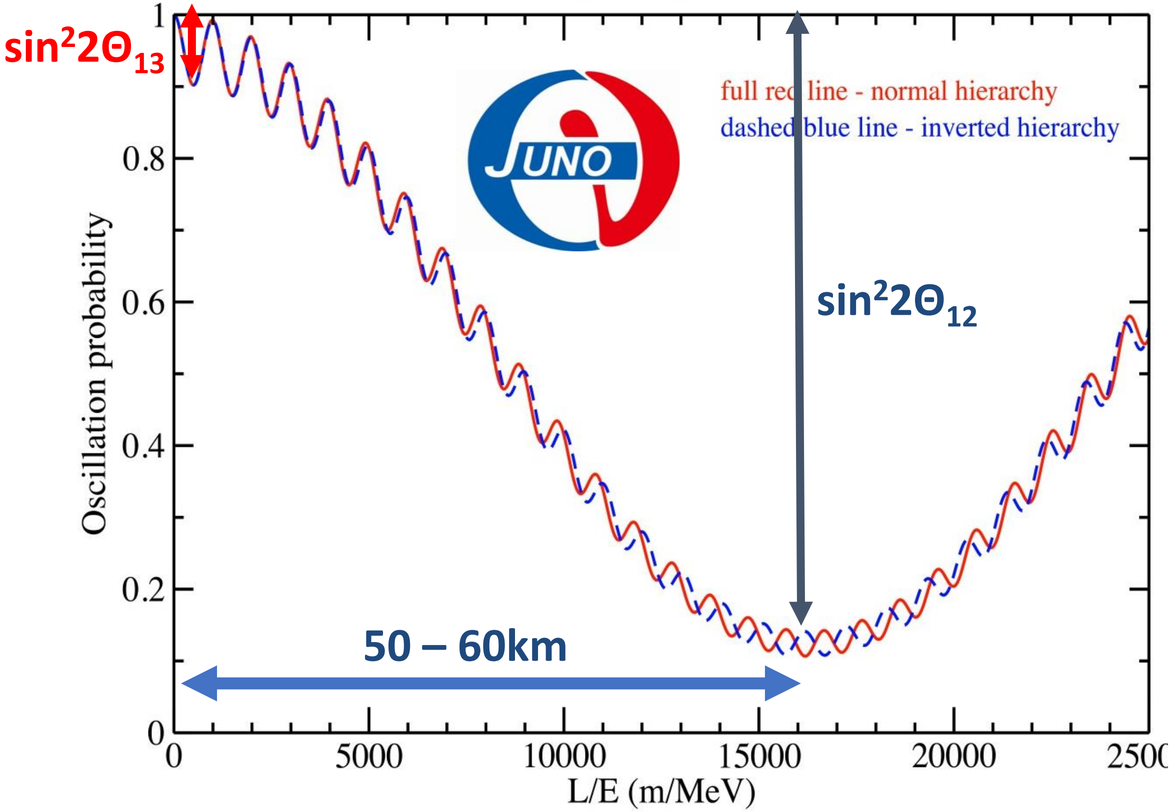
With $\Delta_{ij} = 1.27\ |\Delta m^2_{ji}\,(\mathrm{eV}^2)|\ L(\mathrm{m})/E(\mathrm{MeV})$

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}:\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}:\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

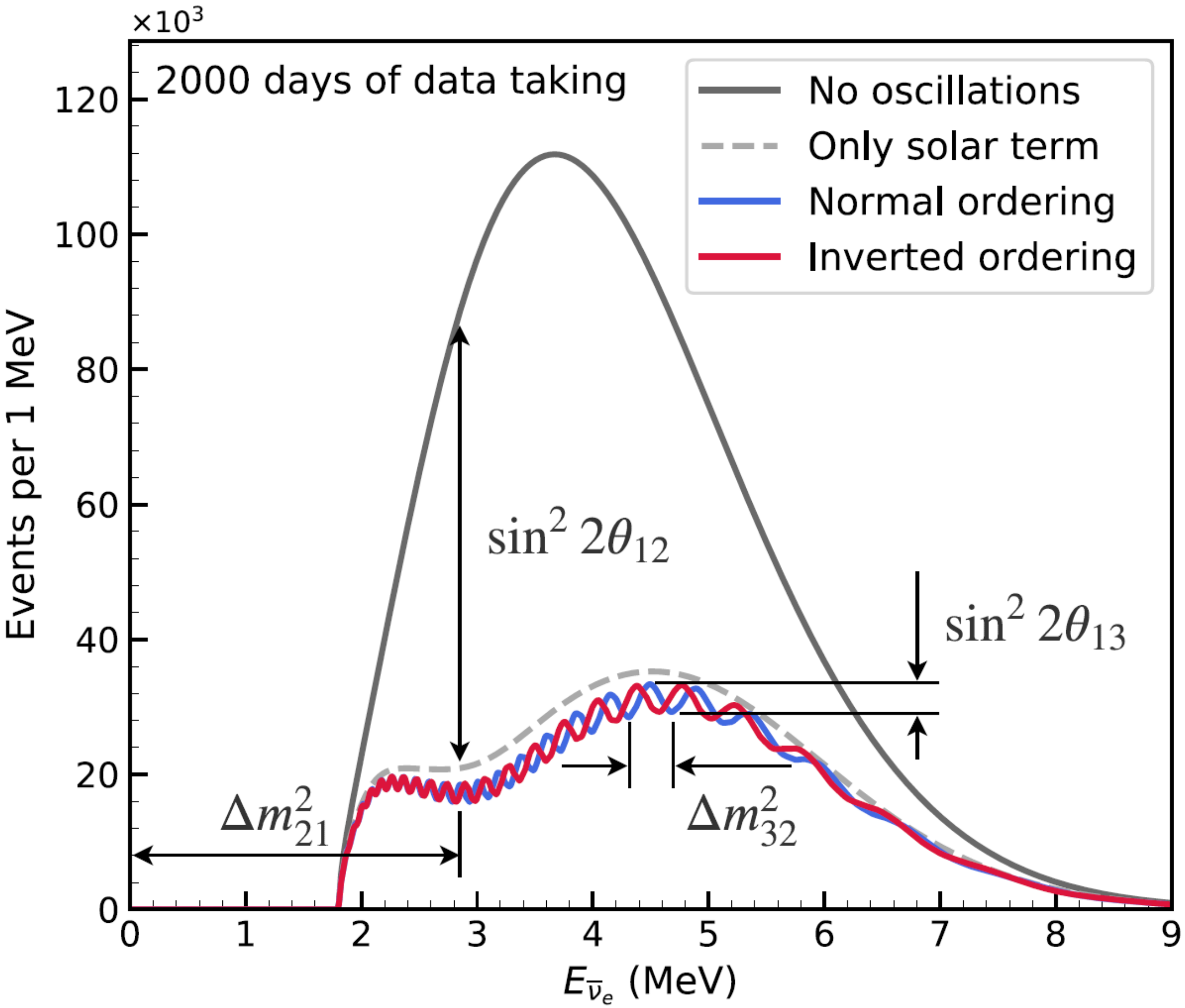


Vacuum oscillation probability $P(\nu_e \to \nu_e)$

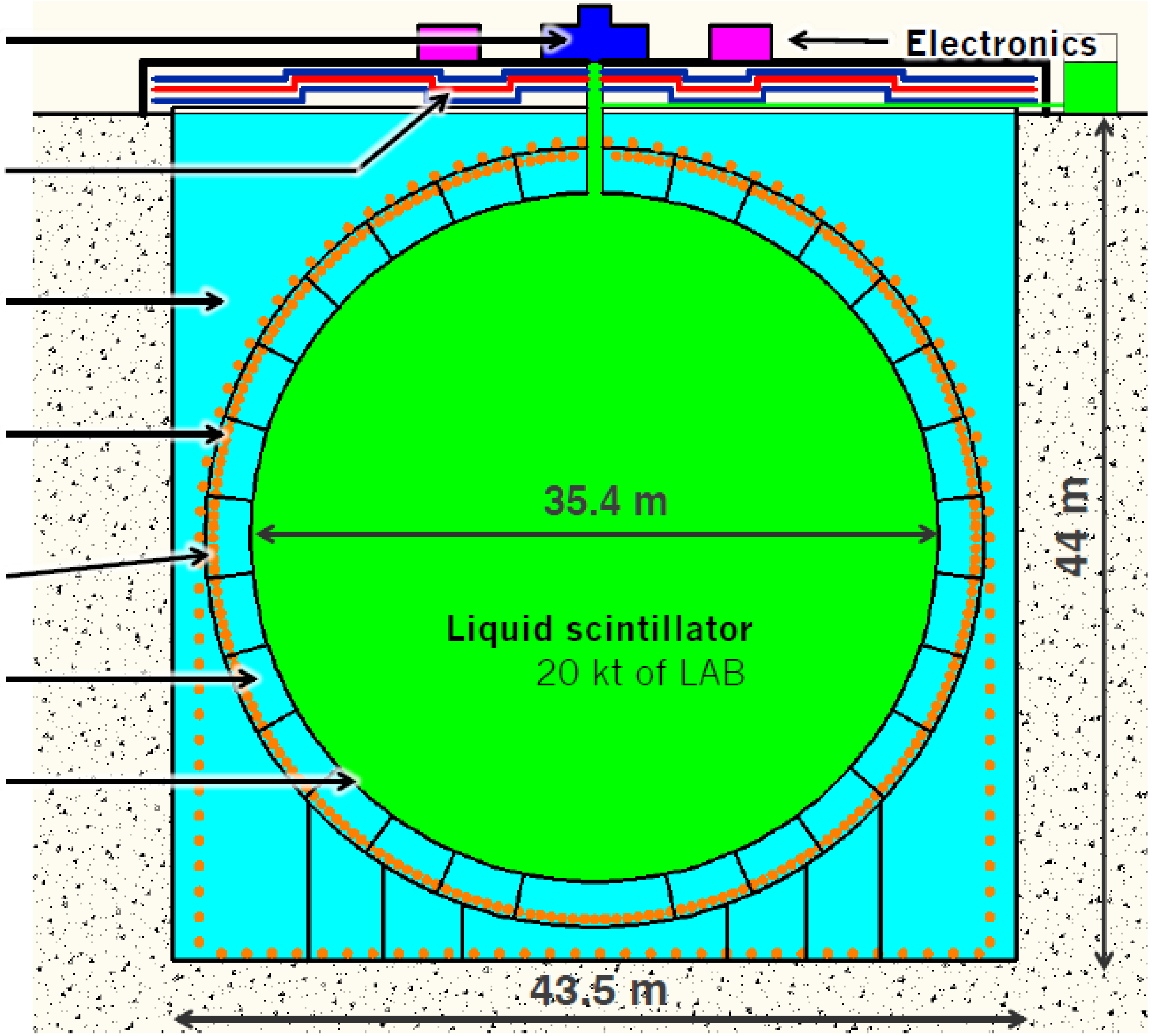
Here for $\Delta m^2_{31} + \Delta m^2_{32} = 2\mathrm{x}2.49\mathrm{x}10^{-3}\ \mathrm{eV}^2$



What we hope to observe in JUNO



JUNO: Detector Concept



Calibration

Top muon veto
Scintillator panels

Outer water tank
Muon Cherenkov veto

Steel support structure
optical separation

18,000 PMTs (20‘‘)
36,000 PMTs (3‘‘)

water buffer (2m)

Acrylic sphere
diameter: 35.4m

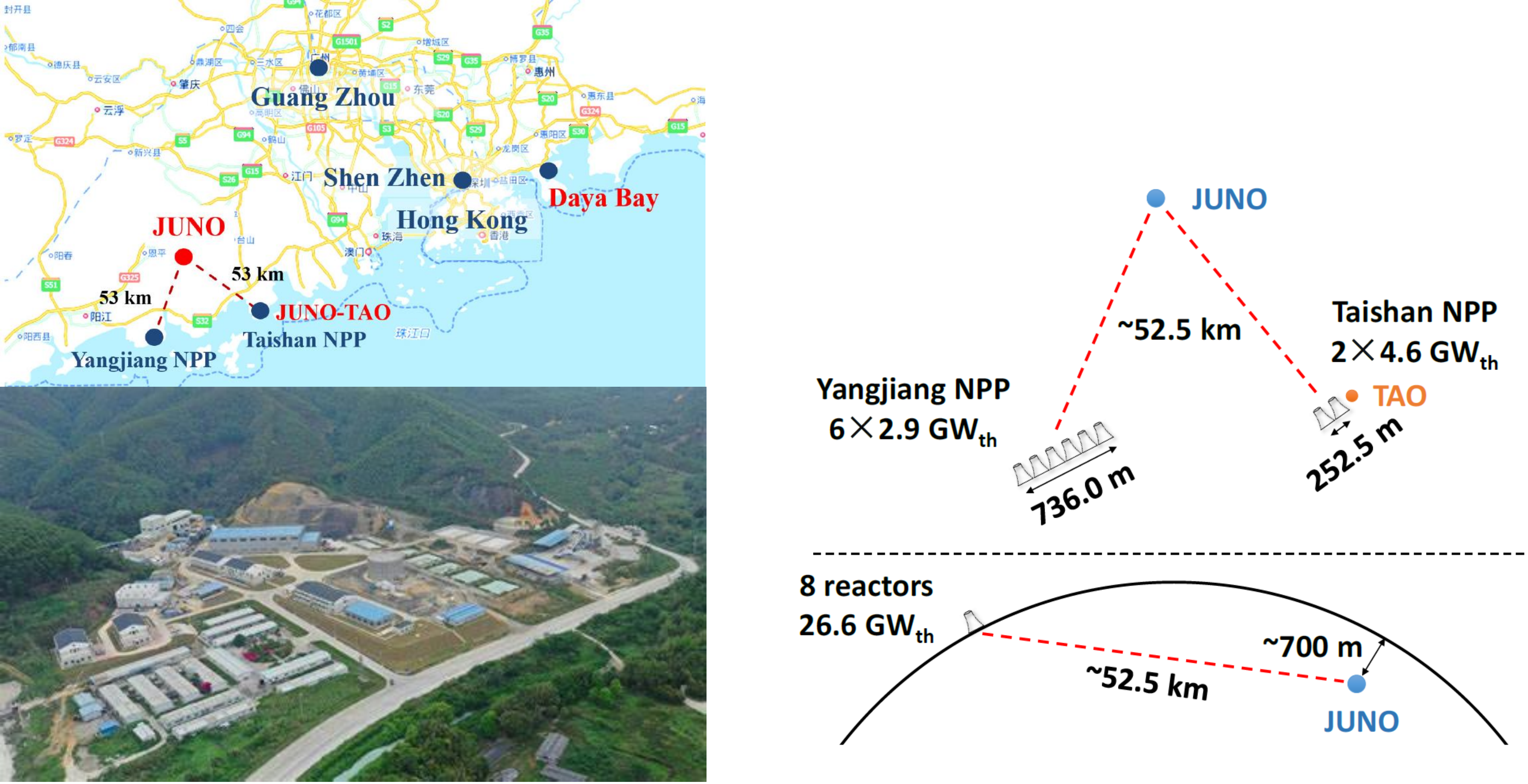


Figure 1: Setup of the JUNO experiment. The main 20 kton JUNO detector, indicated in blue, is located in an experimental cavern at a depth of about 700 m with respect to the surface and 650 m of overburden (1800 m.w.e), at a baseline of $\sim$52.5 km from six 2.9 GW$_{\text{th}}$ reactor cores in the Yangjiang NPP and two 4.6 GW$_{\text{th}}$ cores in the Taishan NPP. The 2.8 ton TAO detector, indicated in orange, is located about 30 m away from one of the Taishan reactor cores.

How JUNO can improve the precision on neutrino parameters

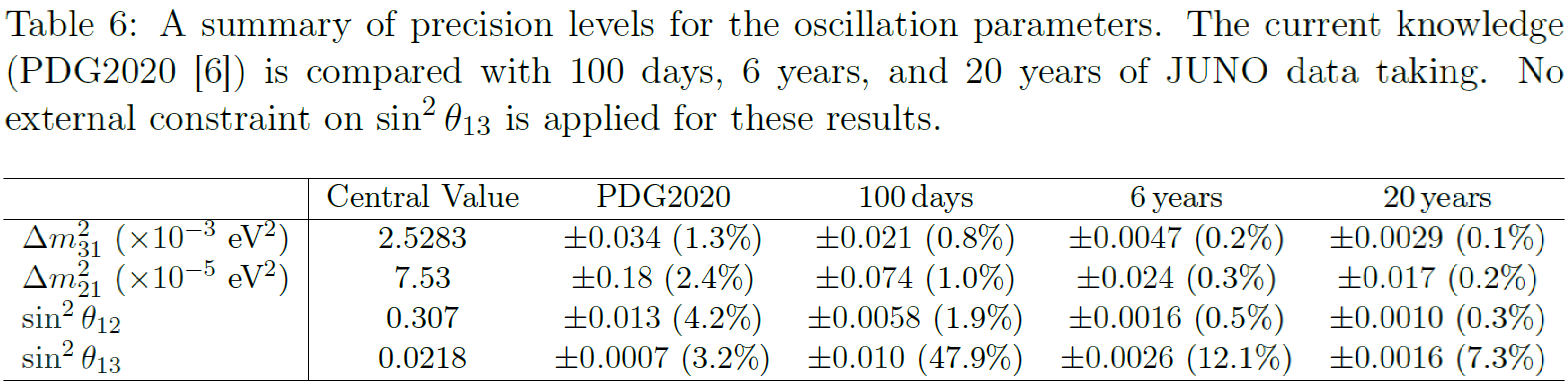


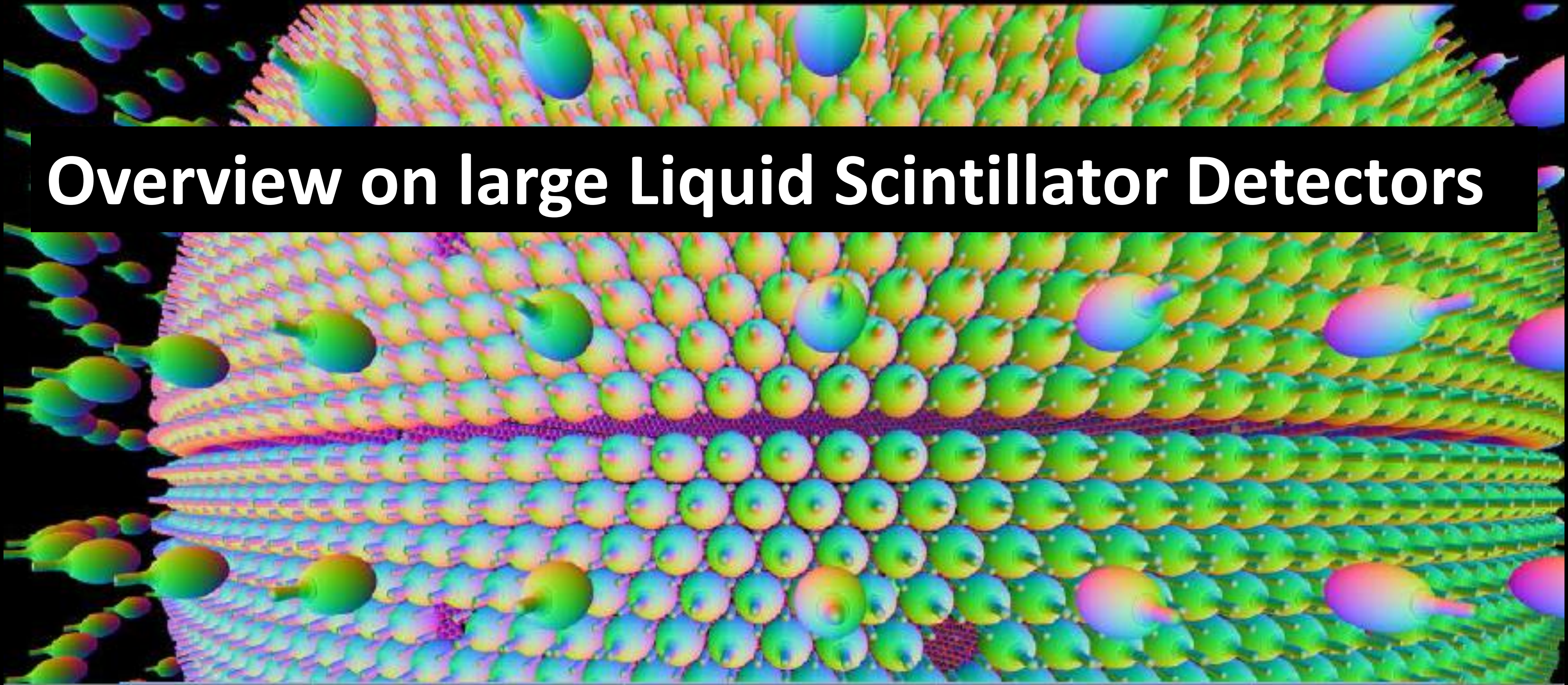
Table 6: A summary of precision levels for the oscillation parameters. The current knowledge (PDG2020 [6]) is compared with 100 days, 6 years, and 20 years of JUNO data taking. No external constraint on $\sin^2\theta_{13}$ is applied for these results.

	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%)

Why do we need more precision?

- Input for other experiments (e.g. CP-violation searches)
- Provide constraints for model building
- Enable more searches for physics beyond SM in neutrino sector
- Probing unitarity of U_{PMNS} at 1% level, more precise than CKM-Matrix

Overview on large Liquid Scintillator Detectors



Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	~80%
Energy resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E
Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~ 1200 p.e. / MeV

1345 p.e. / MeV (CDR)

More photons, how and how many ?

Energy resolution function

$$\frac{\Delta E}{E} = \sqrt{\frac{a^2}{E} + b^2 + \frac{c^2}{E^2}}$$

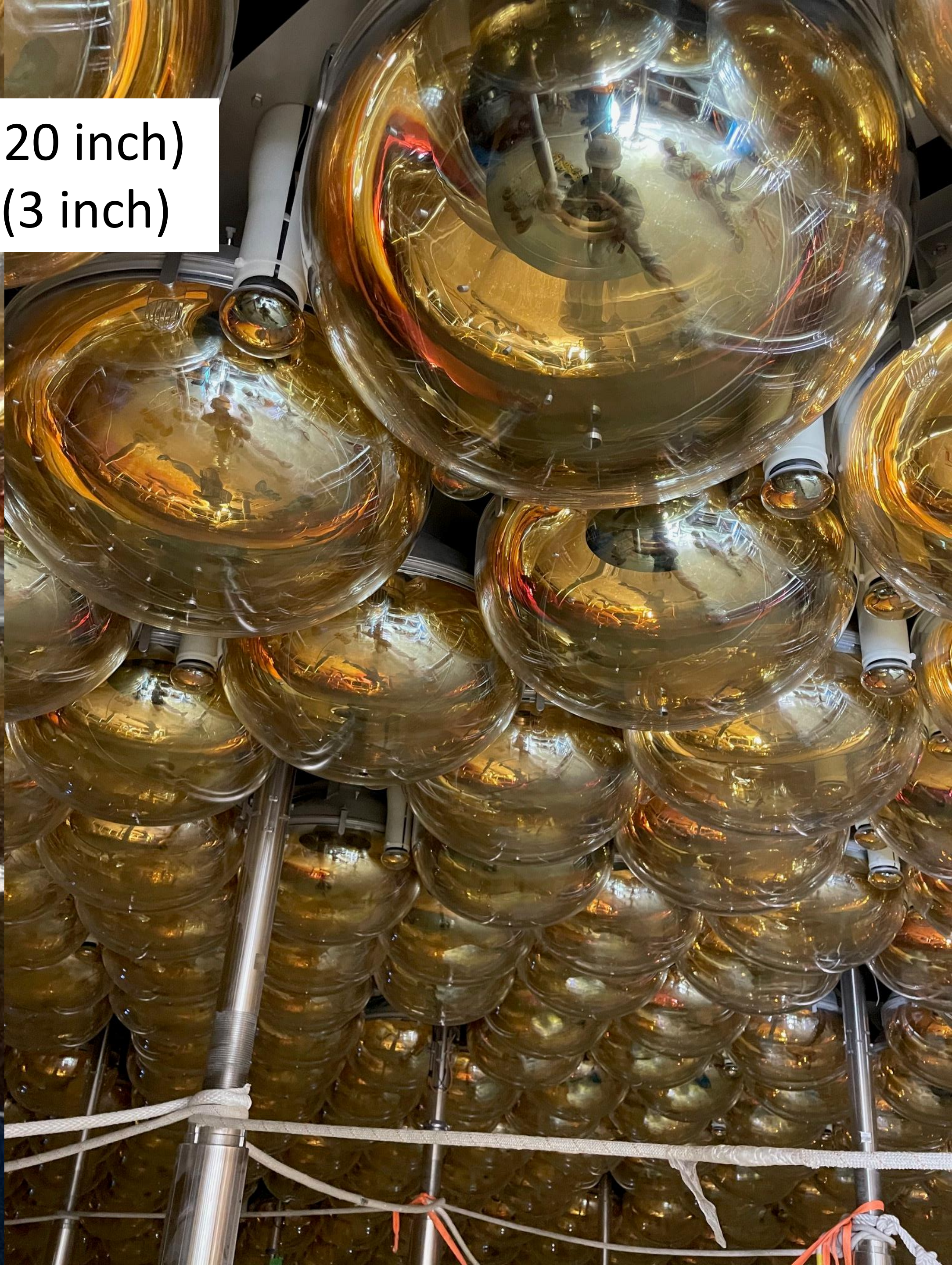
a term:
stochastic term (*photon statistics*)

b & c terms:
systematic contributions (*detector effects*)

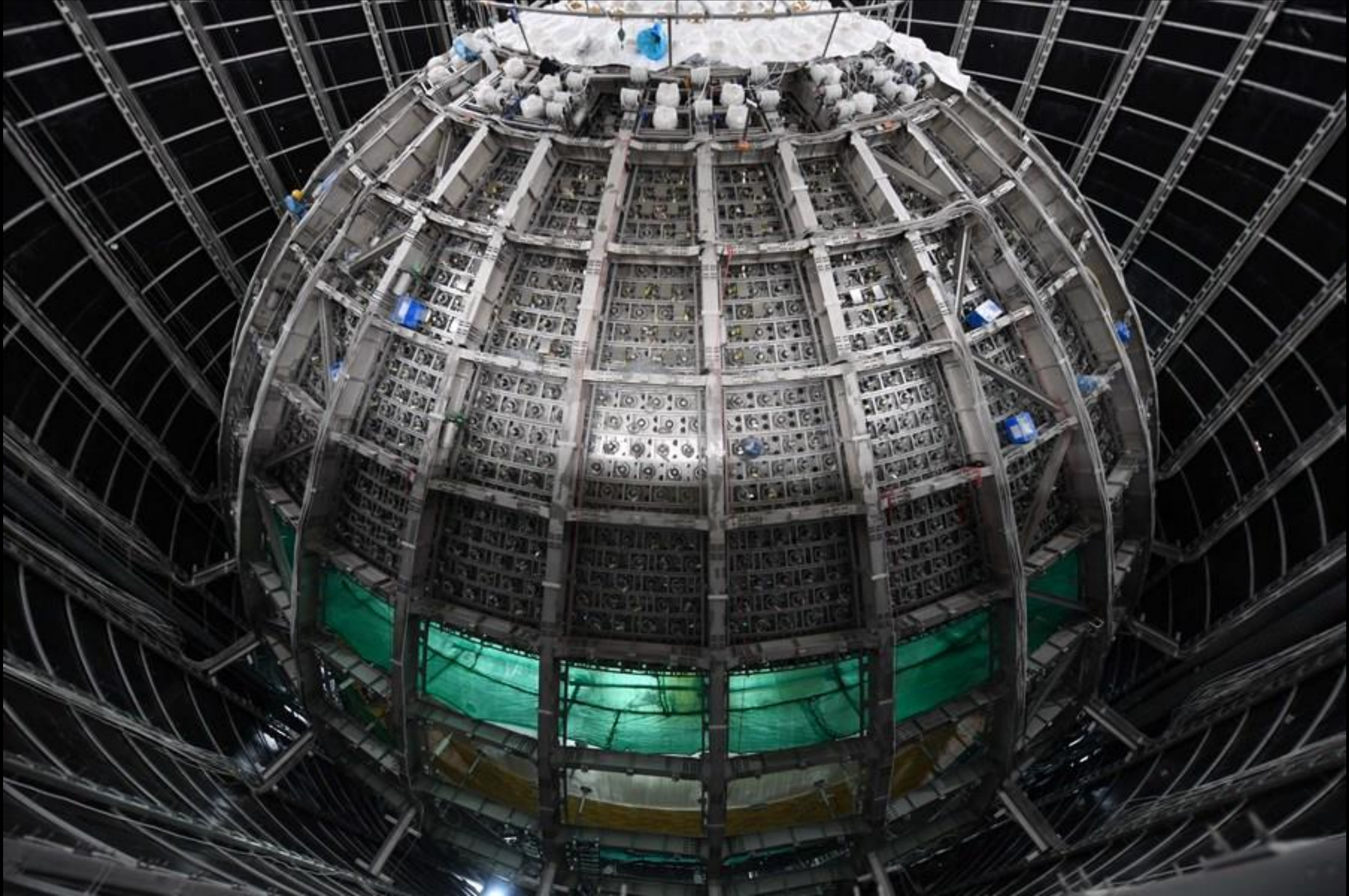
- PMT dark noise
- linearity of electronics
- position reconstruction uncertainty
- ...

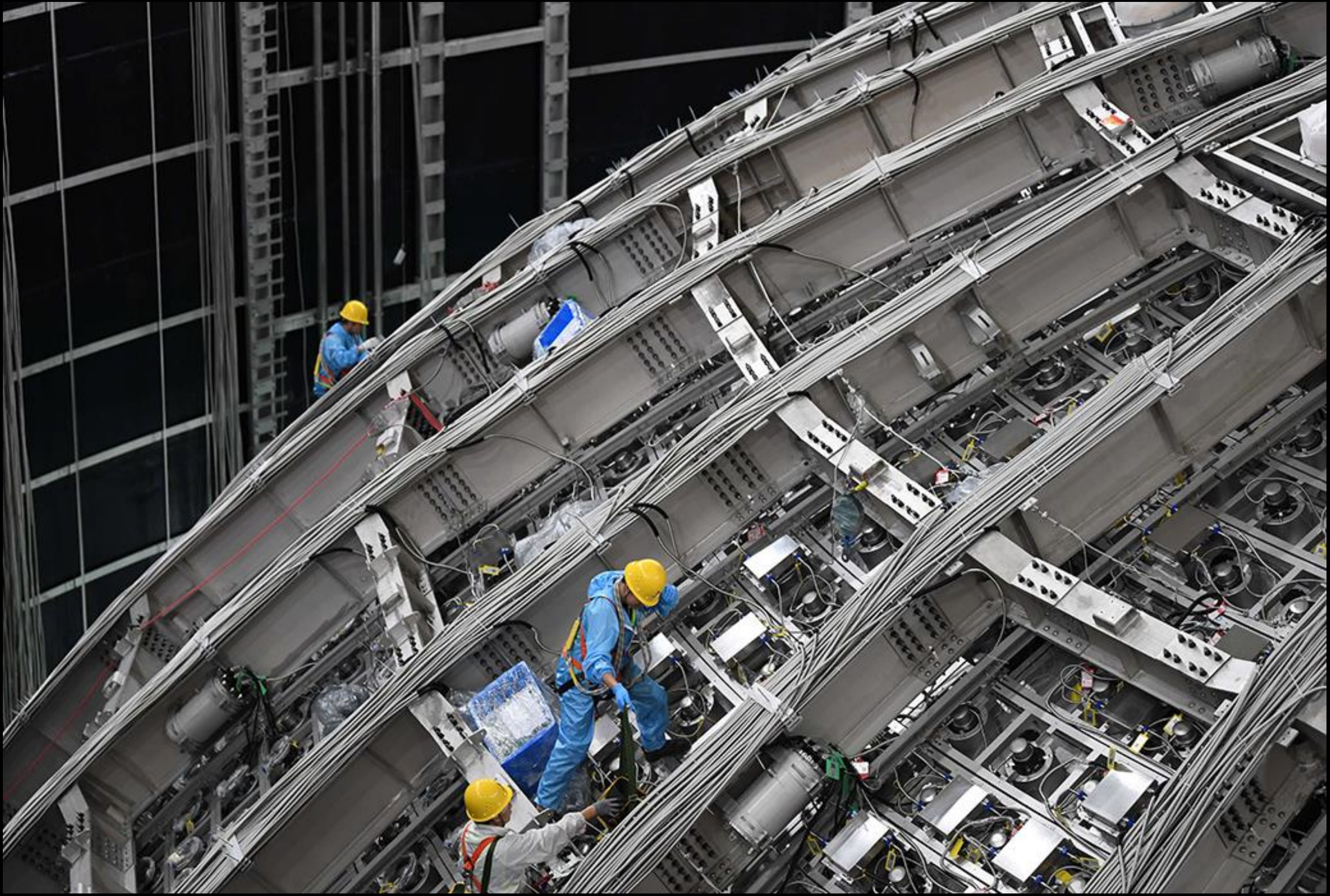
- **Highly transparent liquid scintillator:**
  - **Attenuation length/D:**
    15m/16m → 30m/34m
- **High light yield liquid scintillator:**
  - **KamLAND: 1.5g/l PPO → 5g/l PPO**
    Light Yield: 30%→ 45%
- **Photocathode coverage :**
  - **KamLAND: 34% → ~ 80%**
- **High QE "PMT" :**
  - **25% → 35%**

5.0 → (3.0 – 2.5)% /√E



17612 Large PMTs (20 inch)
25600 Small PMTs (3 inch)





Research	Expected signal	Energy region	Major backgrounds
Reactor antineutrino	60 IBDs/day	0–12 MeV	Radioactivity, cosmic muon
Supernova burst	5000 IBDs at 10 kpc 2300 elastic scattering	0–80 MeV	Negligible
DSNB (w/o PSD)	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Solar neutrino	hundreds per year for ^{8}B	0–16 MeV	Radioactivity
Atmospheric neutrino	hundreds per year	0.1–100 GeV	Negligible
Geoneutrino	$\sim$ 400 per year	0–3 MeV	Reactor ν

Table 2: Summary of detectable neutrino signals in the JUNO experiment and the expected signal rates and major background sources.