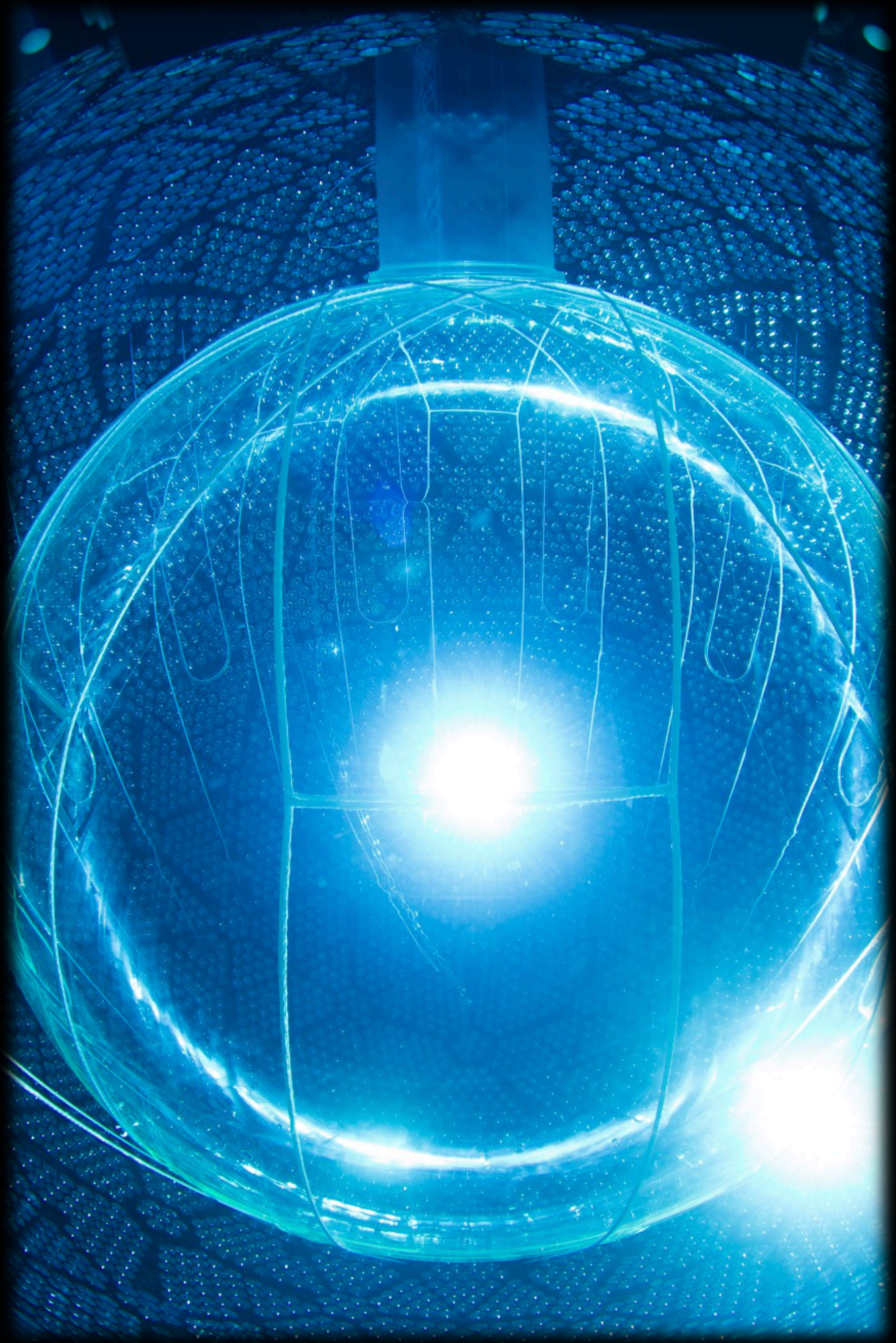


NEUTRINO SCIENCE 4

J. MANEIRA
LIP, LISBON, PORTUGAL

SUSI 2024
SNOLAB UNDERGROUND SCIENCE INSTITUTE
JULY 22 - AUGUST 2, 2024 SUDBURY, CANADA

OVERALL PLAN OF THE 5 LECTURES

1. Neutrinos in the Standard Model.
2. Neutrino interactions, detectors. Solar and atmospheric neutrino problems.
3. Neutrino oscillations in 2 flavors. SNO and SK.
4. Neutrino oscillations in 3 flavors. Future experiments.
5. Theory and search for neutrino masses. Neutrinoless double-beta decay. Neutrinos in Cosmology and Astrophysics.

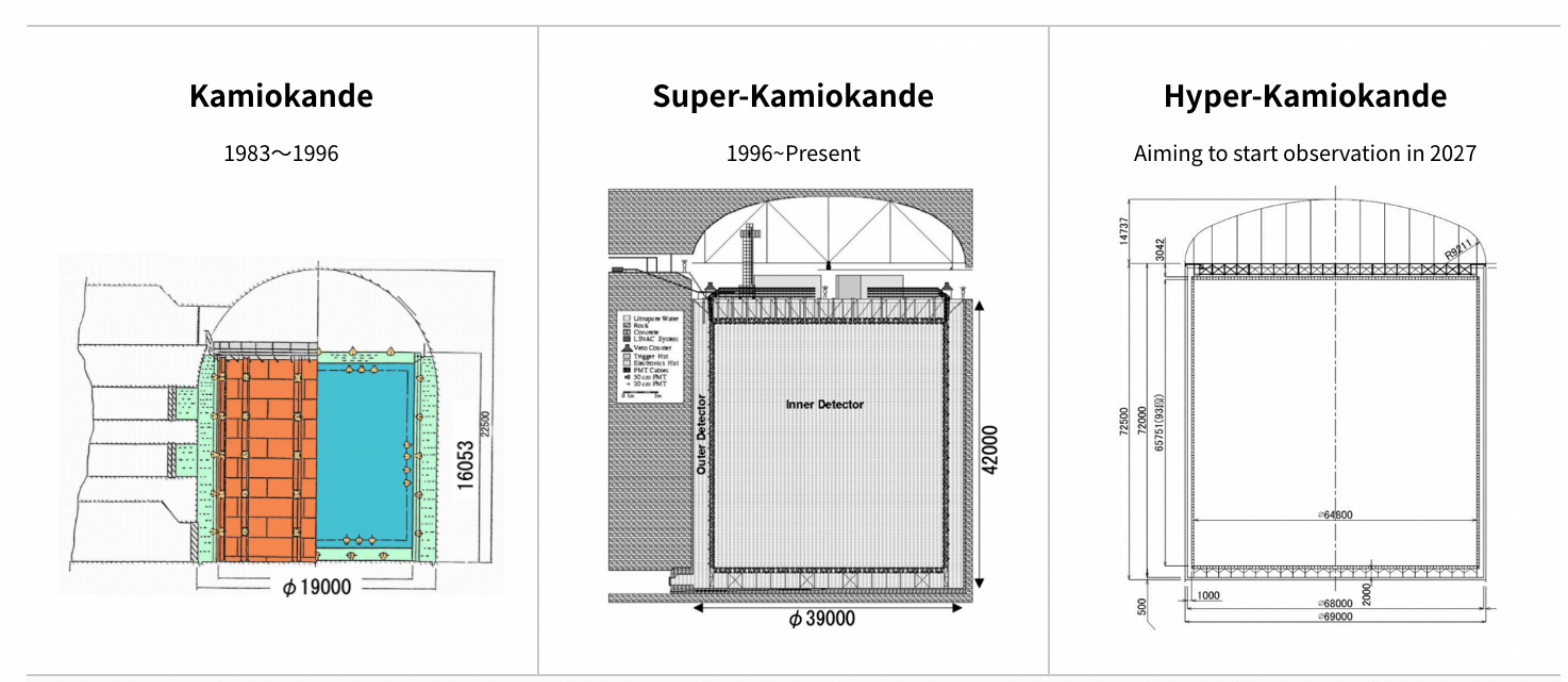
- Theory and experiment will be strongly mingled.
- Every lecture will have some of both.

PLAN FOR LECTURE 4

- Finding evidence for oscillations
  - with atmospheric neutrinos: Super-Kamiokande
  - … and early confirmations with terrestrial sources: K2K, MINOS
- Three-flavor neutrino mixing
  - Neutrino mass ordering
  - Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix and three-flavor oscillations
  - CP violation and matter effects
- Current experimental status
- Future experiments

SUPER-KAMIOKANDE

CHERENKOV DETECTORS IN JAPAN



Kamiokande

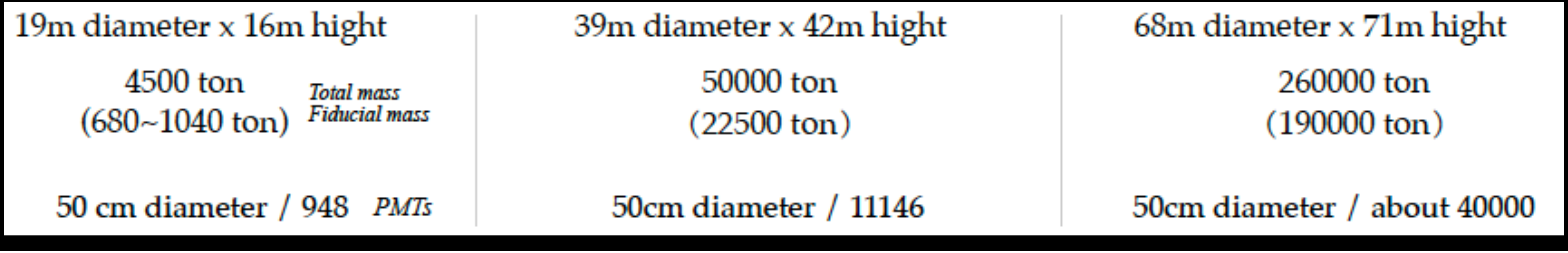
1983〜1996

Super-Kamiokande

1996~Present

Hyper-Kamiokande

Aiming to start observation in 2027



19m diameter x 16m hight		39m diameter x 42m hight	68m diameter x 71m hight
4500 ton	*Total mass*	50000 ton	260000 ton
(680~1040 ton)	*Fiducial mass*	(22500 ton)	(190000 ton)
50 cm diameter / 948	*PMTs*	50cm diameter / 11146	50cm diameter / about 40000

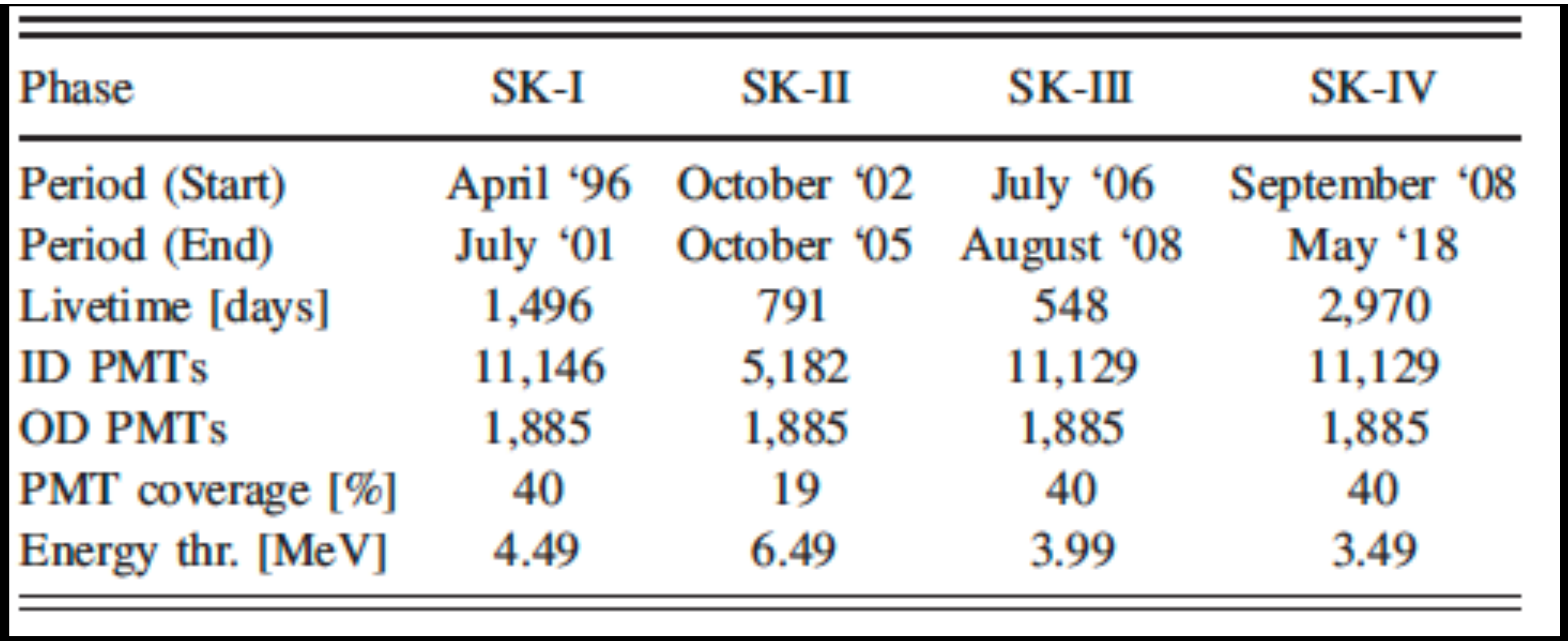
SUPER-KAMIOKANDE

- Largest detector sensitive to solar neutrino energies: 22.5 kton fiducial
- Recently published: complete analysis of SK phases I - IV: over 20 years of data!!
  - Significant improvements in energy reconstruction and uncertaities
- Since 2020: SK-V (prep for Gd), SK-VI (0.01% Gd), SK-VII (0.03% Gd)

SUPER-KAMIOKANDE SOLAR

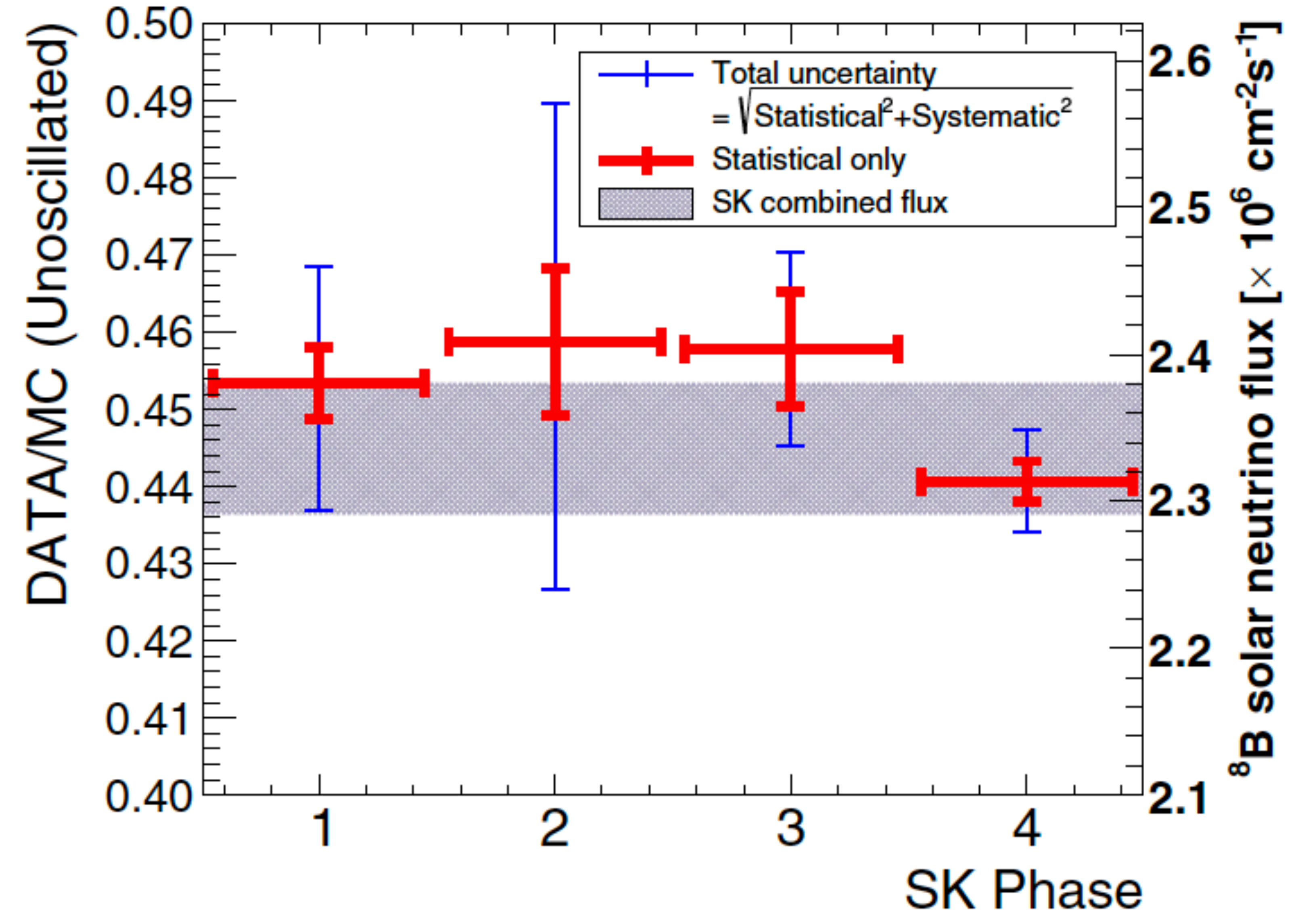
Following slides from my recent talk at Neutrino 2024

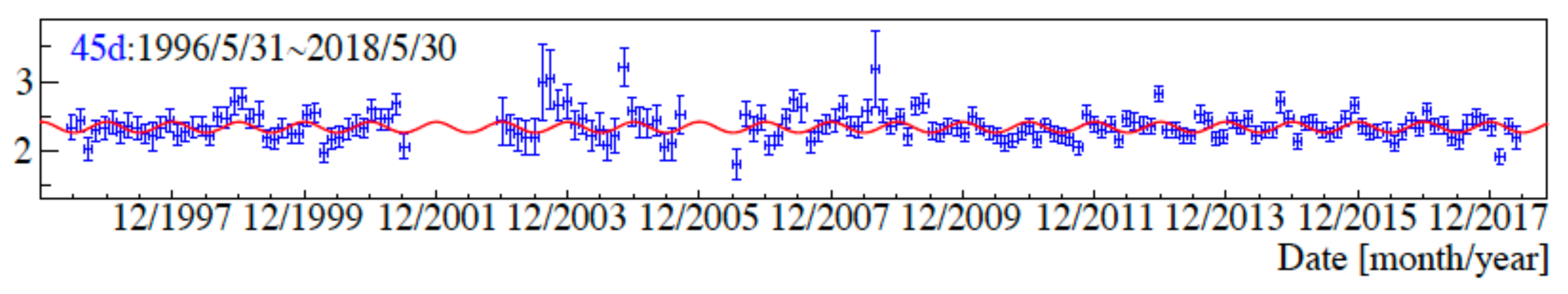
TIME VARIATIONS OF ^{8}B FLUX



Phase	SK-I	SK-II	SK-III	SK-IV
Period (Start)	April '96	October '02	July '06	September '08
Period (End)	July '01	October '05	August '08	May '18
Livetime [days]	1,496	791	548	2,970
ID PMTs	11,146	5,182	11,129	11,129
OD PMTs	1,885	1,885	1,885	1,885
PMT coverage [%]	40	19	40	40
Energy thr. [MeV]	4.49	6.49	3.99	3.49

Very precise rate measurement, consistent among various phases

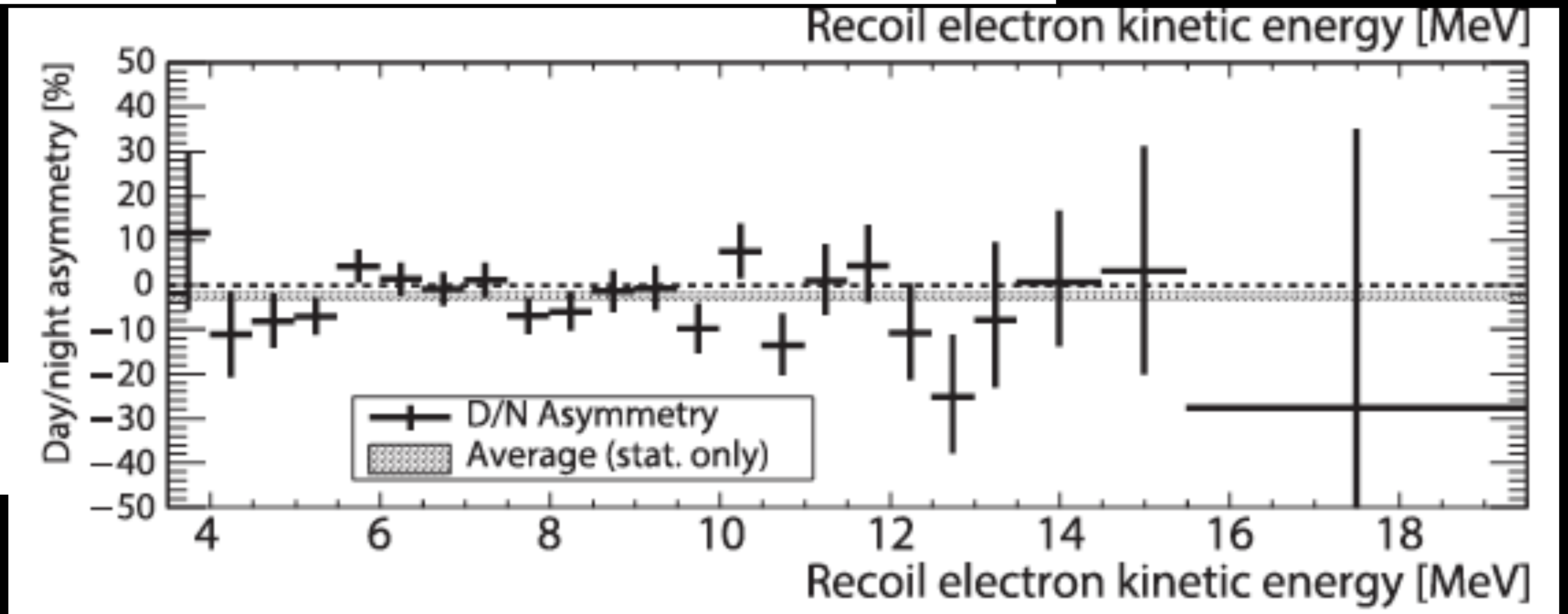




Day/night Asymmetry

SK-IV only, calc.

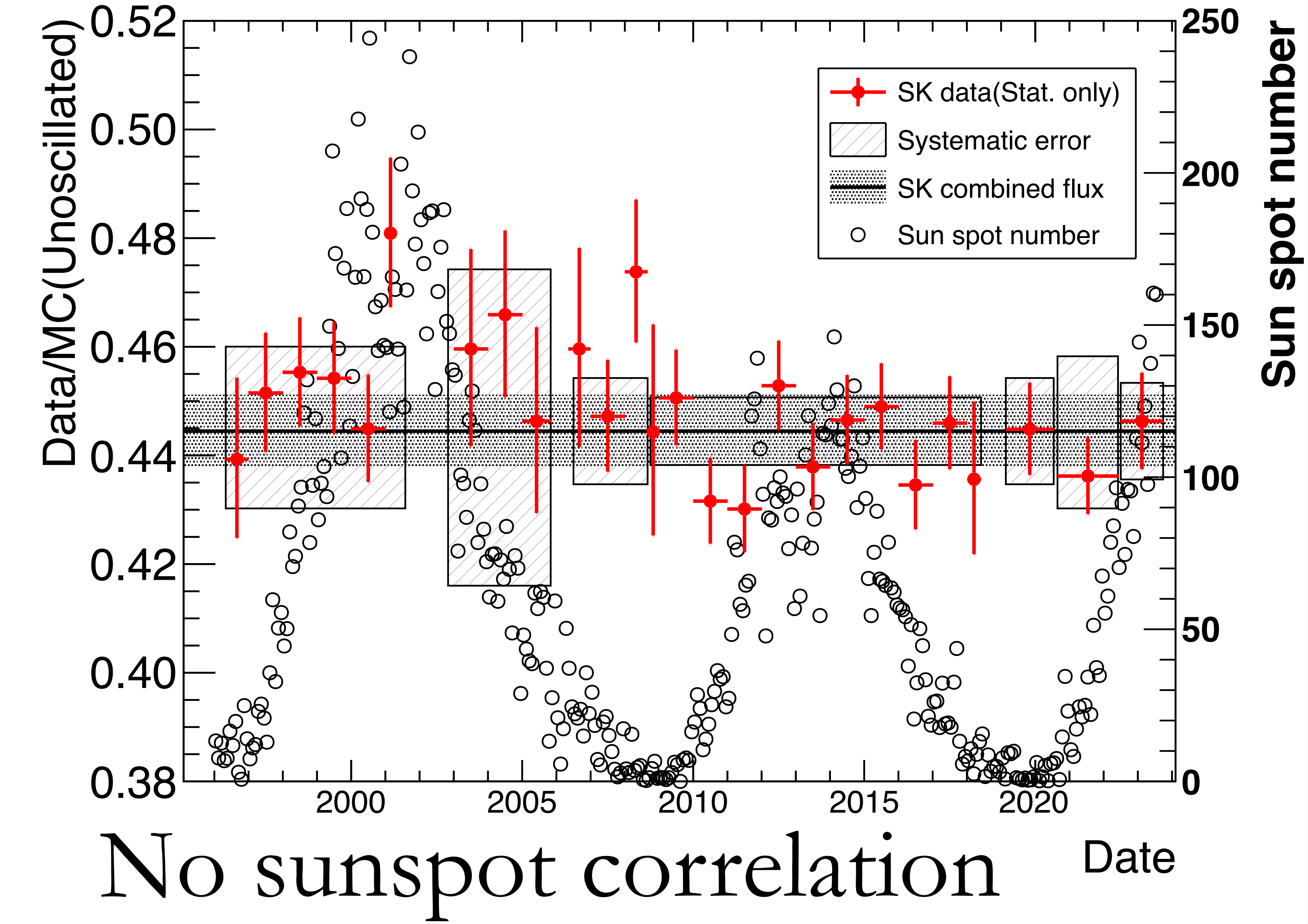
$$A_{\mathrm{D/N}}^{\text{SK-IV, calc}} = -0.025 \pm 0.012(\text{stat.}) \pm 0.014(\text{syst.}).$$



SK I-IV combined fit, > 3 σ

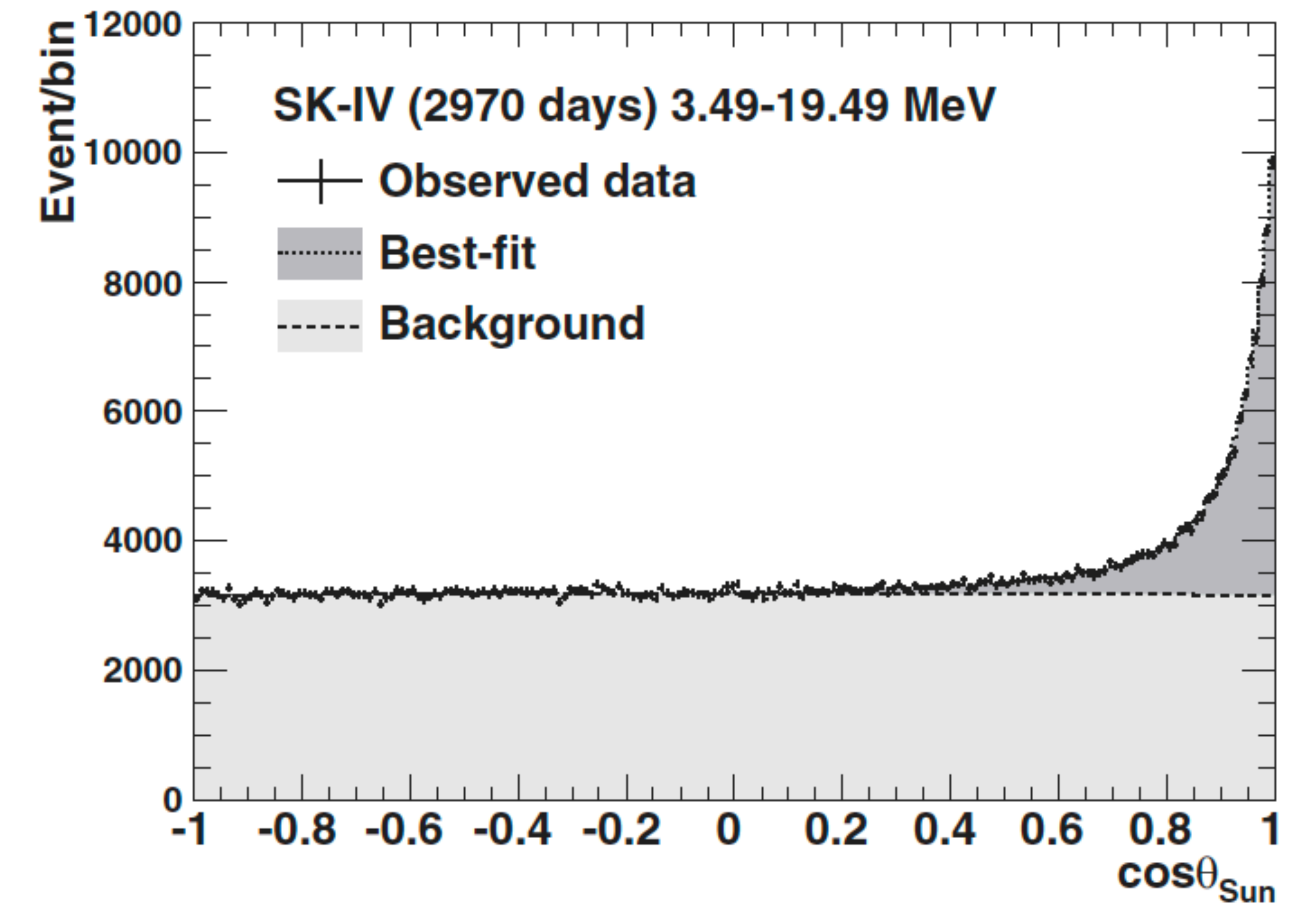
$$A_{\mathrm{D/N}}^{\text{SK, fit}} = -0.0286 \pm 0.0085\,(\text{stat.}) \pm 0.0032\,(\text{syst.}).$$

No statistically signicant time variations beyond eccentricity and day/night (compatible with MSW oscillations)

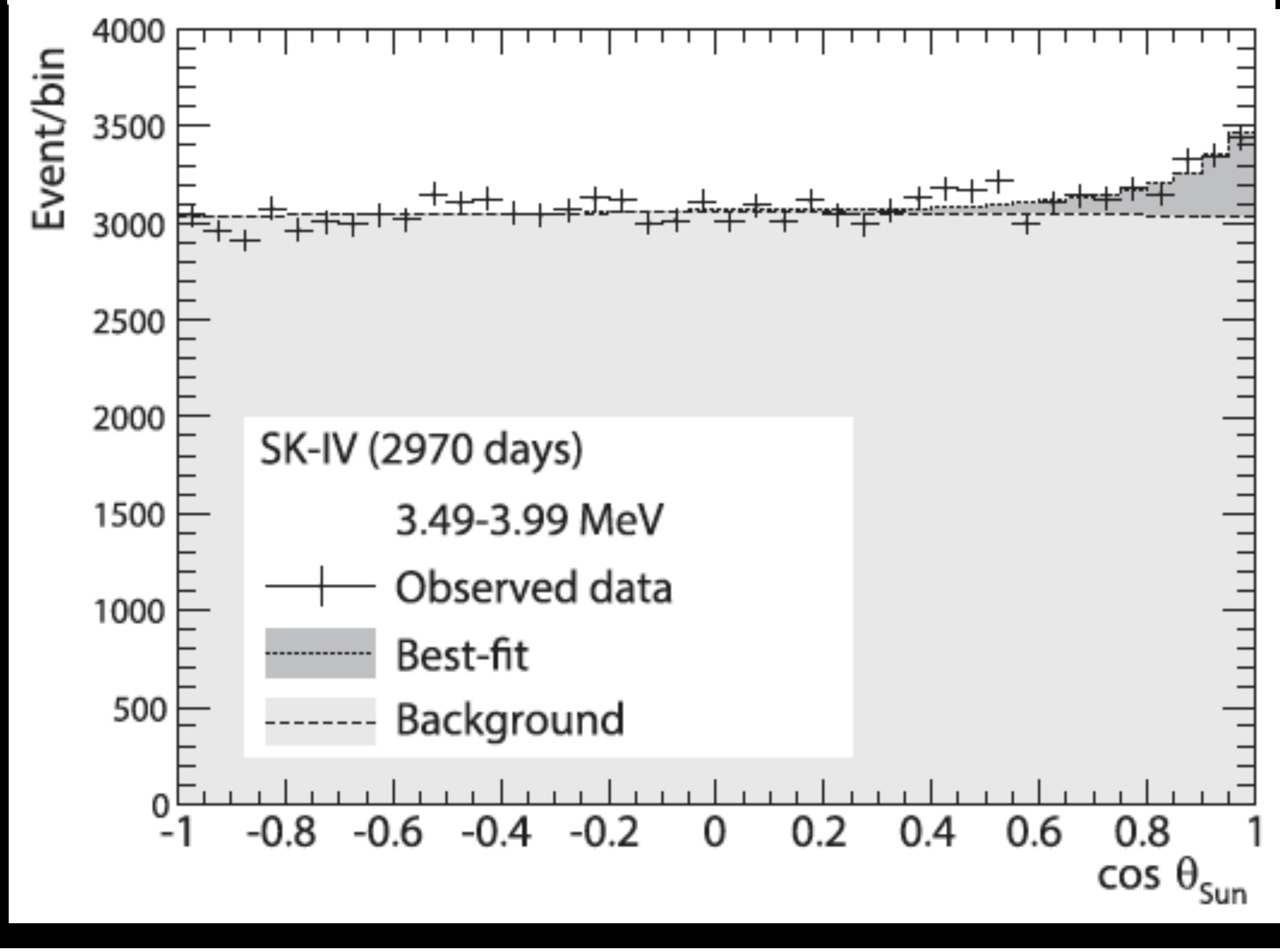


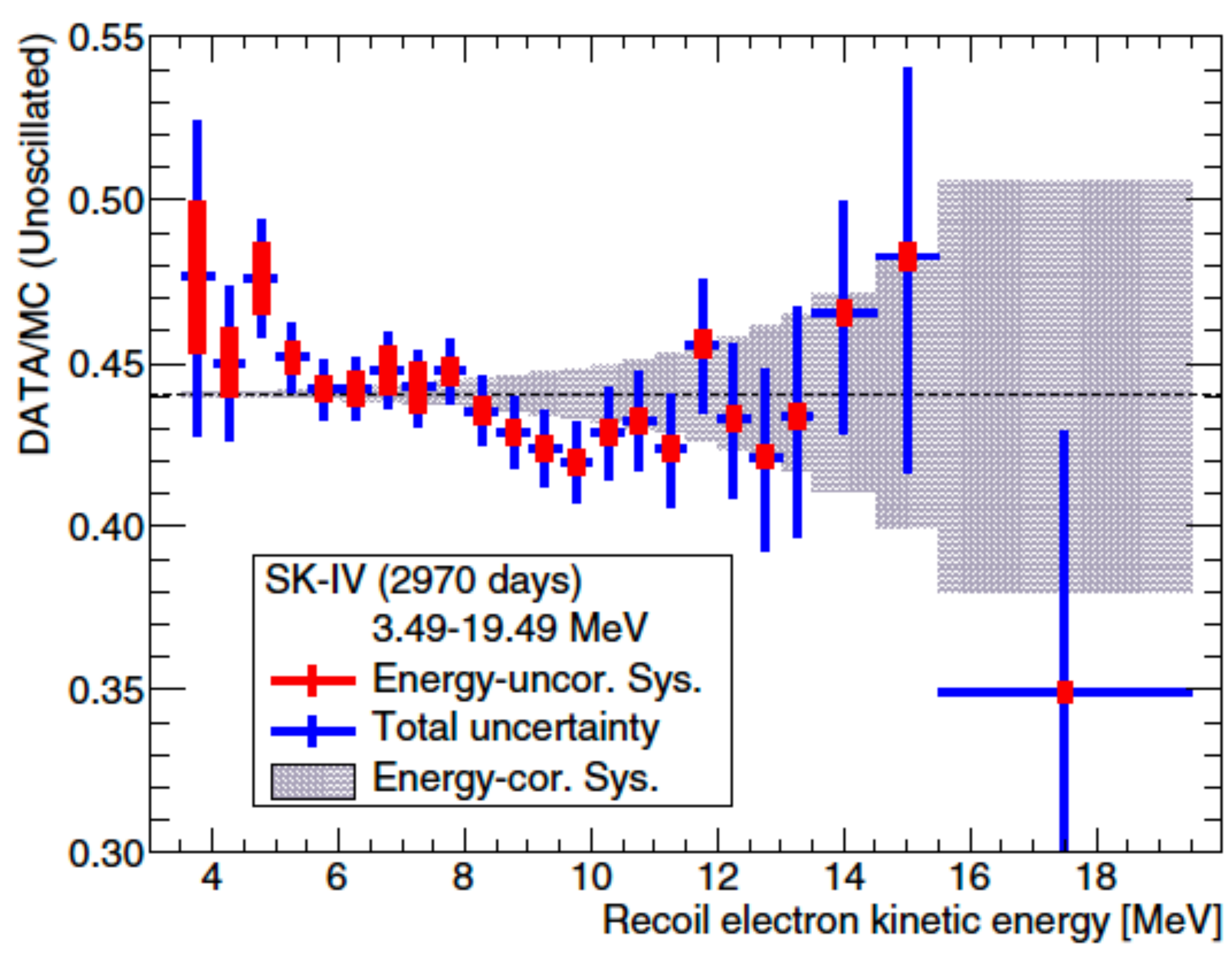
No sunspot correlation

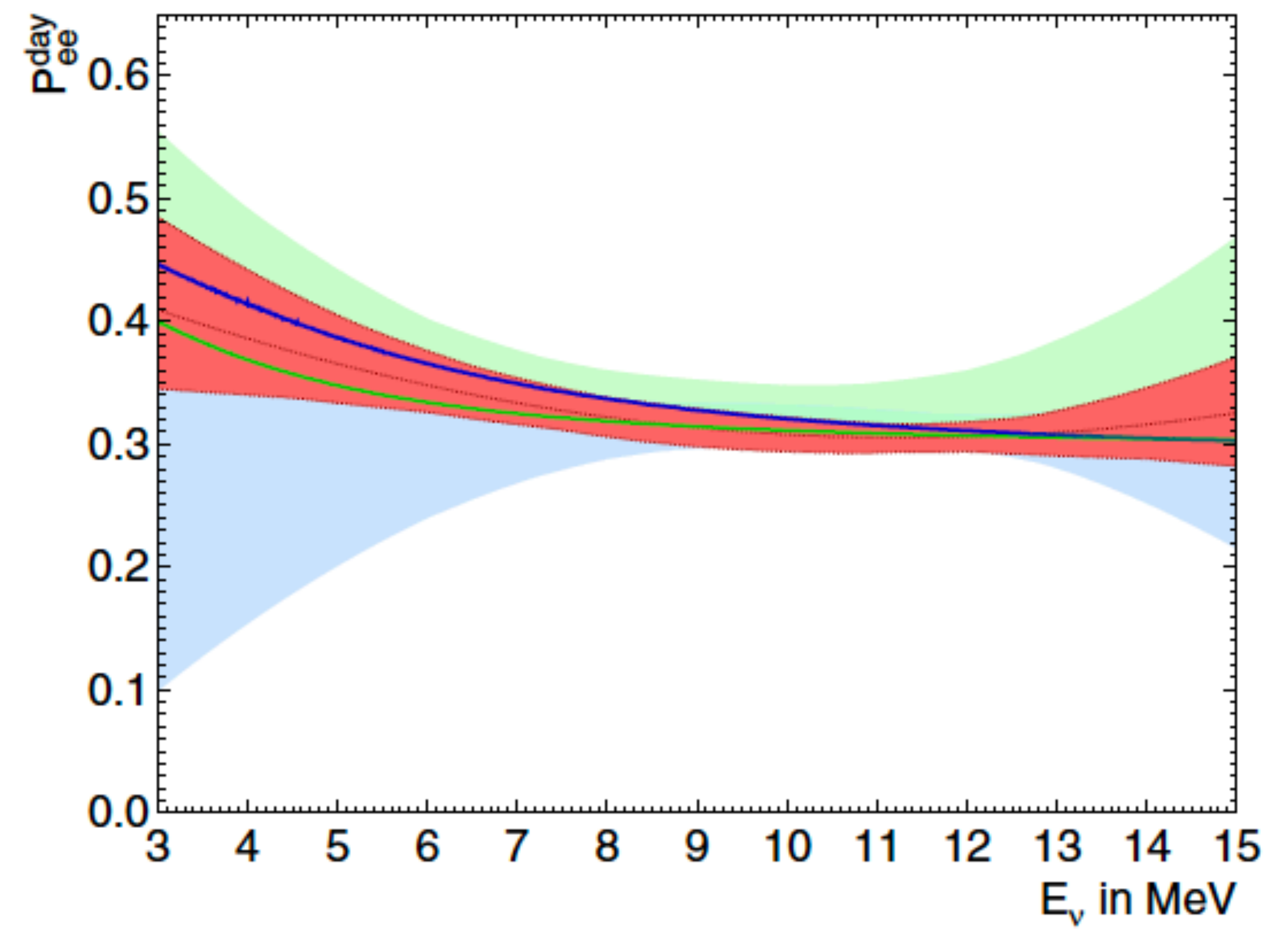
^{8}B SOLAR NEUTRINO SPECTRUM



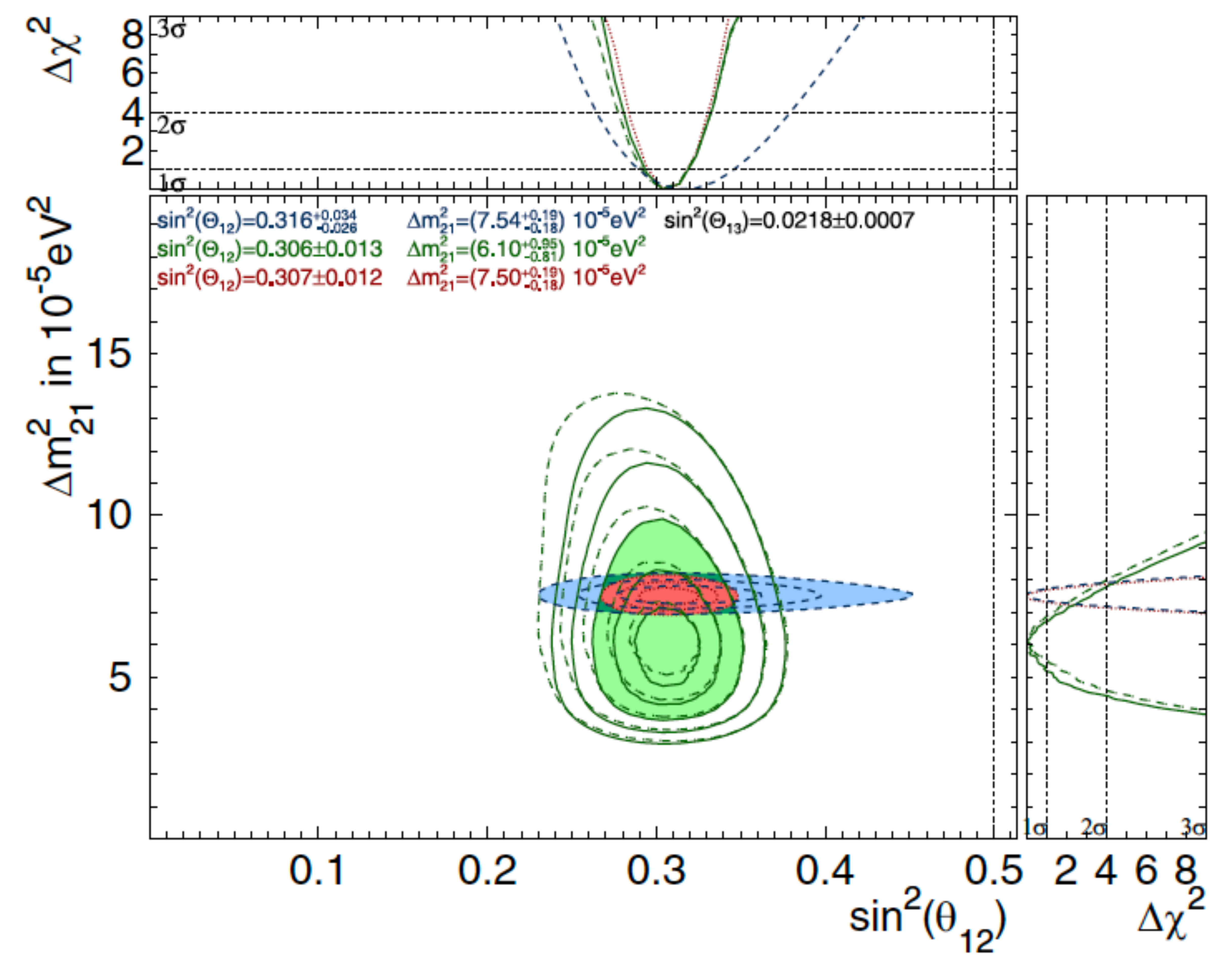
- Impressive precision, clear observation at 3.5 MeV threshold
- Spectrum still compatible with flat survival probability, but predicted low energy upturn is favored at 1.2 σ . Jointly with SNO data, at 2.1 σ.







SK OSCILLATIONS GLOBAL FIT



SK fit, fixed θ_{13}

- Solar best-fit value updated to:

$$\Delta m^2_{21} = 6.10^{+0.95}_{-0.81} \times 10^{-5} eV^2$$

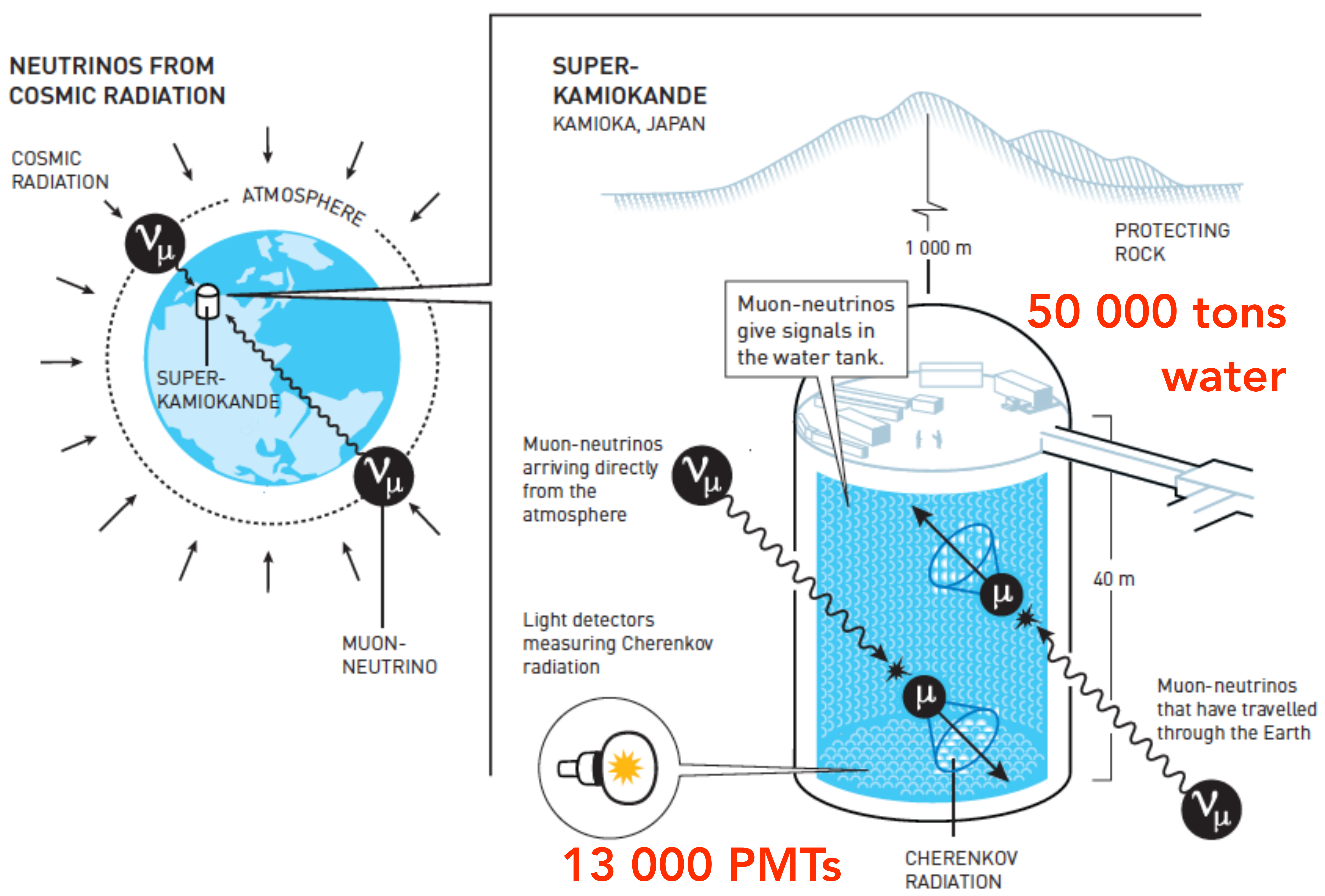
- ~1.5 σ away from KamLAND

NEW PHASES CONTINUE…

Higher backgrounds as expected, but 4 /4.5 MeV threshold is clearly possible !

SUPER-KAMIOKANDE ATMOSPHERIC

SK ATMOSPHERIC NEUTRINOS



50 000 tons water

13 000 PMTs

SK - TYPES OF EVENTS

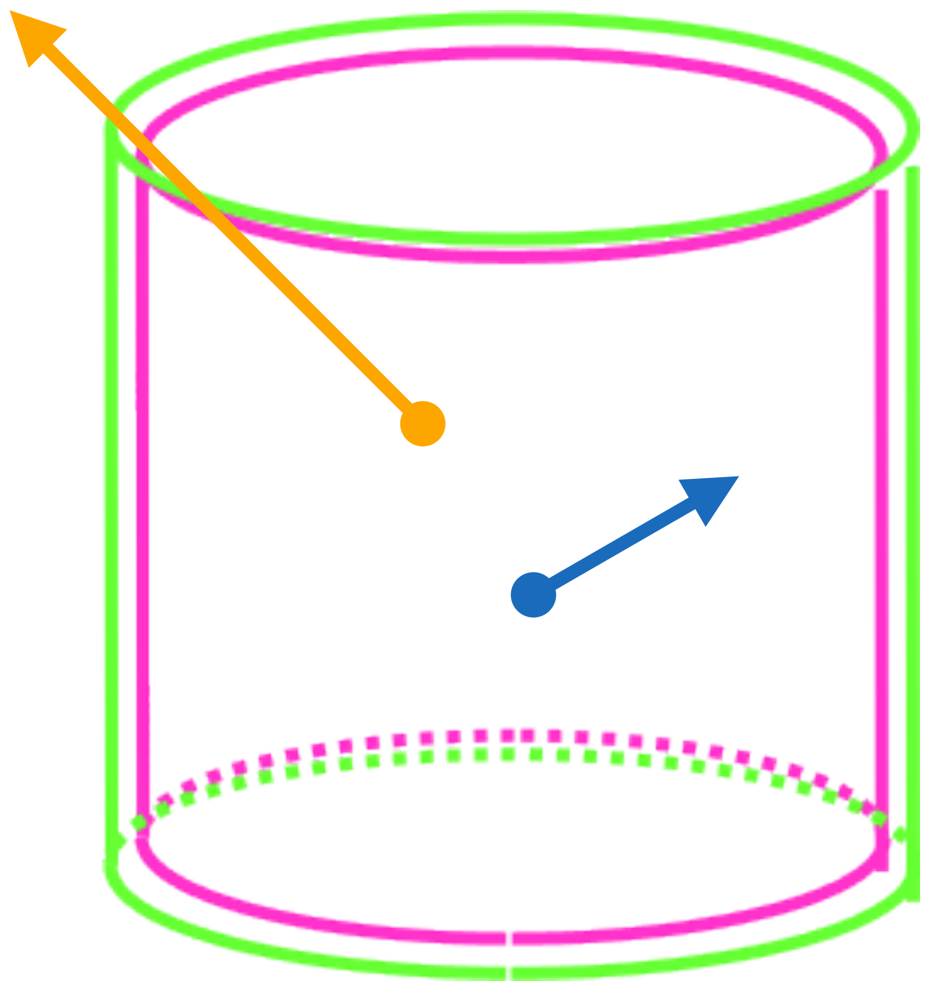
Range in detector strongly correlated to energy

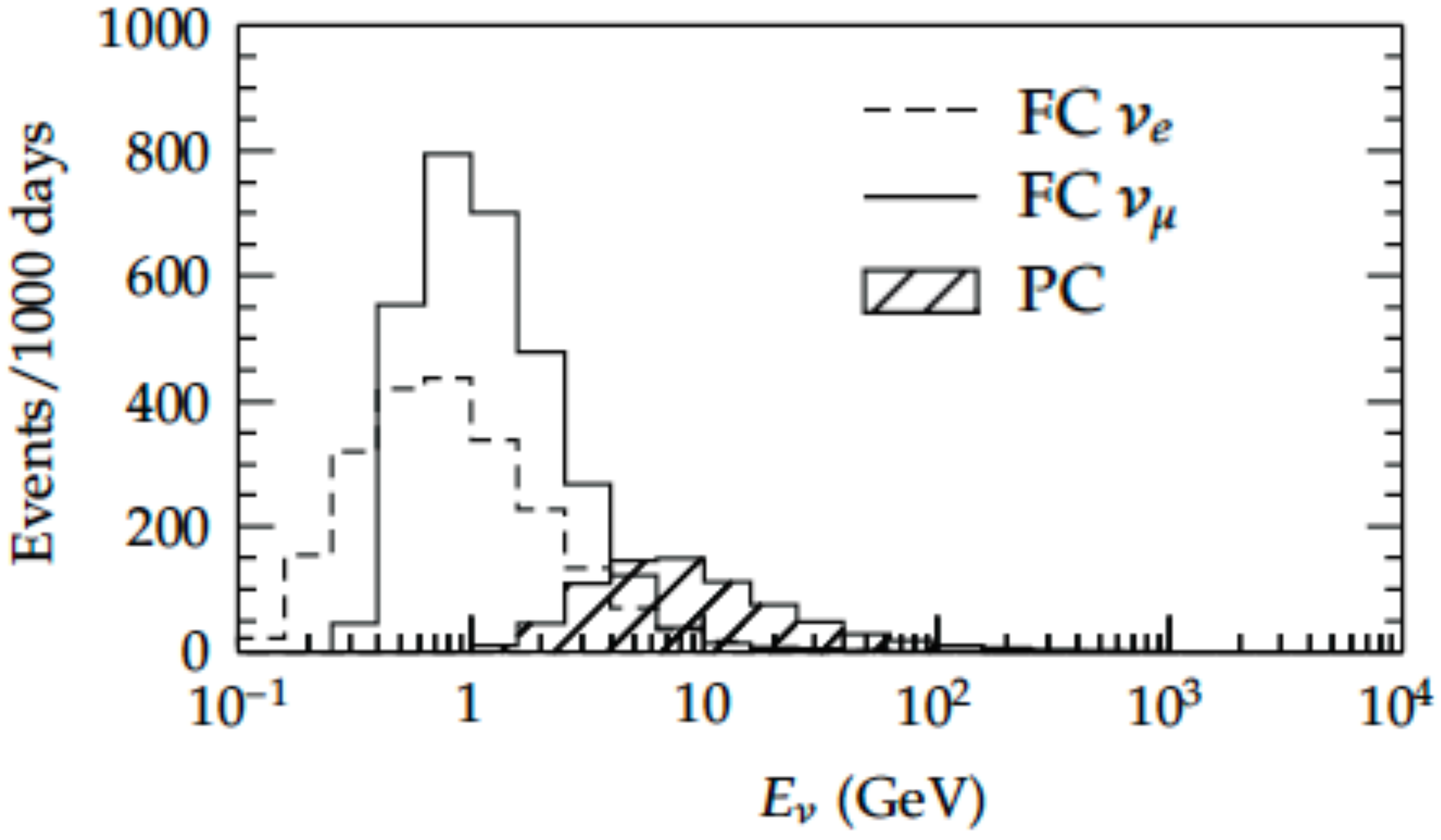
Fully Contained

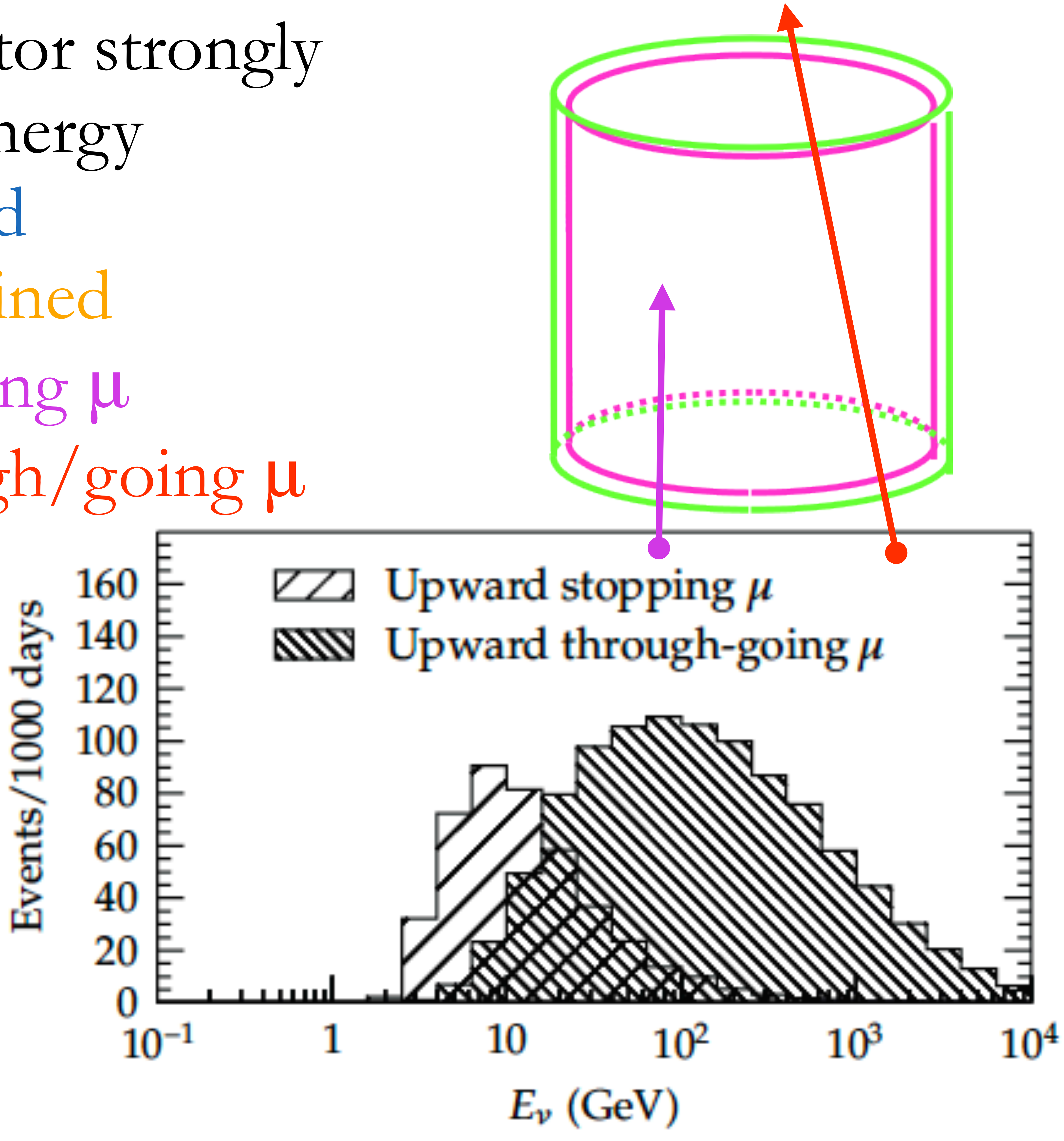
Partially Contained

Upward stopping μ

Upward through/going μ

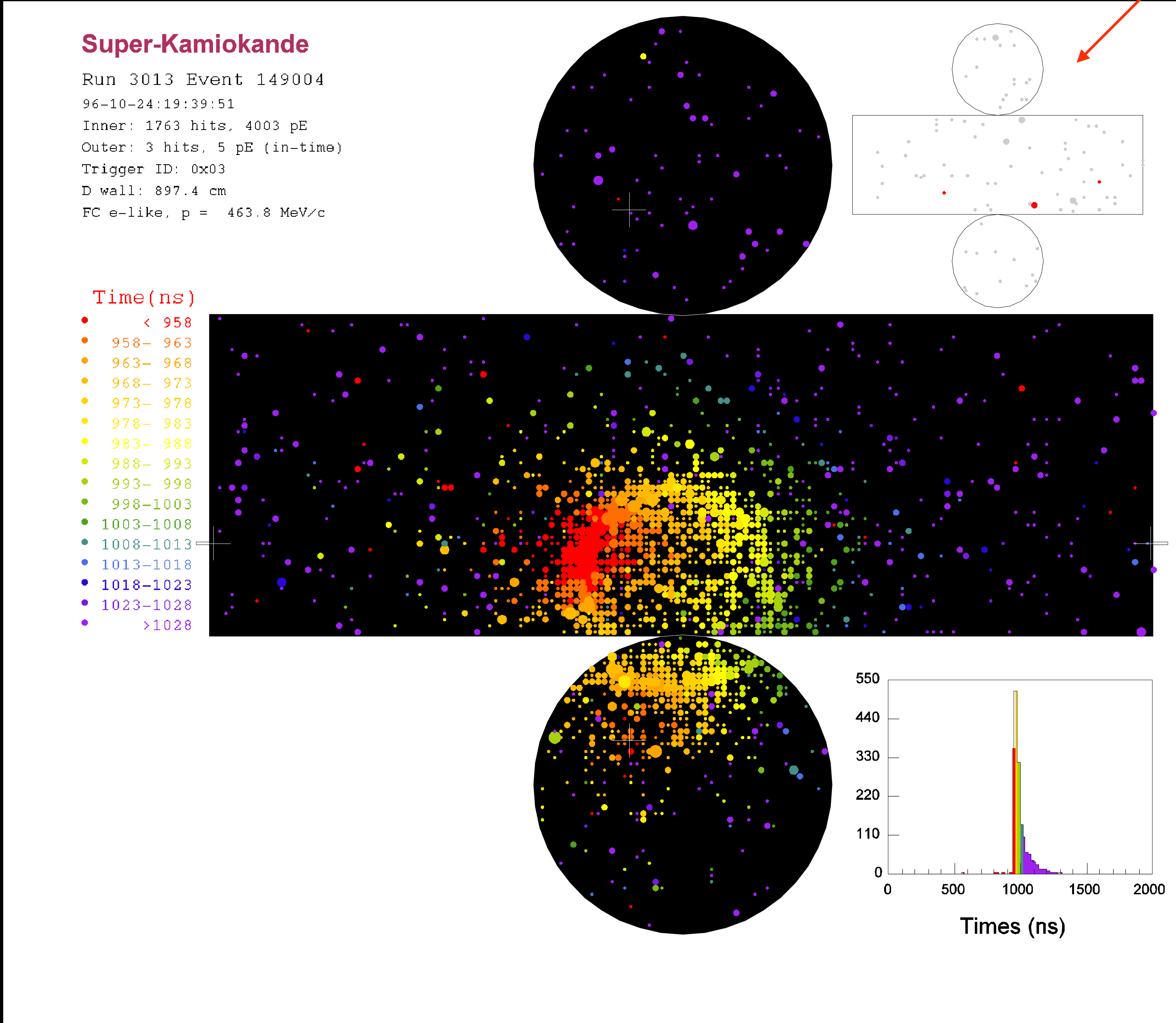






FULLY CONTAINED

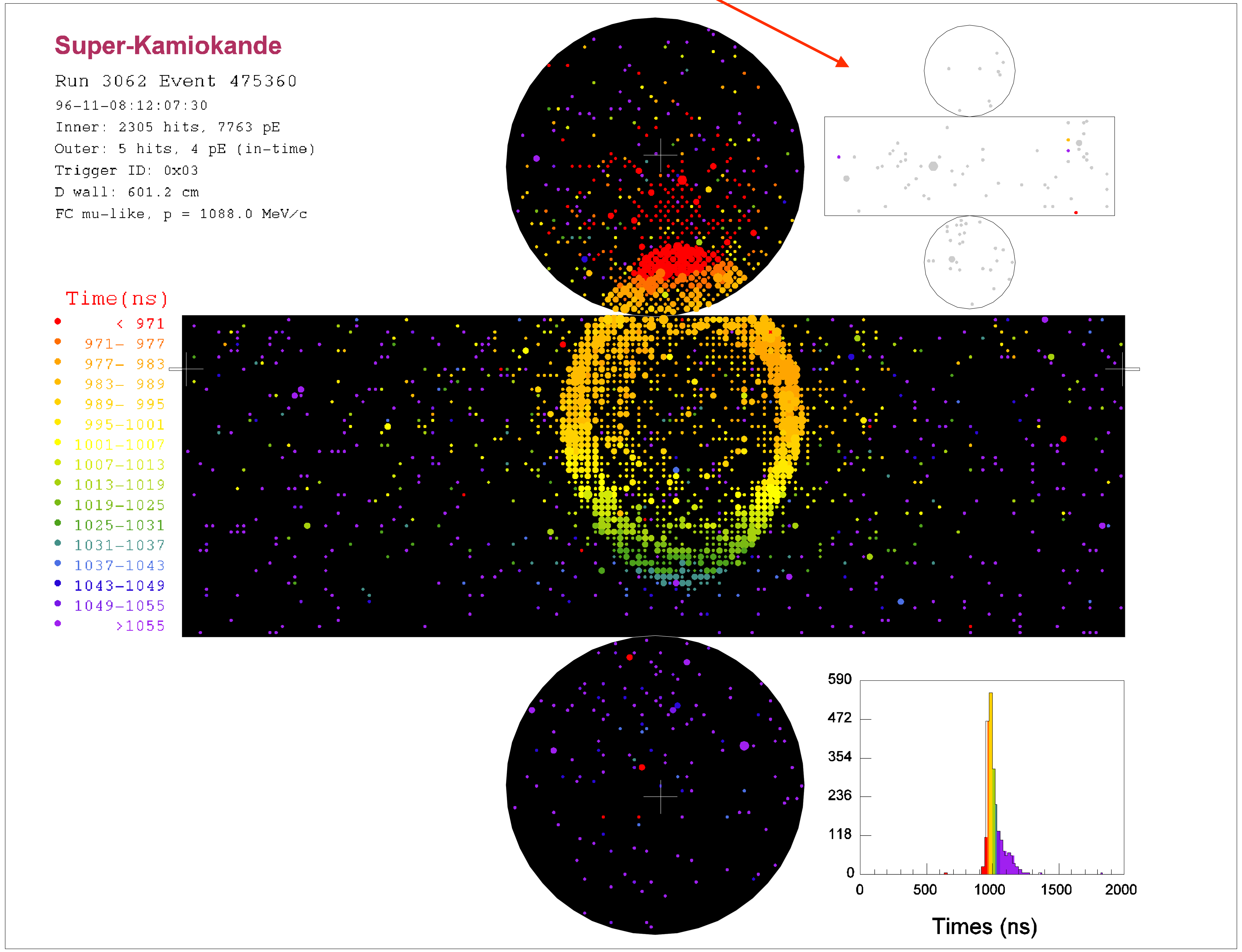
no signal in outer detector



Super-Kamiokande

```
Run 3013 Event 149004
96-10-24:19:39:51
Inner: 1763 hits, 4003 pE
Outer: 3 hits, 5 pE (in-time)
Trigger ID: 0x03
D wall: 897.4 cm
FC e-like, p =  463.8 MeV/c
```

electron-like



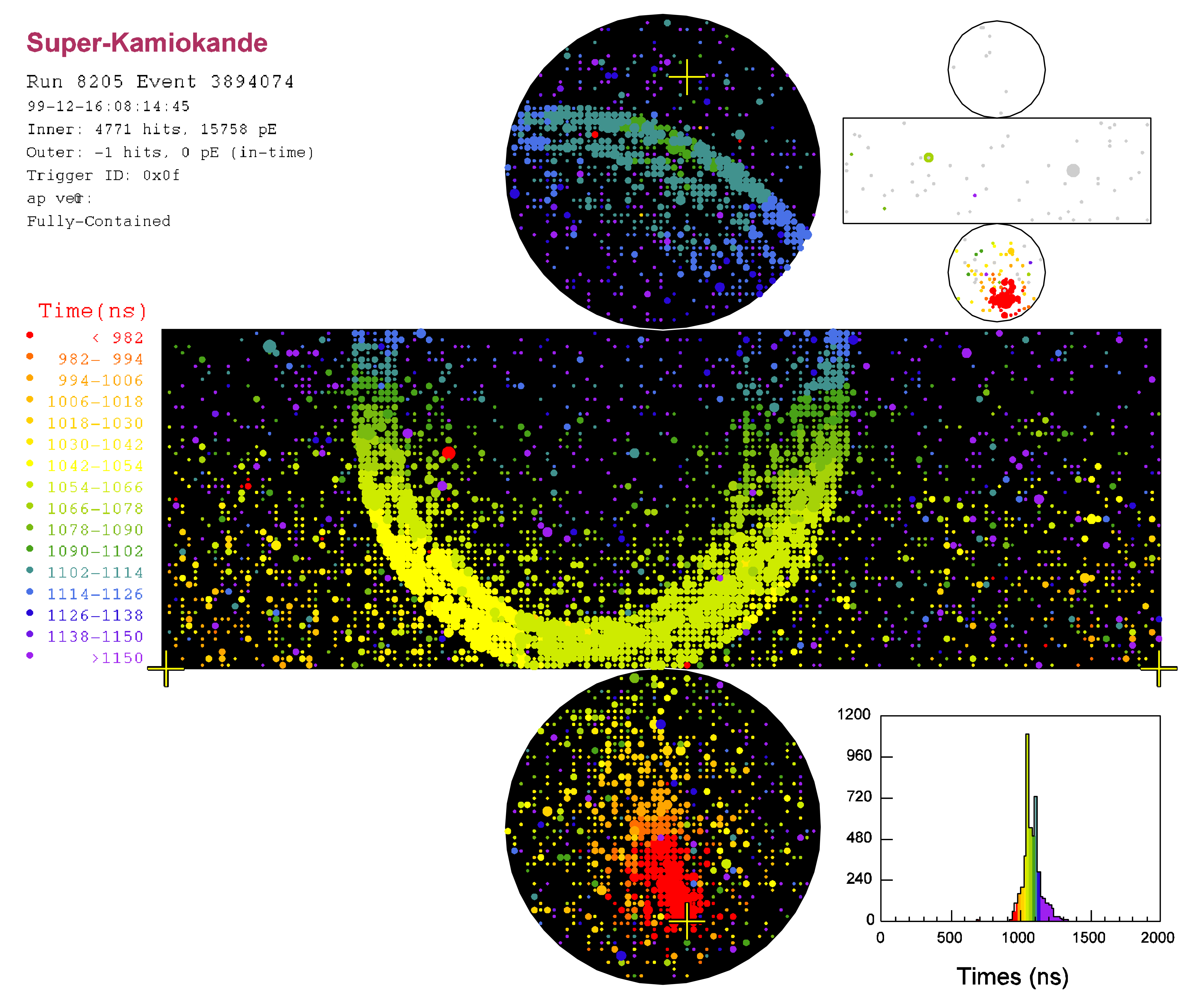
Super-Kamiokande

```
Run 3062 Event 475360
96-11-08:12:07:30
Inner: 2305 hits, 7763 pE
Outer: 5 hits, 4 pE (in-time)
Trigger ID: 0x03
D wall: 601.2 cm
FC mu-like, p = 1088.0 MeV/c
```

muon-like

PARTIALLY CONTAINED

one cluster in outer detector

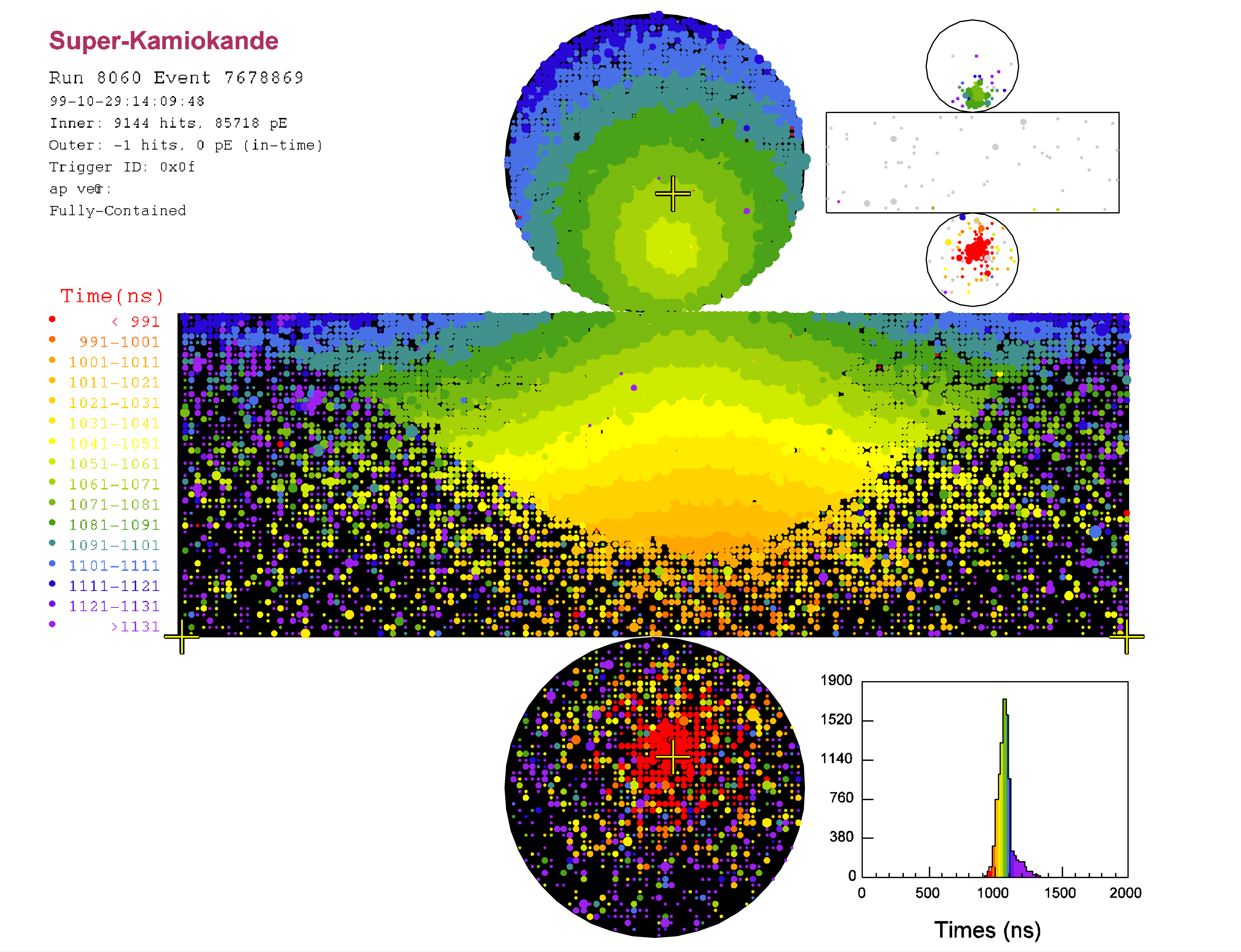


Super-Kamiokande

```
Run 8205 Event 3894074
99-12-16:08:14:45
Inner: 4771 hits, 15758 pE
Outer: -1 hits, 0 pE (in-time)
Trigger ID: 0x0f
ap veto:
Fully-Contained
```

stopping muon

two clusters in outer detector

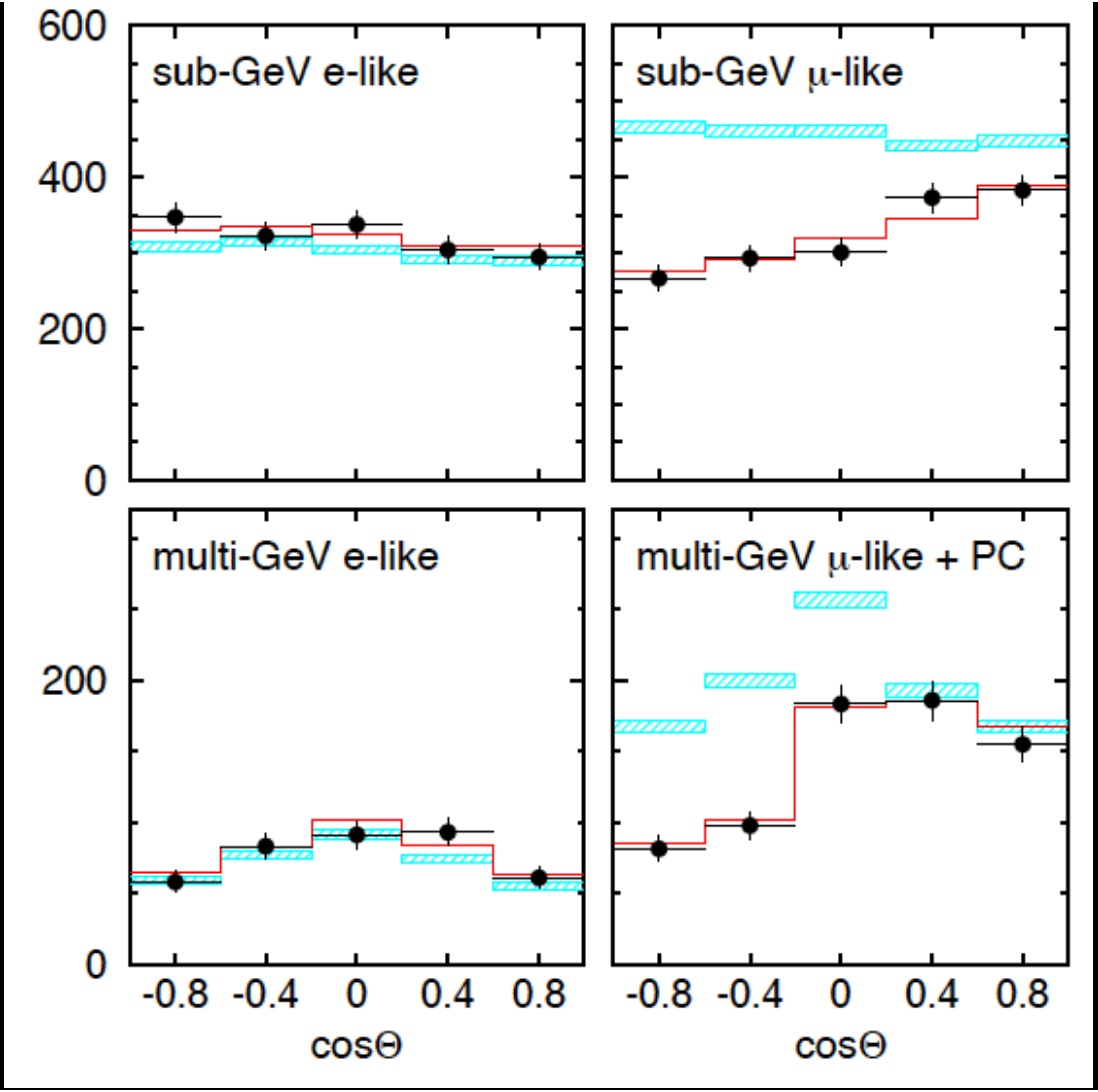


Super-Kamiokande

```
Run 8060 Event 7678869
99-10-29:14:09:48
Inner: 9144 hits, 85718 pE
Outer: -1 hits, 0 pE (in-time)
Trigger ID: 0x0f
ap veto:
Fully-Contained
```

upward throughgoing muon

THE "SMOKING GUN" PLOTS



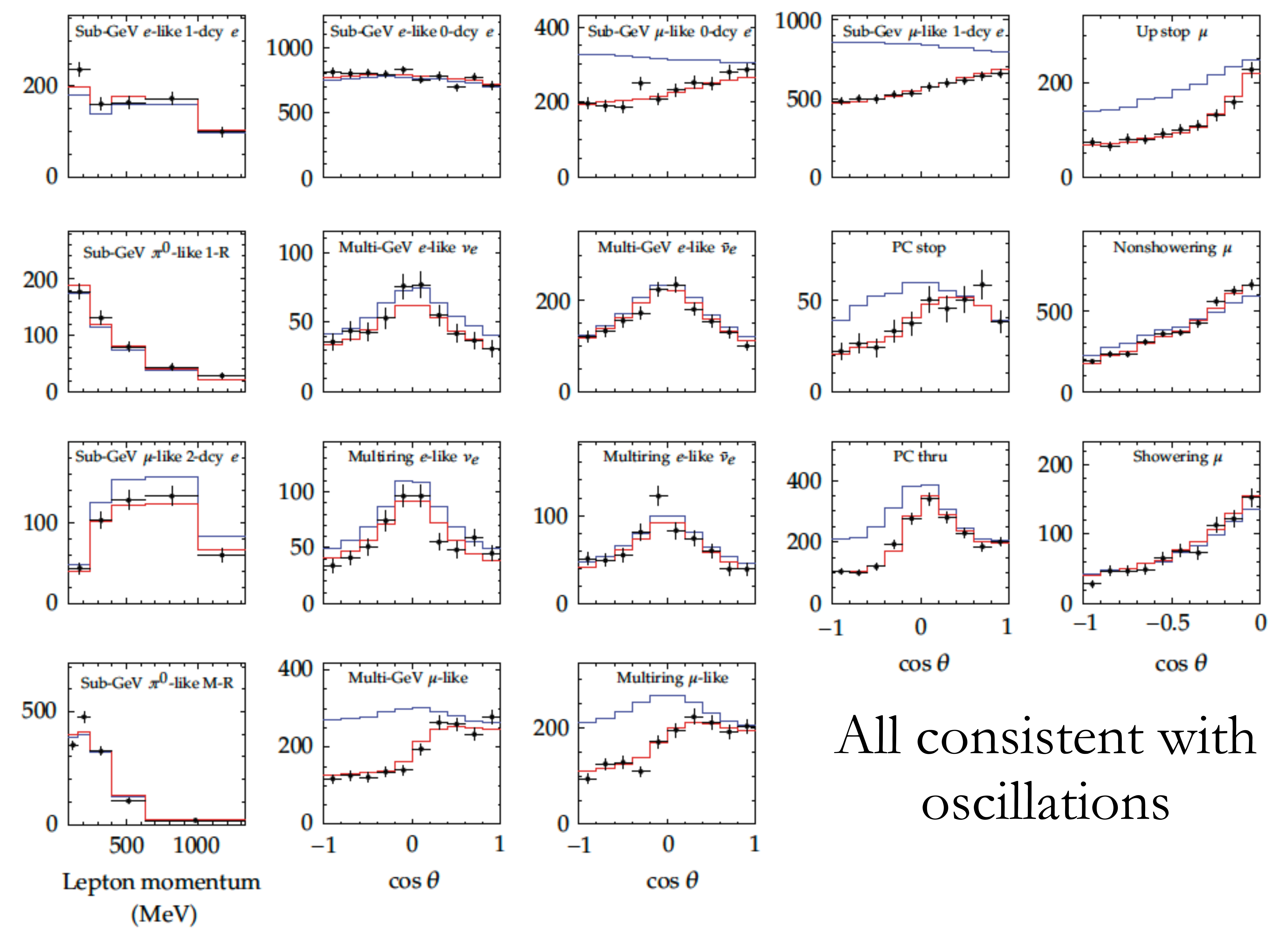
Expected, no oscillations

Fit to data, oscillations

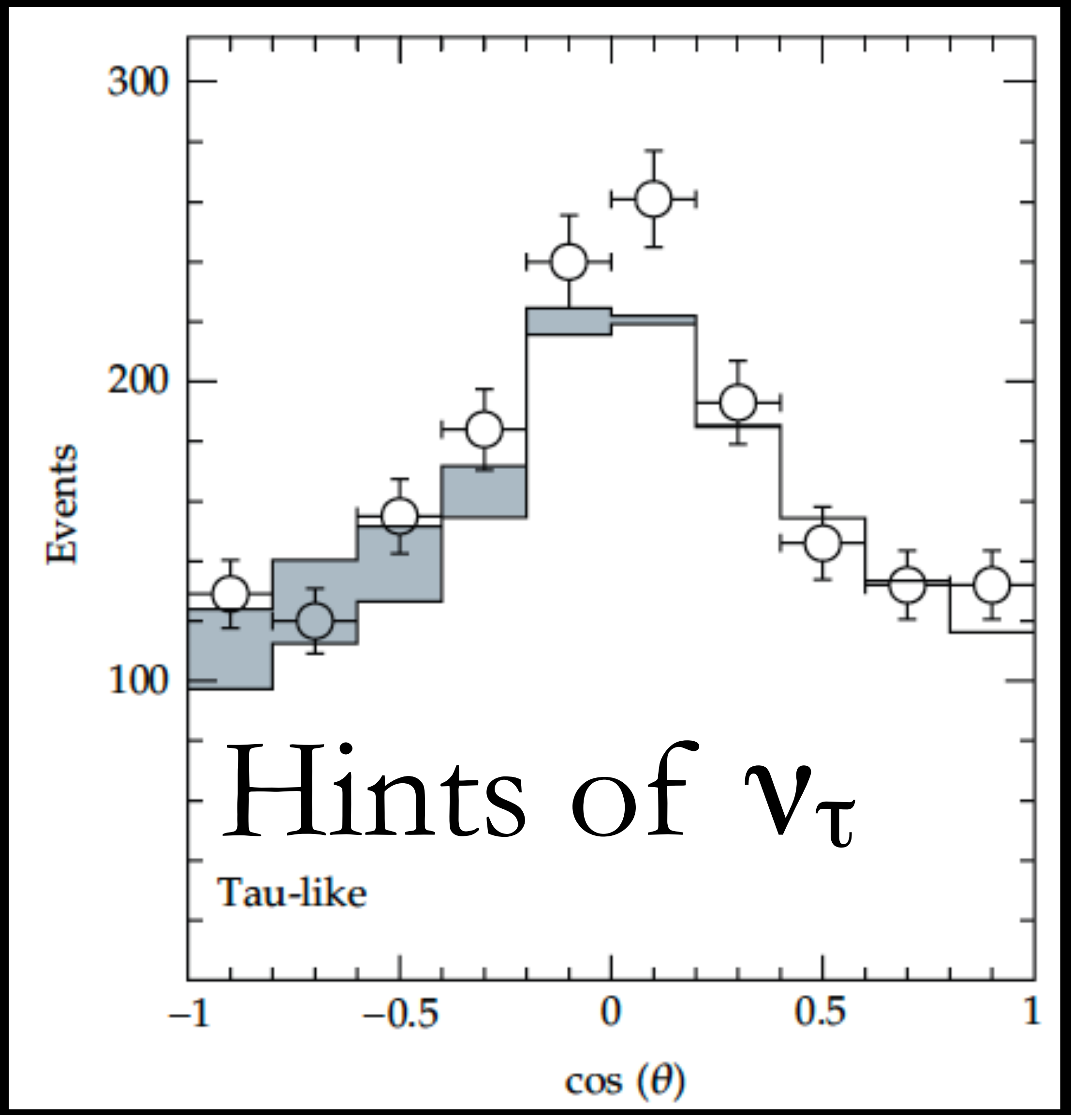
Neutrino "disappearance" depends on energy and direction (path length)

Discovery of neutrino oscillations!

A WEALTH OF DATA…

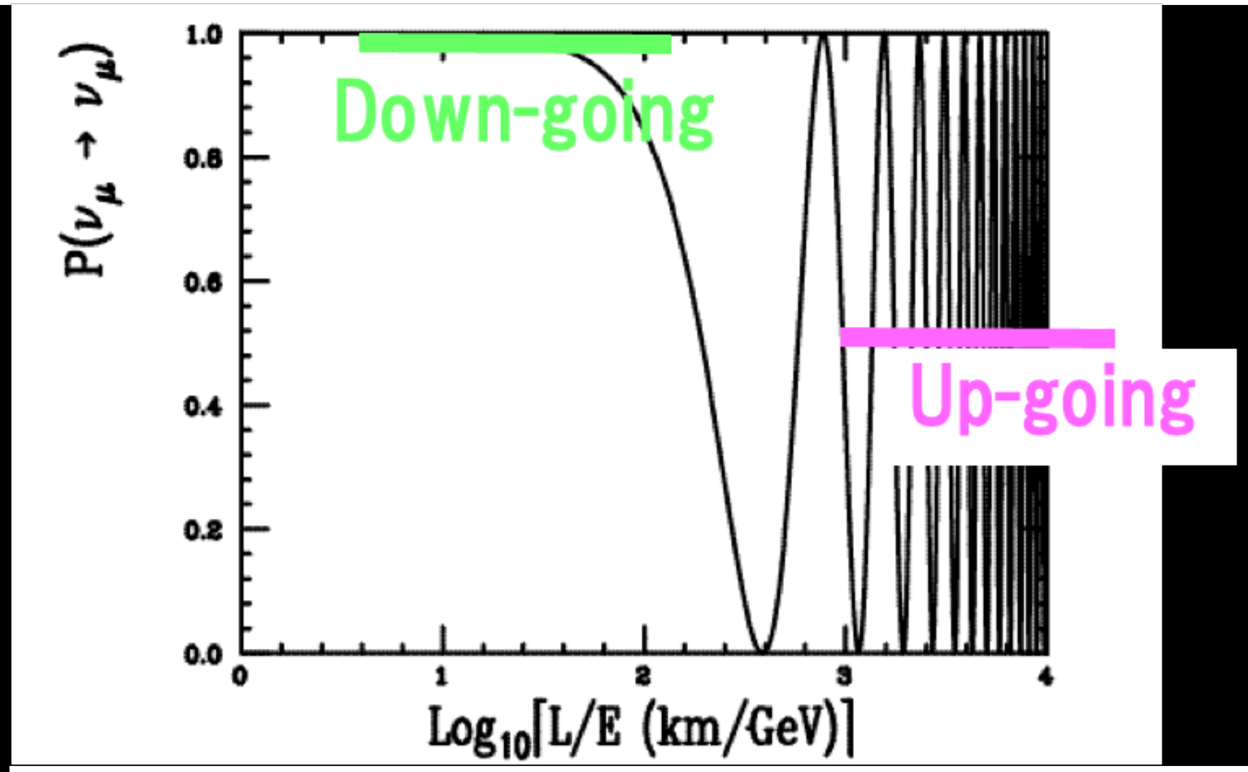


All consistent with oscillations

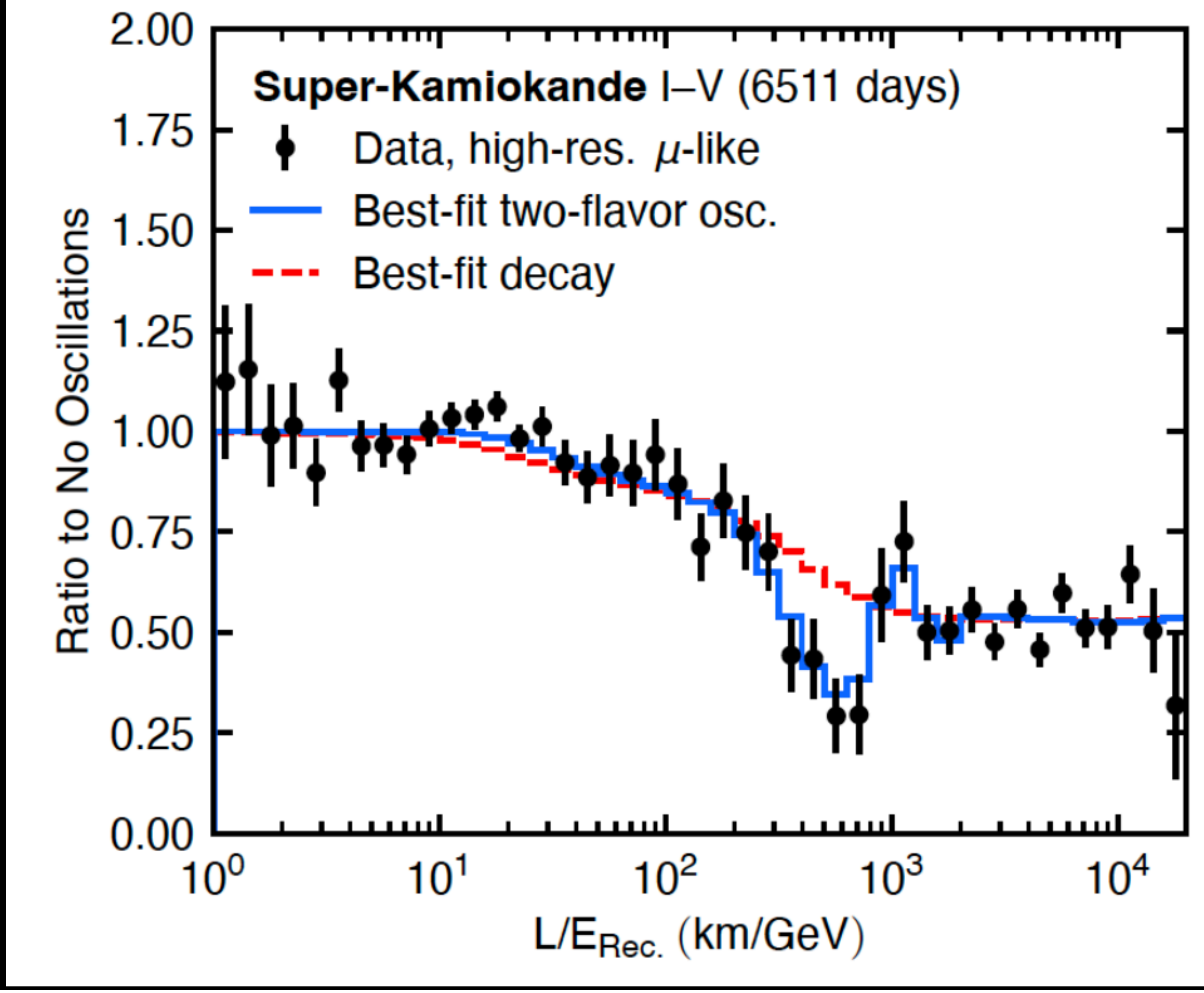


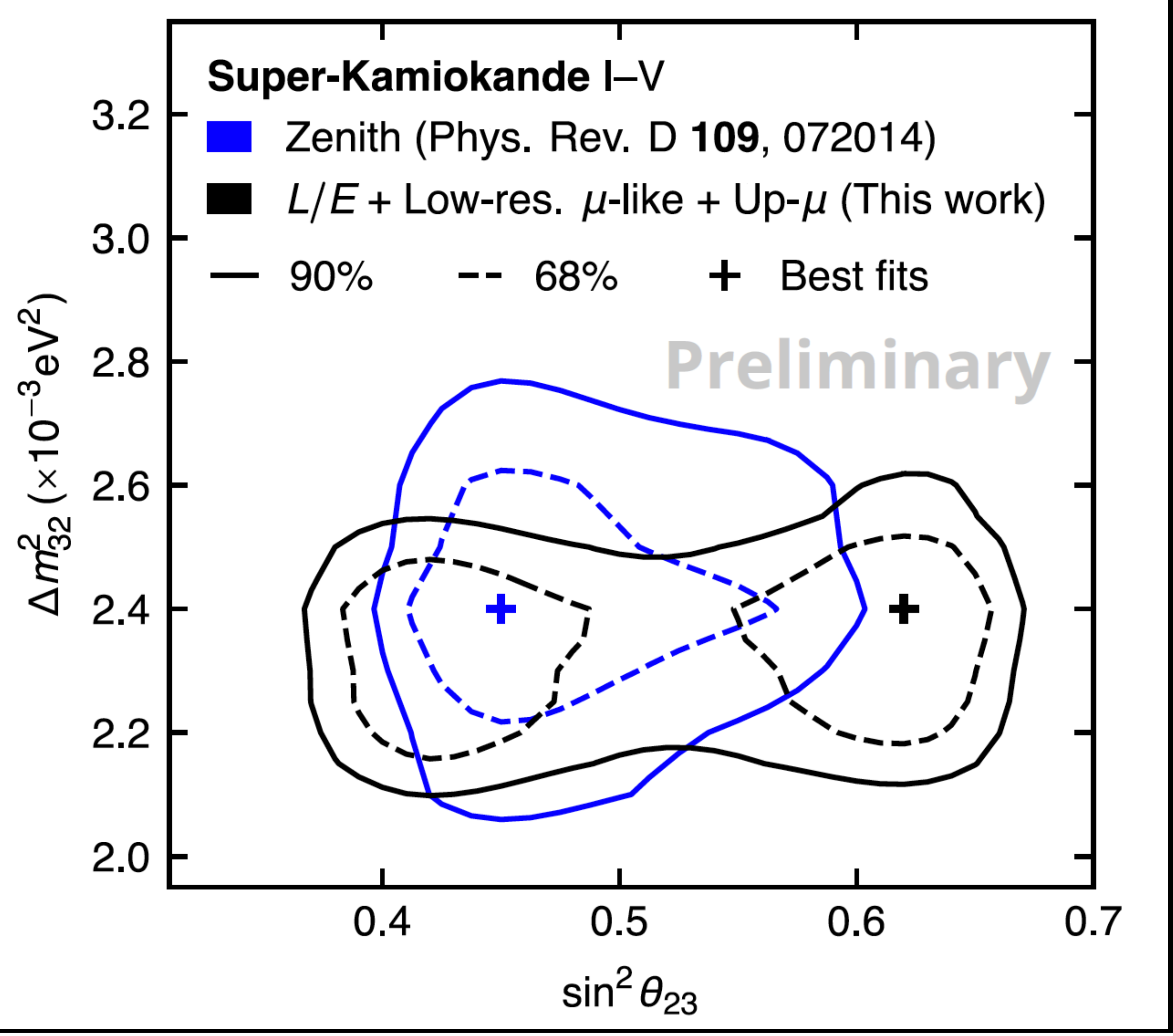
Hints of ν_τ

LATEST RESULTS, NEUTRINO 2024



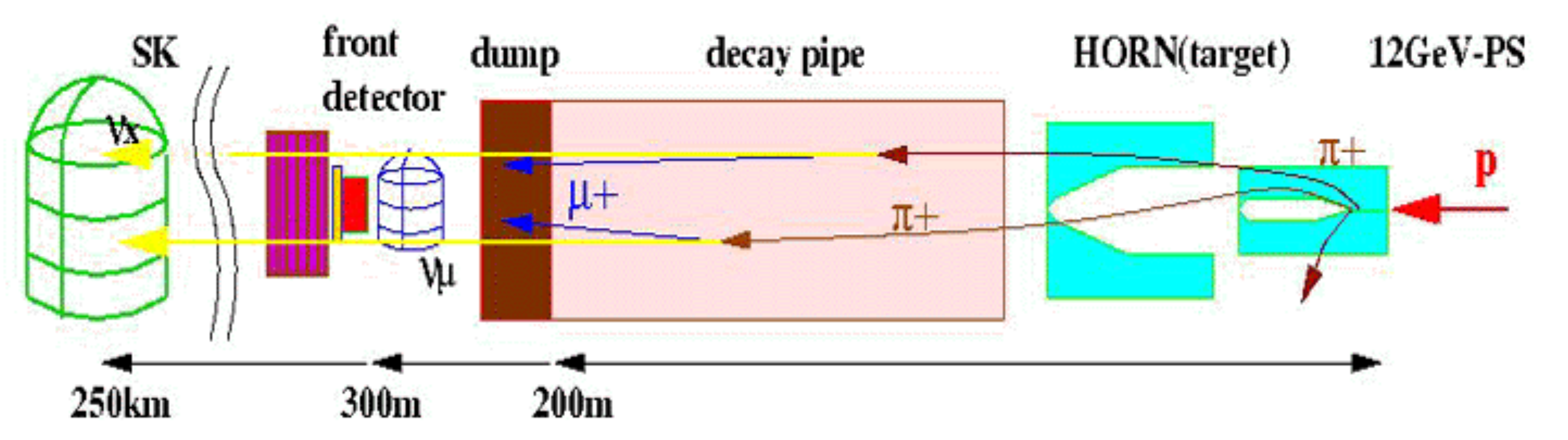
- Δm^2 much larger than for solar. Partly $\nu_\mu \to \nu_\tau$. Therefore these have to be different oscillations from what explains solar.

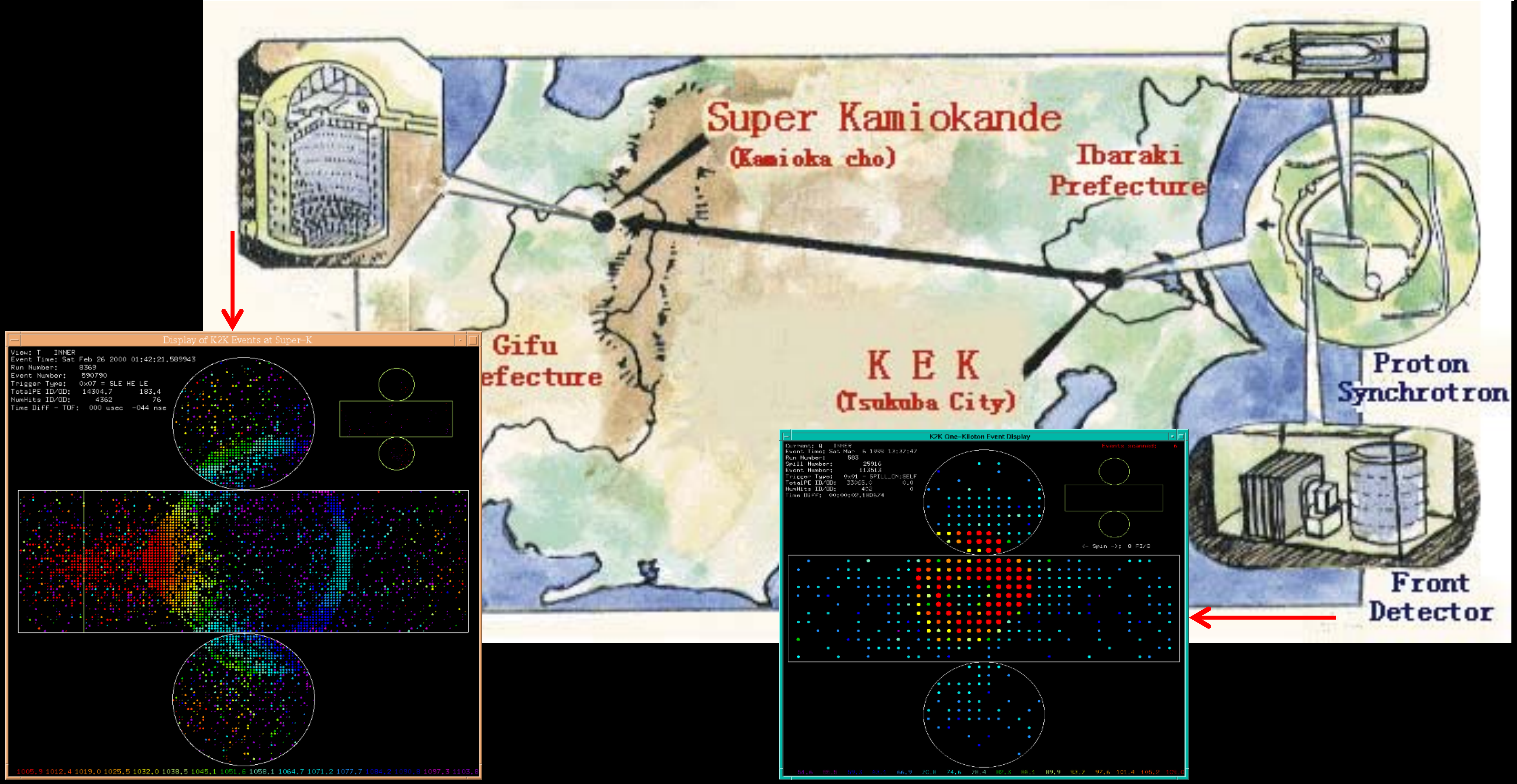




EARLY CONFIRMATION

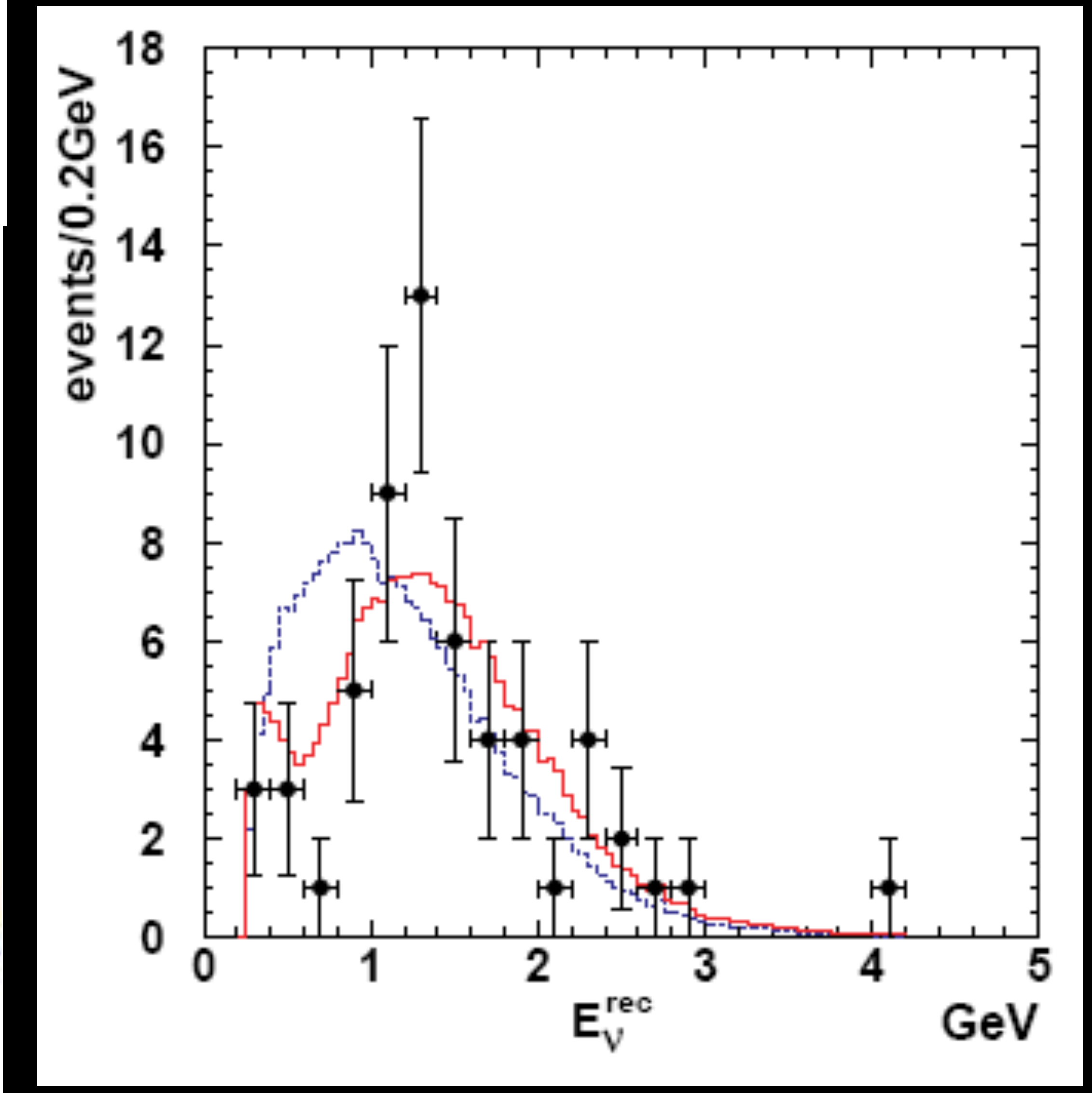
K2K - FROM KEK TO KAMIOKA





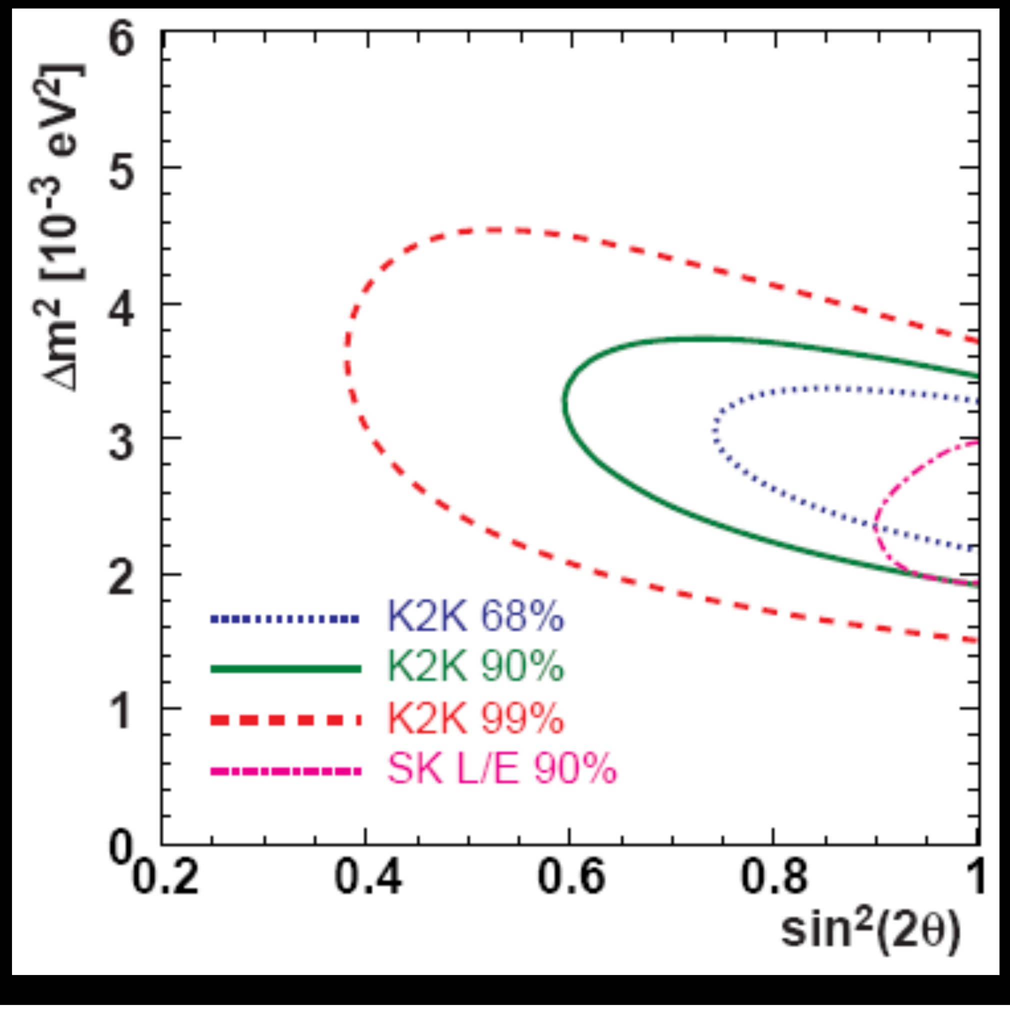
Far detector (FD) event Near detector (ND) event

- First long baseline accelerator neutrino experiment!

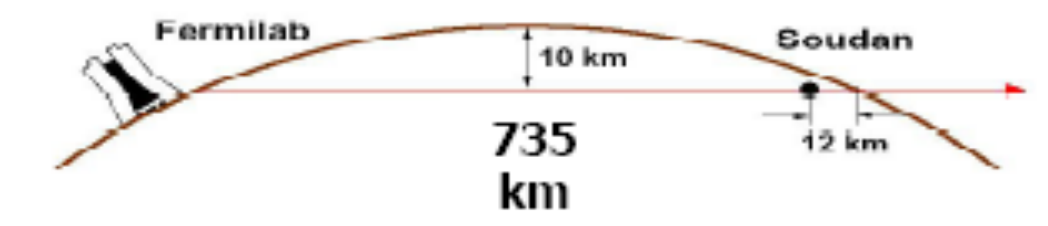


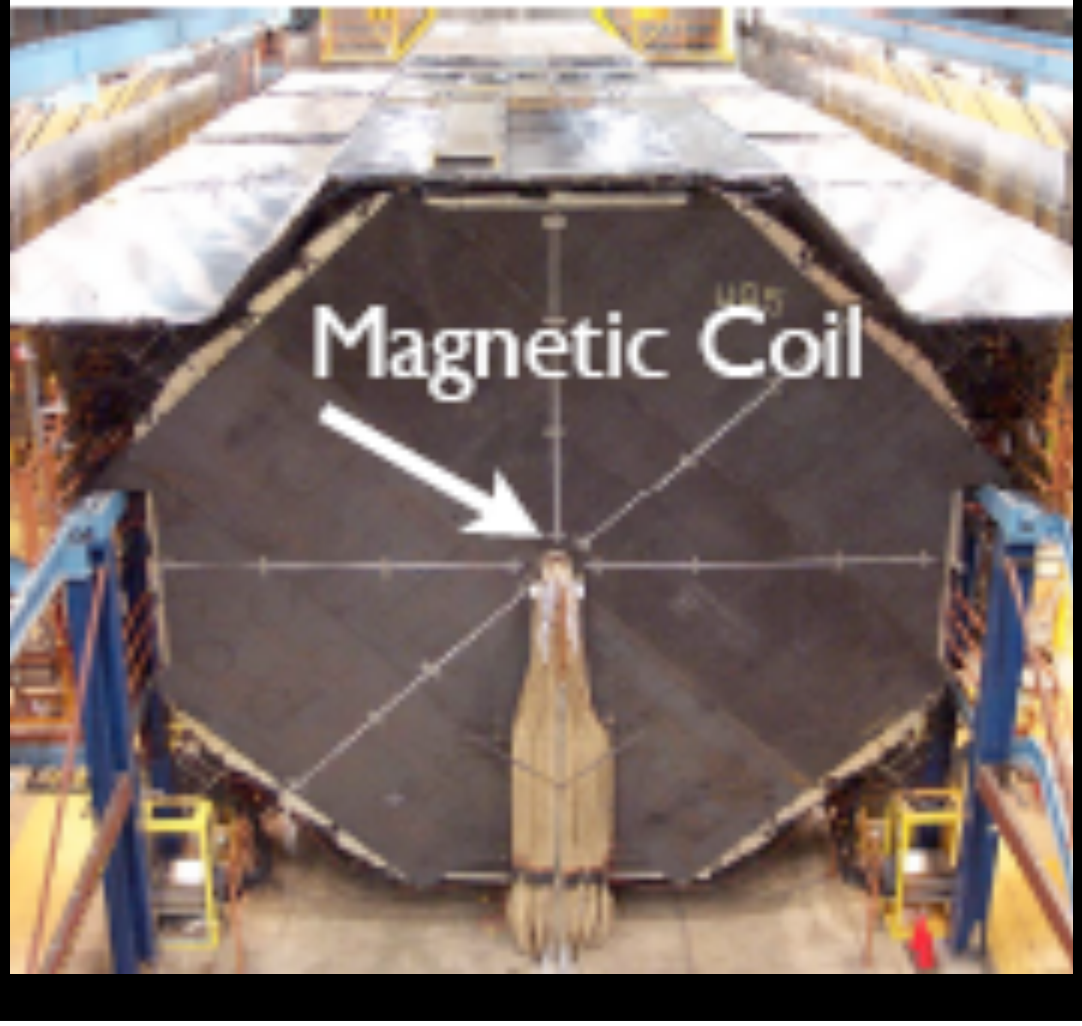
Use ND data to predict non-oscillated FD spectrum

Spectral distortion compatible with atmospheric oscillation parameters

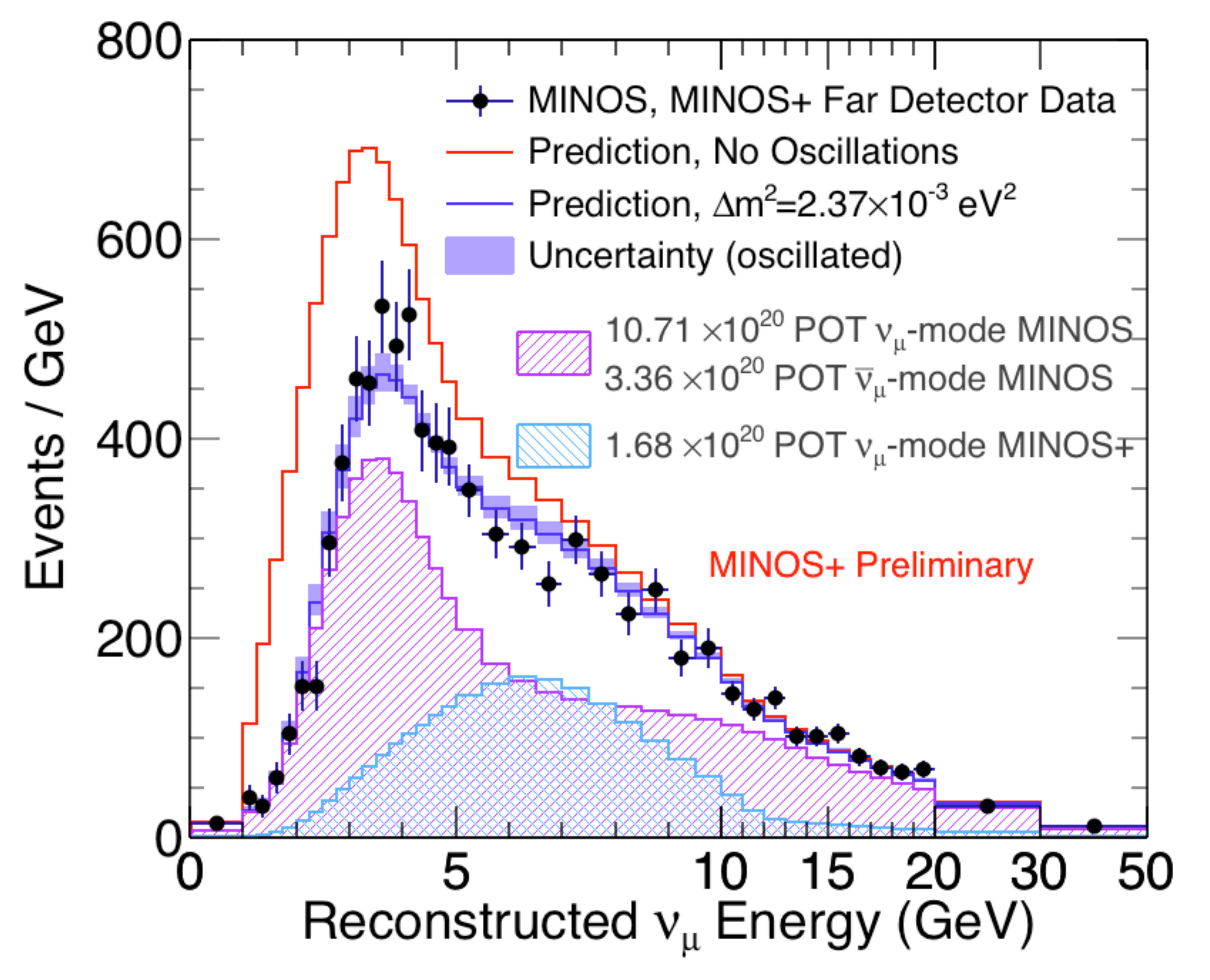


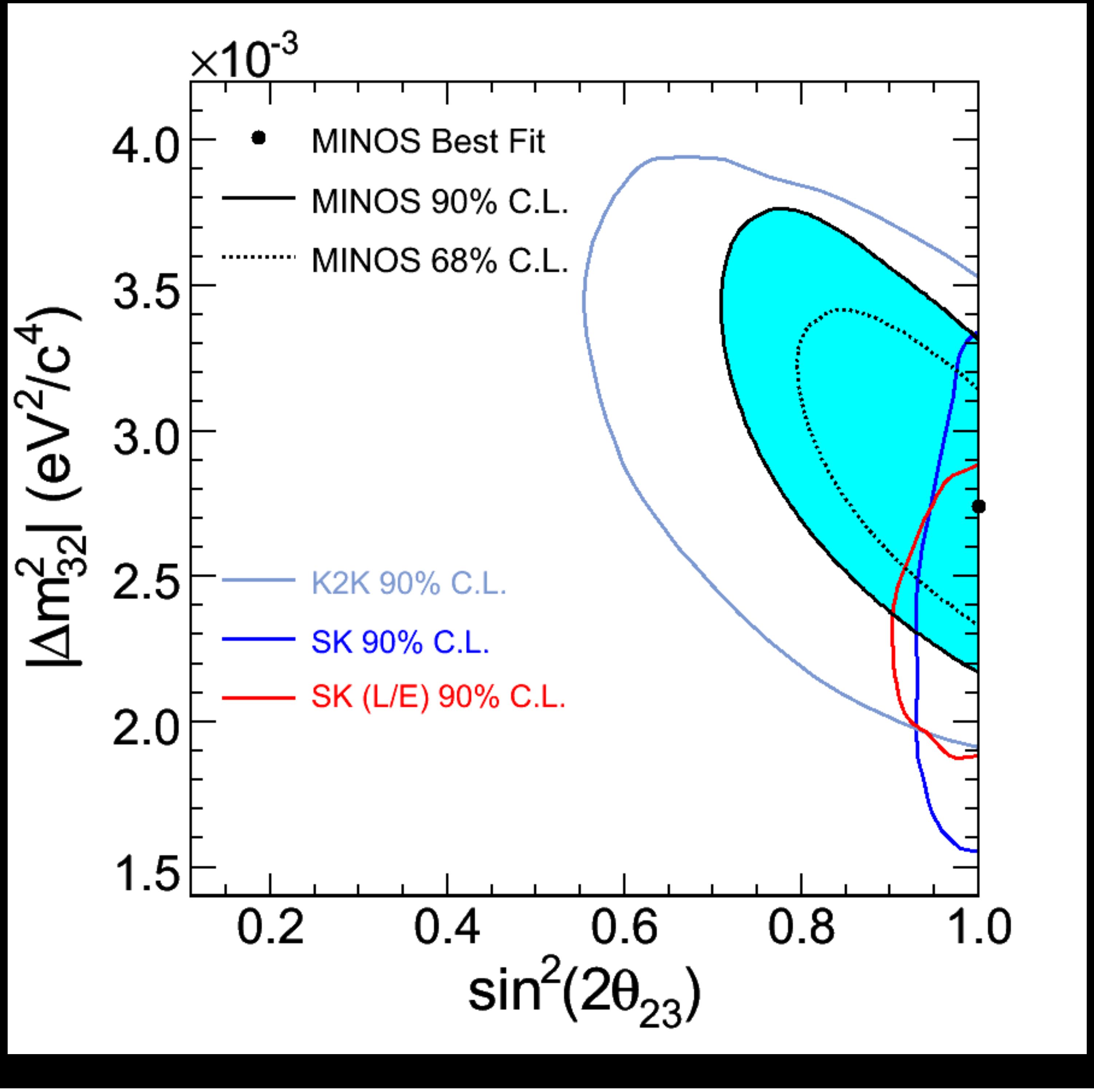
MINOS





- Long-baseline experiment at Soudan with Fermilab beam (735 km)
- W/r K2K, beam is more intense and higher energy (~same L/E)
- Magnetized iron and plastic scintillator detector: better energy resolution
- Confirms SK and K2K with better precision on Δm^2

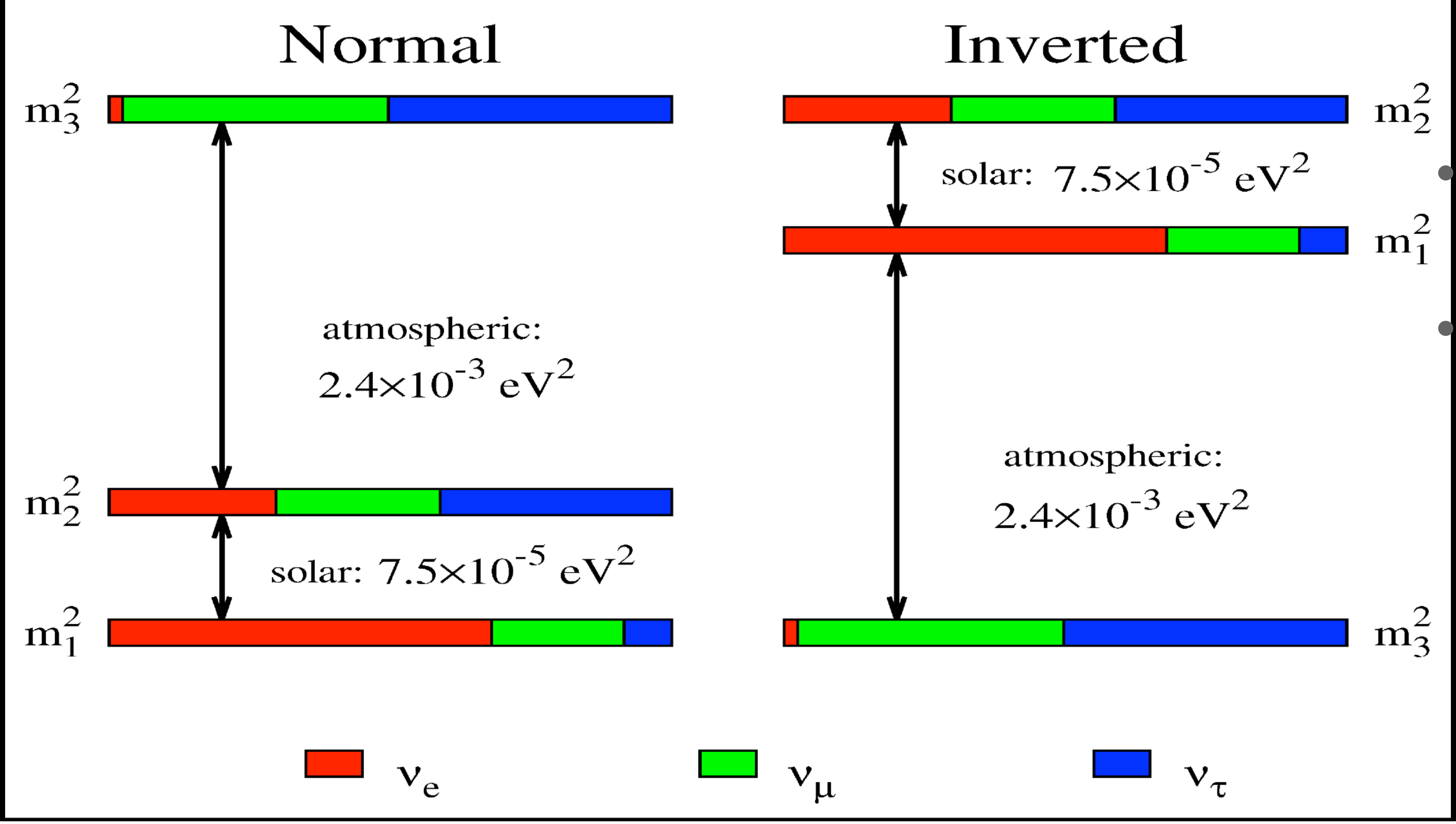




OSCILLATIONS WITH 3 FLAVORS

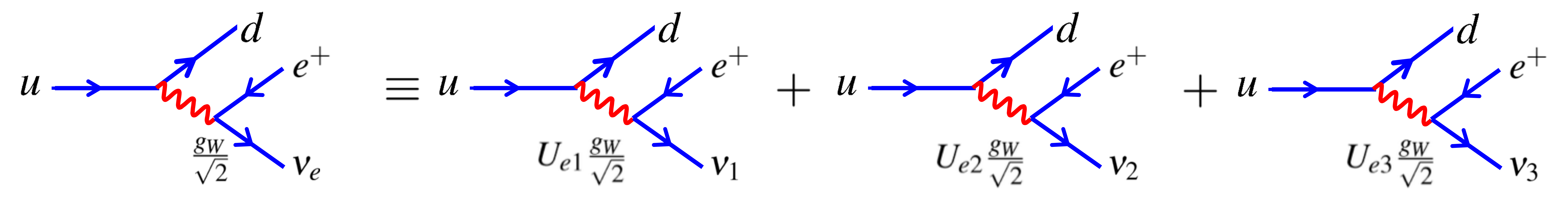
NEUTRINO MASS ORDERING

- With 3 neutrinos, have 2 independent mass splittings $m_3^2 - m_1^2 = (m_3^2 - m_2^2) + (m_2^2 - m_1^2)$
- But that's OK, since
  - $|\Delta m^2_{sol}| \sim |\Delta m^2_{reaLBL}| \sim |\Delta m^2_{21}| \sim 7.5 \times 10^{-5} eV^2$
  - $|\Delta m^2_{atm}| \sim |\Delta m^2_{accLBL}| \sim |\Delta m^2_{32}| \sim 2.4 \times 10^{-3} eV^2$
- MSW effect in the Sun: we know $\Delta m^2_{21} > 0$. Still, 2 possible orderings:



- $\Delta m^2_{31} \approx \Delta m^2_{32}$ is a common approximation but it's of course not true!
- How to determine the order?
  - make a precision measurement of $|\Delta m^2_{31}|$
  - measure sign of Δm^2_{32} as well, with matter effects

3 FLAVOR NEUTRINO MIXING



- Simple extension of the two-neutrino mechanism
  - U elements are complex, in the general case

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

- Mixing matrix has to be unitary to preserve probability

$$U^\dagger U = I \qquad \Rightarrow \qquad U^{-1} = U^\dagger = (U^*)^T$$

- Inverse matrix

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

- Unitarity constraints
  - 18 -> 9 d.o.f

$$\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}U^*_{e1} & U^*_{\mu1} & U^*_{\tau1}\\ U^*_{e2} & U^*_{\mu2} & U^*_{\tau2}\\ U^*_{e3} & U^*_{\mu3} & U^*_{\tau3}\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}$$

SURVIVAL PROBABILITY

- flavor states $|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$
- mass states

$\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$ $\nu_k = \nu_1, \nu_2, \nu_3$

$$|\psi(t=0)\rangle = |\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

$$|\psi(L)\rangle = U_{e1}|\nu_1\rangle e^{-i\phi_1} + U_{e2}|\nu_2\rangle e^{-i\phi_2} + U_{e3}|\nu_3\rangle e^{-i\phi_3}$$

$$\phi_i = p_i.x = E_i t - |\vec{p}|L = (E_i - |\vec{p}_i|)L$$

expressing ν_1, ν_2, ν_3 as a function of ν_e, ν_μ, ν_τ and re-arranging the terms

$$\begin{aligned} |\psi(L)\rangle &= (U_{e1}U^*_{e1}e^{-i\phi_1} + U_{e2}U^*_{e2}e^{-i\phi_2} + U_{e3}U^*_{e3}e^{-i\phi_3})|\nu_e\rangle \\ &+ (U_{e1}U^*_{\mu 1}e^{-i\phi_1} + U_{e2}U^*_{\mu 2}e^{-i\phi_2} + U_{e3}U^*_{\mu 3}e^{-i\phi_3})|\nu_\mu\rangle \\ &+ (U_{e1}U^*_{\tau 1}e^{-i\phi_1} + U_{e2}U^*_{\tau 2}e^{-i\phi_2} + U_{e3}U^*_{\tau 3}e^{-i\phi_3})|\nu_\tau\rangle \end{aligned}$$

$$\begin{aligned} P(\nu_e \to \nu_e) &= |\langle \nu_e|\psi(L)\rangle|^2 \\ &= |U_{e1}U^*_{e1}e^{-i\phi_1} + U_{e2}U^*_{e2}e^{-i\phi_2} + U_{e3}U^*_{e3}e^{-i\phi_3}|^2 \end{aligned}$$

making use of unitarity relations

$$\begin{aligned} P(\nu_e \to \nu_e) = 1 &+ 2|U_{e1}|^2|U_{e2}|^2\Re\{[e^{-i(\phi_1-\phi_2)} - 1]\} \\ &+ 2|U_{e1}|^2|U_{e3}|^2\Re\{[e^{-i(\phi_1-\phi_3)} - 1]\} \\ &+ 2|U_{e2}|^2|U_{e3}|^2\Re\{[e^{-i(\phi_2-\phi_3)} - 1]\} \end{aligned}$$

SURVIVAL PROBABILITY

$$\begin{aligned}P(\nu_e \rightarrow \nu_e) = 1 \quad &+ \quad 2|U_{e1}|^2|U_{e2}|^2\Re\{[e^{-i(\phi_1-\phi_2)} - 1]\}\\ &+ \quad 2|U_{e1}|^2|U_{e3}|^2\Re\{[e^{-i(\phi_1-\phi_3)} - 1]\}\\ &+ \quad 2|U_{e2}|^2|U_{e3}|^2\Re\{[e^{-i(\phi_2-\phi_3)} - 1]\}\end{aligned}$$

$$\begin{aligned}\Re\{e^{-i(\phi_1-\phi_2)} - 1\} &= \cos(\phi_2 - \phi_1) - 1\\ &= -2\sin^2\left(\frac{\phi_2-\phi_1}{2}\right)\\ \boxed{\phi_i \approx \frac{m_i^2}{2E}L} \longrightarrow &= -2\sin^2\left(\frac{(m_2^2-m_1^2)L}{4E}\right)\end{aligned}$$

$$\Delta m_{21}^2 = m_2^2 - m_1^2$$

$$\Delta_{21} = \frac{(m_2^2-m_1^2)L}{4E} = \frac{\Delta m_{21}^2 L}{4E} = 1.27\frac{\Delta m_{21}^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}$$

$$\boxed{P(\nu_e \rightarrow \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2\sin^2\Delta_{21} - 4|U_{e1}|^2|U_{e3}|^2\sin^2\Delta_{31} - 4|U_{e2}|^2|U_{e3}|^2\sin^2\Delta_{32}}$$

- Let’s examine this. Survival (or disappearance) probability:
  - Depends only on module of U elements, not on phases
  - Depends on Δs only via $\sin^2$, so does not depend on sign of any Δm^2.

GENERAL EXPRESSION

- General expression for both survival and oscillation:

$$A^{ij}_{\alpha\beta} = U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}$$

$$P\left(\nu_\alpha \to \nu_\beta\right) = \left|\langle \nu_\beta | \nu_\alpha(L)\rangle\right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i\left(\frac{m_i^2 L}{2E}\right)} \right|^2$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re e A^{ij}_{\alpha\beta} sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2 \sum_{i>j} \Im m A^{ij}_{\alpha\beta} sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

- Let’s examine this as well. If $\alpha \neq \beta$, oscillation (or appearance) probability:
  - Depends also on phases
  - Depends on Δs also via a sin term, so it does depend on sign of Δm^2
    - But not if U is real, since in that case $\mathscr{I}m A^{ij}_{\alpha\beta} = 0$

TIME REVERSAL

$$P\left(\nu_\beta \to \nu_\alpha\right) = \left|\langle \nu_\alpha | \nu_\beta(L)\rangle\right|^2 = \left|\sum_i U_{\alpha i} U^*_{\beta i} e^{-i\left(\frac{m_i^2 L}{2E}\right)}\right|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re e(A^{ij}_{\alpha\beta})^* sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \Im m(A^{ij}_{\alpha\beta})^* sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

- If the U matrix is not real, then

$$P\left(\nu_\alpha \to \nu_\beta\right) \neq P\left(\nu_\beta \to \nu_\alpha\right)$$

- Not time-symmetric!

CP AND CPT IN WEAK INTERACTIONS

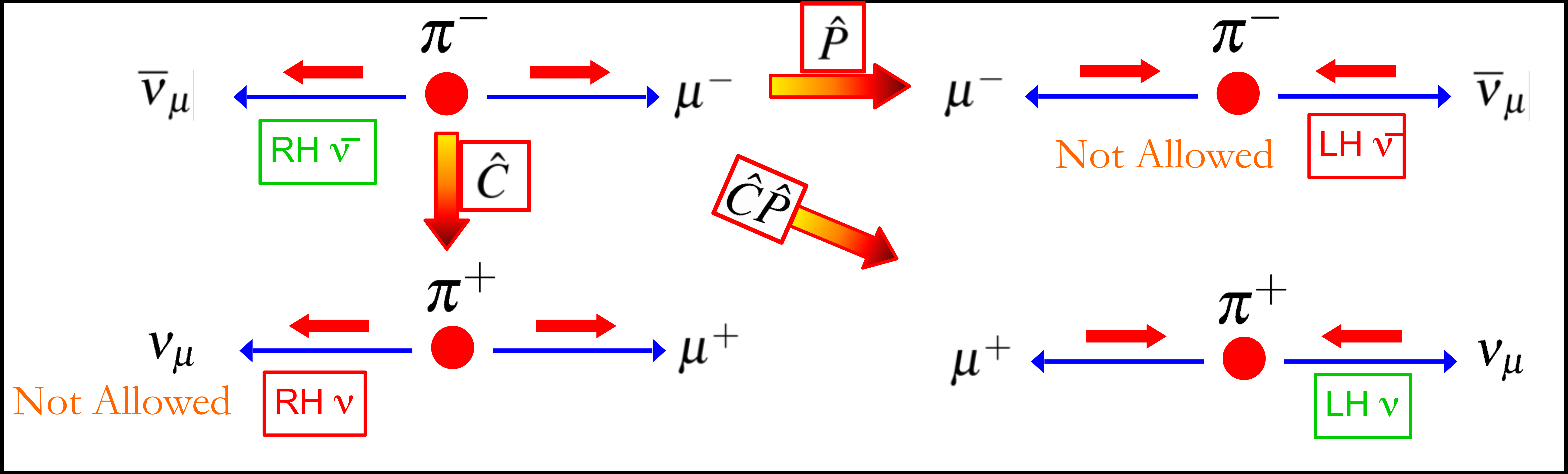
- In addition to parity, two other discrete symmetries

Parity $\hat{P} : \vec{r} \longrightarrow -\vec{r}$

Time Reversal $\hat{T} : t \longrightarrow -t$

Charge Conjugation $\hat{C} :$ Particle ⟷ Anti-particle

- Weak interactions violate P. CPT must be conserved. But what about C and CP ?



Appears invariant…

CP IN NEUTRINO OSCILLATIONS

- Effect of discrete symmetries in neutrino oscillations:

$\boxed{\text{T}}$	$\nu_e \to \nu_\mu$	$\xrightarrow{\hat{T}}$	$\nu_\mu \to \nu_e$
$\boxed{\text{CP}}$	$\nu_e \to \nu_\mu$	$\xrightarrow{\hat{C}\hat{P}}$	$\overline{\nu}_e \to \overline{\nu}_\mu$
$\boxed{\text{CPT}}$	$\nu_e \to \nu_\mu$	$\xrightarrow{\hat{C}\hat{P}\hat{T}}$	$\overline{\nu}_\mu \to \overline{\nu}_e$

- CPT conservation implies: $P(\nu_e \to \nu_\mu) = P(\overline{\nu}_\mu \to \overline{\nu}_e)$ $P(\nu_\mu \to \nu_e) = P(\overline{\nu}_e \to \overline{\nu}_\mu)$

- But we saw that, if the PMNS matrix is not real, then $P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$
- Therefore $P(\nu_e \to \nu_\mu) \neq P(\overline{\nu}_e \to \overline{\nu}_\mu)$

- So, if the PMNS matrix is not real, CP is violated in neutrino oscillations!

IMPORTANT IMPLICATIONS ON THE MATTER/ANTIMATTER ASYMMETRY IN THE UNIVERSE!

PMNS MATRIX PARAMETRIZATION

- PMNS matrix degrees of freedom?
  - 3x3 complex numbers, so 18 real numbers. Minus 9 unitarity constraints = 9 d.o.f
  - 3 real angles and 6 complex phases, but the charged leptons are Dirac particles, their fields can be phase rotated.
  - So 3 angles - $\theta_{12}, \theta_{13}, \theta_{23}$ - and 3 phases $(\delta_{CP}, \alpha, \beta)$

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

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

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- The Majorana phases (α, β) appear in the diagonal, so no effect on oscillations

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\theta_{23} \approx 49^\circ \quad \text{Atmospheric}} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar} \quad \theta_{12} \approx 33.4^\circ}$$

OSCILLATION PROBABILITY

- We can now write the oscillation probability as a function of the angles and phase

$$\begin{aligned} P(\nu_e \to \nu_\mu) &= |\langle \nu_\mu | \psi(L) \rangle|^2 \\ &= |U_{e1}U^*_{\mu 1}e^{-i\phi_1} + U_{e2}U^*_{\mu 2}e^{-i\phi_2} + U_{e3}U^*_{\mu 3}e^{-i\phi_3}|^2 \end{aligned}$$

$$\begin{aligned} P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq{} & \sin^2\theta_{23}\sin^2 2\theta_{13} \\ & \frac{\sin^2(\Delta_{31} - \boxed{aL})}{(\Delta_{31} - \boxed{aL})^2}\Delta_{31}^2 \\ & + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12} \\ & \times \frac{\sin(\Delta_{31} - \boxed{aL})}{(\Delta_{31} - \boxed{aL})}\Delta_{31} \\ & \times \frac{\sin\boxed{aL}}{\boxed{aL}}\Delta_{21}\cos(\Delta_{31} \boxed{\pm \delta_{\mathrm{CP}}}) \\ & + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2 \end{aligned}$$

Matter Effects

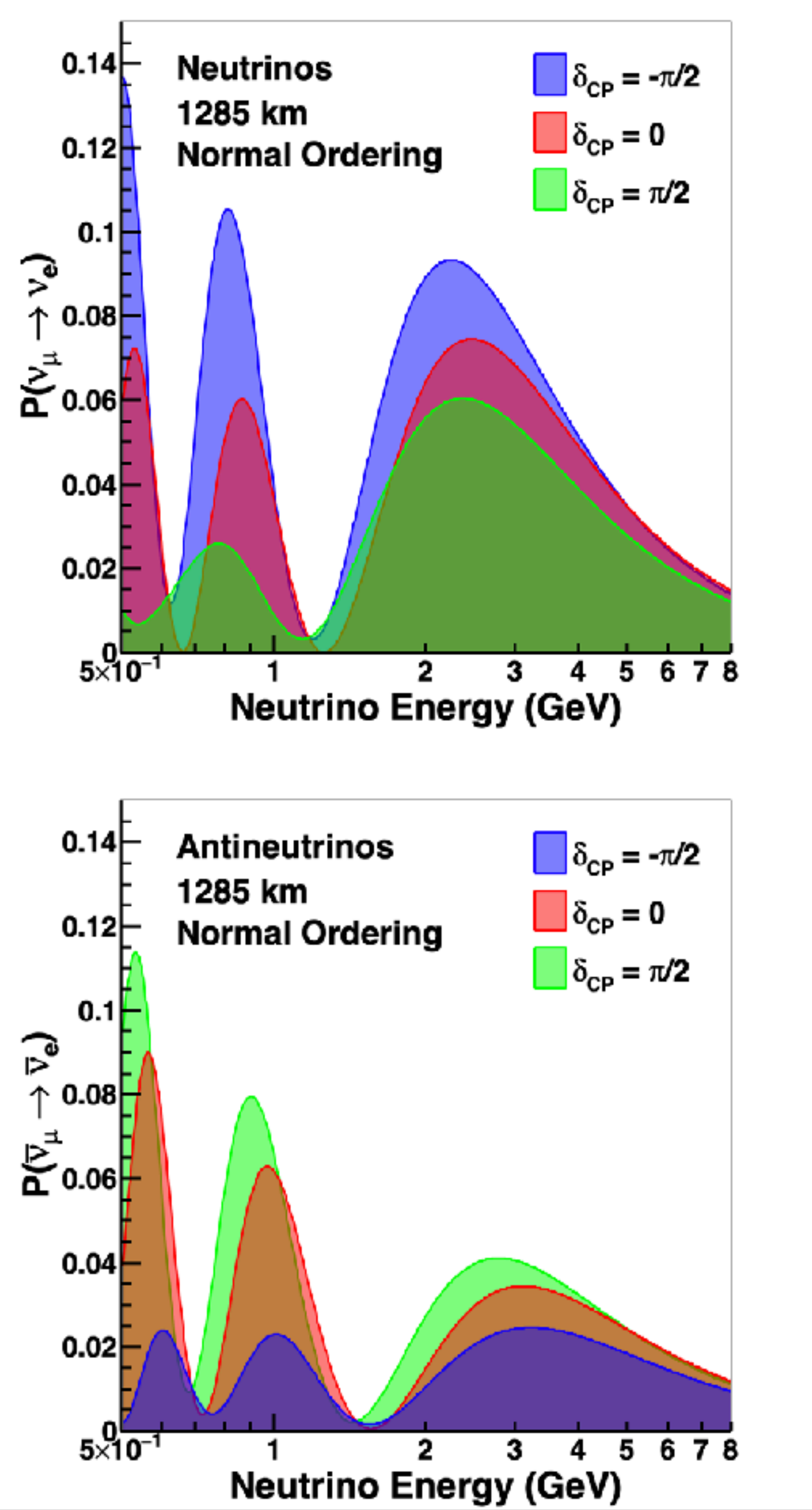
$$a = \pm\frac{G_F N_e}{\sqrt{2}}$$

+Neutrinos

– Antineutrinos

CP violation

$$\Delta_{ij} = 1.267\,\Delta m^2_{ij} L/E_\nu$$



BEST STRATEGY FOR EACH ANGLE?

- Since the mass splittings are quite different, the best experiment to measure each mixing angle is different

VACUUM OSCILLATION LENGTH	E ~3 MEV (REACTORS)	E ~1 GEV (ATM, ACC)
$\lvert\Delta m^2_{21}\rvert \sim 7.5\times10^{-5}eV^2$	50 KM (LBL)	16,000 KM (TOO BIG!)
$\lvert\Delta m^2_{13}\rvert \sim \lvert\Delta m^2_{23}\rvert \sim 2.4\times10^{-3}eV^2$	1.5 KM (SBL)	515 KM (LBL)

S(L)BL=
Short (Long)
Baseline

ACC LBL

REACTOR SBL, ACC LBL

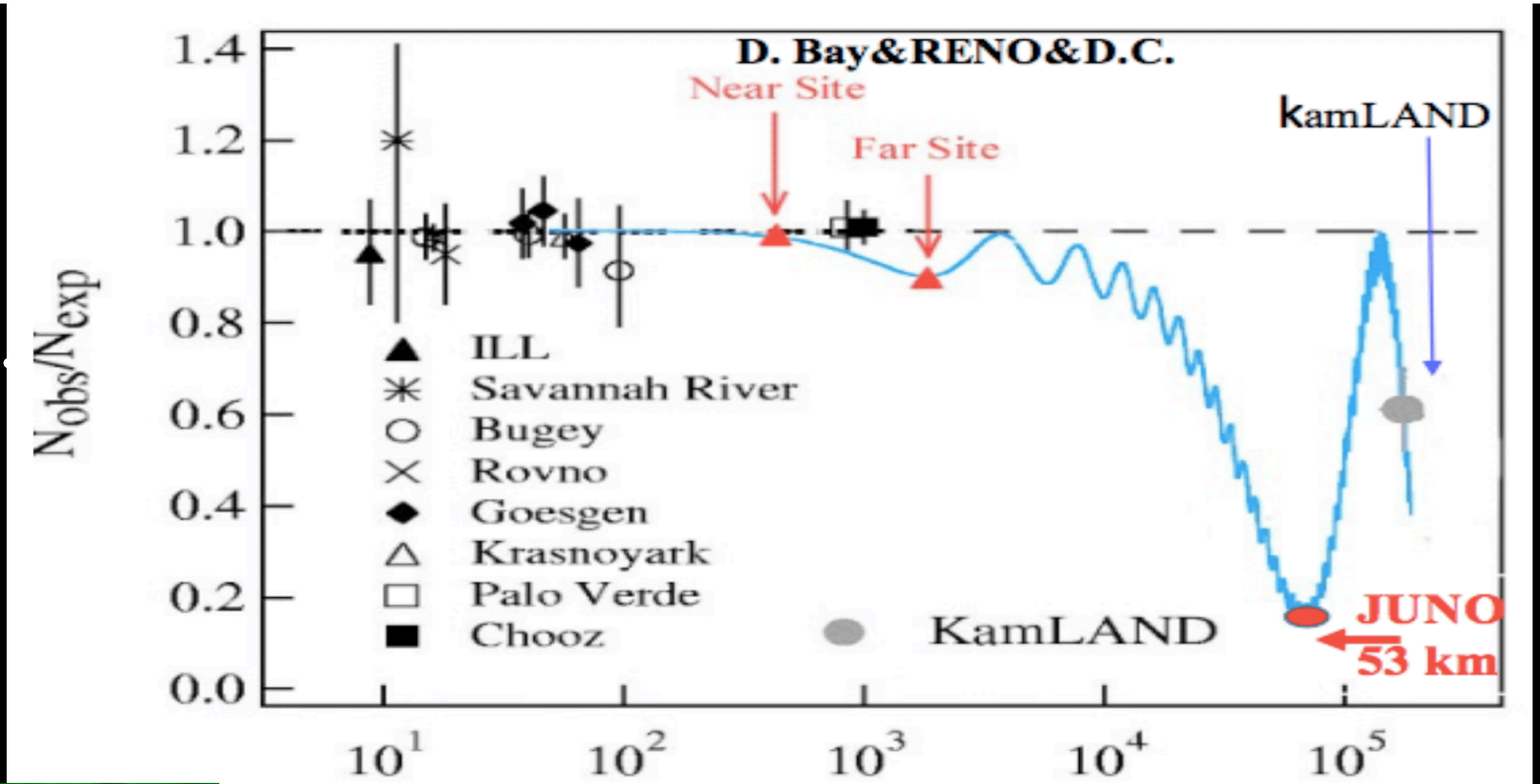
SOLAR (MSW), REACTOR LBL

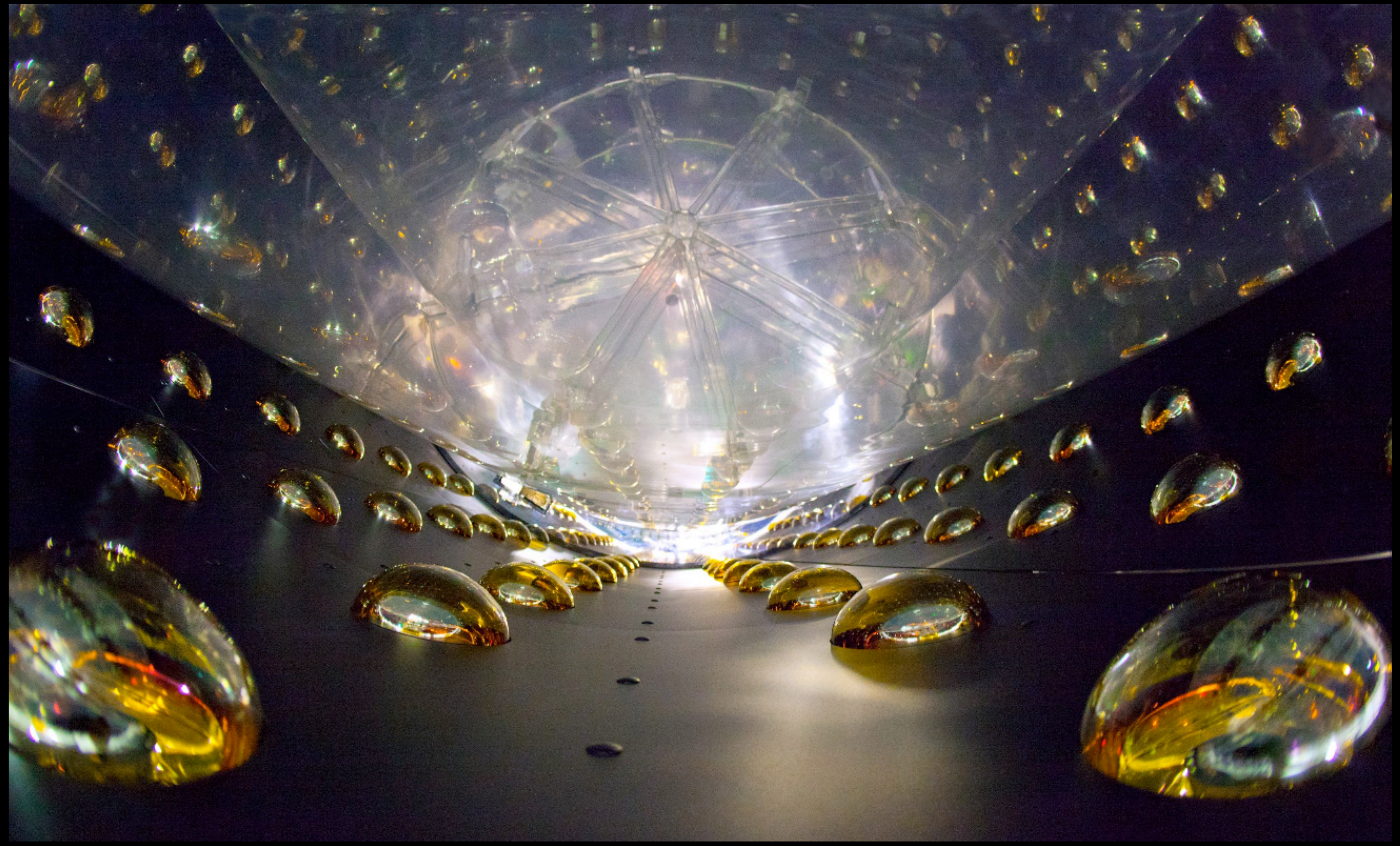
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

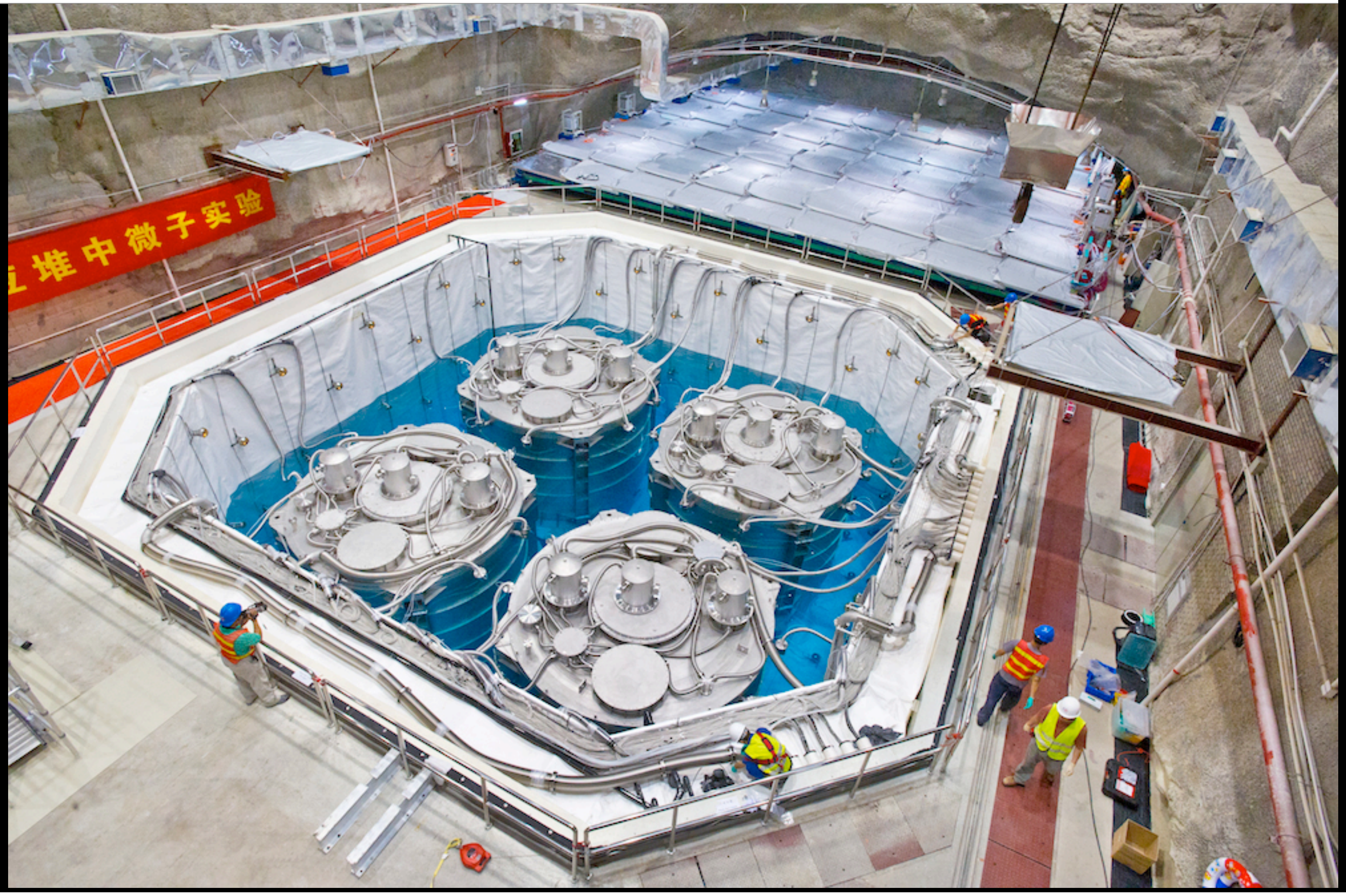
CURRENT STATUS, REACTOR AND ACCELERATOR EXPERIMENTS

DAYA BAY AND THETA 13

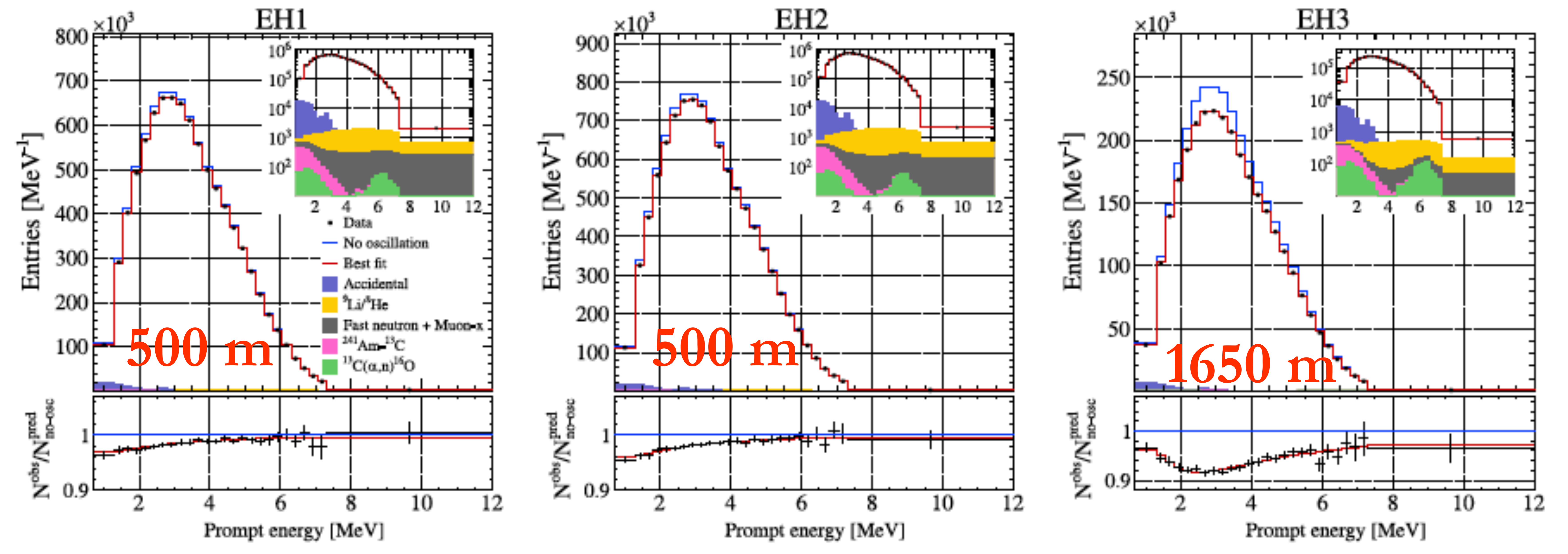
- Next: how to measure θ_{13}?
  - Coupled to Δm^2_{31}. At reactor neutrino energies, oscillation length ~ 1 km. Previous exp. too close.
  - Also, if θ_{13} is small, amplitude also small.
- The key experiment was Daya Bay in China
  - Two sets of near detectors, one of far detectors
  - All identical, so systematic uncertainties cancel

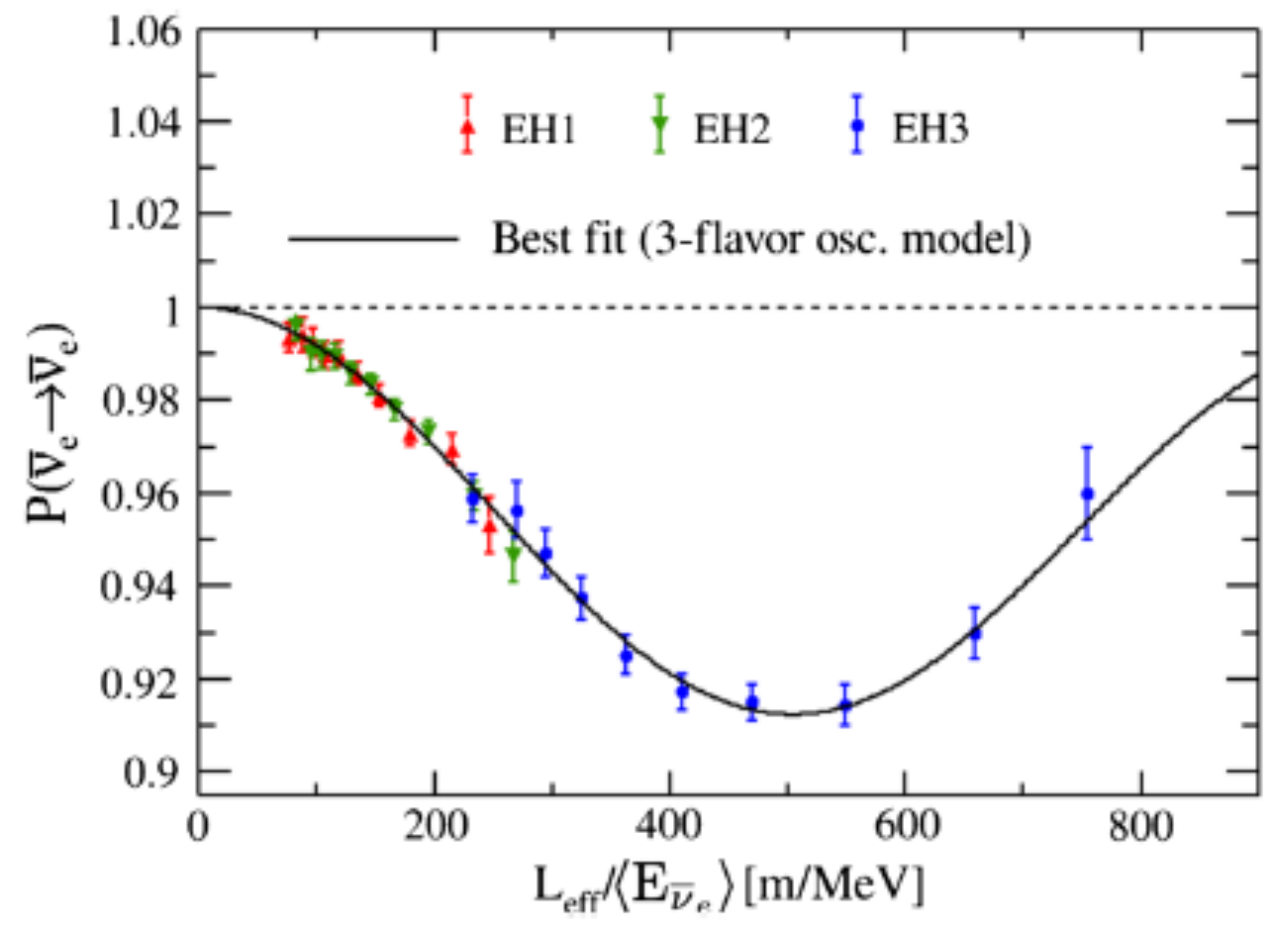




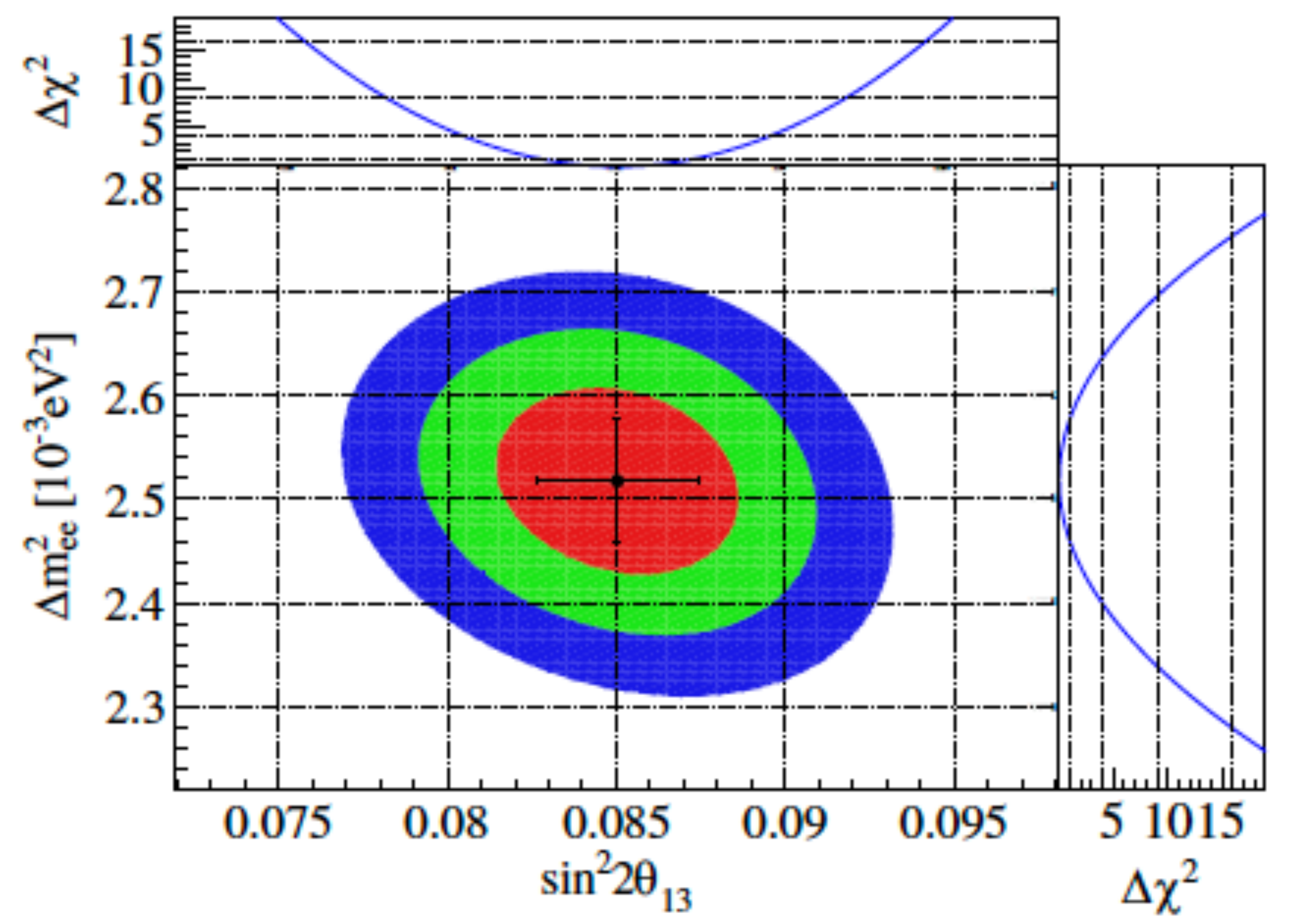


DAYA BAY RESULTS



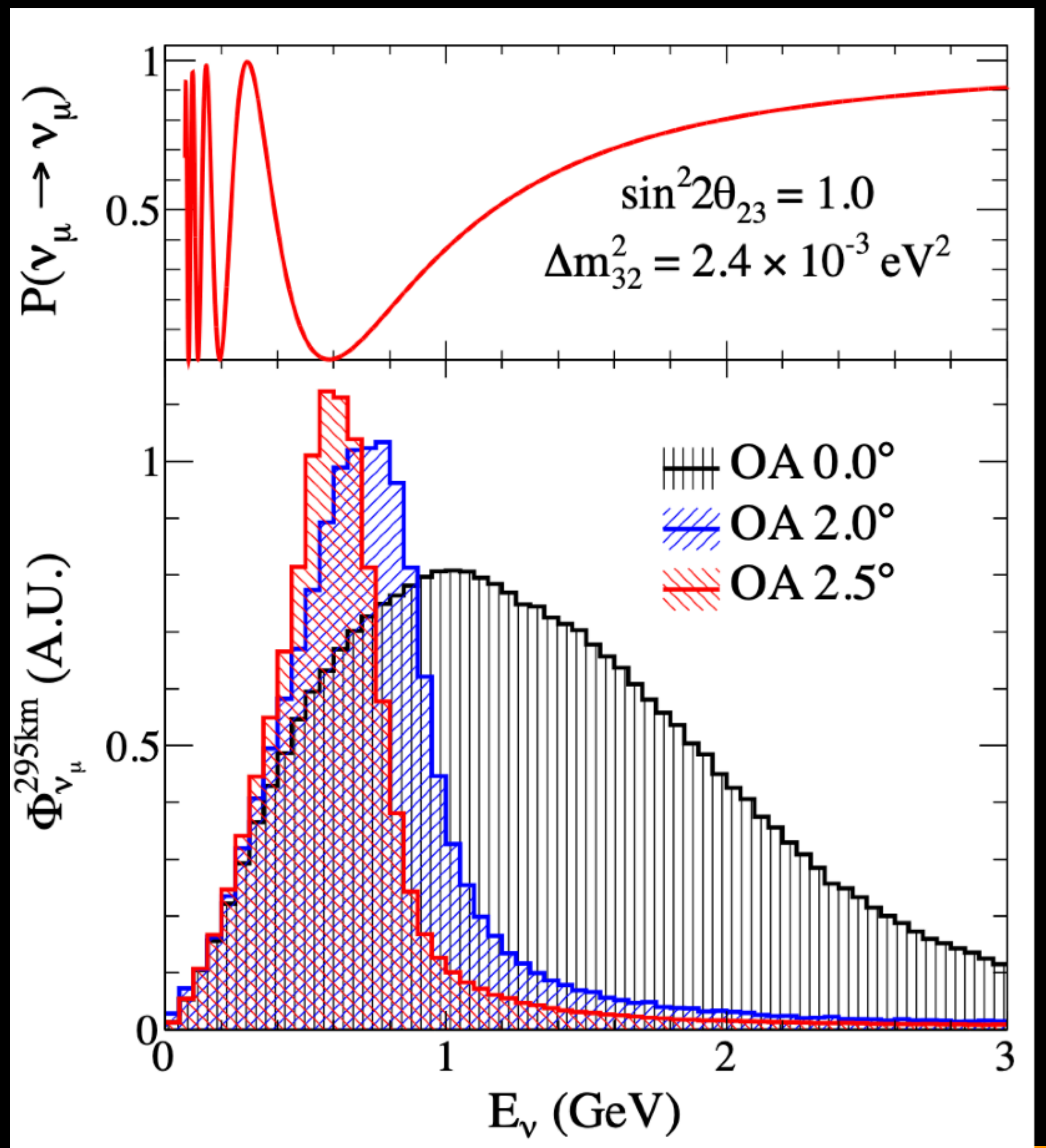


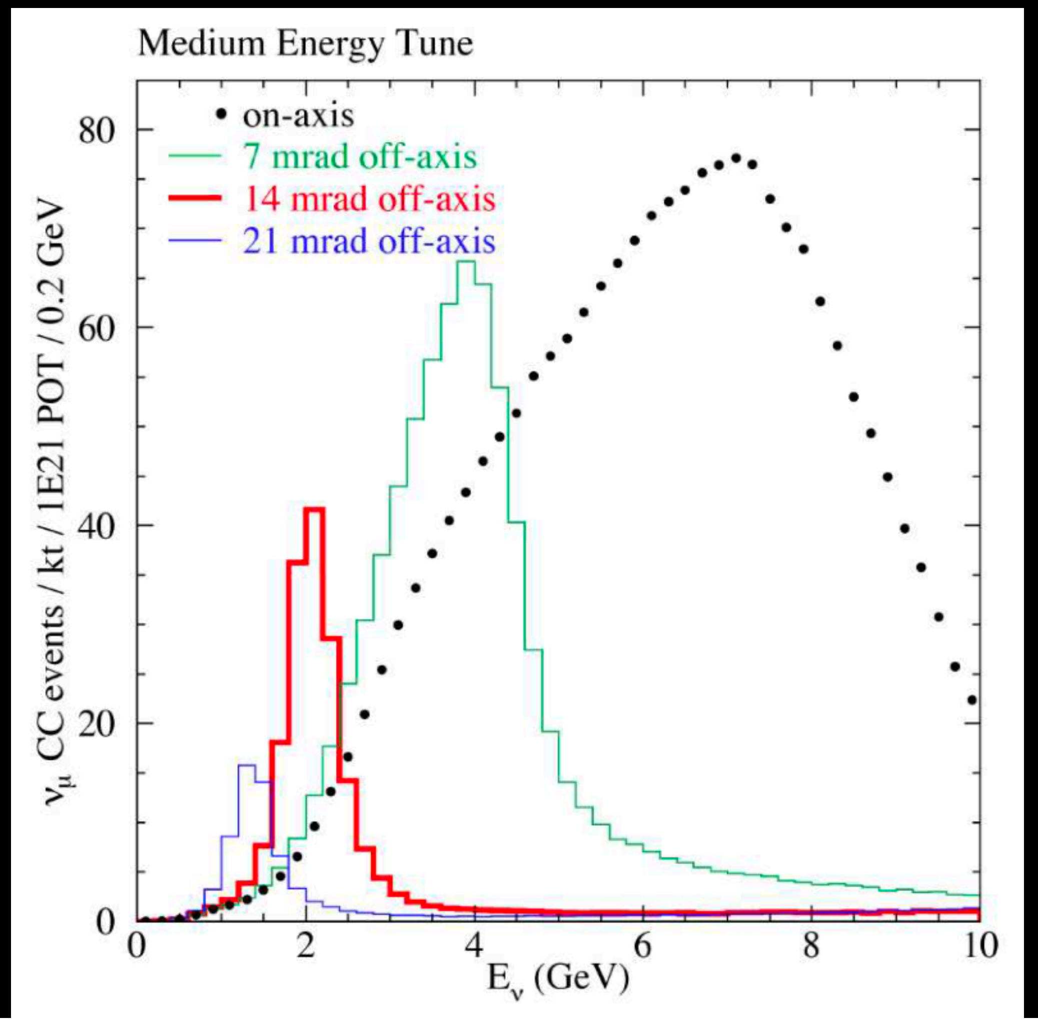
- Outstanding precision
- Even with a small amplitude, very good measurement

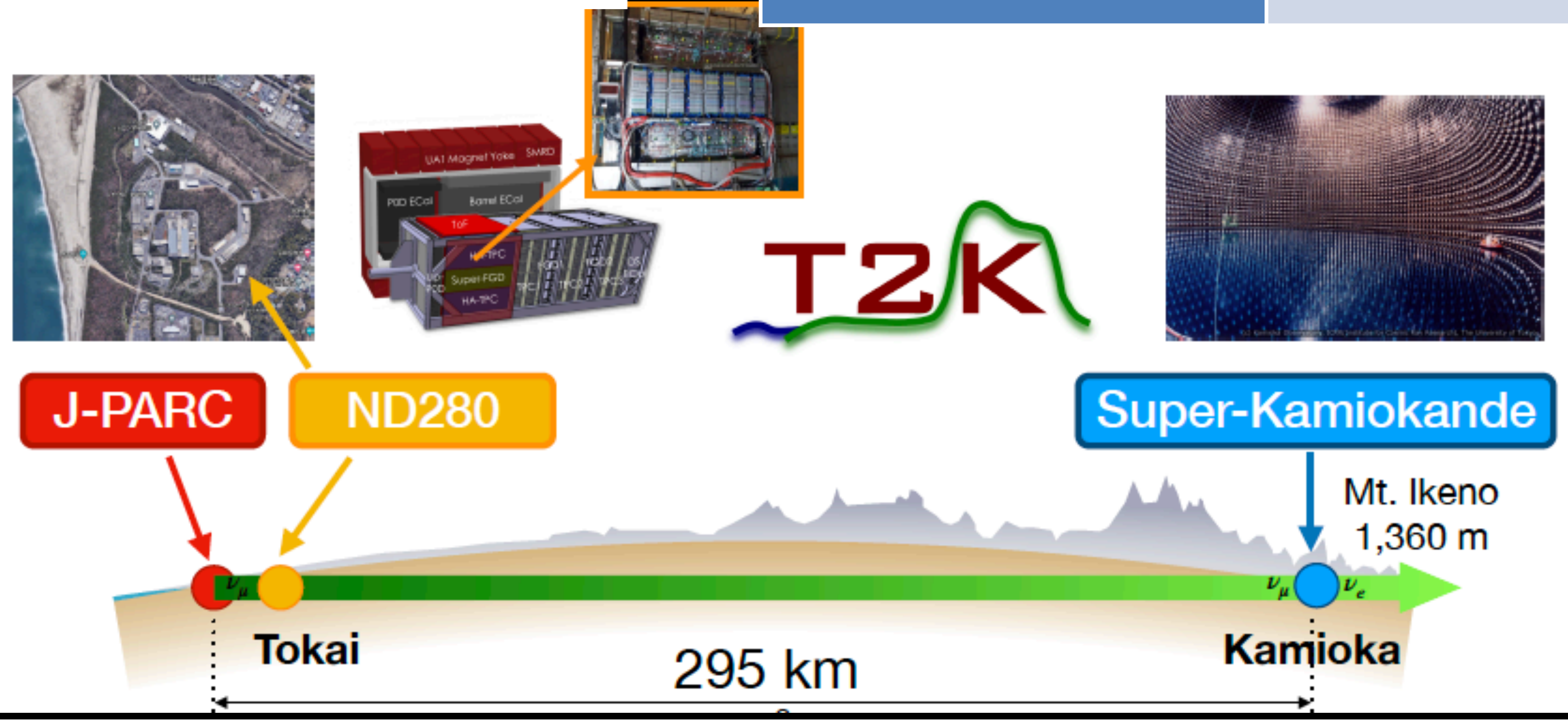


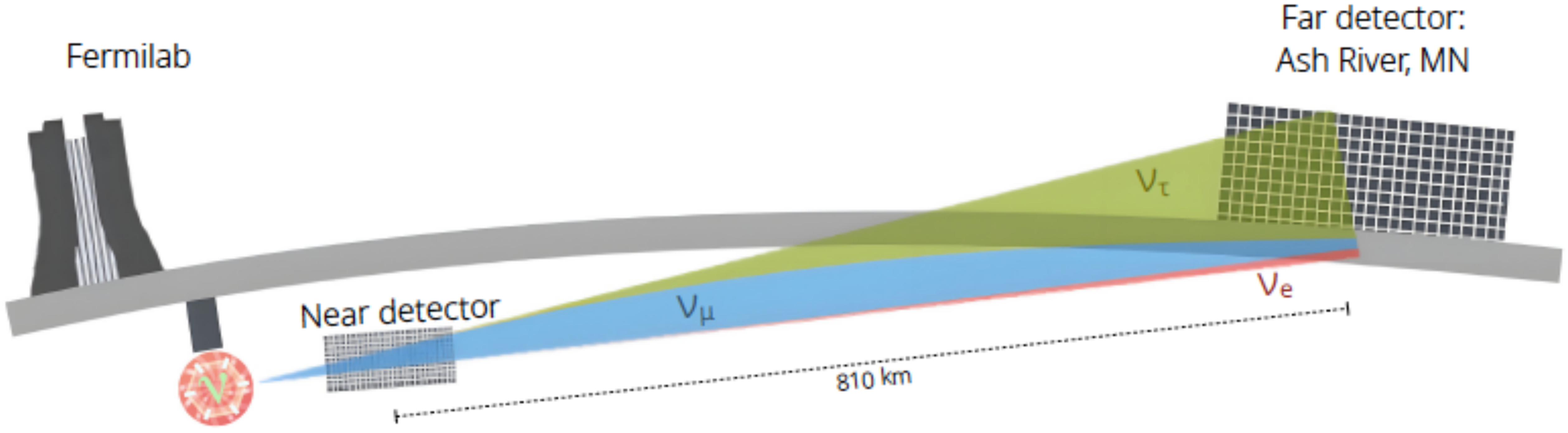
LBL ACCELERATOR: T2K & NOVA

Beam	JPARC (515 kW)	NuMI, FNAL (700 kW)
Baseline	295 km, off-axis	810 km, off-axis
Peak Energy@FD	0.6 GeV	2 GeV
Far detector	SK, WCD (50 kt)	segmented LS (14 kt)
Near detector	on-axis (INGRID), off-axis (ND280)	functionally identical (300 t)

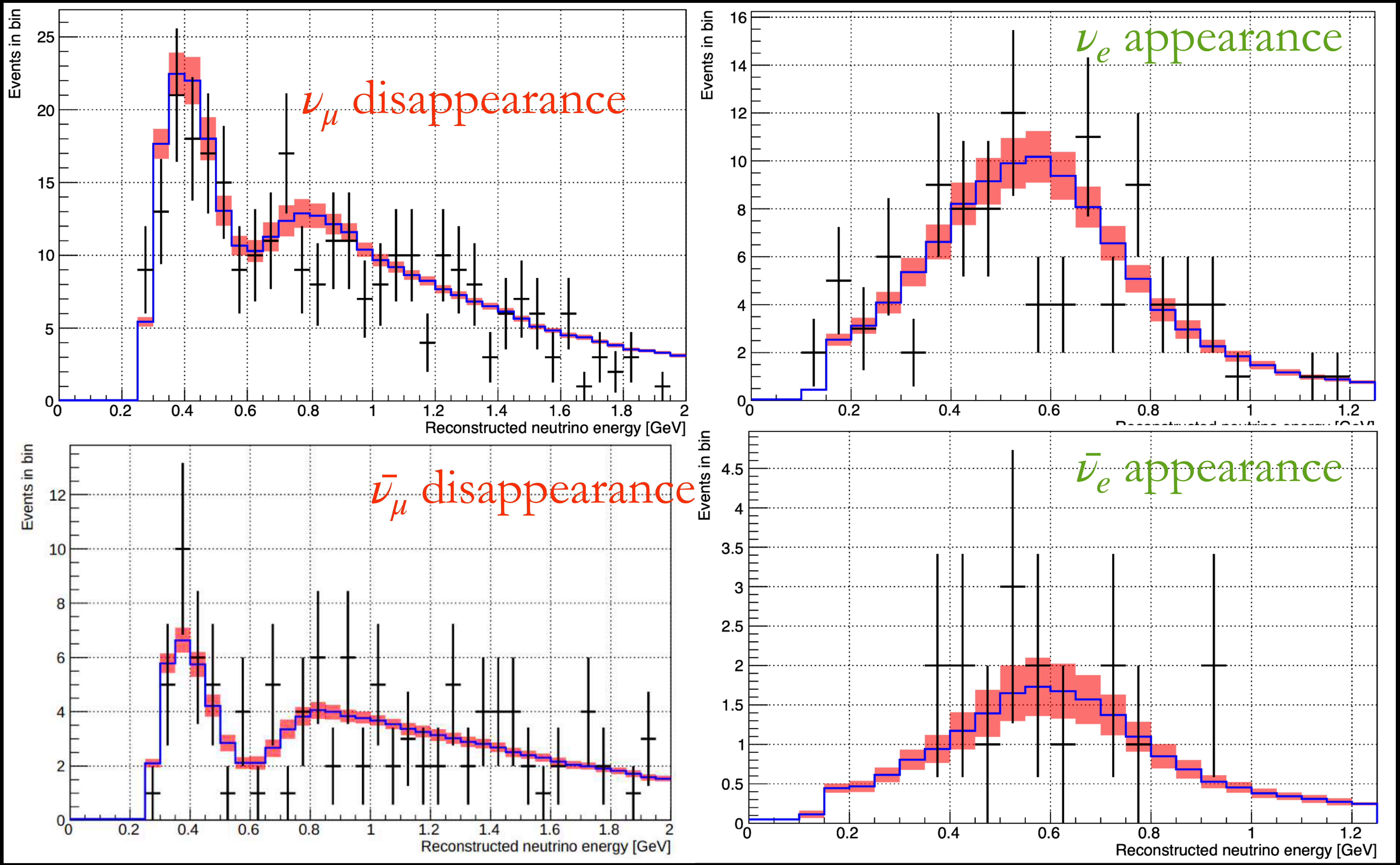




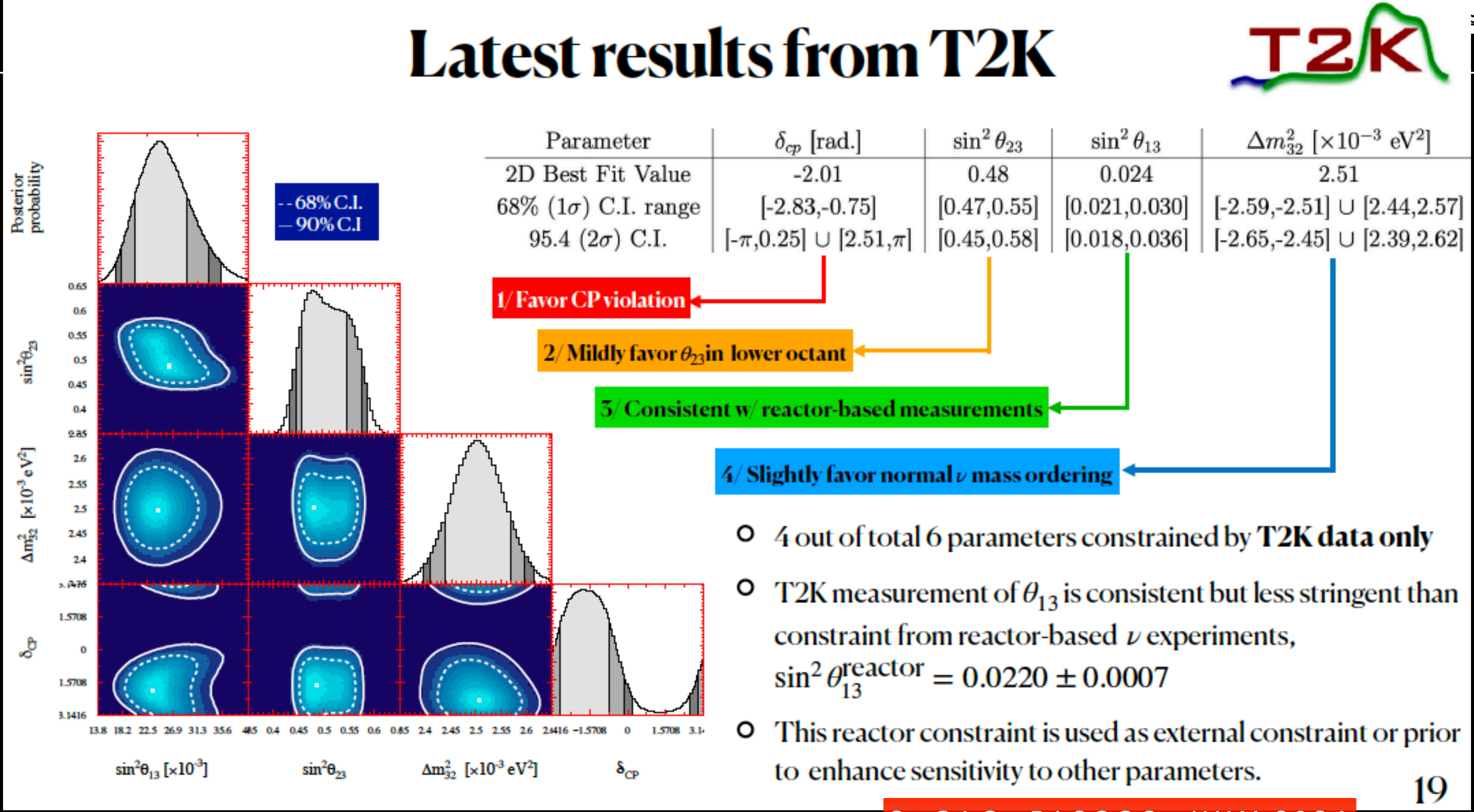




LATEST T2K RESULTS



With these 4 observation channels, sensitive to many oscillation parameters



Latest results from T2K

Parameter	δ_{cp} [rad.]	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	Δm^2_{32} [$\times10^{-3}$ eV^2]
2D Best Fit Value	-2.01	0.48	0.024	2.51
68% (1σ) C.I. range	[-2.83,-0.75]	[0.47,0.55]	[0.021,0.030]	[-2.59,-2.51] ∪ [2.44,2.57]
95.4 (2σ) C.I.	[$-\pi$,0.25] ∪ [2.51,π]	[0.45,0.58]	[0.018,0.036]	[-2.65,-2.45] ∪ [2.39,2.62]

1/ Favor CP violation

2/ Mildly favor θ_{23} in lower octant

3/ Consistent w/ reactor-based measurements

4/ Slightly favor normal ν mass ordering

- 4 out of total 6 parameters constrained by **T2K data only**
- T2K measurement of θ_{13} is consistent but less stringent than constraint from reactor-based ν experiments, $\sin^2\theta_{13}^{\text{reactor}} = 0.0220 \pm 0.0007$
- This reactor constraint is used as external constraint or prior to enhance sensitivity to other parameters.

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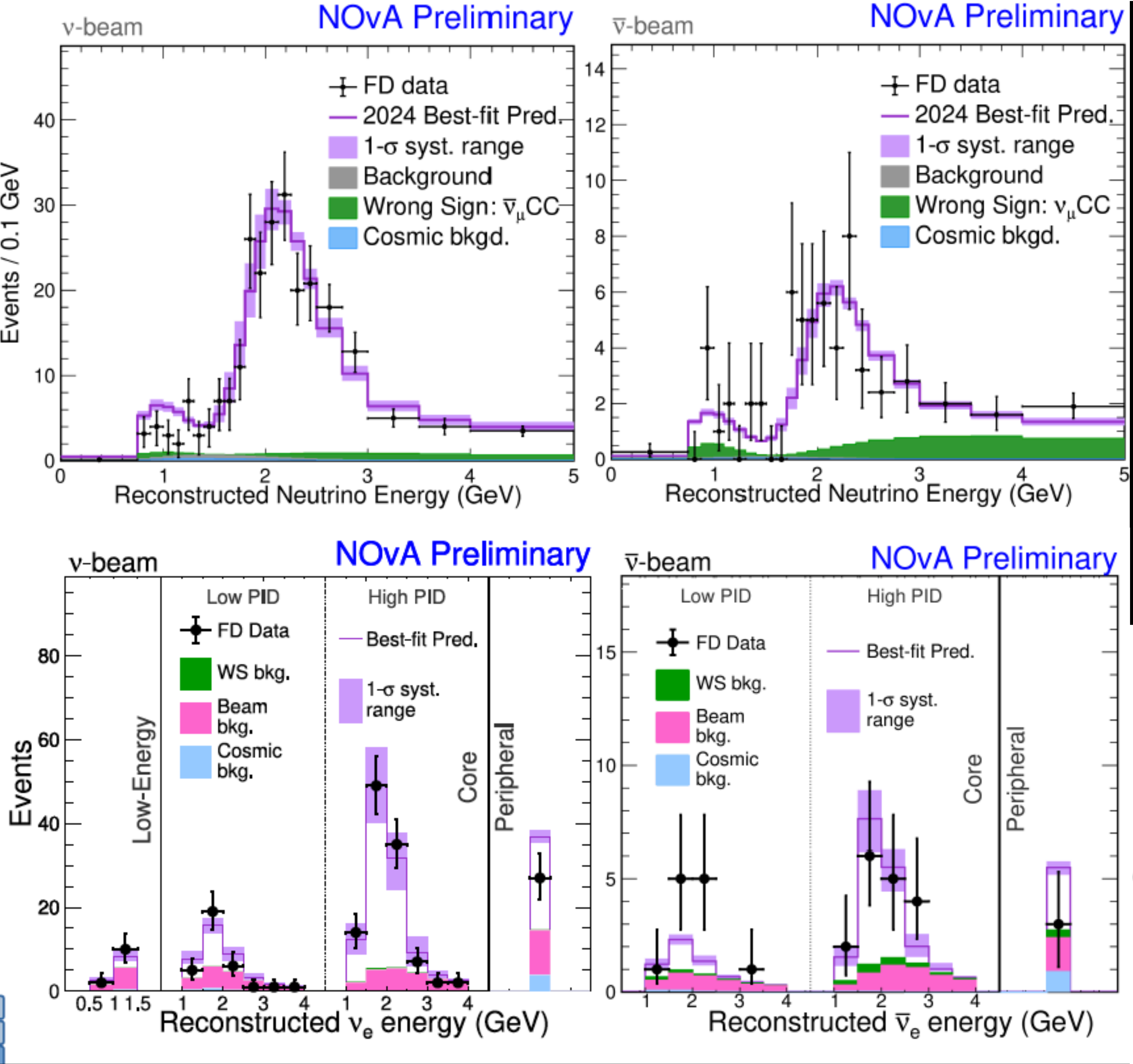
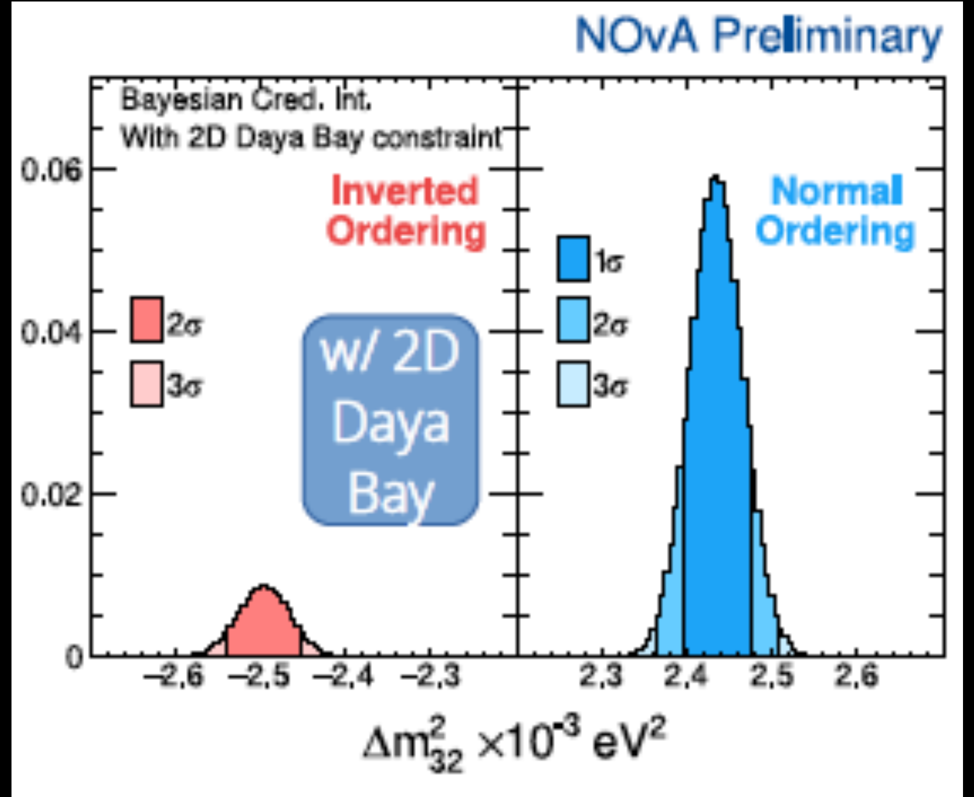
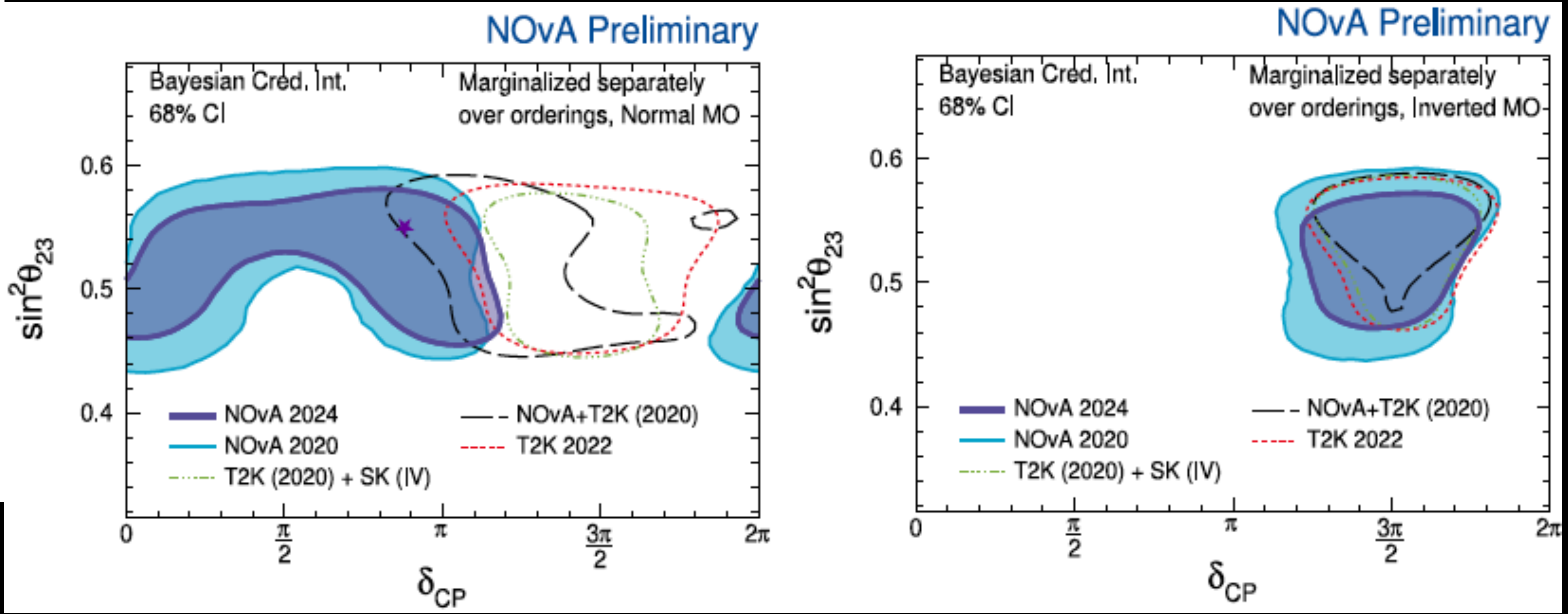
NOVA RESULTS



- Mild preference for:
  - Normal ordering
  - $sin^2\theta_{23} > 0.5$
- CP violation
  - cons. for NO, viol. for IO
  - tension with T2K



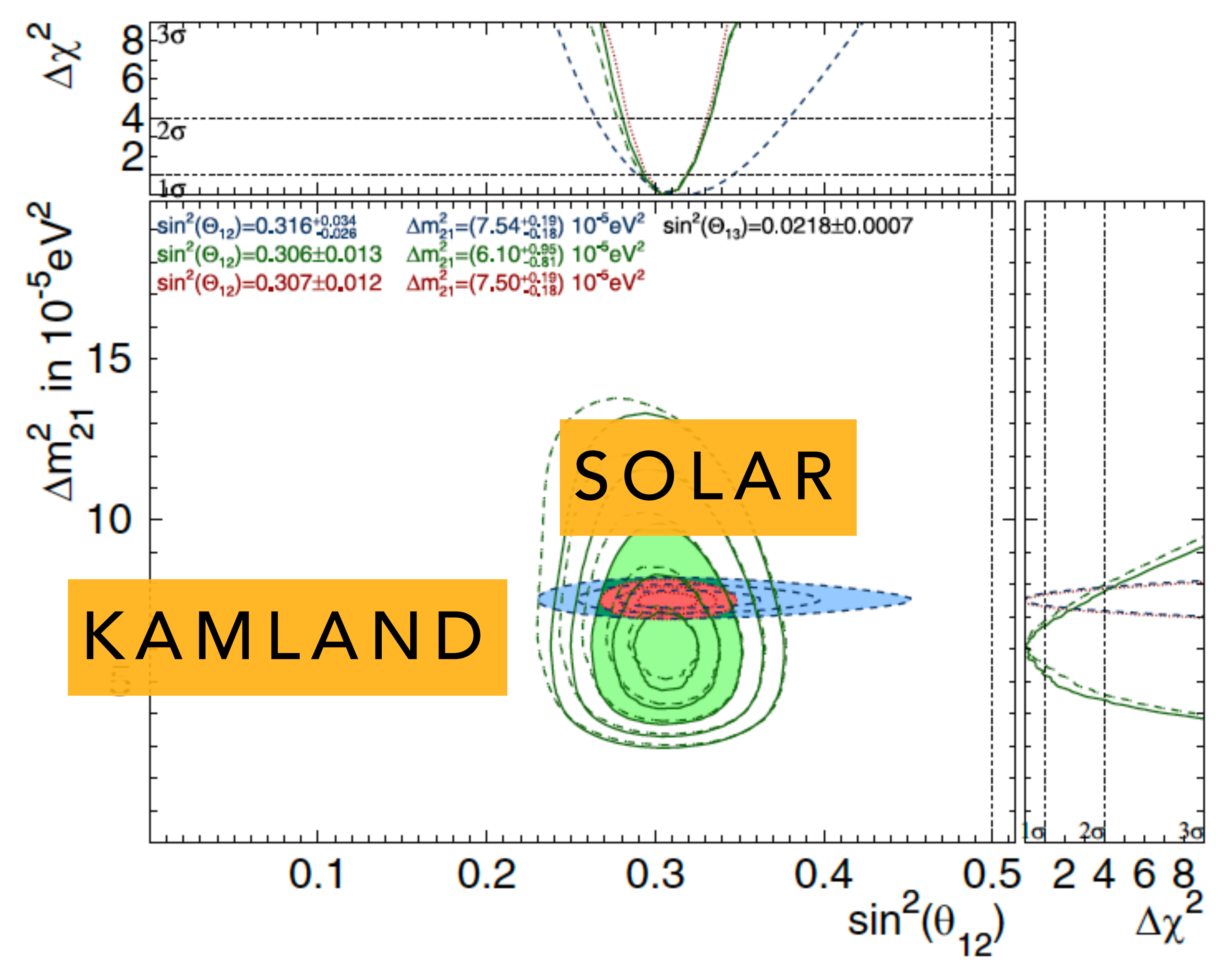
Daya Bay ($\sin^2 2\theta_{13}$, Δm^2_{32})
N.O. preference:
87% (Bayes factor: 6.8)
Frequentist significance*: 1.6σ

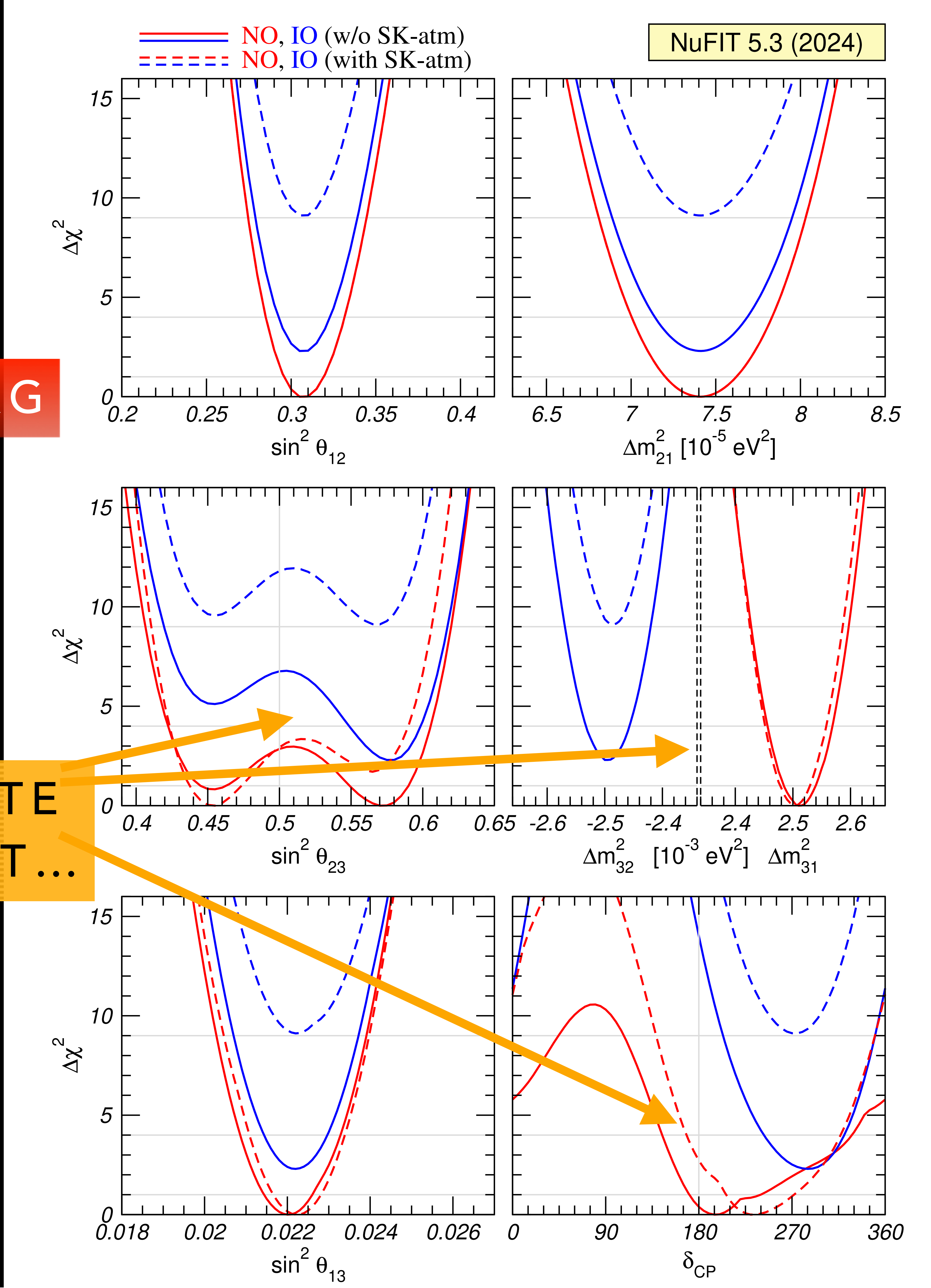


GLOBAL FITS

GLOBAL OSCILLATION FITS

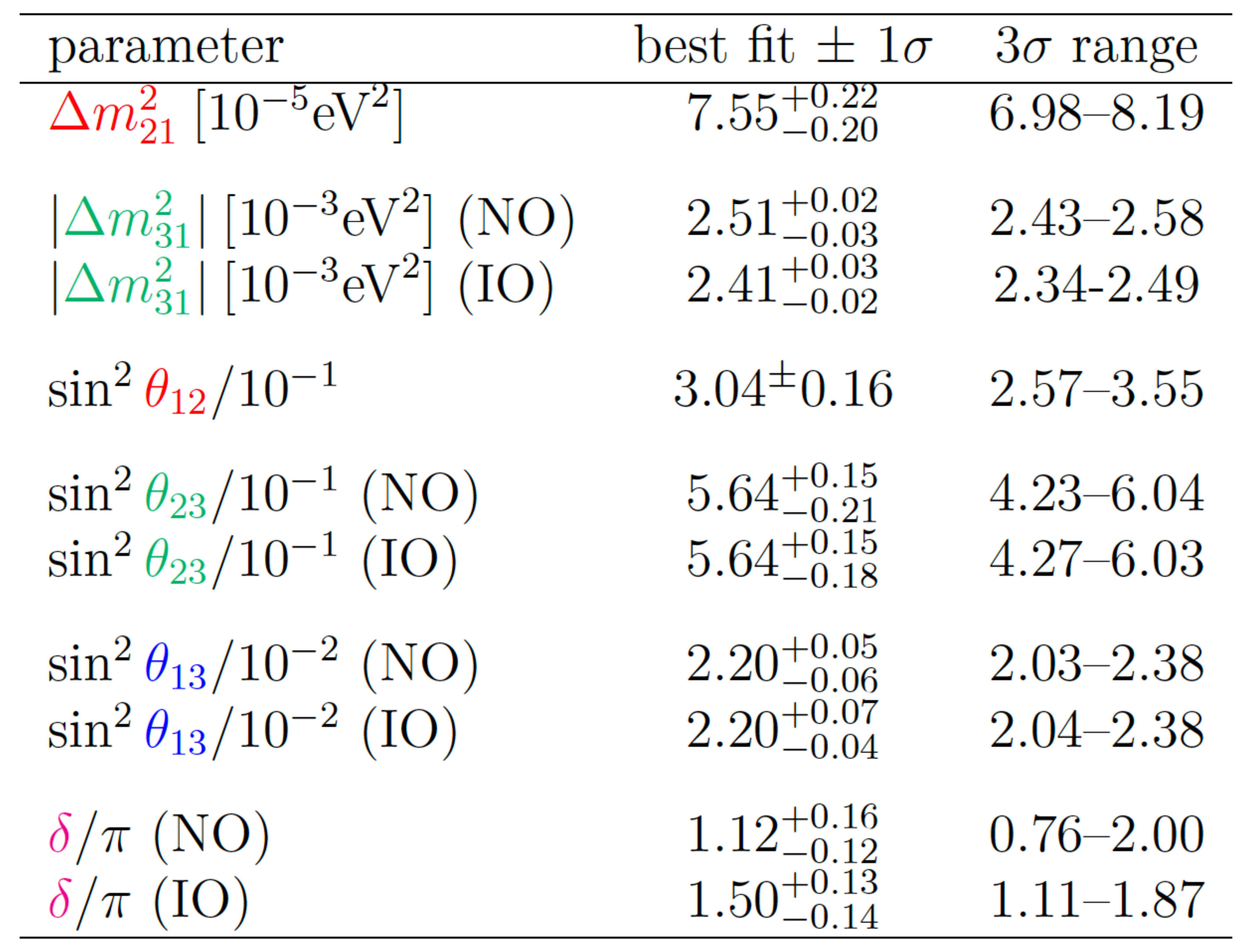
- Consistent results favoring the 3-flavor neutrino oscillation framework
- Best precision for the parameters comes from combination of all available solar, reactor, atmospheric and accelerator data HTTP://WWW.NU-FIT.ORG
- Tension may point to new physics… or the need for more data…





NOT QUITE THERE YET…

GLOBAL FITS RESULTS



parameter	best fit ± 1σ	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49
$\sin^2\theta_{12}/10^{-1}$	$3.04^{\pm}0.16$	2.57–3.55
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87

HTTPS://GLOBALFIT.ASTROPARTICLES.ES/

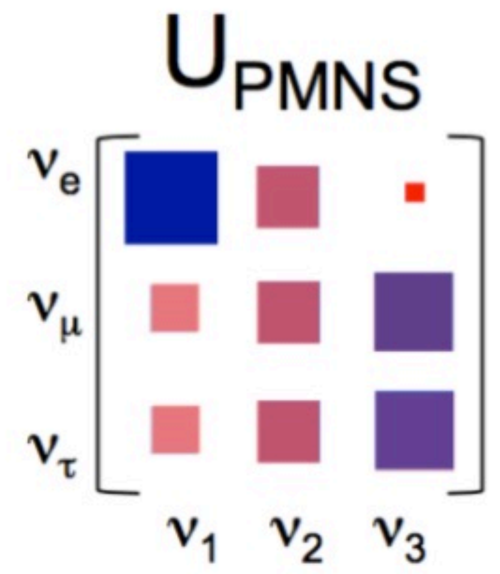
PMNS VS. CKM

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

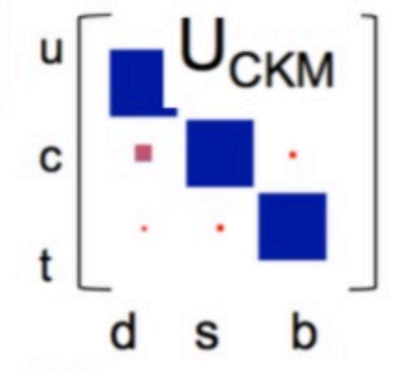
far from diagonal - two large angles

$\delta_{CP} = ?$

$$J_{\mathrm{CP}}^{\mathrm{quarks}} = (2.96^{+0.20}_{-0.16}) \times 10^{-5}$$



Mixing	Neutrinos	Quarks
θ_{12}	$(33.6 \pm 0.8)^o$	$(13.04 \pm 0.05)^o$
θ_{23}	$(45 \pm 3)^o$	$(2.38 \pm 0.06)^o$
θ_{13}	$(8.5 \pm 0.15)^o$	$(0.201 \pm 0.011)^o$
δ_{CP}	$(-90\ ?\ )^o$	$(67\pm5)^o$



almost diagonal - all angles small

$$|V_{\mathrm{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

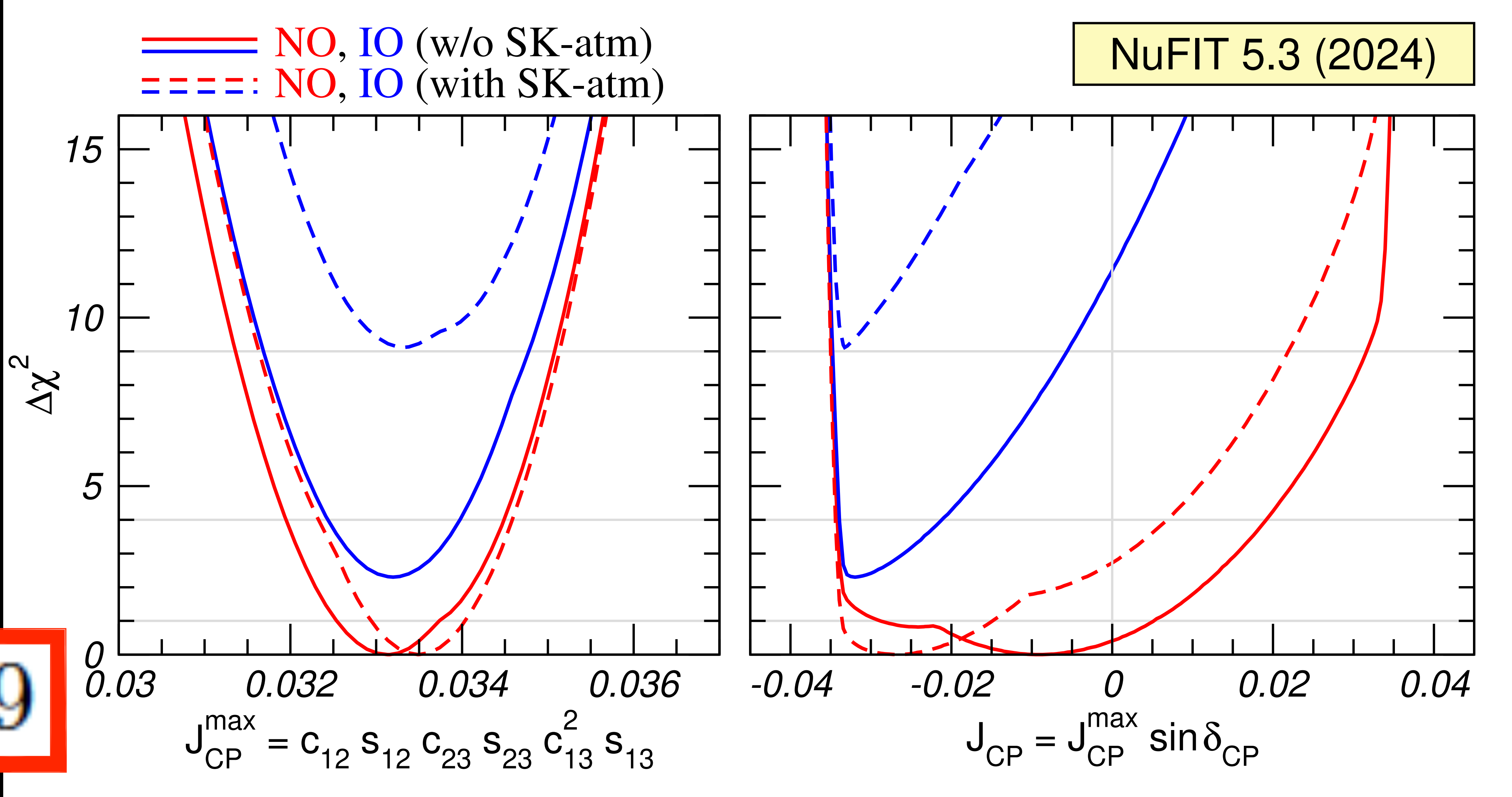
$\delta_{CP} = 68^\circ$

$$\equiv J_{\mathrm{CP}}^{\max} \sin\delta_{\mathrm{CP}}$$

$$J_{\mathrm{CP}}^{\max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

- CP violation effects proportional to Jarlskog invariant, depends on angles too
- With neutrinos can be 3 orders of magnitude larger than with quarks!

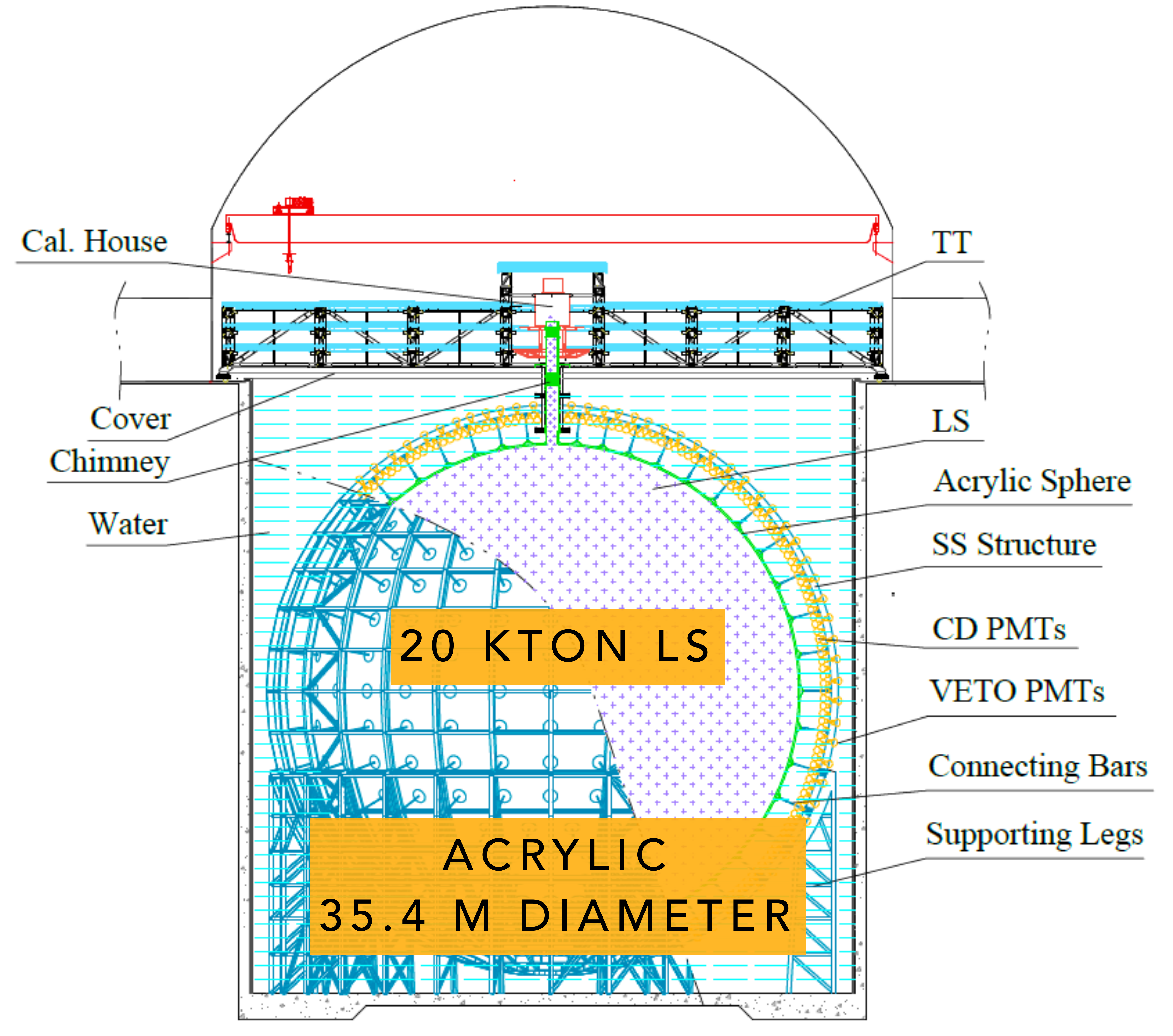
$$J_{\mathrm{CP}}^{\max} = 0.0329 \pm 0.0009$$



FUTURE EXPERIMENTS

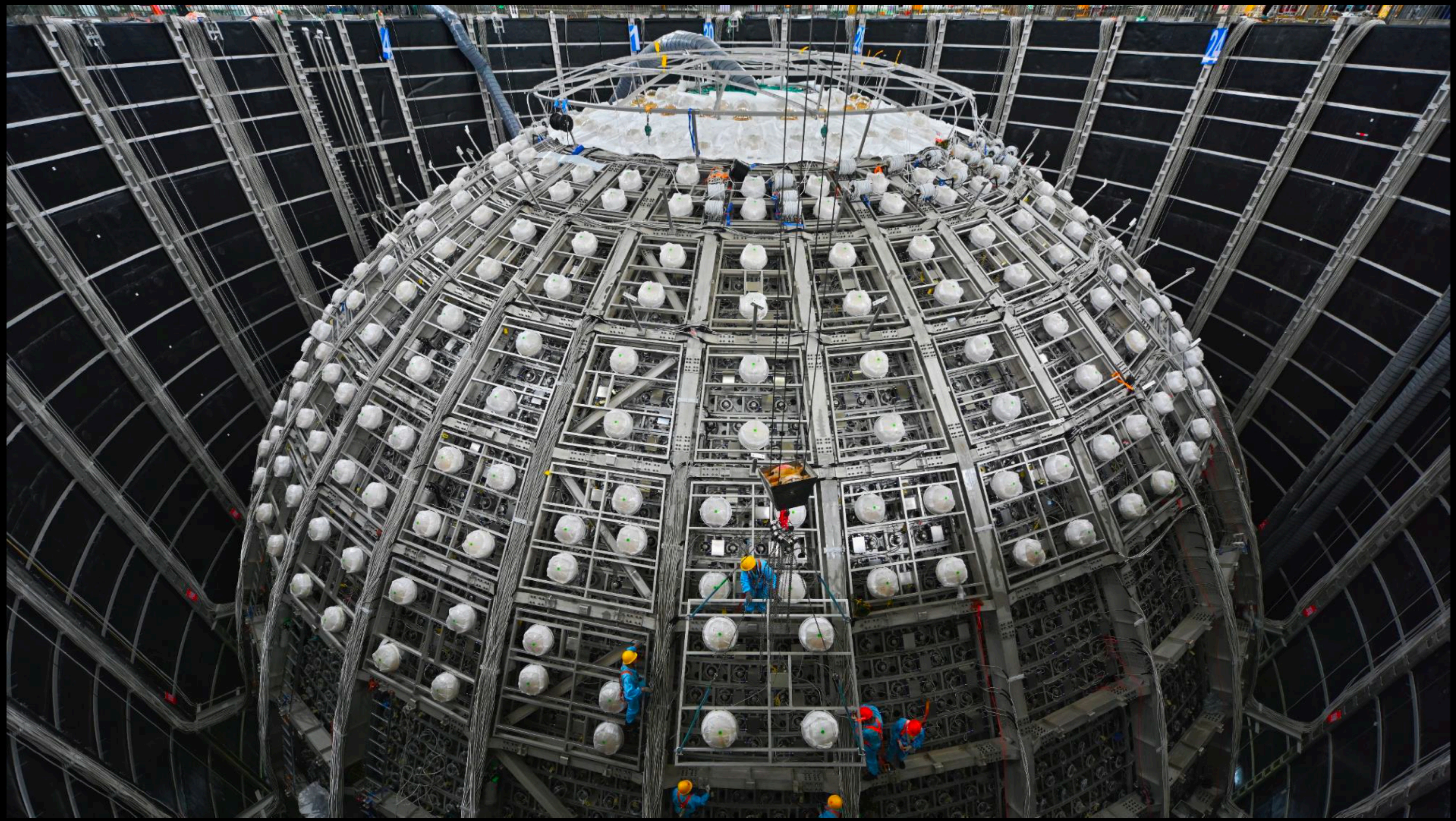
JUNO REACTOR EXPERIMENT

- Follow-up of Daya Bay
- Biggest liquid scintillator (LS) detector ever
- 17612 20-inch PMTs, 25600 3-inch PMTs
- 50 km baseline to powerful reactors
- Starting 2025



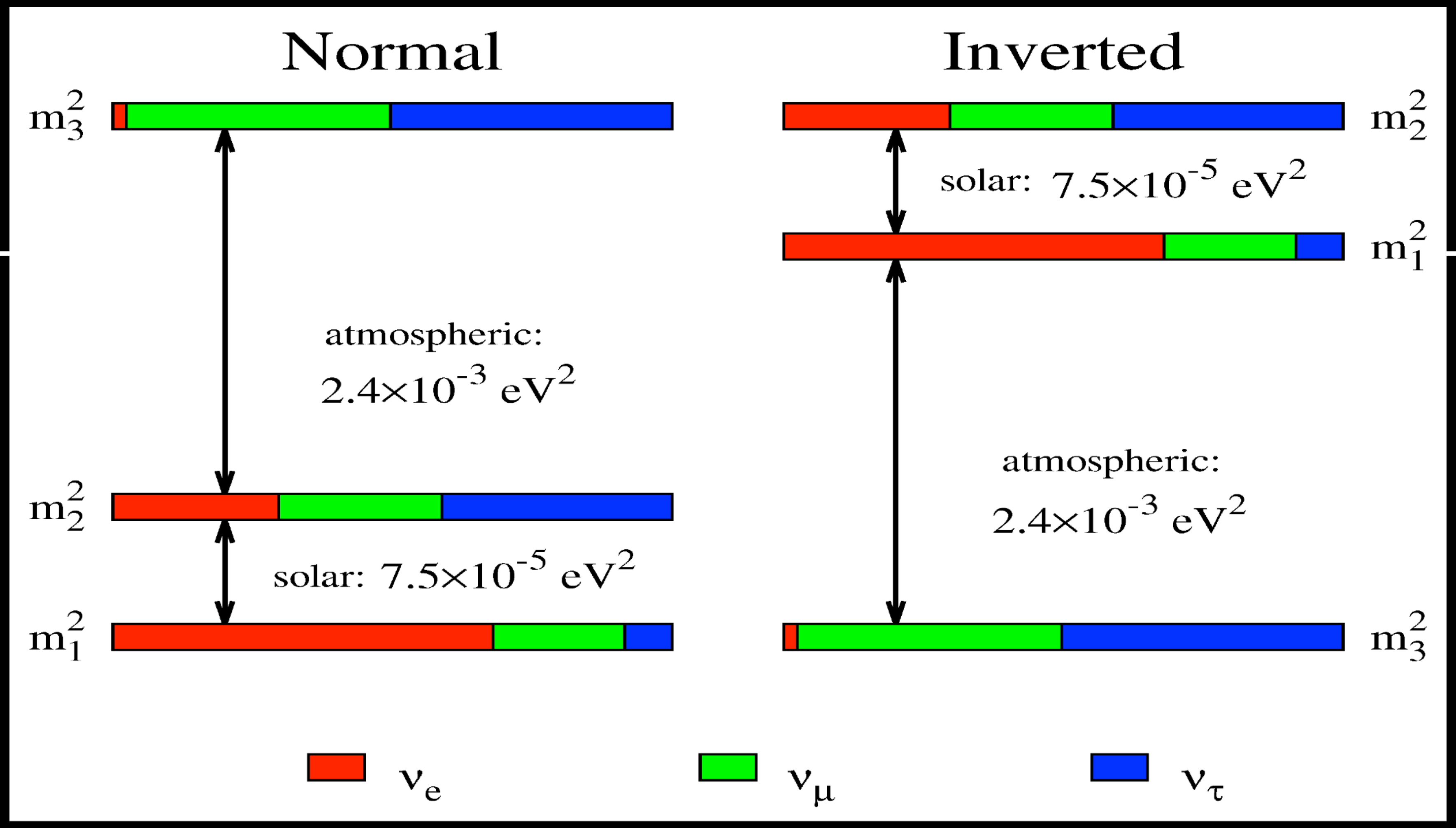
20 KTON LS

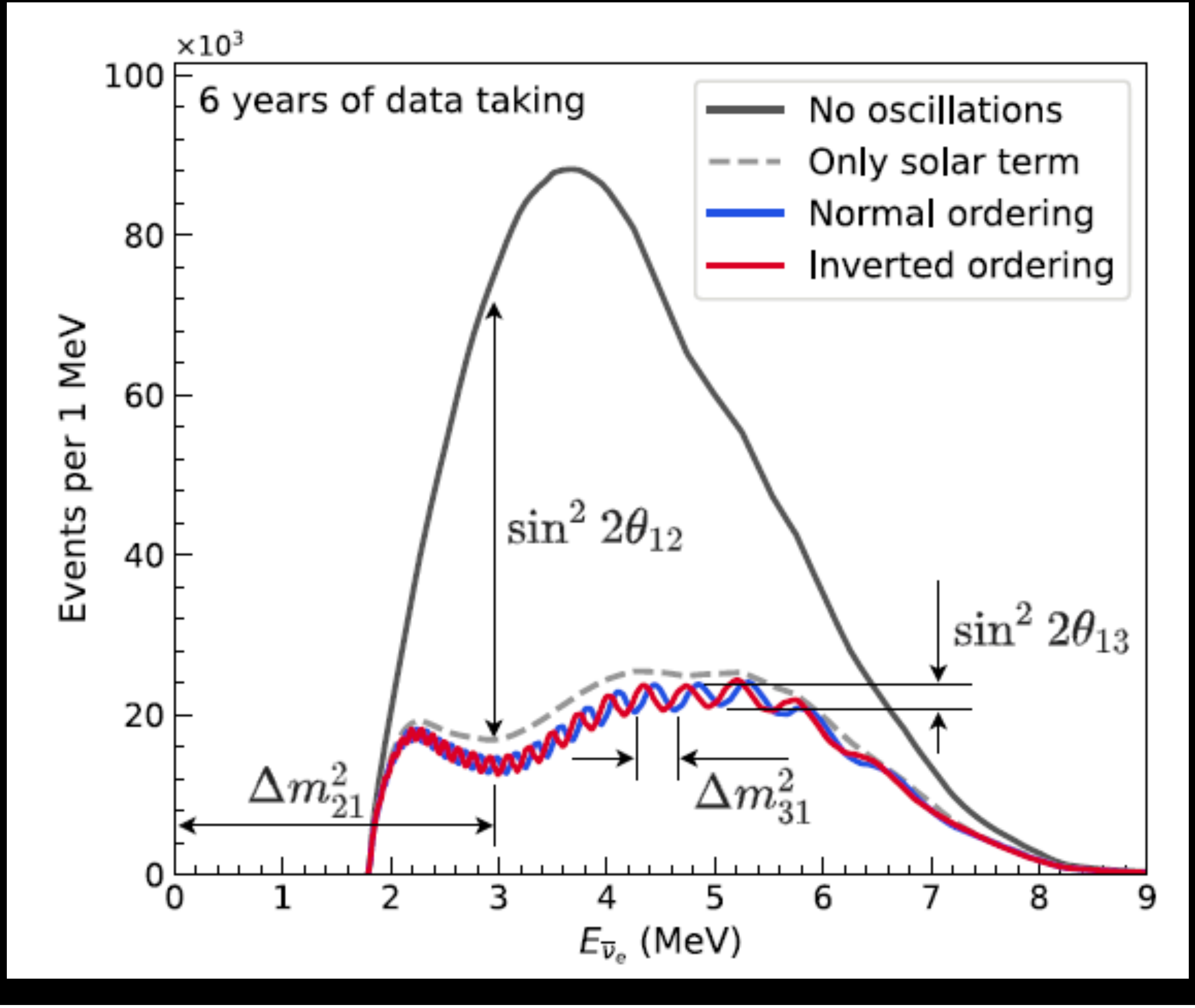
ACRYLIC
35.4 M DIAMETER



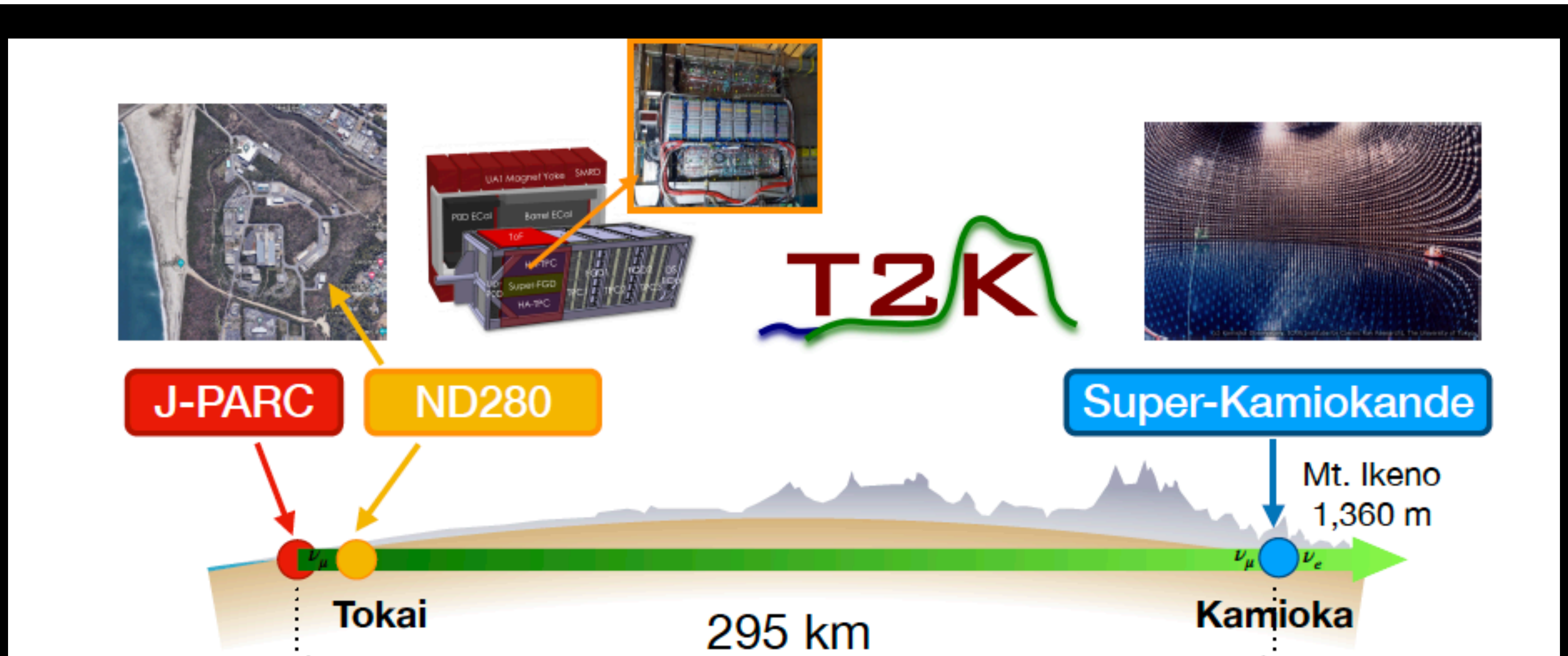
JUNO PHYSICS

- By definition $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$
- We know that $\Delta m^2_{21} > 0$ (MSW solar)
- How to determine the mass ordering?
  - Normal: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$
  - Inverted: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$
  - But the difference is small, since $\Delta m^2_{21} \approx 3\% \times |\Delta m^2_{32}|$
- Requires distinguishing small details in oscillation pattern
- Expected energy resolution: 2.95% @1MeV
- Expected 3σ sensitivity @ ~6 yrs*26.6 GWth



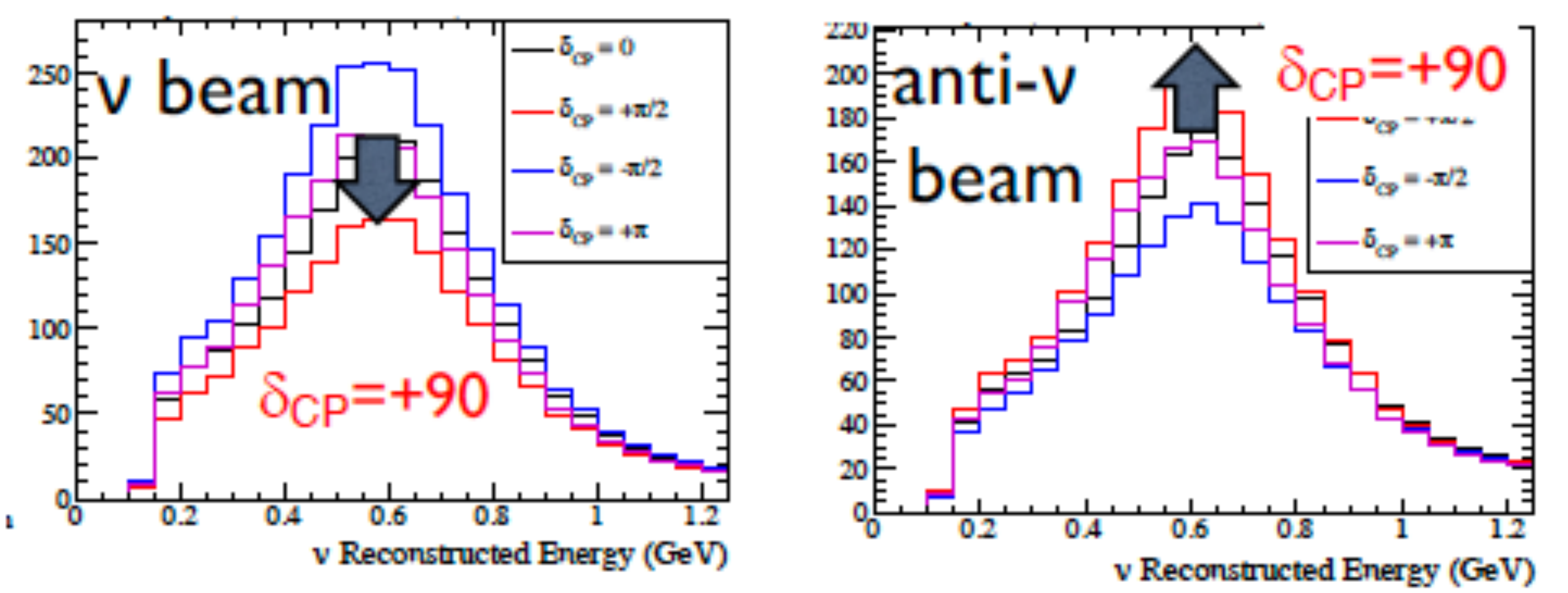


HYPER-KAMIOKANDE

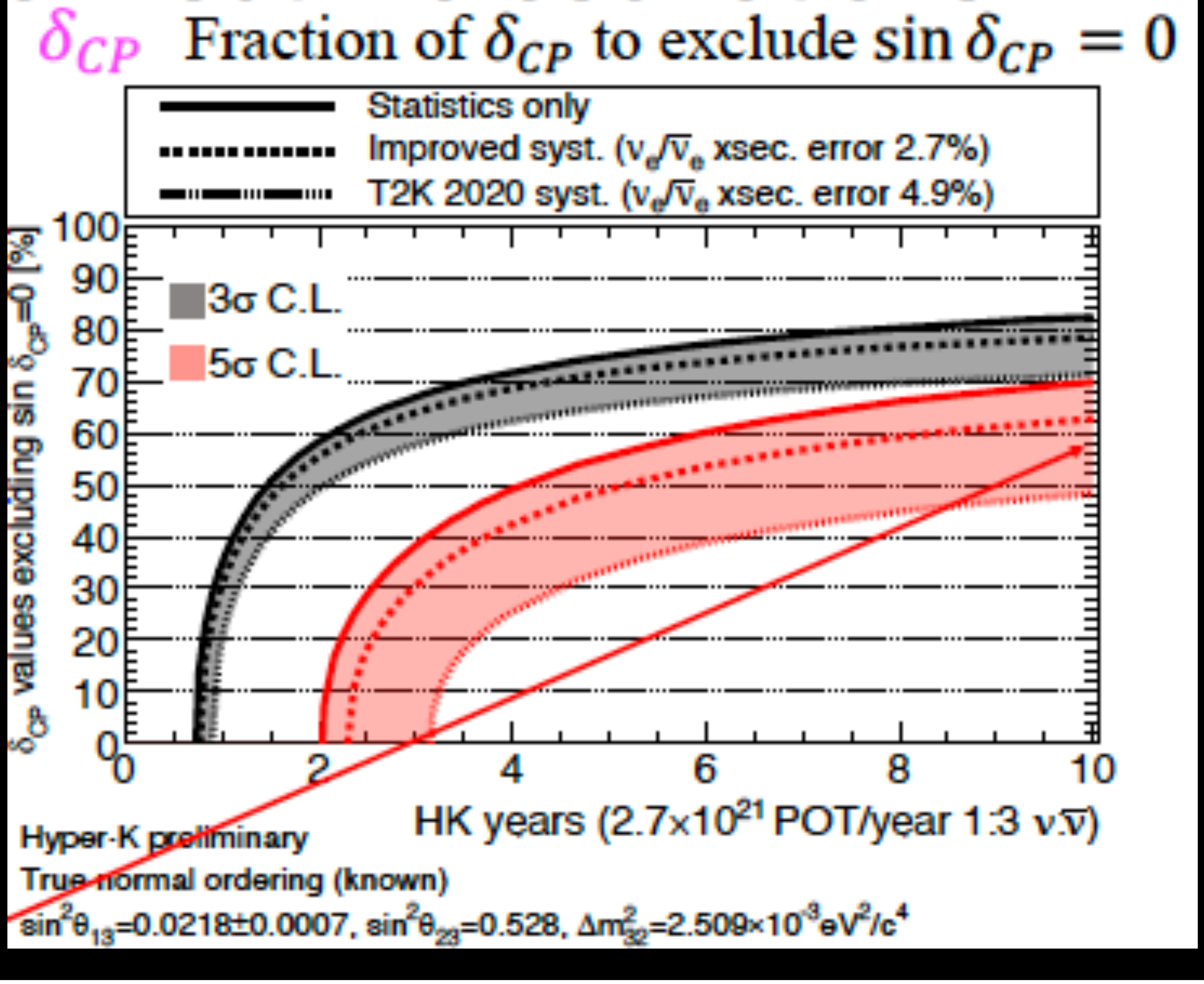


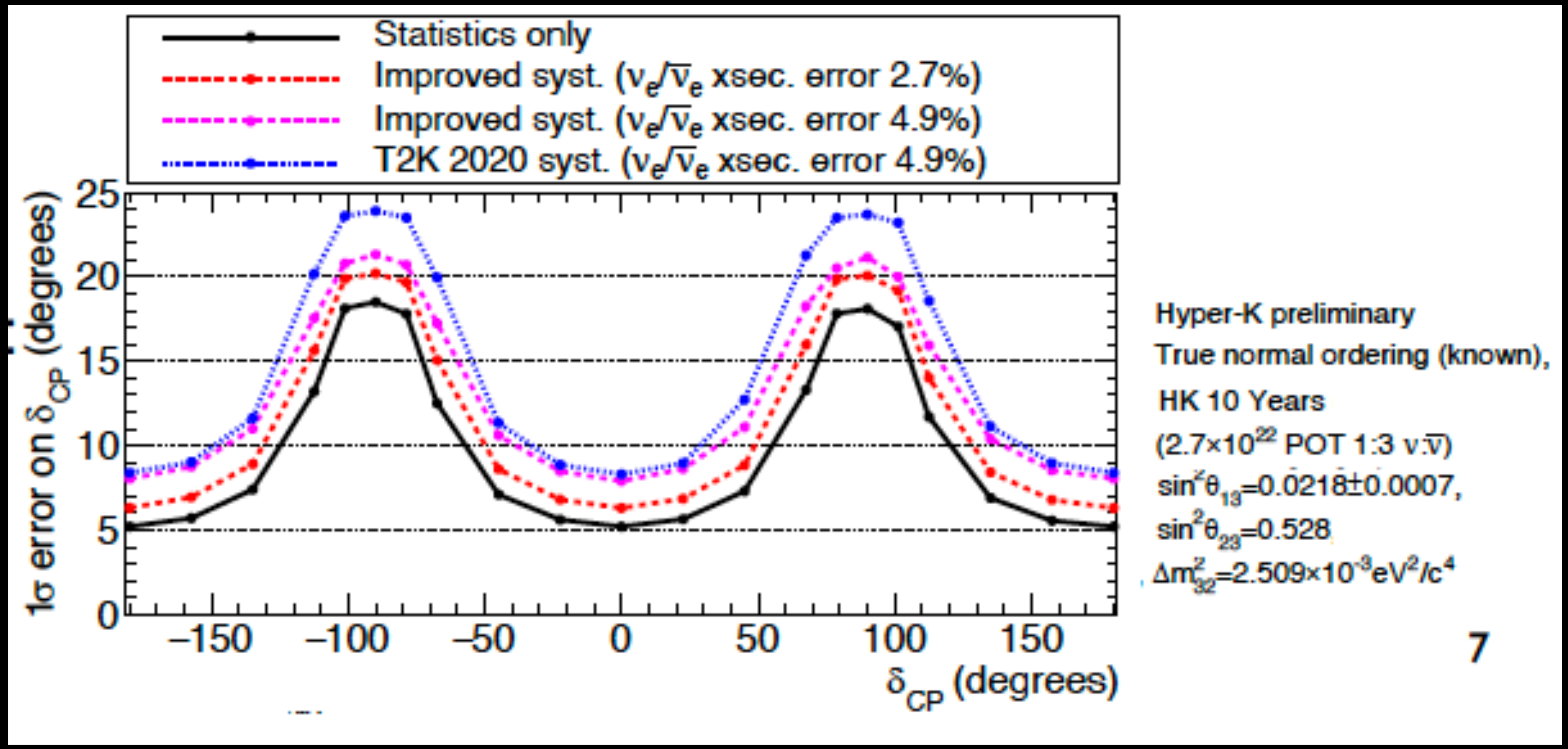
- 260 kton (188 kt fiducial)
- upgrade of the T2K beam and near detectors
- 2.5 deg off-axis
- upgraded PMTs with better QE and timing
- cavity in contruction
- expect start of data in 2027

HK PROJECTED SENSITIVITY



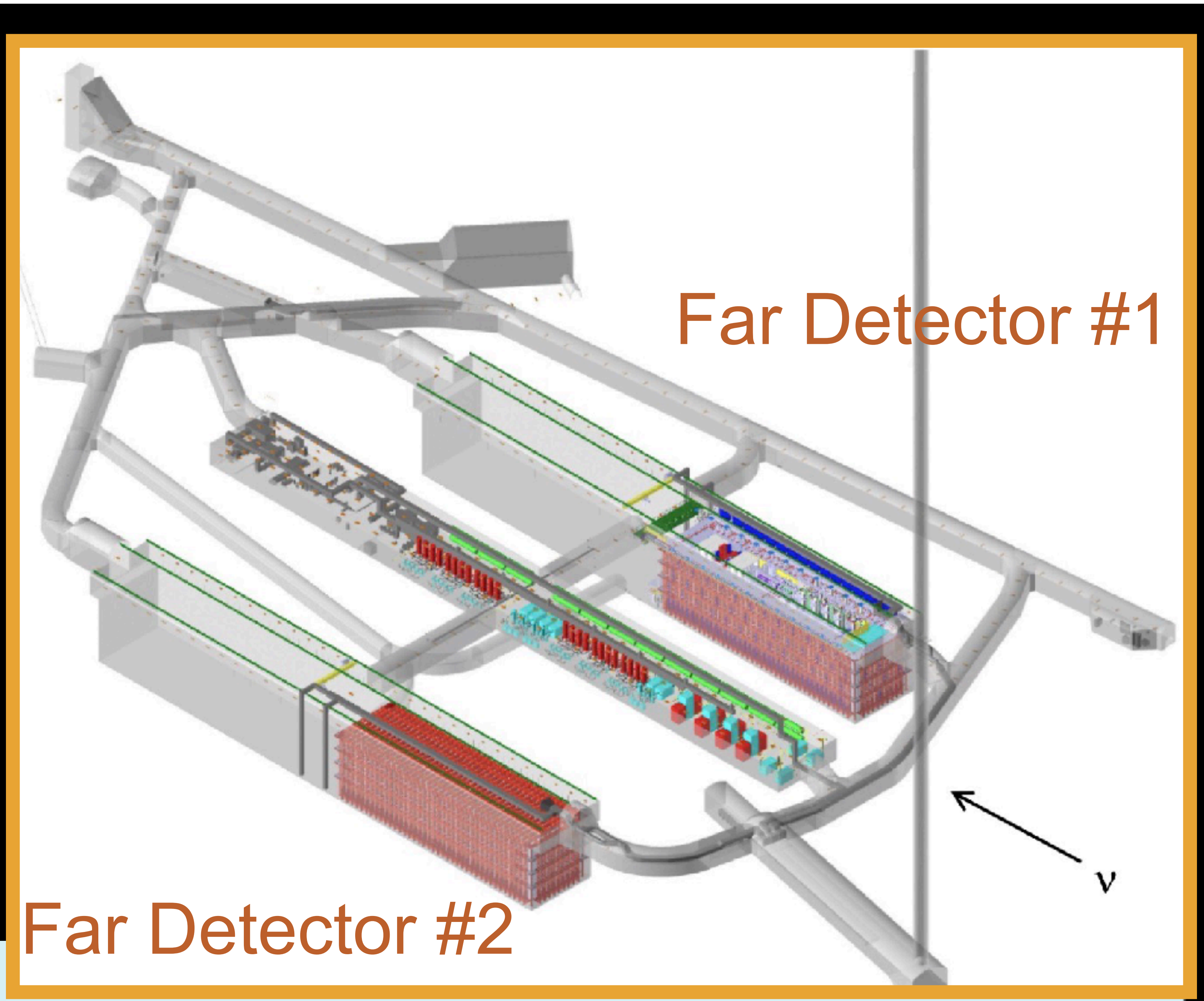
- $\nu_e(\bar{\nu}_e)$ appearance in $\nu_\mu(\bar{\nu}_\mu)$ beam
- Energy <1 GeV: mostly QE
- Short distance: small matter effects
- Very high statistics -> CP violation discovery (5σ) in 60% of the values in 10yrs

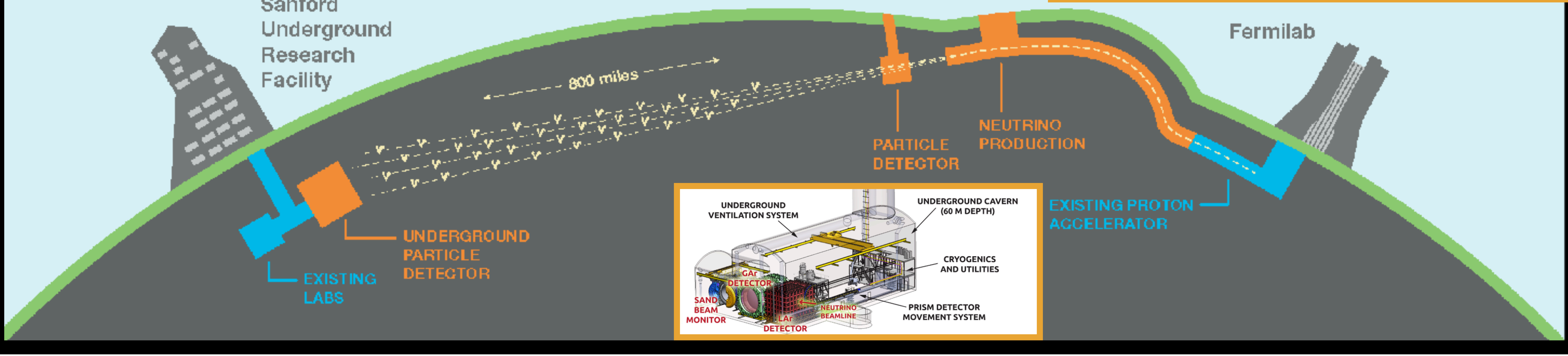




DEEP UNDERGROUND NEUTRINO EXPERIMENT

- DUNE overview
  - Fermilab makes intense ν_μ and $\bar{\nu}_\mu$ beams
  - Near Detector characterizes beam and cross-sections
  - Beams reach Sanford lab, 1285 km away, 1.5 km underground
  - 70 kt Far Detector, divided in 4 modules, at least 3 of which use LArTPC technology (see lecture 2)

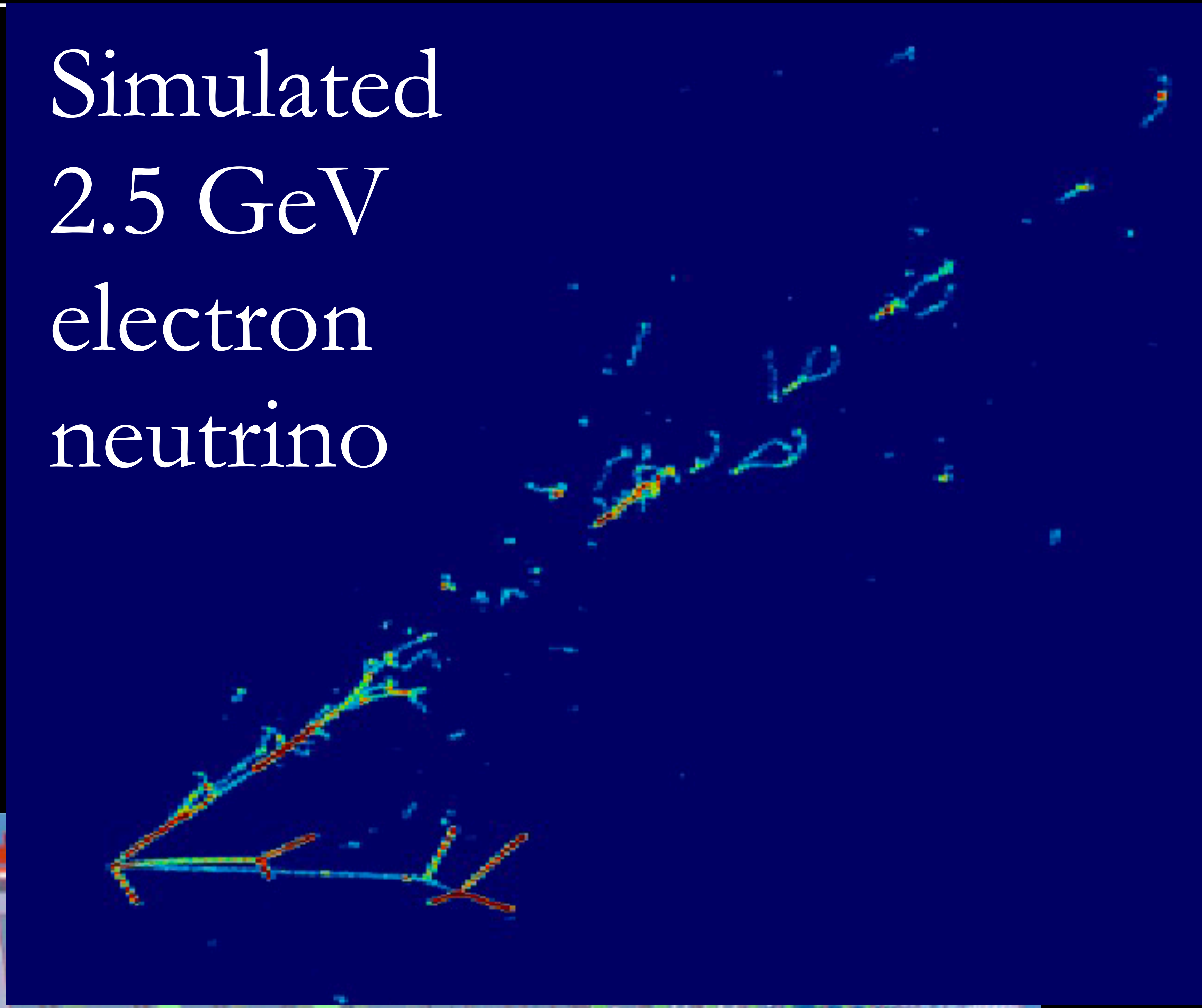


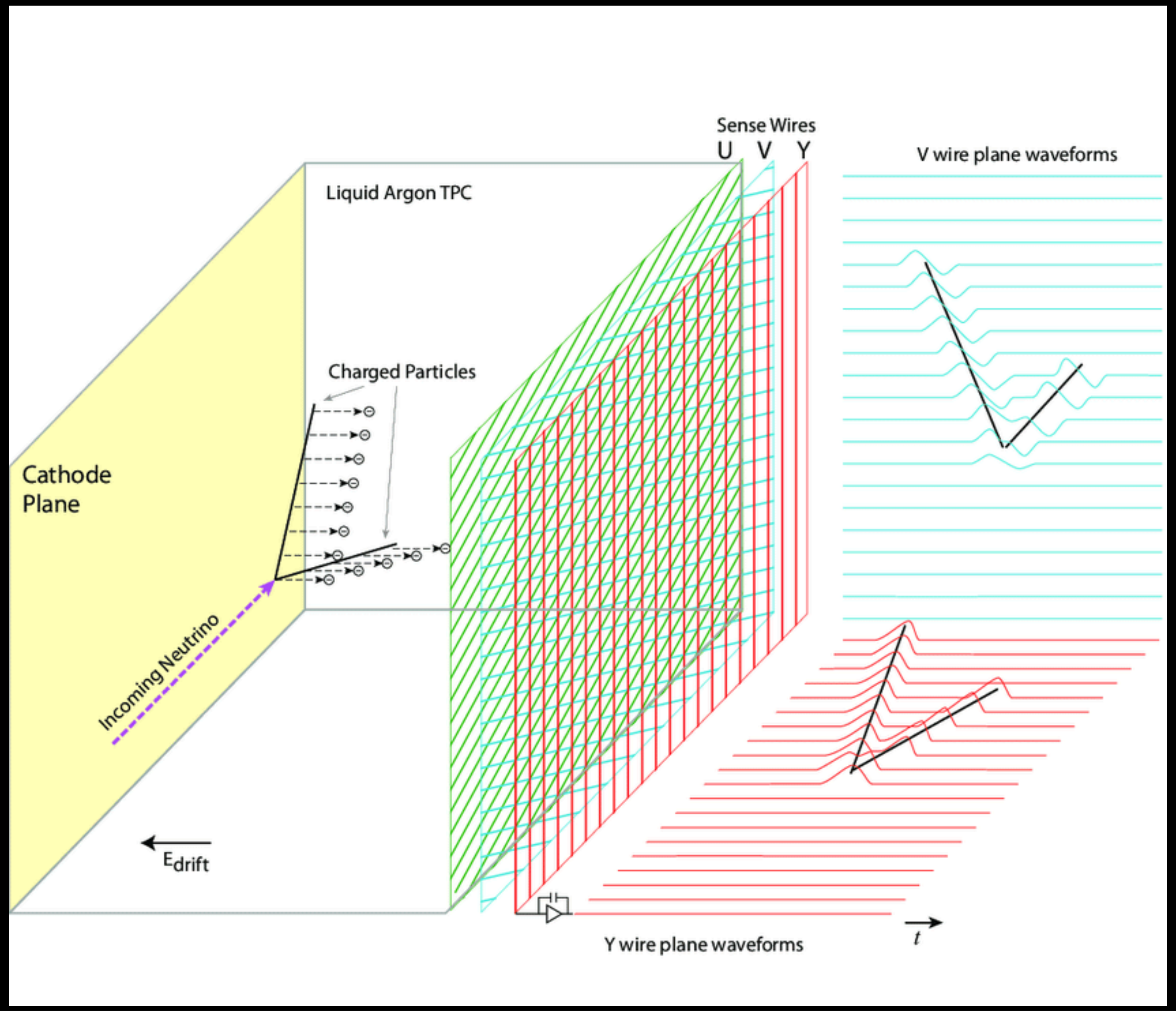


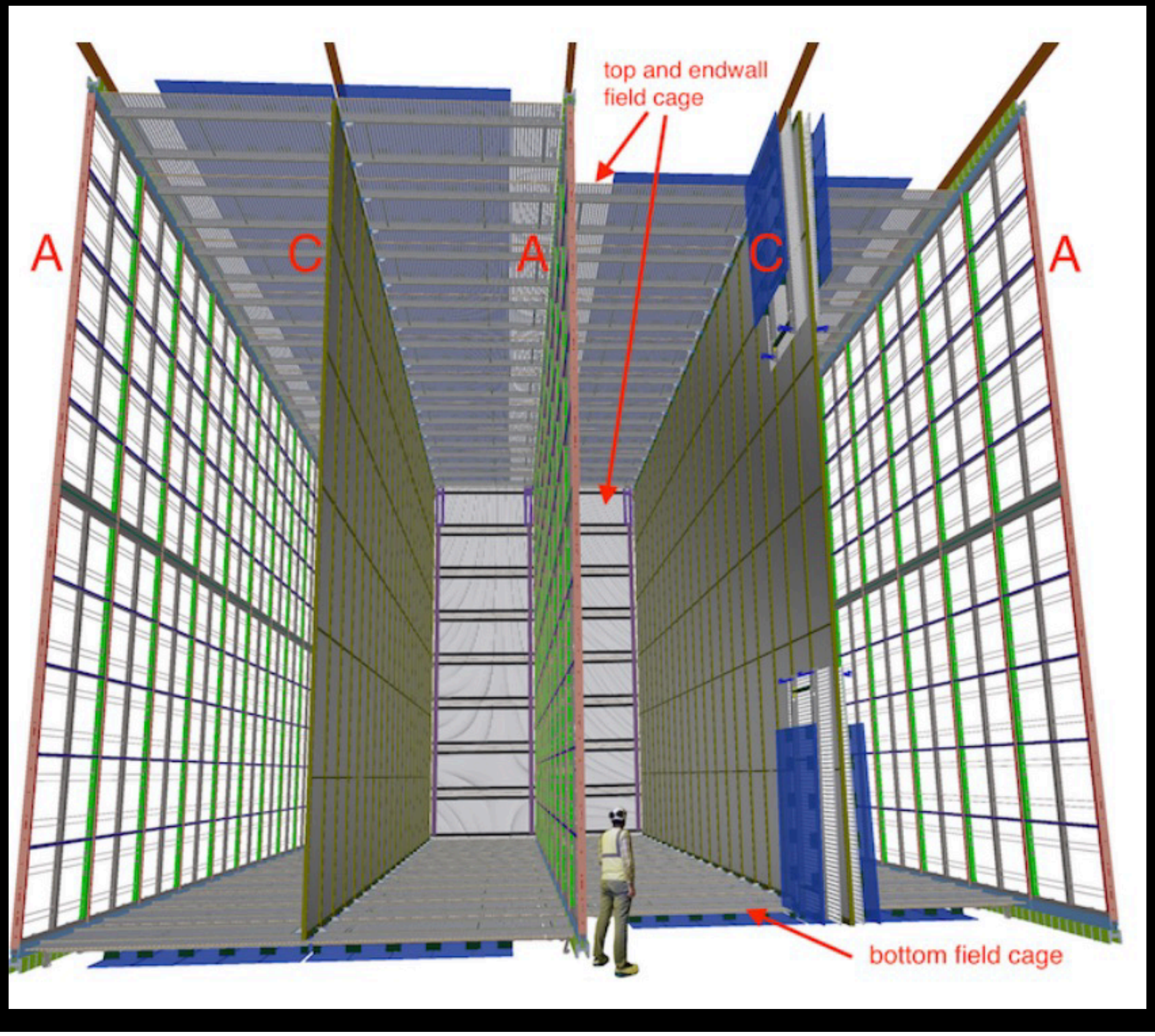
1.5 km deep, 4 Far Detecto

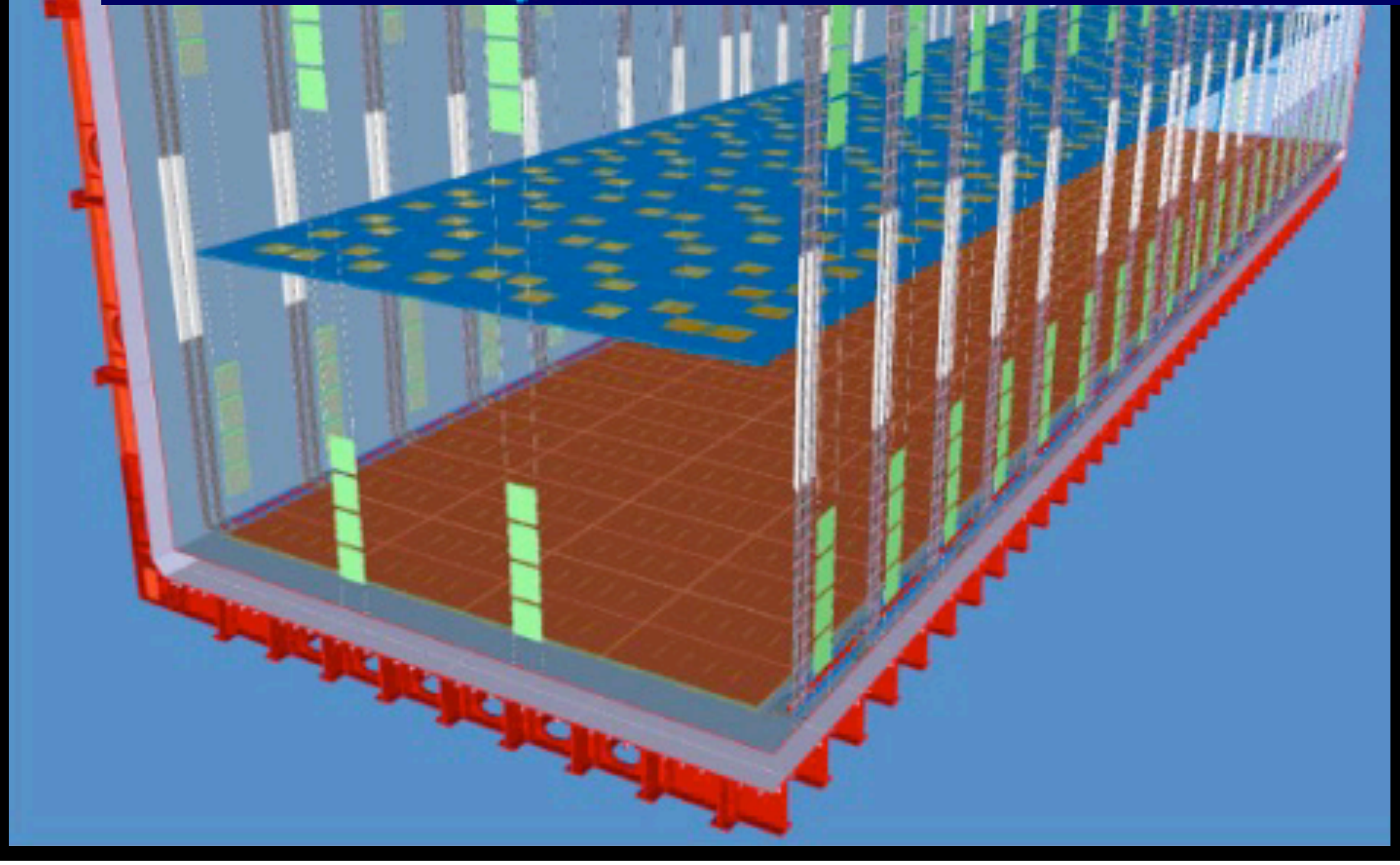
DUNE DETECTOR TECHNOLOGIES

- Liquid Argon Time Projection Chambers
  - Horizontal Drift (Far Detector 1)
  - Vertical Drift (Far Detector 2, possibly 3)
- Precision tracking (5 mm wire pitch)
- Detects all charges -> full calorimetry
- Full event (ν ID and energy) reconstruction

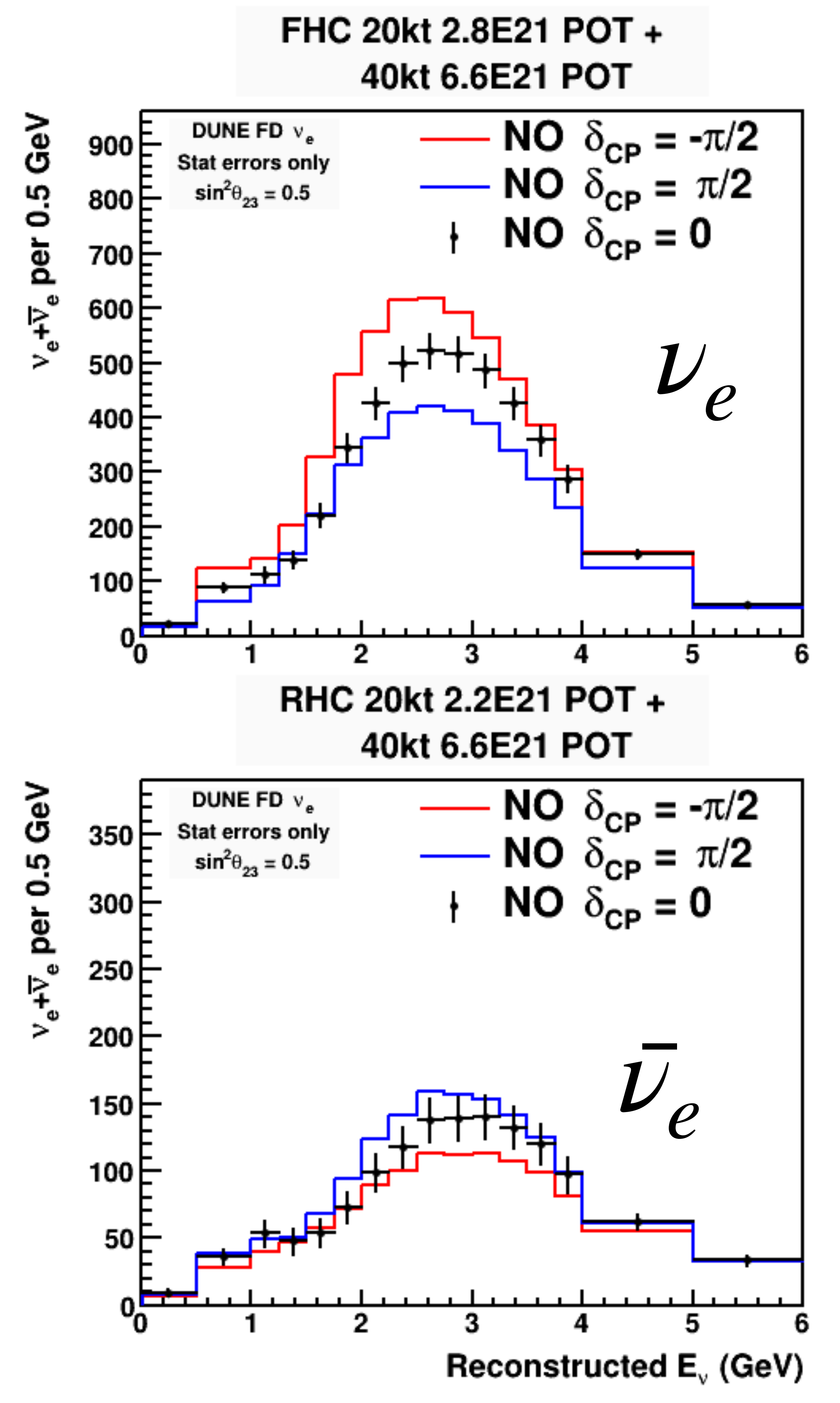

Simulated 2.5 GeV electron neutrino



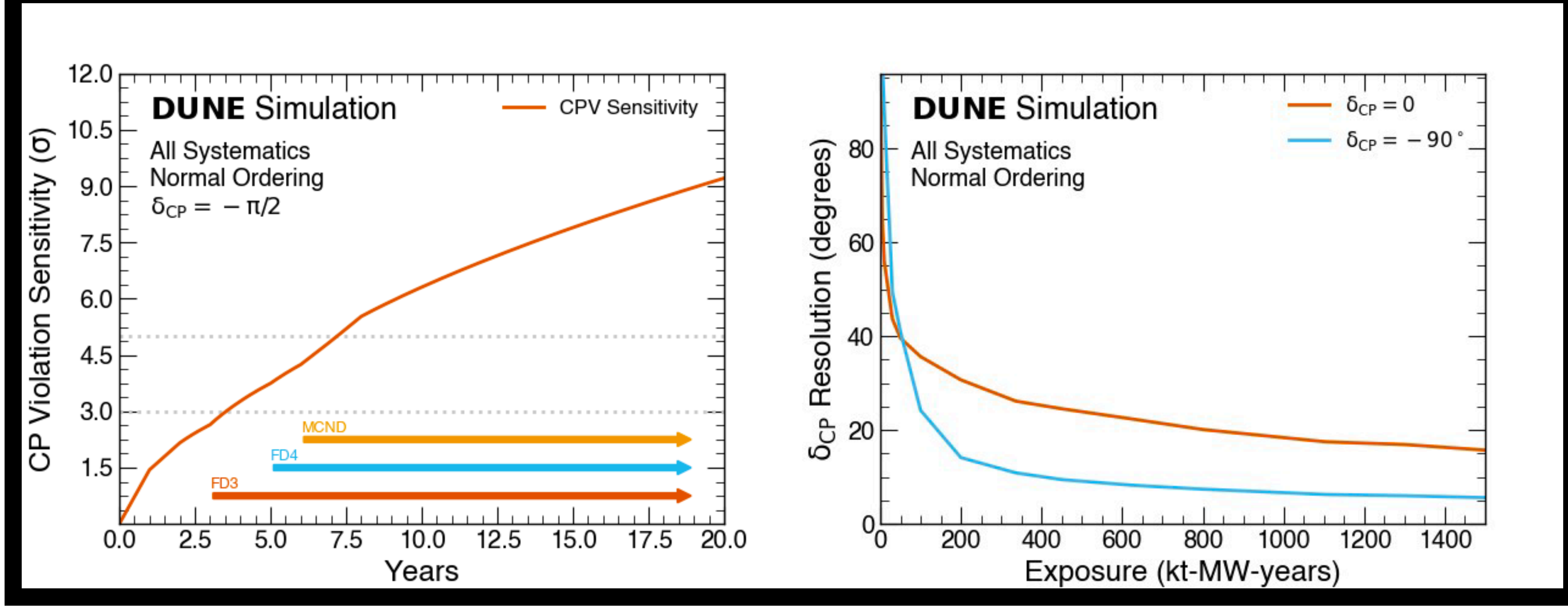




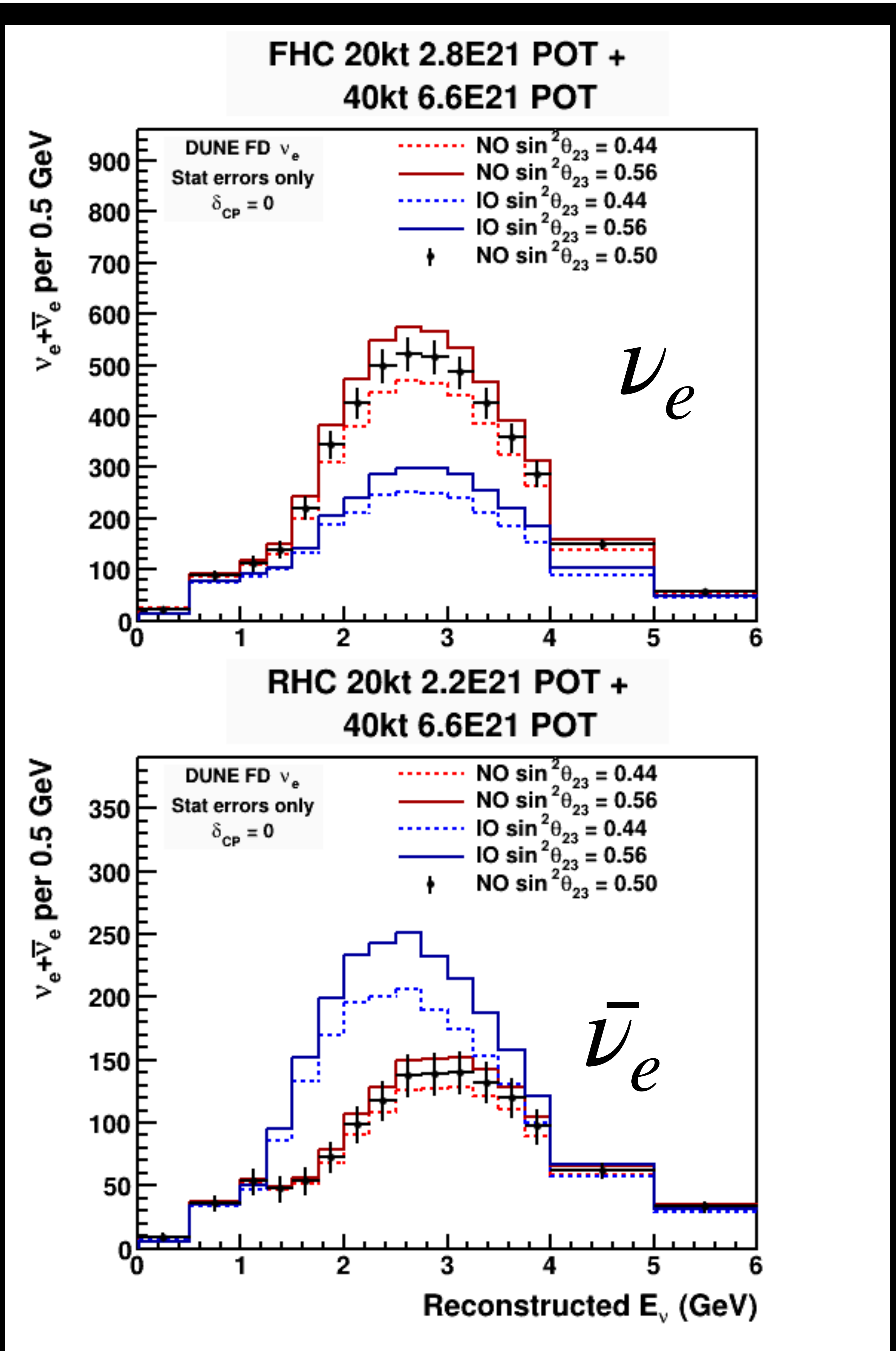
DUNE EXPECTED SPECTRA



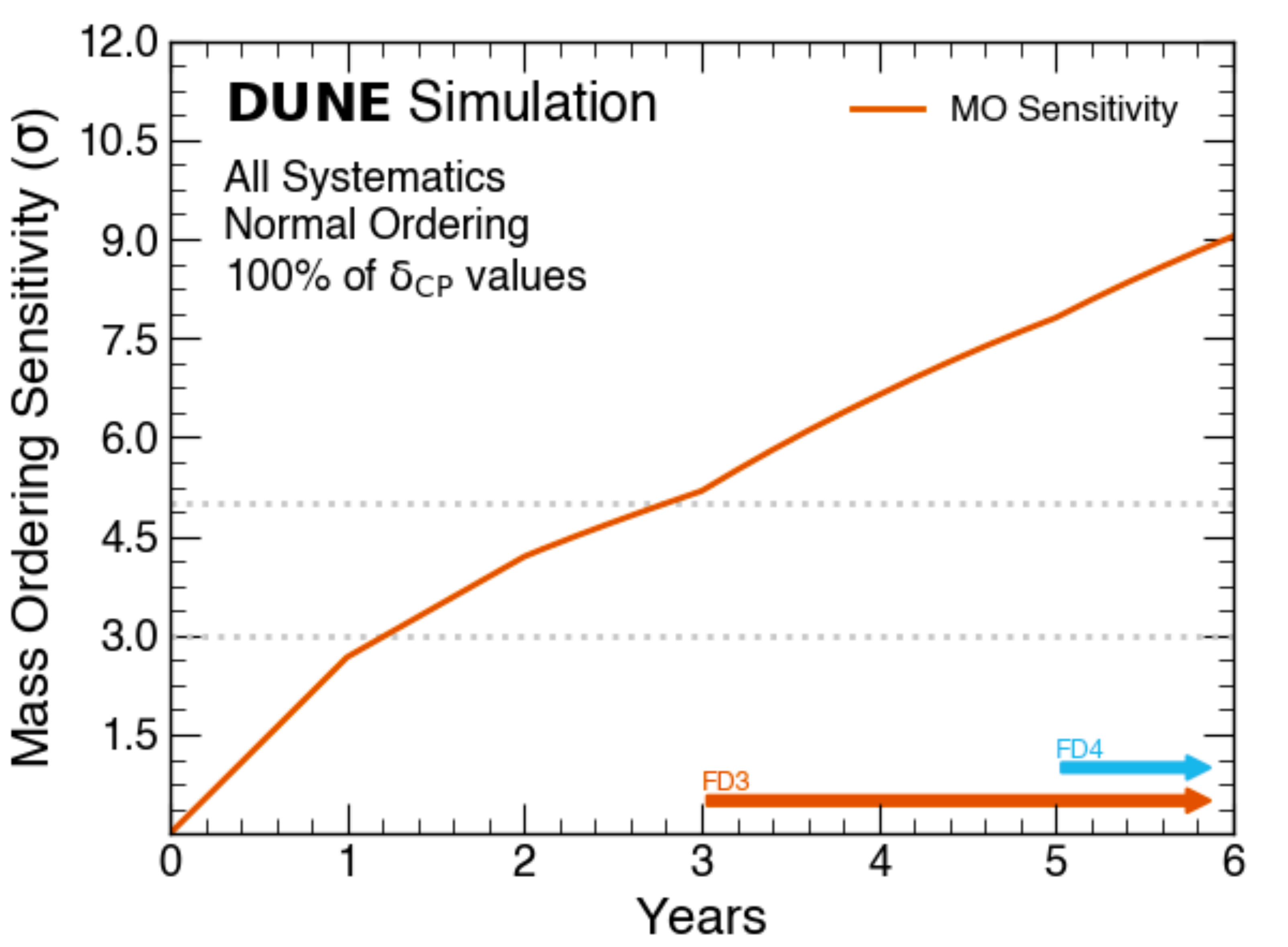
- Wide-band beam: two oscillation minima (p.33)
- If $\delta_{CP} \sim -\pi/2$, DUNE will measure an enhancement in ν_e appearance, and a reduction in $\bar{\nu}_e$ appearance



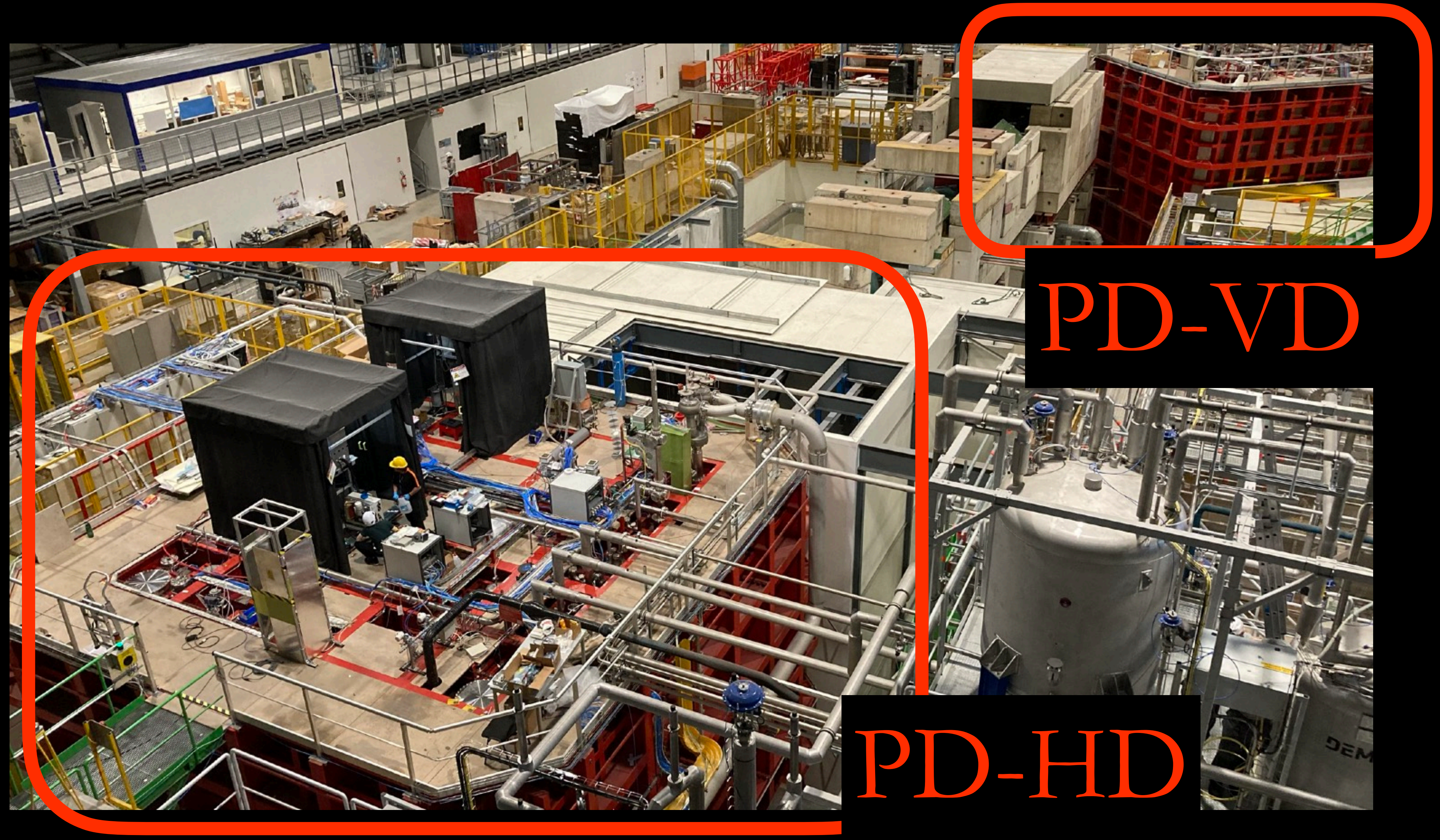
DUNE EXPECTED SPECTRA

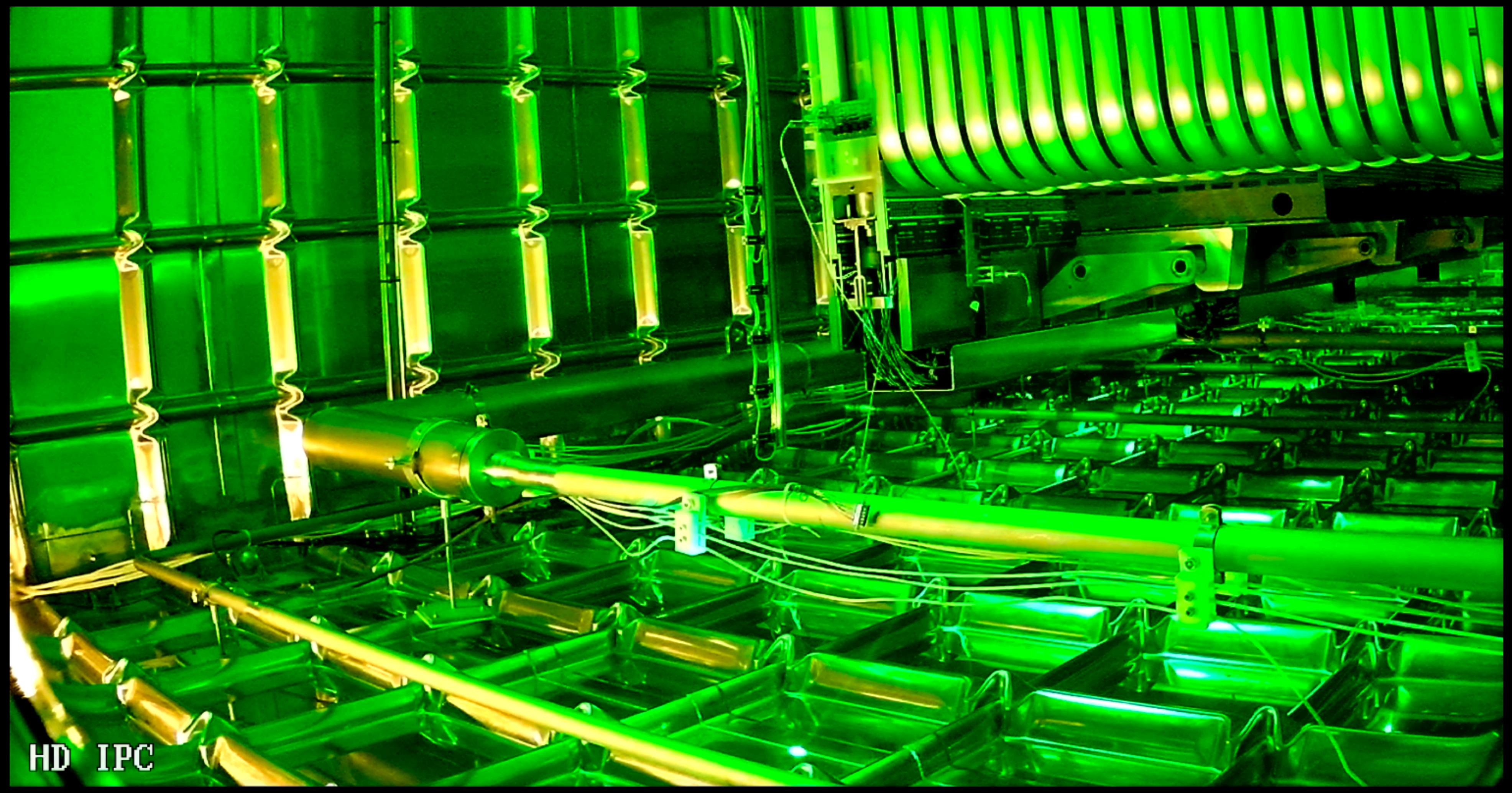


- Long baseline gives DUNE sensitivity to mass ordering (MO) through matter effects
- If the mass ordering is normal, DUNE will measure a much larger enhancement in ν_e appearance, and a reduction in $\bar{\nu}_e$ appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shapes → additional handle on resolving degeneracies



DUNE AND PROTODUNE STATUS





- ProtoDUNEs @ CERN
  - HD detector taking data with beam, cosmics and calibration systems
  - VD detector starting in the fall
- Far Detector
  - Excavation complete, installation in 2026-27
  - Physics in 2028 or early 2029
  - Beam physics with Near Detector 2031