The Case of the Missing Antimatter

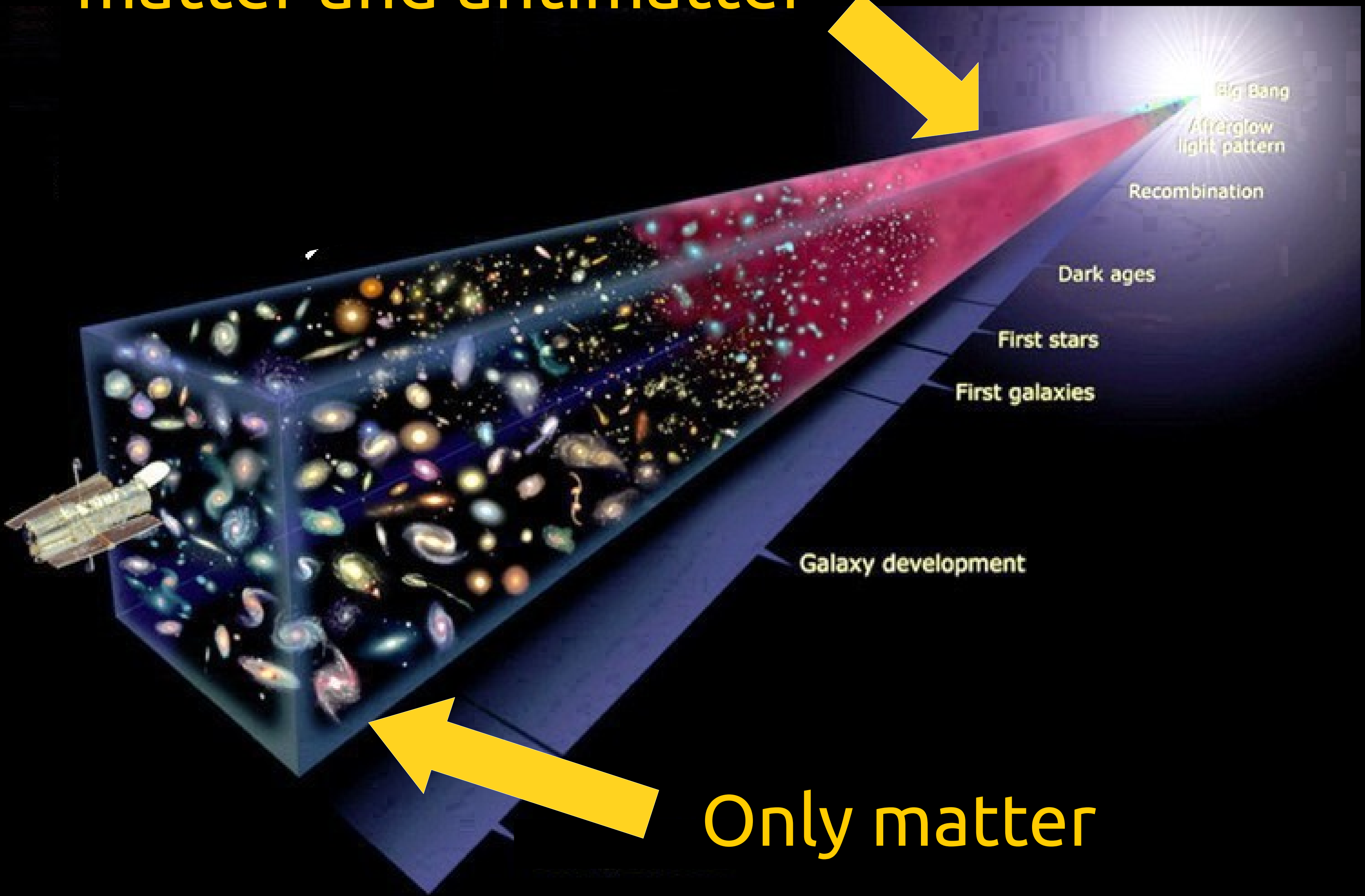
Steve Boyd
University of Warwick

THE UNIVERSITY OF WARWICK

- The problem with antimatter
- CP violation
- Neutrinos and neutrino flavour oscillations
- Long-baseline neutrino oscillation experiments
  - The T2K experiment
- Looking ahead


Why isn’t there any
anti-matter?

Equal amounts of matter and antimatter

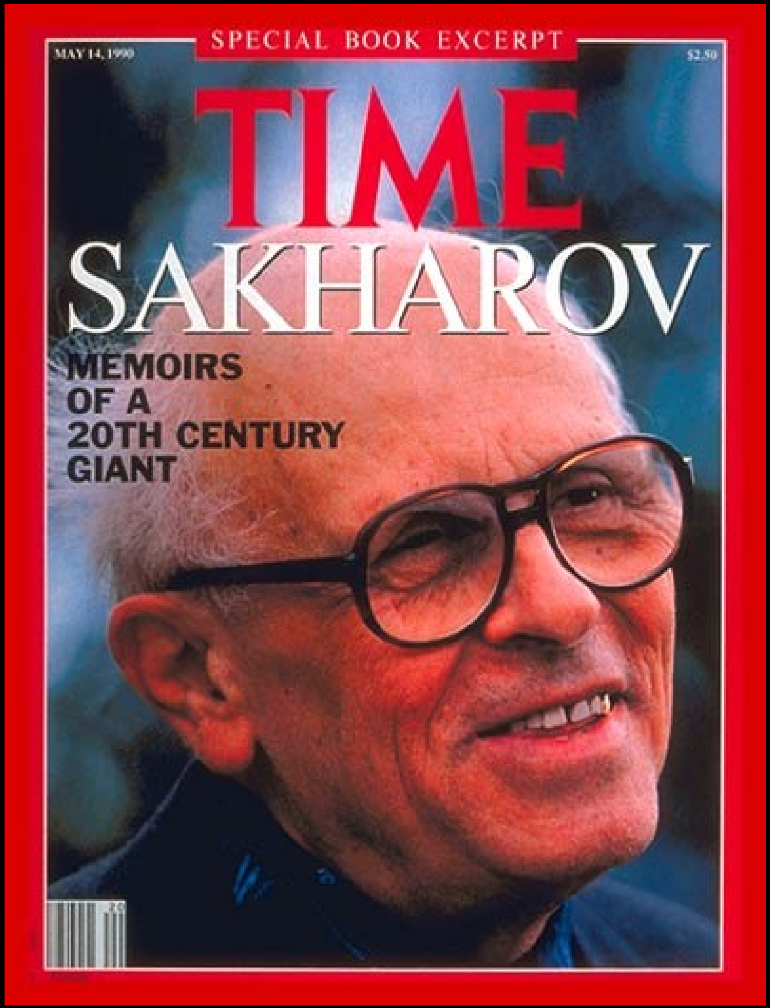


Only matter

Baryon Asymmetry

How would a matter-only universe develop?

- Sakharov Conditions (1967)
- We need some difference between matter and antimatter
- We have to violate CP symmetry



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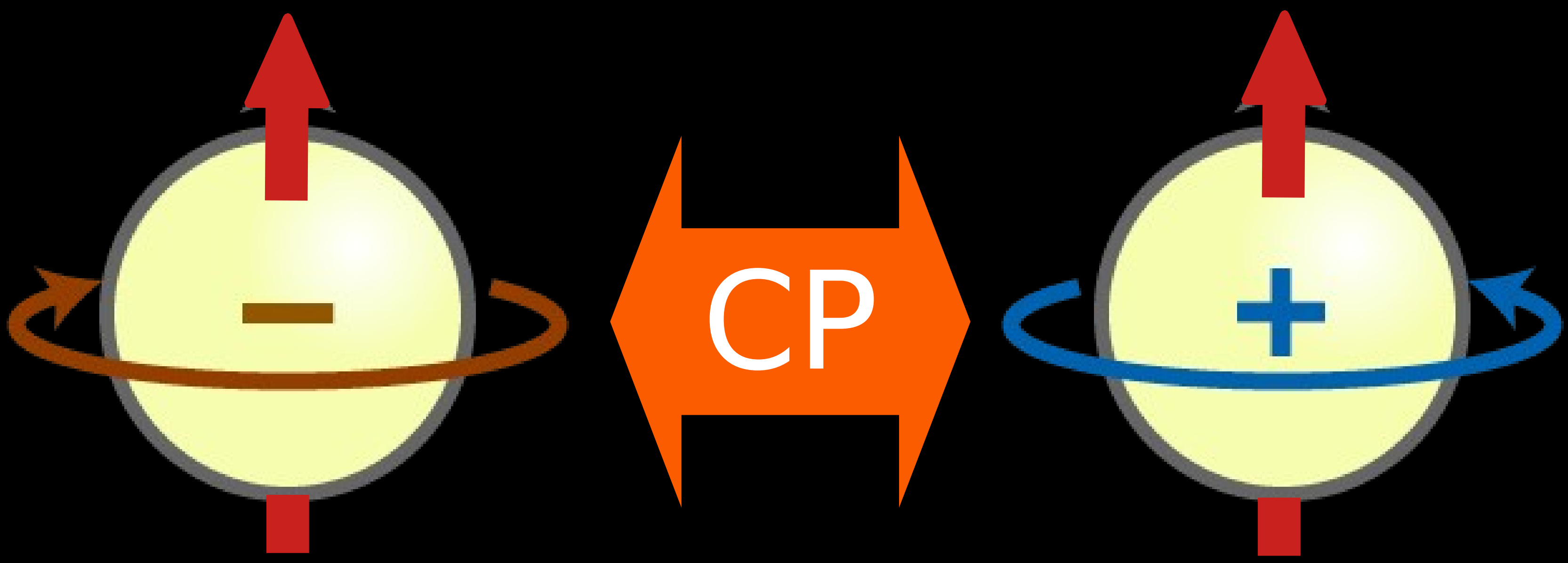
CP Violation

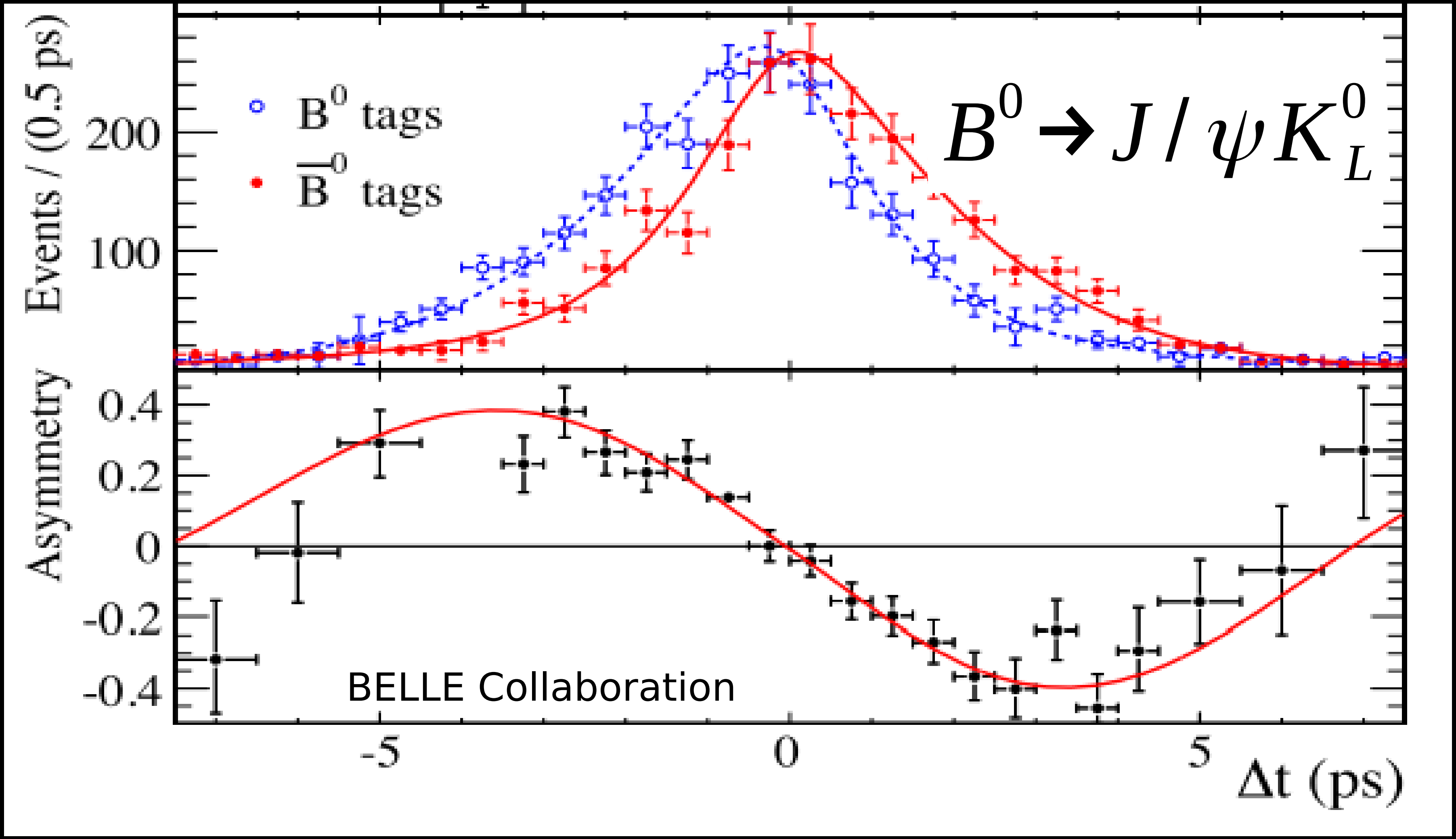


Left-handed (LH) Right-handed (RH)

CP Symmetric Universe:

$$\mathrm{Prob}(A_{LH} \rightarrow B_{LH}) = \mathrm{Prob}(\bar{A}_{RH} \rightarrow \bar{B}_{RH})$$

CP Violation



I.Adachi et al. "Precise measurement of the CP violation parameter sin $2\phi_1$ in B0 → (cc)K0 decays". Phys. Rev. Lett. 108, 171802 (2012). 1201.4643.

Taken from : A. J. Bevan et al., "The Physics of the B Factories", Eur. Phys. J. 74 (2014),.

CP Violation

The baryon-antibaryon symmetry determined from the Cosmic Microwave Background

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-10}$$

Canetti et al 2012 New J. Phys. 14 095012

Using the measured CP violation in the quark sector :

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-17}$$

C. Jarlskog, Phys. Rev. Lett. 55, 1039

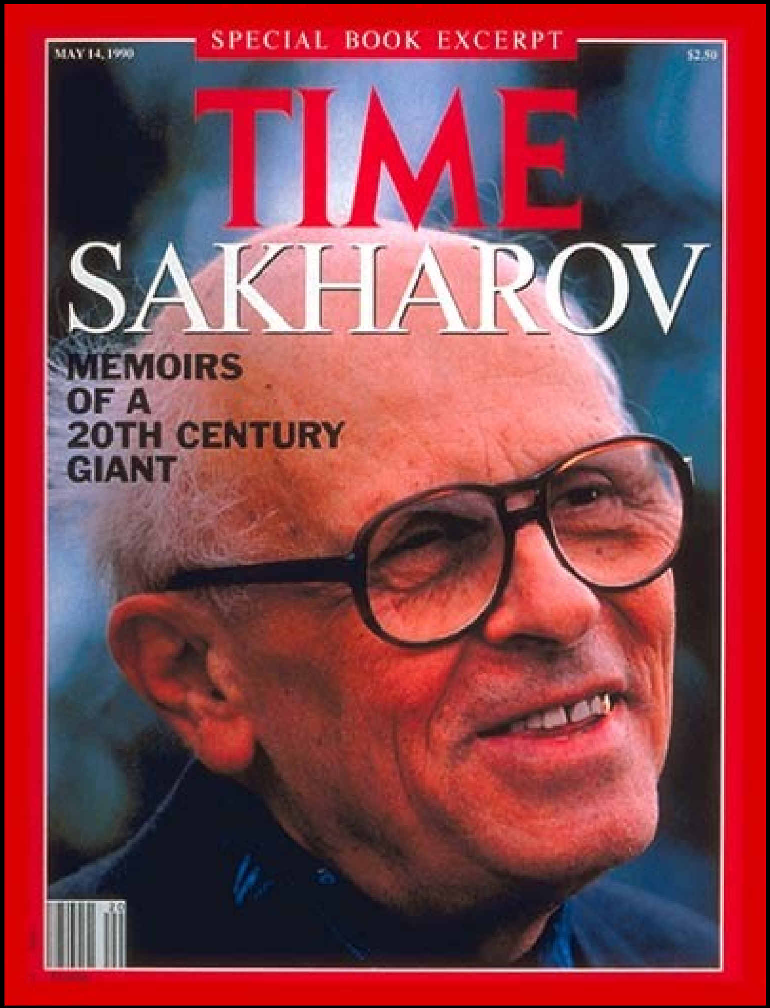
We need more sources of CP violation

What about the leptons?

Baryon Asymmetry

How would a matter-only universe develop?

- Sakharov Conditions (1967)
- We need some difference between matter and antimatter
- We have to violate CP symmetry
- CP violation in the quark sector is not big enough
- CP violation in the neutrino sector might be!
- Leptogenesis → Baryogenesis



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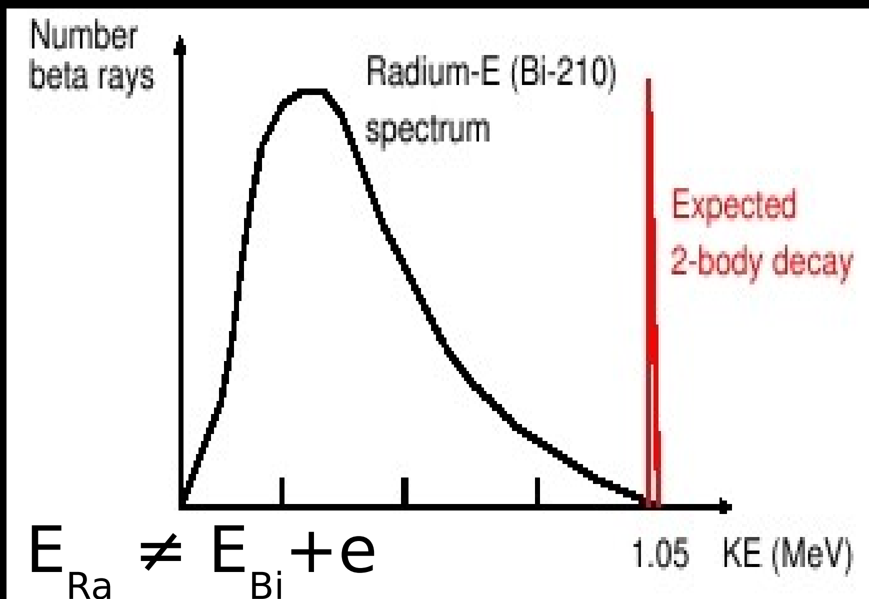
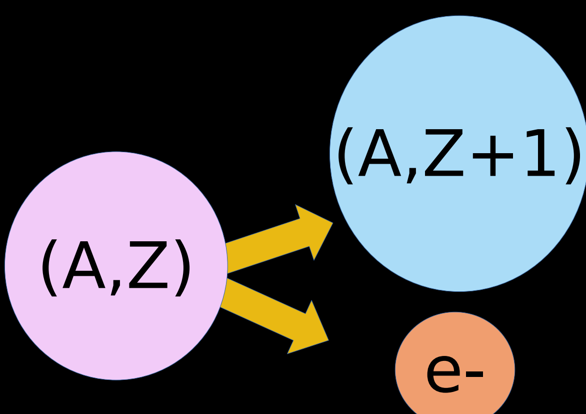
Pascoli, et al., arXiv:hep-ph/0609125v3

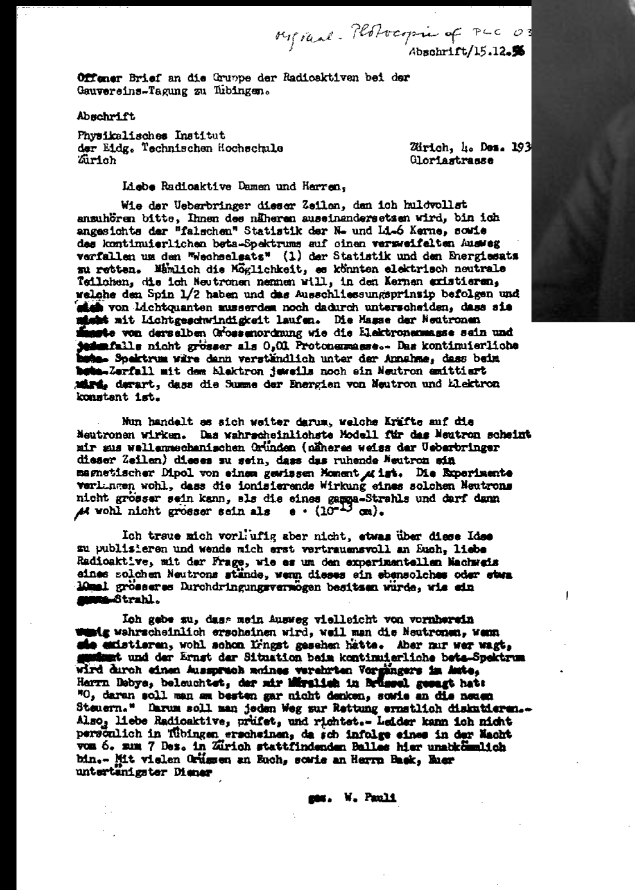
Neutrinos

1914 – the field of atomic physics is in trouble. β decay data just looks weird.





1930, Zurich



Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 193
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

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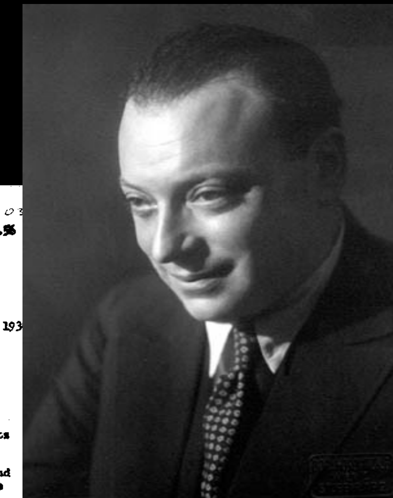
gez. W. Pauli



“Desperate remedy.....”
“I do not dare publish this idea....”
“I admit my way out may look improbable....”
“Weigh it and pass sentence....””

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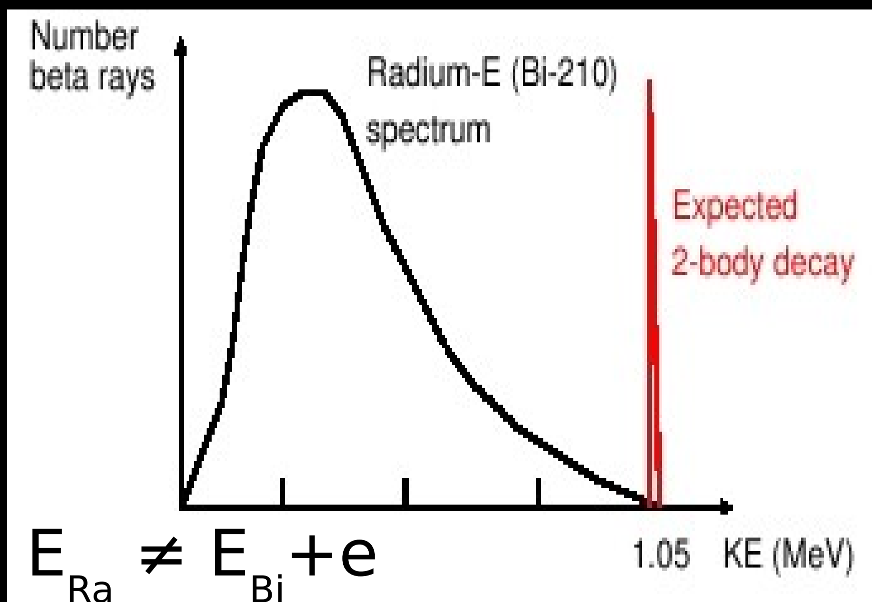

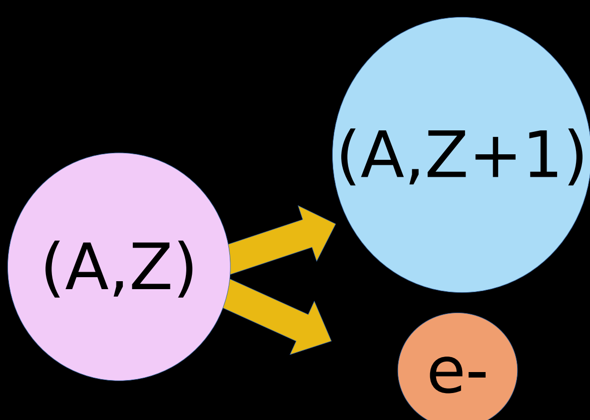

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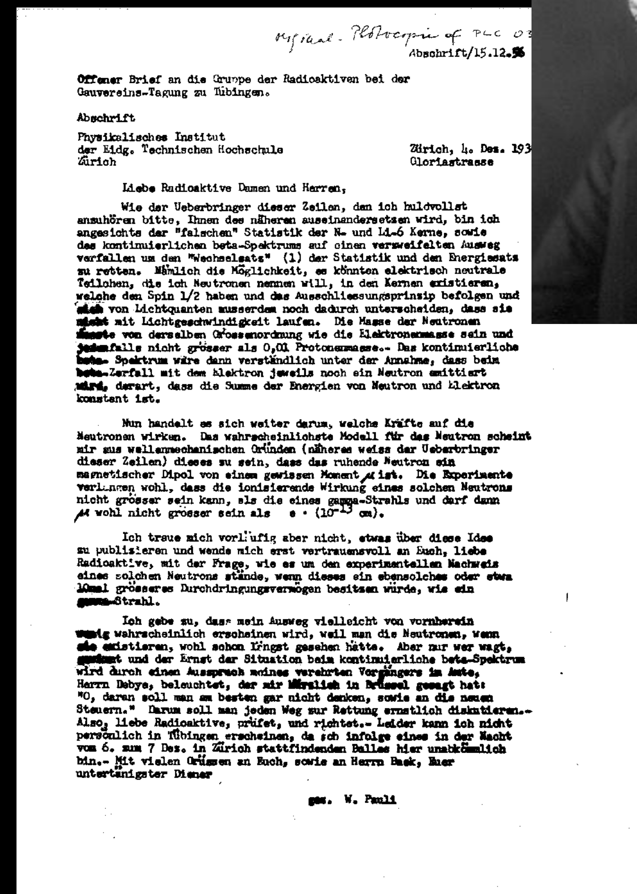

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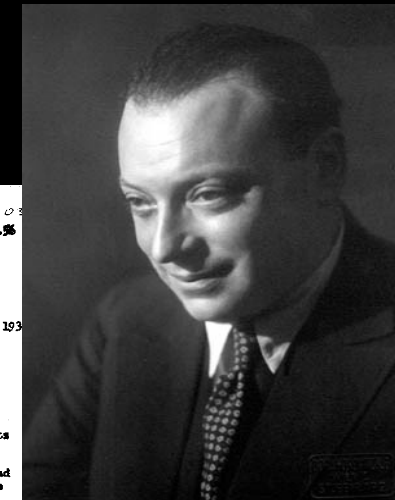

"Unfortunately I can't appear at Tubingen since I am indispensable here in Zurich because of a ball."

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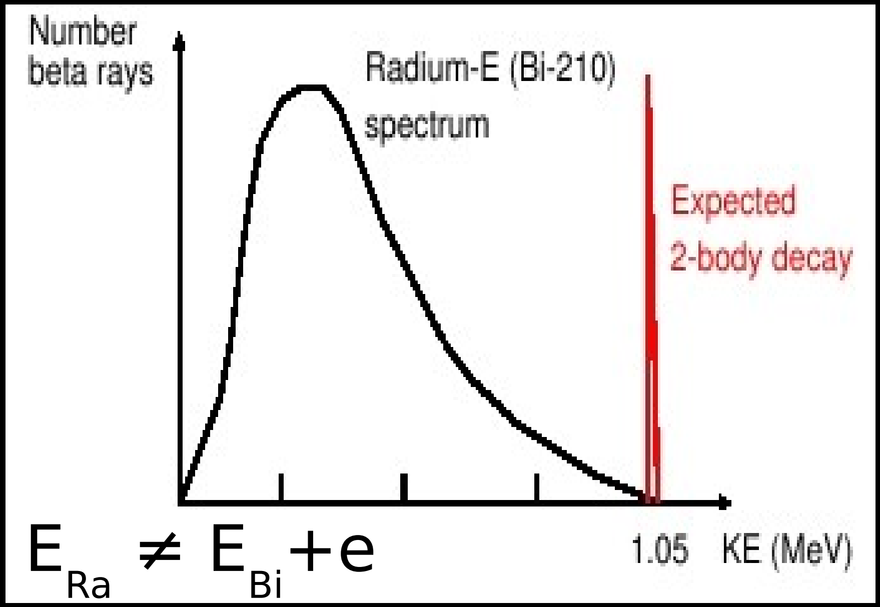
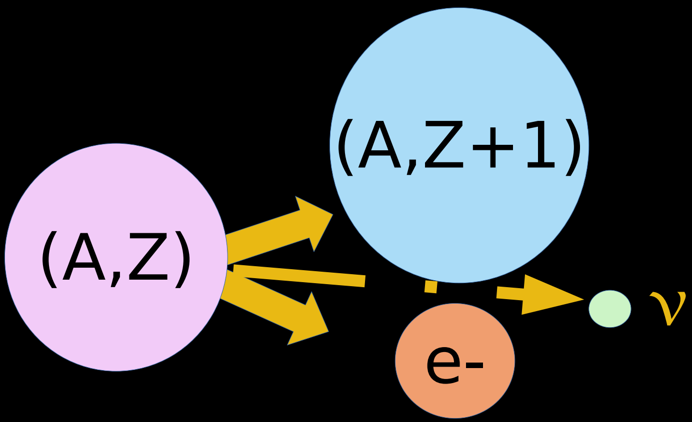




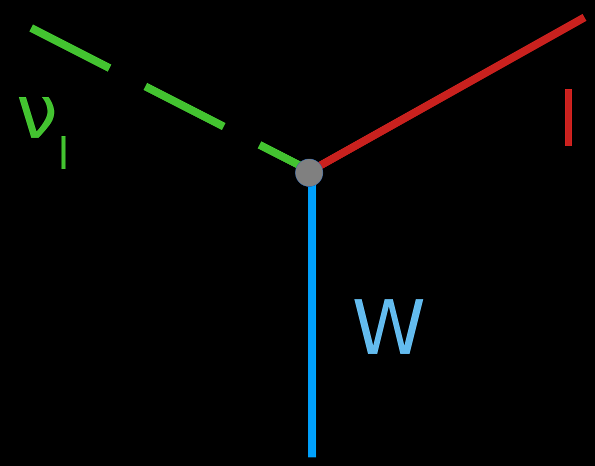
Add a new particle to the particle universe (p,e^-)

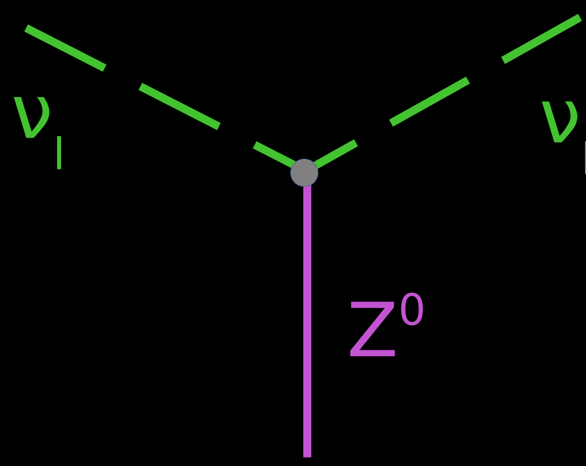
- very light
- spin $\hbar/2$
- practically unobservable

"I have done a terrible thing. I have postulated a particle that cannot be detected; it is something no theorist should ever do."

- Three flavours; associated with charged partner
- Spin ½
- no electric or colour charge; they interact only via the weak force
- Lightest fermions : masses are less than 1 eV/c^2

Neutrino Interactions





Charged Current Interaction

Preserves neutrino/lepton flavour

Energy threshold for creating the final state lepton

Neutral Current Interaction

Happens for all flavours with equal probability

No energy requirementt

Neutrino Flavour Oscillations

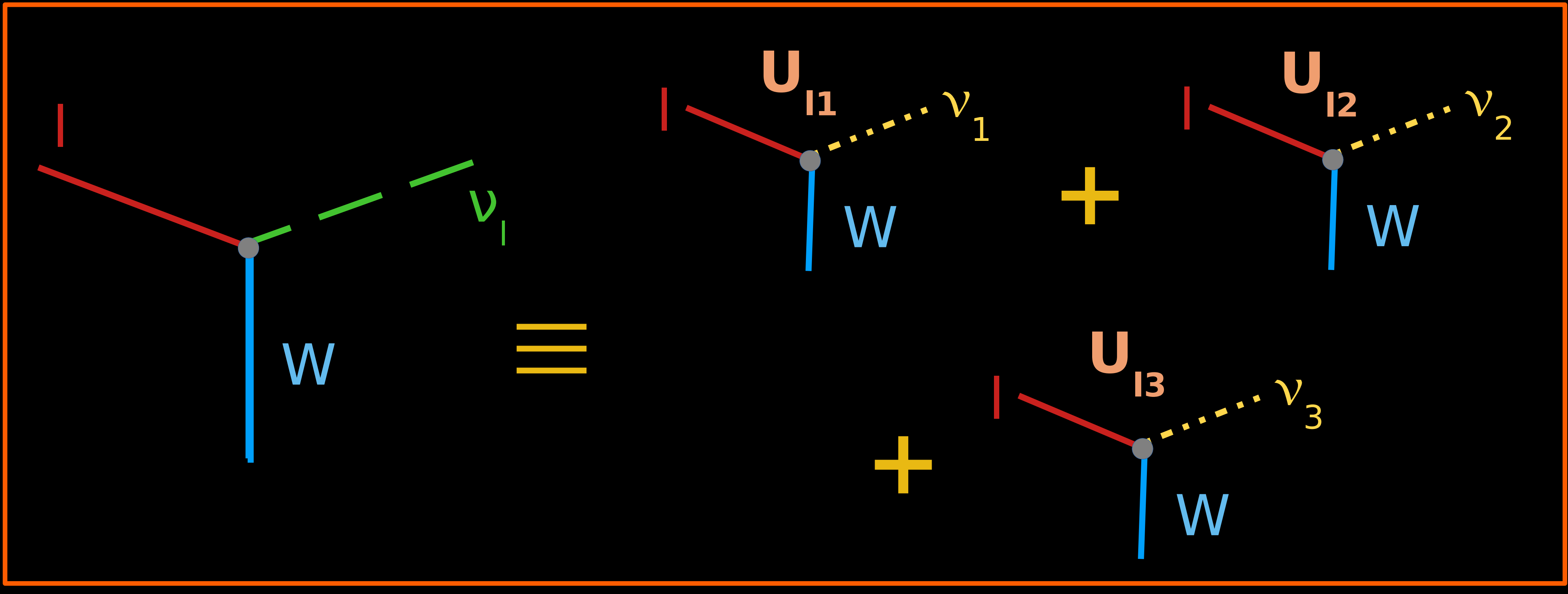
Neutrino Mixing

Pontecorvo

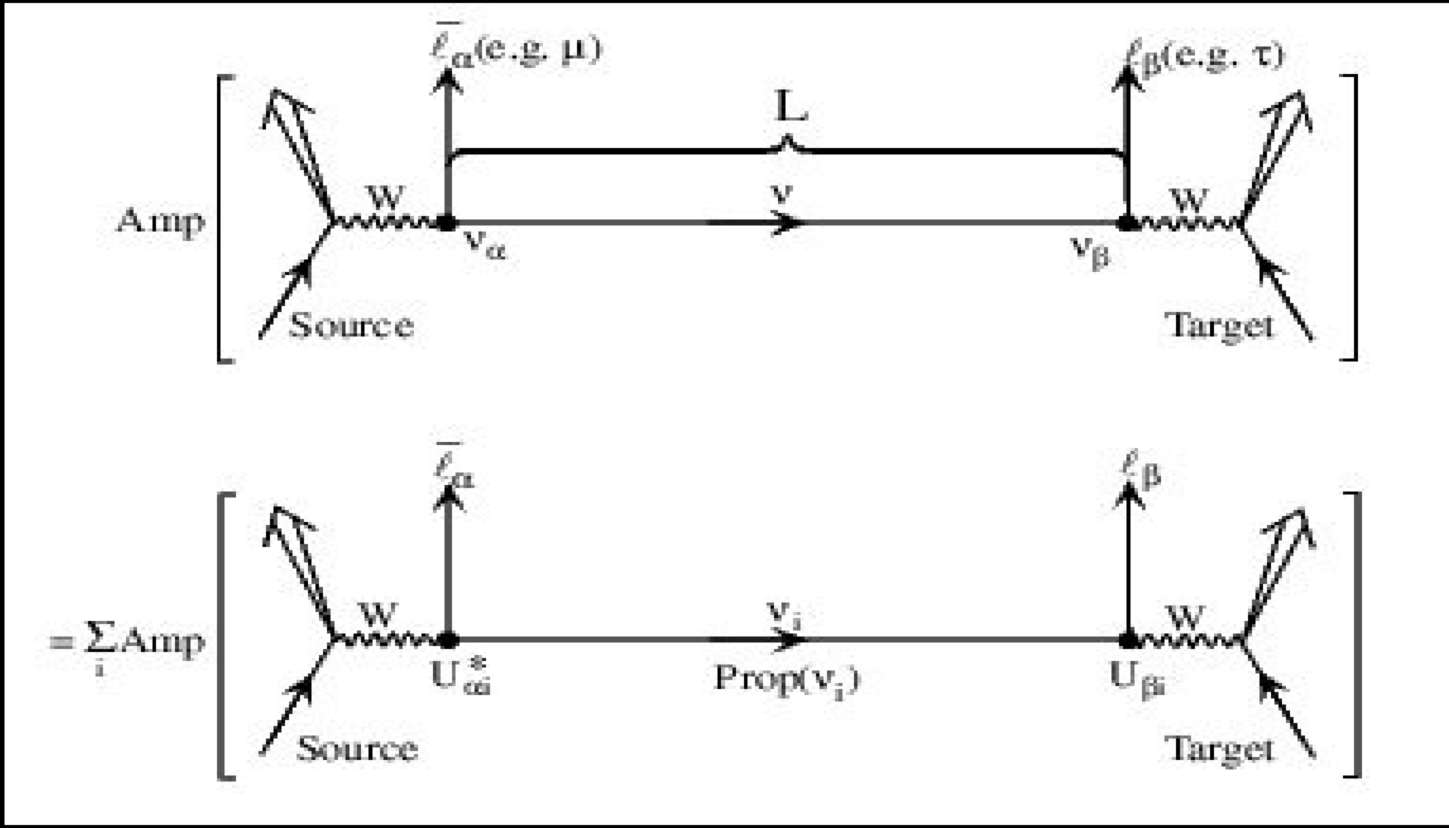
Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968

Flavour states $(\nu_e, \nu_\mu, \nu_\tau)$ $\neq$ Mass states (ν_1, ν_2, ν_3)



Neutrino Flavour Oscillations



$$Prob\left(\nu_\alpha \rightarrow \nu_\beta\right) \propto \left|\sum_i U^*_{\alpha i} \mathrm{Prop}\left(\nu_i\right) U_{\beta i}\right|^2$$

If we don't know which mass state was created then the the amplitude involves a coherent sum of ν_i states

Neutrino Flavour Oscillations

Let’s live in a universe with only two neutrino species.
Mixing means:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_e(0,0)> = \cos\theta |\nu_1(0,0)> + \sin\theta |\nu_2(0,0)>$$

$$|\nu_\mu(t,x)> = -\sin\theta |\nu_1(t,x)> + \cos\theta |\nu_2(t,x)>$$
$$= -\sin\theta |\nu_1(0,0) e^{i p_1 \cdot x}> + \cos\theta |\nu_2(0,0) e^{i p_2 \cdot x}>$$

Probability that you start with a ν_e and later measure a ν_μ is

$$P(\nu_\mu(t,x)|\nu_e(0,0)) = |<\nu_\mu(t,x)|\nu_e(0,0)>|^2$$

Neutrino Flavour Oscillations

$$P(\nu_\mu(t,x)|\nu_e(0,0)) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2_{12}\frac{L}{E}\right)$$

$m_1^2 - m_2^2$

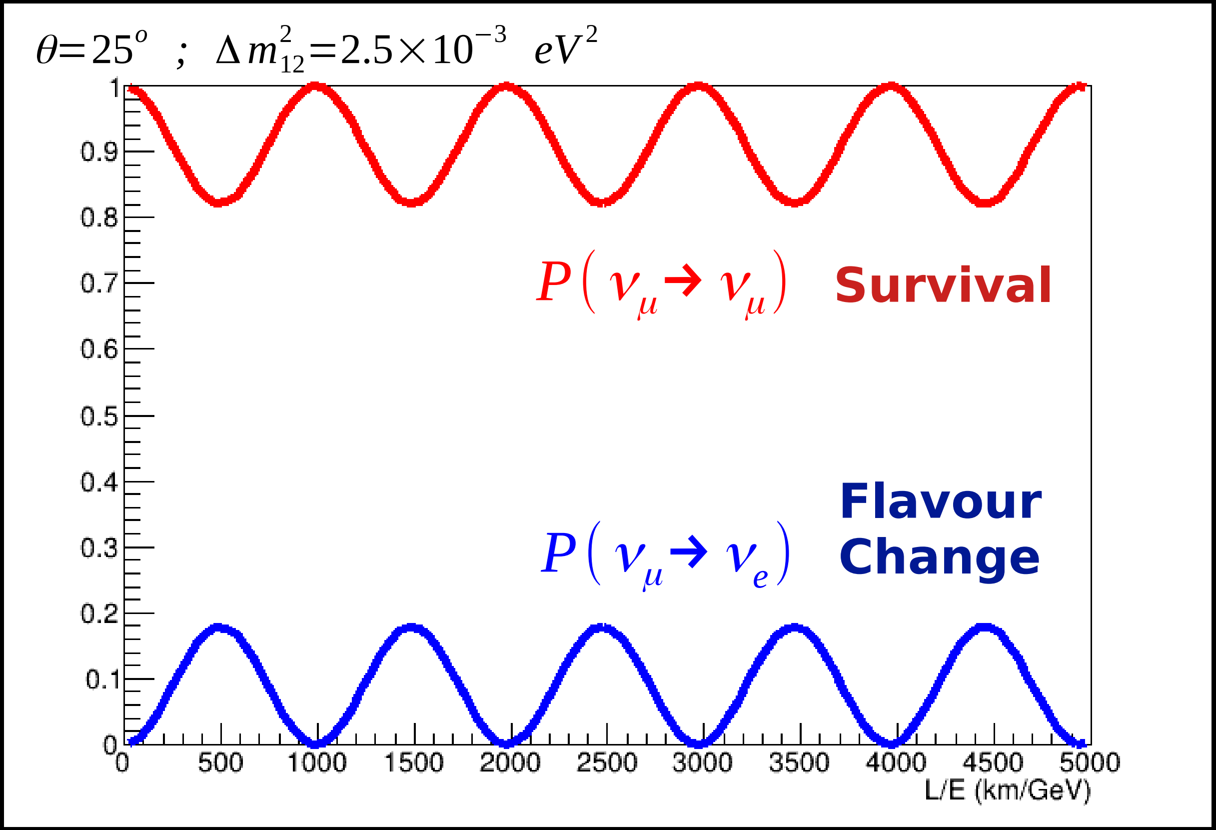
Physics parameters :

- $\Delta m_{12}^{\ 2}$: Wavelength
- θ : Amplitude

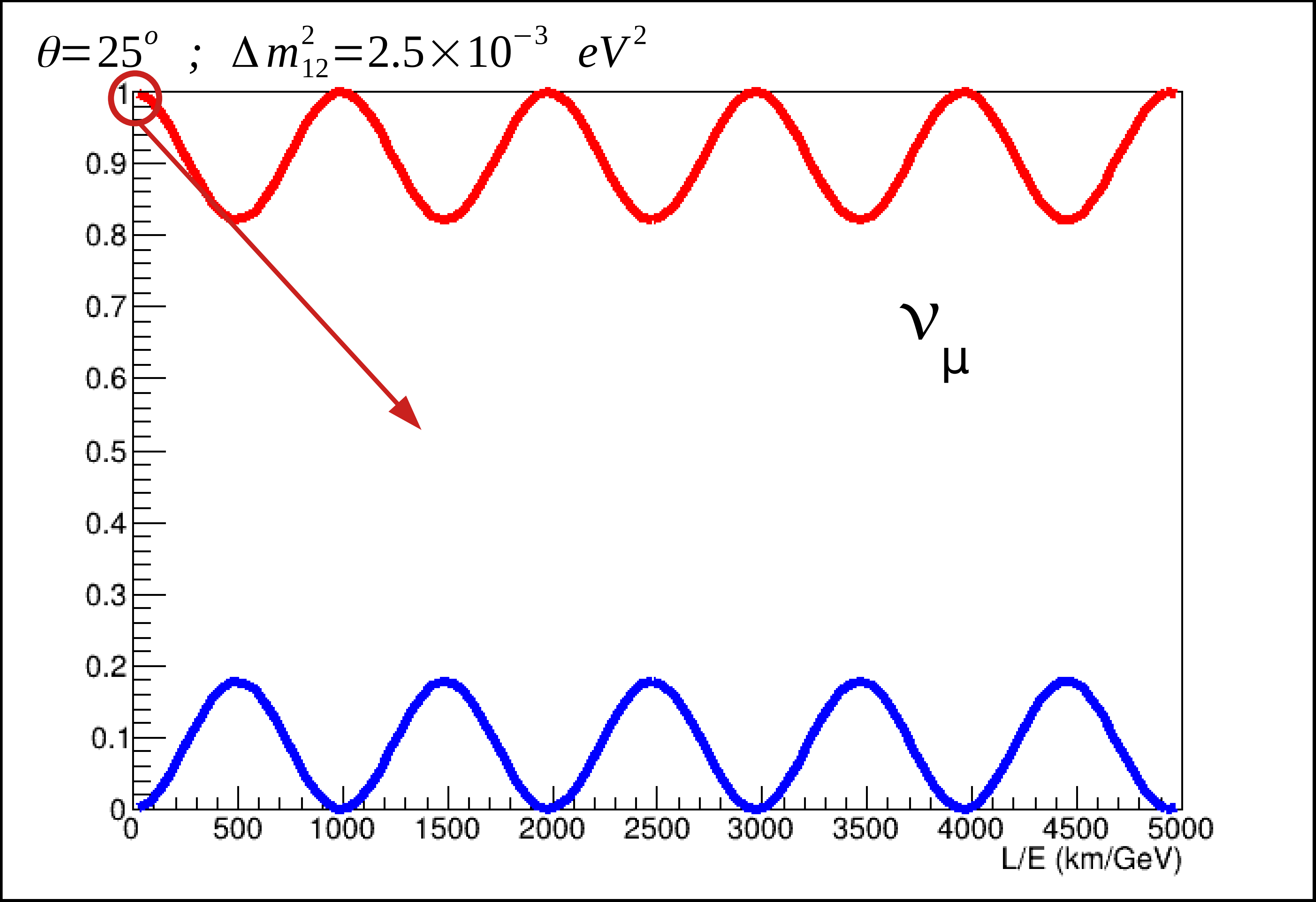
Experimental parameters:

- L : Distance travelled
- E : Neutrino energy

Choose L and E to target favourite $\Delta m_{12}^{\ 2}$



Disappearance Experiment



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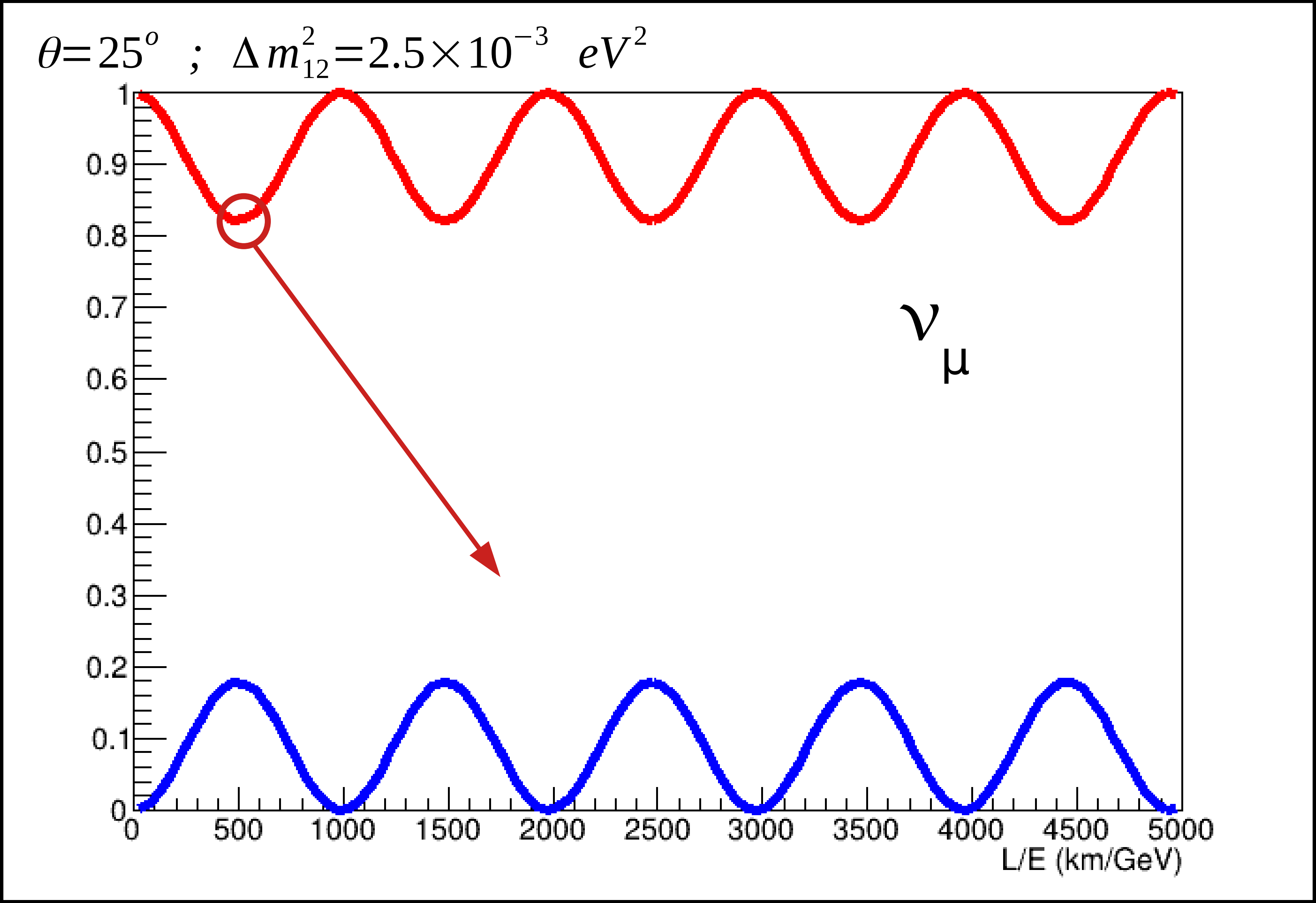
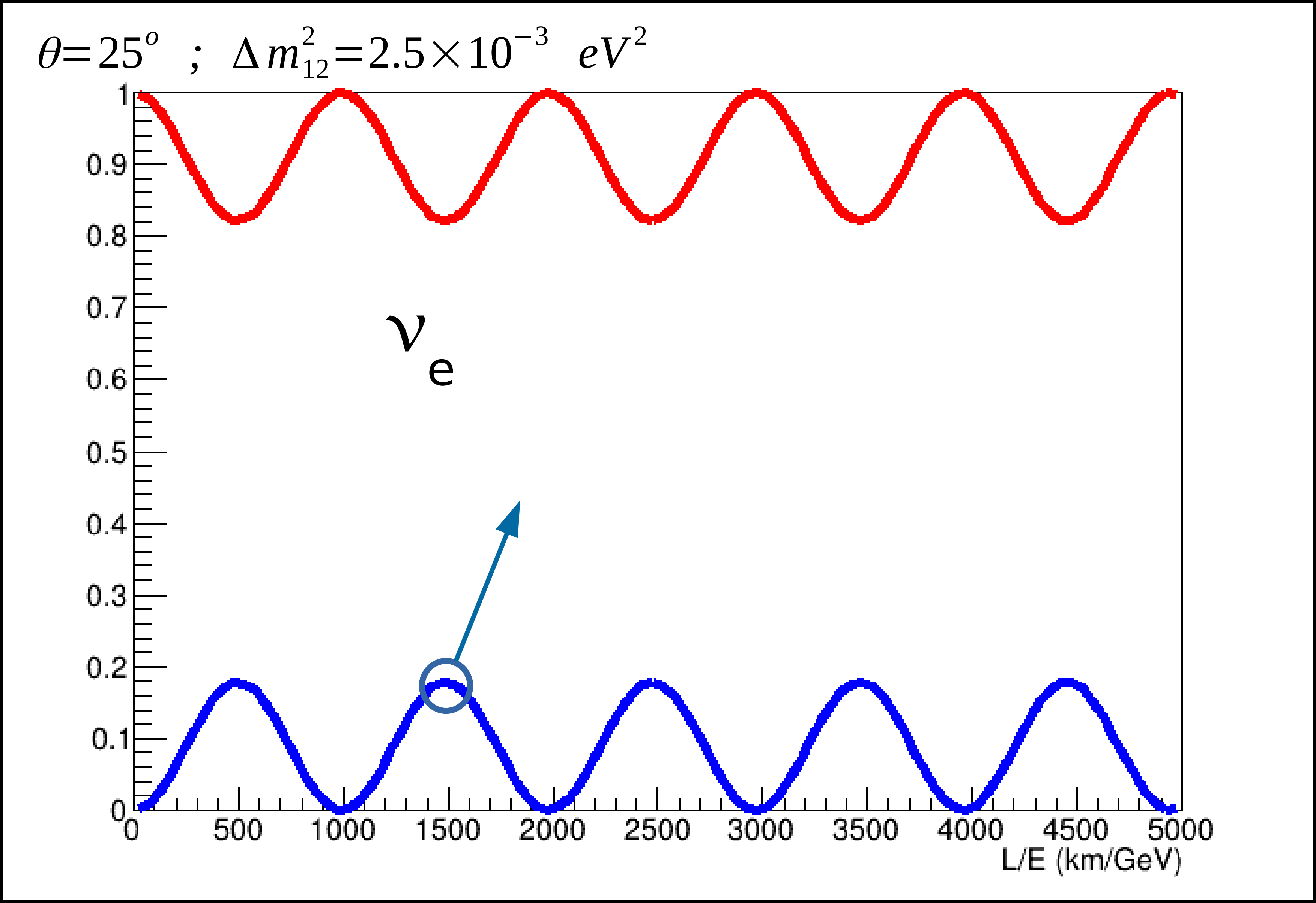


Appearance Experiment



Three Neutrino Flavours

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

U is the Pontecorvo-Maskawa-Nakayama-Sakata (PMNS) matrix

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\Delta m^2_{ij} \frac{L}{2E}\right)$$

Three Neutrino Flavours

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

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

Three Neutrino Flavours

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Two independent Δm^2

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \left(\Delta m^2_{ij} \frac{L}{4E} \right)$$

$$+ 2 \sum_{i>j} \Im (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \left(\Delta m^2_{ij} \frac{L}{2E} \right)$$

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$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Three mixing angles : $\theta_{12}, \theta_{23}, \theta_{13}$

$$Prob(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \left(\Delta m^2_{ij} \frac{L}{4E} \right)$$

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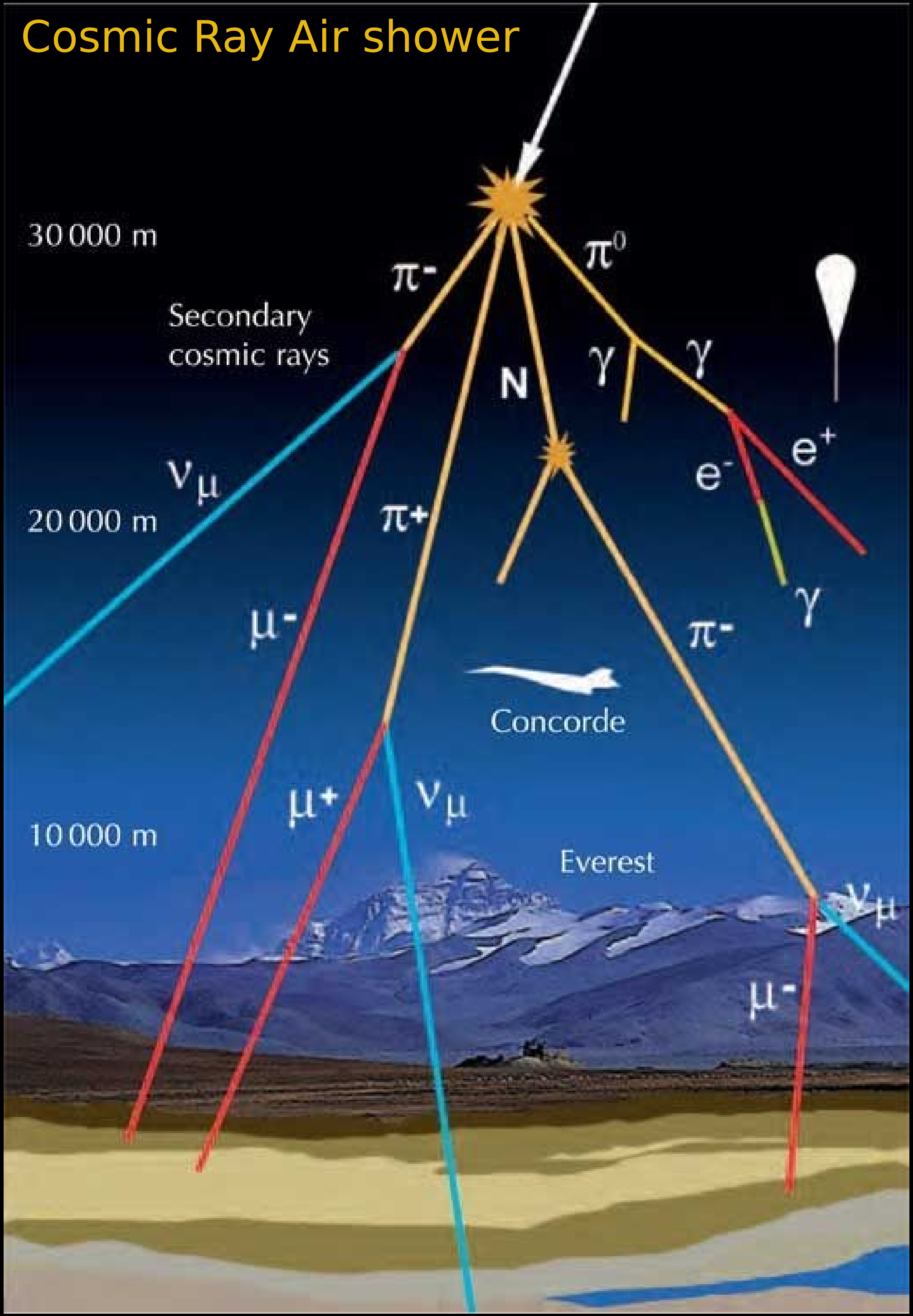
One (potentially CP violating) phase

$$Prob(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

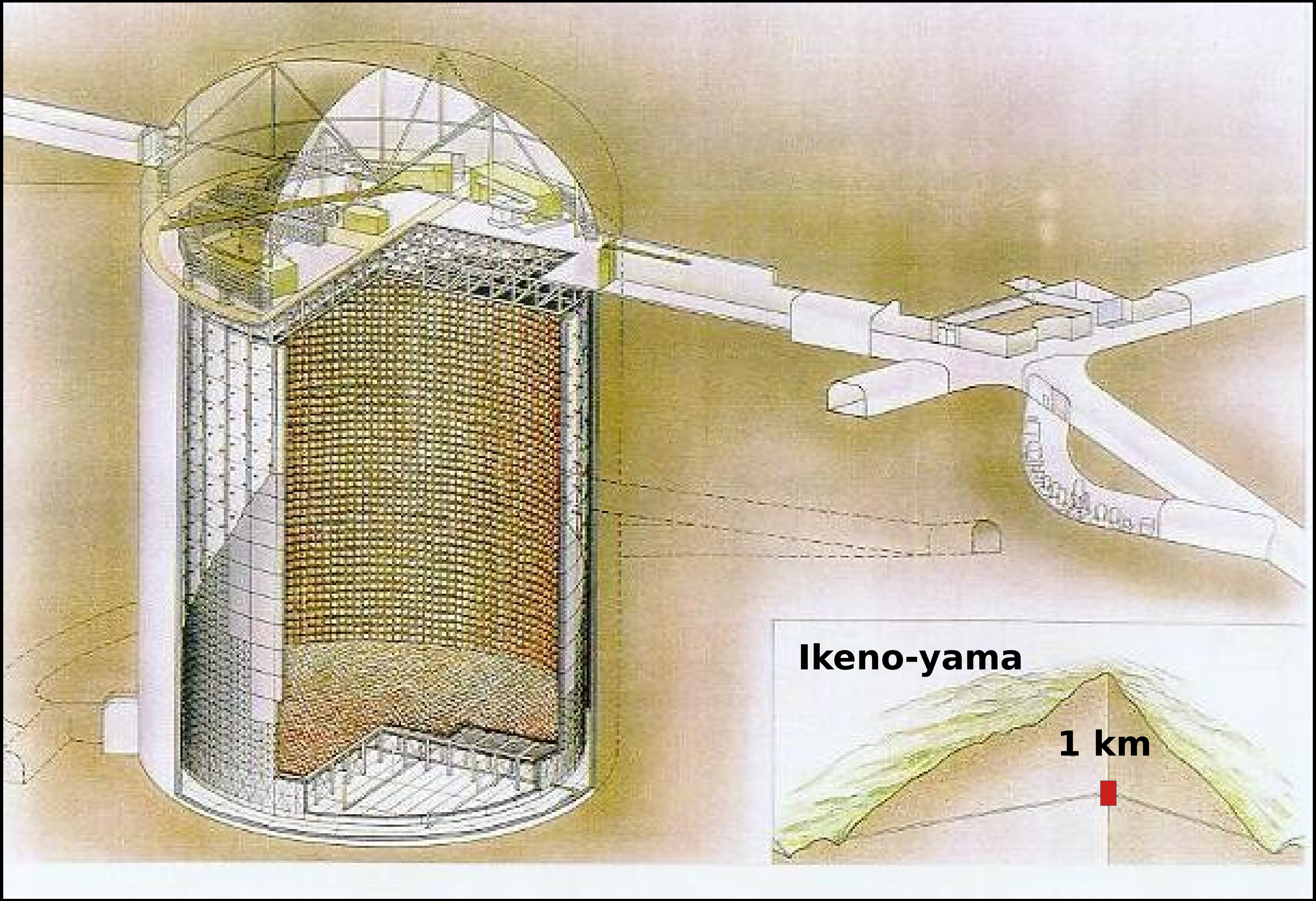
$$+ 2 \sum_{i>j} \Im (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \left(\Delta m^2_{ij} \frac{L}{2E}\right)$$

Status of neutrino oscillation measurements

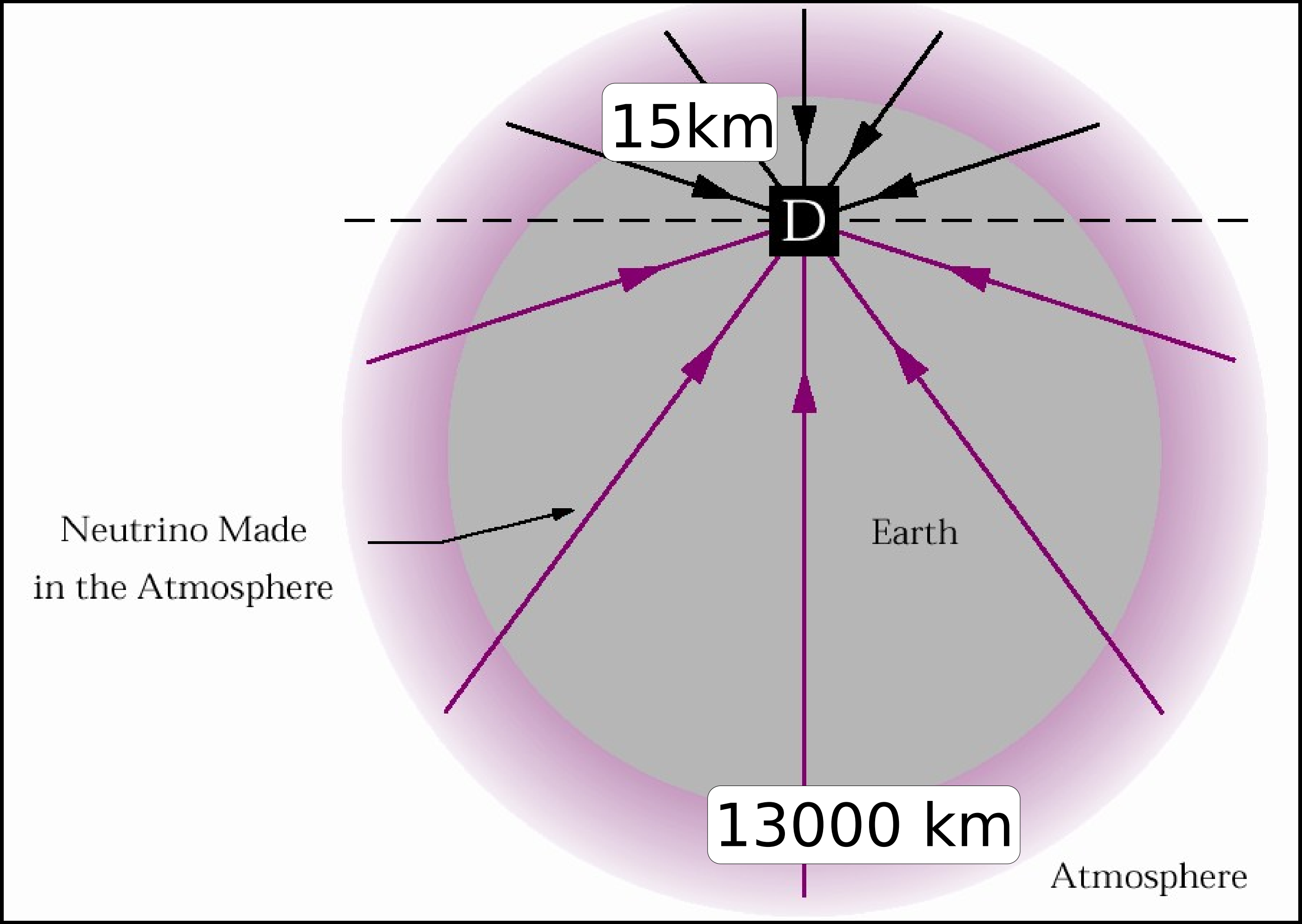
Atmospheric Neutrino Anomaly



Super-Kamiokande



Baseline Scan



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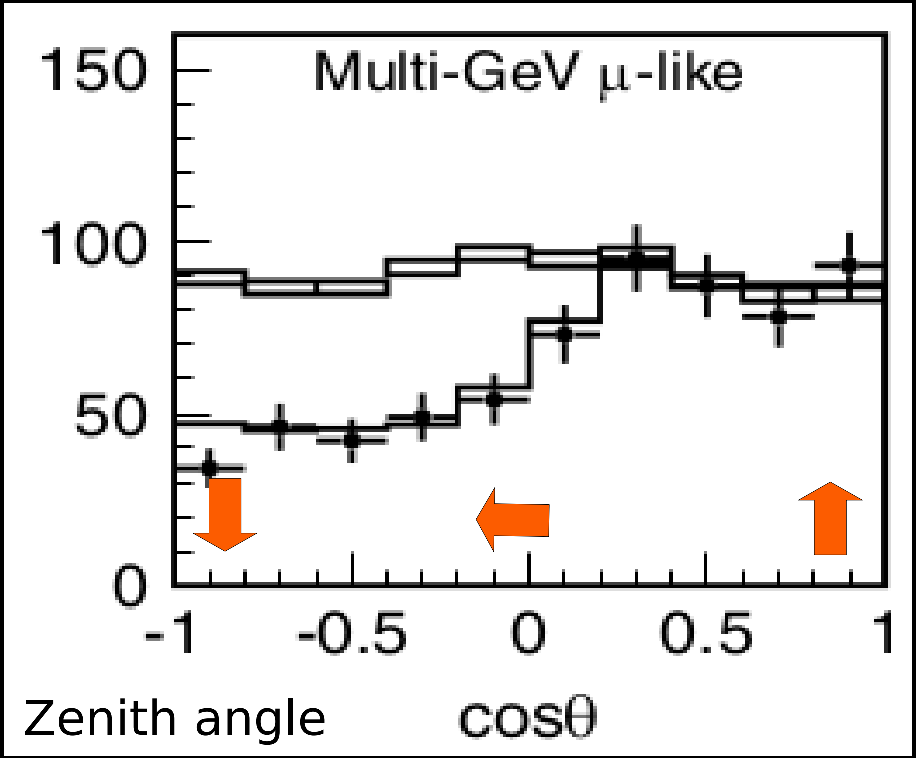
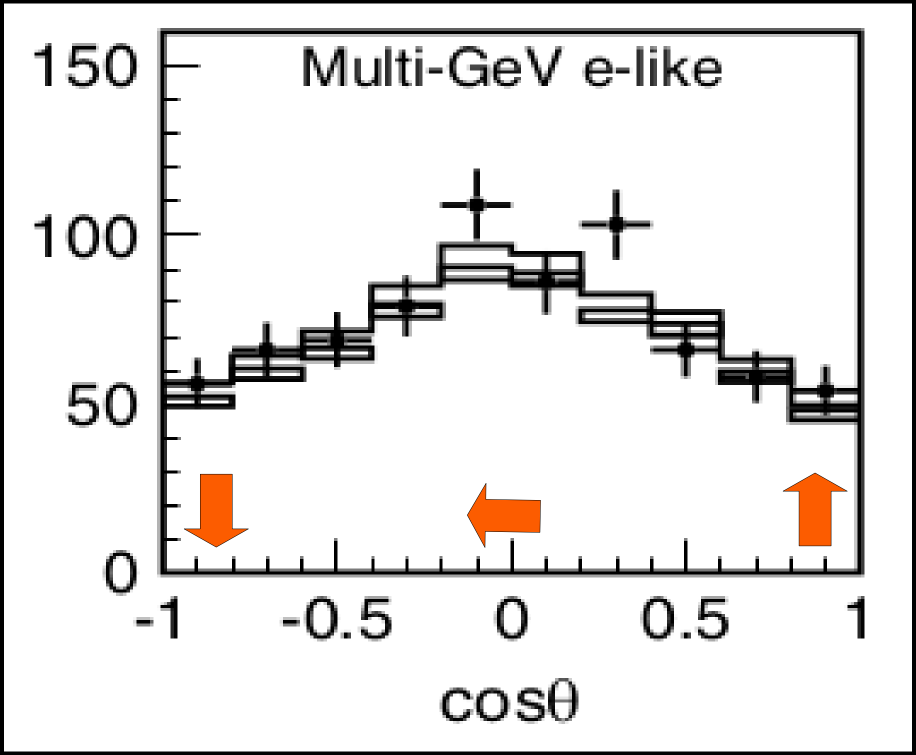
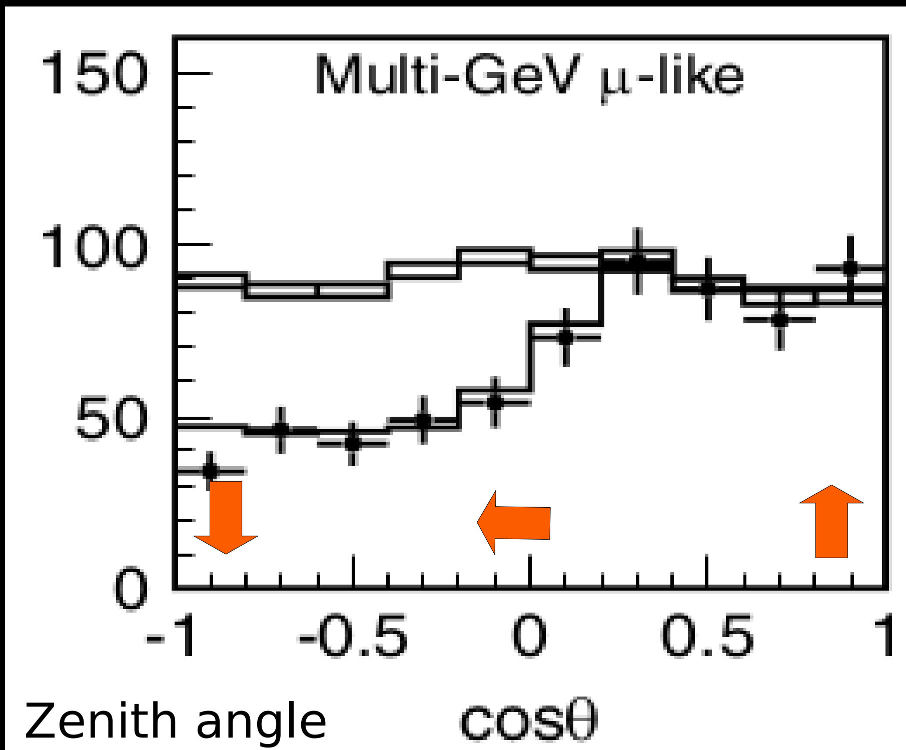
Atmospheric Anomaly





Super-Kamiokande
Phys.Rev.D71 112005

Atmospheric Anomaly



2015 Nobel prize
Takaaki Kajita

Atmospheric Sector

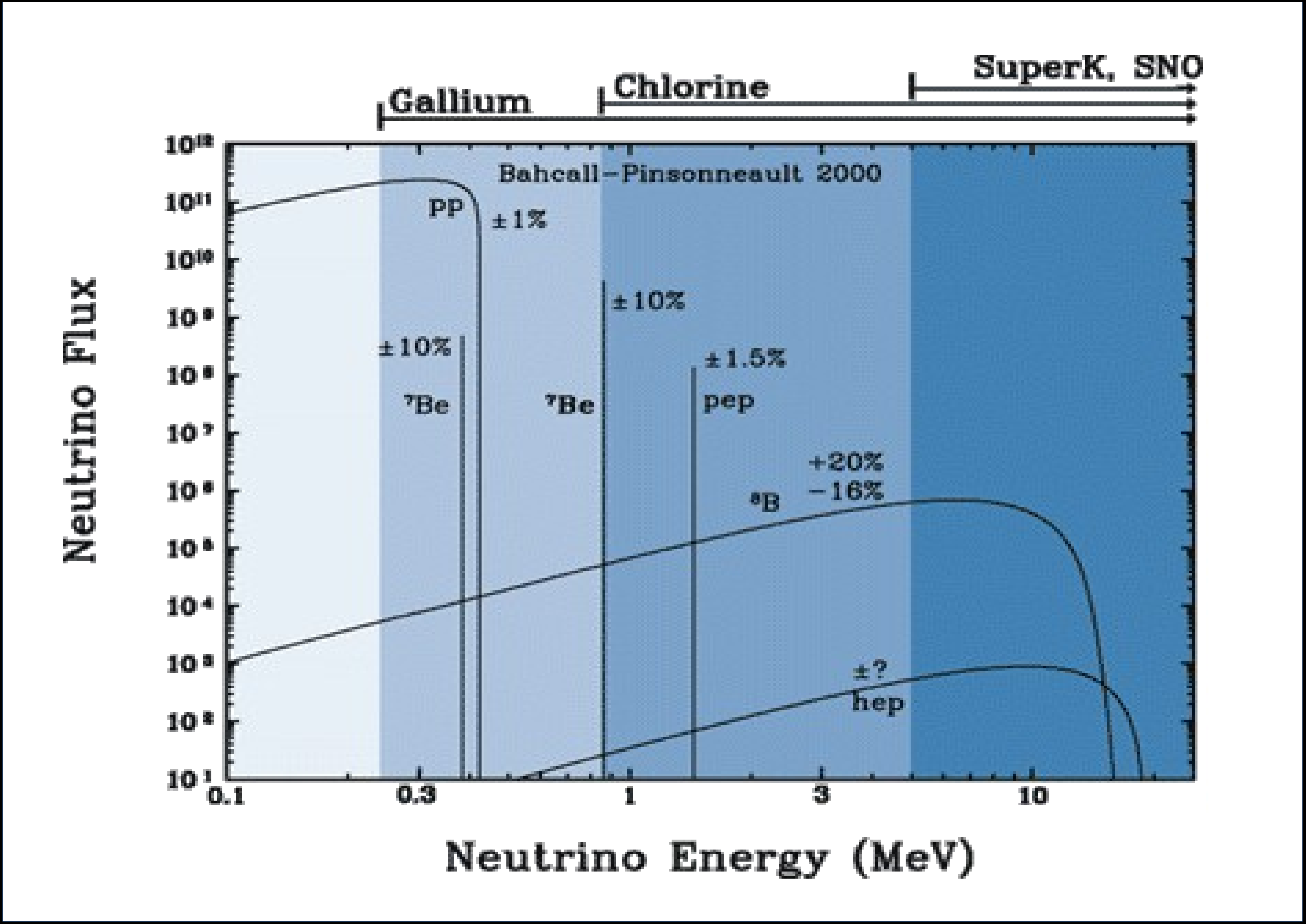
$$\nu_\mu \rightarrow \nu_\tau$$

$$\theta_{23} = (48.6 \pm 1.4)^o$$

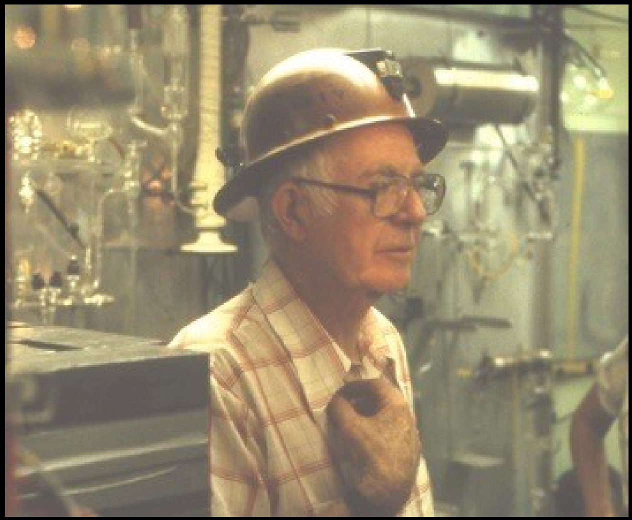
$$\Delta m^2_{23} = (2.45 \pm 0.03) \times 10^{-3}\, eV^2$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

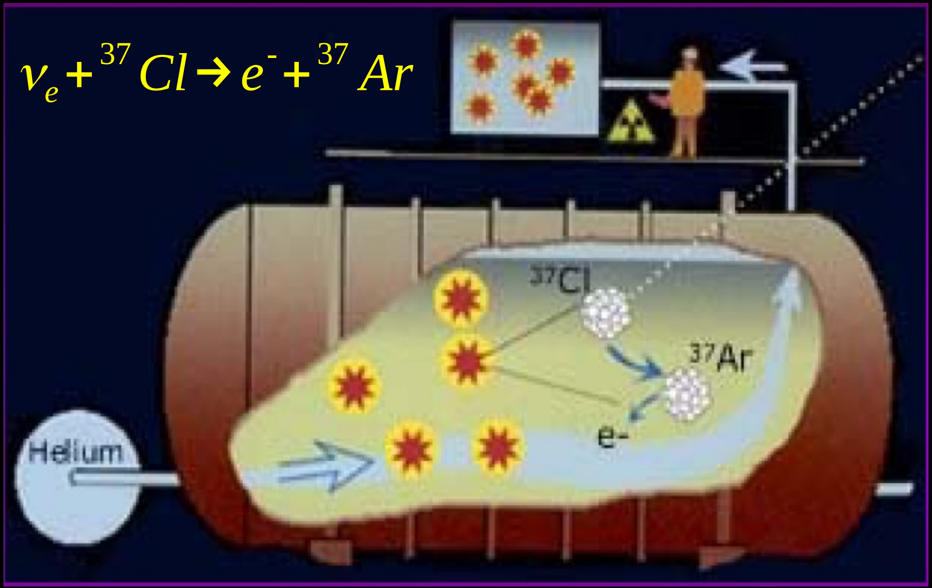
Solar Neutrino Problem

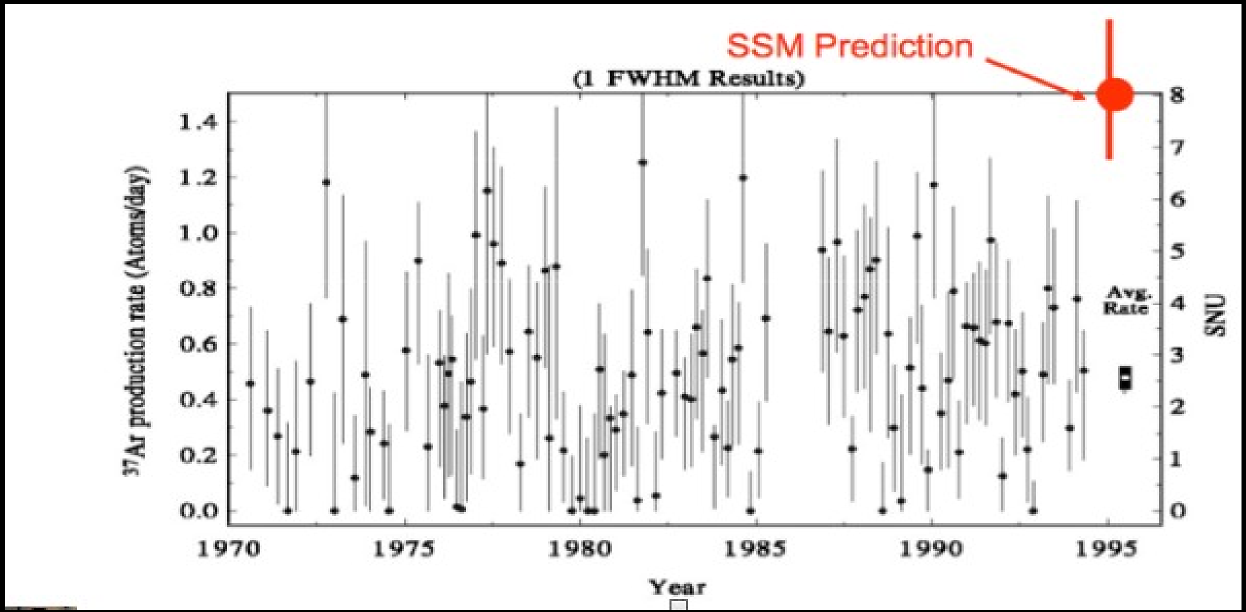


Solar Neutrino Problem



Ray Davis





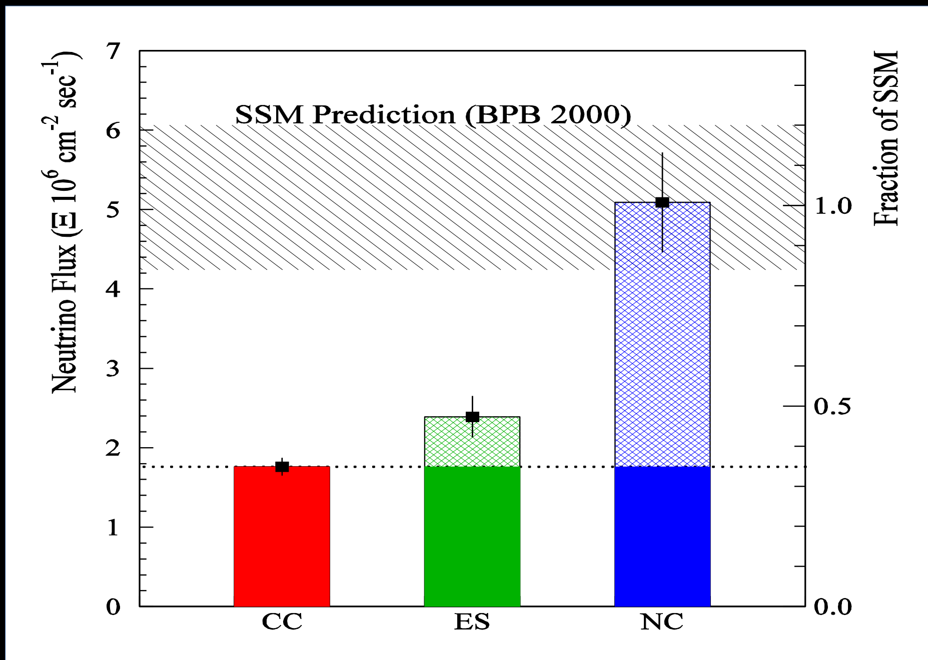
Observed 1/3 of expected ν_e rate

Reaction threshold : 800 keV

Insensitive to other flavours

2002 Nobel for R. Davis

Solar Neutrino Oscillations



SNO Experiment
Phys.Rev.Lett.89.011301 (2002)

A. MacDonald
2015 Nobel Prize

Solar Oscillation Sector

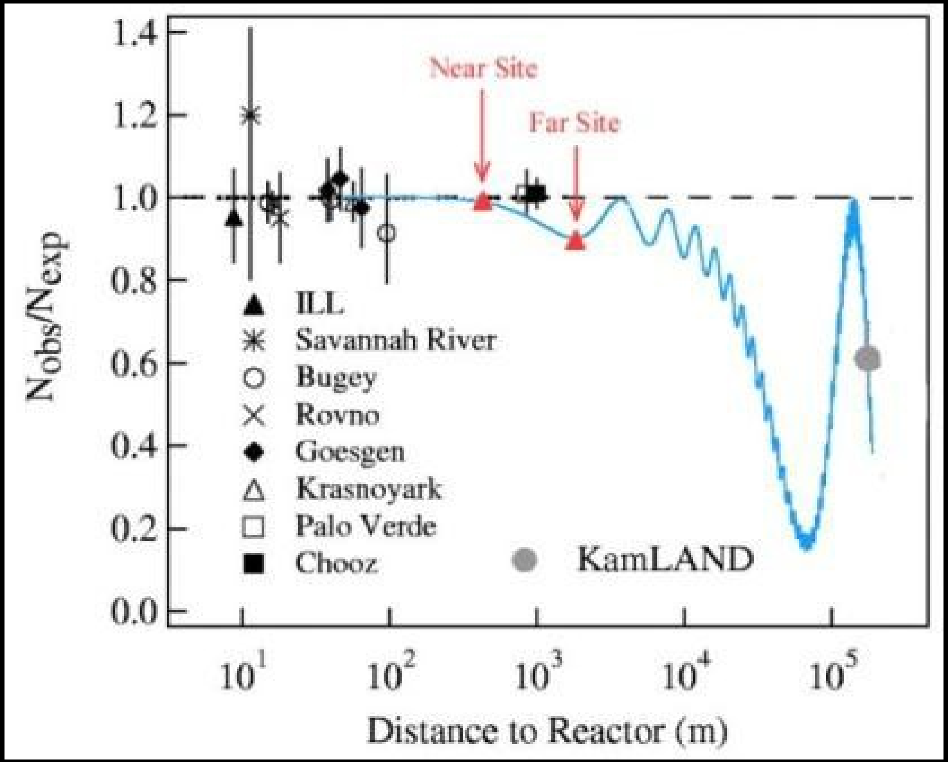
$$\nu_e \rightarrow \nu_\mu$$

$$\theta_{12} = (33.8 \pm 0.8)^o$$

$$\Delta m^2_{12} = (7.4 \pm 0.2) \times 10^{-5} eV^2$$

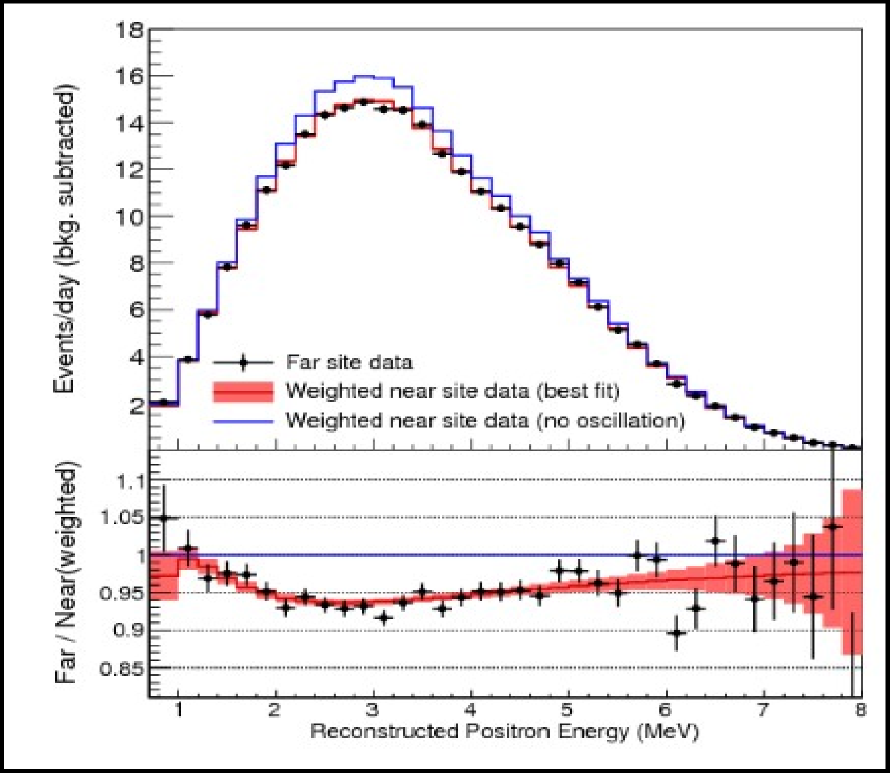
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Reactor Sector



- Link between atmospheric and solar sector
- Subdominant oscillations
  - wavelength controlled by Δm_{23}^2 overlaid on the solar oscillation.
  - amplitude controlled by θ_{13}
- $\bar{\nu}_e$ disappearance at reactors (no sensitivity to δ_{CP})
- ν_e appearance at accelerator experiments

Reactor Sector



Daya Bay
Phys. Rev. Lett. 108 171803

13 Oscillation Sector

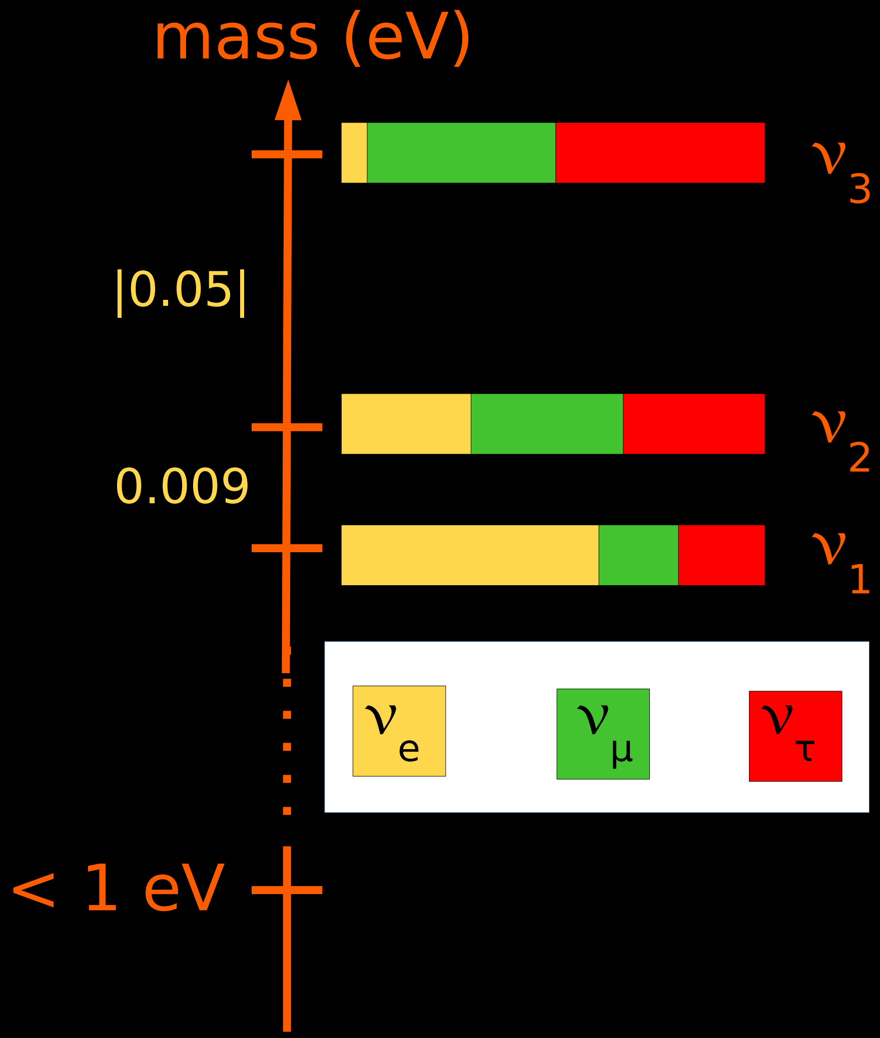
$$\bar{\nu}_e \rightarrow \bar{\nu}_X$$

$$\theta_{13} = (8.6 \pm 0.1)^o$$

$$\Delta m^2_{23} = (2.45 \pm 0.03) \times 10^{-3} eV^2$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Current Picture



Parameter	Value
Δm_{23}^2	$(2.45 \pm 0.03) \times 10^{-3}\ eV^2$
Δm_{12}^2	$(7.4 \pm 0.2) \times 10^{-5}\ eV^2$
θ_{12}	$(33.8 \pm 0.8)^o$
θ_{23}	$(48.6 \pm 1.6)^o$
θ_{13}	$(8.6 \pm 0.1)^o$
δ_{CP}	?????????????

Particle Data Group
pdg.lbl.gov

Measuring δ_{CP}

- CP violation shows up as an asymmetry between ν and $\bar{\nu}$ oscillations

$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$

- To first order, we can express this in terms of mixing angles as

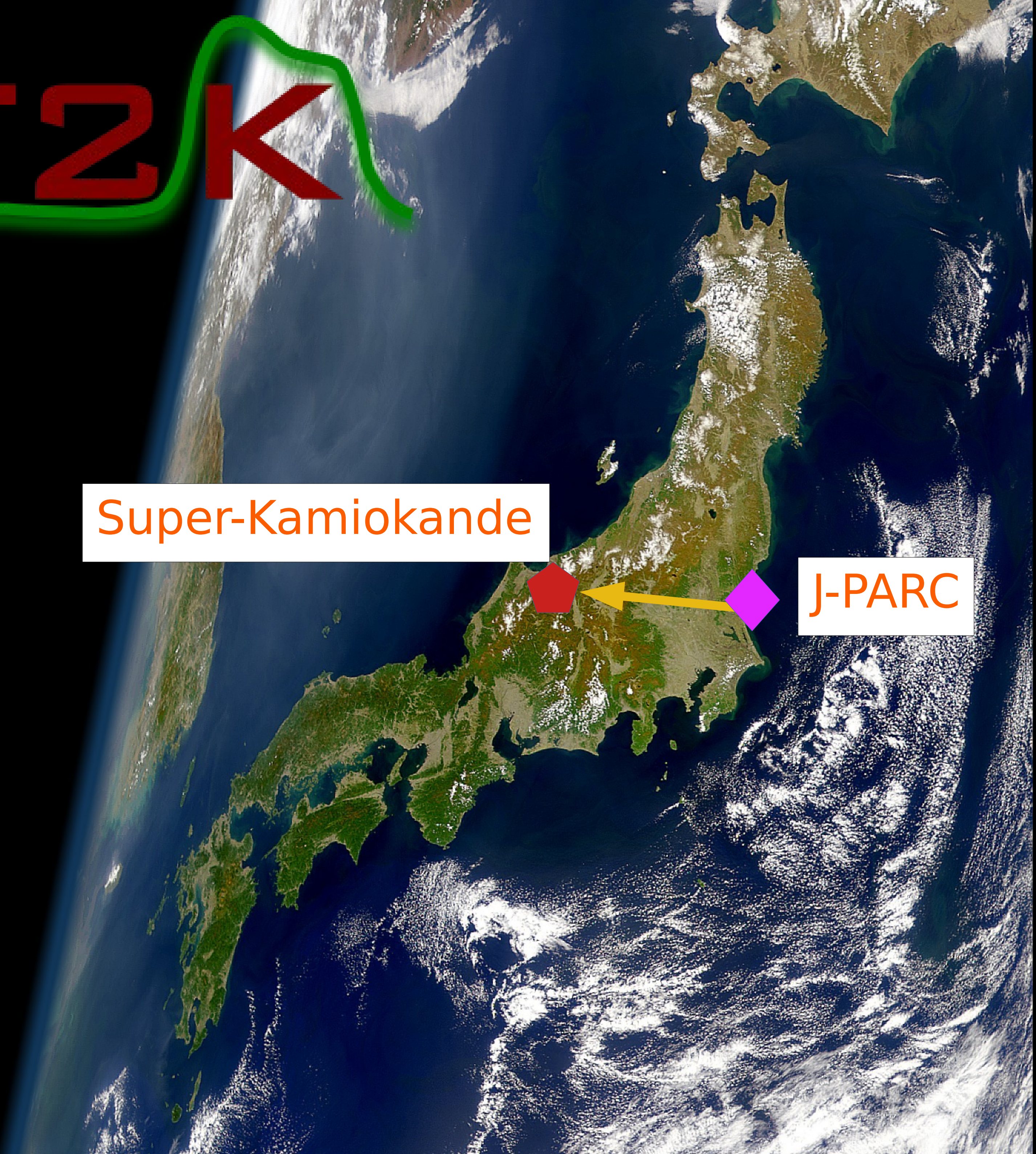
$$\mathcal{A}_{CP} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{\rm CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects}$$

- Forward scattering of ν_e on electrons in matter modifies oscillation probability from that seen by $\bar{\nu}_e$.
- Should separate matter effects from true CP violation

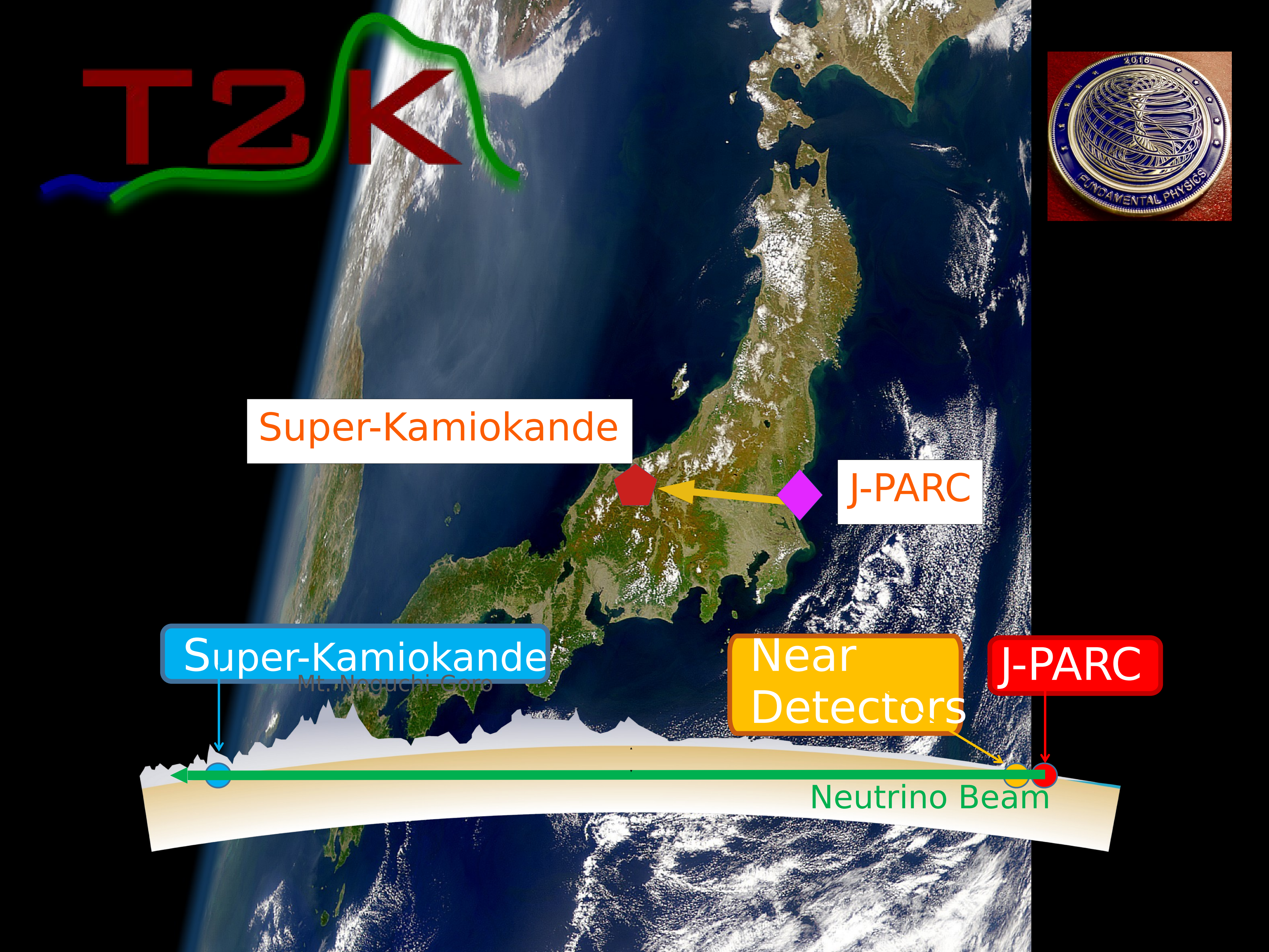
- Current generation : NOvA and T2K
- Next generation : DUNE and Hyper-Kamiokande

The design of long baseline oscillation experiments

T2K: A case study


T2K
Super-Kamiokande
J-PARC

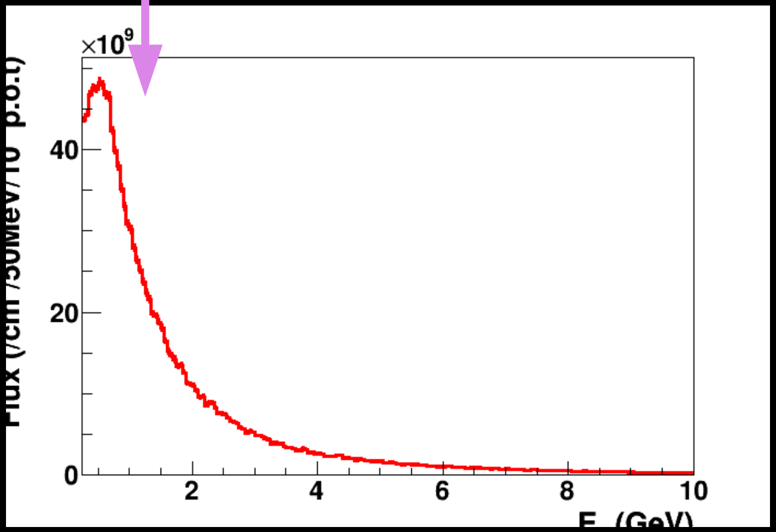

2016
FUNDAMENTAL PHYSICS

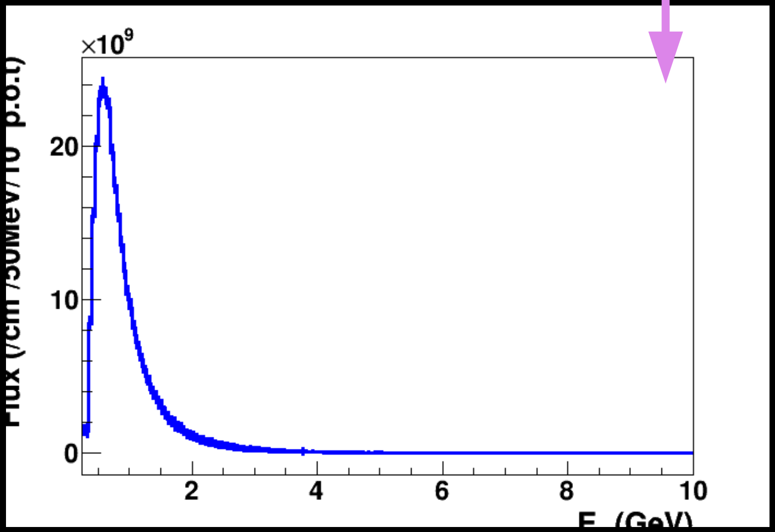

T2K
2016
FUNDAMENTAL PHYSICS
Super-Kamiokande
J-PARC
Super-Kamiokande
Mt. Noguchi-Goro
Near Detectors
J-PARC
Neutrino Beam

Sketch of an oscillation experiment

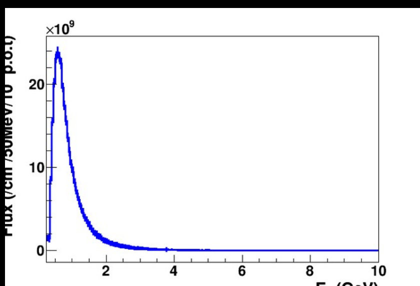
Estimate ν_μ (say) flux before oscillations start

Measure ν_μ flux at far detector

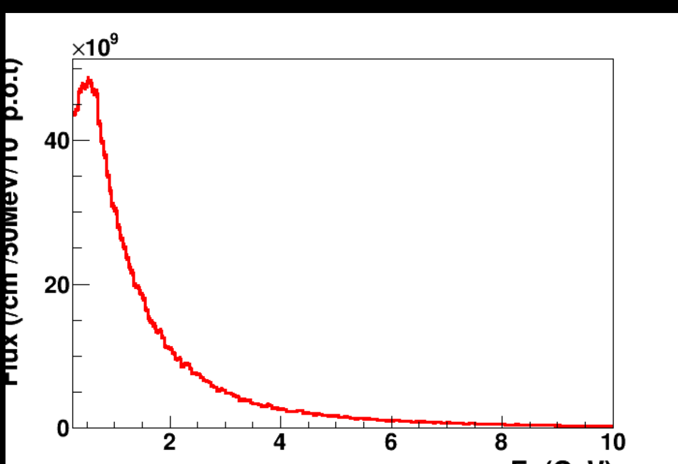




Sketch of an oscillation experiment



$$\times\left(\frac{\Phi_{NEAR}}{\Phi_{FAR}}\right)(E_\nu)$$



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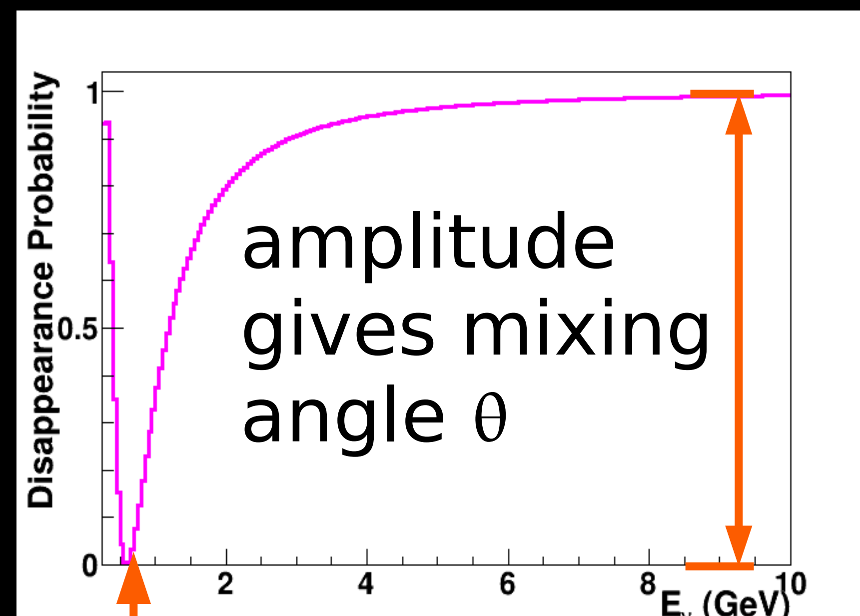

energy at dip gives Δm^2

It’s not that easy….

We measure neutrino interactions – not neutrino flux

It’s not that easy….

We measure neutrino interactions – not neutrino flux

$$N\left(E_\nu^{rec}\right)=N_{targets}\int \Phi\left(E_\nu^{true}\right)\frac{d^n\sigma\left(E_\nu^{true}\right)}{d\,\xi_n}M\left(E_\nu^{true},E_\nu^{rec}\right)d\,\xi_n dE_\nu^{true}$$

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Flux must be modelled
→ hadronic physics
introduces uncertainties

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Neutrino interactions are encoded
by (more or less) poorly known neutrino cross
sections.

It's not that easy....

We measure neutrino interactions – not neutrino flux

Flux must be modelled
→ hadronic physics
introduces uncertainties

Detector isn't perfect.
Particles can be lost, or
are undetectable
Quantities must be
"reconstructed"

$$N\left(E_\nu^{rec}\right) = N_{targets} \int \Phi\left(E_\nu^{true}\right) \frac{d^n \sigma\left(E_\nu^{true}\right)}{d\,\xi_n} M\left(E_\nu^{true}, E_\nu^{rec}\right) d\,\xi_n\, dE_\nu^{true}$$

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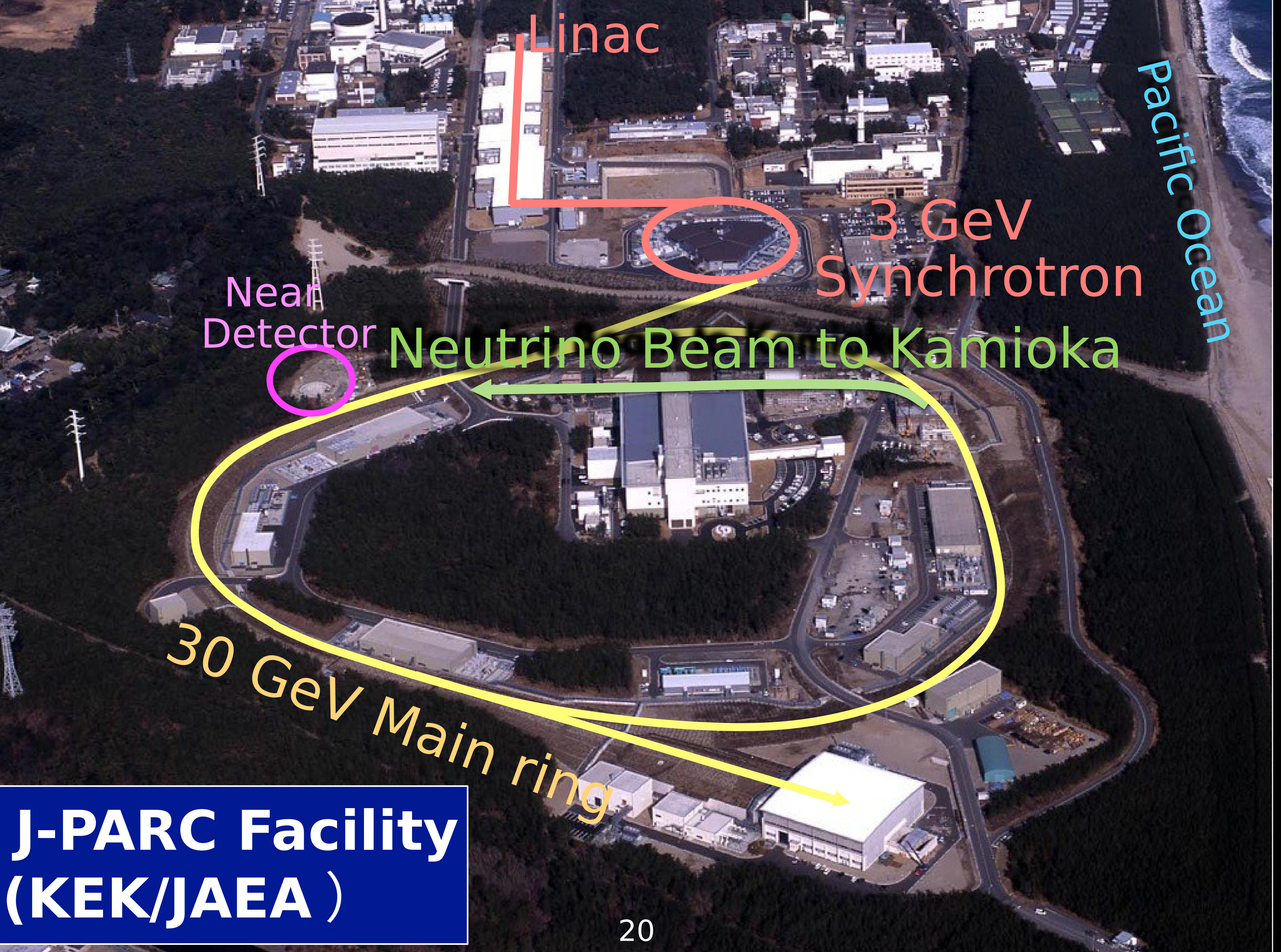
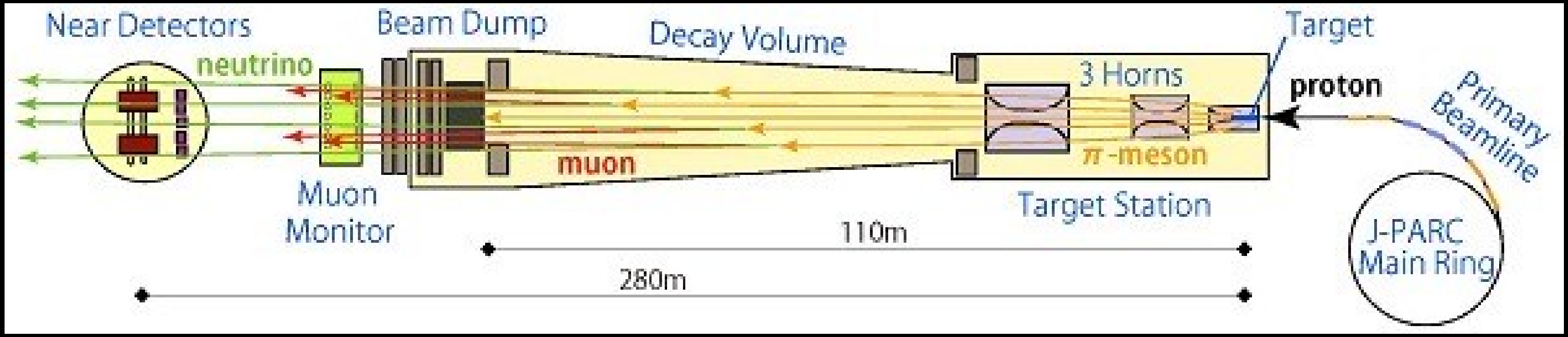
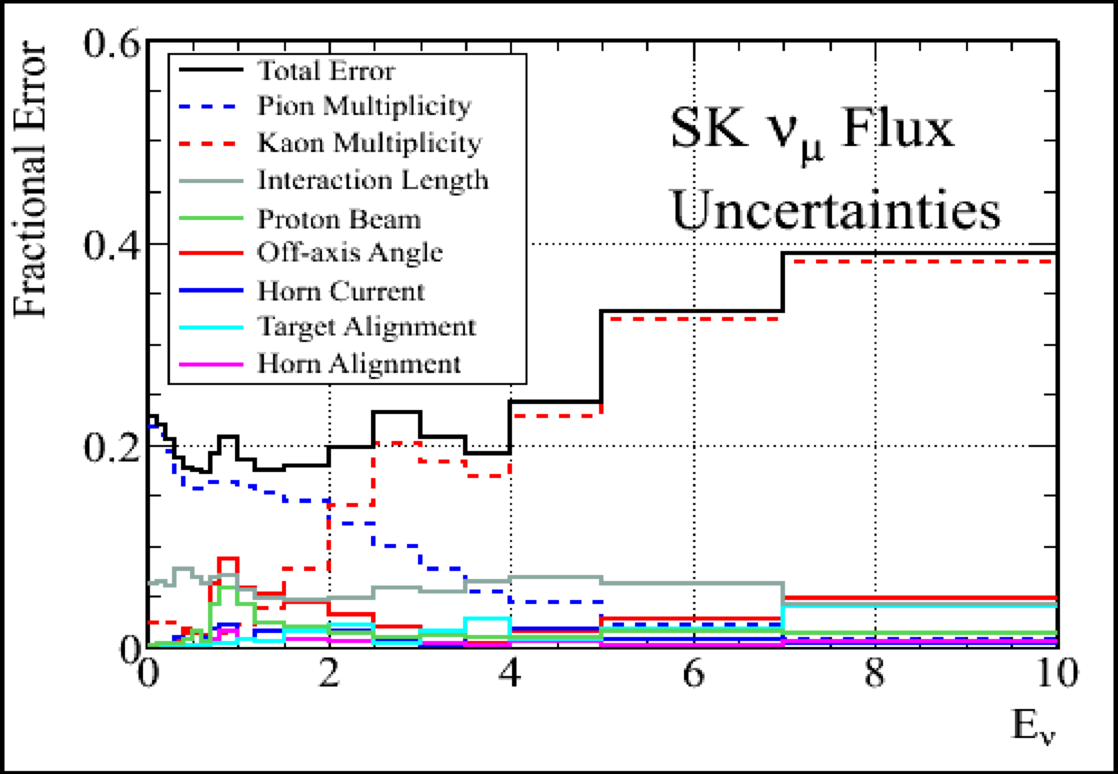


J-PARC Facility (KEK/JAEA）

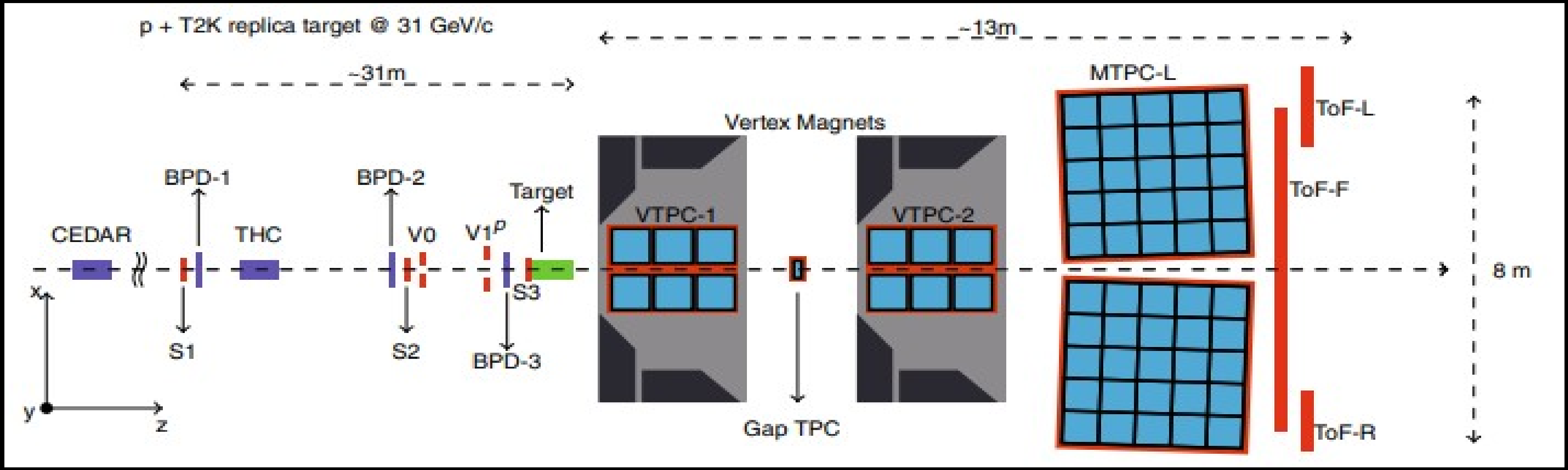
Making a neutrino beam



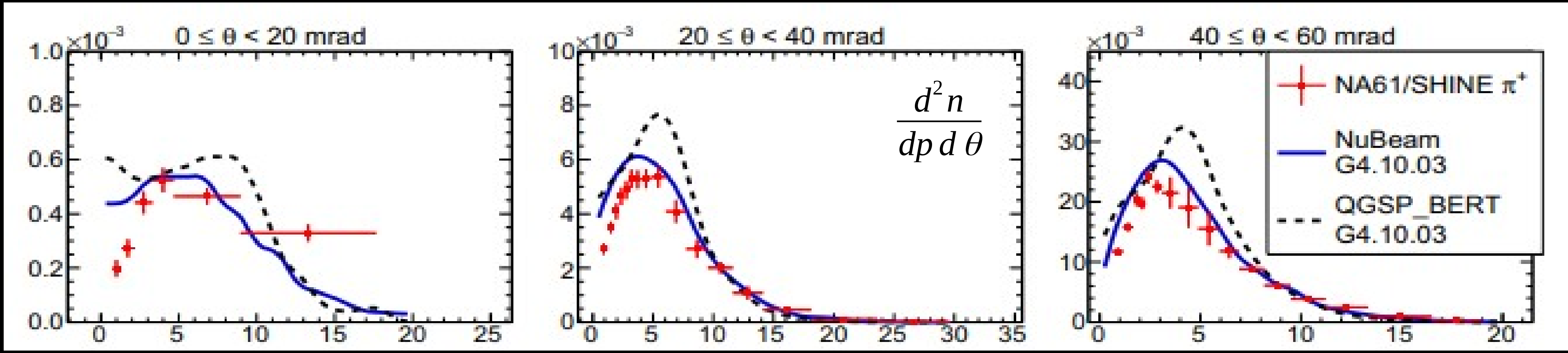


- 2010 T2K flux uncertainty
- Dominated by uncertainty on meson multiplicity in the proton-graphite collisions

NA61/SHINE @ CERN

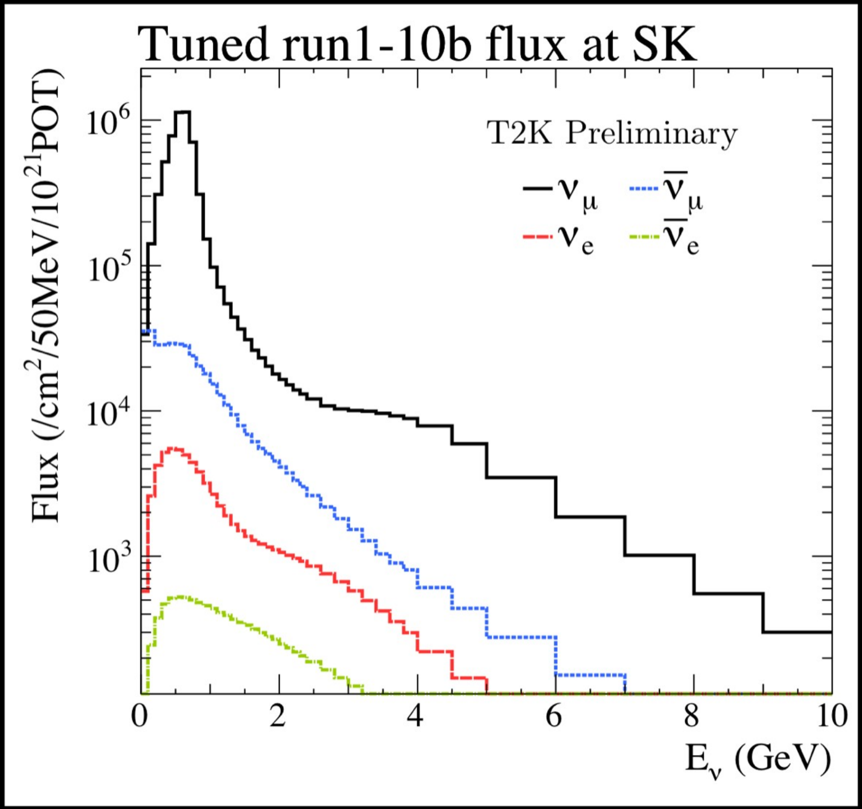


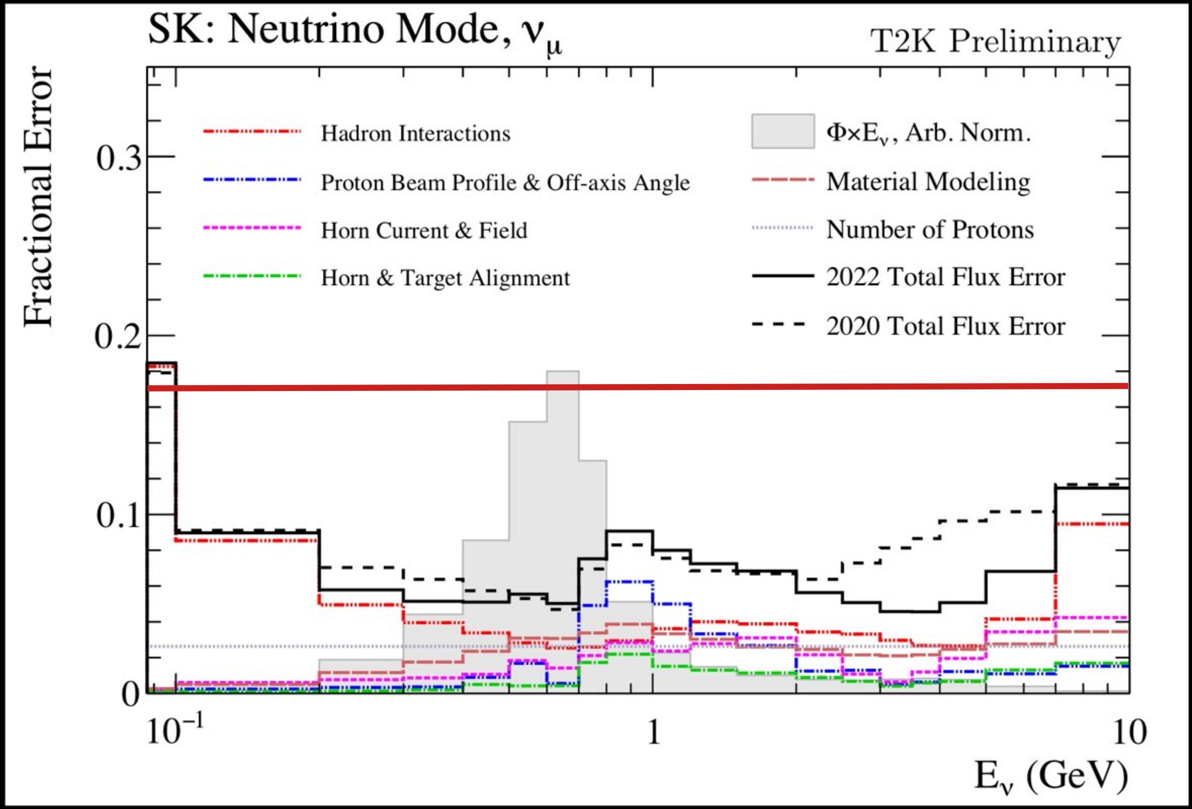
Doubly differential π^+ yield from p-T2K target interactions



N.Abgrall et al. Eur. Phys. J. C (2019) 79:100

Flux Uncertainties





- A priori prediction of the neutrino flux at far detector was a 15-20% from 0.1-5 GeV
  - Using hadron production data from CERN NA61/SHINE
  - Using in-beam monitor data
- 2022 Flux uncertainty has been brought down to 5-6%

It’s not that easy….

We observe neutrino interactions – not flux and not neutrinos

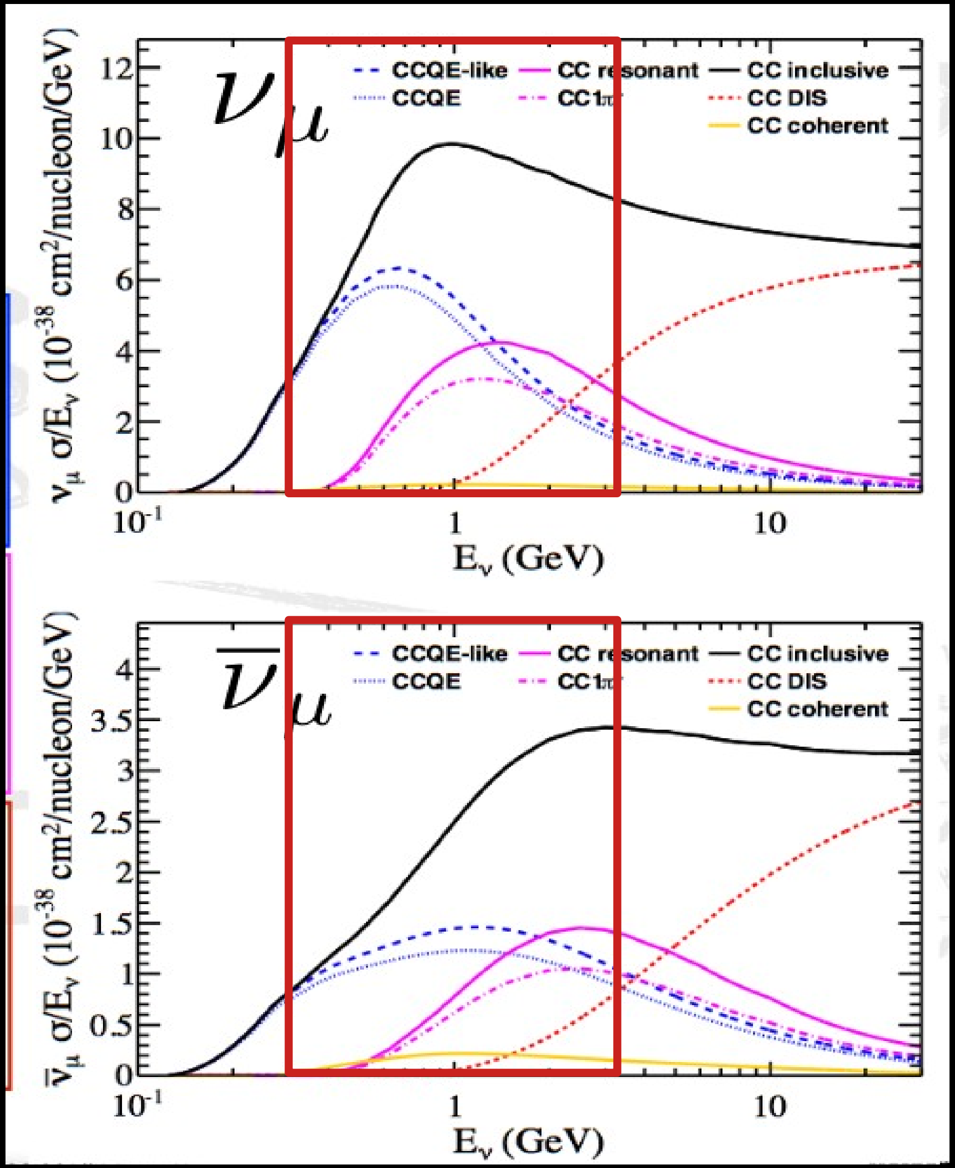
Flux must be modelled
→ hadronic physics
introduces uncertainties

Detector isn’t perfect.
Particles can be lost, or
are undetectable
Quantities must be
“reconstructed”

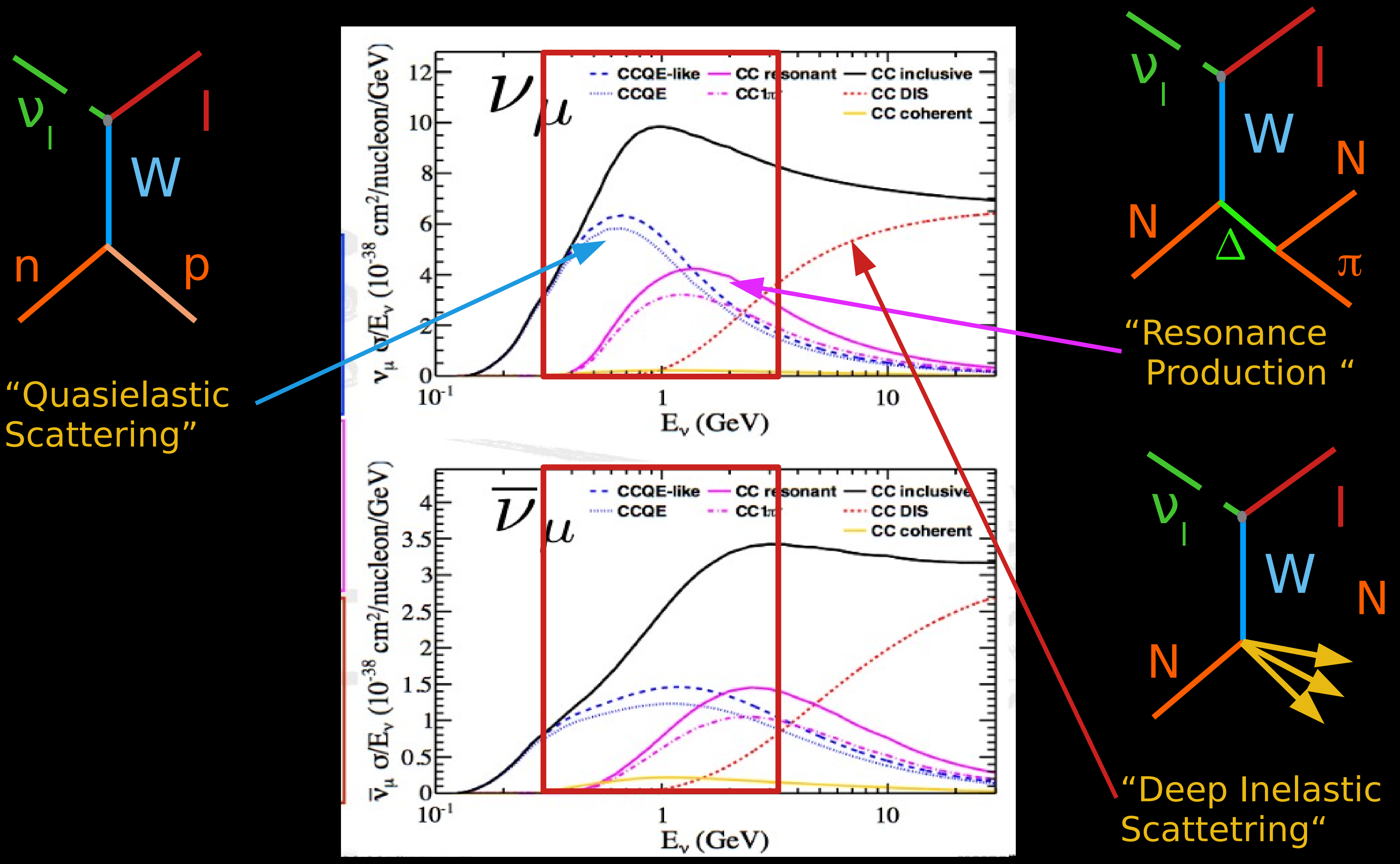
$$N\left(E_\nu^{rec}\right)=N_{targets}\int \Phi\left(E_\nu^{true}\right)\frac{d^n\sigma\left(E_\nu^{true}\right)}{d\,\xi_n}M\left(E_\nu^{true},E_\nu^{rec}\right)d\,\xi_n dE_\nu^{true}$$

Neutrino interactions are encoded
by poorly known neutrino cross
sections.

Neutrino Interactions

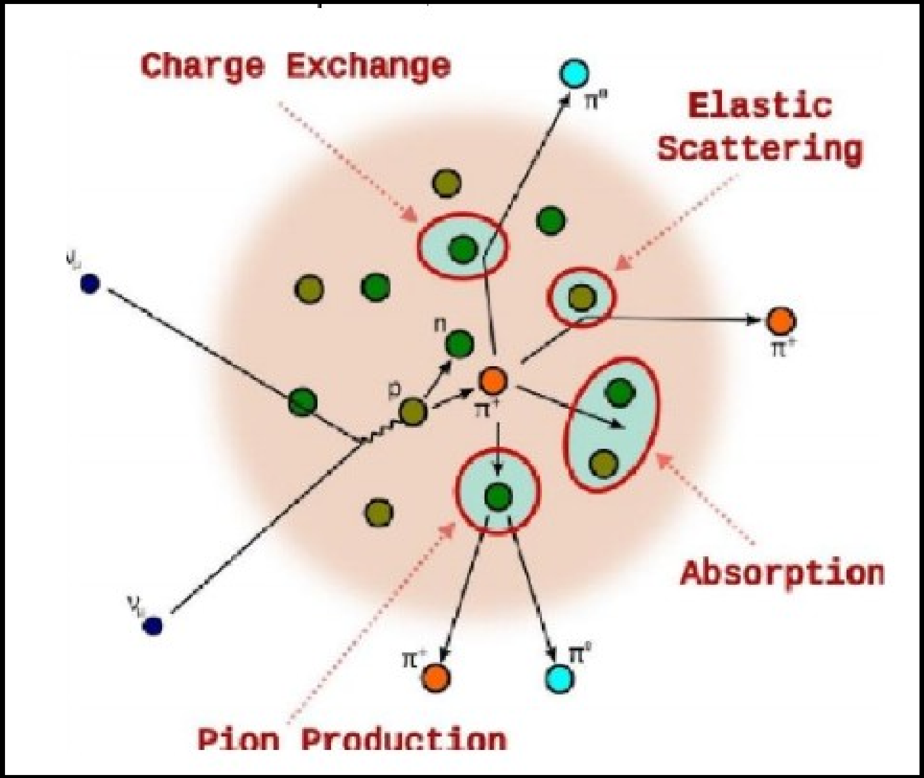


Neutrino Interactions



Neutrino Interactions

- Target is moving in a nuclear potential
- Initial State Model



- Final state particles have to get out of the nucleus
- Final State Interaction model

- Bare interaction modified by nuclear effects
- What you see in the detector is not necessarily what happened!

It’s not that easy....

We observe neutrino interactions – not flux and not neutrinos

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Neutrino interactions are encoded
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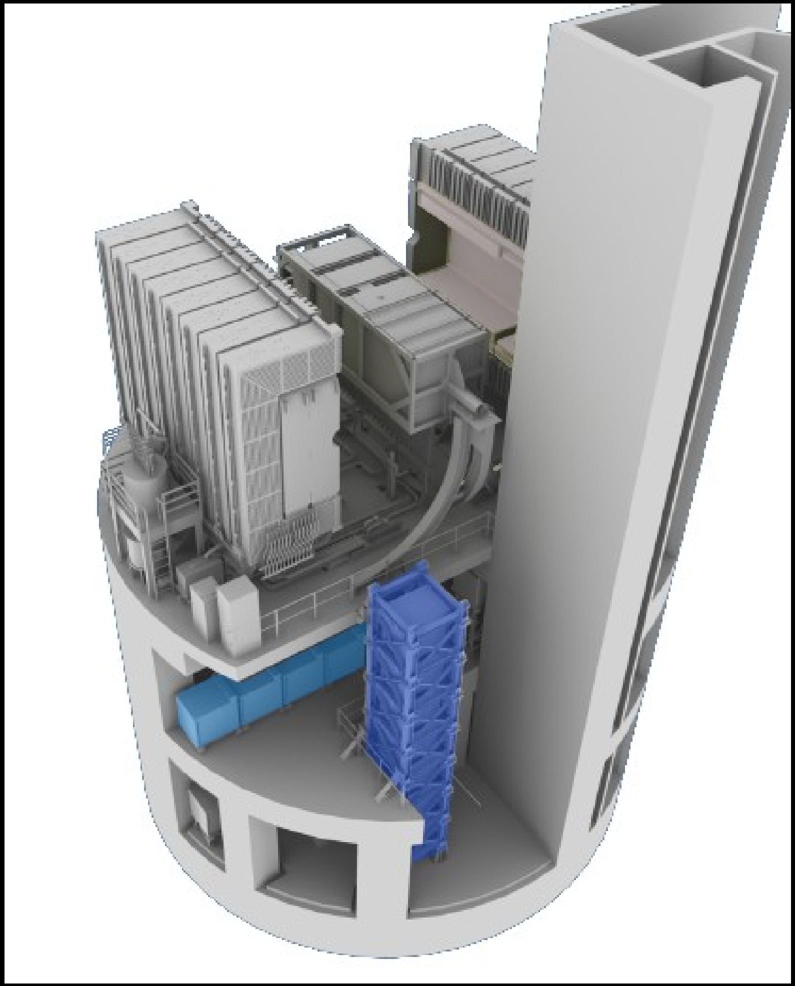
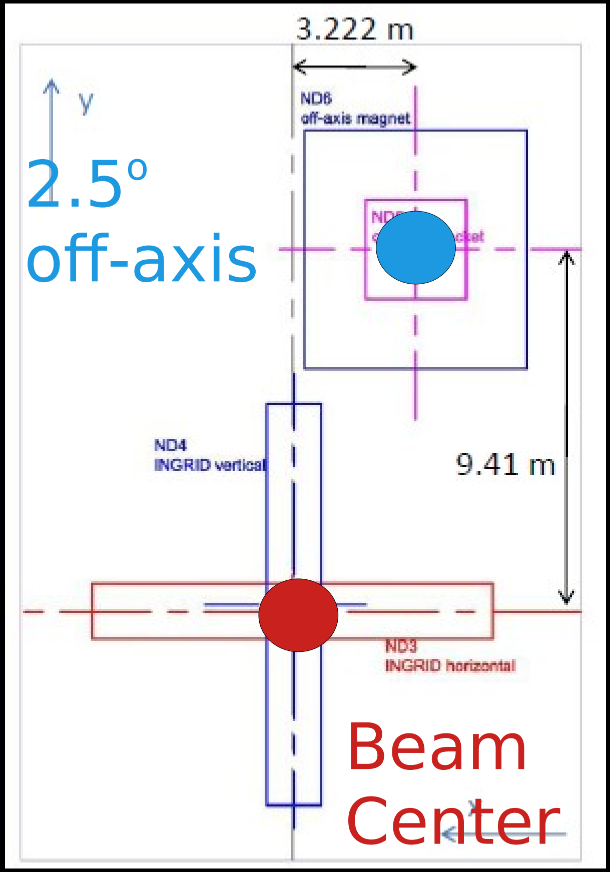
sections.

Near Detector Suite

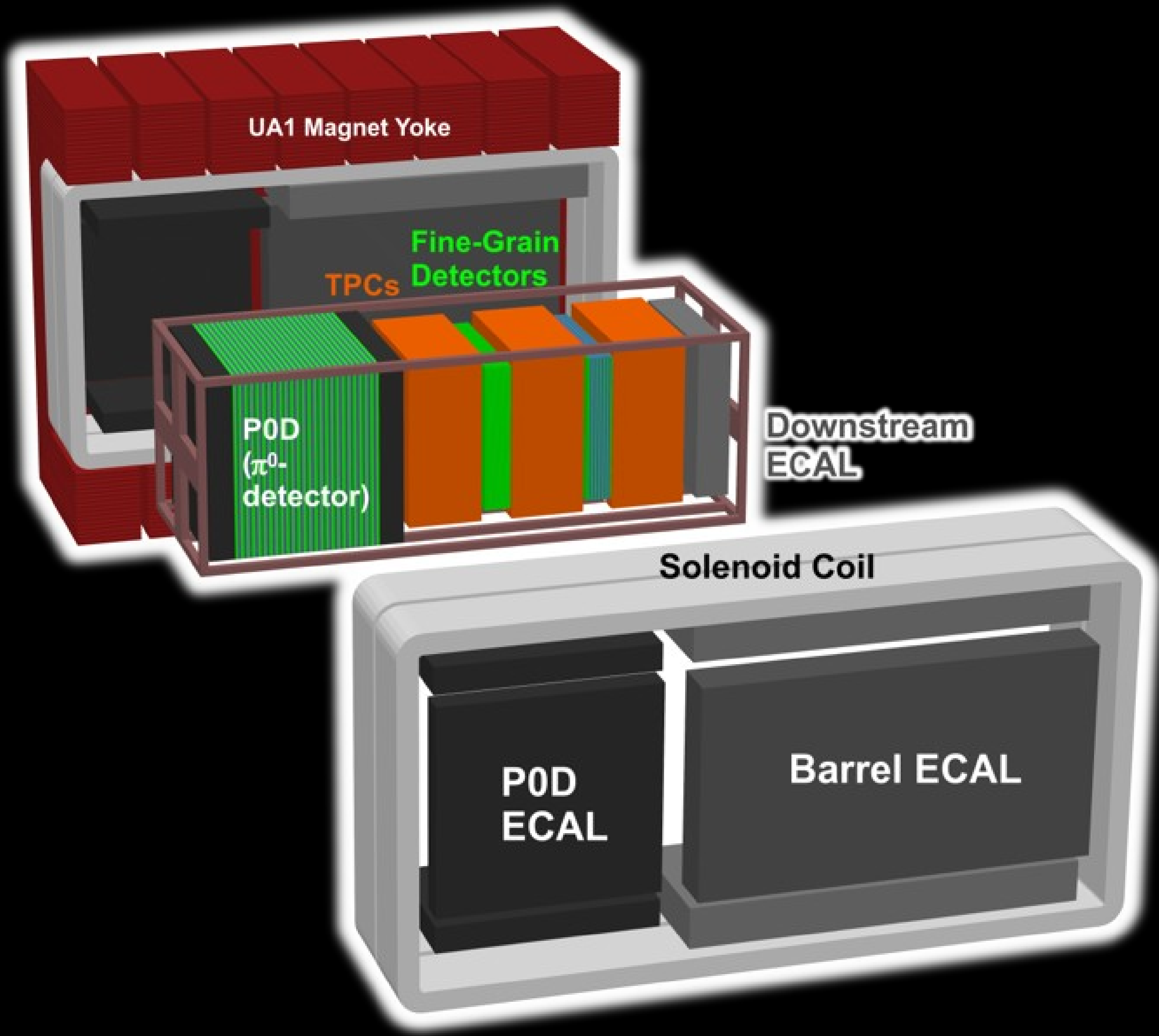




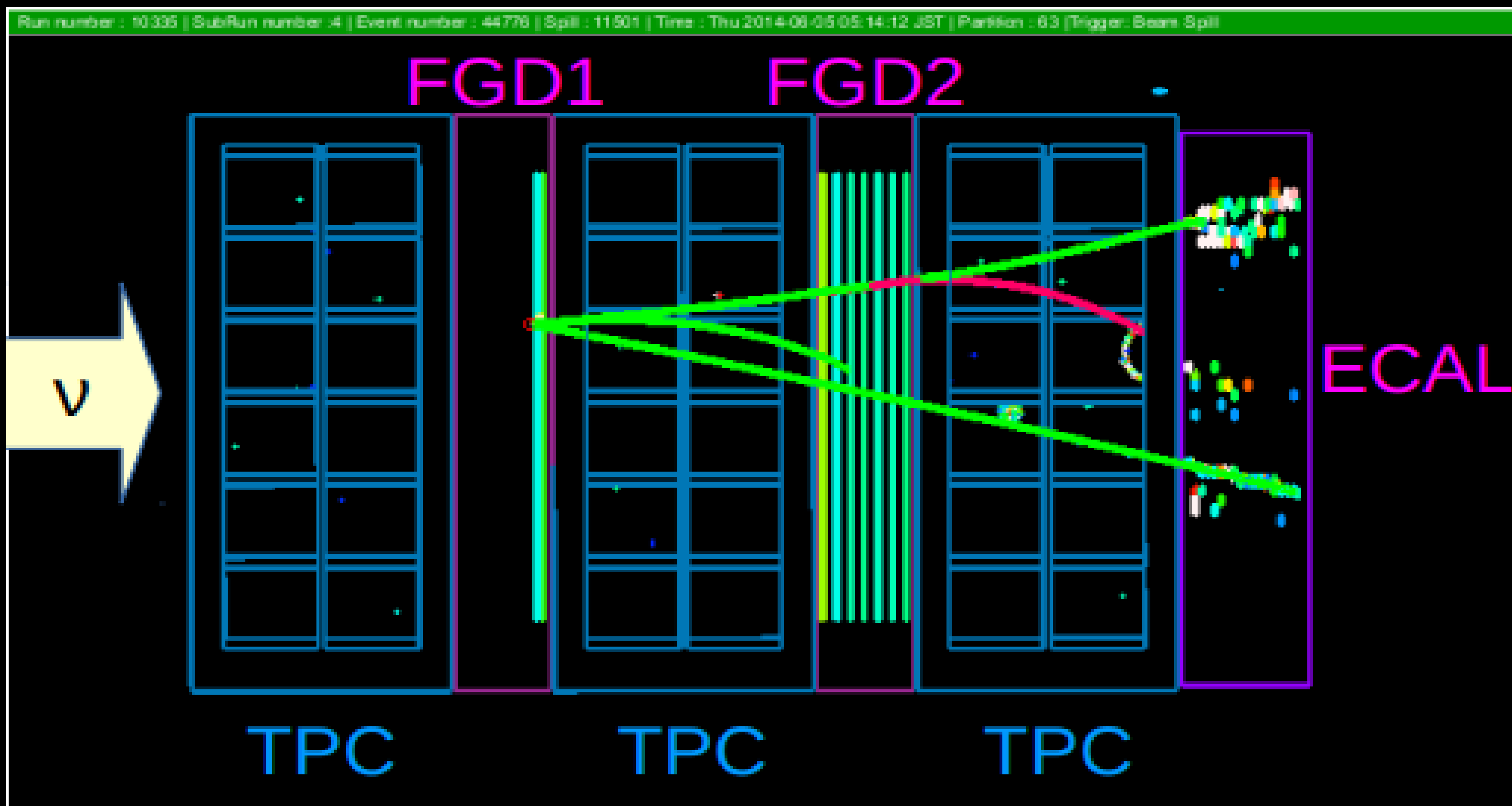
280 m from neutrino production targettt

INGRID : monitors beam direction
ND280 : monitors beam flux and tests interaction models

ND280

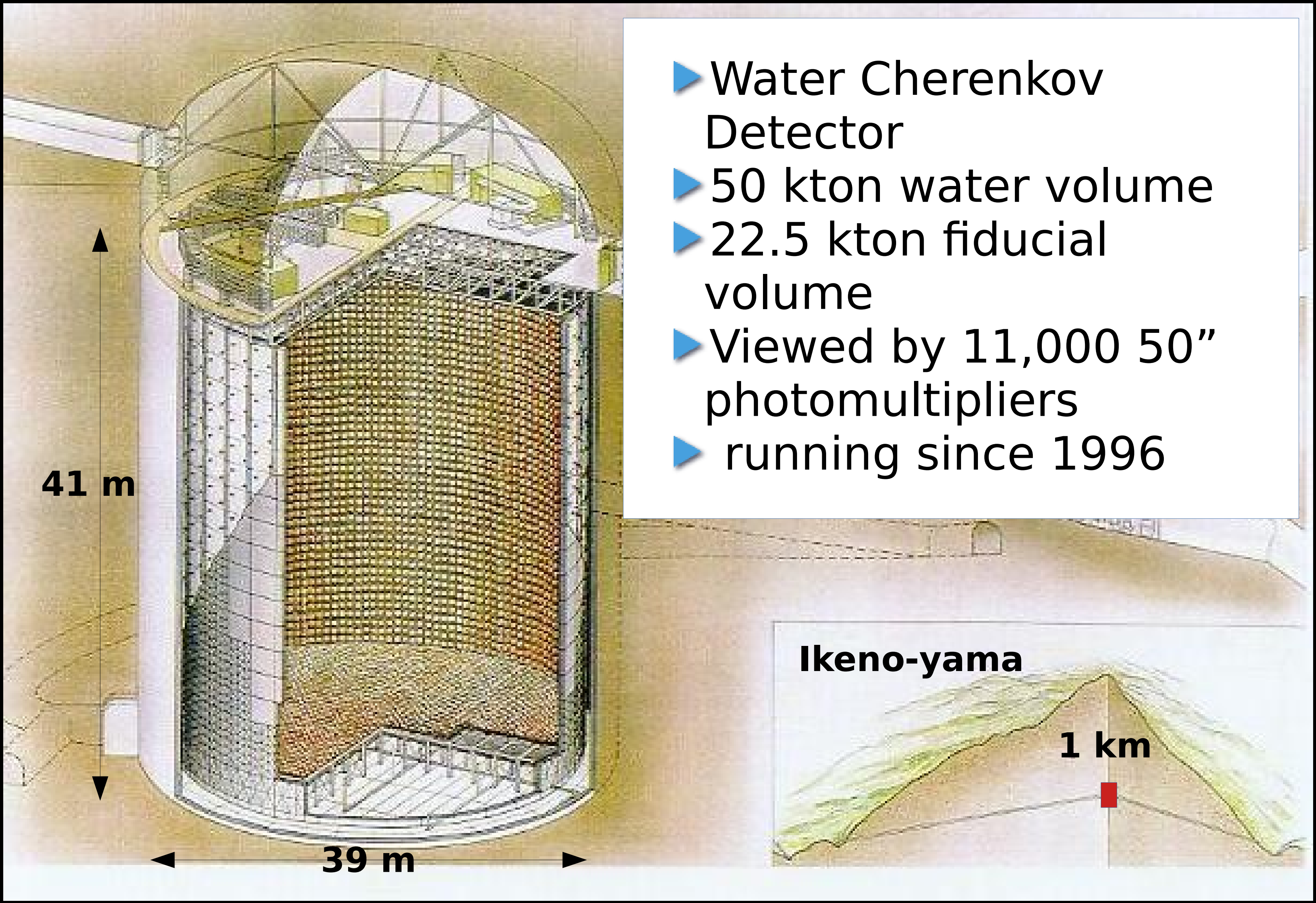

UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
P0D (π^0-detector)
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL

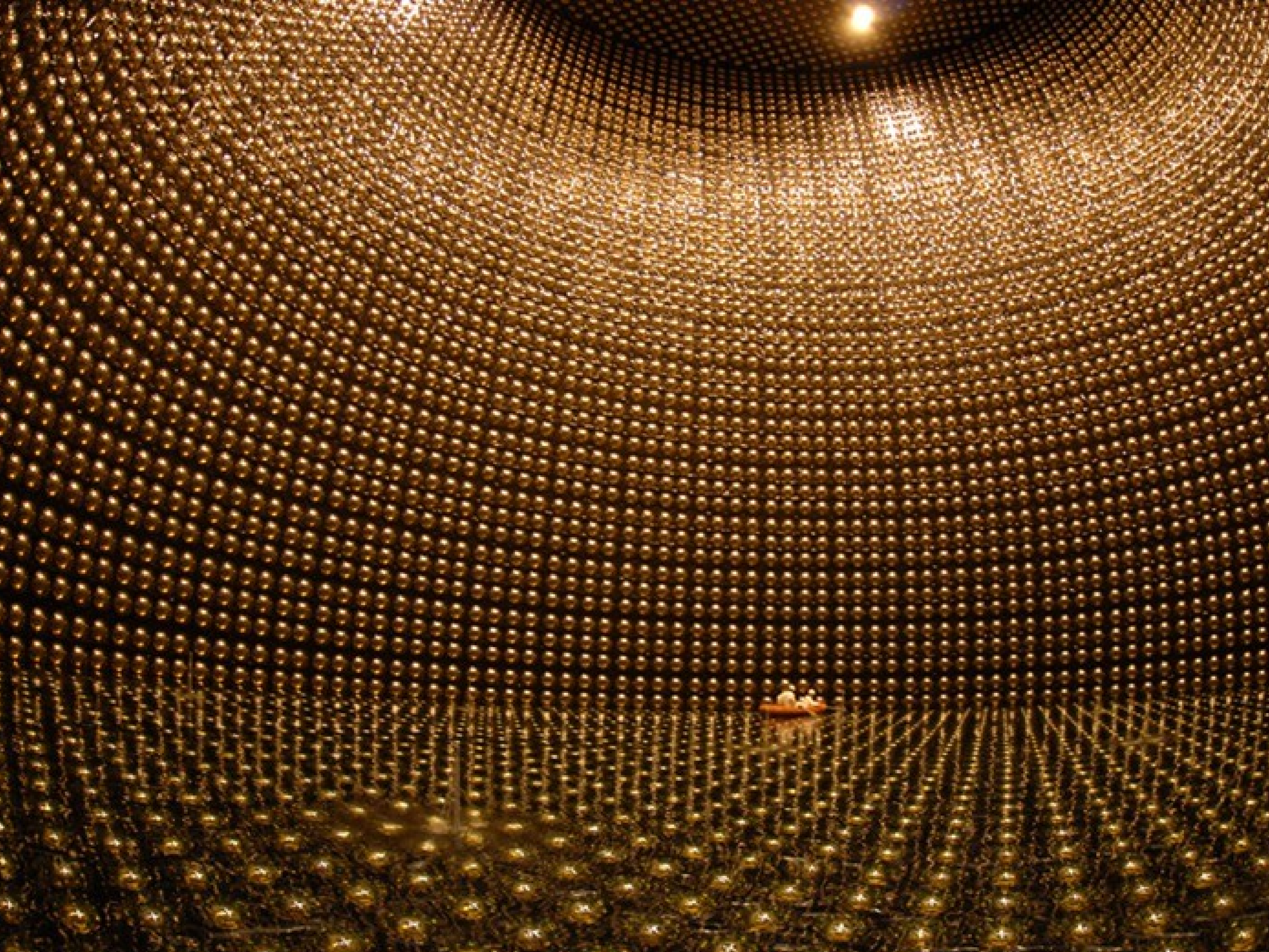
ND280


Run number : 10335 | SubRun number :4 | Event number : 44776 | Spill : 11501 | Time : Thu 2014-06-05 05:14:12 JST | Partition : 63 |Trigger: Beam Spill
FGD1
FGD2
ν
ECAL
TPC
TPC
TPC

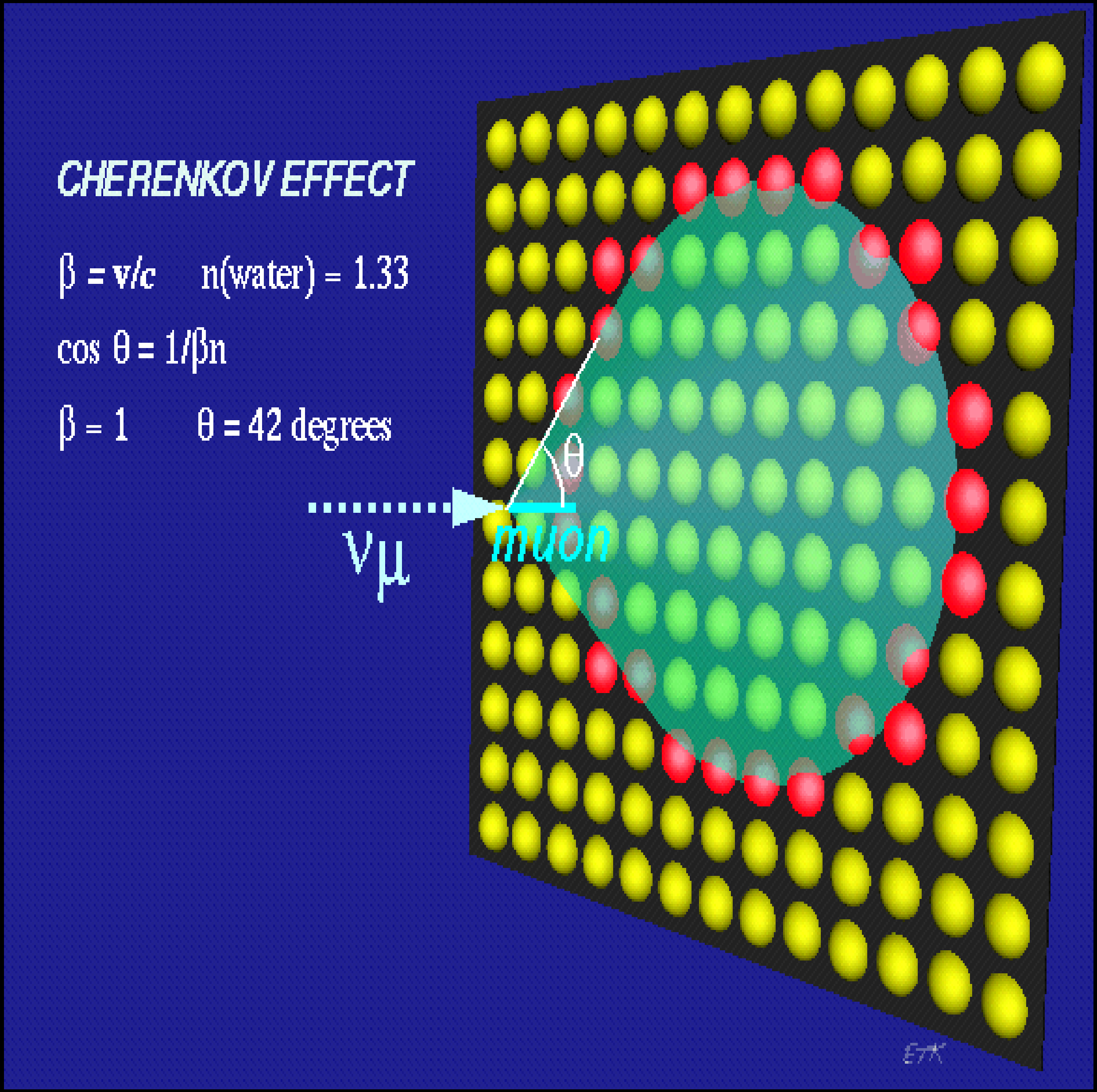
Far Detector - Super-Kamiokande

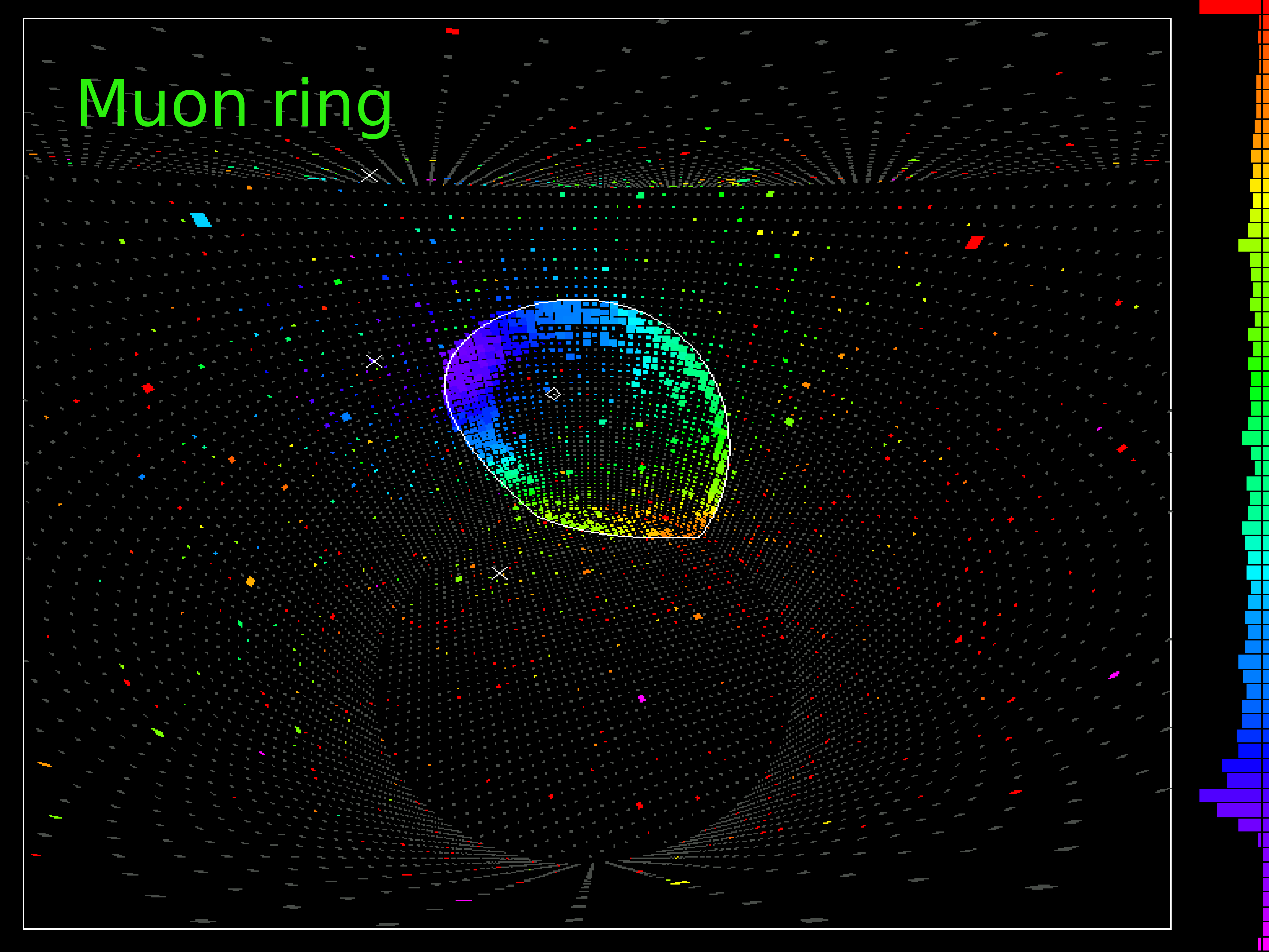
- Water Cherenkov Detector
- 50 kton water volume
- 22.5 kton fiducial volume
- Viewed by 11,000 50” photomultipliers
- running since 1996



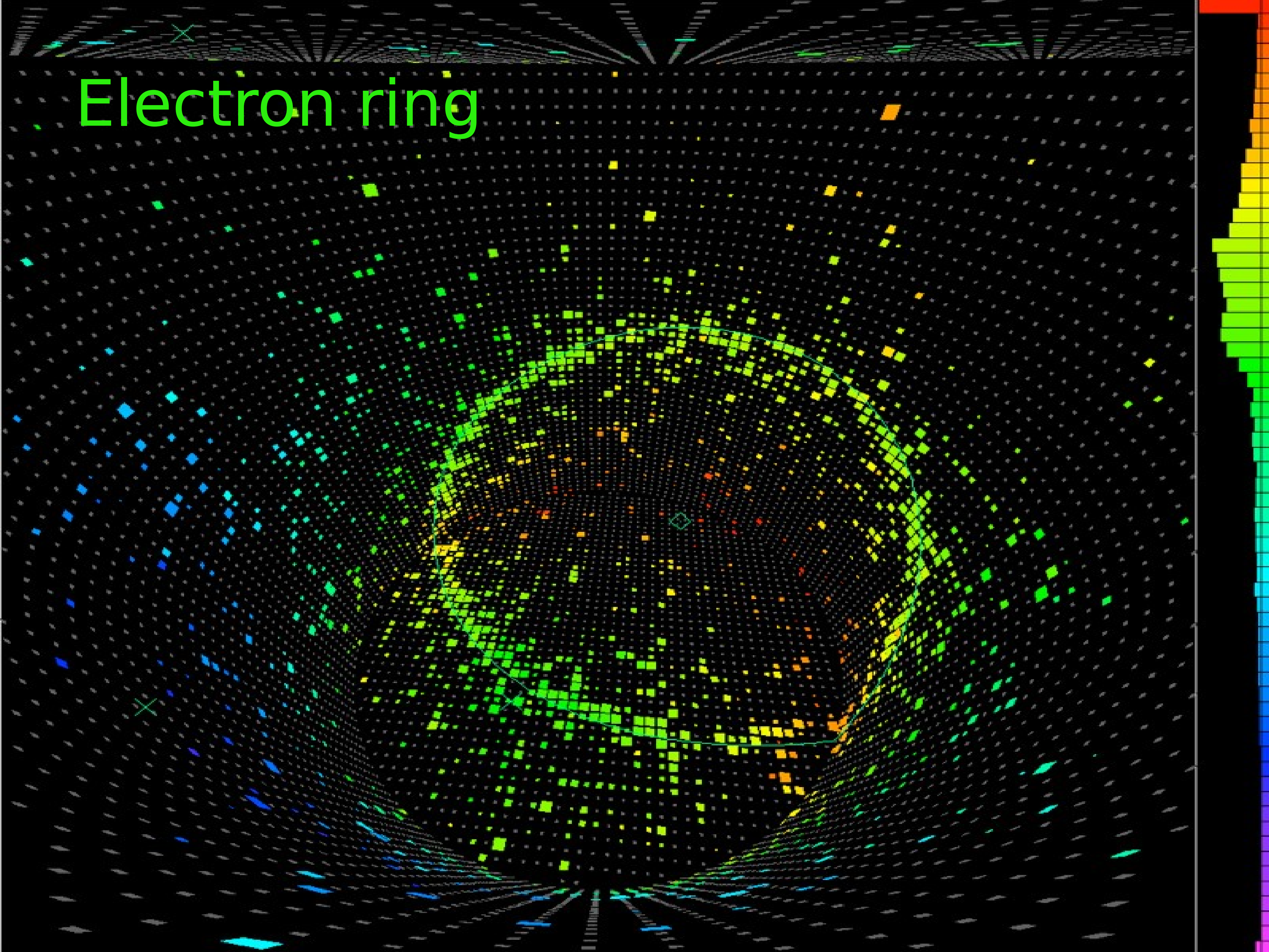


Principle of water Cherenkov

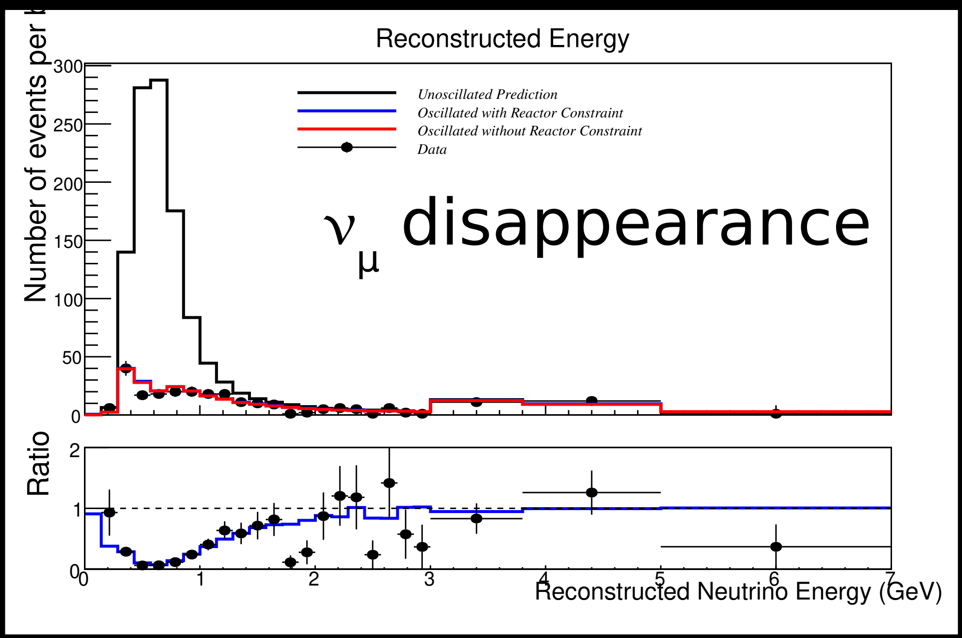


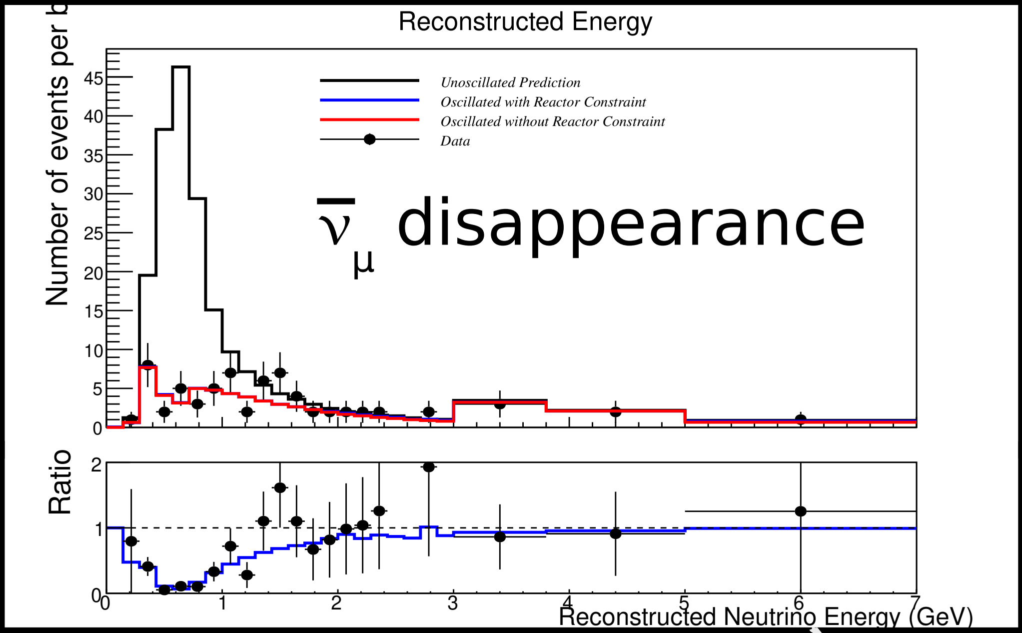

Muon ring

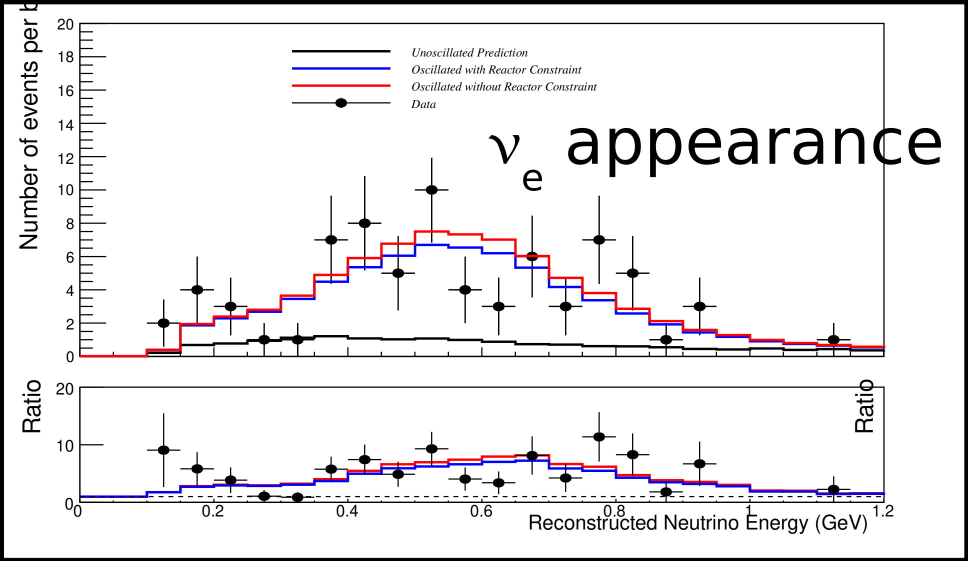
Electron ring

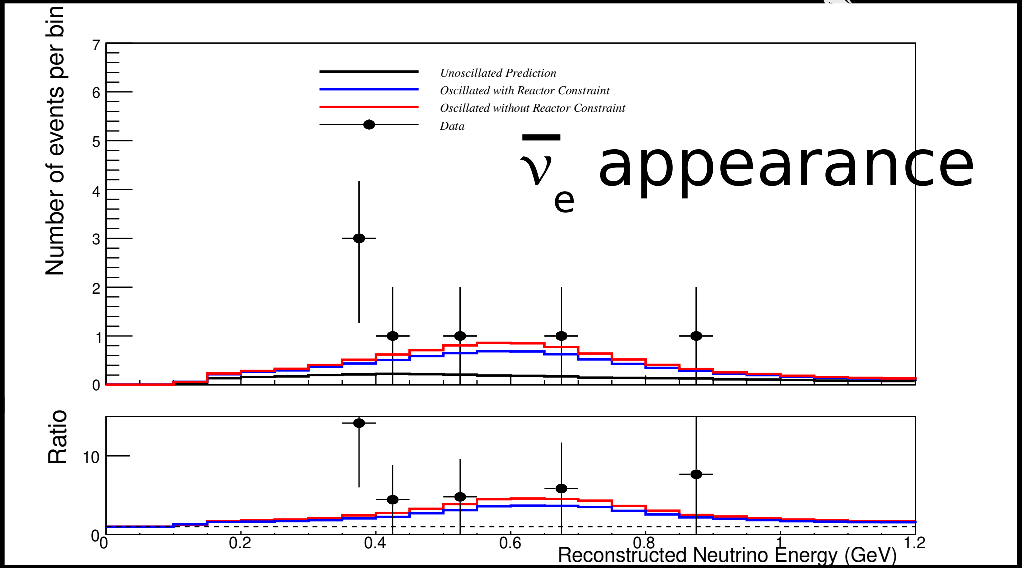


T2K Results

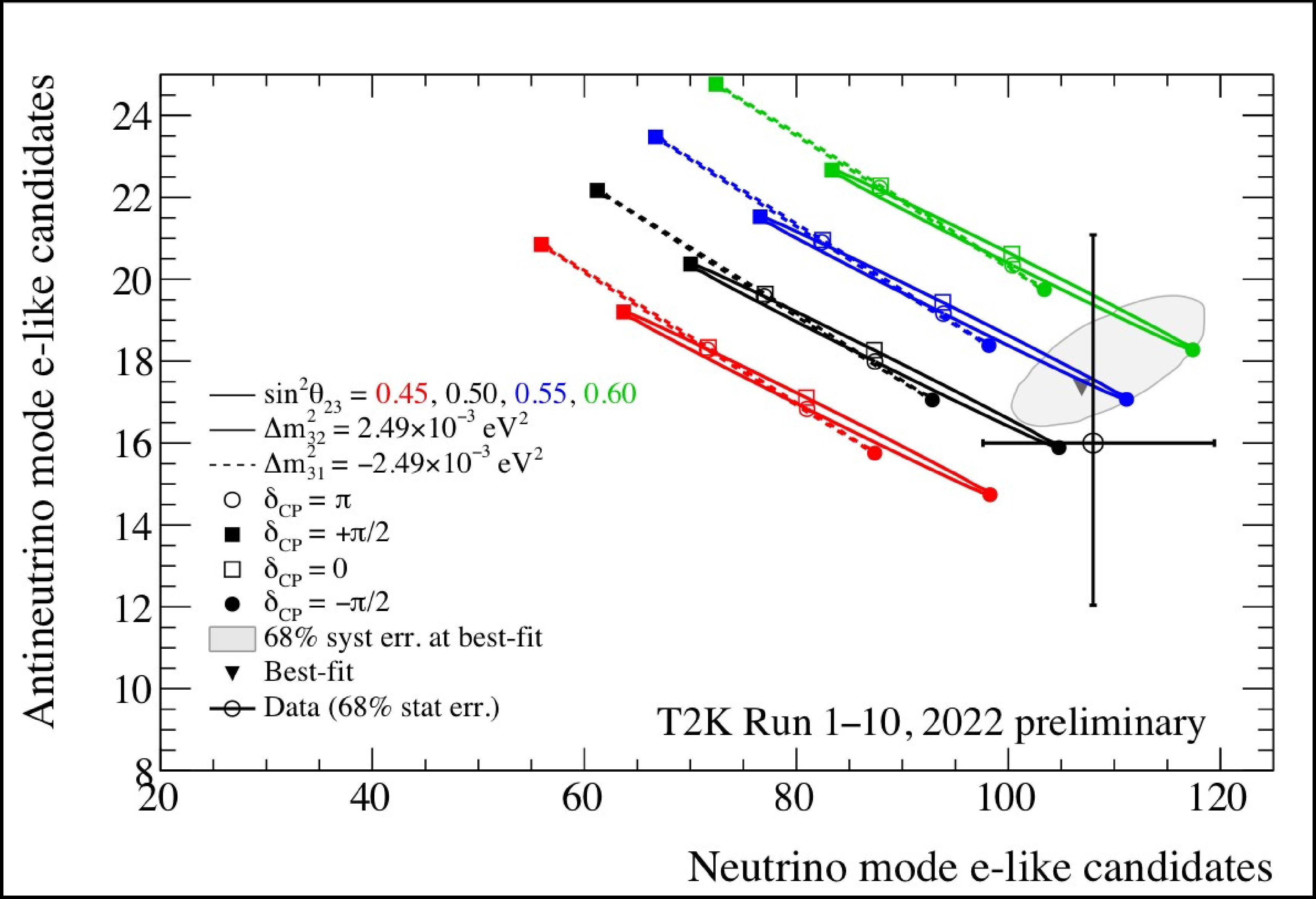

Reconstructed Energy
Number of events per bin
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
ν_μ disappearance
Ratio
Reconstructed Neutrino Energy (GeV)


Reconstructed Energy
Number of events per bin
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
$\bar{\nu}_\mu$ disappearance
Ratio
Reconstructed Neutrino Energy (GeV)

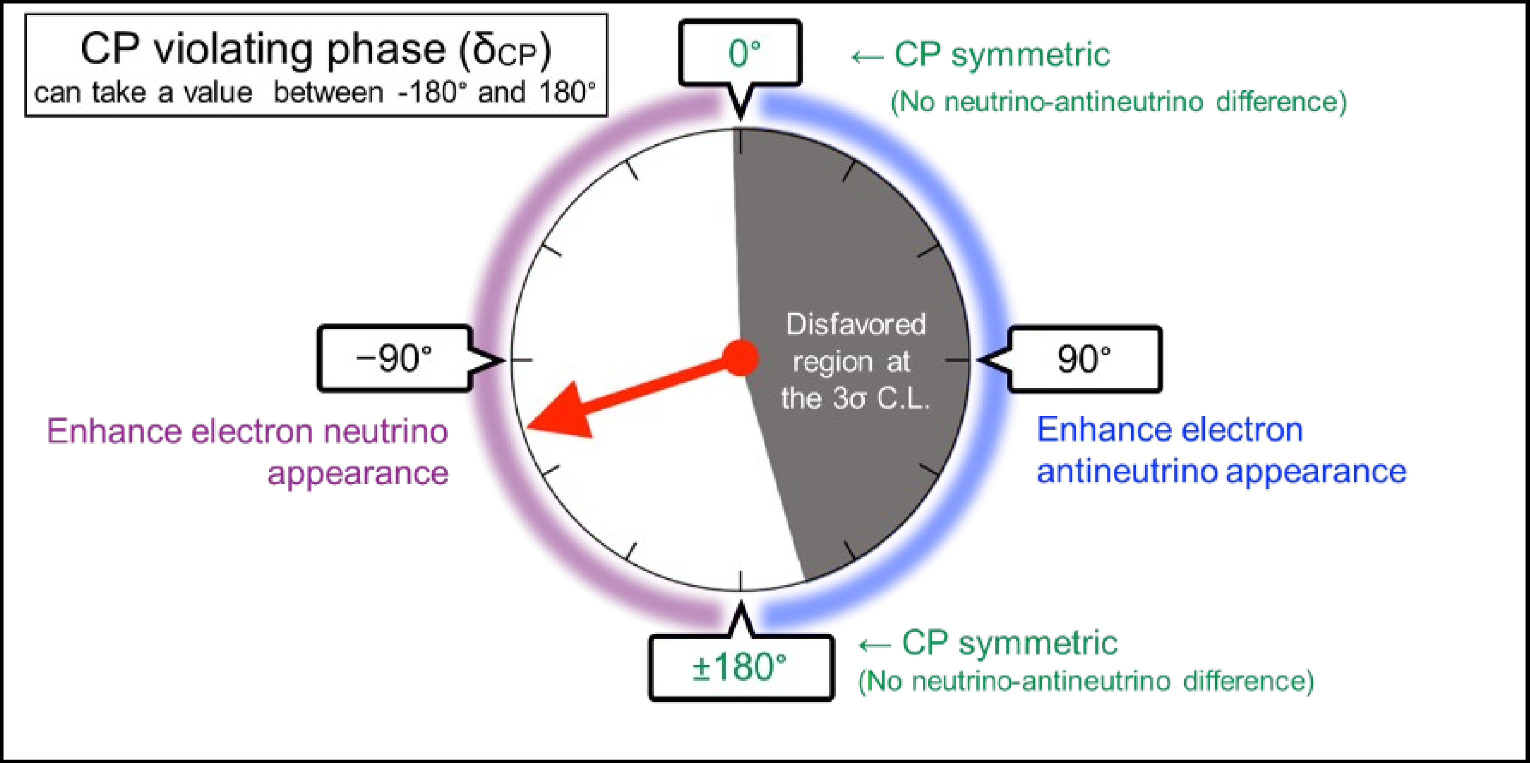

Number of events per bin
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
ν_e appearance
Ratio
Reconstructed Neutrino Energy (GeV)


Number of events per bin
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
$\bar{\nu}_e$ appearance
Ratio
Reconstructed Neutrino Energy (GeV)

CP Violation



CP Violation



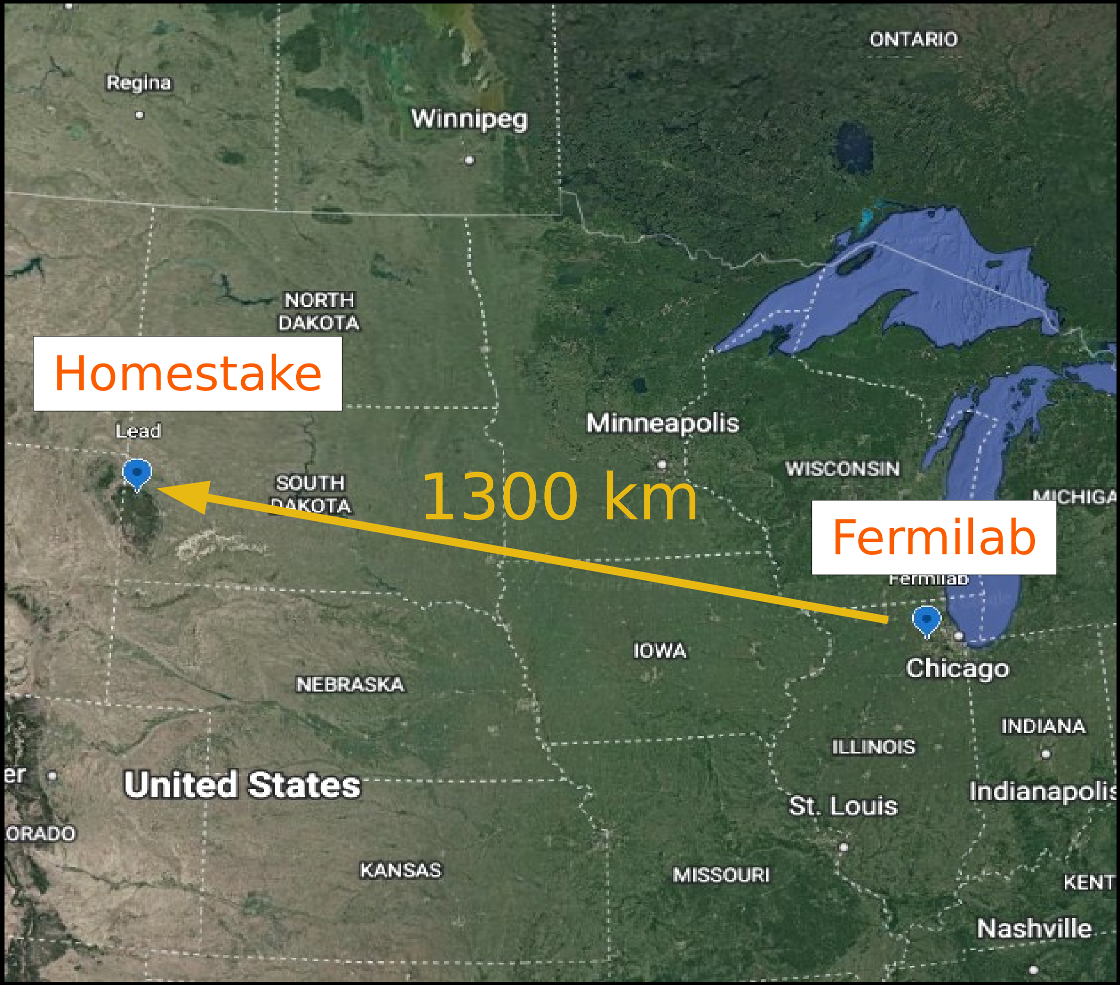
CP conservation is disfavoured at around 2-3σ

Compatible with maximal CP violation

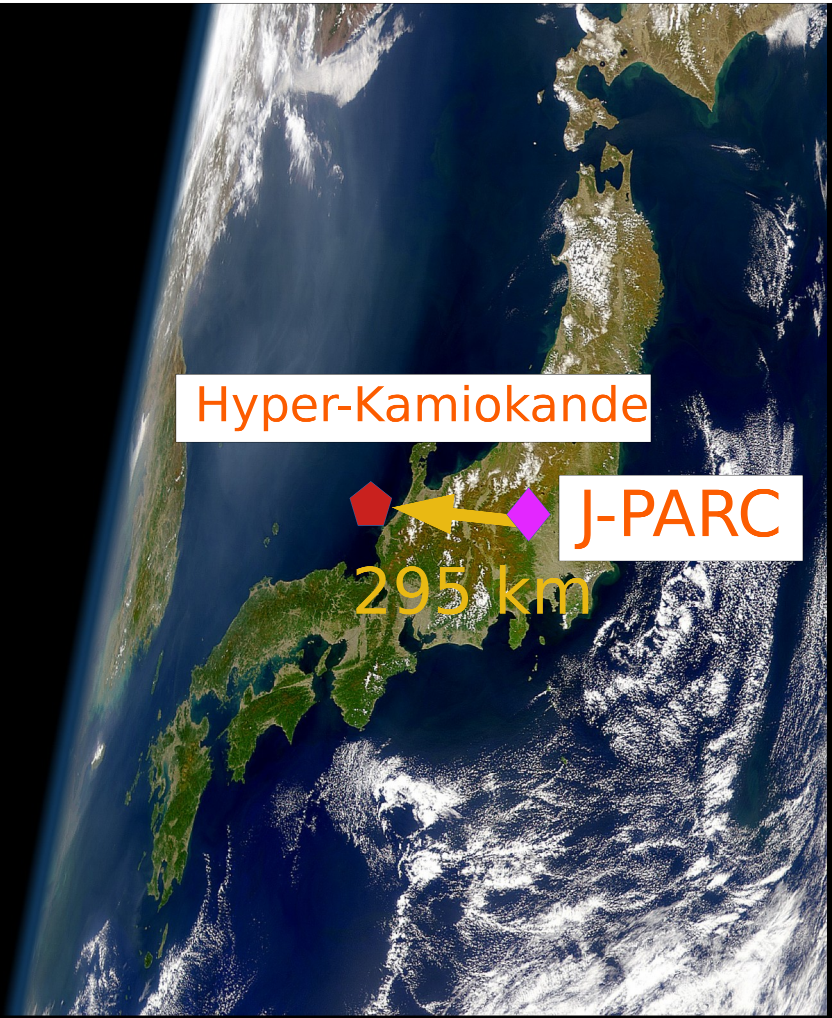
Future Program

Next Generation

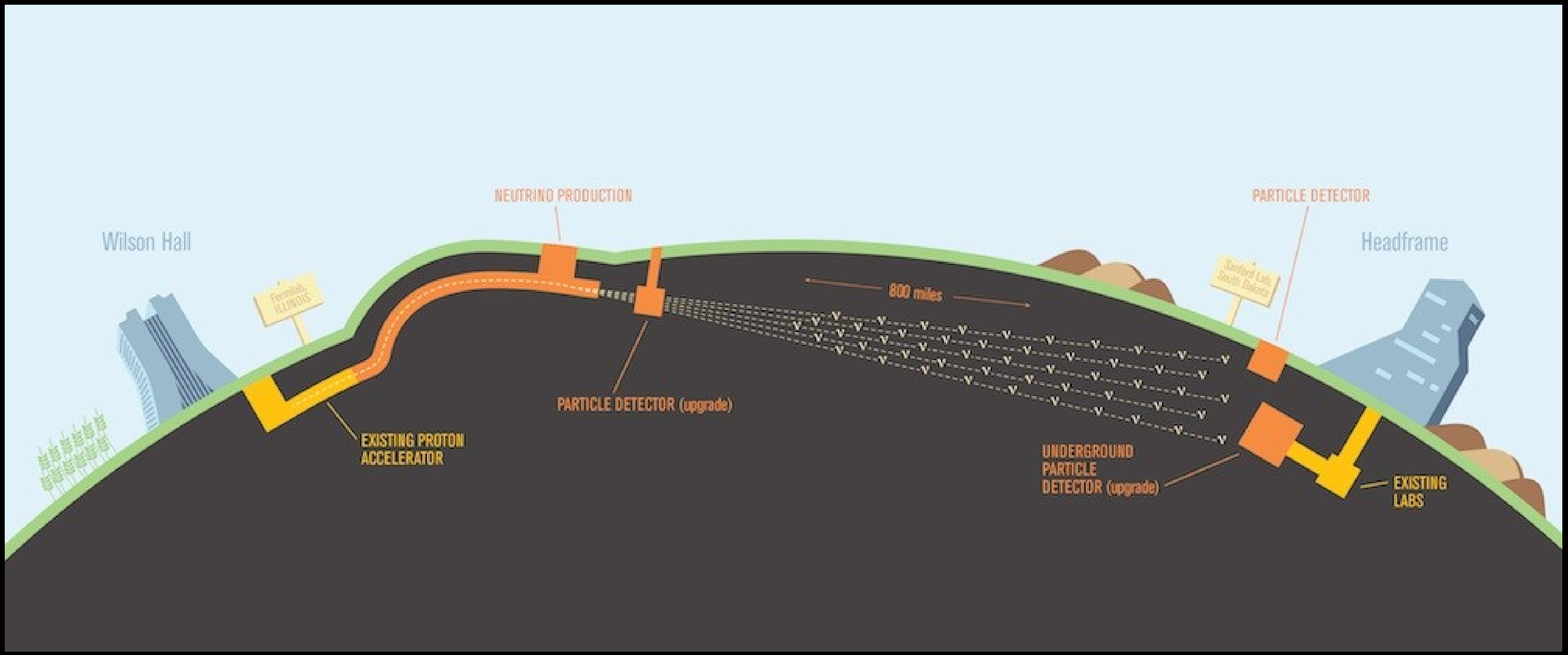
DUNE



Hyper-Kamiokande

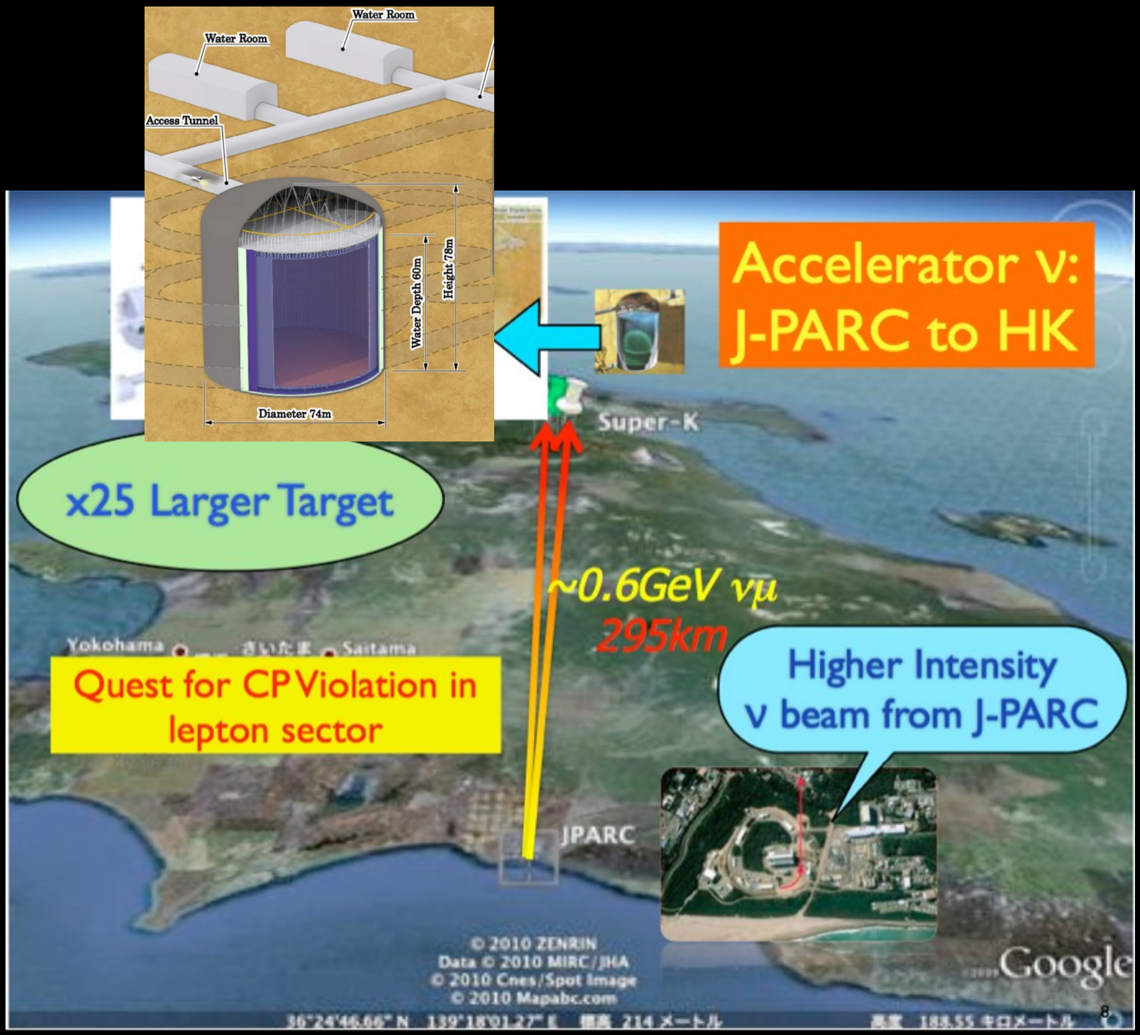


DUNE



- 1300 km baseline (Fermilab to Homestake, South Dakota)
- Wideband neutrino beam (1 – 8 GeV neutrino beam)
- 1.2 MW Beam Power (upgradeable to 2.4 MW)
- Minimal near detector suite
- Far detector : 40 kton liquid argon TPC

Hyper-Kamiokande



- 295 km baseline (Tokai to Kamioka)
- Same beam as T2K but upgraded to reach twice the power (1 MW)
- Upgraded near detector suite
- Far detector : 560 kton water Cherenkov detector

well…new’ish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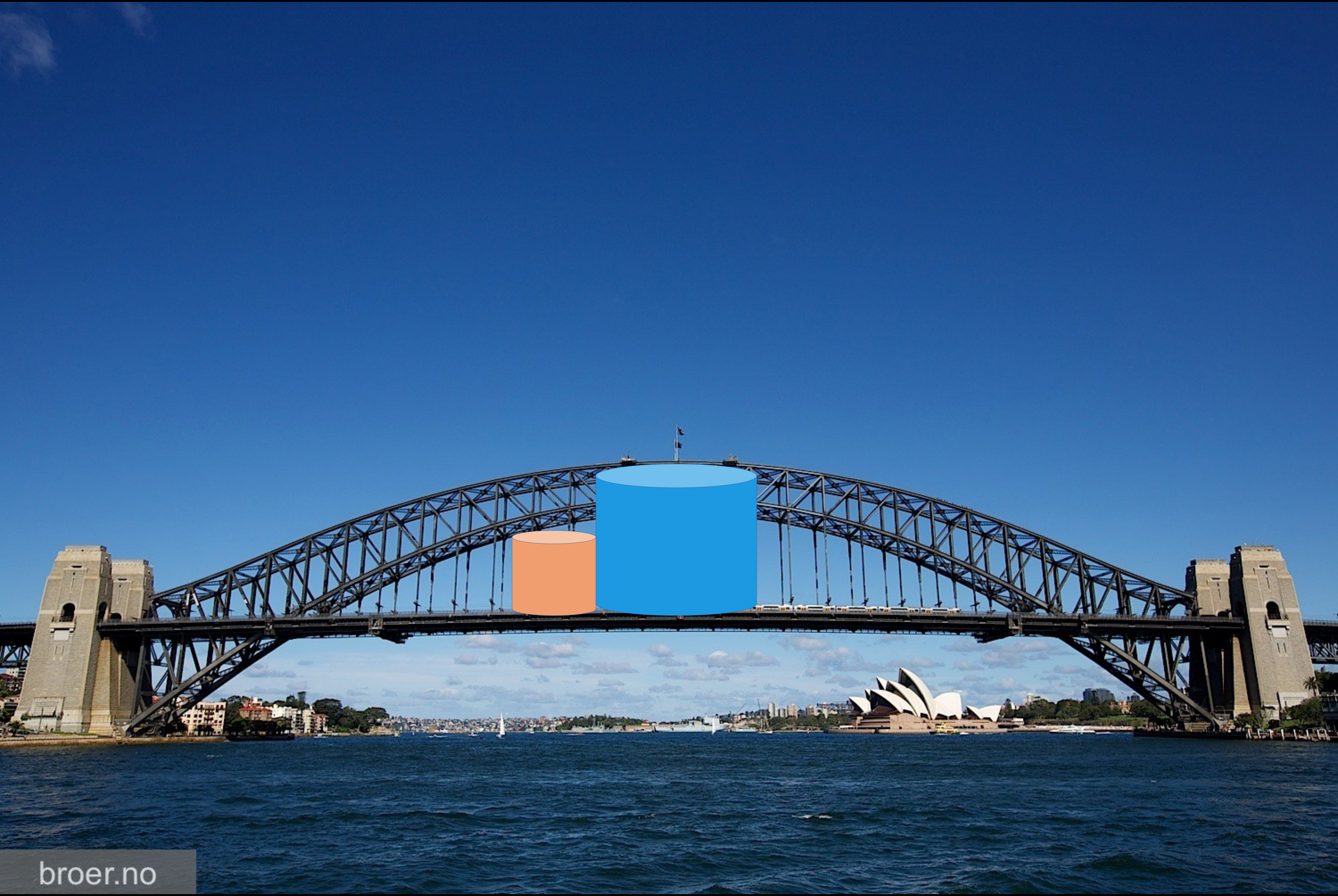
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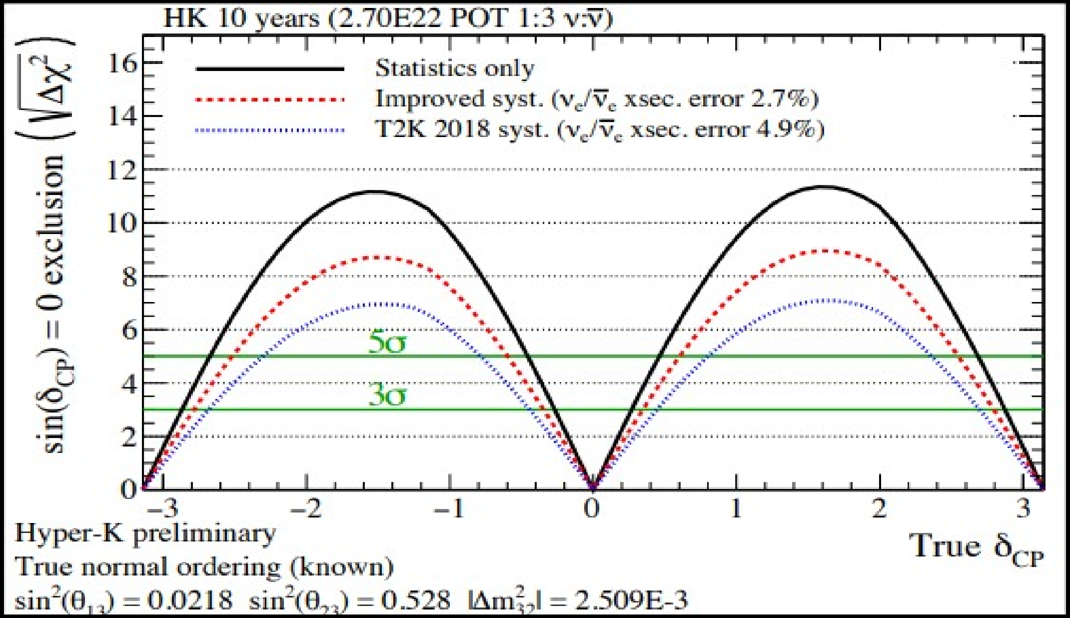
Complementarity

Hyper-Kamiokande	**DUNE**
295 km baseline	1300 km baseline
Peak E_ν = 0.6 GeV	Peak E_ν = 3.0 GeV
Very weak matter effects	Strong matter effects
Narrow-band beam	Wide-band beam
Water Cherenkov : Simple, robust detector	Liquid Argon TPC : Powerful, complex detector
Oxygen target	Argon target

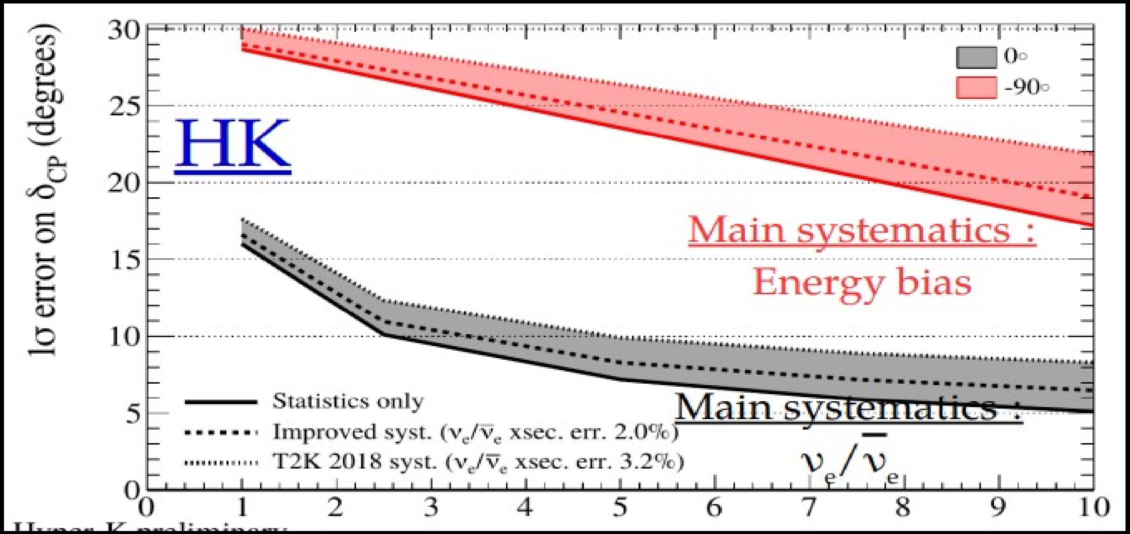
Complementary coverage of physics phase space, but with different technologies, systematic uncertainties and energy ranges.

Measuring δ_{CP}



- Non-zero δ_{CP} will be discovered at > 5σ over 60% of true δ_{CP} after 10 years of data taking

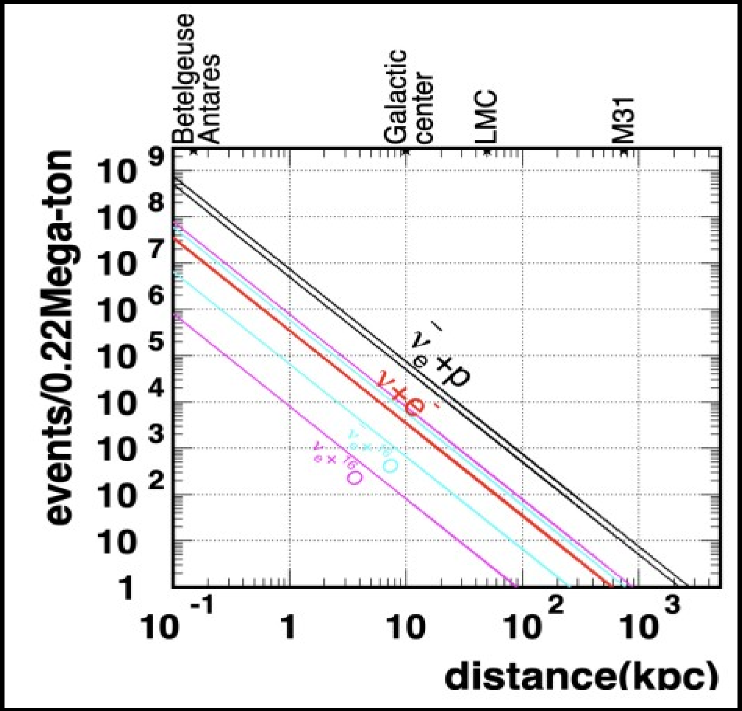
- 1σ error on δ_{CP} is around 20-25° if δ_{CP}= -π/2 after 4-7 years of data taking

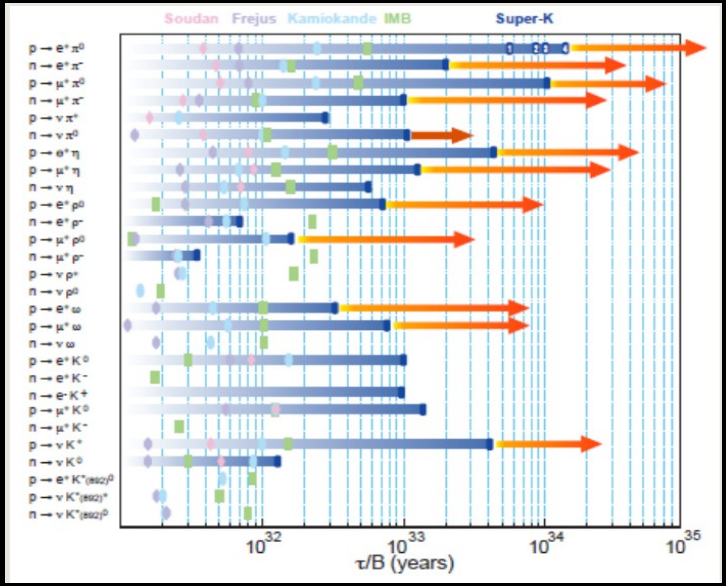


Other physics

- Kamiokande detected 11 events from SN1987A (50 kpc away)
- Hyper-K would detect ~ 10,000 events

- Also would be sensitive to supernova remnants – supernovae from the very early universe



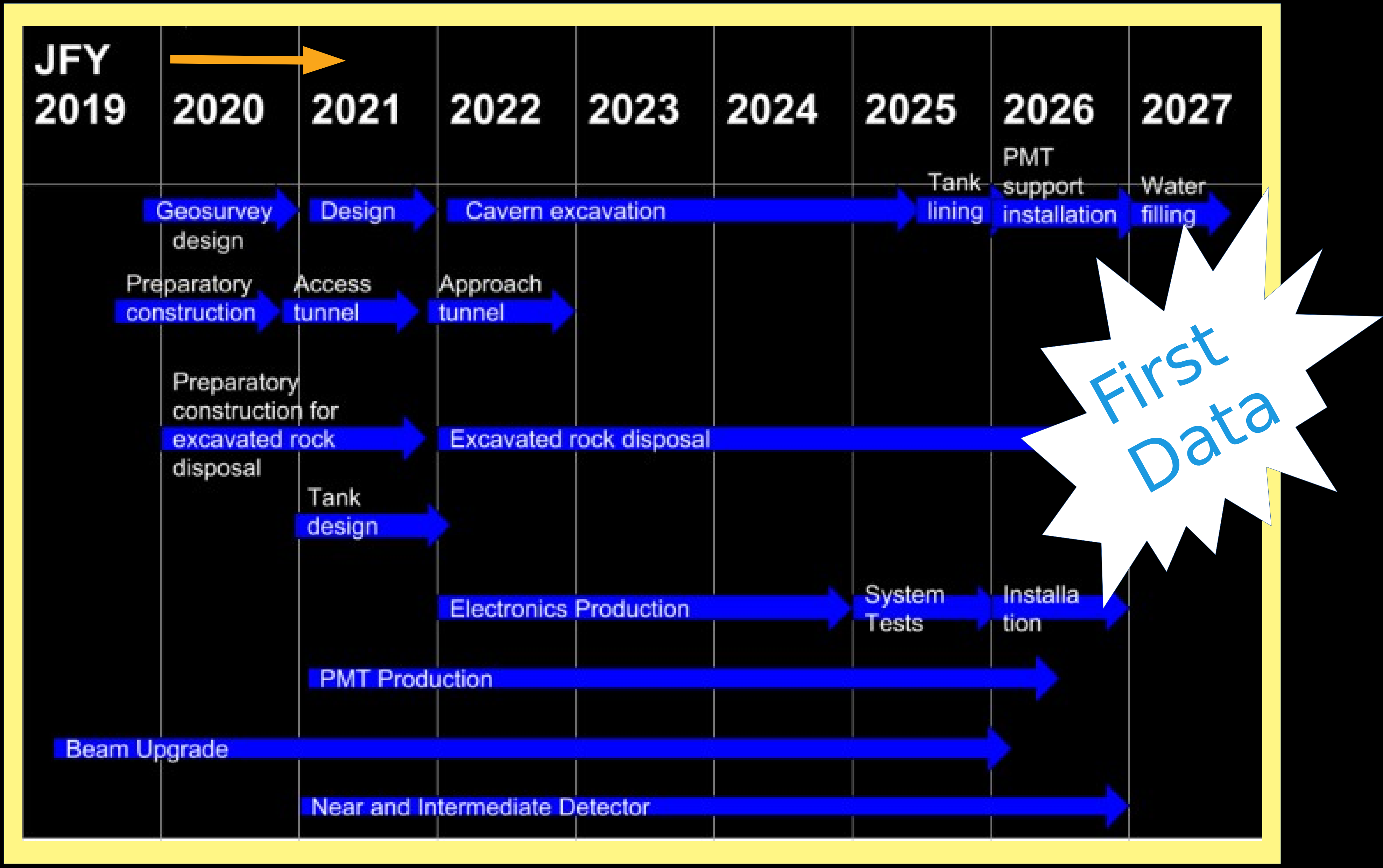


- Limits on some proton decay modes could be increased by an order of magnitude or more

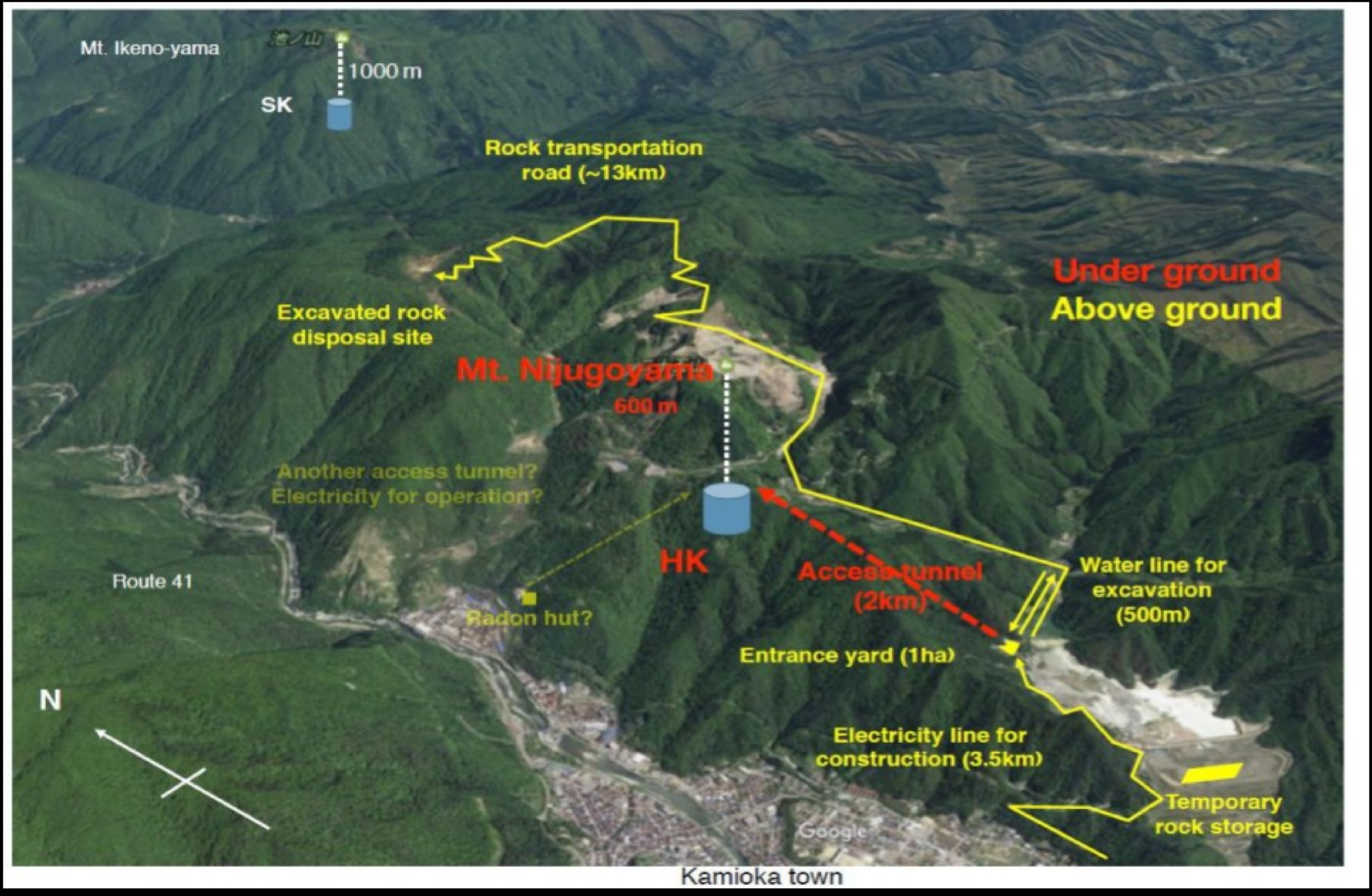
DUNE Schedule

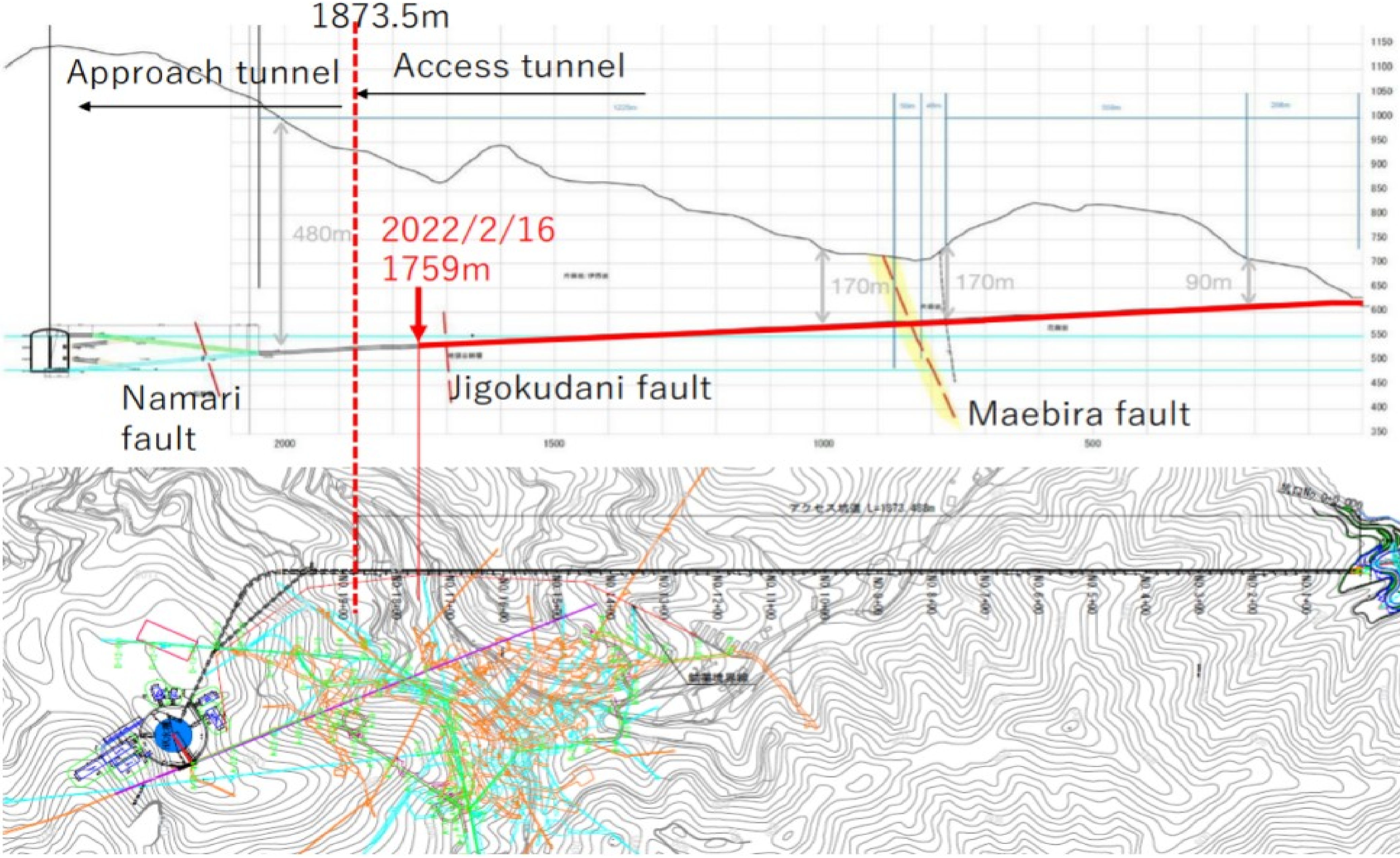
Component	Ready for operation	Comment
Far Detector	2029	Non-beam related physics (e.g. atmospheric neutrinos)
Neutrino beamline	2031	Oscillation physics can be begin
Near Detector Complex	2032	Better control of systematics

Hyper-K Schedule



Construction is Underway




1873.5m
Approach tunnel
Access tunnel
480m
2022/2/16
1759m
170m
170m
90m
Namari fault
Jigokudani fault
Maebira fault
2000
1500
1000
500
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
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450
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850
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750
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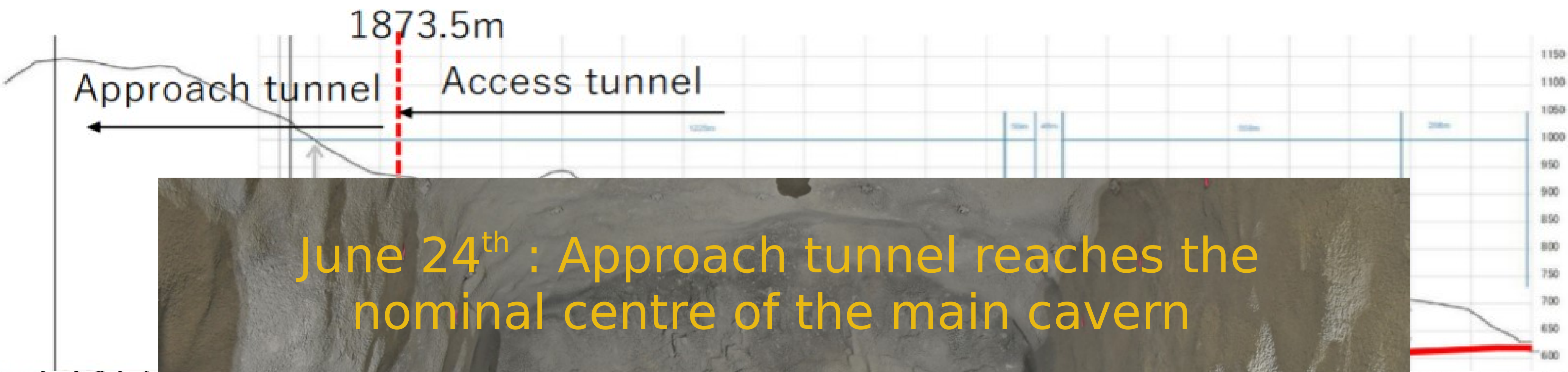
650
600


Air
Power and network line
Water

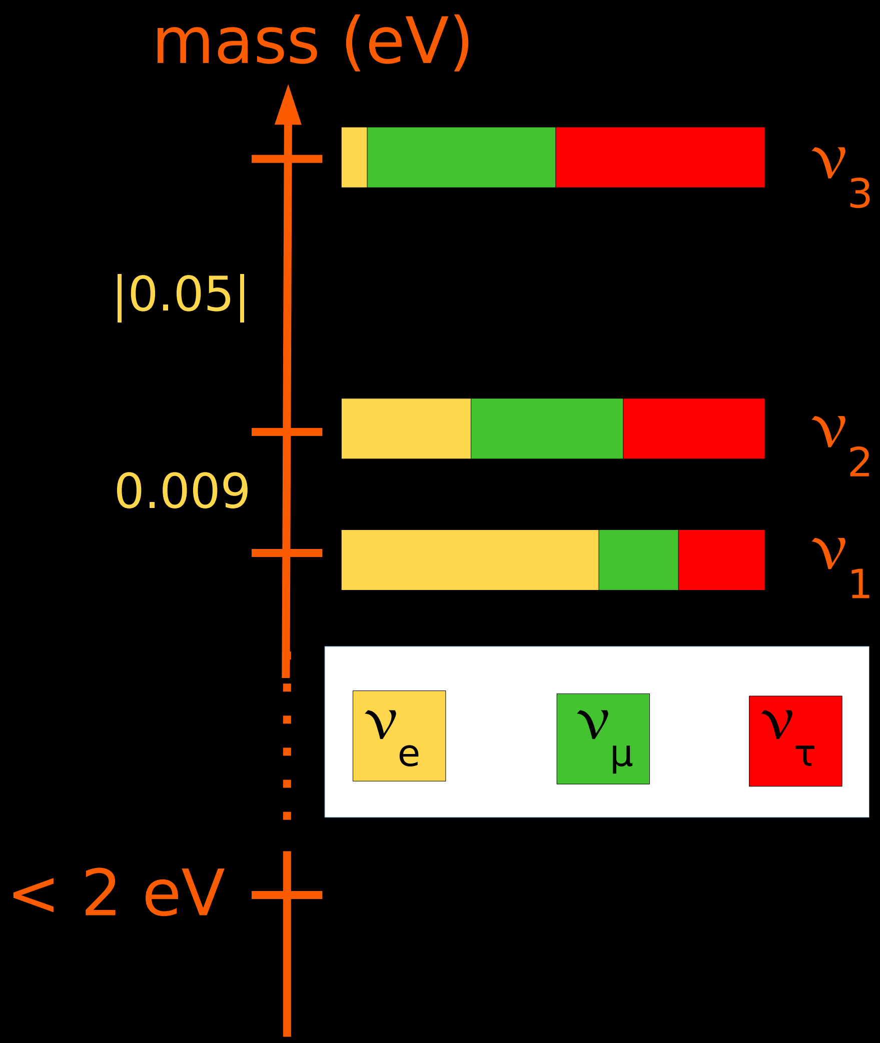
June 24th : Approach tunnel reaches the nominal centre of the main cavern



Summary

- The source of the matter-antimatter asymmetry in the observable Universe is a mystery
- CP violation in the lepton sector may hold the key to understanding this.
- Neutrino flavour oscillations is the right tool to explore this question.
- The current T2K experiment excludes CP conservation at 2σ
- HyperK will take first data in 2027 and will exclude CP conservation at 5σ by 2030
- A measurement of CP violation in the neutrino sector is in reach!

Open Questions



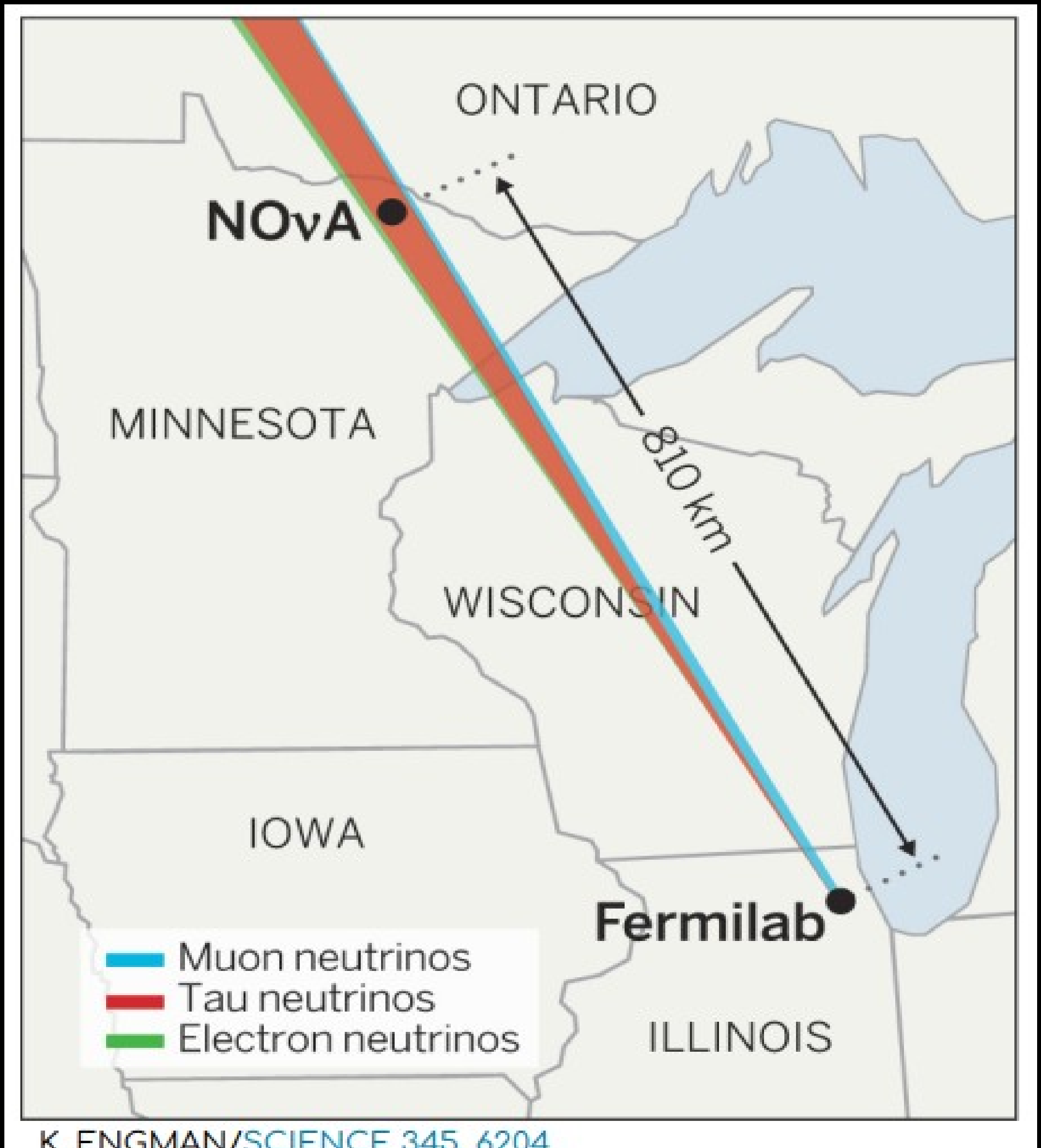
- What is the value of δ_{CP}?
- What is the mass ordering?
- Better values for the other mixing angles
- Is the PMNS matrix, as currently written, correct?

- What is the absolute mass scale?
- Is the neutrino a Dirac or Majorana particle?
- Are there sterile neutrino states?

HK Physics Goals

Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		7.5 MW $\times$ 10^7 sec
– CP phase precision	$< 19°$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– CPV discovery coverage	76% ($3\,\sigma$), 58% ($5\,\sigma$)	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– $\sin^2\theta_{23}$	± 0.015	1σ @ $\sin^2\theta_{23} = 0.5$
Atmospheric neutrino study		10 years observation
– MH determination	$> 3\,\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
– θ_{23} octant determination	$> 3\,\sigma$ CL	@ $\sin^2\theta_{23} < 0.46$ or $\sin^2\theta_{23} > 0.56$
Nucleon Decay Searches		10 years data
– $p \to e^+ + \pi^0$	1.3×10^{35} yrs (90% CL UL)	
	5.7×10^{34} yrs ($3\,\sigma$ discovery)	
– $p \to \bar{\nu} + K^+$	3.2×10^{34} yrs (90% CL UL)	
	1.2×10^{34} yrs ($3\,\sigma$ discovery)	
Astrophysical neutrino sources		
– ^{8}B ν from Sun	200 ν's / day	7.0 MeV threshold (total energy) w/ osc.
– Supernova burst ν	170,000∼260,000 ν's	@ Galactic center (10 kpc)
	30∼50 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν's / 10 years	
– WIMP annihilation at Sun		5 years observation
(σ_{SD}: WIMP-proton spin	$\sigma_{SD} = 10^{-39}\mathrm{cm}^2$	@ $M_{\mathrm{WIMP}} = 10\,\mathrm{GeV}$, $\chi\chi \to b\bar{b}$ dominant
dependent cross section)	$\sigma_{SD} = 10^{-40}\mathrm{cm}^2$	@ $M_{\mathrm{WIMP}} = 100\,\mathrm{GeV}$, $\chi\chi \to W^+W^-$ dominant

NOvA



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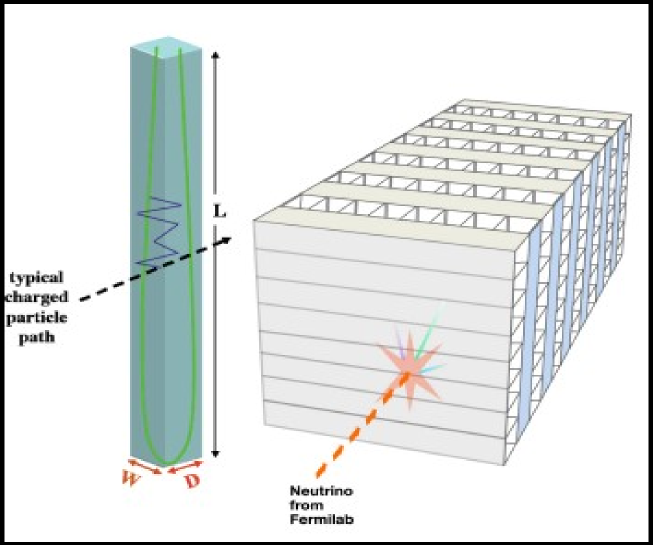
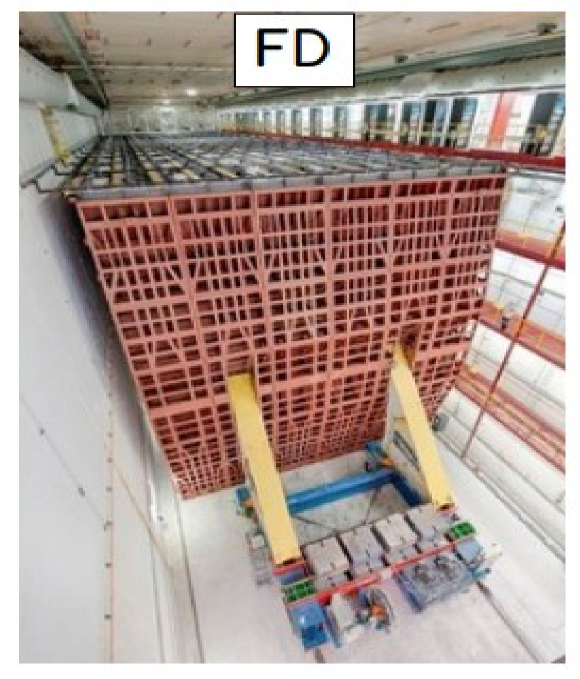
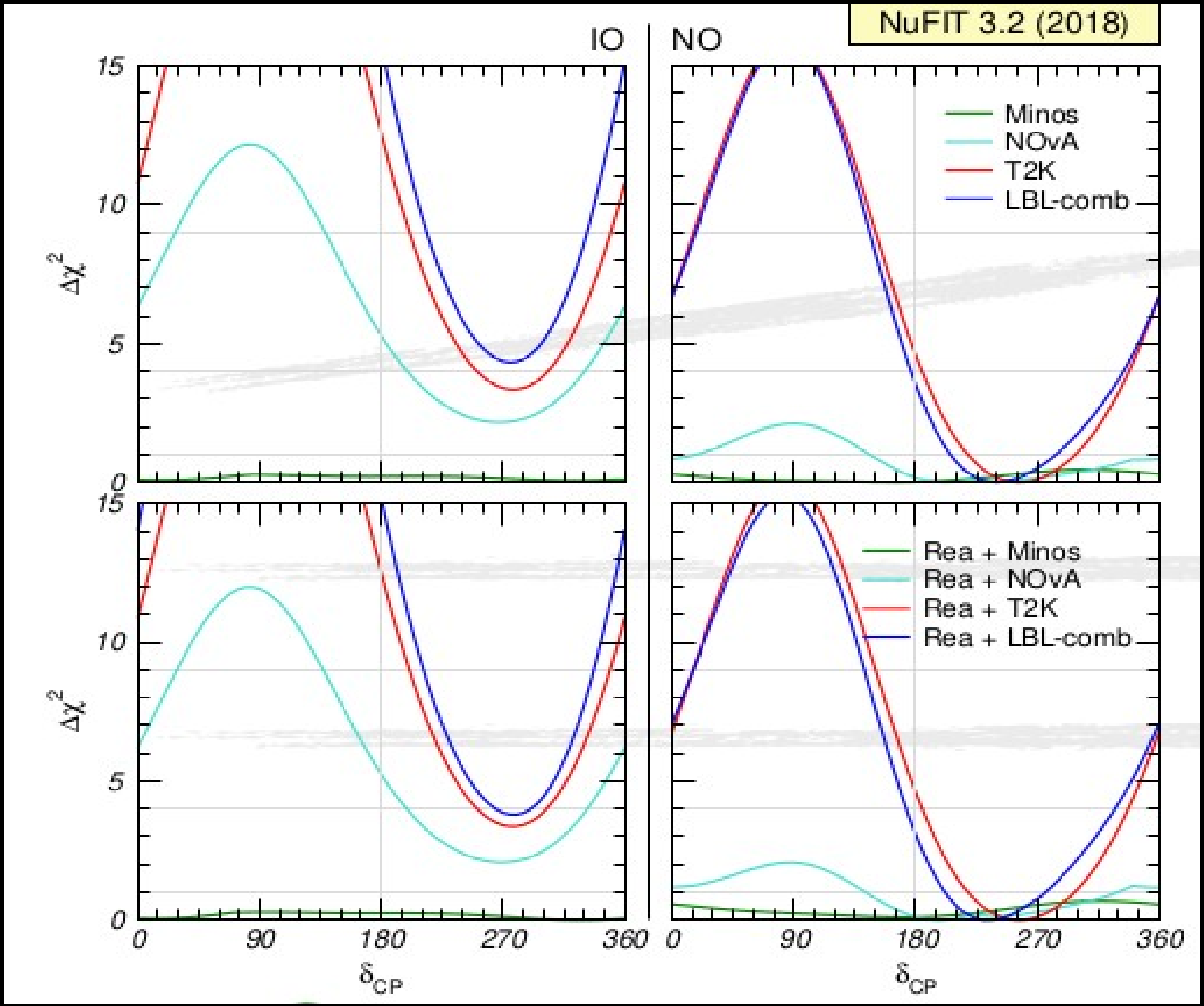




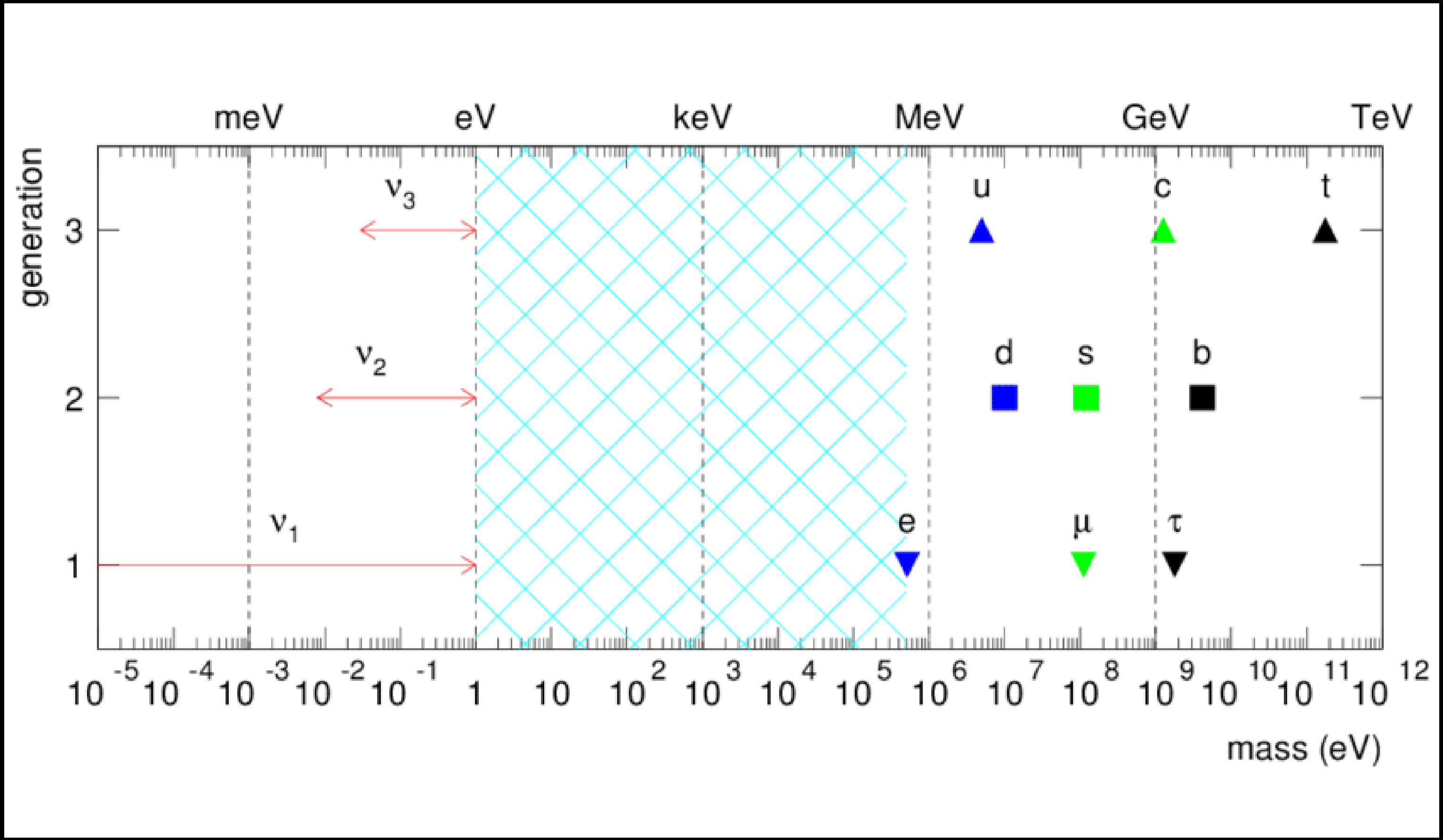
NOvA



- NOvA favours normal mass ordering
- T2K and NOvA are consistent

Open Questions

Neutrino Mass

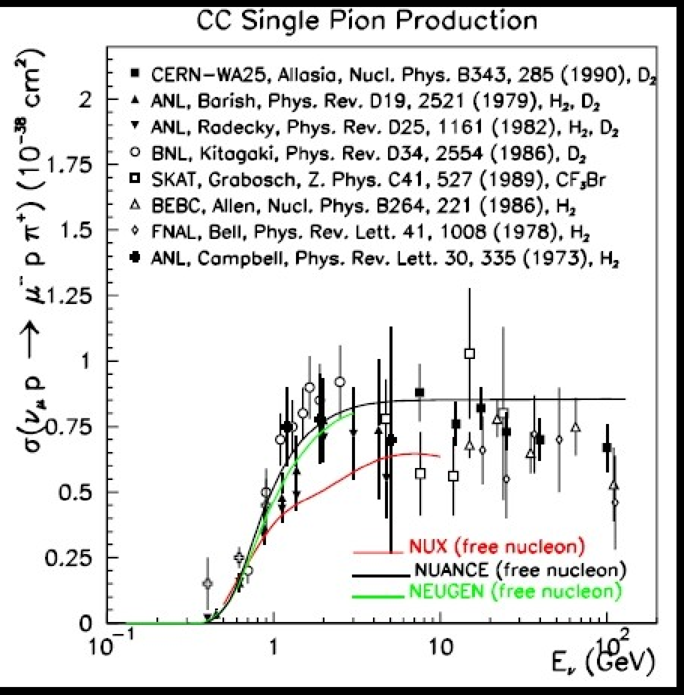


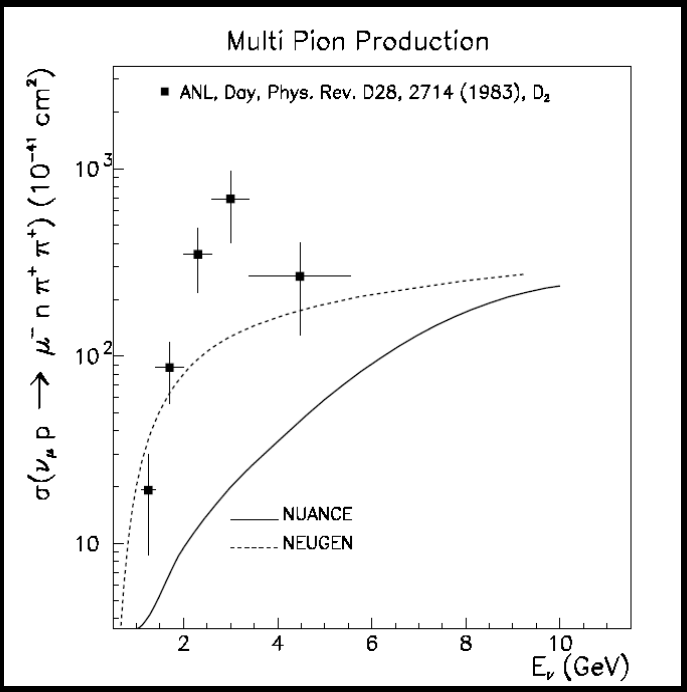
$m(\nu_e) < 1.1 \ eV$ — Tritium β-decay (KATRIN)

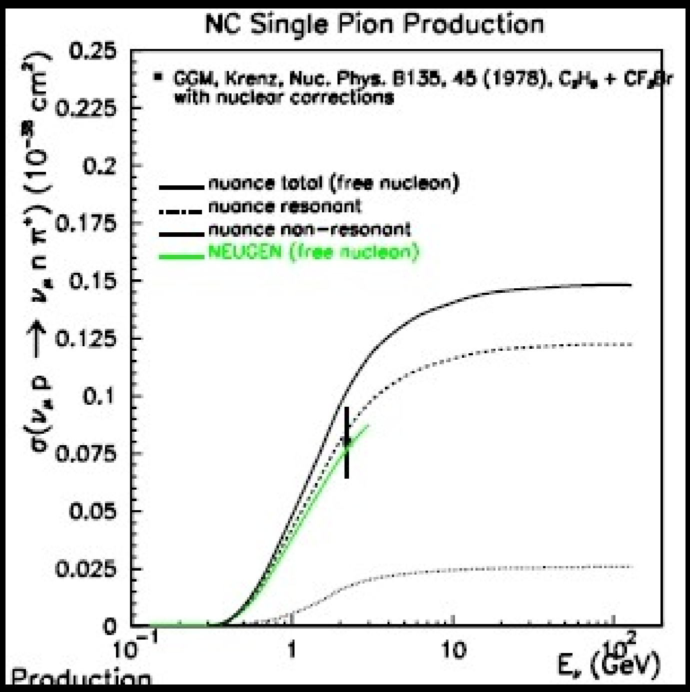
$m(\nu_\mu) < 190 \ keV$ — Stopped pion decay

$m(\nu_\tau) < 18.2 \ MeV$ — Tau lepton decay

Xsec data pre-2007

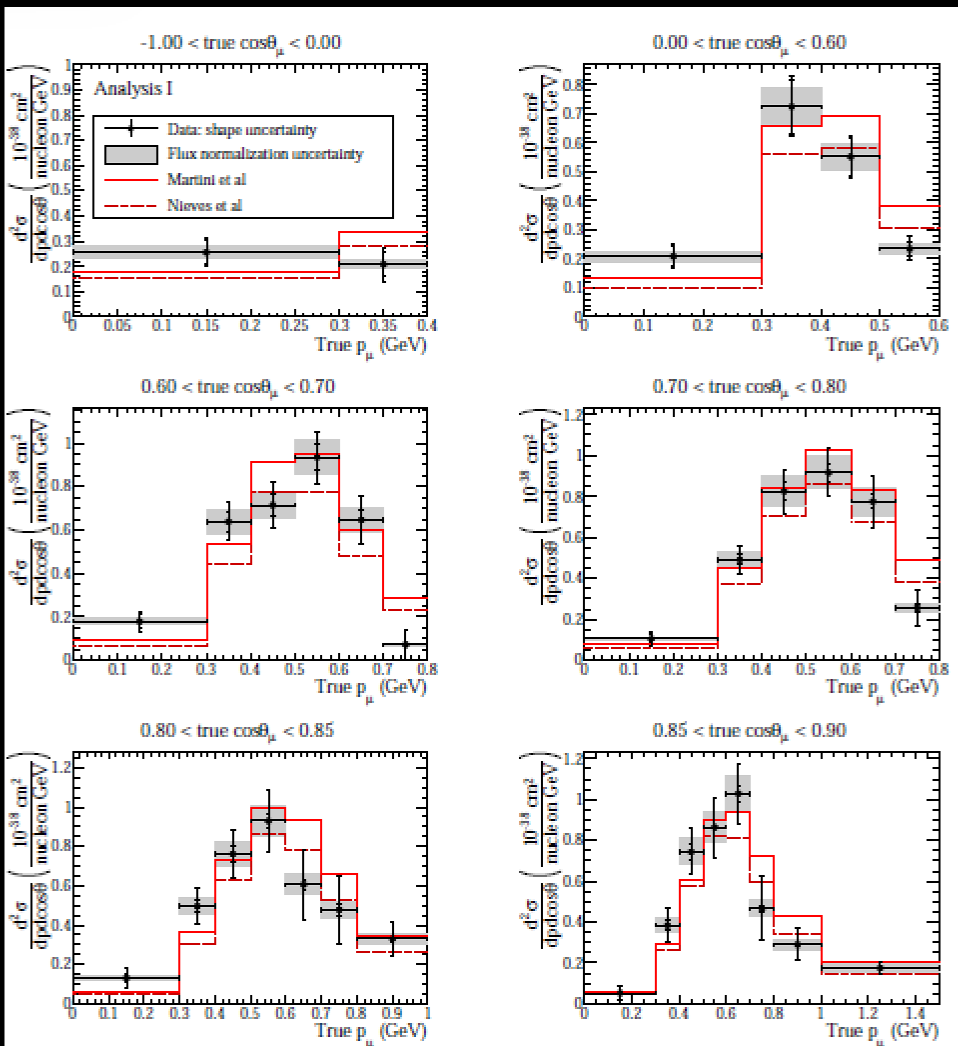




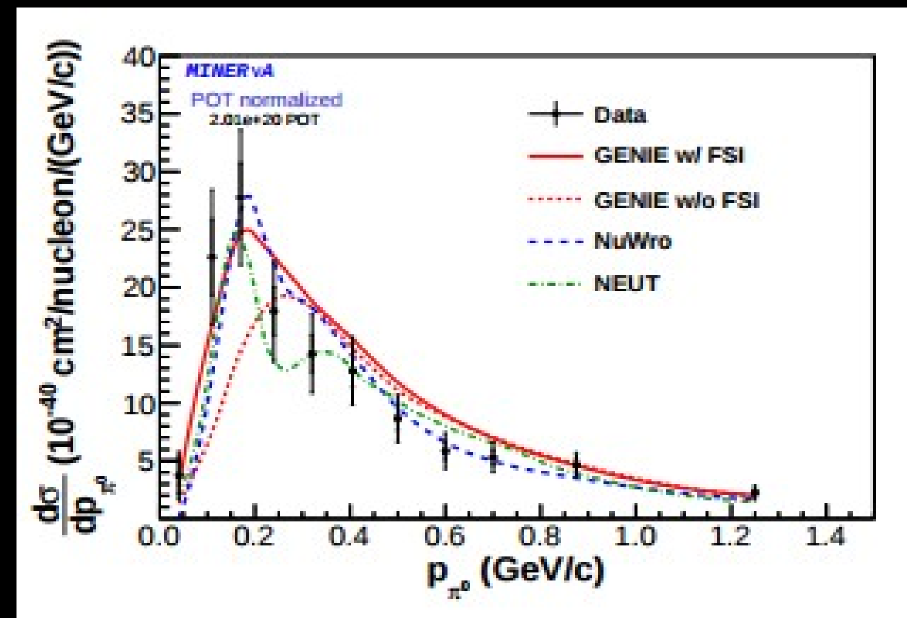


$\nu_\mu p \rightarrow \mu^- p \pi^+$ $\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+$ $\nu_\mu p \rightarrow \nu_\mu n \pi^+$

It's slowly getting better



CC 0π differential Xsec from T2K
arXiv:1602.03652



CC π^0 differential xsec from MINERvA
Phys.Lett. B749 (2015) 130-136

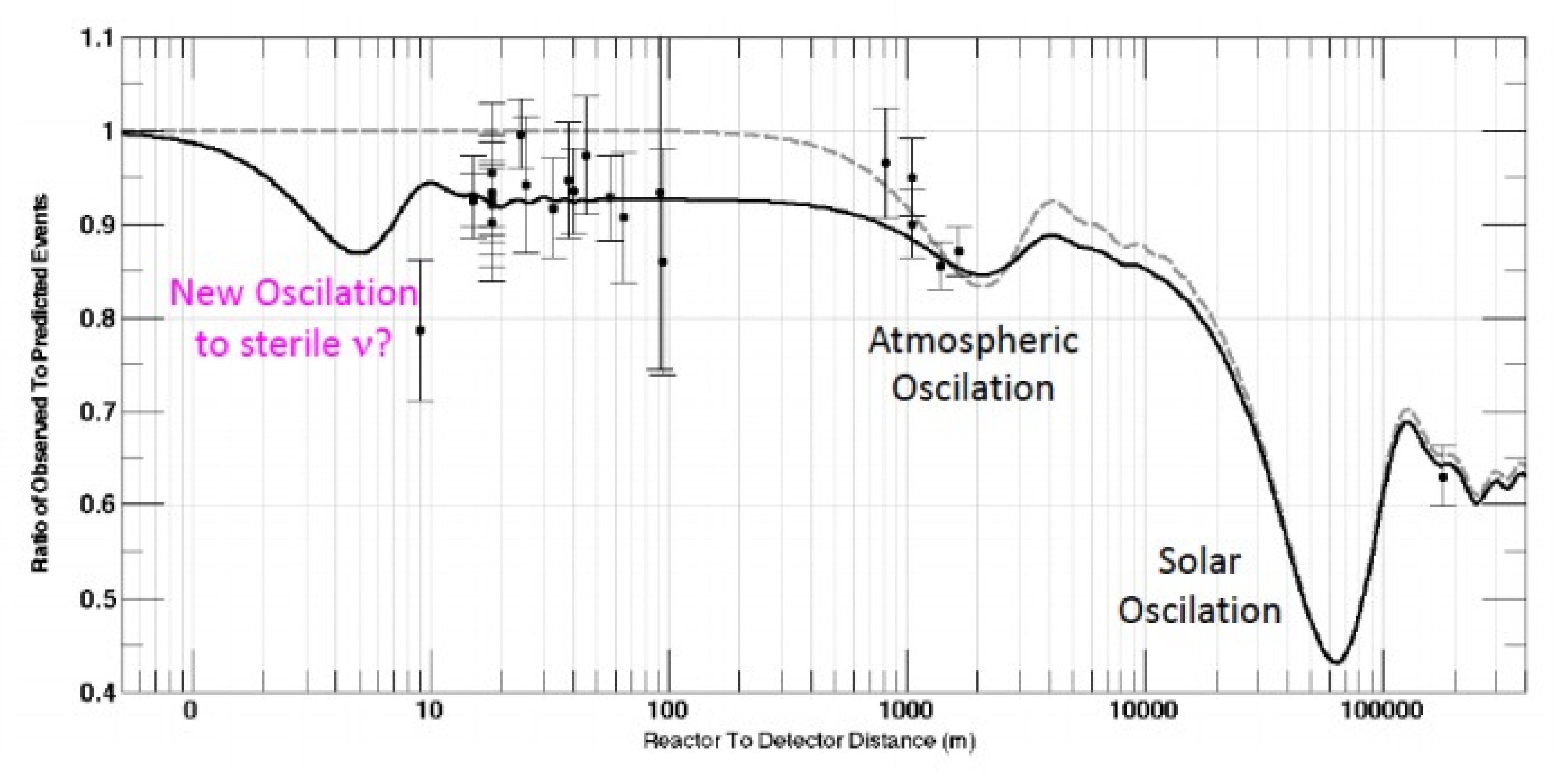
Lot's of effort going into trying to understand neutrino interaction cross sections

The state of steriles

Over the past 20 years or so, some anomalies in neutrino oscillation data has been interpreted as weak evidence of the existence of one (or more) sterile, neutrino states with a masses of around 1 eV/c^2

- LSND – miniBooNE electron neutrino excess
- Apparent electron antineutrino deficit in Gallium decay
- Apparent electron antineutrino flux deficit in reactors

e.g. Reactor Anomaly



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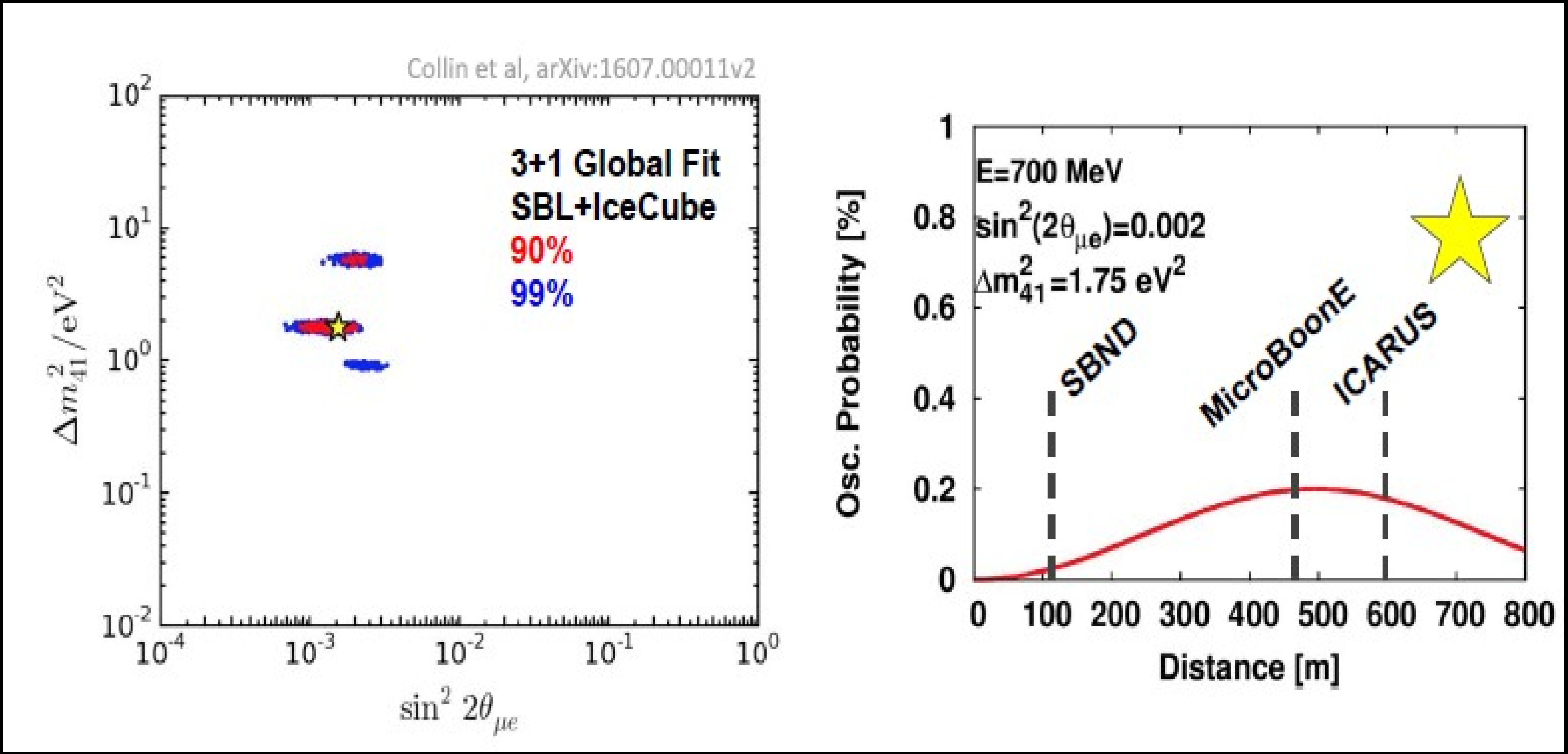
Could also be interpreted with:

- Unknown backgrounds
- Inaccurate production cross sections
- Inaccurate reactor flux predictions

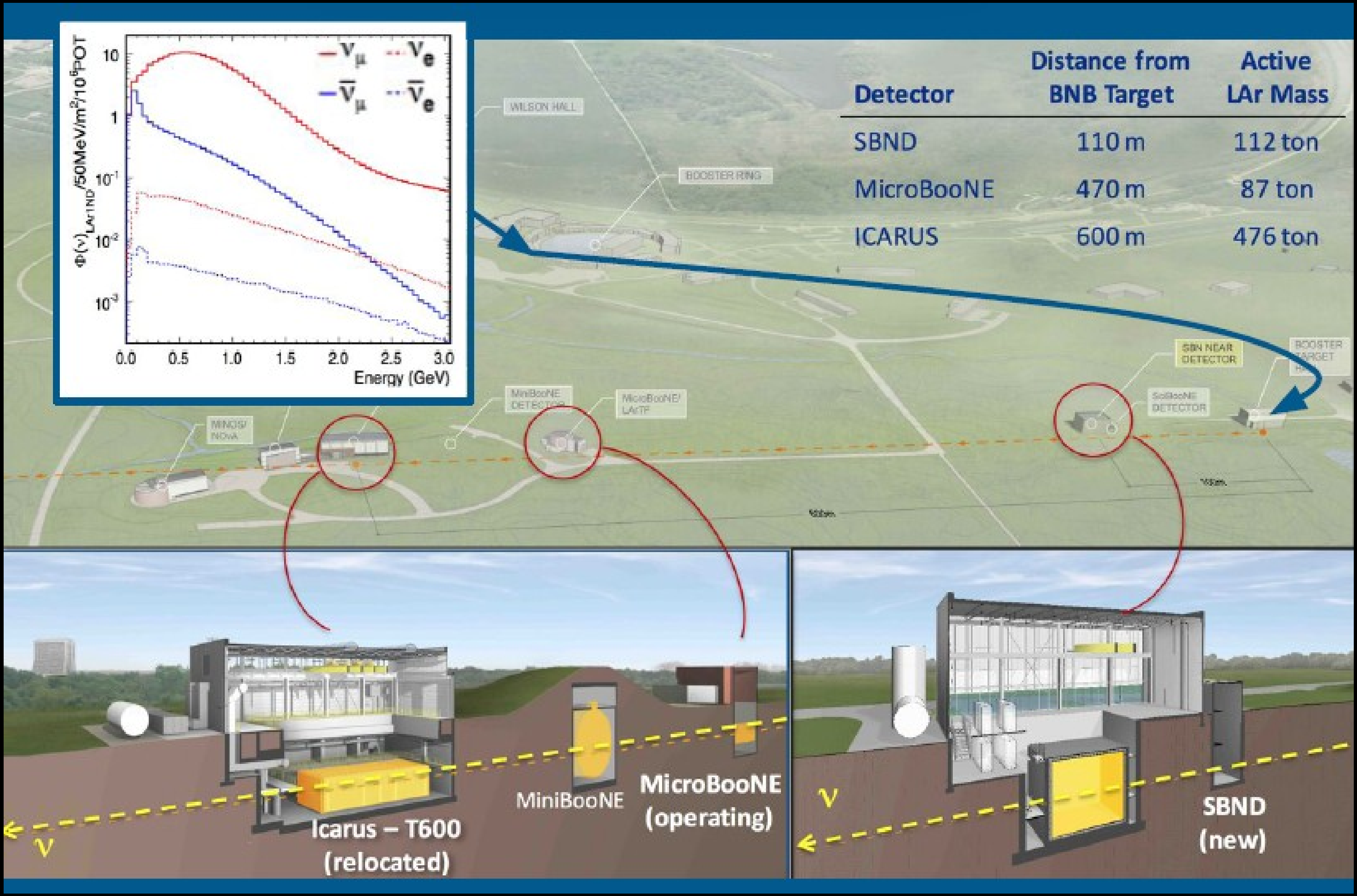
Theoretically, it's very hard to fit all data into a single model

SBND



Experiment being built now – switches on this year

SBND

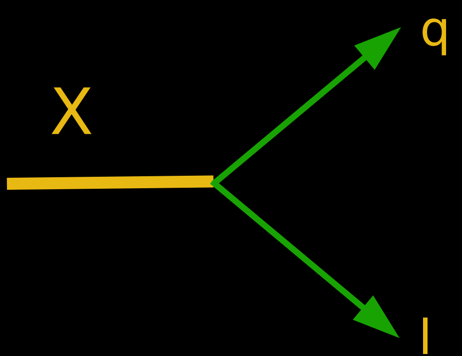


Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

Experiment being built now – switches on this year

Sakharov Conditions

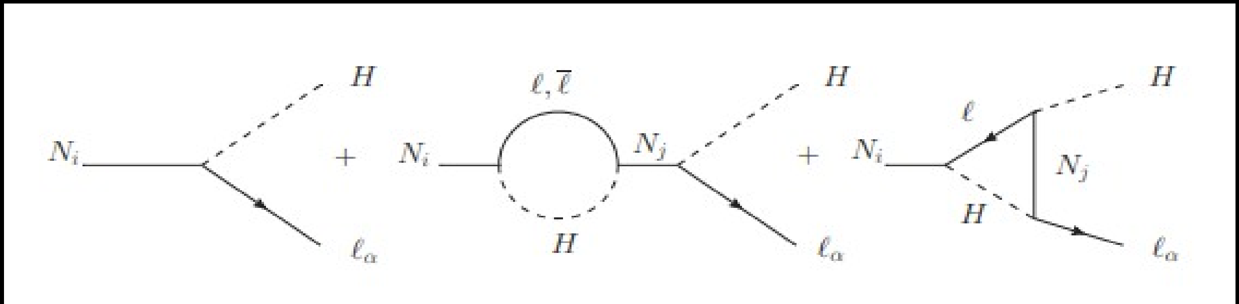
Dynamic generation of a baryon-antibaryon asymmetry is possible if:



- Baryon number is violated
  - X (B#=0) → Y (B#=0) + B (B#≠0)
- C and CP are violated
- Production out of thermal equilibrium
  - Expanding (cooling) universe
  - Γ(X → Y + B) ≠ Γ(Y + B → X)

Leptogenesis

- Suppose that the early universe supported the existence of a very heavy, right-handed, Majorana, neutral lepton
- Also suppose that this lepton could mix, and experience C and CP violation.



$$\Gamma\left(N \rightarrow H\, l\right) \neq \Gamma\left(N \rightarrow H\, \bar{l}\right)$$

$$\Delta L \neq 0$$

- B-L is conserved. Non-perturbative sphaleron transitions If Δ(B-L) = 0 but ΔL $\neq$ 0 $\rightarrow$ ΔB $\neq$ 0
- Baryon-antibaryon asymmetry dynamically generated from lepton sector

T2K Strategy