Universidad de Granada

Neutrino Physics

Experimental - Part I

TAE 2024 - International Workshop on High Energy Physics

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Benasque, 10 September 2024

Why do we study neutrinos?

① Fundamental Particle

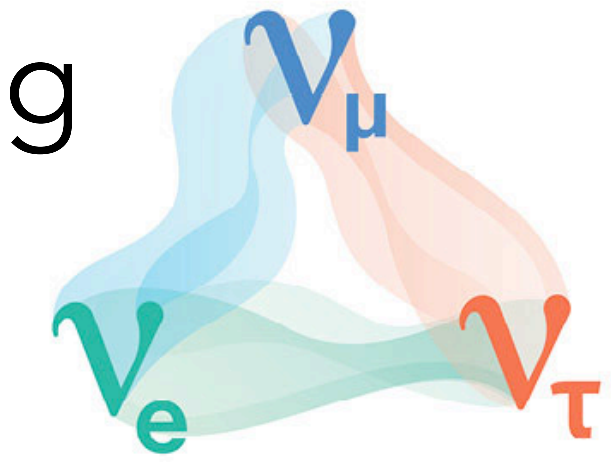
② Abundant

Massive particle more abundant in Nature

③ Elusive

Difficult but not impossible to catch

④ Oscillating



⑤ Lightweight

The weight almost nothing

⑥ Many different sources

⑦ Mysterious

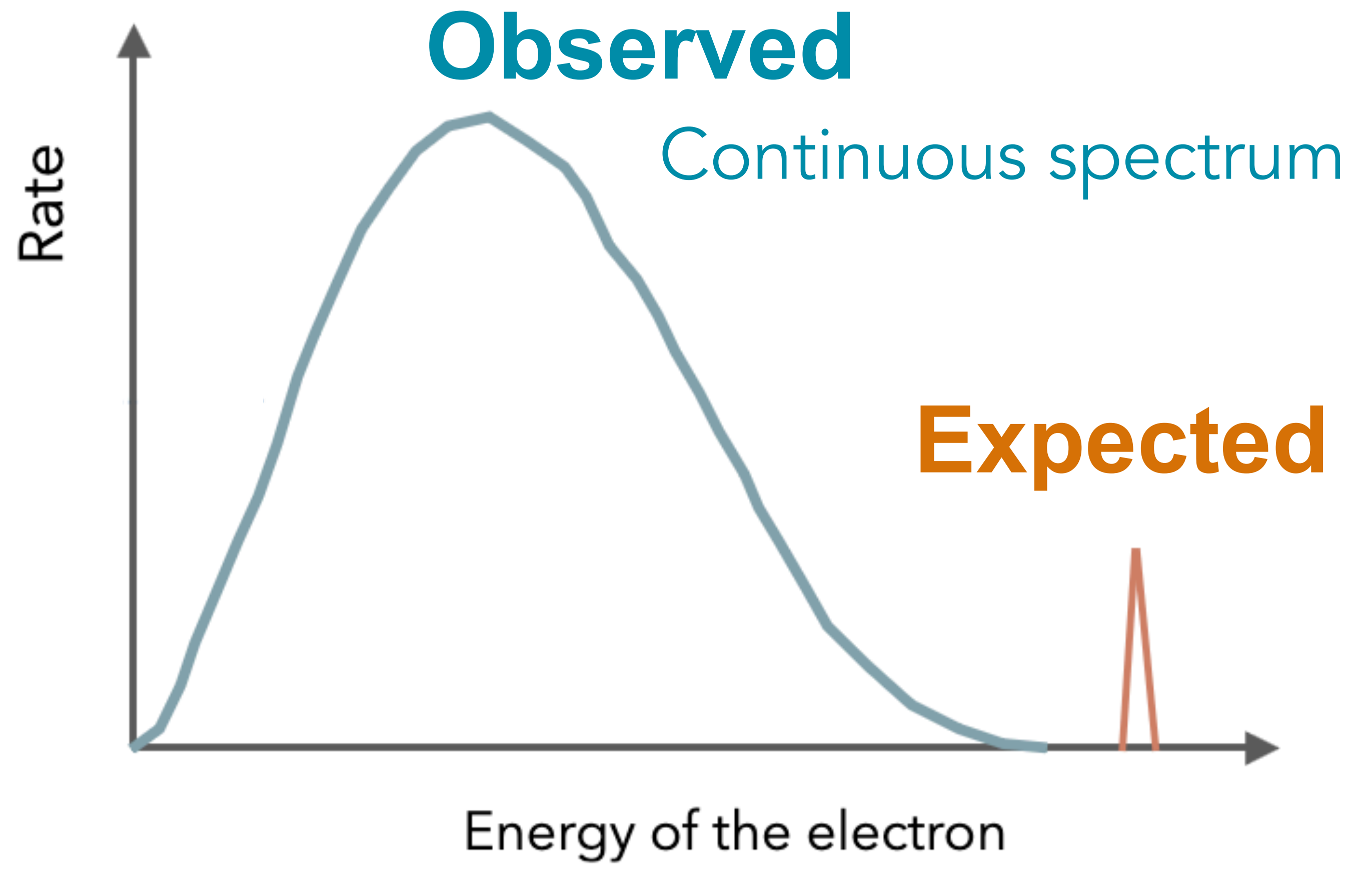
Not fully understood yet

⑧ Key to understand the Universe

Are neutrino and anti-neutrino the same particle?

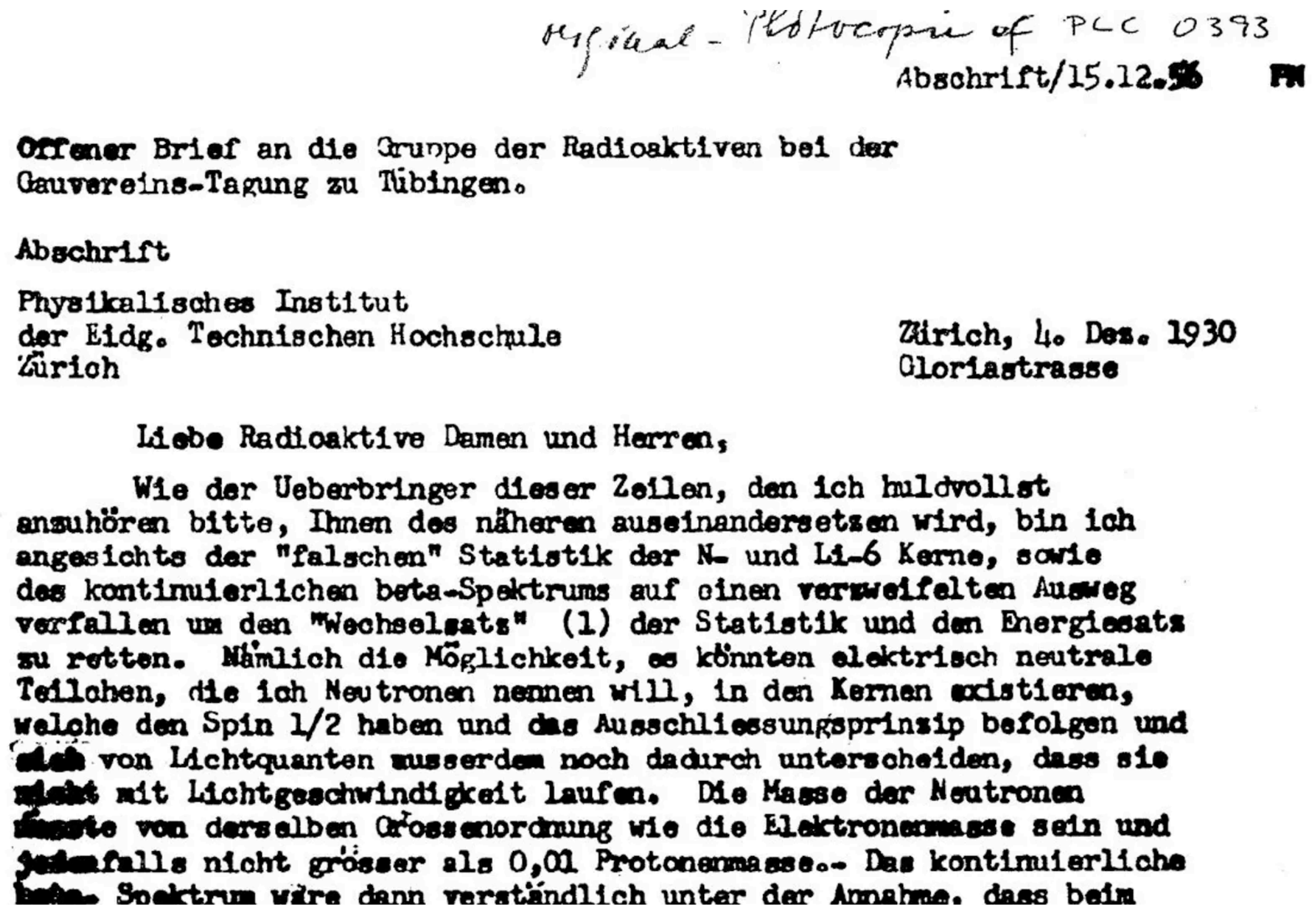
Some history

- **December 4, 1930:** Wolfgang Pauli proposed a desperate way out for a paradox that had arisen in the field of nuclear physics in the famous letter: "Liebe Radiaktive Damen und Herren…."
- **Problem:** Disappearance of energy in the decay of certain nuclei (beta decays) Lise Meitner experiments



$$ {}^{3}_{1}H \longrightarrow {}^{3}_{2}He + e^{-} + ? $$

Energy and momentum not conserved?



Original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
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

- **Solution:** a new neutral light-weight subatomic particle (undetectable) $n \longrightarrow p + e^{-} + \bar{\nu}_e$
- **1933:** Enrico Fermi proposed his beta decay theory including this particle, the neutrino

Neutrino Discovery

- **1956:** First observation of neutrino interactions by Clyde Cowan and Frederick Reines at the Savannah River Reactor (South Carolina). ~30 years after Pauli's proposal

- **Reaction:** Inverse beta decay with neutrinos from a nuclear reactor

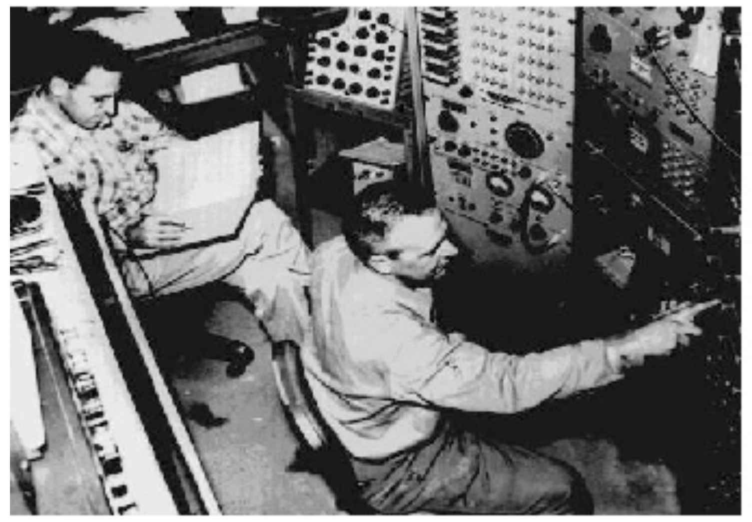
$$p + \bar{\nu}_e \longrightarrow n + e^+$$

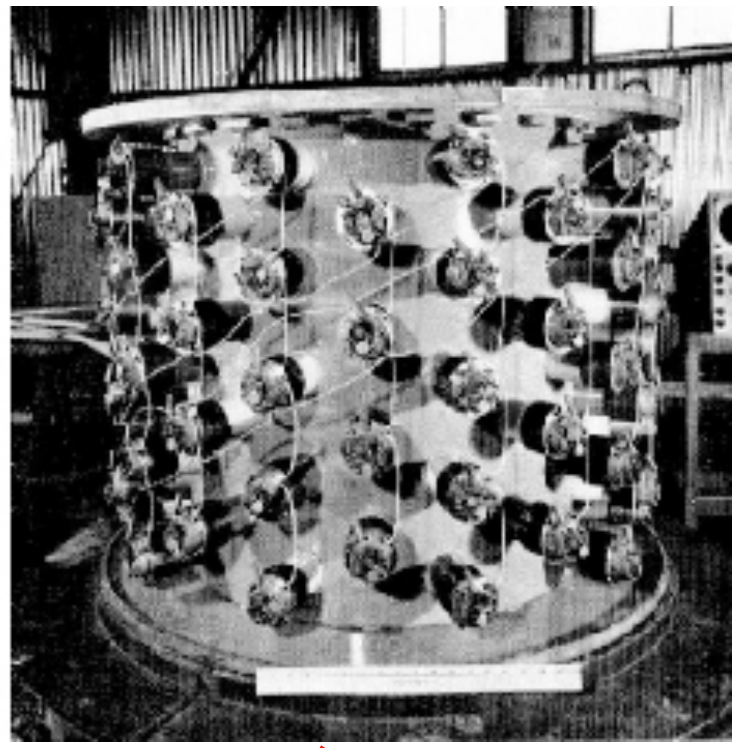
- **Detector:** 400 l water + $CdCl_2$ seen by 90 photodetectors

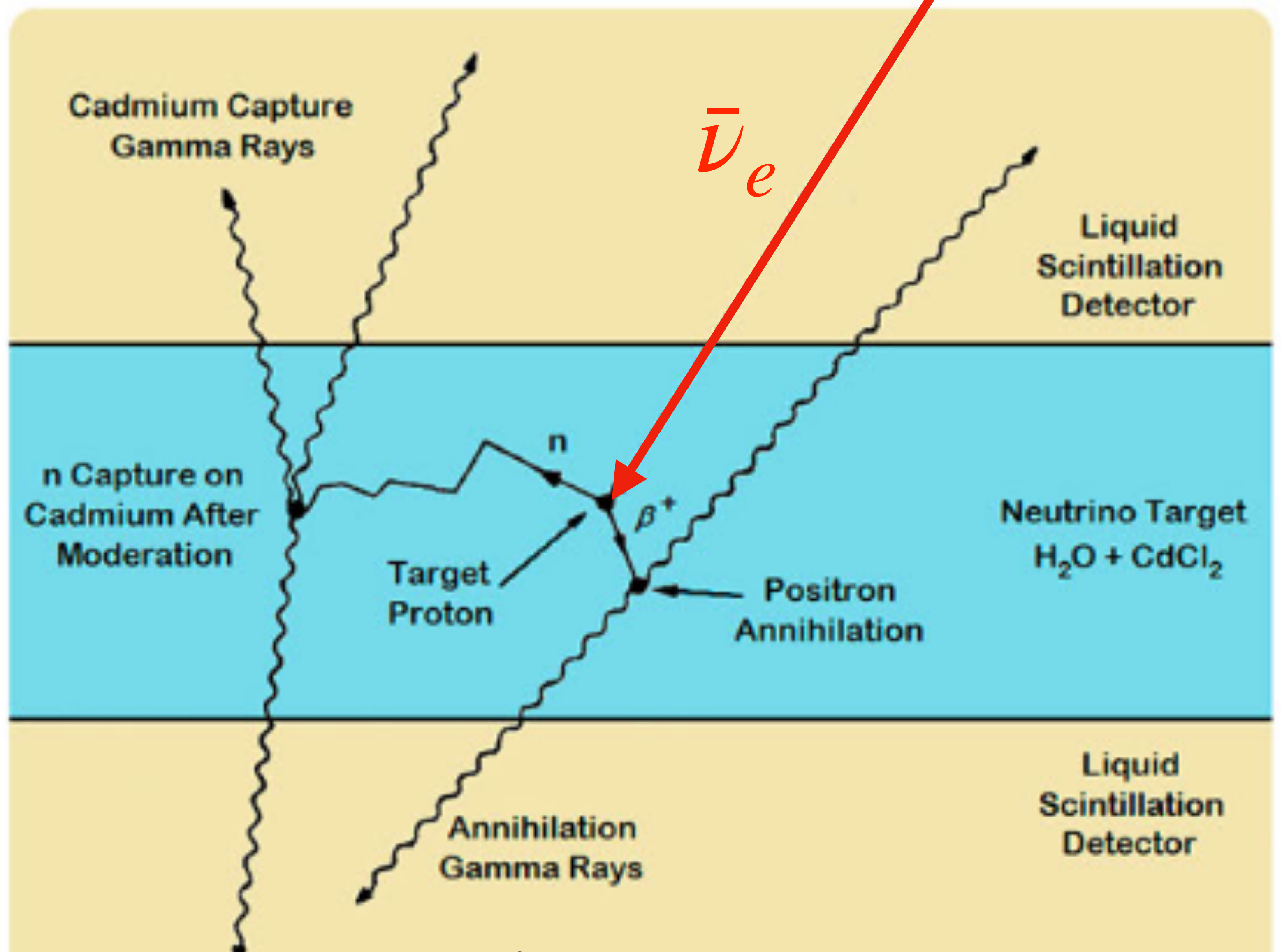
1) prompt signal: $e^+ + e^- \longrightarrow \gamma + \gamma$

2) delayed signal: $n +^{108} Cd \longrightarrow^{109} Cd^* \longrightarrow^{109} Cd + \gamma'$

Signal: delayed (few μs) coincidence reactions





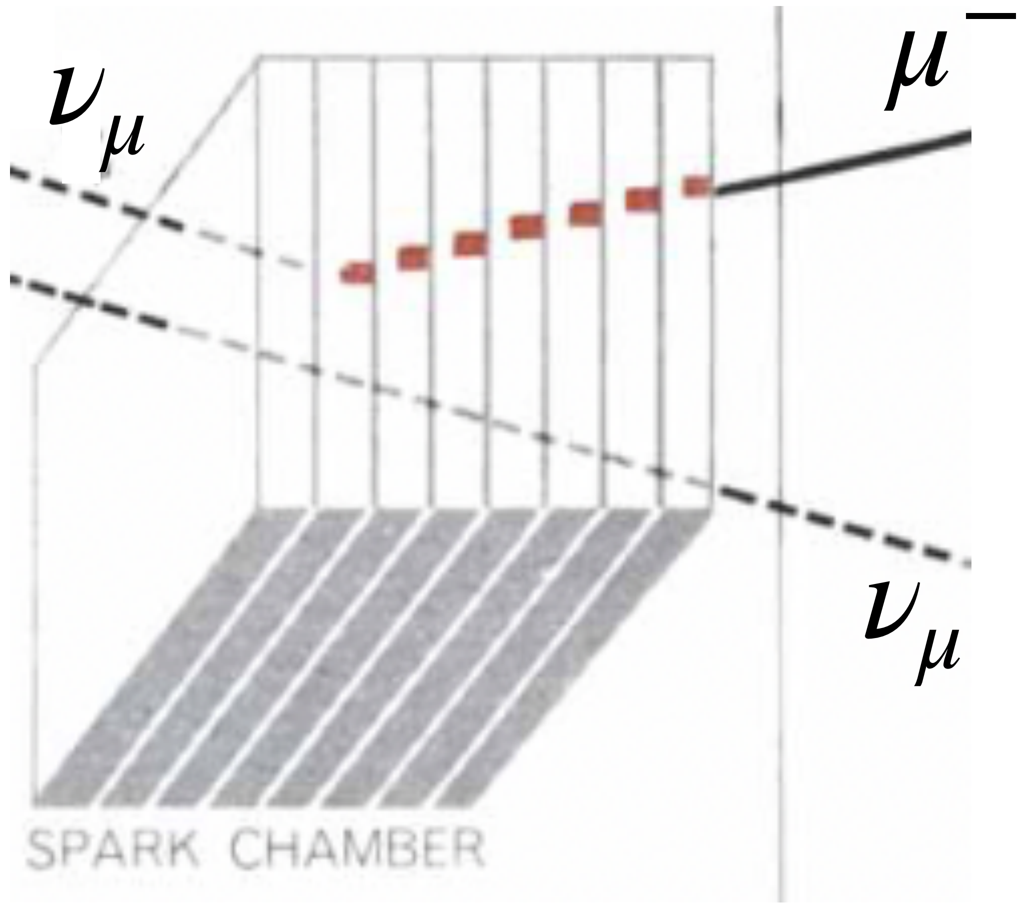


Adapted from Nuclear News December 2020

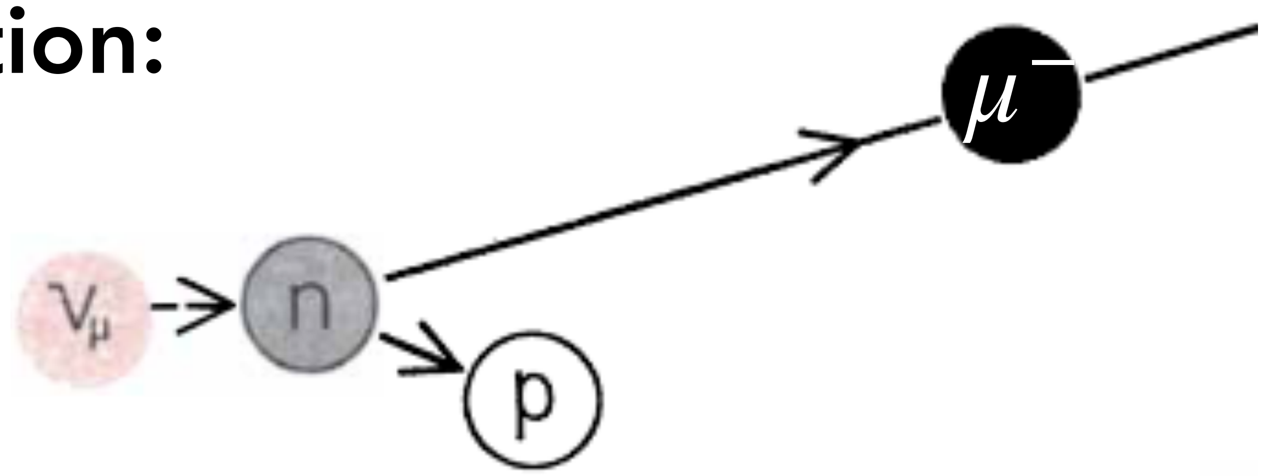
1995: (1/2) Nobel prize to Frederick Reines "for the detection of the neutrino" 

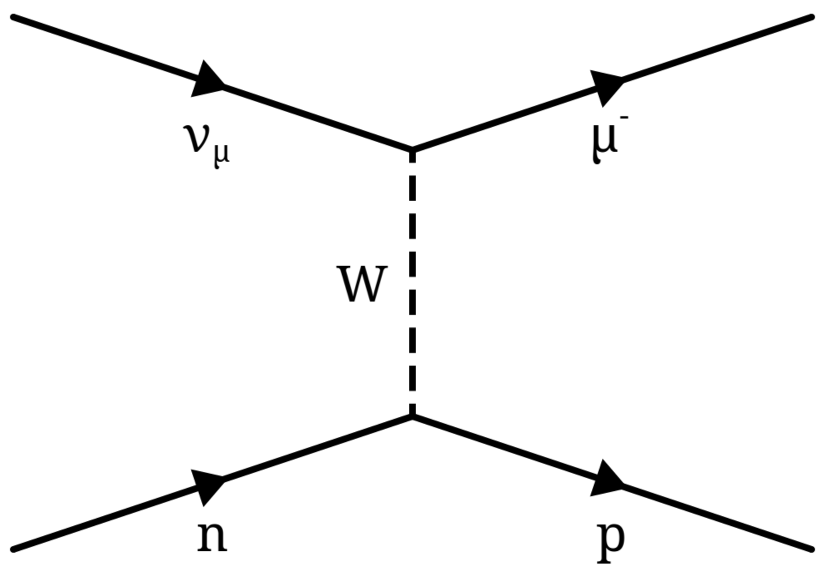
1988: Nobel prize

Discovery of another type of neutrino



- **1962:** Leon Lederman, Melvin Schwartz, and Jack Steinberger found another type of neutrino using the most powerful accelerator in the world at that time
- **Accelerator:** Brookhaven's Alternating Gradient Synchrotron (AGS)
- **Reaction:**

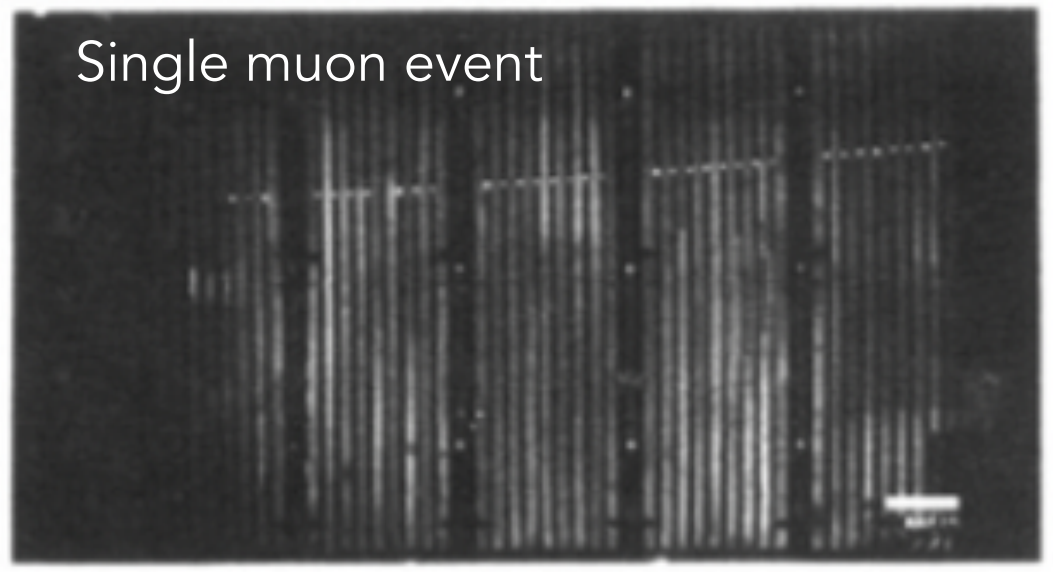




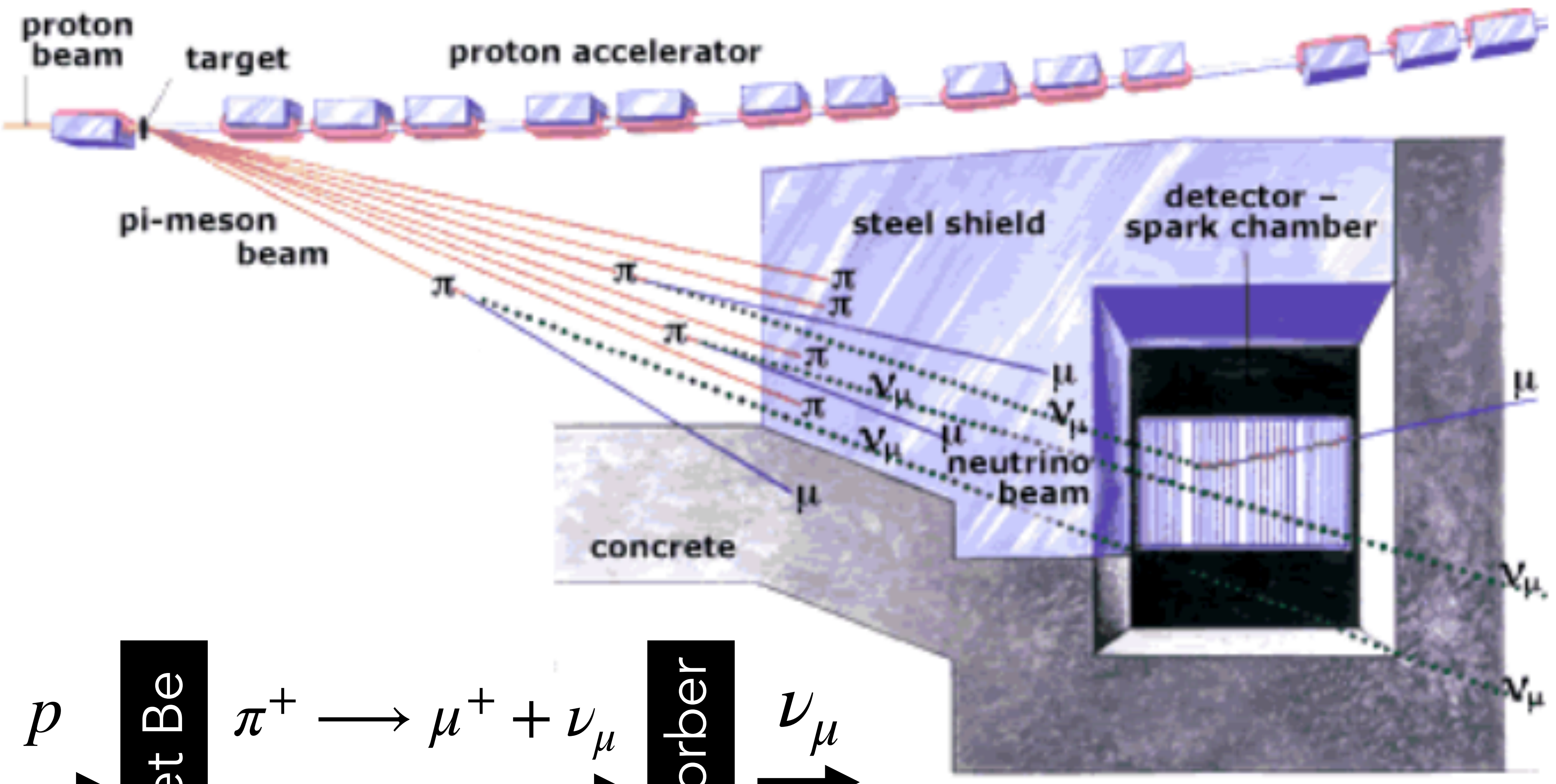
CC interaction

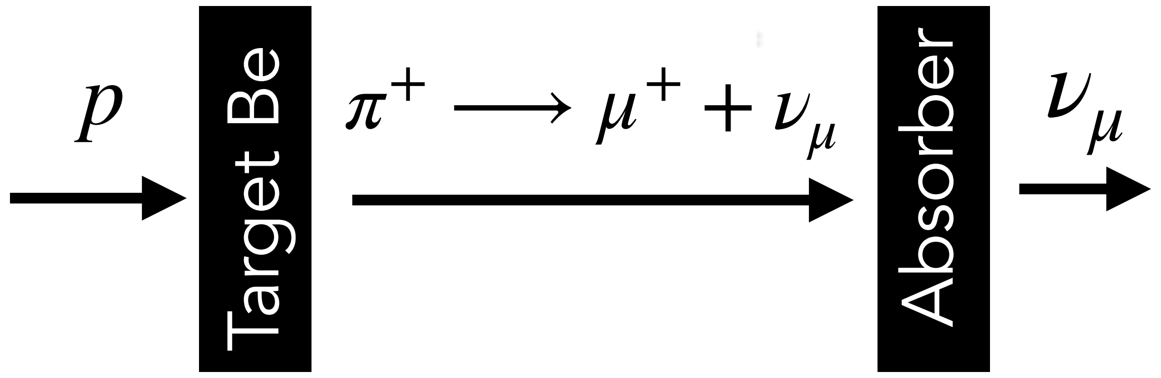
First detection of accelerator neutrinos

- **Detector:** Spark Chamber to observe clear tracks



Electrons produce showers, muons produce clear tracks





Based on a drawing in Scientific American (1963)

Number of light neutrinos: 3

- **1989:** The 4 detectors of LEP (previous to LHC at CERN) determine the number of light neutrino families

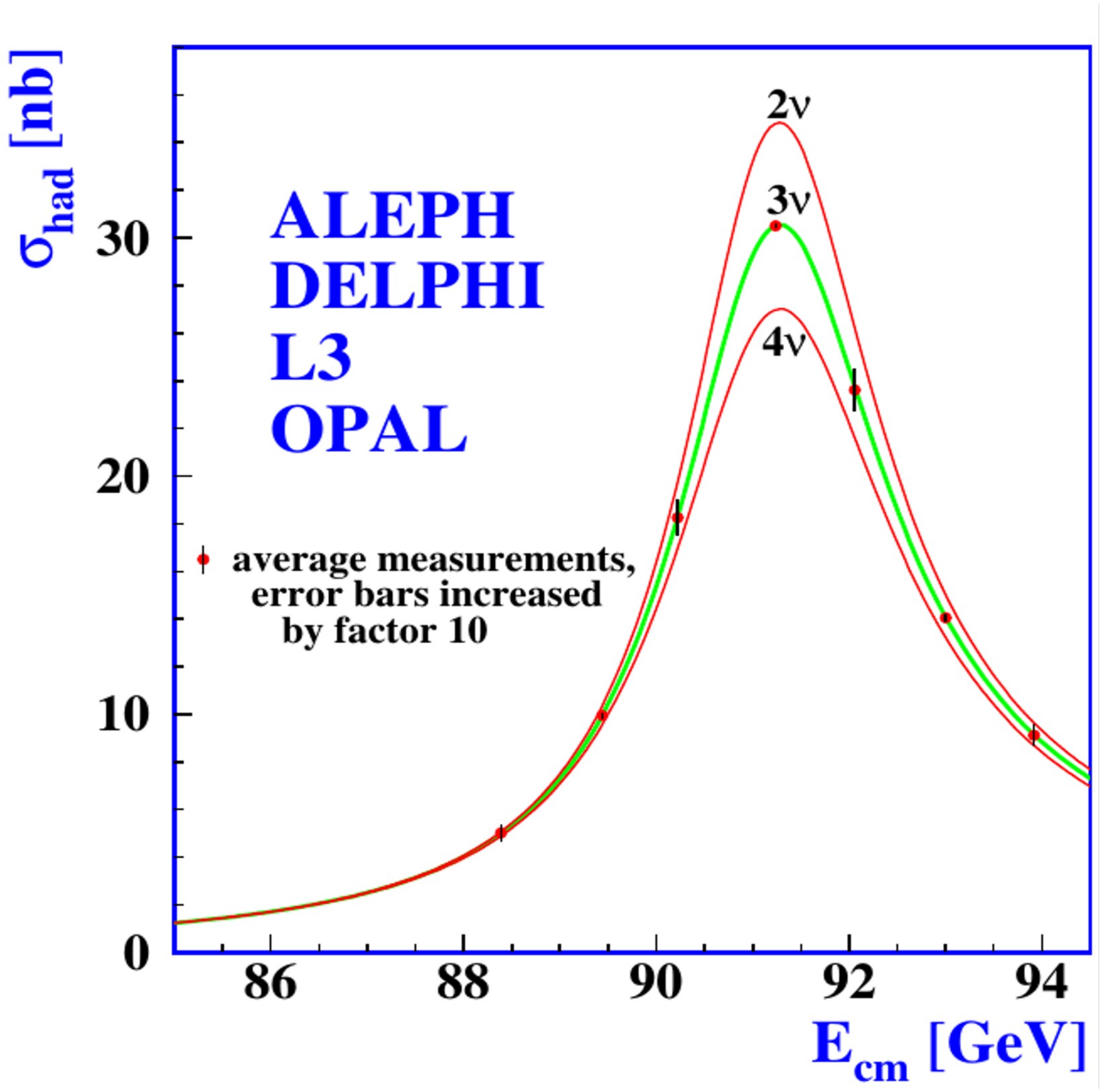
- Unstable particles have an intrinsic uncertainty or (width) in the measurement of their mass. From Heisenberg's principle

- This width, Γ, is proportional to the number of decay modes

$$\Gamma_Z = 3\Gamma_l + \Gamma_h + N_\nu \Gamma_\nu$$

The result at CERN was:

$$N_\nu = 2.984 \pm 0.008$$



Γ_z is ~2.5 GeV

20% of the times decay to neutrinos

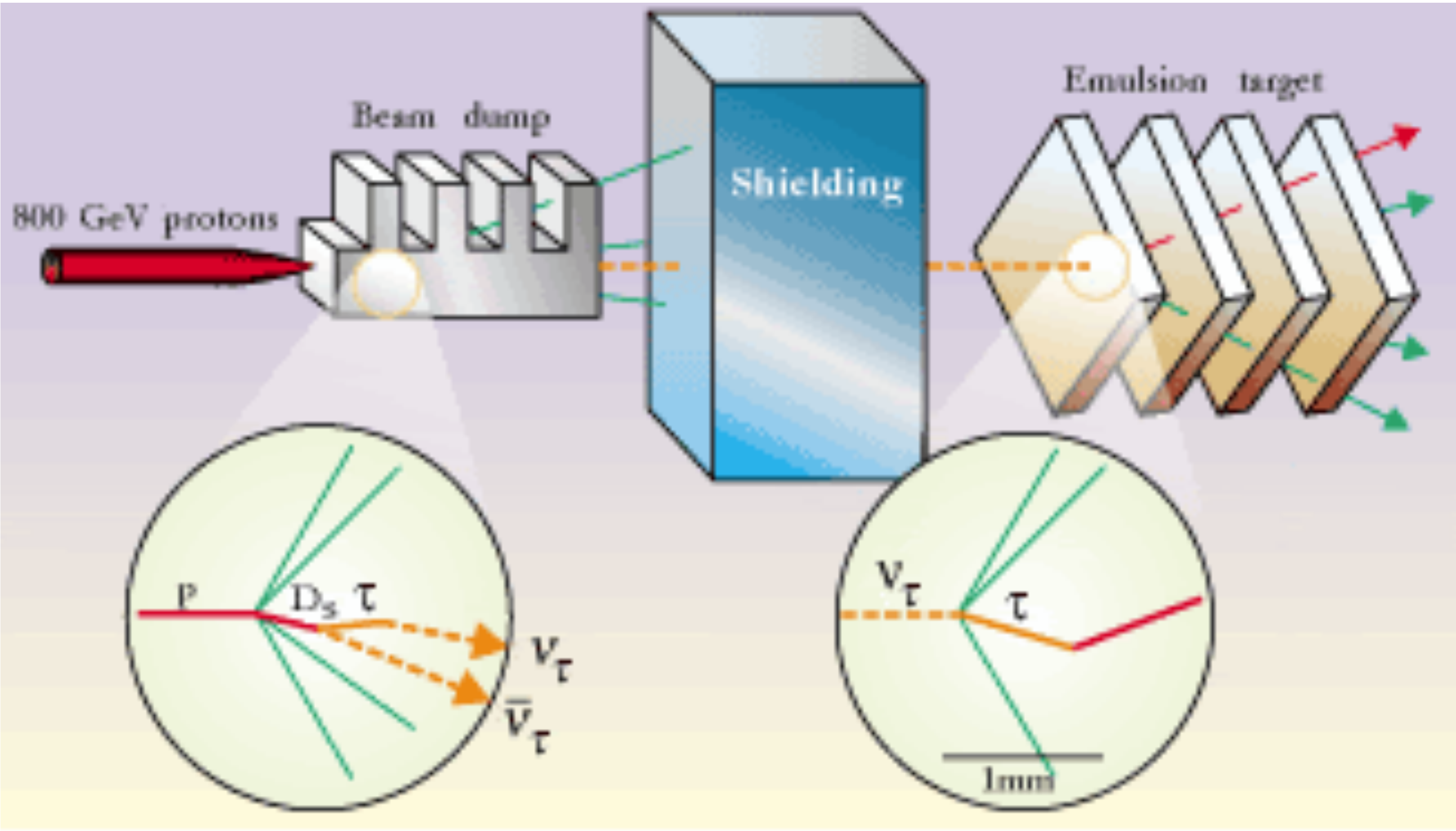
Only three lights and active neutrinos

Very heavy neutrinos?

Sterile neutrinos?

Direct observation of the tau neutrino

Protons produced at Tevatron



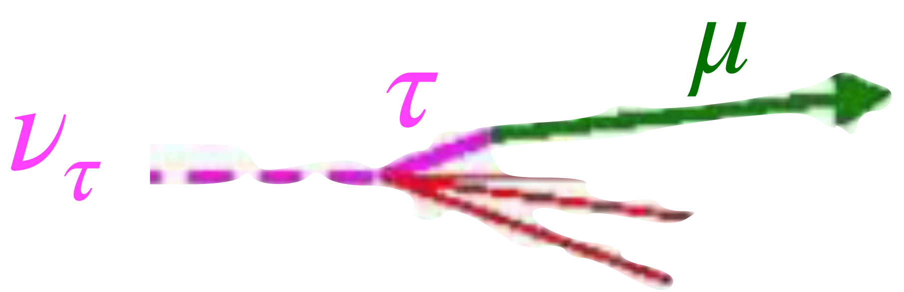
- **2000:** DONUT experiment at Fermilab

  Direct **O**bservation of **NU T**au

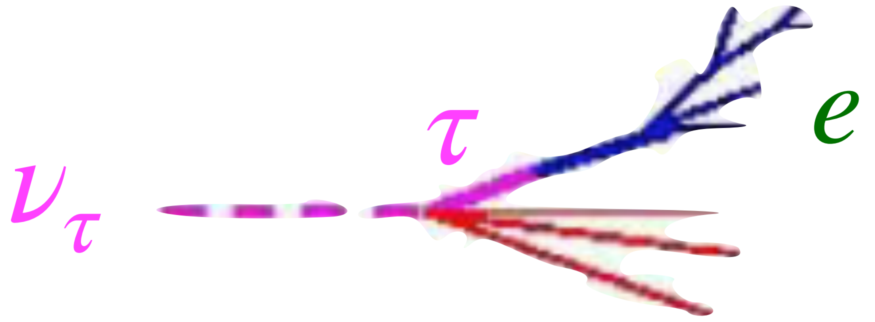
  DONUT

- A crucial piece of the neutrino puzzle was missing for some time
- "It's simply been accepted that this guy exists" said few senior scientist of the DONUT collaboration at the time

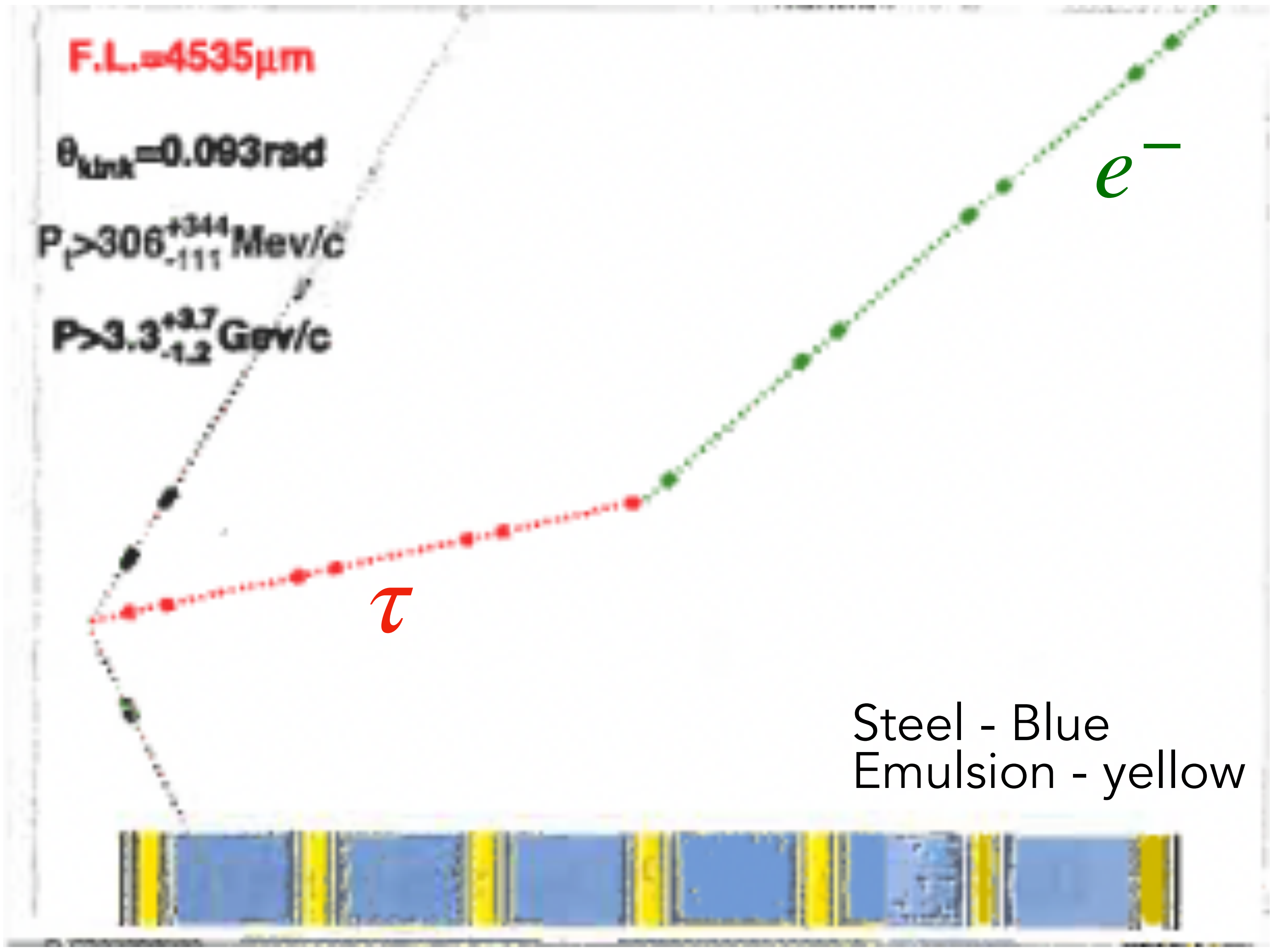
Tau neutrino interactions are more difficult to observe, for the short lifetime of the tau lepton (2.9 x10^{-13} s)



$$\tau^- = \mu^- + \bar{\nu}_\mu + \nu_\tau$$ ~18%



$$\tau^- = e^- + \bar{\nu}_e + \nu_\tau$$ ~18%

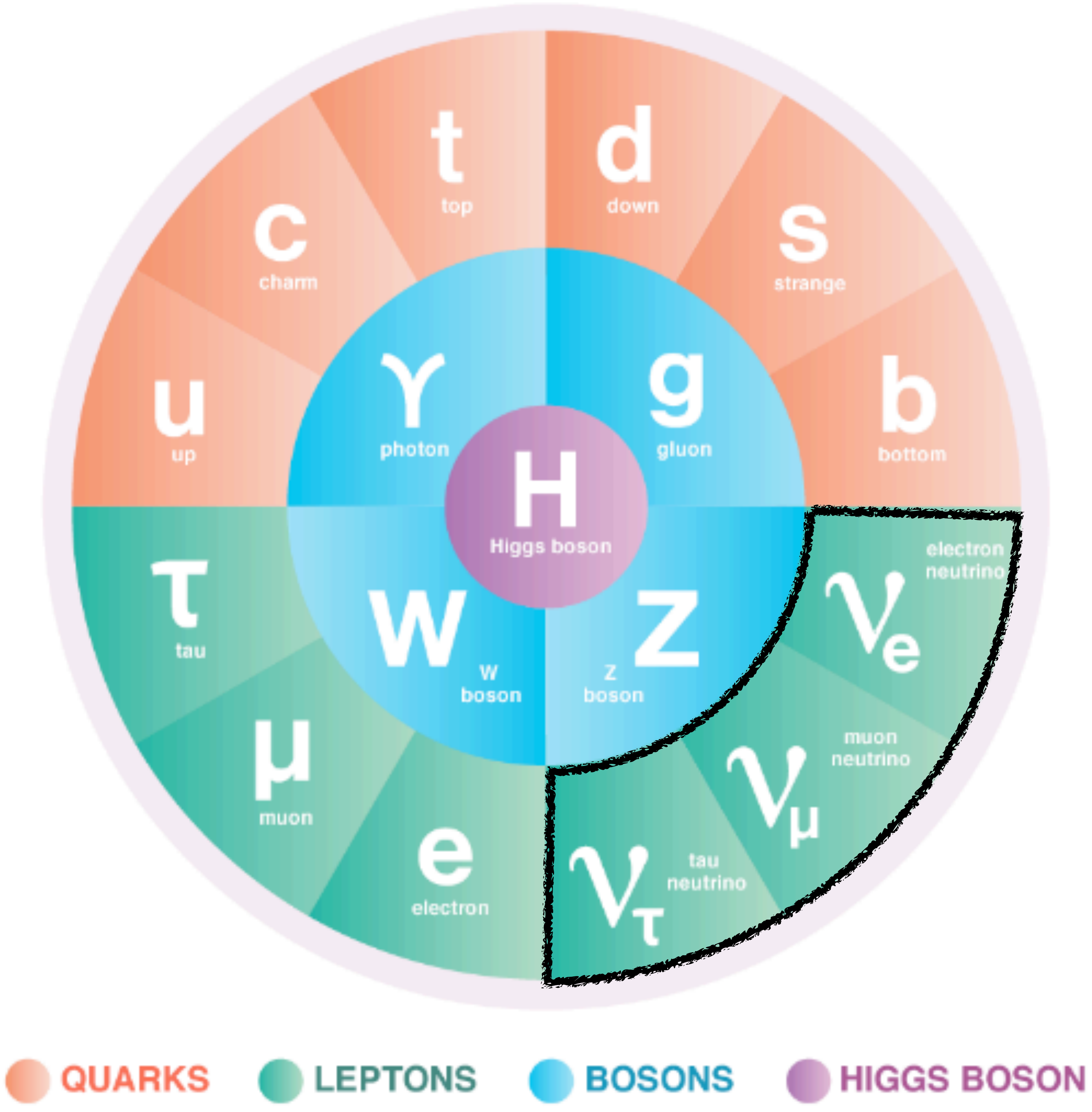


Neutrinos in the Standard Model

Particles of the Standard Model (SM)

- Standard Model leptons
- Neutral charge
- 3 neutrino flavours
- Spin 1/2
- Weak interaction (and gravitational)

In the SM the lepton number is conserved and neutrinos are massless



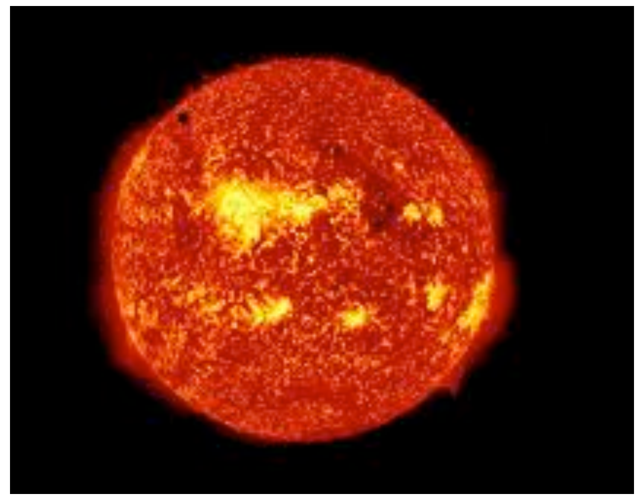
symmetrymagazine.org

Neutrino sources

- There are many known neutrino sources


Reactors

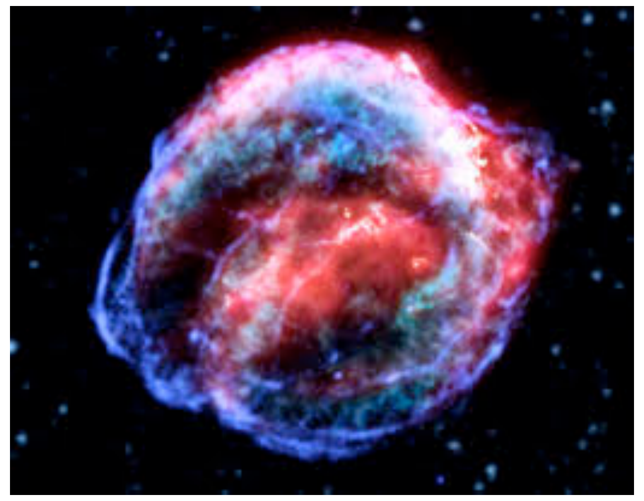

Accelerators


Sun


Atmospheric


Terrestrial


Extra- & Galactic


Supernova

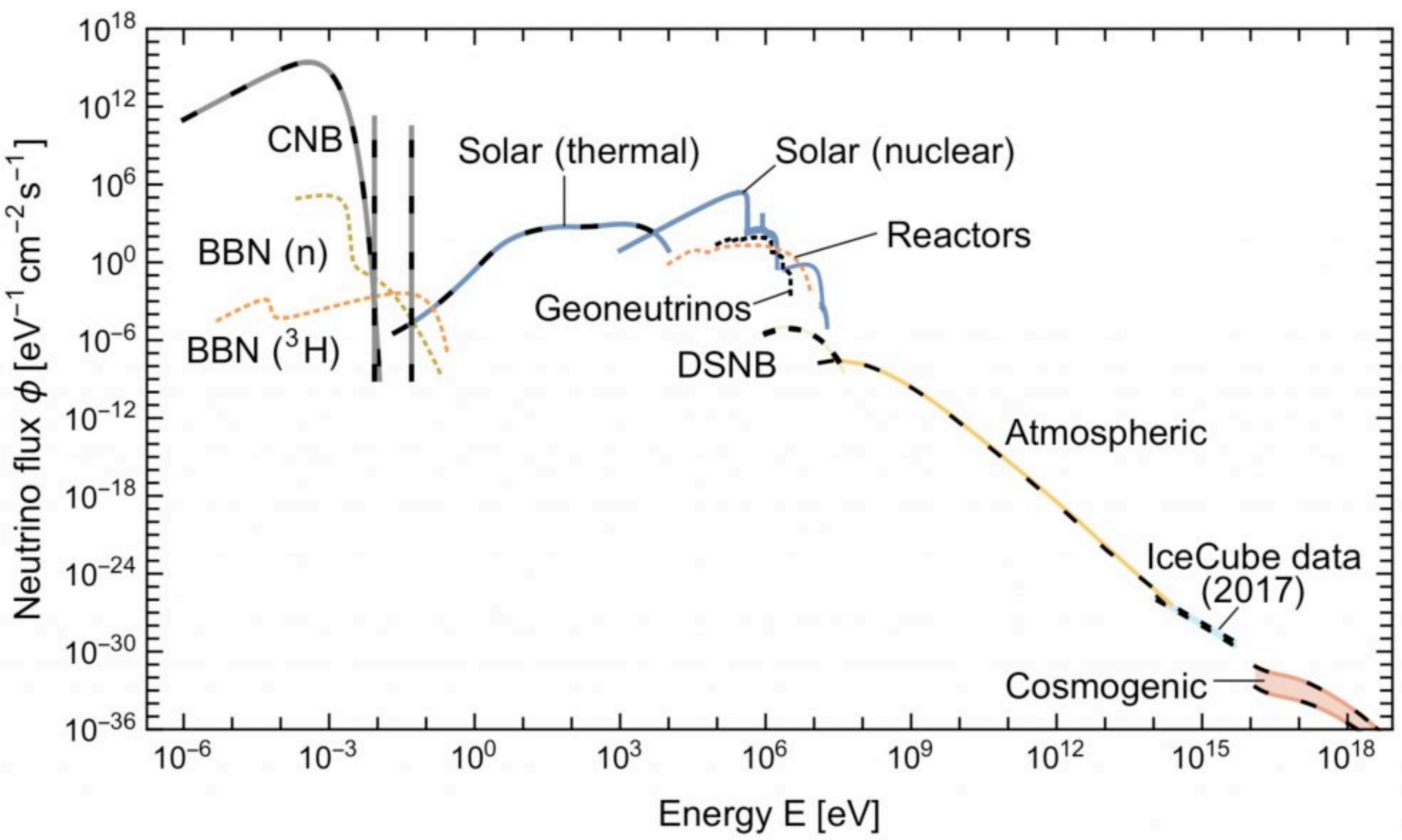

Big Bang

Source	Neutrino Type
Reactor	$\bar{\nu}_e$
Accelerator	$\nu_\mu \ \bar{\nu}_\mu$
Sun	ν_e
Atmospheric	$\nu_\mu \ \bar{\nu}_\mu \ \nu_e \ \bar{\nu}_e$
Terrestial	$\bar{\nu}_e$
Extra-Galactic	$\nu_\mu \ \bar{\nu}_\mu \ \nu_e \ \bar{\nu}_e$
Supernova	$\nu_e \ \bar{\nu}_e \ \nu_\mu \ \bar{\nu}_\mu \ \nu_\tau \ \bar{\nu}_\tau$
BigBang	$\nu_e \ \bar{\nu}_e \ \nu_\mu \ \bar{\nu}_\mu \ \nu_\tau \ \bar{\nu}_\tau$

as produced in the source

Neutrino energy spectrum

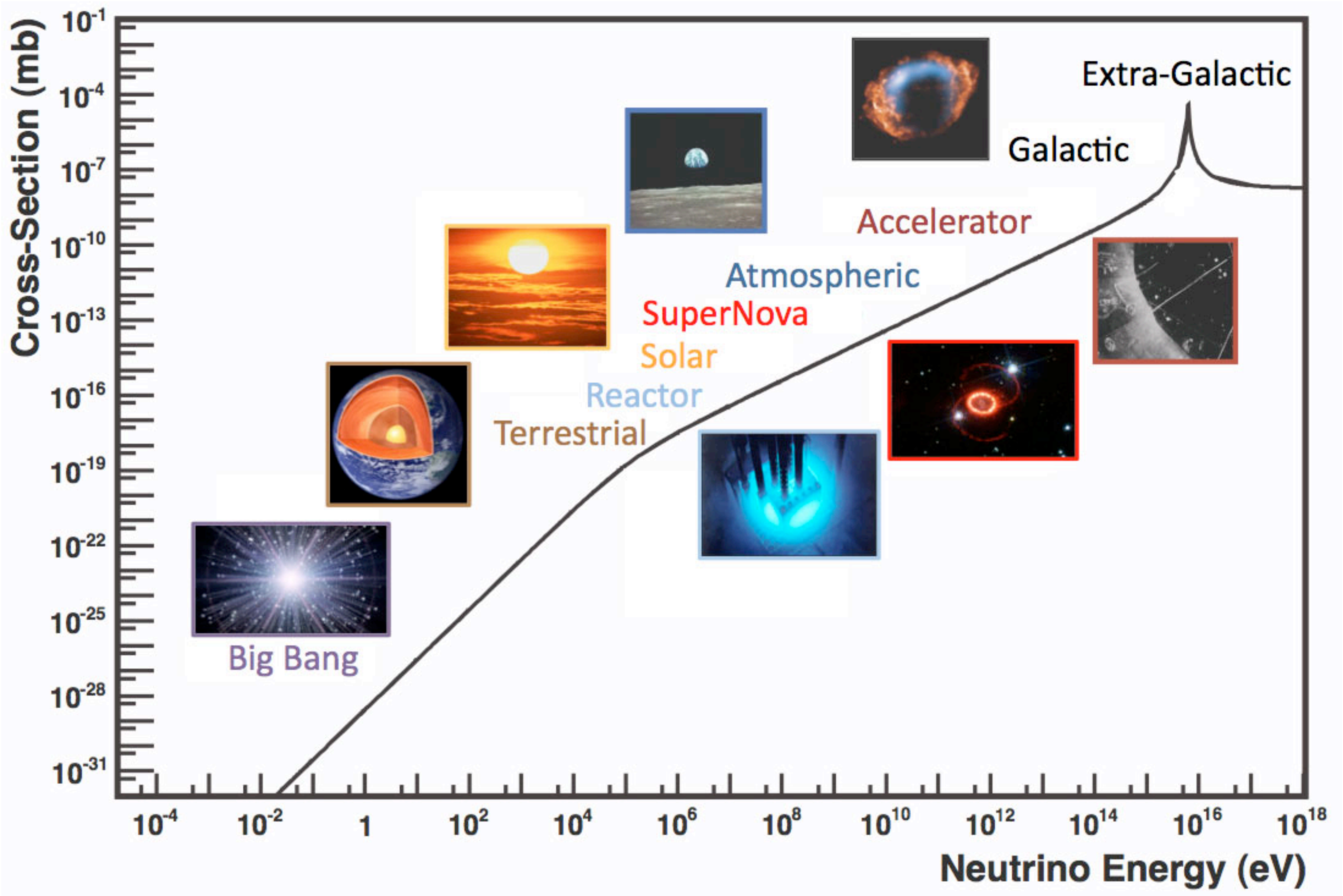
- Covering an energy range that extends over more than 20 orders of magnitude



Rev. Mod. Phys. 92 (2020) 45006

Neutrino interaction cross-section

- Interaction very very weakly



Cross-section: indication of likelihood of two interacting particles

$$1mb = 10^{-31}cm^2$$

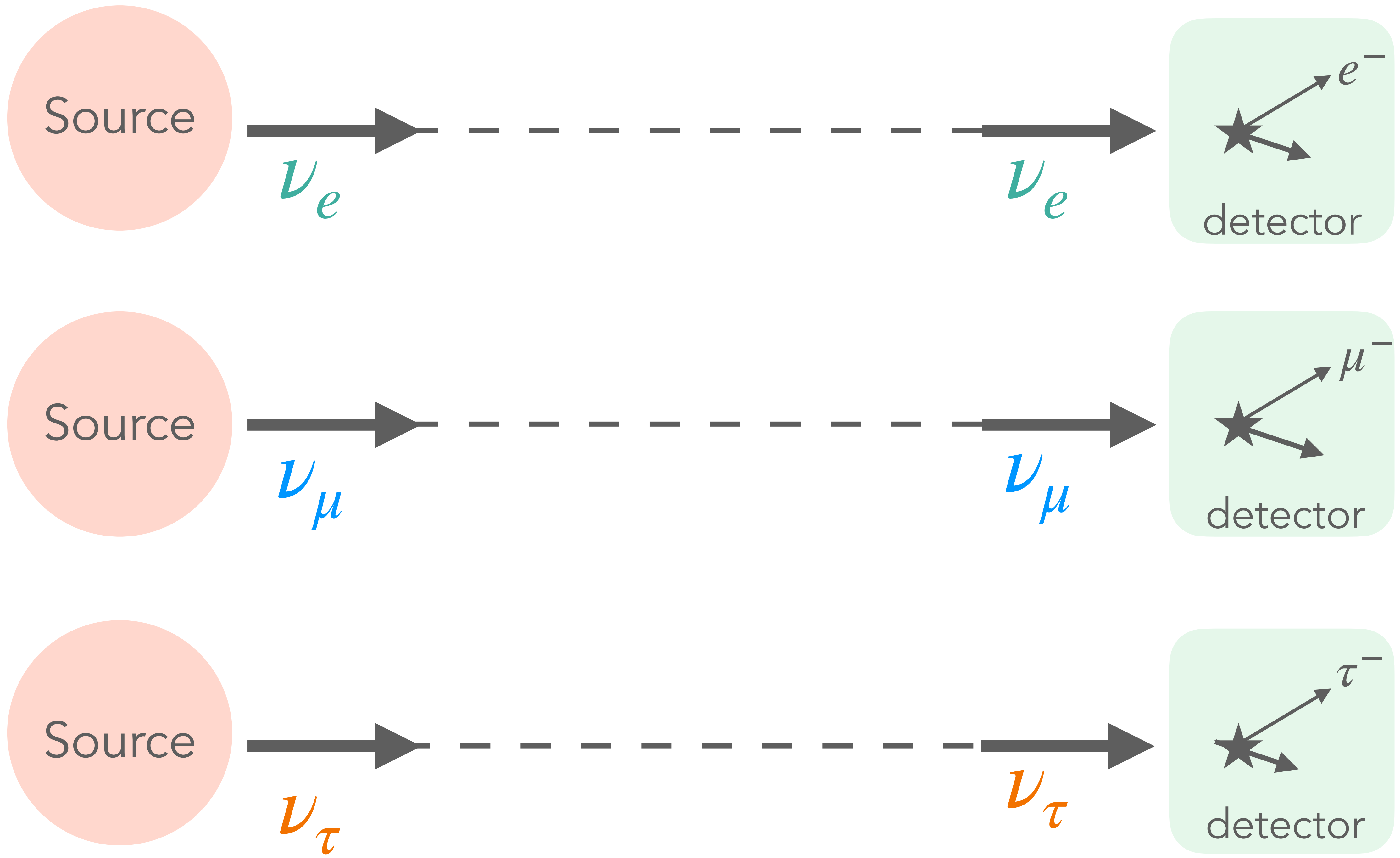
Example:

The cross-section of a 10 MeV photon interacting with an atom is 1b

Neutrinos: evidence of physics beyond the SM

the only experimental evidence

According to the SM neutrinos come in 3 flavours and can be detected through the corresponding lepton



However, if the journey is long enough, the situation can be different

Neutrinos oscillate among flavours

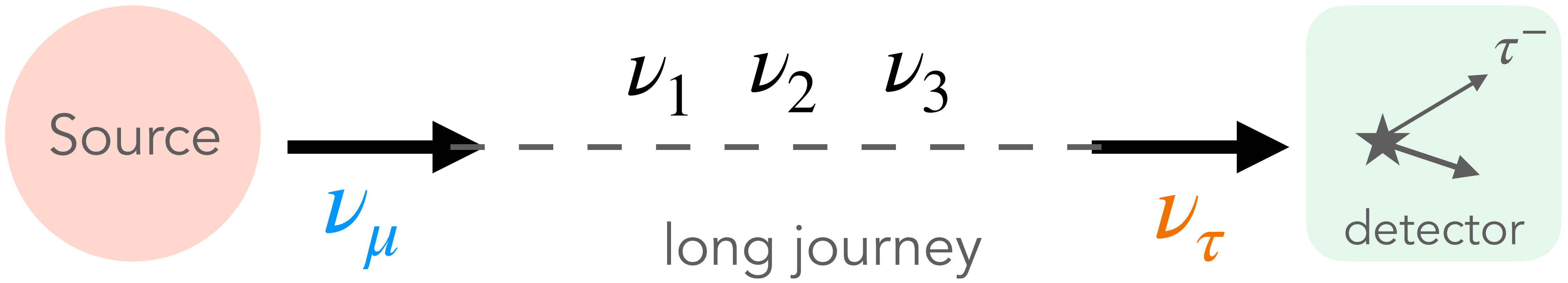
⇩

Non-zero masses

Laura Baudis, Fermilab Talk 2020

Neutrino Oscillations

Neutrino oscillations: theory



- Neutrinos produced/detected as defined flavour states: ν_e ν_μ ν_τ
- Neutrinos propagates as defined mass states: ν_1 ν_2 ν_3
- Flavour and mass states related by a **mixing matrix**
- Determined by: **3 mixing angles and 1 CP violating phase**

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (1962)

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

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

data from atmospheric + accelerator neutrinos

data from reactor neutrinos

data from solar neutrinos

Oscillation probability for three flavours

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

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

Neutrino oscillations described by 6 oscillation parameters

$$\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{21}, \Delta m^2_{31}, \delta_{CP}$$

Depending on L and E, different experiments will be sensitive to a different set of parameters

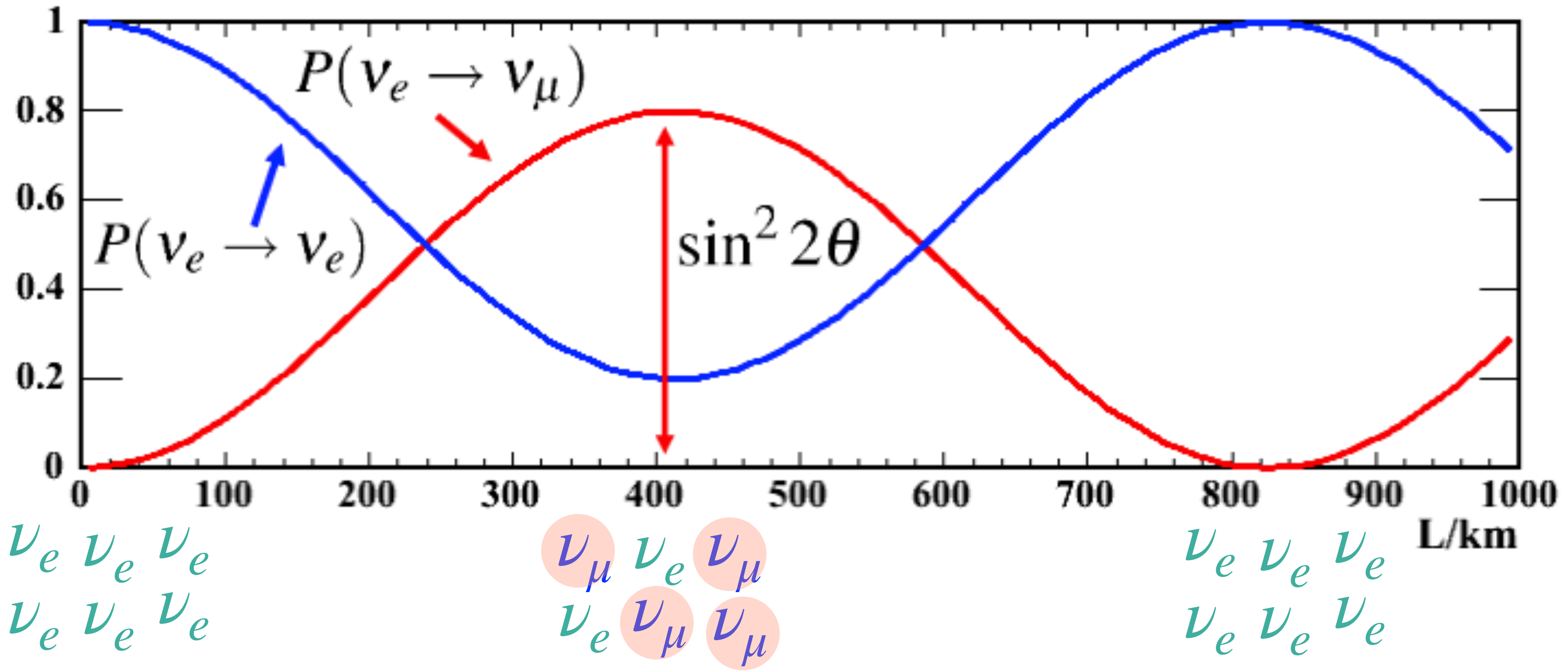


Illustration for two flavour mixing

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

$$P(\nu_e \to \nu_e) = 1 - P(\nu_e \to \nu_\mu)$$

$\Delta m^2_{21} = 0.003eV$ $\quad sin^2\theta = 0.8$ $\quad E = 1GeV$

Oscillation probability for three flavours

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

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

Neutrino oscillations described by … parameters

NEUTRINOS DO HAVE A NON-ZERO MASS

Depending on L and E, diff… …ents will be sensitive to a different set of parameters

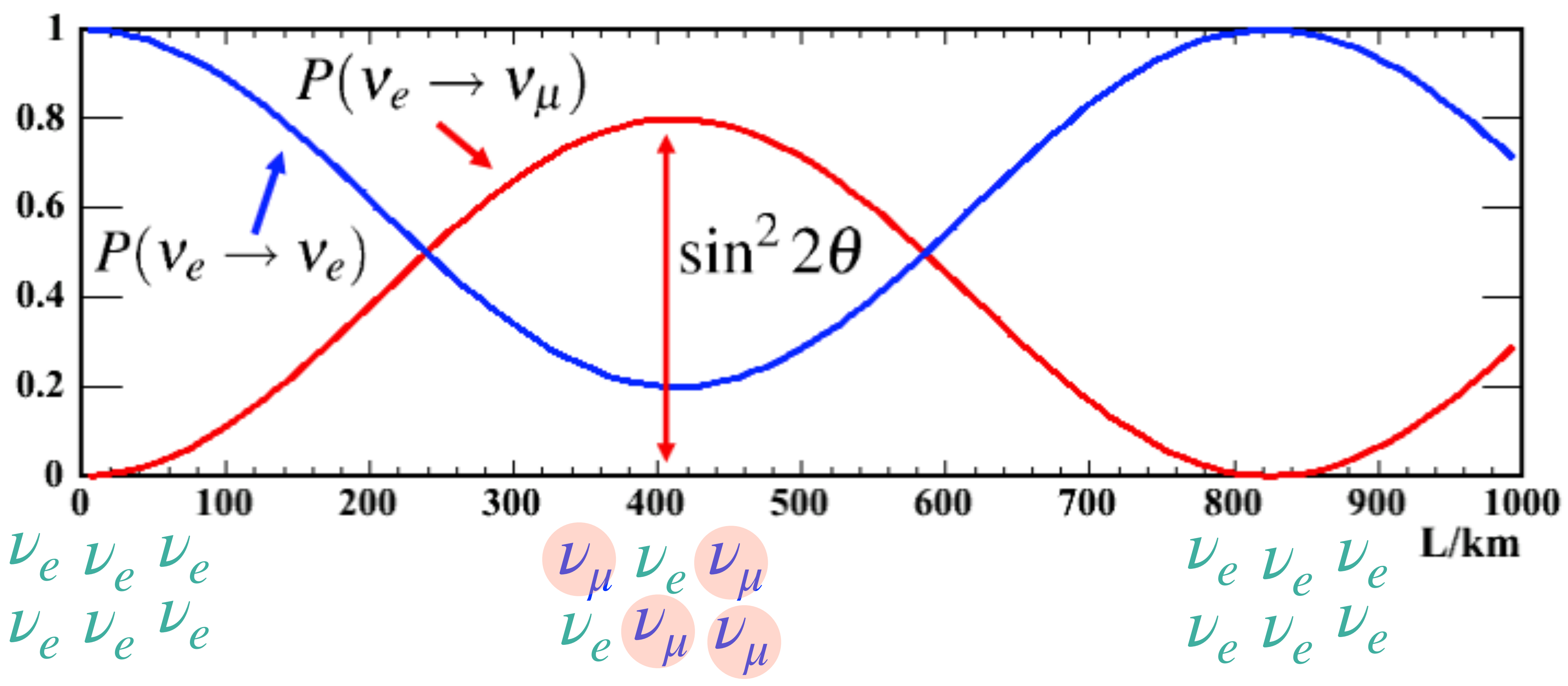


Illustration for two flavour mixing

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

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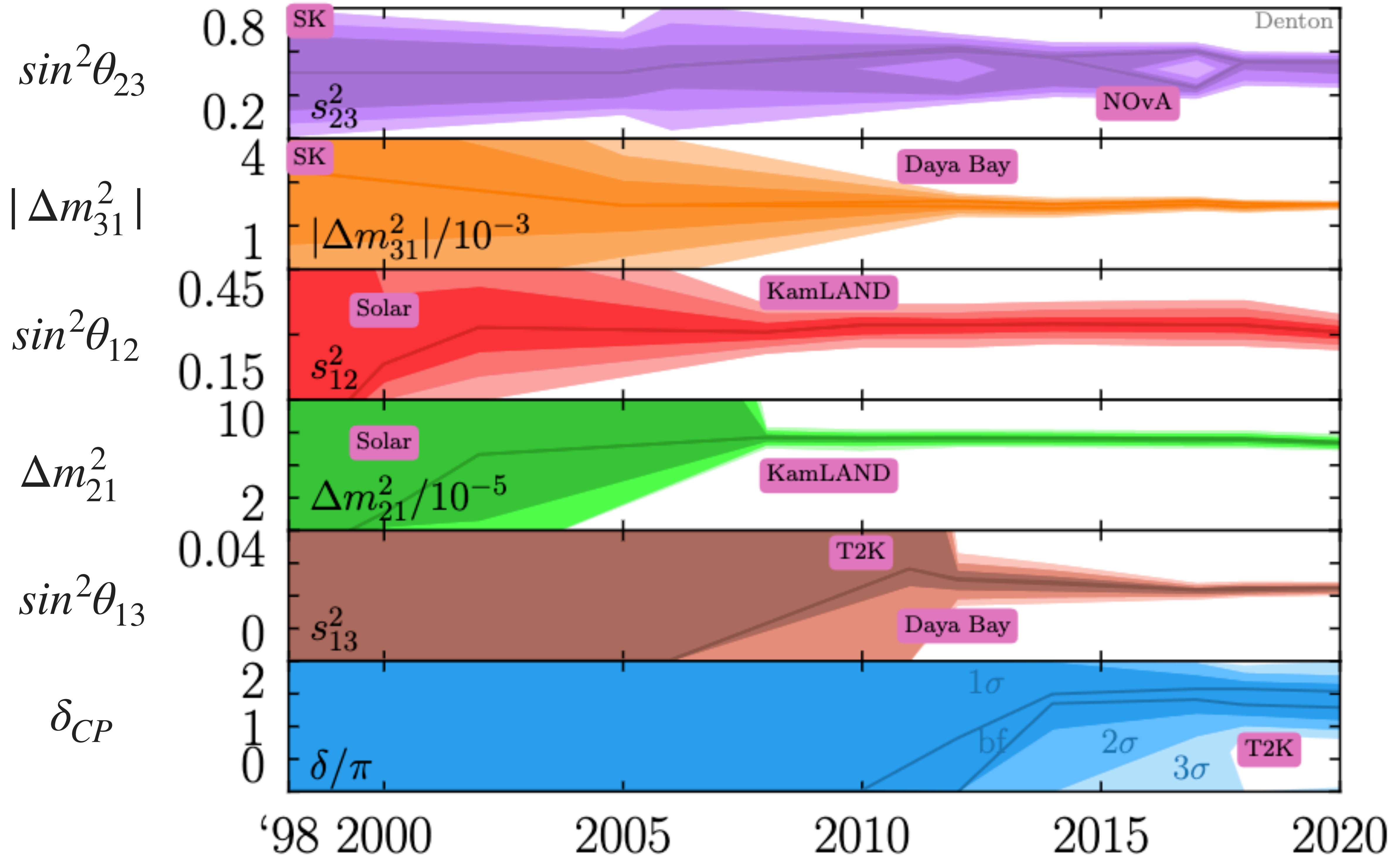
$\Delta m^2_{21} = 0.003eV$ $\quad sin^2\theta = 0.8$ $\quad E = 1GeV$

Knowledge on oscillation parameters

P. Denton, arXiv:2212.00809



M. Tortola, Neutrino2024

parameter	best fit $\pm 1\sigma$	3σ range	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	**2.7 %**
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	**1.0 %**
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (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	**5.4%**
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	**3-4%**
$\sin^2\theta_{23}/10^{-1}$ (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	**2.6%**
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38	
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	**10-15%**
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87	

Global fit

Known parameters: $\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{31}|$

Unknown parameters: Mass ordering (sign of Δm^2_{31}) and δ_{CP}

The unknown parameters and their implications

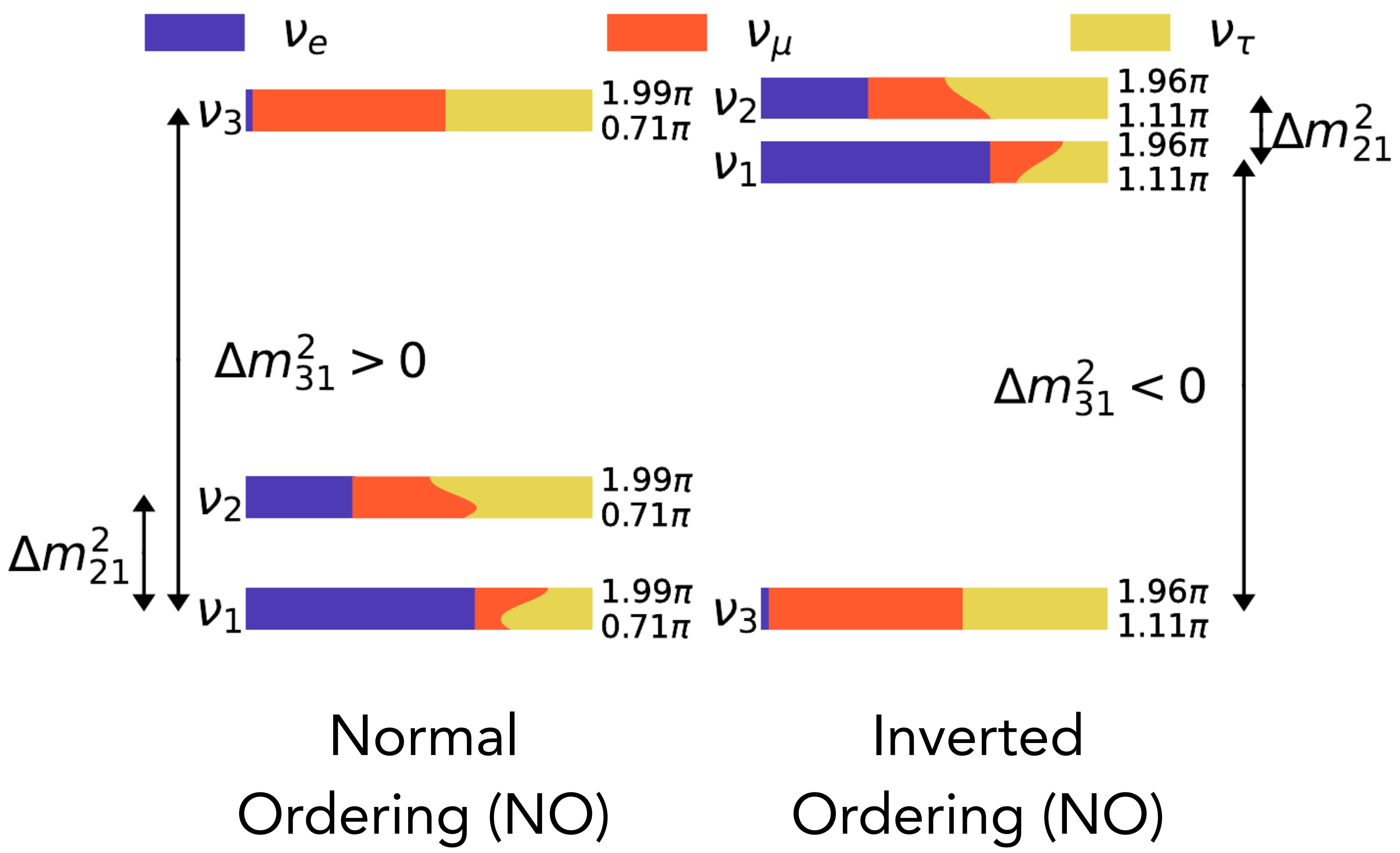
Unknown parameters: Mass ordering (sign of Δm^2_{31}) and δ_{CP}

- Neutrinos have mass. What are value of the masses?
- What is the mass ordering?
- What is the origin the small neutrino masses?

  The mass scale of neutrinos is very different from other particles in the SM. This points to physics beyond the SM

- Is the CP phase non-zero? What is its value?

  Do neutrinos and antineutrinos behave in the same way?



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

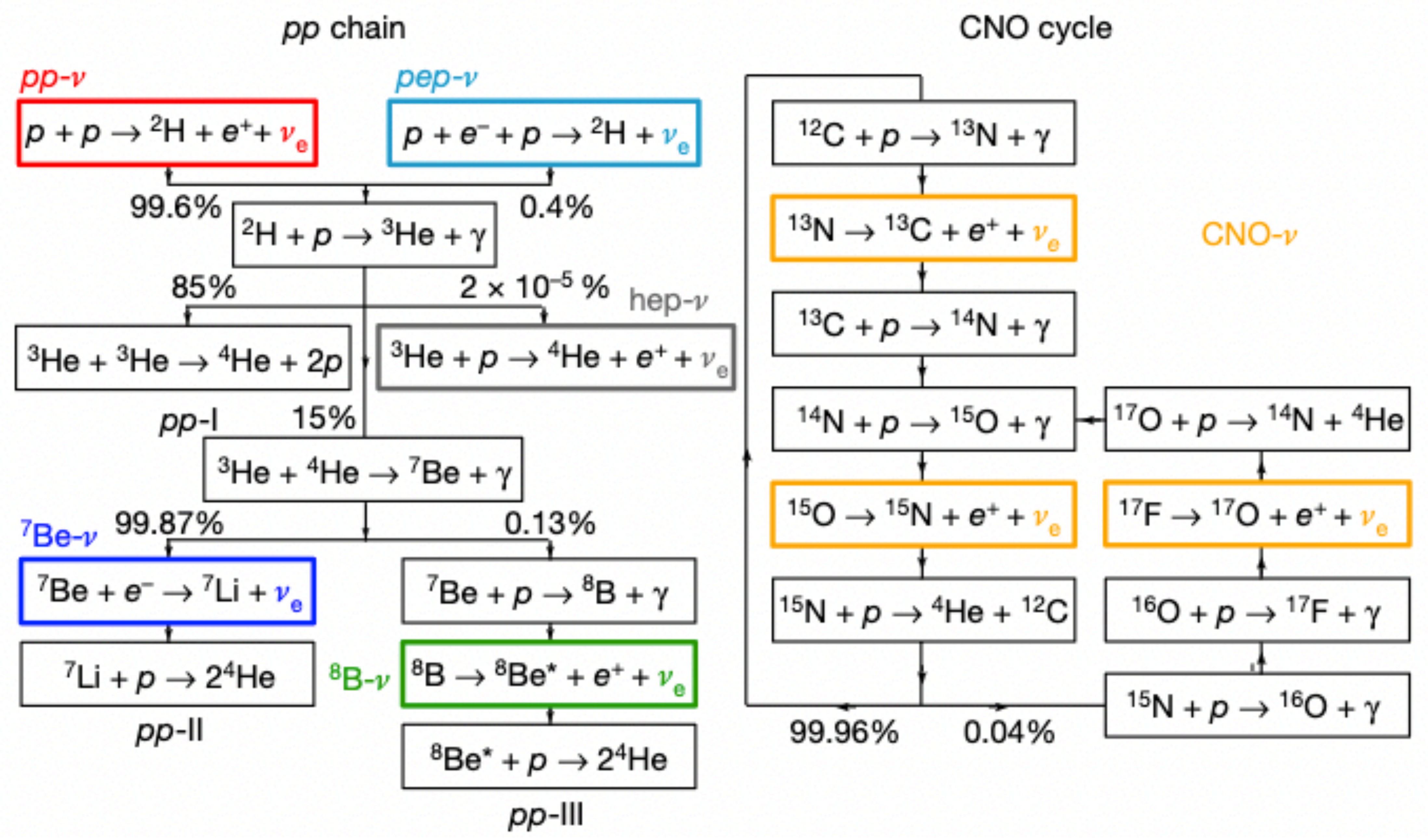
$$|\Delta m^2_{32}| \approx |\Delta m^2_{31}|$$

How it all began…

The solar neutrino problem and its final interpretation

Solar Neutrinos

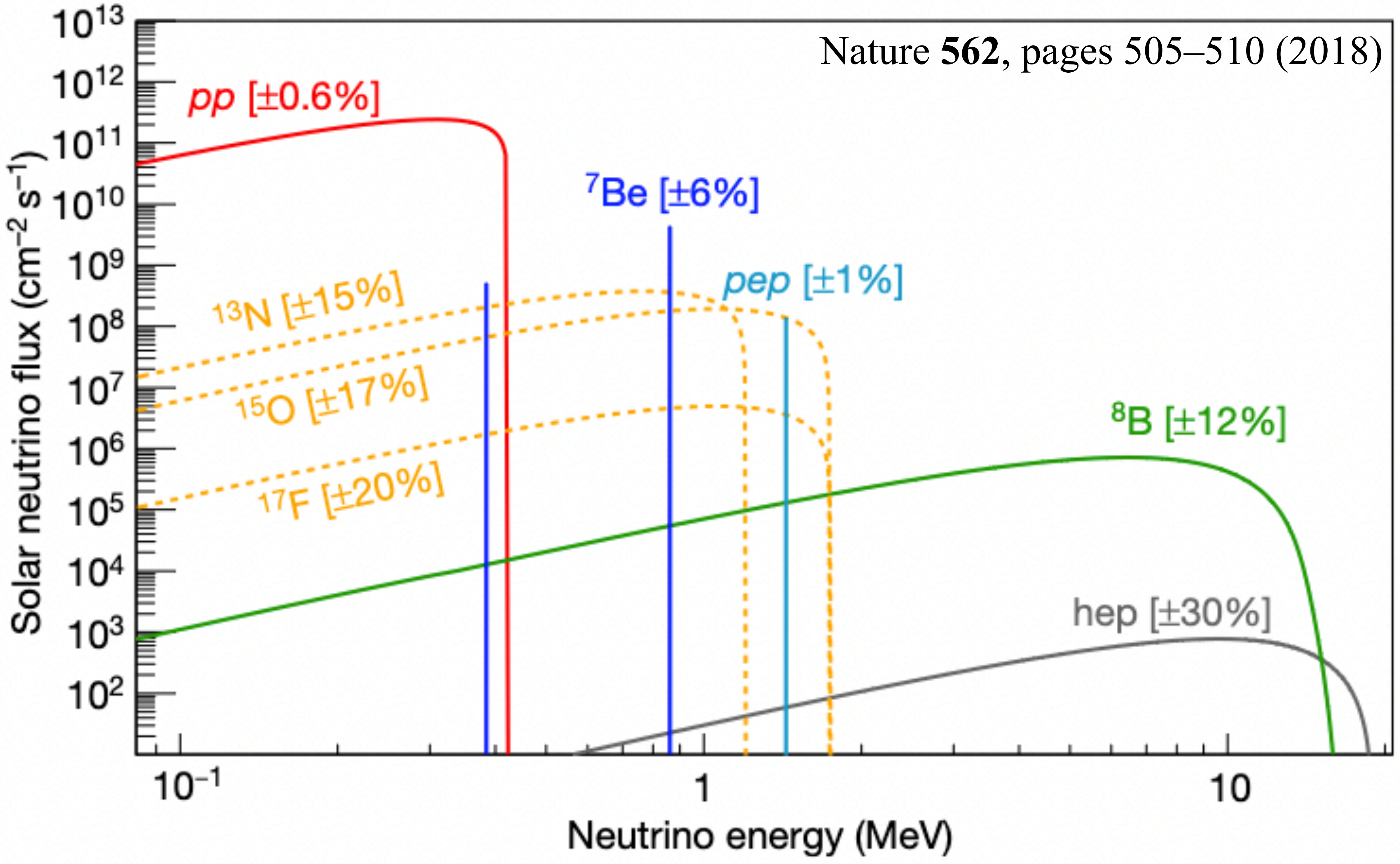
- Nuclear fusion in the Sun produces a large flux of ν_e



Flux: 6×10^{10} neutrinos/cm^2/s

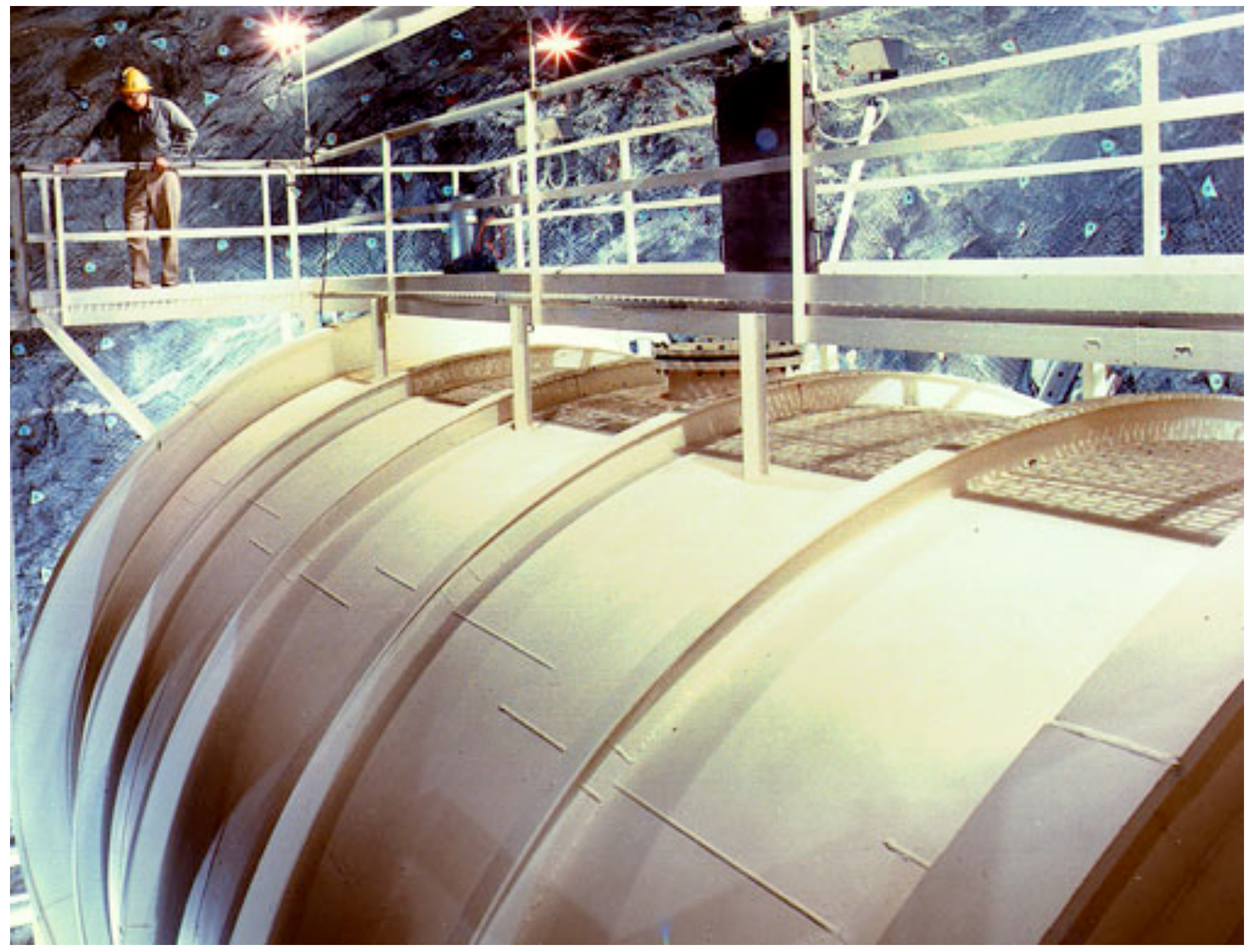
Only tool to probe the Sun's core

- **Spectrum:** according to the standard solar model (SSM)



Dominated by pp-neutrinos at low energies and by ^{8}B-neutrinos at higher values

Solar Neutrino Problem: Homestake



- **1968:** Raymon Davis proposed an experiment to detect solar neutrinos (ν_e)

  Homestake Experiment (1970 - 1994)

- **Detector:** 615 tons C_2Cl_4 (dry cleaning fluid) + 1478 m underground

- **Reaction:** Inverse beta decay (neutrino induced)

$$^{37}Cl + \nu_e \longrightarrow ^{37}Ar + e^-$$

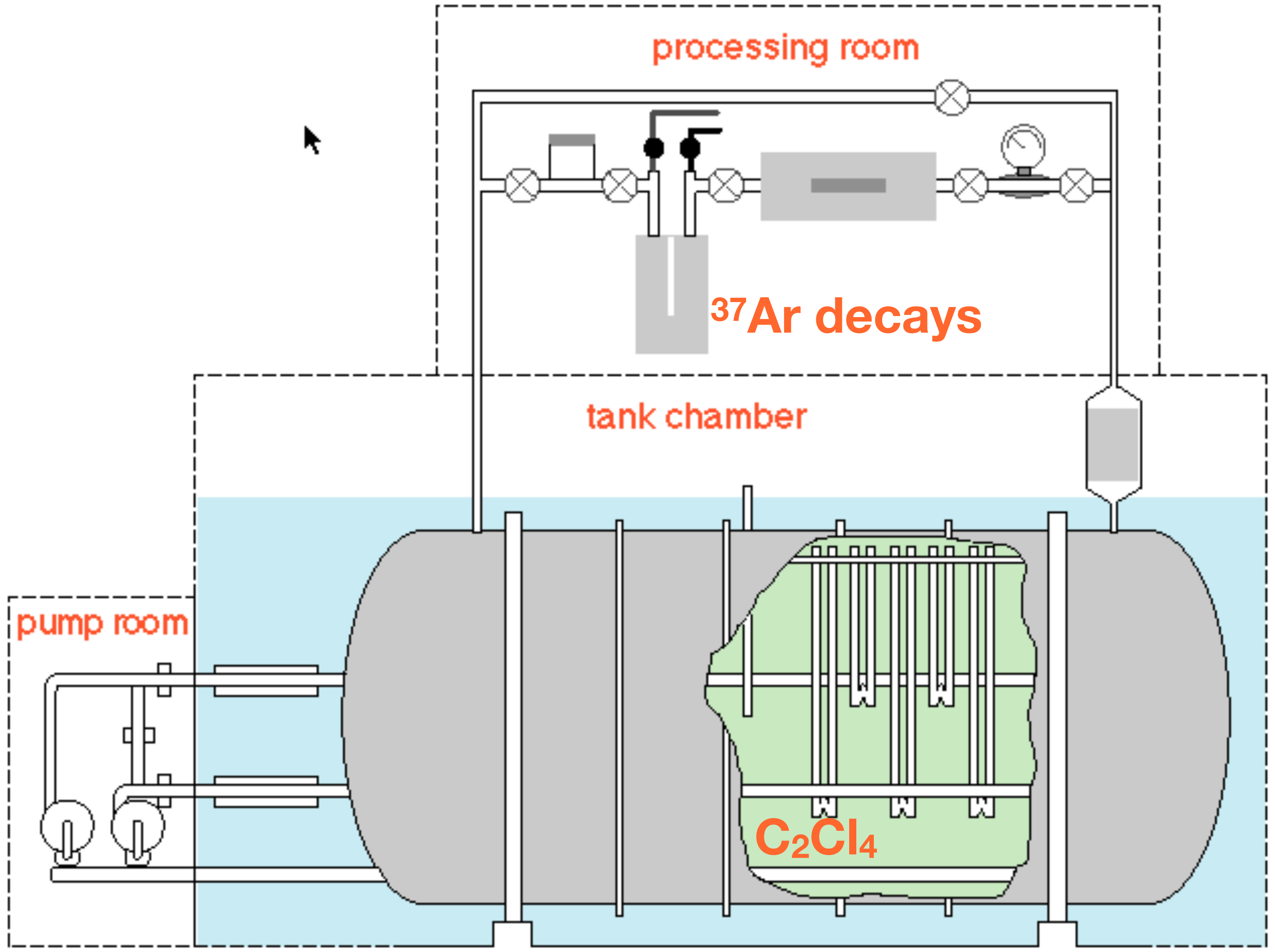
- **Energy Threshold:** 0.814 MeV (mainly ^8B neutrinos)

- **Signal:** ^{37}Ar decays by e^- capture to ^{37}Cl with half-life of 35 d

  ^{37}Ar recover by flushing He through the tank

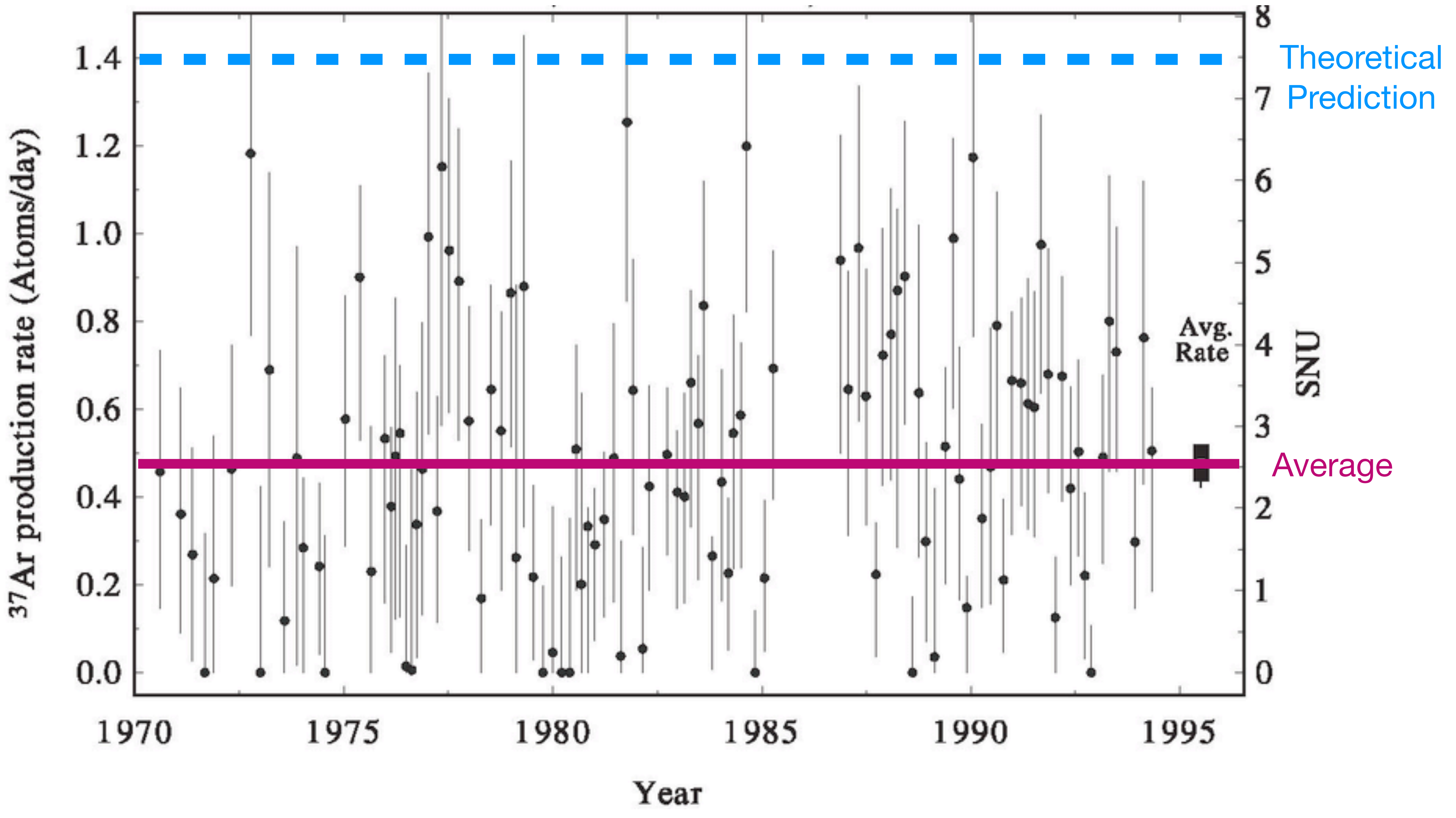
- **Problem:** they measured solar neutrinos, but less than expected

  1/3 of the prediction by solar model



Solar Neutrino Problem: Homestake

Collection of data along 20 years: **Observation of just 1/3 of the prediction**



SNU = Solar neutrino unit = 10^{-36} captures per target atom per second

- For more than 20 years the experiment showed a clear discrepancy with the predictions of the solar model
- **FIRST EXPLANATION**: theory and/or experiment were wrong
- In the 90's similar experiments tried to measure solar neutrinos as well

- SAGE (^{71}Ga) $\quad ^{71}Ga + \nu_e \longrightarrow ^{71}Ge + e^-$
- GALLEX (^{71}Ga) $\quad ^{71}Ga + \nu_e \longrightarrow ^{71}Ge + e^-$
- Kamiokande (H_20) $\quad \nu_e + e^- \longrightarrow \nu_e + e^-$

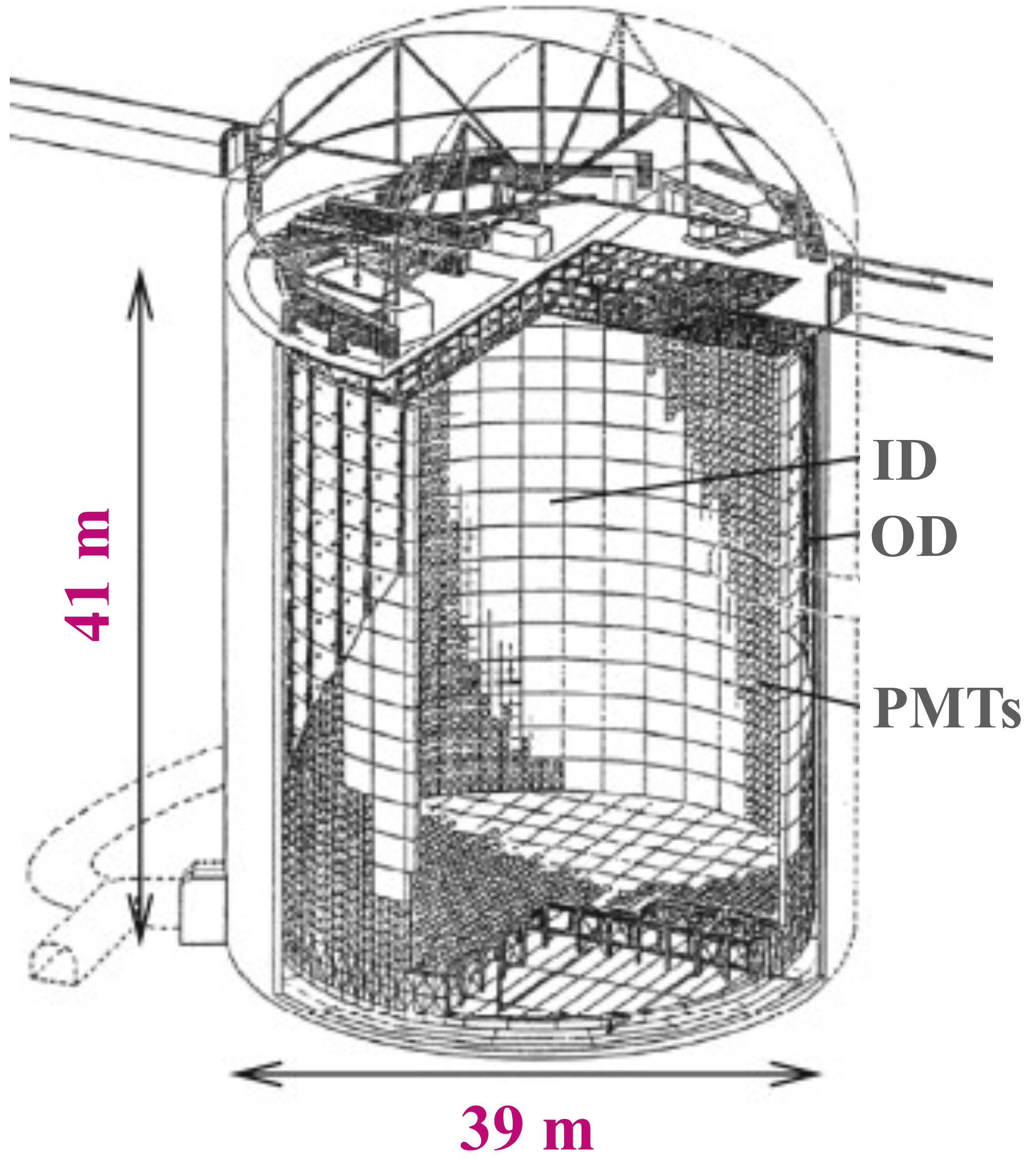
Solar Neutrino Problem: Super-Kamiokande

2002: Nobel prize
M. Koshiba

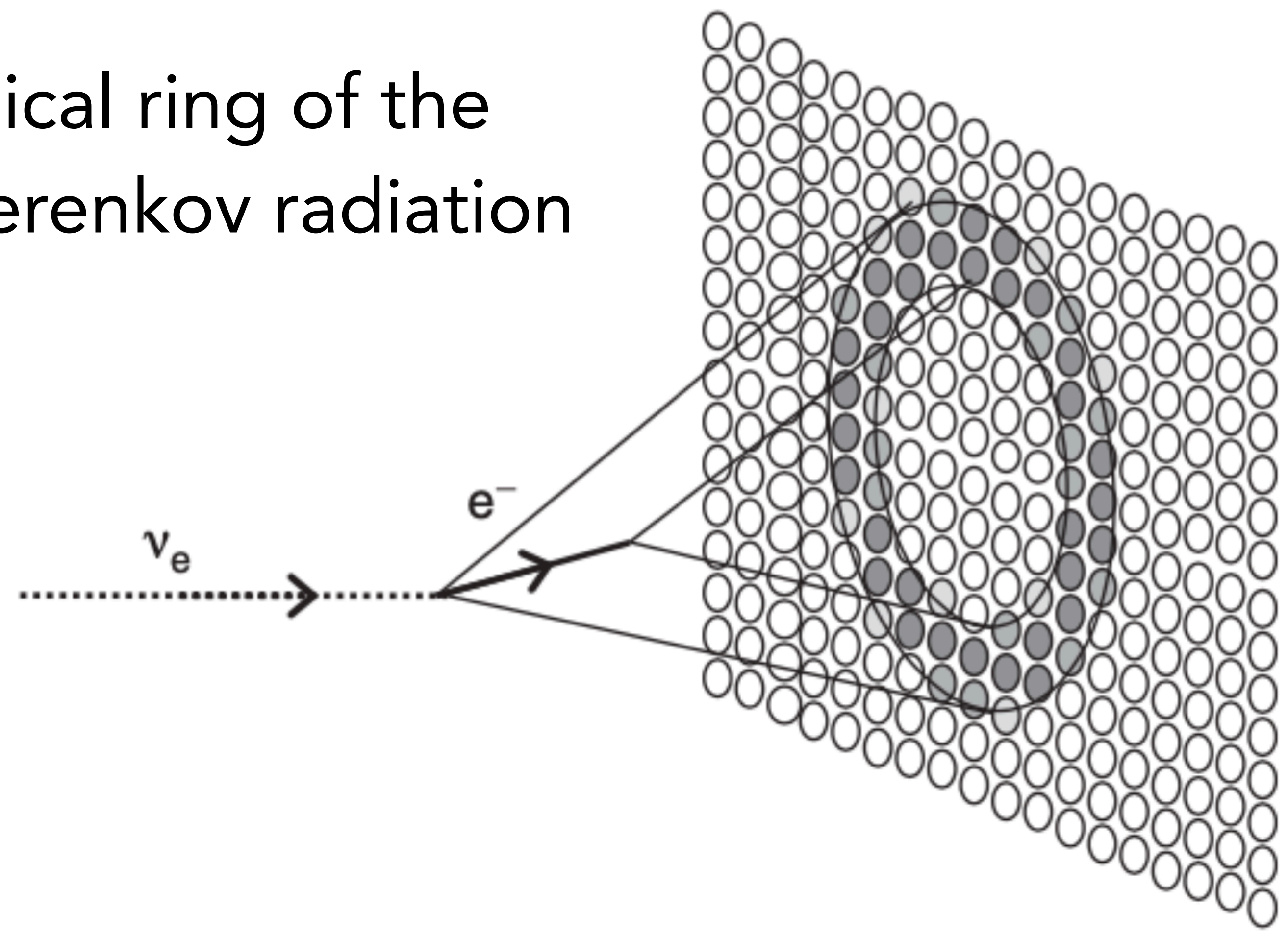
- **Predecesor:** KamiokaNDE, small size for nucleon decay searches (1983)
- **Detector:** 50000 tons of water seen by 11146 large PMTs (50 cm ⌀) (At the Kamioka mine)
- **Reaction:** neutrino-electron scattering (CC interaction forbidden in O-nuclei)

$$\nu_e + e^- \longrightarrow \nu_e + e^- \quad E_\nu > 5\ \mathrm{MeV}$$

- **Technique:** detect Cherenkov radiation

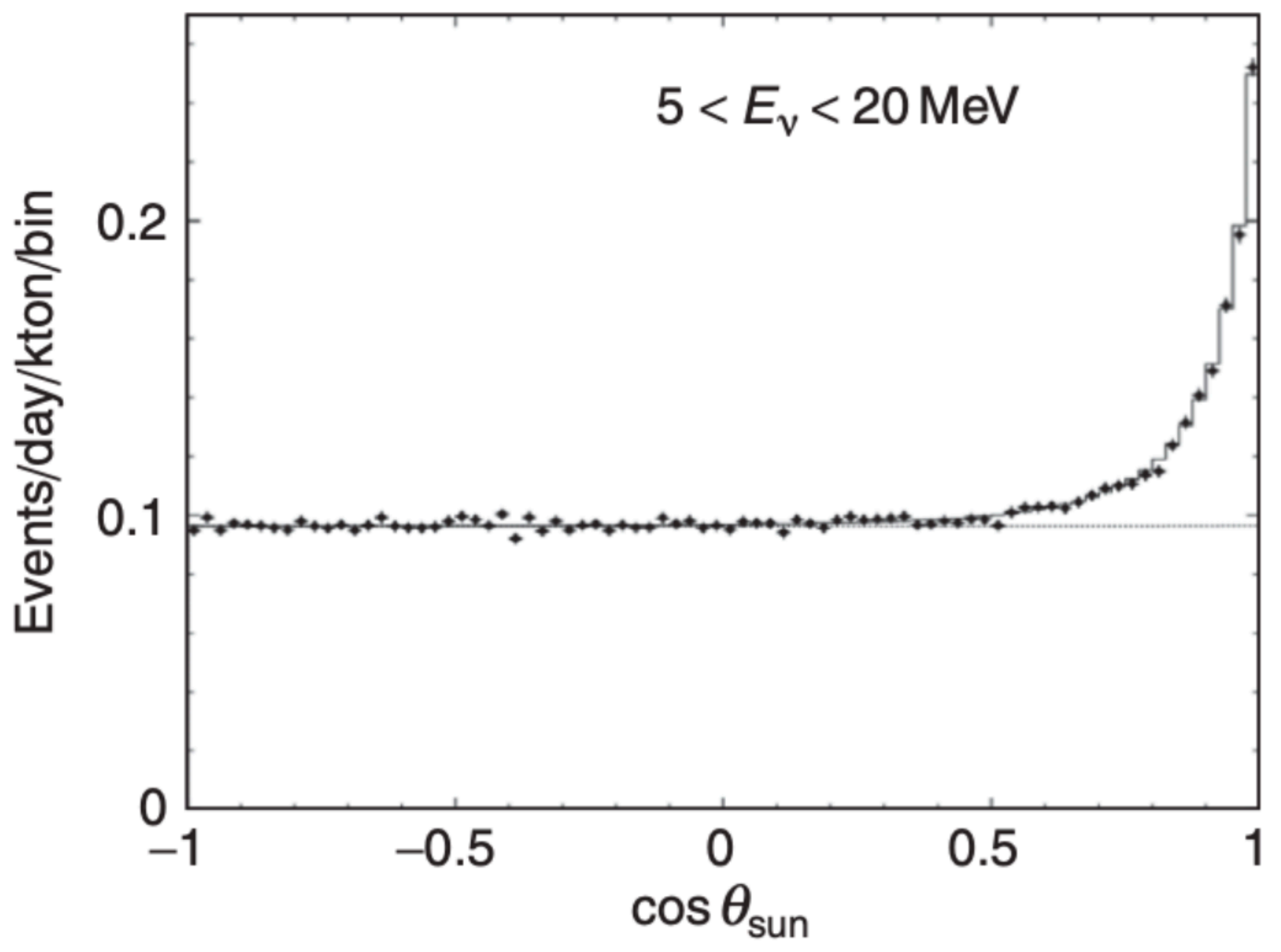


Typical ring of the Cherenkov radiation



- Measure of the energy (calorimetry)
- Measure of the direction

FIRST Results (1996)



1) Neutrinos do come from the Sun

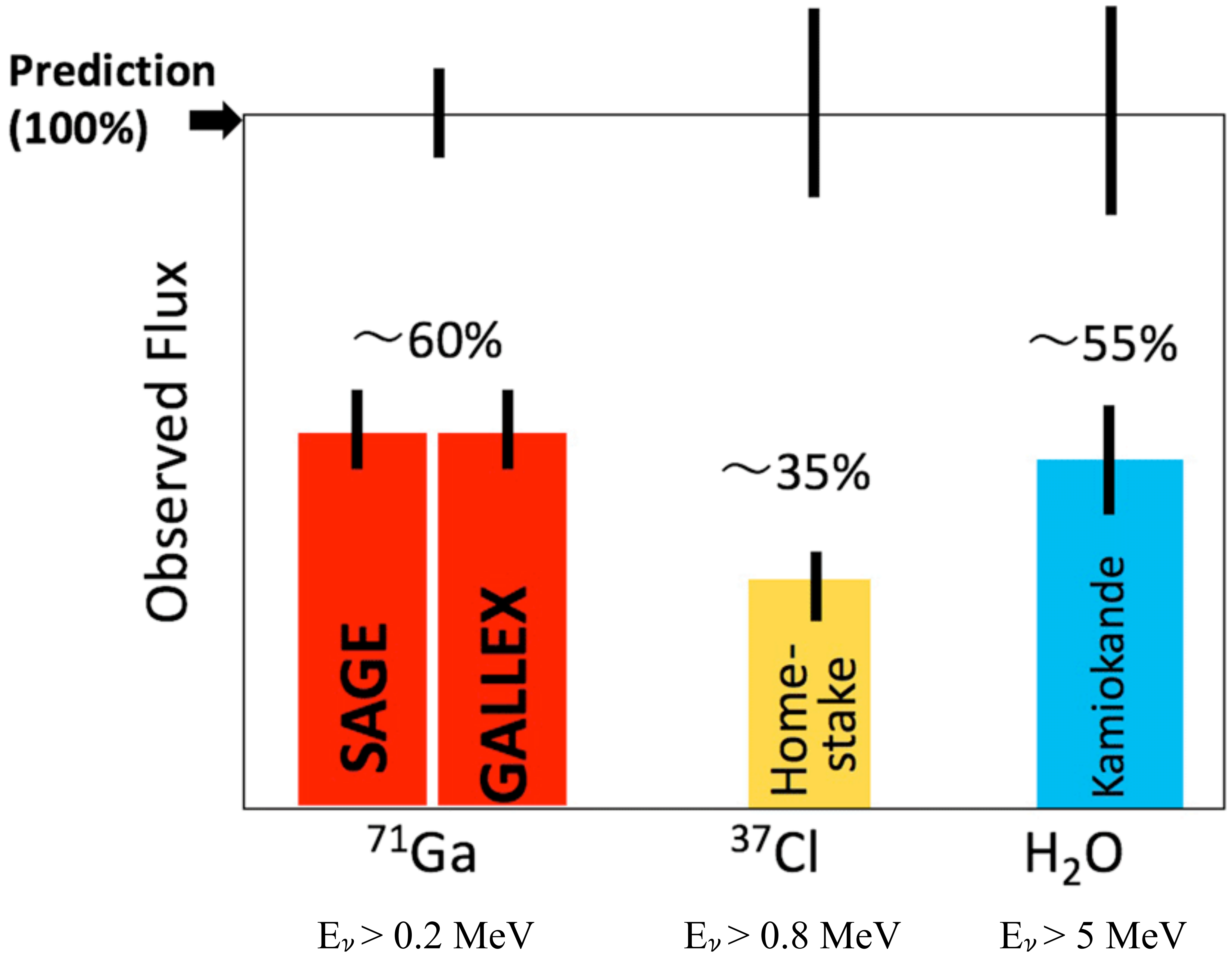
2) Only 50% of the prediction

Solar Neutrino Problem: overview

Theory of flavour oscillations rounding some minds

PMNS theory since 1962

Situation of the solar neutrino community in the middle of 90's



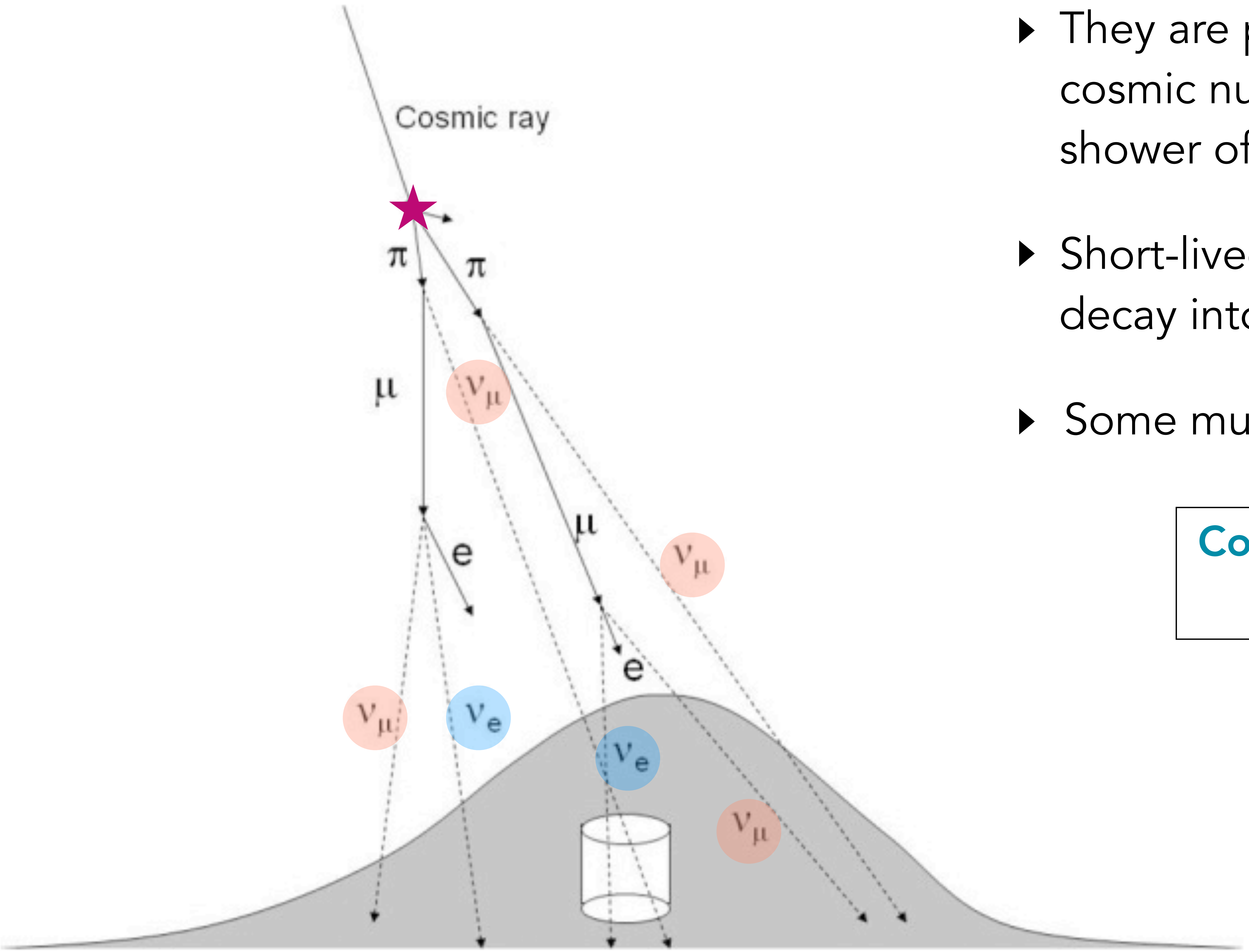
By this time it was clear that:

- The problem was not Homestake
- Something was happening to the neutrinos in their journey from the Sun to the Earth

Note:

Different deficit due to the different energy sensitivity and the detection technique of each experiment

Atmospheric Neutrinos



T. Kajita (10.2183/pjab.86.303)

- They are produced when a cosmic ray (extremely energetic cosmic nucleus) interact with the atmosphere, producing a shower of particles ~15 km above ground
- Short-lived mesons (mainly pions) are produced. These decay into muons + muon-neutrinos
- Some muons decay into electrons + electron&muon neutrinos

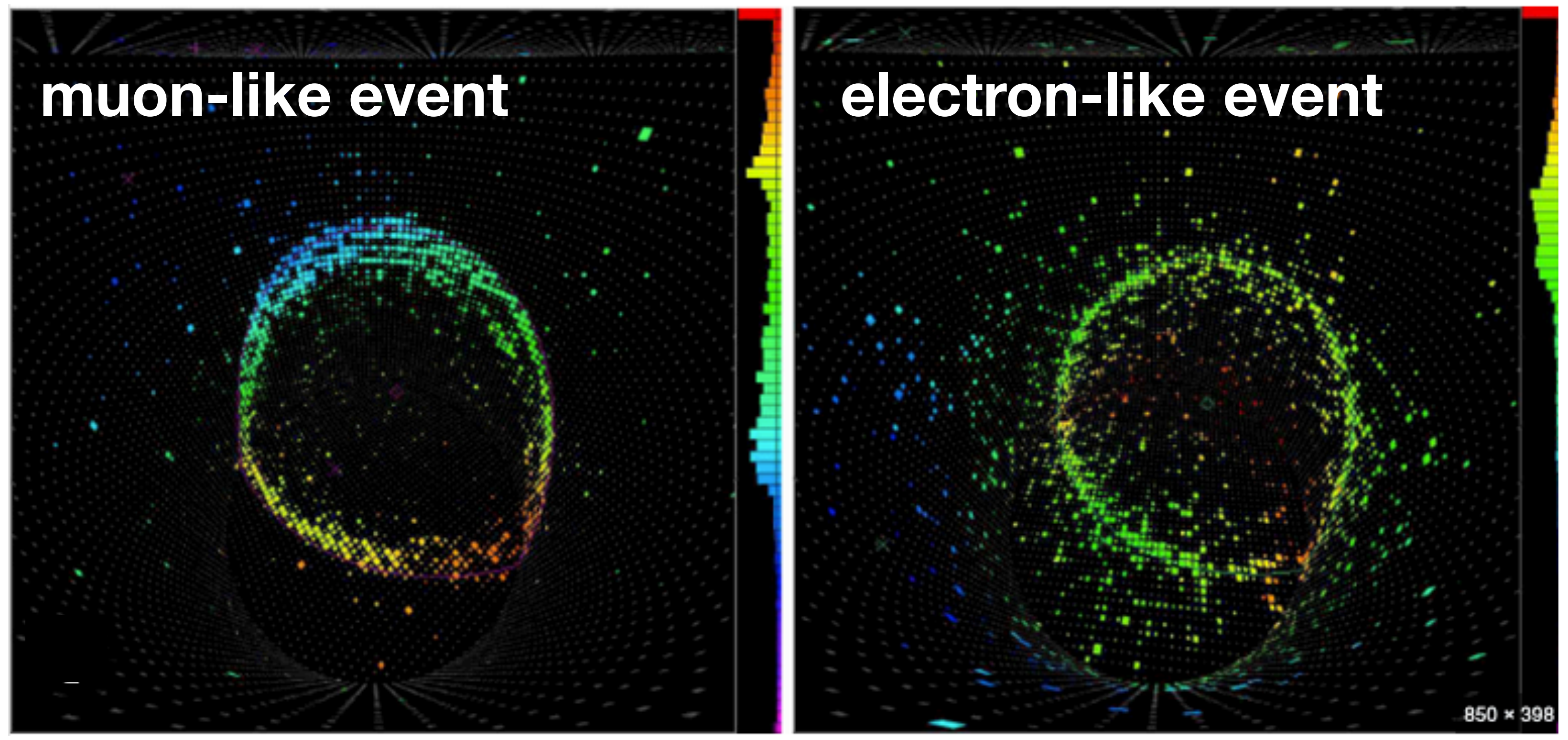
Composition: two-thirds are ν_μ and one-third is ν_e (with corresponding anti-neutrinos)

Energy: 1GeV - 10^6 GeV

2015: Nobel prize
T. Kajita

Atmospheric neutrino anomaly

- **1988-1992:** Two water-Cherenkov experiments (Kamiokande & IMB) observed a deficit of ν_μ
  - they could distinguish between ν_μ and ν_e interactions
  - ratio between ν_μ and ν_e did not fit the expectation



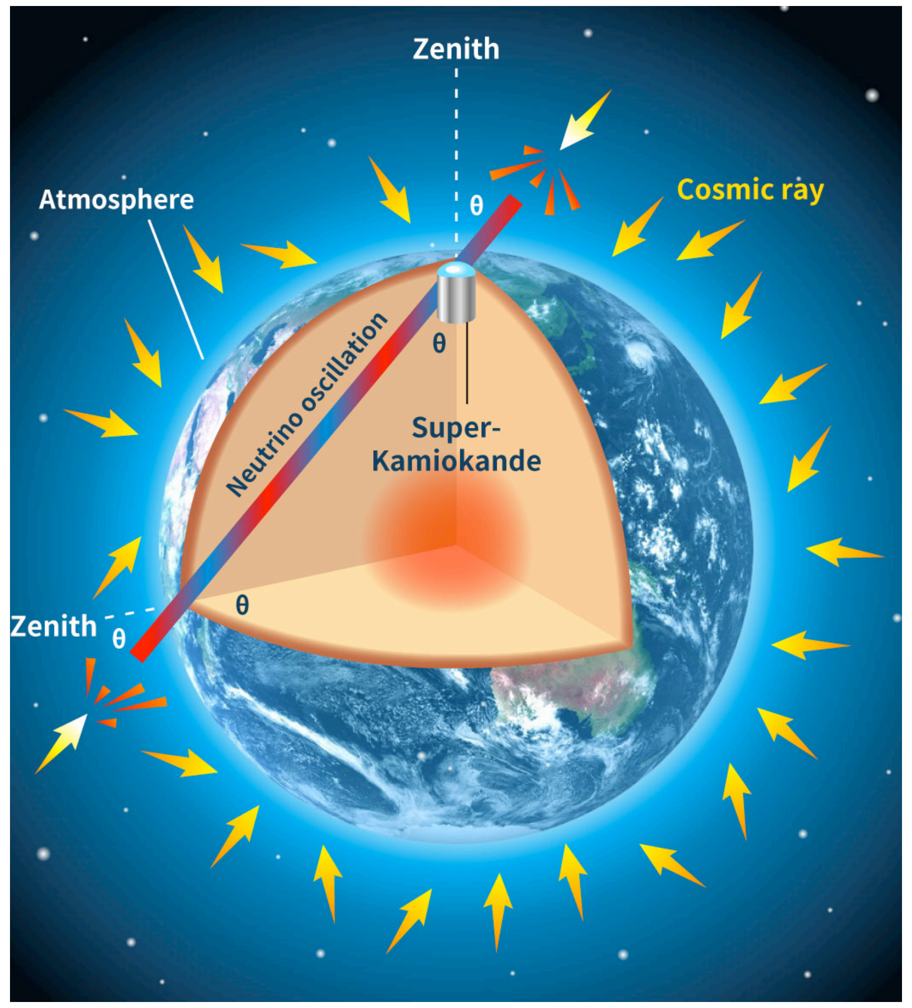
1998: Super-Kamiokande solved the mystery

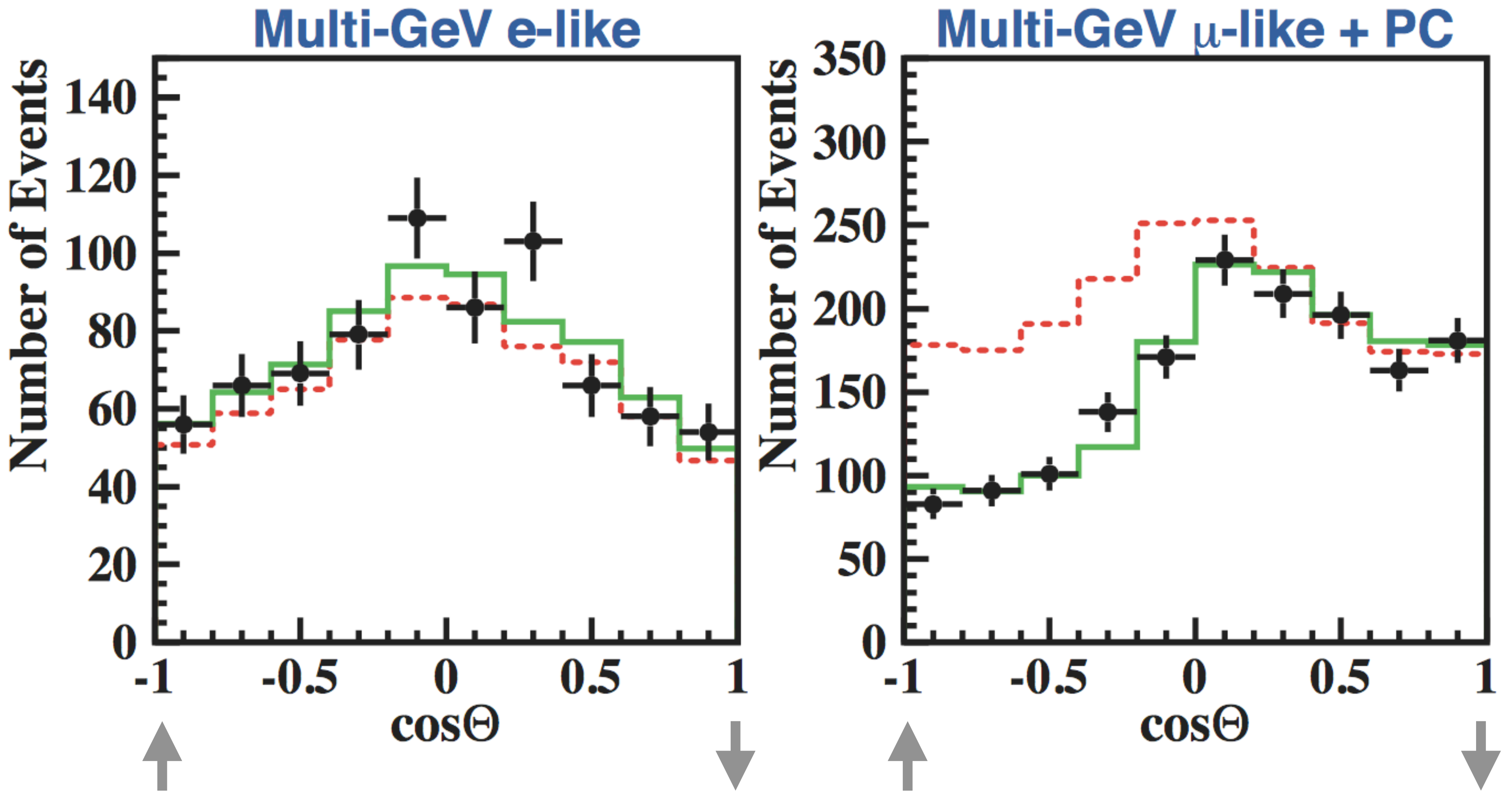
Explanation:

1) ν_e do not change

2) ν_μ from above do not change ($\cos\theta = 1$)

3) Many ν_μ from below oscillate to ν_τ ($\cos\theta = 1$)





Effect caused by the different travel distances

The final explanation with the SNO experiment

- **1999:** The Sudbury Neutrino Observatory (SNO) experiment in Canada was designed to measure both $\mathbf{\nu_e}$ and **total** neutrino flux from the Sun

- **Detector:** 1000 tons of heavy water (D_2O) inside a 12 m diameter vessel observed by 9600 PMTs

- **Detection technique:** Cherenkov Radiation

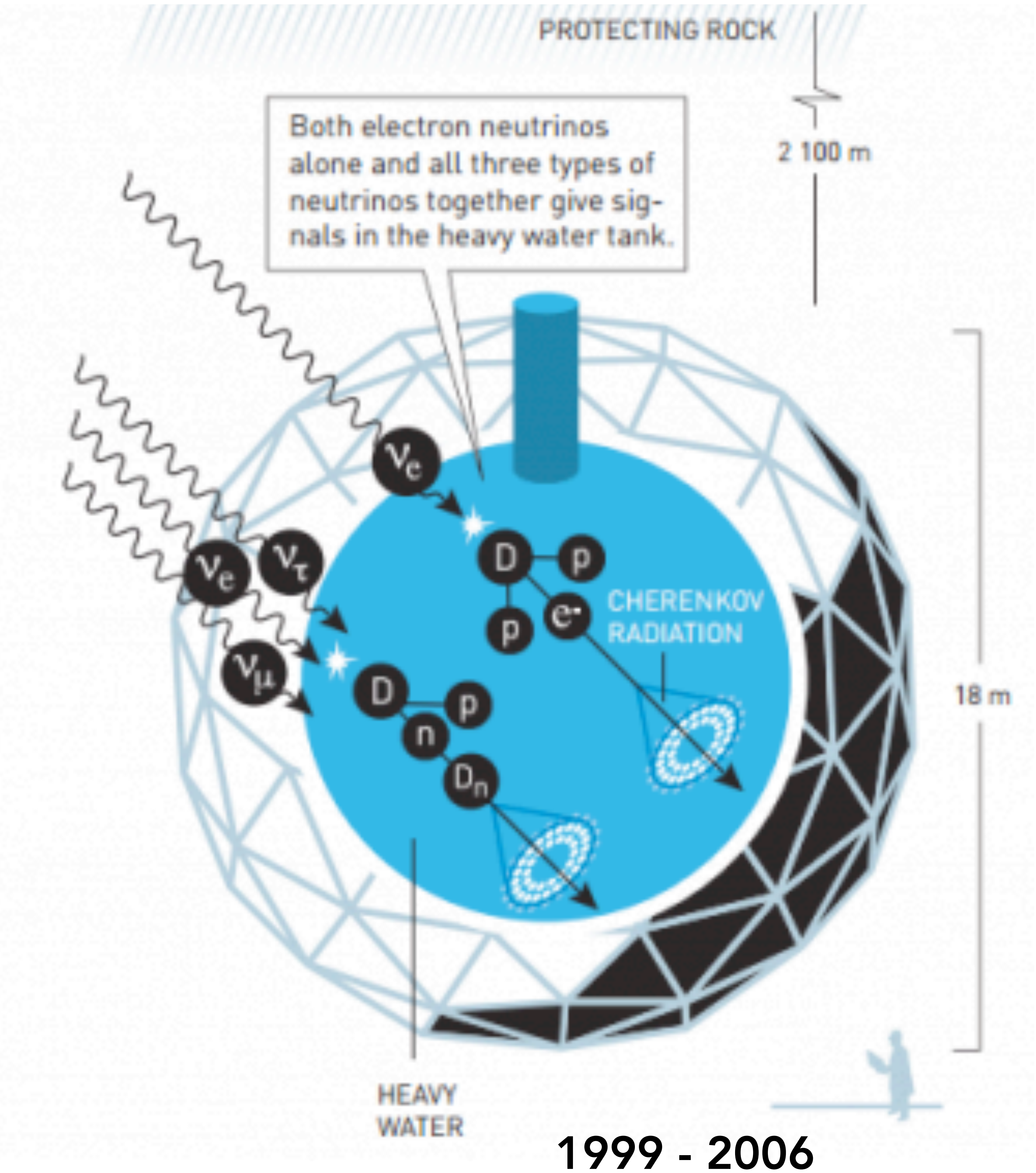
- **Key Feature:** the deuteron, bound state of a proton and a neutron, has a binding energy of 2.2 MeV, relatively small compared to the energies of the ^8B solar neutrinos

- **Reactions:**

$$\nu_e + D \longrightarrow p + p + e^-$$ (Charge Current interaction)

$$\nu_x + D \longrightarrow \nu_x + p + n$$ (Neutral Current interaction)

$$\nu_x + e^- \longrightarrow \nu_x + e^-$$ (Elastic Scattering)



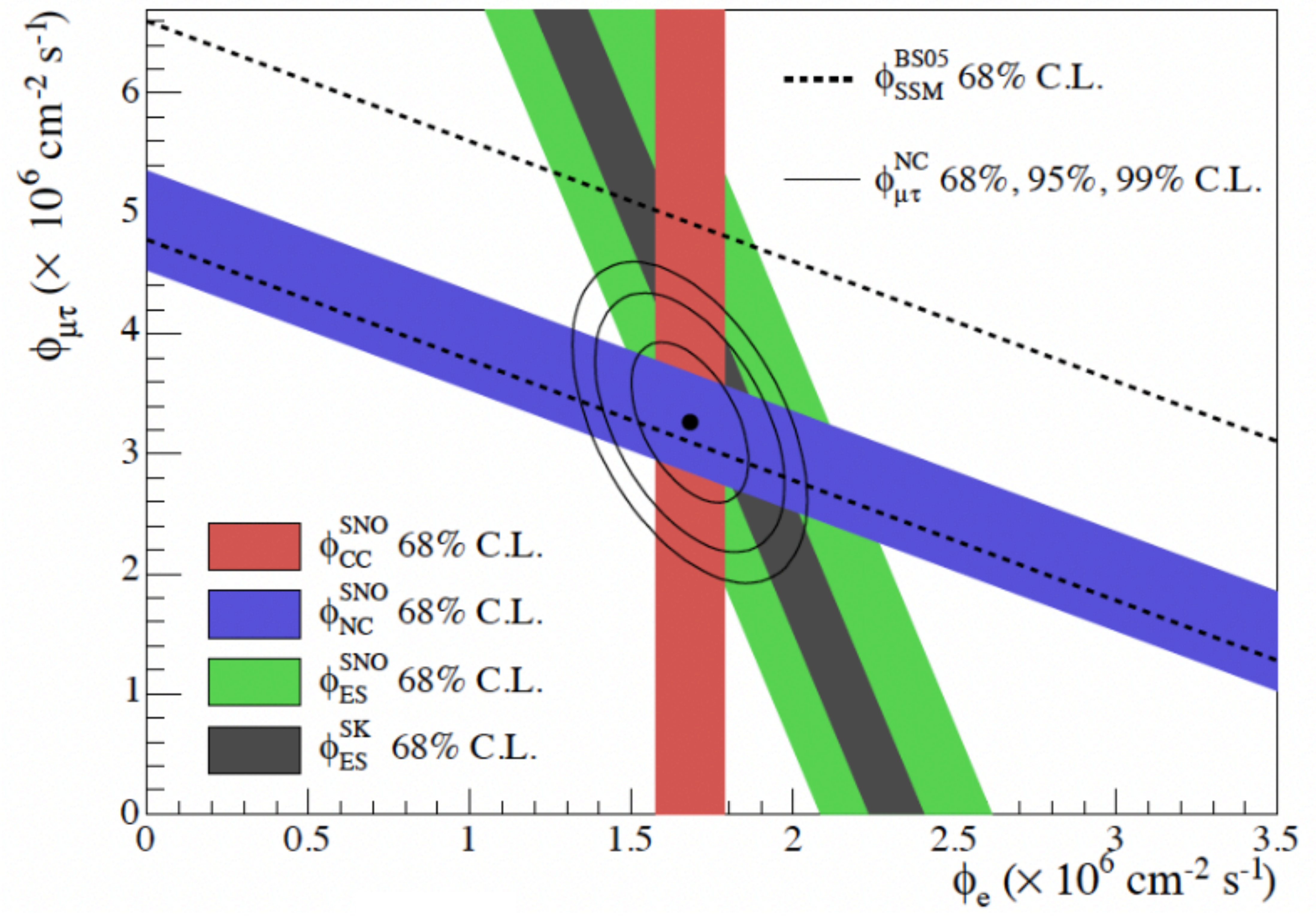
1999 - 2006

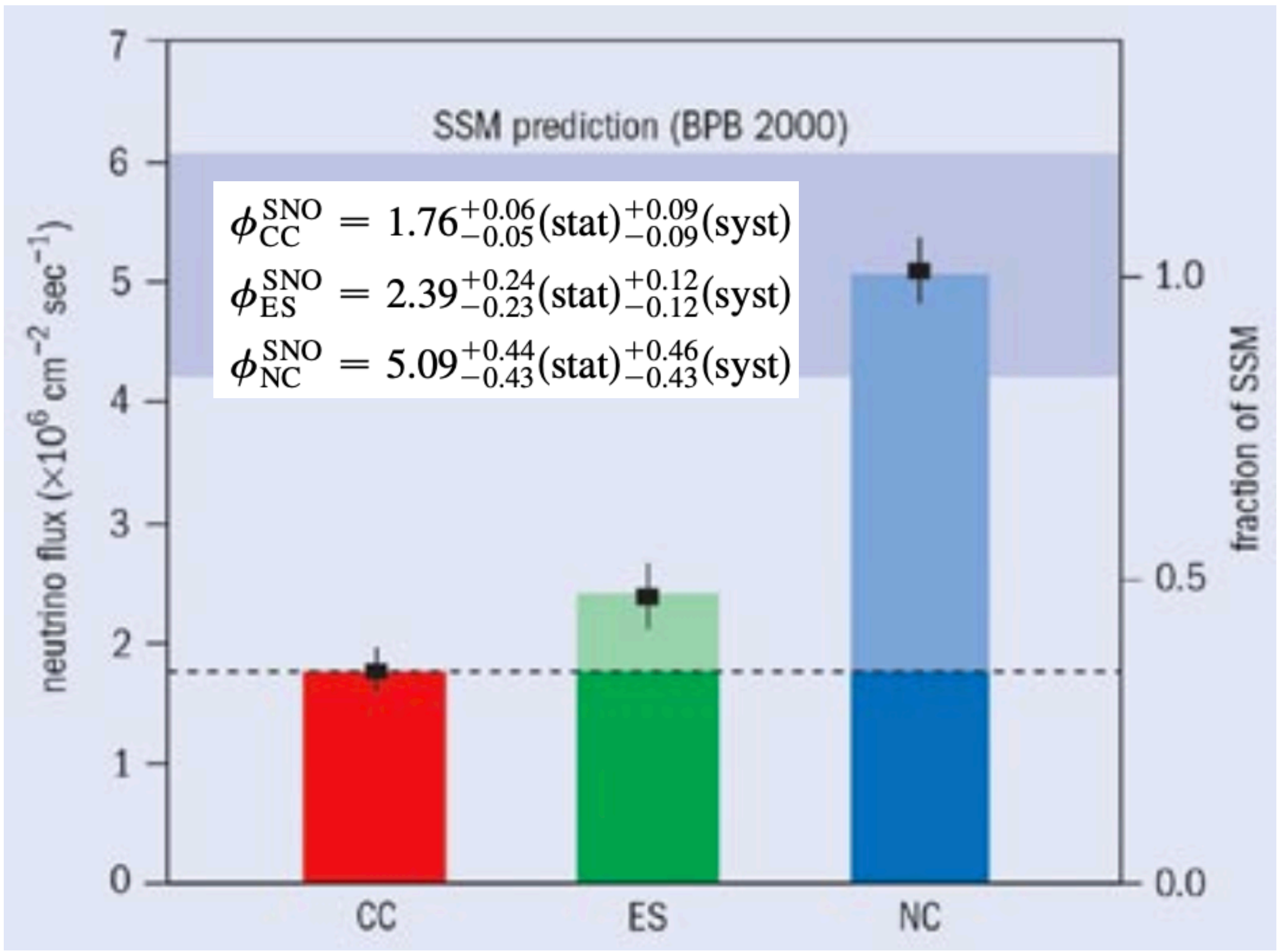
2015: Nobel prize

A. McDonald 

SNO Results: everything agrees

- **2001:** Conclusive results. The total neutrino flux agrees with the prediction of the standard solar model (SSM)



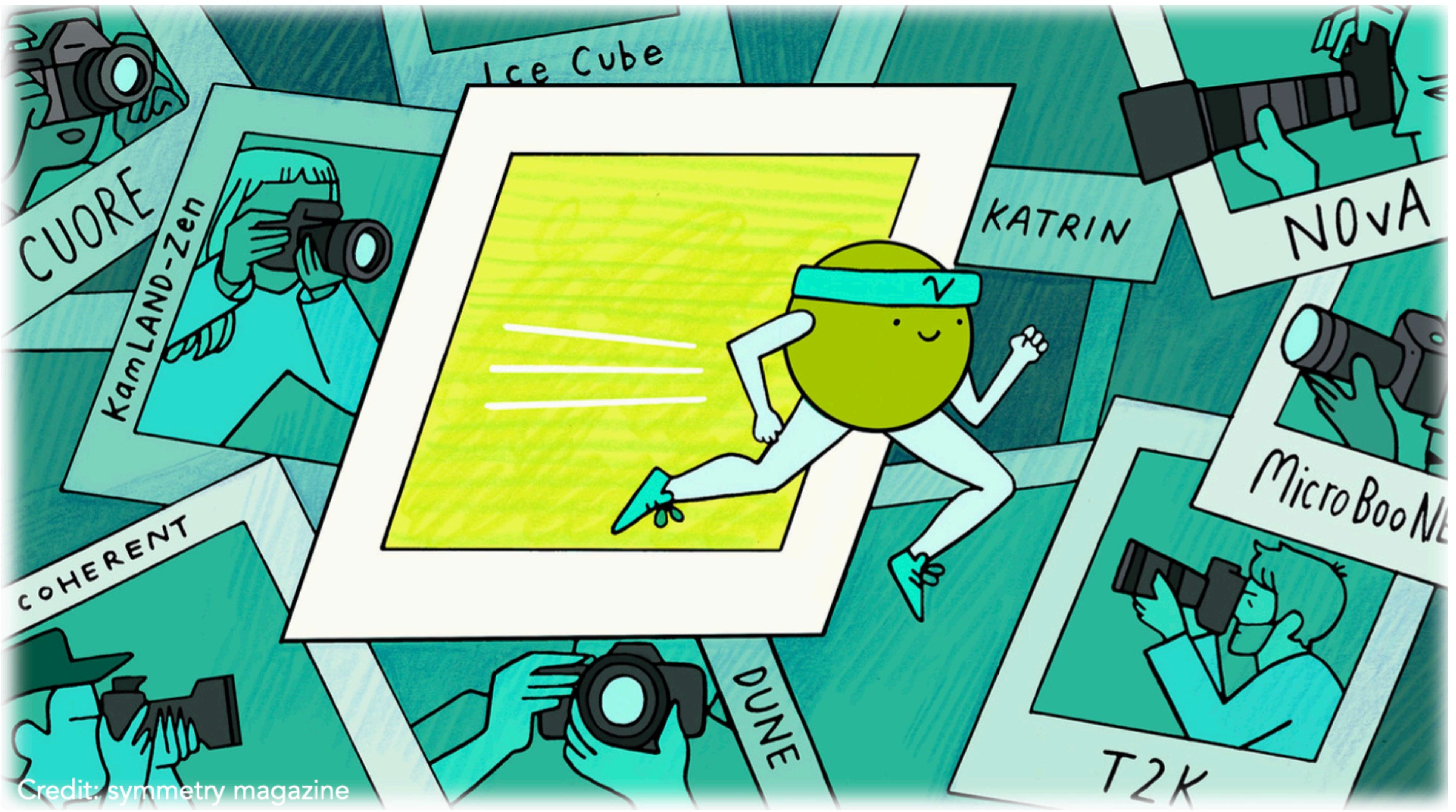


Results of the previous experiments correct

SNO results showed evidence of neutrino flavour oscillation over large distances

Conclusions from 1970 - 2003

- Firmly stablished the flavour oscillation framework
- Neutrinos do have non-zero masses
- No clue of the absolute mass scale
- Solely experimental evidence of Physics Beyond the SM



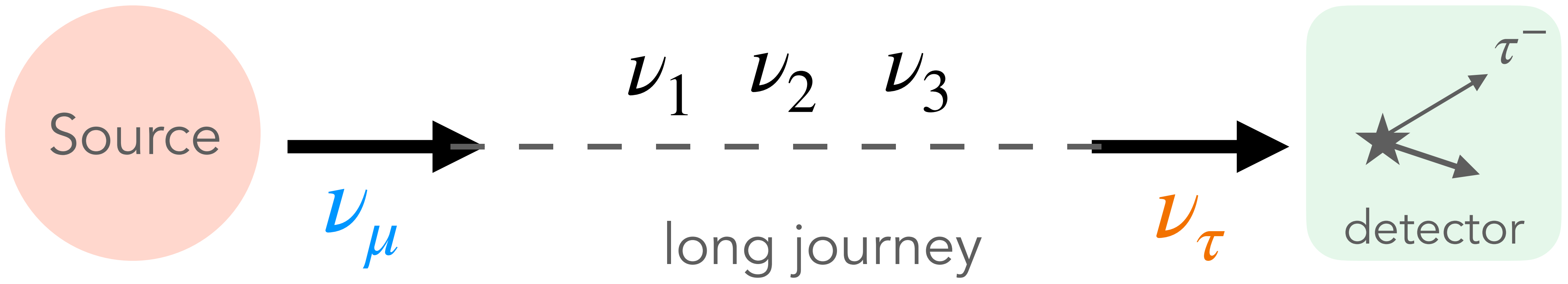
What happened next?

Since we knew neutrinos oscillate, we have been working on characterise all the parameters describing this phenomenon and the rest of unknowns around the neutrino nature

Neutrino Oscillation Experiments

Solar, Reactor and Accelerator sectors

Neutrino oscillations: back to present



- Neutrinos produced/detected as defined flavour states: ν_e ν_μ ν_τ
- Neutrinos propagates as defined mass states: ν_1 ν_2 ν_3
- Flavour and mass states related by a **mixing matrix**
- Determined by: **3 mixing angles and 1 CP violating phase**

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

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (1962)

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

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

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

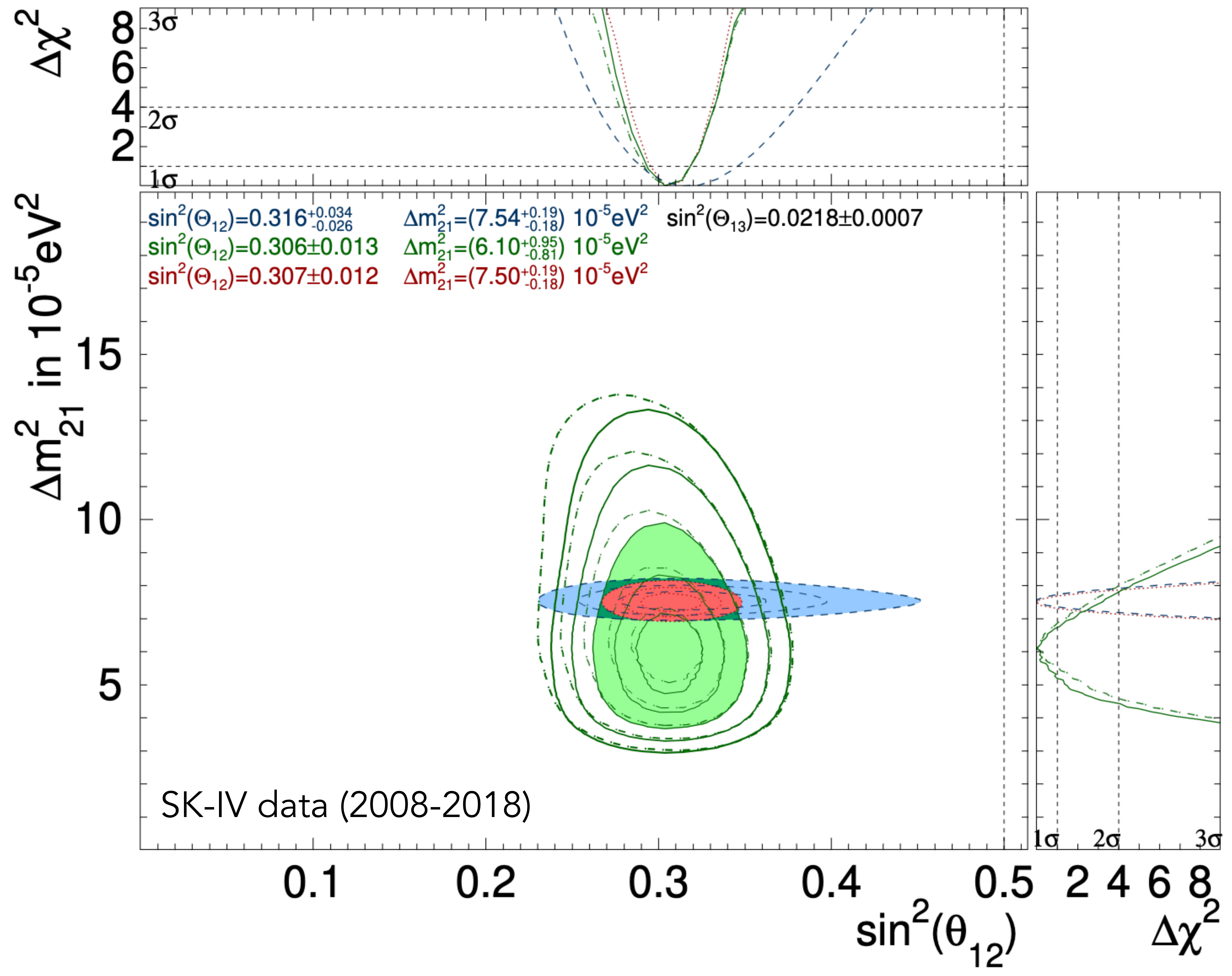
ATMOSPHERIC + ACCELERATOR SECTOR

REACTOR SECTOR

SOLAR SECTOR

1. Results from the solar sector: θ_{12} Δm^2_{21}

Phys. Rev. D. 109, 092001 (2024)



Results from KamLAND + Solar Experiments

(KamLAND + Homestake + SAGE + Borexino + SK + SNO)

Green Area —> Solar experiments

Blue Area —> KamLAND

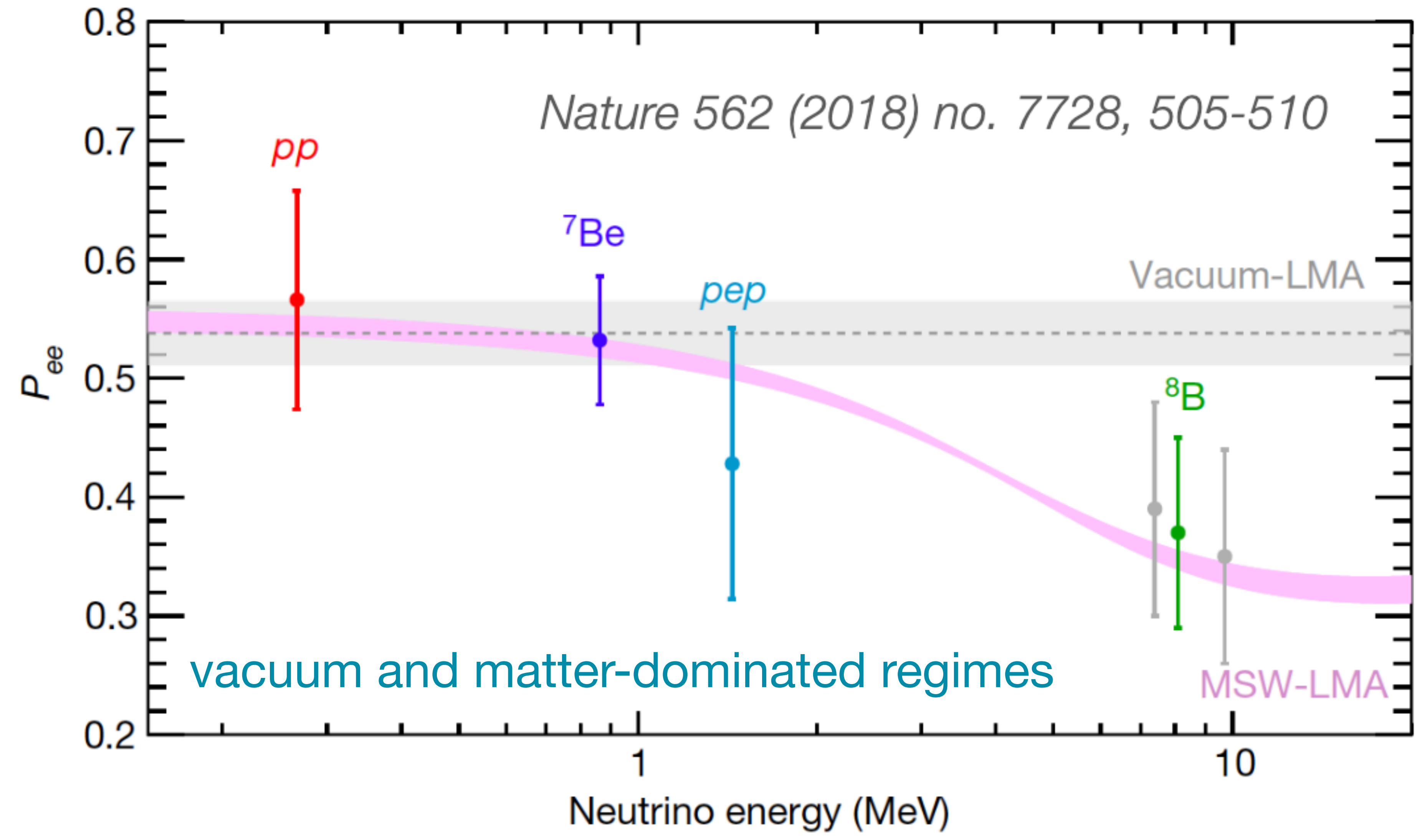
Red Area —> Combined

$$\sin^2\theta_{12,\mathrm{global}} = 0.307 \pm 0.012,$$
$$\Delta m^2_{21,\mathrm{global}} = (7.50^{+0.19}_{-0.18}) \times 10^{-5}\ \mathrm{eV}^2$$

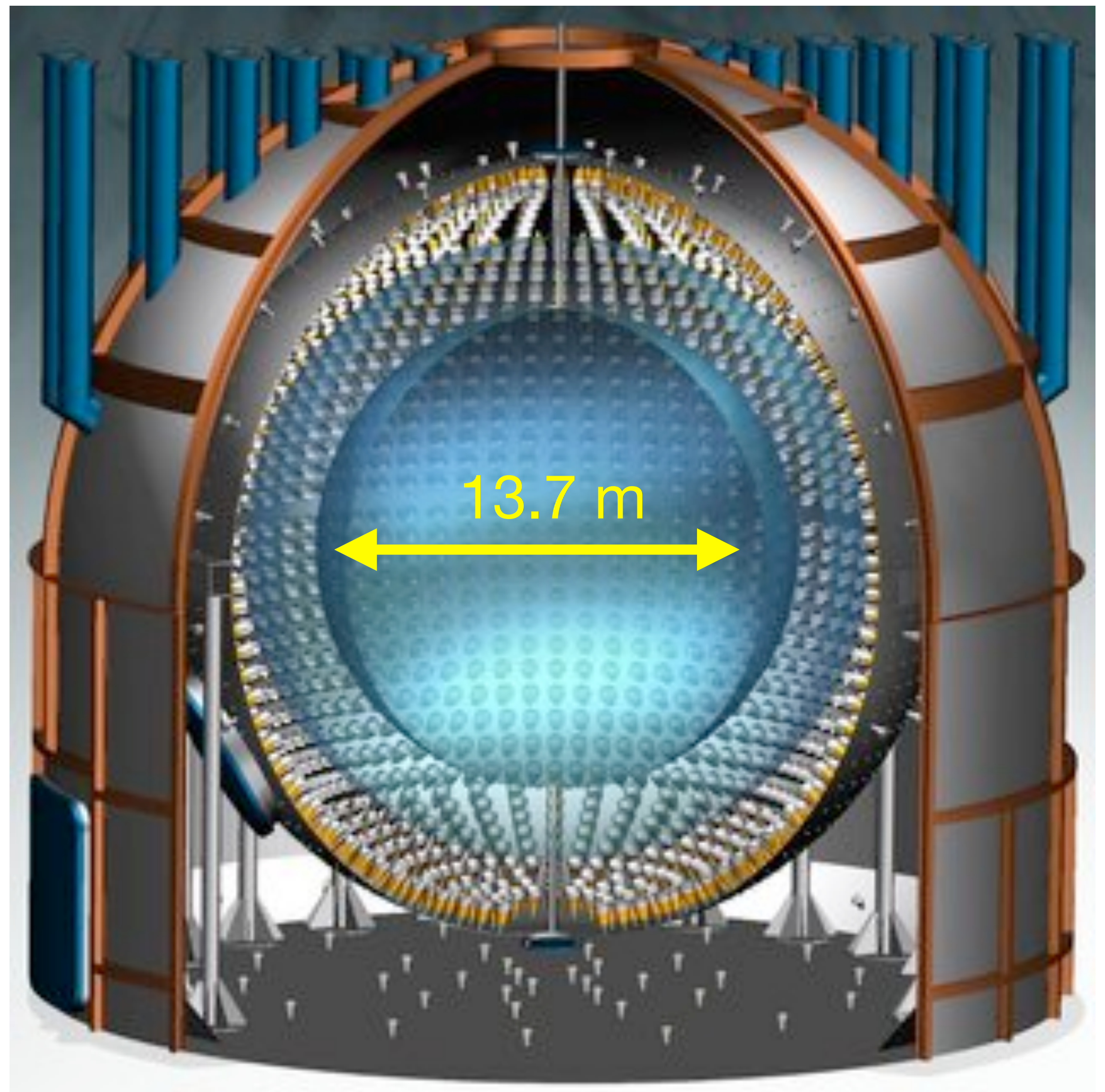
The sing of Δm^2_{21} from matter effects in the sun

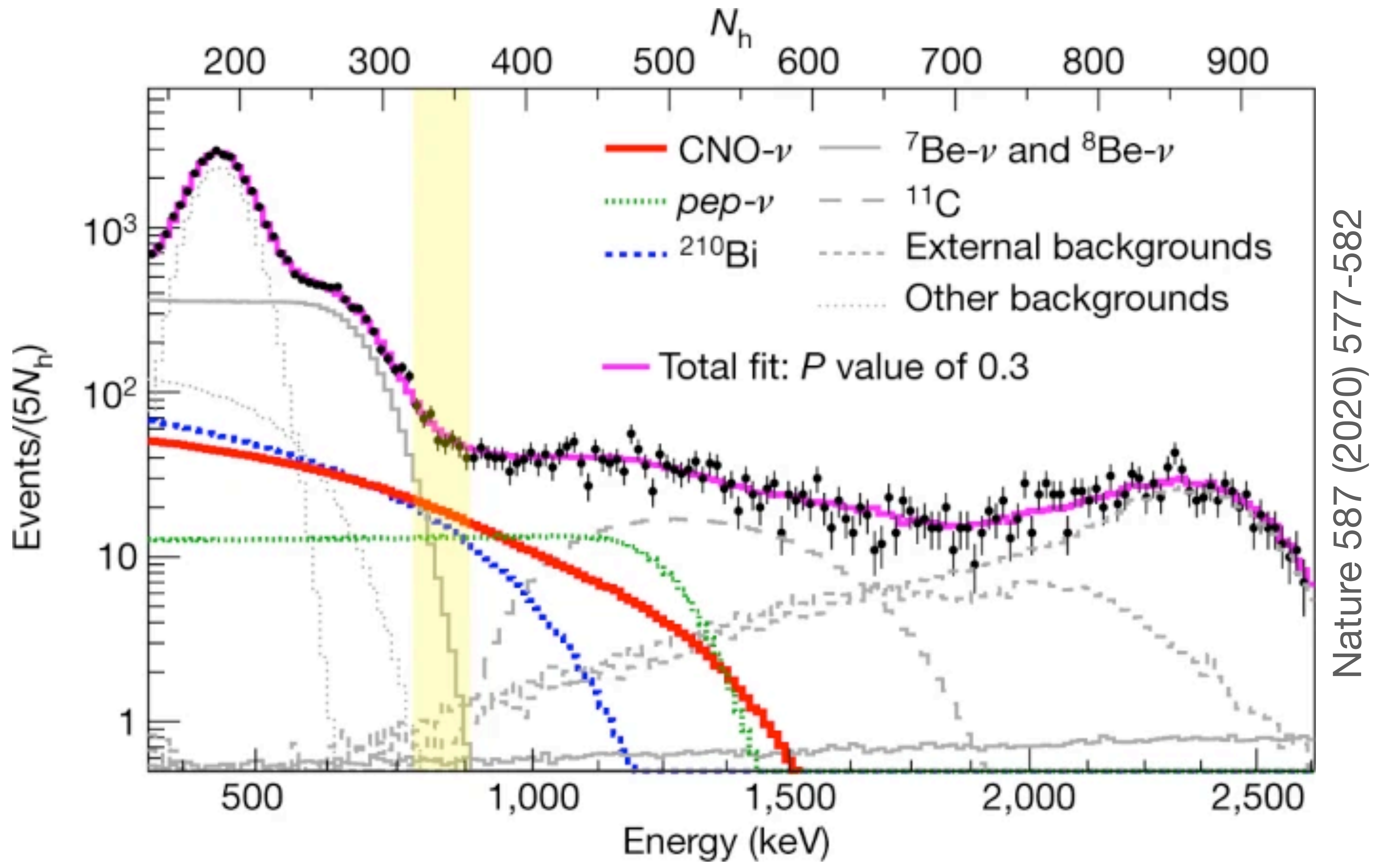
Borexino Detector

- **Detector:** 278 tons of liquid scintillator (13.7m ⌀ + 2200 PMTs)
- **Location**: Laboratori Nazionali del Gran Sasso (3700 m.w.e)
- **Reaction**: $\nu_x + e^- \longrightarrow \nu_x + e^-$
- **Excellent energy resolution:** ~5% at 1 MeV
- **Energy threshold:** ~150 keV neutrinos from pp-chain and above
- Very low background level
- Since 2007 to 2021

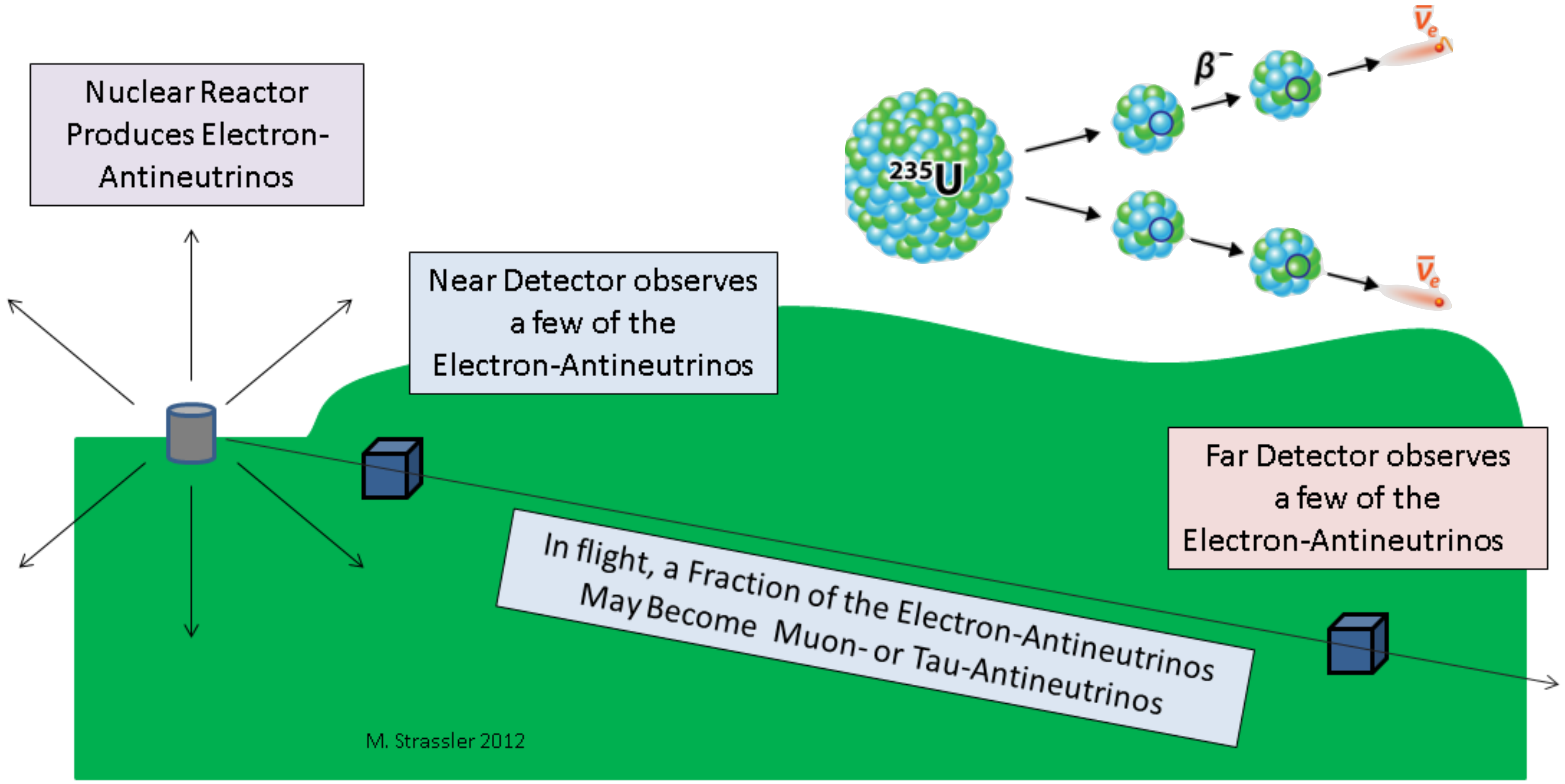


first spectroscopy of pp, 7Be, pep and CNO neutrinos





2. Results from the reactor sector: θ_{13} Δm^2_{31}



Short Baseline: L ~ 100 m -1 km E < 10 MeV

- **Physic Channel:** disappearance

$$\bar{\nu}_e \longrightarrow \bar{\nu}_e$$

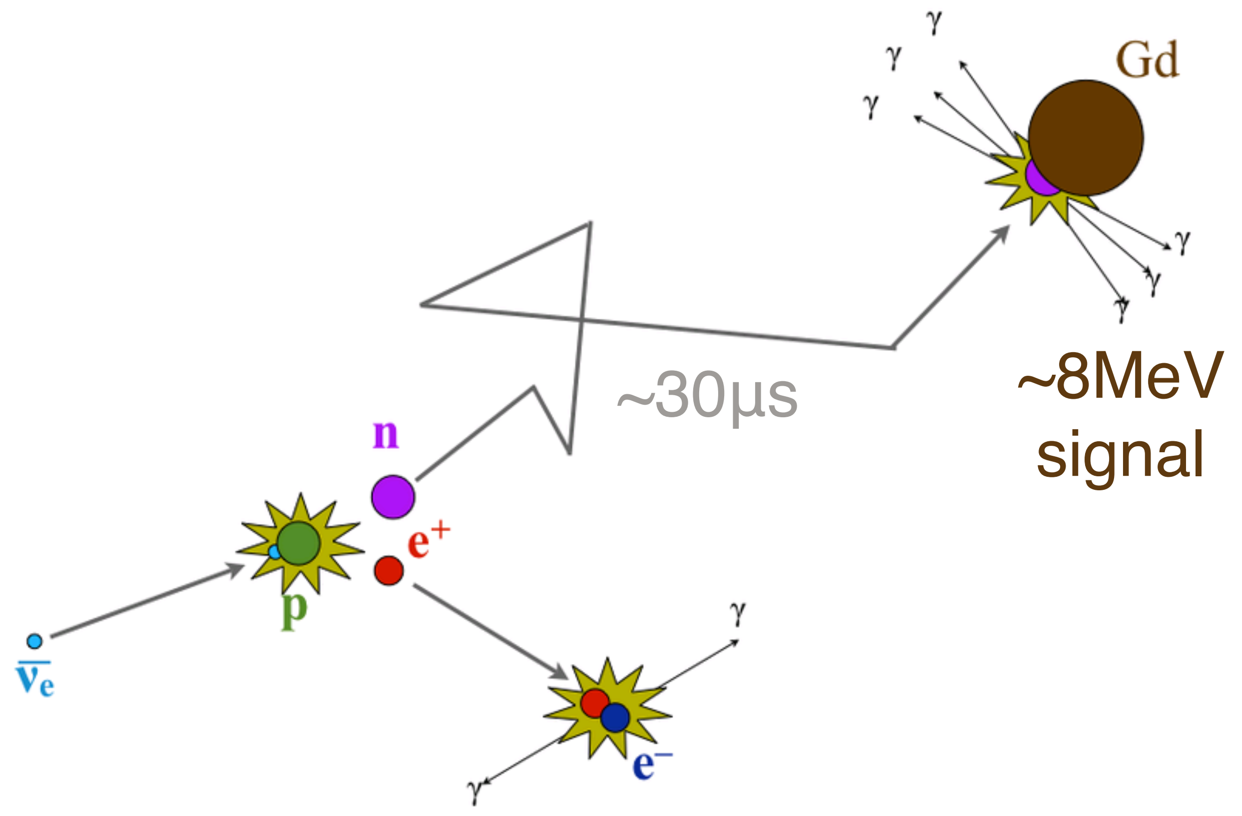
Search for the missing neutrinos from a flavour present in the source

- **Detection Technique:**

Inverse beta decay

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

LS doped with Gd



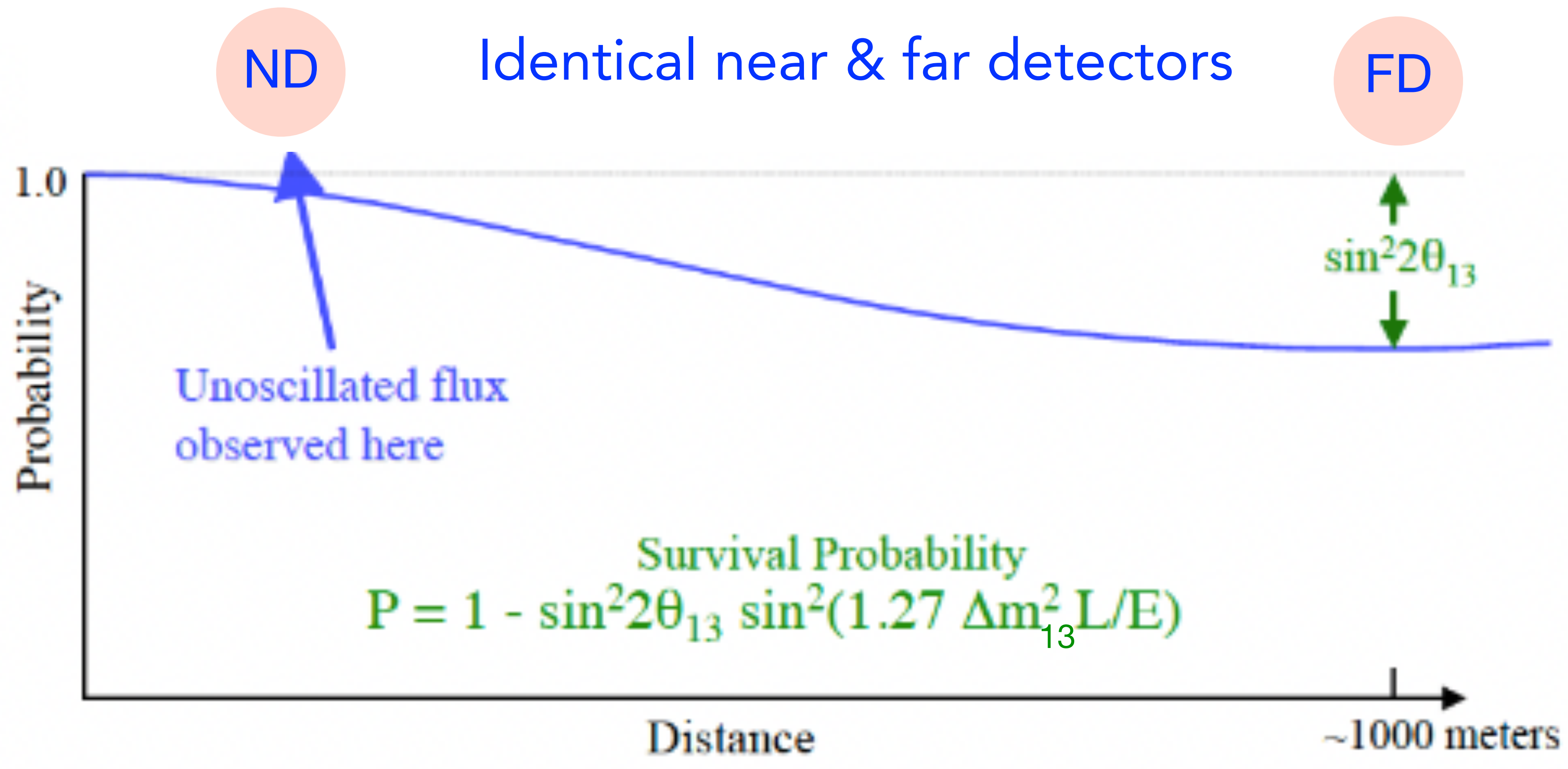
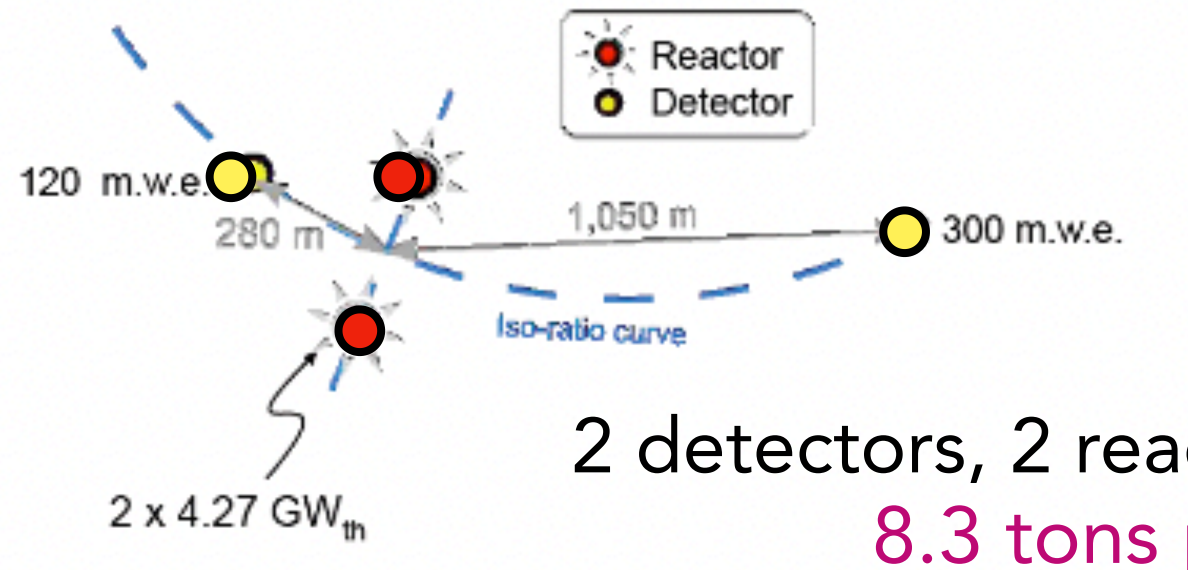


Figure: M. Tórtola, Neutrino2024

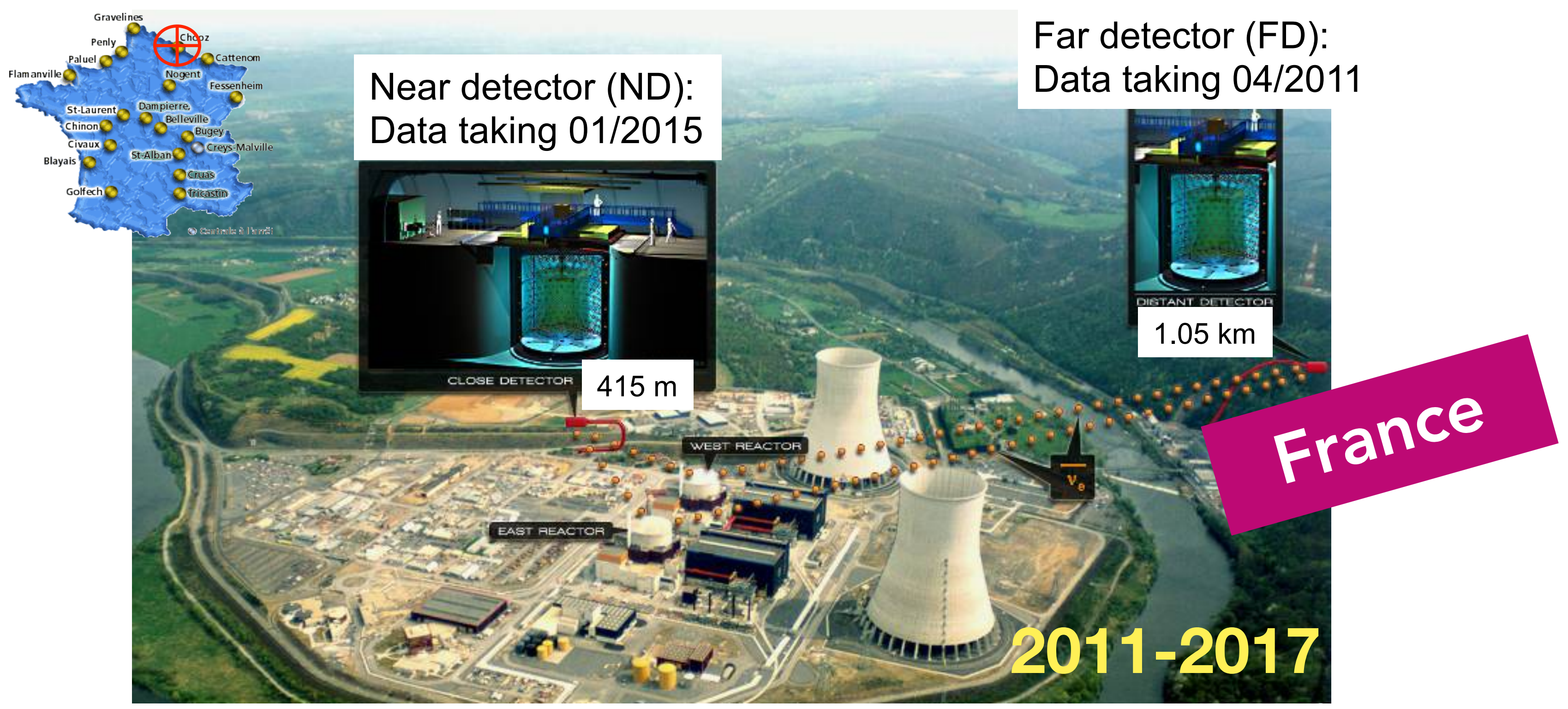
2. Results from the reactor sector: θ_{13} Δm^2_{31}

Double Chooz

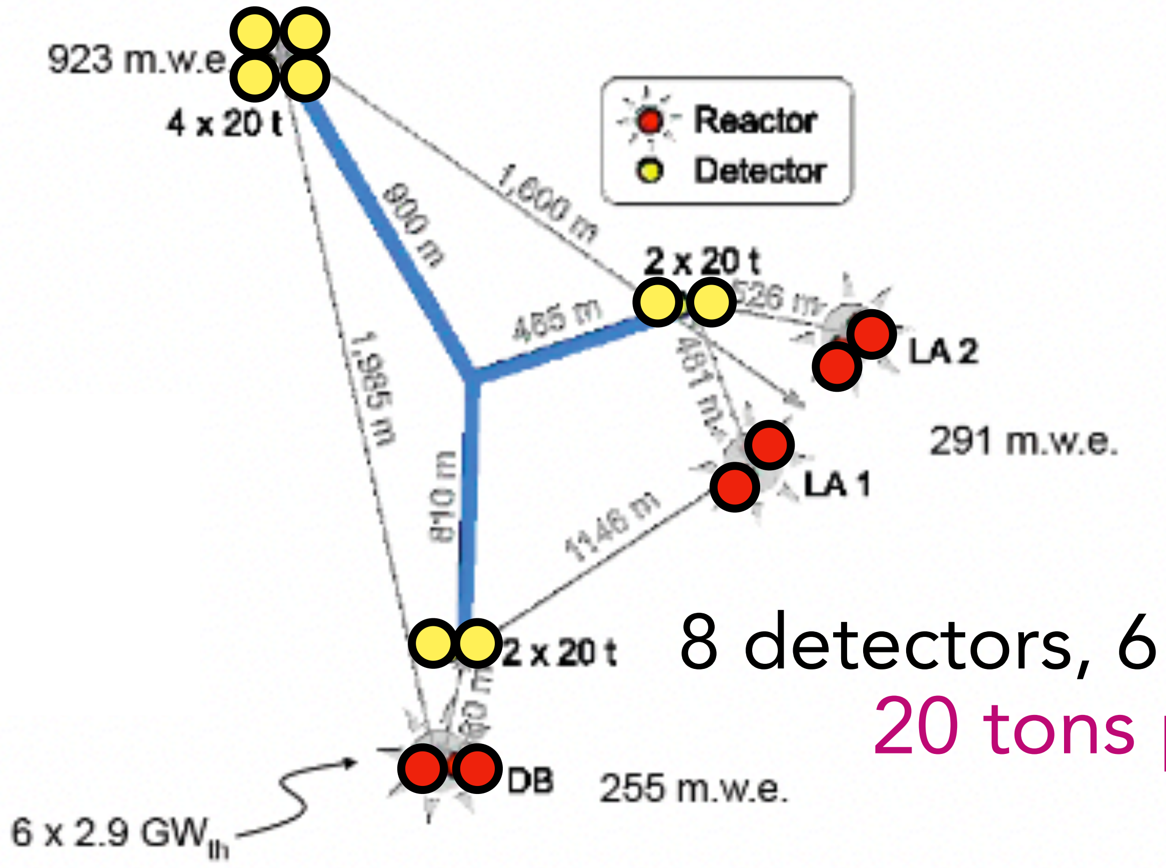


2 detectors, 2 reactors

8.3 tons per detector

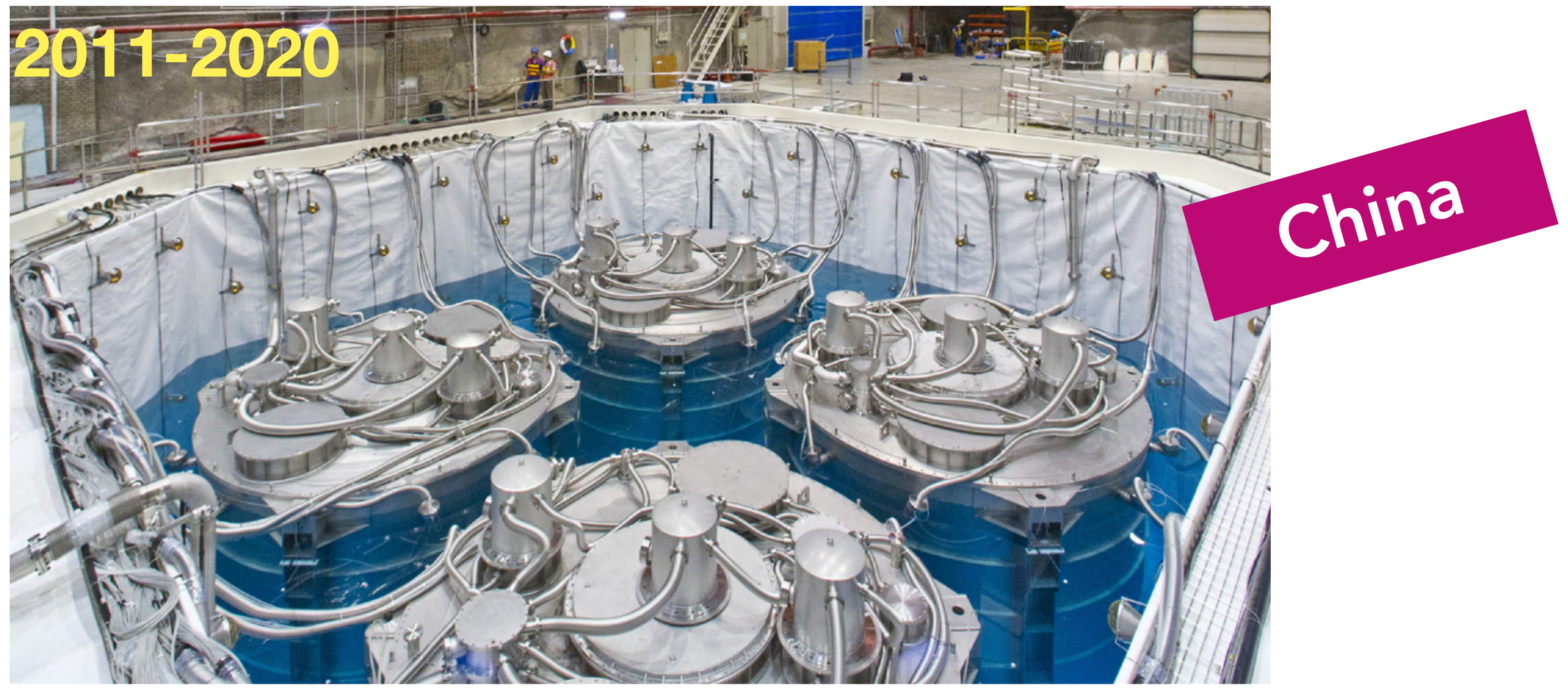


Daya Bay

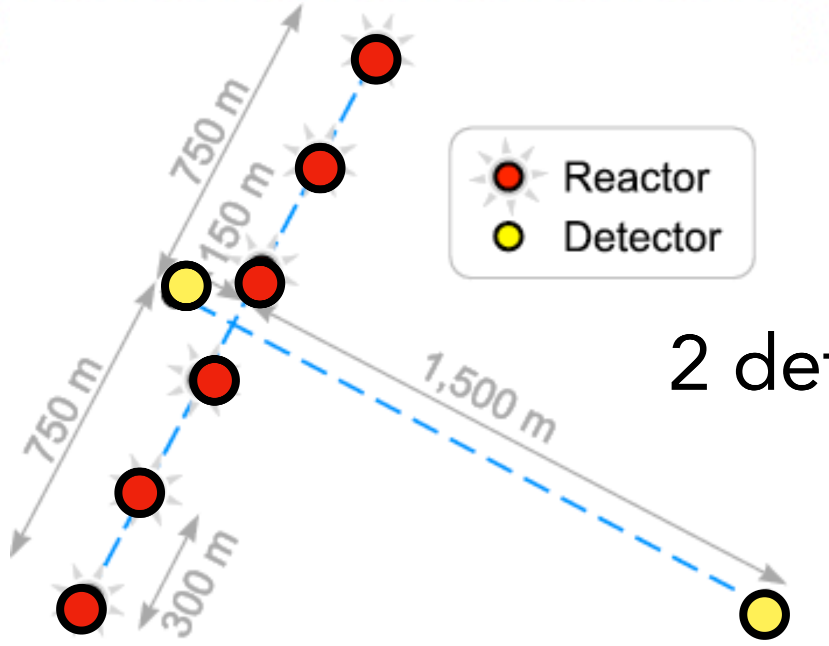


8 detectors, 6 reactors

20 tons per detector



RENO

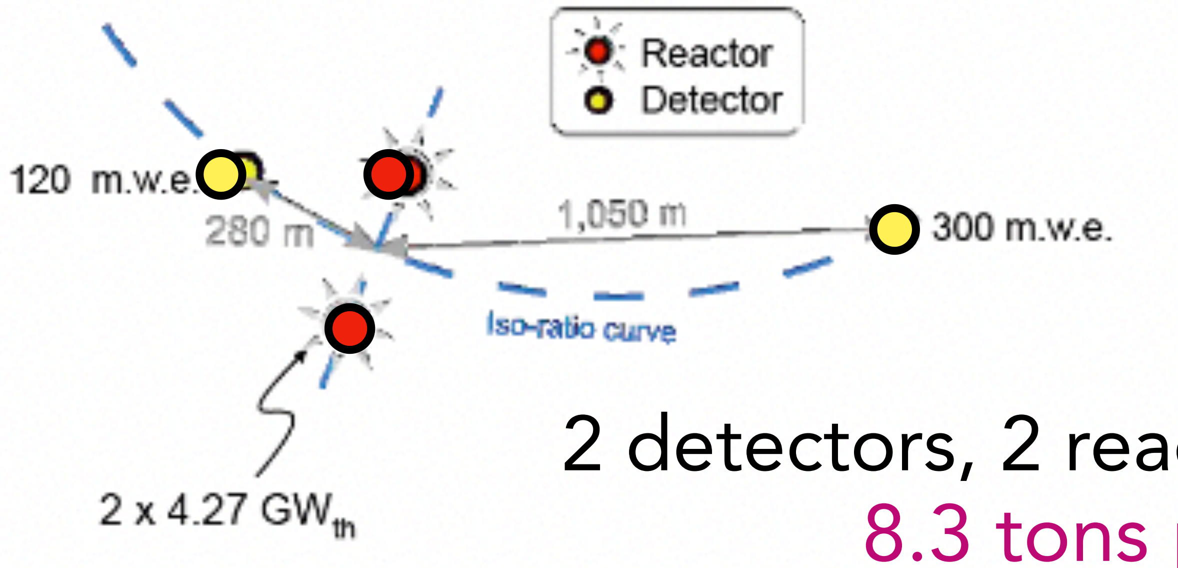


2 detectors, 6 reactors

16.5 tons per detector

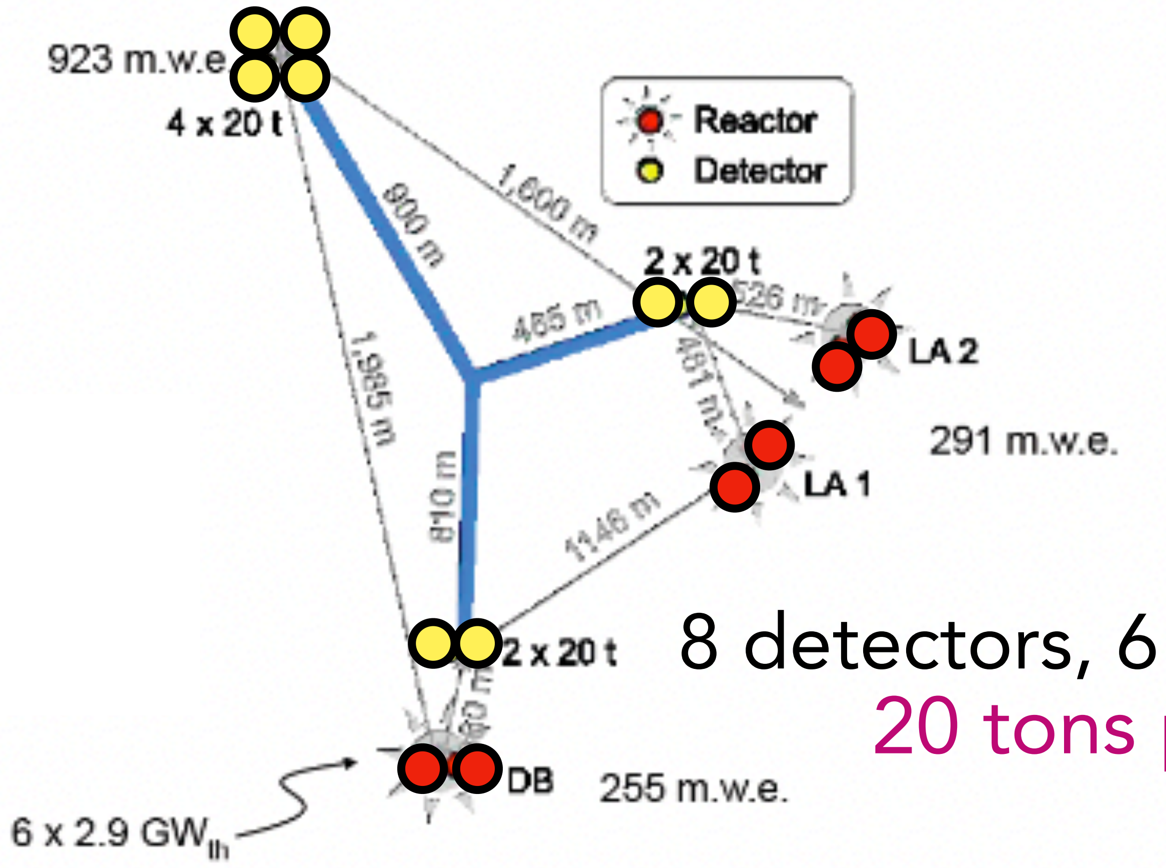
2. Results from the reactor sector: θ_{13} Δm^2_{31}

Double Chooz



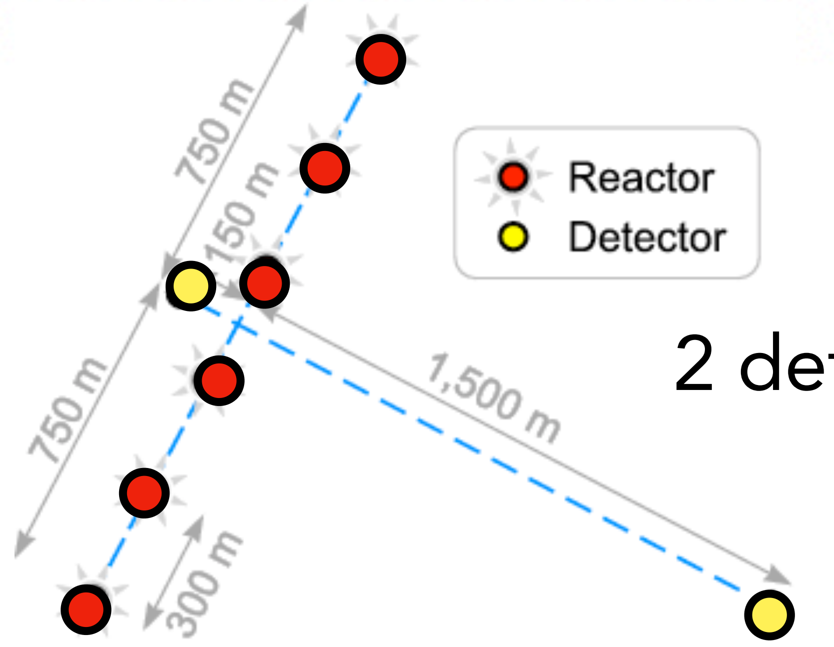
2 detectors, 2 reactors
8.3 tons per detector

Daya Bay



8 detectors, 6 reactors
20 tons per detector

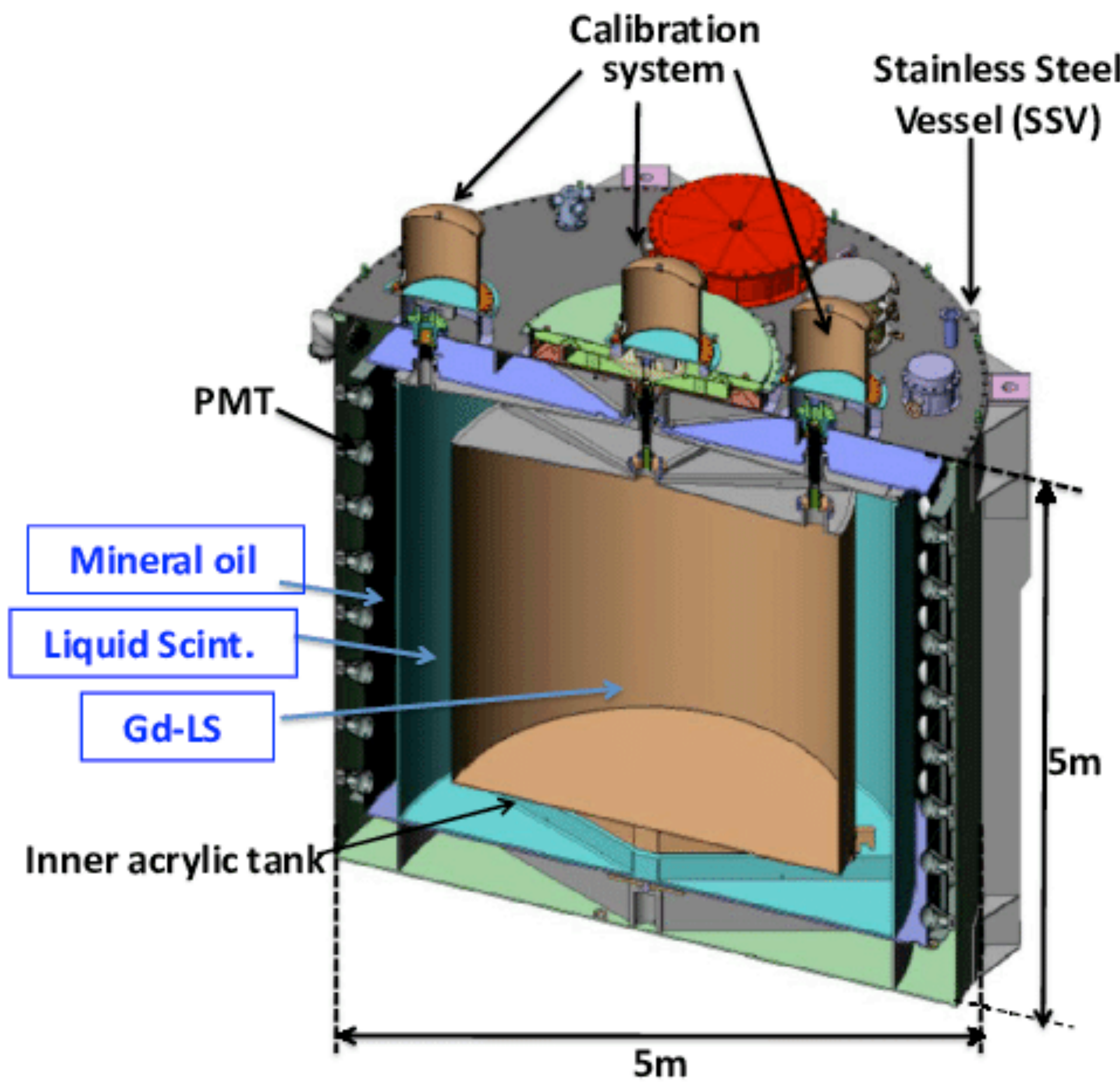
RENO



2 detectors, 6 reactors
16.5 tons per detector

The detectors are typically "three zone" cylindrical modules immersed in water pools

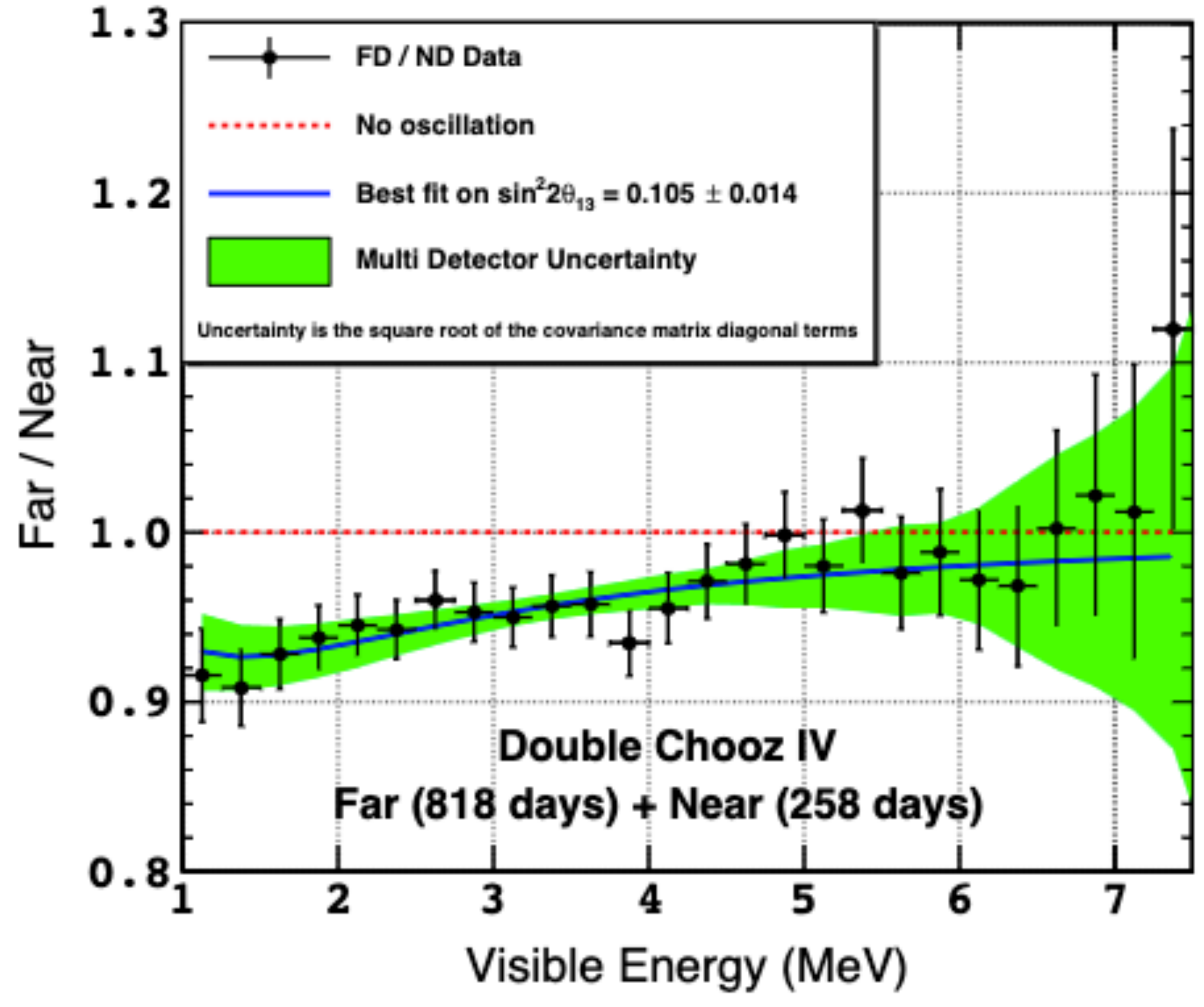
Gd-LS + LS + Mineral Oil



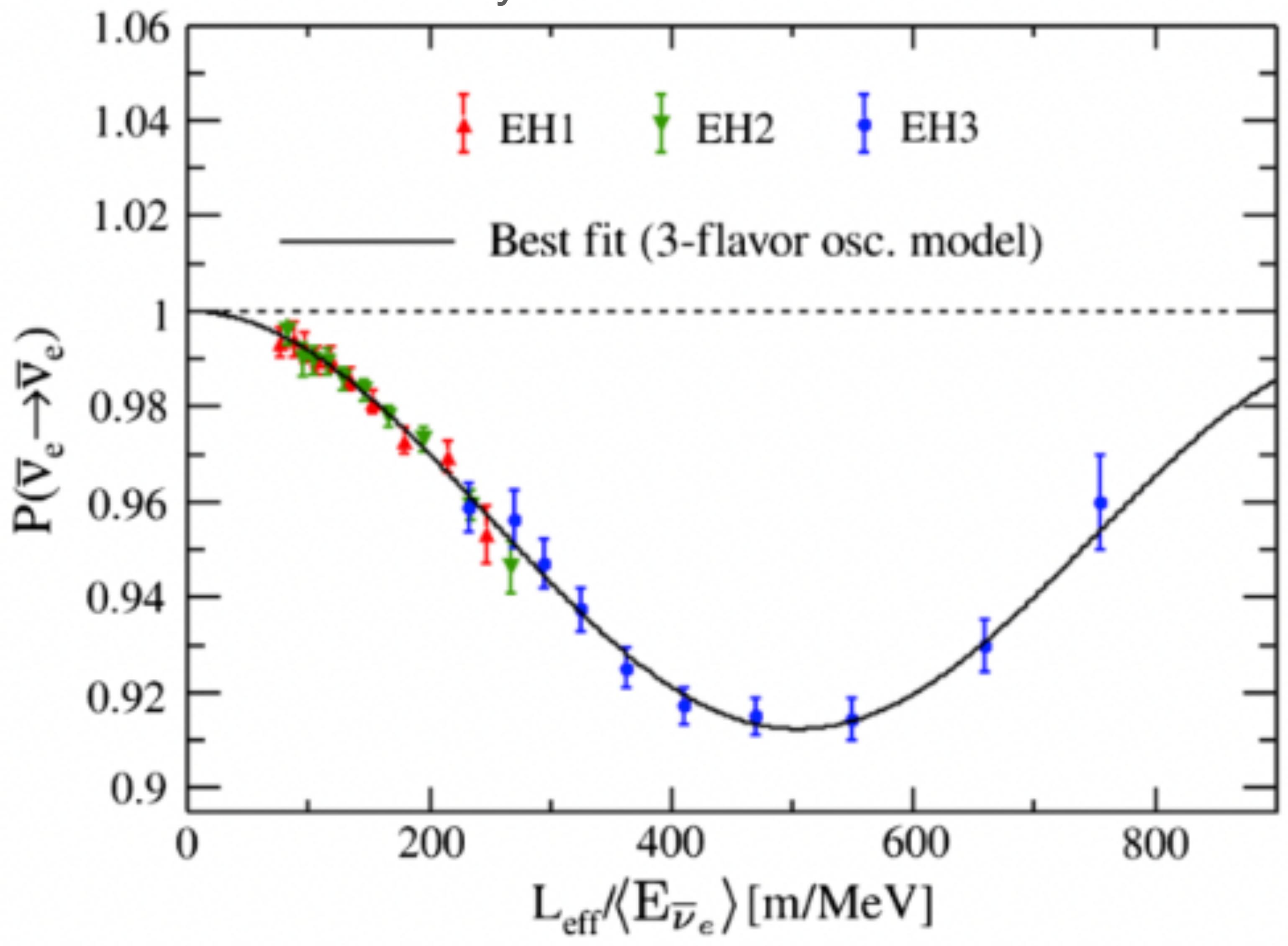
Example of Daya Bay

2. Results from the reactor sector: θ_{13} Δm^2_{31}

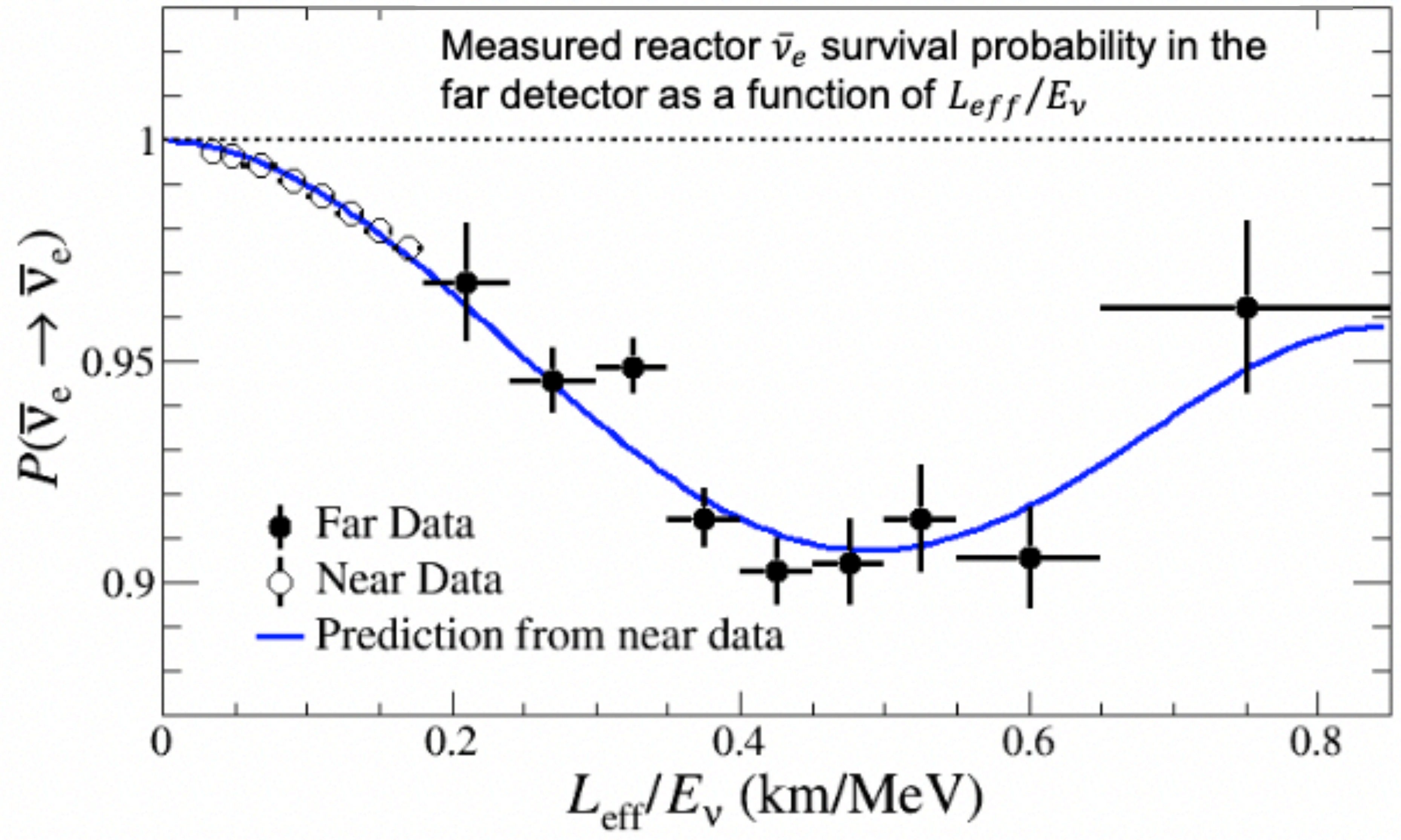
Nature 16 (2020) 558-564



Phys. Rev. Lett. 130 161802



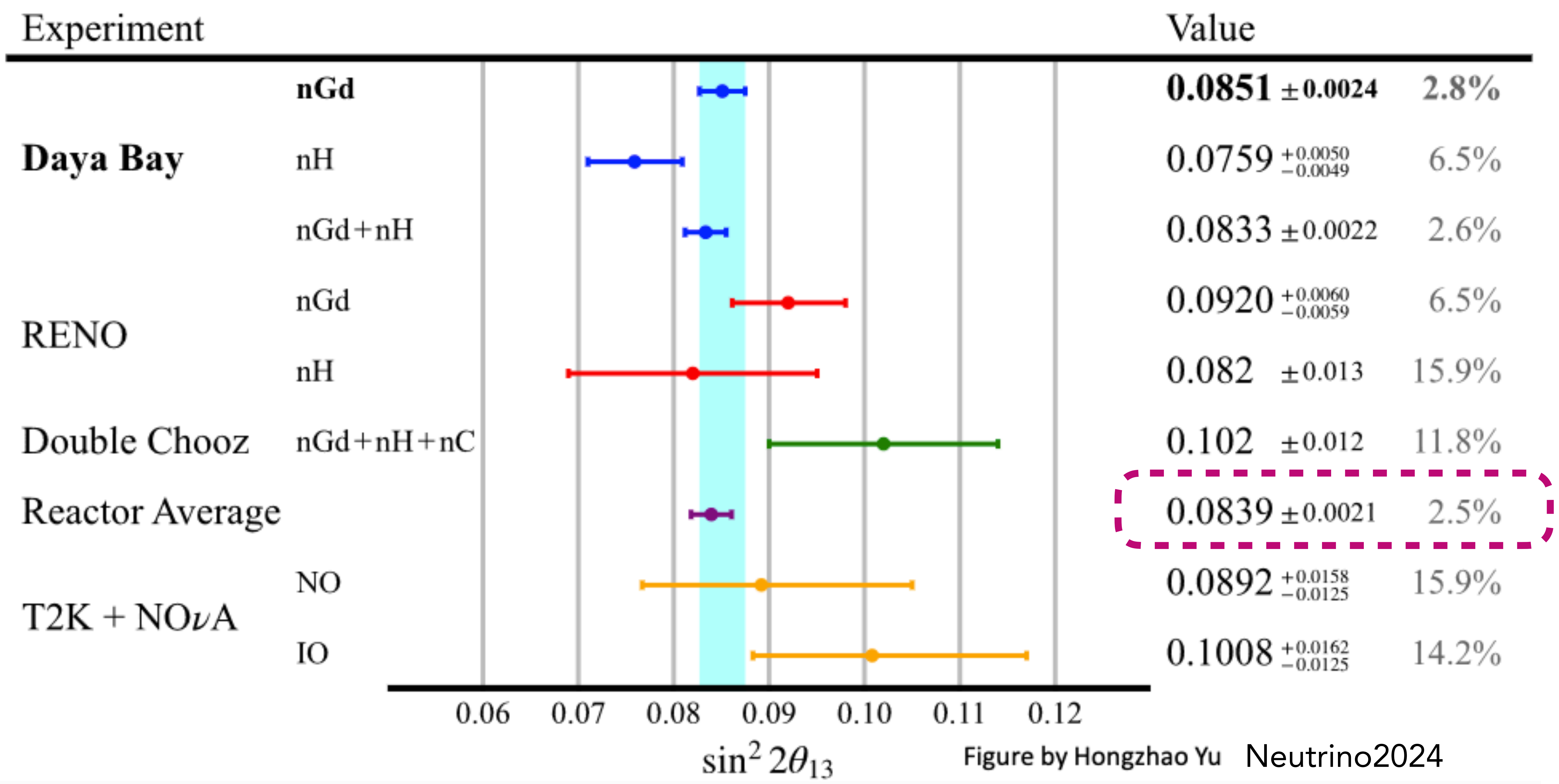
Neutrino 2024



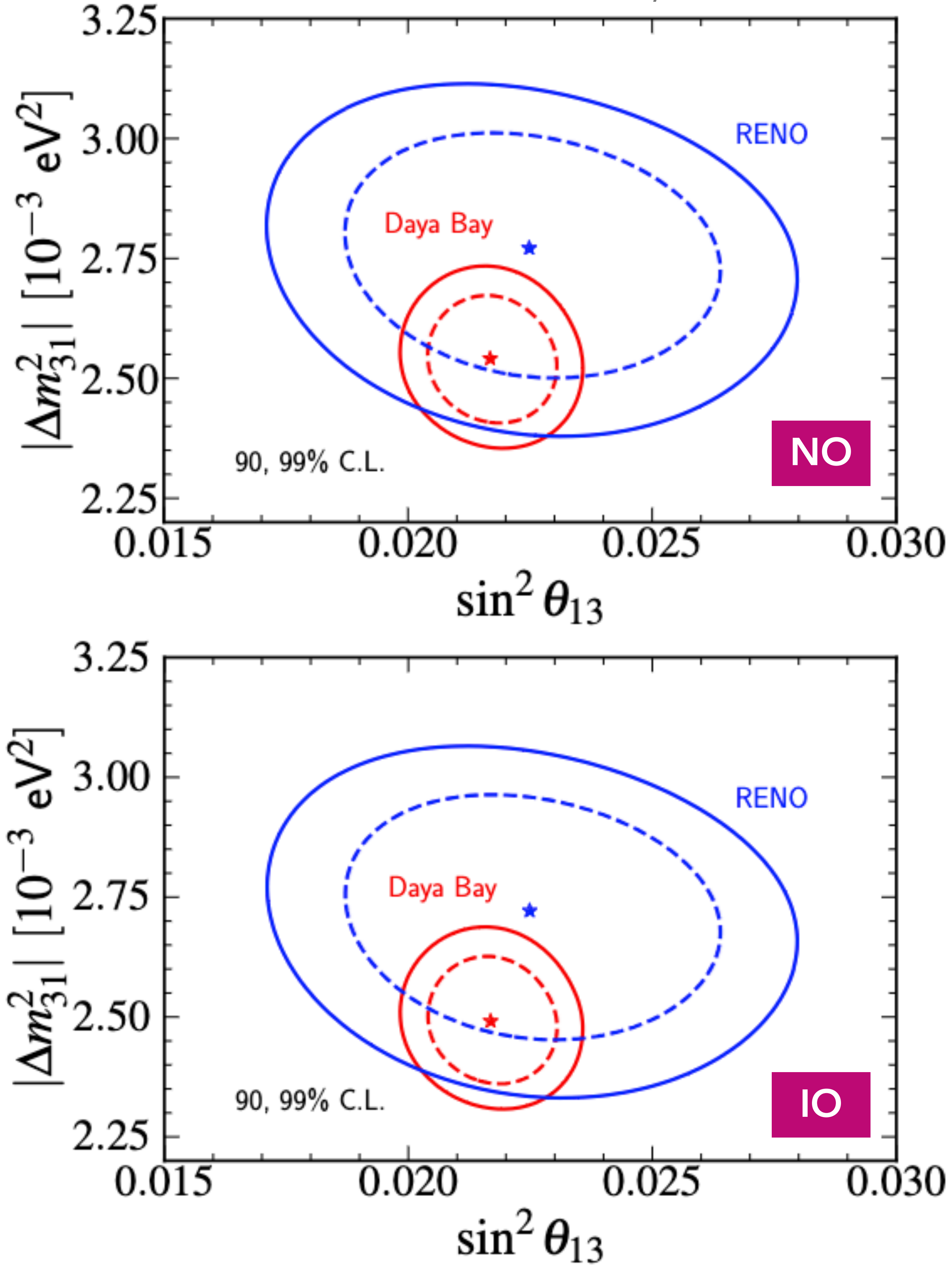
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(1.27 \frac{\Delta m^2_{13}(eV^2) L(m)}{E_\nu(MeV)}\right)$$

2. Results from the reactor sector: θ_{13} Δm^2_{31}

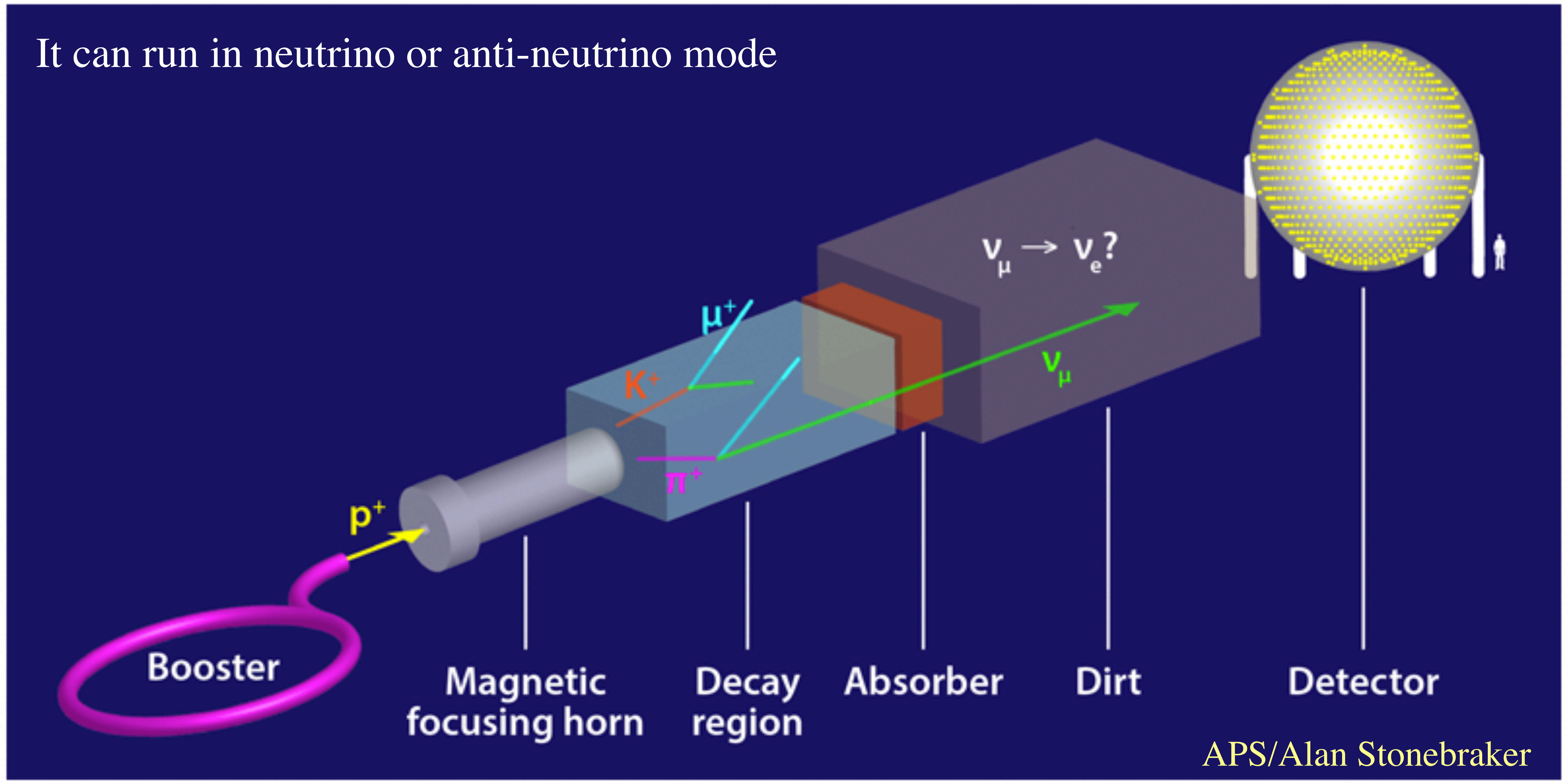
- **Daya Bay leads the precision measurements**
- Results compatibles with accelerators measurements measurements



M. Tórtola, Neutrino2024



3. Results from accelerator neutrinos θ_{23} Δm^2_{32}



Long Baseline: L > 100 km E > 1 GeV

Two Physic Channel

Disappearance	Appearance
$\nu_\mu \longrightarrow \nu_\mu$	$\nu_\mu \longrightarrow \nu_e$

Disappearance:

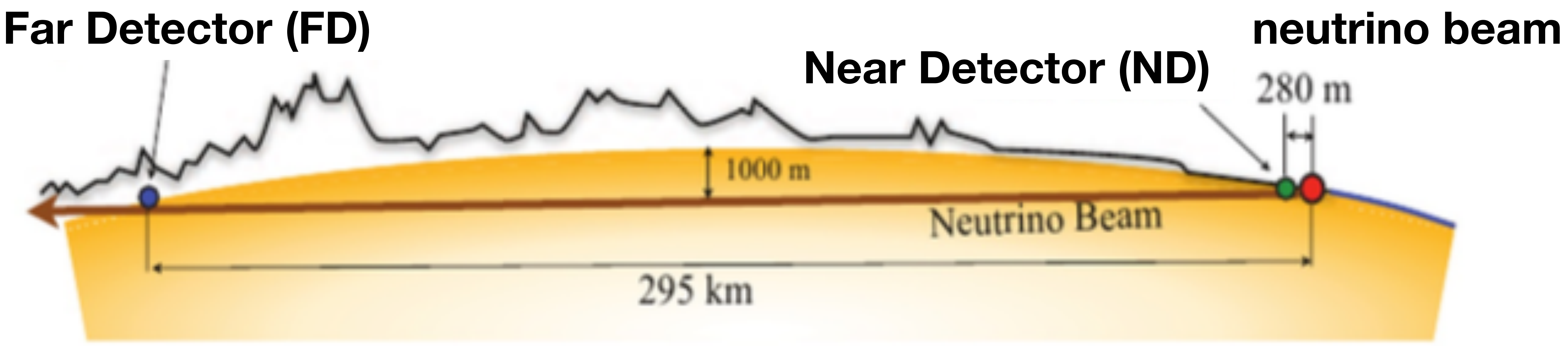
- sensitive to θ_{23} & Δm^2_{32}

Appearance:

- sensitive to Δm^2_{32} & Δm^2_{31}
- sensitive to θ_{23} & θ_{13}
- sensitive to δ_{CP}

Two detectors two characterise the neutrino flux (near and far)

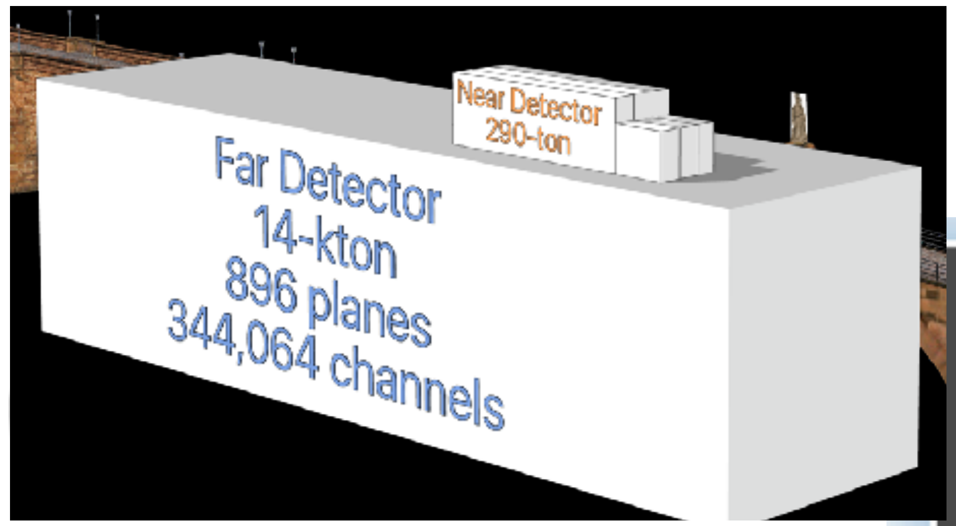
- after traveling long distances many ν_μ disappear.



3. Results from accelerator neutrinos θ_{23} Δm^2_{32}

Based at Fermilab (EEUU)

MINOS



NOVA FD

810 km, 14 kton

MINOS FD

735 km, 5.4 kton

MINOS ND

1 km, 980 ton

steel & scintillator tracking calorimeter to contain muons

Highly active liquid scintillator

NOVA ND

1 km, 290 ton

Same experimental concept:

ND measures before the oscillations and the FD looks for changes relatives to the ND

ND & FD same technology (scintillator)

MINOS/MINOS+:

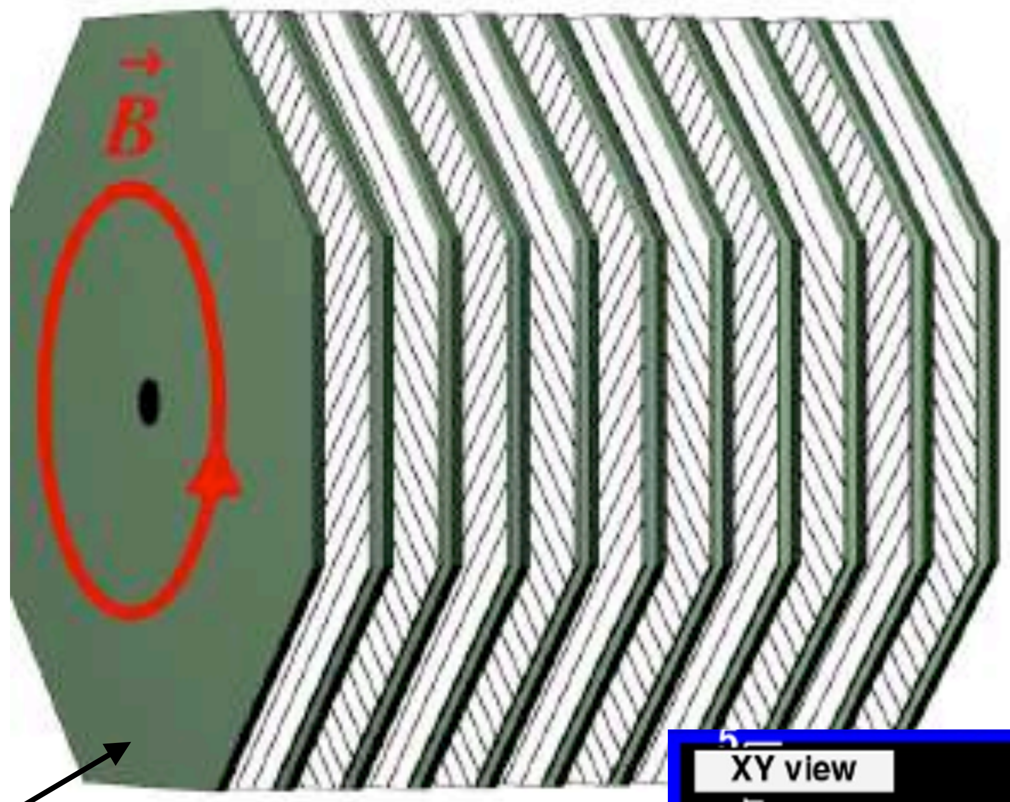
- 2004 - 2016
- For $\nu_\mu \longrightarrow \nu_\mu$
- On-axis
- 350 - 700 kW beam
- E_{peak} 4 - 7 GeV

NOvA:

- 2014 - Present
- For $\nu_\mu \longrightarrow \nu_e$
- Off-axis (14 mrad)
- 700 kW beam
- E_{peak} ~ 2 GeV

3. Results from accelerator neutrinos θ_{23} Δm^2_{32}

MINOS Technology



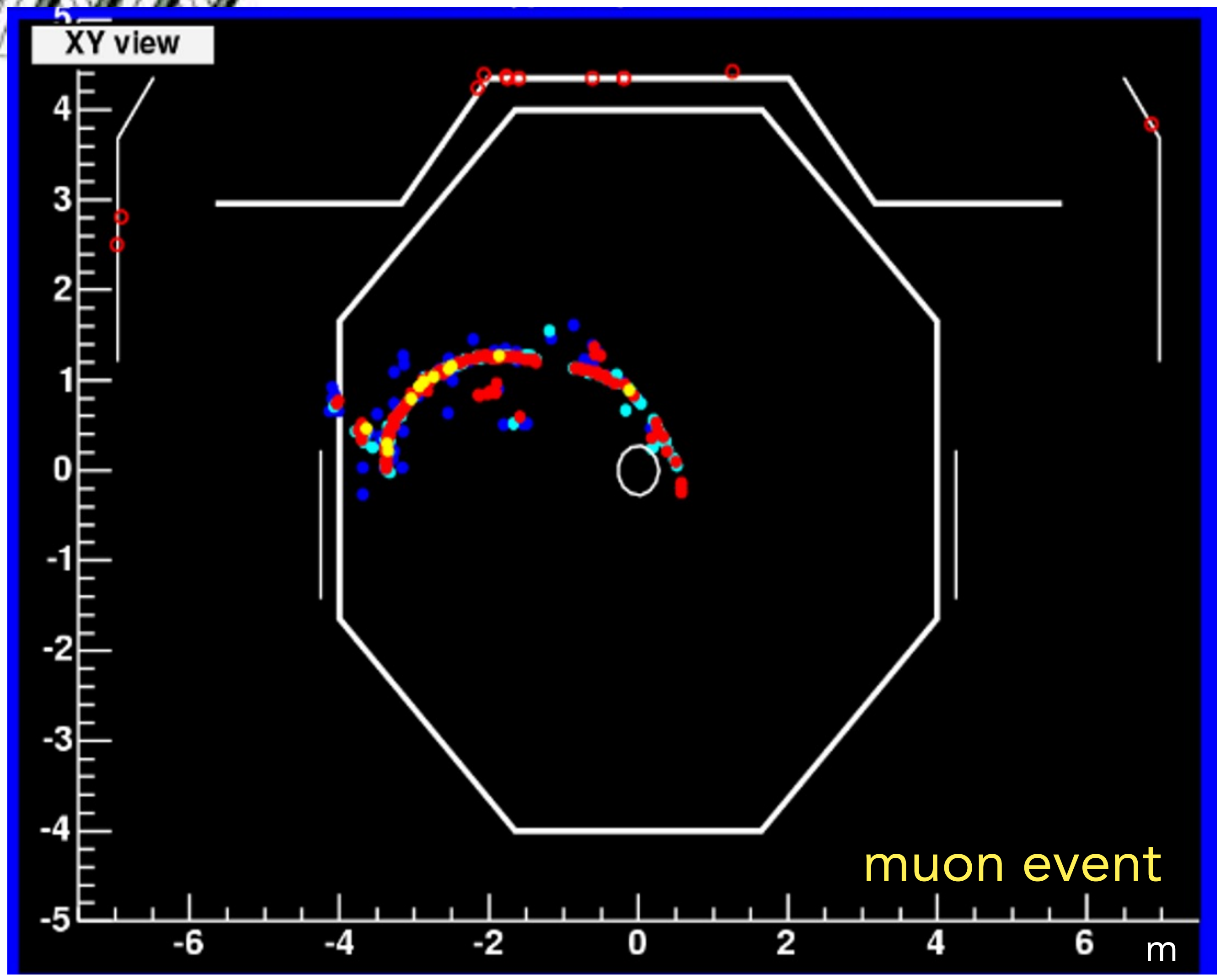
Magnetised steel & plastic scintillators

- 700 m underground

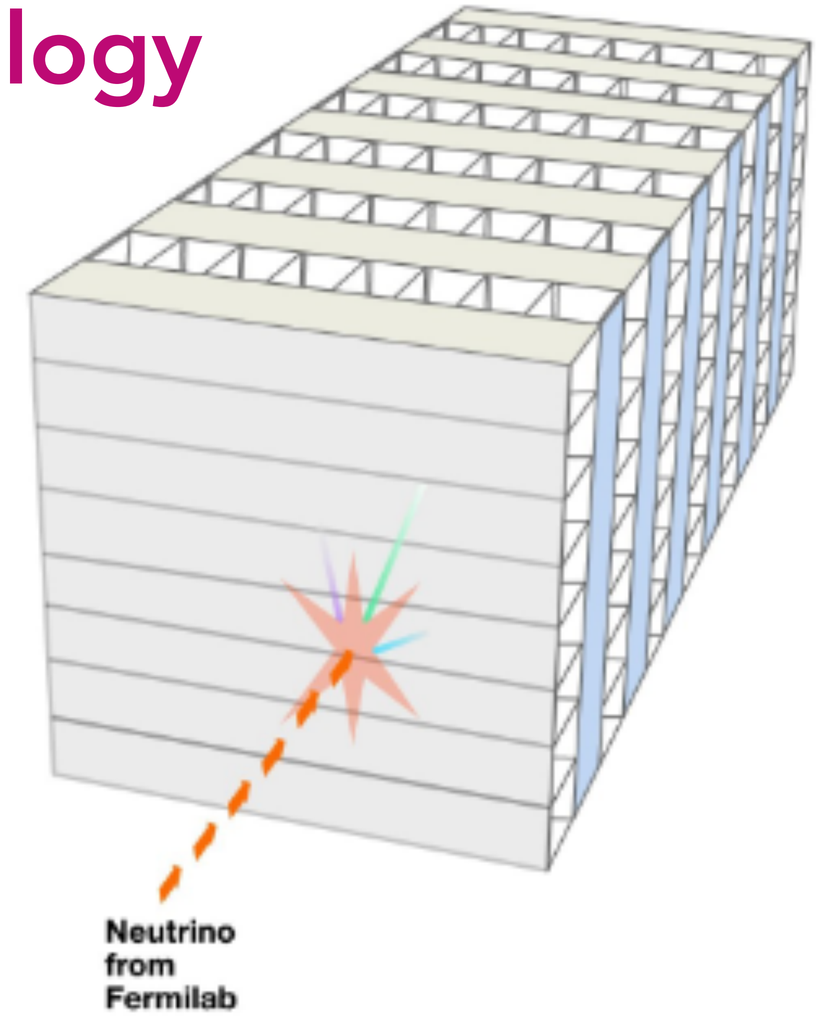
steel

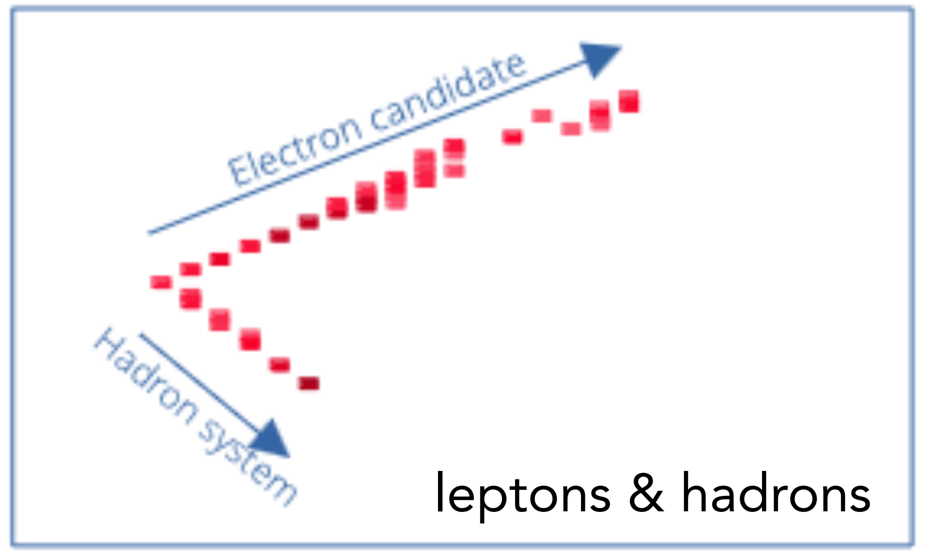
scintillator

- Scintillator (tracks + calorimetry)
- Magnetised steel (charge of the particle)

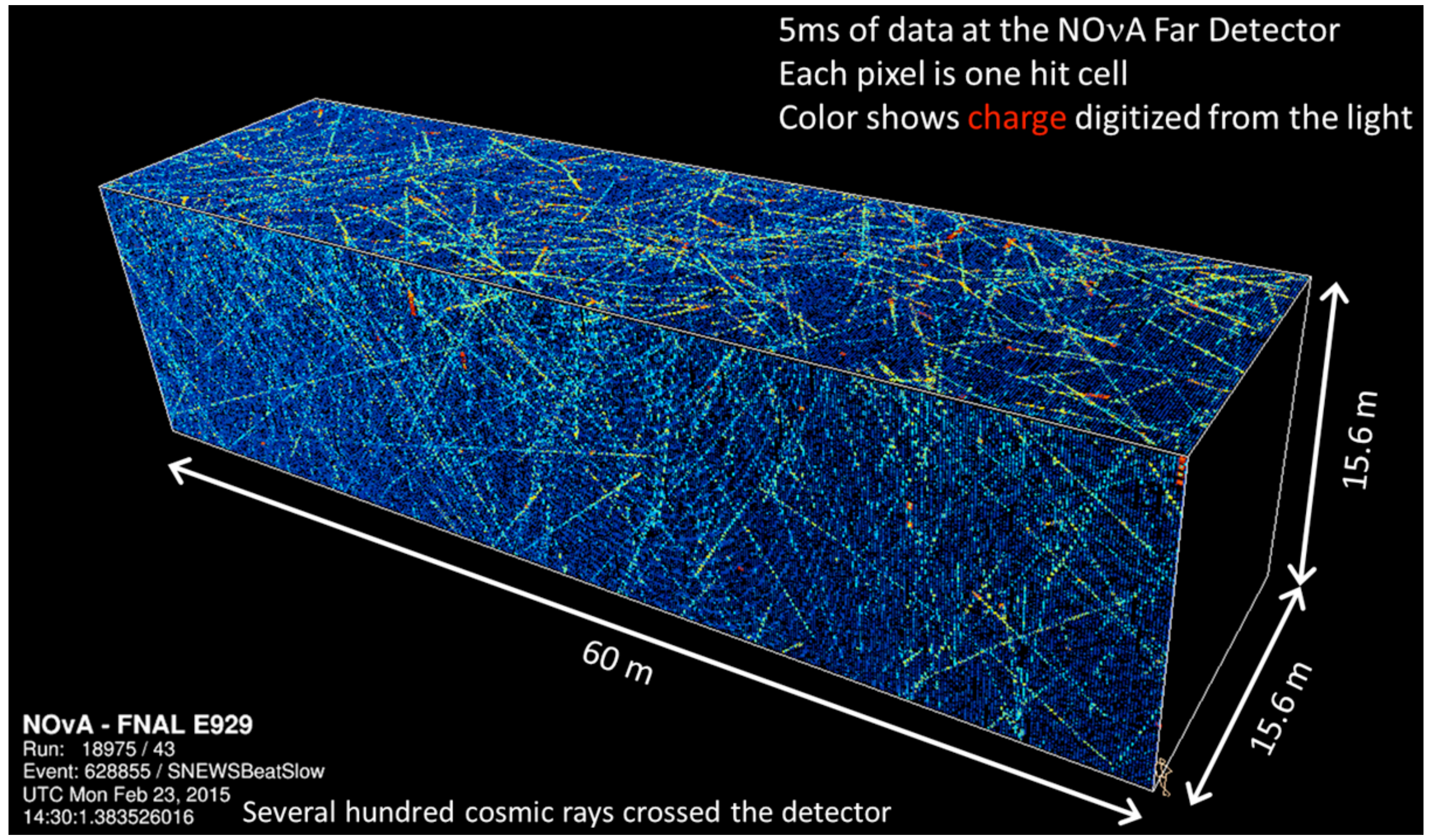


NOVA Technology





344000 cells of PVC filled with liquid scintillator



- Scintillator (tracks + calorimetry)

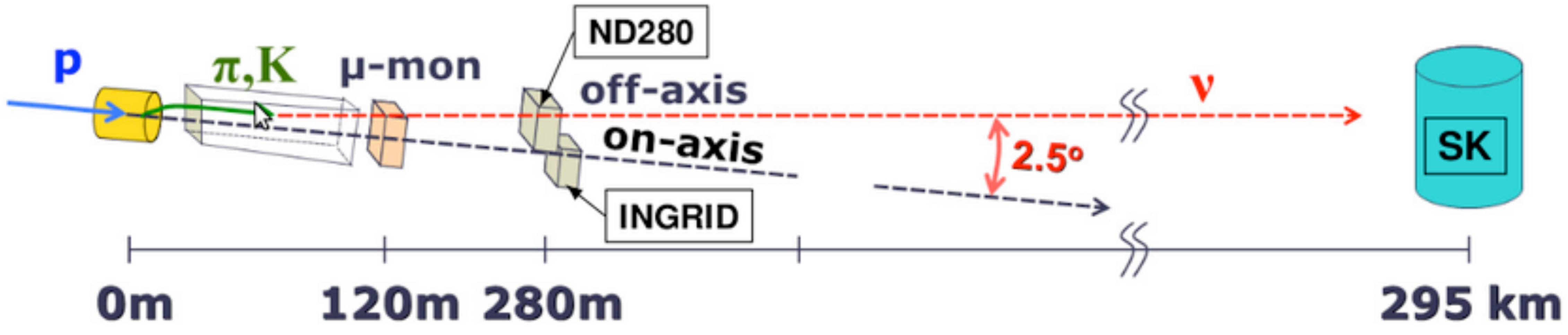
3. Results from accelerator neutrinos θ_{23} Δm^2_{32}

T2K

Tokai to Kamioka

2010 - Present

295 km, 50 kton

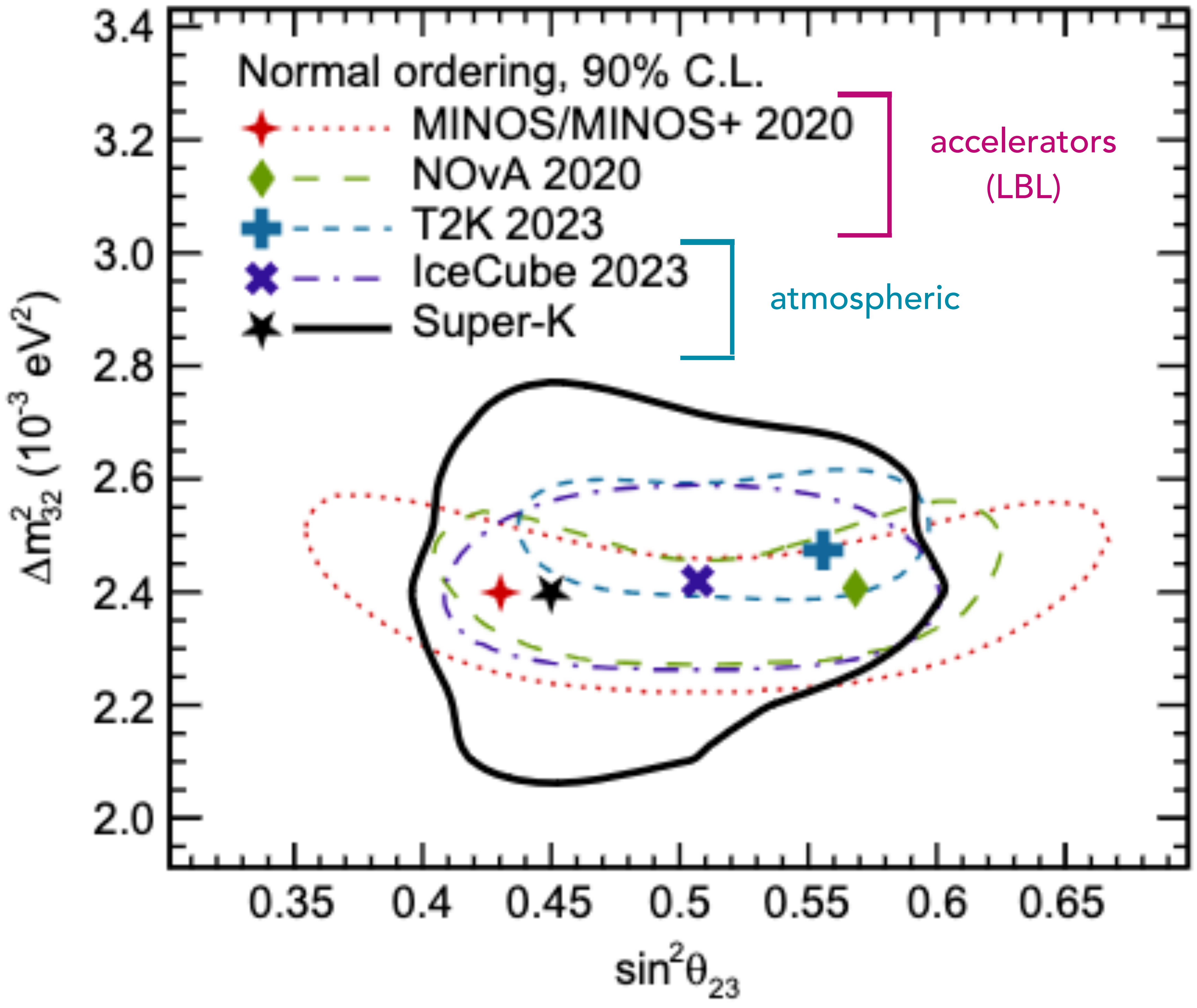


Near detectors with different technology

- ND complex: experiment ND280 (off-axis) + INGRID (on-axis)
- FD: Super-Kamiokande (off-axis)
- 500 kW baseline beam (800 kW in 2024)
- E_{peak} ~ 600 MeV

3. Results from accelerator neutrinos θ_{23} Δm^2_{32}

Phys. Rev. D 109 (2024) 072014



- Combination of experimental results determines

$$sin^2\theta_{23} = 0.564$$ M. Tórtola, Neutrino2024

$$\theta_{23} = 48.7^{\circ}$$

- Δm^2_{32} is 100 times bigger than Δm^2_{21}

$$|\Delta m^2_{32}| = 2.4 \times 10^{-3} eV$$ M. Tórtola, Neutrino2024

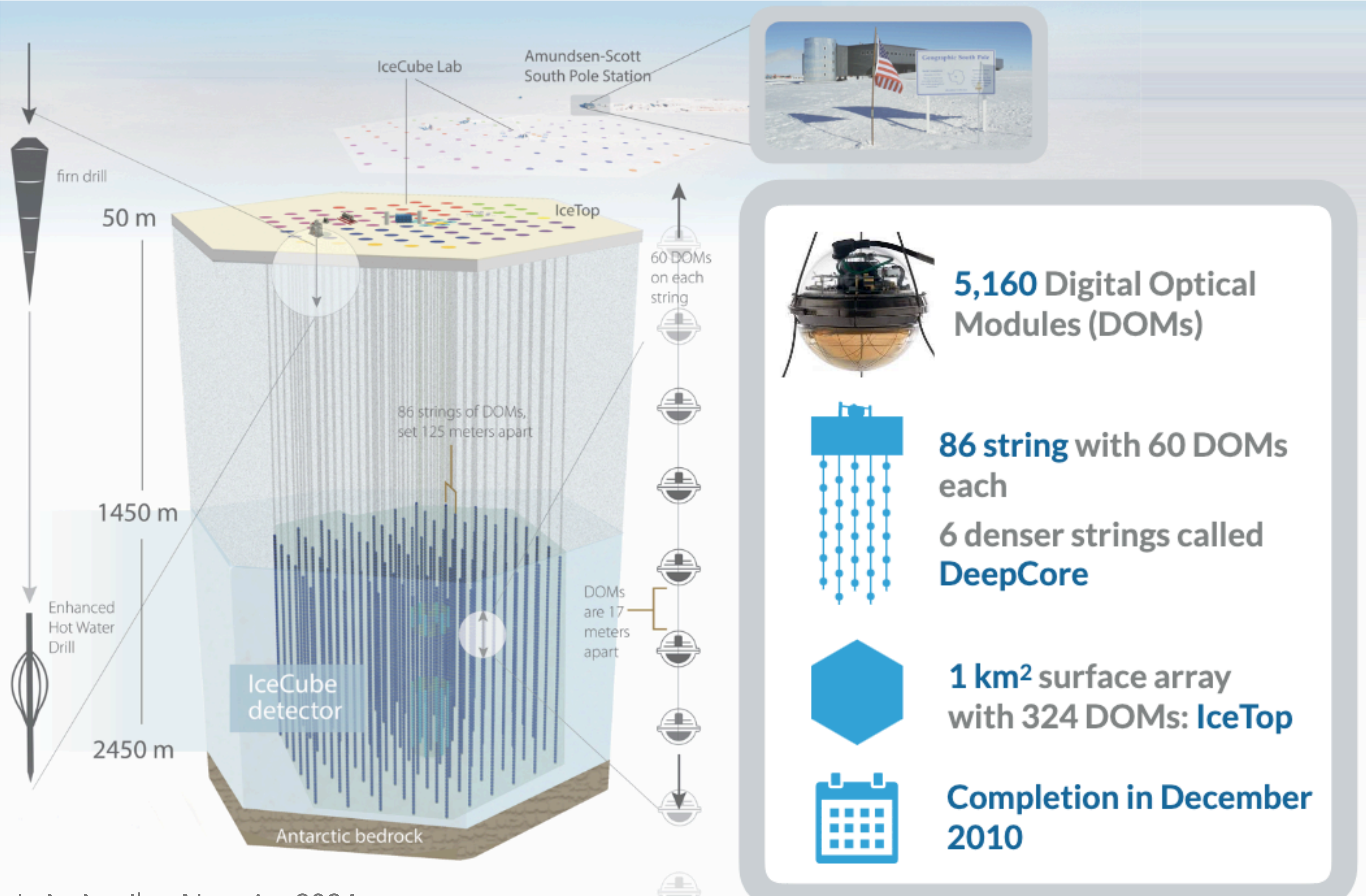
Unlike in the solar sector, the sign of Δm^2_{32} not accesible with the current experiments

- The sign of Δm^2_{32} still unknown

two possible orderings are allowed

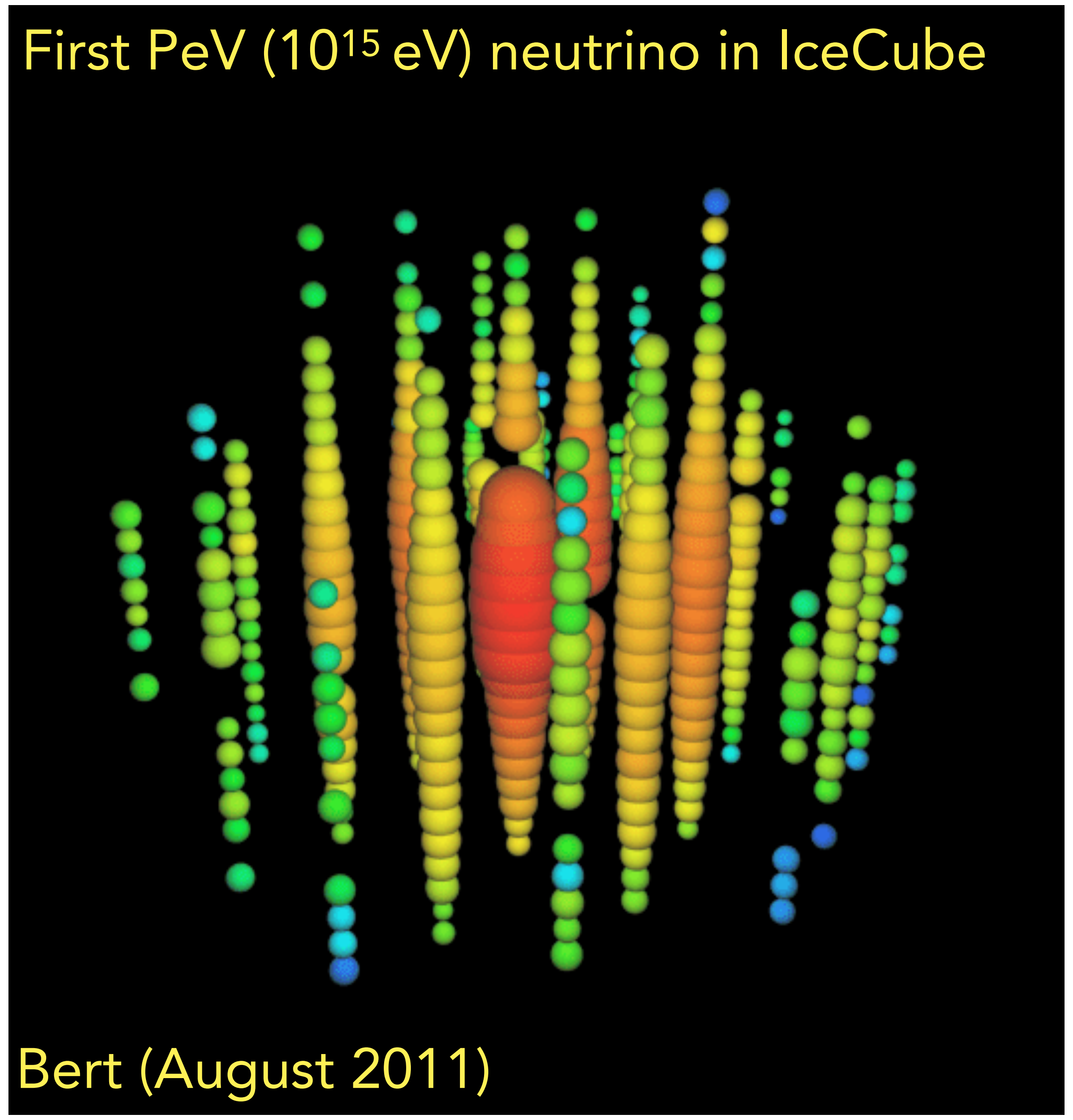
Ultra high energy neutrinos

IceCube Neutrino Observatory

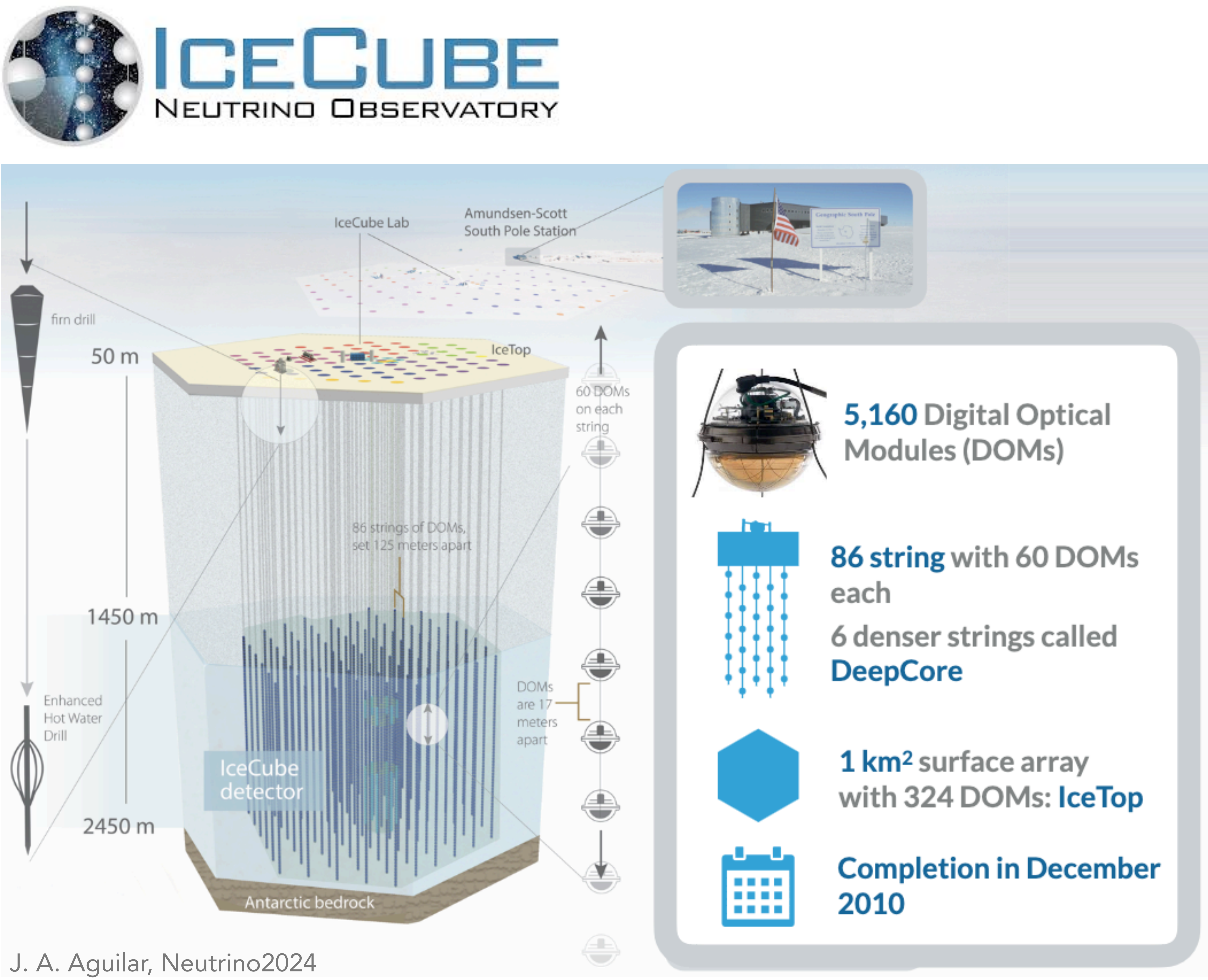


J. A. Aguilar, Neutrino2024

- **Detector:** 1km^3 ice at the South Pole
- **Detection technique:** Cherenkov Radiation
- **Main Goal:** Observe high energy neutrinos

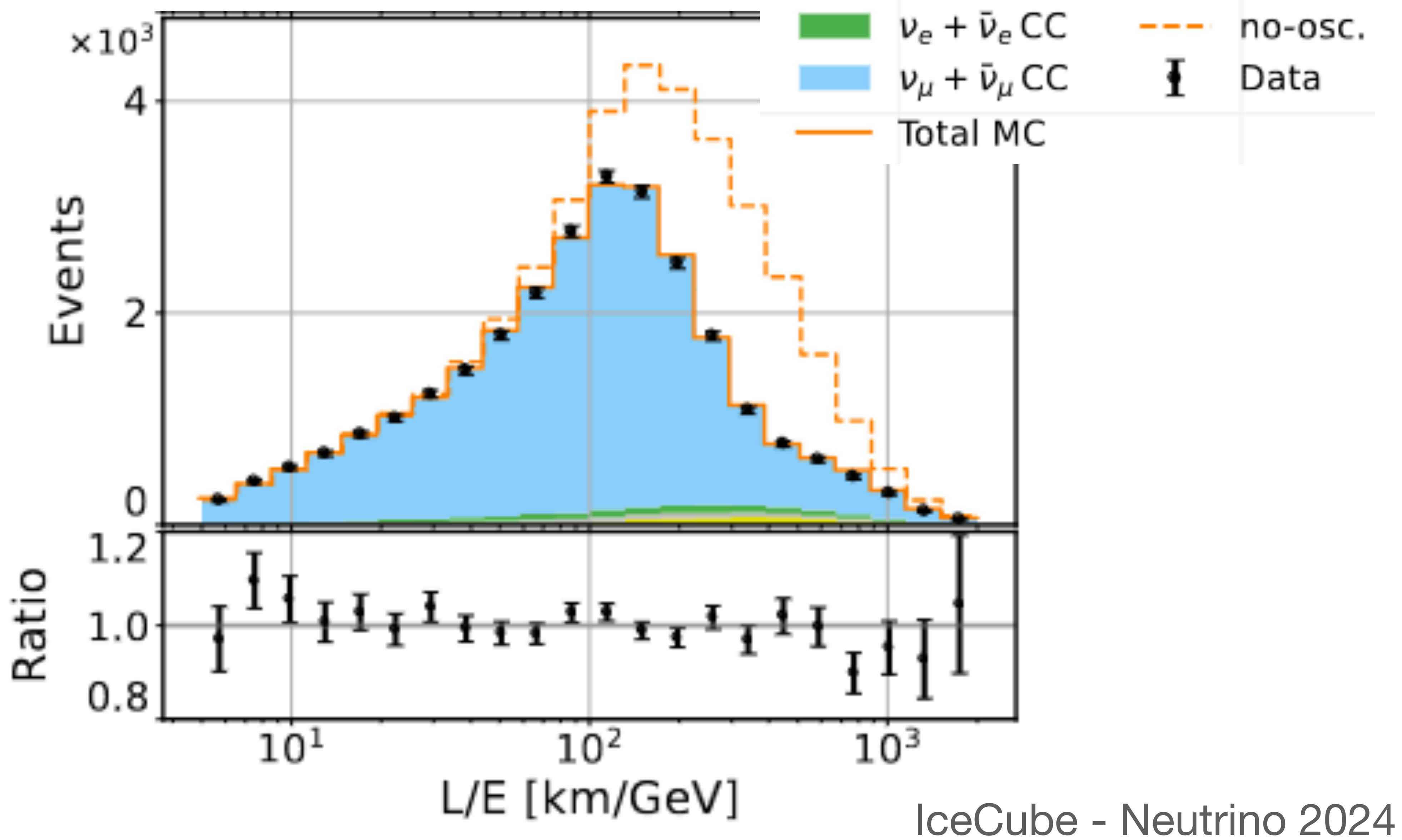


Ultra high energy neutrinos



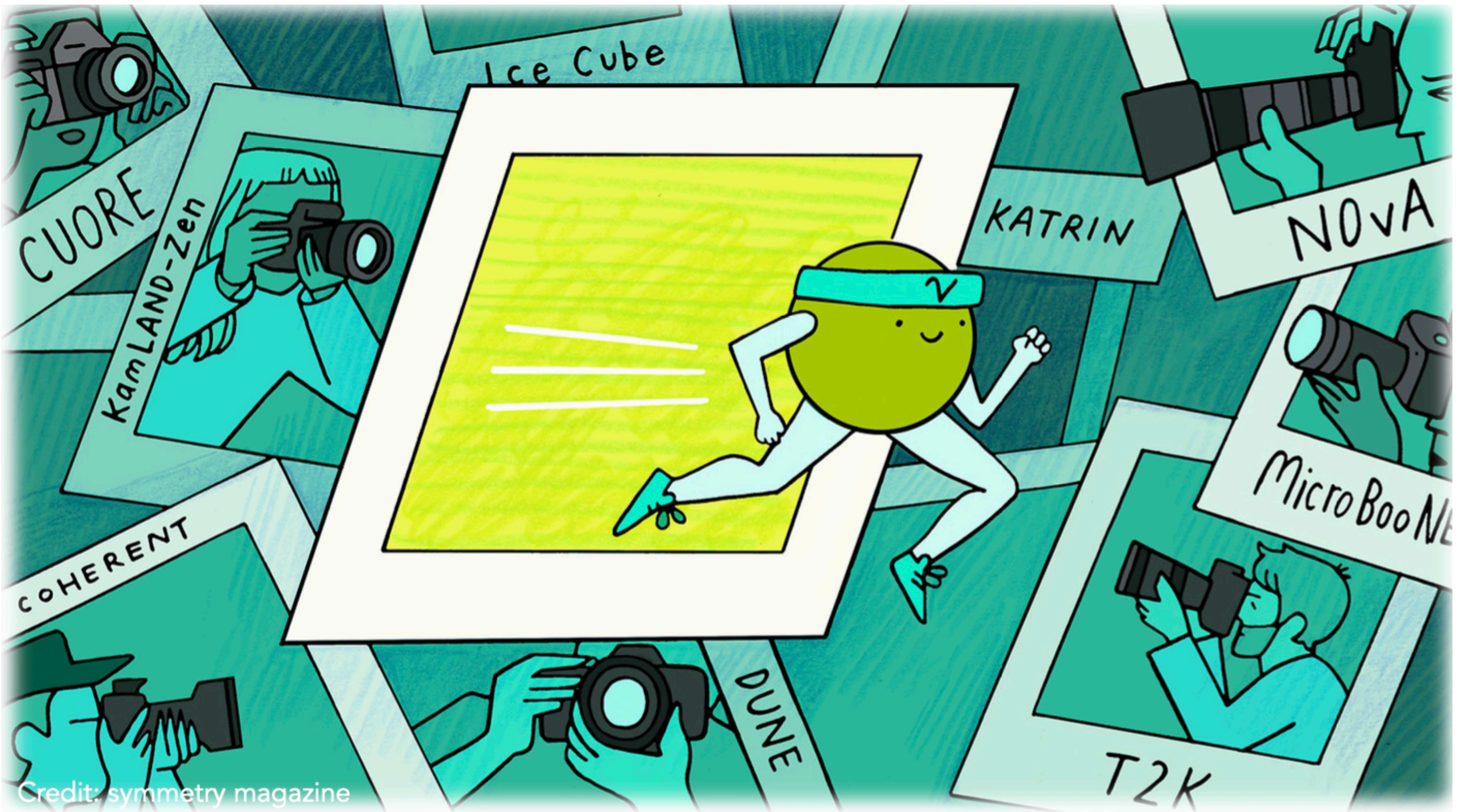
J. A. Aguilar, Neutrino2024

- **Detector:** 1km^3 ice at the South Pole
- **Detection technique:** Cherenkov Radiation
- **Other Goal:** Atmospheric neutrino oscillations
- **How:** DeepCore (dense array of detectors)



IceCube - Neutrino 2024

Conclusions from 2004 - 2024



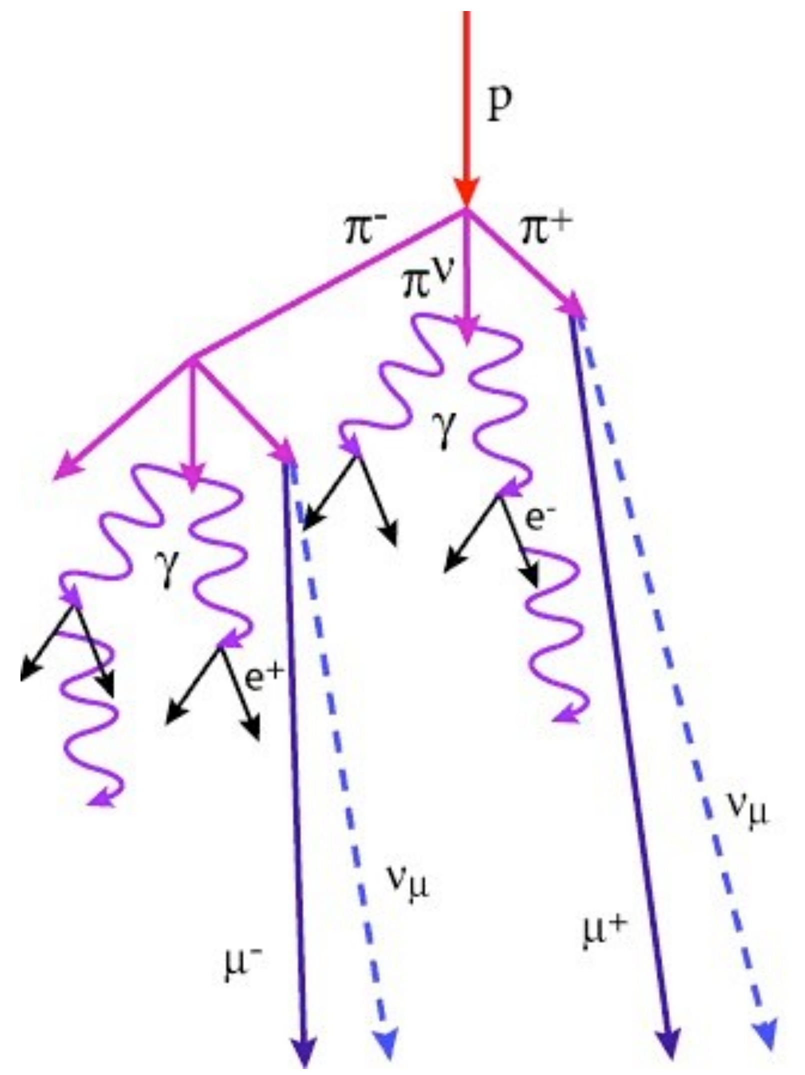
- Firmly stablished the flavour oscillation framework
- Neutrinos do have non-zero masses
- No clue of the absolute mass scale
- Solely experimental evidence of Physics Beyond the SM
- Neutrino oscillation parameters measured experimentally using different neutrino sources (solar, reactors, accelerators + atmospheric) and detector technologies

What next?

Many projects ahead to figure out all the neutrino properties still unknowns

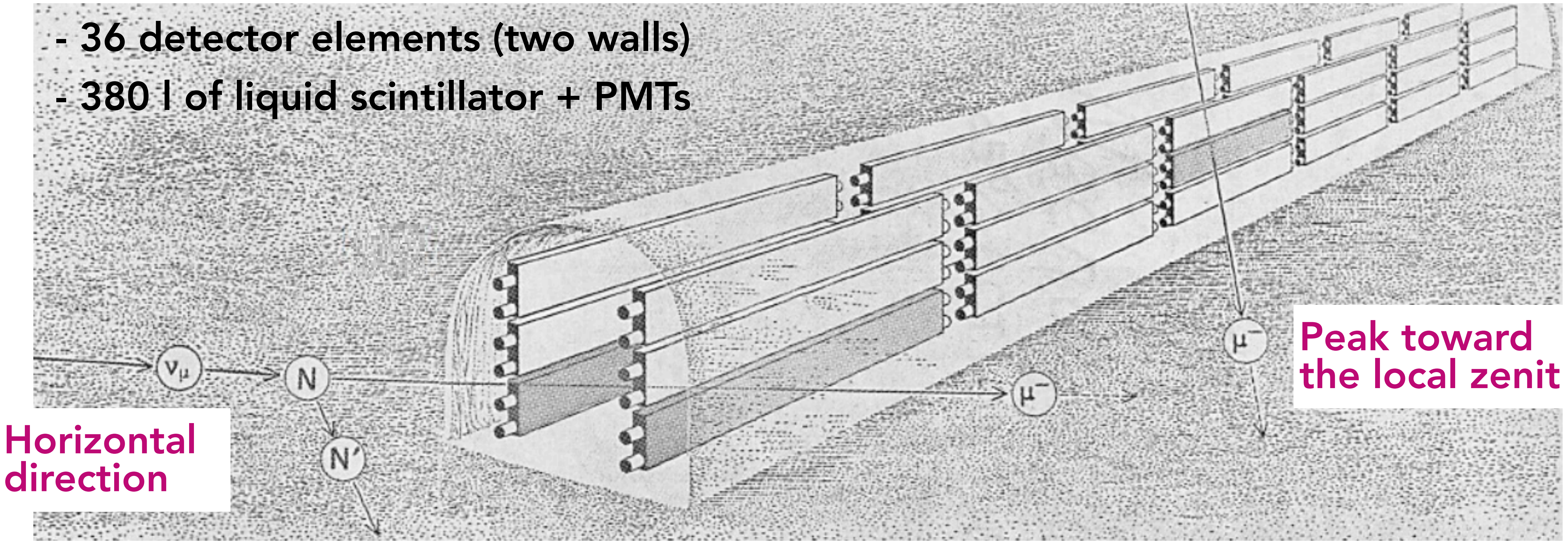
Back Up

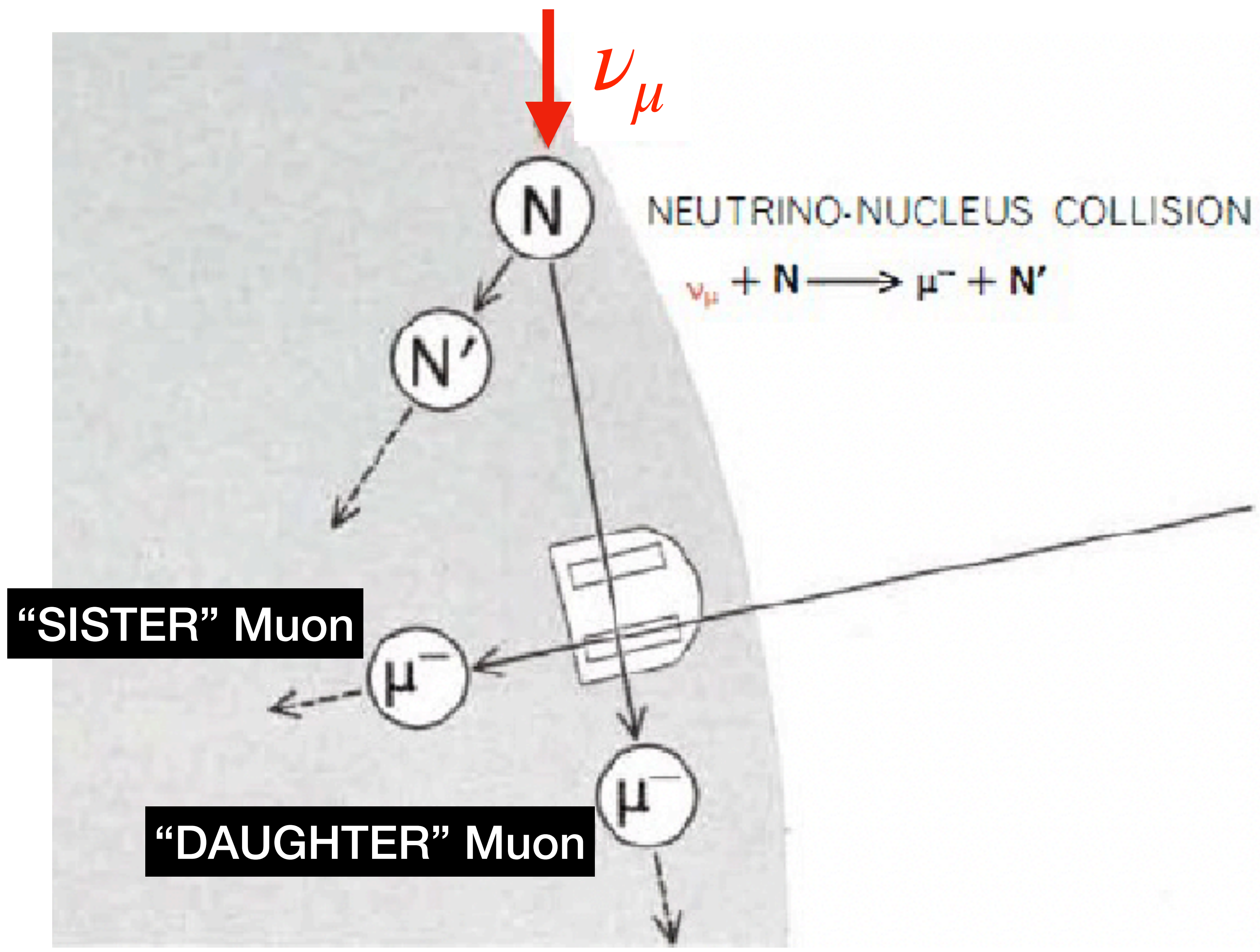
Discovery of the first natural neutrino



- **1965:** Detection of neutrinos from cosmic rays at the deepest mine at the time
  Frederic Reines & Jacques Pierre Friedel Sellschop
- **Location:** East Rand Proprietary Mine (South Africa). 3200 m underground
- **Goal:** Distinguish *sister* muons (produced in the atmosphere) from *daughter* muons (from $\nu\mu$ interaction)

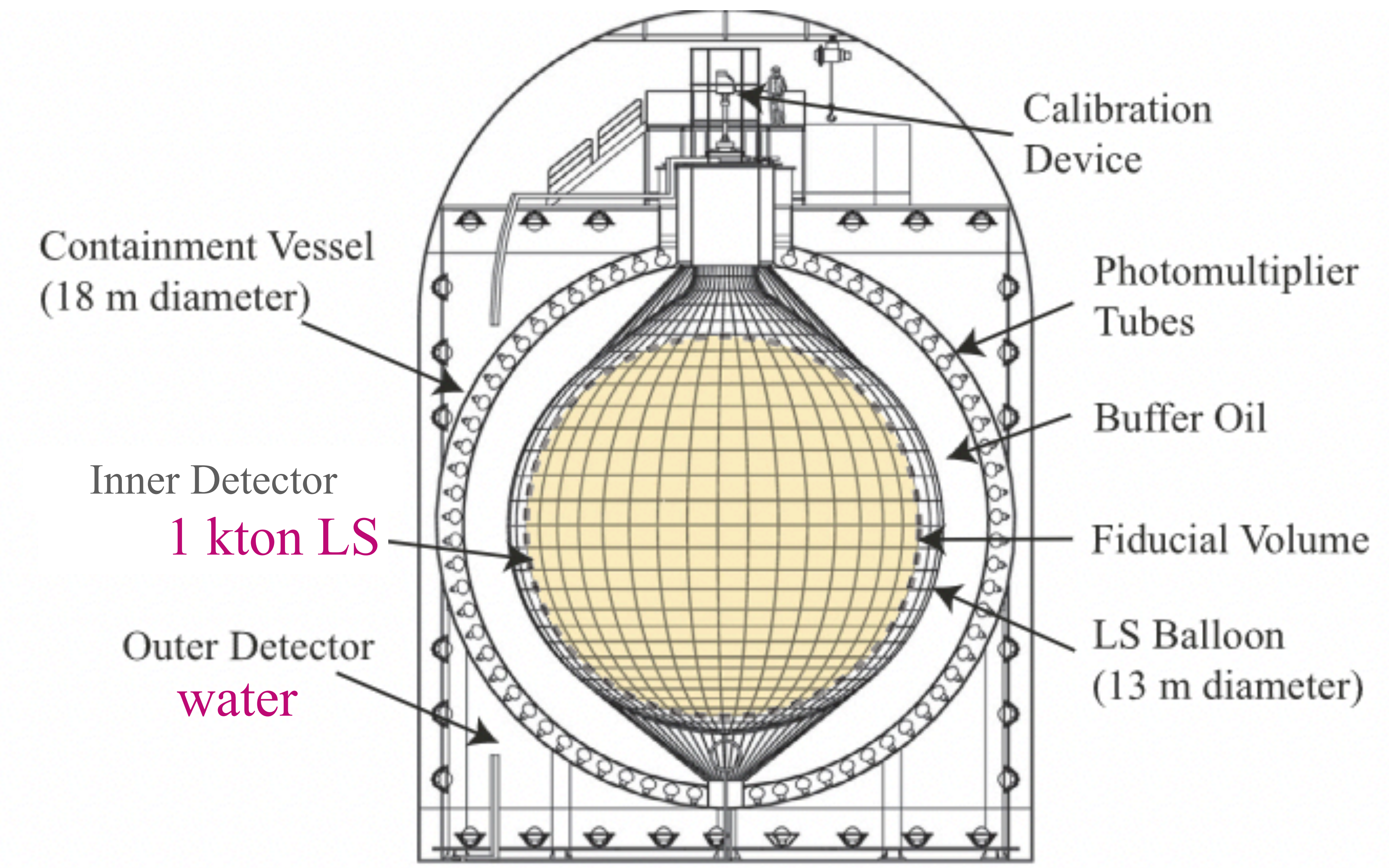
Detector deep underground to reduce the rate of daughter muons





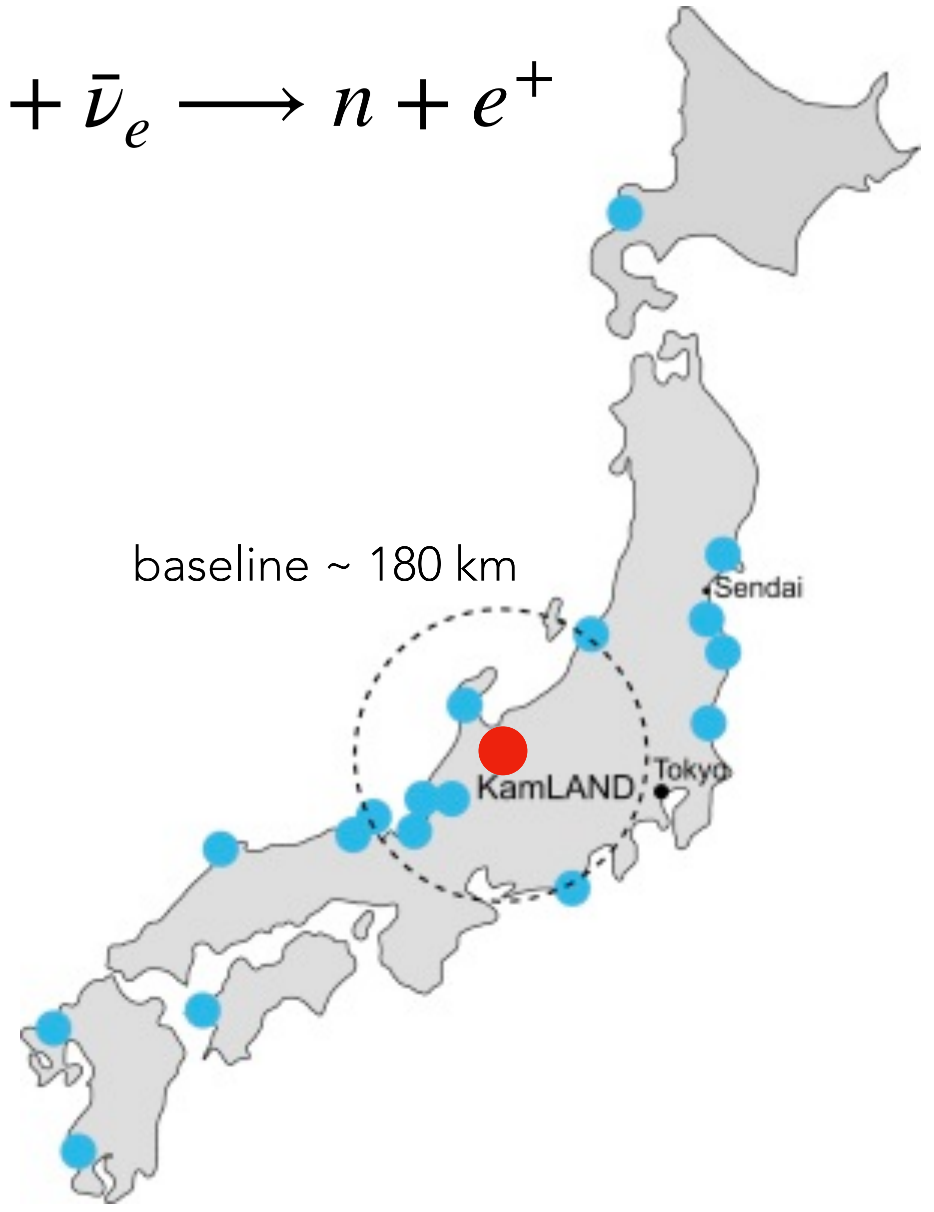
Final confirmation: the KamLAND experiment

KamLAND: Kamioka **L**iquid scintillator **AN**tineutrino **D**etector

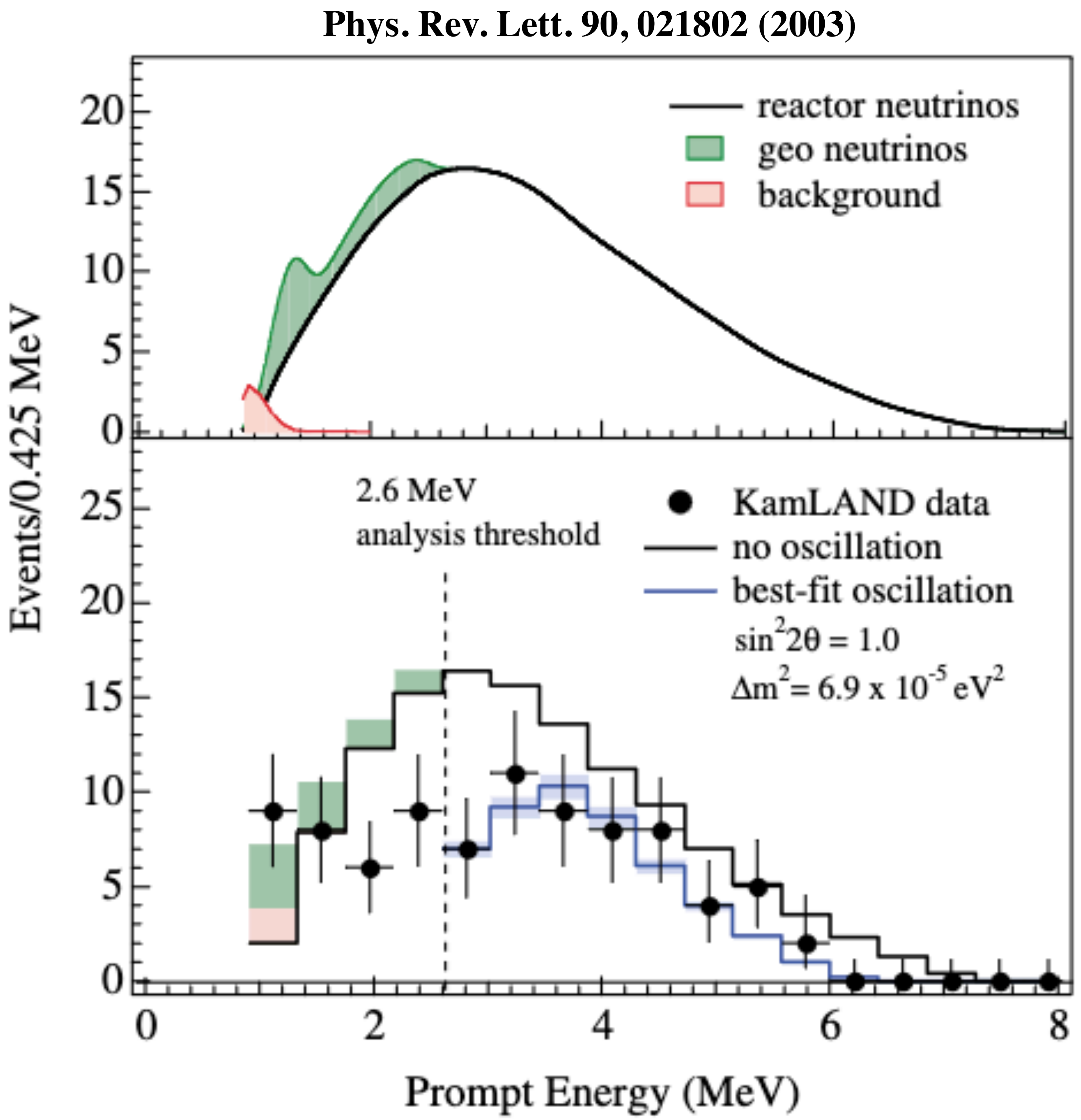


in the Kamioka mine

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



- **2003:** *99,95% CL confirmation of neutrino flavour oscillation*



- **Goal:** Oscillations with neutrinos from all nuclear reactors in Japan
  -> increase statistics
- **Technology:** Liquid scintillator (LS)

  Charge particles (and γ-rays) produced light that is detected by PMTs

Neutrino Discovery

- **1956:** First observation of neutrino interactions by Clyde Cowan and Frederick Reines at the Savannah River Reactor (South Carolina). ~30 years after Pauli's proposal

- **Reaction:** Inverse beta decay with neutrinos <u>from a nuclear reactor</u>

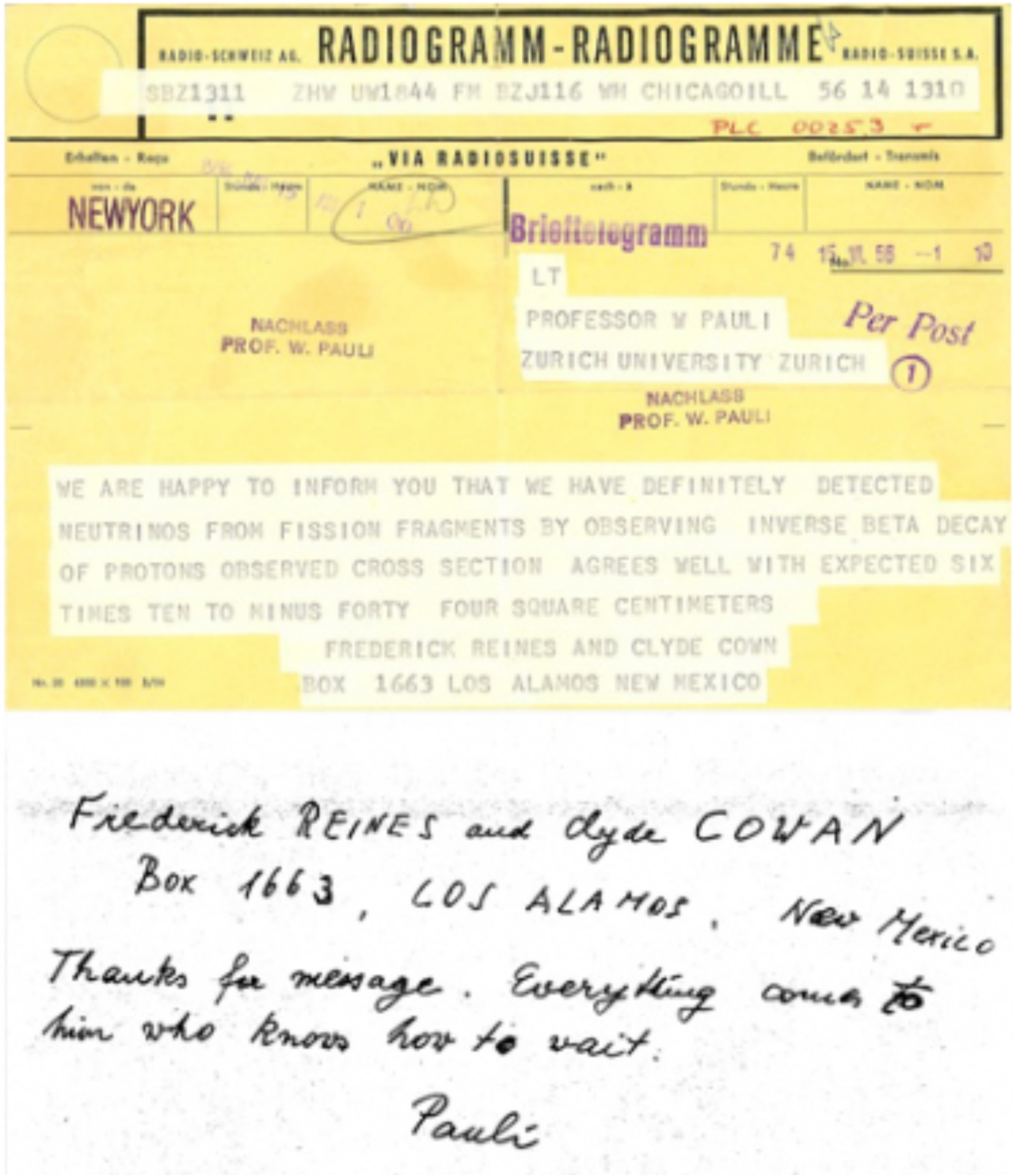
$$p + \bar{\nu}_e \longrightarrow n + e^+$$

- **Detector:** 400 l water + $CdCl_2$ seen by 90 photodetectors

1) prompt signal: $e^+ + e^- \longrightarrow \gamma + \gamma$

2) delayed signal: $n + ^{108}Cd \longrightarrow ^{109}Cd^* \longrightarrow ^{109}Cd + \gamma'$

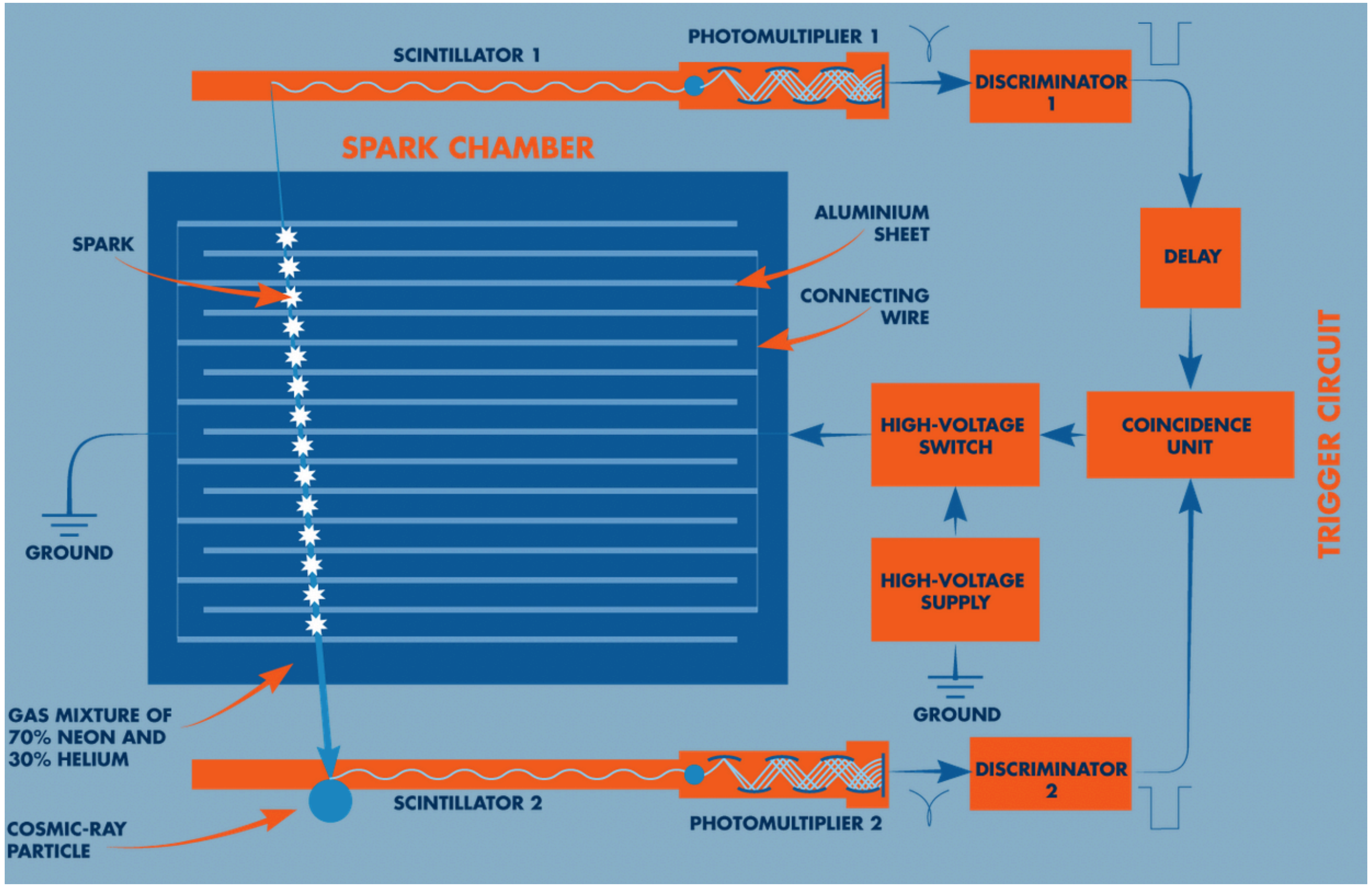
Signal: delayed (few μs) coincidence reactions


RADIOGRAMM-RADIOGRAMME
NEWYORK
Briefteiegramm
LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

1995: (1/2) Nobel prize to Frederick Reines "for the detection of the neutrino" 

Spark Chamber



- Several metal plates in a sealed box
- Filled with a gas (He or Ne)
- High voltage among the plates
- Charged particles ionised the gas while passing through
- Due to the high voltage the ionisation produces sparks along the trajectory of the particle

Decay width or decay constant, Γ

- Γ : decay rate or decay width

$$dN = -\Gamma N dt \qquad N(t) = N(0)e^{-\Gamma t} \qquad \tau = \frac{1}{\Gamma}$$ lifetime

- Heisenberg's principle suggests that particles with extremely short lifetimes (Δt << 0) there will be a significant uncertainty in the measured energy

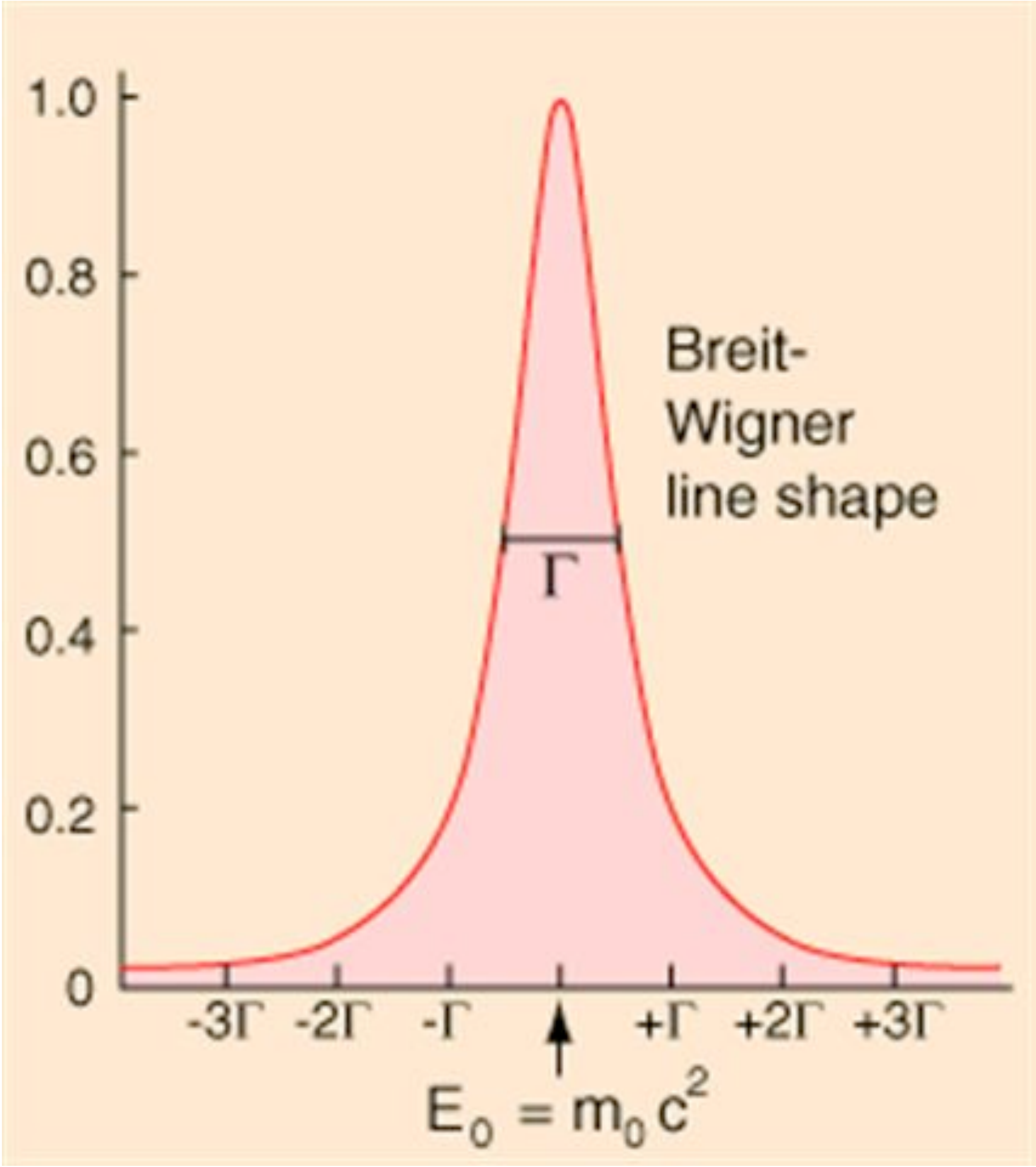
$$\Delta E \Delta t > \hbar/2$$

- When measuring the rest mass of an unstable particle a distribution is obtained. The width of this distribution is Γ

$$2\Delta E = \frac{\hbar}{\Delta t} = \frac{\hbar}{\tau} = \Gamma$$ natural units

- When using natural units Γ has the same dimension as the mass (energy)

- For several decay modes: $Br_i = \frac{\Gamma_i}{\Gamma_{total}}$ Branching ratios



Neutrino oscillations: theory

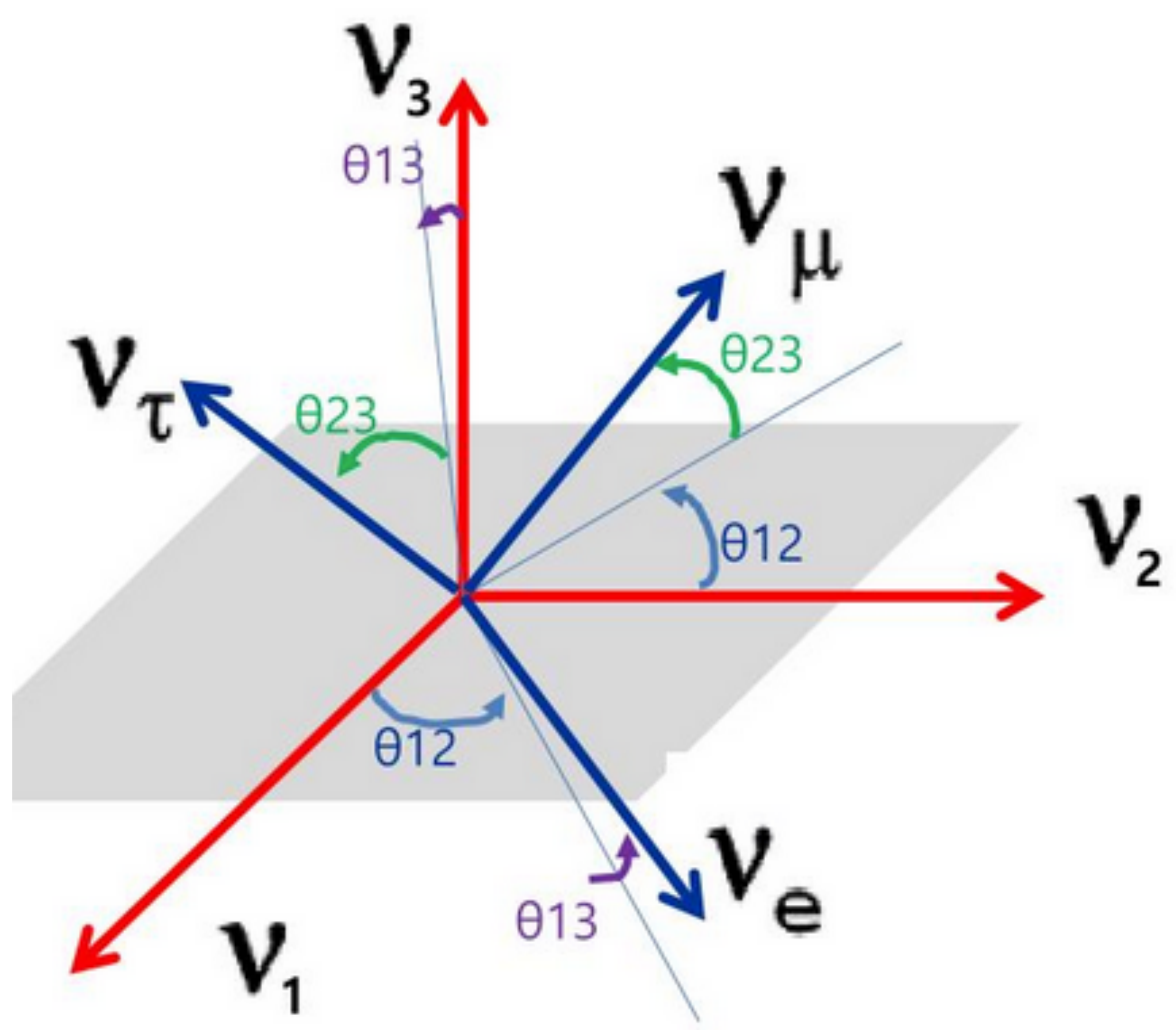
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (1962)

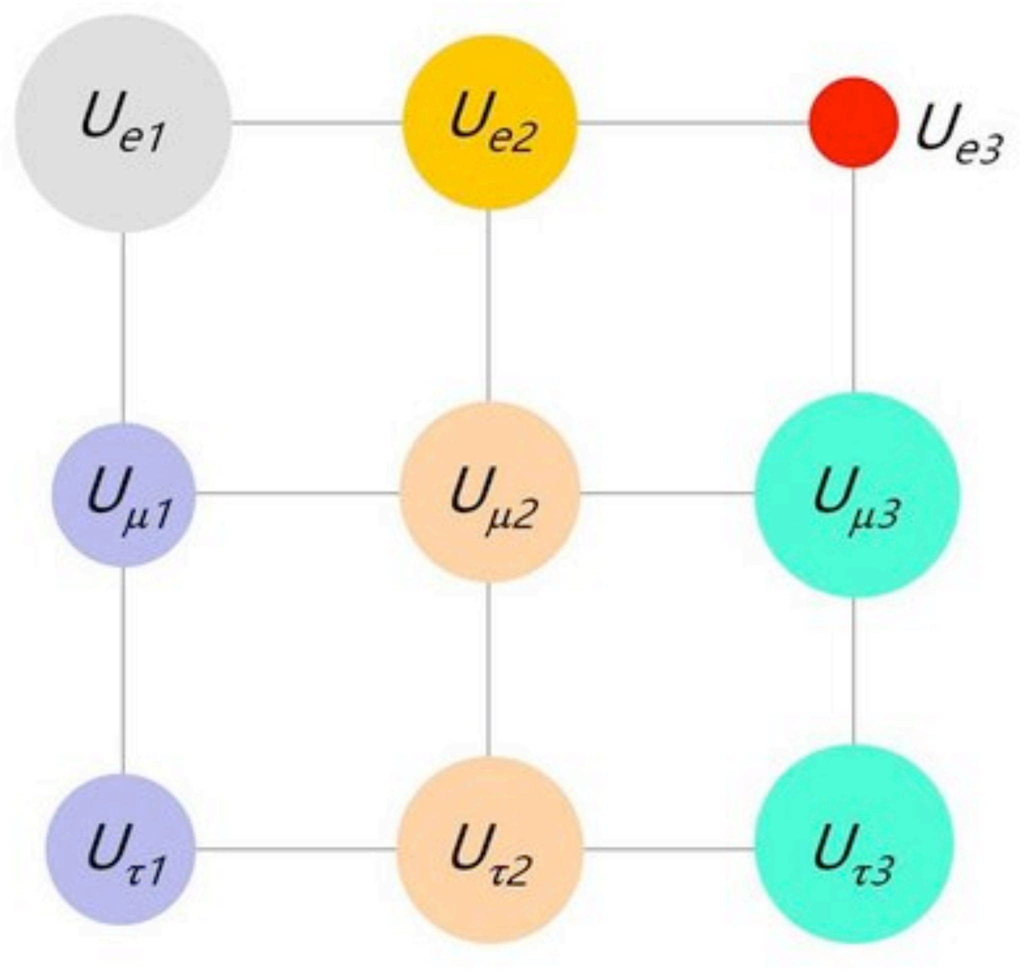
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12}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

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

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

Interpretation in terms of a 3D rotation in the space



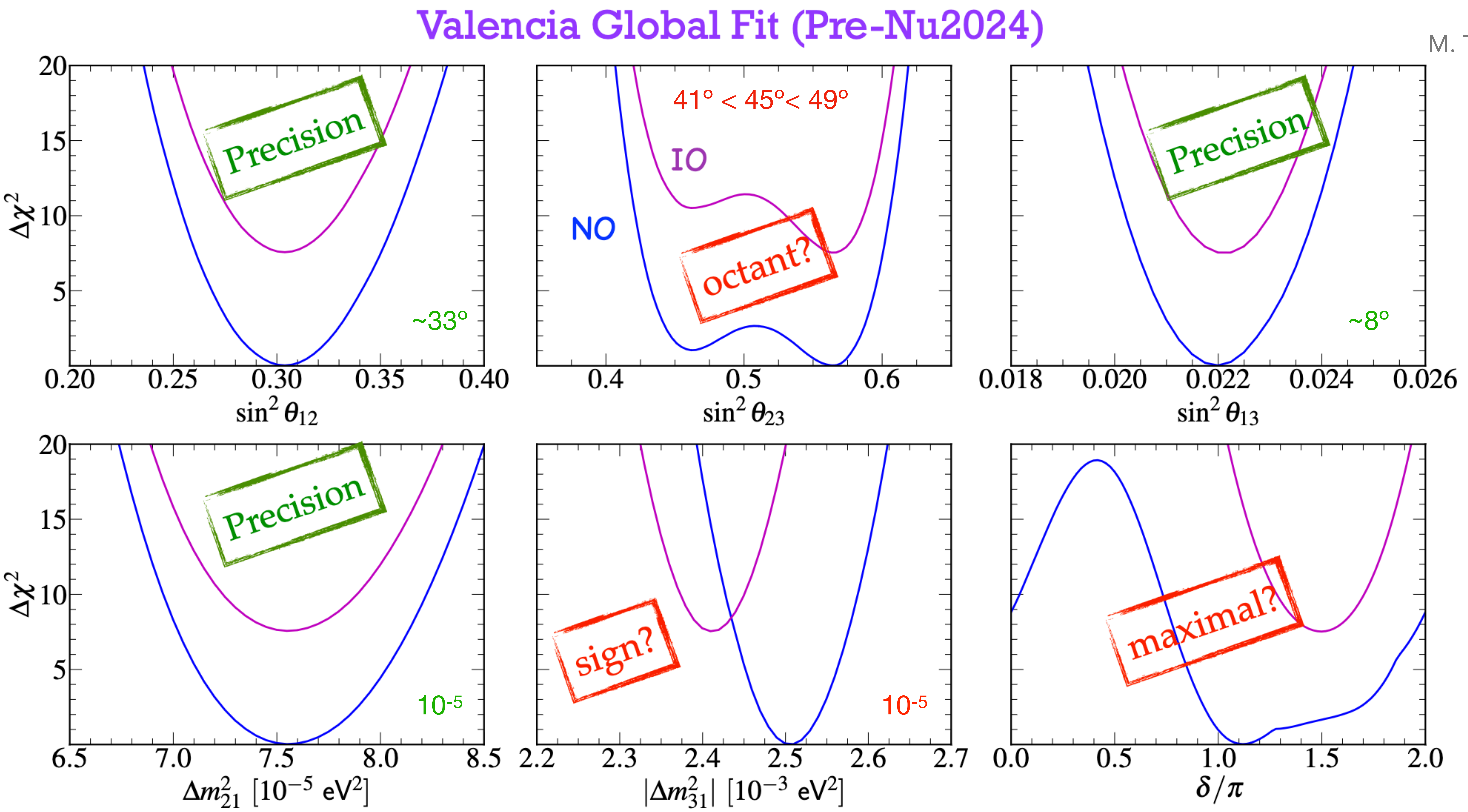


(b) PMNS lepton flavor mixing

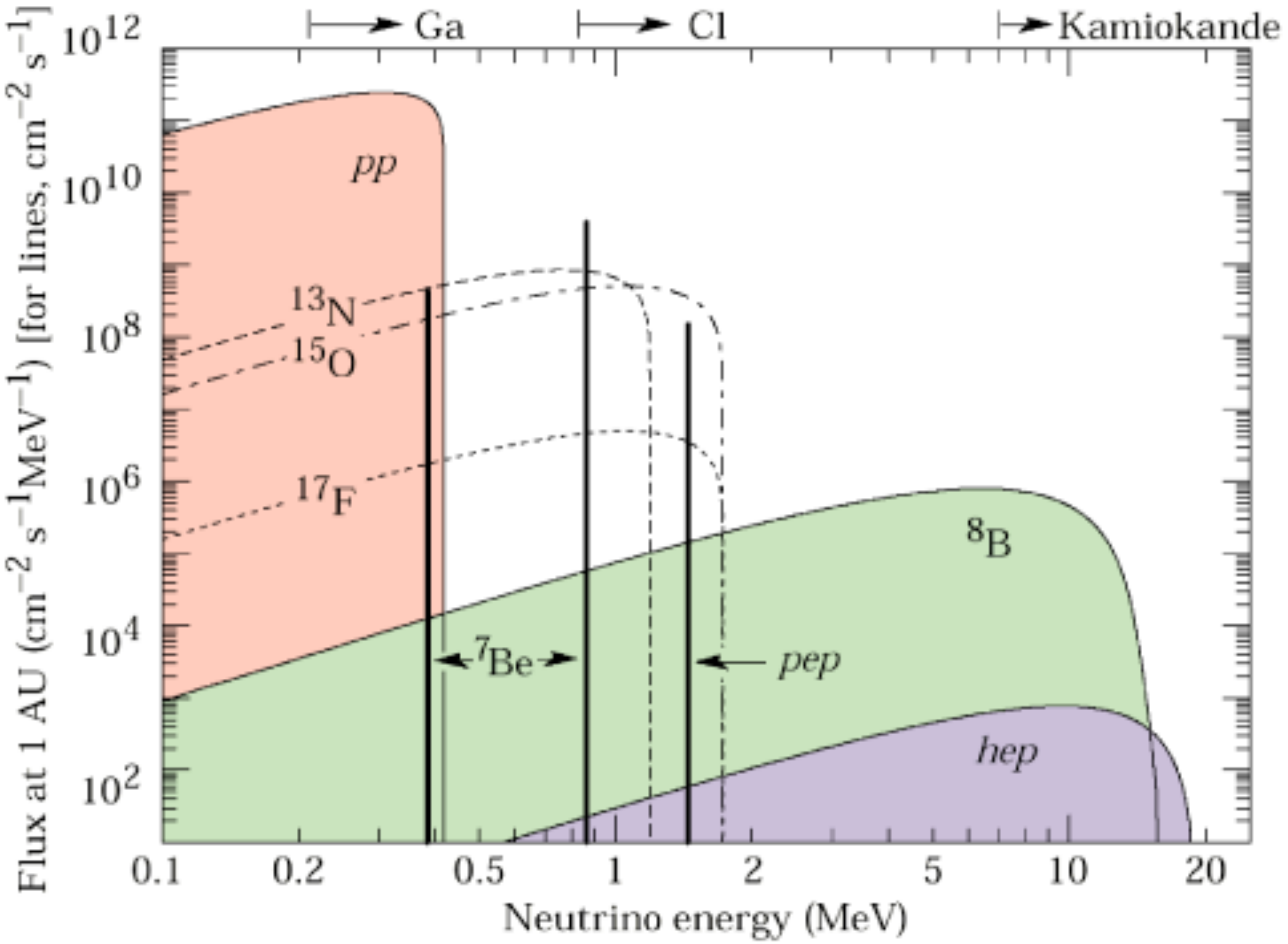
$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Neutrino oscillations: global fit

M. Tortola, Neutrino2024

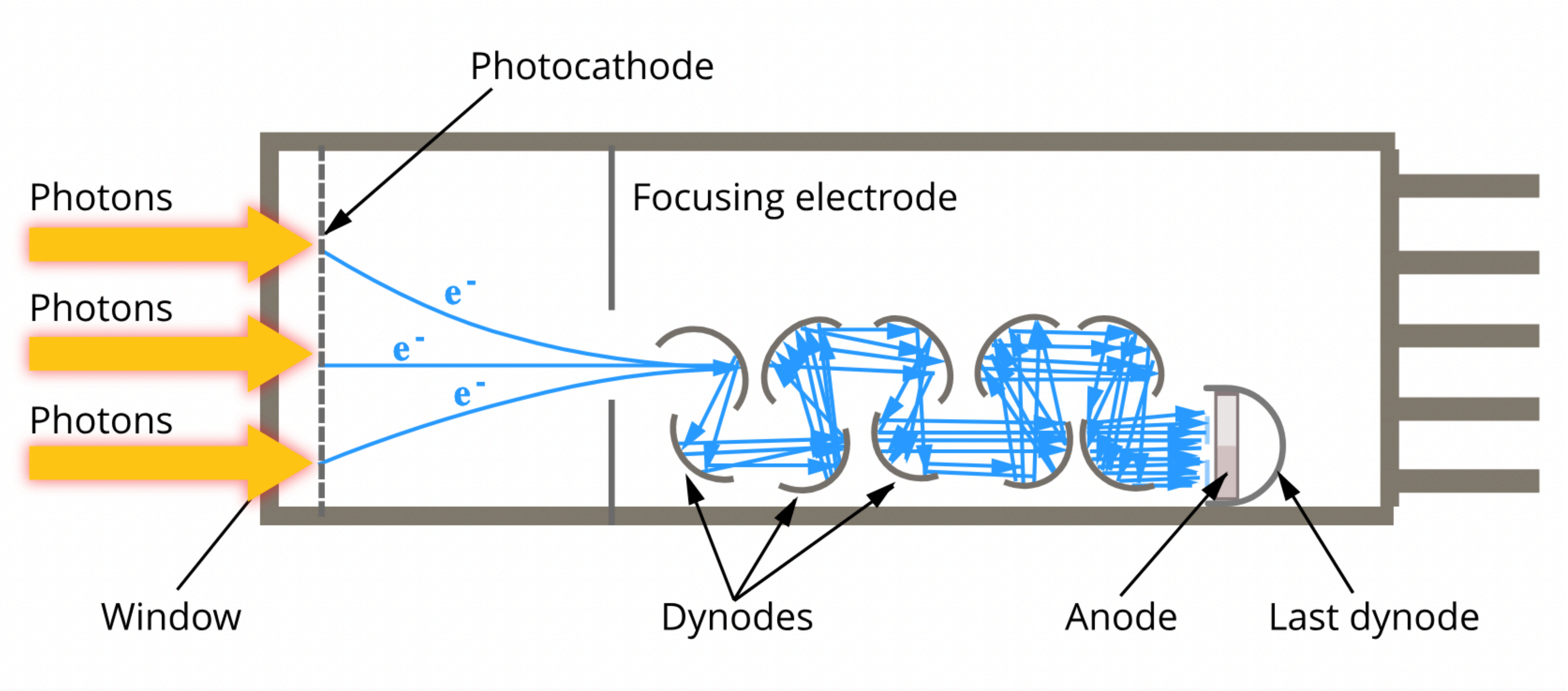


Solar Neutrinos



The observed deficit was different in each experiment because each one was sensitive to a different range of the spectrum

The Photomultiplier Tube (PMT)



Cherenkov Radiation

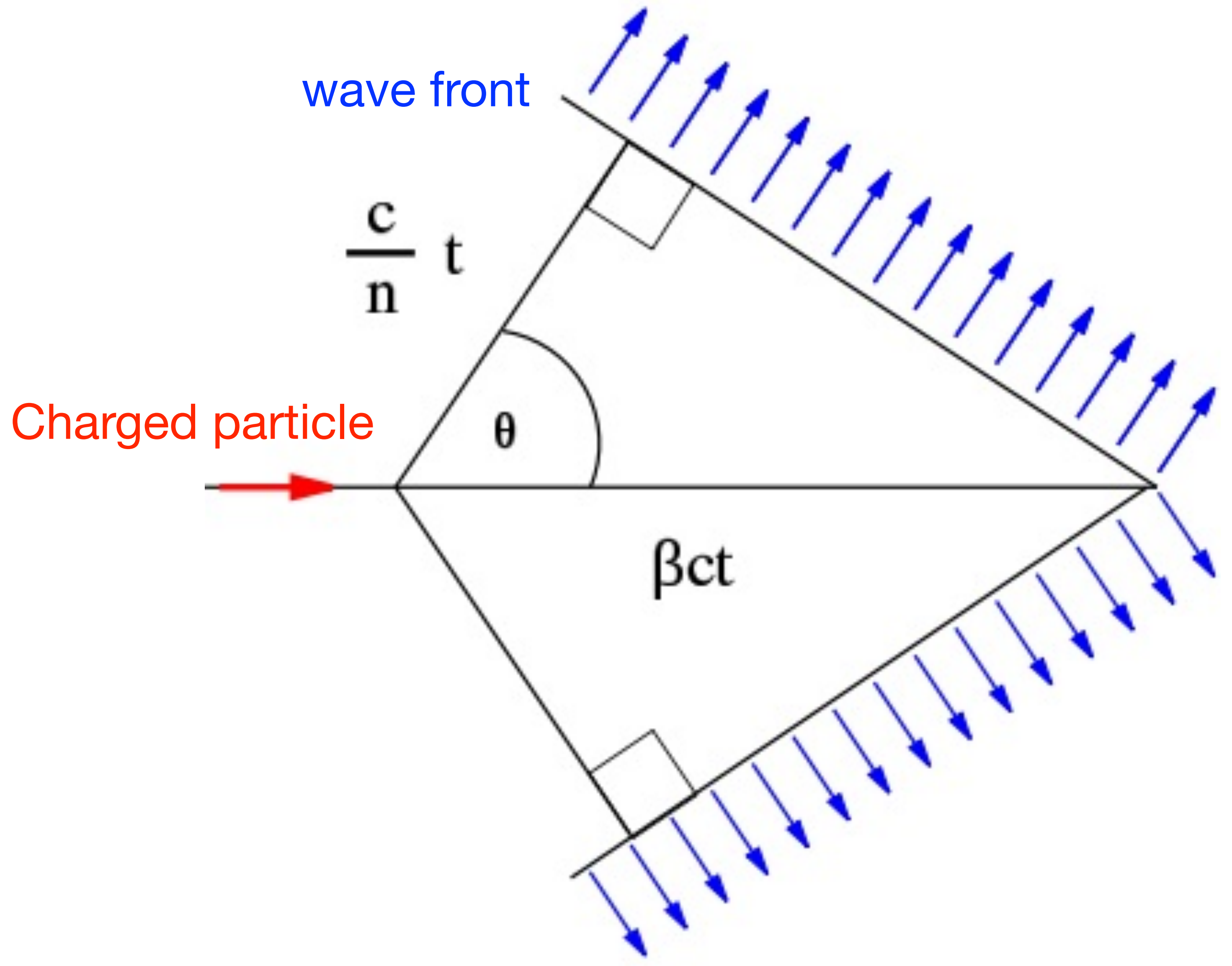
- This radiation appears when a charged particle in a medium moves with a velocity (v) faster that the speed of light in that medium (c/n)

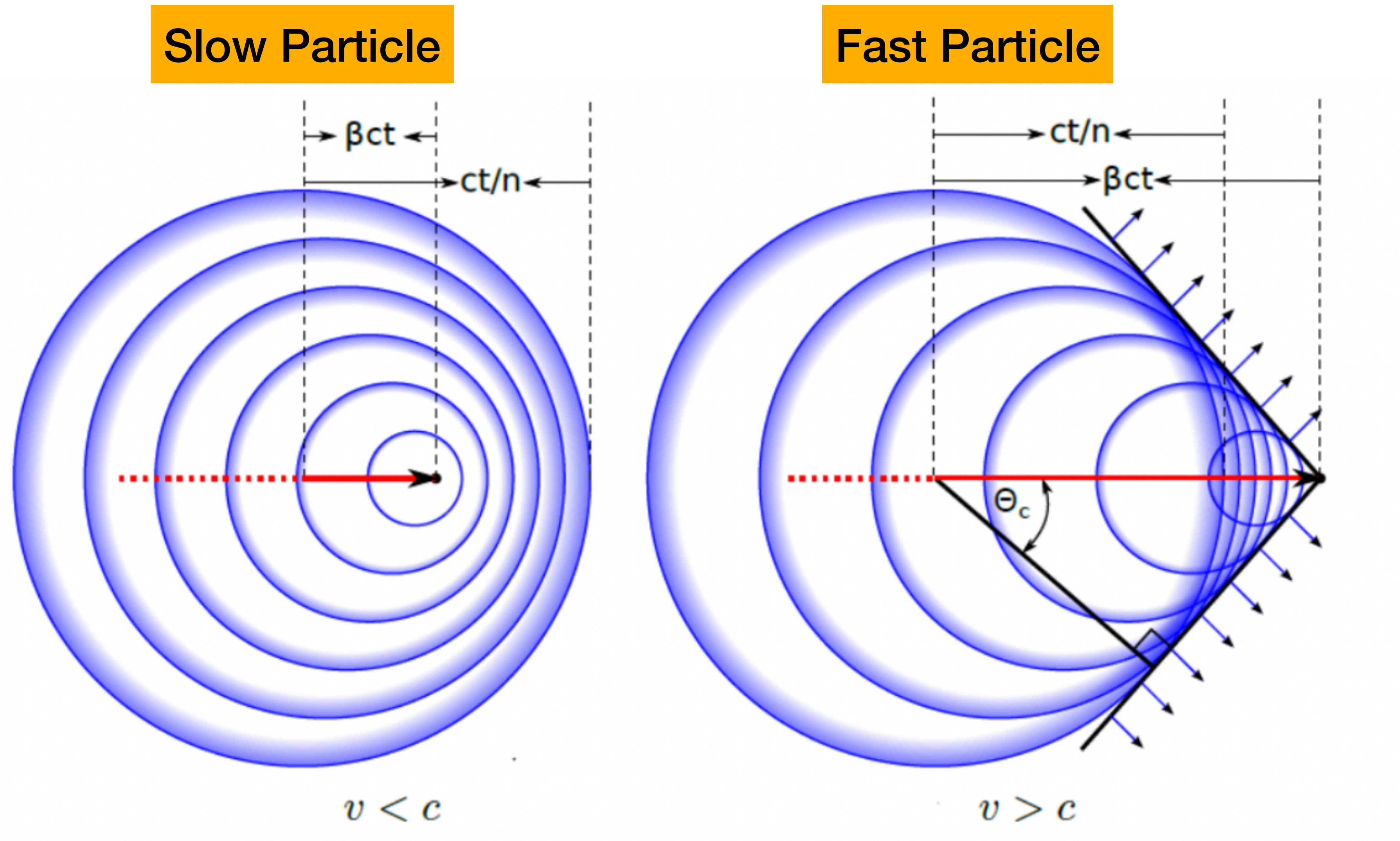
$$v_{particle} > c/n$$

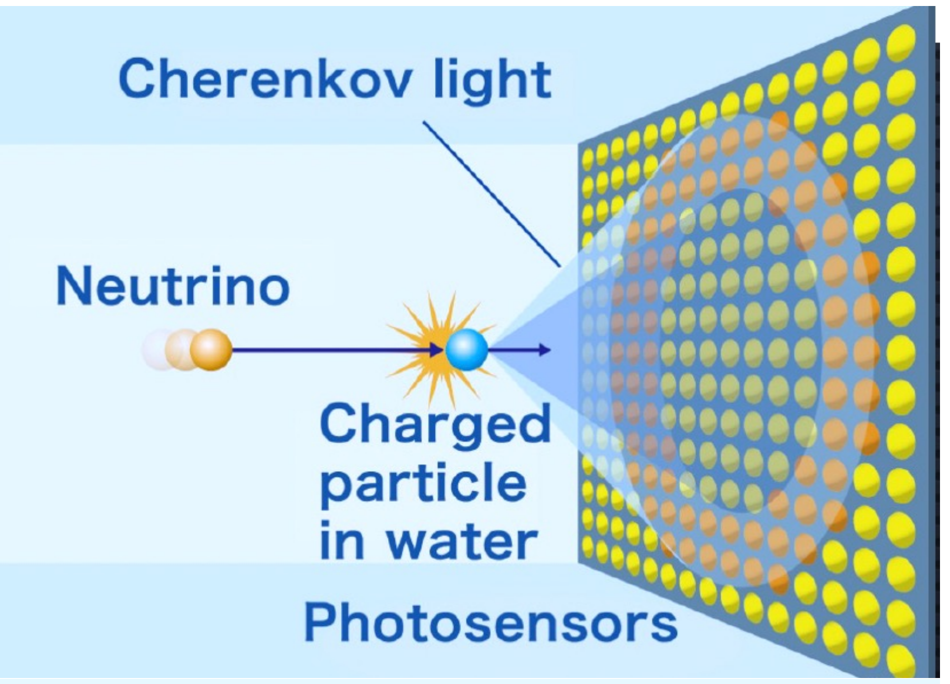
n: refraction index of the medium

1) Threshold for light emission ⟶ $v_{particle}/c = \beta > 1/n$ ⟶ $\beta_{threshold} = 1/n$

2) Angle of emission ⟶ $\cos\theta_c = 1/n(\lambda)\beta$







Charged particles propagating in a medium with a speed exceeding that of light in that medium emit Cerenkov radiation. Detected as a ring by large area photo-multipliers.

Note: energy loss due to Cherenkov radiation very small compared to ionisation (<1%)

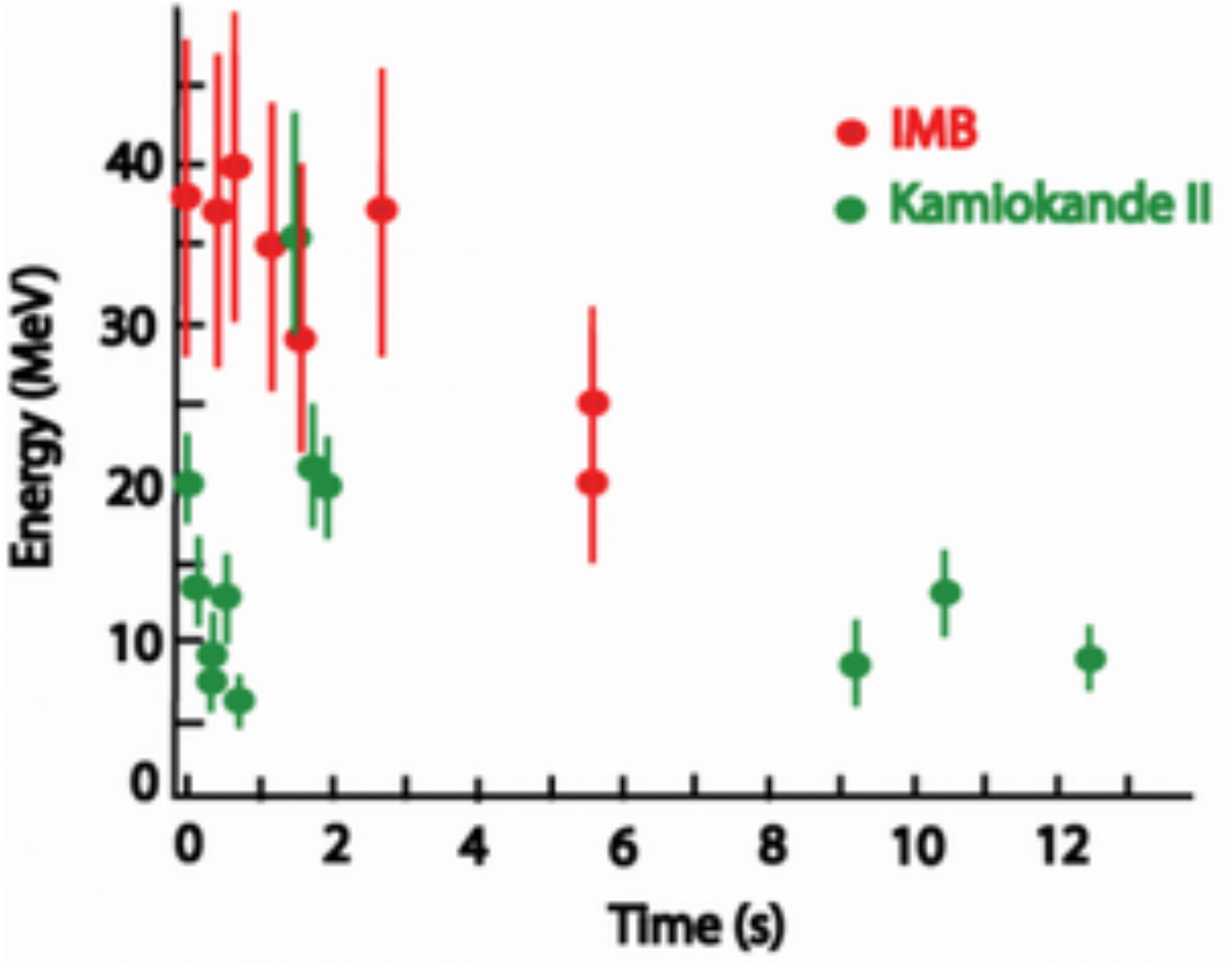
Kamiokande: neutrinos from the 1987 supernova

- **KamiokaNDE:** Kamioka Nucleon Decay Experiment
- Soon upgraded to detect neutrinos (Kamiokande-II)
- 3000 tons of water + 1000 PMTs
- 12 events observed in ~12 s

BEFORE AFTER

Credit: David Malin / Australian Astronomical Observatory

Supernova SN-1987A

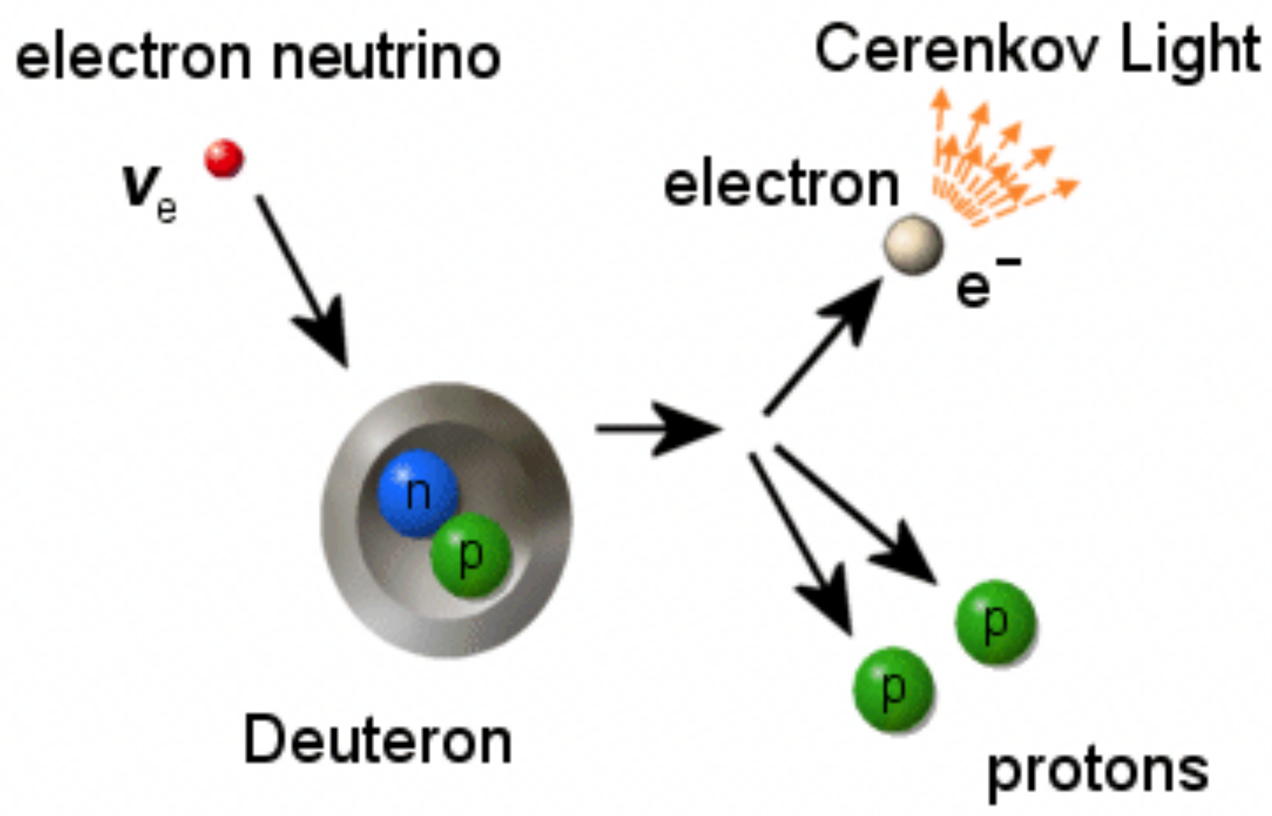


Note: IMB another Cherenkov detector

Different signals at the SNO experiment

CC interaction

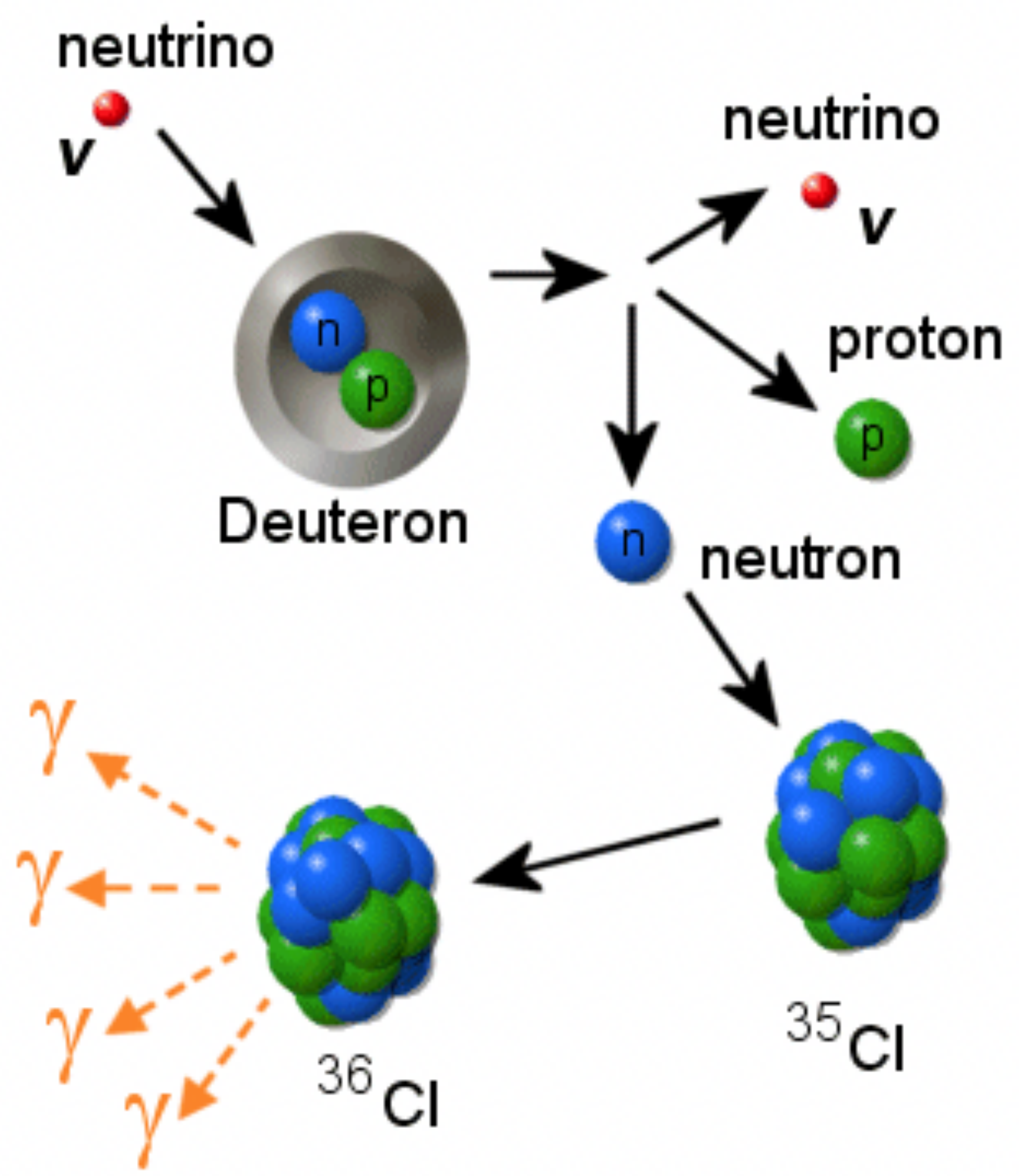
$E_\nu > 1.4$ MeV



The Cherenkov light emitted by the electron in the final estate is detected by the PMTs

NC interaction

$E_\nu > 2.2$ MeV

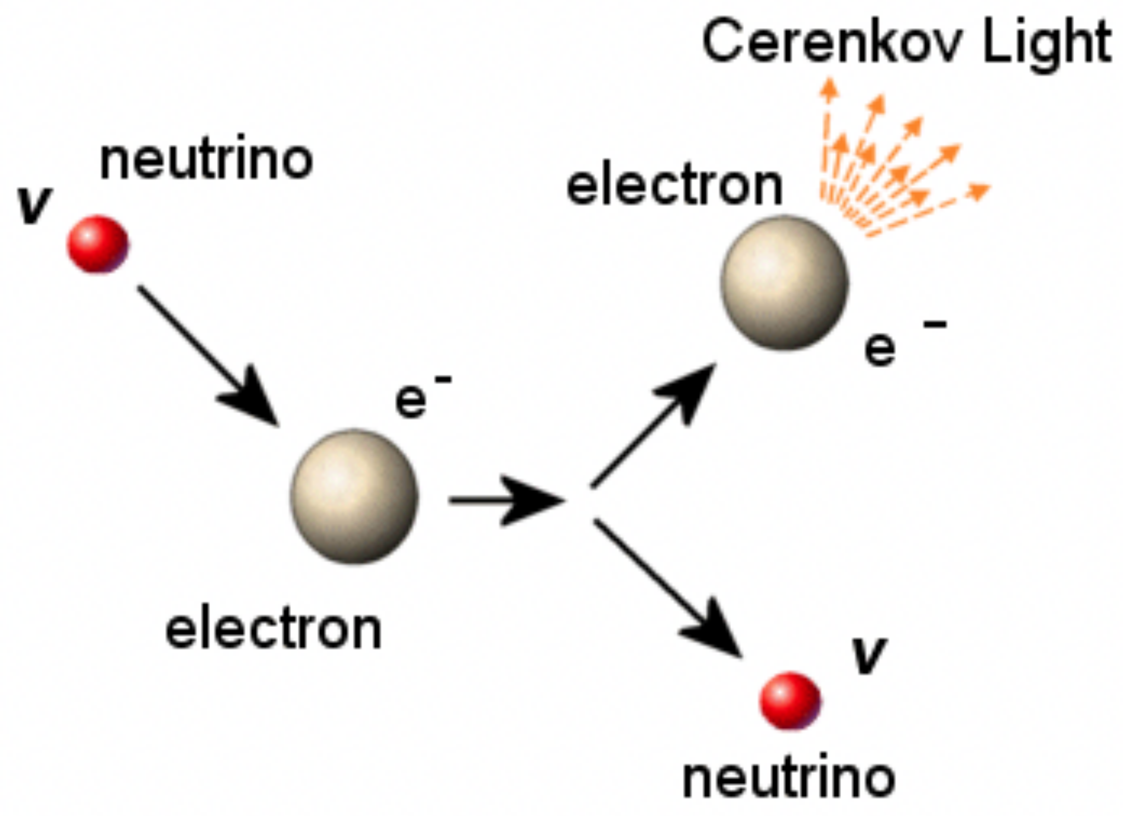


The neutron is thermalised and capture by a nucleus. Then it releases gammas

In the first stage ^2H (n, gamma)^3H

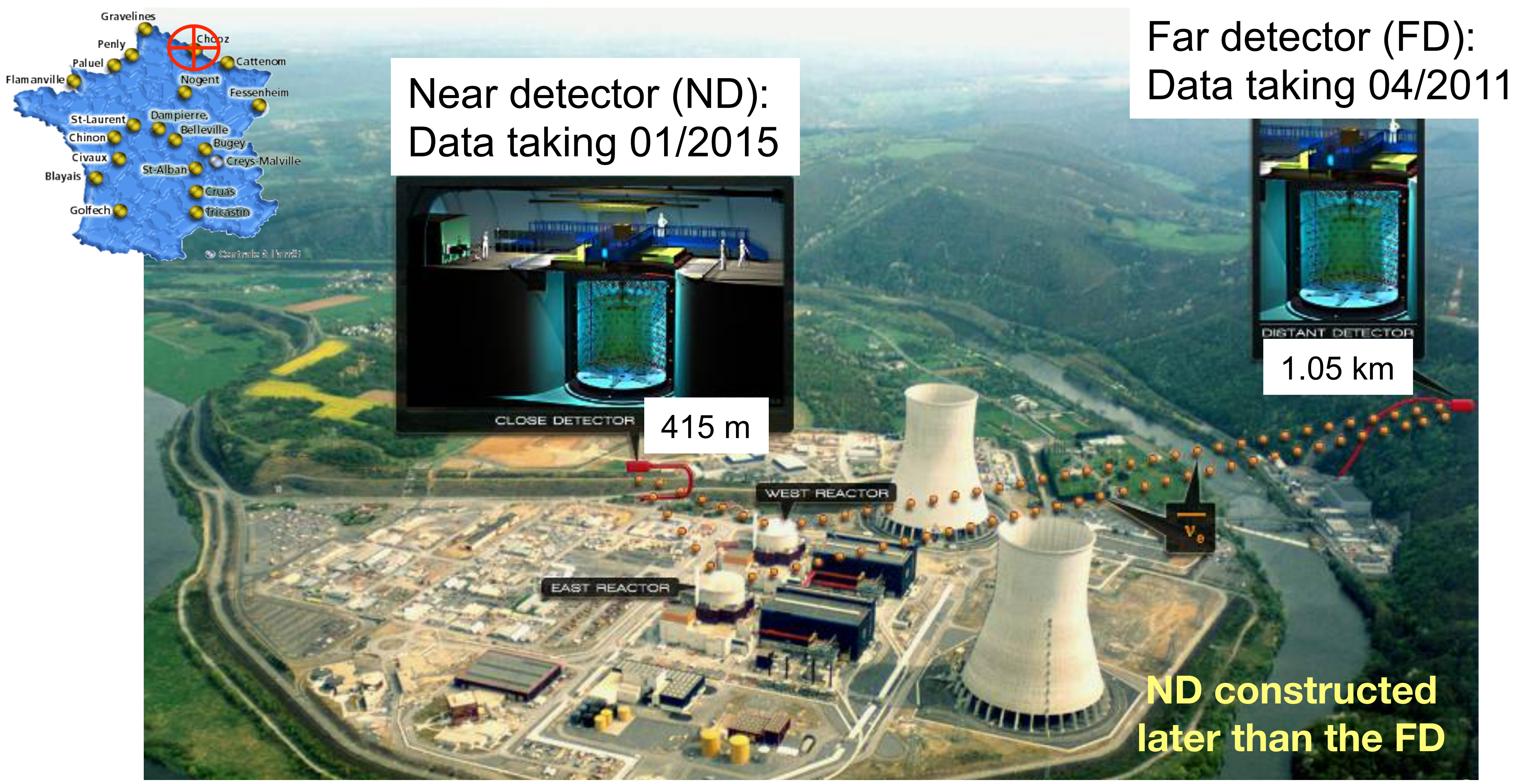
ES

$E_\nu > 0$ MeV

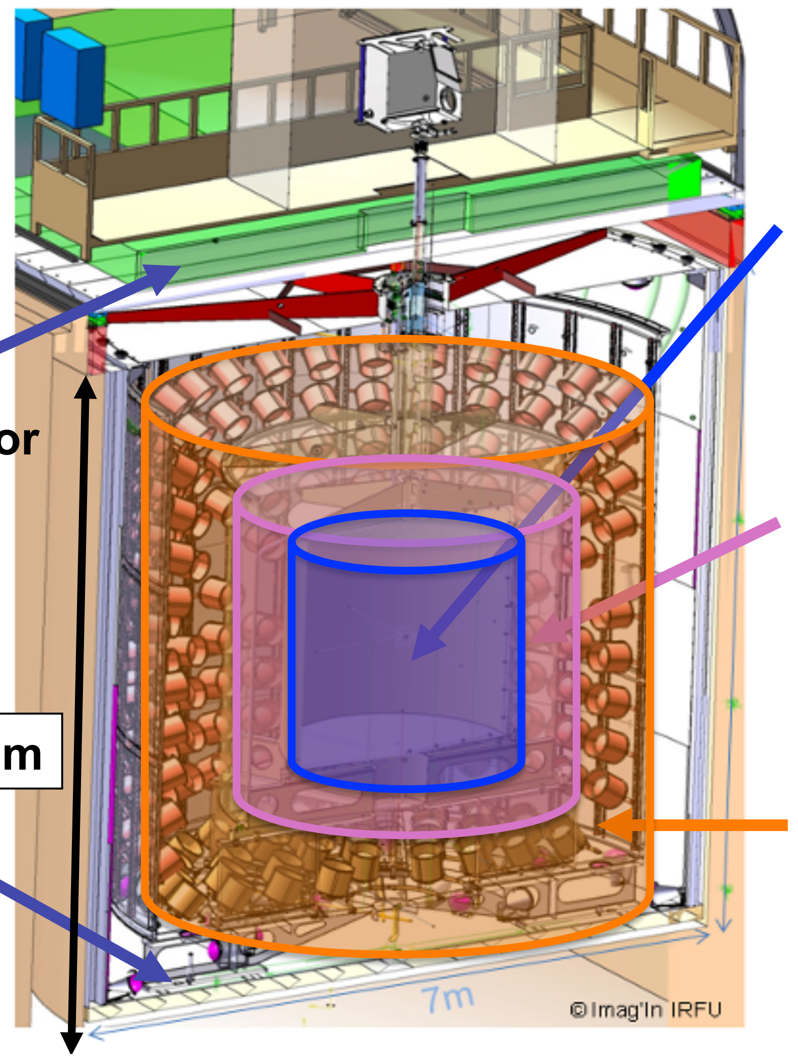


The Cherenkov light emitted by the electron in the final estate is detected by the PMTs

Double Chooz (France)



The detectors are again “three zone” cylindrical modules



Outer Veto: Plastic scintillator

Inner Veto:
- Steel
- 70 t LS
- 78 PMTs (8”)

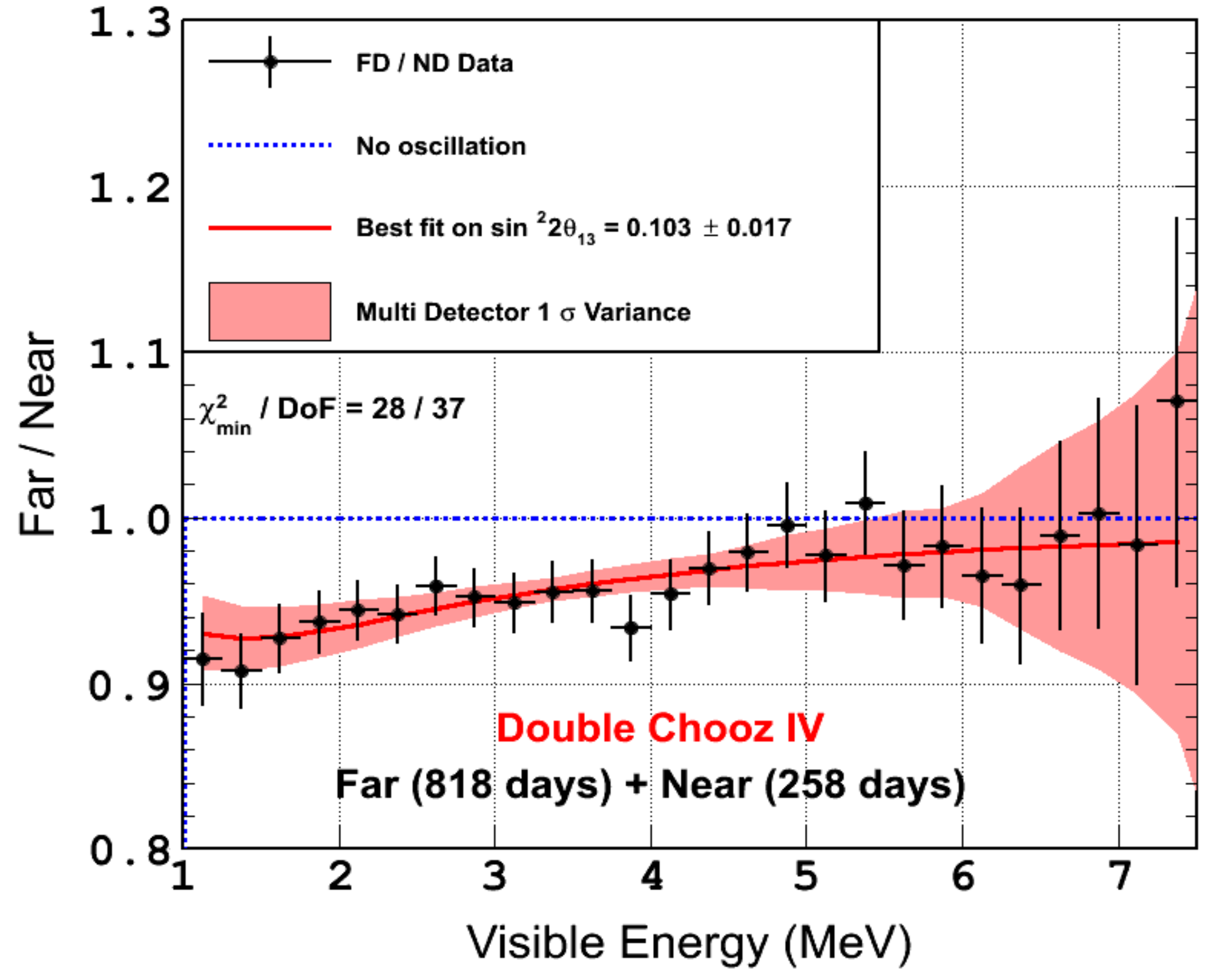
Inner detector:

Target (r = 1.2 m):
- Acrylic vessel
- 8.3 t Gd-scintillator (1 g/l Gd)

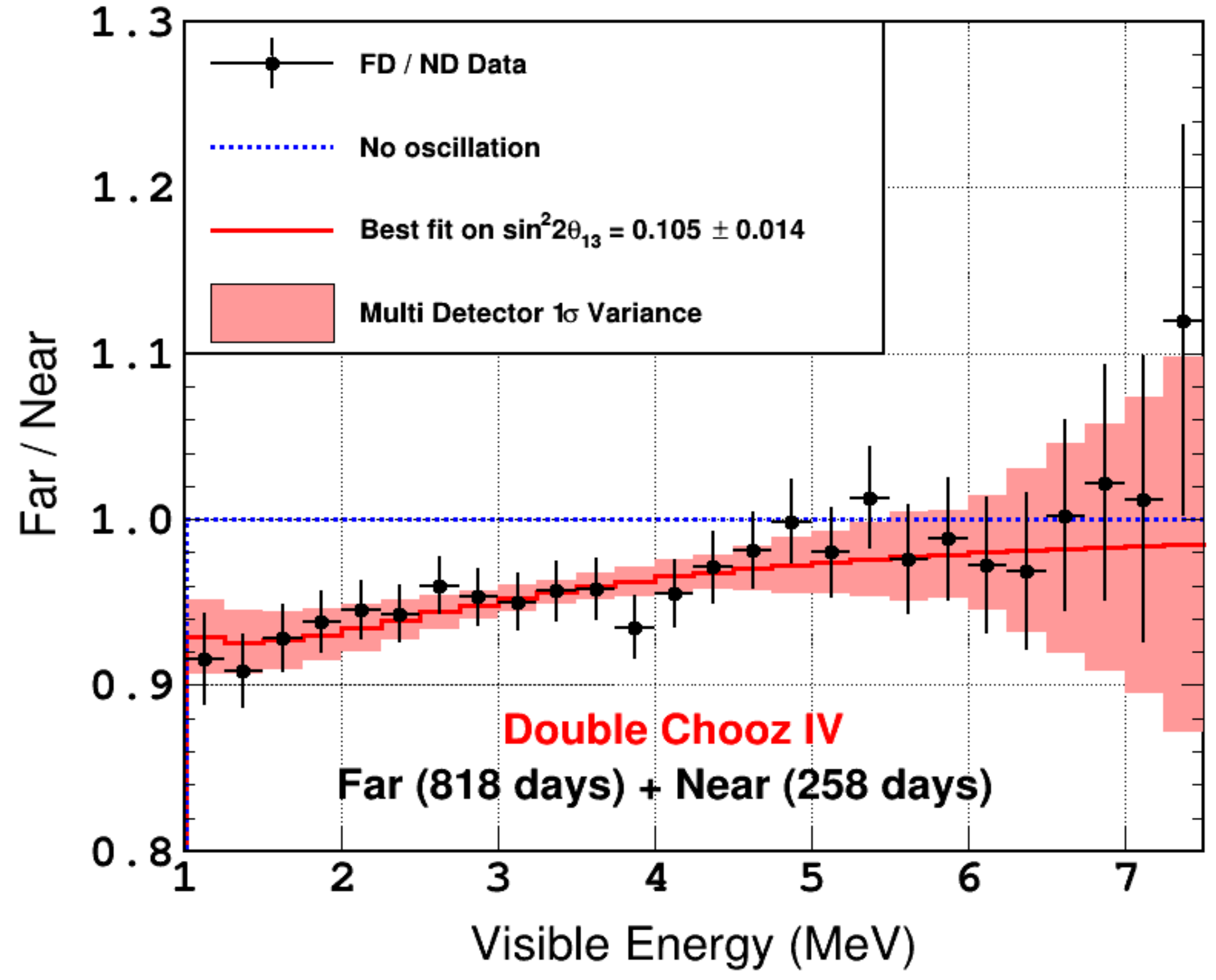
Gamma Catcher (0.55 m):
- Acrylic vessel
- 18 t liquid scintillator

Buffer (1.05 m):
- Steel vessel
- 80 t “oil”
- 390 PMTs (10”)

Data/data

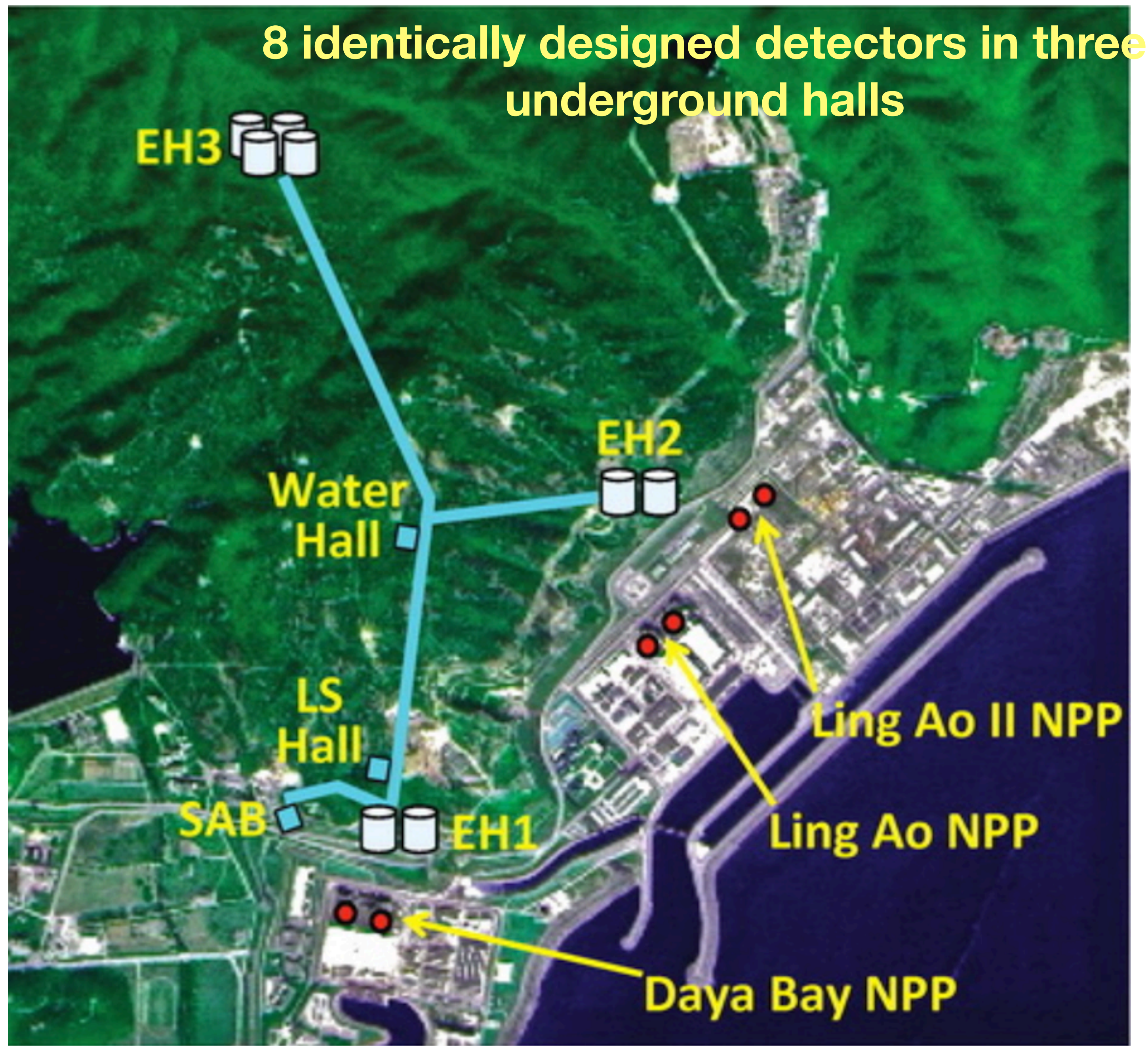


Data/MC ratio plot

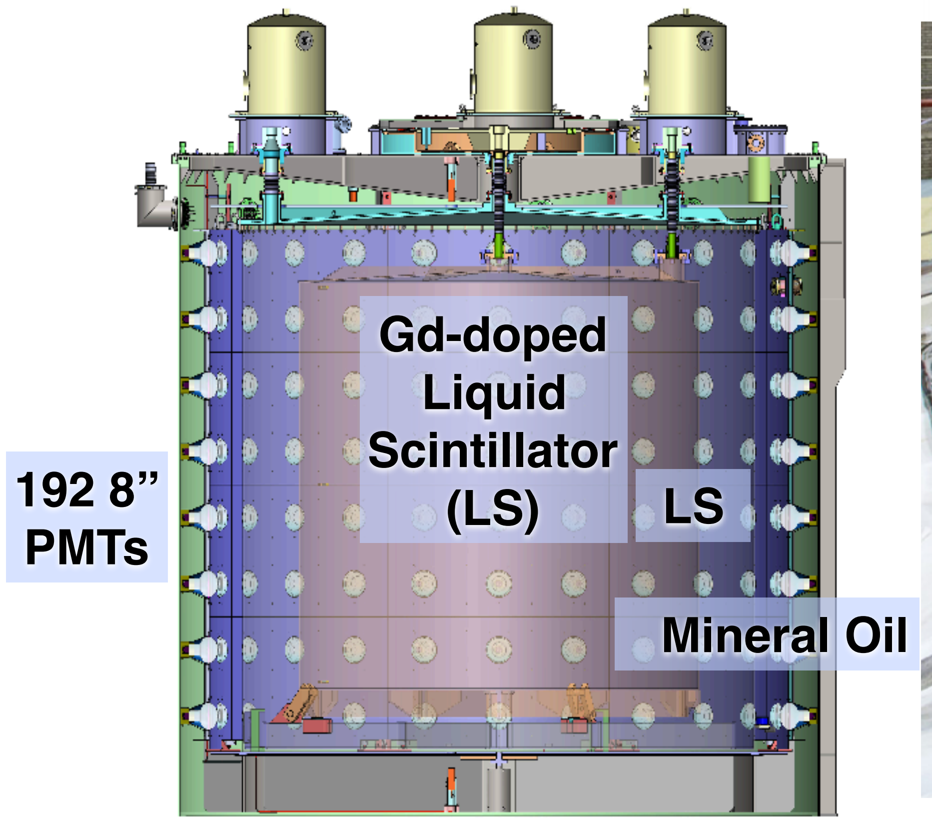


$$\sin^2 2\theta_{13} = 0.103 \pm 0.017$$

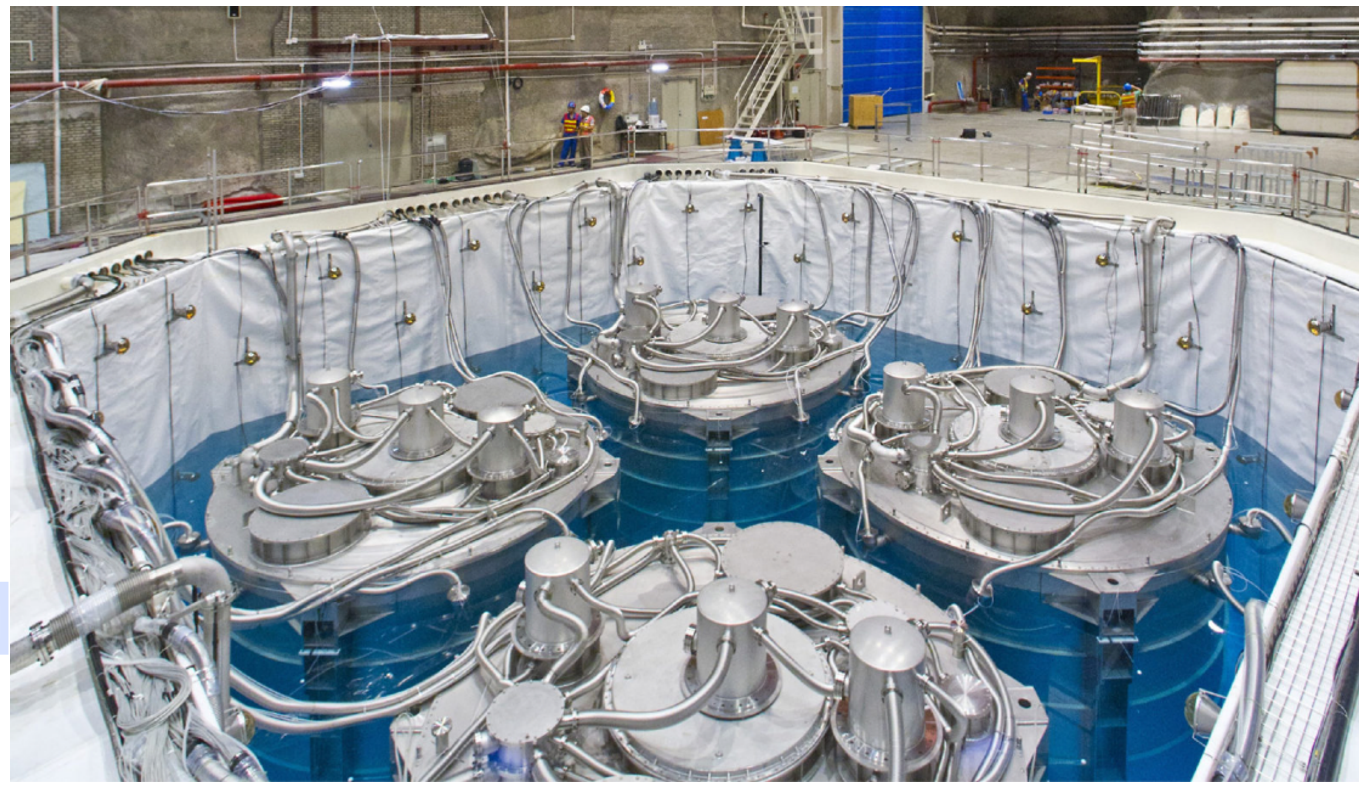
Daya Bay (China)



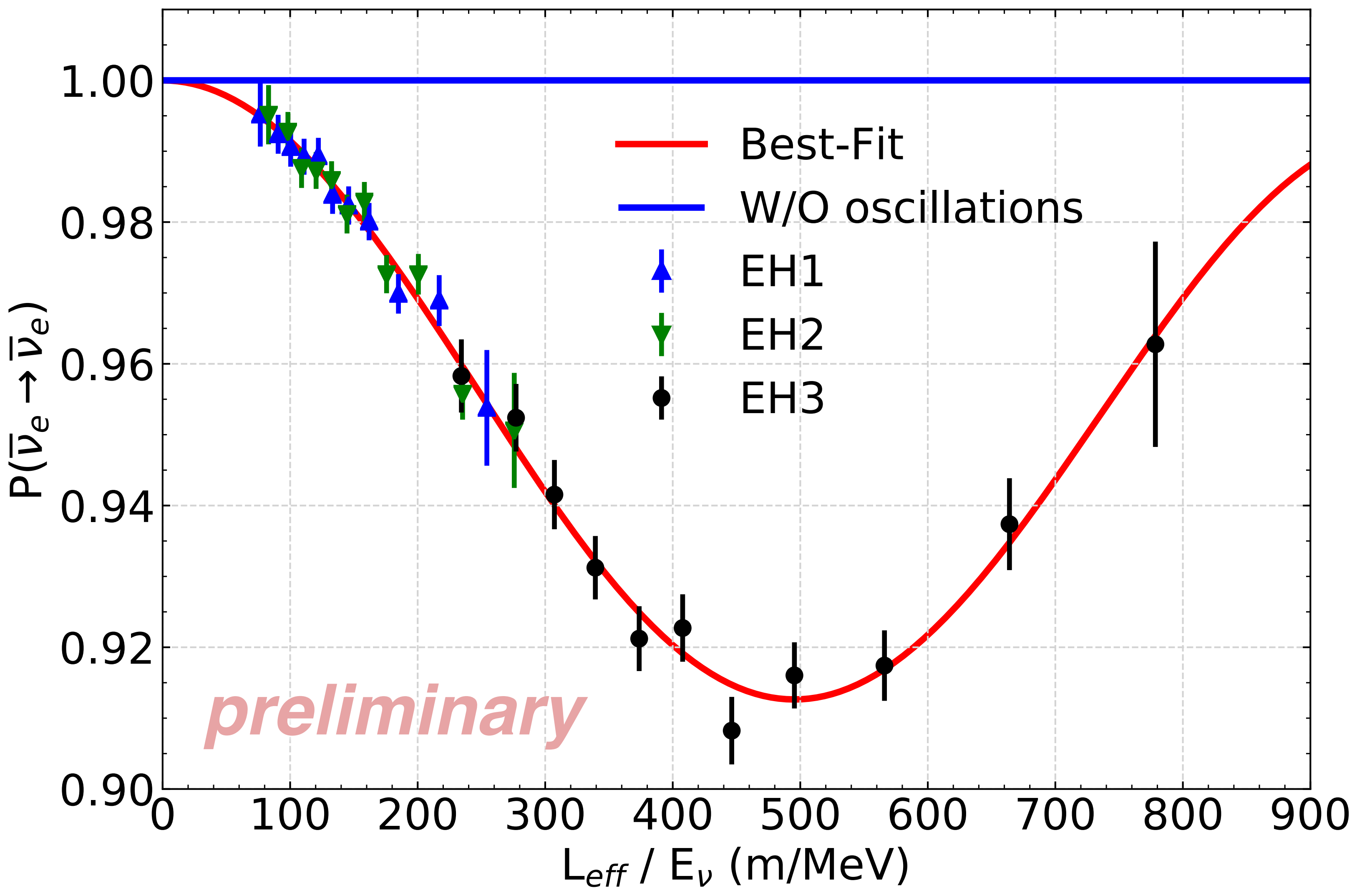
The detectors are “three zone” cylindrical modules immersed in water pools



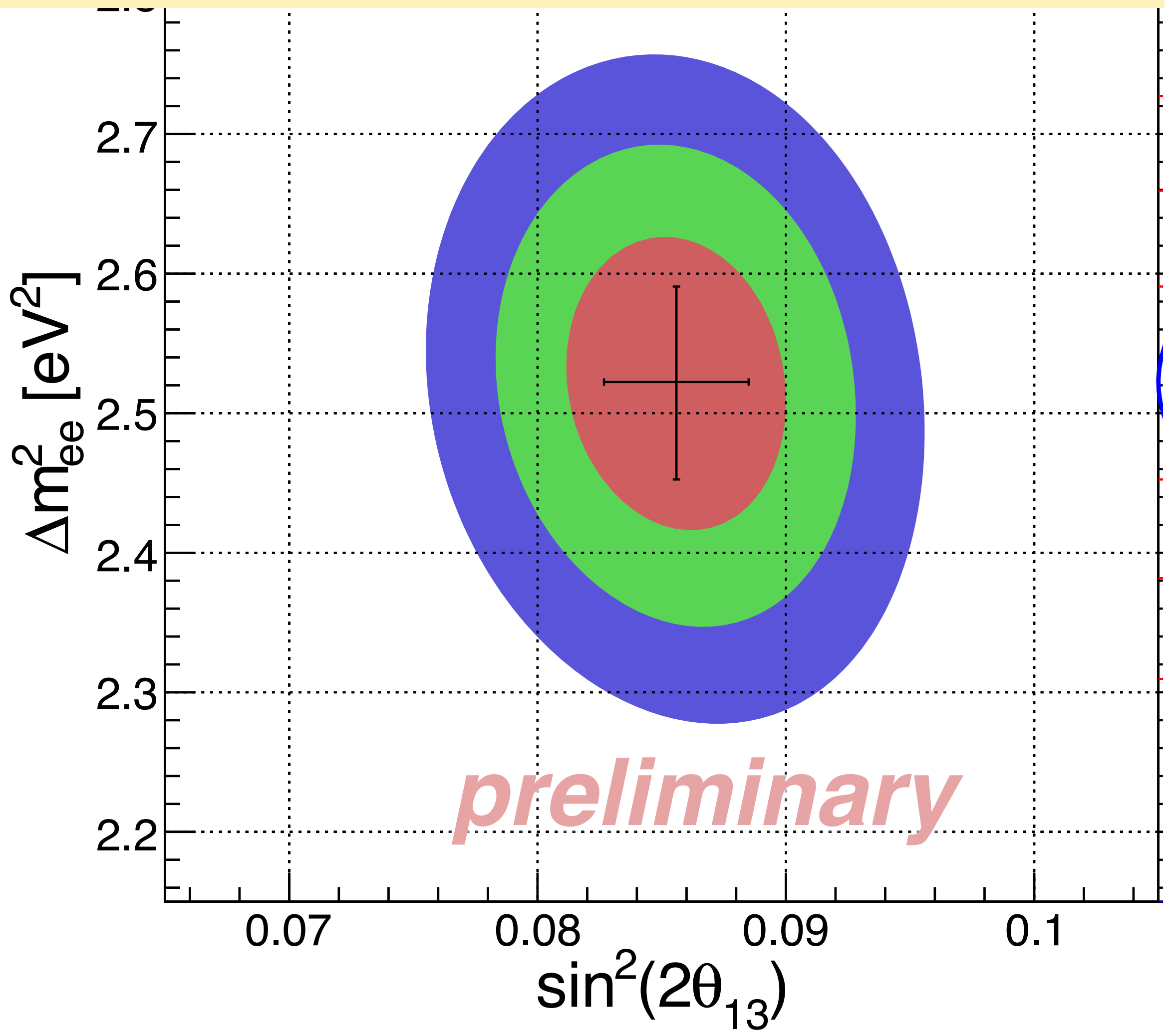
H_{inner} = 3 m   20 ton



Oscillation Results with 1958 days

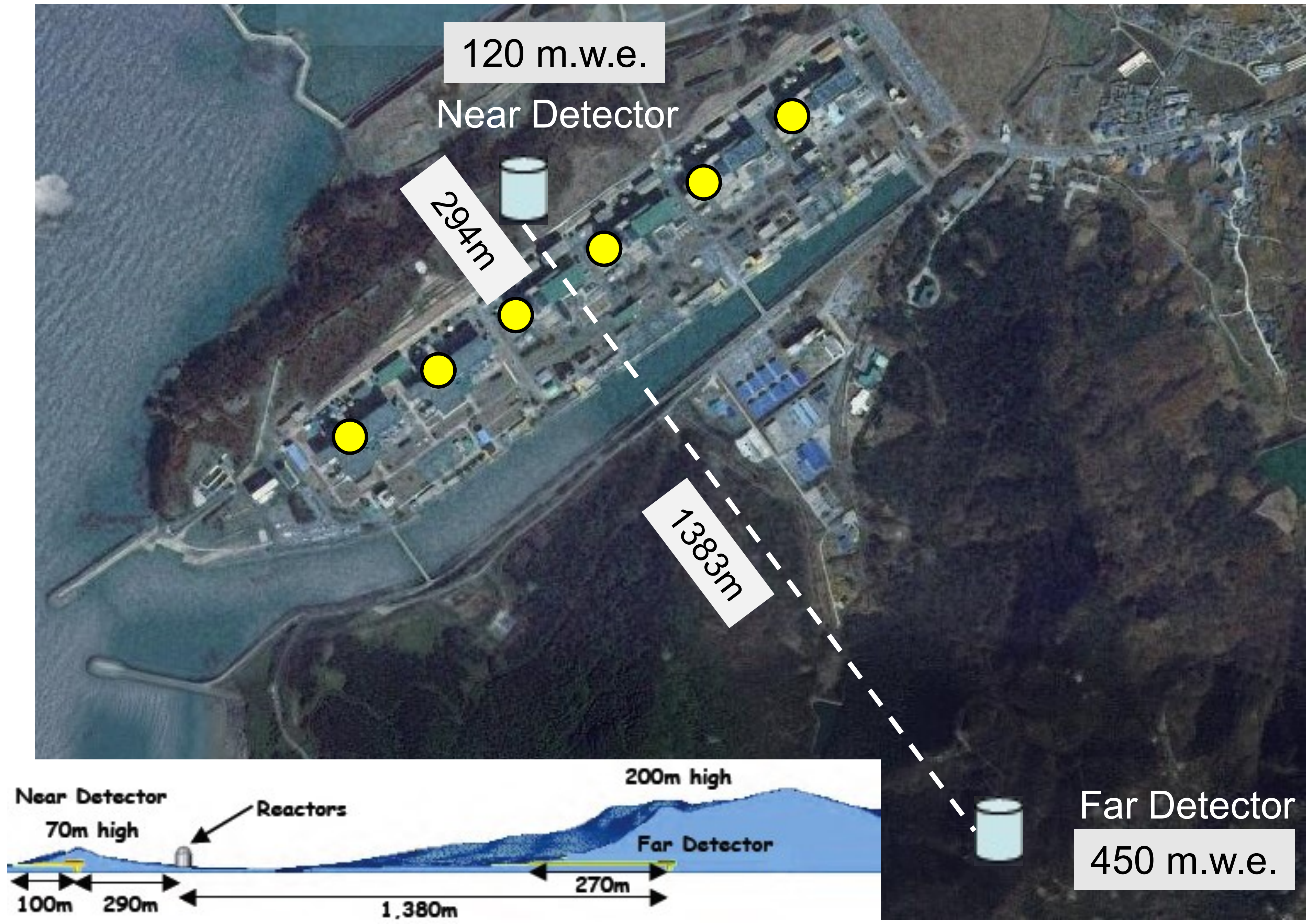


$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

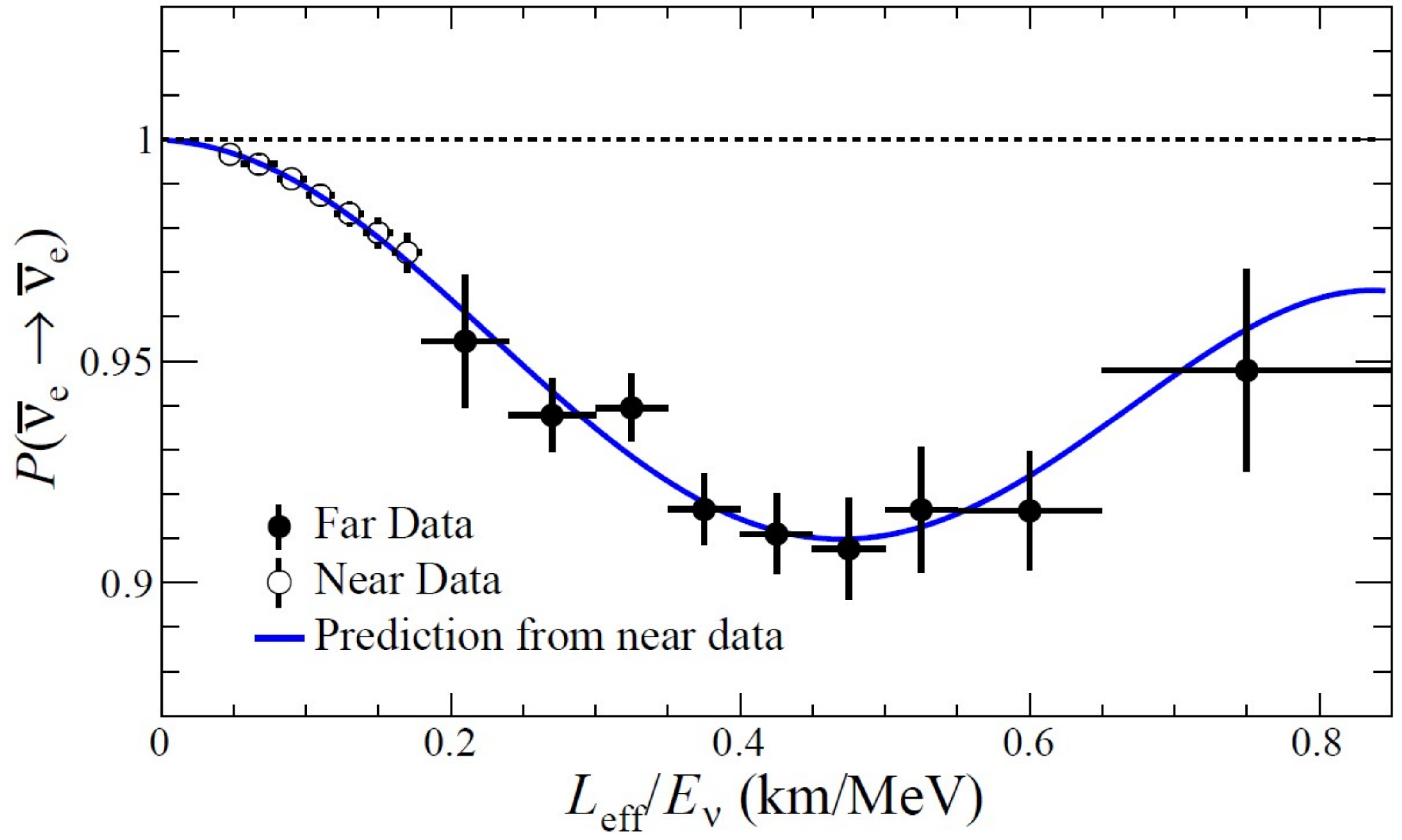


RENO (Korea)

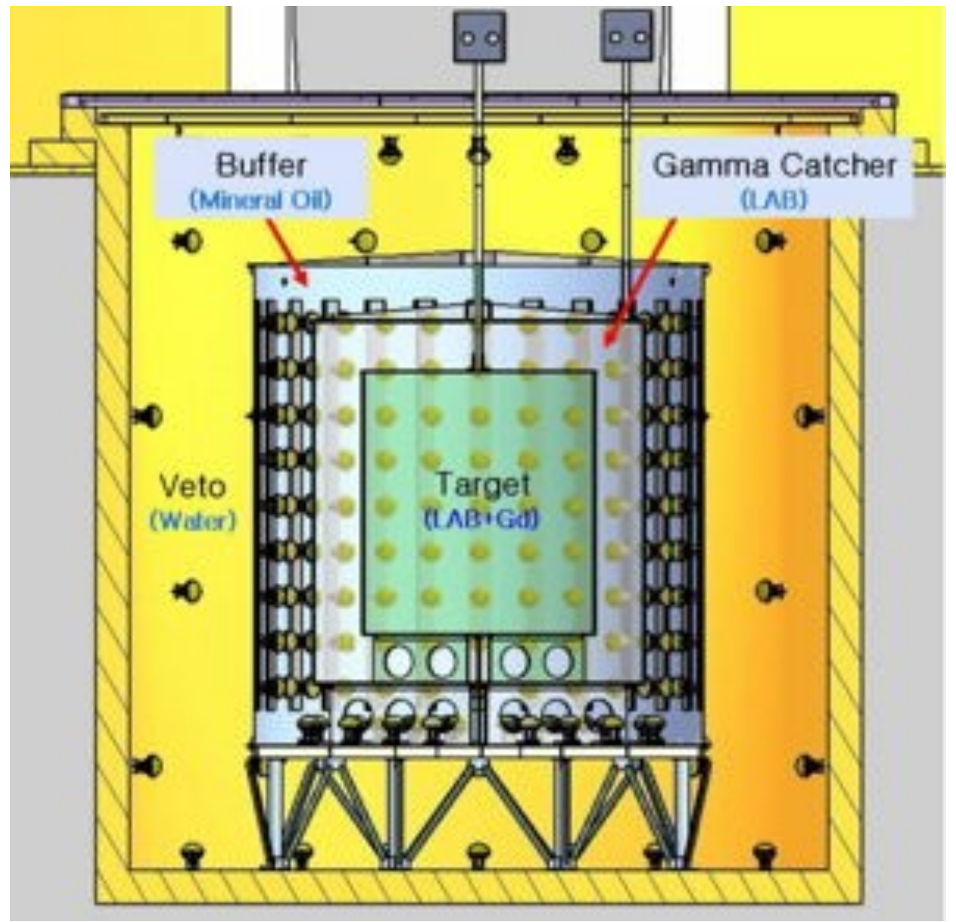
Results of RENO (Korea)



Oscillation Results with 2200 days



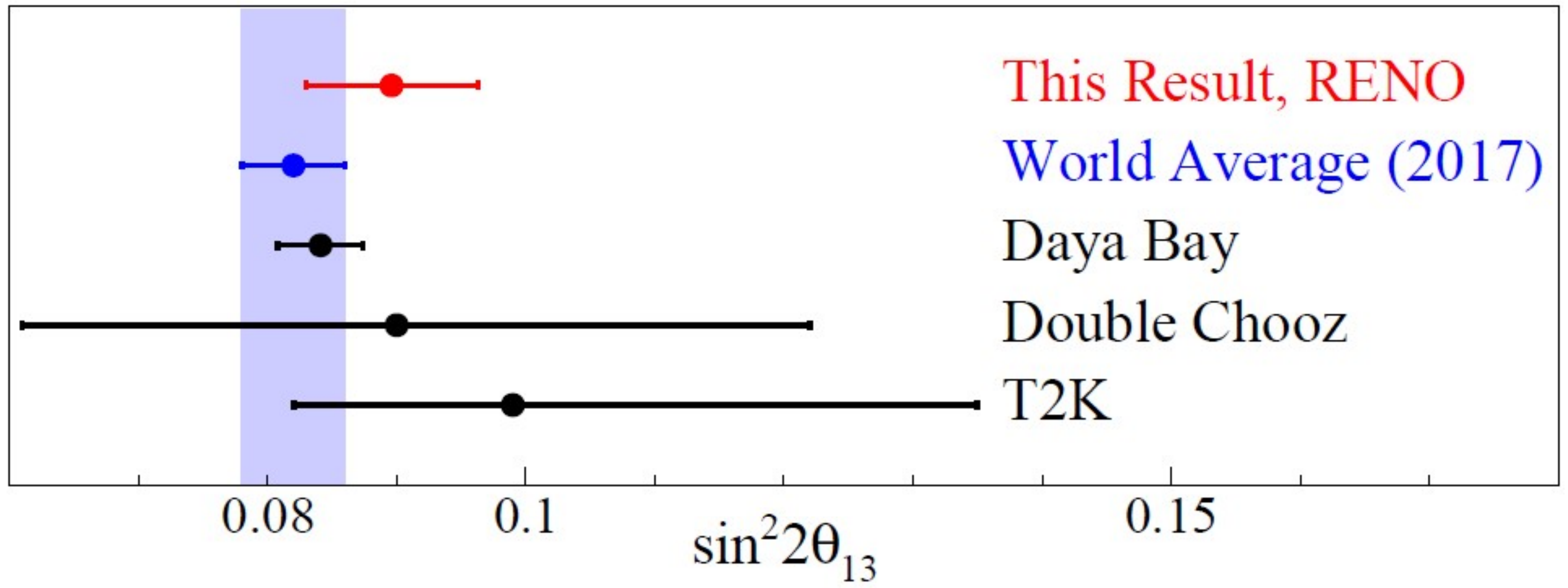
The detectors are cylindrical modules



H_{inner} = 3.2 m

16.5 ton

Comparison with the rest of the experiments



Daya Bay has the smallest errors

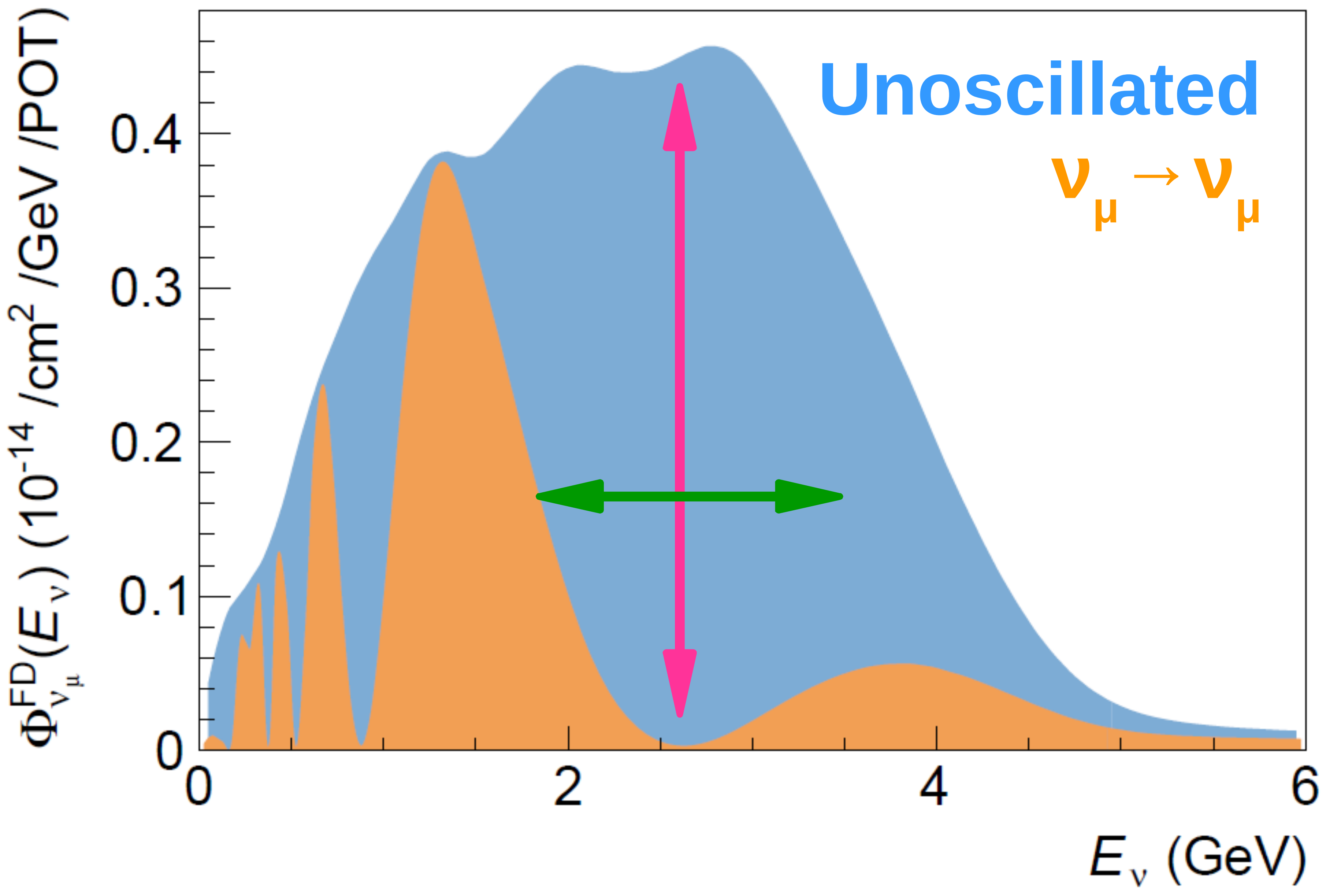
DUNE: muon (anti) neutrino disappearance

Precision measurement for oscillation parameters

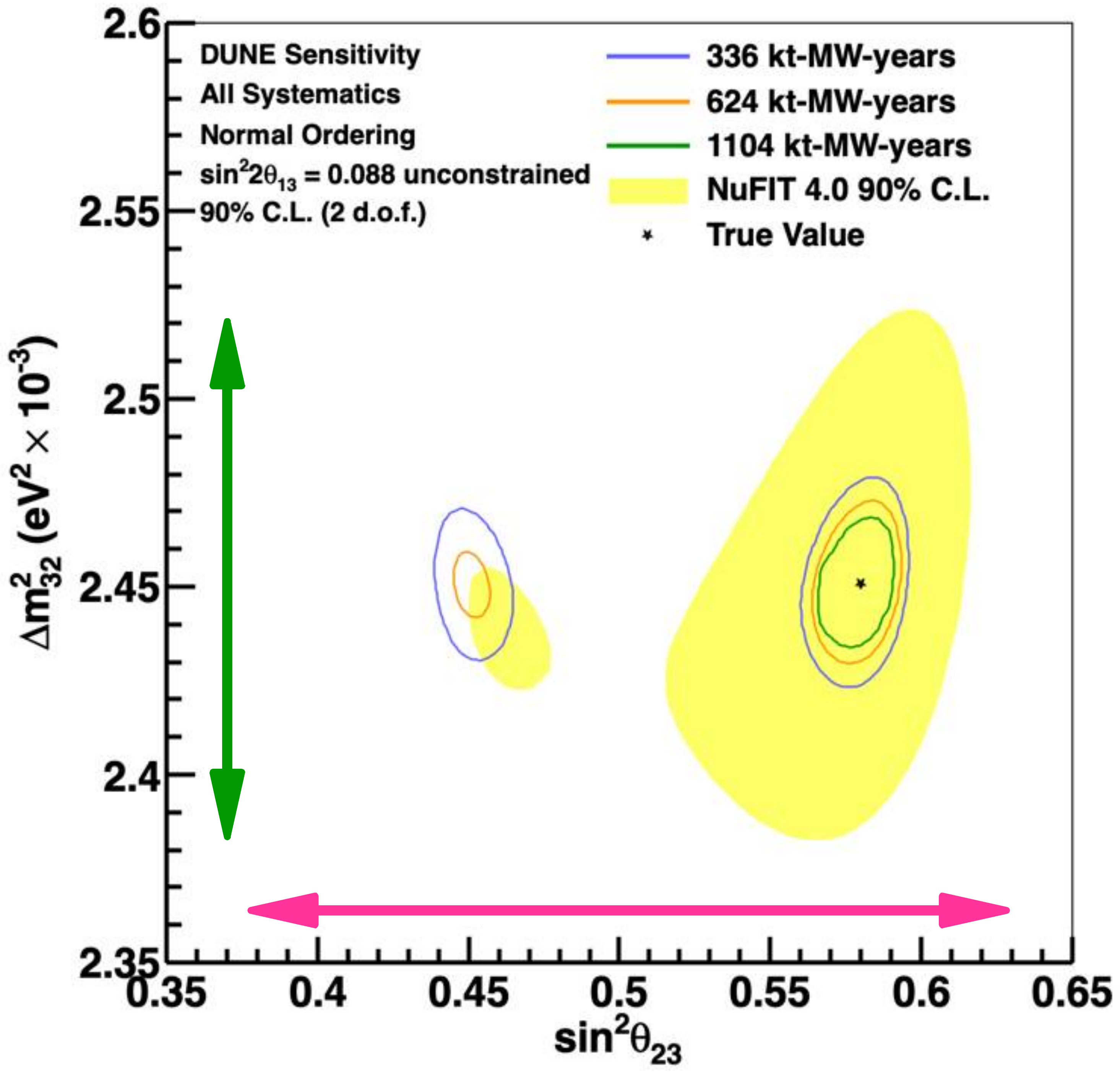
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) = 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\Phi_{32} + \ldots$$

sensitive to θ_{23} & Δm^2_{32}

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$



90% confidence



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DUNE: electron (anti) neutrino appearance

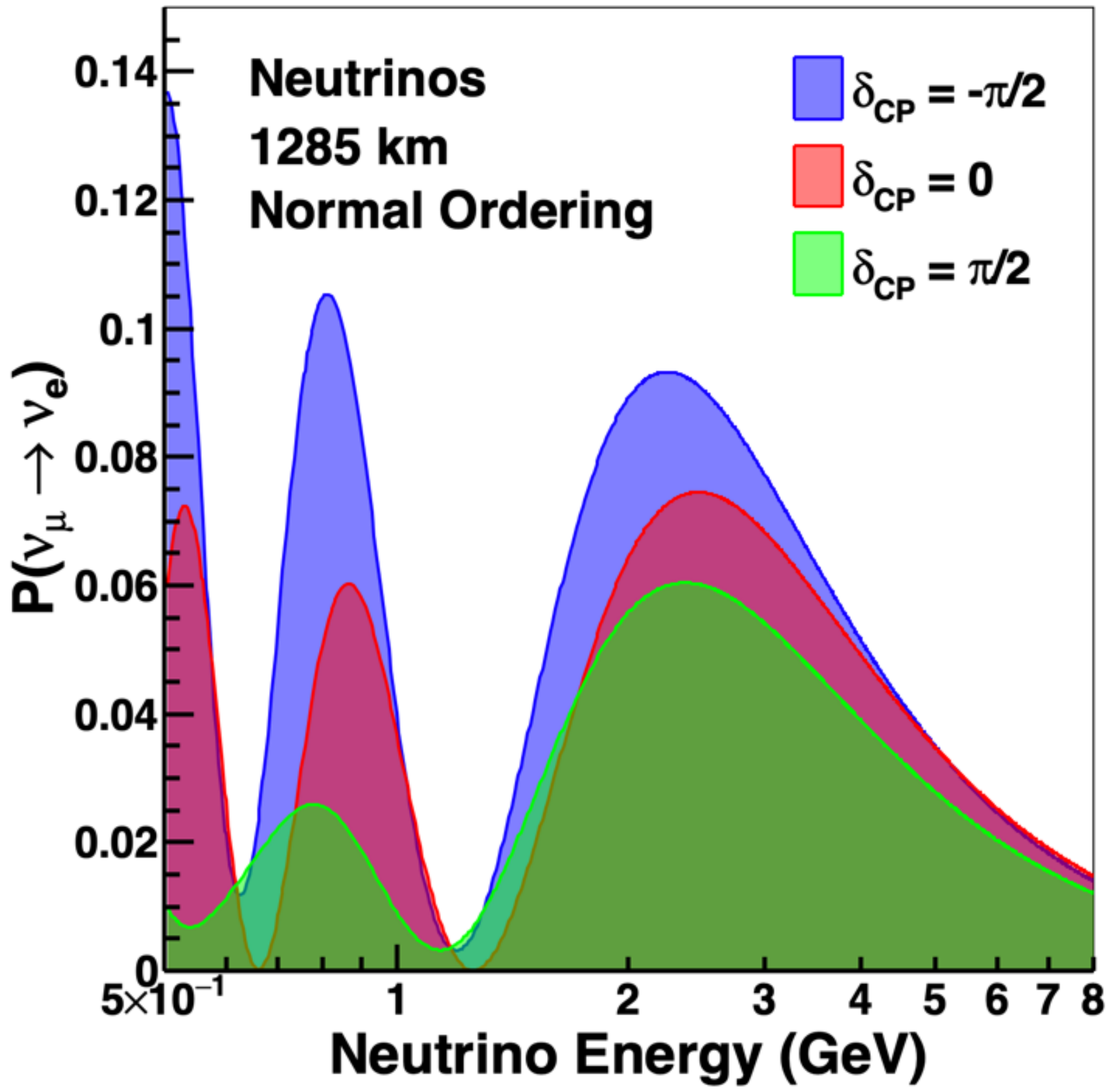
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Phi_{31}-aL)}{(\Phi_{31}-aL)^2}\Phi_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\boxed{\frac{\sin(\Phi_{31}-aL)}{(\Phi_{31}-aL)}}\Phi_{31}\frac{\sin(aL)}{(aL)}\Phi_{21}\boxed{\cos(\Phi_{31}\pm\delta_{CP})}$$
$$+\dots$$

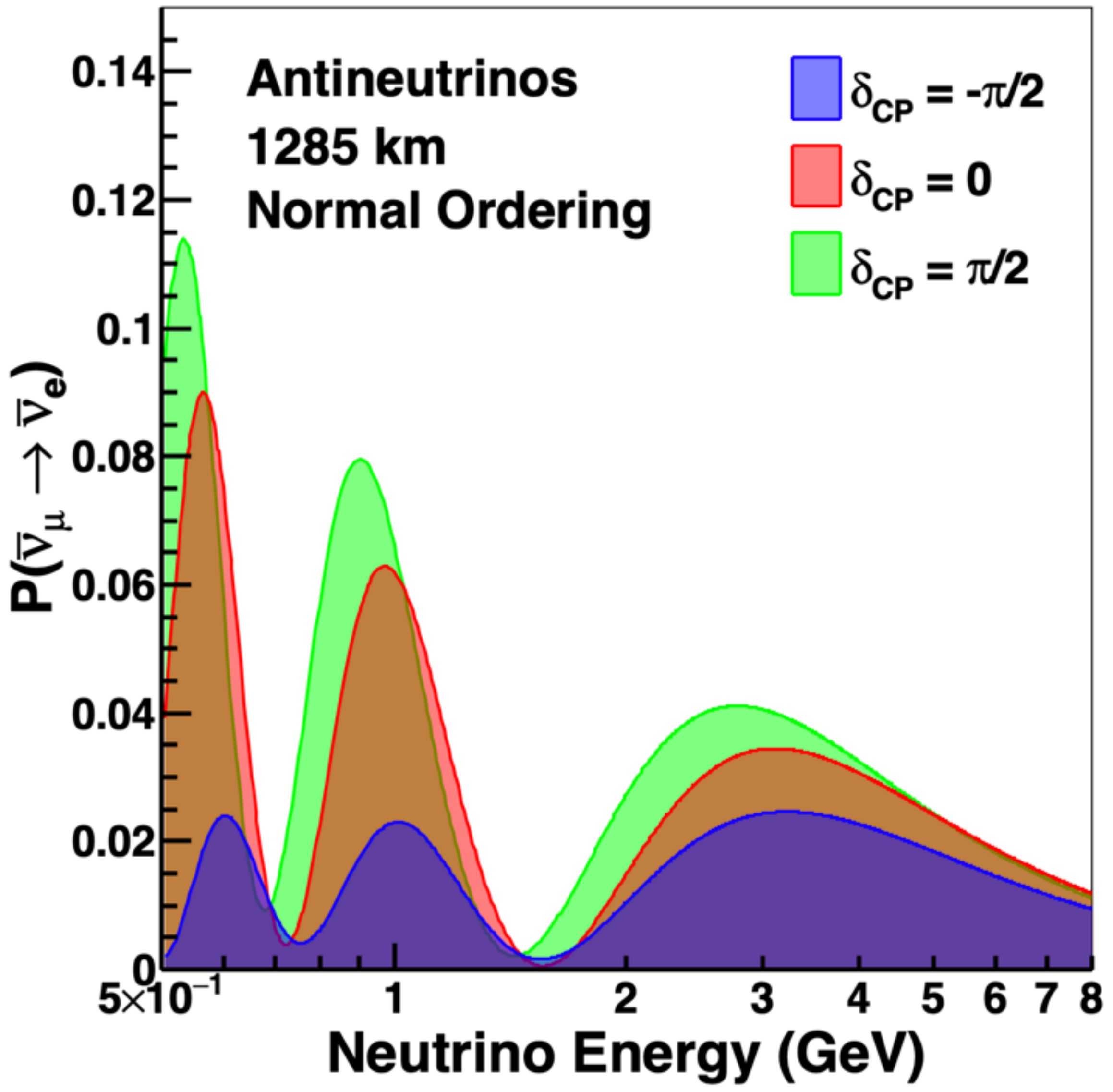
$$\Phi_{ji} = \frac{1.27\Delta m_{ji}^2 L}{E_\nu} \qquad a = \pm\frac{G_F N_e}{\sqrt{2}}$$

Sign change for ν_e and $\bar{\nu}_e$

- sensitive to Δm^2_{32} & Δm^2_{31}
- sensitive to θ_{23} & θ_{13}
- sensitive to δ_{CP}

Interplay between mass ordering and CP-phase

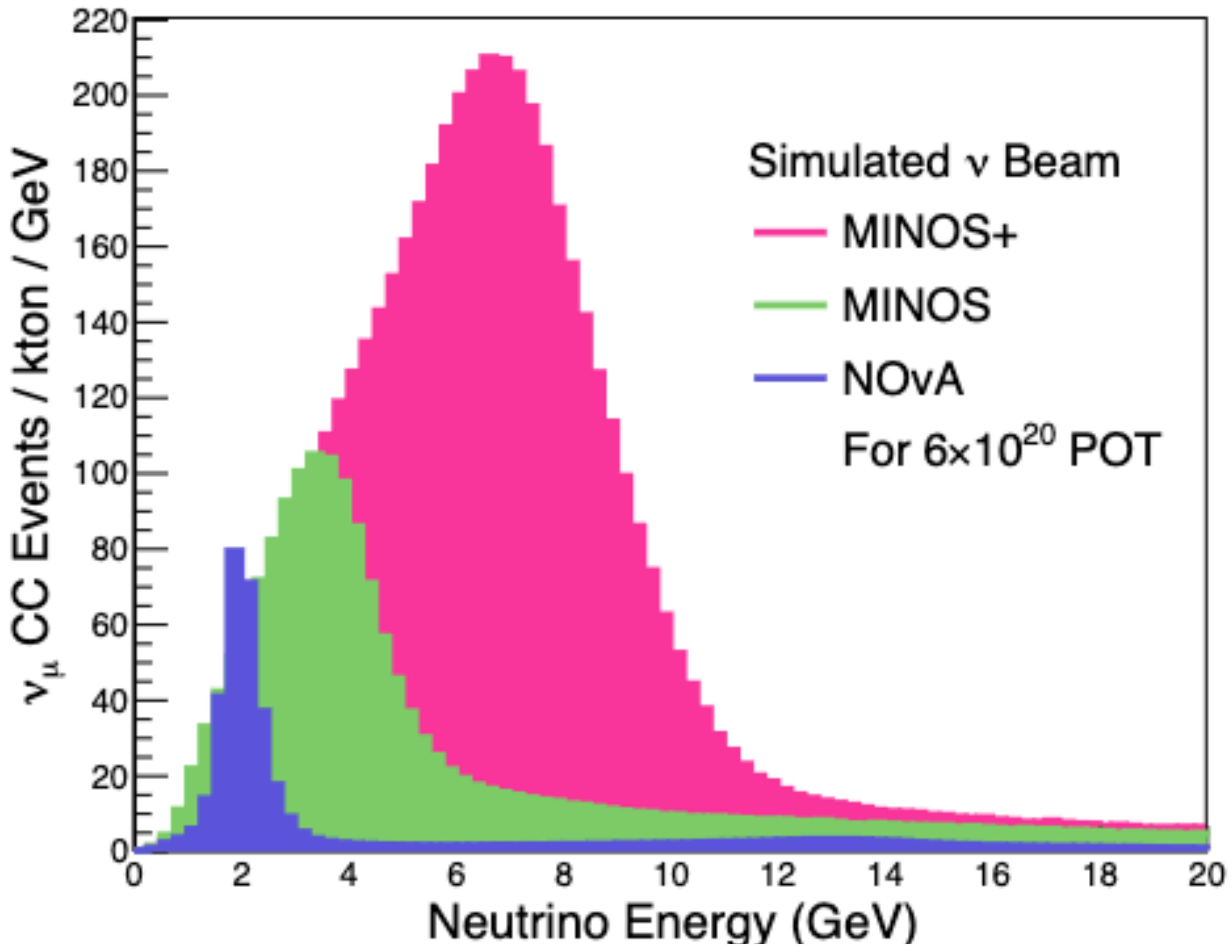




Matter effect increases with E_ν, Enhances NO sensitivity

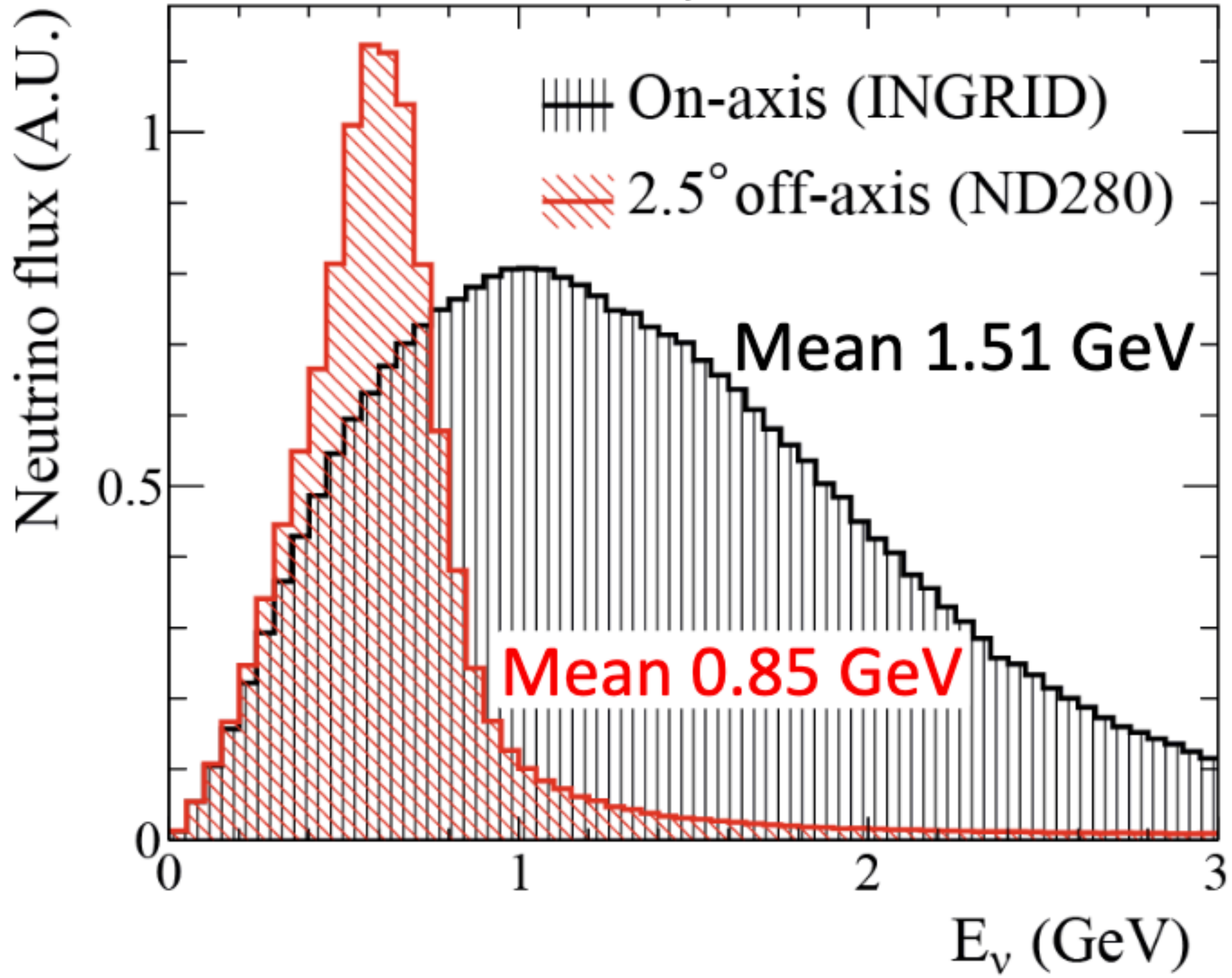
Peak energy of the LBL experiments

Fermilab Experiments



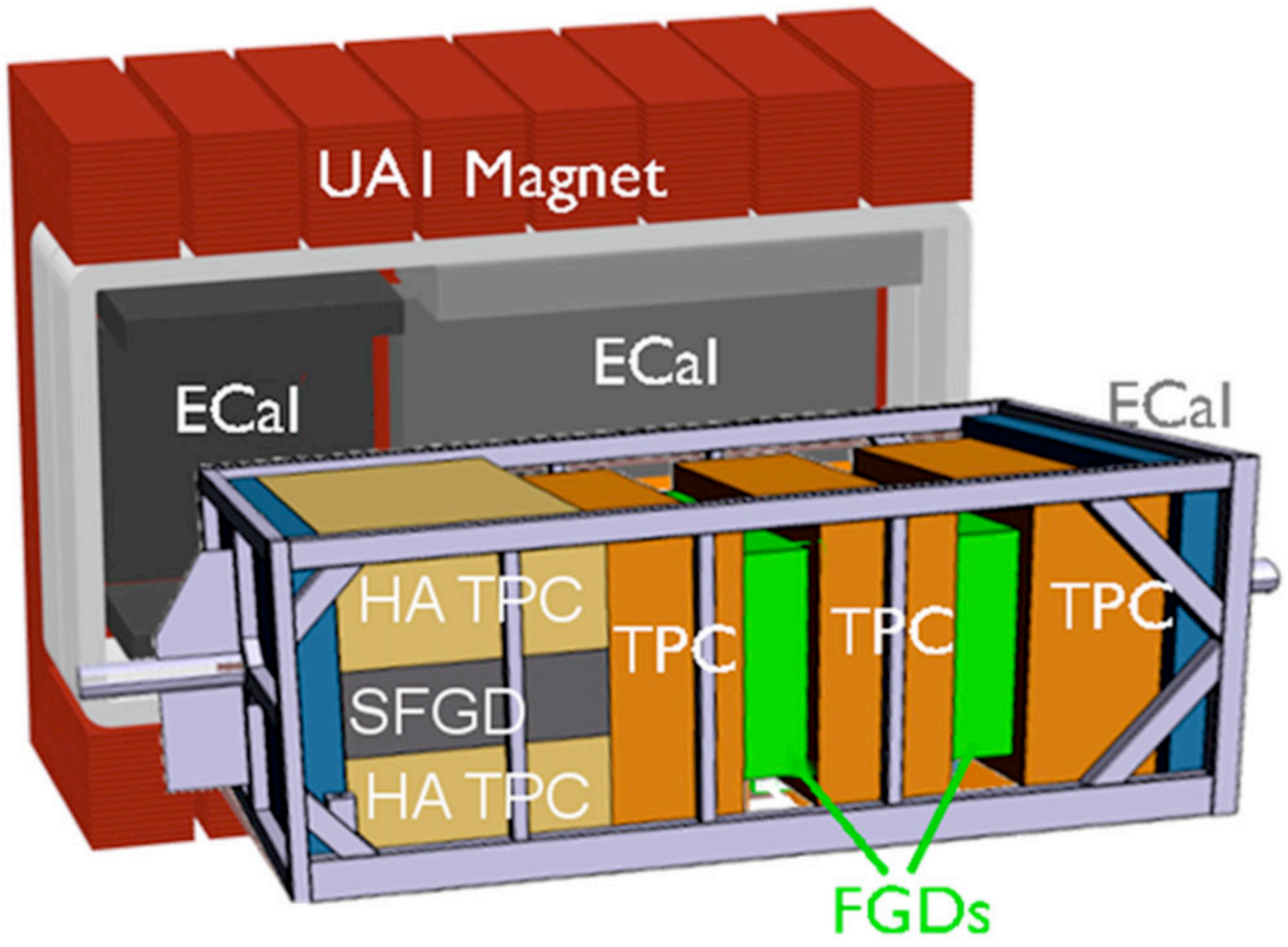
NOvA is the most collimated because of the off-axis location (~0.8 grad)

T2K ν_μ flux



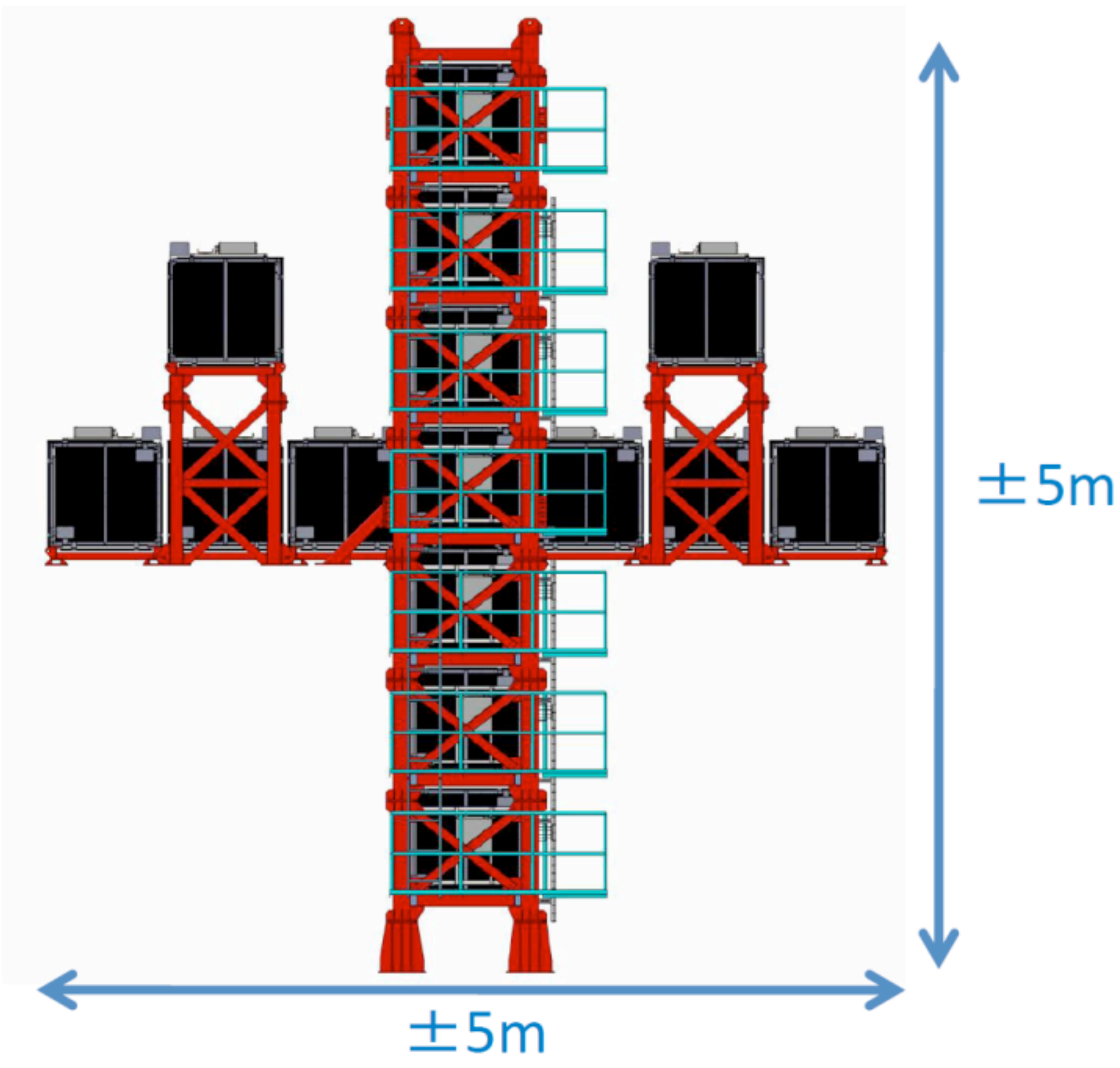
T2K near detectors (ND280 + INGRID)

ND280



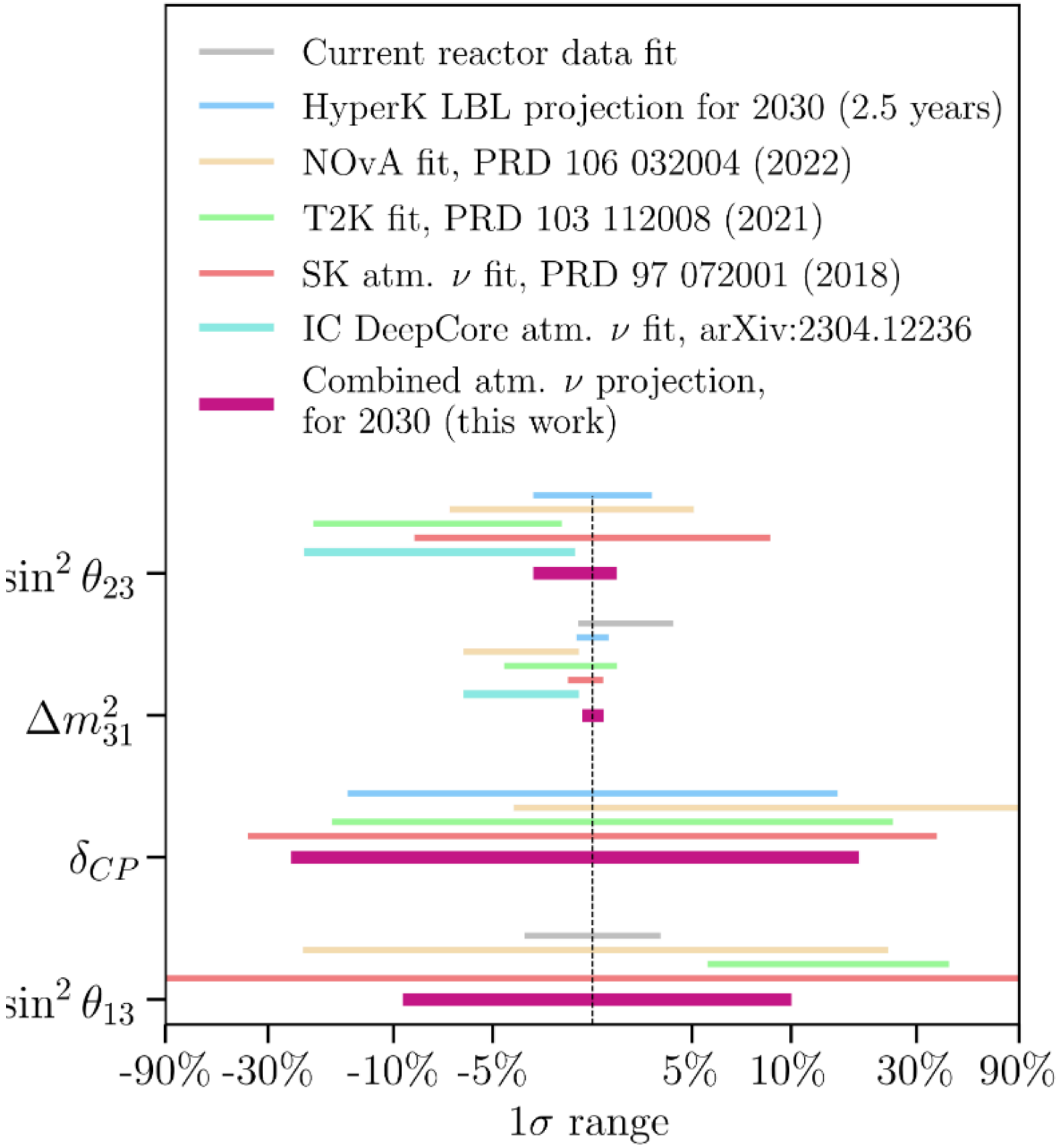
Several technologies

INGRID



Based on liquid scintillator

Atmospheric Neutrinos (combined result Neutrino 2024)



Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

Ultra high energy neutrinos

KM3NeT

- Next generation neutrino telescopes (1km^3)
- Volumes between megaton and several cubic kilometres of clear sea water in the Mediterranean.
  - With the ARCA telescope, KM3NeT scientists will search for neutrinos from distant astrophysical sources such as supernovae, gamma ray bursters or colliding stars.
  - The ORCA telescope is the instrument for KM3NeT scientists studying neutrino properties exploiting neutrinos generated in the Earth's atmosphere.