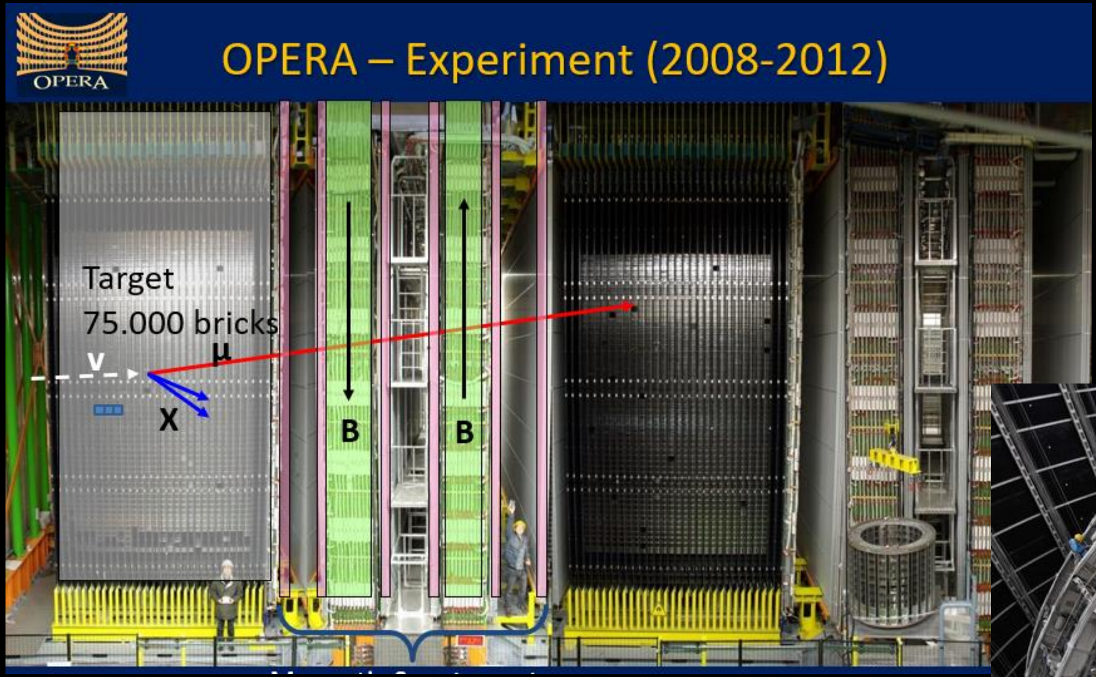
Neutrino Oscillations

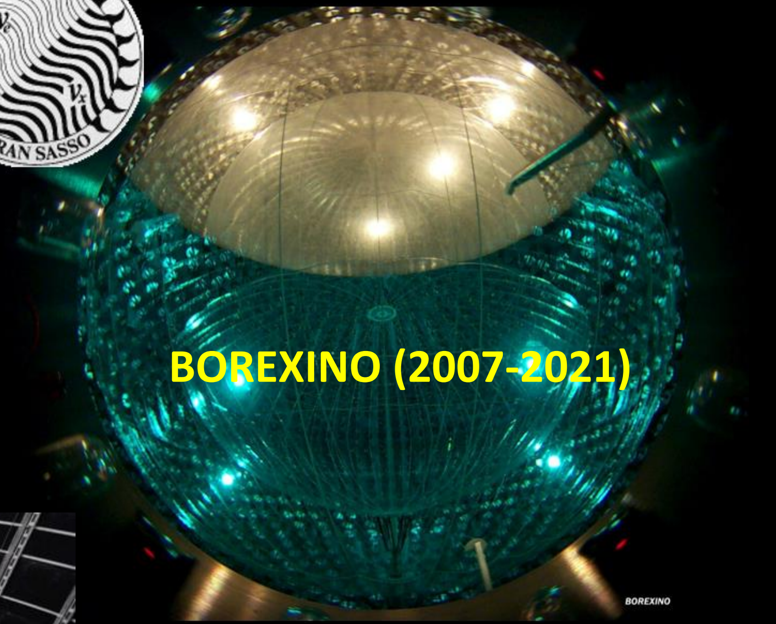
Caren Hagner
Universität Hamburg

Strasbourg Summer School,
1st July 2025

my personal neutrino experience

(Some experiments I participated)





Todays Topics:

1 Some Basic Facts on Neutrinos

2 Basic Oscillation Mechanism

3 The Pioneers & Discovery

4 Why Matter matters, even for Neutrinos

5 The third Mixing Angle – towards Precision

6 Into the Unknown

7 Summary and Outlook

Neutrino Basics

Neutrinos in the Standard Model

$$\underbrace{\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}}_{\text{Quarks}} \qquad \underbrace{\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}}_{\text{Leptons}}$$

3 active Neutrinos

Neutrinos interact **only** via **weak interaction**

SM: Neutrinos are massless

Neutrinos are left handed,

Antineutrinos are right handed,

Neutrinos are stable

Neutrino Oscillations

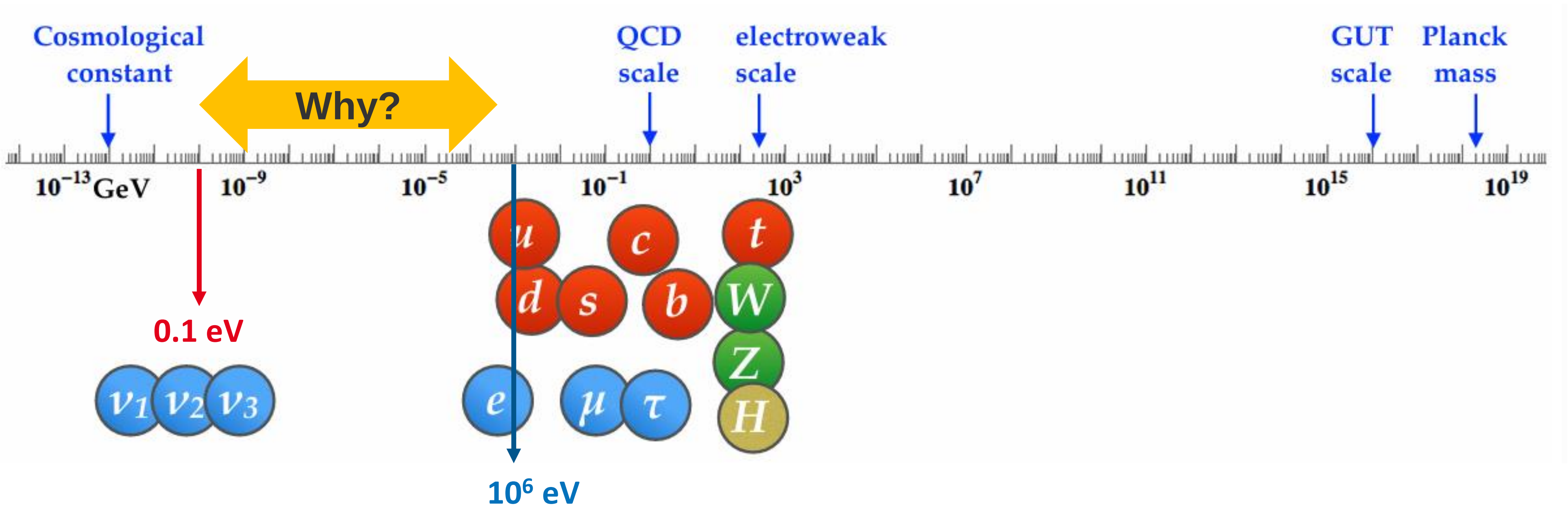
Extension of SM: Neutrinos have masses

Do right handed neutrinos exist?

Majorana neutrinos: $\nu \equiv \bar{\nu}$?

Neutrinos can decay

Why are neutrino masses so much smaller?



KATRIN: m < 0.45 eV

Neutrino Oscillations: m(heaviest neutrino) > 0.05 eV

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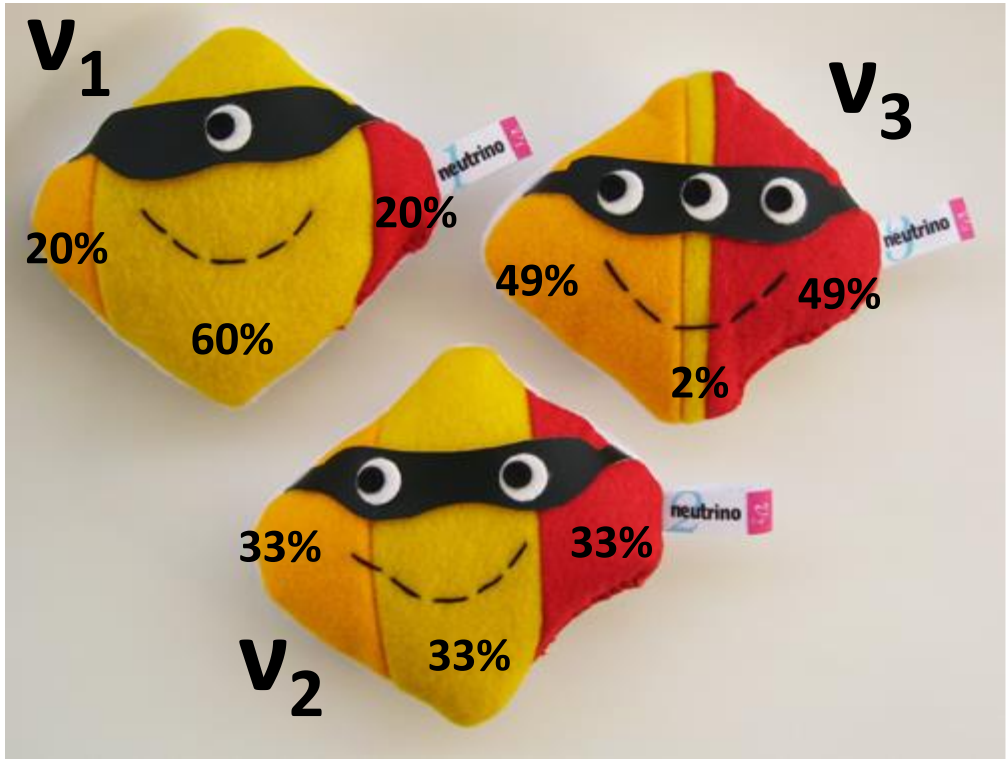
Neutrino Mixing

Mass-Eigenstates



Flavor-Eigenstates

Neutrino Mass and Mixing

Precondition: neutrino masses $m_1, m_2, m_3 \gtrsim 0$

flavor eigenstates $\neq$ mass eigenstates

ν_e, ν_μ, ν_τ $\quad$ ν_1, ν_2, ν_3

$\nu_\alpha \quad \alpha = e, \mu, \tau$ $\quad$ $\nu_i \quad i = 1, 2, 3$

Neutrino Mixing:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

$\to |U_{e1}|^2$ probability that ν_e contains ν_1

$|\langle\nu_1|\nu_e\rangle|^2$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{Neutrino Mixing Matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Matrix

Pontecorvo
Maki
Nakagawa
Sakata

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

9 complex elements:
+ conditions for unitarity of U
+ if neutrinos are Dirac: can rotate away 2 global phases

⬇

4 parameters to describe U **(Dirac case)**

Most popular parametrization: 3 mixing angles θ_{12}, θ_{13}, θ_{23} and 1 phase δ

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{+i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} = 48.5^{+0.7}_{-0.9}\,^{\circ}$ (between 41° and 50°)
$|\Delta m^2_{32}| = (2.534^{+0.025}_{-0.023}) \times 10^{-3}\,\text{eV}^2$

$\Theta_{13} = (8.5 \pm 0.5)^{o}$

$\theta_{12} = 33.7 \pm 0.7^{\circ}$
$\Delta m^2_{21} = (7.5 \pm 0.2) \times 10^{-5}\,\text{eV}^2$

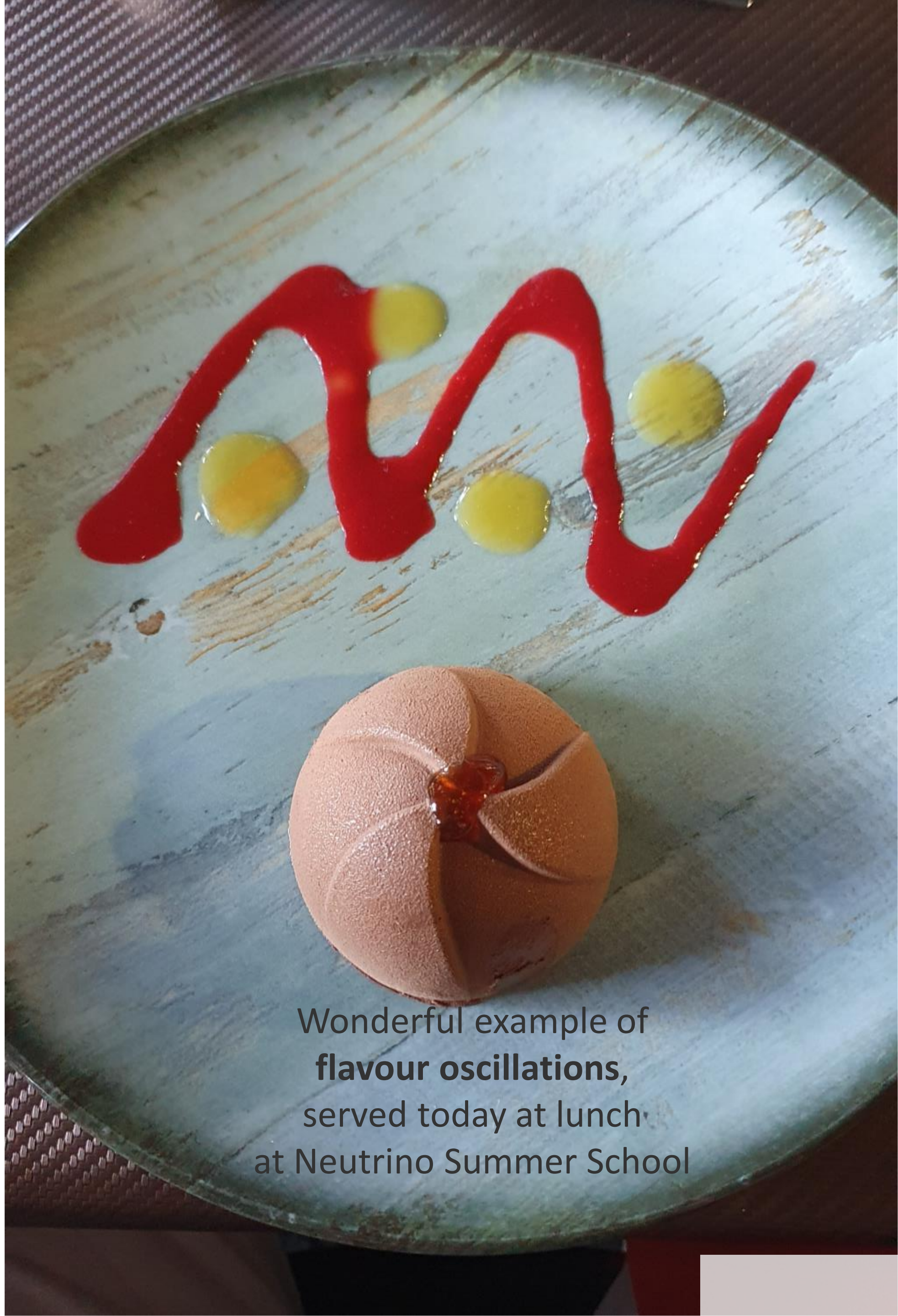
What is δ?

Mass ordering?

Octant problem: Is $\theta_{23} < 45°$ or $> 45°$?

2

Basic Oscillation Mechanism



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Neutrino Oscillations (simplified)

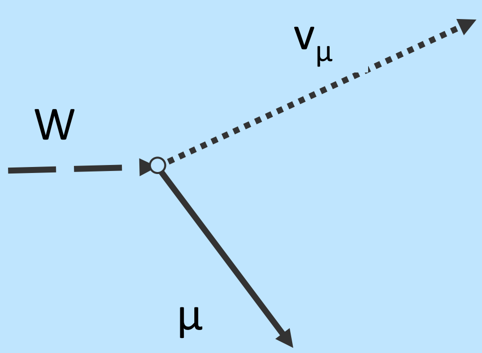
For $\Theta \approx 45^o$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} +1 & +1 \\ -1 & +1 \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

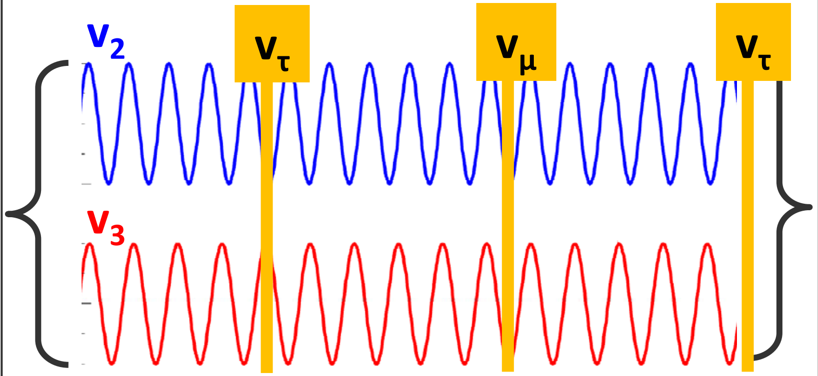
Flavor Eigenstates
ν_μ, ν_τ

Mass Eigenstates
ν_2,ν_3 with m_2, m_3

Source produces
Flavor-Eigenstates



Propagation in vacuum:
Mass-Eigenstates

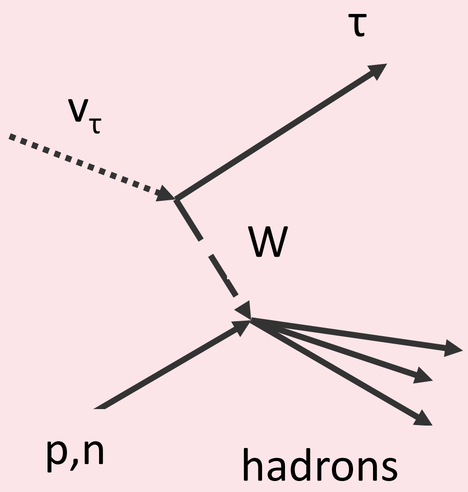


$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

$$|\nu_\mu\rangle = 1/\sqrt{2}\left(|\nu_2\rangle + |\nu_3\rangle\right)$$

$$|\nu_\tau\rangle = 1/\sqrt{2}\left(-|\nu_2\rangle + |\nu_3\rangle\right)$$

Detection process:
Flavor-Eigenstates

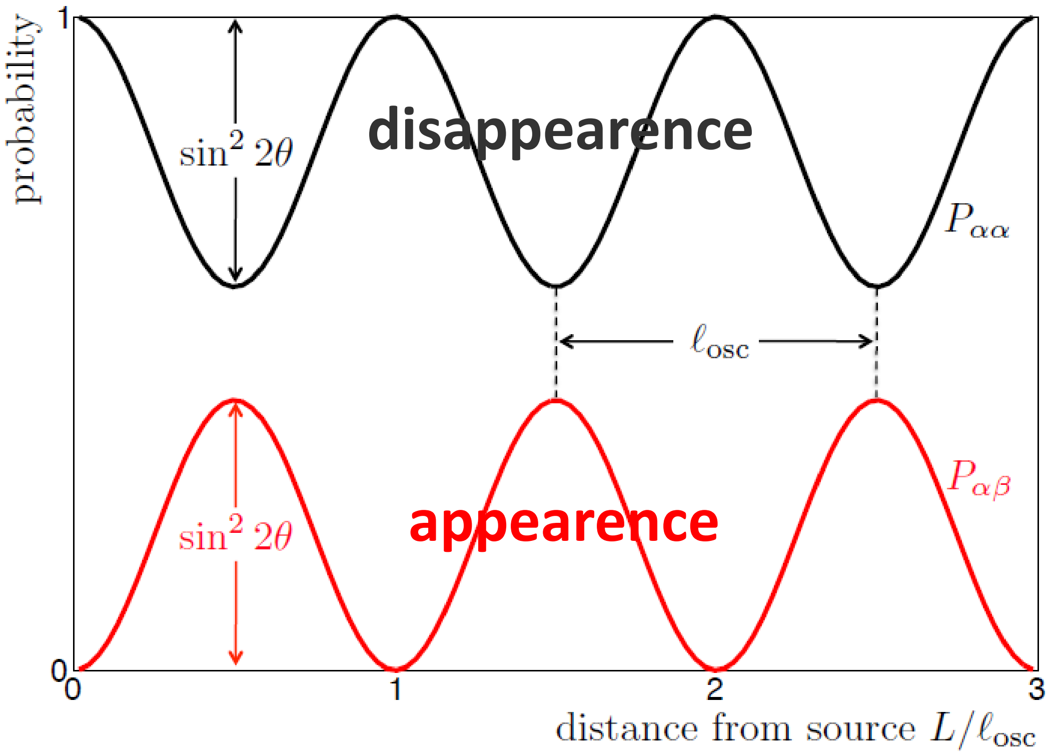


Neutrino Oscillations (2 Flavors)

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(1.267 \frac{\Delta m_{23}^2(\text{in eV}^2) \cdot L(\text{in km})}{E(\text{in GeV})}\right)$$

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

$$l_{\text{osc}} = 2.48 \frac{E(\text{in GeV})}{\Delta m_{23}^2(\text{in eV}^2)} \text{km}$$



Example:
for $\Delta m^2 = 2.5 \cdot 10^{-3} eV^2$
and E_ν = 1GeV we get
l_{osc} = 1000km

Theoretical Prediction of Neutrino Oscillations:

Bruno Pontecorvo
(1913 – 1993)

- 1957-58: **Pontecorvo:**
  states for first time possibility of **Neutrino Oscillations**
  (But: at that time only ν_e were known, so he was thinking of Neutrino ↔ Anti-Neutrino oscillations)
  B. Pontecorvo, J.Exptl. Theoret. Phys.34(1958) 247 [Sov. Phys. JETP7(1958) 172]

- 1962 **Maki, Nakagawa, Sakata:**
  describe **mixing of 2 flavors** and discuss transitions between neutrino flavors.

- 1967 **Pontecorvo :**
  thorough discussion of 2 flavor mixing,
  oscillations of solar-neutrinos
  and possible existence of sterile neutrinos.
  Also possibility of Cl-Ar experiments

Very nice overview on history:
Samoil M. Bilenky „Neutrino oscillations: brief history and present status"
arXiv:1408.2864v1 [hep-ph] 12 Aug 2014

One of last great unsolved cold-war science mysteries

S. *Turchetti*, The Pontecorvo Affair. A Cold War Defection and Nuclear Physics, Univ. of Chicago Press, Chicago (2012)

Die Affäre Pontecorvo

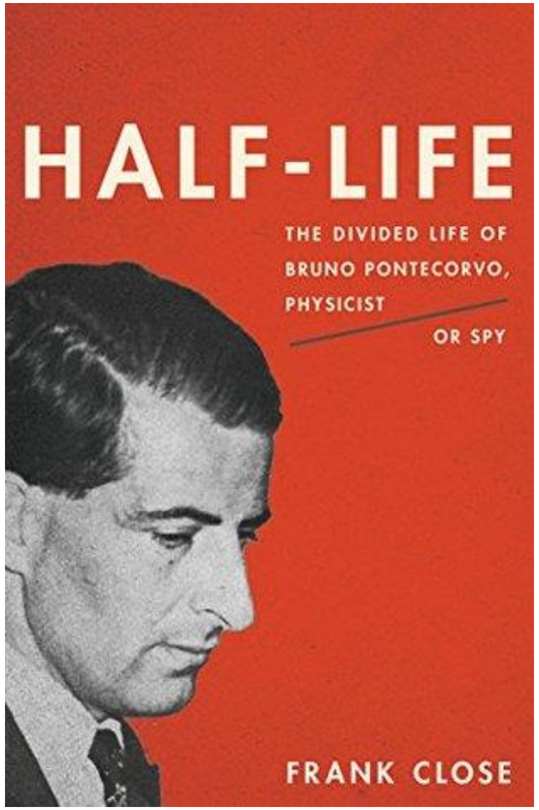
Die ungewöhnliche Karriere des italienischen Kernphysiker

Simone Turchetti

Dipartimento di Fisica, Sapienza – Università Roma

Bruno Pontecorvo (links) im Jahr 1949, ein Jahr vor seinem rätselhaften Verschwinden zusammen mit Enrico Fermi (2. von rechts) bei der Besichtigung einer Fabrik von Olivetti, dem italienischen Hersteller für Büro- und Rechenmaschinen.

in german: Physik Journal 12 (2013) Nr.10



…and here a talk by F. Close

https://youtu.be/d4rCjoWiOrw

And a discussion of this book in Nature
https://www.nature.com/articles/518032a

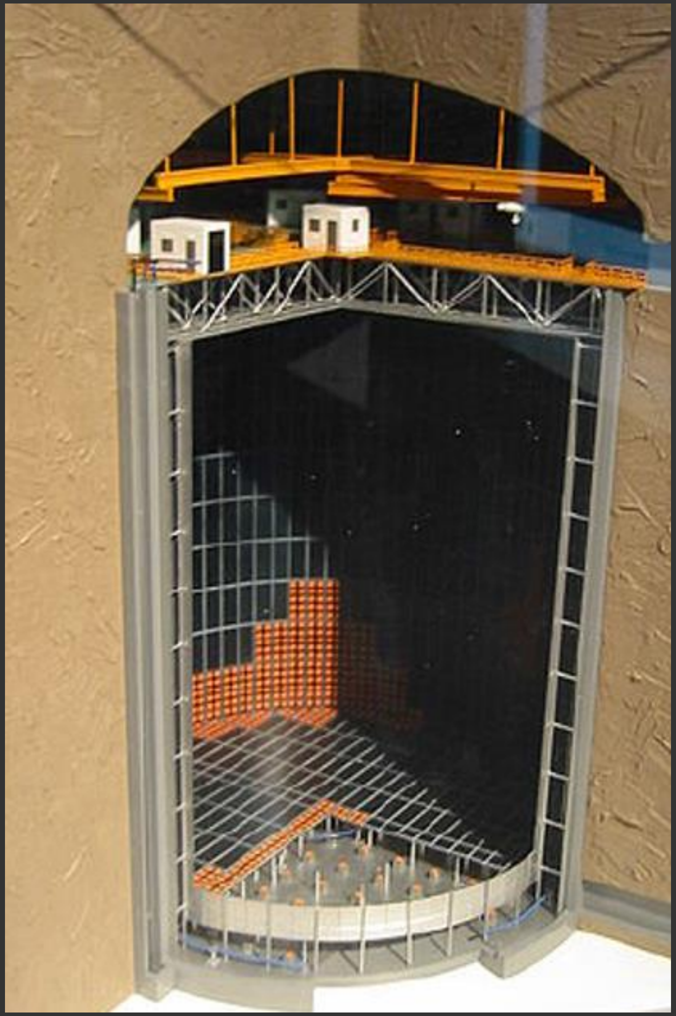
3

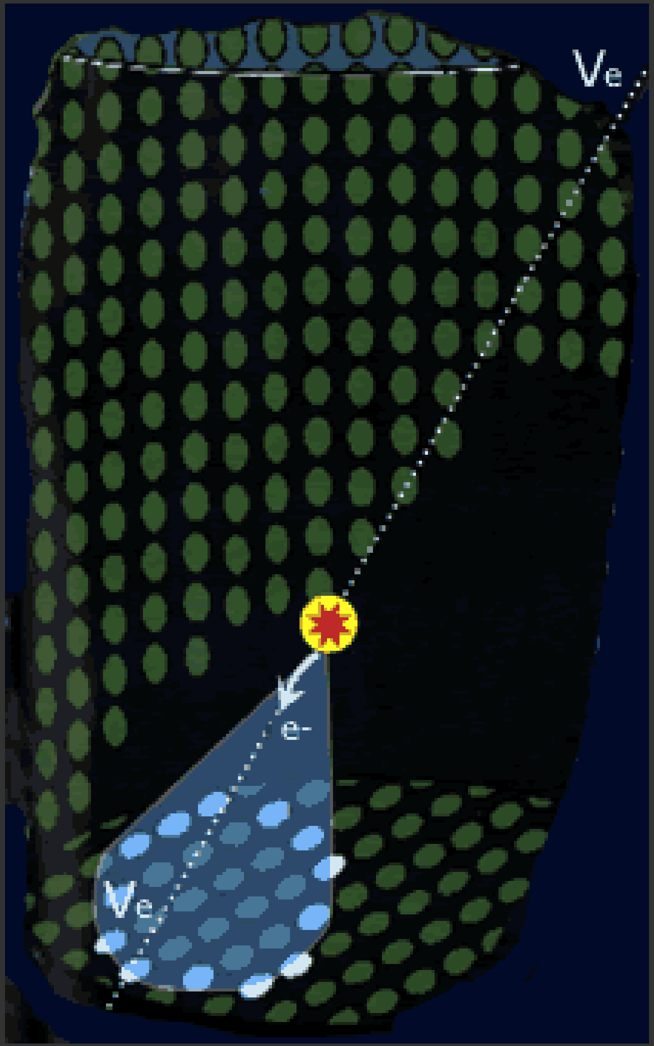
The Pioneers & Discovery

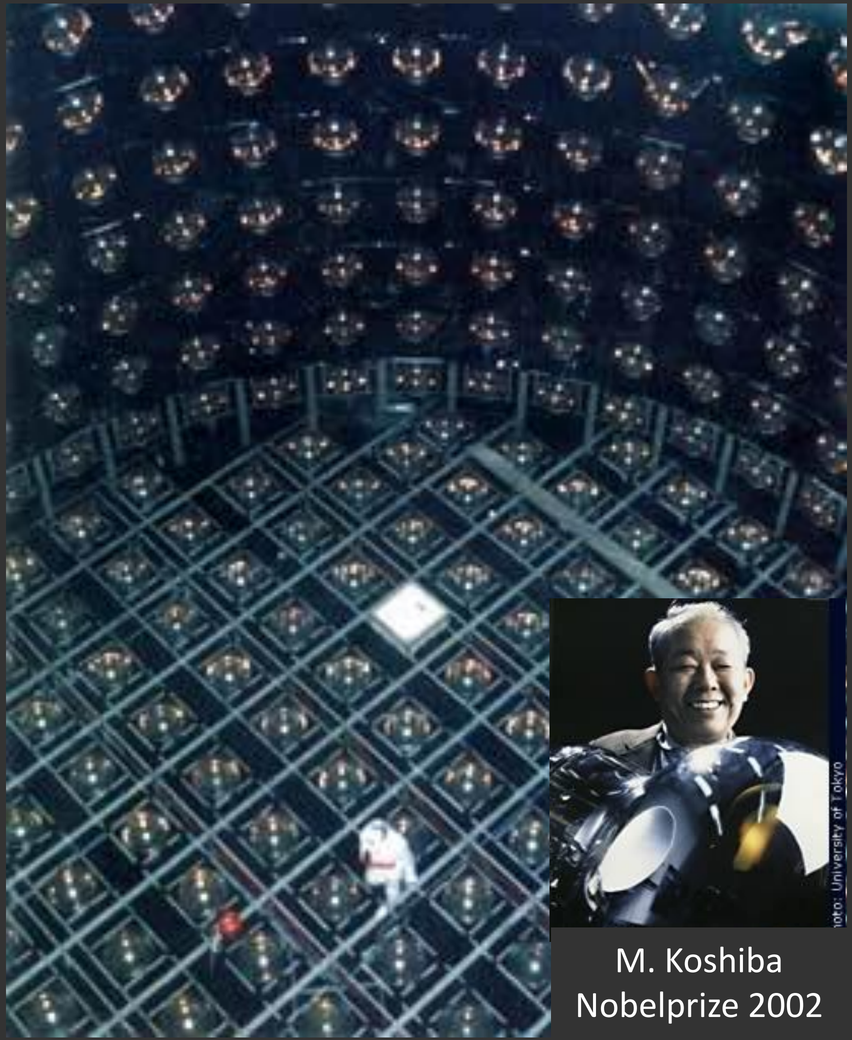
KamiokaNDE

Nucleon Decay Experiment

3 kt Water Cerenkov detector, build for searching proton decay







M. Koshiba
Nobelprize 2002

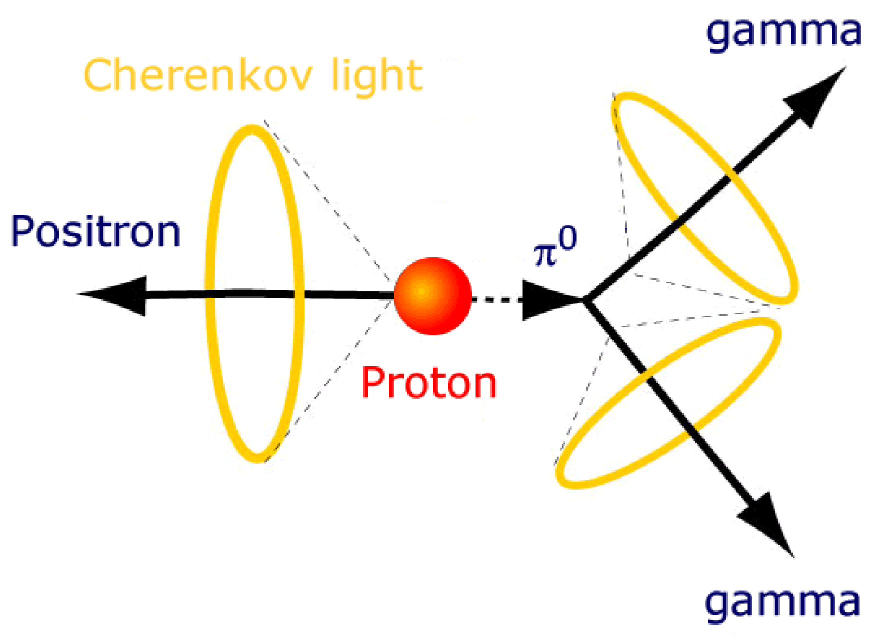
"for pioneering contributions to astrophysics, in particular **for the detection of cosmic neutrinos**"

„Possible" mode of proton decay:
GUT theories

$$p \rightarrow e^+ + \pi^0$$

Energy threshold for
Cerenkov emmission (in water):

- Muon: > 170 MeV
- Electron: > few MeV



In 10 kt H_2O $\approx 10^{33}$ protons

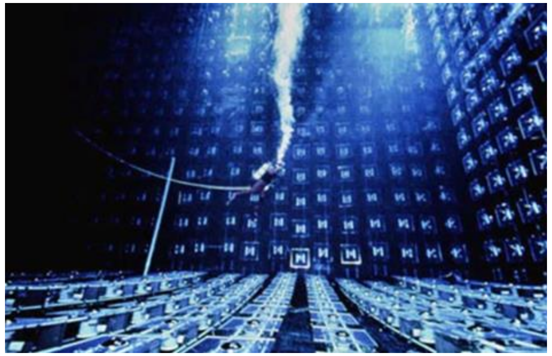
$\rightarrow$ Can test $\tau_p \gtrsim 10^{33} - 10^{34}$ y (prediction of some GUT theories or other beyond SM)

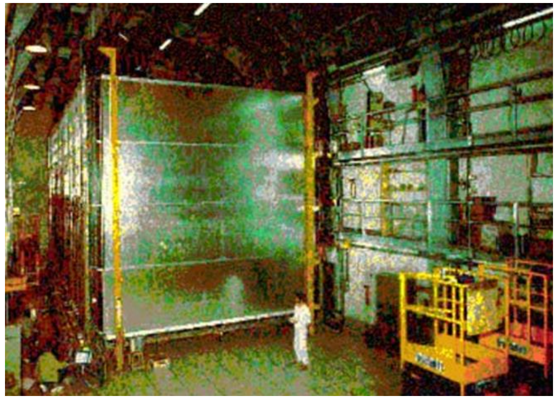
compare to $T_{Universe} \approx 10^{10}$ y

Proton Decay Experiments in the 1980s

- KamiokaNDE (water cerenkov, FV = 1000t)
- IMB (water cerenkov, FV = 3300t)
- NUSEX (iron tracking calorimeter, FV = 130t)
- Frejus (iron tracking calorimeter, FV = 700t)
- …

Atmospheric neutrinos had been discovered in 1965 and were considered as a **background**





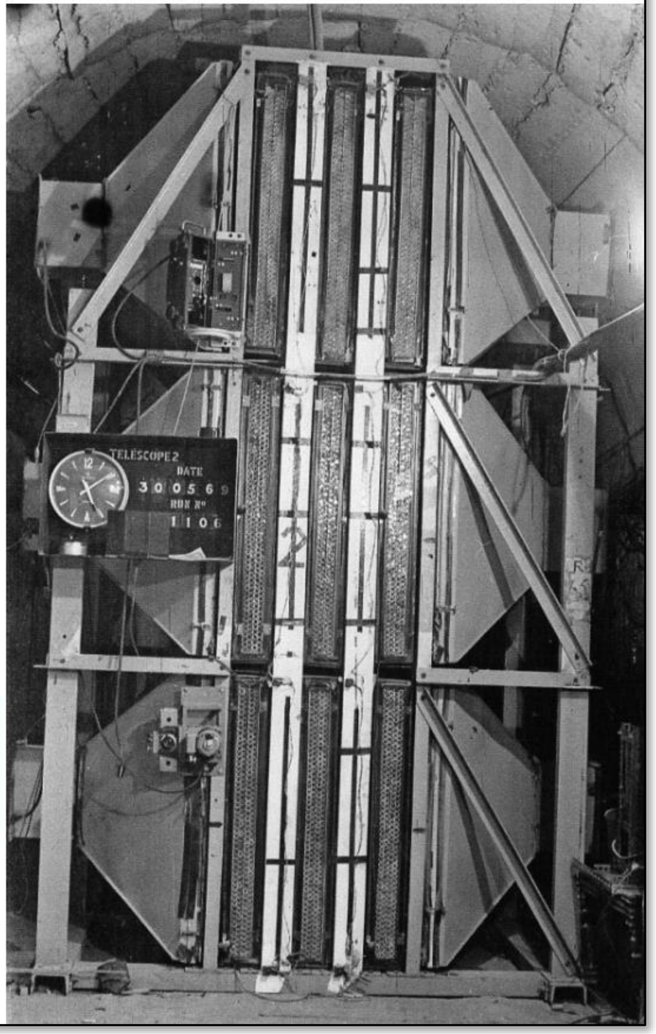
After muon neutrino was discovered in 1962 (in accelerator experiments)

Discovery of atmospheric neutrinos (1965)

In 1965, atmospheric neutrinos were observed for the first time by detectors located very deep underground.

← In South Africa
F. Reines et al., PRL 15, 429 (1965)

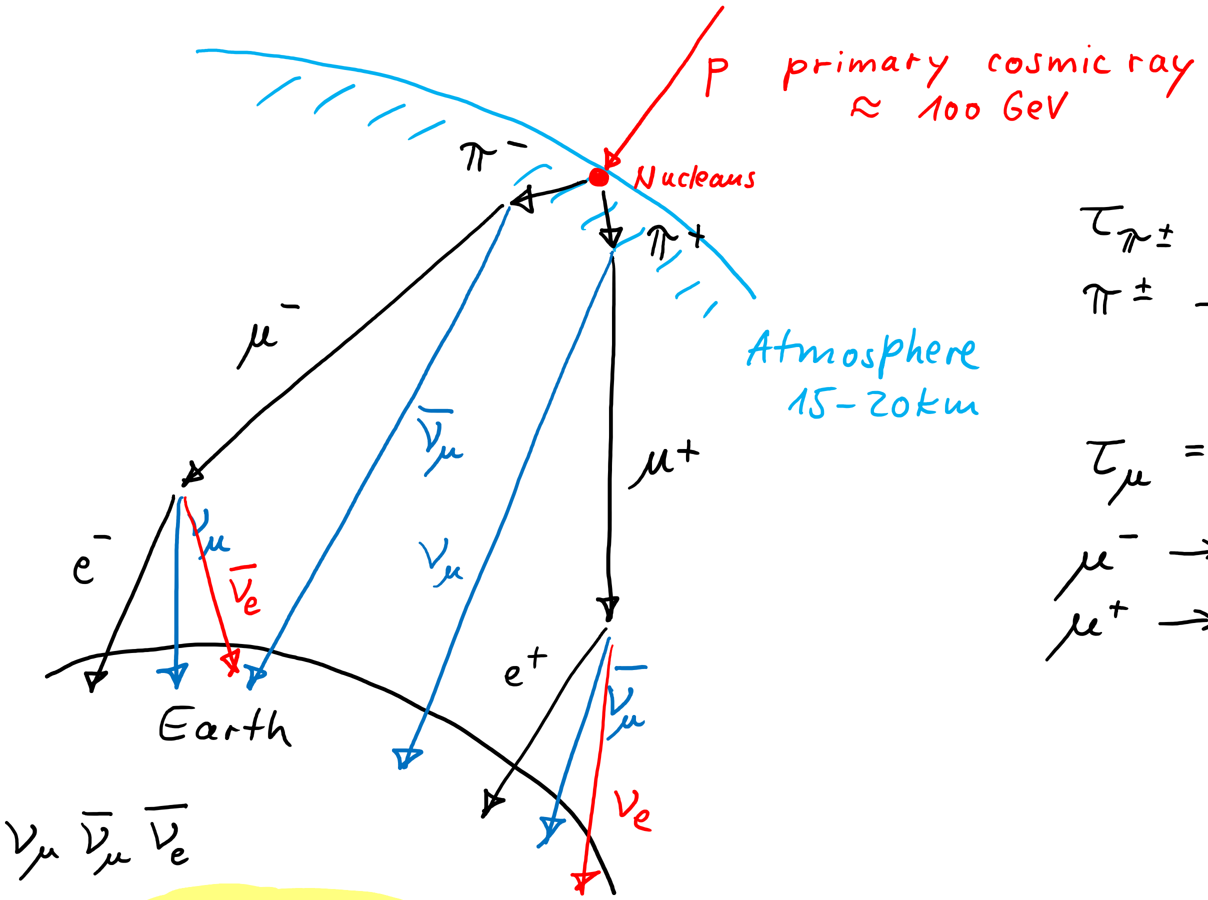
→ In India
C.V. Achar et al., PL 18, 196 (1965)



Slide by T.Kajita

Also interesting:
„PERSPECTIVES OF EXPERIMENTAL NEUTRINO PHYSICS IN INDIA“, V.S.Narasimham
Proc Indian Natn Sci Acad, 70, A, No.1, January 2004, pp.11–25

Atmospheric neutrinos



$\tau_{\pi^\pm} = 26\,\text{ns}$

$\pi^\pm \to \mu^\pm \overset{(-)}{\nu}_\mu$

$\tau_\mu = 2.2\,\mu\text{s}$

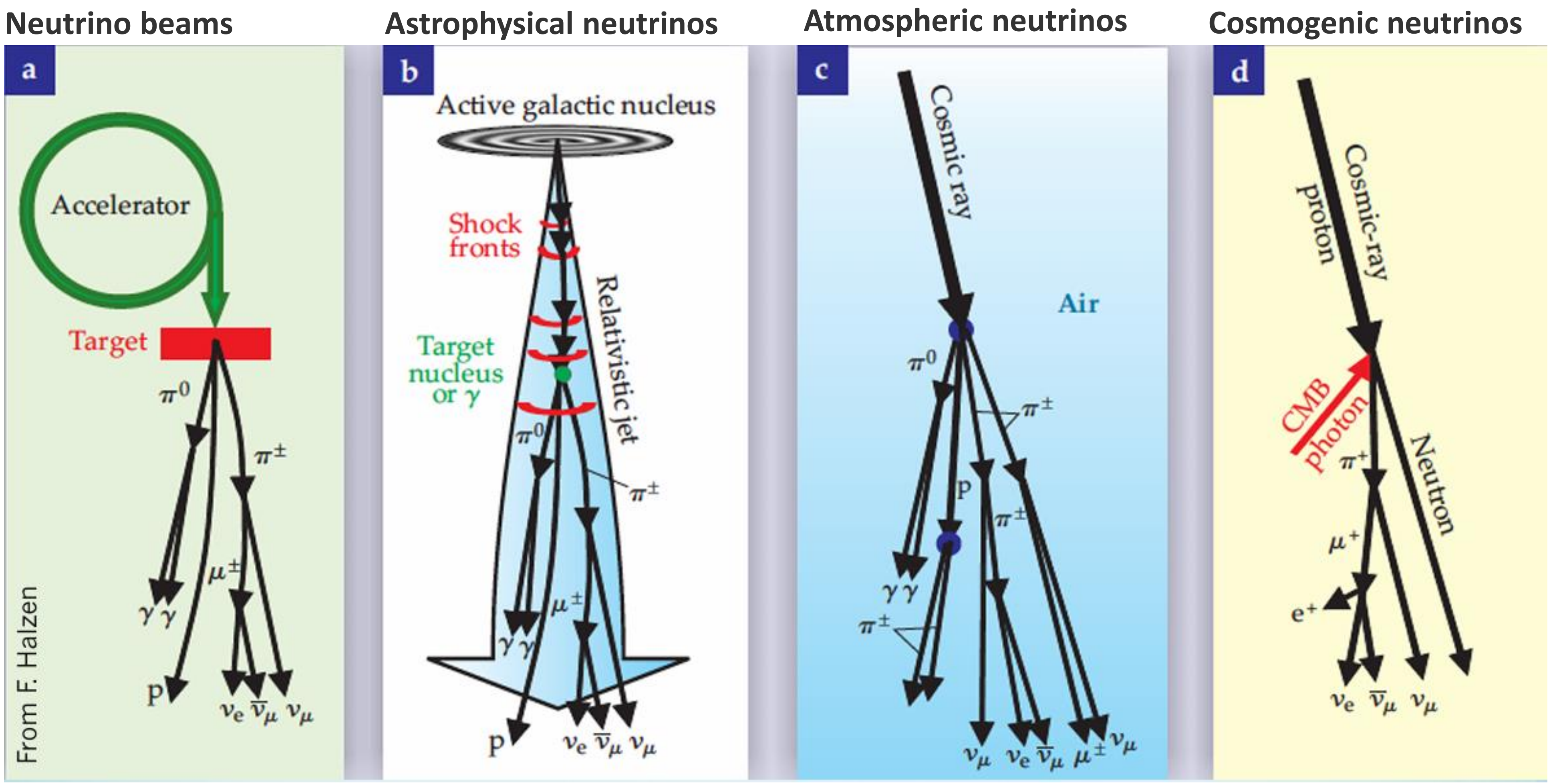
$\mu^- \to e^- \nu_\mu \bar{\nu}_e$

$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$

$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

observed number of events

Neutrino production by protons hitting a target



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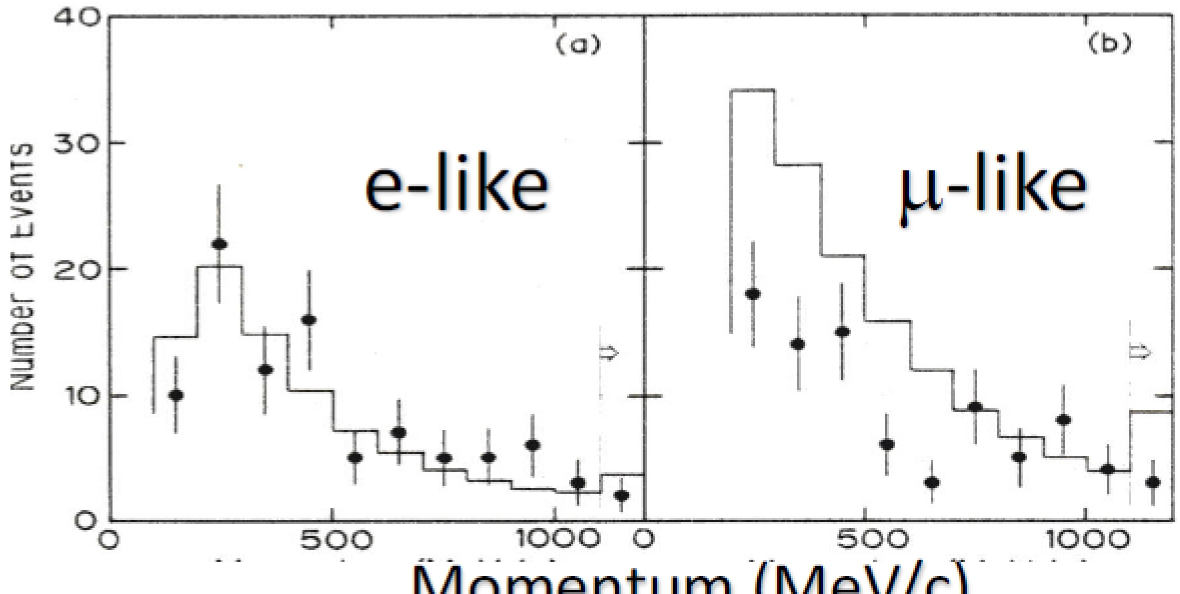
But then: Kamiokande sees something strange in 1988…

1988: atmospheric neutrino anomaly

– Kamiokande Observed fewer μ-like events in atmospheric ν interactions than expected

R= (Obs./MC)μ-like = 59±7% (stat.)

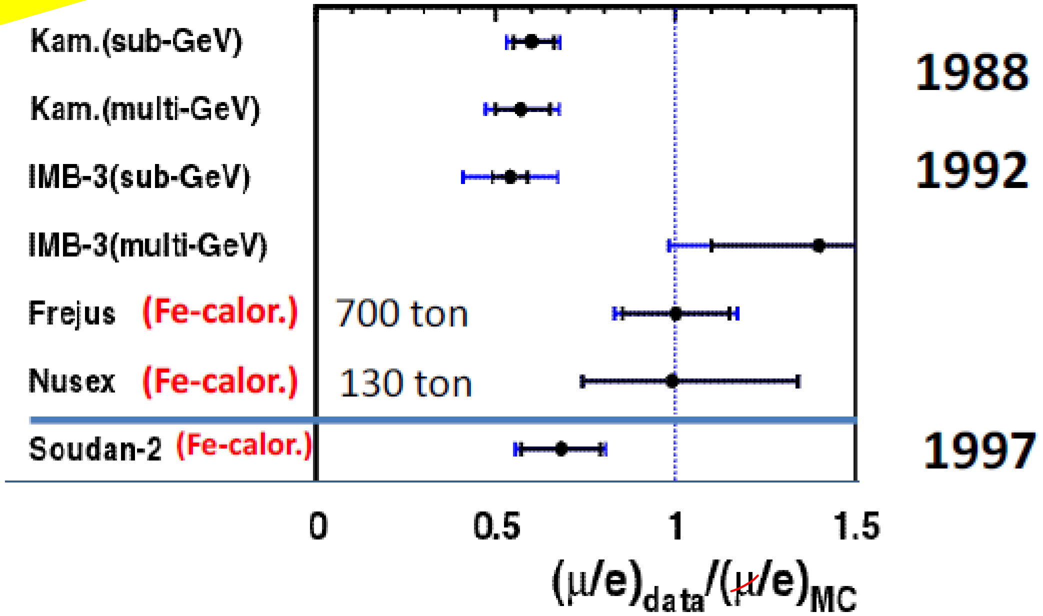


17/9/4

Y. Suzuki @Brexino10thAnn in Gran Sasso

Other experiments start looking at this so called atmospheric neutrino anomaly…

Result: Confusion!



Half of the muon neutrinos seem to be missing!
But only in the water Cerenkov detectors?

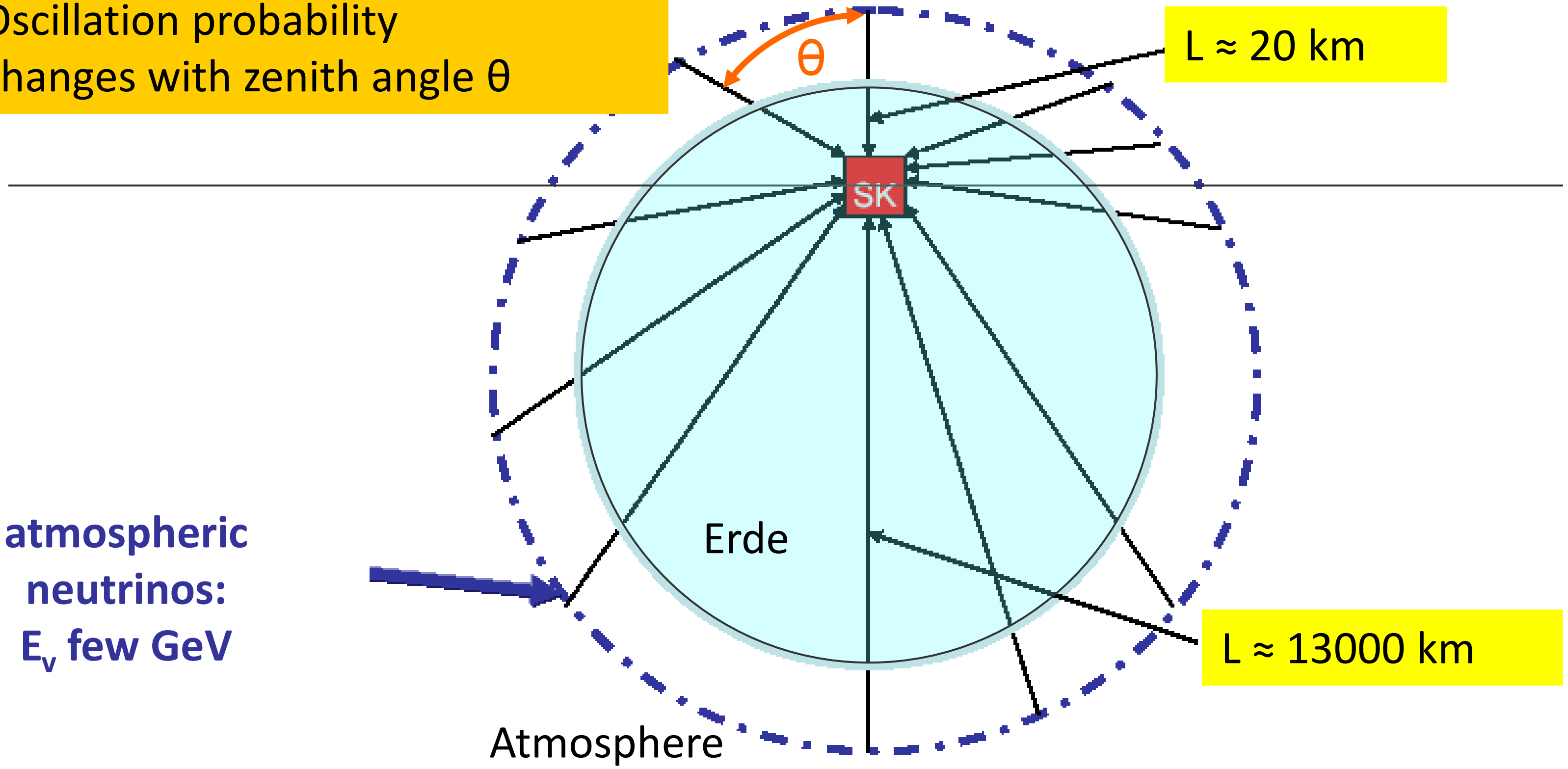
Conclusion: Need bigger and better detector (SuperKamiokande) to solve the puzzle

Super-Kamiokande

Fig. 1. Location of Super-Kamiokande in Japan.

Zenith angle distribution

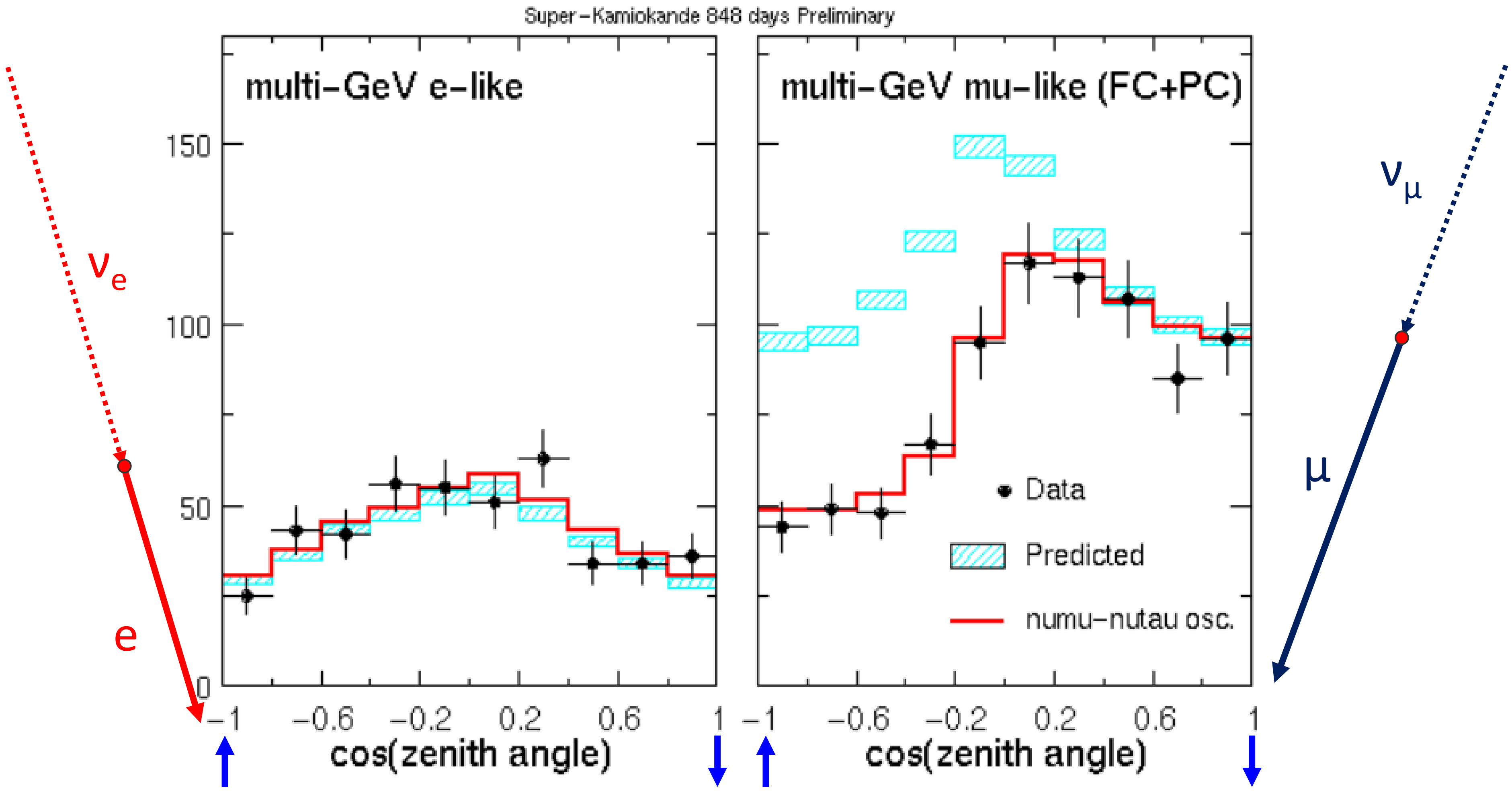
Oscillation probability changes with zenith angle θ



atmospheric neutrinos: E_ν few GeV

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{atm} \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E_\nu}\right)$$

SuperK – First Evidence for Neutrino Oscillations 1998

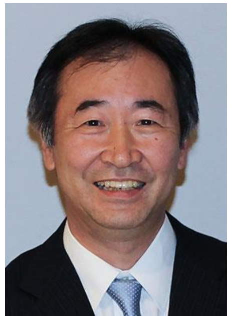


$$A_{\exp} = 0 \text{ for } \nu_e, \text{ but for } \nu_\mu\text{: } A_{\exp} = -0.296 \pm 0.048_{stat} \pm 0.010_{syst}$$

VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

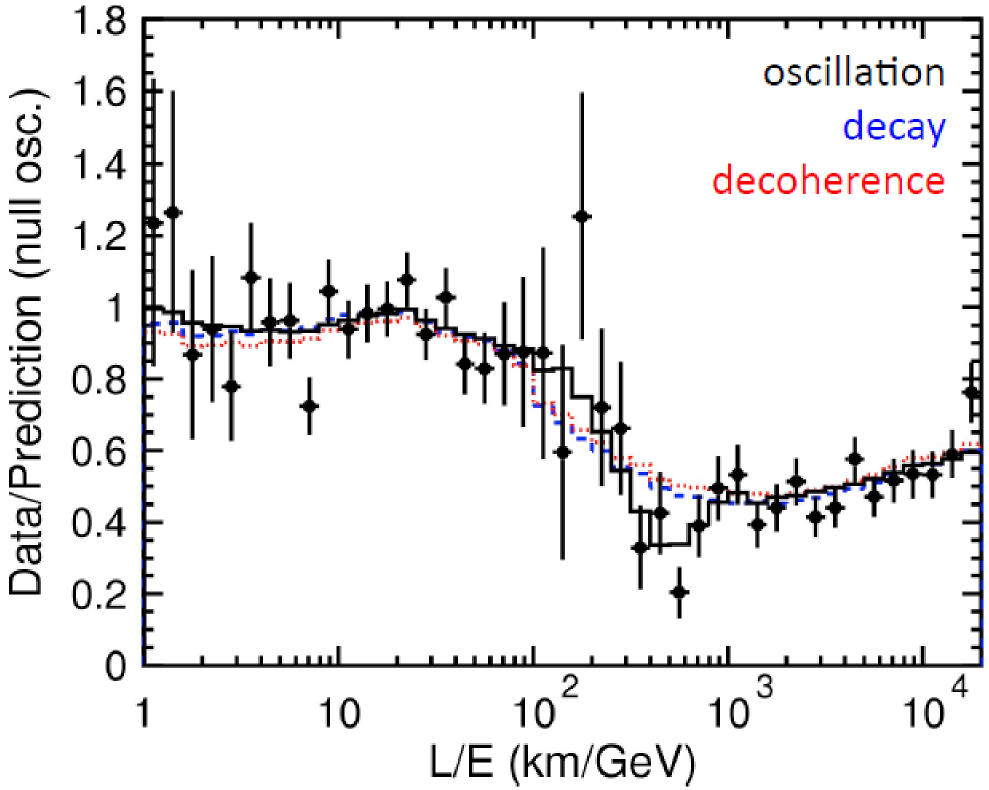
Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M. D. Messier,[2] K. Scholberg,[2] J. L. Stone,[2] L. R. Sulak,[2] C. W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P. G. Halverson,[4,*] J. Hsu,[4] W. R. Kropp,[4] L. R. Price,[4] F. Reines,[4] M. Smy,[4] H. W. Sobel,[4] M. R. Vagins,[4] K. S. Ganezer,[5] W. E. Keig,[5] R. W. Ellsworth,[6] S. Tasaka,[7] J. W. Flanagan,[8,†] A. Kibayashi,[8] J. G. Learned,[8] S. Matsuno,[8] V. J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9] K. Nakamura,[9] K. Nishikawa,[9] Y. Oyama,[9] A. Sakai,[9] M. Sakuda,[9] O. Sasaki,[9] S. Echigo,[10] M. Kohama,[10] A. T. Suzuki,[10] T. J. Haines,[11,4] E. Blaufuss,[12] B. K. Kim,[12] R. Sanford,[12] R. Svoboda,[12] M. L. Chen,[13] Z. Conner,[13,‡] J. A. Goodman,[13] G. W. Sullivan,[13] J. Hill,[14] C. K. Jung,[14] K. Martens,[14] C. Mauger,[14] C. McGrew,[14] E. Sharkey,[14] B. Viren,[14] C. Yanagisawa,[14] W. Doki,[15] K. Miyano,[15] H. Okazawa,[15] C. Saji,[15] M. Takahata,[15] Y. Nagashima,[16] M. Takita,[16] T. Yamaguchi,[16] M. Yoshida,[16] S. B. Kim,[17] M. Etoh,[18] K. Fujita,[18] A. Hasegawa,[18] T. Hasegawa,[18] S. Hatakeyama,[18] T. Iwamoto,[18] M. Koga,[18] T. Maruyama,[18] H. Ogawa,[18] J. Shirai,[18] A. Suzuki,[18] F. Tsushima,[18] M. Koshiba,[19] M. Nemoto,[20] K. Nishijima,[20] T. Futagami,[21] Y. Hayato,[21,§] Y. Kanaya,[21] K. Kaneyuki,[21] Y. Watanabe,[21] D. Kielczewska,[22,4] R. A. Doyle,[23] J. S. George,[23] A. L. Stachyra,[23] L. L. Wai,[23,‖] R. J. Wilkes,[23] and K. K. Young[23]
(Super-Kamiokande Collaboration)



Nobelprize 2015 for T. Kajita

Super-K L/E Analysis (2005): alternative mechanisms disfavoured



→ Oscillation scenario preferred at >3σ level.

This was confirmed by neutrino beam experiments

Disappearence of ν_μ

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \cdot \sin^2\left(1.267 \frac{\Delta m^2_{23}(\text{in eV}^2) \cdot L(\text{in km})}{E(\text{in GeV})}\right)$$

$\theta_{23} = \mathbf{48.5}^{+0.7}_{-0.9}\,{}^\circ$ (between 41° and 50°)

$|\Delta m^2_{32}| = (\mathbf{2.534}^{+0.025}_{-0.023}) \times \mathbf{10^{-3}}\,\text{eV}^2$

Octant Problem:
This is symmetric around 45°:
e.g. 50° and 40° give same value for $\sin^2 2\theta$

Mass Ordering?:
Same value for
$m_2 < m_3$ and for $m_3 < m_2$

K2K

MINOS

Today:
NOvA, T2K

…further confirmed by atmospheric neutrinos in SK and Icecube

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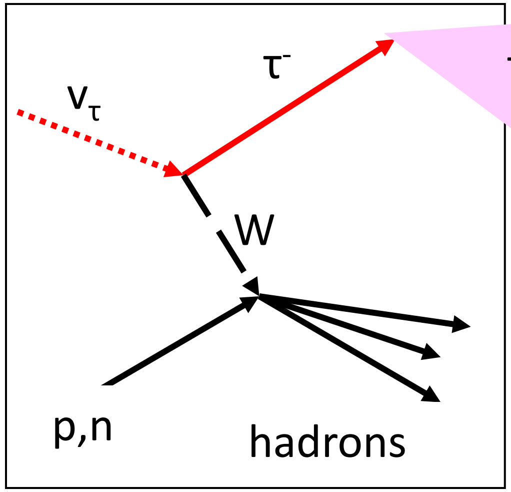
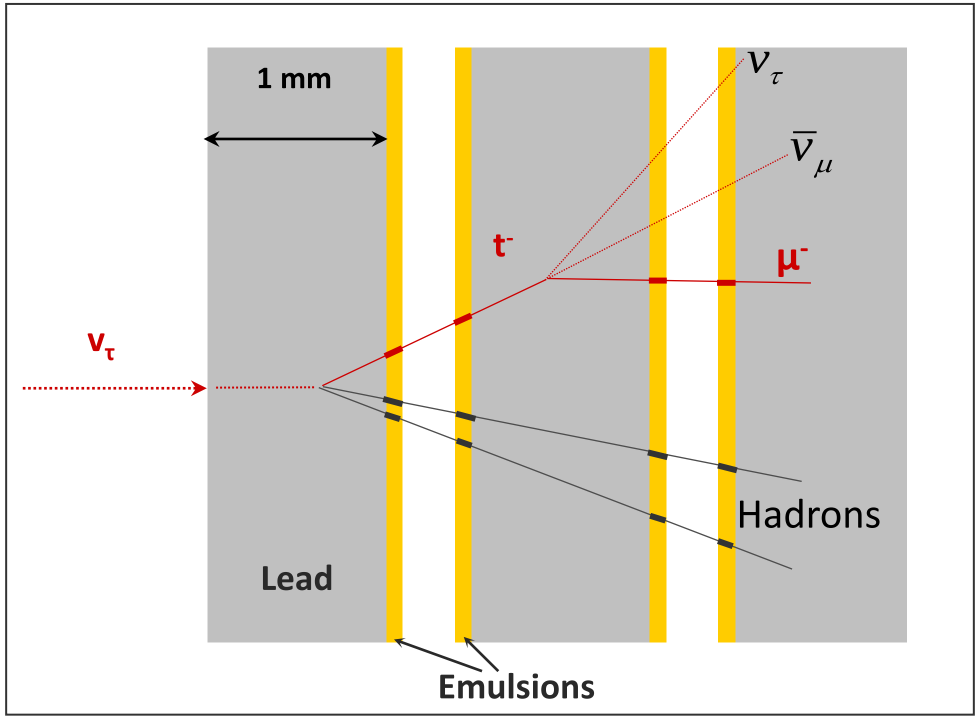
OPERA: Appearence of ν_τ (2015)

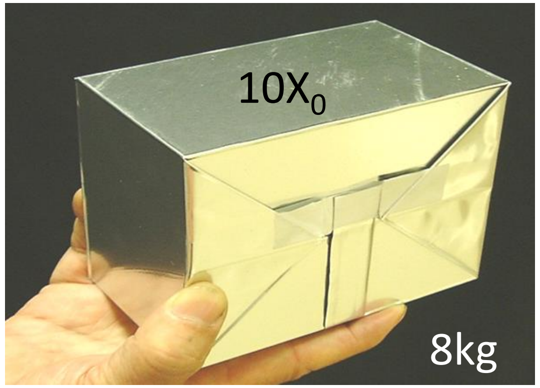


τ-decay:

$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$	18%
$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$	18%
$\tau^- \to \pi^-(n\pi^0) + \nu_\tau$	48%
$\tau^- \to \pi^-\pi^-\pi^+(n\pi^0) + \nu_\tau$	15%

Typical topology of τ-decay:
"Kink" within 1mm from vertex



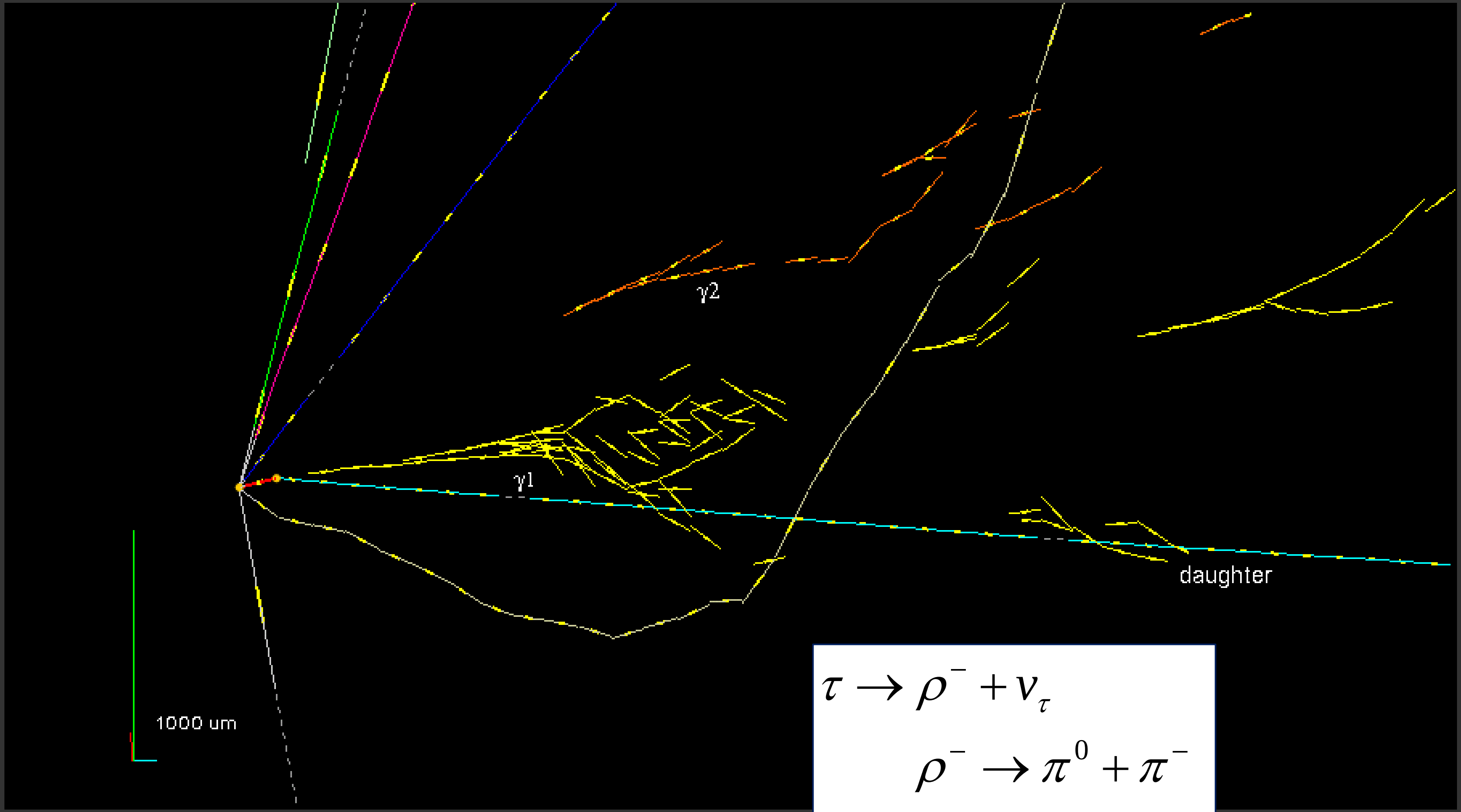


lead-emulsion-brick
(total ≈ 150.000)

target mass:
≈ 1,35 kton

First ν_{Tau} Candidate Event (22/08/2009)

Opera Coll., “Search for nu-mu - nu-tau oscillation with the OPERA experiment in the CNGS beam”, New J. Phys. 14 (2012) 033017



$$\tau \rightarrow \rho^- + \nu_\tau$$

$$\rho^- \rightarrow \pi^0 + \pi^-$$

$$\pi^0 \rightarrow \gamma\gamma$$

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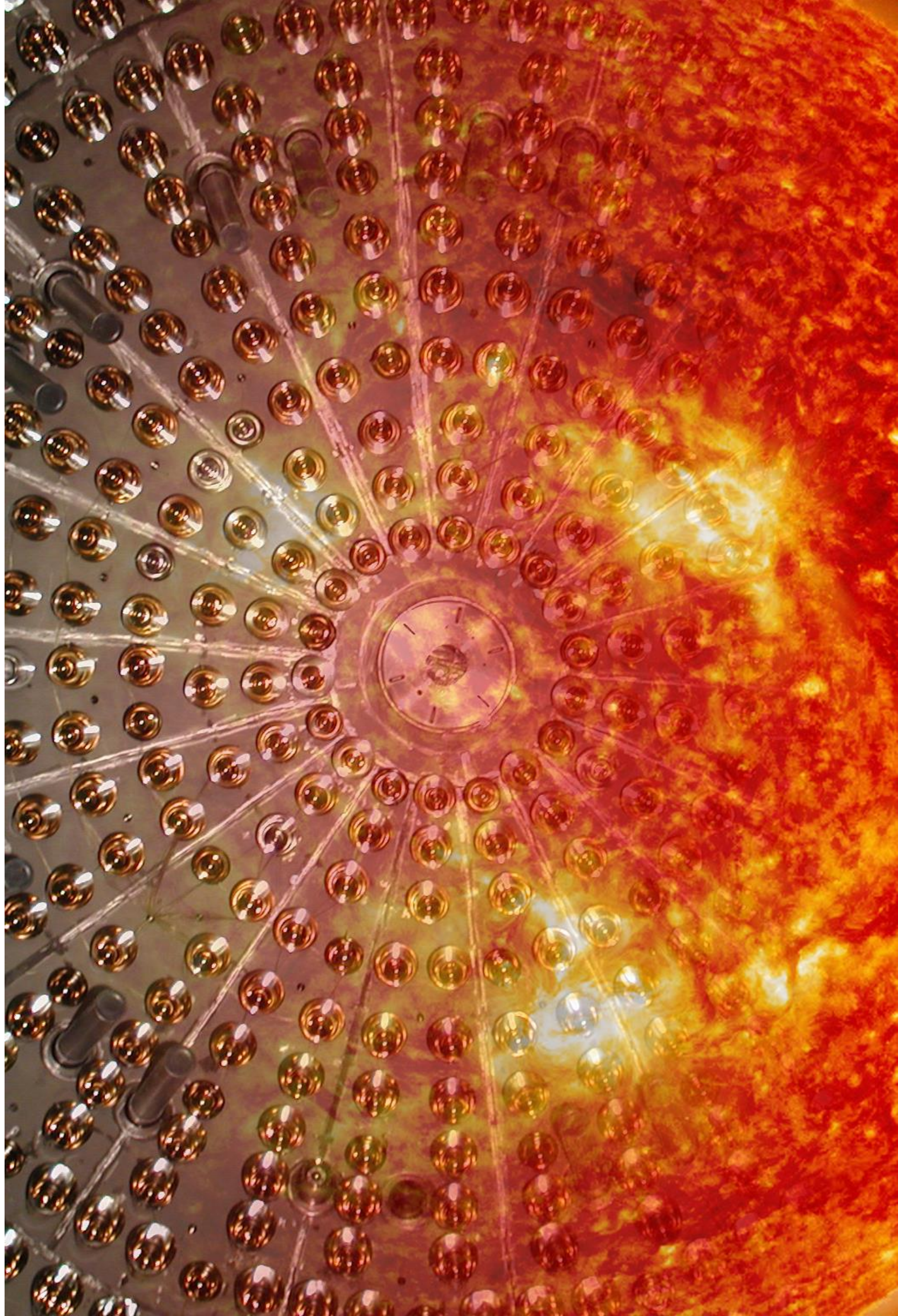
4

Why Matter matters, even for neutrinos



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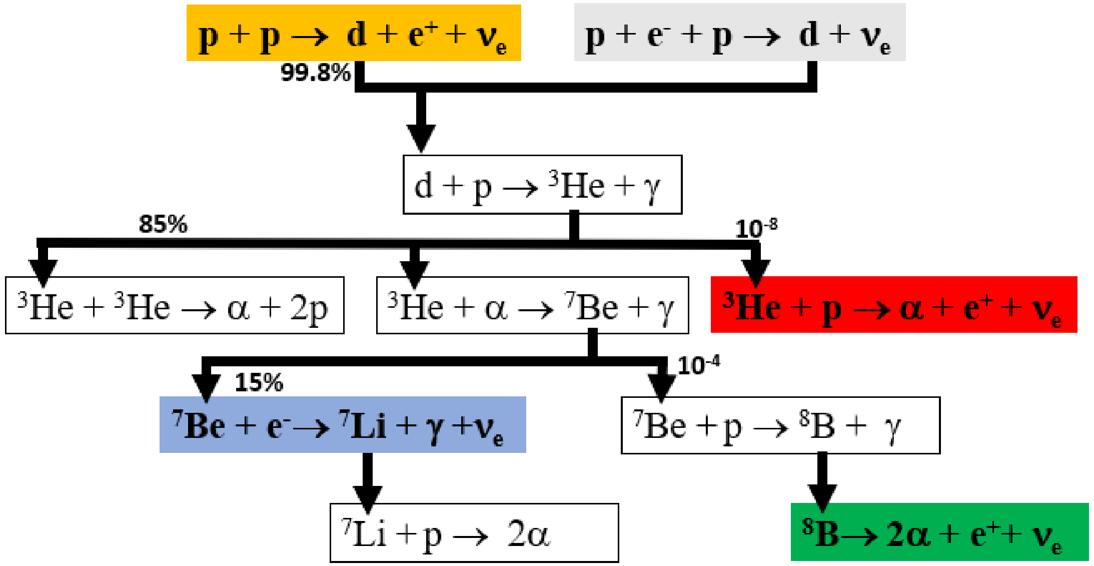
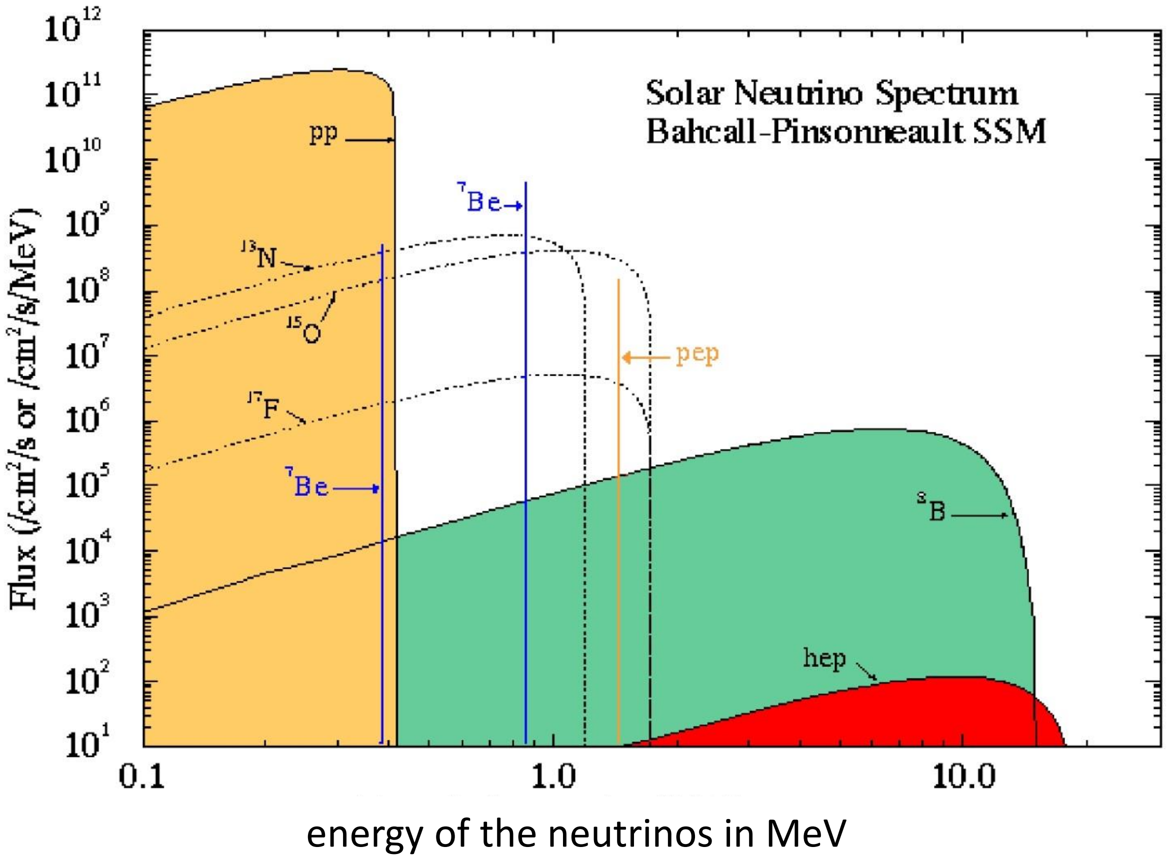
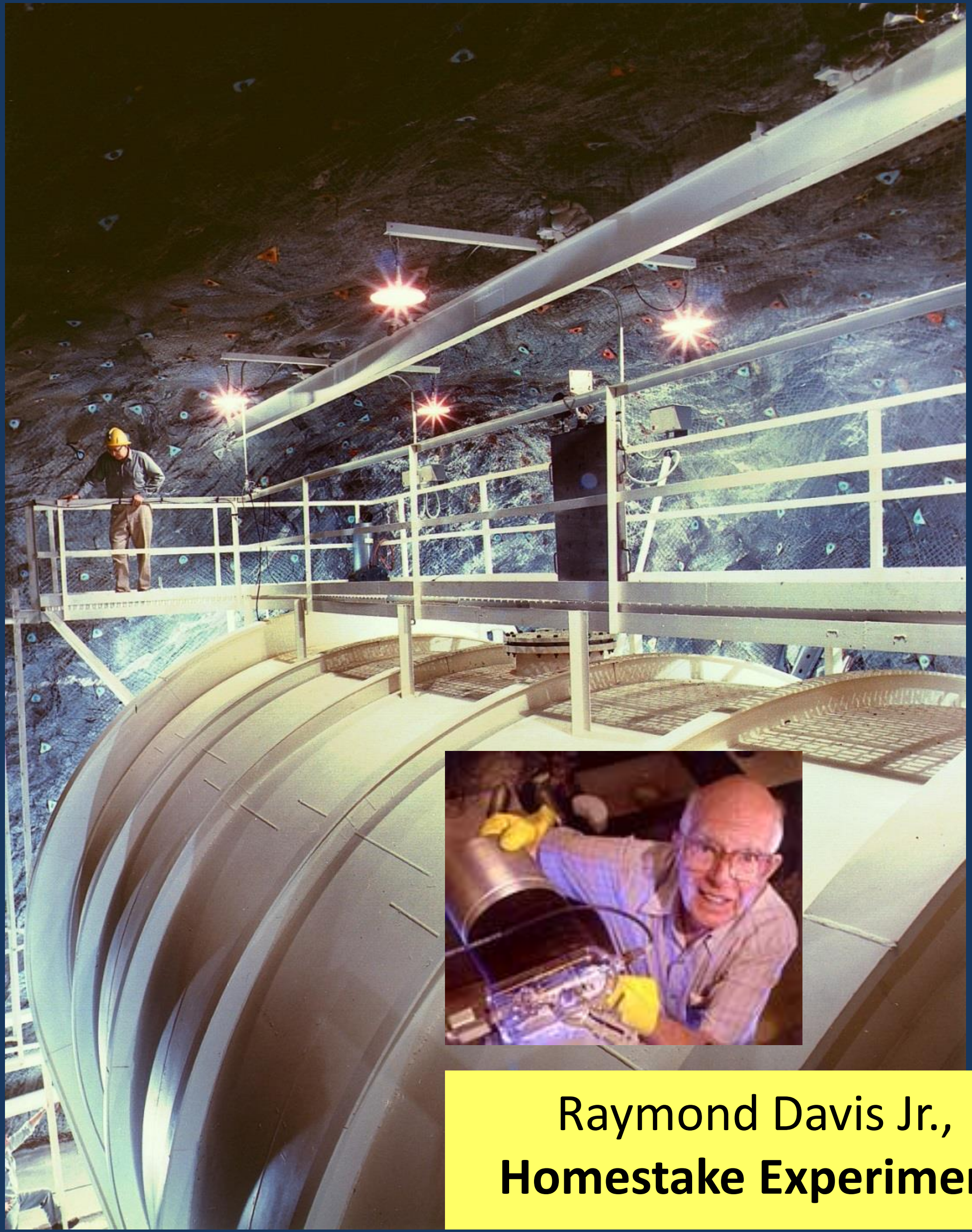
Standard Solar Model (SSM) predicted solar neutrino fluxes





Solar Neutrinos: First Detection



Raymond Davis Jr.,
Homestake Experiment

1970 - 1994

$\nu_e + {}^{37}\text{Cl}$

$E_\nu > 814$ keV (^{8}B, ^{7}Be Neutrinos)

radiochemical experiments

$$R = N_{Target} \cdot \int \phi_\nu(E) \cdot \sigma(E)\, dE$$

To produce 1 Atom per day (here ^{37}Ar)

$$\left.\begin{array}{l}\phi \sim 10^{10} \frac{1}{cm^2 s} \\ \sigma \sim 10^{-45} cm^2\end{array}\right\} \text{need } 10^{30} \text{ target Atoms}$$

$6 \cdot 10^{23}$ Atom in 1 mol $\Rightarrow$ few 1000 tons

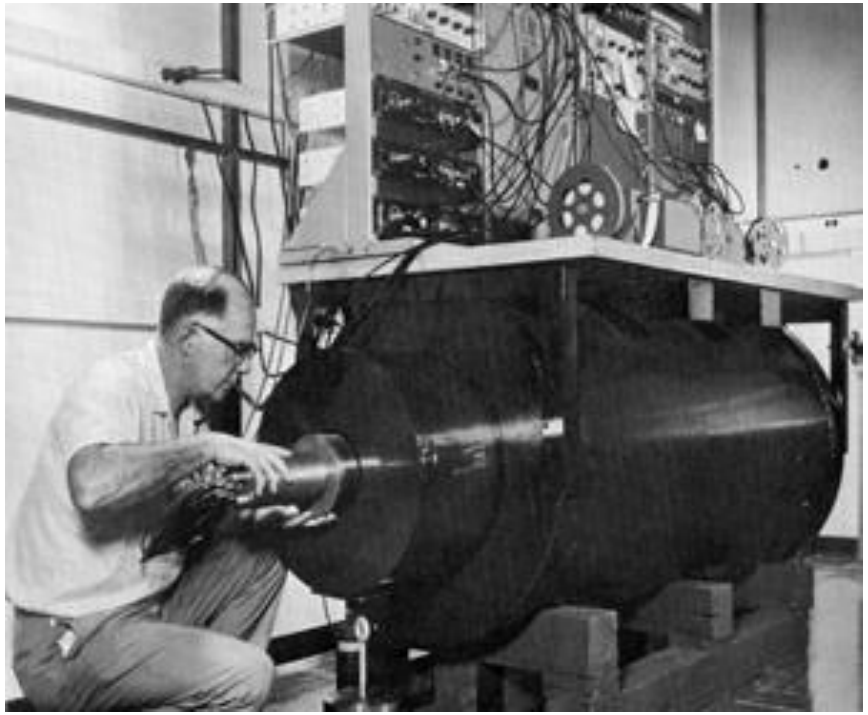
Here: 4 500 m^3 of Perchlorethylene

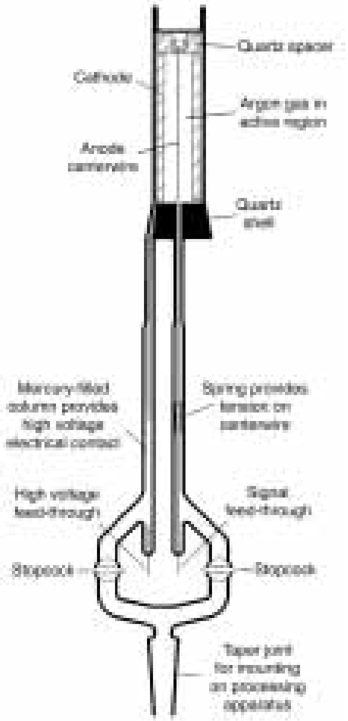
How to count single ^{37}Ar atoms

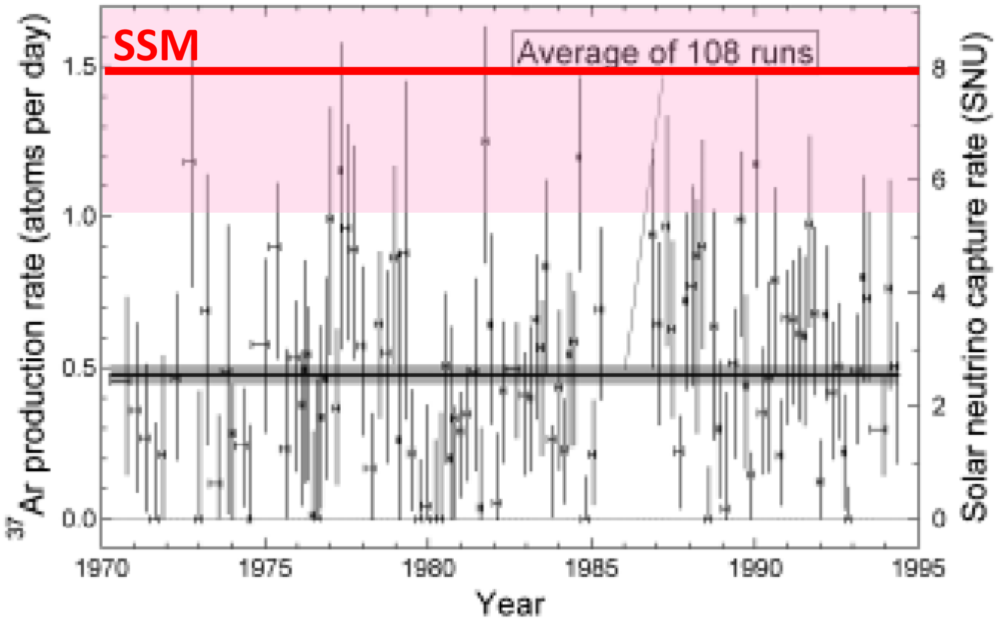
Electron capture:

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

+ X-rays







First detection of solar neutrinos

BUT: $R_{exp} = 0.34 \times R_{SSM}$

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Бруно Понтекорво

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79.   Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31   April 6/10 1972

Prof. J.N.Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

B.Pontecorvo

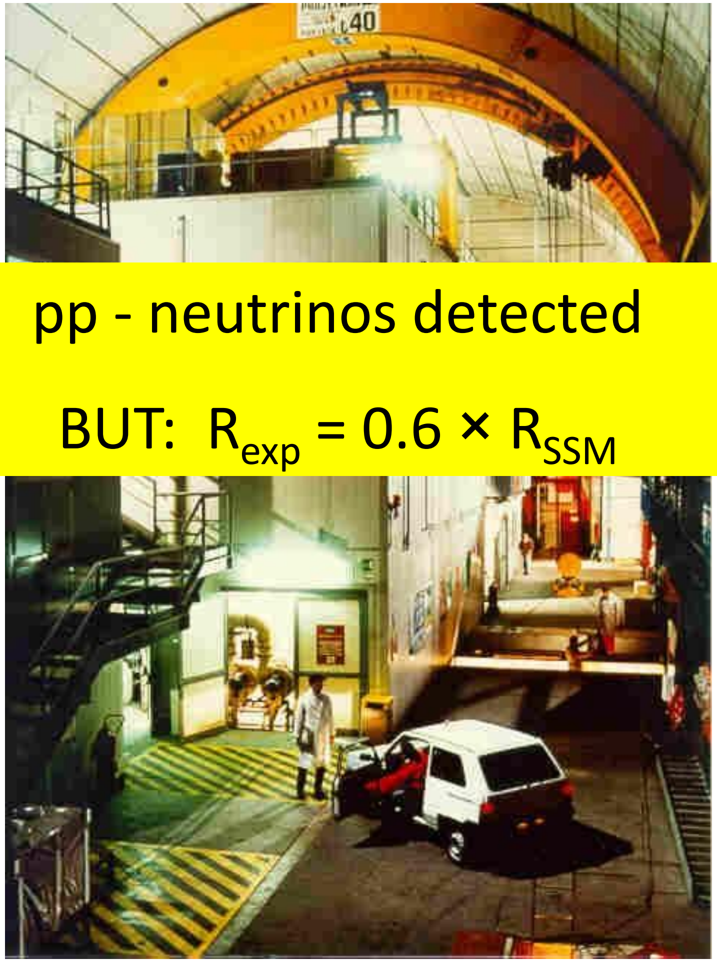
Davis & Bahcall (1964)

GALLEX/GNO Experiment at LNGS (SAGE at Baksan)

(1992-2004)

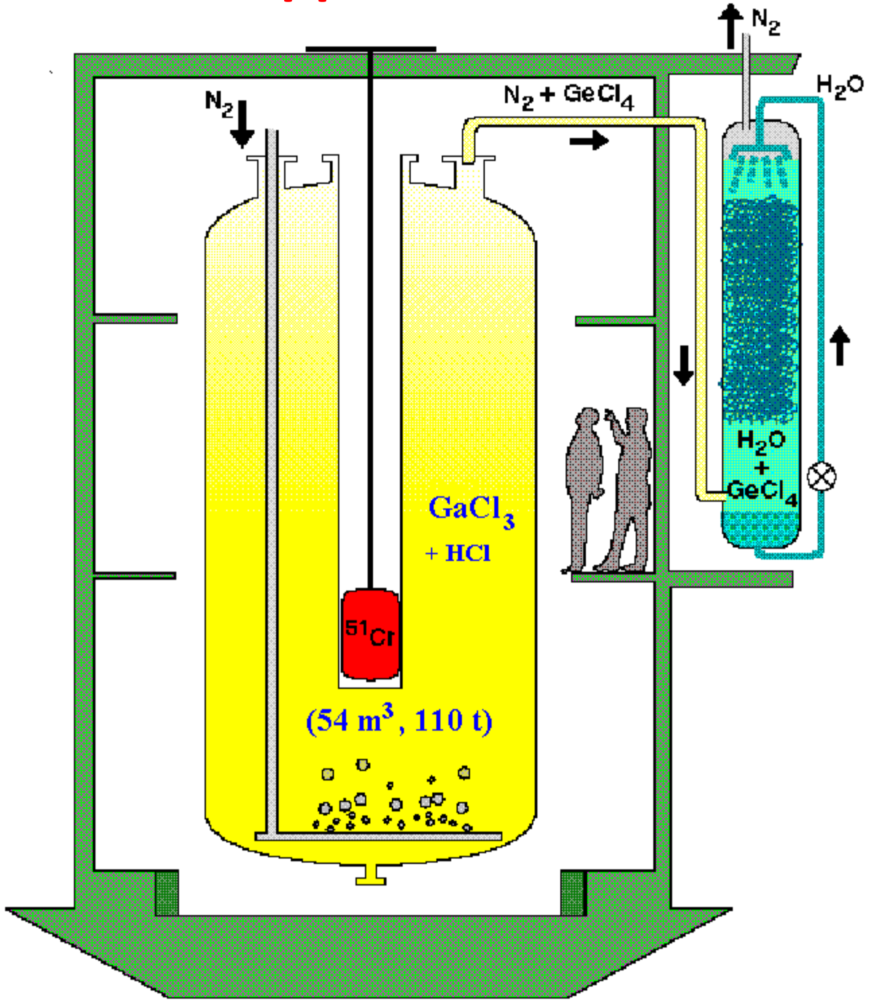
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

$E_\nu > 233$ keV, **pp-neutrinos!**



pp - neutrinos detected

BUT: $R_{exp} = 0.6 \times R_{SSM}$



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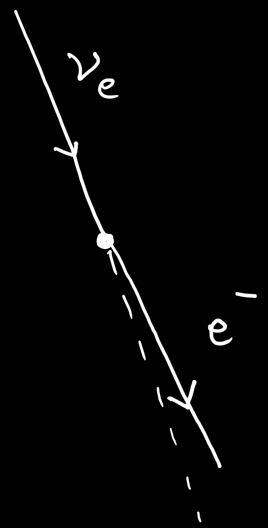
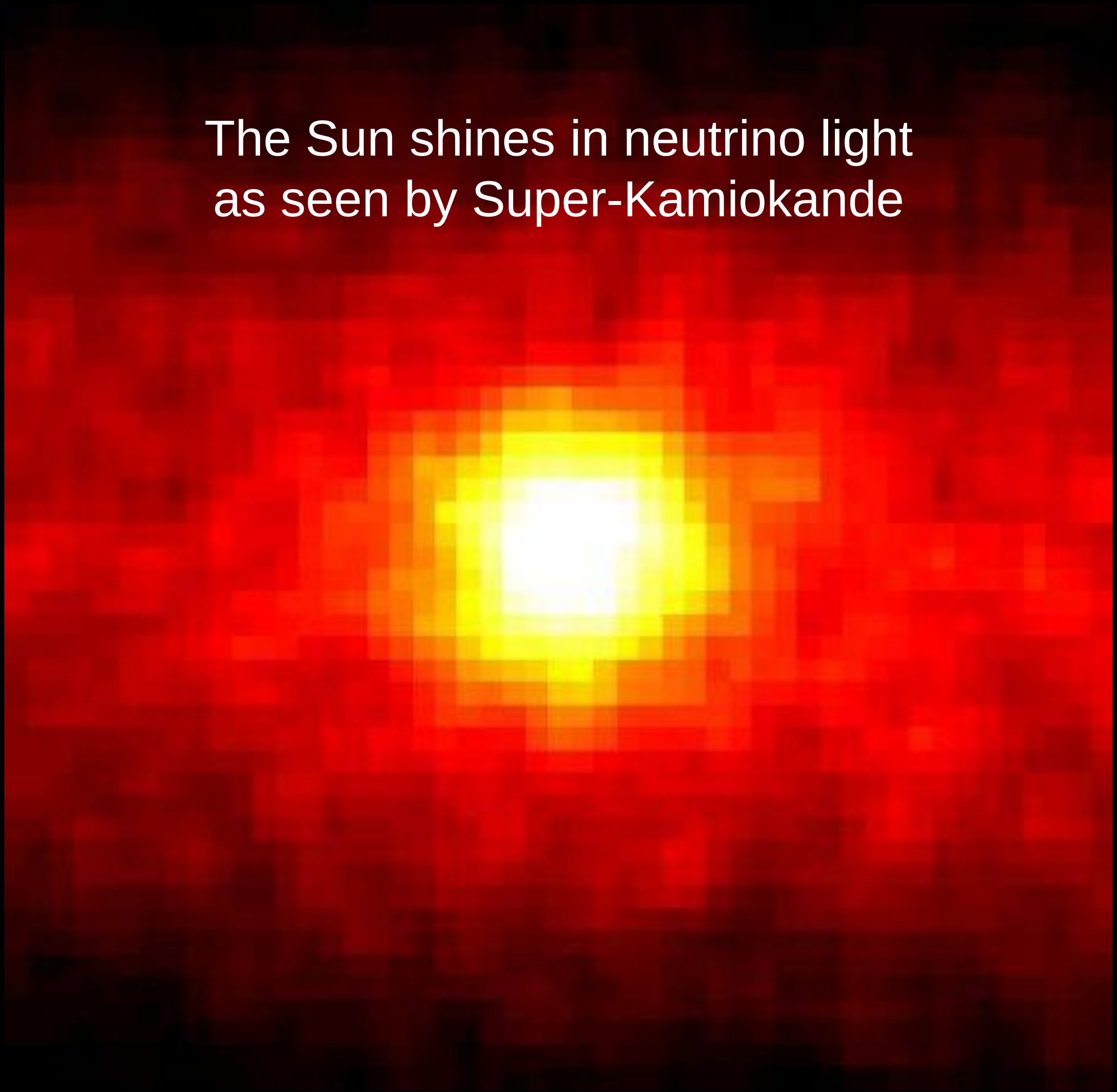
$\nu_e + e^- \rightarrow \nu_e + e^-$



e^- points to Sun
(for signal)



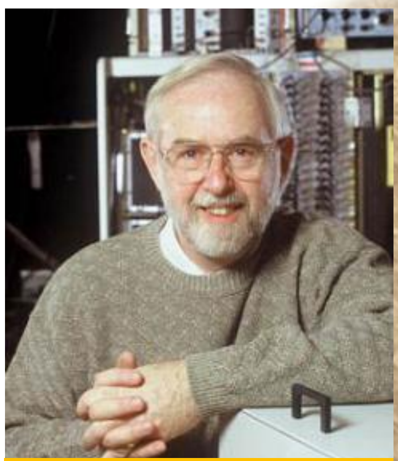
The solar neutrino puzzle (around 1995)

neutrino energy < 1 MeV: 60% of v_e observed

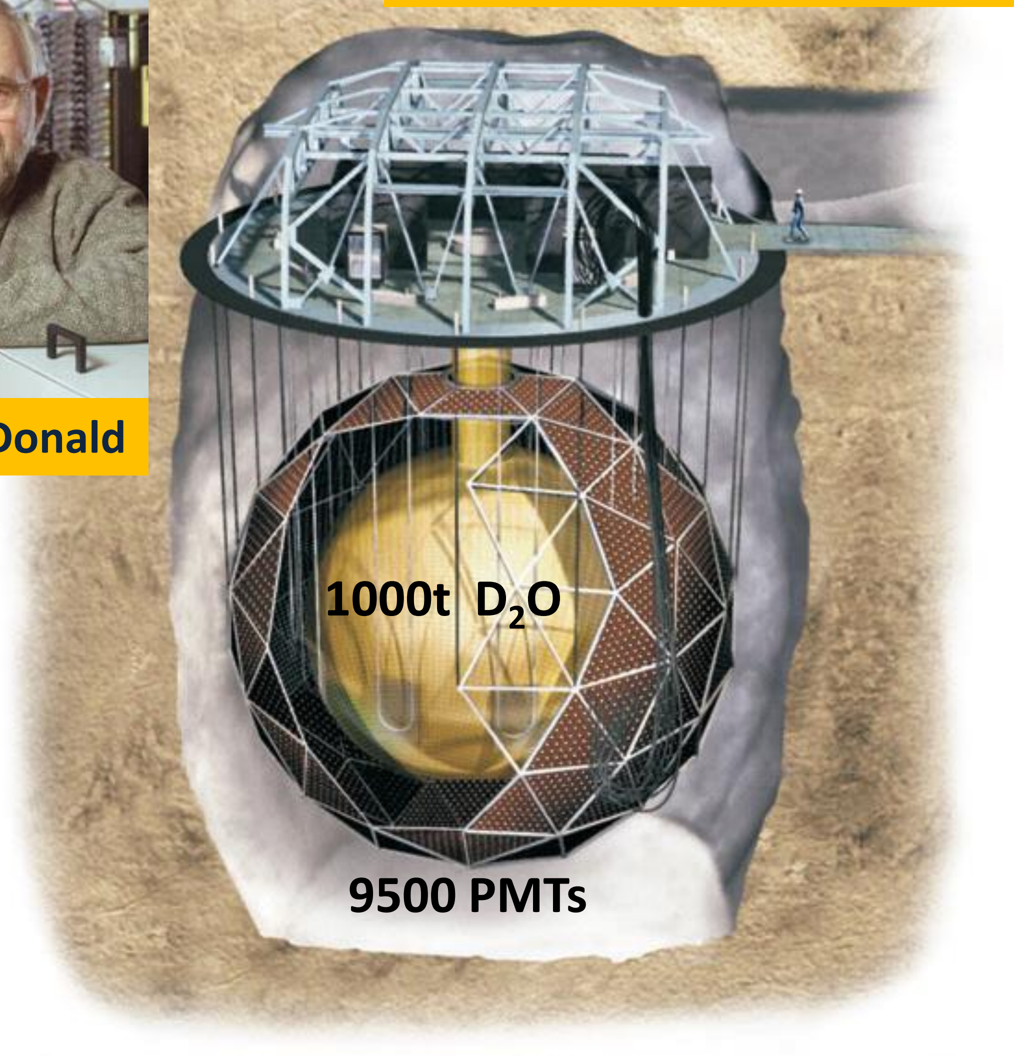
neutrino energy > 1 MeV: 30% of v_e observed

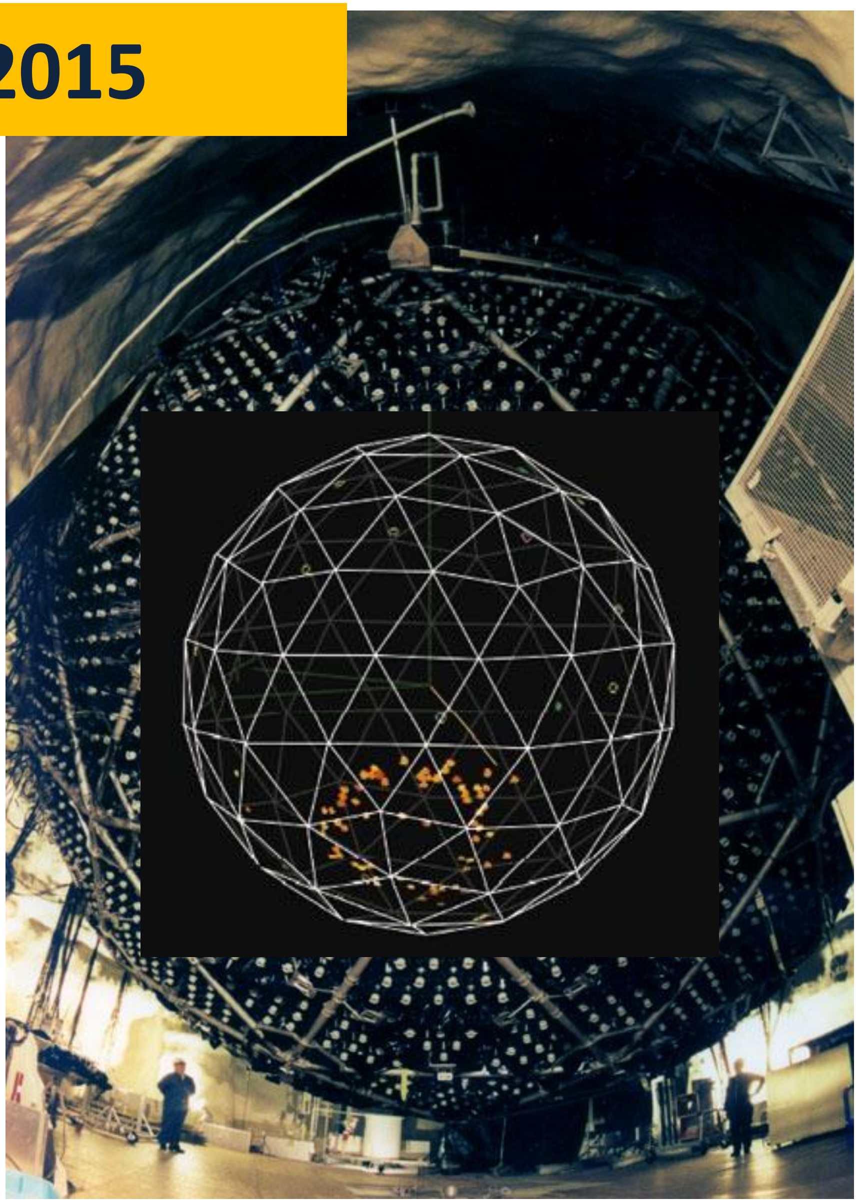
SNO: The Solution of the Solar Neutrino Puzzle

Nobelprize 2015



Arthur McDonald

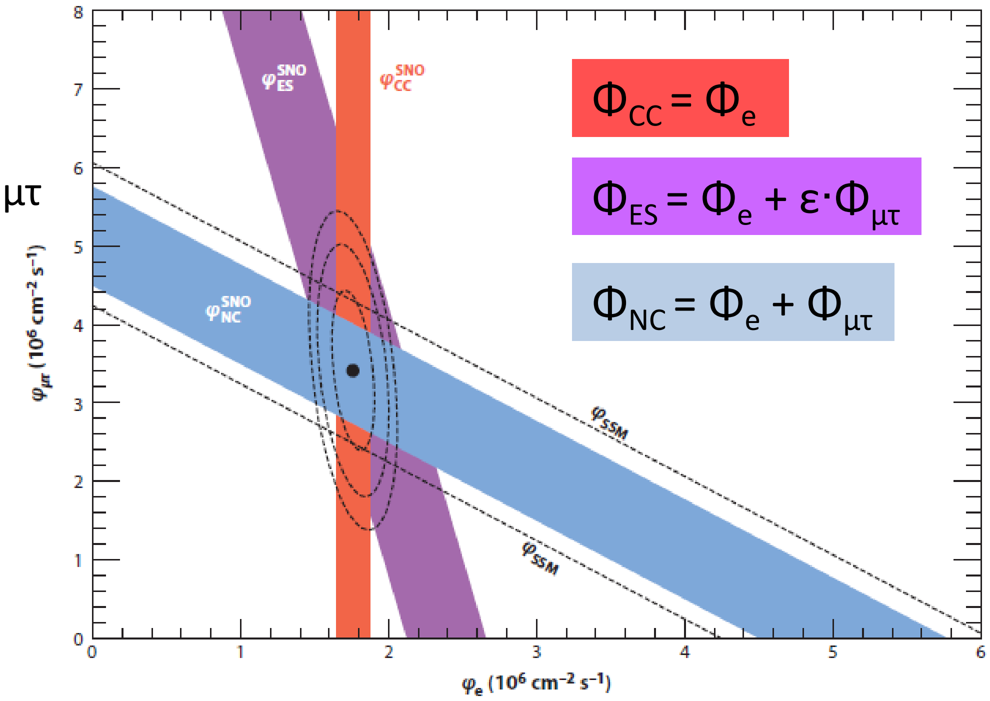




Only ^{8}B Neutrinos:

CC	$\nu_e + d \rightarrow p + p + e^-$
ES	$\nu_{e(\mu\tau)} + e^- \rightarrow \nu + e^-$
NC	$\nu_{e\mu\tau} + d \rightarrow p + n + \nu$

$\Phi_{\mu\tau}$



Φ_e

SNO Result (salt-phase, PRL 92, 181301, 2004):

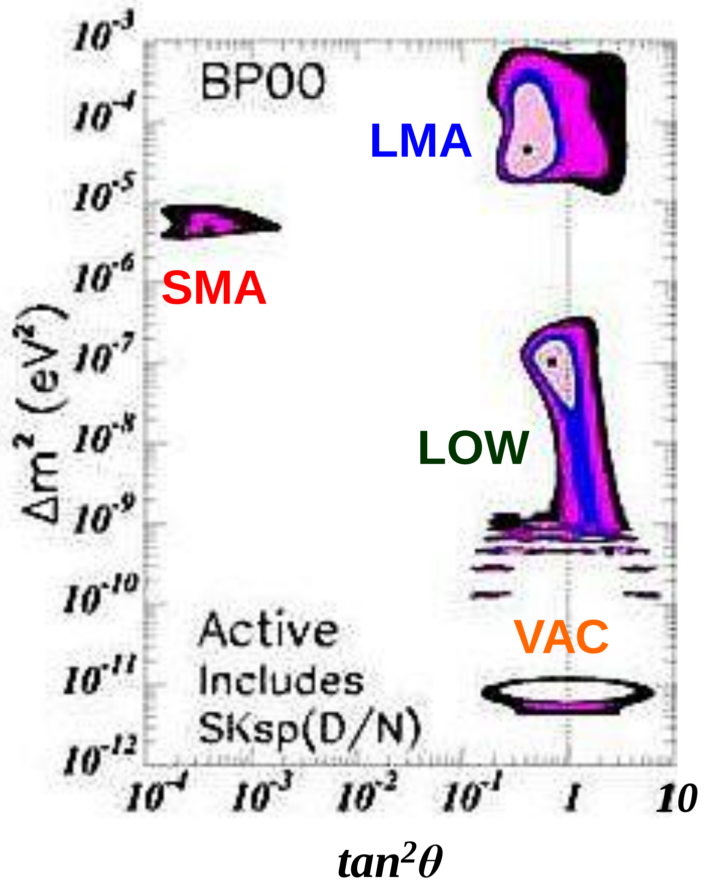
The total number of neutrinos agrees with SSM

$$\phi(^{8}B)_{meas} = (0.88 \pm 0.04\,(exp) \pm 0.23\,(th))\ \phi(^{8}B)_{SSM}$$

And:

- **1/3 of ν_e arrive on Earth as ν_e .**
- **2/3 of ν_e have transformed into ν_μ or ν_τ .**

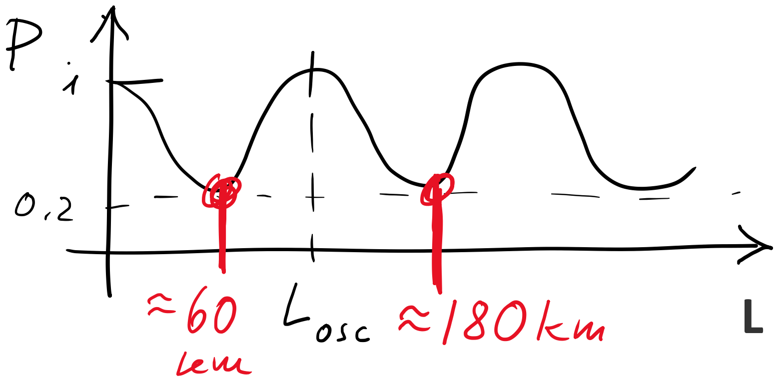
Allowed values for neutrino parameters to explain solar neutrino observations
Spring 2002

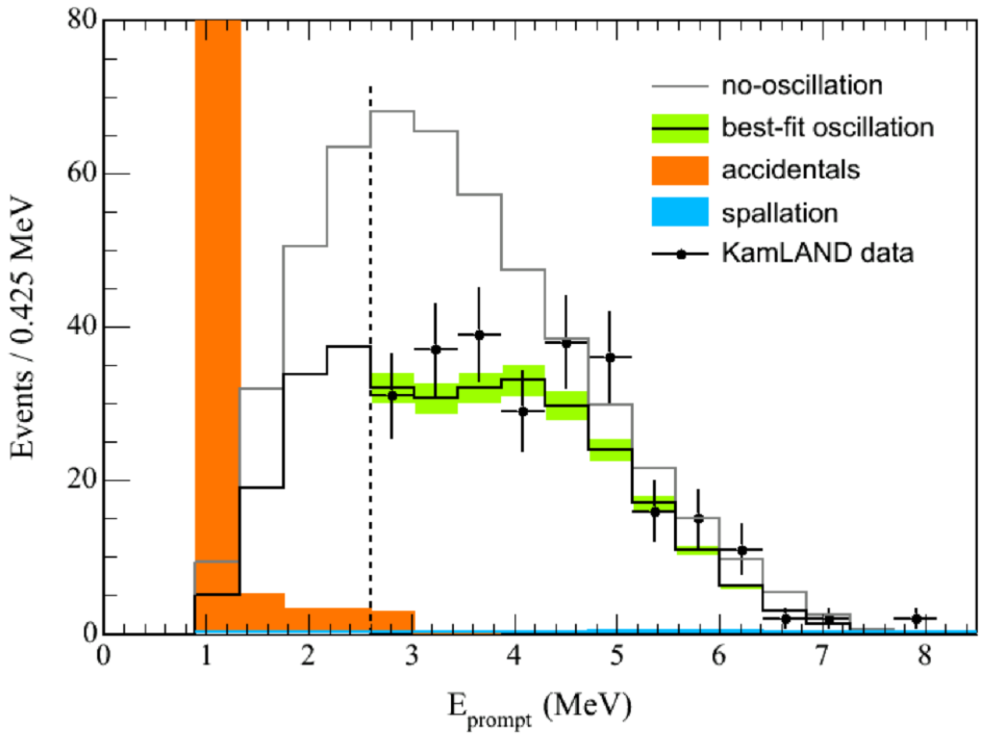


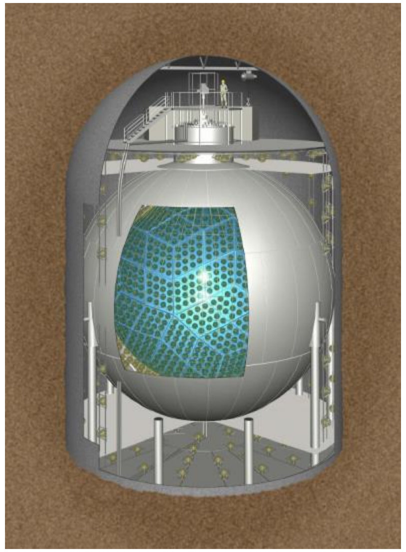
KamLAND result 2004

Average distance of japanese nuclear power plants to KamLAND: 175km

Oscillation length for 125km







Best Fit :

$$\Delta m_{12}^2 = 8.3 \times 10^{-5}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{12} = 0.83$$

„First evidence of deformation in energy spectrum for solar/reactor neutrinos“

Is this the explanation for all solar neutrino results?

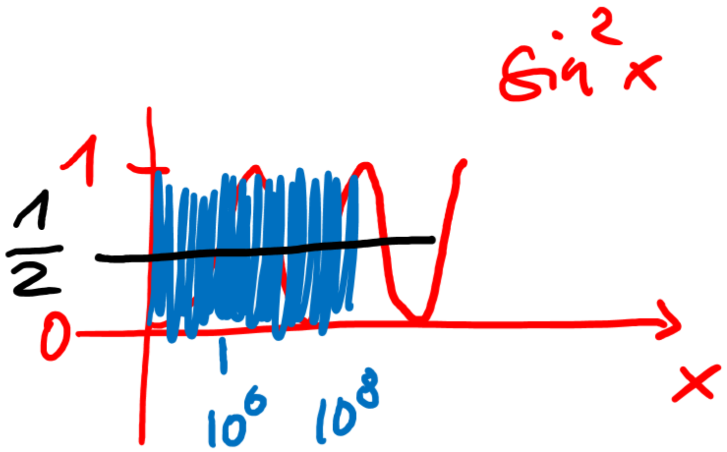
Let us assume: $\Delta m_{12}^2 = 8 \times 10^{-5}\,\text{eV}^2,\ \theta_{12} = 33°$

2 Flavour Oscillation in Vacuum:

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{12}) \cdot \sin^2\left(1.27 \cdot \frac{\Delta m_{12}^2 L}{E}\right)$$

Δm_{12}^2: $8 \cdot 10^{-5}$ eV^2 L: $1.5 \cdot 10^{11}$ m E: 0.1-10 MeV

$$\delta = 1{,}27 \cdot \frac{8 \cdot 10^{-5} \cdot 1{,}5 \cdot 10^{11}}{10^{-1} \ldots 10^{1}} \approx 10^6 - 10^8$$



Therefore the sin^2 averages out to ½ (incoherent mixture) and we loose the energy/distance dependence, the survival probability for ν_e is then:

$$P(\nu_e \to \nu_e) = 1 - {}^{1}\!/_{2}\ \sin^2(2\theta_{12}) = 0.6$$

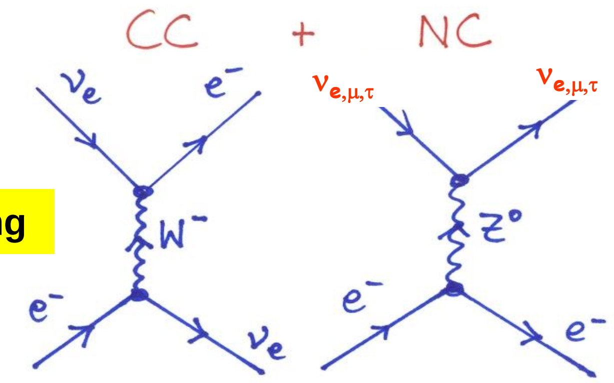
Explains the low energy (E < 1MeV) part of solar neutrino experiments (Gallex/GNO,Sage)

Need other mechanism for E > 1 MeV

Neutrino Propagation in Matter (Overview)

Important: ν_e and $\nu_{\mu,\tau}$ have different interaction with matter

(ν_e can do both CC and NC, $\nu_{\mu,\tau}$ only NC!)



Relevant for propagation is elastic forward scattering

Vacuum:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta & \Delta m^2 \sin 2\theta\\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Matter:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta + 2\sqrt{2}G_F N_e E & \Delta m^2 \sin 2\theta\\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta - 2\sqrt{2}G_F N_e E\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$2\sqrt{2}G_F \underbrace{N_e}_{\frac{Y_e\rho}{m}} E = 1.53\cdot 10^{-7}\,\mathrm{eV}^2\left(\frac{Y_e\rho}{\mathrm{g/cm}^3}\cdot\frac{E}{\mathrm{MeV}}\right)$$

Center of the Sun: $\frac{Y_e\rho}{\mathrm{g/cm}^3} \cong 100$

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$$\Delta m_m^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - 2\sqrt{2} G_F N_e E\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\left(\frac{2\sqrt{2} G_F N_e E}{\Delta m^2} - \cos 2\theta\right)^2 + \left(\sin 2\theta\right)^2}}$$

$$2\sqrt{2} G_F N_e E \approx 1.53 \cdot 10^{-7}\, eV^2 \left(\frac{Y_e \rho}{g/cm^3} \cdot \frac{E}{MeV}\right)$$

$\frac{Y_e \rho}{g/cm^3} \approx 100$ in the Sun

Quasi Vacuum

$$2\sqrt{2} G_F N_e E \ll \Delta m^2 \cos 2\theta$$

$\hookrightarrow$

$$\Delta m_m^2 \simeq \Delta m^2$$

$$\theta_m \simeq \theta$$

pp-neutrinos, ^{7}Be-neutrinos

Resonance

$$2\sqrt{2} G_F N_e E = \Delta m^2 \cos 2\theta$$

for $\Delta m^2 = 8 \cdot 10^{-5} eV^2$; $\theta = 33°$

$\Downarrow$

$E \approx 1\text{-}2$ MeV

$$\Delta m_m^2 = \Delta m^2 \sin 2\theta$$

$$\theta_m = \frac{\pi}{4}$$

Matter dominated

$$2\sqrt{2} G_F N_e E \gg \Delta m^2 \cos 2\theta$$

$$\Delta m_m^2 \rightarrow 2\sqrt{2} G_F N_e E$$

$$\theta_m \rightarrow \frac{\pi}{2} \; (90°)$$

In the Sun, for $E_\nu = 5$ MeV

with $\Delta m^2 = 8 \cdot 10^{-5} eV^2$, $\theta = 33°$

$Y_e \rho = 90\, g/cm^3$

$\hookrightarrow \theta_m \approx 73°$

^{8}B-neutrinos

In these equations the sign of Δm^2 matters!

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For ^{8}B Neutrinos at center of the Sun:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos 73^\circ & \sin 73^\circ \\ -\sin 73^\circ & \cos 73^\circ \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

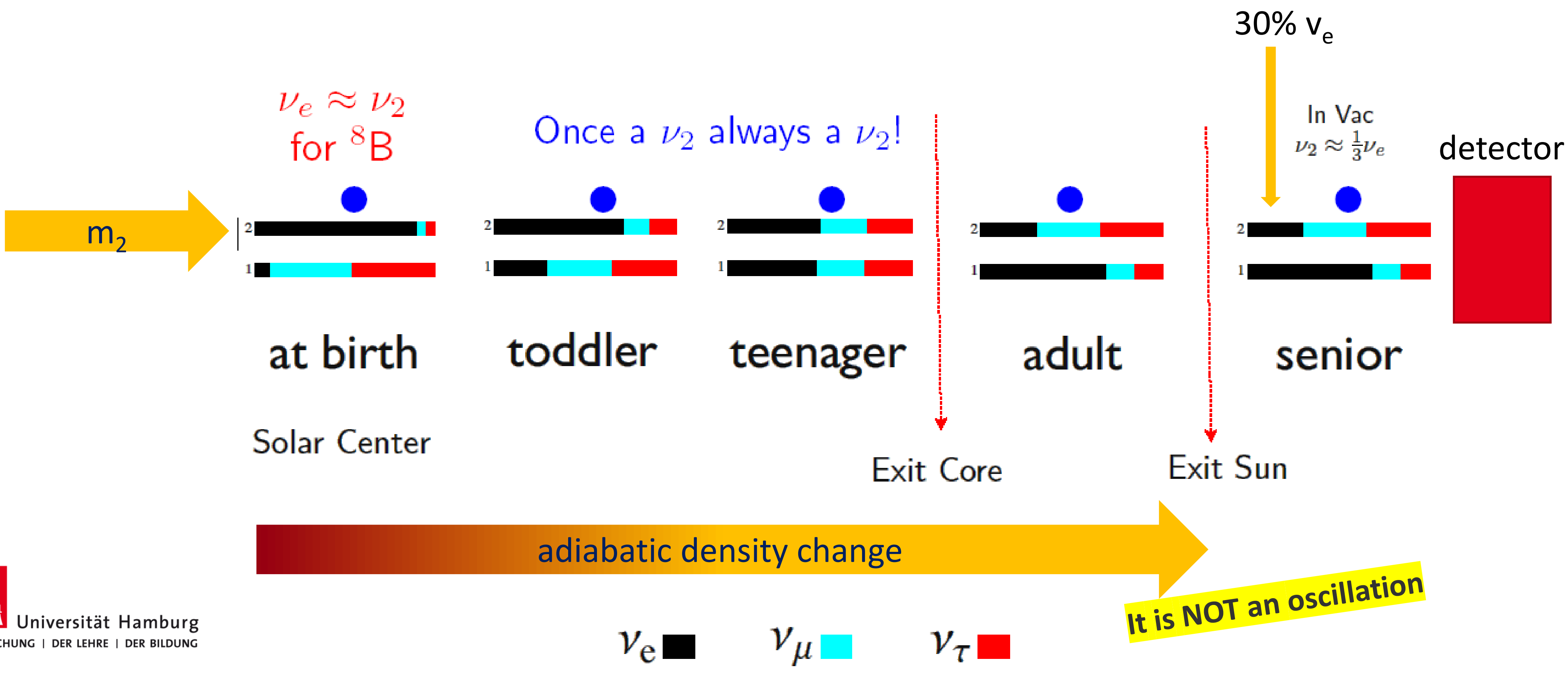
This means, the probability that ν_e has mass m_2 is $\sin^2(73°) = 91\%$

For ^{8}B Neutrinos in vacuum (at earth):

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & -\sin \theta_{12} \\ \sin \theta_{12} & \cos \theta_{12} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

The probability that ν_2 is a ν_e is $\sin^2\theta_{12}$

Life of a Boron-8 Solar Neutrino:



Neutrino Propagation in Matter: MSW mechanism

Stanislav **Mikheev** (1940-2011)

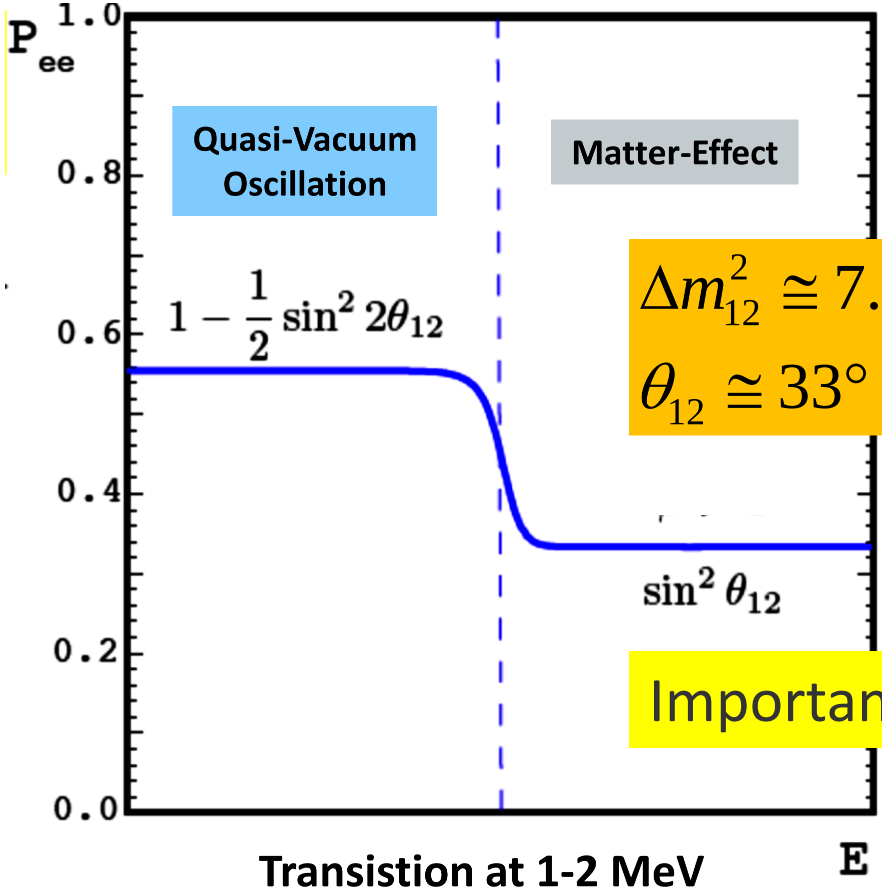
Alexei **Smirnov**

Lincoln **Wolfenstein** (1923-2015)

L. Wolfenstein, Phys. Rev. D17 (1978) 2369
S. P. Mikheev and A. Yu. Smirnov, Nuovo Cim.C9 (1986)17

Interaction of ν_e and $\nu_{\mu,\tau}$ with electrons different.
→ Effective masses, effective mixing angles depending on electron density N_e and energy of neutrino

Important for solar neutrinos:
Survival probability



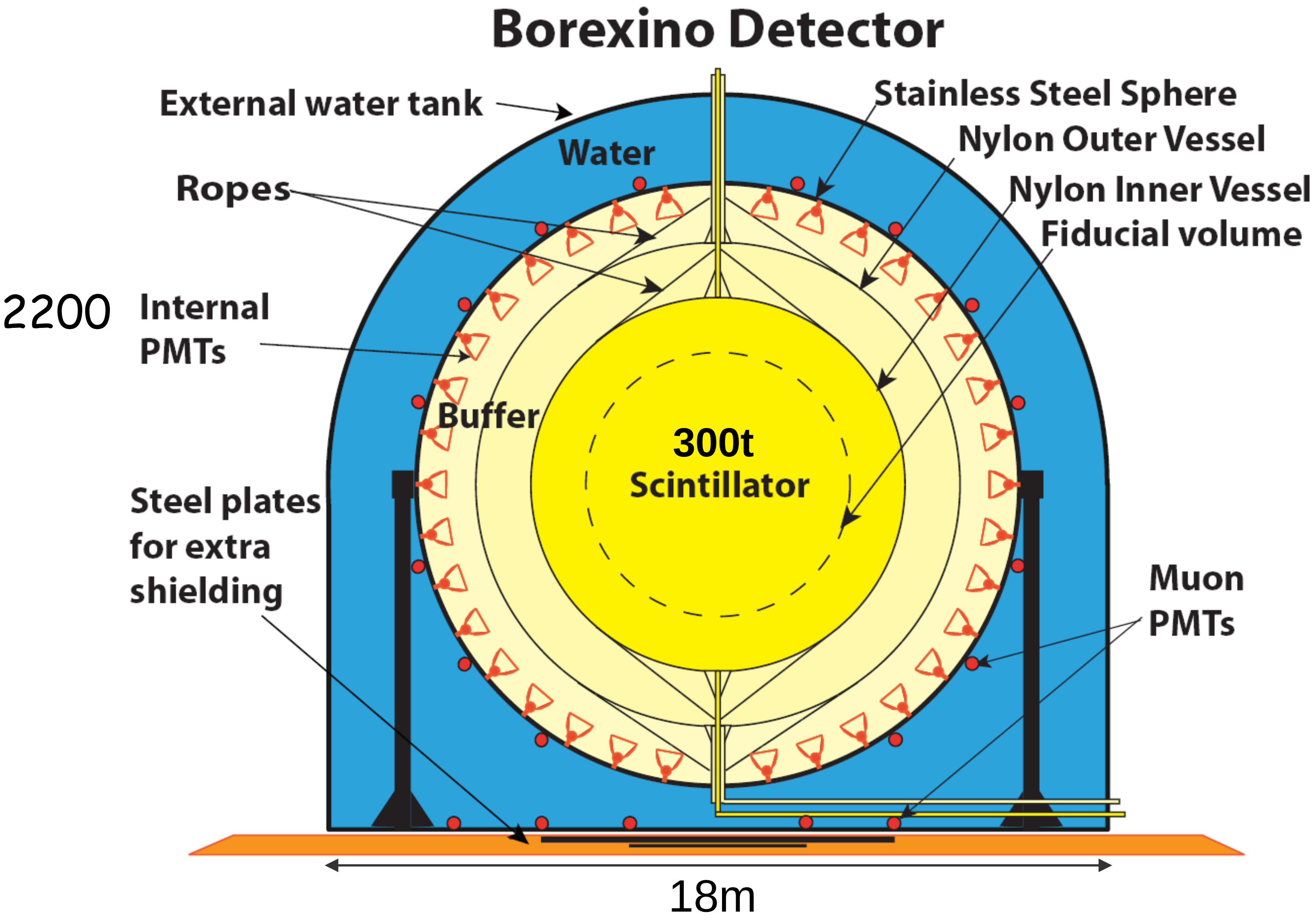
Transistion at 1-2 MeV

$\Delta m_{12}^2 \cong 7.5 \cdot 10^{-5} \mathrm{eV}^2$

$\theta_{12} \cong 33°$

Important: $m_2 > m_1$

BOREXINO at LNGS



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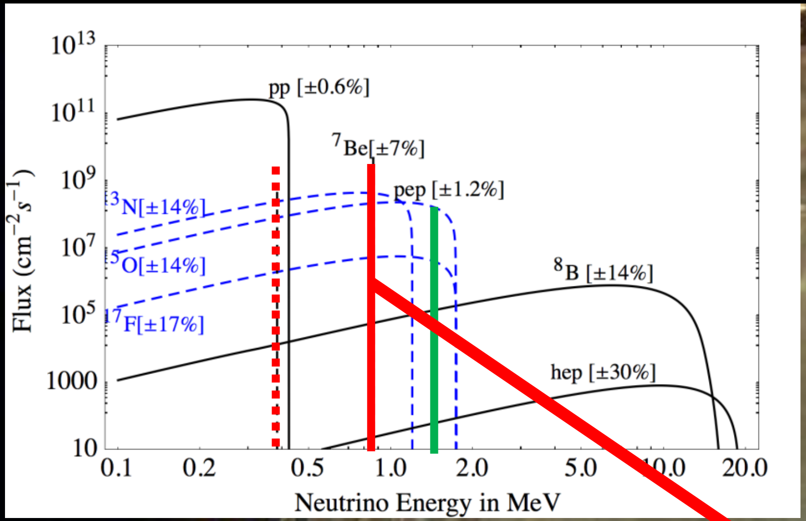
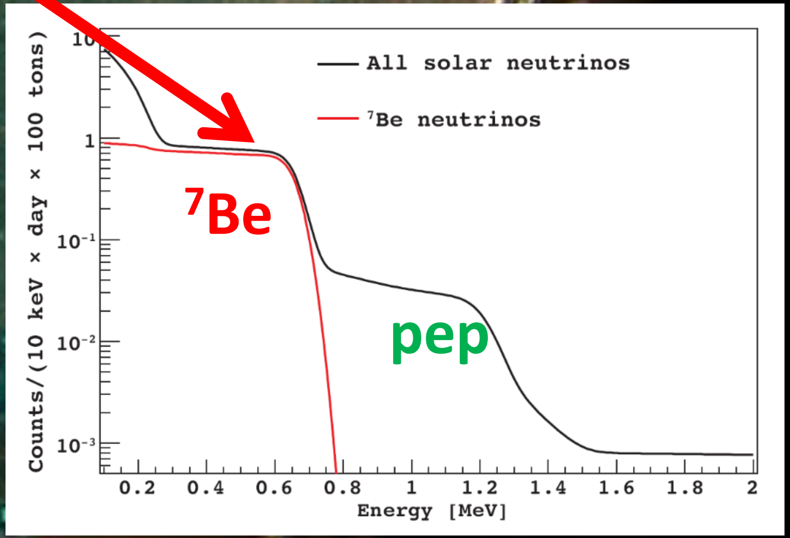
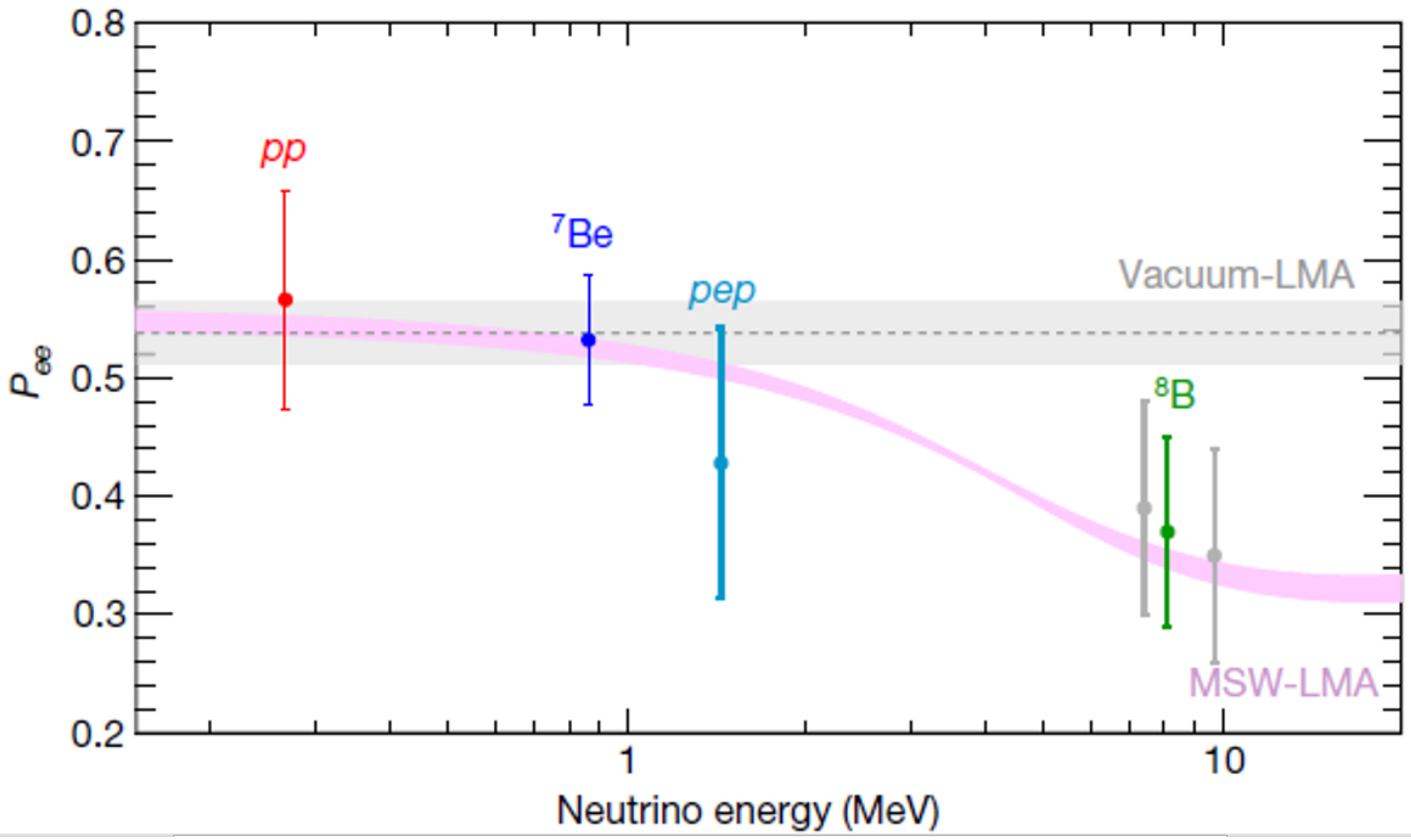
Photomultipliers and light concentrators in Borexino



elastic scattering of neutrinos on electrons:
neutrino „lines“ → Compton-like edge in spectrum of recoil electrons



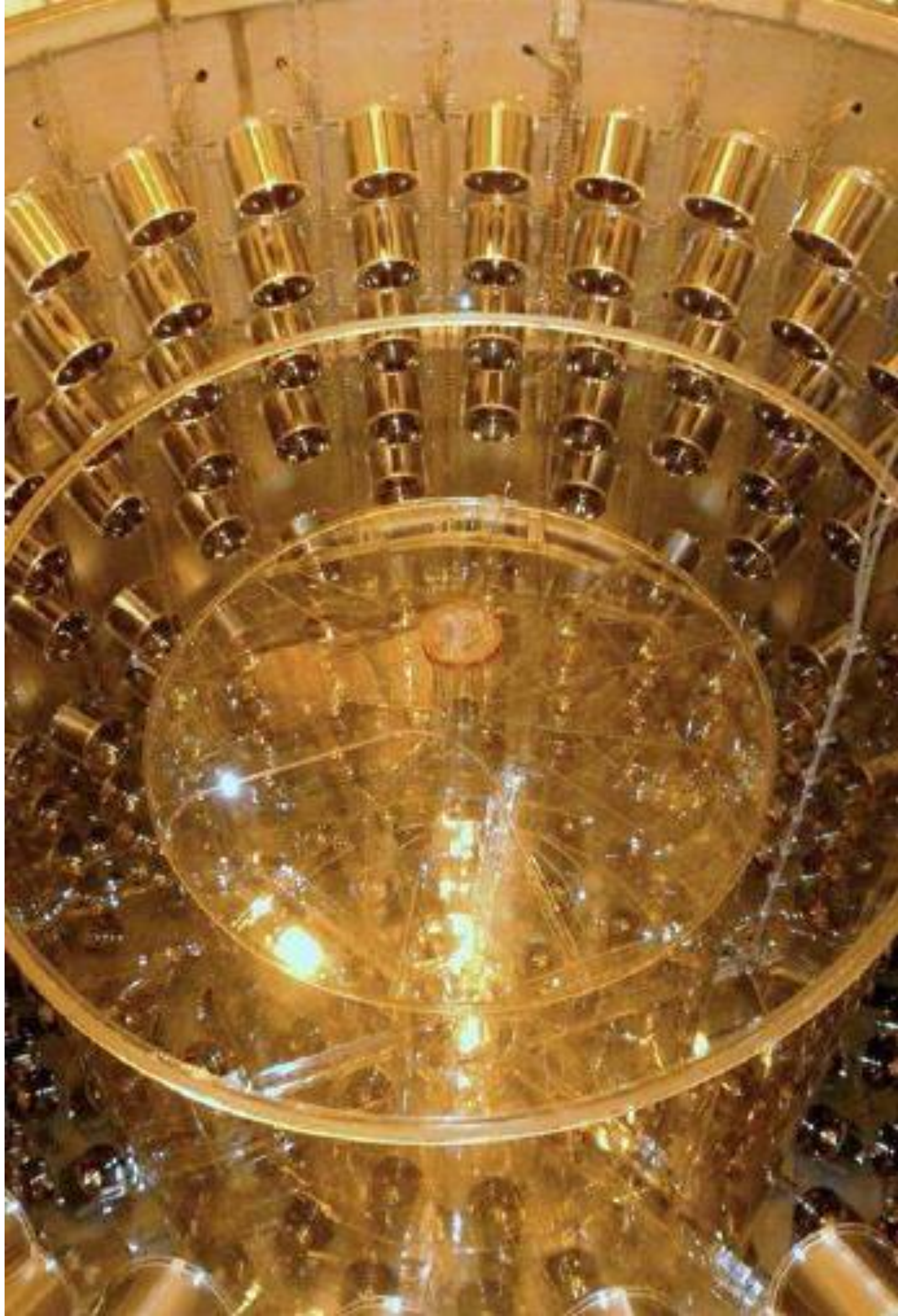
BX Analysis 2018: Flavor Transition in Matter



Borexino Coll. „Comprehensive measurement of pp-chain solar neutrinos“, Nature Vol562, pages505–510 (2018)

5

The third mixing angle: towards precision



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$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\boldsymbol{\theta_{23}} & \sin\boldsymbol{\theta_{23}} \\ 0 & -\sin\boldsymbol{\theta_{23}} & \cos\boldsymbol{\theta_{23}} \end{pmatrix} \begin{pmatrix} \cos\boldsymbol{\theta_{13}} & 0 & \sin\boldsymbol{\theta_{13}}\boldsymbol{e^{-i\delta}} \\ 0 & 1 & 0 \\ -\sin\boldsymbol{\theta_{13}}\boldsymbol{e^{+i\delta}} & 0 & \cos\boldsymbol{\theta_{13}} \end{pmatrix} \begin{pmatrix} \cos\boldsymbol{\theta_{12}} & \sin\boldsymbol{\theta_{12}} & 0 \\ -\sin\boldsymbol{\theta_{12}} & \cos\boldsymbol{\theta_{12}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} = 48.5^{+0.7}_{-0.9}\,^\circ$ (between 41° and 50°)
$|\Delta m^2_{32}| = (2.534^{+0.025}_{-0.023}) \times 10^{-3} \mathrm{eV}^2$

Θ_{13}?

$\theta_{12} = 33.7 \pm 0.7°$
$\Delta m^2_{21} = (7.5 \pm 0.2) \times 10^{-5} \mathrm{eV}^2$

Around 2010 many experiments started to measure it:
It was assumed, that likely it would be very small .
Two methods were used:

- Appearence of ν_e in ν_μ beams
- Disappearence of anti-ν_e from nuclear power plants

3 Flavour Oscillation effect, needs precision

Neutrino Mixing and Oscillations (3 flavours)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e1} & U_{e1}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

c_{12} stands for $\cos\vartheta_{12}$, s_{12} stands for $\sin\vartheta_{12}$ etc., δ is the Dirac CP-phase

Probability for neutrino oscillation (neutrino with energy E, after distance L) from flavour α to flavour β

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i} U_{\beta i}^{*} U_{\alpha j}^{*} U_{\beta j}\, e^{-i2\Delta_{ij}}$$

with: $\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E} \underset{\hbar, c}{=} 1.27 \frac{\Delta m_{ij}^2}{eV^2} \cdot \frac{L}{km} \cdot \frac{GeV}{E}$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - \underbrace{4\sum_{k>j} \mathrm{Re}\left(U_{\alpha k} U_{\beta k}^{*} U_{\alpha j}^{*} U_{\beta j}\right)\sin^2\Delta_{jk}}_{\text{CP conserving}} - \underbrace{2\sum_{k>j} \mathrm{Im}\left(U_{\alpha k} U_{\beta k}^{*} U_{\alpha j}^{*} U_{\beta j}\right)\sin(2\Delta_{jk})}_{\text{CP violating}}$$

lat

CP conserving

CP violating
if α=β, this is 0

Survival of ν_e from nuclear power plants: θ_{13}

Simplification for $E_\nu \approx 3\,MeV$

and $L = 1\,km$

$\Delta m_{12}^2 = 8 \cdot 10^{-5}\,eV^2$, $\Delta m_{13}^2 \approx \Delta m_{23}^2 = 2.5 \cdot 10^{-3}\,eV^2$

$\rightarrow P = 1 - 4 \sin^2\theta_{13} \cos^2\theta_{13} \sin^2\Delta_{13} - 4 \ldots\ldots \sin^2\Delta_{12}$

$\sin^2\Delta_{12}$: $1{,}27 \cdot 8{,}5 \cdot 10^{-5} \cdot 1 \cdot \frac{GeV}{3\,MeV}$ (with $\frac{GeV}{3\,MeV} \approx 3 \cdot 10^2$)

very small $\ll 1$

$\sin^2\Delta_{12} \approx 0$

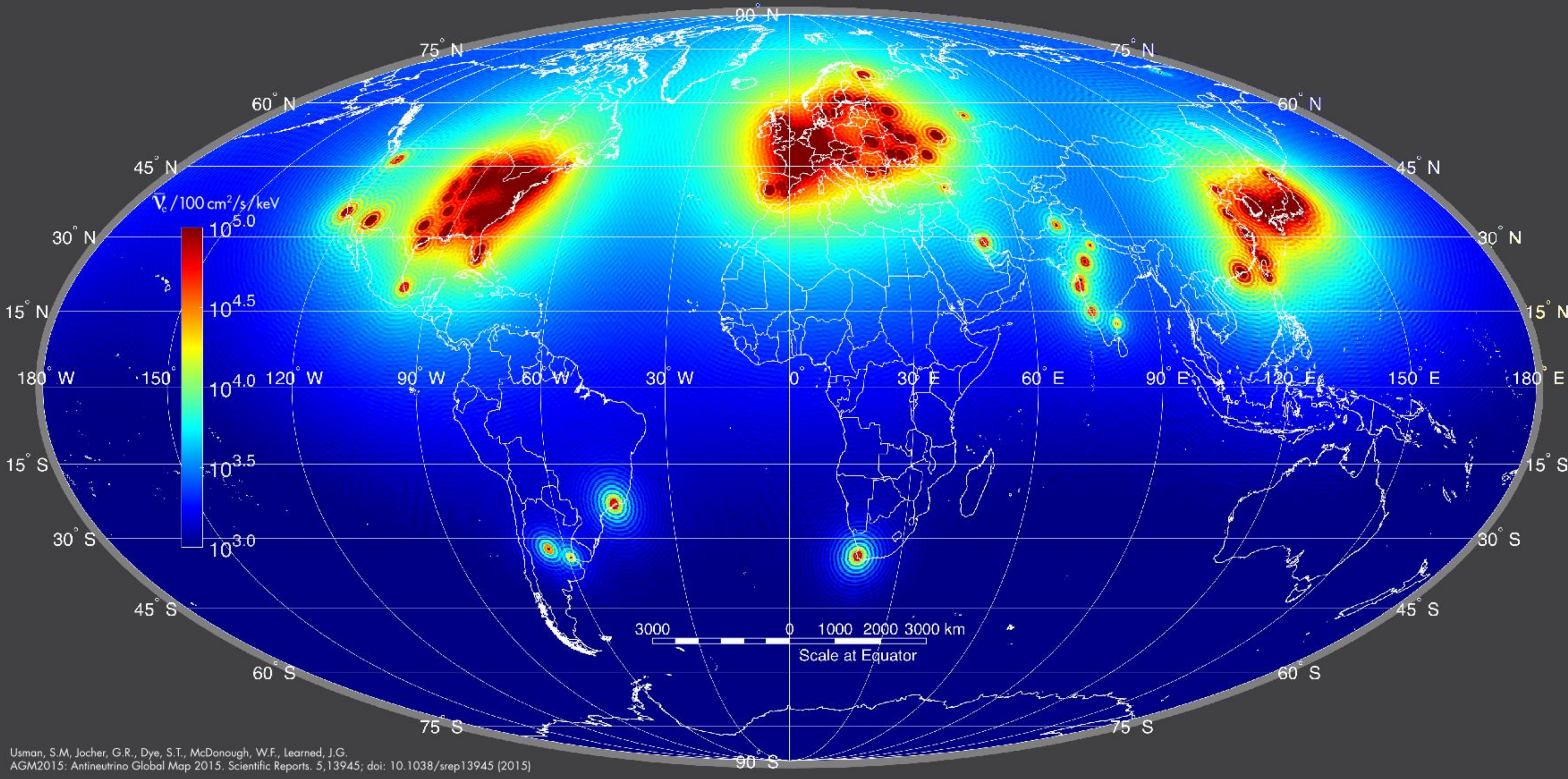
$$P = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)$$

$\Downarrow$

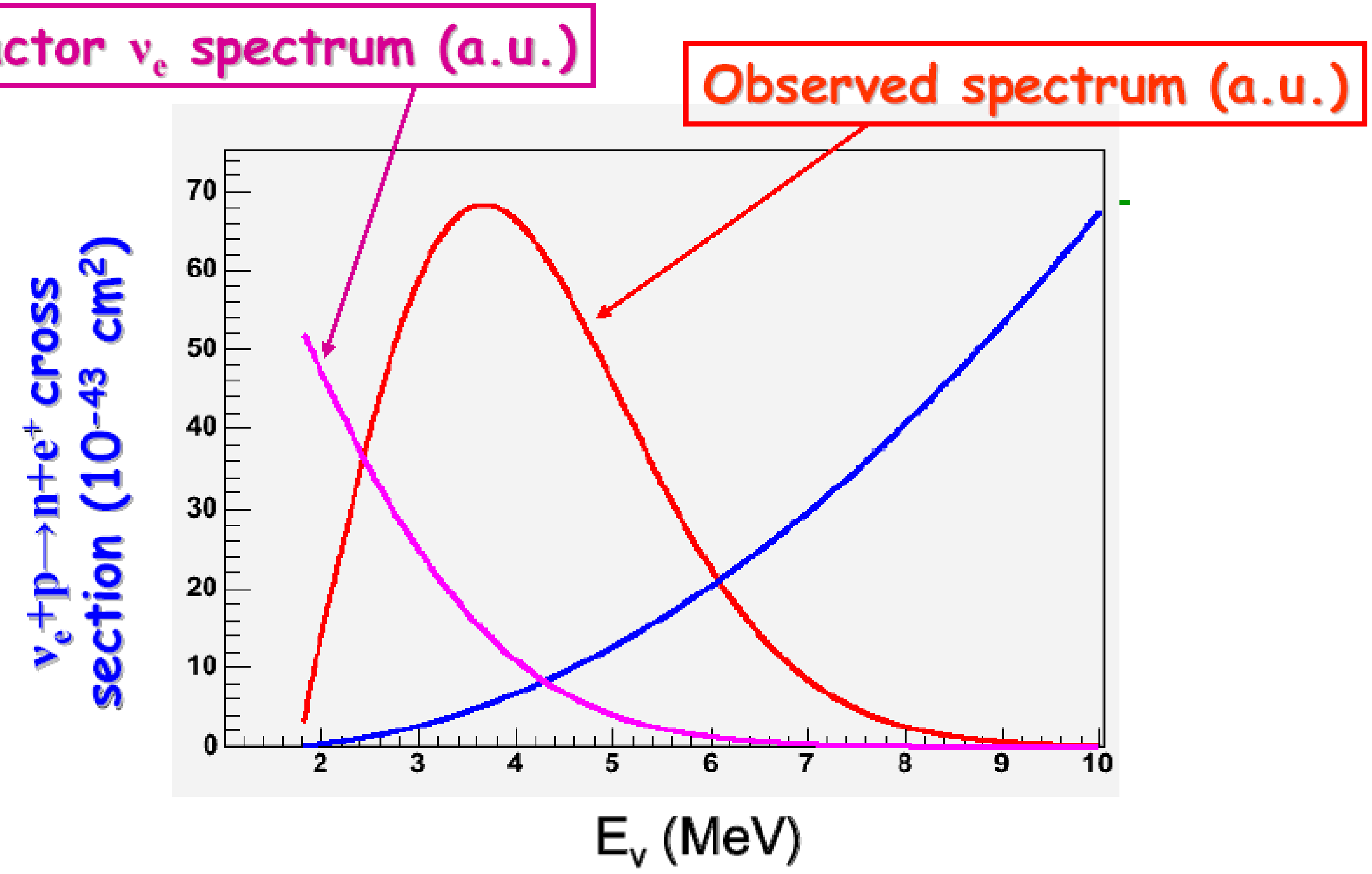
With $\bar{\nu}_e \rightarrow \bar{\nu}_e$ experiments at 1 km (reactor ν)

you can measure θ_{13}

$\overline{\nu}_e$- flux from nuclear power plants



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

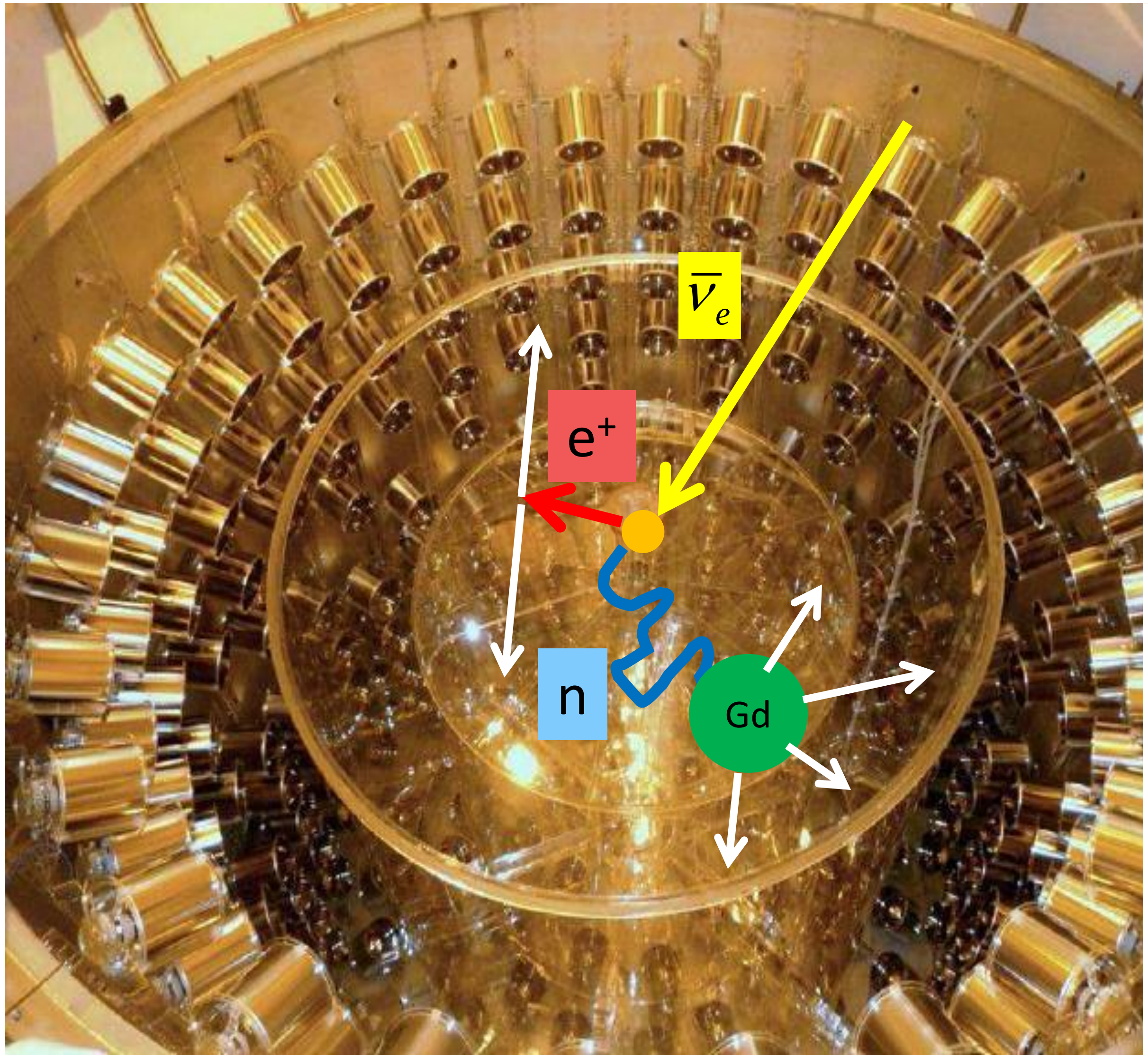


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

prompt signal
E_ν – 0.77MeV

delayed signal

Antineutrino Detection in Reactor Experiments



Inverse Beta Decay:

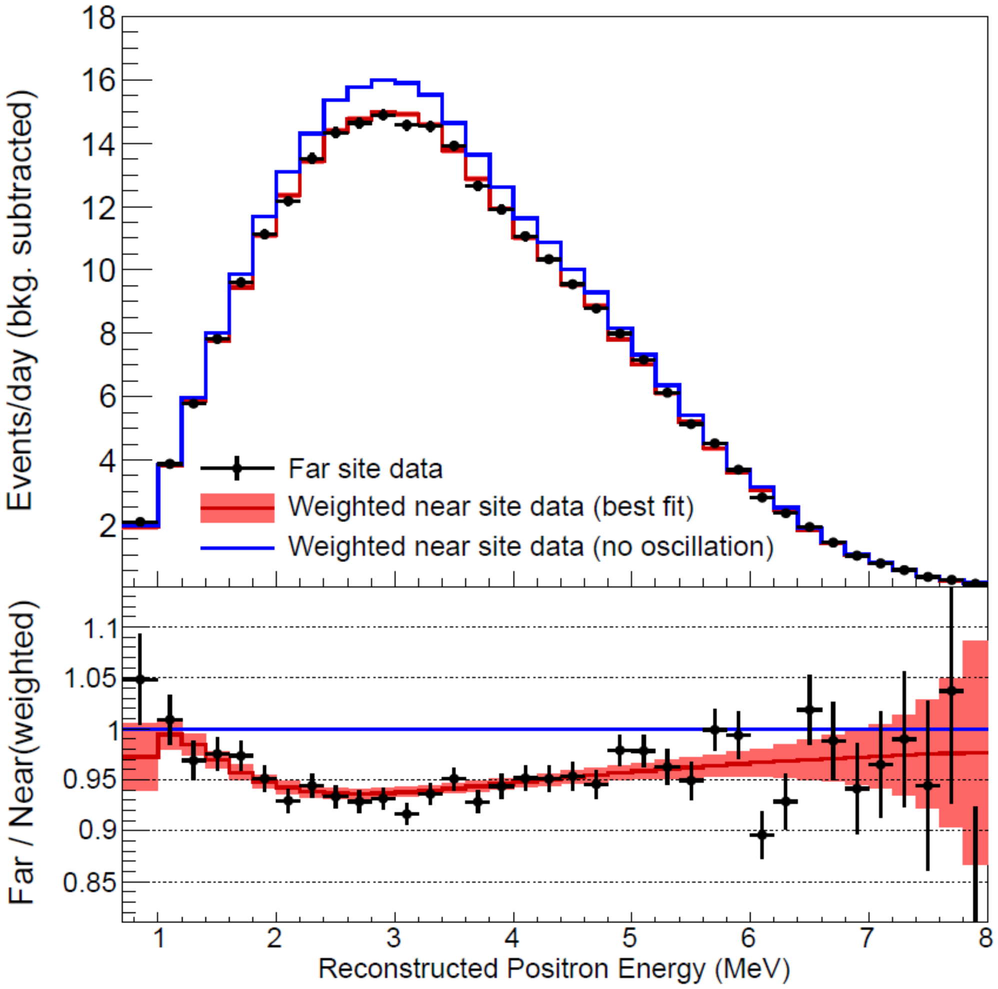
$$\bar{\nu}_e + p \rightarrow n + e^+$$

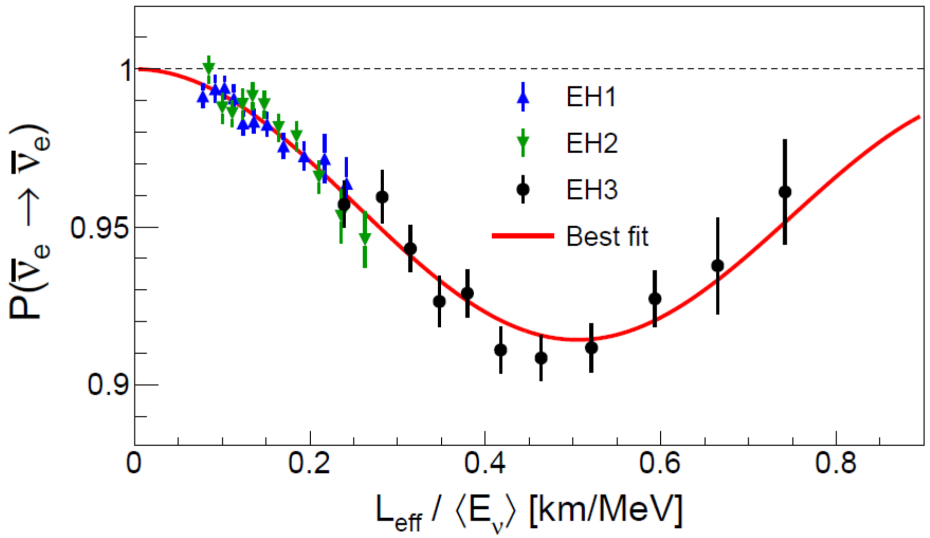
Prompt Event: e^+
gives neutrino energy E_ν

$$E_\nu = E_{vis} + 1.8\text{MeV} - 2m_e$$

Delayed Event: n
capture on Gd
(8MeV γ-emmission)
Delay: ca. 30µs

Daya Bay Result: precision measurement of Θ_{13}





$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$\Theta_{13} \approx 9^o$

Globat Fit: $\Theta_{13} = (8.5 \pm 0.5)^o$ (nu-fit, 09/24)

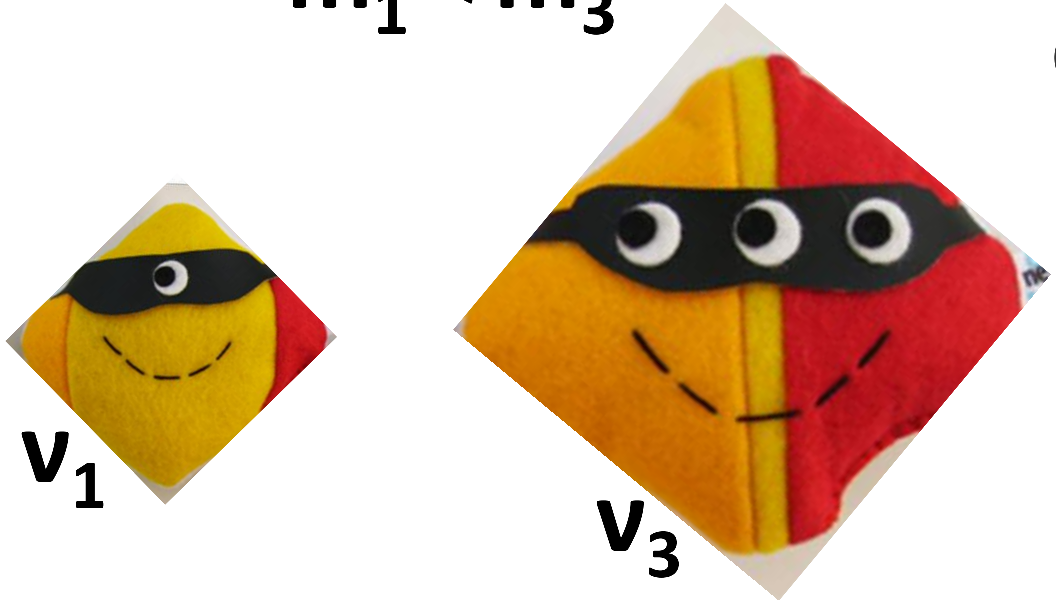
Daya Bay Coll.,**PRL 115, 111802 (2015)**

6

Into the Unknown

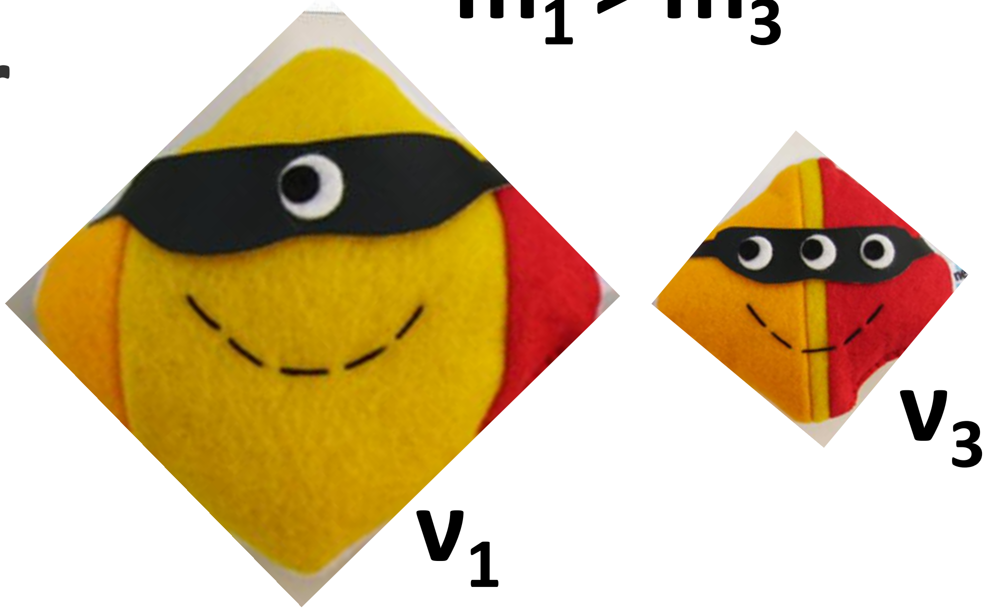
What is the Mass Ordering of Neutrinos?

$m_1 < m_3$



or

$m_1 > m_3$



Normal Ordering

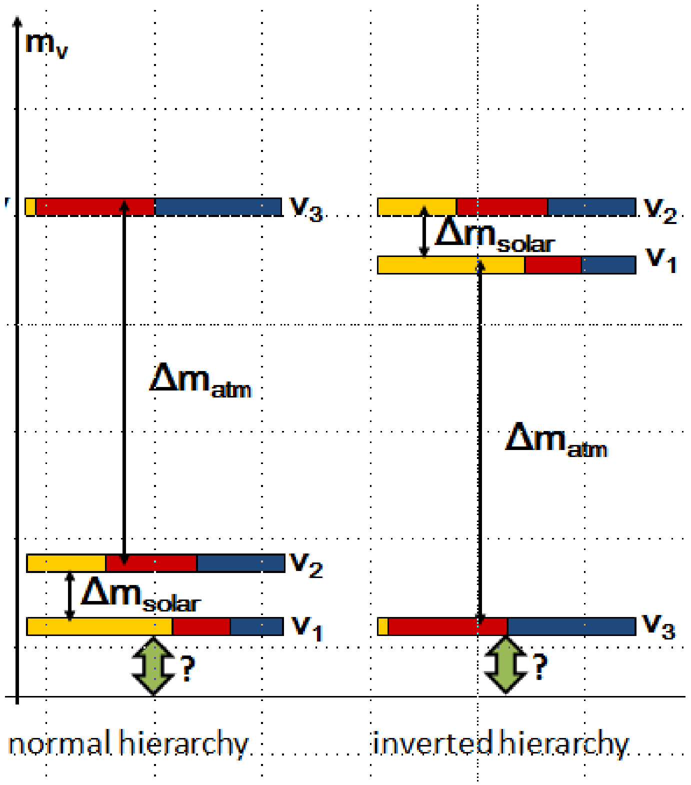
Inverted Ordering

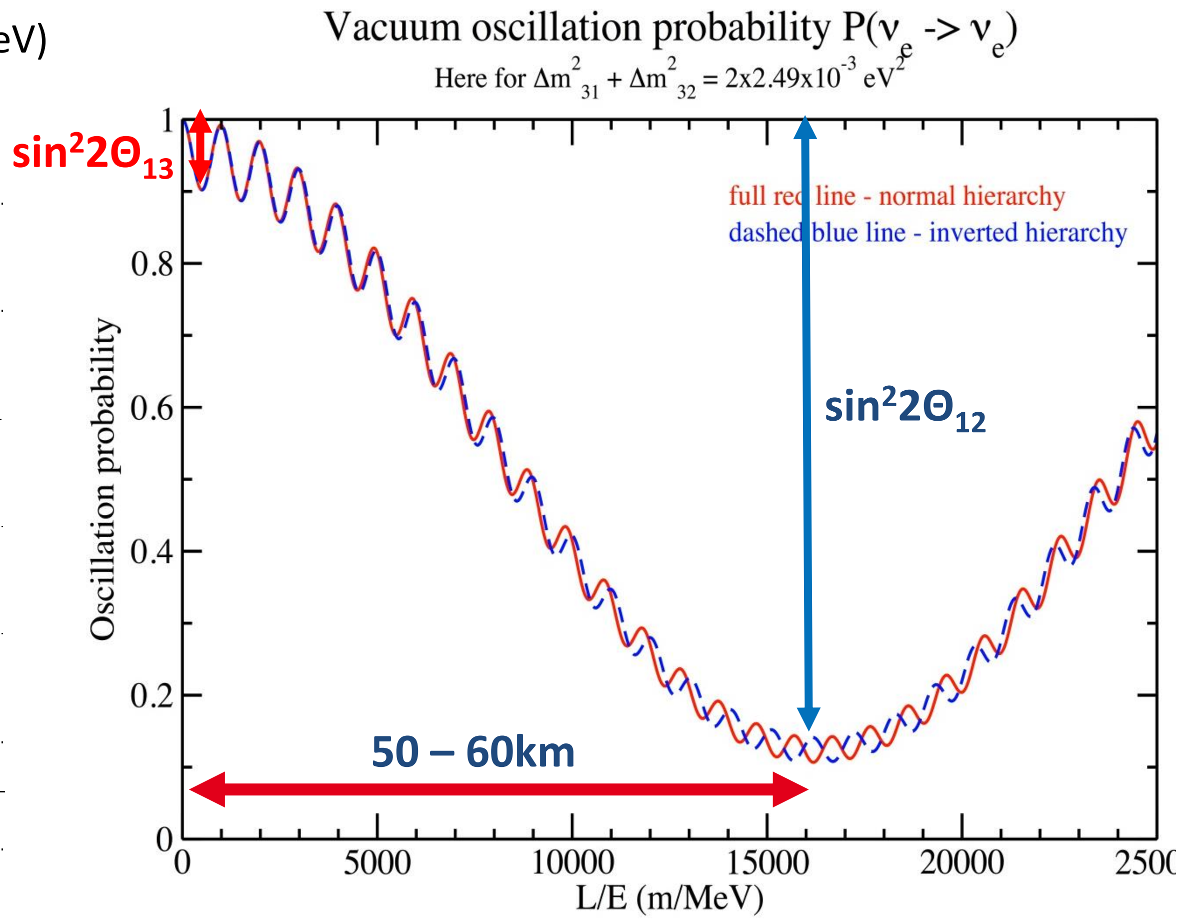
Determination of MO in a Reactor Neutrino Experiment

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

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

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





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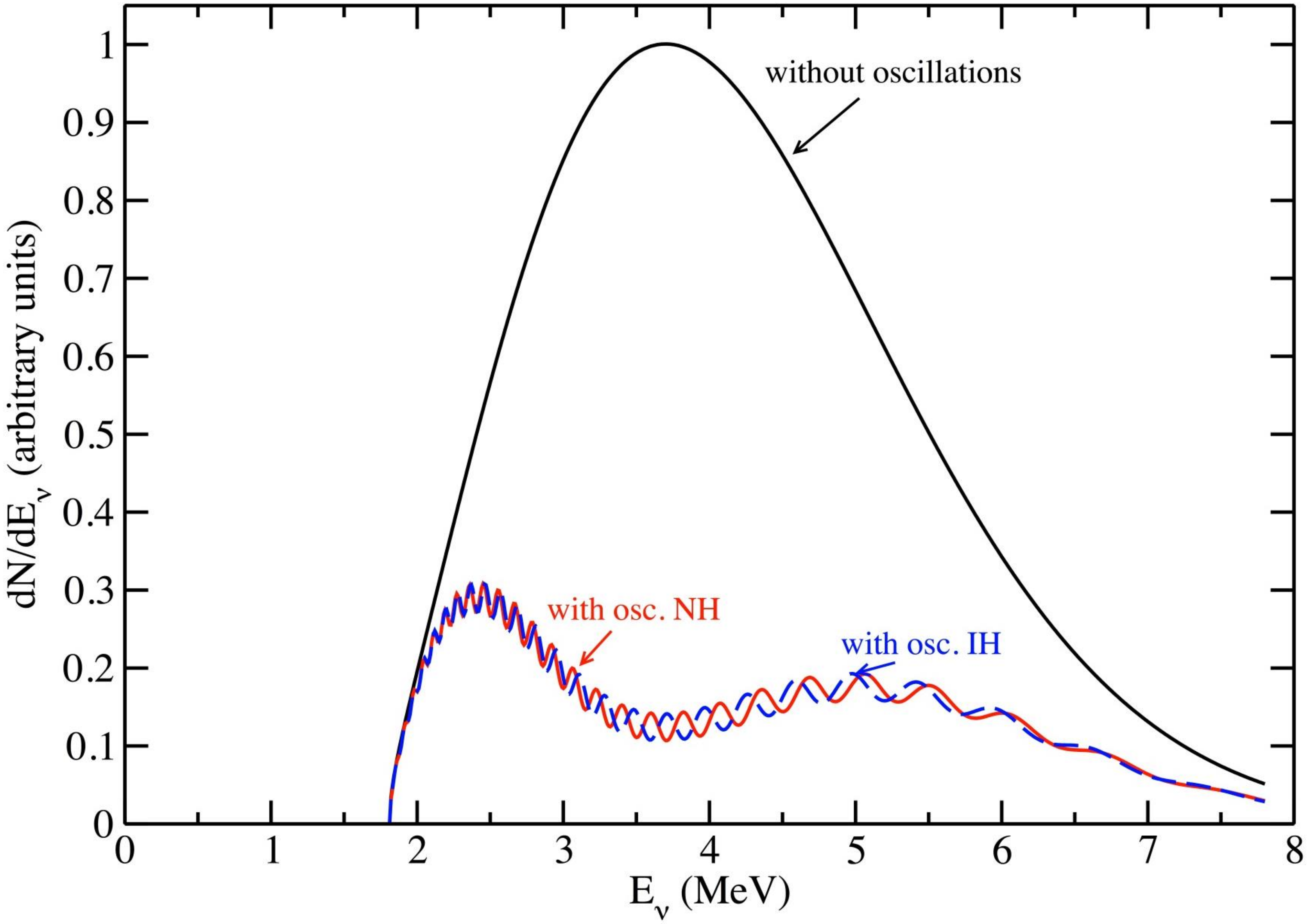
Anti-neutrino Energy Spectrum at 52.5 km from Nuclear Power Plant



JUNO: Detector Concept

Calibration

Top muon veto
Scintillator panels

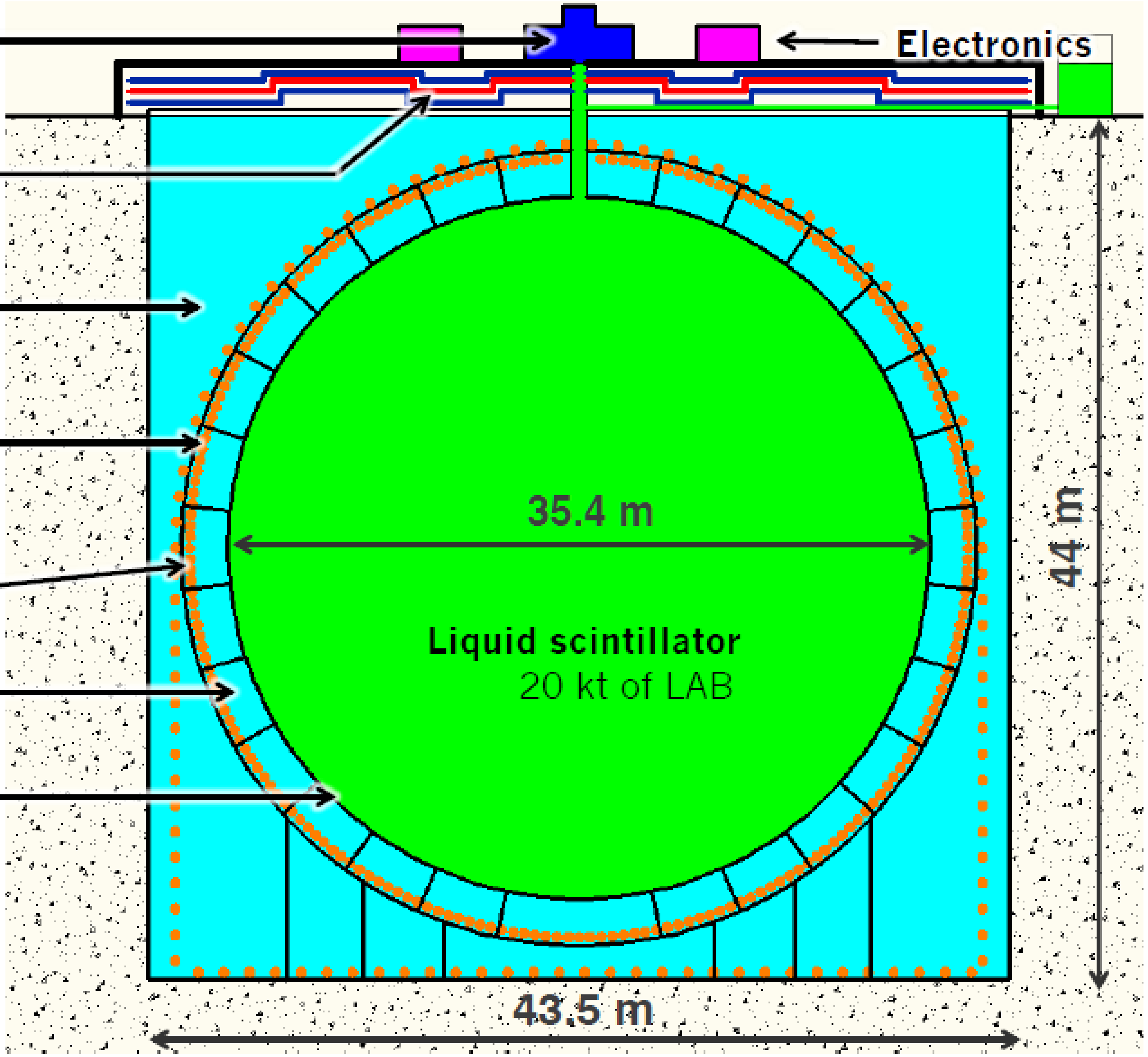
Outer water tank
Muon Cherenkov veto

Steel support structure
optical separation

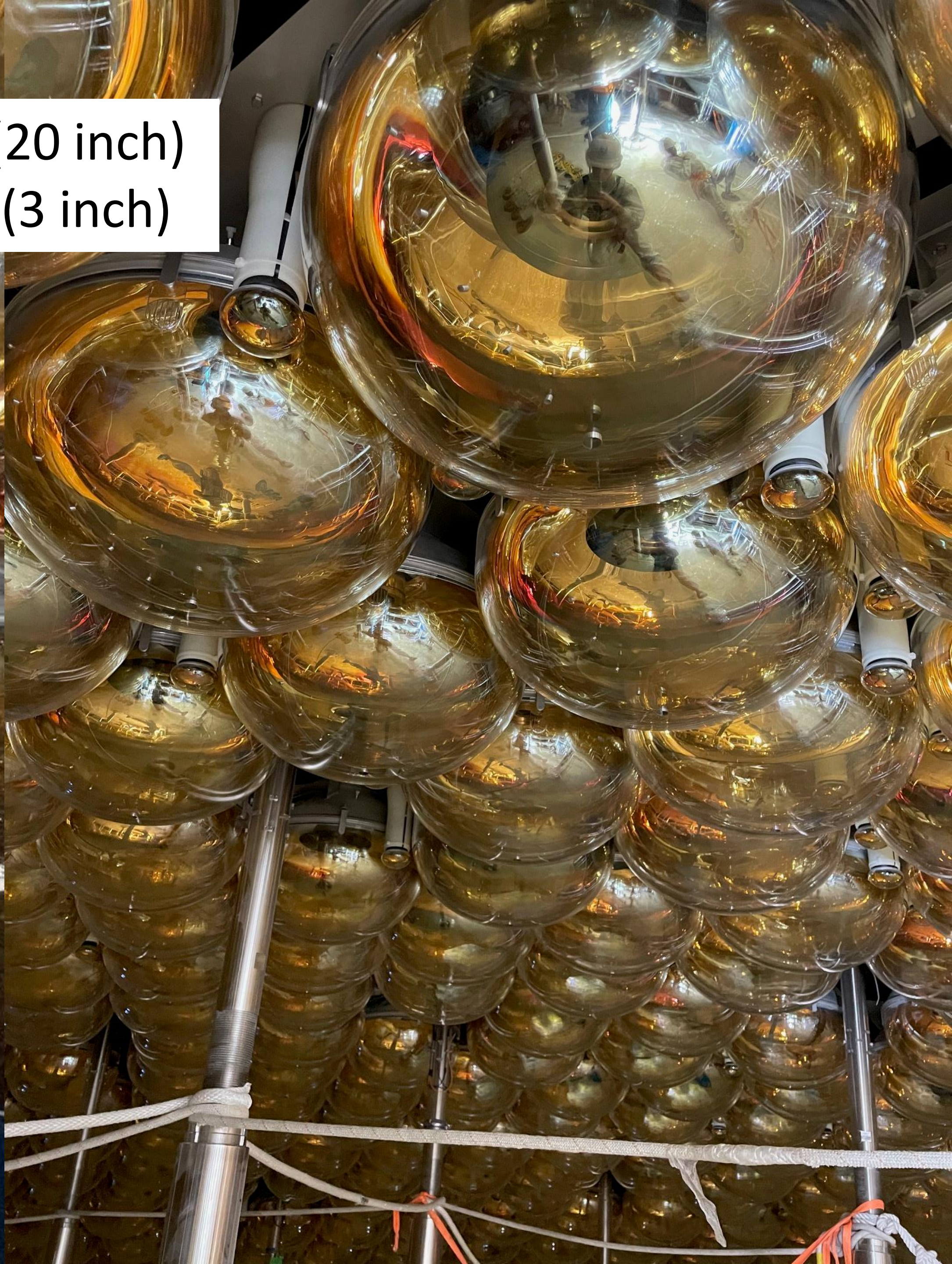
18,000 PMTs (20'')
36,000 PMTs (3'')

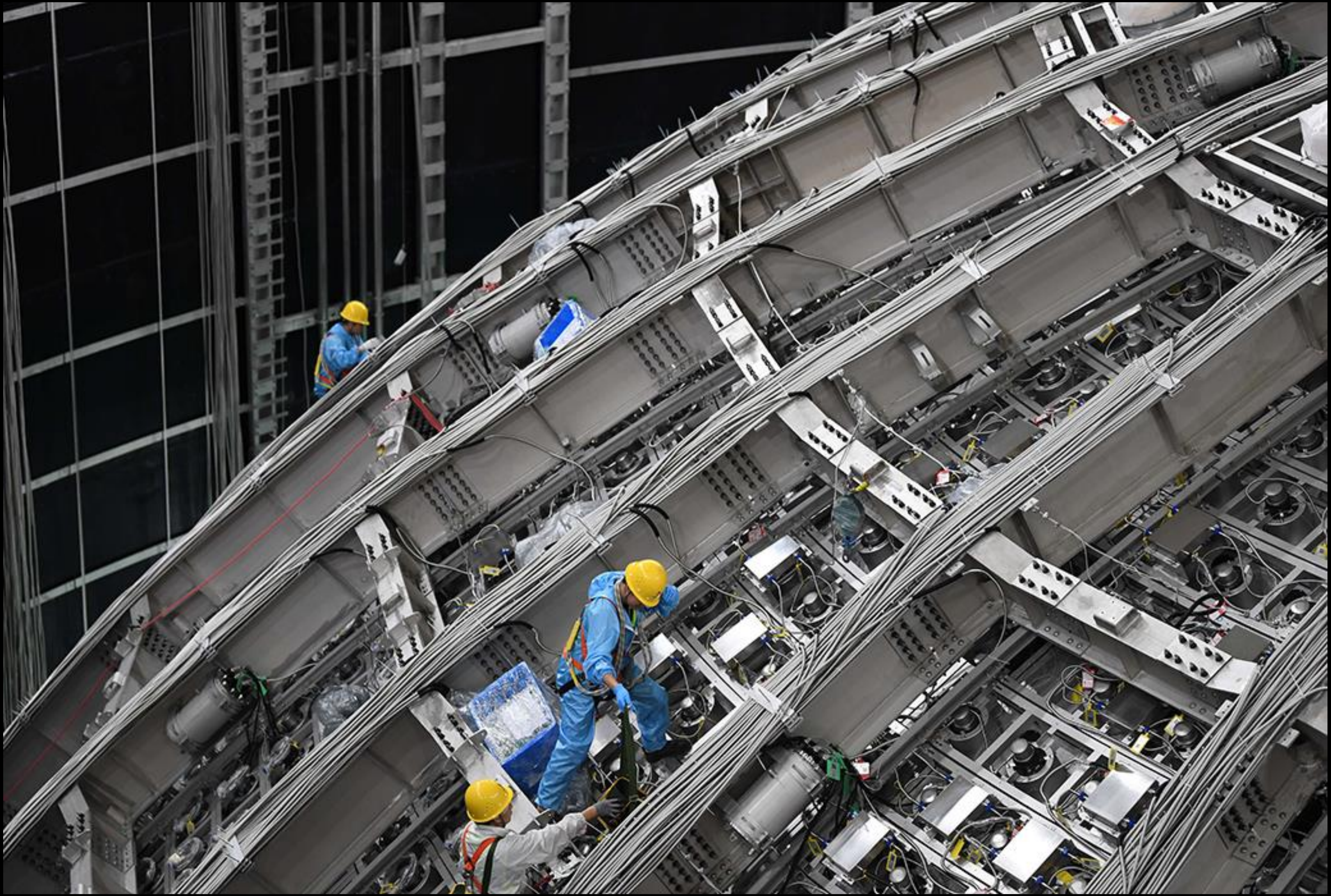
water buffer (2m)

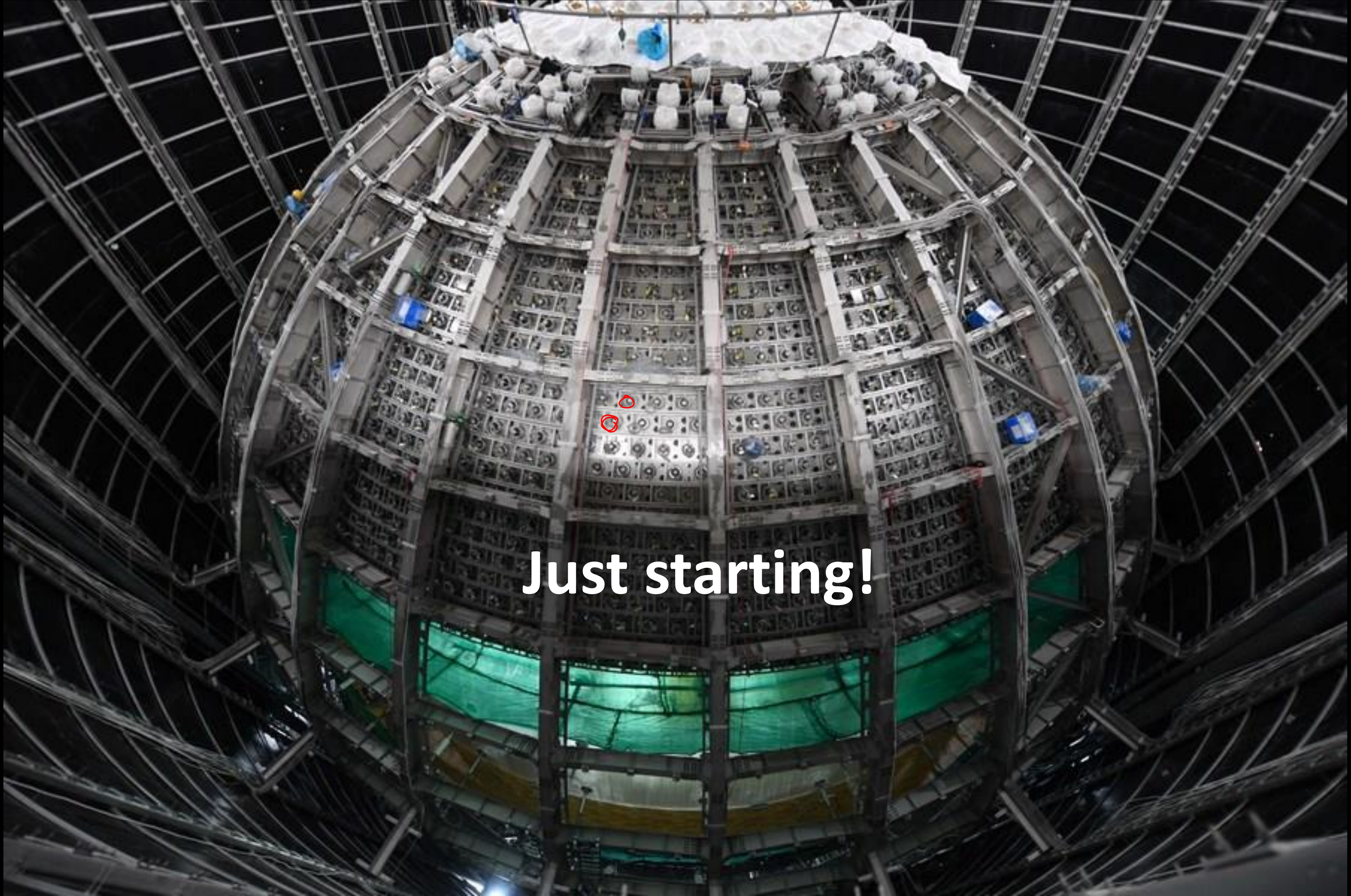
Acrylic sphere
diameter: 35.4m



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






Just starting!

How to search for CP-phase: Appearance of ν_e in a beam of ν_μ

Oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ is approximately given by (expansion by order of small parameter α):

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

$$\mp\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\ldots - \hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$\ldots\frac{\ldots 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

Compare $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

with: $\alpha = \Delta m^2_{21} / \Delta m^2_{31} << 1$

$\Delta = \Delta m^2_{31} L / 4E$

matter dependent quantities:

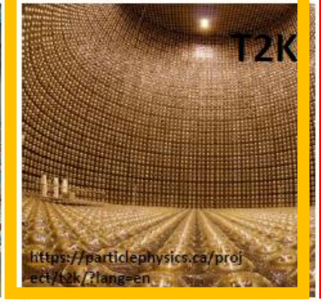
$\hat{A} = 2VE / \Delta m^2_{31}$

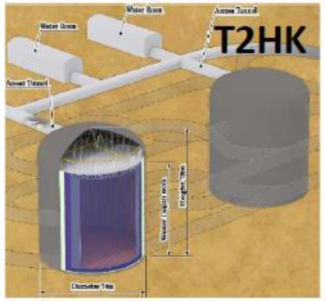
$V = \sqrt{2} G_F n_e$, **with electron density** n_e

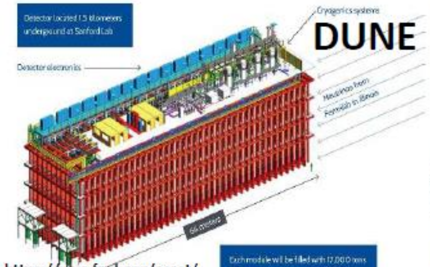
- Leading term ~ Θ_{13}
- Octant of Θ_{23}
- Matter effects enhance ν_e(NH), $\bar{\nu}_e$ (IH)
- **Sign change for anti-neutrinos (measurement of δ_{CP})**

Long-baseline Experiments (Selected Experiments)

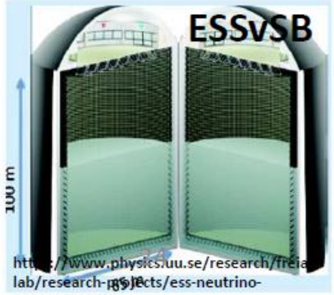
	1st generation	2nd generation	2nd generation	3rd generation	3rd generation	4th generation
Detecting technique	**Steel-scintillator**	**Water Cherenkov**	**Liquid scintillator**	**Water Cherenkov**	**Time Projection Chamber**	**Water Cherenkov**
Experiment example	**MIONS/MINOS+**	**T2K**	**NOvA**	**T2HK**	**DUNE**	**ESSvSB**
Operating period	2005 - 2016	2010 – to date	2014 – to date	Next-generation	Next-generation	N-n-generation
Peak E_ν [GeV]	3	0.7	2	0.6	2.6	0.3
Baseline [km]	735	295	810	295	1300	540
On/Off axis	On-axis	Off-axis	Off-axis	Off-axis	On-(Off- for ND)axis	On-axis



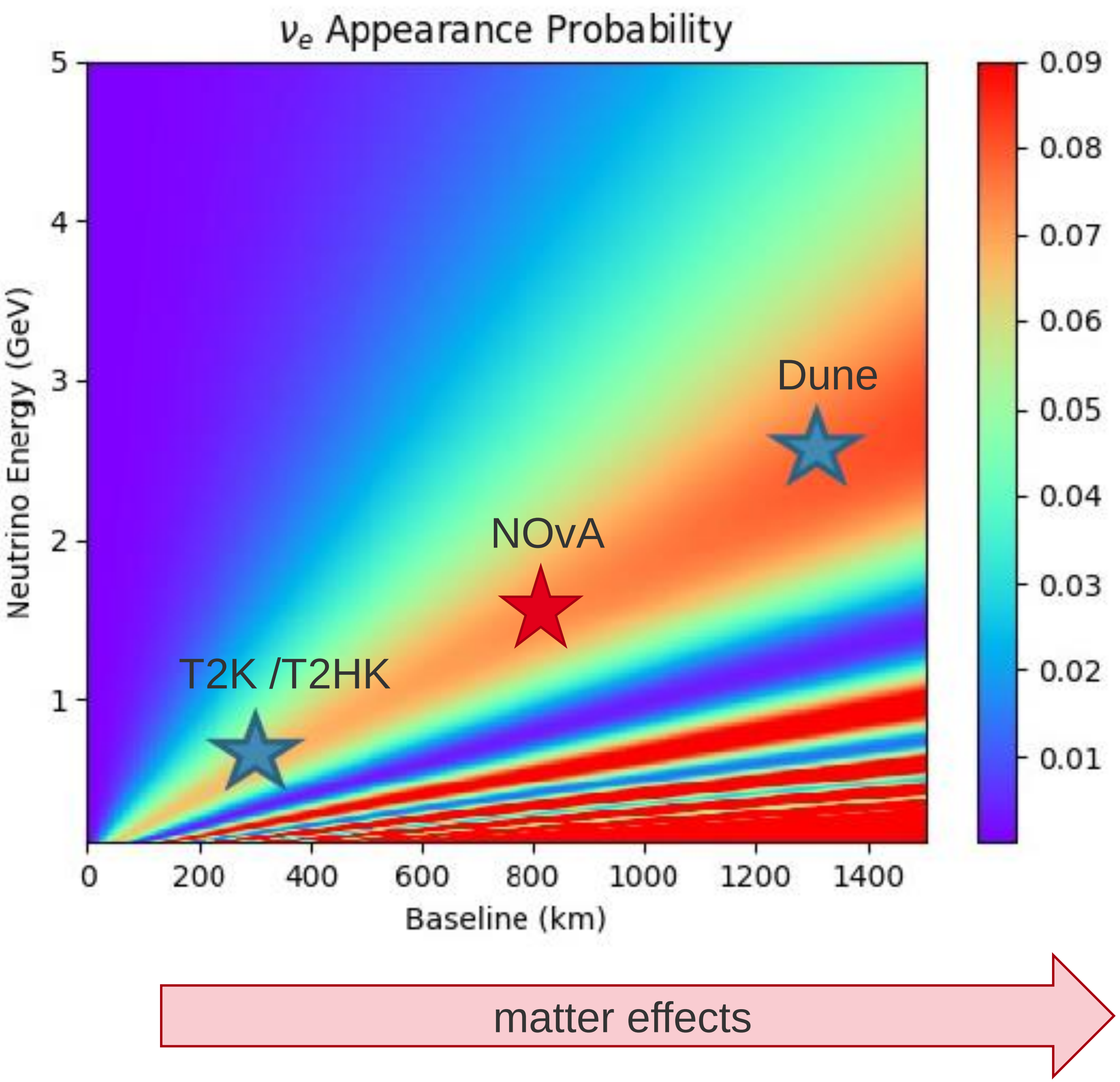




https://vms.fnal.gov/asset/detail?recid=1961263



Slide by Tamer Tolba



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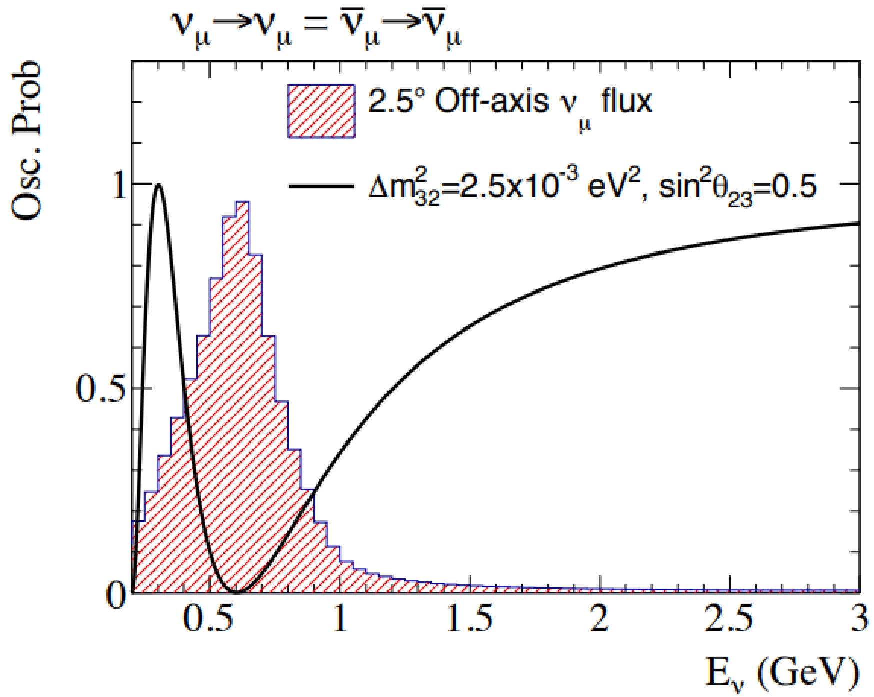
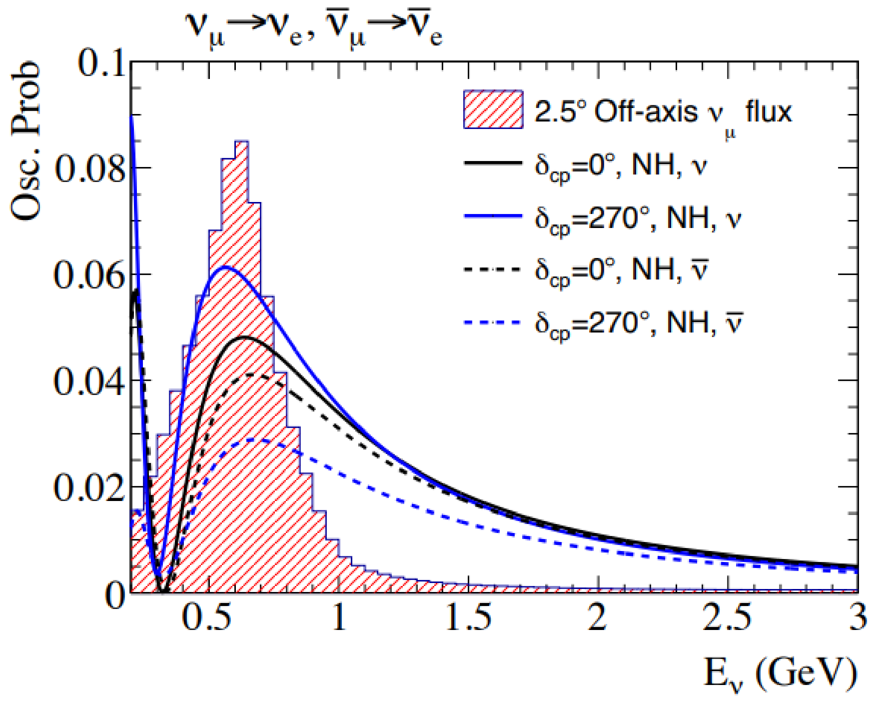
How to measure oscillation parameters with $\nu_\mu/\bar{\nu}_\mu$ beams

disappearance of $\nu_\mu/\bar{\nu}_\mu$:



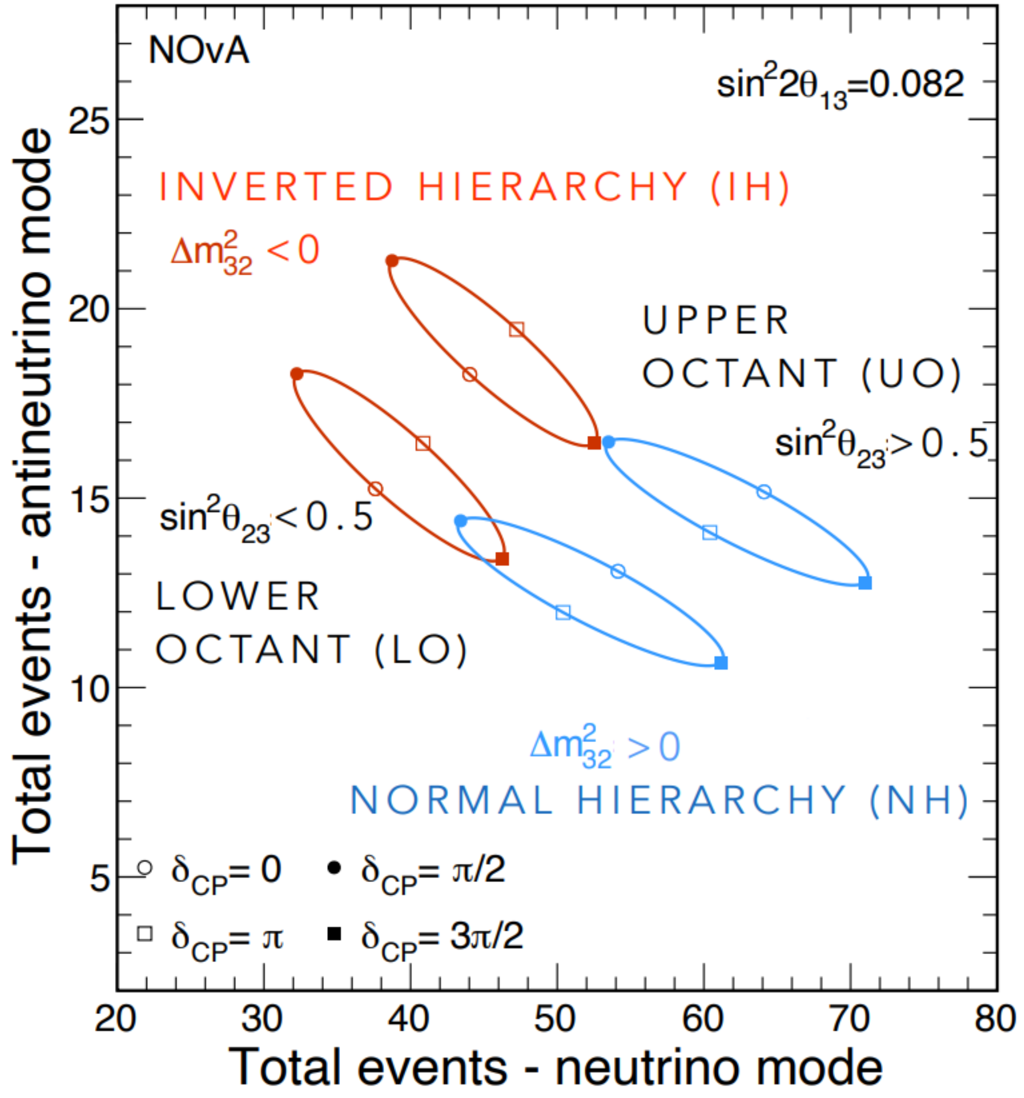
- leading order dependence on **$\sin^2 2\theta_{23}$** little power to distinguish whether $\theta_{23} < 45°$, $\theta_{23} = 45°$ or $\theta_{23} > 45°$.
- leading order dependence on **$|\Delta m^2_{23}|$**. Does not depend on mass ordering.

appearance of $\nu_e/\bar{\nu}_e$:



- leading order dependence on **$\sin^2 2\theta_{13}$** and **$\sin^2\theta_{23}$**. **Can separate octant**, meaning whether $\theta_{23} < 45°$, $\theta_{23} = 45°$ or $\theta_{23} > 45°$.
- sub-leading order dependence on **$\sin^2 2\theta_{13}$** and **$\sin^2 2\theta_{23}$**. **Can detect CP-violation.**
- sub-leading order dependence on **$|\Delta m^2_{23}|$** through matter effect. **Can measure mass ordering.**

How to measure CPV by comparing appearance of $\nu_e / \bar{\nu}_e$ in $\nu_\mu / \bar{\nu}_\mu$ beams



Difficult to disentangle **degeneracies** between parameters in one experiment alone

Can be solved by **combining** results from **different experiments** with different baselines

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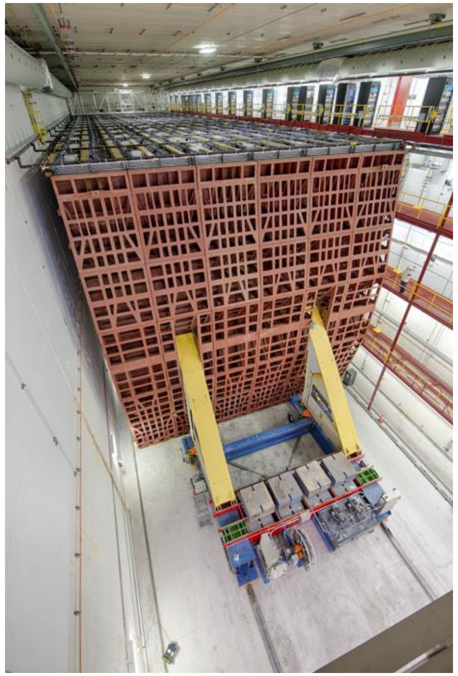
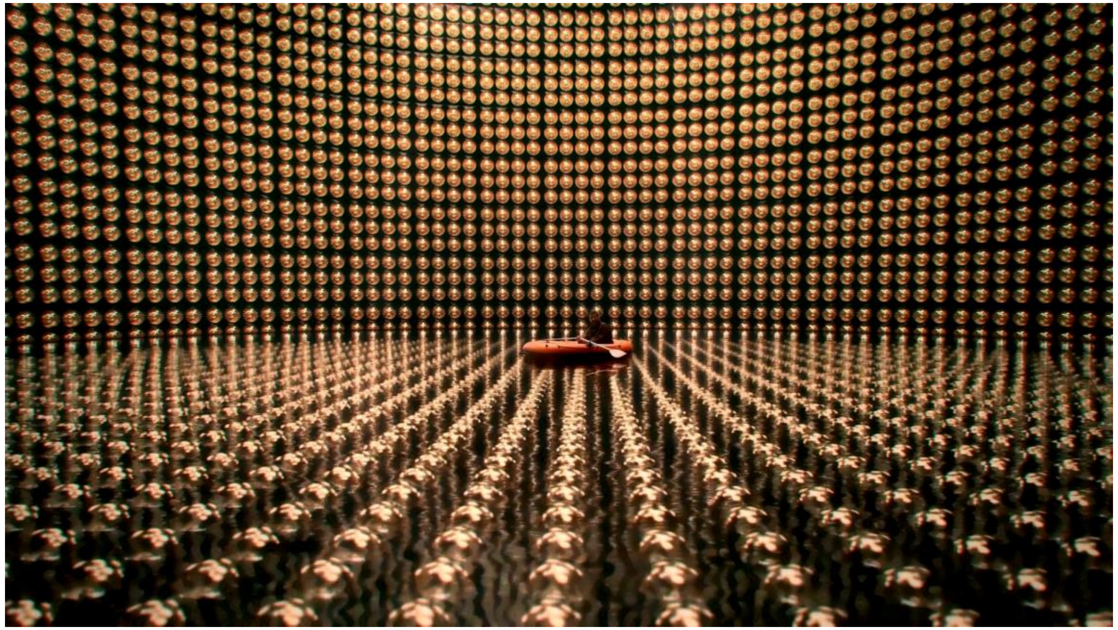
Running since >10 years: NOvA and T2K

NOvA:
Distance ND – FD: **810 km**
both detectors 14mrad off-axis
neutrino flux peak at **1.8 GeV**,
typical **beam power 900 kW**
FD: 14kton Liquid Scintillator in cells



T2K:
Distance ND – FD: **295 km**
2.5° off-axis
neutrino flux peak at **0.6 GeV**,
Plan to increase **beam power 1300 kW (2027)**
FD: SK 50kton Water Cerenkov, ND different



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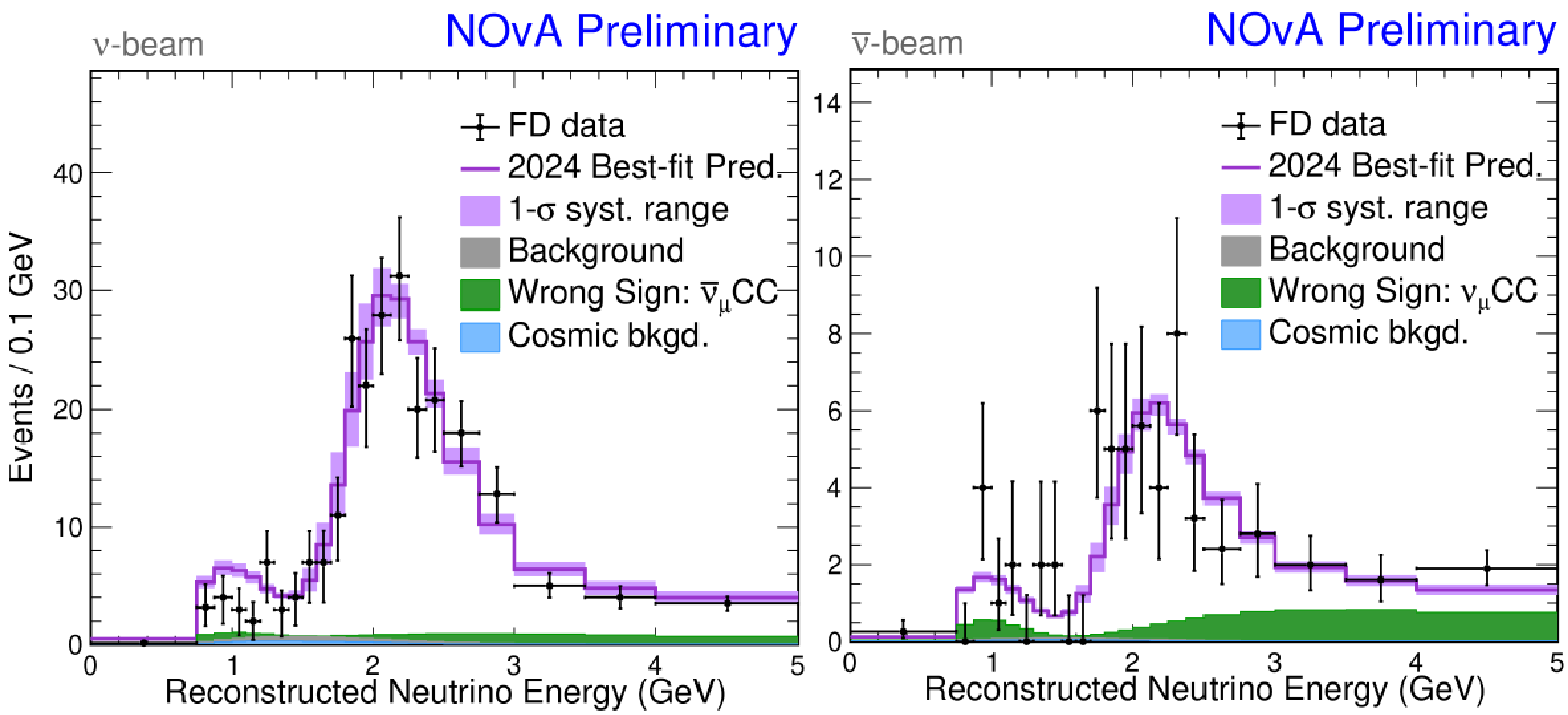
NOvA result on disappearance of $\nu_\mu/\bar{\nu}_\mu$ (26.6x10^{20}pot)

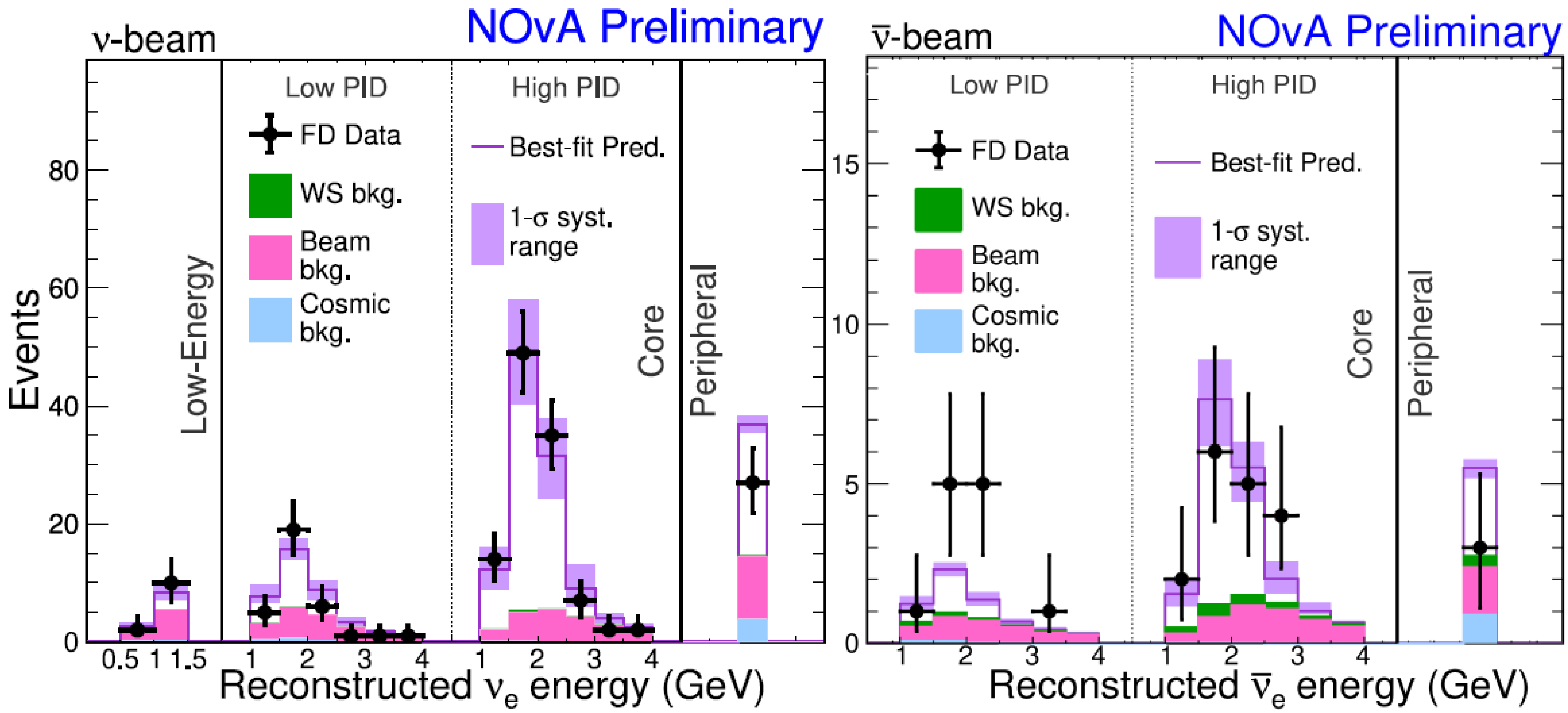


384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

From J. Wolcott Neutrino24

NOvA result on appearance of $\nu_e/\bar{\nu}_e$ (26.6x10^{20}pot)

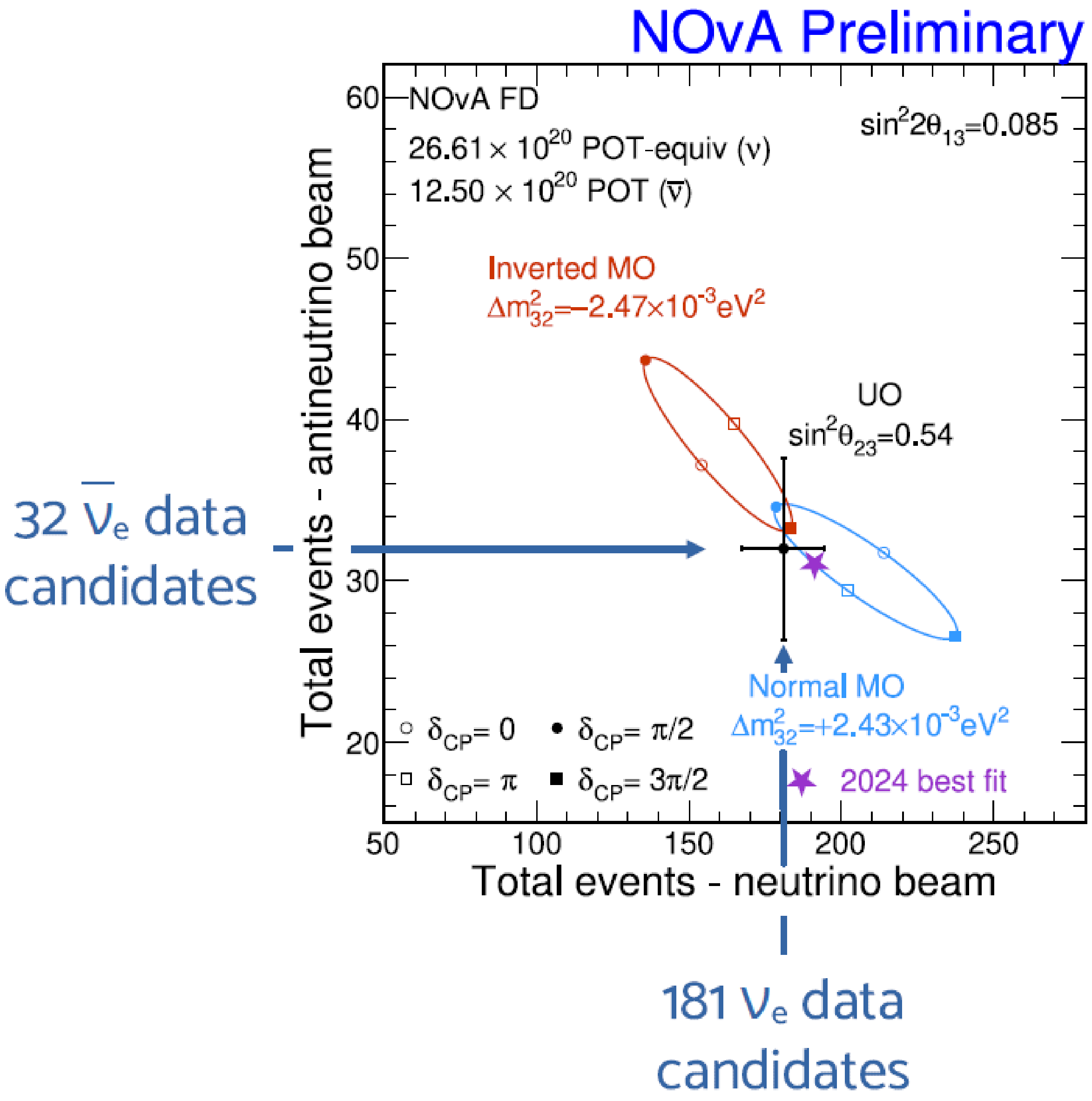


Observed 181 events,
expect 62 from background

Observed 32 events,
expect 12 from background

From J. Wolcott Neutrino24

NOvA analysis of appearance of $\nu_e/\bar{\nu}_e$ (26.6x10^{20}pot)

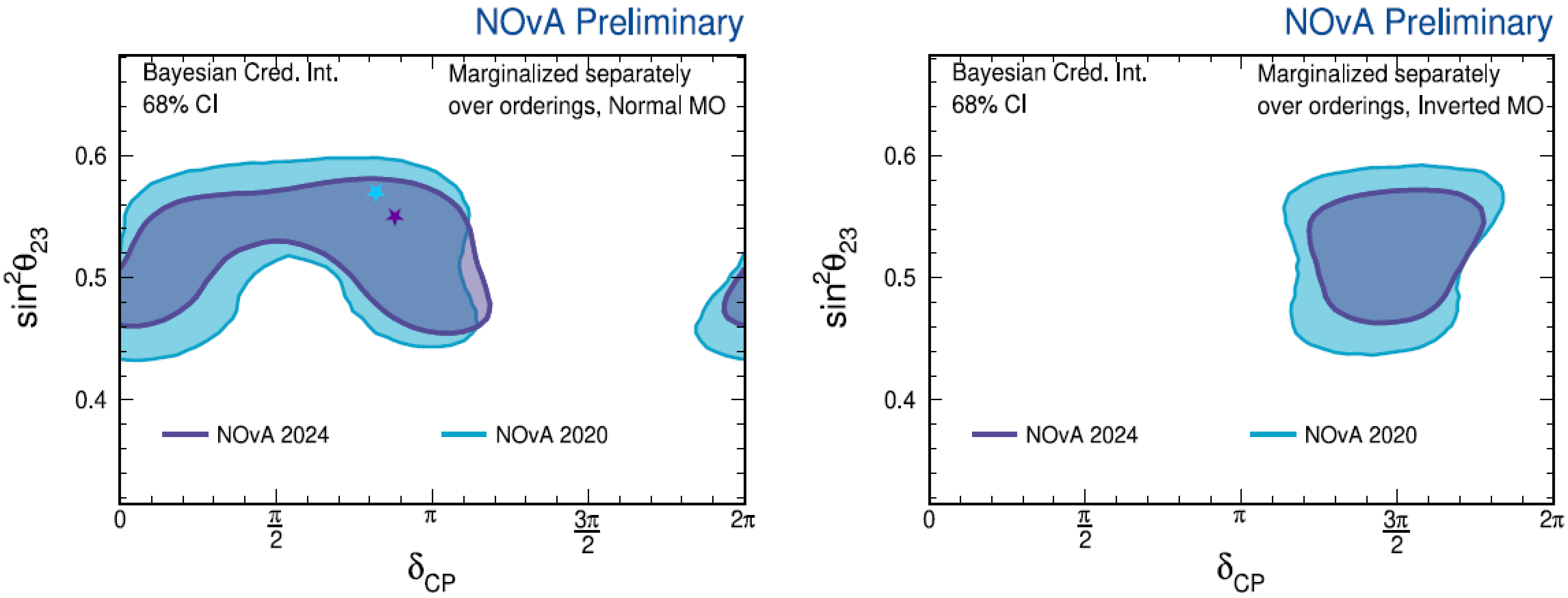


Strong synergy with reactor exp:

- Constraint on θ_{13} enhances Upper Octant preference
- Constraint on Δm^2_{32} enhances Normal Ordering preference

From J. Wolcott Neutrino24

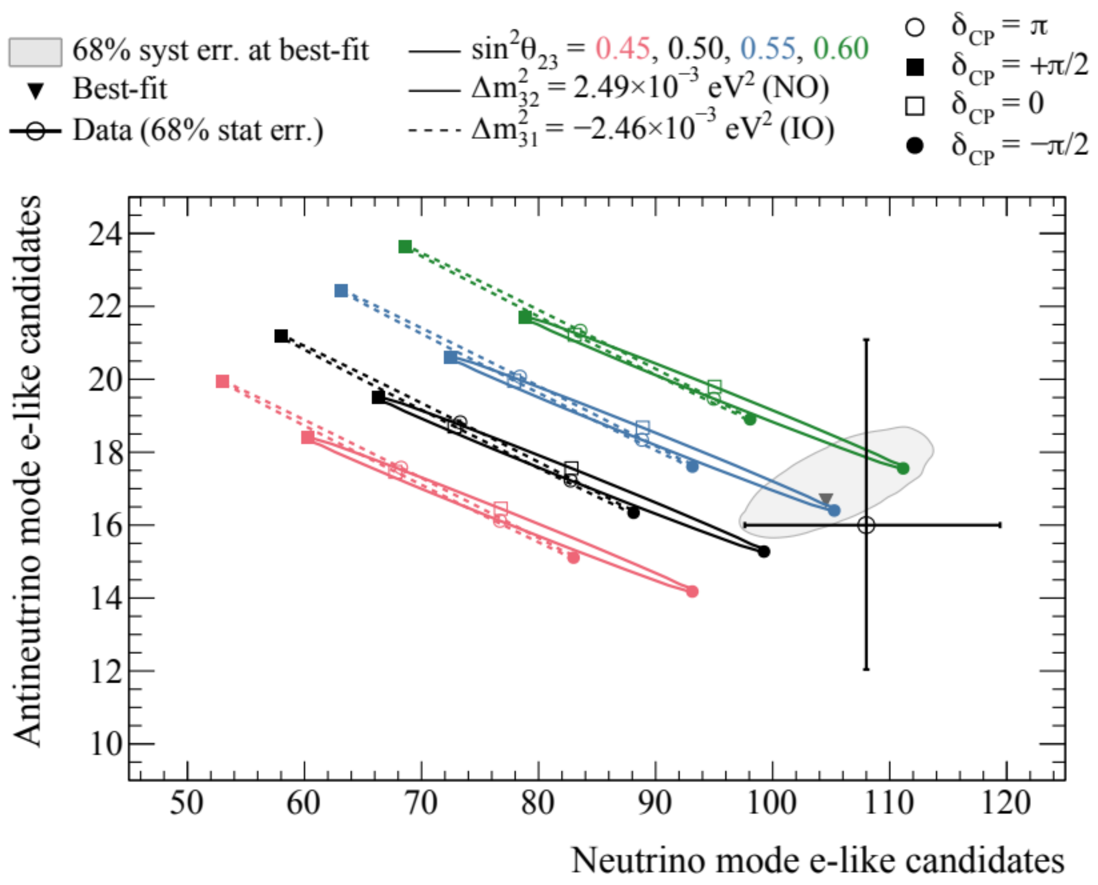
NOvA analysis of mass ordering and CPV (26.6×10^{20}pot)

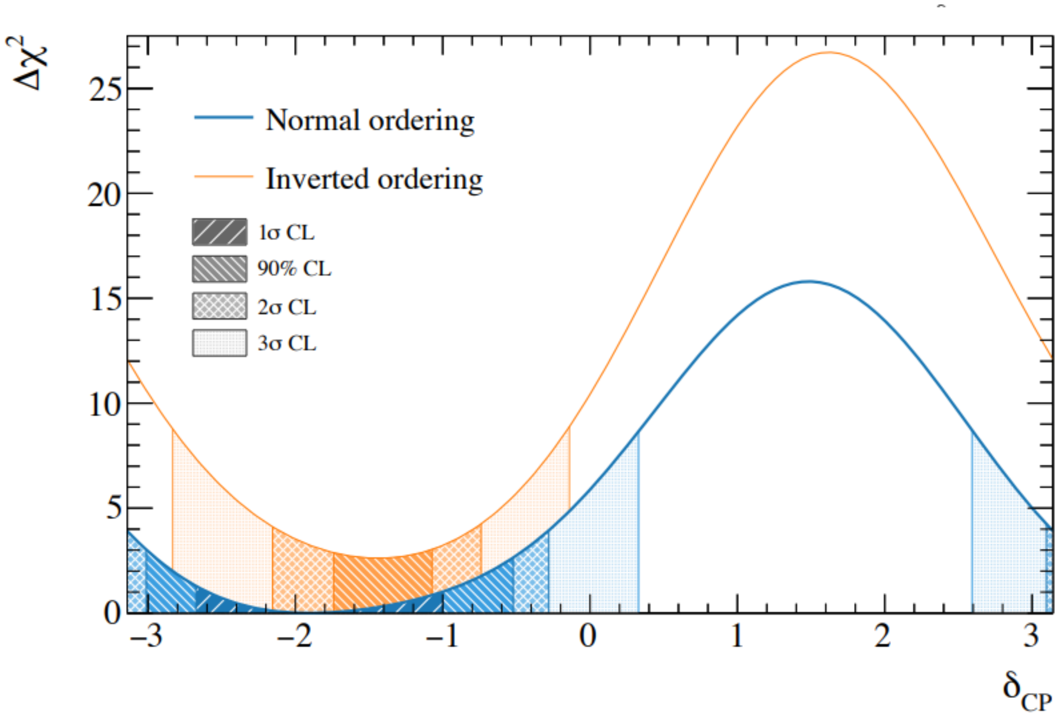


From J. Wolcott Neutrino24

T2K result on appearance of $\nu_e/\bar{\nu}_e$ (2023)

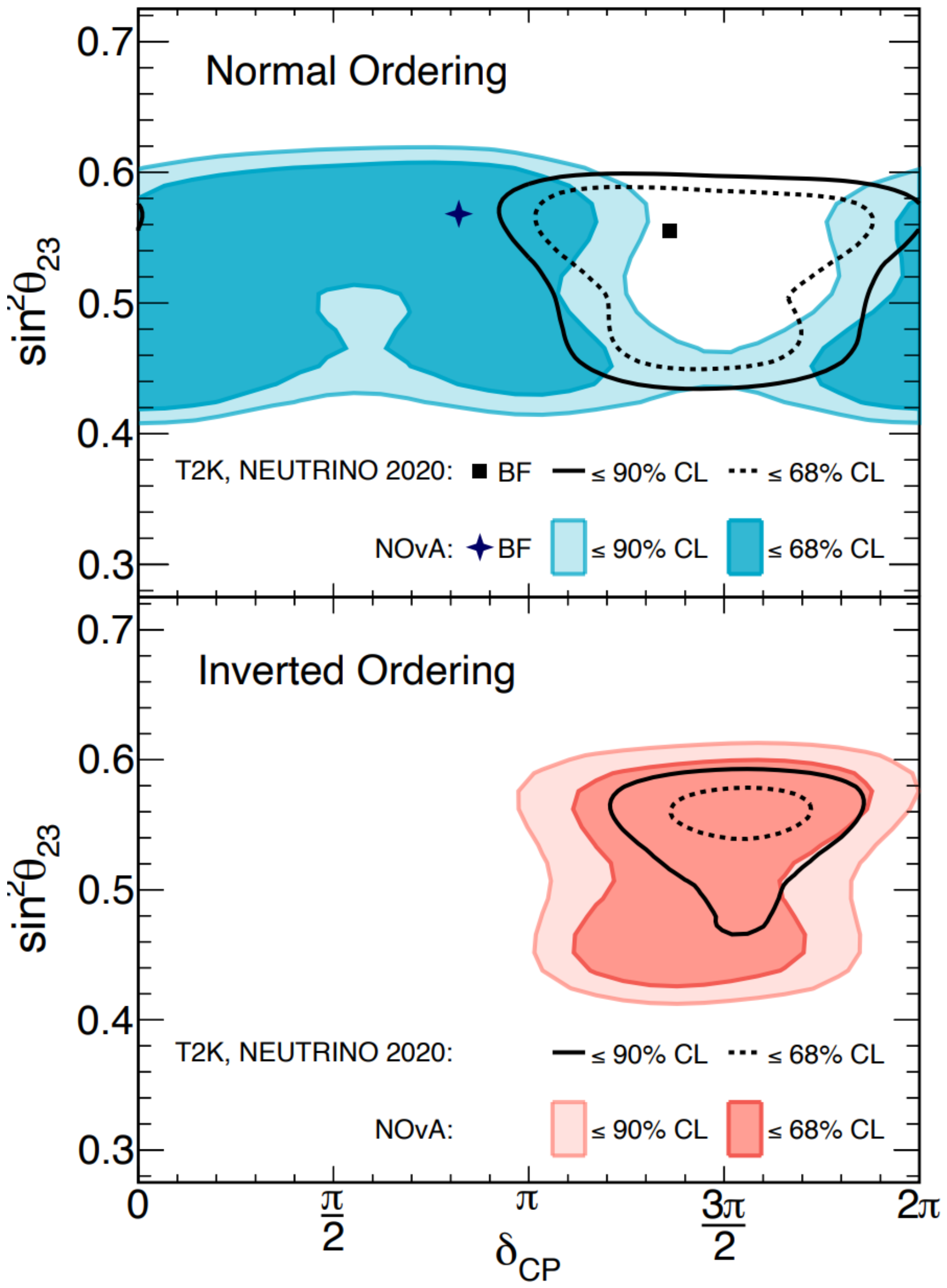
In contrast to NOvA they see a strong asymmetry between electron neutrino and antineutrino event numbers





Attention: T2K use other convention for CP-phase:
- ½ π instead of 3/2 π

- Values that maximize asymmetry are favoured
- Normal ordering and upper octant are favoured, with nearly maximally CP-violating phase



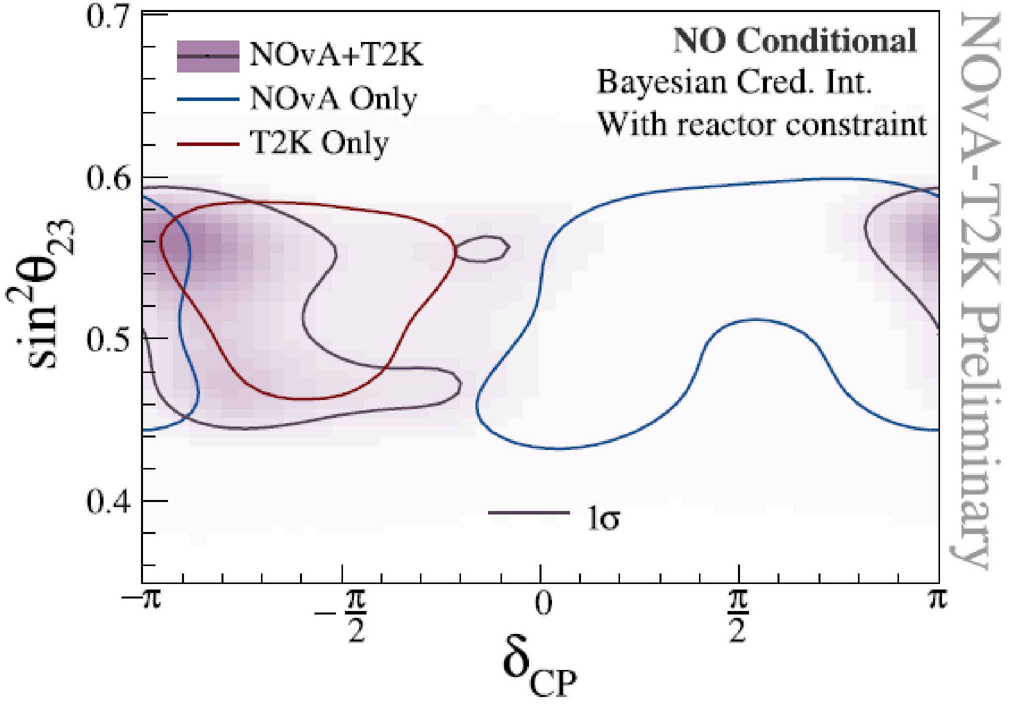
Combining NOvA and T2K results:

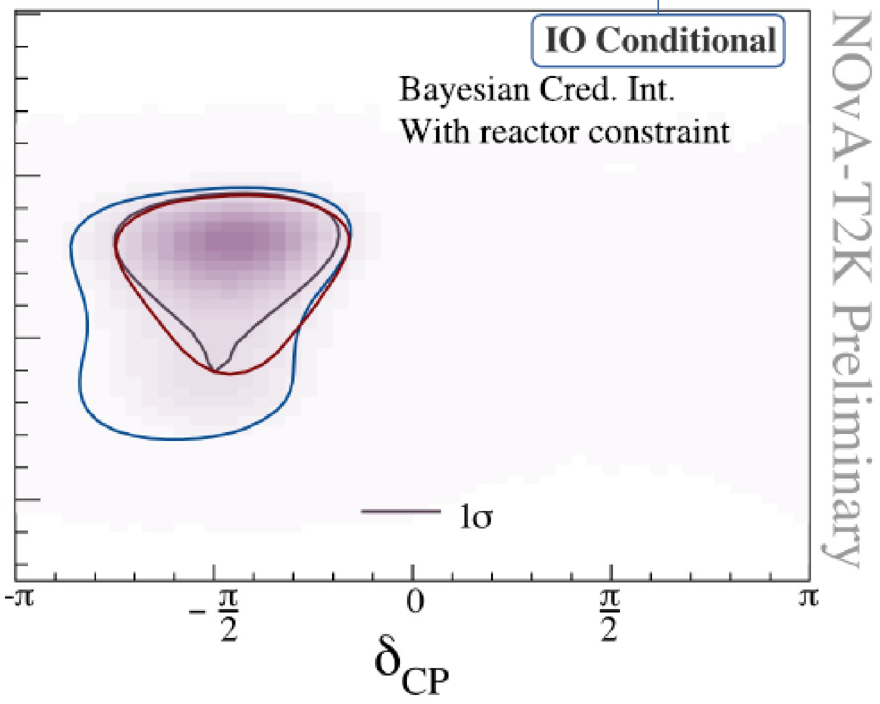
- Still compatible at > 90%
- However, favoured regions of CP-phase are opposite in NO

NOvA-T2K joint fit: PMNS parameters

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

"assuming IO is true"
(does not include relative probability of IO vs. NO)





NOvA & T2K's **first joint results**:

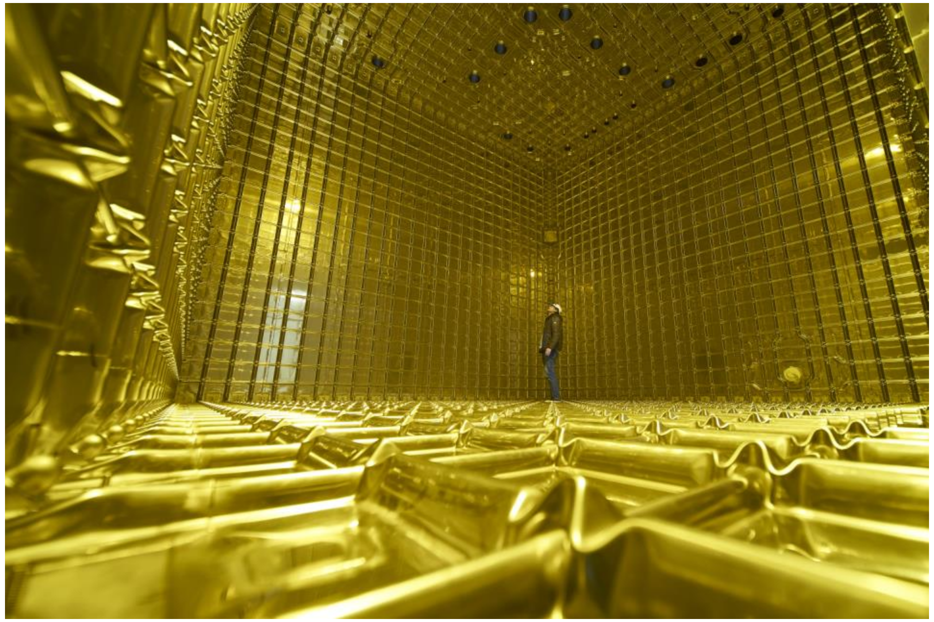
- Yield **strong constraint on Δm^2_{32}**
- Weakly prefer IO or NO depending on which reactor constraint is applied
- **Strongly favor CP violation in Inverted Ordering**

(slides by Jeremy Wolcott, Neutrino24)

The Future: DUNE & Hyper-K, ESSvsb

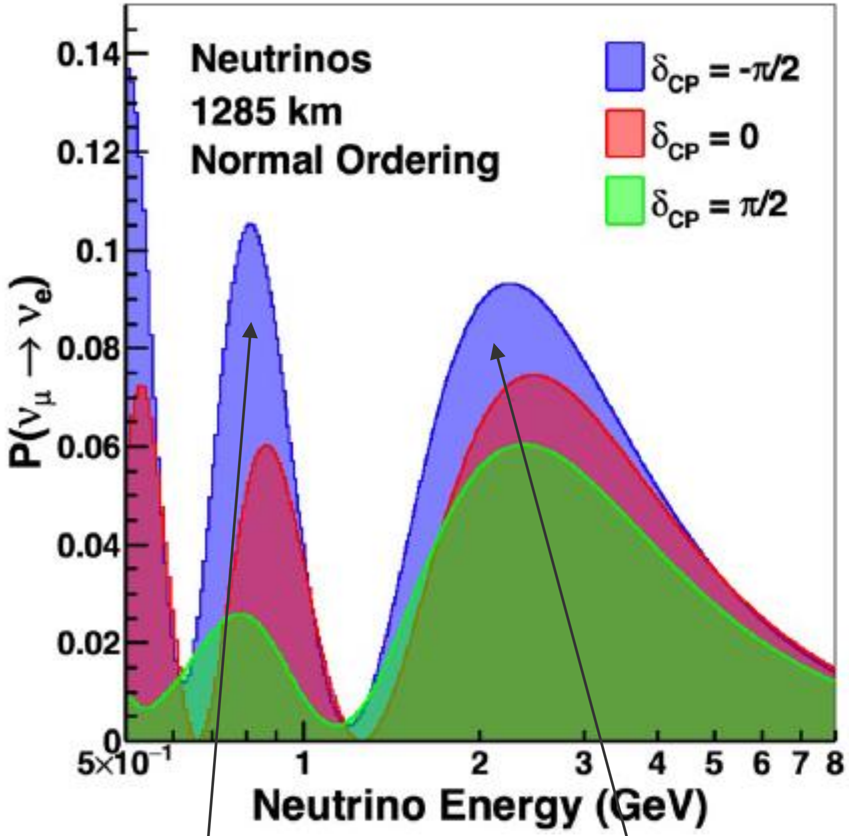
DUNE:
Distance ND – FD: **1300 km**
both detectors 14mrad off-axis
neutrino flux peak at **1.8 GeV**,
typical **beam power > 2000 kW**
FD: 40kton Liquid Argon TPC

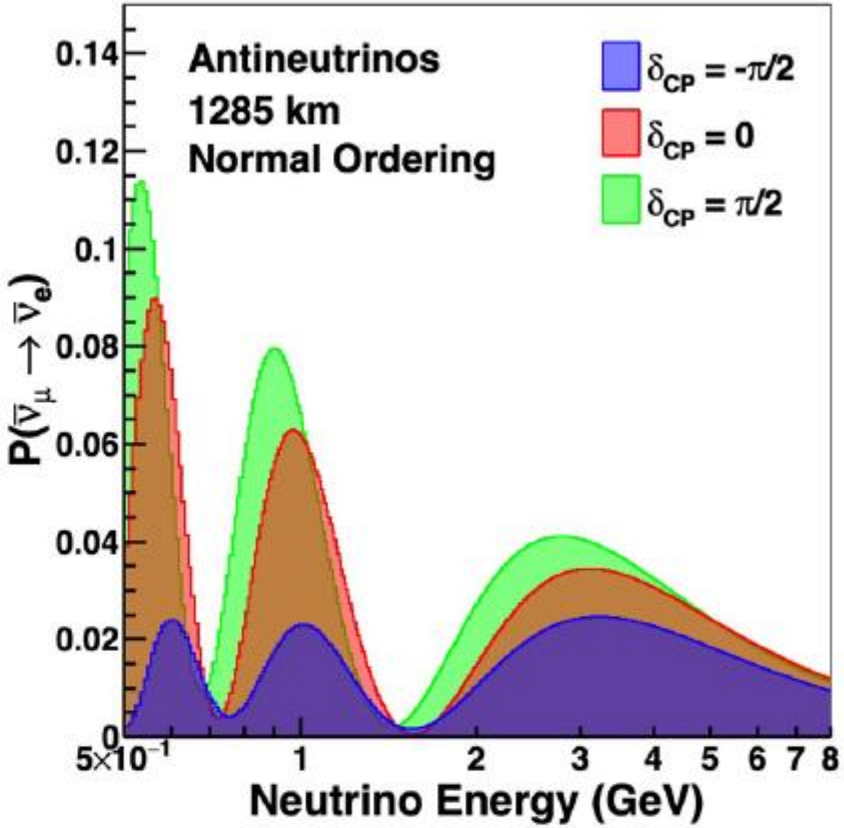
Hyper-K:
Distance ND – FD: **295 km**
2.5° off-axis
neutrino flux peak at **0.6 GeV**,
Plan to increase **beam power 1300 kW (2027)**
FD: 5 x SK 50kton Water Cerenkov

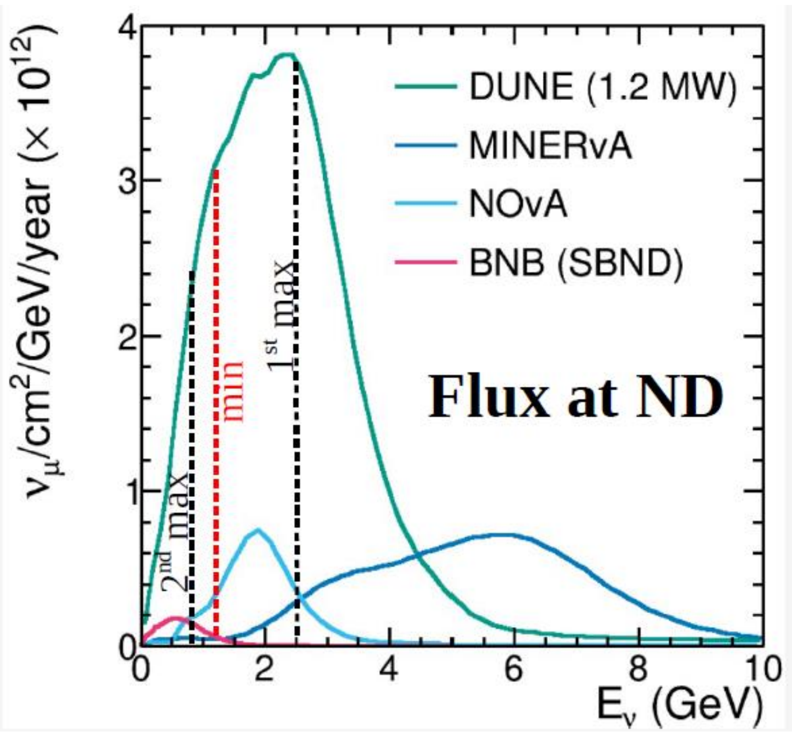


Oct. 3, 2023 Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)

CP-violation measurement in DUNE



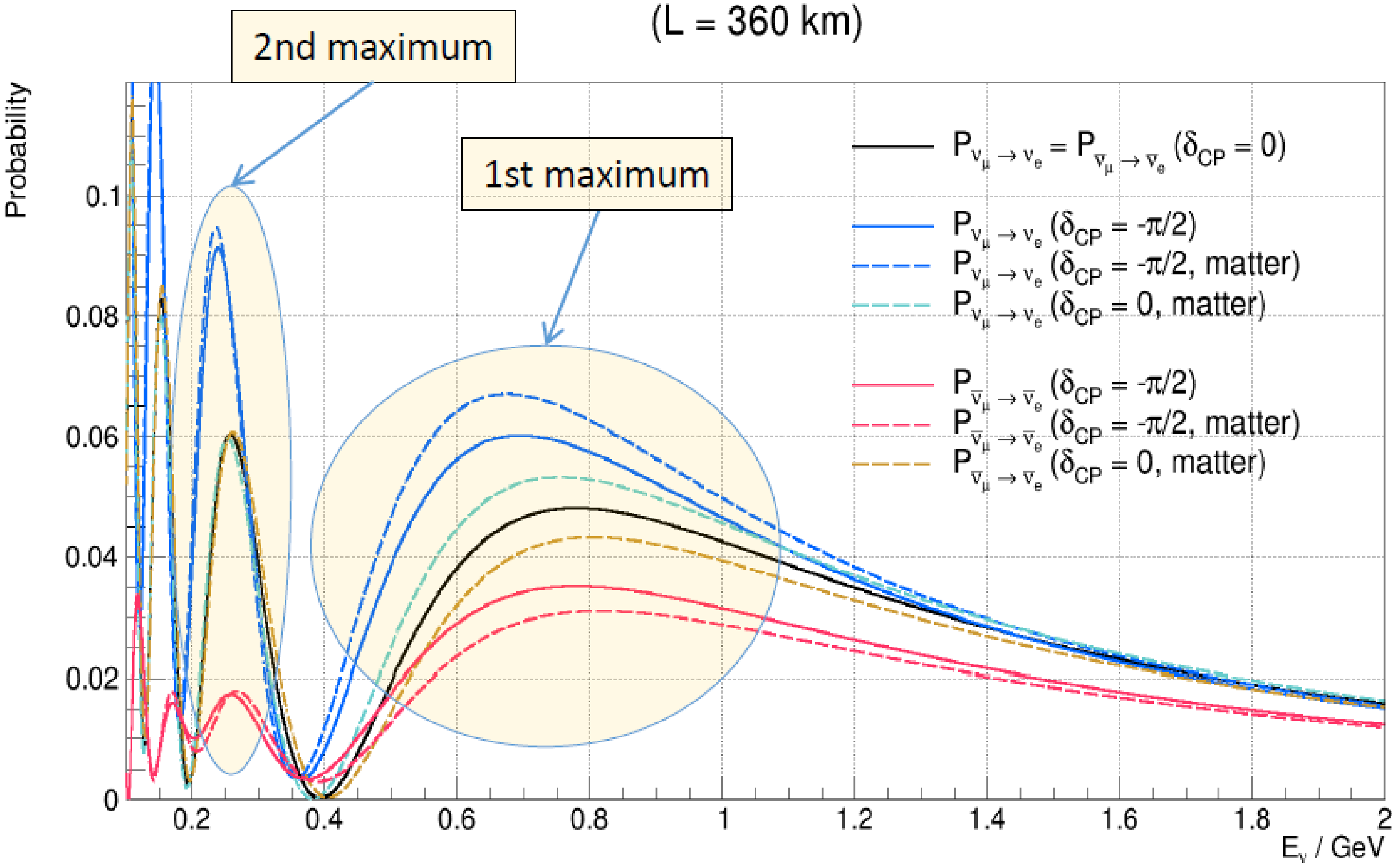


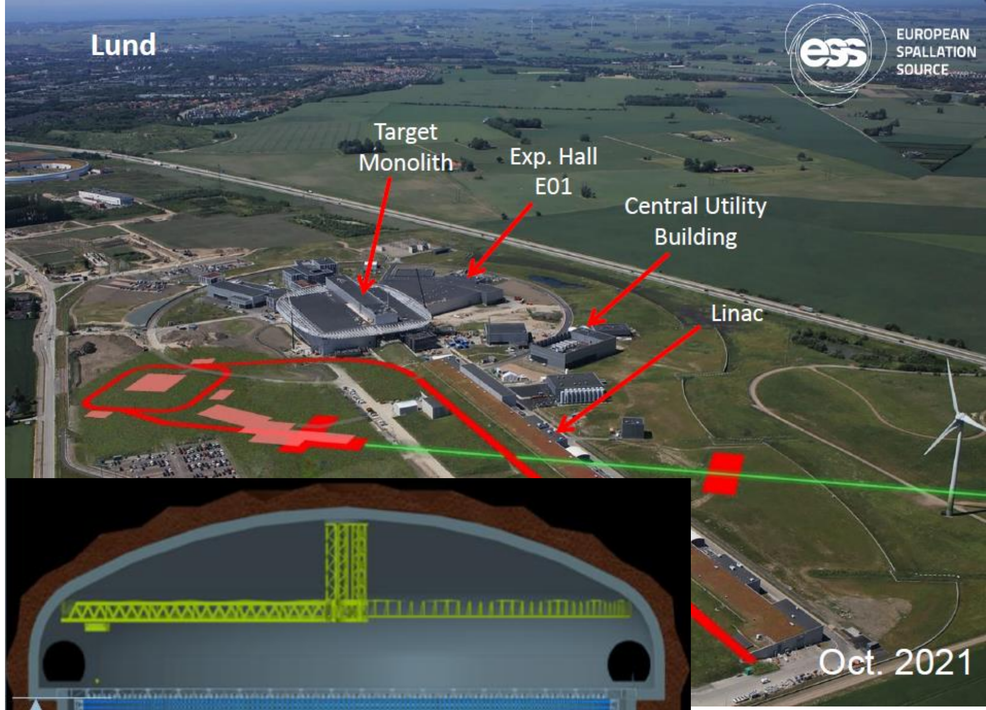


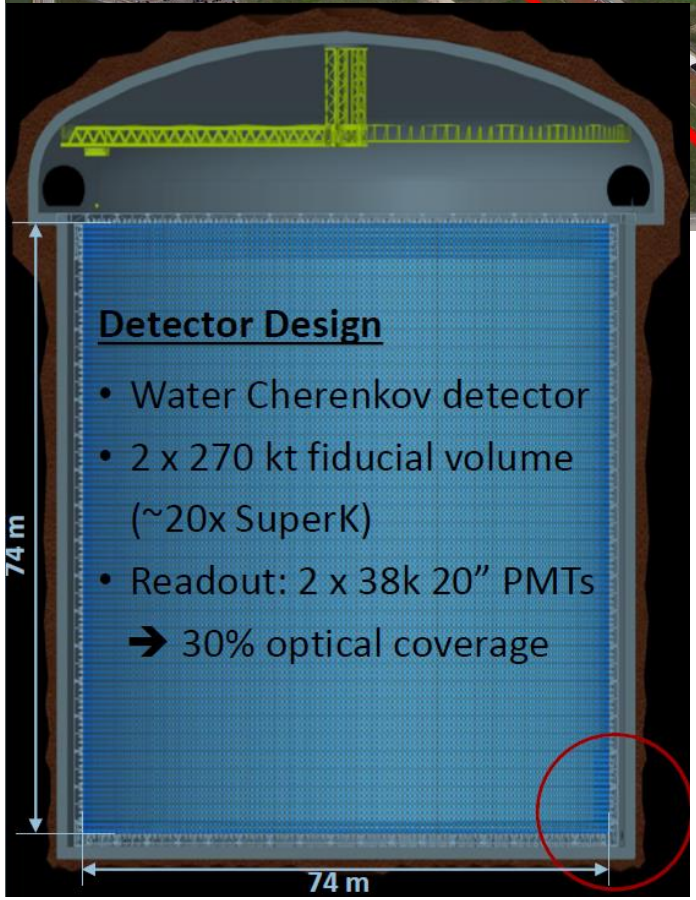
2nd osc. max. 1st osc. max.

build wideband beam to observe both

The European Spallation Source (ESS, under construction in Lund, Sweden) with ESSnuSB (ESS neutrino super beam) beam power: 5MW







7

Summary & Outlook

Global Fit on (almost) all experimental data

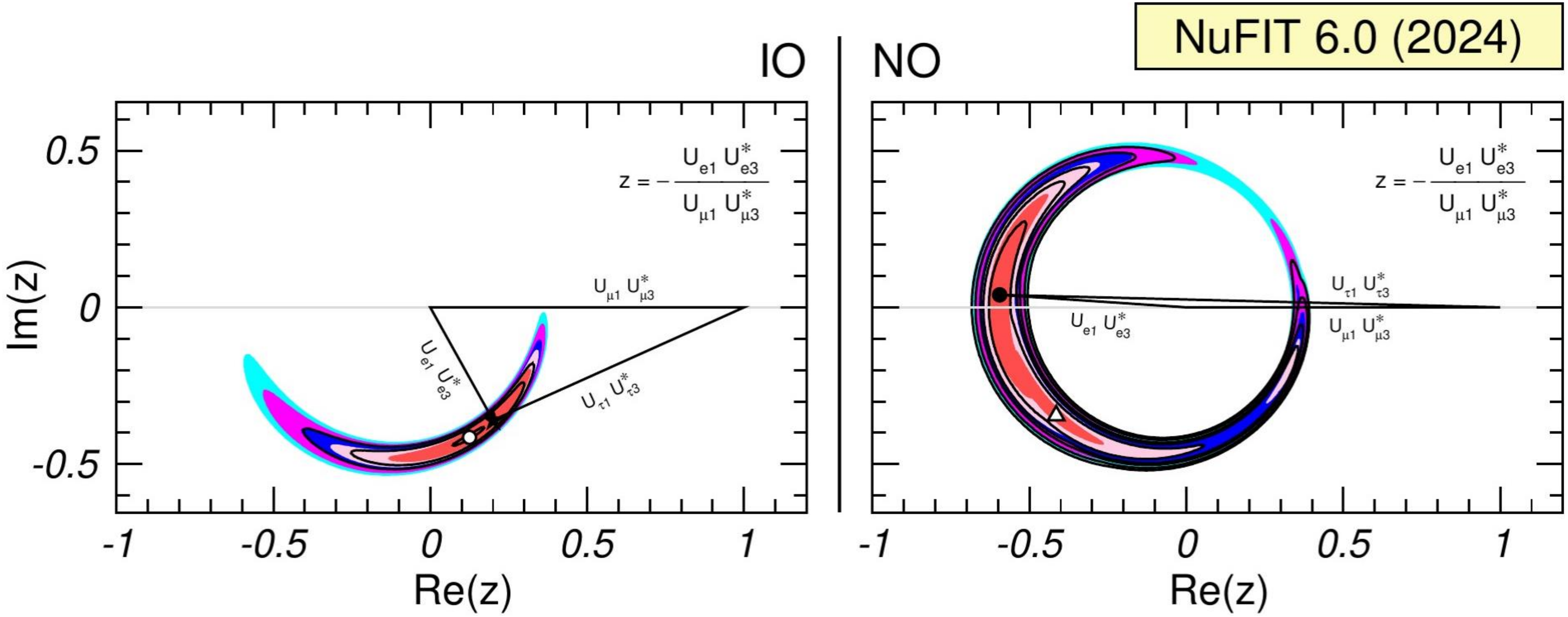
Here from: **www.nu-fit.org**

NuFIT 6.0 (2024)

IC24 with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

Precision Era: Unitary Triangle for Leptonic Sector



What can we learn from oscillation experiments?

- **What is the neurtino mass ordering?**
- **Is CP-symmetry violated?**

- **What is behind neutrino flavor structure?**
  - Why is the structure of lepton mixing so different from quark mixing?

Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

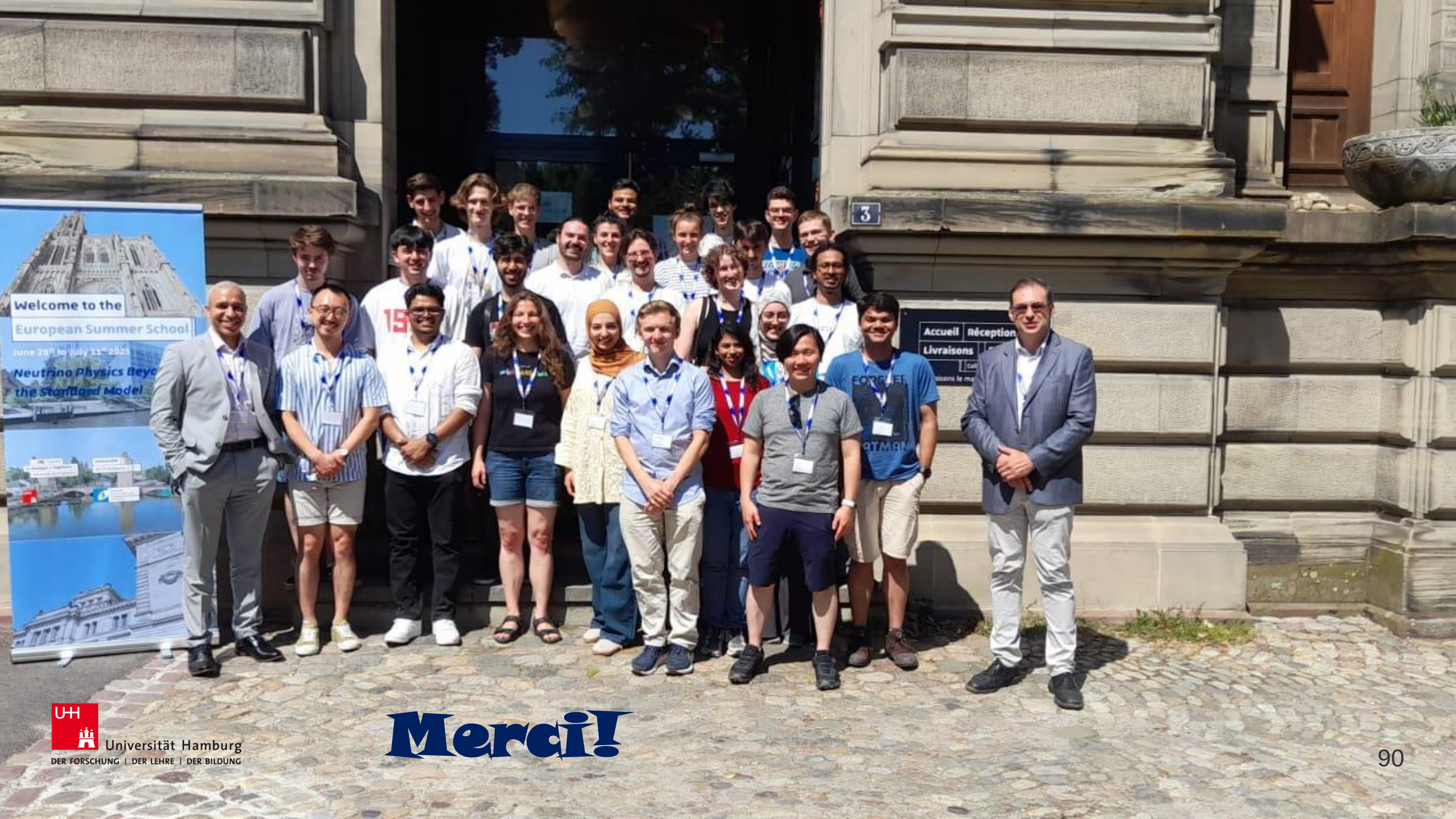
Quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

  - What flavor symmetry can produce this pattern of mixing and how is it broken?
  - Is $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric (octant)? If so, why – possible new symmetry?

- **Is the neutrino mixing matrix unitary?** Are there BSM effects impacting neutrino oscillation?

- **Precision measurements** allow model discrimination



Merci!

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