Neutrino Oscillation experiments
13th IDPASC School
Palermo 17-27/09/2024

Natalia Di Marco
GSSI & LNGS-INFN

Outline

Resources

- Fundamentals of neutrino physics and astrophysics, C. Giunti, C.W. Kim. Oxford University Press (2007)

- Introduction to Particle and Astroparticle Physics, A. De Angelis, M Pimenta. 2nd edition, Spriger (2018)

- PDG-neutrino reviews (https://pdg.lbl.gov/2024/reviews/contents_sports.html)

- From eV to EeV: Neutrino Cross Sections Across Energy Scales, J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012) https://arxiv.org/abs/1305.7513

A little (and incomplete) history

1895

Rontgen

Discovery of X-ray

1896-1900

Discovery of β,α, γ radioactivity

(**Marie e Pierre Curie** , **Becquerel, Rutherford**)

1897

Thomson

Discovery of electron

1900

Max Planck suggests that radiation manifests itself in discrete quantities

1905

Einstein: photoelectric effect explanation

1911-1913-1915

Atomic model from **Rutherford** and from **Bohr**

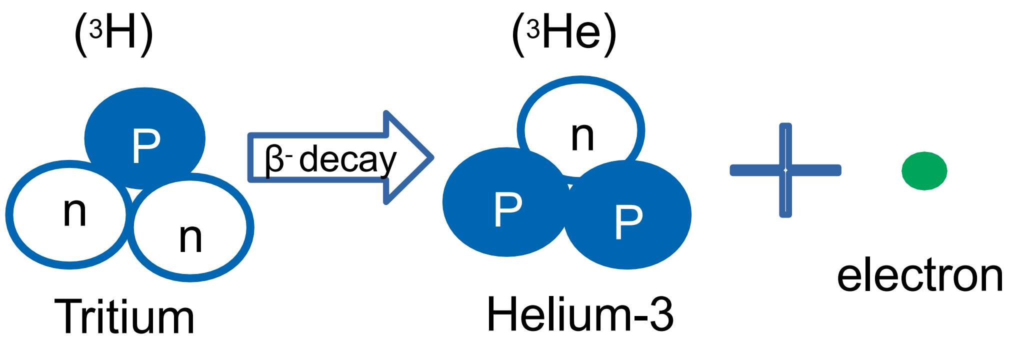
Einstein: General Relativity Theory

1928

Paul Dirac unify quantum mechanics and special relativity to describe the electron

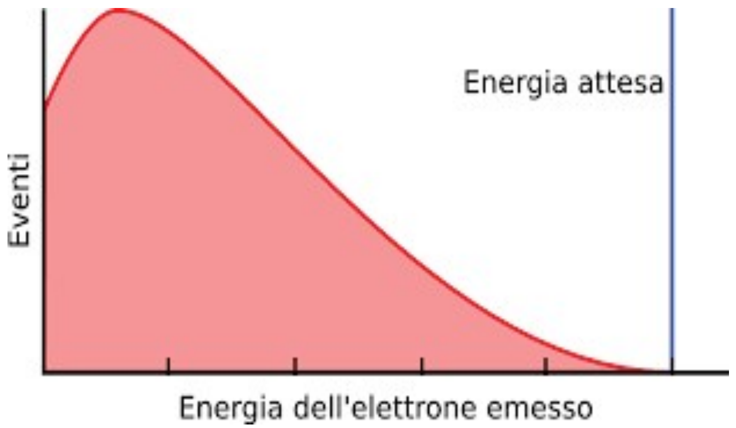
A little (and incomplete) history

$$\mathrm{e} + e^-$$



$$n \rightarrow \mathrm{p} + e^-$$

1914 Chadwick
1927 Ellis & Wooster



Conservations
- Electric charge (ok)
- Energy (?)
- Spin (?)

A little (and incomplete) history

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

A little (and incomplete) history

1932

Chadwick discover the neutron

1933

Fermi names Pauli's particle "neutrino" and in 1934 formulates the Fermi Theroy of β-decay

1934

Yukawa's theory of nuclear interaction (exchange of "meson" particles with mass of ~100 MeV)

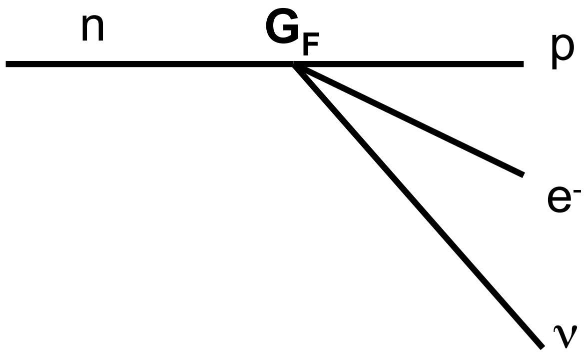
1937

(1947) Discovery of muon

1947

B. Pontecorvo proposes the universality of Fermi interactions. This is the born of the concept of "family"

Fermi's theory of β-decay



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

$$\Gamma_{fi} = \frac{2\pi}{\hbar} \left|\langle f|\mathcal{H}'|i\rangle\right|^2 \rho(E_f)$$

"... their mass can not be very much more than the electron mass. In order to distinguish them from heavy neutrons**, mister Fermi has proposed to name them "neutrinos"**. **It is possible that the proper mass of neutrinos be zero...** It seems to me plausible that neutrinos have a spin 1/2... **We know nothing about the interaction of neutrinos with the other particles of matter and with photons**."

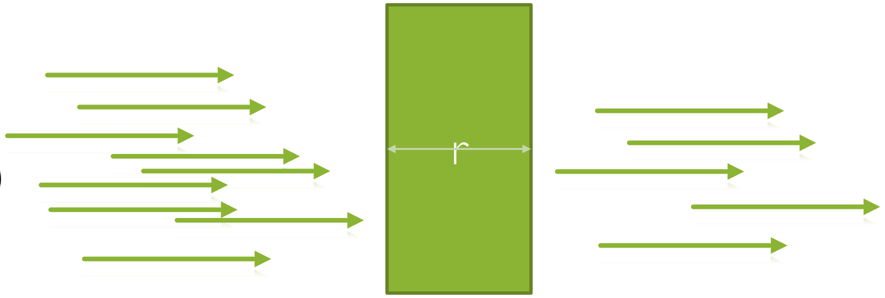
*W. Pauli (*International Solvay Conference, 1933)

Bethe-Peierls (1934): calculate the neutrino cross section using Fermi's theory:

$$\sigma \sim 10^{-44}\,\text{cm}^2, \quad E(\nu) = 2\,\text{MeV}$$

How to detect a neutrino

Φ_0



$$\Phi(r) = \Phi_0 e^{-r/\lambda}$$

$$\lambda = (n\sigma)^{-1} = \left(\rho \frac{\mathcal{N}_A}{\cancel{A}} \sigma = 1 \times \frac{6 \times 10^{23}}{18} 10^{-44}\right)^{-1}$$

$$\sim 10^{21}\,\mathrm{cm} \sim 1000\,\mathrm{ly}$$

"there is not practically possible way of detecting a neutrino"

Bethe and Peierls

"there is not practically possible way of detecting a neutrino"

Bethe and Peierls

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do..."

Wolfgang Ernst Pauli

"there is not practically possible way of detecting a neutrino"

Bethe and Peierls

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do..."

Wolfgang Ernst Pauli

1956: **Reines e Cowan...** discovery of the neutrino

How do you detect a particle impossible to be detected?

John Beacom @NOW 2018

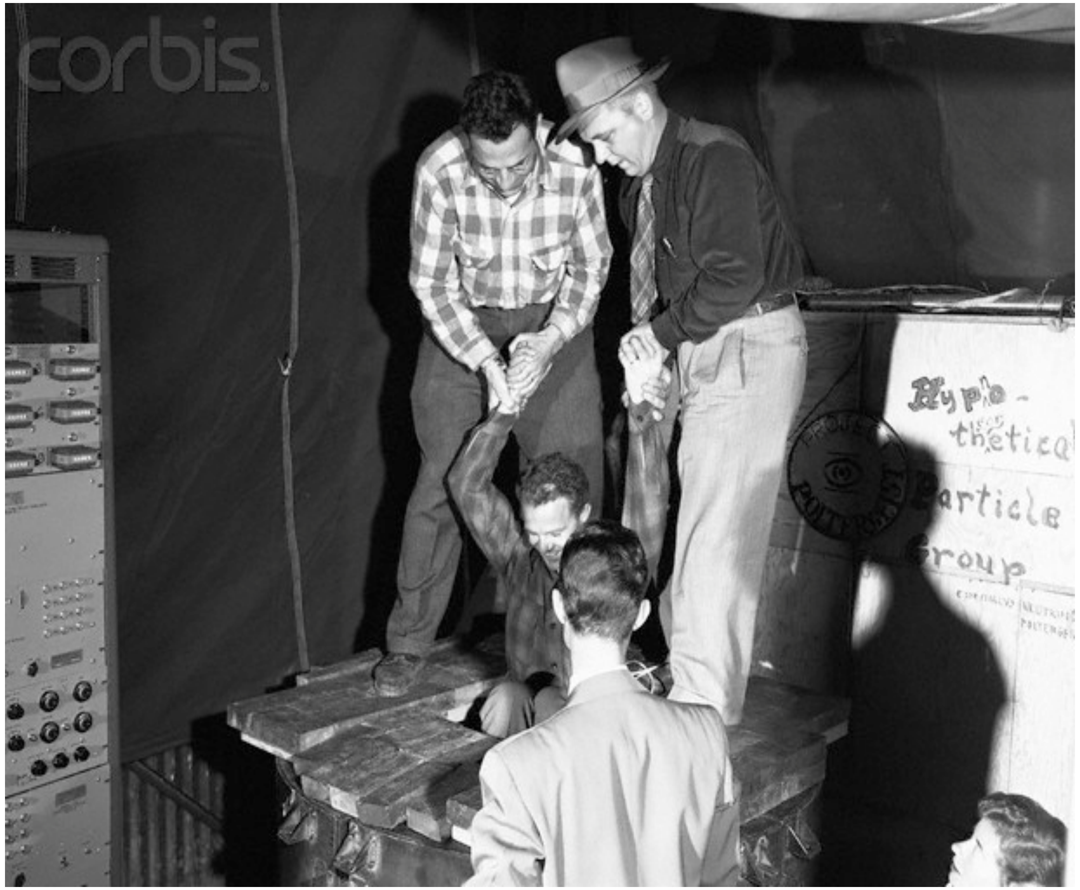
How do you detect a particle impossible to be detected?

John Beacom @NOW 2018

How do you detect a particle impossible to be detected?

John Beacom @NOW 2018

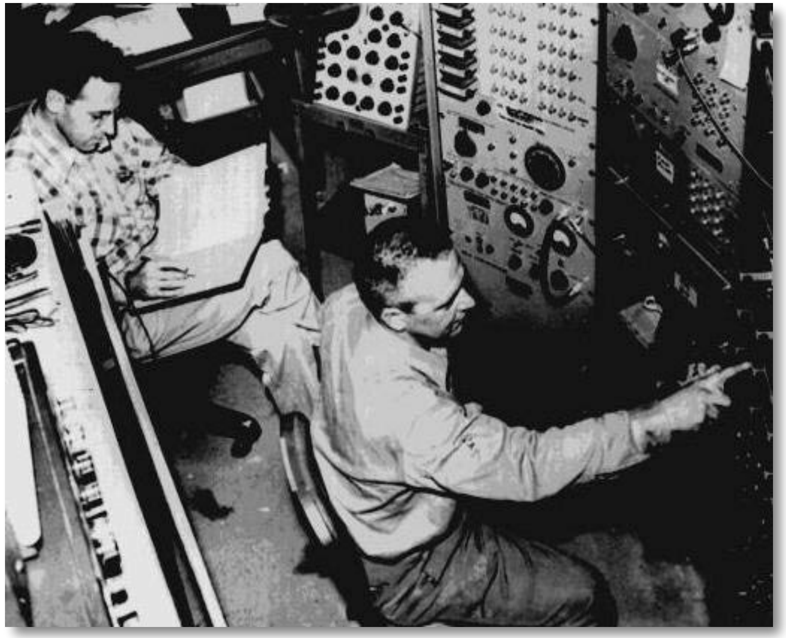
How do you detect a particle impossible to be detected?

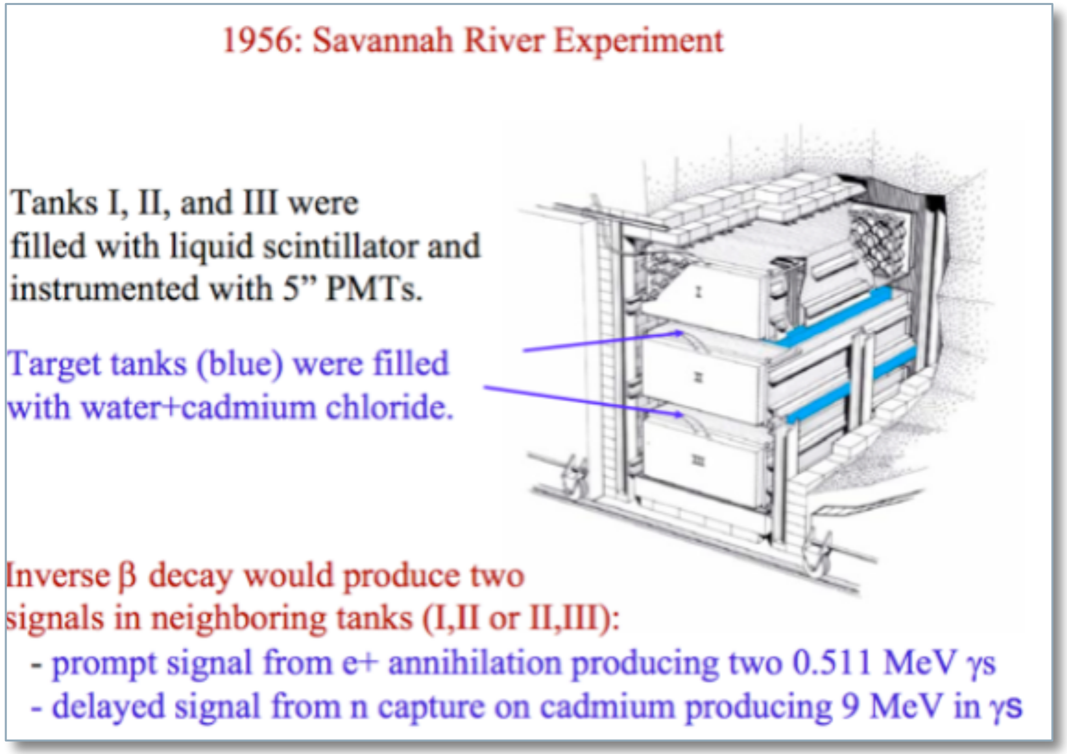


John Beacom @NOW 2018

Reines and Cowan experiment, 1956

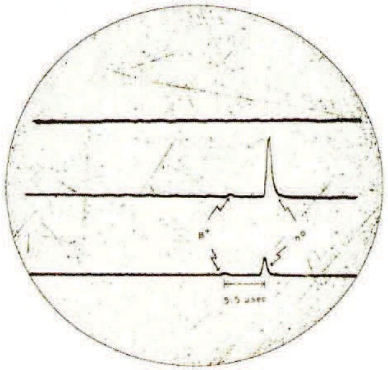
$$\bar{\nu} + p \rightarrow n + e^+$$

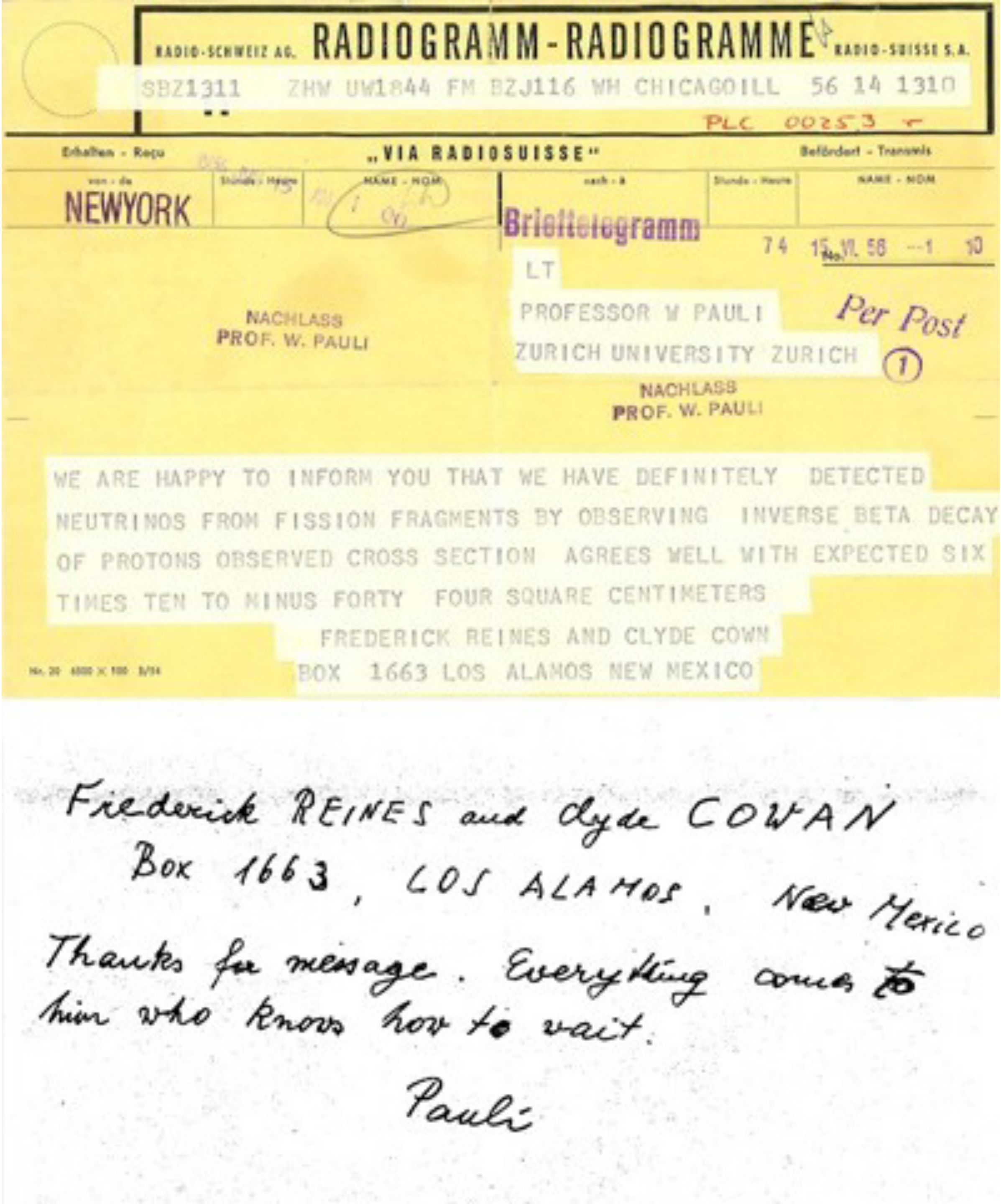




Delayed coincidence

$$(1)\; e^+ + e^- \rightarrow 2\gamma$$
$$(2)\; n + Cd \rightarrow Cd^*$$
$$Cd^* \rightarrow Cd + \gamma' s$$

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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

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

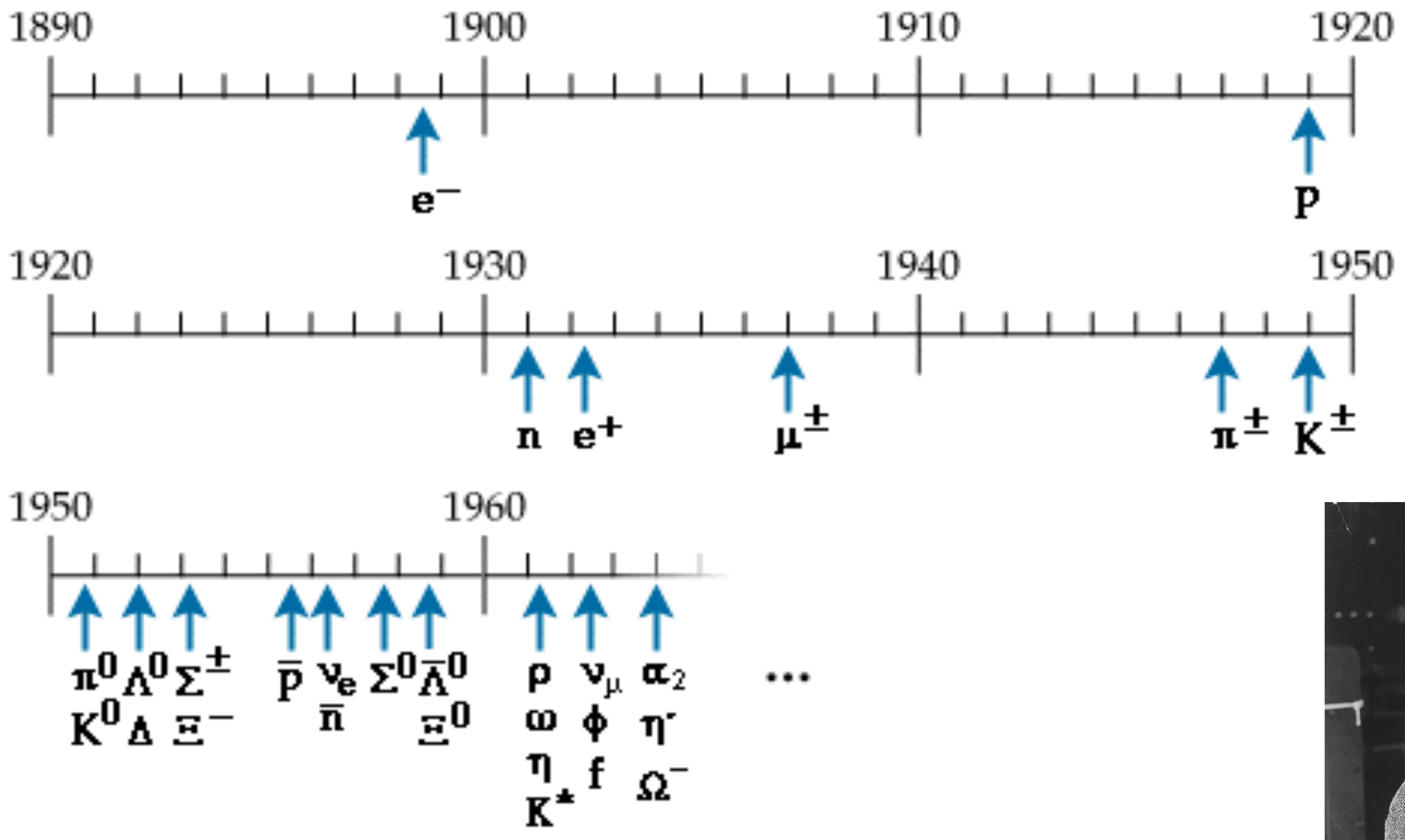
BOX 1663 LOS ALAMOS NEW MEXICO

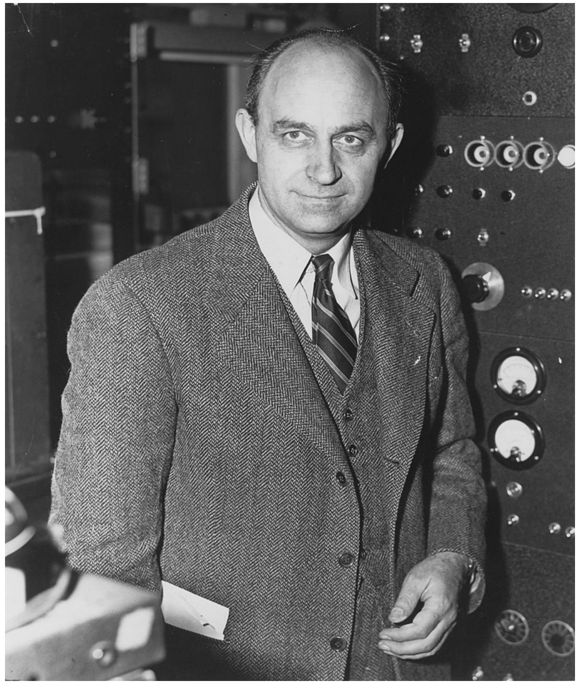
Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

More and more new particles!





"If I could remember the names of all these particles,
I would have been a botanist!"

E. Fermi

ν_μ discovery

Pontecorvo in 1957 proposes that the neutrino accompanying the μ it's different from that of the beta-decay

$$\nu_\mu + p \to n + \mu^-$$

$$\nu_\mu + p \not\to n + e^-$$

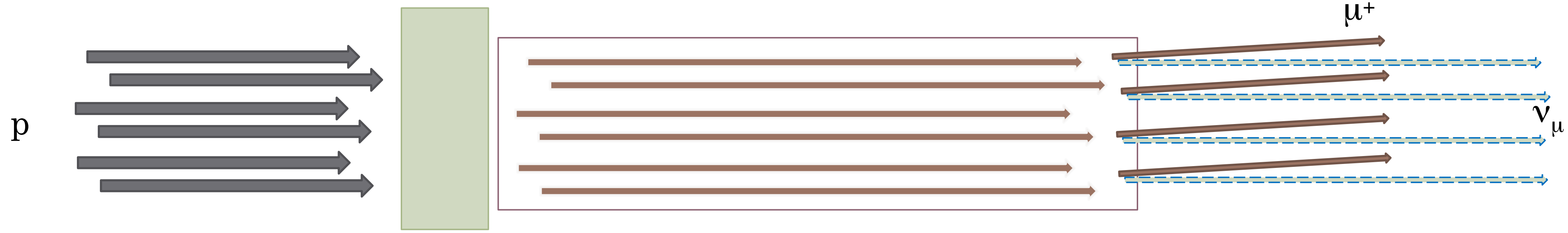
ν_μ discovery

Pontecorvo in 1957 proposes that the neutrino accompanying the μ it's different from that of the beta-decay

$$\nu_\mu + p \to n + \mu^-$$

~~$\nu_\mu + p \to n + e^-$~~

Pontecorvo proposes the use of a neutrino beam!



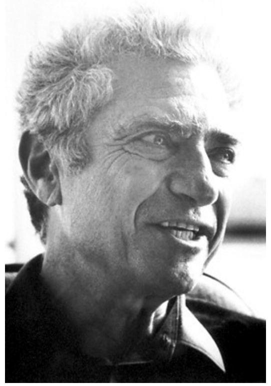
$\pi^+ \to \mu^+ + \nu_\mu$

$p + N \to \pi^+, K^+$

Discovery of ν_μ


Lederman


Schwartz

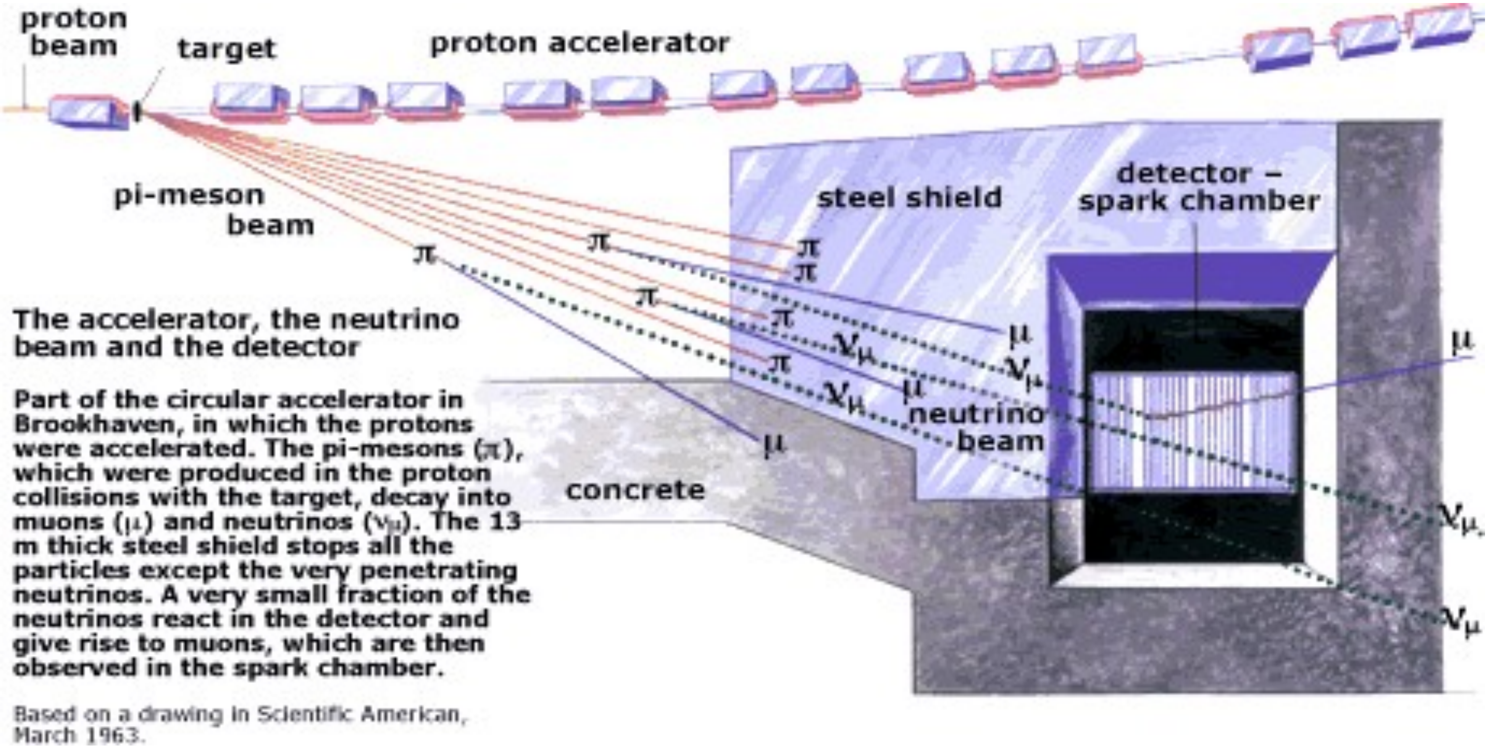

Steinberger

1962
@Brookhaven National Laboratory

Nobel Prize in 1988

$$p + N \rightarrow \pi^+, K^+$$

$$\hookrightarrow \mu^+ + \nu_\mu$$



A little (and incomplete) history

1967
Glashow-Weinberg-Salam Standard Model (SM) + Higgs mechanism (1964)

1973
Discovery of neutral currents Gargamelle exp.@CERN

1974
J/ψ ($c\bar{c}$) discovery

1976
Dsicovery of τ lepton (M. Perl)
(m_τ= 3500 m_e)

1977
Bottom quark discovery

1983
Discovery of $W^\pm$ and Z^0 bosons

1990
LEP: only 3 ν generations

1995
Top quark discovery

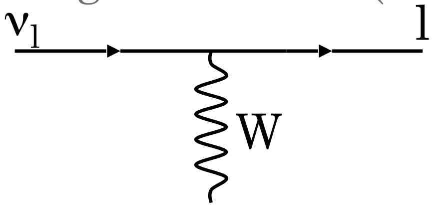
2000
ν_τ discovery

2012
Higgs boson discovery

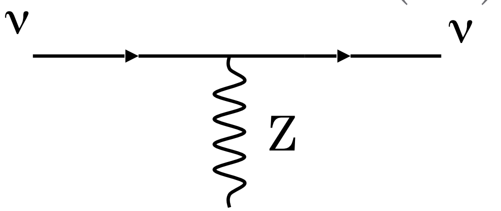
Neutrinos in the SM

Neutrinos are **neutral, massless** fermions. They interact with quarks and leptons via weak interactions. Only **left-handed neutrinos** or **right-handed anti-neutrinos** exist.

Charged currents (CC)



Neutral currents (NC)



Lepton Number (L) = 1 for e^-, μ^-, τ^-, ν_e, ν_μ, ν_τ

L = -1 for antiparticles

Lepton Number (L) is conserved.

Family lepton numbers (L_α) are conserved.

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

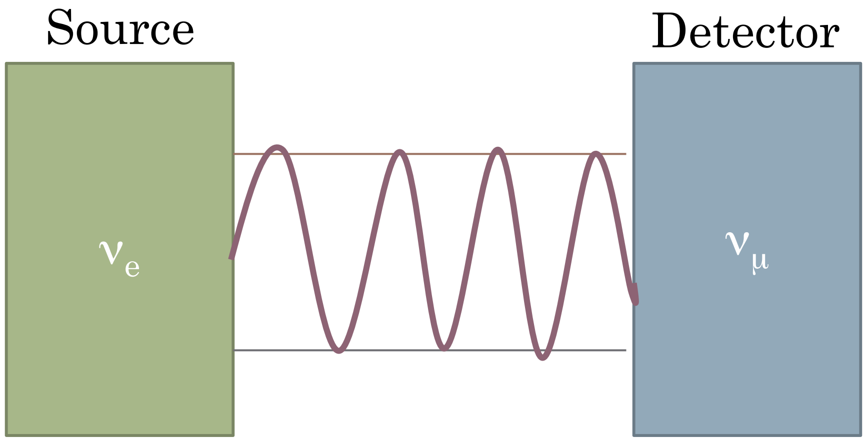
~~$\nu_\mu + p \rightarrow n + e^-$~~

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

~~$\mu \rightarrow e + \gamma$~~

Nevertheless…

1957 Pontecorvo's hypothesis of netrino oscillation:

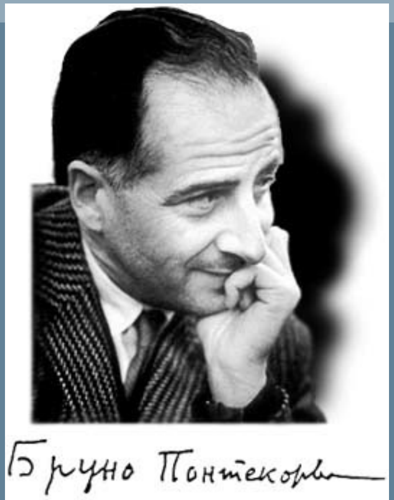


Oscillation are possible only if flavor eigenstates (ν_α, α=e,μ,τ) do not coincide with mass eigenstates (ν_j, j=1,2…n) and if the neutrino mass is not null.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} x \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_l\rangle = \sum_j U^*_{lj} |\nu_{jL}\rangle \qquad l = e, \mu, \tau$$

Pontecorvo-Maki-Nakagawa-Sakata matrix



“Although what is written above is at best extremely rough and at worst entirely wrong..."

A little (and incomplete) history

...of neutrino oscillation theory

1962 **Maki**, **Nakagawa**, and **Sakata** considered for the first time a model with the mixing of different neutrino flavors

1967 **Pontecorvo** predicted the Solar Neutrino Problem as a consequence of $\nu_e \to \nu_\mu$ (or $\nu_e \to \nu_{sterile}$) transitions **even before the first measurement of the solar electron neutrino flux in the Homestake experiment**

1967 Pioneering solar neutrino experiment by **Davis** and collaborators at Homestake using 615 ton of tetrachlorethylene and measuring 2/3 of νs expected from the Sun

1969 Gribov and Pontecorvo discussed solar neutrino oscillations due to neutrino mixing

The standard theory of neutrino oscillations in the plane-wave approximation was developed in **1975–76** by:

- Eliezer and Swift [S. Eliezer and A. R. Swift, Nucl. Phys., B105, 45, 1976]
- Fritzsch and Minkowski [H. Fritzsch and P. Minkowski, Phys. Lett., B62, 72, 1976],
- Bilenky and Pontecorvo [S. M. Bilenky and B. Pontecorvo, Sov. J. Nucl. Phys., 24, 316–319, 1976, S. M. Bilenky and B. Pontecorvo, Nuovo Cim. Lett., 17, 569, 1976]
- and elegantly reviewed by Bilenky and Pontecorvo in 1978 [S. M. Bilenky and B. Pontecorvo, Phys. Rep., 41, 225, 1978]

(Nobel) Prize game

- **1988 Lederman, Schwartz and Steinberger** awarded the Physics Nobel Prize for the **discovery of the muon neutrino**.
- **1995 Frederick Reines** and Martin Perl share the Physics Nobel Prize for **discovery of electron neutrinos** (and observation of supernove neutrinos) and the tau lepton, respectively.
- **2002 Masatoshi Koshiba and Raymond Davis** win Nobel Prize for **measuring solar neutrinos** (as well as supernova neutrinos).
- **2015 Arthur McDonald, Takaaki Kajita** for the discovery of neutrino oscillations, which shows **that neutrinos have mass**

So neutrinos are massive and mixed.
But in the SM this is not the case…

Neutrino oscillations

Credits: Fundamentals of neutrino physics and astrophysics, C. Giunti, C.W. Kim. Oxford University Press (2007)

Neutrinos ν_α with flavor $\alpha = e, \mu, \tau$ are produced in charged-current (CC) weak interaction processes from a charged lepton ℓ_α^- (i.e. $\ell_\alpha^- \to \nu_\alpha$ transitions) or together with a charged antilepton ℓ_α^+ (i.e. creation of a ℓ_α^+, ν_α pair)

$$\mathscr{L}_{\mathrm{I,L}}^{(\mathrm{CC})} = -\frac{g}{2\sqrt{2}} \left(j^{\rho}_{W,\mathrm{L}} W_\rho + j^{\rho\dagger}_{W,\mathrm{L}} W^{\dagger}_{\rho} \right)$$

Charged-current leptonic interaction Lagrangian

$$j^{\rho}_{W,\mathrm{L}} = 2 \sum_{\alpha=e,\mu,\tau} \overline{\nu_{\alpha L}}\, \gamma^\rho\, \ell_{\alpha L} = 2 \sum_{\alpha=e,\mu,\tau} \sum_k U^*_{\alpha k}\, \overline{\nu_{kL}}\, \gamma^\rho\, \ell_{\alpha L}$$

Leptonic charged current

valid both in the case of Dirac or Majorana massive neutrinos

Neutrino oscillations

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$$

Flavor state

Decomposition in terms of the massive neutrino contribution

- The number of active flavor neutrinos is three
- The number of massive neutrinos must be $\geq$ 3.
- If the number of massive neutrinos is greater than three, the additional neutrinos in the flavor basis are **sterile**, i.e. they do not participate in weak interactions (i.e. sterile neutrinos interact with ordinary matter only through gravitational interactions or exotic interactions beyond those in the SM)
- Transitions of active flavor neutrinos into sterile ones can be observed only through the **disappearance** of active neutrinos

Neutrino oscillations

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$$

Flavor state

$$\mathscr{H} |\nu_k\rangle = E_k |\nu_k\rangle$$

$$E_k = \sqrt{\vec{p}^2 + m_k^2}$$

Hamiltonian eigenvalues

$$i \frac{\mathrm{d}}{\mathrm{d}t} |\nu_k(t)\rangle = \mathscr{H} |\nu_k(t)\rangle$$

Schrödinger equation

$$|\nu_k(t)\rangle = e^{-iE_k t} |\nu_k\rangle$$

neutrino states evolve in time as plane waves

Neutrino oscillations

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k}\, e^{-iE_k t}\, |\nu_k\rangle$$ Flavor state

$$U^\dagger U = \mathbf{1} \quad \Longleftrightarrow \quad \sum_\alpha U^*_{\alpha k}\, U_{\alpha j} = \delta_{jk} \qquad |\nu_k\rangle = \sum_\alpha U_{\alpha k}\, |\nu_\alpha\rangle$$

$$|\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} \left(\sum_k U^*_{\alpha k}\, e^{-iE_k t}\, U_{\beta k} \right) |\nu_\beta\rangle$$

The superposition of massive neutrino states $|\nu_\alpha(t)>$, which is the pure flavor state given t = 0, becomes a superposition of different flavor states at t > 0

$$A_{\nu_\alpha\to\nu_\beta}(t) \equiv \langle \nu_\beta | \nu_\alpha(t) \rangle = \sum_k U^*_{\alpha k}\, U_{\beta k}\, e^{-iE_k t}$$ Amplitude of $\nu_\alpha \to \nu_\beta$ transitions vs time

$$P_{\nu_\alpha\to\nu_\beta}(t) = \left| A_{\nu_\alpha\to\nu_\beta}(t) \right|^2 = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, e^{-i(E_k - E_j)t}$$ Transition probability

Neutrino oscillations

For ultrarelativistic neutrinos

$$E_k \simeq E + \frac{m_k^2}{2E} \,.$$

$$\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$$

$$E = |\vec{p}|$$

$$E_k - E_j \simeq \frac{\Delta m_{kj}^2}{2E}$$

Therefore, assuming also t = L, the transition probability can be approximated by:

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^* \, \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right) \qquad [1]$$

Amplitude of ν oscillations — Phase of ν oscillations

Note: the quartic products do not depend on the specific parameterization of the mixing matrix and on the choice of phases. In fact, the quartic products in eqn (1) are invariant under the rephasing transformation $U_{\alpha k} \to e^{i\psi_\alpha} \, U_{\alpha k} \, e^{i\phi_k}$

Neutrino oscillations

Mixing matrix parametrization:
3 angles (ϑ_{12}, ϑ_{23}, ϑ_{13}), 1 CP-violating phase (δ_{13}), 2 Majorana CP-violating phases ($\lambda_{2,3}$)

$$U = U^{\mathrm{D}}\, D^{\mathrm{M}}$$

$$U^{\mathrm{D}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$D^{\mathrm{M}} = \mathrm{diag}\left(e^{i\lambda_1}, e^{i\lambda_2}, e^{i\lambda_3}\right), \quad \text{with} \quad \lambda_1 = 0$$

$c_{ab} = \cos\vartheta_{ab}$

$s_{ab} = \sin\vartheta_{ab}$

$0 \le \vartheta_{ab} \le \pi/2$

$0 \le \delta_{13} \le 2\pi$

$$U_{\alpha k} = U^{\mathrm{D}}_{\alpha k}\, e^{i\lambda_k}$$

NOTE: Majorana phases **cannot be measured** in neutrino oscillation experiments. Neutrino oscillations are independent of the Majorana phases, which are always factorized in a diagonal matrix on the right of the mixing matrix. In particular, CP and T violations in neutrino oscillations depend only on the Dirac phases.

Neutrino oscillations

$\alpha \neq \beta$ Transition probability

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{k>j} \Re\mathfrak{e}\left[U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}\right]\, \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

$$+ 2\sum_{k>j} \Im\mathfrak{m}\left[U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}\right]\, \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$$

$\alpha = \beta$ Survival probability

$$P_{\nu_\alpha \to \nu_\alpha}(L,E) = 1 - 4\sum_{k>j} |U_{\alpha k}|^2\, |U_{\alpha j}|^2\, \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

Neutrino oscillations

Antineutrino case

$\alpha \neq \beta$ Transition probability

$$P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \Re\mathfrak{e}\left[U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

$$- 2 \sum_{k>j} \Im\mathfrak{m}\left[U_{\alpha k}^{*}\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^{*}\right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$$

Neutrino oscillations

Physical neutrinos and antineutrinos are **related by a CP transformation** which interchanges neutrinos with antineutrinos and reverses the helicity (in the case of Majorana neutrinos, where the C transformation coincides with the identity, it is conventional to call neutrinos the states with negative helicity and antineutrinos the states with positive helicity)

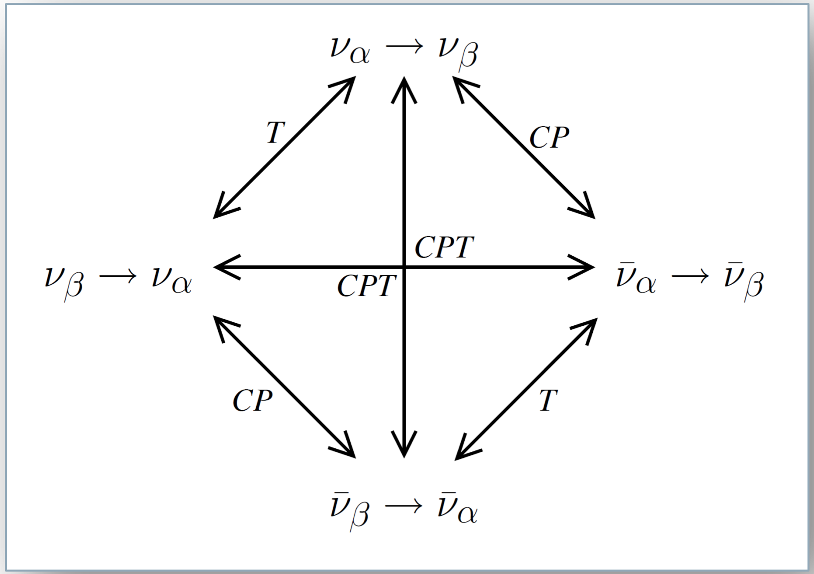
$$\nu_\alpha \xleftrightarrow{\text{CP}} \bar{\nu}_\alpha$$

A T transformation interchanges the initial and final states:

$$\nu_\alpha \to \nu_\beta \xleftrightarrow{\text{T}} \nu_\beta \to \nu_\alpha$$

CPT transformation:

$$\nu_\alpha \to \nu_\beta \xleftrightarrow{\text{CPT}} \bar{\nu}_\beta \to \bar{\nu}_\alpha$$



Neutrino oscillations

The oscillation probabilities of neutrinos and antineutrinos ***differ only in the sign*** of the terms depending on the imaginary parts of the quartic products of the elements of the mixing matrix. Thus, only these terms contribute to the CP asymmetry, leading to

$$A^{\mathrm{CP}}_{\alpha\beta}(L,E) = 4\sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

CP asymmetry can be measured ***only in the transitions between different flavors***, since, for $\alpha = \beta$, the imaginary parts in the above equation vanish.

If CPT is a symmetry of nature, the violation of CP symmetry implies the violation of T symmetry. In neutrino oscillation experiments it is possible to observe T violations by measuring the T asymmetries of neutrinos and antineutrinos

$$A^{\mathrm{T}}_{\alpha\beta} = P_{\nu_\alpha \to \nu_\beta} - P_{\nu_\beta \to \nu_\alpha}$$
$$\bar{A}^{\mathrm{T}}_{\alpha\beta} = P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} - P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$$

$$A^{\mathrm{T}}_{\alpha\beta} = -\bar{A}^{\mathrm{T}}_{\alpha\beta} = A^{\mathrm{CP}}_{\alpha\beta}$$

Measuring a CP asymmetry is equivalent to measuring a T asymmetry

Neutrino oscillations

Two-neutrino mixing

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2 2\vartheta \, \sin^2\left(1.27\,\frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

$$= \sin^2 2\vartheta \, \sin^2\left(1.27\,\frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

$$L^{\mathrm{osc}} = 2.47\,\frac{E\,[\mathrm{MeV}]}{\Delta m^2\,[\mathrm{eV}^2]}\,\mathrm{m} = 2.47\,\frac{E\,[\mathrm{GeV}]}{\Delta m^2\,[\mathrm{eV}^2]}\,\mathrm{km}$$

Neutrino Oscillation Experiments

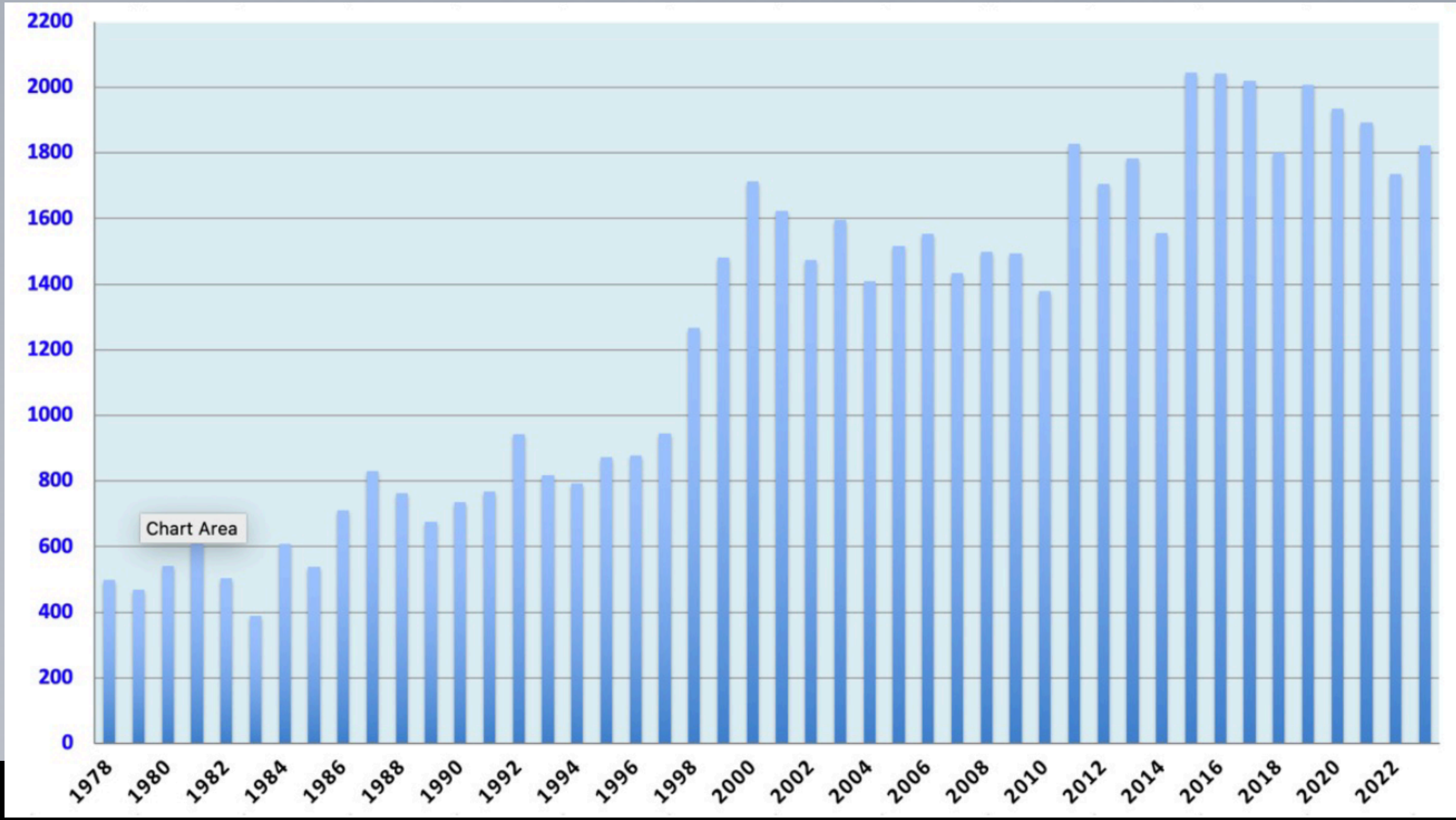
- Appearance
- Disappearance

- Sensitivity: since the value of Δm^2 is fixed by nature, different experiments can be designed in order to be sensitive to different values of Δm_2, by choosing appropriate values of the ratio L/E.

$$\frac{\Delta m^2 L}{2E} \sim 1$$

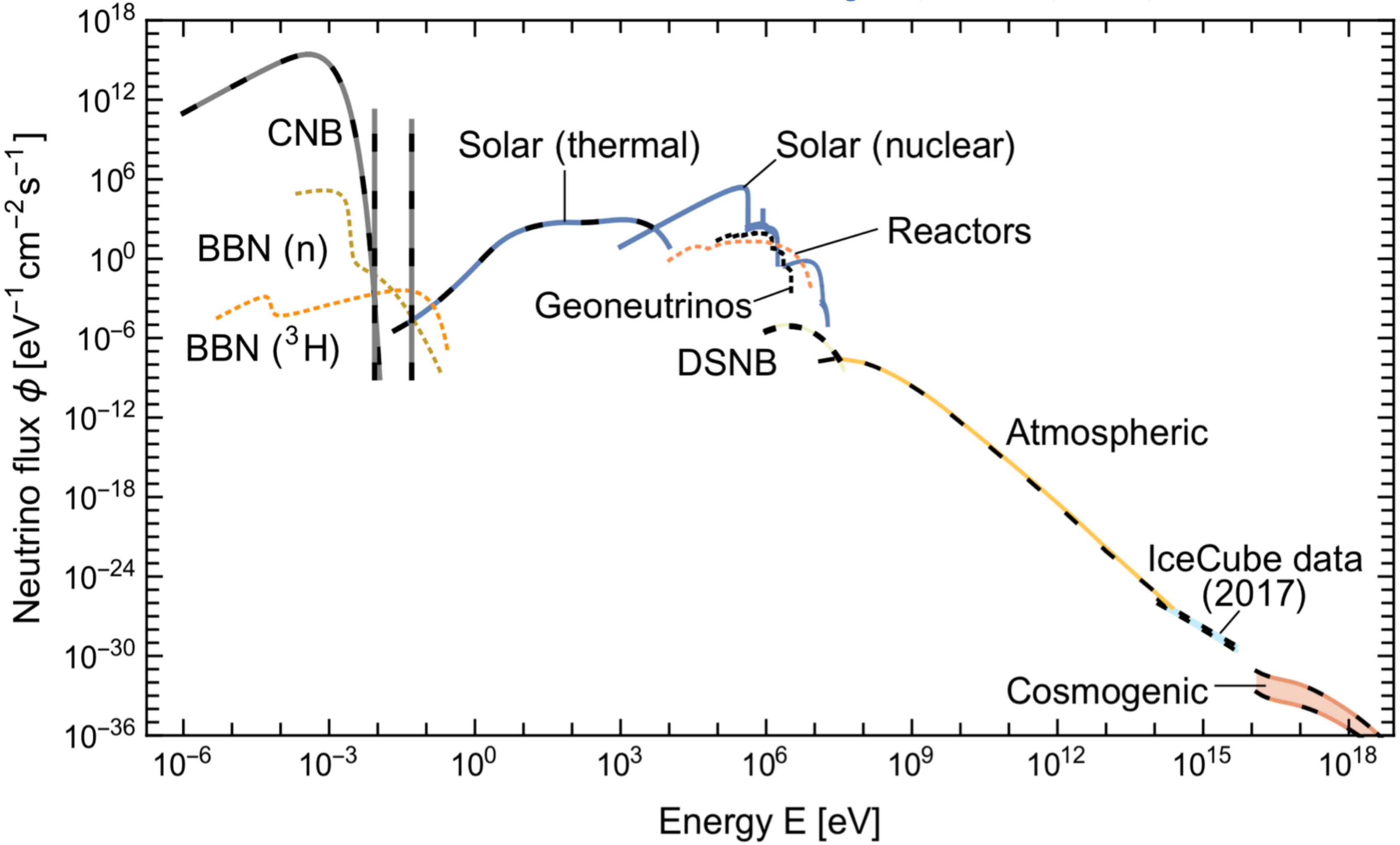
Type of experiment	L	E	Δm^2 sensitivity
Reactor SBL	$\sim 10\,\text{m}$	$\sim 1\,\text{MeV}$	$\sim 0.1\,\text{eV}^2$
Accelerator SBL (Pion DIF)	$\sim 1\,\text{km}$	$\gtrsim 1\,\text{GeV}$	$\gtrsim 1\,\text{eV}^2$
Accelerator SBL (Muon DAR)	$\sim 10\,\text{m}$	$\sim 10\,\text{MeV}$	$\sim 1\,\text{eV}^2$
Accelerator SBL (Beam Dump)	$\sim 1\,\text{km}$	$\sim 10^2\,\text{GeV}$	$\sim 10^2\,\text{eV}^2$
Reactor LBL	$\sim 1\,\text{km}$	$\sim 1\,\text{MeV}$	$\sim 10^{-3}\,\text{eV}^2$
Accelerator LBL	$\sim 10^3\,\text{km}$	$\gtrsim 1\,\text{GeV}$	$\gtrsim 10^{-3}\,\text{eV}^2$
ATM	20–$10^4\,\text{km}$	0.5–$10^2\,\text{GeV}$	$\sim 10^{-4}\,\text{eV}^2$
Reactor VLB	$\sim 10^2\,\text{km}$	$\sim 1\,\text{MeV}$	$\sim 10^{-5}\,\text{eV}^2$
Accelerator VLB	$\sim 10^4\,\text{km}$	$\gtrsim 1\,\text{GeV}$	$\gtrsim 10^{-4}\,\text{eV}^2$
SOL	$\sim 10^{11}\,\text{km}$	0.2–$15\,\text{MeV}$	$\sim 10^{-12}\,\text{eV}^2$

N. of #neutrino# papers in the last 45 years (1978-2023) from inSPIRE



Neutrino oscillations

Vitagliano, Tamborra, Raffelt, arXiv: 1910.11878



Neutrino oscillations

Mixing matrix parametrization:
3 angles (ϑ_{12}, ϑ_{23}, ϑ_{13}), 1 CP-violating phase (δ_{13})

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ab} = \cos\vartheta_{ab}$

$s_{ab} = \sin\vartheta_{ab}$

$0 \leq \vartheta_{ab} \leq \pi/2$

$0 \leq \delta_{13} \leq 2\pi$

Atmo ν, LBL accelator ν

SBL reactor ν

Solar ν, LBL reactor ν

Type of experiment	L	E	Δm^2 sensitivity
Reactor SBL	$\sim 10\,\mathrm{m}$	$\sim 1\,\mathrm{MeV}$	$\sim 0.1\,\mathrm{eV}^2$
Accelerator SBL (Pion DIF)	$\sim 1\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 1\,\mathrm{eV}^2$
Accelerator SBL (Muon DAR)	$\sim 10\,\mathrm{m}$	$\sim 10\,\mathrm{MeV}$	$\sim 1\,\mathrm{eV}^2$
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Reactor LBL	$\sim 1\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-3}\,\mathrm{eV}^2$
Accelerator LBL	$\sim 10^3\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-3}\,\mathrm{eV}^2$
ATM	20–$10^4\,\mathrm{km}$	0.5–$10^2\,\mathrm{GeV}$	$\sim 10^{-4}\,\mathrm{eV}^2$
Reactor VLB	$\sim 10^2\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-5}\,\mathrm{eV}^2$
Accelerator VLB	$\sim 10^4\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-4}\,\mathrm{eV}^2$
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Outline

Introduction

Solar ν

Atmospheric ν

Accelerator ν

Reactor ν

Future oscillation experiment

Thermonuclear energy production

Thermonuclear reactions release energy because the total mass of a nucleus is less than the total mass of the constituent nucleons

$$m(A,Z) = Zm_p + (A - Z)m_n - B(A,Z) \ ,$$

→ *Binding energy*

The Sun is powered by the two groups of thermonuclear reactions known as the **pp chain** and the **CNO cycle**, the result of both is the conversion of 4 protons and 2 electrons into a ^{4}He nucleus plus two electron neutrinos

$$4p + 2e^- \rightarrow 4He + 2\,\nu_e + Q$$

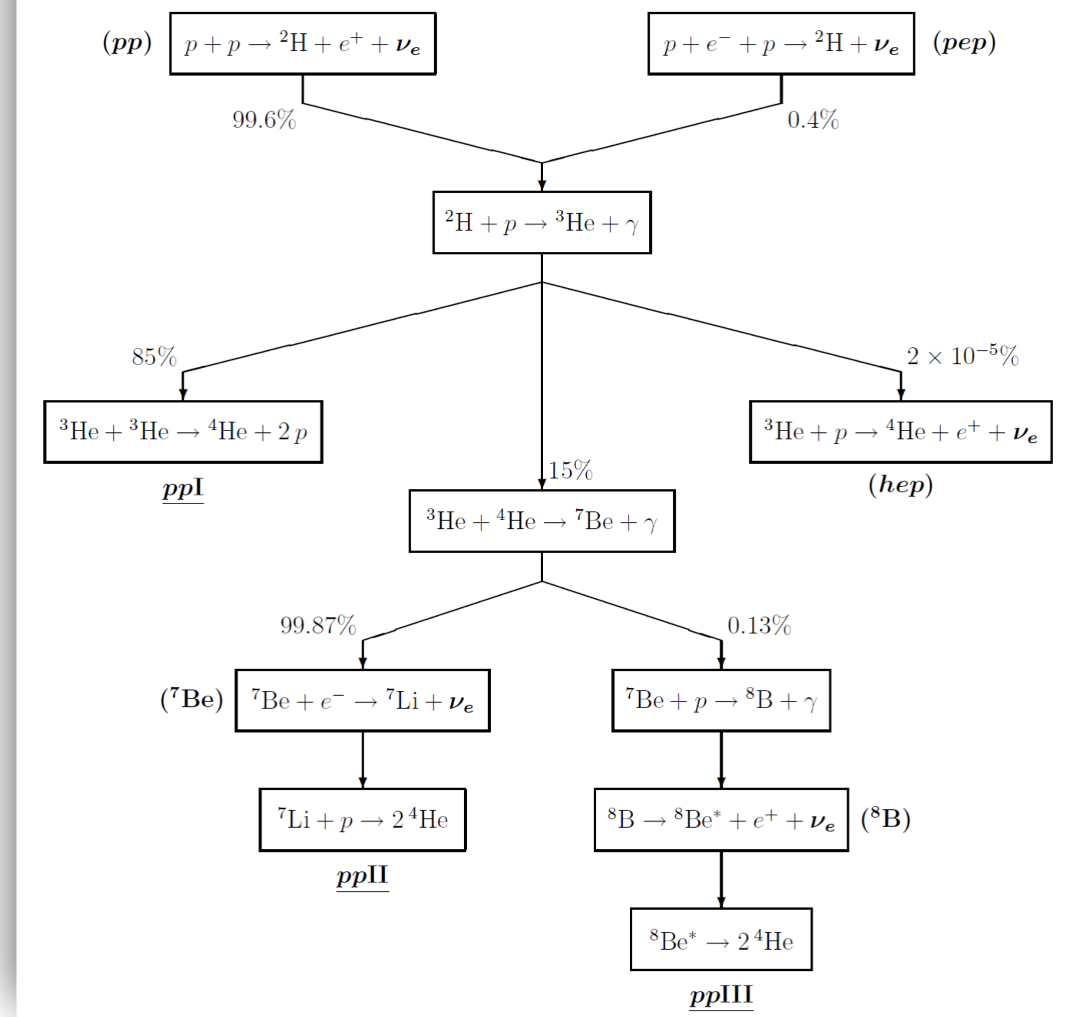
→ *Q-value*

$$Q = 4mp + 2me - m_{4He} = B(4, 2) + 2me - 2\,(mn - m_p) = 26.731 MeV$$

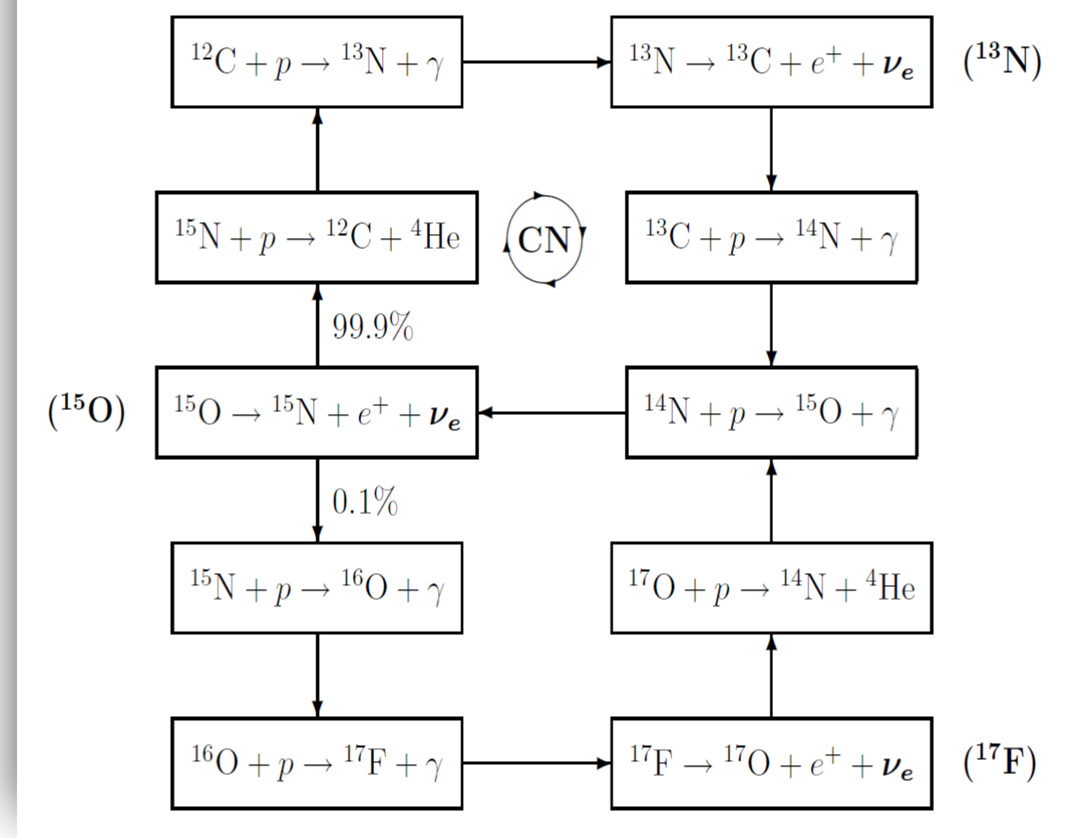
This energy is released in the form of **photons** or **kinetic energy** of the **neutrinos**

Thermonuclear energy production

pp – cycle



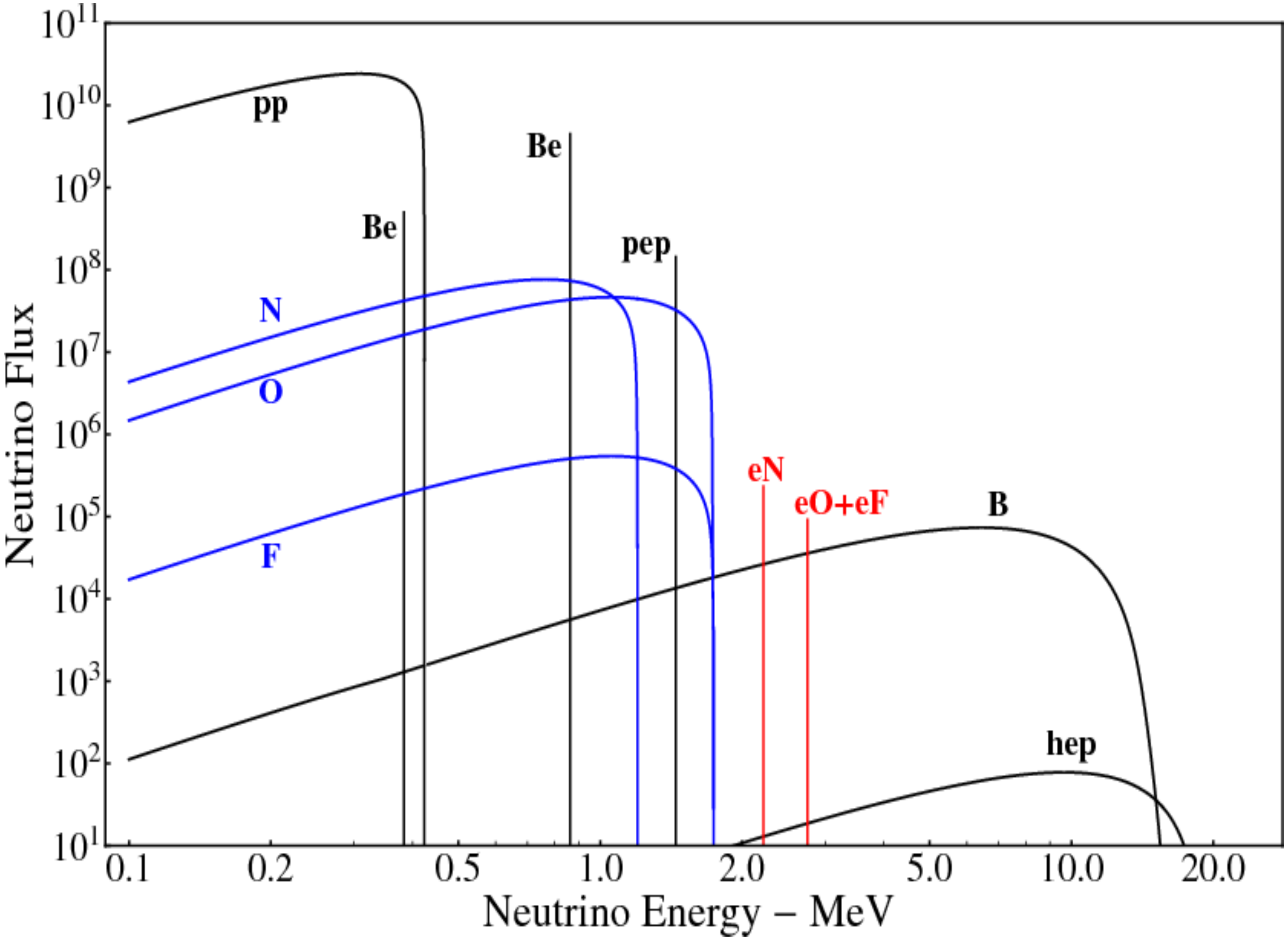
CNO



The **pp chain** is responsible for about 99% of the total energy (and neutrino) production.

C, N and O nuclei are used as catalysts for hydrogen fusion. CNO is responsible for about 1% of the total neutrino (and energy) budget.

Solar Neutrino Fluxes



Solar Neutrino Fluxes

Neutrinos

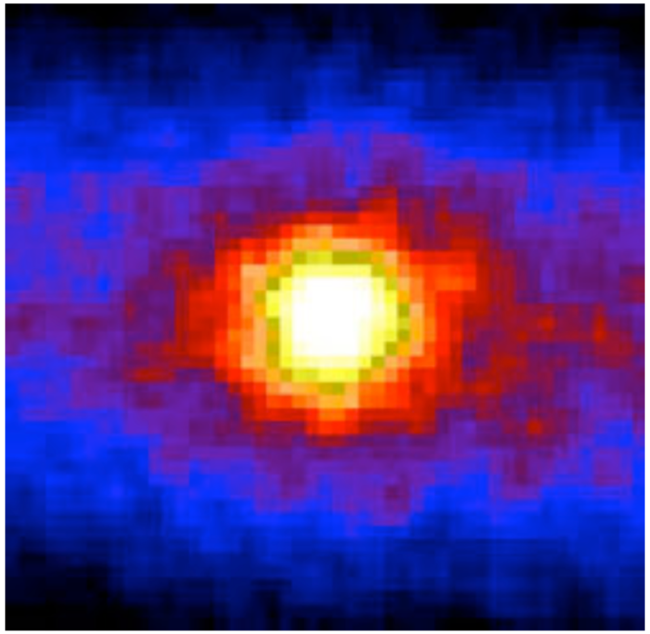
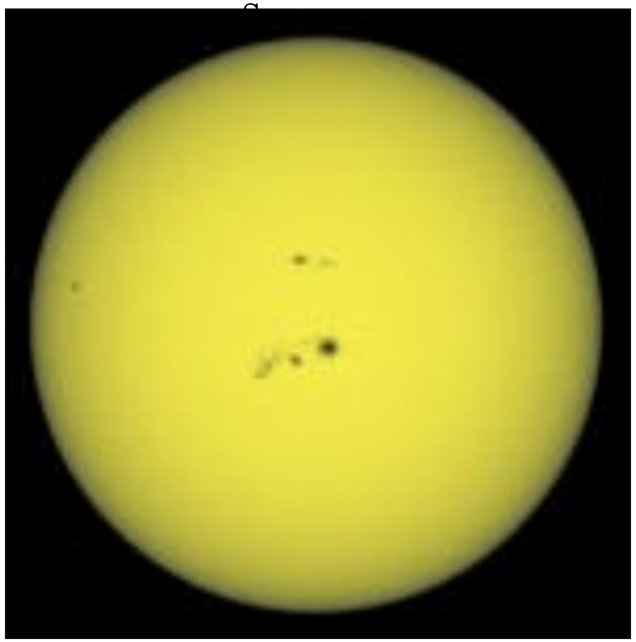


Image credits: Super-Kamiokande Coll.

Photon



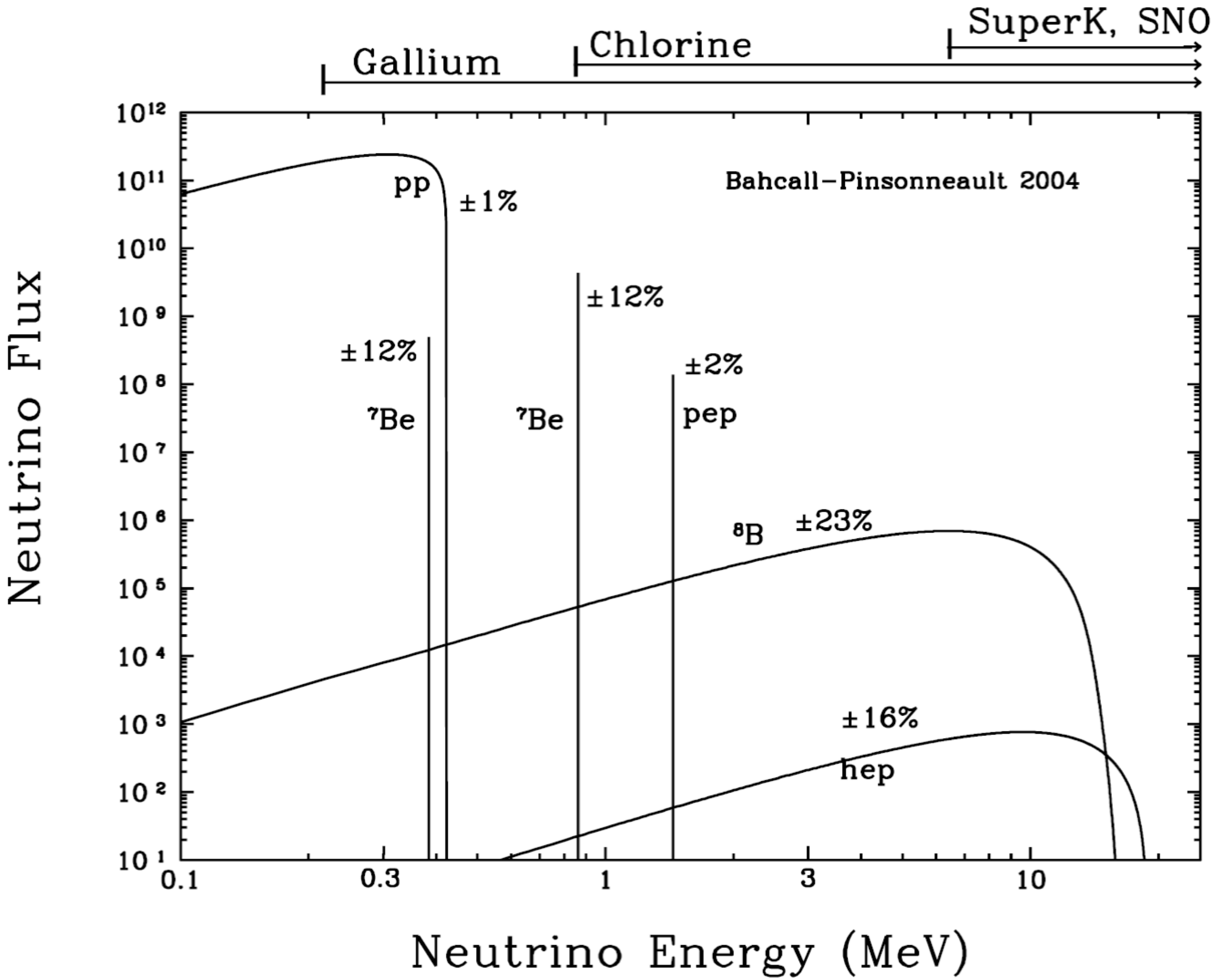
Neutrinos escape the Sun in about 2 seconds, whereas thermal energy takes more than 10^4 years to reach the surface:

8 minutes to reach the earth → direct information on the energy producing region.

Brief historical overview

- 1970, **Homestake** experiment, first solar neutrino experiment (taking data for 24 yr)
- Late 1980s, **Kamiokande** experiment obtained the first real-time neutrino image of the Sun
- 1990 **GALLEX/GNO** and **SAGE** experiments measure the low energy neutrinos produced in the fundamental pp.
- Late 1990s, **Super-Kamiokande** and **SNO** experiments provide important high-precision data on the high-energy part of the solar neutrino flux
- 2007 – 2020 **Borexino** era

Solar Neutrino Experiments



Homestake experiment

WHERE
Radiochemical experiment@Homestake Solar Neutrino Observatory
1478m below the surface in the Homestake Gold Mine at Lead, South Dakota, USA
[*] 4200 m.w.e. → 4 $\mu/m^2/d$, $\langle E_\mu \rangle = 300$ GeV

DETECTOR
consists of a single horizontal steel tank 6.1 m in diameter and 14.6 m long (a volume of 6×10^5 liters), containing 2.16×10^{30} atoms of ^{37}Cl (133 ton) in the form of 615 ton of tetrachloroethylene (C_2Cl_4, solvent used in laundries).

PROCESS

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

Pontecorvo-Alvarez inverse β-decay

(threshold 814 keV)
^8B neutrinos

HOW it works
Argon in the tank is extracted through chemical methods and the radioactive ^{37}Ar is counted using miniature **proportional counters** which detect the Auger electron produced in the electron-capture of the ^{37}Ar nuclei with a lifetime of about 35 days

(Main) **BACKGROUND**:

This [*] cosmic ray flux generates an ^{37}Ar production background of 0.047 ± 0.013 atoms/day

GALLEX/GNO

WHERE

Radiochemical experiment@LNGS
1400 m of rocks under Gran Sasso mountain
3500 m.w.e. → 1 $\mu/m^2/h$, $<E_\mu>=270$ GeV

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

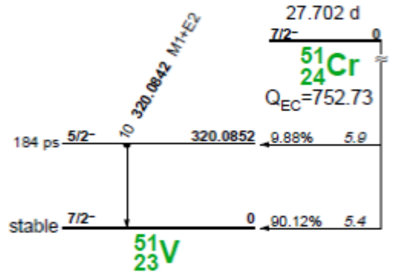
(threshold 233 keV)
All neutrinos

DETECTOR

101 ton of a liquid gallium chloride ($GaCl_3$-HCl) solution containing 30.3 ton of gallium.
GALLEX from May 1991 to January 1997
Gallium Neutrino Observatory (**GNO**) from May 1998 to April 2003 (with the same detector and an improved extraction equipment)

CALIBRATION

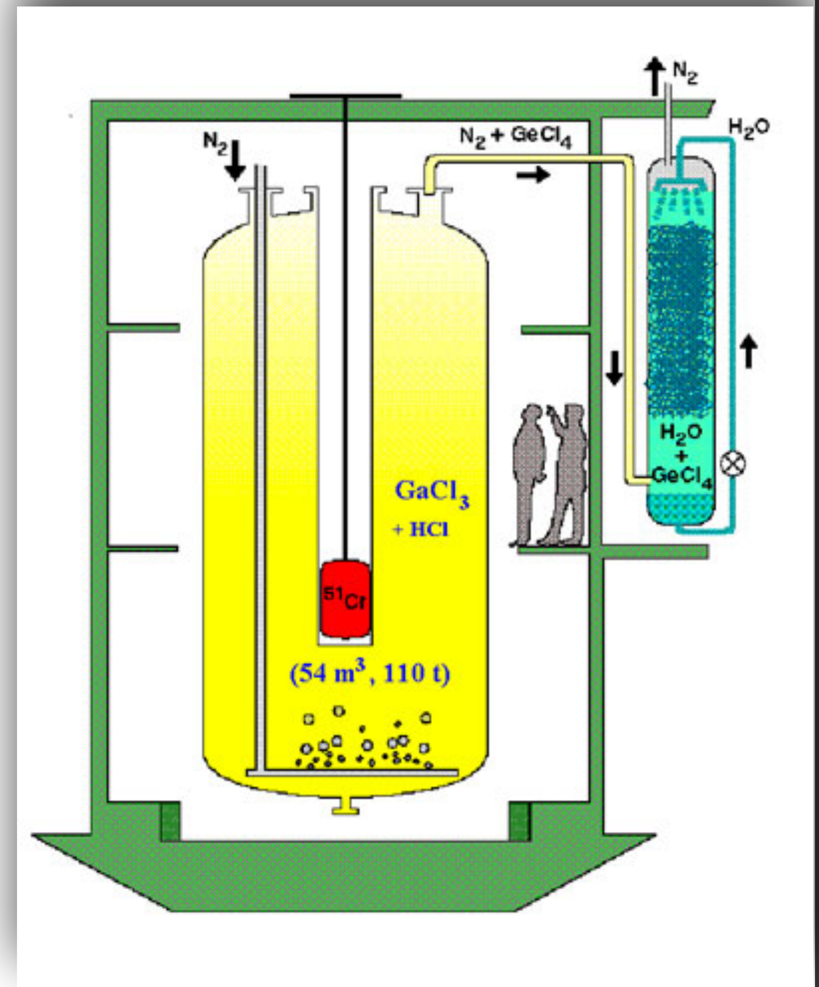
^{51}Cr neutrino source



$$e^- + {}^{51}Cr \rightarrow {}^{71}V + \nu_e$$

$$R^{GALLEX}_{^{71}Ga}\,({}^{51}Cr) = 0.93 \pm 0.08$$

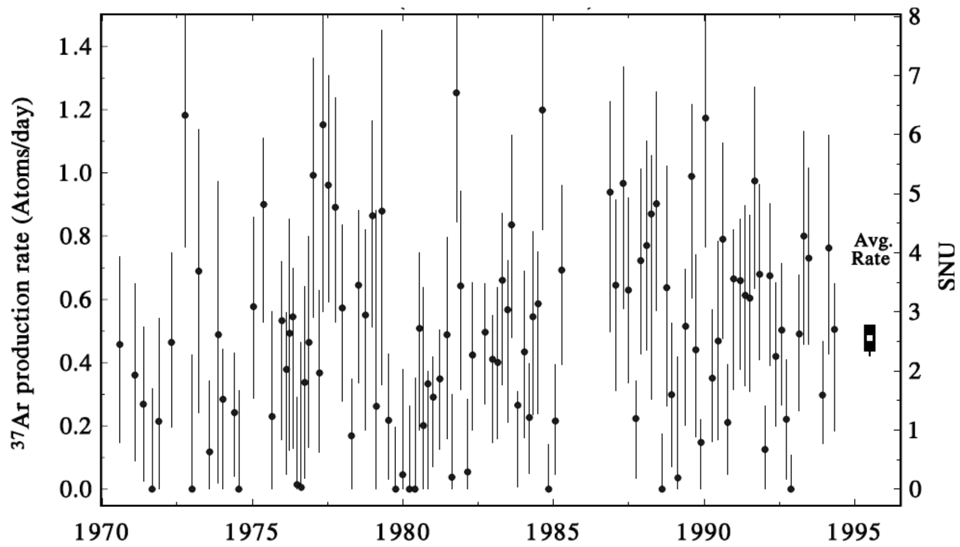
ratio of the measured and predicted neutrino capture rates



^{71}**Ge recovery efficiency** has been tested by adding to the gallium solution known amounts of ^{71}As, decaying throght EC,β+ into^{71}Ge with a half-life of 65.28 days

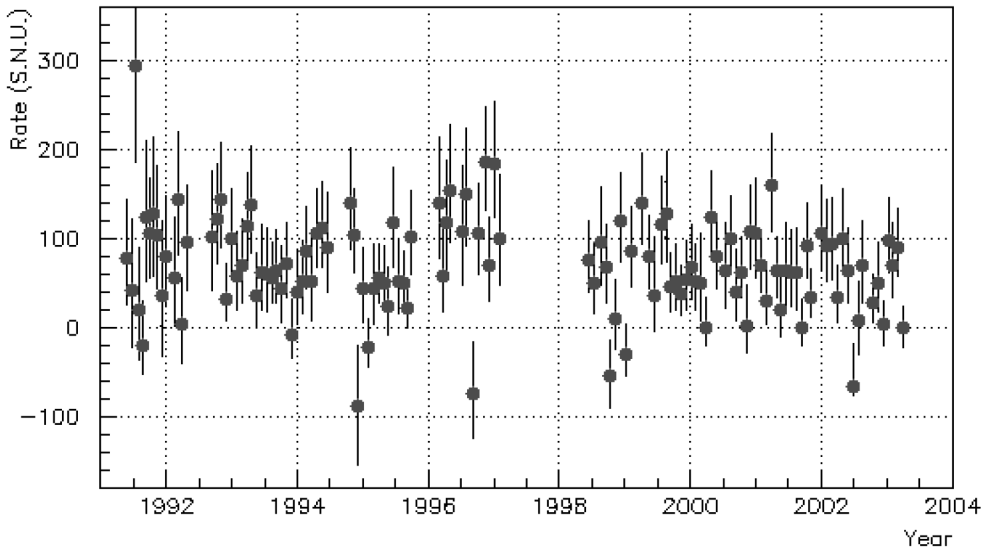
$$\varepsilon_{recovery}\ 0.998 \pm 0.008$$

Radiochemical experiment results



$$R^{exp}_{^{37}Cl} = 2.56 \pm 0.16 \pm 0.16 \text{ SNU} = 2.56 \pm 0.23 \text{ SNU}$$

The solar neutrino rate measured in the Homestake experiment is about **one third of that predicted by the SSM**, with a discrepancy of more than 3σ



$$R^{GALLEX/GNO}_{^{71}Ga} = 69.3 \pm 4.1 \pm 3.6 \text{ SNU} = 69.3 \pm 5.5 \text{ SNU}$$

half of that predicted by the SSM, with a discrepancy of more than 5σ

Super-Kamiokande

WHERE (MAP)
Kamioka Mine, Japan, 500 m from the KAMIOKANDE site (now site of KamLAND)

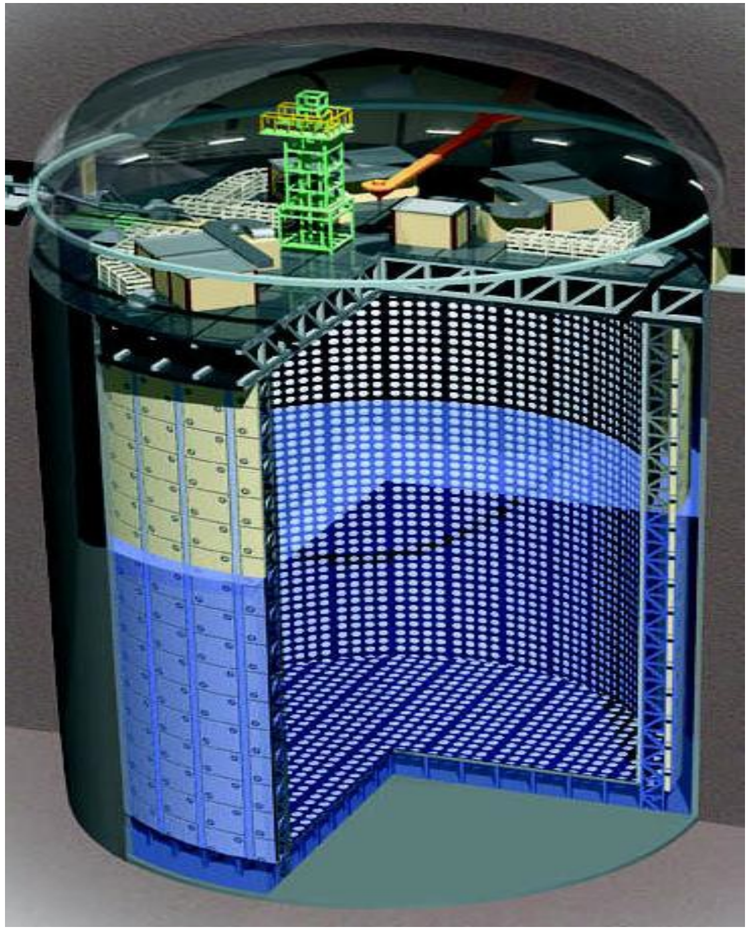
$$\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

DETECTOR
50 kton of ultra-pure water, 22,5 kton fiducial mass

Two concentric, optically separated, water Cherenkov detectors contained in a cylindrical steel tank with a diameter of 39.3 m and a height of 42 m.

Inner detector: diameter=33.8 m, height=36.2 m. 11129 large (50 cm diameter PMTs), 40% coverage
Outer detector: 1885 PMTs (20 cm diameter PMTs).

E^{th}_e= 3.5 MeV



PHASES:

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

Since 2020: SK-V (prep for Gd), SK-VI (0.01% Gd), SK-VII (0.03% Gd)

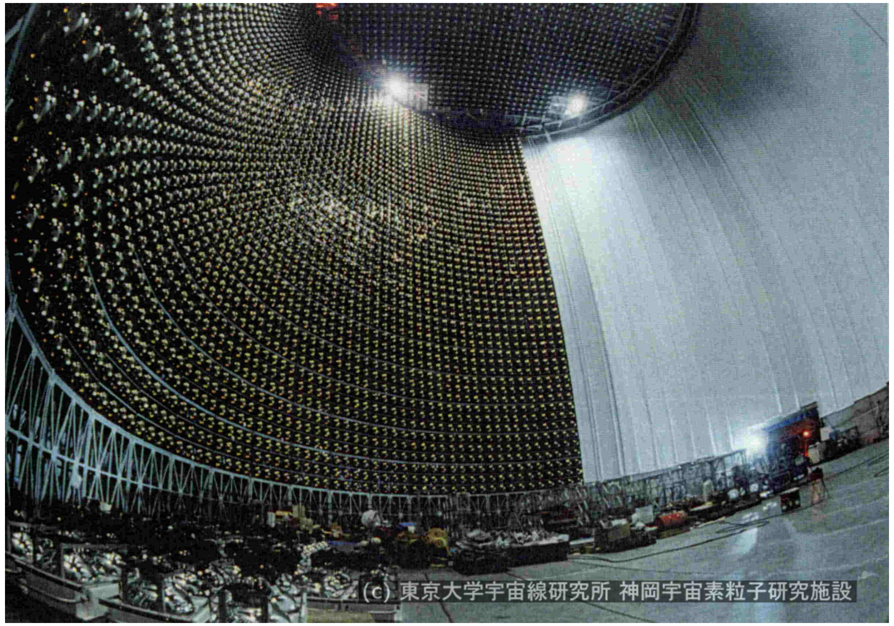
Super-Kamiokande

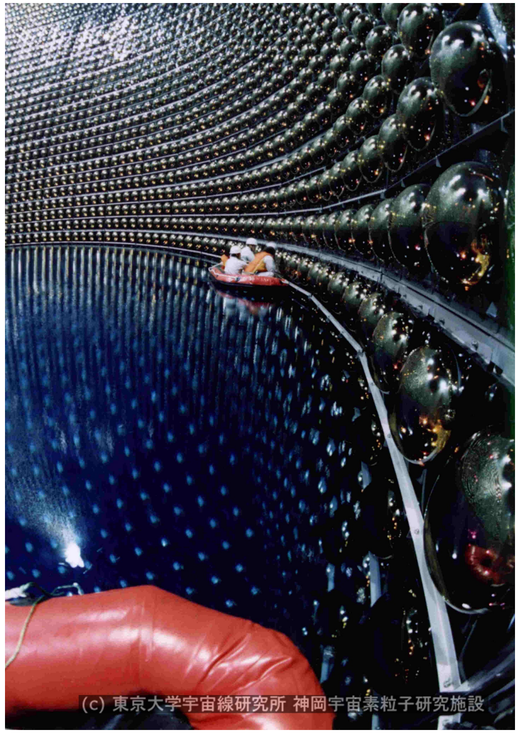
http://www-sk.icrr.u-tokyo.ac.jp/sk/tankopen2018/vr-skid4.html

Inner detector

The rock in the mine contains the radioactive material (**radon**) whose decay products become one of the background sources to neutrino observations. To avoid contamination of the radioactive material emitted from the rock, the ceiling and the wall are **sealed by the polyethylene** Mineguard . Furthermore, a **"radon-free" air is piped into the tank top from the outside** to further hold back contaminated mine air.

Super-Kamiokande detector is optically separated into two concentric cylindrical regions by PMT support structures and pairs of opaque sheets

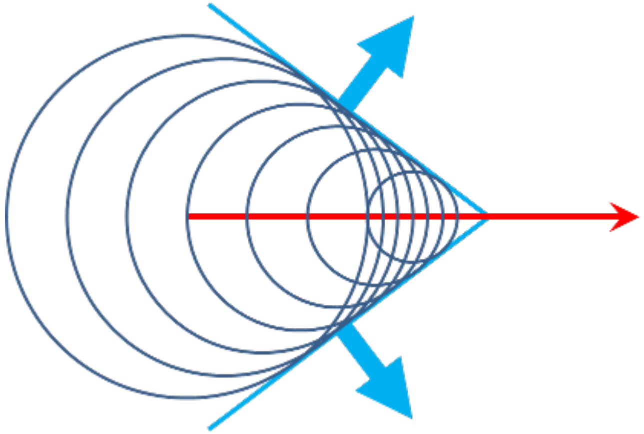




Super-Kamiokande

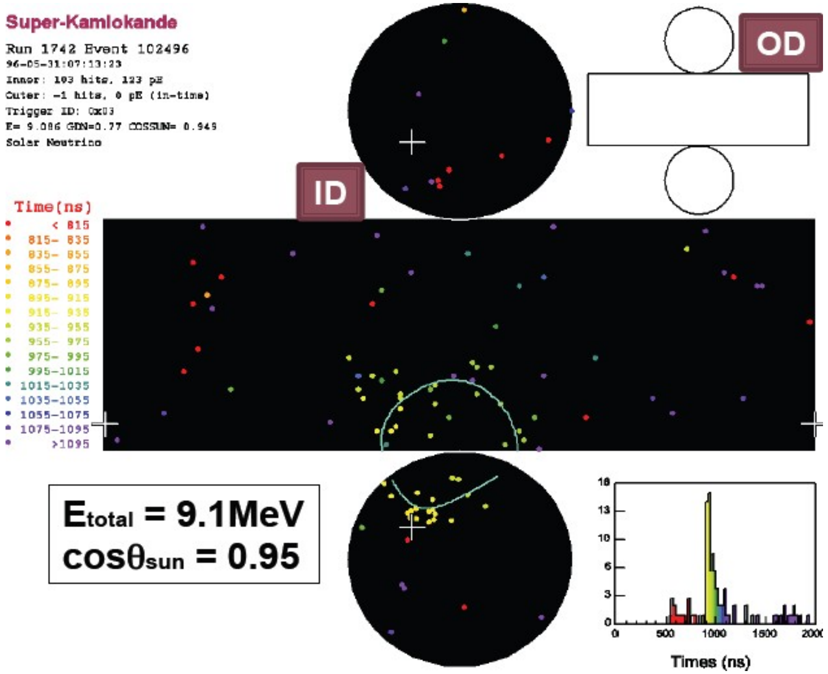
More on…
HOW it works

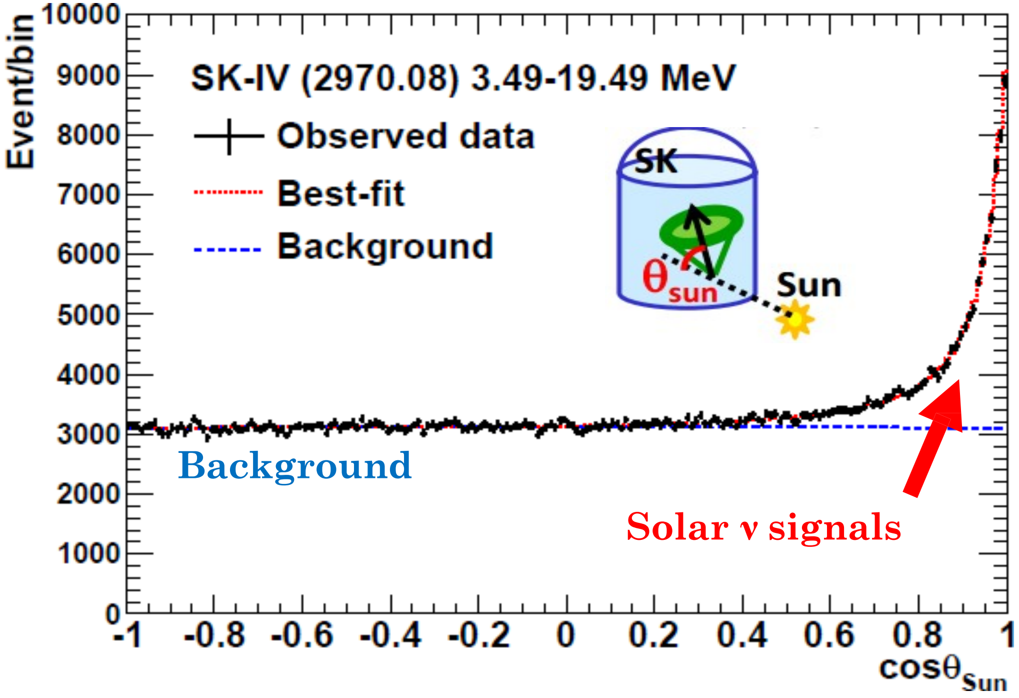
The axis of the cone gives the **direction** of the particle, and the light yield gives the particle energy.



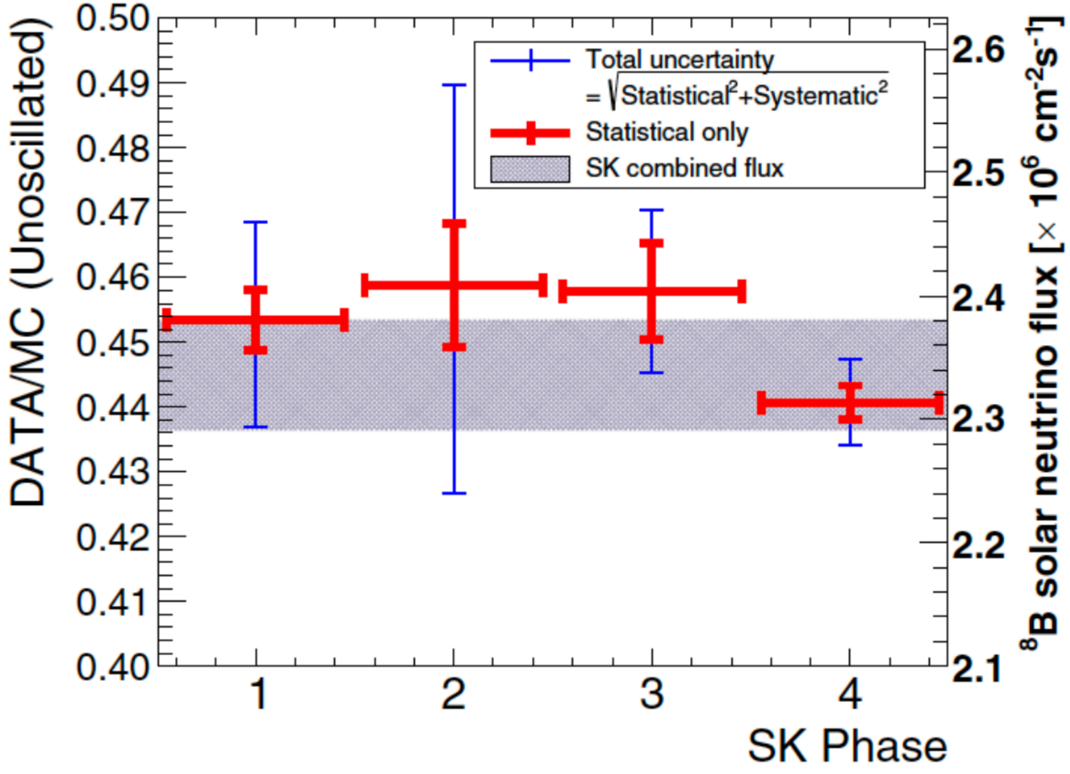
1. Timing → vertex position & real-time measurement
2. Ring pattern → direction of the incoming neutrino
3. No. of hit PMTs → energy (~6 PMT hits/MeV)

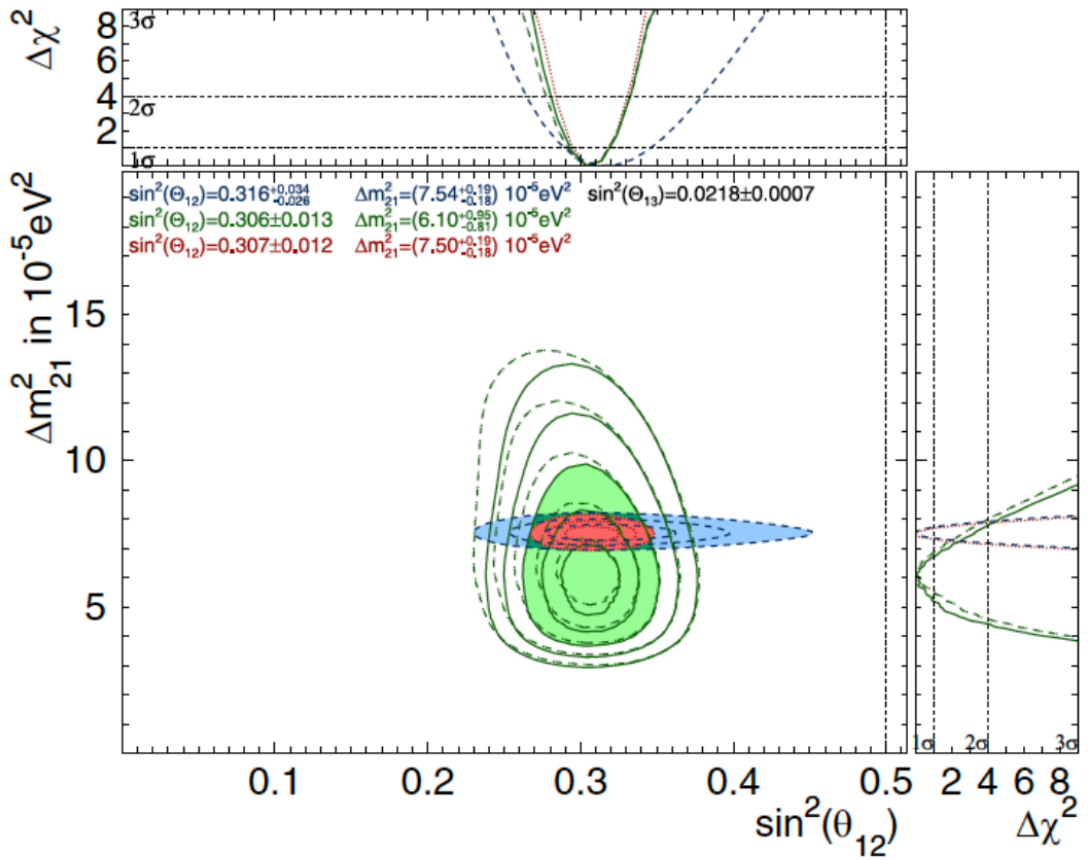
Neutrino events and **cosmic ray muon events** can be distinguished by the number of photons detected by the PMTs of the outer detector. A cosmic muon is detected both in the outer and in the inner volume, while a neutrino is not.





SK solar results





Solar best-fit value updated to:

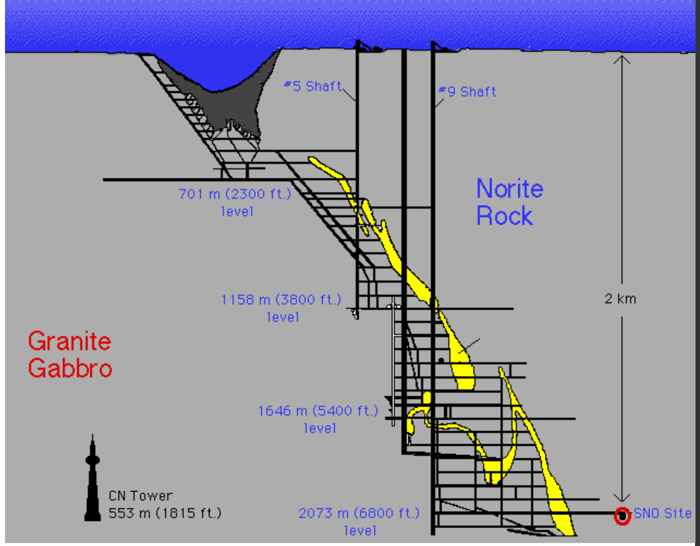
$$\Delta m^2_{21} = 6.10^{+0.95}_{-0.81} \times 10^{-5} eV^2$$

~1.5 σ away from KamLAND

SNO

WHERE

Creighton mine (INCO Ltd.), near Sudbury (Ontario, Canada)
2092 m, 6010 m.w.e, 65 μ/day

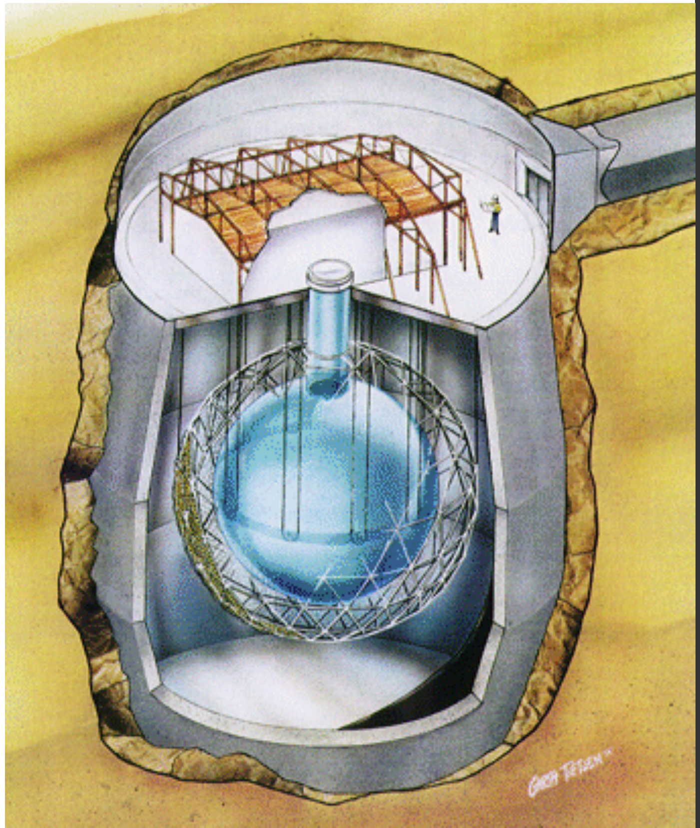


DETECTOR

1 kton of 99.92% **isotopically pure D_2O** contained inside a spherical 12 m diameter acrylic vessel

9456 20-cm photomultiplier tubes (PMTs) mounted on a spherical stainless steel geodesic structure with a diameter of 18 m.

The acrylic vessel and the geodesic sphere are immersed in **ultrapure water (H2O)** which provides shielding against radioactive background from the geodesic structure and the cavity rock.



HOW it works

CC $\nu_e + d \rightarrow p + p + e^-$
NC $\nu_\alpha + d \rightarrow p + n + \nu_\alpha$
ES $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$

SNO

SNO experiment have proved that the SNP is due to neutrino flavor transitions:
In the **SNO salt phase** 2176±78 CC events, 2010±85 NC events, and 279±26 ES events have been observed, corresponding to

$$\Phi_{CC}^{SNO} = \left(1.68 \pm 0.06^{+0.08}_{-0.09}\right) \times 10^6\ cm^{-2}s^{-1} \longrightarrow \Phi_{\nu_e}^{SNO}$$

$$\Phi_{NC}^{SNO} = \left(4.94 \pm 0.21^{+0.38}_{-0.34}\right) \times 10^6\ cm^{-2}s^{-1} \longrightarrow \Phi_{\nu_e}^{SNO} + \Phi_{\nu_{\mu,\tau}}^{SNO}$$

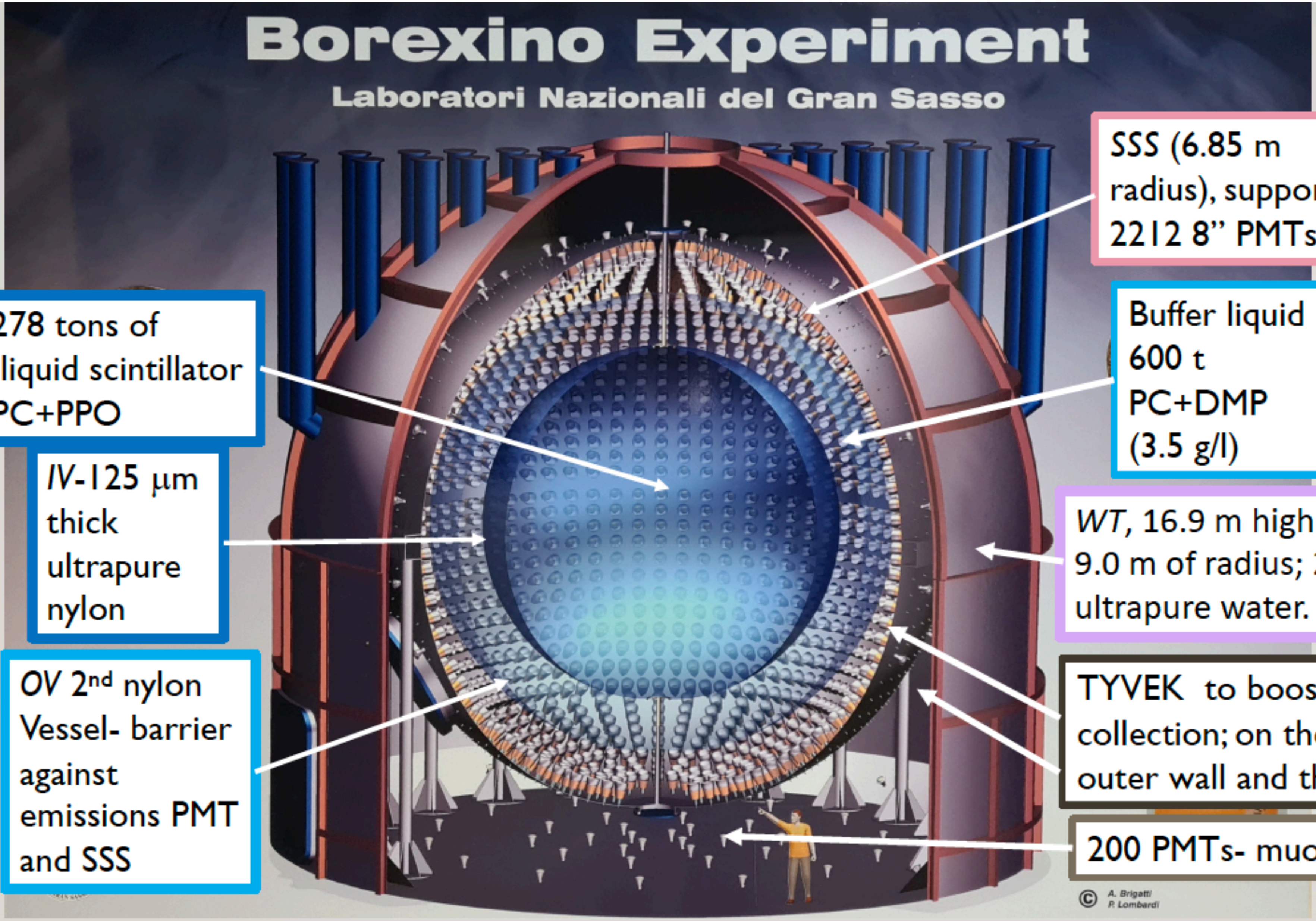
$$\Phi_{ES}^{SNO} = \left(2.35 \pm 0.22 \pm 0.15\right) \times 10^6\ cm^{-2}s^{-1} \longrightarrow \Phi_{\nu_e}^{SNO} + 0.1553\ \Phi_{\nu_{\mu,\tau}}^{SNO}$$

This data are not compatible, indeed:

$$\frac{\Phi_{CC}^{SNO}}{\Phi_{NC}^{SNO}} = 0.340 \pm 0.023^{+0.029}_{-0.031}$$

which deviates from unity by 17 standard deviations. Such a large discrepancy implies that SNO data exclude that ^{8}B solar electron neutrinos arrive on the Earth unchanged. About two thirds of the ^{8}B solar electron neutrino flux are converted into ν_μ or ν_τ on their way to the Earth.

BOREXINO



278 tons of liquid scintillator PC+PPO

IV-125 μm thick ultrapure nylon

OV 2nd nylon Vessel- barrier against emissions PMT and SSS

SSS (6.85 m radius), supports 2212 8” PMTs

Buffer liquid 600 t PC+DMP (3.5 g/l)

WT, 16.9 m high and 9.0 m of radius; 2400 t ultrapure water.

TYVEK to boost light collection; on the SSS outer wall and the WT

200 PMTs- muon veto

PC=pseudocumene-1,2,4, trimethylbenzene. PPO=2,5, diphenyloxazole

BOREXINO

PROCESS

$$\nu_\alpha + e \rightarrow \nu_\alpha + e$$

A fraction of the primary neutrino energy E_ν is ransferred to the electron, which is then stopped by the scintillator, giving rise to the scintillation signal

Solar ν	T_e^{max} [keV]	σ_e [10^{-46} cm^2]	$\sigma_{\mu/\tau}$ [10^{-46} cm^2]	P_{ee}	GS98 rate [cpd/100 t]	AGSS09 rate [cpd/100 t]	Main background
pp	261	11.38	3.22	0.542±0.016	130.8 ± 2.4	131.9 ± 2.4	^{14}C, pileup
^{7}Be (384 keV)	231	19.14	5.08	0.537±0.015	1.90 ± 0.14	1.73 ± 0.12	^{85}Kr, ^{210}Bi
^{7}Be (862 keV)	665	57.76	12.80	0.524±0.014	46.48 ± 3.35	42.39 ± 3.05	^{85}Kr, ^{210}Bi
pep	1220	108.49	22.08	0.514±0.012	2.73 ± 0.05	2.79 ± 0.06	^{11}C, ^{210}Bi, ext γ
CNO[a]	1517	~70	~15	~0.517	5.24 ± 0.54	3.74 ± 0.37	^{11}C, ^{210}Bi
^{8}B	14500	596.71	106.68	0.384±0.009	0.44 ± 0.07	0.37 ± 0.05	ext γ

For each solar neutrino component, the table shows the maximum energy of the recoiled electrons T^{max}_e , the total cross sections σ_e averaged on the spectral shape and $\sigma_{\mu,\tau}$, the electron neutrino survival probability *Pee* (weighted for the spectral shape) and the predicted solar neutrino interaction rates in Borexino (in counts-per-day per 100 ton) according to the *high-Z* (GS98) and *low-Z* (AGSS09) SSMs [G. Bellini et al. (Borexino), Phys. Rev. **D89**, 112007 (2014)]

BOREXINO

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The low count rate of a few or a few tens of counts-per-day per 100 ton (cpd/100 ton) defines the need of a superb radio-purity for the detector. In fact, **scintillation light is isotropic** and any information about the initial direction of the incoming particle is lost. Thus, neutrino-induced events in liquid scintillators are intrinsically indistinguishable on an event-by-event basis from radioactive backgrounds.

BOREXINO

PROCESS

$$\nu_\alpha + e \rightarrow \nu_\alpha + e$$

A fraction of the primary neutrino energy E_ν is ransferred to the electron, which is then stopped by the scintillator, giving rise to the scintillation signal

Solar ν	T_e^{max} [keV]	σ_e [10^{-46} cm^2]	$\sigma_{\mu/\tau}$ [10^{-46} cm^2]	P_{ee}	GS98 rate [cpd/100 t]	AGSS09 rate [cpd/100 t]	Main background
pp	261	11.38	3.22	0.542±0.016	130.8 ± 2.4	131.9 ± 2.4	^{14}C, pileup
^{7}Be (384 keV)	231	19.14	5.08	0.537±0.015	1.90 ± 0.14	1.73 ± 0.12	^{85}Kr, ^{210}Bi
^{7}Be (862 keV)	665	57.76	12.80	0.524±0.014	46.48 ± 3.35	42.39 ± 3.05	^{85}Kr, ^{210}Bi
pep	1220	108.49	22.08	0.514±0.012	2.73 ± 0.05	2.79 ± 0.06	^{11}C, ^{210}Bi, ext γ
CNO[a]	1517	~70	~15	~0.517	5.24 ± 0.54	3.74 ± 0.37	^{11}C, ^{210}Bi
^{8}B	14500	596.71	106.68	0.384±0.009	0.44 ± 0.07	0.37 ± 0.05	ext γ

For each solar neutrino component, the table shows the maximum energy of the recoiled electrons T^{max}_e , the total cross sections σ_e averaged on the spectral shape and $\sigma_{\mu,\tau}$, the electron neutrino survival probability *Pee* (weighted for the spectral shape) and the predicted solar neutrino interaction rates in Borexino (in counts-per-day per 100 ton) according to the *high-Z* (GS98) and *low-Z* (AGSS09) SSMs [G. Bellini et al. (Borexino), Phys. Rev. **D89**, 112007 (2014)]

The low count rate of a few or a few tens of counts-per-day per 100 ton (cpd/100 ton) defines the need of a superb radio-purity for the detector. In fact, **scintillation light is isotropic** and any information about the initial direction of the incoming particle is lost. Thus, neutrino-induced events in liquid scintillators are intrinsically indistinguishable on an event-by-event basis from radioactive backgrounds.

The activity corresponding to the interaction rate of solar neutrinos in Borexino is equivalent to *a few 10^{-9} Bq/kg*
Typical ***natural radioactivity O(Bq/kg)***

BOEXINO detector must be at least 9 ÷ 10 orders of magnitude less radioactive than anything on Earth

BOREXINO

G. Bellini@Neutrino24

- Simultaneous measurement of the **individual fluxes of neutrino-emitting reactions: pp, pep, 7Be; 8B measurement** [Nature, 512 (2014) 383; Nature, 562 (2018) 505]

- **Observation of neutrino oscillation in vacuum** and measurement of the **ratio Pee-vacuum/Pee-matter** [Nature, 562 (2018) 505]

- First experimental evidence of the **existence of the CNO cycle** [Nature, 587 (2020) 577; Phys. Rev. D 108 (2023)102005].

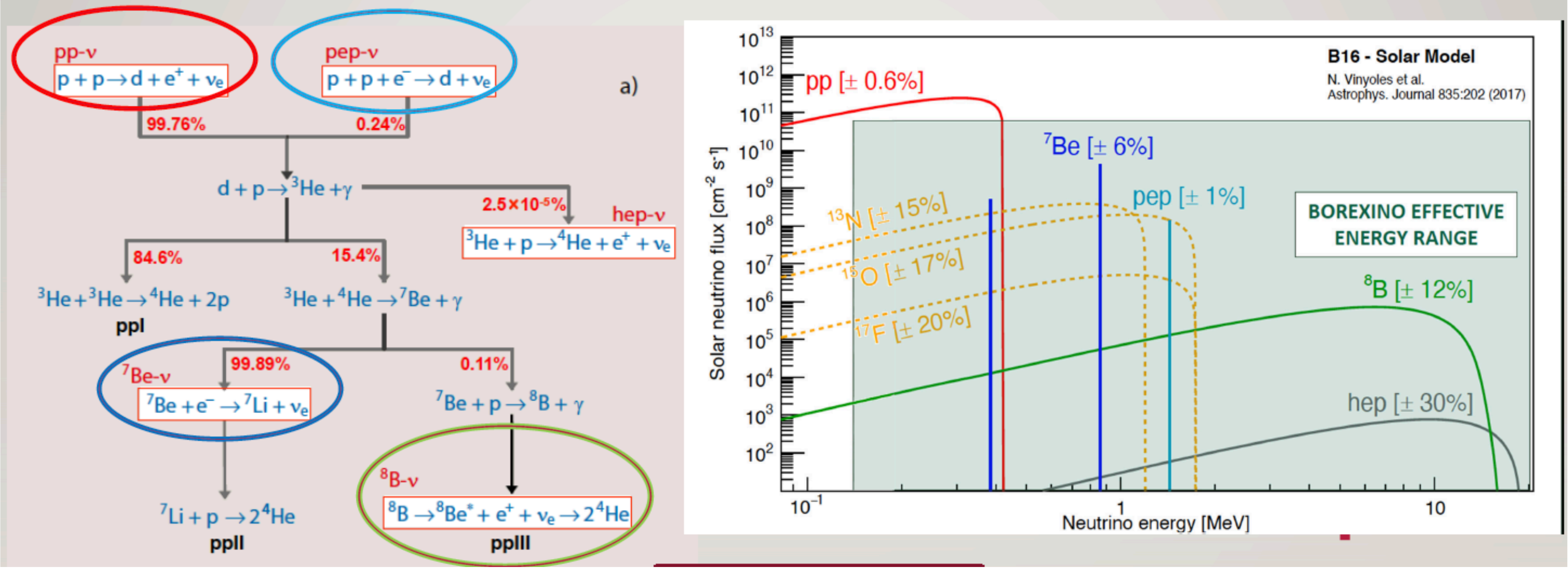
- Addressing the HZ vs LZ puzzle **with a good hint in favor of high metallicity** [Phys. Rev. Lett. 129 (2022) 252701]

- Study of **geoneutrinos** [Phys. Rev. D 101(2020)012009,, La Rivista del Nuovo Cimento 45 (2022)]

- **Upper limits** of rare events such as Pauli principle violation events, neutrino magnetic moment, electron decay and nucleon decay

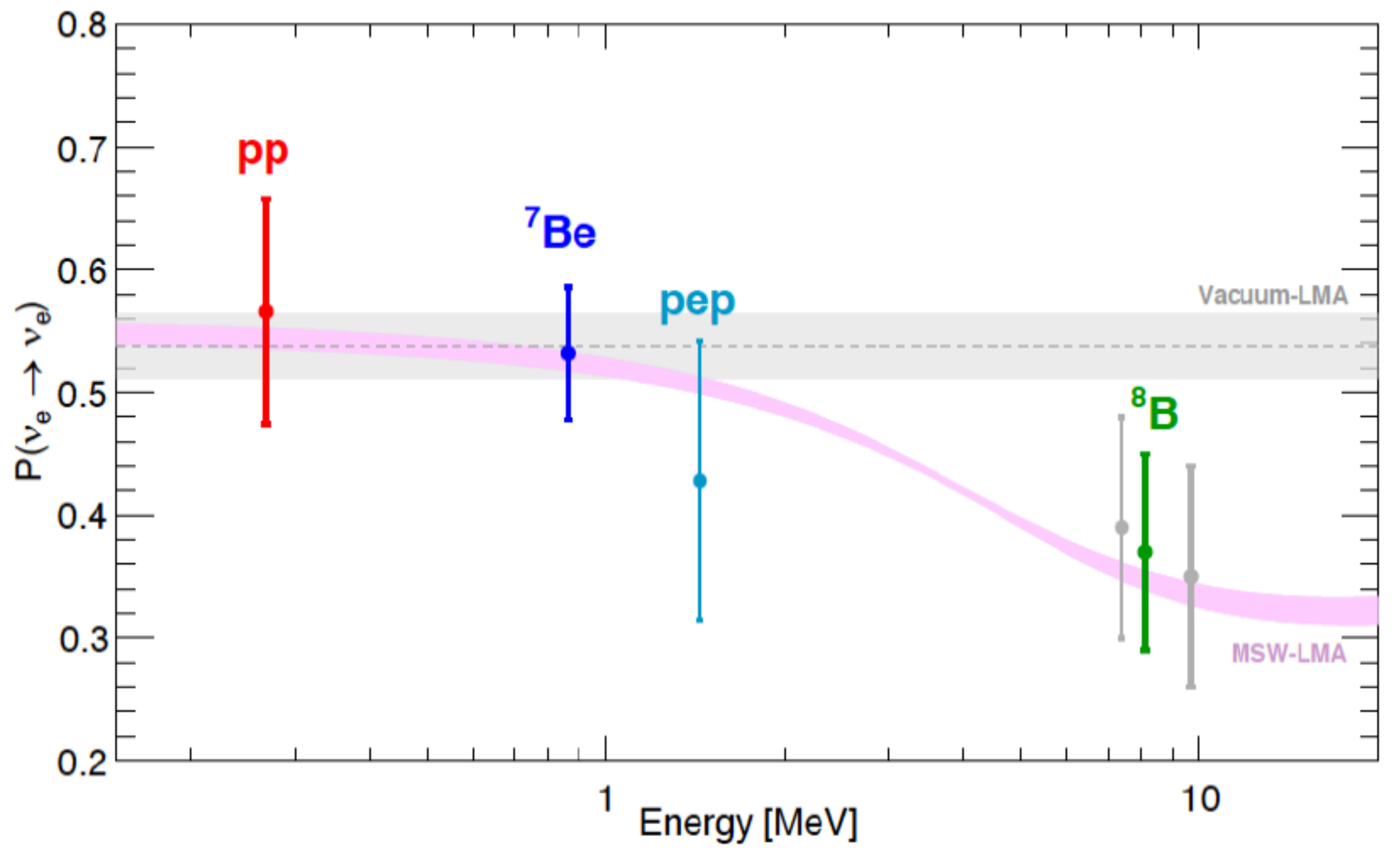
BOREXINO

G. Bellini@Neutrino24



BOREXINO

G. Bellini@Neutrino24



day/night effect found null by Borexino in the ^{7}Be energy window. This excludes at more than 8.5σ the Δm^2_{12} energy range 10^{-6}-10^{-7} eV^2 (**low** solution)–

Singles out the LMA solution with solar neutrinos only, without KamLAND antineutrinos, then without CPT assumption

Outline

Atmospheric Neutrinos

Created by the interactions of primary cosmic rays with the nuclei in the atmosphere

Primary cosmic rays are mainly composed of protons, with a small component of heavier nuclei

The interactions of primary cosmic rays with the nuclei in the atmosphere generate secondary cosmic rays, which include all the hadrons and their decay products.

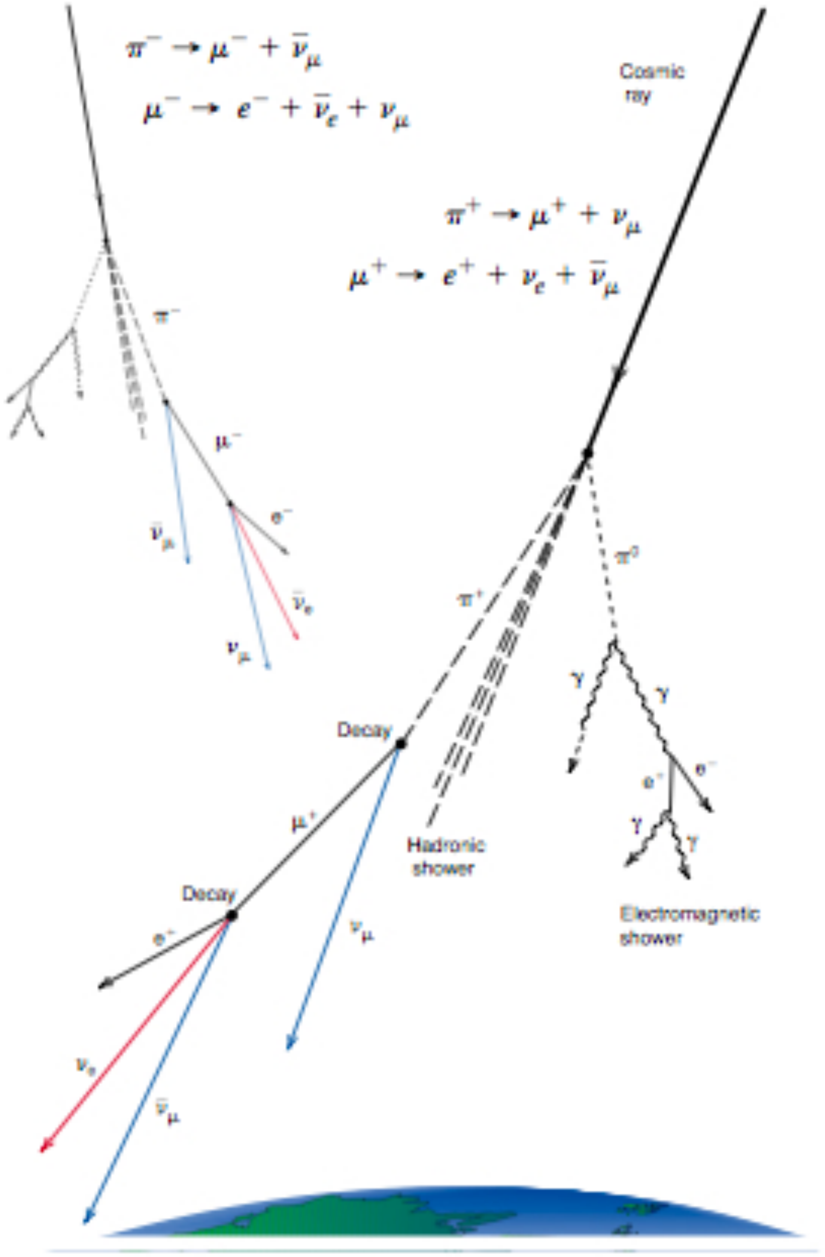
Many secondary pions are produced:

$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

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

At low energies (E $\lesssim$1 GeV),

$$\frac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} \simeq 2 \qquad \frac{\phi_{\nu_\mu}}{\phi_{\bar{\nu}_\mu}} \simeq 1 \qquad \frac{\phi_{\nu_e}}{\phi_{\bar{\nu}_e}} \simeq \frac{\phi_{\mu^+}}{\phi_{\mu^-}}$$



Atmospheric Neutrinos

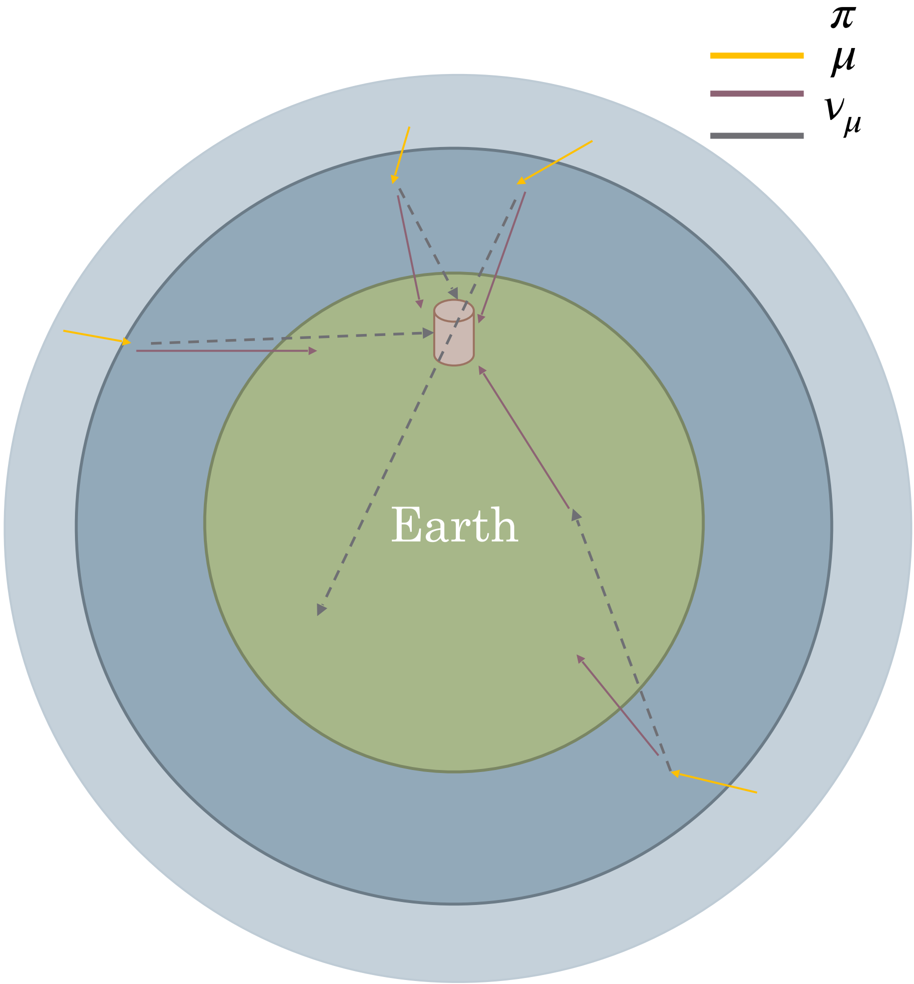
A little history

1965: first observation of atmospheric neutrinos@ 8000 m.w.e
- Kolar Gold Field Mine in South India
- East Rand Proprietary Gold Mine in South Africa

Detector → **scintillator** (no discrimination between upward-going muons and downward-going muons

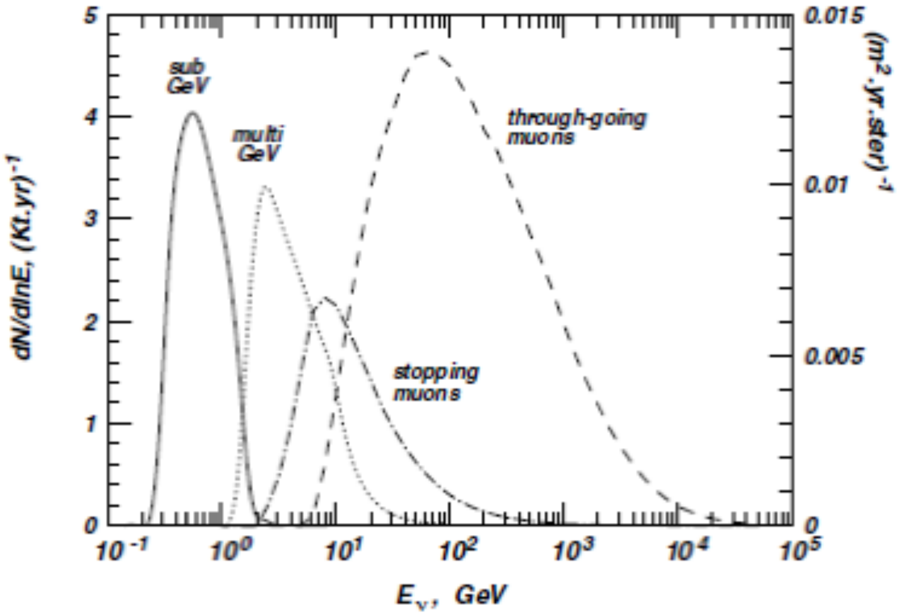
1971-1998: other observation with UG **scintillator** detectors in India, South Africa, Utah (USA), Baksan (Russia)

1985-today: directional detection
- **Water Cherenkov** experiments: Kamiokande, IBM, Super Kamiokande
- Fine-grained iron **tracking** detectors: NUSEX, Frejus, Soudan 2, MACRO



Atmospheric Neutrinos

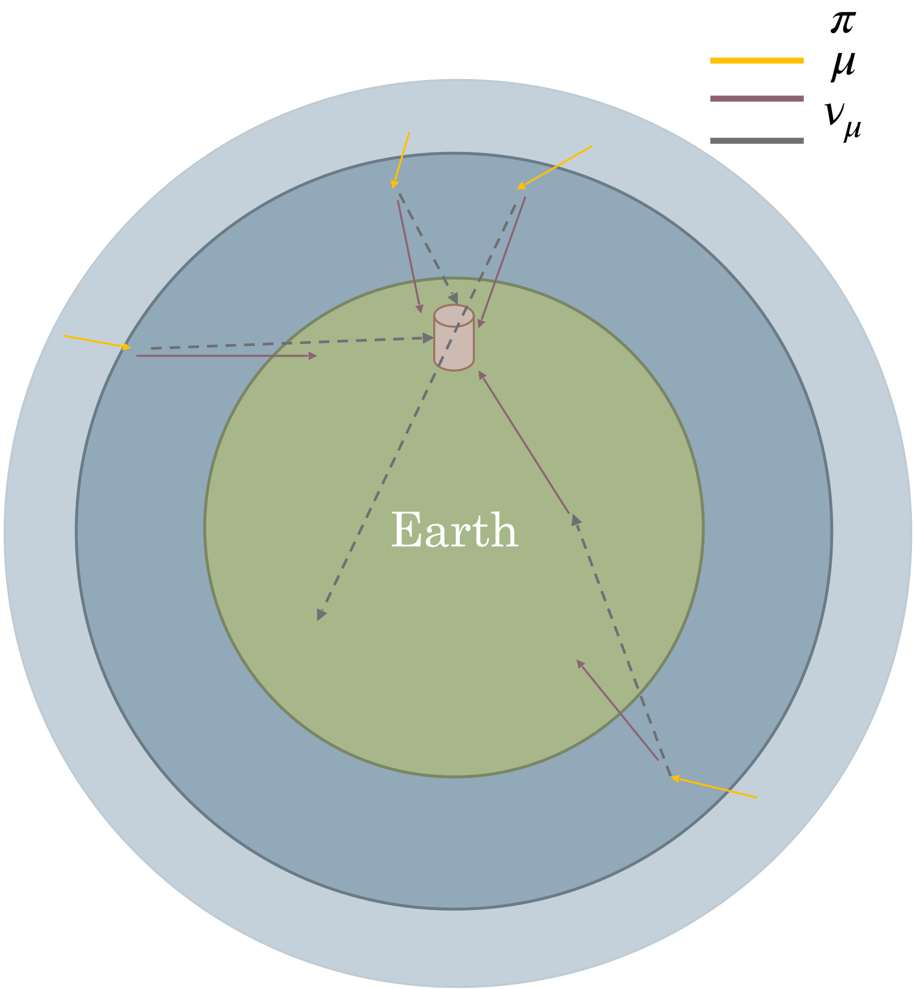
Sensitivity



Neutrino energies → about five orders of magnitude

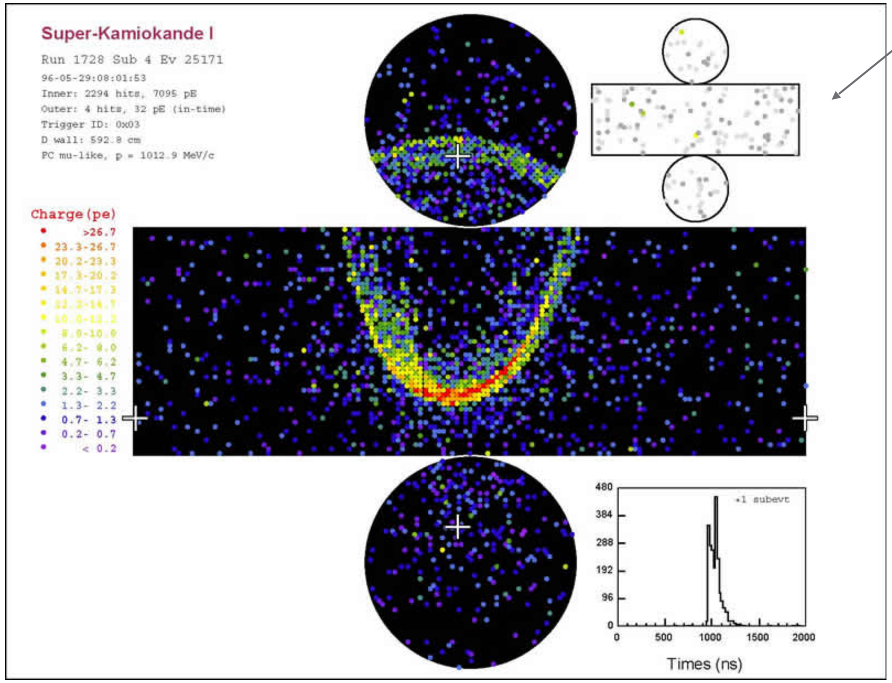
Range of pathlengths →
from about 20 km for vertical downward-going neutrinos to about 1.3× 10^4 km for vertical upward-going neutrinos.

Δm^2 → 10^{-1} eV^2 - 10^{-4} eV^2

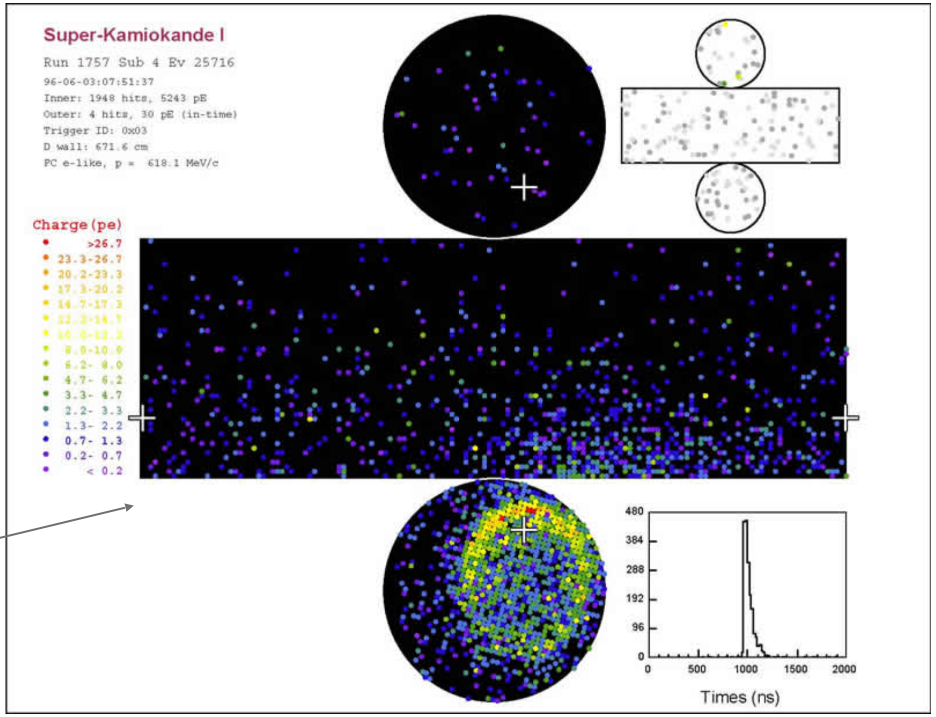


Super-Kamiokande

Muons and **electrons** can be separated quite efficiently using ring morphology. A muon will typically produce a clean, sharp-edged ring, whereas an electron will scatter more and will produce a much fuzzier ring. This enables to tag the flavour of the incoming neutrino, which is critical for $\nu_\mu \rightarrow \nu_e$ oscillations where it is necessary to detect and identify the ν_e.

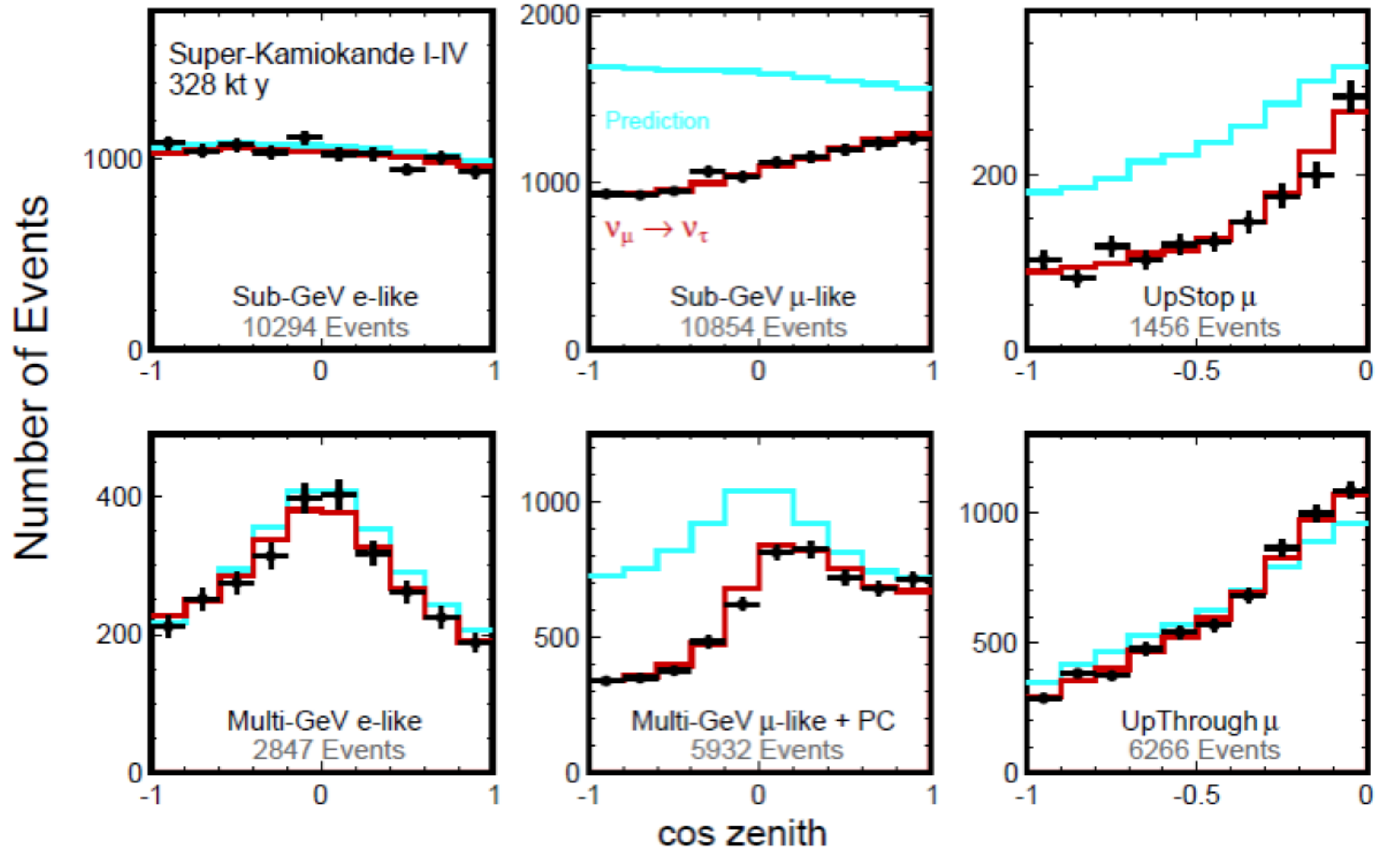


A Cherenkov ring occurred by a **muon neutrino**. A muon neutrino interacts with a nucleon in water and transforms to a muon. The outer detector has few hits in the right-upper display



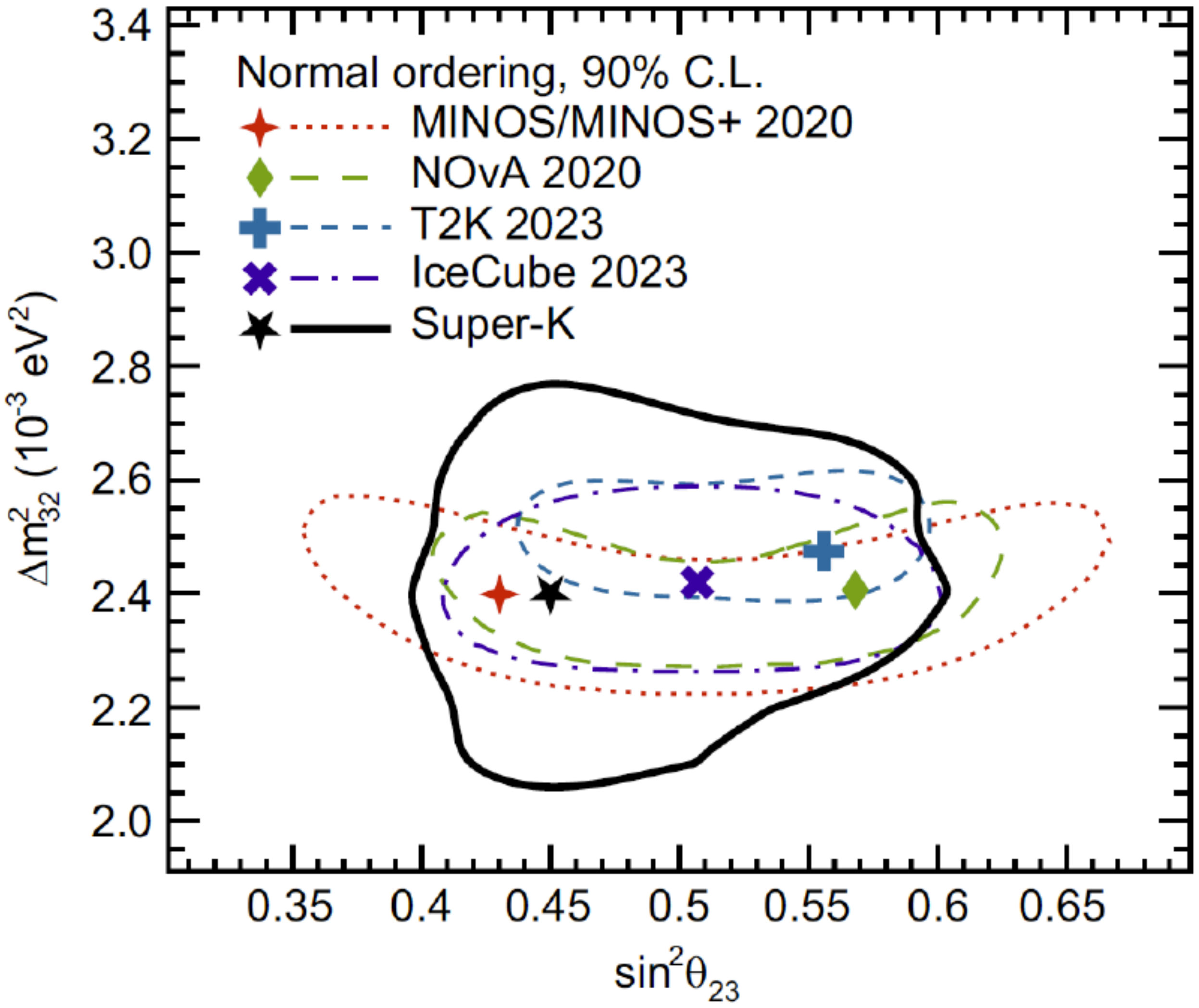
An **electron neutrino** event. An electron neutrino scatters an electron in water. The emitted electron generates an electromagnetic shower, leading to the fuzzy edge of the Cherenkov ring.

Super-Kamiokande



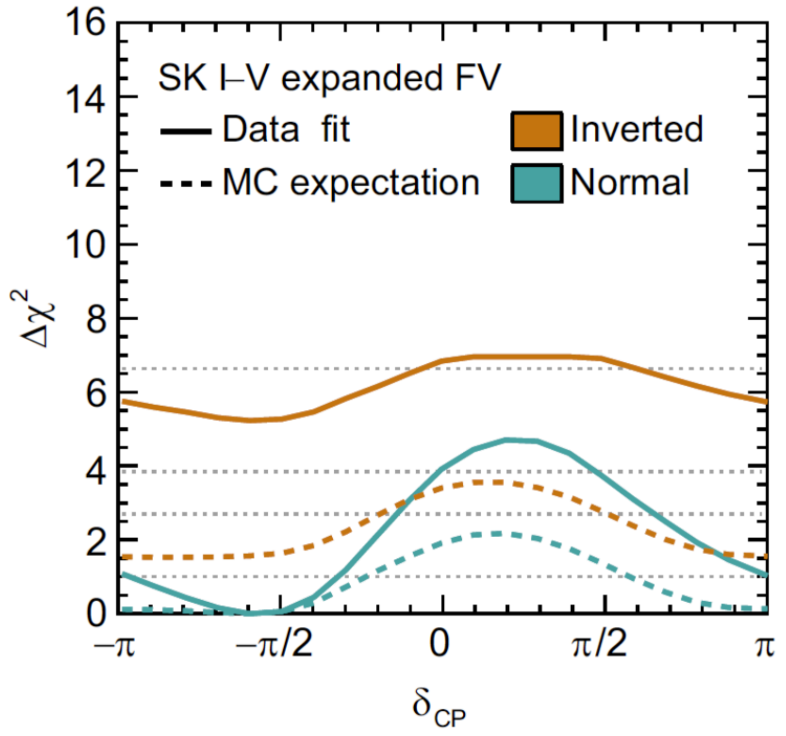
The zenith angle distributions of Super-Kamiokande atmospheric neutrino events. Fully contained 1-ring *e*-like and μ-like events with visible energy < 1.33 GeV (sub-GeV) and > 1.33 GeV (multi-GeV), as well as upward stopping and upward stopping μ samples are shown. Partially contained (PC) events are combined with multi-GeV μ-like events. **The blue histograms show the non-oscillated Monte Carlo events**, and the **red histograms show the best-fit expectations for μ- oscillations**.

Super-Kamiokande



Super-K I-V atmospheric data (6511.3 live days, expanded FV)

SK Collab, PRD 109 (2024) 072014



N. Di Marco - 13th IDPASC School - Palermo 2024

Outline

Introduction

Solar ν

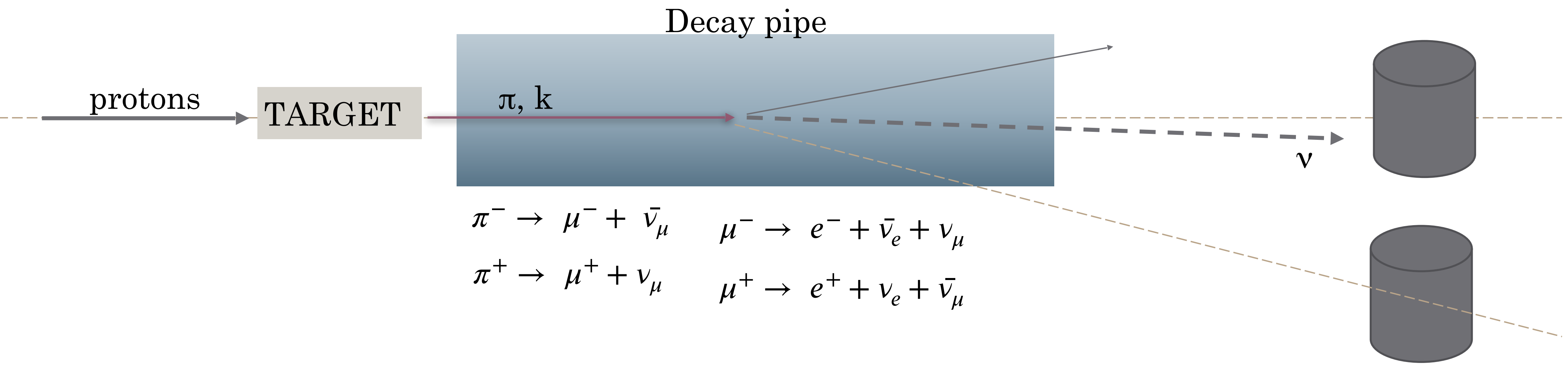
Atmospheric ν

Accelerator ν

Reactor ν

Future oscillation experiment

Neutrino Beams



$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$$E_\nu = \frac{\left[1 - \left(m_\mu/m_\pi\right)^2\right] E_\pi}{1 + \gamma^2 \vartheta^2}$$

For $\theta = 0$, the energy of neutrino is linearly proportional to the energy of pion.
In this case, a narrow band beam can be made by selecting the momentum of pions.

For $\theta \neq 0$, the energy of neutrino is not strongly dependent on the parent energy for a wide range of pion energy, but dependent on the *off-axis angle*

A comprehensive description of the accelerator neutrino beams is found in S. E. Kopp, Phys. Rept. **439**, 101 (2007), [arXiv:physics/0609129]
More didactic material: Giunti's book, Cap 12, pag 450

Neutrino Beams

Two different scales of baselines for accelerator-based experiments to study different ranges of Δm^2.

The atmospheric mass splitting $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$ gives rise to the first oscillation maximum at *L/E* ~ 500 GeV/km. In order to study this parameter region with 1 GeV accelerator neutrino beam, a long baseline of a **few hundreds to thousand km** is necessary → ***Long-baseline experiments***.

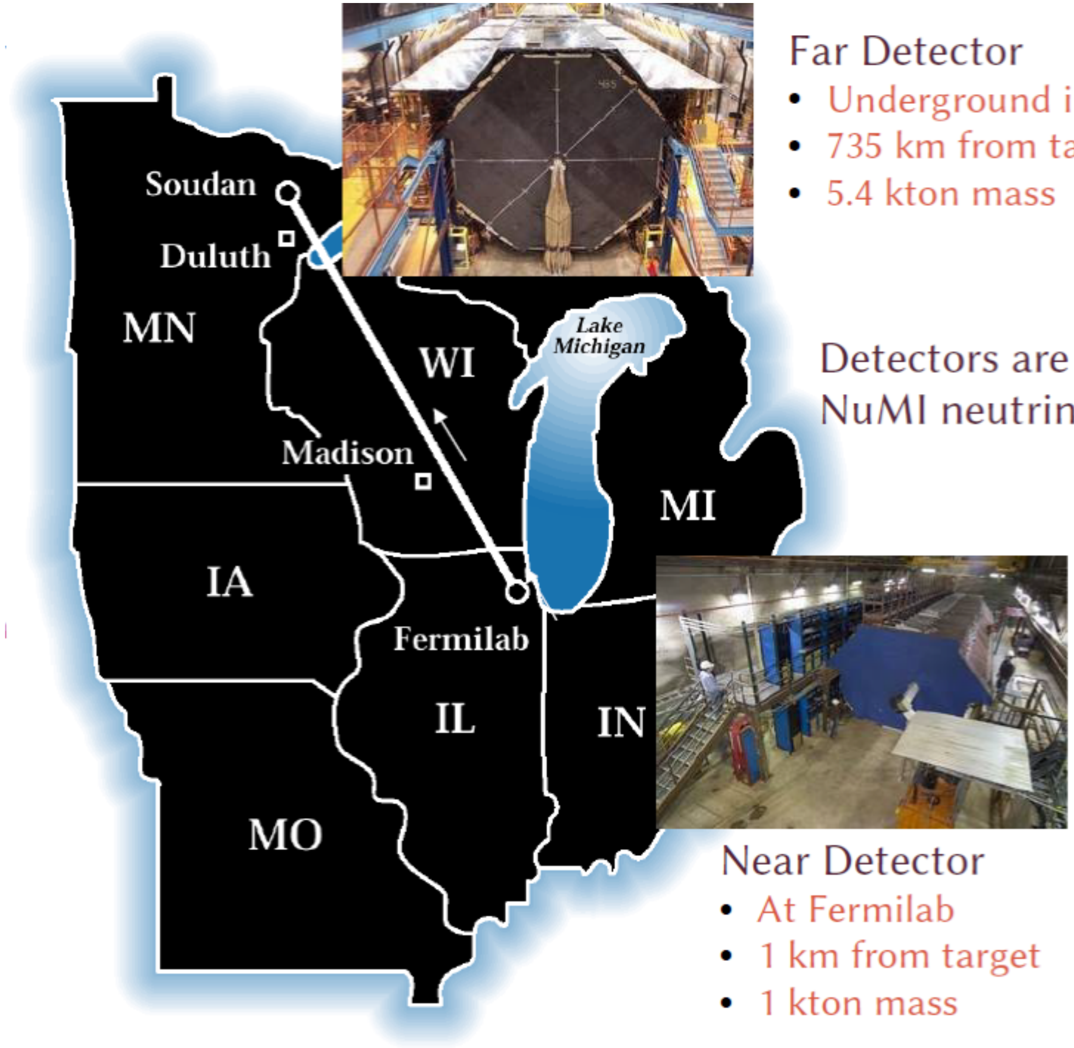
Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–

On the other hand, there have been reports of possible neutrino oscillations at 1 eV^2 scale, which can be studied at 1 km baseline with neutrinos from accelerators. These experiments are called ***short-baseline oscillation experiments***.

Channel	Experiments
$\nu_\mu \to \nu_\mu$	CHARM [212]
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$	CDHSW [396], CCFR [983]
$\nu_\mu \to \nu_e$	BEBC [89], CHARM [212], LSND [121], NOMAD [116]
$\bar{\nu}_\mu \to \bar{\nu}_e$	LAMPF-0645 [460], LSND [37], KARMEN [105]
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	BNL-E776 [265], CCFR [910], NuTeV [130]
$\nu_\mu \to \nu_\tau$	FNAL-E531 [1030], CHARM [212], CHORUS [422], NOMAD [115]
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$	CCFR [789]
$\nu_e \to \nu_\tau$	CHORUS [422], NOMAD [115]
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\tau$	CCFR [823])
Beam dump	BEBC [465, 559], CHARM [388], CDHSW [208]

MINOS - MINOS+

Far Detector
- Underground in Soudan mine
- 735 km from target
- 5.4 kton mass



Detectors are on-axis for NuMI neutrino beam

Near Detector
- At Fermilab
- 1 km from target
- 1 kton mass

Iron-scintillator tracking calorimeters to contain muons

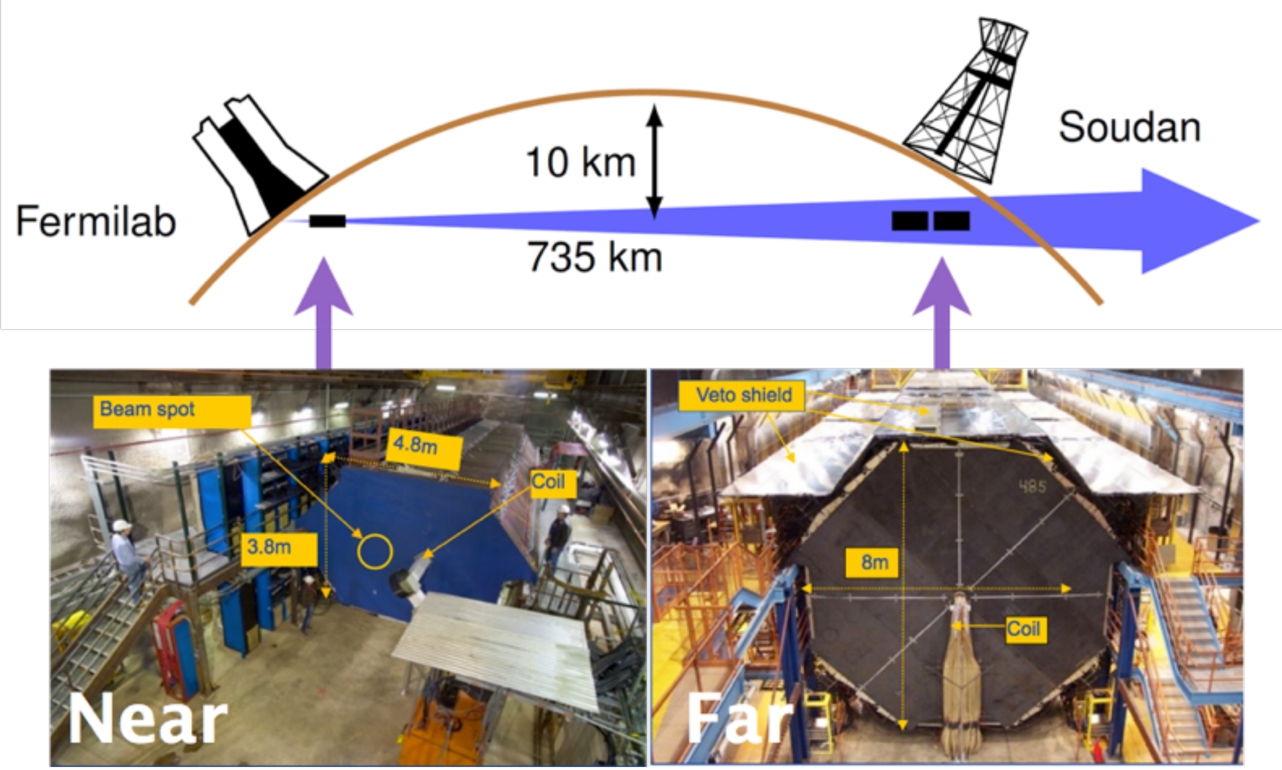
Functionally identical for systematic uncertainty reduction

Magnetized for sign selection and energy estimation

MINOS - MINOS+

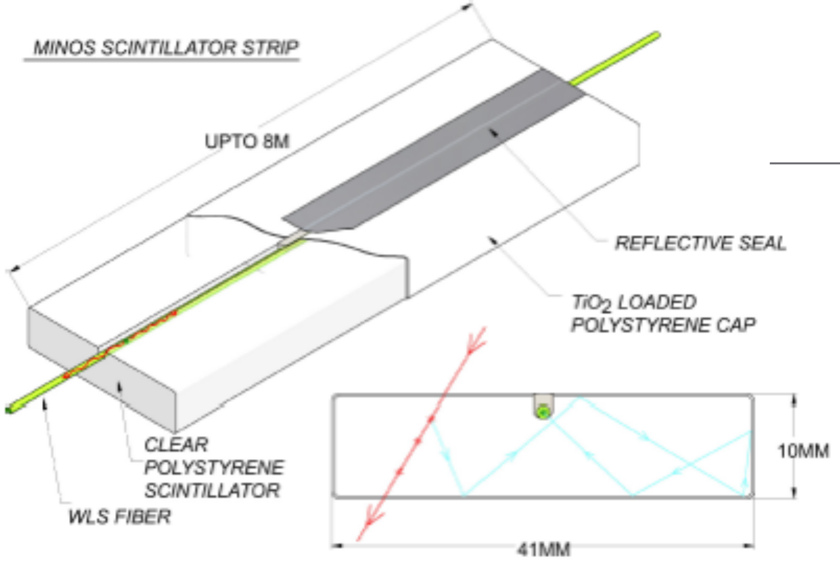
The MINOS ND and FD are two functionally identical **magnetized steel-scintillator tracking sampling calorimeters**. The near identical nature of the two detectors permits the cancellation or mitigation of many sources of systematic **uncertainties**, such as neutrino cross-sections, and beam flux uncertainties

Steel planes with thickness 2.54 cm oriented transversely to the beamline and instrumented on the downstream face with polystyrene scintillator strips. The distance between consecutive steel planes is 5.95 cm.



0.98 kt
100 m UG (225 m.w.e.)

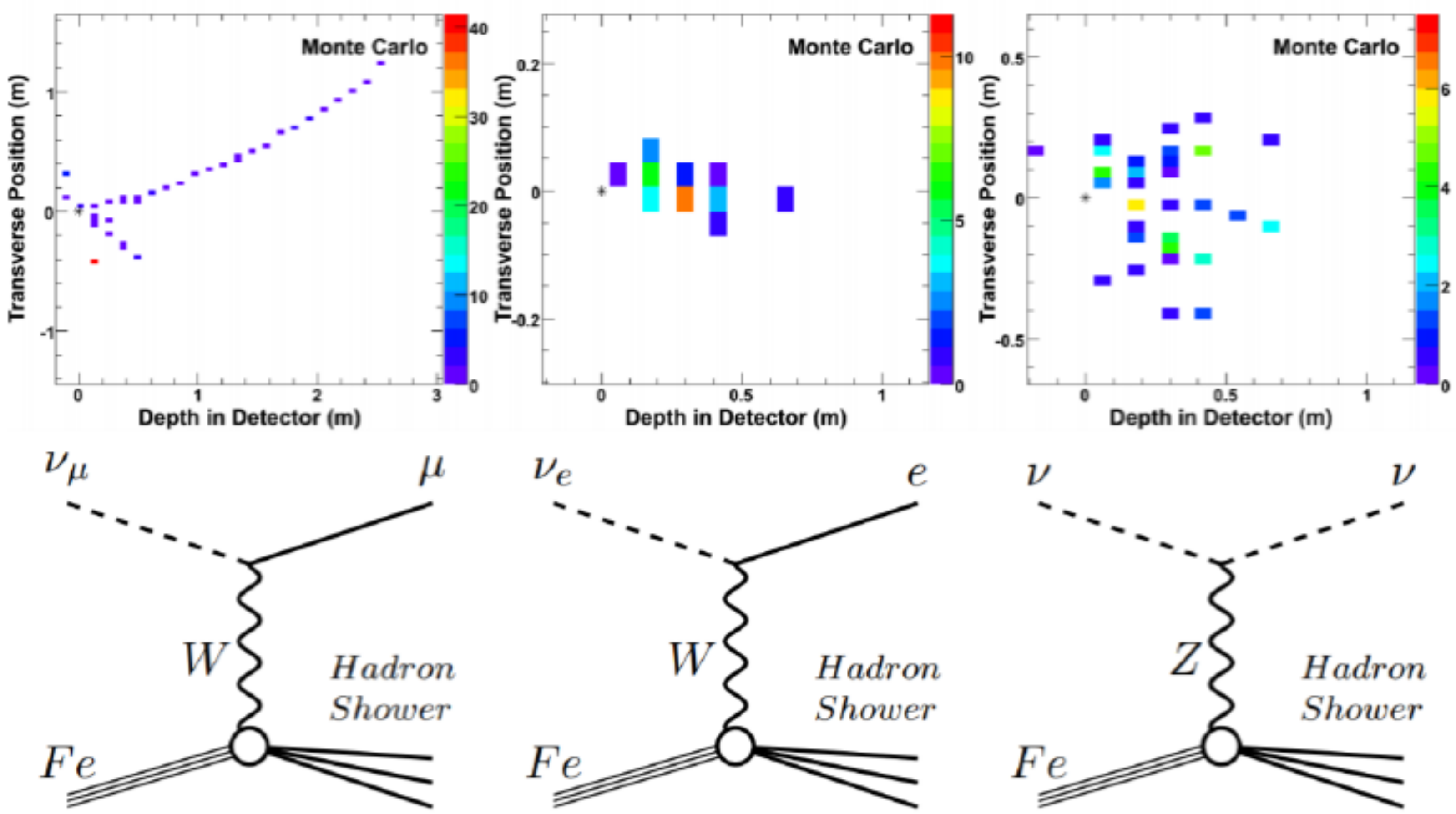
5.4 kt
705 m UG (2070 m.w.e.)



In order to provide stereo readout of track hits, alternating scintillator planes are oriented with the long axis of the modules +45 degrees, the V-planes, or -45 degrees, the U-planes, from the vertical such that these planes are perpendicular to each other.

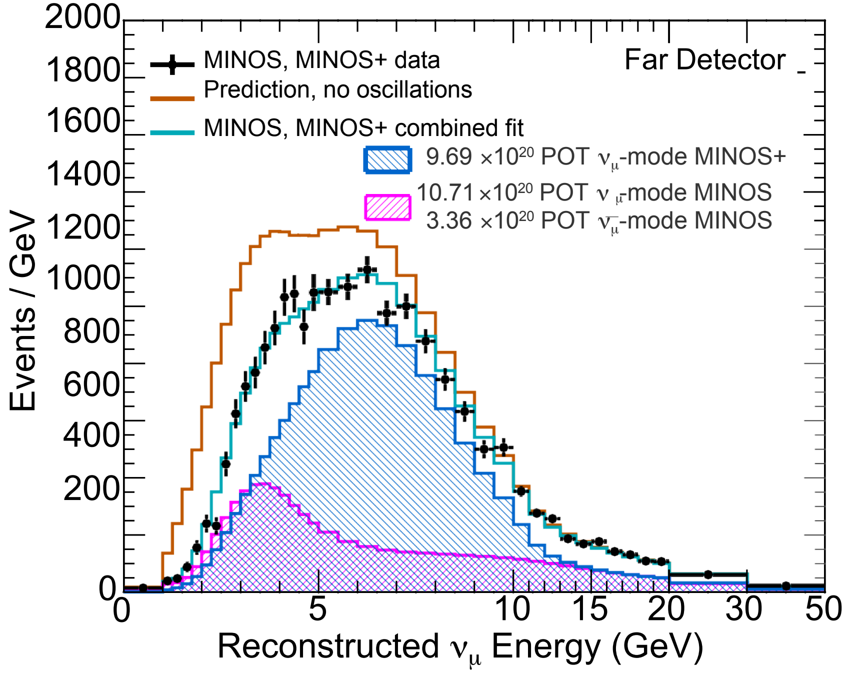
The detectors are both **magnetized** using an electromagnetic coil passing through the planes in the direction of the beamline. The resulting magnetic field allows the determination of the charge of particles produced in the detectors, and thus the isolation of neutrino and antineutrino samples.

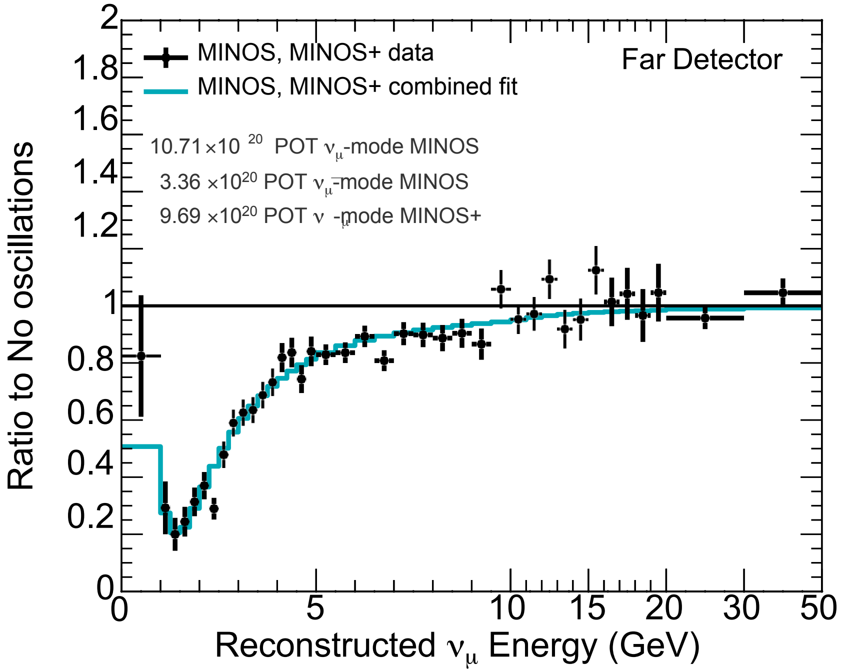
MINOS - MINOS+



Simulated MC event topologies in the MINOS detectors for ν_μ- CC (left), ν_e-CC (center), and NC (right) interactions.

MINOS - MINOS+





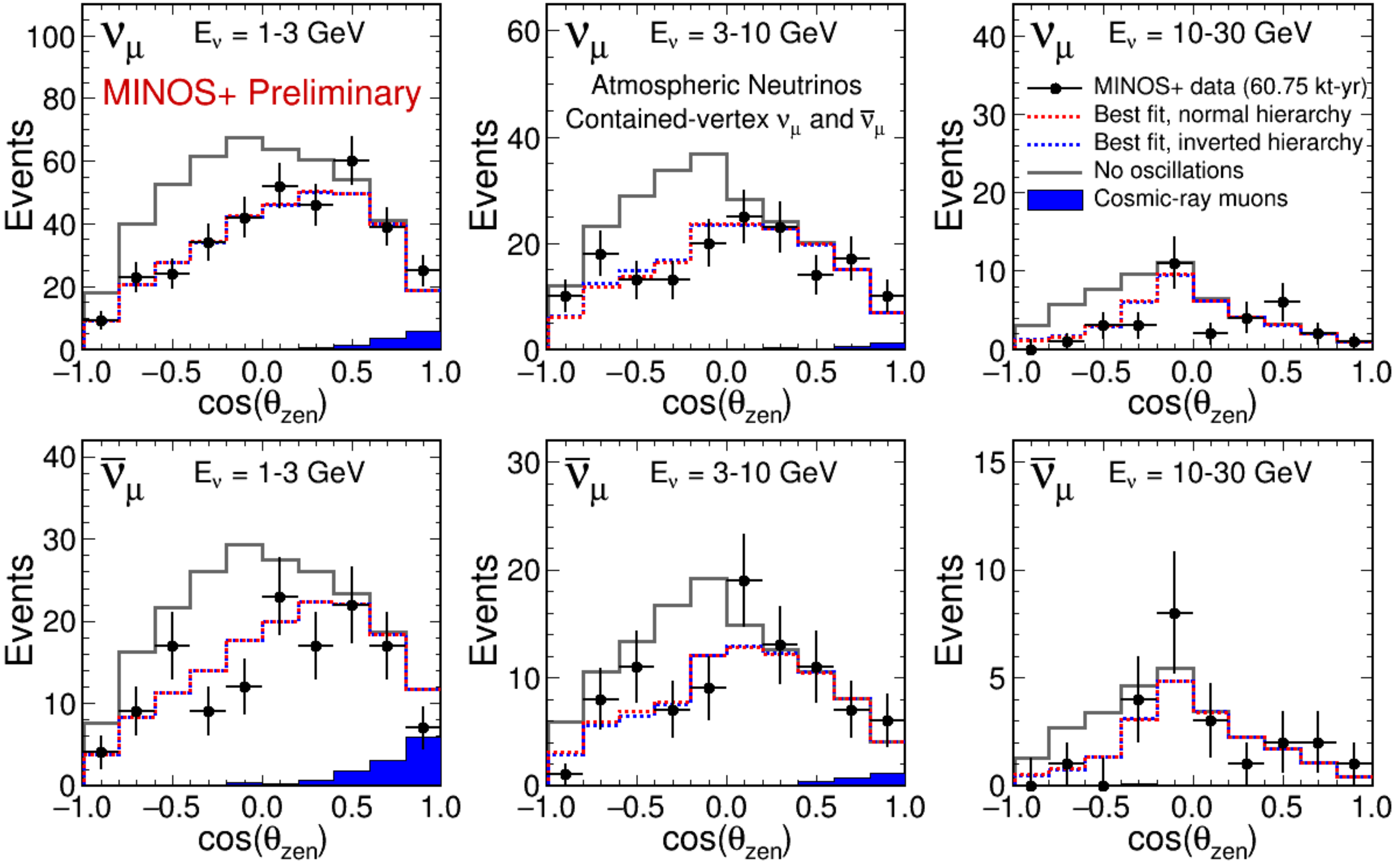
$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \cos^2\theta_{13} \sin^2(2\theta_{23}) \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$

T. Carroll, UW-Madison

MINOS - MINOS+

ν_μ

$\bar{\nu}_\mu$



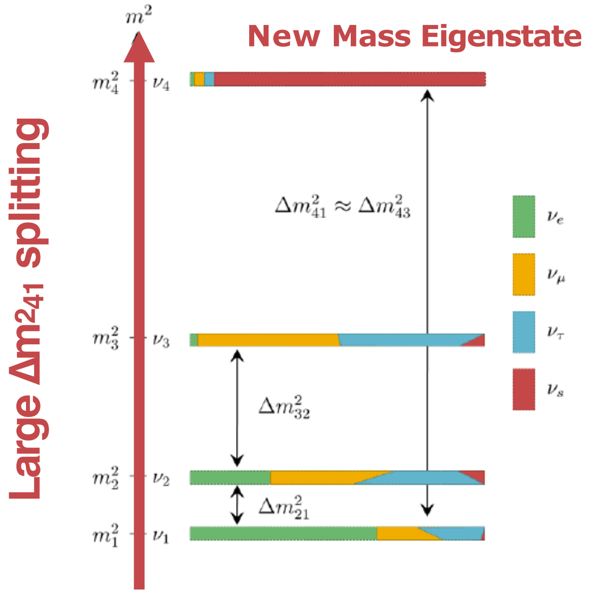
T. Carroll, UW-Madison

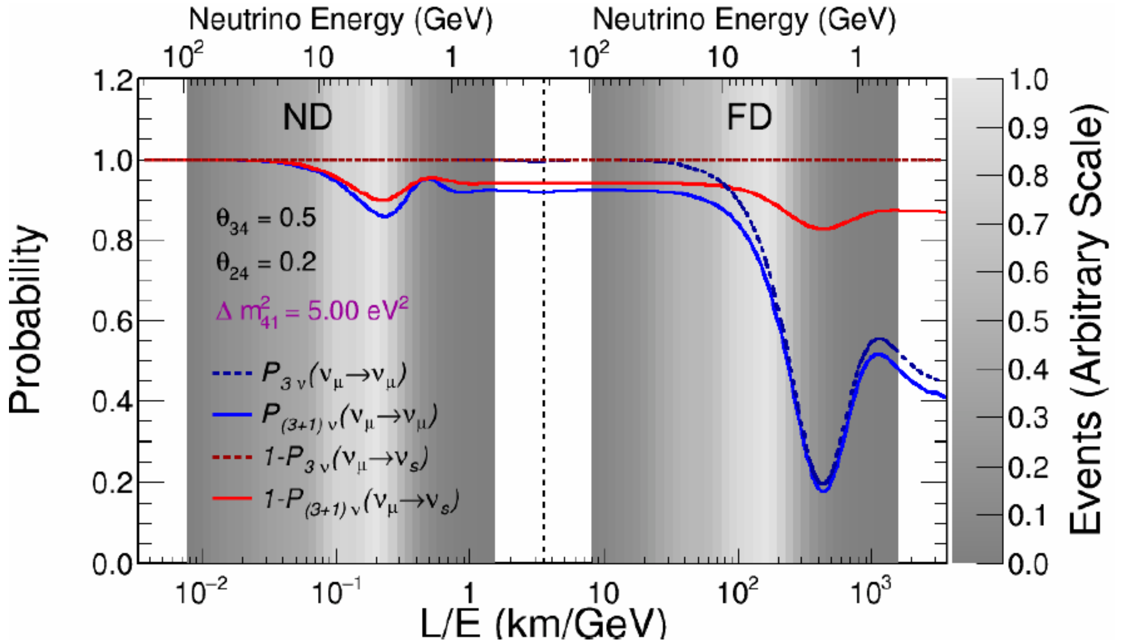
- Fit in neutrino energy and $\cos(\theta_{zen})$
- Complements beam neutrinos with different baselines

3+1 Neutrino Model

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

3 mass scales: Δm^2_{21}, Δm^2_{32}, Δm^2_{41}
6 mixing angles: θ_{12}, θ_{23}, θ_{13}, θ_{14}, θ_{24}, θ_{34}
3 CP-violating phases: δ_{13}, δ_{14}, δ_{24}





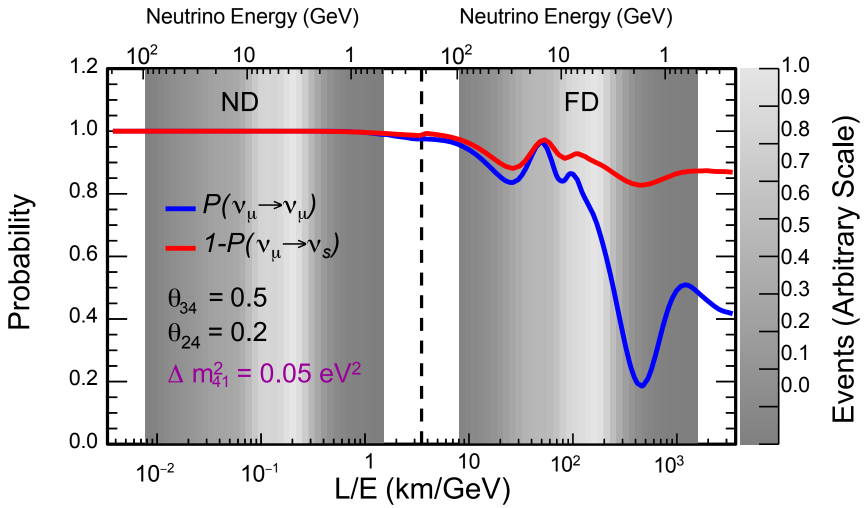
T. Carroll, UW-Madison

4-Flavor Oscillations at MINOS

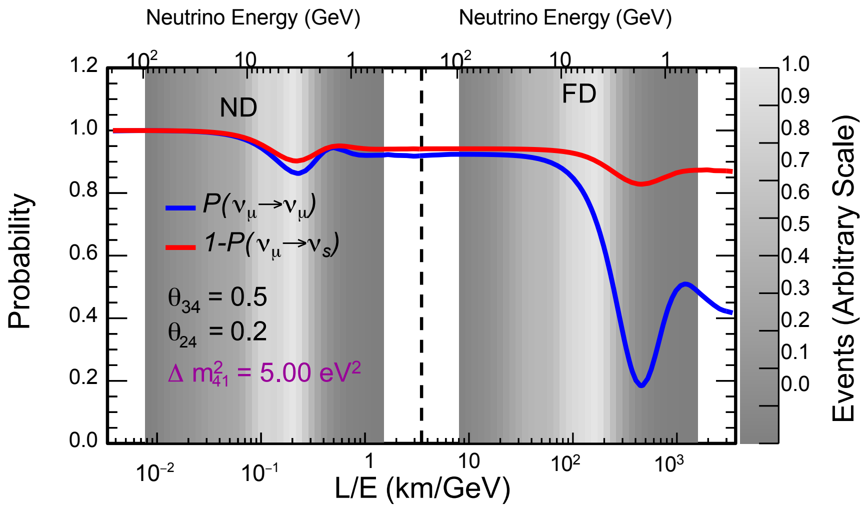
Small

Δm^2_{41}

Large



Small Δm^2_{41} :
Oscillations at the FD

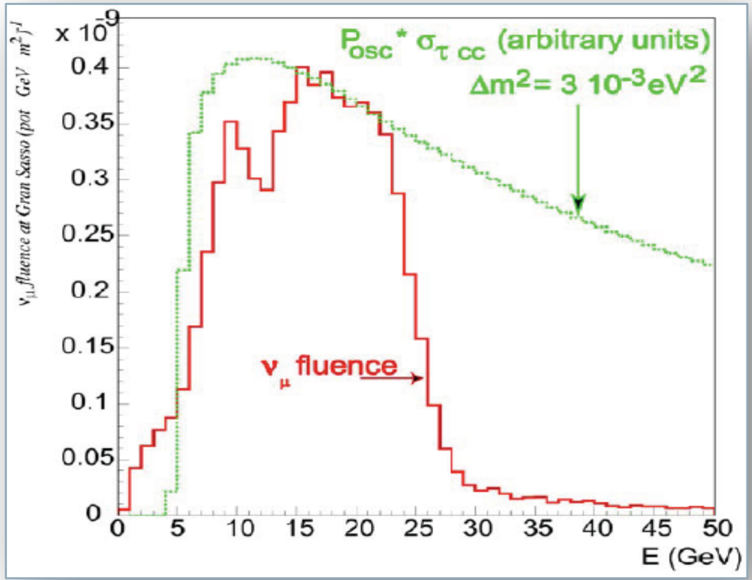


Large Δm^2_{41}:
Large oscillations at the ND

T. Carroll, UW-Madison

OPERA

Oscillation Project with Emulsion tRacking Apparatus



CNGS: conventional ν_μ beam, optimized for ν_τ appearance maximize the number of ν_τ CC interactions

- τ production threshold (3.5 GeV) and ν_τ CC cross section high energy beam
- "off peak" w.r.t. maximum oscillation probability (1.5 GeV)

➢ Long baseline neutrino oscillation experiment in the CNGS (Cern Neutrino to Gran Sasso) ν_μ beam

➢ Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in **appearance mode**

➢ Search for the subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

Beam parameters

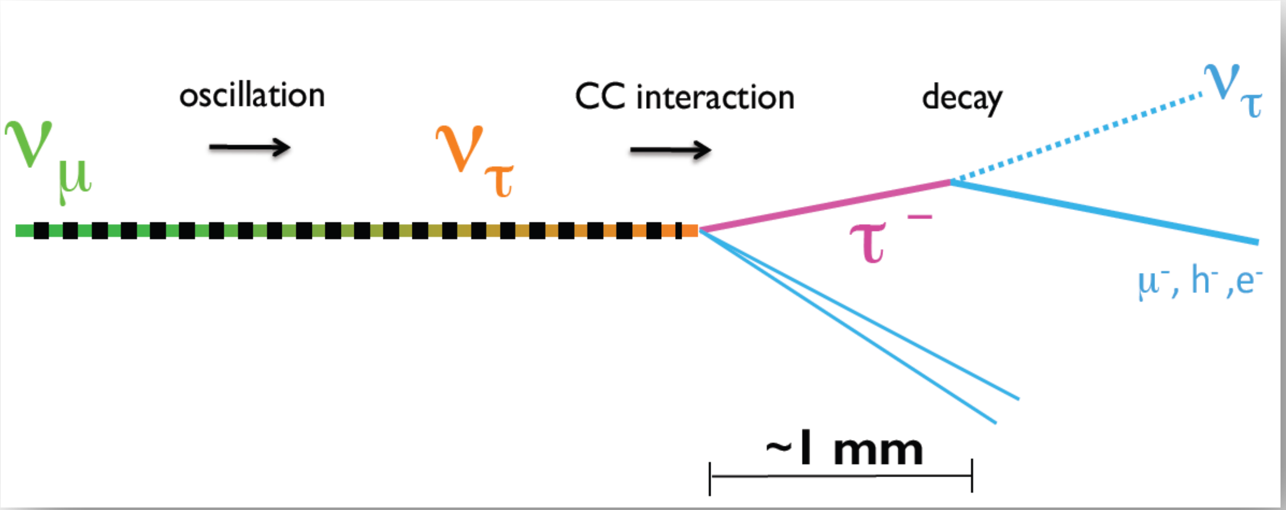
$< E_{\nu_\mu} >$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.89, 0.06 %
$\bar{\nu}_\mu/\nu_\mu$	2.1 %
ν_τ prompt	negligible
pot/year	4.5×10^{19}

Contaminations given in terms of interaction rates in OPERA

OPERA

ν_τ appearance: detection principle

Event-by-event separation of ν_τ CC interactions from dominant ν_μ interactions by direct observation of τ lepton decay



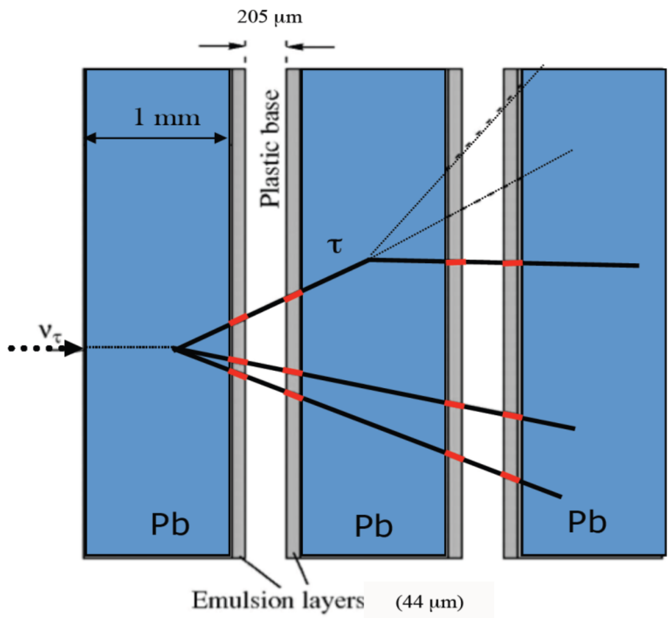
τ decay channel	B.R (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	15.0

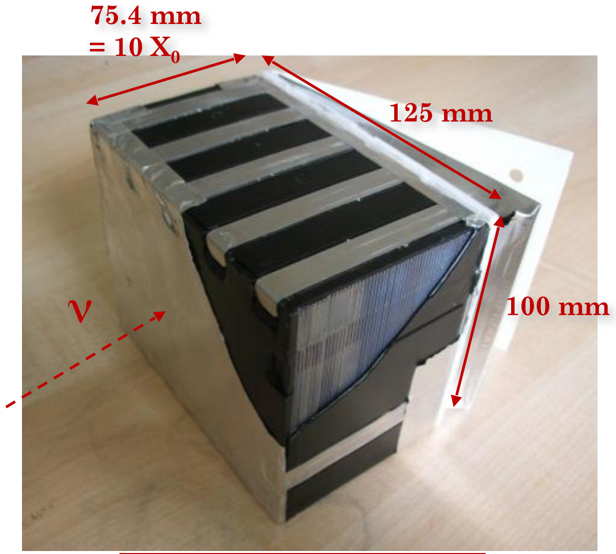
- Target mass O(kton)
  (low ν interaction cross-section)
- High granularity detector
  (τ decay detection, background rejection)

OPERA

Neutrino interaction detector: ECC

- Target basic unit: **brick** of 57 nuclear emulsions interleaved by lead plates + 2 interface emulsions (CS)
- unambiguous measurement of the kink





Brick weight = 8.3 kg

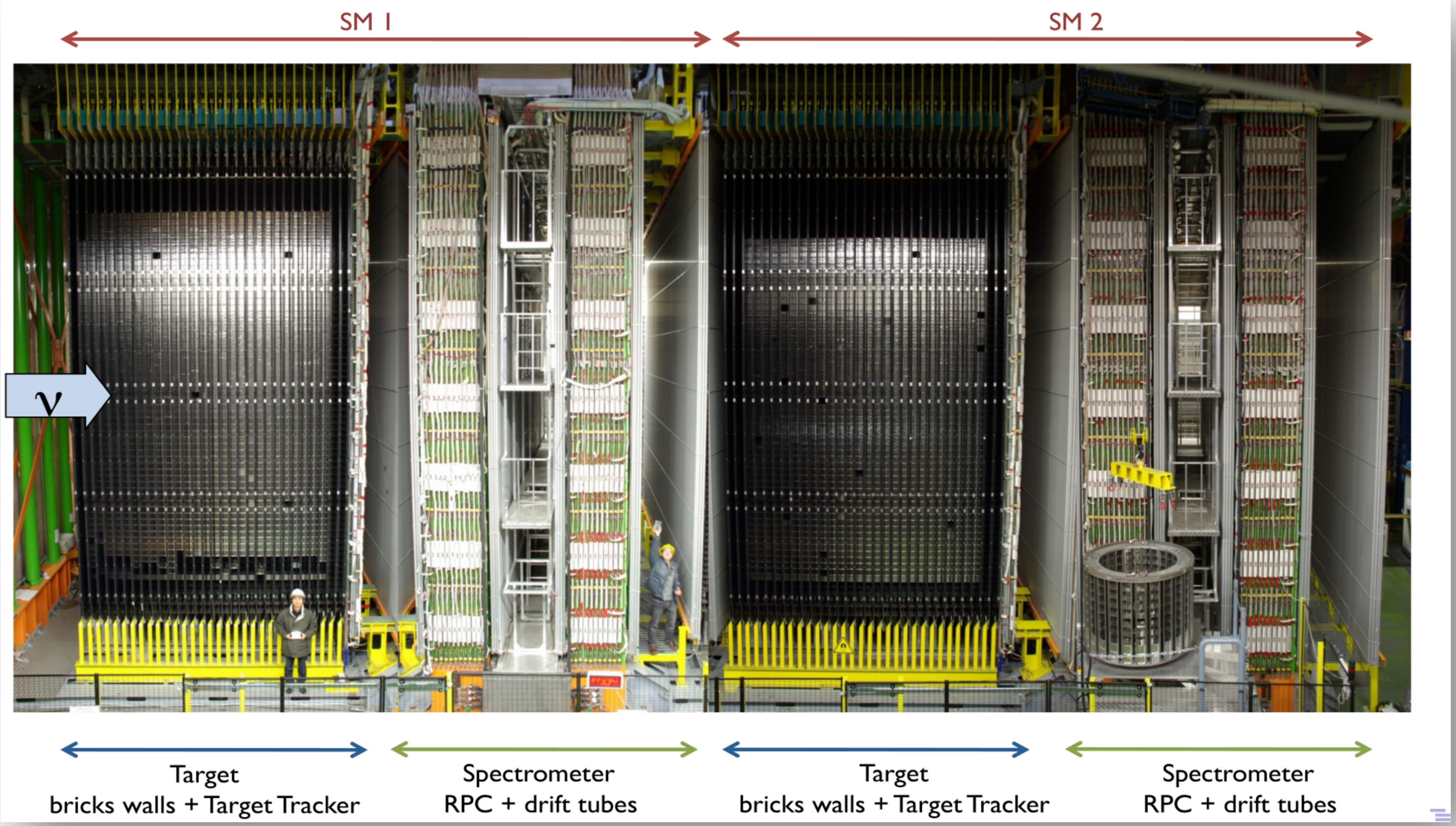
Total OPERA target : ~ 150000 bricks → 1.25 Kton

OPERA

The OPERA detector

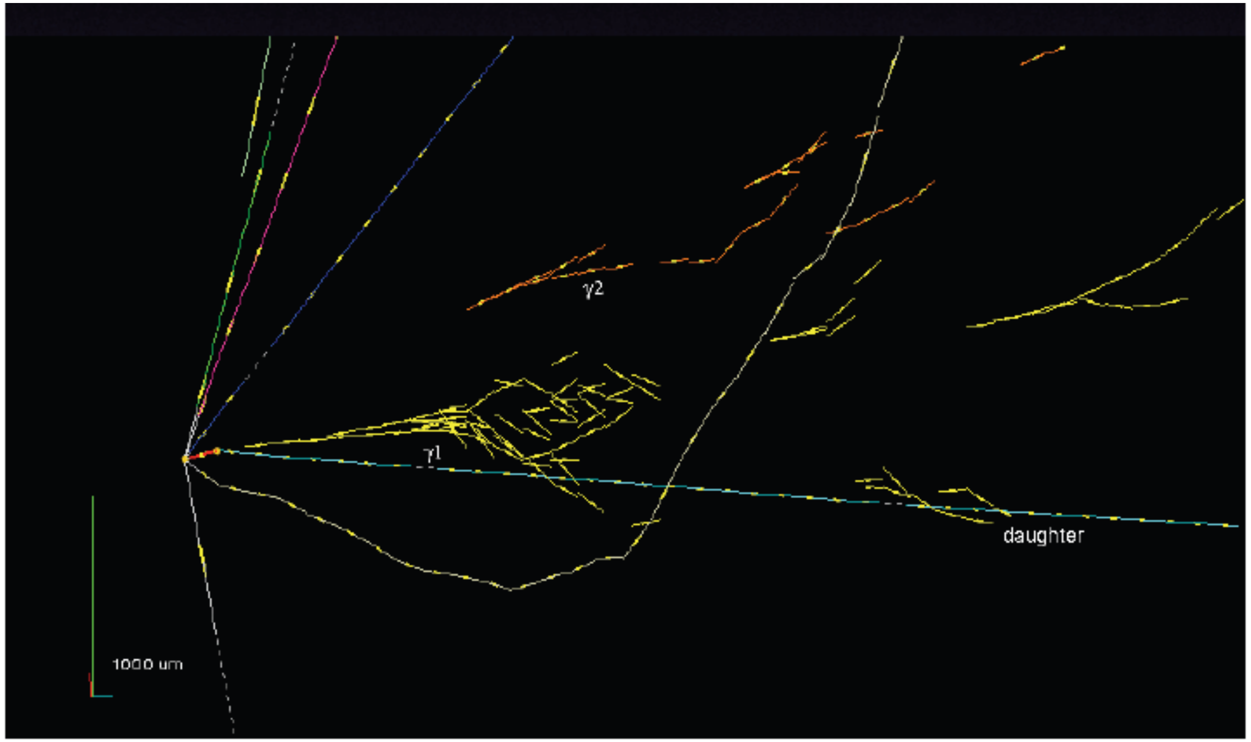
Spectrometers:

- Muon ID, momentum and charge measurement
- Track measurements are performed by RPC planes inserted in the magnet yoke (1.5 T field) and by drift tubes planes to add more precision

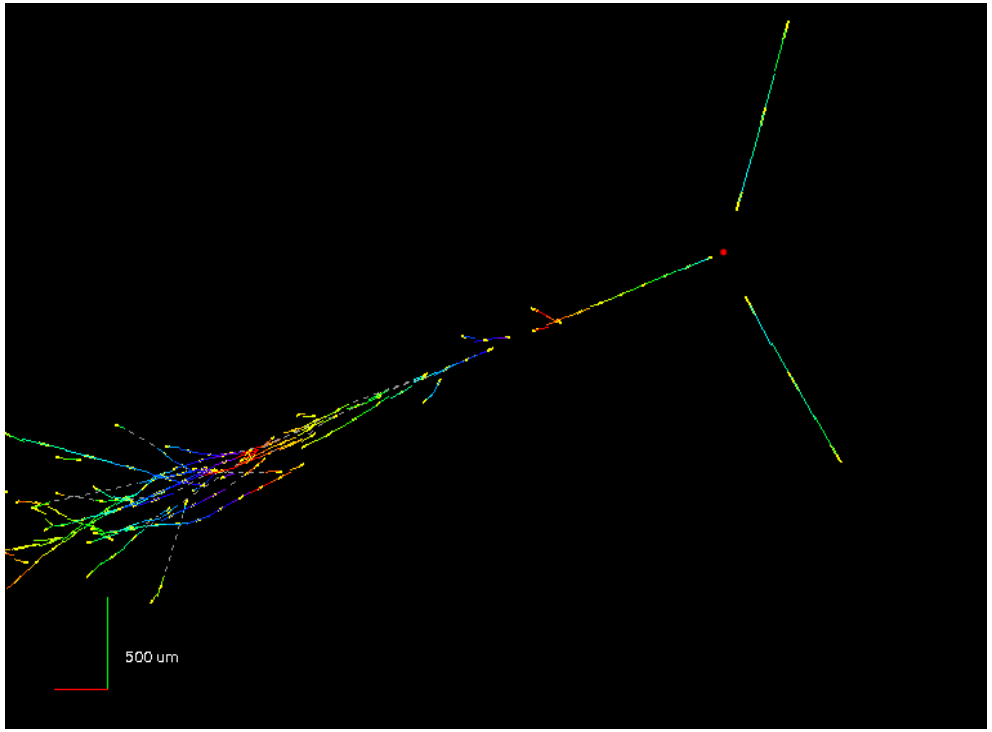


OPERA

First ν_τ candidate event



ν_e candidate event



- **5 ν_τ candidate events** fulfilling kinematical selection [Phys. Rev. Lett. 115, 121802 (2015)]
- **10 ν_τ candidate events** looser kinematical selection [Phys.Rev.Lett. 120 (2018)]
- **35 ν_e candidate events** localized **[**JHEP 1806 (2018)**]**
- **50 ν_μ interaction with charm production [**Eur.Phys.J. C 74 (2014) 8]

Discovery! 5.1 σ

6.1 σ

OPERA

3+1 model test

Phys.Rev.Lett. 120 (2018)

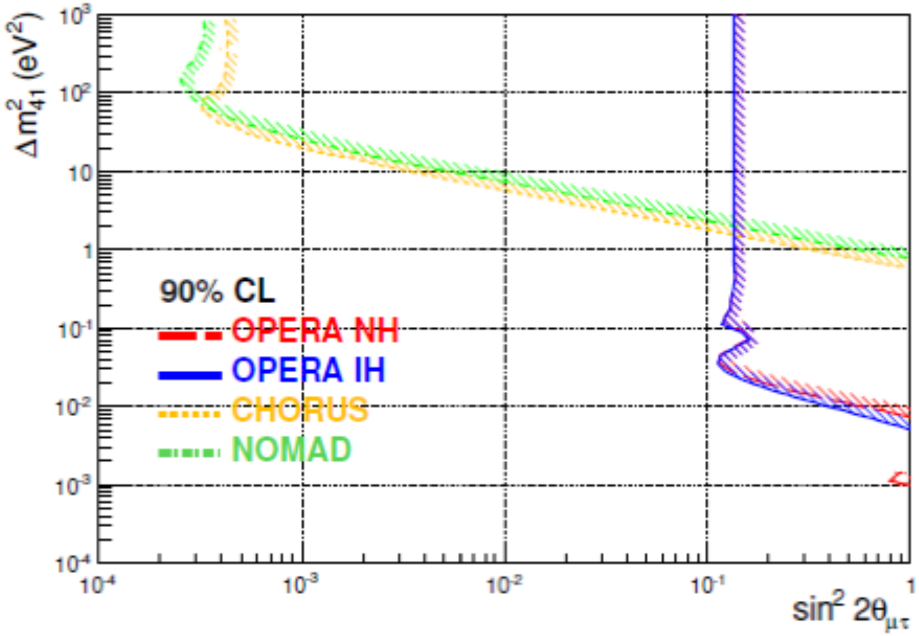


Figure 4. OPERA 90% CL exclusion limits in the Δm^2_{41} vs $\sin^2 2\theta_{\mu\tau}$ parameter space for the normal (NH, dashed red) and inverted (IH, solid blue) hierarchy of the three standard neutrino masses. The exclusion plots by NOMAD [14] and CHORUS [15] are also shown. Bands are drawn to indicate the excluded regions.

JHEP 1806 (2018)

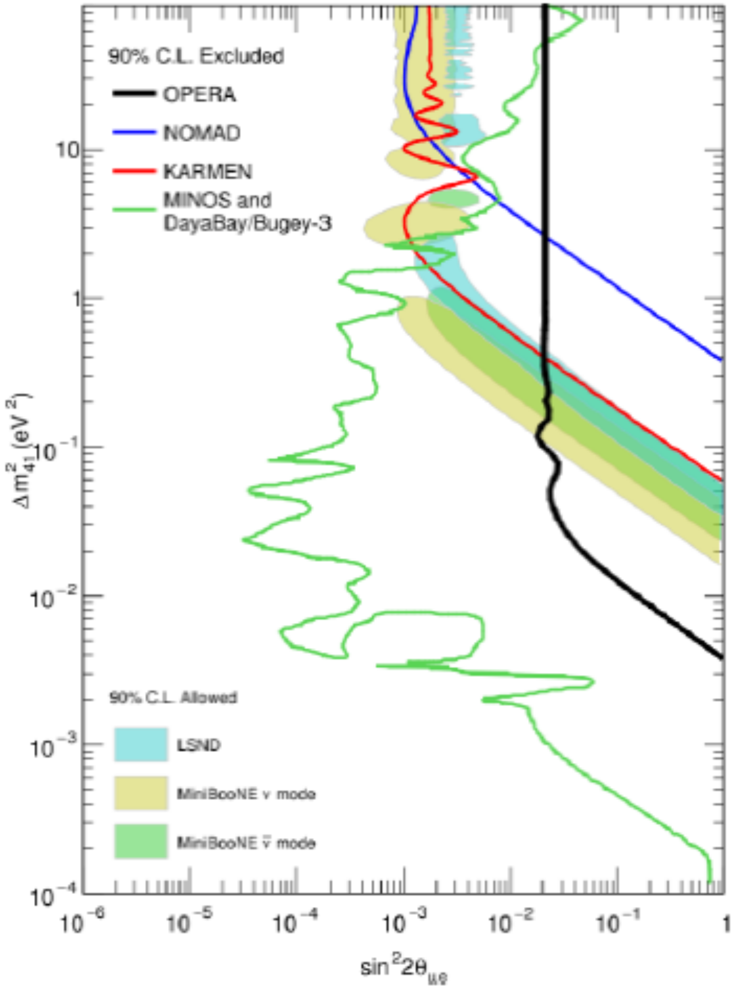
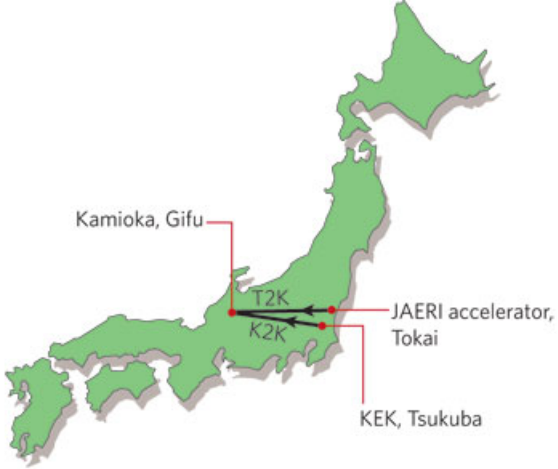


Figure 4. The 90% C.L. exclusion plot in the Δm^2_{41} and $\sin^2 2\theta_{\mu e}$ plane is shown (black line) together with the 90% C.L. allowed region obtained by LSND (cyan) and MiniBooNE (yellow and green for ν and $\bar{\nu}$ mode, respectively). The blue, red and green lines represent the 90% C.L. exclusion regions obtained by NOMAD [31], KARMEN [32] and the MINOS and DayaBay/Bugey-3 joint analysis [33], respectively.

T2K

T2K (Tokai-to-Kamioka) : L = 295 km, E~0.6 GeV
Off-axis 2.5°



T2K employs a set of near detectors at about 280 m from the production target. The on-axis detector, called **INGRID**, is an array of iron-scintillator sandwich trackers to monitor the beam intensity, direction and profile. The off-axis detector **ND280**, consisting of several sub-detectors inside a magnet, is placed in the direction of far detector to measure the neutrino beam properties and to study neutrino interactions

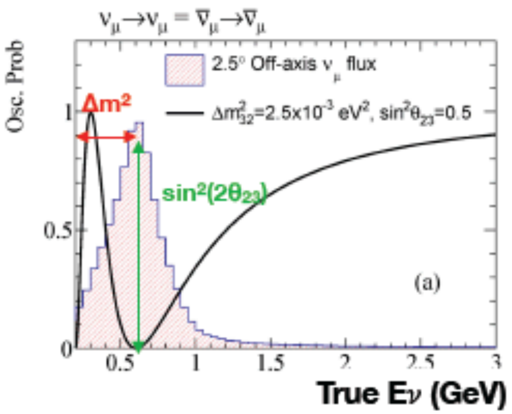
T2K

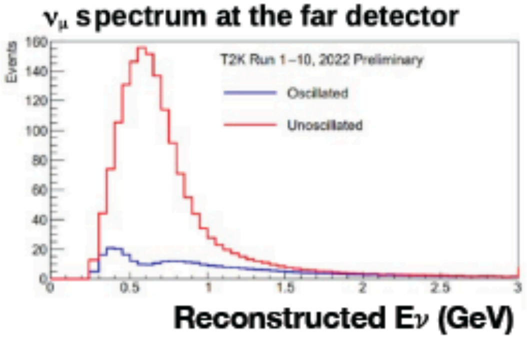
ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}





ν_e and $\bar{\nu}_e$ appearance

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}]$$

$$(\mp)\alpha\frac{J_0 \sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}]$$

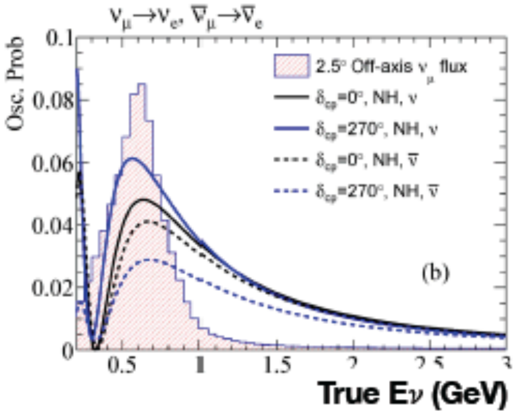
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

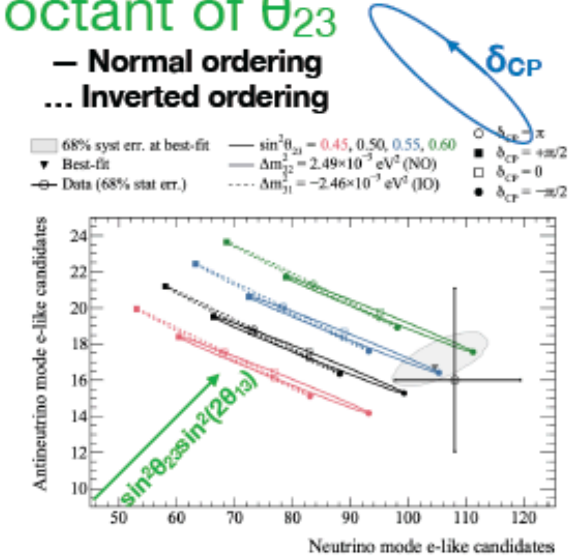
$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$

$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$

$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$

Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}





T2K

Constraint on the matter–antima ×

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Article | Published: 15 April 2020

Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

The T2K Collaboration

Nature **580**, 339–344(2020) | Cite this article

Abstract

The charge-conjugation and parity-reversal (CP) symmetry of fundamental particles is a symmetry between matter and antimatter. Violation of this CP symmetry was first observed in 1964[1], and CP violation in the weak interactions of quarks was soon established[2]. Sakharov proposed[3] that CP violation is necessary to explain the observed imbalance of matter and antimatter abundance in the Universe. However, CP violation in quarks is too small to support this explanation. So far, CP violation has not been observed in non-quark elementary particle systems. It has been shown that CP violation in leptons could generate the matter–antimatter disparity through a process called leptogenesis[4]. Leptonic mixing, which appears in the standard model's charged current interactions[5,6], provides a potential source of CP violation through a complex phase δ_{CP}, which is required by some theoretical models of leptogenesis[7,8,9]. This CP violation can be measured in muon neutrino to electron neutrino oscillations and the corresponding

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Matter–antimatter symmetry violated

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NOνA

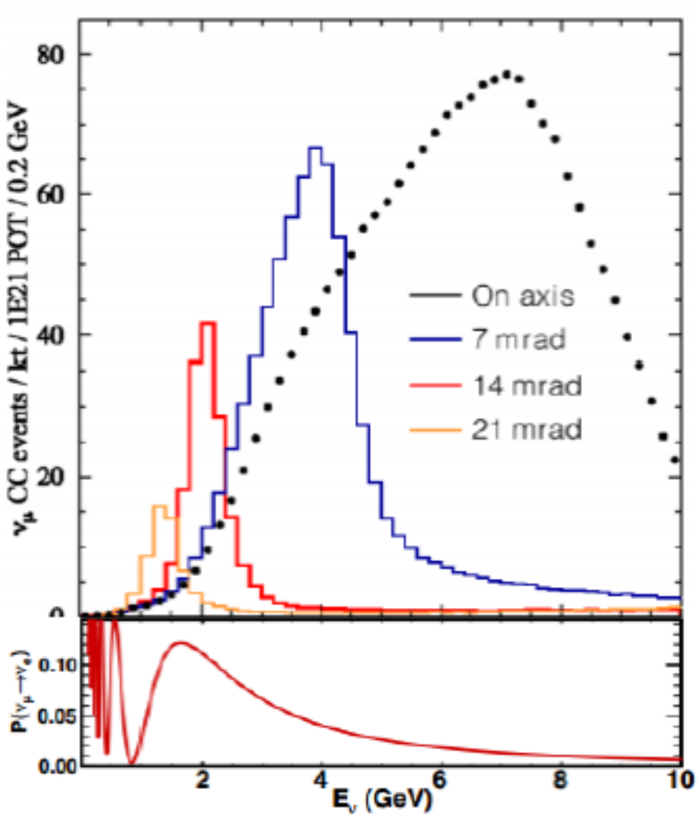
2014-today

The NOvA experiment uses the NuMI beamline with a 14.6 mrad off-axis configuration. The neutrino energy spectrum at the far detector has a peak around 2 GeV

The 14 kt NOvA **far detector** is located near Ash River, Minnesota, 810 km away from the source., corresponding to the first oscillation maximum at 810 km baseline.

The **near detector**, located around 1 km from the source, has a functionally identical design to the far detector with a total active mass of 193 t.

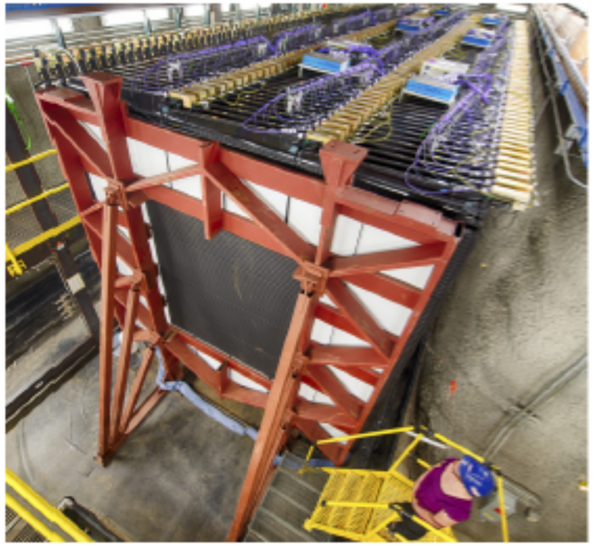
Both detectors are **tracking calorimeters** consisting of planes of polyvinyl chloride cells alternating in vertical and horizontal orientation filled with liquid scintillator.

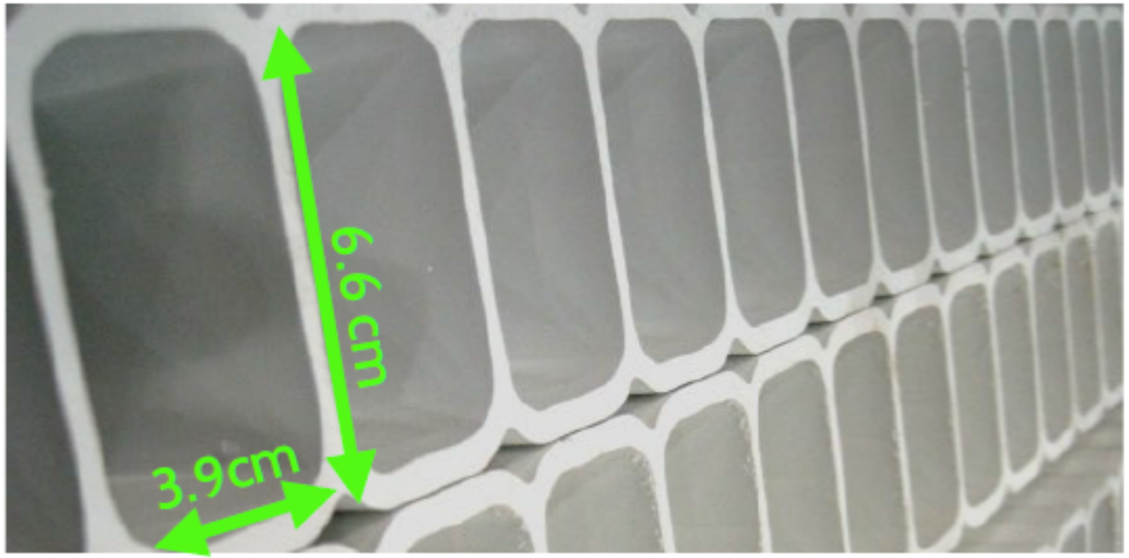


The oscillation maximum at L=810 km is ~2GeV

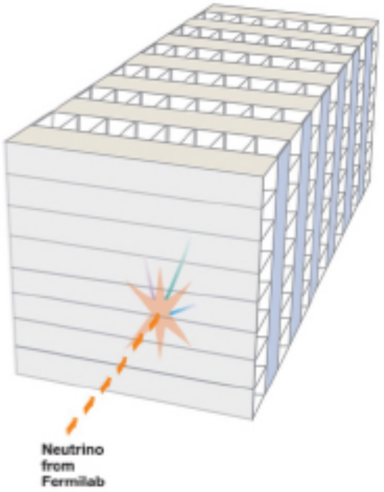
Constraining the energy improves background rejection.

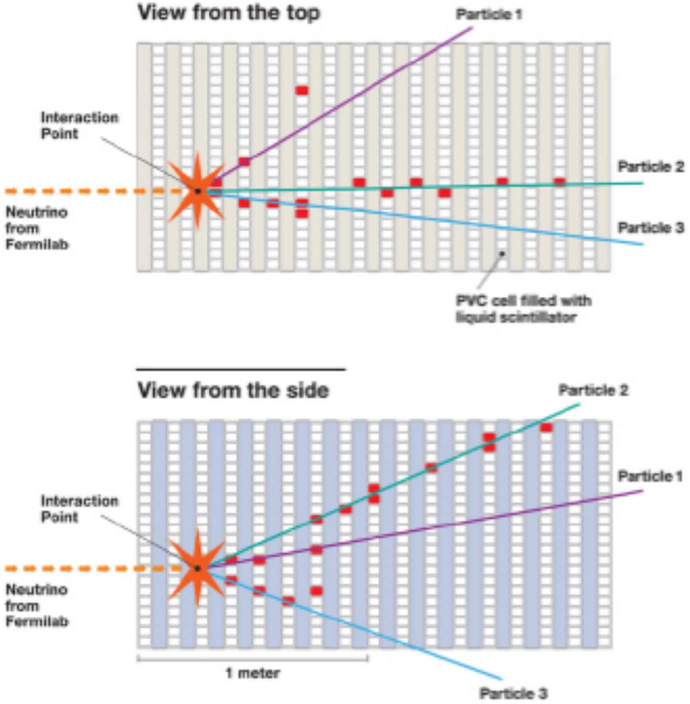
NOνA

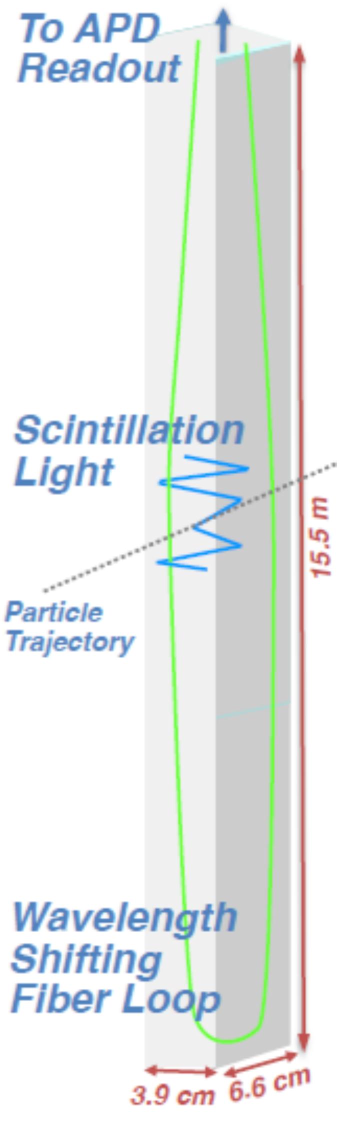




3D schematic of
NOvA particle detector

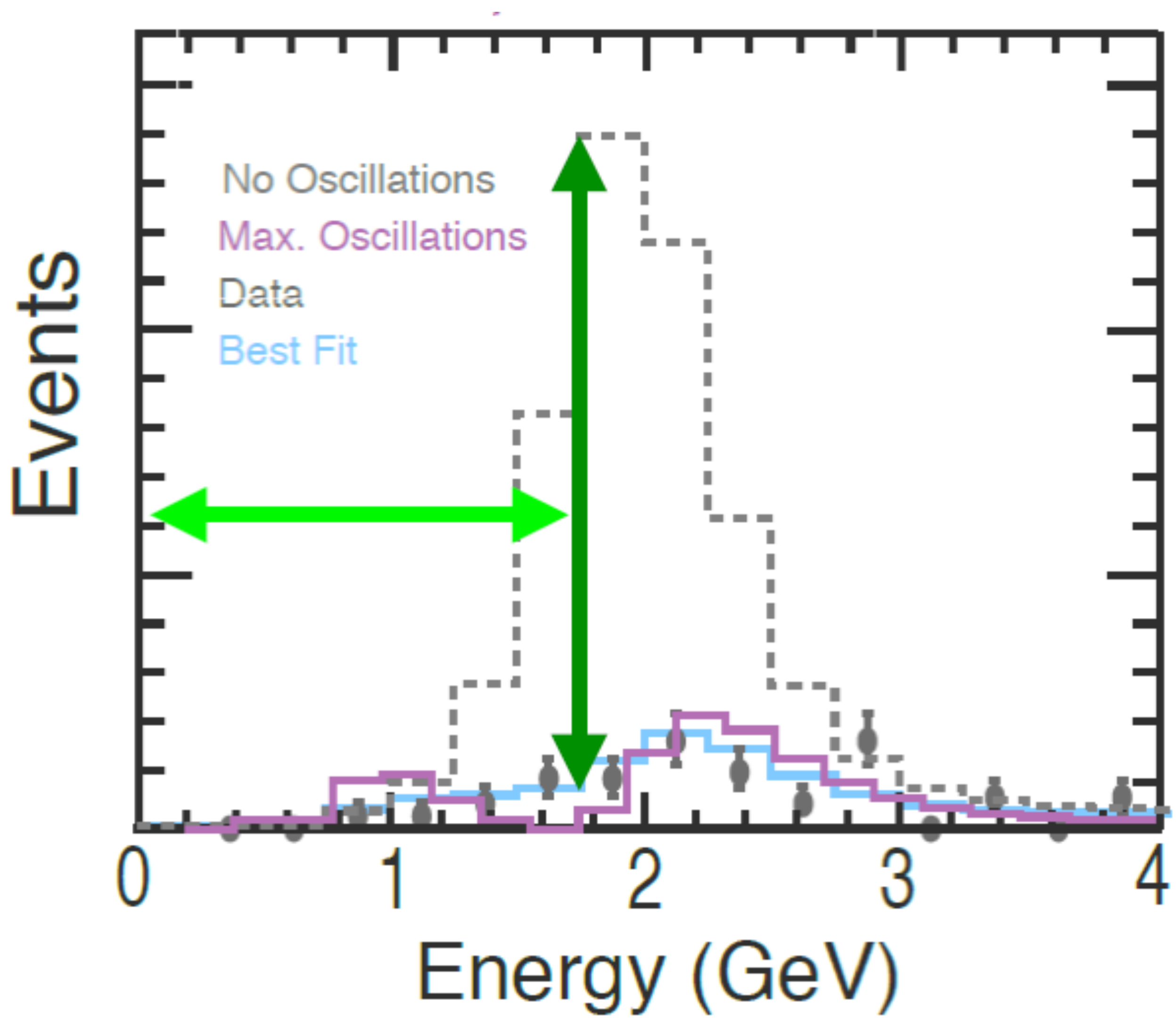






NOνA

Measuring ν_μ disappearance



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

[Nunokawa, Parke, Valle, Prog. Part. Nucl. Phys. 60, 338]

$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) \approx \left|\sqrt{P_{\rm atm}}\, e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}}\right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\,(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP})$$

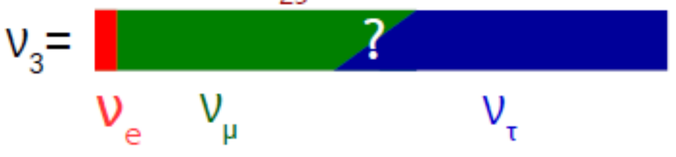
ν vs $\bar{\nu}$

with

$$\sqrt{P_{\rm atm}} \equiv \sin\theta_{23}\sin 2\theta_{13}\sin\Delta_{31}$$

$$\sqrt{P_{\rm sol}} \equiv \cos\theta_{23}\cos\theta_{13}\sin 2\theta_{12}\sin\Delta_{21}$$

(Is θ_{23} <, >, = 45°?)



$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

Is δ_{CP}/π non-integral?

(in *vacuum*)

[Nunokawa, Parke, Valle, Prog. Part. Nucl. Phys. 60, 338]

$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) \approx \left|\sqrt{P_{\rm atm}}\,e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}}\right|^2$$

ν vs $\bar{\nu}$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

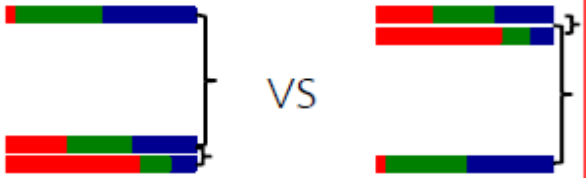
with

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\,\sin(2\theta_{13})\,\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\,\Delta_{31}$$

$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

Is δ_{CP}/π non-integral?

(Is θ_{23} <, >, = 45°?)

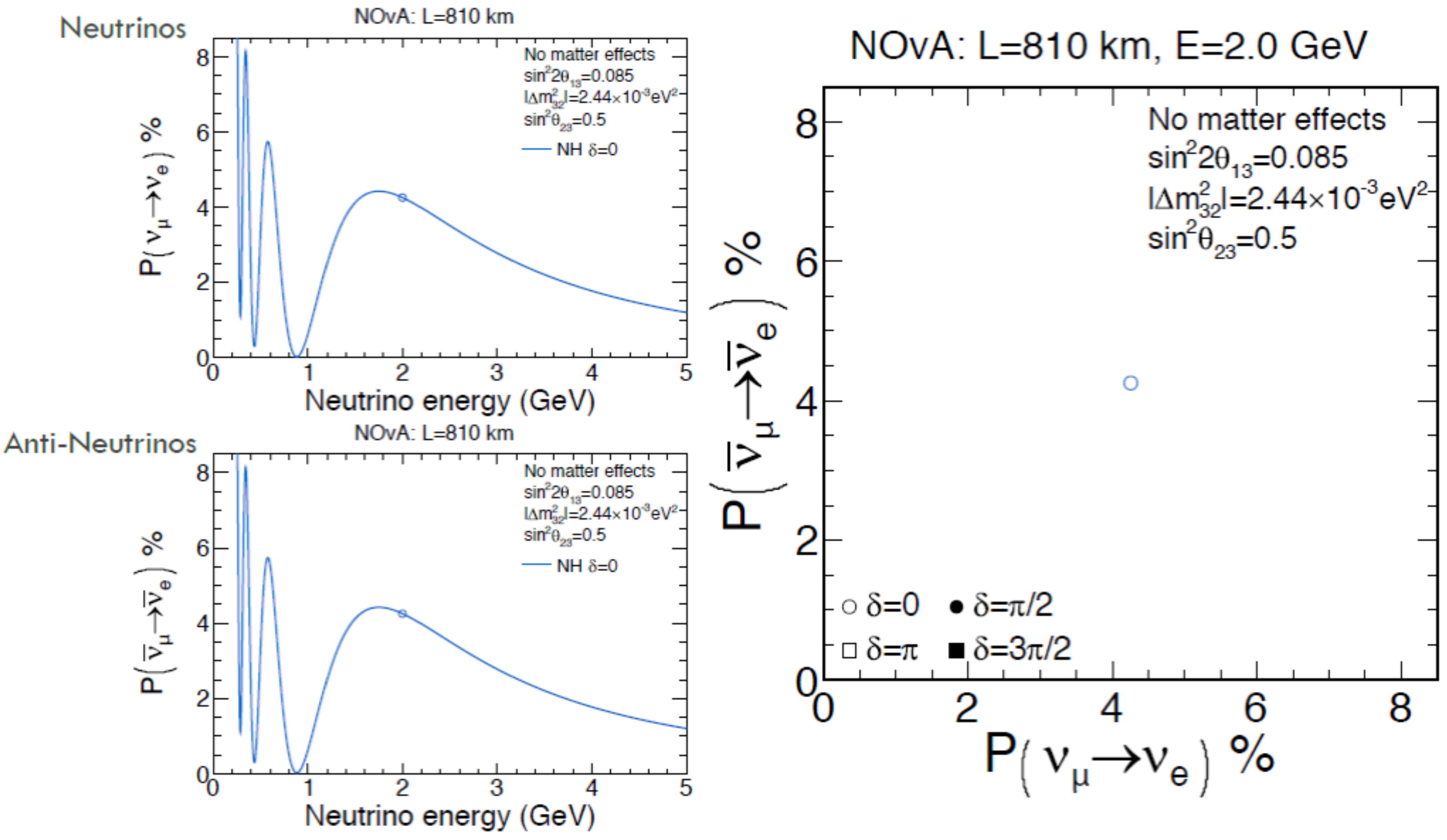


Is the mass hierarchy "normal" or "inverted?"

(in *matter*)

NOvA

Measuring ν_e and $\bar{\nu}_e$ appearance



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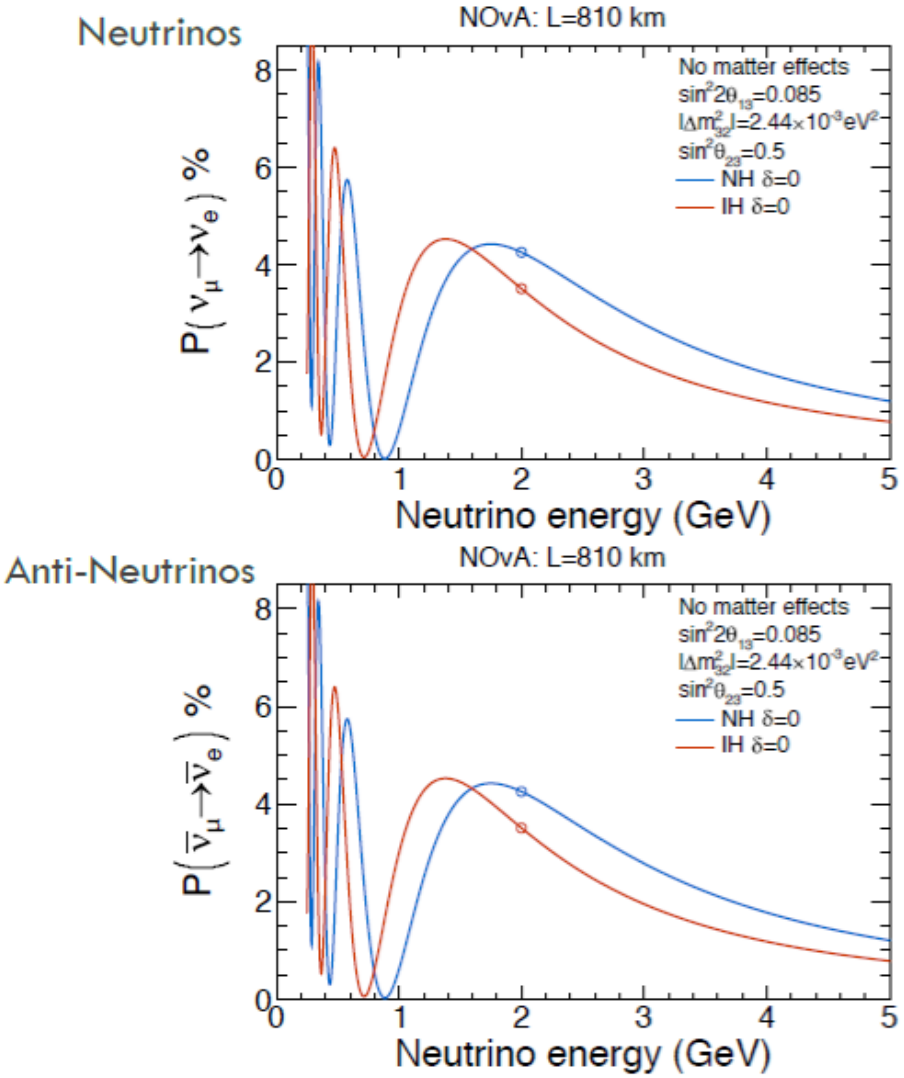
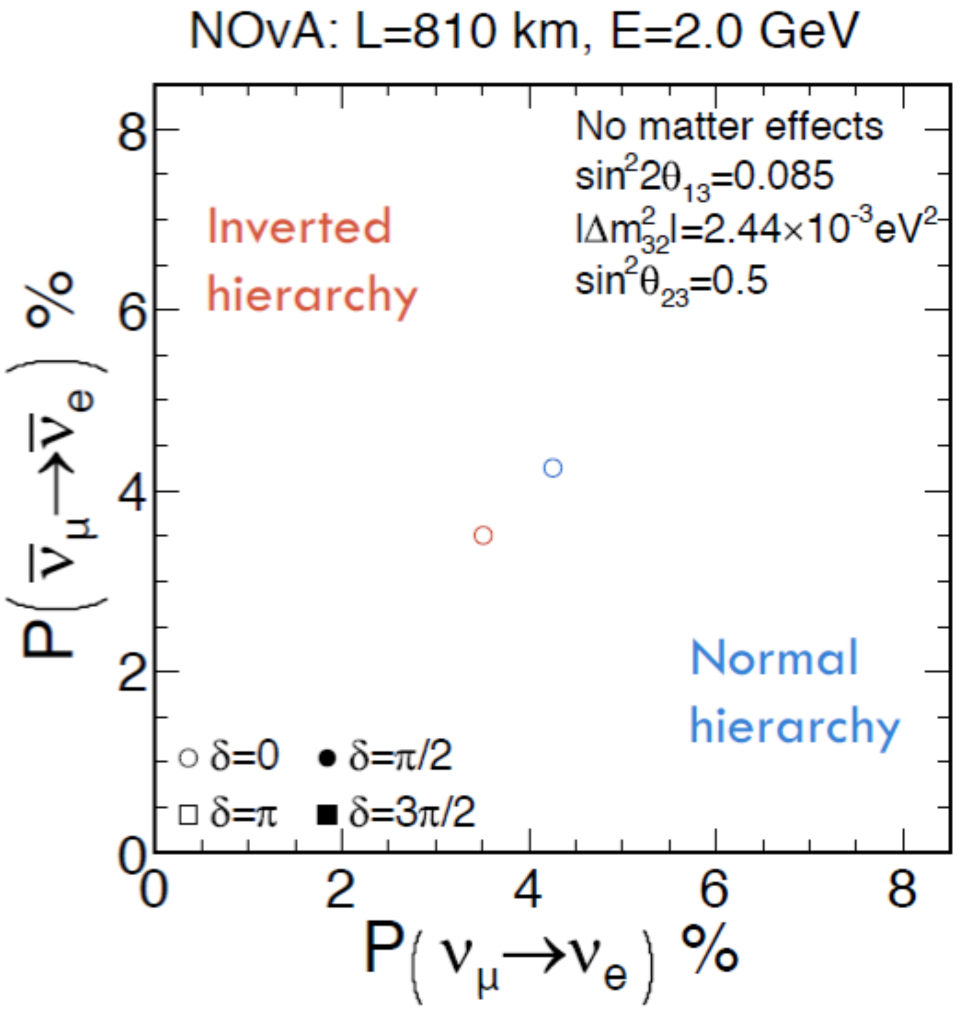
NOvA

Measuring ν_e and $\bar{\nu}_e$ appearance





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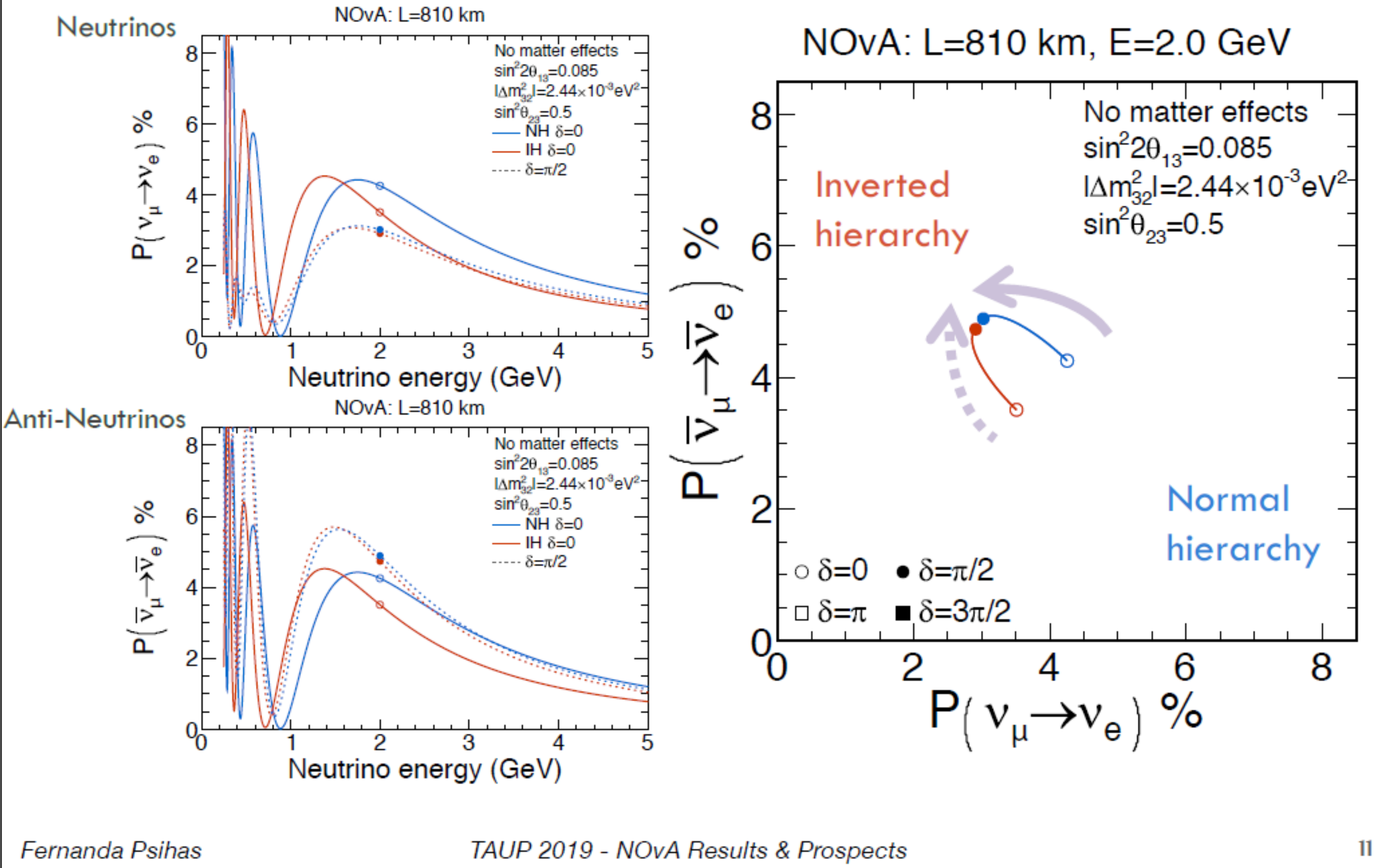
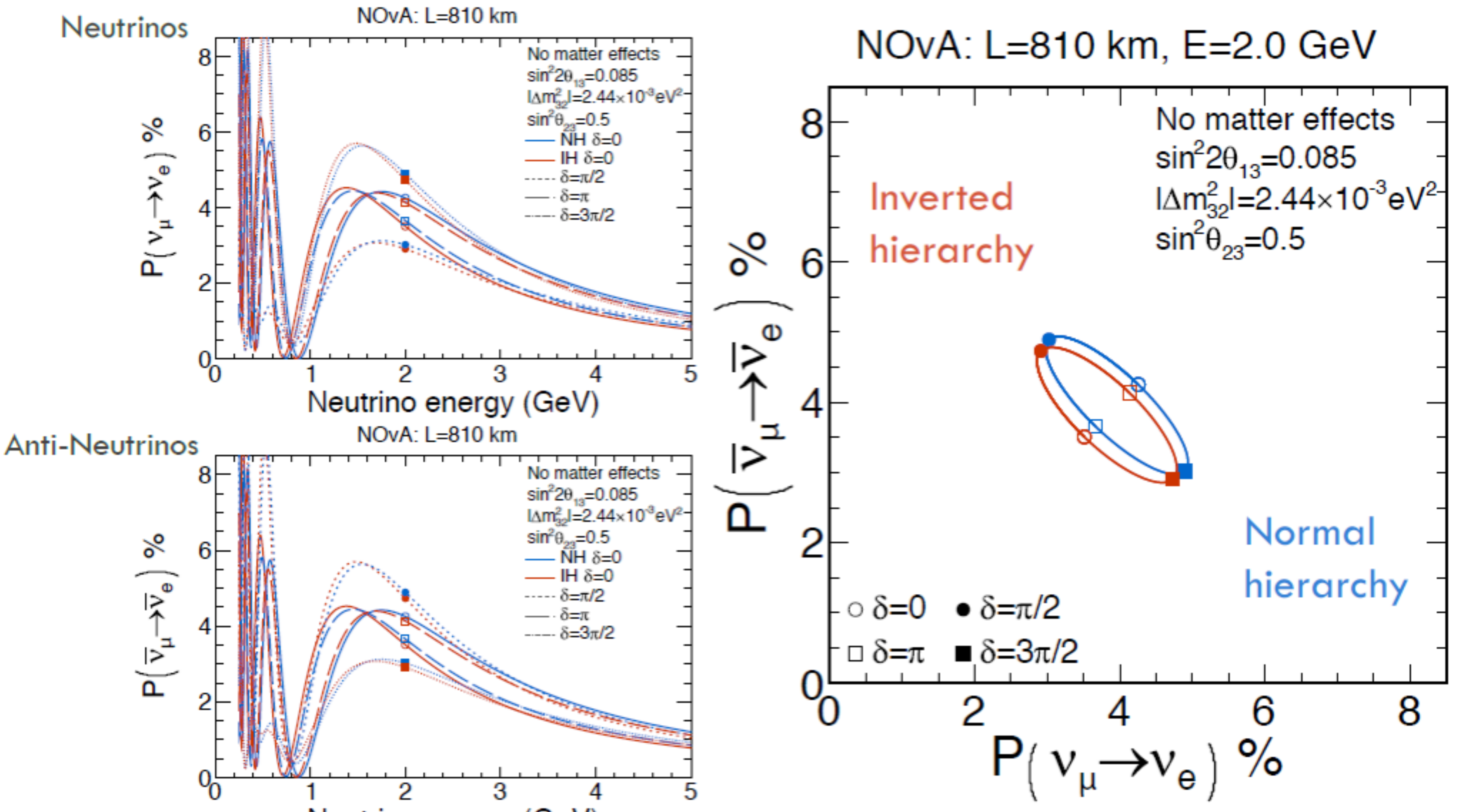
NOvA

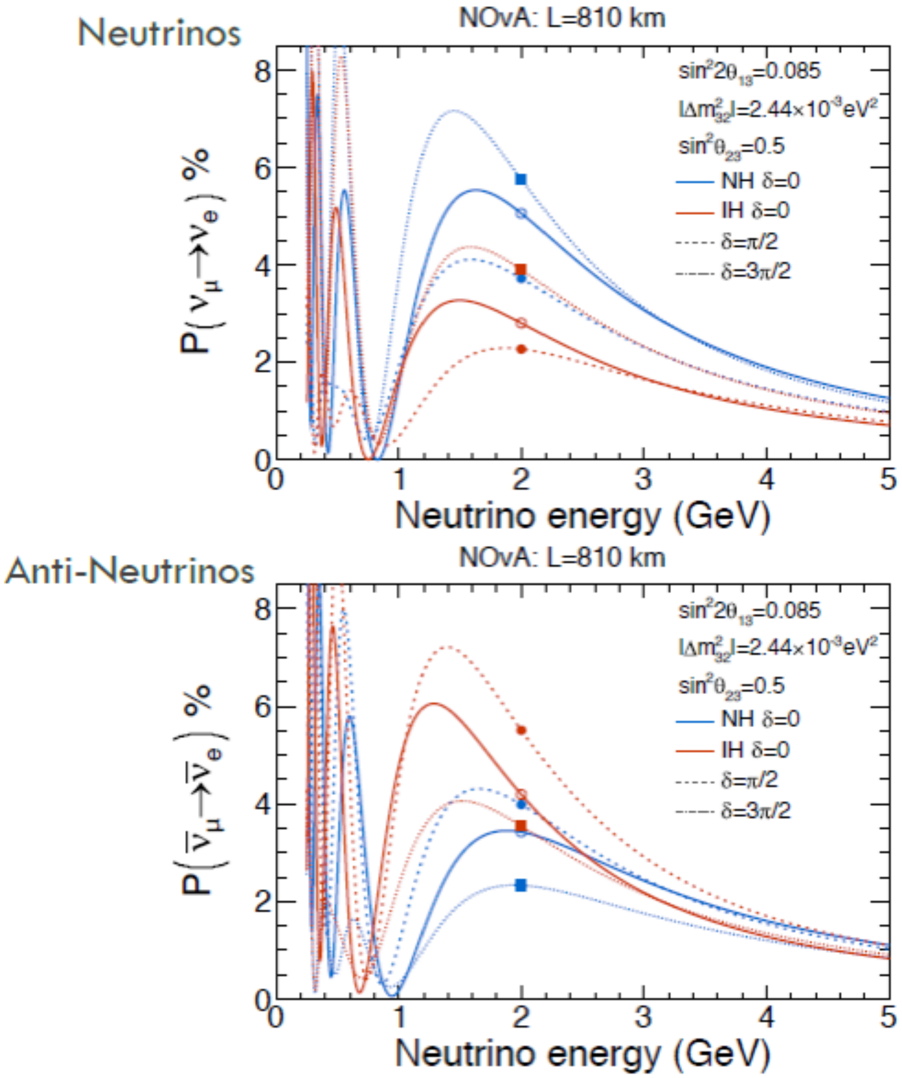
Measuring ν_e and $\bar{\nu}_e$ appearance

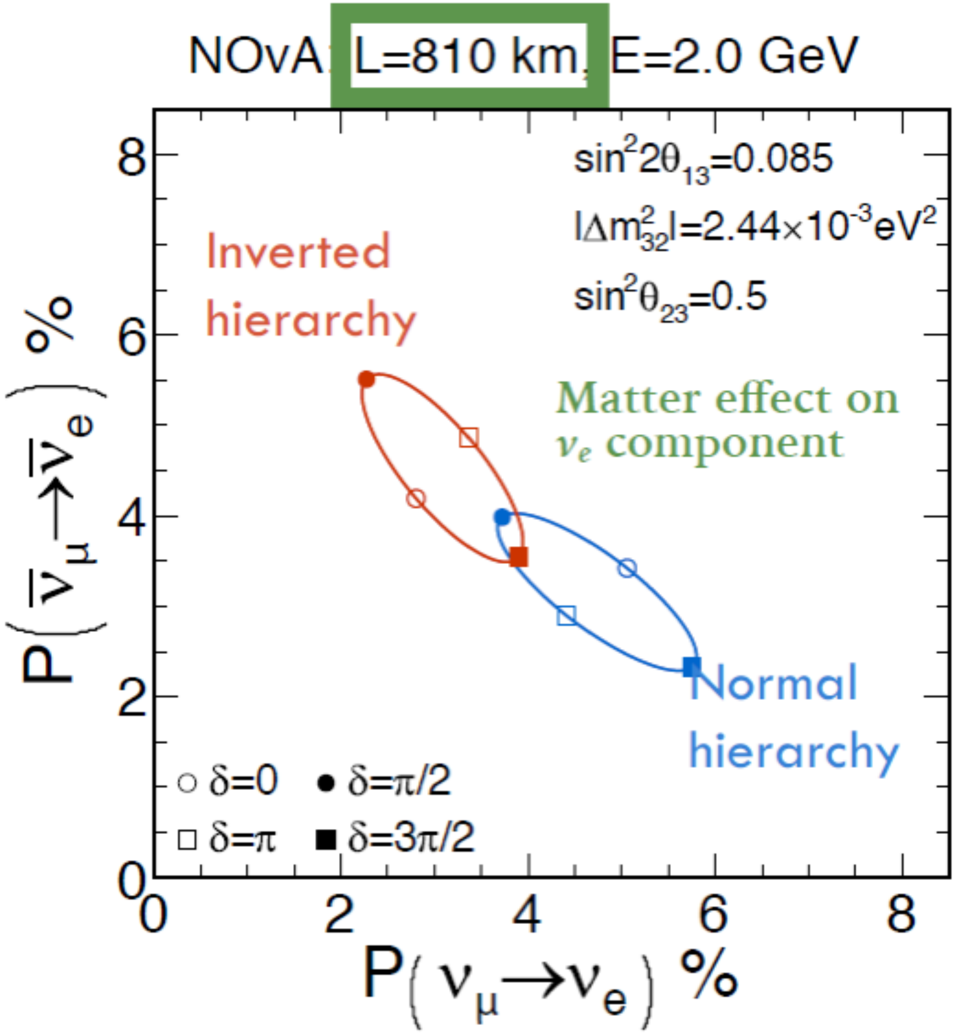


Measuring ν_e and $\bar{\nu}_e$ appearance



Measuring ν_e and $\bar{\nu}_e$ appearance

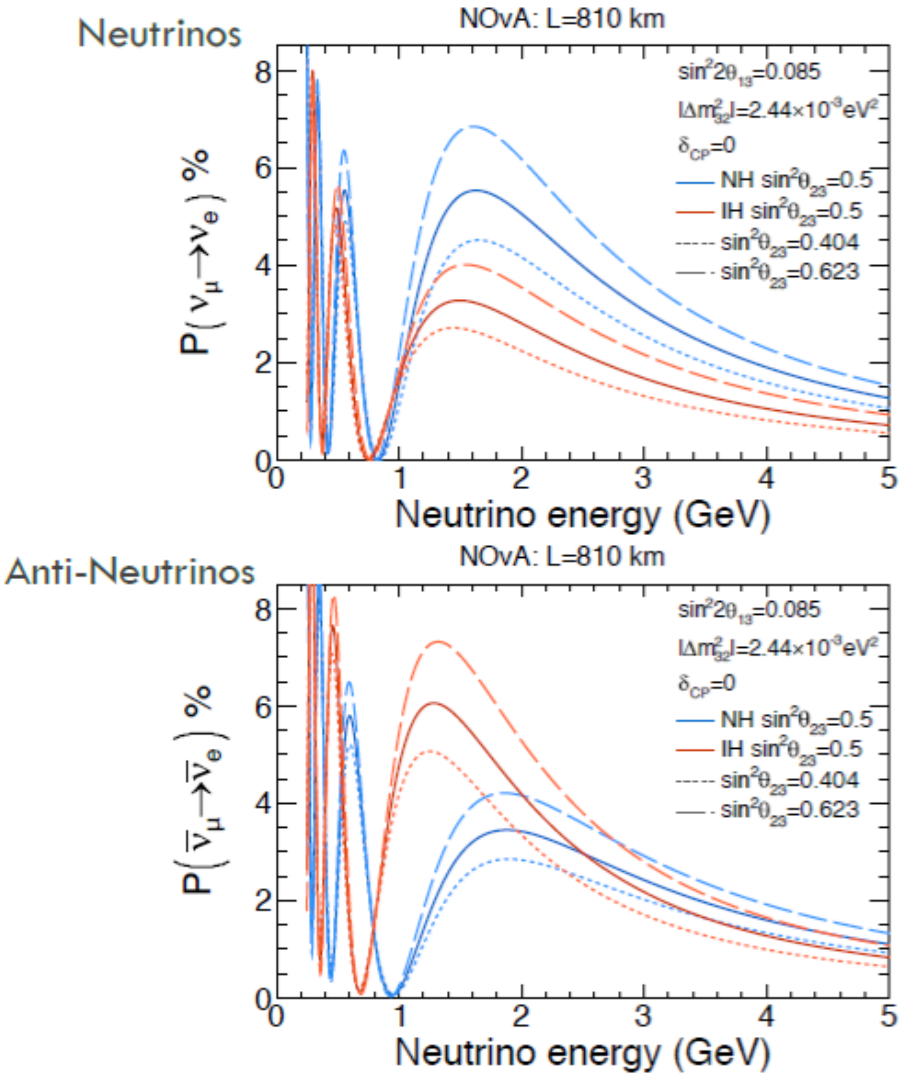


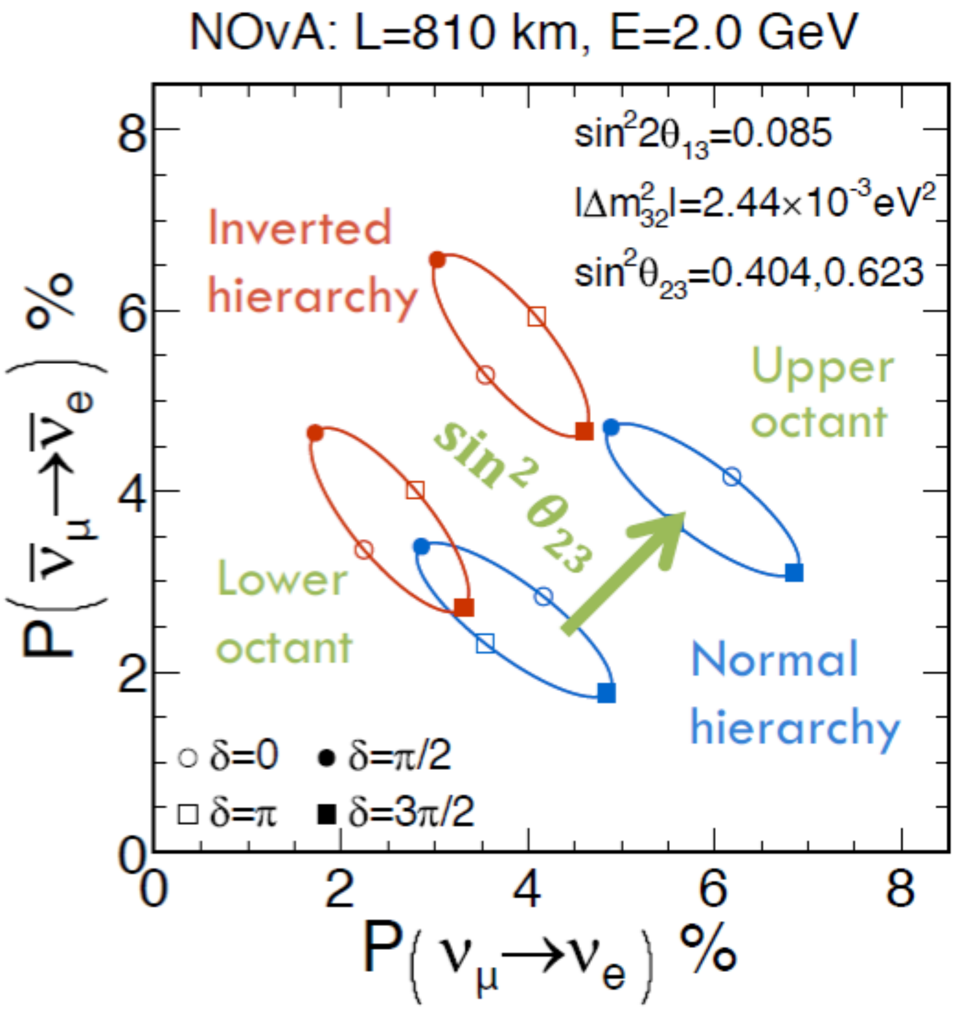


Larger matter effect at longer baselines like DUNE!

NOνA

Measuring ν_e and $\bar{\nu}_e$ appearance





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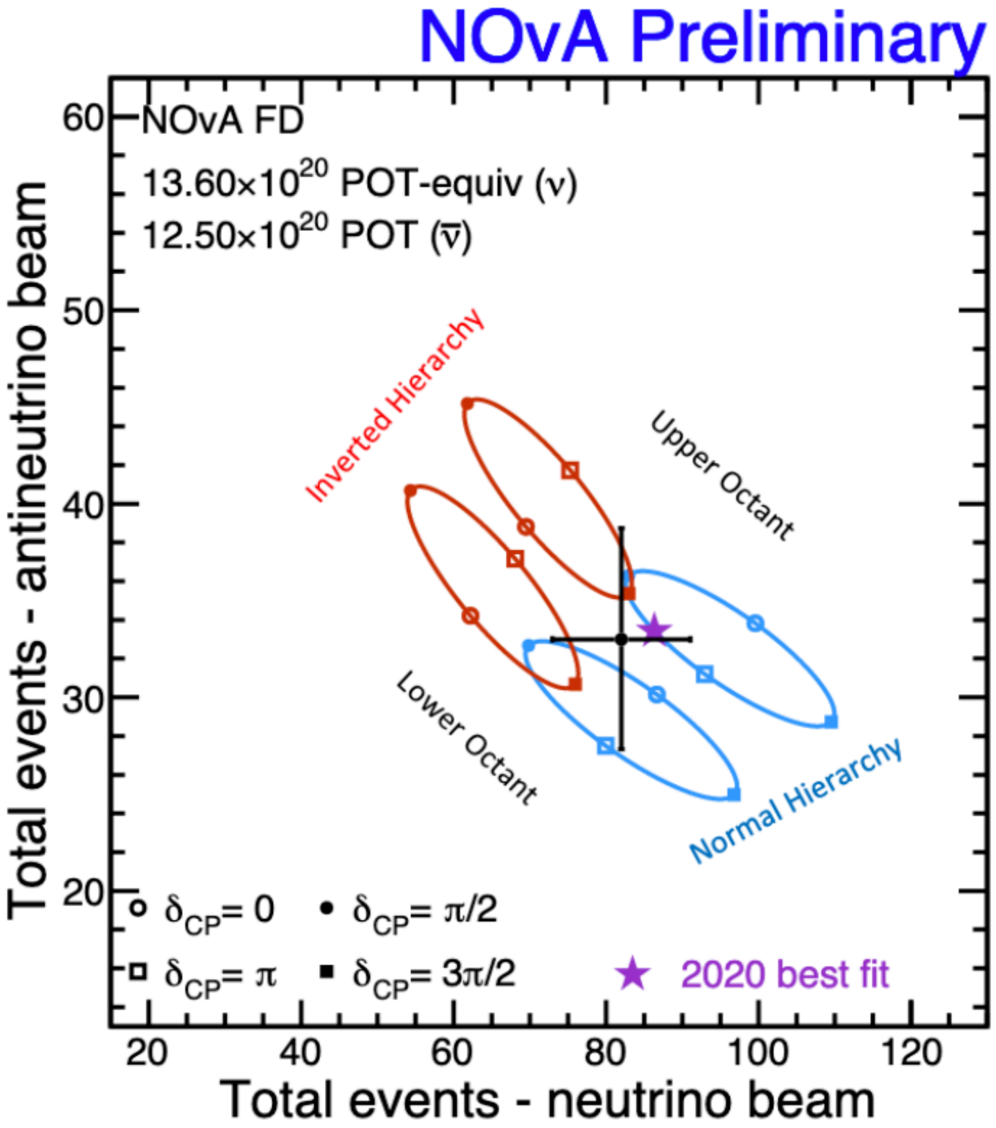
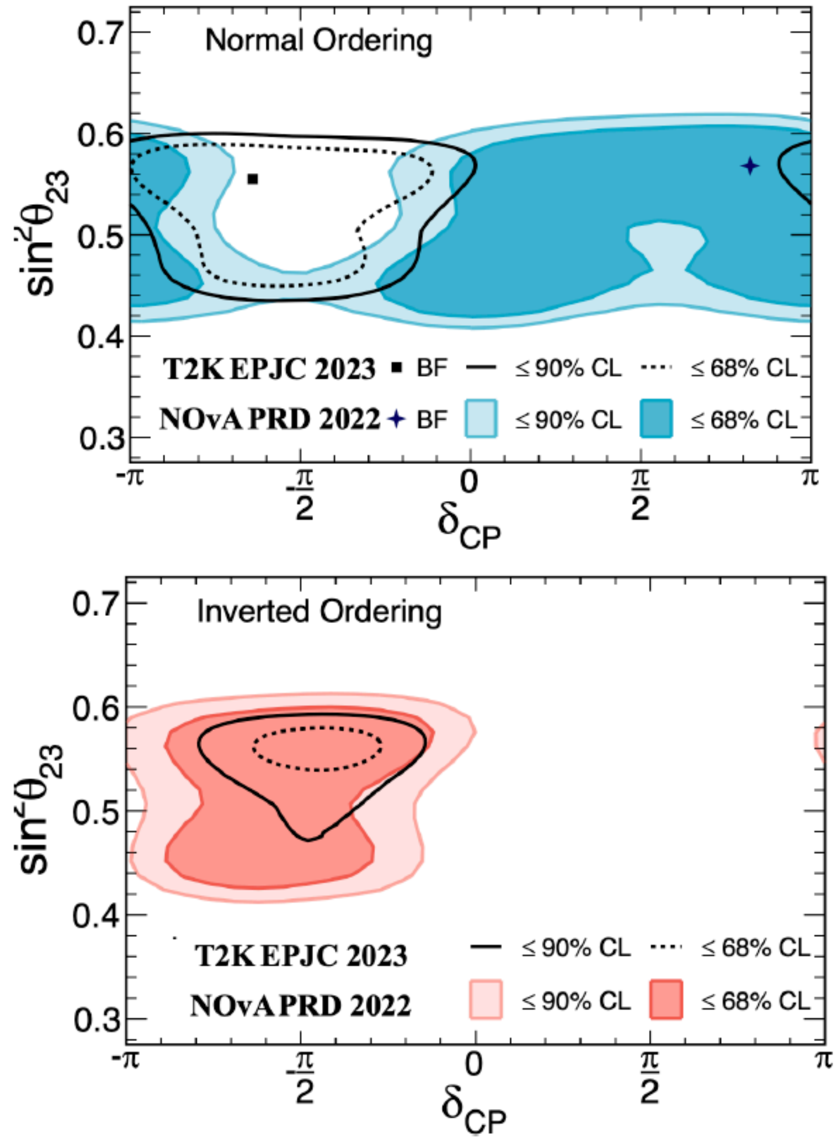
NOvA

Slight tension T2K & NOvA for NO



P Vahle, TAUP 2021



A. Booth, 2024

Short-baseline experiments

Channel	Experiments
$\nu_\mu \to \nu_\mu$	CHARM [212]
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$	CDHSW [396], CCFR [983]
$\nu_\mu \to \nu_e$	BEBC [89], CHARM [212], LSND [121], NOMAD [116]
$\bar{\nu}_\mu \to \bar{\nu}_e$	LAMPF-0645 [460], LSND [37], KARMEN [105]
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	BNL-E776 [265], CCFR [910], NuTeV [130]
$\nu_\mu \to \nu_\tau$	FNAL-E531 [1030], CHARM [212], CHORUS [422], NOMAD [115]
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$	CCFR [789]
$\nu_e \to \nu_\tau$	CHORUS [422], NOMAD [115]
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\tau$	CCFR [823])
Beam dump	BEBC [465, 559], CHARM [388], CDHSW [208]

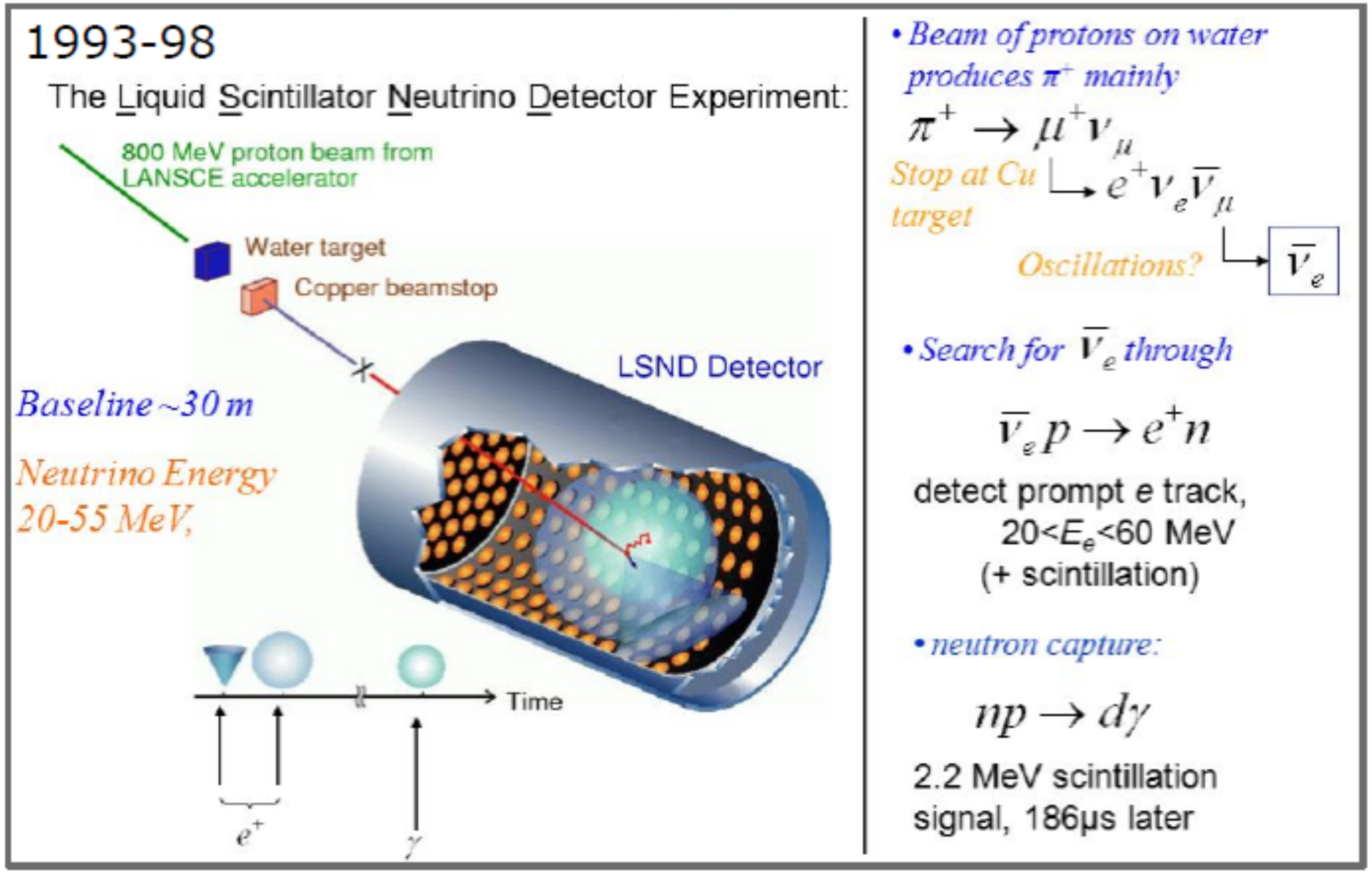
All the SBL accelerator experiments did not find any indication of neutrino oscillations, except for the LSND experiment, which found a signal in the $\bar{\nu}_\mu -> \bar{\nu}_e$channel and a weaker signal in the $\nu_\mu \to \nu_e$ channel

LSND

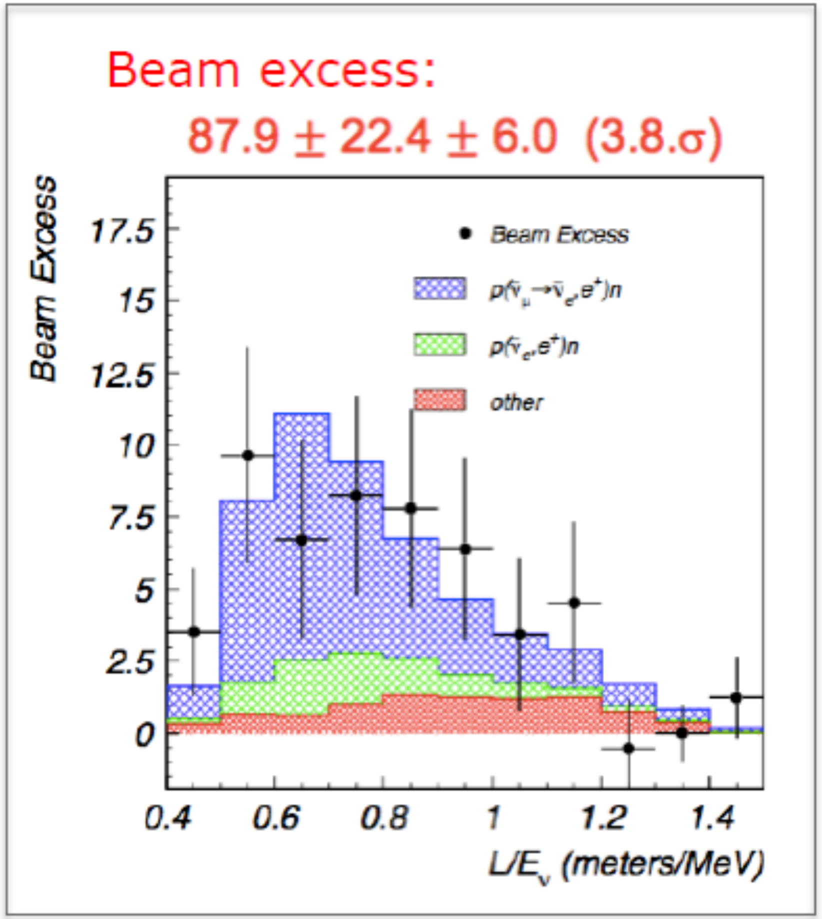
The LSND experiment searched for neutrino oscillation using neutrinos from stopped pions at Los Alamos.

A 800 MeV linac was used to produce pions which stopped in the target. Most of π^-s are absorbed by the nuclei inside the target, while π^+ s and their daughter μ^+ s decay and produce neutrinos. Therefore, the produced neutrinos are mostly **ν_μ, $\bar{\nu}_\mu$ and ν_e with very small contamination of $\bar{\nu}_e$** .

The detector was a tank filled with 167 t of diluted liquid scintillator, located about ***30 m from the neutrino source***. LSND searched for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance using the inverse beta decay process, $\bar{\nu}_e + p \longrightarrow e^+ + n$, and found an excess of 87.9 ± 22.4 ± 6.0 events over the expected background.



(Pedro Ochoa)



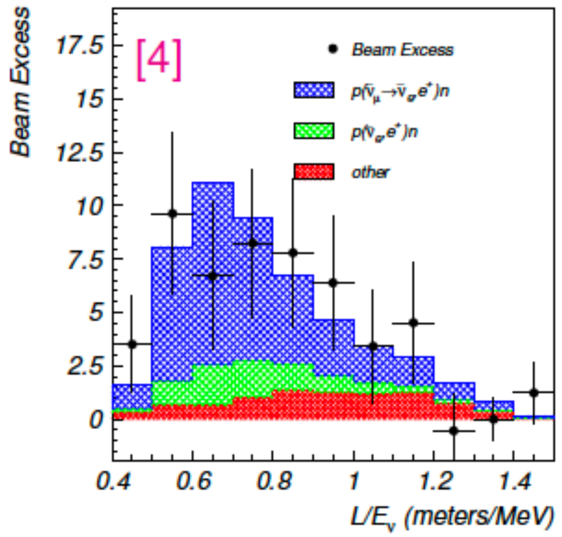
PRD 64, 112007 (2002)

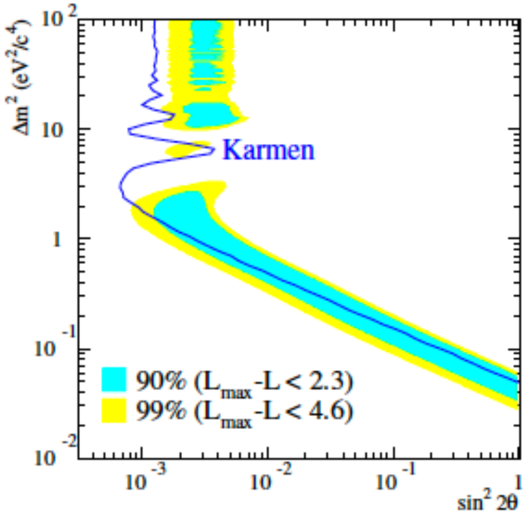
A long time ago... the LSND anomaly

- Back in the 90's, the LSND experiment observed an excess of $\bar\nu_e$ events in a $\bar\nu_\mu$ beam ($E_\nu \sim 30$ MeV, $L \simeq 35$ m) [4];
- the Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [5];
- the signal is compatible with $\bar\nu_\mu \to \bar\nu_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV^2;
- on the other hand, global neutrino data give (at 3σ):

$$\Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5} \text{ eV}^2 ,$$
$$|\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3} \text{ eV}^2 ;$$

- hence, to explain LSND with mass-induced ν oscillations one needs **new** neutrino mass eigenstates;
- MiniBooNE: much larger E_ν and L but similar L/E_ν.

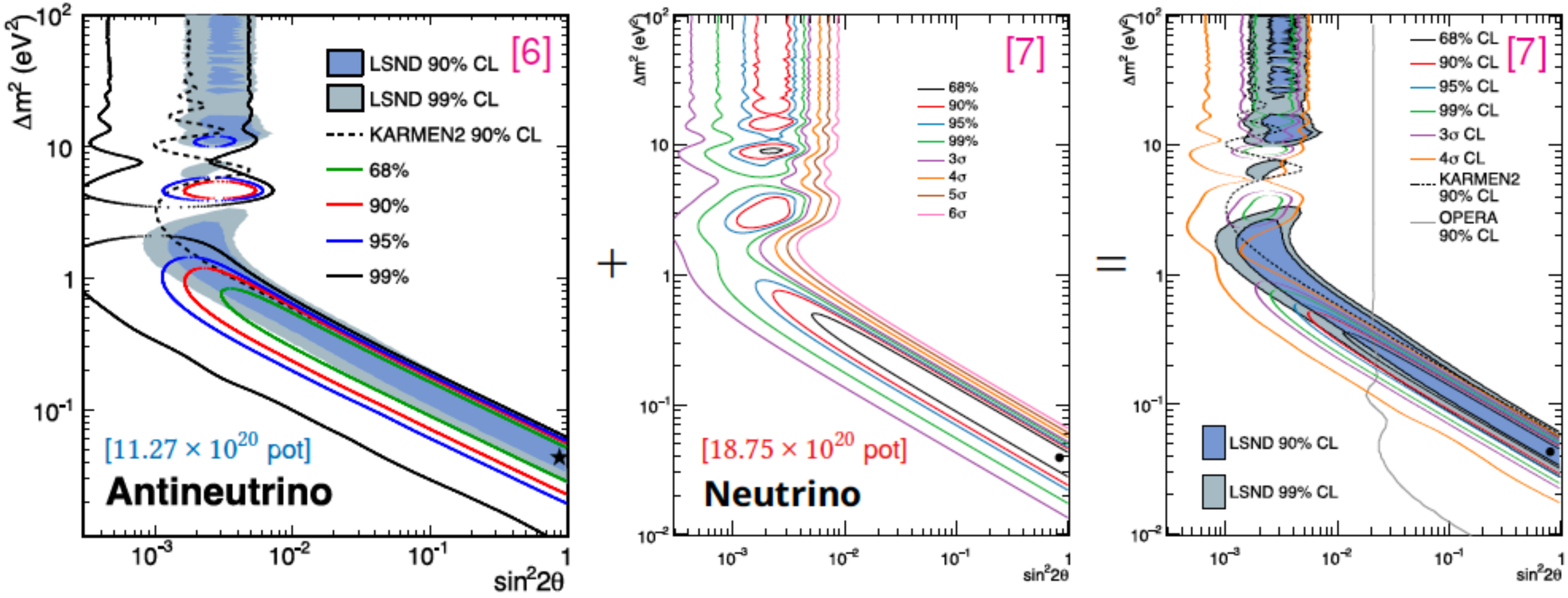




[4] A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007 [hep-ex/0104049]
[5] B. Armbruster *et al.* [KARMEN collab], Phys. Rev. D **65** (2002) 112001 [hep-ex/0203021]

The MiniBooNE experiment

- MiniBooNE searched for $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$ conversion ($E = 200 \to 1250$ MeV, $L \simeq 541$ m);
- excess in both $\bar\nu$ and $\nu \Rightarrow$ oscillations compatible with LSND (ev $= 4.8\sigma$, gof $= 12.3\%$);
- however, the low energy part of the excess **cannot** be accounted just by oscillations…



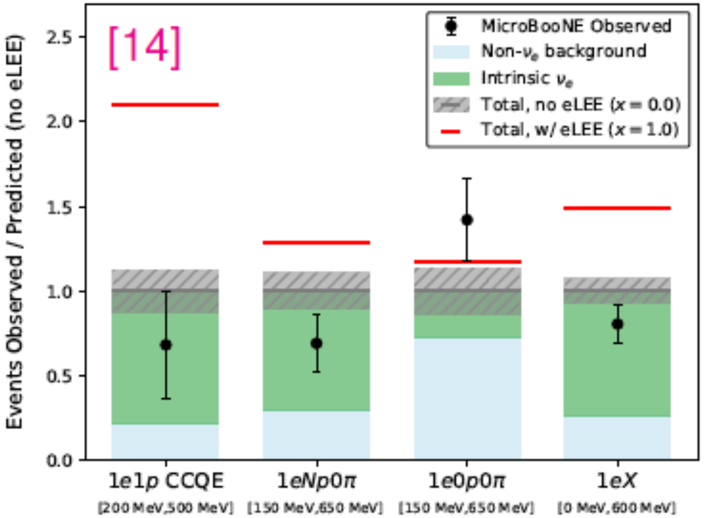
[6] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801 [arXiv:1303.2588]
[7] A. Hourlier, talk at Neutrino 2020, Fermilab (online), USA, 22/6-2/7/2020

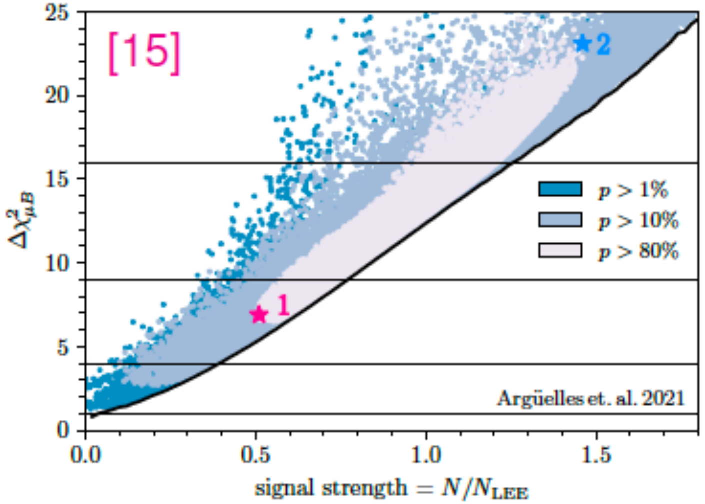
The MicroBooNE experiment

- Baseline = 468.5 m (72.5 m upstream of MiniBooNE);
- LArTPC ⇒ imaging with mm-scale spatial resolution;

⇒ perfectly suited to cross-check MiniBooNE excess;

- first results presented in fall 2021:
  - no evidence of enhanced π^0 or γ production [13];
  - no evidence of ν_e excess over SM prediction [14];
- however, rejection of MB signal in [14] based on the assumption that the entire ν_e excess matches the difference between data and best-fit MB background;
- but in [15] it was noticed that various signal/background compositions can fit MB equally well, but lead to different μB sensitivity ⇒ rejection **not** model-independent…

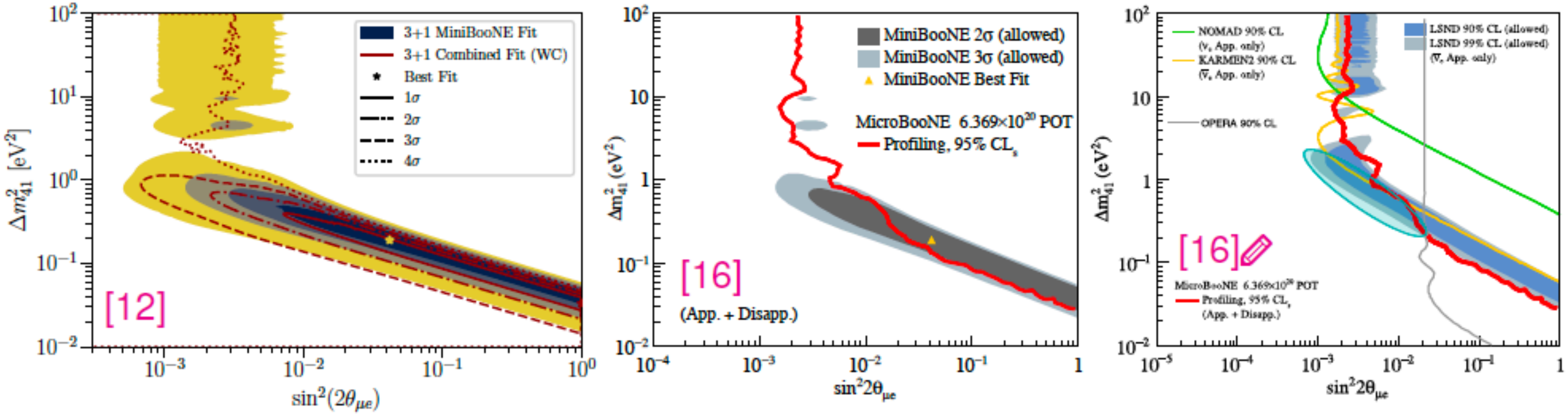




[13] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 111801 [arXiv:2110.00409]
[14] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 241801 [arXiv:2110.14054]
[15] C.A. Argüelles *et al.*, Phys. Rev. Lett. **128** (2022) 241802 [arXiv:2111.10359]

Comparison of MicroBooNE and MicroBooNE results

- MiniBooNE: updated analysis including μB bounds [12] $\Rightarrow 3\sigma$ region at $\Delta m^2_{41} \lesssim 1$ eV;
- MicroBooNE: global 4ν analysis [16] disfavors MB/LSND but does not rule it out completely;
- other experiments exclude large Δm^2 (NOMAD) and large $\theta_{\mu e}$ (ICARUS, OPERA);
- remaining allowed region at $0.1 \lesssim \Delta m^2_{41}/\text{eV}^2 \lesssim 1$ and $10^{-3} \lesssim \sin^2\theta_{\mu e} \lesssim \text{few} \times 10^{-2}$;
- Short Baseline Neutrino Program @ Fermilab: see next talks; ⇝ [Caratelli, Gibin, …]
- Japan: JSNS^2 will provide an independent check of LSND/MiniBooNE excess. ⇝ [Marzec]



[12] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]
[16] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **130** (2023) 011801 [arXiv:2210.10216]

Outline

Reactor neutrino experiments

Nuclear reactors are very intense sources of $\bar{\nu}_e$'s **in the MeV energy region**, which are generated in β-decays of the fission products of heavy isotopes (mainly ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu).

About 6 $\bar{\nu}_e\,'s$ + 200 MeV of energy released per fission: 1 GWth (thermal power) reactor produces about $2 \times 10^{20}\ \bar{\nu}_e/s$

The detailed estimate of $\bar{\nu}_e$ flux and energy spectrum can be obtained by either **summing up the spectra of beta decays** involved using available nuclear data information of each fission fragment and its decays, or using **measurements of cumulative electron spectra** associated with the beta decays of fission fragments: the fission of four main fuel isotopes involves thousands of beta-decay branches,

Reactor Neutrino Anomaly (RAA)

- Phys. Rev. **C83**, 054615 (2011), Phys. Rev. **C84**, 024617 (2011): predict about 3% higher normalization for the energy averaged antineutrino fluxes compared to the original analyses of ILL (Institute Laue-Lanvegin reactor @ Grenoble, 1980) data.

- Flux measurement at Daya Bay [Phys. Rev. **D100**, 5, 052004 (2019)] is consistent with the old flux predictions.

- An excess of $\bar{\nu}_e$ flux around 5 MeV, compared to the prediction, has been observed by recent reactor experiments [DOUBLE CHOOZ, DAYA BAY, RENO].

- Measurements of a fuel-dependent reactor $\bar{\nu}_e$ rate by Daya Bay [Phys. Rev. Lett. **118**, 25, 251801 (2017)] and RENO [Phys. Rev. Lett. **122**, 23, 232501 (2019)], and individual antineutrino spectra from ^{235}U and ^{239}Pu by Daya Bay [Phys. Rev. Lett. **123**, 11, 111801 (2019)] showed a discrepancy between the observed and predicted rate and spectrum from ^{235}U

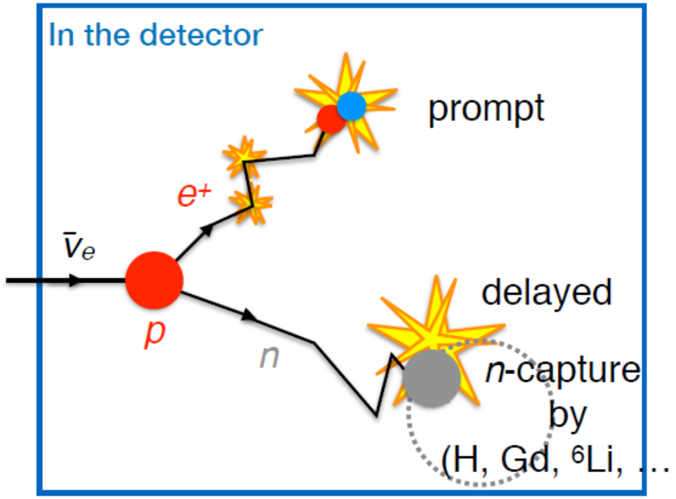
See also Mention *et al., Phys.Rev.D* 83 (2011) 073006

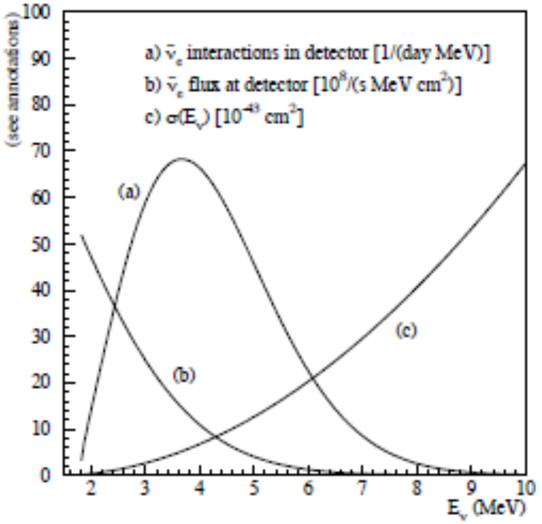
Reactor neutrino exp.

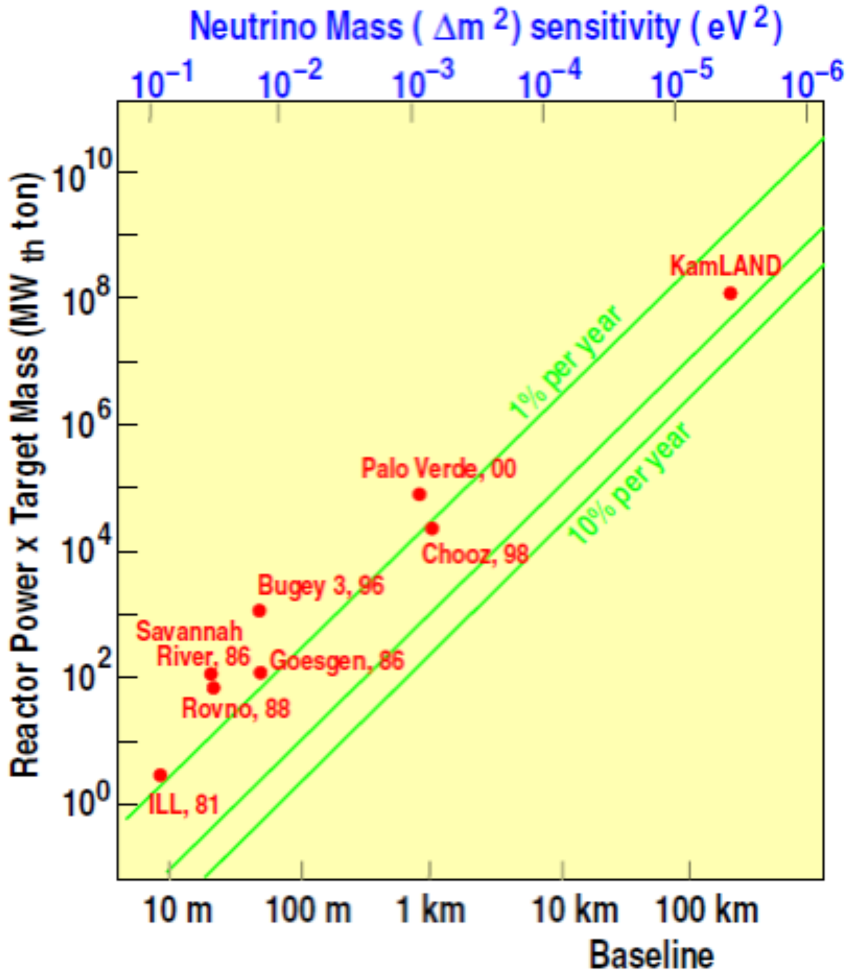
PROCESS :

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

delayed coincidence of the positron with a 2.2 MeV γ ray from neutron capture







Name	Reactor power ($\mathrm{GW_{th}}$)	Baseline (km)	Detector mass (t)	Year
KamLAND	various	180 (ave.)	1,000	2001–
Double Chooz	4.25×2	1.05	8.3	2011–2018
Daya Bay	2.9×6	1.65	20×4	2011–
RENO	2.8×6	1.38	16	2011–
JUNO	26.6 (total)	53	20,000	

KamLAND

55% of total flux from:

KamLAND uses the entire Japanese nuclear power industry as a 180 GW_{th} long-baseline source!

1-kton ultra-pure liquid scintillator detector contained in a 13-m diameter spherical balloon@ Kamiokande's site (Japan).

SBL reactor neutrino experiments

Following the establishment of neutrino oscillations with atmospheric, solar, accelerator, and reactor experiments, the measurement of the **remaining mixing angle θ_{13}** was recognized as the next major milestone.

A reactor neutrino experiment with a baseline of 1 km can make an almost pure measurement of $\sin^2 2\theta_{13}$ from disappearance of $\bar{\nu}_e$.

To be sensitive to a small value below the limit set by CHOOZ and Palo Verde, experiments with two detectors were proposed: Double Chooz (France), Daya Bay (China) and RENO (Korea).

Mixing matrix parametrization:
3 angles (ϑ_{12}, ϑ_{23}, ϑ_{13}), 1 CP-violating phase (δ_{13})

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmo ν, LBL accelator ν — SBL reactor ν — Solar ν, LBL reactor ν

$$c_{ab} = \cos\vartheta_{ab}$$
$$s_{ab} = \sin\vartheta_{ab}$$

$$0 \le \vartheta_{ab} \le \pi/2$$
$$0 \le \delta_{13} \le 2\pi$$

SBL reactor neutrino experiments

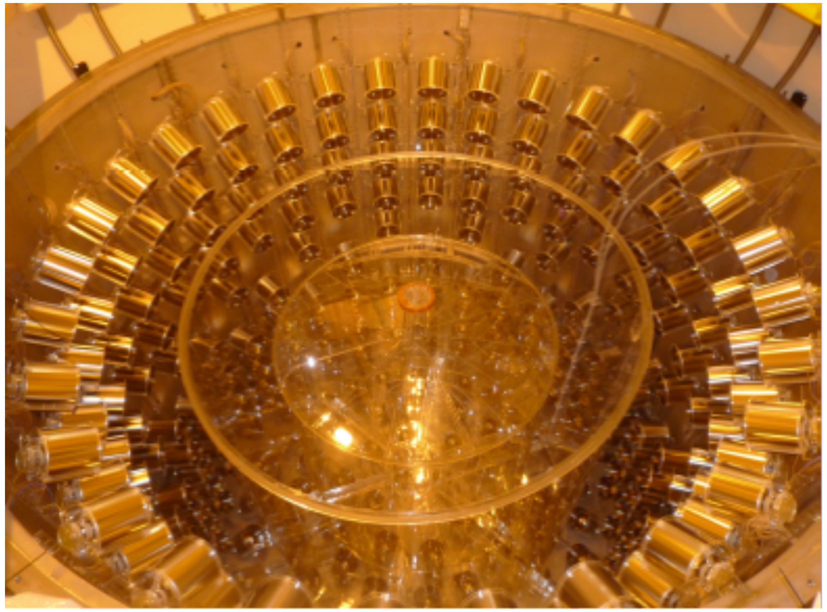
1. Cylindrical stainless steel vessel housing two nested acrylic cylindrical vessels.

2. The innermost vessel is filled with gadolinium-doped liquid scintillator as the primary antineutrino target.

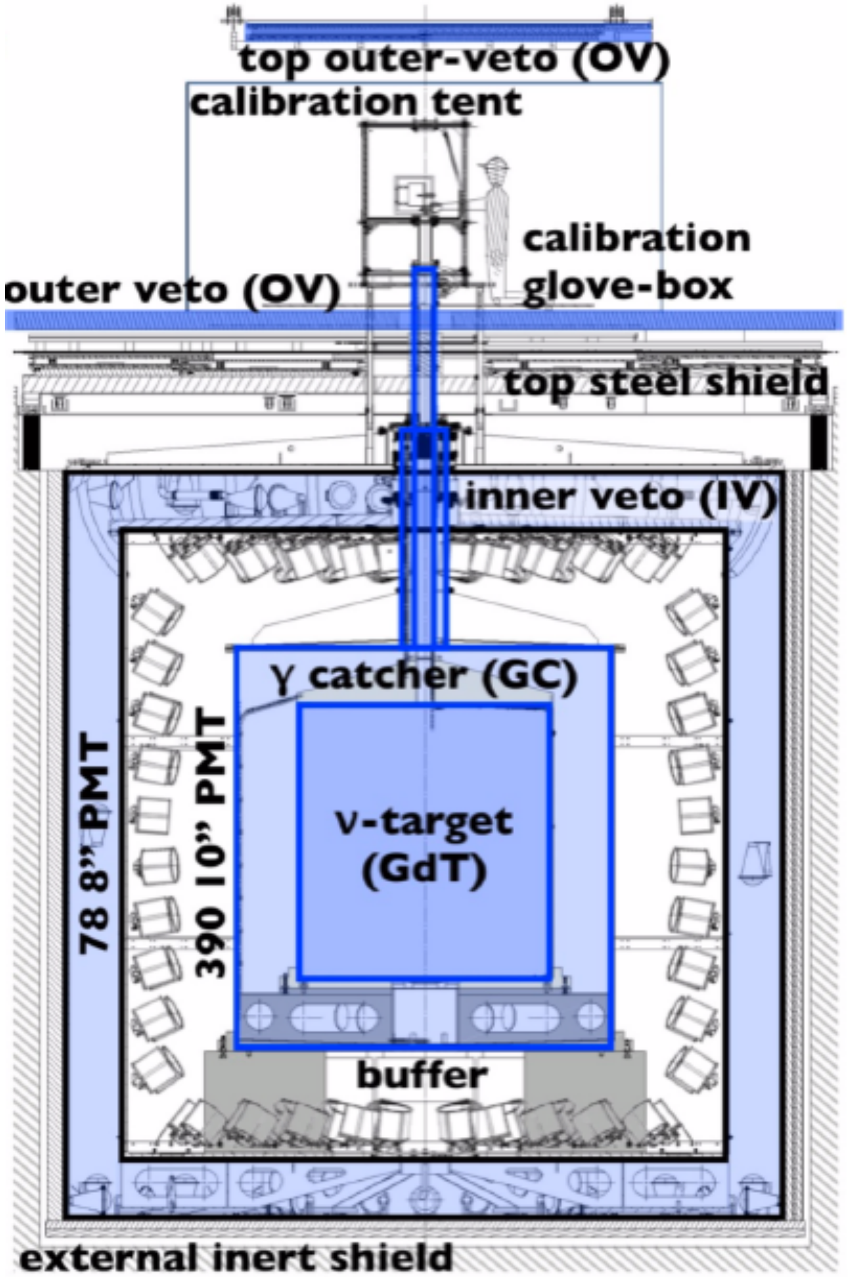
3. It is surrounded by a liquid scintillator layer to contain γ rays from the target volume.

4. A buffer layer of mineral oil is placed an outside to shield inner volumes from radioactivity of PMTs and surrounding rock. The light from liquid scintillator is detected by an array of PMTs mounted on the stainless steel vessel.

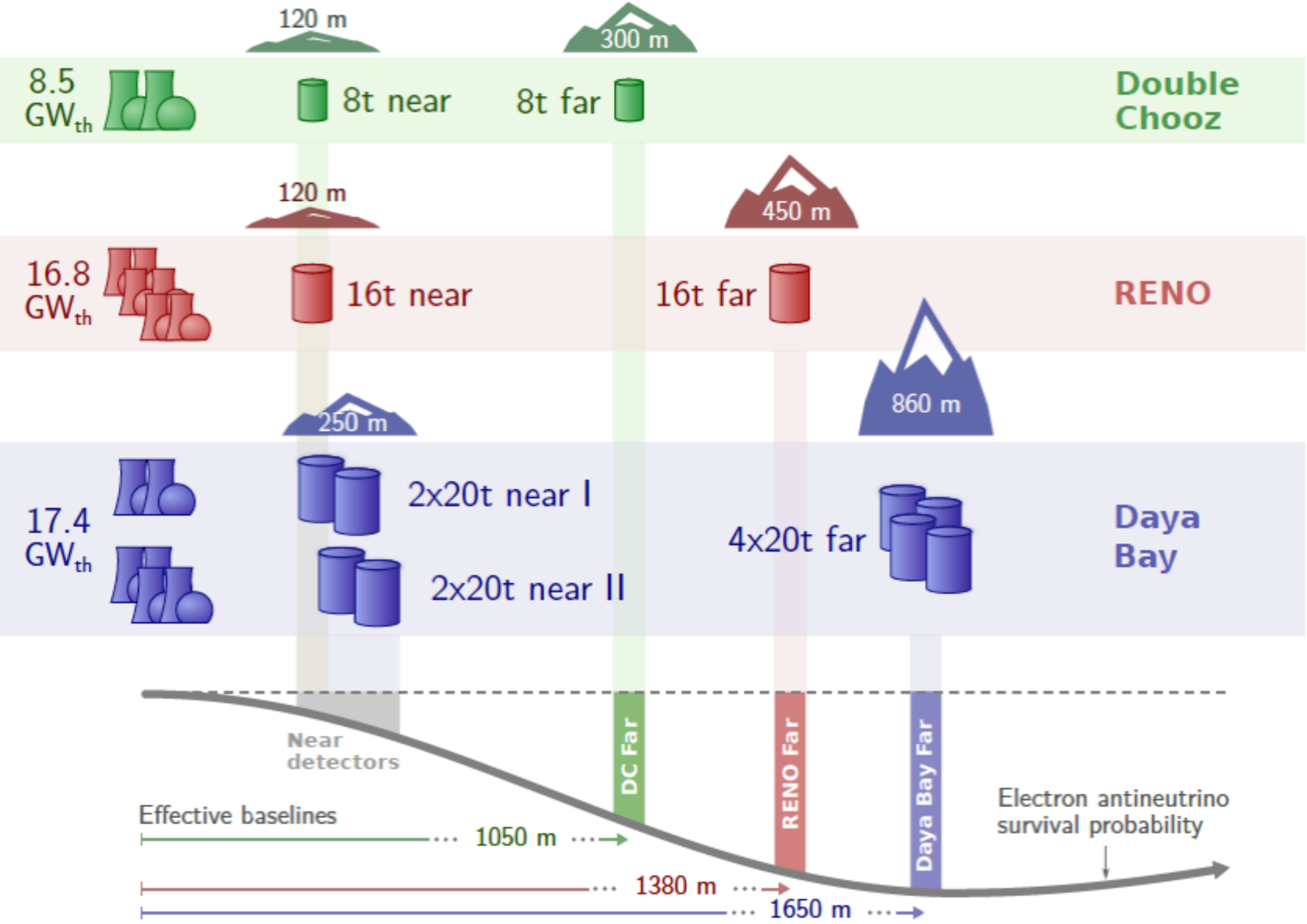
5. Optically separated by the stainless steel vessel, outside region is instrumented as a veto detector with either liquid scintillator (Double Chooz) or water Cherenkov (Daya Bay and RENO) detector



DOUBLE-CHOOZ



SBL reactor neutrino experiments



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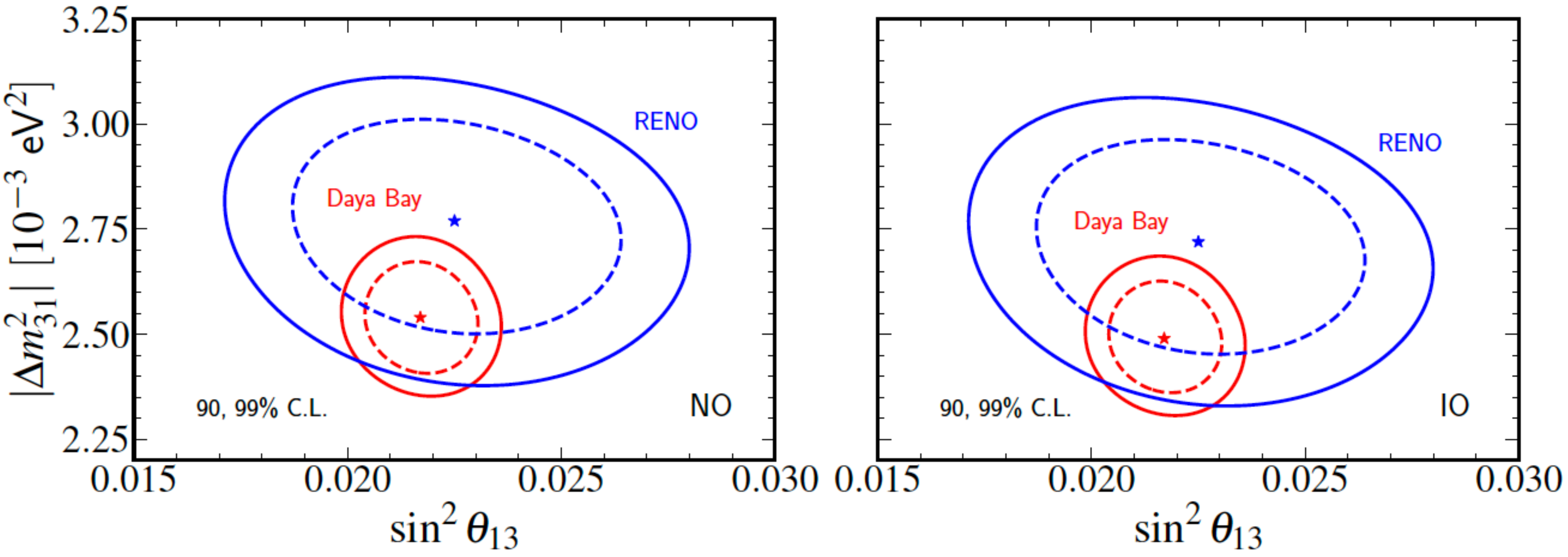
DOUBLE CHOOZ, DAYA BAY, RENO results

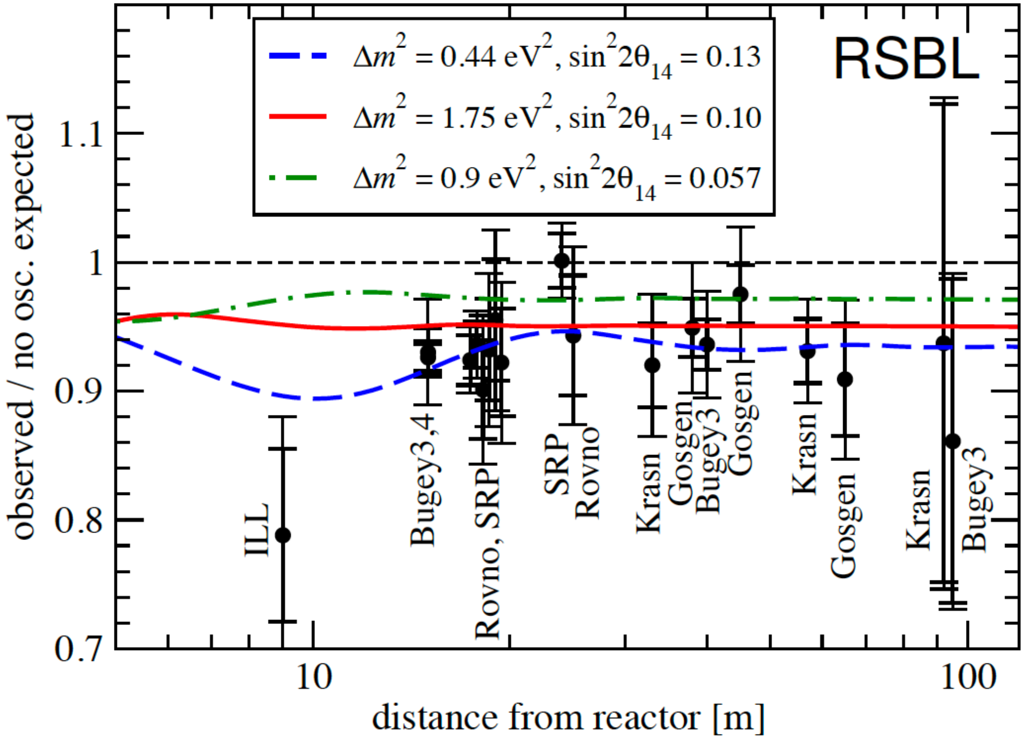


DOUBLE CHOOZ $\sin^2 2\theta_{13} = 0.105 \pm 0.014$

DAYA BAY $\sin^2 2\theta_{13} = 0.0853 \pm 0.0024$ [Daya Bay Collaboration] PRL 130 (2023),16180

RENO $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$ J. Yoo [RENO Collaboration] @ Neutrino-2020

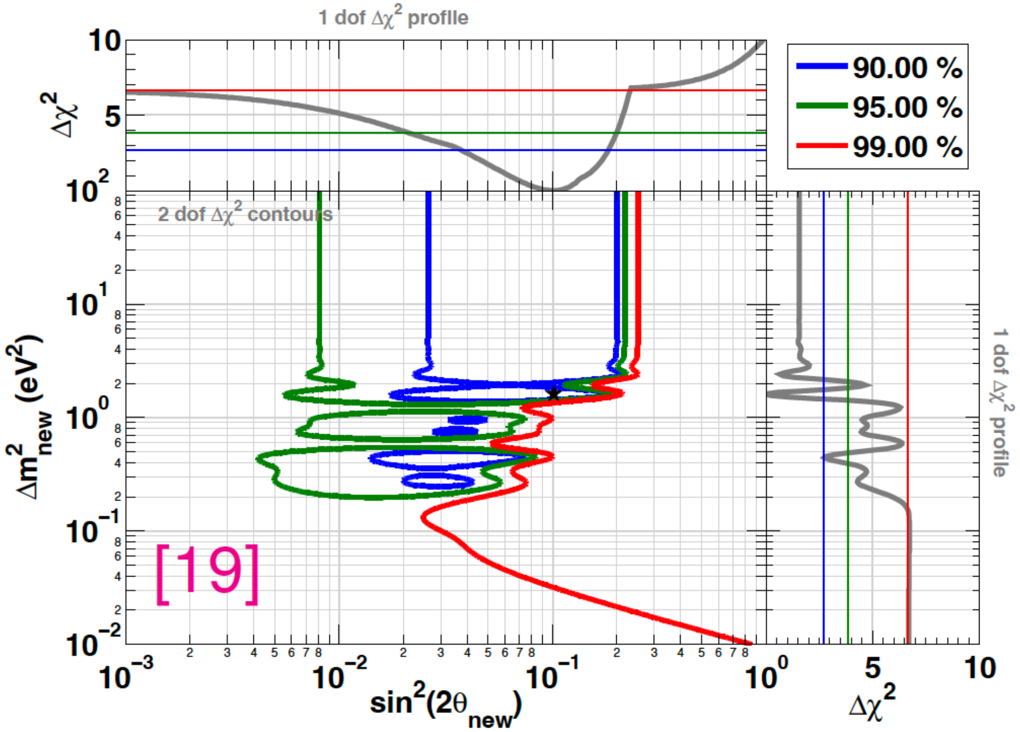
Search@O(eV²) scale



$$\Delta m^2 \gtrsim 1 eV^2$$

The new flux calculations result in a small increase by ~ 3.5 %

Hence, all reactor SB (RBSL) finding no evidence are actually observing a DEFICIT!



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Search@O(eV²) scale

O(10 m) $\rightarrow \Delta m^2 \sim 1 eV^2$

Name	Reactor power (MW_{th})	Baseline (m)	Detector mass (t)	Detector technology	S/B
NEOS	2,800	24	1	Gd-LS	22
DANSS	3,100	10–12	0.9	Gd-PS	∼30
STEREO	57	9–11	1.7	Gd-LS	0.9
PROSPECT	85	7–9	4	^{6}Li-LS	1.3
NEUTRINO-4	100	6–12	1.5	Gd-LS	0.5
SoLid	80	6–9	1.6	^{6}Li-PS	

Detectors: organic scintillators, (liquid scintillator (LS) or solid plastic scintillator (PS))

Hydrogen = target for inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)

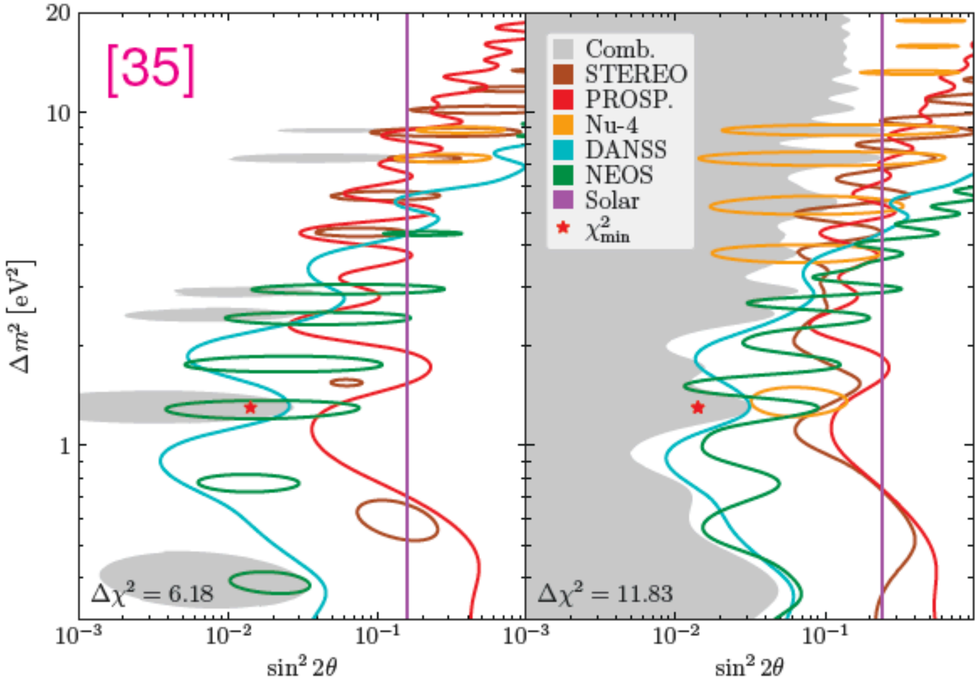
Signal identification: neutron capture on either gadolinium (Gd) or ^{6}Li detected with delayed coincidence

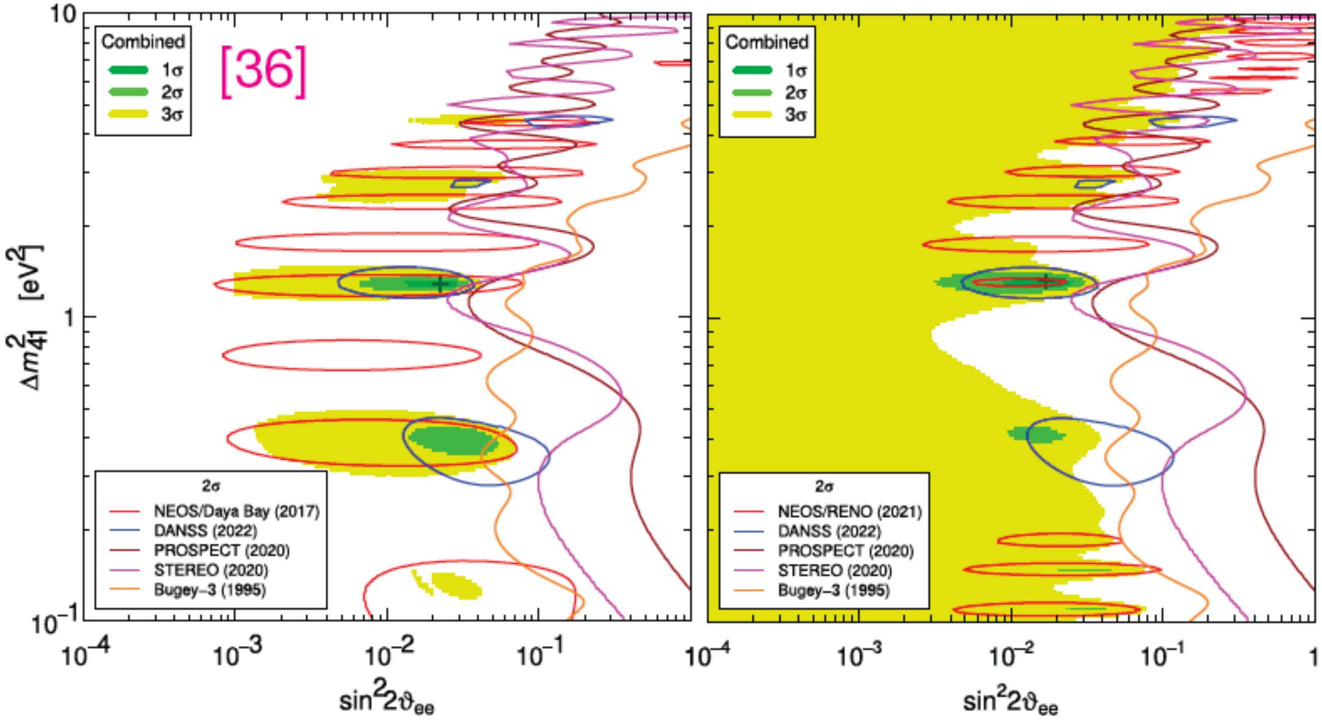
To be independent from the reactor neutrino spectrum uncertainties, some experiments compare the spectra at different baselines by using a segmented detector or moving the detector

Search@O(eV^2) scale

Search@O(eV²) scale

No consistent patterns from various hints!





[35] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]
[36] C. Giunti *et al.*, JHEP **10** (2022) 164 [arXiv:2209.00916]

Outline

Neutrinos oscillate…

- Atmospheric ν_μ and $\bar{\nu}_\mu$ disappear most likely converting ν_τ and $\bar{\nu}_\tau$.

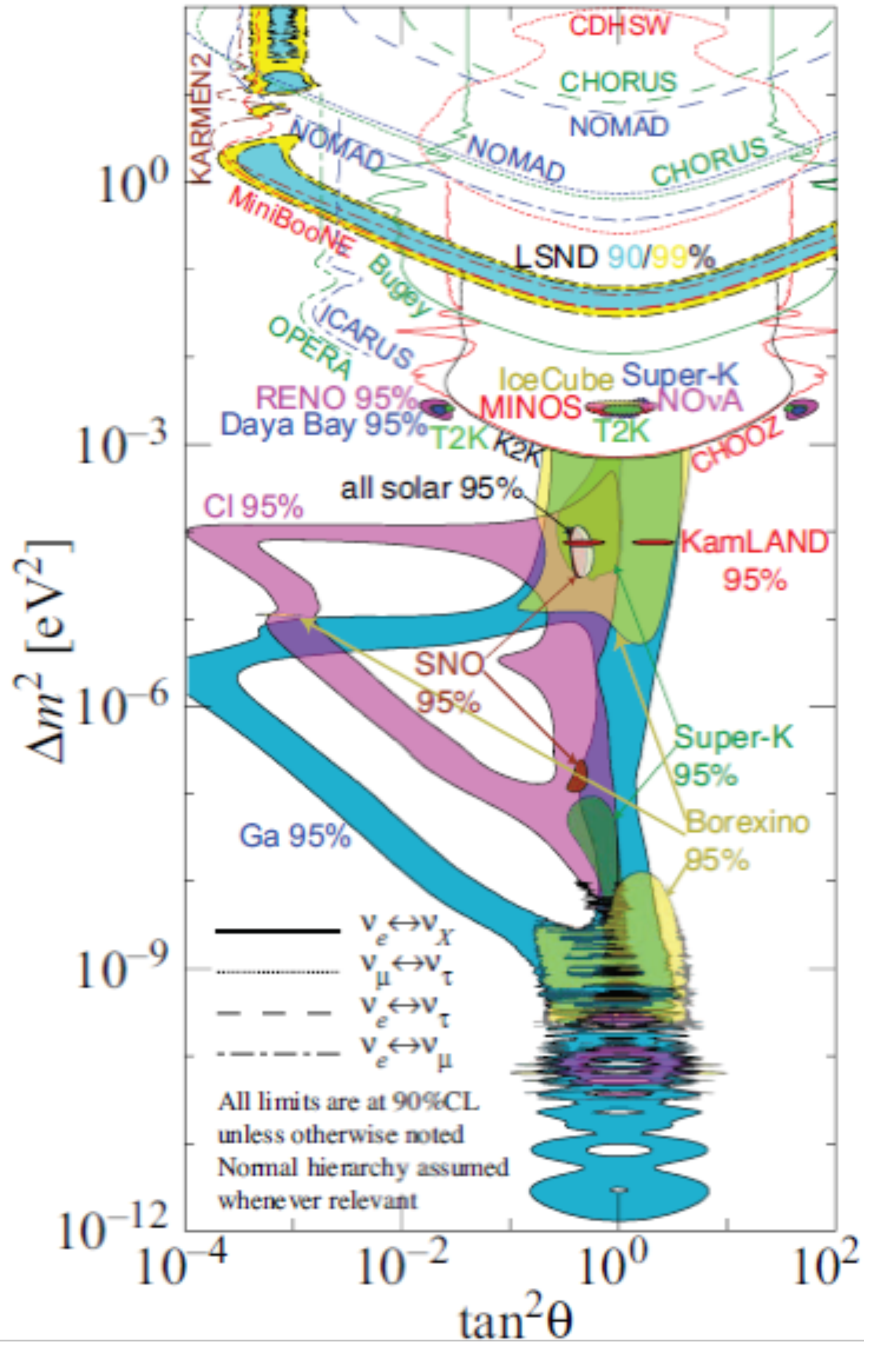
- Accelerator ν_μ and $\bar{\nu}_\mu$ disappear over distances of 200 to 800 km. The energy spectrum of the results show a clear oscillatory behaviour also in accordance with mass-induced oscillations with wavelength in agreement with the effect observed in atmospheric neutrinos

- Accelerator ν_μ and $\bar{\nu}_\mu$ appear as ν_e and $\bar{\nu}_e$ at distances 200 to 800 km

- Solar ν_e convert to ν_μ and/or ν_τ. The observed energy dependence of the effect is well described by massive neutrino conversion in the Sun matter according to the MSW effect

- Reactor $\bar{\nu}_e$ disappear over distances of 200 km and 1.5 km with different probabilities. The observed energy spectra show two different mass-induced oscillation wavelengths: at short distances in agreement with the one observed in accelerator ν_μ disappearance, and a long distance compatible with the required parameters for MSW conversion in the Sun.

Experiment		L (m)	E (MeV)	$\lvert\Delta m^2\rvert$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	SBL	$10^2 - 10^3$	1	$10^{-2} - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$



PdG 2016 (http://hitoshi.berkeley.edu/neutrino)

The 3ν paradigm

There are at least two independent squared-mass differences: Δm^2_{ATM} and Δm^2_{SOL} The minimal possibility of just two independent squared-mass differences is realized in three-neutrino mixing schemes

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k} \nu_{kL}$$

The three light massive neutrinos could have a Dirac nature or a Majorana nature or they could be generated by a Dirac–Majorana mass term through the see-saw mechanism.

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 , \quad \Delta m^2_{31} \equiv m^2_3 - m^2_1 , \quad \Delta m^2_{32} \equiv m^2_3 - m^2_2 , \qquad \text{but} \qquad \Delta m^2_{32} + \Delta m^2_{21} - \Delta m^2_{31} = 0$$

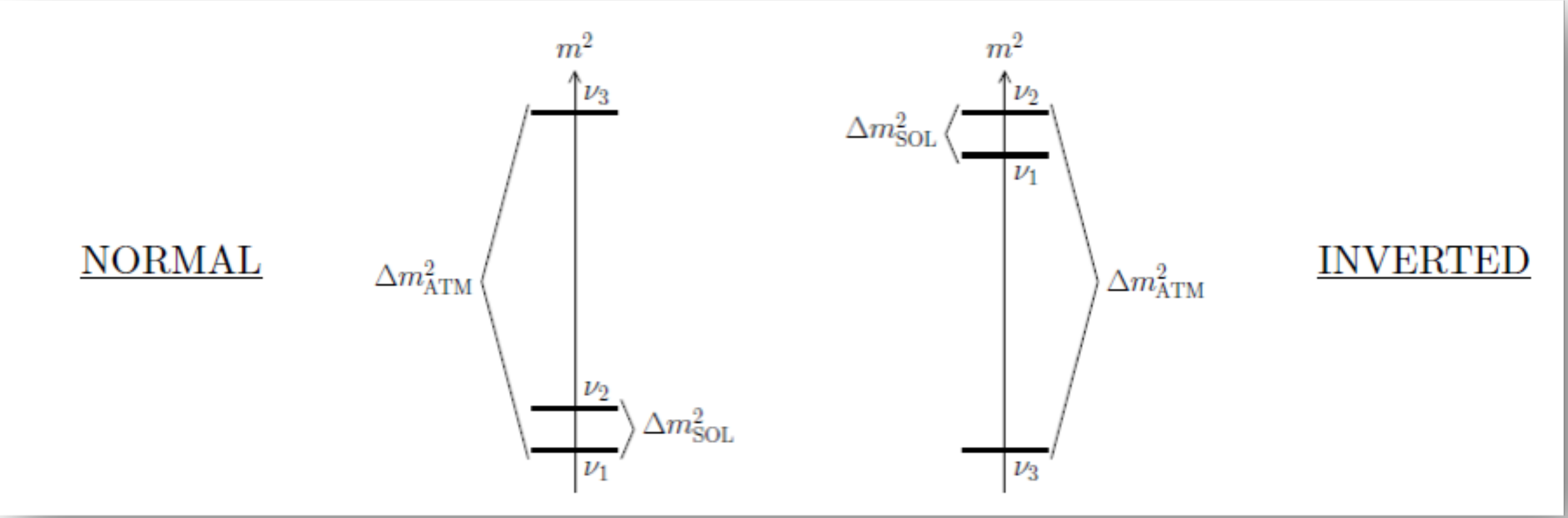
$$\Delta m^2_{\mathrm{SOL}} \ll \Delta m^2_{\mathrm{ATM}} \quad \Longrightarrow \quad \Delta m^2_{\mathrm{SOL}} = \Delta m^2_{21} , \qquad \Delta m^2_{\mathrm{ATM}} = |\Delta m^2_{31}| ,$$

$$\Delta m^2_{21} \ll \Delta m^2_{31} \simeq \Delta m^2_{32}$$

The 3ν paradigm

$$\Delta m^2_{\rm SOL} \ll \Delta m^2_{\rm ATM}$$

$$\Delta m^2_{\rm SOL} = \Delta m^2_{21}\,, \qquad \Delta m^2_{\rm ATM} = |\Delta m^2_{31}|\,,$$
$$\Delta m^2_{21} \ll \Delta m^2_{31} \simeq \Delta m^2_{32}$$



The 3ν paradigm

3 channels: $\nu_e \leftrightarrows \nu_\mu$ $\nu_e \leftrightarrows \nu_\tau$ $\nu_\mu \leftrightarrows \nu_\tau$ (same for antineutrinos)

6 parameters: 2 Δm^2, 3 mixing angles, 1 Dirac phase

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ab} = \cos\vartheta_{ab}$
$s_{ab} = \sin\vartheta_{ab}$

$0 \leq \vartheta_{ab} \leq \pi/2$
$0 \leq \delta_{13} \leq 2\pi$

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

$$P_{\nu_\alpha \to \nu_\alpha}(L,E) = 1 - 4 \sum_{k>j} |U_{\alpha k}|^2 |U_{\alpha j}|^2 \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

[Giunti's book, Cap 6 and 7]

The 3ν paradigm

3 channels: $\nu_e \leftrightarrows \nu_\mu$ $\nu_e \leftrightarrows \nu_\tau$ $\nu_\mu \leftrightarrows \nu_\tau$ (same for antineutrinos)

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$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathfrak{Re}\left[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right) + 2 \sum_{k>j} \mathfrak{Im}\left[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*\right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$$

$$P_{\nu_\alpha \to \nu_\alpha}(L,E) = 1 - 4 \sum_{k>j} |U_{\alpha k}|^2 |U_{\alpha j}|^2 \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

$$P_{\bar\nu_\alpha \to \bar\nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathfrak{Re}\left[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right) - 2 \sum_{k>j} \mathfrak{Im}\left[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*\right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$$

[Giunti's book, Cap 6 and 7]

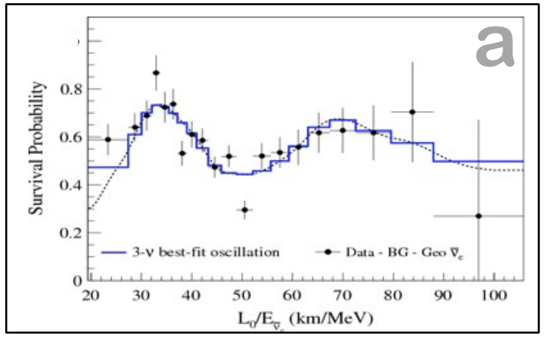
The 3ν paradigm

3 channels: $\nu_e \leftrightarrows \nu_\mu$ $\nu_e \leftrightarrows \nu_\tau$ $\nu_\mu \leftrightarrows \nu_\tau$ (same for antineutrinos)

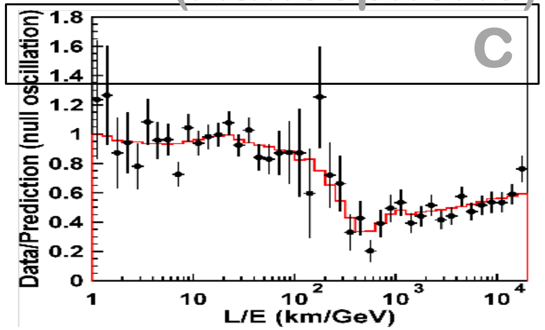
Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

Beautiful ν oscillation data have established this 3ν paradigm…

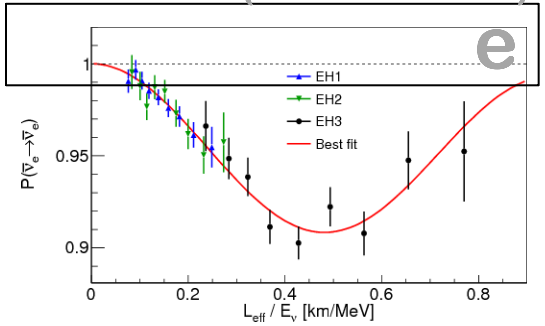
e→e (KamLAND, KL)



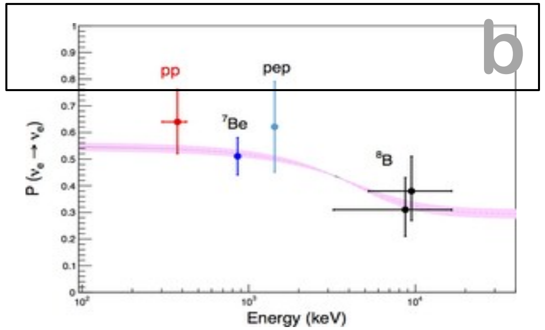
μ→μ (Atmospheric)



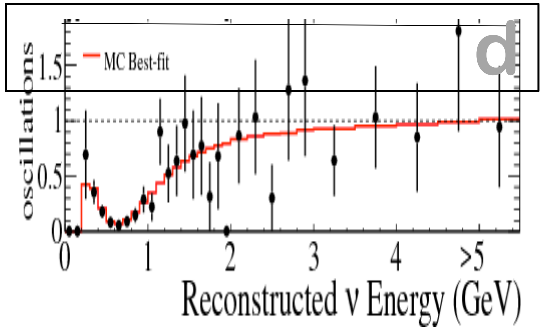
e→e (SBL Reac.)



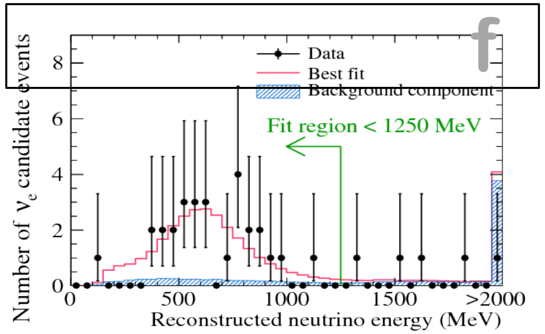
e→e (Solar)



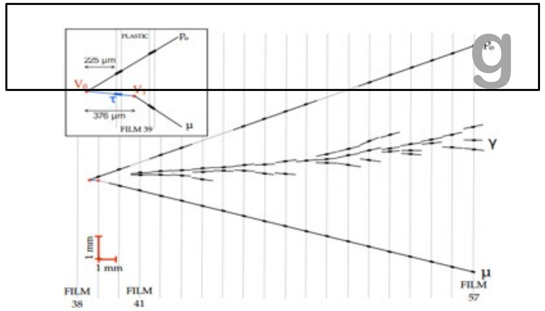
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

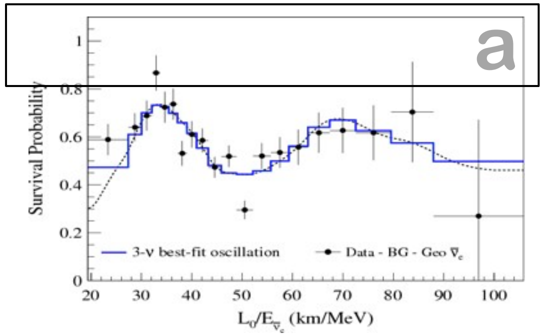


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline LBL accelerator, (e) short-baseline SBL reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

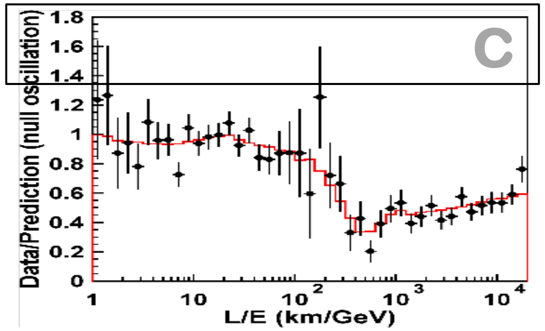
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/ GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K and IC-CD atmospheric.

… and consistently measured five ν mass-mixing parameters

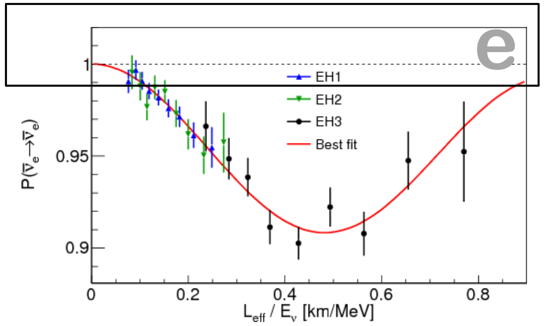
e→e (δm^2 , θ_{12})



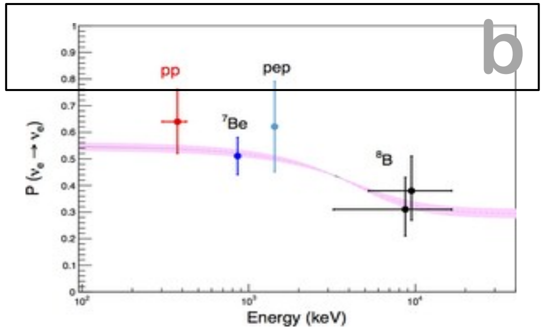
μ→μ (Δm^2 , θ_{23})



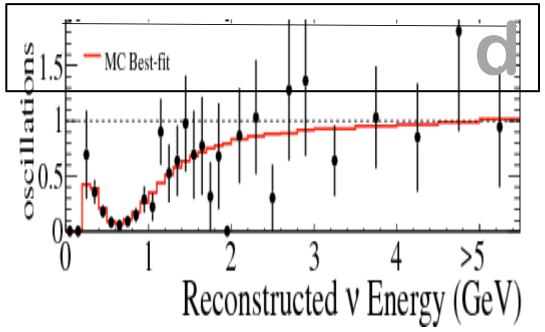
e→e (Δm^2 , θ_{13})



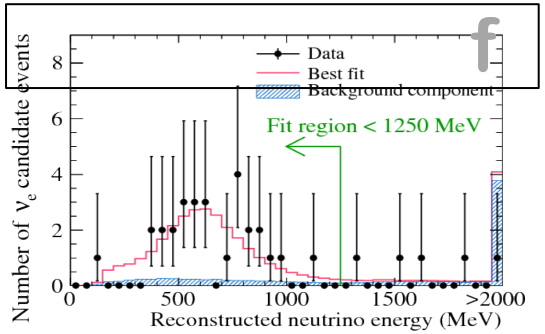
e→e (δm^2 , θ_{12})



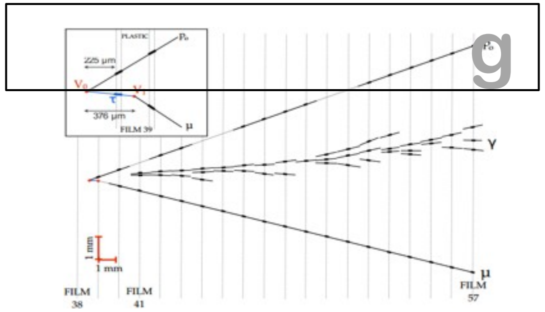
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



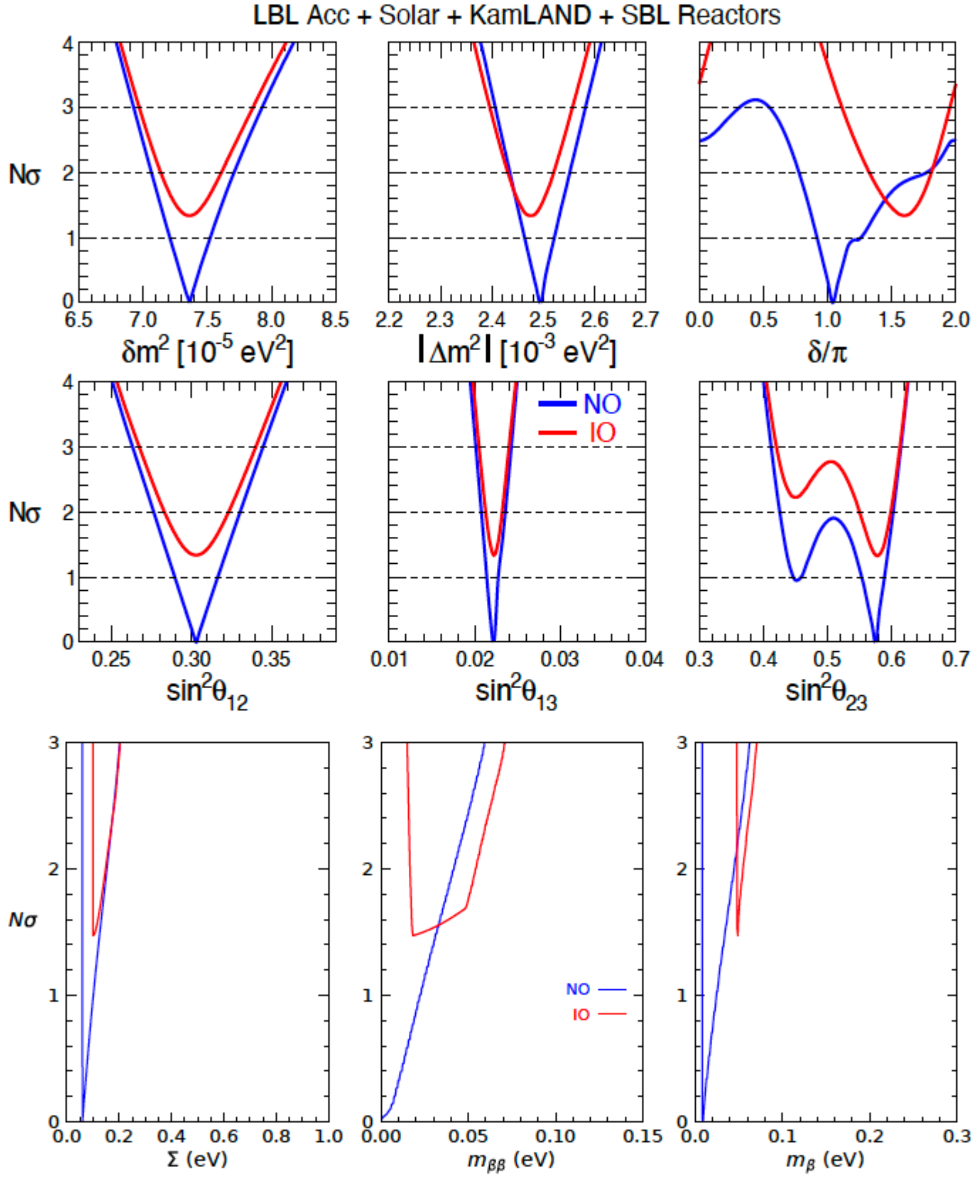
μ→τ (Δm^2 , θ_{23})



Each leading oscillation parameters (over)constrained by at least two classes of measurements → 3ν consistency

Subleading effects involve **CPV** and **NO vs IO** difference, essentially via μ→**e** in LBL accel. and atmospher. expts

The 3ν paradigm



Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.485	2.454 – 2.508	2.427 – 2.537	2.401 – 2.565	1.1
	IO	2.455	2.430 – 2.485	2.403 – 2.513	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.30	2.11 – 2.37	2.04 – 2.44	3.0
	IO	2.23	2.17 – 2.29	2.10 – 2.38	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.40 – 4.73	4.27 – 5.81	4.16 – 5.99	6.7
	IO	5.69	5.48 – 5.82	4.30 – 5.94	4.17 – 6.06	5.5
δ/π	NO	1.24	1.11 – 1.42	0.94 – 1.74	0.77 – 1.97	16
	IO	1.52	1.37 – 1.66	1.22 – 1.78	1.07 – 1.90	9
$\Delta\chi^2_{\rm IO-NO}$	IO−NO	+6.5				

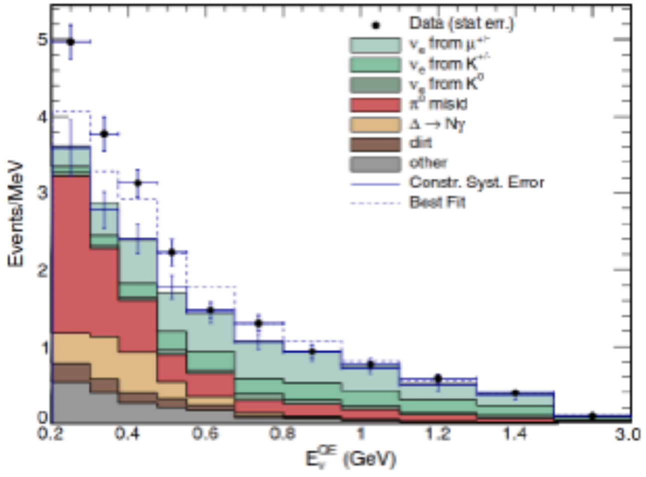
F. Capozzi *et al.*, Phys. Rev. D **104** (2021) 083031 [arXiv:2107.00532]

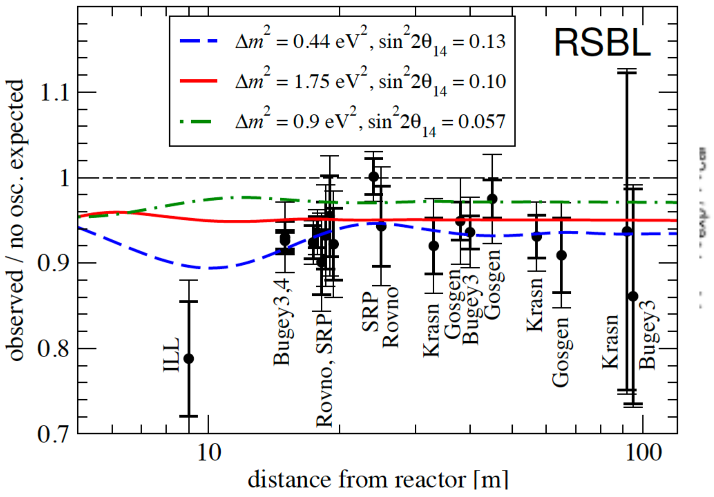
Beyond 3ν paradigm

MiniBooNE & LSND anomalies

reactor anomaly

MiniBooNE, PRL **121**, 221801 (2018)





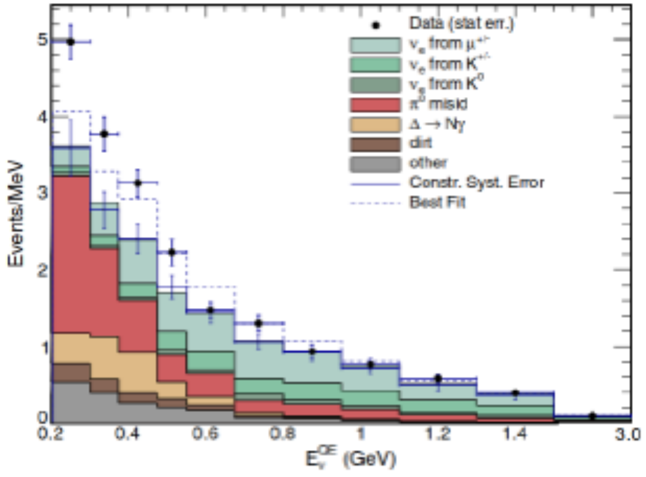
4-5 σ ν_e / $\bar{\nu}_e$ excess

2-3 σ $\bar{\nu}_e$ deficit

Beyond 3ν paradigm

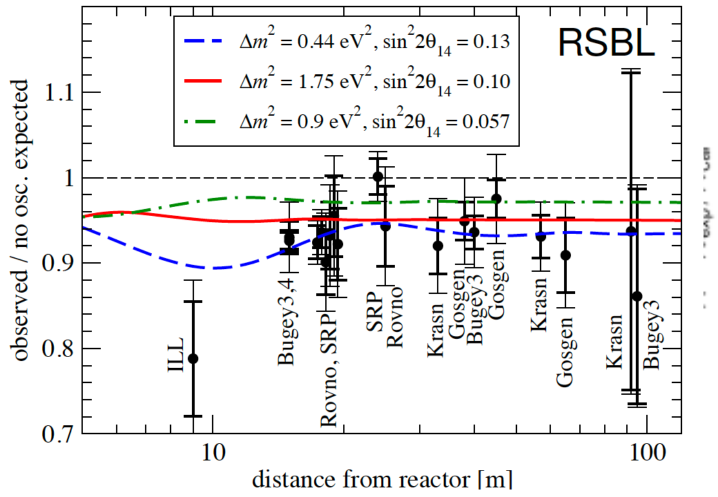
MiniBooNE & LSND anomalies

MiniBooNE, PRL **121**, 221801 (2018)



4-5 σ ν_e / $\bar{\nu}_e$ excess

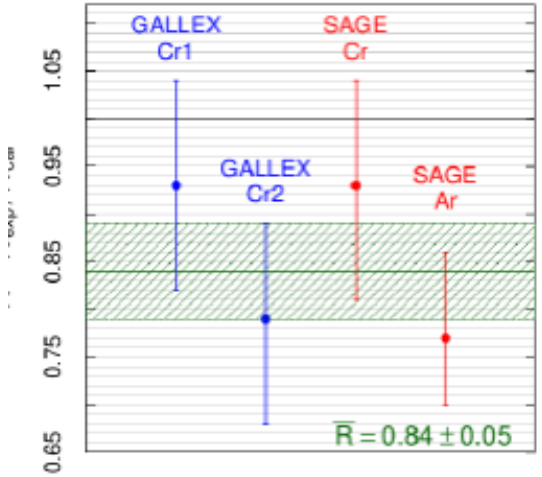
reactor anomaly



2-3 σ $\bar{\nu}_e$ deficit

gallium anomaly

arXiv:1906.01739v2 [hep-ex]



2-3 σ ν_e deficit

significant tension between expected and measured neutrino rate

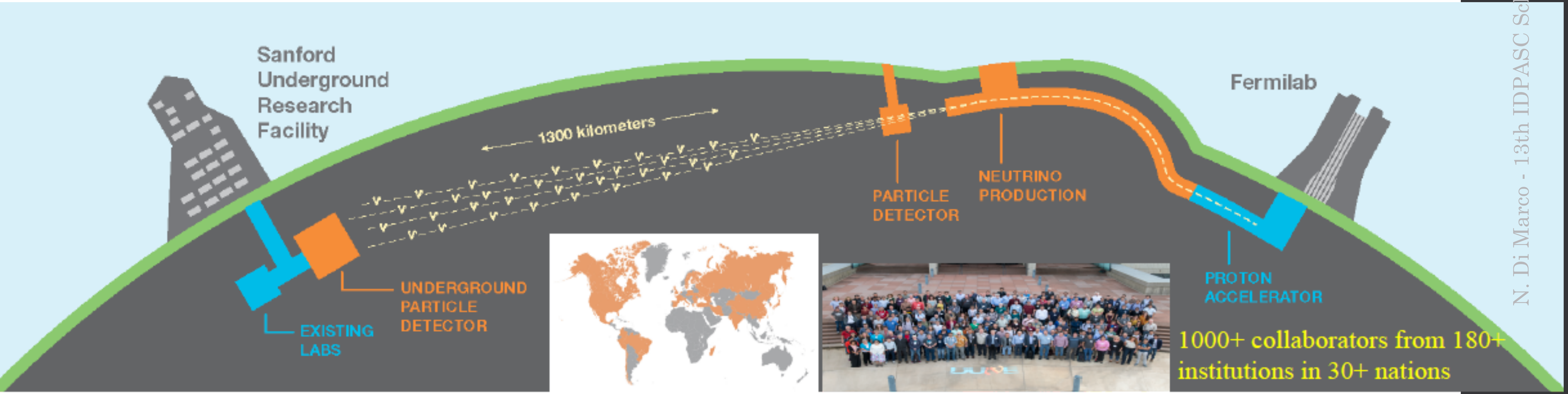
- 3+1 model? excluded at 4.7σ [M. Dentler *et al.*, JHEP **08**, 010 (2018), [arXiv:1803.10661]]
- 3+2 model?
- ??

Future oscillation searches

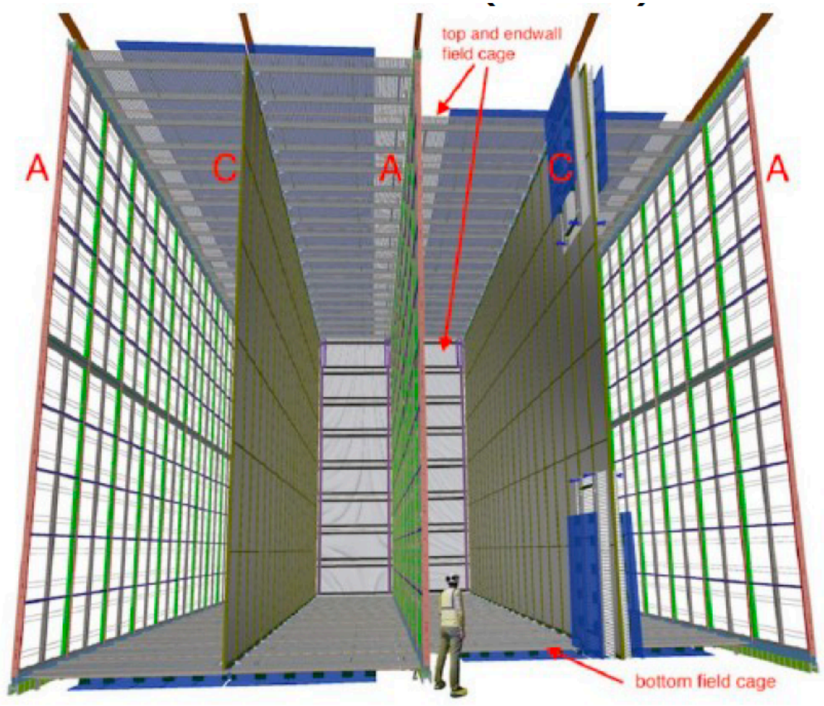
DUNE

Deep underground neutrino experiment

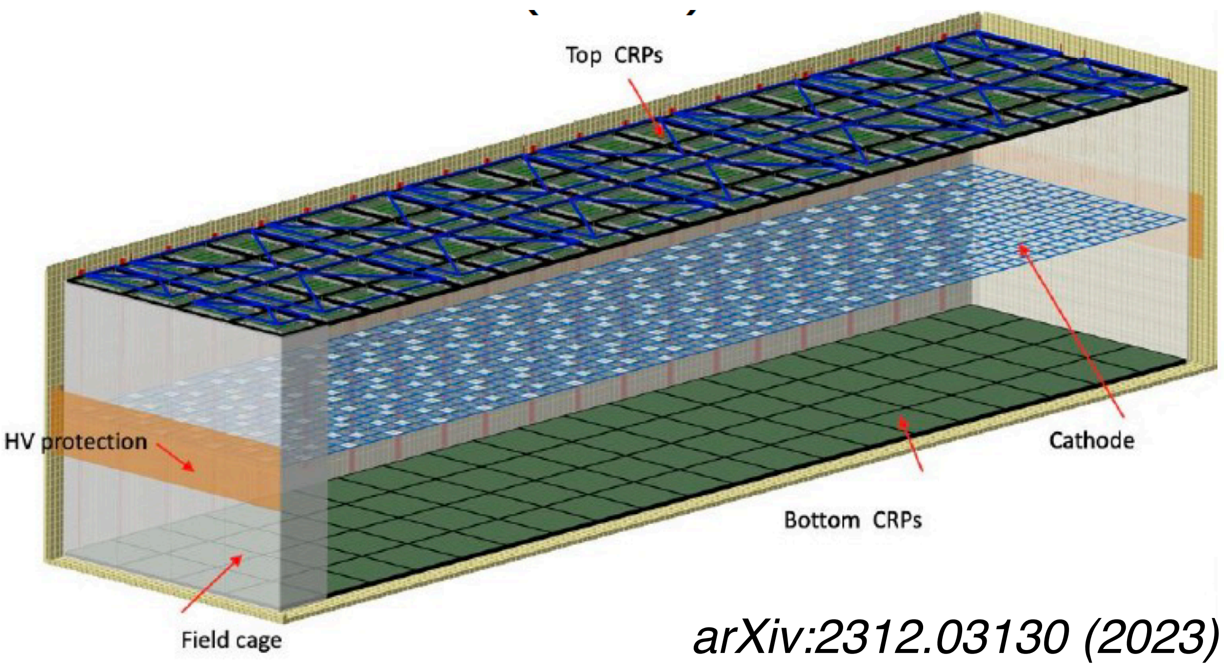
- New beam at Fermilab (1.2 MW@80 GeV protons, upgradeable to 2.4 MW), 1300 km baseline
- On-Axis 40 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Near detector at Fermilab
- ν_e appearance and ν_μ disappearance → Measure MH, CPV and mixing angles
- Large detector, deep underground, high intensity beam → Supernova burst neutrinos, atmospheric neutrinos, nucleon decay and other BSM, etc



DUNE



JINST 15 T08010 (2020)

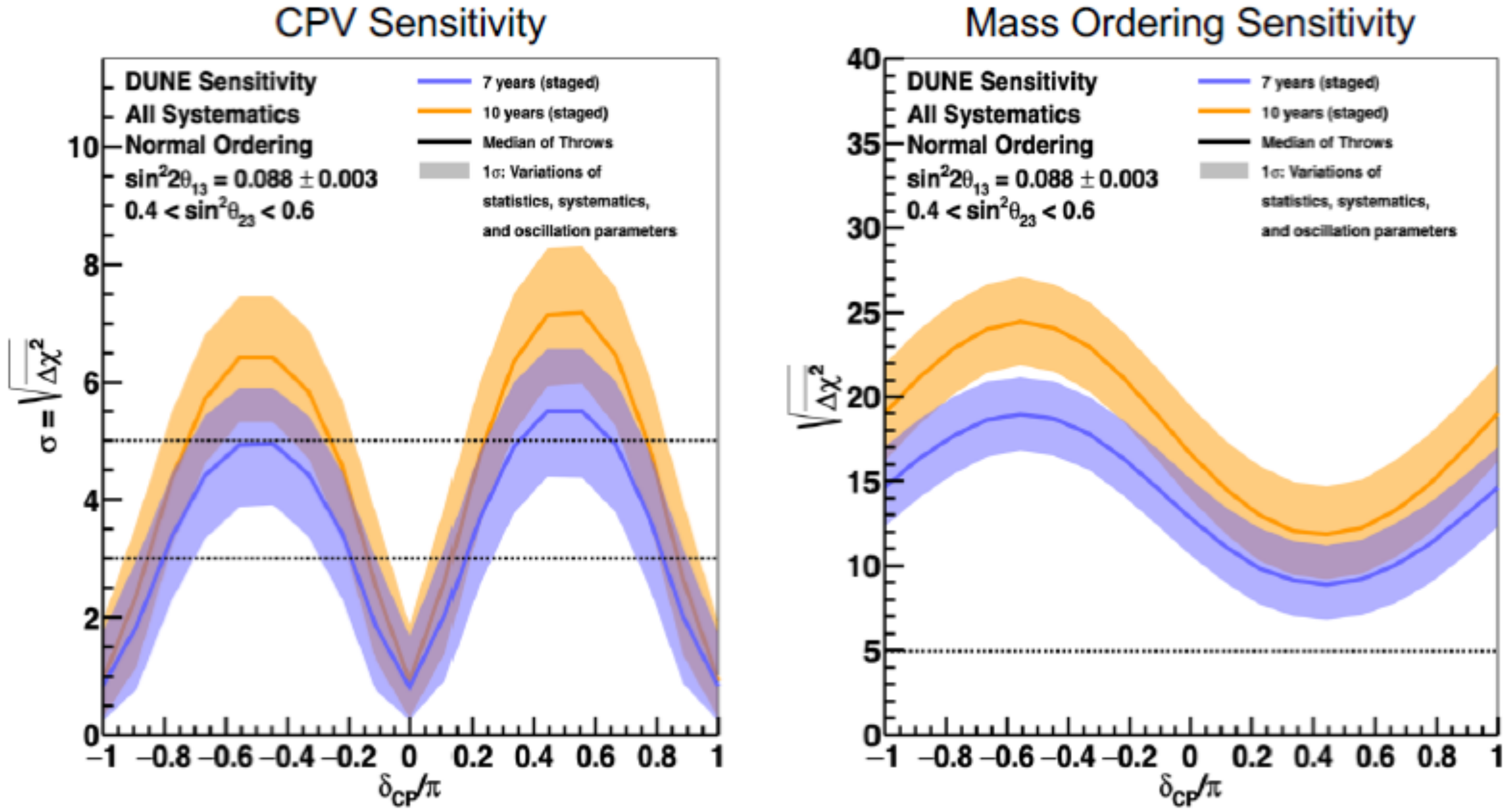


arXiv:2312.03130 (2023)

FAR DETECTOR: two read-out technologies

- Horizontal drift (HD, left) using wire readout planes, four drift region
- Vertical drift (VD, right) using two 6.25m drift regions and central cathode
- Simpler to install → first DUNE FD module will use vertical drift
- VD is baseline design for modules 3 and 4

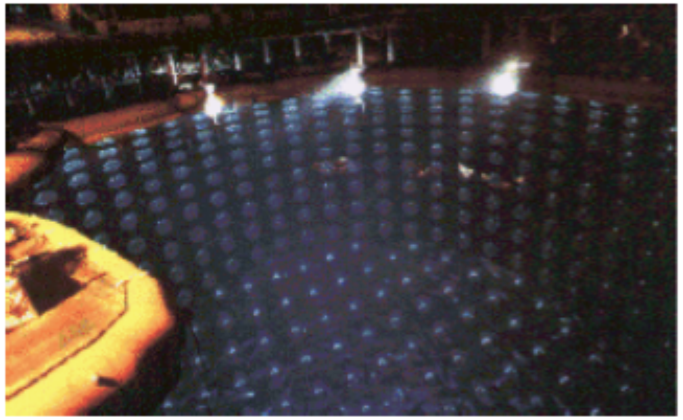
DUNE



- >5σ CPV discovery over a wide range of δ_{CP}
- >5σ Mass Ordering determination for all δ_{CP} values

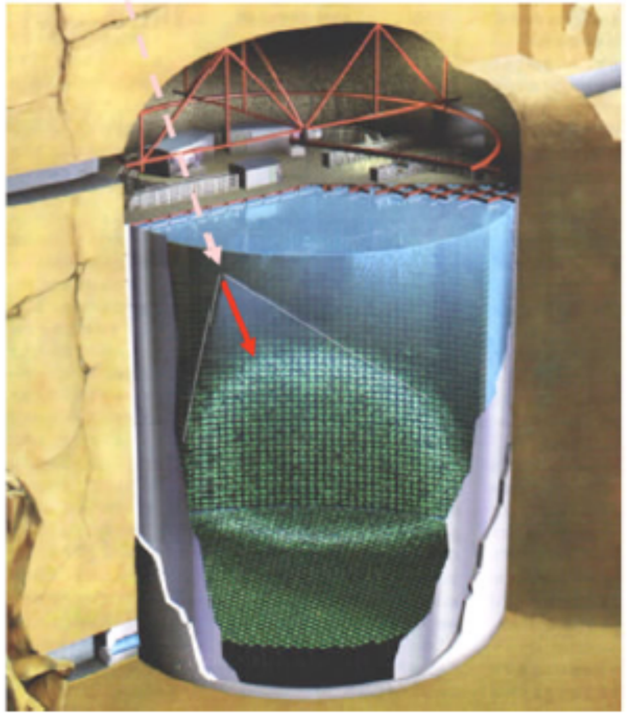
HK

Kamiokande
(1983-1996)



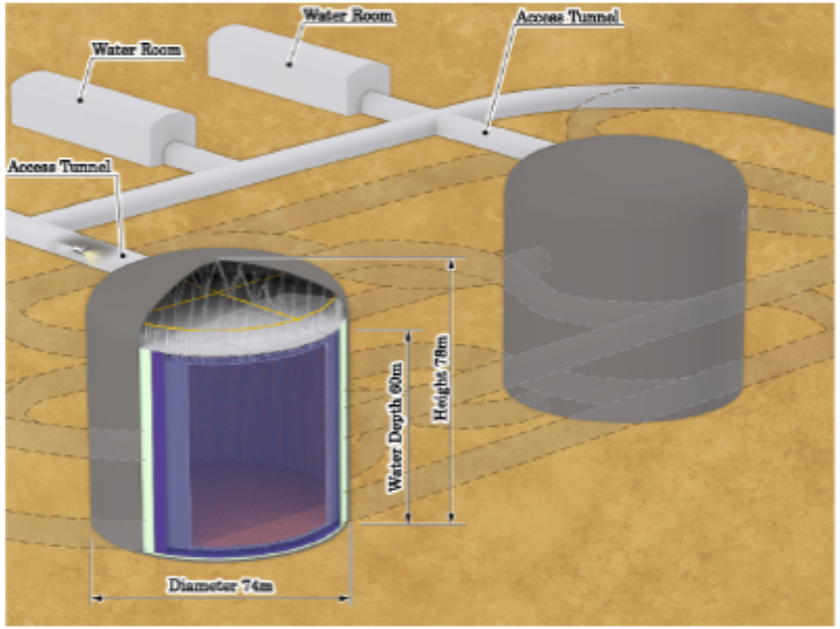
3 kton

Super-Kamiokande
(1996-)



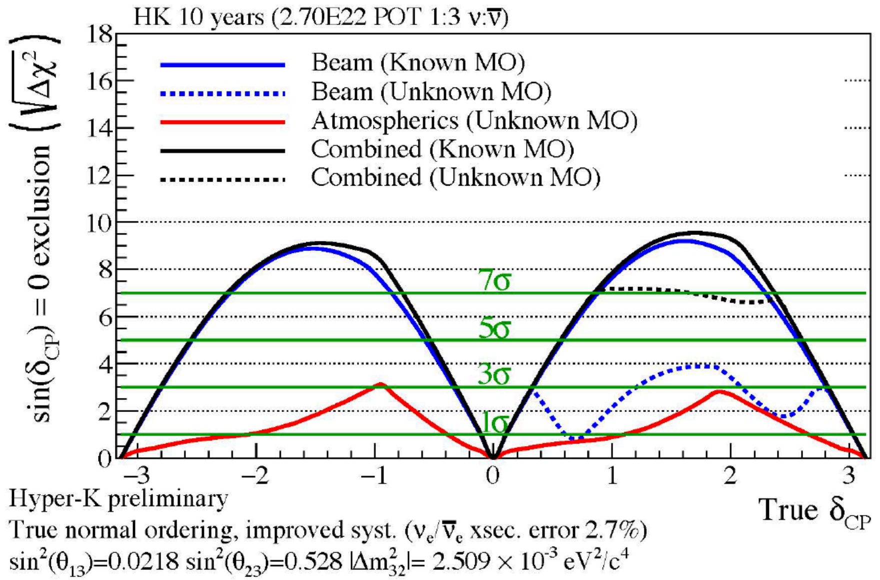
50 kton

Hyper-Kamiokande
(2026-)



520 kton

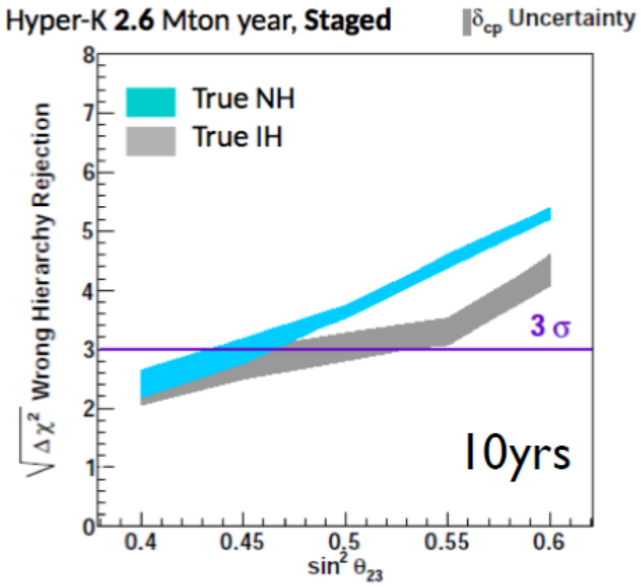
HK



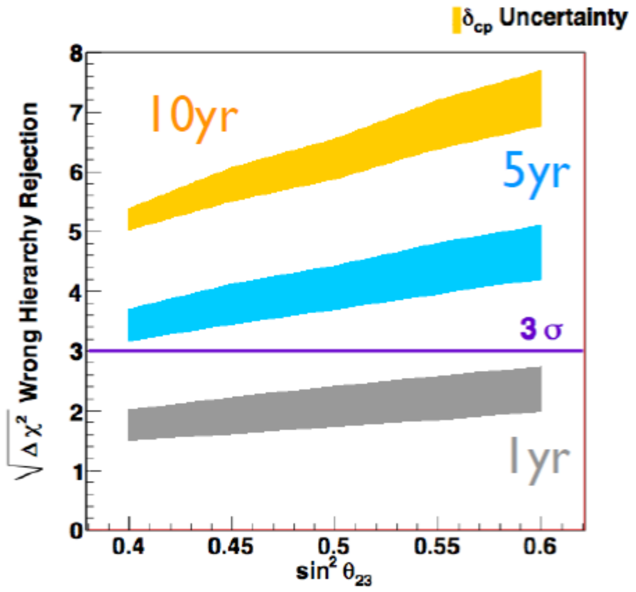
Bian et al. (Hyper-Kamiokande), Snowmass 2021

Abe et al. (Hyper-Kamiokande), arXiv:1803.04163

HK atmospheric only



HK atmospheric + beam

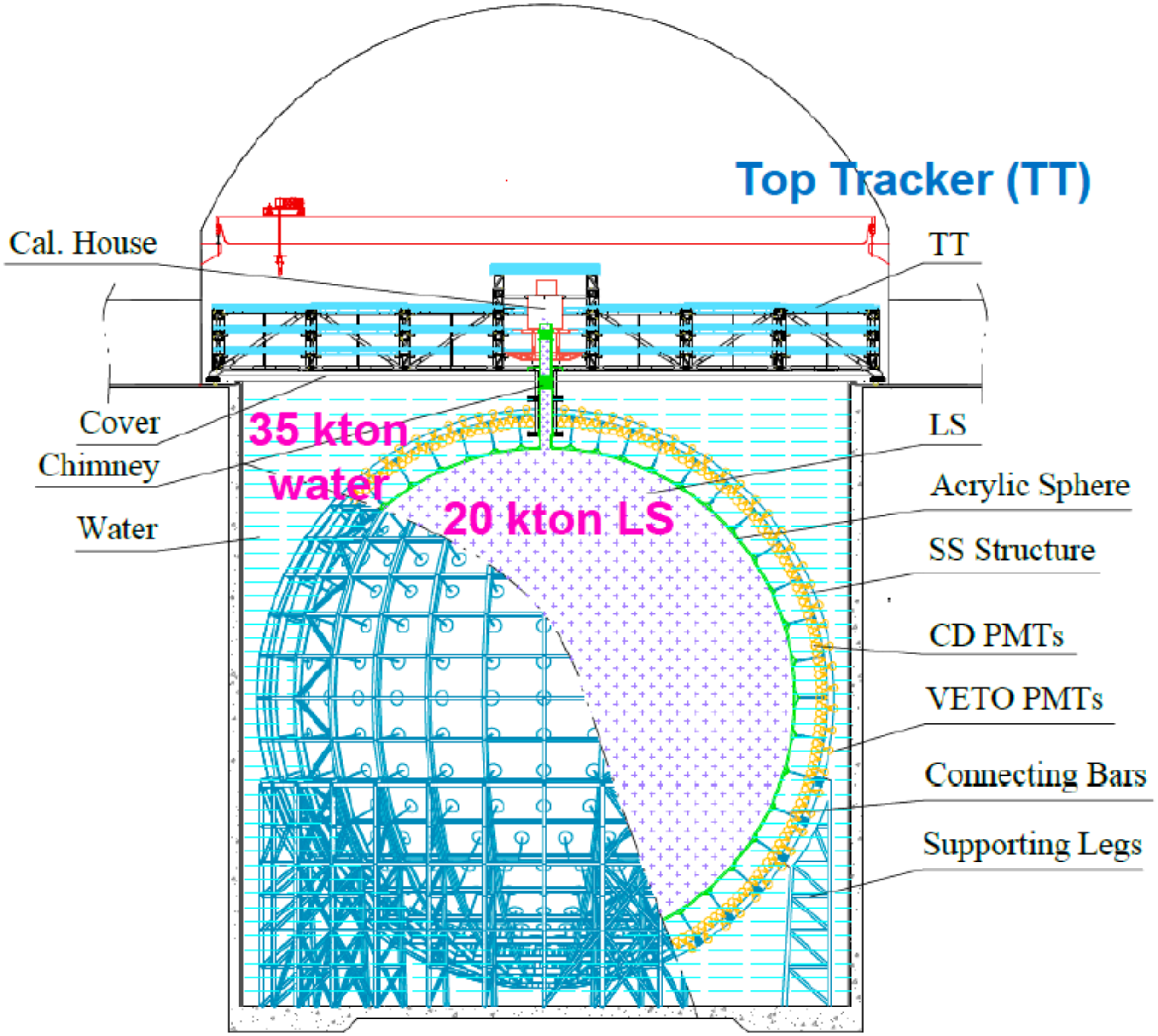


- ~>3σ sensitivity to the mass hierarchy with atm ν only
- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

JUNO

- **Proposed as a reactor neutrino experiment for mass ordering in 2008** (PRD78:111103,2008; PRD79:073007,2009)
  - ⇨ **driving the design specifications: location, 20 kton LS, 3% energy resolution, 700 m underground**
- **Rich physics program in solar, supernova, atmospheric, geo-neutrinos, proton decay, exotic searches**
- **Approved in 2013. Construction in 2015-2024**

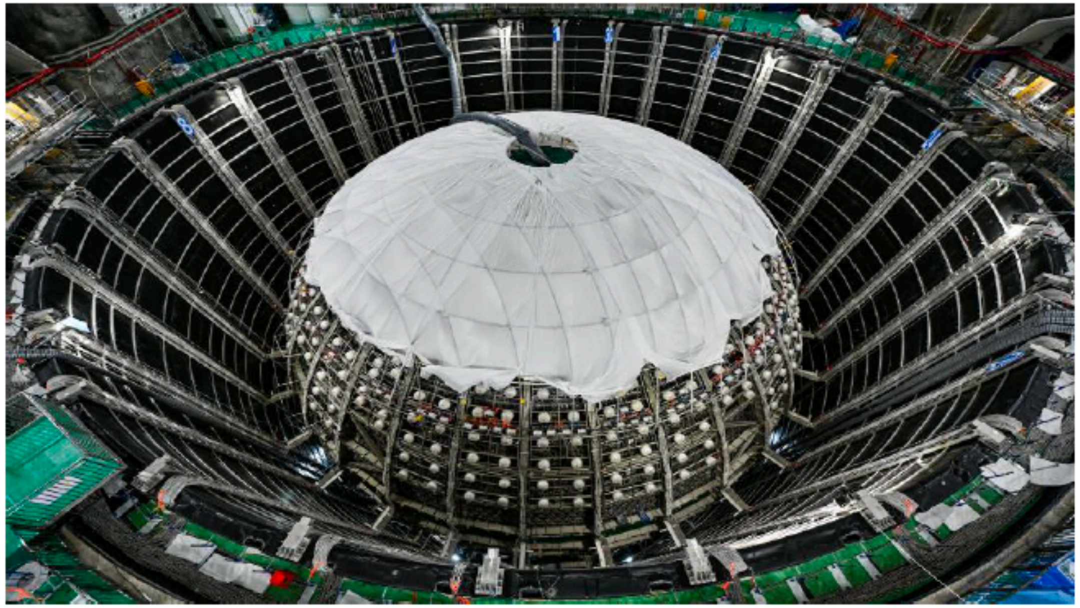
JUNO



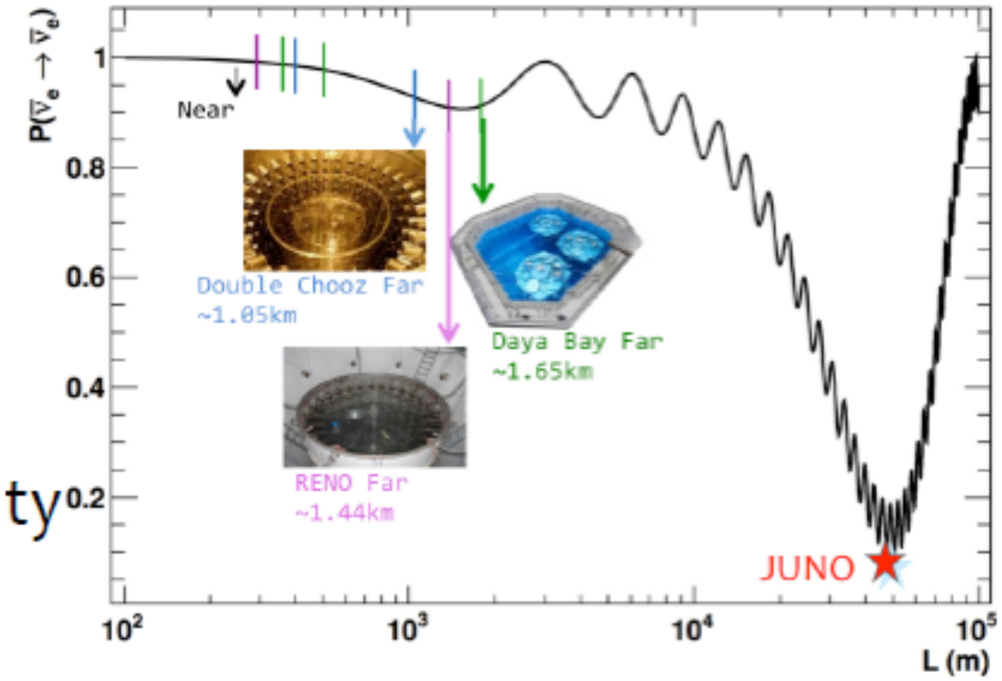
Acrylic Sphere:
- Inner Diameter (ID): 35.4 m
- Thickness:12 cm

Stainless Steel (SS) Structure:
- ID: 40.1 m, Outer Diameter (OD): 41.1 m
- **17612** 20-inch PMTs, **25600** 3-inch PMTs

Water pool:
- ID: 43.5 m, Height: 44 m, Depth: 43.5 m
- **2400** 20-inch PMTs



JUNO

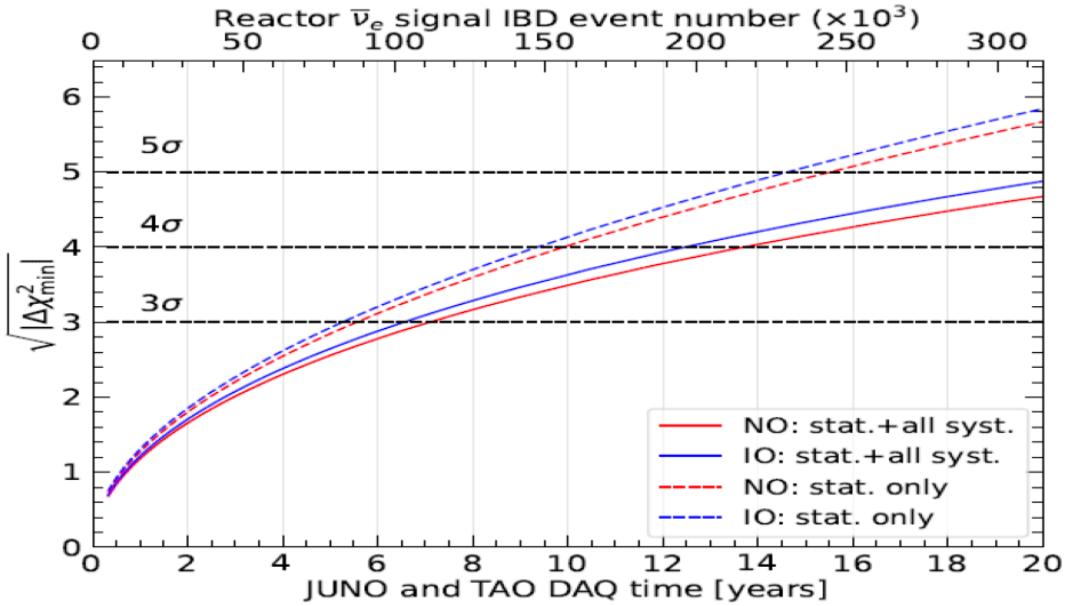


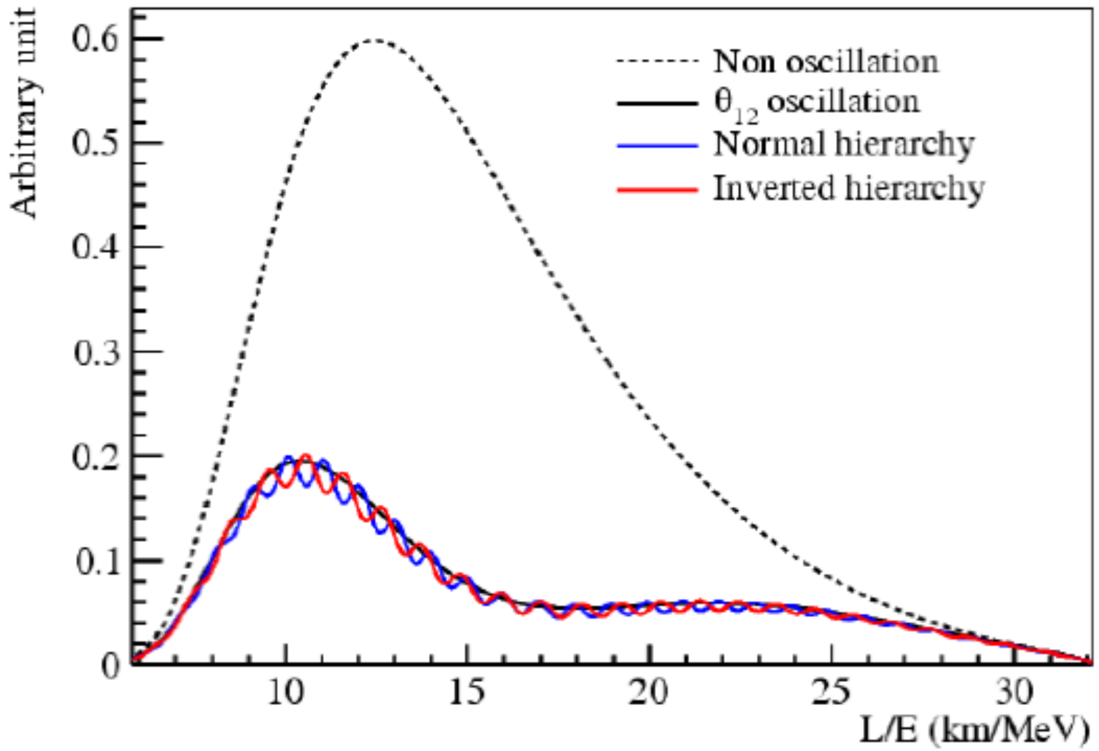
ty

$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e}(L,E) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E} - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right]$$

3 oscillation frequencies:

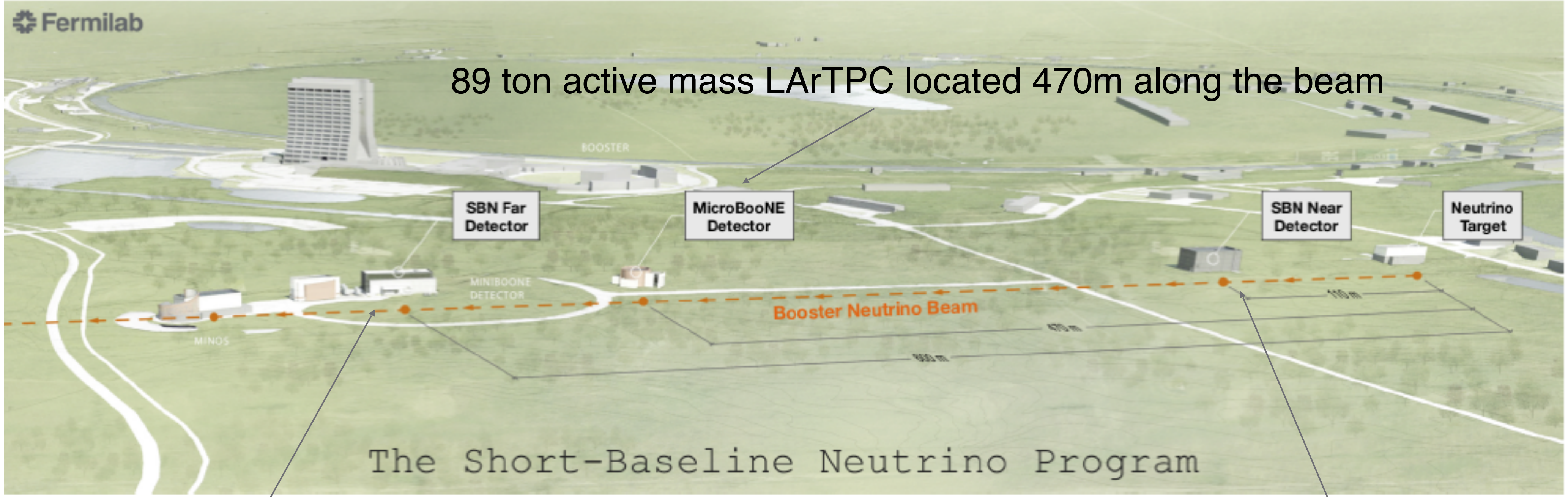
- Low frequency Δm^2_{21} (~ 7.54 x10^{-5} eV^2)
- High frequencies: Δm^2_{31} and Δm^2_{32} (2.43 x10^{-3} eV^2)





SBL FermiLAB neutrino program

89 ton active mass LArTPC located 470m along the beam

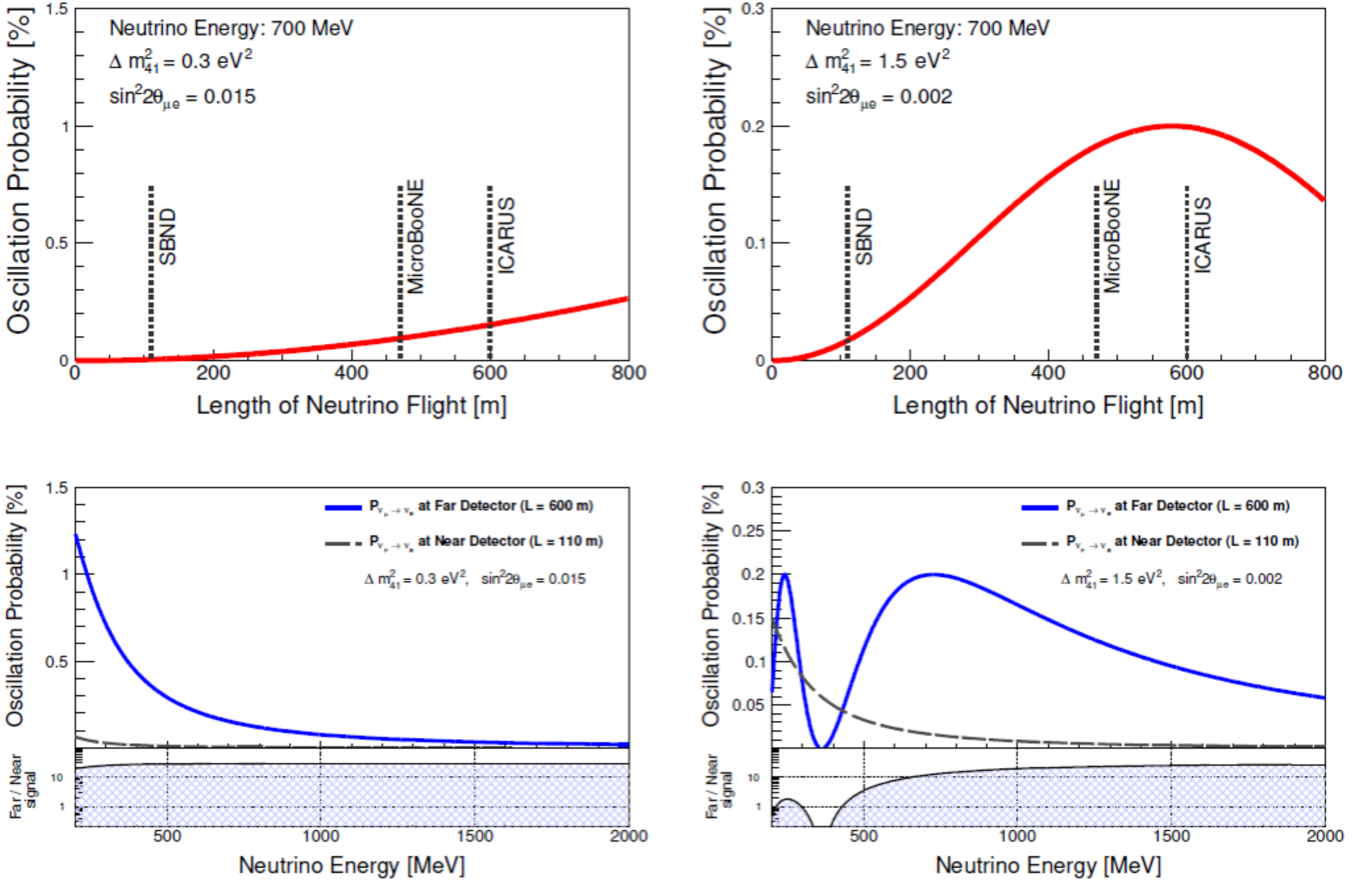


The neutrino beam target area where 8 GeV protons from the Booster accelerator impinge a beryllium target. The beam is focused along the orange dashed line (approximately 7m below grade) traveling toward the left (north). The Near Detector, MicroBooNE, and Far Detector building locations are indicated.

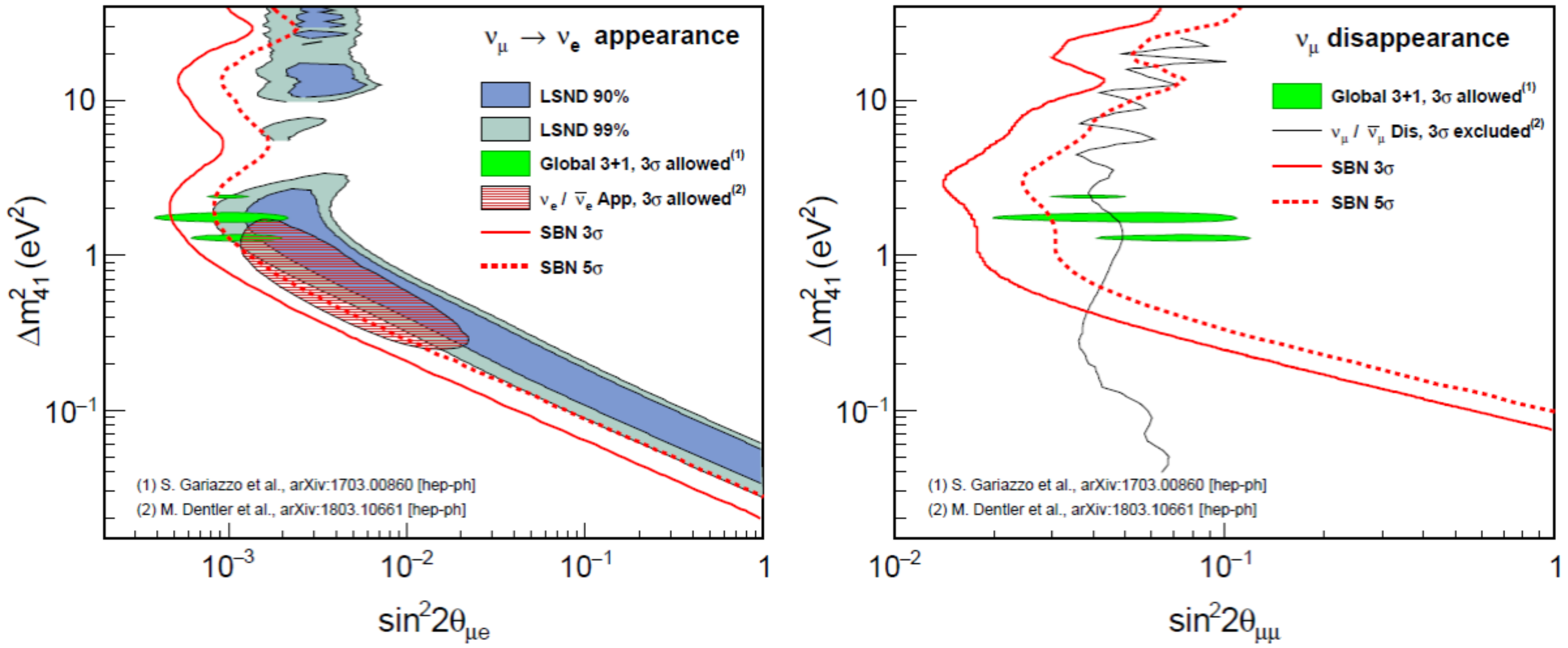
476 ton active mass ICARUS-T600 detector

SBND (or the Short-Baseline Near Detector), will be an all new 112 ton active mass LArTPC sited only 110m from the neutrino production target

SBL FermiLAB neutrino program



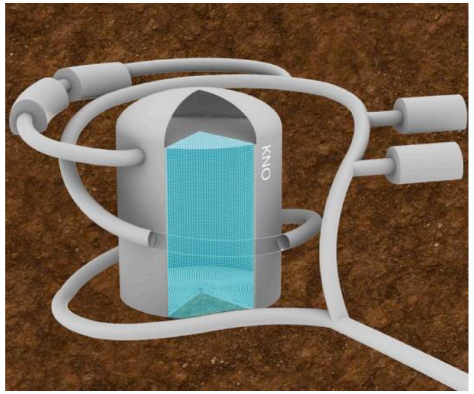
SBL FermiLAB neutrino program



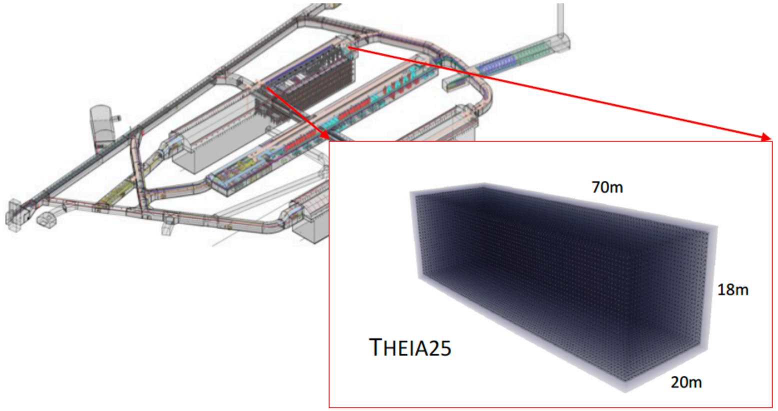
See → Betancourt@Neutrino2020 about SBL neutrino program

+ new (crazy ?) ideas

- Korean Neutrino Observatory (KNO): similar size to HyperK, significantly more overburden



- THEIA: FD4 - DUNE 4th module ("Module of Opportunity")



- LiquidO

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

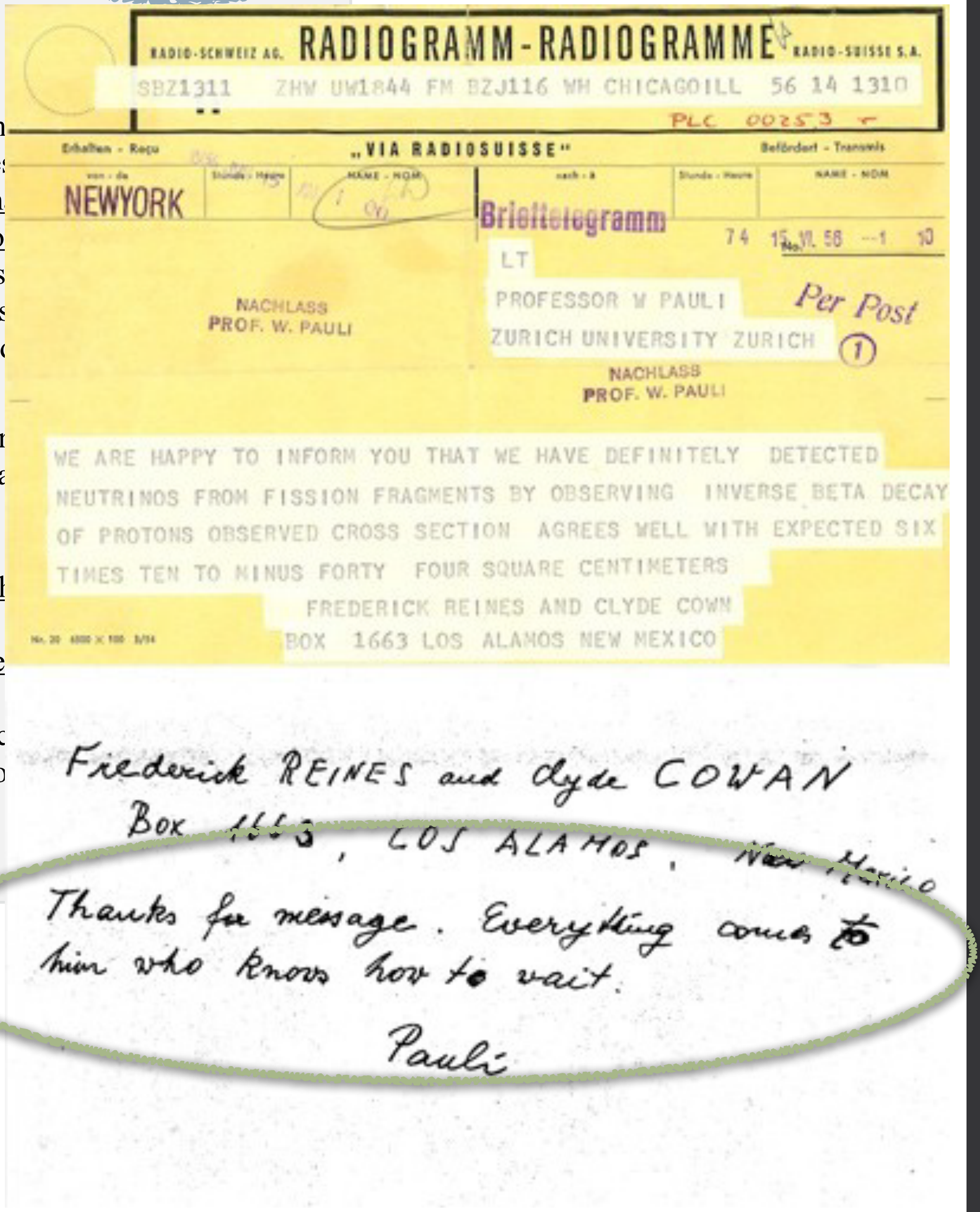
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in m "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a des "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility th exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusio differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons s of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous make sense with the assumption that in beta decay, in addition to the electron a neutron is emitted energies of neutron and electron is constant.

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear the question of how likely it is to find experimental evidence for such a neutron if it would have the sa larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen th for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me rece better not to think about this at all, like new taxes." Therefore one should seriously discuss every radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen sinc in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also servant

signed W. Pauli

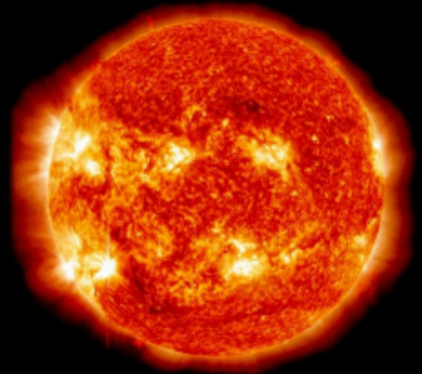
Almost 100 years of neutrino hunting. Still counting…



Backup

THE SNO+ EXPERIMENT

Multi-purpose experiment at SNOLAB - Sudbury, Ontario, Canada

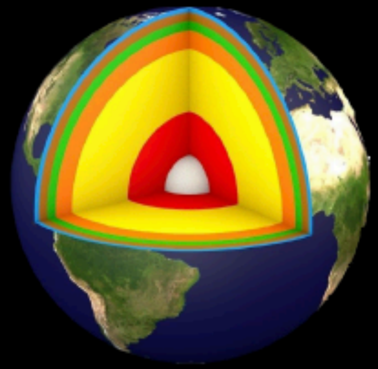


Solar Neutrinos

Reactor Neutrinos

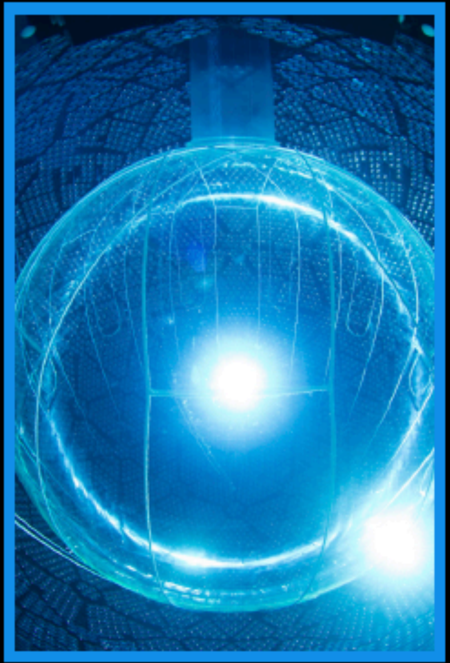
Supernova Neutrinos
+ exotics

Geo-Neutrinos



SNO+ TIMELINE

2017 2018 2019 2020 2021 2022 2023 2024 2025



Water phase

- High Rn
- Low Rn

Partial fill phase

Scintillator over water.
Stop in fill due to Covid.

Scintillator phase

- Low PPO
- Nominal PPO
- Added bis-MSB

REF. 7

Next:
Tellurium-loaded phase

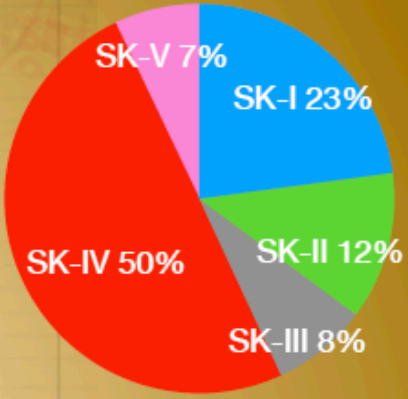
REF. 8

POSTER 581 / B. TAM, S. MANECKI

The Super-Kamiokande experiment

- Super-Kamiokande has been taking data since 1996 and has come through seven run periods
- Densely packed PMTs (40% / 20% for SK-II) and good water quality provide excellent sensitivity for various physics targets.
- In 2020 we have added Gd sulfate to the water in order to increase the sensitivity for neutron capture.

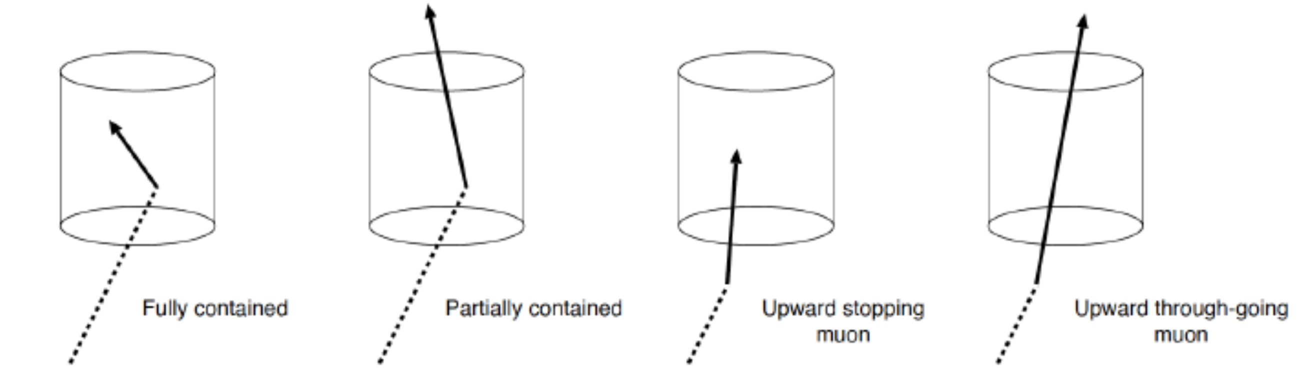
Zenith angle atmospheric neutrino oscillation analysis



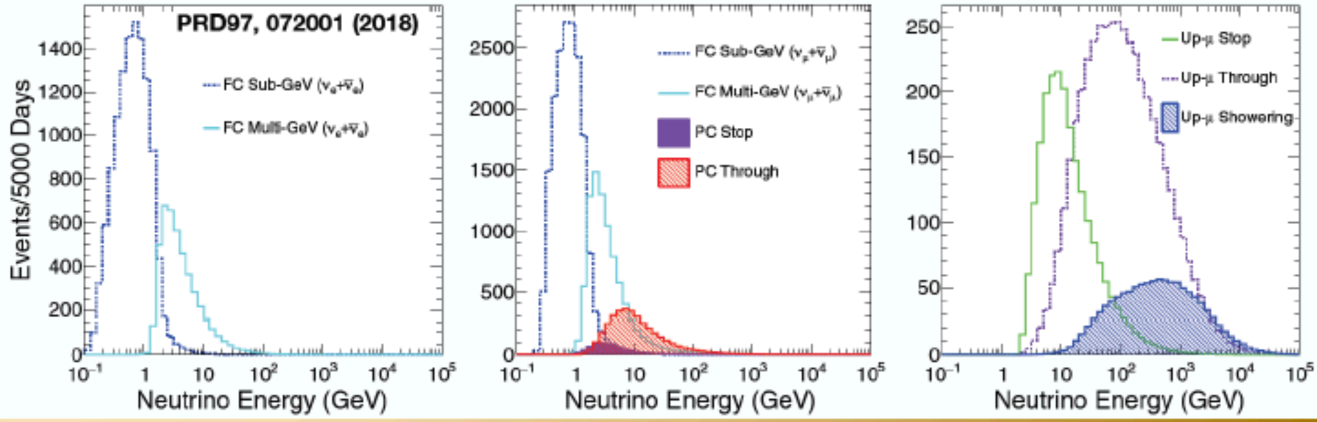
- Latest results with **full SK pure water phase (SK1-5)**:
  - Latest publication - Phys. Rev. D 109, 072014 - Published on 24 April 2024
  - Previously published results: Phys. Rev. D97, 072001 (2018)

- Updates since the previous analysis:
  - **Expansion of fiducial volume and more lifetime: 6511 days, 484 kt·yr in total +50% of statistics**
  - **Event selection with neutron tagging on hydrogen (SK4-5)**
  - New multi-ring event classification using a Boosted Decision Tree (BDT)
    - Improved charged current/neutral current separation
- Atmospheric ν oscillation fit with external constrains
  - θ_{13} from reactors

★ Atmospheric neutrino events at Super-K are classified into several categories:



Expected energy spectra of atm-ν samples

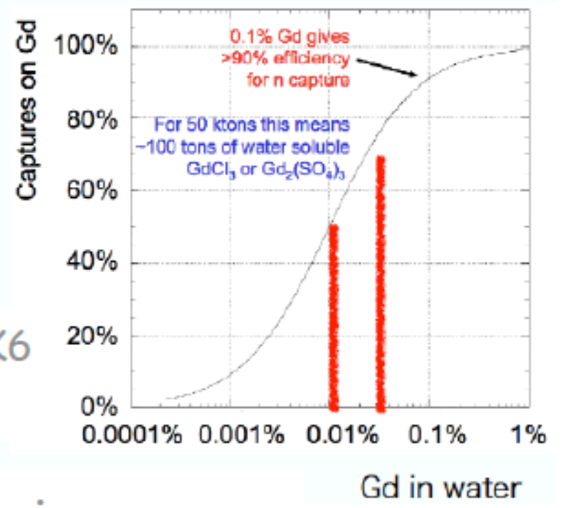


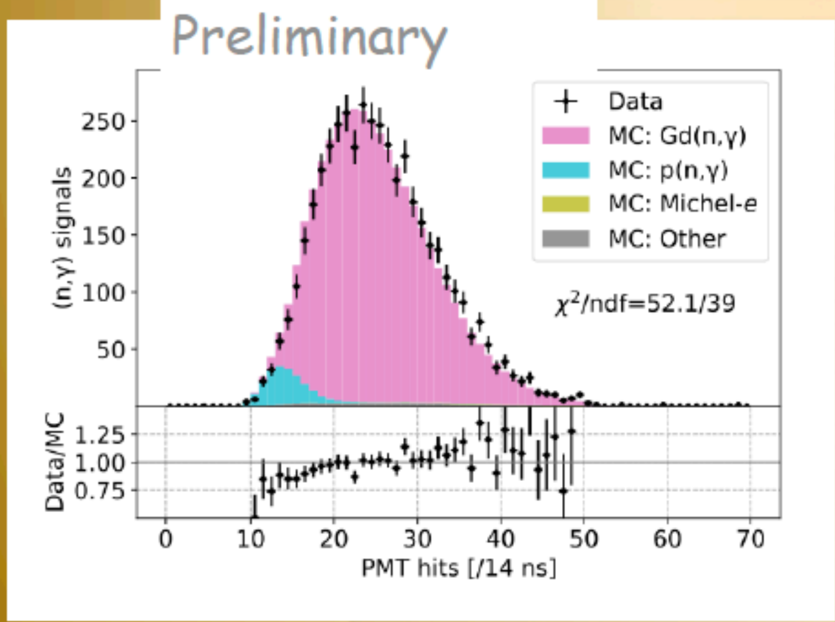
Why Gd salt was added ?

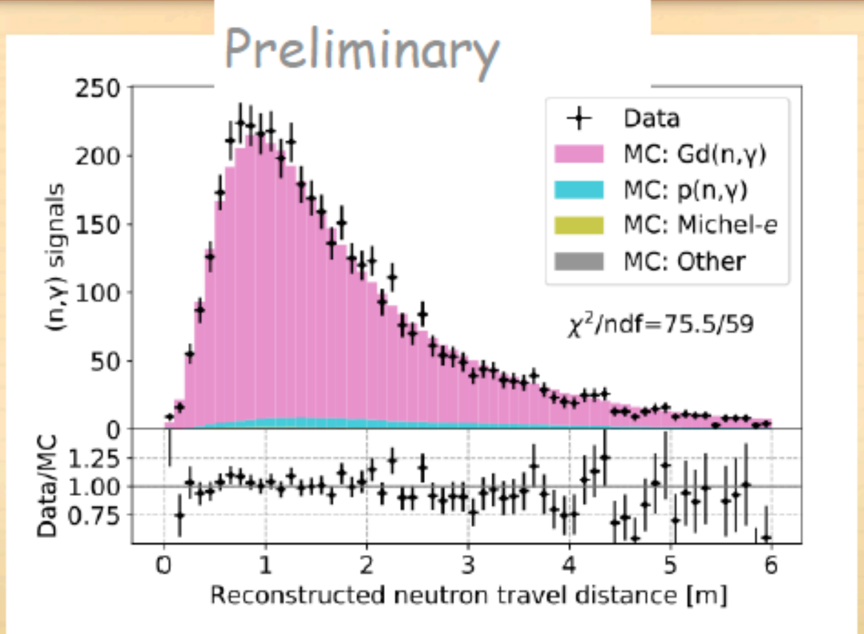
Dissolve Gadolinium into Super-K
J.Beacom and M.Vagins, Phys.Rev.Lett.93(2004)171101

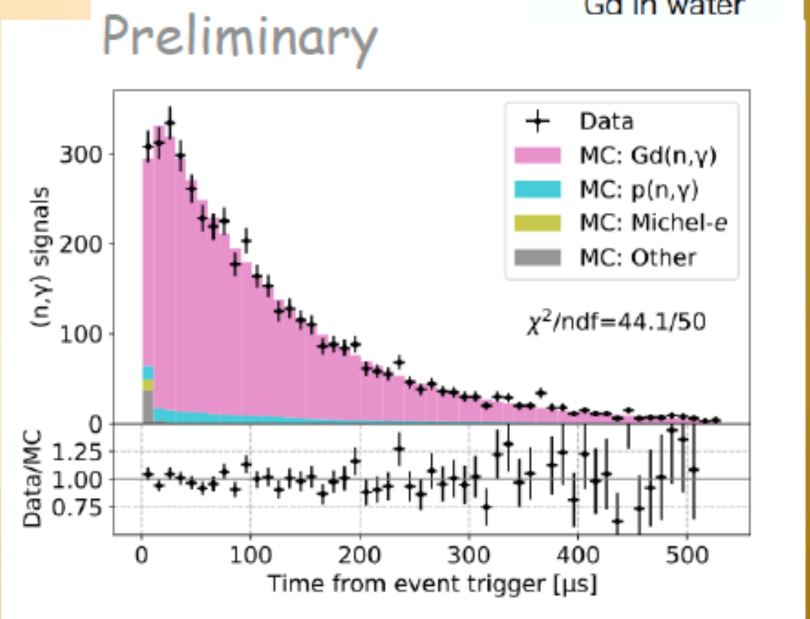
- SK-Gd: add Gd sulphate to ultra pure water to enhance neutron tagging efficiency.
- Physics targets:
  - Detection of the world's first (DSNB) -see Harada-san talk
  - Improvement of supernova direction pointing accuracy
  - Enhancement of ν and $\bar{\nu}$ identification and improvement of E_ν reconstruction in atmospheric ν and T2K analyses
  - Reduction of background in nucleon decay search

Gd: 0.01% SK6
0.03% SK7









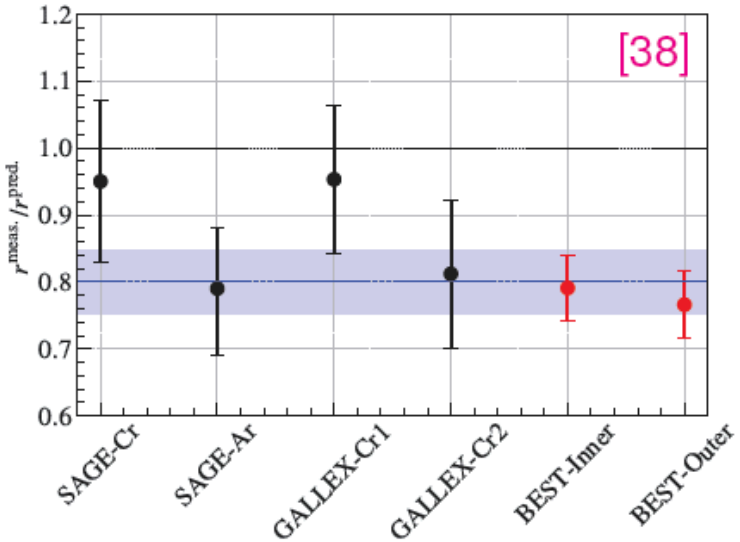
ν_e disappearance: the gallium anomaly

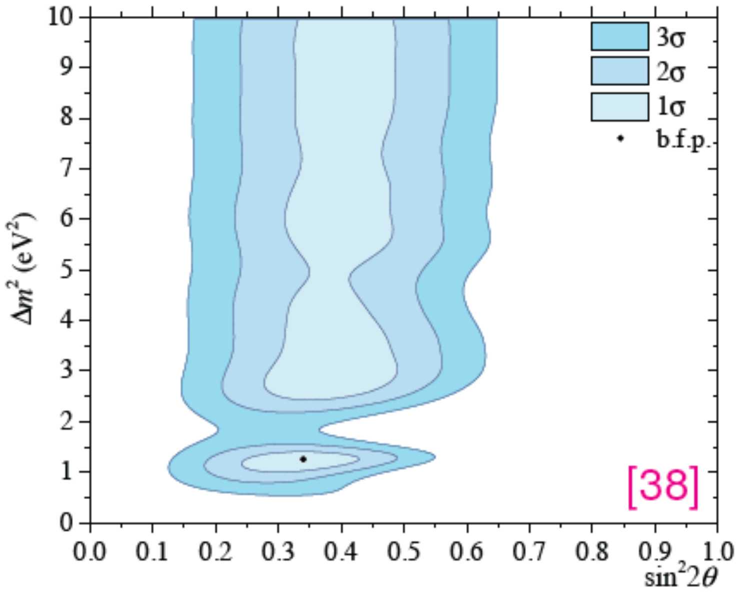
- $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}\ \nu$ capture cross-section was calibrated with intense $^{51}\mathrm{Cr}$ and $^{37}\mathrm{Ar}$ sources by GALLEX & SAGE (20 years ago) as well as BEST (2022);
- these measurements show a significant deficit with respect to the predicted values [38]:

$$\begin{aligned}
\text{GALLEX:}\ & \begin{cases} R_1(\mathrm{Cr}) = 0.953 \pm 0.11 \\ R_2(\mathrm{Cr}) = 0.812 \pm 0.11 \end{cases} \\
\text{SAGE:}\ & \begin{cases} R_3(\mathrm{Cr}) = 0.95 \pm 0.12 \\ R_4(\mathrm{Ar}) = 0.79 \pm 0.095 \end{cases} \\
\text{BEST:}\ & \begin{cases} R_5(\mathrm{I}) = 0.791 \pm 0.05 \\ R_6(\mathrm{O}) = 0.766 \pm 0.05 \end{cases}
\end{aligned} \Rightarrow \boxed{0.80 \pm 0.047}$$

⇝ [Gorbunov]

- such deficit can be interpreted in terms of oscillations;
- data suggest $\Delta m^2 \gtrsim 1\ \mathrm{eV}^2$ but require very large θ_{ee}.





[38] V.V. Barinov *et al.* [BEST], Phys. Rev. C **105** (2022) no.6, 065502 [arXiv:2201.07364]