COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Nature's tiniest fundamental particles - Neutrinos!

Georgia Karagiorgi, Columbia University

Barnard College and Nevis Labs Online Colloquium Series 2020
July 23, 2020

Neutrinos, they are very small
They have no charge and have no mass
And do not interact at all

John Updike, "Cosmic Gall," 1960

Outline

- Neutrinos within the context of the Standard Model
- Experimental signatures of neutrino oscillation

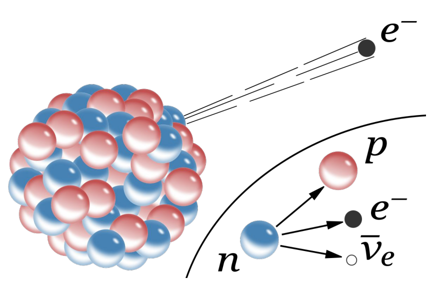
- Historically significant experiments
  – Ray Davis' solar neutrino experiment
  – Kamiokande/Super-Kamiokande atmospheric neutrino experiments
  – SNO solar neutrino experiment
-
- Recent and current oscillation experiments
  – Reactor-based, accelerator-based
  – How everything fits together…
- Future experiments

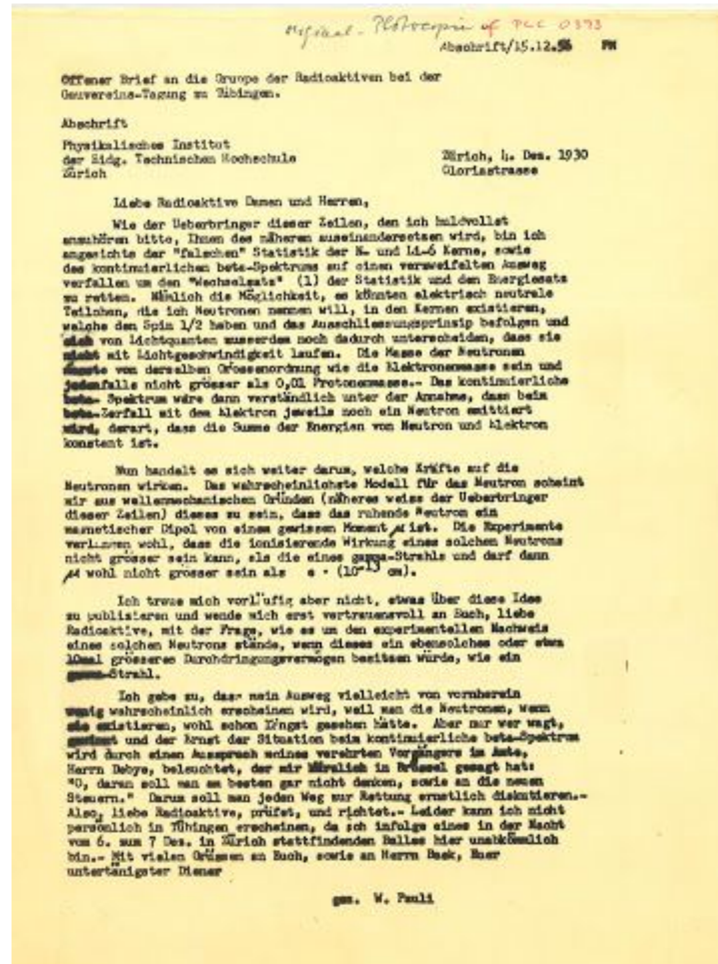
A brief history...

- First postulated in 1930's (Pauli)

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

A "desperate remedy" to save conservation of energy in radioactive beta decay!





Abschrift/15.12.56 PM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

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

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

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Pauli's letter in 1930

A brief history...

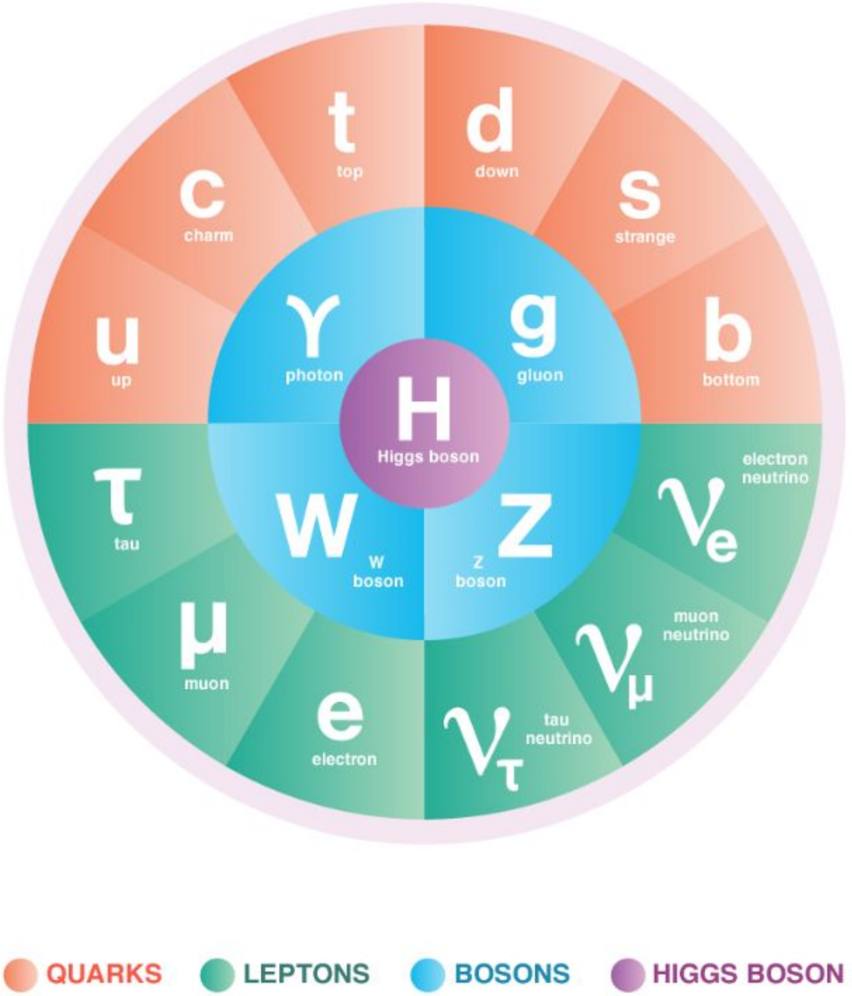
- First postulated in 1930's (Pauli)
- First detected in 1950's (Reines & Cowan)

Clyde Cowan conducting the neutrino experiment *circa* 1956

Neutrinos in the Standard Model

- Three neutrino flavors:
  electron, muon, and tau neutrino

- Weakly interacting
- Only left-handed neutrinos, and only right-handed antineutrinos
- Do not couple to the Higgs
  → Massless!



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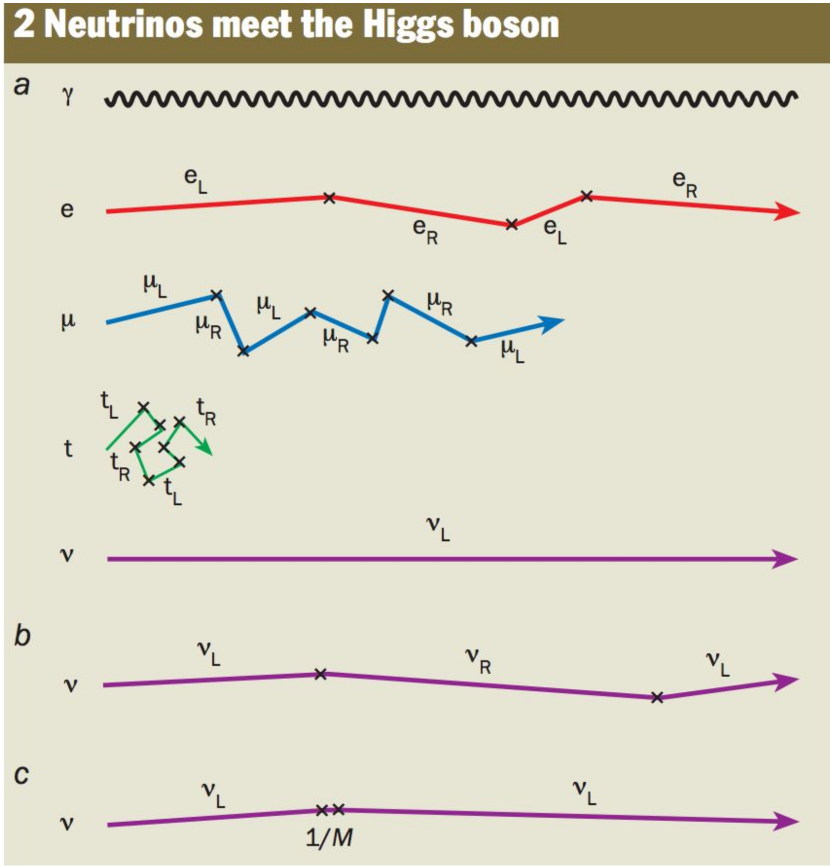
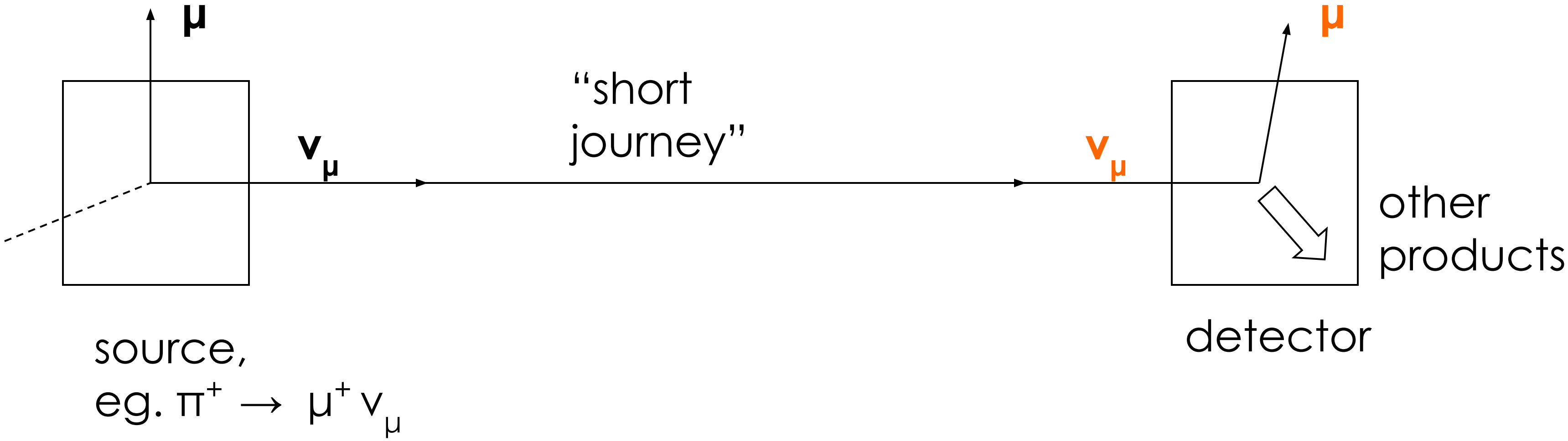


Neutrinos c. 1998

The observation of **neutrino oscillation** implies that neutrinos have mass!
(The Standard Model is incomplete!)

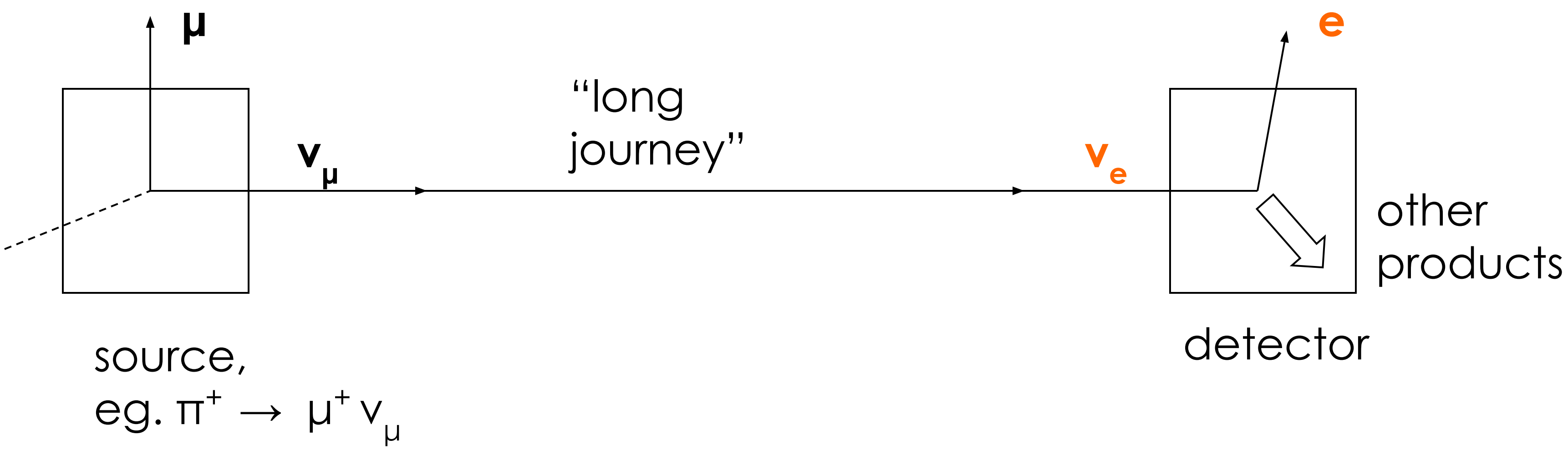
Neutrino oscillation

How do we detect neutrinos experimentally?



Neutrino oscillation

Experimental effect of neutrino oscillations:



This change from one state to another is what we call ***oscillation.***

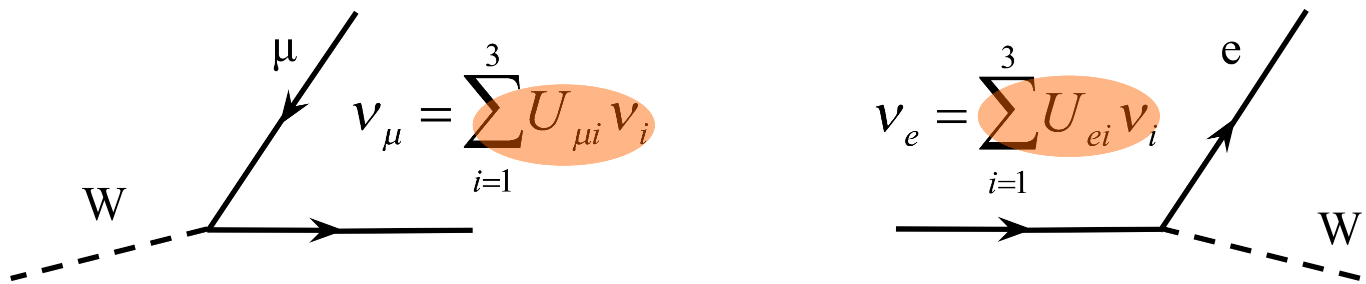
Neutrino oscillation formalism

Neutrinos are produced and detected as one of three definite weak eigenstates: ν_e, ν_μ, ν_τ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak eigenstates — 3×3 unitary mixing matrix *U* — mass eigenstates

Neutrino oscillation formalism



$$\nu_\mu = \sum_{i=1}^{3} U_{\mu i}\nu_i$$

$$\nu_e = \sum_{i=1}^{3} U_{ei}\nu_i$$

neutrino production

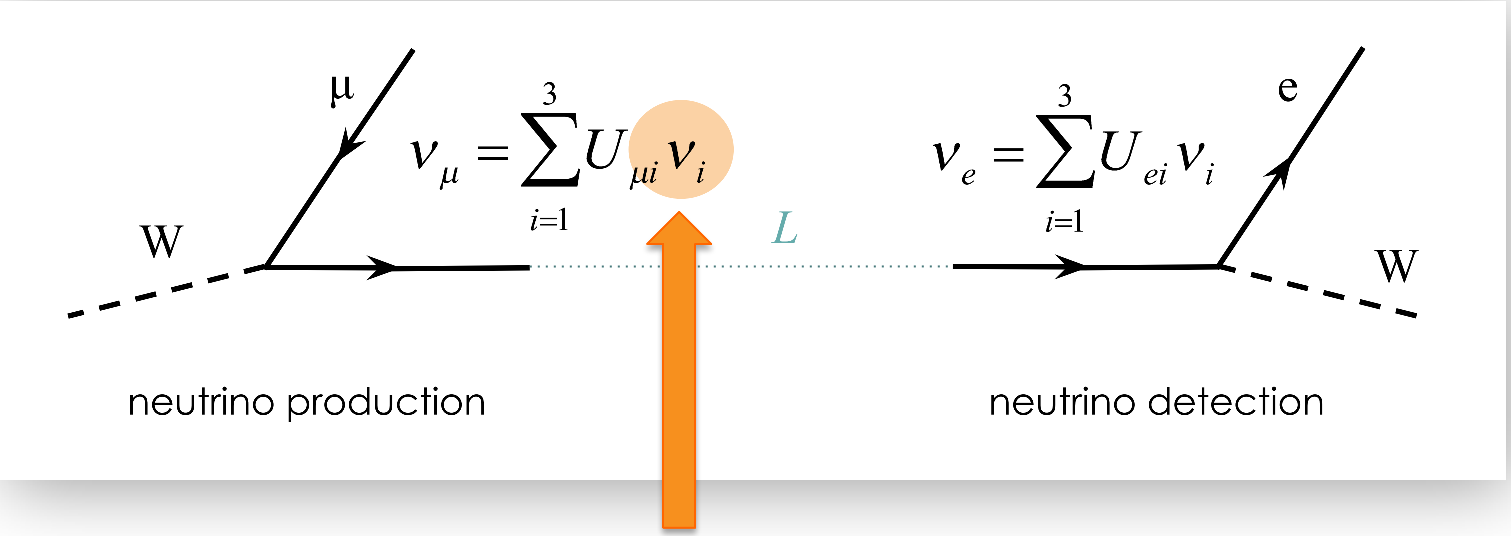
neutrino detection

Neutrinos are produced and detected
as one of three definite ~~weak eigenstates: ν_{e}, ν_{μ}, ν_{τ}~~
sums over three mass eigenstates: ν_1, ν_2, ν_3

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

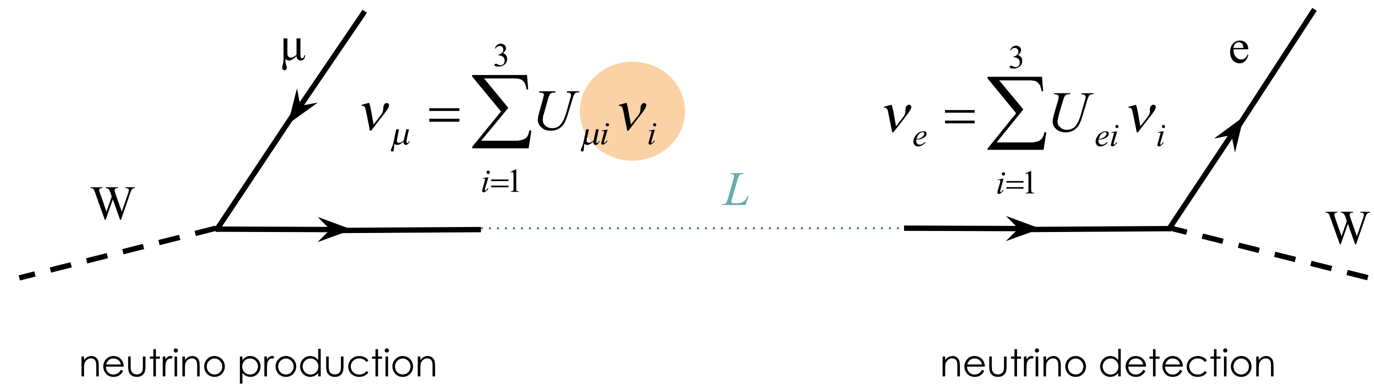
weak eigenstates — 3×3 unitary mixing matrix *U* — mass eigenstates

Neutrino oscillation formalism



If m_i are distinct, after traveling some distance L, the ν_i get out of phase with each other. Their sum no longer corresponds to a ν_μ!

Neutrino oscillation formalism



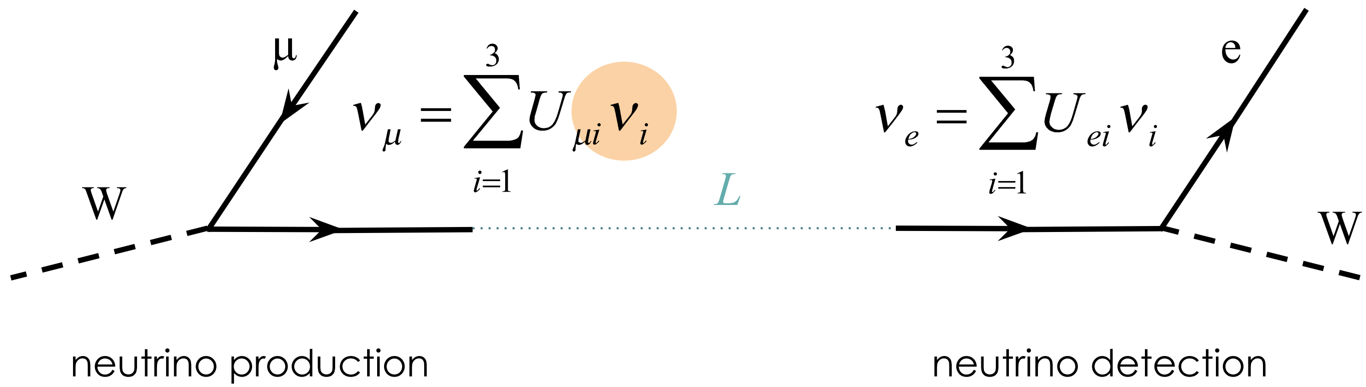
Probability of ν_α production followed by ν_β detection after some distance L:

$$P(\nu_\alpha \to \nu_\beta) = \left|\left\langle \nu_\beta \middle| \nu_\alpha(t) \right\rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left\{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right\} \sin^2\left[1.27 \Delta m^2_{ij} L/E\right]$$

$$+2\sum_{i>j} \mathrm{Im}\left\{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right\} \sin\left[2.54 \Delta m^2_{ij} L/E\right]$$

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

Neutrino oscillation formalism



Probability of ν_α production followed by ν_β detection after some distance L:

$$P\left(\nu_\alpha \to \nu_{\beta\neq\alpha}\right) = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(1.27\Delta m^2 L / E\right)$$

$$P\left(\nu_\alpha \to \nu_\alpha\right) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(1.27\Delta m^2 L / E\right)$$

"two-neutrino approximation"

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

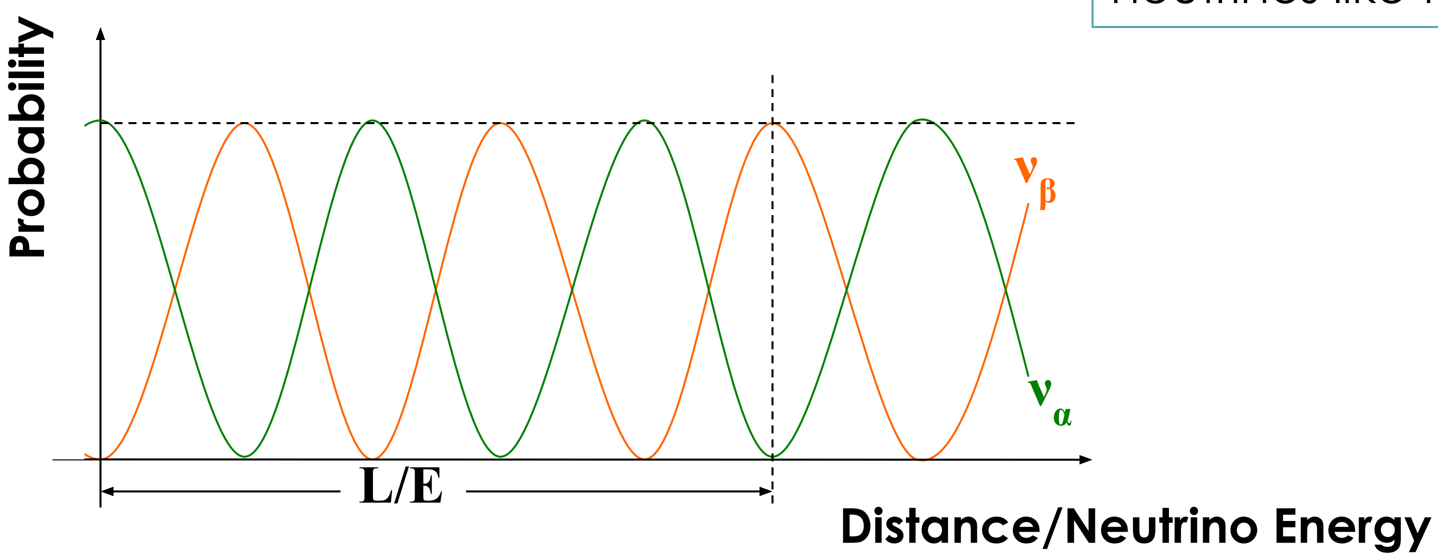
Neutrino oscillation Signatures

$$P\left(\nu_\alpha \to \nu_{\beta\neq\alpha}\right) = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(1.27\Delta m^2 L / E\right)$$

$$P\left(\nu_\alpha \to \nu_\alpha\right) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(1.27\Delta m^2 L / E\right)$$

oscillation amplitude; "how much" neutrinos like to oscillate

oscillation frequency; "how quickly," as a function of L/E, neutrinos like to oscillate

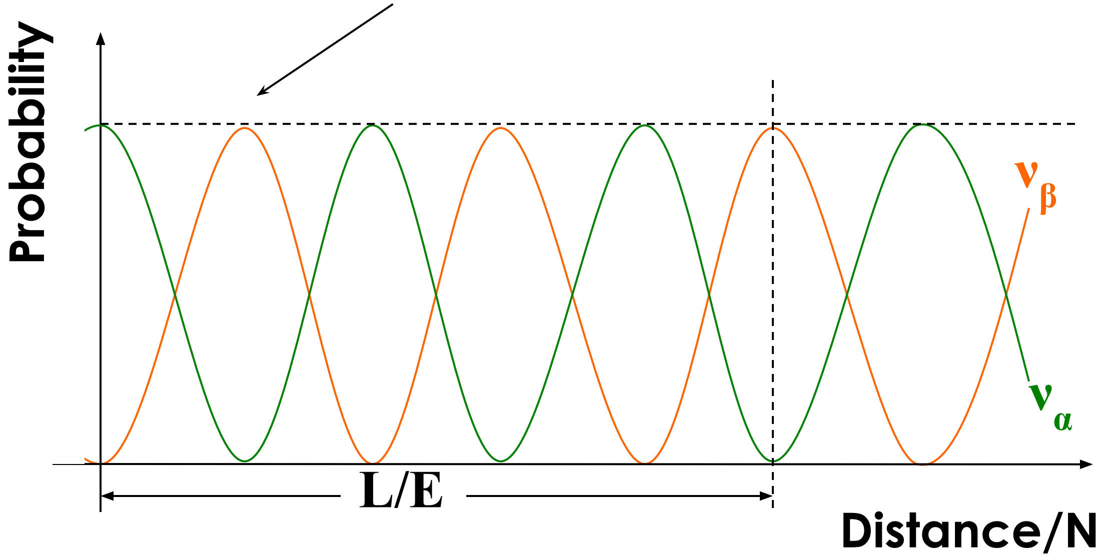


Neutrino oscillation Signatures

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\vartheta_{\alpha\beta} \sin^2(1.27\Delta m^2 L/E)$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2(1.27\Delta m^2 L/E)$$

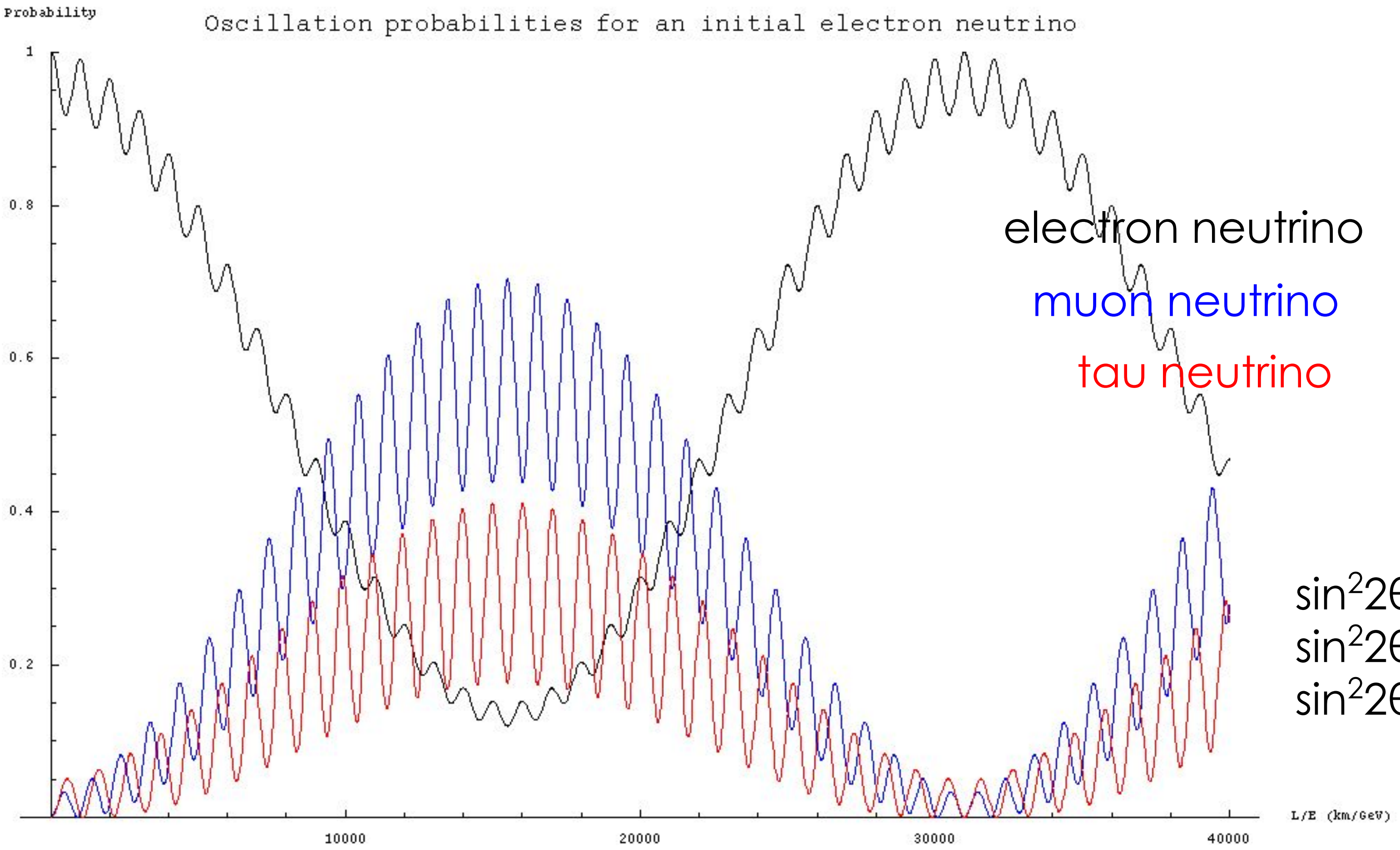
"First oscillation maximum": $(1.27\ \Delta m^2\ L/E) = \pi/2$



L and E are key for designing an oscillation experiment!

Neutrino oscillation Signatures

Of course, there are **three neutrinos, and two oscillation frequencie**s…

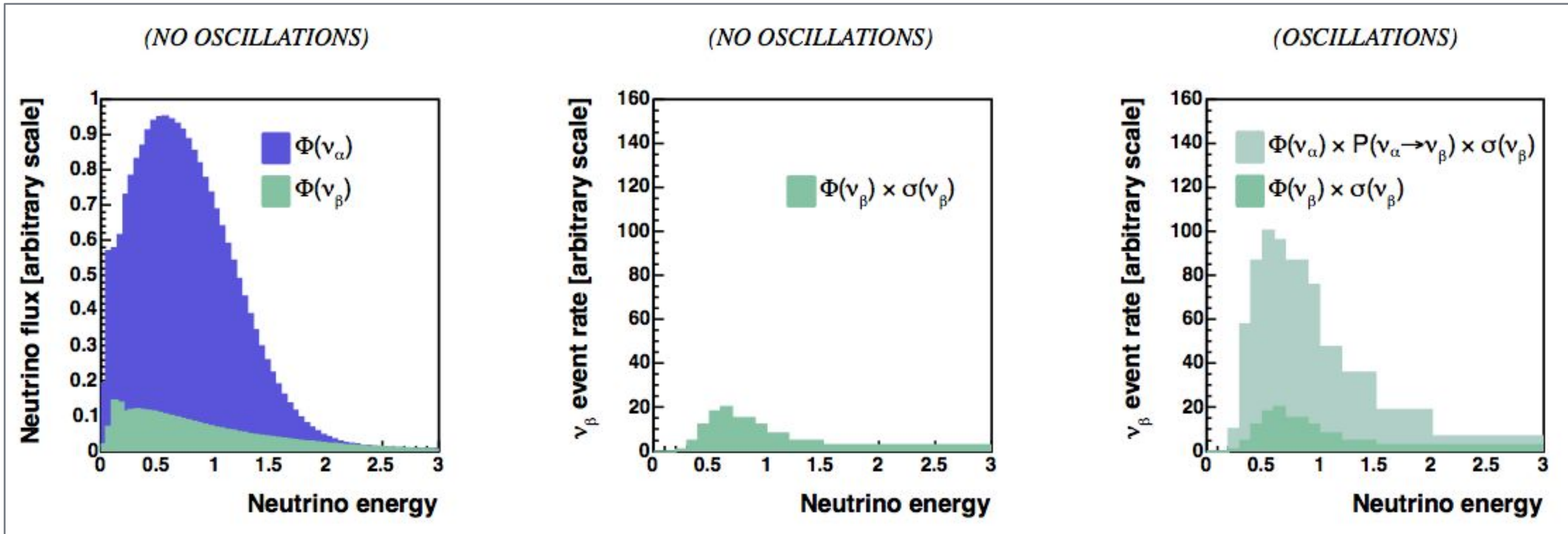


$\sin^2 2\theta_{12} \sim 0.86$
$\sin^2 2\theta_{13} \sim 0.08$
$\sin^2 2\theta_{23} \sim 0.97$

Neutrino oscillation Signatures

Neutrino appearance signature:

$$\nu_\alpha \to \nu_{\beta\neq\alpha}$$

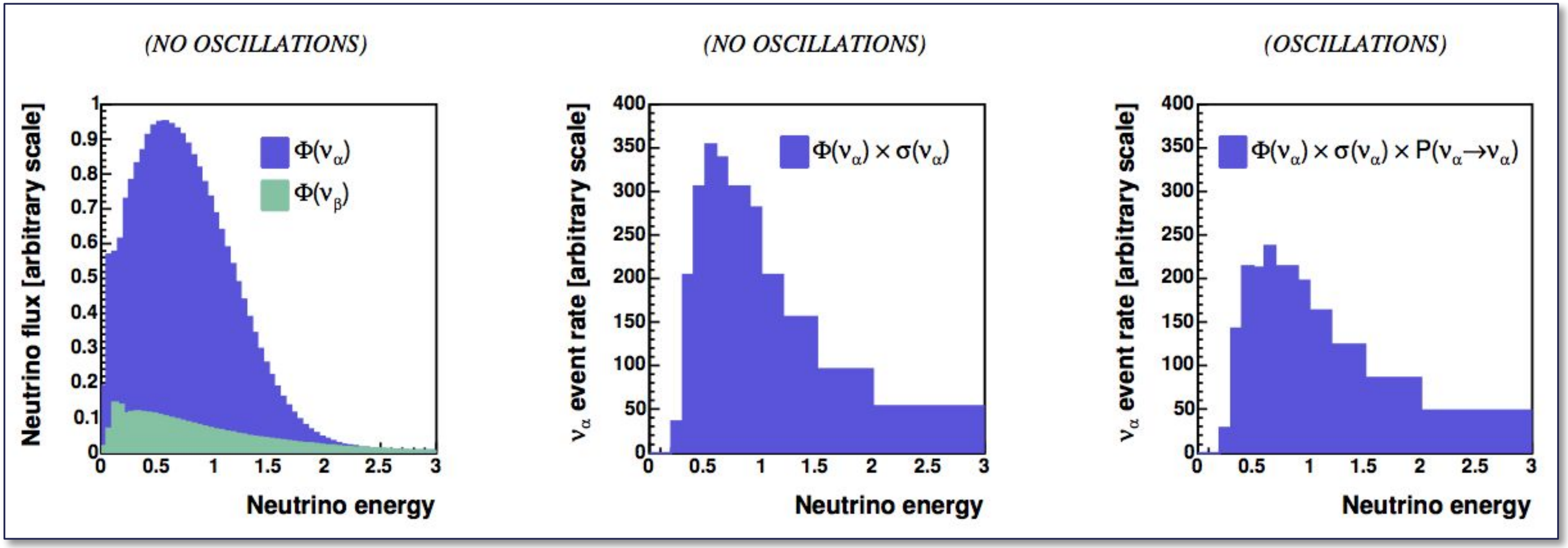


$$P\left(\nu_\alpha \to \nu_{\beta\neq\alpha}\right) = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(1.27\Delta m^2 L / E\right)$$

- Neutrino flux is primarily ν_α, with very small ν_β contamination.
- **Look for excess ν_β events with the "right" energy dependence.**

Neutrino oscillation Signatures

Neutrino disappearance signature: $\nu_\alpha \rightarrow \nu_\alpha$



$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(1.27\Delta m^2 L / E\right)$$

- Neutrino flux is primarily ν_α, with very small ν_β contamination.
- **Look for deficit of ν_α events with the "right" energy dependence.**

Neutrino oscillation Signatures

- Experiments compare oscillation and no-oscillation predictions to data, fitting to $\sin^2 2\theta$ and Δm^2
- Allowed oscillation parameter space is compared to that from other experiments to arrive at a global neutrino oscillation picture…

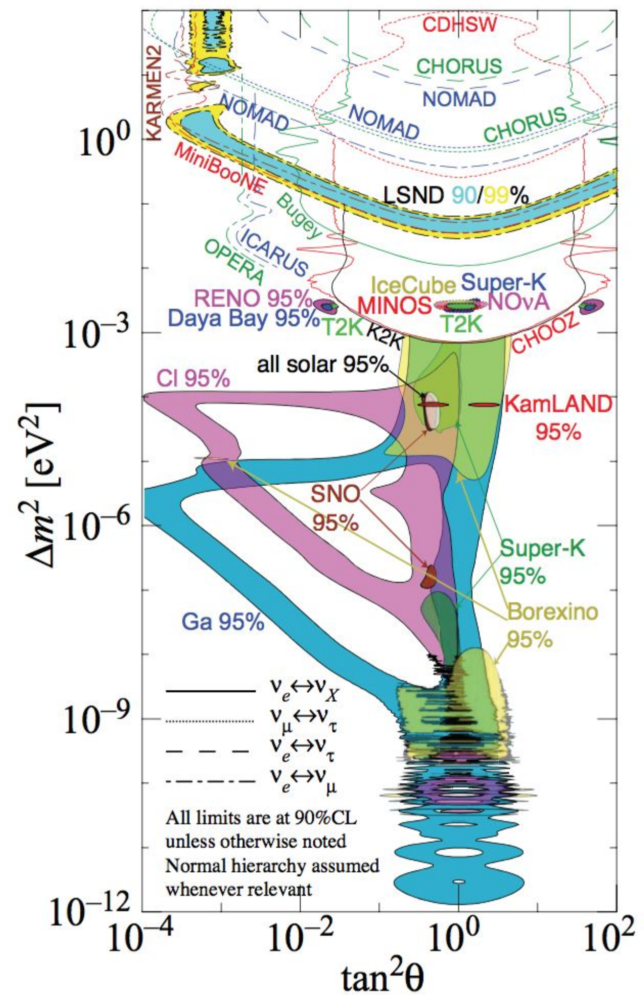
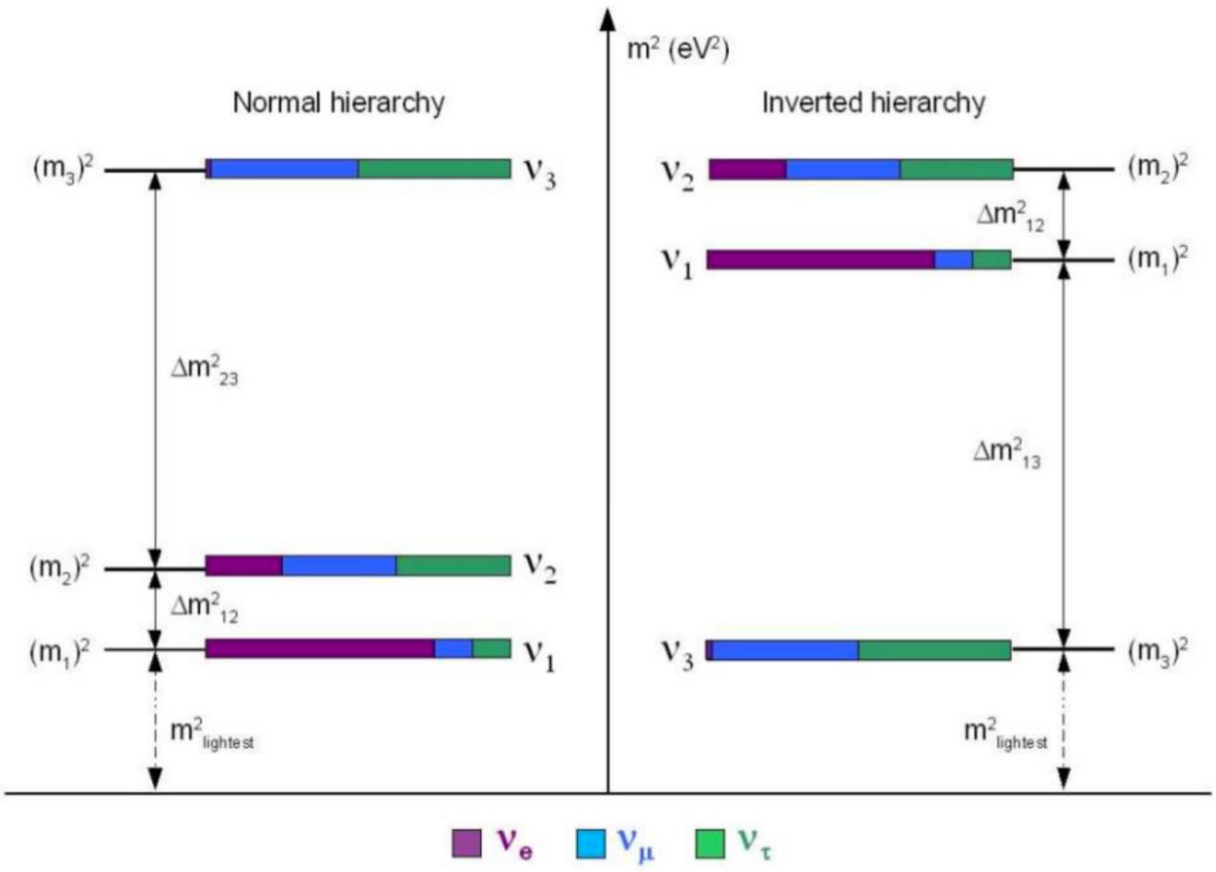


Figure 14.16: The regions of squared-mass splitting and mixing angle favored or excluded by various neutrino oscillation experiments. The figure was contributed by H. Murayama (University of California, Berkeley, and Kavli IPMU, University of Tokyo). References to the data used in the figure and the description of how the figure was obtained can be found at `http://hitoshi.berkeley.edu/neutrino`.

[PDG2017]

Three-neutrino picture

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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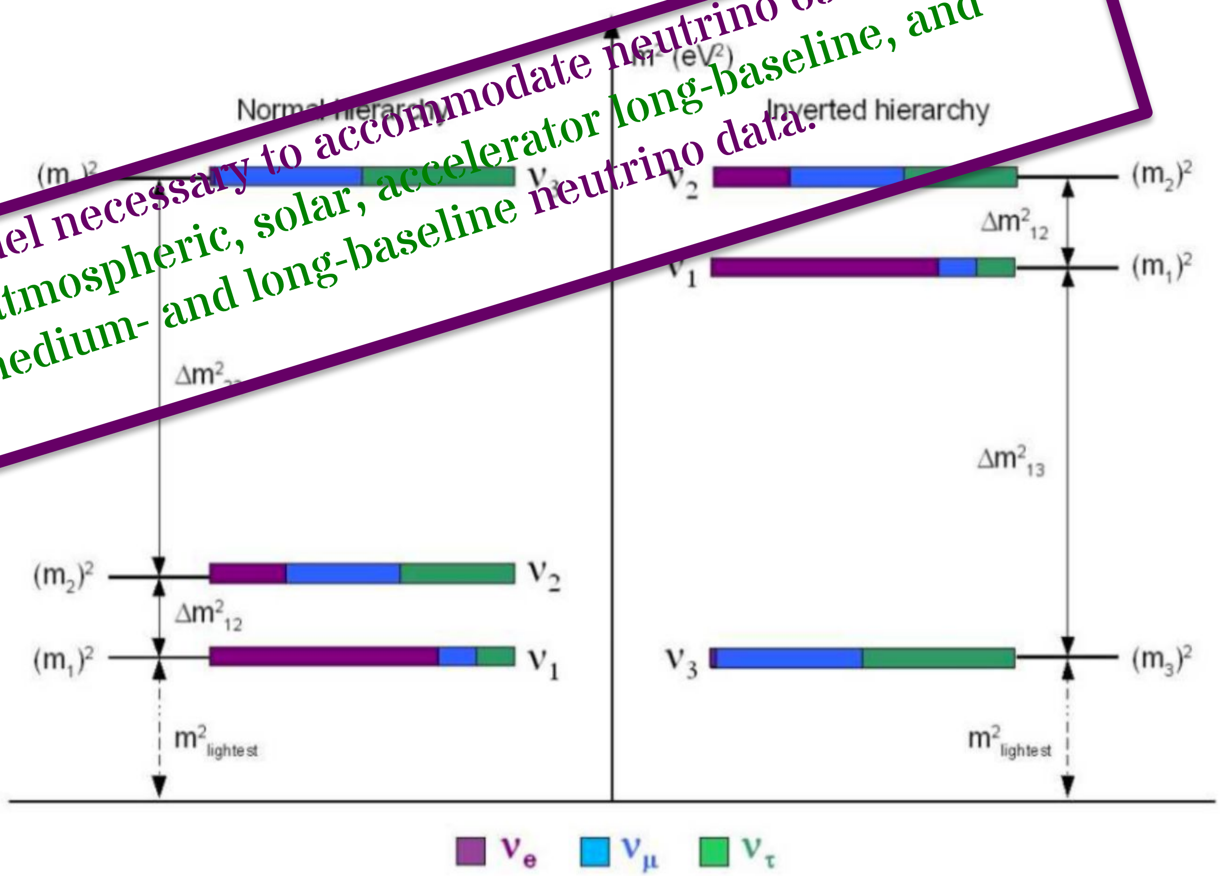
The most minimal model necessary to accommodate neutrino oscillations AS DICTATED BY atmospheric, solar, accelerator long-baseline, and reactor medium- and long-baseline neutrino data.



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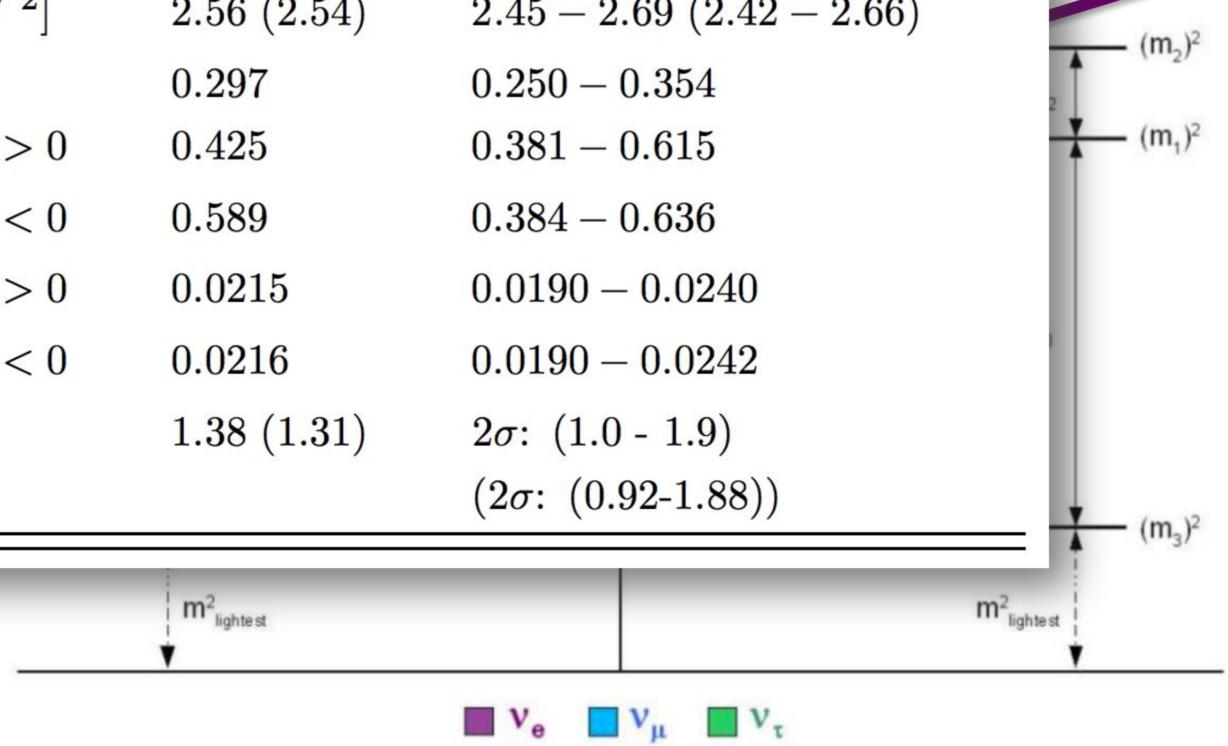
[PDG 2017]

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))



Three-neutrino picture

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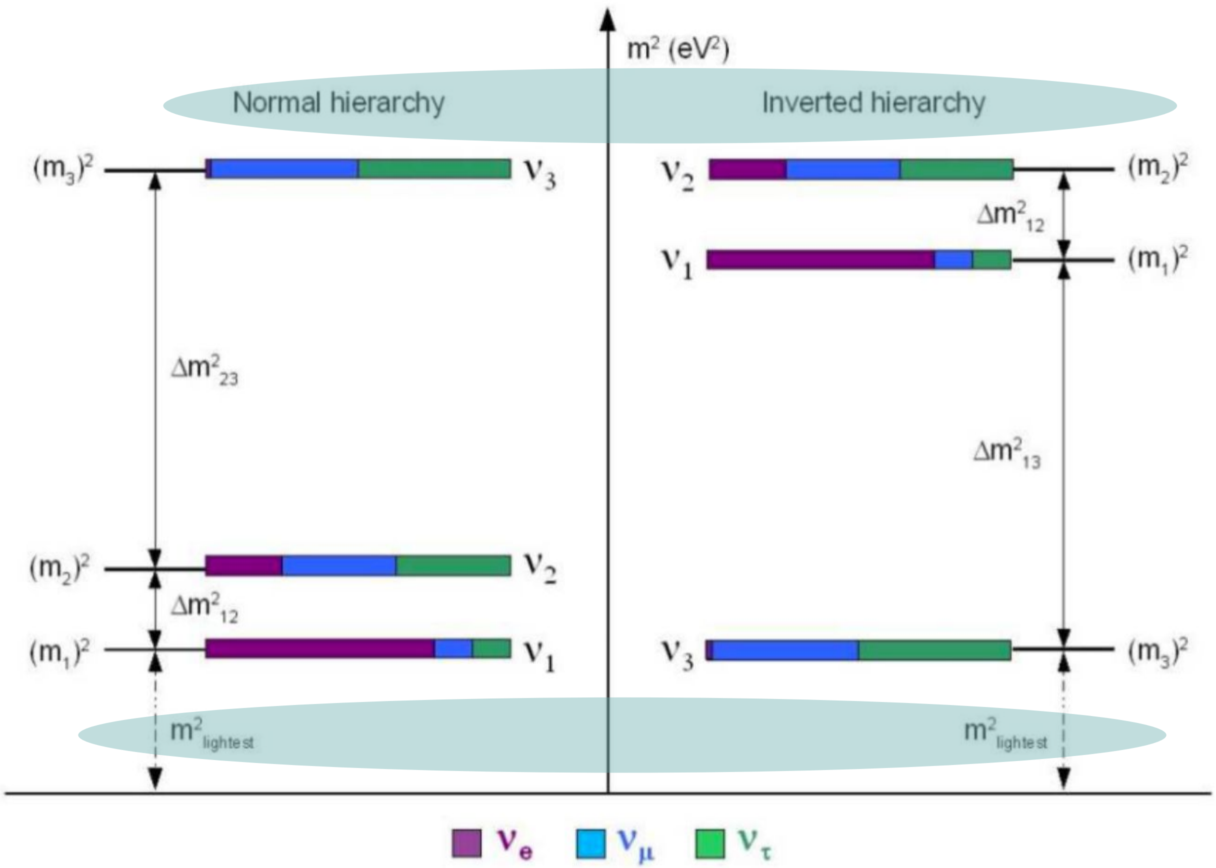
Parameters which
are yet to be determined.

CP violation phase

If non-zero, could provide clues about matter-antimatter asymmetry in our universe.



It took decades for this picture to arise!

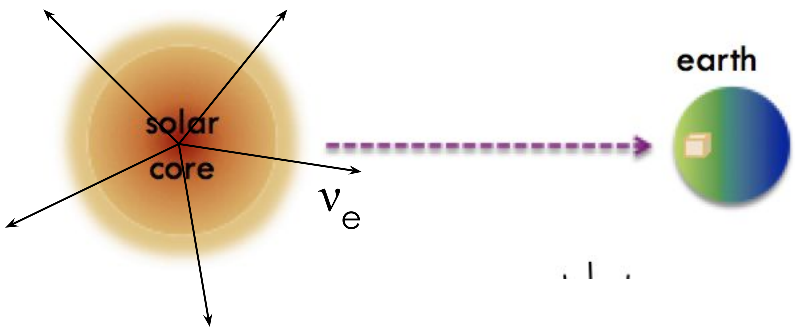
- Key experiments:
  - Ray Davis' solar neutrino experiment
  - Kamiokande/Super-Kamiokande atmospheric neutrino experiments
  - SNO solar neutrino experiment

The "solar" and "atmospheric" neutrino anomalies (1960s – 1990s)

Very first measurement of solar neutrinos:

- **Ray Davis' experiment** at Homestake Mine (1960s-1990s)

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



$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.7\,MeV$$

- Observation of **only ~1/3 of ν_e rate expected from calculation** of solar neutrino flux (by J. Bachall)

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Very first measurement of solar neutrinos:

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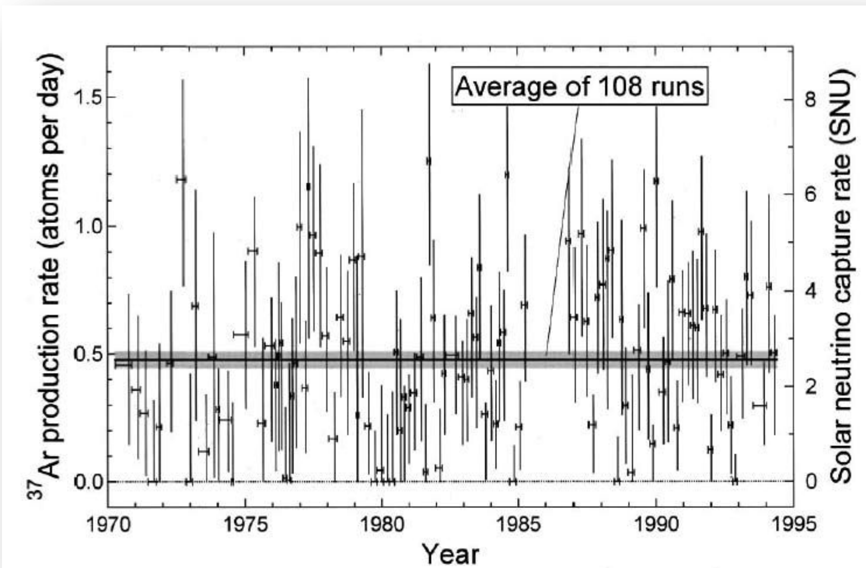
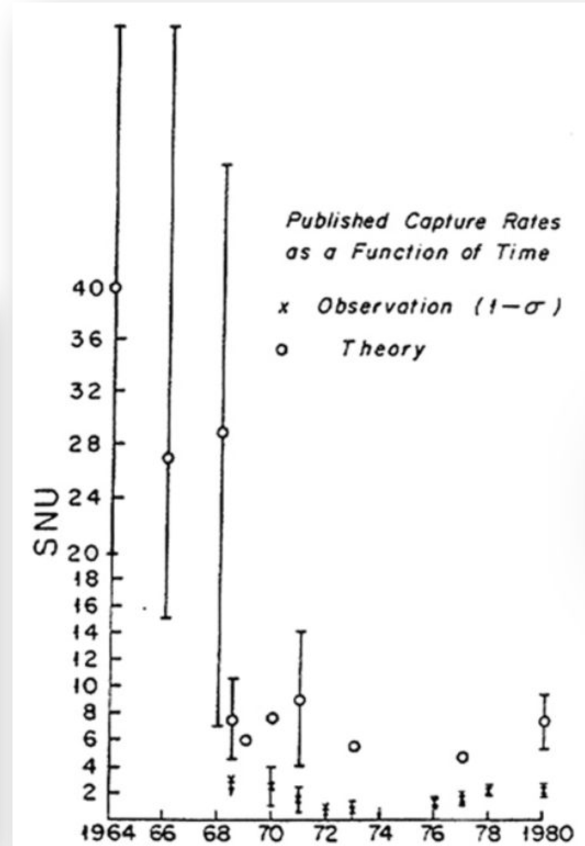




- Observation of **only ~1/3 of ν_e rate expected from calculation** of solar neutrino flux (by J. Bachall)

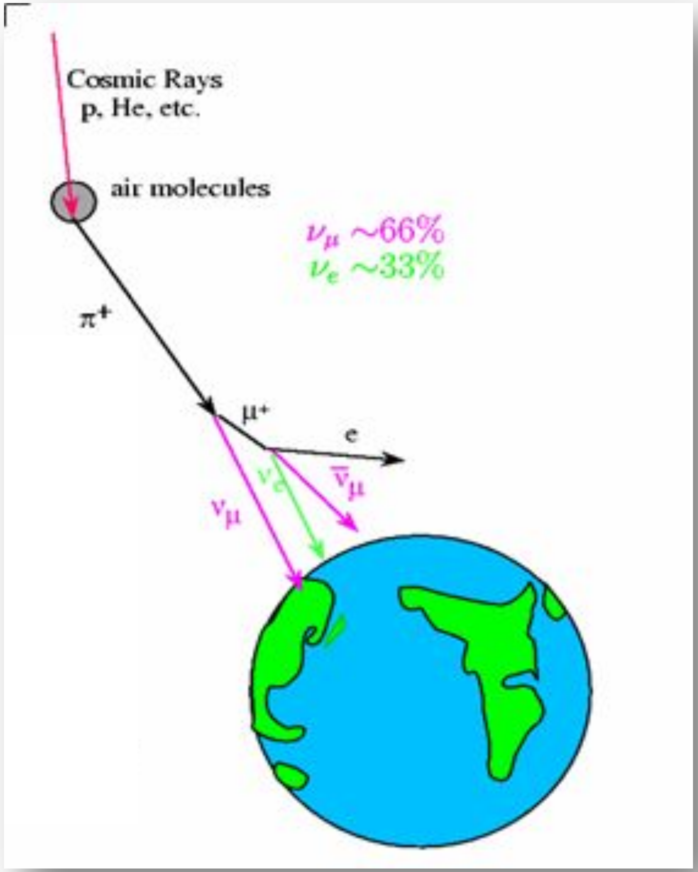
The "solar" and "atmospheric" neutrino anomalies (1960s – 1990s)

Early measurements of atmospheric neutrinos:

- **Kamiokande experiment** at Kamioka Mine (1970s-1980s)

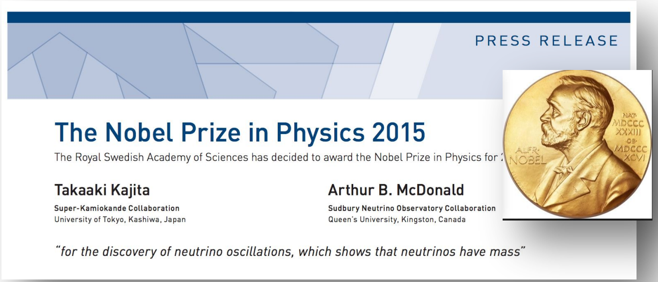
A proton decay search experiment, deep underground.

Atmospheric neutrinos were predicted to be a background to this search.



- Observation of **deficit of atmospheric muon neutrinos** in 1988

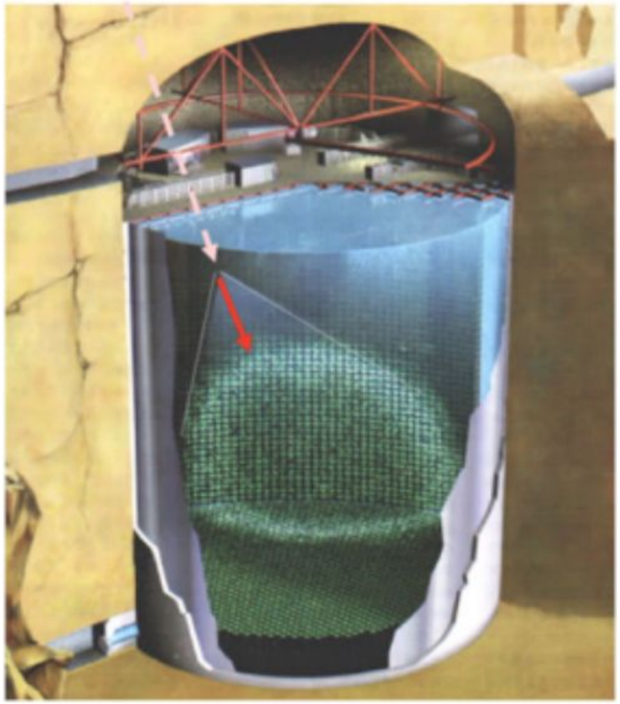
Resolution (1/2)



Follow-up measurements and resolution of atmospheric neutrino deficit:
Super-Kamiokande experiment at Kamioka Mine (1990s-…)

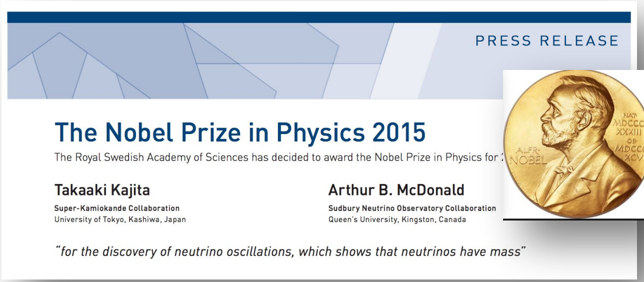
50 kton water Cherenkov detector
22.5 kton fiducial volume at 2,700 m.w.e. underground

20+ years of running, ~50,000+ atmospheric neutrino events!



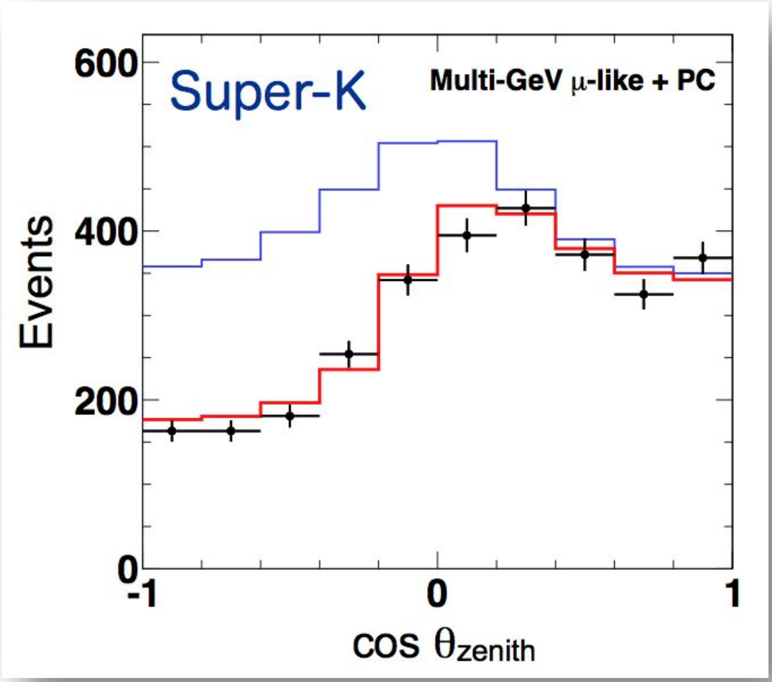
Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III(2005-2008) SK-IV(2008-Present)

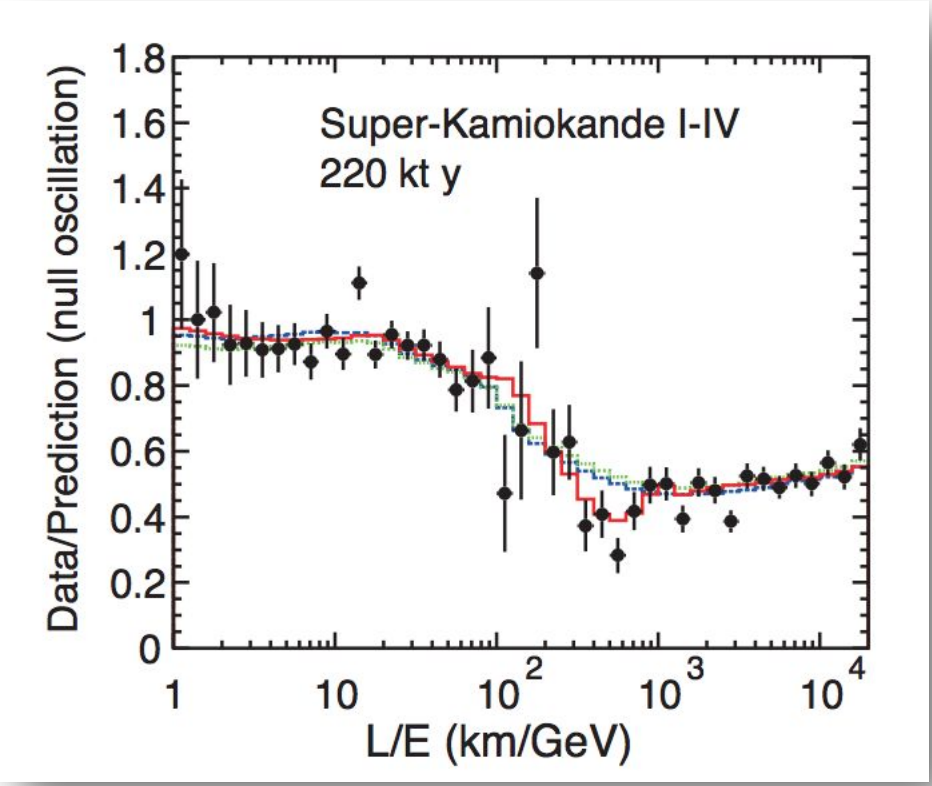
Resolution (1/2)



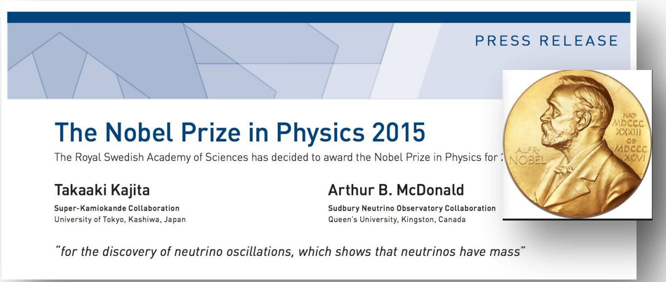
Follow-up measurements and resolution of atmospheric neutrino deficit:
Super-Kamiokande experiment at Kamioka Mine (1990s-…)

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{32} L/E)$$



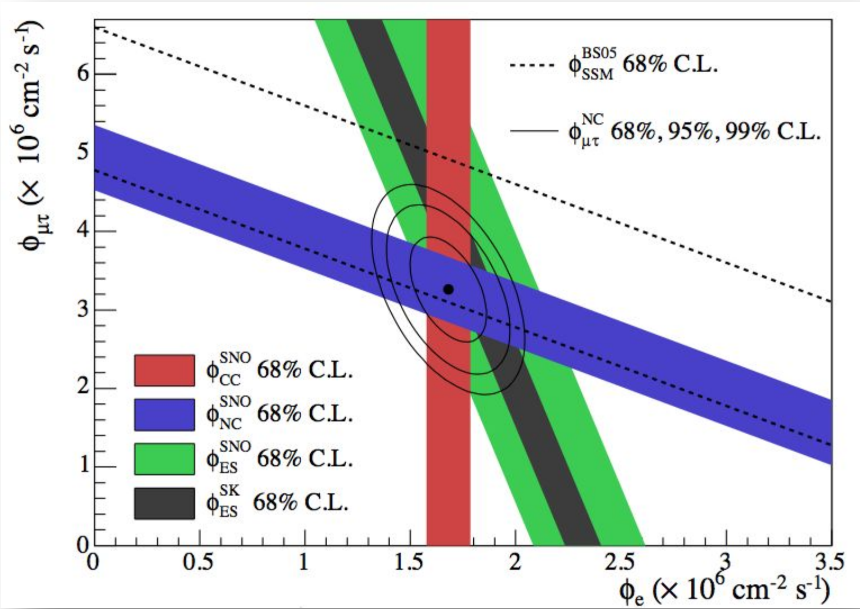


Resolution (2/2)



Follow-up measurements and resolution of solar neutrino deficit:
SNO experiment in Sudbury, Canada, 2001

Past radiochemical experiments sensitive to only ne.
SNO: sensitive to ν_e, ν_μ, ν_τ through **neutral-current** (NC) interactions, and to ν_e through **charged-current** (CC) interactions



$$\frac{\varphi^{CC}}{\varphi^{NC}} \sim \frac{|U_{e2}|^2}{\sum_\alpha |U_{\alpha 2}|^2} \sim \frac{1}{3}$$

What has happened since then?

Experiments have been ongoing since to determine all oscillation parameters and overconstrain the three-neutrino picture/look for new physics in the neutrino sector!

Three-neutrino oscillation picture

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Atmospheric"
$\theta_{23} \sim 45$ deg

"Reactor" medium-baseline
$\theta_{13} \sim 10$ deg
"access" to δ_{CP}

"Solar"
$\theta_{12} \sim 35$ deg

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

Three-neutrino oscillation picture

Corroborated evidence of oscillations parametrized by the 3 independent θ_{ij} and 2 independent Δm^2 splittings has been provided from multiple other **experiments** measuring not only solar and atmospheric, but also **reactor, and accelerator-produced neutrinos**:

"Solar" sector:
Gallex/GNO, SAGE, **KamLAND**, Super-K, Borexino, …

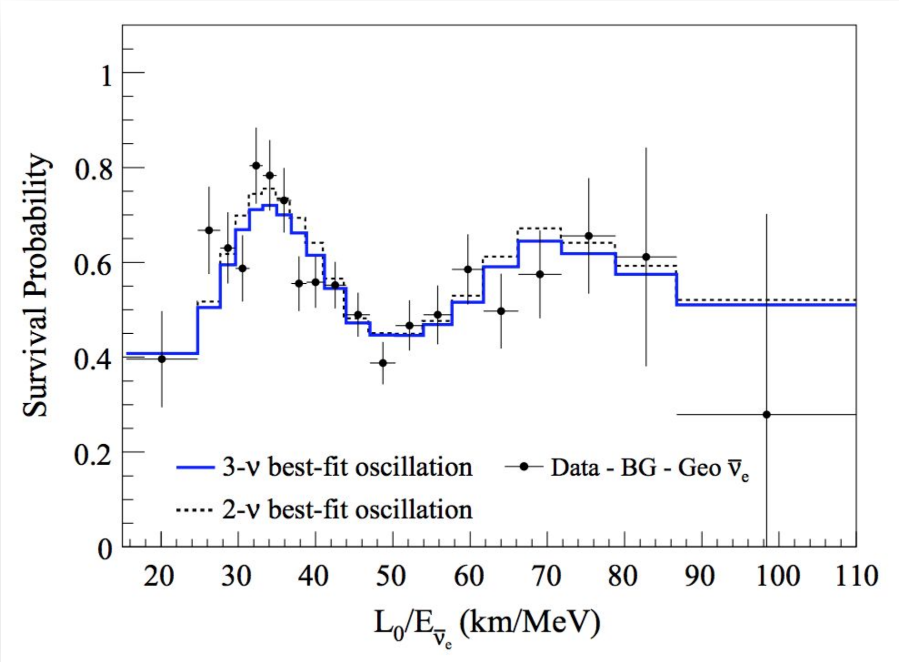
"Atmospheric" sector:
MINOS, K2K, IceCube, **T2K**, **NOvA**, …

"Reactor" medium-baseline sector:
Double-Chooz, **Daya Bay**, RENO, …

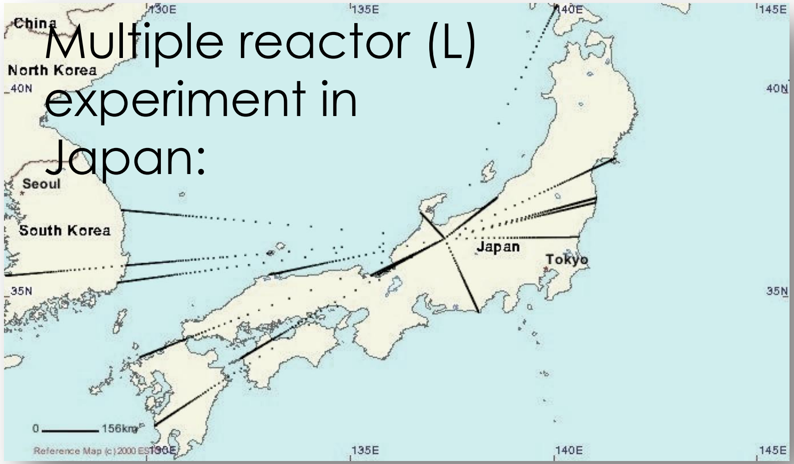
“Solar” sector oscillations

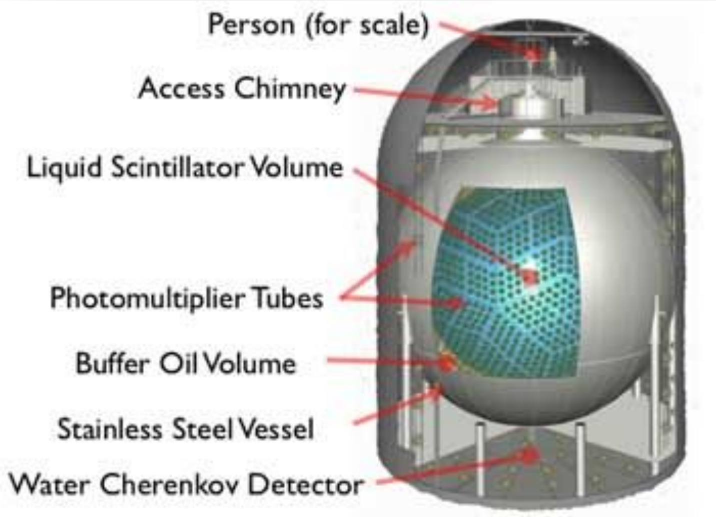
KamLAND reactor-based neutrino experiment confirmed **oscillation** nature of solar neutrino deficit

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

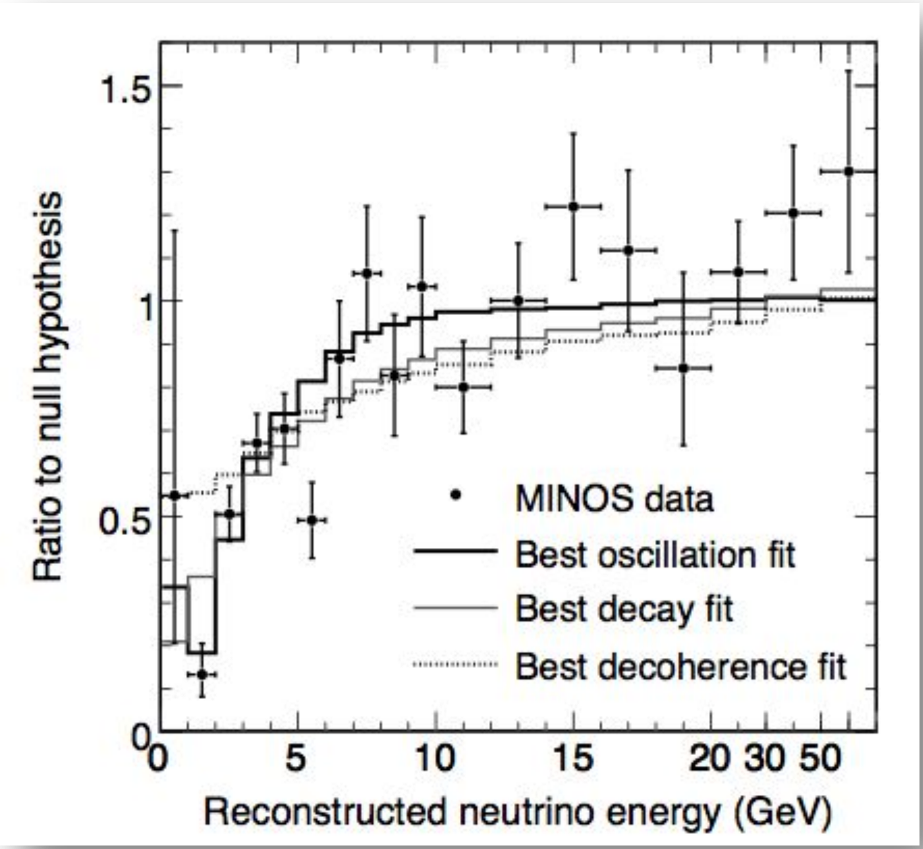


Multiple reactor (L) experiment in Japan:





“Atmospheric” sector oscillations

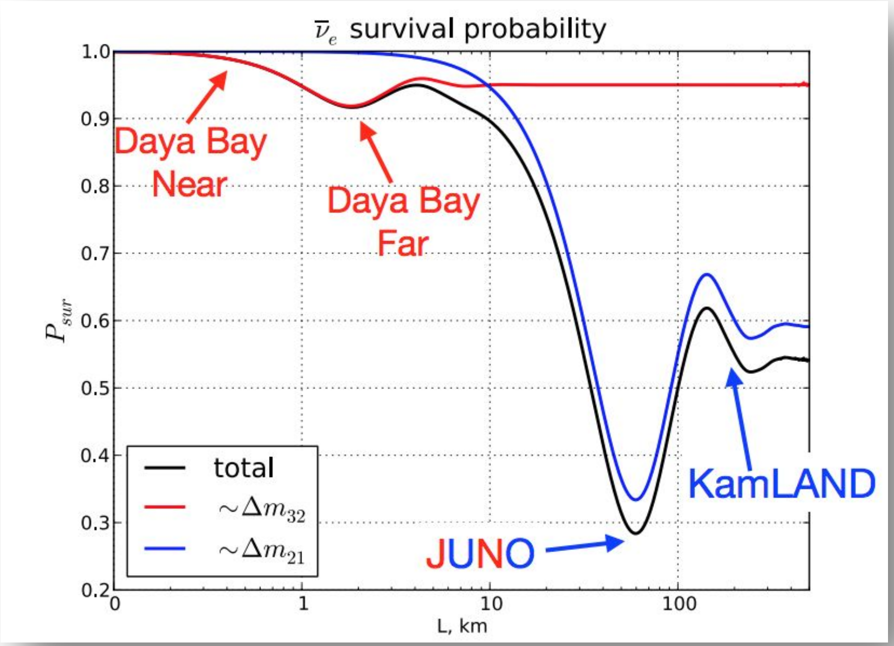


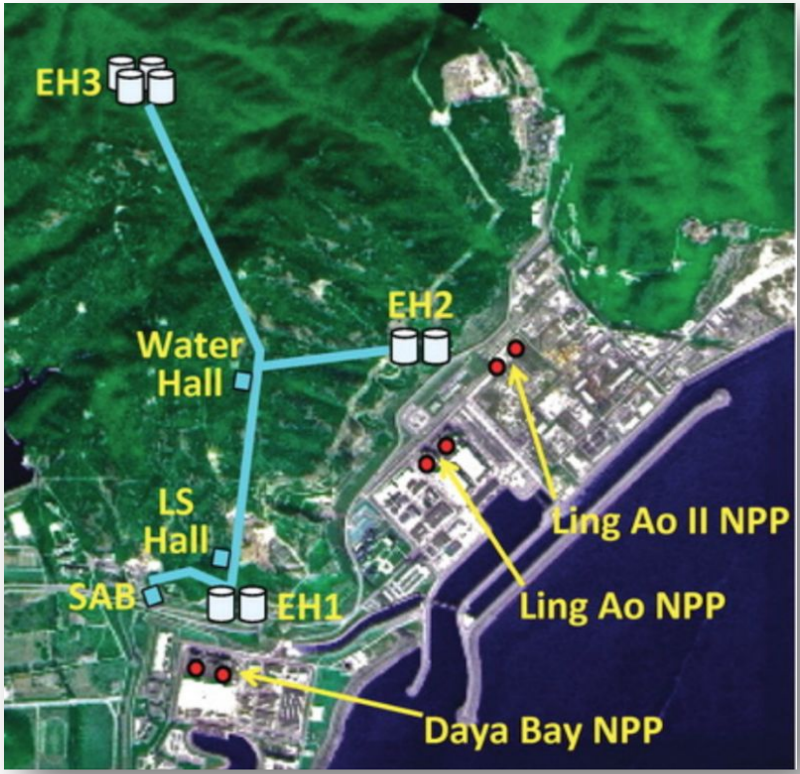
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$$

MINOS accelerator-based neutrino experiment independently confirmed Super-K results

“Reactor” medium-baseline **sector**

Daya Bay is a medium-baseline reactor-based experiment with highest sensitivity to θ_{13}





Daya Bay employs 8 identical detectors at one of the most powerful reactor power complexes in the world.

New-generation of accelerator-based experiments: T2K and NOvA

- Experiments at long baselines (100's of km), utilizing high-intensity, almost pure ν_μ beams from accelerators (E ~1 GeV)
- Sensitive to $\boldsymbol{\nu_\mu}$ **disappearance** at "atmospheric" Δm^2
- Sensitive to $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ **appearance** due to all Δm^2, including **interference terms**:

$$P(\nu_\mu \rightarrow \nu_e) \simeq \boxed{\sin^2\theta_{23}}\boxed{\sin^2 2\theta_{13}}\frac{\sin^2(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})^2}\Delta_{31}^2$$
$$+\boxed{\sin 2\theta_{23}}\boxed{\sin 2\theta_{13}}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})}\Delta_{31}\frac{\sin\boxed{aL}}{\boxed{aL}}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}})$$
$$+\boxed{\cos^2\theta_{23}}\sin^2 2\theta_{12}\frac{\sin^2\boxed{aL}}{\boxed{aL}^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

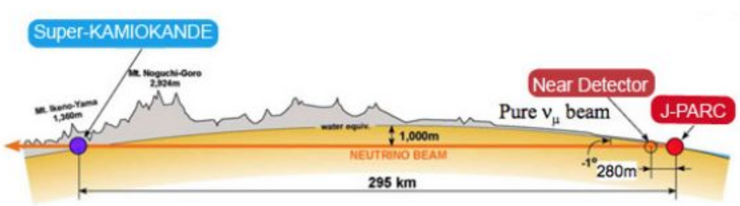
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Provides sensitivity to the CP-violating phase of the neutrino mixing matrix!

T2K and NOvA: currently running

T2K: Tokai to Kamioka

- Beam: J-PARC
- Far detector: SuperK
  - WCD (50 kt)
- Baseline: 295 km
- Far detector located off-axis such that observed ν flux is peaked at ~600 MeV



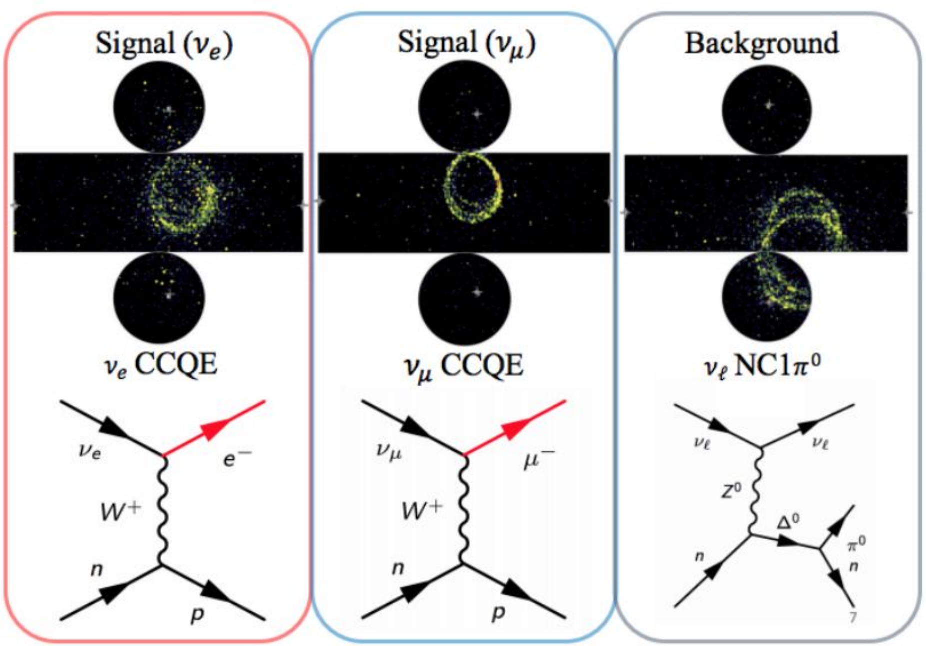
NOvA: FNAL to Ash River

- Beam: NuMI (FNAL)
- Far detector: segmented liquid scintillator detector (14 kt)
- Baseline: 810 km
- Far detector located off-axis such that observed ν flux is peaked at ~2 GeV

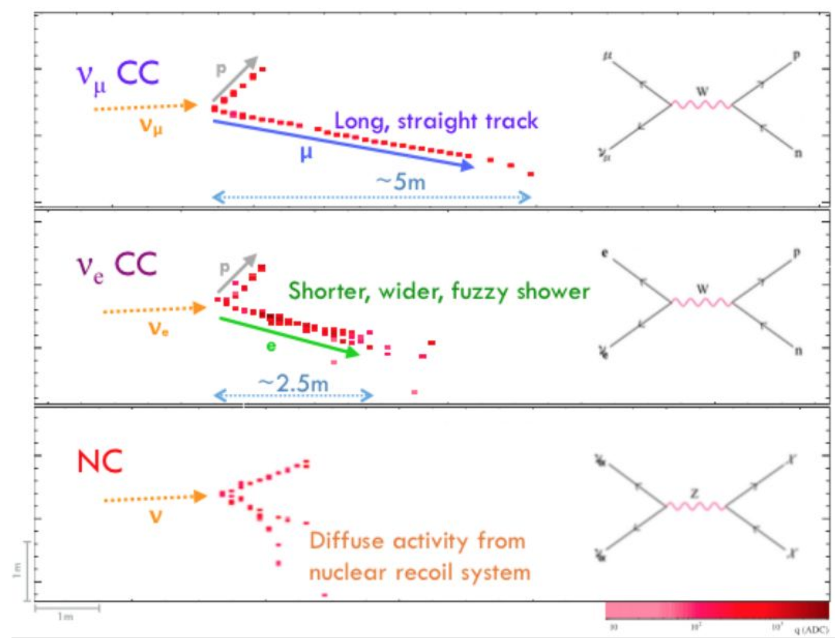
T2K and NOvA

- Both experiments have performed:
  - ν_μ disappearance searches
  - ν_e appearance searches with sensitivity to δ_{CP} and mass hierarchy
- Three-neutrino picture nearly over-constrained!

Neutrino detection in T2K

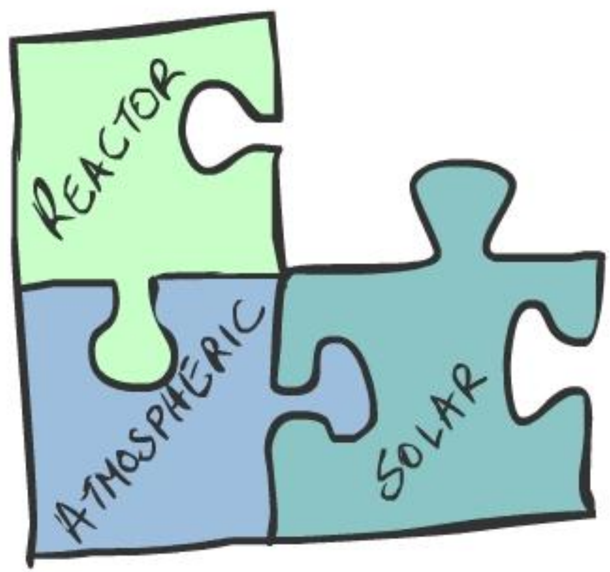


Neutrino detection in NOvA



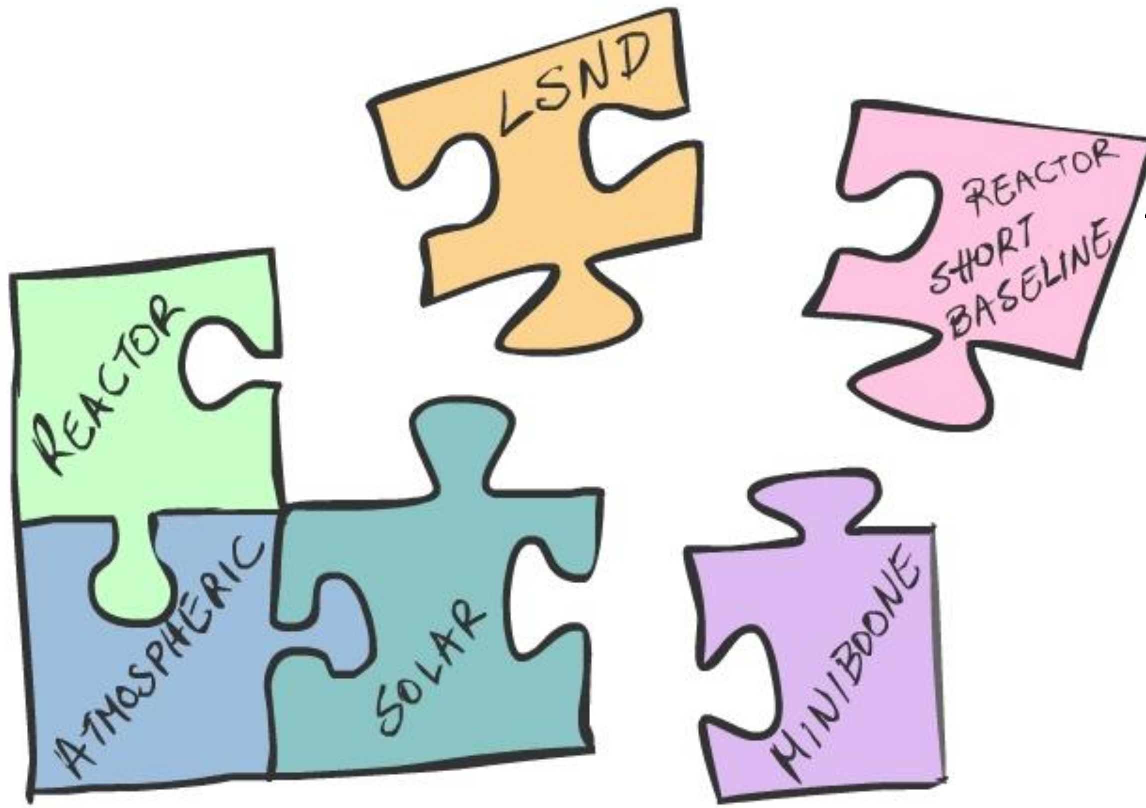
everything fits together!

Global 3-ν picture



Almost everything fits together!

??



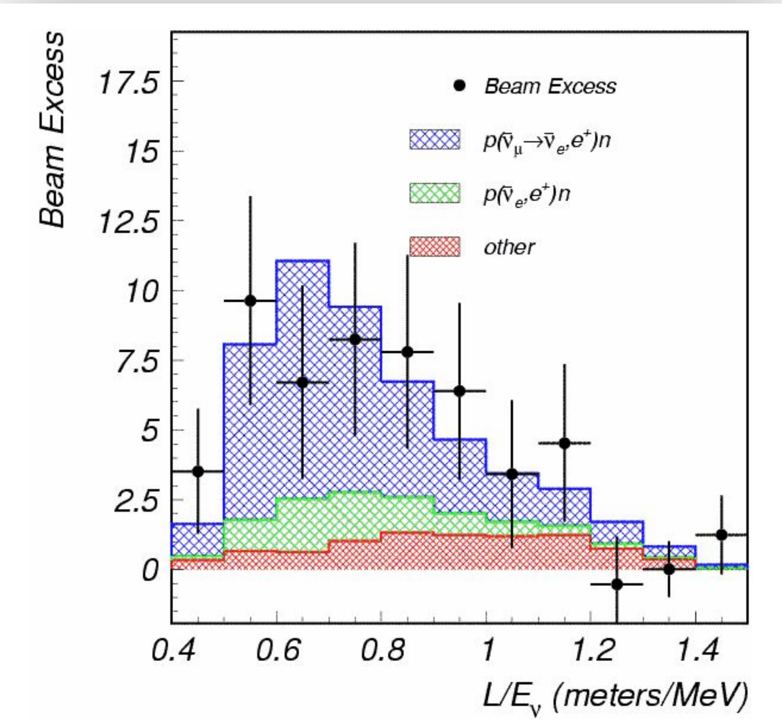
?

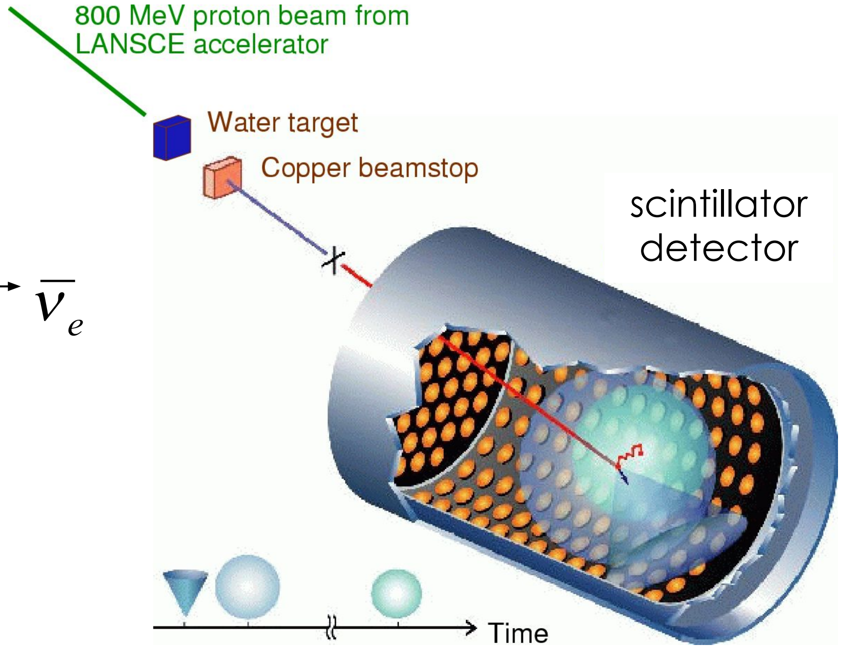
LSND puzzle piece

μ^+ decay-at-rest experiment: $\pi^+ \to \mu^+ \nu_\mu$

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

$\hookrightarrow \bar{\nu}_e$?





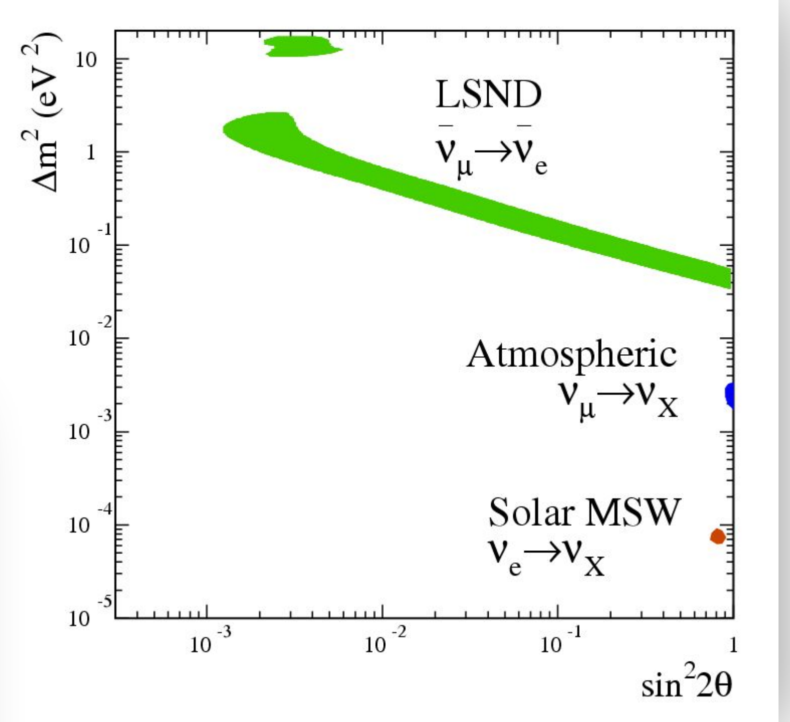
Observed excess of $\bar{\nu}_e$
described by oscillation probability:
$P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\ \%$

(3.8σ evidence)

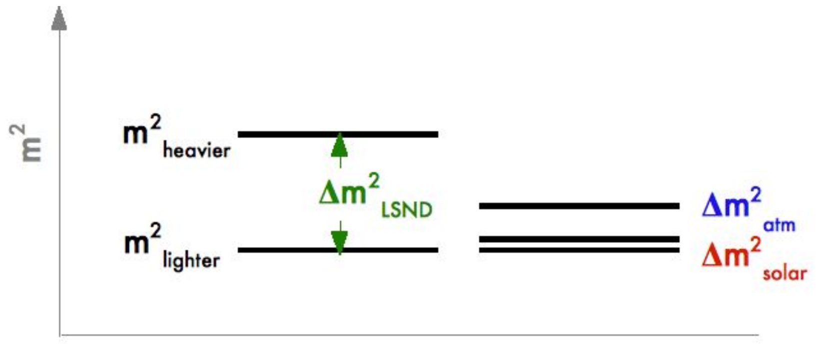
LSND puzzle piece

Points to large Δm^2
if interpreted as
two-neutrino oscillations:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27 \Delta m^2 L / E)$$

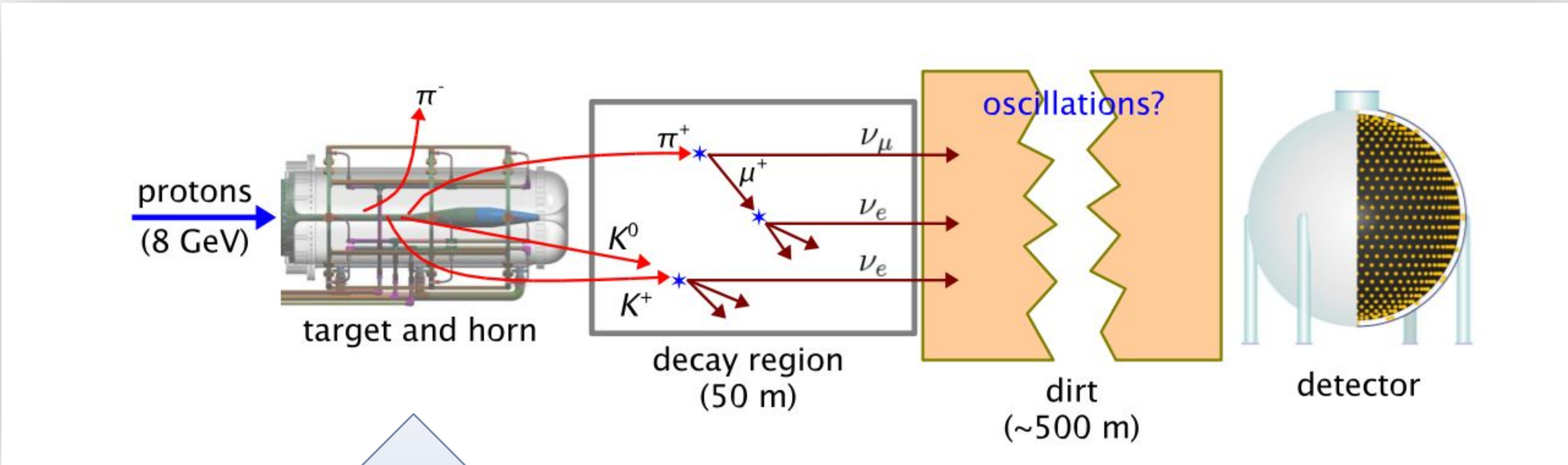


Much larger Δm^2 cannot be reconciled in 3-neutrino model!



Also implies oscillations at short-baselines…

MiniBooNE puzzle piece



magnetic field polarity selects ν or $\bar{\nu}$

$$\pi^+ \rightarrow \mu^+ \nu_\mu \xrightarrow{?} \nu_e$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \xrightarrow{?} \bar{\nu}_e$$

Similar L/E as LSND

but

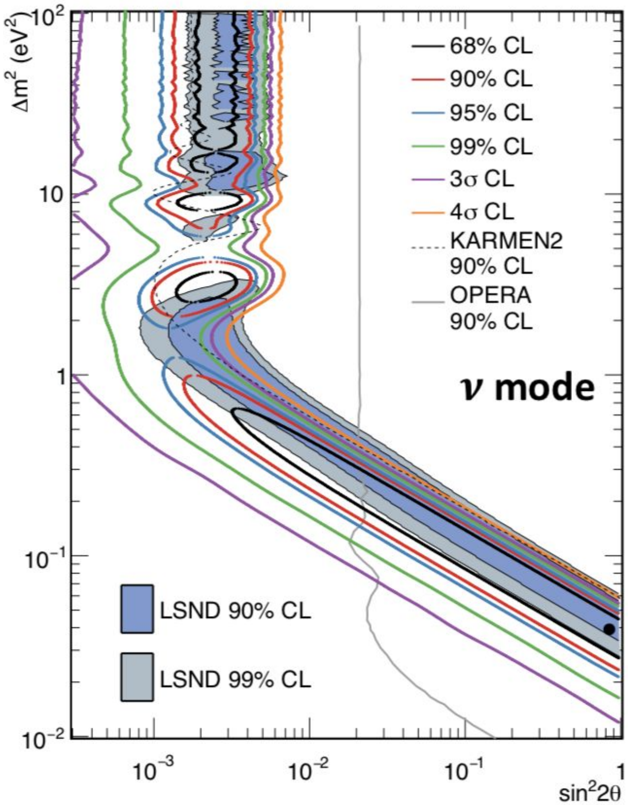
Different energy, beam and detector systematics

Different event signatures and backgrounds (Cherenkov detector)

MiniBooNE puzzle piece

[2018 results]

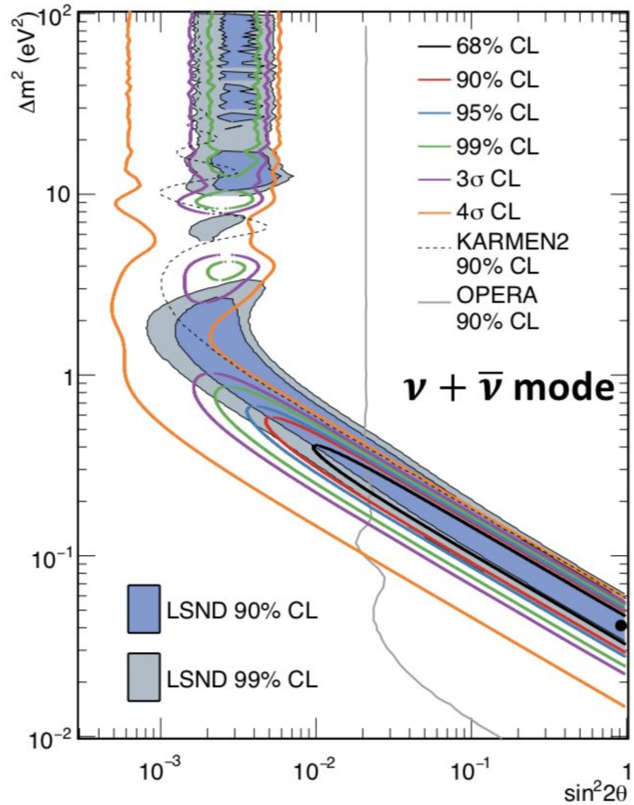
Neutrino combined (12.84E20 POT)



$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$

$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

Neutrino + antineutrino combined



$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$

$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

Neutrino and antineutrino fits are consistent with LSND allowed regions

Neutrino physics: The **bigger** picture?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} & \cdots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \cdots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$

(and more CP-violating phases…)

Q: Why only 3x3 ?

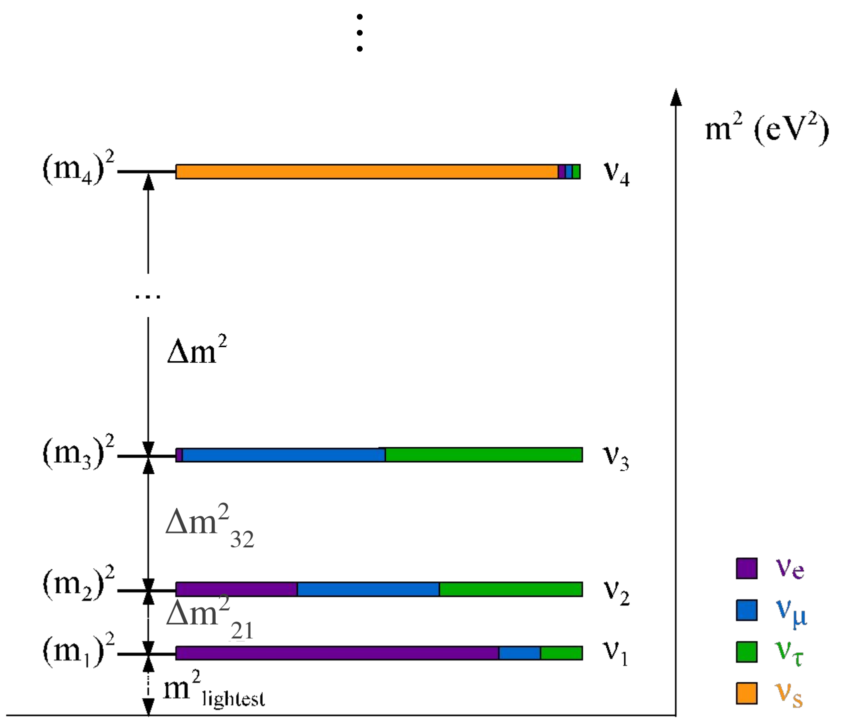
Additional, (mostly) sterile neutrinos

sterile neutrino
/ˈstɛrʌɪl/ /njuːˈtriːnəʊ/

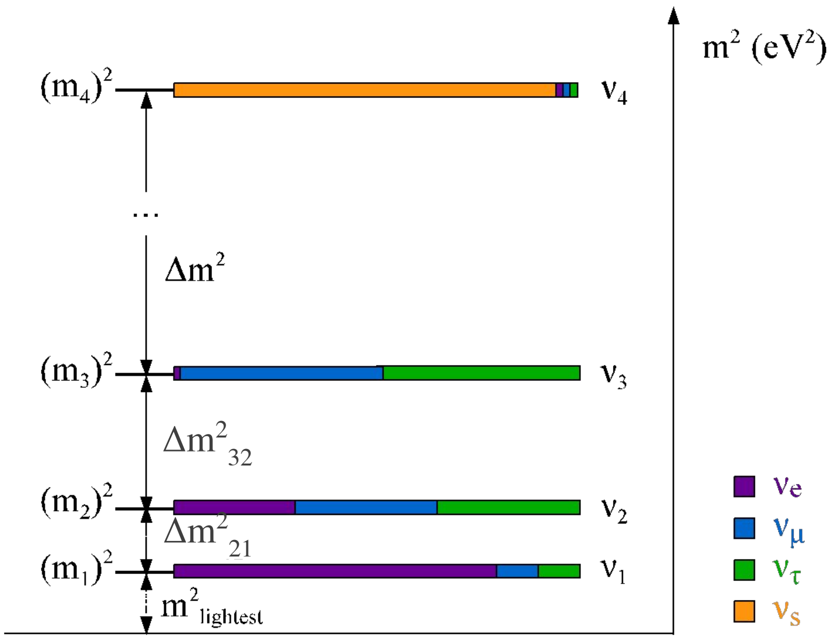
Additional neutrino “flavor” states which **do not experience weak interactions** (through the standard model W/Z bosons)

The additional mass states associated with them are assumed to be produced through mixing with the standard model neutrinos

→ Can affect neutrino oscillations through mixing



Simplest (3+1) sterile neutrino model



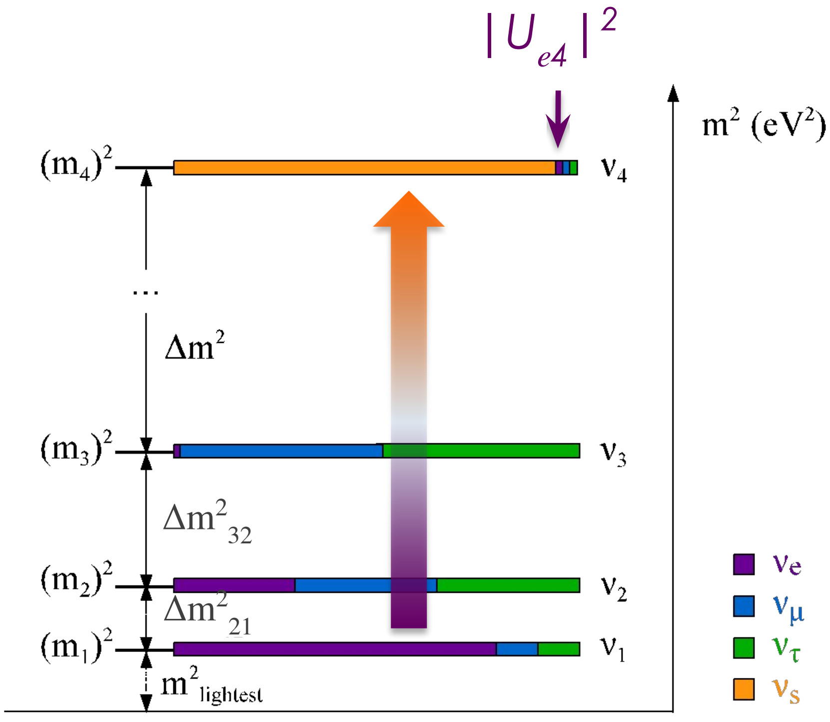
Simplest (3+1) sterile neutrino model

Large Δm^2 implies oscillations manifest at baselines much shorter than those between three known neutrinos. Can approximate $m_1 \sim m_2 \sim m_3 \sim 0$.

ν_e disappearance:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27 \Delta m^2 L/E)$$

$$\rightarrow 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)$$



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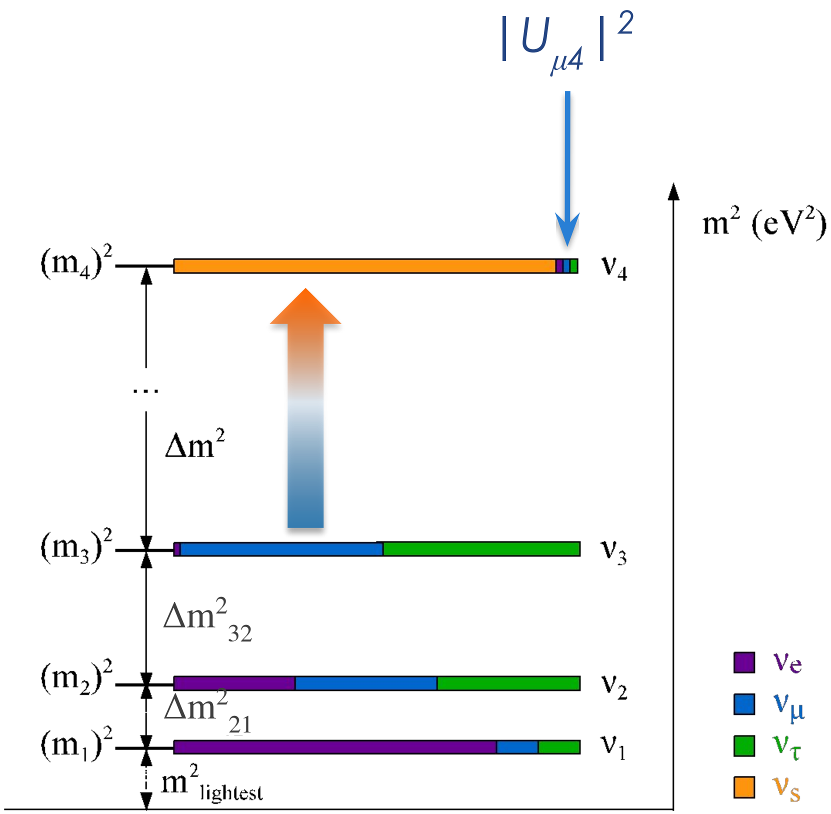
ν_e disappearance:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

ν_μ disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

$$\rightarrow 4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right)$$



Simplest (3+1) sterile neutrino model

Large Δm^2 implies oscillations manifest at baselines much shorter than those between three known neutrinos. Can approximate $m_1 \sim m_2 \sim m_3 \sim 0$.

ν_e disappearance:

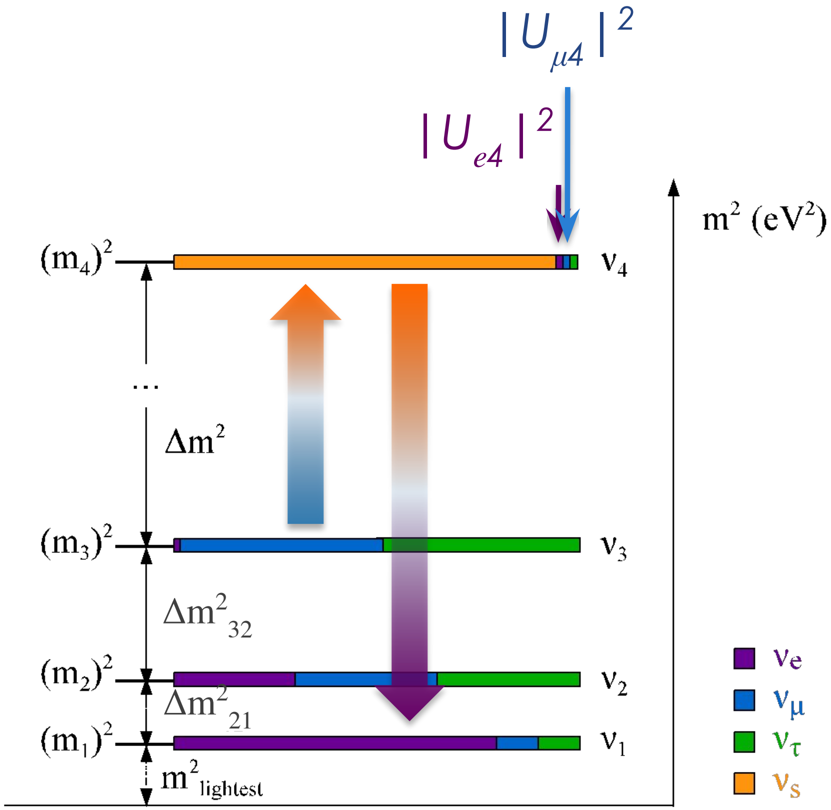
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

$\nu_\mu \to \nu_e$ appearance:

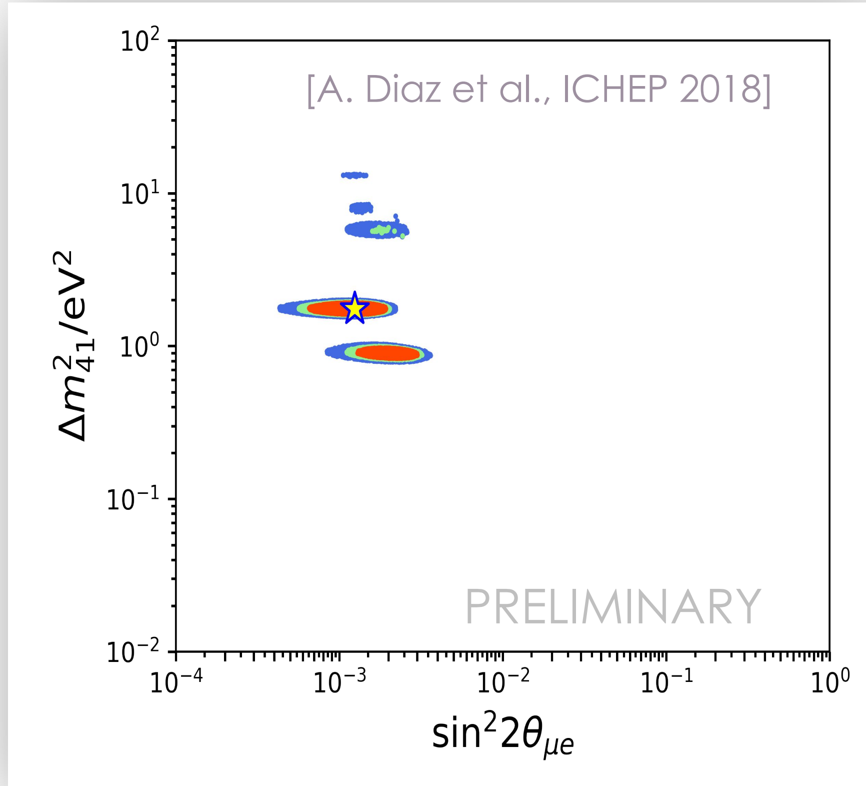
$$P(\nu_\mu \to \nu_e) = \underbrace{\sin^2 2\vartheta_{\mu e}}_{4|U_{e4}|^2|U_{\mu 4}|^2} \sin^2(1.27\Delta m^2 L/E)$$



Note: $\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee}$

Global picture of sterile neutrinos

When combined with all available experimental constraints, MiniBooNE and LSND **seem to indicate a preference for a (3+1) signal**



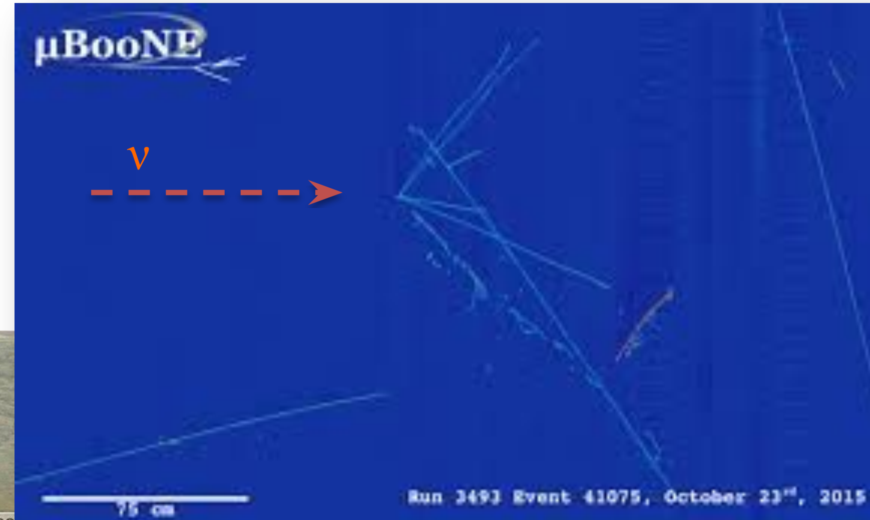
BUT, results are still inconclusive, due to tension with ν_μ disappearance searches at short baselines ($\sin^2 2\theta_{\mu e} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$ implies non-zero ν_μ disappearance, but none has been seen!)

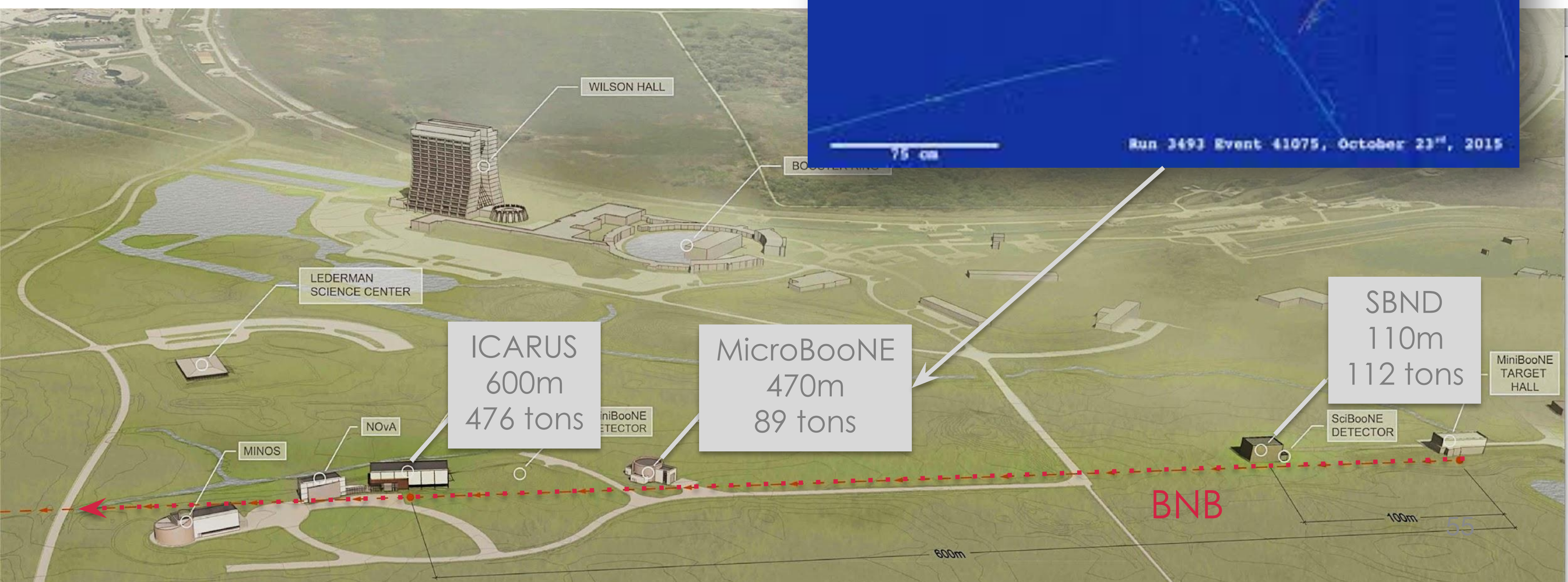
What comes next?

SBN: Upcoming search for sterile neutrinos

(Short Baseline Neutrino program in the US)

Using Liquid Argon Time Projection Chamber (LArTPC) detectors: provide high-resolution 2D→3D imaging of charged particles produced in neutrino interactions in liquid argon.





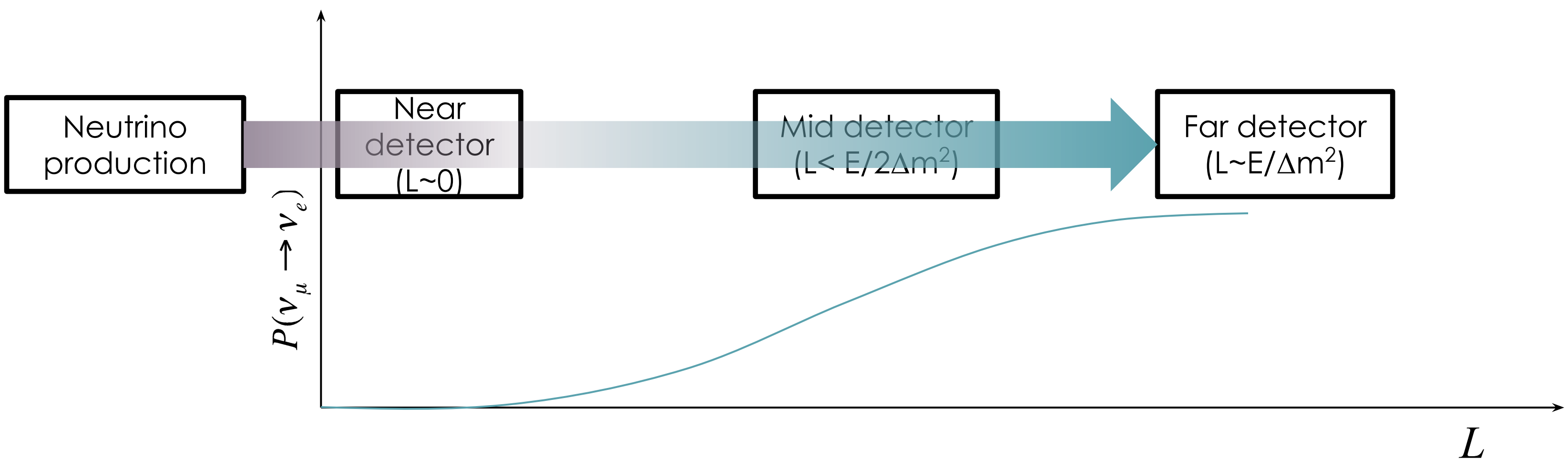
SBN: Upcoming search for sterile neutrinos

The goal is to minimize uncertainties!

- Neutrino production modeling
- Neutrino interaction modeling
- Detector modeling

Multi-baseline search:
Determination of un-oscillated event rate at L~0 handles systematics in a less model-dependent way

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

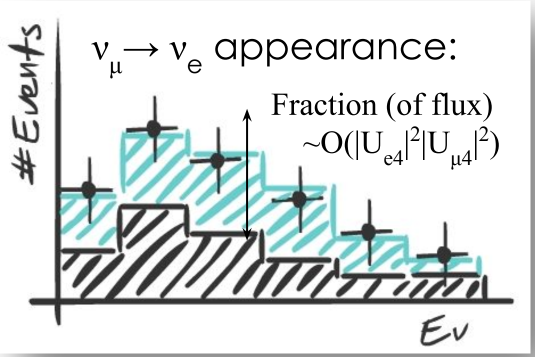


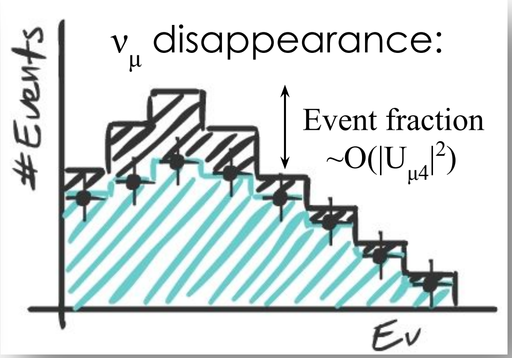
SBN: Upcoming search for sterile neutrinos

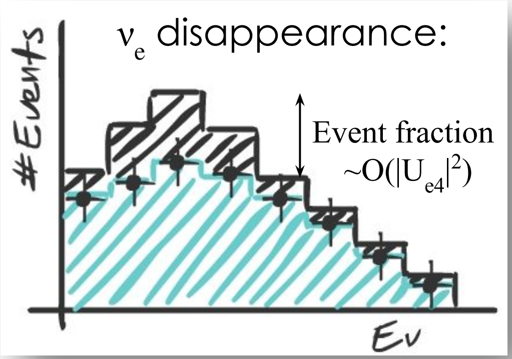
The goal is to minimize uncertainties!

- Neutrino production modeling
- Neutrino interaction modeling
- Detector modeling

Multi-channel search:
In any given detector (L), appearance and disappearance signals are correlated!



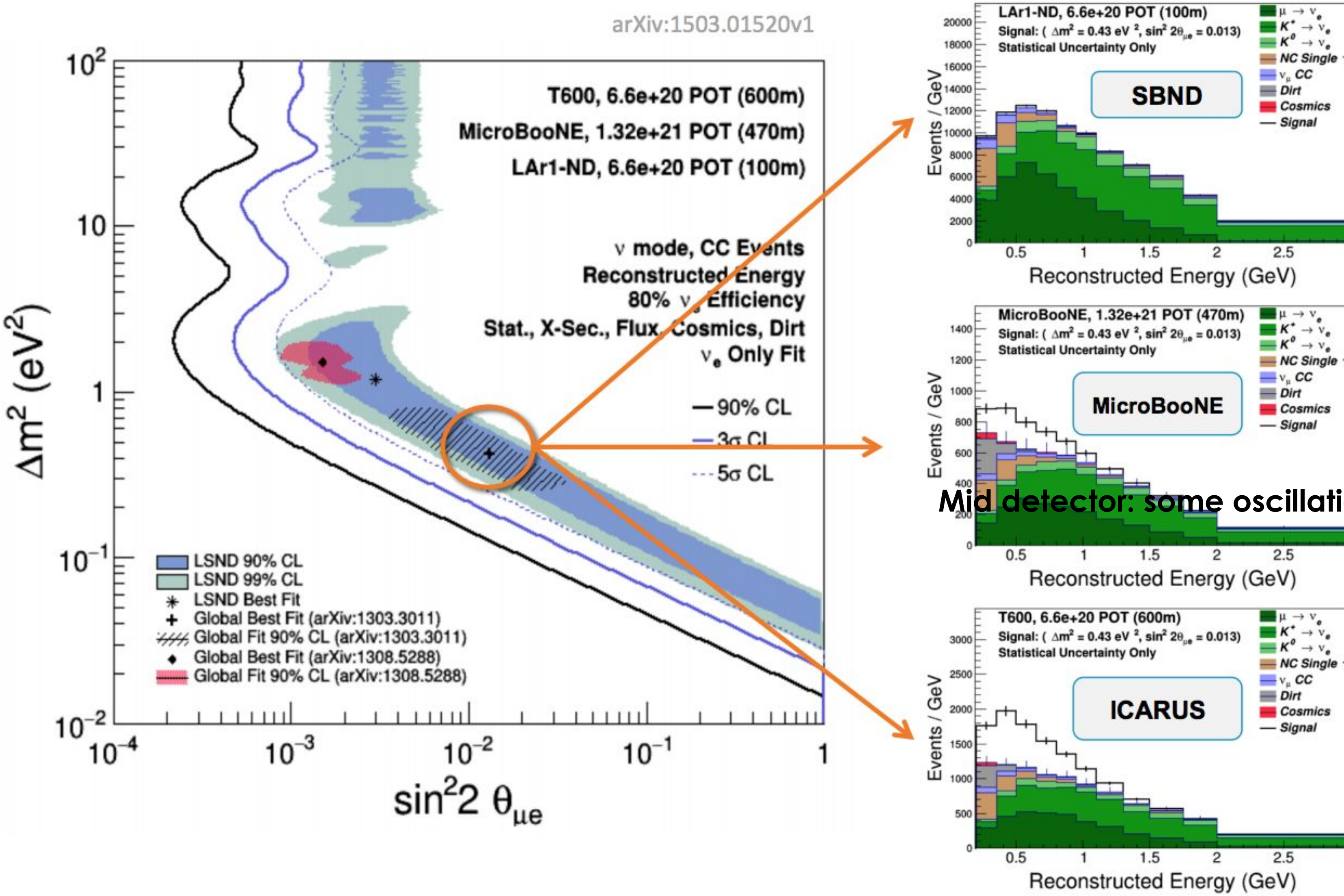




$$\sin^2 2\theta_{\mu e} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

What would SBN see?

Near detector: ~no oscillation



Far detector: ~max oscillation

DUNE: Deep Underground Neutrino Experiment

DUNE aims to complete the three-neutrino picture:

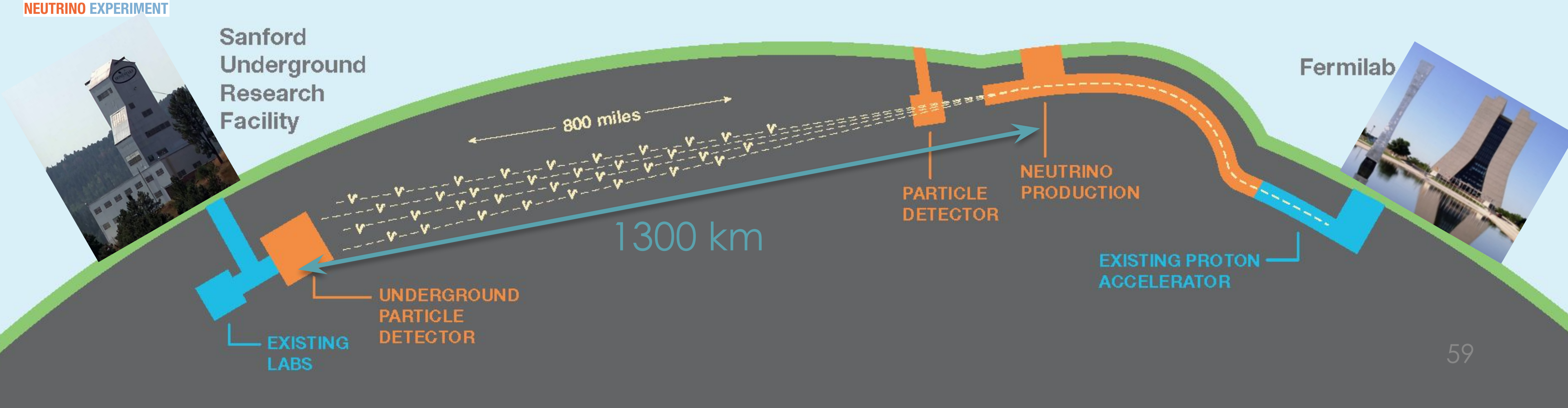
Discover CP violation + neutrino mass hierarchy

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_\mu \to \nu_e) \stackrel{?}{=} P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

$$\sin\delta \stackrel{?}{=} 0$$

DEEP UNDERGROUND NEUTRINO EXPERIMENT

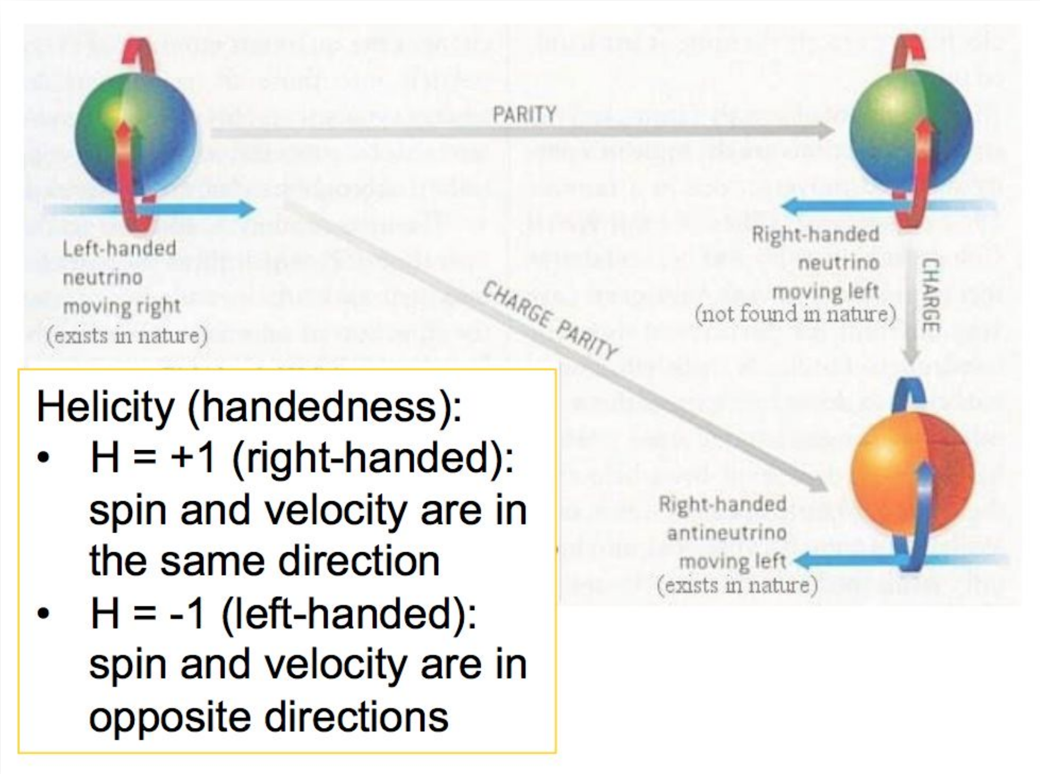


CP violation

- Three discrete symmetries:
  - C: charge conjugation particle $\longleftrightarrow$ antiparticle
  - P: parity inversion $(x,y,z) \longleftrightarrow (-x,-y,-z)$
  - T: time reversal $t \longleftrightarrow -t$
- Discovery of P violation in weak interactions in 1957 by C. S. Wu, et al.
- CP violation in weak interactions found in 1964 by Christenson, et al.
  - Existence of CP violation in kaon decays required the existence of a 3rd quark generation before experimental observation of top and bottom quark

CP violation in neutrinos

- Parity: left-handed to right-handed
- Charge conjugation: neutrino to antineutrino



CP: left-handed neutrino to right-handed antineutrino

$$CP\ (\nu_\mu \rightarrow \nu_e) = \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

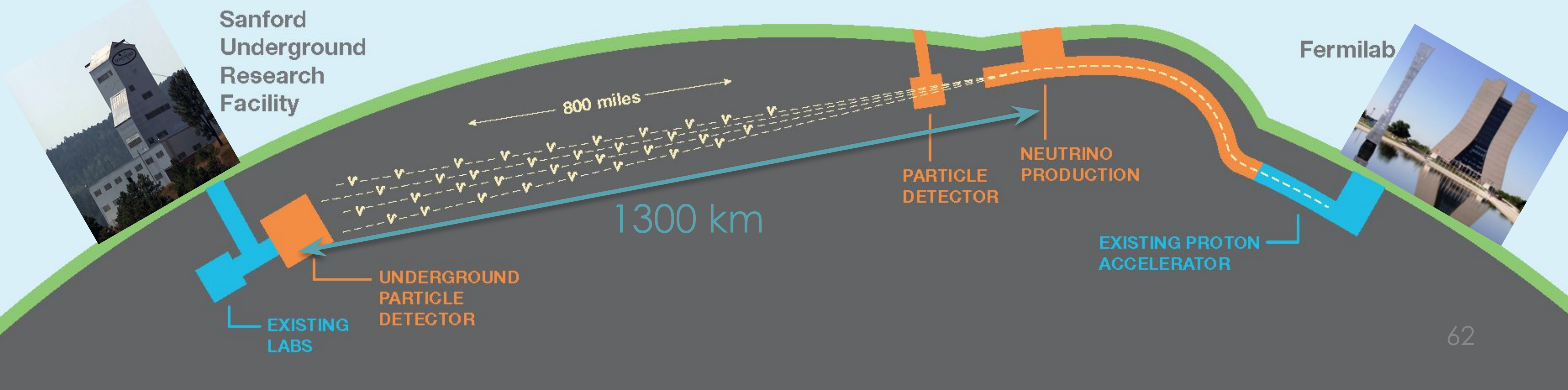
DUNE: Future search for CP violation

Why is δ so special?

It offers a connection
to the matter-antimatter asymmetry in our universe (Leptogenesis)

Underlying model of neutrino mass predicts "heavy neutrino partners"

CP violating decays of heavy neutrinos in the early universe → lepton-antilepton asymmetry in early universe → baryon-antibaryon asymmetry



Summary

Nature's tiniest fundamental particles--neutrinos--have been a source of mystery for nearly 100 years!

While we've come a long way, through decades of experimentation, there are still questions to answer and puzzles to solve.

An army of neutrino physicists (that you can join!) and cutting-edge detectors are working to provide some of the biggest discoveries to come over the next decades!

Summary

Nature's tiniest fundamental particles--neutrinos--have been a source of mystery for nearly 100 years!

While we've come a long way, through decades of experimentation, there are still questions to answer and puzzles to solve.

An army of neutrino physicists (that you can join!) and cutting-edge detectors are working to provide some of the biggest discoveries to come over the next decades!

In the ~hour that it took you to listen to this talk

10^{20} = 100,000,000,000,000,000,000

neutrinos zipped thru your body!