COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Neutrino Oscillation Experiments

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Columbia University

2018 Neutrino University Lecture Series at Fermilab
July 26, 2018

Disclaimers and acknowledgements

- Too many experiments to cover in one hour!
  - My goal: give you a “flavor” of neutrino oscillation experiments (pun intended!)

- My apologies if your favorite neutrino oscillation experiment is not discussed today

- Many slides and material borrowed by past lectures (thank you!)

Outline

- 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
  - KamLAND, MINOS, Daya-Bay, T2K, NOvA
  - How everything fits together... or not!
- Future oscillation experiments
  - DUNE, SBN

Outline

- **Experimental signatures of neutrino oscillation**
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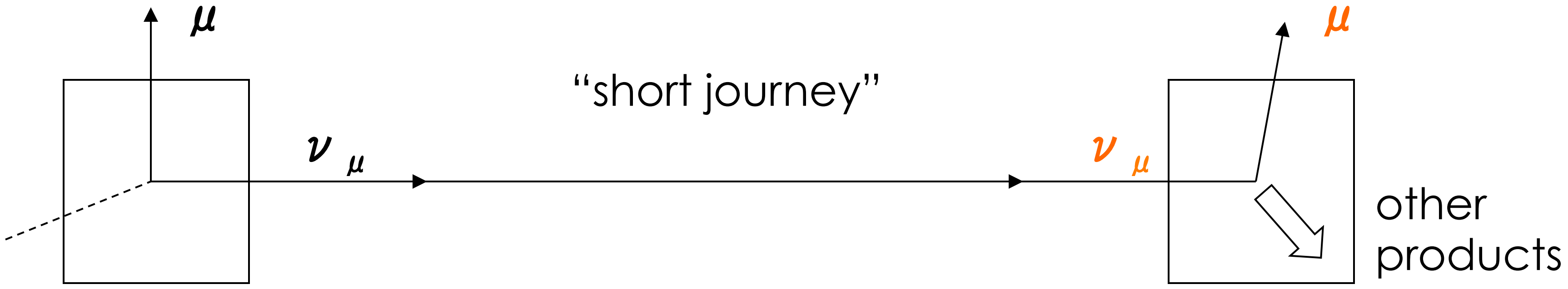
Neutrino oscillation

How do we detect neutrinos experimentally?



μ

ν_μ

“short journey”

ν_μ

μ

other products

source,
eg. $\pi^+ \rightarrow \mu^+ \nu_\mu$

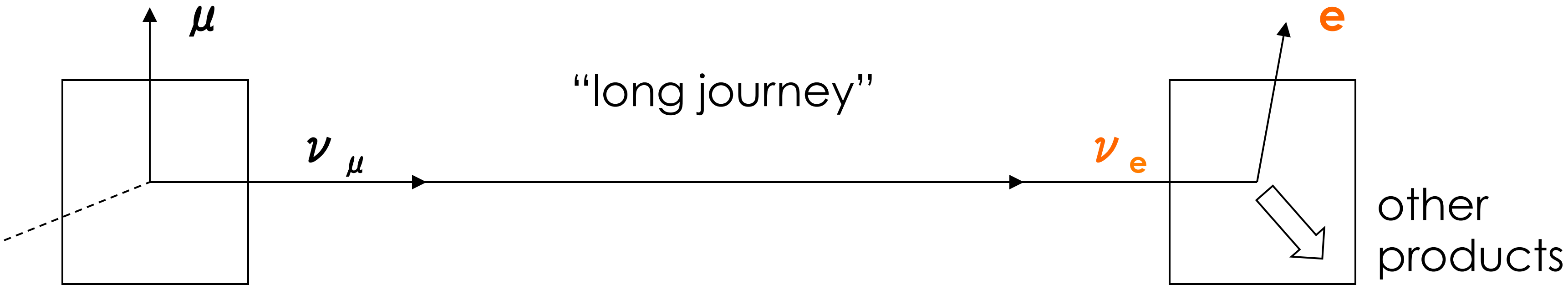
detector

Sources, production:
See lectures by S. Parke
and T. Kobilarcik

Detection:
See lectures by J. Raaf
and C. Mariani

Neutrino oscillation

Experimental effect of neutrino oscillations:



μ

"long journey"

ν_μ

ν_e

e

other products

source,
eg. $\pi^+ \rightarrow \mu^+ \nu_\mu$

detector

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

Neutrino oscillation formalism

For more neutrino theory:
See lecture by B. Kayser

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

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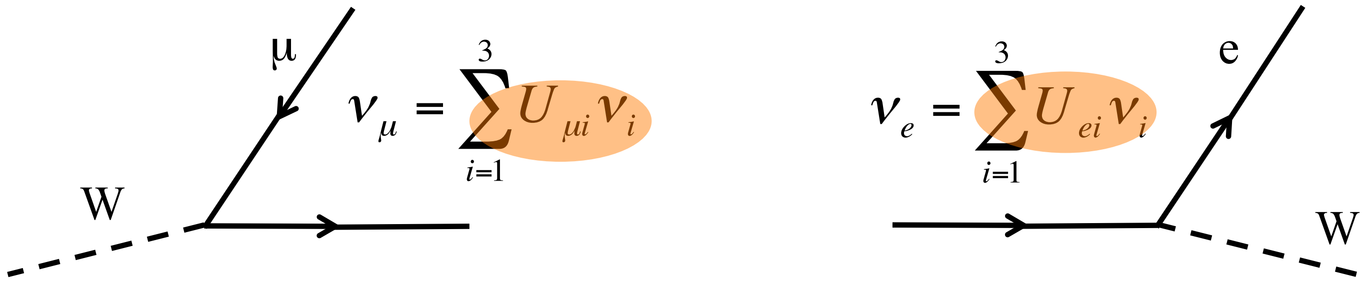
See lecture by B. Kayser



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

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

neutrino production

neutrino detection

Neutrinos are produced and detected
as one of three definite ~~**weak eigenstates:** $\nu_{e}, \nu_{\mu}, \nu_{\tau}$~~
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

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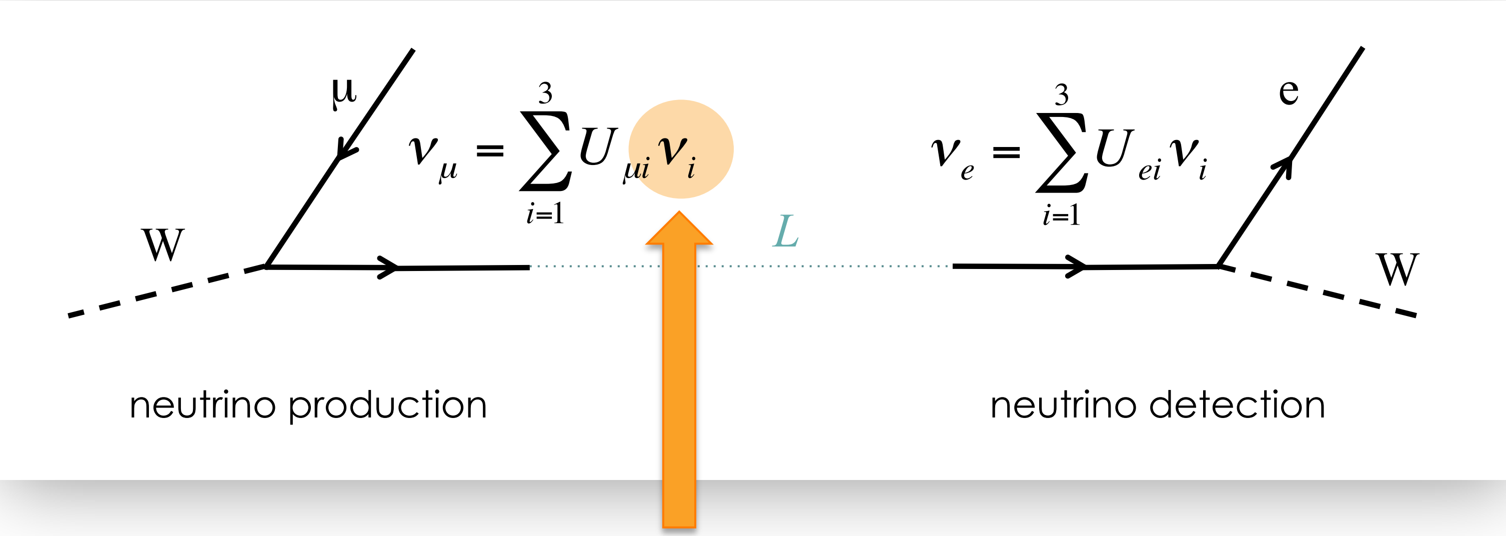


$$\nu_\mu = \sum_{i=1}^{3} U_{\mu i} \nu_i$$

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

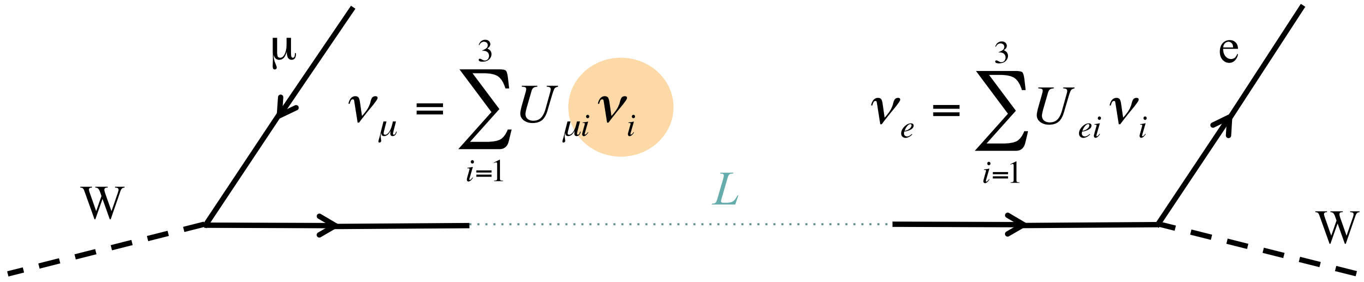
neutrino production

neutrino detection

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

For more neutrino theory:
See lecture by B. Kayser



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

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

neutrino production

neutrino detection

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

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

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

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

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

“two-neutrino approximation”

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

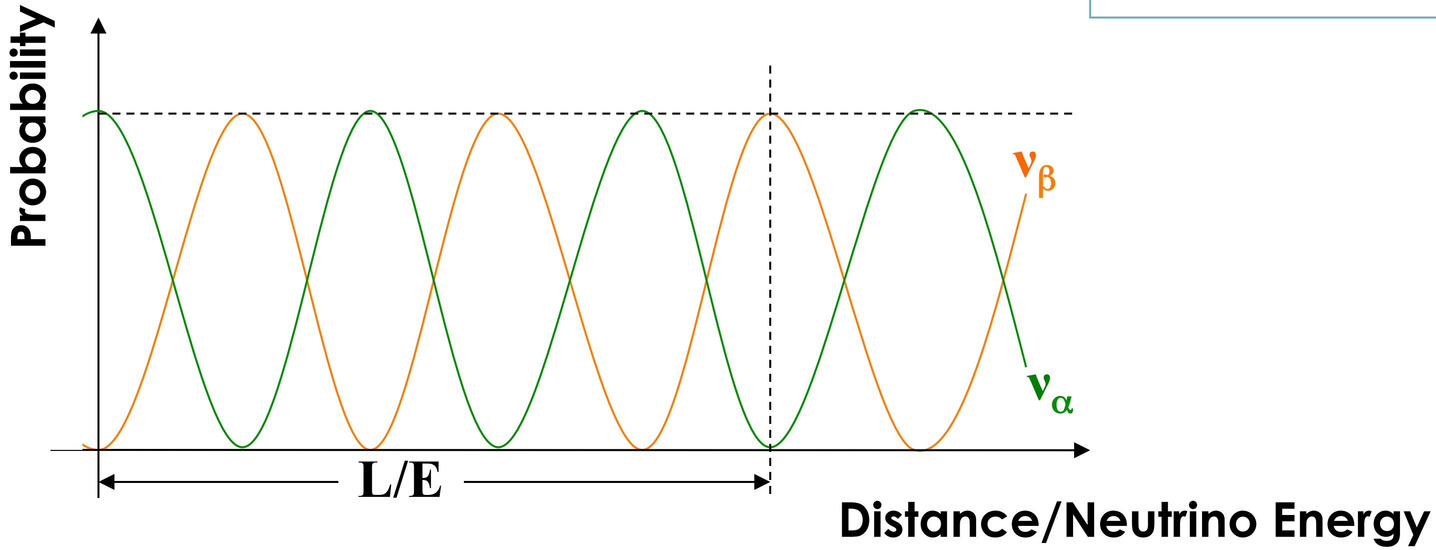
Neutrino oscillation *Signatures*

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

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

oscillation amplitude; "how much" neutrinos like to oscillate

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

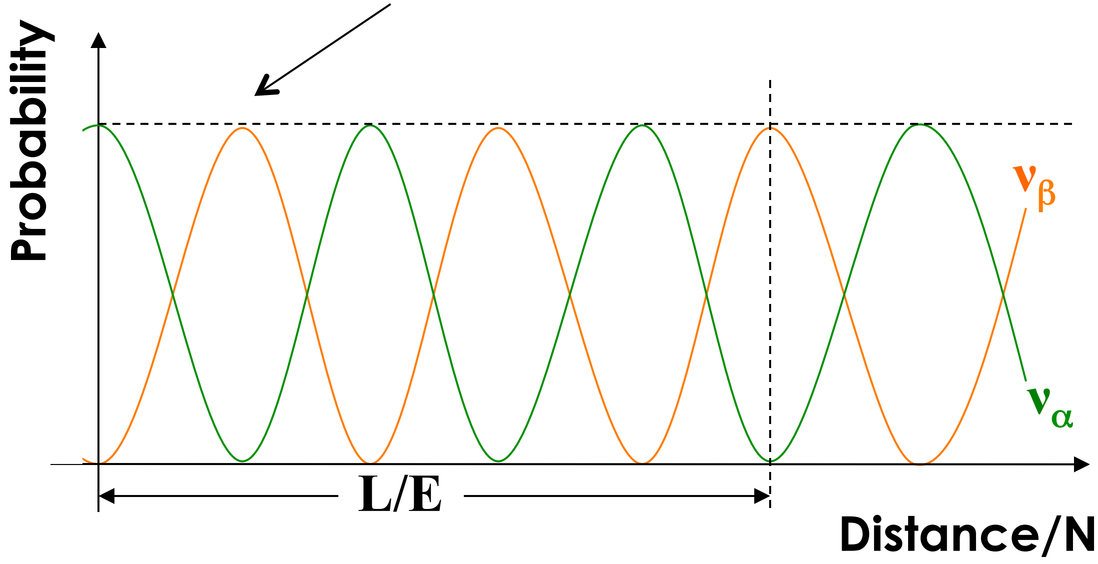


Neutrino oscillation *Signatures*

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

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

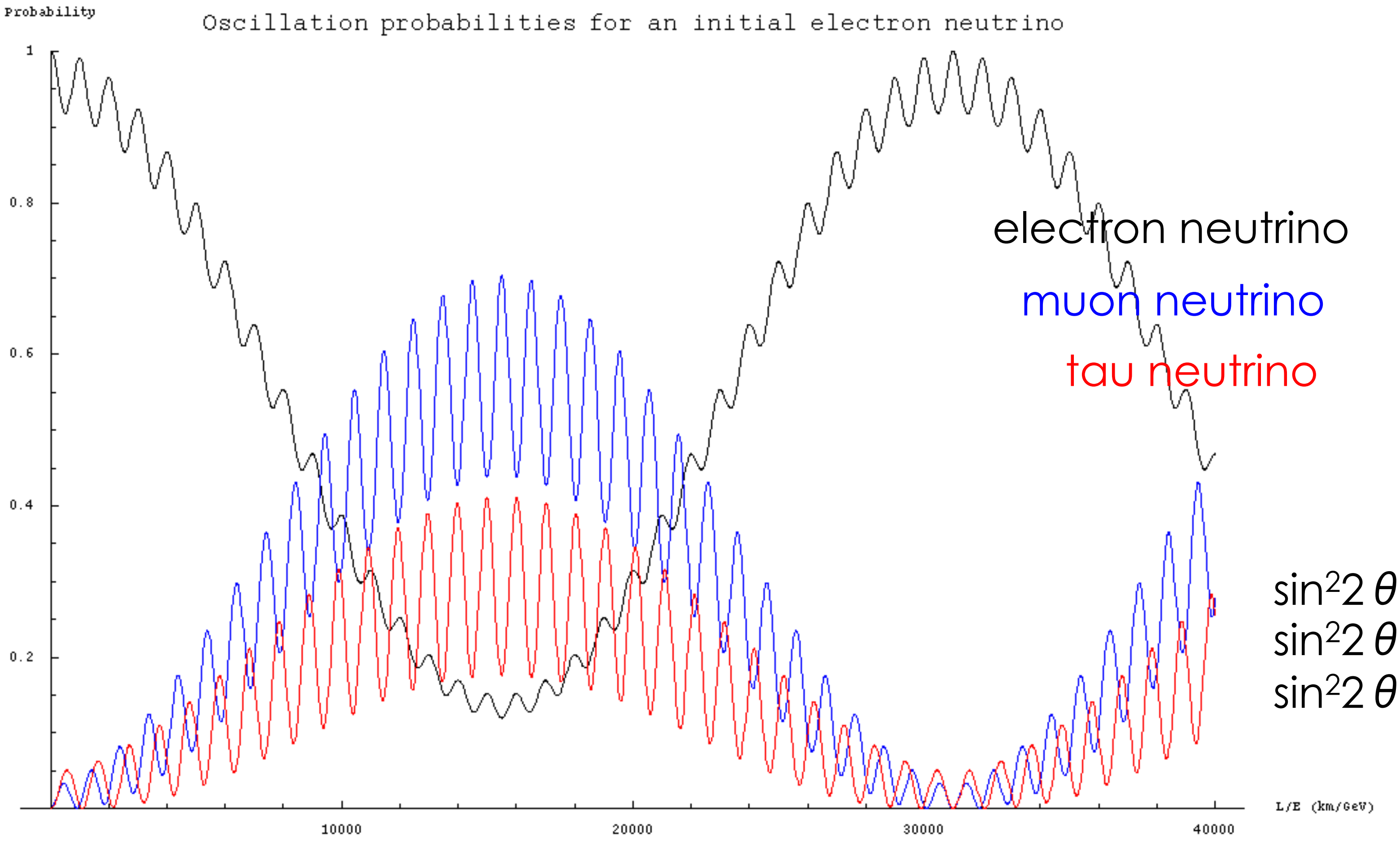
"First oscillation maximum": $(1.27\ \Delta m^2\ L/E) = \pi/2$



L and E are key for designing an oscillation experiment!

Neutrino oscillation *Signatures*

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

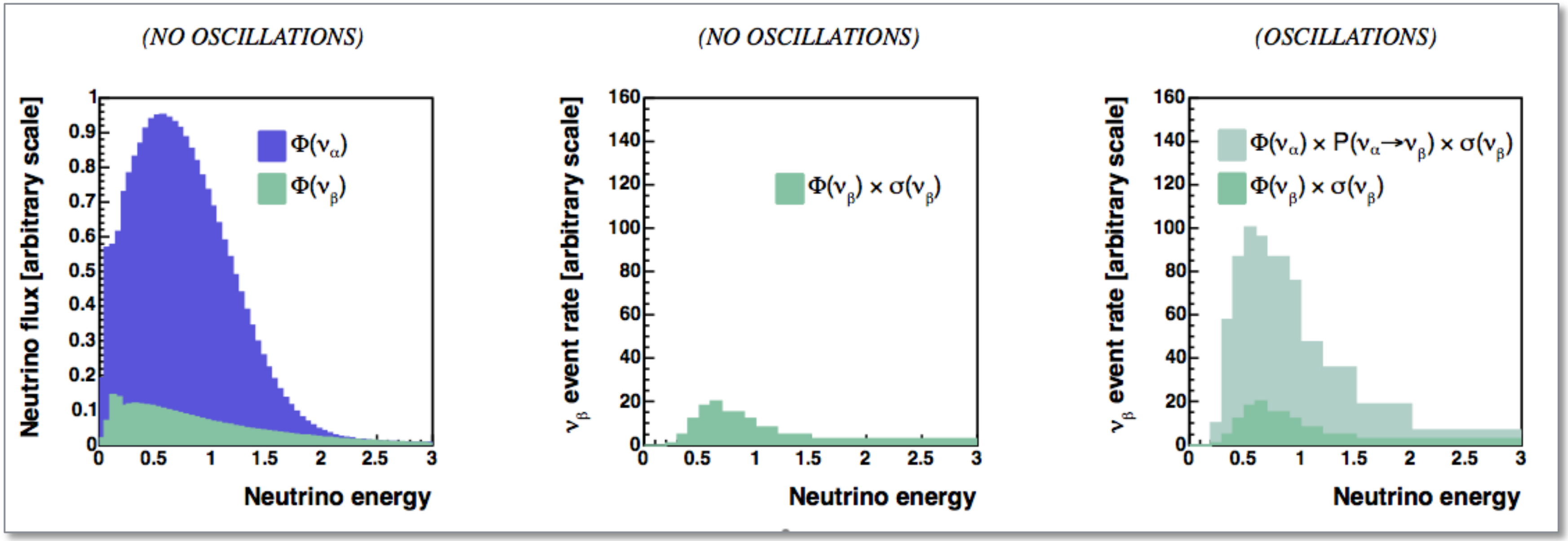


$\sin^2 2\theta_{12} \sim 0.86$
$\sin^2 2\theta_{13} \sim 0.08$
$\sin^2 2\theta_{23} \sim 0.97$

Neutrino oscillation Signatures

Neutrino appearance signature:

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



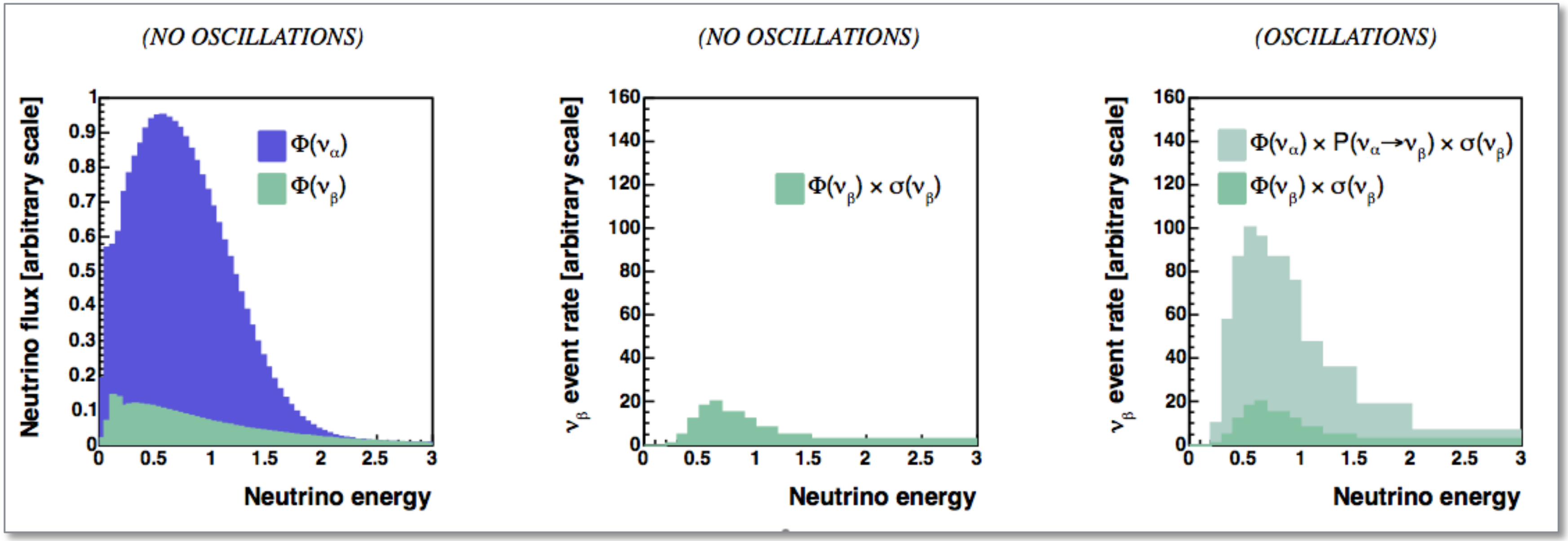
$$P\left(\nu_\alpha \to \nu_{\beta\neq\alpha}\right) = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(1.27\Delta m^2 L / E\right)$$

- 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 appearance signature:

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



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

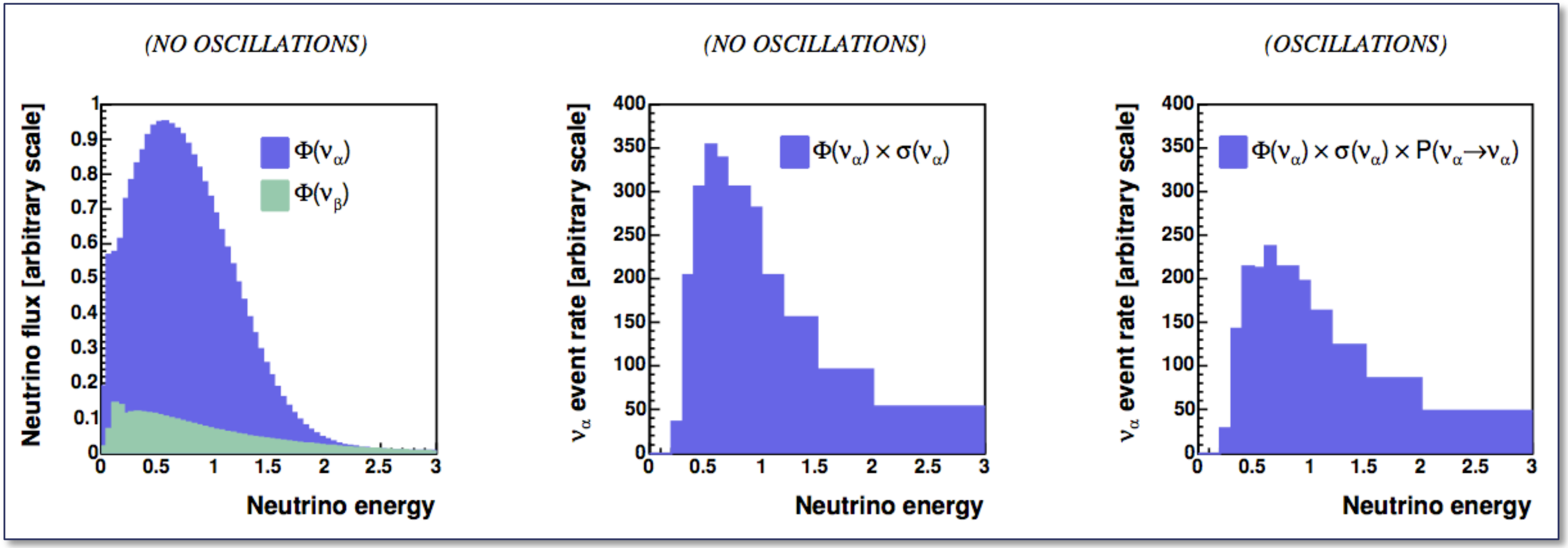
number of signal events (E) =

ν_α flux (E) x oscillation probability (E) x ν_β cross section (E) x detector efficiency (E)

Neutrino oscillation *Signatures*

Neutrino disappearance signature:

$$\nu_\alpha \rightarrow \nu_\alpha$$

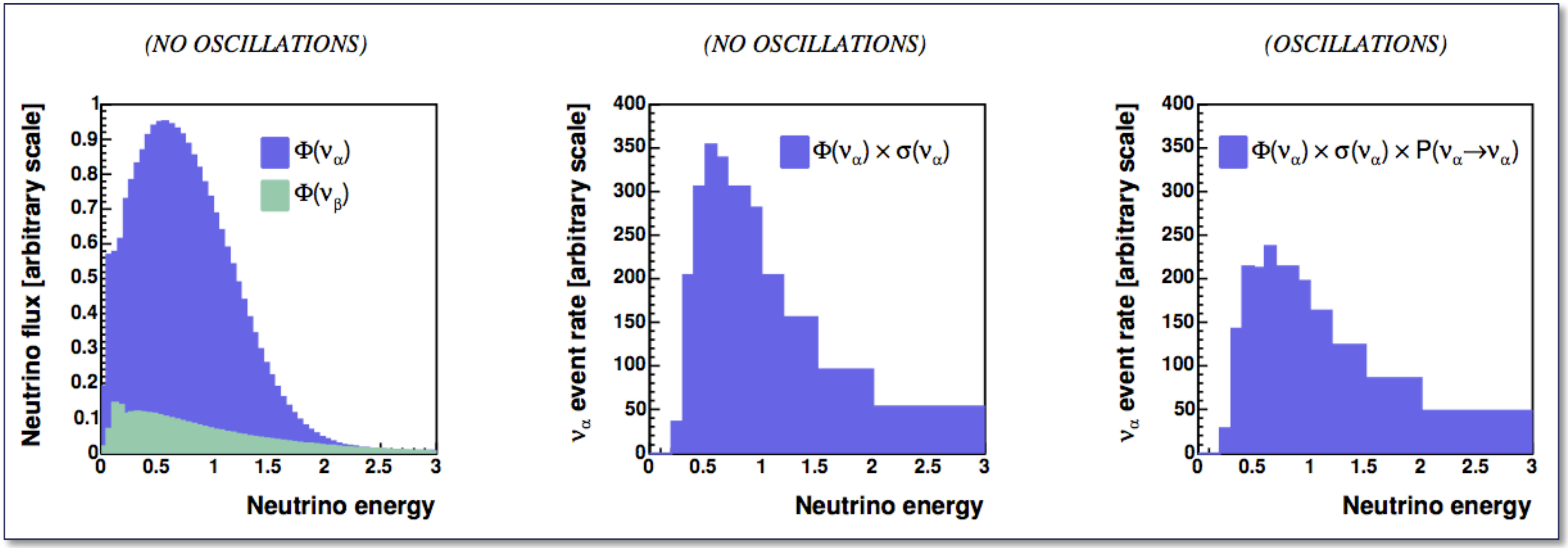


$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(1.27\Delta m^2 L / E\right)$$

- 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*

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



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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…

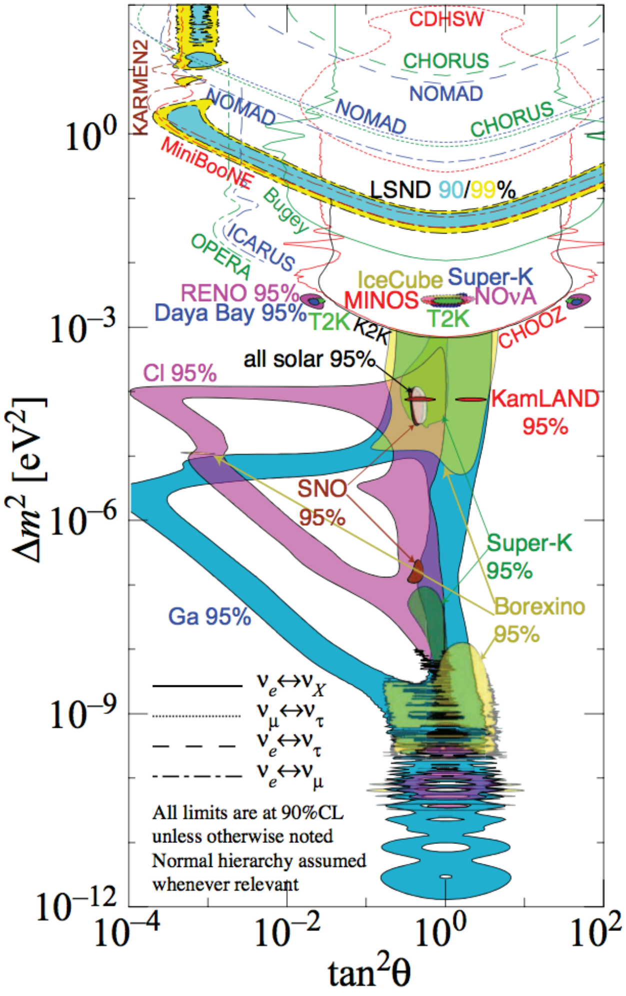
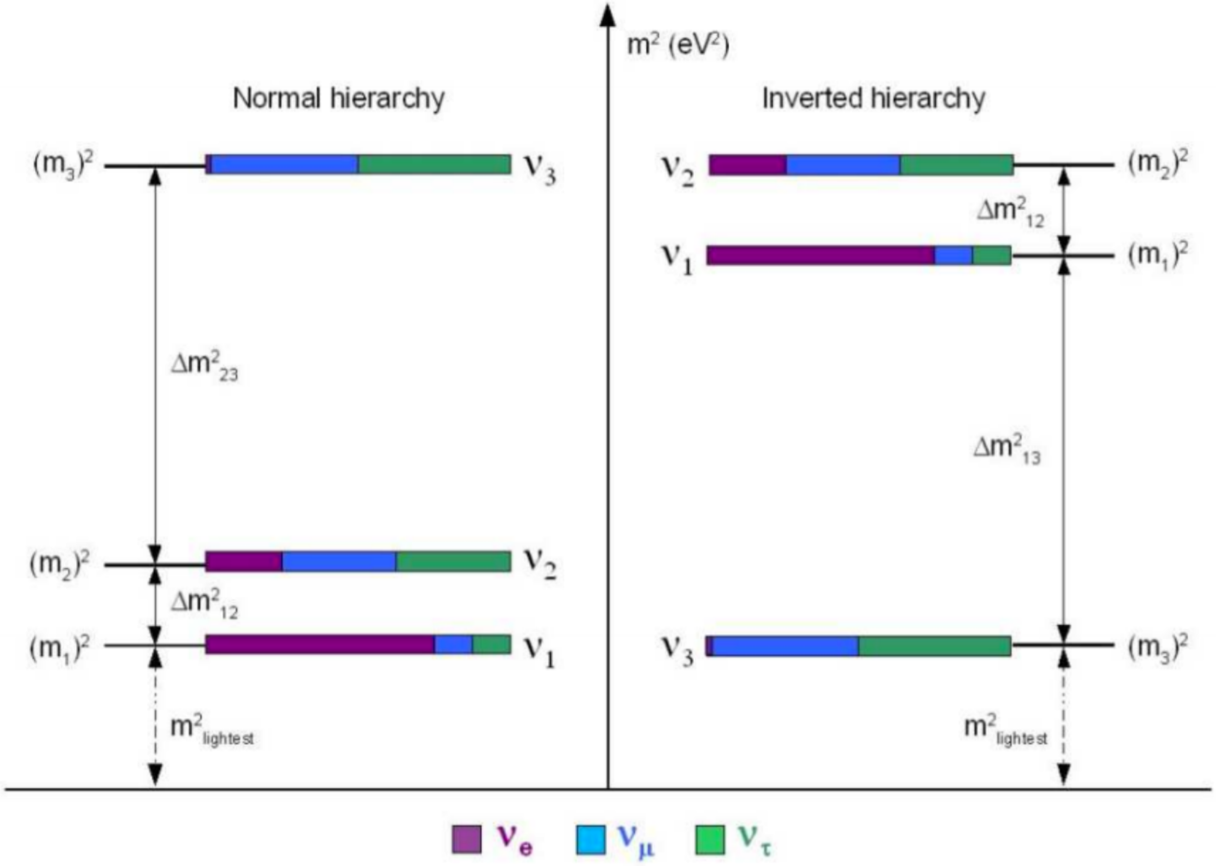


Figure 14.16: The regions of squared-mass splitting and mixing angle favored or excluded by various neutrino oscillation experiments. The figure was contributed by H. Murayama (University of California, Berkeley, and Kavli IPMU, University of Tokyo). References to the data used in the figure and the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

[PDG2017]

Three-neutrino picture

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}e^{i\delta}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



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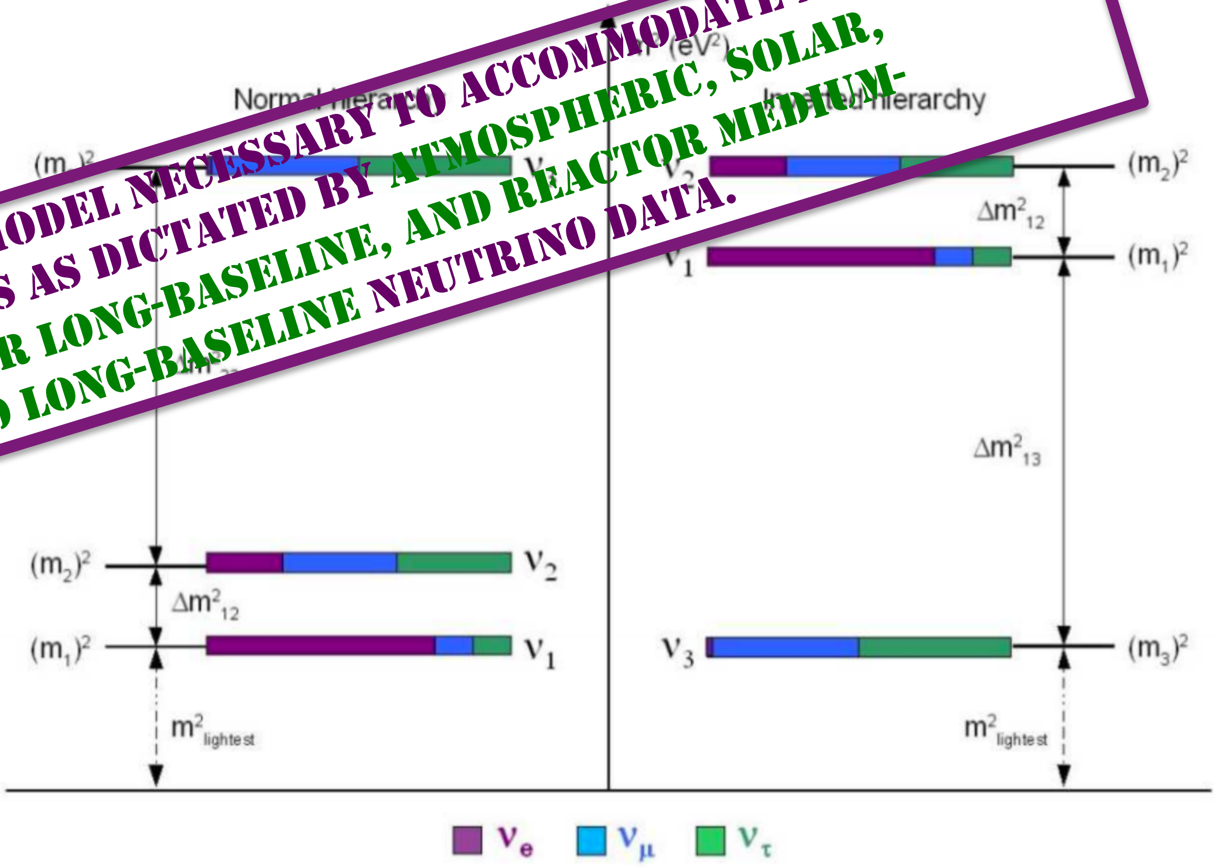
THE MOST MINIMAL MODEL NECESSARY TO ACCOMMODATE NEUTRINO OSCILLATIONS AS DICTATED BY ATMOSPHERIC, SOLAR, ACCELERATOR LONG-BASELINE, AND REACTOR MEDIUM- AND LONG-BASELINE NEUTRINO DATA.



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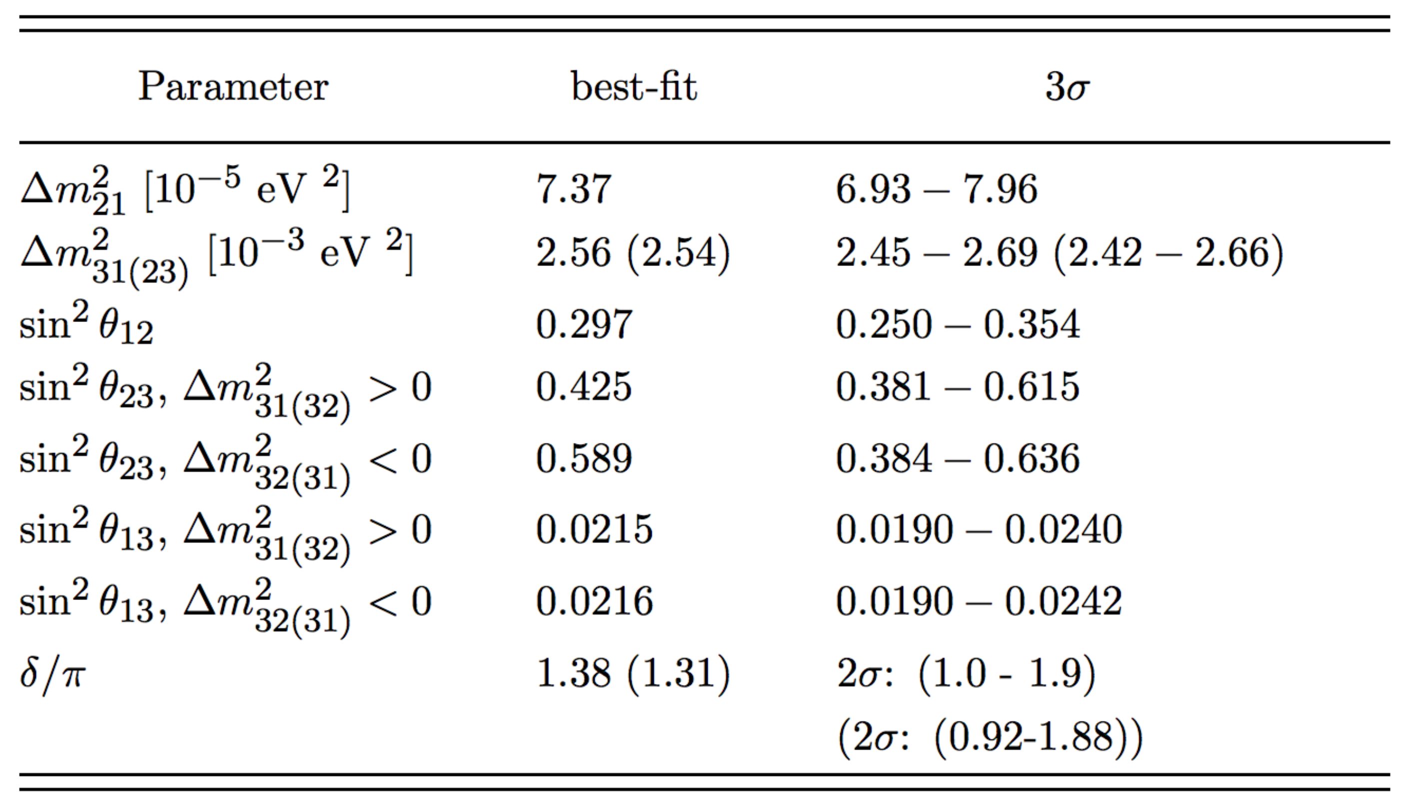
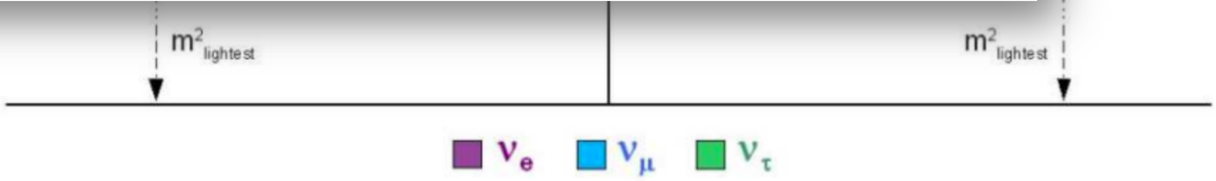
[PDG 2017]



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))



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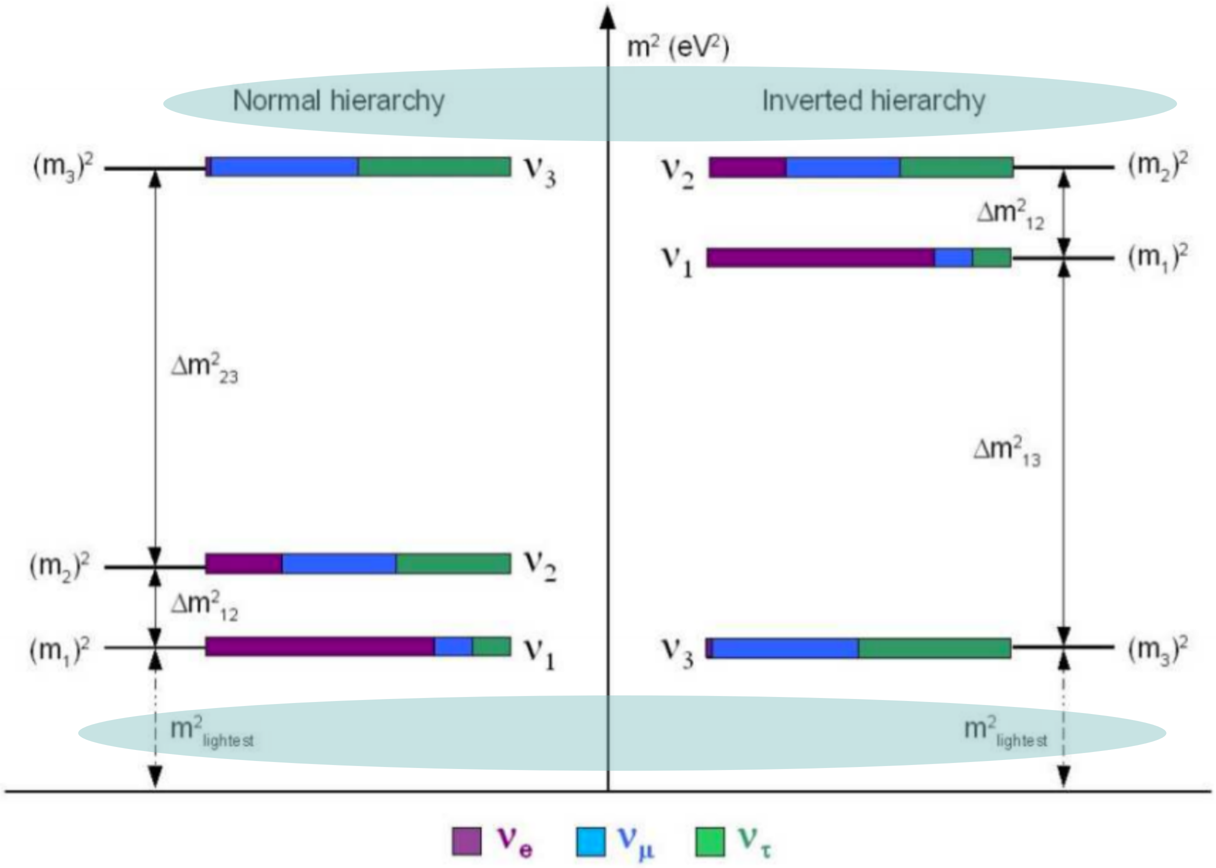
Parameters which
are yet to be determined.

CP violation phase

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



Outline

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- **Historically significant experiments**
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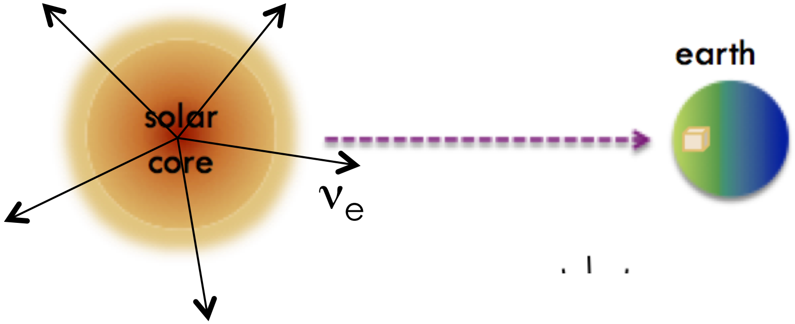
The "solar" and "atmospheric" neutrino anomalies (1960s – 1990s)

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 ~1/3 of ν_e rate expected from calculation of solar neutrino flux (by John Bachall)

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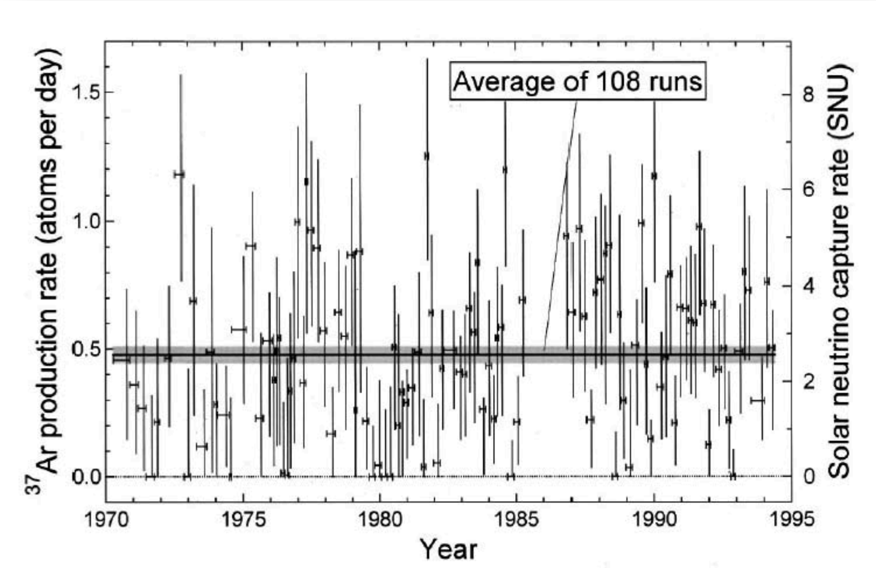
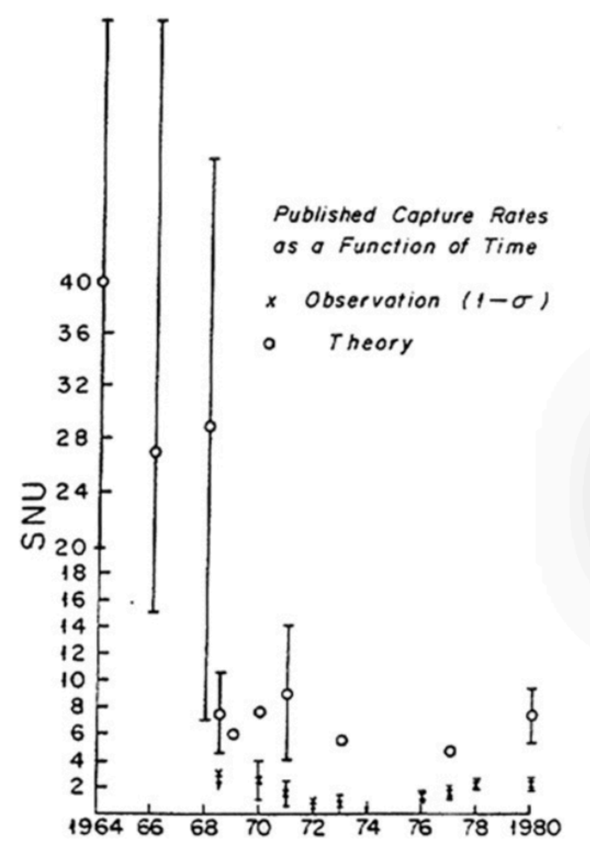




- Observation of **only ~1/3 of ν_e rate expected from calculation** of solar neutrino flux (by J. Bachall)

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

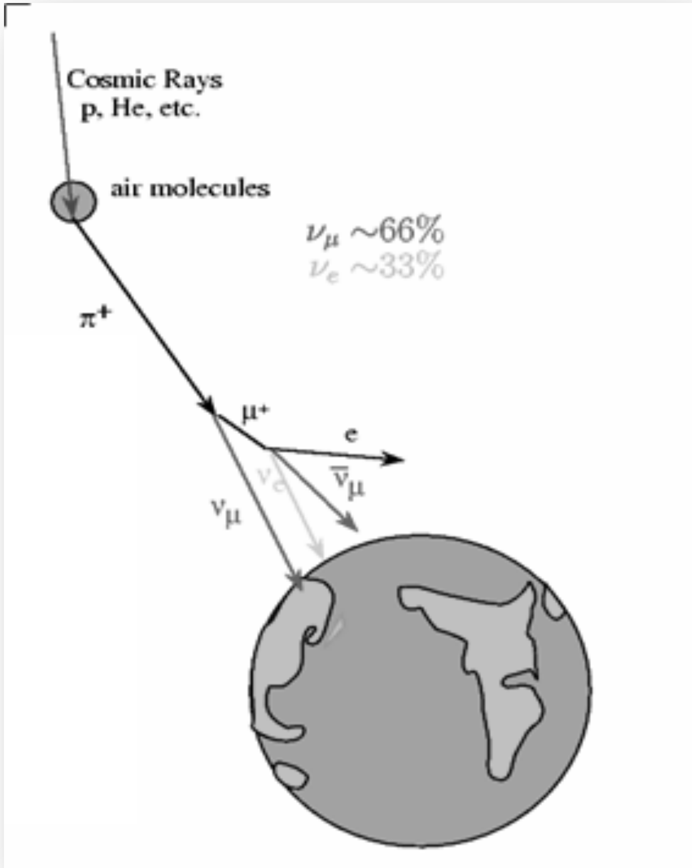
Early measurements of atmospheric neutrinos:

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

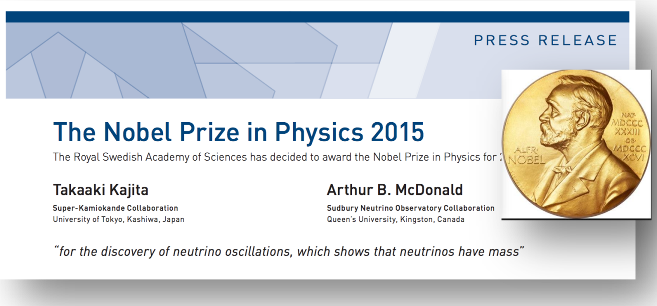
A proton decay search experiment, deep underground.

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

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



Resolution (1/2)



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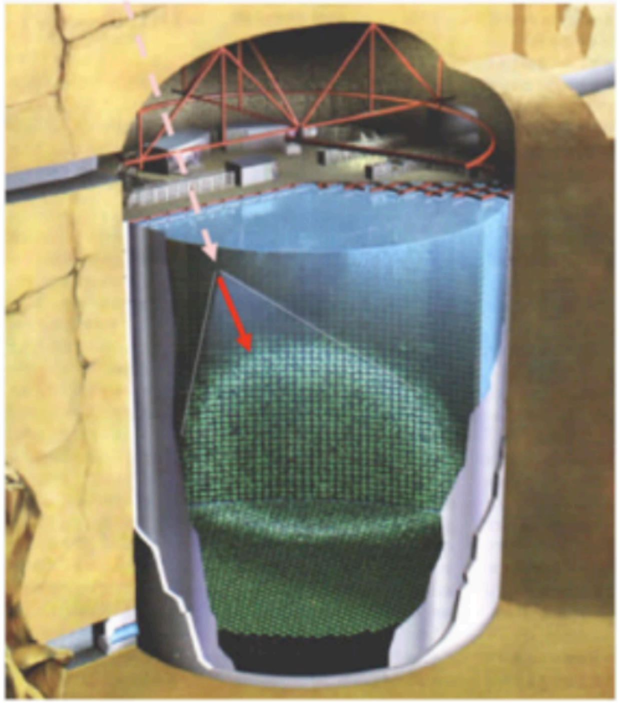
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

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

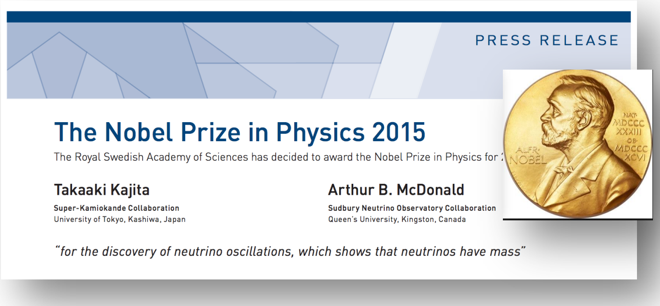
50 kton water Cherenkov detector
22.5 kton fiducial volume at 2,700 m.w.e. underground

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)



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Follow-up measurements and resolution of atmospheric neutrino deficit:
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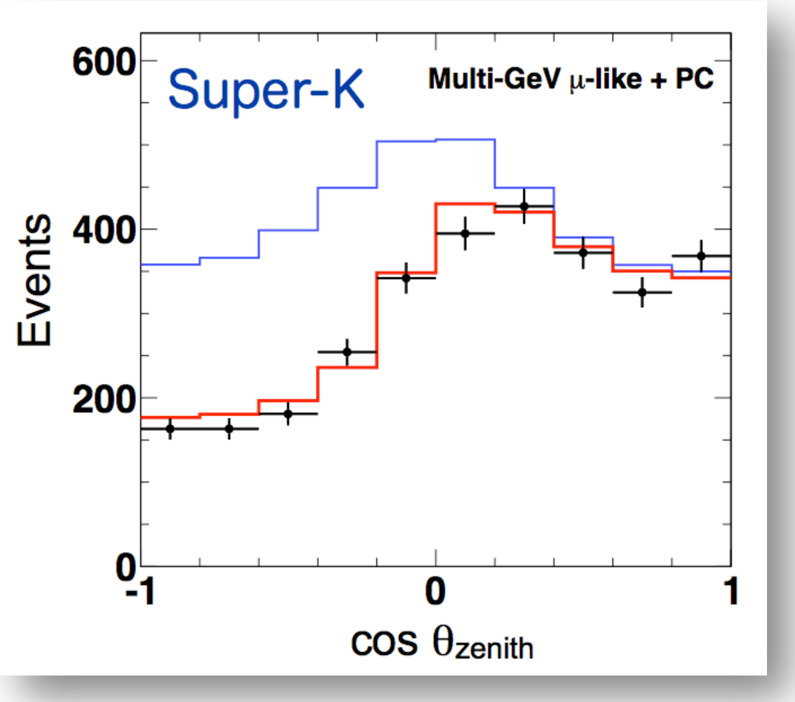
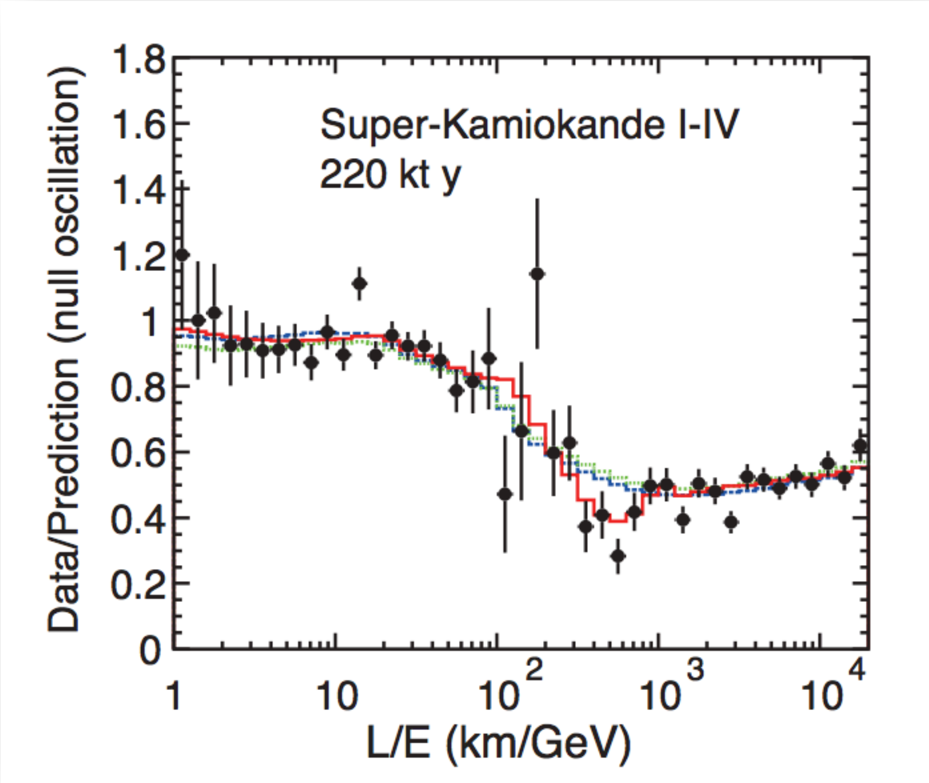
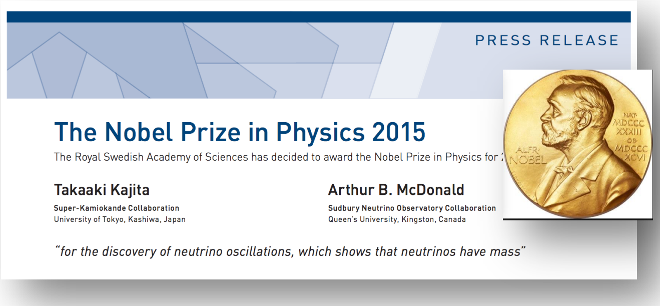
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$$





Resolution (2/2)



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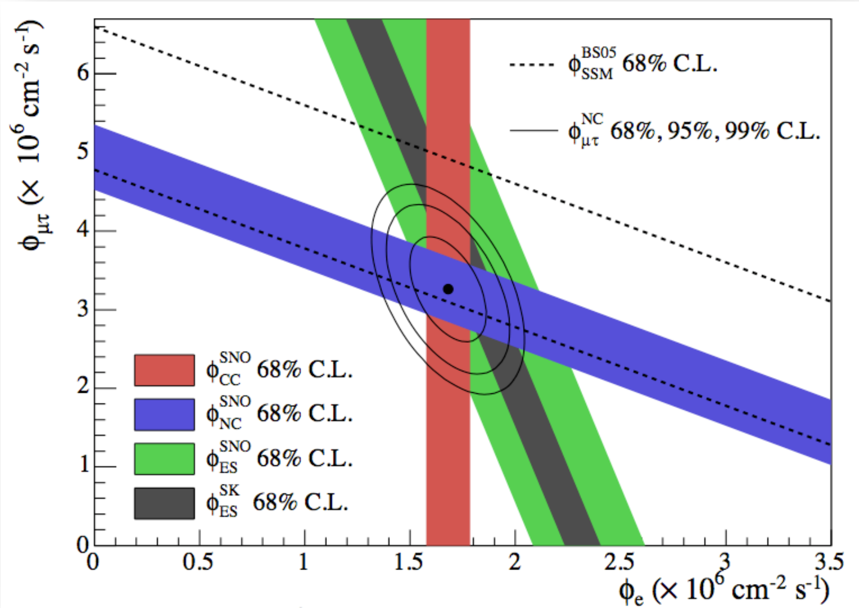
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

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



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

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Three-neutrino oscillation picture

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

"Atmospheric"
θ_{23} ~ 45 deg

"Reactor" medium-baseline
θ_{13} ~ 10 deg
"access" to δ_{CP}

"Solar"
θ_{12} ~ 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 **solar, atmospheric, reactor, and accelerator-produced neutrinos**:

“Solar” sector:

Gallex/GNO, SAGE, **KamLAND**, Super-K, Borexino, …

“Atmospheric” sector:

MINOS, K2K, IceCube, **T2K**, **NOvA**, …

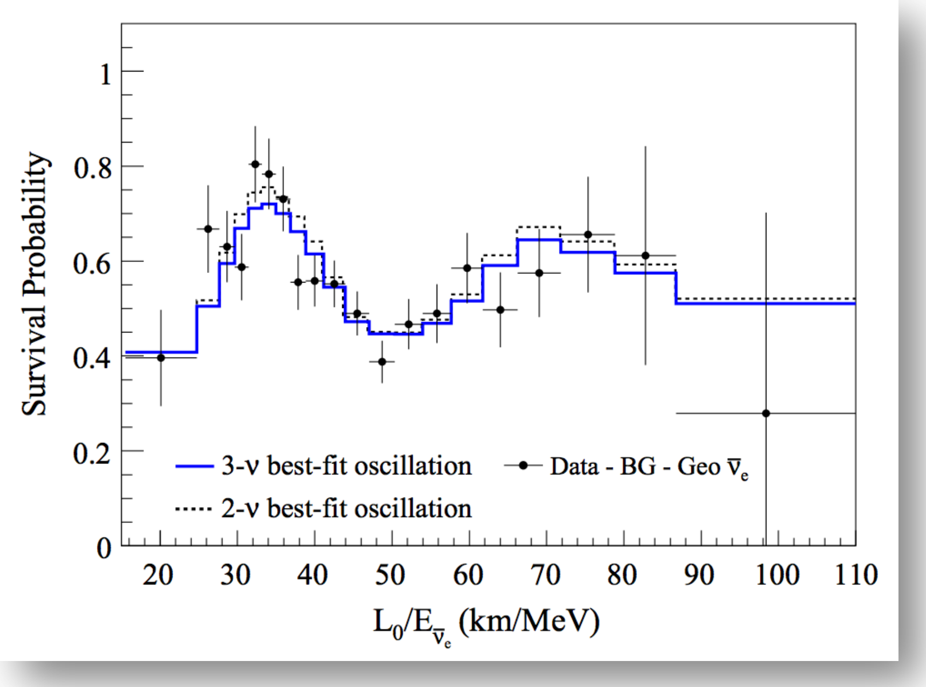
“Reactor” medium-baseline sector:

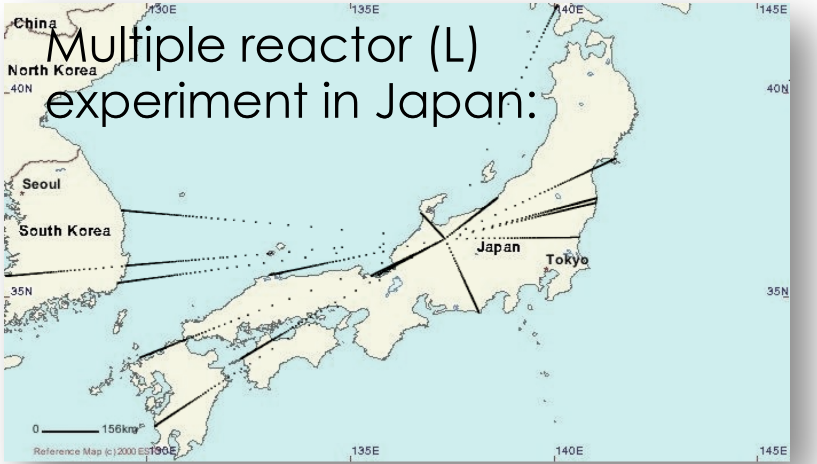
Double-Chooz, **Daya Bay**, RENO, …

“Solar” sector oscillations

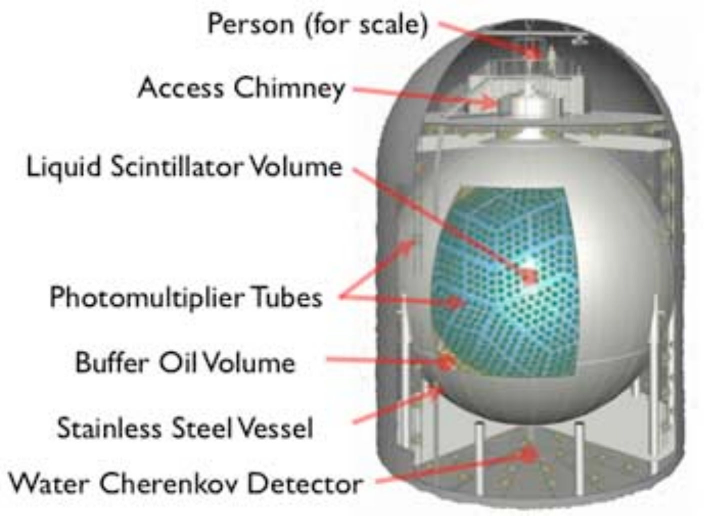
KamLAND reactor-based neutrino experiment confirmed **oscillation** nature of solar neutrino deficit

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



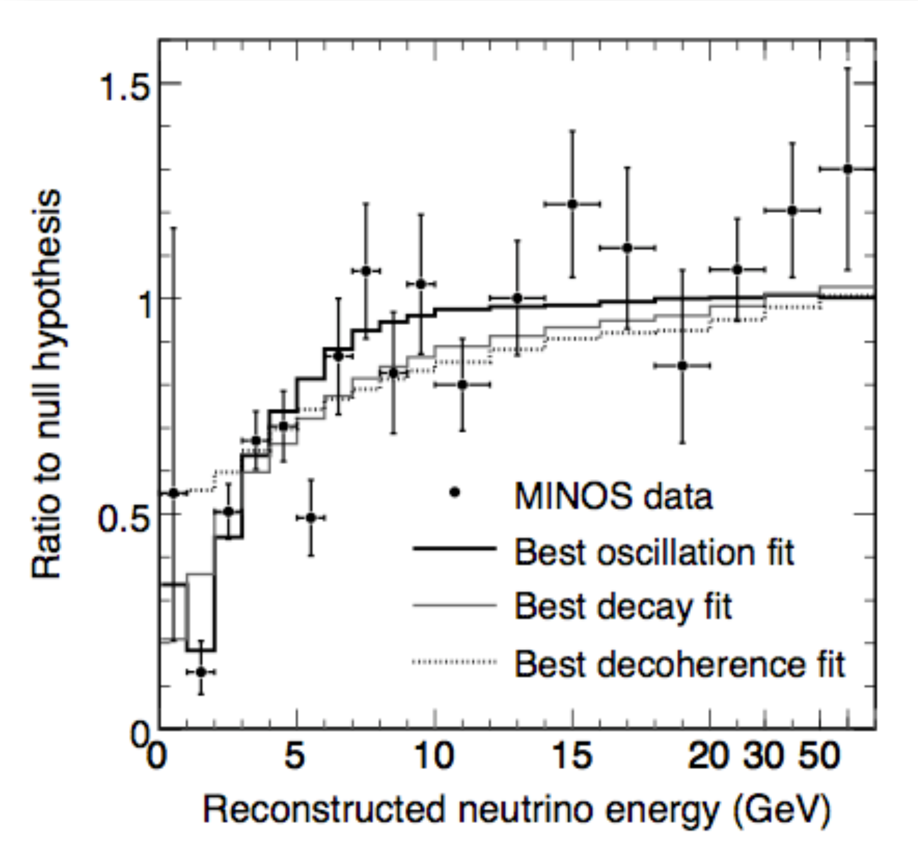


Multiple reactor (L) experiment in Japan:



“Atmospheric” sector oscillations

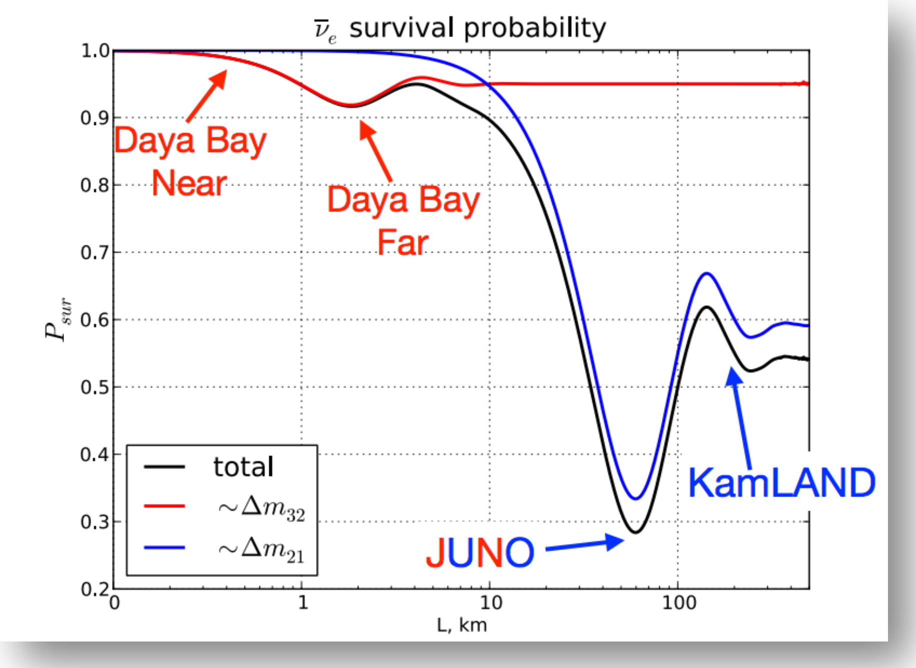
MINOS accelerator-based neutrino experiment independently confirmed Super-K results

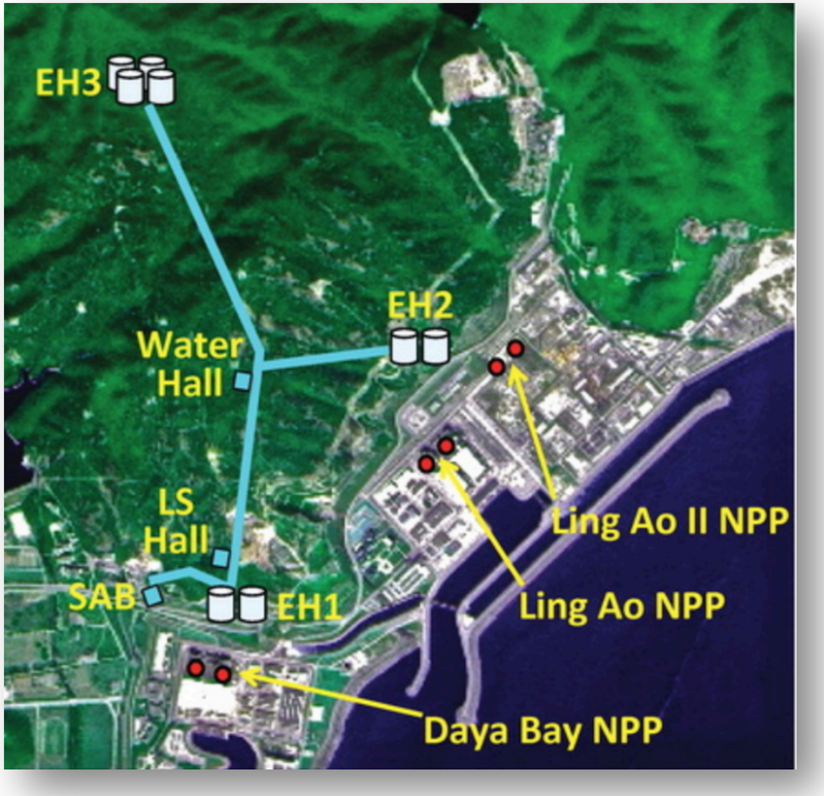


$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$$

"Reactor" medium-baseline sector

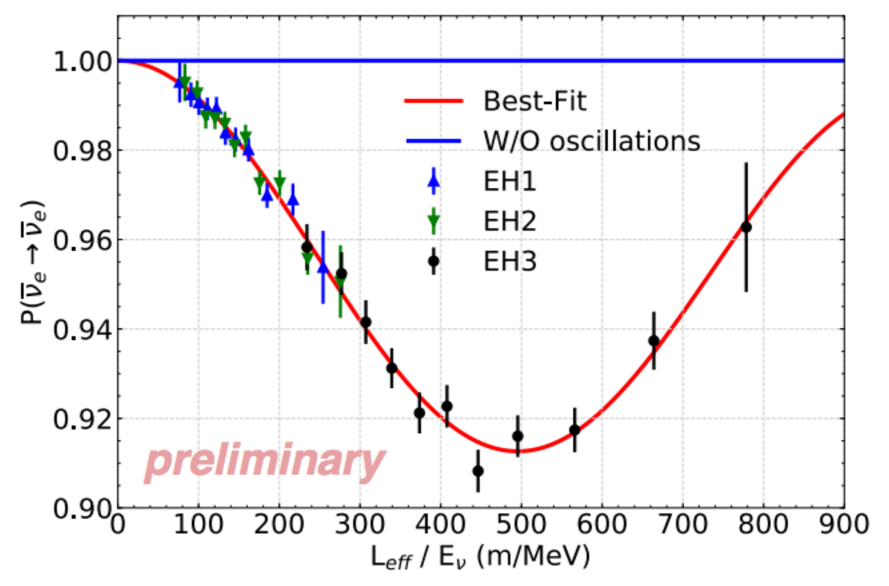
Daya Bay is a medium-baseline reactor-based experiment with highest sensitivity to θ_{13}

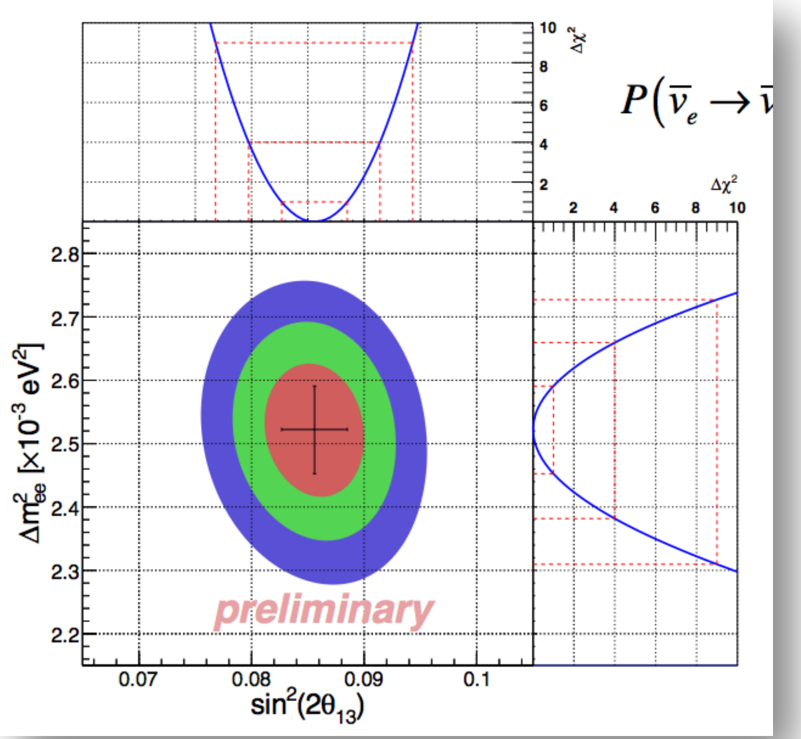




Daya Bay employs 8 identical detectors at one of the most powerful reactor power complexes in the world.

“Reactor” medium-baseline sector





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

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2\ \mathrm{(NH)}$$

[J. Pedro Ochoa-Ricoux, Neutrino 2018]

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

- Experiments at long baselines, 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**:

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

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

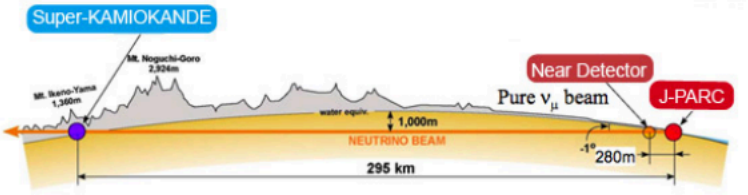
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

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

T2K and NOvA

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



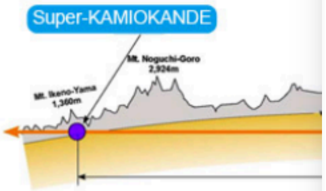
NOvA: FNAL to Ash River

- 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

T2K: Tokai to Kamioka

- Beam: J-PARC
- Far detector: SuperK
  - WCD (50 kt)
- Baseline:
- Far detect
such that
peaked at



NOvA: FNAL to Ash River

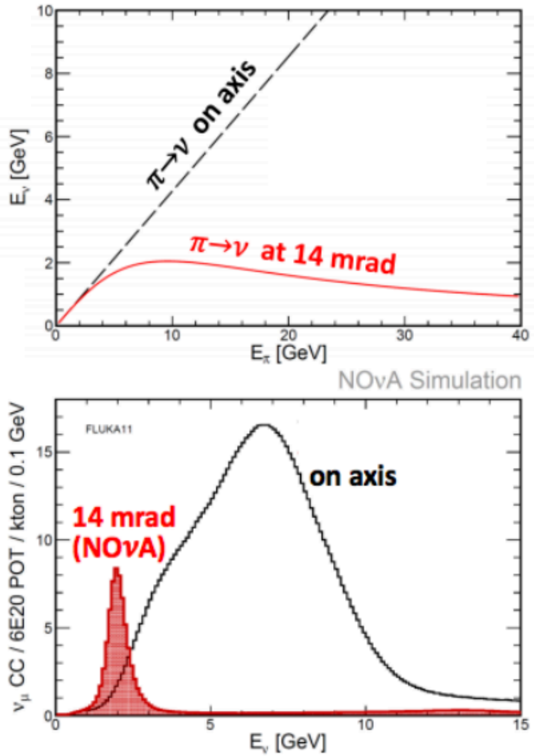
- Beam: NuMI (FNAL)
- Far detector: segmented liquid scintillator detector (14 kt)

is
s

NuMI off-axis beam for NOvA

Off-axis beam technique exploits relativistic kinematics at production to narrow beam energy distribution.

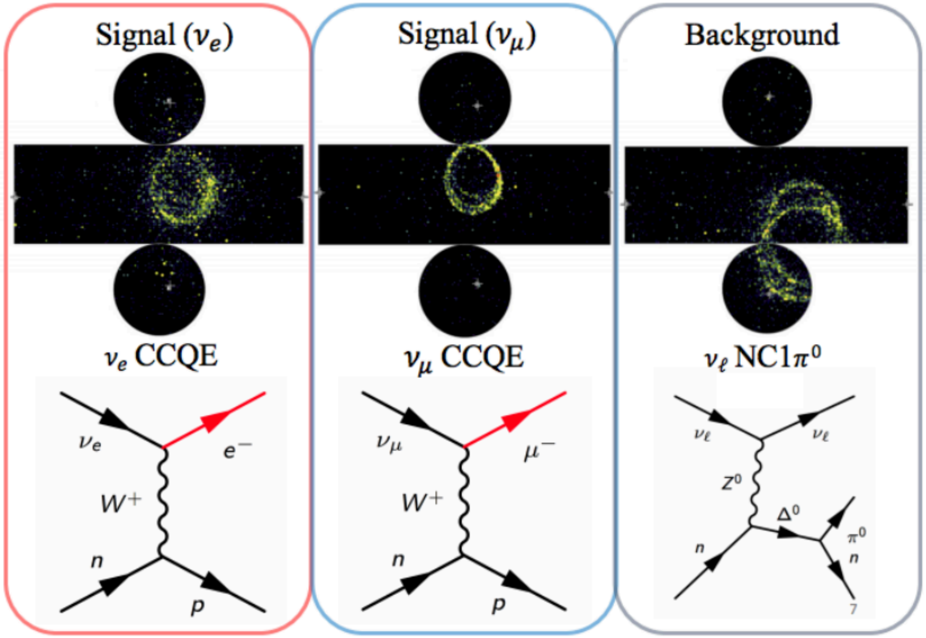
Reduces NC and beam ν_e CC backgrounds in the oscillation analyses while maintaining high ν_μ flux at osc. max.



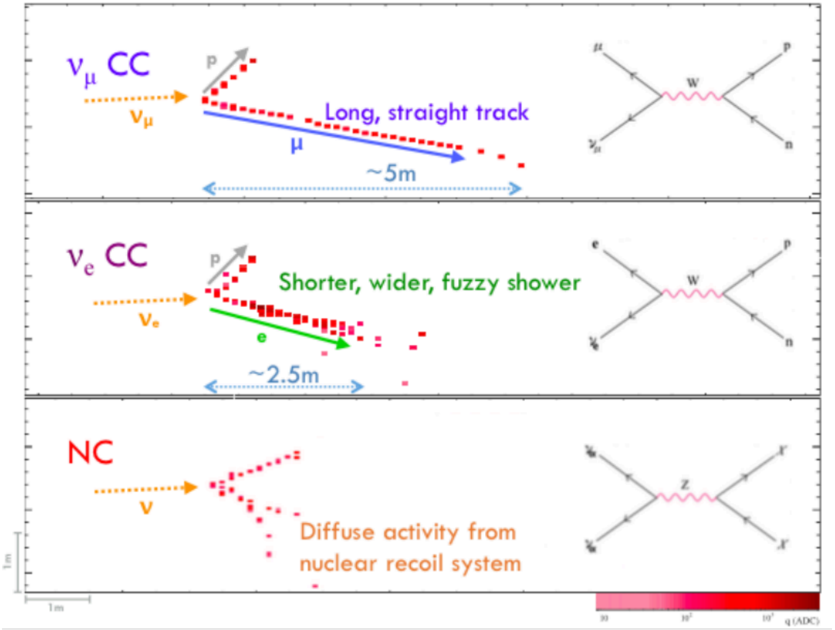
T2K and NOvA

- Both experiments can perform:
  - ν_μ disappearance searches
  - ν_e appearance searches with sensitivity to δ_{CP} and mass hierarchy

Neutrino detection in T2K

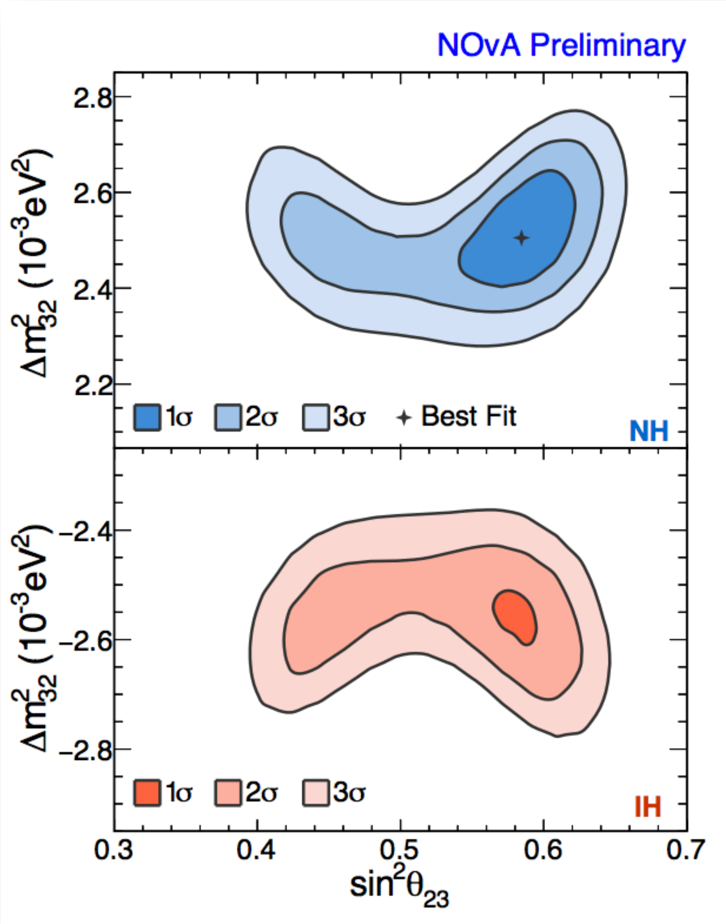


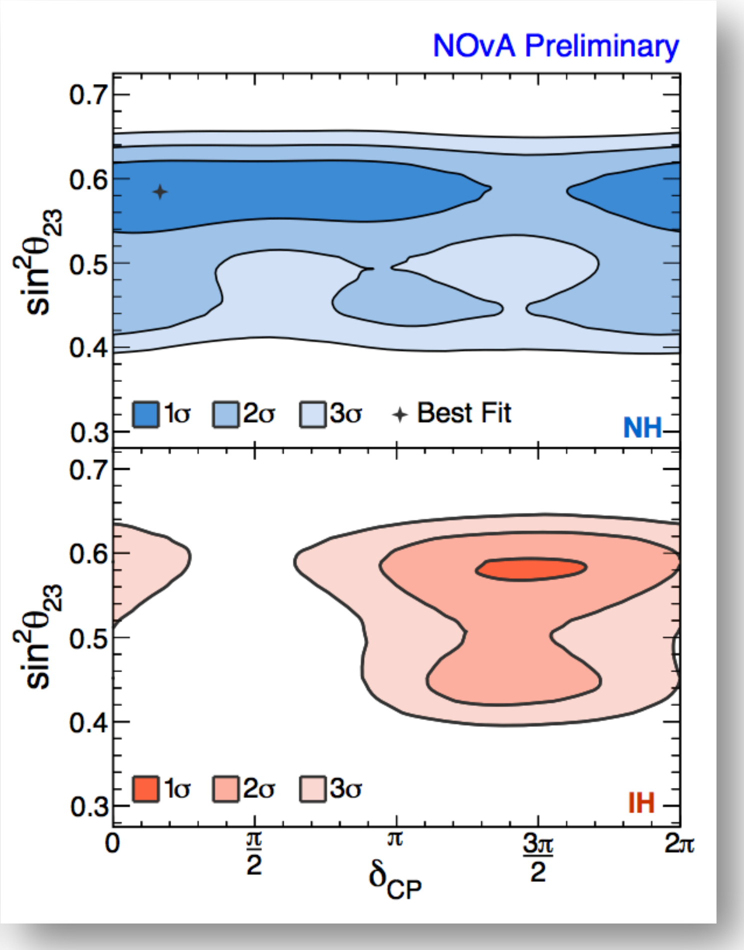
Neutrino detection in NOvA



T2K and NOvA

NOvA joint ν_μ disappearance and ν_e disappearance fit constrain both "atmospheric" sector and δ_{CP}!



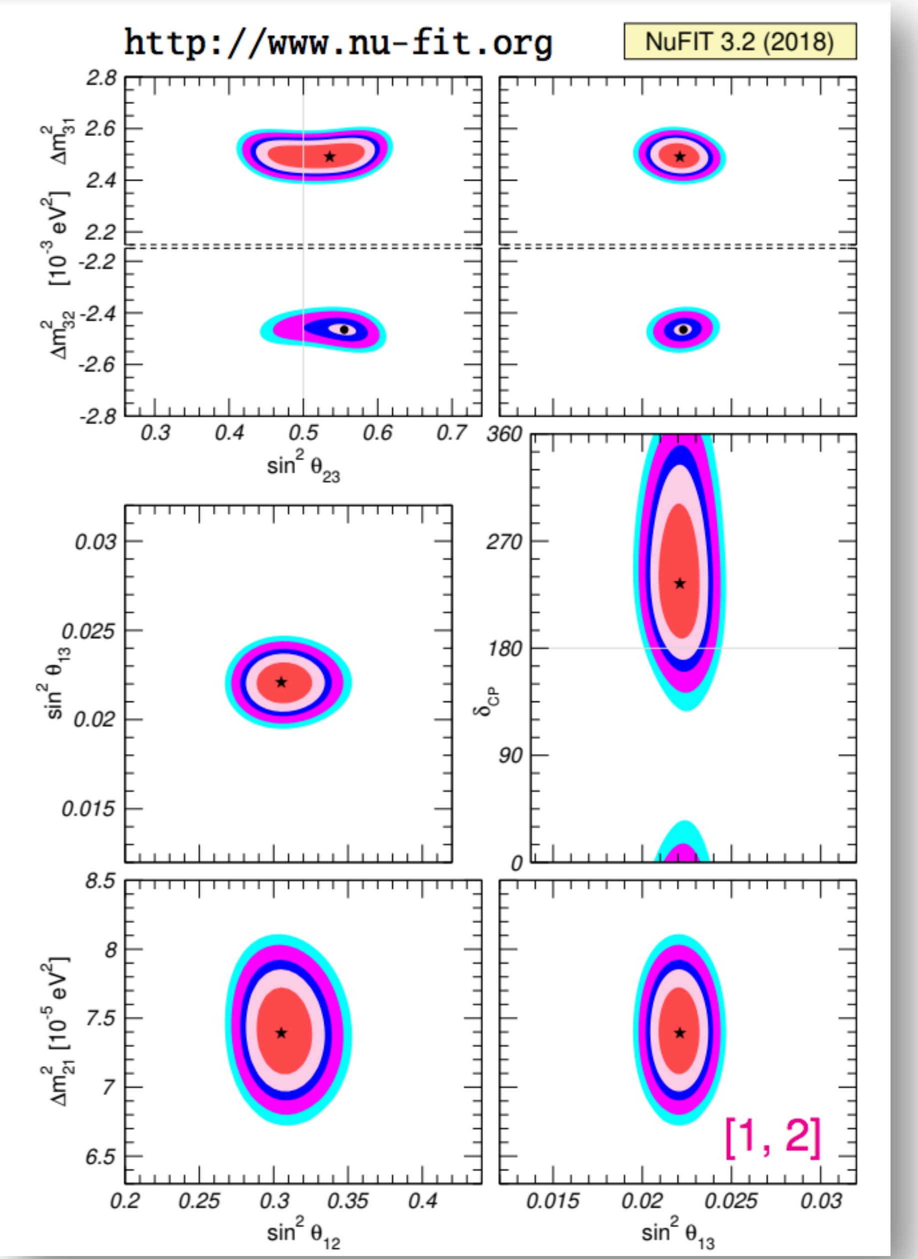


[M. Sanchez, Neutrino 2018]

Global picture

Global 6-parameter fit (including δ_{CP}):

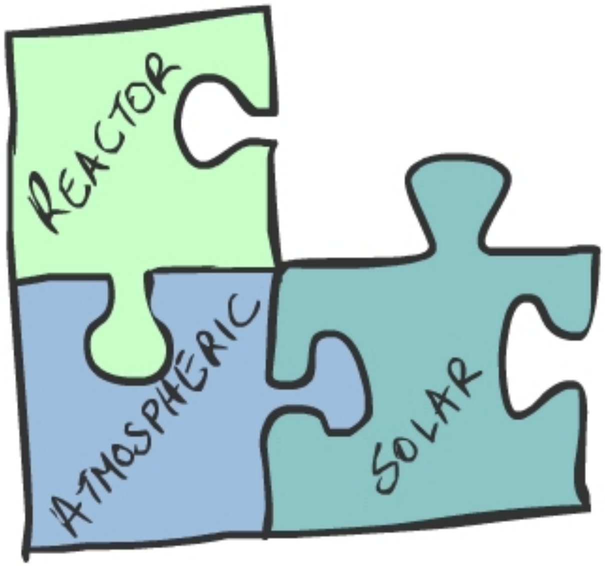
- Solar ν: Cl + Ga + SK(1-4) + SNO-full (I+II+III) + Borexino
- Atmospheric ν: IceCube
- Reactor ν: KamLAND + Double-Chooz + Daya Bay + RENO
- Accelerator ν: MINOS + T2K + NOvA



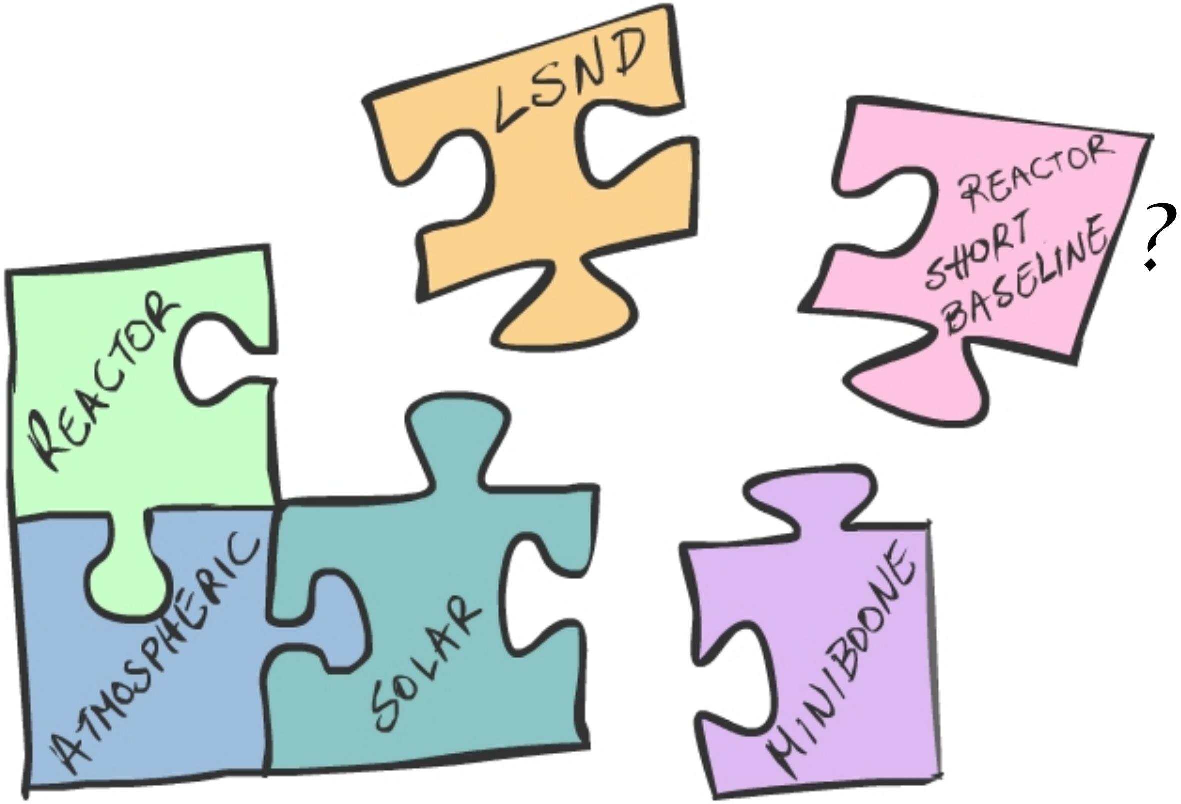
[1, 2]

[M. Maltoni, Neutrino 2018]

everything fits together!



Almost everything fits together!

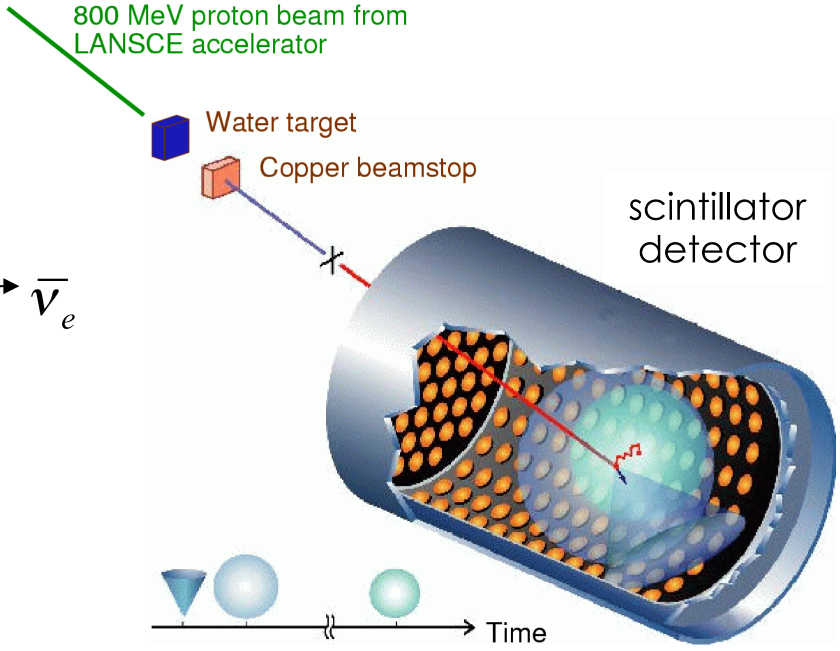


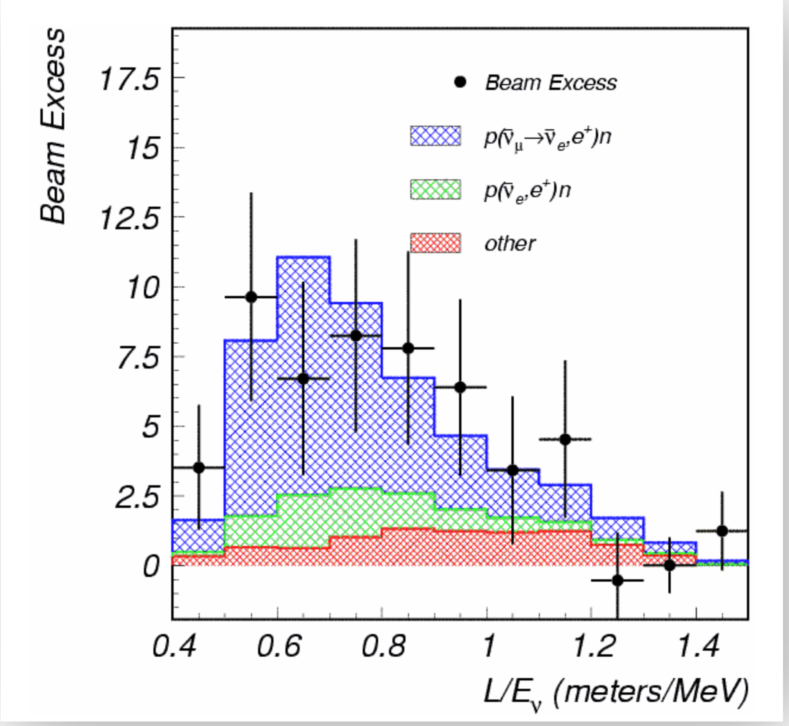
LSND puzzle piece

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

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

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





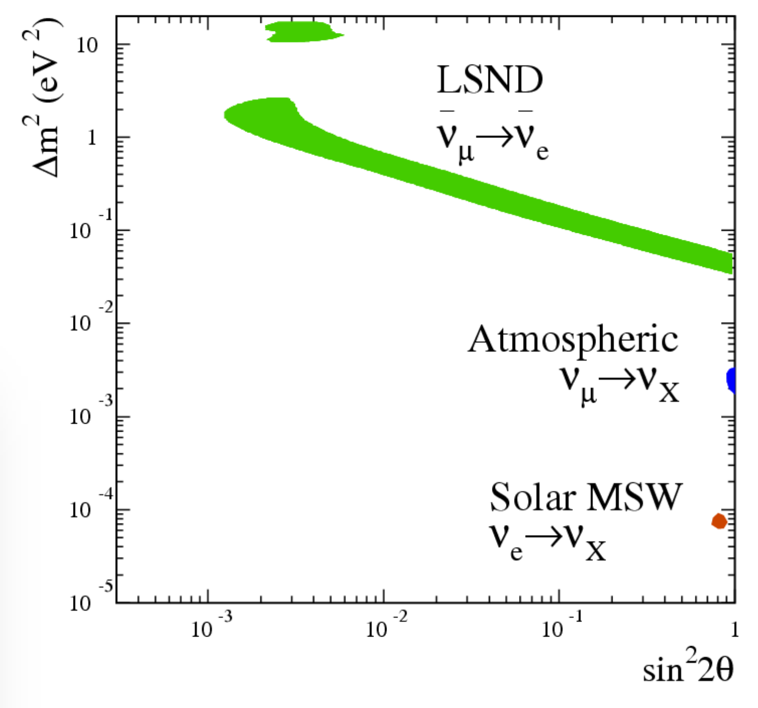
Observed excess of $\bar{\nu}_e$ described by oscillation probability:
$P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\ \%$

(3.8σ evidence)

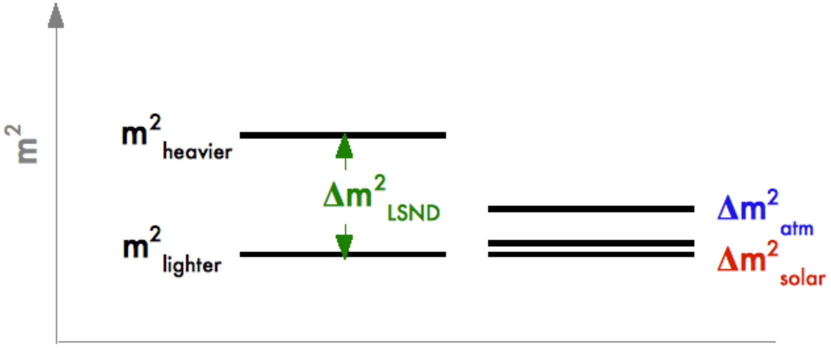
LSND puzzle piece

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

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

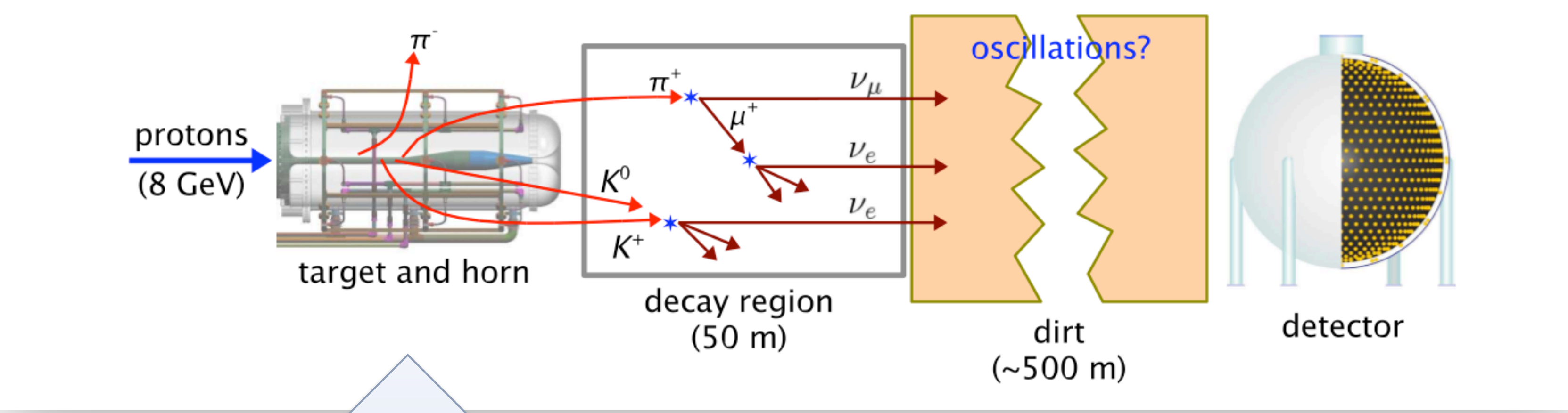


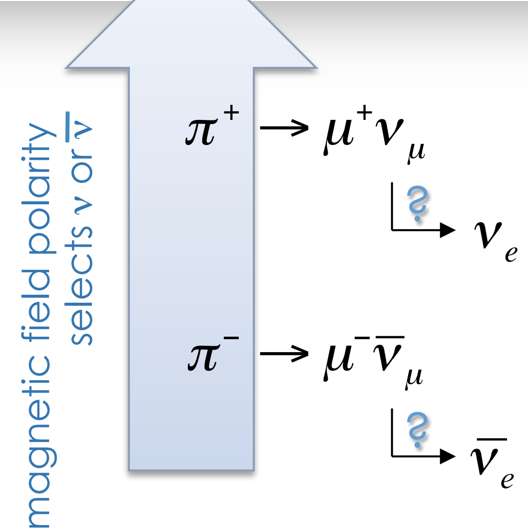
Much larger Δm^2 cannot be reconciled in 3-neutrino model!



Also implies oscillations at short-baselines…

MiniBooNE puzzle piece





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

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

Similar L/E as LSND

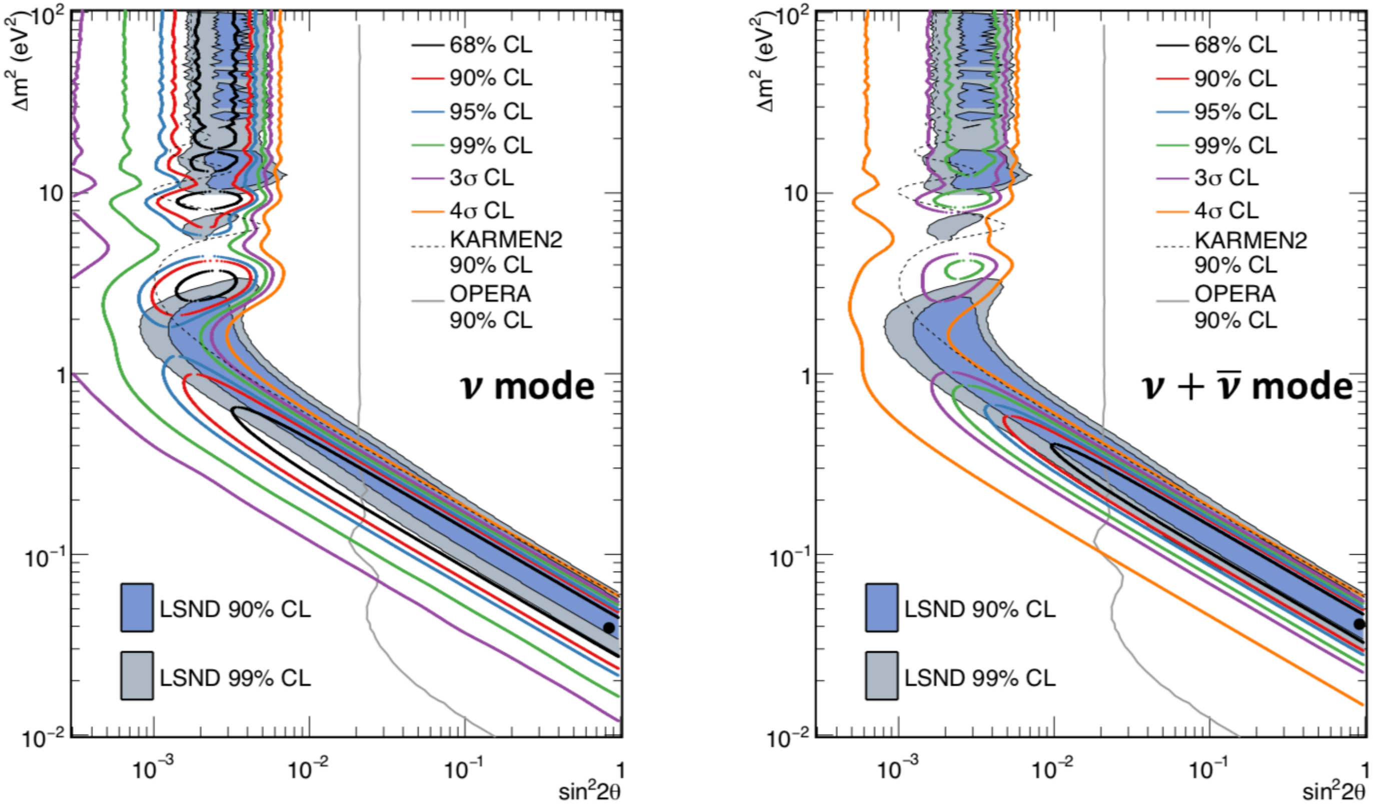
but

Different energy, beam and detector systematics

Different event signatures and backgrounds (Cherenkov detector)

MiniBooNE puzzle piece

Recently updated results (May 2018)



Neutrino combined (12.84E20 POT)

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

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

Neutrino + antineutrino combined

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

$\chi^2/ndf = 19.5/15.4$ (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

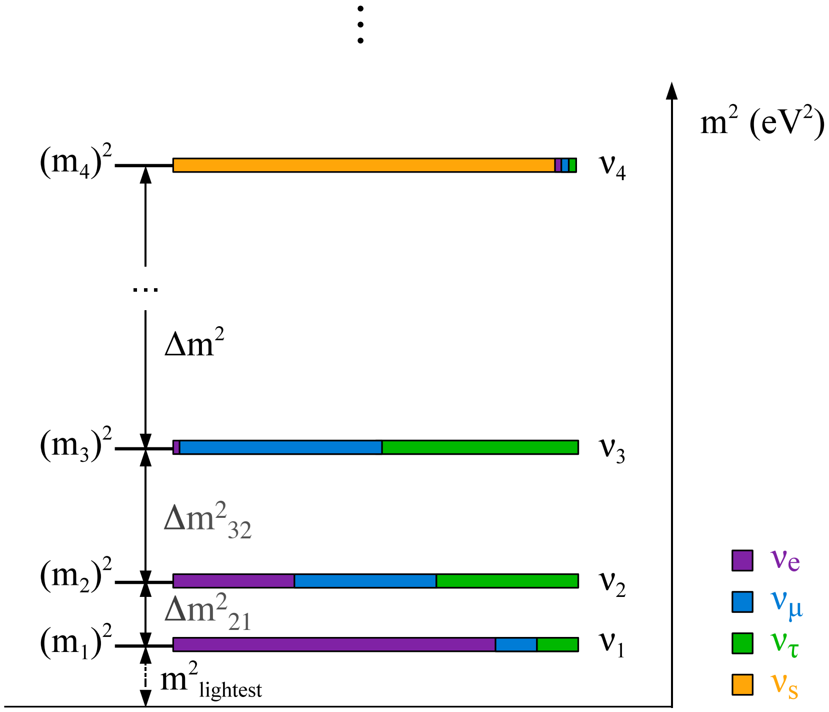
sterile neutrino

/ˈstɛrʌɪl/ /njuːˈtriːnəʊ/

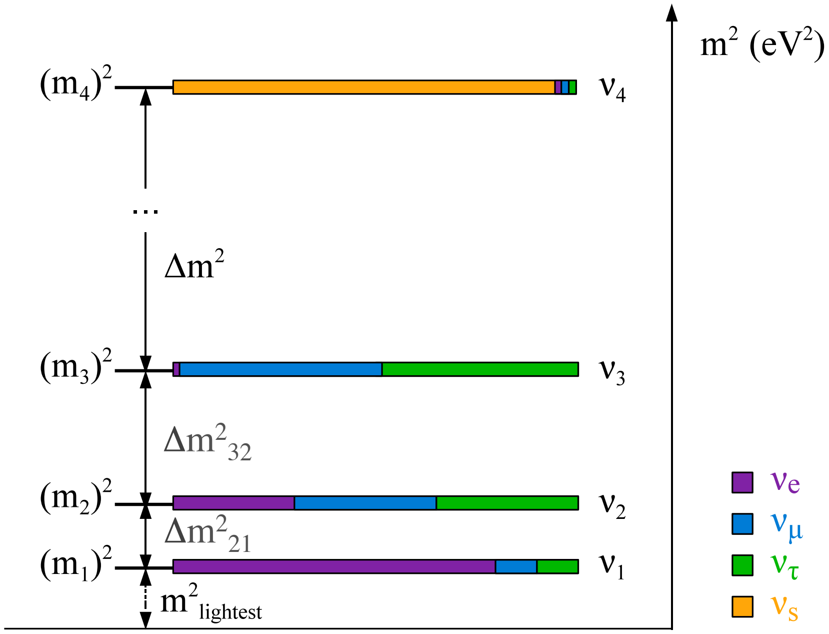
Additional neutrino "flavor" states which **do not experience weak interactions** (through the standard model W/Z bosons)

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



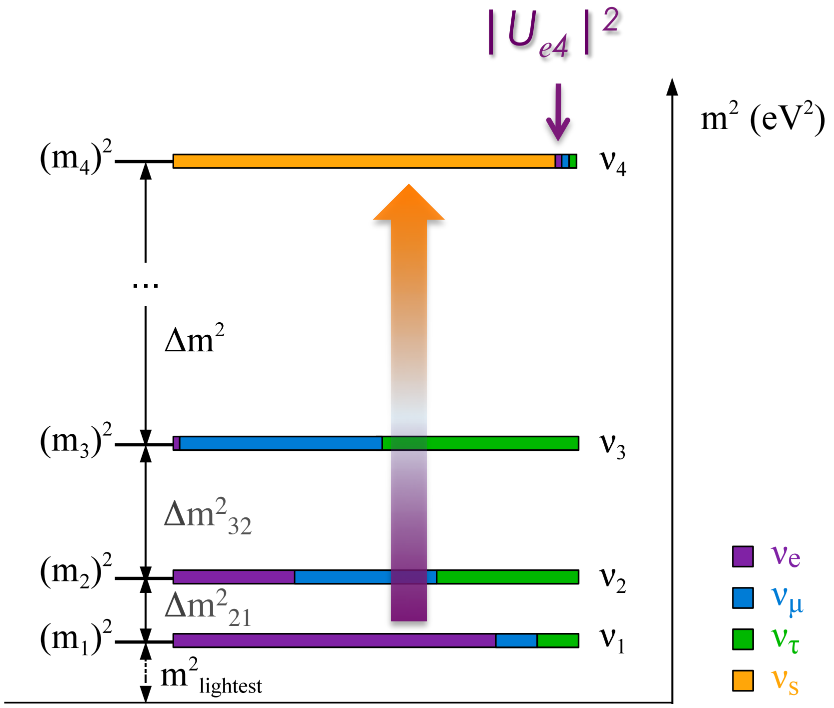
Simplest (3+1) sterile neutrino model

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:

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

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



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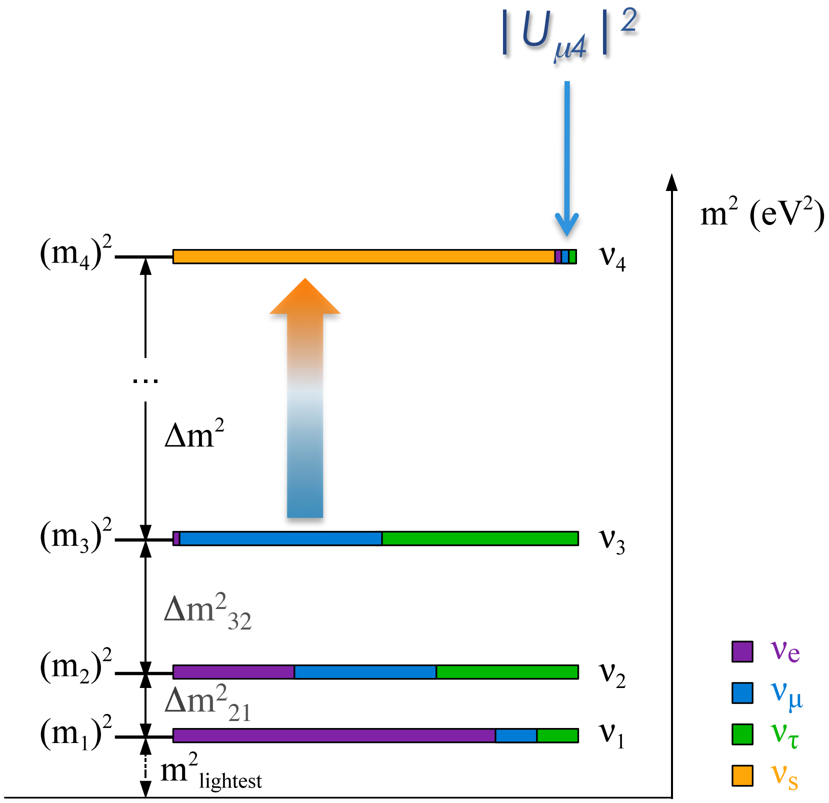
ν_μ disappearance:

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

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



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ν_μ disappearance:

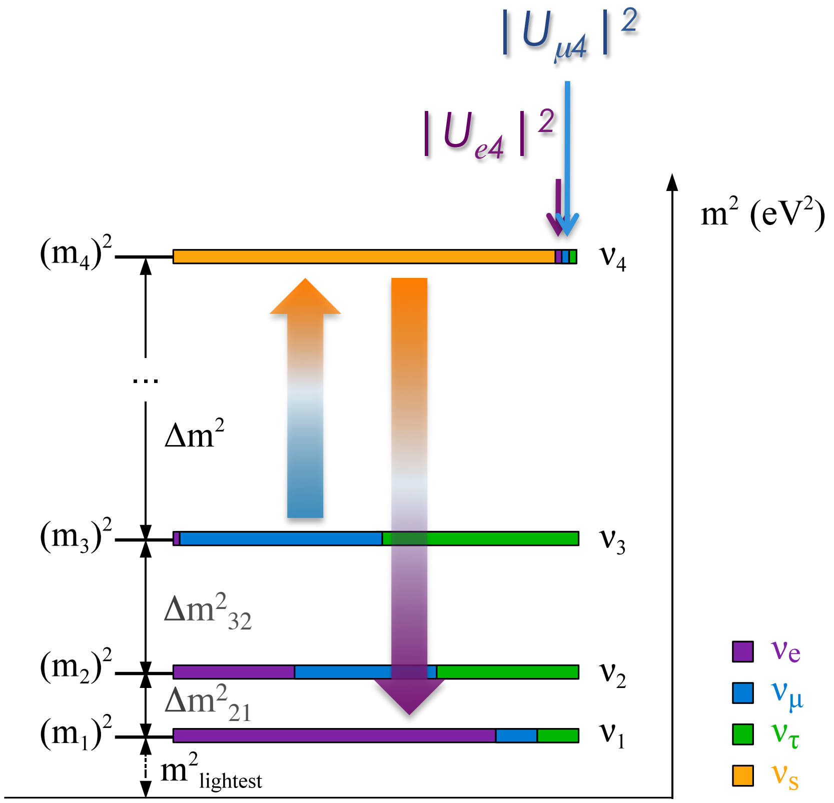
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

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

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

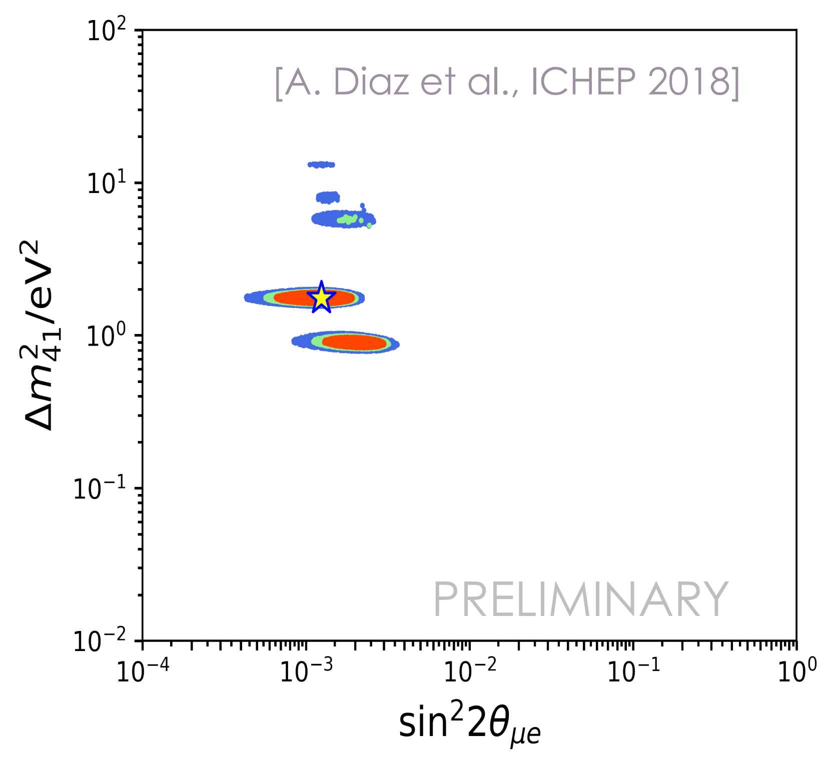
$$\hookrightarrow 4|U_{e4}|^2|U_{\mu 4}|^2$$

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



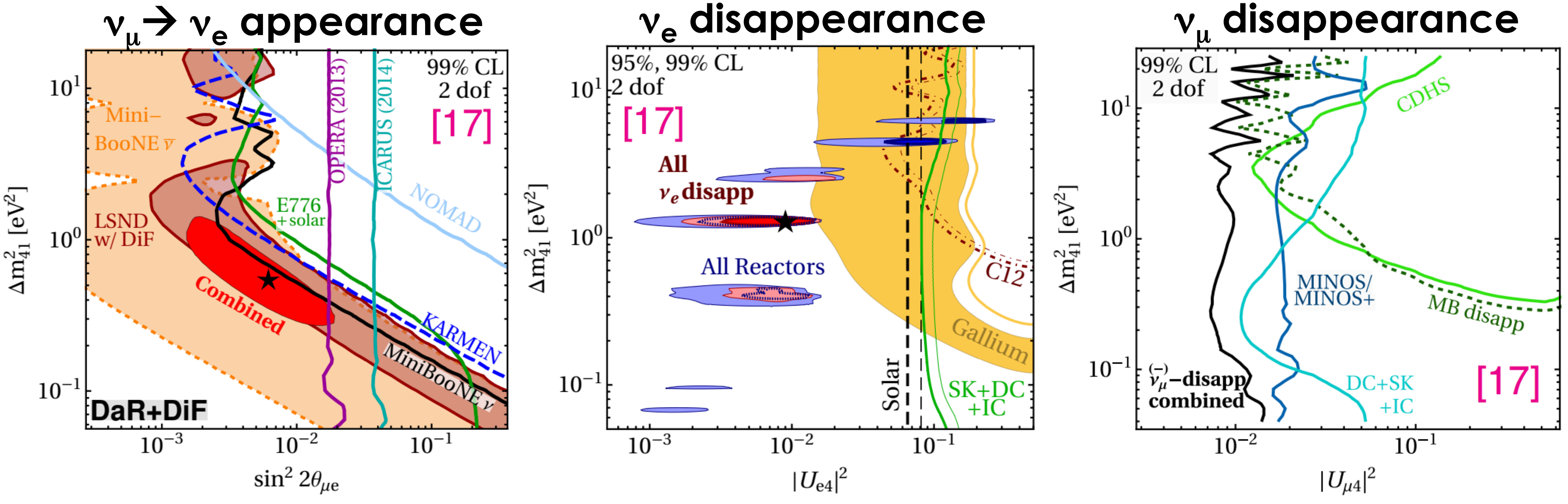
Global picture of sterile neutrinos

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!)

Global picture of sterile neutrinos


$\nu_\mu \rightarrow \nu_e$ appearance

ν_e disappearance

ν_μ disappearance

[M. Maltoni, Neutrino 2018]

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!)

Global picture of sterile neutrinos

A large number of **experiments at "(very) short baselines"** have been/are being deployed to resolve this: SoLiD, DANNS, NEOS, STEREO, PROSPECT, SBN…

"very short baselines":

Accelerator based: L/E ~ 1km/GeV
Reactor based, radioactive source experiments: L/E ~ 1m/MeV

Also searches are possible at ongoing and planned **long-baseline accelerator-based experiments** (using their near detectors) and **atmospheric neutrino experiments** (using high-energy atmospheric neutrinos)

Outline

- Experimental signatures of neutrino oscillation
- Historical experiments
  - Ray Davis' solar neutrino experiment
  - Super-Kamiokande atmospheric neutrino experiment
  - SNO solar neutrino experiment
- Recent and current oscillation experiments
  - KamLAND, MINOS, Daya-Bay
  - How everything fits together... or not!
- **Future oscillation experiments**
  - **SBN, DUNE**

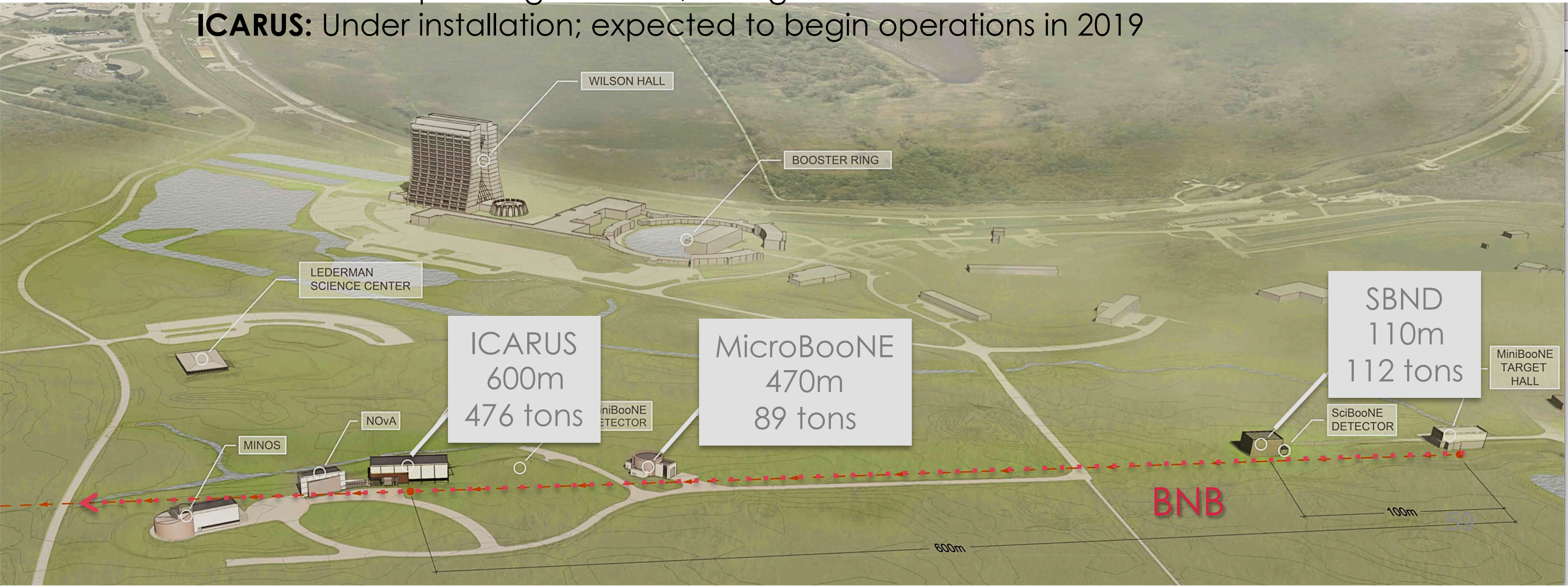
SBN: Short Baseline Neutrino Program

A **trio of liquid argon time projection chamber (LArTPC) detectors** in the Booster Neutrino Beam (BNB) at Fermilab.

Aim: Search for short-baseline neutrino oscillations (sterile neutrinos) and perform a definitive test of MiniBooNE/LSND sterile neutrino oscillation interpretation.

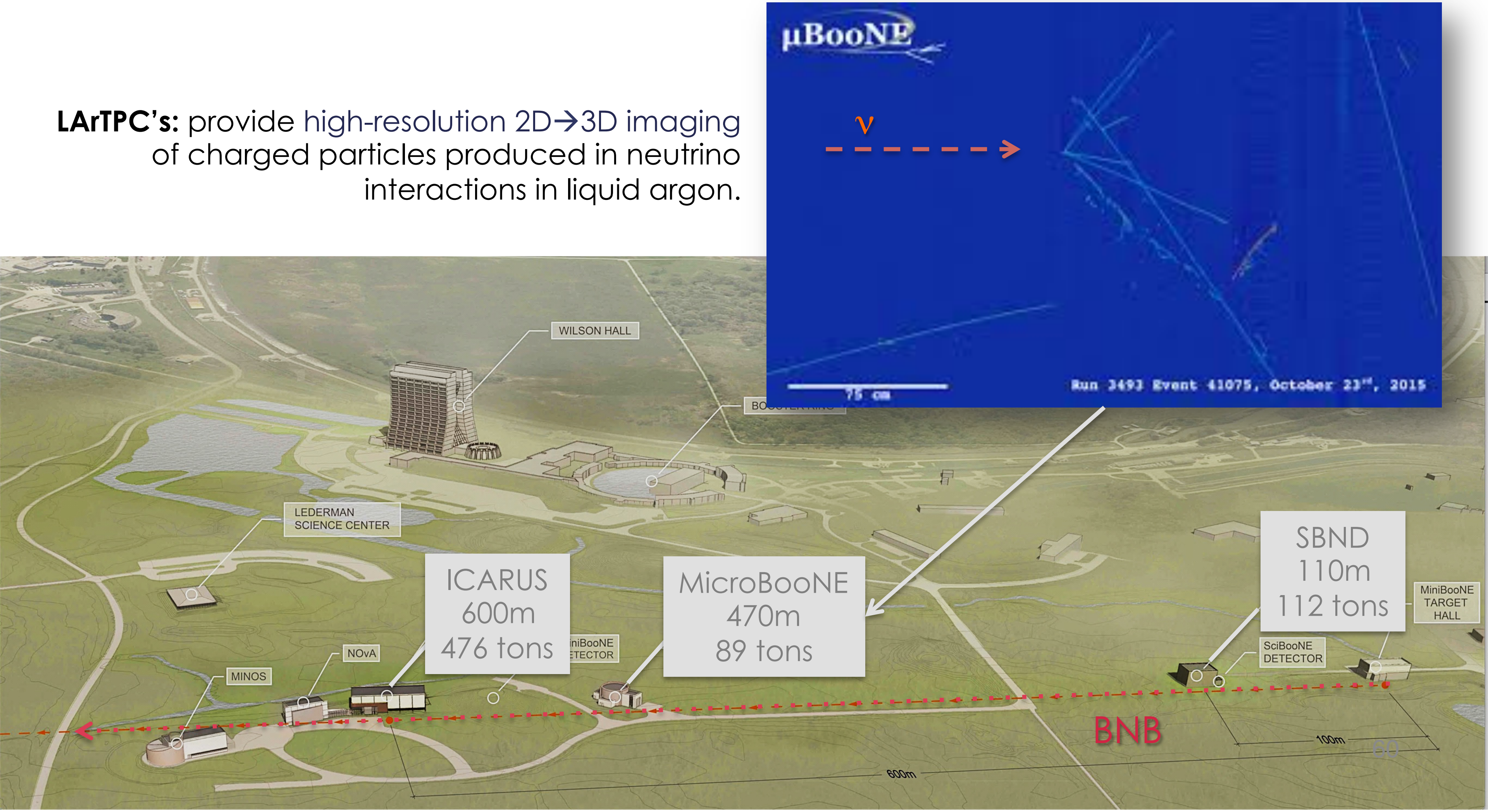
The SBN program is coming together at Fermilab:

SBND: Under construction; expected to begin operations in early 2020
MicroBooNE: Operating detector, taking data since Oct. 2015!
ICARUS: Under installation; expected to begin operations in 2019



SBN: Future search for sterile neutrinos

LArTPC's: provide high-resolution 2D→3D imaging of charged particles produced in neutrino interactions in liquid argon.



SBN: Future search for sterile neutrinos

Measuring percent-level event rate (= flux x cross-section) **effects is challenging!**

For accelerator-produced neutrinos (E~0.5-1 GeV),

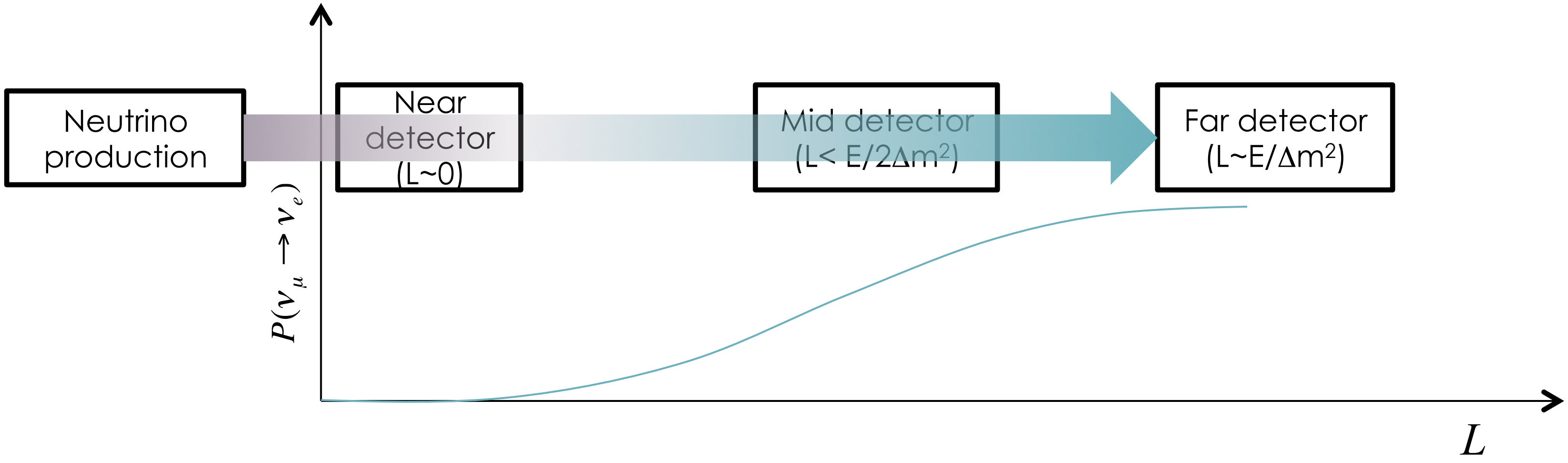
- flux uncertainties are ~15%;
- cross-section uncertainties are ~20%.

→ Single-detector measurements are difficult.

Cross-sections:
See lecture by C. Mariani

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

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



SBN: Future search for sterile neutrinos

Measuring percent-level event rate (= flux x cross-section) **effects is challenging!**

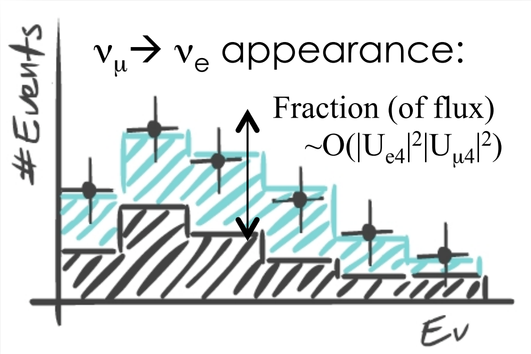
For accelerator-produced neutrinos (E~0.5-1 GeV),

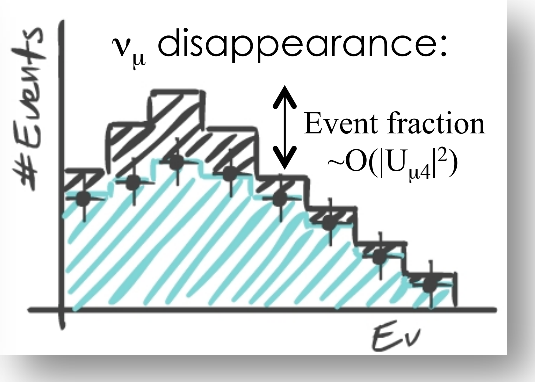
- flux uncertainties are ~15%;
- cross-section uncertainties are ~20%.

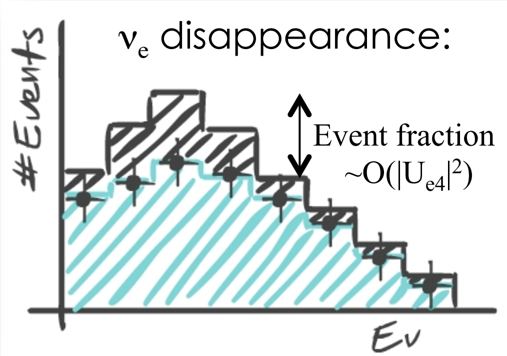
→ Single-detector measurements are difficult.

Multi-channel search:

In any given detector (L), appearance and disappearance signals are correlated!

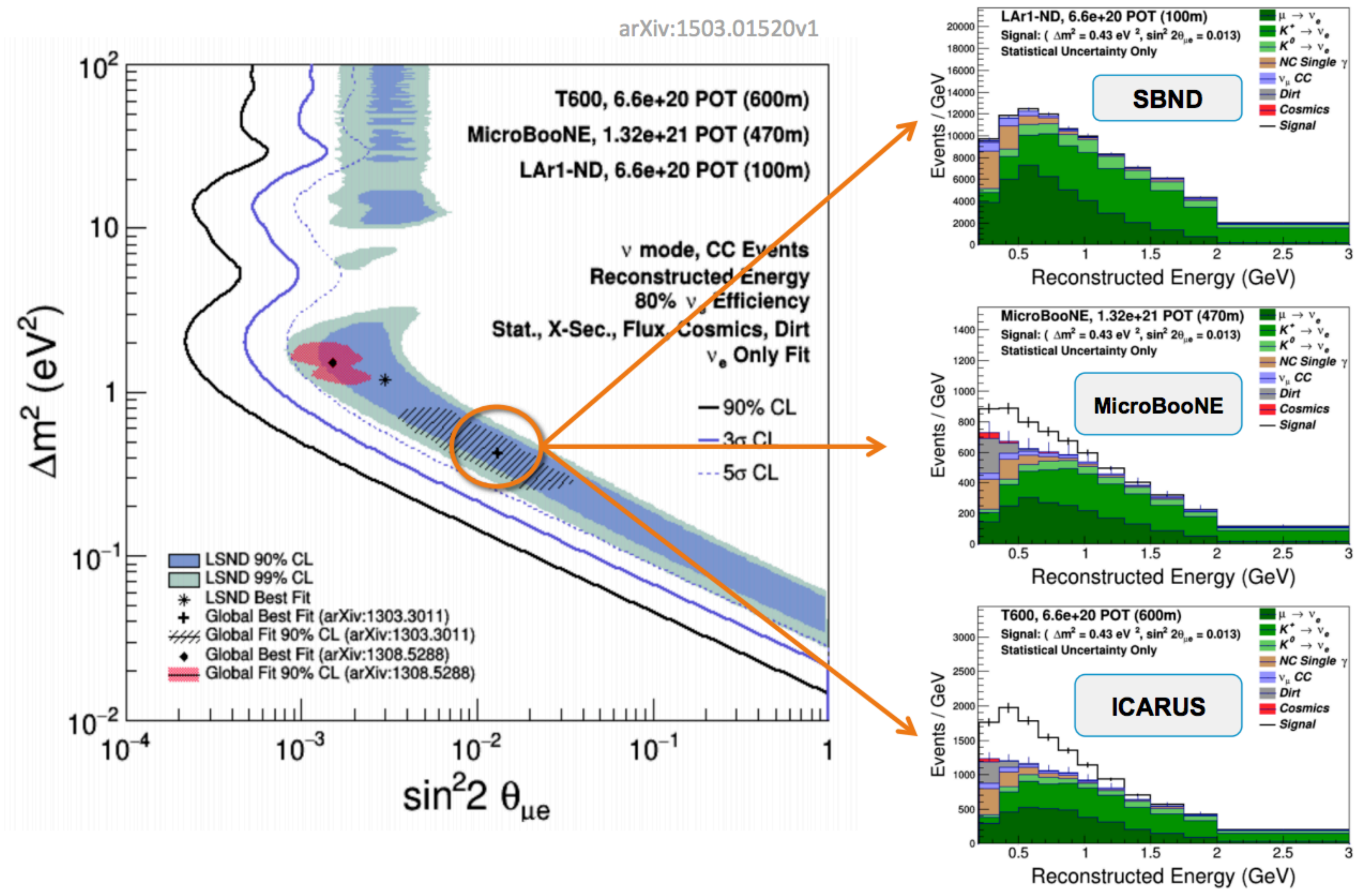






$$\sin^2 2\theta_{\mu e} \sim \tfrac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

SBN: Future search for sterile neutrinos



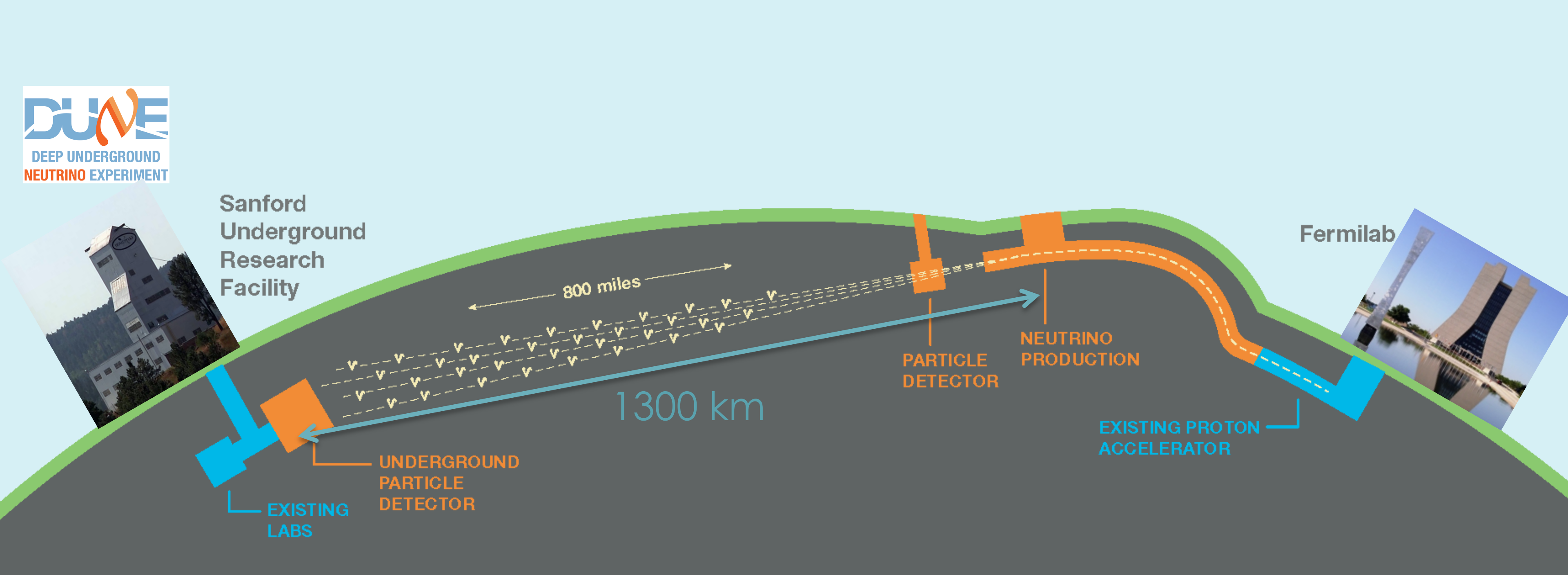
DUNE: Deep Underground Neutrino Experiment

DUNE aims to complete the three-neutrino picture:
Discover CP violation + neutrino mass hierarcy

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

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

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

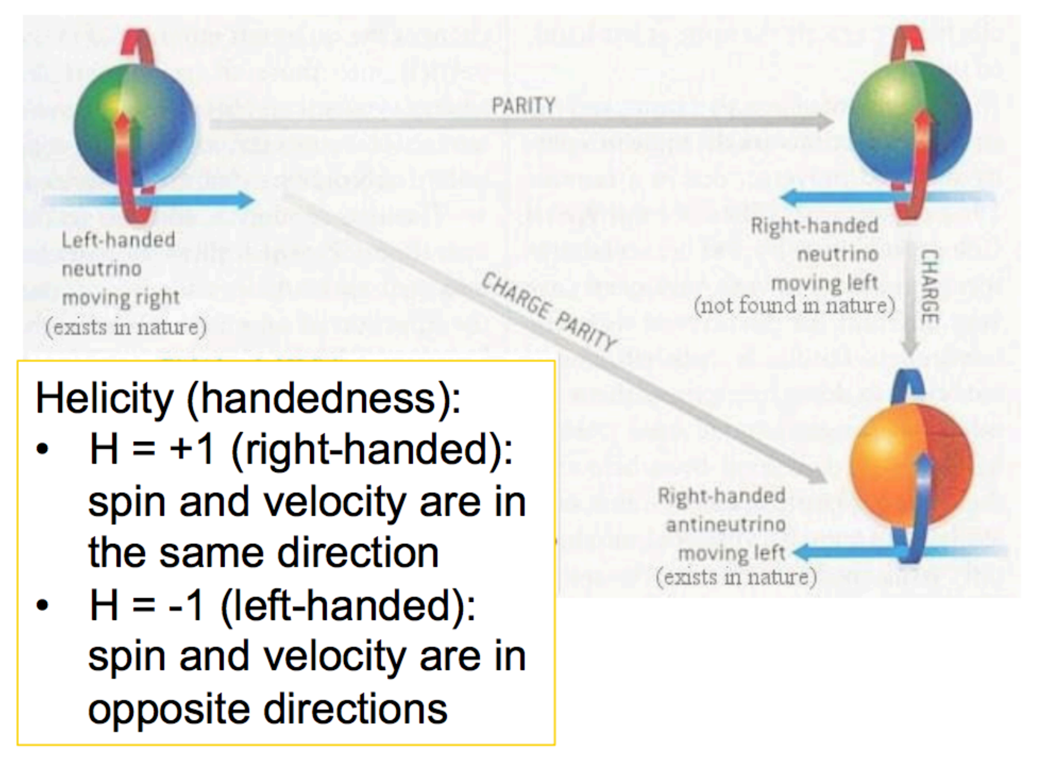


CP violation

- Three discrete symmetries:
  - C: charge conjugation particle ←→ antiparticle
  - P: parity inversion (x,y,z) ←→ (-x,-y,-z)
  - T: time reversal t ←→ -t
- Discovery of P violation in weak interactions in a957 by Wu et al.
- CP violation in weak interactions found in 1964 by Christenson, et al.
  - Existence of CP violation in K 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



Helicity (handedness):
- H = +1 (right-handed): spin and velocity are in the same direction
- H = -1 (left-handed): spin and velocity are in opposite directions

CP: left-handed neutrino to right-handed antineutrino

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

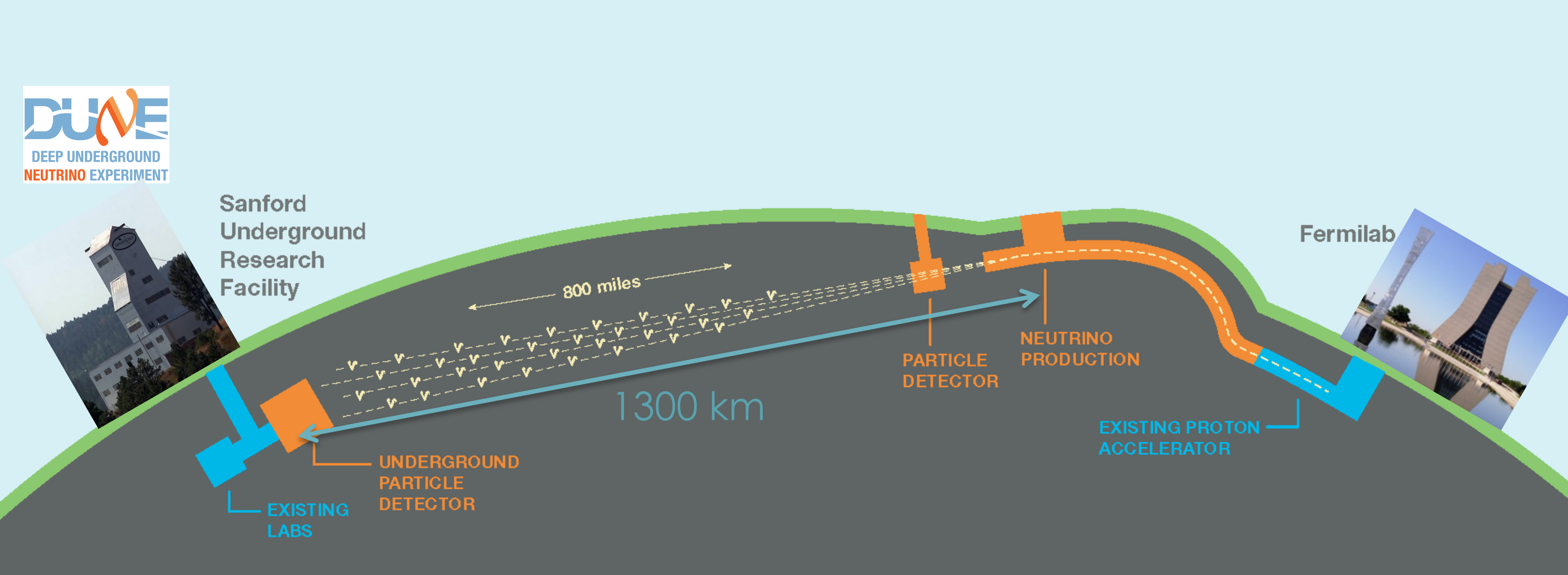
DUNE: Future search for CP violation

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

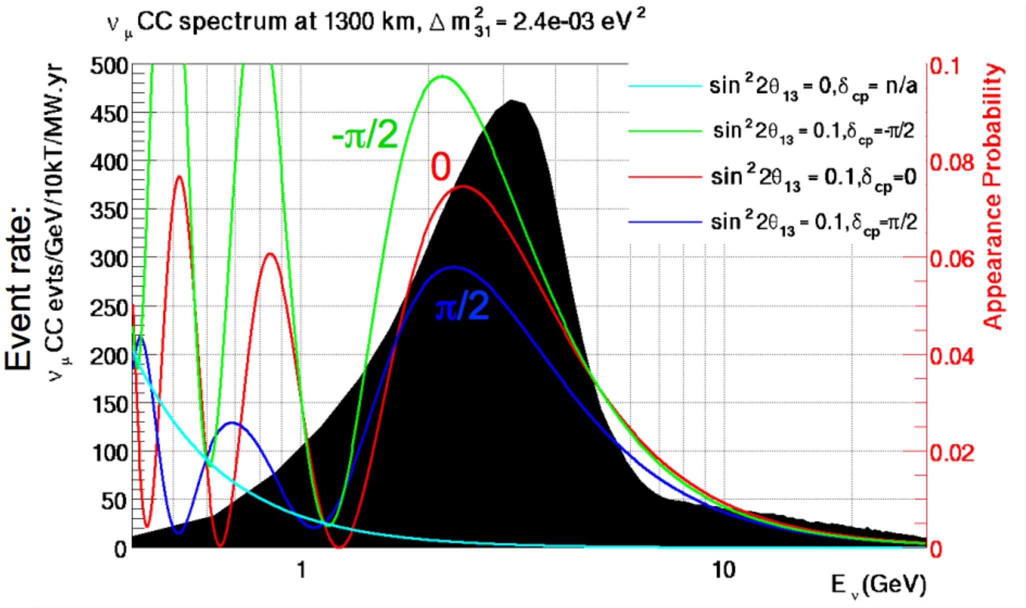


CP violation at long baselines

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

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

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



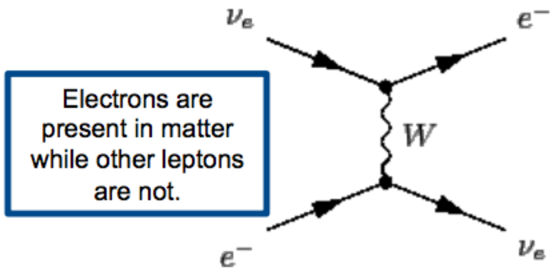
- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

[L. Worcester]

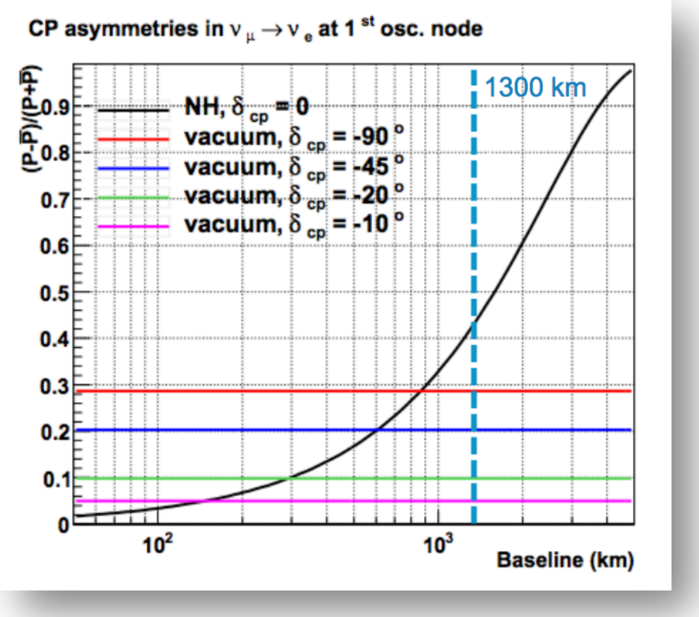
CP violation at long baselines

- **Matter (earth) is flavor-asymmetric**: electrons and no muons or tau!

Charged-current coherent forward scattering on electrons:



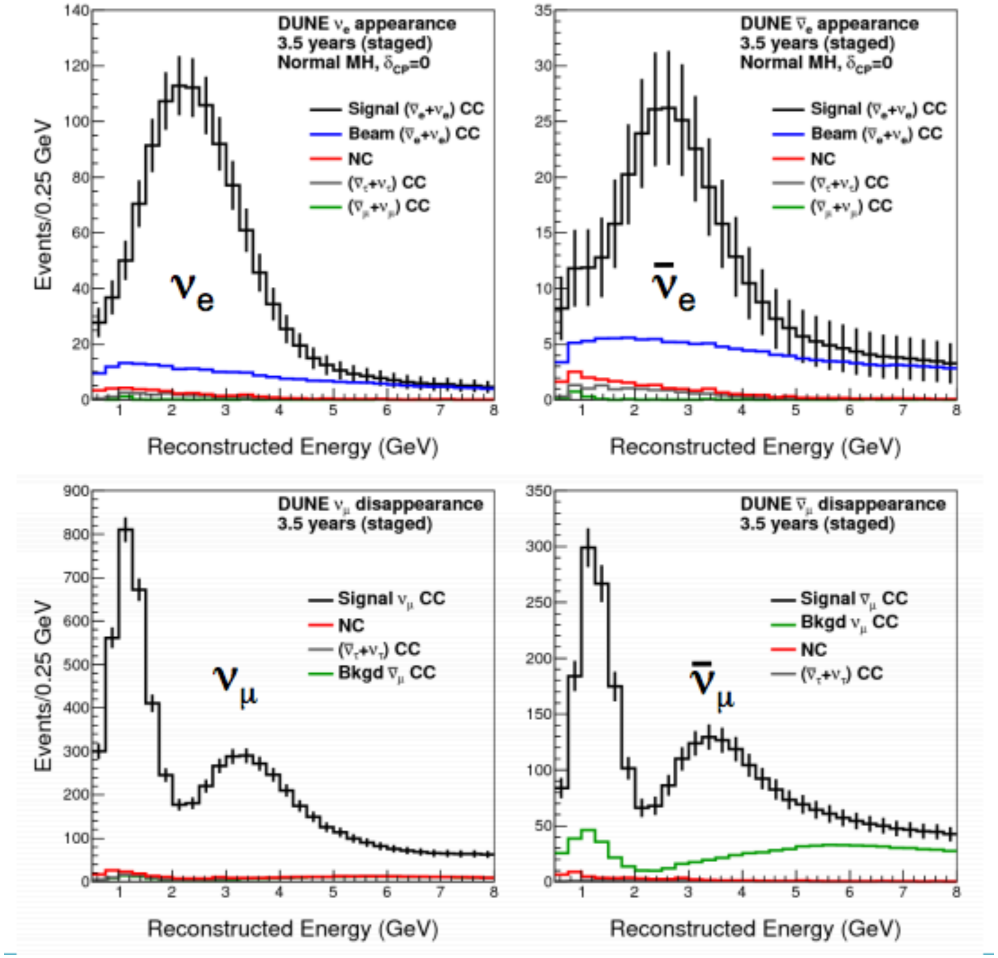
Electrons are present in matter while other leptons are not.



- CC process occurs for electron neutrinos only. Muon and tau neutrinos only have NC interactions with electrons.
- Effective “matter potential” experienced only by electron neutrinos **enhances appearance probability for neutrinos** and suppresses it for antineutrinos (opposite for IH)

DUNE: Future search for CP violation

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148

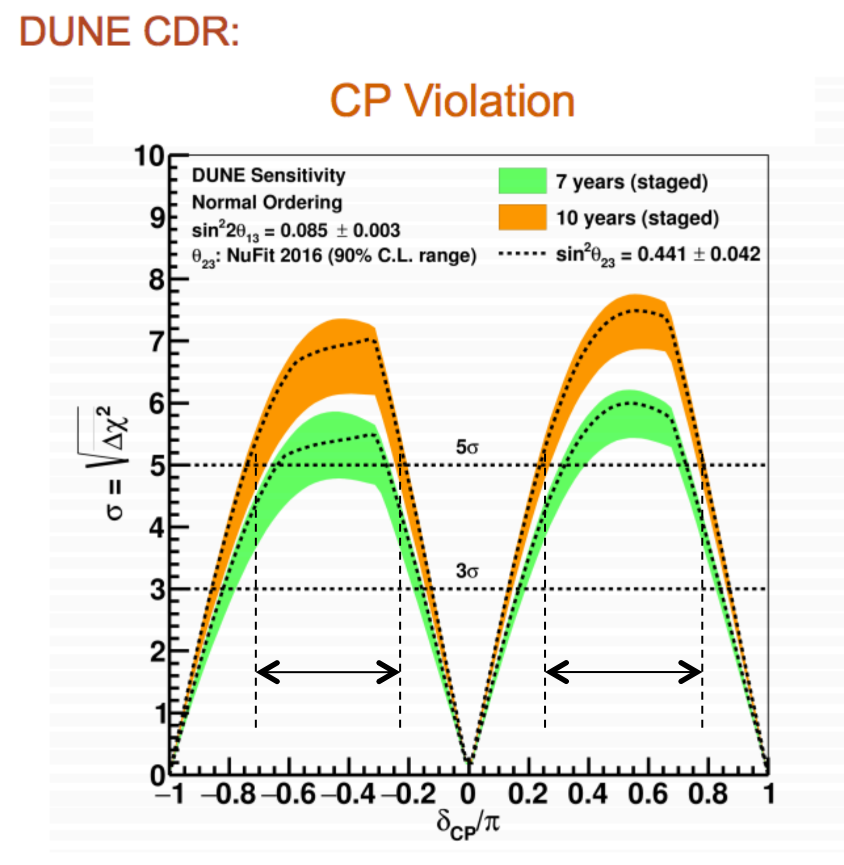


DUNE expects to measure ~1000 ν_e signal events in ~7 years of equal running in neutrino and antineutrino beam modes

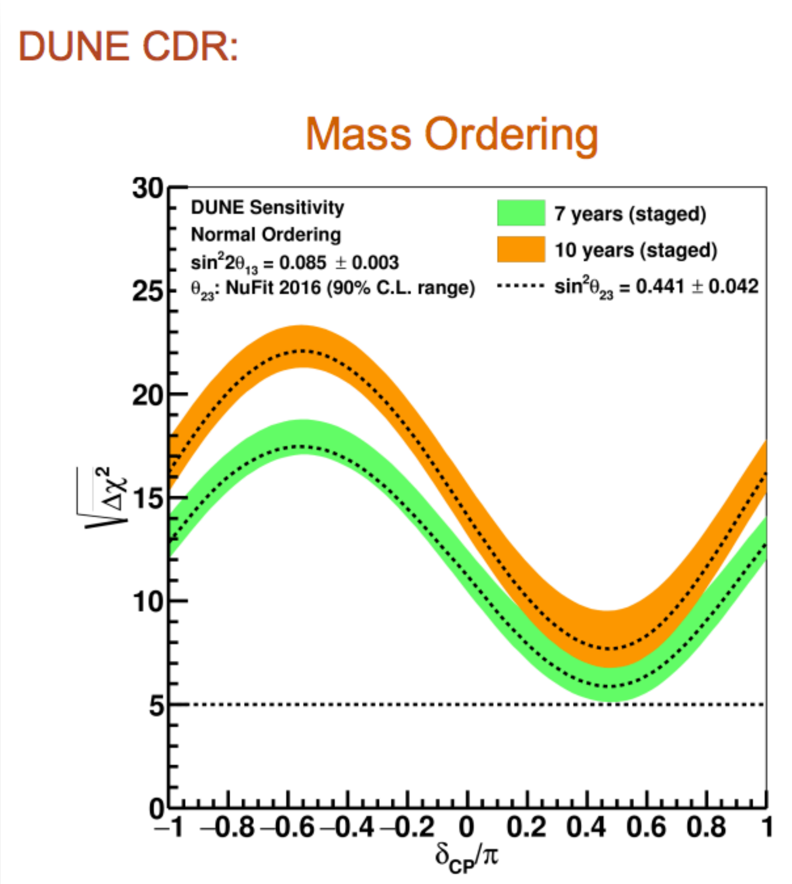
The DUNE near detector will provide constraints to systematic uncertainties

Will extract oscillation parameters by a simultaneous fit to all four spectra (neutrino, antineutrino, ν_e and ν_μ)

DUNE: Future search for CP violation


DUNE CDR:

CP Violation

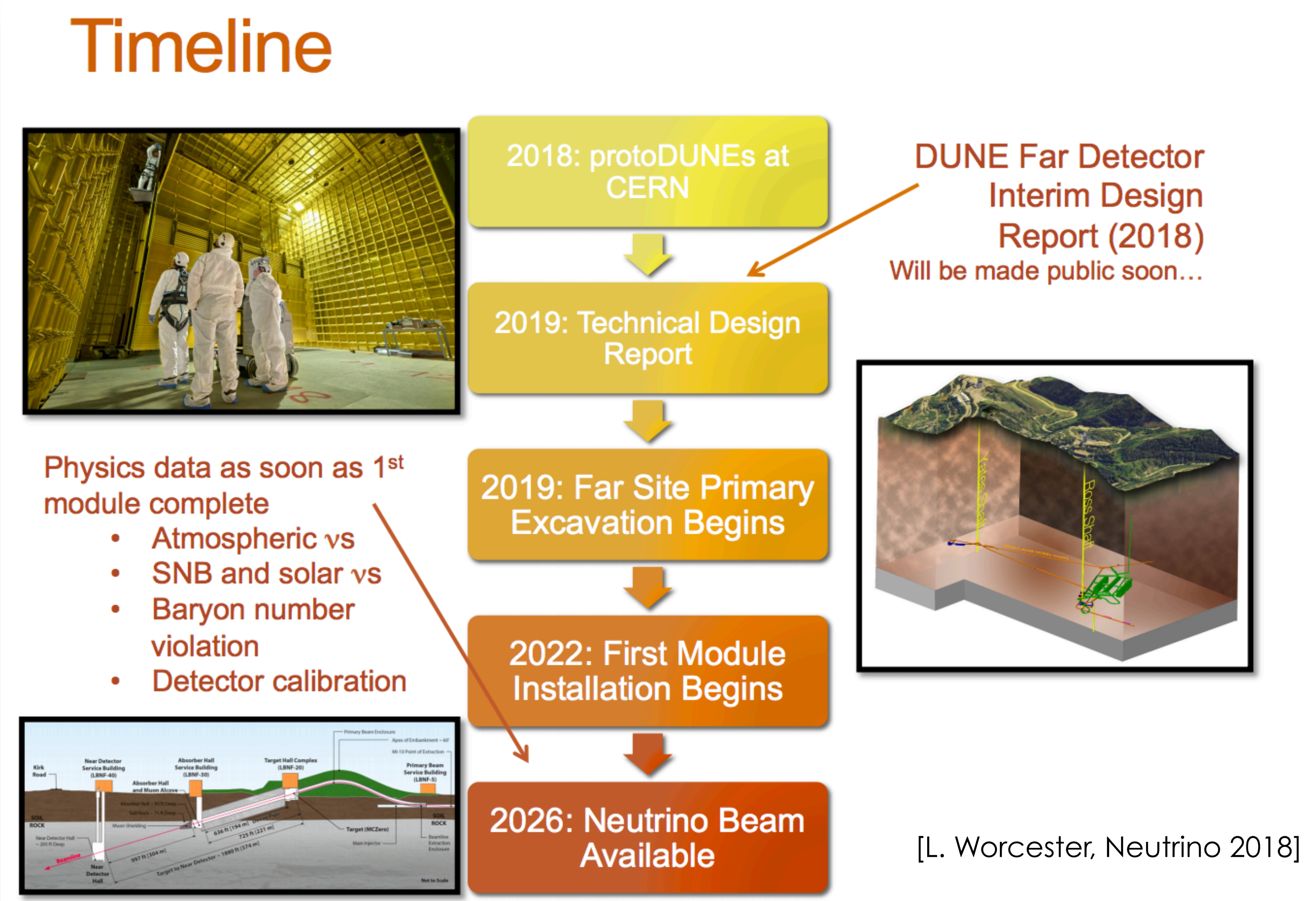

DUNE CDR:

Mass Ordering

Width of band indicates variation in possible central values of θ_{23}

DUNE sensitivity assuming normal ordering:
5σ discovery for a wide range of δ_{CP} values
5σ discovery of mass hierarchy

DUNE: Future search for CP violation



Timeline

2018: protoDUNEs at CERN

2019: Technical Design Report

2019: Far Site Primary Excavation Begins

2022: First Module Installation Begins

2026: Neutrino Beam Available

DUNE Far Detector Interim Design Report (2018)
Will be made public soon…

Physics data as soon as 1st module complete

- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration

[L. Worcester, Neutrino 2018]

Summary

Now: Long-baseline Reactor, Super-K, IceCube, MicroBooNE, T2K, Nova, SoLid,DANSS, NEOS, STEREO

Near Future: SBND, ICARUS, PROSPECT

Future: Hyper-K, DUNE, IsoDAR?, …

A wonderful playground for neutrino physics and more!

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!