Sterile Neutrinos, and the Consequences

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Happy Major Birthday,
Marek Zrałek!

Best wishes for many happy and fruitful years to come.

Sterile Neutrino

One that does not couple to the Standard Model (SM) W or Z boson

A "sterile" neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

There could be sterile neutrinos at any mass scale.

The most straightforward version of ***Leptogenesis***, an outgrowth of the See-Saw mechanism, explains the baryon asymmetry of the universe in terms of the early-universe decays of heavy sterile neutrinos ***N*** with

$$M_N \gtrsim 10^{(9-10)}\ \text{GeV}.$$

Are there MeV-scale sterile neutrinos?

MeV-scale sterile neutrinos *N* light enough to be produced in pion and kaon decays can be sought by looking for their decays, such as $N \longrightarrow \ell^{\mp}\pi^{\pm}$ and $N \longrightarrow \nu\gamma$.

(Ballett, Pascoli, Ross-Lonergan)

Are there keV-scale sterile neutrinos?

These are candidates for the Dark Matter. A possible 3.5 keV X-ray emission line could be from their EM decays.

(Dodelson, Widrow; Cappelluti et. al.)

Our Focus

Are there eV-scale sterile neutrinos?

Several anomalies in Short Baseline (SBL) experiments suggest that they may exist.

Should they be real, they will impact Long Baseline (LBL) experiments.

Neutrino Oscillation – Briefly

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

$$(W \rightarrow e\,\nu_e \text{ or } \mu\,\nu_\mu \text{ or } \tau\,\nu_\tau)$$

are superpositions of the mass eigenstates:

$$|\nu_\alpha> = \sum_i U^*_{\alpha i}\, |\nu_i> \quad .$$

Neutrino of flavor

α = e, μ, or τ

Neutrino of definite mass m_i

Leptonic Mixing Matrix

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta\right) =$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin^2\left(\overbrace{\Delta m_{ij}^2}^{m_i^2 - m_j^2}\frac{L}{4E}\right)$$

$$\underset{(-)}{+} 2\sum_{i>j}\mathrm{Im}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin\left(\Delta m_{ij}^2\frac{L}{2E}\right)$$

$P\left(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta\right) \neq P\left(\nu_\alpha \rightarrow \nu_\beta\right)$ would violate CP invariance.

In neutrino oscillation, CP non-invariance comes from phases in the leptonic mixing matrix U.

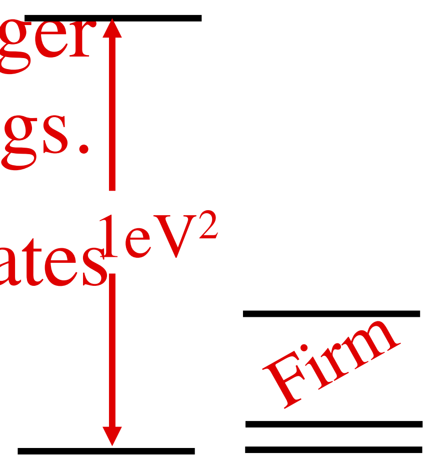
Note: Including $\hbar$ and c, $\Delta m_{ij}^2 \frac{L}{4E} = 1.27\,\Delta m_{ij}^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{m})}{E(\mathrm{MeV})}$

The Hints of eV-Mass Sterile Neutrinos

$$\text{Probability}(\text{Oscillation}) \propto \sin^2\left[1.27\Delta m^2\left(\text{eV}^2\right)\frac{L(\text{m})}{E(\text{MeV})}\right]$$

There are several hints of oscillation with $L(\text{m})/E(\text{MeV}) \sim 1$:

These $\Rightarrow$ a $\Delta m^2 \sim 1\ \text{eV}^2$, bigger than the two established splittings.



$\Rightarrow$ At least **4** mass eigenstates

$\Rightarrow$ At least **4** flavors

Then $$\frac{\Gamma\left(Z \to \nu\bar{\nu}\right)\Big|_{\text{Exp}}}{\Gamma\left(Z \to \text{One } \nu\bar{\nu} \text{ Flavor}\right)\Big|_{\text{SM}}} = 2.984 \pm 0.009$$

$\Rightarrow$ At least **1** sterile neutrino

The neutrino experiments point to one or more large Δm^2.

Only when the measured Z width is taken into account does a large Δm^2 point to a ***sterile*** neutrino.

No short-baseline (SBL) experiment has yet reported the direct observation of actual short-wavelength

oscillatory

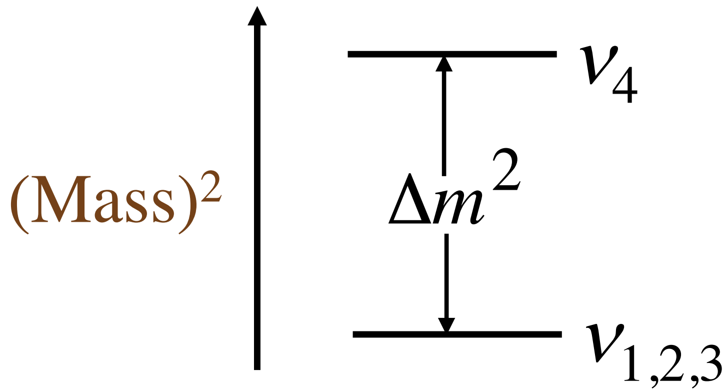
behavior.

The Hints of eV^2-Scale Δm^2

Experiment	Possible Oscillation	Comment
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Interesting
MiniBooNE	$\nu_\mu \rightarrow \nu_e$	Low energy excess?
		Not consistent with LSND (Carlo Giunti)
MiniBooNE	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Low energy excess?
Reactor Exps.	$\bar{\nu}_e \rightarrow \text{Not } \bar{\nu}_e$	Flux uncertain and time dependent (Daya Bay)
^{51}Cr and ^{37}Ar Source Exps.	$\nu_e \rightarrow \text{Not } \nu_e$	Detection efficiency?

Oscillation When There Are 4 Mass Eigenstates, But Only 1 Visible Splitting

Short-baseline experiments



Appearance

Travel distance

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_{\beta\neq\alpha}\right) = \underbrace{\sin^2 2\theta_{\alpha\beta}} \sin^2\left[1.27\,\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

Energy

Different parameters between 0 and 1

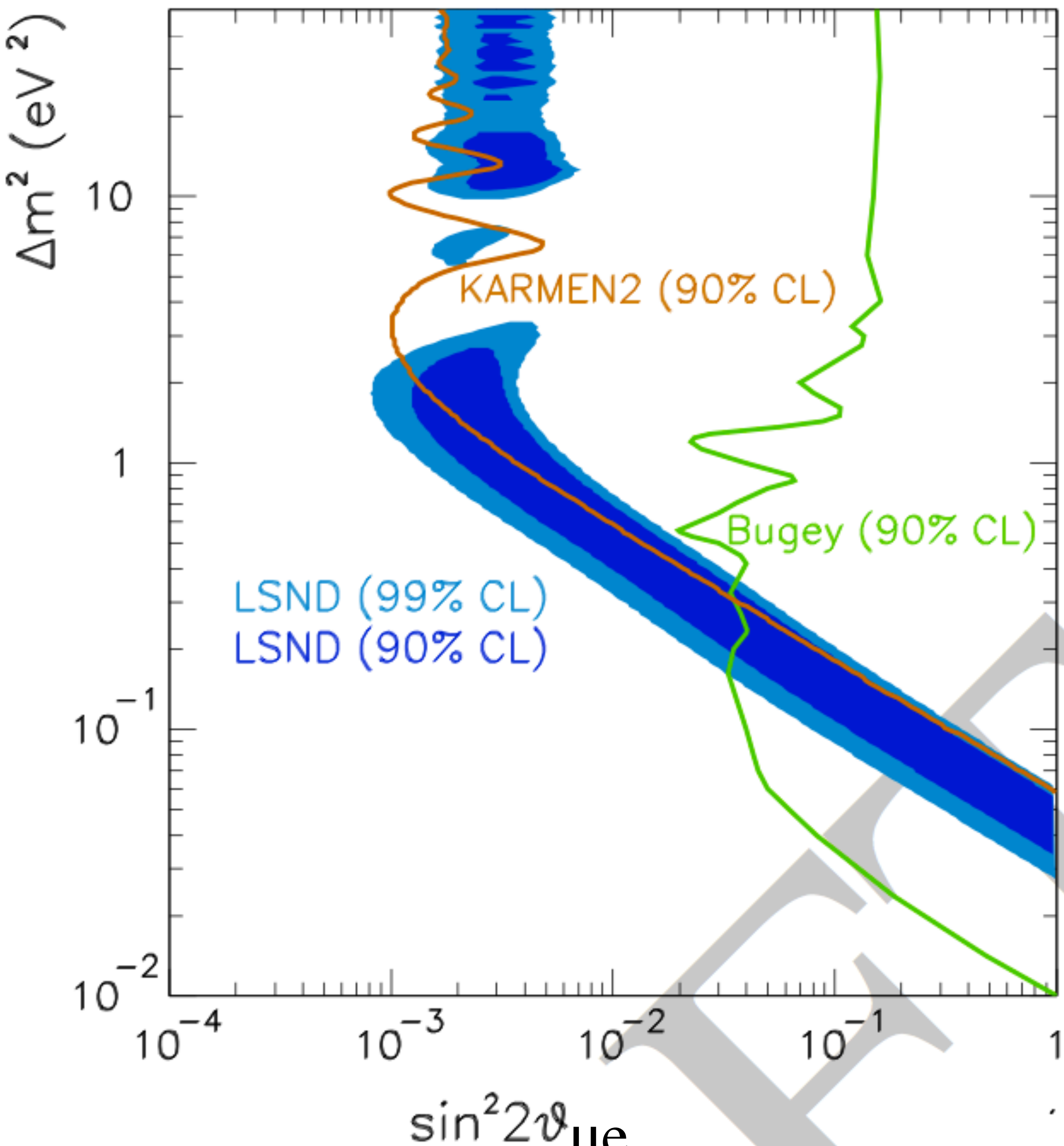
$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_{\cancel{\alpha}}\right) = \overbrace{\sin^2 2\theta_{\alpha\alpha}} \sin^2\left[1.27\,\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

Disappearance

The disappearance probability is the sum of the various possible appearance probabilities:

$$\sin^2 2\theta_{\alpha\alpha} = \sum_{All\ \beta\neq\alpha} \sin^2 2\theta_{\alpha\beta}$$

The region favored by LSND $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



The Hint From MiniBooNE

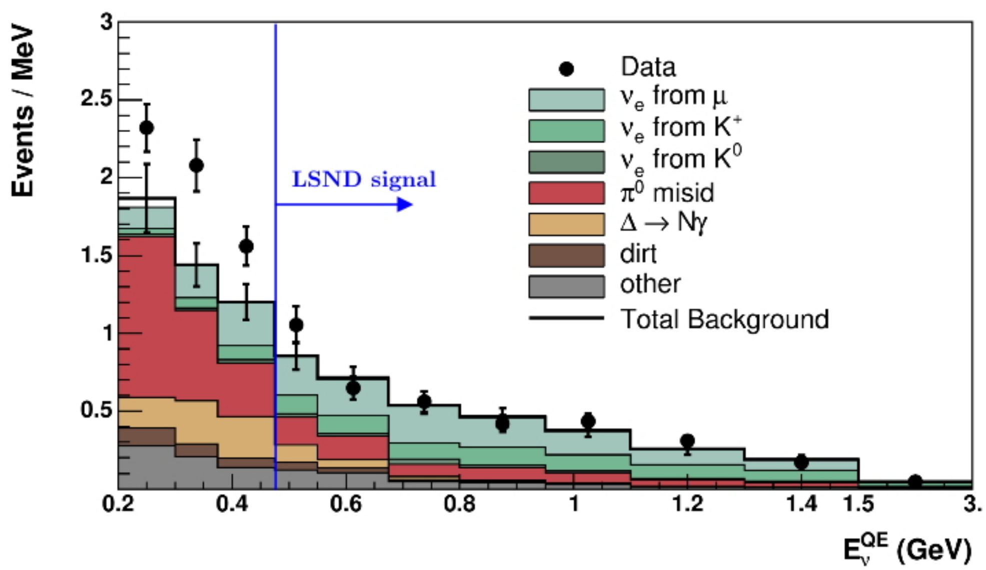
In MiniBooNE, both L and E were ~ 17 times larger than they were in LSND, but L/E was comparable.

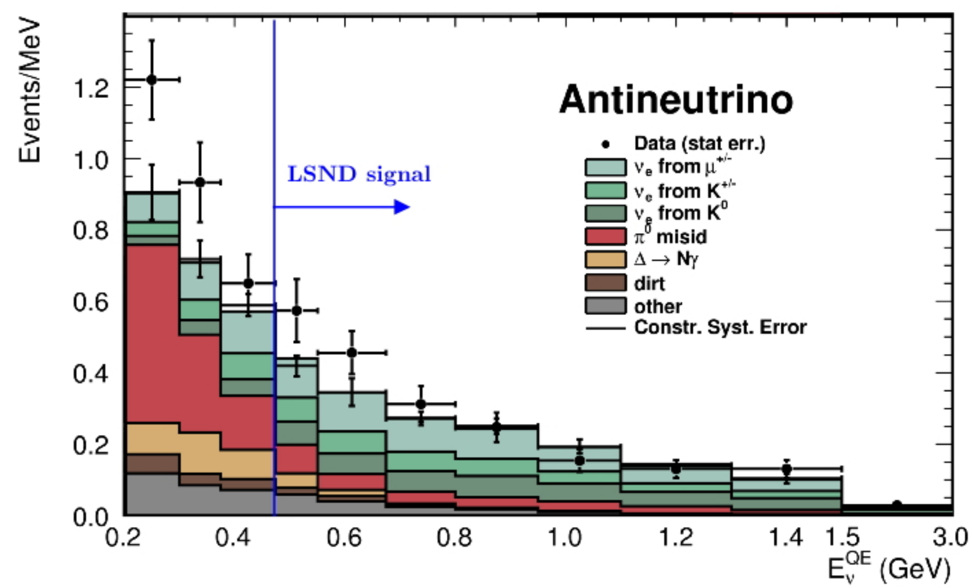
MiniBooNE reported both $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ results.

MiniBooNE

$L \simeq 541\,\mathrm{m}$ $\qquad$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802] $\qquad$ $\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]





- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with – other data?
- **Not the low *E* MB excess**
- Low-energy anomaly! $\Rightarrow$ MicroBooNE

The Hint From Reactors

The measured $\overline{\nu}_e$ flux at (10 – 100)m from reactor cores is ~ 6% below the theoretically expected value.

(Mention et al., Mueller et al., Huber)

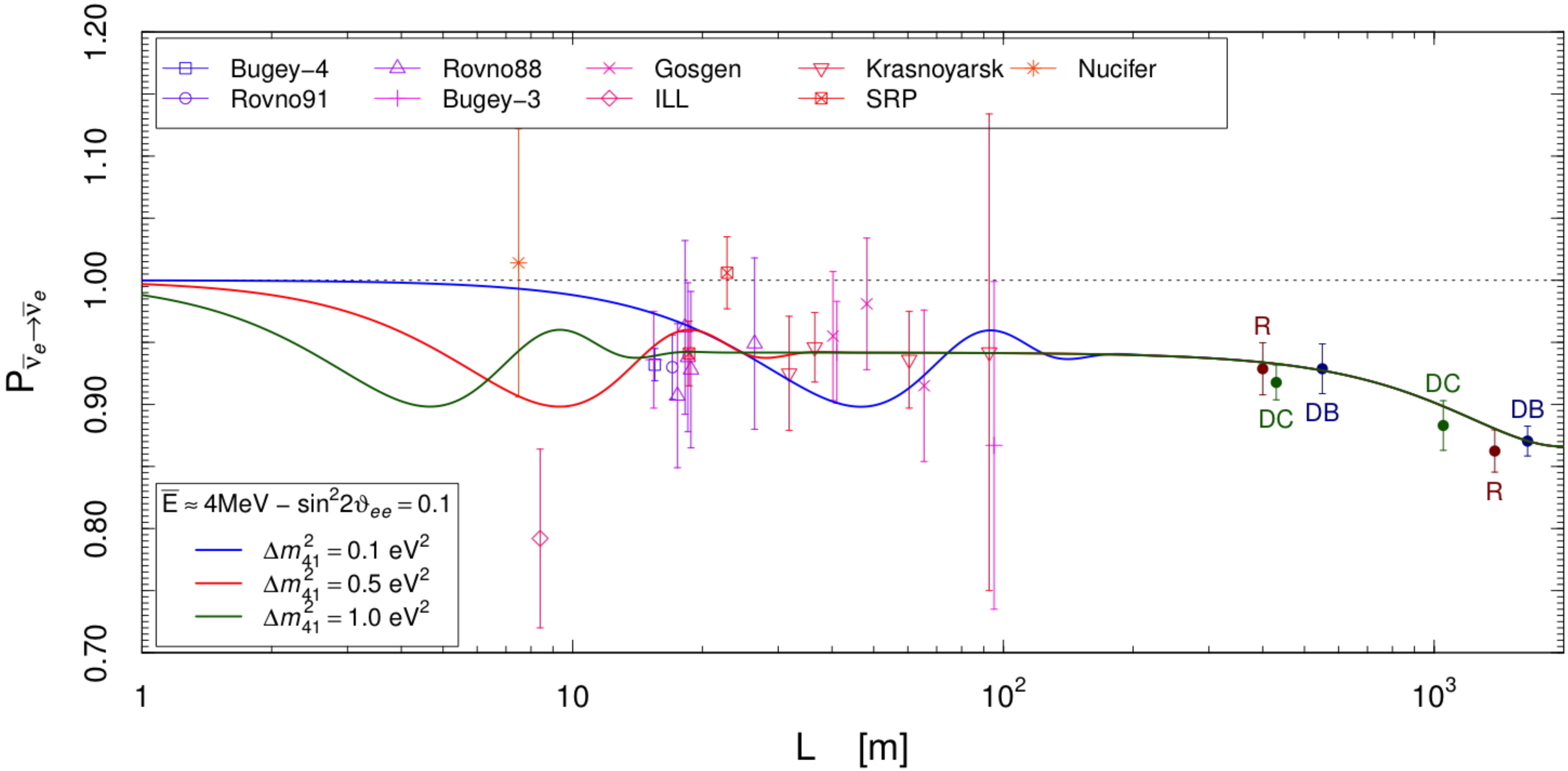
Are the $\overline{\nu}_e$ disappearing by oscillating into another flavor?

The $\overline{\nu}_e$ energy is ~ 3 MeV, so at, say, 15m,

$$L(\mathrm{m})/E(\mathrm{MeV}) = L(\mathrm{km})/E(\mathrm{GeV}) \sim 5.$$

If the $\overline{\nu}_e$ are oscillating away,

$$\sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right] \sim 1 \;\Longrightarrow\; \Delta m^2\left(eV^2\right) \sim 1\,.$$



(From Carlo Giunti)

(R = RENO, DC = Double Chooz, DB = Daya Bay)

The Hint From ^{51}Cr and ^{37}Ar Sources

These radioactive e – capture ν_e sources were used to test gallium solar ν_e detectors.

$$\frac{\text{Measured event rate}}{\text{Expected event rate}} = 0.84 \pm 0.05$$

(Giunti, Laveder)

Rapid disappearance of ν_e flux due to oscillation with a large Δm^2??

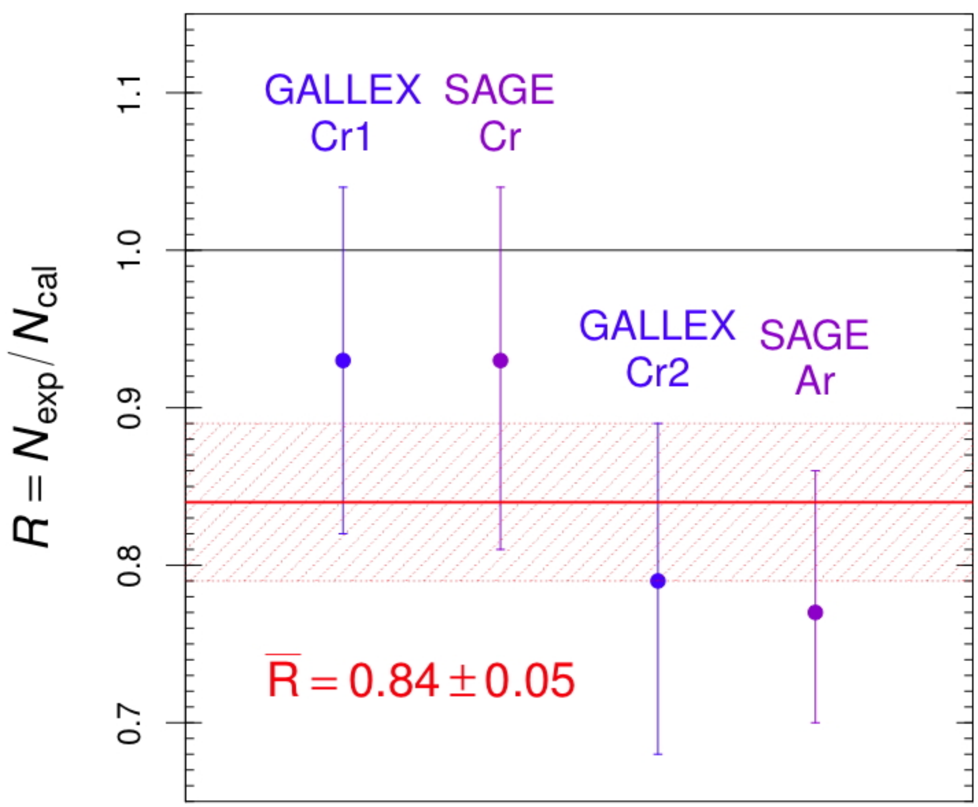
Gallium Anomaly

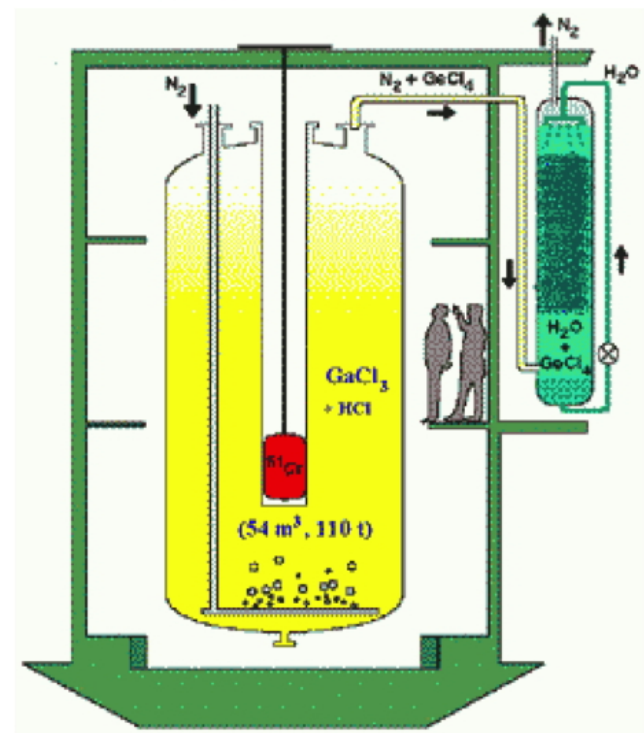
Gallium Radioactive Source Experiments: GALLEX and SAGE

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

$E \simeq 0.75\,\text{MeV}$ $\quad E \simeq 0.81\,\text{MeV}$

Test of Solar ν_e Detection: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$





$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$ $\quad \langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

$\approx 2.9\sigma$ deficit

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

Disappearance with $E \sim 1$ MeV and $L \sim 1$m suggests oscillation with $\Delta m^2 \sim 1\text{eV}^2$.

But the radioactive sources were originally meant to ***calibrate*** the solar neutrino detectors.

So how do we know the detection efficiency of these detectors?

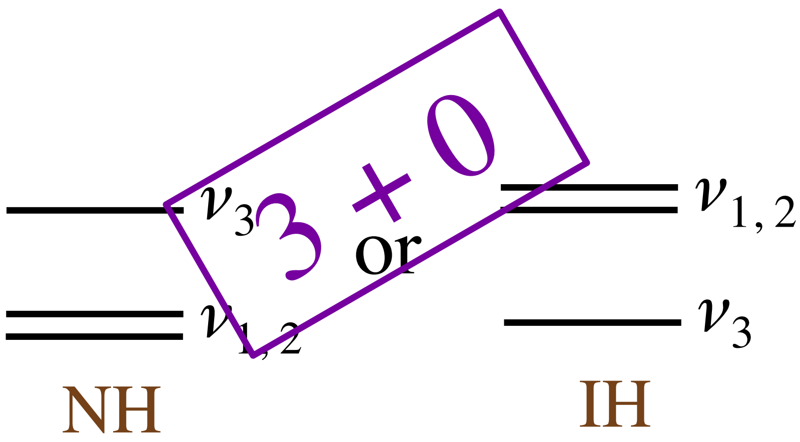
Tension Between Disappearance and Appearance

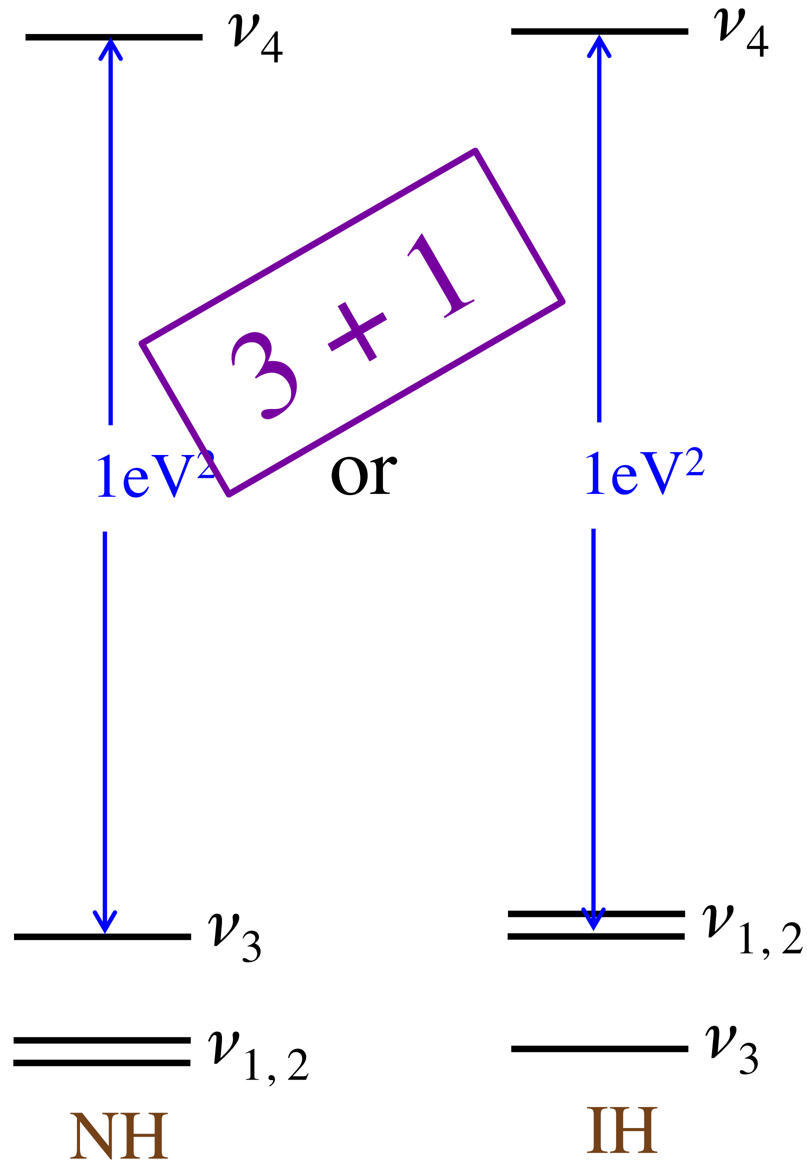
Neither $\nu_\mu \to \nu_e$ nor $\bar{\nu}_\mu \to \bar{\nu}_e$ can occur without both $\nu_\mu \left(\bar{\nu}_\mu\right)$ and $\nu_e \left(\bar{\nu}_e\right)$ **disappearance**.

(assuming CPT invariance)

To get a feeling for the quantitative connection between **appearance** and **disappearance**, let us continue to assume that there is just one extra mass eigenstate, ν_4, and correspondingly just one sterile flavor.

The Spectrum





The Mixing Matrix

$$U = \begin{array}{c} \\ \\ \end{array}\begin{array}{cccc} \nu_1 & \nu_2 & \nu_3 & \nu_4 \end{array}$$

$$U = \begin{array}{c|c} \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} & \begin{array}{c} e \\ \mu \\ \tau \\ s \end{array} \end{array}$$

$\boxed{\text{Presumably unitary}}$

The bounds on the various mixings between the sterile flavor and the active ones tell us that the elements $U_{\alpha 4}$ are small for $\alpha = e, \mu, \tau$, so that ν_4 is mostly sterile.

The Short-Baseline Oscillation Probabilities

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \sin^2 2\theta_{\mu e} \sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

$$P\left(\nu_\mu \rightarrow \nu_{\cancel{\mu}}\right) = \sin^2 2\theta_{\mu\mu} \sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

$$P\left(\nu_e \rightarrow \nu_{\cancel{e}}\right) = \sin^2 2\theta_{ee} \sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

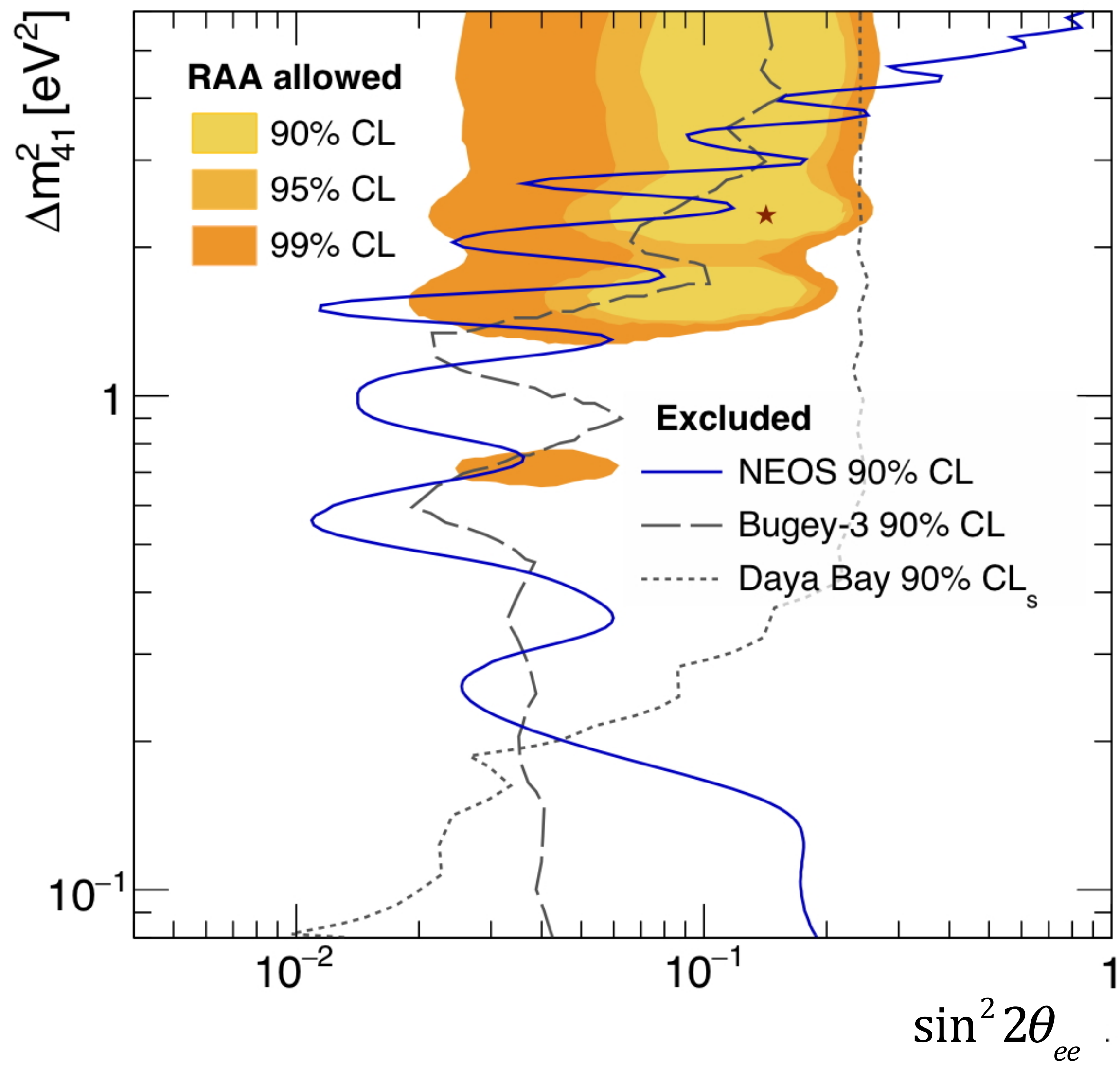
(The same expressions hold for antineutrinos. No ~~CP~~.)

For small $\left|U_{\mu 4}\right|^2$ and $\left|U_{e4}\right|^2$, experiments that average over the short-wavelength oscillations should find —

$$\boxed{P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_{\cancel{\mu}}\right) P\left(\bar{\nu}_e \rightarrow \bar{\nu}_{\cancel{e}}\right) \cong 2P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)}$$

Perhaps ν_e and $\overline{\nu}_e$ disappearance have been seen (the gallium and reactor anomalies).

However, not all searches for this disappearance report a signal.



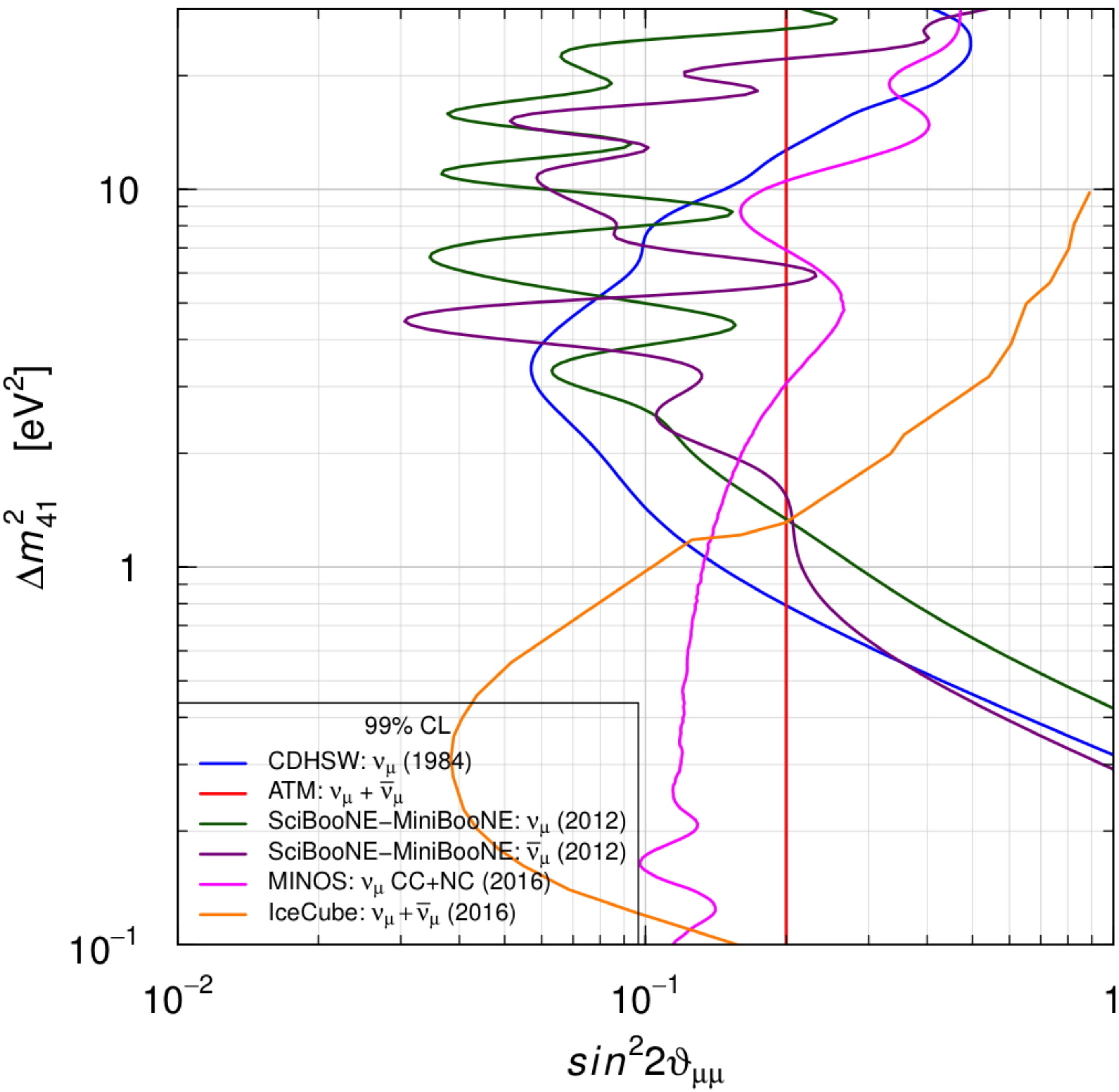
NEOS, Bugey-3, Daya Bay Reactor Experiments

ν_μ and $\overline{\nu}_\mu$ Disappearance Searches

No experiment has reported a signal of ν_μ or $\overline{\nu}_\mu$ disappearance.

There are only limits on the corresponding parameters.

ν_μ and $\bar{\nu}_\mu$ Disappearance



Attempting to fit all data, both appearance and disappearance, assuming 3+1 results in a poor goodness of fit of 0.019%, indicating strong tension between the appearance and the disappearance data.

Excluding the low-energy MiniBooNE excess allows a fit to all remaining data with a goodness of fit of 2.7%

(Gariazzo, Giunti, Laveder, Li)

Caution: We have at present no confirmed reason to exclude the low-energy MiniBooNE excess. But MicroBooNE is exploring the possibility that this excess is caused by photons, not electrons from electron neutrinos. MiniBooNE cannot distinguish between these possibilities.

Sterile Neutrinos and the Long-Baseline Experiments

Major goals of the long-baseline neutrino experiments

- ***Establish, or bound, CP violation in neutrino oscillation***
- ***Determine the neutrino mass hierarchy***

If the eV-scale sterile neutrinos hinted at by the short-baseline (SBL) anomalies are real, how is the pursuit of these goals at long-baseline affected?

Focus owing to familiarity on work by —

Gandhi, B. K., Masud, Prakash	1508.06275
Dutta, Gandhi, B. K., Masud, Prakash	1607.02152
Gandhi, B. K., Prakash, Roy	1708.01816

Related work —

Hollander, Mocioiu	1408.1749
Klop, Palazzo	1412.7524
Berryman, de Gouvêa, Kelly, Kobach	1507.03986
Agarwalla, Chatterjee, Dasgupta, Palazzo	1601.05995
Agarwalla, Chatterjee, Palazzo	1603.03759
Capozzi, Giunti, Laveder, Palazzo	1612.07764
Coloma, Forero, Parke	1707.05348

To get a feeling for the LBL consequences of extra, mostly sterile, neutrino mass eigenstates, we shall continue to assume that there is just 1 of them, ν_4.

This is the 3+1 model.

In the 3 + 1 model, the mixing matrix U^{3+1} is a 4 x 4 unitary matrix. It contains 6 mixing angles, and 3 oscillation-relevant CP-violating phases.

(When there are only 3 neutrinos, the mixing matrix is 3 x 3, and contains only 3 mixing angles and 1 oscillation-relevant CP-violating phase.)

Possible Effect of the Extra Degrees of Freedom

If there are more than 3 neutrino mass eigenstates, it is possible for CP to be violated in ***some*** oscillations, even if not violated in $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$.

The channel to be studied first

This is impossible when there are only 3 mass eigenstates.

The Freedom a 4th Flavor Gives to CP Violation

Let $P\left[\nu_\alpha \to \nu_\beta\right] - P\left[\bar{\nu}_\alpha \to \bar{\nu}_\beta\right] \equiv \Delta P_{\alpha\beta}$ be a CP-violating $\nu - \bar{\nu}$ difference in vacuum.

Assuming CPT invariance, $P\left[\nu_\beta \to \nu_\alpha\right] = P\left[\bar{\nu}_\alpha \to \bar{\nu}_\beta\right]$.

Then $\Delta P_{\beta\alpha} = -\Delta P_{\alpha\beta}$. In particular, $\Delta P_{\alpha\beta} = 0$ when $\beta = \alpha$.

Conservation of probability

$$\Rightarrow \sum_{\text{All }\beta} P\left(\nu_\alpha \to \nu_\beta\right) = \sum_{\text{All }\beta} P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right) = 1 .$$

Then $\boxed{\sum_{\text{All }\beta} \Delta P_{\alpha\beta} = \sum_{\beta \neq \alpha} \Delta P_{\alpha\beta} = 0}$.

When there are only 3 neutrino flavors, there are only 3 independent (potentially) nonzero CP-violating differences $\Delta P_{\alpha\beta}$ to be measured: $\Delta P_{e\mu}$, $\Delta P_{\mu\tau}$, and $\Delta P_{\tau e}$.

$$\sum_{\beta\neq\alpha} \Delta P_{\alpha\beta} = 0 \quad \Rightarrow$$

$$\Delta P_{e\mu} + \Delta P_{e\tau} = 0 \quad \text{and} \quad \Delta P_{\mu e} + \Delta P_{\mu\tau} = 0 \; .$$

Then $\boxed{\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e}}$.

If CP is not violated in $\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}$, then it is not violated in ***any*** oscillation channel.

When there are 4 neutrino flavors, assuming CPT invariance, there are 6 independent (potentially) nonzero CP-violating differences $\Delta P_{\alpha\beta}$:

$\Delta P_{e\mu}$, $\Delta P_{\mu\tau}$, $\Delta P_{\tau e}$, ΔP_{es}, $\Delta P_{\mu s}$, and $\Delta P_{\tau s}$.

Sterile flavor

Now $\sum_{\beta \neq \alpha} \Delta P_{\alpha\beta} = 0$ only implies such relations as —

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} + \Delta P_{\mu s}$$

The CP-violating differences $\Delta P_{\alpha\beta}$ in different active-to-active oscillation channels are no longer required to be equal.

DUNE (L = 1300 km) As An Illustration Of Possible Impacts On LBL Experiments

We consider the processes DUNE will compare to seek CP violation: $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$.

Can we tell whether CP is violated or not? That is, whether CP violation in $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ is substantial or at most very small?

To explore this question, we look at the ***asymmetry***

$$A(\nu - \bar{\nu}) \equiv \frac{\left[P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)\right]}{\left[P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)\right]}$$

We write the 4 x 4 mixing matrix U^{3+1} in the form —

$$U^{3+1} = \underbrace{O(\theta_{34},\delta_{34})O(\theta_{24},\delta_{24})O(\theta_{14})}_{\text{Sterile-active mixing}}\underbrace{O(\theta_{23})O(\theta_{13},\delta_{13})O(\theta_{12})}_{3+0}$$

Here, $O(\theta_{34},\delta_{34})$ is a 2-dimensional rotation in the 34 subspace through an angle θ_{34}, and with a phase δ_{34}.

The new mixing angles are taken to be in the ranges —

$$0° \leq \theta_{14} \leq 20°, \quad 0° \leq \theta_{24} \leq 10°, \quad 0° \leq \theta_{34} \leq 30°$$

(Disappearance constraints from Kopp, Machado, Maltoni, and Schwetz)

{We update, tighten the constraints later.}

$$O\left(\theta_{34}, \delta_{34}\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \mathrm{c}_{34} & \mathrm{s}_{34} e^{-i\delta_{34}} \\ 0 & 0 & -\mathrm{s}_{34} e^{i\delta_{34}} & \mathrm{c}_{34} \end{bmatrix},$$

where $\mathrm{c}_{34} \equiv \cos\theta_{34}$, $\mathrm{s}_{34} \equiv \sin\theta_{34}$.

We vary the CP-violating phases
δ_{13}, δ_{24}, and δ_{34} from $-\pi$ to $+\pi$.

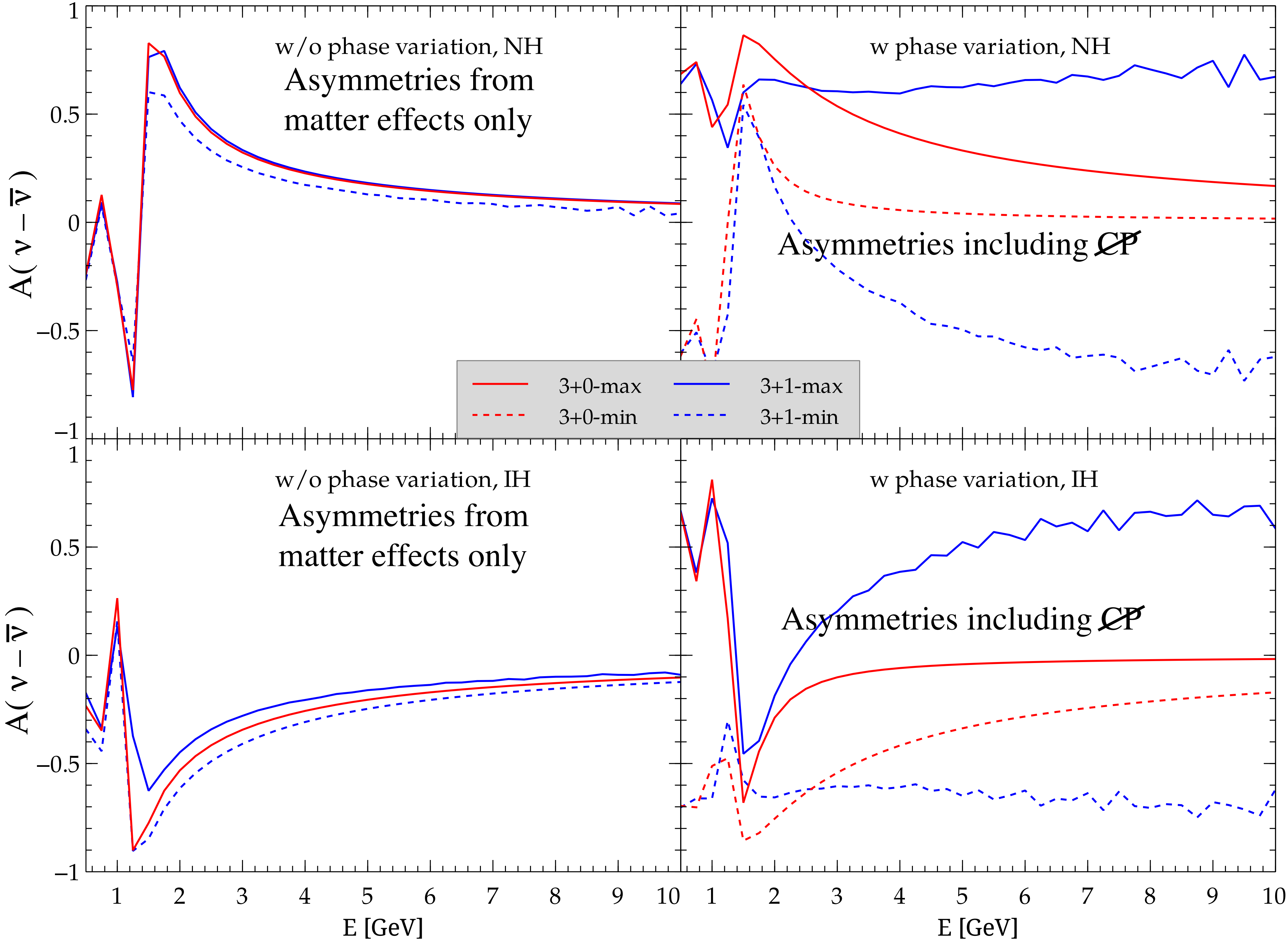
We take the "established" parameters to be —

$$\left|\Delta m^2_{31}\right| \cong 2.4\times10^{-3}\,\mathrm{eV}^2 \qquad \Delta m^2_{21} = 7.5\times10^{-5}\,\mathrm{eV}^2$$

$$\theta_{12} = 33.5^\circ,\ \theta_{13} = 8.5^\circ,\ \theta_{23} = 45^\circ$$

(Guided by Gonzalez-Garcia, Maltoni, and Schwetz)

For purposes of illustration, we take $\Delta m^2_{41} = 1\,\mathrm{eV}^2$.



w/o phase variation, NH
Asymmetries from matter effects only
w phase variation, NH
Asymmetries including $\cancel{CP}$
w/o phase variation, IH
Asymmetries from matter effects only
w phase variation, IH
Asymmetries including $\cancel{CP}$
3+0-max
3+0-min
3+1-max
3+1-min
$A(\nu - \overline{\nu})$
E [GeV]

When there is ***no*** ~~CP~~, the (matter-induced) asymmetries in 3+0 and 3+1 are quite similar.

But when there ***is*** ~~CP~~, the asymmetries in 3+0 and 3+1 can be quite different.

Why is the difference between 3+0 and 3+1 potentially quite large?

$\cancel{CP}$ phases cause $\cancel{CP}$ through ***interference*** terms
in the oscillation amplitude.

In 3+0, there is only one interference term. In 3+1, there is an additional one. At the *L*/*E* where the LBL experiments work, the two interference terms now present can easily be comparable in size.

Then if the phases are right,
3+1 can be quite different from 3+0.

(Klop and Palazzo)

The DUNE Sensitivity to CP Violation

The tightened mixing angles are taken to be in the ranges —

$$0^\circ \le \theta_{14} \le 13^\circ , \quad 0^\circ \le \theta_{24} \le 7^\circ , \quad 0^\circ \le \theta_{34} \le 26^\circ$$

(Constraints from Daya Bay, IceCube, and MINOS)

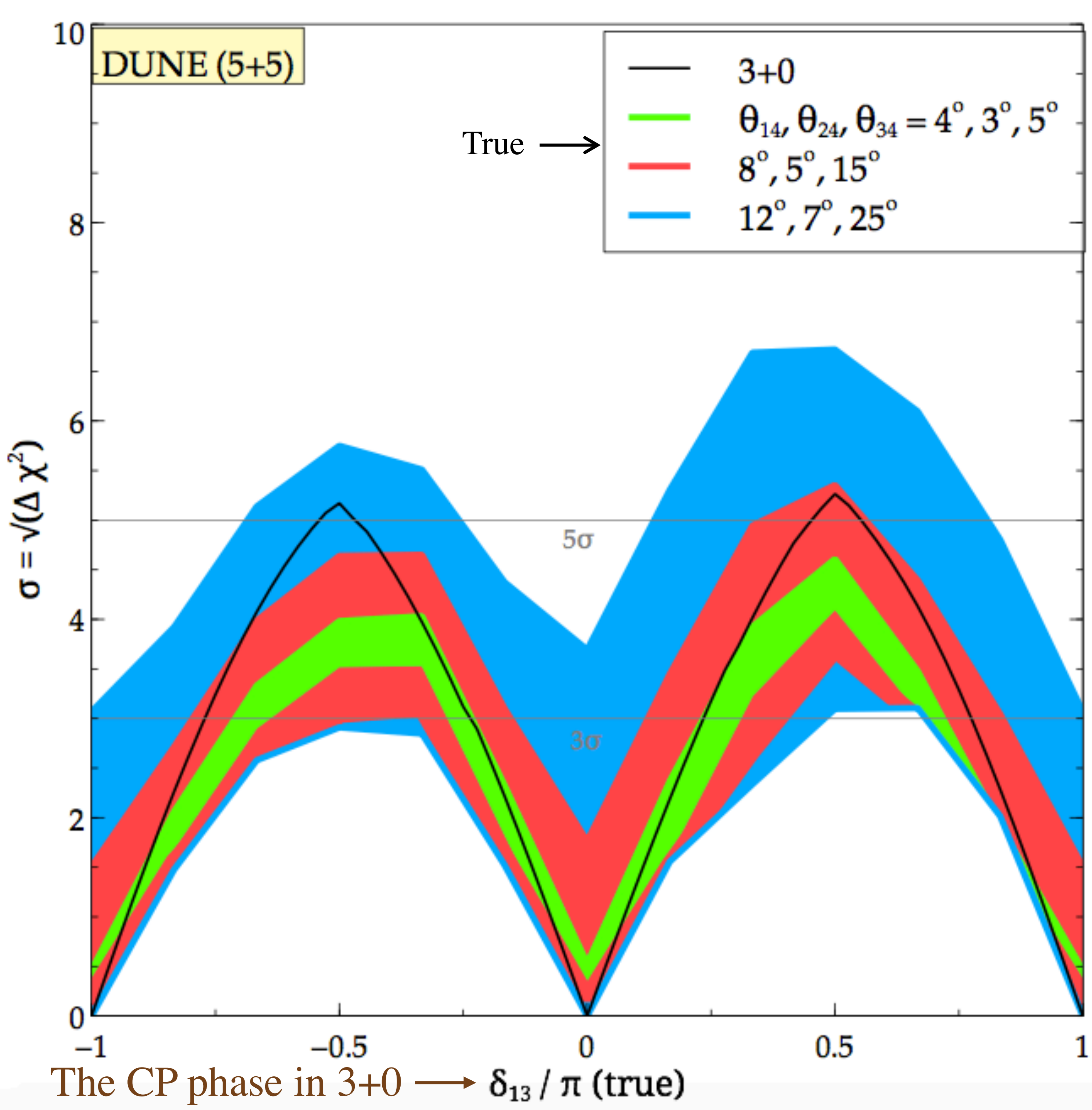
We use the **General Long Baseline Experiment Simulator GLoBES** to generate simulated long-baseline event rates.

We assume a 35 x 10^{22} kton-POT-yr total exposure, divided evenly between neutrinos and antineutrinos, a 5% signal normalization error, and other features of the experiment from Bass et al., 1311.0212.

DUNE sensitivity to ~~CP~~

Mass hierachy assumed known to be normal.

θ_{14}, θ_{24}, θ_{34} assumed unknown.

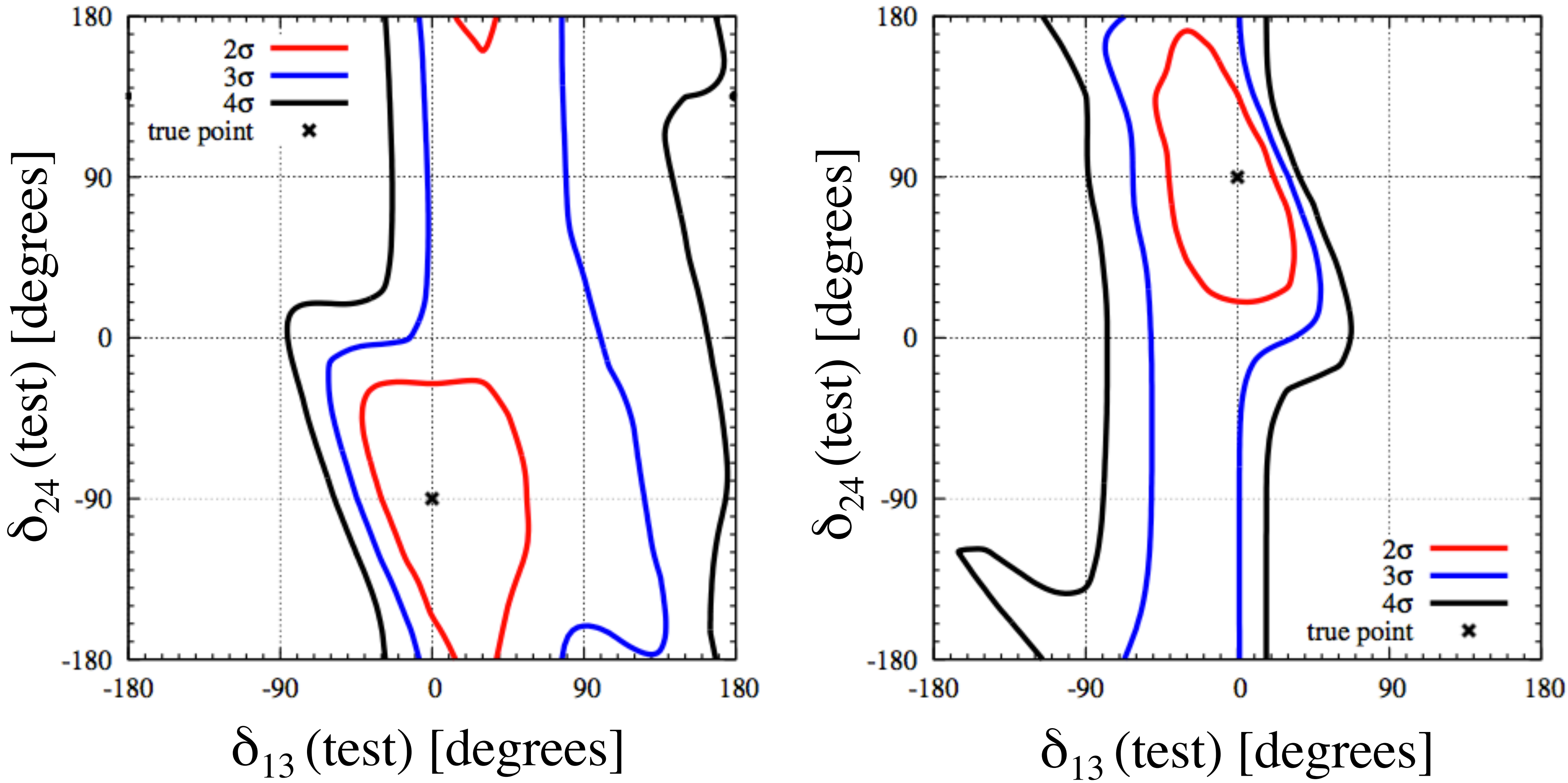


When the true sterile-active mixing angles are nonzero but small, the ability to establish $\cancel{CP}$ is reduced, because one has more unknown parameters with which to fit any data.

When the true sterile-active mixing angles are larger, the extra $\cancel{CP}$ phases can lead to more $\cancel{CP}$, and hence more ability to establish $\cancel{CP}$.

In 3+1, there can be $\cancel{CP}$ even when the 3+0 phase $\delta_{13} = 0$.

DUNE May Not Be Able To Tell Which Phase(s) Cause An Observed ~~CP~~



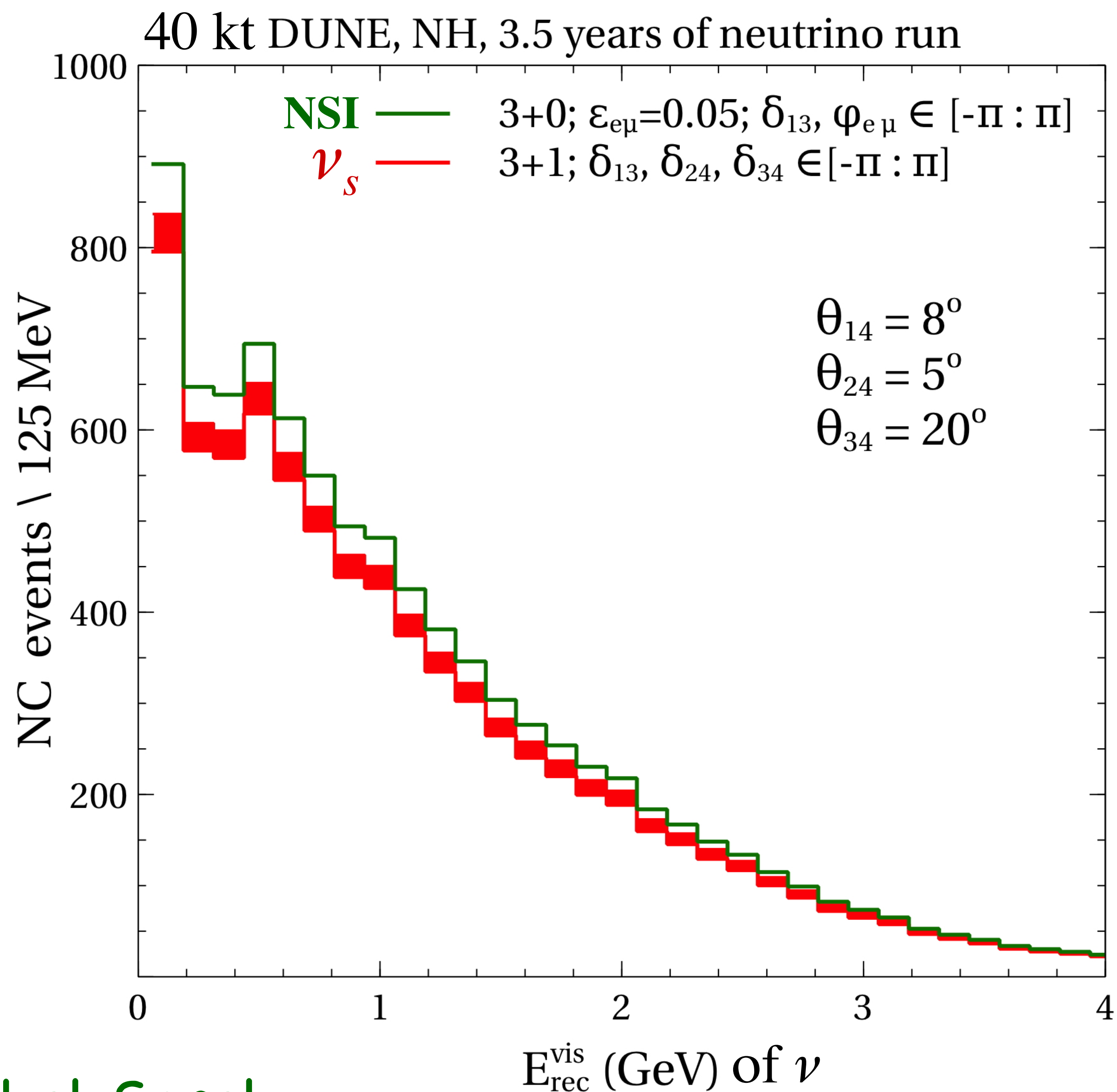
True $(\theta_{14}, \theta_{24}, \theta_{34}, \delta_{34}) = (12^o, 7^o, 25^o, 0^o)$

What Neutral Current Measurements Can Reveal

The SM Z boson couples identically to the three active neutrino flavors, ν_e , ν_μ , and ν_τ , but does not couple to sterile neutrinos.

Neutral-current (NC) neutrino event rates, driven by Z exchange, ***will be reduced*** if some of an initially active neutrino flux oscillates into a sterile flavor.

However, ***there will be no reduction or oscillation*** of the NC event rate if there are only the three active flavors, even if the neutrinos undergo non-SM interactions (NSI) during propagation.



NC in DUNE could distinguish between a sterile neutrino and NSI in propagation, at 90% CL.

Thanks to Michel Sorel

What SBL Neutral Current Measurements Can Reveal

If there is one extra, mostly-sterile, neutrino mass eigenstate, there may well be more than one.

If there are two extra neutrinos, visible CP violation ($\cancel{CP}$) can occur at SBL.

$$\cancel{CP} \text{ in } \nu_\mu \to \nu_e \text{ is} \propto \mathrm{Im}\left[U^*_{\mu 5} U_{\mu 4} U_{e5} U^*_{e4}\right]. \quad (U \text{ is } 5 \text{ x } 5)$$

$$\text{But } \cancel{CP} \text{ in NC event rates is} \propto \mathrm{Im}\left[U^*_{\mu 5} U_{\mu 4}\left(U_{s_1 5} U^*_{s_1 4} + U_{s_2 5} U^*_{s_2 4}\right)\right].$$

$\cancel{CP}$ in the NC rate probes different phases and a different sector of U than $\cancel{CP}$ in $\nu_\mu \to \nu_e$.

What Is Needed?

The existing hints of eV-scale sterile neutrinos are not convincing, and there is tension between appearance and disappearance data.

However, if the existence of sterile neutrinos were confirmed, that would be a very major discovery, suggesting New Physics beyond the neutrinos themselves.

In addition, if the eV-scale sterile neutrinos are real, the interpretation of LBL measurements could be significantly affected.

∴ It is important to either confirm the existence of the sterile neutrinos, or to rule them out at the level that could influence LBL experiments.

Numerous accelerator, reactor, and source experiments to probe the existence of eV-scale sterile neutrinos are either ongoing or proposed.

A convincing confirmation of their existence would be the observation of short-wavelength oscillatory *behavior.*

Assuming CPT invariance, a sufficiently tight upper limit on the disappearance of ν_μ, $\bar{\nu}_\mu$, ν_e, or $\bar{\nu}_e$ would exclude the reported $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance processes as well.

We await the future experimental results.