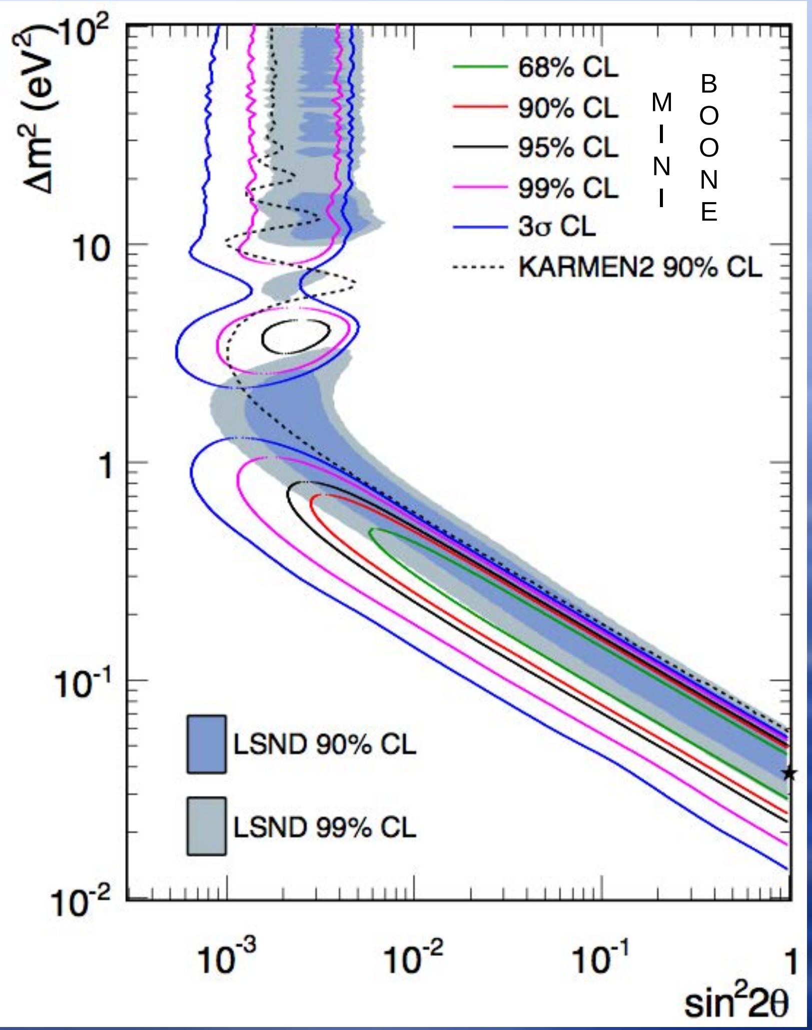
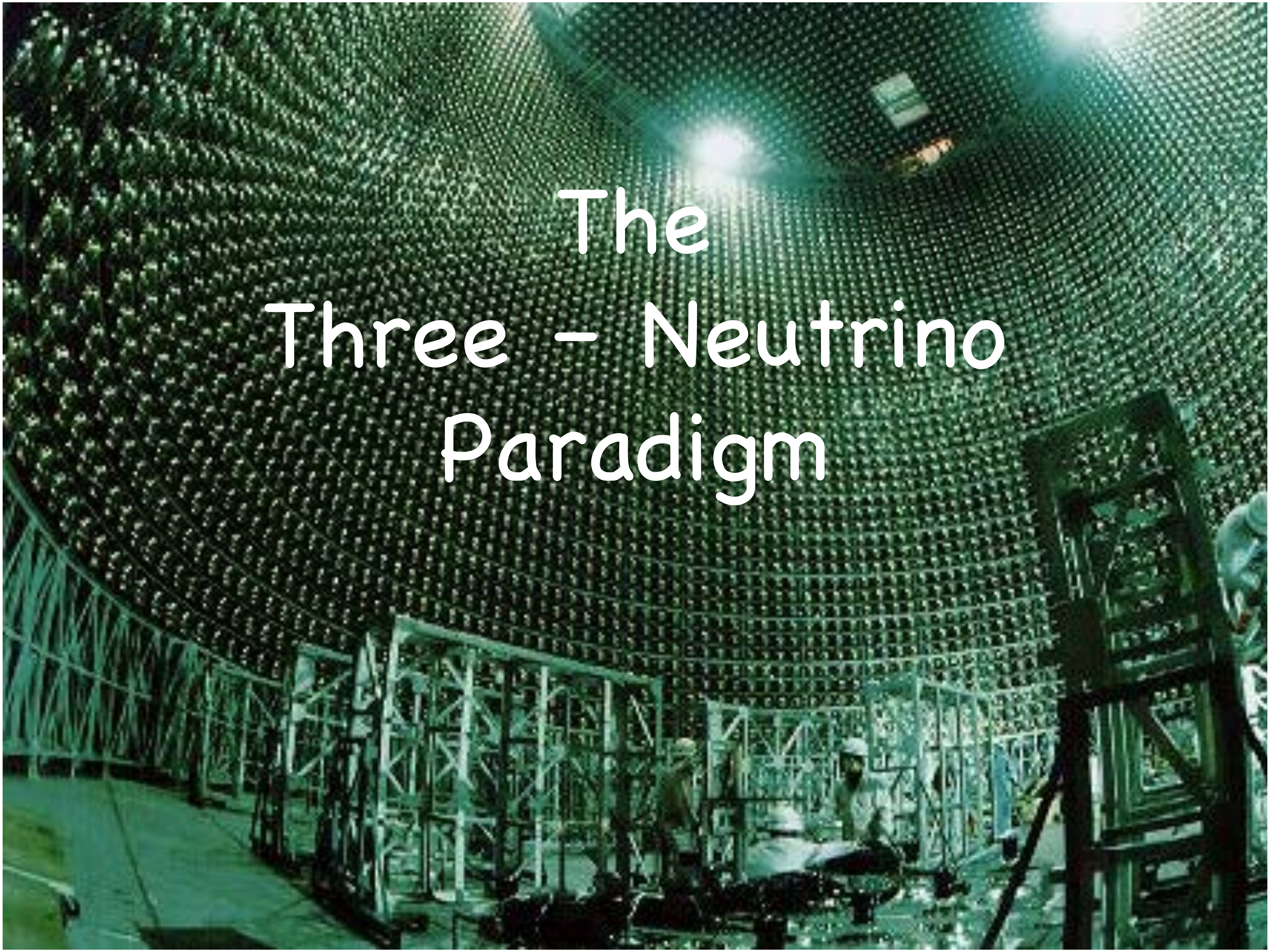
Oscillation Physics Beyond 3 Neutrinos



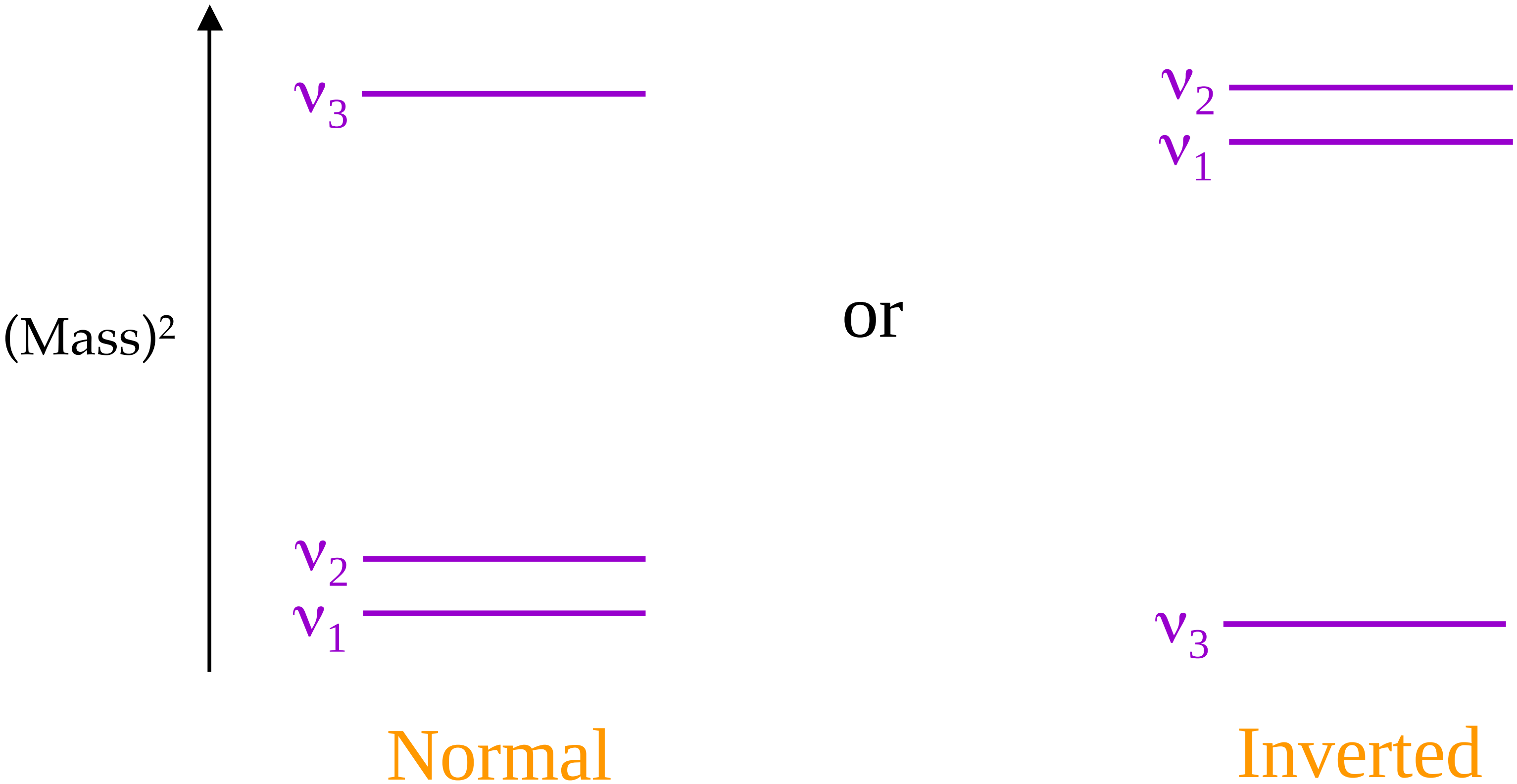
Boris Kayser, Fermilab

νSTORM 2012 Workshop

The Three – Neutrino Paradigm



The (Mass)^2 Spectrum

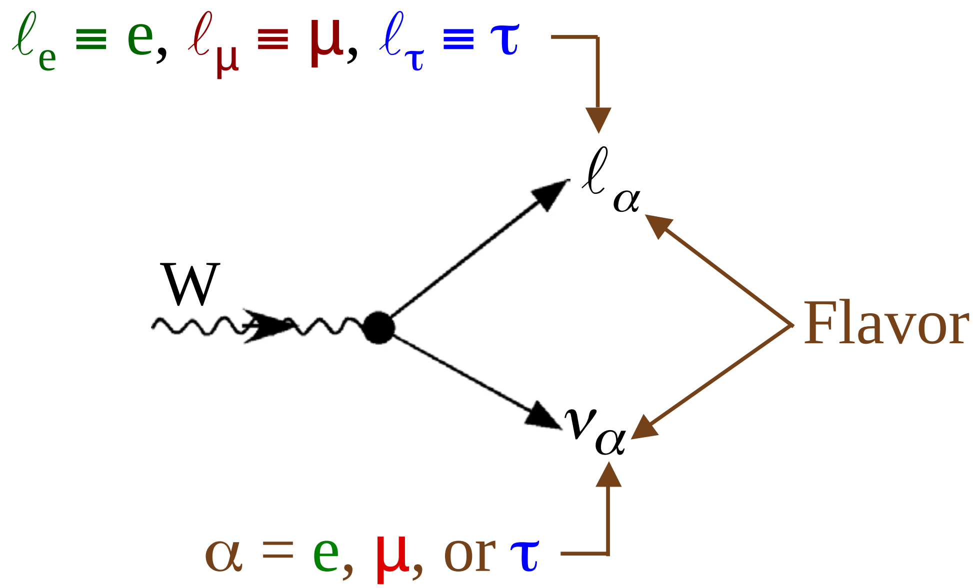


$\Delta m^2_{21} \cong 7.5 \times 10^{-5}\ \mathrm{eV}^2$, $\quad \Delta m^2_{32} \cong 2.4 \times 10^{-3}\ \mathrm{eV}^2$

The Interactions

The interactions of the neutrinos are assumed to be those of the Standard Model (SM), modified to incorporate leptonic mixing.

The neutrino couplings to the W:



But the neutrinos $\nu_{e,\mu,\tau}$ of definite flavor are superpositions of the neutrinos of definite mass:

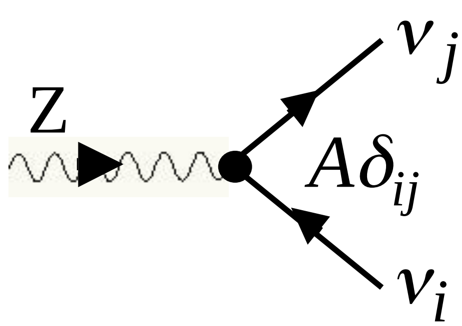
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \quad .$$

Neutrino of flavor α = e, μ, or τ

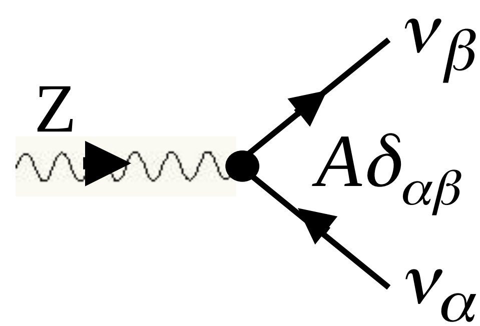
Neutrino of definite mass

Unitary leptonic mixing matrix

The neutrino couplings to the Z:



and



Oscillation among ν_e, ν_μ, and ν_τ
does not change the Neutral Current event rate.

The Mixing Matrix *U*

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

$$\times \underbrace{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Does not affect oscillation}}$$

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

$\theta_{12} \approx 34°$, $\theta_{23} \approx 39\text{-}51°$, $\theta_{13} \approx 8\text{-}10°$ ***No more worry!***

δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. *CP violation*

Note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

The 3-ν paradigm successfully describes many experimental results,

but not all.

Are There

More Than 3

Mass Eigenstates?

Are There

Sterile Neutrinos?

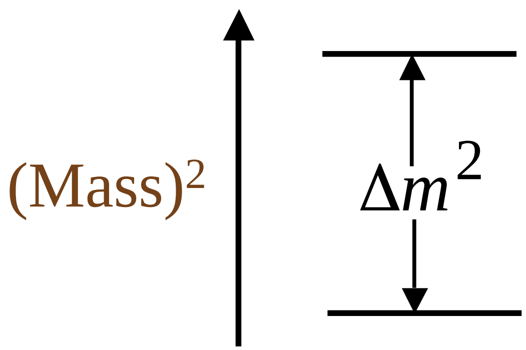
Sterile Neutrino

One that does not couple to the 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.

Oscillation

<u>When the neutrino spectrum has effectively only 2 levels</u>



Travel distance

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

Energy

Parameters that are ≤ 1

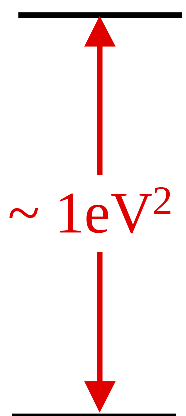
$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - \overbrace{\sin^2 2\theta_{\alpha\alpha}}\,\sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

The Hint From LSND

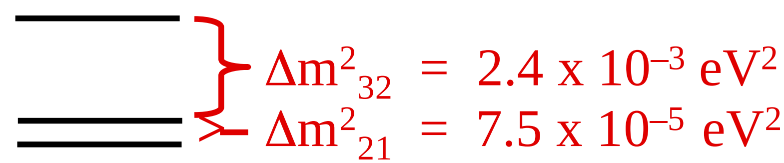
The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at *L(km)/E(GeV)* ~ 1.

$$P\left(\overline{\nu_\mu} \rightarrow \overline{\nu_e}\right) = \sin^2 2\theta \, \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right] \sim 0.26\%$$

From μ^+ decay at rest; E ~ 30 MeV



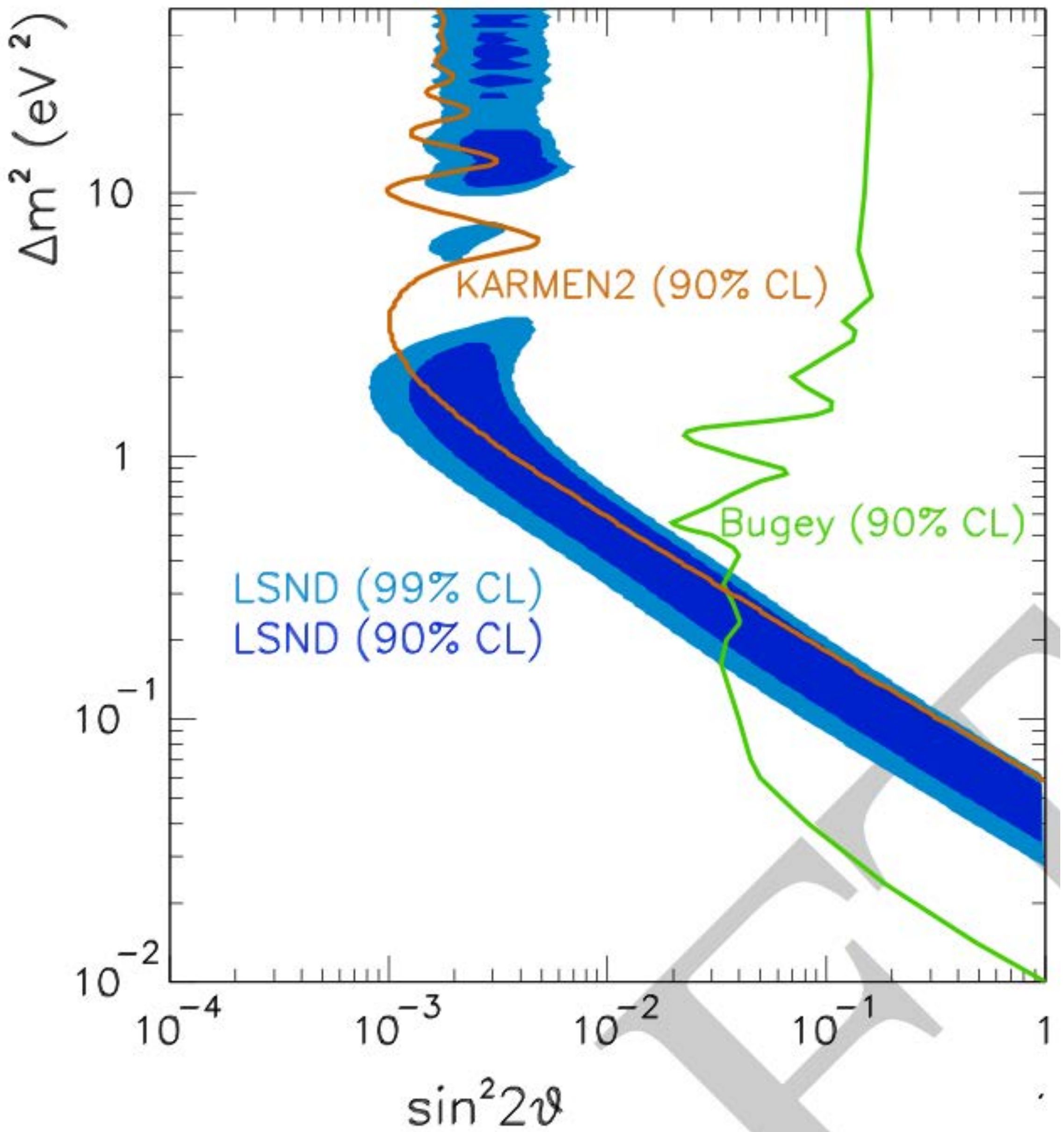
in contrast to



At least **4** mass eigenstates

{from measured $\Gamma(Z \rightarrow \nu\bar{\nu})$} At least **1** sterile neutrino

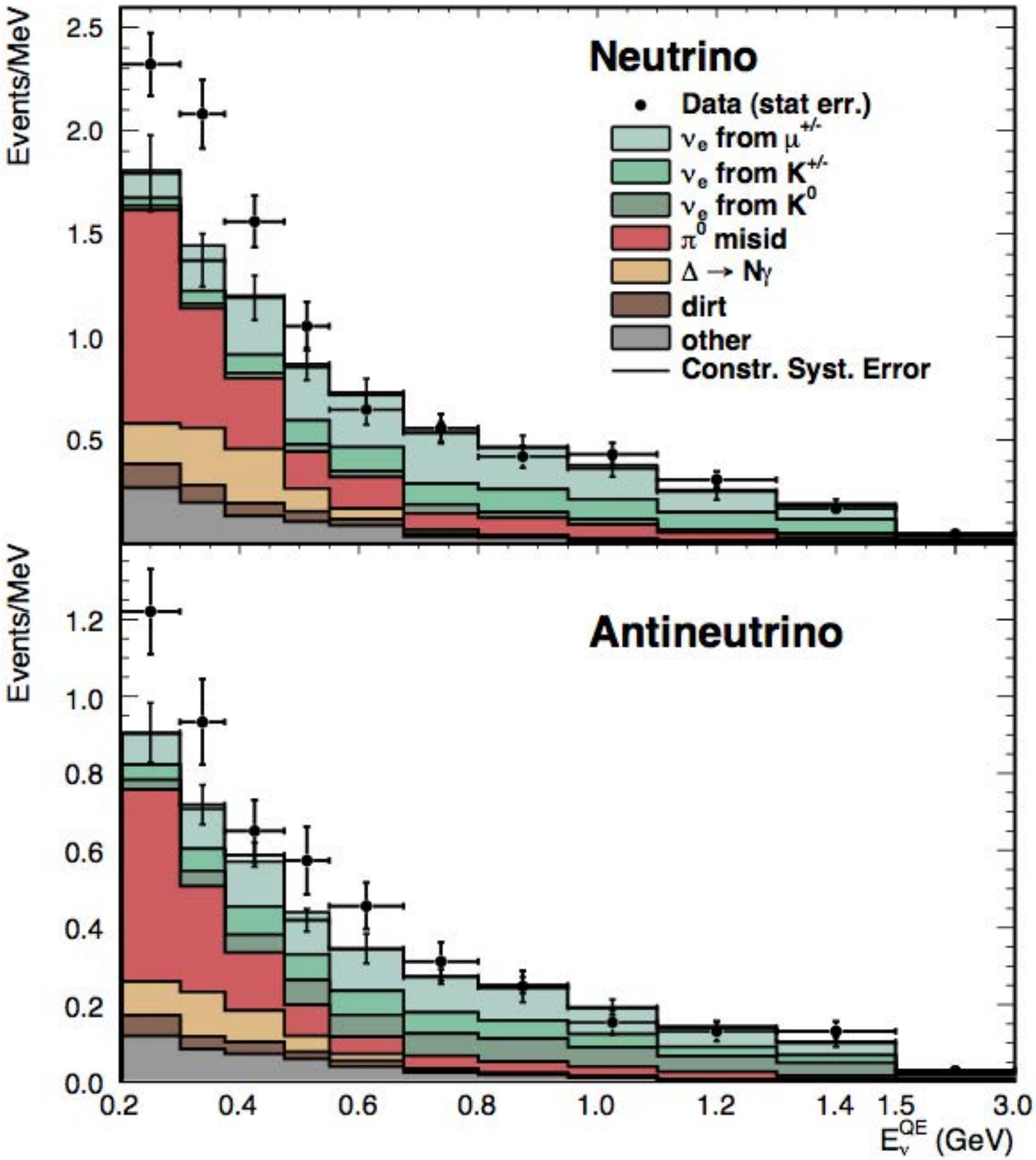
The LSND-favored region



The Hint From MiniBooNE

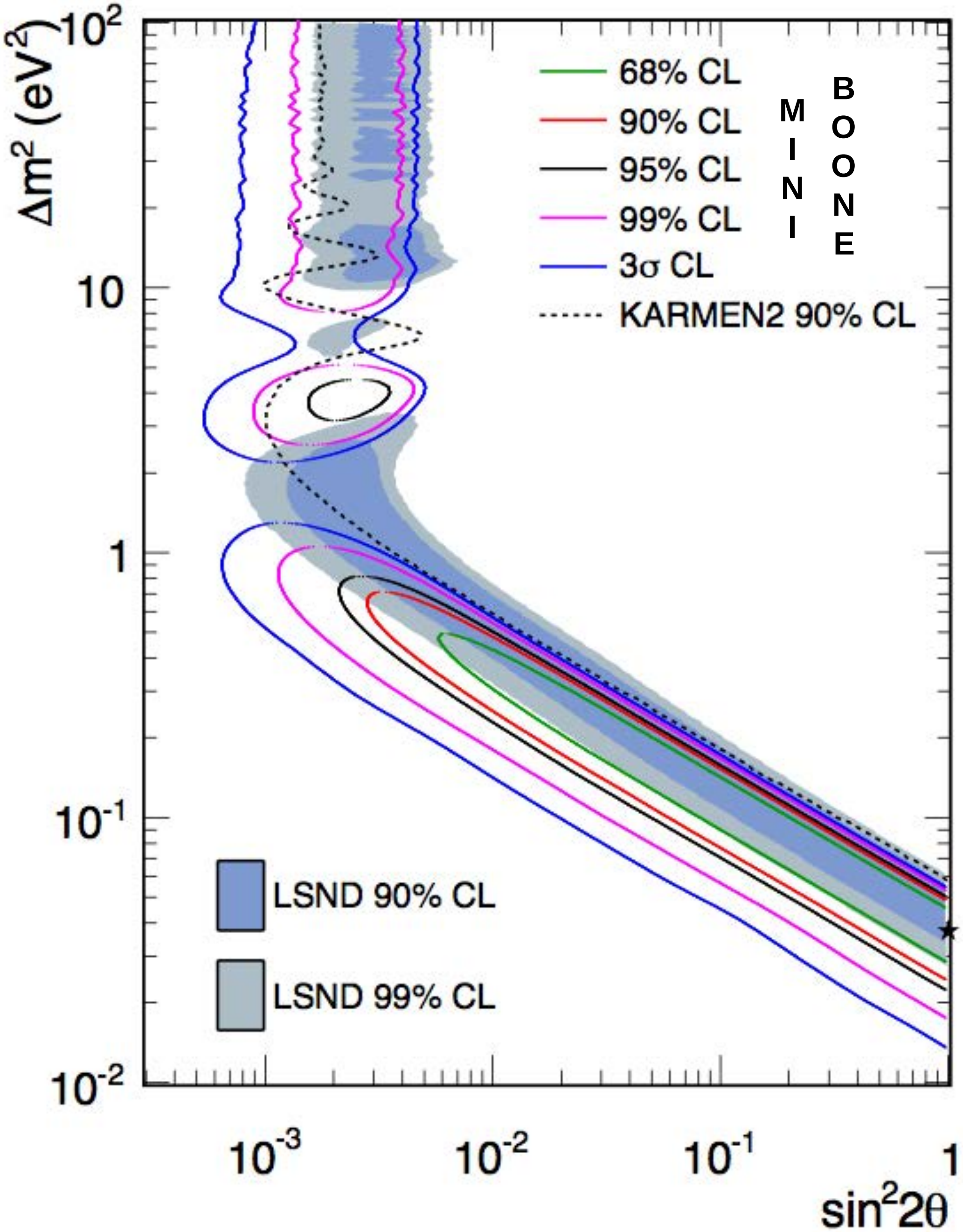
In MiniBooNE, both L and E are ~ 17 times larger than they were in LSND, and L/E is comparable.

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



MiniBooNE
1207.4809

Together, ν and $\bar{\nu}$ show an excess of 240.3 ± 62.9 events.



Regions allowed by:

1. Both ν and $\bar{\nu}$ MiniBooNE data with $E_\nu > 200$ MeV
2. LSND
3. Karmen

Two-level mass spectrum assumed in all cases.

From 1207.4809

The Hint From Reactors

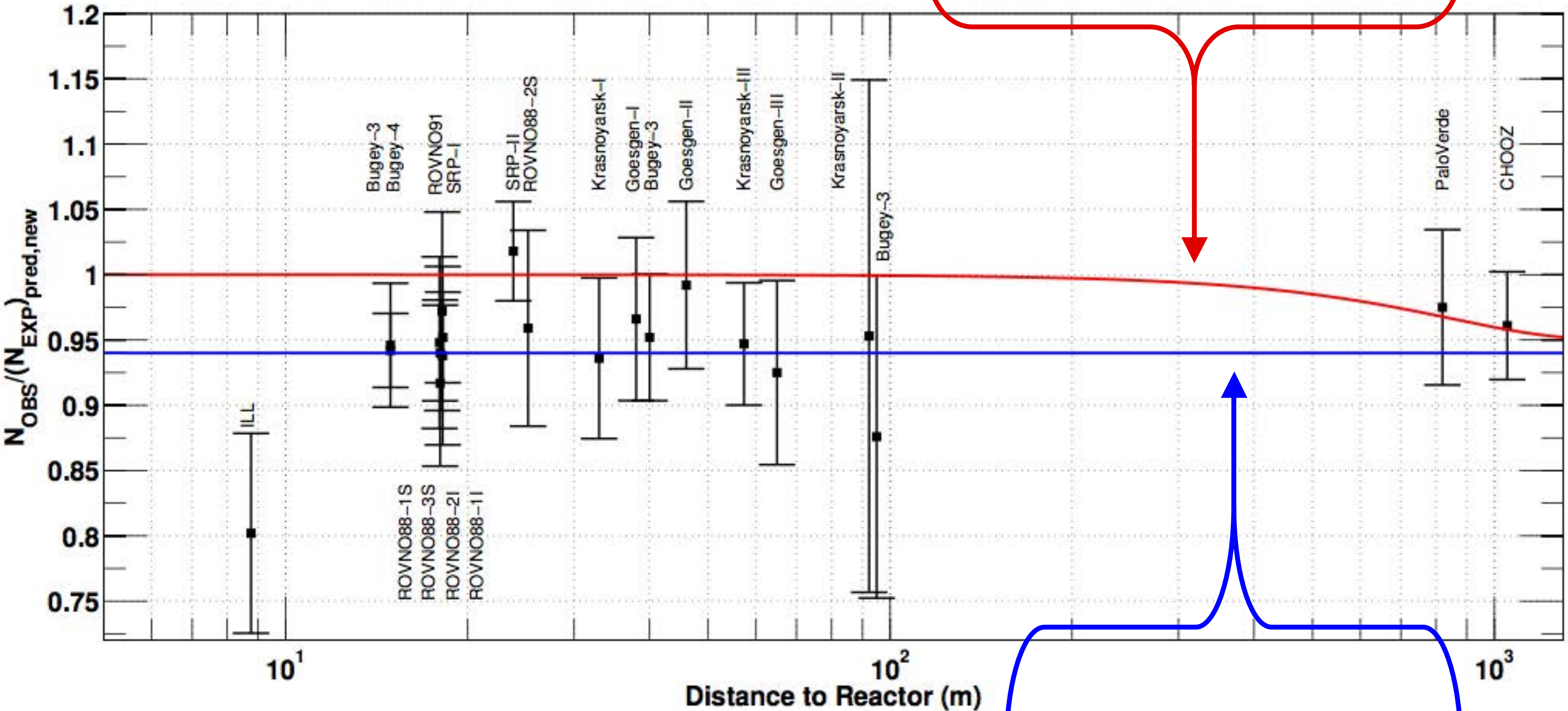
The prediction for the un-oscillated $\overline{\nu}_e$ flux from reactors, which has $\langle E \rangle \sim 3$ MeV, has increased by about 3%.

(Mueller et al., Huber)

Measurements of the $\overline{\nu}_e$ flux at (10 – 100)m from reactor cores now show a ~ 6% disappearance.

(Mention et al.)

Oscillation with only 3ν
and $\sin^2 2\theta_{13} = 0.06$



Oscillation with 4ν
and one $\Delta m^2 >> 1$ eV^2

Disappearance at L(m)/E(MeV) $\gtrsim 1$ suggests oscillation with $\Delta m^2 \gtrsim 1$ eV^2, like LSND and MiniBooNE.

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

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

$$\frac{\text{Measured event rate}}{\text{Expected event rate}} = 0.86 \pm 0.05$$

(Giunti, Laveder)

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

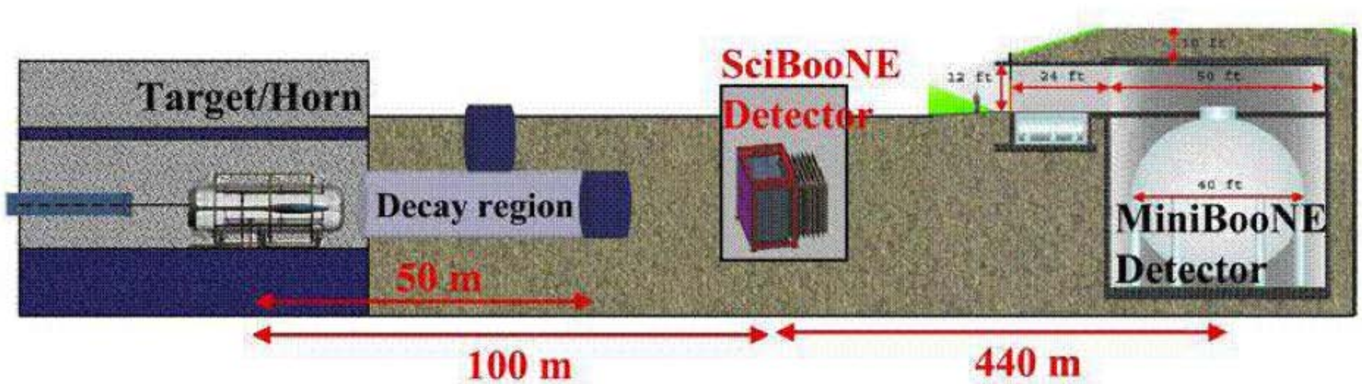
The Limits On $\overset{(-)}{\nu}_\mu$ Disappearance

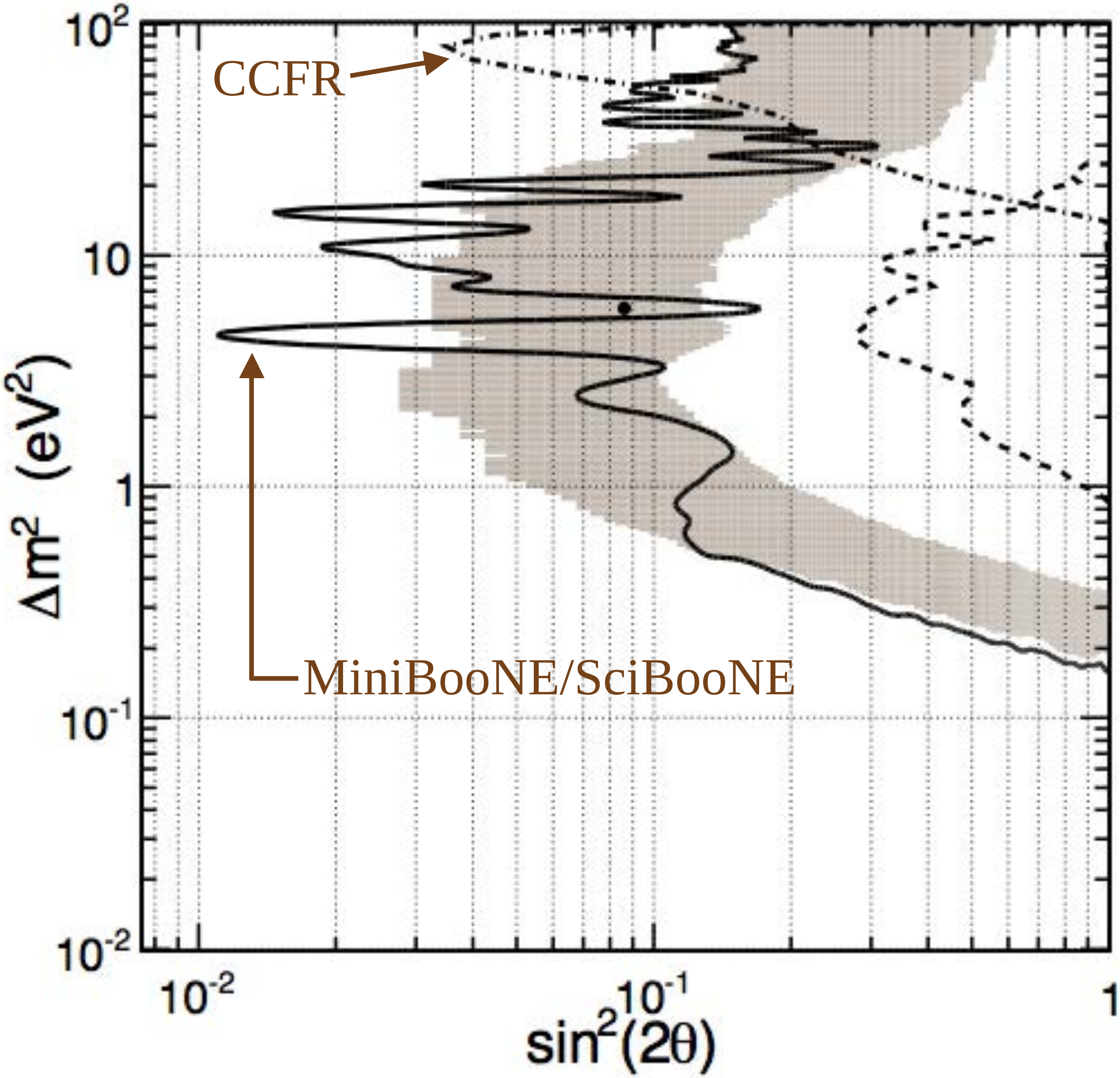
Assuming CPT invariance,

$$P\left(\bar{\nu}_\alpha \rightarrow \bar{\nu}_{\not\alpha}\right) = P\left(\nu_\alpha \rightarrow \nu_{\not\alpha}\right)$$

Therefore, I will not distinguish between neutrino and antineutrino disappearance.

The most recent and most stringent limit on $\bar{\nu}_\mu$ disappearance comes from a joint analysis of SciBooNE and MiniBooNE data.



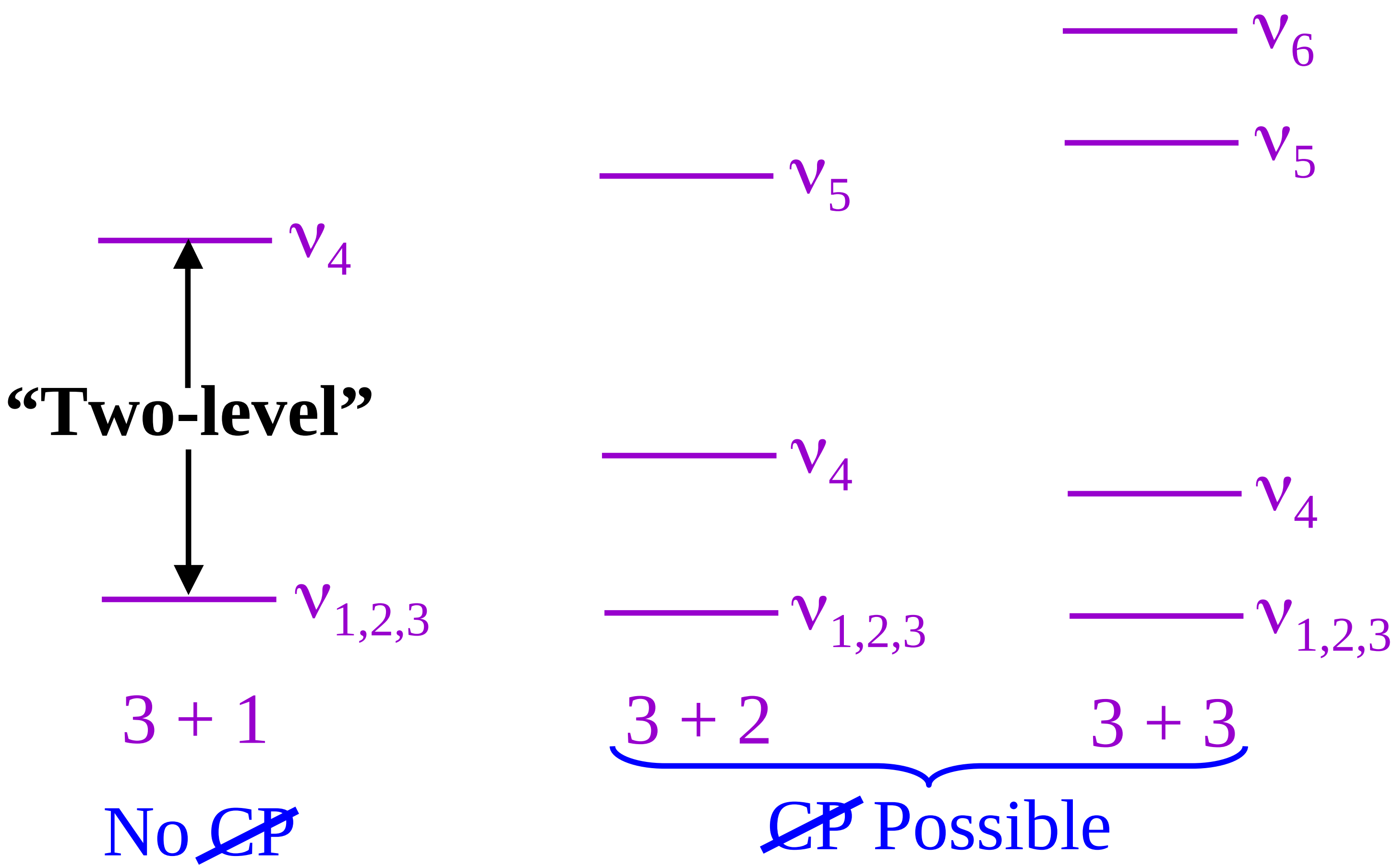


Regions excluded at 90% CL by no $\overline{\nu}_\mu$ disappearance

Two-level mass spectrum assumed

The Mass Spectrum and the Connection Between Appearance and Disappearance

The Spectra That Are Tried



Short-Baseline experiments have an L/E too small to see the splitting between ν_1, ν_2, and ν_3.

The Mixing Matrix When There Are Extra Neutrinos

It's bigger.

With 3 + N neutrino mass eigenstates, there can be 3 + N lepton flavors, N of them sterile. For example, for N = 3:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s_1} \\ \nu_{s_2} \\ \nu_{s_3} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & U_{e6} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & U_{\mu 6} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & U_{\tau 6} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & U_{s_1 5} & U_{s_1 6} \\ U_{s_2 1} & U_{s_2 2} & U_{s_2 3} & U_{s_2 4} & U_{s_2 5} & U_{s_3 6} \\ U_{s_3 1} & U_{s_3 2} & U_{s_3 3} & U_{s_3 4} & U_{s_3 5} & U_{s_3 6} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{pmatrix}$$

The Disappearance – Appearance Connection

Assuming ***only*** the CPT-invariance constraint —

$$P\left(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta\right) = P\left(\nu_\beta \rightarrow \nu_\alpha\right) ,$$

we must have —

$$\underbrace{P\left(\bar{\nu}_e \rightarrow \bar{\nu}_{\cancel{e}}\right)}_{\text{Perhaps 0.06 from reactors}} \geq \underbrace{P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)}_{\text{Reported as 0.0026 by LSND}} .$$

Clearly, it would be interesting to have non-reactor probes of $\overset{(-)}{\nu}_e$ disappearance.

Assuming a **3 + 1** spectrum —

$$P\left(\nu_\mu \to \nu_e\right) = 4\left|U_{\mu 4}\right|^2 \left|U_{e4}\right|^2 \sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

$$P\left(\nu_\mu \to \nu_{\cancel{\mu}}\right) = 4\left|U_{\mu 4}\right|^2 \left(1 - \left|U_{\mu 4}\right|^2\right) \sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

$$P\left(\nu_e \to \nu_{\cancel{e}}\right) = 4\left|U_{e4}\right|^2 \left(1 - \left|U_{e4}\right|^2\right) \sin^2\left[1.27\Delta m_{41}^2 \frac{L}{E}\right]$$

(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 —

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

For a **3 + 2** spectrum, the oscillation probabilities are more complicated.

However, if the extra neutrino mass eigenstates are mostly sterile, experiments that average over the short-wavelength oscillations should find —

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

(Conrad, B.K., Kopp)
(Maltoni, Schwetz)

For a **3 + 3** spectrum, the oscillation probabilities are more complicated still…..

The upshot —

If $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 1\%$, it is reasonable to expect that $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_{\cancel{\mu}})$ and $P(\bar{\nu}_e \rightarrow \bar{\nu}_{\cancel{e}})$ are both ~ 10%.

The Hint From Cosmology

Big Bang Nucleosysthesis (BBN) and CMB
anisotropies count the effective number
of relativistic degrees of freedom, N_{eff}, at early times.

Light sterile neutrinos mixed with the active ones
as required by the terrestrial anomalies
would very likely have thermalized in the early universe.

Then N_{eff} grows by 1 for each sterile species.

The evidence suggests that perhaps $N_{\mathrm{eff}} > 3$.

N_{eff} From BBN

Model	Data	N_{eff}	Ref.
η+N_{eff}	η_{CMB}+Y_{p}+D/H	$3.8^{(+0.8)}_{(-0.7)}$	[10]
	η_{CMB}+Y_{p}+D/H	$< (4.05)$	[11]
	Y_{p}+D/H	3.85 ± 0.26	[13]
		3.82 ± 0.35	[13]
		3.13 ± 0.21	[13]
η+N_{eff}, ($\Delta N_{\mathrm{eff}} \equiv N_{\mathrm{eff}} - 3.046 \geq 0$)	η_{CMB}+D/H	3.8 ± 0.6	[12]
	η_{CMB}+Y_{p}	$3.90^{+0.21}_{-0.58}$	[12]
	Y_{p}+D/H	$3.91^{+0.22}_{-0.55}$	[12]

N_{eff} From CMB

Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[26]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[26]
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$	[29]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[26]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[18]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[18]
	W-7+ACT	5.3 ± 1.3	[23]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[23]
	W-7+SPT	3.85 ± 0.62	[24]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[24]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[30]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[31]
$N_{\text{eff}}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[32]
$N_{\text{eff}}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[31]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[32]
$N_{\text{eff}}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[31]
$N_{\text{eff}}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[32]
$N_{\text{eff}}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[33]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[33]

More precise information will come from the Planck satellite.

$\sum_i m(\nu_i)$ In the Early Universe

Large Scale Structure in the universe and the CMB suggest that —

$$\sum_i m(\nu_i) < (0.17 - 1.0) \text{ eV}$$

$\left(\begin{array}{c}\text{Seljak, Slosar, McDonald} \\ \text{Hannestad; Pastor}\end{array}\right)$

Possible tension with terrestrial experiments if $\Delta m^2 > 1 \text{ eV}^2$.

However, in cosmology, there are parameter degeneracies.

Global Fits To Short-Baseline Terrestrial Data

The Bottom Line

(Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz)

(Maltoni; Talk at Galileo Galilei Institute)

A 3 + 1 spectrum does not provide a good fit to all the data.

Assuming 3 + 1, the appearance and disappearance data call for very different values of Δm^2_{41}, as do the ν and $\bar{\nu}$ data.

A 3 + 2 spectrum can violate CP, so the ν vs. $\bar{\nu}$ tension is reduced, but the appearance and disappearance data still call for very different mass splittings.

A 3 + 3 spectrum contains one more mass splitting, and improves the fit, but there is still tension between appearance and disappearance data.
(Perhaps the MiniBooNE low-energy appearance excess is not due to oscillation.)

So, Are There Sterile Neutrinos?

Many people, including myself,
feel personally that —

Individually or taken together,
the hints are certainly not convincing.

But —

**They are interesting enough
to call for further,
hopefully definitive,
investigation.**

Fermilab Short Baseline Neutrino Focus Group

Steve Brice (FNAL)

Bonnie Fleming (Yale)

Steve Geer[1)] (FNAL)

Andre de Gouvea (NW)

Debbie Harris (FNAL)

Patrick Huber (Virginia Tech)

Boris Kayser[2)] (FNAL)

Geoff Mills (LANL)

Koichiro Nishikawa (KEK)

Stephen Parke (FNAL)

Chris Polly (FNAL)

Andre Rubbia (Zurich)

Bob Tschirhart[3)] (FNAL)

Richard Van de Water (LANL)

Sam Zeller[4)] (FNAL)

Bob Zwaska[5)] (FNAL)

1) Chair
2) Tensions Group Facilitator
3) Options Group Facilitator
4) Cross-Section and Fluxes Group Facilitator
5) Facilities Group Facilitator

In June, 2012, this group came to the same conclusion.

The group's recommendations included —

A new experiment to search for $\nu_\mu \rightarrow \nu_e$ and/or $\nu_e \rightarrow \nu_\mu$ transitions.The experiment should be capable of both excluding sterile neutrinos over the entire allowed LSND/MiniBooNE parameter space with a significance of at least 5σ, and of discovering sterile neutrinos if they exist within this region of parameter space, also with a significance of at least 5σ.

Ideas For Future Experiments

I would just like to illustrate the ***diversity*** of ideas being proposed.

Channels and Processes To Explore Via Complementary Experiments

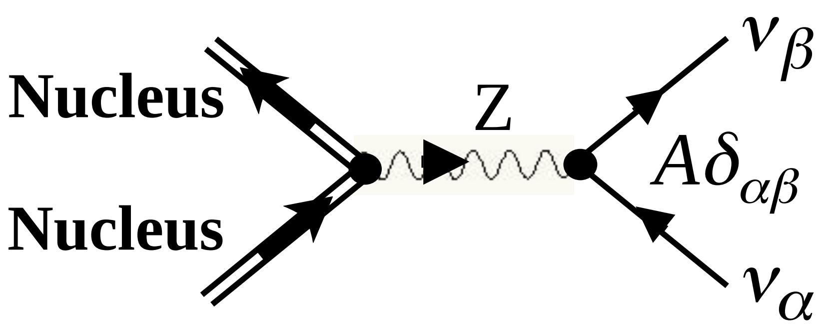
Flavor Transition	CPT Conjugate
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_{\cancel{e}}$	$\bar{\nu}_e \rightarrow \bar{\nu}_{\cancel{e}}$
$\nu_\mu \rightarrow \nu_{\cancel{\mu}}$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_{\cancel{\mu}}$

$\bar{\nu}_\tau$ appearance channels could also be interesting.

Both charged-current and neutral-current event rates are interesting.

How much of this can νSTORM do on its own?

Coherent Neutral-Current Scattering



This process has the same rate for any incoming ***active*** neutrino, ν_e, ν_μ, or ν_τ.

But the Z does not couple to $\nu_{sterile}$.

If $\nu_{active} \rightarrow \nu_{sterile}$, the coherent scattering event rate will oscillate with it.

Ideas—

Electron-capture monoenergetic ν_e source

Kinetic energy of nuclear recoil ~ Few x 10 eV.

Use bolometric cryogenic detectors.

(Formaggio, Figueroa-Feliciano, Anderson)

Cyclotron pion & muon decay-at-rest neutrino source

Two sources — one detector

Kinetic energy of nuclear recoil ~ keV.

Detection via DM-inspired detectors.

(Anderson et al.)

Caveat: If $\Delta m^2 >> 1$ eV^2, the oscillation may be too fast to see.

Position Dependence Within One Detector

For $E \sim 30$ MeV $\bar{\nu}_\mu$ from μ^+ decay at rest, and $\Delta m^2 \sim 1$ eV^2, the oscillation maximum is at ~ 40 m.

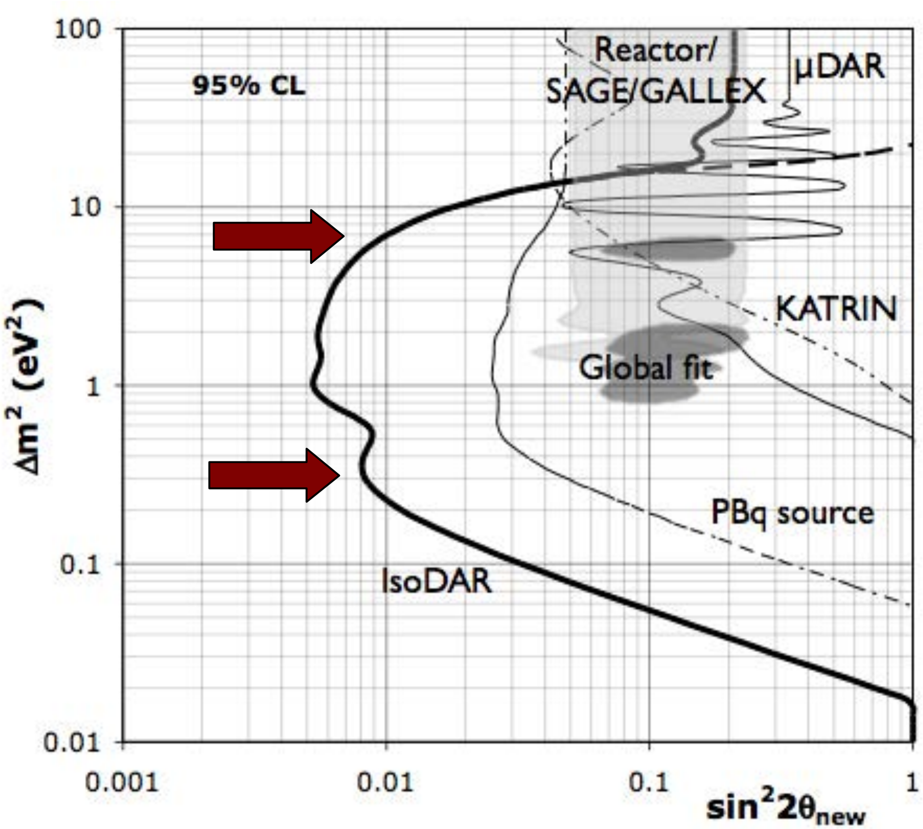
Look for ***oscillatory*** behavior.

(Agarwalla, Conrad, Shaevitz)

$\bar{\nu}_e$ From ^{8}Li Decay

Use a cyclotron to make the ^{8}Li, a $\bar{\nu}_e$ emitter.

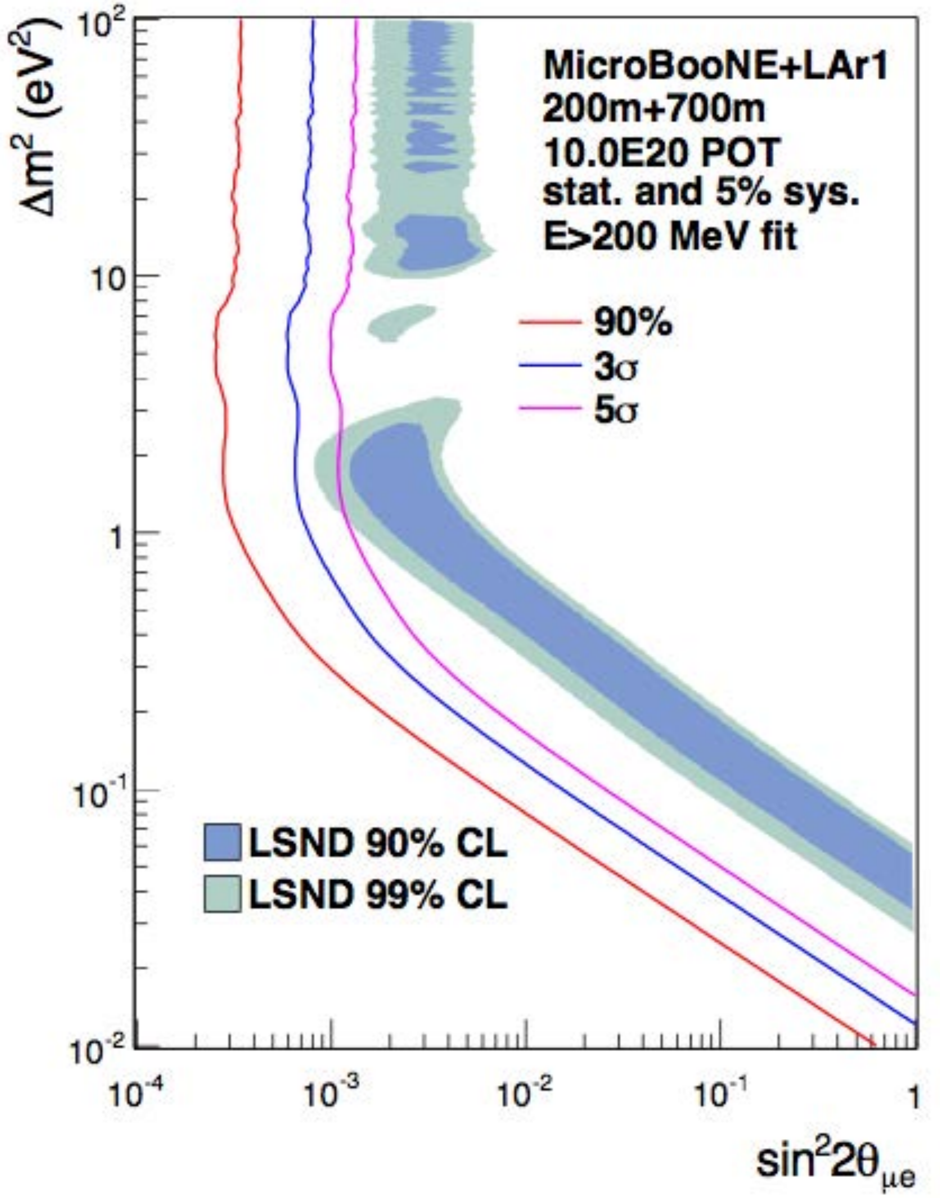
Use a kton-scale scintillator detector to detect the $\bar{\nu}_e$ via $\bar{\nu}_e\, p \rightarrow e^+ n$.



Sensitivity to $\bar{\nu}_e$ disappearance in a 5-year run

(Bungau et al.)

Two LAr Detectors In the FNAL Booster Beam



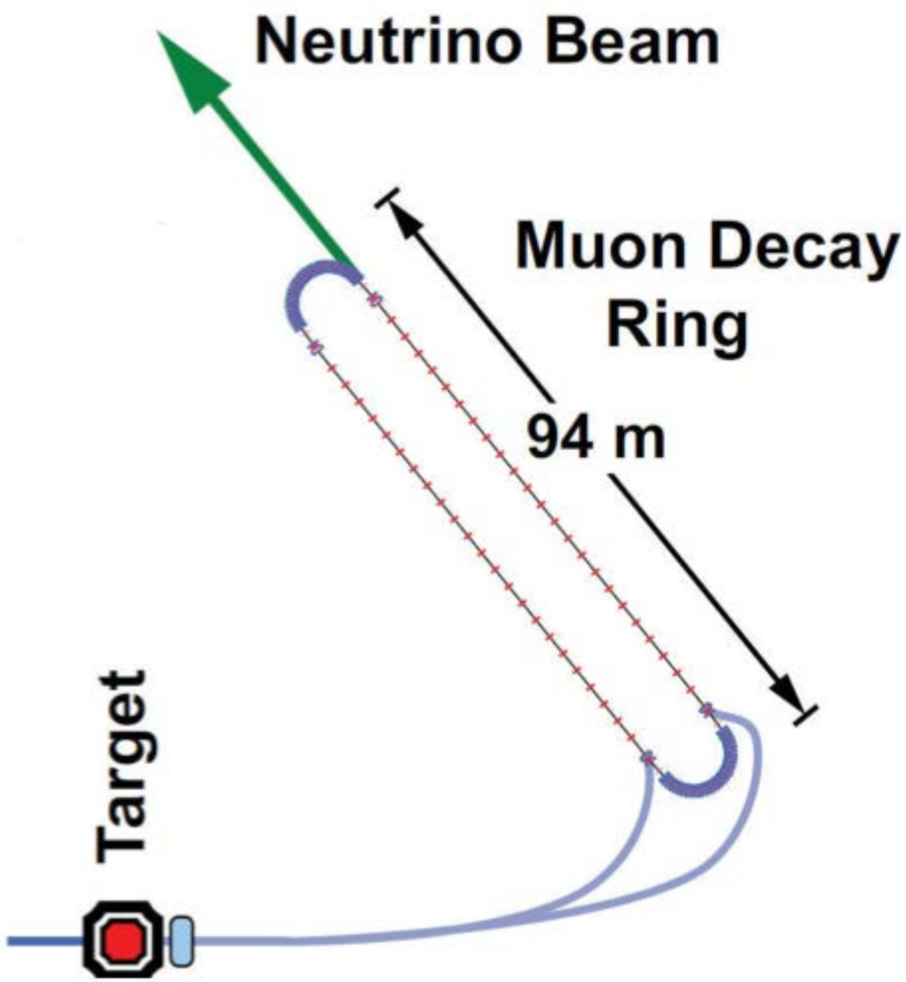
Sensitivity to

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

From the LAr1 LOI

A Very Low Energy Neutrino Factory

(νSTORM)



$E_\mu \sim$ **4 GeV**

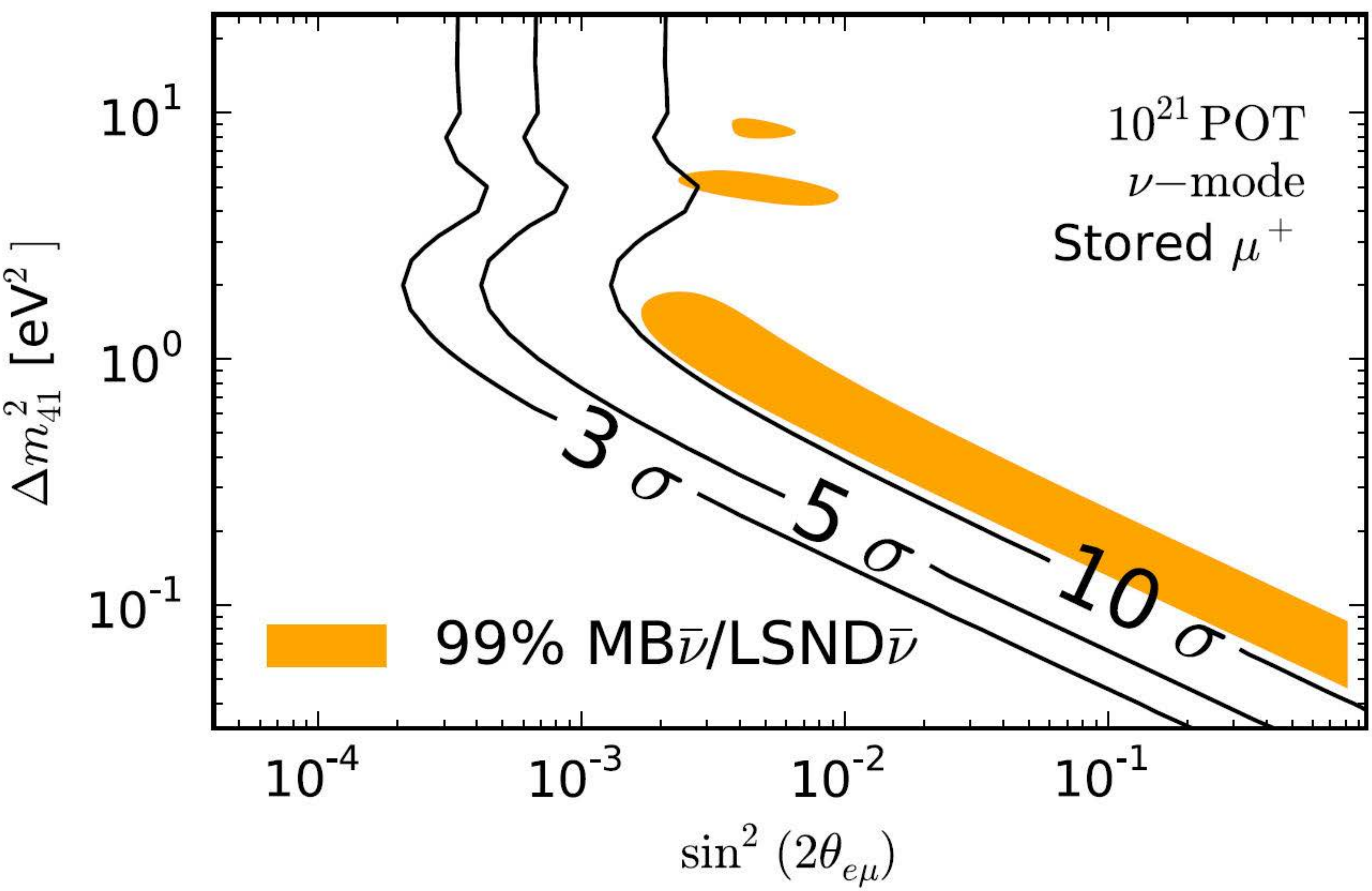
If store μ^+,
can study—

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

followed by —

$$\nu_e \to \nu_\mu \ .$$

LSND reported $\bar{\nu}_\mu \to \bar{\nu}_e$. $\quad P(\nu_e \to \nu_\mu) \underset{\mathrm{CPT}}{=} P(\bar{\nu}_\mu \to \bar{\nu}_e)$



10^{21} POT
ν−mode
Stored μ^+
3 σ
5 σ
10 σ
99% MB$\bar{\nu}$/LSND$\bar{\nu}$
Δm^2_{41} [eV^2]
10^1
10^0
10^{-1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2(2\theta_{e\mu})$

(Bross et al.)

A Resource —

Light Sterile Neutrinos: A White Paper

K. Abazajian, et al.

arXiv:1204.5379

Conclusion

There is intriguing physics
for νSTORM to explore.