
Neutrino
Phenomenology
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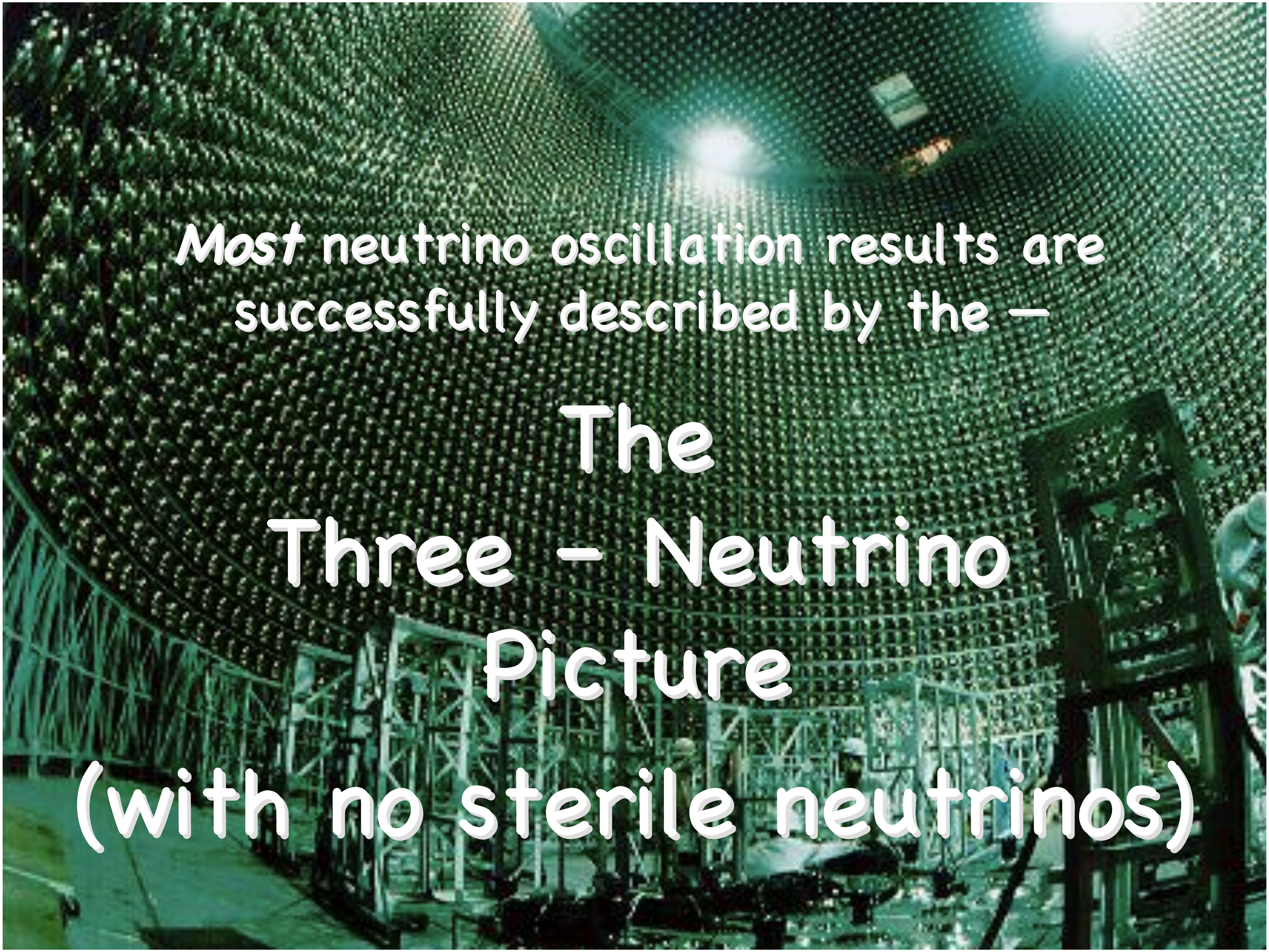
INSS
August, 2013
Part 3
NASA Hubble Photo

Are There Sterile Neutrinos?

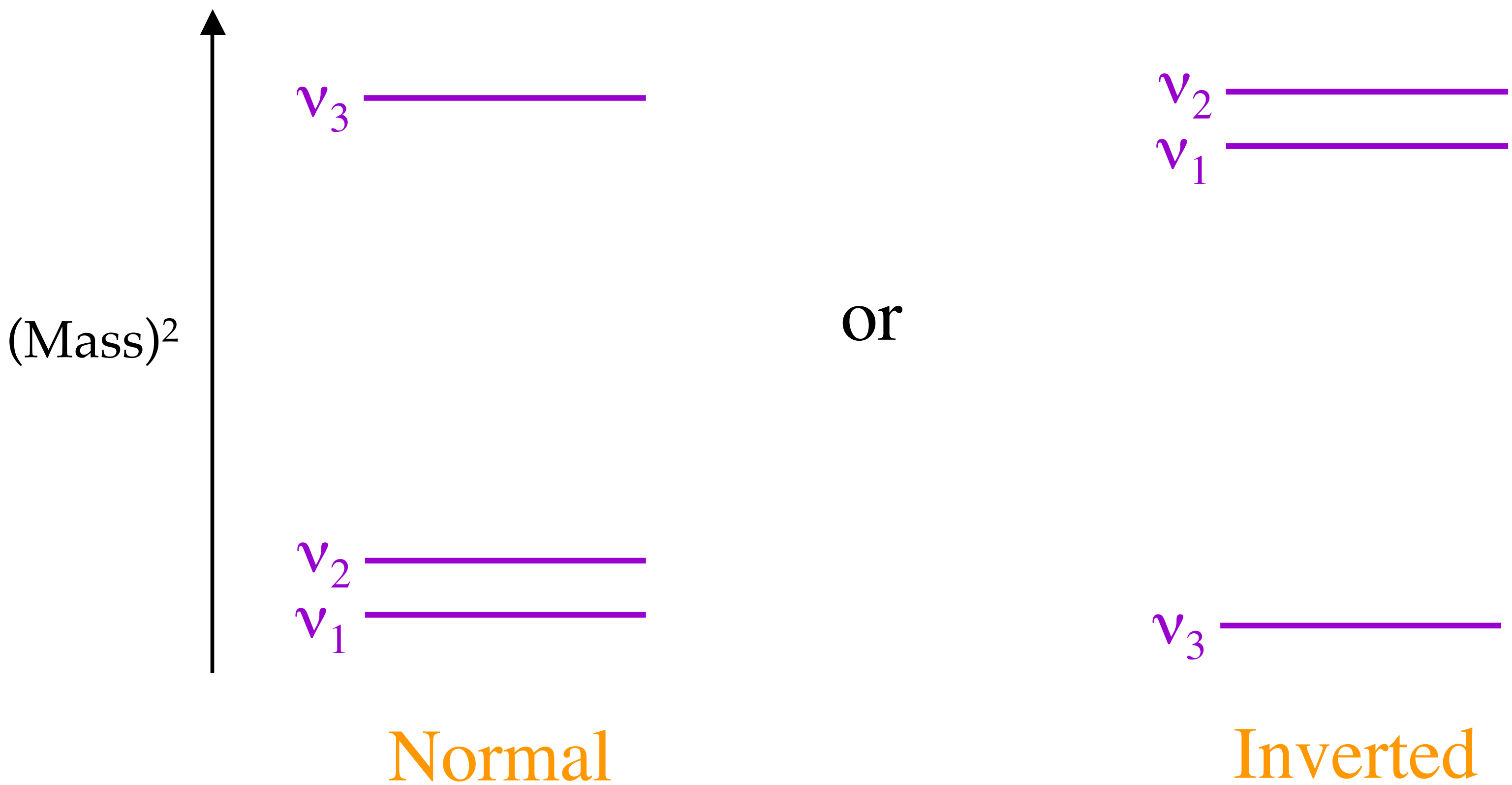
Sterile Neutrino

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.


Most neutrino oscillation results are successfully described by the —
The
Three – Neutrino
Picture
(with no sterile neutrinos)

The $(\text{Mass})^2$ Spectrum



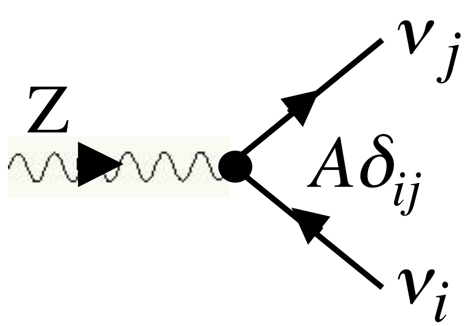
$$\Delta m^2_{21} \cong 7.5 \times 10^{-5}\ \text{eV}^2, \qquad \Delta m^2_{32} \cong 2.4 \times 10^{-3}\ \text{eV}^2$$

The Interactions

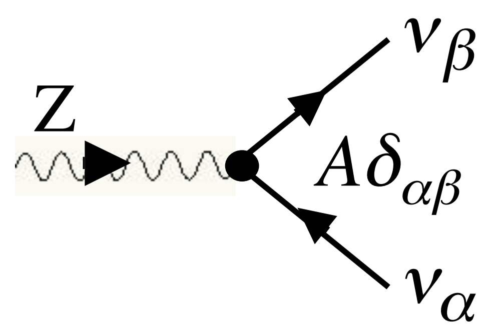
The interactions of the neutrinos are assumed to be those of the Standard Model (SM), modified to incorporate leptonic mixing.

We have already discussed the neutrino couplings to the W.

The neutrino couplings to the Z:



and

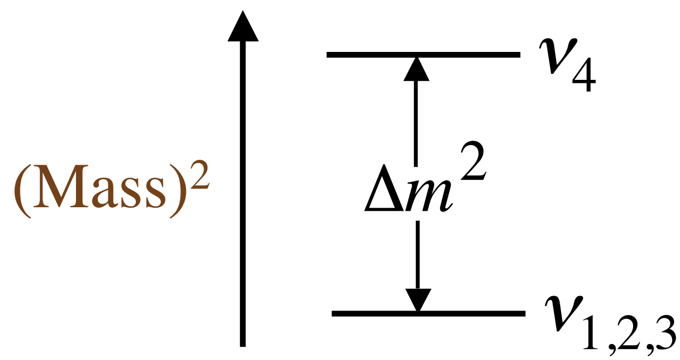


Oscillation among ν_e, ν_μ, and ν_τ
does not change the Neutral Current event rate.

The 3-ν picture successfully describes many experimental results,

but not all.

Oscillation When There Is Only 1 Visible Splitting



Appearance

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

Different parameters
between 0 and 1

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_{\not\alpha}\right) = \sin^2 2\theta_{\alpha\alpha} \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

Disappearance

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

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

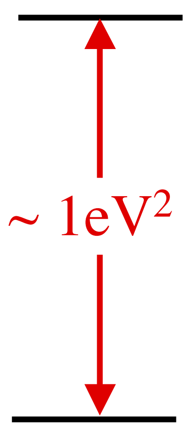
The Hints That There Are Sterile Neutrinos

The Hint From LSND

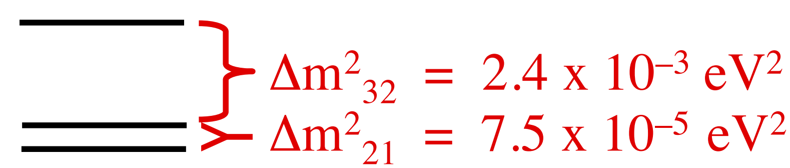
The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

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

From μ^+ decay at rest; E ~ 30 MeV



in contrast to



At least **4** mass eigenstates

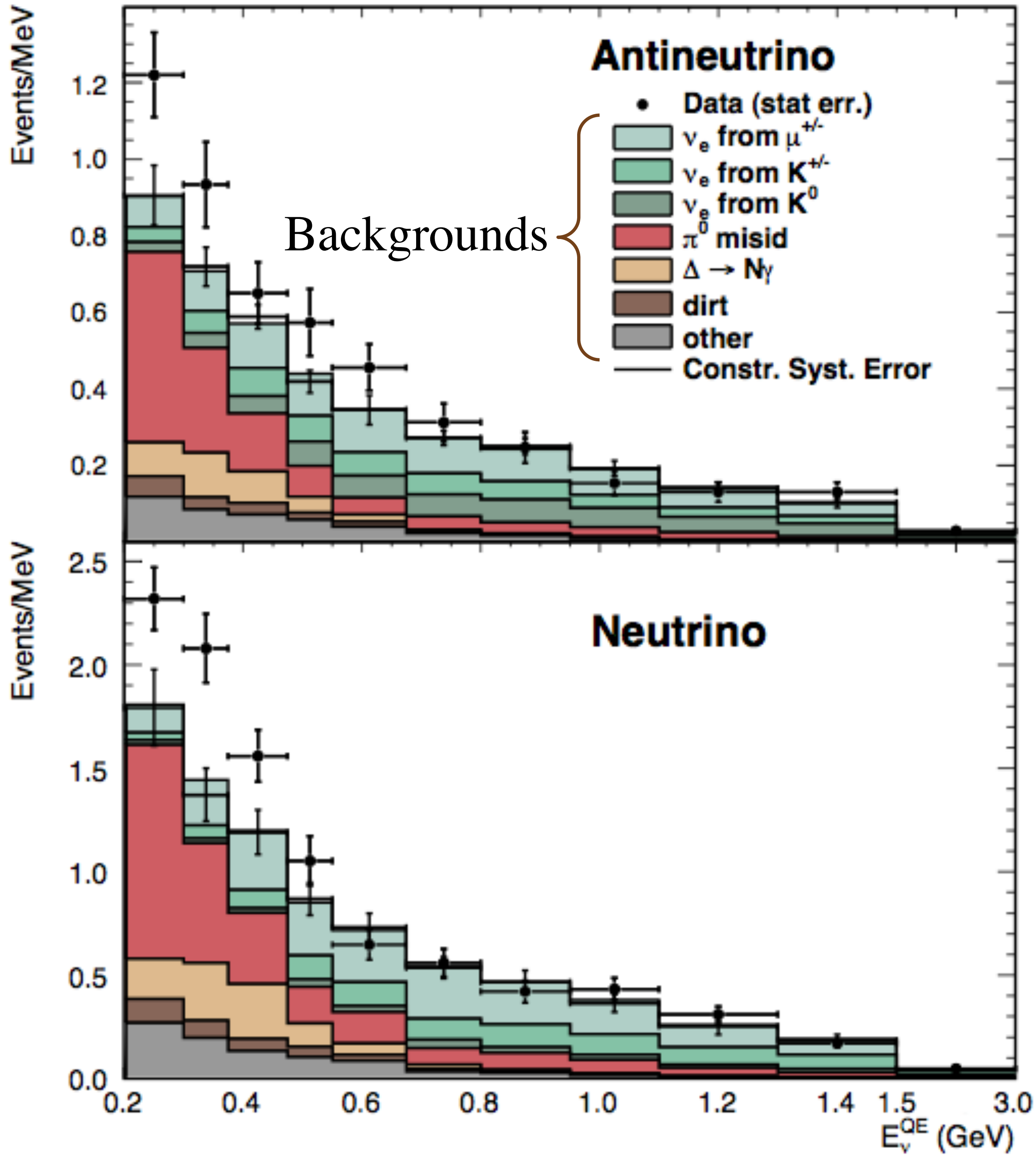
{from measured $\Gamma(Z \to \nu\bar{\nu})$} At least **1** sterile neutrino

The Hint From MiniBooNE

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

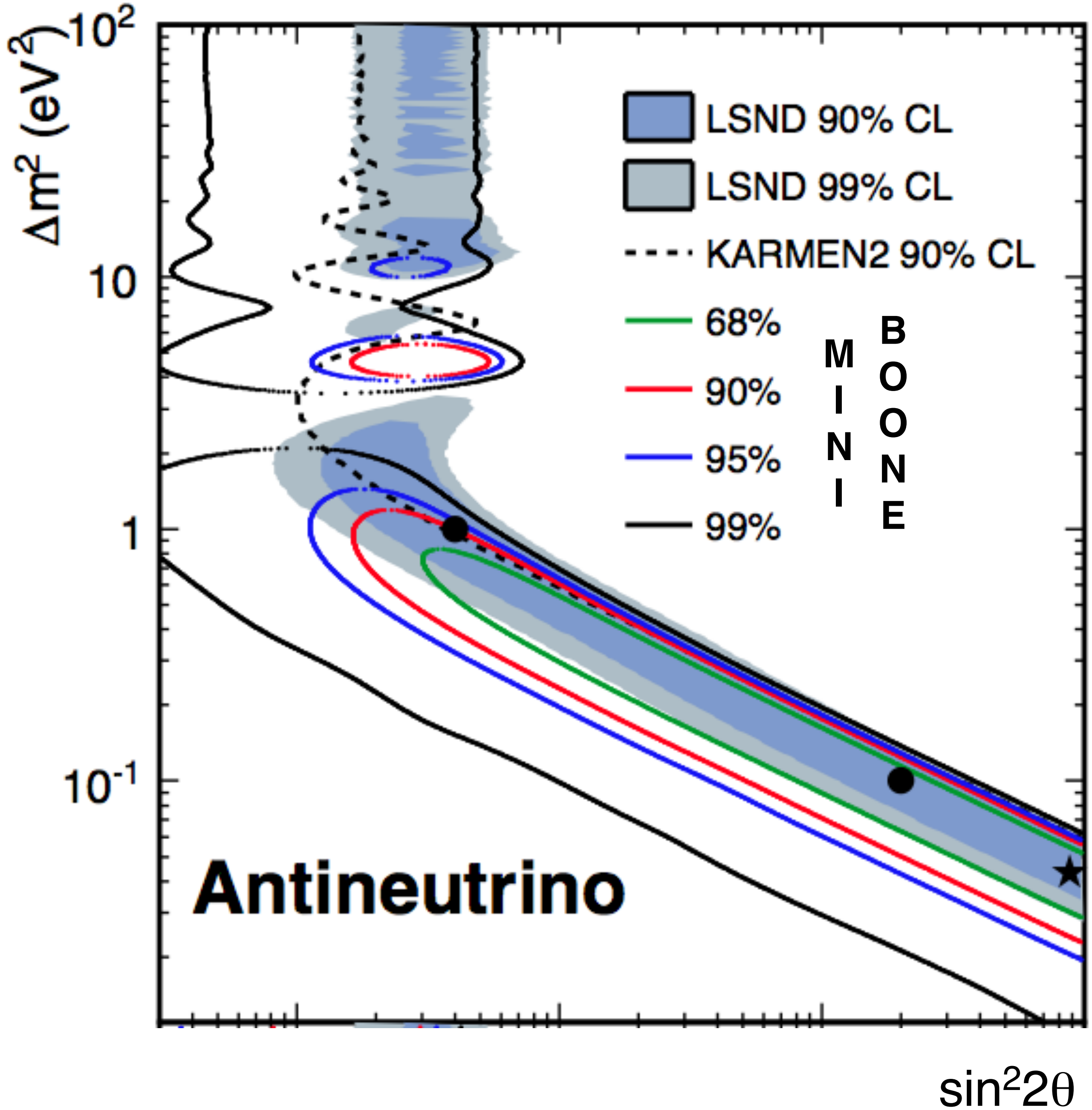
MiniBooNE has reported both $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ results.

MiniBooNE runs in a ν_μ ($\bar{\nu}_\mu$) beam, and then reports the number of ν_e ($\bar{\nu}_e$) candidate events.



MiniBooNE
1303.2588

78.4 ± 28.5 excess $\bar{\nu}$ events, and 162.0 ± 47.8 excess ν events



MiniBooNE and LSND allowed regions overlap.

Two-level mass spectrum assumed.

From 1303.2588

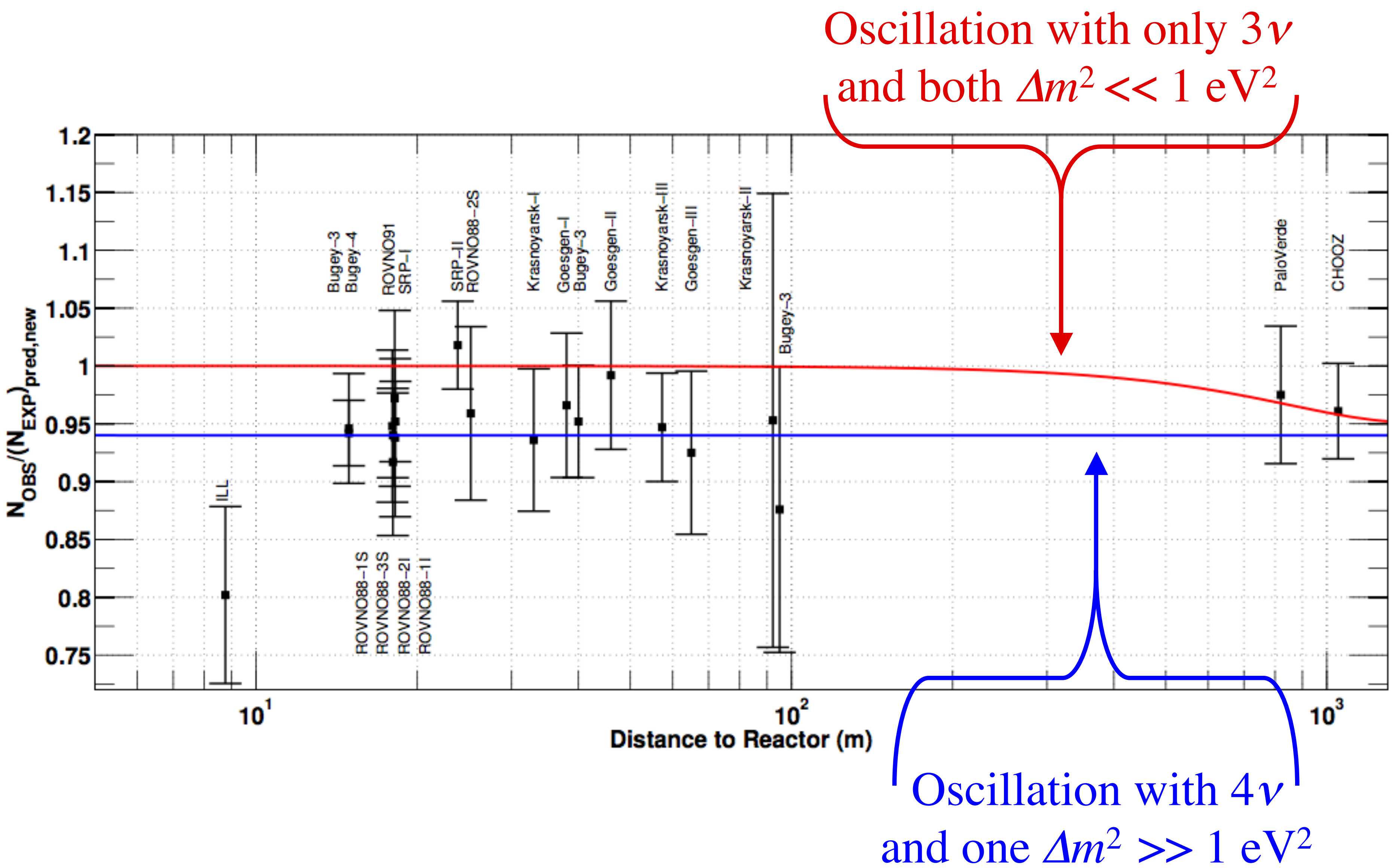
The Hint From Reactors

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%.

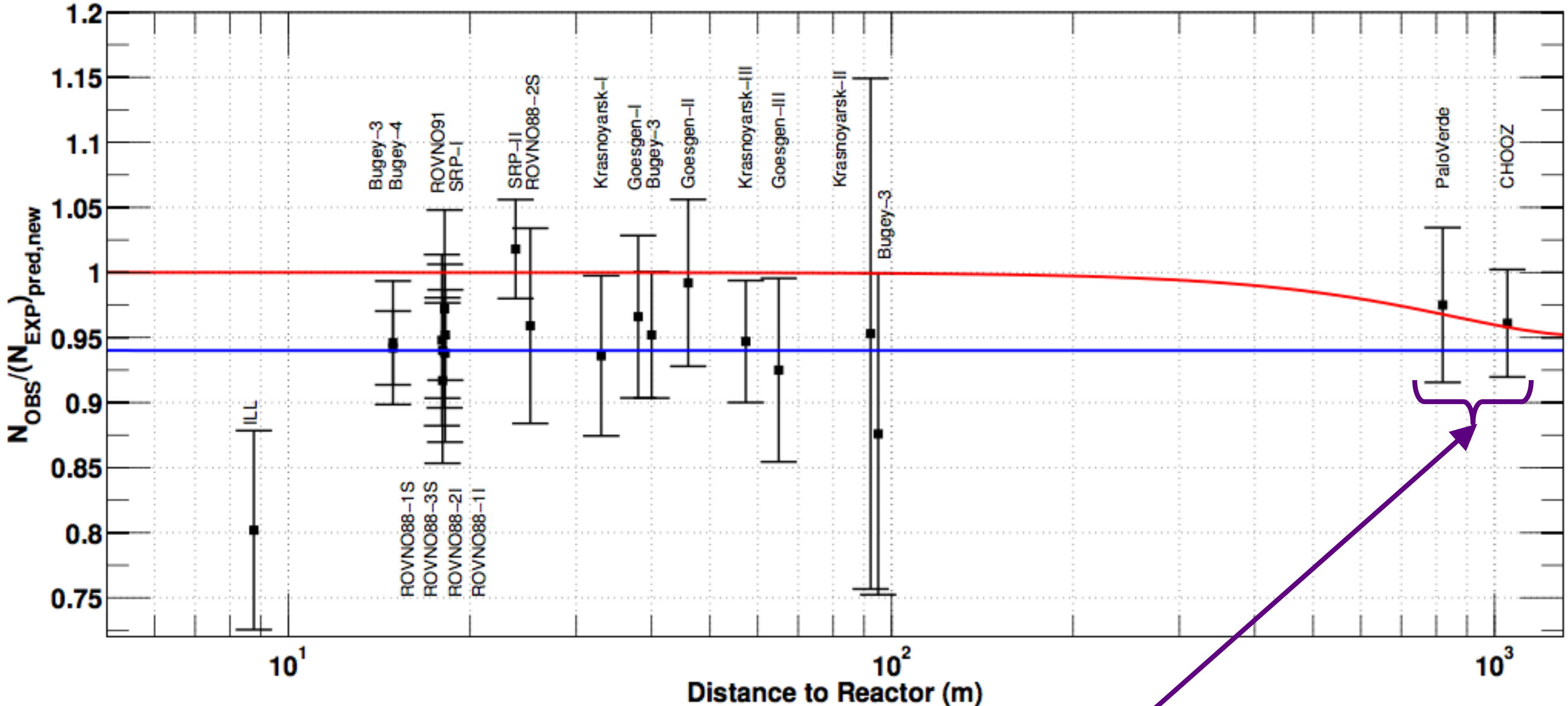
(Mueller et al., Huber)

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

(Mention et al.)



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



Inclusion of data from the more distant detectors in the 4ν fit appears to reduce the anomaly from 6% to 4%, and only 1.4σ.

(Zhang, Qian, and Vogel)

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??

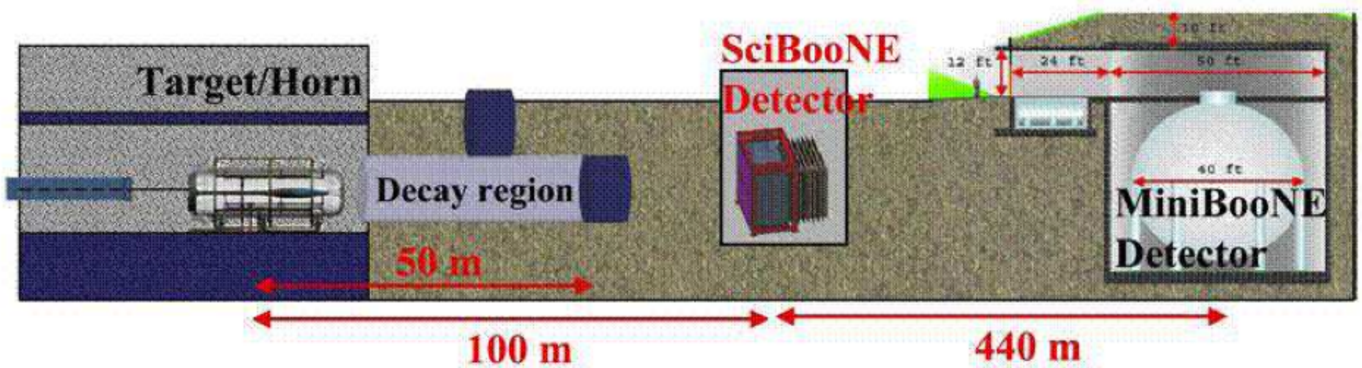
The Limits On $\overset{(-)}{\nu}_\mu$ Disappearance

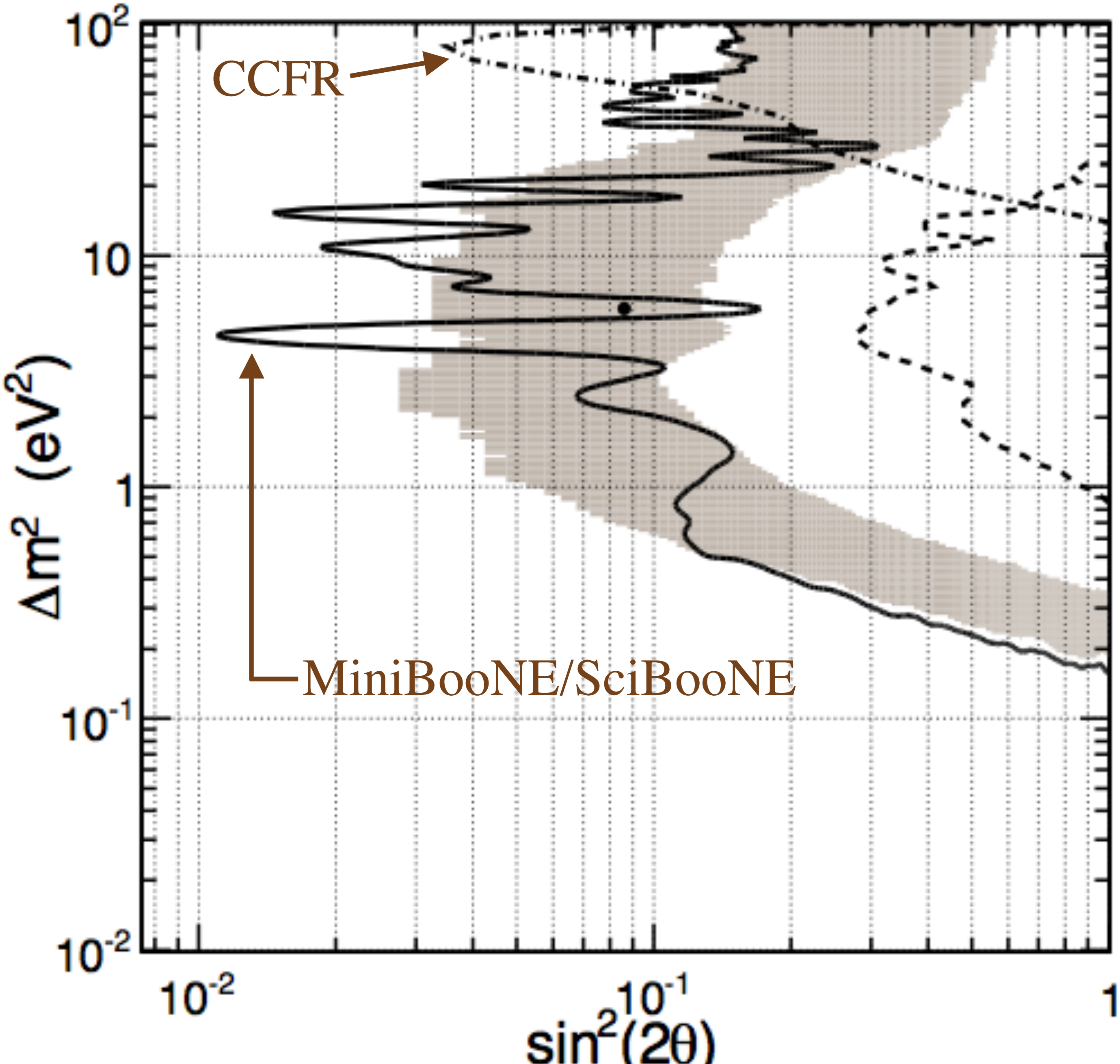
Assuming CPT invariance,

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

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.





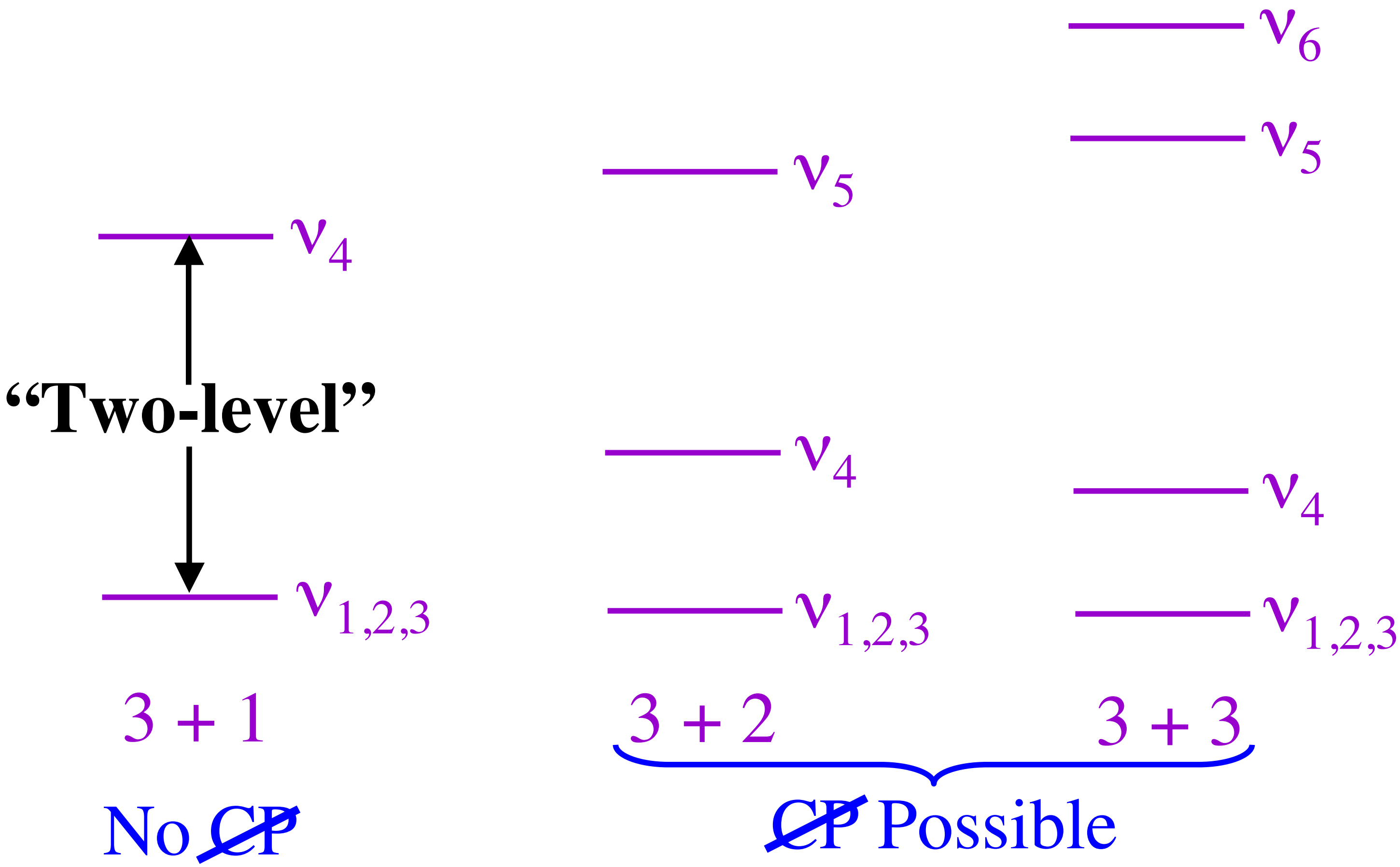
Regions excluded at 90% CL by no $\overline{\nu}_\mu$ disappearance

Two-level mass spectrum assumed

From 1208.0322

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 —

$$\underbrace{P\left(\bar{\nu}_e \rightarrow \bar{\nu}_{\not e}\right)}_{\text{Perhaps 0.06 from reactors}} \geq \underbrace{P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)}_{\text{Reported as 0.0026 by LSND}} .$$

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

Assuming a **3 + 1** spectrum —

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

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

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

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

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

$$\boxed{P(\bar{\nu}_\mu \to \cancel{\bar{\nu}_\mu}) P(\bar{\nu}_e \to \cancel{\bar{\nu}_e}) \cong 2P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

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

The Constraint (?) From Cosmology

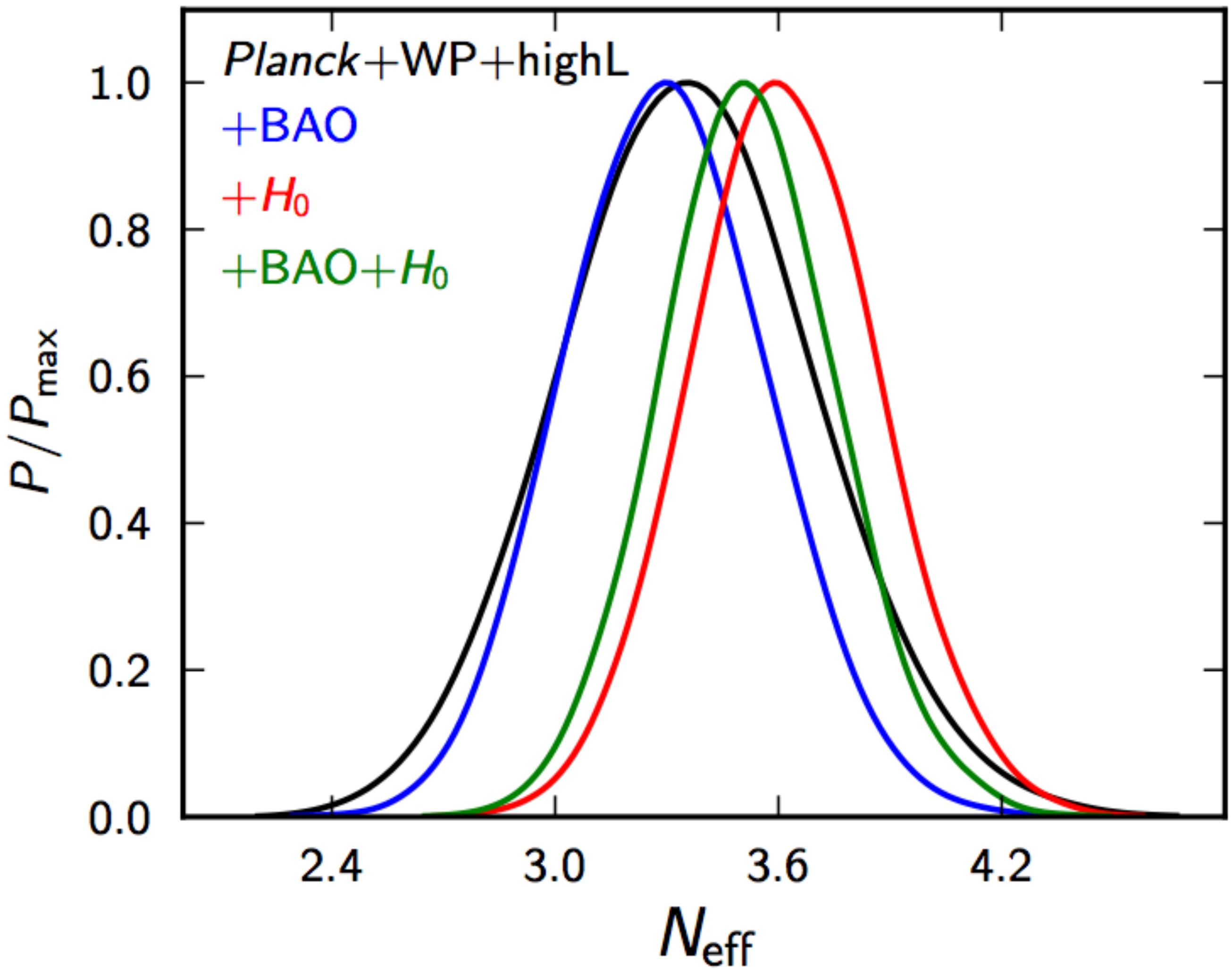
Big Bang Nucleosysthesis (BBN) and CMB
anisotropies count the effective number
of relativistic degrees of freedom, N_{eff}, at early times.

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.

There is recent evidence from ***Planck*** CMB data on N_{eff} .

The favored N_{eff} depends on whether one takes into account a competing value of the Hubble constant H_0.



So, is $N_{eff} = 3$, or more than 3?

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

Large Scale Structure in the universe and the CMB probe this sum of the neutrino masses, ***assuming*** that all ν_i have thermalized in the early universe.

$$\sum_i m(\nu_i) < 0.23 \text{ eV} \quad \begin{pmatrix} \text{Planck + WP +} \\ \text{high L + BAO} \end{pmatrix}$$

Remember this?

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)

(Kopp, Machado, Maltoni, Schwetz)

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.

Also, the $\overset{(-)}{\nu}_\mu$ disappearance limits are too small for the amount of appearance .

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, and the $\overset{(-)}{\nu}_{\mu}$ disappearance limits are too small for the amount of appearance.

A 3 + 3 spectrum contains one more mass splitting, and improves the fit, but there is still tension between appearance and disappearance data.

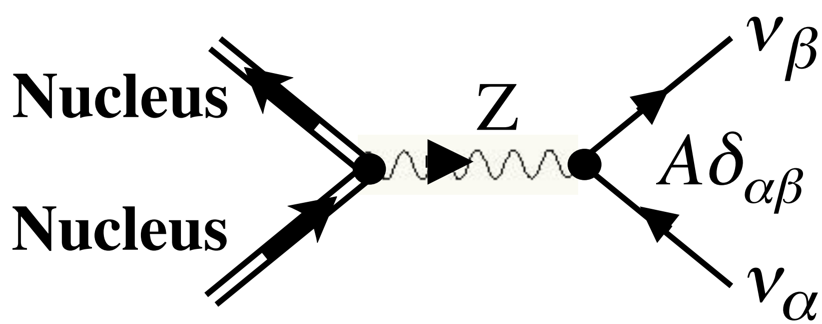
(Perhaps the MiniBooNE low-energy appearance excess is not due to oscillation.)

So, Are There Sterile Neutrinos?

Ideas For Future Experiments

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

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

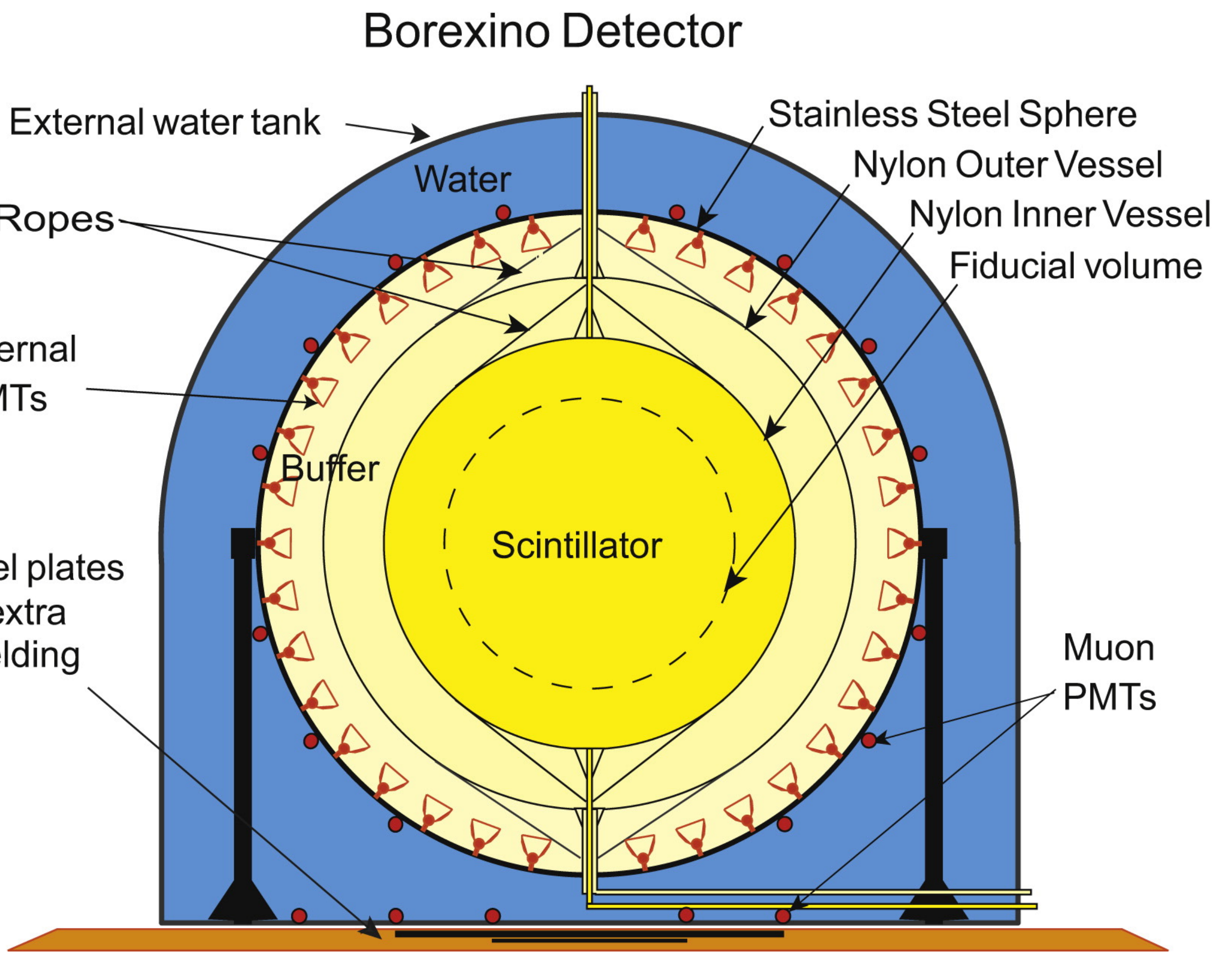
Kinetic energy of nuclear recoil ~ keV.

Detection via DM-inspired detectors.

(Anderson et al.)

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

A Radioactive Source Near a Detector



Place a ^{51}Cr ν_e source near Borexino.

Detect ν_e via $\nu_e - e$ scattering.

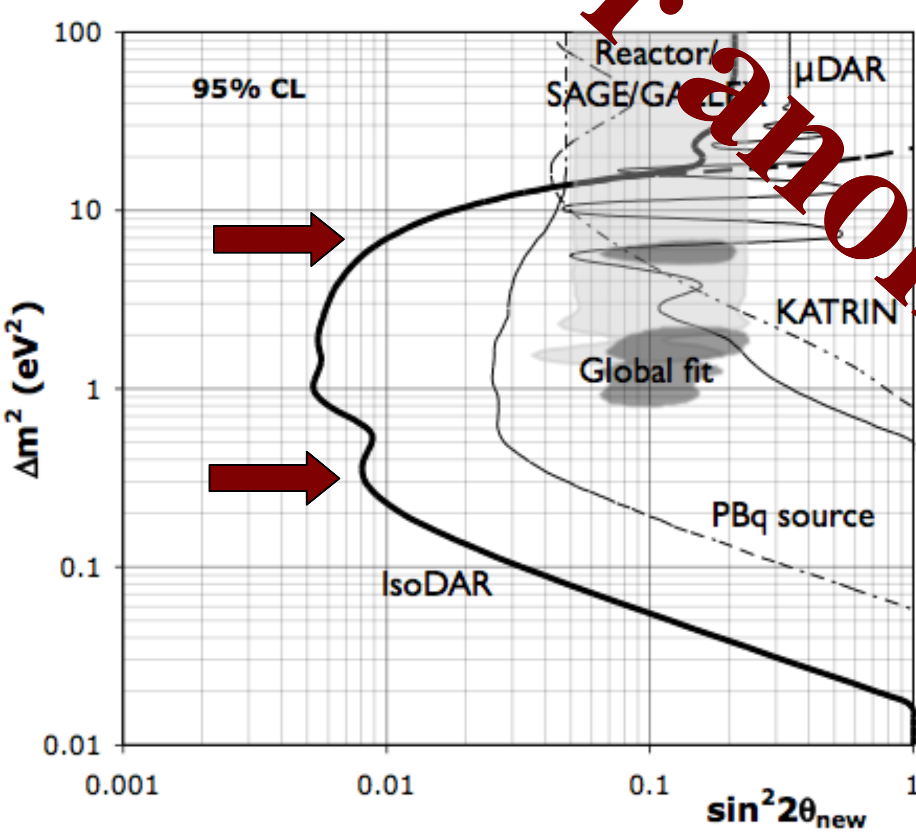
(Borexino Intensity Frontier Whitepaper)

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

Is reactor anomaly real?

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

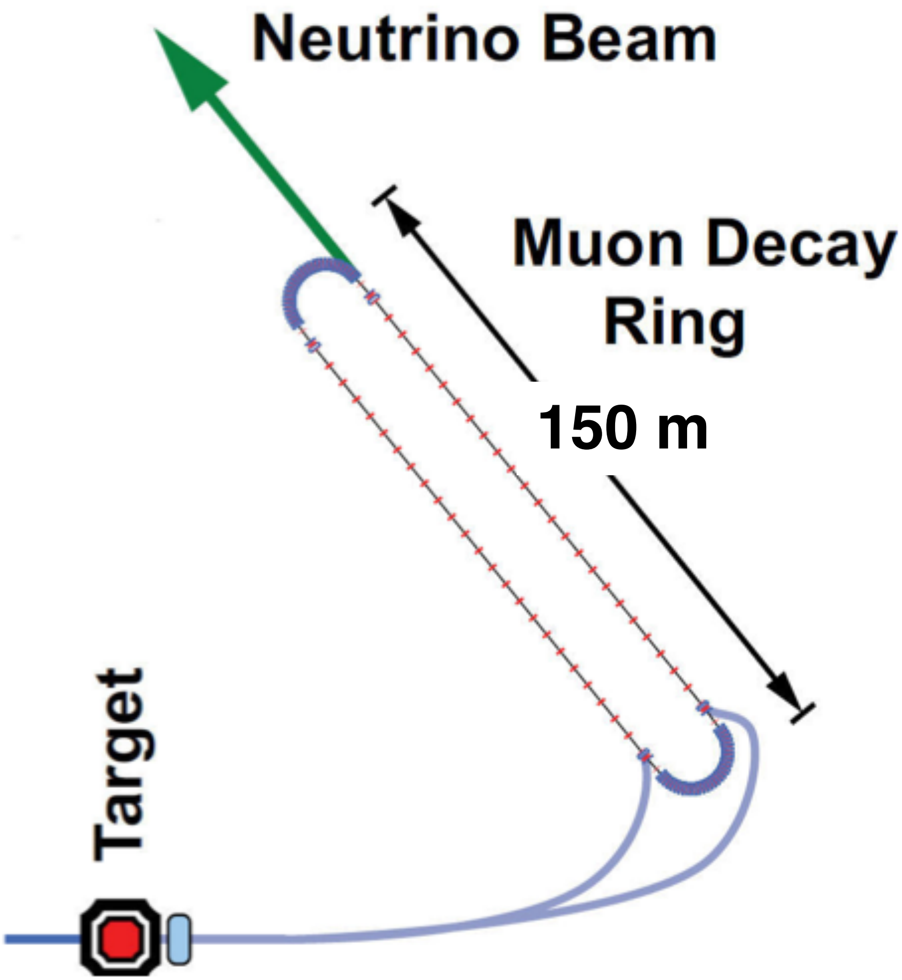
Use a kton-scale scintillator detector to detect the $\overline{\nu}_e$ via $\overline{\nu}_e\, p \to e^+ n$.



Sensitivity to $\overline{\nu}_e$ disappearance (the reactor anomaly) in a 5-year run

(Bungau et al.)

A Very Low Energy Neutrino Factory (νSTORM)



E_μ ~ 4 GeV

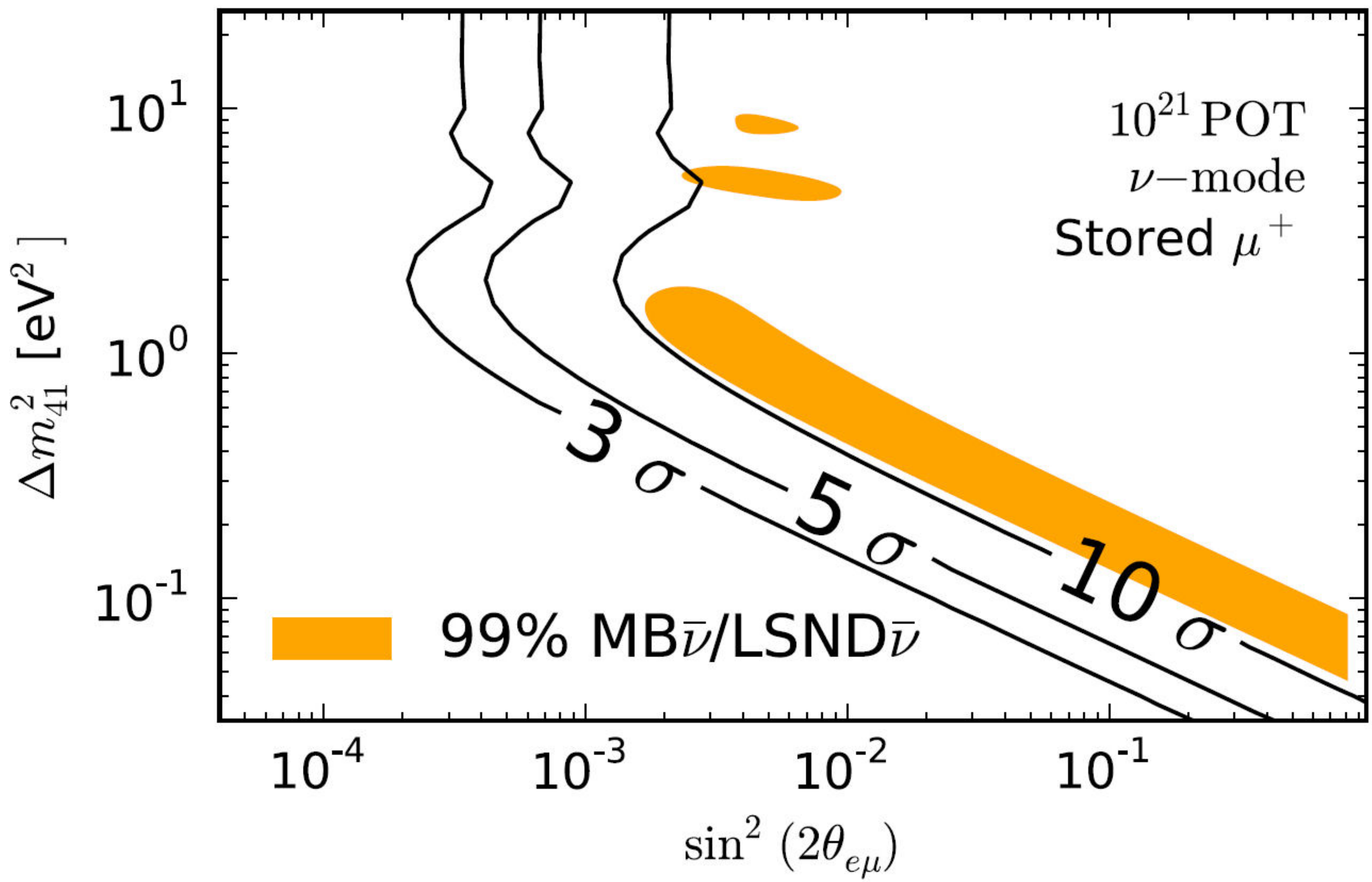
If store μ^+, can study—

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

followed by —

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

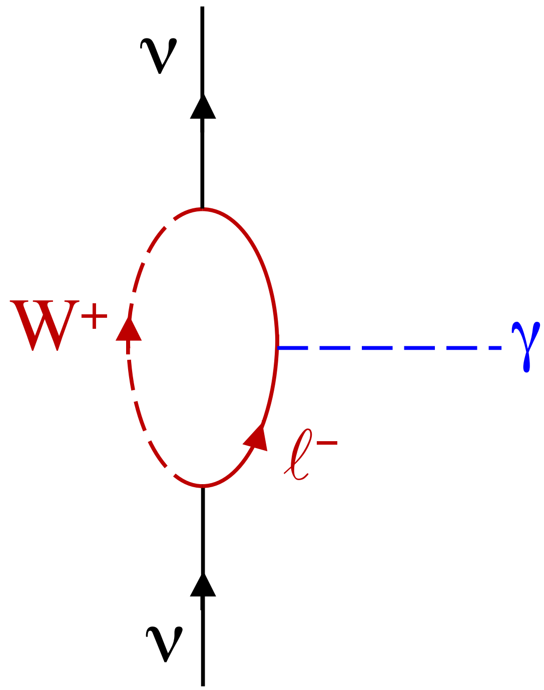
LSND reported $\bar{\nu}_\mu \to \bar{\nu}_e$. $P(\nu_e \to \nu_\mu) \underset{\text{CPT}}{=} P(\bar{\nu}_\mu \to \bar{\nu}_e)$


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.)

What Are the Neutrino **Dipole Moments**?

In the Standard Model, loop diagrams like —



produce, for a *Dirac* neutrino of mass m_ν,
a magnetic dipole moment —

$$\mu_\nu = 3 \times 10^{-19} \, (m_\nu/1\mathrm{eV}) \, \mu_B$$

(Marciano, Sanda; Lee, Shrock; Fujikawa, Shrock)

A *Majorana* neutrino cannot have a magnetic or electric dipole moment:

$$\vec{\mu}\left[\ \underset{e^+}{\Uparrow}\ \right] = -\,\vec{\mu}\left[\ \underset{e^-}{\Uparrow}\ \right]$$

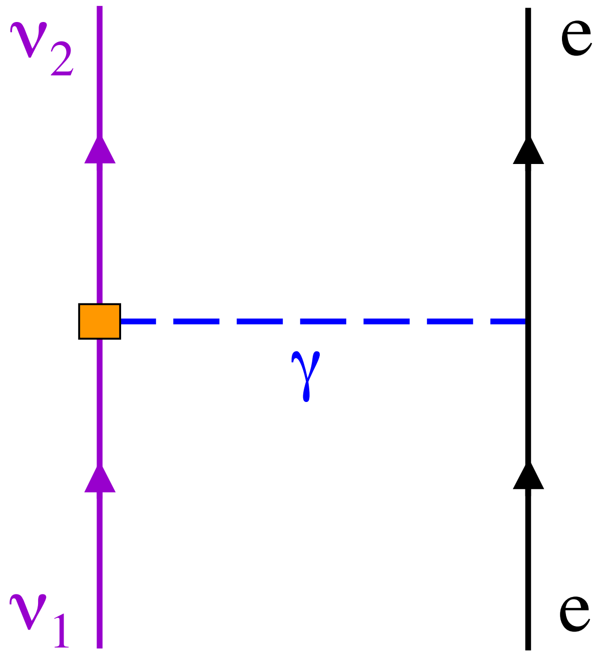
But for a Majorana neutrino,

$$\overline{\nu_i} = \nu_i$$

Therefore,

$$\vec{\mu}\,[\overline{\nu_i}] = \vec{\mu}\,[\nu_i] = 0$$

Both *Dirac* and *Majorana* neutrinos can have ***transition*** dipole moments, leading to —



One can look for the dipole moments this way.

To be visible, they would have to *vastly* exceed Standard Model predictions.

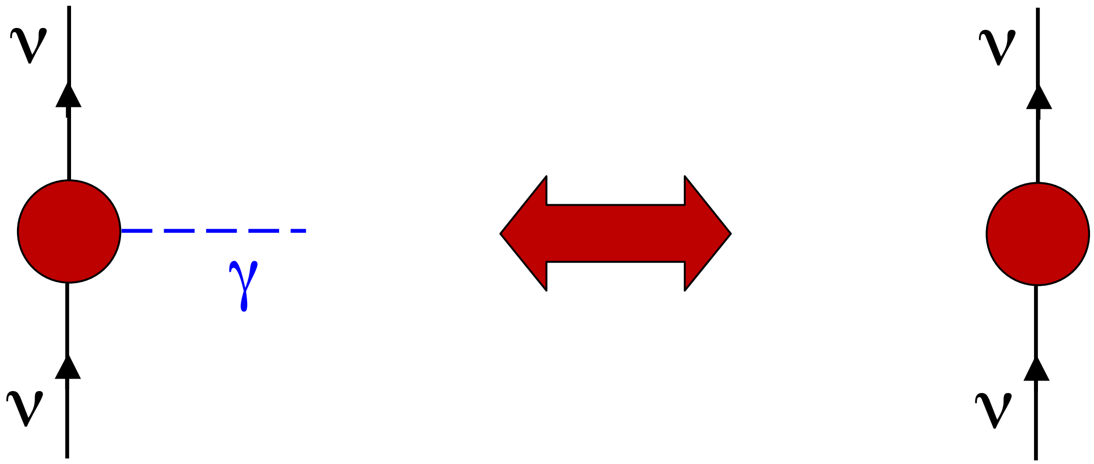
Present Bounds On Dipole Moments

$$\text{Upper bound} = \begin{cases} 1.3 \times 10^{-11}\, \mu_B & ;\ \text{Wong et al. (Reactor)} \\ 5.4 \times 10^{-11}\, \mu_B & ;\ \text{Borexino (Solar)} \\ 3 \times 10^{-12}\, \mu_B & ;\ \text{Raffelt (Stellar E loss)} \end{cases}$$

New Physics can produce larger dipole moments than the $\sim 10^{-20}\mu_B$ SM ones.

But the dipole moments cannot be arbitrarily large.

The Dipole Moment – Mass Connection



Dipole Moment

Mass Term

$$\mu_\nu \sim \frac{eX}{\underbrace{\Lambda}_{\text{Scale of New Physics}}}$$

$$m_\nu \sim X\Lambda$$

$$\Rightarrow \quad m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

(Bell *et al.*)

Any dipole moment leads to a contribution to the neutrino mass that grows with the scale Λ of the new physics behind the dipole moment.

The dipole moment must not be so large as to lead to a violation of the upper bound on neutrino masses.

The constraint —

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

can be evaded by some new physics.

But the evasion can only go so far.

In the *Majorana* case, a *symmetry* suppresses the contribution of the dipole moment to the neutrino mass. So a bigger dipole moment is permissible. One finds —

For *Dirac* neutrinos, $\mu < 10^{-15}\, \mu_B$ for $\Lambda > 1$ TeV

For *Majorana* neutrinos, $\mu <$ ***Present Bound***

(Bell, Cirigliano, Davidson, Gorbahn, Gorchtein, Ramsey-Musolf, Santamaria, Vogel, Wise, Wang)

An observed μ below the present bound but well above $10^{-15}\ \mu_B$ would imply that neutrinos are Majorana particles.

A dipole moment that large requires L-violating new physics $\lesssim$ 1000 TeV.

Neutrinoless double beta decay at the planned level of sensitivity only requires this new physics at ~ 10^{15} GeV, near the Grand Unification scale.

Searching for $0\nu\beta\beta$ is the more conservative way to probe whether $\bar{\nu} = \nu$.

But there may be surprises!

Good luck!