Neutrino Phenomenology

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INSS
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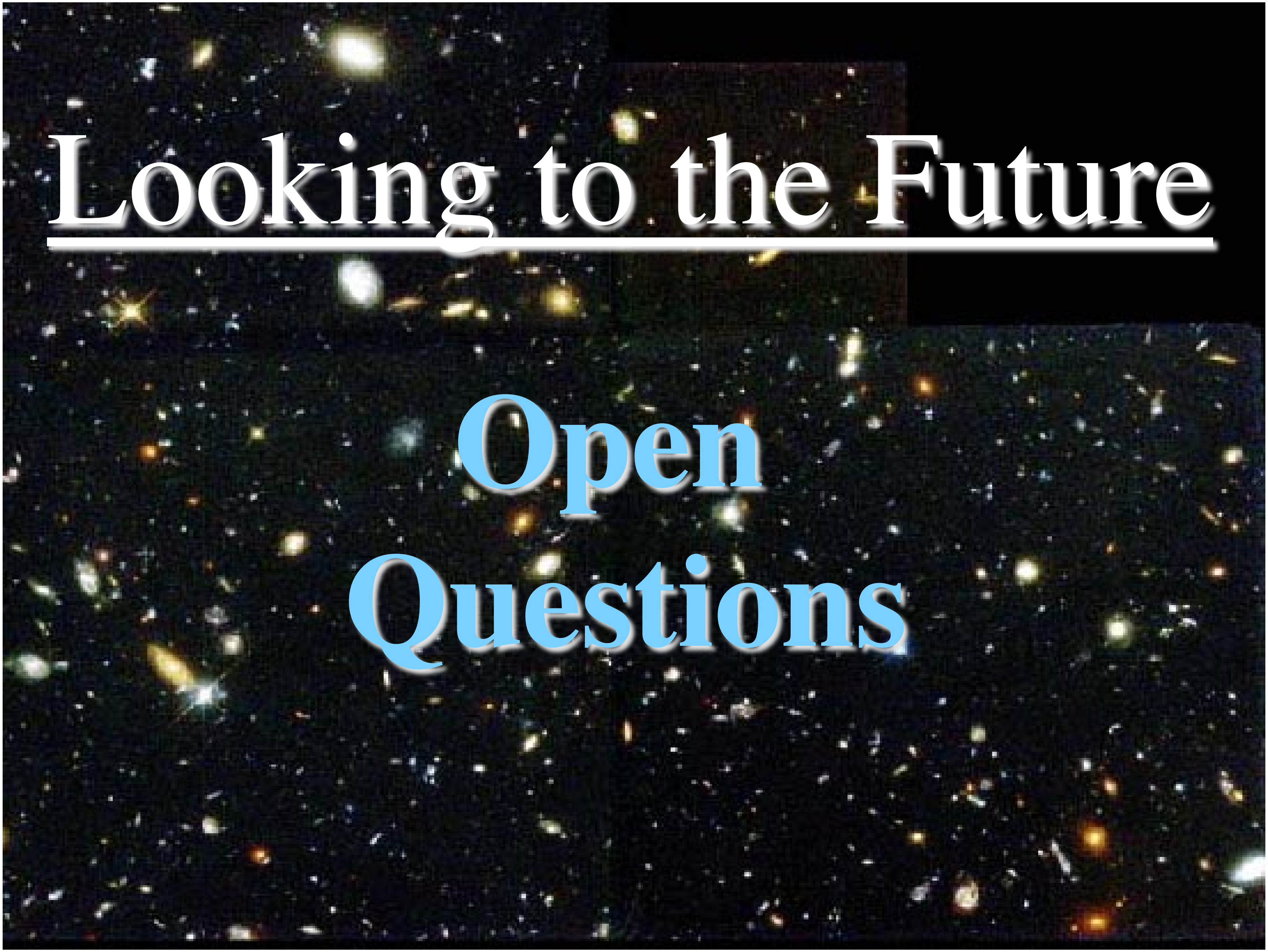
Part 3

NASA Hubble Photo



Looking to the Future

Open Questions

- Do neutrino interactions violate CP?

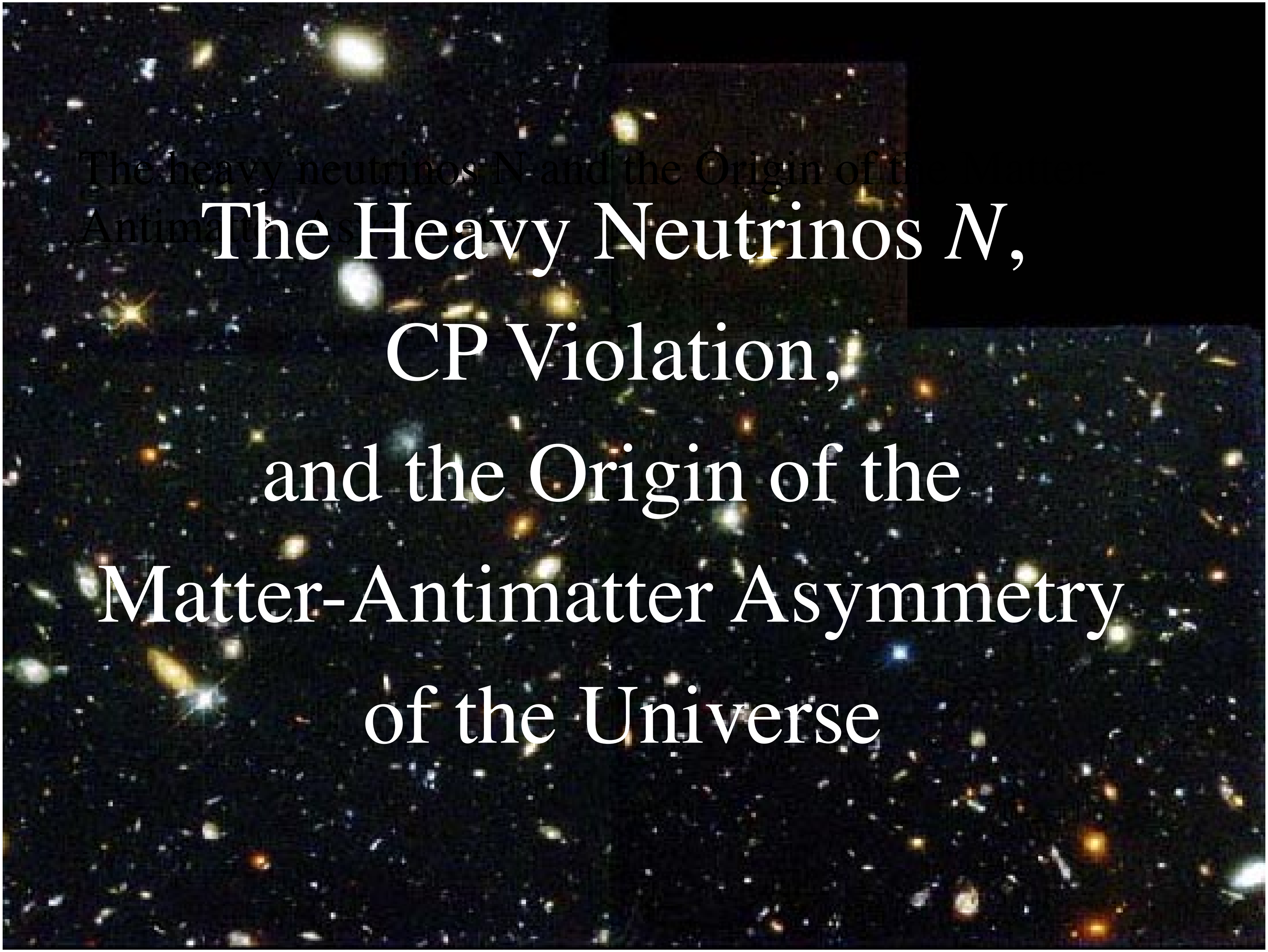
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

- Is CP violation involving neutrinos the key to understanding the matter – antimatter asymmetry of the universe?

- What can neutrinos and the universe tell us about one another?

- Are there ***more*** than 3 mass eigenstates?
  - Are there non-weakly-interacting “sterile” neutrinos?

- Do neutrinos break the rules?
  - Non-Standard-Model interactions?
  - Violation of Lorentz invariance?
  - Violation of CPT invariance?
  - Departures from quantum mechanics?



The heavy neutrinos N and the Origin of th
Antima As

The Heavy Neutrinos *N*,
CP Violation,
and the Origin of the
Matter-Antimatter Asymmetry
of the Universe

The Cosmic Puzzle

Today: $B \equiv \#(\text{Baryons}) - \#(\text{Antibaryons}) \neq 0$.

Standard cosmology: Right after the Big Bang, $B = 0$.

Also, $L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}) = 0$.

How did $B = 0 \Longrightarrow B \neq 0$?

Sakharov: $B = 0 \Longrightarrow B \neq 0$ requires $\cancel{C}$ and $\cancel{CP}$.

$\not{C}$ is easy to achieve, but the required degree and kind of $\cancel{CP}$ is harder.

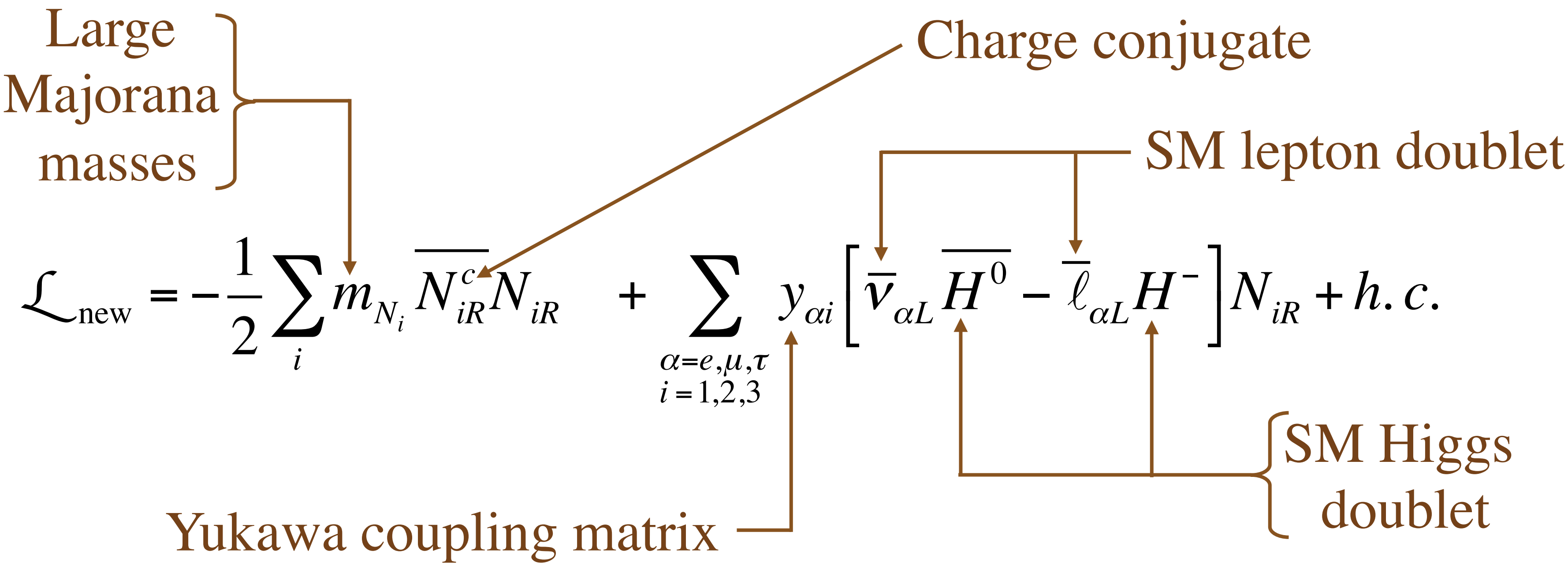
The $\cancel{CP}$ in the quark mixing matrix, seen in B and K decays, leads to much too small a $B - \overline{B}$ asymmetry.

If ***quark*** $\cancel{CP}$ cannot generate the observed $B - \overline{B}$ asymmetry, can some scenario involving ***leptons*** do it?

The candidate scenario: ***Leptogenesis***, a very natural consequence of the See-Saw picture.

(Fukugita, Yanagida)

The straightforward (type-I) See-Saw model adds to the SM 3 heavy neutrinos N_i, with —



Large Majorana masses

Charge conjugate

SM lepton doublet

$$\mathcal{L}_{\text{new}} = -\frac{1}{2}\sum_i m_{N_i}\,\overline{N^c_{iR}}N_{iR} + \sum_{\substack{\alpha=e,\mu,\tau\\ i=1,2,3}} y_{\alpha i}\left[\bar{\nu}_{\alpha L}\overline{H^0} - \bar{\ell}_{\alpha L}H^-\right]N_{iR} + h.c.$$

SM Higgs doublet

Yukawa coupling matrix

The Yukawa interaction causes the decays —

$$N \to \ell^- + H^+,\ \ N \to \ell^+ + H^-,$$

$$N \to \nu + H^0,\ \ N \to \bar{\nu} + \overline{H^0}.$$

($\overline{N} = N$, so the decays in each line are C and CP mirror images.)

The N_i are heavy, but they would have been made during the ***hot*** Big Bang.

They would then have quickly decayed via the decay modes we just identified.

Phases in the Yukawa coupling matrix y would have led to $\cancel{C}$ and $\cancel{CP}$ effects.

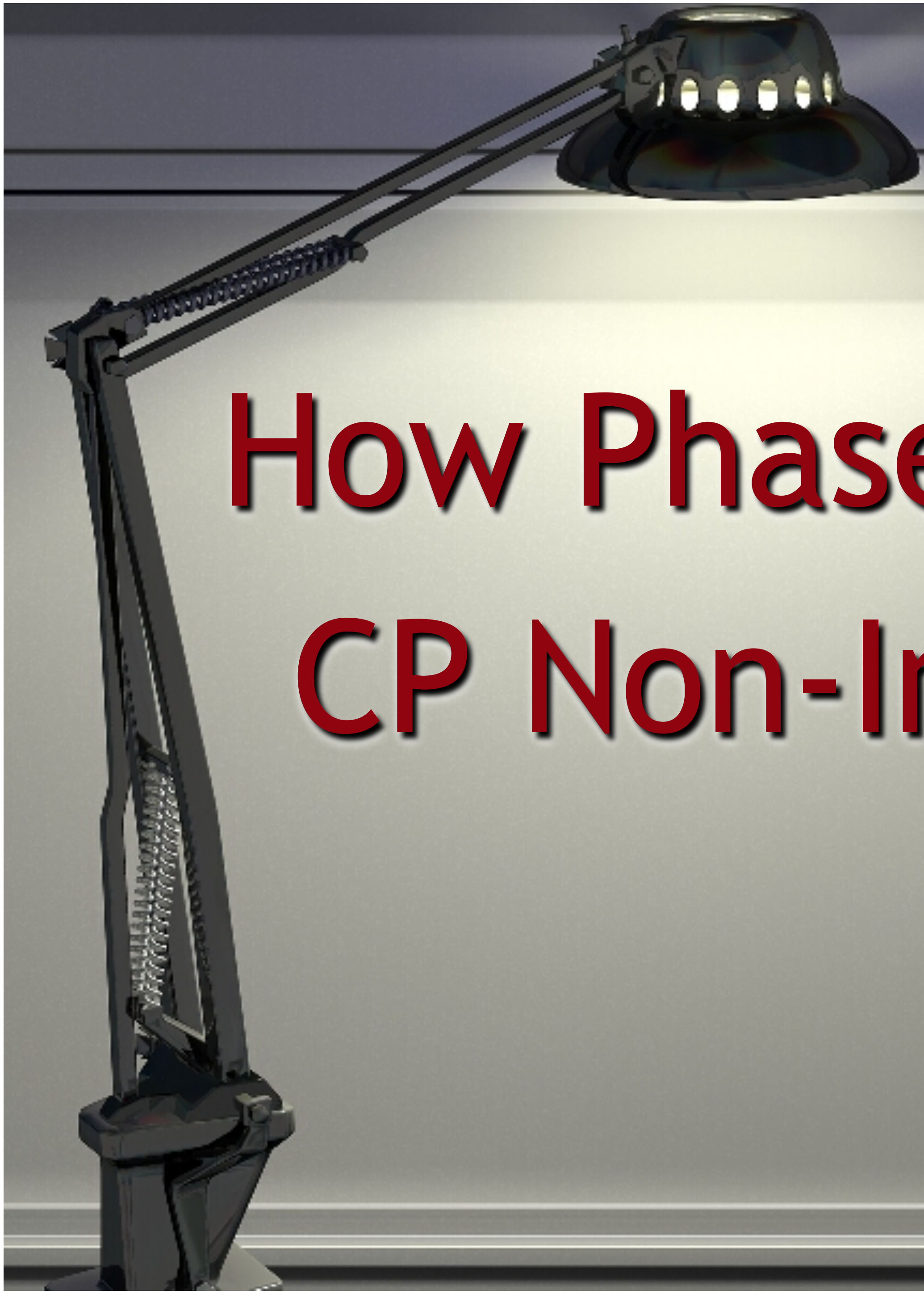
In particular, such phases would have led to —

$$\Gamma\left(N \rightarrow \ell^- + H^+\right) \neq \Gamma\left(N \rightarrow \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \rightarrow \nu + H^0\right) \neq \Gamma\left(N \rightarrow \overline{\nu} + \overline{H^0}\right)$$

$\cancel{C}$ and $\cancel{CP}$



How Phases Lead To CP Non-Invariance

~~CP~~ ***always*** comes from ***phases***.

Therefore, ~~CP~~ always requires an ***interference*** between (at least) two amplitudes.

For example, an interference between two Feynman diagrams.

Let us consider how a CP-violating rate difference between two CP-mirror-image processes, such as $B^+ \to D^0 K^+$ and $B^- \to \overline{D}^0 K^-$, arises.

Suppose some process P has the amplitude —

$$A = \underbrace{M_1}_{\text{CP-invariant magnitude}} e^{i\underbrace{\theta_1}_{\text{CP-even “strong” phase}}} e^{i\underbrace{\delta_1}_{\text{CP-odd “weak” phase from constants}}} + M_2 e^{i\theta_2} e^{i\delta_2}$$

Then the CP-mirror-image process $\overline{\mathrm{P}}$ has the amplitude —

$$\overline{A} = M_1 e^{i\theta_1} e^{-i\delta_1} + M_2 e^{i\theta_2} e^{-i\delta_2}$$

Then the rates for $\overline{\mathrm{P}}$ and P differ by —

$$\overline{\Gamma} - \Gamma = \left|\overline{A}\right|^2 - \left|A\right|^2 = 4 M_1 M_2 \sin\left(\theta_1 - \theta_2\right) \sin\left(\delta_1 - \delta_2\right)$$

$$\overline{\Gamma} - \Gamma = \left|\overline{A}\right|^2 - \left|A\right|^2 = 4 M_1 M_2 \sin\left(\theta_1 - \theta_2\right) \sin\left(\delta_1 - \delta_2\right)$$

A CP-violating rate difference requires 3 ingredients:

- Two interfering amplitudes
- These two amplitudes must have different CP-even phases
- These two amplitudes must have different CP-odd phases

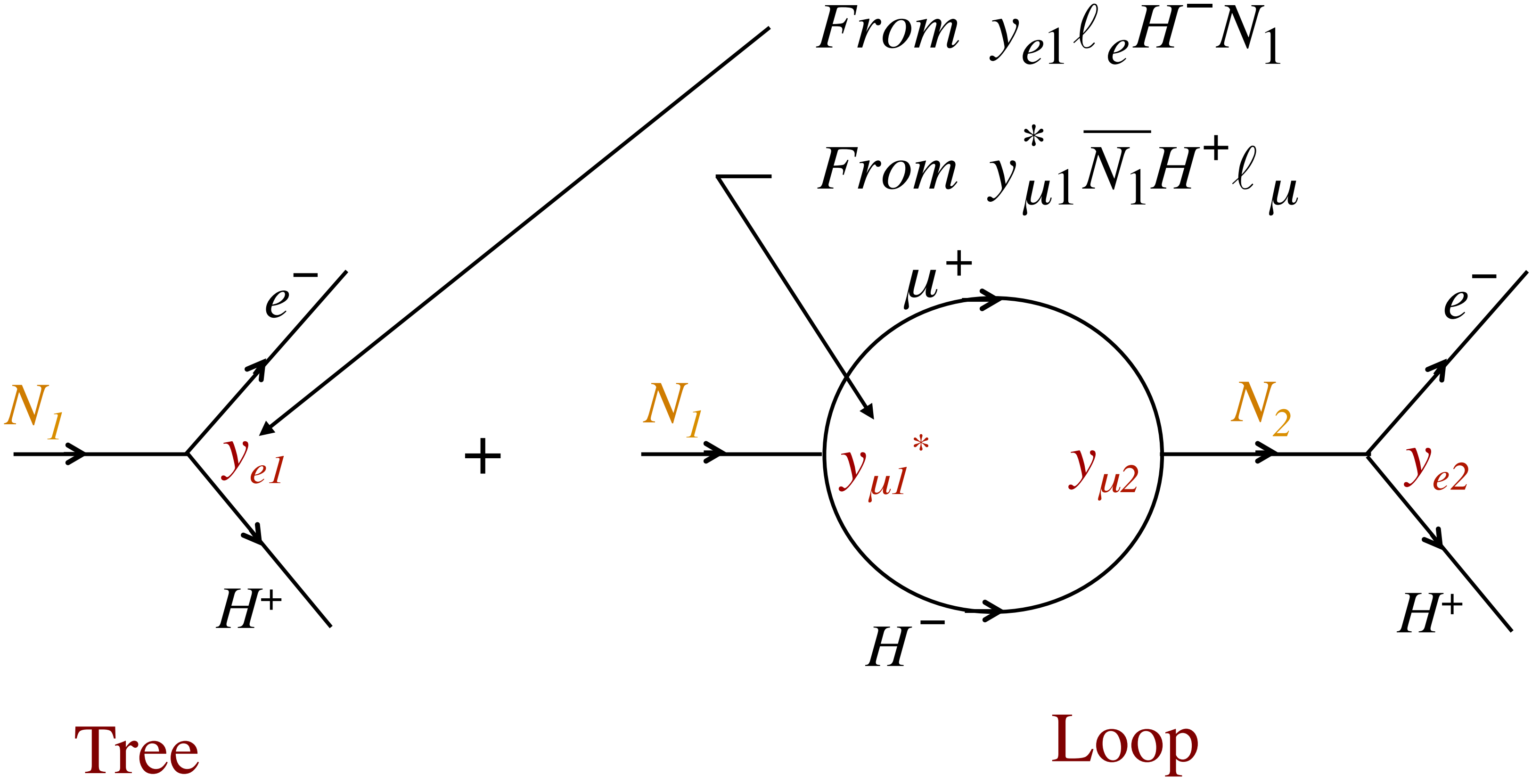
How Do $\cancel{CP}$ Inequalities Between *N* Decay Rates Come About?

Let us look at an example.

This example illustrates that $\cancel{CP}$ in ***any decay***
always involves amplitudes ***beyond*** those
of lowest order in the Hamiltonian.

From $y_{e1}\overline{\ell_e}H^- N_1$

From $y^*_{\mu 1}\overline{N_1}H^+\ell_\mu$



$$\Gamma\left(N_1 \to e^- + H^+\right) = \left| y_{e1} K_{\text{Tree}} + y^*_{\mu 1} y_{\mu 2} y_{e2} K_{\text{Loop}} \right|^2$$

Kinematical factors

$$\Gamma\left(N_1 \to e^- + H^+\right) = \left| y_{e1} K_{\text{Tree}} + y_{\mu 1}^* y_{\mu 2} y_{e2} K_{\text{Loop}} \right|^2$$

When we go to the CP-mirror-image decay, $N_1 \to e^+ + H^-$, all the coupling constants get complex conjugated, but the kinematical factors do not change.

$$\Gamma\left(N_1 \to e^+ + H^-\right) = \left| y_{e1}^* K_{\text{Tree}} + y_{\mu 1} y_{\mu 2}^* y_{e2}^* K_{\text{Loop}} \right|^2$$

All three ingredients needed for ~~CP~~ are present.

$$\begin{aligned} &\Gamma\left(N_1 \to e^- + H^+\right) - \Gamma\left(N_1 \to e^+ + H^-\right) \\ &= 4\,\text{Im}\left(y_{e1}^* y_{\mu 1}^* y_{e2} y_{\mu 2}\right) \text{Im}\left(K_{\text{Tree}} K_{\text{Loop}}^*\right) \end{aligned}$$

The inequalities —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \overline{\nu} + \overline{H^0}\right)$$

violate CP in the leptonic sector, and violate lepton number L.

Starting with a universe with $L = 0$, these decays would have produced one with $L \neq 0$.

Next —

The Standard-Model ***Sphaleron*** process,
which does not conserve Baryon Number *B*,
or Lepton Number *L*, but does conserve *B* – *L*, acts.

$B_i = 0$

$L_i \neq 0$

Sphaleron Process

$B_f \cong -\frac{1}{3} L_i$

$L_f \cong \frac{2}{3} L_i \cong -2B_f$

Initial state
from N decays

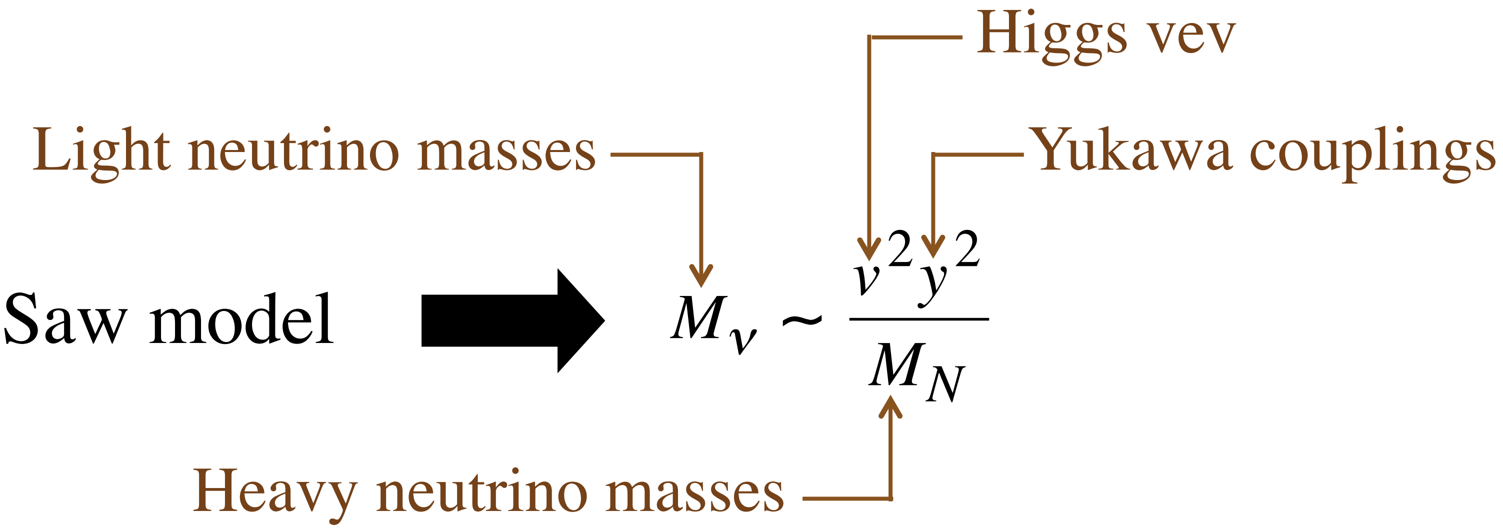
Final state

***There is now a nonzero** Baryon Number B.*

There are baryons, but ~ no antibaryons.

***Reasonable couplings y give the observed value of** B.*

What *N* masses are required?



Higgs vev

Light neutrino masses

Yukawa couplings

The See-Saw model ⇒ $$M_\nu \sim \frac{v^2 y^2}{M_N}$$

Heavy neutrino masses

The light neutrino masses $M_\nu \sim 0.1$ eV.

$v = 174$ GeV.

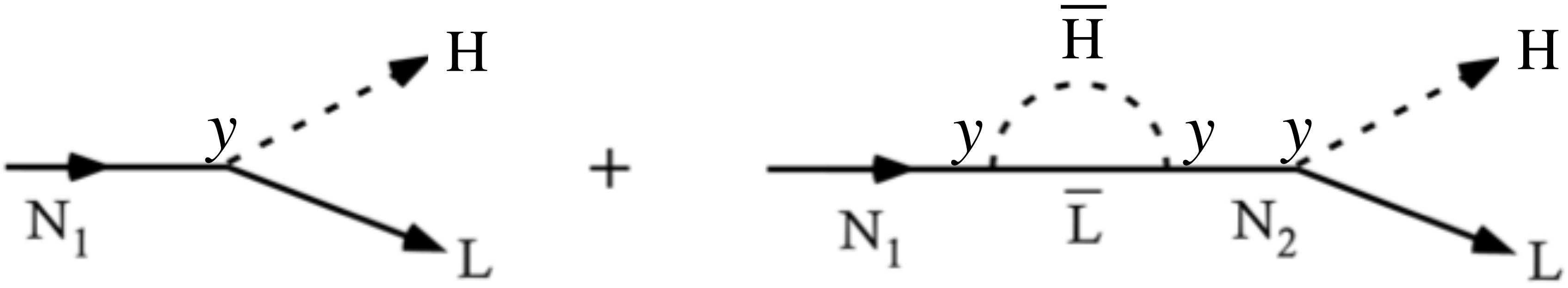
y^2 is constrained by the observed Baryon Number per unit volume.

The CP-violating asymmetry between the N decay rates,

$$\epsilon_{CP} \equiv \frac{\Gamma(N \rightarrow \overset{\nu \text{ or } \ell^-}{\downarrow{L}}\,\overset{H^0 \text{ or } H^+}{\downarrow{H}}) - \Gamma(N \rightarrow \overline{L}\,\overline{H})}{\Gamma(N \rightarrow LH) + \Gamma(N \rightarrow \overline{L}\,\overline{H})} \quad ,$$

which produces a nonzero Lepton Number,

arises from interference between diagrams such as —



Note ϵ_{CP} is $\propto (y^4/y^2) = y^2$.

Getting the observed Baryon Number requires $y^2 \sim 10^{-5}$.

Then the see-saw relation —

$$M_\nu \sim \frac{v^2 y^2}{M_N}$$

⇒ $M_N \sim 10^{(9-10)}$ GeV.

The heavy neutrinos N cannot be produced at the LHC.

⇒ ***The possibility of Leptogenesis must be explored through experiments with the light neutrinos ν.***

Generically, leptogenesis and light-neutrino ~~CP~~ imply each other.

They both come from phases in the Yukawa coupling matrix y.

Looking the other way: If the oscillation CP phase δ proves to be large, it could explain almost the entire Baryon – Antibaryon asymmetry by itself.

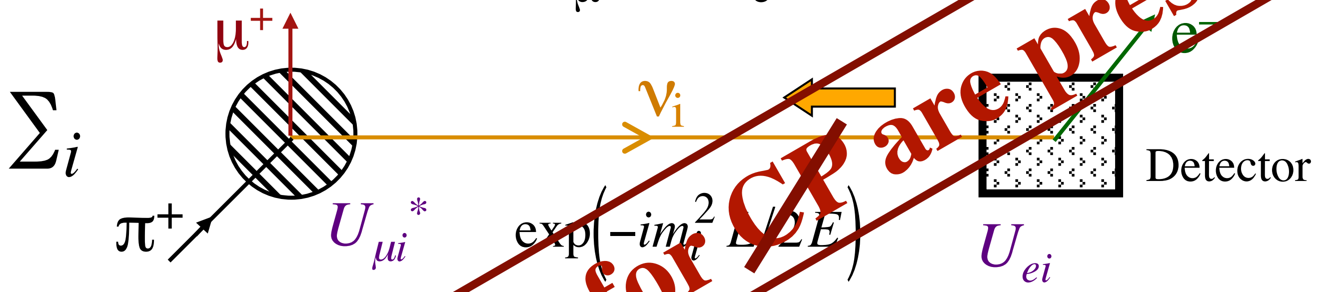
(Pascoli, Petcov, Riotto)

Experiments to look for ~~CP~~
in light-neutrino oscillation
are being contemplated in
Europe, Japan, and the US.

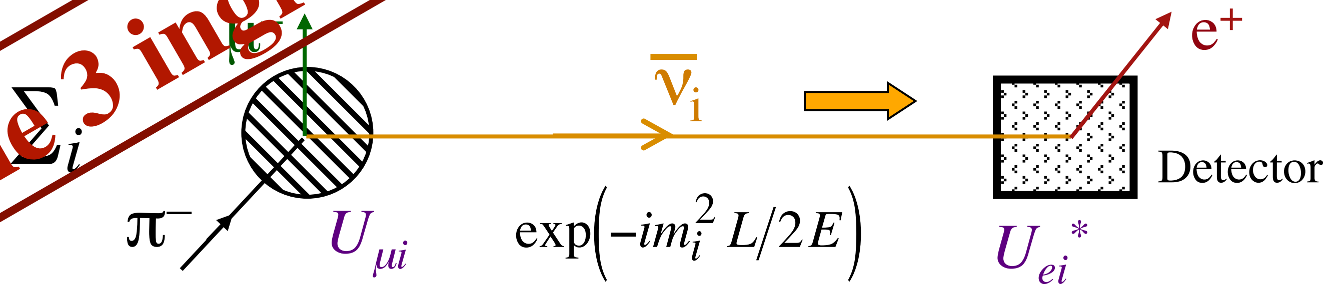
Q : *Can CP violation still lead to* $\mathcal{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq \mathcal{P}(\nu_\mu \rightarrow \nu_e)$ *when* $\bar{\nu} = \nu$*?*

A : *Certainly!*

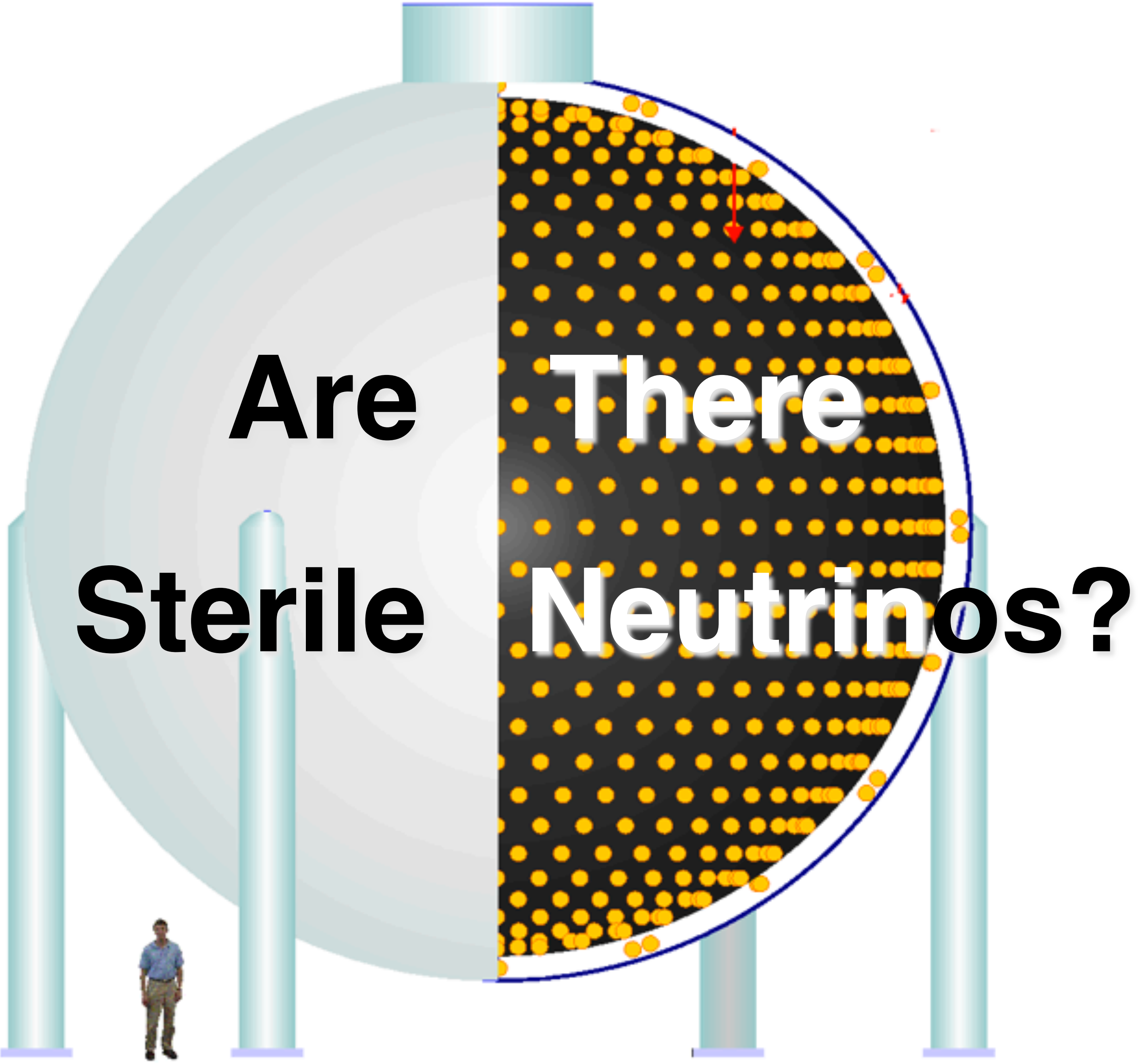
Compare $\nu_\mu \rightarrow \nu_e$



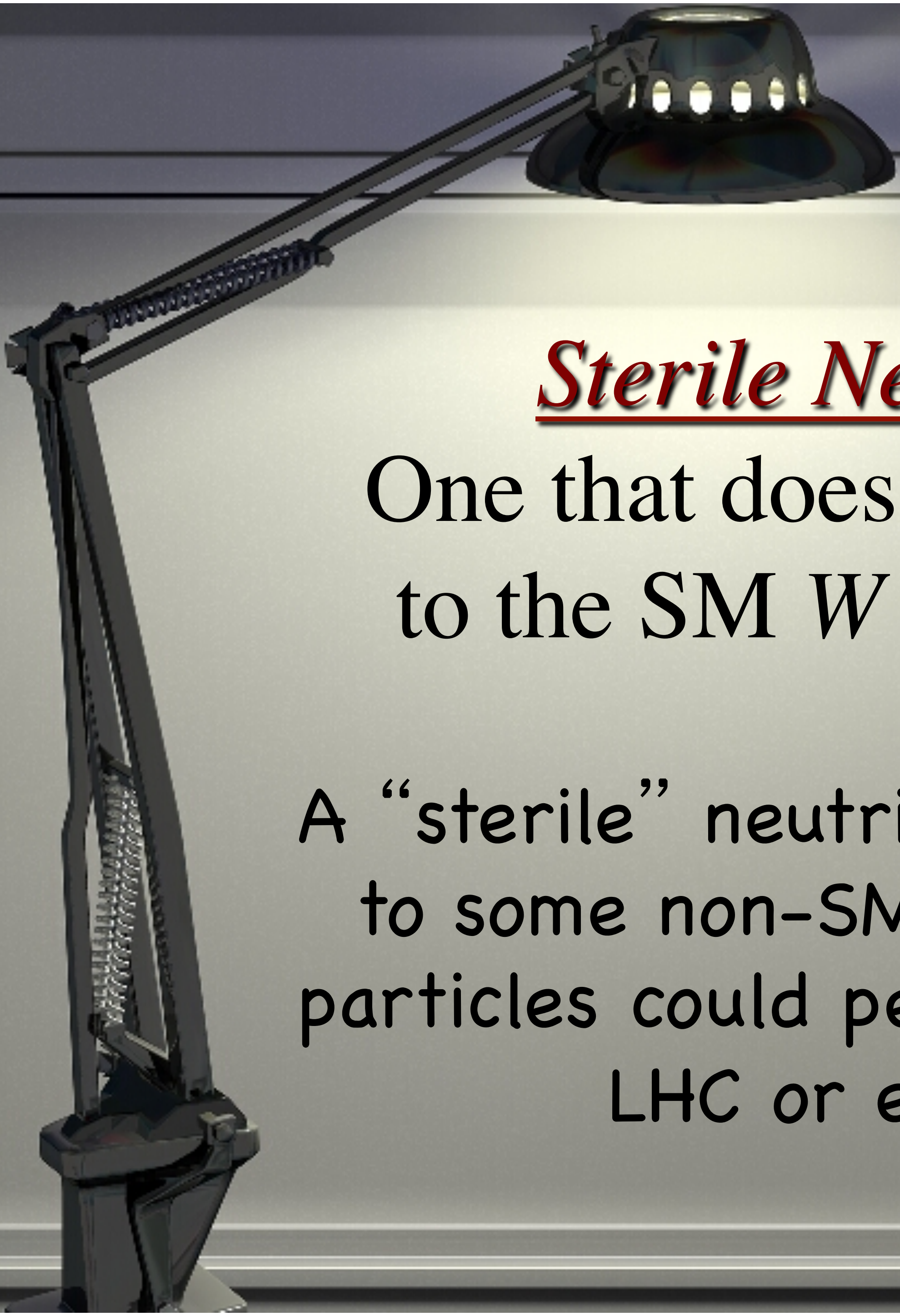
with "$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$"



The 3 ingredients for $\cancel{\text{CP}}$ are present.



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.

The heavy See-Saw partner neutrinos N_i interact with the rest of the world only through the Yukawa coupling —

SM lepton doublet

$$\mathcal{L}_{\text{Yukawa}} = \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} y_{\alpha i}\left[\bar{\nu}_{\alpha L}\overline{H^0} - \bar{\ell}_{\alpha L}H^-\right]N_{iR} + h.c.$$

Yukawa coupling matrix

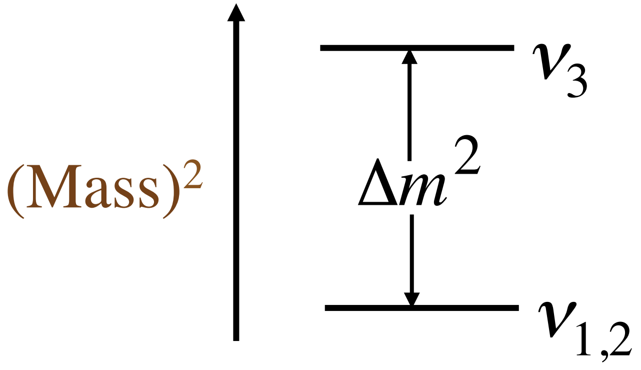
SM Higgs doublet

The N_i do not couple to the SM W or Z boson.

∴ The N_i are sterile neutrinos.

Are there also ***light*** sterile neutrinos with masses ~ 1 eV?

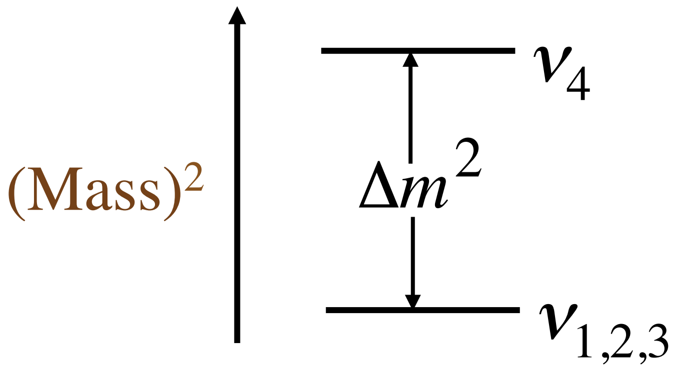
Oscillation When There Is Only 1 Visible Splitting



$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_{\beta\neq\alpha}\right) = \underbrace{\sin^2 2\theta_{\alpha\beta}}_{\text{A parameter between 0 and 1}} \sin^2\left[1.27\,\Delta m^2\left(eV^2\right)\frac{\overset{\text{Travel distance}}{L(km)}}{\underset{\text{Energy}}{E(GeV)}}\right]$$

Oscillation When There Is Only 1 Visible Splitting

Short-baseline experiments



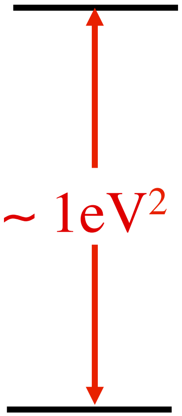
$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_{\beta\neq\alpha}\right) = \underbrace{\sin^2 2\theta_{\alpha\beta}}_{\text{A parameter between 0 and 1}} \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{\overset{\text{Travel distance}}{L(km)}}{\underset{\text{Energy}}{E(GeV)}}\right]$$

The Hint From LSND

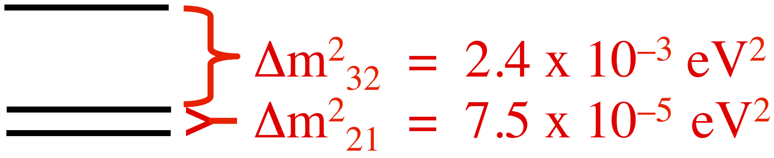
The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

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

From μ^+ decay at rest; E ~ 30 MeV



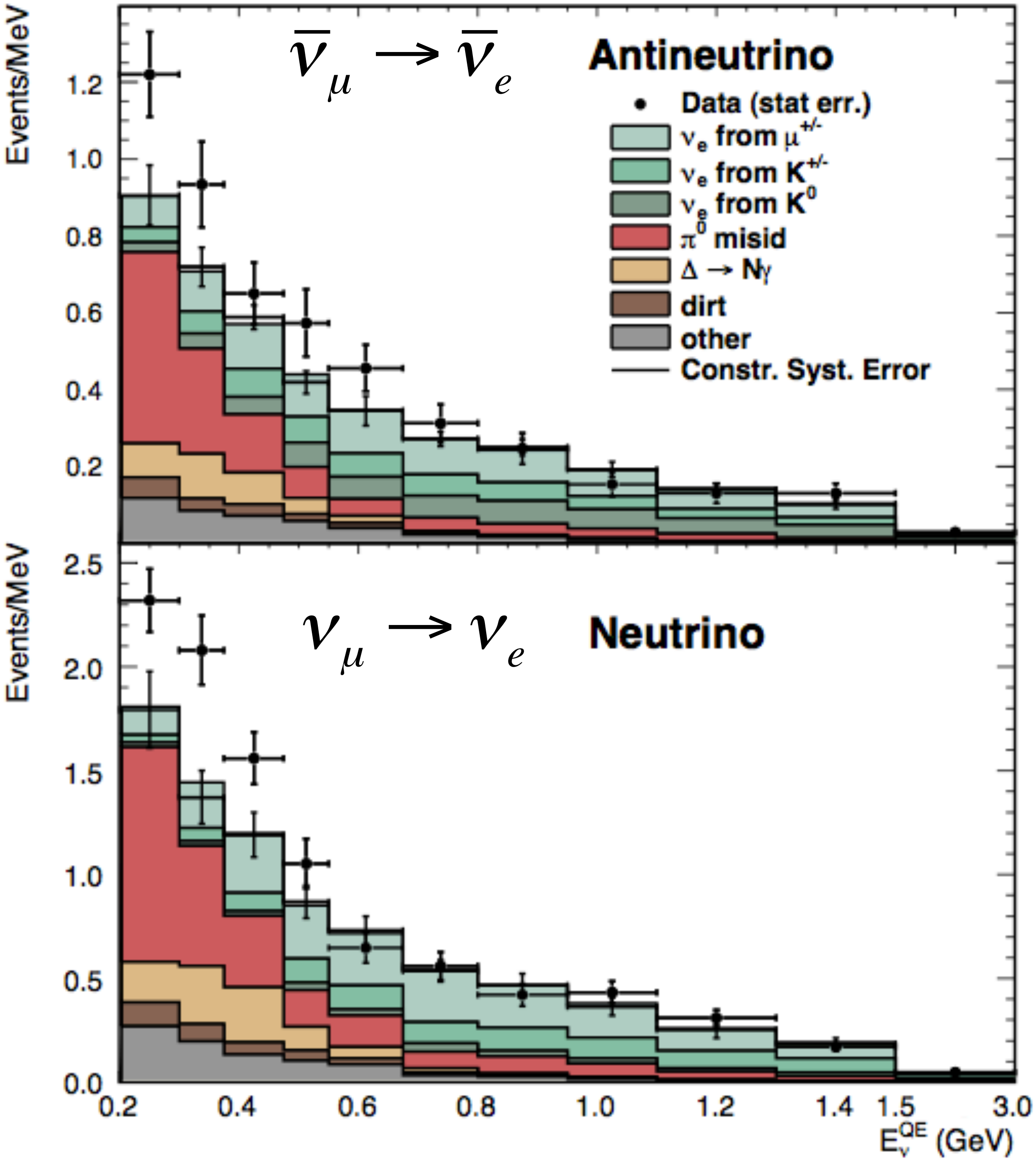
in contrast to



At least **4** mass eigenstates

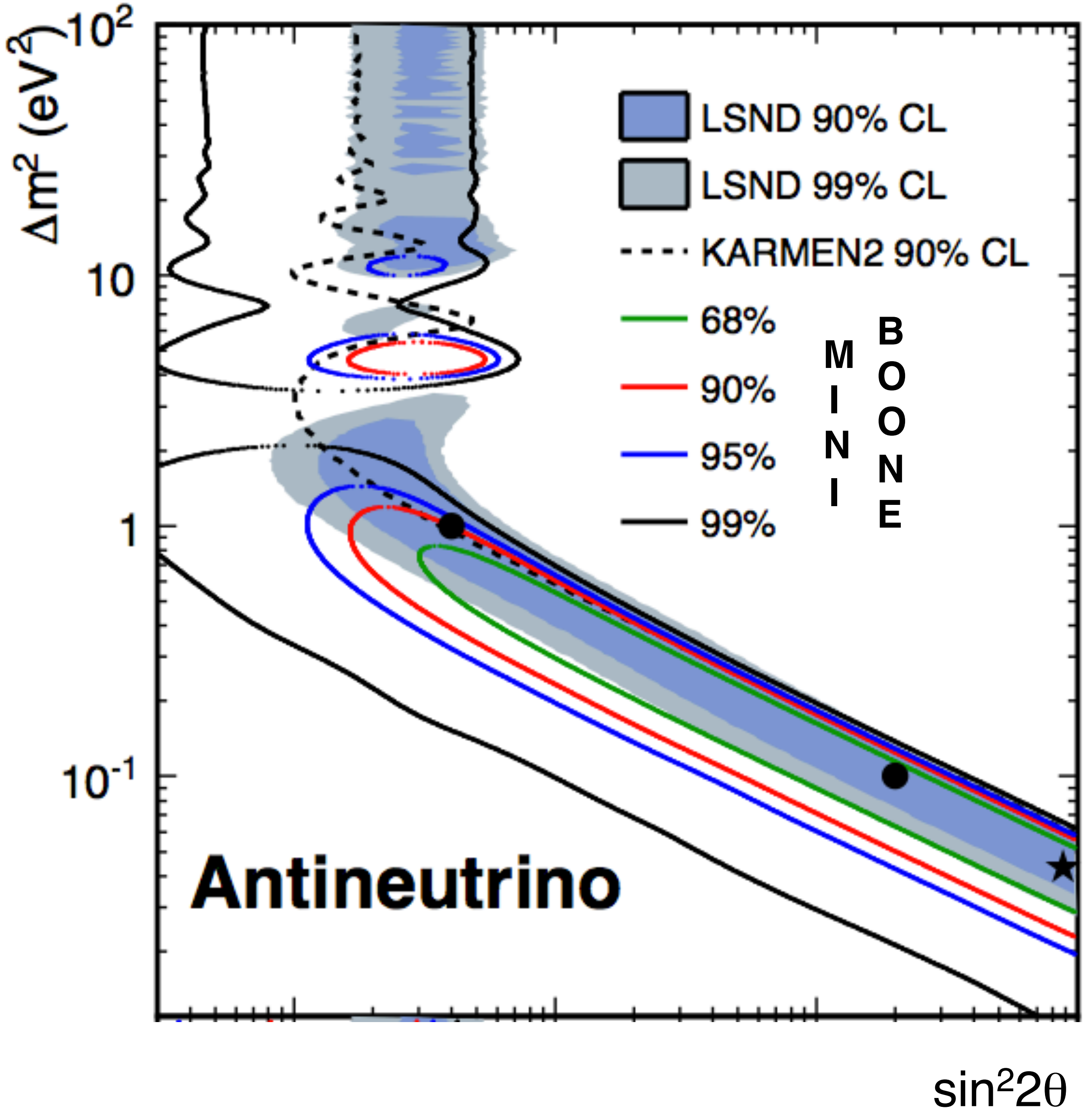
{from measured $\Gamma(Z \rightarrow \nu\bar{\nu})$} At least **1** sterile neutrino

The Hint From MiniBooNE



78.4 ± 28.5 excess events

162.0 ± 47.8 excess events

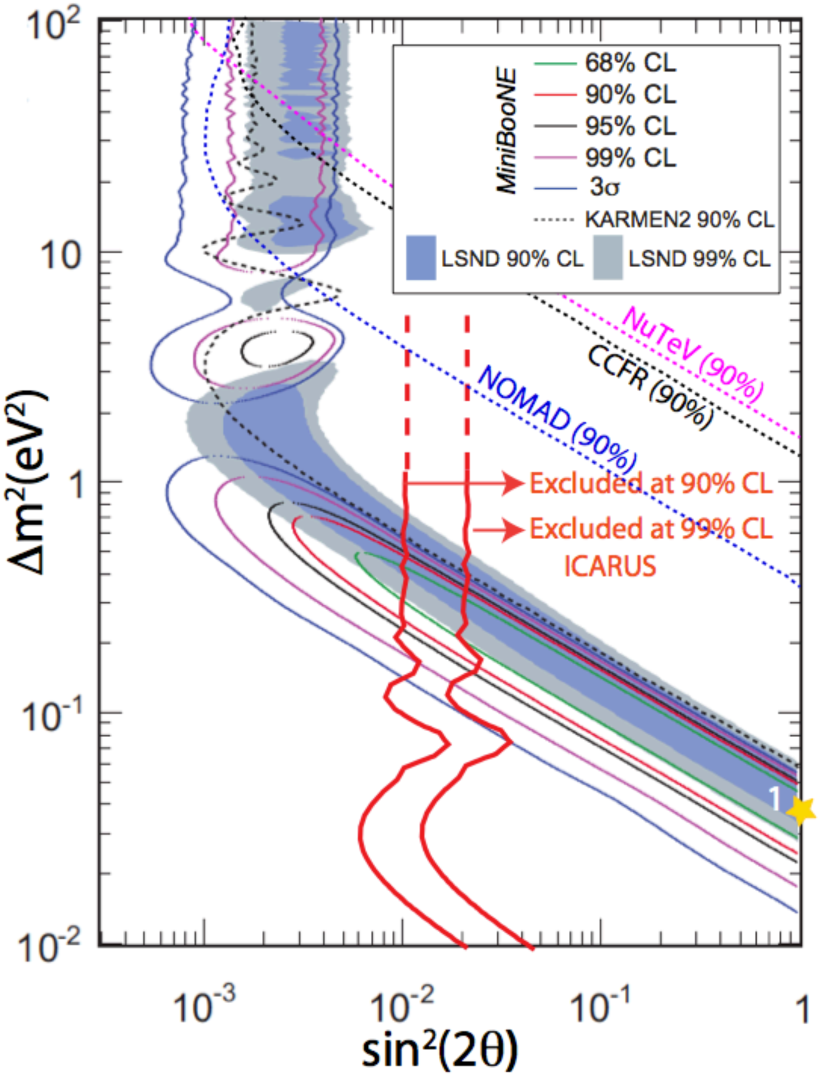


MiniBooNE and LSND allowed regions overlap.

Two-level mass spectrum assumed.

From 1303.2588

ICARUS and OPERA, at $L/E \approx 35$ km/GeV, have not seen $\nu_\mu \rightarrow \nu_e$. This disfavors somewhat a $\nu_\mu \rightarrow \nu_e$ interpretation of the low-energy MiniBooNE ν_e excess.



ICARUS exclusion

A Hint From Reactors

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

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

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

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

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

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

But the uncertainty in the initial flux is as big as the effect.
(Hayes, et al.)

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)

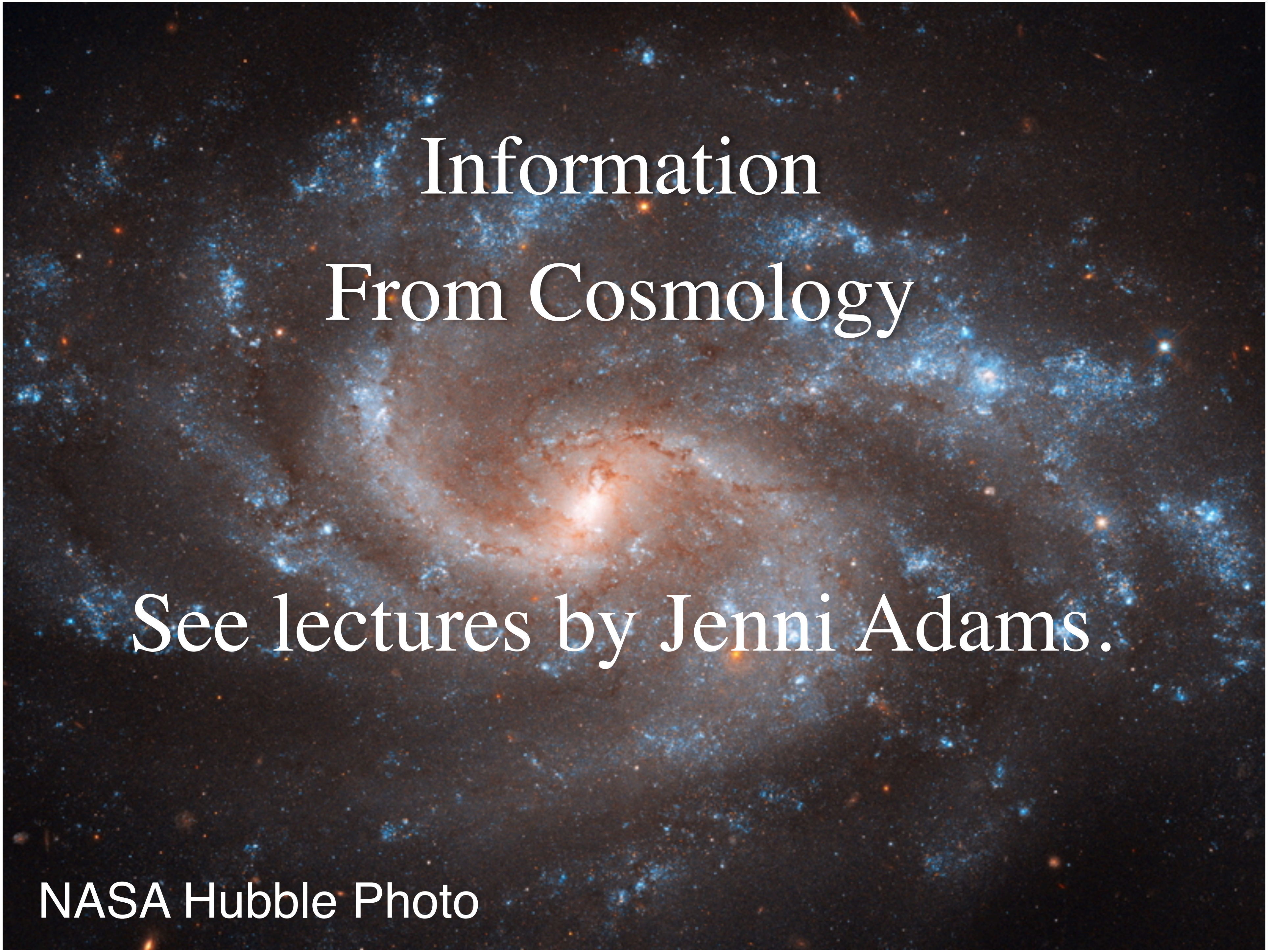
Rapid disappearance of ν_e flux
due to oscillation with a large Δm^2??

The 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:

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



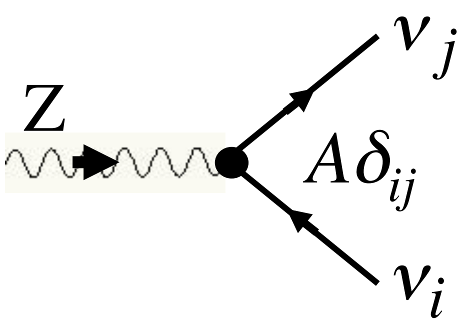
Information From Cosmology

See lectures by Jenni Adams.

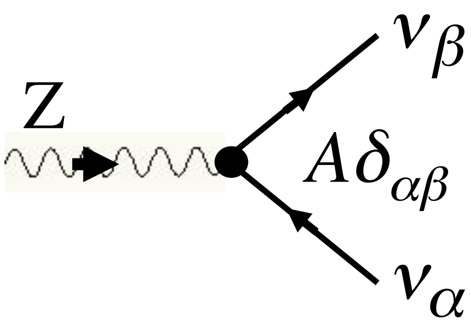
NASA Hubble Photo

Illustrative Ideas For Future Experiments

The neutrino couplings to the Z:

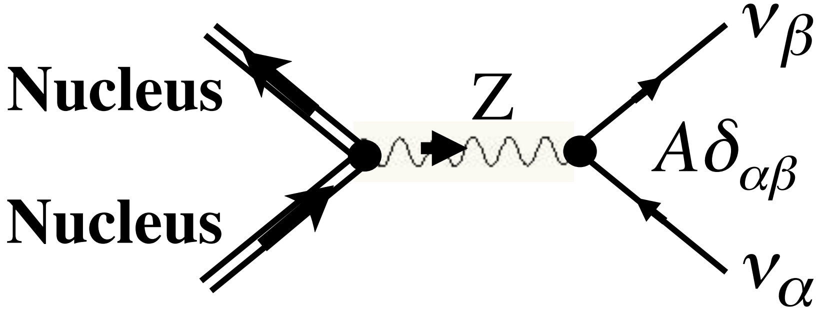


and



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

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 $\nu_{sterile}$.

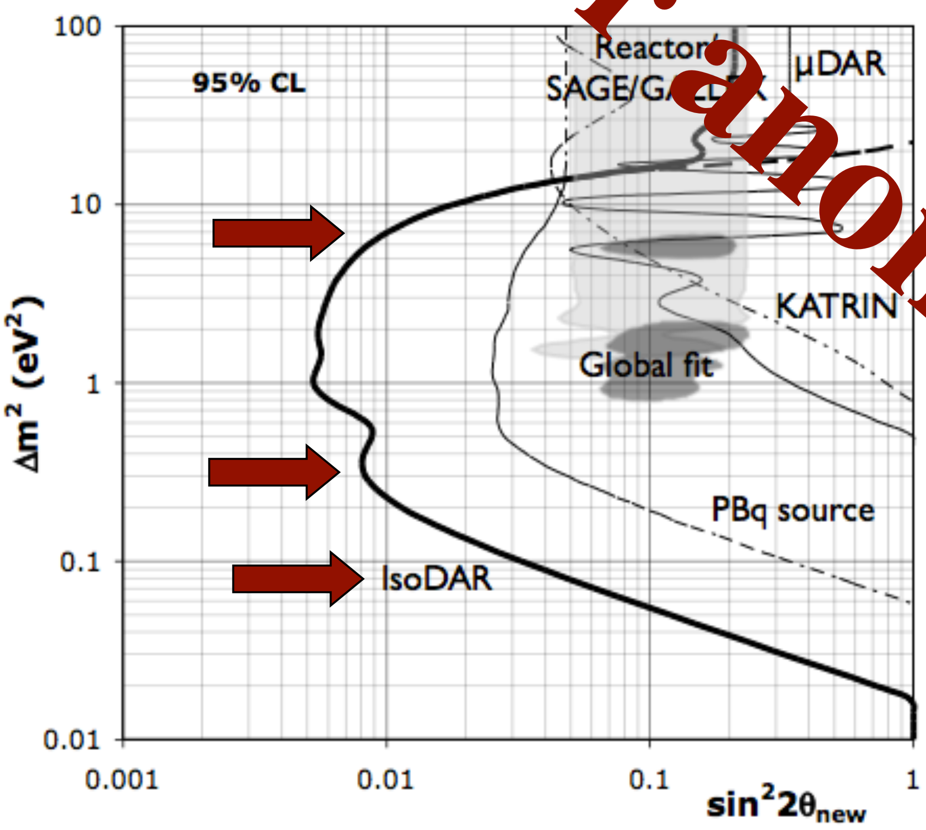
If $\nu_{active} \rightarrow \nu_{sterile}$, the coherent scattering event rate will oscillate with it.

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

Is reactor anomaly real?

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

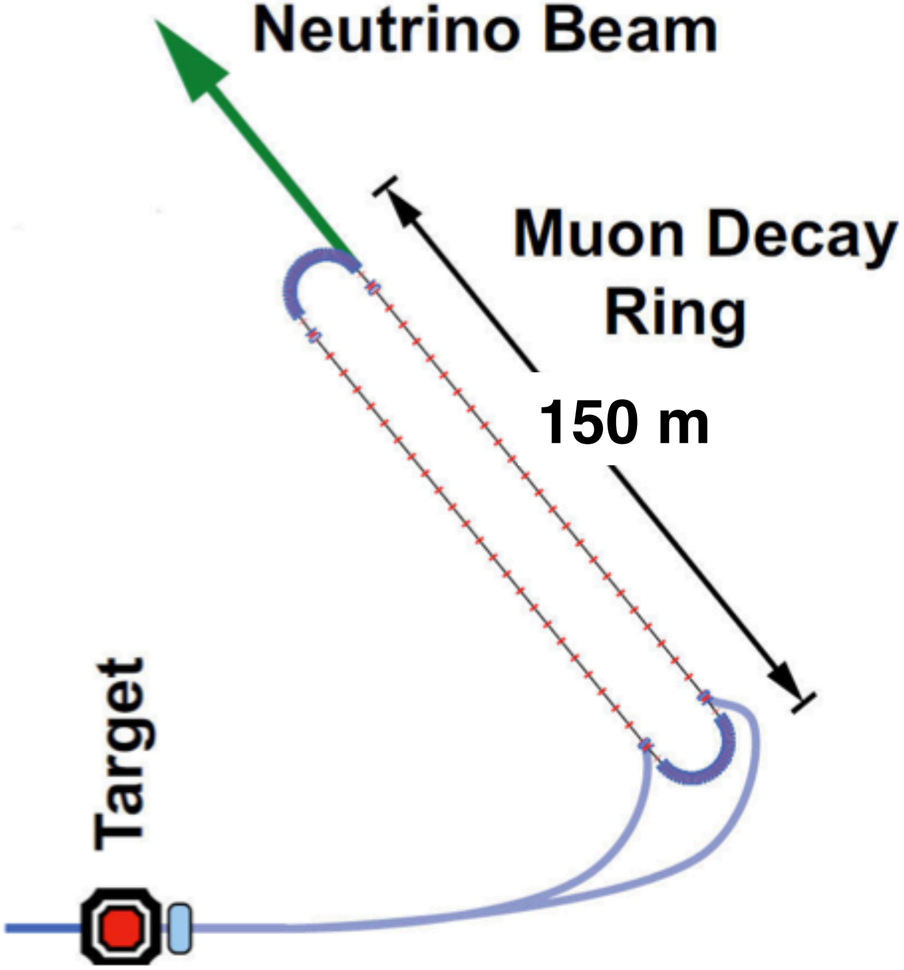
Use a kton-scale scintillator detector
to detect the $\overline{\nu}_e$ via $\overline{\nu}_e\, p \rightarrow e^+ n$.



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

(Bungau et al.)

A Very Low Energy Neutrino Factory (νSTORM)



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

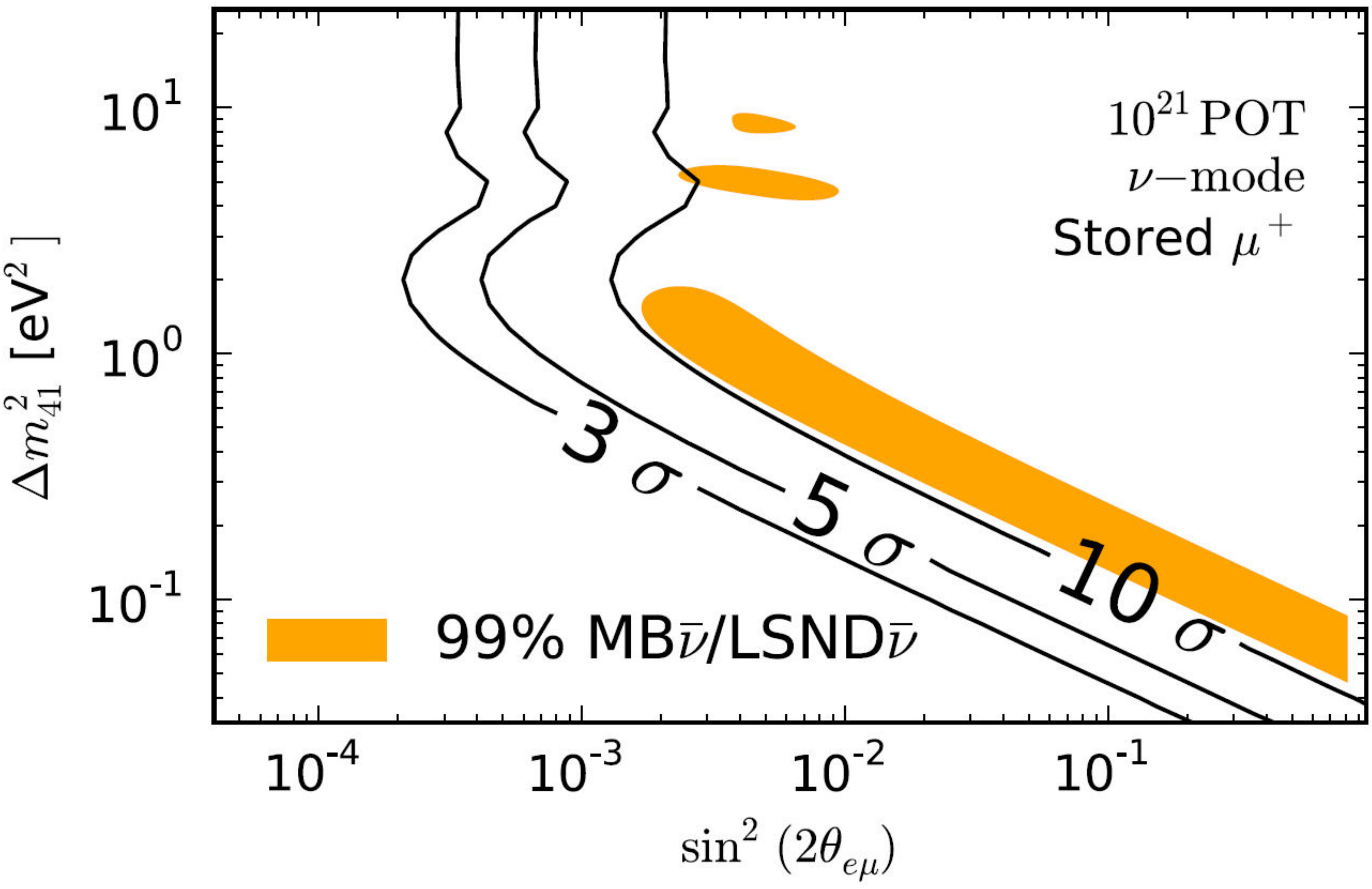
If store μ^+, can study—

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

followed by —

$$\nu_e \rightarrow \nu_\mu \ .$$

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


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

(Bross et al.)

References

Books

The Physics of Massive Neutrinos, B. K., with F. Gibrat-Debu and F. Perrier (World Scientific, Singapore, 1989).

Physics of Neutrinos, M. Fukugita and T. Yanagida (Springer, Berlin/Heidelberg, 2003).

Fundamentals of Neutrino Physics and Astrophysics, C. Giunti and C. Kim (Oxford University Press, Oxford, 2007).

The Physics of Neutrinos, V. Barger, D. Marfatia, and K. Whisnant (Princeton University Press, Princeton, 2012).

Papers

“Neutrino Mass, Mixing, and Oscillations,”
K. Nakamura and S. Petcov, in J. Beringer et al. (The Particle Data Group), Phys. Rev. D **86**, 010001 (2012). Also at http://pdg.lbl.gov/2013/reviews/rpp2012-rev-neutrino-mixing.pdf

“Neutrino Mass, Mixing, and Flavor Change,” B. K., in **Neutrino Mass**, eds. G. Altarelli and K. Winter (Springer, Berlin/Heidelberg, 2003). Also eprint hep-ph/0211134. This paper discusses quite a few of the topics covered in the lectures.

“Neutrino Oscillation Physics,” B. K., in **Proceedings of the International School on AstroParticle Physics**, eds. G. Bellini and L. Ludhova (IOS Press, Amsterdam, 2012), and in **Proceedings of the 2011 European School of High-Energy Physics**, eds. C. Grojean and M. Mulders (CERN, Geneva, 2014). Also arXiv:1206.4325. This paper derives the probability for neutrino oscillation without assuming that all neutrino mass eigenstates in a beam have the same energy, or else the same momentum.

“Light Sterile Neutrinos: A White Paper,” K. Abazajian et al., arXiv:1204.5379.

Good luck!