The Neutrinos

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Annecy
May 4 – 5, 2017
Part 4

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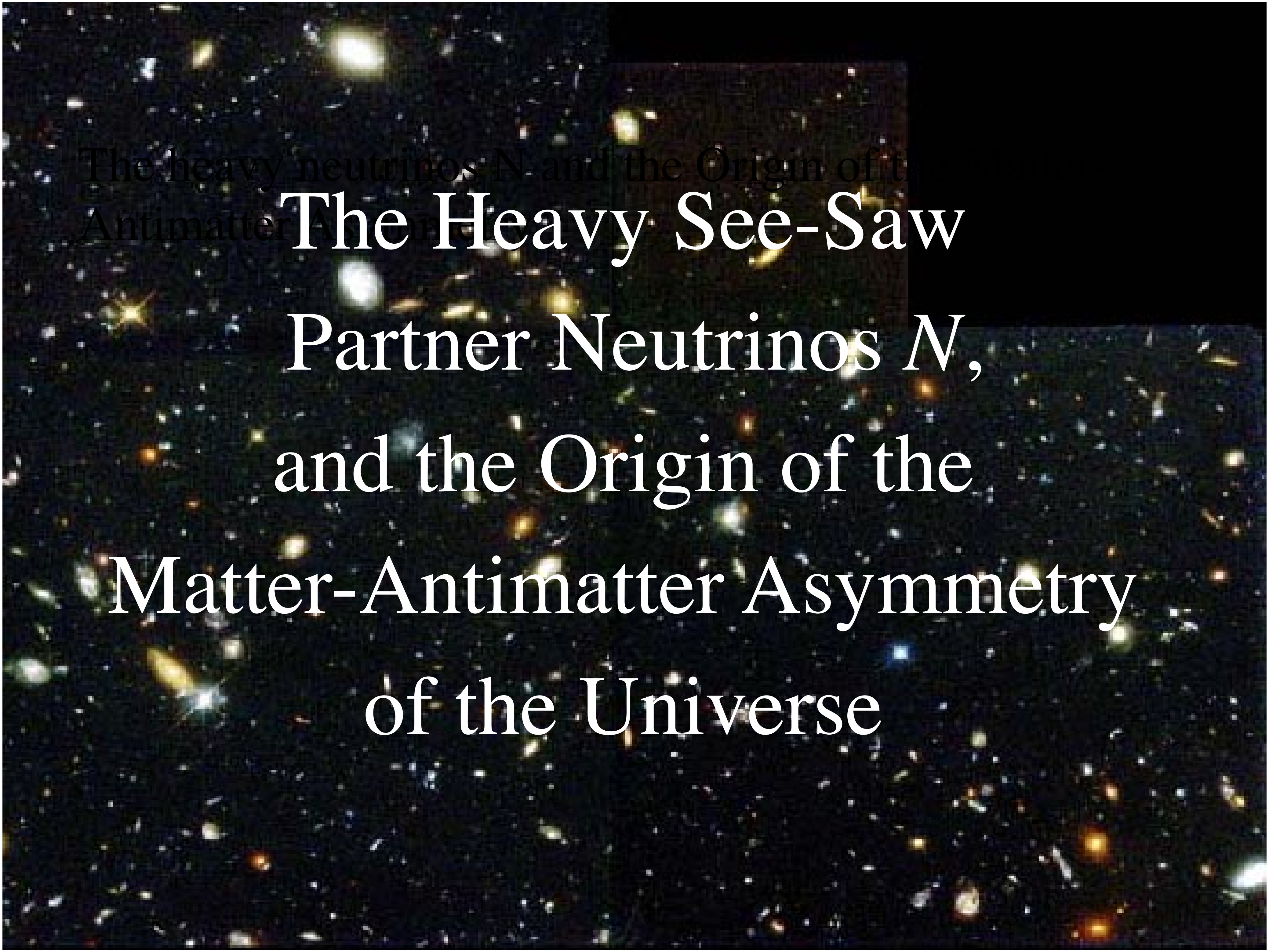


The heavy neutrinos N and the Origin of t
Antimatter A

The Heavy See-Saw Partner Neutrinos *N*, 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 $\cancel{CP}$.

$\cancel{C}$ 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.

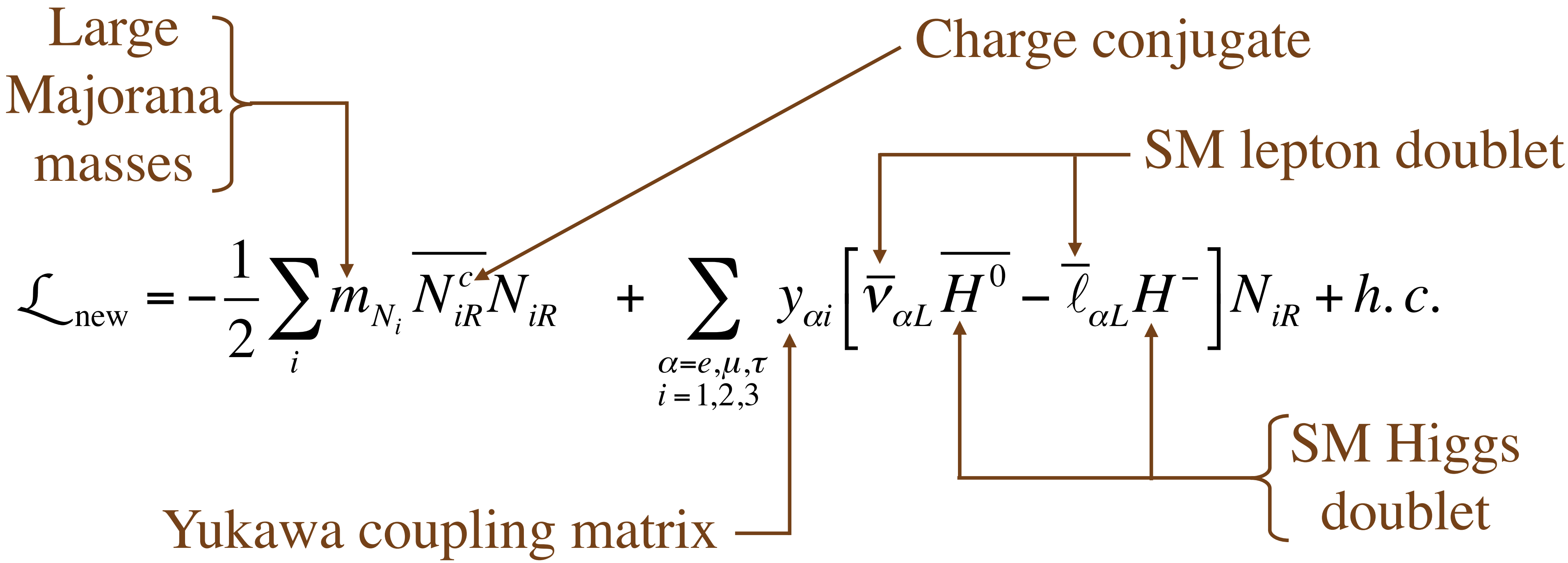
If ***quark*** $\cancel{CP}$ cannot generate the observed $B - \overline{B}$ asymmetry, can some scenario involving ***leptons*** do it?

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

(Fukugita, Yanagida)

We will now need the See-Saw picture with ***several*** neutrinos.

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

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

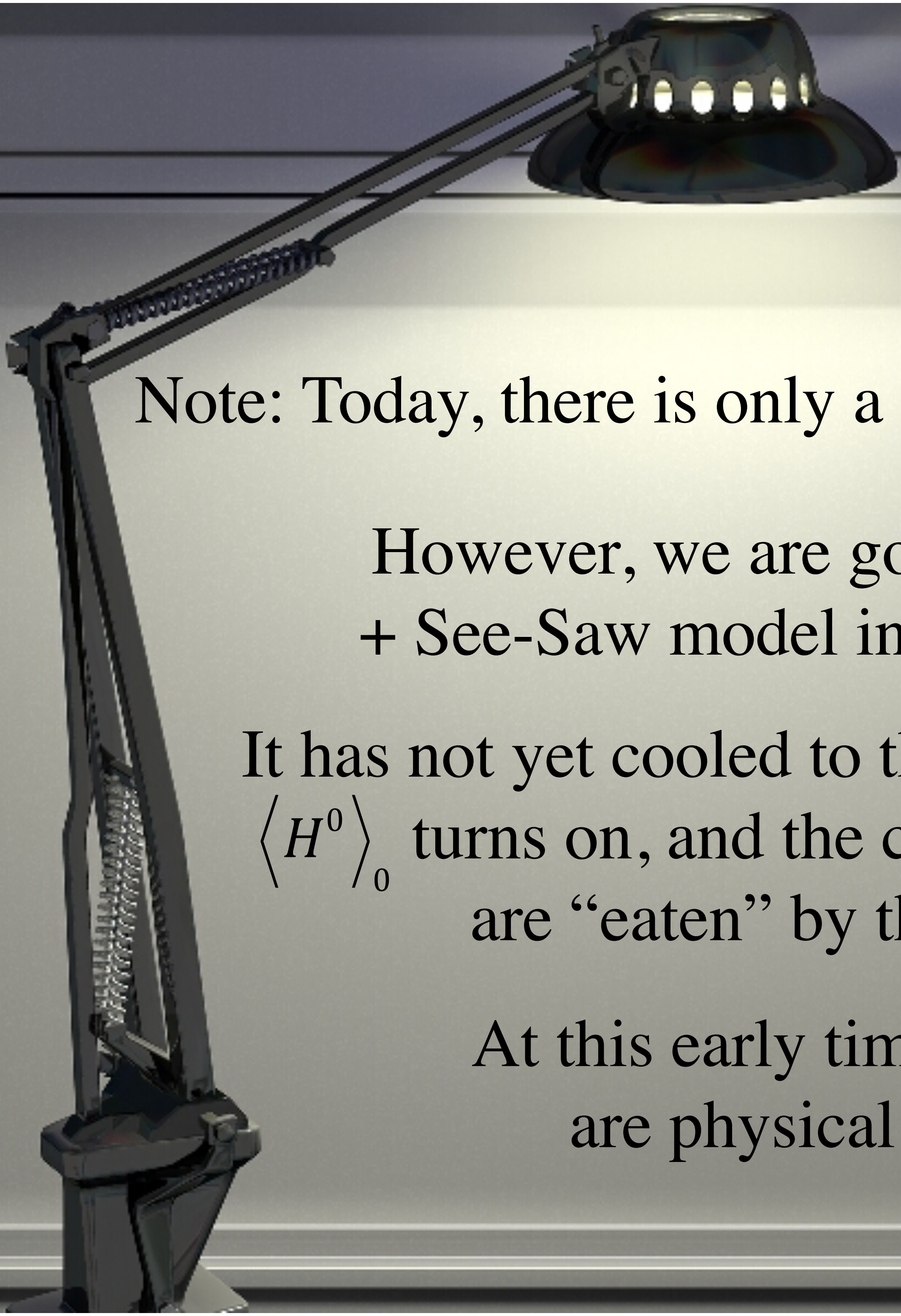
SM Higgs doublet

Yukawa coupling matrix

The Yukawa interaction causes the decays —

$$N \rightarrow \ell^- + H^+,\ \ N \rightarrow \ell^+ + H^-,$$
$$N \rightarrow \nu + H^0,\ \ N \rightarrow \overline{\nu} + \overline{H^0}.$$

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



Note: Today, there is only a ***neutral*** SM Higgs particle.

However, we are going to use the SM
+ See-Saw model in the early universe.

It has not yet cooled to the temperature at which
$\left\langle H^0 \right\rangle_0$ turns on, and the charged Higgs particles
are "eaten" by the W bosons.

At this early time, H^+ and H^-
are physical particles.

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.

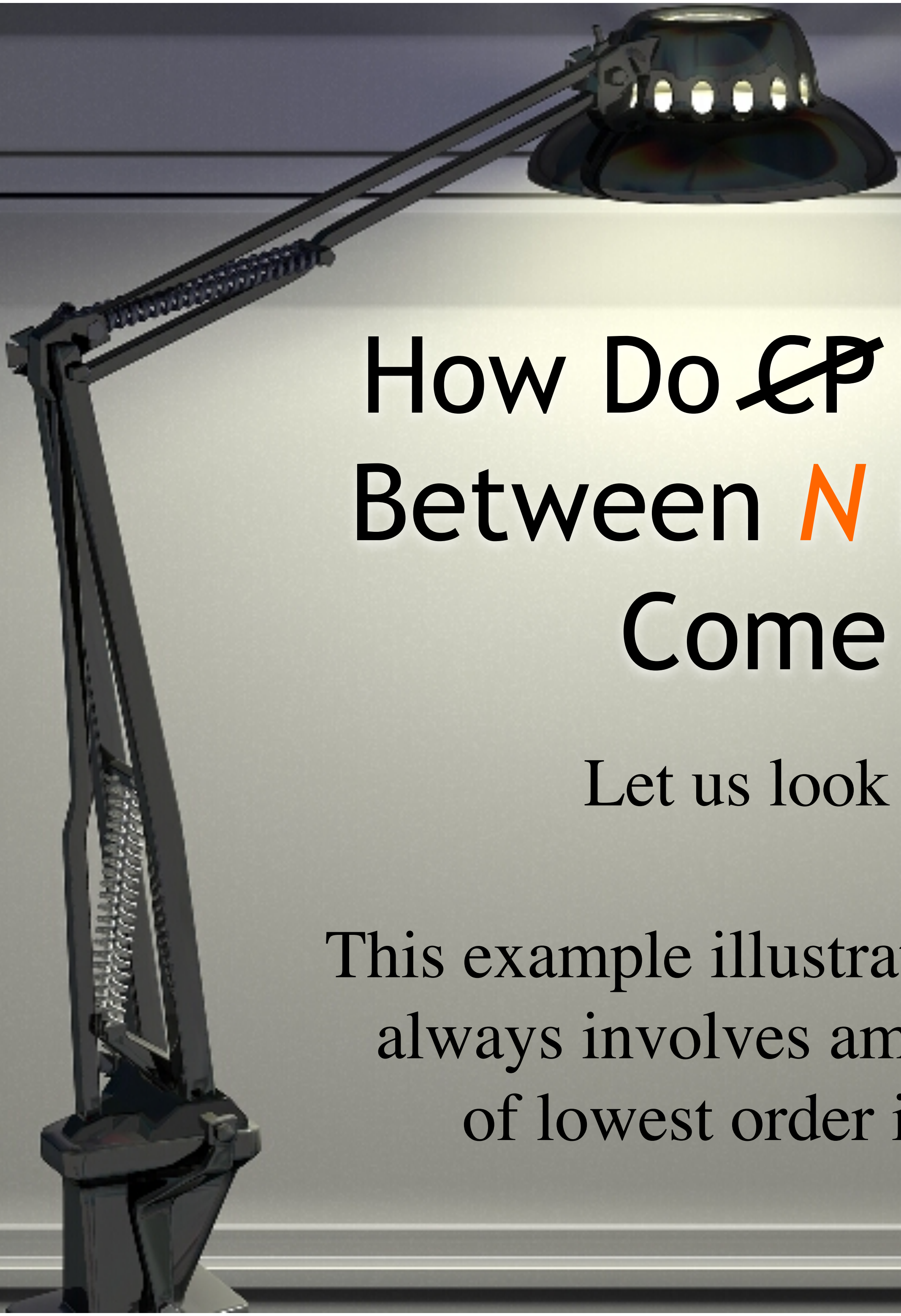
In particular, such phases would have led to —

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

and

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

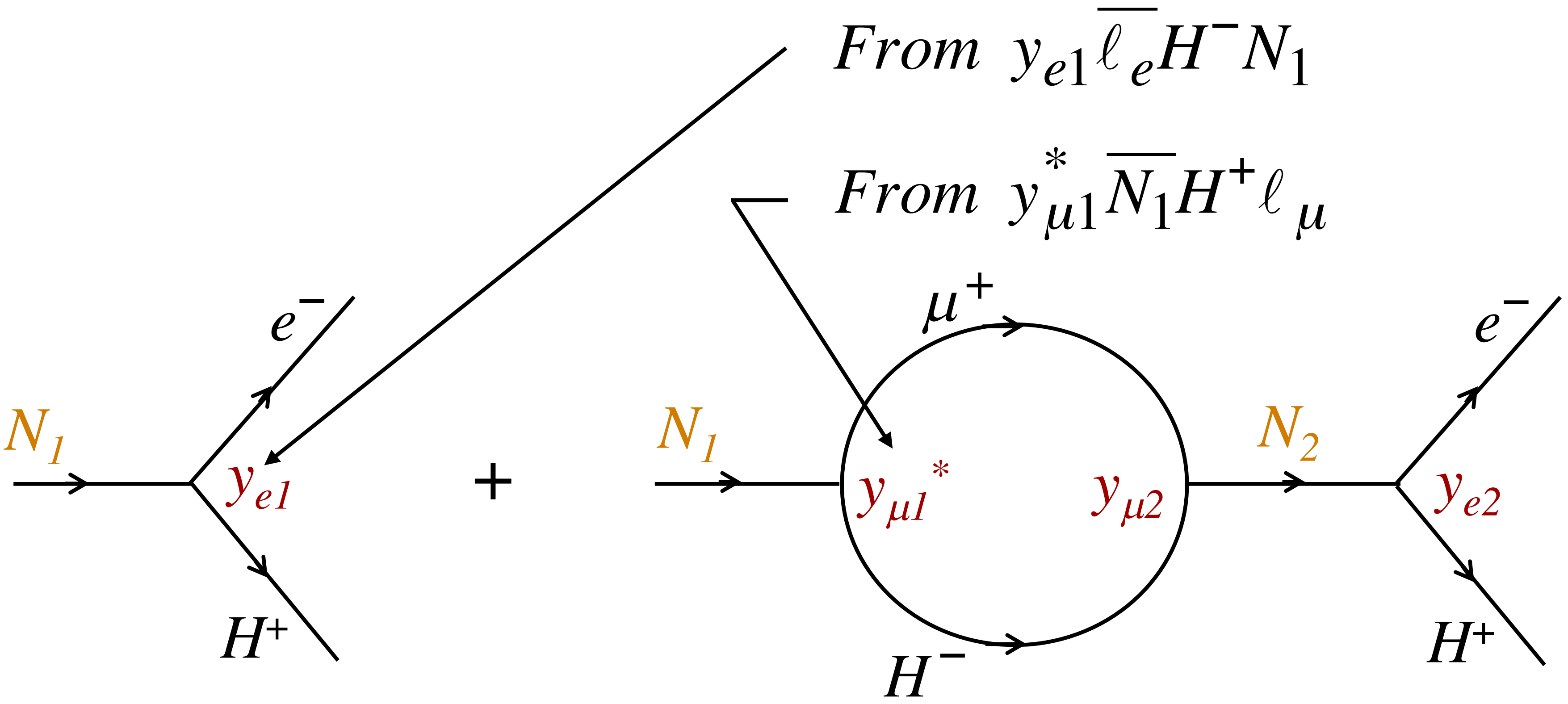
$$\Gamma\left(N \rightarrow \nu + H^0\right) \neq \Gamma\left(N \rightarrow \overline{\nu} + \overline{H^0}\right)$$



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 $y^*_{\mu1}\overline{N_1}H^+\ell_\mu$

Tree

Loop

$$\Gamma\left(N_1 \rightarrow e^- + H^+\right) = \left| y_{e1}K_{\text{Tree}} + y^*_{\mu1}y_{\mu2}y_{e2}K_{\text{Loop}} \right|^2$$

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.

From Hermiticity of H

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

Then —

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

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 $L \neq 0$,
containing unequal numbers
of SM leptons and antileptons.

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**.**

Eventually, there are baryons, but ~ no antibaryons.

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

How Heavy Must the N_i Be?

Once the Higgs vev turns on,

$$y\bar{\nu}_L\overline{H^0}N_R \Rightarrow y\bar{\nu}_L\left\langle\overline{H^0}\right\rangle_0 N_R \equiv m_D\bar{\nu}_L N_R$$

This is the Dirac mass term in the See-Saw model.

SM Higgs vev

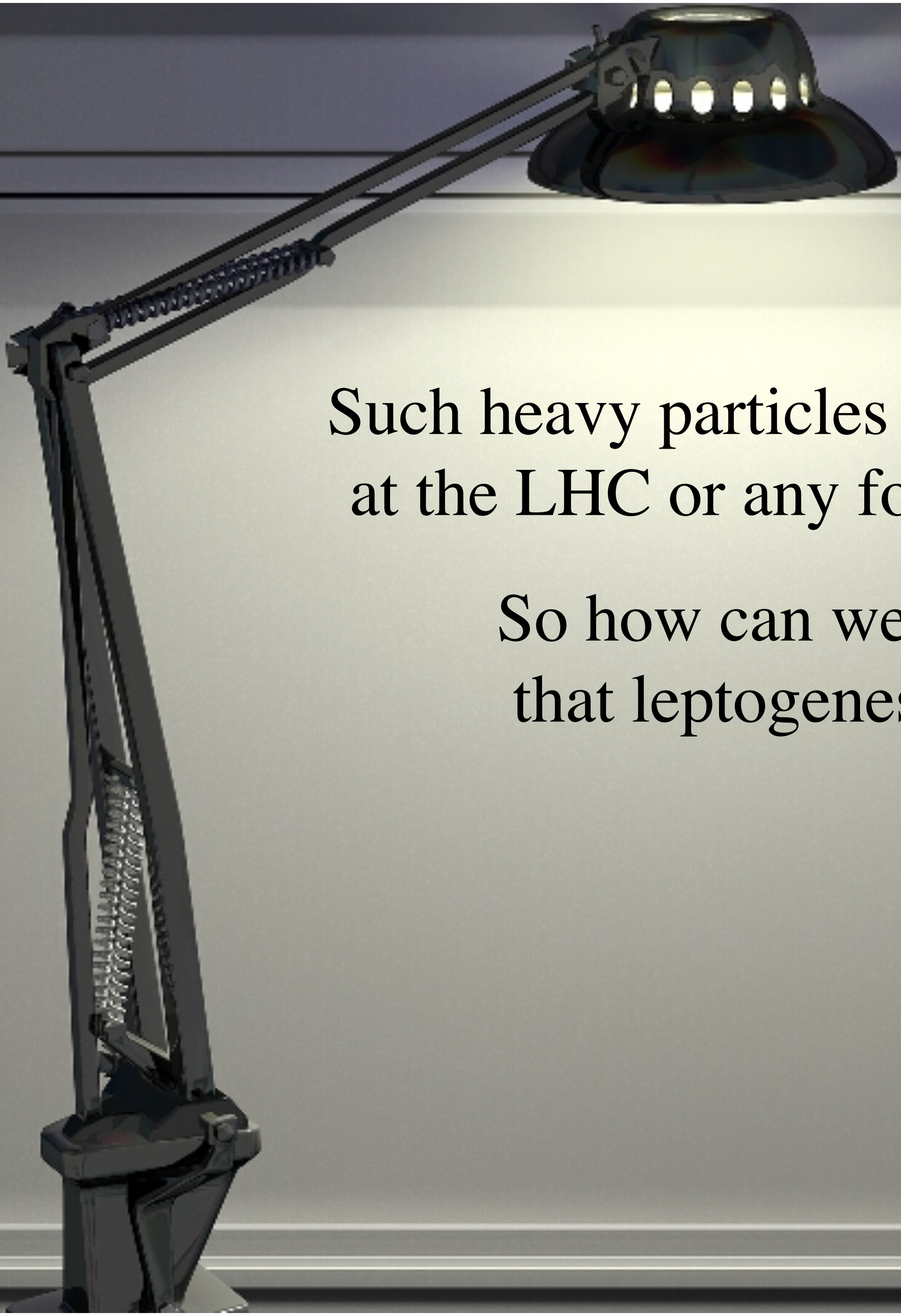
The see-saw relation is then $M_\nu \sim \dfrac{v^2y^2}{M_N}$.

Yukawa coupling

Light neutrino

This relation, the light ν masses, and the $y^2 \sim 10^{-5}$ called for by the observed cosmic baryon asymmetry,

⇒ $M_N \gtrsim 10^{(9\,-\,10)}$ GeV.



Such heavy particles cannot be produced
at the LHC or any foreseen accelerator.

So how can we get evidence
that leptogenesis occurred?

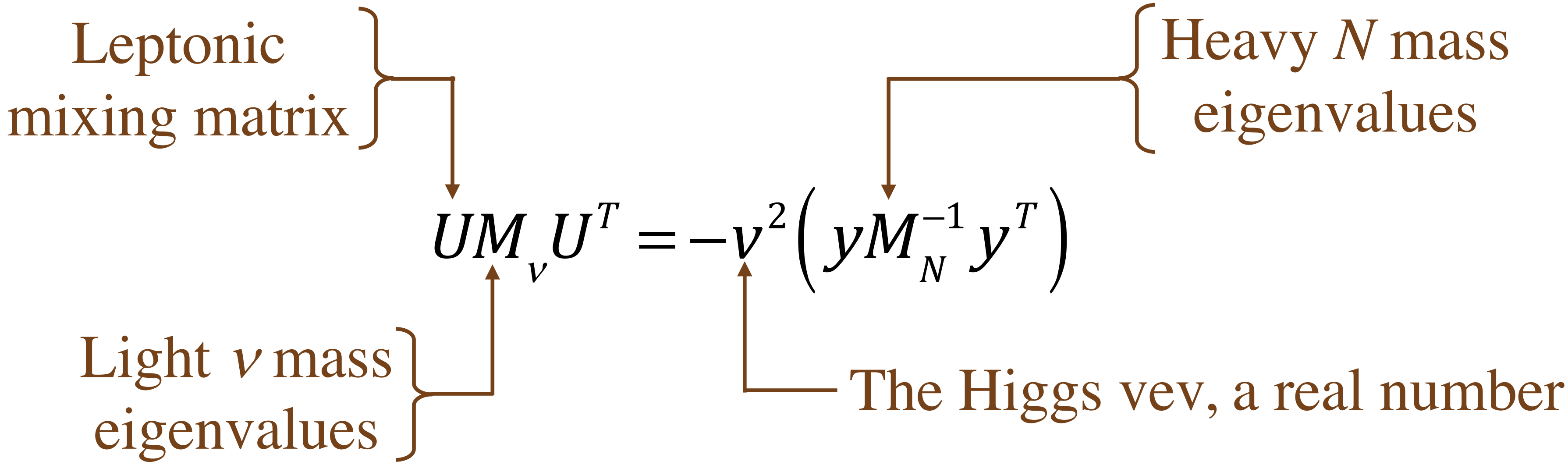
Generically, leptogenesis and light-neutrino ~~CP~~ imply each other.

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

The Oscillation — Leptogenesis Connection

(B.K.)

The See-Saw Relation



Leptonic mixing matrix

Heavy N mass eigenvalues

$$UM_\nu U^T = -v^2\left(yM_N^{-1}y^T\right)$$

Light ν mass eigenvalues

The Higgs vev, a real number

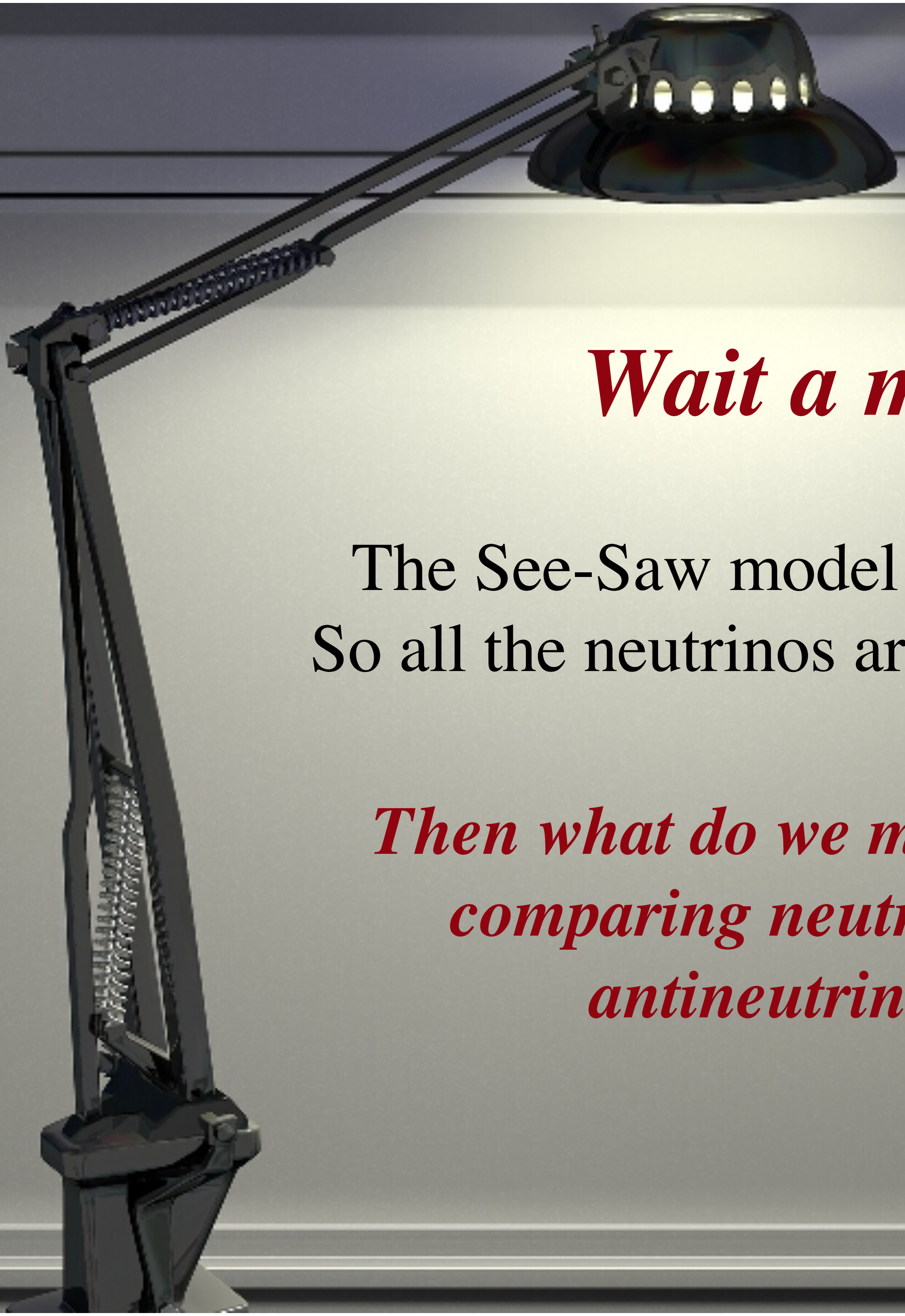
$$\left(\underbrace{UM_\nu U^T}_{\text{Outputs}} = -v^2\underbrace{\left(yM_N^{-1}y^T\right)}_{\text{Inputs, in } \mathcal{L}}\right)$$

Through ***U***, the phases in ***y*** lead to $\cancel{CP}$ in light neutrino oscillation.

$$P(\underset{\uparrow}{\overset{(-)}{\nu}_\alpha} \rightarrow \overset{(-)}{\nu}_\beta) =$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$\underset{(-)}{+}2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$



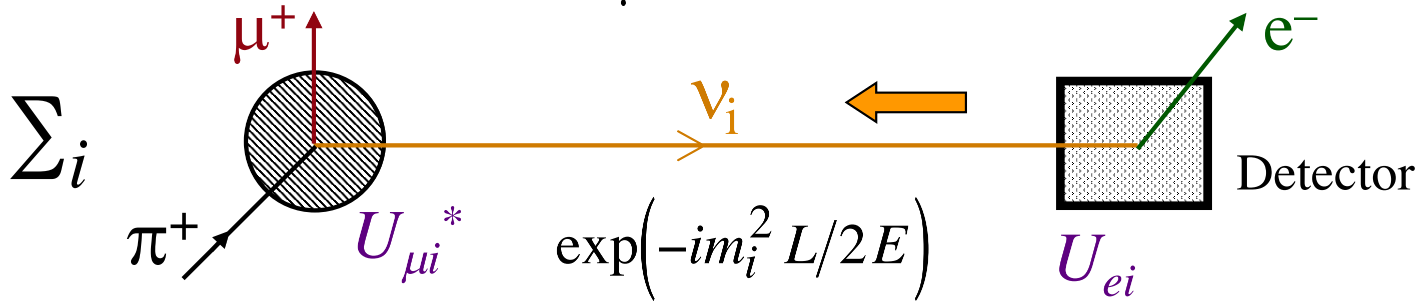
Wait a minute!

The See-Saw model has Majorana massses.
So all the neutrinos are their own antiparticles.

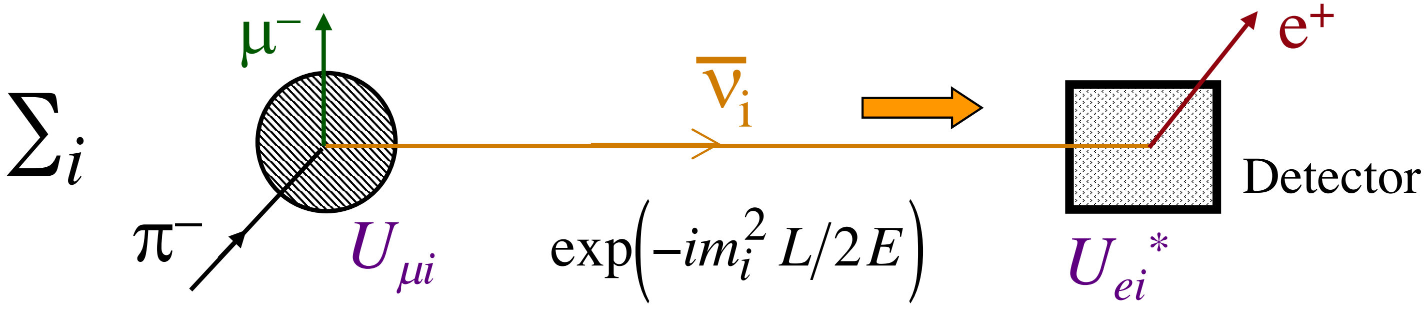
Then what do we mean when we speak of comparing neutrino oscillation with antineutrino oscillation??

To confirm ~~CP~~ in oscillation, compare two CP-mirror-image oscillations.

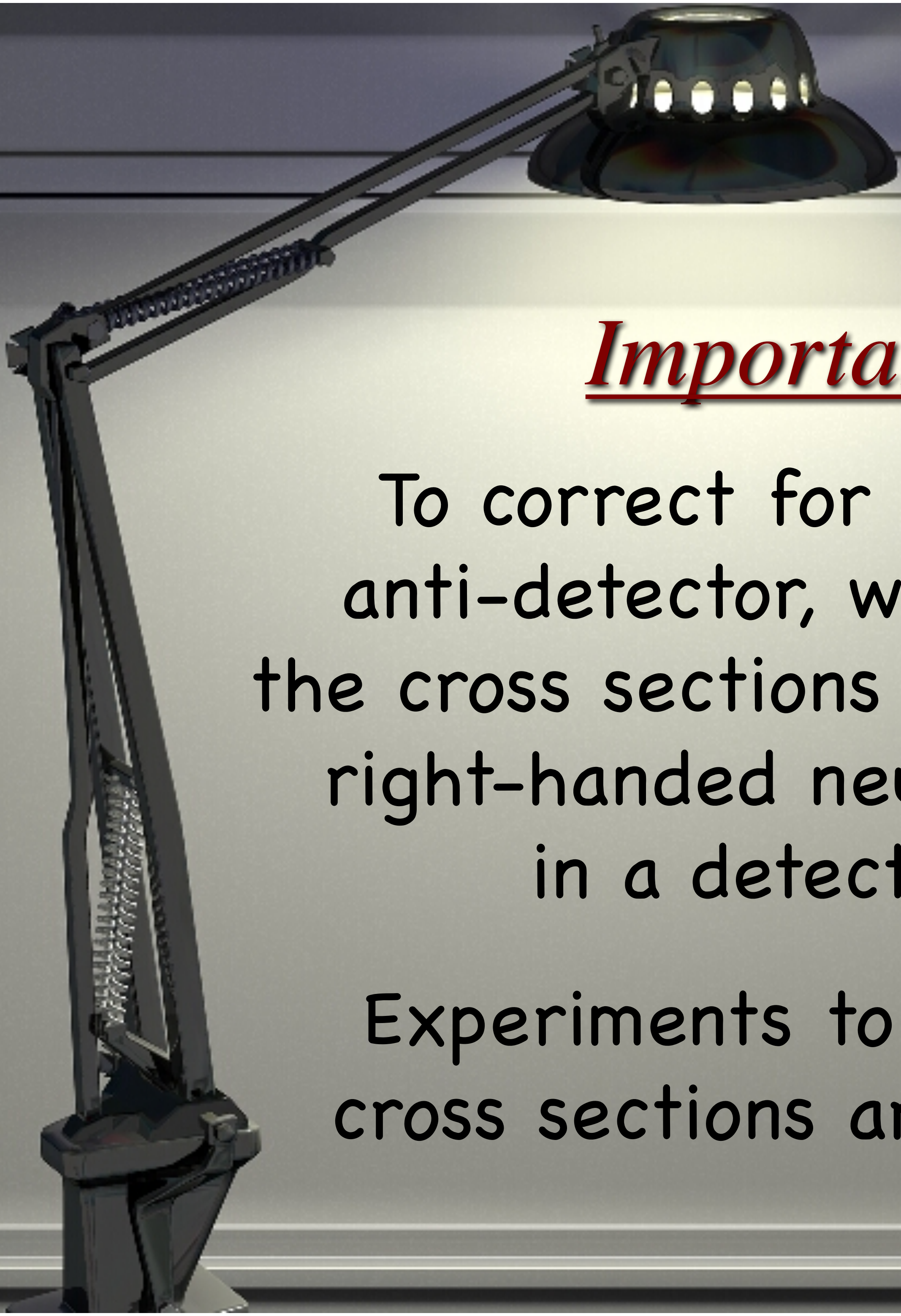
Compare $\nu_\mu \to \nu_e$



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



Do these two processes have different rates?

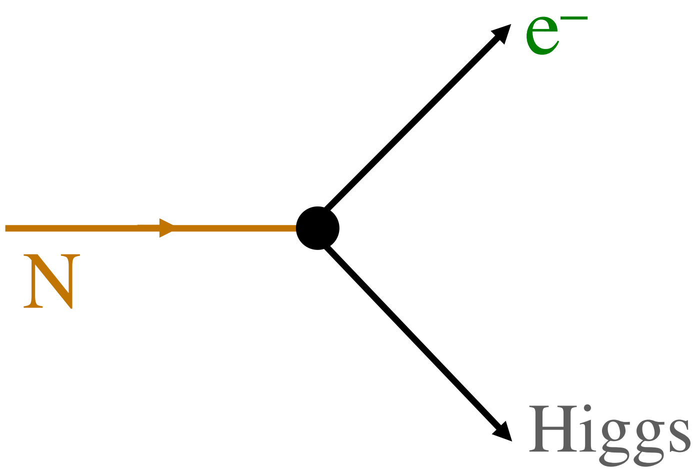


Important Notice

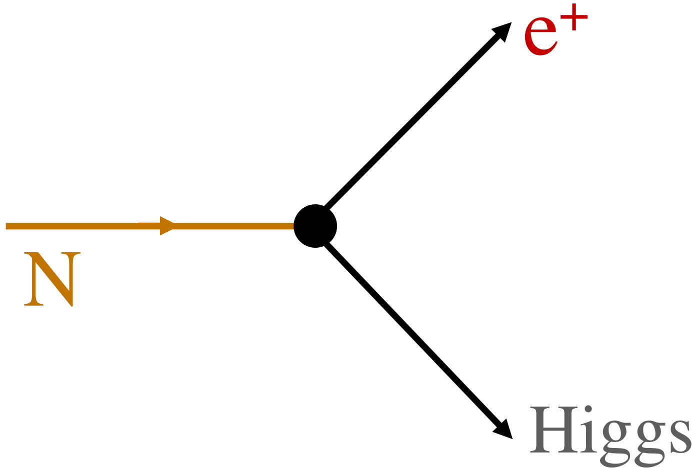
To correct for our not using an anti-detector, we must know how the cross sections for left-handed and right-handed neutrinos to interact in a detector compare.

Experiments to determine these cross sections are very important.

The coming ~~CP~~ experiments are today's version of comparing —



with —



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

(Pascoli, Petcov, Riotto)

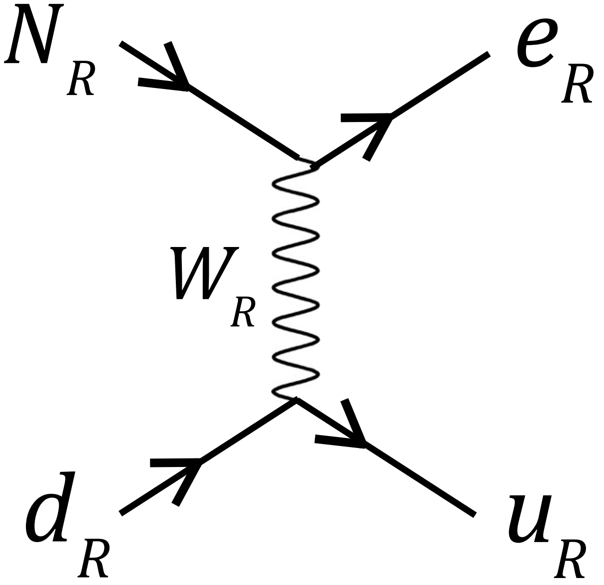
Falsifying Leptogenesis At the LHC

Certain discoveries that could be made at the LHC would falsify high-mass-scale Leptogenesis.

(Frere, Hambye, Vertongen; Deppisch, Harz, Hirsch;
Deppisch, Harz, Hirsch Huang, Päs)

A W_R found at LHC would have allowed early-universe *CP-conserving* decays $N_R \to W_R \ell_R$.

This W_R would also have induced W_R-exchange scatterings such as —



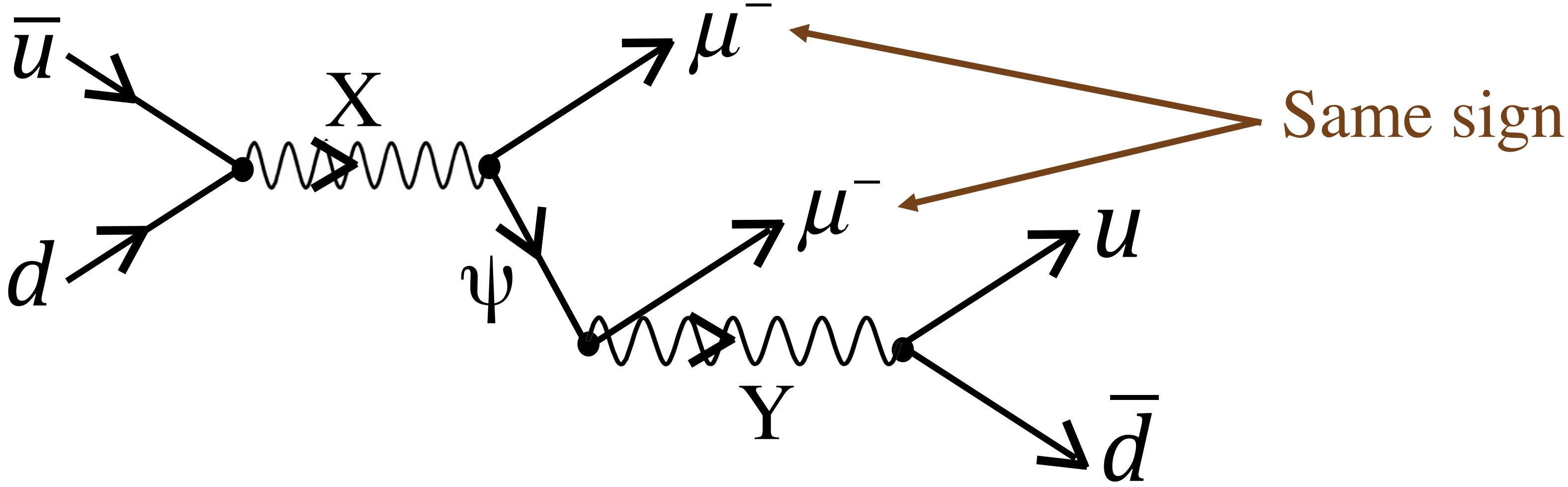
Such scatterings would have eliminated some of the N_R, on whose decays leptogenesis depends.

If N_R is much heavier than W_R, there will be no $W_R \rightarrow N_R \ell_R$ at the LHC.

However, one can try to identify the W_R by looking for the RH helicity of the top quark from $W_R \rightarrow t\bar{b}$.

The discovery of ***lepton number non-conservation*** at the LHC could also falsify high-scale leptogenesis.

Suppose one sees, for example —



That is, more generally, $pp \rightarrow \ell^{\pm}\ell^{\pm} + 2\,\text{jets}$.

$$\boxed{|\Delta L| = 2}$$

The non-conservation of L resulting from this process would washout the nonzero L, and the consequent nonzero B, resulting from the decays of any heavy neutrino N heavier than X. High-scale leptogenesis would be falsified.

The observed cross section for the L-violating process need only be > 0.01 fb or so for this statement to hold.

Note: One has to see $pp \rightarrow \ell^{\pm}\ell^{\pm} + 2\,\text{jets}$ with all three flavors of ℓ.

"Low-scale" leptogenesis, involving a heavy neutrino N with $M_N < M_X$, hence light enough to be produced at the LHC, is still possible.

Of course, discovering this heavy neutrino and observing directly the CP violation in its decays that drove leptogenesis in the early universe would be a major achievement!

The LHC has an important role to play in connection with leptogenesis.

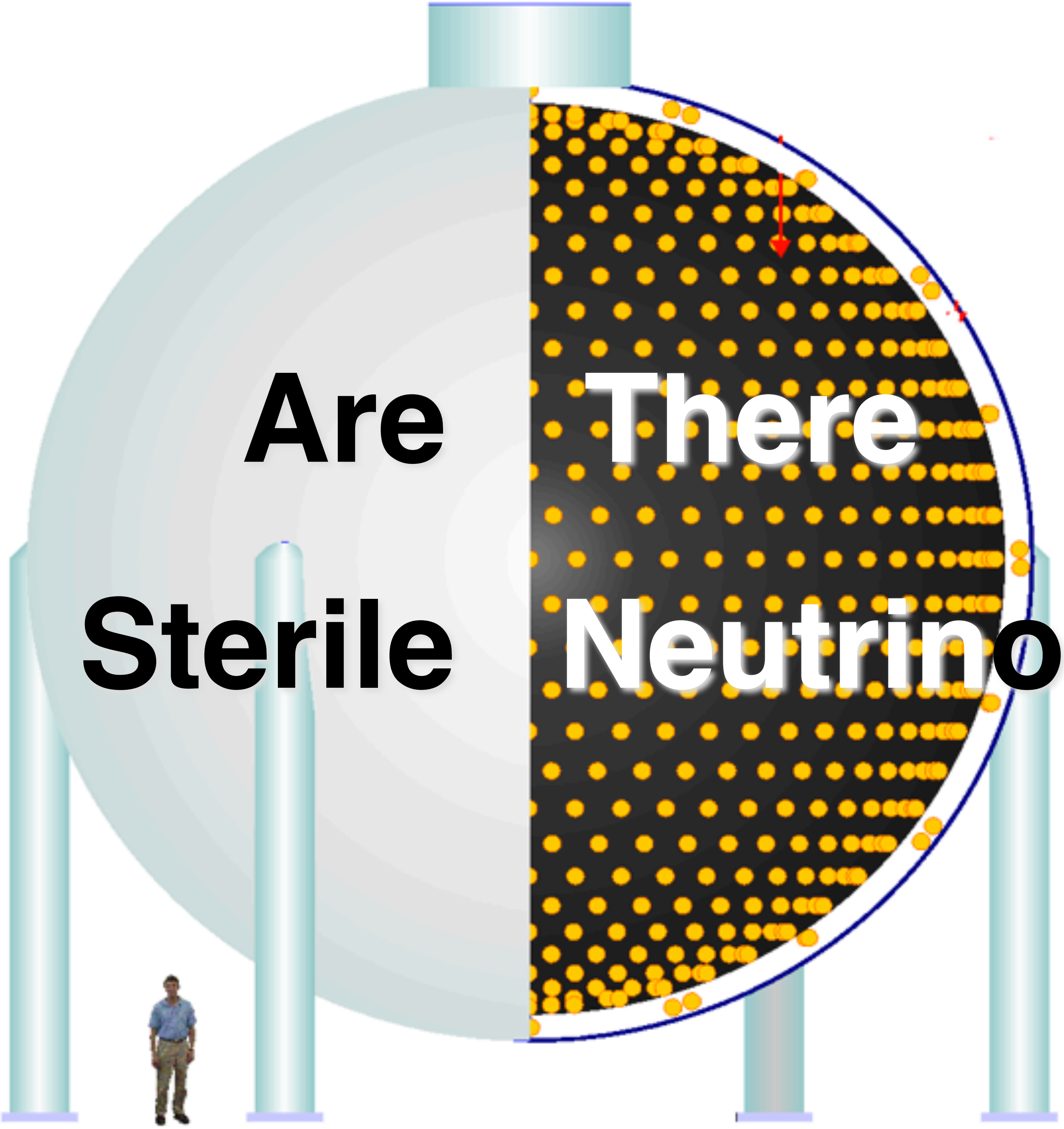
What About 0νββ?

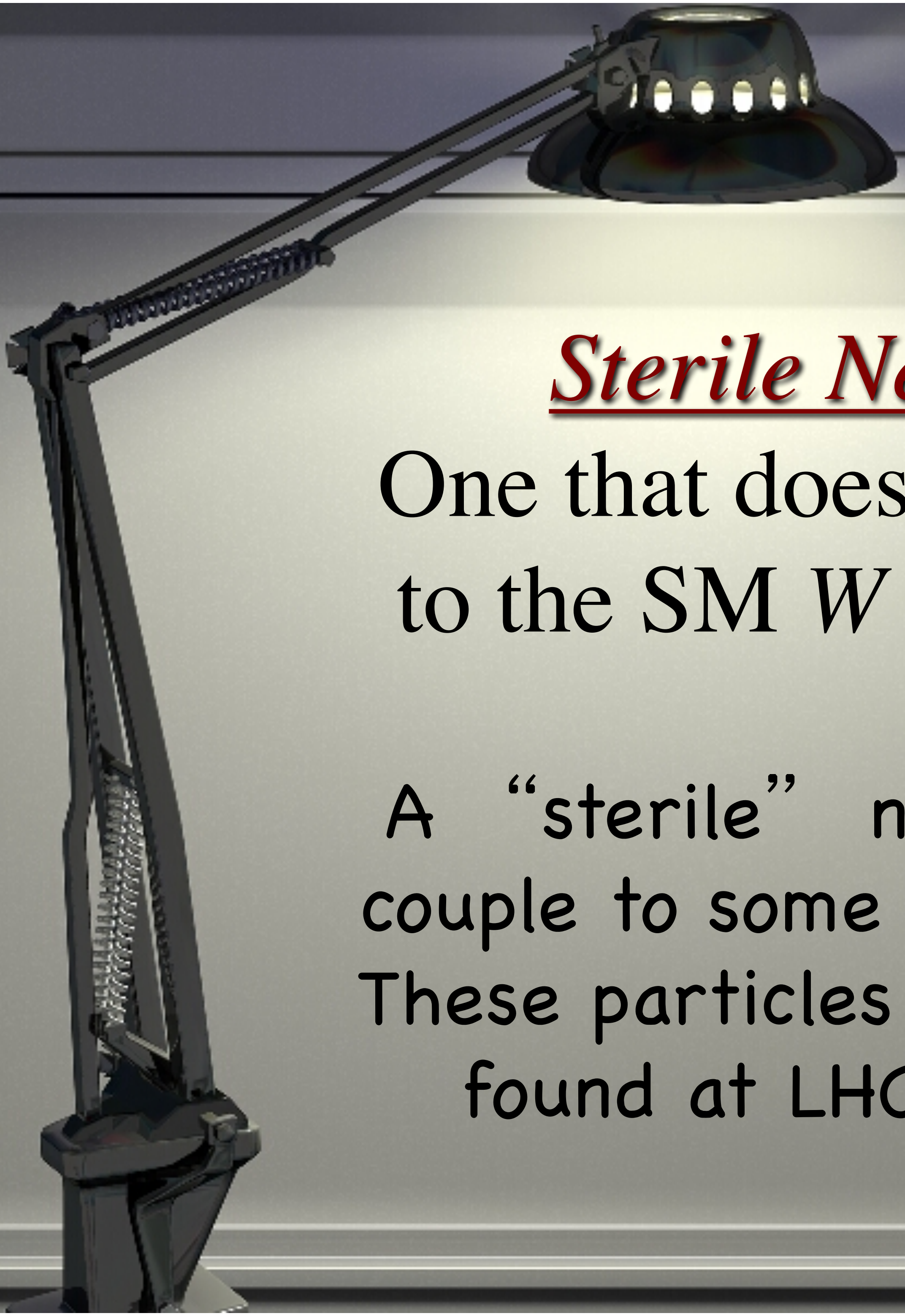
Although 0νββ violates L conservation, with $\Delta L = 2$, the observation of this process would *not* falsify leptogenesis.

The limits on the rate for 0νββ are already so good that any future observation could be explained by physics at such a high mass scale that leptogenesis could still occur at a lower scale without subsequent washout.

If it could be established that 0νββ is being caused by some process other than light neutrino exchange, then high-scale baryogenesis, and not just via leptogenesis, is called into question.

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.

There could be sterile neutrinos at any mass scale.

The heavy neutrinos ***N***, with $M_N \gtrsim 10^{(9-10)}$ GeV,
that drive the most straightforward version of leptogenesis,
are sterile neutrinos.

Leptogenesis with sterile neutrinos light enough
to be experimentally accessible, say at CERN,
has been explored. For example —

Baryogenesis via Neutrino Oscillations

(Akhmedov, Rubakov, Smirnov)

So, are there GeV-scale sterile neutrinos?

One can seek such neutrinos at the SPS with ***SHiP***.

They can drive baryogenesis.

(Hernandez, Kekic, Lopez-Pavon, Racker, Rius, Salvado)

Are there MeV-scale sterile neutrinos?

MeV-scale sterile neutrinos would not lead to observable oscillations. At the nearest detector of the Short Baseline Neutrino program (SBN) at Fermilab, a 1 MeV neutrino would lead to —

$$\sin^2\underbrace{\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]}_{10^{11}}$$

But 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.)

Are there eV-scale sterile neutrinos?

Several experimental anomalies suggest that they may exist.

Should they be real, they could have major consequences for Long-Baseline (LBL) oscillation experiments.*

Are there meV-scale sterile neutrinos?

DUNE's ability to exclude them has been analyzed by Berryman, de Gouvea, Kelly, Kobach.

*

Hollander, Mocioiu

Klop, Palazzo

Berryman, de Gouvêa, Kelly, Kobach

Gandhi, B. K., Masud, Prakash

Agarwalla, Chatterjee, Dasgupta, Palazzo

Agarwalla, Chatterjee, Palazzo

Dutta, Gandhi, B. K., Masud, Prakash

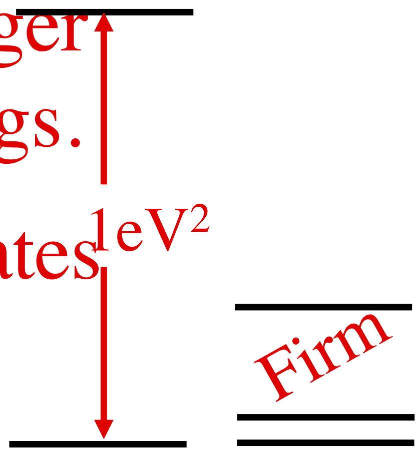
Capozzi, Giunti, Laveder, Palazzo

The Hints of eV-Mass Sterile Neutrinos

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

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

These ⇒ a $\Delta m^2 \sim 1$ eV^2, bigger than the two established splittings.



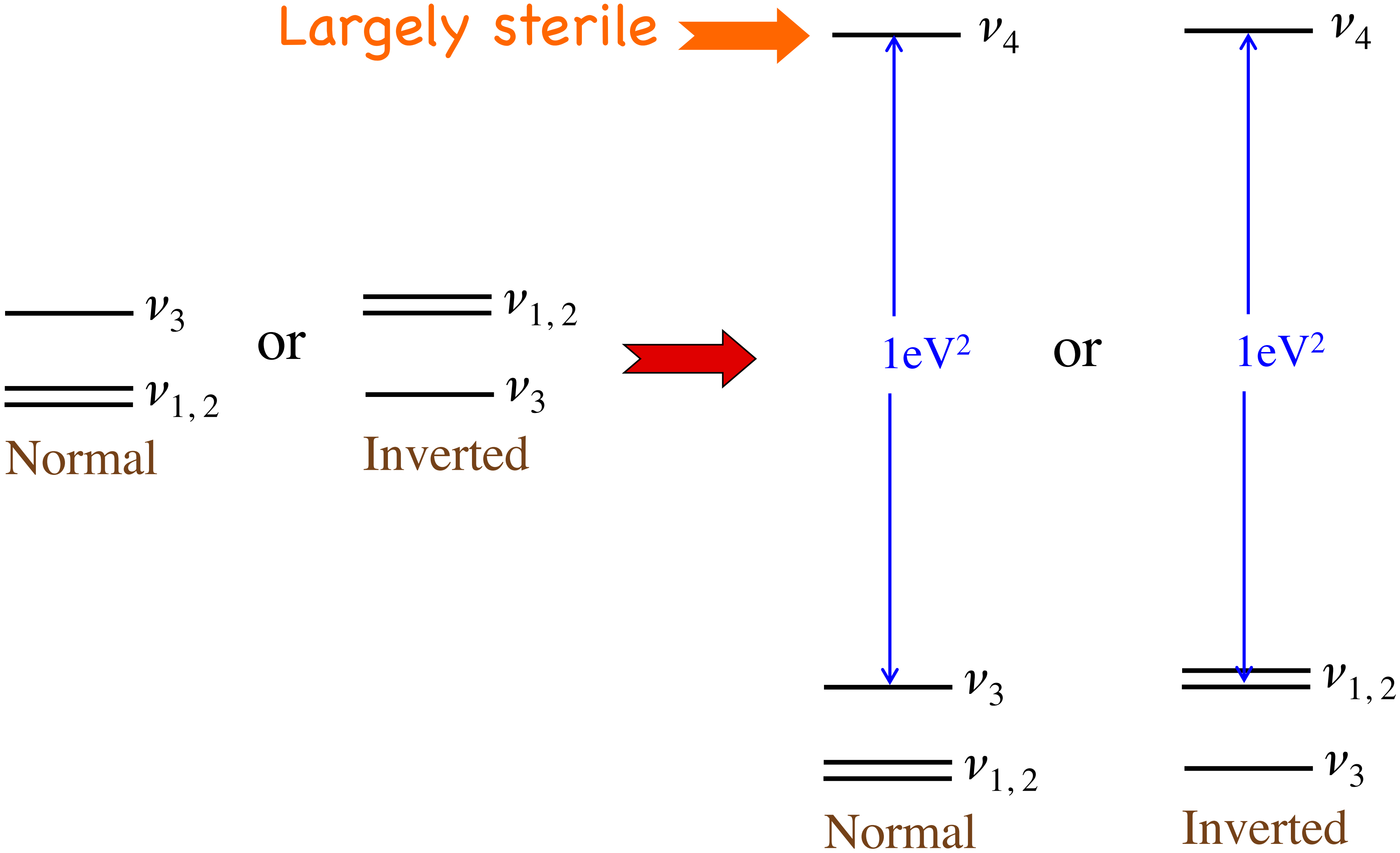
⇒ At least **4** mass eigenstates

⇒ At least **4** flavors

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

⇒ At least **1** sterile neutrino

The change in the mass-eigenstate spectrum is, for example,



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 Hints of eV^2-Scale Δm^2

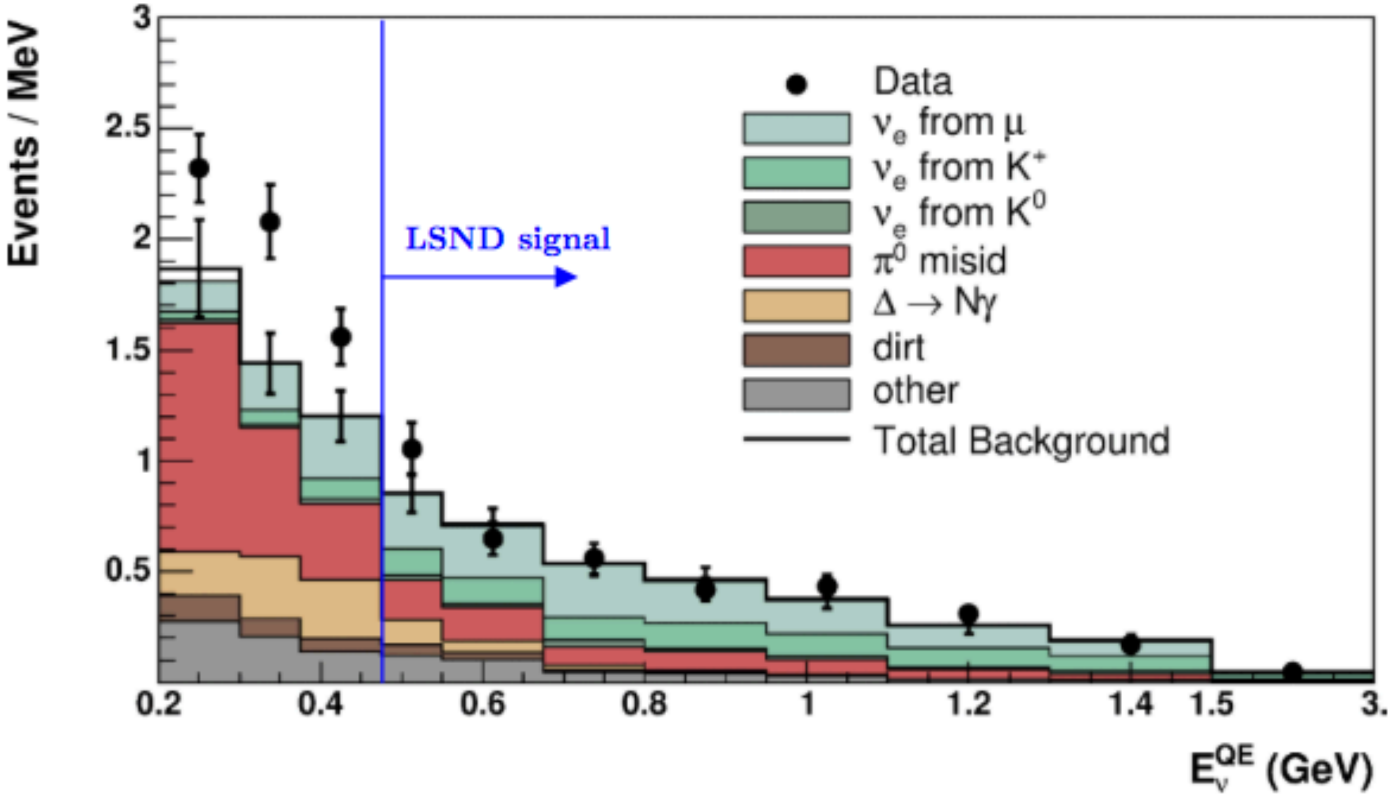
Experiment	**Possible Oscillation**	**Comment**
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	Interesting
MiniBooNE	$\nu_\mu \to \nu_e$	Low energy excess?
MiniBooNE	$\bar{\nu}_\mu \to \bar{\nu}_e$	Low energy excess?
Reactor Exps.	$\bar{\nu}_e \to \text{Not } \bar{\nu}_e$	Flux uncertainty ~ 6% size of effect
^{51}Cr and ^{37}Ar Source Exps.	$\nu_e \to \text{Not } \nu_e$	Detection efficiency?

Present Status

There is tension between appearance data and disappearance data, primarily due to the MiniBooNE low-energy excess. Is this excess perhaps due to something other than oscillations?

$\nu_\mu \rightarrow \nu_e$

MiniBooNE



MicroBooNE is probing whether this low-E excess is from $\nu_e \rightarrow e$ or from photons.

Numerous present experiments are constraining the extra mass-squared splittings and mixing angles introduced by sterile neutrinos.

The evidence for 1 eV scale sterile neutrinos is certainly not convincing, but neither can it be ignored.

1 eV scale sterile neutrinos, if real, could greatly affect the interpretation of the CP-violation studies of the long-baseline experiments.

For example, long-baseline data that, when analyzed disregarding the possibility of sterile neutrinos, indicate that CP violation is very small or absent, could in fact hide quite large CP violation.

(Gandhi, B.K., Masud, Prakash)

The theoretical motivation for sterile neutrinos much lighter than the ones predicted by the straightforward version of the See-Saw picture is not strong.

However, such light sterile neutrinos are certainly theoretically possible.

Comment: Before Dark Matter was discovered, the theoretical motivation for ***that*** was not strong either.

The presence or absence of 1 eV scale sterile neutrinos needs to be settled experimentally, and many experiments to do that, using neutrinos from sources, reactors, accelerators, or elsewhere, are in progress or planned.

To confirm their existence, it would be nice to see actual

Oscillatory Behavior **a la**