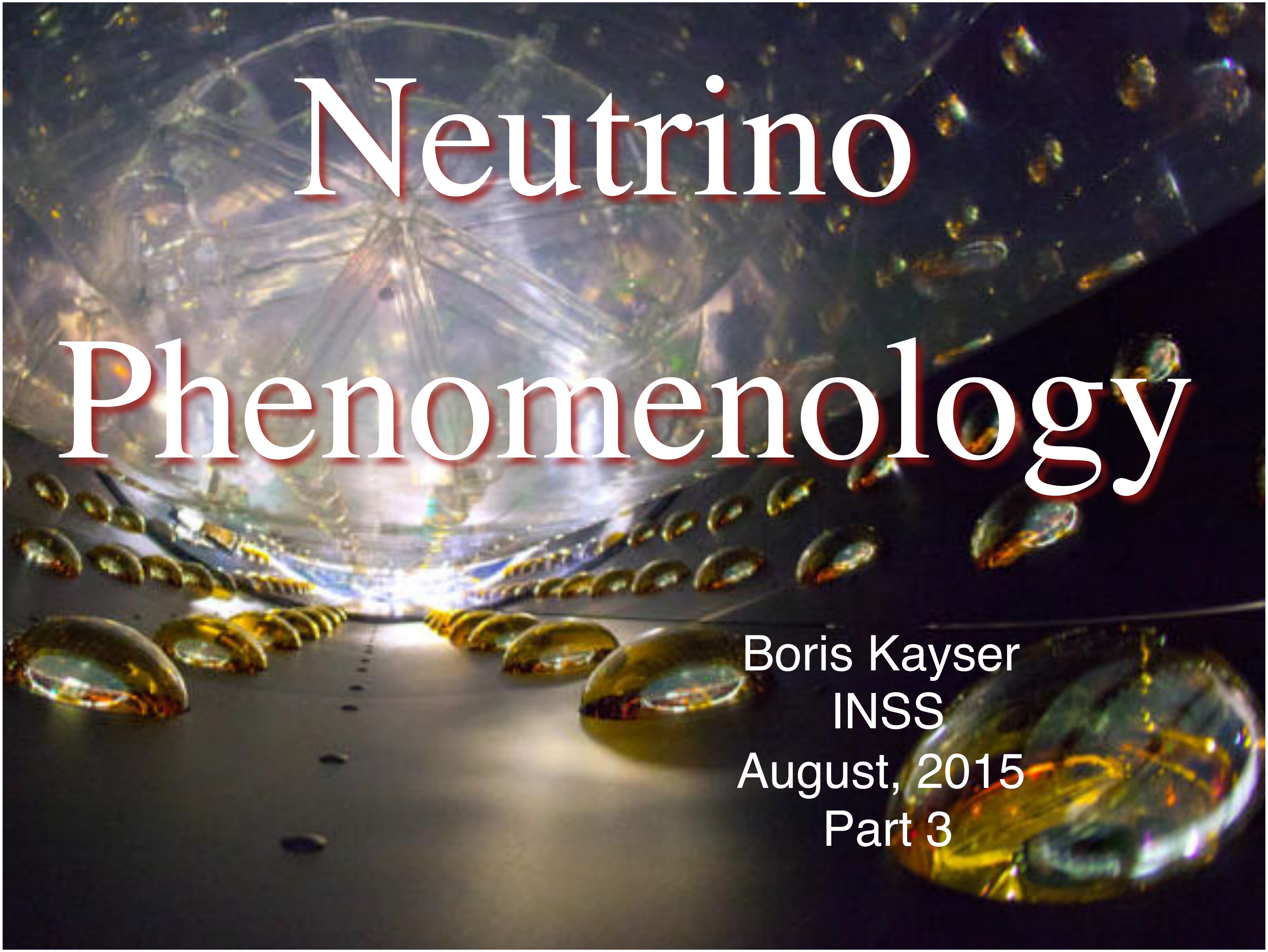

Neutrino Phenomenology

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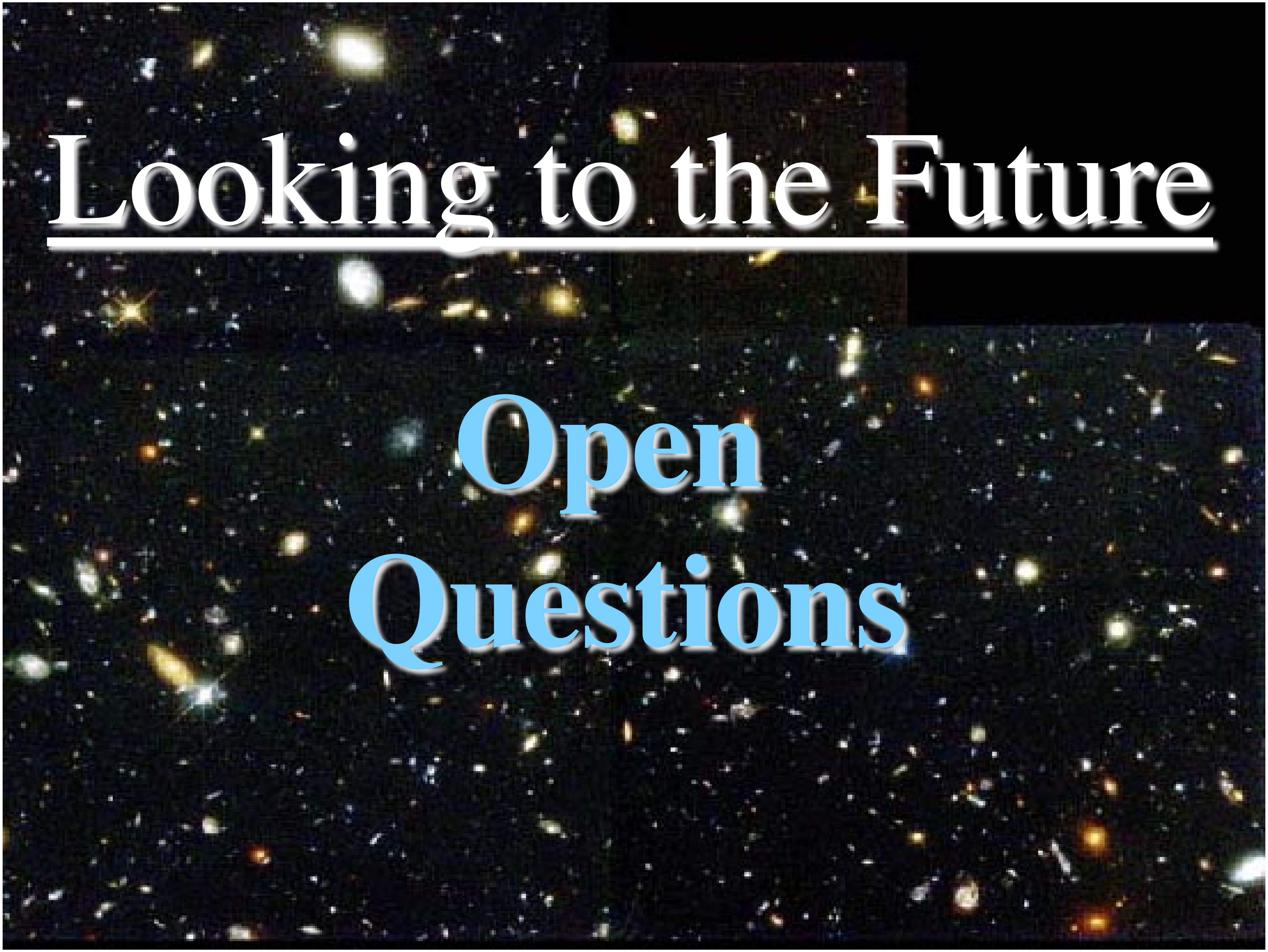
INSS
August, 2015
Part 3


Looking to the Future
Open
Questions

- Is the physics behind the masses of neutrinos different from that behind the masses of all other known particles?
- Are neutrinos their own antiparticles?

- Is the $(\text{mass})^2$ spectrum like  or  ?

- What is the absolute scale of neutrino mass?

- 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?
- Are we descended from heavy neutrinos?

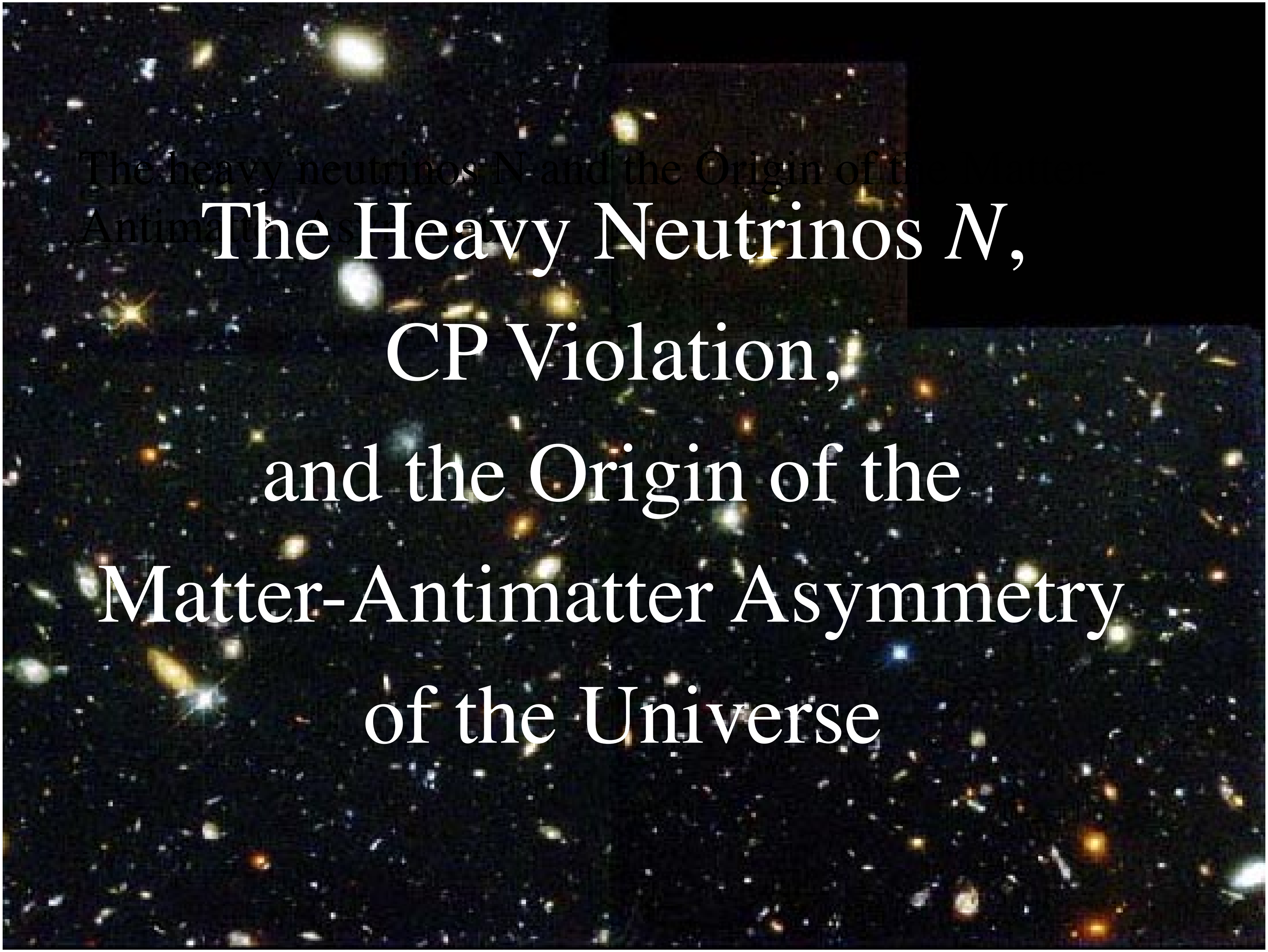
- What can neutrinos and the universe tell us about one another?

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

- Do neutrinos have Non-Standard-Model interactions?

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

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



The Cosmic Puzzle

Today: $B \equiv$ #(Baryons) – #(Antibaryons) $\neq 0$.

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

Also, $L \equiv$ #(Leptons) – #(Antileptons) $= 0$.

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

Sakharov: $B = 0 \Rightarrow B \neq 0$ requires $\not{C}$ and $\not{CP}$.

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

The $\not{CP}$ in the quark mixing matrix, seen in B and K decays, leads to much too small a $B - \bar{B}$ asymmetry.

If ***quark*** $\not{CP}$ cannot generate the observed $B - \bar{B}$ 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

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

Yukawa coupling matrix

SM Higgs doublet

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.)

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 $\not{C}$ and $\not{CP}$ effects.

In particular, such phases would have led to —

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

and

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

← $\not{C}$ and $\not{CP}$

How Phases Lead To CP Non-Invariance

$\not{CP}$ ***always*** comes from ***phases***.

Therefore, $\not{CP}$ 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 —

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

- M_1: CP-invariant magnitude
- θ_1: CP-odd "weak" phase from constants
- δ_1: CP-even "strong" phase

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 —

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

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

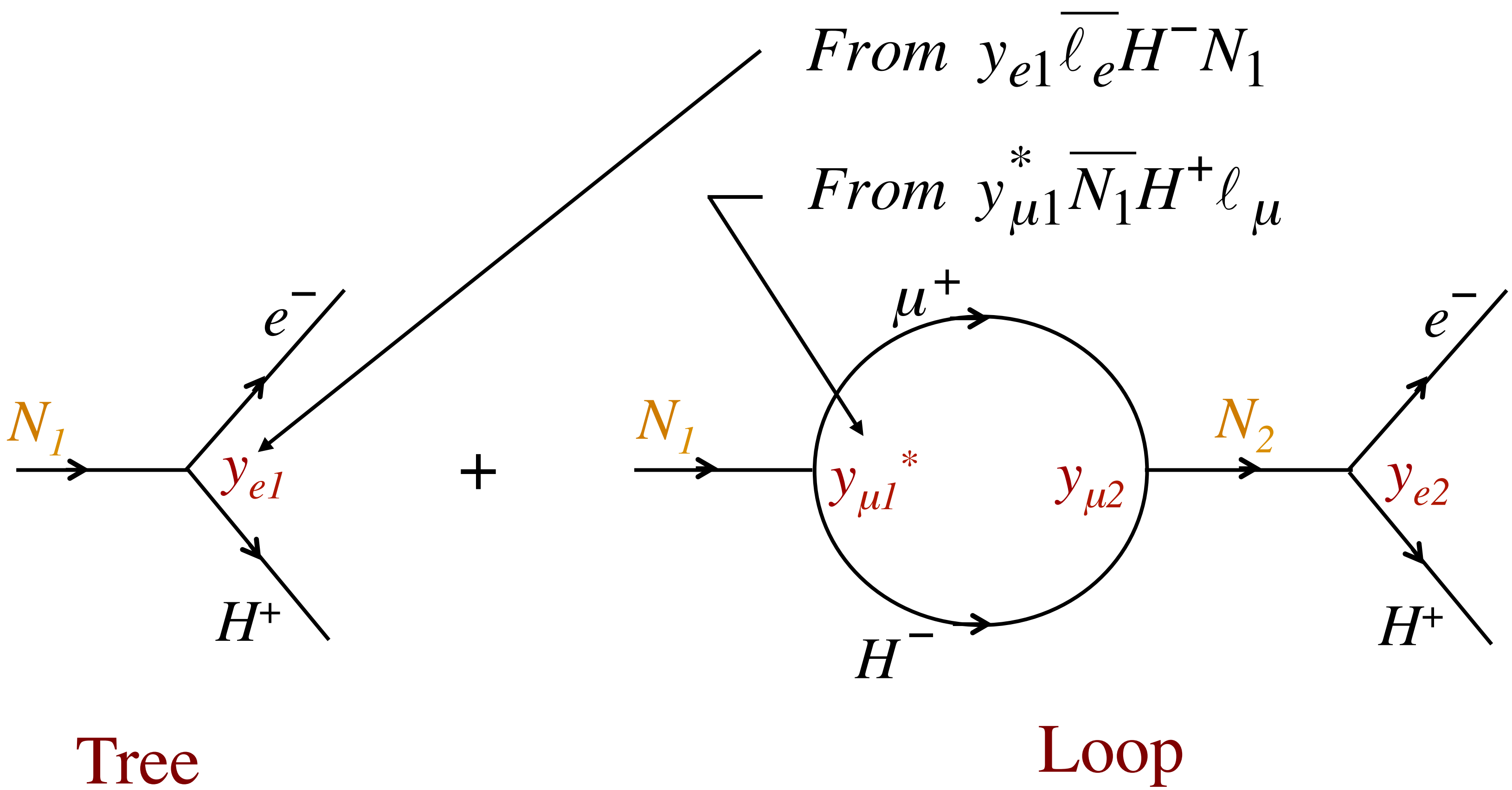
A CP-violating rate difference requires 3 ingredients:

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

How Do ~~CP~~ Inequalities Between *N* Decay Rates Come About?

Let us look at an example.

This example illustrates that ~~CP~~ in ***any decay*** always involves amplitudes ***beyond*** those of lowest order in the Hamiltonian.



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

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.

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

The inequalities —

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

and

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

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.

$$B_i = 0$$
$$L_i \neq 0$$

Initial state from N decays

→ **Sphaleron Process** →

$$B_f \cong -\frac{1}{3} L_i$$
$$L_f \cong \frac{2}{3} L_i \cong -2B_f$$

Final state

There is now a nonzero $\mathcal{B}$*aryon* $\mathcal{N}$*umber* $\mathcal{B}$**.**

Eventually, there are baryons, but ~ no antibaryons.

Reasonable couplings y give the observed value of $\mathcal{B}$**.**

What *N* masses are required?

The See-Saw model ⇒

Light neutrino masses; Higgs vev; Yukawa couplings; Heavy neutrino masses

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

See-Saw relation

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.

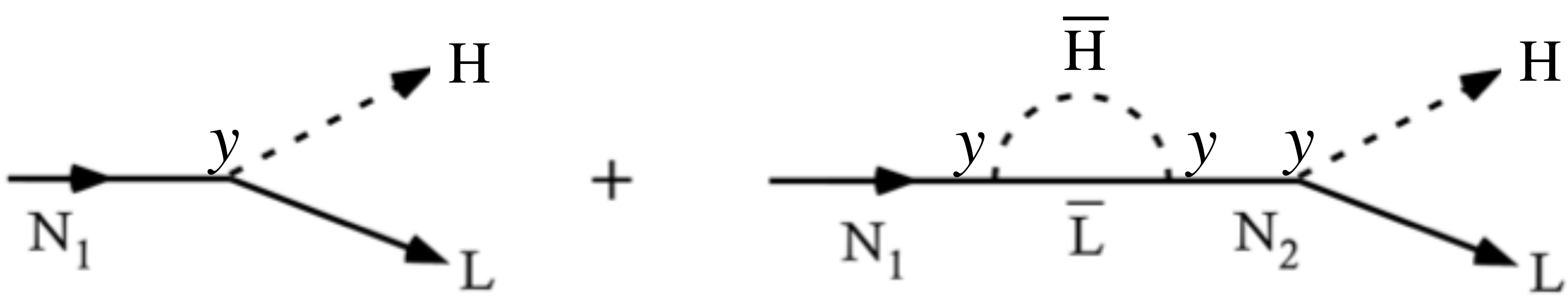
The CP-violating asymmetry between the N decay rates,

ν or ℓ^- → L; H^0 or H^+ → H

$$\varepsilon_{CP} \equiv \frac{\Gamma(N \to LH) - \Gamma(N \to \overline{L}\overline{H})}{\Gamma(N \to LH) + \Gamma(N \to \overline{L}\overline{H})} \quad ,$$

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.

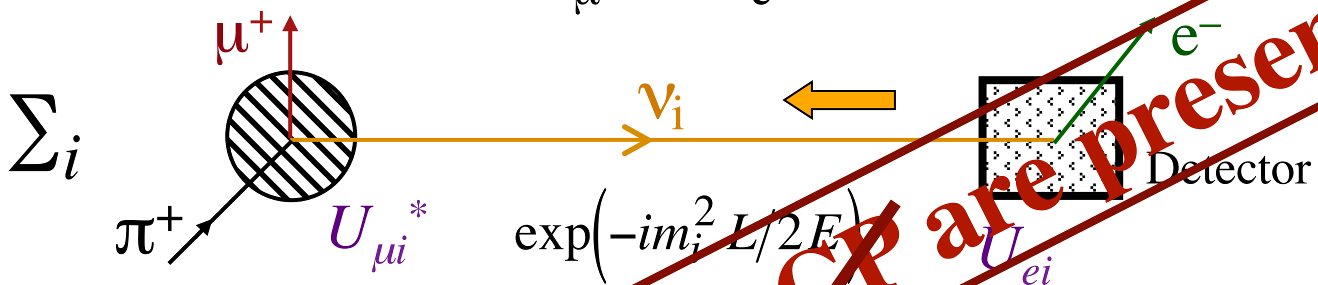
Looking the other way: If the oscillation CP phase δ proves to be large, it could explain almost the entire Baryon – Antibaryon asymmetry by itself.

(Pascoli, Petcov, Riotto)

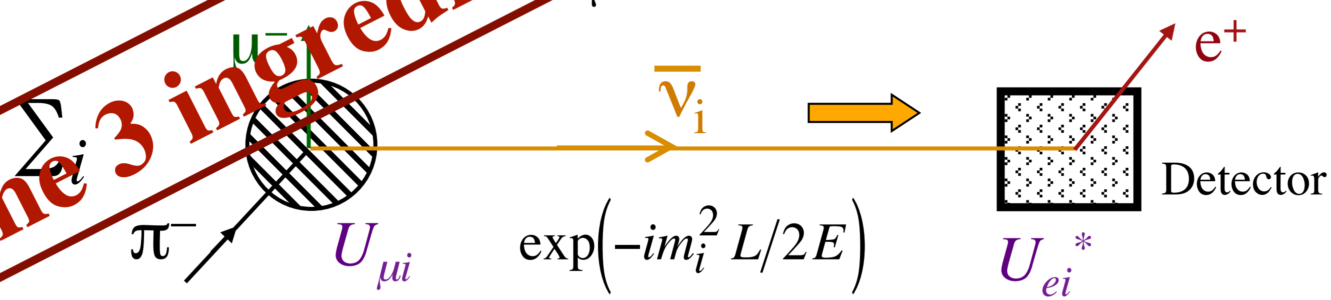
Hosting international experiments to look for ~~CP~~ in light-neutrino oscillation is being contemplated in the US and in Japan.

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

Compare $\nu_\mu \rightarrow \nu_e$



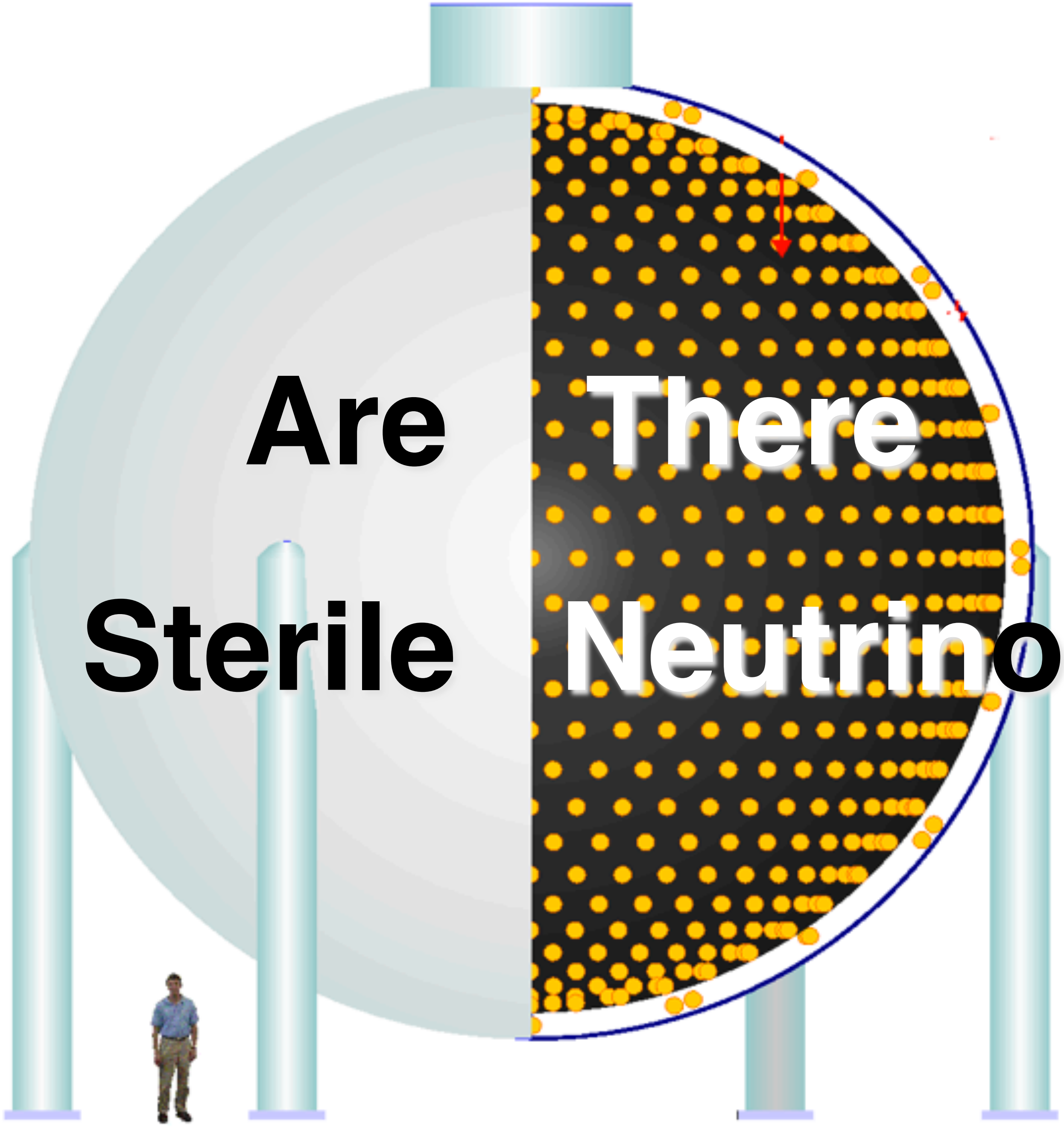
with "$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$"



The 3 ingredients for CP̸ are present.

Do these two processes have different rates?

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 —

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

SM lepton doublet: $\overline{\nu}_{\alpha L}$, $\overline{\ell}_{\alpha L}$

SM Higgs doublet: $\overline{H^0}$, H^-

Yukawa coupling matrix: $y_{\alpha i}$

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

∴ The N_i are sterile neutrinos.

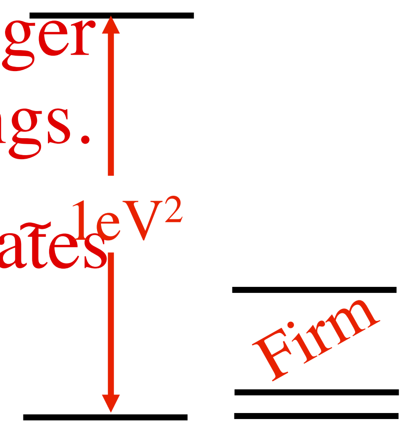
Are there also ***light*** sterile neutrinos with masses ~ 1 eV?

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



⇒ At least **4** mass eigenstates

⇒ At least **4** flavors

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

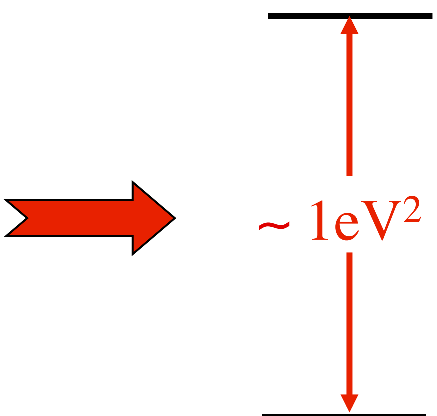
⇒ At least **1** sterile neutrino

The Hint From LSND

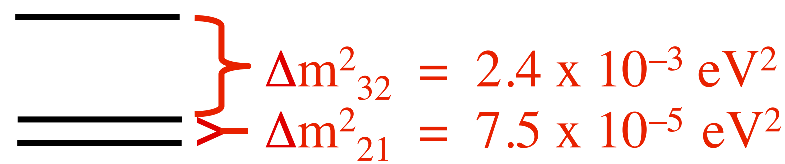
The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at $L(m)/E(MeV) \sim 1$.

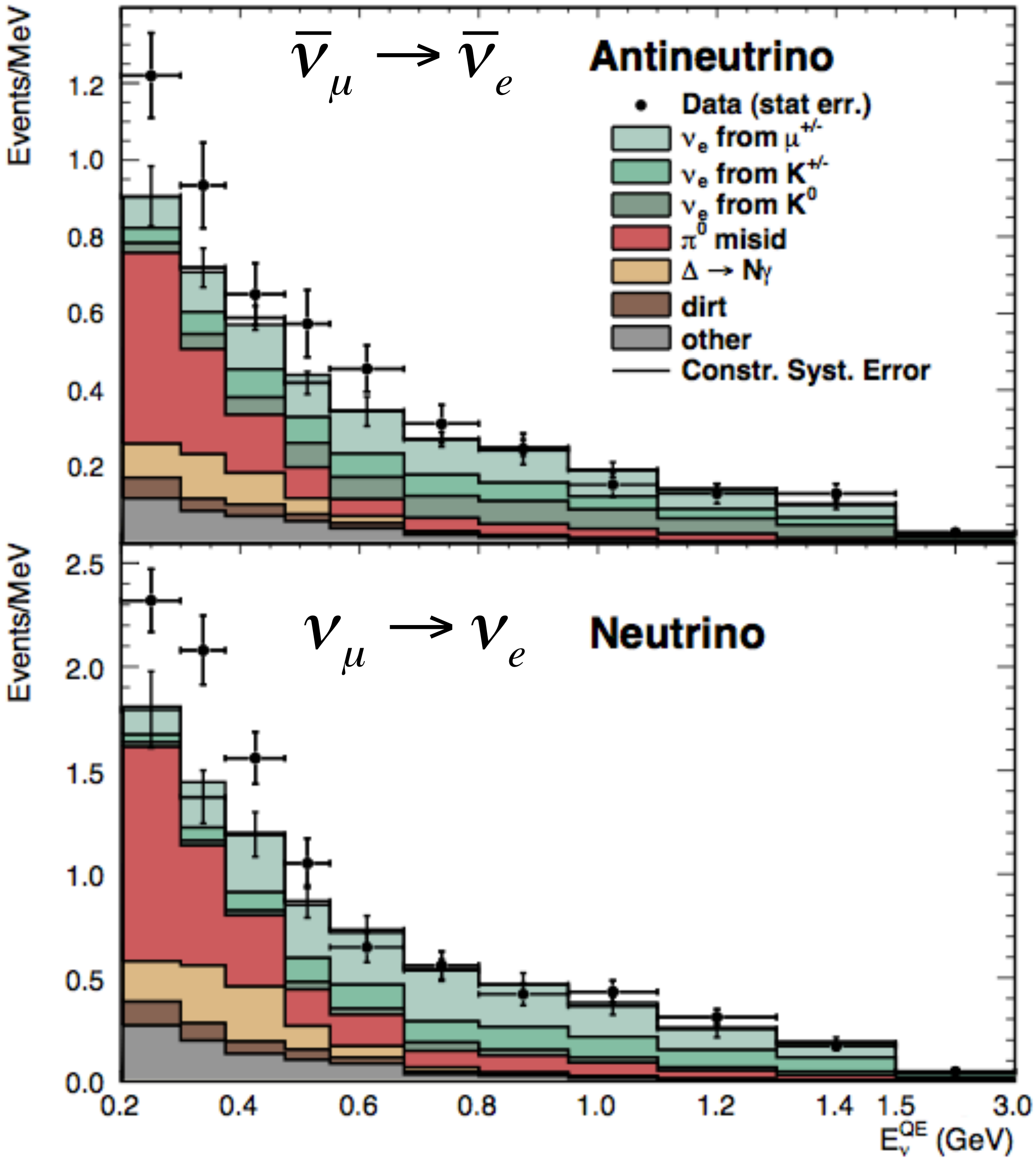
$$P\left(\overline{\nu_\mu} \rightarrow \overline{\nu_e}\right) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(m)}{E(MeV)}\right] \sim 0.26\%$$

From μ^+ decay at rest; E ~ 30 MeV



in contrast to

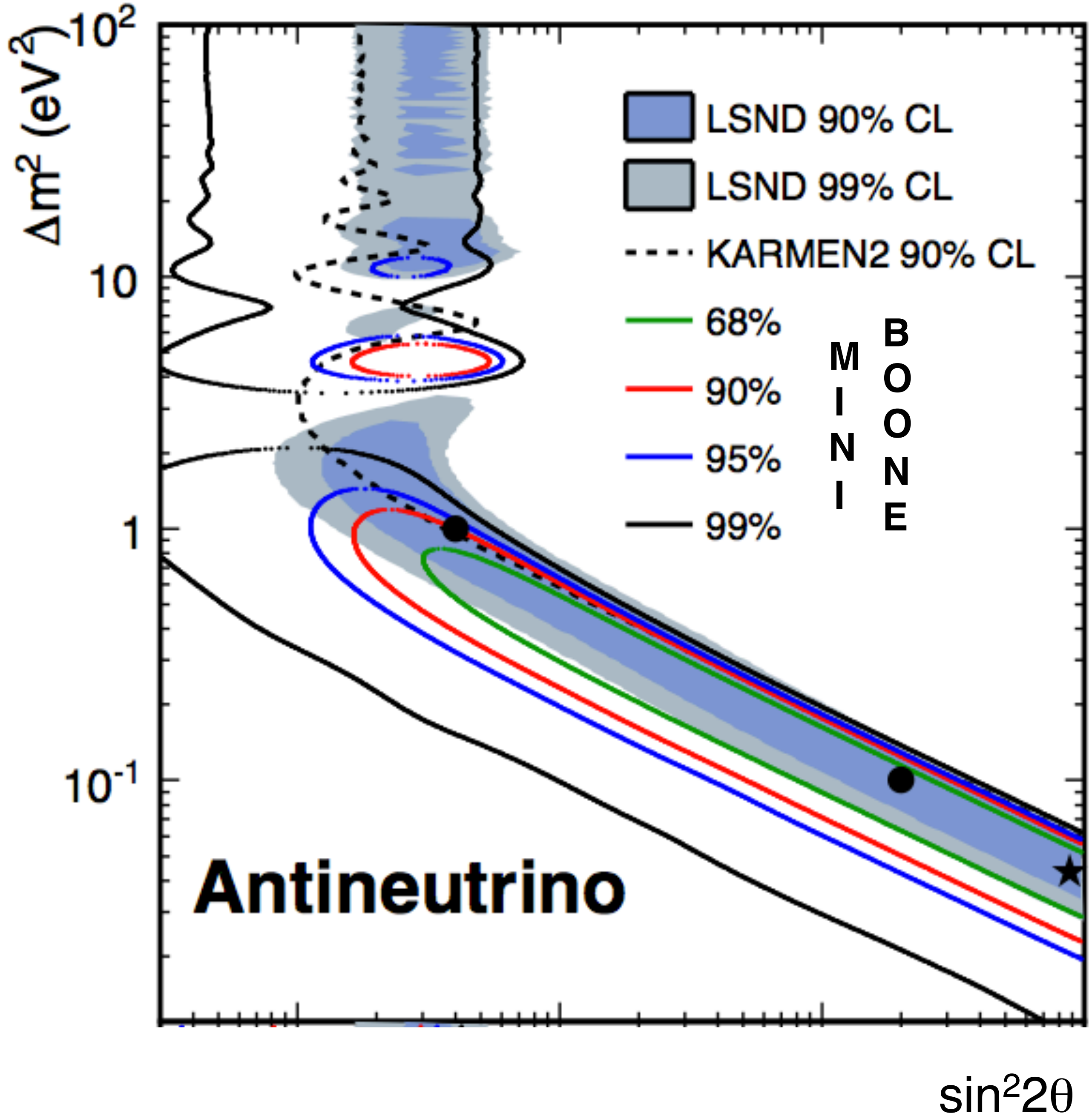




The Hint From MiniBooNE

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 $\nu_\mu \to \nu_e$. This disfavors somewhat a $\nu_\mu \to \nu_e$ interpretation of the low-energy MiniBooNE ν_e excess, but it does not exclude it.

ICARUS and OPERA do not constrain the $\bar{\nu}_\mu \to \bar{\nu}_e$ interpretation of the low-energy MiniBooNE $\bar{\nu}_e$ excess.

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,

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

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

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

But the uncertainty in the initial flux is as big as the effect.

(Hayes, et al., Huber)

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

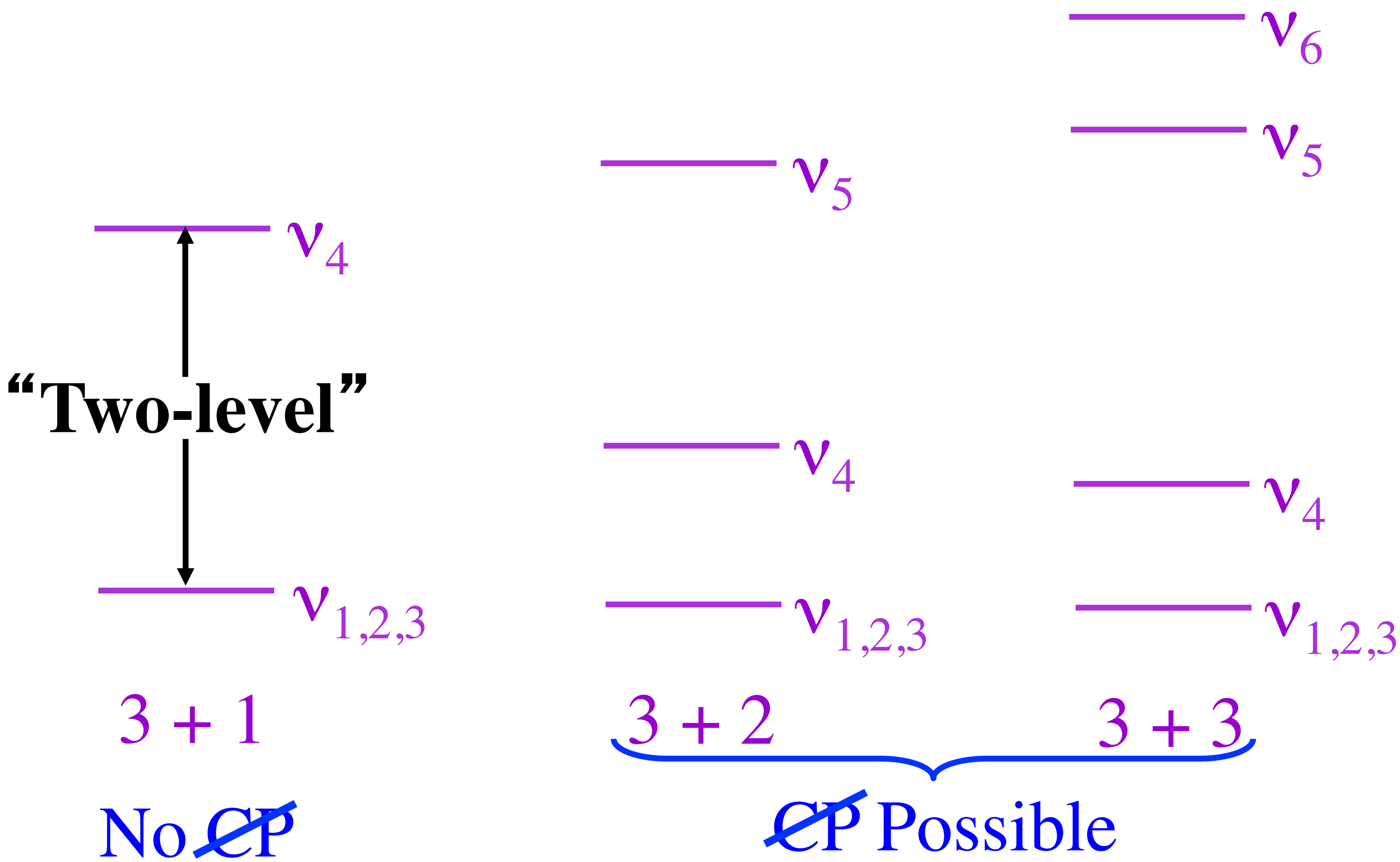
These radioactive sources were used to test the gallium solar ν_e detectors GALLEX and SAGE.

$$\frac{\text{Measured event rate}}{\text{Expected event rate}} \approx (75-85)\%$$

(Giunti, Laveder, Li, Long)

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

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.

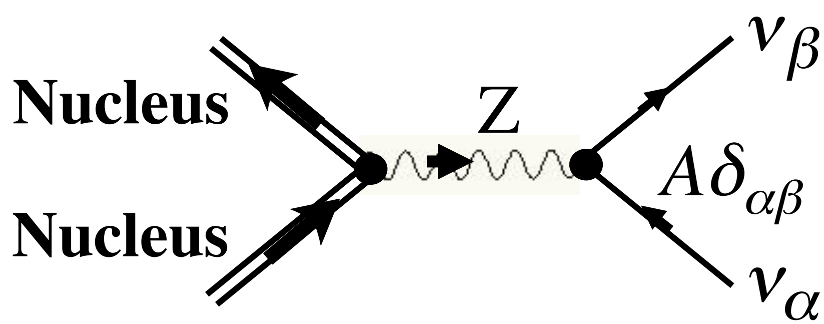
With 3 + N neutrino mass eigenstates, there can be 3 + N lepton flavors, N of them sterile. For example, for N = 3:

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

Ideas For Future Experiments

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

Coherent Neutral-Current Scattering

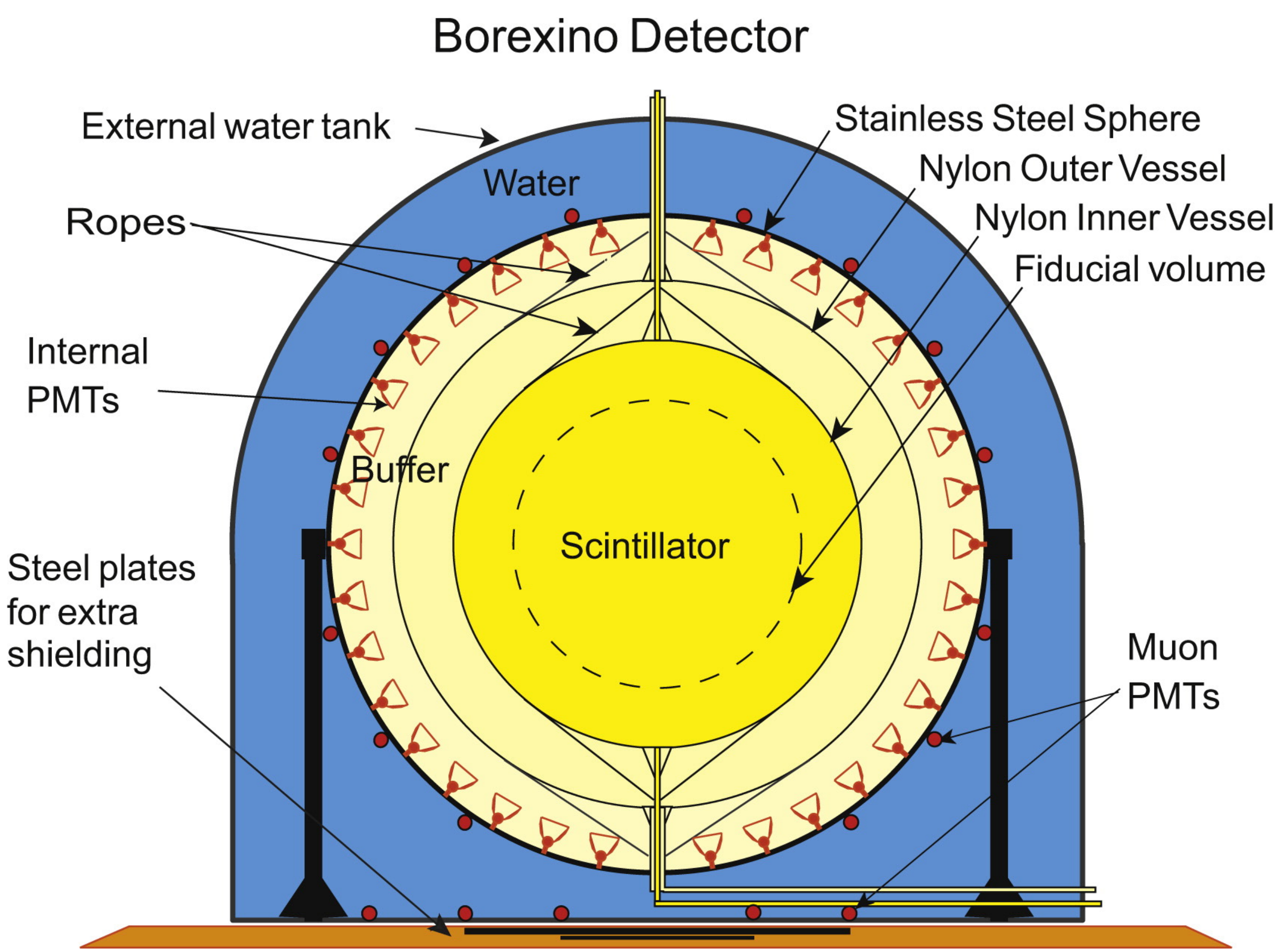


This process has the same rate for any incoming ***active*** neutrino, ν_e, ν_μ, or ν_τ.

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

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

A Radioactive Source Near a Detector (SOX)



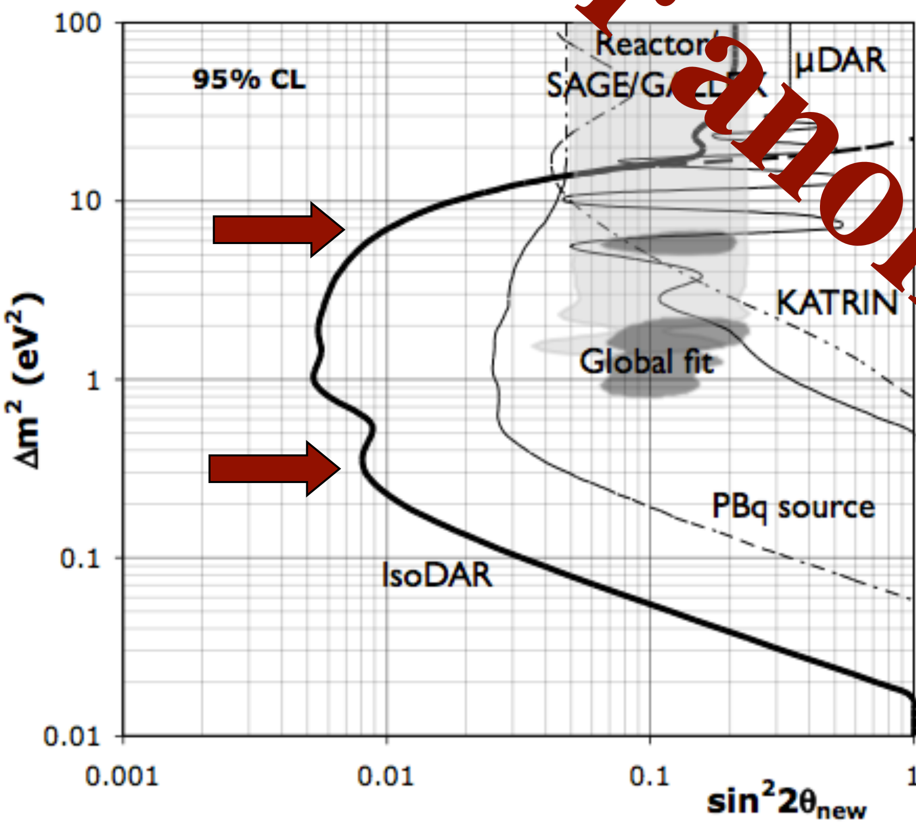
Place a ^{51}Cr ν_e source or ^{144}Ce-^{144}Pr $\overline{\nu}_e$ source near or in Borexino.

1304.7721

$\bar{\nu}_e$ 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 (the reactor anomaly) in a 5-year run

(Bungau et al.)

Is reactor anomaly real?

Multi-Detector Short Baseline Experiments At Accelerators

Compare event rates in several detectors,
at different distances from the source at Fermilab.

This is a good way to deal with flux uncertainties,
so long as the neutrinos have not already oscillated
before reaching the near detector.

Good luck!