

The background of the slide is a deep space image featuring a dense field of stars and several prominent galaxies. A bright, yellowish-white galaxy core is visible near the center, surrounded by blue and purple nebulae and star clusters. The overall color palette is dark with vibrant highlights from the celestial objects.

Electromagnetic Leptogenesis


Boris Kayser
Moriond
March 12, 2009



The Challenge

The universe contains baryons,
but essentially no antibaryons.

$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10} \quad ; \quad \frac{n_{\bar{B}}}{n_B} \lll 1$$

Standard cosmology: Any initial
baryon - antibaryon asymmetry
would have been erased.

How did $n_B = n_{\bar{B}}$  $n_B \gg n_{\bar{B}}$
?

Sakharov $n_B = n_{\bar{B}}$  $n_B \gg n_{\bar{B}}$ 
requires CP.

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

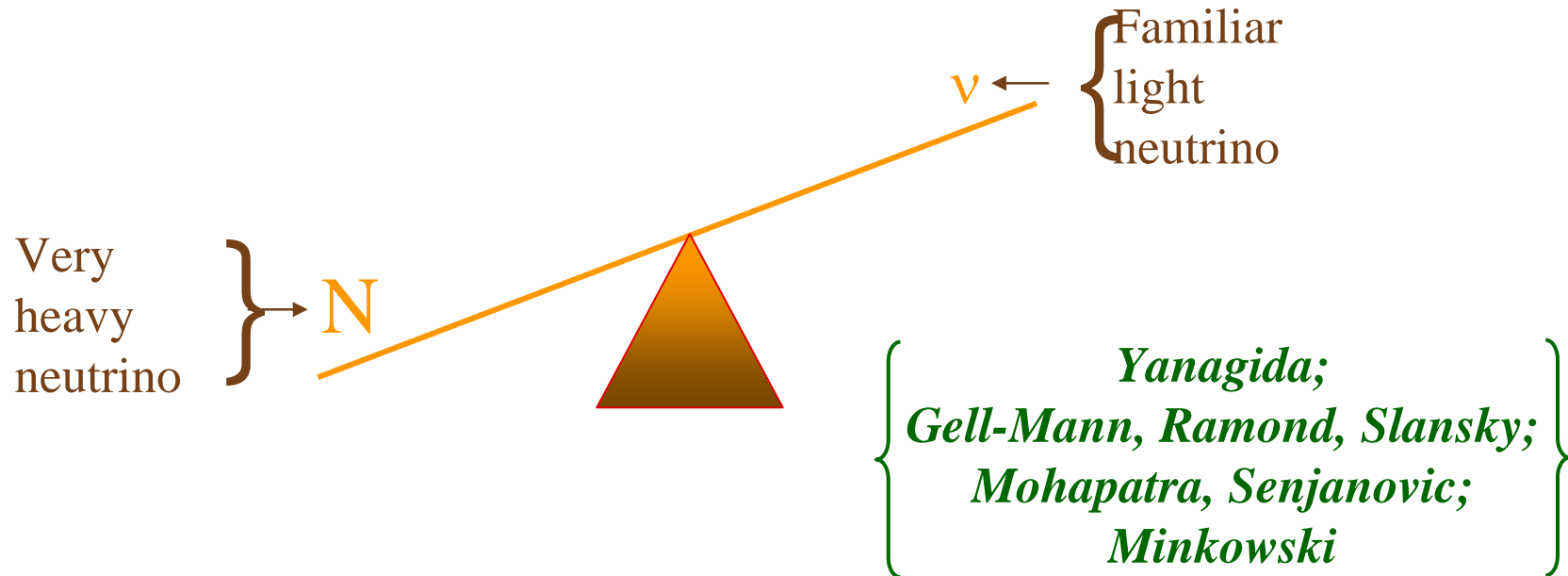
If **quark** ~~CP~~ cannot generate
the observed $B-\bar{B}$ asymmetry,
can some scenario involving
leptons do it?

The candidate scenario:
Leptogenesis.

Leptogenesis – The General Idea

Leptogenesis is an outgrowth of the most popular theory of why neutrinos are so light —

The See-Saw Mechanism



The *very* heavy neutrinos **N** would have been made in the hot Big Bang.

Leptogenesis — Step 1

The heavy neutrinos N , like the light ones ν , are Majorana particles. Thus, an N can decay into l^- or l^+ .

If ν oscillation violates CP, then quite likely so does N decay. In the See-Saw, these two CP violations have a common origin: One Yukawa coupling matrix, y .

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

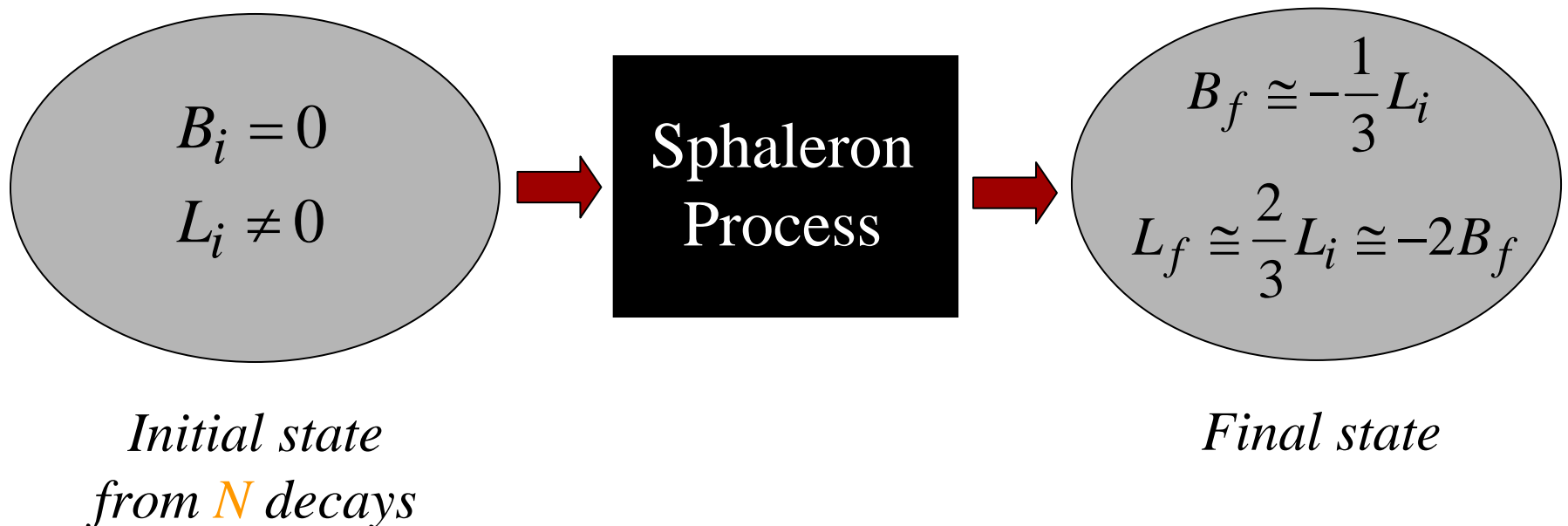
$$N \rightarrow l^- + \phi^+ \quad \text{and} \quad N \rightarrow l^+ + \phi^-$$

Standard-Model Higgs

*This produces a universe with unequal numbers of **leptons** and **antileptons**.*

Leptogenesis — Step 2

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



There is now a Baryon Asymmetry.

Leptogenesis In Greater Depth

The see-saw model adds to the Standard Model —

$$\begin{aligned}
 \text{Mass of } N_k & \downarrow \\
 \mathcal{L}_{\text{new}} = & - \sum_{k=1}^3 \frac{M_k}{2} \overline{N_{kR}^c} N_{kR} - \sum_{j,k=1}^3 y_{jk} \left[\overline{\nu_{jL}} \overline{\varphi^0} - \overline{\ell_{jL}} \varphi^- \right] N_{kR} + h.c. \\
 & \uparrow \qquad \qquad \qquad \uparrow \qquad \qquad \uparrow \qquad \qquad \uparrow \qquad \qquad \uparrow \\
 & \text{SM lepton doublet} \quad \quad \quad \text{SM Higgs doublet} \\
 & \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad I_W = 0
 \end{aligned}$$

Yukawa couplings

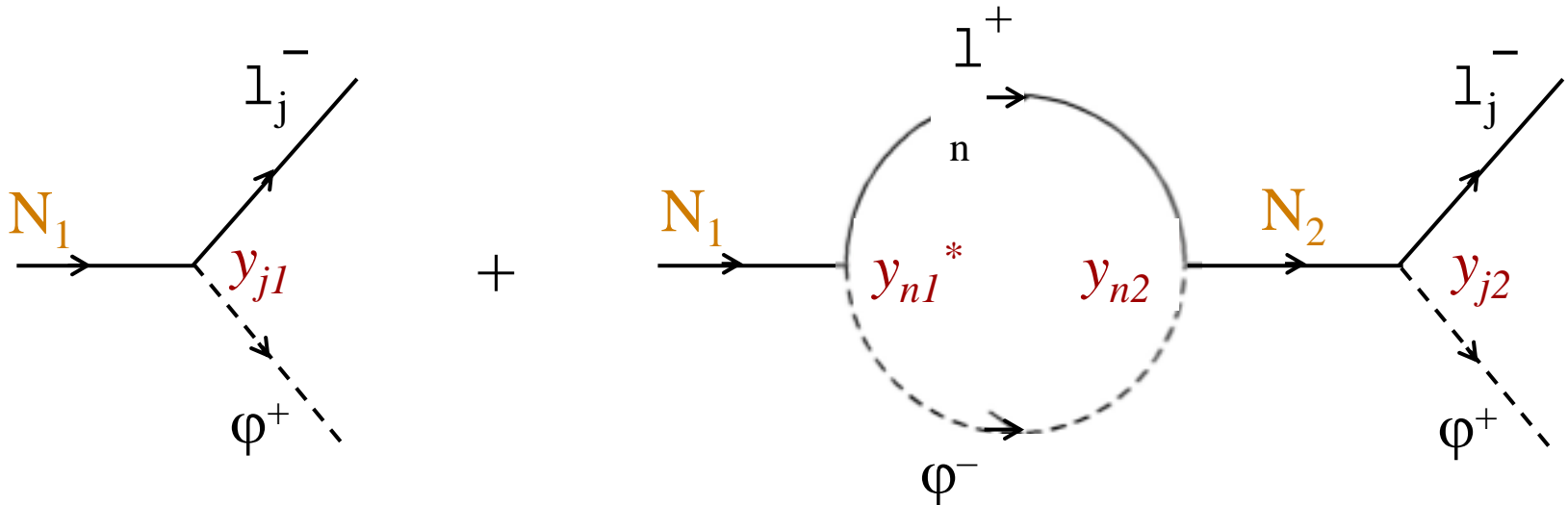
The Yukawa couplings y_{jk} cause —

$$N_k \rightarrow \ell_j^{\mp} + \varphi^{\pm} \quad \text{and} \quad N_k \rightarrow \overline{\nu_j} + \overline{\varphi^0} .$$

~~CP~~ In N Decay

All CP-violating phases must come from the Yukawa coupling matrix y .

Tree – loop interferences lead to ~~CP~~. Example:



$$\Rightarrow \Gamma(N_1 \rightarrow \ell_j^- + \phi^+) - \Gamma(N_1 \rightarrow \ell_j^+ + \phi^-) \propto \Im m(y_{j1}^* y_{n1}^* y_{j2} y_{n2})$$

Simplest picture:

The leptonic asymmetry comes from decay of the lightest \mathbf{N} , \mathbf{N}_1 , and the final lepton flavors, e , μ , and τ , may be treated identically.

Then, summing over the final lepton flavors, the \mathcal{CP} asymmetry is —

$$\begin{aligned}\varepsilon &\equiv \frac{\Gamma(N_1 \rightarrow L\phi) - \Gamma(N_1 \rightarrow \bar{L}\bar{\phi})}{\Gamma(N_1 \rightarrow L\phi) + \Gamma(N_1 \rightarrow \bar{L}\bar{\phi})} \\ &= \frac{1}{8\pi} \frac{1}{(y^\dagger y)_{11}} \sum_m \Im m \left[\{(y^\dagger y)_{1m}\}^2 \right] K \left(\frac{M_m^2}{M_1^2} \right)\end{aligned}$$

Kinematical function

$$\varepsilon \sim y^2/10$$

To explain $n_B/n_\gamma \sim 10^{-9}$ requires $\varepsilon \sim 10^{-6}$.

The N Masses Required For Leptogenesis

After the EW phase transition (which is after the N_k have decayed), $\langle \phi^0 \rangle_0 \equiv v \cong 250 \text{ GeV}$. Then —

$$\overline{\nu_L} y \phi^0 N_R \quad \longrightarrow \quad \overline{\nu_L} (y v) N_R = \overline{\nu_L} \underbrace{M_D}_{\text{Neutrino Dirac mass matrix}} N_R$$

In the see-saw picture, where the N masses are $\gg M_D$, the light ν masses M_ν are —

$$M_\nu \sim M_D^2 / M_N \sim (y v)^2 / M_N \sim 10^{-1} \text{ eV}.$$

$$M_\nu \sim M_D^2/M_N \sim (yv)^2/M_N \sim 10^{-1} \text{eV}.$$

For leptogenesis, we required that —

$$\varepsilon \sim y^2/10 \sim 10^{-6}$$

Together, these requirements imply that —

$$M_N \sim 10^9 \text{ GeV}.$$

*Leptogenesis requires very heavy neutrinos,
far beyond the range of LHC.*

Leptogenesis and \cancel{CP} In Light ν Oscillation

In a basis where the charged-lepton mass matrix is diagonal, our Yukawa coupling matrix ***y is the only source of CP violation*** among the leptons.

Though M_D , the \cancel{CP} phases in ***y*** feed into the leptonic mixing matrix ***U***.

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

Electromagnetic Leptogenesis

(Nicole Bell, B.K.,
Sandy Law)

Suppose new physics at a high mass scale $\Lambda > M_N$
leads to the electromagnetic N decay mode —

$$N \rightarrow \nu + \gamma \quad \text{Toy Model}$$

or the mode —

$$N \rightarrow \underbrace{L + \phi}_{\text{Emitted in standard leptogenesis}} + (\gamma \text{ or } Z \text{ or } W)$$

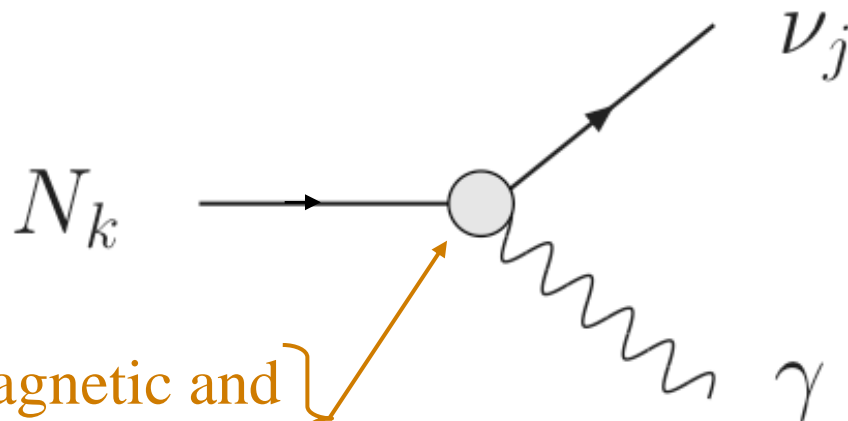
More realistic;
respects SM
conservation laws

Emitted in standard
leptogenesis

Q: Could \cancel{CP} in such decays be a successful alternative to the standard leptogenesis scenario?

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

The $N \rightarrow \nu + \gamma$ Toy Model



Transition magnetic and
electric dipole moments

No ~~CP~~ In Any Decays In Lowest Order

Tree-level interference between an Electric DM and a Magnetic DM cannot lead to —


$$\Gamma(N_k \rightarrow \nu_j + \gamma) \neq \Gamma(N_k \rightarrow \bar{\nu}_j + \gamma).$$

There can never be a difference between the rates for CP-conjugate decay modes in first order in the Hamiltonian.

If $T \equiv i(S - I)$ is the transition operator for the decay $Q \rightarrow a_1 + a_2 + \dots$,

CPT – invariance 

$$\begin{aligned} & \left| \langle a_1(\vec{p}_1, \lambda_1) a_2(\vec{p}_2, \lambda_2) \dots | T | Q(J_z) \rangle \right|^2 \\ &= \left| \langle \overline{a_1}(\vec{p}_1, -\lambda_1) \overline{a_2}(\vec{p}_2, -\lambda_2) \dots | T^\dagger | \overline{Q}(-J_z) \rangle \right|^2 \end{aligned}$$


Helicity
Spin projection

To first order in the Hamiltonian \mathcal{H} , $T = \mathcal{H}$. Then $T^\dagger = T$.

Then —

$$\Gamma(Q \rightarrow a_1 + a_2 + \dots) = \Gamma(\overline{Q} \rightarrow \overline{a_1} + \overline{a_2} + \dots)$$

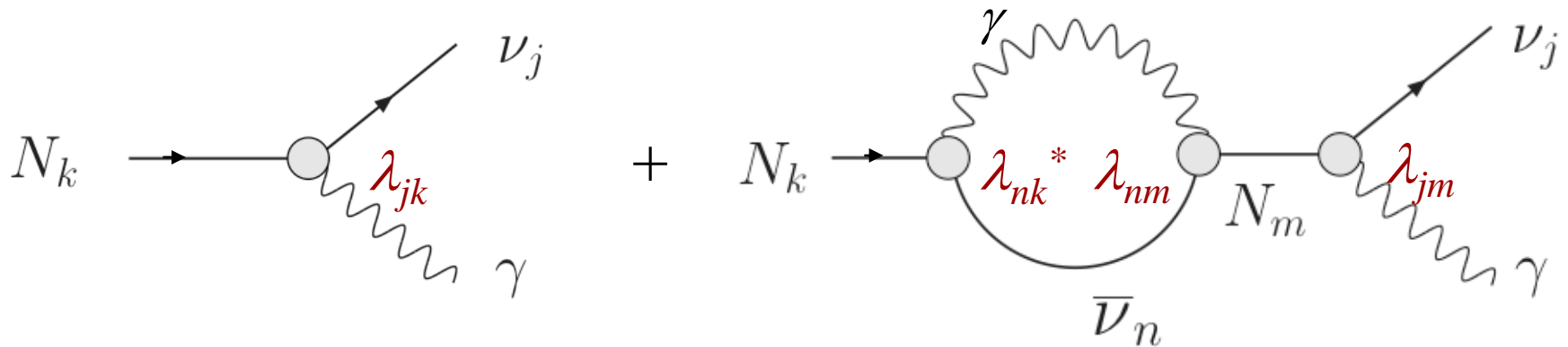
~~CP~~ In the $N \rightarrow \nu + \gamma$ Toy Model From Tree – Loop Interference

The assumed effective EM coupling of the neutrinos is —

$$-L_{\text{EM-Toy}} = \frac{1}{\Lambda} \sum_{j,k=1}^3 \overline{\nu_{jL}} \sigma^{\alpha\beta} \lambda_{jk} N_{kR} F_{\alpha\beta} + h.c.$$

Dimensionless dipole
coupling constant } EM field

An example of tree-loop interference:



$$\Rightarrow \Gamma(N_k \rightarrow \nu_j + \gamma) - \Gamma(N_k \rightarrow \bar{\nu}_j + \gamma) \propto \Im m \left(\lambda_{jk}^* \lambda_{nk}^* \lambda_{nm} \lambda_{jm} \right)$$

This model leads to a ~~\mathcal{CP}~~ asymmetry ε rather similar to the one from standard leptogenesis, with $y \Rightarrow \lambda$.

The ~~\mathcal{CP}~~ phases are now in λ .

EM leptogenesis can succeed.

~~CP~~ In the $N \rightarrow L + \phi + (\gamma \text{ or } Z \text{ or } W)$ Model From Tree – Loop Interference

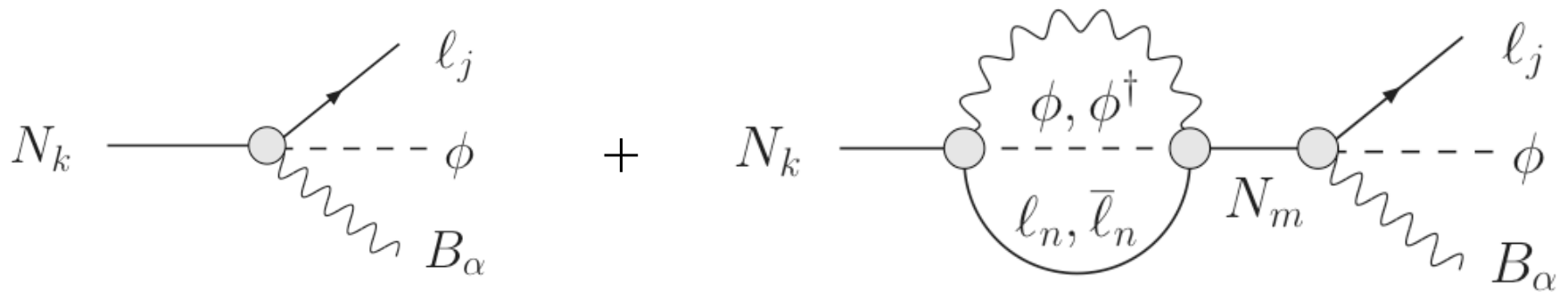
The effective “EM” interaction is now —

$$-L^{\text{EM}} = \frac{1}{\Lambda^2} \sum_{j,k=1}^3 \overline{L_{jL}} \sigma^{\alpha\beta} \left[\lambda'_{jk} B_{\alpha\beta} + \vec{\lambda}'_{jk} \vec{\tau} \cdot \vec{W}_{\alpha\beta} \right] \phi N_{kR} + h.c.$$

Lepton doublet \nearrow $\overline{L_{jL}}$
 $I_W = 0$ gauge field \nearrow $B_{\alpha\beta}$
 $I_W = 1$ gauge field \nearrow $\vec{W}_{\alpha\beta}$
 Higgs doublet \nearrow ϕ

This \longrightarrow N decays such as $N \rightarrow l^- + \phi^0 + W^+$

An example of tree-loop interference:



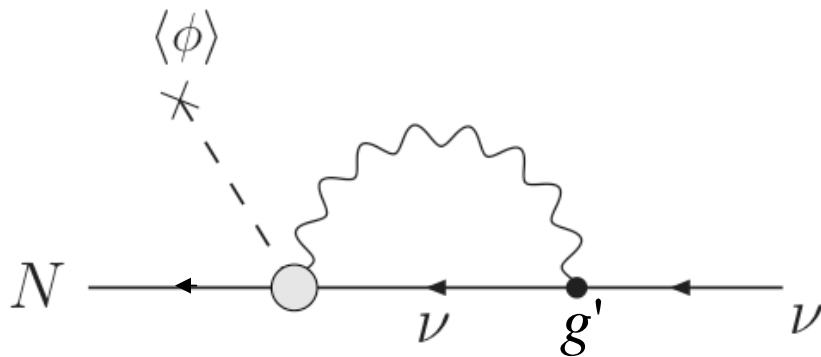
This interference and its toy model counterpart lead to \mathcal{CP} asymmetries ε related by —

$$\left| \varepsilon_{\text{EM}}(\lambda') \right| = \left(\frac{M_k}{8\pi\Lambda} \right)^2 \left| \varepsilon_{\text{Toy-Model}}(\lambda) \right|.$$

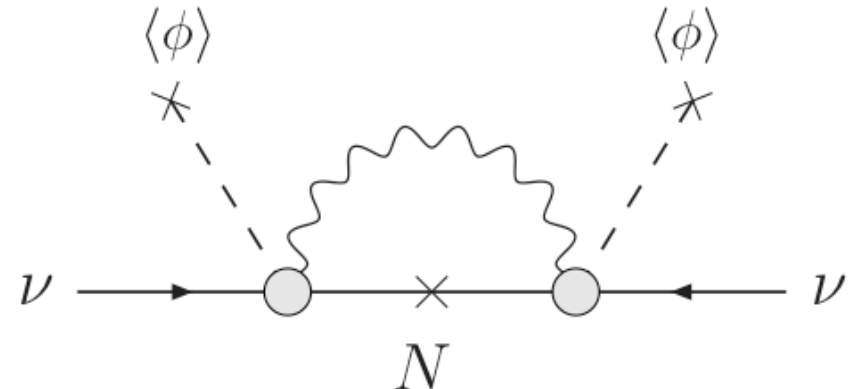
Apart from the suppression factor, the “EM” and toy models give similar asymmetries. Hence, the “EM” model and standard leptogenesis give similar asymmetries.

The New EM Physics and the Masses of the Light Neutrinos

Once $\langle \phi^0 \rangle_0 \neq 0$, L_{EM} leads to —



Dirac mass, leading to
Majorana mass m_ν^A



Majorana mass m_ν^B

EM leptogenesis and the light ν masses are connected.

A Comparison

Standard	Electromagnetic
$\Gamma_1 = \frac{1}{8\pi} (y^\dagger y)_{11} M_1$	$\Gamma_1 = \frac{1}{2\pi} \left(\lambda'^\dagger \lambda' \right)_{11} M_1 \left(\frac{M_1^2}{8\pi\Lambda^2} \right)^2$
$\varepsilon \sim \frac{1}{8\pi} \frac{\Im m(y^\dagger y)_{1m}^2}{(y^\dagger y)_{11}} \frac{M_1}{M_m}$	$\varepsilon \sim \frac{1}{2\pi} \frac{\Im m \left(\lambda'^\dagger \lambda' \right)_{1m}^2}{\left(\lambda'^\dagger \lambda' \right)_{11}} \frac{M_1}{M_m} \left(\frac{M_1^2}{8\pi\Lambda^2} \right)^2$
$m_\nu \sim y^T M_N^{-1} y \langle \varphi \rangle^2$	$m_\nu^A \sim \lambda'^T M_N^{-1} \lambda' \langle \varphi \rangle^2 \left(\frac{g'}{16\pi^2} \right)^2$ $m_\nu^B \sim \frac{\lambda'^T M_N \lambda'}{\Lambda^2} \langle \varphi \rangle^2 \frac{1}{16\pi^2}$

A Specific Example

Suppose the new “EM” interactions dominate over the Yukawa interactions of standard leptogenesis.

Disregarding matrix structure,

$$A \sim 10M_2 \sim 20M_1 \text{ and } \lambda' \sim 35 \text{ gives } \varepsilon \sim 10^{-6}.$$

With these parameters, m_ν^B dominates the light neutrino masses, whose value, ~ 0.1 eV, requires that —

$$M_1 \sim 10^{13} \text{ GeV}.$$

Like standard leptogenesis, EM leptogenesis requires that the heavy neutrinos **N** be far above the LHC range.

Our Two Questions

Q: Could \cancel{CP} in EM decays be a successful alternative to the standard leptogenesis scenario?

A : Yes.

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

A : No.

The Link Between the *Baryon Asymmetry* and Light ν ~~CP~~

In standard leptogenesis, all leptonic ~~CP~~ comes from the Yukawa coupling matrix y .

~~CP~~ in light ν oscillation and the ~~CP~~ that led to the *Baryon Asymmetry* are linked.

One expects ~~CP~~ in both places or in neither.

In EM leptogenesis, leptonic ~~CP~~ has a different source — the new “EM” interactions.

But ~~CP~~ in light ν oscillation and the ~~CP~~ that led to the *Baryon Asymmetry* are still linked.

The new EM couplings lead to neutrino masses.

If leptogenesis is driven by these new couplings,
then the neutrino masses probably are too.

CP-violating couplings will lead to CP-violating
mass matrices, which in turn will lead to CP
violation in oscillation.

*Experiments to look for \cancel{CP} in light ν oscillation
are very strongly motivated.*

