# Right-handed Neutrino Magnetic Moments

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# Outline

# Evidence for $m_\nu \neq 0$

- Solar and atmospheric neutrino fluxes differ from expectations for massless neutrinos.
- Best explanation in terms of neutrino oscillations.
- In agreement with accelerator and reactor experiments at different baselines.
- Cosmology and $\nu\mathrm{less}2\beta$ some important additional information.
- One can perform a global fit that yields, up to some uncertainties, $\nu$ masses and mixings.

# Global Fit

Global fit give ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)

$$\Delta m_{21}^2 = (7.9 \pm 0.3) \times 10^{-5}\,\mathrm{eV}^2,$$

$$|\Delta m_{31}^2| = (2.5 \pm 0.2) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.3 \pm 0.03\,, \quad \sin^2\theta_{23} = 0.5 \pm 0.08\,, \quad \sin^2\theta_{13} < 0.02$$

Global scale not fixed (although from cosmology $m_\nu \lesssim 1\,\mathrm{eV}$).
Three possibilities for $\Delta m_{21}^2 = \Delta_S \ll \Delta_A = |\Delta m_{31}^2|$ :

- Normal hierarchy (NH): $m_3 \gg m_2 > m_1$;
- Inverse hierarchy (IH): $m_1 \simeq m_2 \gg m_3$;
- Degenerate $m_1 \simeq m_2 \simeq m_3$

In any case $m_\nu \lesssim 1\,\mathrm{eV}$ and probably $m_\nu \lesssim 0.05\,\mathrm{eV}$

# Neutrino Masses

How can we modify the SM to include massive neutrinos?
Simpler explanation: add $\nu_R$

$$\mathscr{L}_{YL} = -\bar{\ell} Y_e \phi e_R - \bar{\ell} Y_\nu \tilde{\phi} \nu_R + \text{h.c.}$$

This is like the quark sector. But

- Why $m_\nu$ are so small?
- Why do we omit terms like $\overline{\nu_R^c} \nu_R$ in the Lagrangian?

Solution to the two questions: they are not omitted

$$\mathscr{L}_{YL} \to \mathscr{L}_{YL} = -\bar{\ell} Y_e \phi e_R - \bar{\ell} Y_\nu \tilde{\phi} \nu_R - \frac{1}{2} \overline{\nu_R^c} M \nu_R + \text{h.c.}$$

after SSB leads to the mass term

$$\mathscr{L}_{\nu M} = -\frac{1}{2}\left(\bar{\nu}_L, \overline{\nu_R^c}\right)\begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

if $M \gg M_D$ (“seesaw” mechanism):

- 3 **heavy** Majorana neutrinos$\sim \nu_R$ with masses $\sim M$
- 3 **light** Majorana neutrinos$\sim \nu_L$ with masses $\sim M_D^2/M$

Naturally one obtains $m_\nu < 1\,\text{eV}$ if $M > 10^{15}\,\text{GeV}$.
Simple and natural explanation of small $\nu$ masses.

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**Problems:**

- Difficult to test: sterile $\nu_R$ with masses $\sim 10^{15}\,\text{GeV}$
- Strong hierarchy problem: $\delta m_H^2 \simeq M^2/(4\pi)^2$

# Neutrino Mass Models

- Plain Dirac neutrino masses
- Type I seesaw mechanism (very natural)
- Triplet of scalars or fermions (type II and III seesaw)
- Inverse see-saw
- Radiative neutrino masses (Zee and Zee-Babu models)
- SUSY models without R-parity
- $\nu$ masses from extra dimensions
- $\nu$ masses from Little Higgs models
- ...

Too many possibilities
Can we perform a model independent analysis of $\nu$ masses?

# EFT Approach

Assumptions:

- The SM is a low-energy approximation of a more complete theory
- The only light particles ($m \lesssim 250\,\mathrm{GeV}$) are those of the SM (excluding $\nu_R$)

then

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_5 + \mathscr{L}_6 + \cdots$$

$$\mathscr{L}_{\mathrm{SM}} = i\bar{\ell}\,\not{D}\,\ell + i\overline{e_R}\,\not{D}\,e_R - (\bar{\ell}\,Y_e e_L\,\phi + \mathrm{h.c.}) + \cdots$$

$\mathscr{L}_5$, $\mathscr{L}_6$, $\cdots$ contain dim 5, dim 6, $\cdots$ gauge invariant operators built with SM fields.
Their effects are suppressed by $1/\Lambda_{NP}$, $1/\Lambda_{NP}^2$, $\cdots$ being $\Lambda_{NP}$ the scale of new physics.

# Weinberg Operator

Only one dim 5 gauge invariant operator built with SM fields

$$\mathscr{L}_5 = \frac{1}{\Lambda_{\rm NP}} \left(\bar{\tilde{\ell}}\phi\right)\left(\tilde{\phi}^{\dagger}\ell\right)$$

- Does not conserve lepton number
- After SSB gives rise to Majorana neutrino masses

$$m_\nu \sim \frac{v^2}{\Lambda_{\rm NP}} \ll v\,, \quad \text{if} \qquad \Lambda_{\rm NP} \gg v$$

- Natural and very general explanation of light neutrino masses.
- Can parametrize most of the neutrino mass models
- Models are only distinguished by the effects of the operators with higher dimensions.
- It provides an explanation of why the presence of $\nu$ masses is the first hint we have seen of new physics!

# Disadvantages

- Very difficult to test:
  - After SSB in the unitary gauge it just gives $\nu$ masses and $H$-$\nu$ couplings proportional to $m_\nu/v$ which are very small.
  - One has to rely on the effects of higher dimension operators which are suppressed by higher powers of $1/\Lambda_{NP}$
- Not general enough: it cannot accommodate all the models; in particular it cannot accommodate plain Dirac neutrino masses.

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**Generalizations**

Allow for more light degrees of freedom (masses smaller than the electroweak scale). This will change the form and number of higher dimension operators.
The natural candidates are $\nu_R$ neutrinos

# Dimension 5 Effective Lagrangian with $\nu_R$

Allow for $\nu_R$ among the light degrees of freedom

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\nu_{\rm R}} + \mathscr{L}_5 + \cdots$$

$$\mathscr{L}_{\nu_R} = i\overline{\nu'_R}\partial\!\!\!/\, \nu'_R - \left(\frac{1}{2}\overline{\nu'^c_R} M \nu'_R + \text{h.c.}\right) - \left(\bar{\ell} Y_\nu \nu'_R \tilde{\phi} + \text{h.c.}\right)$$

Only three dimension 5 effective operators

$$\mathscr{L}_5 = \mathscr{L}_\chi + \mathscr{L}_\zeta + \mathscr{L}_\xi$$

$$\mathscr{L}_\chi = \left(\bar{\tilde{\ell}}\phi\right) \chi \left(\tilde{\phi}^\dagger \ell\right) + \text{h.c.}$$

$$\mathscr{L}_\zeta = \overline{\nu'^c_R} \zeta \sigma^{\mu\nu} \nu'_R B_{\mu\nu} + \text{h.c.}$$

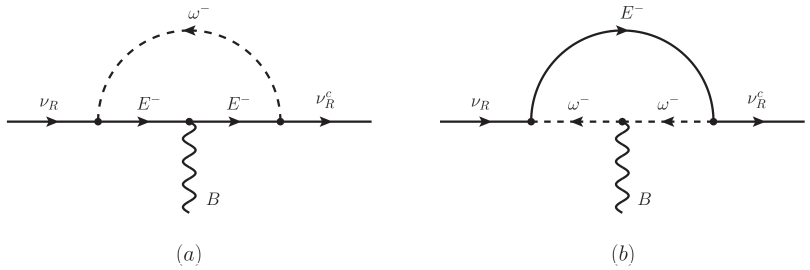
$$\mathscr{L}_\xi = -\left(\phi^\dagger \phi\right) \overline{\nu'^c_R} \xi \nu'_R + \text{h.c.}$$

# Models

- $\nu_L$ Majorana mass term operator $\left(\overline{\tilde{\ell}}_i \phi\right)\left(\tilde{\phi}^\dagger \ell_j\right)$
  - Scalar isotriplet of hypercharge 1,
  - Zero hypercharge fermion isotriplet
  - Fermion isosinglet of zero hypercharge
- $\nu_R$ Majorana mass term operator $\left(\phi^\dagger \phi\right) \overline{\nu'^c_{iR}} \nu'_{jR}$
  - Scalar isosinglet of vanishing hypercharge
  - Fermion isodoublet of hypercharge $1/2$
- $\nu_R$ electroweak coupling $\left(\overline{\nu'^c_{iR}} \sigma^{\mu\nu} \nu'^c_{jR}\right) B_{\mu\nu}$ (at one loop)
  - Scalar-fermion pair $\{\omega, E\}$, with opposite (non-zero) hypercharges that have couplings $\omega \overline{E} \nu'_R$ and $\omega \overline{E} \nu'^c_R$
  - Vector-fermion pair $\{W'_\mu, E\}$, with opposite (non-zero) hypercharges that have couplings $W'_\mu \overline{E} \gamma^\mu \nu'_R$

# Example Model

$$\mathscr{L}_Y = \overline{\nu_R^c} h' E \,\omega^+ + \overline{\nu_R} h E \,\omega^+ + \text{h.c.}$$




$$\zeta_{ij} = \frac{g' f(r)}{(4\pi)^2 4 m_E} \left( h'_i h_j^* - h'_j h_i^* \right)$$

$$f(r) = \frac{1}{1-r} + \frac{r}{(1-r)^2} \log(r)\,, \qquad r = (m_\omega / m_E)^2$$

# Mass Eigenstate Lagrangian

$$\begin{aligned} \nu'_L &= P_L \left( U_\nu \nu + \varepsilon U_N N + \cdots \right); \\ \nu'_R &= P_R \left( U_N N - \varepsilon^T U_\nu \nu + \cdots \right); \end{aligned}$$

$$\varepsilon \approx M_D M_R^{-1}, \qquad |\varepsilon_{ij}| \lesssim \sqrt{\frac{m_\nu}{m_N}};$$

$$\mathscr{L}_\zeta = \left( \overline{N} U_N^\dagger - \overline{\nu} U_\nu^\dagger \varepsilon^* \right) \sigma^{\mu\nu} \left( \zeta P_R + \zeta^\dagger P_L \right) \left( U_N N - \varepsilon^T U_\nu \nu \right)$$

$$\times \left( c_W F_{\mu\nu} - s_W Z_{\mu\nu} \right)$$

$$\mathscr{L}_\xi = -vH\overline{N} \left( \xi P_R + \xi^\dagger P_L \right) N + \cdots$$

# Collider effects

Right-handed neutrinos have no EW interactions.
The only interaction with SM particles is the Yukawa coupling, which must be very small in type I seesaw scenarios if heavy neutrinos are light enough to be produced at colliders:
$\nu_R$ difficult to produce at colliders
The new right-handed neutrino interactions can give access to $\nu_R$ properties:

- The magnetic moment interaction can enhance $\nu_R$ production at colliders ($Z$ and $\gamma$ exchange at $e^+e^-$ colliders and Drell-Yan at hadron colliders)
- It can also affect the way they could be detected.
- The $\mathscr{L}_\xi$ can affect dramatically Higgs boson decays.

For simplicity we will only consider the two lighter $N$'s, $N_2$ and $N_1$ with $m_2 > m_1$.

# $N_2$ Decay Rates and Decay Lengths

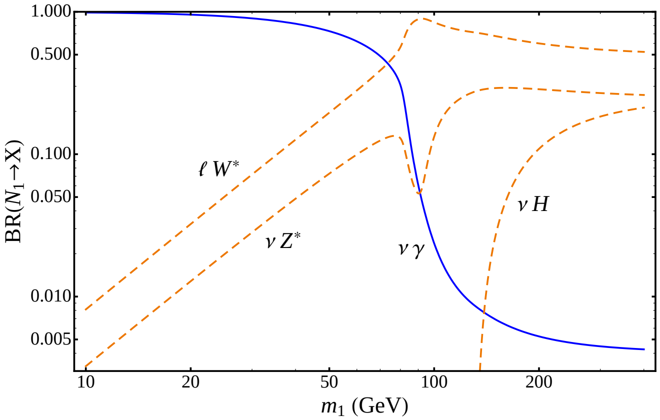
- If the magnetic-moment interaction is strong enough to produce $N_2$-$N_1$ pairs the $N_2$ will decay mainly to $N_1\gamma$ (or $N_1 Z$ if allowed kinematically).
- For relatively heavy $N_2$, $m_2 > 10\,\mathrm{GeV}$, the produced photons will be hard and could be measured.
- The lifetime will be very small and the decay length very short; for example, we find that for $N_2$ produced at center of mass (CM) energies ranging from $100 - 1000\,\mathrm{GeV}$, the decay lengths of the $N_2$ are typically well below $10^{-8}$ m.

# $N_1$ Decay BR and Decay Lengths

- $N_1$ must decay into SM particles and these decays are suppressed by the mixing parameter $\varepsilon$ (which we take as $\varepsilon = 10^{-6}$ for our estimates); the corresponding decay lengths will be much longer.
- All the decay widths of the $N_1$ proportional to $\varepsilon$, branching ratios will depend weakly on $\varepsilon$.
- $N_1 \to \nu\gamma$ needs the new magnetic moment interaction.
- $N_1 \to eW$, $N_1 \to eZ$,$N_1 \to eH$ do not need it.
- Relative values of BR sensitive to the magnetic moment coupling $\zeta_{12} = 1/\Lambda_{NP}$

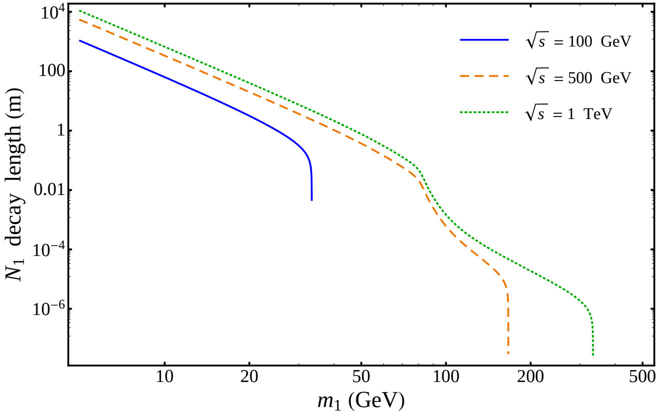
# $N_1$ BR

## $N_1$ decay branching ratios for $\Lambda_{NP} = 10$ TeV



# $N_1$ Decay Lengths

## $N_1$ $N_2$ pair produced at CM ($m_2 = 2m_1$, $\Lambda_{NP} = 10\,\text{TeV}, \varepsilon = 10^{-6}$)



# Heavy Neutrinos in $e^+e^-$ Collider

- If $N_1$, $N_2$ are light enough they could have been produced in $e^+e^-$ at LEP1 by $Z$ exchange and at LEP2 by $\gamma$ and $Z$ exchange and have not been seen: strong limits
  - Even if $N_1$ and $N_2$ escaped undetected the measurement of the invisible $Z$ width places strong bounds.
  - If $N_2 \to N_1\gamma$ fast enough the photon could have been detected and some bounds can be set.
- If they are heavier they could be produced at future $e^+e^-$ colliders such as the ILC: worth to be studied.

# Invisible $Z$ Decay Width

If $N_1, N_2$ are produced but undetected additional contribution to $Z \to \text{invisible}$

$$\Gamma_{inv} = 3\Gamma^{SM}_{\bar{\nu}\nu} + \Gamma(Z \to N_1 N_2) = 499.0 \pm 1.4\,\text{MeV}$$

then

$$\Gamma(Z \to N_1 N_2) = \Gamma_{inv} - 3\left(\frac{\Gamma_{\bar{\nu}\nu}}{\Gamma_{\bar{\ell}\ell}}\right)^{SM} \Gamma_{\bar{\ell}\ell} \simeq -2.6 \pm 1.5\,\text{MeV}$$

gives

$$\Gamma(Z \to N_1 N_2) < 0.72\,\text{MeV} \qquad 90\%\,\text{CL}\,,$$

in terms of

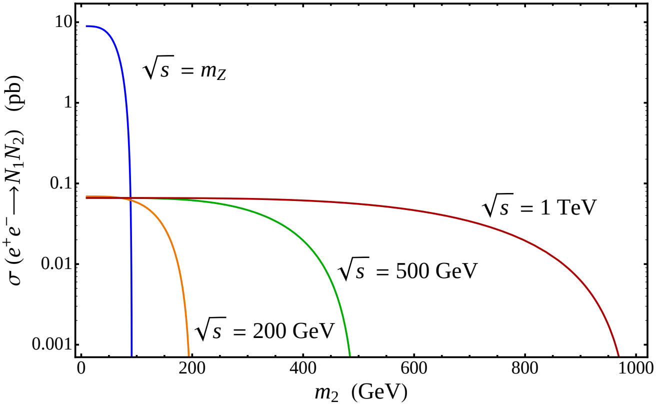
$$\Lambda_{NP} = \frac{1}{|\zeta_{12}|} > 7\sqrt{f_Z(m_Z, m_1, m_2)}\,\text{TeV}\,,$$

# Visible $N_2$ decays

- $e^+e^- \to N_1 N_2 \to N_1 N_1 \gamma$ could provide a visible channel if $E_\gamma > 10\,\mathrm{GeV}$.
- LEP1 searches give $\Lambda_{NP} = 1/|\zeta_{12}| > 10\,\mathrm{TeV}$ for $m_{N_2} < m_Z$.
- LEP2 searches give worse bounds $\Lambda_{NP} = 1/|\zeta_{12}| > 10\,\mathrm{TeV}$ but for $m_{N_2}$ masses up to $200\,\mathrm{GeV}$.
- LEP bounds based on visible $N_2$ decays depend more strongly on the $N_1$ and $N_2$ masses (for instance, they are completely lost lost if $m_2 - m_1 \lesssim 10\,\mathrm{GeV}$) but they could be important if some signal of this type is seen at the LHC.

# $e^+e^- \to N_1 N_2$ Cross section

## $m_1 = 0$ and $\Lambda_{NP} = 10\,\mathrm{TeV}$




Except for collisions at the $Z$ peak or close to the threshold of production, cross sections are quite independent on the CM energy and are of the order of $0.1\,\mathrm{pb}$.

# $N_1, N_2$ Production at the LHC

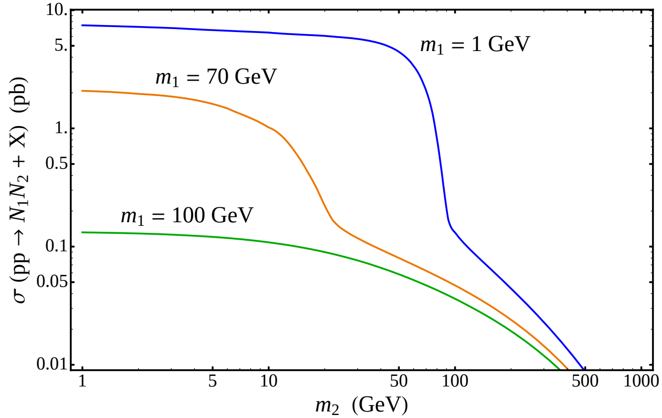
Heavy neutrinos will be produced at the LHC through the Drell-Yan process.
Computed in terms of the the partonic cross sections

$$d\sigma(pp \to N_1 N_2 + X) =$$

$$\sum_q \int_0^1 dx_1 \int_0^1 dx_2 \left( f_q(x_1, \hat{s}) f_{\bar{q}}(x_2, \hat{s}) + (q \leftrightarrow \bar{q}) \right) d\hat{\sigma}(q\bar{q} \to N_1 N_2, \hat{s})$$

$\hat{s} = x_1 x_2 s$ the partonic center of mass invariant square mass
$\hat{\sigma}(q\bar{q} \to N_1 N_2, \hat{s})$ the partonic cross section
$f_q(x_1, \hat{s})$, $f_{\bar{q}}(x_2, \hat{s})$ the parton distribution functions of the proton.

## $\Lambda_{NP} = 10\,\mathrm{TeV}$ and $\sqrt{s} = 14\,\mathrm{TeV}$




Cross sections above $100\,\mathrm{fb}$ are easily obtained but only for $m_1 + m_2 \lesssim m_Z$, where LEP bounds apply. For larger masses the cross section decreases very fast.

# Higgs Decay into Heavy Neutrinos

Let us pay a bit of attention to the $\mathscr{L}_\xi$ interaction

$$\mathscr{L}_\xi = -\left(\phi^\dagger\phi\right)\overline{\nu_R'^c}\,\xi\,\nu_R' + \mathrm{h.c.}$$

After diagonalization of mass matrices and SSB in the unitary gauge

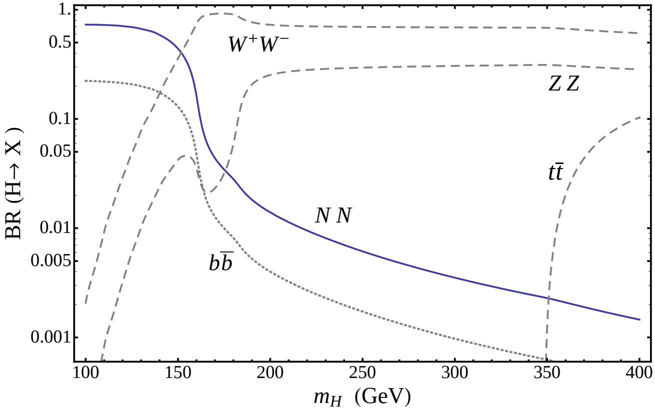
$$\mathscr{L}_\xi = -vH\overline{N}\left(\xi P_R + \xi^\dagger P_L\right)N + \cdots$$

If $N$'s light enough and the $\xi$ interaction strong enough

$$H \to N_i N_j$$

could be important when other channels are closed or suppressed ($m_H < 160\,\mathrm{GeV}$)

## $1/\xi = 10$ TeV, $m_N \ll m_H$



# Astrophysical Effects

The week magnetic moment interaction gives rise to transition magnetic moment interactions among $N'$s and $\nu$'s

$$\mathscr{L}_{\rm em} = (\overline{N} - \overline{\nu} U_\nu^\dagger \varepsilon^*)\, \sigma^{\mu\nu}\, (\zeta P_R + \zeta^\dagger P_L) \left(N - \varepsilon^T U_\nu \nu\right) c_W F_{\mu\nu}$$

Since $N$ and $\nu$ have very weak interactions they scape freely from stars.

Any interaction that allows the conversion of $\gamma' s$ into $N$'s and/or $\nu$'s provides an extra cooling mechanism of stars. Those are very well constrained.

For our interaction we found that the best limits come from

- Plasmon decays in red giants (for $m_N \lesssim 10\,\mathrm{keV}$)
- $\gamma + \nu \to N$ in SN ( for $m_N \lesssim 30\,\mathrm{MeV}$)

# Plasmon Decay

In a plasma photons have massive excitations called plasmons. If $N_1 N_2$ have magnetic moments, and are light enough, plasmons could decay into $N_1 N_2$ and produce an extra cooling mechanism.

We find ($\omega_P$ plasma frequency, $\omega$ plasmon energy)

$$\Gamma(\mathrm{plasmon} \to NN) = \frac{\mu_{\mathrm{eff}}^2}{24\pi} \frac{\omega_P^4}{\omega}$$

$$\mu_{\mathrm{eff}}^2 = 16 c_{\mathrm{W}}^2 \sum_{\mathrm{all}} \left|\zeta_{ij}\right|^2 f_Z(\omega_P, m_i, m_j)\,,$$

The observational limits from red giant stars cooling imply

$$\mu_{\mathrm{eff}} < 3 \times 10^{-12} \mu_B\,,$$

Then for $m_{i,j} \ll \omega_P \simeq 8.6\,\mathrm{KeV}$

$$|\zeta_{ij}| < 8.5 \times 10^{-13} \mu_B; \quad \mathrm{and} \quad \Lambda_{NP} \gtrsim 4 \times 10^6\,\mathrm{TeV}$$

# $\gamma + \nu \to N$ in SN

In the SN core $\nu$'s are trapped while, in principle, $N$ escape freely.

Any process transforming $\nu$'s into $N$'s can potentially destabilize the standard SN cooling.

Therefore, $\gamma + \nu \to N$, induced by our $\nu$-$N$ transition magnetic moment, will be strongly bounded:

Using that the coupling for this process is suppressed $\sim \zeta\varepsilon \sim \left(\sqrt{m_\nu/m_N}\right)/\Lambda_{NP}$ one finds

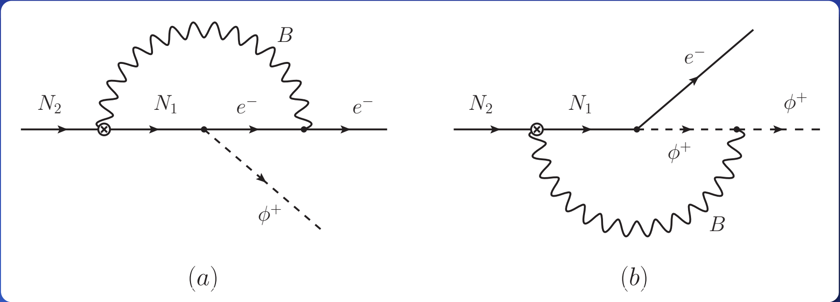
$$\Lambda_{NP} \gtrsim 4 \times 10^6 \times \sqrt{m_\nu/m_N}\,\mathrm{TeV}\,, \qquad m_N < 30\,\mathrm{MeV}$$

These limits are interesting in the region $10\,\mathrm{keV} < m_N < 30\,\mathrm{MeV}$, where red giant bounds do not apply.

But depend strongly on the assumptions on $\varepsilon$.

# CP asymmetries

Leptogenesis is a very interesting mechanism to explain the matter-antimatter asymmetry in the universe.
One of the ingredients is the existence of CP asymmetries in leptonic decays, which in turn needs phases in the couplings and loop diagrams absorptive contributions.
The electroweak moment interaction provides additional phases in the couplings and additional absorptive parts, will contribute to the CP asymmetries and potentially can affect leptogenesis.



we find

$$\varepsilon_{\not{C}\not{P}} \equiv \frac{\Gamma(N_2 \to e^- \phi^+) - \Gamma(N_2 \to e^+ \phi^-)}{\Gamma(N_2 \to e^- \phi^+) + \Gamma(N_2 \to e^+ \phi^-)}$$

$$= -\frac{g'}{2\pi}(m_2^2 - m_1^2)\frac{m_1}{m_2^3}\,\mathrm{Im}\left\{\frac{Y_{e2}Y_{e1}^*}{|Y_{e2}|^2}(\zeta_{12}^* m_2 + \zeta_{12} m_1)\right\}$$

right-handed neutrino electroweak moments do generate additional contributions to CP violating asymmetries in heavy neutrino decays.

- Only relevant for the decay of the heavier neutrinos.
- Proportional to $m_2^2 - m_1^2$

The possible relevance for leptogenesis requires a more complete study we have not yet performed.

# Summary of Bounds and Prospects

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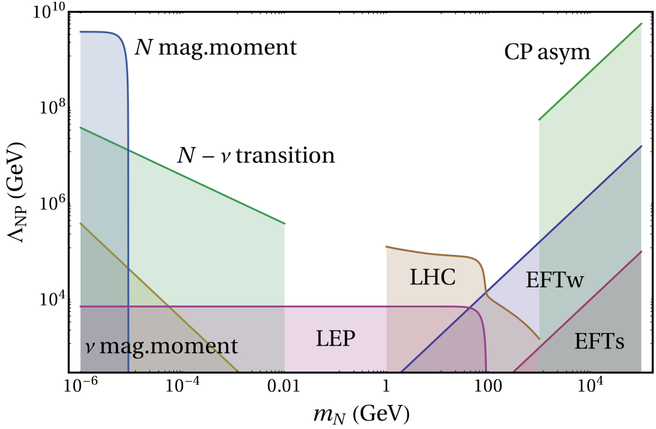

# Conclusions

- Strong bounds from red giants cooling for $m_N \lesssim 10\,\mathrm{keV}$ ( $\Lambda_{NP} > 4 \times 10^9\,\mathrm{GeV}$). In this case negligible effects in collider experiments.
- For $10\,\mathrm{keV} \lesssim m_N \lesssim 10\,\mathrm{MeV}$ SN, $\gamma\nu \to N$, provides very strong bounds. However depend on $\varepsilon$.
- For $m_N \lesssim m_Z$, the invisible $Z$ decays impose $\Lambda_{NP} \gtrsim 7 \times 10^3\,\mathrm{GeV}$, depending on the details of the heavy neutrino spectrum.
- For $m_N \sim 1\text{–}200\,\mathrm{GeV}$ and $7\,\mathrm{TeV} < \Lambda_{NP} < 100\,\mathrm{TeV}$, heavy neutrinos could be produced at the LHC with cross sections above $100\,\mathrm{fb}$. The heaviest will decay rapidly into hard photons. The lightest is quite long-lived and, in part of the parameter space, could produce non-pointing photons.

# Outlook

- The magnetic coupling may have effects in the early universe because it can potentially alter the equilibrium conditions of the *N* and their decoupling temperature. Mandatory to compute relic abundances.
- Searches for hard photons in the Galaxy X-ray background could impose tight on the new interactions.
- Heavy neutrinos with masses $\sim 1\,\mathrm{keV}$ could be a good dark matter candidate. The right-handed neutrino magnetic moments could change significantly the analysis of this possibility.
- One should evaluate carefully the effects of the Majorana magnetic couplings on non-thermal leptogenesis.
- For sufficiently large $\zeta$, this same coupling might lead to the trapping of the right-handed neutrinos in the supernova core.