# Right-handed sneutrinos as asymmetric DM in a neutrinophilic model

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**New Perspectives in Dark Matter**

Institut de Physique Nucléaire de Lyon

# Motivation





## Standard Thermal Mechanism

Correct Relic Density for annihilation cross section

$$\langle \sigma v \rangle_{th} = 3 \cdot 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\ .$$

WIMPs: $\langle \sigma v \rangle_{\mathrm{WIMP}} \sim \langle \sigma v \rangle_{th}$

HOWEVER, (in practice) WIMPs relic abundance varies over many orders of magnitude as function of the unknown parameters of the BSM theory.

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(same order of magnitude, $\Omega_{DM}/\Omega_b \simeq 5.4$)

ALTERNATIVE: possible connection between the mechanisms responsible for the DM and baryon abundances

Asymmetry between DM particles and antiparticles

(conserved quantum number)

# Candidates



In a supersymmetric framework:

1) **Sneutrinos** (RH or mixture with LH)
   lepton number
2) **Higgsinos**
   non-vanishing ch. potential before EWPT

Their asymmetry is related to the baryon asymmetry through

◇ **equilibrium processes in the early Universe**:
(always conserving $B - L$)

- Isospin violating interactions mediated by $W^{\pm}$ bosons
- Yukawa interactions
- Flavor changing interactions in the baryonic sector
- Triscalar interactions involving sparticles

◇ **sphaleron processes**,
which violate $B + L$ but respect $B - L$

# Self-annihilations



Assuming sneutrino DM,
with $N$, $N^\star$ the sneutrinos and antisneutrinos, respectively…

In the ADM paradigm, $N$, $N^\star$ should annihilate with a c.s. larger than the thermal c.s., so that after the annihilations froze-out, only one of $N$, $N^\star$ would remain (e.g. $N$).

HOWEVER, self-annihilation processes tend to destroy the asymmetry short after the particles become non-relativistic.

$\rightsquigarrow$ $N$, $N$ self-annihilation should be suppressed.

We define $R \equiv \dfrac{A_\infty}{A_0}$ with

- $A_\infty$: present-day asymmetry
- $A_0$ : initial asymmetry after sphaleron froze-out (related to baryon asymmetry)

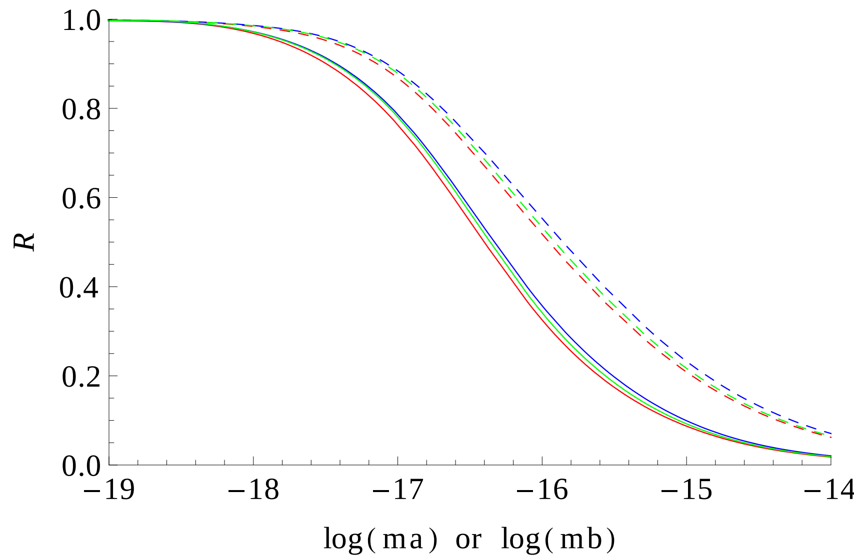
- For the asymmetry to play an important role on the DM density determination: $\boxed{R \text{ should be } \mathcal{O}(1)}$.

# Boltzmann equations



## Solving the Boltzmann eqs. for the two species

(*U.Ellwanger, P.M.*, arXiv:1205.0673)




$$\langle \sigma v \rangle \simeq a + b x^{-1}$$

| $R >$ | (s-wave) $ma \lesssim$ [GeV$^{-1}$] | (p-wave) $mb \lesssim$ [GeV$^{-1}$] |
|---|---|---|
| $0.5$ | $5 \cdot 10^{-17}$ | $1 \cdot 10^{-16}$ |
| $0.1$ | $1 \cdot 10^{-15}$ | $5 \cdot 10^{-15}$ |

(solid line: $log(ma)$ if $\langle \sigma v \rangle = a$,
dashed line: $log(mb)$ if $\langle \sigma v \rangle = b x^{-1}$)

- Sneutrinos or higgsinos self-annihilation is mediated by gauginos in t-channel.

For $R > 0.1$ and assuming the universality condition $M_2 = 2M_1$:

**sneutrino ADM** (with $\sin\delta$ the LH comp.)

$$\sin^2\delta \lesssim 3 \cdot 10^{-5} \frac{M_2}{300\,\text{GeV}} \sqrt{\frac{10\,\text{GeV}}{m}}$$

**higgsino ADM**

$$M_2 \gtrsim 10^4\,\text{TeV} \sqrt{\frac{m}{10\,\text{GeV}}}$$

# Sneutrino Asymmetric DM



Characteristics for a successful model:

1. Sneutrino-antisneutrino c.s. larger that the thermal c.s. , in order that the less abundant species have been completely depleted.
   $\rightsquigarrow$ large neutrino couplings
2. Almost purely RH sneutrino LSP.
   $\rightsquigarrow$ small neutrino Dirac masses
3. Oscillations among sneutrinos and antisneutrinos should start not before their asymmetry has frozen-out,
   $\Rightarrow$ mass splitting induced by Majorana mass terms should be extremely small.
   $\rightsquigarrow$ favors Dirac neutrinos
4. No GUT scale masses of RH sneutrinos.

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Among various mechanisms for neutrino mass generation (inverse and linear seesaw, Dirac masses from SUSY breaking terms. . . )

ONLY neutrinos with large Yukawas and masses originating from a small vev of a new Higgs fulfill all the above criteria.

# Neutrinophilic Higgs Doublet Models



Neutrinophilic Higgs Doublet Model with Dirac neutrino masses:

*Davidson and Logan*, arXiv:0906.3335

global $U(1)$ (forbidding Majorana mass terms)
broken explicitly $\Rightarrow$ a very light scalar is avoided

- The additional Higgs doublets in a SUSY version still allow to be embedded into a grand unified symmetry

  (*Haba et al*, arXiv:1204.4254)

- The proton stability is not spoiled

  (the additional Higgs doublets couple only to leptons)

# The model

# Next-to-Minimal Supersymmetric Standard Model



We incorporate the neutrinophilic Higgs mechanism to the NEXT-TO-MINIMAL SUPERSYMMETRIC STANDARD MODEL:

1. Solves the $\mu$-problem of the MSSM by introducing a singlet Higgs superfield $\widehat{S}$: $\boldsymbol{\mu \widehat{H}_u \cdot \widehat{H}_d \to \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d}$
2. the SM-like Higgs is naturally heavier due to the additional $\lambda$ coupling: **a Higgs mass $\sim$ 125 GeV is easier to explain**.

OTHERWISE, the singlet plays no particular role for our purposes: its vev could be replaced by a constant dimensionful parameter

<u>EXTENSION</u>

NMSSM + 3 RH neutrino superfields $\widehat{\nu}^c_R$ (one for each generation)
+ an additional pair of Higgs doublets $\widehat{H}^\nu_u$, $\widehat{H}^\nu_d$.

The **new** fields are charged under a global $U(1)$ symmetry as:

$$\nu^c_R : -1, \qquad H^\nu_u : +1, \qquad H^\nu_d : -1.$$

(the common NMSSM fields remain uncharged)

# Lagrangian



Superpotential & soft SUSY breaking masses and couplings:

$$W = W^{\text{NMSSM}} + y_\nu \widehat{L} \cdot \widehat{H}_u^\nu \widehat{\nu}_R^c + \lambda_\nu \widehat{S} \widehat{H}_u^\nu \cdot \widehat{H}_d^\nu$$

$$-\mathcal{L}_{\text{soft}} = -\mathcal{L}_{\text{soft}}^{\text{NMSSM}} + m_{H_u^\nu}^2 |H_u^\nu|^2 + m_{H_d^\nu}^2 |H_d^\nu|^2 + m_{\nu_R}^2 |\nu_R|^2 + y_\nu A_\nu L \cdot H_u^\nu \nu_R^c + \lambda_\nu A_{\lambda_\nu} S H_u^\nu \cdot H_d^\nu$$

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$$+ y_\nu A_\nu L \cdot H_u^\nu \nu_R^c + \lambda_\nu A_{\lambda_\nu} S H_u^\nu \cdot H_d^\nu$$
$$+ A_{\lambda_1} S H_u \cdot H_d^\nu + A_{\lambda_2} S H_u^\nu H_d$$

2 additional terms that break the $U(1)$ symmetry

(required in order for the Higgs to acquire a vev and give masses to neutrinos)

- Natural in the 't Hooft sense for the trilinear couplings $A_{\lambda_i}$ to assume small values.
- These terms appear only in the soft SUSY breaking Lagrangian.

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EXAMPLE: Small values of $A_{\lambda_i}$ can be obtained through higher dimensional operators involving SUSY and $U(1)$ symmetry breaking spurion fields.

- $\frac{1}{M_{Pl}^2} \left| \widehat{X}^2 \widehat{S} \widehat{H}_u^\nu \cdot \widehat{H}_d \right|_F \sim \frac{F^{3/2}}{M_{Pl}^2} S H_u^\nu \cdot H_d$ with $\frac{F^{3/2}}{M_{Pl}^2} \sim 10^{-7}$ GeV if $\langle X \rangle = \theta^2 F + \sqrt{F}$ and $F = m_I^2$ with $m_I = \sqrt{v M_{Pl}}$.
- The corresponding terms in the superpotential are suppressed by several orders of magnitude.

# Neutrinos and sneutrinos



Vacuum Expectation Values for the $H_u^\nu$, $H_d^\nu$:

$$v_u^\nu = \frac{A_{\lambda_2} s}{m^2_{H_u^\nu}} v_d \quad \text{and} \quad v_d^\nu = \frac{A_{\lambda_1} s}{m^2_{H_d^\nu}} v_u$$

for $A_{\lambda_1} s \simeq A_{\lambda_2} s \sim 10^{-5}\,\text{GeV}^2$ and $m_{H_u^\nu} \simeq m_{H_d^\nu} \sim \mathcal{O}(1) TeV$
$\Rightarrow$ Dirac neutrino masses of the correct order if $y_\nu \sim \mathcal{O}(1)$.

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Sneutrinos mass squared matrix:

basis: $(\nu_l, \nu_R)$

$$\mathcal{M}^2_{\tilde{\nu}} = \begin{pmatrix} y_\nu^2 v_u^{\nu 2} + \frac{1}{2} g^2 (v_d^2 - v_u^2) + m^2_{\nu_L} & y_\nu v_u^\nu (\lambda_\nu s + A_\nu) \\ & y_\nu^2 v_u^{\nu 2} + m^2_{\nu_R} \end{pmatrix}$$

$$\simeq \text{diag}\left[\frac{1}{2} g^2 (v_d^2 - v_u^2) + m^2_{\nu_L}, m^2_{\nu_R}\right]$$

- Left- and right-handed sneutrinos are practically unmixed.
- Mixing among generations in the RH sector is also suppressed.

# ADM Density – Sneutrino Mass Range



(assuming all requirements for the asymmetry to survive are satisfied)

DM and baryon densities relation: $\dfrac{\Omega_N}{\Omega_b} = \dfrac{\eta_N}{B}\dfrac{m_N}{m_p}$.

Using relations for chemical potentials of (s)particles in equilibrium:

I) Rapid sphaleron processes only above the EWPT

- $B \simeq 0.14(B-L)$ and $\eta_N \simeq -0.10(B-L)$ : **light sleptons** $(\sim 2T_c)$
  $\Rightarrow$ $\boxed{m_N \simeq 7.1\ \text{GeV}}$
- $B \simeq 0.18(B-L)$ and $\eta_N \simeq -0.12(B-L)$ : **heavy sleptons**
  $\Rightarrow$ $\boxed{m_N \simeq 7.6\ \text{GeV}}$

II) Rapid sphaleron processes also below the EWPT

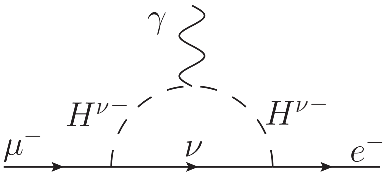
- $B \simeq 0.18(B-L)$ and $\eta_N \simeq -0.10(B-L)$ : **all sparticles heavy**
  $\Rightarrow$ $\boxed{m_N \simeq 9.2\ \text{GeV}}$
- $B \simeq 0.31(B-L)$ and $\eta_N \simeq -0.07(B-L)$ : **light LH sneutrinos** $(\sim T_c)$
  $\Rightarrow$ $\boxed{m_N \simeq 23\ \text{GeV}}$

# Constraints

# A. General Constraints



## i. Lepton Flavor Violation




$$\text{Br}(\mu \to e\gamma) = \frac{\alpha}{4\pi}\left(\frac{v}{v_\nu m_{H^{\nu+}}}\right)^4 \left|\sum_j m_j^2 U_{ej}^\star U_{\mu j}\right|^2$$

(*Fukuyama, Tsumura*, arXiv:0809.5221)

MEG: $\text{Br}(\mu \to e\gamma) \lesssim 5.7 \cdot 10^{-13}$

$$\Rightarrow \boxed{m_{H^{\nu+}} \gtrsim 300\ \text{GeV}}$$

## ii. Relativistic degrees of freedom during BBN

Planck: $\mathcal{N}_{\text{eff}} = 3.30 \pm 0.27$ (or, with $\mathcal{N}_{\text{eff}} = 3 + \Delta N_\nu$, $\Delta N_\nu \leq 0.57$ at $1\sigma$)

- RH neutrinos contribute to $\mathcal{N}_{\text{eff}}$ even if they have decoupled before BBN, at a temperature $T_{R,d}$:

$$\Delta N_\nu = 3\left(\frac{43}{4g(T_{R,d})}\right)^{4/3},$$

$g(T_{R,d})$: Relativistic dof at the temperature the RH sneutrinos decoupled.

Planck $\to g(T_{R,d}) \gtrsim 37.25$

$\Rightarrow$ decoupling before the quark-hadron phase transition

$(g_{\text{before}} = 51.25,\ g_{\text{after}} = 17.25)$ $\Rightarrow T_{R,d} \gtrsim 200$ MeV

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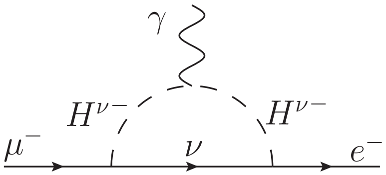


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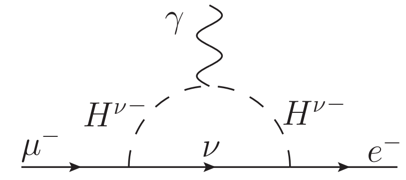


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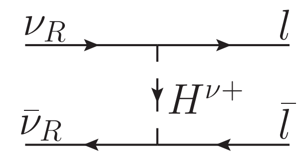
RH neutrinos stay in equilibrium through:




*decoupling condition*: $n(T_{R,d})\langle\sigma v\rangle(T_{R,d}) = H(T_{R,d})$

$$\Rightarrow \boxed{\frac{m_{H^{\nu+}}}{y_\nu^{li}} \gtrsim 3 \text{ TeV}}$$

# B. Asymmetric DM



i. **Sneutrino – antisneutrino oscillations**

ii. **Self-annihilation**

iii. **Sneutrino–antisneutrino pair annihilation**

## i. Sneutrino – antisneutrino oscillations

- rate $\Gamma(N \leftrightarrow N^\star) \sim \delta m$
  $N - N^\star$ conversion starts to become significant
  only for temperatures $T \simeq \left( \frac{g_\star^{1/2}}{h_{\rm eff}} \sqrt{\frac{45}{4\pi^3}} M_{Pl} \delta m \right)^{1/2}$
- $\delta m$ is due to a Majorana mass term,
  with $\delta m \simeq \frac{m_M^2}{m_D}$ for $m_M \ll m_D$
- Considering the spurion field that breaks the $U(1)$,
  it can induce a Majorana mass through the operator

$$\frac{1}{M_{Pl}^4} \left| X^4 S N^2 \right|_F$$

$\rightsquigarrow \delta m \sim 10^{-33}$ GeV $\longrightarrow$ AFTER the sneutrino–antisneutrino annihilations freeze-out

## ii. Self-annihilation

No constraints:
- LH components of $N$ and $N^\star$ are sufficiently small.
- Since $\nu$-higgsinos are Dirac particles, there is no RH sneutrino self-annihilation through u- or t-channel $\nu$-higgsino exchange.

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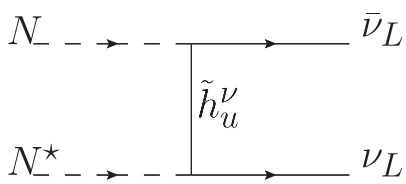
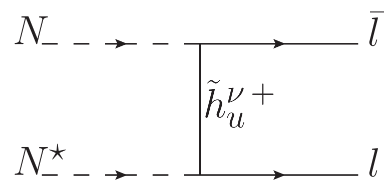
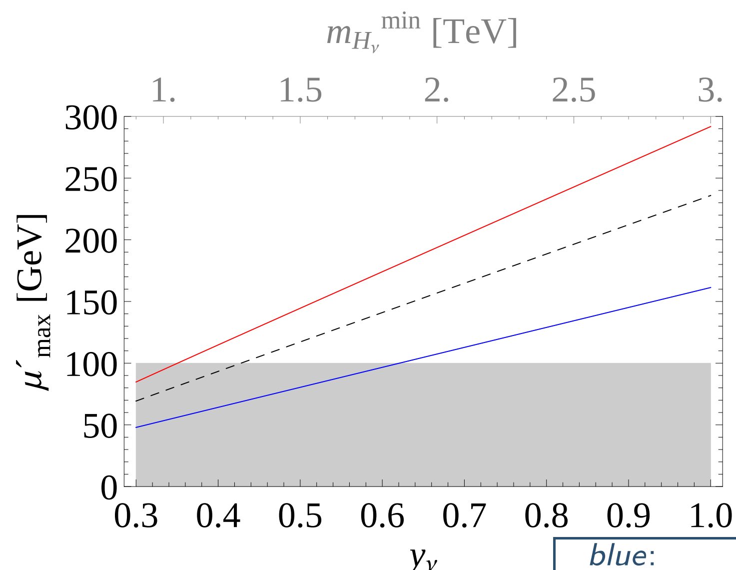



$$\langle \sigma v \rangle \simeq f \frac{y_\nu^4}{8\pi} \frac{m_N^2}{(m_N^2 + \mu'^2)^2} x^{-1}$$

$$\boxed{\langle \sigma v \rangle > \langle \sigma v \rangle_{th} \simeq 3 \cdot 10^{-26}\,\text{cm}^3\,\text{s}^{-1}}$$




| | |
|---|---|
| *blue*: | 7 GeV |
| *dashed*: | 15 GeV |
| *red*: | 23 GeV |

- Heavy scalar $\nu$-Higgs
  $\rightsquigarrow$ large soft SUSY breaking mass for the $\nu$-Higgs
- Relatively light $\nu$-higgsino
  $\rightsquigarrow$ small $\lambda_\nu$ (compared to $\lambda$)

## i. Direct Detection

- **No** tree-level contribution to the scattering cross section
- At one loop: Z exchange with
  LH sneutrinos and $\nu$-higgsinos in the loop

Well below the bounds for $A_\nu \sim \mathcal{O}(1)$ TeV

## ii. Observations of old neutron stars

If the scattering cross section is too large, the accumulation of ADM inside neutron stars can form a black hole which would potentially destroy the star.

$\sigma \gtrsim 10^{-50}\,\text{cm}^3\,\text{s}^{-1}$ excluded for $5\,\text{GeV} \lesssim m_{\text{ADM}} \lesssim 16\,\text{GeV}$

(No limit for heavier DM due to Hawking evaporation)

*Kouvaris and Tinyakov*, arXiv:11040382
*McDermott, Yu and Zurek*, arXiv:1103.5472

## iii. **Indirect Detection**

- ◇ Pure asymmetric DM does not give rise to detectable signals
  - absence of either DM particles or antiparticles.
  - the self-annihilation is required to be too small to generate measurable signals.
- ◇ Possible repopulation of antisneutrinos through oscillations
  - At tree level, the s-wave $N$, $N^\star$ annihilation is helicity suppressed.
  - Box loop with sleptons and charged $\nu$-Higgs

    $\rightsquigarrow$ monochromatic photon line with $\langle\sigma v\rangle_{\gamma\gamma} \propto \left(\frac{y_\nu A_\nu}{m_{H^{\nu+}}}\right)^4$

(*Choi and Seto*,arXiv:1305.4322)

FERMI-LAT: $\langle\sigma v\rangle_{\gamma\gamma} \lesssim 5 \cdot 10^{-29}$ cm$^3$ s$^{-1}$

Satisfied if $A_\nu \lesssim 300$ GeV

# Summary

Small neutrino masses and sneutrino asymmetric DM through the introduction of a pair of neutrinophilic Higgs doublets.

- Correct DM density, related to the baryon asymmetry through equilibrium interactions in the early Universe, for a DM mass range

$$\sim 7 - 23\,\text{GeV}\,,$$

depending on sparticle masses and the sphaleron processes.

✓ mass $\gtrsim 16\,\text{GeV}$ being favored by observations of neutron stars.

- Large soft mass for $H^\nu$ and neutrino Yukawa couplings $\mathcal{O}(1)$ in order:
  - for $\mathcal{N}_{\text{eff}}$ to fit the Planck result and
  - for the $N$, $N^\star$ c.s. to be larger than the thermal c.s. .
- *If* anti-sneutrinos have been regenerated through oscillations: trilinear soft coupling $A_\nu \lesssim 300\,\text{GeV}$

  (monochromatic photon detection)