Asymmetric Dark Matter and Leptogenesis

Adam Falkowski
LPT Orsay

le 15 avril 2011.

AA, Josh Ruderman and Tomer Volansky, **1101.4936**
AA, Eric Kuflik, Josh Ruderman and Tomer Volansky, *in progress*

Outline

1. Brief Review of Asymmetric Dark Matter

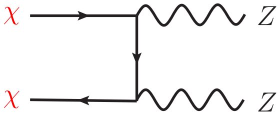
2. Two-Sector Leptogenesis
   - The Model
   - Boltzmann Equation Landscape

3. Variations
   - Repopulating Symmetric DM with Late Decays
   - Sterile Neutrino DM

Brief Review of Asymmetric DM

WIMP Miracle

Thermal freezeout provides a compelling paradigm for dark matter.



$$\Omega_{DM} h^2 \sim 0.1 \left(\frac{\sigma_{thermal}}{\sigma}\right)$$

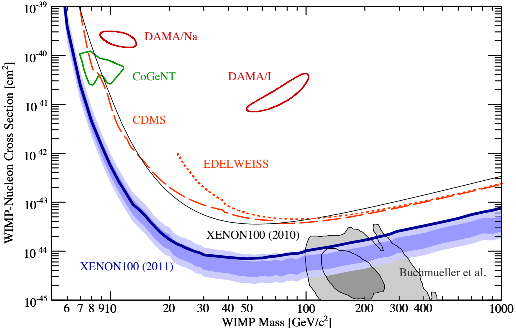
$$\sigma_{thermal} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\ \mathrm{sec} \sim \left(\frac{1}{20\ \mathrm{TeV}}\right)^2$$

Weak scale mass DM with weakish interaction strength is attractive because it suggests

- Dark matter can be observed at the LHC and in direct and/or indirect detection experiments
- It may be related to the sector that breaks the electroweak symmetry of the SM

The WIMP miracle has received a lot of attention from the theory and experimental communities;

But we should keep an open mind, because DM may not come from the WIMP miracle...



An alternative framework is Asymmetric Dark Matter (ADM),

1. DM carries a conserved quantum number, e.g. $U(1)_B$, $U(1)_L$
2. An asymmetry is generated in the early universe, $n_{\Delta\chi} = n_\chi - n_{\bar{\chi}} > 0$
3. The symmetric component is annihilated away, $\chi + \bar{\chi} \to a + b$

$$\sigma > \sigma_0 = 3 \times 10^{-26} \text{ cm}^3/\text{ sec}$$

Now the abundance is set by $n_{\Delta\chi}$ instead of σ

$$\text{if } n_{\Delta\chi} \sim n_B \text{ then } \Omega_{DM} \sim \Omega_B \text{ for } m_\chi \sim m_p \sim \text{ GeV}$$

S. Nussinov **1985**, *D. B. Kaplan* **1992**,
D. E. Kaplan, M. Luty and K. Zurek **2009**

$m_\chi \sim$ GeV is nice, but not a miracle unless you explain why $m_\chi \sim \Lambda_{QCD}$

Now we must ask, what sets $n_{\Delta\chi}$?

- Can start with $n_{\Delta L} > 0$ and transfer to DM,

$$\mathcal{O}_5 = \frac{\chi\phi LH}{M}$$

$n_{\Delta\chi}$ depends on what temperature $\mathcal{O}_5$ decouples, T_d

$$n_{\Delta\chi} \sim \begin{cases} n_{\Delta L} & T_d > m_\chi \quad \Rightarrow \quad m_\chi \sim \mathrm{GeV} \\ n_{\Delta L} e^{-m_\chi/T_d} & T_d < m_\chi \quad \Rightarrow \quad m_\chi \sim \mathrm{TeV} \end{cases}$$

Cohen, Zurek **2009**

- Or can start with $n_{\Delta\chi}$ and transfer it leptons or baryons.

Shelton, Zurek **2010**

Some recent developments in ADM:
Aidnogenesis, Baryomorphosis, Darkogenesis, Hylogenesis, Xogenesis

AA,Ruderman,Volansky [1101.4936]

Why consider yet-another genesis?

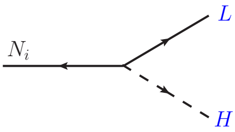
- A UV completion to the transfer operator
- It becomes natural that $n_{\Delta\chi}$ and $n_{\Delta L}$ can be generated at the same time.
- We will see that a wider range of $n_{\Delta\chi}$ are possible, allowing for $m_\chi \sim \text{keV} - 10\ \text{TeV}$
- To our credit, we have not introduce another name ;-)

Earlier work connecting leptogenesis and ADM: Cosme et al [hep-ph/0506320] , Gu et al. [0906.3103] , Gu et al [0909.5463] , An et al. [0911.4463] , Chun [1009.0983]

Two-Sector Leptogenesis

1-Slide Review of Thermal Leptogenesis

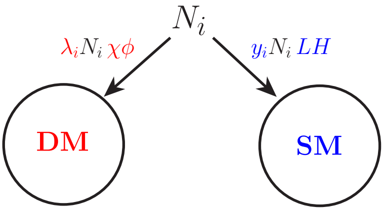
$$-\mathcal{L} \supset \frac{1}{2} M_i N_i^2 + y_i N_i L H + h.c.$$



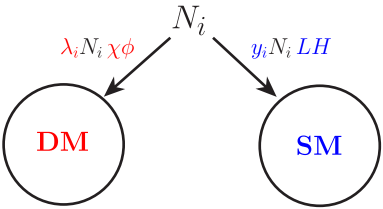
- N_i decays out of equilibrium, $N_i \to LH$
- CP violation, due to phases of y_i, leads to an asymmetry, $n_{\Delta L}$
- the asymmetry is frozen in at $T \ll M_i$
- sphalerons convert the lepton asymmetry to a baryon asymmetry at the EW scale, $n_B \sim n_{\Delta L}$
- integrating out N_i generates neutrino masses,

$$m_\nu \sim y^2 \frac{v_{EW}^2}{M_i}$$

The Model



$$-\mathcal{L} \supset \frac{1}{2} M_i N_i^2 + \lambda_i N_i \chi\phi + y_i N_i LH + h.c.$$



$$-\mathcal{L} \supset \frac{1}{2} M_i N_i^2 + \lambda_i N_i \chi\phi + y_i N_i LH + h.c.$$

Comments:

- There is an approximate lepton number, $U(1)_L$, with charges:

$$Q_{N_i} = -1 \qquad Q_L = 1 \qquad Q_\chi + Q_\phi = 1$$

- This symmetry is exact as $M_i \to \infty$.
- We require at least two N_i, because with only one the phases can be rotated away.

The Model: Dark Sector

$$-\mathcal{L} \supset \frac{1}{2} M_i N_i^2 + \lambda_i N_i \chi \phi + y_i N_i L H + h.c.$$

We imagine that χ belongs to a *dark sector* whose dynamics:

- generate a Dirac mass for χ, with another fermion $\tilde{\chi}$

$$-\mathcal{L} \supset m_\chi \chi \tilde{\chi} + h.c.$$

- generate a mass for ϕ

$$-\mathcal{L} \supset m_\phi |\phi|^2 \quad \text{or} \quad \mathcal{L} \supset \mathrm{m}_\phi \phi \tilde{\phi}$$

- annihilate away the symmetric component of DM

  for example gauge the $U(1)_d$ where χ and ϕ have opposite charge

$$\chi + \bar{\chi} \to \gamma_d + \gamma_d$$

DM stability follows from the $\mathcal{Z}_2$ where χ and ϕ are charged, if $m_\chi < m_\phi$

We will consider three variations of this model:

1. The ϕ asymmetry is quickly washed out, $\phi \leftrightarrow \phi^\dagger$ (much as Higgs asymmetry in the SM)
2. the ϕ asymmetry is preserved, $n_{\Delta\phi} = n_{\Delta\chi}$
3. ϕ gets a VEV, $\langle\phi\rangle$

We begin by focusing on scenario (1), and will return later in the talk to (2) and (3).

The Boltzmann Equation Landscape

Now we will determine the asymmetries, $n_{\Delta L}$, $n_{\Delta\chi}$ produced by leptogenesis.

For simplicity, we focus on a toy model that captures the important physics:

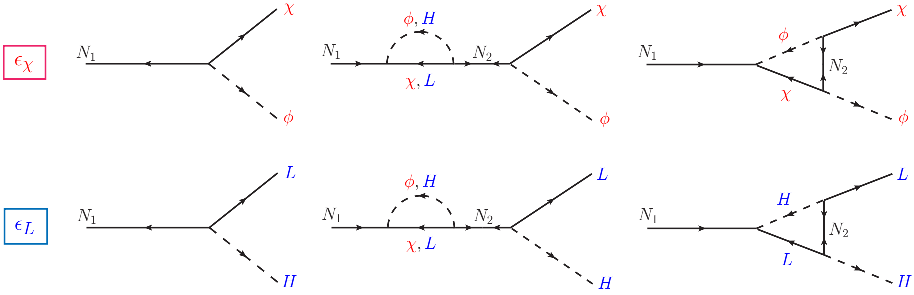
$$-\mathcal{L} \supset \frac{1}{2}M_i N_i^2 + \lambda_i N_i \chi\phi + y_i N_i LH + h.c.$$

- minimum N_i content, $i = 1, 2$
- one flavor approximation for L
- neglect effects on Boltzmann equations from gauge and additional Yukawa interactions
- ignore $SU(2)$ structure and take L and H to be singlets

We also specialize to the hierarchical limit, $M_1 \ll M_2$

We will need to know the asymmetries in N_1 decays,

$$\epsilon_\chi = \frac{\Gamma(N_1 \to \chi\phi) - \Gamma\left(N_1 \to \bar{\chi}\phi^\dagger\right)}{\Gamma_1} \qquad \epsilon_L = \frac{\Gamma(N_1 \to LH) - \Gamma\left(N_1 \to \bar{L}H^\dagger\right)}{\Gamma_1}$$



We go to a basis where the couplings are:

$$y_1,\ y_2 e^{i\phi_L} \qquad \lambda_1,\ \lambda_2 e^{i\phi_\chi}$$

$$\epsilon_\chi \simeq \frac{1}{16\pi(y_1^2+\lambda_1^2)}\frac{M_1}{M_2}\left(2\lambda_1^2\lambda_2^2\sin\left(2\phi_\chi\right)+y_1y_2\lambda_1\lambda_2\sin\left(\phi_L+\phi_\chi\right)\right)$$

$$\epsilon_L \simeq \frac{1}{16\pi(y_1^2+\lambda_1^2)}\frac{M_1}{M_2}\left(2y_1^2y_2^2\sin\left(2\phi_L\right)+y_1y_2\lambda_1\lambda_2\sin\left(\phi_L+\phi_\chi\right)\right)$$

In particular,

$$\frac{\epsilon_L}{\epsilon_\chi} \simeq \frac{2r\sin(2\phi_L)+\sin(\phi_L+\phi_\chi)}{2r^{-1}\sin(2\phi_\chi)+\sin(\phi_L+\phi_\chi)} \qquad r=\frac{y_1y_2}{\lambda_1\lambda_2}$$

for generic angles, $\epsilon_L/\epsilon_\chi \sim r$

This means that N_1 decays can have very different asymmetries into the two sectors if the Yukawa couplings display a hierarchy

Warmup for Boltzmann equations

We will use the variables:

- $z = M_{N_1}/T$ for evolution
- $Y_x = n_x/s$ for abundance

From the Bolrtzmann equations one finds

$$\begin{aligned} Y^{\infty}_{\Delta L} &= \epsilon_L \eta_L \, Y^{eq}_{N_1}(0) \\ Y^{\infty}_{\Delta \chi} &= \epsilon_\chi \eta_\chi \, Y^{eq}_{N_1}(0) \end{aligned}$$

$$Y^{eq}_{N_1}(0) = \frac{135\zeta(3)}{4\pi^4 g_*} = 3.5 \times 10^{-3} \left(\frac{120}{g_*}\right)$$

And η_L, η_χ encode the efficiency of the asymmetry generation.
The final answer must be:

$$\begin{aligned} Y^{\infty}_{\Delta L} &\simeq 2.6 \times 10^{-10} \\ Y^{\infty}_{\Delta \chi} &\simeq 4 \times 10^{-10} \left(\frac{\mathrm{GeV}}{m_\chi}\right) \end{aligned}$$

A prediction for η_χ translate to a prediction for m_χ.

The Mass Range of ADM

- **Heavy DM**: $m_\chi \lesssim 10\ \mathrm{TeV}$

  Above this mass, the symmetric component cannot be annihilated away perturbatively.

  Heavier masses may be allowed if the hidden sector confines, $\Lambda_d \ll m_\chi$

- **Light DM:** $m_\chi \gtrsim 1\ \mathrm{keV}$

  This limit comes from saturating perturbativity in N_1 decays, $\epsilon_\chi \lesssim 0.1$

$$Y_{\Delta\chi}^{\infty} = \epsilon_\chi \eta_\chi \, Y_{N_1}^{eq}(0) \lesssim 4 \times 10^{-4}$$

Coincidentally, this roughly corresponds to the astrophysical limit on warm DM.

Boltzmann Equations for 2-component leptogenesis

Schematic form of Boltzmann equations

$$\begin{aligned}\frac{dY_{N_1}}{dz} &\approx \frac{\Gamma_{N_1}}{H} f_D(z)\left(Y_{N_1}^{eq} - Y_{N_1}\right)\\ \frac{dY_{\Delta a}}{dz} &= -\frac{\Gamma_{N_1}}{H}\Bigg[\epsilon_a f_D(z)(Y_{N_1}^{eq} - Y_{N_1}) + \mathrm{Br}_a f_{ID}(z) Y_{\Delta a}\\ &\quad + \frac{\Gamma_{N_1}}{M_{N_1}}\mathrm{Br}_a^2 f_W(z) Y_{\Delta a} + \frac{\Gamma_{N_1}}{M_{N_1}}\mathrm{Br}_a \mathrm{Br}_b f_T(z) Y_{\Delta b}\Bigg],\end{aligned}$$

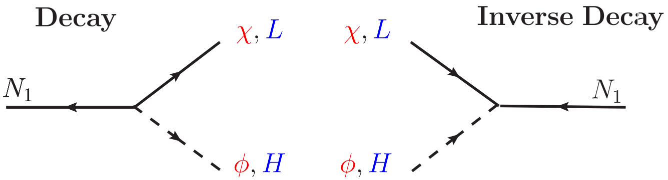
where $a, b = L, \chi$ and $a \neq b$

- Γ_{N_1}/H governs departure from equilibrium, where $H = H|_{T=M_1}$
- $\Gamma_{N_1}/H\,\mathrm{Br}_a$ sets the strengths of wash-out effects due to inverse decays
- $(\Gamma_{N_1}/H)(\Gamma_{N_1}/M_{N_1})\,\mathrm{Br}_a\mathrm{Br}_b$ sets the strengths of transfer effects

Boltzmann Equations in Narrow-Width Limit

In the narrow-width limit, $\Gamma_1 \ll M_1$, we can neglect $2 \leftrightarrow 2$ interactions, and the Boltzmann equations for $\Delta\chi$ and ΔL are decoupled,

$$
\begin{aligned}
Y'_{N_1} &= -\frac{\Gamma_{N_1}}{H}\left(Y_{N_1} - Y^{\rm eq}_{N_1}\right) \\
Y'_{\Delta\chi} &= \frac{\Gamma_{N_1}}{H}\left[\epsilon_\chi \left(Y_{N_1} - Y^{\rm eq}_{N_1}\right) - \frac{Y_{\Delta\chi}}{2Y^{\rm eq}_\chi}\,{\rm Br}_\chi\right] \\
Y'_{\Delta L} &= \frac{\Gamma_{N_1}}{H}\left[\epsilon_L \left(Y_{N_1} - Y^{\rm eq}_{N_1}\right) - \frac{Y_{\Delta L}}{2Y^{\rm eq}_L}\,{\rm Br}_L\right]
\end{aligned}
$$

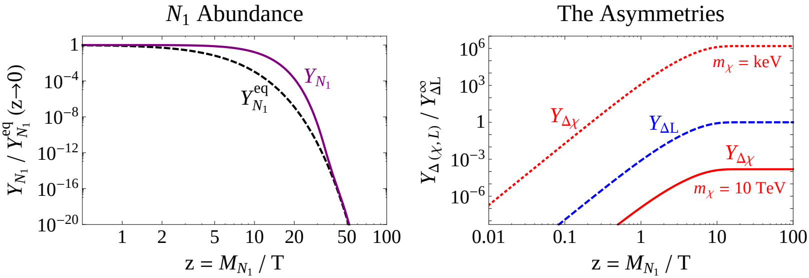


- **weak washout:** ${\rm Br}_a \Gamma_{N_1} \ll H$
- **strong washout:** ${\rm Br}_a \Gamma_{N_1} \gg H$

Vanilla case: Weak-Weak Washout

- We begin by considering the *weak washout* regime, $\Gamma_{N_1} \ll H$.
- With weak washout, and starting with thermal initial condition for N_1 and both sectors, $\eta_L = \eta_\chi = 1$, that is

$$\begin{aligned} Y_{\Delta L}^{\infty} &= \epsilon_L \, Y_{N_1}^{eq}(0) \\ Y_{\Delta \chi}^{\infty} &= \epsilon_\chi \, Y_{N_1}^{eq}(0) \end{aligned}$$



- Asymmetries determined simply by the decay asymmetries: $\epsilon_L, \epsilon_\chi$.

$$\frac{Y_{\Delta L}^{\infty}}{Y_{\Delta \chi}^{\infty}} \sim \frac{\epsilon_L}{\epsilon_\chi} \sim \frac{y_1 y_2}{\lambda_1 \lambda_2} \qquad (1)$$

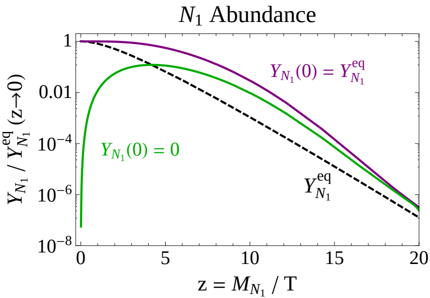
Narrow width: variations

More generally, the efficiencies can be parametrically suppressed, depending on:

- Initial conditions for the heavy neutrino, if it does not start in thermal equilibrium
- Washout effect, if $\mathrm{Br}_a \Gamma_{N_1} \gg H$ for $a = \chi$ or L

Narrow width: initial conditions

The asymmetries depend on whether N_1 begins in equilibrium, or is thermalized by the see-saw Lagrangian...



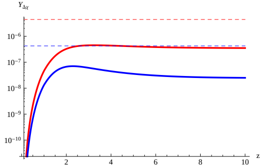
- For $Y_{N_1}(0) = 0$ asymmetry suppressed: negative asymmetry generated at $z \ll 1$ cancels against positive asymmetry generated at $z > 1$
- Small asymmetry arises thanks to the washout effects being different at small and at large z.

$$\eta_L \simeq \frac{\Gamma^2_{N_1}}{H^2}\mathrm{Br}_L\,, \qquad \eta_\chi \simeq \frac{\Gamma^2_{N_1}}{H^2}\mathrm{Br}_\chi\,.$$

Hierarchies in Yukawas enhanced in the asymmetries ratio

$$\frac{Y^\infty_{\Delta L}}{Y^\infty_{\Delta\chi}} \sim \frac{\epsilon_L \mathrm{Br}_L}{\epsilon_\chi \mathrm{Br}_\chi} \sim \frac{y_1^3 y_2}{\lambda_1^3 \lambda_2} \qquad (2)$$

Now assume strong-strong wash-out: $\mathrm{Br}_a \Gamma_{N_1}/H \gg 1$. Due to inverse decays, the efficiency is suppressed...



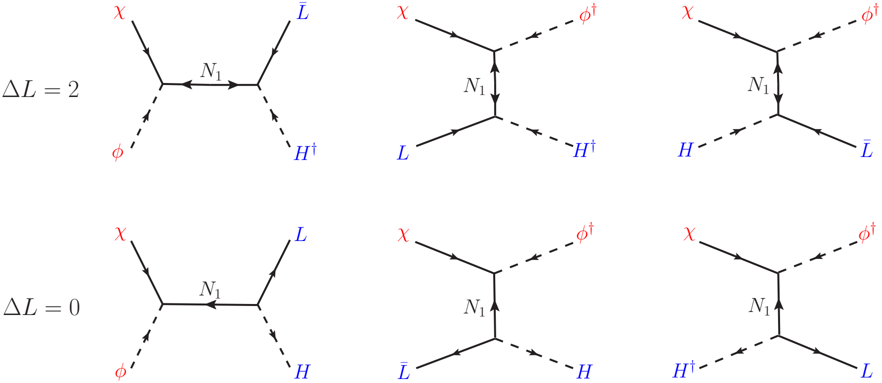
$$\eta_L \simeq \frac{1}{\Gamma_{N_1}/H} \frac{1}{\mathrm{Br}_L} \,, \qquad \eta_\chi \simeq \frac{1}{\Gamma_{N_1}/H} \frac{1}{\mathrm{Br}_\chi} \,.$$

The ratio of the asymmetries:

$$\frac{Y^\infty_{\Delta L}}{Y^\infty_{\Delta\chi}} \sim \frac{\epsilon_L \mathrm{Br}_\chi}{\epsilon_\chi \mathrm{Br}_L} \sim \frac{\lambda_1 y_2}{y_1 \lambda_2} \tag{3}$$

$2 \leftrightarrow 2$ transfer

- So far we've been focusing on the narrow width limit, $\Gamma_{N_1} \ll M_{N_1}$
- At larger width, one has to include $2 \leftrightarrow 2$ interactions in the BE



- These include operators that transfer the asymmetry between the two sectors, coupling the BEs for $Y_{\Delta\chi}$ and $Y_{\Delta L}$

Transfer effects

- At $z \gg 1$ Boltzmann equations dominated by 2-to-2 washout and transfer (inverse decays suppressed by e^{-z})

$$\begin{bmatrix} Y'_{\Delta L} \\ Y'_{\Delta\chi} \end{bmatrix} = -\frac{W}{z^2} M \cdot \begin{bmatrix} Y_{\Delta l} \\ Y_{\Delta\chi} \end{bmatrix} \quad M = \begin{pmatrix} 6\mathrm{Br}_L^2 + \mathrm{Br}_L \mathrm{Br}_\chi & \mathrm{Br}_L \mathrm{Br}_\chi \\ \mathrm{Br}_L \mathrm{Br}_\chi & 6\mathrm{Br}_\chi^2 + \mathrm{Br}_L \mathrm{Br}_\chi \end{pmatrix}$$

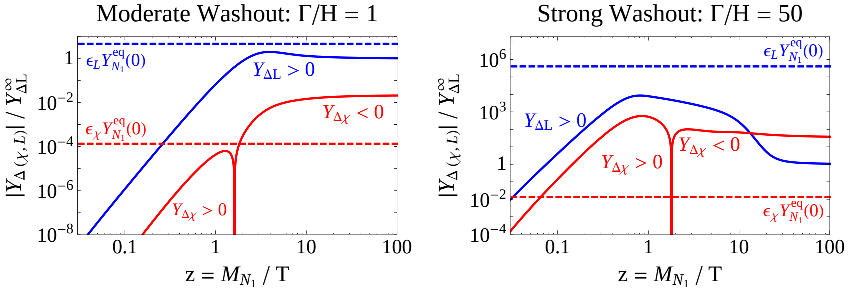
where $W = (32/\pi)(\Gamma_{N_1}/M_{N_1})(\Gamma_{N_1}/H)$

- For $\mathrm{Br}_\chi \ll 1$, $\mathrm{Br}_L \sim 1$ the asymptotic abundance is

$$\frac{Y^\infty_{\Delta L}}{Y^\infty_{\Delta\chi}} \sim -\mathrm{Br}_\chi,$$

- The asymmetries do *not* equilibrate, unless $\mathrm{Br}_\chi \sim \mathrm{Br}_L$ (transfer and wash-out effects correlated in this model).
- *Larger* asymmetry for the sector with *smaller* branching fraction
- Particle domination in one sector = Antiparticle domination in the other

Solutions with Transfer



- Here, the DM abundance is dominated by the transfer, and $\eta_\chi \gg 1$
- Morally, this behavior is similar to *classic* ADM where an asymmetry begins in one sector and is transferred to the other. But the asymmetries do *not* equilibrate, unless $\mathrm{Br}_\chi \sim \mathrm{Br}_L$.

Zoology of Solutions

The abundance ratio in a variety of limits:

$$\frac{Y^{\infty}_{\Delta\chi}}{Y^{\infty}_{\Delta L}} = \frac{\eta_\chi \epsilon_\chi}{\eta_L \epsilon_L}$$

DM/SM	$Y_{N_1}(0) = Y^{eq}_{N_1}$	$Y_{N_1}(0) = 0$
weak/weak	$\frac{\epsilon_\chi}{\epsilon_L} \sim \frac{\lambda_1 \lambda_2}{y_1 y_2}$	$\frac{\mathrm{Br}_\chi \epsilon_\chi}{\mathrm{Br}_L \epsilon_L} \sim \frac{\lambda_1^3 \lambda_2}{y_1^3 y_2}$
strong/strong	$\frac{\mathrm{Br}_L \epsilon_\chi}{\mathrm{Br}_\chi \epsilon_L} \sim \frac{y_1 \lambda_2}{\lambda_1 y_2}$	
weak/strong	$\frac{\Gamma_{N_1}}{H} \frac{\epsilon_\chi}{\epsilon_L} \sim \frac{\Gamma_{N_1}}{H} \frac{\lambda_1 \lambda_2}{y_1 y_2}$	$\left(\frac{\Gamma_{N_1}}{H}\right)^2 \frac{\mathrm{Br}_\chi \epsilon_\chi}{\epsilon_L} \sim \left(\frac{\Gamma_{N_1}}{H}\right)^2 \frac{\lambda_1^3 \lambda_2}{y_1 y_2}$
strong/weak	$\frac{H}{\Gamma_{N_1}} \frac{\epsilon_\chi}{\epsilon_L} \sim \frac{H}{\Gamma_{N_1}} \frac{\lambda_1 \lambda_2}{y_1 y_2}$	$\left(\frac{H}{\Gamma_{N_1}}\right)^2 \frac{\epsilon_\chi}{\mathrm{Br}_L \epsilon_L} \sim \left(\frac{H}{\Gamma_{N_1}}\right)^2 \frac{\lambda_1 \lambda_2}{y_1^3 y_2}$

A bunch of different behaviors are possible, and the bottom line is that the abundances can be very different.

Towards complete model

Three SM generations and $SU(2)_W$ doublets

$$-\mathcal{L} \supset \frac{1}{2} M_i N_i^2 + Y_{i\alpha} N_i L_\alpha H + \lambda_i N_i \chi \phi + h.c.$$

The asymmetries pick up factors of 2,3...

$$\begin{aligned} \epsilon_L &\simeq \frac{M_{N_1}}{8\pi} \frac{\mathrm{Im}[(3Y^* Y^T + \lambda^* \lambda) M^{-1} Y Y^\dagger]_{11}}{[2YY^\dagger + \lambda\lambda^*]_{11}} , \\ \epsilon_\chi &\simeq \frac{M_{N_1}}{8\pi} \frac{\mathrm{Im}[(Y^* Y^T + \lambda^* \lambda) M^{-1} \lambda\lambda^*]_{11}}{[2YY^\dagger + \lambda\lambda^*]_{11}} , \end{aligned}$$

SM Yukawas related to low-energy neutrino masses and mixings

$$[YY^\dagger]_{ij} = M_{N_i}^{1/2} M_{N_j}^{1/2} [R \ m_\nu \ R^\dagger]_{ij} / v_{EW}^2$$

SM typically in the strong washout regime

$$\frac{\mathrm{Br}_L \Gamma_{N_1}}{H} = \frac{M_{\mathrm{Pl}}}{\sqrt{g_*/90}} \frac{[R \, m_\nu \, R^\dagger]_{11}}{8\pi^2 v_{\mathrm{EW}}^2} \simeq 25 \frac{m_\nu^{\max}}{0.05 \ \mathrm{eV}} ,$$

Dark Davidson Ibarra Bound

- The SM asymmetry expressed as

$$\epsilon_L \leq \frac{3 M_{N_1} m_\nu^{\max}}{16\pi v_{\rm EW}^2}\, C \simeq 10^{-7} \left(\frac{M_{N_1}}{10^9\ {\rm GeV}}\right) C\,. \qquad (4)$$

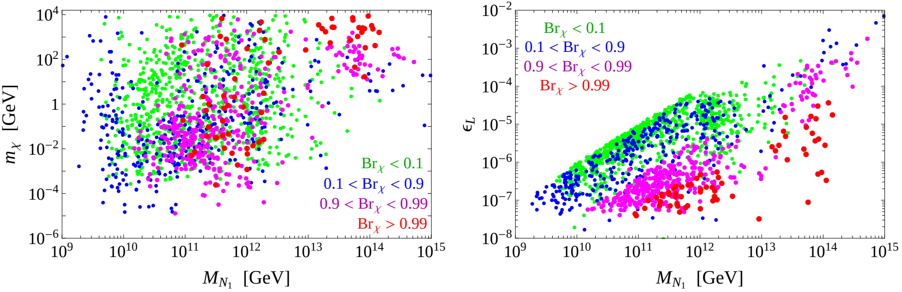
$$C \simeq \begin{cases} 1 & {\rm Br_L} \gg {\rm Br}_\chi \\ (\lambda_2^2 M_{N_1}/\lambda_1^2 M_{N_2})^{1/2} & {\rm Br_L} \ll {\rm Br}_\chi \end{cases} \qquad (5)$$

- For ${\rm Br_L} \gg {\rm Br}_\chi$ the standard Davidson-Ibarra bound,

$$M_{N_1} \gtrsim 10^9\ {\rm GeV}$$

  where we used the requirement that $\epsilon_L \gtrsim 10^{-7}$
- For ${\rm Br_L} \ll {\rm Br}_\chi$ typically $C < 1$ (because $M_{N_1} \ll M_{N_2}$ by assumption here, and λ_1 is large when ${\rm Br}_\chi$ dominate)

Possible solutions to the BE that are consistent with generating the correct neutrino masses and mixings and the correct lepton asymmetry:



Model Variations

1. the ϕ asymmetry is preserved, $n_{\Delta\phi}$

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   symmetric DM can be restored by late decays

2. ϕ gets a VEV, $\langle\phi\rangle$

   sterile neutrino DM

ϕ Asymmetry

- What if ϕ has an asymmetry too?
- Then N_i decays produce equal asymmetries in χ and ϕ,

$$n_{\Delta\chi} = n_{\Delta\phi}$$

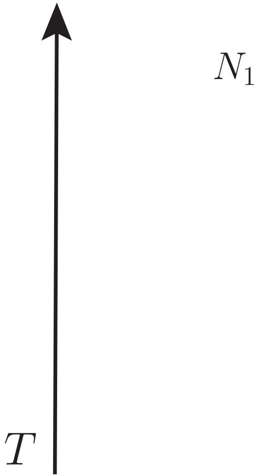
- Integrating out N_i we see that ϕ can decay to $\bar{\chi}$ at late times

$$-\mathcal{L} \supset \frac{1}{2}M_1 N_1^2 + \lambda N_1 \chi\phi + y N_1 LH + h.c.$$

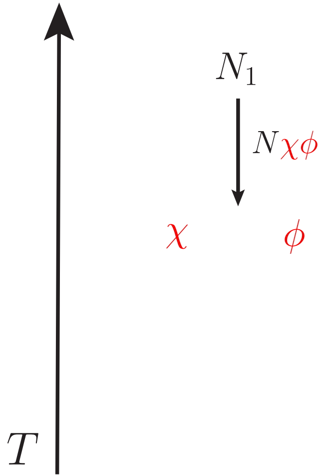
$$-\mathcal{L} \supset \lambda y \frac{\chi\phi LH}{M_1}$$

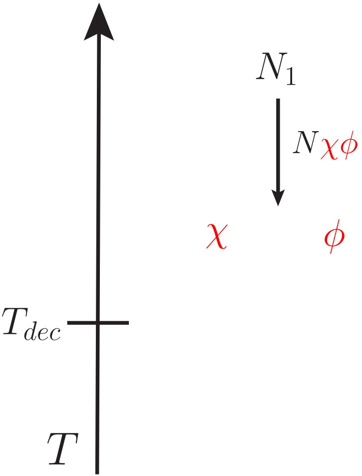
- Symmetric dark matter is restored, and by assumption has a *boosted* annihilation rate!

$$\langle \sigma_\chi v \rangle \gg 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

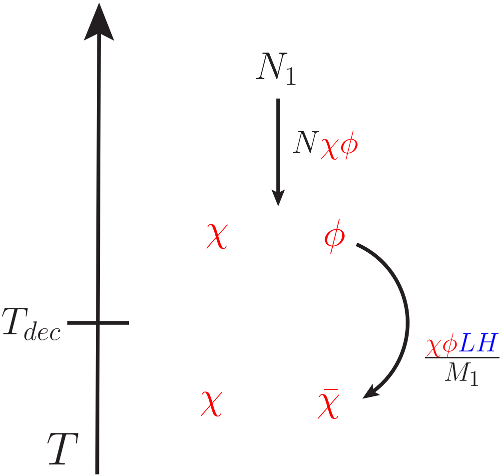

N_1
T

ϕ Asymmetry



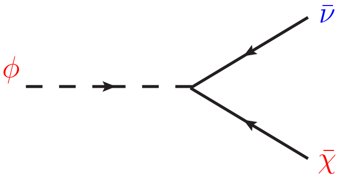

N_1
$N \chi\phi$
χ
ϕ
T_{dec}
T

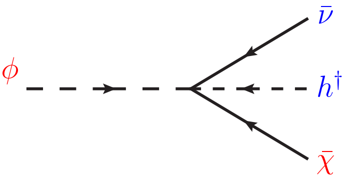
ϕ Asymmetry



$$-\mathcal{L} \quad \supset \quad \lambda y \frac{\chi \phi L H}{M_1}$$

There are 2-body and 3-body decays,





$$\Gamma_2 = \frac{\lambda^2}{16\pi} \frac{m_\nu}{M_1} m_\phi \left(1 - \frac{m_\chi^2}{m_\phi^2}\right)^2 \qquad \frac{\Gamma_3}{\Gamma_2} \sim \frac{m_\phi^2}{24\pi^2 v^2}$$

$$\tau_\phi \simeq 10^{-2}\ \mathrm{sec} \times \left(\frac{0.1}{\lambda}\right)^2 \left(\frac{0.05\ \mathrm{eV}}{m_\nu}\right) \left(\frac{M_1}{10^{10}\ \mathrm{GeV}}\right) \left(\frac{100\ \mathrm{GeV}}{m_\phi}\right)$$

Limits on ϕ Decay

- The decay must occur late enough to avoid recoupling DM annihilations

$$\tau_\phi^{-1} < H(T_{dec}) = s\, Y_\chi \langle \sigma v \rangle$$
$$\tau_\phi > 10^{-5}\,\mathrm{sec}\, \frac{1}{\sqrt{g_*}} \left(\frac{m_\chi}{100\ \mathrm{GeV}} \right)^2 \left(\frac{10^{-24}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right)^2$$

- And early enough to avoid constraints from BBN, which depends on the branching ratio to (hadronic) 3-body decays

$$\mathrm{Br}_3 < 10^{-6} \Rightarrow \tau_\phi \lesssim 10^6\ \mathrm{sec}$$
$$\mathrm{Br}_3 < 10^{-3} \Rightarrow \tau_\phi \lesssim 10^2\ \mathrm{sec}$$
$$\mathrm{Br}_3 \sim \mathcal{O}(1) \Rightarrow \tau_\phi \lesssim 1\ \mathrm{sec}$$

T. Kanzaki, M. Kawasaki, K. Kohri, T. Moroi **2007**

Mixed Warm/Cold DM

Suppose that:

1. there happens to be a mass hierarchy between ϕ and χ, $m_\phi \gg m_\chi$
2. ϕ decays after χ kinetically decouples, so that χ doesn't thermalize

Then χ might not redshift enough to cool down.

$$v_{\bar{\chi}} = 10^{-5} \frac{\mathrm{km}}{\mathrm{s}} \left(\frac{m_\phi}{m_\chi} \right) \sqrt{\frac{\tau_\phi}{1\ \mathrm{s}}}$$

$\bar{\chi}$ is warm for $m_\phi \sim \mathrm{TeV}$, $m_\chi \sim 10\ \mathrm{MeV}$, and $\tau_\chi \sim 1\ \mathrm{sec}$.

This means that χ can be cold and $\bar{\chi}$ warm!

Let's now see what happens when ϕ gets a VEV.

$$\mathcal{L} \supset -m_\chi \chi \tilde{\chi} + \frac{1}{2} M_1 N_1^2 + \lambda \, N_1 \, \chi \, \langle \phi \rangle + y \, N_1 L \, \langle H \rangle + h.c.$$

Integrating out N_1,

$$\mathcal{L} \supset -m_\chi \, \chi \tilde{\chi} - \frac{\mu_\chi}{2} \chi^2 - \frac{m_\nu}{2} \nu^2 - \mu_{\chi\nu} \, \chi \nu + h.c.$$

where,

$$\mu_\chi = \lambda^2 \frac{v_\phi^2}{M_{N_1}} \,, \qquad m_\nu = y^2 \frac{v_{\mathrm{EW}}^2}{M_{N_1}} \,, \qquad \mu_{\chi\nu} = \left(\frac{\lambda}{y} \frac{v_\phi}{v_{\mathrm{EW}}} \right) m_\nu$$

We see that:

- ν's get a Majorana mass as usual
- χ/ν mixing (χ is *sterile neutrino DM*)
- μ_χ induces $\chi \leftrightarrow \bar{\chi}$ oscillations

DM Oscillations

It is essential to check whether the $\chi \leftrightarrow \bar{\chi}$ oscillations turn on before, or after, DM decouples:

- **Before**: Symmetric DM is restored and σ, and not $Y_{\Delta\chi}$, determines the DM abundance
- **After:** At late times, $P_{\chi\to\bar{\chi}} \sim 1$ so the annihilation rate today is enhanced.

Cohen, Zurek **2009**
Cai, Kaplan, Luty **2009**

The BE for oscillations of χ into $\bar{\chi}$ is given by,

$$\frac{dY_{\bar{\chi}}}{dz} = \frac{z}{2} \langle P_{\chi\to\bar{\chi}}(t)\rangle \frac{\Gamma_\chi}{H_1} (Y_\chi - Y_{\bar{\chi}})$$

Where Γ_χ is the total interaction rate, and the oscillation probability is:

$$P_{\chi\to\bar{\chi}}(t) = \sin^2\left(\frac{\mu_\chi}{2} t\right)$$

- Oscillations are decoupled whenever $\langle P \rangle \, \Gamma_\chi < H$.
- It is sufficient to make sure that:

$$\begin{aligned} \langle P_{\chi \to \bar{\chi}} \rangle \, \Gamma_\chi(T_{dec}) &\lesssim H(T_{dec}) \\ \mu_\chi &\lesssim \sqrt{\Gamma_\chi \Gamma_{ann}(T = T_{dec})} \end{aligned}$$

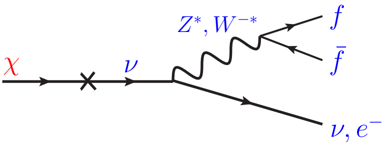
This leads to a rather stringent limit on the quantity λv_ϕ,

$$\frac{\lambda \, v_\phi}{m_\chi} \lesssim 3 \times 10^{-7} \left(\frac{M_1}{10^{10}\ \mathrm{GeV}} \right)^{1/2} \left(\frac{10^{-24}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{ann} v \rangle} \right) \left(\frac{\langle \sigma_{tot} v \rangle}{\langle \sigma_{ann} v \rangle} \right)^{1/4} g_*^{-1/4}$$

Meanwhile, if this condition is satisfied, $\chi \leftrightarrow \bar{\nu}$ oscillations, induced by $\mu_{\chi\nu}$, are always decoupled, because of the small mixing angle, $\theta_{\mu\nu} \sim \mu_{\chi\nu}/m_\chi$

One important effect of χ/ν mixing is that it induces DM decays.

For example taking $m_\chi < m_Z$,



$$\Gamma_{\chi \to \nu f \bar{f}} \simeq \frac{\alpha_2^2\, \theta_{\chi\nu}^2}{4\pi} \left(\frac{m_\chi}{m_Z}\right)^4 m_\chi$$

In order to be consistent with cosmic rays and diffuse gammas, $\tau_\chi \gtrsim 10^{26}$ s.

$$\frac{\lambda\, v_\phi}{m_\chi} \lesssim 10^{-9} \left(\frac{\mathrm{GeV}}{m_\chi}\right)^{5/2} \left(\frac{M_1}{10^{10}\ \mathrm{GeV}}\right)^{1/2} \left(\frac{0.05\ \mathrm{eV}}{m_\nu}\right)^{1/2}$$

This is a stronger limit than oscillations for $m_\chi \gtrsim 0.1$ GeV, and saturating it may lead to observable DM decays.

What's next?

- We've just considered thermal leptogenesis, but this scenario can be extended to include: soft, resonant, and Dirac leptogenesis.

- Here we took DM and SM to begin in thermal equilibrium. Another possibility is to reheat the DM sector through N_i decays. This allows for a cooler hidden sector with symmetric DM.

AA, E. Kuflik, J. Ruderman, and T. Volansky, **in progress**

Take Away Points

- It's worthwhile (and fun) to explore alternatives to the thermal WIMP paradigm, and ADM is an interesting example.
- Leptogenesis provides a simple way to generate the DM and lepton asymmetries at the same time, $N_i \chi \phi + N_i LH$
- This framework allows for very different $n_{\Delta\chi}$ and $n_{\Delta L}$, and therefore ADM can include DM masses from keV to 10 TeV
- if ϕ has an asymmetry, late decays repopulate symmetric DM, leading to a large σ
- if ϕ gets a VEV, χ mixes with neutrinos so decays to SM, and there are late-time $\chi \leftrightarrow \bar{\chi}$ oscillations.