Emergent Dark Matter, Baryon and Lepton Numbers

Yanou Cui

Harvard University & University of Maryland

with Lisa Randall and Brian Shuve


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Outline

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2. Review of Existing ADM models, Novel alternative: asymmetry transfer via mass mixing
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Brief Review of Dark Matter Theories

Dark Matter:

- **Significant** part of universe: $\Omega_{DM} \approx 23\%$ vs. $\Omega_B \approx 4\%$
- **Limited clues** for its microscopic features so far $\Rightarrow$
  Appealing candidate Theories for DM: not many

**Conventional Favorite:** **WIMP**

- weak scale mass, weak scale interaction with SM, $\Omega_{DM}$
- from thermal freezeout
Horizon beyond WIMP...

WIMP:

- **Merits:** Good connection with new particle physics at weak scale; natural fit to desired $\Omega_{DM} - \text{WIMP miracle}$
- **Challenge:** Not as ‘natural’ as naively expected
  - Limited parameter space in concrete EWSB models: e.g. SUSY WIMP
  - Combining direct detection bounds with $\Omega_{DM}$ requirement $\Rightarrow$ Limited possibilities left: based on $\sigma_{DiDt} - \sigma_{ann}$ correlation by crossing Feynmann diagrams ($\Rightarrow$ higgs-like mediator, dark sector or leptophilic annihilation, on-resonance annihilation...) (general operator analysis Cui, Mason and Randall, 2010)

$\Rightarrow$ DM theories beyond standard WIMP, yet with sound motivations?

**A relatively over-looked clue:** $\Omega_{DM} - \Omega_{B}$ coincidence—two sectors with distinctive constituents, very weak interaction, after long-time evolution, end up with comparable $\Omega$...
Paths of addressing $\Omega_{DM} - \Omega_B$ coincidence

**Origin of $\Omega_B$:**

1. Baryogenesis generates asymmetry $(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$
2. Annihilation (e.g. $q\bar{q} \rightarrow \nu\bar{\nu}$) is on until late time, depletes symmetric component

$\Rightarrow n_B(t \rightarrow \infty) = n_B - n_{\bar{B}}$, i.e. $\Omega_B$ is ‘asymmetric’

**$\Omega_{DM} - \Omega_B$ Connection?**

Direction-1: $\Omega_{DM}$ is also ‘asymmetric’

Dark matter is also ‘asymmetric’, with connection to $\Delta B(L)$, symmetric component of DM annihilates away later like $B$
Review of Existing ADM Works:

- Co-generation of dark and B asymmetries
  - Embed in EW baryogenesis via sphalerons: DM is new chiral $SU(2)_L$ doublet (Kaplan, 1982; Nussinov, 1985...), ruled out by recent direct detection bound...
  - Generalized GUT-baryogenesis or leptogenesis: heavy particle decay to both DM and B (or L) (‘Hylogenesis’: Davoudiasl et. al 2010, ‘Cladogenesis’: Allahverdi et. al 2010, ‘ADM from Leptogenesis’: Falkowski et. al 2011...)

- Asymmetry is generated in one sector first, then transferred to another asymmetry by thermalization via higher-dim transfer operator (‘Asymmetric Dark Matter’: D. E. Kaplan et. al 2009)... E.g. (SUSY) via $\Delta W_{eff} = \frac{1}{M} X^2 LH_u$
  - in equilibrium $\mu_B \sim \mu_X$, $n_B/n_X \sim n_B^{eq}/n_X^{eq}$ ($T_D$) freeze in when transfer decouples at $T_D (\Gamma \lesssim H) – \text{thermal relation/suppression}$, most work: $m_{DM} \sim O(\text{GeV}) (m_X/T_D < 1)$, $m_{DM} \sim m_{EW}$ ($m_X/T_D > 1$) – Randall and Buckley, 2010
Motivation: DM-B (L) coincidence

Review of Existing ADM models, Novel alternative: asymmetry transfer via mass mixing

Example models

Conclusions

⇒ $\Omega_{DM} - \Omega_B$ coincidence: an intriguing clue, yet not well explored – mechanisms, mass range (most work in the past two years) ...

More general possibilities to address the coincidence?

Focus of this talk: **Mass mixing as asymmetry transfer operator in ADM framework**

Another novel possibility out of ADM frame–combine both WIMP miracle and ADM merits: **Wimpy Leptogenesis**, work in progress with L. Randall and B. Shuve, See Brian’s talk
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Existing ADM models:

- Employ higher dim operator;
- Its origin? ↔ UV completion requires additional structure: messenger sector, new scale...—less economic, less compelling

More economic alternative: Mass mixing between $X$ and $L(B)$

- No odd ops, no odd scales: Renormalizable op, or generated by Plack suppressed ops
- Qualitatively different from higher dim op: interplay between neutrino-like oscillation and thermal interaction, new way to accommodate heavier $m_X$...
- Are $B(L)$ and $X$ separately conserved, esp. in the early universe? Maybe not...⇒ Emergent $X$, $B/L$ number
ADM Models with Mass Mixing Transfer

**Guidelines:**

*XL* mixing on at early universe to transfer asymmetry, but off today $\Rightarrow$ Dynamical mechanism: $\langle \phi \rangle_{XL}$ where $\phi$ is a scalar field with $\langle \phi \rangle \neq 0 \rightarrow \langle \phi \rangle = 0$ transition

$\langle \phi \rangle = 0 \rightarrow \langle \phi \rangle \neq 0$: vanilla phase transition pattern for symmetry breaking

The opposite $\langle \phi \rangle \neq 0 \rightarrow \langle \phi \rangle = 0$ is GENERIC as well:

- **Rapid shutoff** of $\langle \phi \rangle$ triggered by interaction with another scalar: inspiration from ‘hybrid inflation’ (Linde, 1994), ‘Two Stage Phase Transition in Two Higgs Models’ (Land and Carlson, 1992)

- $\langle \phi \rangle$ **gradual rolling** to 0: ubiquitous– cosmic background energy density (e.g. KE) $\propto T^4$; $\phi$ as moduli field with flat potential e.g. pseudo-Goldstone boson, SUSY Polonyi field, SUSY flat direction moduli in Affleck-Dine baryogenesis, string theory moduli...; **generic feature**: start at large VEV at early time, then slowly roll down to true vacuum $\langle \phi \rangle = 0$
Ex-I: Rapid Mixing Shutoff–Two-Higgs Model

1. High scale baryogenesis (leptogenesis) generate B and L asymmetries ($n_L \sim n_B$ via sphalerons)

2. Consider EW scale two Higgs model: $SU(2)_L$ doublets $\sigma, \phi$

   where $\sigma$ is SM Higgs, $\phi$ is DM-L ‘mixer’, DM $X_L, X_R$ are a vector-like Dirac fermion pair. Generic PT pattern in 2-higgs model: $\phi \neq 0$ during an intermediate period of EW phase transition when $L$ is transferred to $X$ via mass mixing $\phi X_L$, then $\phi \to 0$ by rapid tunneling to true vacuum at later time

The model: (New $Z_2$ symmetry to prevent $\phi \sigma$ mixing, as well as ensure $X$ stability)

$$
\mathcal{L} \supset m_X X_i \bar{X}_i + y_X \Phi X_i L_i + V(H, \Phi) + \text{h.c.},
$$

$$
V(T = 0) = 4k_1 |H|^4 - 4\mu_1^2 |H|^2 + 4k_2 |\Phi|^4 - 4\mu_2^2 |\Phi|^2 + 4k_3 |\Phi|^2 |H|^2,
$$
Two-step phase transition in 2-higgs model: generic, large parameter space

1. At $T > T_{c2} = \frac{\mu_2}{\sqrt{\alpha_2}}$, $\langle \phi \rangle = \langle \sigma \rangle = 0$

2. First PT at $T_{c2} = \frac{\mu_2}{\sqrt{\alpha_2}}$: minimum (energy $V_2$) $\langle \phi \rangle \neq 0, \langle \sigma \rangle = 0$

3. Around $T_{c1} = \frac{\mu_1}{\sqrt{\alpha_1}}$ a new minimum (energy $V_1$) develops with $\langle \phi \rangle = 0, \langle \sigma \rangle \neq 0$,

$V_1 = V_2$ at $T_d = (\frac{\sqrt{\lambda_2} \mu_2^2 - \sqrt{\lambda_1} \mu_2^2}{\sqrt{\lambda_2} \alpha_1 - \sqrt{\lambda_1} \alpha_2})^{1/2}$ Second PT (1st order) tunneling occurs at later $T_t$ when $\langle \phi \rangle \rightarrow 0$ via tunneling–mixing shuts off

Asymmetry transfer Period: $T_{c2} < T < T_t$
Computing the amount of $L \rightarrow X$ transfer via $\langle \phi \rangle XL$—three factors to consider:

- Coherent oscillation induced by mass mixing (like neutrino oscillation): $\Gamma_{osc} \sim \frac{\Delta m^2}{E}$

- Thermalization via scatterings in equilibrium: $\Gamma_{therm} \sim \sin^2 \theta \Gamma_0$, mixing angle $\theta \sim y \langle \phi \rangle / m_X$, $\Gamma_0 \sim g_{EW}^4 T$

- State projection: at $T_t$, mixed basis $\Rightarrow$ no-mixing (flavor) basis

$(X' = c_\theta X + s_\theta L, L' = -s_\theta X + c_\theta L)$
**Asymmetry Transfer in 2-Higgs Model-I**

**Simplification:** at $T \sim T_{EW}$, $\Gamma_{therm}(T_{EW}) \gg H(T_{EW}) \Rightarrow$ rapid thermalization, can apply *equilibrium distribution* in instantaneous mass basis. Final asymmetries from state projection at $T_t$:

$$n^f_L = n^eq_L(T_t)c^2_\theta(T_t) + n^eq_X(T_t)s^2_\theta(T_t)$$

$$n^f_X = -n^eq_L(T_t)s^2_\theta(T_t) + n^eq_X(T_t)c^2_\theta(T_t)$$

Asymmetry ratio:

$$\frac{\Delta_X}{\Delta n_L} = -\frac{(1 + \cos^2 \theta)\Delta n_X^eq + \sin^2 \theta \Delta n_L^eq}{\cos^2 \theta \Delta n_L^eq + \sin^2 \theta \Delta n_X^eq}$$
Motivation: DM-B (L) coincidence

Review of Existing ADM models, Novel alternative: asymmetry transfer via mass mixing

Example

Two-Higgs Model: Rapid Mixing Shutoff

Three cases and numerical results:

- **Relativistic X:** \( T_t \gg m_X, \frac{\Delta X}{\Delta n_L} \approx -\frac{2}{3}, m_X \sim O(\text{GeV}) \)

- **Thermally suppressed X:** \( \tan^2 \theta \ll \frac{n_X^{eq}}{n_L^{eq}}, \frac{\Delta X}{\Delta n_L} \approx -6\sqrt{\frac{2M^3}{\pi^3 T^3}} e^{-M/T}, m_X \sim 300 - 500 \text{GeV (fix } m_h = 120 \text{GeV)} \)

- **Novel-Mixing-angle-suppressed X:** \( \frac{n_X^{eq}}{n_L^{eq}} \ll \tan^2 \theta, \frac{\Delta X}{\Delta n_L} = -\tan^2 \theta, m_X \sim 400 - 500 \text{GeV} \)

Ex: Viable regions (unshaded) with \( y_X = 1.7 \) and \( \mu_2 = 54 \text{ GeV} \)
Phenomenology

- **DM direct detection**: loop-suppressed $X$–nucleon coupling induced by doublet $\phi$:

$$\sigma_{dd} \approx (4 \times 10^{-46} \text{ cm}^2) \left( \frac{Z/A}{0.4} \right)^2 \left( \frac{500 \text{ GeV}}{m_\phi/y_X} \right),$$

similar to arxiv:0909.2035, Cohen and Zurek –can be tested by next generation DM detectors

- **LHC search**: most promising—pair production of $\phi^\pm$, then $\phi^\pm \rightarrow X(MET) + \ell^\pm$

Ex II: Moduli induced mass mixing

In early universe, various types of moduli fields can take on large VEV due to thermal effect or initial condition, then slowly rolls down to 0: String moduli, SUSY Polonyi field, SUSY flat direction... These $\phi$ fields are typically gauge singlets $\Rightarrow L$ in $\phi LX$ needs to be sterile ($N$) (EW doublet $X$ is ruled out)

1. Minimal scenario: $N$ as the sterile Dirac partner of SM $L$, both $N, L$ asymmetries are generated with equal amount by *Dirac leptogenesis* at high $T$ (E.g. Murayama and Pierce, 2002)
   Caveat: moduli decay may dilute $X, B(L)$ densities $\rightarrow$ late decay–light moduli, or heavy moduli with efficient leptogenesis (resonance enhanced or Affleck-Dine)

2. DM a vector-like Dirac pair $X, \bar{X}, \phi$ is a moduli taking $\langle \phi \rangle \sim M_p$ at the end of inflation

3. DM-L mixing, asymmetry transfer via e.g. fermionic DM w/ heavy moduli: $c \frac{|\phi|^2 X N}{M_p}$
Dynamics of moduli $\phi$

- **Toy model scalar potential:**

\[
V = (m^2 - a^2 H(t)^2)|\phi|^2 + \frac{1}{2M_p^2}(m^2 + b^2 H^2)|\phi|^4
\]

where $-a^2 H(t)^2$ ($H(t)$: Hubble scale) is thermal mass correction from coupling to background density

- **Instantaneous VEV:** above $T_c \sim \sqrt{2ma \cdot M_p}$:

\[
\langle \phi \rangle = M_p \sqrt{(a^2 H(t)^2 - m^2)/(b^2 H(t)^2 + m^2)}
\]

below $T_c$: $\langle \phi \rangle = 0$

- **True instantaneous $\phi$ coupling to $XN$—solve e.o.m.:**

\[
\ddot{\phi} + 3H\dot{\phi} + 2(m^2 - a^2 H^2)\phi + \frac{2}{M_p^2}(m^2 + b^2 H^2)\phi^3 = 0
\]
Time-variation of Mass Mixing

Solution of e.o.m $\tilde{\phi}$ tracks $\langle \phi \rangle$ well when $H(t) \gg m$, starting $H(t) \sim m$, slowly approaching true vev: damping oscillation around $\langle \phi \rangle = 0$, ($\phi_0 \sim 10^{10}\text{GeV}$)

$$\tilde{\phi}(t) = \frac{\phi_0}{(mt)^{3/2}} \sin(mt)$$

$\Rightarrow$ Mass mixing is on yet gradually falling towards 0 after $H(t) \sim \mu_X$

A rough estimate of transfer rate $N \rightarrow X$:

$$\Gamma_{\text{transfer}} \approx \sin^2 \theta \sin^2 \left( \frac{\epsilon_+ - \epsilon_-}{\Gamma_0} \right) \Gamma_0$$

$\epsilon_+ - \epsilon_-:$ mass splitting between $X$ and $N$, $\theta$: mass mixing angle, $\Gamma_0$: thermal interaction rate of $X$, $N$ within its own sector

At high $T$ (leptogenesis), could well be $\Gamma_{\text{transfer}} \ll H(t) \Rightarrow \text{non-equilibrium process}$, cannot directly apply $n^{eq}$ as in EW 2-higgs model
Computing $N \to X$ in non-equilibrium

Solve density matrix evolution equations for $\rho_{XX}(t \to +\infty)$:

$$i\dot{\rho} = [\mathcal{H}^{(1)}, \rho] - i\{\mathcal{H}^{(2)}, \rho\}$$

$\mathcal{H}^{(1)}$ (from $|M(T)|^2$)–oscillation, $\mathcal{H}^{(2)}$–thermal collisions

Ex. fermionic $(N, X)$ system:

$$\frac{d}{dt} \begin{pmatrix} \rho_{NN} \\ \rho_{XX} \\ \rho_{NX} \\ \rho_{XN} \end{pmatrix} = \frac{1}{6T} \begin{pmatrix} 0 & 0 & i\mu M_{13} & -i\mu M_{13} \\ 0 & 0 & -i\mu M_{13} & i\mu M_{13} \\ i\mu M_{13} & -i\mu M_{13} & -6\Gamma_0 T + i(\mu^2 - M_{13}^2 - \lambda_{32}^2 T^2) & 0 \\ -i\mu M_{13} & i\mu M_{13} & 0 & -6\Gamma_0 T - i(\mu^2 - M_{13}^2 - \lambda_{32}^2 T^2) \end{pmatrix} \begin{pmatrix} \rho_{NN} \\ \rho_{XX} \\ \rho_{NX} \\ \rho_{XN} \end{pmatrix}$$
Numerical Results

Constraints:

- $T_{lep} \lesssim T_{RH}$ to avoid dilution from inflaton decay
- Efficient depletion of the symmetric component of $X$: annihilation coupling should be $g \sim \mathcal{O}(1)$
- $y \ll 1$ for the heavy field in leptogenesis to decay out of equilibrium ($y : y_N, y_L$ in $y_N N H_u \bar{\psi} + y_L L \chi \bar{\psi}$).
- Avoid thermal suppression of $X, N$: $m_X, m_N(T = T_{lep}) < T_{lep}$
- Heavy Moduli– decay before BBN: $m_\phi \gtrsim 50 \text{TeV}$; Light moduli–stable until today, $\rho_\phi < \rho_B$: $m_\phi \lesssim \text{keV}$

Benchmark points:

- Heavy moduli:
  $T_{RH} \sim 10^8 - 10^{10} \text{GeV} : m_{DM} \sim \mathcal{O}(\text{GeV}) - 100 \text{TeV}$
- Light stable moduli:
  $T_{RH} \sim 10^9 - 10^{11} \text{GeV} : m_{DM} \sim \mathcal{O}(\text{GeV}) - 100 \text{TeV}$
Ex. III: Mixing induced by background energy

**More generic** mass mixing at early universe: coupling to fields dominating cosmic bkg energy

- E.g. Scalar X, N (SUSY); coupling to KE of relativistic thermal fermion $\psi$

$$\Delta \mathcal{L} \supset \frac{c}{M_\phi^2} \left( i \psi^\dagger \gamma^\mu D_\mu \psi \right) (XN + \text{h.c.}) .$$

with

$$\langle \psi^\dagger_\Sigma \gamma^\mu D_\mu \psi_\Sigma \rangle = \frac{\pi^2}{30} g_* T^4 ,$$

- Similar analysis as in moduli case (solve density matrix evolution),

**Benchmark points:** $T_{RH} \sim 10^{16} \text{GeV}, m_X \sim 1 - 100 \text{TeV}$. 

Mixing induced by cosmic background energy
Conclusions

- Asymmetric Dark Matter: well motivated by $\Omega_{DM} - \Omega_B$ coincidence;

  Most existing work: *rely on higher-dim operator* for transfer–UV completion? extra structure...

- **We consider a novel, economic alternative:** mass mixing as transfer operator –renormalizable or $M_{pl}$ suppressed;

  DM, baryon/lepton number may not be separately preserved in early universe...

- **Example models:** two higgs, moduli induced transfer, background energy induced transfer;

  Numerics work well with natural inputs: *accommodate heavier (weak scale) DM mass beyond $O(\text{GeV})$ range.*