Emergent Dark Matter, Baryon and Lepton Numbers

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Outline

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, Ω_{DM} from thermal freezeout

Horizon beyond WIMP...

WIMP:

- Merits: Good connection with new particle physics at weak scale; natural fit to desired Ω_{DM}–*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 Ω_{DM} requirement⇒Limited possibilities left: based on $\sigma_{DiDt} - \sigma_{ann}$ correlation by crossing Feynmann diagrams (⇒ higgs-like mediator, dark sector or leptophilic annihilation, on-resonance annihilation...) (general operator analysis Cui, Mason and Randall, 2010)

⇒ 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 Ω...

Paths of addressing $\Omega_{DM} - \Omega_B$ coincidence

Origin of Ω_B:

1. Baryogenesis generates asymmetry $(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$
2. Annihilation (e.g. $q\bar{q} \to \nu\bar{\nu}$) is on until late time, depletes symmetric component
   $\Rightarrow n_B(t \to \infty) = n_B - n_{\bar{B}}$, i.e. Ω_B is ‘asymmetric’

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

Direction-1: Ω_{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 $\Delta W_{eff} = \frac{1}{M} X^2 L H_u$

  –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 ($\Gamma \lesssim H$) – **thermal relation/suppression**, most work: $m_{DM} \sim O(\mathrm{GeV}) (m_X / T_D < 1)$, $m_{DM} \sim m_{EW}\ (m_X / T_D > 1)$–Randall and Buckley, 2010

- $\Rightarrow \Omega_{DM} - \Omega_B$ 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 ⇒ Dynamical mechanism: $\langle\phi\rangle XL$ where ϕ 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) $\propto T^4$; ϕ 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 σ, ϕ where σ is SM Higgs, ϕ 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 ϕXL, then $\phi \rightarrow 0$ 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)

$$\begin{aligned} \mathcal{L} &\supset m_X X_i \bar{X}_i + y_X \Phi X_i L_i + V(H,\Phi) + \mathrm{h.c.}, \\ V(T=0) &= 4k_1|H|^4 - 4\mu_1^2|H|^2 + 4k_2|\Phi|^4 - 4\mu_2^2|\Phi|^2 + 4k_3|\Phi|^2|H|^2, \end{aligned}$$

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 $T_d = \left(\frac{\sqrt{\lambda_2}\mu_1^2 - \sqrt{\lambda_1}\mu_2^2}{\sqrt{\lambda_2}\alpha_1 - \sqrt{\lambda_1}\alpha_2}\right)^{1/2}$ Second PT (1st order) tunneling occurs at later T_t when $\langle\phi\rangle \to 0$ via tunneling–mixing shuts off

Asymmetry transfer Period: $T_{c2} < T < T_t$
Computing the amount of $L \to X$ 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 ⇒ 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:

$$\begin{aligned} n_L^f &= n_L^{eq}(T_t)c_\theta^2(T_t) + n_X^{eq}(T_t)s_\theta^2(T_t) \\ n_X^f &= -n_L^{eq}(T_t)s_\theta^2(T_t) + n_X^{eq}(T_t)c_\theta^2(T_t) \end{aligned}$$

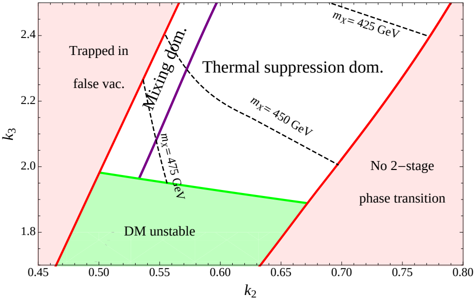
Asymmetry ratio:

$$\frac{\Delta_X}{\Delta n_L} = -\frac{(1+\cos^2\theta)\Delta n_{\bar{X}'}^{eq} + \sin^2\theta \Delta n_{L'}^{eq}}{\cos^2\theta \Delta n_{L'}^{eq} + \sin^2\theta \Delta n_{\bar{X}'}^{eq}}$$

Three cases and numerical results:

- Relativistic X: $T_t \gg m_X$, $\frac{\Delta_X}{\Delta n_L} \approx -\frac{2}{3}$, $m_X \sim O(\mathrm{GeV})$
- Thermally suppressed X: $\tan^2\theta \ll \frac{n_X^{eq}}{n_L^{eq}}$, $\frac{\Delta_X}{\Delta n_L} \approx -6\sqrt{\frac{2M^3}{\pi^3 T^3}}\, e^{-M/T}$, $m_X \sim 300 - 500\mathrm{GeV}$ (fix $m_h = 120\mathrm{GeV}$)
- *Novel*-Mixing-angle-suppressed X: $\frac{n_X^{eq}}{n_L^{eq}} \ll \tan^2\theta$, $\frac{\Delta_X}{\Delta n_L} = -\tan^2\theta$, $m_X \sim 400 - 500\mathrm{GeV}$

Ex: Viable regions (unshaded) with $y_X = 1.7$ and $\mu_2 = 54$ GeV



Phenomenology

- DM direct detection: loop-suppressed $X-$nucleon coupling induced by doublet ϕ:

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

  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 $\phi^\pm \rightarrow X(MET) + \ell^\pm$
  (Related independent, detailed studies of 'flavored DM': Chacko et.al, Batell et.al arXiv:1105.1781 [hep-ph]... and their talks yesterday)

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 ϕ fields are typically gauge singlets$\Rightarrow L$ in ϕLX 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 $X, \bar{X}$, ϕ 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: $c\frac{|\phi|^2 XN}{M_p}$

Dynamics of moduli ϕ

- 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 ϕ coupling to XN–solve e.o.m.:

$$\ddot{\phi} + 3H\dot{\phi} + 2(m^2 - a^2 H^2)\phi + \frac{2}{M_p^2}(m^2 + b^2 H^2)\phi^3 = 0$$

Moduli Driven Transfer–Gradual Mixing Shutoff

- **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 $\langle\phi\rangle = 0$, ($\phi_0 \sim 10^{10}\mathrm{GeV}$)

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

  $\Rightarrow$ Mass mixing is on yet gradually falling towards 0 after $H(t) \sim \mu_X$
- **A rough estimate of transfer rate $N \to X$:**

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

  $\epsilon_+ - \epsilon_-$: mass splitting between X and N, θ: mass mixing angle, Γ_0: thermal interaction rate of X, N within its own sector
- At high T (leptogenesis), could well be $\Gamma_{transfer} \ll H(t) \Rightarrow$ 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 $y_N N H_u \psi + y_L L \chi \bar{\psi}$).
- Avoid thermal suppression of X, N: $m_X, m_N(T = T_{lep}) < T_{lep}$
- Heavy Moduli– decay before BBN: $m_\phi \gtrsim 50\mathrm{TeV}$; Light moduli–stable until today, $\rho_\phi < \rho_B$: $m_\phi \lesssim \mathrm{keV}$

Benchmark points:

- Heavy moduli:
  $T_{RH} \sim 10^8 - 10^{10}\mathrm{GeV} : \mathrm{m_{DM}} \sim \mathrm{O(GeV)} - 100\mathrm{TeV}$
- Light stable moduli:
  $T_{RH} \sim 10^9 - 10^{11}\mathrm{GeV} : \mathrm{m_{DM}} \sim \mathrm{O(GeV)} - 100\mathrm{TeV}$

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 ψ

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

  with

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

- Similar analysis as in moduli case (solve density matrix evolution),
  Benchmark points: $T_{RH} \sim 10^{16}\mathrm{GeV}, \mathrm{m_X} \sim 1 - 100\mathrm{TeV}$

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 $O(\mathrm{GeV})$ range.