New Perspectives on Dark Matter-Baryon Coincidence

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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$\Rightarrow$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 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 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) ...
- New Perspectives to explore?
  Goal of our Work: More general possibilities on asymmetry transfer or co-generation?

Focus on two very intriguing directions

- ✓ **Mass mixing as asymmetry transfer operator**: existing ADM models employ higher dim operator–introduce a new scale
  More ‘economic’, renormalizable operator, with no extra scale? $\Rightarrow$ mass mixing XL–qualitatively different from higher dim transfer operator, a fun interplay between neutrino-like oscillation and thermal interaction, and new way to accommodate heavier m_X...
- **(See Brian Shuve’s talk for more detail)** A peculiar co-generation: WIMP-leptogenesis– with CP-, L-violation in WIMP σ_{ann}, WIMP freezeout can provide all Sakharov conditions and trigger baryogenesis!–both $\Omega_{DM} - \Omega_B$ freeze out around T_D and correlated, in analogy to out-of-equilibrium decay of heavy N in leptogenesis

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 ϕ is a scalar field with $\langle\phi\rangle \neq 0 \to \langle\phi\rangle = 0$ transition

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

The opposite $\langle\phi\rangle \neq 0 \to \langle\phi\rangle = 0$ 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 density (e.g. KE) as $\phi \propto T^4$; 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 $\langle\phi\rangle = 0$

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 $\phi \to 0$ 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)

$$
\begin{aligned}
V(\sigma, \phi, T) &= \frac{1}{2}(\alpha_1 T^2 - \mu_1^2)\sigma^2 + \frac{1}{2}(\alpha_2 T^2 - \mu_2^2)\phi^2 + \frac{1}{2}g^2\sigma^2\phi^2 + \frac{\lambda_1}{4}\sigma^4 + \frac{\lambda_2}{4}\phi^4 \\
V(X) &= y\phi\bar{L}X_R + m_X\bar{X}_L X_R + h.c.
\end{aligned}
$$

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 $\langle\phi\rangle = 0, \langle\sigma\rangle \neq 0$,

   Second PT (1st order) occurs when $V_1 = V_2$ at $T_t = \left(\frac{\sqrt{\lambda_2}\mu_1^2 - \sqrt{\lambda_1}\mu_2^2}{\sqrt{\lambda_2}\alpha_1 - \sqrt{\lambda_1}\alpha_2}\right)^{1/2}$

   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 $\Rightarrow$ no-mixing (flavor) basis $(X' = c_\theta X + s_\theta L, L' = -s_\theta X + c_\theta L)$

Asymmetry Transfer in 2-Higgs Model

- **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:

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

Asymmetry ratio: $\frac{n_L^f}{n_X^f} \sim \max\{\tan^2\theta(T_t), n_X^{eq}/n_L^{eq}(T_t)\}$

- **Two limits:** $\tan^2\theta \ll \frac{n_X^{eq}}{n_L^{eq}}$ – thermal suppression, $\frac{n_X^{eq}}{n_L^{eq}} \ll \tan^2\theta$ (generic for weak scale X with $m_X > T_t$) – *novel*: mixing suppression
- **Numeric results:** A large range of parameter space can work– e.g. with $m_H = 130\mathrm{GeV}$, $m_X \subset (30, 450)\mathrm{GeV}$

Models with a Flat Potential Moduli: Gradual Mixing Shutoff

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: cosmic background density, SUSY flat direction, string moduli, SUSY Polonyi field... These ϕ fields are typically gauge singlets$\Rightarrow$$L$ in ϕLX needs to be sterile (EW doublet X is ruled out)

Model:

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) (Majorana leptogenesis can work, yet less economic...)
2. DM a vector-like Dirac pair X, X', ϕ is a moduli taking $\langle\phi\rangle \sim M_p$ at the end of inflation (e.g. string moduli, SUSY Polonyi field)
3. DM-L mixing, asymmetry transfer via $c\frac{|\phi|^2 XN}{M_p}$

Dynamics of FD moduli ϕ

- 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.:

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

- **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 $N \to X$:**

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

  $\epsilon_+ - \epsilon_-$: 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 $L \to X$ in non-equilibrium

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

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

$\mathcal{H}^{(1)}$–oscillation, $\mathcal{H}^{(2)}$–thermal collisions
For (N, X) system:

$$\frac{d}{dt}\begin{pmatrix}\rho_{NN}\\ \rho_{XX}\\ \rho_{NX}\\ \rho_{XN}\end{pmatrix} = \frac{1}{2T}\begin{pmatrix} 0 & 0 & -i\mu_X\Delta M & i\mu_X\Delta M \\ 0 & 0 & i\mu_X\Delta M & -i\mu_X\Delta M \\ -i\mu_X\Delta M & i\mu_X\Delta M & -2\Gamma_0 T - i\left(\mu_X^2 - g_2^2T^2\right) & 0 \\ i\mu_X\Delta M & -i\mu_X\Delta M & 0 & -2\Gamma_0 T + i\left(\mu_X^2 - g_2^2T^2\right) \end{pmatrix}\begin{pmatrix}\rho_{N}\\ \rho_{X}\\ \rho_{N}\\ \rho_{X}\end{pmatrix}$$

$\Rightarrow$ Large range of m_{DM} (e.g. $O(\mathrm{GeV}) - \mathrm{O}(\mathrm{TeV})$) could be accommodated, depends on T_{lep}, m_ϕ.

Conclusions

With interest of expanding the horizon of DM theories motivated by $\Omega_{DM} - \Omega_B$ coincidence:

- We consider mass mixing as a novel way to transfer Dark-Baryon asymmetries, as well as accommodate heavier DM beyond $O(\mathrm{GeV})$. We find generic, working models with both rapid and gradual shutoff of the mixing
- *(Details in Brian Shuve's talk–)* We explore a novel mechanism to connect $\Omega_{DM} - \Omega_B$ at creation level (WIMP-leptogenesis): WIMP freezeout as a trigger for leptogenesis at weak scale. Numerics work well with natural inputs.

$\Omega_{DM} - \Omega_B$ coincidence is an intriguing clue for DM theories, worth further exploring...