Particle - Antiparticle Asymmetries from Scattering

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Outline

- Generation of particle – antiparticle asymmetries
  → Asymmetries via scattering and annihilation
- Model #1
  Neutron Portal – Baryogenesis - EFT
- Model #2
  Neutrino Portal – Asymmetric Dark Matter – UV complete
- Summary

Introduction

Particle–antiparticle asymmetries can be generated dynamically in scenarios where the 3 Sakharov conditions are satisfied:

- Violation of Baryon number
- Violation of C and CP
- Departure from thermal equilibrium

Many mechanisms exist:

- Out-of-equilibrium decay of heavy particle
- Electroweak Baryogenesis
- Afflect-Dine Baryogenesis
- …

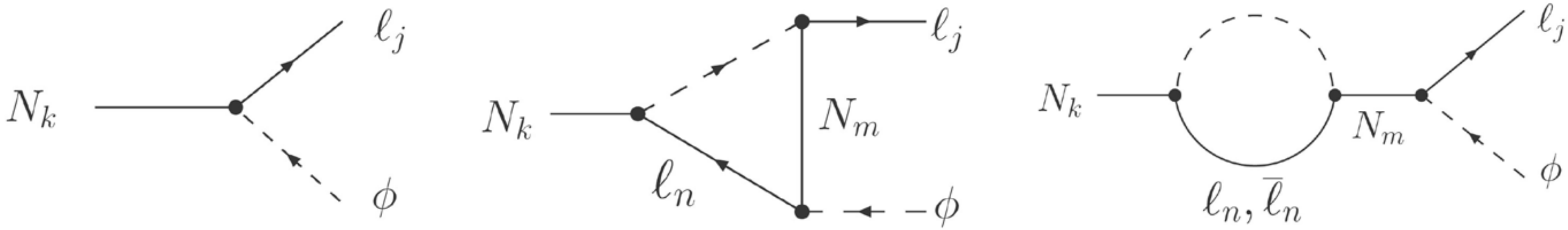
What about CP violating 2→2 processes?

- Asymmetry generation via out-of-equilibrium decay has been well-studied in the context of GUT baryogenesis, Leptogenesis, etc

- Can 2→2 scattering or annihilation processes generate asymmetries?
  → In general they can contribution to source terms for asymmetry generation, and also to wash out terms.

  → Can 2→2 process dominate the asymmetry generation?

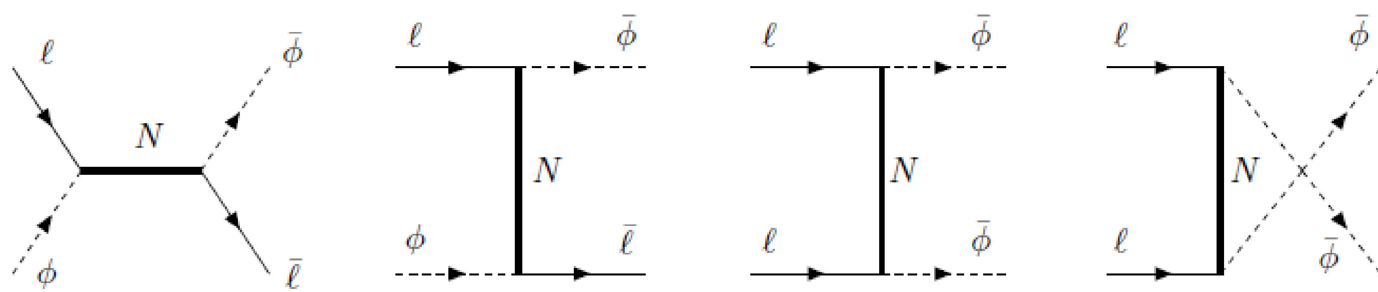
Leptogenesis



Interference of tree-level with absorptive part of loop diagrams → CP asymmetry

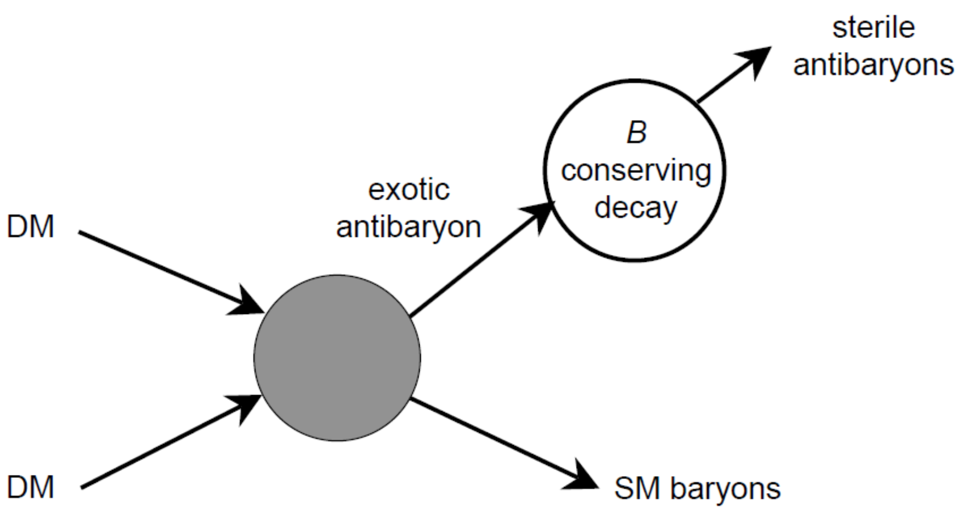
$$\varepsilon = \frac{\Gamma(N \to \ell \phi^*) - \Gamma(N \to \bar{\ell}\phi)}{\Gamma(N \to \ell \phi^*) + \Gamma(N \to \bar{\ell}\phi)}$$

There are also B & CP violating scattering diagrams, but decay processes dominate the asymmetry generation.

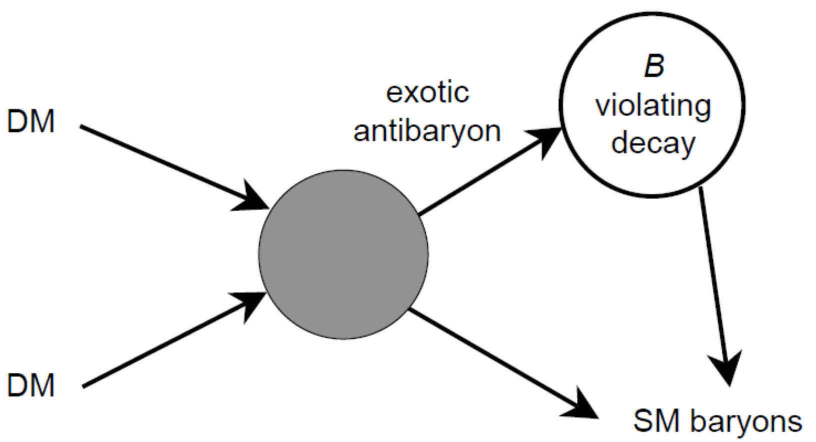


WIMPy baryogensis

Require WIMP annihilation satisfy the Sakharov conditions
→ a baryon asymmetry can be generated from DM annihilations



DM annihilation creates asymmetry in exotic antibaryons, then sequestered in sterile sector



Asymmetry in exotic antibaryons, which decay to SM baryons

Cui, Randall and Shuve, 1112.2704

Questions

- Can CP violating 2→ 2 processes contribute to asymmetry generation?
  (Yes. But such scenarios are relatively unexplored.)

- Can 2→2 processes dominate over decays? Under what circumstances?

- Can we use 2→2 processes to generate both matter-antimatter asymmetries in both the ordinary and dark matter (asymmetric dark matter)? What features would such a model have?

Unitarity + CPT

Initial and final states related as $|f\rangle = S|i\rangle$
where the S matrix $S = 1 + iT$ satisfies $S^\dagger S = SS^\dagger = 1$
and matrix elements $\mathcal{M}$ related to the transition matrix T as

$$iT_{\beta\alpha} = (2\pi)^4 \delta^4 \left(\sum_i p_{\alpha_i} - \sum_i p_{\beta_i} \right) i\mathcal{M}(\alpha \to \beta)$$

This implies:

$$\sum_\beta |\mathcal{M}(\alpha \to \beta)|^2 = \sum_\beta |\mathcal{M}(\beta \to \alpha)|^2 = \sum_\beta \left|\mathcal{M}(\bar{\alpha} \to \bar{\beta})\right|^2 = \sum_\beta \left|\mathcal{M}(\bar{\beta} \to \bar{\alpha})\right|^2$$

CPT

where $\bar{\alpha}$ is the CP conjugate of α, and the sum runs over all possible β

Boltzmann Equations

$$\frac{dn_X}{dt} + 3Hn_X = C(X)$$

where the collision term has the form:

$$W(\beta \to \alpha) - W(\alpha \to \beta) = \int d\Pi_{\alpha 1} \dots d\Pi_{\alpha n}\, d\Pi_{\beta 1} \dots d\Pi_{\beta m}$$

$$\times\, \delta^4\!\left(\sum p_i - \sum p_j\right)(2\pi)^4 \{f_{\beta 1} \dots f_{\beta m} |\mathcal{M}(\beta \to \alpha)|^2 - f_{\alpha 1} \dots f_{\alpha n} |\mathcal{M}(\alpha \to \beta)|^2\}$$

with $f_\psi = e^{(\mu_\psi - E_\psi)/T}$.

When thermal and chemical equilibrium hold, the rates satisfy:

$$\sum_\beta W(\alpha \to \beta) = \sum_\beta W(\beta \to \alpha) = \sum_\beta W(\bar{\alpha} \to \bar{\beta}) = \sum_\beta W(\bar{\beta} \to \bar{\alpha})$$

For the non-equilibrium rates (assuming Maxwell-Boltzmann stats) we can factor out the chemical potential and thus take:

$$W^{\mathrm{neq}}(\alpha \to \beta) = \frac{n_{\alpha 1} \ldots n_{\alpha n}}{n_{\alpha 1}^{\mathrm{eq}} \ldots n_{\alpha n}^{\mathrm{eq}}} W(\alpha \to \beta)$$

The Unitarity conditions

→ ensure no particle-antiparticle asymmetry can be generated without departure from equilibrium.

→ Require at least two different scattering channels

- A single scattering channel is not enough to generate an asymmetry (even if we violate B, C, and CP).

Consider the rate: $W(\alpha \to \beta_1) = (1+\epsilon_1)W_1$

and the C conjugate: $W(\bar{\alpha} \to \overline{\beta_1}) = (1-\epsilon_1)W_1$

If this were the only channel, CPT + Unitarity ⇒ $\epsilon_1 W_1 = 0$ and so we can not generate an asymmetry.

- If we have two channels: $W(\alpha \to \beta_1) = (1+\epsilon_1)W_1$

$W(\alpha \to \beta_2) = (1+\epsilon_2)W_2$

CPT+Unitarity ⇒ $\epsilon_1 W_1 + \epsilon_2 W_2 = 0.$

[But if, e.g., β_1 and β_2 have the same baryon number, the asymmetry source terms will be proportional to $n_\alpha(\epsilon_1 W_1 + \epsilon_2 W_2) = 0$]

So we need at least two (non-trivially) different scattering channels.

Construct a model

We want a model with these features:

- $2 \to 2$ scattering
- violates B and CP
- involves a heavy particle that goes out of equilibrium

Start by considering baryogenesis (ordinary matter) only.

(Generalizations to asymmetric dark matter scenarios will be possible.)

Neutron Portal - $\bar{X} u_R \overline{d_R^c} d_R$

$$\mathcal{L} = \kappa_1 \overline{X_{1L}} u_R \overline{(s_R)^c} b_R + \kappa_2 \overline{X_{2L}} u_R \overline{(s_R)^c} b_R + \kappa_3 \overline{u_R} X_{1L} \overline{X_{2L}} u_R + \kappa_4 \overline{u_R} X_{1L} \overline{X_{1L}} u_R + \kappa_5 \overline{u_R} X_{2L} \overline{X_{2L}} u_R + H.c.$$

X_α are Majorana fermions. κ has dimension $(\mathrm{mass})^{-2}$

For simplicity:

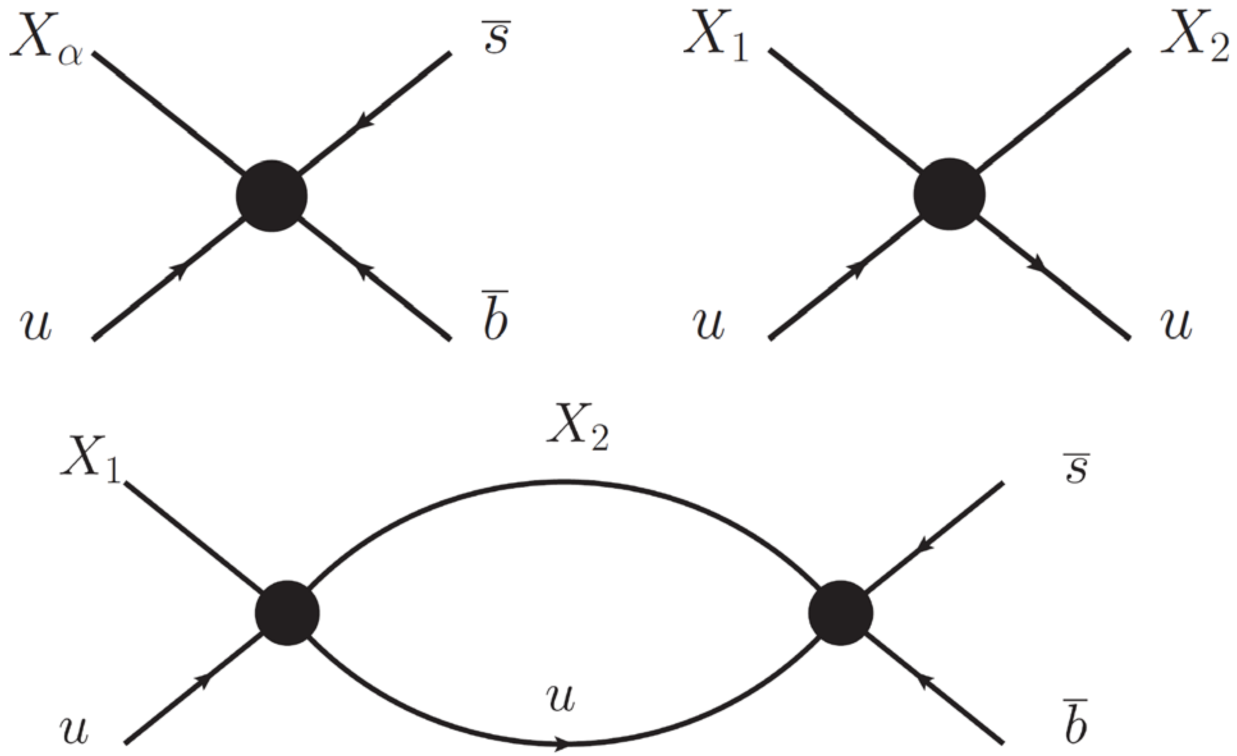
- consider coupling to only u, s, b
- After rephrasing, we are left with two complex phases.

A baryon asymmetry could be produced through:

- CP violating scattering of the form $u_i X_{\alpha L} \to \overline{d_i d_j}$
- CP violating decays of X_2

Scatterings

CP violating from interference of tree and one-loop scattering diagrams



Unitarity - Scatterings

Parametrise CP violating collision terms as

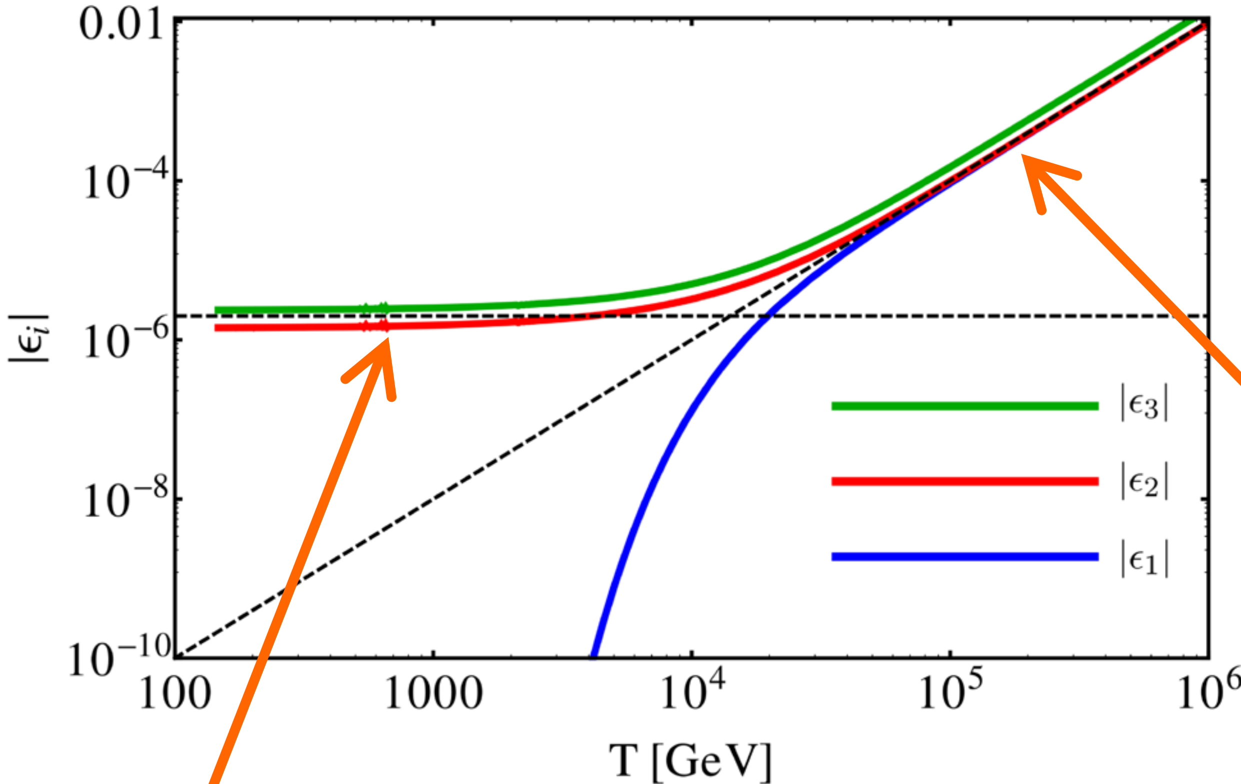
$$W(u + X_1 \to \bar{s} + \bar{b}) \equiv (1 + \epsilon_1) W_1$$
$$W(u + X_2 \to \bar{s} + \bar{b}) \equiv (1 + \epsilon_2) W_2$$
$$W(u + X_1 \to u + X_2) \equiv (1 + \epsilon_3) W_3$$

with CP conjugate rates obtained by $\epsilon \to -\epsilon$

Unitarity conditions enforce:

$$\epsilon_1 W_1 + \epsilon_3 W_3 = 0$$
$$\epsilon_2 W_2 - \epsilon_3 W_3 = 0$$
$$\epsilon_1 W_1 + \epsilon_2 W_2 = 0$$

CP violation in scatterings



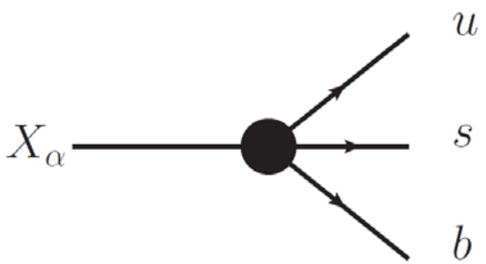
M_{X2}= 100 TeV,
M_{X1} = 50 TeV,
κ_a= 10^{-14} GeV^{-2}

$T \gg M_{X2}, \epsilon \sim \kappa T^2$

$T \ll M_{X2}, \epsilon \sim \frac{\kappa}{16\pi} M_{X2}^2$

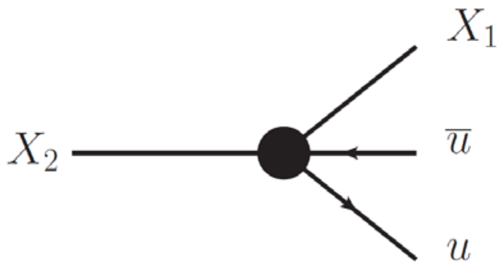
Decays

$X_\alpha \to usb$



$$\Gamma_{\alpha A} = \frac{|\kappa_\alpha|^2 (M_{X\alpha})^5}{512\pi^3}$$

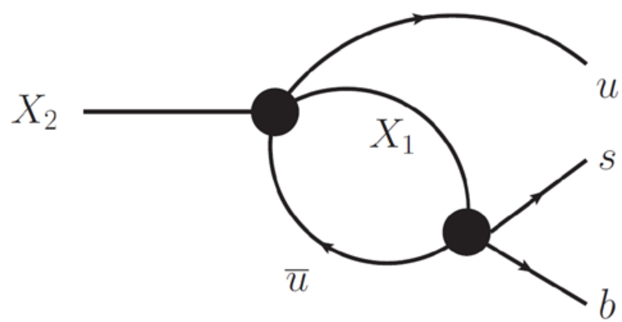
$X_2 \to X_1 u\bar{u}$



$$\Gamma_{2B} = \frac{|\kappa_3|^2 (M_{X2})^5}{1024\pi^3}$$

CP violation arises from interference of tree and 1-loop diagrams:

$$\Gamma(X_2 \to usb) = \frac{1}{2}(1+\epsilon_D)\Gamma_{2A},$$
$$\Gamma(X_2 \to \overline{usb}) = \frac{1}{2}(1-\epsilon_D)\Gamma_{2A}.$$



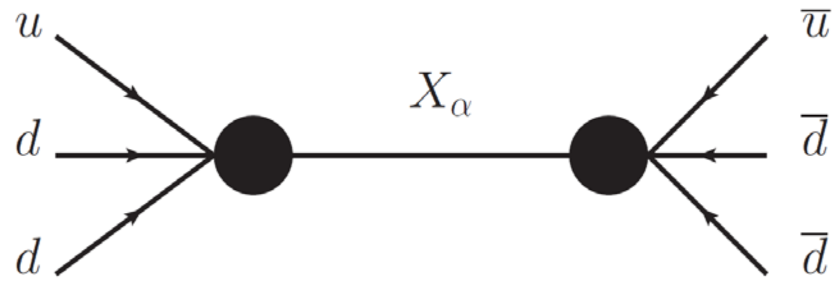
with $\epsilon_D \sim \frac{1}{16\pi} \frac{\mathrm{Im}[\kappa_1^* \kappa_2 \kappa_3^*]}{|\kappa_2|^2} M_{X2}^2 \sim \frac{\kappa}{16\pi} M_{X2}^2$

Unitarity-Decays

Consider $usb \rightarrow \overline{usb}$ mediated by an X_2 (with the on-shell part subtracted to avoid double counting)

CP violating scattering rate is:

$W(usb \rightarrow \overline{usb}) = (1 + \epsilon_{OS})W_{OS}$



Unitarity condition relates CP violation in decays and scattering:

$$\epsilon_{OS}W_{OS} = \frac{1}{2}\epsilon_D n_2^{\text{eq}}\Gamma_{2A}$$

which are balanced when in thermal equilibrium.

The CP symmetric part of $W(usb \rightarrow \overline{usb})$ → washout → negligible for our parameters.

Boltzmann Equations

- Take both scattering and decay process into account
- Assume X_1 and X_2 in kinetic equilibrium with bath

- Define $r_i \equiv \frac{n_i}{n_i^{\mathrm{eq}}} = \mathrm{Exp}\left(\frac{\mu_i}{T}\right)$ such that
$W^{\mathrm{neq}}(ij \rightarrow kl) = r_i r_j W(ij \rightarrow kl)$

- Express $Y = \frac{n}{s}$, where s is the entropy
- Solve the coupled Boltzmann eqns for $Y_{X_1}, Y_{X_2}, Y_{B-L}$

- EW sphalerons redistribute the baryon asymmetry among quarks and leptons

Asymmetry source term:

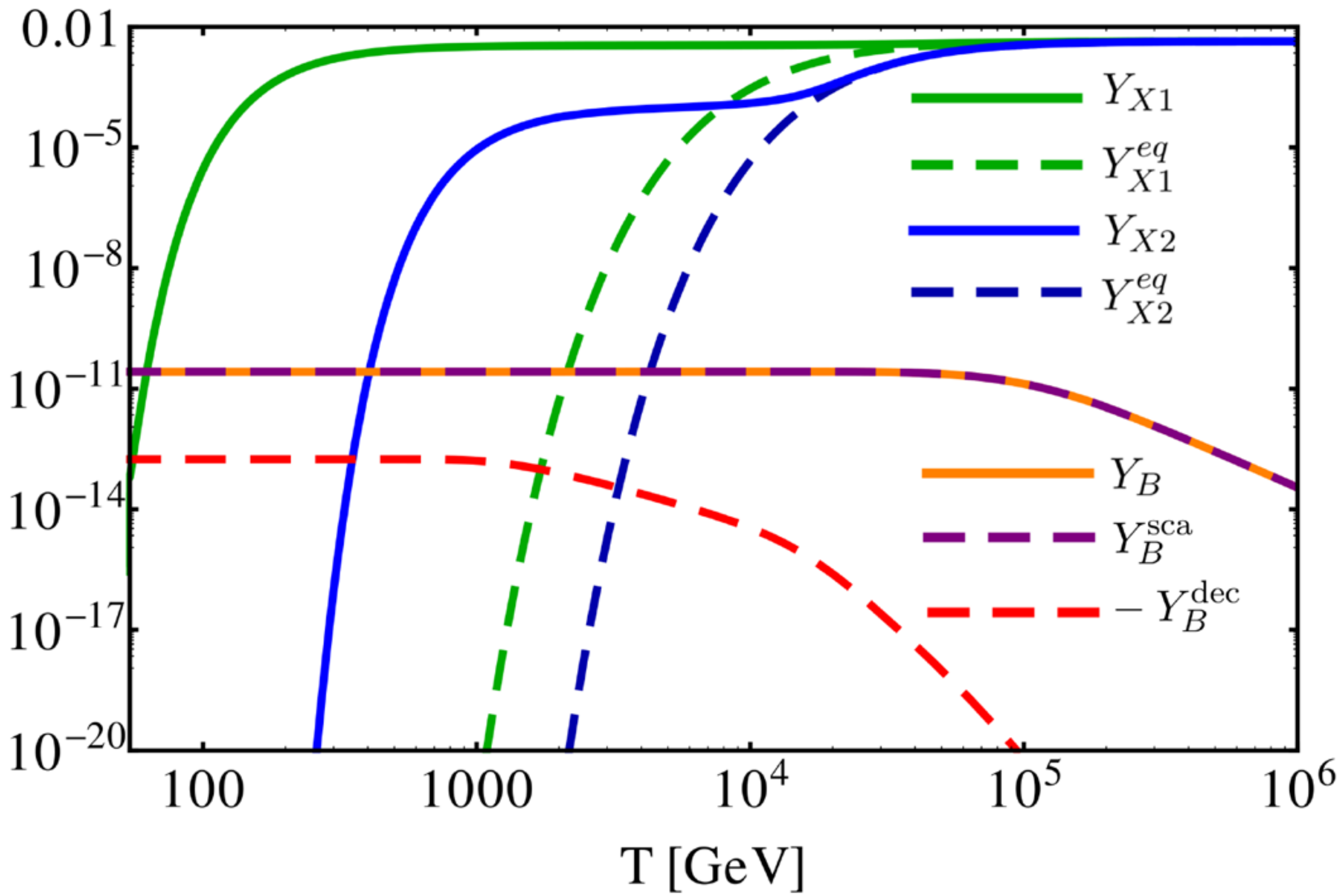
$$\frac{dn_{B-L}}{dT} + 3Hn_{B-L} = (\text{source terms}) + (\text{washout terms})$$

$$\begin{aligned}\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \epsilon_3 W_3 \Big[(r_{X1}\overline{r_u} + r_{X1} r_u) - (r_{X2}\overline{r_u} + r_{X2} r_u) \Big] \\ + \epsilon_D \Gamma_{X2a} n_{X2}^{eq} \Big[r_{X2} - (\overline{r_u r_d r_d} + r_u r_d r_d)/2 \Big] \\ + (\text{Washout terms})\end{aligned}$$

where: $r_\Psi \equiv \frac{n_\Psi}{n_\Psi^{eq}}$

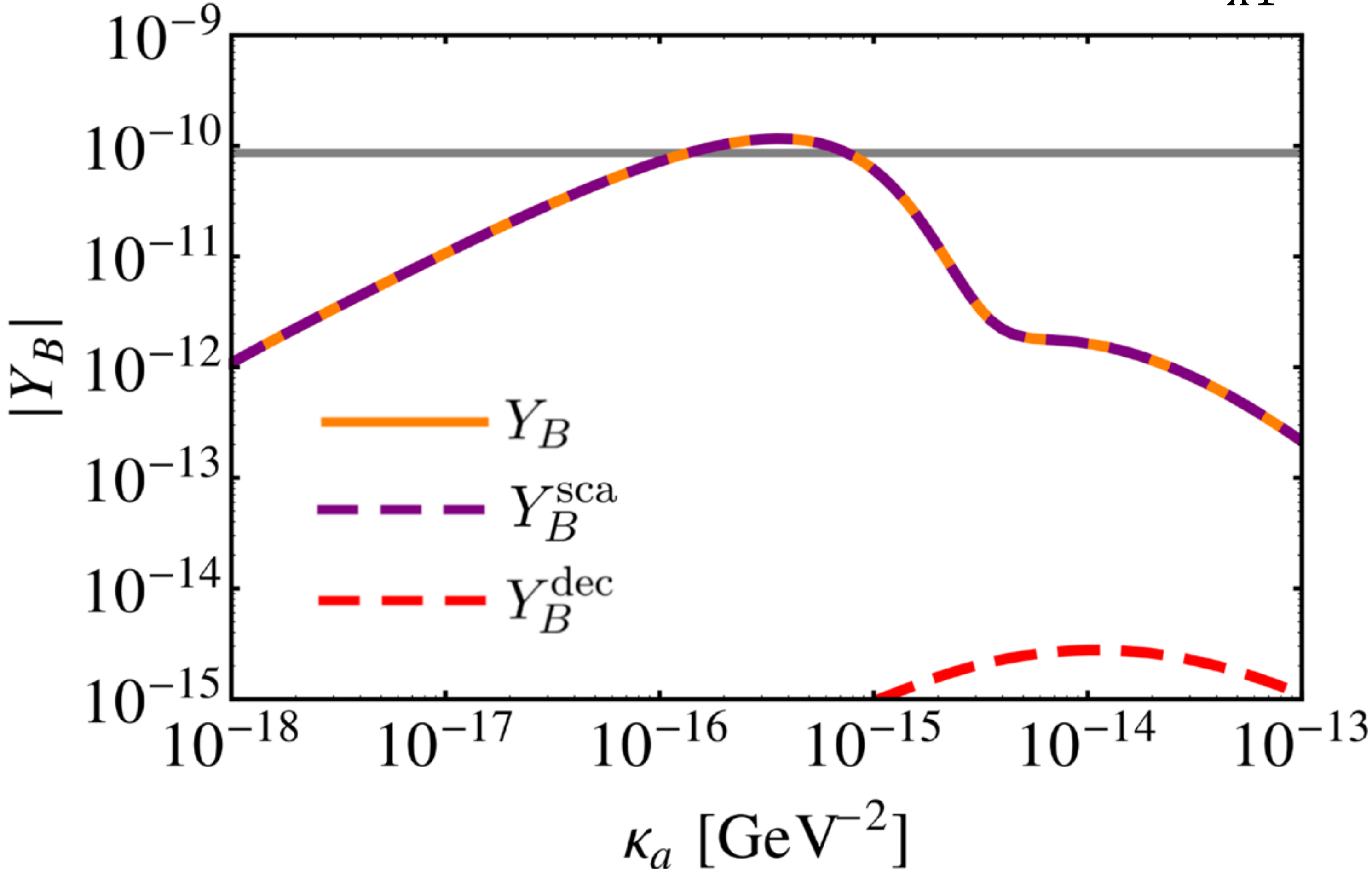
Example Solution

$M_{X2} = 100$ TeV, $M_{X1} = 50$ TeV, $\kappa_a = 10^{-16}$ GeV^{-2}



Final Asymmetry

$M_{X2}= 100$ TeV
$M_{X1} = 90$ TeV



Thermal evolution

- Expansion of universe $\Longrightarrow X_\alpha$ never exactly in equilibrium.
- As temperature drops, deviation from equilibrium increases & the asymmetry grows.
- Asymmetry plateaus when $T \sim M_X$

Importantly: asymmetry production via scattering dominates over decay for much of the parameter space.

- Occurs because the CP violation in scattering – which scales as κT^2 – can be relatively high at freezeout.
- CP violation in decays is small at freezeout (for couplings small enough to have significant departure from equilibrium)

Neutron Portal	Leptogenesis
Scattering and decay both present	Scattering and decay both present
Strong temperature dependence of CP violating difference of scattering rates $\epsilon \sim \kappa T^2$	No strong temperature dependence of CP violating difference of scattering rates.
Scattering dominates	Decay dominates

Can we write down a viable UV complete version that retains the $\epsilon \sim T^2$ feature?

Can we have an asymmetric dark matter version?

The neutron portal operator $\bar{X} u_R \overline{d_R^c} d_R$ is problematic because X tends to decay, so can't be dark matter.

Possible solutions:

- Assume couplings have strong temp dependence (e.g. Farrar and Zaharijas) or

- Introduce another particle and a stabilising symmetry:

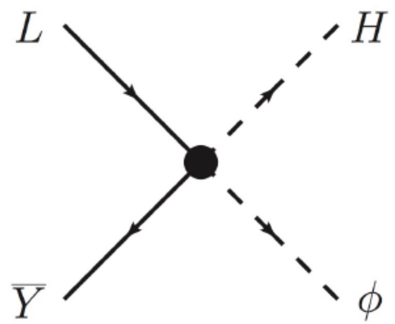
$$\bar{X} u_R \overline{d_R^c} d_R \sigma$$

……but UV completions tend to have large 2→2 scattering rates that maintain equilibrium. (Asymmetry generation would now be 2→3 processes.)

Asymmetric Dark Matter

- Aim to generate asymmetries in both ordinary and dark mater (asymmetric dark matter) in a UV complete model

- We consider the Neutrino Portal



$$g\bar{L}YH\phi$$

where
  - L and H are the usual lepton and Higgs doublets
  - Y is a new Majorana fermion
  - ϕ is complex scalar dark matter, carrying dark baryon number, $D = N_\phi$

The interaction preserves $B - L - D$ but breaks $B - L + D$

UV complete version

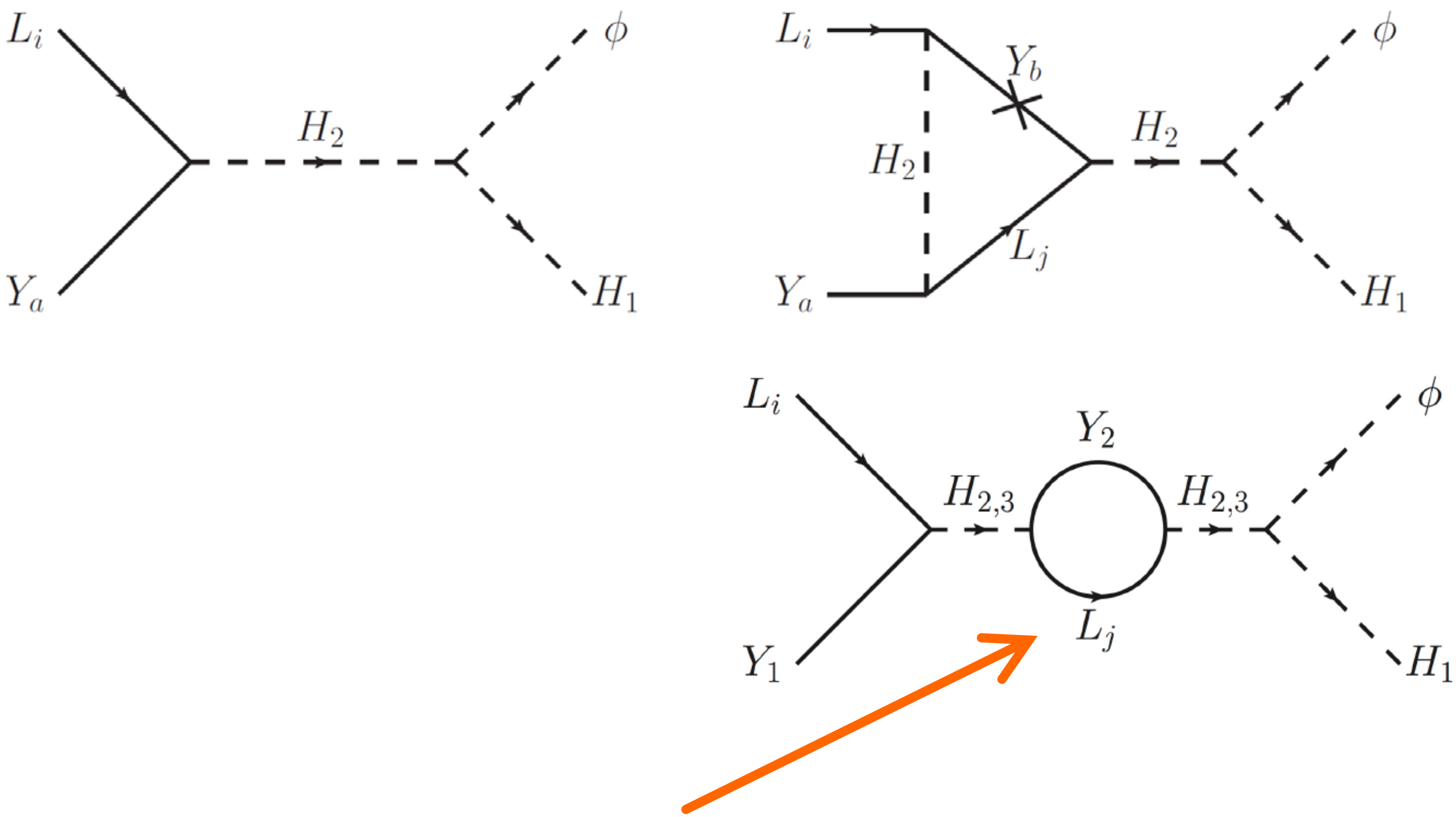
Consider an Inert Higgs Doublet completion of the Neutrino Portal operator.

$$\Delta\mathcal{L} = -m_{H_p}^2 |H_P|^2 - \lambda_{iap} H_p \overline{L_i} Y_a - \kappa_p H_1 H_p^\dagger \phi + H.c.$$

- H_p $(p = 2, 3)$ are two heavy $SU(2)$ doublets that do not acquire a VEV.
- κ are complex parameters, the source of CP violation

The Neutrino Portal operator $g\bar{L}YH\phi$ is obtained if $H_{2,3}$ are integrated out.

CP violating scatterings



The closed fermion loop graphs dominate the CP violation and provide the critical temperature dependence: $\epsilon \sim \kappa T^2$

CP violating scattering

$$W(Y_a L \to H_1 \phi) \overset{\text{CPT}}{=} W(\phi^* H_1^* \to \overline{L} Y_a) = (1+\epsilon_a) W_a,$$
$$W(\overline{L} Y_a \to \phi^* H_1^*) \overset{\text{CPT}}{=} W(H_1 \phi \to Y_a L) = (1-\epsilon_a) W_a,$$

CP conserving scattering

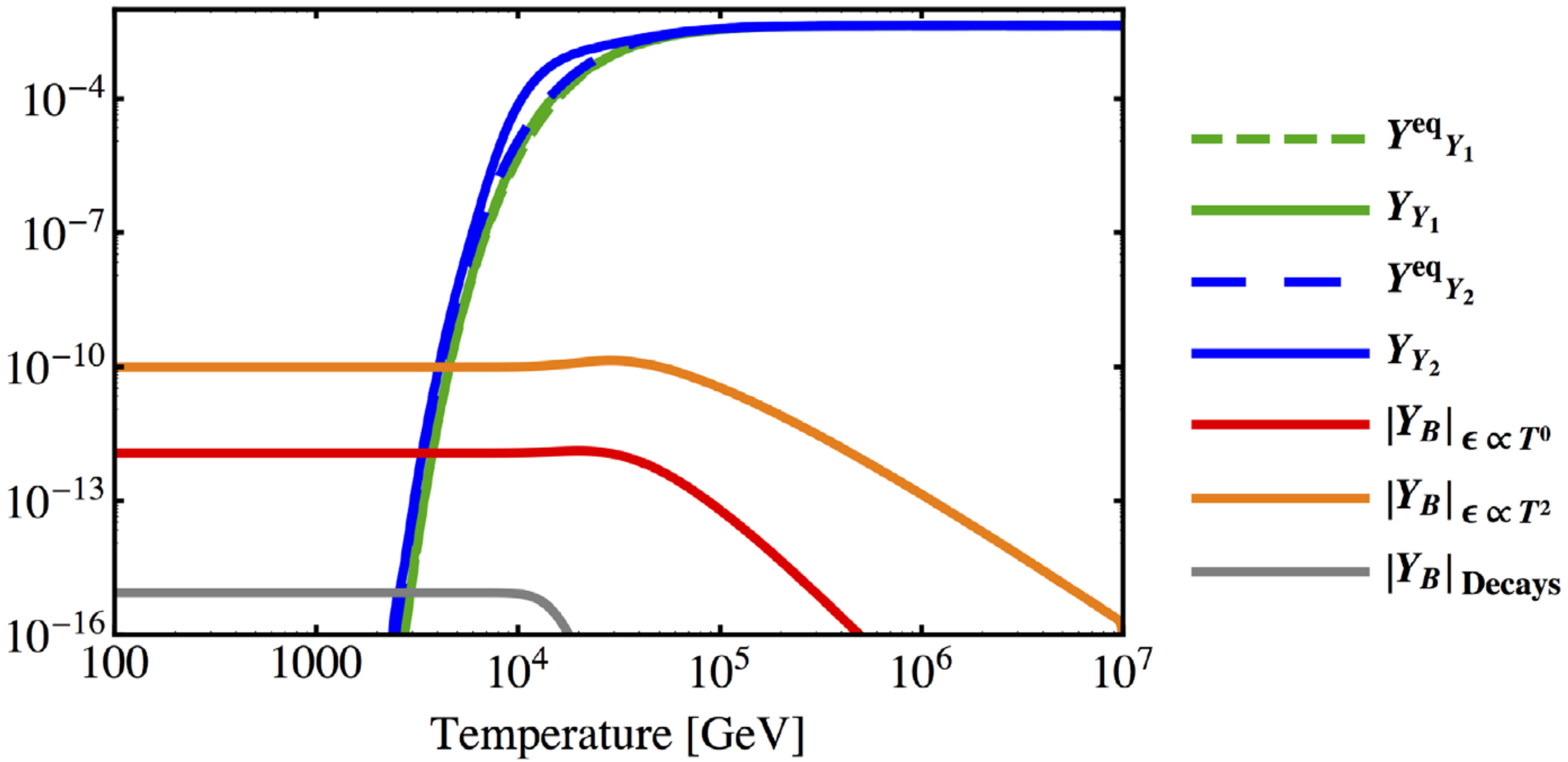
$$W(Y_a H_1 \to L \phi^*) = T_a,$$
$$W(Y_a \phi \to H_1^* L_i) = U_a,$$
$$W(Y_a L \to Y_b L) = S_{ab},$$
$$W(\overline{L} L \to Y_a Y_b) = P_{ab}.$$

Decays

$$\Gamma(H_1 \to Y_a L \phi^*) = \Gamma_{H_1 \to Y_a}$$
$$\Gamma(Y_2 \to Y_1 \overline{L} L) = \Gamma_{2A}$$
$$\Gamma(Y_2 \to \overline{L} H_1 \phi) = \frac{1}{2}(1+\epsilon_D)\Gamma_{2B}$$
$$\Gamma(Y_2 \to L H_1^* \phi^*) = \frac{1}{2}(1-\epsilon_D)\Gamma_{2B}$$
$$\Gamma(Y_1 \to \overline{L} H_1 \phi) = \Gamma(Y_1 \to L H_1^* \phi^*) = \frac{1}{2}\Gamma_1$$

Example solution

$M_{Y2}= 100$ TeV, $M_{Y1} = 90$ TeV, $\kappa \sim m_Y, m_{H_{2,3}} \sim 10^2 \, m_Y$



ADM scenario

Successfully generated Dark Matter and Baryon asymmetry of the required size.

It would be appealing if we could use the scattering to create the asymmetry AND annihilate the symmetric DM component.

Unfortunately this is more difficult because would require a freezeout temp of $T \sim m_{DM}/25$.
→ Need larger couplings to delay freezeout until this time
→ decay/inverse-decays strong enough to maintain equilib.
→ Sakharov conditions not met.

So, like all ADM models, an additional interaction is needed to annihilate the symmetric component.

Summary

- Asymmetry generation via scattering interactions is a relatively unexplored possibility

- There are viable models in which 2→ 2 interactions dominate over decays
  - Interactions which violate CP, with $\epsilon \sim T^2$ dependence are important.

- Baryogenesis and ADM models can be constructed.