Baryon Asymmetry from a Majorana Fermion Pair Coupled to Quarks

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Talk Outline

- Baryogenesis general aspects
- Majorana fermion $\mathcal{X}$ carrying baryon number B
  - coupled to UDD
- Baryon asymmetry in decay and scattering
  - UV completion details
- neutron-antineutron $(n - \bar{n})$ oscillation

Baryogenesis basics

- Today we only have matter in the (observable) Universe
  $\eta_B \equiv \frac{(n_B - n_{\bar{B}})}{n_\gamma} = 6 \times 10^{-10} \frac{\Omega_b h^2}{0.0222}$
  - What happened to all the anti-matter?
  - Particle physics explanation is most compelling
- Sakharov conditions for Baryogenesis
  - B violation
  - C and CP violation
  - Departure from Thermal Equilibrium
- When did baryogenesis happen?
  - EW, Leptogenesis, GUT, ...

Our study: baryogenesis in $\mathcal{X} \to UDD$

$$\mathcal{L} \supset -M_\chi \bar{\chi}\chi + \frac{1}{\Lambda^2}\,[\overline{D^c}\gamma_\mu D]\,[\overline{\chi}(g_L P_L + g_R P_R)\gamma^\mu U]$$
$$\mathcal{L}_{B\ viol} \supset -\bar{\chi^c}(\tilde{M}_L P_L + \tilde{M}_R P_R)\chi$$

VV interaction: Dirac fermion χ with $Q = (U, D)$

$B(Q) = 1/3,\ B(\chi) = +1$

Dirac mass: M_χ

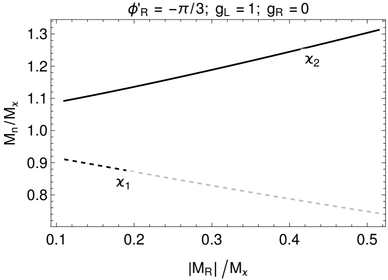
$\to UDD$

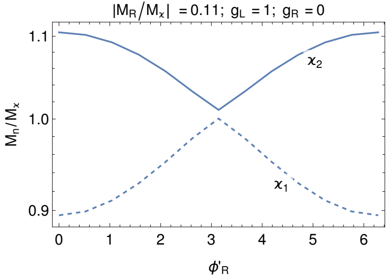
- Sakharov conditions
  - B violation: **Majorana mass** $\tilde{M}_{L,R}$
  - C and CP violation: complex $g_{L,R}, \tilde{M}_{L,R}$:
  - Departure from Thermal Equilibrium: Hubble expansion
- When did Baryogenesis happen?
  - At scale M_χ

Majorana mass $\Longrightarrow$ Dirac χ to Majorana pair $\mathcal{X}_n$

Majorana mass $\tilde{M}$ splits Dirac χ into a **pair** of Majorana fermions $\mathcal{X}_n = (\mathcal{X}_1, \mathcal{X}_2)$ with **indefinite baryon number**, mass eigenvalues M_n

$$\chi = (\mathcal{U}_{1n} P_L + \mathcal{U}^*_{2n} P_R)\mathcal{X}_n$$





$$\mathcal{L}^{\rm VV}_{\rm int} = \frac{\epsilon^{abc}}{2\Lambda^2}\left\{\left[\overline{D^c_b}\,\gamma^\mu D_a\right]\ \left[\bar{\mathcal{X}}_n\, G^n_{V\mu} U_c\right]\right\} \qquad G^n_{V\mu} \equiv \gamma_\mu\left(g_L\,\mathcal{U}^*_{1n} P_L + g_R\,\mathcal{U}_{2n} P_R\right)$$

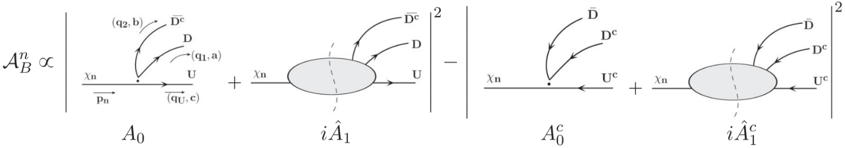
Baryon asymmetry in Decay $\mathcal{X}_n \to UDD$

Amplitude (tree+loop): Process $\mathcal{A} = \mathcal{A}_0 + \mathcal{A}_1$; Conjugate process $\mathcal{A}^c = \mathcal{A}_0^c + \mathcal{A}_1^c$

Decay rate: $\Gamma = \frac{1}{2M_n} \int d\Pi_3 \, |\mathcal{A}|^2$; $\Gamma^c = \frac{1}{2M_n} \int d\Pi_3 \, |\mathcal{A}^c|^2$

$$\mathcal{A}_B \equiv \frac{\Gamma - \Gamma^c}{\Gamma + \Gamma^c}$$

CP violation needs nonzero **weak phase** (ϕ) and **strong phase** ($\delta = \pi/2$)

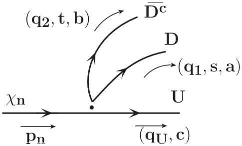


Interference term $\hat{\mathcal{A}}_{01} \equiv \hat{\mathcal{A}}_1 \mathcal{A}_0^*$, $\hat{\mathcal{A}}_{01}^c \equiv \hat{\mathcal{A}}_1^c \mathcal{A}_0^{c*}$

$$\Delta\hat{\Gamma}_{01} = \frac{1}{2M_n} \int d\Pi_3 \, \mathrm{Im}(\hat{\mathcal{A}}_{01} - \hat{\mathcal{A}}_{01}^c) \; ; \quad \mathcal{A}_B \approx -\frac{\Delta\hat{\Gamma}_{01}}{\Gamma_0^n}$$

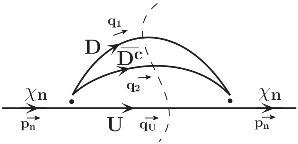
$\mathcal{X}_n$ Decay at tree-level

At tree level: $\mathcal{A}_0 \propto$



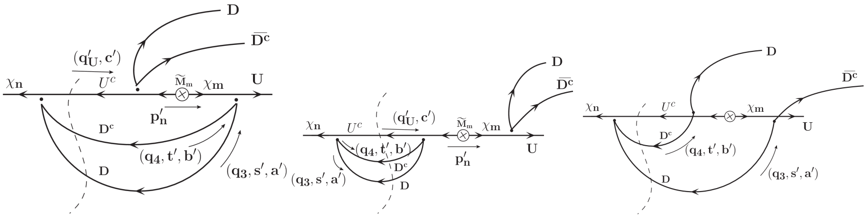
Tree-level decay width as a loop:

$\Gamma_0 \propto |\mathcal{A}_0|^2 =$



Cutkosky rule: $1/(k^2 - m^2 + i\epsilon) \to -2\pi i \delta(k^2 - m^2)$

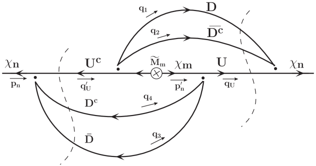
$\mathcal{X}_n$ Decay at loop level



Arrow clash ↔ Majorana mass ↔ B violation

$\mathcal{X}_n$ Decay tree-loop interference term

Eg. Diagram A tree-loop interference term



Compute $\hat{\mathcal{A}}_{01}$:

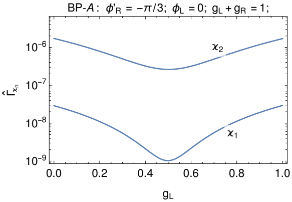
- Dirac traces and the matrix element
- Loop integral
- Fold in phase-space (as loop integral) and integrate

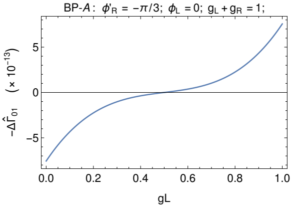
Baryon asymmetry from decay

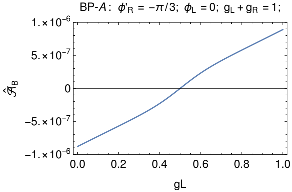
Benchmark point: **BP-A** (all masses scaled with M_χ):

$M_D = 0.25,\ M_U = 0.375,\ M_\chi = 1,\ \tilde{M}_L = 0.1,\ |\tilde{M}_R| = 0.11,\ \phi'_R = -\pi/3$

Compute the integrals numerically, compute B Asym. (*FeynCalc*, *Mathematica*)







Scaling factors $(M_\chi^5/\Lambda^4, M_\chi^9/\Lambda^8, M_\chi^4/\Lambda^4)$

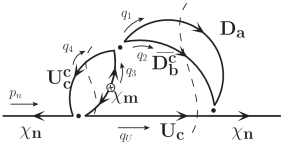
$\mathcal{A}_B$ is phenomenologically interesting

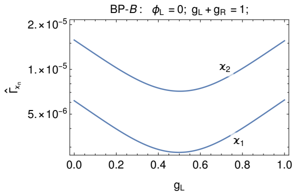
Multiple operator contributions

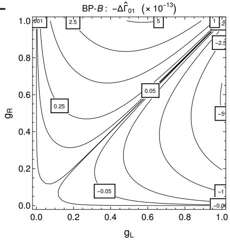
$$\text{Add } \mathcal{L} \supset -\frac{1}{\Lambda^2}\,[\bar{U}_c \bar{G}^n_{V\mu} \mathcal{X}_n]\,[\overline{\mathcal{X}}_m G^{m\mu}_V U_c]$$

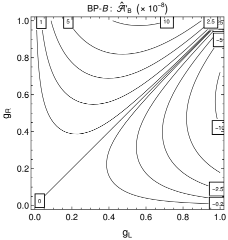
Benchmark point: **BP-B**:

$M_D = 0.05,\ \ M_U = 0.05,\ \ M_\chi = 1,\ \ \tilde{M}_L = 0.1,\ \ |\tilde{M}_R| = 0.11,\ \ \phi'_R = -\pi/3$









Scaling factors $(M_\chi^5/\Lambda^4,\ M_\chi^7/\Lambda^6,\ M_\chi^2/\Lambda^2)$

UV completion example

In loops or phase-space, if $p \gtrsim \Lambda$, UV completion relevant.

Example: introduce color triplet, vector ξ^a_μ with $Q(\xi) = -2/3$:

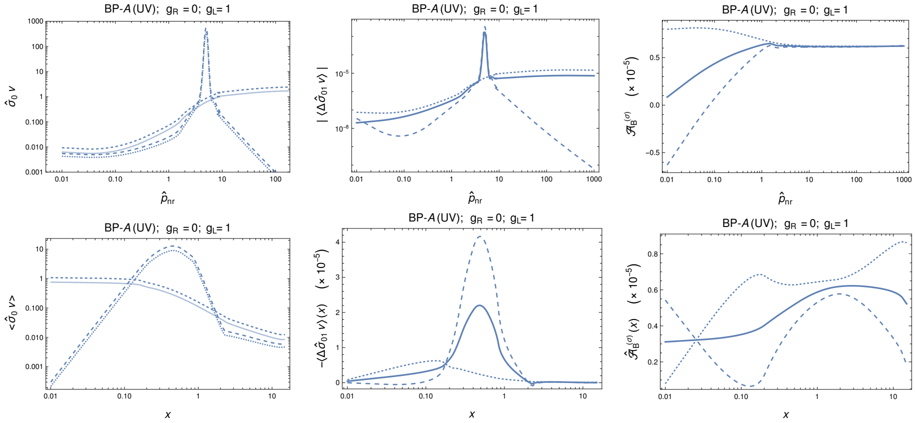
$$\mathcal{L}^{(A)}_{UV} \supset -\frac{1}{2}\,\epsilon^{abc}[\overline{D^c_b}\,\tilde{g}\gamma^\mu D_a]\,\xi^{c\,*}_\mu - [\bar{\chi}\,\gamma^\mu(g_L P_L + g_R P_R)U_c]\,\xi^c_\mu + \mathrm{h.c.}$$

Scattering B Asym ($\mathcal{X}\bar{Q} \to QQ$ vs. $\mathcal{X}Q \to \bar{Q}\bar{Q}$)

SC-1: $\mathcal{X}_n(p_n)\overline{D}(k_i) \to D(q_1)U(q_2)$

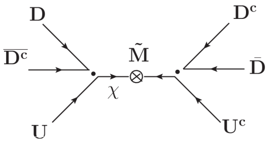
SC-2: $\mathcal{X}_n(p_n)\overline{U}(k_i) \to D(q_1)\overline{D^c}(q_2)$

$$\hat{\mathcal{A}}_B^{(\sigma)} \equiv \frac{\langle\sigma v\rangle - \langle\sigma^c v\rangle}{\langle\sigma v\rangle + \langle\sigma^c v\rangle} \approx -\frac{\langle\Delta\hat{\sigma}_{01} v\rangle}{\langle\sigma_0 v\rangle}$$



Scaling factors $(M_\chi^2/\Lambda^4, M_\chi^6/\Lambda^8, M_\chi^4/\Lambda^4)$ $\quad (x = M/T)$

neutron-antineutron ($n - \bar{n}$) oscillation



$$\tau_{n-\bar{n}} \geq 4.7 \times 10^8 \text{ s at 90 \% C.L.}$$ [SuperK, 2021]

$$\implies (\Delta m_{n-\bar{n}})_{\rm expt} \lesssim 10^{-34} \text{ GeV}$$

$$\tilde{g}^2 G_V G_\Lambda s_{\rm eff}^2 \frac{\Lambda_{\rm QCD}^6 \langle \hat{Q}_i \rangle}{\Lambda^4 M_\chi} \lesssim 10^{-34} \text{ GeV} \implies \Lambda \gtrsim s_{\rm eff}^{2/5} 10^3 \text{ TeV (for } G_V \sim \mathcal{O}(1))$$

[Refinement in future work]

Conclusions

- Majorana pair $\mathcal{X}_n$ with dim-6 VV interaction to UDD studied
- $\mathcal{X} \to UDD$ decay B asym computed
- $\mathcal{X}\bar{Q} \to QQ$ scattering B asym computed
- These will be inputs (collision terms) to the Boltzmann equation for computing BAU (ongoing work)
- $n - \bar{n}$ oscillation rate estimated