Baryogenesis from a Majorana Fermion Coupled to Quarks

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IMSc, Chennai, and HBNI

[2211.12115; 2311.14636; 2411.13231][PRD]
(with Rakesh Tibrewala, LNMIIT, Jaipur)

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Talk Outline

- Baryogenesis from dim-6 Vector-Vector (VV) eff. op: $\frac{1}{\Lambda^2}(D\Gamma^\mu D)(\chi\gamma_\mu U)$
  - χ Majorana mass breaks B
- Baryon asymmetry in $\mathcal{X}$ decay and scattering
  - UV completion details
- Solve Boltzmann Equations
  - match to observed Baryon Asymmetry of the Universe (BAU)
- Terrestrial probes
  - neutron-antineutron $(n - \bar{n})$ oscillation

Baryogenesis basics

- Today we only have matter in the (observable) Universe
  $\eta_B \equiv \frac{n_B}{n_\gamma} = \frac{(n_b - n_{\bar{b}})}{n_\gamma} = 6 \times 10^{-10} \frac{\Omega_b h^2}{0.0222}$; $Y_B \equiv \frac{n_B}{s} = 0.85 \times 10^{-10}$
  - 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 $\mathcal{X}$ Decay and Scattering

$$\mathcal{L}_{Dirac\ M} \supset -M_\chi\,\bar{\chi}\chi - M_U\,\bar{U}U - M_D\,\bar{D}D$$

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VV interaction: χ with $Q = (U, D)$

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

Dirac mass: M_χ

Majorana mass: $\widetilde{M}_{L,R}$

Decay and Scattering processes:

- $\mathcal{X} \leftrightarrow UDD$ vs. $\mathcal{X} \leftrightarrow U^c D^c D^c$
- $\mathcal{X} Q^c \leftrightarrow QQ$ vs. $\mathcal{X} Q \leftrightarrow Q^c Q^c$
- $UDD \leftrightarrow U^c D^c D^c$ vs. $U^c D^c D^c \leftrightarrow UDD$

Our study: baryogenesis in $\mathcal{X}$ Decay and Scattering

$$\mathcal{L}_{Dirac\ M} \supset -M_\chi\, \bar{\chi}\chi - M_U\, \bar{U}U - M_D\, \bar{D}D$$
$$\mathcal{L}_{VV} \supset \frac{g_{L,R}}{\Lambda^2}\, [\overline{D^c}\gamma_\mu D]\, [\overline{\chi}\gamma^\mu P_{L,R} U]$$
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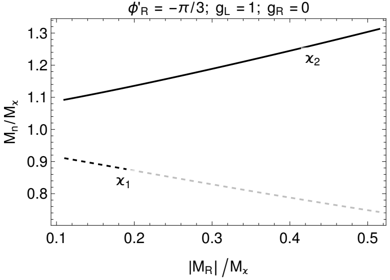
- $UDD \leftrightarrow U^c D^c D^c$ vs. $U^c D^c D^c \leftrightarrow UDD$

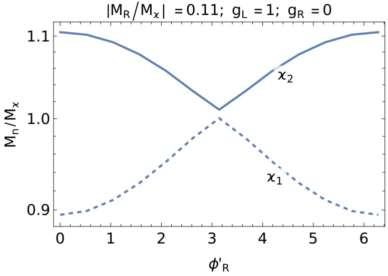
- Sakharov conditions
  - B violation: **Majorana mass** $\tilde{M}_{L,R}$
  - C and CP violation: complex $g_{L,R}, \tilde{M}_{L,R}$:
  - Departure from Thermal Equilibrium: Hubble expansion
- When did Baryogenesis happen?
  - At scale M_χ

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 $\mathcal{X}_n \to UDD$

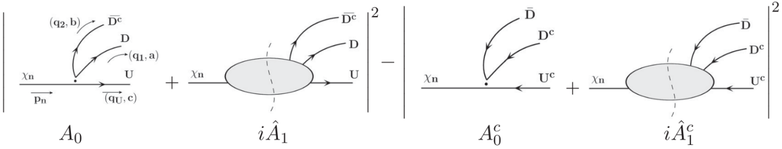
Amplitude (tree+loop): Process $\mathcal{A} = \mathcal{A}_0 + \mathcal{A}_1$; Conjugate process $\mathcal{A}^c = \mathcal{A}_0^c + \mathcal{A}_1^c$

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** ($\delta = \pi/2$)

$\mathcal{A}_B^n \propto$



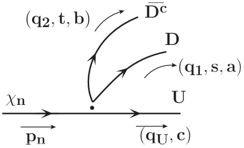
Interference term $\hat{\mathcal{A}}_{01} \equiv \hat{\mathcal{A}}_1 \mathcal{A}_0^*$, $\hat{\mathcal{A}}_{01}^c \equiv \hat{\mathcal{A}}_1^c \mathcal{A}_0^{c*}$

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

[S.Gopalakrishna, R. Tibrewala: 2211.12115]

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

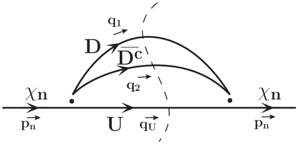
At tree level: $\mathcal{A}_0 \propto$



$\to$ *UDD*

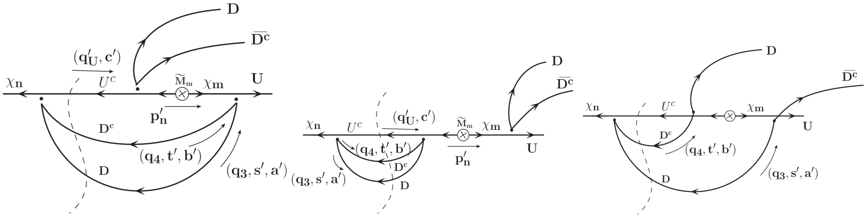
Tree-level decay width as a loop:

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

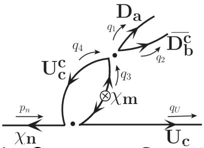


Cutkosky rule: $1/(k^2 - m^2 + i\epsilon) \to -2\pi i \delta(k^2 - m^2)$

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



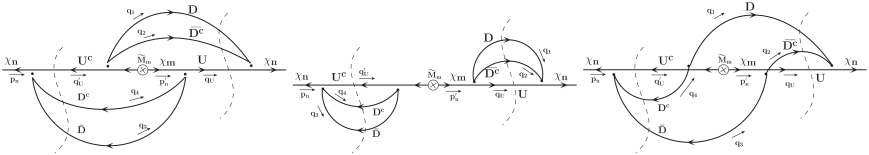
Single Operator Contributions

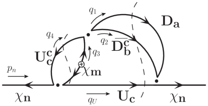


Multiple Operator Contribution

Arrow clash $\leftrightarrow$ Majorana mass $\leftrightarrow$ B violation

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





Multiple Operator Contribution

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

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

Benchmark points: BP-A, BP-B, BP-C

Table 1: The Benchmark Points (BP) parameters, and the $g, M_\chi/\Lambda$ scaling factors.

	$\hat{M}_Q$	$\hat{\Gamma}_0$ $(\times\lvert g\rvert^2 M_\chi^4/\Lambda^4)$	$\Delta\hat{\Gamma}_{01}$ $(\times\mathrm{Im}(g^4)M_\chi^6/\Lambda^6)$	$\langle\hat{\sigma}_0 v\rangle$ $(\times\lvert g\rvert^2 M_\chi^4/\Lambda^4)$	$\langle\Delta\hat{\sigma}_{01} v\rangle$ $(\times\mathrm{Im}(g^4)M_\chi^6/\Lambda^6)$	$\langle\hat{\Gamma}'_0\rangle$ $(\times\lvert g\rvert^4 M_\chi^8/\Lambda^8)$
BP-A	1/4	1.7×10^{-6}	$-1.4\times10^{-9}M_\chi^2/\Lambda^2$	12.7	$-0.04\,M_\chi^2/\Lambda^2$	0.4
BP-B	1/20	2×10^{-5}	-6×10^{-11}	3.5	-0.3	6.4
BP-C	1/20	10^{-4}	-10^{-7}	12.7	-10^{-5}	0.4

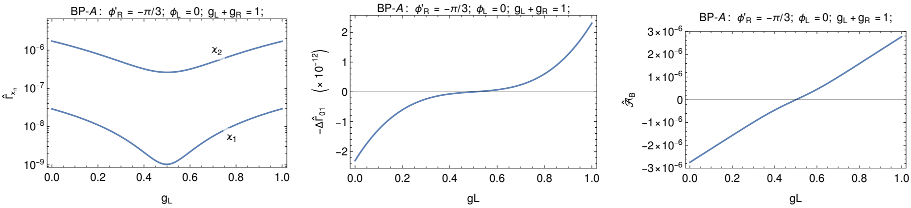
	BP-1A	BP-1B	BP-1C	BP-2A	BP-2B	BP-2C	BP-3A	BP-3B	BP-3C
M_χ (GeV)	10^{12}			10^9			10^6		
M_χ/Λ	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/50	1/10
g	0.25	0.008	0.048	0.065	0.009	0.065	0.024	0.022	0.087
Modified parameters							$(2/5)\,\langle\hat{\sigma}_0 v\rangle$ $(5/2)\,\langle\Delta\hat{\sigma}_{01} v\rangle$		$(1/30)\,\hat{\Gamma}_0$

$M_\chi = 1,\ \tilde{M}_L = 0.1,\ |\tilde{M}_R| = 0.11,\ \phi'_R = -\pi/3$ (all masses scaled with M_χ)

Compute (numerically) the integrals, baryon asymmetry, solve Boltzmann Eqn.

(*FeynCalc*, *Mathematica*)

Decay $\mathcal{A}_B$: Single Operator contrib: BP-A

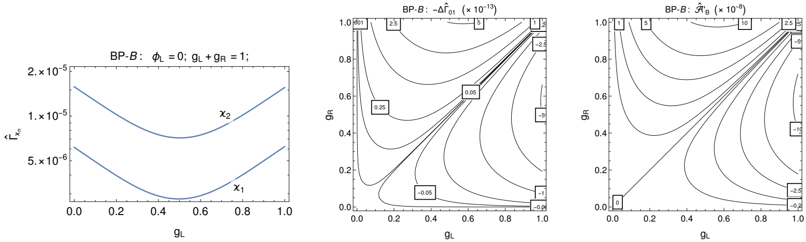


Scaling factors $(M_\chi^5/\Lambda^4, M_\chi^9/\Lambda^8, M_\chi^4/\Lambda^4)$

$\mathcal{A}_B$ is phenomenologically interesting

[S.Gopalakrishna, R. Tibrewala: 2311.14636]

Decay $\mathcal{A}_B$: Multiple operator contrib: BP-B



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

$\mathcal{A}_B$ is phenomenologically interesting

UV completion example

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

- Particularly relevant in scattering

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

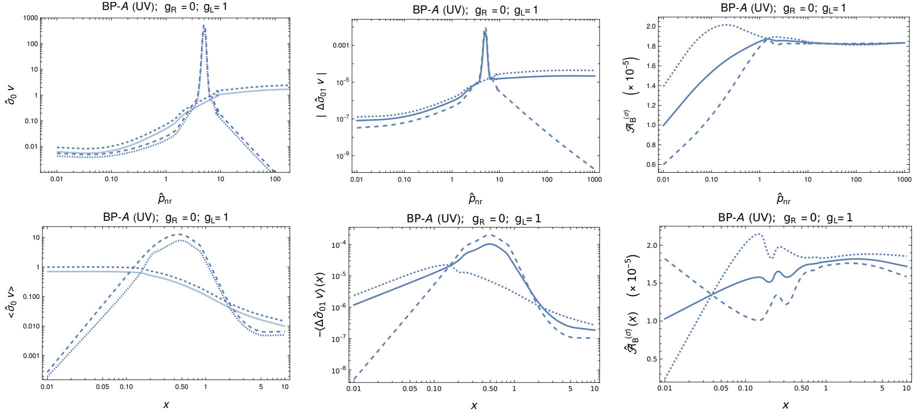
$$\mathcal{L}^{(A)}_{UV} \supset -\frac{1}{2}\,\epsilon^{abc}[\overline{D^c_b}\,\tilde{g}\gamma^\mu D_a]\,\xi^{c\,*}_\mu - [\bar{\chi}\,\gamma^\mu(g_L P_L + g_R P_R)U_c]\,\xi^c_\mu + \mathrm{h.c.}$$

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

[S.Gopalakrishna, R. Tibrewala: 2311.14636]

Boltzmann Equations: expanding Universe at T

Early Universe at temperature T: time $t \approx (0.301/\sqrt{g_*})M_{Pl}/T^2$

Hubble expansion rate $H(T) = 1.66\sqrt{g_*}T^2/M_{Pl}$

Track number densities: $n_\chi(t), n_Q(t), n_{\bar{Q}}(t)$; $n_B(t) = (n_Q - n_{\bar{Q}})/3$

- $n_\chi(t)$, $n_B(t)$: $n_B(t_b) = 0$, $n_B(t_e) \sim BAU$

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Boltzmann Equations

$$\frac{d}{dt}n_\chi + 3Hn_\chi = -\langle\Gamma\rangle(n_\chi - n_\chi^{(0)}) + ...$$

$$\frac{d}{dt}n_B + 3Hn_B = \langle\Delta\Gamma\rangle(n_\chi - n_\chi^{(0)}) - \langle\Gamma\rangle\, n_\chi^{(0)}\, n_B/n_Q^{(0)} ...$$

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Boltzmann Equations

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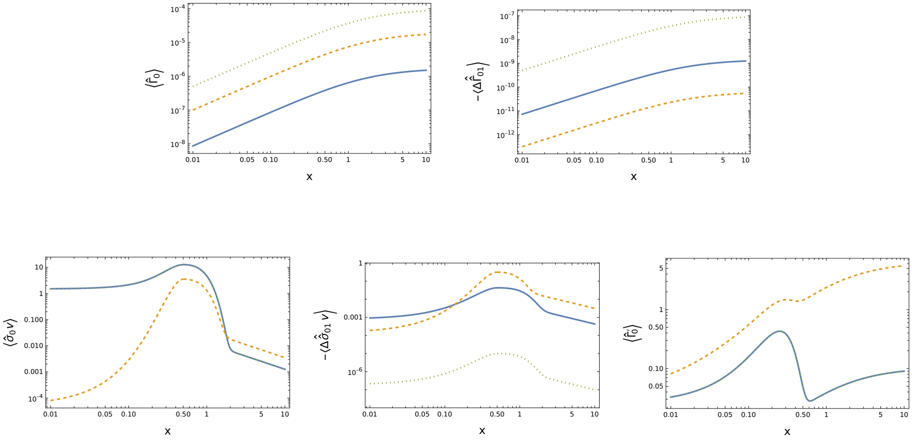
$$\frac{d}{dt}n_B + 3Hn_B = \langle\Delta\Gamma\rangle(n_\chi - n_\chi^{(0)}) - \langle\Gamma\rangle\, n_\chi^{(0)}\, n_B/n_Q^{(0)} \ldots$$

Equivalently solve BE for $Y_\chi = n_\chi/s$, $Y_B = n_B/s$

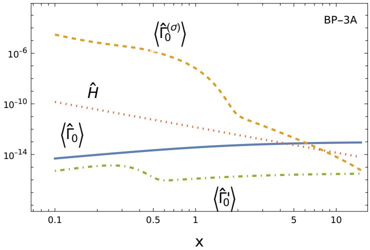
vs. $t \to$ temperature $T \to x = M_\chi/T$

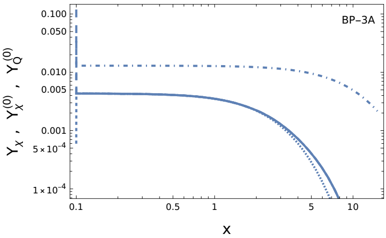
- $Y_\chi(x), Y_B(x)$; $Y_B(x_b) = 0$, $Y_B(x_e) \sim Y_B^{obs}$

Thermally averaged rates

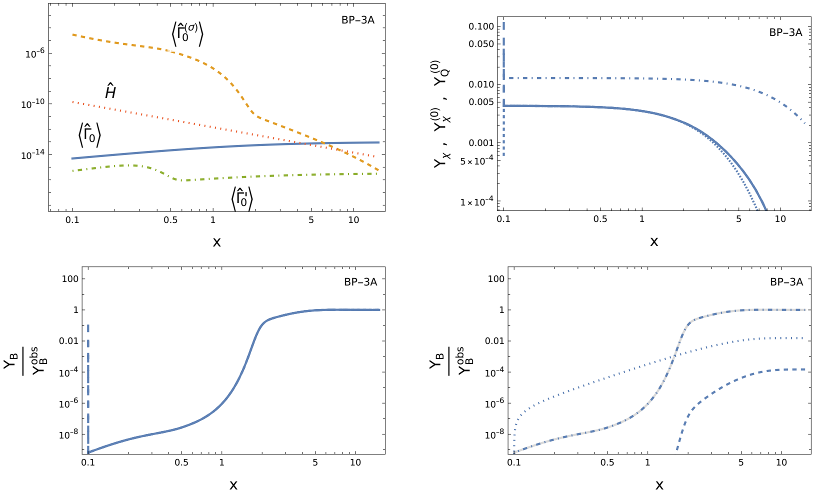


Boltzmann Equation Solution: BAU in BP-3A





Boltzmann Equation Solution: BAU in BP-3A



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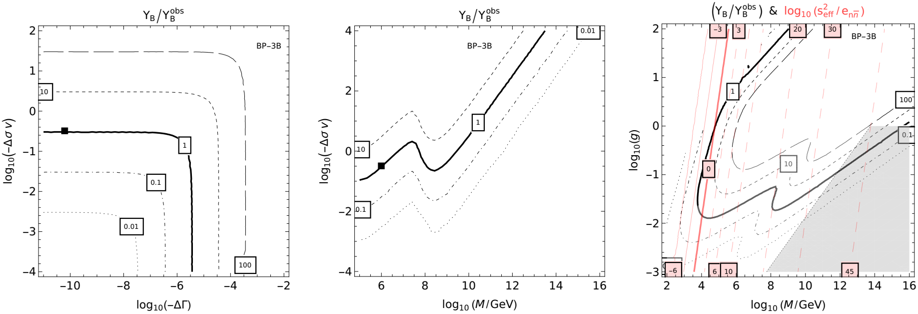
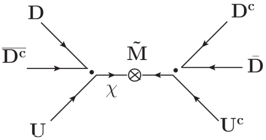
Boltzmann Equation Solution: BAU in BP-3B



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

$\Delta B = 2$ process



$\tau_{n-\bar{n}} \geq 4.7 \times 10^8$ s at 90 % C.L. [SuperK, 2021] $\Longrightarrow$ $(\Delta m_{n-\bar{n}}) \leq 10^{-34}\ \mathrm{GeV}$

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

$$Q \equiv \epsilon^{abc}\epsilon^{a'b'c'}\,(\bar{u^c_{c'}}\gamma^\nu\gamma^\mu P_{L,R}\,u_c)\,(\bar{d^c_b}\gamma_\mu d_a)\,(\bar{d^c_{b'}}\gamma_\nu d_{a'})$$

Lattice computation of the matrix element not available;

for now use scalar operator in the Fierz rearrangement

$$10^{\kappa_{n\bar{n}}} \equiv \frac{s_{\rm eff}^2}{e_{n\bar{n}}} = 2.5 \times 10^{-31} \left(\frac{13}{\langle \hat{Q}\rangle}\right)\left(\frac{M_\chi}{1\ \mathrm{GeV}}\right)^5 \left[\frac{1}{g\,(M_\chi/\Lambda)^2}\right]^2$$

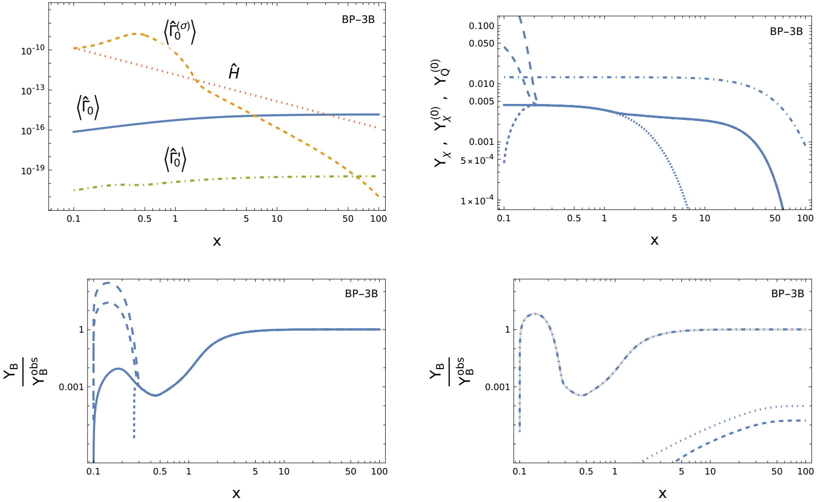
Conclusions

- Majorana $\mathcal{X}$ with dim-6 VV interaction to UDD studied
  - Sakharov conditions satisfied
- Baryon Asymmetry due to decay and scattering computed
- Boltzmann Equations solved to match to observed BAU
  - $M_\chi \in (10^4, 10^{16})\ GeV$
- Terrestrial probes
  - $n - \bar{n}$ oscillation
  - Flavor probes?

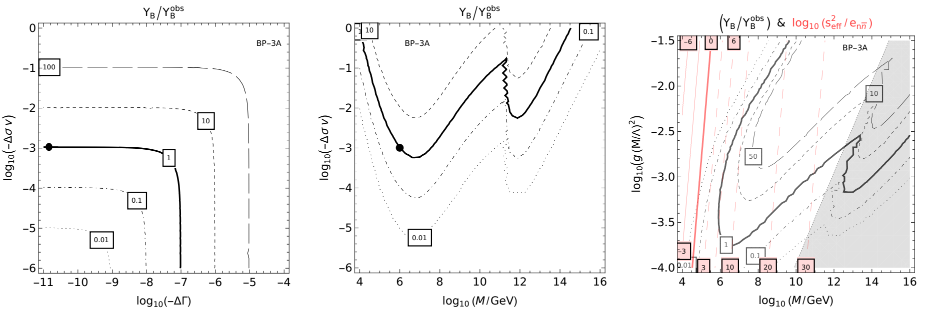
Backup Slides

BACKUP SLIDES

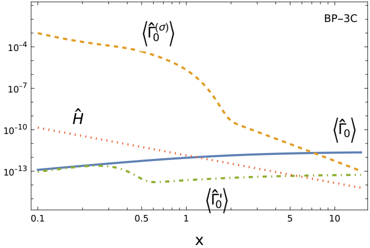
BAU in BP-3B

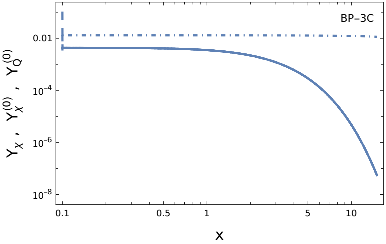

BP-3B
$\langle \hat{\Gamma}_0^{(\sigma)} \rangle$
$\hat{H}$
$\langle \hat{\Gamma}_0 \rangle$
$\langle \hat{\Gamma}'_0 \rangle$
10^{-10}
10^{-13}
10^{-16}
10^{-19}
0.1 0.5 1 5 10 50 100
x
BP-3B
Y_χ , $Y_\chi^{(0)}$, $Y_Q^{(0)}$
0.100
0.050
0.010
0.005
0.001
5×10^{-4}
1×10^{-4}
0.1 0.5 1 5 10 50 100
x
BP-3B
$\frac{Y_B}{Y_B^{obs}}$
1
0.001
0.1 0.5 1 5 10 50 100
x
BP-3B
$\frac{Y_B}{Y_B^{obs}}$
1
0.001
0.1 0.5 1 5 10 50 100
x

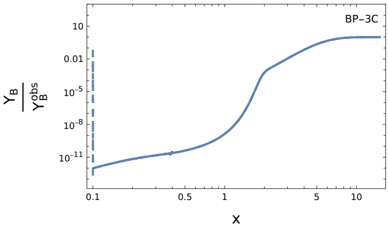
BAU in BP-3A

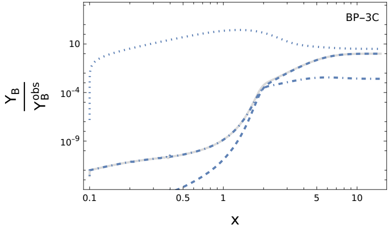

Y_B/Y_B^{obs}
BP-3A
$\log_{10}(-\Delta\sigma v)$
$\log_{10}(-\Delta\Gamma)$
$\log_{10}(M/\text{GeV})$
(Y_B/Y_B^{obs}) & $\log_{10}(s_{eff}^2/e_{n\bar{n}})$
$\log_{10}(g(M/\Lambda)^2)$

BAU in BP-3C

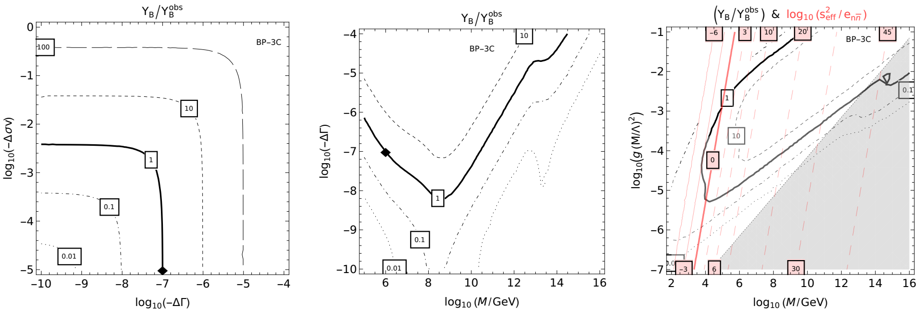

BP–3C
$\langle \hat{\Gamma}_0^{(\sigma)} \rangle$
$\hat{H}$
$\langle \hat{\Gamma}_0 \rangle$
$\langle \hat{\Gamma}'_0 \rangle$
10^{-4}
10^{-7}
10^{-10}
10^{-13}
0.1
0.5
1
5
10
x


BP–3C
Y_χ , $Y_\chi^{(0)}$, $Y_Q^{(0)}$
0.01
10^{-4}
10^{-6}
10^{-8}
0.1
0.5
1
5
10
x


BP–3C
$\frac{Y_B}{Y_B^{obs}}$
10
0.01
10^{-5}
10^{-8}
10^{-11}
0.1
0.5
1
5
10
x


BP–3C
$\frac{Y_B}{Y_B^{obs}}$
10
10^{-4}
10^{-9}
0.1
0.5
1
5
10
x

BAU in BP-3C


Y_B/Y_B^obs
BP-3C
100
10
1
0.1
0.01
log10(−Δσv)
log10(−ΔΓ)
log10(M/GeV)
(Y_B/Y_B^obs) & log10(s_eff^2/e_nn̄)
log10(g(M/Λ)^2)