Maximal CP violation from long-range forces

Anna Socha

LPENS & Sorbonne Université, Paris

based on: M.M Flores, K. Petraki, **AS** 25XX.XXXXX

SORBONNE UNIVERSITÉ CRÉATEURS DE FUTURS DEPUIS 1257

LPENS LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

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Outline

Introduction

Contact-type interactions

$m_{\rm med} \gtrsim M, \quad \lambda_{\rm B} \gtrsim m_{\rm med}^{-1}$

vs

Long-range interactions

$m_{\rm med} \ll M, \quad \lambda_{\rm B} \ll m_{\rm med}^{-1}$

Contact-type interactions

$$m_{\rm med} \gtrsim M, \quad \lambda_{\rm B} \gtrsim m_{\rm med}^{-1}$$

VS

Long-range interactions

$$m_{\rm med} \ll M, \quad \lambda_{\rm B} \ll m_{\rm med}^{-1}$$

Non-perturbative effects

Dark Matter phenomenology

Sommerfeld effect

distortion of scattering-state wavefunctions alters the cross-sections

J. Hisano, S. Matsumoto, M. M. Nojiri (2003)

Bound States

unstable BS $\Rightarrow$ DM interaction rate, DM abundance, indirect detection signals

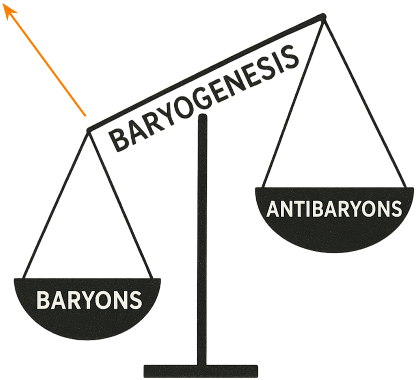
B. von Harling, K. Petraki (2014)

stable BS $\Rightarrow$ elastic scattering, novel indirect detection signals, inelastic DM-nucleon scattering

K. Petraki, R. R. Volkas (2013)

Baryon-to-entropy density ratio

$Y_B = (8.69 \pm 0.01) \times 10^{-11}$



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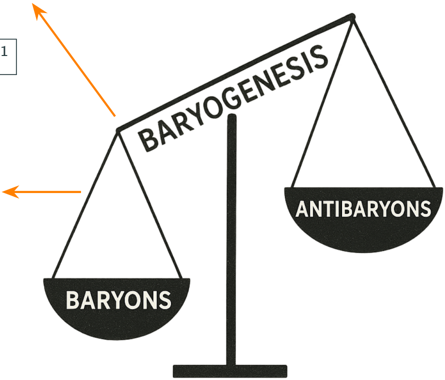
Dynamical asymmetry generation



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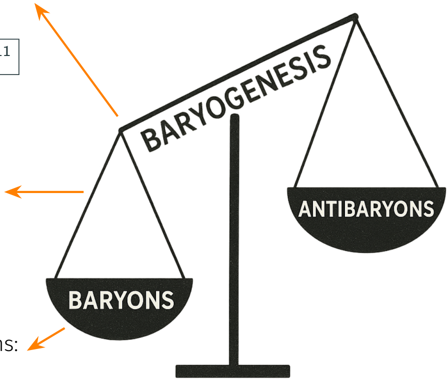
Dynamical asymmetry generation

Three Sakharov conditions:

1. Baryon number violation
2. C and CP symmetry violation
3. Departure from thermal equilibrium



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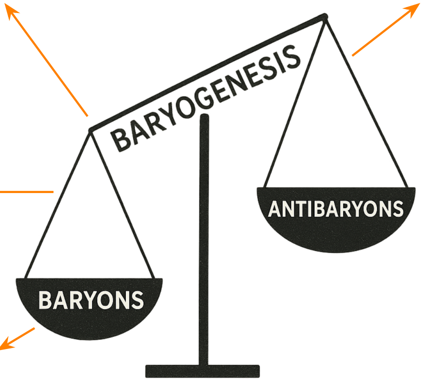
BSM phenomenon

$$Y_B^{\mathrm{SM}} \sim 10^{-18} - 10^{-20}$$



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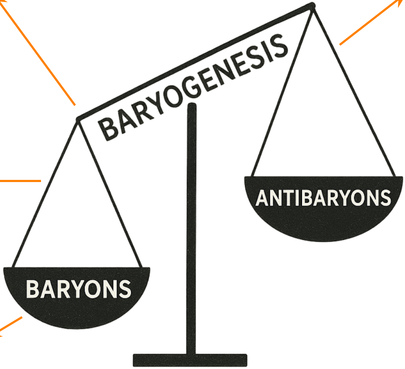


BSM phenomenon

$$Y_B^{\mathrm{SM}} \sim 10^{-18} - 10^{-20}$$

Many possible explanations

1. GUT baryogenesis
2. Electroweak baryogenesis
3. Leptogenesis
4. Affleck-Dine mechanism
5. ...

Model

Particle content

We consider the $U_{\mathrm{B-L}}(1)$ extension of the Standard Model. The particle content includes:

- two, heavy, non-relativistic and nearly-mass degenerate Dirac fermions $X_{1,2} \sim (1, 1, 0, -1)$,
- doubly-charged scalar $\rho \sim (1, 1, 0, -2)$, which breaks the B-L symmetry
- Gauge boson V_μ of $U_{\mathrm{B-L}}(1)$,
- three SM-singlet Weyl fermions χ, which cancel the gauge and gravitational anomalies.

Assumed mass hierarchy

$$\Delta m \equiv m_2 - m_1 \to 0,\ m_x \equiv m_2, m_1 \gg v_{\mathrm{B-L}},\ m_{\mathrm{med}}^{-1} \gg (\mu v_{\mathrm{rel}})^{-1}$$

Lagrangian

The model is described by the Lagrangian density

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{0}_{\mathrm{BSM}} + \mathcal{L}^{\mathrm{int}}_{\mathrm{BSM}} - V^{\rho}_{\mathrm{BSM}},$$

where

$$\mathcal{L}^{0}_{\mathrm{BSM}} \equiv -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (\mathcal{D}_{\mu}\rho)^{\dagger}(\mathcal{D}^{\mu}\rho) + \frac{1}{2}\sum_{k=1}^{2}\bar{\chi}_{k}\mathbb{i}\not{\partial}\chi_{k} + \sum_{i=1}^{2}\left(\bar{X}_{i}\mathbb{i}\not{\mathcal{D}}X_{i} - m_{i}\bar{X}_{i}X_{i}\right),$$

with

Gauge coupling

$$\mathcal{D}_{\mu} = \mathcal{D}^{\mathrm{SM}}_{\mu} + \mathbb{i}\, g_{\mathrm{B-L}}\, q_{\mathrm{B-L}}\, V_{\mu},$$

Yukawa coupling

SM portal

$$\mathcal{L}^{\mathrm{int}}_{\mathrm{BSM}} \equiv -\sum_{i,j=1}^{2}\left(\frac{y^{\mathrm{R}}_{ij}}{2^{\delta_{ij}}}\rho^{\dagger}\bar{X}^{c}_{\mathrm{R},i}X_{\mathrm{R},j} + \frac{y^{\mathrm{L}}_{ij}}{2^{\delta_{ij}}}\rho^{\dagger}\bar{X}^{c}_{\mathrm{L},i}X_{\mathrm{L},j}\right) - \sum_{l=1}^{3}\sum_{i=1}^{2}\lambda^{\mathrm{X}}_{il}\,\bar{L}_{l}\tilde{\mathcal{H}}X_{\mathrm{R},i} + \mathrm{h.c.},$$

$$V^{\rho}_{\mathrm{BSM}} \equiv -\mu^{2}_{\rho}|\rho|^{2} + \frac{1}{4}\lambda_{\rho}|\rho|^{4} + \lambda_{\rho\mathcal{H}}|\mathcal{H}|^{2}|\rho|^{2}.$$

B-L symmetry breaking

Asymmetries

The CP asymmetry is generated by the Yukawa interactions

$$\mathcal{L}_{\mathrm{BSM}}^{\mathrm{int}} \equiv -\sum_{i,j=1}^{2}\left(\frac{y_{ij}^{\mathrm{R}}}{2^{\delta_{ij}}}\rho^{\dagger}\bar{X}_{\mathrm{R},i}^{c}X_{\mathrm{R},j} + \frac{y_{ij}^{\mathrm{L}}}{2^{\delta_{ij}}}\rho^{\dagger}\bar{X}_{\mathrm{L},i}^{c}X_{\mathrm{L},j}\right) + h.c.$$

The Yukawa matrices $y^{\mathrm{R,L}}$ are symmetric and generally complex, with $N^2 = 4$ irreducible phases, for $N = 2$ generations.

For convenience, we define

$$\mathrm{y}_{ij} \equiv (y_{ij}^{\mathrm{L}} + y_{ij}^{\mathrm{R}})/2, \quad \mathrm{w}_{ij} \equiv (y_{ij}^{\mathrm{L}} - y_{ij}^{\mathrm{R}})/2, \quad \alpha_{ij} \equiv |\mathrm{y}_{ij}|^2/4\pi, \quad \alpha_{\mathrm{B-L}} \equiv g_{\mathrm{B-L}}^2/4\pi.$$

$N(N-1)/2 = 1$ irreducible phase is associated with the y_{ij} coupling, and $N(N+1)/2 = 3$ with w_{ij}.

We use the parametrization

$$\mathrm{y}_{ii} = \sqrt{4\pi\alpha_{ii}} > 0, \qquad \mathrm{y}_{ij} = \sqrt{4\pi\alpha_{ij}}e^{\mathbb{i}\theta_{ij}}, \qquad \theta_{ij} \in [0, 2\pi).$$

We also assume that $\boxed{\alpha_{ii}, \alpha_{ij} \gg \alpha_{\mathrm{B-L}}}$.

Asymmetries

The X-number violation occurs via

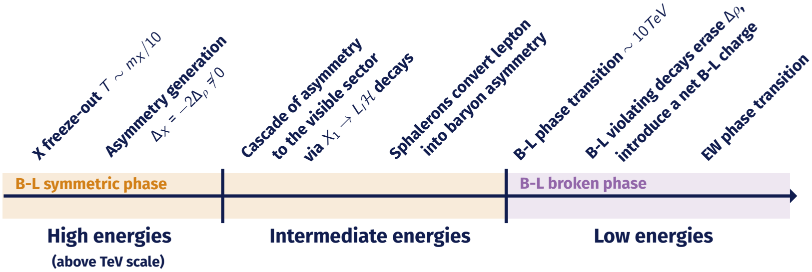
1. $X_2 \to \bar{X}_1 \rho$,
2. $X_i X_j \to \rho V_\mu$,
3. $X_i V_\mu \to \bar{X}_j \rho$.

The CP asymmetry is generated here both

1. perturbatively - through the interference of tree and loop diagrams in various processes $\sim \mathcal{O}(\mathrm{y}^6)$
2. non-perturbatively - in long-range $X_i \bar{X}_j \to X_{i'} \bar{X}_{j'}$ flavour-changing scatterings and $X_1 \bar{X}_2 \to \rho\rho^*$ annihilations.

⇓

$$\Delta X \equiv \Delta X_1 + \Delta X_2 = -2\,\Delta\rho \neq 0.$$


X freeze-out $T \sim m_X/10$
Asymmetry generation $\Delta_X = -2\Delta_\rho \neq 0$
Cascade of asymmetry to the visible sector via $X_1 \to L_i\mathcal{H}$ decays
Sphalerons convert lepton into baryon asymmetry
B-L phase transition $\sim 10 TeV$
B-L violating decays erase $\Delta\rho$, introduce a net B-L charge
EW phase transition
B-L symmetric phase
B-L broken phase
High energies
(above TeV scale)
Intermediate energies
Low energies

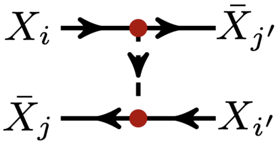
Long-range interactions

Long-range interactions in a nutshell

Exchange of light force mediators ⇨ **Distortion of the particle wavefunction**

Breakdown of perturbative approach!

Low-momentum transfer in the loops $|\boldsymbol{q}| \sim \mu v_{\rm rel} \ll \mu$

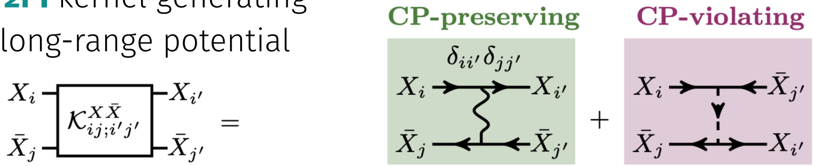


Every loop introduces a factor $\alpha / v_{\rm rel}$

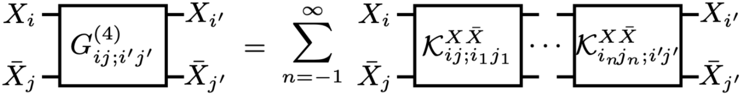
Amplitude enhancement at low velocities
Resummation

Resummation

The **2PI** kernel generating the long-range potential



The resummation of the 2PI kernel leads to the **Dyson-Schwinger** equation for 4-point function



$$G^{(4)}_{ij,i'j'} = D_{ii'} D_{jj'} \left(1 + \sum_{i'',j''} \mathcal{K}_{ij,i''j''} G^{(4)}_{i''j'',i'j'}\right)$$

K. Petraki, M. Postma, M. Wiechers (2015)

R. Oncala, K. Petraki (2011)

In the non-relativistic regime, **Dyson-Schwinger** equation yields a system of coupled **Schrödinger** equations:

$$\sum_{i',j'}\left[-\frac{\nabla^2}{2\mu_{ij}}\delta_{ii'}\delta_{jj'}+[V_{X\bar{X}}(r)]^{ij}_{i'j'}\right]\Psi^{\mathcal{S}}_{i'j'}(\mathbf{r})=\mathcal{E}^{\mathcal{S}}_{ij}\,\Psi^{\mathcal{S}}_{ij}(\mathbf{r}),$$

Unrotated wavefunction

$$\mathcal{E}^{\mathcal{S}}_{ij}\equiv E^{\mathcal{S}}-m_i-m_j.$$

Total energy in the CM frame

The projections of a state $\mathcal{S}$ on flavor eigenstates ij

$$\Psi^{\mathcal{S}}(x)=\left(\Psi^{\mathcal{S}}_{1\bar{1}}(x),\Psi^{\mathcal{S}}_{1\bar{2}}(x),\Psi^{\mathcal{S}}_{2\bar{1}}(x),\Psi^{\mathcal{S}}_{2\bar{2}}(x)\right)^{\mathrm{T}},$$

$$\Psi^{\mathcal{S}}_{i\bar{j}}(x)\equiv\langle\Omega|\mathrm{T}\left[X_i(x/2)\bar{X}_j(-x/2)\right]|\mathcal{S}\rangle_{x^0=0}.$$

Long-range potential

XX and $X\bar{X}$ pairs interact via V_μ and ρ boson exchange, which generates long-range potentials

$$V_t(\mathrm{r}) = \frac{\mathbb{i}}{4M\mu}\int \frac{d^3q}{(2\pi)^3}\mathbb{i}\mathcal{K}_t(\mathrm{q})e^{\mathbb{i}\mathrm{q}\cdot\mathrm{r}}$$

$$V_u(\mathrm{r}) = \frac{\mathbb{i}\,(-1)^\ell}{4M\mu}\int \frac{d^3q}{(2\pi)^3}\mathbb{i}\mathcal{K}_u(\mathrm{q})e^{\mathbb{i}\mathrm{q}\cdot\mathrm{r}}$$

The $X\bar{X}$ potential matrix reads

Thermal mass

$$\mathbb{V}_{X\bar{X}}(r) = -\frac{\alpha_{\mathrm{B-L}}}{r}\times\mathbb{1} \quad -(-1)^{\ell+s}\frac{e^{-m_\rho r}}{r}\times\begin{pmatrix}\alpha_{11} & A_{11}^* & A_{11} & \alpha_{12}\\ A_{11} & \alpha_{12} & A & A_{22}^*\\ A_{11}^* & A^* & \alpha_{12} & A_{22}\\ \alpha_{12} & A_{22} & A_{22}^* & \alpha_{22}\end{pmatrix}$$

contains complex phase

$$\alpha_{\mathrm{B-L}} \equiv \frac{g_{\mathrm{B-L}}^2}{4\pi}, \qquad \alpha_{ij} \equiv \frac{|y_{ij}|^2}{4\pi}, \qquad A_{ii} \equiv \frac{y_{ii}y_{12}^*}{4\pi}, \qquad A \equiv \frac{y_{11}y_{22}^*}{4\pi},$$

Hermitian, but not necessarily real!

Analytic approximation — Schrödinger equations

In the limit $\Delta m \to 0$, $m_\rho \to 0$, a system of coupled **Schrödinger equations** can be diagonalized

$$\left[-\frac{\nabla^2}{2\mu} + \mathbb{V}^{\mathrm{diag}}_{X\bar{X}}(r)\right]\hat{\Psi}^{\mathcal{S}}(\mathbf{r}) = \mathcal{E}^{\mathcal{S}}\,\hat{\Psi}^{\mathcal{S}}(\mathbf{r}),$$

r-independent unitary matrix, whose columns are $\mathbb{V}_{X\bar{X}}$ eigenvectors

Diagonal static potential

$$\mathbb{V}^{\mathrm{diag}}_{X\bar{X}}(r) \equiv \mathbb{P}^\dagger\,\mathbb{V}_{X\bar{X}}(r)\,\mathbb{P} = -\frac{1}{r}\,\mathrm{diag}\{a_1, a_2, a_3, a_4\},$$

real eigenvalues

Rotated wavefunction

$$\hat{\Psi}^{\mathcal{S}}(\mathrm{r}) \equiv \mathbb{P}^\dagger\,\Psi^{\mathcal{S}}(\mathrm{r}), \qquad \mathcal{E}^{\mathcal{S}} = \mathbf{k}^2/(2\mu), \qquad \mathbf{k} = \mu v_{\mathrm{rel}}.$$

Analytic approximation — Coulomb wavefunctions

The rotated wavefunction can be expressed as

$$\hat{\Psi}^{\mathcal{S}}_{\mathbf{k}}(\mathbf{r}) = \underbrace{\Phi_{\mathbf{k}}(\mathbf{r})}_{\text{diagonal } 4\times 4 \text{ matrix}} \cdot \underbrace{\mathcal{N}^{\mathcal{S}}}_{\text{vector determining the asymptotic behavior}}$$

$$\mathcal{N}^{\mathcal{S}} \equiv (N^{\mathcal{S}}_{1\bar{1}}, N^{\mathcal{S}}_{1\bar{2}}, N^{\mathcal{S}}_{2\bar{1}}, N^{\mathcal{S}}_{2\bar{2}})^{\mathrm{T}}$$

Asymptotically

Incoming plane-wave — Outgoing spherical-wave

$$\Phi_{\mathbf{k}}(\mathbf{r}) \overset{r\to\infty}{\simeq} e^{\mathbb{i}\mathbf{k}\cdot\mathbf{r}} \times \mathbb{1} + \frac{e^{\mathbb{i}kr}}{r} \times \mathbb{F}_{\mathbf{k}}(\Omega_{\mathbf{r}}),$$

$$\mathbb{F}_{\mathbf{k}} = \mathrm{diag}\{f^{a_1}_{\mathbf{k}}, f^{a_2}_{\mathbf{k}}, f^{a_3}_{\mathbf{k}}, f^{a_4}_{\mathbf{k}}\}.$$

Analytic approximation — Coulomb wavefunctions

We seek solutions that asymptote to a pure flavor state at $r \to \infty$

$$\Psi^{\mathcal{S}}_{\mathbf{k}}(\mathbf{r}) \overset{r\to\infty}{\simeq} e^{\mathbb{i}\mathbf{k}\cdot\mathbf{r}} \times \mathcal{U}^{\mathcal{S}} + \frac{e^{\mathbb{i}kr}}{kr} \times \mathcal{T}^{\mathcal{S}}_{\mathbf{k}}(\Omega_{\mathbf{r}}), \qquad \mathcal{U}^{\mathcal{S}} \equiv (\delta^{\mathcal{S}}_{1\bar{1}}, \delta^{\mathcal{S}}_{1\bar{2}}, \delta^{\mathcal{S}}_{2\bar{1}}, \delta^{\mathcal{S}}_{2\bar{2}})^{\mathrm{T}}.$$

Hence

$$\mathcal{U}^{\mathcal{S}} = \mathbb{P} \cdot \mathcal{N}^{\mathcal{S}}, \qquad \mathcal{T}^{\mathcal{S}}_{\mathbf{k}} = k\, \mathbb{P}\, \mathbb{F}_{\mathbf{k}}\, \mathcal{N}^{\mathcal{S}} = k\, \mathbb{P}\, \mathbb{F}_{\mathbf{k}}\, \mathbb{P}^{\dagger}\, \mathcal{U}^{\mathcal{S}}.$$

The **transition amplitude** from $\mathcal{S} = \{ij\}$ to $\mathcal{S}' = \{i'j'\}$ is

$$[\mathcal{T}_{\mathbf{k}}]^{\mathcal{S}}_{\mathcal{S}'} = k\, \mathcal{U}^{\mathcal{S}'\dagger}\, \mathbb{P}\, \mathbb{F}_{\mathbf{k}}\, \mathbb{P}^{\dagger}\, \mathcal{U}^{\mathcal{S}} = k \sum_{a} \mathbb{P}^{\mathcal{S}'a}\, f^{a}_{\mathbf{k}}\, (\mathbb{P}^{\mathcal{S}a})^{*},$$

and the unrotated wavefunction reads

$$\Psi^{\mathcal{S}}_{\mathbf{k}}(\mathbf{r}) = \mathbb{P}\, \Phi_{\mathrm{k}}(\mathbf{r})\, \mathbb{P}^{\dagger}\, \mathcal{U}^{\mathcal{S}}.$$

Partial wave analysis

Partial-wave expansion

$$\mathcal{T}^{\mathcal{S}}_{\mathbf{k}}(\Omega_{\mathbf{r}}) = \sum_{\ell=0}^{\infty} (2\ell+1)\, P_\ell(\hat{\mathbf{k}}\cdot\hat{\mathbf{r}})\, \mathcal{T}^{\mathcal{S}}_{|\mathbf{k}|,\ell}$$

$$f^{a}_{\mathbf{k}}(\Omega_{\mathbf{r}}) = \sum_{\ell=0}^{\infty} (2\ell+1)\, P_\ell(\hat{\mathbf{k}}\cdot\hat{\mathbf{r}})\, f^{a}_{|\mathbf{k}|,\ell}$$

For the Coulomb wavefunctions:

$$f^{a}_{|\mathbf{k}|,\ell} \equiv \frac{e^{\mathbb{i}2\Delta_\ell(\zeta_a)} - 1}{2\mathbb{i}\,k}, \qquad e^{2\mathbb{i}\Delta_\ell(\zeta_a)} = \frac{\Gamma(1+\ell+\mathbb{i}\zeta_a)}{\Gamma(1+\ell-\mathbb{i}\zeta_a)}$$

Velocity dependence

$\zeta_a \equiv a/v_{\mathrm{rel}}$

The partial-wave cross-sections

$$\frac{\sigma_\ell^{\mathcal{S}\to\mathcal{S}'}}{\sigma_\ell^{U}} = \left|[\mathcal{T}_{|\mathrm{k}|,\ell}]^{\mathcal{S}}_{\mathcal{S}'}\right|^2,$$

Unitarity bound

$$\sigma_\ell^{U} \equiv 4\pi\frac{2\ell+1}{\mathrm{k}^2}$$

Asymmetries

CP asymmetries

We parametrize the CP asymmetries as

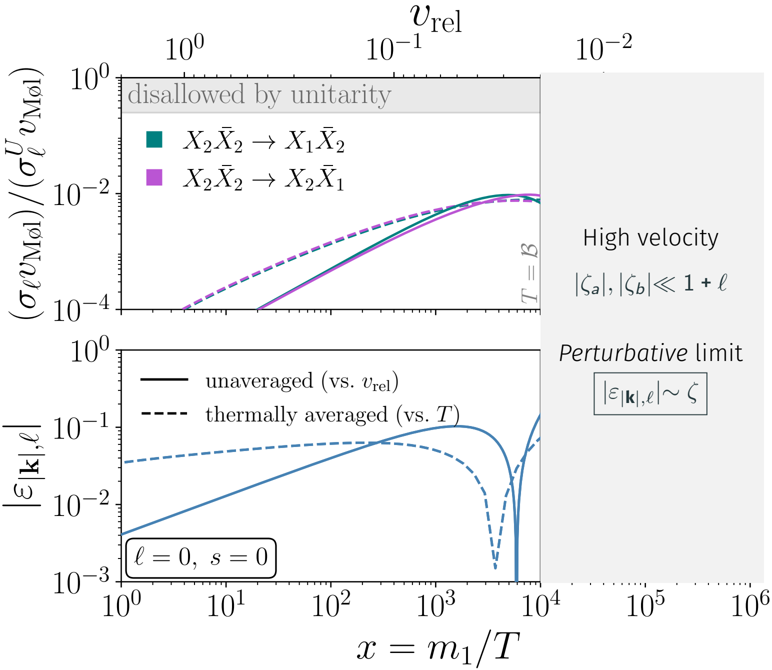
$$[\varepsilon_{|\mathsf{k}|,\ell}]_{\mathcal{S}\to\mathcal{S}'} = \frac{|[\mathcal{T}_{|\mathsf{k}|,\ell}]^{\mathcal{S}}_{\mathcal{S}'}|^2 - |[\mathcal{T}_{|\mathsf{k}|,\ell}]^{\bar{\mathcal{S}}}_{\bar{\mathcal{S}}'}|^2}{|[\mathcal{T}_{|\mathsf{k}|,\ell}]^{\mathcal{S}}_{\mathcal{S}'}|^2 + |[\mathcal{T}_{|\mathsf{k}|,\ell}]^{\bar{\mathcal{S}}}_{\bar{\mathcal{S}}'}|^2}$$

Having complex LG potential is crucial to generate an asymmetry!

$$= \frac{\sum_{a,b} \mathrm{Im}\left[f^a_{|\mathsf{k}|,\ell} f^{b\,*}_{|\mathsf{k}|,\ell}\right] \mathrm{Im}\left[\mathbb{P}^{\mathcal{S}a}(\mathbb{P}^{\mathcal{S}'a})^* \, \mathbb{P}^{\mathcal{S}'b}(\mathbb{P}^{\mathcal{S}b})^*\right]}{\sum_{a,b} \mathrm{Re}\left[f^a_{|\mathsf{k}|,\ell} f^{b\,*}_{|\mathsf{k}|,\ell}\right] \mathrm{Re}\left[\mathbb{P}^{\mathcal{S}a}(\mathbb{P}^{\mathcal{S}'a})^* \, \mathbb{P}^{\mathcal{S}'b}(\mathbb{P}^{\mathcal{S}b})^*\right]}.$$

Unitarity & CPT invariance: $[\mathcal{T}_{|\mathsf{k}|,\ell}]^{1\bar{1}}_{2\bar{2}} = [\mathcal{T}_{|\mathsf{k}|,\ell}]^{2\bar{2}}_{1\bar{1}}, \quad [\mathcal{T}_{|\mathsf{k}|,\ell}]^{1\bar{2}}_{2\bar{1}} = [\mathcal{T}_{|\mathsf{k}|,\ell}]^{2\bar{1}}_{1\bar{2}}$

CP violation arises in the $j\bar{j} \to 1\bar{2}, 2\bar{1}$ scatterings.

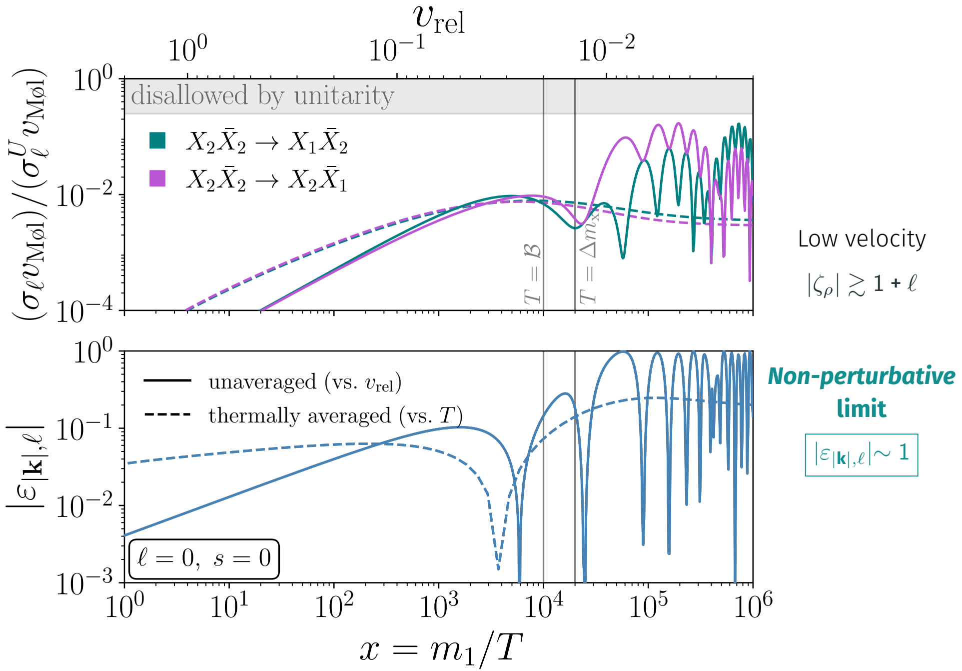


High velocity

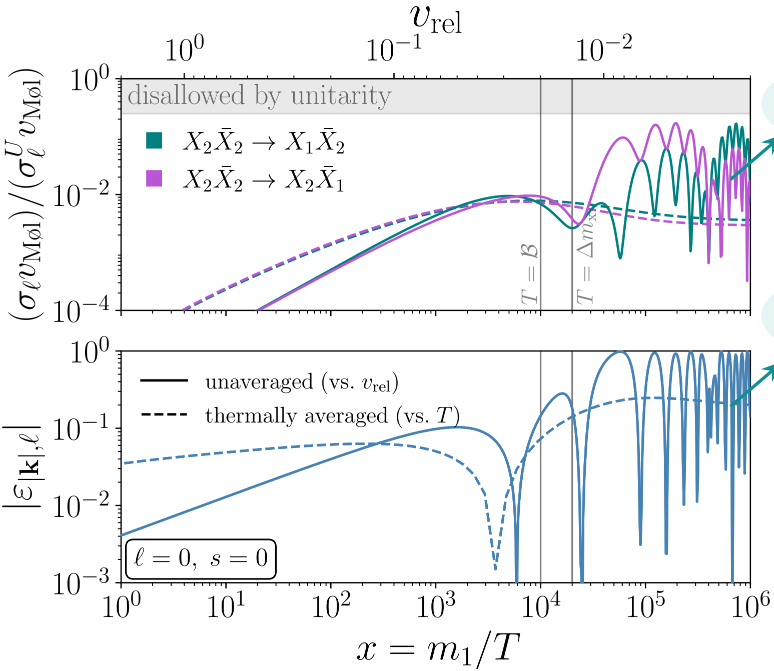
$|\zeta_a|, |\zeta_b| \ll 1 + \ell$

Perturbative limit

$|\varepsilon_{|\mathbf{k}|,\ell}| \sim \zeta$

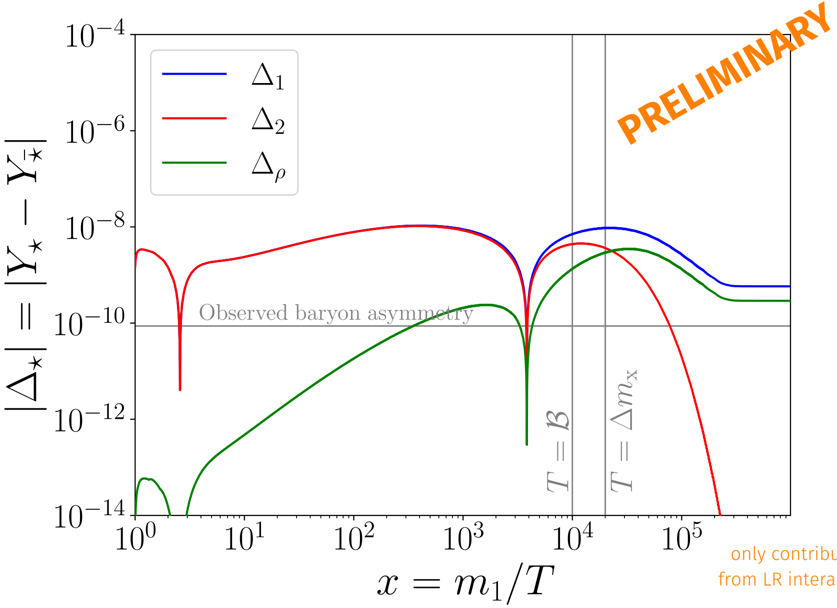


$v_{\rm rel}$
10^0 10^{-1} 10^{-2}
$(\sigma_\ell v_{\rm M\o l})/(\sigma_\ell^U v_{\rm M\o l})$
disallowed by unitarity
$X_2\bar{X}_2 \to X_1\bar{X}_2$
$X_2\bar{X}_2 \to X_2\bar{X}_1$
$T = \mathcal{B}$
$T = \Delta m_{\rm x}$
Low velocity
$|\zeta_\rho| \gtrsim 1 + \ell$
$|\varepsilon_{|\mathbf{k}|,\ell}|$
unaveraged (vs. $v_{\rm rel}$)
thermally averaged (vs. T)
$\ell = 0,\ s = 0$
Non-perturbative limit
$|\varepsilon_{|\mathbf{k}|,\ell}| \sim 1$
$x = m_1/T$



Saturation of the unitarity bound

Maximal CP asymmetry even for small couplings



only contribution
from LR interactions

Conclusions

Conclusions

- We study a novel baryogenesis scenario involving long-range interactions between non-relativistic particles.
- CP violation necessitates $\mathbb{V}_{X\bar{X}}$ to be complex.
- $|\epsilon_{|\mathbf{k},\ell|}| \sim 1$ can be attained even for weak couplings at low velocities.
- Long-range CP-violating interactions saturate the unitarity bound in a continuum of momenta.
- Non-perturbative dynamics can alter the phenomenological predictions of various well-established theories!