Neutron-antineutron oscillation improvements and baryogenesis

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Apologies for few references. Many in our paper – please consult

Outline

Introduction

NNbar oscillations for free neutrons

EFT for Nnbar oscillations

Minimal EFT for ΔB=2 baryogenesis

Calculations of baryon asymmetry and n-nbar oscillations

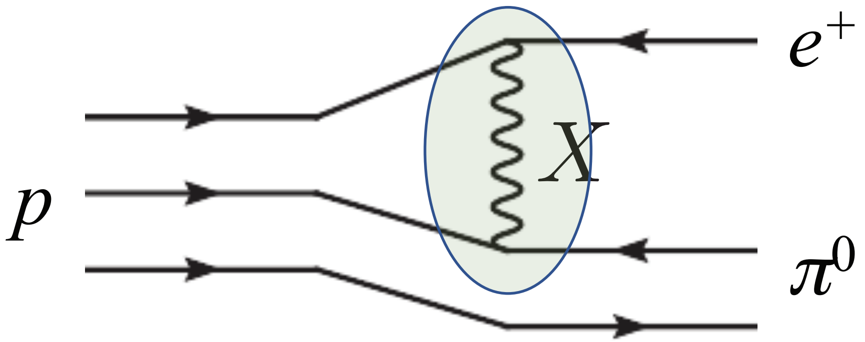
Conclusion

B and L are accidental symmetries of SM – subject to violation

Proton decay can occur by higher-dim operator. $$\frac{1}{\Lambda_p^2}(\bar{d}^c \bar{u}^c\, q\, \ell) + \cdots$$

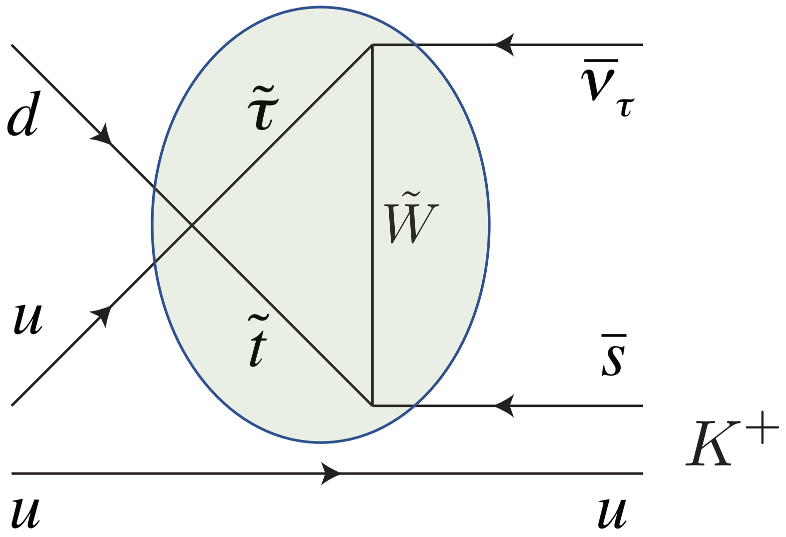
This operator likely exists with Planck suppressed couplings at least. ΔB=ΔL=1

This operator could exist with smaller scale suppression in GUT theories, etc..



$$p \to e^+\pi^0$$

(SUSY and Non-SUSY GUTs)

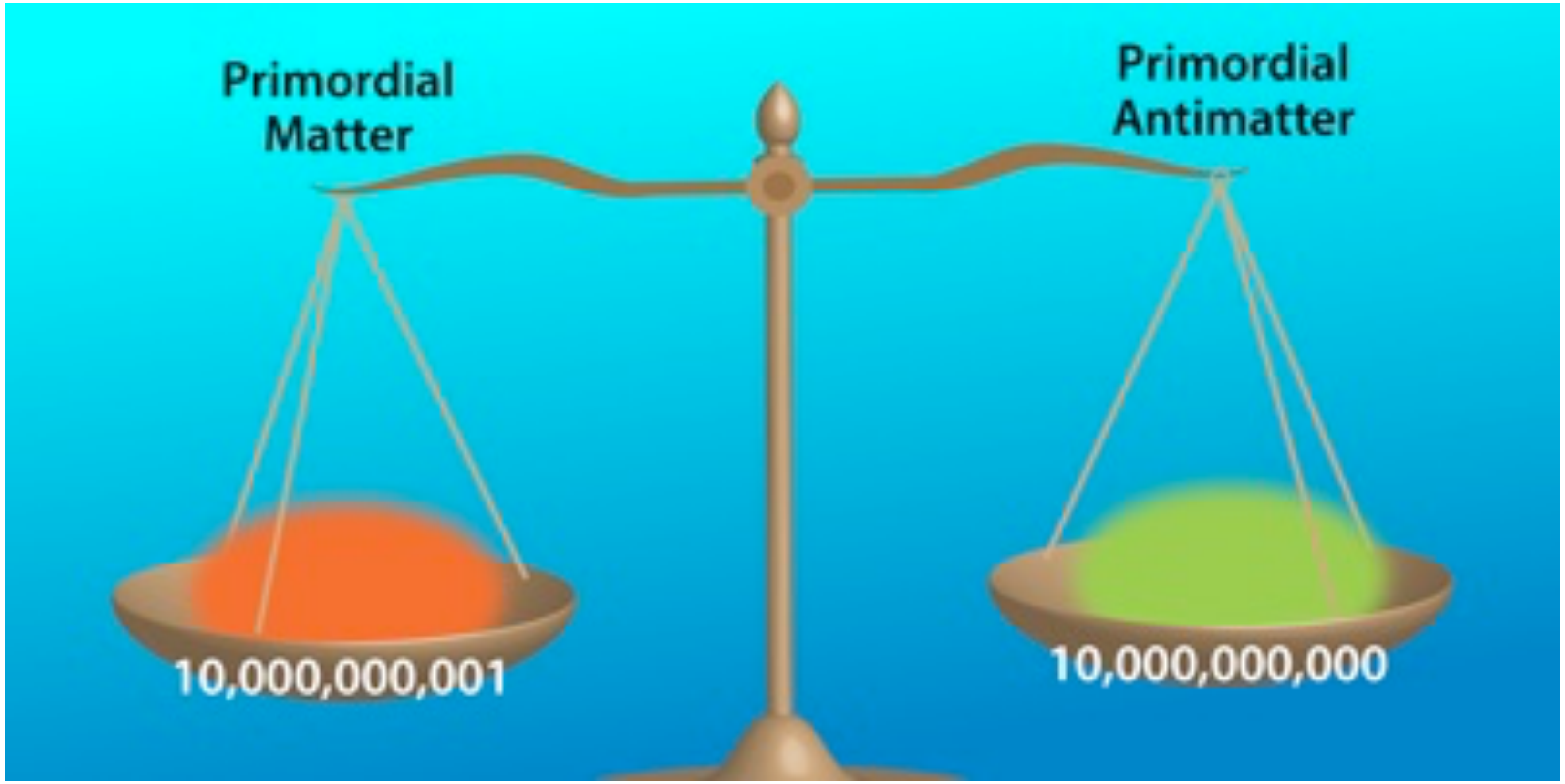


$$p \to \bar{\nu} K^+$$

(SUSY GUTs)

B, L violation connected to baryon asymmetry puzzle

B-L violation required to avoid sphaleron washout above EW scale – proton decay conserves B-L



M.G. Strauss

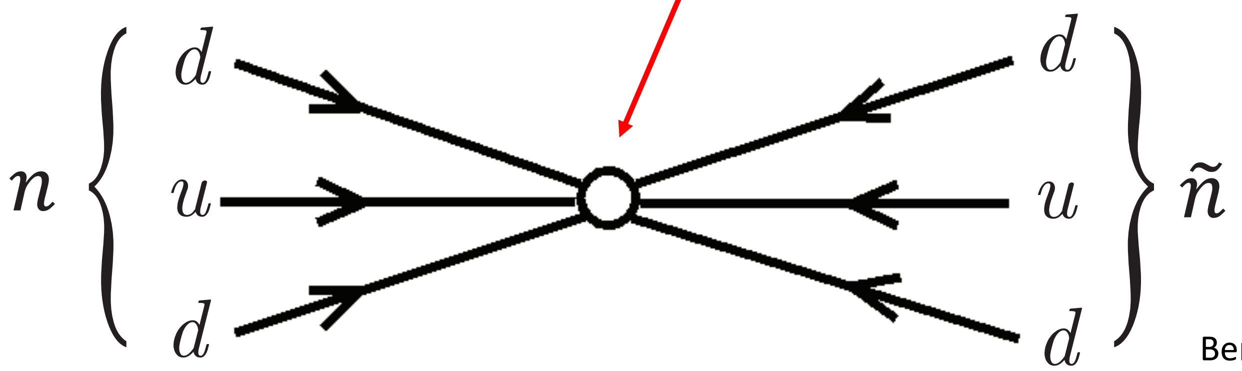
Let’s look to more direct connections to B violation.

ΔB=2 baryon number violating interaction in EFT

Dimension 9 operator

$$\frac{1}{\Lambda_n^5}$$

Non-renormalizable interaction
→ mass^5 in denominator.



Berezhiani, Vainshtein, 2018

Other $|\Delta B| = 2$, $\Delta L = 0$ processes include dinucleon decays: $nn \to \pi^0\pi^0$, $pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$ probe the same operators as n-$\bar{n}$ oscillation, while $pp \to K^+K^+$ can be relevant for B-violating new physics with suppressed couplings to first-generation quarks.

Past and future experimental sensitivities to oscillation lifetime

- Current free neutron bound τ ~ 10^8 s from ILL, and somewhat better at Super-K
- Future prospects at ESS (free neutrons), DUNE and Hyper-K up to τ ~ 10^{9-10} s
- Such oscillation times probe new physics scales up to Λ_{new}~ $(\tau\Lambda_{QCD}{}^6)^{1/5}$ ~ 10^{5-6} GeV.
- Probes beyond LHC scales (albeit in only just this way)

Quantum mechanics of neutron-antineutron oscillations

Evolution governed by Schrödinger equation:

$$\mathcal{H}_{\mathrm{eff}}|\psi\rangle = i\frac{\partial}{\partial t}|\psi\rangle$$

Where Hamiltonian given by

$$\begin{aligned}
\mathcal{H}_{\mathrm{eff}}|n\rangle &= \left(m_n - i\frac{\Gamma}{2} + \mathcal{E}_n\right)|n\rangle + \delta|\bar{n}\rangle \\
\mathcal{H}_{\mathrm{eff}}|\bar{n}\rangle &= \left(m_n - i\frac{\Gamma}{2} + \mathcal{E}_{\bar{n}}\right)|\bar{n}\rangle + \delta|n\rangle
\end{aligned}$$

JW, "Neutron-antineutron oscillations", 2018

The matrix $\langle \mathcal{H}_{\text{eff}} \rangle$ in the $\{n, \bar{n}\}$ basis is

$$\langle \mathcal{H}_{\text{eff}} \rangle = \begin{pmatrix} m_n - i\frac{\Gamma}{2} + \mathcal{E}_n & \delta \\ \delta & m_n - i\frac{\Gamma}{2} + \mathcal{E}_{\bar{n}} \end{pmatrix}$$

where m_n is mass of the neutron, Γ is the decay width (i.e., neutron lifetime is $\tau_n = 1/\Gamma$), δ is contribution from $\mathcal{H}_{\text{eff}}$ that enables $n \leftrightarrow \bar{n}$ transitions, and $\mathcal{E}_n$ and $\mathcal{E}_{\bar{n}}$ are any other additional contributions to the energy of the n and $\bar{n}$ states respectively. If the neutrons were propagating completely freely in space with no other matter around and no magnetic field, etc., $\mathcal{E}_{n,\bar{n}} = 0$. But since that is never the case in experimental configurations, we must keep this term.

If the neutron and antineutron mix then energy eigenstates (or, “mass eigenstates”) $\mathcal{H}_{\text{eff}}$ are mixtures of n and $\bar{n}$ which we denote as n_1 and n_2:

$$\begin{pmatrix} |n_1\rangle \\ |n_2\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |n\rangle \\ |\bar{n}\rangle \end{pmatrix}$$

Assuming $|n_i>$ are eigenstates of Heff

$$\mathcal{H}_{\text{eff}}|n_i\rangle = E_i|n_i\rangle$$

one then expands evolves the wave function

$$|\psi\rangle(t) = c_1|n_1\rangle e^{-iE_1 t} + c_2|n_2\rangle e^{-iE_2 t}$$

Subjecting it to boundary condition $|\psi>(0)=|n>$ we find

$$|\psi\rangle(t) = \left(\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t}\right)|n\rangle + \cos\theta\sin\theta\left(e^{-iE_1 t} - e^{-iE_2 t}\right)|\bar{n}\rangle$$

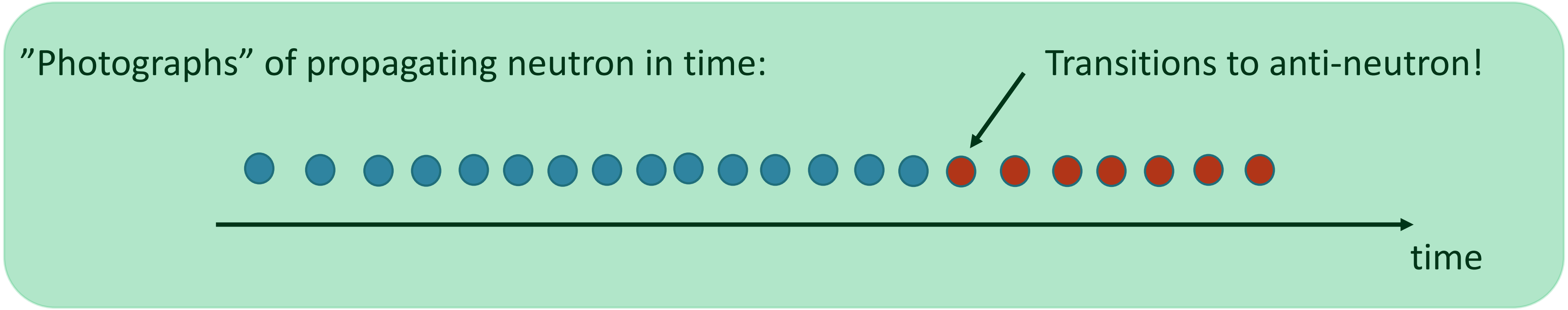
$$|\psi\rangle(t) = \left(\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t}\right)|n\rangle + \cos\theta\sin\theta\left(e^{-iE_1 t} - e^{-iE_2 t}\right)|\bar{n}\rangle$$

We compute the probability that $|\psi\rangle(t)$ is measured to be a $\bar{n}$ by the standard probability computation in quantum mechanics,

$$P[\bar{n}(t)] = |\langle\bar{n}|\psi\rangle(t)|^2 = e^{-\Gamma t}\sin^2(2\theta)\sin^2\left(\frac{\Delta E\, t}{2}\right), \quad \text{where,}$$

$$\Gamma = \mathrm{Im}(E_1 + E_2), \quad \text{and} \quad \Delta E = E_1 - E_2.$$

The first term, $e^{-\Gamma t}$, is associated with the lifetime of the neutron.



Approximations valid for reactor environment

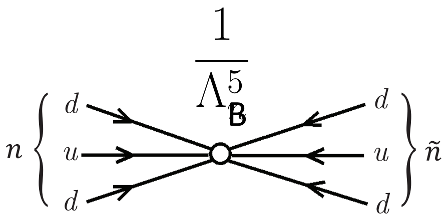
For $m_n \gg |\mathcal{E}_n - \mathcal{E}_{\bar{n}}| \gg \delta$, which will be justified later in the nuclear reactor experimental context, one can make the approximations

$$E_1 \simeq m_n + \mathcal{E}_n - i\frac{\Gamma}{2}, \quad E_2 \simeq m_n + \mathcal{E}_{\bar{n}} - i\frac{\Gamma}{2}, \quad \text{where} \quad \mathcal{E}_n = -\mathcal{E}_{\bar{n}} = -\mu_n \cdot B$$

$$\Delta E = E_1 - E_2 = \mathcal{E}_n - \mathcal{E}_{\bar{n}}, \quad \text{and} \quad \sin 2\theta = \frac{2\delta}{\mathcal{E}_n - \mathcal{E}_{\bar{n}}}.$$

Under these assumptions we can now rewrite the transition probability as

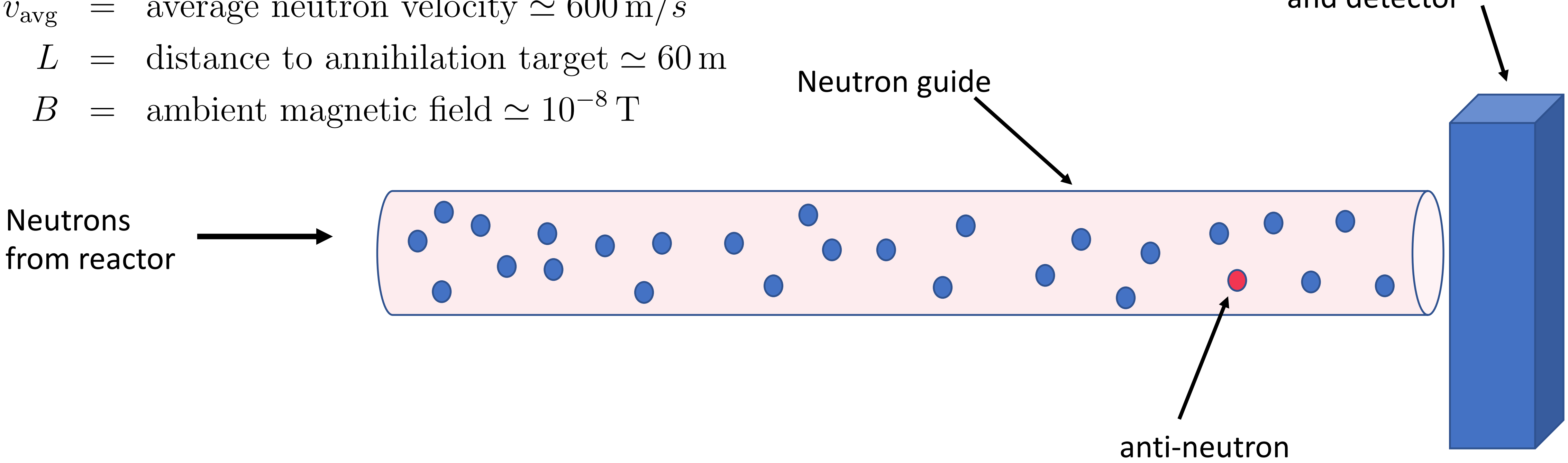
$$\boxed{P[\bar{n}(t)] = e^{-\Gamma t}\left(\frac{2\delta}{\mathcal{E}_n - \mathcal{E}_{\bar{n}}}\right)^2 \sin^2\left(\frac{(\mathcal{E}_n - \mathcal{E}_{\bar{n}})t}{2}\right).}$$



Recall, δ is the interaction that allows neutron to antineutron transition!

$$\delta = m_n^6/\Lambda_B^5$$

$$
\begin{aligned}
F &= \text{Flux of neutrons} \simeq 1.25 \times 10^{11}\,\text{neutrons}/s \\
v_{\text{avg}} &= \text{average neutron velocity} \simeq 600\,\text{m}/s \\
L &= \text{distance to annihilation target} \simeq 60\,\text{m} \\
B &= \text{ambient magnetic field} \simeq 10^{-8}\,\text{T}
\end{aligned}
$$



From the average velocity data, the average time for the neutron to make it to the annihilation target is $t_{\text{avg}} = L/v_{\text{avg}} \simeq 0.1\,s$. This is where the state $|\psi\rangle(t)$ is measured and its wave function collapses to n or $\bar{n}$, at time $= t_{\text{avg}}$ when it interacts with the annihilation target.

$$
P[\bar{n}(t_{\text{avg}})] \simeq \delta^2 t_{\text{avg}}^2 = 10^{-18}\left(\frac{10^8\,s}{\tau_{n\bar{n}}}\right)^2\left(\frac{t_{\text{avg}}}{0.1\,s}\right)^2, \Longrightarrow \tau_{n\bar{n}} \simeq (2\times 10^8\,s)\left(\frac{F}{1.25\times 10^{11}\,\text{neutrons/s}}\right)^{1/2}\left(\frac{T_{\text{run}}}{1\,\text{yr}}\right)^{1/2}.
$$

where $\tau_{n\bar{n}} \equiv 1/\delta$ (oscillation time)

~ Current limit!

Let’s explore connection of n-nbar oscillations with baryogenesis

Assume: simple minimal EFT with minimal new particle content that achieves baryogenesis through B violating decays.

These new particles can simultaneously allow n-nbar oscillations → correlated

One direction (“Majorana fermion baryogenesis”)

Other directions: EW baryogenesis, Affleck–Dine baryogenesis, leptogenesis, …

Lowest dimensional operator contributing to n-nbar oscillations is dimension 9

$$\mathcal{O}_{n\bar{n}} \sim (uudddd)$$

We will focus on just one of these operators for illustration, and because it matches the low-scale EFT of the minimal scenario for baryogenesis.

$$\mathcal{L} \supset c_1 \frac{1}{2} \epsilon_{ijk}\epsilon_{i'j'k'} (\bar{u}_i^c P_R d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) + \text{h.c.}\,,$$

$$\text{with } c_1 \equiv \left(\Lambda_{n\bar{n}}^{(1)}\right)^{-5}.$$

We performed state-of-the-art RG evolution of the operator coefficient

$$\frac{c_1(\mu_0)}{c_1(M)} = \left[\frac{\alpha_s^{(4)}(m_b)}{\alpha_s^{(4)}(\mu_0)}\right]^{\frac{6}{25}} \left[\frac{\alpha_s^{(5)}(m_t)}{\alpha_s^{(5)}(m_b)}\right]^{\frac{6}{23}} \left[\frac{\alpha_s^{(6)}(M)}{\alpha_s^{(6)}(m_t)}\right]^{\frac{2}{7}}$$

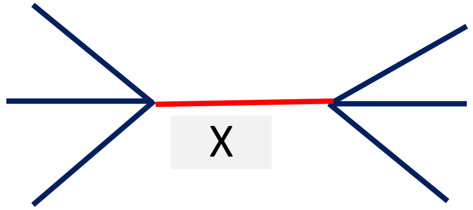
$$= \left\{0.726\,,\;\; 0.684\,,\;\; 0.651\,,\;\; 0.624\right\},$$

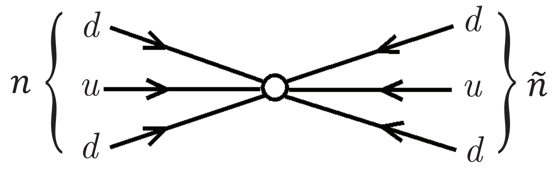
$$\text{for}\;\; M = \left\{10^3\,,\;\; 10^4\,,\;\; 10^5\,,\;\; 10^6\right\}\text{GeV}\,.$$

Majorana fermion and B violating operators – but no baryogenesis

Simple way to get n-nbar operator is introduce Majorana fermion X of mass M, coupling to SM by

$O_6 \sim \frac{1}{\Lambda^2} X u d d$





Problems creating baryogenesis:

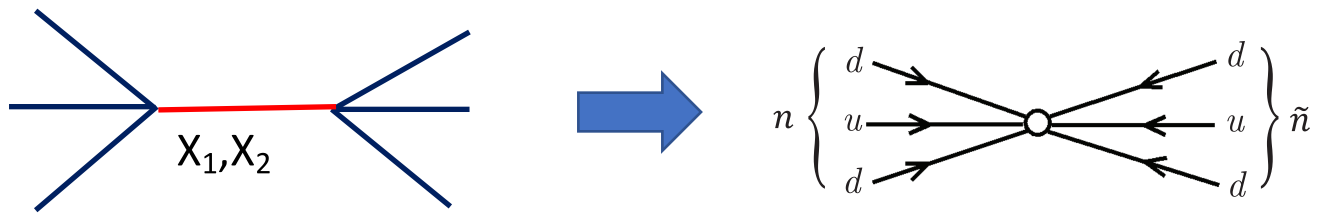
- Nanopoulos-Weinberg theorem: without B-conserving channels no baryon asymmetry
- 2→2 process such as $uX \to \bar{d}\bar{d}$ and $\bar{u}X \to dd$ have same rate and do not violate CP

Introduce a second Majorana and it can work – "minimal model"

$$\begin{aligned}
\mathcal{L} \quad \supset \quad & \eta_{X_1}\, \epsilon^{ijk} (\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_1) \\
& + \eta_{X_2}\, \epsilon^{ijk} (\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_2) \\
& + \eta_c\, (\bar{u}^i P_L X_1)(\bar{X}_2 P_R u_i) + \text{h.c.}\,, \\
& \text{with} \;\; |\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}\,,\;\; |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}\,,\;\; |\eta_c| \equiv \Lambda_c^{-2}\,.
\end{aligned}$$

Both X_1 and X_2 mediate n-$\bar{n}$ oscillation — integrating them out at tree level gives

$$c_1 = \frac{1}{\left(\Lambda_{n\bar{n}}^{(1)}\right)^5} = \frac{1}{M_{X_1}\Lambda_{X_1}^4} + \frac{1}{M_{X_2}\Lambda_{X_2}^4}\,.$$



Baryogenesis capability

Calculation of the baryon asymmetry — The relevant processes for baryogenesis include

- B violating processes: single annihilation $uX_{1,2} \to \bar{d}\bar{d}$, $dX_{1,2} \to \bar{u}\bar{d}$, decay $X_{1,2} \to udd$, and off-resonance scattering $udd \to \bar{u}\bar{d}\bar{d}$;
- B conserving processes: scattering $uX_1 \to uX_2$, co-annihilation $X_1X_2 \to \bar{u}u$, and decay $X_2 \to X_1\bar{u}u$;

as well as their inverse and CP conjugate processes. CP

Calculating baryon asymmetry

We solve set of coupled Boltzmann equations for abundances of $X_{1,2}$ and Y_{B-L} above T=140 GeV (sphalerons active above 140 GeV) and and Y_B below T=140 GeV.

Find regions of parameter space where Y_B=8.6 x 10^{-11}

We scan over all the parameters to achieve the proper baryon asymmetry.

Highest priority is getting baryon asymmetry correct – check n-nbar after.

Equal interaction scales gives baryogenesis but not n-nbar signal

$\Lambda_{X1} \sim \Lambda_{X2} \sim \Lambda_c$ is “equal interaction scale” case

For $M_{X1} \sim M_{X2} > 10^4$ GeV, Λ needs to be high to kick system out of efficient interactions that would otherwise suppress $X_{1,2}$ abundances too much.
→ *Λ too high for n-nbar signal*

For $M_{X1} \sim M_{X2} < 10^4$ GeV, Λ still needs to be somewhat high for out-of-equilibrium but then $\varepsilon_{CP} \sim M^2_{X2}/\Lambda^2$ is too low for baryogenesis.
→ *Cannot work well for baryogenesis when we force down M_{Xi} in this scenario*.

Conclusion: $\Lambda_{X1} \sim \Lambda_{X2} \sim \Lambda$ case maximum possible Y_B that also has n-nbar visible at ESS is $O(10^{-13})$, which is two orders of magnitude too low.

Therefore:

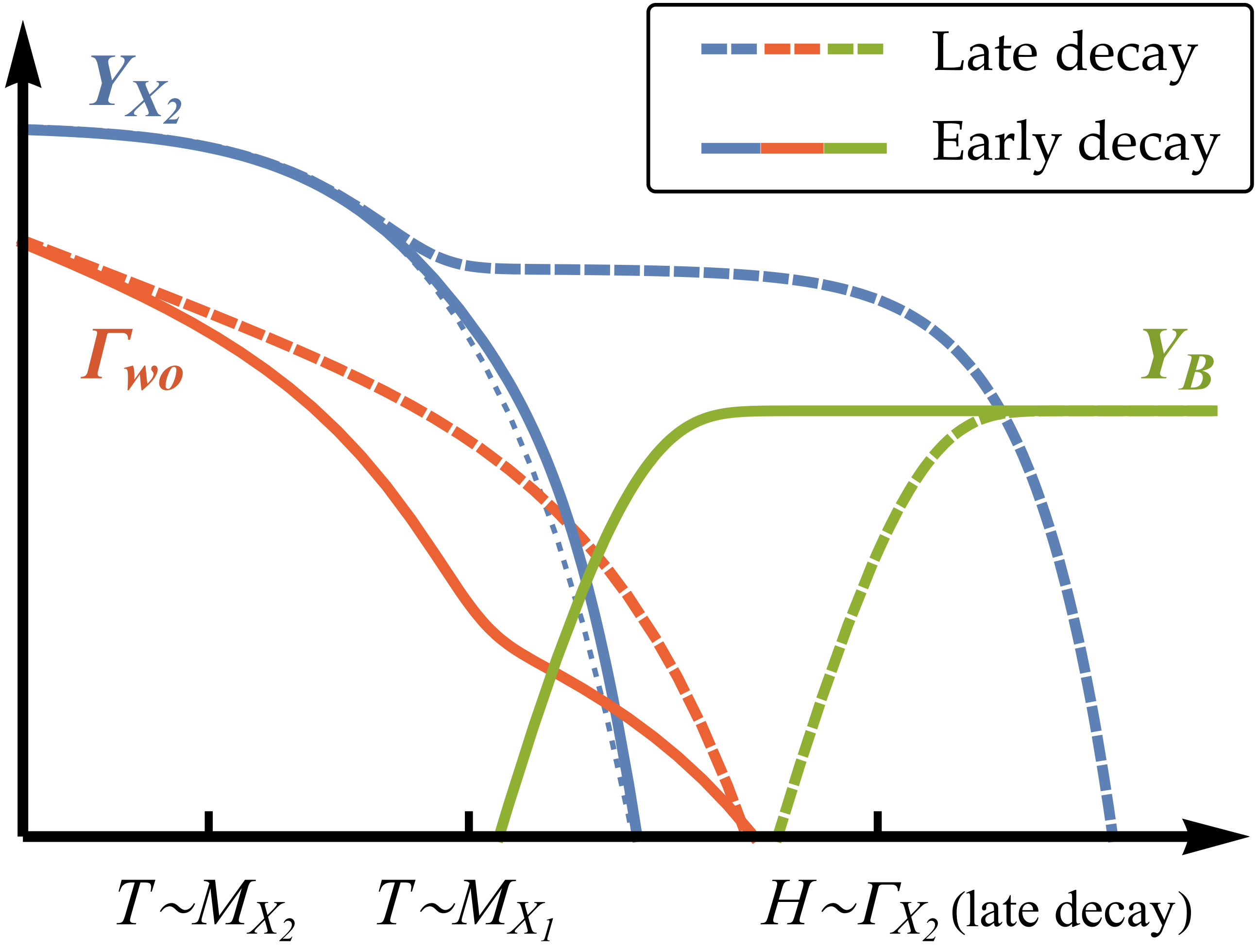
Hierarchy of Λ's needed for good baryogenesis and visible n-nbar oscillation

- Scenario possible for hierarchy in UV theory

- Or EFT generated at different loop orders

Baryogenesis and n-nbar visibility is compatible in two distinct scenarios:
Late decays of X_2 and earlier decays.

Schematic of Late decay and early decay scenarios for baryon asymmetry



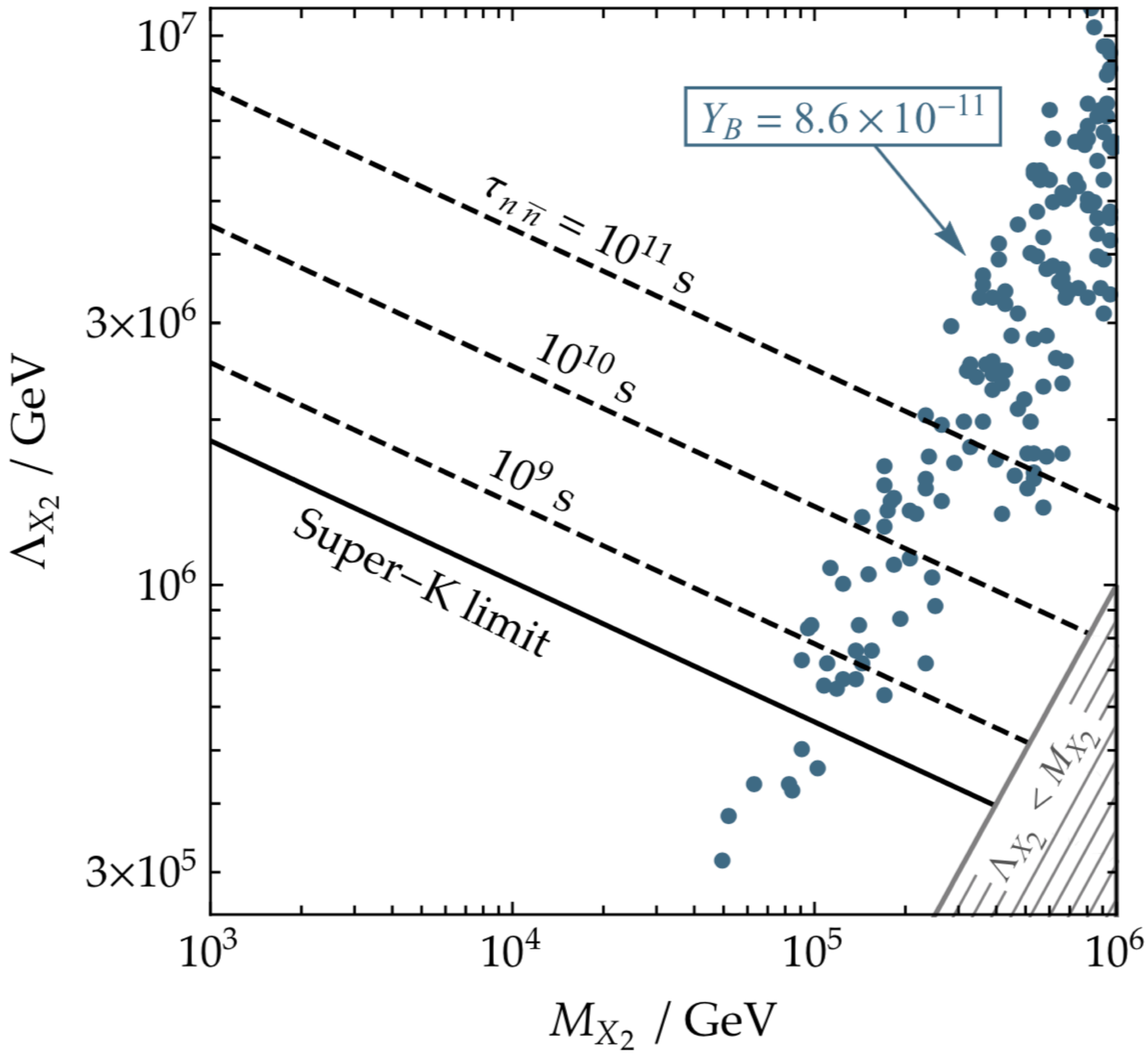


FIG. 3. Parameter space of the minimal EFT probed by n-$\bar{n}$ oscillation for the early decay scenario, assuming $M_{X_2} = 4\,M_{X_1}$. Points represent solutions with $Y_B = 8.6 \times 10^{-11}$ found in a scan over $\Lambda_{X_2} < \Lambda_{X_1} < 100\,\Lambda_{X_2}$, $M_{X_2} < \Lambda_c < \Lambda_{X_2}$. For all these points, $\Lambda_{X_1} \sim 10\,\Lambda_{X_2}$ is needed to suppress washout. The gray shaded region marks $\Lambda_{X_2} < M_{X_2}$, where EFT validity requires greater than $\mathcal{O}(1)$ coupling.

Grojean, Shakya, JW, Zhang, PRL 2018

Possibility there for discovery of n-nbar oscillations directly correlated with baryogenesis.

Conclusion

Baryon number conservation is a soft principle that we should expect to be violated.

Baryon violation is needed for baryogenesis – many ideas to implement that.

A minimal, two-state Majorana solution can provide needed baryogenesis

This theory also predicts n-nbar oscillation lifetime

1) τ < *current limit* (ruled out parameter space)

2) τ > *future projected limits* (never will be seen this way – sad)

3) *Current limit* < τ < *future projected limits* (discovery! – how likely?)