GENERALITAT VALENCIANA Gen—T

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The new physics potential of free neutron-antineutron oscillations at the ESS

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ESS: European Spallation Source

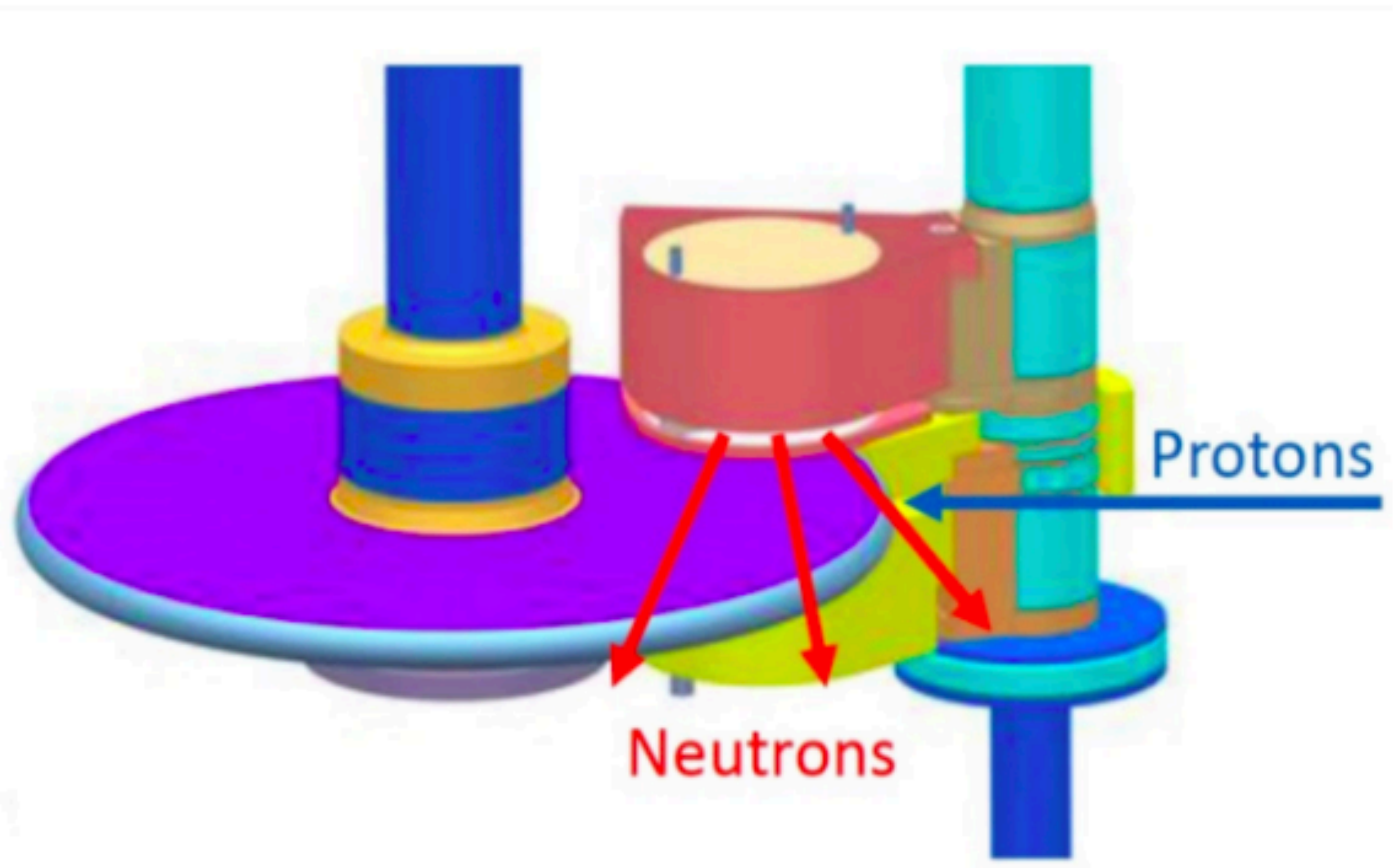
Located at: Lund, Sweden

A high intensity spallation source: neutron factory

2 GeV protons (3ms long pulse hit rotating tungsten target)

Cold neutrons after interaction with moderators $10^{(12-13)}\ n/s$

nnbar.eu



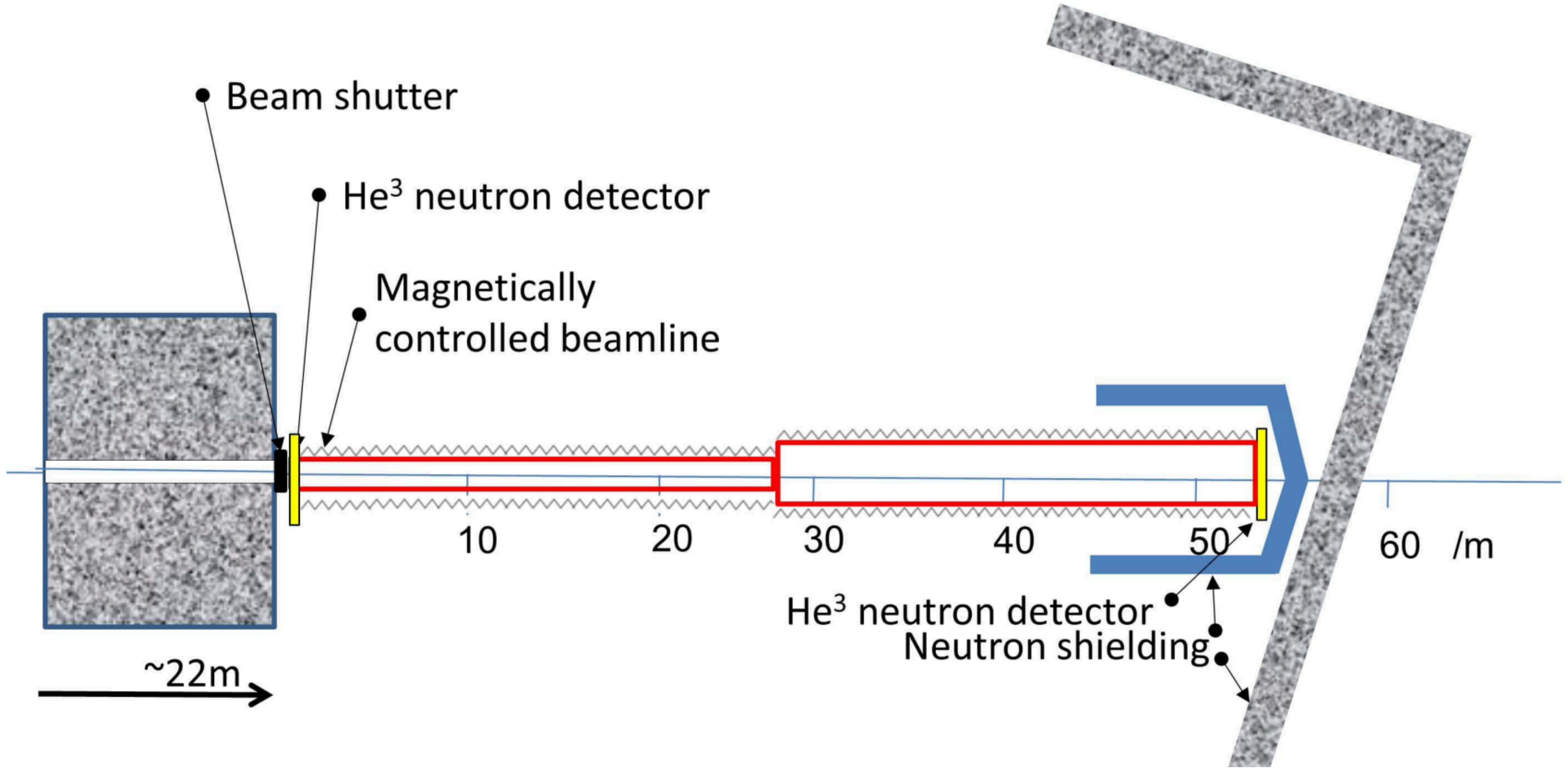
HIBEAM and NNBAR @ESS

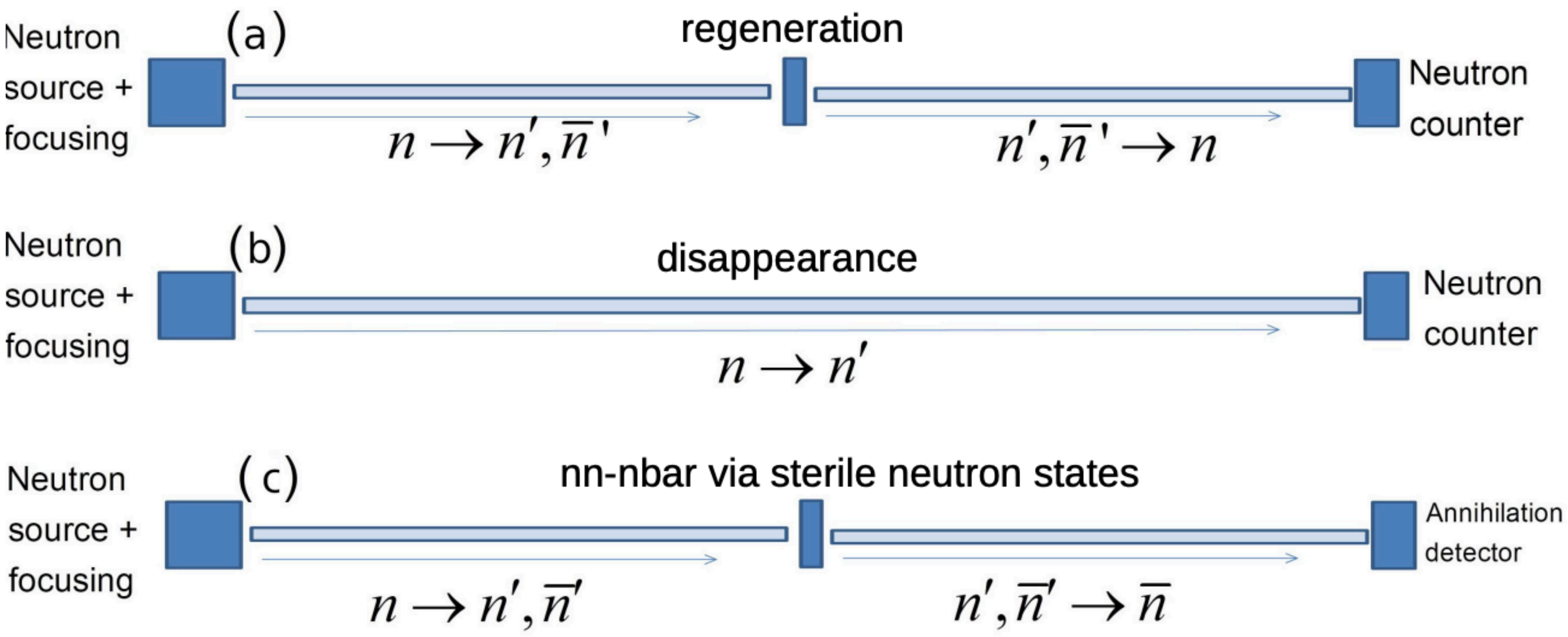
1st stage: HIBEAM

High **I**ntensity **B**aryon

Extraction **a**nd **M**easurement

$6.4 \times 10^{10} n/s$

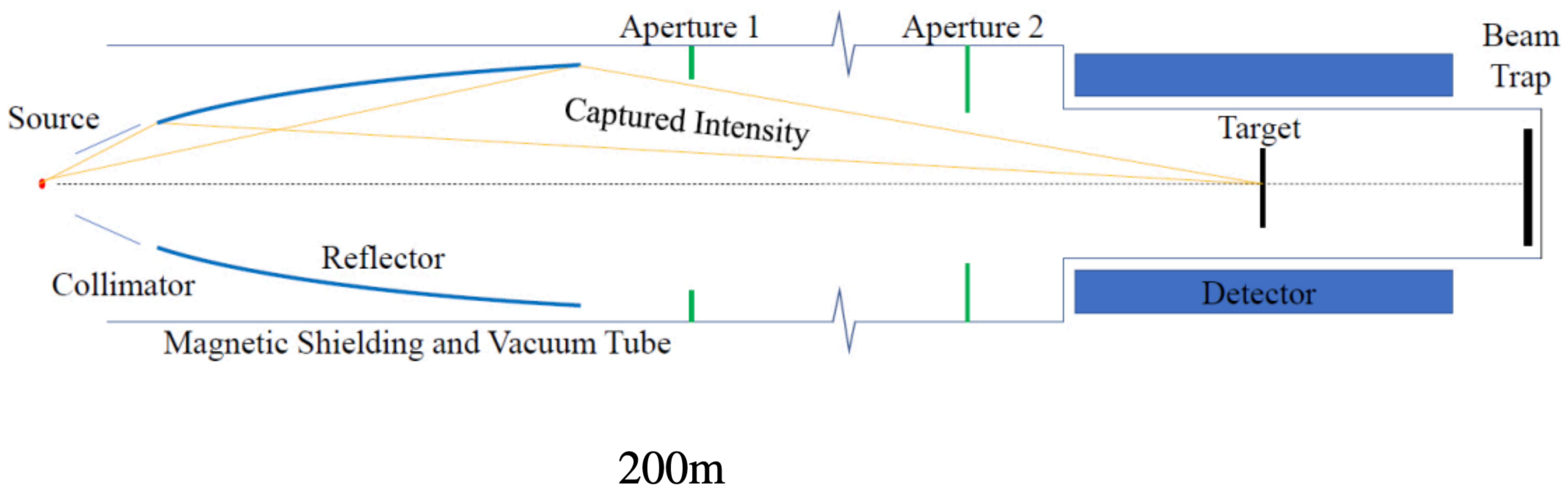


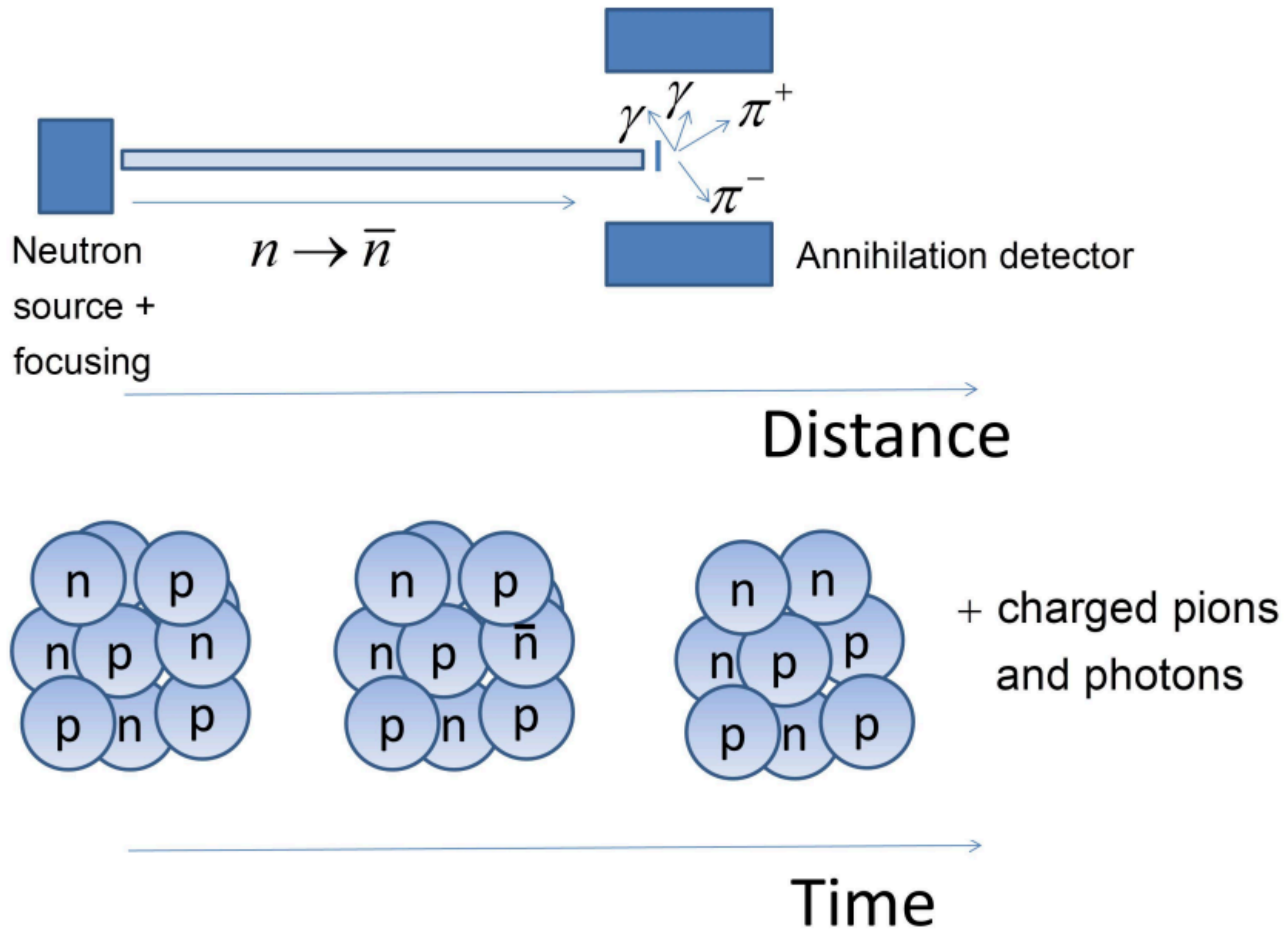


HIBEAM and NNBAR @ESS

2nd stage: NNBAR

Search for free $n - \bar{n}$ oscillations : pure baryon number violation by 2 units





Why Free neutron-antineutron oscillations

nuclear suppression factor

bound to free lifetime conversion:

subject to assumptions

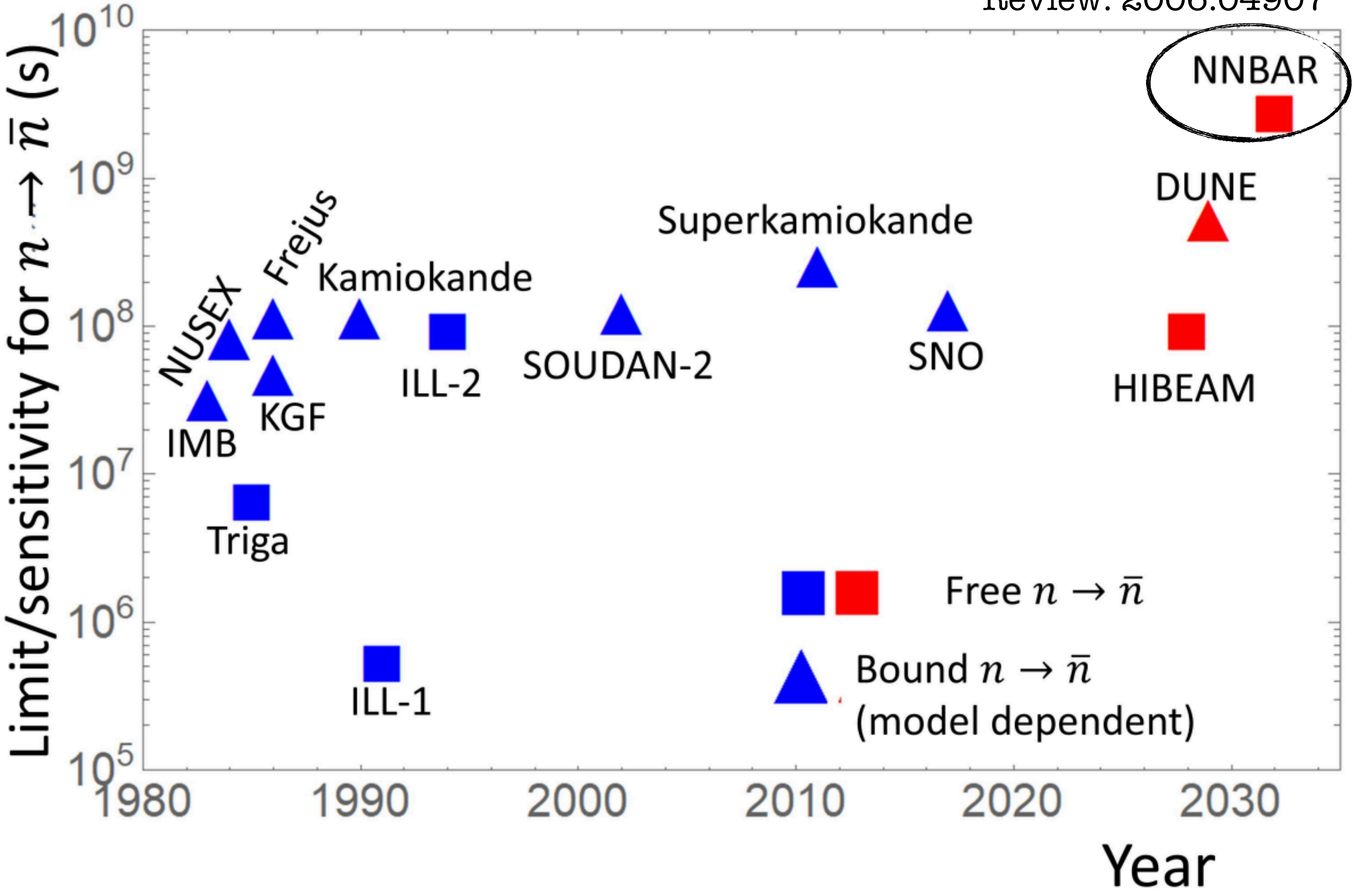
BNV condensates

1507.05478

New long range forces

1606.08374

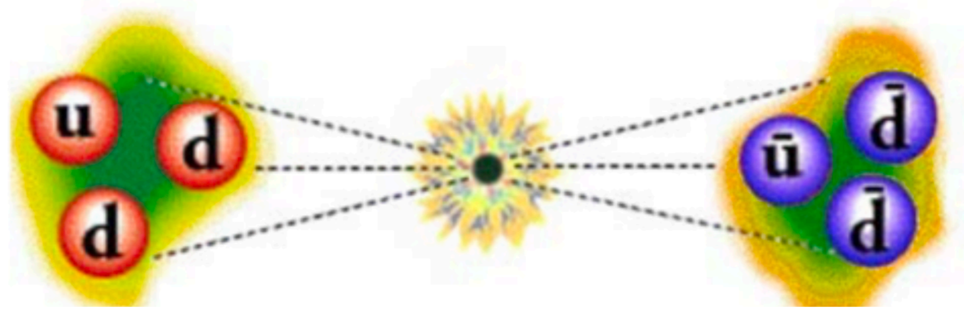
Review: 2006.04907



Why these searches are exciting?

Access to baryon number violating new physics in TeV-PeV scale

$\Delta B = 2$



Expected sensitivity at ESS: $\tau_{n\bar{n}} \sim 10^{10} s$

Dimensional analysis: $\tau_{n\bar{n}}^{-1} \sim \frac{\Lambda_{\mathrm{QCD}}^6}{\Lambda_{\mathrm{NP}}^5} \implies \Lambda_{\mathrm{NP}} \sim 10^6$ **GeV**

Baryon number violation (BNV)

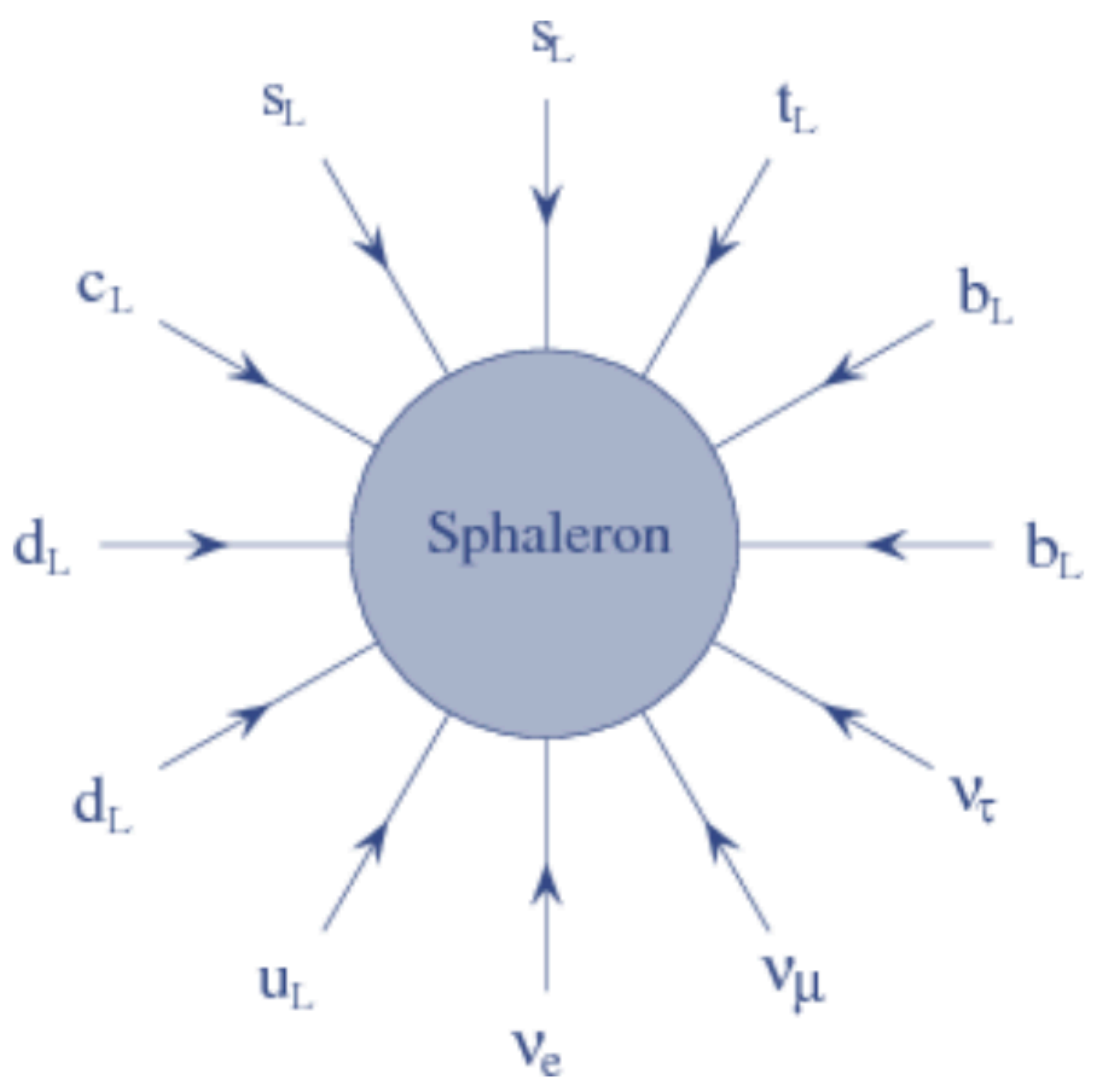
Within the SM baryon number (B) is a good global symmetry

Any observation of BNV: smoking gun for BSM physics

Nonperturbative instanton effects in the SU(2) sector of the SM break B and L but conserves B-L

Explanation of the baryon asymmetry of the Universe

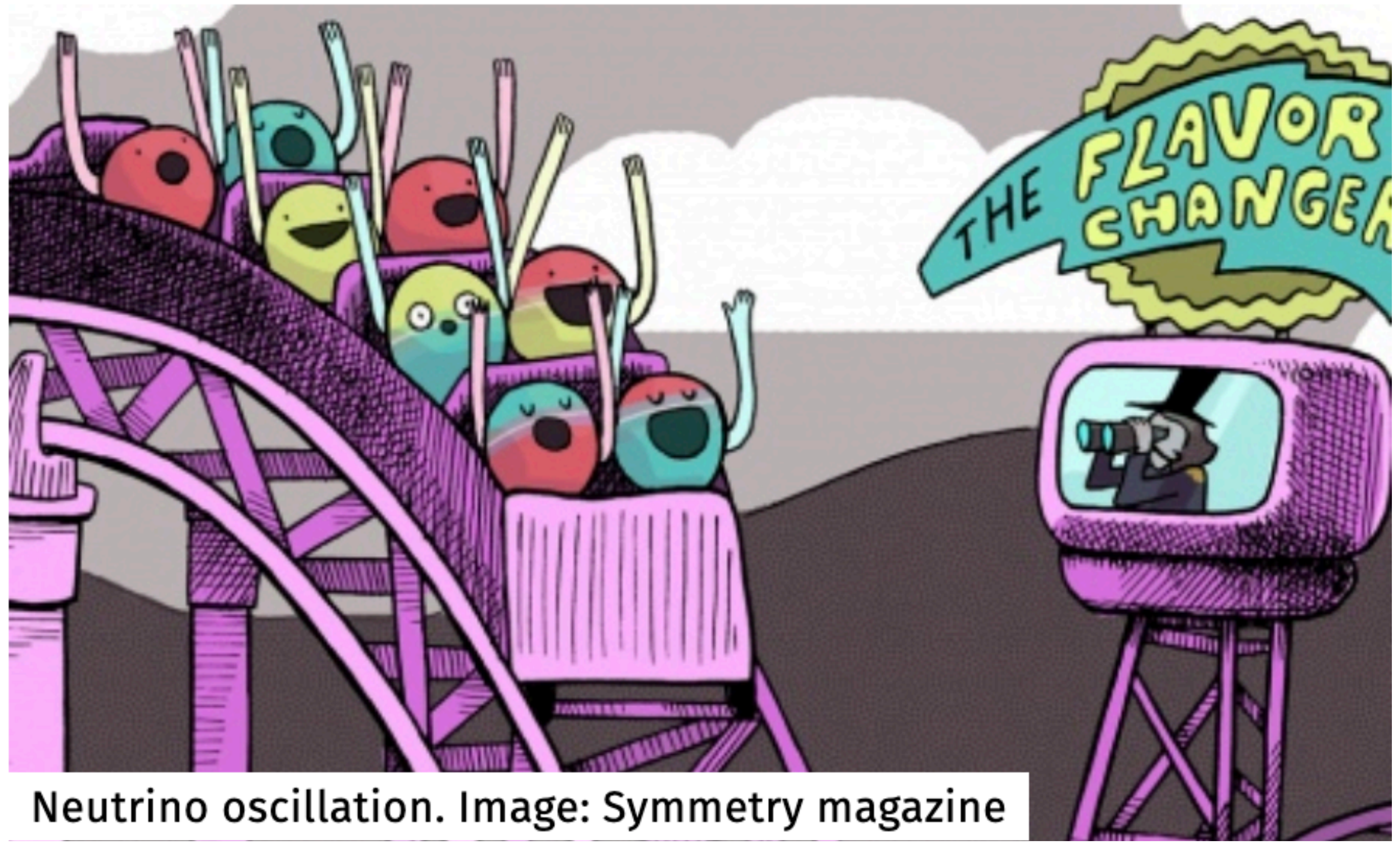
Unification and many other motivated UV naturally lead to BNV



$\Delta B = \Delta L = \pm 3$

Neutrino masses and Lepton Number Violation

The only laboratory evidence of BSM physics : Neutrino Oscillations

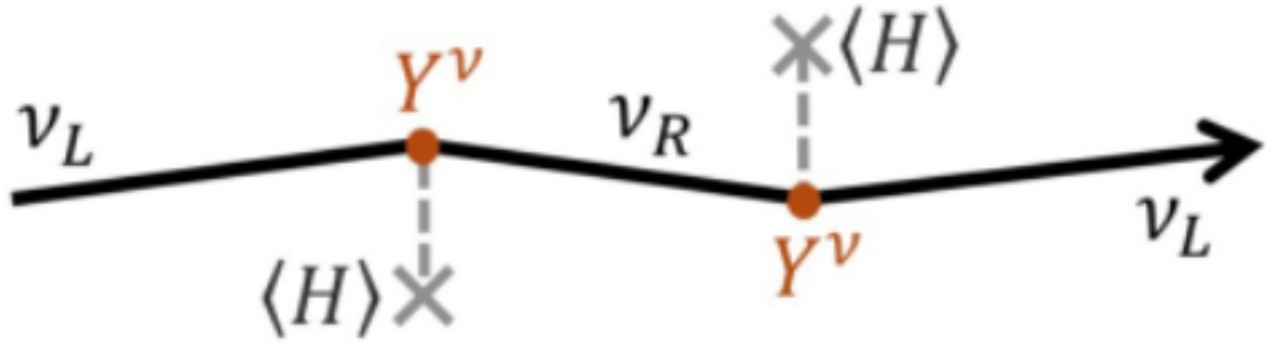


Neutrino oscillation. Image: Symmetry magazine

Purely SM:

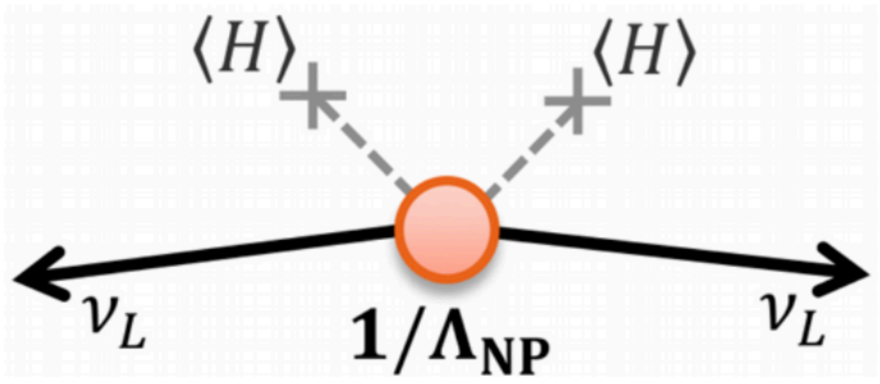
- strictly massless neutrinos
- conservation of lepton number and flavours

Two possibilities for neutrino masses:



$$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$$

VS.



$$m_M \overline{\nu}_L \nu_L^c$$

Dirac: like other fermions,

but tiny Yukawa couplings ~10^{-12}

finetuning, symmetry, ...?

Majorana: $\nu = \nu^c$: Lepton Number Violation!

Can be probed at experiments, if we are lucky!

Connection to Leptogenesis?

$\Delta B = 2$ Neutron-antineutron oscillation

Like neutrinos neutrons can also have Majorana mass:

$$\mathscr{L} \supset \frac{\varepsilon_{n\bar{n}}}{2}\left(\bar{n}n^C + \text{h.c.}\right)$$

Induced by BNV interaction at dimension-9:

$$\mathscr{L}_{\Delta B=2} \supset \frac{1}{\Lambda^5}(udd)^2 + \text{h.c.}$$

$$\varepsilon_{n\bar{n}} = \mathcal{O}(1) \times \frac{\Lambda^6_{\text{QCD}}}{\Lambda^5}$$

↑

$$\langle \bar{n} \,|\, \mathcal{O}_{\Delta B=2} \,|\, n \rangle$$

Experiment →

pure neutron beam

$$|\Psi(t=0)\rangle = |n\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

↓

let it propagate

$$|\Psi(t)\rangle = \begin{pmatrix} \psi_n(t) \\ \psi_{\bar{n}}(t) \end{pmatrix} = e^{-i\hat{\mathscr{H}}t}\,|\Psi(t=0)\rangle$$

$$\hat{\mathscr{H}} = \begin{pmatrix} E_n & \varepsilon_{n\bar{n}} \\ \varepsilon_{n\bar{n}} & E_{\bar{n}}, \end{pmatrix}$$

↓

look for $\bar{n}$ annihilation signal

Experimental challenge: Earth's magnetic field

$$\Delta E = E_n - E_{\bar{n}} \qquad \Delta E/2 = |\vec{\mu}_n \vec{B}| \approx (B/1\ \text{G}) \times 10^{-11}\ \text{eV}$$

$$P_{n\bar{n}}(t) = \frac{\varepsilon^2_{n\bar{n}}}{(\Delta E/2)^2 + \varepsilon^2_{n\bar{n}}} \sin^2\left[t\sqrt{(\Delta E/2)^2 + \varepsilon^2_{n\bar{n}}}\right] e^{-t/\tau_n} \quad \rightarrow \quad \varepsilon^2_{n\bar{n}} t^2 = \frac{t^2}{\tau^2_{n\bar{n}}} = \left(\frac{t}{0.1\ \text{s}}\right)^2 \left(\frac{10^8\ \text{s}}{\tau_{n\bar{n}}}\right)^2 \times 10^{-18}$$

Neutron-mirror (sterile) neutron oscillation

Mirror neutron conversion $\Delta B = -\Delta B' = 1$:

$$\mathscr{L} \supset \frac{\varepsilon_{nn'}}{2}\left(\bar{n}n' + \text{h.c.}\right)$$

Induced by BNV interaction at dimension-9:

$$\mathscr{L}_{\Delta B=2} \supset \frac{1}{\Lambda^5}(\bar{u}\bar{d}\bar{d})(u'd'd') + \text{h.c.}$$

$$\alpha_{nn'} = C \times \frac{\Lambda^6_{\text{QCD}}}{\Lambda^5}$$

$$\langle \bar{n} | \mathscr{O}_{\Delta B=1} | n' \rangle$$

Experiment

pure neutron beam

$$|\Psi(t=0)\rangle = |n\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

let it propagate

$$\hat{\mathscr{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \alpha_{nn'} + \kappa \vec{\mu}_n \vec{B} + \kappa' \vec{\mu}_n \vec{B}' \\ \alpha_{nn'} + \kappa \vec{\mu}_n \vec{B} + \kappa' \vec{\mu}_n \vec{B}' & m_{n'} + \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$

look for $\bar{n}$ disappearance/regeneration

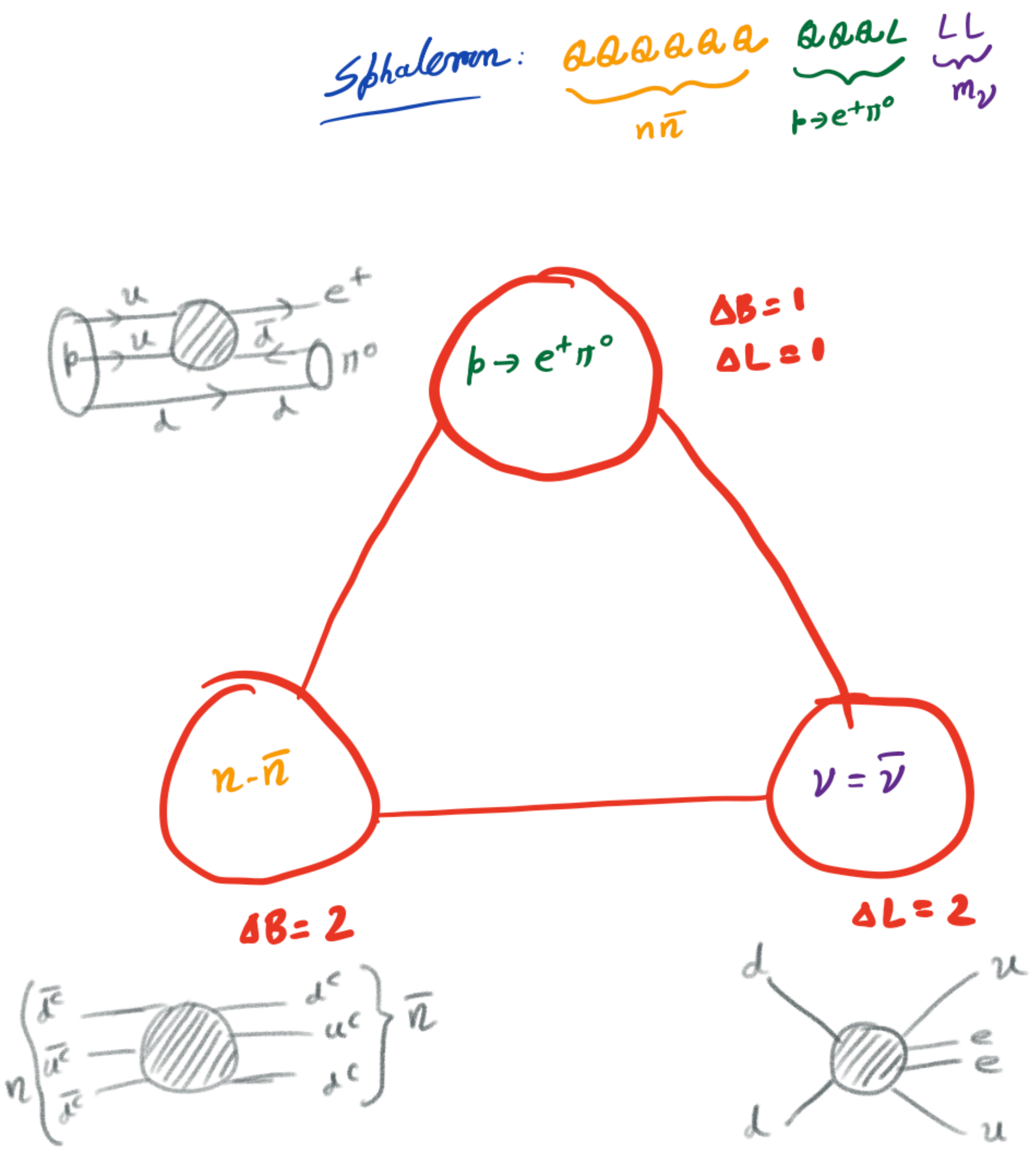
Earth's + dark magnetic field: Review: 2006.04907

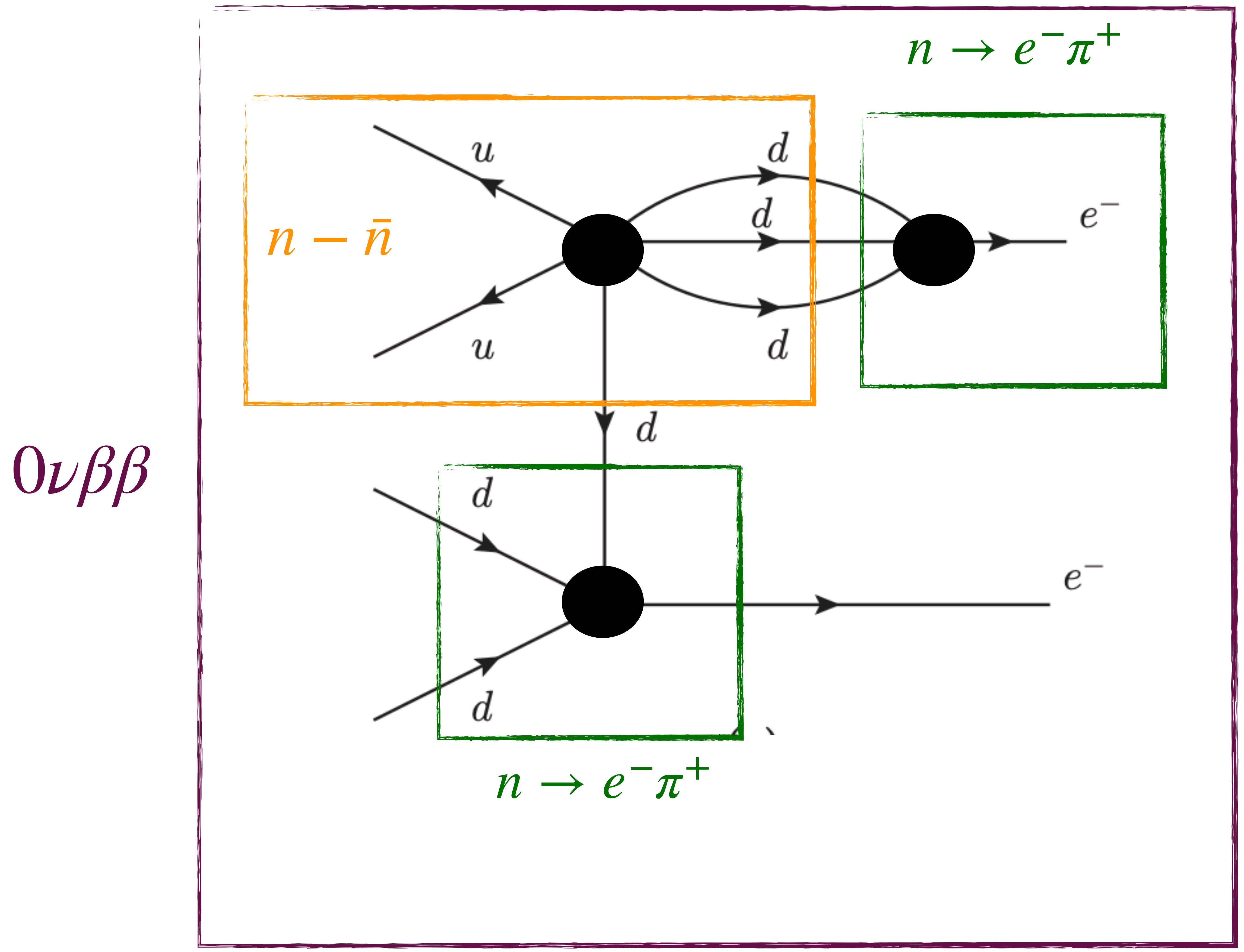
ionization and flow of gravitationally captured dark material

Ionization of dark gas cloud, dark atom capture, dark photon mixing

Depending on $\alpha_{nn'}$ κ , κ' , and $(|\mu_n B| - |\mu_n B'|)$ different probabilities

The $(B-L)$ triangle: a feature in many (B-L) violating UV models





Babu, Mohapatra '80

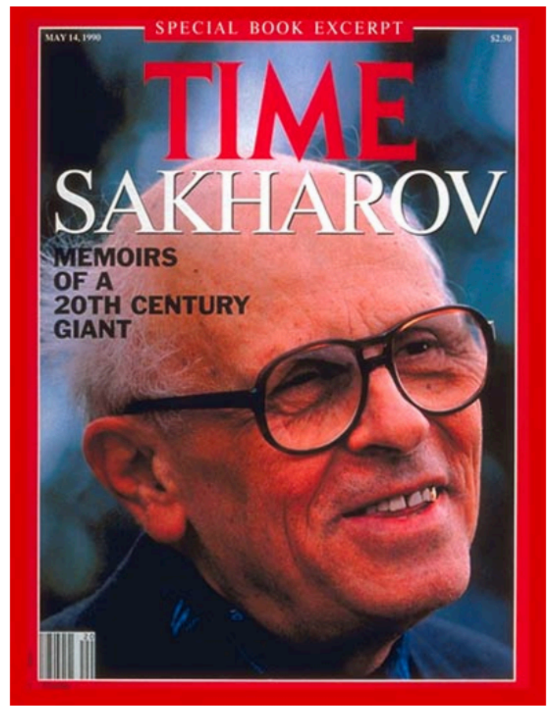
"B" and "L" violation can be intimately connected!

Small "L" violation can be probed by BNV modes

Baryogenesis/Leptogenesis: understanding matter-antimatter asymmetry

In the SM

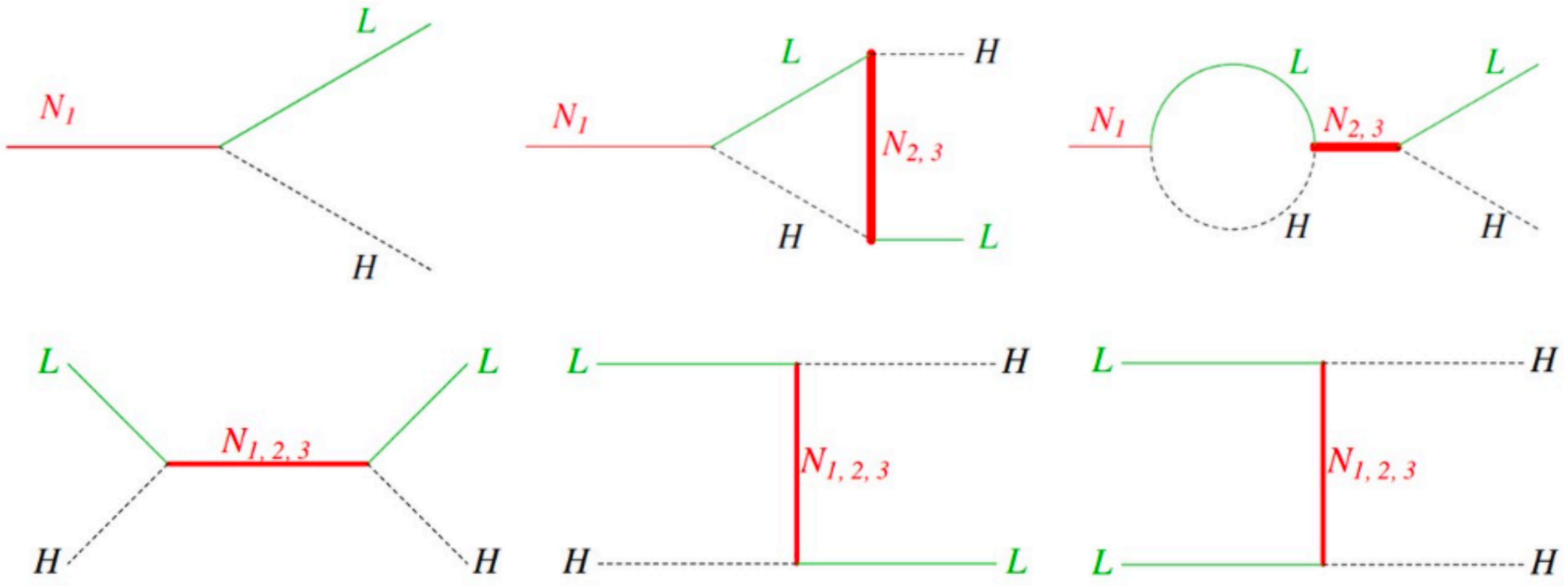
- ✓ baryon number violation
- ✗ C and CP violation
- ✗ departure from thermal equilibrium



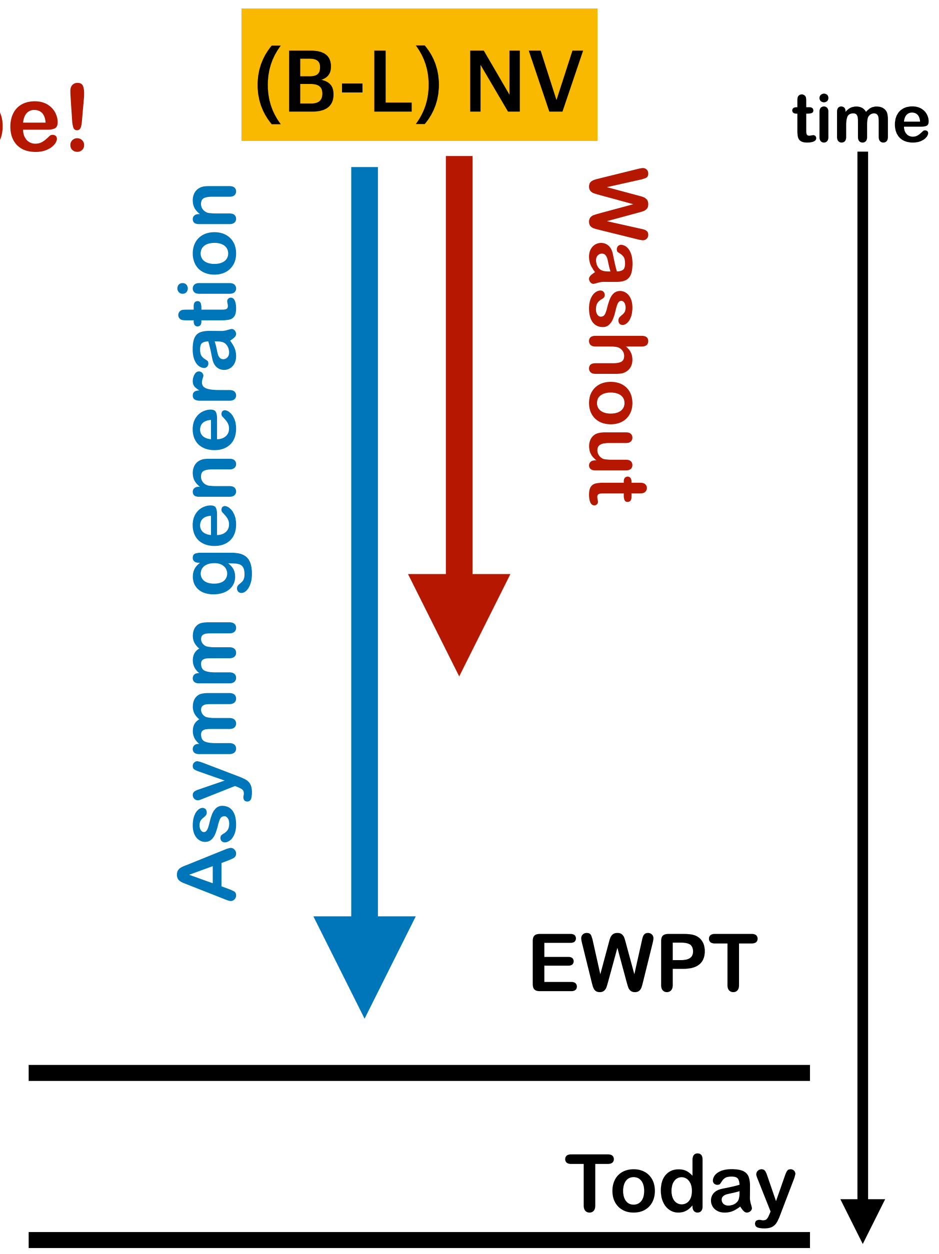
Simple example: thermal leptogenesis

Fukugita, Yanagida 84

Guidice et al. 04



High-scale case notoriously difficult to probe!



Source term

Washout term

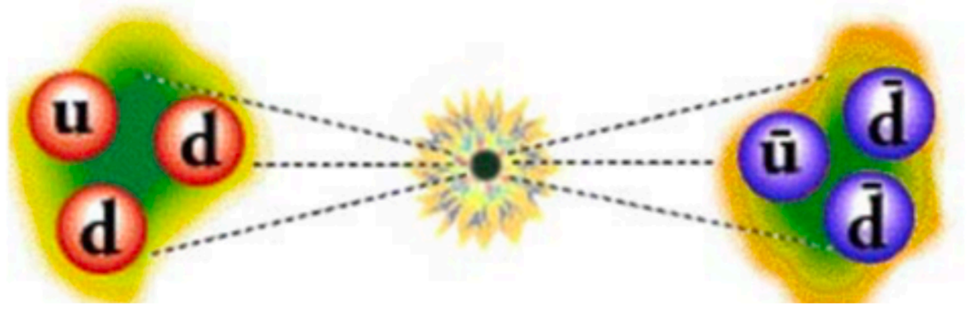
Heavy "X" decays:

$$\frac{dY_{B-L}}{dt} = \epsilon_{CP}\,\Gamma_X^{B/LV}\,(Y_X - Y_X^{eq}) - \Gamma_{\rm WO}\, Y_{B-L}$$

$n-\bar{n}$ oscillations and washout: a simple picture

signal at experiment

$\Delta B = 2$

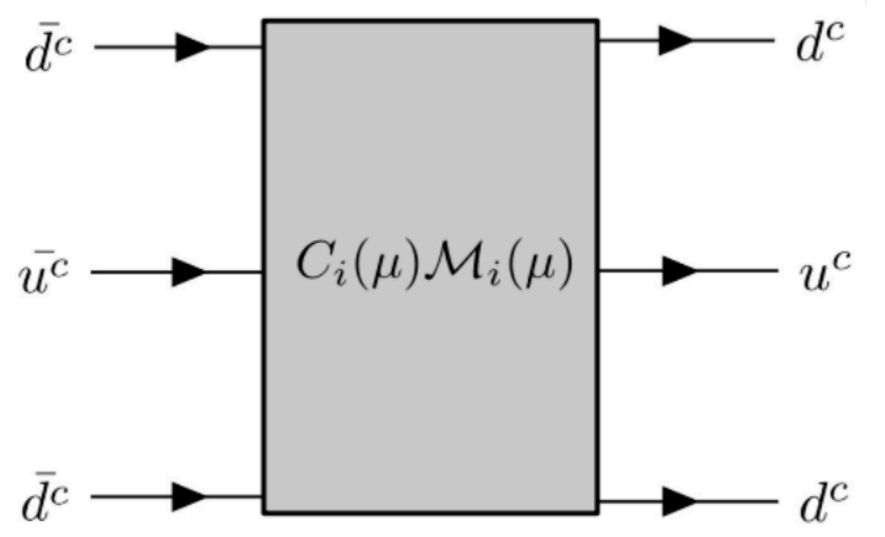


Example operators

$$\mathcal{O}_1 = -4\mathcal{O}^3_{RRR} = (\psi C P_R i\tau^2\psi)(\psi C P_R i\tau^2\psi)(\psi C P_R i\tau^2\tau^+\psi)T^{AAS}$$
$$\mathcal{O}_2 = -4\mathcal{O}^3_{LRR} = (\psi C P_L i\tau^2\psi)(\psi C P_R i\tau^2\psi)(\psi C P_R i\tau^2\tau^+\psi)T^{AAS}$$
$$\mathcal{O}_3 = -4\mathcal{O}^3_{LLR} = (\psi C P_L i\tau^2\psi)(\psi C P_L i\tau^2\psi)(\psi C P_R i\tau^2\tau^+\psi)T^{AAS},$$

++

$\Delta B = 2$ washout processes
In early universe



Measured $n-\bar{n}$ rate: $\tau_{n\bar{n}}$

$$\mathcal{L}^{\bar{n}n}_{\mathrm{WET}} = \sum_i C_i\mathcal{O}_i + \mathrm{h.c.}$$

$$\tau^{-1}_{n\bar{n}} = \langle \bar{n}|\mathcal{L}^{n\bar{n}}_{\mathrm{WET}}|n\rangle = |C_1(\mu)\mathcal{M}_1(\mu)|$$

$$\mathcal{M}_i(\mu) = \langle \bar{n}|\mathcal{O}_i(\mu)|n\rangle \longrightarrow$$ **Lattice QCD**

Rinaldi et. al. 19

RG running

$$\Gamma \propto |C_i\mathcal{M}_i|^2 \propto \left|\frac{1}{\Lambda^5}\right|^2$$

washouts active roughly till

$$\Gamma_{\mathrm{WO}}/H > 1$$

$$C \sim \frac{1}{\Lambda^5}$$ scale of the operator: Λ

Fridell, Harz, **CH** JHEP '21

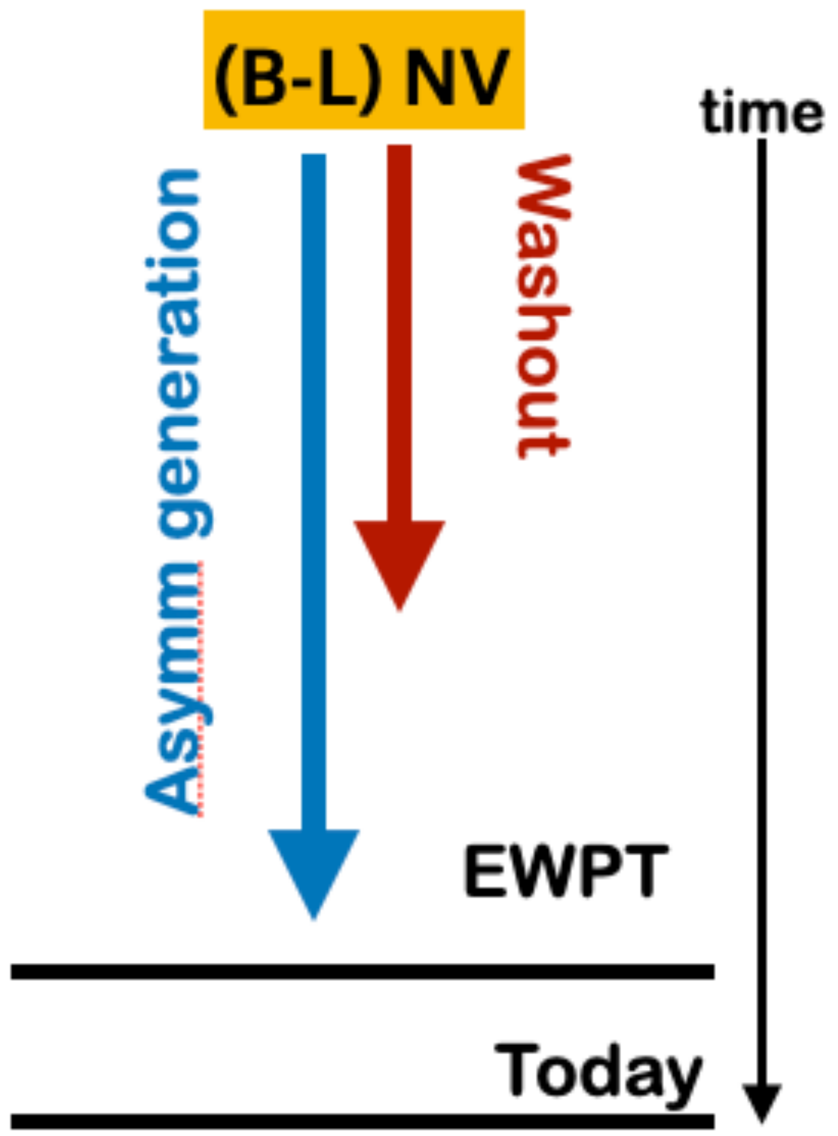
$n-\bar{n}$ oscillations and washout: a simple picture

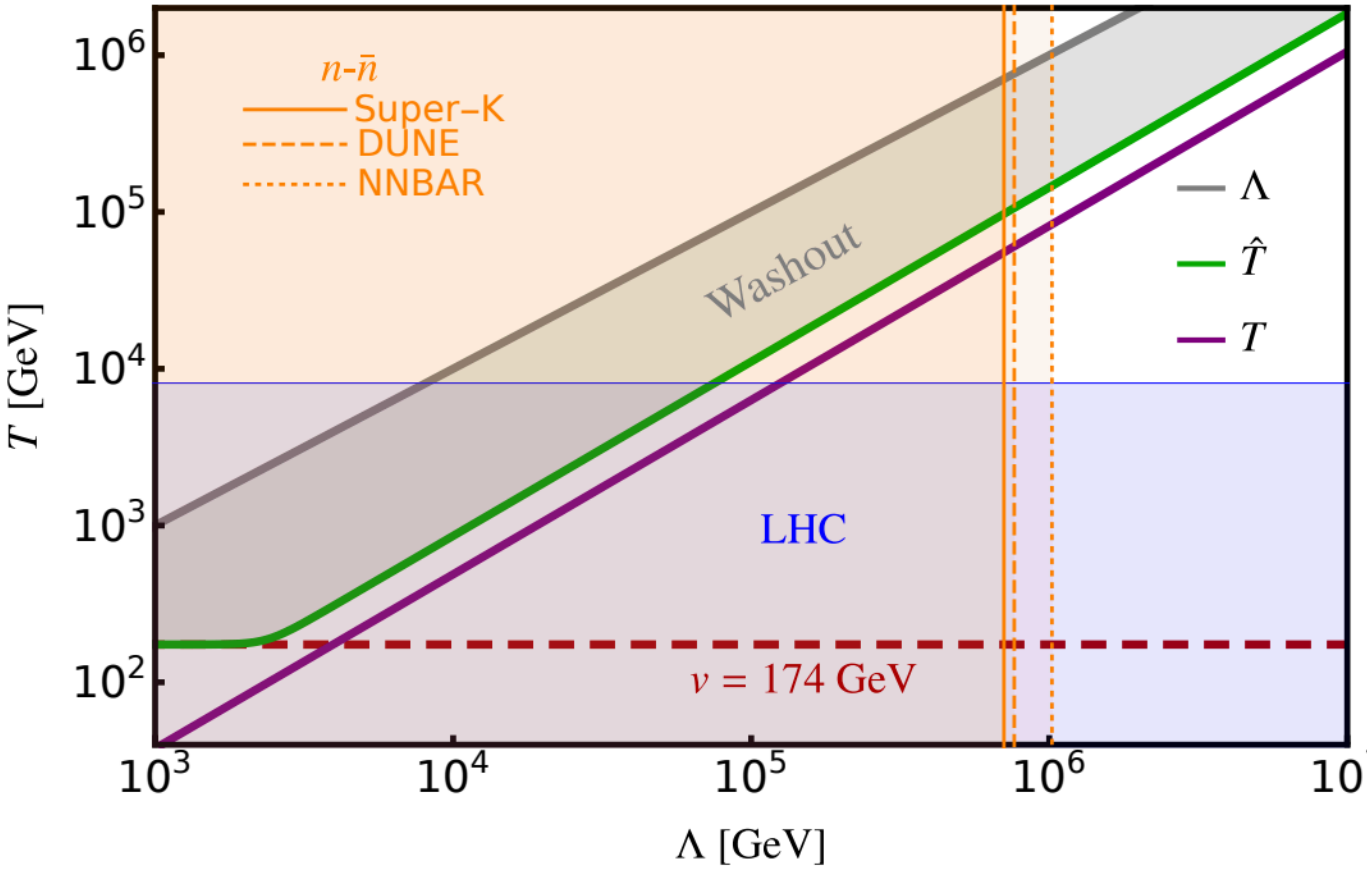
Out of equilibrium temperature of washout processes: $\Gamma \sim H, \quad \Gamma \propto \left|C_i \mathcal{M}_i\right|^2 \propto \left|\frac{1}{\Lambda^5}\right.$ ← **Experimental rate of $n-\bar{n}$**

$$zHn_\gamma \frac{d\eta_X}{dz} = -\sum_{a,i,j,\cdots} [Xa\cdots \leftrightarrow ij\cdots],$$

chemical potential relations=>

$$zHn_\gamma \frac{d\,\eta_{\Delta B}}{d\,z} = -c\frac{T^{14}}{\Lambda^{10}}\eta_{\Delta B}$$





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Caveats: validity of the EFT treatment e.g. hierarchical NP scales, CPV sources

$n - \bar{n}$ oscillations and washout: a simple picture

Out of equilibrium temperature of washout processes: $\Gamma \sim H, \quad \Gamma \propto \left|C_i \mathcal{M}_i\right|^2 \propto \left|\frac{1}{\Lambda^5}\right.$ ← Experimental rate of $n - \bar{n}$

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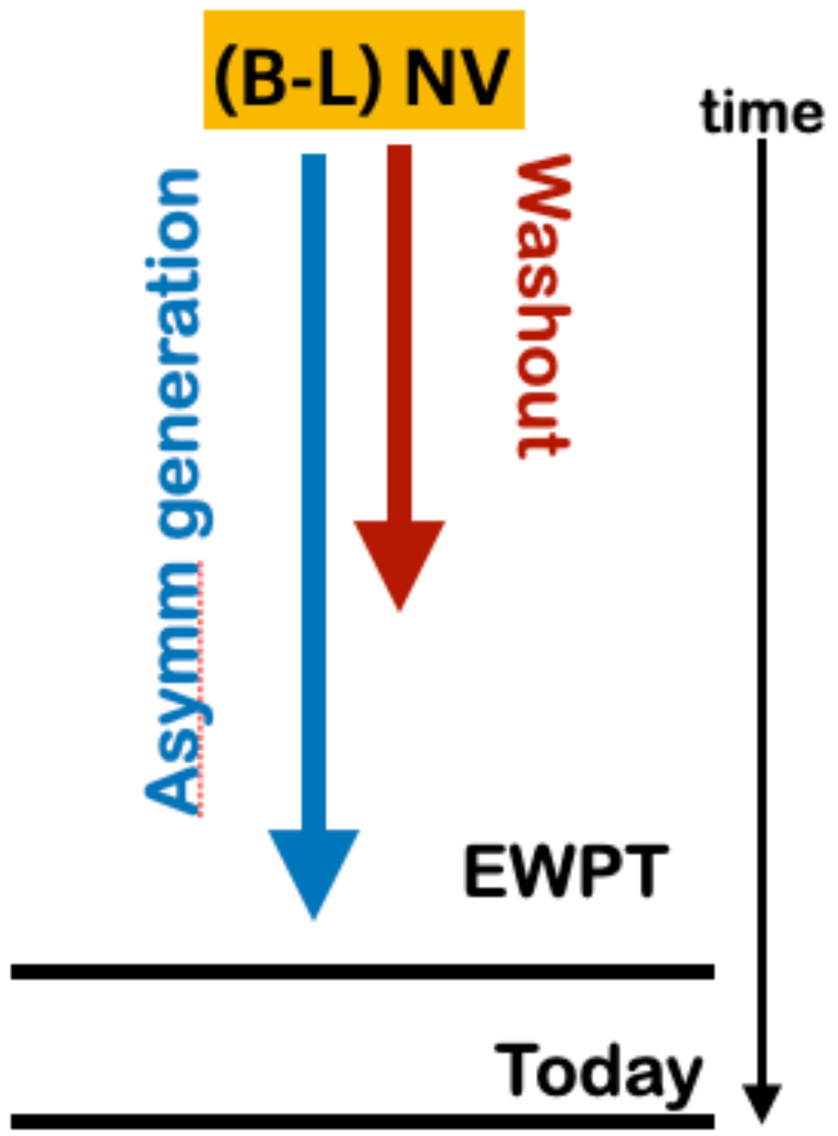

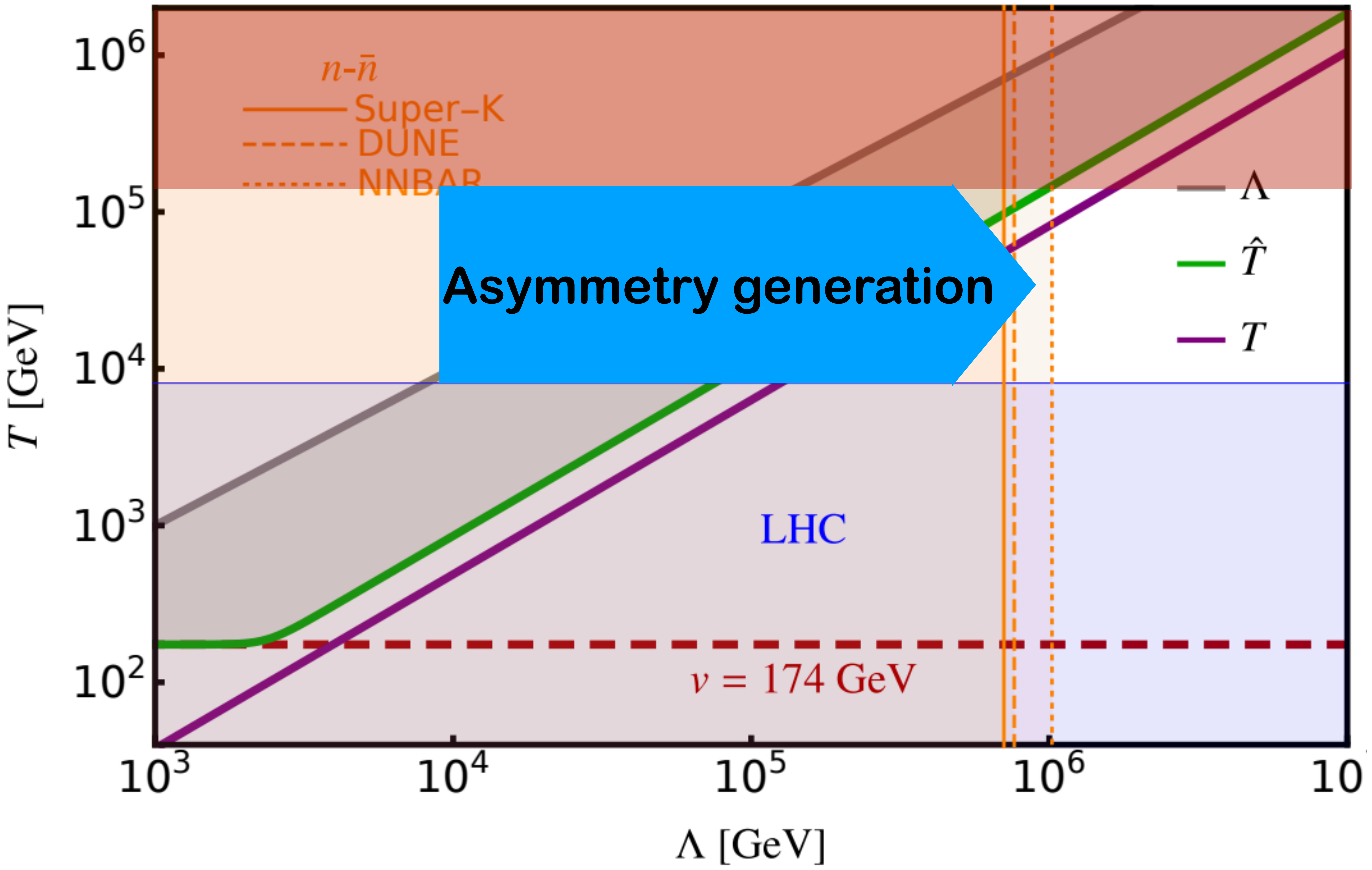

Caveats: validity of the EFT treatment e.g. hierarchical NP scales, CPV sources

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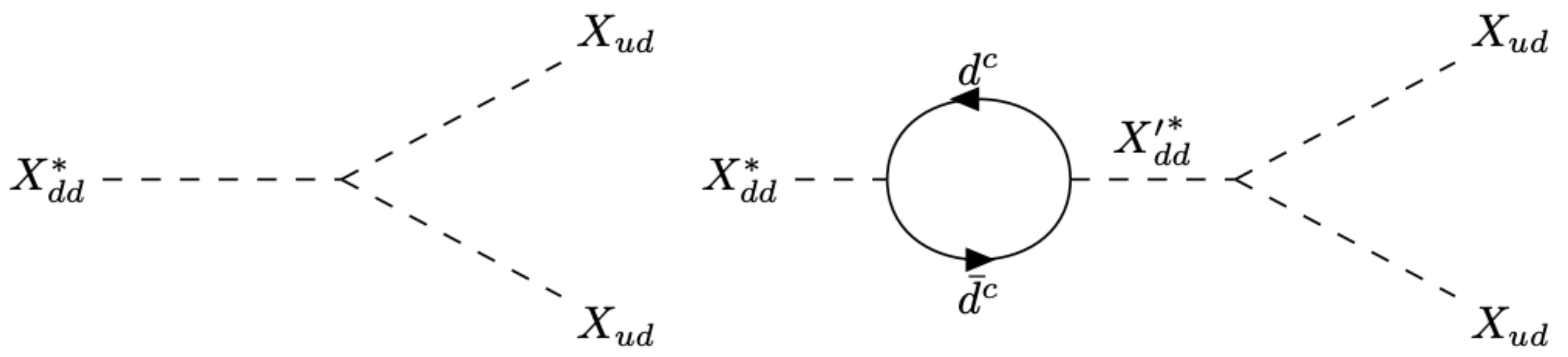
$n - \bar{n}$ oscillations and baryogensis: a more detailed view

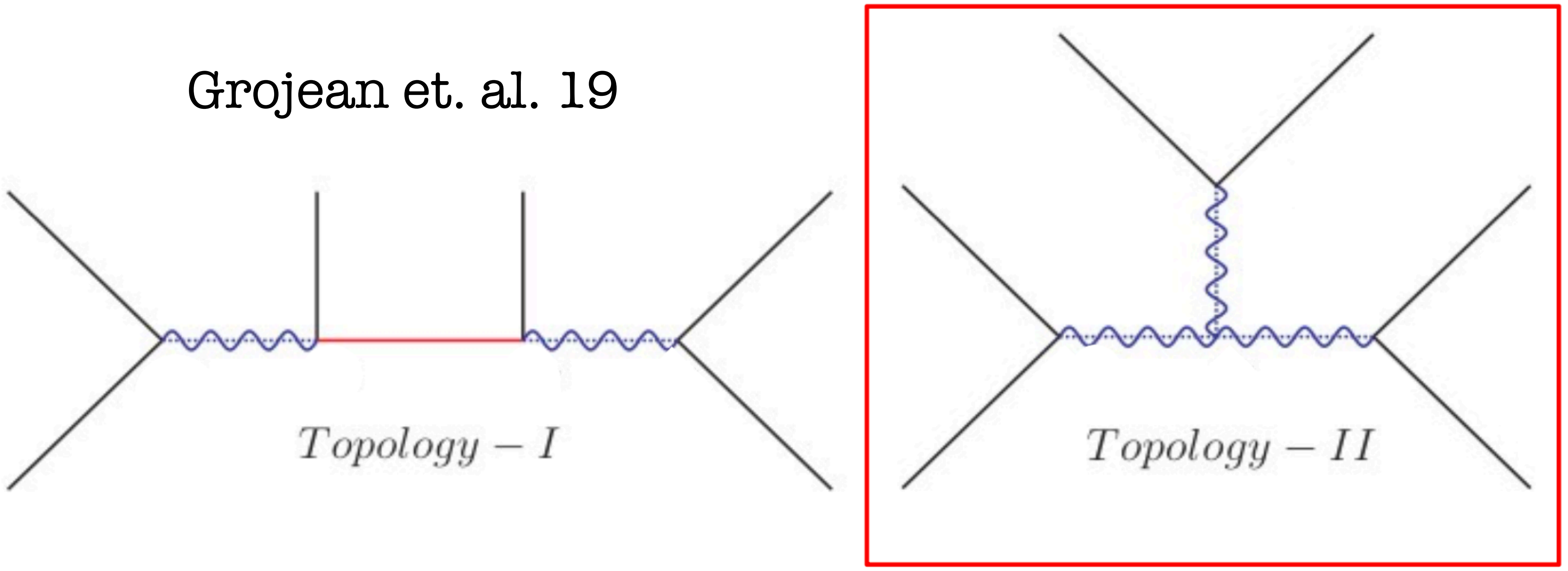
source of CP violation

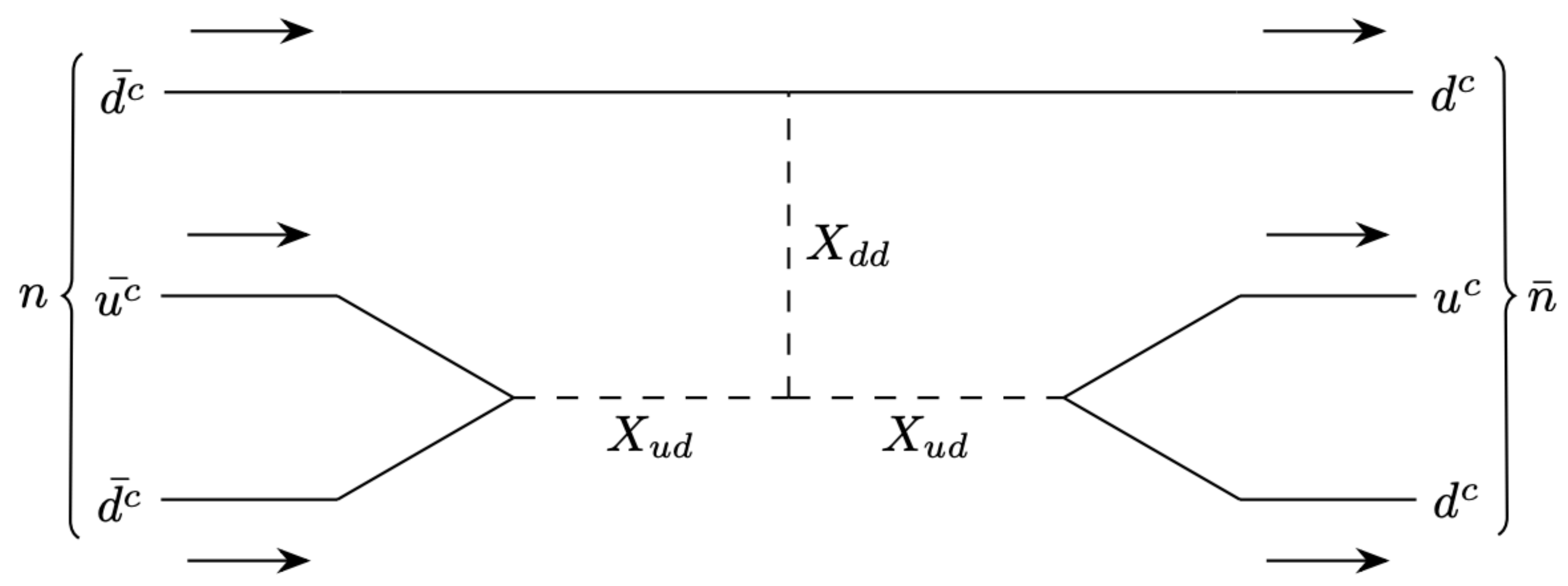


$$\epsilon = \frac{\Gamma_{X_{dd}\to X^*_{ud}X^*_{ud}} - \Gamma^*_{X_{dd}\to X_{ud}X_{ud}}}{\Gamma_{X_{dd}\to X^*_{ud}X^*_{ud}} + \Gamma^*_{X_{dd}\to X_{ud}X_{ud}}}$$

$$\mathcal{L}^{\rm eff}_{II} \supset f^{dd}_{ij} X_{dd}\bar{d}^c_i\bar{d}^c_j + \frac{f^{ud}_{ij}}{\sqrt{2}} X_{ud}(\bar{u}^c_i\bar{d}^c_j + \bar{u}^c_j\bar{d}^c_i) + \lambda\xi X_{dd}X_{ud}X_{ud} + \text{h.c.}$$

Grojean et. al. 19





Diquarks: naturally embedded in SO(10)

X_{dd} **GUT scale,** X_{ud} **TeV scale: high-scale scenario**

X_{dd} **,** X_{ud} **similar scale: low-scale scenario**

Decomposition of 126 multiplet of $SO(10)$

Mohapatra, Marshak '80

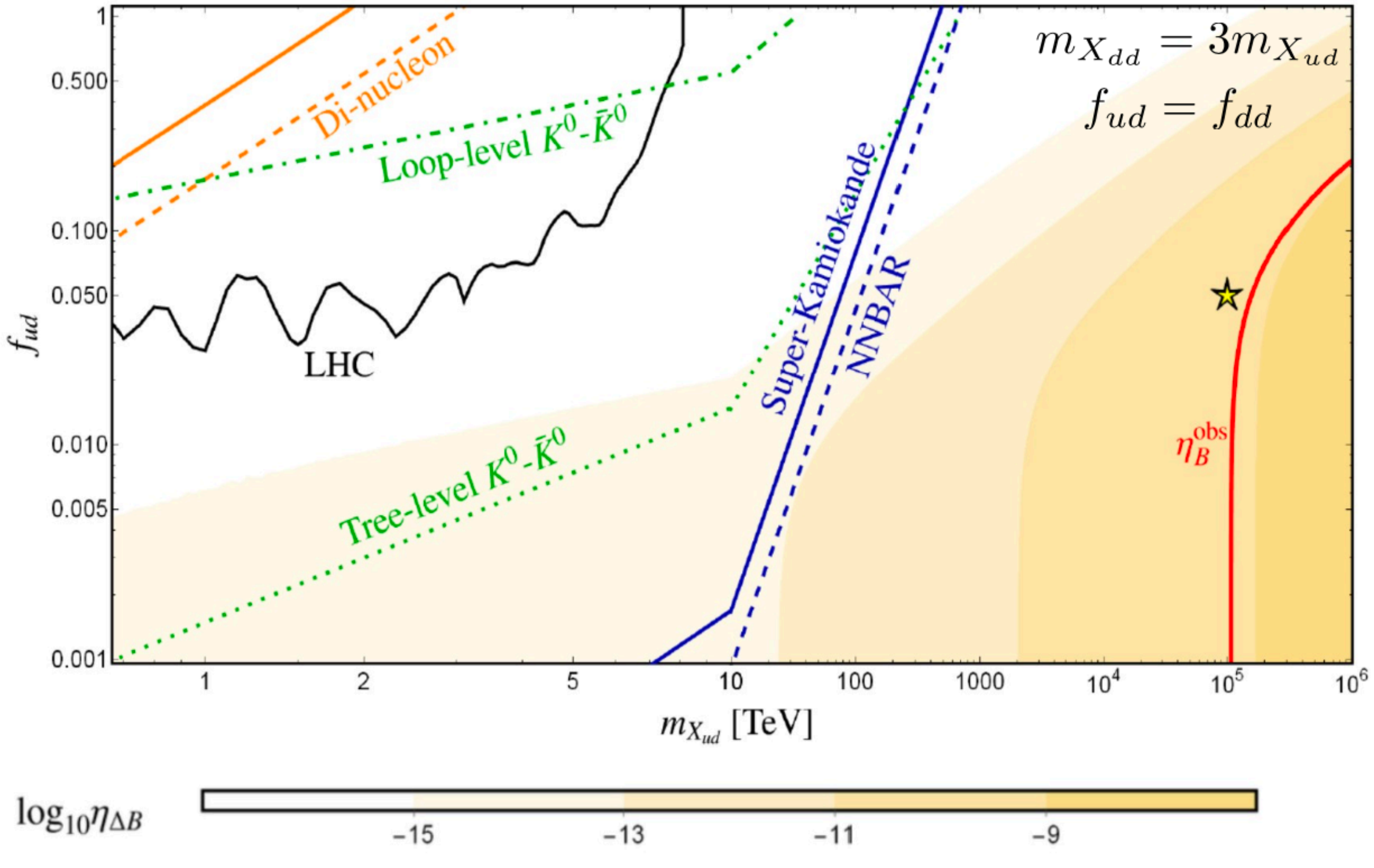
$G_{\rm PS}$	$G_{\rm LR}$	$G_{\rm SM}$
$(\mathbf{1},\mathbf{3},\overline{\mathbf{10}})$	$(1,1,3,+2)$	$(\mathbf{1},\mathbf{1},\mathbf{0}) \oplus (1,1,+1) \oplus (1,1,+2)$
	$(\bar{3},1,3,+\frac{2}{3})$	$(\bar{3},1,-\frac{2}{3}) \oplus (\bar{3},1,+\frac{1}{3}) \oplus (\bar{3},1,+\frac{4}{3})$
	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{3},-\frac{\mathbf{2}}{\mathbf{3}})$	$(\bar{\mathbf{6}},\mathbf{1},-\frac{\mathbf{4}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}},\mathbf{1},-\frac{\mathbf{1}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}},\mathbf{1},+\frac{\mathbf{2}}{\mathbf{3}})$

$n - \bar{n}$ oscillations and baryogensis: low-scale scenario

A signal of $n - \bar{n}$ + a signal @ LHC
→ too strong washout
→ under-abundance

TeV scale baryogenesis is disfavoured (in agreement with simple EFT results)

-> Post-sphaleron baryogenesis



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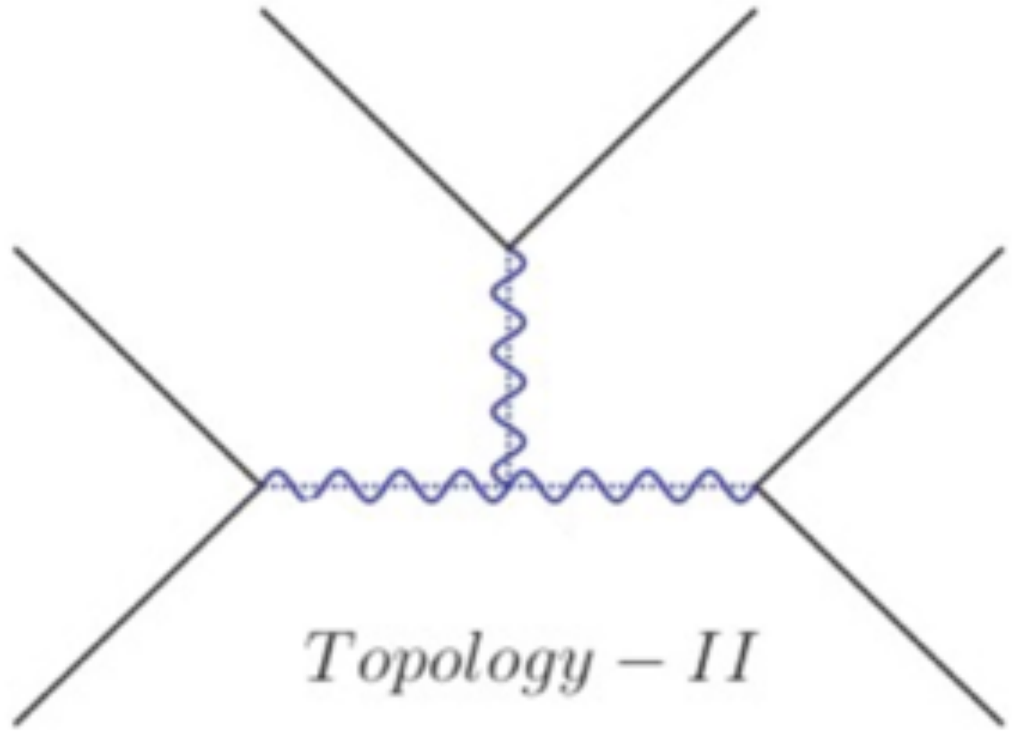
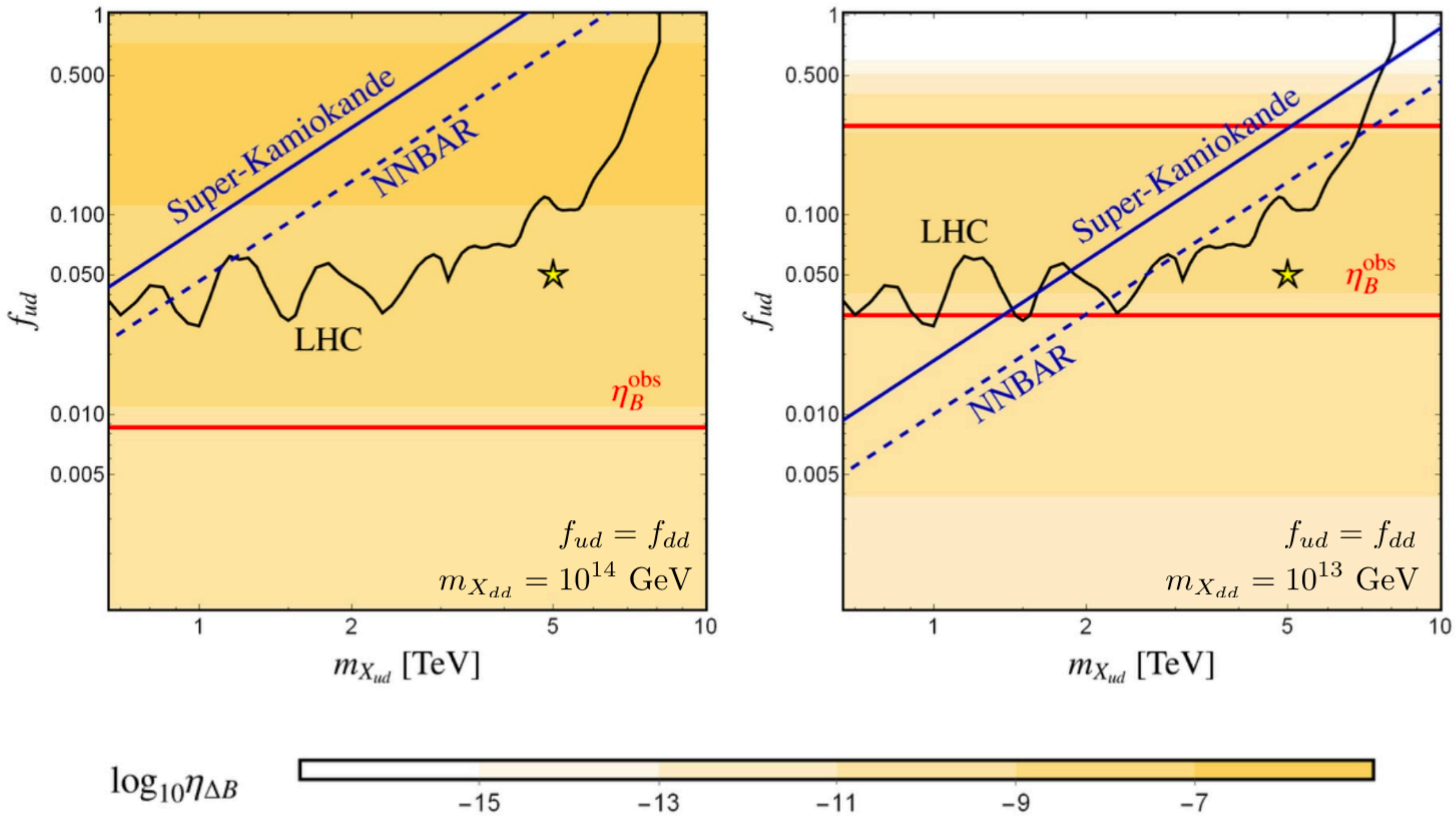
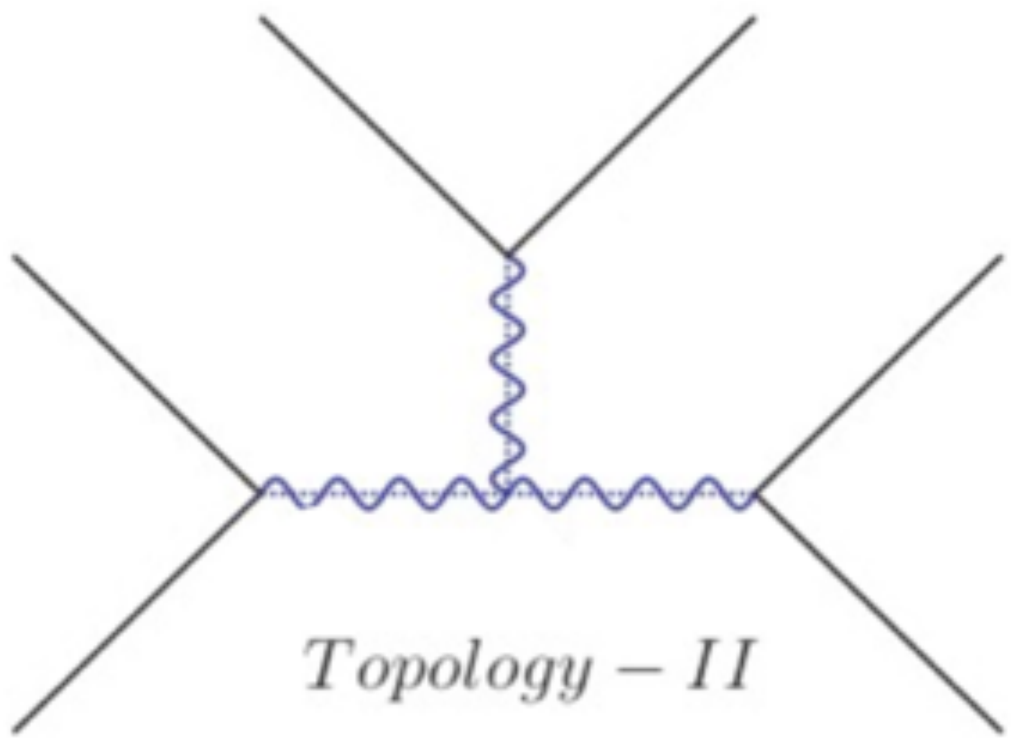


X_{dd} , X_{ud} similar scale: low-scale scenario

$n - \bar{n}$ oscillations and baryogensis: high-scale scenario





X_{dd} **GUT scale,** X_{ud} **TeV scale:**

high-scale scenario

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A viable scenario for baryogenesis (simple EFT picture invalid!)

Exciting prospects for the upcoming n – n‾ oscillation searches

Conclusions

BNV can provide smoking gun for NP beyond the SM

NNBAR@ESS will improve the ILL limits for free $n - \bar{n}$ oscillations by three orders of magnitude

Sensitivity to TeV-PeV scale BNV new physics

Possibility to probe a variety of NP scenarios and difficult to probe mechanisms for baryogenesis

Combined with other searches can help in cornering the much awaited BSM physics