



BLV 2022

BARYON AND LEPTON NUMBER VIOLATION

Baryogenesis via relativistic bubble walls

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2010.02590, 2106.14913, 2207.02230

5 September 2022

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Sabyasachi Chackraborty

Wen Yin

Giulio Barni

Sakharov conditions as guideline for baryogenesis

Idea of baryogenesis with relativistic bubble walls

- **Out-of-equilibrium situation**
- **CP-violation**
- **B-number violation**

Baryogenesis and bubble wall velocity ?

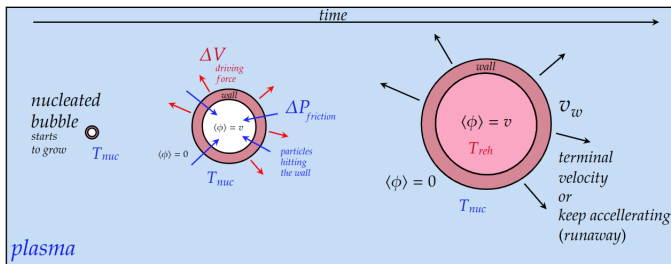
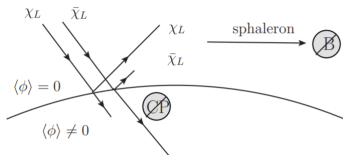


Figure: Credit: Giulio Barni, thanks to him



Relation BAU and velocity:

BAU	0,	v_w	0
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Credit: T. Konstandin [1302.6713]

Sakharov conditions as guideline for baryogenesis

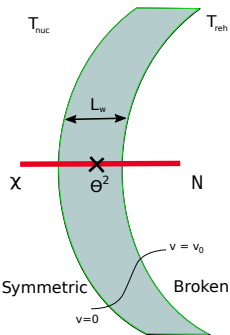
Idea of baryogenesis with relativistic bubble walls

- **Out-of-equilibrium situation?**

Production of out-of-equilibrium heavy states via wall [2010.02590]: Idea

Out-of-equilibrium heavy states

scalar, light fermion, N heavy fermion: $L_{int} = Y \bar{\chi} N + M \bar{N} N$
 $n_N(M, T) \approx (MT)^{3/2} e^{-M/T} \ll 1$.

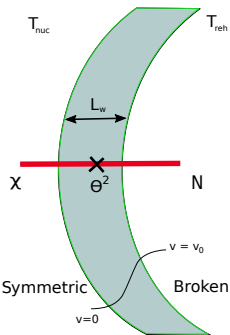


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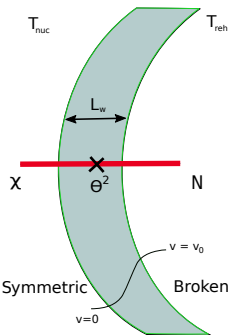
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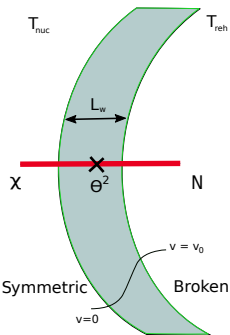
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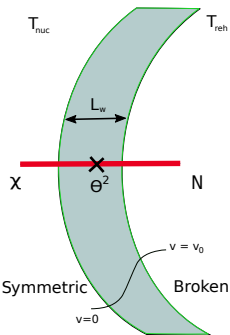


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- **No wall:** $(2\pi)^4 \delta^4(p - p_N) : N$ possible?
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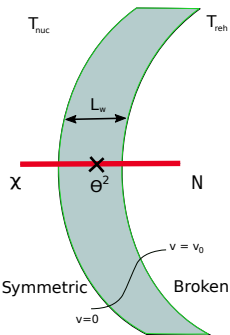
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- **No wall:** $(2\pi)^4 \int d^4p (p - p_N) : N$ forbidden
 - **With wall:** if $E > M$, N allowed

$$d^3x e^{i p \cdot x} \int dz e^{i z p_z} = (2\pi)^3 \int d^3p \frac{\sin p_z L_w}{p_z L_w}$$

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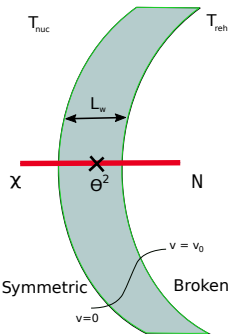
$$d^3x e^{i p \cdot x} \int dz e^{i z p_z} = (2\pi)^3 \int dz e^{i z p_z} \frac{\sin p_z L_w}{p_z L_w}$$

- Exchange momentum bound: $p_z \lesssim 1/L_w \sim v$ $p_z \sim E$

Production of out-of-equilibrium heavy states via wall [2010.02590]: computation

Out-of-equilibrium heavy states

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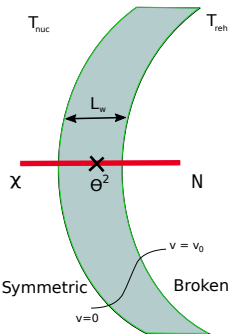


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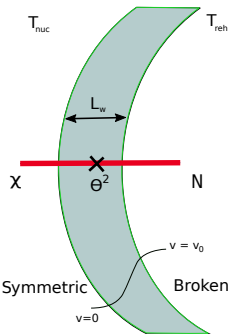


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- In the wall frame: $E = \rho = \gamma_w T_{nuc} \gg v$

Production of out-of-equilibrium heavy states via wall [2010.02590]: computation

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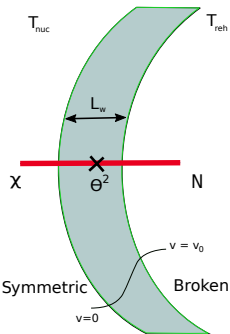


- Assume very fast wall: $\gamma_w = \frac{1}{\sqrt{1-v_w^2}} \gg 1$
- In the wall frame: $E = \gamma_w (E' + v' p_z)$, $p_z = \gamma_w (p_z' + v' E')$
- $\frac{1}{M^2} \approx Y^2 v^2 \times \frac{E}{p_z} \frac{\sin \frac{p_z L_w}{2}}{p_z L_w}$, $p_z = E - \sqrt{E^2 - M^2} \approx \frac{M^2}{2E}$

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- Assume very fast wall: $\gamma_w = \frac{1}{\sqrt{1-v_w^2}} \gg 1$
- In the wall frame: $E = \gamma_w T_{nuc} + \gamma_w v p_z$
- $|M|^2 = Y^2 v^2 \times \frac{E}{p_z} \frac{\sin \frac{p_z L_w}{p_z L_w}}{\frac{p_z L_w}{p_z L_w}} \quad p_z = E - \sqrt{E^2 - M^2} \approx \frac{M^2}{2E}$
- $P(N) \approx 2 \times (\gamma_w T_{nuc} - M^2 L_w) \times \frac{Y v}{M}$

Creation of out-of-equilibrium states: consequences

- Each production induces a kick [2010.02590]: $p_z \sim \frac{M^2}{2E}$

$$P \sim n \times p_z \times P(N) \sim \frac{Y^2 v^2 T^2}{48} (w_p T_{\text{nuc}} - M^2 L_w) \quad (\text{pressure on the wall})$$

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- Production of stable states (Dark Matter) via portal [2101.05721]:
- out-of-equilibrium abundance of N via [2106.14913]: baryogenesis
- Particle receiving a mass from the transition also out-of-equilibrium (Mass Gain): VUB-ULB: [2106.15602]

We focus on Baryogenesis

Possible baryogenesis in our production setting?

Idea of baryogenesis with relativistic bubble walls

- **Out-of-equilibrium situation:** N via relativistic bubble expansion

Possible baryogenesis in our production setting?

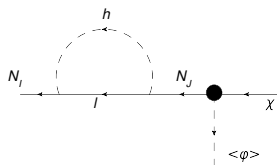
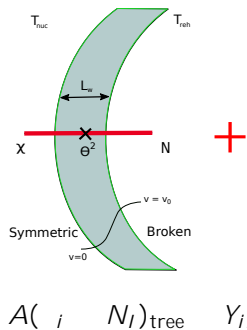
Idea of baryogenesis with relativistic bubble walls

- **Out-of-equilibrium situation:** N via relativistic bubble expansion
- **CP-violation:** $(N_I) = (-\bar{N}_I) ??$

CP violation inside the bubble wall

Ingredients: Higgs field H , scalar, 2 heavy N_I , SM $SU(2)_L$ -fermions L , and ℓ_i light fermions

$$L = -M_I \bar{N}_I N_I - Y_{iI} \bar{N}_I P_R \ell_i - y_I (H \bar{L}) P_R N_I + h.c.$$



$$A(i, N_I)_{1-loop} + \sum_{j, I} Y_{iJ} Y_{jI} \times f_{IJ}^{(HL)}$$

$$\frac{\left(\begin{matrix} N_I \\ N_I \end{matrix} \right) - \left(\begin{matrix} - \\ - \end{matrix} \bar{N}_I \right)}{\left(\begin{matrix} N_I \\ N_I \end{matrix} \right) + \left(\begin{matrix} - \\ - \end{matrix} \bar{N}_I \right)} = \frac{2 \sum_{j, I} \text{Im}(Y_{iI} Y_{iJ} Y_{jI}) \text{Im} f_{IJ}^{(HL)}}{\sum_{i, I} |Y_{iI}|^2}$$

and

$$\text{Im}[f_{IJ}^{(HL)}(x)] = \frac{1}{16} \frac{\bar{x}}{1-x}, x = \frac{M_J^2}{M_I^2}$$

Possible baryogenesis in our production setting?

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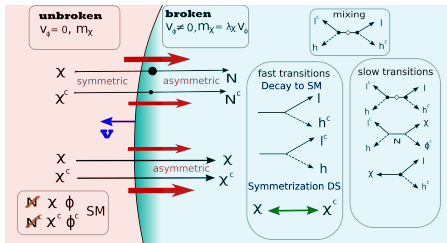
- **Out-of-equilibrium situation:** N via relativistic bubble expansion
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- **B-number violation:** B or L-violating interactions

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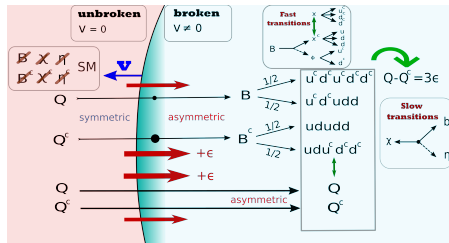
- **Out-of-equilibrium situation:** N via relativistic bubble expansion
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Phase transition induced leptogenesis



Or

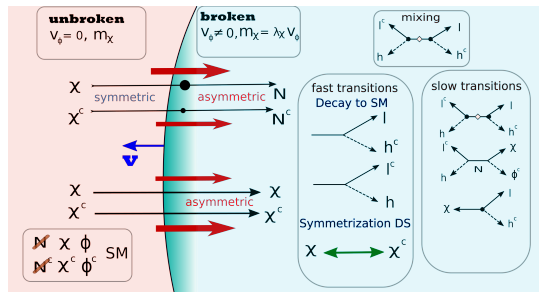
EWPT Baryogenesis with relativistic walls



Phase transition induced leptogenesis

$$\underbrace{Y_{ll}(\bar{l}_i)P_L N_l + Y_{ll}\bar{N}_l P_R(l^{\dagger}_i)}_{\text{production sector}} - V(\phi) + \underbrace{M_l \bar{N}_l N_l}_{\text{Majorana mass}} + \underbrace{y_l(H\bar{L}_{SM})P_R N_l}_{\text{CP-violation}}$$

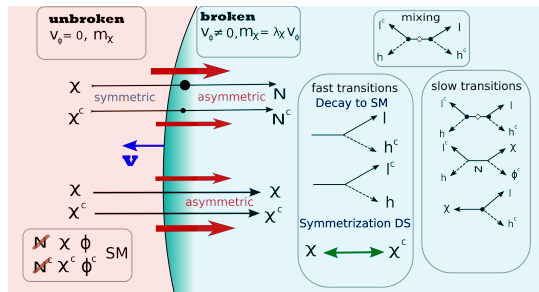
- l_i Majorana, ϕ scalar, N_l Heavy Dirac RHN:
 $U_L(1) : L(\bar{l}) = -1, L(N) = 1, L(\phi) = 2.$



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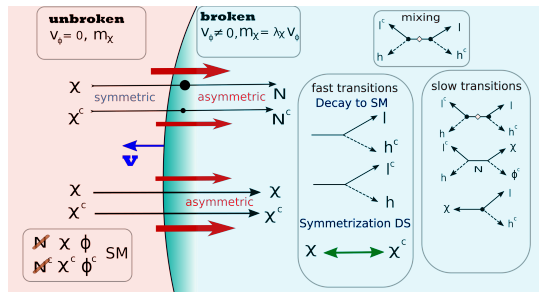
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- Production $P(l_i N_l) = P(l_i^c N_l^c)$ $\frac{2}{ll}$



Phase transition induced leptogenesis

$$\underbrace{Y_{iI}(\bar{\nu}_i)P_L N_I + Y_{iI}\bar{N}_I P_R(\nu_i)}_{\text{production sector}} - V(\phi) + \underbrace{\frac{1}{2} \bar{\nu}_i^c \nu_i + \frac{1}{2} M_I \bar{N}_I N_I}_{\text{Majorana mass}} + \underbrace{y_{iI}(H\bar{L}_{i,SM})P_R N_I}_{\text{CP-violation}}$$

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- $\frac{n_L}{s} \approx \frac{2}{g} \frac{T_{nuc}}{T_{reh}} \times \frac{|y_I|^2}{|y_I|^2 + |Y_{iI}|^2}$



Phase transition induced leptogenesis

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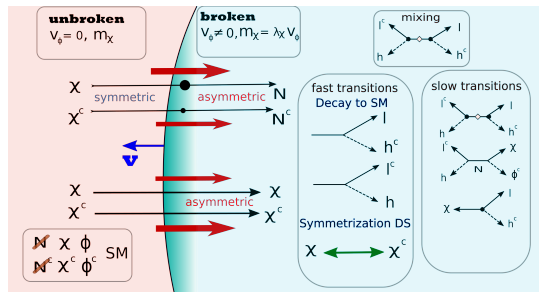
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$$\bullet \frac{n_L}{s} \approx \frac{1}{g} \times \frac{2}{g} \times \frac{T_{nuc}}{T_{reh}} \times \frac{|y_i|^2}{|y_i|^2 + |Y_{ii}|^2}$$

- Wash-outs impose:

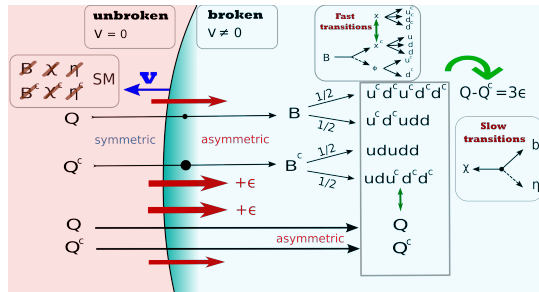
$$\underbrace{10^9 \text{ GeV}}_{\text{mass neutrino}} \cdot \underbrace{v}_{\text{L-violating int}} \cdot \underbrace{10^{13} \text{ GeV}}_{\text{L-violating int}}, \quad \frac{v}{T_{reh}} \lesssim 15$$



Low energy baryogenesis

$$L_{SM} + \sum_{I=1,2} Y_I \underbrace{(\bar{B}_I H) P_L Q + M_I \bar{B}_I B_I}_{\text{production}} + y_I \underbrace{c P_L B_I + c b t}_{\text{decay dark sector}} + \frac{1}{2} \underbrace{m^{-c}}_{\text{B-violating}} + m^2 / \beta^2.$$

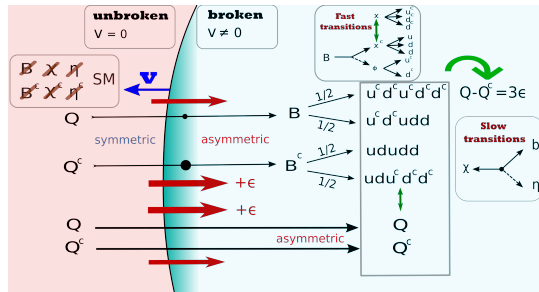
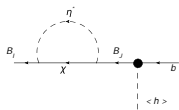
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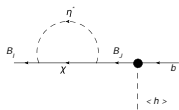
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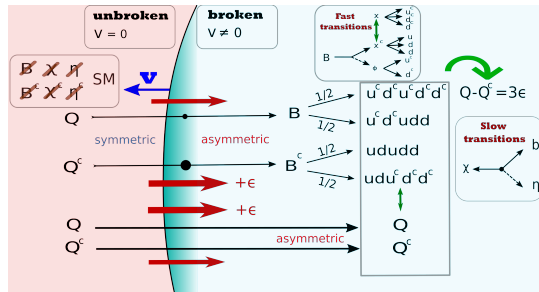
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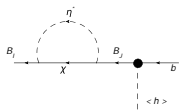
- Production: $P(Q \rightarrow B_i) = P(Q^c \rightarrow B_i^c)$



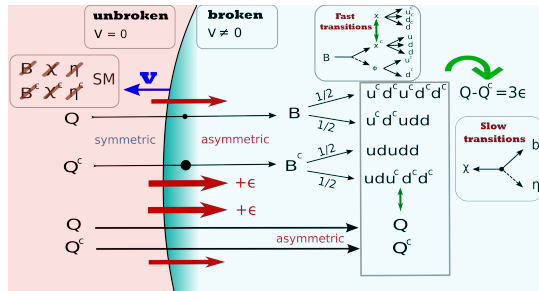
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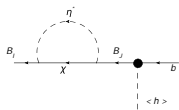
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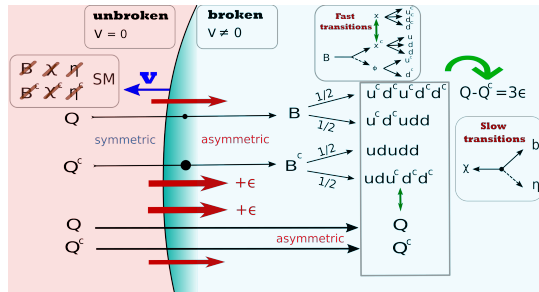
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- $n_B = n_{SM-q} - n_{SM-\bar{q}} = 3n_b^0, \quad \frac{2}{3} \quad 1$
- $N = \bar{N}$, Flavor, collider constraints

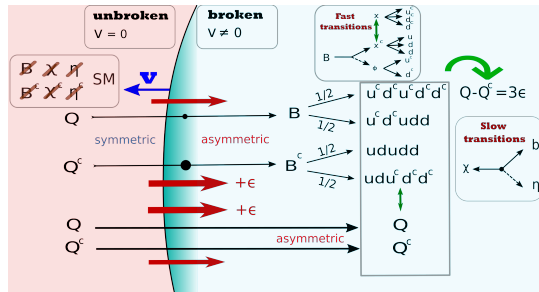
$$2 \text{ TeV} \cdot m \quad m \quad M_B \cdot 20 \text{ TeV}$$



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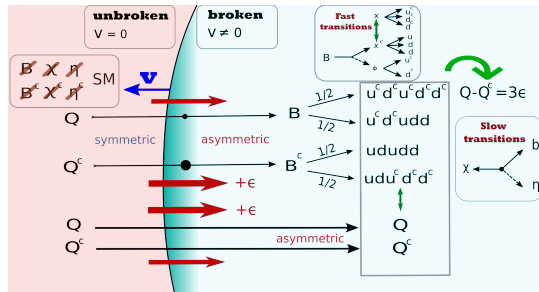
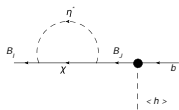
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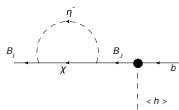
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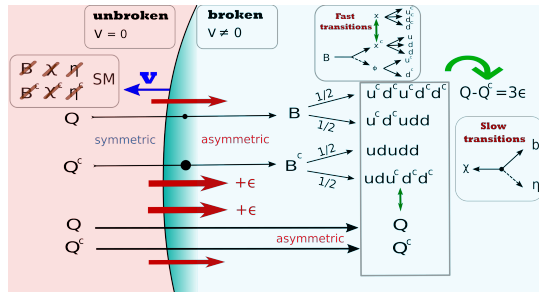
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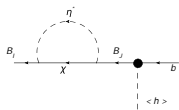
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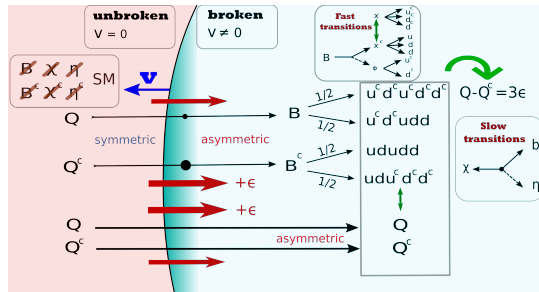
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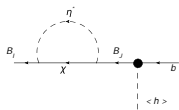
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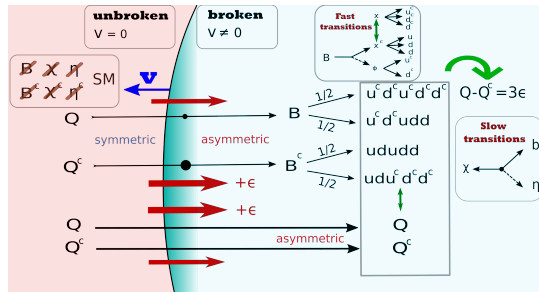
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- $N = \bar{N}$, Flavor, collider constraints

$$2 \text{ TeV} \cdot m \quad m \quad M_B \cdot 20 \text{ TeV}$$



Conclusion baryogenesis

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IV. No PT: the **system remains stuck** in the FV and never nucleates