Relativistic expansion of bubbles in the early universe and baryogenesis

Miguel Vanvlasselaer
mvanvlas@sissa.it

SISSA and INFN Trieste

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Production of heavy states with relativistic bubble walls

Outline

- Introduction of phase transitions in the early universe
- Production of heavy particles: [arXiv:2010.02590] with *Aleksandr Azatov*
- Baryogenesis with *relativistic* bubble walls: [arXiv:2106.14913] with *Aleksandr Azatov* and *Wen Yin*
- Singlet extension of EWPT with relativistic walls: [arXiv:2205.xxxxx] with *Aleksandr Azatov*, *Wen Yin*, *Sabyasachi Chakraborty* and *Giulio Barni*

Optimistically, we can make all of that!

Phase transitions in the early universe

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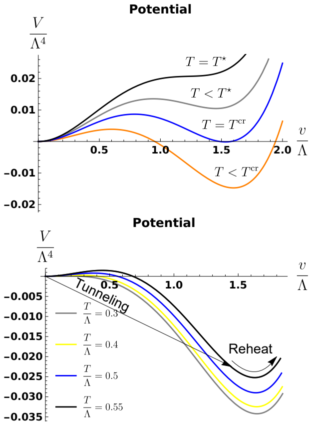
First order phase transition (FOPT) in the early universe

- QFT = landscape of minima ⇒ PT



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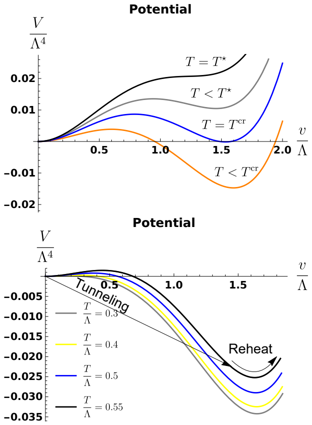

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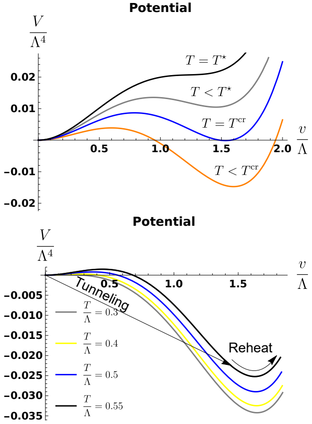

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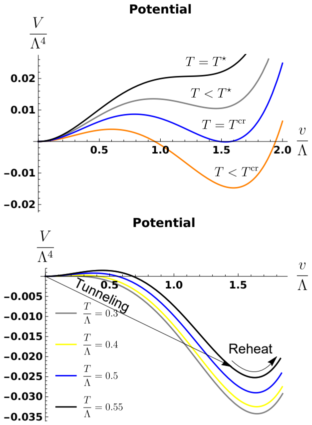

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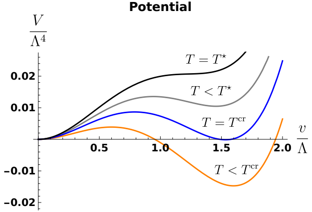
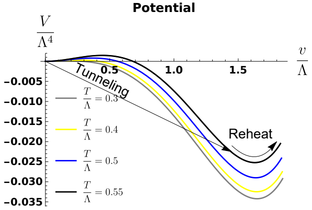
- Nucleation controlled by bounce solution

$$\Gamma \sim T^4 Exp\left[-\frac{S_3}{T}\right]$$

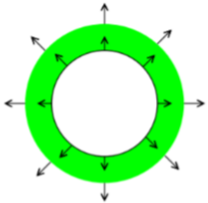




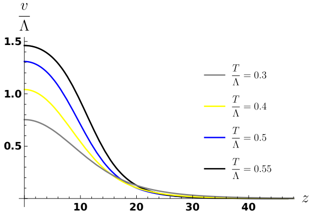
Nucleation and early expansion

- Energy released $\Delta V \Rightarrow$ Driving energy:

$$E_{\text{driving}} = -\frac{4}{3}\pi \Delta V R^3$$



Bounce solution



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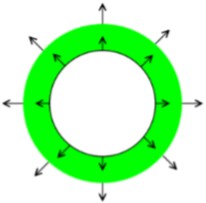

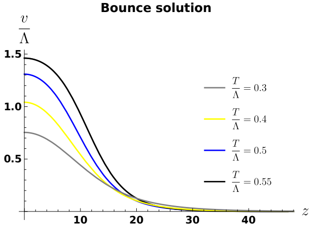

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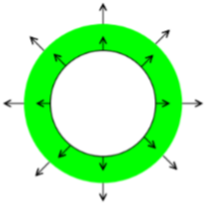

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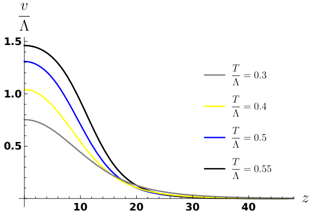

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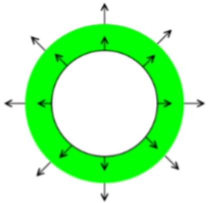

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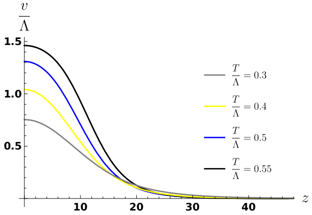

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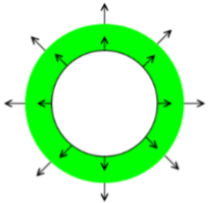
- Reheat behind the wall

$$T_r \approx (1+\alpha)^{1/4} T_{\text{nuc}}, \quad \alpha \equiv \frac{\Delta V}{\rho_r}$$



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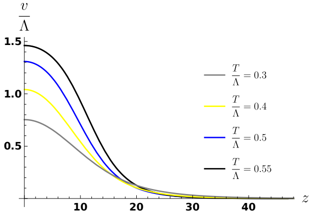

Production of heavy particles

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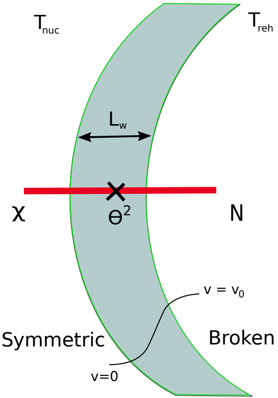
[arXiv:2010.02590] with *Aleksandr Azatov*

Production of heavy states and wall suppression[2010.02590]:Idea

Scale of the transition and particles involved

CLAIM: *transition is dictated by fields* $M \lesssim T_{\rm nuc} \sim v_\phi$ *because* $n_{\rm heavy} \propto e^{-M/T_{\rm nuc}}$



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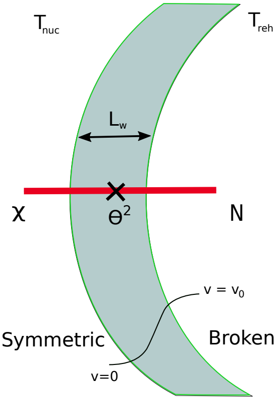

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- Conservation of momentum: *Origins*

$$\text{No wall: } \int d^4x e^{ip\cdot x} \quad \propto \quad (2\pi)^4\delta^4(p), \quad p = p_N - p_\chi$$

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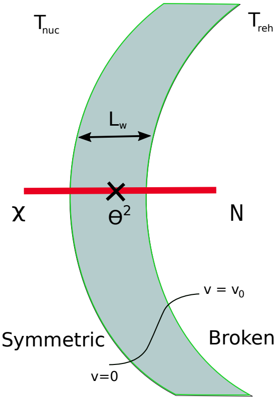

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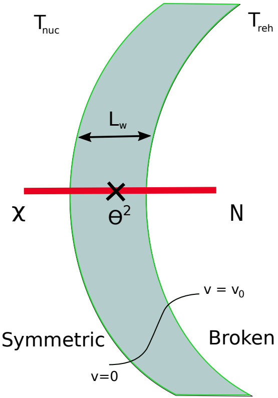

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- With wall: $p = p_N - p_\chi$ not conserved: if $E > M$, $\chi \to N$ allowed

$$\int d^3x_\perp e^{ip_\perp \cdot x_\perp} \int \langle\phi\rangle(z) e^{izp_z} dz \propto (2\pi)^3\delta^3(p_\perp)\frac{\sin \Delta p_z L_w}{\Delta p_z L_w}$$

Production of heavy states and wall suppression[2010.02590]: computation

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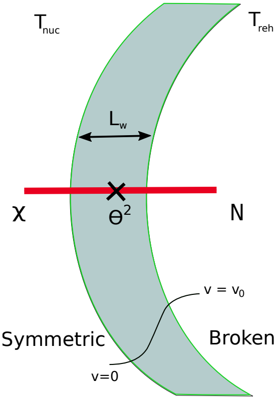

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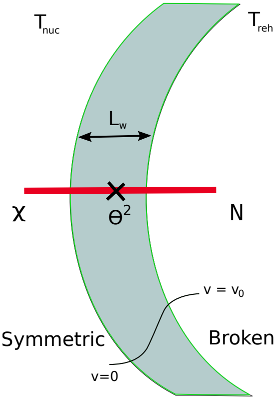

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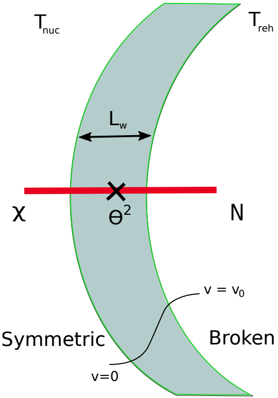

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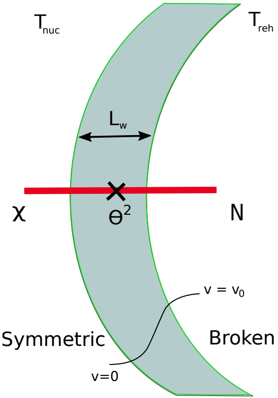

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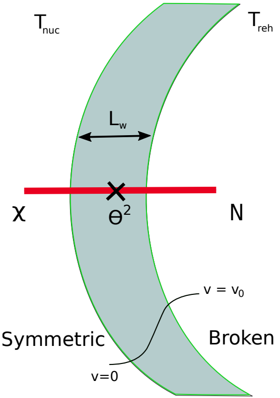

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- Claim WRONG: *states with* $M \gg T_{\rm nuc}$ *can become dynamical during PT*

Idea: production of heavy states

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- Cosmological consequences: 1) Pressure on the bubble wall, 2) Non-thermal DM (1 to 2 splittings), 3) Baryogenesis ...

We focus on Baryogenesis

Baryogenesis with relativistic walls

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[arXiv:2106.14913] with *Aleksandr Azatov* and *Wen Yin*

Baryogenesis

- **B-number violation**; B-violating interactions, sphalerons
- **CP-violation**; *physical* phase into the yukawa matrix
- **Out-of-equilibrium situation**; expansion of the universe, first-order phase transition

Electroweak baryogenesis

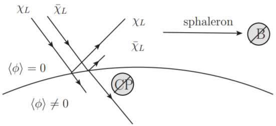


Figure: Credit:T.Konstandin [1302.6713]

Scattering of quarks with CP-violating yukawas off the *slow* bubble wall. B-violation via *sphalerons*

VS

Leptogenesis

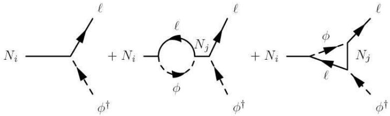


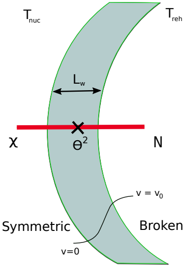
Figure: Credit:T.Konstandin [1302.6713]

Out-of-equilibrium decay of heavy L-violating RH neutrinos. B-violation via sphalerons. CP violation via *loops*

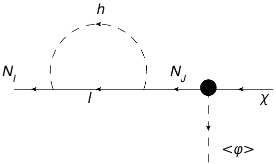
CP violation inside the bubble wall

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

$$\mathcal{L} = i\bar{\chi}_i P_R \not{\partial}\chi_i + i\bar{N}_I \not{\partial} N_I - M_I \bar{N}_I N_I - Y_{iI}\varphi \bar{N}_I P_R \chi_i - y_{I\alpha}(H\bar{L}_\alpha)P_R N_I + h.c.$$



$$A(\chi_i \to N_I)_{\text{tree}} \propto Y_{iI}$$



$$A(\chi_i \to N_I)_{1-\text{loop}} \propto + \sum_{\alpha,J} Y_{iJ} y^*_{\alpha J} y_{\alpha I} \times f^{(hl)}_{IJ}$$

$\Rightarrow$

$$\frac{\Gamma(\chi \to N_I) - \Gamma(\bar{\chi} \to \bar{N}_I)}{\Gamma(\chi \to N_I) + \Gamma(\bar{\chi} \to \bar{N}_I)} = \frac{2\sum_{\alpha,J,i} \mathrm{Im}(Y_{iI} Y^*_{iJ} y_{\alpha J} y^*_{\alpha I})\mathrm{Im} f^{(hl)}_{IJ}}{\sum_i |Y_{iI}|^2}.$$

and

$$\mathrm{Im}[f^{(hl)}_{IJ}(x)] = \frac{1}{16\pi}\frac{\sqrt{x}}{1-x}, x = \frac{M_J^2}{M_I^2}$$

Possible baryogenesis in our production setting?

Idea of baryogenesis with relativistic bubble walls

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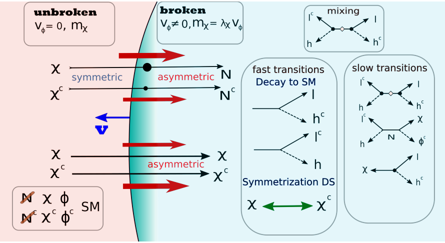
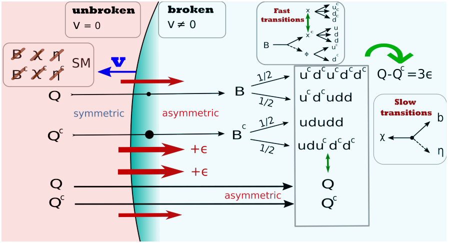
phase transition induced leptogenesis



Or

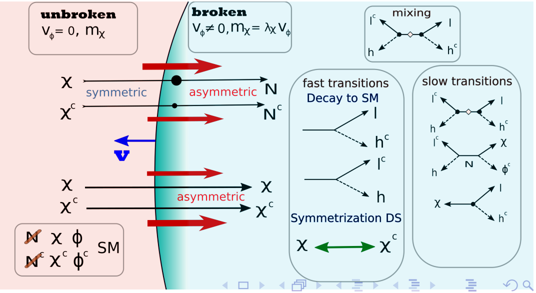
EWPT Baryogenesis with relativistic walls



Two models; phase transition induced leptogenesis

$$\sum_{iI}\underbrace{\left(Y_{iI}(\phi\bar{\chi}_i)P_L N_I + Y^\star_{iI}\bar{N}_I P_R(\phi^\dagger\chi_i)\right)}_{\text{production sector}} - V(\phi) + \underbrace{\sum_i \lambda_\chi \phi \bar{\chi}^c_i \chi_i}_{\text{Majorana mass}} + \sum_I M_I \bar{N}_I N_I + \underbrace{\sum_{\alpha I} y_{\alpha I}(H\bar{L}_{\alpha,SM})P_R N_I}_{\text{CP-violation}}$$

- χ_i Majorana, ϕ scalar, N_I Heavy Dirac RHN: $U_L(1): L(\chi) = -1, L(N) = 1, L(\phi) = 2.$



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$$\underbrace{\sum_{iI}\left(Y_{iI}(\phi\bar{\chi}_i)P_L N_I + Y^\star_{iI}\bar{N}_I P_R(\phi^\dagger\chi_i)\right)}_{\text{production sector}} - V(\phi) + \underbrace{\sum_i \lambda_\chi \phi \bar{\chi}^c_i \chi_i}_{\text{Majorana mass}} + \sum_I M_I \bar{N}_I N_I + \underbrace{\sum_{\alpha I} y_{\alpha I}(H\bar{L}_{\alpha,SM})P_R N_I}_{\text{CP-violation}}$$

- χ_i Majorana, ϕ scalar, N_I Heavy Dirac RHN: $U_L(1) : L(\chi) = -1, L(N) = 1, L(\phi) = 2$.
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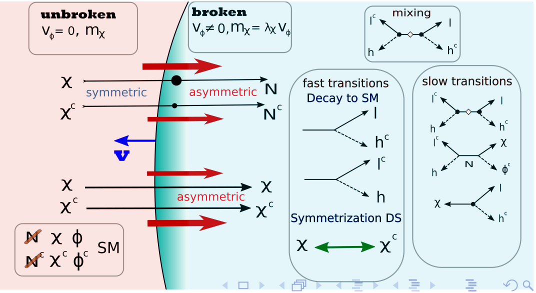

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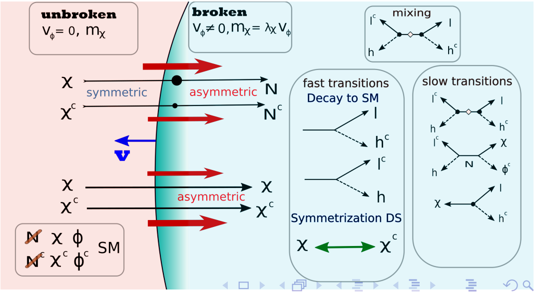

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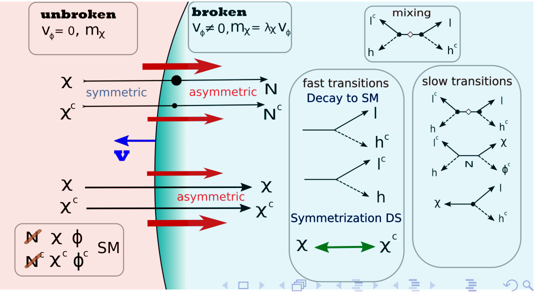
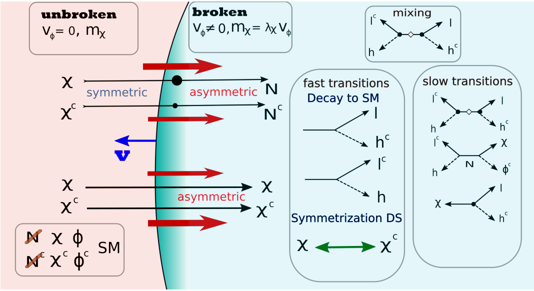
- **Fast interactions**;
  1. $\chi \leftrightarrow \chi^c$: *Annihilation* in light sector
  2. $N_I \to LH$: *Transfer* to SM
  3. $N_I \to \phi\chi$: *Wash-out*



Two models; phase transition induced leptogenesis

$$\text{Lepton asym produced} \approx \frac{\Delta n_L}{s} \sim \sum_{il\alpha} \epsilon_{il} \times \frac{\theta_{il}^2}{g_*} \left(\frac{T_{nuc}}{T_{reh}} \right)^3 \times \frac{|y_{I\alpha}|^2}{|y_{I\alpha}|^2 + |Y_{il}|^2}$$

- **Slow interactions**: sphalerons $\Delta L \to \Delta B$



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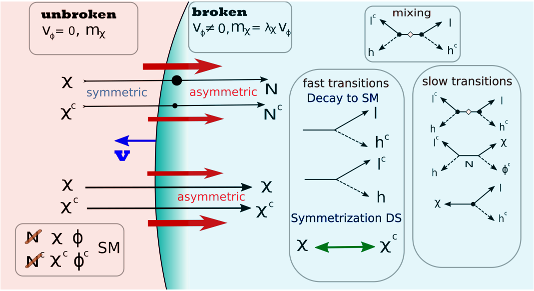

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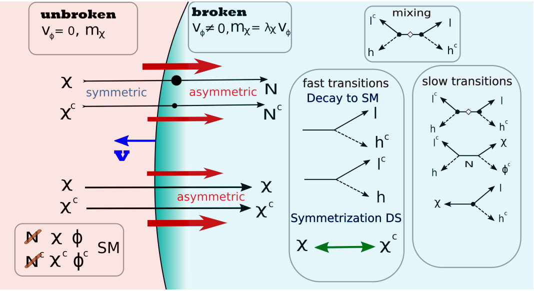
- But... Wash-outs from L-violating;

$$\boxed{H^c L \to H L^c} \Rightarrow T_{reh} < 10^{13} \text{ GeV}$$

$$\boxed{HL \to \chi} \Rightarrow \frac{m_\chi}{T_{reh}} > 15$$



Two models; low energy baryogenesis

$$\mathcal{L}_{SM} + \sum_{I=1,2} \underbrace{Y_I(\bar{B}_I H) P_L Q}_{\text{production}} + M_I \bar{B}_I B_I + \underbrace{y_I \eta \chi^c P_L B_I + \kappa \eta^c du}_{\text{decay dark sector}} + \underbrace{\frac{1}{2} m_\chi \bar{\chi}^c \chi}_{\text{B-violating}} + m_\eta^2 |\eta|^2 .$$

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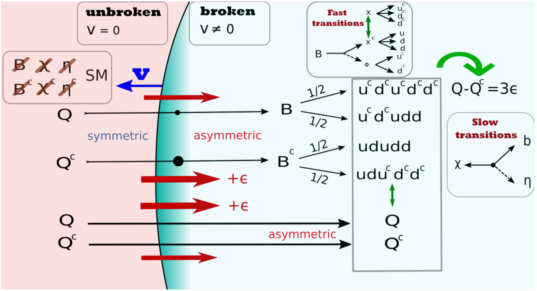

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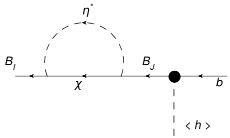

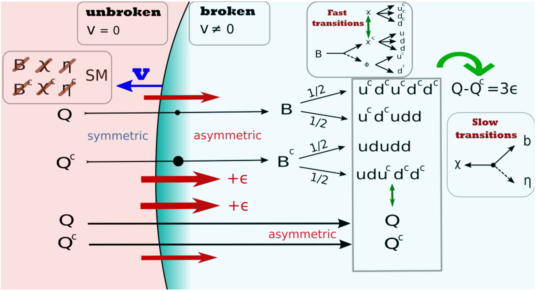

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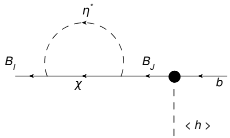

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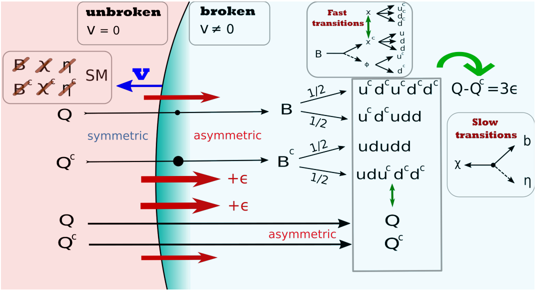

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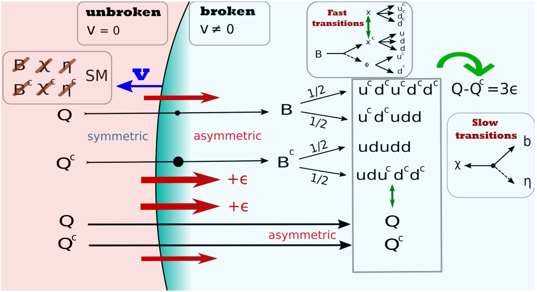

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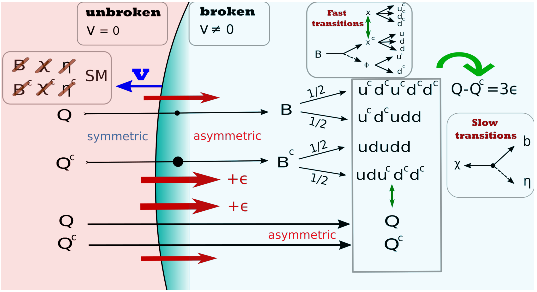

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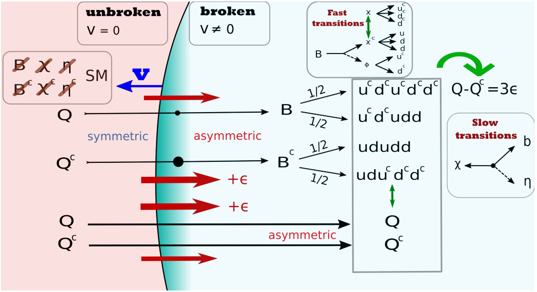
- Experimental signatures: $N \leftrightarrow \bar{N}$, Flavor, collider push: $\boxed{m_\chi \sim m_\eta \sim M_B \gtrsim 2 \text{ TeV}}$ and $d = b, u = t$



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.

- Question: How can we make EWPT with ultra-fast bubble walls ?

EWPT with relativistic walls

EWPT with relativistic walls

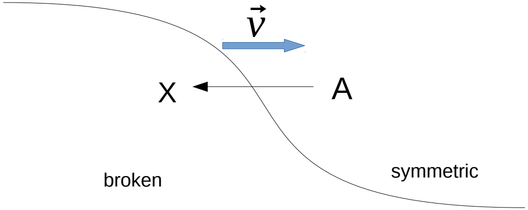
[arXiv:2205.xxxxx] with *Aleksandr Azatov*, *Wen Yin*, *Sabyasachi Chakraborty* and *Giulio Barni*

Velocity

Final velocity $\gamma_{wp}^{MAX} = \frac{1}{\sqrt{1-v_{MAX}^2}}$ of the wall set by

$$\Delta V = \Delta \mathcal{P}(\gamma_{wp}^{MAX}) \quad \Rightarrow \quad \text{determination } \gamma_{wp}^{MAX}$$

- ΔV independent of the velocity of the wall



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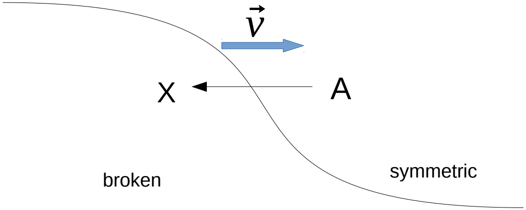

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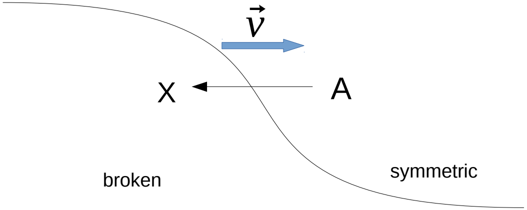
- $\Delta\mathcal{P}(\gamma_{wp}^{MAX})$ very difficult to compute in general and depends on the velocity
- Generic method: solve the full coupled system of Boltzmann equations

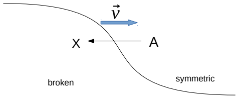
$$p^\mu \partial_\mu f_i + \frac{1}{2}\partial_z m_i[\phi]\partial_{p_z} f_i = \mathcal{C}[f_i, \phi]$$

$$\Box\phi + \frac{dV}{d\phi} + \sum_i \frac{dm_i^2[\phi]}{d\phi}\int \frac{d^3p}{(2\pi)^3}\frac{1}{2E_i} f_i = 0$$



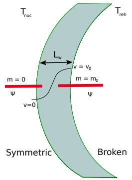
Primer on pressure in relativistic regime

$$\Delta\mathcal{P}_{A\to X} = \int \frac{p_z d^3p}{p_0(2\pi)^3} f_A(p) \times \sum_X \int d\Delta P_{A\to X} \Delta p$$



LO pressure [0903.4099]

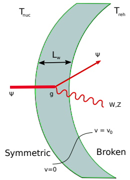
$$\Delta\mathcal{P}_{LO} \approx \sum_i \frac{\Delta m_i^2 T^2}{24}, \quad \Delta m_i^2 \equiv m_{bro,i}^2 - m_{sym,i}^2$$



Condition for relativistic wall $\boxed{\Delta V > \mathcal{P}_{LO}}$

Theories with gauge bosons V [1703.08215]

$$\Delta\mathcal{P}_{NLO} \sim \sum_i g_i \frac{g_{\rm gauge}^3 v}{16\pi^2} \gamma_{wp} T^3$$

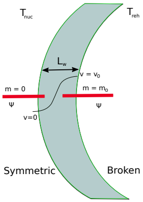


Primer on pressure in relativistic regime: case of the EWPT

LO pressure:

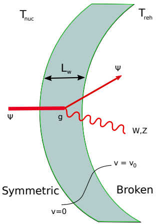
$$\Delta\mathcal{P}_{\rm LO}^{SM} \approx T_{\rm nuc}^2 v_{EW}^2 \left(\frac{y_t^2}{8} + \frac{g^2+g'^2}{32} + \frac{g^2}{16}\right) \approx 0.17\, T_{\rm nuc}^2 v_{EW}^2 .$$

Condition for relativistic wall $\boxed{\Delta V > 0.17\, T_{\rm nuc}^2 v_{EW}^2}$



NLO pressure: [arXiv:2112.07686]: Gouttenoire, Jinno, Sala

$$\Delta\mathcal{P}_{\rm NLO}^{SM} \approx \left[\sum_{abc} \nu_a g_a \beta_c C_{abc}\right] \frac{\kappa\zeta(3)}{\pi^3} \times \alpha M_Z(v_{EW}) \gamma_{wp} T_{\rm nuc}^3$$



Terminal velocity

$$\Delta V - \Delta\mathcal{P}_{\rm LO}^{SM} = \Delta\mathcal{P}_{\rm NLO}^{SM} \Rightarrow \gamma_{wp}^{\rm terminal} \approx 50 \times \left(\frac{40\ \text{GeV}}{T_{\rm nuc}}\right)^3 \left(\frac{\Delta V}{v_{EW}^4}\right)^{1/4}$$

Intuition on supercooling and ultra-relativistic walls

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- With a singlet S with a Z_2 symmetry ?

$$V(h,S) = -\frac{m_h^2}{2}h^2 + \frac{\lambda}{4}h^4 - \frac{m_s^2}{4}S^2 + \frac{\lambda_s}{4}S^4 + \frac{\lambda_{hs}}{2}S^2h^2,$$

Model studied: singlet extension with a Z_2 and patterns

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Criterion for relativistic: $\underbrace{\Delta V}_{\text{E released}} > \underbrace{\Delta \mathcal{P}_{\rm rel}(T_{\rm nuc})}_{\text{pressure at LO}}, \qquad \mathcal{P}_{\rm rel}(T_{\rm nuc}) \approx C \times T_{\rm nuc}^2 v_{EW}^2$

$$m_{\rm eff}^2(T) = -\frac{m_h^2}{2} + C \times T^2 \qquad \Rightarrow T_{\rm min}^2 = \frac{m_h^2}{2C} \qquad \mathcal{P}_{\rm rel}^{\rm min} = \boxed{\frac{m_h^2 v_{EW}^2}{4} > \Delta V}$$

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- **Mixing scenario**:$(0,0) \to (v_{EW}, v_s \neq 0)$: strong bounds on mixing angle from colliders.
- **Spectator singlet**: $(0,0) \to (v_{EW}, 0)$: unlikely to produce ultra-relativistic walls.

Criterion for relativistic: $\underbrace{\Delta V}_{\text{E released}} > \underbrace{\Delta \mathcal{P}_{\text{rel}}(T_{\text{nuc}})}_{\text{pressure at LO}}, \qquad \mathcal{P}_{\text{rel}}(T_{\text{nuc}}) \approx C \times T_{\text{nuc}}^2 v_{EW}^2$

$$m_{\text{eff}}^2(T) = -\frac{m_h^2}{2} + C \times T^2 \qquad \Rightarrow T_{\text{min}}^2 = \frac{m_h^2}{2C} \qquad \mathcal{P}_{\text{rel}}^{\text{min}} = \boxed{\frac{m_h^2 v_{EW}^2}{4} > \Delta V}$$

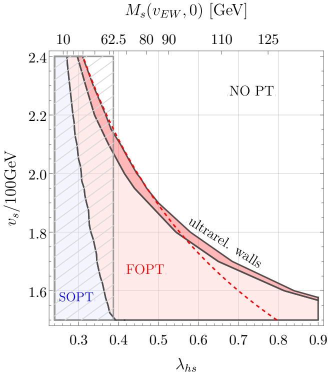
- **Two-steps PT**: $\boxed{(0,0) \xrightarrow{SOPT} (0, v_s) \xrightarrow{FOPT} (v_{EW}, 0)}$

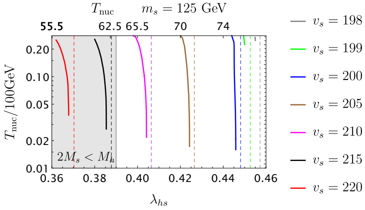
  In the second PT:

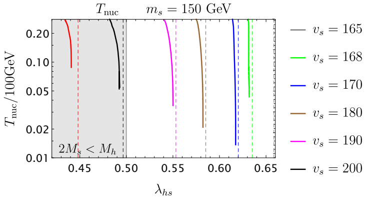
$$m_{\text{eff}}^2(T) = -\frac{m_h^2}{2} + \frac{\lambda_{hs}}{2}v_s^2 + C \times T^2$$

Scan of parameter space

$$M^{MAX} \approx \sqrt{v_{EW} T_{\rm nuc} \gamma_w} \approx 700 \text{ GeV} \times \left(\frac{40 \text{ GeV}}{T_{\rm nuc}}\right) \left(\frac{\Delta V}{v_{EW}^4}\right)^{1/8}$$







$$M^{MAX} \in [1, 20] \text{ TeV}$$

Conclusion ultra-relativistic EWPT

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- Second transition is FOPT and has relativistic walls in a sizable region of parameter space
- Ultra-relativistic walls exist in a tuned region of parameter space when $M_s \sim 70 - 100$ GeV

Back-up

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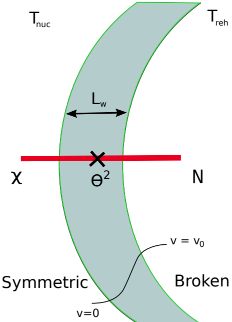
Production of heavy states and wall suppression[2010.02590]

Scale of the transition and particles involved

Claim: *transition is dictated by fields* $M \lesssim T_{\rm nuc} \sim v_{\rm trans}$ *because* $n_{\rm heavy} \propto e^{-M/T_{\rm nuc}}$



- **Adiabatic transition $\Delta pL > 1$**

$$\frac{M}{T} < \gamma_{wp} < \frac{M^2 L_w}{T}$$

light to light $\chi \to \chi'$ only

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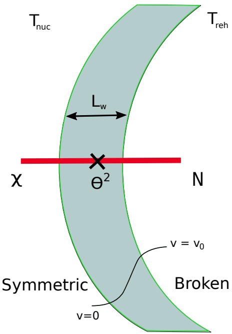


- **Adiabatic transition** $\Delta pL > 1$

$$\frac{M}{T} < \gamma_{wp} < \frac{M^2 L_w}{T}$$

light to light $\chi \to \chi'$ only

- **non-adiabatic transition** $\Delta pL < 1$

$$\gamma_{wp} > \frac{M^2 L_w}{T}$$

light to heavy $\chi \to N$ unsuppressed

Falkowski and No bubble wall production

Production of heavy states during the collision of bubbles. arXiv:1211.5615

- Can be non thermal DM: arXiv:1211.5615
- Or make a barygenesis mechanism: arXiv 1608.00583

Necessary ingredients

- Portal coupling similar to ours.
- Runaway bubble (otherwise, energy dissipated in the plasma): not operative in EWPT.
- Elastic collision (restoration of the false vacuum in between the bubble)

Constraints and experimental signatures on the EWBG proposed

1. **Neutron-anti-neutron oscillations**: baryon number violation by 2 units

$$\frac{1}{\Lambda_{n\bar{n}}^5}\overline{u^c d^c d^c}udd \equiv \frac{(\sum \kappa\theta_I y_I)^2}{M_\eta^4 m_\chi}\overline{u^c d^c d^c}udd \qquad \Rightarrow \qquad \delta m_{\bar{n}-n} \sim \frac{\Lambda_{QCD}^6}{M_\eta^4 m_\chi}(\sum \kappa\theta_I y_I)^2$$

Current bounds on this mixing mass are of order $\delta m_{\bar{n}-n} \lesssim 10^{-33}$

$$\Lambda_{n\bar{n}} \gtrsim 10^6\mathrm{GeV} \quad (M_\eta, m_\chi) \gtrsim 10^5\mathrm{GeV}$$

2. **Flavor violation**: Need to couple strongly only to t_R, b_R
3. **Contribution to electron EDM**:

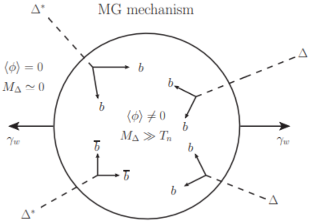
$$\frac{d_e}{e} \sim \frac{m_e(yYe)^2}{(4\pi)^6}\left(\frac{1}{\Lambda_{EDM}^2}\right) \sim 3\times 10^{-33} \times \left(\frac{10\mathrm{TeV}}{\Lambda_{EDM}}\right)^2 \mathrm{cm}$$

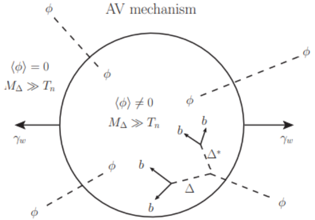
while experimental bound is $|d_e| < 1.1\times 10^{-29}\mathrm{cm}\cdot e$

Comparison with proposal in arXiv:2106.15602

Baryogenesis with relativistic walls by Baldes et al. arXiv:2106.15602

- Relativistic walls $\gamma_{wp} \gg 1$
- scalar model $\Delta\mathcal{L} = -\frac{\lambda}{2}\phi^2 h^2 + \frac{M_\phi^2}{2}\phi^2$ with production of heavy scalar ϕ
- ϕ in $(3, 1, 2/3)$ of the SM and $\Delta\mathcal{L} = y_{di}\phi_i \bar{d}_R d'_R + y_{ui}\phi_i \bar{N}_R u^c_R$ with physics phase in y'
- CP and B violation in decay $\phi \to bb$





Full expression

PT leptogenesis: CP violation in production+decay

$$\frac{n_B - n_{\bar{B}}}{s} \simeq -\frac{28}{79} \times \frac{135\zeta(3) g_\chi}{8\pi^4 g_*} \times \sum_I \theta_I^2 \sum_{\alpha,J} \mathrm{Im}(Y_I Y_J^* y_{\alpha J} y_{\alpha I}^*) \mathrm{Im} f_{IJ}^{(hl)}$$

$$\times \left(\frac{2}{|Y_I|^2} - \frac{1}{\sum_\alpha |y_{\alpha I}|^2} \right) \left(\frac{T_{nuc}}{T_{reh}} \right)^3 \frac{\sum_\alpha |y_{\alpha I}|^2}{\sum_\alpha |y_{\alpha I}|^2 + |Y_I|^2}$$

EWPT baryogenesis: CP violation in production+decay

$$\frac{\Delta n_{Baryon}}{s} \approx \frac{135\zeta(3)}{8\pi^4} \sum_{I,J} \theta_I^2 \frac{|y_I|^2}{|y_I|^2 + |Y_I|^2} \times \frac{g_b}{g_\star} \left(\frac{T_{\mathrm{nuc}}}{T_{reh}} \right)^3$$

$$\times \mathrm{Im}(Y_I Y_J^* y_I^* y_J) \left(-\frac{2\mathrm{Im}[f_B^{IJ}]}{|Y_I|^2} + \frac{4\mathrm{Im}[f_B^{IJ}]|_{m_\chi,\eta \to 0}}{|y_I|^2} \right).$$