



SUSY 2023



## Relativistic expansion of bubbles & EW Baryogenesis

SISSA & INFN TRIESTE  
Julio Barni  
[gbarni@sissa.it](mailto:gbarni@sissa.it)

**Collaborators:** A. Azatov, M. Vanvlasselaer, W. Yin, S. Chackraborty

# Outline

- ① FOPT: What & bubbles dynamic
- ② FOPT: Why?
- ③ Simplest *BSM* extension of the *SM*: What & Why?
- ④ Ultrarelativistic EWPT
- ⑤ EW Baryogenesis

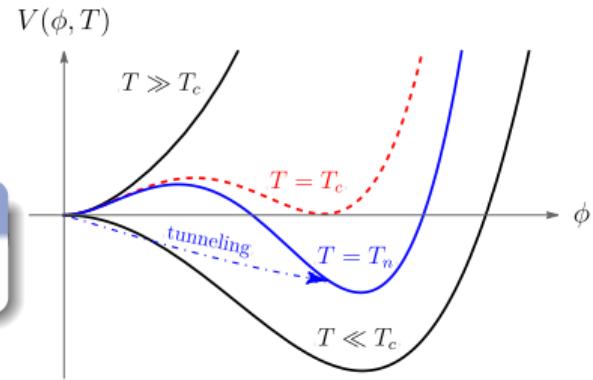
# FOPT: What?

# FOPT: What?

**Hot PT:** A FOPT can occur when two minima are separated by a barrier

Tunneling decay rate of the false vacuum

$$\Gamma \sim T^4 e^{-S_3/T}, \quad \text{Euclidean action}$$



# FOPT: What?

**Hot PT:** A FOPT can occur when two minima are separated by a barrier

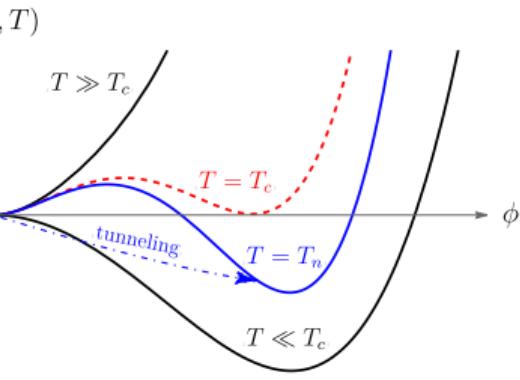
Tunneling decay rate of the false vacuum

$$\Gamma \sim T^4 e^{-S_3/T}, \quad \text{Euclidean action}$$

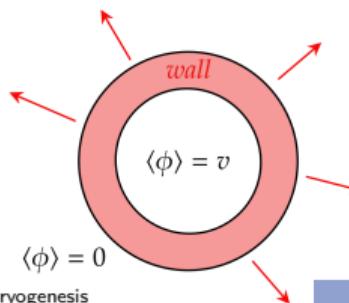
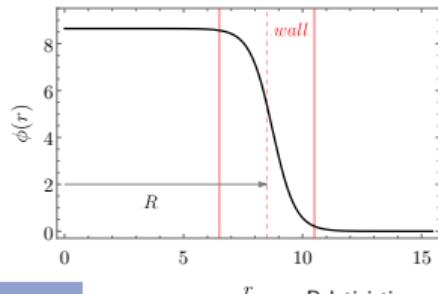
Solution w/  
minimal action

$\Rightarrow$

$$O(d) \text{ spherical symm.} \\ \phi \equiv \phi(r), \quad r = \sqrt{\tau^2 + x^2}$$

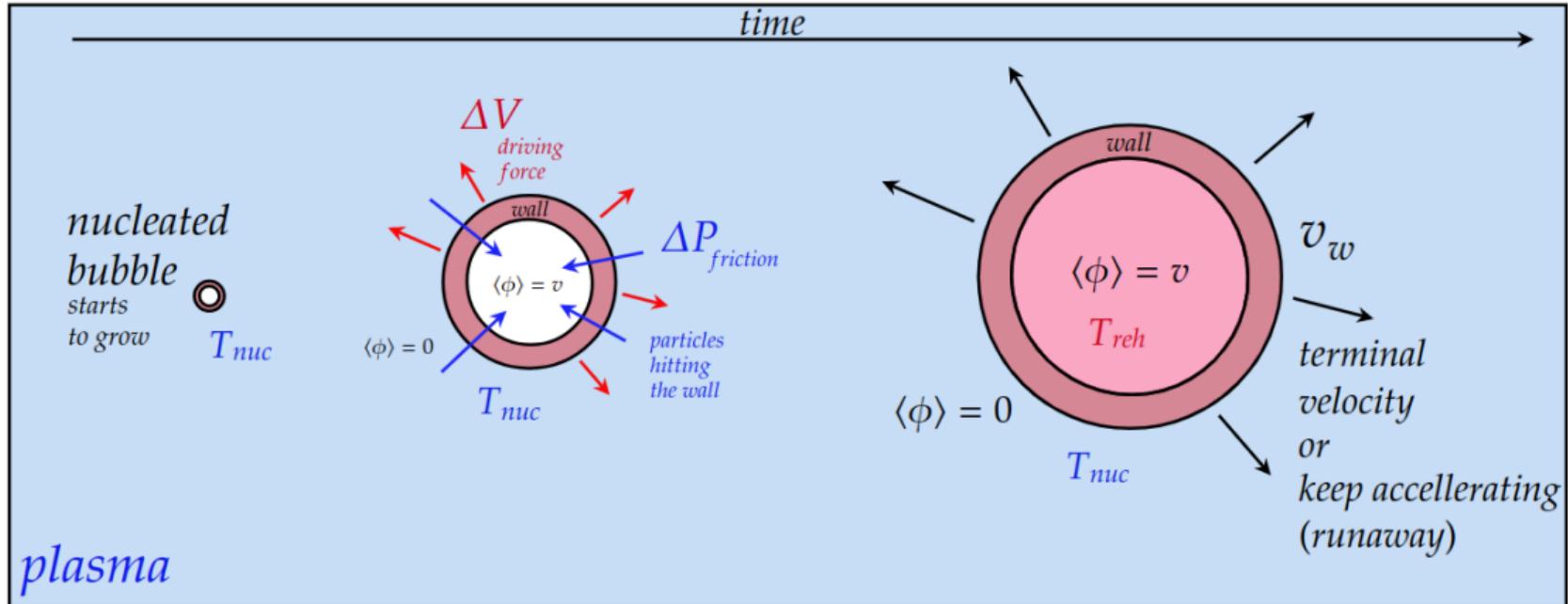


Bubbles!



Relativistic expansion of bubbles & EW Baryogenesis

# FOPT: Bubble dynamic



# FOPT: Bubble dynamic (General case)

**Equilibrium velocity** of the bubbles (or runaway),  $\gamma_w^{\max}$ , is setted by

$$\Delta V = \Delta \mathcal{P}(\gamma_w^{\max})$$

- $\Delta V$  is independent on the velocity of the wall
- $\Delta \mathcal{P}(\gamma_w^{\max})$  very difficult to compute in general and depends on the velocity

# FOPT: Bubble dynamic (General case)

**Equilibrium velocity** of the bubbles (or runaway),  $\gamma_w^{\max}$ , is setted by

$$\Delta V = \Delta \mathcal{P}(\gamma_w^{\max})$$

- $\Delta V$  is independent on the velocity of the wall
- $\Delta \mathcal{P}(\gamma_w^{\max})$  very difficult to compute in general and depends on the velocity

GENERAL CASE: solve coupled differential system

$$\begin{cases} p^\mu \partial_\mu \mathbf{f}_i + \frac{1}{2} \partial_z m_i[\phi] \partial_{p_z} \mathbf{f}_i = \mathcal{C}[\mathbf{f}_i, \phi] \\ \square \phi + \frac{dV}{d\phi} + \sum_i \frac{dm_i^2[\phi]}{d\phi} \int \frac{d^3 p}{(2\pi)^3} \frac{\mathbf{f}_i}{2E_i} = 0 \end{cases}$$

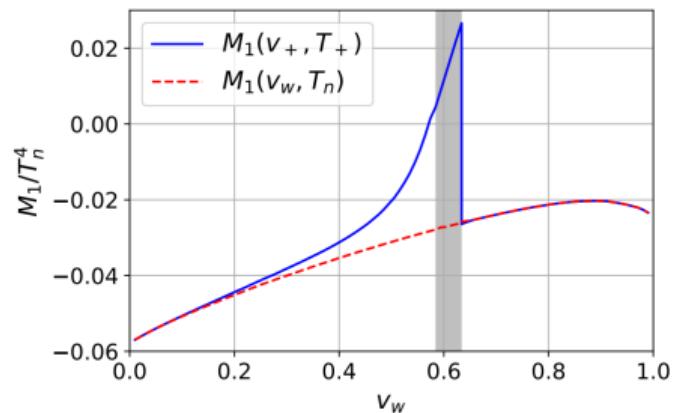


Figure: Friction acting on the bubble expansion.  
[2102.12490]

# FOPT: Bubble dynamic (General case)

**Equilibrium velocity** of the bubbles (or runaway),  $\gamma_w^{\max}$ , is setted by

$$\Delta V = \Delta \mathcal{P}(\gamma_w^{\max})$$

- $\Delta V$  is independent on the velocity of the wall
- $\Delta \mathcal{P}(\gamma_w^{\max})$  very difficult to compute in general and depends on the velocity

Relativistic case ( $\gamma_w \gg 1$ )

$$\begin{cases} \mathcal{C} \rightarrow 0 \text{ (ballistic regime)}, & f_i \gg f_i^{\text{eq}} \\ \square\phi + \frac{dV_T}{d\phi} = 0 \end{cases}$$

$$\boxed{\Delta \mathcal{P} = \int \frac{d^3 p}{(2\pi)^3} \frac{p_z}{p_0} f_A^{\text{eq}} \times \sum_X \int d\mathbb{P}_{A \rightarrow X} \Delta p_z}$$

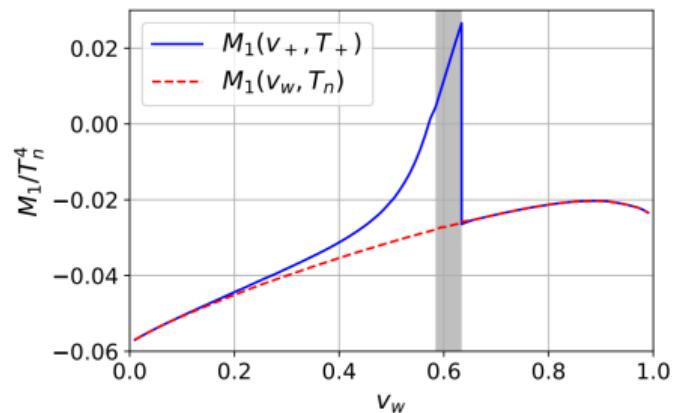


Figure: Friction acting on the bubble expansion.  
[2102.12490]

# FOPT: Bubble dynamic ( $\gamma_w \gg 1$ )

[JCAP05(2009)009] & [JCAP05(2017)025]: Bodeker, Moore

Relativistic regime → simple computation:

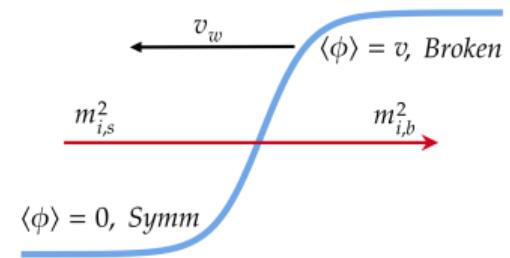
# FOPT: Bubble dynamic ( $\gamma_w \gg 1$ )

[JCAP05(2009)009] & [JCAP05(2017)025]: Bodeker, Moore

Relativistic regime → simple computation:

- ➊ recoil of particles getting mass passing through the wall

$$\Delta\mathcal{P}_{LO} \sim \sum_i c_i \frac{\Delta m_i^2}{24} T_{\text{nuc}}^2, \quad \Delta m_i^2 = m_{i,\text{bro}}^2 - m_{i,\text{symm}}^2$$



# FOPT: Bubble dynamic ( $\gamma_w \gg 1$ )

[JCAP05(2009)009] & [JCAP05(2017)025]: Bodeker, Moore

Relativistic regime → simple computation:

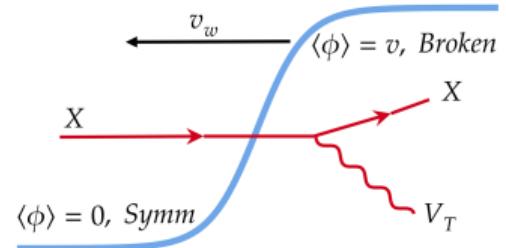
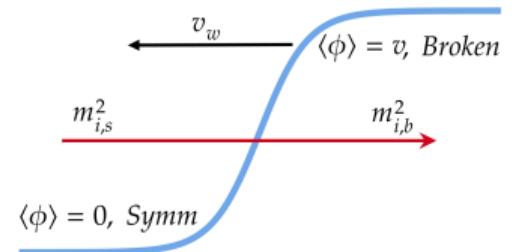
- ① recoil of particles getting mass passing through the wall

$$\Delta\mathcal{P}_{LO} \sim \sum_i c_i \frac{\Delta m_i^2}{24} T_{\text{nuc}}^2, \quad \Delta m_i^2 = m_{i,\text{bro}}^2 - m_{i,\text{symm}}^2$$

- ② Transition radiation emission from soft vector bosons

$$\Delta\mathcal{P}_{NLO} \sim \sum_i \frac{g_i}{16\pi^2} g^2 m_{V,i} \gamma_w T_{\text{nuc}}^3$$

The less  $T_{\text{nuc}}$  the more  $\gamma_w$ .



# FOPT: Bubble dynamic ( $\gamma_w \gg 1$ )

[JCAP05(2009)009] & [JCAP05(2017)025]: Bodeker, Moore

Relativistic regime → simple computation:

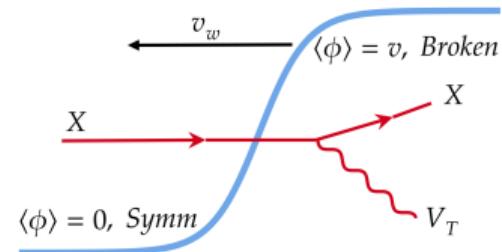
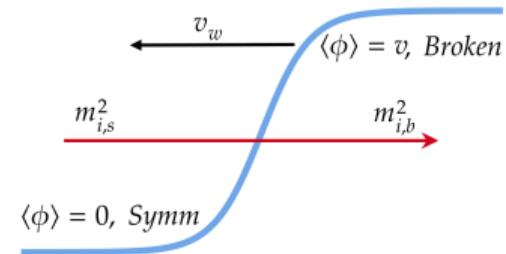
- ① recoil of particles getting mass passing through the wall

$$\Delta\mathcal{P}_{LO} \sim \sum_i c_i \frac{\Delta m_i^2}{24} T_{\text{nuc}}^2, \quad \Delta m_i^2 = m_{i,bro}^2 - m_{i,symm}^2$$

- ② Transition radiation emission from soft vector bosons

$$\Delta\mathcal{P}_{NLO} \sim \sum_i \frac{g_i}{16\pi^2} g^2 m_{V,i} \gamma_w T_{\text{nuc}}^3$$

**Weaknesses:**  $\left\{ \begin{array}{l} \text{WKB not consistent} \\ \text{Longitudinal pol. not properly considered} \\ \dots \end{array} \right.$



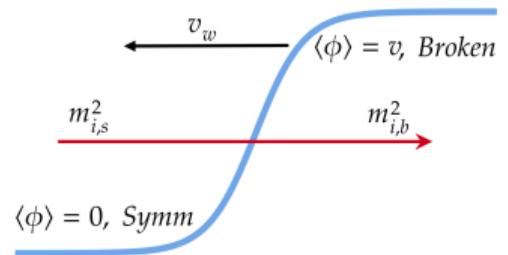
# FOPT: Bubble dynamic ( $\gamma_w \gg 1$ )

[JCAP05(2009)009] & [JCAP05(2017)025]: Bodeker, Moore

Relativistic regime → simple computation:

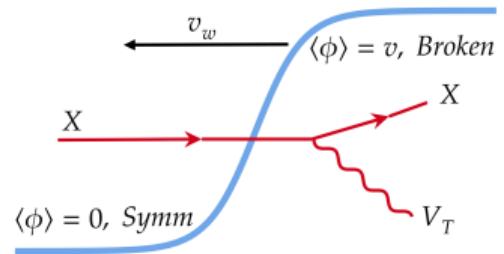
- ➊ recoil of particles getting mass passing through the wall

$$\Delta\mathcal{P}_{LO} \sim \sum_i c_i \frac{\Delta m_i^2}{24} T_{\text{nuc}}^2, \quad \Delta m_i^2 = m_{i,bro}^2 - m_{i,symm}^2$$



- ➋ Transition radiation emission from soft vector bosons

$$\Delta\mathcal{P}_{NLO} \sim \sum_i \frac{g_i}{16\pi^2} g^2 m_{V,i} \gamma_w T_{\text{nuc}}^3$$



[2308.xxxxx]

# FOPT: Why?

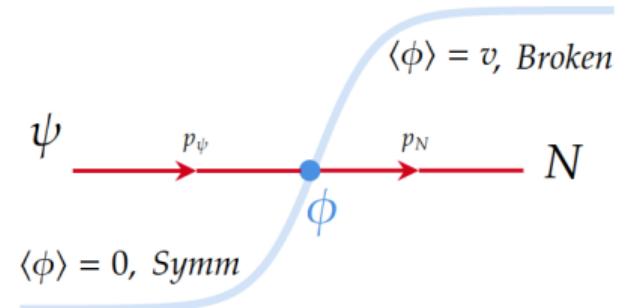
- ② Heavy states can be produced if the walls are **ultra-relativistic** ( $\gamma \gg 1$ )

- ② Heavy states can be produced if the walls are **ultra-relativistic** ( $\gamma \gg 1$ )

Plasma particle hitting the DW ( $\equiv$  Higgs at rest)

Wall frame:  $p_\psi = (\gamma T, 0, 0, \gamma T)$     $p_\phi = (m_\phi, 0, 0, 0)$

$$\sqrt{s} \sim M_N \sim \sqrt{\gamma T m_\phi} \gg m_\phi, T$$



- ② Heavy states can be produced if the walls are ultra-relativistic ( $\gamma \gg 1$ )

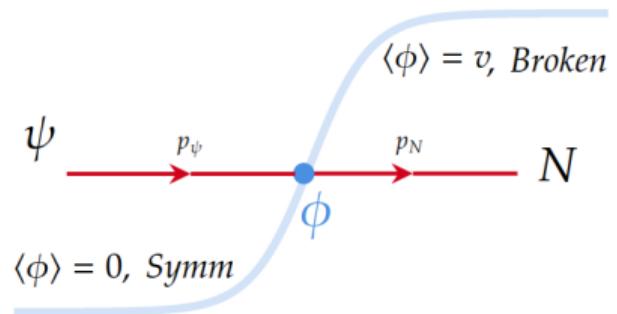
Plasma particle hitting the DW ( $\equiv$  Higgs at rest)

Wall frame:  $p_\psi = (\gamma T, 0, 0, \gamma T)$     $p_\phi = (m_\phi, 0, 0, 0)$

$$\sqrt{s} \sim M_N \sim \sqrt{\gamma T m_\phi} \gg m_\phi, T$$

Applications:

- Heavy DM production
- FOPTs +  **$C/CP$ -violating &  $B$ -violating** interactions w/ heavy states  $\Rightarrow$  **Baryogenesis**





# Ultrarelativistic FOPTs

Aim: find general features for relativistic FOPT & explicit relativistic EWPT

Aim: find general features for relativistic FOPT & explicit relativistic EWPT

- Well-known that in *SM* all the PT are  $2^{nd}$  order
- simplest extension of the *SM* with FOPT: *SM*+ real  $Z_2$  singlet.

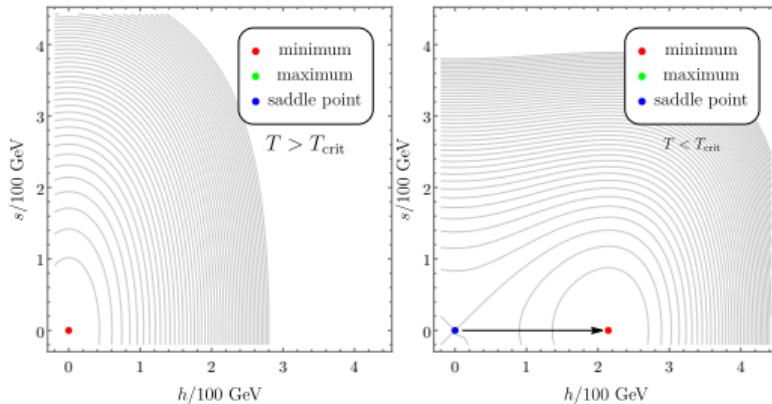
$$V_0(\mathcal{H}, s) = \underbrace{-\frac{m_h^2}{2}(\mathcal{H}^\dagger \mathcal{H}) + \lambda(\mathcal{H}^\dagger \mathcal{H})^2}_{\text{Higgs potential}} - \underbrace{\frac{m_s^2}{4}s^2 + \frac{\lambda_s}{4}s^4}_{\text{real singlet}} + \underbrace{\frac{\lambda_{hs}}{2}s^2(\mathcal{H}^\dagger \mathcal{H})^2}_{\text{mixing}}$$

- Already studied in detail but previous studies not focused on relativistic bubbles.  
(usual EW Baryogenesis required slow bubbles)

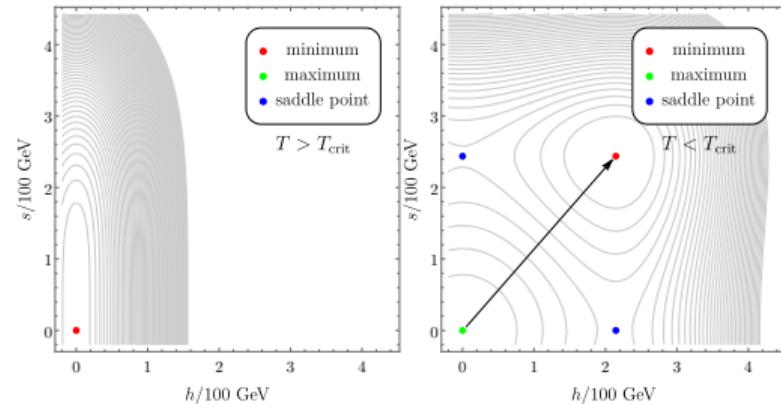
# Relativistic EWPT: 1-step PT

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

$(0, 0) \rightarrow (v_{EW}, 0)$



$(0, 0) \rightarrow (v_{EW}, v_s)$

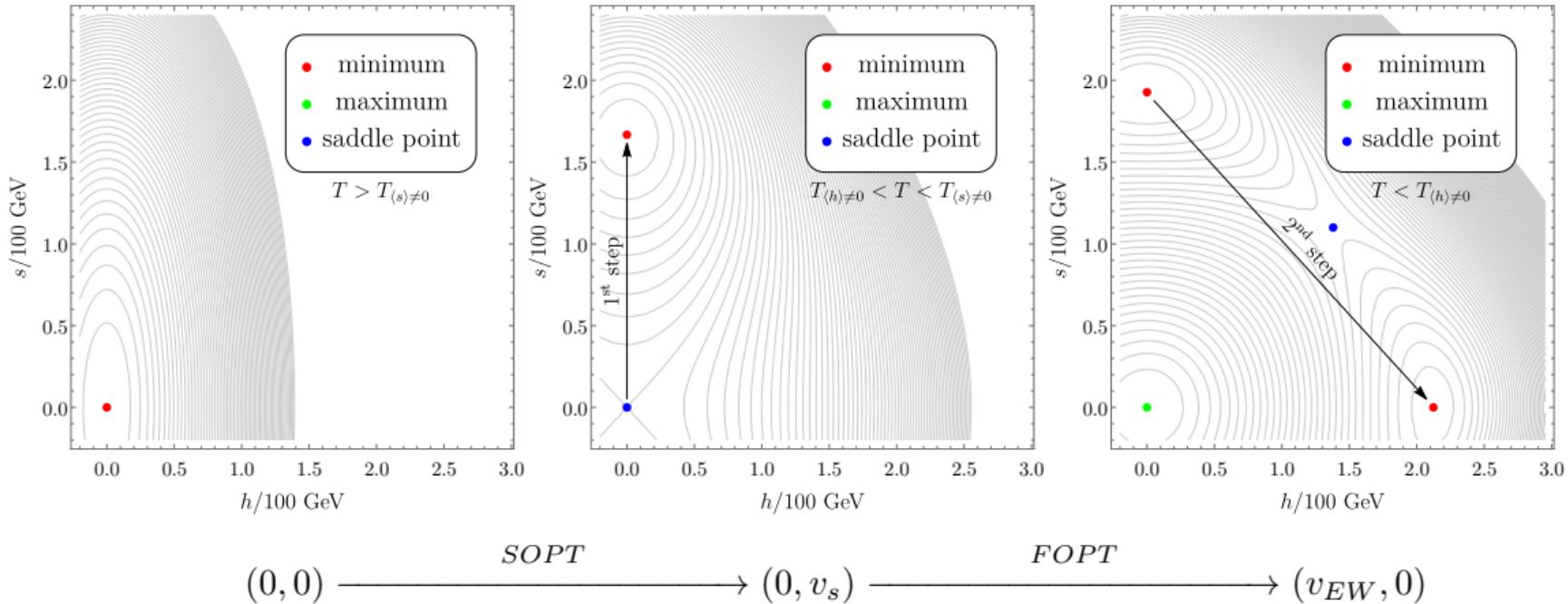


$$T_{\min}^{\text{nuc}} \gtrsim O(100) \text{ GeV} \quad \rightarrow \quad \gamma_w \lesssim O(10)$$

+ Collider constraints on Higgs-scalar mixing

# Relativistic EWPT: 2-step PT

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin



Euclidean action  $S_3/T$   
**contains all the info**  
about the PT

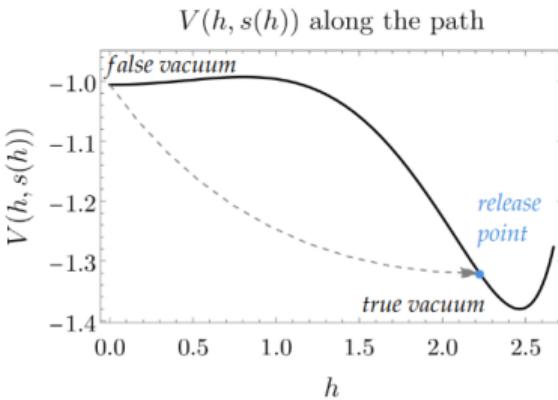
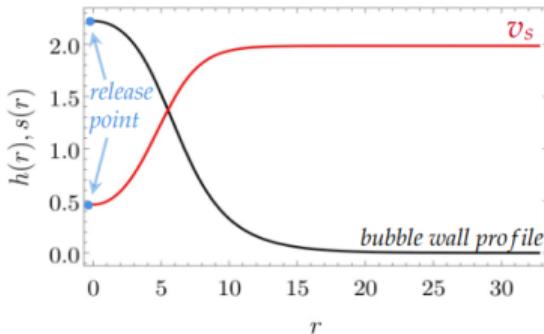
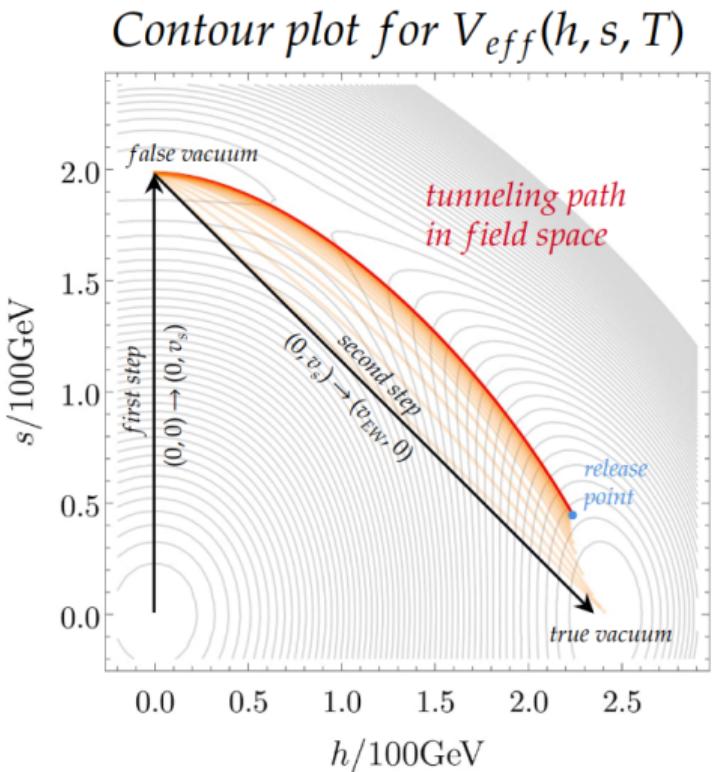
# EWPT: Bounce action

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

Euclidean action  $S_3/T$   
contains all the info  
about the PT



We built our own code  
for the computation of  
 $S_3/T$



# Relativistic EWPT: Parameter scan

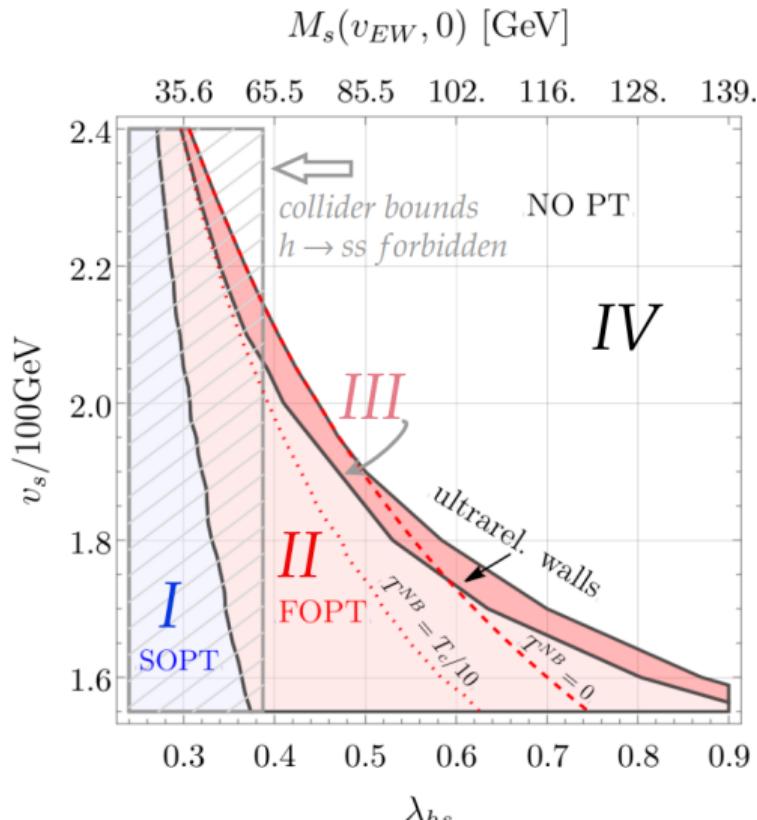
[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

I. SOPT: there is **never a barrier** separating the two minima

II. FOPT

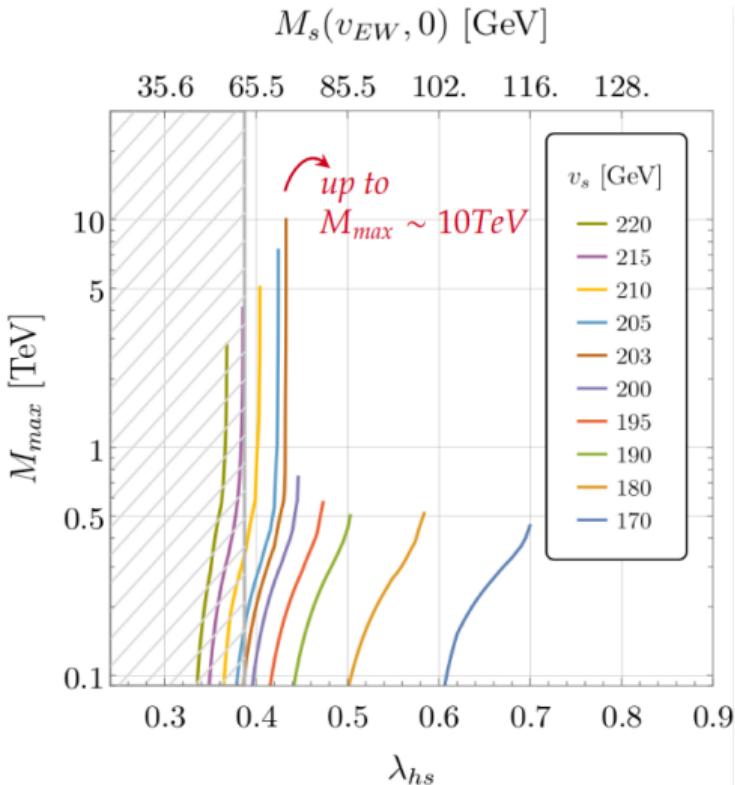
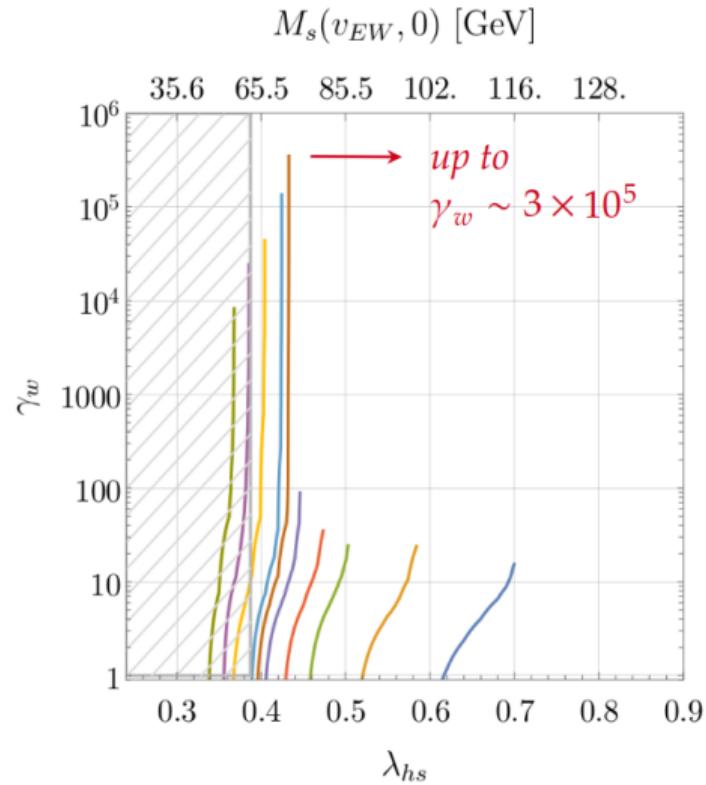
III. Ultrarelativistic FOPT

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



# Results for $m_s = 125$ GeV

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin





# back to Particle Physics...

# Baryogenesis

# Baryogenesis: Sakharov Conditions

- $B$ -violating interactions or sphaleron
- $C/CP$ -violating interactions due to physical phases in Yukawa matrices
- Out-of-equilibrium states: possibly produced during the expansion of the Universe or FOPTs

Electroweak Baryogenesis

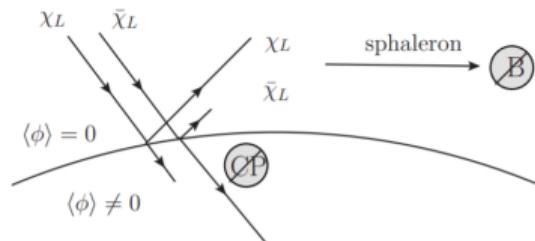


Figure: from [1302.6713]

- Scattering of quarks with  $CP$ -violating Yukawas off the (*slow*) bubble wall.
- $B$ -violation via sphalerons

Leptogenesis

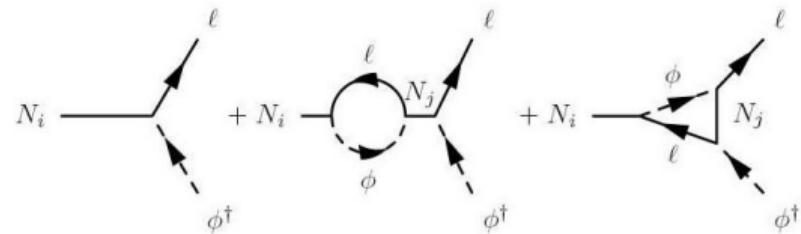


Figure: from [1302.6713]

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

# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
with  $\textcolor{blue}{Y}_I, y_I$ :  $CP$  – violating

$$-\mathcal{L} = -\mathcal{L}_{SM} + M_I \bar{B}_I B_I + \underbrace{\textcolor{blue}{Y}_I (\bar{B}_I H) P_L Q}_{B_I \text{ production}} + \underbrace{\textcolor{blue}{y}_I \eta^* \bar{B}_I P_R \chi + \kappa \eta^c du}_{\text{dark sector decay}} + \underbrace{\frac{1}{2} m_\chi \chi^c \chi + m_\eta^2 |\eta|^2}_{B-\text{violating}}$$

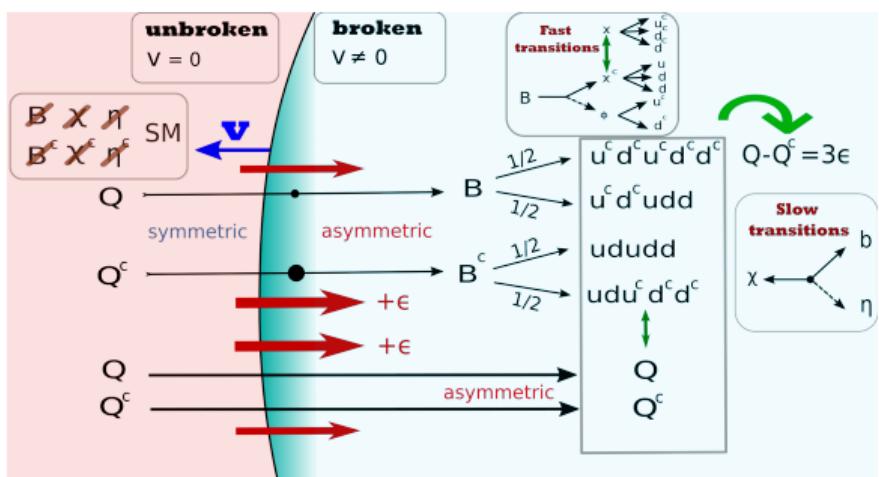
# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
 with  $\textcolor{blue}{Y}_I, y_I$ :  $CP$  – violating

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

- $B(\eta) = 2/3, B(\chi) = 1$



# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

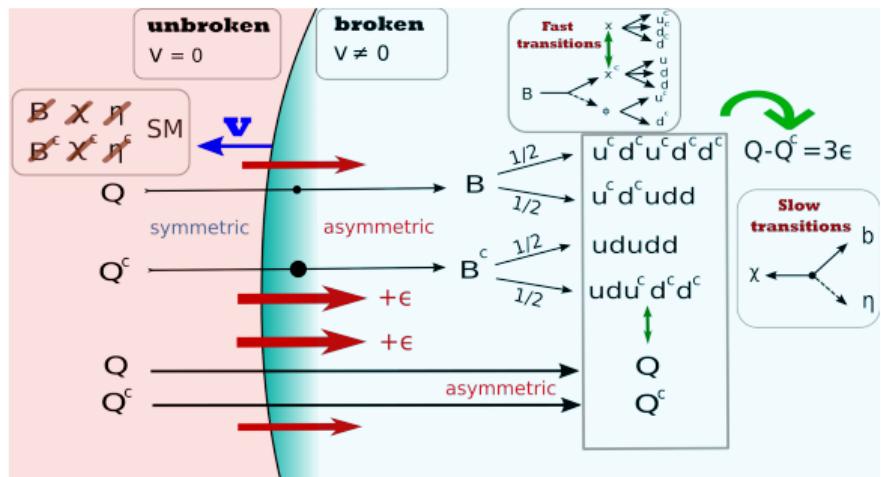
Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
with  $\textcolor{blue}{Y}_I, y_I$ :  $CP$  – violating

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

- $B(\eta) = 2/3$ ,  $B(\chi) = 1$
- $\mathcal{M}(Q \rightarrow B_I) \neq \mathcal{M}(Q^c \rightarrow B_I^c)$  then collision of  $b$ -quarks with bubbles produce asymmetry in  $B_I, \bar{B}_I$

$$\sum_I (n_{B_I} - n_{B_I^c}) = - \sum_I \theta_I^2 \epsilon_I n_b^0 = -(n_b - n_{b^c})$$

$\theta_I = b - B$  mixing angle,  $\epsilon_I$  = asymm. due to  $\cancel{CP}$



# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
with  $Y_I, y_I$ :  $CP$ -violating

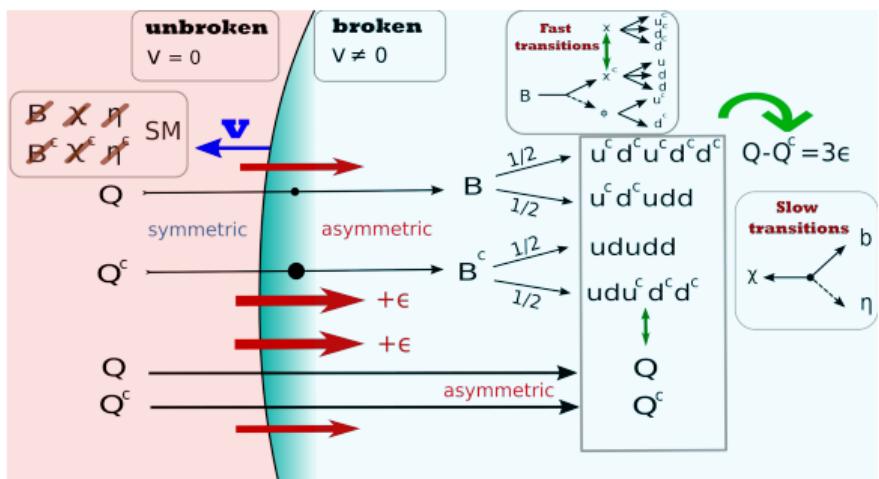
$$-\mathcal{L} = -\mathcal{L}_{SM} + M_I \bar{B}_I B_I + \underbrace{Y_I (\bar{B}_I H) P_L Q}_{B_I \text{ production}} + \underbrace{y_I \eta^* \bar{B}_I P_R \chi + \kappa \eta^c du}_{\text{dark sector decay}} + \underbrace{\frac{1}{2} m_\chi \chi^c \chi + m_\eta^2 |\eta|^2}_{B\text{-violating}}$$

- $B(\eta) = 2/3$ ,  $B(\chi) = 1$
- $\mathcal{M}(Q \rightarrow B_I) \neq \mathcal{M}(Q^c \rightarrow B_I^c)$  then collision of  $b$ -quarks with bubbles produce asymmetry in  $B_I, \bar{B}_I$

$$\sum_I (n_{B_I} - n_{B_I^c}) = - \sum_I \theta_I^2 \epsilon_I n_b^0 = -(n_b - n_{b^c})$$

$\theta_I = b - B$  mixing angle,  $\epsilon_I$  = asymm. due to  $CP$

- $CP$ -violation via loop
- $B$ -violation by  $m_\chi$ , 2 units



# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
with  $\textcolor{blue}{Y}_I, \textcolor{blue}{y}_I$ :  $CP$  – violating

$$-\mathcal{L} = -\mathcal{L}_{SM} + M_I \bar{B}_I B_I + \underbrace{\textcolor{blue}{Y}_I (\bar{B}_I H) P_L Q}_{B_I \text{ production}} + \underbrace{\textcolor{blue}{y}_I \eta^* \bar{B}_I P_R \chi + \kappa \eta^c du}_{\text{dark sector decay}} + \underbrace{\frac{1}{2} m_\chi \chi^c \chi + m_\eta^2 |\eta|^2}_{B-\text{violating}}$$

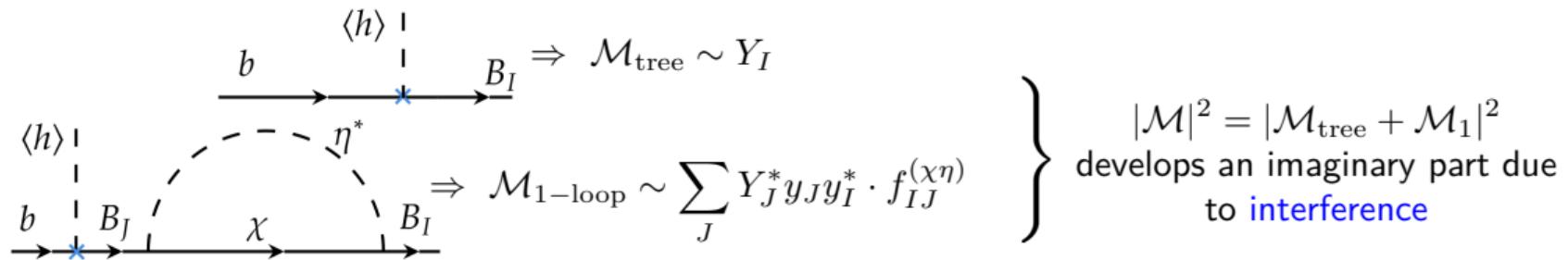
# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
with  $Y_I, y_I$ :  $CP$ -violating

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

## 1) Asymmetry in $B_I$ production:



$$\epsilon_I = \frac{\mathcal{M}(b \rightarrow B_I) - \mathcal{M}(\bar{b} \rightarrow \bar{B}_I)}{\mathcal{M}(b \rightarrow B_I) + \mathcal{M}(\bar{b} \rightarrow \bar{B}_I)} \simeq \frac{2 \sum_J \text{Im}(Y_I Y_J^* y_J y_I^*) \text{Im} f_{IJ}^{(\chi\eta)}}{|Y_I|^2}$$

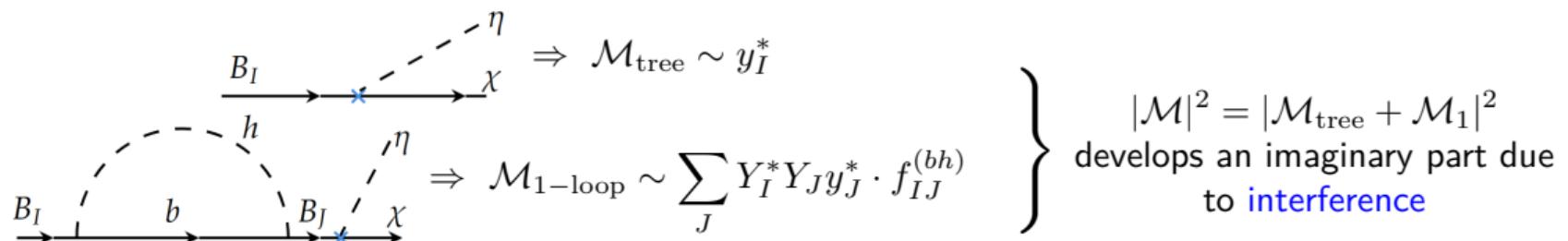
# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
 with  $\mathbf{Y}_I, y_I$ :  $CP$  – violating

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

## 2) Asymmetry in $B_I$ decay:



$$\epsilon_I \Big|_{\text{decay}} \simeq \frac{2 \sum_J \text{Im}(Y_I^* Y_J y_J y_I^*) \text{Im} f_{IJ}^{(bh)}}{|y_I|^2}$$

# EWBG via relativistic walls

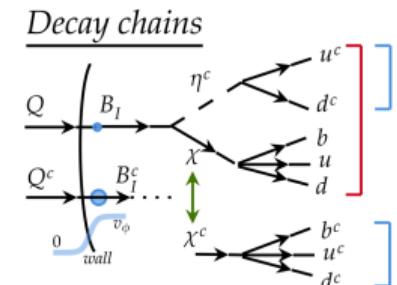
[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
 with  $Y_I, y_I$ :  $CP$ -violating

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

Baryon asymmetry: ( $\theta_I$  = mixing angle,  $\epsilon_I^{\text{tot}} = \epsilon_I + \epsilon_I|_{\text{decay}}$ )

$$\frac{\Delta n_B}{s} \equiv \frac{1}{3} \frac{n_q - n_{\bar{q}}}{s(T_{\text{reh}})} \approx \frac{1}{3s} \sum_I \underbrace{3n_b^0 \theta_I^2 \epsilon_I^{\text{tot}}}_{n_{B_I} - n_{B_I^c}} \times \underbrace{BR(B_I \rightarrow \chi \eta^c)}_{\text{decay back of } B_I \rightarrow \chi \eta^c} \times \underbrace{BR(\eta \rightarrow ud)}_{\text{decay back of } \eta \rightarrow ud}$$



wash-out :  $B_I \rightarrow budu^c d^c$   
 $B_I^c \rightarrow b^c u^c d^c u d$   
 $B_I \rightarrow bh$   
 asymmetry :  $B_I \rightarrow bc u^c d^c u^c d^c$   
 $B_I^c \rightarrow budud$

# EWBG via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content:  $SM + 2 B_I$  (vectorlike  $b$ -like quarks) + Majorana  $\chi$  + colored scalar  $\eta$  w/  $Q(\eta) = \frac{1}{3}$   
 with  $\textcolor{blue}{Y}_I, y_I$ :  $CP$ -violating

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

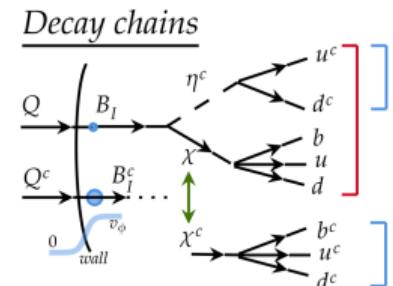
Baryon asymmetry: ( $\theta_I$  = mixing angle,  $\epsilon_I^{\text{tot}} = \epsilon_I + \epsilon_I|_{\text{decay}}$ )

$$\frac{\Delta n_B}{s} \equiv \frac{1}{3} \frac{n_q - n_{\bar{q}}}{s(T_{\text{reh}})} \approx \frac{1}{3s} \sum_I \underbrace{3n_b^0 \theta_I^2 \epsilon_I^{\text{tot}}}_{n_{B_I} - n_{B_I^c}} \times \underbrace{\text{BR}(B_I \rightarrow \chi \eta^c)}_{\text{decay back of } B_I \rightarrow \chi \eta^c} \times \underbrace{\text{BR}(\eta \rightarrow ud)}_{\text{decay back of } \eta \rightarrow ud}$$



wash-out from slow transitions ( $b\eta \rightarrow \chi, \eta b \rightarrow \eta^c b^c$ ):

$$\frac{m_{B,\chi,\eta}}{T_{\text{reh}}} \gtrsim 30$$



wash-out :  $B_I \rightarrow budu^c d^c$   
 $B_I^c \rightarrow b^c u^c d^c u d$   
 $B_I \rightarrow bh$   
 asymmetry :  $B_I \rightarrow bcu^c dcu^c d^c$   
 $B_I^c \rightarrow budud$

❶ **Neutron oscillations:**  $\frac{1}{\Lambda_{n\bar{n}}^5} u^c \bar{d}^c d^c u \bar{d} d \rightarrow \delta m_{n\bar{n}} \stackrel{\text{exp.}}{\lesssim} 10^{-33} \text{ GeV} \rightarrow m_{\eta, \chi} \gtrsim 10^5 \text{ GeV}$

Weaker bound if new particles couples only to the 3<sup>rd</sup> generation.

❷ **FCNC:** absent at tree level for  $\eta$ , but loop effects (strongly) constraint  $\eta du$  coupling.

- $d_q \sim \text{Im}[y_I^2] \frac{\theta_I^2 m_b}{16\pi^2} \frac{1}{\Lambda_{EDM}^2} \sim 6 \times 10^{-26} \text{ cm} \quad |d_q^{\text{exp}}| \lesssim 1.2 \times 10^{-22} \text{ cm}$

❸ **EDMs:**

- $\frac{d_e}{e} \sim \frac{m_e (y Y e)^2}{(4\pi)^6} \sim 3 \times 10^{-33} \text{ cm} \quad |d_e^{\text{exp}}| \lesssim 1.1 \times 10^{-29} \text{ cm} \cdot e$

❹ **Gravitational Waves:** SGWB peaked at  $f_{peak} \sim 10^{-3} \frac{T_{reh}}{\text{GeV}} \text{ mHz}$

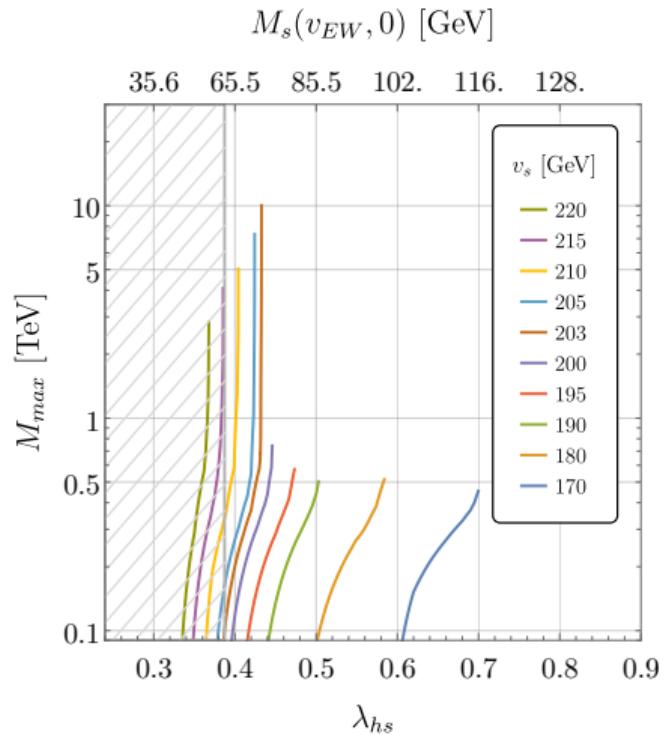
❺ **Direct production @ collider:**  $m_{LCP} \gtrsim 2 \text{ TeV}$   $LPC = \text{lightest colored particle}$

**Upshot: Model favored for  $M_B \sim m_\chi \sim m_\eta \in [2, 20] \text{ TeV}$**

# Relativistic EWPT: Conclusion

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

- It has been studied **in detail** an explicit **relativistic realisation of the EWPT** focusing on **ultra-relativistic parameter space**.
- walls Lorentz factor  $\gamma_w^{max} \sim 10^5$   
maximal mass of heavy states  $M_{max} \in [2, 10]$  TeV
- This model can account for **EW Baryogenesis**  
[JHEP10(2021)043]





Thanks for your attention!

# Backup slides

# Why emission of vector bosons?

# Vertex interactions

[JCAP05(2017)025]: Bodeker, Moore

In the relativistic regime the friction can be computed as

$$\Delta\mathcal{P} = \int \frac{d^3 p}{(2\pi)^3} \frac{p_z}{p_0} f_A^{\text{eq}} \times \sum_{b,c} \int d\mathbb{P}_{a \rightarrow b,c} \Delta p_z$$

where  $b$  is soft and

$$\int d\mathbb{P}_{a \rightarrow b,c} \sim \int d^2 k_\perp \int dx |\mathcal{M}(a \rightarrow b, c)|^2, \quad x \equiv \frac{E_c}{E_a}$$

The matrix element is related to the interaction via

$$\mathcal{M}(a \rightarrow b, c) = \int dz \chi_a(z) \chi_b^*(z) \chi_c^*(z) V(z), \quad V(z) : \text{vertex}$$

Soft singularity in  $x$  matters!  $\rightarrow$  **emission of vector bosons!**

$a(p) \rightarrow b(k)c(p-k)$	$ V^2 $
$S \rightarrow V_T S$	$4g^2 C_2[R] \frac{1}{x^2} k_\perp^2$
$F \rightarrow V_T F$	$4g^2 C_2[R] \frac{1}{x^2} k_\perp^2$
$V \rightarrow V_T V$	
$S \rightarrow V_L S$	$4g^2 C_2[R] \frac{1}{x^2} m^2$
$F \rightarrow V_L F$	$4g^2 C_2[R] \frac{1}{x^2} m^2$
$V \rightarrow V_L V$	
$F \rightarrow F V_T$	$2g^2 C_2[R] \frac{1}{x} (k_\perp^2 + m_b^2)$
$V \rightarrow F F$	$2g^2 T[R] \frac{1}{x} (k_\perp^2 + m_b^2)$
$S \rightarrow S V_T$	$4g^2 C_2[R] k_\perp^2$
$F \rightarrow S F$	$y^2 (k_\perp^2 + 4m_a^2)$
$S \rightarrow S S$	$\lambda^2 \varphi^2$

# Finite temperature effective potential

$$V_{\text{eff}}(h, s, T) = \underbrace{V_0(h, s)}_{\text{tree-level}} + \sum_{i \in SM} \underbrace{V_{CW} \left( \overbrace{m_i^2(h, s)}^{\text{field-dependent masses}} + \Pi_i(T) \right)}_{\text{1-loop quantum corr.}} + \underbrace{V_T \left( m_i^2(h, s) + \Pi_i(T), T \right)}_{\text{thermal corr.}}$$

- $V_{CW}(m_i^2(\phi)) = (-1)^{F_i} g_i \left[ \frac{m_i^4(\phi)}{64\pi^2} \left( \log \left( \frac{m_i^2(\phi)}{m_i^2(v_\phi)} \right) - \frac{3}{2} \right) + 2m_i^2(\phi)m_i^2(v_\phi) \right]$  (on-shell ren. scheme)
- $V_T(m_i^2(\phi)) = (-1)^{F_i} \frac{g_i}{2\pi^2} T^4 J_{B/F} \left( \frac{m_i^2(\phi)}{T^2} \right)$   $J_{B/F}(y^2) = \int_0^\infty dx \ x^2 \log \left[ 1 \mp \exp \left\{ -\sqrt{x^2 + y^2} \right\} \right]$
- Thermal masses from Daisy Resummation (TFD):  $\Pi_i(T) = c_i T^2$

Scalar:  $\Pi_h(T) = T^2 \left( \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{\lambda_{hs}}{24} \right), \quad \Pi_s(T) = T^2 \left( \frac{\lambda_{hs}}{6} + \frac{\lambda_s}{4} \right),$

Gauge:  $\Pi_g^L(T) = T^2 \text{diag} \left( \frac{11}{6}g^2, \frac{11}{6}(g^2 + g'^2) \right), \quad \Pi_g^T(T) = 0,$

# Conditions for 2–step phase transition

# Relativistic EWPT: 2-step PT

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

$$\text{2-step PT : } V_{\text{eff}}(h, s, T) \stackrel{\text{high-}T}{\approx} \underbrace{\left( -\frac{m_h^2}{4} + c_h T^2 \right)}_{m_{\text{eff}}^2(T)} h^2 + \underbrace{\frac{m_h^2}{8v_{EW}^2} h^4}_{\text{mexican-hat potential}} + \underbrace{\left( -\frac{m_s^2}{4} + c_s T^2 \right)}_{\text{mixing}} s^2 + \underbrace{\frac{m_s^2}{8v_s^2} s^4}_{\text{mixing}}$$

- ① **Correct vacuum at  $T = 0$ :**  $m_s^2 v_s^2 < m_h^2 v_{EW}^2$
- ② **first step**  $(0, 0) \xrightarrow{SOPT} (0, v_s \neq 0)$ : we need  $T_{\langle s \rangle \neq 0} > T_{\langle h \rangle \neq 0}$   $[c_s < c_h]$
- ③ **second step**  $(0, v_s \neq 0) \xrightarrow{FOPT} (v_{EW}, 0)$ : first order if there is a potential **barrier in  $h$ -direction**, i.e.

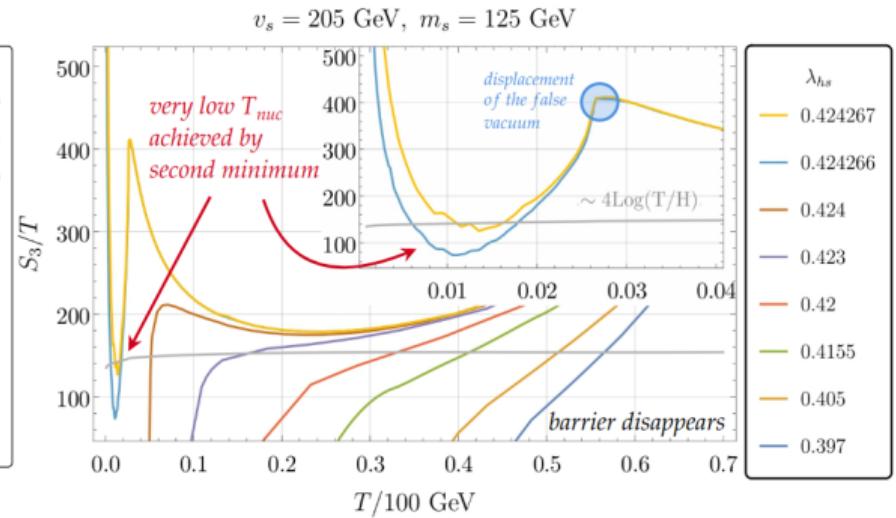
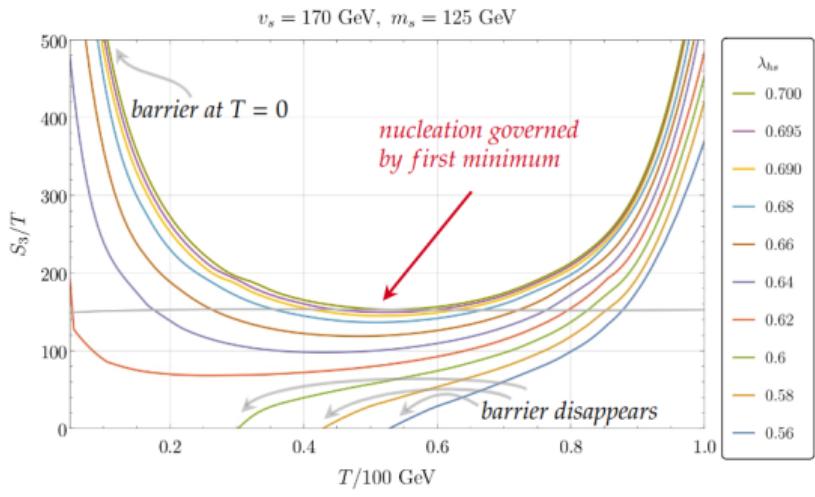
$$\frac{\partial^2 V}{\partial h^2} \Big|_{v_s, h \rightarrow 0} > 0 \quad \rightarrow \quad T^{\text{no barr.}} = \sqrt{\frac{m_h^2 - \lambda_{hs} v_s^2}{4c_h}}$$

$\lambda_{hs}$  controls the size of the barrier  $\rightarrow (0, v_s)$  local minimum even at  $T = 0$

# Bounce action

# EWPT: Bounce action (II)

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin



Lowest nucleation temperature  $T_{\text{nuc}} \sim 1 \text{ GeV}!$

# 2D Tunneling

# 2D Tunneling

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

$$\text{EOM : } \frac{d^2\vec{\phi}}{dr^2} + \frac{d-1}{r} \frac{d\vec{\phi}}{dr} = \vec{\nabla}V[\vec{\phi}]$$

$$\lim_{r \rightarrow \infty} \vec{\phi}(r) = \text{FV}, \quad \left. \frac{d\vec{\phi}}{dr} \right|_{r=0} = 0$$

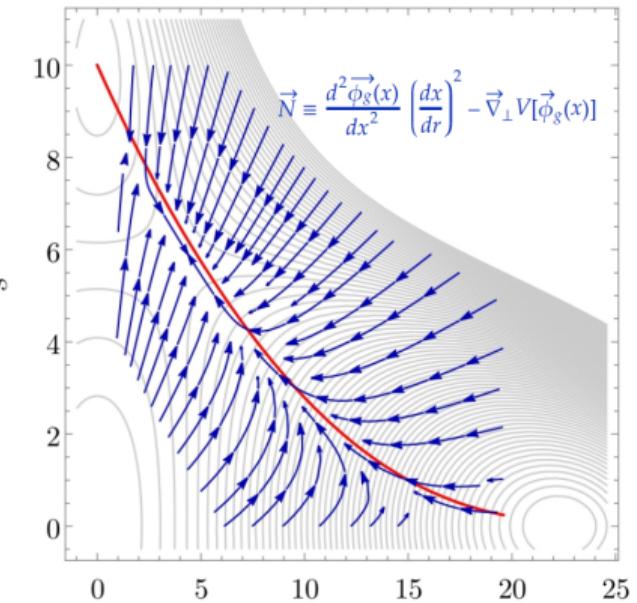
Difficult to solve, so we can disentangle parallel/perpendicular directions parametrising the path as  $(h, s) \equiv (h, s(h))$

$$\text{Curvilinear abscissa (2D): } x(h) = \int_{h_{\text{fv}}}^h \sqrt{1 + \left( \frac{ds(h')}{dh'} \right)^2} dh'$$

$$\begin{cases} \frac{d^2x}{dr^2} + \frac{d-1}{r} \frac{dx}{dr} = \partial_x V[\vec{\phi}_g(x)] \\ \frac{d^2\vec{\phi}_g(x)}{dx^2} \left( \frac{dx}{dr} \right)^2 = \vec{\nabla}_{\perp} V[\vec{\phi}_g(x)] \end{cases}$$

**undershoot/overshoot problem in 1D**

can be thought as a force field deforming the path

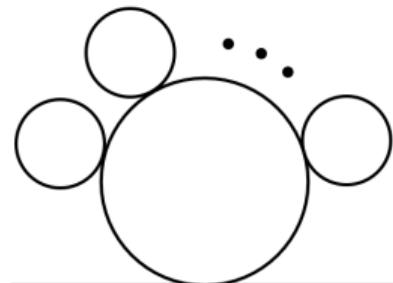


# Daisy resummation

# Daisy resummation

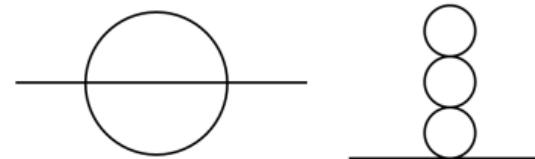
$$D = \text{superficial degree of divergence of a Feynman diagram } (\mathcal{G}) \rightarrow \mathcal{G} \sim \begin{cases} T^D & D > 0 \\ T & D \leq 0 \end{cases}$$

- **CW+thermal correction** = 1-loop resummation
- In FTQFT w/ massive scalar there are **two scales**:  $m$  &  $T \Rightarrow$  **large ratio  $T/m$  must be resummed**
- Daisy resummation takes into account  **$n$ -loops contribution to the mass**



$$\delta m_n^2 \sim \frac{m^3}{T^2} \left( \lambda \frac{T^2}{m^2} \right)^n \sim \frac{m^3}{T^2} \alpha^n \Rightarrow \begin{cases} m_{\text{eff}}^2(T) \rightarrow m_{\text{eff}}^2(T) + \Pi(T) \\ \Pi(T) = \lambda T^2 + \dots \quad \text{FD procedure} \\ \Pi(T) = \lambda T^2 \quad \text{TFD procedure} \end{cases}$$

- Still missing (but **negligible if  $\alpha \ll 1$** )



# Heavy particles production through the wall

# Heavy particles production through the wall

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

If  $\gamma_w \gg 1$  non zero probability of **production of heavy particles**,  $P(\text{light} \rightarrow \text{heavy}) \neq 0$ :

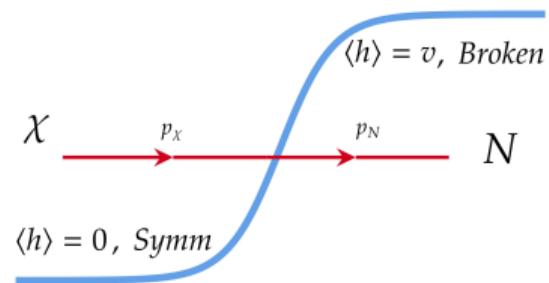
# Heavy particles production through the wall

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

If  $\gamma_w \gg 1$  non zero probability of **production of heavy particles**,  $P(\text{light} \rightarrow \text{heavy}) \neq 0$ :

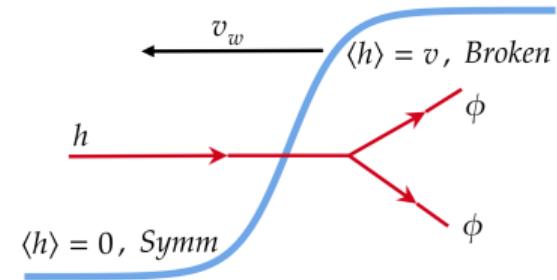
- ➊ **Fermionic transition:**  $\mathcal{L} \supset -y h \bar{N} \chi - M_N \bar{N} N$   
 $\chi$ : light,  $N$ : heavy,  $h = \tilde{h} + v$

$$P(\chi \rightarrow N) \approx \frac{y^2 v^2}{M_N^2} \theta(p_z - M_N^2 L_w) \quad [p_z \sim \gamma_w T_{\text{nuc}}]$$



- ➋ **Scalars emission:**  $\mathcal{L} \supset -\frac{\lambda_{h\phi}}{2} \phi^2 h^2 - \frac{1}{2} M_\phi^2 \phi^2$   
 $\phi$ : heavy,  $h = \tilde{h} + v$

$$P(h \rightarrow \phi\phi) \approx \frac{1}{24\pi^2} \frac{\lambda_{h\phi}^2 v^2}{M_\phi^2} \theta(p_z - M_\phi^2 L_w)$$

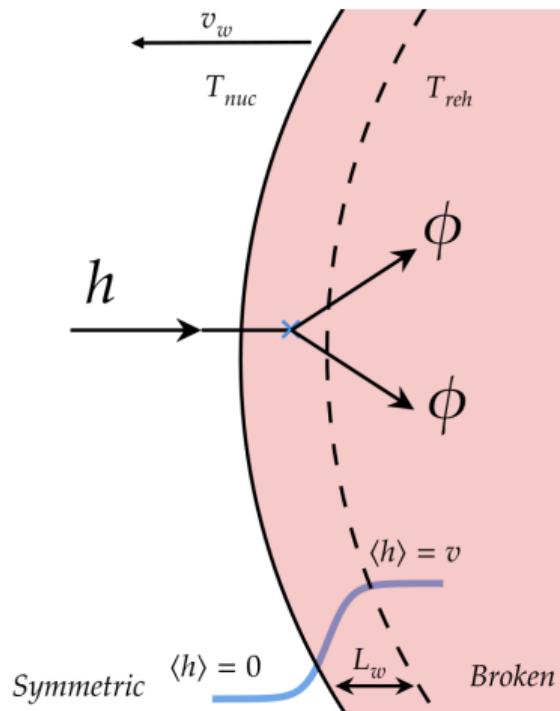


# Heavy Scalars emission

# Heavy Scalars emission (I)

[JCAP01(2021)058]: Azatov, Vanvlasselaer

Q: Transition dictated by fields w/  $M_\phi \lesssim T_{nuc} \sim v_\phi$ ?  $\Rightarrow n_{heavy} \sim e^{-M_\phi/T_{nuc}}$



- Toy model w/  $\phi$  heavy:

$$-\mathcal{L}_{int} = \frac{\lambda_{h\phi}}{2} h^2 \phi^2 + \frac{1}{2} m_\phi^2 \phi^2 \quad M_\phi \gg T_{nuc}$$

- Kinematics in the wall-frame

$$p_a^h = \left( E, 0, 0, \sqrt{E^2 - m_h^2} \right)$$

$$p_b^\phi = \left( (1-x)E, 0, 0, \sqrt{(1-x)^2 E^2 - k_\perp^2 - M_\phi^2} \right)$$

$$p_c^\phi = \left( xE, 0, 0, \sqrt{x^2 E^2 - k_\perp^2 - M_\phi^2} \right)$$

when no wall  $h \rightarrow \phi\phi$  forbidden.

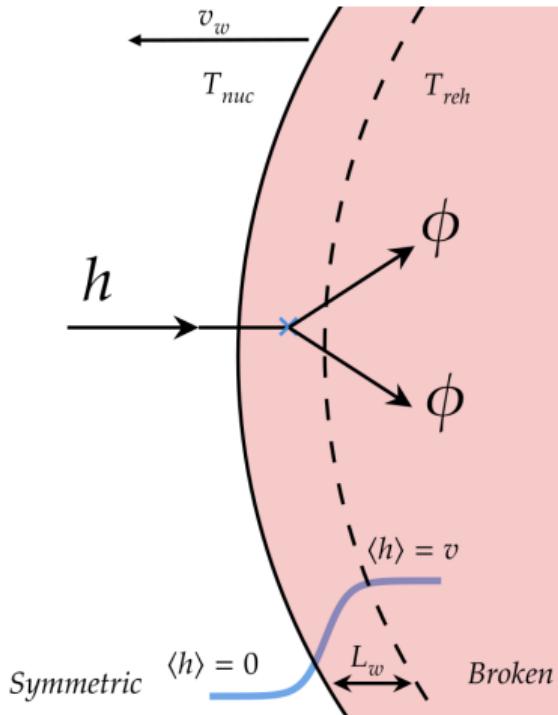
- In presence of the wall  $\sum_i p_{z,i}$  is no longer conserved:

$h \rightarrow \phi\phi$  allowed.

- $\Delta p_z = p_a^z - p_b^z + p_c^z \sim \frac{M_\phi^2 + k_\perp^2}{2E_\phi}$

# Heavy Scalars emission (II)

[JCAP01(2021)058]: Azatov, Vanvlasselaer



- Matrix element  $\mathcal{M}$ :

$$\mathcal{M} = \int dz \chi_a(z) \chi_b^*(z) \chi_c^*(z) V(z), \quad V(z) : \text{vertex}$$

- WKB approximation

$$\chi(z) \simeq \sqrt{\frac{p_{z,s}}{p_z(z)}} \exp \left( i \int_0^z dz' p_z(z') \right)$$

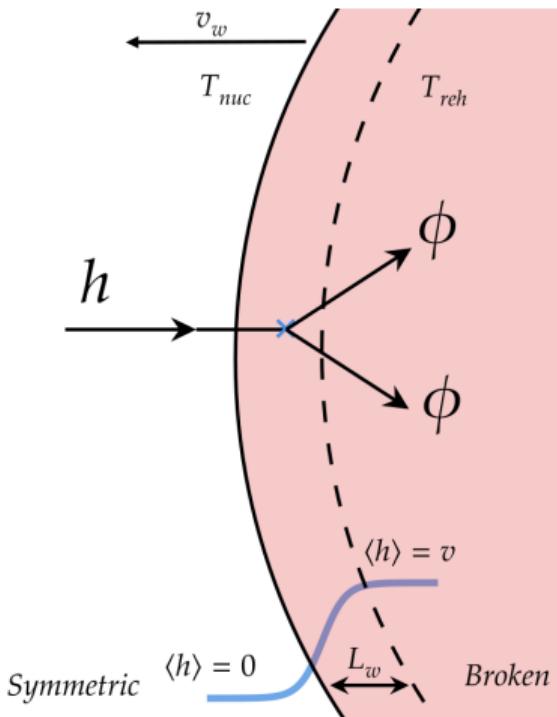
- Assuming a linear wall:

$$h(z) = v \frac{z}{L_w} \left( \theta(z) + \theta(L_w - z) - 1 \right) + v\theta(z - L_w)$$

$$|\mathcal{M}|^2 \simeq \frac{\lambda_{h\phi}^2 v^2}{\Delta p_z^2} \left( \frac{\sin \alpha}{\alpha} \right)^2, \quad \alpha = \frac{L_w \Delta p_z}{2}$$

# Heavy Scalars emission (III)

[JCAP01(2021)058]: Azatov, Vanvlasselaer



- In the wall frame:  $E_h \sim p_h^z \sim \gamma_w T_{nuc} \gg v$
- Transition probability  $P(h \rightarrow \phi\phi) = \int d\mathbb{P}_{h \rightarrow 2\phi} |\mathcal{M}(h \rightarrow 2\phi)|^2$

$$P(h \rightarrow \phi\phi) \approx \frac{\lambda_{h\phi}^2 v_\phi^2}{24\pi^2 M_\phi^2} \times \underbrace{\left( \frac{\sin(\Delta p_z L_w)}{\Delta p_z L_w} \right)^2}_{\text{wall shape effect*}} \xrightarrow{\Delta p_z L_w \rightarrow 0} \Theta(\gamma_w T_{nuc} - M_\phi^2 L_w)$$

\* = assuming a linear wall profile

States w/  $M_\phi \gg T_{nuc}$  can become **dynamical** during the PT

Efficient production:  $M_\phi < M_{max} \sim \sqrt{\frac{\gamma_w T_{nuc}}{L_w}} \sim \sqrt{\gamma_w T_{nuc} \langle h \rangle}$

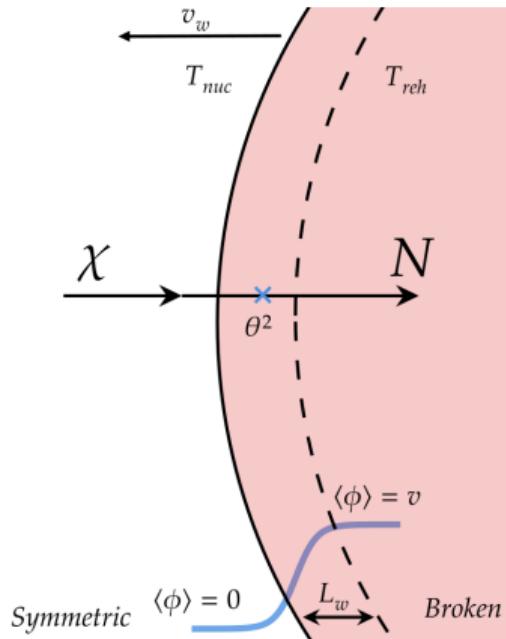
# Heavy Fermion transition

# Heavy Fermion transition (I)

[JCAP01(2021)058]: Azatov, Vanvlasselaer

Q: Transition dictated by fields w/  $M \lesssim T_{nuc} \sim v_\phi$ ?  $\Rightarrow$

$$n_{heavy} \sim e^{-M/T_{nuc}}$$



- Toy model w/  $\chi$  light,  $N$  heavy:

$$-\mathcal{L}_{int} = Y\phi\bar{\chi}N + M\bar{N}N, \quad M \gg T_{nuc}$$

- In the  $\chi$  frame

$$p_\chi = (E, 0, 0, E) \quad p_N = (E, 0, 0, \sqrt{E^2 - M^2})$$

when **no wall**  $\chi \rightarrow N$  forbidden.

- In presence of the wall  $\sum_i p_{z,i}$  is no longer conserved:

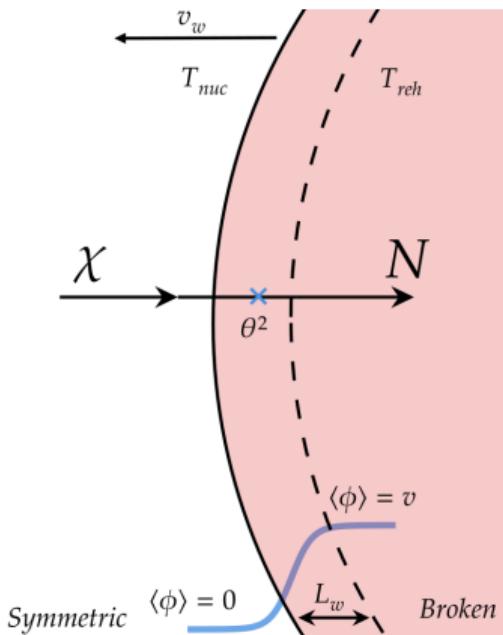
$\chi \rightarrow N$  allowed.

- $\Delta p_z = p_\chi^z - p_N^z \sim \frac{M^2}{2E_\chi}$

# Heavy Fermion transition (II)

[JCAP01(2021)058]: Azatov, Vanvlasselaer

Q: Transition dictated by fields w/  $M \lesssim T_{nuc} \sim v_\phi$ ?  $\Rightarrow n_{heavy} \sim e^{-M/T_{nuc}}$



- In the wall frame:  $E_\chi \sim p_\chi^z \sim \gamma_w T_{nuc} \gg v_\phi$
- Transition probability  $P(h \rightarrow \phi\phi) = \int d\mathbb{P}_{h \rightarrow 2\phi} |\mathcal{M}(h \rightarrow 2\phi)|^2$

$$P(\chi \rightarrow N) \approx \underbrace{\frac{Y^2 v_\phi^2}{M^2}}_{=\theta^2} \times \underbrace{\left( \frac{\sin(\Delta p_z L_w)}{\Delta p_z L_w} \right)^2}_{\text{wall shape effect*}} \xrightarrow{\Delta p_z L_w \rightarrow 0} \Theta(\gamma_w T_{nuc} - M_\phi^2 L_w)$$

\* = assuming a linear wall profile,  $\theta$  = mixing angle

States w/  $M \gg T_{nuc}$  can become **dynamical** during the PT

Efficient production:  $M < M_{max} \sim \sqrt{\frac{\gamma_w T_{nuc}}{L_w}} \sim \sqrt{\gamma_w T_{nuc} \langle \phi \rangle}$

# Heavy DM production

# Heavy DM production via Bubble Expansion (BE)

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

After  $h$  transition the abundance of massive  $\phi$ ,  $n_{\text{BE}}^\phi$  is

$$\begin{aligned} n_{\text{BE}}^\phi &\approx \frac{2}{\gamma_w} \int \frac{d^3 p}{(2\pi)^3} \frac{p_z}{p_0} f_h(p, T_{\text{nuc}}) \cdot P(h \rightarrow \phi\phi) \\ &\approx \frac{2}{24\pi^2} \frac{\lambda_{h\phi}^2 v^2}{M_\phi^2} \cdot T_{\text{nuc}}^3 \cdot \exp \left[ -\frac{M_\phi^2}{2\gamma_w v T_{\text{nuc}}} \right] + \mathcal{O}(1/\gamma_w) \end{aligned}$$

2  $\phi$  emission, back to plasma frame, incident flux, transition probability

After redshifting to today

$$\Omega_{\text{BE},\phi}^{\text{today}} h^2 \approx 5.4 \cdot 10^5 \left( \frac{\lambda_{h\phi}^2 v}{M_\phi g_{\star,s}(T_{\text{reh}})} \right) \left( \frac{v}{1\text{GeV}} \right) \left( \frac{T_{\text{nuc}}}{T_{\text{reh}}} \right)^3 \exp \left[ -\frac{M_\phi^2}{2\gamma_w v T_{\text{nuc}}} \right]$$

# DM production vs observations

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

$$\Omega_{\phi,\text{tot}}^{\text{today}} h^2 = \Omega_{\phi,\text{BE}}^{\text{today}} h^2 + \Omega_{\phi,\text{FO}}^{\text{today}} h^2 \approx 0.1$$

# DM production vs observations

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

$$\Omega_{\phi, \text{tot}}^{\text{today}} h^2 = \Omega_{\phi, \text{BE}}^{\text{today}} h^2 + \Omega_{\phi, \text{FO}}^{\text{today}} h^2 \approx 0.1$$

- ① Inside the isocontours DM is **under-produced**, outside is **over-produced**.
- ② **Upper curve:** DM production dominated by BE.
- ③ **Lower curve:** DM production dominated by FO.
- ④ **Vertical line:** thermal production after reheating.

