
O
G
D
O
O
O
O
D

Ultra relativistic EW bubbles from simplest Higgs portal

Giulio Barni gbarni@sissa.it

Supervisor: Alexandr Azatov

Collab.: Miguel Vanvlasselaer
S. Chakraborty
Wen Yin

Summary

1. What: Bubble dynamic, Friction and terminal velocity
   ⓐ FOPT & spherical bubbles ⓑ Friction: 3 types ⓒ w/ NLO terminal velocity

2. Why: stochastic GW background & application
   ⓐ stochastic GW bkg ⓑ Scattering off the wall ⓒ application

3. Ultra relativistic FOPT: Z_2 real singlet extension of the SM [JHEP 10(2022)017]
   ⓐ Model ⓑ Effective potential ⓒ 1-step PT vs 2-step PT

4. Computation of S_3/T
   ⓐ Algorithm ⓑ Features of S_3/T

5. Parameter scan & result
   ⓐ Regions of the scan ⓑ Maximal mass produced

6. Application to DM production
   ⓐ Scalar DM coupled w/ Higgs ⓑ Singlet portal DM ⓒ Fermion mediated DM

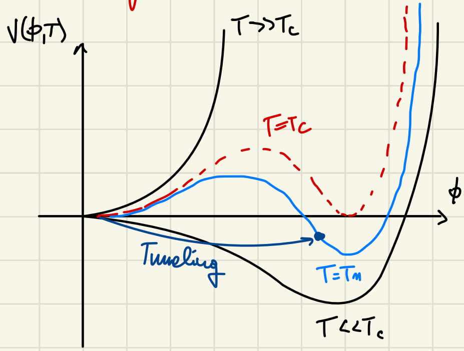
7. Conclusion

Backup

- 2D Tunneling (+ unbounded potential)
- Daisy resummation and effective potential
- 3D reduction, Computation of the wall velocity from first principle, γ vs γ^2 in NLO

① Bubble dynamic, friction & terminal velocity

A FOPT can occur when $\exists\ T_c$ s.t. two degenerate minima separated by a barrier develop.

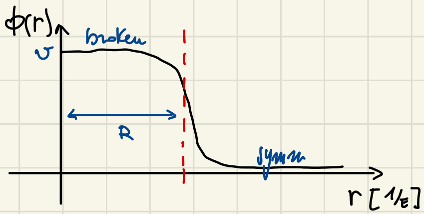


Tunneling decay rate of the FV

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

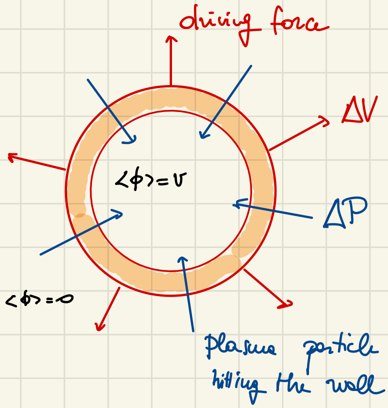
Solution w/ minimal action $\longrightarrow$ $O(d)$ spherical symm. $\phi=\phi(r)$ $\quad r=\sqrt{\tau^2+x^2}$ $\longrightarrow$ Bubbles

[Callan, Coleman, 1977]



Friction

When plasma particles hit the wall they slow down its expansion. Full computation of these effects is quite involved, but for relativistic expansion, $\gamma_w >> 1$, they become much simpler.



The most relevant contributions to the friction are the following

① Recoil of the particles getting mass passing through the wall

$$\Delta P_{LO} \simeq \sum_i g_i\, c_i \frac{\Delta m_i^2}{24} T_{nuc}^2$$

$g_i = \#$ dof, $\quad c_i = \begin{cases} 1 & B \\ 1/2 & F \end{cases}$. [BM '09]

(2) In presence of mixing between light and heavy particles

$$\Delta P_{LO}^{mixing} \simeq \frac{T^2 y^2}{48} \langle\phi\rangle^2 \,\theta\left(\gamma_w T_{nuc} - M^2 L_w\right) \qquad \mathcal{L} \supset y\,\phi\,\bar{\Psi} N + h.c.$$

[AA et al., '21]

(3) In presence of gauge bosons which gain mass during PT

$$\Delta P_{NLO} \simeq \sum_i \frac{g_i}{16\pi^2}\, g^2_{gauge}\, m_{V,i}\, \gamma_w\, T^3_{nuc}$$

[BM, '17]

(1) + (2) only

if $\Delta V > \Delta P_{tot}$ the bubbles will keep accelerating until the collision (runaway)

$$\gamma_{w,max} \simeq \frac{2R_*}{3R_0}\left(1 - \frac{\Delta P_{LO}}{\Delta V}\right) \sim \frac{M_{pl} T_{nuc}}{\langle\phi\rangle^2}$$

where $R_* = \dfrac{(8\pi)^{1/3} v_w}{\beta(T_{perc})}$, $R_0 \sim 1/T_{nuc}$

(1) + (2) + (3)

Vector bosons partecipating the PT. Equating friction and driving force gives terminal γ_w

$$\boxed{\gamma_w^{terminal} \simeq \frac{\Delta V - \Delta P_{LO+mixing}}{g^2_{gauge}\, m_V\, T^3_{nuc}}}$$

NOTE: the Lorentz factor γ_{max} can be computed equating the surface energy of the bubble to the gain in the potential energy

$$4\pi R_*^2 \gamma_{max} \sigma = \frac{4}{3}\pi R_*^3 (\Delta V - P_{LO})$$

$$\gamma_{max} = \frac{R_*}{3\sigma}(\Delta V - P_{LO})$$

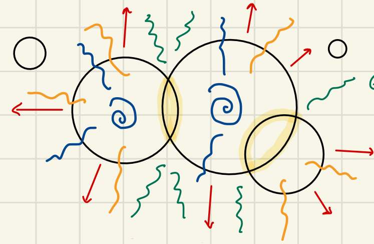
We can find the critical radius extremizing the action

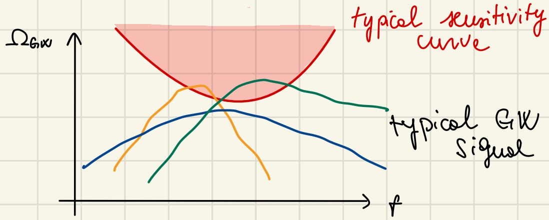
$$R_c = \frac{2\sigma}{\Delta V} \Rightarrow \gamma_{max} = \frac{2R_*}{3R_c}\left(1 - \frac{P_{LO}}{\Delta V}\right)$$

② Why: stochastic GW background & application

If bubbles collide they can produce a stochastic GW background from

1. bubble collision
2. sound waves
3. turbulence



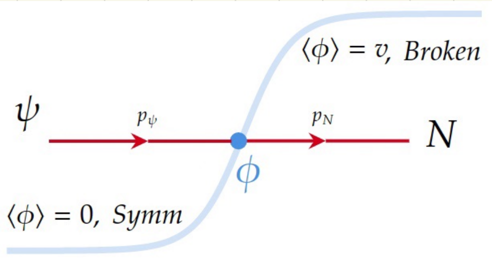


$\Rightarrow$ primordial GWs could be observed soon (if they exist)

We can produce heavy states if the wall are ultra-relativistic

$p_\psi \simeq (\gamma T, 0, 0, \gamma T)$ $\qquad$ $p_\phi = (m_\phi, 0, 0, 0)$

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



particle hitting the DW
(DW ≡ Higgs at rest)

Applications

1. Heavy DM production
2. FOPT + C/CP-violating &
   B-violating interaction w/ heavy states $\Rightarrow$ Baryogenesis

③ Ultra relativistic FOPT: Z_2 real singlet extension of the SM

Aim: find general features for relativistic FOPT & explicit realisation of relativistic EWPT.

Well known that all the PT in the SM are 2^{nd} order,
We consider the simplest extension of the SM w/ FOPT
$\Rightarrow$ SM + real Z_2 singlet $\left(\lambda_s = \frac{m_s^2}{2 v_s^2}\right)$

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

why Z_2?

(m_s, v_s, λ_{hs}) free parameters

Finite temp. effective potential

It can be computed in different ways
a) From Euclidean PI compactifying time of $\beta = 1/T$ summing over Matsubara modes
b) Quantum corrections + free energy of relativistic massive particles

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

the sum runs over $Z, W, h, s, t, G^\pm, G^0$ since we are in Landau gauge to avoid ghost compensating terms.

where $H = \begin{pmatrix} G^+ \\ \frac{h + i G^0}{\sqrt{2}} \end{pmatrix}$ and

$$V_{CW}(m_i^2(\phi)) = (-1)^{F_i} g_i \left[\frac{m_i^4(\phi)}{64\pi^2} \left(\log \frac{m_i^2(\phi)}{m_i^2(v_\phi)} - \frac{3}{2} \right) + 2 m_i^2(\phi) m_i^2(v_\phi) \right] \quad (*) \text{ on-shell ren. sch.}$$

$$V_T(m_i^2(\phi)) = (-1)^{F_i} \frac{g_i}{2\pi^2} T^4 J_{B/F}\left(\frac{m_i^2(\phi)}{T^2}\right)$$

(*) Note on on shell ren. scheme

$$\left.\frac{dV_{eff}}{dh}\right|_{(h,s)=(v_{EW},0)} = 0 \qquad \left.\frac{d^2 V_{eff}}{dh^2}\right|_{TV} = m_h^2$$

Issue w/ GB since $M_{GB}^2(TV) = 0$

$$\frac{d^2 V_{eff}}{dh^2} = m_h^2 - \Sigma(p^2 = m_h^2) + \Sigma(0)$$

in this way $M^2_{G=0}(TV) \longrightarrow m_h^2$ only in the log!

The thermal masses in the TFD procedure are $\Pi_i(T) = c_i T^2$:

$$\Pi_h(T) = \left(\frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{\lambda_{hs}}{24}\right) T^2$$

$$\Pi_s(T) = \left(\frac{\lambda_{hs}}{6} + \frac{\lambda_s}{4}\right)$$

$$\Pi_g^L = T^2 \,\mathrm{diag}\left[\frac{11}{6}g^2, \frac{11}{6}(g^2+g'^2)\right] \qquad \Pi_g^T = 0 \rightarrow \text{gauge inv.}$$

$$\Pi_f(T) = 0 \rightarrow \text{chiral symmetry protection}$$

Other, more refined, resummation schemes are

- Partial Dressing $\quad$ [Gap equations $\delta m_j^2 = \sum_i \left[\frac{\partial^2}{\partial \phi_j^2} V_{cw}^i(m_i^2 + \delta m_i^2) + \frac{\partial^2}{\partial \phi_j^2} V_T(m_i^2 + \delta m_i^2, T)\right]$]
- Optimized Partial Dressing $\quad$ [Piece wise $J_{B/F}$ w/ Gap equations]

1-step vs 2-step

- $(0,0) \longrightarrow (v_{EW}, 0)$

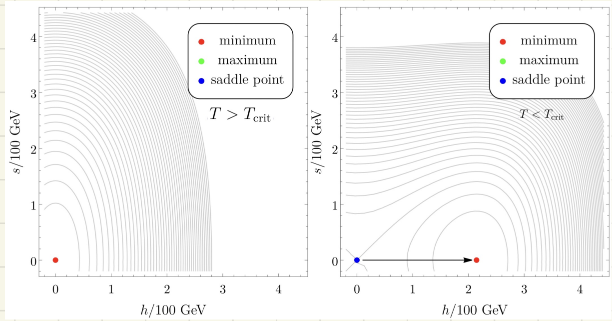
(well studied, and 1d)

Relativistic bubble are unlikely

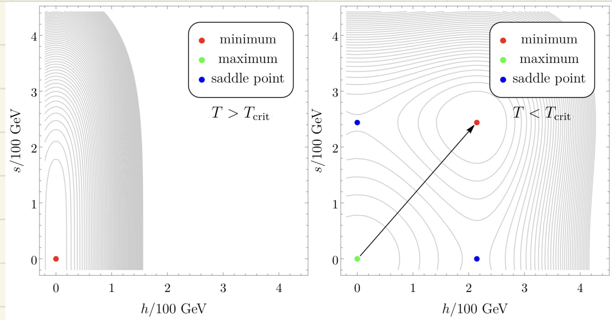
$$V_{dom}(h\to 0, s=0, T) \sim \frac{m^2_{eff}(T)}{2} h^2 + \dots$$

FOPT only for $m^2_{eff} > 0$

$$\boxed{T_{nuc}^{min} \gtrsim 100\ \mathrm{GeV} \Rightarrow \gamma_w \lesssim 10}$$

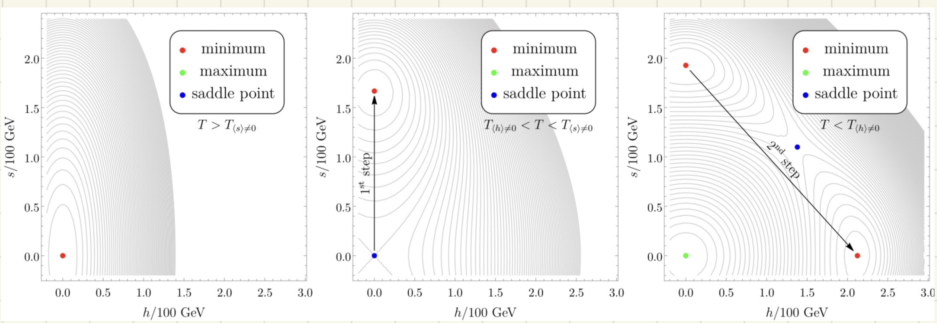


- $(0,0) \longrightarrow (v_{EW}, v_s)$



Very constrained from exp via Higgs - Scalar mixing!

- $(0,0) \longrightarrow (0, v_s) \longrightarrow (v_{EW}, 0)$



$$V_{eff}(h,s,T) \overset{\text{high-}T}{\approx} \left(-\frac{m_h^2}{4} + c_h T^2\right) h^2 + \frac{m_h^2}{8 v_{EW}^2} h^4 + \left(-\frac{m_s^2}{4} + c_s T^2\right) s^2 + \frac{m_s}{8 v_s^2} s^4 + \frac{\lambda_{sh}}{4} s^2 h^2$$

What we need for 2-step PT (with 1. SOPT & 2. FOPT)

① Correct vacuum at $T=0$: $\boxed{m_s^2 v_s^2 < m_h^2 v_{EW}^2}$

② first step $(0,0) \xrightarrow{\text{SOPT}} (0, v_s \neq 0)$ $\boxed{T_{\langle s\rangle \neq 0} > T_{\langle h\rangle \neq 0}}$ $\left[\left.\frac{d^2 V_{eff}}{ds^2}\right|_{(0,0)} > 0\right]$

This can be obtained easily playing w/ thermal masses since $c_s < c_h$.

③ **second step** $(0, v_s \neq 0) \xrightarrow{\text{FOPT}} (v_{EW}, 0)$: it is 1^{st} order if there is a potential barrier in h-direction

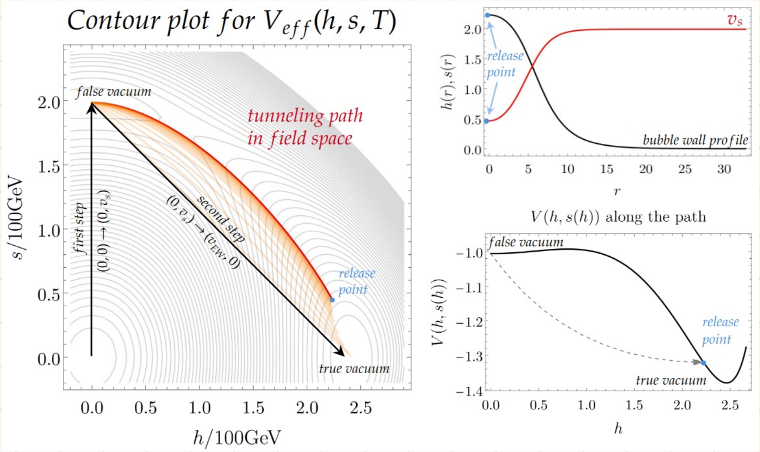
$$\frac{\partial^2 V_{eff}}{\partial h^2} > 0 \longrightarrow \boxed{T^{NB} = \sqrt{\frac{m_h^2 - \lambda_{hs} v_s^2}{4 c_h}}}$$

λ_{hs} **controls the size of the barrier**, and if $\lambda_{hs} > \frac{m_h^2}{v_s^2}$ then the FV $(0, v_s)$ is a local minimum even at $T=0$.

④ Computation of S_3/T

The Euclidean action S_3/T contains all the infos we need to study the PT.

The PT does not follow a straight line, need to develop an code.



Algorithm

We split the 2D coupled eqns

$$
\begin{cases}
\dfrac{d^2\vec{\phi}}{dr^2} + \dfrac{d-1}{r}\dfrac{d\vec{\phi}}{dr} = \vec{\nabla} V(\vec{\phi}) \\
d\vec{\phi}/dr \big|_{r=0} = 0 \\
\lim\limits_{r\to\infty} \vec{\phi}(r) = FV
\end{cases}
$$

along the parallel and perpendicular direction. In order to do this we can guess a path, $\vec{\phi}_g(h,s)$, parametrize it as $(t, f(t)) \equiv (h, s(h))$, then we can introduce the curvilinear abscisse

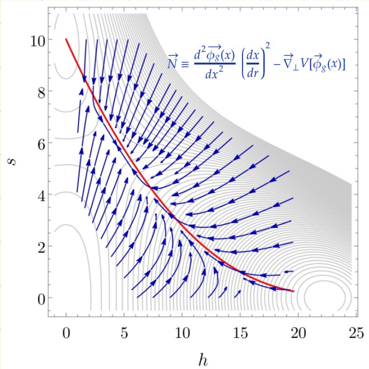
$$
x(h) = \int_{h_{FV}}^{h} \sqrt{1 + \left(\frac{d s(h')}{dh'}\right)^2}\, dh'
$$

then the EOM w/ the guessed path becomes

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

1d tunneling w/ overshoot / undershoot method

The second eq can be seen as a condition that the bounce solution has to satisfy and can be thought as a force field acting on the path



$$\vec{N} \equiv \frac{d^2\vec{\phi}_g(x)}{dx^2}\left(\frac{dx}{dr}\right)^2 - \vec{\nabla}_\perp V[\vec{\phi}_g(x)]$$

Once we computed the bounce according to our guessed path, we modify the guessed path according to $\vec{N}$ and we iteratively do so until the path is no longer modified.

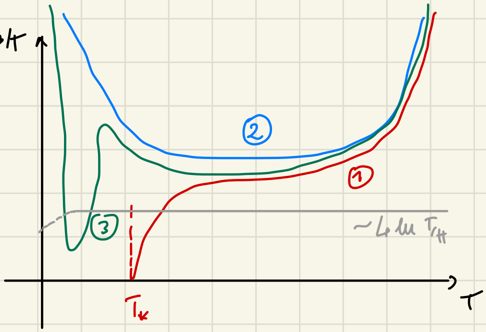
Features of S_3/T

In computing the Euclidean action we found 3 different behaviour

1. the barrier disappears @ $T=0$

2. the barrier remains even @ $T=0$, i.e. the FV is a local minimum @ $T=0$

3. Same as 2 but the FV @ $T=0$ is displaced from its high-T value

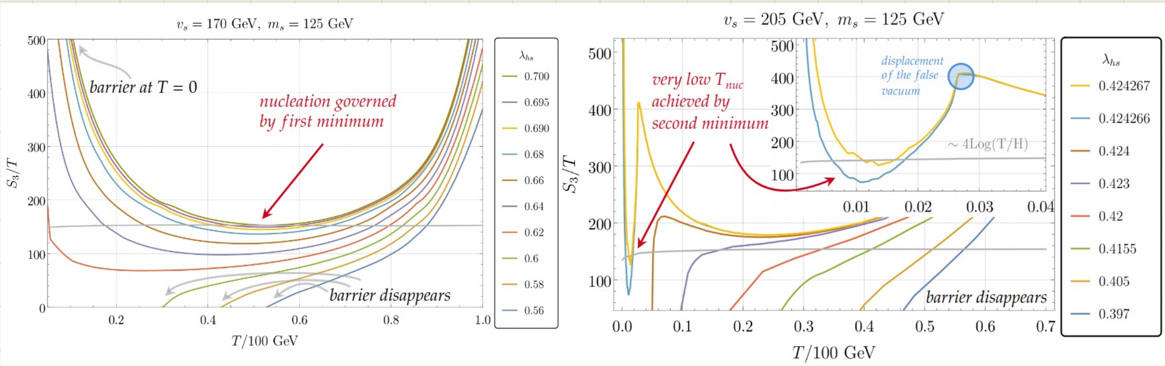


1. Since the barrier disappears @ $T=0$ the PT has to complete before T^{NB} and $S_3/T \to 0$, so $\Gamma \to 1$.

2. Since the barrier remains even @ $T=0$ at some point the temp. don't play any role, then $S_3 \xrightarrow[T\to 0]{} \text{const}$ and consequently $S_3/T \xrightarrow[T\to 0]{} \infty$

3. In this case we found that in a certain region of our parameter space at sufficiently low temp the action starts to be constant

as long as T is decreasing, but at some point a cancellation happens between the mixing and the CW potential from the top and the FV shift a bit.
This shift cause a sudden decrease of the action, that in some case could allow the system to make the PT.
In these case we can achieve nucleation temperatures as low as 1 GeV, leading to γ_w up to 10^5.



NOTE (Cancellation @ T=0)

There is a $\overbrace{\text{region of parameter space}}^{\text{very low } T}$ where purely polynomial potential has no local minimum at $(0, v_s)$, the FV but the effect from the CW contribution of the top field does the job

$$V_{CW}^{t} \propto - \frac{3M_t^2(h)}{8\pi^2} \log \frac{M_t^2(h)}{M_t(v_{EW})}$$

Only a log contribution could have caused a shift of the vacuum, not a polinomial pot.

then the FV shift towards a new minimum @ $(\delta v_h, v_s + \delta v_s)$.
We can see that the minima are nearer, so less path to do in field space. It is for this reason that S_3 decreases.

⑤ Parameter scan & result

ⓐ Regions of the scan

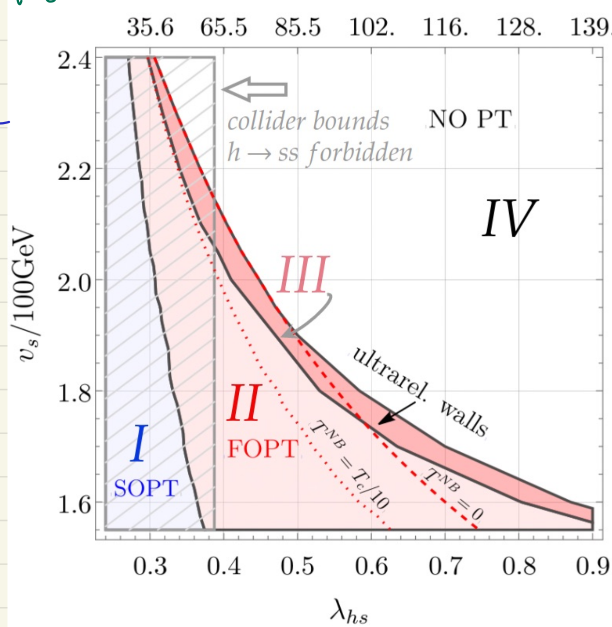
I. SOPT: there is never a barrier separating the two minima

II. FOPT (w/out rel. walls)

III. Ultrarelativistic FOPT ($\gamma_w \gg 1$ increasing λ_{hs} a fixed v_s)

IV. NO PT: the system remains stuck in the FV and never nucleate.

[$M_s = 125$ GeV]



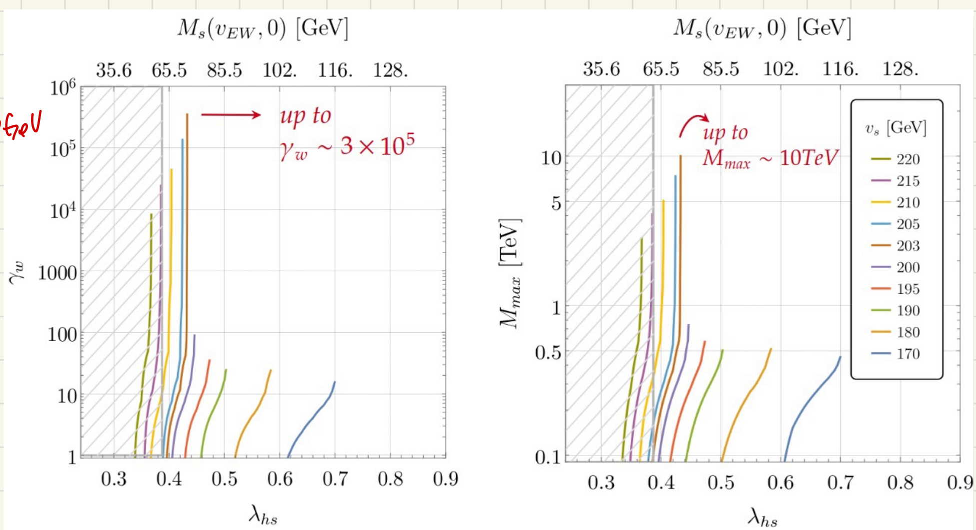
NOTE super fine tuned region between $T^{NB} = 0$ curve and "NO PT" curve
$\delta \lambda_{hs} \sim O(10^{-4})$, 10^{-2} smaller than the full region

ⓑ Maximal mass produced

$$\boxed{M_{max} \simeq \sqrt{\gamma_w T_{nuc} v_{EW}}}$$

Works for

$M_s(v_{EW}, 0) \sim 70$-100 GeV



⑥ Application to DM production & EW Baryogenesis

In the assumption of a FOPT w/ $\gamma_w^{\text{terminal}} \gg 1$ the production of heavy particles during plasma - bubble-wall collision can be realized

1. Fermionic transition $\qquad \mathcal{L}_{int} \supset -Y h \bar{N} q - M_N \bar{N} N$

   where q: light, N: heavy, $h = \tilde{h} + v$

$$P(q \to N) \simeq \frac{Y^2 v^2}{M_N^2} \, \theta\left(\gamma_w T_{nuc} - M_N^2 L_w\right) \qquad \theta(P_z - M_N^2 L_w)$$

2. Scalar transition $\qquad \mathcal{L}_{int} \supset -\frac{\lambda_{h\phi}}{2} \phi^2 h^2 + \frac{1}{2} M_\phi^2 \phi^2 \qquad h = \tilde{h} + v$

$$P(h \to \phi\phi) \approx \frac{1}{24\pi^2} \frac{\lambda_{\phi h}^2 v^2}{M_\phi^2} \, \theta\left(\gamma_w T_{nuc} - M_\phi^2 L_w\right)$$

Now we will apply result for bubble velocity to DM model building

ⓐ Scalar DM coupled w/ Higgs

We assume heavy scalar ϕ coupled to SM via Higgs portal

$$\mathcal{L}_{DM} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2} M_\phi^2 \phi^2 - \frac{\lambda_{\phi h}}{2} h^2 \phi^2$$

where the DM field can be stabilized imposing a $\mathbb{Z}_2^\phi$ symm.
After the Higgs transition the abundance of massive ϕ, n_ϕ^{BE}, is given by

$$n_\phi^{BE} \approx \frac{\overset{\text{emission of } 2\phi}{2}}{\gamma_w v_w} \int \frac{d^3p}{(2\pi)^3} \frac{P_z}{P_0} f_h(p, T_{nuc}) \cdot P(h \to \phi\phi) \qquad \text{[wall rest frame]}$$

This strongly depends on the density of the Higgs field available at the nucleation temperature, $f_h(p, T_{nuc})$. The relevant parameter will be the ratio

$$\frac{1}{T}\sqrt{\left.\frac{d^2V}{dh^2}\right|_{FV}} = \frac{m_H^{\text{false}}}{T}$$

Since as soon as $m_H^f/T > 1$ we have the usual Boltzmann suppression

$$\int \frac{d^3p}{(2\pi)^3} f_h(p, T_{nuc}) \simeq \begin{cases} \frac{\zeta(3)}{\pi^2} T_{nuc}^3 & m_H^f < T \\ \left(\frac{m_H^f T_{nuc}}{2\pi}\right)^{3/2} e^{-m_H^f/T_{nuc}} & m_H^f > T \end{cases}$$

Here we have

$$f_h(p, T_{nuc}) = \left\{ \exp\left[\gamma_w \left(\frac{E_h - v_w p_z^h}{T_{nuc}} \right) \right] - 1 \right\}^{-1} \simeq \exp\left[-\gamma_w \left(\frac{E_h - v_w p_z^h}{T_{nuc}} \right) \right]$$

$$E_h = \sqrt{p_z^2 + p_\perp^2}$$

and the presence of the $\Theta[..]$ that changes a bit the things

$$\int \frac{dp}{(2\pi)^3} \frac{p_z}{p_0} f_h(p, T_{nuc})\, \Theta\left(p_z - M_\phi^2/v\right) = \int \frac{dp_z}{2\pi} \frac{dp_\perp^2}{4\pi} \cdot e^{-\gamma_w \frac{\sqrt{p_\perp^2 + p_z^2} - v_w p_z^h}{T_{nuc}}} \Theta\left(p_z - M_\phi^2/v\right)$$

$$= \int \frac{dp_z}{2\pi} \frac{2}{4\pi} \left(1 + \frac{p_z \gamma_w}{T_{nuc}}\right) \cdot \frac{T_{nuc}^2}{\gamma_w^2} e^{-\frac{\gamma_w (1-v_w) p_z}{T_{nuc}}} \Theta\left(p_z - M_\phi^2/v\right)$$

$$= \frac{1}{4\pi^2} \cdot \frac{T_{nuc}^2}{\gamma_w^2} e^{-\frac{\gamma}{T}\frac{M^2}{v}(1-v_w)} \left[\frac{M^2}{v(1-v_w)} + \frac{T}{\gamma_w} \frac{2 - v_w}{(1-v_w)^2} \right]$$

$$\gamma_w (1 - v_w) = \gamma_w - \sqrt{\gamma_w^2 - 1} \longrightarrow 1/2\gamma_w \qquad 1 - v_w = 1 - \sqrt{1 - 1/\gamma_w^2} \simeq \frac{1}{2\gamma_w^2}$$

$$= \frac{T_{nuc}^2}{4\pi^2 \gamma_w^2} \left[\frac{M^2}{v} \cdot 2\gamma_w^2 + T \cdot 2\gamma \cdot 2\gamma_w^2 \right] e^{-\frac{M^2}{T} 2\gamma_w v}$$

$$\left\{ n^\phi_{BE} = \frac{2}{\gamma_w v_w} \frac{1}{24\pi^2} \frac{\lambda_{\phi h}^2 v^2}{M_\phi^2} [\ldots] \right\} = \gamma_w \cdot T_{nuc}^3 \exp\left[-\frac{M^2}{2\gamma_w v T_{nuc}} \right] + O(\gamma_w^0)$$

After red shifting to today the stable produced abundance takes the form

$$\Omega^{today}_{BE,\phi} h^2 = \frac{\rho_\phi}{\rho_c/h^2} \cdot \left(\frac{a(T_{reh})}{a(T_0)} \right)^3 = \frac{M_\phi n_\phi^{BE}}{\rho_c/h^2} \frac{g^0_{*,s} T_0^3}{g_{*,s}(T_{reh}) T_{reh}^3}$$

$$= 5.4 \cdot 10^5 \left(\frac{\lambda_{h\phi}^2 v_{EW}}{M_\phi\, g_{*,s}(T_{reh})} \right) \left(\frac{v_{EW}}{1\,\text{GeV}} \right) \left(\frac{T_{nuc}}{T_{reh}} \right)^3 e^{-\frac{M_\phi^2}{2\sigma v_{EW} T_{nuc}}}$$

$\rho_c = 1.054 \cdot 10^{-5} h^2\ \text{GeV cm}^{-3}$, $g^{today}_{*,s} \simeq 3.94$, $T_0 \simeq 0{,}24$ meV

This expression has to be supplemented w/ FO contribution which is produced before the phase transition

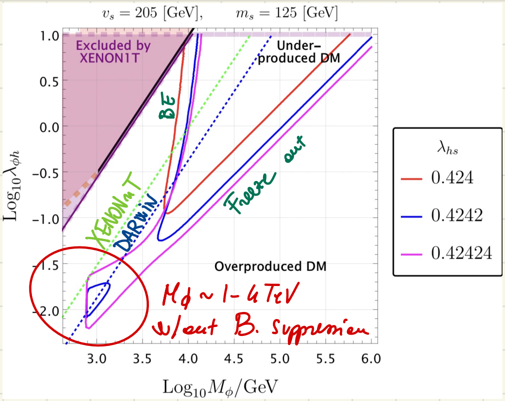
$$\Omega_{FO} = \frac{\rho_{DM}}{\rho_c}\left(\frac{a(t_{reh})}{a(t_{today})}\right)^3$$

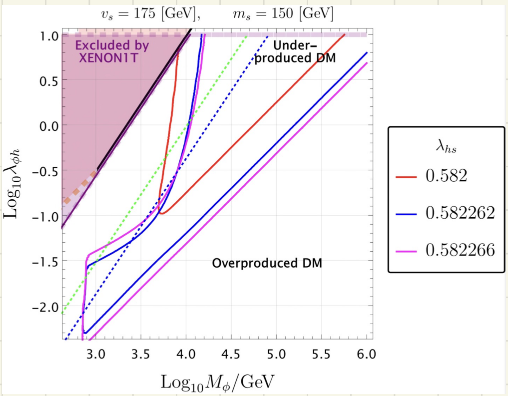
$$\Omega^{today}_{\phi,FO} h^2 \simeq 0.1 \cdot \underbrace{\left(\frac{T_{nuc}}{T_{reh}}\right)^3}_{\text{due to the brief stage of inflation during the PT.}} \cdot \left(\frac{0.03}{\lambda_{\phi h}}\right)^2 \left(\frac{M_\phi}{100\,\text{GeV}}\right)^2$$

$$\rho_{DM} = M_{DM}\cdot n_{FO} = M_{DM}\cdot Y(\infty)\, s_0\, M_{DM} \simeq \frac{M_{DM}^2}{\alpha}$$

Then

$$\Omega^{today}_{\phi,tot} = \Omega^{today}_{\phi,BE} h^2 + \Omega^{today}_{\phi,FO} h^2 \simeq 0.1$$





Features of the plot

1. Inside the isocontours under-produced
   outside the isocontours over-produced.

2. Upper curve: DM production dominated by BE. Steepness due to the fact that $\exp[-M_\phi^2/2 \lambda_{hs} v_{EW} T_{nuc}] \ll 1$ in all the region

3. Lower curve: DM production dominated by FO

4. Vertical line connecting the two: thermal production after reheating.

$\Rightarrow$ So in general the model predicts large over production of DM in BE unless Boltzmann suppression plays a role.

NOTE Can s be DM? (NO!)

Suppose very precise Z_2, after PT $T \sim 40$ GeV, the singlet is in thermal eq. then freeze FO

$$\Omega^{today}_{S,FO} h^2 \simeq 0.1 \left(\frac{0.06}{\lambda_{hs}}\right)^2 \left(\frac{M_S(v_{EW},0)}{100\text{ GeV}}\right)^2 \quad \text{but} \quad \lambda_{hs} \sim 0.3 - 0.6$$

ⓑ Singlet portal DM

DM coupling w/ singlet portal

$$\mathcal{L}_{int} \supset -\frac{\lambda_{s\phi}}{2}\phi^2 s^2 + \frac{1}{2} M_\phi^2 \phi^2 \qquad P(s \to \phi^2) \approx \left(\frac{\lambda_{s\phi} v_s}{M_\phi}\right)^2 \frac{1}{24\pi^2}\, \Theta(\gamma_w T_{nuc} - M_\phi^2 L_w^s)$$

Here difference w.r.t. previous case is that the singlet in the FV is massive, then Boltzmann suppression plays an important role. This makes a shift to the left in the plot.

ⓒ Fermion mediated DM

Here we consider a massless Fermionic DM particle in the symm. phase, so by definition it does not suffer from Boltzmann suppression.

$$\mathcal{L} = \mathcal{L}_{SM} + Y_* \bar{L} H N + M_N \bar{N} N + Y_{DM} \bar{N} \chi \phi$$

L, H : lepton, Higgs doublet

N : vector-like neutral fermion (singlet under SM) (heavy)

χ : fermion

ϕ : scalar

$\left.\begin{array}{l}\chi \\ \phi\end{array}\right\} \mathbb{Z}_2 \text{ odd} \Big\}$ DM sector

the production mechanism : $L \xrightarrow[PT]{} N$, $N \xrightarrow{\text{decay}} \chi\phi$ (DM sector), $N \to LH$ (SM)

$$P^{tree}(L \to N) \simeq \frac{Y_*^2 v_{EW}^2}{M_N^2}\, \Theta(\gamma_w T_{nuc} - M_N^2 L_w)$$

then unstable heavy N accumulate behind the wall w/

$$n_N^{BE} \simeq \frac{Y_*^2 v_{EW}^2}{M_N^2} \cdot \frac{1}{\gamma_w v_w} \int \frac{d^3p}{(2\pi)^3} \frac{p_z}{p_0} \times f_L(p, T_{nuc})\, \Theta\left(p_z - M_N^2/v_{EW}\right)$$

$$\simeq \frac{Y_*^2 v_{EW}^2}{2\pi^2 M_N^2} T_{nuc}^3\, e^{-M_N^2/2\gamma_w v_{EW} T_{nuc}} + \mathcal{O}(1/\gamma_w)$$

then the abundance of χ, ϕ after the transitision is suppressed by

$$n_\phi \simeq n_\chi \simeq \frac{Y_{DM}^2}{Y_{DM}^2 + Y_*^2}\, n_N^{BE}$$

$$\simeq \frac{Y_{DM}^2}{Y_{DM}^2 + Y_*^2}\, \frac{Y_*^2 v_{EW}^2}{2\pi^2 M_N^2}\, T_{nuc}^3\, e^{-M_N^2/2\gamma_w v_{EW} T_{nuc}}$$

and the final relic adbundace redshifted to today reads

$$\Omega^{today}_{\phi,BE} h^2 \simeq 1.5 \cdot 10^8 \frac{Y_{DM}^2 Y_*^2}{Y_{DM}^2 + Y_*^2} \cdot \frac{2M_\phi}{M_N} \left(\frac{v_{EW}}{M_N}\right)\left(\frac{v_{EW}}{246\,GeV}\right)\left(\frac{T_{nuc}}{T_{reh}}\right)^3 e^{-M_N^2/2\gamma_w v_{EW} T_{nuc}}$$

For the freeze-out we have $\phi\phi \to LH\,LH$ by neglecting co-annihilation. The cross section is highly phase space suppressed

$$\sigma_{\phi\phi \to (LH)^* LH} \sim \frac{M_\chi^2 (Y_{DM} Y_*)^4}{(16\pi^2)\, 4\pi M_N^4}$$

then the adbundace today is

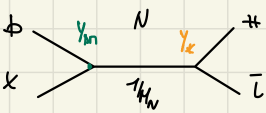
$$\Omega^{today}_{\phi,FO} h^2 = 10^3 \left(\frac{T_{nuc}}{T_{reh}}\right)^3 \frac{M_N^4/M_\chi^2}{(6\,TeV)^2} \frac{10}{(Y_{DM} Y_*)^4}$$

The total density is the sum of the two. This scenario leads to the over production of DM when $M_\phi, M_\chi \leq 10$ GeV.

NOTE Valid only for heavy DM candidates which do not go back to equilibrium after the PT. Otherwise we need to take $(T_{nuc}/T_{reh})^3$ out from the estimate.

Let us now investigate the regime w/ $M_\phi \simeq M_\chi$, precisely $|M_\phi - M_\chi| < M_\phi/20$ when the co-annihilation takes place. In this case we have

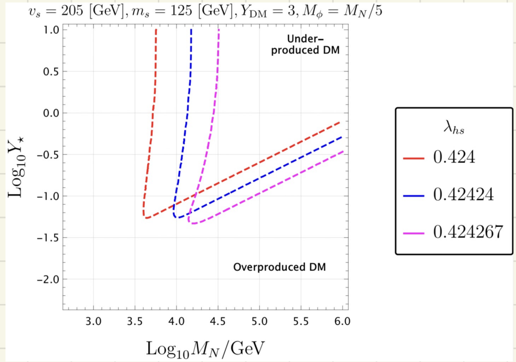
$$\sigma_{\phi\chi \to H\bar{L}} \sim \frac{(Y_{DM} Y_*)^2}{4\pi M_N^2}$$



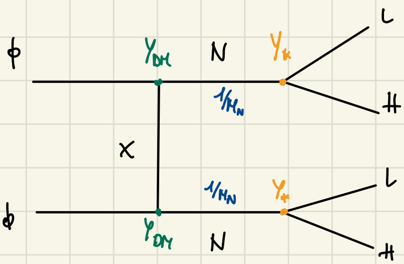
Therefore we have

$$\Omega^{today}_{\phi,FO,C_0}\, h^2 \sim 0.1 \left(\frac{T_{unc}}{T_{reh}}\right)^3 \cdot \frac{M_N^2}{(10\,TeV)^2} \cdot \frac{1}{(Y_{DM} Y_k)^2}$$

Summing all of this we find that become possible to reproduce the observed DM abundance.
BE tends to over produce the DM and the relic abundance from BE can be reproduced iff $\exp[-M_N^2/2\gamma_m v_{EW} T_{unc}]$ starts playing a role in suppressing DM relic density.



NOTE



$$\sigma_{\phi\phi\to LHLH} \simeq \overbrace{\left(\frac{M_\chi^2}{16\pi^2}\right)^2}^{\text{phase space}} \cdot \left[\underbrace{\frac{(Y_{DM}\cdot Y_k)^2}{M_\chi\ M_N^2}}_{\mathcal{M}}\right]^2$$

then for the abundance

$$\Omega h^2 \simeq \frac{M_\chi\, Y(\infty)\, s_0}{\rho_c/h^2} \sim \frac{1}{\langle\sigma v\rangle}$$

since $Y(\infty) \sim g_*^{-1/2} \dfrac{x_{f.o.}}{M_{pl} M_\chi} \cdot \dfrac{1}{\langle\sigma v\rangle}$.

7 Conclusions

1. First explicit realisation of ultra relativistic FOPT for EW Baryogenesis & DM production

2. Singlet extension of SM w/ 2 step PT

$$(0,0) \xrightarrow{\text{SOPT}} (0, v_S) \xrightarrow{\text{FOPT}} (v_{EW}, 0)$$

3. T_{nuc} as low as 1-2 GeV

4. Mechanism most efficient for $M_S(v_{EW}, 0) \sim 70-100$ GeV
   It will be probed by HL-LHC