Electroweak Bubble Wall Expansion: Baryogenesis and Gravity Waves in SM-like plasma

Marco Merchand
University of Warsaw
With M. Lewicki and M. Zych
To appear soon

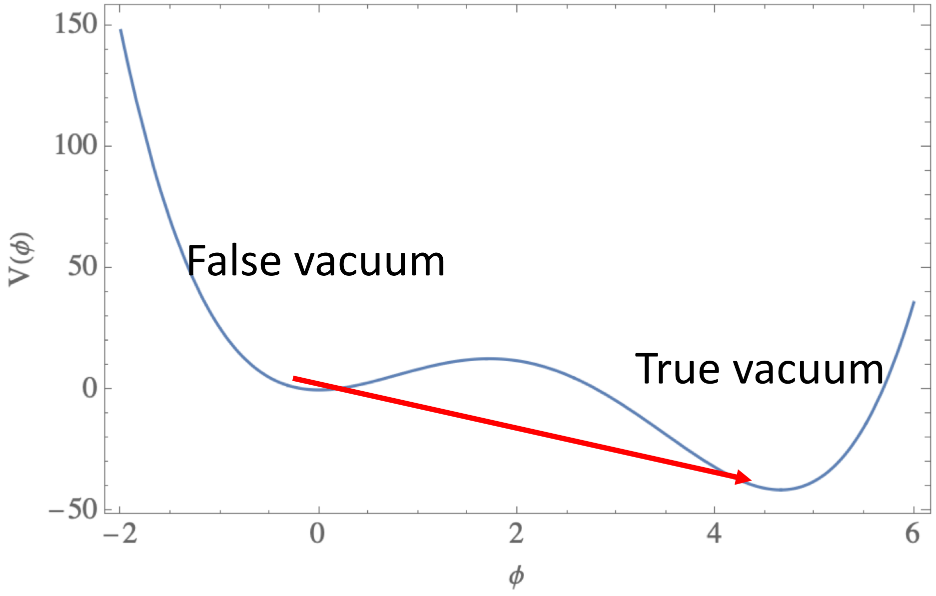
CORFU workshop 2021, 05 September 2021

Outline

- First Order Phase Transition (FOPT)
- Fluid Approximation
- Hydrodynamic treatment of the plasma
- The models:
  -SMEFT with dim-6 operator
  -Scalar singlet extension with parity symmetric potential
- Results
- Conclusions

FOPT

- No FOPT in the SM (Higgs is too heavy!) but can easily arise in simple extensions.
- Condition for EWBG (Sakharov).
- Renewed interest due to GW observations.



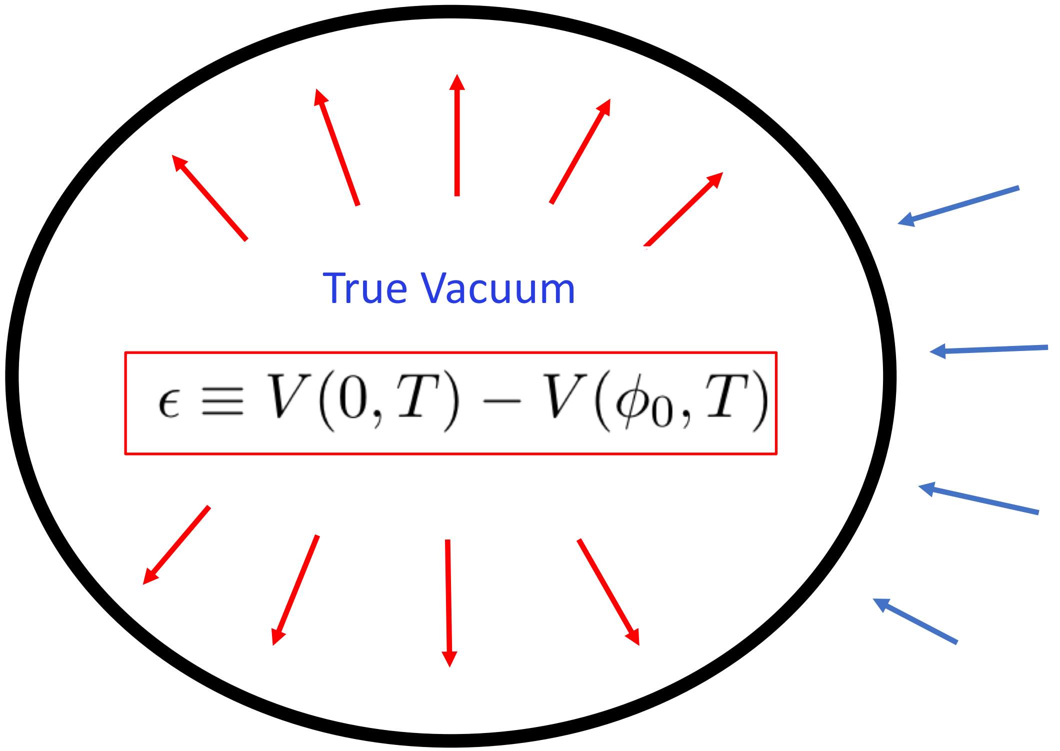
Transition probability:

$$\Gamma(T) = A(T)\mathrm{e}^{-S},$$

$$A(T) = \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} T^4$$

Bubble Nucleation

$$\int_{t_c}^{t_n} dt \frac{\Gamma(t)}{H(t)^3} = 1$$



$$\epsilon \equiv V(0,T) - V(\phi_0, T)$$

False Vacuum

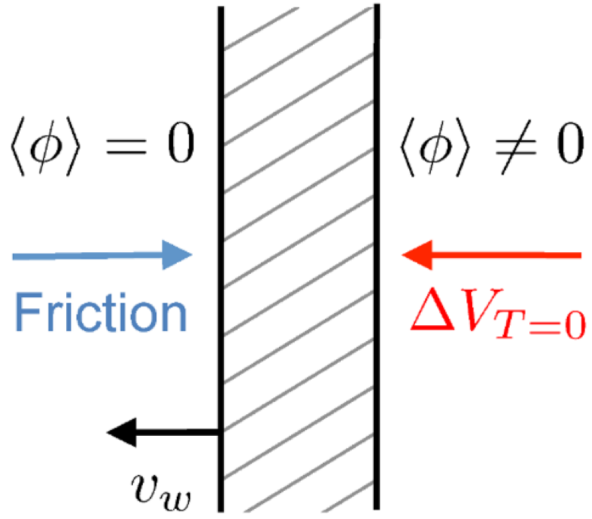
Pressure from collision with the SM plasma particles

The balance between the two pressures causes the wall to reach a steady state with a final terminal velocity

Does the wall reach a steady state?

Semiclassical Fluid Approximation

1. Small Departure from equilibrium.
2. Phase transition time scale shorter than the expansion rate of the universe.
3. WKB; the bubble is thicker than the thermal wavelength.
4. Planar limit.



1506.04741

CP-even Equations

-Cline, Laurent 2007.10935 (Wall Speed)
-Cline, Kainulainen 2001.00568 (Baryogenesis)

Fluid ansatz

$$f \approx f_v - f_v' \delta \bar{X} + \delta f_u + \mathcal{O}(\delta f^2)$$

Equilibrium distribution

$$f_v = \frac{1}{e^{\beta\gamma(E - v p_z)} \pm 1}, \quad f_v' = \frac{d f_v}{d \beta \gamma E}$$

Perturbations

$$\boxed{\delta \bar{X} = \mu + \beta\gamma\delta\tau(E - v p_z)}$$

Leading order in gradients

$$\left[\frac{p_z}{E}\partial_z - \frac{(m^2)'}{2E}\partial_{p_z}\right]\left(f_v - f_v'\delta\bar{X} + \delta f_u\right) = C[f]$$

2007.10935
2001.00568

With a three parameter ansatz we cannot impose that the Boltzmann equation to be satisfied but we can use a moment expansion, e.g.

$$\int \frac{d^3p}{(2\pi)^3}\frac{1}{T^3}, \quad \int \frac{d^3p}{(2\pi)^3}\frac{E}{T^4}, \quad \int \frac{d^3p}{(2\pi)^3}\frac{1}{T^3}\frac{p_z}{E}$$

$$\boxed{A\vec{q}\,' + \Gamma\vec{q} = S}$$

Only tops, W and Z bosons contribute signficantly

$$q = (\mu, \delta\tau, u)^{\mathrm{T}}$$

$$C_v^{m,n} = T^{m-n-3}\int \frac{d^3p}{(2\pi)^3}\frac{p_z^n}{E^m}(-f_v')$$

$$D_v^{m,n} = T^{m-n-3}\int \frac{d^3p}{(2\pi)^3}\frac{p_z^n}{E^m}f_v$$

$$A_v = \begin{pmatrix} C_v^{1,1} & \gamma v C_0^{-1,0} & D_v^{0,0} \\ C_v^{0,1} & \gamma(C_v^{-1,1} - vC_v^{0,2}) & D_v^{-1,0} \\ C_v^{2,2} & \gamma(C_v^{1,2} - vC_v^{2,3}) & D_v^{1,1} \end{pmatrix}$$

$$S = \gamma v \frac{(m^2)'}{2T^2}\begin{pmatrix} C_v^{1,0} \\ C_v^{0,0} \\ C_v^{2,1} \end{pmatrix}$$

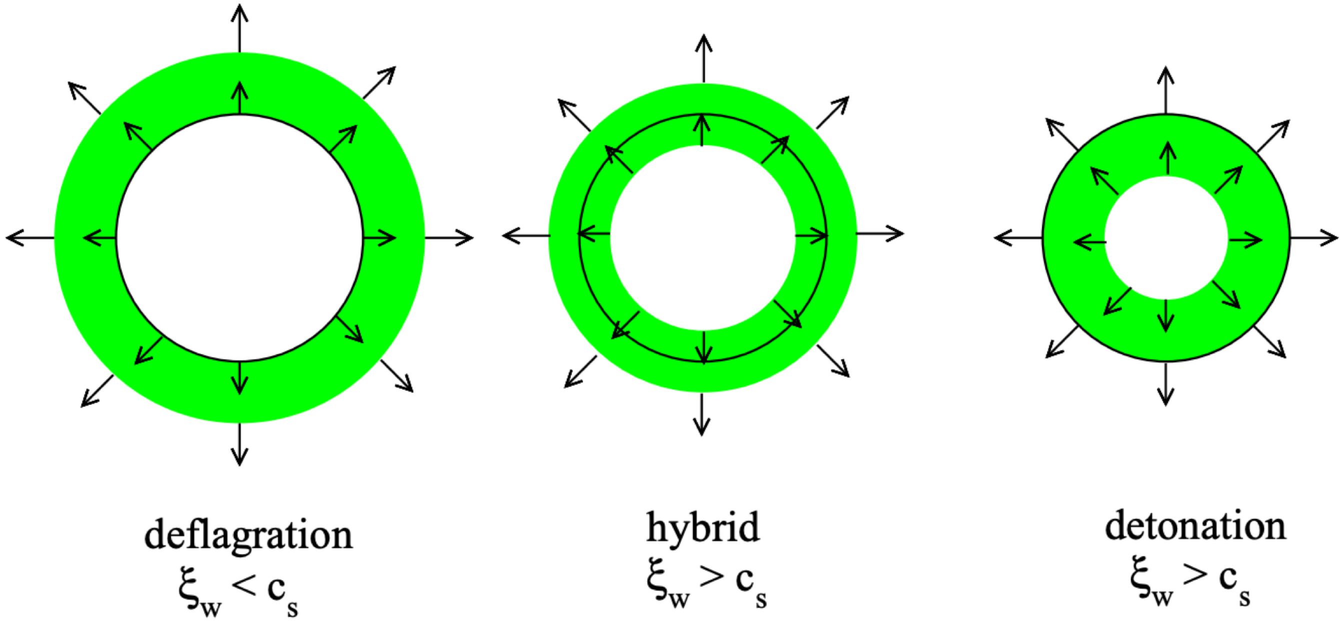
Source term

Hydrodynamic Equations

1004.4187

$$(\xi - v)\frac{\partial_\xi e}{w} = 2\frac{v}{\xi} + [1 - \gamma^2 v(\xi - v)]\partial_\xi v$$

$$(1 - v\xi)\frac{\partial_\xi p}{w} = \gamma^2(\xi - v)\partial_\xi v.$$



Wall Velocity Algorithm

v_w, L_w, h_0

1. Initial guess → $h(z) = \frac{h_0}{2}\left[\tanh\left(\frac{z}{L_h}\right) + 1\right]$ → From Bounce Solution

2. Hydrodynamic eqns.

$$(\xi - v)\frac{\partial_\xi e}{w} = 2\frac{v}{\xi} + [1 - \gamma^2 v(\xi - v)]\partial_\xi v$$

$$(1 - v\xi)\frac{\partial_\xi p}{w} = \gamma^2(\xi - v)\partial_\xi v$$

3. Perturbations from Thermodynamic equilbrium. → $A_v\vec{q}\,' + \Gamma\vec{q} = S$

4. EOM →

$$E_h \equiv \Box\phi + \frac{dV_{\rm eff}(\phi, T)}{d\phi} + \sum_i \frac{dm_i^2}{d\phi}\int \frac{d^3p}{(2\pi)^3}\frac{\delta f_i(p, x)}{2E} = 0$$

Friction term

5. Moments

$$M_1 \equiv \int dz E_h h' dz = 0$$

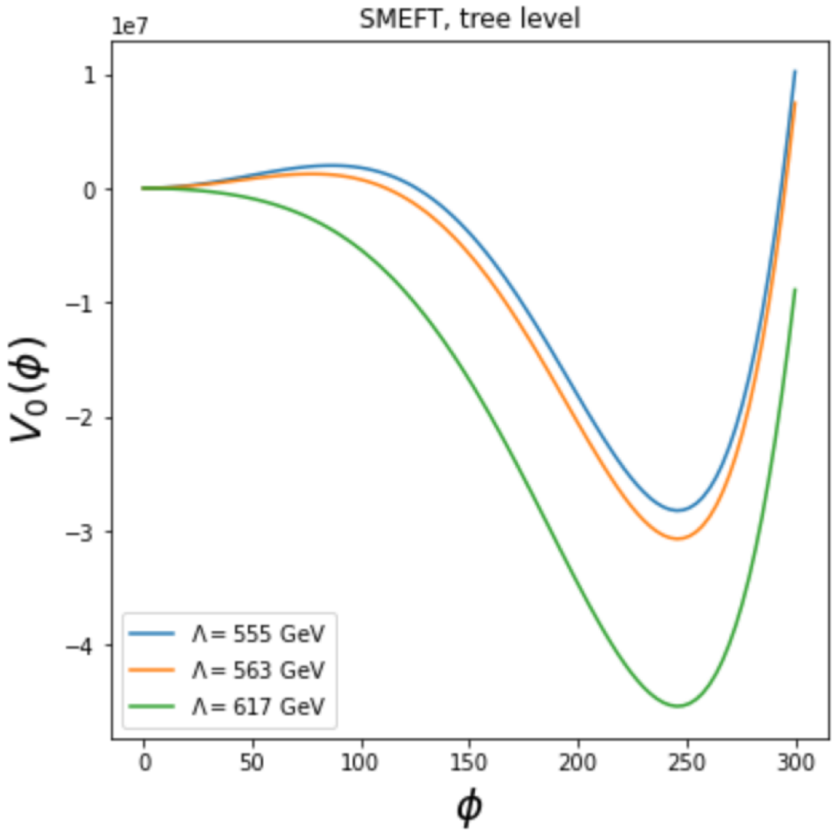
$$M_2 \equiv \int dz E_h h'[2h(z) - h_0]dz = 0$$

SMEFT

$$V_0 = -m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \kappa(\Phi^\dagger\Phi)^6$$

$$\kappa \equiv 1/\Lambda^2$$

$$m^2 = \frac{m_h^2}{2} - \frac{3v^4}{4\Lambda^2}, \quad \lambda = \frac{m_h^2}{2v^2} - \frac{3v^2}{2\Lambda^2}$$

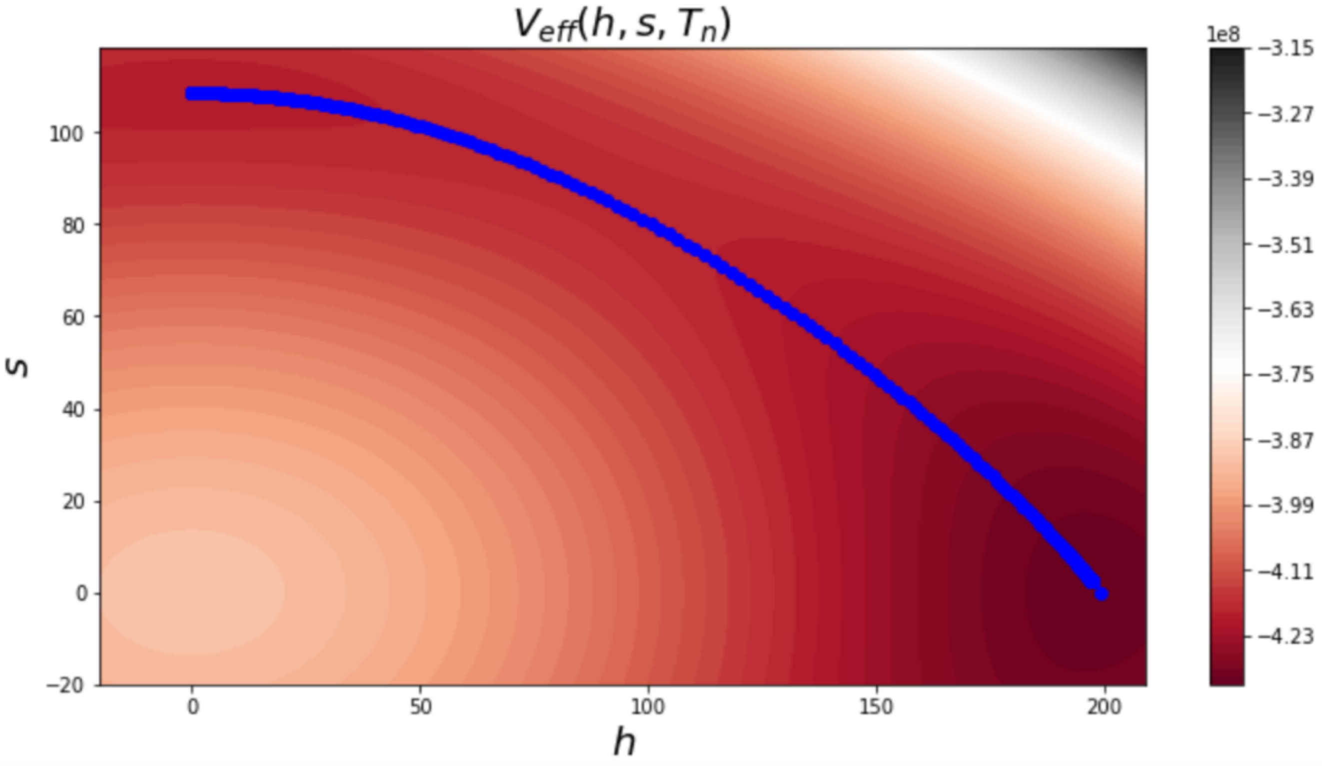


Scalar Singlet Model

$$V_0(\Phi, s) = -\mu_h^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2 + \left(m_s^2 - \frac{\lambda_{hs} v^2}{2}\right)\frac{s^2}{2} + \frac{\lambda_s}{4} s^4 + \frac{\lambda_{hs}}{2} s^2 \Phi^\dagger \Phi.$$

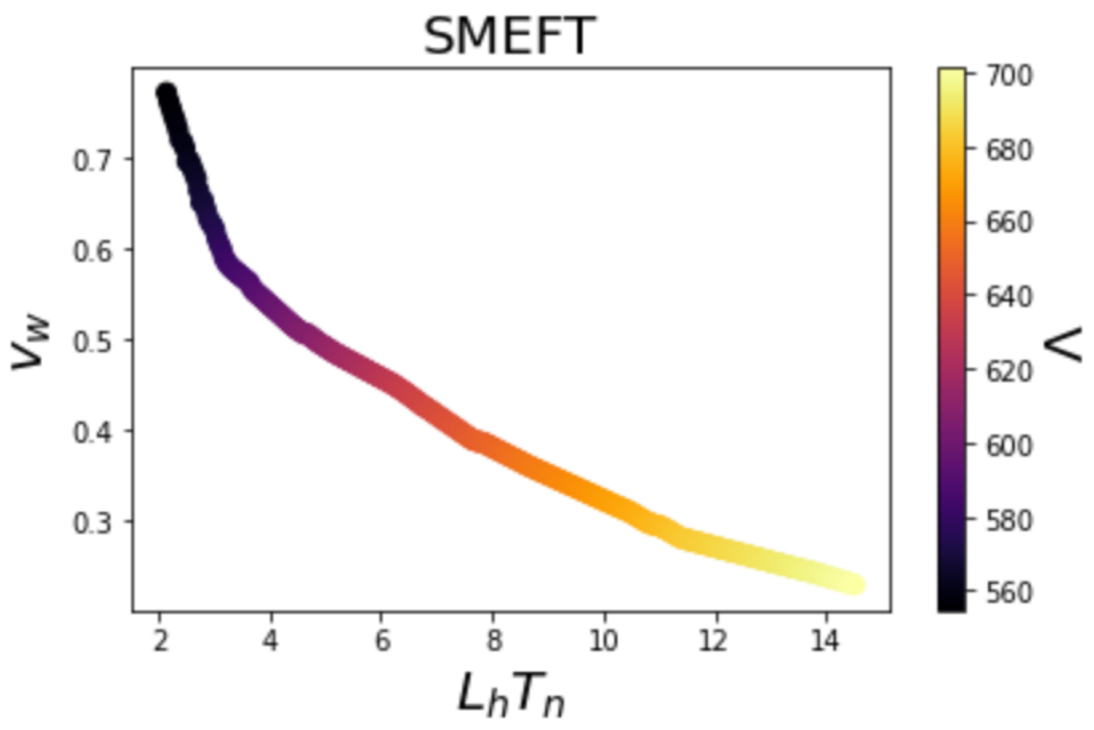
- Three free parameters: $m_s, \lambda_{hs}, \lambda_s$
- Two-step FOPT
- No EDM constraints

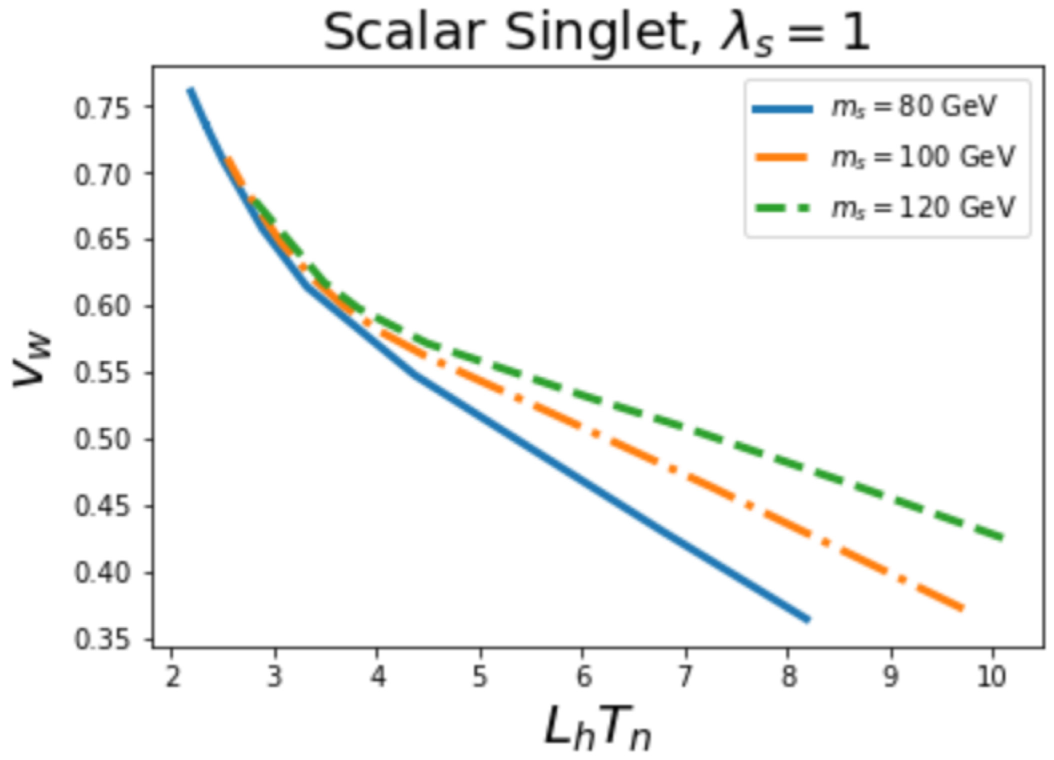
$$\mathcal{L}_{\text{Yukawa}} \supseteq y_t \bar{Q} \Phi t_R \left(1 + \frac{is}{\Lambda_{\text{CP}}}\right)$$



Wall Velocity Results

v_w, L_w, h_0 ← Wall parameters → $v_w, L_h, h_0, L_s, s_0, \delta_s$





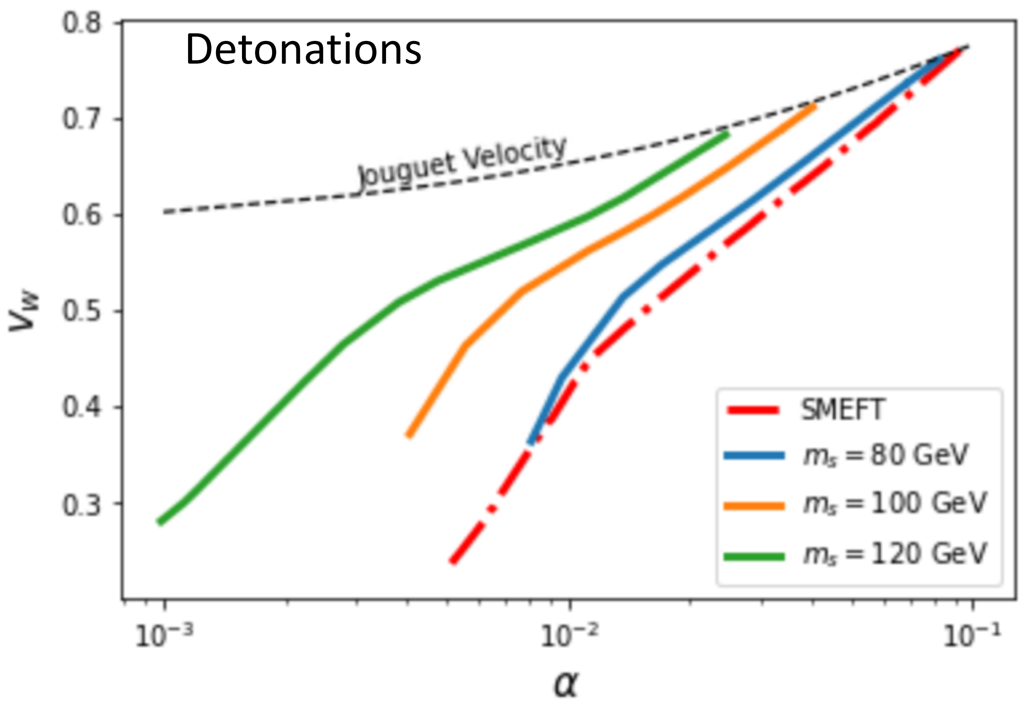
Generic trademarks of simple BSM models:

- Stronger transitions lead to faster walls
- Slower walls are thicker
- Faster walls correspond to bigger profile amplitudes

Wall Speed Limit

$$\alpha \equiv \frac{1}{\rho_r}\left(\Delta V_{eff}(\phi,T) - \frac{T}{4}\Delta\frac{\partial V_{eff}(\phi,T)}{\partial T}\right)$$

- Fluid approximation stops working at the Jouguet velocity. Only deflagrations and hybrid solutions can be found.
- Detonations do not have solutions for the moment equations. No balance of pressures.
- We expect the wall to keep on accelerating becoming thinner and violating the premises of the approximation.
- Other approaches are necessary .

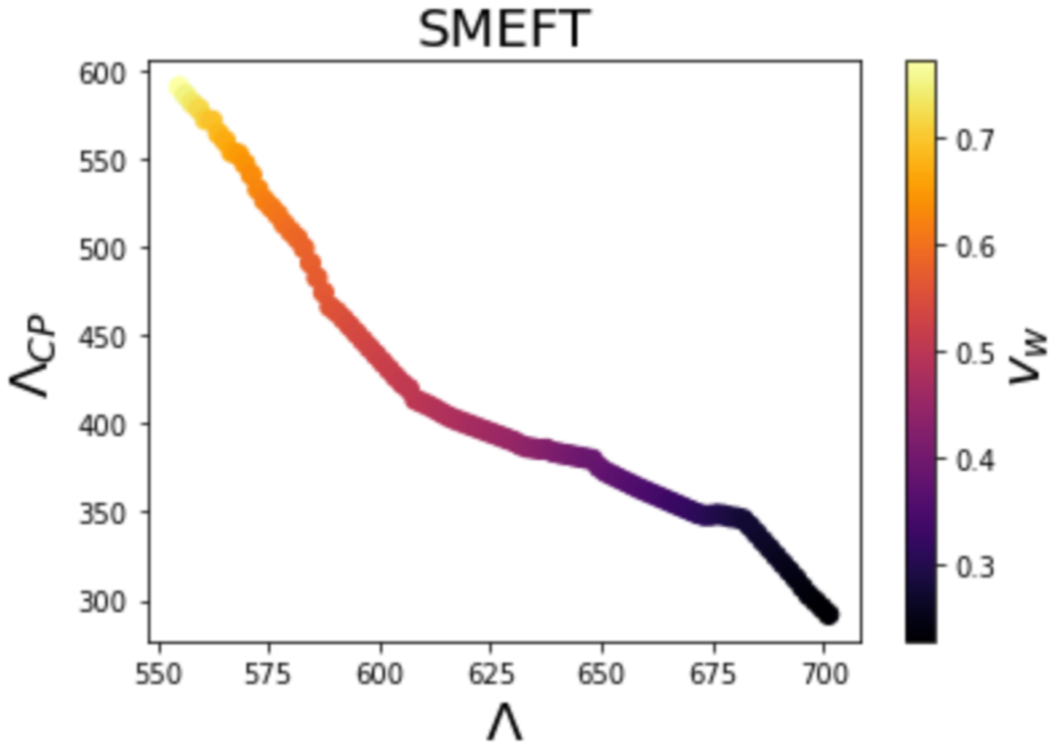


EWBG in SMEFT

$$\mathcal{L}_{\text{Yukawa}} \supseteq \ y_t \bar{Q} \Phi t_R + \frac{y'}{\Lambda_{\text{CP}}^2} \bar{Q} \Phi t_R (\Phi^\dagger \Phi)$$

EDM constraint: $\Lambda_{\text{CP}} > 2.5\ \text{TeV}$

SMEFT is not suitable for EWBG!

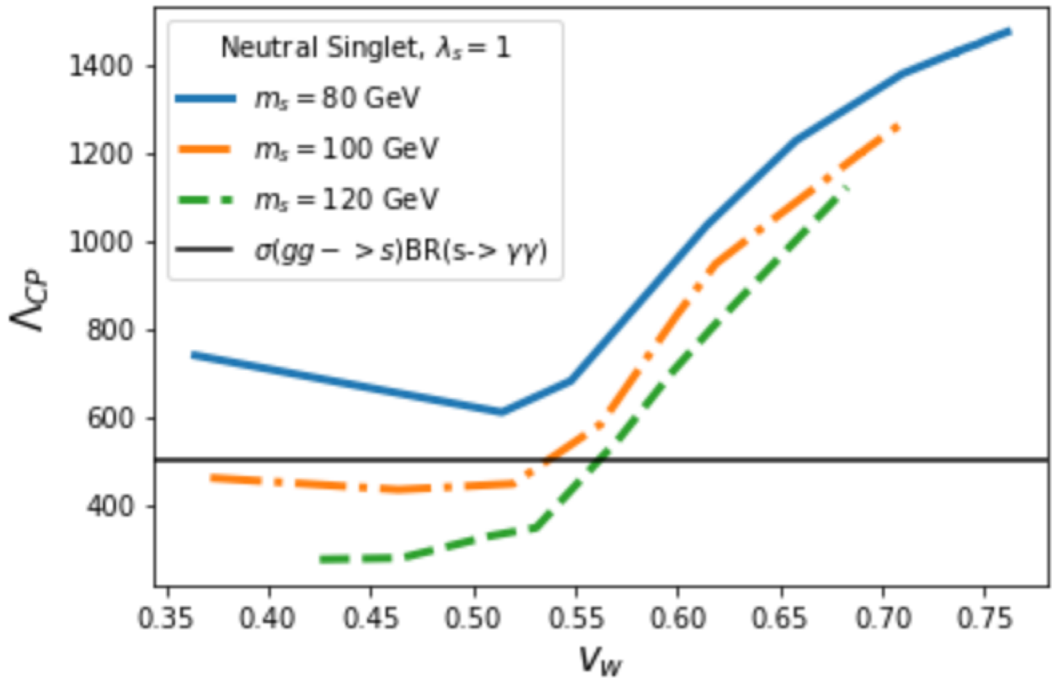


EWBG in Scalar Singlet

$$\mathcal{L}_{\text{Yukawa}} \supseteq y_t \bar{Q} \Phi t_R \left(1 + \frac{is}{\Lambda_{\text{CP}}}\right)$$

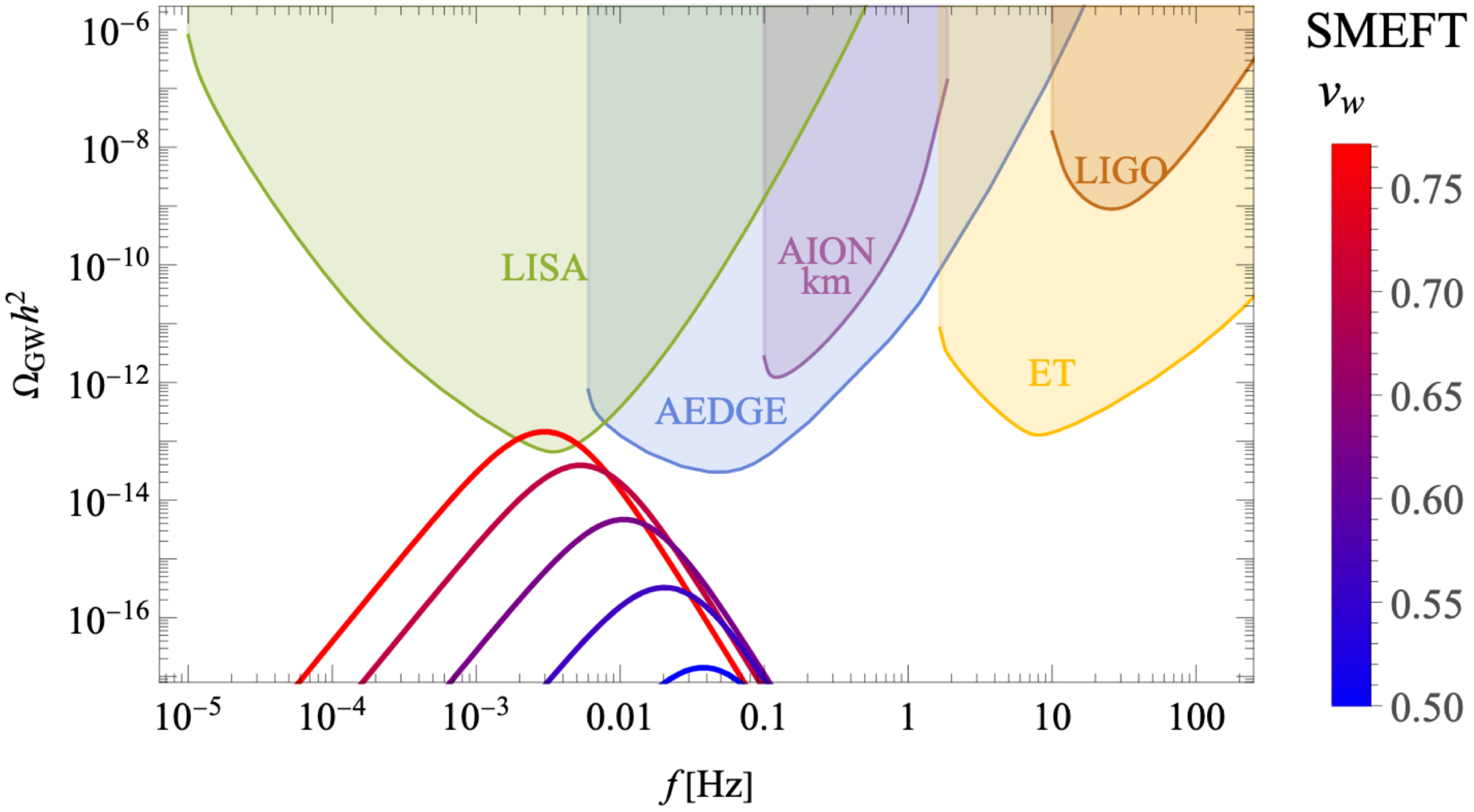
Collider constraint: $\Lambda_{\text{CP}} > 500 \text{ GeV}$

Can easily accomodate BAU!

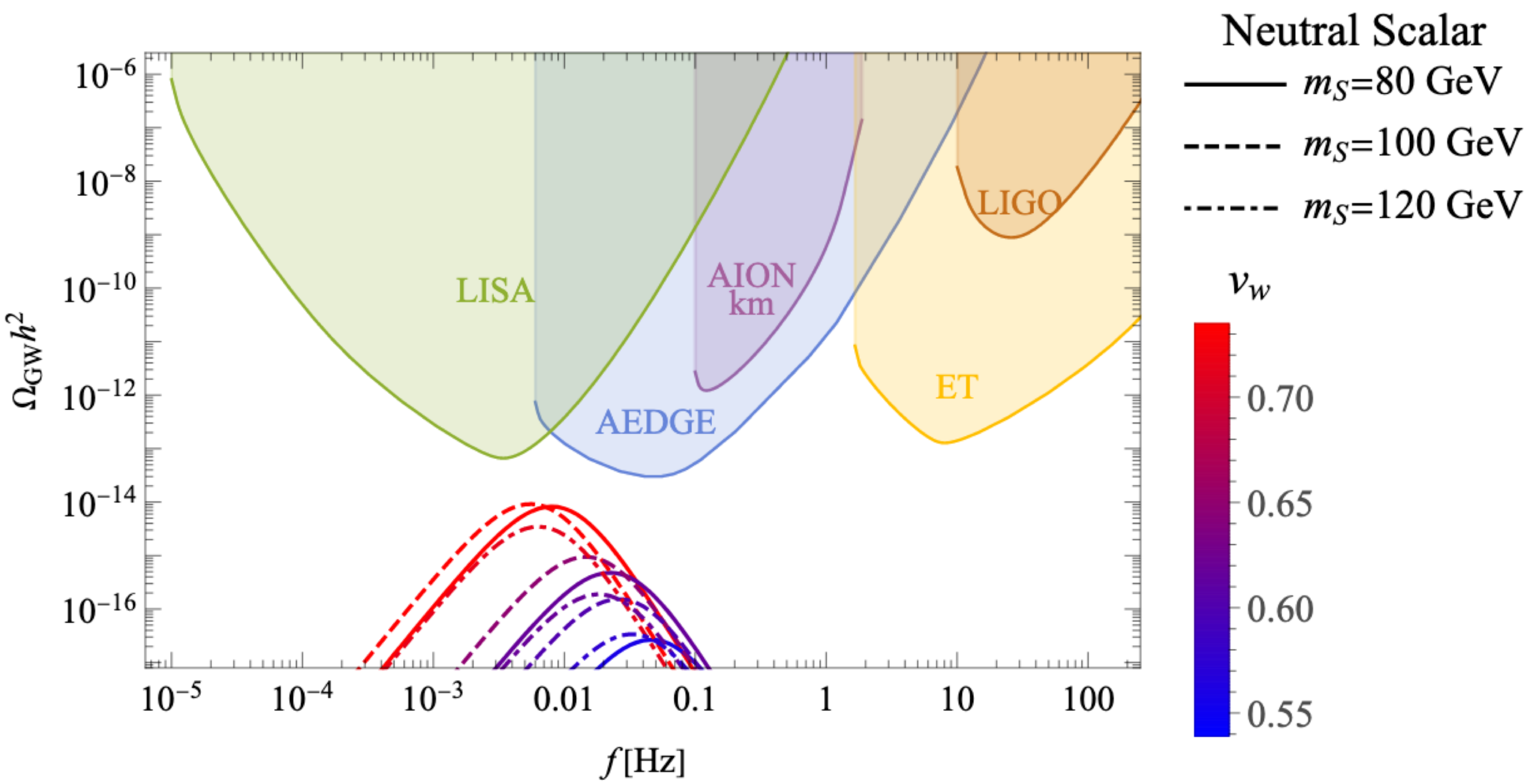


GW predictions (SMEFT)

- Transitions are relatively weak and velocities not highly relativistic.
- GW sourced by plasma motion.



GW predictions (Scalar Singlet)



Conclusions

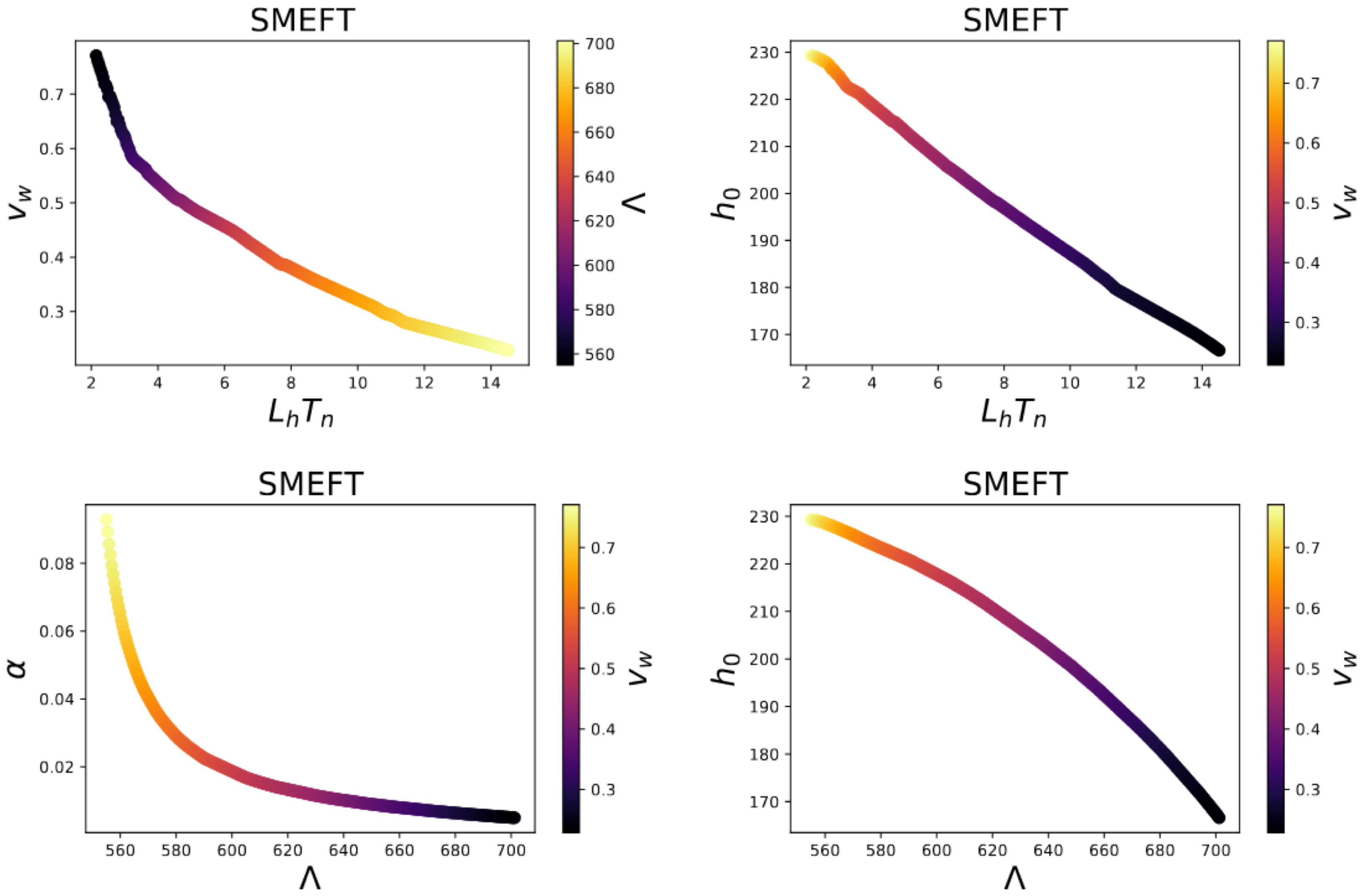
Generic:

- Determination of the bubble wall properties from first principles is of crucial importance for accurately assesing the viability of EWBG and for the prediction of GWs.
- The fluid approximation only works for a small region of parameter space. Other assumptions are needed in those cases.
- Detonations are not realized using this approximation.
- Hydrodynamic treatment is crucial.

Models studied:

- Scalar singlet model is useful for EWBG but doesn’t lead to observable GWs.
- SMEFT not suitable for EWBG but lead to observable GWs.


Thank you


SMEFT
v_w
$L_h T_n$
Λ
SMEFT
h_0
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α
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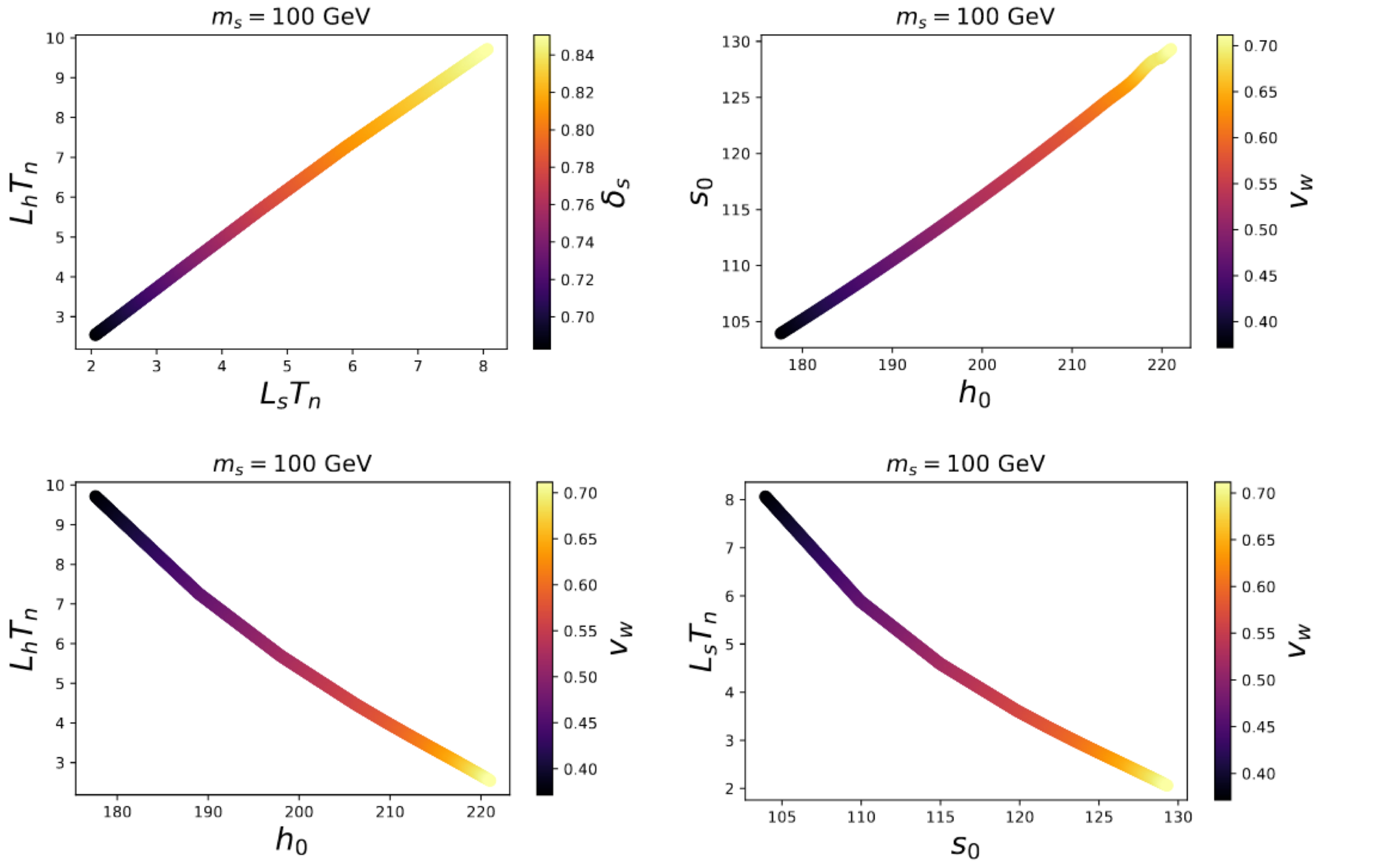
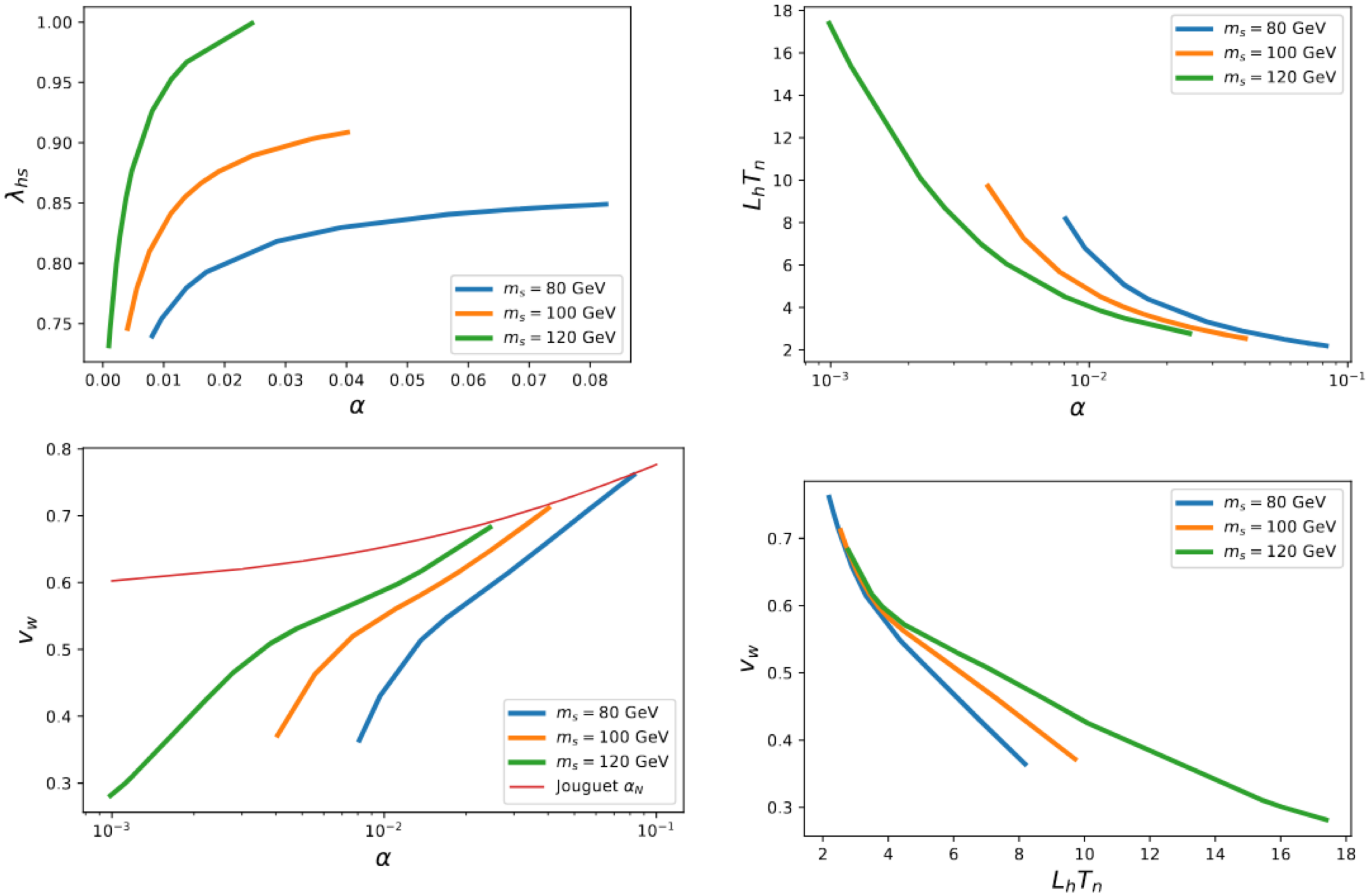


$m_s = 100$ GeV
$L_h T_n$
$L_s T_n$
δ_s
s_0
h_0
v_w



λ_hs
α
m_s = 80 GeV
m_s = 100 GeV
m_s = 120 GeV
L_h T_n
α
m_s = 80 GeV
m_s = 100 GeV
m_s = 120 GeV
v_w
α
m_s = 80 GeV
m_s = 100 GeV
m_s = 120 GeV
Jouguet α_N
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L_h T_n
m_s = 80 GeV
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m_s = 120 GeV

FOPT in xSM

$$\alpha \equiv \frac{1}{\rho_r}\left(\Delta V_{eff}(\phi, T) - \frac{T}{4}\Delta\frac{\partial V_{eff}(\phi, T)}{\partial T}\right)$$

Sphaleron washout condition: $\frac{v}{T} \gtrsim 1$