Minimal Electroweak Baryogenesis with Domain Walls

Jacopo Azzola

with O. Matsedonskyi, A. Weiler

JHEP 04 (2025) 103

arXiv:2412.10495

Motivation

- Matter-Antimatter asymmetry: $\eta = \frac{n_B - n_{\bar{B}}}{s} \approx 10^{-10}$

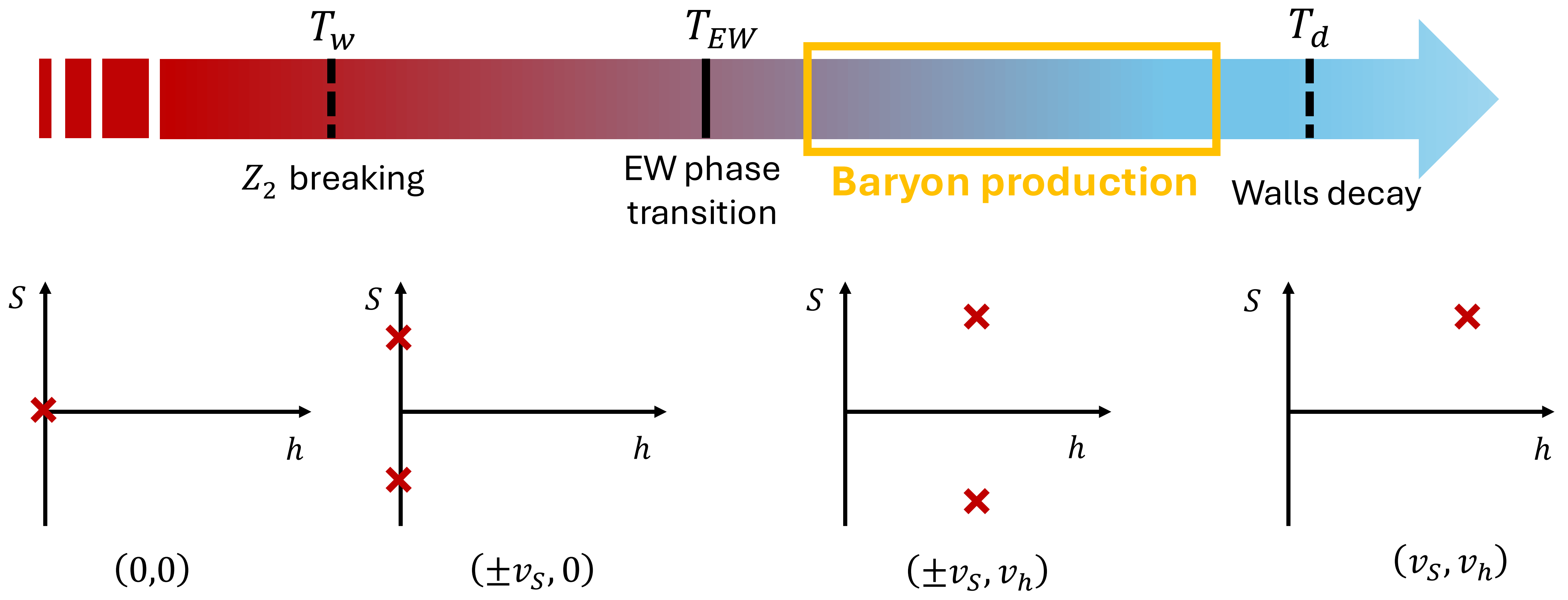
- No explanation in Standard Model

- Singlet extension:

  - **Usually:** 1st order EWPT $\longrightarrow$ difficult to probe

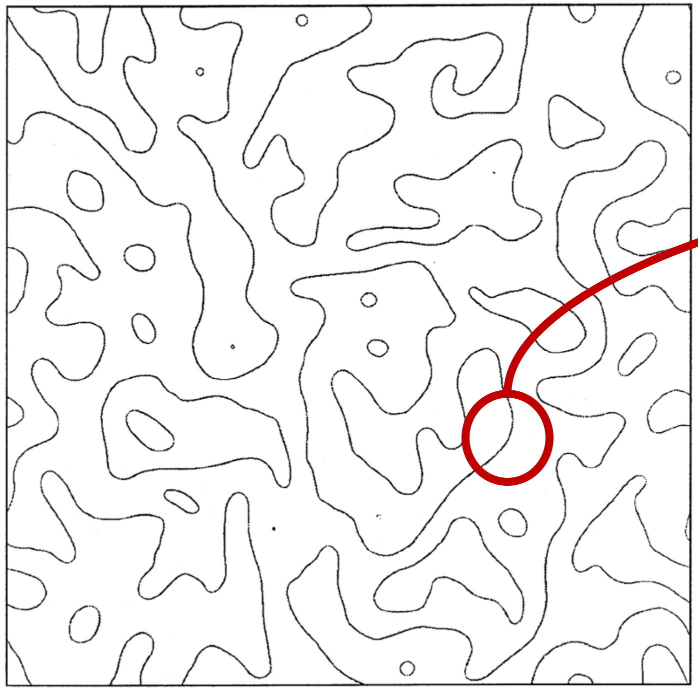
  - **Here:** topological defect mediated, first from *Brandenberger et al, 1996*

Timeline

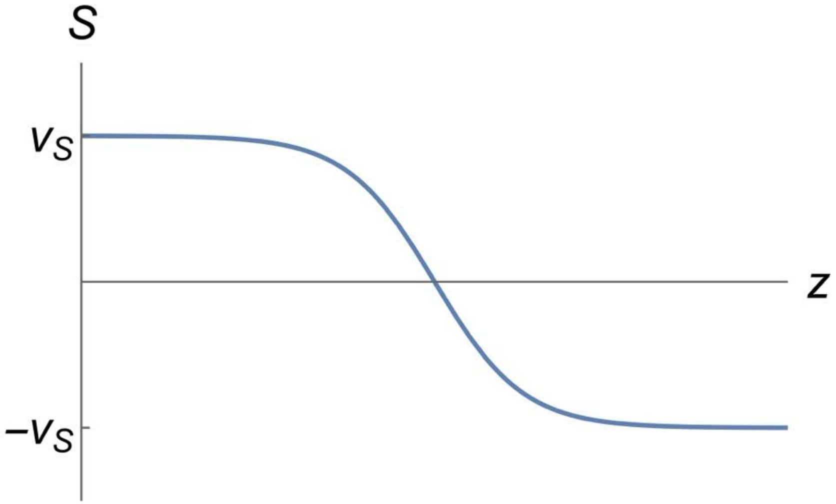

T_w
T_{EW}
T_d
Z_2 breaking
EW phase transition
Baryon production
Walls decay
S
h
$(0,0)$
$(\pm v_S, 0)$
$(\pm v_S, v_h)$
(v_S, v_h)

Mechanism

Step 0: S-domain wall formation



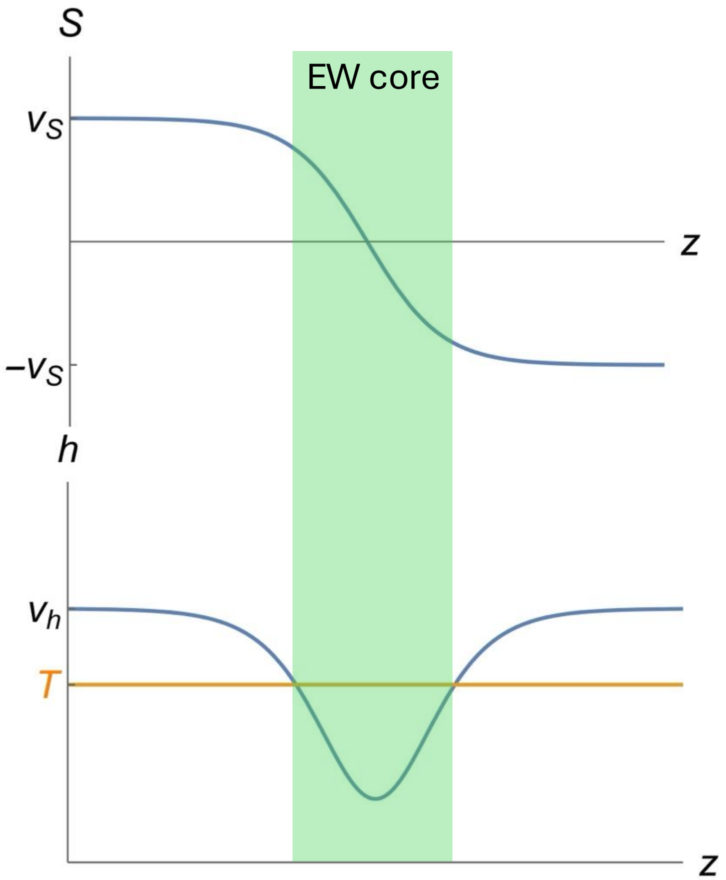
Press, Ryden, Spergel 1989

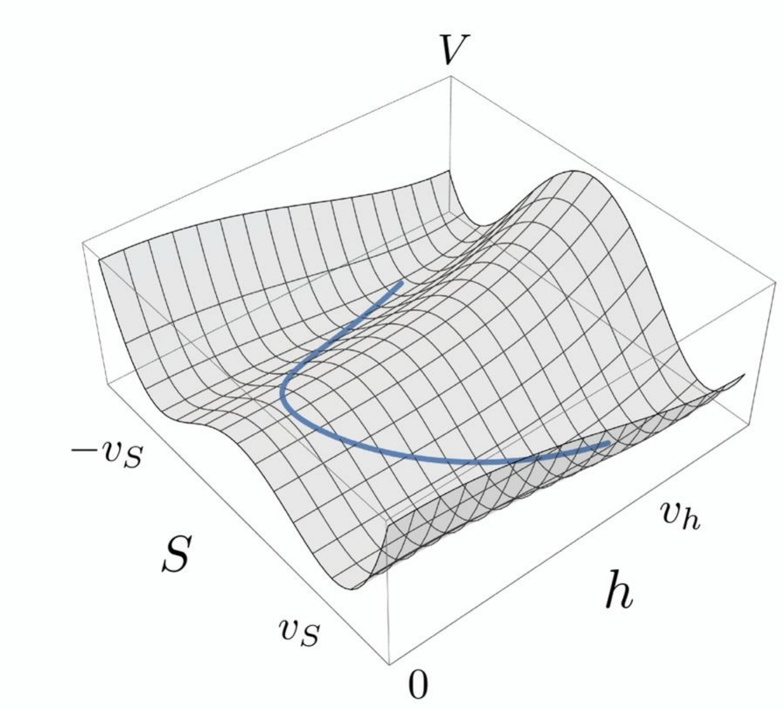


$$S(z) = v_s Tanh\left(\frac{m_S}{2} z\right)$$

Mechanism

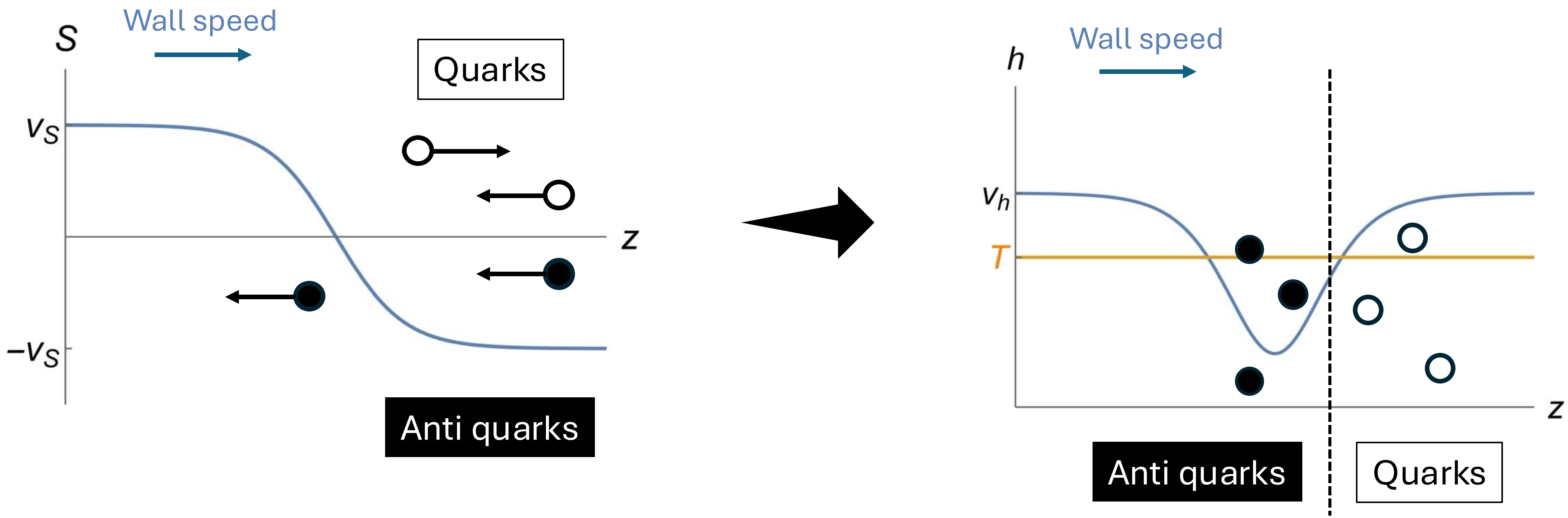
Step 1: EW phase transition





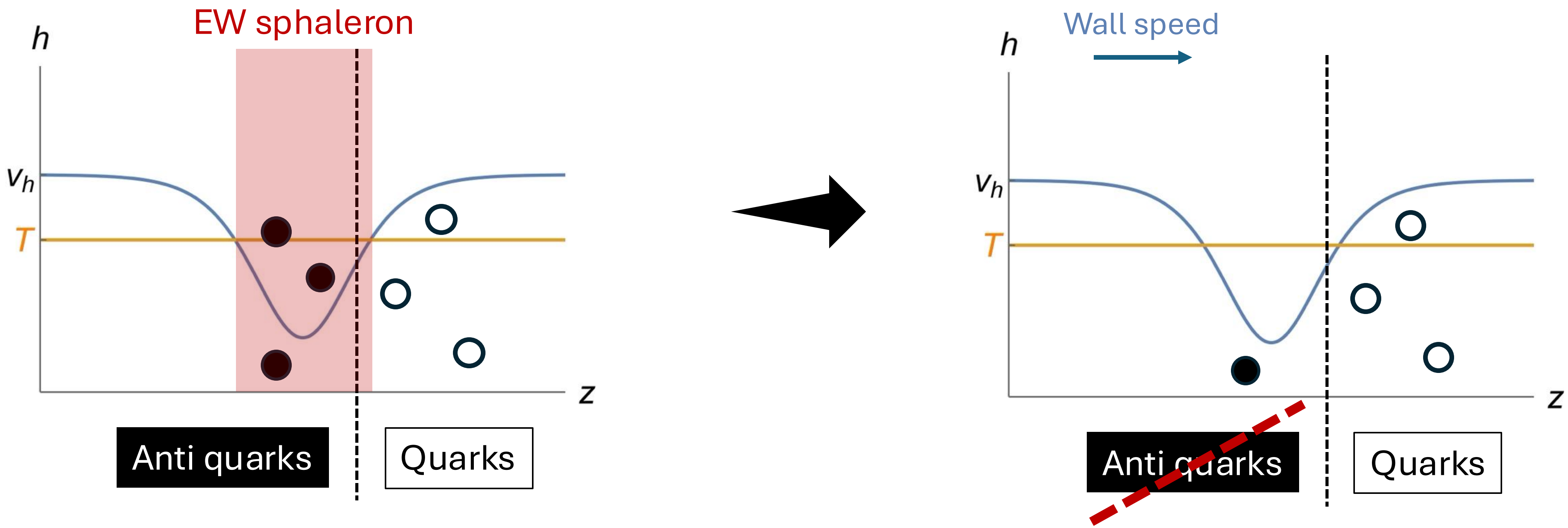
Mechanism

Step 2: CP violation



Mechanism

Step 3: EW sphaleron



Free Parameters

- Minimal extension

$$\mathcal{L} \supset +\mu_h^2|H|^2 + \frac{\lambda_h}{2}|H|^4 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda_S}{4}S^4 - \frac{|\lambda_{hS}|}{2}|H|^2S^2 + \delta V_{\cancel{\mathbb{Z}_2}}$$

- Parameter space

$$\boxed{m_S \qquad \sin\theta_{hS} \qquad v_S}$$

Wall Network Evolution

- Baryon asymmetry only in volume swept
- Evolution steps:

   i. Scaling regime

   ii. Collapse

Wall Network Evolution

- Baryon asymmetry only in volume swept

- Evolution steps:

  i. Scaling regime

  ~~ii. Collapse~~

  Walls too fast (?)

Wall Network Evolution

- Baryon asymmetry only in volume swept

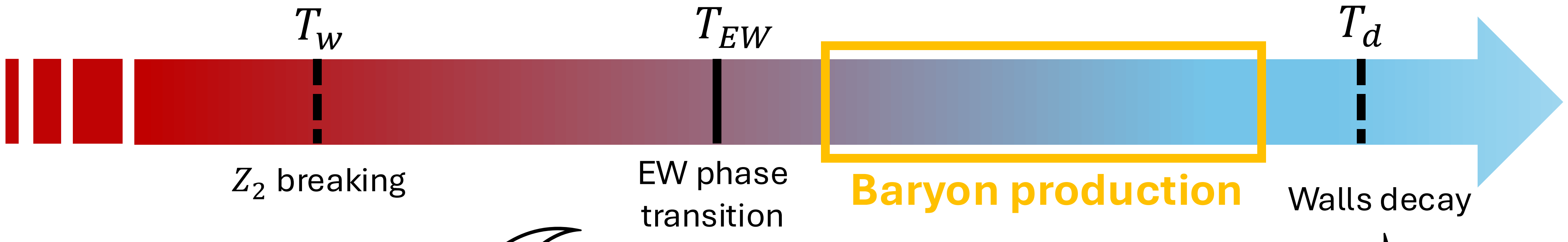
- Evolution steps:

  i. Scaling regime $\frac{V_c}{A_c} \sim \epsilon(\eta - \eta_w)$ $\longrightarrow$ $\boxed{\frac{\delta V_c}{V_c} \sim ln \frac{T_i}{T_f}}$

  Press, Ryden, Spergel 1989

  ~~ii. Collapse~~

  Walls too fast (?)



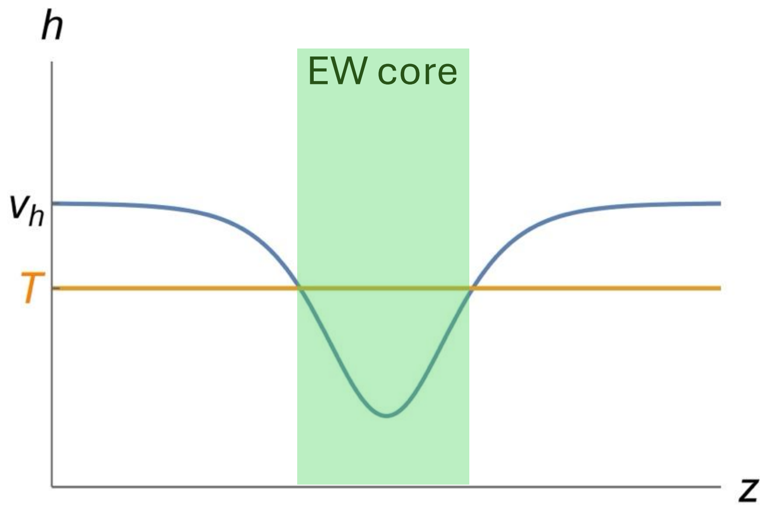
Not delayed for

$$|\sin\theta_{hs}| \lesssim m_S/m_h$$

Avoid DW domination

$$|\sin\theta_{hs}| \gtrsim \sqrt{\frac{m_S}{M_P}\frac{v_h}{T_d}}$$

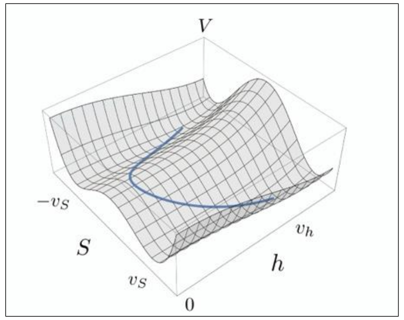
Conditions on Wall Profile



Conditions on Wall Profile

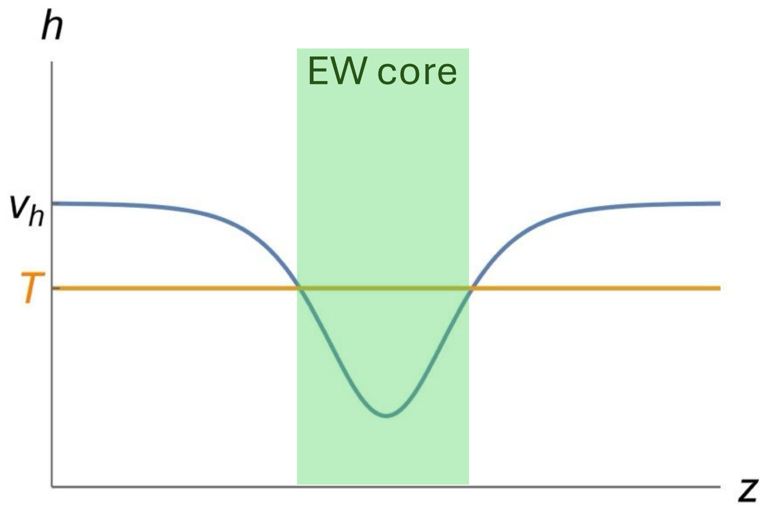
$$v_h(S = 0) \lesssim T$$

$$\downarrow$$



$$\downarrow$$

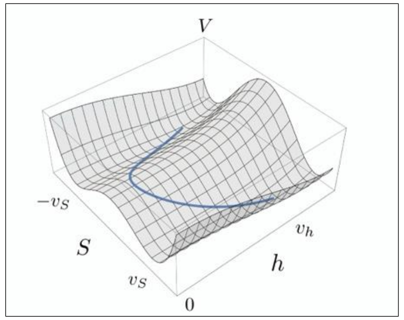
$$v_S \gtrsim v_h / sin\, \theta_{hS}$$



Conditions on Wall Profile

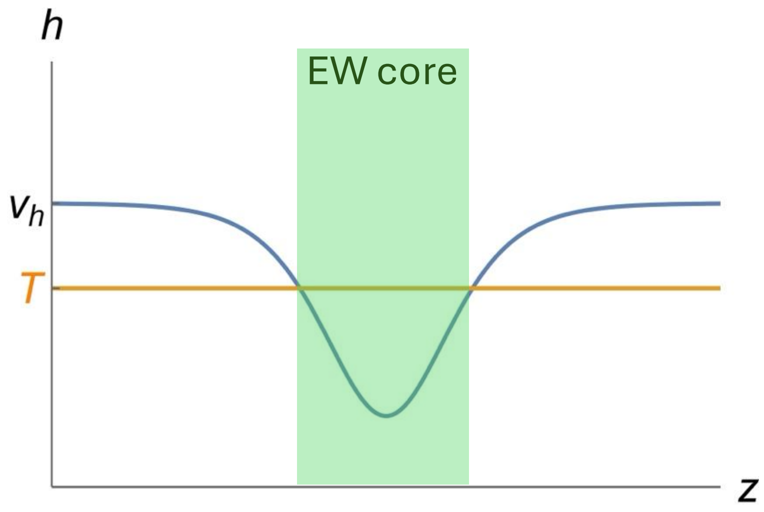
$$v_h(S=0) \lesssim T$$

$\downarrow$



$\downarrow$

$$v_S \gtrsim v_h / \sin\theta_{hS}$$



$$l_w > R_{sph}$$

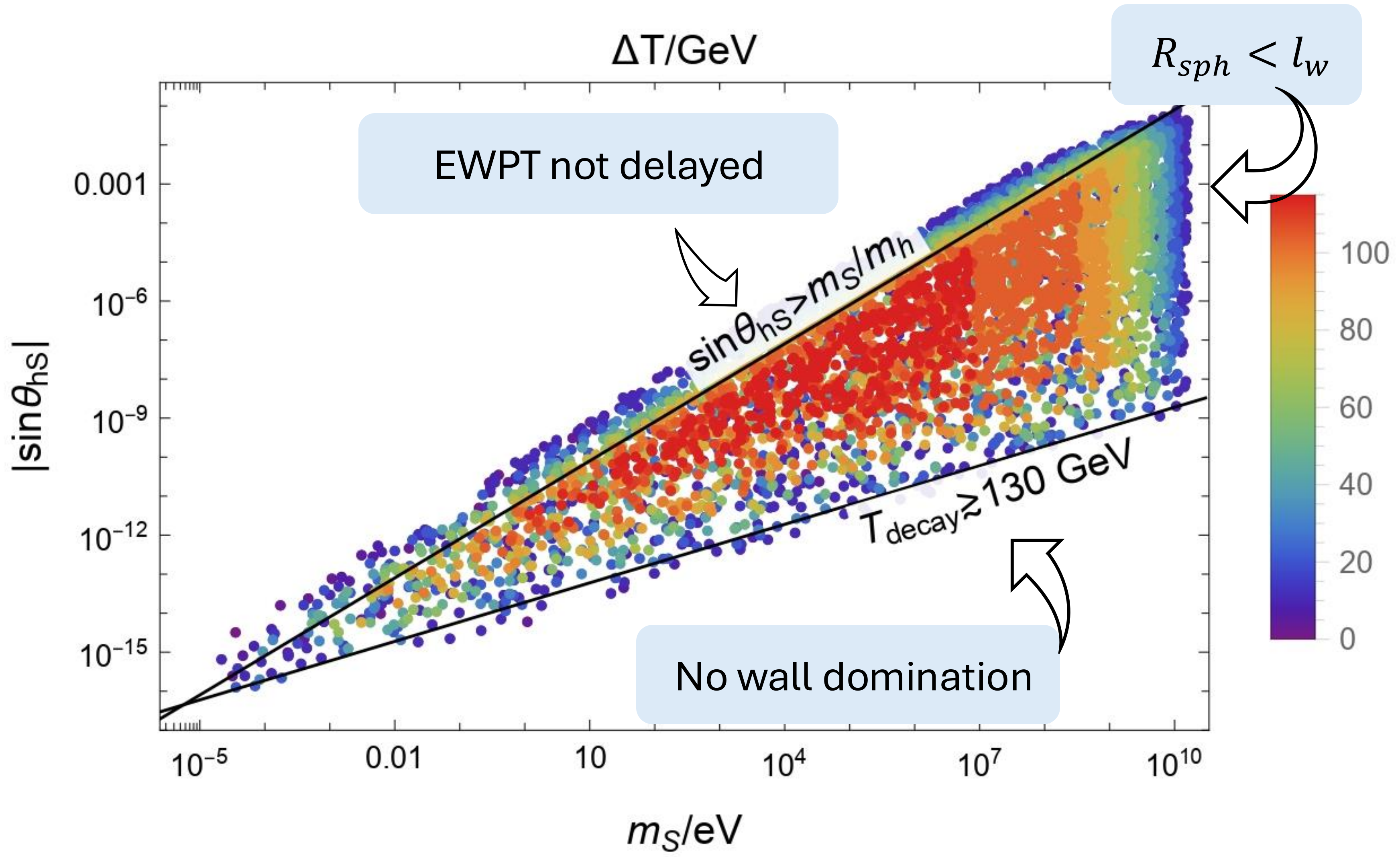
$\downarrow$

$$\frac{1}{m_S} \gtrsim \frac{1}{g^2 T}$$

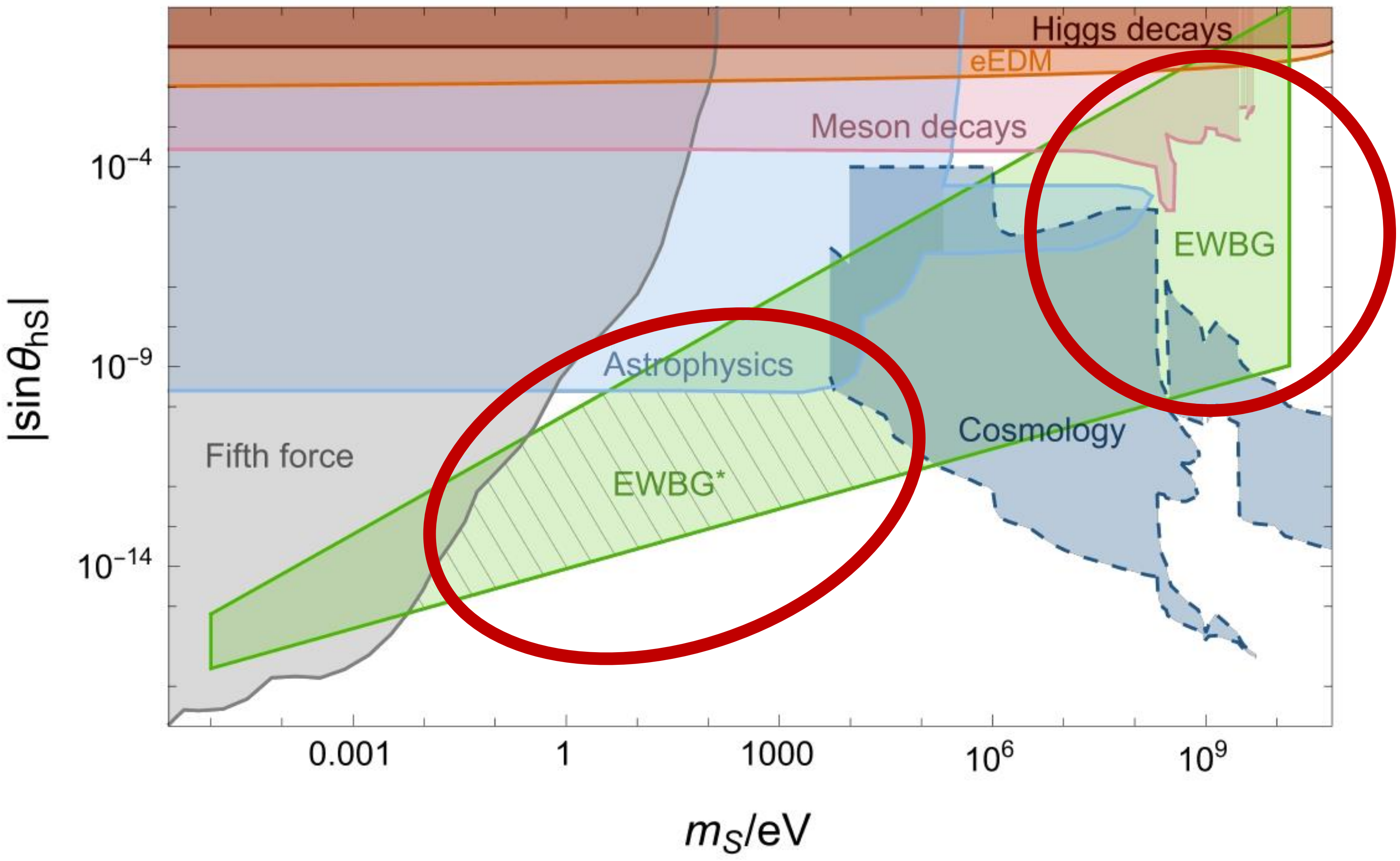
$\downarrow$

$$m_S \lesssim 30 \text{ GeV}$$

Numerical Results



Experimental bounds



Conclusions

Novel mechanism for EWBG in Singlet Extension:

✓ Minimal model, good analytical understanding

✓ Mass range: $10^{-2}\mathrm{eV} \lesssim m_S \lesssim 15\mathrm{GeV}$

✓ Rich phenomenology

Conclusions

Novel mechanism for EWBG in Singlet Extension:

✓ Minimal model, good analytical understanding

✓ Mass range: $10^{-2}\mathrm{eV} \lesssim m_S \lesssim 15\mathrm{GeV}$

✓ Rich phenomenology

Thank you for the attention :)

Minimal EWBG with Domain Walls-Backup Slides

arXiv:2412.10495

Numerical methods

Solve the system: $\begin{cases} h'' = \partial_h V(h,S) \\ S'' = \partial_S V(h,S) \end{cases}$ with $h(\pm\infty) = v_h, S(\pm\infty) = \mp v_S$

Full solution

- $V = V_0 + V_{CW} + V_T + V_{CT}$
- Solution via fictitious time-evolution
- Very slow and unstable

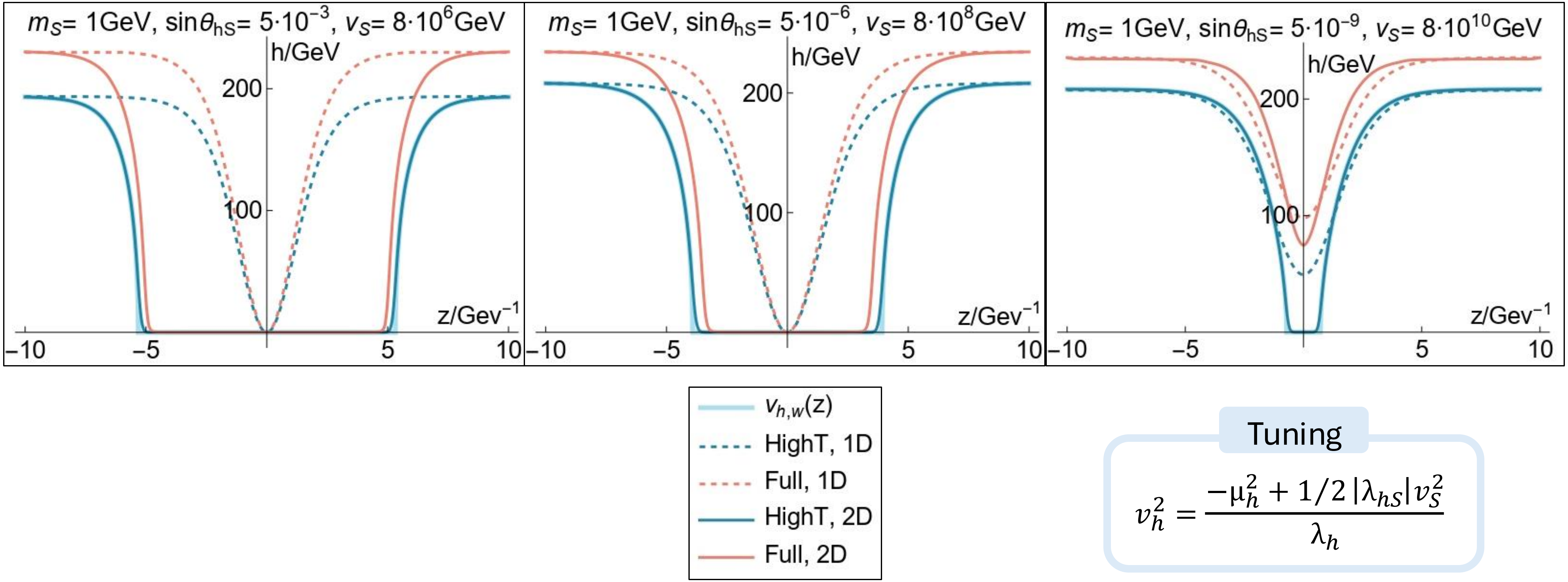
Numerical methods

Solve the system: $\begin{cases} h'' = \partial_h V(h,S) \\ S'' = \partial_S V(h,S) \end{cases}$ with $h(\pm\infty) = v_h, S(\pm\infty) = \mp v_S$

Approximate algorithm

- $V = V_0 + V_{T,\mathrm{high}}$
- Parabolic approximation $h(S) = \frac{v_h - h_0}{v_S^2}(S - v_S) + v_h$ → 1D, 1st order equation
- Bogomolny trick

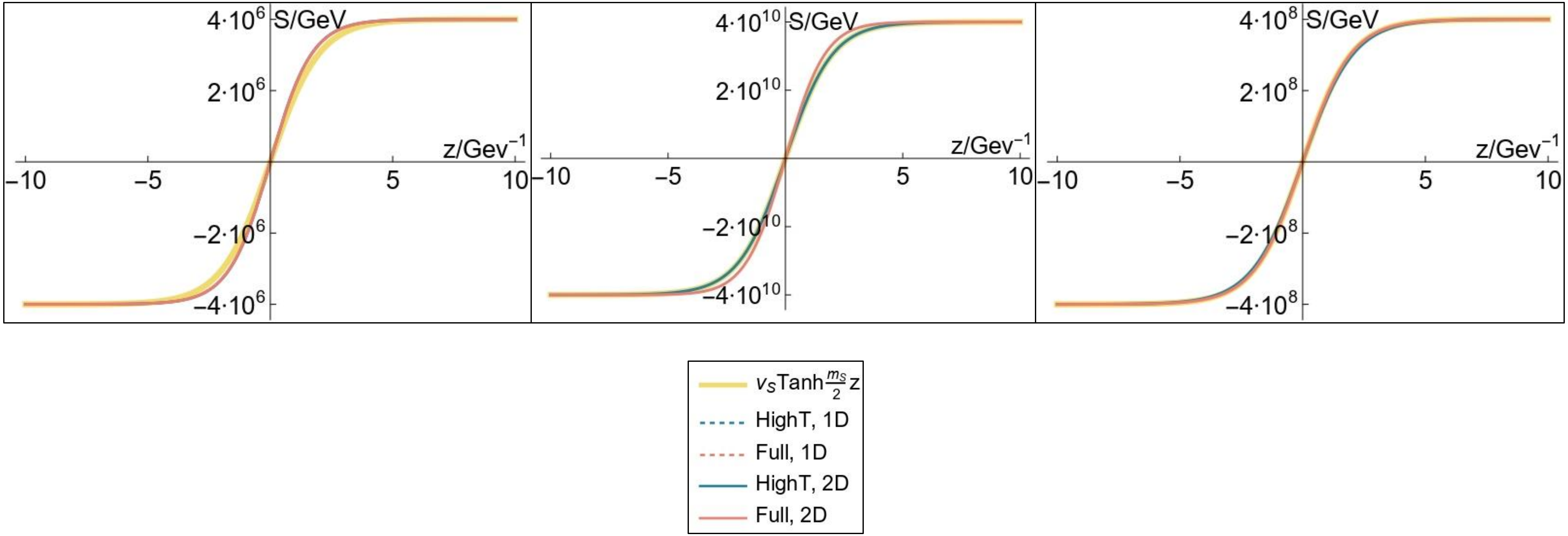
Numerical profiles – *h* field



Tuning

$$v_h^2 = \frac{-\mu_h^2 + 1/2\,|\lambda_{hS}|v_S^2}{\lambda_h}$$

Numerical profiles – S field

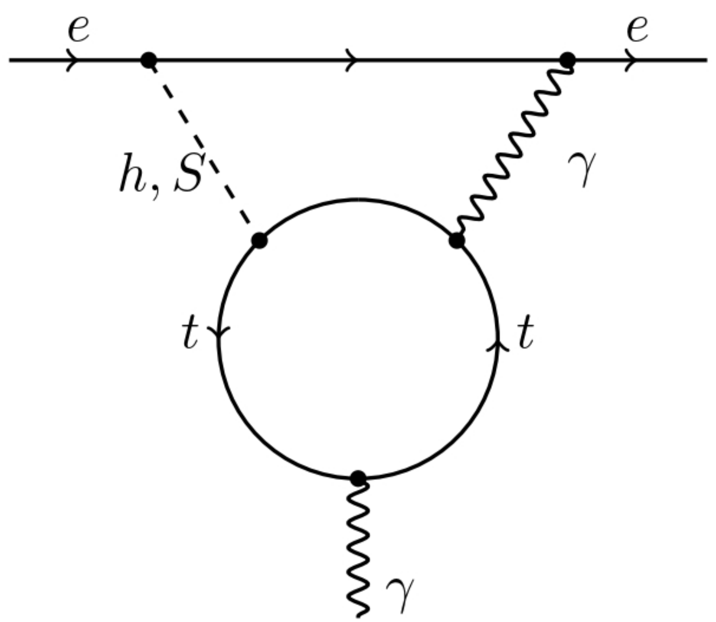


CPV & eEDM bound

- CPV term $\mathcal{L} \supset -\frac{y_t}{\sqrt{2}} \bar{t} t h \left(1 + i \frac{S^2}{f^2}\right) + h.c$

- Contribution from BarrZee diagram

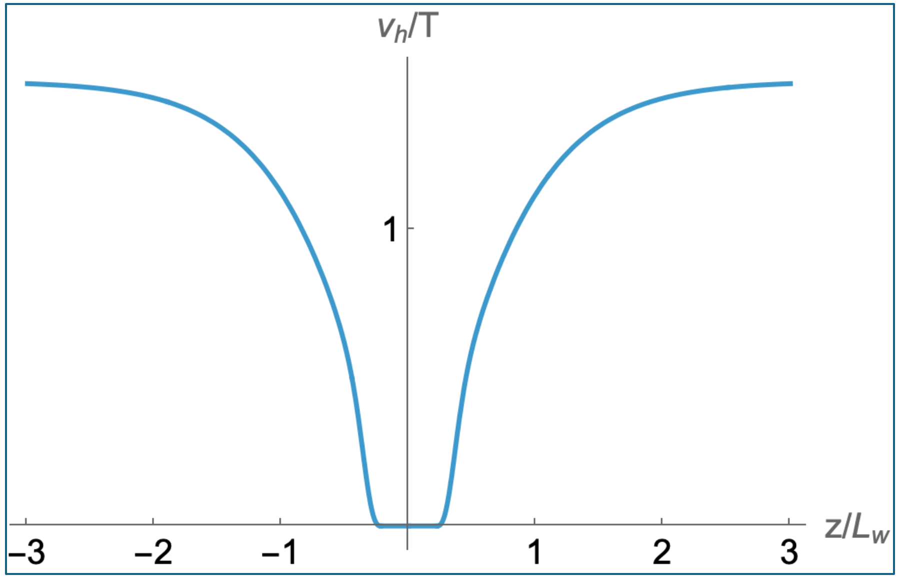
- Result for quadratic CPV:



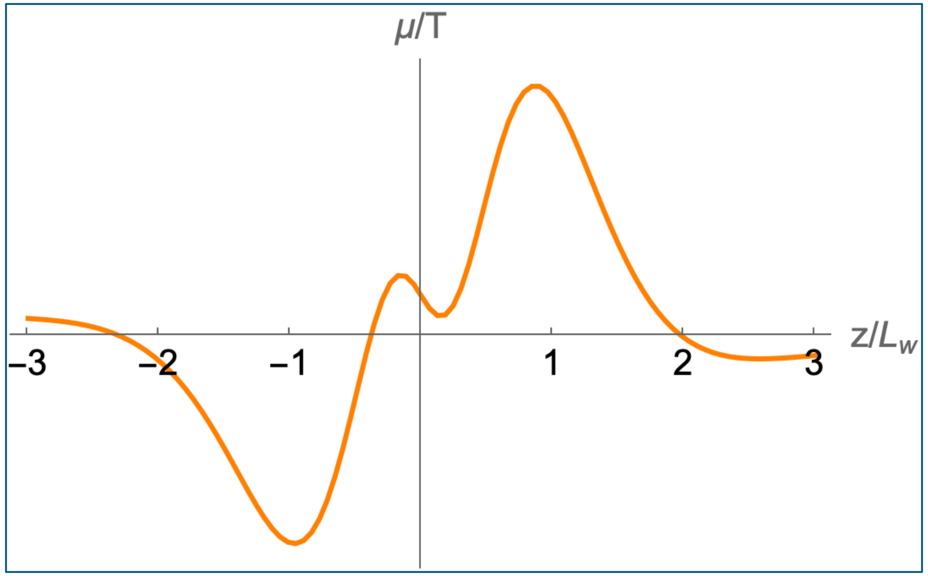
$$d_e = \frac{2e}{3\pi^2} \frac{\alpha G_F}{\sqrt{2}\pi} m_e \frac{v_S M}{f} \frac{v_S}{f} \frac{1}{1 + v_S^4/f^4} \sin\theta_{hS} \cos\theta_{hS} \left(-g(m_t/m_h) + g(m_t/m_S)\right)$$

On CP violation

Work in progress...



Higgs profile



μ_{tL}

EWBG not delayed

$$v_h(T) = v_h(T=0) - T^2\left(\frac{c_T/\lambda_h}{1-\lambda_{hS}^2/4\,\lambda_S\lambda_h} + \dots\right)$$

$$m_S^2 \approx 2\lambda_s v_S^2 - \sin^2\theta_{hS}\, m_h^2$$

$$m_S^2 \approx 2\lambda_S v_S^2\left(1-\frac{\lambda_{hS}^2}{4\lambda_h\lambda_S}\right)$$

$$\sin^2\theta_{hS} \gtrsim m_S^2/m_h^2$$

$$\left(1-\frac{\lambda_{hS}^2}{4\lambda_h\lambda_S}\right) \lesssim 1$$

EW restoration in core

$$v_h^2 = \frac{-\mu_h^2 - \lambda_{hS}/2\ v_S^2}{\lambda_h}$$

$$\Delta T \approx \Delta h \lesssim \frac{\lambda_{hS} v_S^2}{2\,\lambda_h}$$

Require

$$\Delta h^2 \approx v_h^2$$

Use

$$m_h^2 \approx 2\lambda_h v_h^2$$

$$\sin\theta_{hS} \approx \frac{\lambda_{hS} v_h v_S}{m_h^2}$$

$$v_S \gtrsim v_h / \sin\theta_{hS}$$

Domain wall problem

$$\frac{A_p}{V_p} = \frac{1}{\epsilon a(\eta)(\eta - \eta_w)} = \left(\epsilon H(T)\left(1 - \frac{T}{T_w}\right)\right)^{-1}$$

$$\sigma \approx m_S v_S^2$$

$$\rho_w = \sigma_w \frac{A_p}{V_p}$$

$$\frac{\rho_w}{\rho_r} < 1$$

$$m_S v_S^2 < 0.1\sqrt{g_*(T)}M_P T^2$$

Volume swept

Scaling regime

$$\frac{V_c}{A_c} \sim \epsilon(\eta - \eta_w)$$

Volume swept

$$\frac{\delta V_c}{V_c} = v_w \frac{A_c}{V_c} d\eta$$

Integrate

$$\frac{\delta V_c}{V_c} = \frac{v_w}{\epsilon} ln \frac{\eta_f - \eta_w}{\eta_i - \eta_w}$$

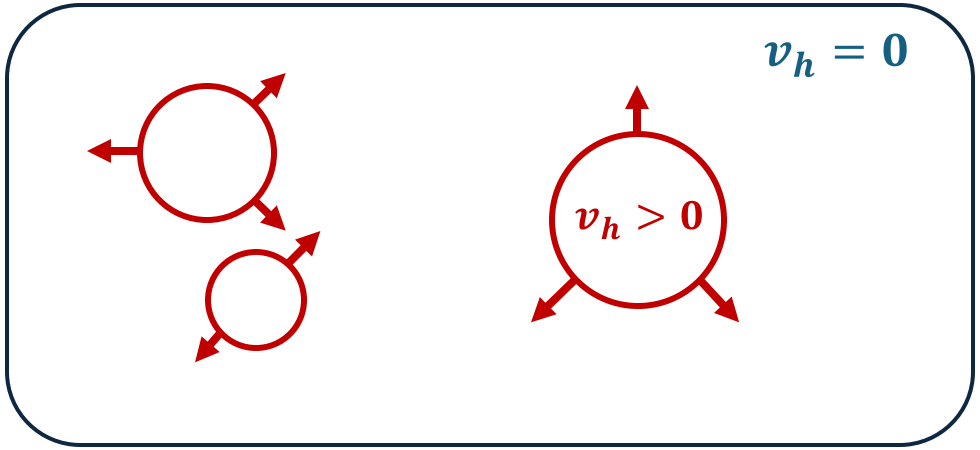
Function of *T*

$$\frac{\delta V_c}{V_c} = \frac{v_w}{\epsilon} ln \frac{T_i}{T_f} + \frac{v_w}{\epsilon} ln \frac{T_w - T_f}{T_w - T_i}$$

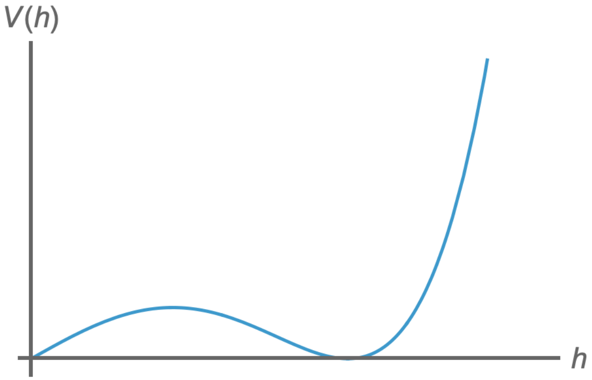
Standard singlet mechanism

$v_h = 0$

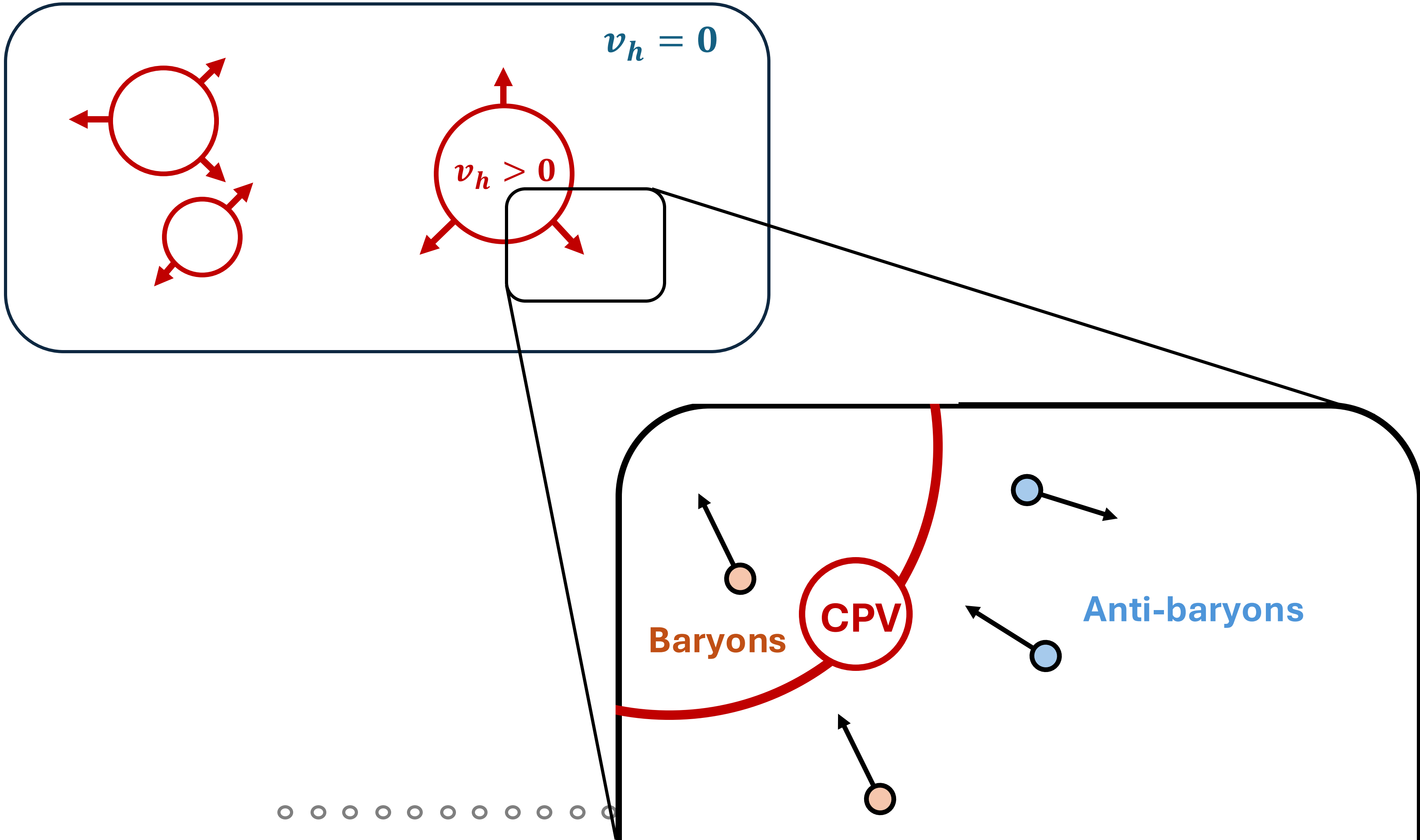
Standard singlet mechanism



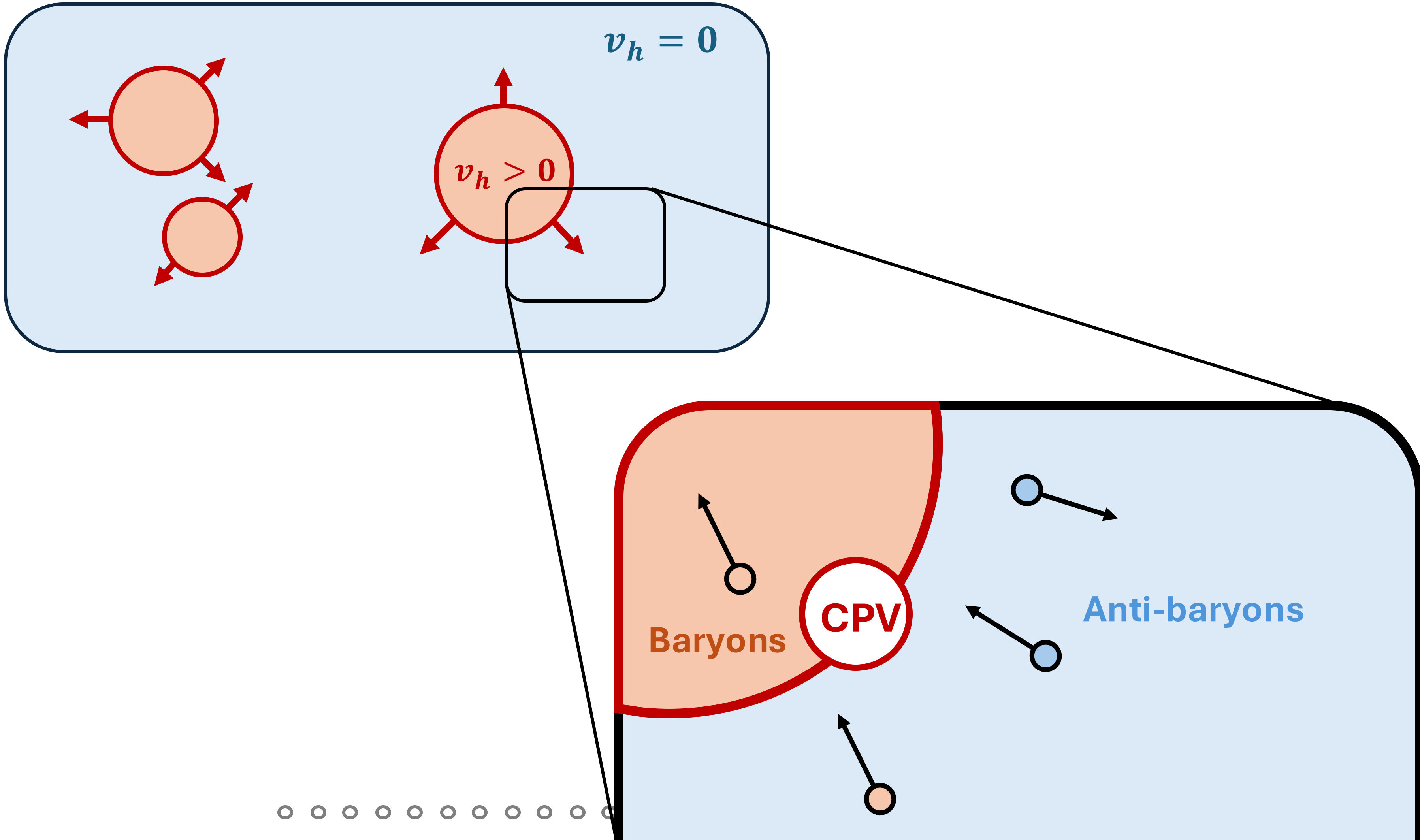
1st order EWPT



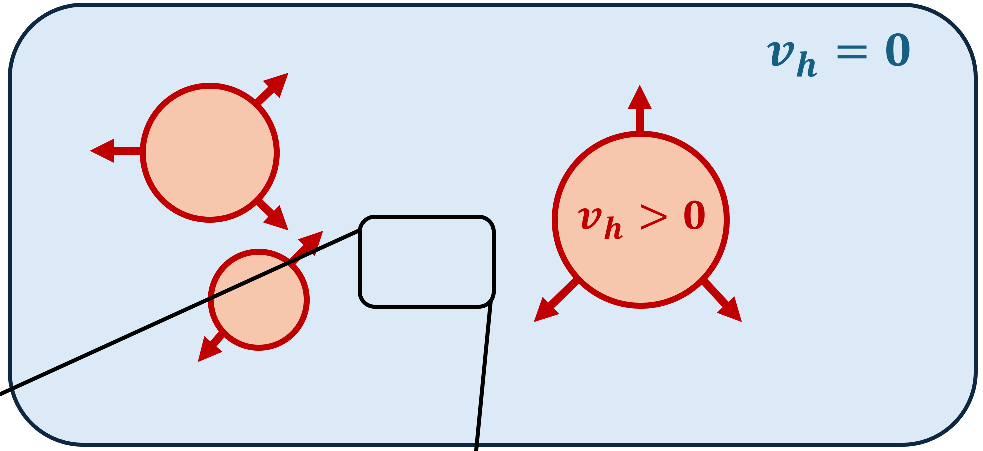
Standard singlet mechanism



Standard singlet mechanism



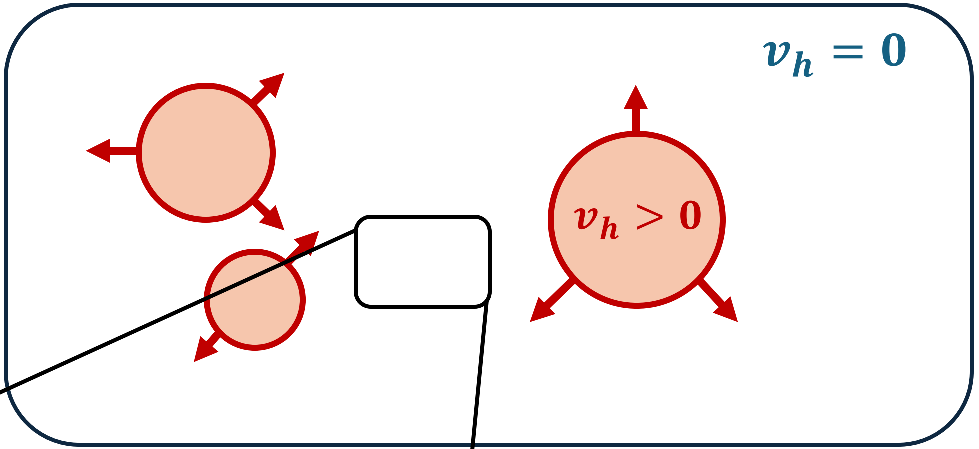
Standard singlet mechanism



EW sphaleron

- Active for $v_h/T \lesssim 1$
- Violates B
- Relaxes anti-baryon abundance

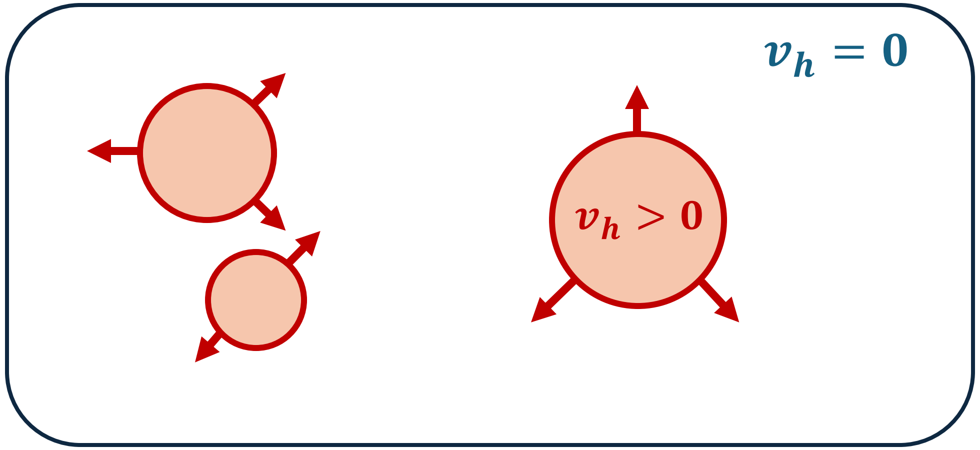
Standard singlet mechanism



EW sphaleron

- Active for
- Violates B
- Relaxes anti-baryon abundance

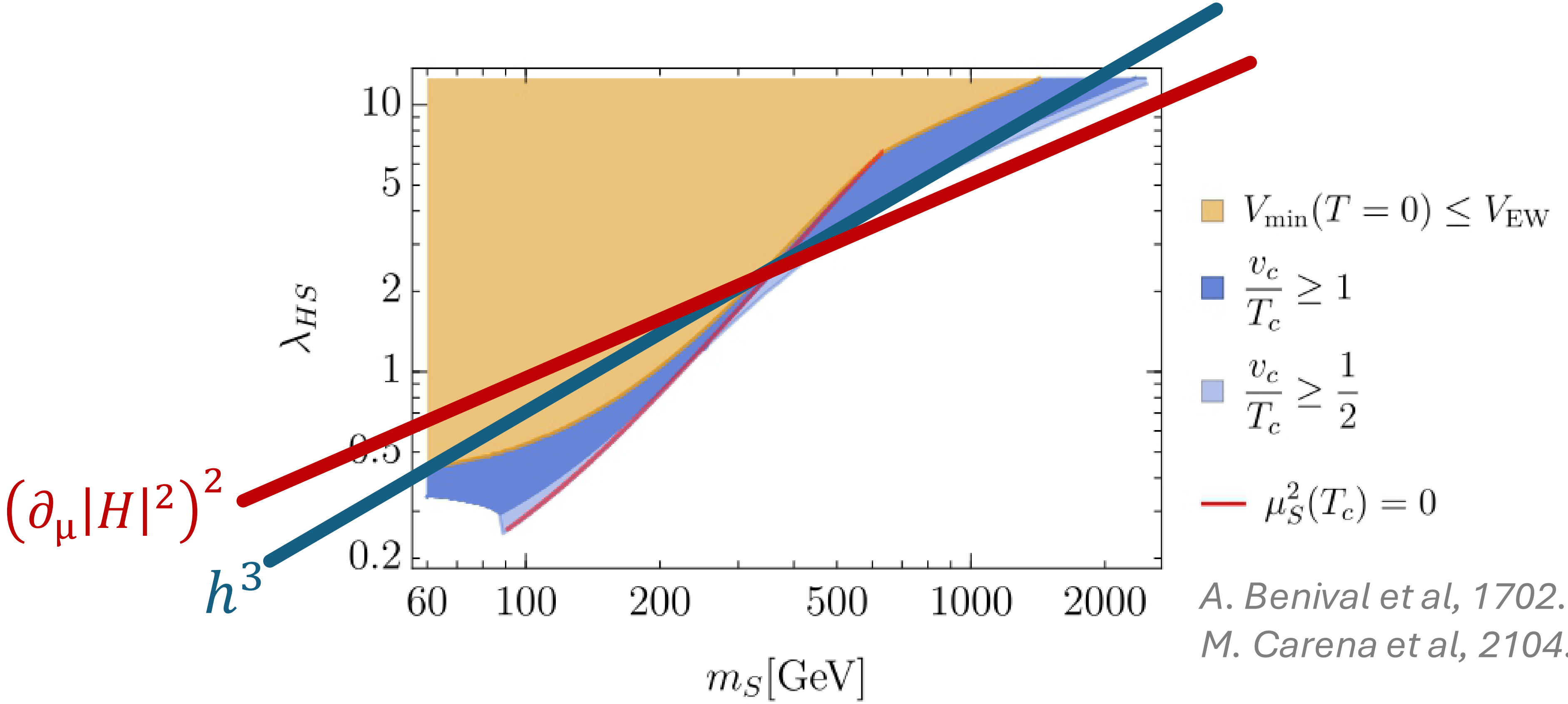
Standard singlet mechanism



Standard singlet mechanism

$$v_h > 0$$

Parameter space



A. Benival et al, 1702.06124
M. Carena et al, 2104.00638