

# Enabling Electroweak Baryogenesis through Dark Matter

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Based on:

M. Lewicki, T. Rindler-Daller and J. D. Wells, arXiv:1601.01681

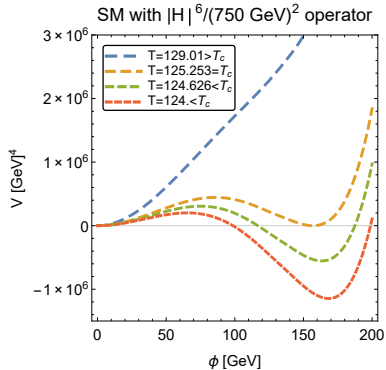
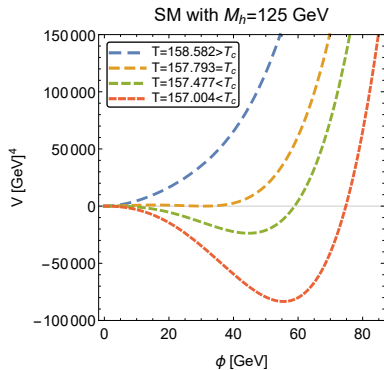


Generating Baryon asymmetry requires:

- C and CP violation
  - ✓ present in SM quark sector  
(needs enhancement... not a part of this talk though)
- Departure from thermal equilibrium
  - 1 order electroweak phase transition
- Baryon number violation
  - ✓  $SU(2)$  sphalerons present in SM

A. D. Sakharov 67'

# Electroweak phase transition



If  $M_h < 85 \text{ GeV}$  in SM we would have a **1** order phase transition

Kajantie, Laine, Rummukainen, Shaposhnikov 97'

# $|H|^6$ effective theory

- We modify the scalar potential

$$V(\phi)_{T=0}^{\text{tree}} = -\frac{m^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{1}{8}\frac{\phi^6}{\Lambda^2}.$$

keeping  $W$ ,  $Z$  and Higgs masses unchanged:

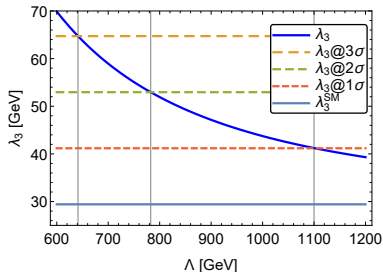
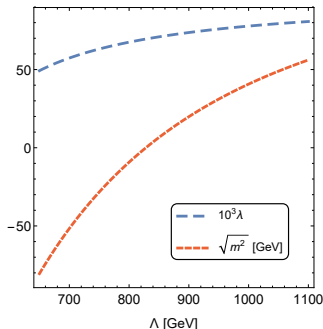
$$V'_{T=0}{}^{1-loop}(\phi)|_{\phi=v_0} = 0$$

$$V''_{T=0}{}^{1-loop}(\phi)|_{\phi=v_0} = m_h^2$$

- Only triple Higgs coupling changes

$$\lambda_3 = \frac{1}{6} \frac{d^3 V_{T=0}^{1-loop}(\phi)}{d\phi^3} \Big|_{\phi=v_0}$$

however its experimental accuracy @ HL-LHC is only 40%



# Phase transition dynamics

**Scalar sphaleron:** static field configuration passing the barrier (excited through thermal fluctuations)

- $\mathcal{O}(3)$  symmetric scalar bubbles

$$\frac{d^2\phi}{dr^2} + \frac{2}{r} \frac{d\phi}{dr} - \frac{\partial V(\phi, T)}{\partial \phi} = 0,$$

$$\phi(r \rightarrow \infty) = 0 \quad \text{and} \quad \dot{\phi}(r=0) = 0.$$

- action

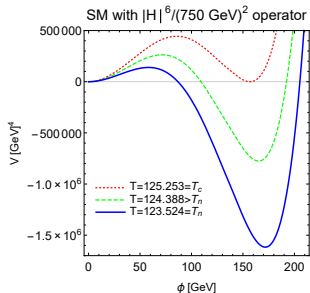
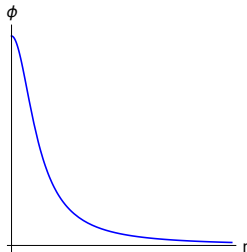
$$S_3(T) = 4\pi \int dr r^2 \left[ \frac{1}{2} \left( \frac{d\phi}{dr} \right)^2 + V(\phi, T) \right].$$

- transition probability

$$\frac{\Gamma}{\mathcal{V}} \approx T^4 \exp\left(-\frac{S_3(T)}{T}\right),$$

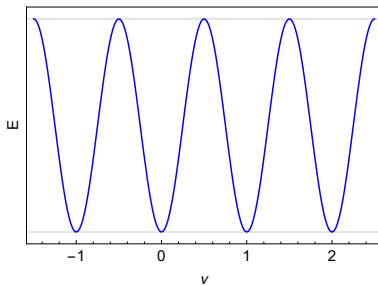
- phase transition occurs when

$$\int_{T_n}^{\infty} \Gamma dT \approx \mathcal{O}(1)$$



# SU(2) vacuum structure

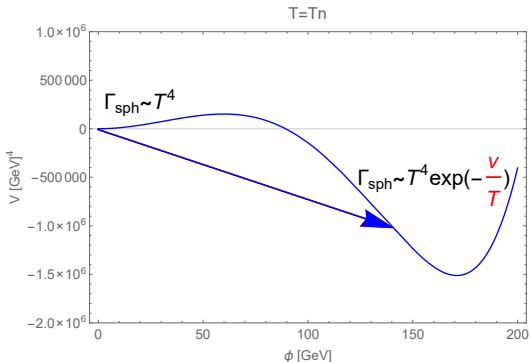
- vacuum:  $F^{\mu\nu} = 0 \rightarrow A^0 = 0, A^i = (i/g)(\partial_i U)U^{-1}$   
 $U(x)$  is a time independent unitary matrix
- winding number  $\nu \in \mathbb{Z}$  characterizes classes of  $U$  not connected via an infinitesimal transformation



- transitions between  $SU(2)$  vacua break Barion number

$$\Delta B = \Delta L = -3$$

# SU(2) sphalerons



- In thermal equilibrium  $SU(2)$  sphalerons wash out the baryon asymmetry.  
→ They **have to be decoupled after the phase transition**
- This leads to the famous bound:

$$\frac{v}{T} \gtrsim 1$$

# Cosmology modification (Experimental bound)

- New energy density component  $\rho_s$

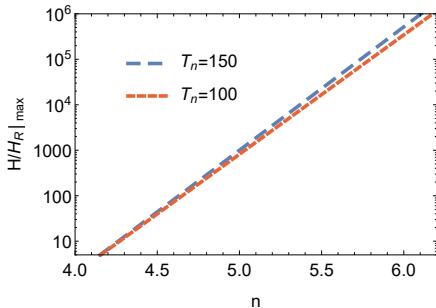
$$H^2 = \frac{8\pi}{3M_p^2} \left( \frac{\rho_R}{a^4} + \frac{\rho_s}{a^n} \right)$$

- At BBN ( $T_{\text{BBN}} = 1 \text{ MeV}$ ) from experiment we have  $N_{\nu\text{eff}} = 3.28$
- SM radiation  $N_\nu^{\text{SM}} = 3.04$

$$\left. \frac{H}{H_R} \right|_{\text{BBN}} = \sqrt{1 + \frac{7}{43} \Delta N_{\nu\text{eff}}} = 1.0187$$

- moving to earlier times (EWSB)

$$\left. \frac{H}{H_R} \right|_{\text{max}} = \sqrt{\left( \left. \frac{H}{H_R} \right|_{\text{BBN}} \right)^2 - 1} \left( \frac{g_{*,\text{BBN}}}{g_*} \right)^{\frac{1-2n}{4}} \left( \frac{T_n}{T_{\text{BBN}}} \right)^{\frac{n-4}{2}}$$





# Cosmology modification - Phase transition

Temperature of the phase transition:

$$\int_{T_n}^{\infty} \Gamma dT = \mathcal{O}(1).$$

Radiation domination ( $H = H_R$ )

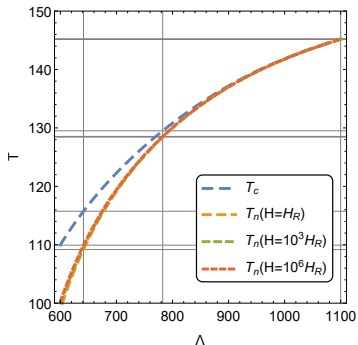
$$H_R^2 = \frac{8\pi}{3M_p^2} \frac{\rho_R}{a^4}$$

$$\int_{T_n}^{\infty} \frac{dT}{T} \left( \frac{2\zeta M_p}{T} \right)^4 \exp\left(-\frac{S_3(T)}{T}\right).$$

New component domination ( $H \gg H_R$ )

$$H^2 \approx \frac{8\pi}{3M_p^2} \frac{\rho_S}{a^n}.$$

$$\int_{T_n}^{\infty} \frac{dT}{T} \frac{M_p^4 2^{\frac{5n-6}{2}} \left(\frac{3}{\pi}\right)^{\frac{4-n}{2}} \xi^n \rho_R^{\frac{n}{2}}}{(n-2)^3 T^{2n-4} \rho_S^2} \exp\left(-\frac{S_3(T)}{T}\right)$$



# Cosmology modification - $SU(2)$ sphaleron decoupling

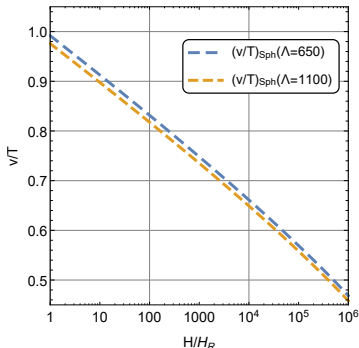
- $SU(2)$  sphaleron rate

$$\Gamma_{\text{sph}} = 2.8 \times 10^5 T^4 \kappa \frac{g}{4\pi} \left(\frac{v}{T}\right)^7 \exp\left(-\frac{4\pi}{g} \frac{v}{T} E_0\right)$$

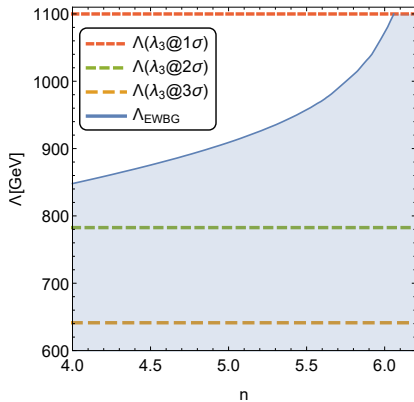
Carson, McLerran, Wang 90'

- Phase transition strength  $\frac{v}{T}$  from a simple decoupling criterion  $\Gamma \leq H$

$$\frac{v}{T} \geq \frac{g}{4\pi E_0} \ln\left(\frac{2.8 \times 10^5 T^4 \kappa \frac{g}{4\pi} \left(\frac{v}{T}\right)^7}{H}\right),$$



# Cosmology modification-resulting bounds



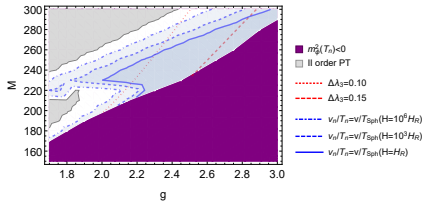
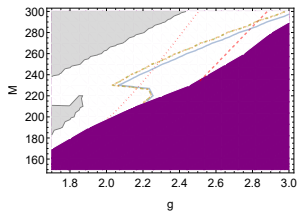
- For  $n \approx 6$  the sphaleron bound can be completely circumvented and only first order phase transition is required
- The source of cosmological modification with  $n = 6$  can be identified with Scalar Field Dark Matter (Rindler-Daller 13')
- Modification of cosmological history can significantly lower requirements for any particle model realising EWBG

Bounds we can put on explicit models of new physics

- new neutral scalar  $\phi$

$$V_\phi = m_S^2 |S|^2 + g |S|^2 |H|^2 + \eta |S|^4$$

$$M = m_S^2 + \frac{g}{2} v^2$$



# Electroweak phase transition-Numerical calculations

- Our EOM

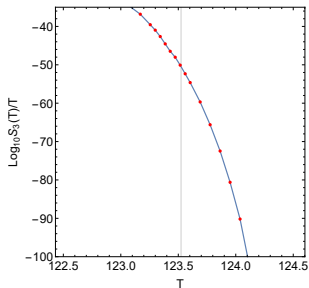
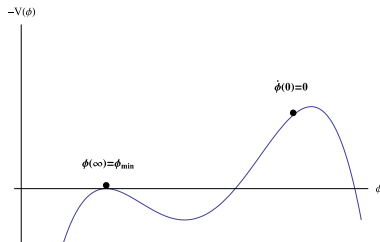
$$\ddot{\phi} + \frac{2}{r}\dot{\phi} = \frac{\partial V(\phi)}{\partial \phi},$$

is an equation of motion of a particle in potential  $-V(\phi)$  with a "time" dependent friction  $\frac{2}{r}\dot{\phi}$ .

We used a simple Overshot/Undershot algorithm

- once we know  $S_3(T)/T$  we can solve  $\int_{T_n}^{\infty} \Gamma dT \approx \mathcal{O}(1)$ :

$$\int_{T_n}^{\infty} \frac{dT}{T} \left( \frac{2\zeta M_p}{T} \right)^4 \exp\left(-\frac{S_3(T)}{T}\right) = 1$$



# $SU(2)$ Sphaleron energy

- starting with the ansatz for the solution  $\xi = gvr$

$$W_i^a \sigma^a dx^i = -\frac{2i}{g} f(\xi) dU U^{-1}, \quad \phi = \frac{v}{\sqrt{2}} h(\xi) U \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad U = \frac{1}{r} \begin{pmatrix} z & x + iy \\ x - iy & z \end{pmatrix}$$

Klinkhamer, Manton 84'

- We compute the  $SU(2)$  sphaleron action  $E_{\text{sph}} = \frac{4\pi v}{g} E_0$

$$\begin{aligned} E_0 &= \frac{g}{4\pi v} \int \left( -\frac{1}{4} F^{a\mu\nu} F_{\mu\nu}^a + -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} + (D\phi)^\dagger (D\phi) + V(\phi) \right) d^3x \\ &= \int_0^\infty d\xi \left( 4f'^2 + \frac{8}{\xi^2} f^2(1-f)^2 + \frac{1}{2} \xi^2 h'^2 + h^2(1-f)^2 + \frac{\lambda}{4g^2} \xi^2 (h^2-1)^2 + \frac{v^2}{8g^2\Lambda^2} \xi^2 (h^2-1)^3 \right) \end{aligned}$$

- Varying this action, we find the field equations for the functions  $f$  and  $h$ ,

$$\begin{aligned} \xi^2 \frac{d^2 f}{d\xi^2} &= 2f(1-f)(1-2f) - \frac{\xi^2}{4} h^2(1-f) \\ \frac{d}{d\xi} \left[ \xi^2 \frac{dh}{d\xi} \right] &= 2h(1-f)^2 + \frac{\lambda}{g^2} \xi^2 (h^2-1)h + \frac{3}{4} \frac{v^2}{g^2\Lambda^2} \xi^2 h(h^2-1)^2. \end{aligned}$$

These are subject to the boundary conditions  $f(0) = h(0) = 0$  and  $f(\infty) = h(\infty) = 1$ .

# $SU(2)$ Sphaleron energy

- we begin with asymptotic solutions

$\xi \rightarrow 0$	$\xi \rightarrow \infty$
$f \approx \xi^2/a_0^2$	$f \approx 1 - a_\infty \exp(-\xi/2)$
$h \approx \xi/b_0$	$h \approx 1 - (b_\infty/\xi) \exp(-\sqrt{\frac{2\lambda}{g^2}} \xi)$

- using Markov chain method we find the full solutions and  $E_0$  as a function of  $\Lambda$

