Enabling Electroweak Baryogenesis through Dark Matter

Marek Lewicki

Institute of Theoretical Physics, Faculty of Physics, University of Warsaw

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Based on:

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

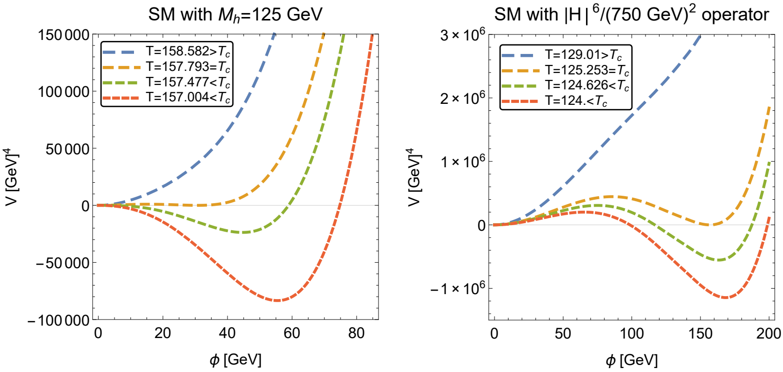
Baryogenesis

Generating Baryon asymmetry requires:

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

A. D. Sakharov 67'

Baryogenesis



If $M_h < 85 GeV$ in SM we would have a I order phase transition

Kajantie, Laine, Rummukainen, Shaposhnikov 97'

$|H|^6$ effective theory

- We modify the scalar potential

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

keeping W, Z and Higgs masses unchanged:

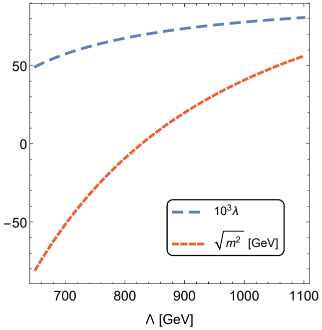
$$V'^{1-loop}_{T=0}(\phi)|_{\phi=v_0} = 0$$

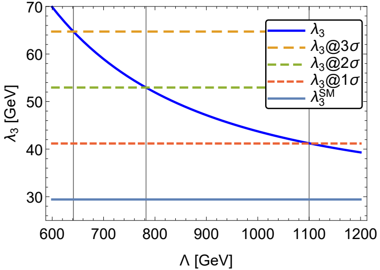
$$V''^{1-loop}_{T=0}(\phi)|_{\phi=v_0} = m_h^2$$

- Only triple Higgs coupling changes

$$\lambda_3 = \frac{1}{6}\left.\frac{d^3V^{1-loop}_{T=0}(\phi)}{d\phi^3}\right|_{\phi=v_0}$$

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





Electroweak phase transition

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

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

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

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

- action

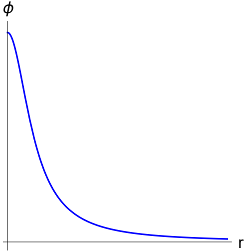
$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V(\phi, T) \right].$$

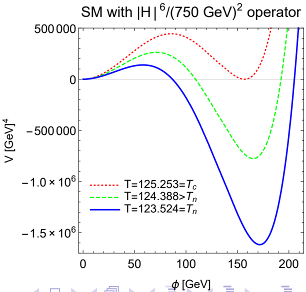
- transition probability

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

- phase transition occurs when

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



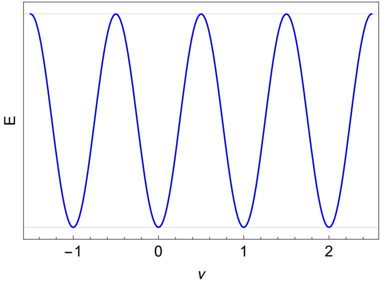


Linde 81' 83'

SU(2) vacuum structure

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

$$\nu = -\frac{1}{24\pi^2} \int \mathrm{tr}(\epsilon^{ijk}(\partial_i \mathrm{U})\mathrm{U}^{-1}(\partial_j \mathrm{U})\mathrm{U}^{-1}(\partial_k \mathrm{U})\mathrm{U}^{-1}) d^3x$$



- tunneling between $SU(2)$ vacua

$$\int \mathrm{tr}(\mathbf{F}\tilde{\mathbf{F}}) d^4x = -\frac{16\pi^2}{g^2}(\nu_1 - \nu_0) \quad \rightarrow \quad S_E = \frac{1}{2}\int \mathrm{tr}(\mathbf{F}^2) d^4x \geq \frac{8\pi^2}{g^2}|\nu_1 - \nu_0|$$

SU(2) sphalerons

- $SU(2)$ sphaleron rate ($T \neq 0$)

$$\Gamma_{\rm sph} \propto exp\left(-\frac{E_{\rm sph}}{T}\right), \quad E_{\rm sph} \propto \frac{S_E}{R}, \quad R^{-1} \approx M_W(T) \propto v$$

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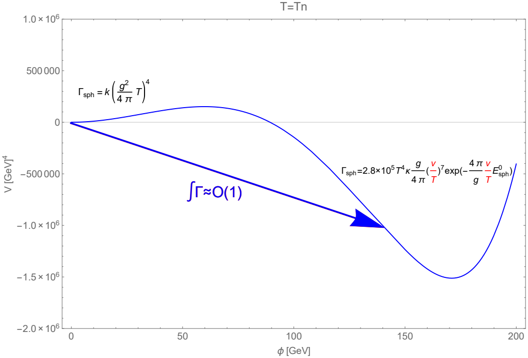
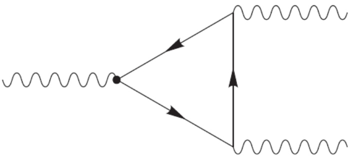


Carson, McLerran, Wang 90'

Sphaleron bound

- chiral anomaly

$$\partial_\mu J_L^\mu = -\frac{g^2}{16\pi^2}\mathrm{tr}(\mathbf{F}\tilde{\mathbf{F}})$$



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

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

Shaposhnikov 85' 86' 87'

Cosmology modification (Experimental bound)

- New energy density component ρ_s

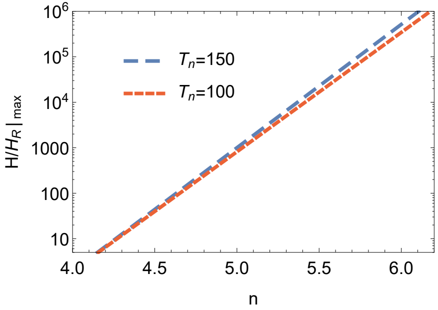
$$H^2 = \frac{8\pi}{3M_p^2}\left(\frac{\rho_R}{a^4} + \frac{\rho_S}{a^n}\right)$$

- At BBN ($T_{\rm BBN} = 1$ MeV) from experiment we have $N_{\nu_{\rm eff}} = 3.28$
- SM radiation $N_\nu^{\rm SM} = 3.046$

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

- moving to earlier times (EWSB)

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



Cosmology modification - Phase transition

Temperature of the phase transition:

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

Radiation domination ($H = H_R$)

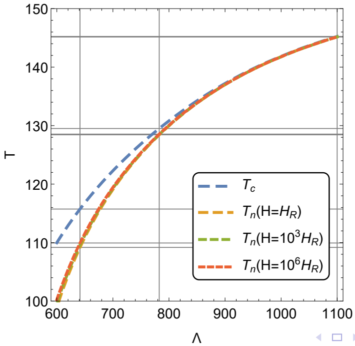
$$H_R^2 = \frac{8\pi}{3M_p^2}\frac{\rho_R}{a^4}$$

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

New component domination ($H >> H_R$)

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

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



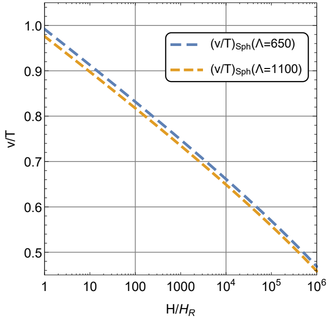
Cosmology modification - $SU(2)$ sphaleron decoupling

- $SU(2)$ sphaleron rate

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

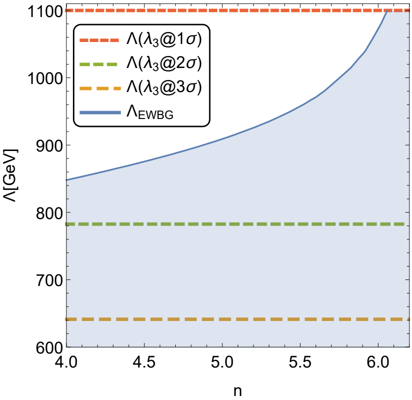
- Phase transition strength $\frac{v}{T}$ from a simple decoupling criterion $\Gamma \leq H$

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



Joyce 96'

Cosmology modification-resulting bounds



Conclusions

- Modification of cosmological history can significantly lower requirements of any model realising EWBG
- **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')

Next Step

Bounds we can put on explicit models of new physics

- new neutral scalar ϕ

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

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