Enabling Electroweak Baryogenesis through Dark Matter

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Based on:

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

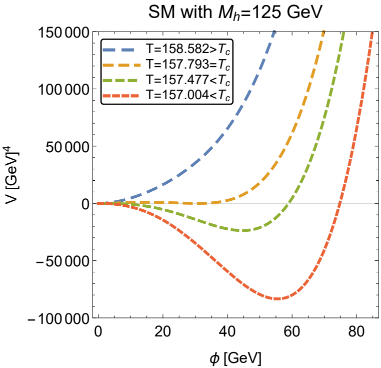
Baryogenesis

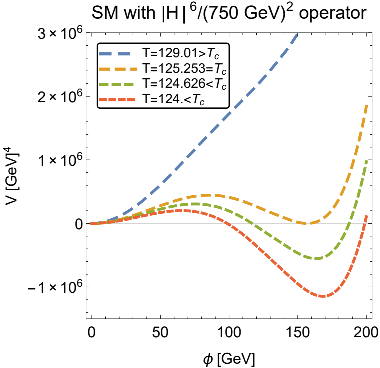
Generating Baryon asymmetry requires:

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

A. D. Sakharov 67'

Electroweak phase transition





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

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

keeping W, Z and Higgs masses unchanged:

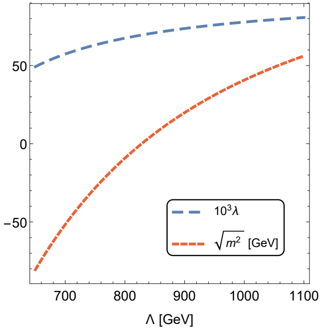
$$V'^{1-loop}_{T=0}(\phi)|_{\phi=v_0} = 0$$

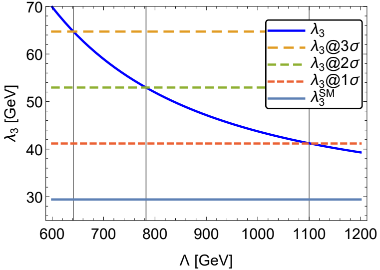
$$V''^{1-loop}_{T=0}(\phi)|_{\phi=v_0} = m_h^2$$

- Only triple Higgs coupling changes

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

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

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

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

- action

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

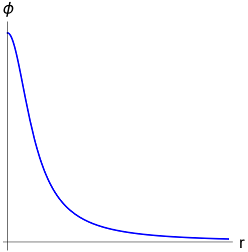
- transition probability

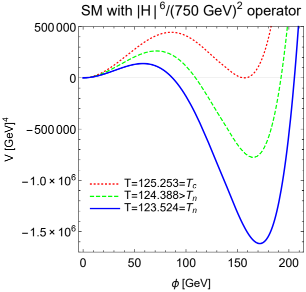
$$\frac{\Gamma}{\mathcal{V}} \approx T^4 \exp\left(-\frac{S_3(T)}{T}\right),$$

- phase transition occurs when

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

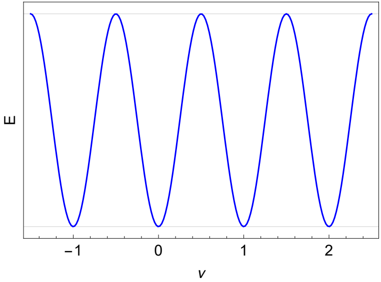
Linde 81' 83'





SU(2) vacuum structure

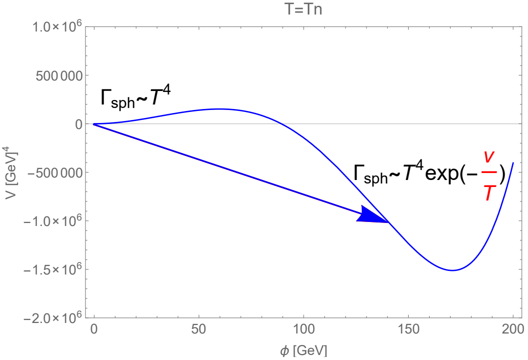
- vacuum: $F^{\mu\nu} = 0 \quad \rightarrow \quad \mathrm{A}^0 = 0,\ \mathrm{A}^i = (i/g)(\partial_i \mathrm{U})\mathrm{U}^{-1}$
  $\mathrm{U}(x)$ is a time independent unitary matrix
- winding number $\nu \in \mathbb{Z}$ characterizes classes of U not connected via an infinitesimal transformation



- 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.
  $\rightarrow$They have to be decoupled after the phase transition
- This leads to the famous bound:

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

Shaposhnikov 85' 86' 87'

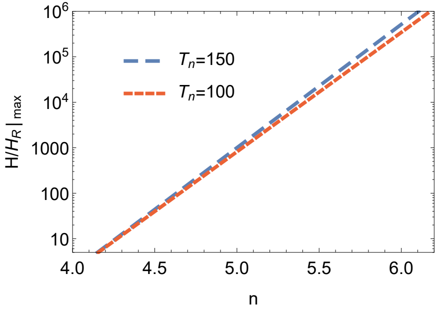
Cosmology modification (Experimental bound)

- 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 $N_\nu^{\rm SM} = 3.04$

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



- 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 ($H = H_R$)

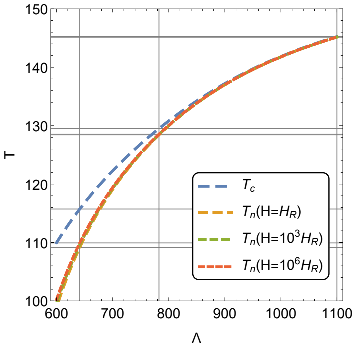
$$H_R^2 = \frac{8\pi}{3M_p^2}\frac{\rho_R}{a^4}$$

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

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

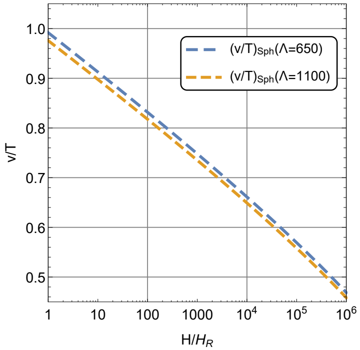
- $SU(2)$ sphaleron rate

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

Carson, McLerran, Wang 90'

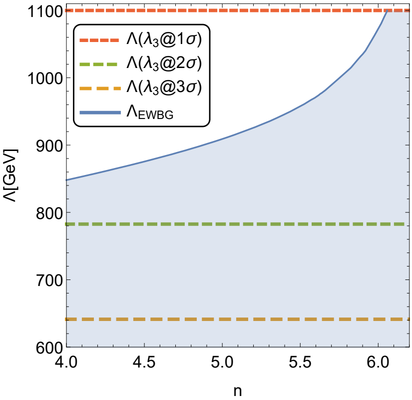
- Phase transition strength $\frac{v}{T}$ from a simple decoupling criterion $\Gamma \leq H$

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



Joyce 96'

Cosmology modification-resulting bounds



Conclusions

- 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

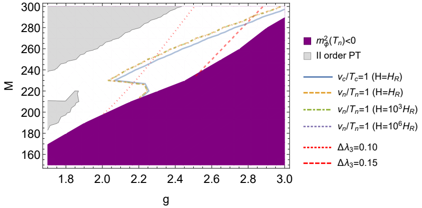
Next Step

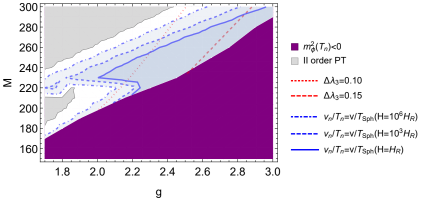
Bounds we can put on explicit models of new physics

- new neutral scalar ϕ

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

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



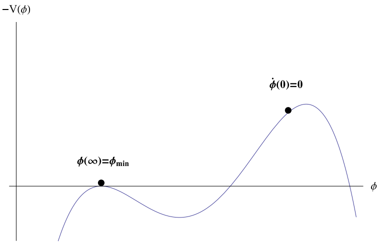


Electroweak phase transition-Numerical calculations

- Our EOM

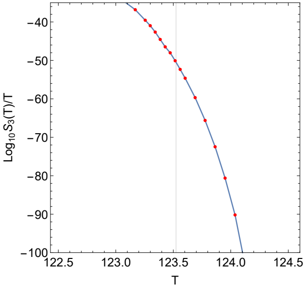
$$\ddot{\phi} + \frac{2}{r}\dot{\phi} = \frac{\partial V(\phi)}{\partial \phi},$$

  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 $\xi = gvr$

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

Klinkhamer, Manton 84'

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

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

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

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

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

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

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