

Gravitational wave, collider and dark matter signals of a singlet scalar electroweak baryogenesis

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Based on:

A. Beniwal, M. Lewicki, J. D. Wells, M. J. White and A. G. Williams
arXiv:1702.06124

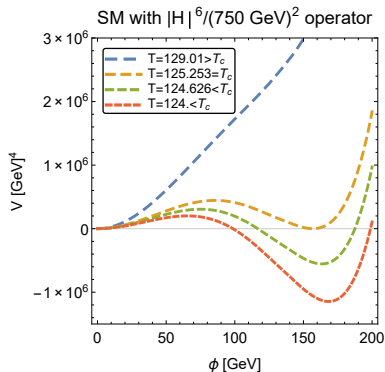
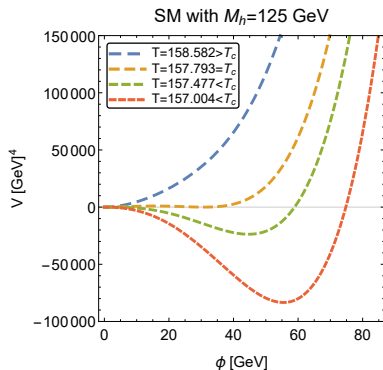
- Baryogenesis
- Singlet scalar model
- Phase transition dynamics
- Experimental probes
 - Collider searches
 - Gravitational Wave signals
 - Dark Matter and direct detection
- Conclusions

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
 - 1 order phase transition \rightarrow BSM needed

A. D. Sakharov 67'

Baryogenesis

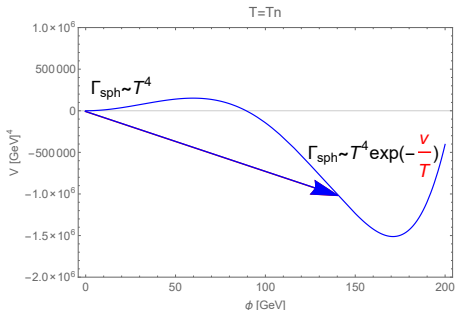


If $M_h < 85 \text{ GeV}$ in SM we would have a **1st order phase transition**

Kajantie, Laine, Rummukainen, Shaposhnikov 97'

Baryon number violation

- $SU(2)$ sphalerons violate baryon number



- 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:

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

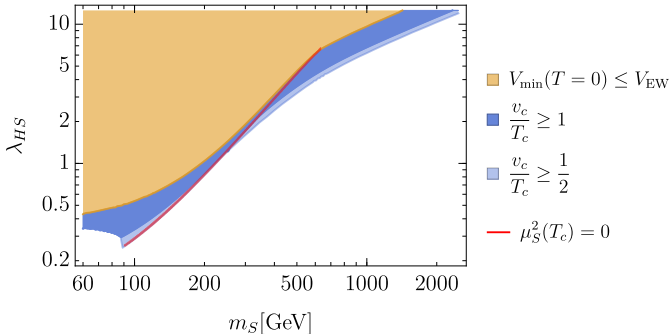
Singlet Scalar

- We add an additional singlet scalar to SM

$$V_{\text{tree}}(h, S) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4.$$

- New scalar physical mass

$$m_S^2 = \mu_S^2 + \lambda_{HS} v_0^2$$



Electroweak phase transition

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

- transition probability

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

- $\mathcal{O}(3)$ symmetric action

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

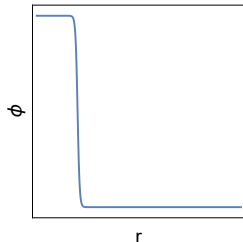
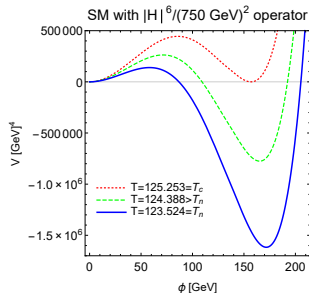
- EOM \rightarrow bubble profile

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

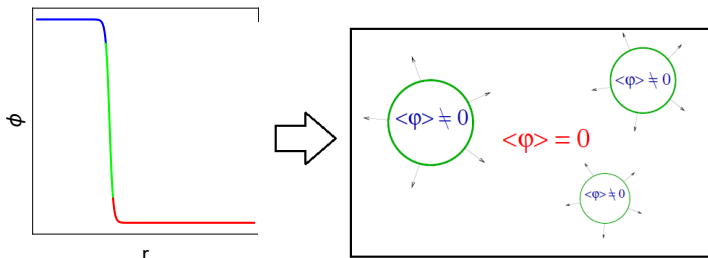
$$\phi(r \rightarrow \infty) = 0 \quad \text{and} \quad \dot{\phi}(r=0) = 0.$$

- phase transition occurs when

$$\int_{T_*}^{\infty} \frac{V}{H} \Gamma \frac{dT}{T} \approx \mathcal{O}(1)$$

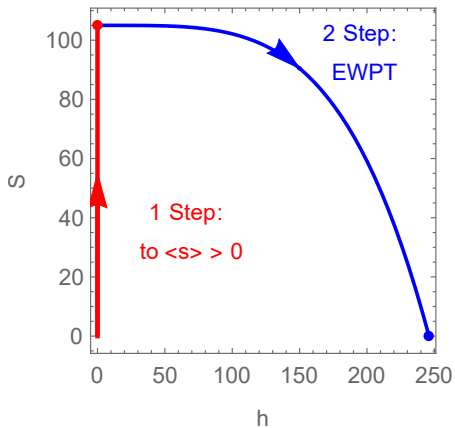


Electroweak phase transition



Morrissey 12'

Two step phase transition



Two step phase transition

Transition from $\langle S \rangle > 0, \langle h \rangle = 0$ vacuum to EW vacuum ($\langle S \rangle = 0, \langle h \rangle = v_0$)

- $\mathcal{O}(3)$ symmetric action for 2 fields

$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2} \left(\frac{dh}{dr} \right)^2 + \frac{1}{2} \left(\frac{dS}{dr} \right)^2 + V(h, S, T) \right]$$

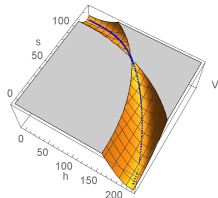
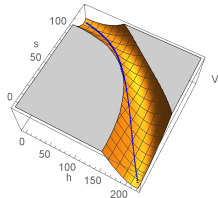
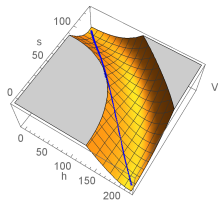
- EOMs in terms of path $\vec{\Phi}(t) = (h(t), S(t))$

$$\frac{d\vec{\Phi}}{dt} \frac{d^2 t}{dr^2} + \frac{d^2 \vec{\Phi}}{dt^2} \left(\frac{dt}{dr} \right)^2 + \frac{2}{r} \frac{d\vec{\Phi}}{dt} \frac{dt}{dr} = \nabla V.$$

- EOMs along the path and in perpendicular direction (assuming $\left| \frac{d\vec{\Phi}}{dt} \right| = 1$)

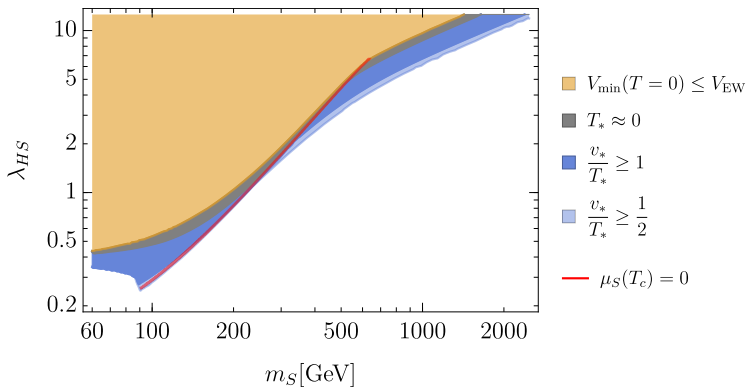
$$\frac{d^2 t}{dr^2} + \frac{2}{r} \frac{dt}{dr} = (\nabla V)_{\parallel} = \frac{dV}{dt}$$

$$\vec{N} = \frac{d^2 \vec{\Phi}}{dt^2} \left(\frac{dt}{dr} \right)^2 - (\nabla V)_{\perp}.$$



Wainwright 11'

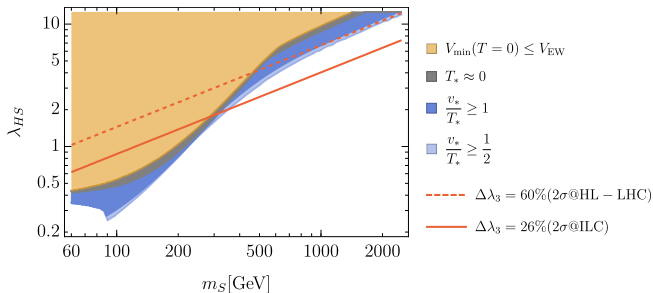
Electroweak phase transition-Numerical results



- Triple Higgs coupling

$$\lambda_3 = \frac{1}{6} \frac{\partial^3 V(h, S=0, T=0)}{\partial h^3} \bigg|_{h=v_0} \approx \frac{m_h^2}{2v_0} + \frac{\lambda_{HS}^3 v_0^3}{24\pi^2 m_S^2}$$

experimental accuracy at HL-LHC will be about 30%, but down to 13% at ILC



Gravitational waves

- Gravitational waves are produced during a first-order phase transition by three main mechanisms:

- collisions of bubble walls

Kamionkowski '93, Huber '08,

- sound waves

Hindmarsh '13 '15

- magnetohydrodynamical turbulence

Caprini '09

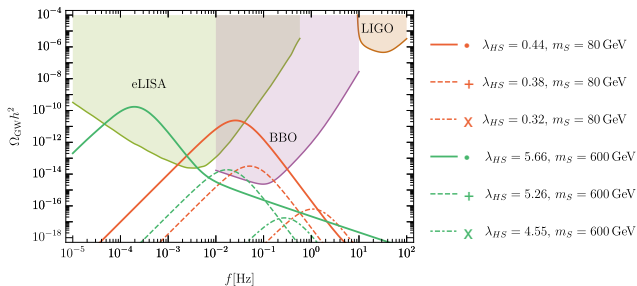
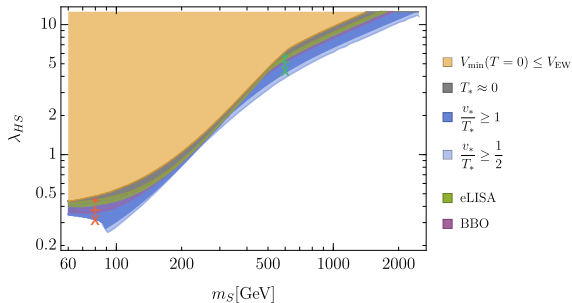
Signals from all of these sources can be described by two parameters characterising the phase transition

$$\alpha = \frac{1}{\rho_R} \left[-(V_{\text{EW}} - V_f) + T \left(\frac{dV_{\text{EW}}}{dT} - \frac{dV_f}{dT} \right) \right] \Big|_{T=T_*},$$

$$\frac{\beta}{H} = \left[T \frac{d}{dT} \left(\frac{S_3(T)}{T} \right) \right] \Big|_{T=T_*}.$$

Grojean '06 Delaunay '06

Gravitational waves



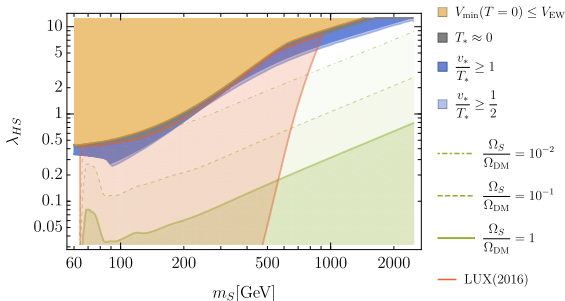
Dark Matter

- To calculate the abundance of S we solve the Boltzmann equation ($x = m_S/T$)

$$\frac{dY}{dx} = \frac{2\pi}{45} \frac{m_S^3}{x^4 H} \left(h_{\text{eff}} + \frac{T}{3} \frac{dh_{\text{eff}}}{dT} \right) \langle \sigma v \rangle (Y_{\text{eq}}^2 - Y^2) \implies Y_0 \propto \frac{x_f H(x_f)}{m_S^3 \langle \sigma v \rangle}$$

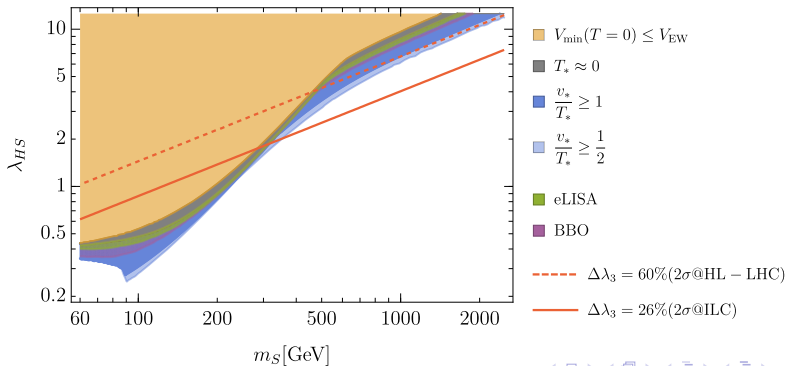
- direct detection limits and the spin-independent scalar-nucleon cross section

$$\sigma_{\text{SI}} = \frac{\lambda_{HS} f_N}{4\pi} \frac{m_n^4}{(m_S + m_n)^2 m_h^4}, \quad \frac{\Omega_S}{\Omega_{\text{DM}}} \sigma_{\text{SI}} > \sigma_{\text{EXP}}$$



Conclusions

- correct DM abundance cannot be obtained simultaneously with a first-order EWPT
- Small abundance is nevertheless enough to lead to exclusion by null results in direct dark matter search experiments
- Significant portion of the model parameter space is accessible at the planned GW experiments but is beyond reach at the future collider experiments



Cosmology modification

- New energy density component ρ_s

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

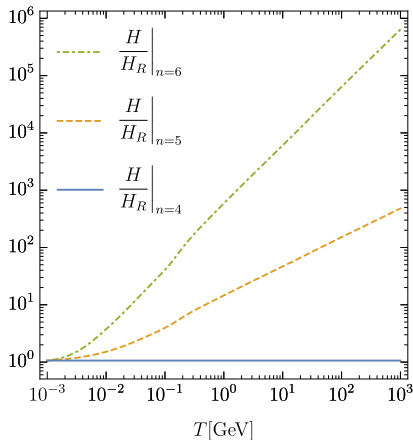
- At BBN ($T_{\text{BBN}} = 1$ MeV) from experiment we have $N_{\nu\text{eff}} = 3.28$

- SM radiation $N_{\nu}^{\text{SM}} = 3.046$

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

- moving to earlier times (EWSB)

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



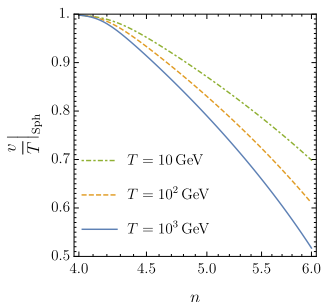
Cosmology modification - $SU(2)$ sphaleron decoupling

- $SU(2)$ sphaleron rate

$$\Gamma_{\text{Sph}} = T^4 \mathcal{B}_0 \frac{g}{4\pi} \left(\frac{v}{T} \right)^7 \exp \left(-\frac{4\pi}{g} \frac{v}{T} \right) \lesssim H,$$

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

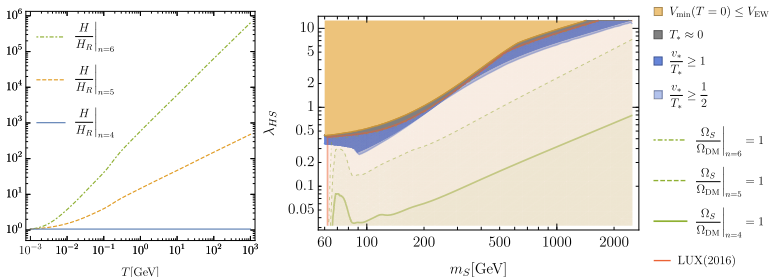
$$\frac{v}{T} \geq \frac{g}{4\pi E_0} \ln \left(\frac{T^4 \mathcal{B}_0 \frac{g}{4\pi} \left(\frac{v}{T} \right)^7}{H} \right),$$



Dark Matter

- To calculate the abundance of S we solve the Boltzmann equation ($x = m_S/T$)

$$\frac{dY}{dx} = \frac{2\pi}{45} \frac{m_S^3}{x^4} H \left(h_{\text{eff}} + \frac{T}{3} \frac{dh_{\text{eff}}}{dT} \right) \langle \sigma v \rangle (Y_{\text{eq}}^2 - Y^2) \Rightarrow Y_0 \propto \frac{x_f H(x_f)}{m_S^3 \langle \sigma v \rangle}$$



- direct detection limits and the spin-independent scalar-nucleon cross section

$$\sigma_{\text{SI}} = \frac{\lambda_{HS} f_N}{4\pi} \frac{m_n^4}{(m_S + m_n)^2 m_h^4}, \quad \frac{\Omega_S}{\Omega_{\text{DM}}} \sigma_{\text{SI}} > \sigma_{\text{EXP}}$$

- Modification of cosmological history can significantly lower requirements for EWBG scenarios and make their detection more difficult
- Dark Matter abundance can be increased by several orders of magnitude, however, this leads to even worse direct detection exclusion