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

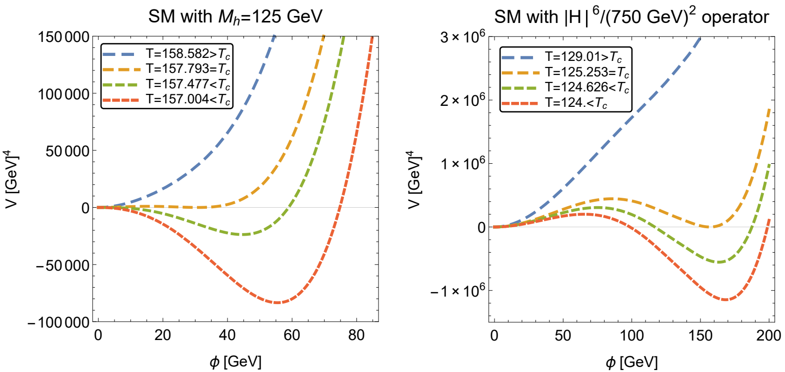
Marek Lewicki

CoEPP & CSSM, University of Adelaide

Madrid, 20 June 2017

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

Electroweak baryogenesis



- We need the phase transition to be strong enough:

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

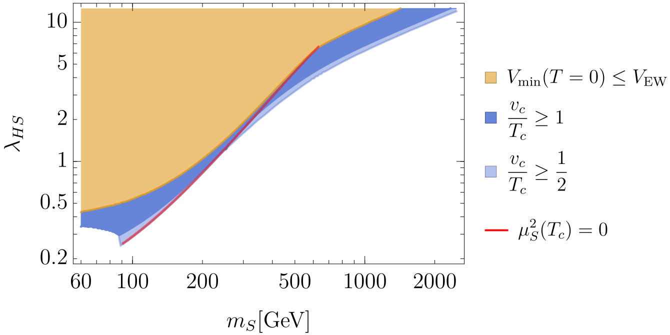
Singlet Scalar

- 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

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

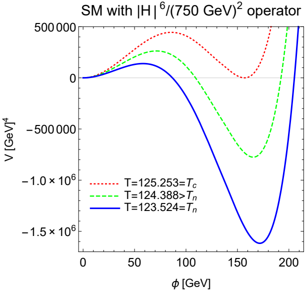


Electroweak phase transition

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

- transition probability

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



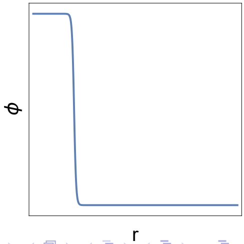
- $\mathcal{O}(3)$ symmetric action

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

- EOM $\rightarrow$ bubble profile

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

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

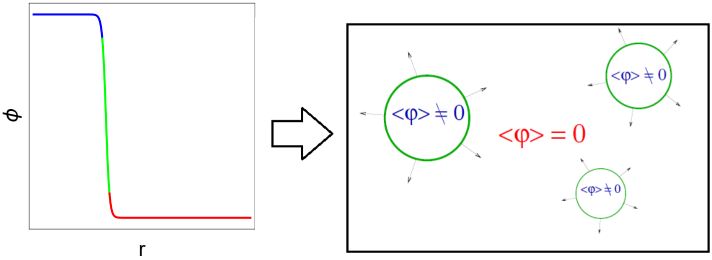


- phase transition occurs when

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

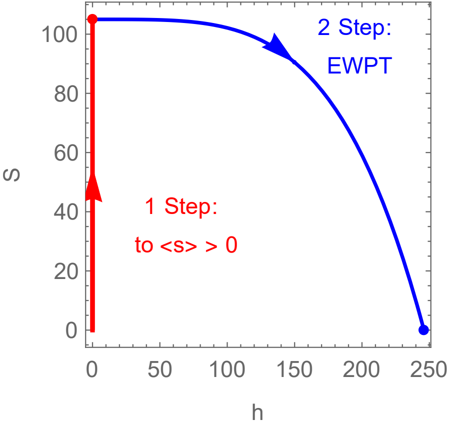
Linde 81' 83'

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

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

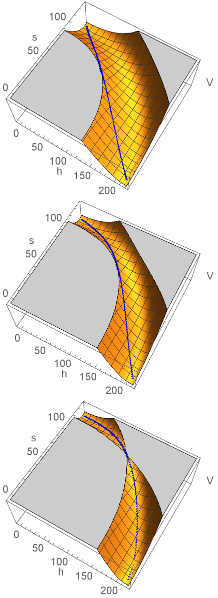
- EOMs in terms of path $\vec{\Phi}(t) = (h(t), S(t))$

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

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

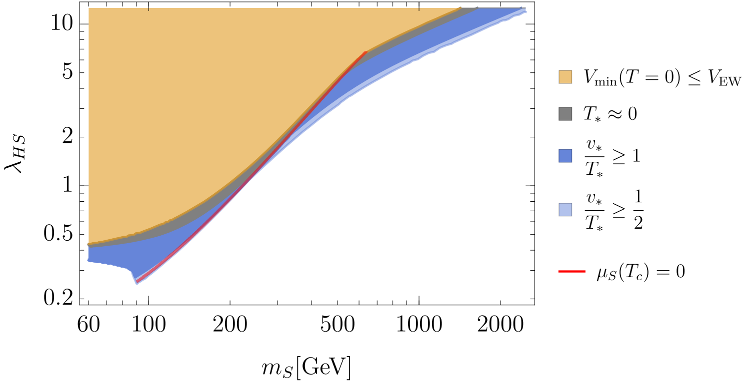
$$\frac{d^2t}{dr^2} + \frac{2}{r}\frac{dt}{dr} = (\nabla V)_{\parallel} = \frac{dV}{dt}$$

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



Wainwright 11'

Electroweak phase transition-Numerical results

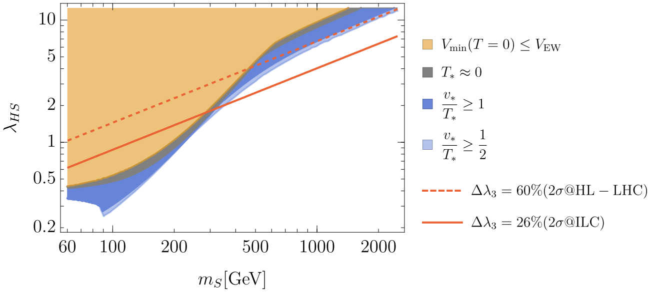


Collider signals

- Triple Higgs coupling

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

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

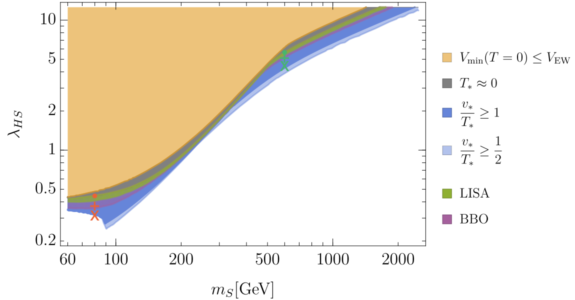
  Signals from all of these sources can be described by two parameters characterising the phase transition

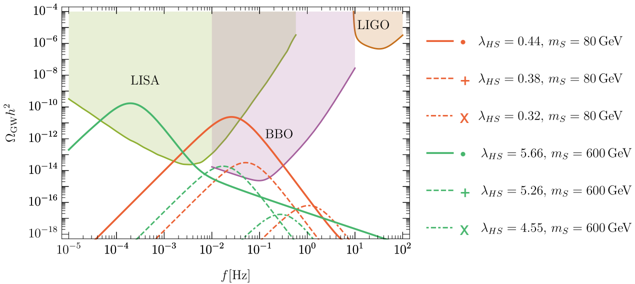
$$\alpha = \frac{1}{\rho_R}\left[-(V_{\rm EW} - V_f) + T\left(\frac{dV_{\rm EW}}{dT} - \frac{dV_f}{dT}\right)\right]\Bigg|_{T=T_*},$$

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

Grojean '06 Delaunay '06

Gravitational waves





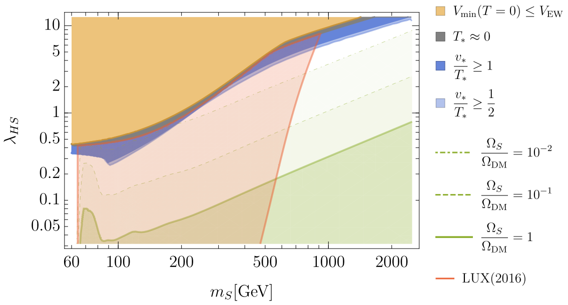
Dark Matter

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

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

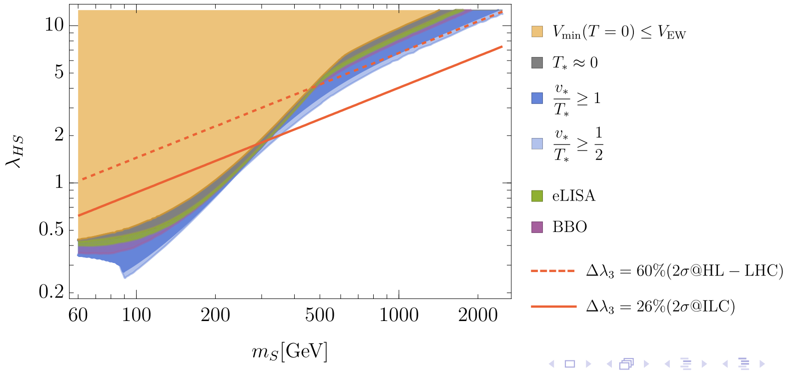
- direct detection limits and the spin-independent scalar-nucleon cross section

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



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



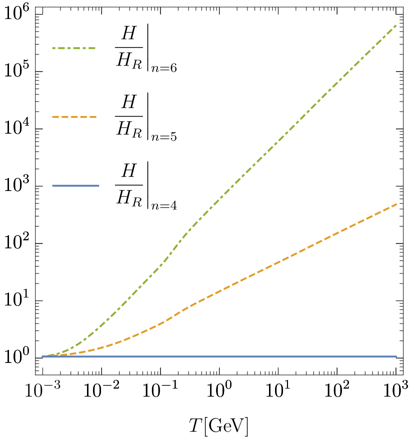
Cosmology modification

- 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 ($T_{\rm BBN} = 1$ 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)

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

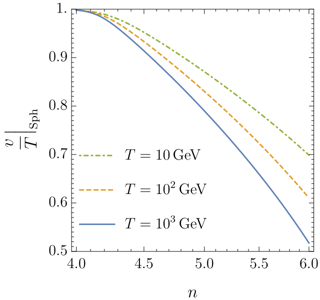
Cosmology modification - $SU(2)$ sphaleron decoupling

- $SU(2)$ sphaleron rate

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

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

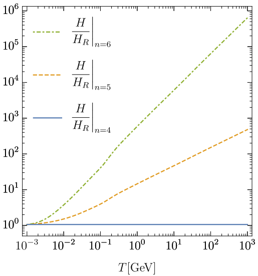
$$\frac{v}{T} \geq \frac{g}{4\pi E_0} \ln\left(\frac{T^4 \mathcal{B}_0 \frac{g}{4\pi}\left(\frac{v}{T}\right)^7}{H}\right),$$

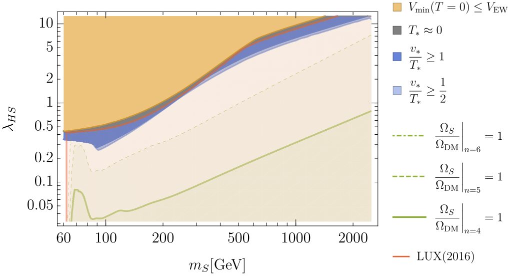


Dark Matter

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

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





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

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

Conclusions 2

- 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