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

Marek Lewicki

CoEPP & CSSM, University of Adelaide

CoEPP Annual Workshop, Adelaide, 23 February 2017

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

Plan

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

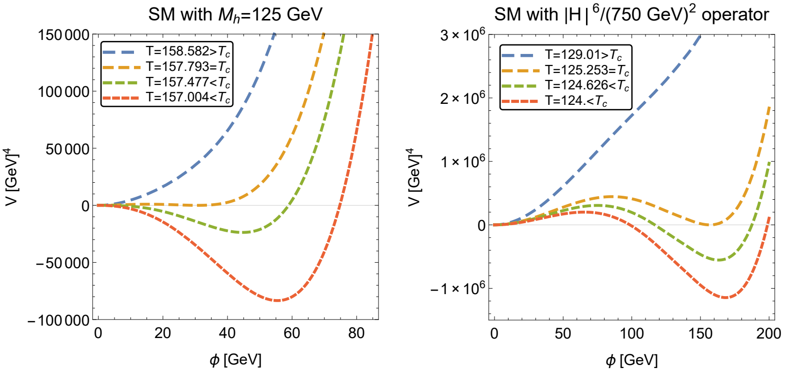
Baryogenesis

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

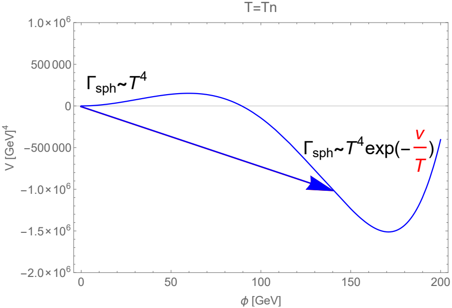


If $M_h < 85 GeV$ in SM we would have a I order phase transition

Kajantie, Laine, Rummukainen, Shaposhnikov 97'

Baryon number violation

- $SU(2)$ sphalerons violate baryon number



- 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'

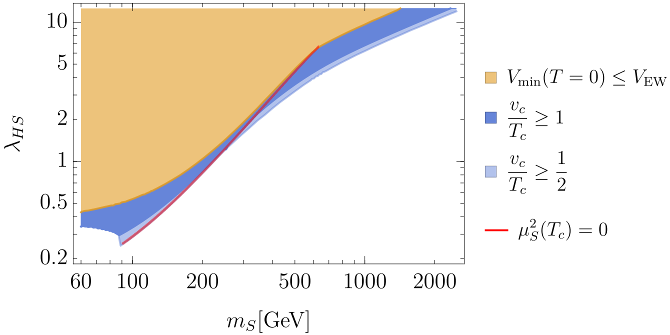
Singlet Scalar

- 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)

- $\mathcal{O}(3)$ 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

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

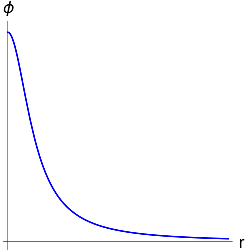
$$\phi(r \rightarrow \infty) = 0 \quad \text{and} \quad \dot{\phi}(r = 0) = 0.$$

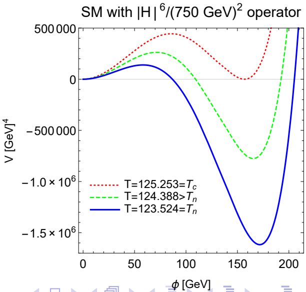
- transition probability

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

- phase transition occurs when

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





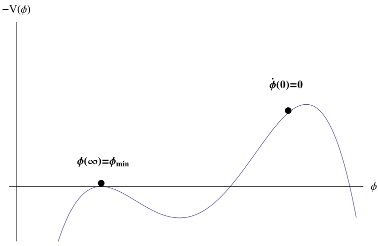
Linde 81' 83'

Electroweak phase transition-Numerical calculations

- Our EOM

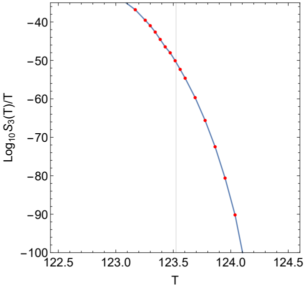
$$\ddot{\phi} + \frac{2}{r}\dot{\phi} = \frac{\partial V(\phi)}{\partial \phi},$$

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

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

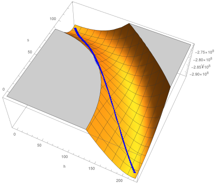


Two step phase transition

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

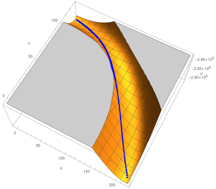
- $\mathcal{O}(3)$ symmetric action for 2 fields

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



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

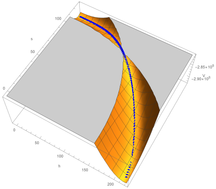
$$\frac{d\vec{\Phi}}{dt} \frac{d^2 t}{dr^2} + \frac{d^2 \vec{\Phi}}{dt^2} \left(\frac{dt}{dr} \right)^2 + \frac{2}{r} \frac{d\vec{\Phi}}{dt} \frac{dt}{dr} = \nabla V.$$



- EOMs along the path and in perpendicular direction (assuming $\left| \frac{d\vec{\Phi}}{dt} \right| = \left(\frac{dh}{dt} \right)^2 = 1$)

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

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



Wainwright 11'

Collider signals

- Triple Higgs coupling

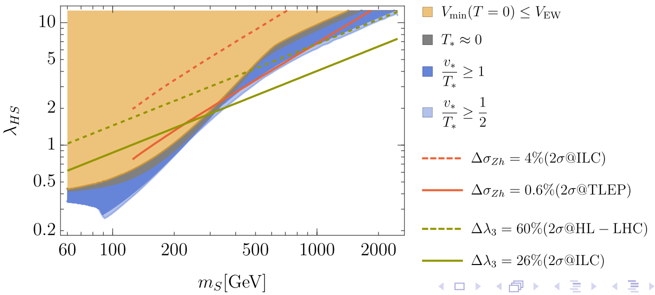
$$\lambda_3 = \frac{1}{6}\frac{\partial^3 V(h, S=0, T=0)}{\partial h^3}\bigg|_{h=v_0} \approx \frac{m_h^2}{2v_0} + \frac{\lambda_{HS}^3 v_0^3}{24\pi^2 m_S^2}$$

experimental accuracy at HL-LHC is only 30%, but down to 13% at ILC

- Modification to the Zh production at lepton colliders

$$\Delta\sigma_{Zh} = \frac{1}{2}\frac{\lambda_{HS}^2 v_0^2}{4\pi^2 m_h^2}\left[1 + F\left(\frac{m_h^2}{4m_S^2}\right)\right], \quad F(\tau) = \frac{\log\left(\frac{1-2\tau-2\sqrt{\tau(\tau-1)}}{1-2\tau+2\sqrt{\tau(\tau-1)}}\right)}{4\sqrt{\tau(\tau-1)}}$$

ILC can achieve a precision of 2% whereas FCC-ee/TLEP will be able probe it with 0.6% accuracy.



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

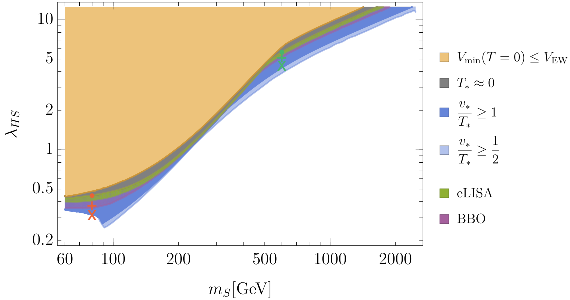
  Signals from all of these sources can be described by two parameters characterising the phase transition

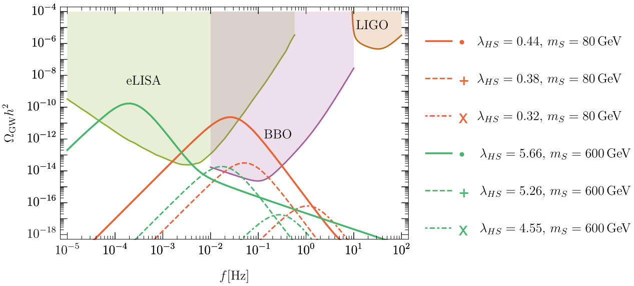
$$\alpha = \frac{1}{\rho_R}\left[-(V_{\mathrm{EW}} - V_f) + T\left(\frac{dV_{\mathrm{EW}}}{dT} - \frac{dV_f}{dT}\right)\right]\Bigg|_{T=T_*},$$

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

Grojean '06 Delaunay '06

Gravitational waves





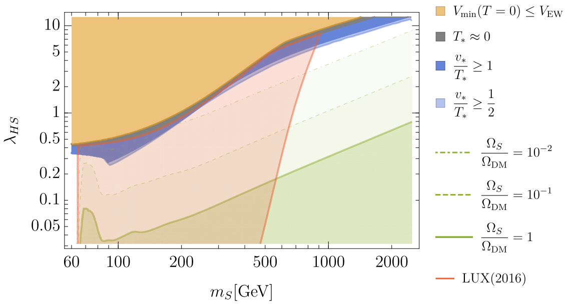
Dark Matter

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

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

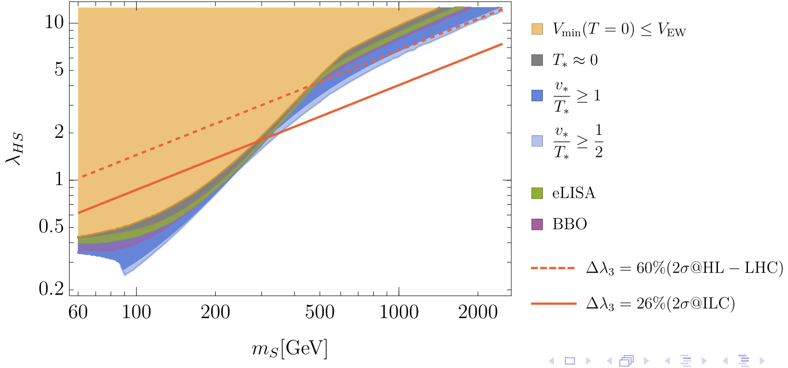
- direct detection limits and the spin-independent scalar-nucleon cross section

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



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

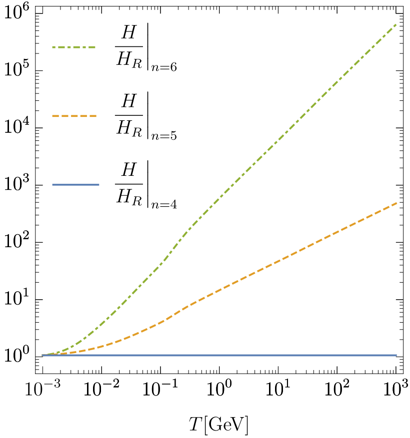
- New energy density component ρ_s

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

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

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

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



- moving to earlier times (EWSB)

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

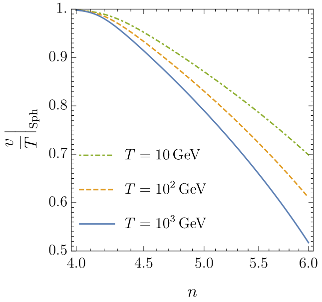
Cosmology modification - $SU(2)$ sphaleron decoupling

- $SU(2)$ sphaleron rate

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

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

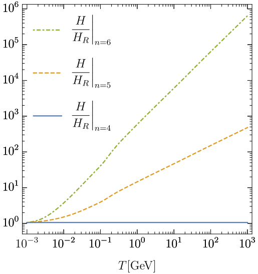
$$\frac{v}{T} \geq \frac{g}{4\pi E_0} \ln\left(\frac{T^4 \mathcal{B}_0 \frac{g}{4\pi}\left(\frac{v}{T}\right)^7}{H}\right),$$

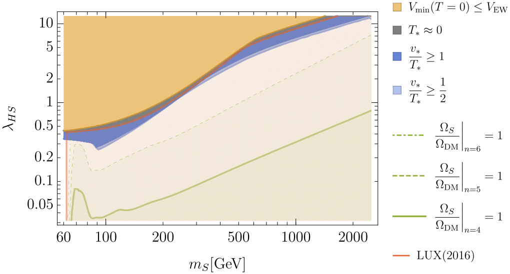


Dark Matter

- 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

$SU(2)$ 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 $E_{\mathrm{sph}} = \frac{4\pi v}{g} E_0$

$$E_0 = \frac{g}{4\pi v} \int \left(-\frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu} + -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} + (D\phi)^\dagger (D\phi) + V(\phi) \right) d^3x$$

$$= \int_0^\infty d\xi \left(4f'^2 + \frac{8}{\xi^2} f^2 (1-f)^2 + \frac{1}{2} \xi^2 h'^2 + h^2 (1-f)^2 + \frac{\lambda}{4g^2} \xi^2 (h^2-1)^2 + \frac{v^2}{8g^2\Lambda^2} \xi^2 (h^2-1)^3 \right)$$

- 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 $f(\infty) = h(\infty) = 1$.