Gravitational Wave Signals of Electroweak Phase Transition Triggered by Dark Matter

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(arXiv:1702.02698)

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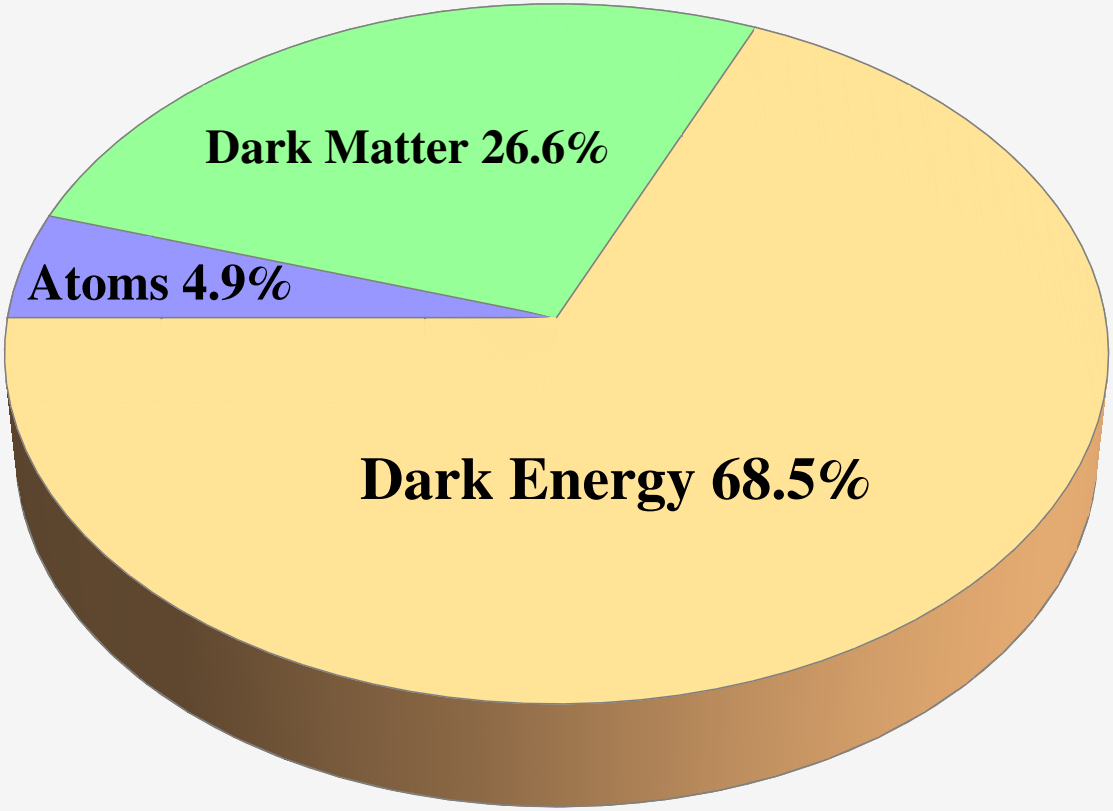
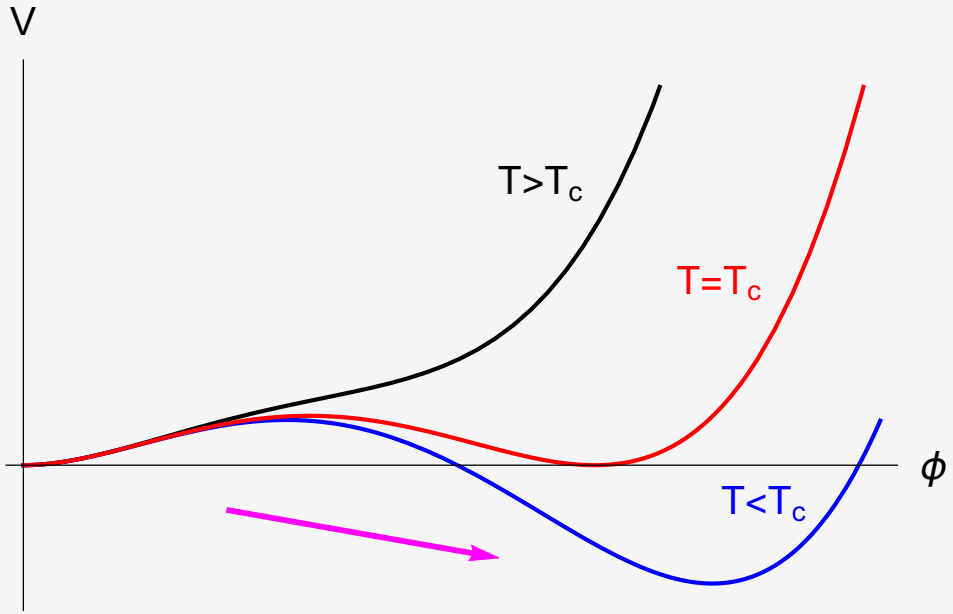
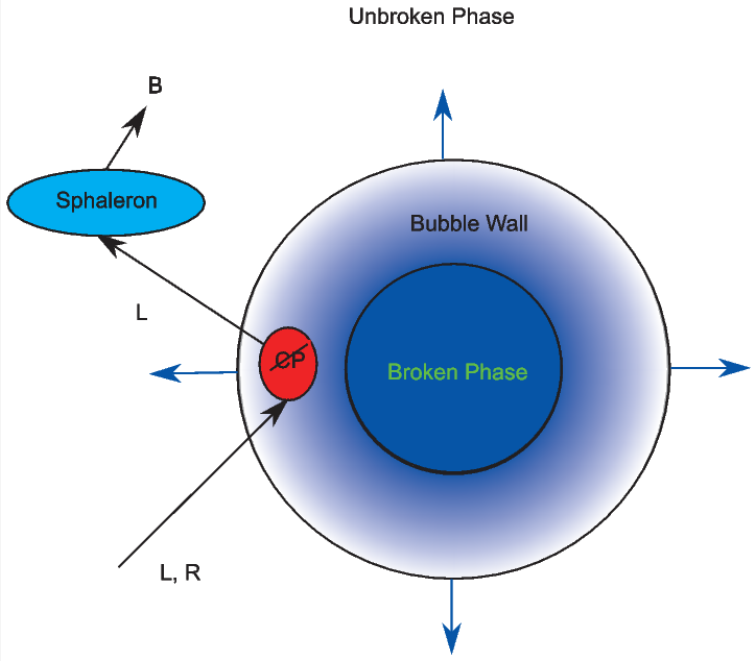
Baryon Asymmetry and Dark Matter



Planck, 2013. Astron.Astrophys. (2014)

Electroweak Baryogenesis: The Standard Picture



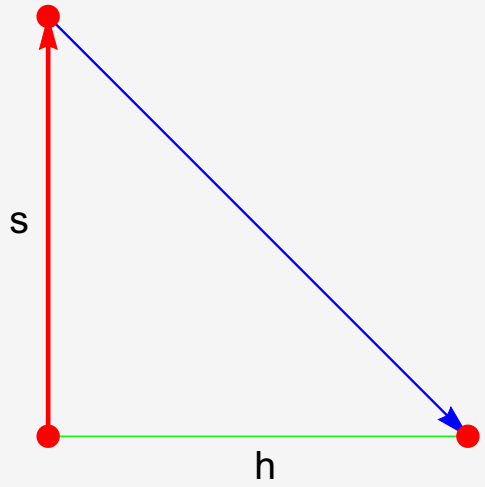


$T \approx 100\text{GeV} \approx 10^{15}\text{K}$

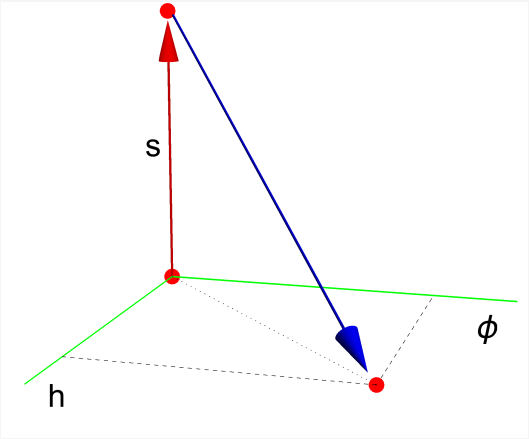
Gravitational Waves (mHz level)

Minimal Extensions of the SM: Dark Matter and EWPT

SM + S (stringent experimental tension)



SM + S + S



SM + DM + Scalar: Model at $T = 0$

A simplified $Z_2 \times Z_2$ symmetric potential:

$$\begin{aligned} V_0 \quad = \quad & -\frac{1}{2}\mu_\Phi^2\Phi^2 + \frac{1}{4}\lambda_\Phi\Phi^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 \\ & -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2 + \lambda_1 S^2 H^\dagger H + \lambda_2 \Phi^2 H^\dagger H \\ & +\lambda_3 S^2\Phi^2, \end{aligned}$$

- $v_S = 0 \quad \Rightarrow \quad$ s is stable
- h, ϕ mix: $\quad \hat{h} = c_\theta h + s_\theta \phi, \qquad \hat{\phi} = -s_\theta h + c_\theta \phi. \qquad (c_\theta > 0.86$ at 95% CL$)$

Physical Parameters:

$$\boxed{\mu_\Phi, \quad \mu_S \quad \mu, \quad \lambda_\Phi, \quad \lambda_S, \quad \lambda, \quad \lambda_1, \quad \lambda_2, \quad \lambda_3}$$

$$\downarrow$$

$$\boxed{v_H, \quad m_H, \quad v_\Phi, \quad m_{\hat{\phi}}, \quad m_S, \quad \lambda_S, \quad \theta, \quad \lambda_1, \quad \lambda_3}$$

$$\uparrow$$

$$\boxed{\text{7 free parameters}}$$

Dark Matter: Turn Off SI Scattering at Tree Level

DM-Nucleaon scattering cross section:

$$\sigma_n = \frac{\mu^2 m_n^2}{\pi v_{\rm EW}^2 m_S^2} \left| \frac{c_\theta a_{\hat{h}}}{m_{\hat{h}}^2} - \frac{s_\theta a_{\hat{\phi}}}{m_{\hat{\phi}}^2} \right|^2 \left(\frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_{T_q}^n \right)^2$$

Two sets of diagrams:

$$\begin{aligned} a_{\hat{h}} : s^2 \hat{h} \quad &: \quad 2\lambda_3 v_\phi s_\theta + \lambda_1 v_H c_\theta \\ a_{\hat{\phi}} : s^2 \hat{\phi} \quad &: \quad 2\lambda_3 v_\phi c_\theta - \lambda_1 v_H s_\theta \end{aligned}$$

Zoomin to the parameter space with a negligible direct detection signal:

$$\lambda_3 = \frac{v_H \lambda_1 (m_{\hat{h}}^2 \tan\theta + m_{\hat{\phi}}^2 \cot\theta)}{2 v_\Phi (m_{\hat{h}}^2 - m_{\hat{\phi}}^2)} \quad \Rightarrow \quad \boxed{\text{6 free parameters}}$$

Effective Potential: Gauge Dependence

$$
\begin{aligned}
V_{\rm eff}^{T}(\phi) &= V^{T=0}(\phi) + V_{\rm CW}^{T=0}(\phi) \\
&+ \frac{T^4}{2\pi^2}\left[\sum_{\rm scalars} J_B(\frac{M^2(\xi)}{T^2}) + 3\sum_{\rm gauge} J_B(\frac{\mu^2}{T^2}) - \sum_{\rm gauge} J_B(\frac{\xi\mu^2}{T^2}) - 4\sum_{\rm fermions} n_C^f J_F(\frac{m_f^2}{T^2})\right],
\end{aligned}
$$

ξ: Gauge fixing parameter in R_ξ-gauge.

$O(T^2)$ terms are ξ-independent & Equivalent to including thermal masses at tree level:

$$
\begin{aligned}
\Pi_h &= \left\{\frac{3g^2+g'^2}{16} + \frac{\lambda}{2} + \frac{h_t}{4} + \frac{\lambda_1+\lambda_2}{12}\right\}T^2, \\
\Pi_s &= \left\{\frac{\lambda_s}{4} + \frac{\lambda_1}{3} + \frac{\lambda_3}{6}\right\}T^2, \\
\Pi_\phi &= \left\{\frac{\lambda_\phi}{4} + \frac{\lambda_2}{3} + \frac{\lambda_3}{6}\right\}T^2.
\end{aligned}
$$

More on this topic: H.Patel, M. Ramsey-Musolf, JHEP 1107 (2011) 029.

Analysis of $\mathcal{O}(T^2)$ Terms

Generic Form:

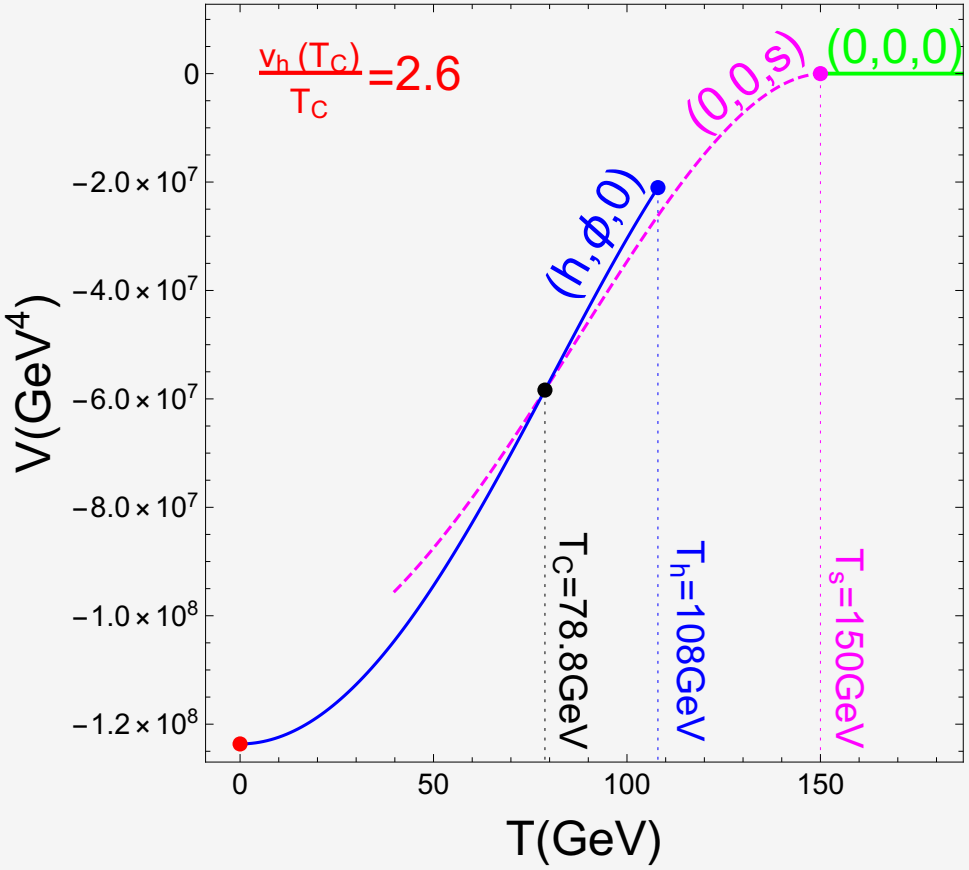
$$
\begin{aligned}
V_{\text{eff}}^T(\phi) = \quad & D_h(T^2 - T_h^2)h^2 + \Lambda_h h^4 \\
+ \quad & D_\phi(T^2 - T_\phi^2)\phi^2 + \Lambda_\phi \phi^4 \\
+ \quad & D_s(T^2 - T_s^2)s^2 + \Lambda_s s^4 \\
+ \quad & \delta_{h\phi} h^2\phi^2 + \delta_{hs} h^2 s^2 + \delta_{\phi s}\phi^2 s^2
\end{aligned}
$$

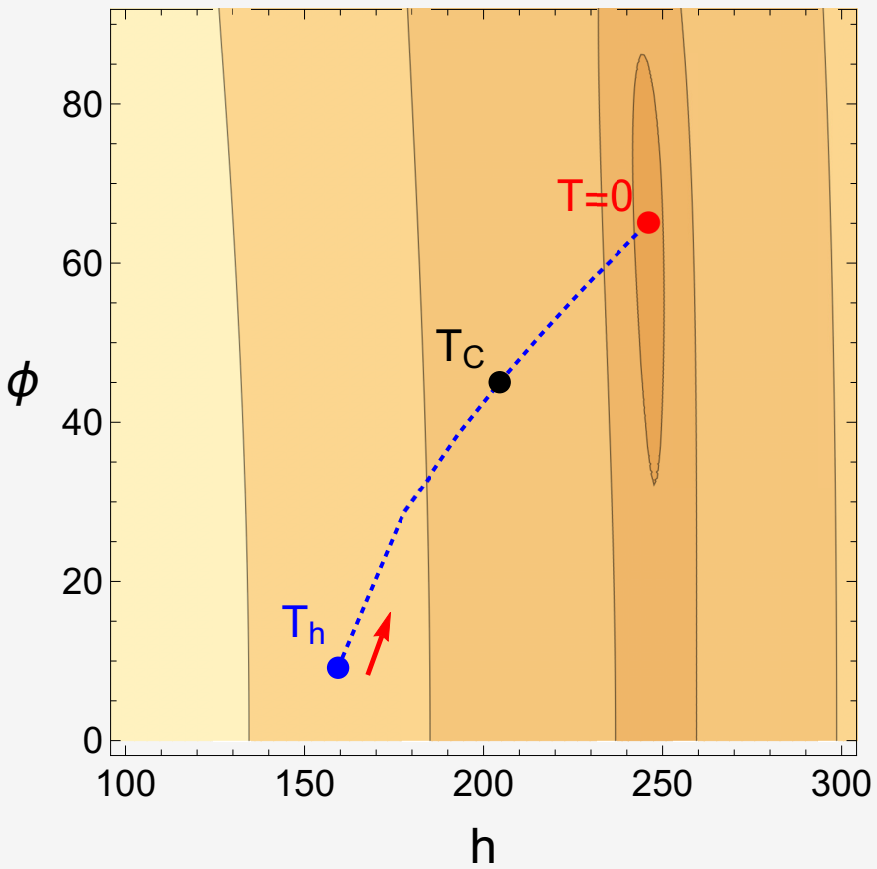
- Basics: $\Lambda_h > 0, \quad \Lambda_\phi > 0, \quad \Lambda_s > 0, \quad \delta_{h\phi} > 0, \quad \Lambda_{hs} > 0, \quad \Lambda_{\phi s} > 0.$
- Symmetry Restoration: $D_h > 0, \quad D_\phi > 0, \quad D_s > 0, \quad T_h^2 > 0, \quad T_\phi^2 > 0, \quad T_s^2 > 0,$
- Two minima: $(0, 0, s)$ and $(h, \phi, 0)$ (Hessian Positive Definite)
- DM develops a vev first: $T_s > T_h, \quad T_s > T_\phi$
- EW minimum $(h, \phi, 0)$ stable at $T = 0$

▶ These two minima will cross at some $T(\equiv T_c)$ in the phase diagram.

Phase History: A Benchmark Point

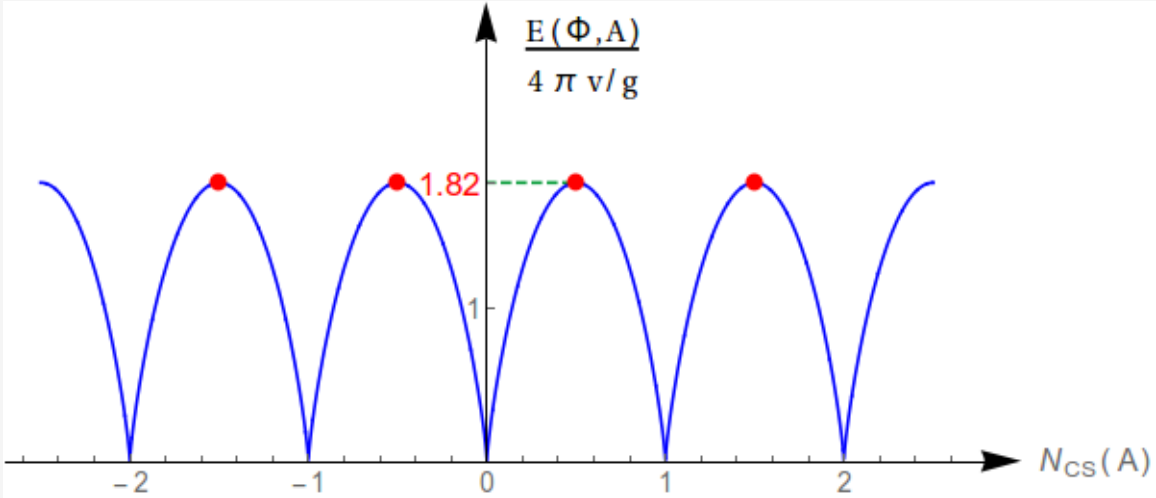
$v_\Phi = 65\text{GeV}$, $m_{\hat{\phi}} = 82\text{GeV}$, $m_S = 71\text{GeV}$, $\lambda_S = 0.015$, $\theta = 0.12$, $\lambda_1 = 0.046$ and $\lambda_3 = 0.57$

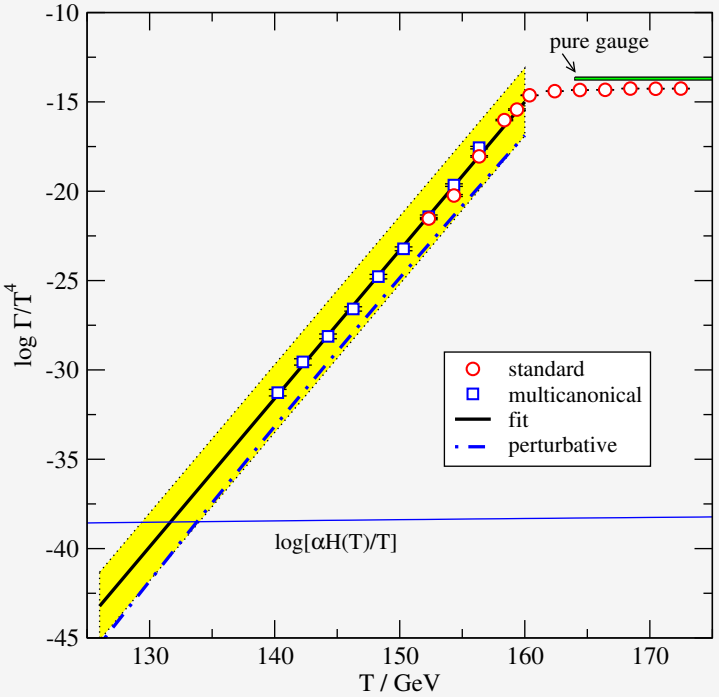




- The first step could also be a 1st order phase transition with a more complete V_{eff}.

Avoid Baryon Washout



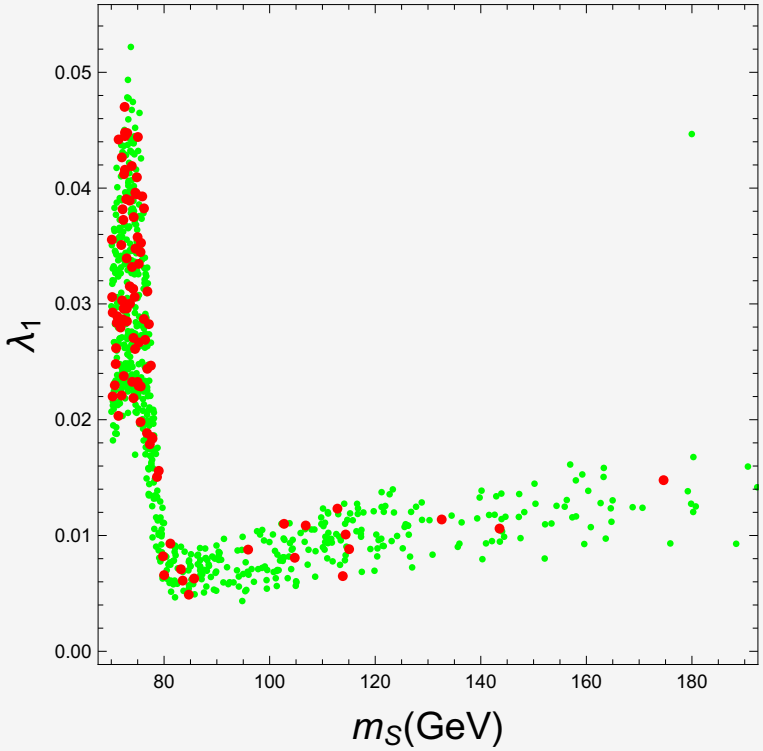


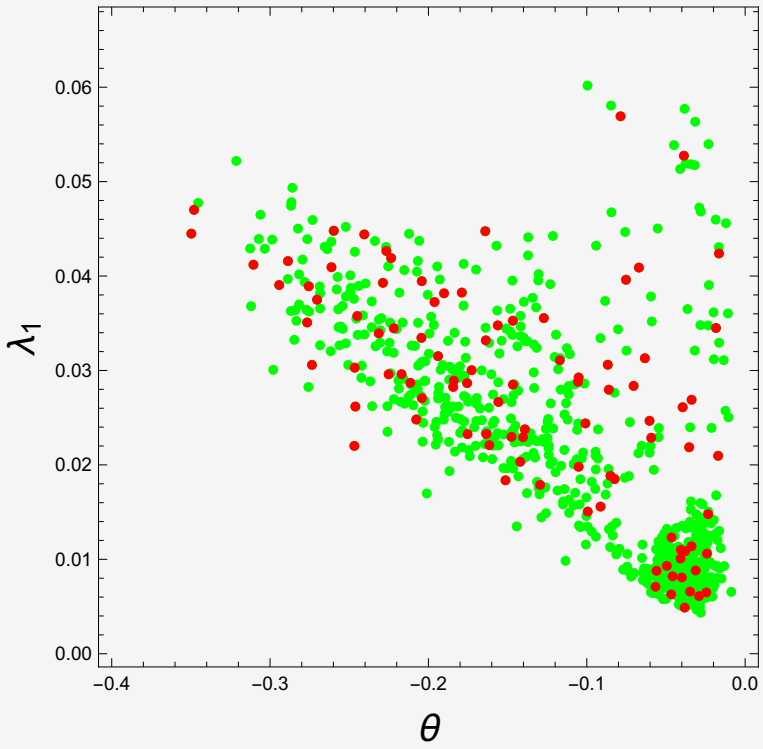
$$\Gamma^{\rm sym} \approx 6 \times (18 \pm 3)\alpha_W^5 T^4, \qquad \Gamma^{\rm brok} \sim T^4 \exp(-\frac{E_{\rm sph}}{T})$$

Sphaleron rate from lattice in SM, Phys.Rev.Lett,113, 141602 (2014).

Strongly first order EWPT criteria: $\frac{v_h(T_C)}{T_C} > 1$ (ξ-dependence)

A Survey of Parameter Space

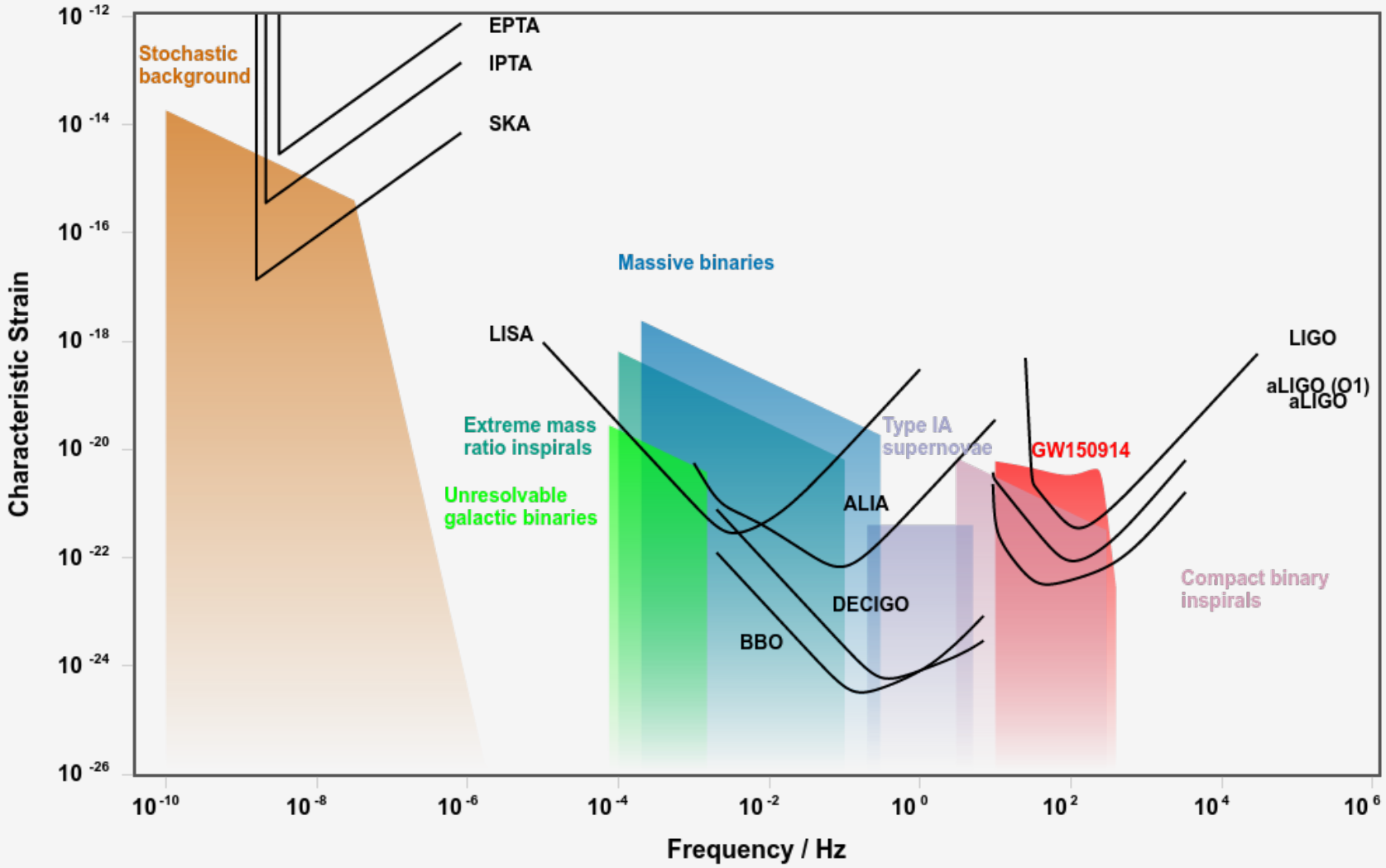




All gives previous EWPT pattern and no SI DM detection signal at tree level.

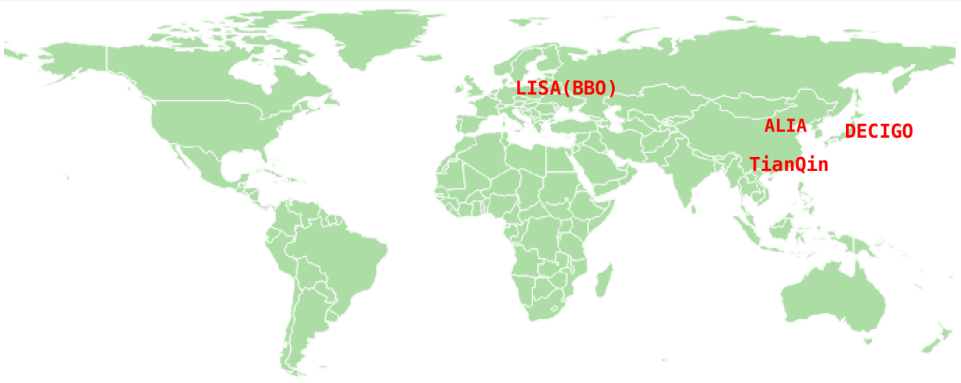
- $\Omega_c h^2 \in (0.03, 0.12)$
- $\Omega_c h^2 \in (0.03, 0.12)$ and $\dfrac{v_h(T_C)}{T_C} > 1$

Gravitational Waves: Experimental



C J Moore et al. Class. Quantum Grav. 32 (2015) 015014.

Gravitational Waves: A Benchmark Point

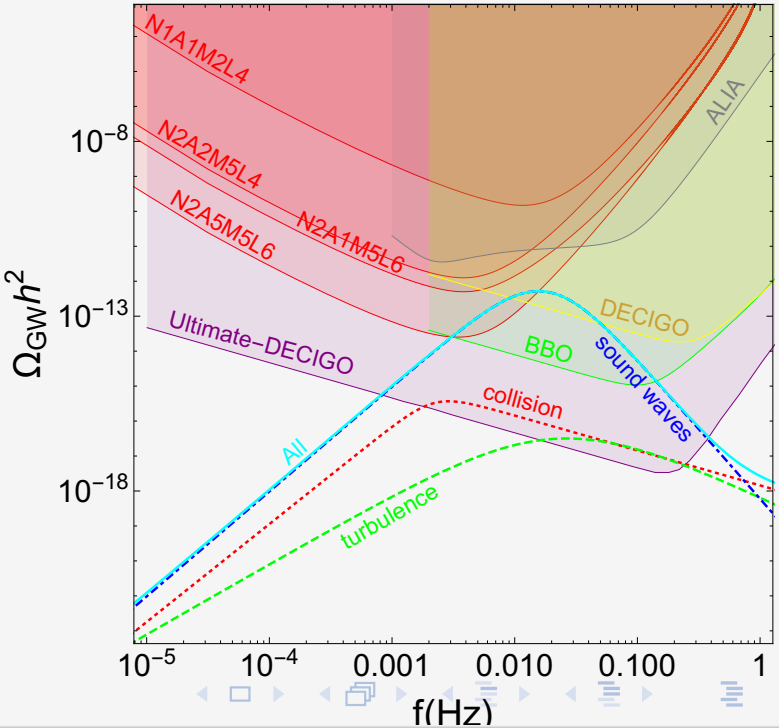


$$\Omega_{\rm GW}h^2 \simeq \Omega_\phi h^2 + \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2$$

Three sources:

- Bubble Collision
- Sound Waves
- Turbulence

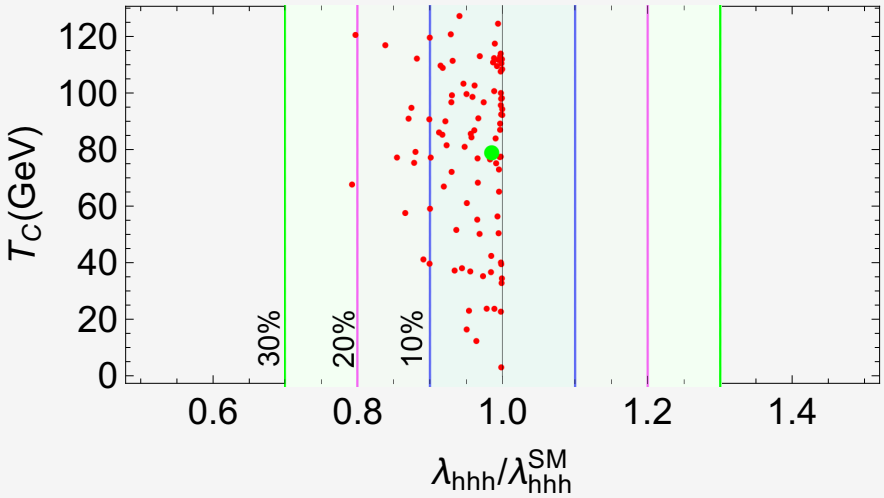
T_n: bubble nucleation temperature
α: strength of phase transition
β: inverse duration of phase transition

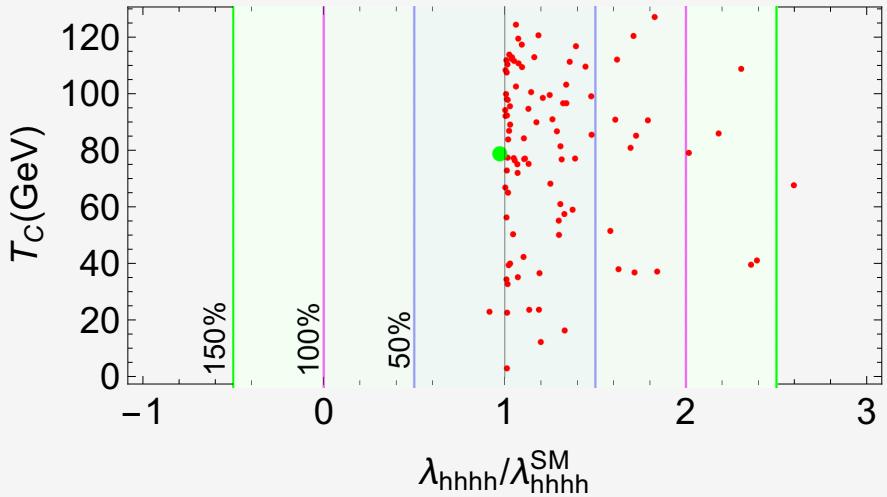


Higgs Couplings

$$\lambda_{\hat{h}\hat{h}\hat{h}} = -\frac{3m_{\hat{h}}^2}{v_H}[1 - \frac{3\theta^2}{2} + \mathcal{O}(\theta^3)]$$

$$\lambda_{\hat{h}\hat{h}\hat{h}\hat{h}} = -\frac{3m_{\hat{h}}^2}{v_H^2}[1 + (\frac{m_{\hat{\phi}}^2}{m_{\hat{h}}^2} - 3)\theta^2 + \mathcal{O}(\theta^3)]$$





- $\Omega_c h^2 \in (0.03, 0.12)$ and $\frac{v_h(T_C)}{T_C} > 1$
- GW benchmark point.

Conclusion

- Dark matter itself could have experienced a phase transition.
- Dark matter might have played a role in EWPT.
- Gravitational waves thus produced can be probed by LISA, etc,.
- Higgs self-couplings measurement serves as a complementary test.

Thanks