Electroweak Baryogenesis and Dark Matter from a Complex Singlet

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Motivation

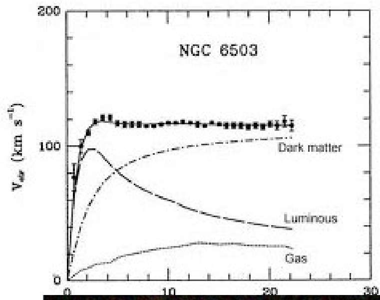
- In spite of the great success of the Standard Model (SM) of particle physics, there are still many puzzles needing to be explained. Among others, two important questions are

  - Dark Matter : In the SM, there is no DM candidate.
  - Matter-Antimatter Asymmetry in our Universe

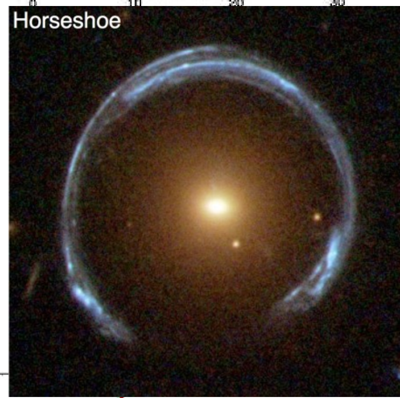
- Both problems require the physics beyond the SM.

Motivation

➢ There are already many established evidences for the existence of dark matter

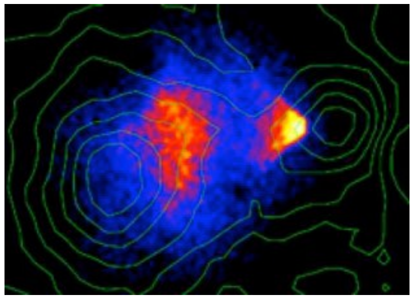


- Rotation Curves of Spiral Galaxies
  Babcock, 1939, Bosma, 1978; Rubin & Ford, 1980

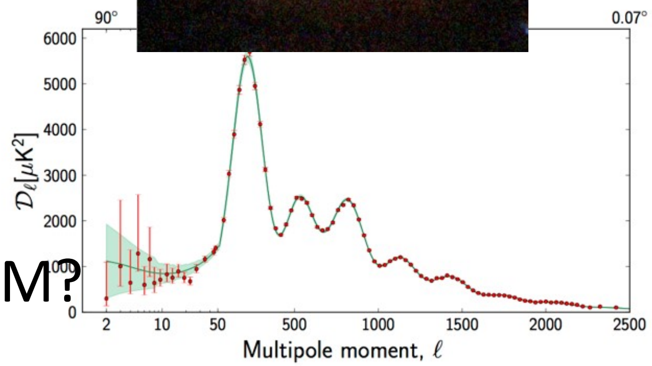


- Gravitational Lensing

- CMB



- Bullet Clusters



But , what is the particle nature of DM?

Motivation

- Observed Baryon Asymmetry: Planck Collaboration, arXiv: 1502.01589

$$\eta_B \equiv \frac{n_B}{s} = (8.61 \pm 0.09) \times 10^{-11}$$

- Three Sakharov criteria for baryogenesis:

A. D. Sakharov, 1967

✓ B violation
✓ C and CP violation
✓ Thermal non-equilibrium

- Situation in the SM:

F. R. Klinkhamer & N.S. Manton 1984

M. E. Shaposhnikov, 1987

✓ B violation: weak sphaleron process
✓ The CP violation due to CKM phase is inadequate
✓ EW phase transition is actually a cross-over, rather than being of strongly first-order.

K. Kajantie et al, hep-ph/9605288

Motivation

- EW Baryogenesis:

V. A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, 1985;
A. G. Cohen, D. B. Kaplan and A. E. Nelson, 1990

✓ new CPV sources

✓ adding new particles with masses of EW scale in order to make the EWPT of strongly first-order, which provides the necessary deviation from an equilibrium.

- Problem: The new CPV source required by the baryogenesis is strongly constrained by the EDMs of electrons and neutrons.

ACME Collaoration, 1310.7534; PDG 2016;

- Possible solution: If the CP is spontaneously broken at high temperatures before the EWPT while restored afterward, then the CPV constraint can be evaded!

J. McDonald, 1994; W. Chao, 1706.01041

The Model

➢ Extend the SM by an EW singlet complex scalar

$$S = (s+ia)/\sqrt{2}.$$

with a Z_2 symmetry: $S \leftrightarrow -S$ and CP symmetry related to S

J. McDonald, 1994, 1995; G.C. Branco et al, 9805302; S. Profumo et al, 0705.2425; …

➢ The scalar potential at zero temperature:

$$H = (0, h/\sqrt{2})^T$$

REAL couplings

$$\begin{aligned} V_0(H,S) = &\lambda_H \left(|H|^2 - \frac{v_0^2}{2} \right)^2 - \mu_1^2 (S^* S)^2 - \frac{\mu_2^2}{2}(S^2 + S^{*2}) \\ &+ \lambda_1 (S^* S)^2 + \frac{\lambda_2}{4}(S^2 + S^{*2})^2 + \frac{\lambda_3}{2}|S|^2 (S^2 + S^{*2}) \\ &+ |H|^2 \left[\kappa_1 (S^* S) + \frac{\kappa_2}{2}(S^2 + S^{*2}) \right] \\ = &-\frac{1}{2}\lambda_H v_0^2 h^2 + \frac{1}{4}\lambda_H h^4 - \frac{1}{2}(\mu_1^2 + \mu_2^2) s^2 - \frac{1}{2}(\mu_1^2 - \mu_2^2) a^2 \\ &+ \frac{1}{4}(\lambda_1 + \lambda_2 + \lambda_3) s^4 + \frac{1}{4}(\lambda_1 + \lambda_2 - \lambda_3) a^4 \\ &+ \frac{1}{4}(\kappa_1 + \kappa_2) h^2 s^2 + \frac{1}{4}(\kappa_1 - \kappa_2) h^2 a^2 + \frac{1}{2}(\lambda_1 - \lambda_2) s^2 a^2 + \text{const.} . \end{aligned}$$

The Model

- Leading-order finite-temperature corrections at high-T expansion

$$V_T = \frac{1}{2}c_h T^2 h^2 + \frac{1}{2}c_s T^2 s^2 + \frac{1}{2}c_a T^2 a^2$$

where

$$c_h = \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda_H}{2} + \frac{\kappa_1}{12}$$
$$c_s = \frac{1}{6}(2\lambda_1 + \kappa_1 + \kappa_2) + \frac{\lambda_3}{4},$$
$$c_a = \frac{1}{6}(2\lambda_1 + \kappa_1 - \kappa_2) - \frac{\lambda_3}{4}.$$

- Total Potential:

$$V_{\rm tot} = V_0 + V_T.$$

EW Phase Transition

- Rewrite the total scalar potential

$$V_{\rm tot} = \frac{\lambda_{hs}}{4}\left(h^2 - v_c^2 + \frac{v_c^2 s^2}{w_c^2\cos^2\alpha}\right)^2 + \frac{\lambda_{ha}}{4}\left(h^2 - v_c^2 + \frac{v_c^2 a^2}{w_c^2\sin^2\alpha}\right)^2$$
$$+\frac{\lambda_{sa}}{4}\left(s^2\sin^2\alpha - a^2\cos^2\alpha\right)^2 + \frac{\kappa_{hs}}{4}h^2 s^2 + \frac{\kappa_{ha}}{4}h^2 a^2$$
$$+\frac{1}{2}(T^2 - T_c^2)[c_h h^2 + c_s s^2 + c_a a^2]$$

- Two vacua: (h, s, a) = (v_c, 0, 0) and (0, w_c cosα, w_c sinα)

- Critical Temperature:

$$T_c^2 = \lambda_H(v_0^2 - v_c^2)/c_h$$

EW Phase Transition

- Further Consistency Constraints:

✓ Strongly First-Order EWPT:

$$v_c/T_c > 1$$

G. D. Moore, hep-ph/9805264

✓ Potential Stability: assume positive couplings

✓ Correct EWPT direction from (0, w_c cosα, w_c sinα) to (v_c, 0, 0)

$$c_h v_c^2 > c_s w_c^2 \cos^2\alpha + c_a w_c^2 \sin^2\alpha$$

✓ Z_2 symmetry: $\alpha \in (-\pi/2, \pi/2)$

✓ Perturbativity: $|\lambda_{1,2,3}, \kappa_{1,2}| \leqslant 5$ M. Nebot et al, 0711.0483

Dark Matter Physics

➢ Depending the mass ordering, either s or a can be DM candidate X

➢ The DM pheno. only depends on Higgs portal coupling

$$\boxed{\lambda_{hX} h^2 X^2/4}$$

J. M. Cline & K. Kainulainen, 1210.4196

with

$$\lambda_{hX} = \begin{cases} \kappa_{hs} + \dfrac{2\lambda_{hs} v_c^2}{w_c^2 \cos^2\alpha}, & X = s \\ \kappa_{ha} + \dfrac{2\lambda_{ha} v_c^2}{w_c^2 \sin^2\alpha}, & X = a \end{cases}$$

➢ The DM relic density is obtained by the freeze-out mechanism, and is calculated with MicrOMEGAs code.

➢ In order to consider the case with subdominant DM, we define the DM fraction:

$$f_X = \frac{\Omega_X h^2}{\Omega_{\rm DM,obs} h^2}$$

with $\Omega_{\rm DM,obs} h^2 = 0.1186$

Dark Matter Physics

- DM Constraints:
  - ✓ DM direct detection: XENON1T
  - ✓ DM Indirect detection: Fermi-LAT, Planck, and AMS-02
  - ✓ SM Higgs Invisible Decay: $\mathrm{Br}(h \to XX) \leqslant 0.24$ PDG 2016
  - ✓ Monojet searches: CMS

High-T CP Violation

- S can acquire a complex VEV before EWPT

$$\langle S \rangle = w_c e^{i\alpha}/\sqrt{2}$$

- With the following dim-6 operator

$$\mathcal{O}_6 = \frac{S^2}{\Lambda^2}\bar{Q}_{3L}\tilde{H}t_R + \text{H.c.}$$

J. R. Espinosa et al., 1110.2876;
J.M. Cline & K. Kainulainen, 1210.4196;
V. Vaskonen, 1611.02073

the CP symmetry is spontaneously broken, which is shown by the induced complex-valued top quark Yukawa coupling

$$\frac{w_c^2 e^{i2\alpha}}{2\Lambda^2}\bar{Q}_{3L}\tilde{H}t_R + \text{H.c.}$$

- Together with top Yukawa, we have a complex top-quark mass

First-Order EWPT

- For a first-order EWPT, the PT proceeds via the bubble nucleation.

- Near the bubble wall, the top acquires a spatially varying complex mass

$$m_t(z) = \frac{y_t}{\sqrt{2}} h(z) \left(1 + \frac{S(z)^2}{y_t \Lambda^2}\right) \equiv |m_t(z)| e^{i\theta(z)}$$

M. Joyce, et al., hep-ph/9410282; J.M. Cline et al., hep-ph/9708393, hep-ph/0006119

- This top mass would generate CPV force that acts on tops and anti-tops differently when they pass through the wall.

$$F_z = -\frac{(m^2)'}{2E_0} \pm s\frac{(m^2\theta')'}{2E_0 E_{0z}} \mp s\frac{\theta' m^2 (m^2)'}{4E_0^3 E_{0z}}$$

L. Fromme & S.J. Huber, hep-ph/0604159

which is the source of CPV in the EW baryogenesis.

First-Order EWPT

- Approximate solution of bubble wall profile:

$$S(z) \equiv \frac{w_c e^{i\alpha}}{2\sqrt{2}}[1 + \tanh(z/L_w)] \,,$$
$$h(z) \equiv \frac{v_c}{2}[1 - \tanh(z/L_w)] \,,$$

J. R. Espinosa, et al, arXiv: 1110.2876

where L_w is the bubble wall width given by

$$L_w = \frac{v_c^2 + w_c^2}{6V_\times}$$

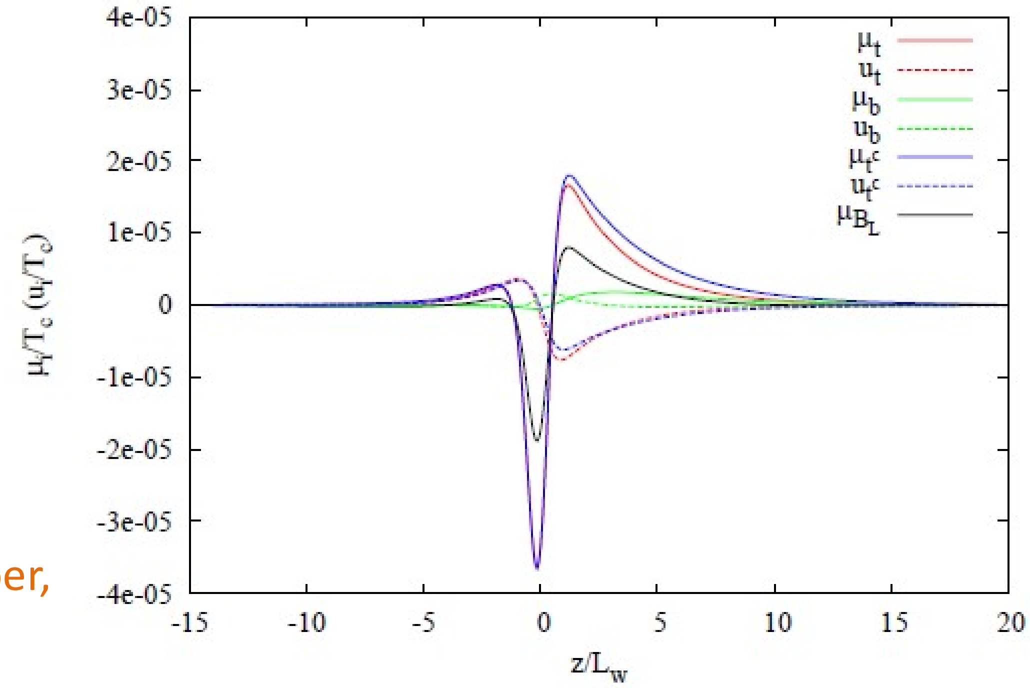
with $V_\times$ the potential energy at the top of the barrier.

First-Order EWPT

➢ The CP violations created around the bubble wall would transport to the EW symmetric phase deeply, where it biases the EW sphaleron processes to generate baryon asymmetry.

➢ The transportation of the CP asymmetry is described by the transport equations of chemical potentials and velocity perturbations of t_L, t_R, b_L and SM Higgs.

L. Fromme & S.J. Huber, hep-ph/0604159

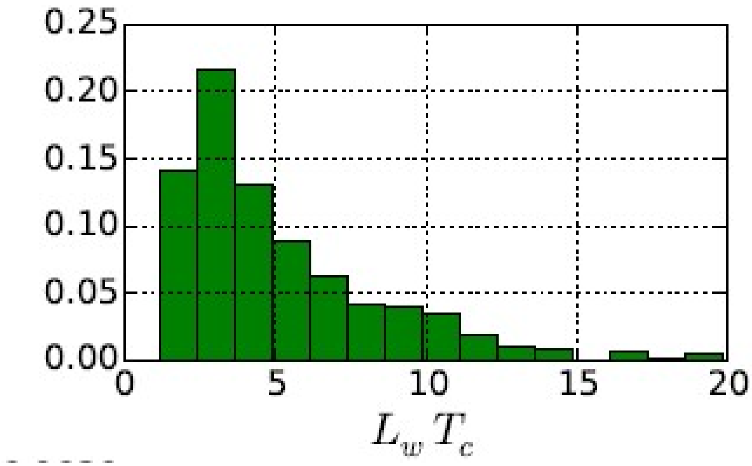


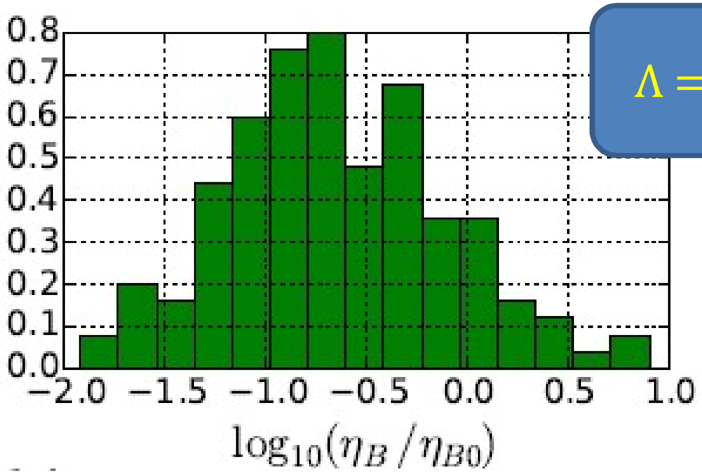
First-Order EWPT

- The final baryon asymmetry density is predicted to be

$$\eta_B = \frac{n_B}{s} = \frac{405\Gamma_{\rm sph}}{4\pi^2 v_w g_* T}\int_0^\infty dz\,\mu_{B_L}(z)e^{-45\Gamma_{\rm sph}|z|/(4v_w)}$$

where $\mu_{B_L} = \frac{1}{2}(1+4K_{1,t_L})\mu_{t_L} + \frac{1}{2}(1+4K_{1,b_L})\mu_{b_L} + 2K_{1,t_R}\mu_{t_R}$, v_w is the bubble wall velocity in the plasma, and $\Gamma_{\rm sph} \simeq 10^{-6}T$ is the sphaleron rate in the symmetric phase. J.M. Cline et al., hep-ph/0006119



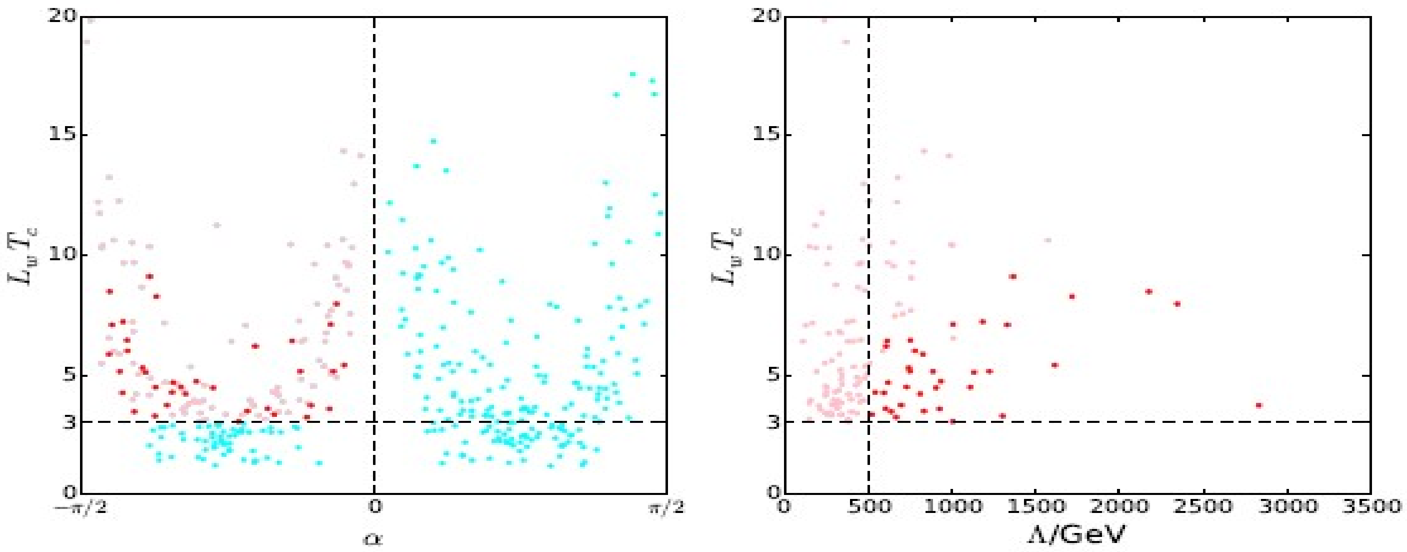


$\Lambda = 1$ TeV

First-Order EWPT

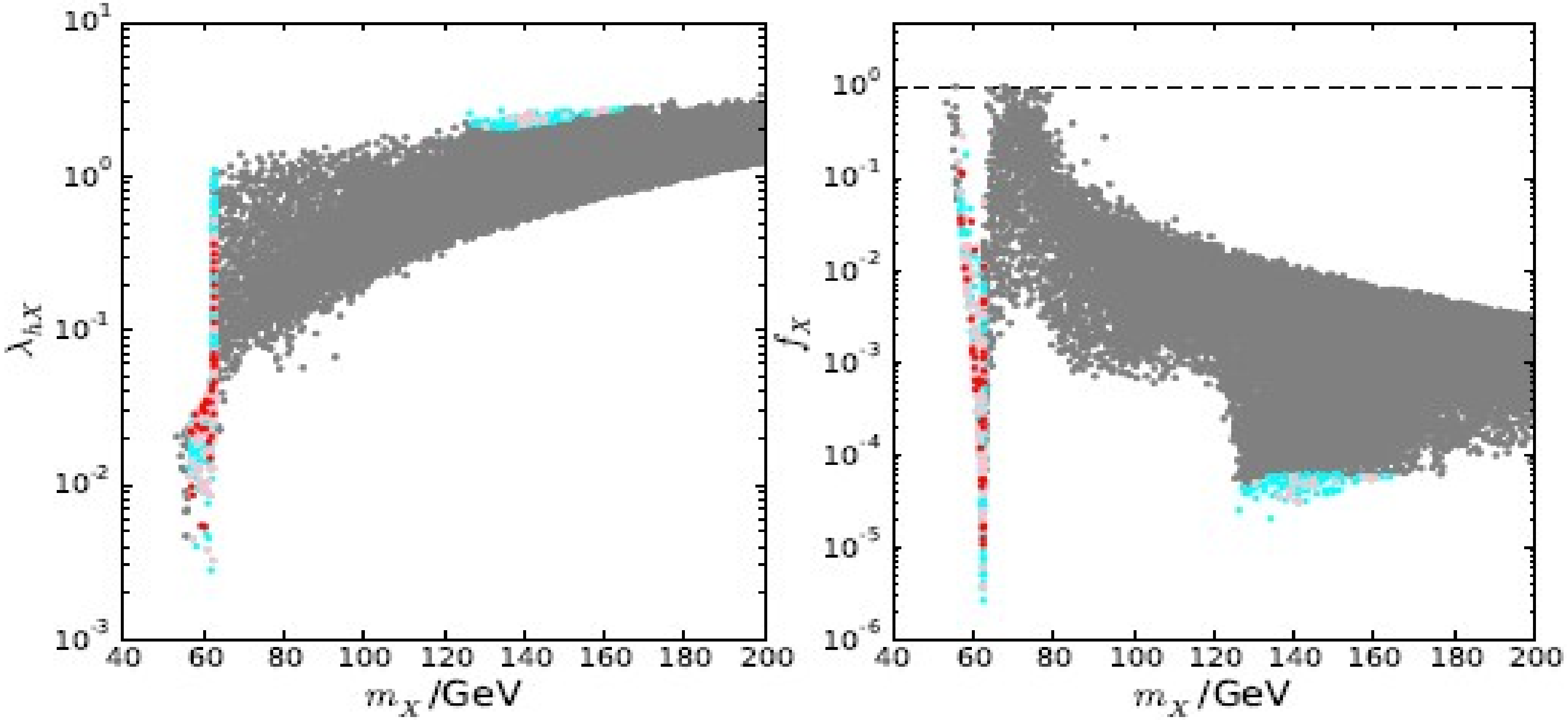
- Additional Constraints:

✓ Positive baryon asymmetry ➡ CPV phase $\alpha < 0$
✓ Validity of semiclassical framework ➡ $L_w T_c \geqslant 3$
✓ Reliable use of O_6 ➡ $\Lambda > 500$ GeV and $w_c^2/\Lambda^2 < 0.5$ for $\eta_B = \eta_B^{obs}$



Scanning Results

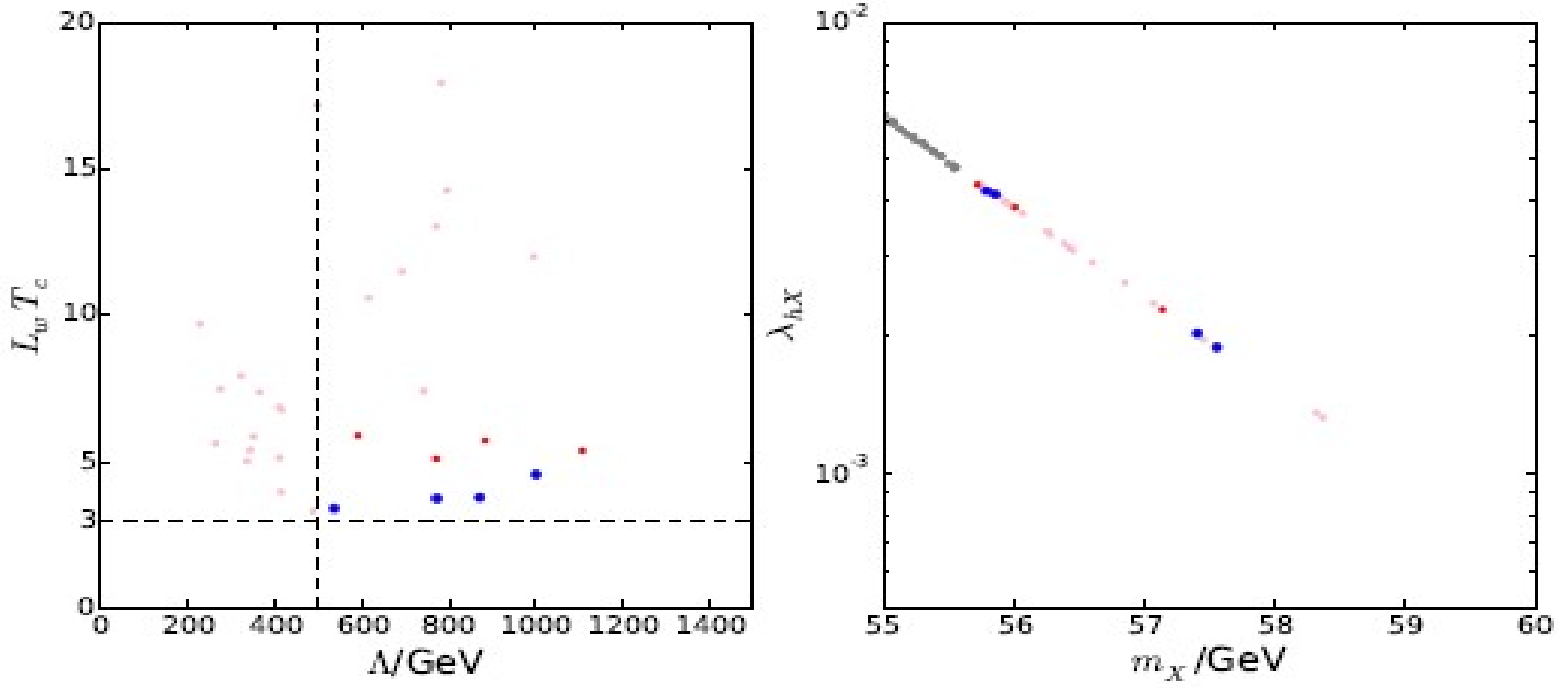
- Implications of EWBG on the DM properties



- Only SM Higgs resonance region can generate the enough cosmological baryon asymmetry without violating any bounds.

Models with Correct DM Density

- ➢ Question: Can this simple model explain the DM relic density and baryon asymmetry simultaneously?
- ➢ Zoom-in Scan near SM Higgs Resonance



Red: $w_c^2/\Lambda^2 < 0.5$

Blue: $w_c^2/\Lambda^2 < 0.2$

Summary

- We explored a new connection between DM and EWBG in a simple EW singlet extension of the SM.

- The model is appealing in that the CPV necessary for the EWBG is only spontaneously generated at temperatures higher than the EWPT, while the CP symmetry is restored at present time, so that the low-energy electron and neutron EDM constraints can be evaded.

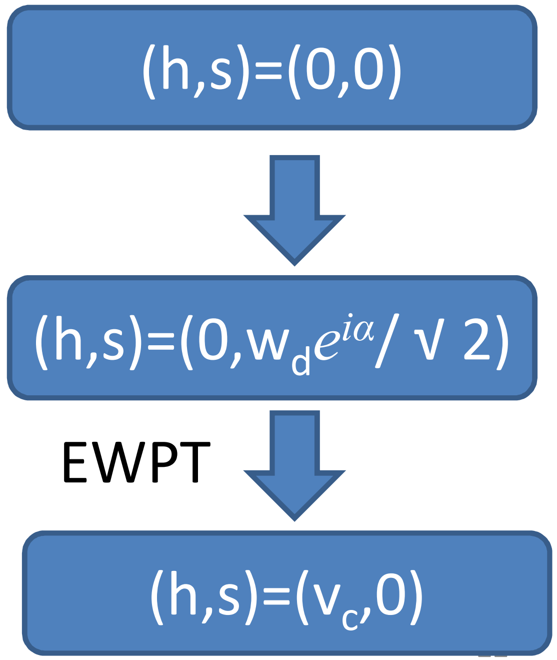
- We show that the model can generate the DM relic density and baryon asymmetry with the DM mass near the SM Higgs resonance.

Thanks for your attention!

Problems with Exact CP Symmetry

- Previously, we assumed that at the time before the EWPT, the Universe is filled with one vacuum with (h,S) = (0, $w_c e^{i\alpha} / \sqrt{2}$).
- However, in the present model, the transition has two steps.
- If Z_2 and CP symmetries are exact, when these two symmetries are broken in the 1st PT, it is expected that there are 4 vacua with $\langle S \rangle = \pm w_d e^{\pm i\alpha}$ left in the Universe, each with the same volume.

D. Comelli, et al., arXiv: 9304267;
J.McDonald, PLB **323**, 339 (1994);
PLB **357**, 19 (1995);



- Note that vacua with positive phases would produce negative baryon asymmetry during EWPT, which would cancel the positive baryon numbers created in vacua of negative phase.

Possible Solution with Explicit CPV

- One possible solution is to introduce a small explicit CPV phase in the scalar potential, which uplifts the vacua degeneracy so that the ones with negative phases are favored.

- Example: Explicit CPV in quartic term S^4

$$V_4 = \frac{\lambda_2 e^{i\delta}}{4} S^4 + \frac{\lambda_2 e^{-i\delta}}{4} S^{*4} + \frac{\lambda_2}{2} |S|^4 ,$$

So that the vacua $(0, \pm w_d e^{i\alpha}/\sqrt{2})$ have the potential density

$$V_T^+ = \frac{1}{8}\lambda_2 w_d^4 \cos(\delta + 4\alpha) + V_T^{CP} ,$$

while the potential for vacua $(0, \pm w_d e^{-i\alpha}/\sqrt{2})$ is

$$V_T^- = \frac{1}{8}\lambda_2 w_d^4 \cos(\delta - 4\alpha) + V_T^{CP} ,$$

D. Comelli, et al., arXiv: hep-ph/9304267; J.McDonald, PLB **323**, 339 (1994); PLB **357**, 19 (1995);

- Potential difference: $\Delta V_T = -\frac{1}{4}\lambda_2 w_d^4 \sin(4\alpha) \sin\delta$

Possible Solution with Explicit CPV

- It is shown that the disappearance of the wrong-sign vacua can proceed via the movement of the domain walls interpolating between the wrong- and right-sign vacua.

  H. Lew and A. Riotto, arXiv: hep-ph/9304203; J.McDonald, PLB **357**, 19 (1995);

- The domain wall begin to move when the energy scale of the potential difference approaches that of its surface energy $\eta_{\rm DM} \sim w_d^3$. Thus, the time for bubble wall movement is

$$t_{\rm DW} \approx \frac{\eta_{\rm DW}}{|\Delta V_T|} \sim \frac{1}{|\lambda_2 \sin(4\alpha)\sin\delta| w_d}.$$

- Our picture of EWBG requires to eliminate the wrong-sign domains at least before the EWPT with the time $t_{\rm EW} \sim M_{\rm Pl}/T_c^2$

$$|\sin\delta| > \frac{T_c^2}{|\lambda_2 \sin(4\alpha)| w_d M_{\rm Pl}} \sim \frac{T_c^2}{|\lambda_2 \sin(4\alpha)| w_c M_{\rm Pl}},$$

Possible Solution with Explicit CPV

➢ Typical EWPT parameters:

$$T_c \sim 100\ \text{GeV},\ w_c \sim 100\ \text{GeV},\ |\sin(4\alpha)| \sim 0.1\,,\ \ |\lambda_2| \sim \mathcal{O}(0.1)$$

the needed CPV phase can be as small as O(10^{-15}).

➢ It is obvious that such a small CPV phase cannot have any visible effects under the current experimental status.

➢ For the domain walls separating the two right-sign vacua $(0, \pm w_d e^{-i\alpha}/\sqrt{2})$, one would worry that they might dominate the energy density and change the evolution of the Universe.

➢ However, these domain walls would decay immediately after the Z_2 symmetry is restored at the EWPT with $T_c \sim$ 100 GeV, which is well before their domination time at $T \sim 10^{-7}$ GeV.

J. R. Espinosa, et al. arXiv: 1110.2876; J. M. Cline and K. Kainulainen, arXiv: 1210.4196

Problems with Exact CP Symmetry

- In the model with an exact dark CP symmetry, when this CP spontaneously breaks at high-T, there must exist regions with positive VEV CPV phase ($\alpha > 0$) with the same volume as the ones with negative phase.

- The regions with positive phase would produce the negative baryon number in the EWPT.

- Thus, when the EWPT finishes, the opposite baryon numbers created in these two kinds of regions will cancel each other, so that there is NO net baryon number left in the Universe.

Scanning Results

➢ Constraining power of DM direct searches