Gravitational waves from CP domain wall collapse and electron EDM in CxSM with dimension-five Yukawa interactions

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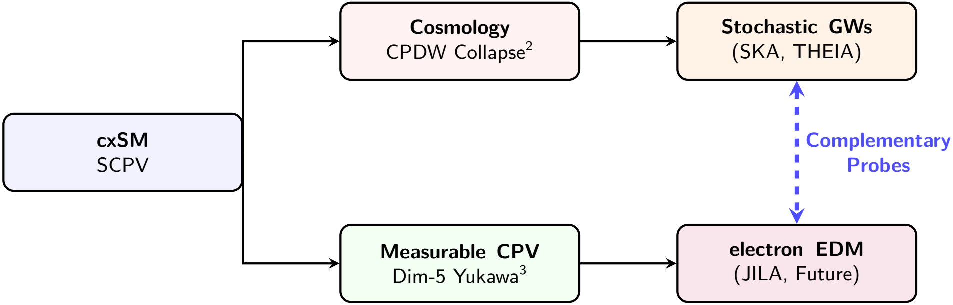
Outline

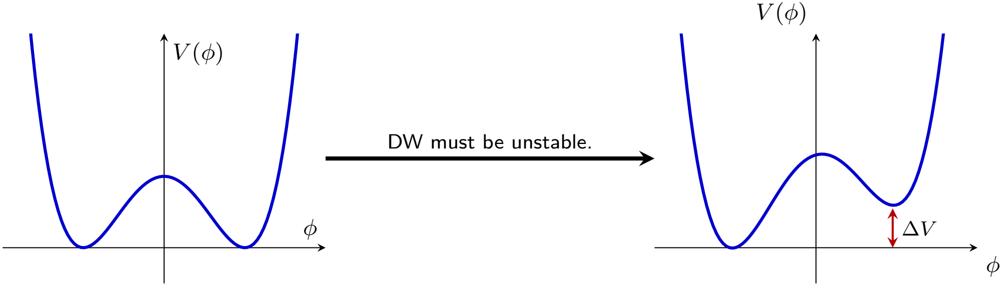
- **The Core Problem:** The Standard Model (SM) lacks sufficient CP Violation (CPV) to explain the Baryon Asymmetry of the Universe[1], which require Beyond SM sources.
- **The cxSM Solution:** A complex scalar singlet extension (complex field S) provides Spontaneous CPV (SCPV) but generates cosmological Domain Walls (DWs).



[1] Sakharov, "Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe".

[2] Chen, Li, and Wu, "The gravitational waves from the collapsing domain walls in the complex singlet model"

[3] Idegawa and Senaha, "Electron electric dipole moment and electroweak baryogenesis in a complex singlet extension of the Standard Model with degenerate scalars"



In cxSM with $\mathbb{Z}_2$ symmetry, 2 degenerated vacuum expectation values (VEVs) at $-v_S^i$ and $+v_S^i$.
The DW tension is approximated as:

$$\sigma_{\mathrm{DW}} \simeq \frac{2}{3} m_{h_3} v_S^{i2}.$$

The DW collapses when the bias, which explicitly breaks the $\mathbb{Z}_2$.
In our model, the bias term is represented as a_1:

$$\Delta V = 2\sqrt{2} |a_1^i v_S^i|.$$

The peak frequency of the GW[4]:

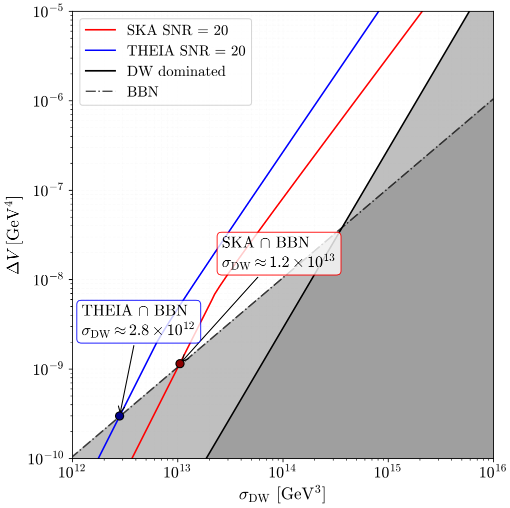
$$f_{\rm peak} \propto t_{\rm ann}^{-1/2} \propto \sigma_{\rm DW}^{-1/2} \Delta V^{1/2},$$

The peak of DW is around the nano-Hertz scale.
And the amplitude of GW at peak[5]:

$$\Omega_{\rm GW} h^2 (f_{\rm peak}) \propto \sigma_{\rm DW}^2 t_{\rm ann}^2,$$

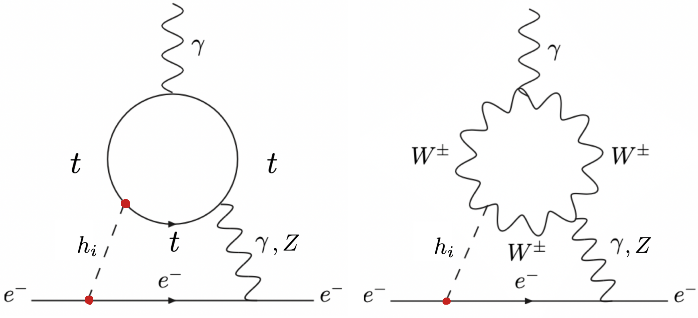
Constraint on DW annihilation:

- Big Bang nucleosynthesis (BBN): $t_{\rm ann} < 0.01{\rm s}$
- The DWs should not dominate the Universe.
- Detectable by the SKA and THEIA: we assume signal-to-noise ratio SNR> 20.



[4]Explicit form in Saikawa, "A review of gravitational waves from cosmic domain walls"

[5]Note that the GW spectrum follow Hiramatsu, Kawasaki, and Saikawa, "On the estimation of gravitational wave spectrum from cosmic domain walls"



The dim-5 Yukawa interaction:

$$Y^{\alpha}_{\rm SM} \to Y^{\alpha} + \frac{C^{\alpha}}{\Lambda} S$$

$(S^r, S^i, H)^T = O(h_1, h_2, h_3)^T$ where $O(\alpha_1, \alpha_2, \alpha_3)$.
Assume: $c_e^i = c_t^i = 0$, $c_e^r / c_t^r \simeq -y_e/y_t$.
The eEDM at 2-loop:

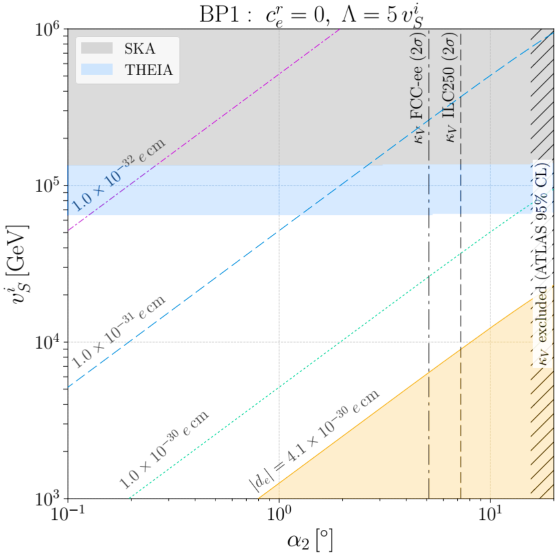
$$d_e \propto \frac{\alpha_2}{\Lambda}.$$

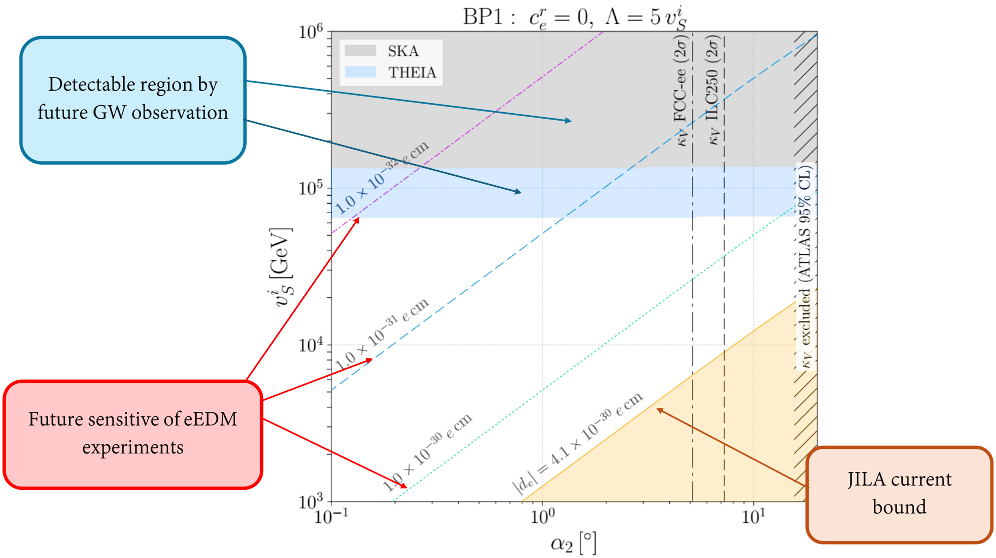
JILA current bound[6]:

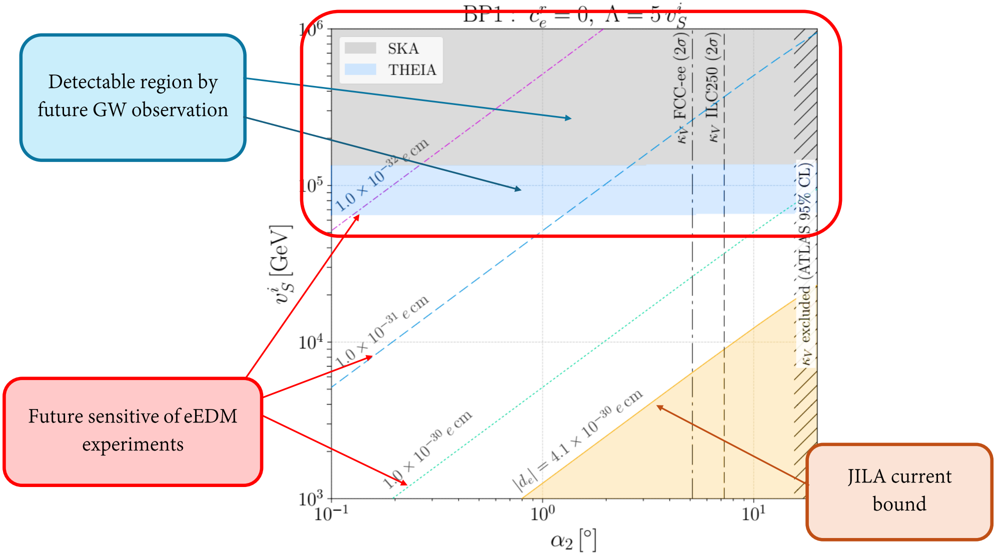
$$d_e = 4.1 \times 10^{-30} e\text{cm}$$

[6] Roussy et al., "An improved bound on the electron's electric dipole moment"

$m_{h_2} = 0.9$ TeV, $m_{h_3} = 1$ TeV




BP1 : $c_e^r = 0,\ \Lambda = 5\,v_S^i$
SKA
THEIA
κ_V FCC-ee (2σ)
κ_V ILC250 (2σ)
κ_V excluded (ATLAS 95% CL)
1.0×10^{-32} e cm
1.0×10^{-31} e cm
1.0×10^{-30} e cm
$|d_e| = 4.1 \times 10^{-30}$ e cm
v_S^i [GeV]
α_2 [°]
Detectable region by future GW observation
Future sensitive of eEDM experiments
JILA current bound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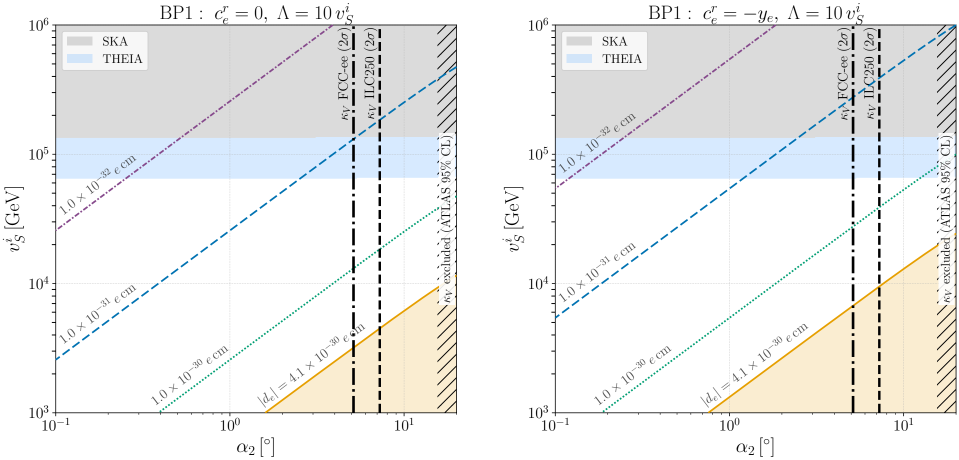
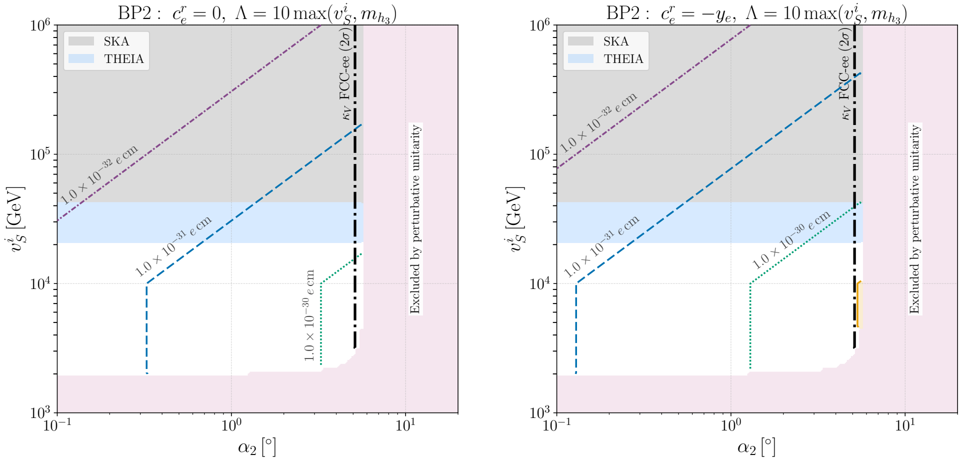
v_S^i [GeV]
α_2 [°]
10^3
10^4
10^5
10^6
10^{-1}
10^0
10^1
Detectable region by future GW observation
Future sensitive of eEDM experiments
JILA current bound

$$\mathrm{BP1}: \quad m_{h_2} = 0.9\ \mathrm{TeV}, \quad m_{h_3} = 1\ \mathrm{TeV}, \quad \Lambda = 10 v_S^i.$$



$$\mathrm{BP2}: \quad m_{h_2} = 9\ \mathrm{TeV}, \quad m_{h_3} = 10\ \mathrm{TeV}, \quad \Lambda = 10\max(m_{h_3}, v_S^i).$$



- **Complementarity:** Probing hidden-sector CPV by combining cosmological GWs (SKA/THEIA) and low-energy precision observables (eEDM).
- **Current Bounds:** Current JILA eEDM limit already excludes a significant region of the mixing angle α_2.
- **Future Prospects:** High-sensitivity future eEDM experiments strongly overlap with the detectable parameter space of future GW observatories.

The full details can be found at arxiv:2605.01318.

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Thank you for your attention!

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Backup slides

The Lagrangian of cxSM with dimension-five Yukawa interaction

$$\mathcal{L} = \mathcal{L}_{\rm cxSM} + \mathcal{L}_{h_i \bar{f} f}^{\rm dim-5}.$$

$$V_0(H,S) = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \boxed{a_1 S + \frac{b_1}{4} S^2 + \text{h.c.}},$$

with $v_S = v_S^r + i v_S^i$. Both a_1 and b_1 break a global U(1), and furthermore, a_1 also breaks the $\mathbb{Z}_2$ symmetry $S \to -S$.

From the dimension-five Yukawa interaction, then

$$Y_{\rm SM}^\alpha \to Y^\alpha + \frac{C^\alpha}{\Lambda} S.$$

$$\mathcal{L}_{h_i \bar{f} f} = -\sum_{i=1}^{3} h_i \bar{f} \left(g_{h_i \bar{f} f}^S + i \gamma_5 g_{h_i \bar{f} f}^P \right) f,$$

$$g_{h_i \bar{f} f}^S = \frac{m_f}{v} O_{1i} + \frac{v}{2\Lambda}(c_f^r O_{2i} - c_f^i O_{3i}),$$

$$\boxed{g_{h_i \bar{f} f}^P = \frac{v}{2\Lambda}(c_f^i O_{2i} + c_f^r O_{3i})},$$

erturbative unitarity

Quadratic term:

$$V(\Phi, \mathbb{S}) \propto \frac{\lambda}{4}|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4$$

with

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} G^+ \\ h + iG^0 \end{pmatrix}, \quad \mathbb{S} = \frac{1}{\sqrt{2}}(s + i\chi),$$

So we have:

$$V(G^\pm, G^0, h, S, \chi) \propto \frac{\lambda}{4}\left(\frac{1}{2}h^2 + \frac{1}{2}(G^0)^2 + G^+G^-\right)^2 + \frac{\delta_2}{4}\left(S^2 + \chi^2\right)\left(\frac{1}{2}h^2 + \frac{1}{2}(G^0)^2 + G^+G^-\right) + \frac{d_2}{16}\left(S^2 + \chi^2\right)^2$$

Perturbative unitarity

Taking the neutral states of $|G^+G^-\rangle$, $\frac{1}{\sqrt{2}}|G^0G^0\rangle$, $\frac{1}{\sqrt{2}}|hh\rangle$, $\frac{1}{\sqrt{2}}|SS\rangle$, $\frac{1}{\sqrt{2}}|\chi\chi\rangle$, we have the s-wave matrix:

$$a_0^+ = \frac{1}{16\pi}\begin{pmatrix} \lambda & \frac{\lambda}{2\sqrt{2}} & \frac{\lambda}{2\sqrt{2}} & \frac{\delta_2}{2\sqrt{2}} & \frac{\delta_2}{2\sqrt{2}} \\ \frac{\lambda}{2\sqrt{2}} & \frac{3\lambda}{4} & \frac{\lambda}{4} & \frac{\delta_2}{4} & \frac{\delta_2}{4} \\ \frac{\lambda}{2\sqrt{2}} & \frac{\lambda}{4} & \frac{3\lambda}{4} & \frac{\delta_2}{4} & \frac{\delta_2}{4} \\ \frac{\delta_2}{2\sqrt{2}} & \frac{\delta_2}{4} & \frac{\delta_2}{4} & \frac{3d_2}{4} & \frac{d_2}{4} \\ \frac{\delta_2}{2\sqrt{2}} & \frac{\delta_2}{4} & \frac{\delta_2}{4} & \frac{d_2}{4} & \frac{3d_2}{4} \end{pmatrix},$$

and for and $|hG^0\rangle$, $|SG^0\rangle$, $|\chi G^0\rangle$, $|\chi S\rangle$:

$$a_0^- = \frac{1}{16\pi}\text{diag}\left(\frac{\lambda}{2}, \frac{\delta_2}{2}, \frac{\delta_2}{2}, \frac{d_2}{2}\right).$$

the s-wave matrix for the charged states $|h\pi^\pm\rangle$, $|\pi^0\pi^\pm\rangle$, $|S\pi^\pm\rangle$ $|\chi\pi^\pm\rangle$:

$$a_\pm = \frac{1}{16\pi}\text{diag}\left(\frac{\lambda}{2}, \frac{\lambda}{2}, \frac{\delta_2}{2}, \frac{\delta_2}{2}\right)$$

Dynamics of the DW

The tension force, defined by the tension in a unit area $p_T \sim \sigma / R_{\text{wall}}$; The friction force, which appears when the particles interact with the DW. With a DW moving with the velocity v, the momentum transfer per collision is $\Delta p \sim Tv$; we can estimate the friction force as:

$$p_F \sim \Delta p n \sim v T^4,$$

When these two forces are balanced, we can obtain the following:

$$v \sim \frac{\sigma}{T^4 R_{\text{wall}}} \sim \frac{\sigma t^2}{m_{\text{pl}}^2 R_{\text{wall}}},$$

we also have $R_{\text{wall}} \sim vt$, so:

$$v \sim \frac{\sigma^{1/2} t^{1/2}}{m_{\text{pl}}}, \quad R_{\text{wall}} \sim \frac{\sigma^{1/2} t^{3/2}}{m_{\text{pl}}}.$$

DW reaches relativity speed as $t \sim m_{\text{pl}}^2 \sigma^{-1}$, recently, $R_{\text{wall}} \sim t$.

$$\rho_{\text{wall}} \sim \frac{\sigma}{t}.$$

The domain wall scale at $\sim t^{-1}$, much slower than the reducing of matter $\sim a^{-3}(t)$ and radiation $\sim a^{-4}(t)$.

The signal-to-noise ratio (SNR) is given by[7]:

$$\text{SNR} = \sqrt{n_{\text{det}}\, t_{\text{obs}} \int_{f_{\text{min}}}^{f_{\text{max}}} df \left(\frac{\Omega_{\text{GW}}(f)h^2}{\Omega_{\text{exp}}(f)h^2} \right)^2}, \tag{1}$$

where $n_{\text{det}} = 1$ for auto-correlated detectors and $n_{\text{det}} = 2$ for cross-correlated detectors.
SKA noise function[8]

$$\Omega_{\text{exp}}(f) = \sqrt{\frac{2}{N_p(N_p - 1)}} \frac{64\sqrt{3}\pi^4 \sigma^2\, \delta t}{H_0^2} f^5, \tag{2}$$

THEIA noise function[9]

$$\Omega_{\text{exp}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_{\text{GW}}^2, \tag{3}$$

with $h_{\text{GW}} = 1.6 \times 10^{-16}\, (1\,\text{year}/t_{\text{obs}})$

[7] Breitbach et al., “Dark, Cold, and Noisy: Constraining Secluded Hidden Sectors with Gravitational Waves”; Schmitz, “New Sensitivity Curves for Gravitational-Wave Signals from Cosmological Phase Transitions”.

[8] Breitbach et al., “Dark, Cold, and Noisy: Constraining Secluded Hidden Sectors with Gravitational Waves”.

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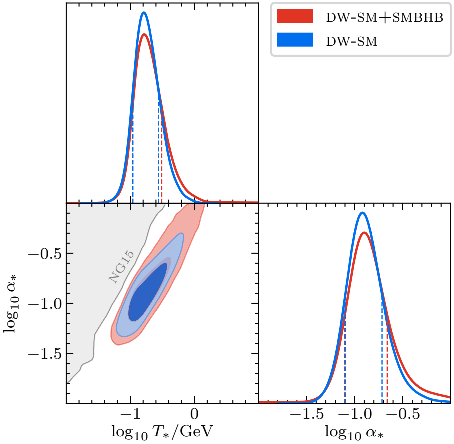

Figure 1: favored region and exception region from NANOGrav15[10]

[10] Afzal et al., "The NANOGrav 15 yr Data Set: Search for Signals from New Physics".