The collapsing domain walls in the BSM new physics

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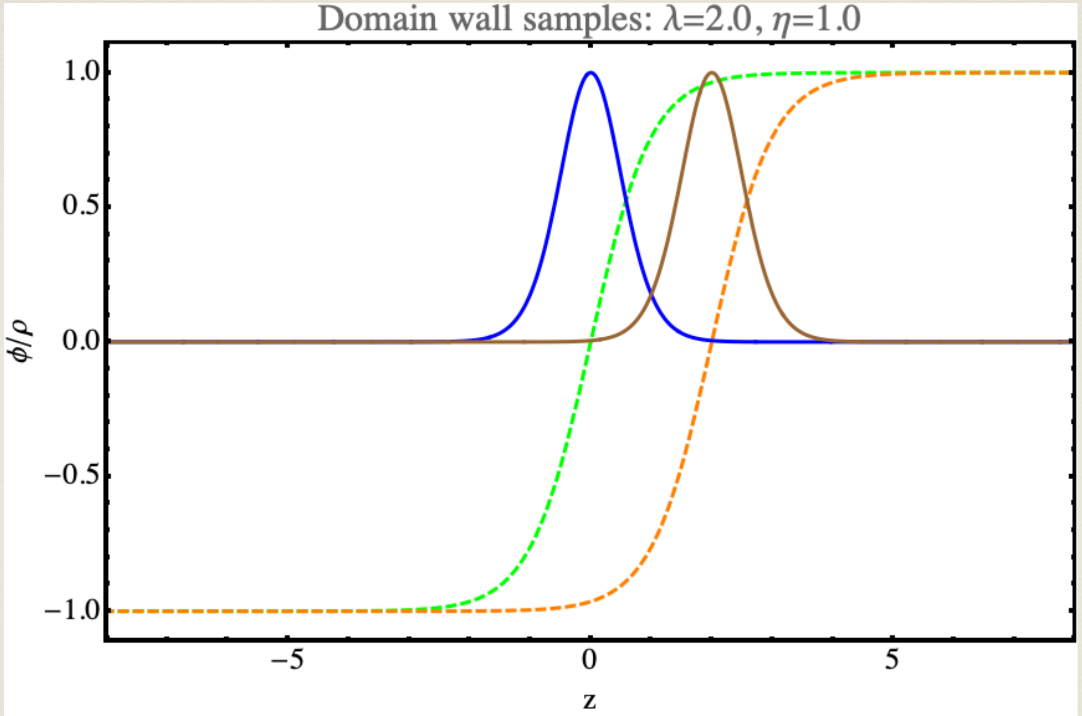
Plan of the talk

* Topological defects: such as **domain walls**, vortices, monopoles. Domain walls && monopoles are problematic in cosmology.
* Gravitational wave signals: complex singlet extension to the SM (cxSM), with decoupling scale of $10 - 100$ TeV.
* SCPV from the 2HDM and domain walls, the probes through the electron electric dipole moments (eEDM).

Domain walls: field theory

* Example with a real scalar: $V = \frac{\lambda}{4}(\phi^2 - \eta^2)^2$, embed the 1+1 dim kink solution into the 3+1 dim.



* A DW is a 2-dim extended object, and sits at some point along the z-axis, with the energy densities concentrated within a region of $\sim (\sqrt{\lambda}\eta)^{-1} \sim m_\phi^{-1}$

* A very important quantity in DW, wall tension (energy per unit area):

$$\sigma \equiv \int dz \rho(z) = \frac{2\sqrt{2}}{3}\sqrt{\lambda}\eta^3 \propto m_\phi \eta^2$$

Domain walls: cosmology

- DWs are problematic in cosmology, with the energy density $\rho_{\rm DW} \propto t^{-1}$. The energy densities for radiation/matter: $\rho_{\rm rad} \propto t^{-2}$, $\rho_{\rm matt} \propto t^{-3/2}$. DWs can overtake the Universe once they are formed.

- Zel'dovich-Kobzarev-Okun bound, the CMBR constraints to the density fluctuation from the DWs:

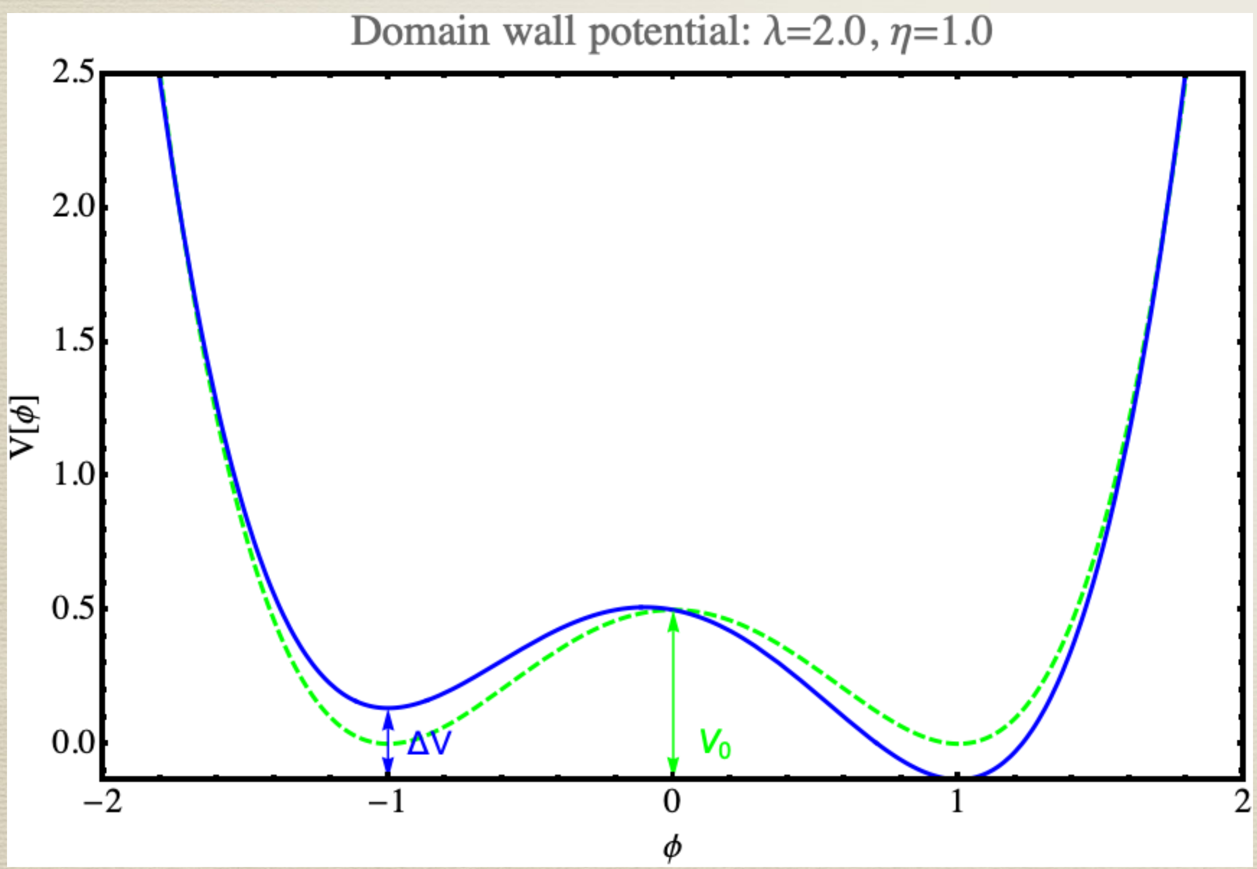
$$\frac{\delta\rho}{\rho} \sim G_N \sigma t_0 \sim 10^{12}(\frac{\sigma}{\rm TeV^3}) \lesssim \mathcal{O}(10^{-5}) \quad \sigma \lesssim \mathcal{O}(1)\,{\rm MeV}^3$$

- In most studies, the parameter spaces leading to DWs in the new physics are avoided.

Domain walls: cosmology

* Some solutions to the domain wall problem:
(1) Inflation (Guth, Tye), typically at high scale of $\Lambda_{\rm GUT} \sim 10^{16}\,{\rm GeV}$, still problematic for ~TeV scale.
(2) The symmetries are approximate, with the “biased terms”:

$$V = \frac{\lambda}{4}(\phi^2 - \eta^2)^2 + \epsilon\eta\phi(\frac{1}{3}\phi^2 - \eta^2)$$



The BBN constraint:

$$t_{\rm ann} \sim 10^{-4}\,{\rm sec}\,\frac{\sigma}{\rm TeV^3}(\frac{\Delta V}{\rm MeV^4})^{-1} \lesssim 10^{-2}\,{\rm sec}$$

$$\Delta V^{1/4} \gtrsim 10^{-4}\,{\rm GeV}\left(\frac{\sigma}{1\,{\rm TeV}^3}\right)^{1/4}$$

Vilenkin (’81)
Gelmini, Gleiser, Kolb, (’89)
Larsson, Sarkar, White (’96)

The domain wall collapse in the cxSM: GW

The cxSM

* The SM plus a complex singlet $\mathbb{S}$, the minimal terms:

$$V(\Phi, \mathbb{S}) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \frac{\delta_2}{2} |\Phi|^2 |\mathbb{S}|^2 + \frac{b_2}{2} |\mathbb{S}|^2 + \frac{d_2}{4} |\mathbb{S}|^4$$

* The global symmetries:
(1) $\mathrm{U}(1)$: $\mathbb{S} \to e^{i\alpha}\mathbb{S}$; (2) CP: $\mathbb{S} \to \mathbb{S}^*$; (3) $\mathbb{Z}_2$: $\mathbb{S} \to -\mathbb{S}$.

* We focus on the SCPV by including two more terms:

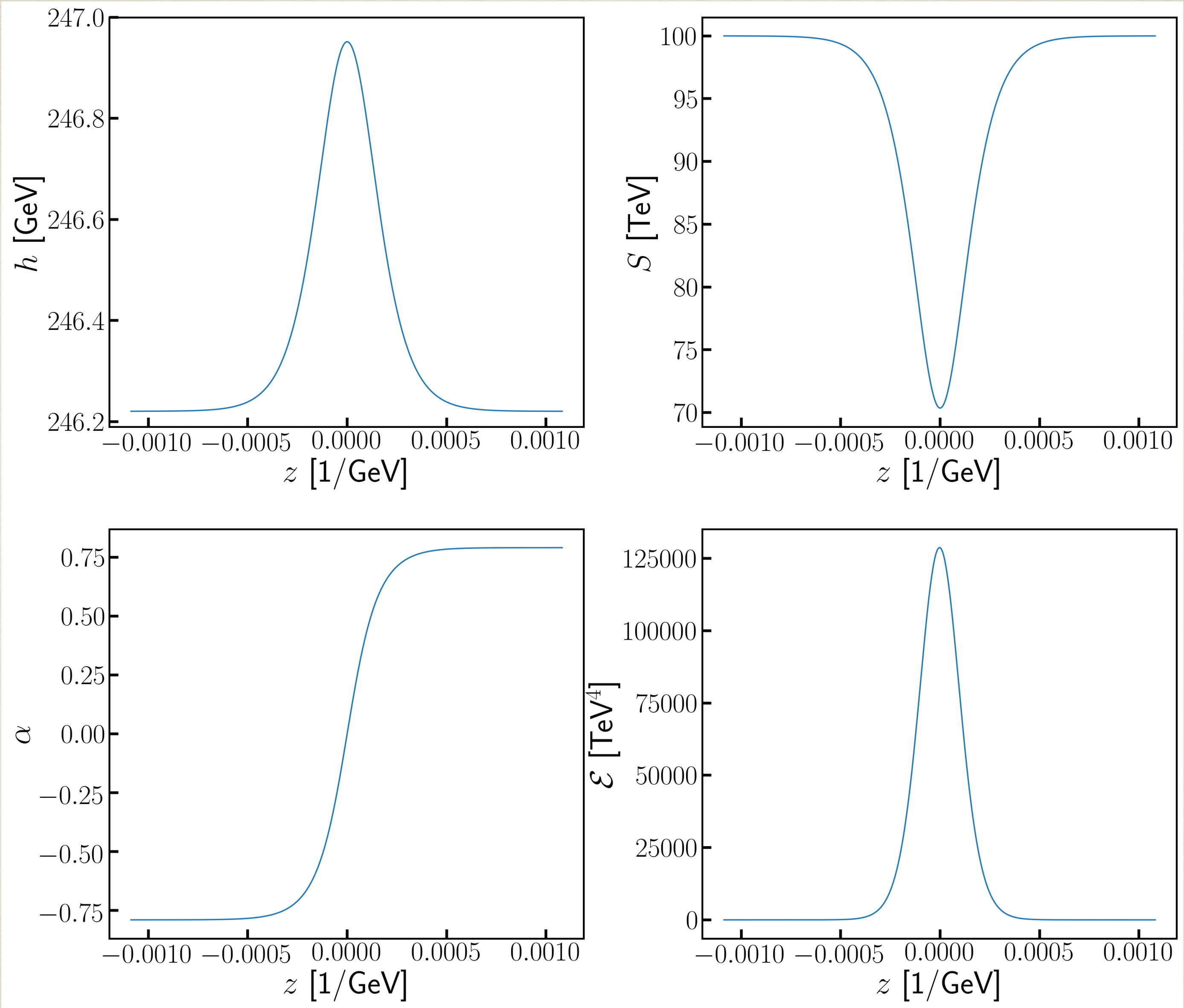
$$V(\Phi, \mathbb{S}) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \frac{\delta_2}{2} |\Phi|^2 |\mathbb{S}|^2 + \frac{b_2}{2} |\mathbb{S}|^2 + \frac{d_2}{4} |\mathbb{S}|^4$$

$$+ \left(\frac{b_1}{4}\mathbb{S}^2 + \frac{d_1}{8}\mathbb{S}^4 + c.c. \right)$$, with $b_1, d_1 \in \mathbb{R}$ and $\langle \mathbb{S} \rangle = \frac{1}{\sqrt{2}} v_s e^{i\alpha}$

* The SCPV domain walls of $\vec{\phi} = (h, S, A)$:

$$\frac{d^2\vec{\phi}}{dz^2} = \vec{\nabla}_\phi V \quad \& \quad \vec{\phi}(z = \mp\infty) = (v, v_s c_\alpha, \mp v_s s_\alpha)$$

SCPV domain wall



$m_1 = 125$ GeV, $(m_2, m_3) = (10, 10.1)$ TeV,
$v_s = 100$ TeV, $(\alpha_1, \alpha_3) = (10^{-3}, 10^{-4})$

$\sigma \sim (100\,\mathrm{TeV})^3 > \ldots > \mathcal{O}(1)\,\mathrm{MeV}^3$

The GW in the cxSM

* The explicit CPV term is necessary:

$$V_{\cancel{CP}}(v\,, v_s\,, \alpha) = -\frac{1}{4}\Big(\Im b_1 \sin(2\alpha) v_s^2 + \frac{\Im d_1}{4}\sin(4\alpha) v_s^4\Big)$$

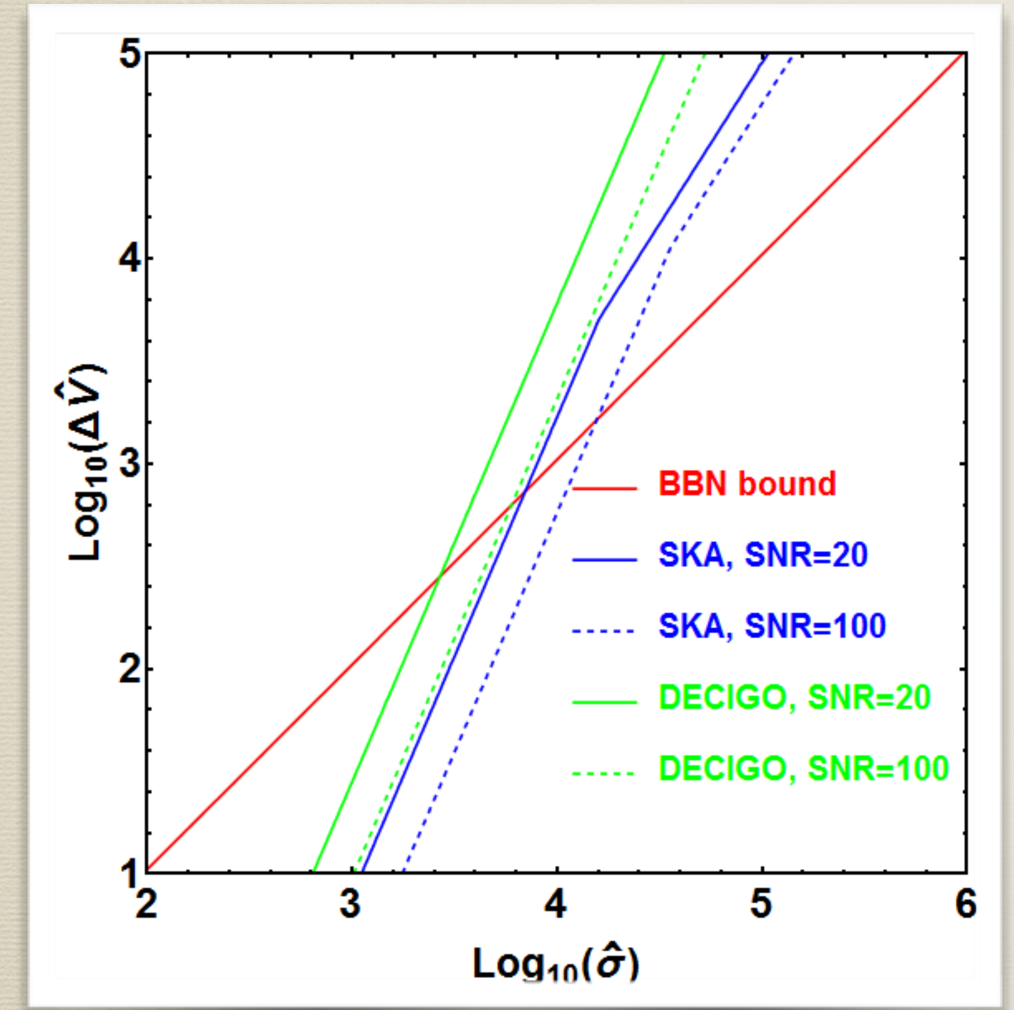
$$\Delta V = \left|\frac{\Im b_1}{2}\sin(2\alpha)v_s^2 + \frac{\Im d_1}{8}\sin(4\alpha)v_s^4\right|_{\alpha=\frac{1}{2}\cos^{-1}\left(\frac{\Re b_1}{-\Re d_1 v_s^2}\right)}$$

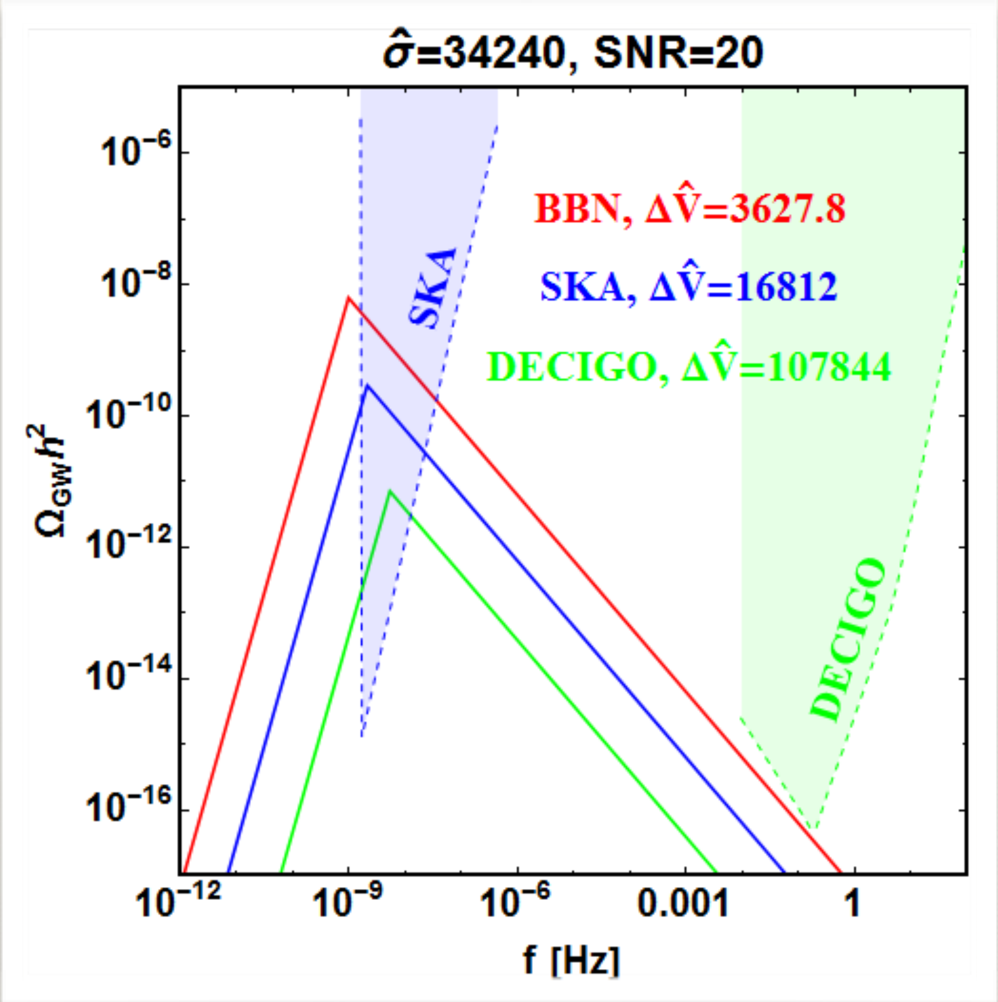
* To evaluate the GW signals, the peak frequency and energy spectrum:

$$f_{\rm peak} \sim 10^{-9}\,{\rm Hz}\left(\frac{\sigma}{1\,{\rm TeV}^3}\right)^{-1/2}\left(\frac{\Delta V}{1\,{\rm MeV}^4}\right)^{1/2}$$

$$\Omega_{\rm GW}^{\rm peak} h^2(t_0) \sim 10^{-20}\left(\frac{\sigma}{1\,{\rm TeV}^3}\right)^{4}\left(\frac{\Delta V}{1\,{\rm MeV}^4}\right)^{-2}$$

The GW in the cxSM

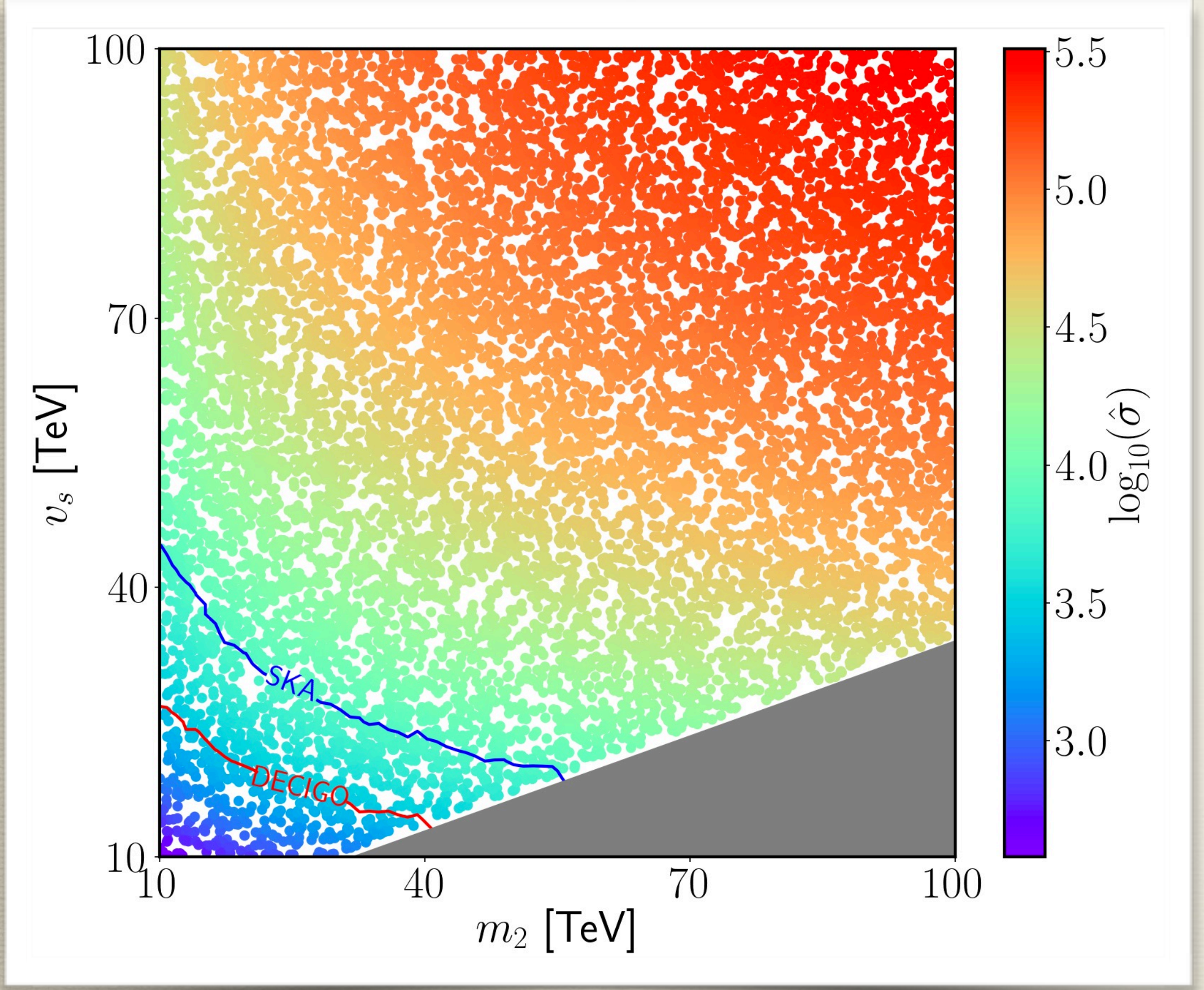


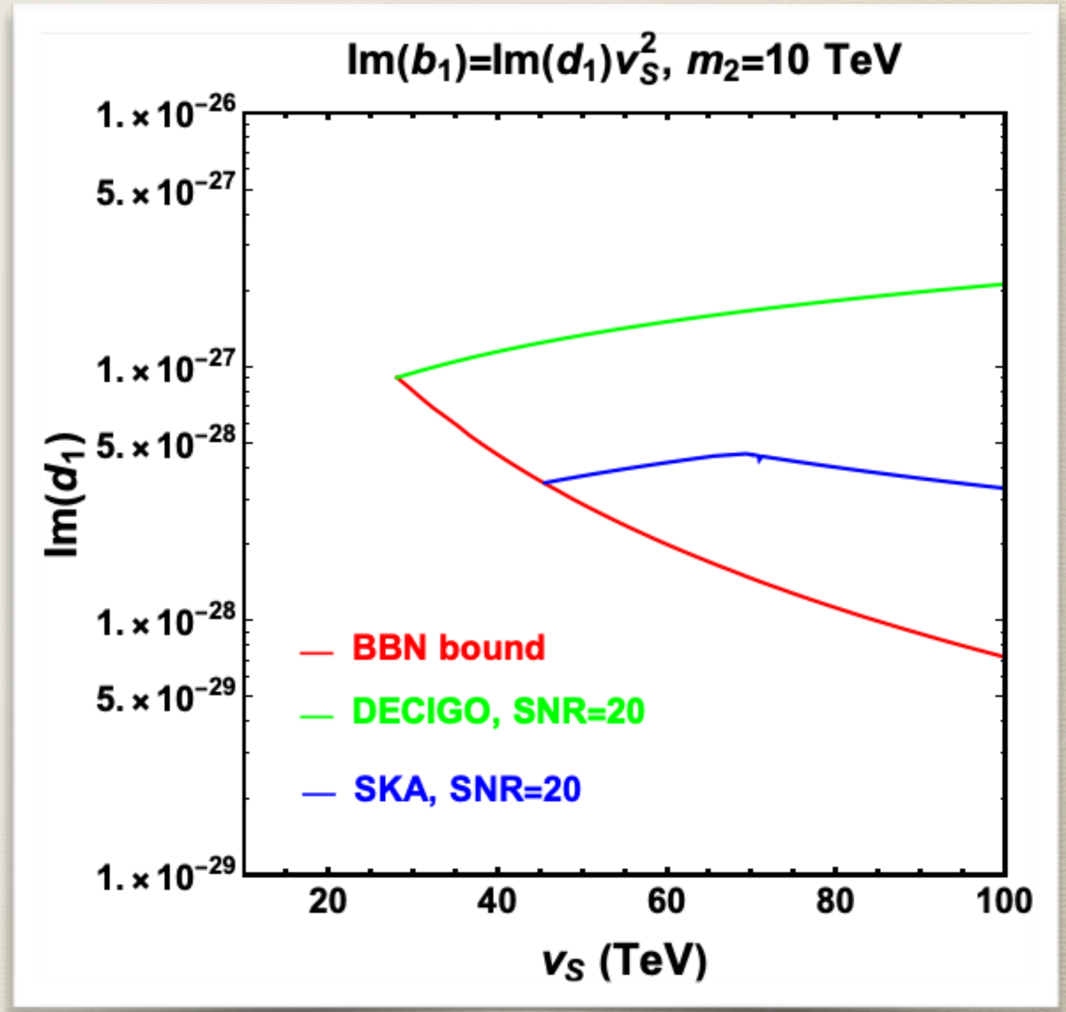


$$\mathrm{SNR} = \sqrt{\mathscr{T}\int_{f_{\min}}^{f_{\max}} df \left[\frac{\Omega_{\rm GW}(f)h^2}{\Omega_{\exp}(f)h^2}\right]^2}$$

can be probed at the SKA, with $f_{\rm peak} \sim$ few nHz

The GW in the cxSM





The domain wall collapse in the 2HDM: EDM

The 2HDM

* The 2HDM was first proposed by T. D. Lee ('74) to incorporate new CPV sources.

Therefore, with only a single complex ϕ^o field, it is not possible to generate a spontaneous T violation. The simplest way to produce a spontaneous T violation is to double the number of neutral spin 0 fields, so that there are two such complex fields, say ϕ_1^o and ϕ_2^o. These two neutral fields must belong to two separate representation spaces, which may or may not be equivalent.

and consequently

$$\langle\phi_1^o\rangle_{vac} = \rho_1 e^{i\theta}, \qquad \text{and} \qquad \langle\phi_2^o\rangle_{vac} = \rho_2. \tag{2.34}$$

The 2HDM: SCPV

* The 2HDM with the SCPV:
$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.)$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.\right]$$

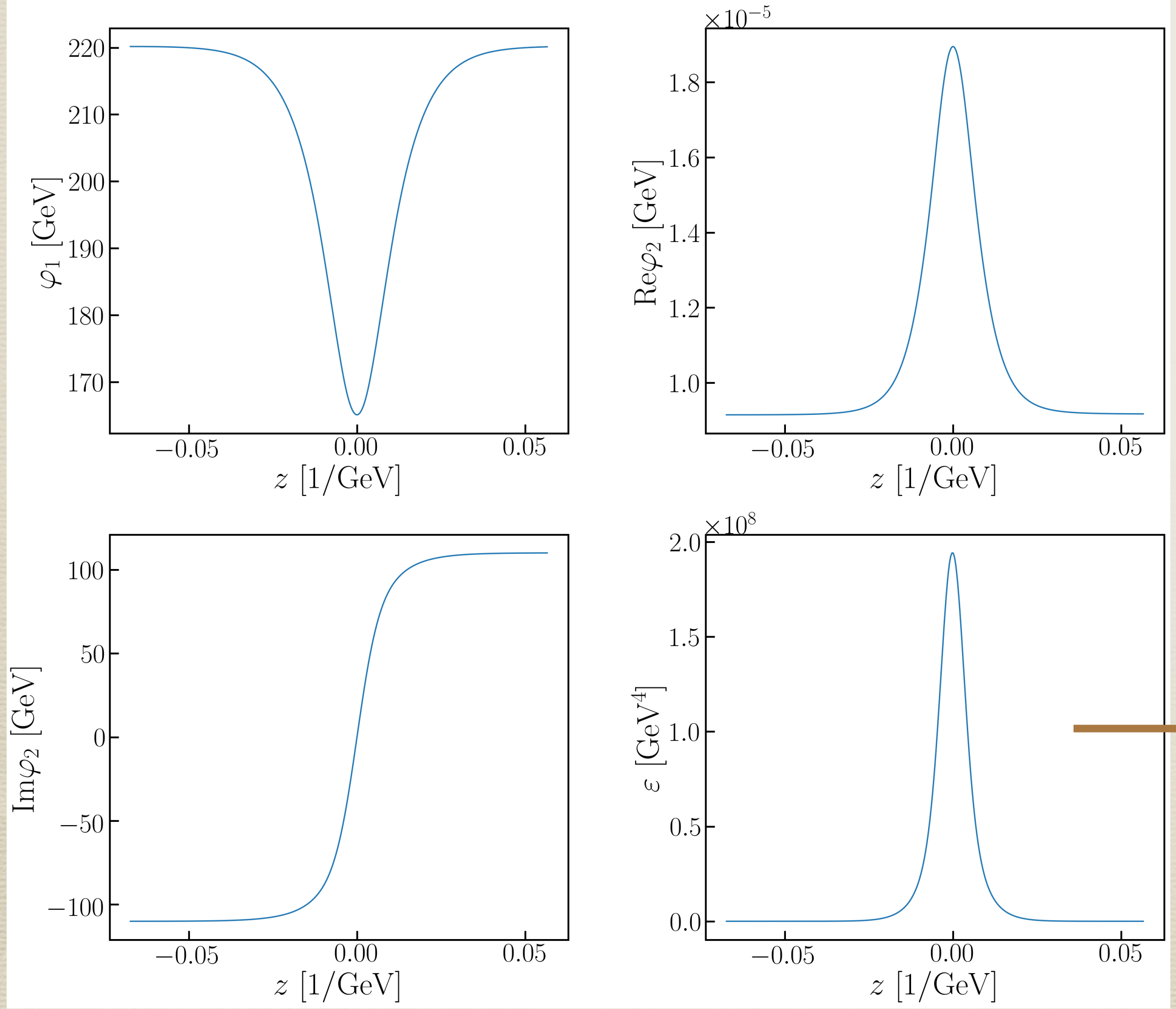
* m_{12}^2 and λ_5 are complex in general, the SCPV occurs when they are both real ($\mathrm{Im}[(m_{12}^2)^2\lambda_5^*] = 0$), while: $\langle\Phi_1\rangle^T = \frac{1}{\sqrt{2}}(0, v_1)$, $\langle\Phi_2\rangle^T = \frac{1}{\sqrt{2}}e^{i\theta}(0, v_2)$.

* The CP symmetry: $\Phi_i \to \Phi_i^*$, $\theta \to -\theta$.

The 2HDM: SCPV

* The SCPV 2HDM domain walls of $\overrightarrow{\phi} = (\varphi_1\,, \mathrm{Re}\varphi_2\,, \mathrm{Im}\varphi_2)$:

$$\frac{d^2\overrightarrow{\phi}}{dz^2} = \overrightarrow{\nabla}_{\phi} V \quad \& \quad \overrightarrow{\phi}(z = \mp\infty) = (v_1\,, v_2 c_\theta\,, \mp v_2 s_\theta)$$



$$\sigma \sim \delta \cdot V_0 \sim (100\,\mathrm{Gev})^3$$
$$> \ldots > \mathcal{O}(1)\,\mathrm{MeV}^3$$

SCPV+ECPV

* The SCPV 2HDM domain walls can collapse with the ECPV terms, by setting (m_{12}^2, λ_5) to be complex in general.

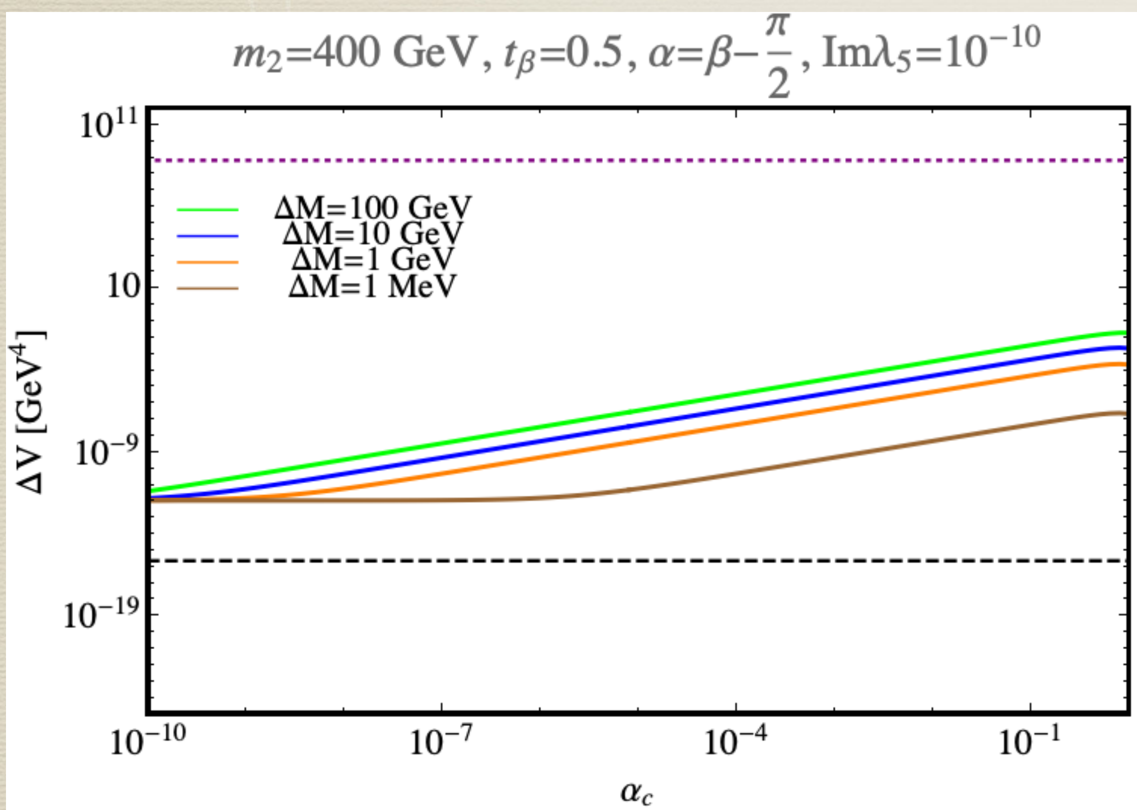
* One subtlety: the SCPV+ECPV is different from the pure ECPV. In many cases with the pure ECPV terms in the 2HDM, one sets $\theta = 0$ to avoid the DW problem. The $\mathrm{Re} m_{12}^2$ is an independent parameter. (1403.4257, 1503.01114, and etc)

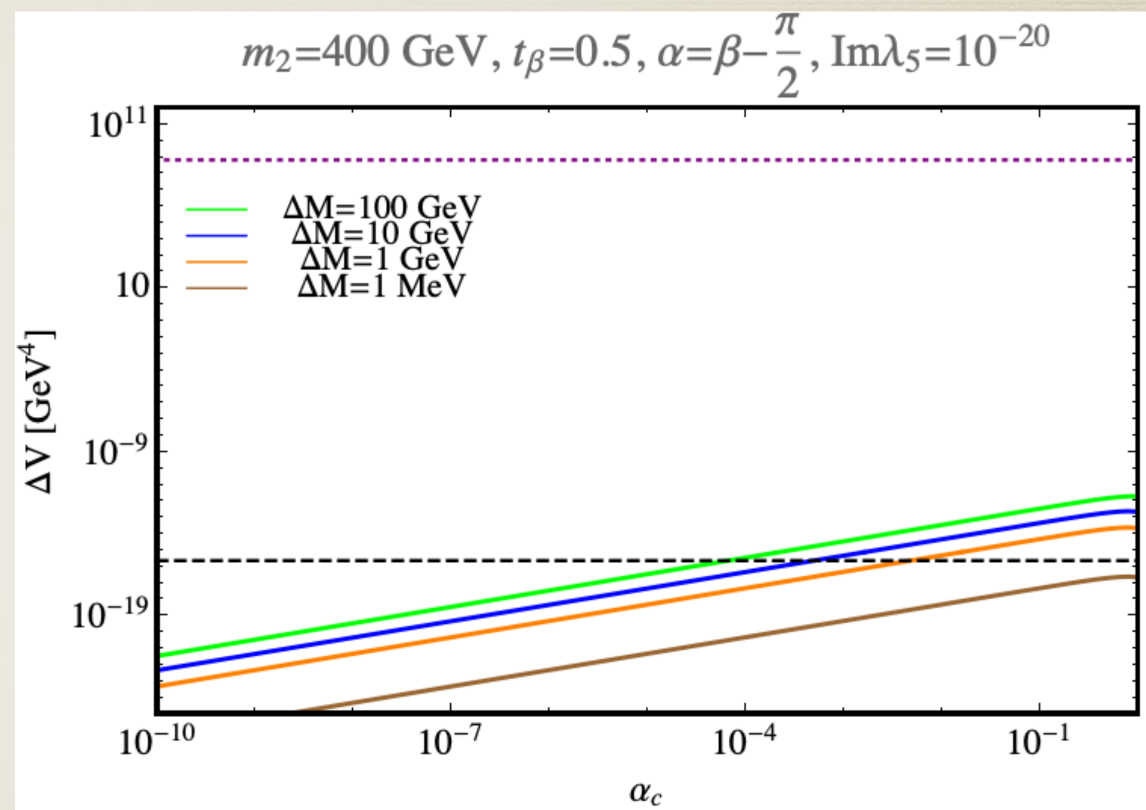
* The SCPV 2HDM domain walls can collapse with the full ECPV terms $V_{\mathrm{ECPV}} = \mathrm{Im} m_{12}^2 v_1 v_2 s_\theta - \frac{1}{4} \mathrm{Im} \lambda_5 v_1^2 v_2^2 s_{2\theta}$, and to solve for the θ:

$$\sum_i m_i^2 \mathcal{R}_{i3}^2 s_\theta c_\theta + \sum_i m_i^2 \mathcal{R}_{i1} \mathcal{R}_{i3} \frac{s_\theta^2}{s_\beta} = \frac{1}{2} \mathrm{Im} \lambda_5 v^2 - \mathrm{Im} m_{12}^2 \frac{c_\theta}{s_\beta c_\beta}$$

SCPV+ECPV

* The size of the biased term ΔV:





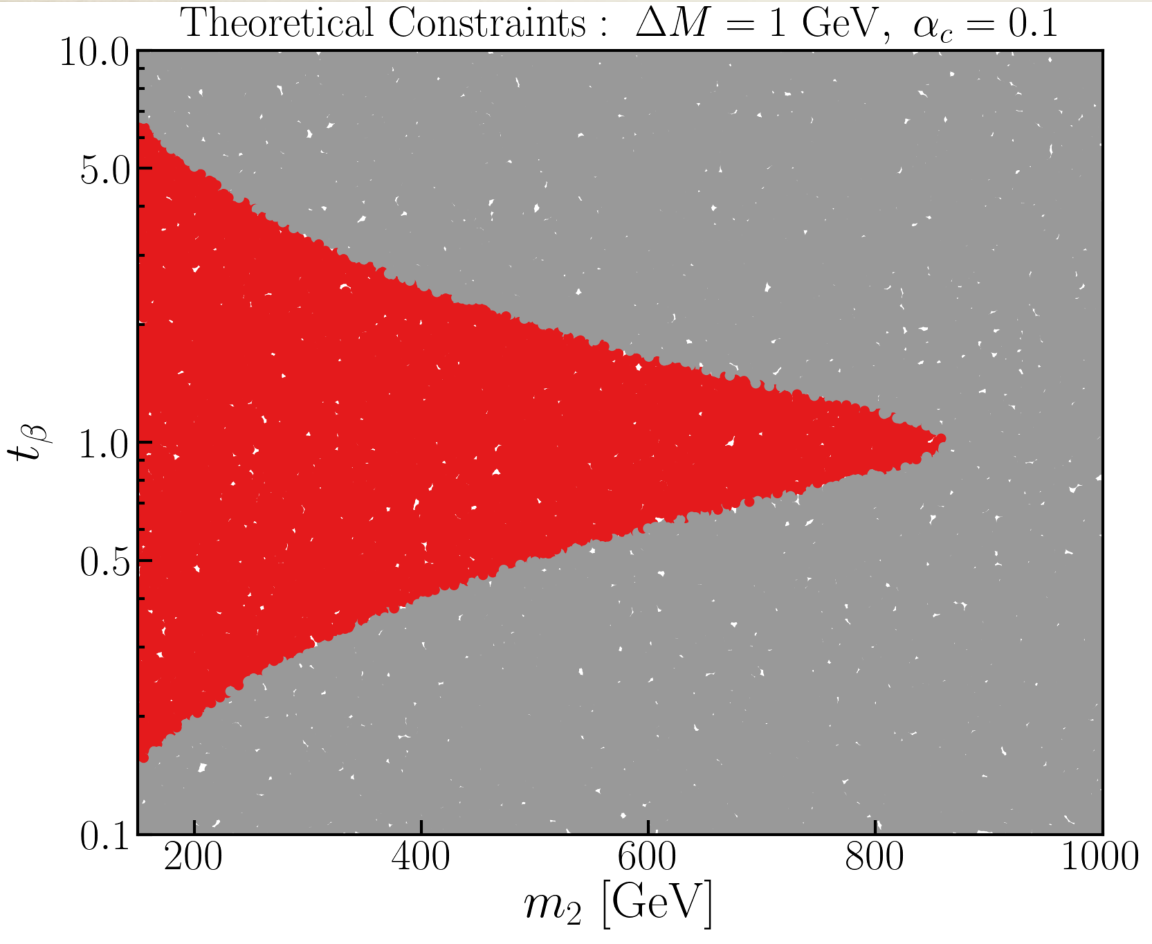
(1) For sufficiently small $\mathrm{Im}\lambda_5$, the CPV mixing angle α_c can be bounded from below, to be constrained by the EDM.

(2) The BBN has ruled out regions with small $\mathrm{Im}\lambda_5 \lesssim 10^{-20}$ and very small mass splitting of $\Delta M \sim 1\,\mathrm{MeV}$.

SCPV+ECPV

* The relations in two basis for the 2HDM with the ECPV:

Generical basis	Physical basis
$\lambda_{1,2,3,4}\,,\mathrm{Re}\lambda_5\,,\mathrm{Im}\lambda_5$	$m_{1,2,3}\,,\ m_\pm\,,\ v$
$m_{11}^2\,,m_{22}^2\,,\mathrm{Re}m_{12}^2\,,\mathrm{Im}m_{12}^2$	$\alpha\,,\alpha_b\,,\alpha_c\,,\beta\,,\theta$



Unitarity: $|\lambda_i| \lesssim 4\pi$

Stability: $\lambda_{1,2} > 0\,, \lambda_3 > -\sqrt{\lambda_1\lambda_2}$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$$

favored region: $0.2 \lesssim t_\beta \lesssim 5,$

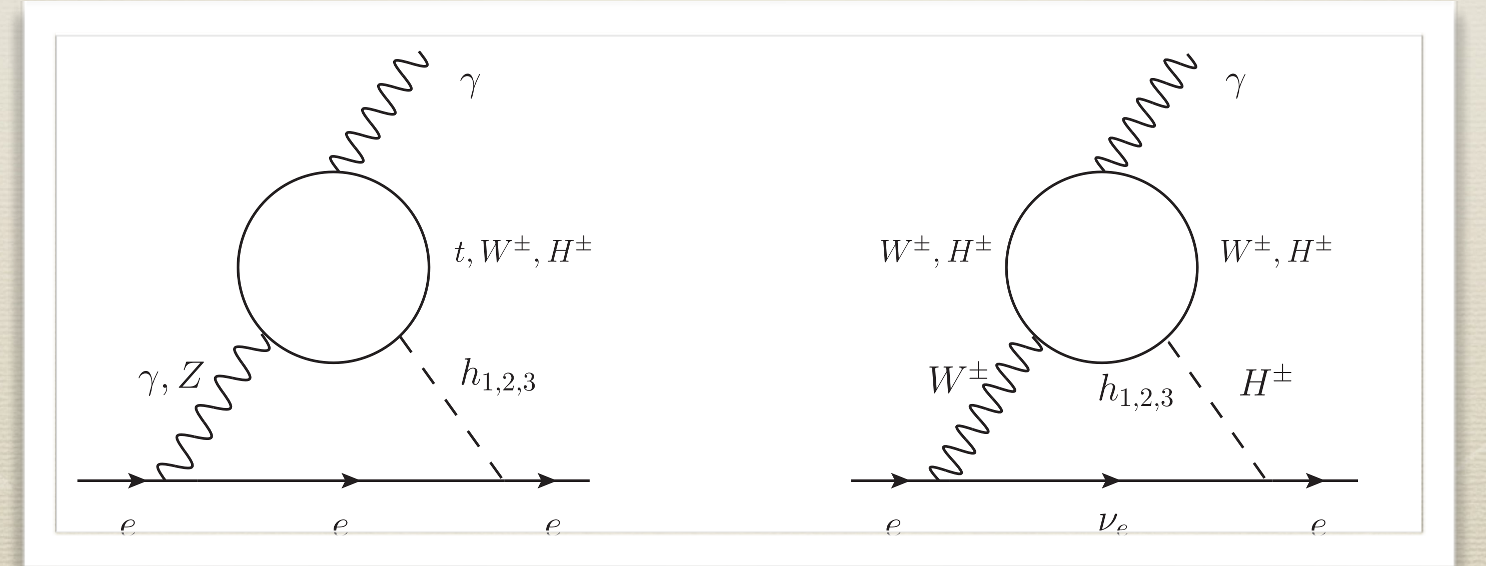
$m_2 \lesssim 800\,\mathrm{GeV}$

The eEDM in the 2HDM

* The current and future eEDM upper bounds:
  ACME-II: $|d_e| \leq 1.1 \times 10^{-29}\, e \cdot \mathrm{cm}$
  ACME-III: $|d_e| \lesssim 1.0 \times 10^{-30}\, e \cdot \mathrm{cm}$ (maybe next 5 years)

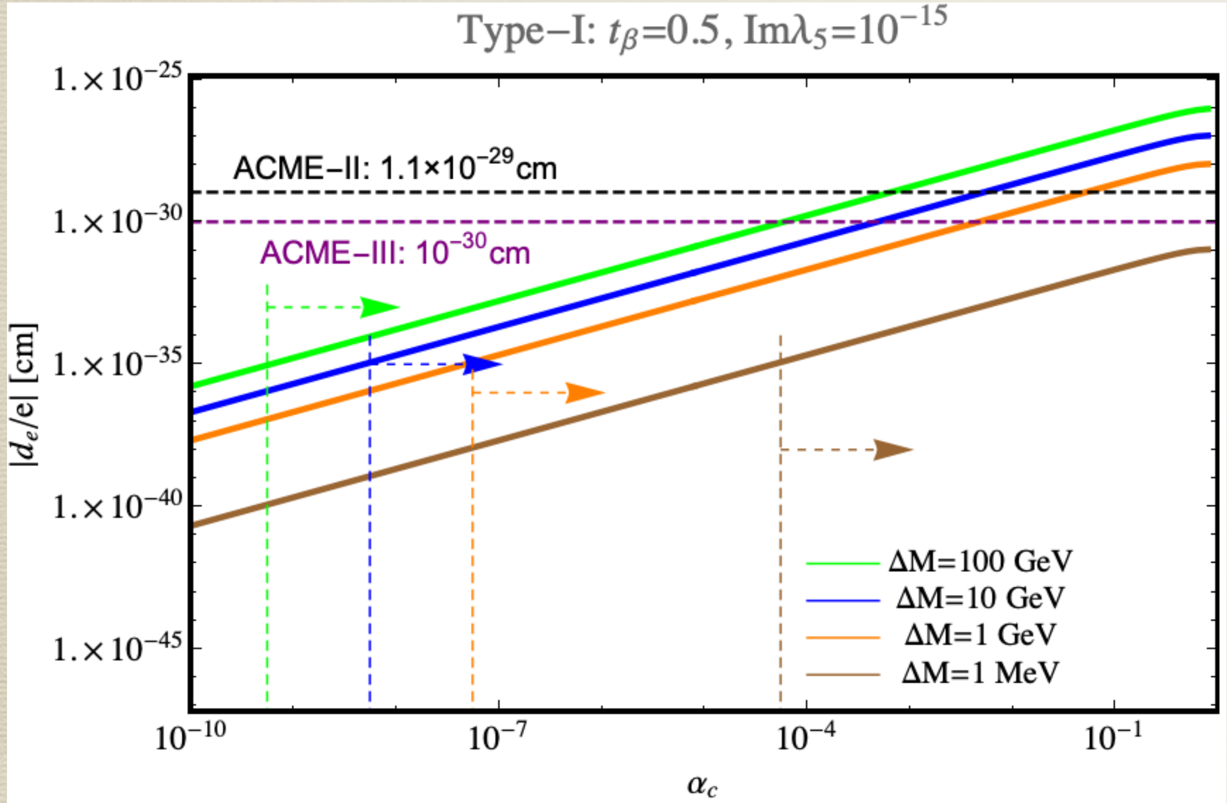
* The SM predictions: $|d_e| \sim 10^{-38} - 10^{-39}\, e \cdot \mathrm{cm}$ (2006.00281)

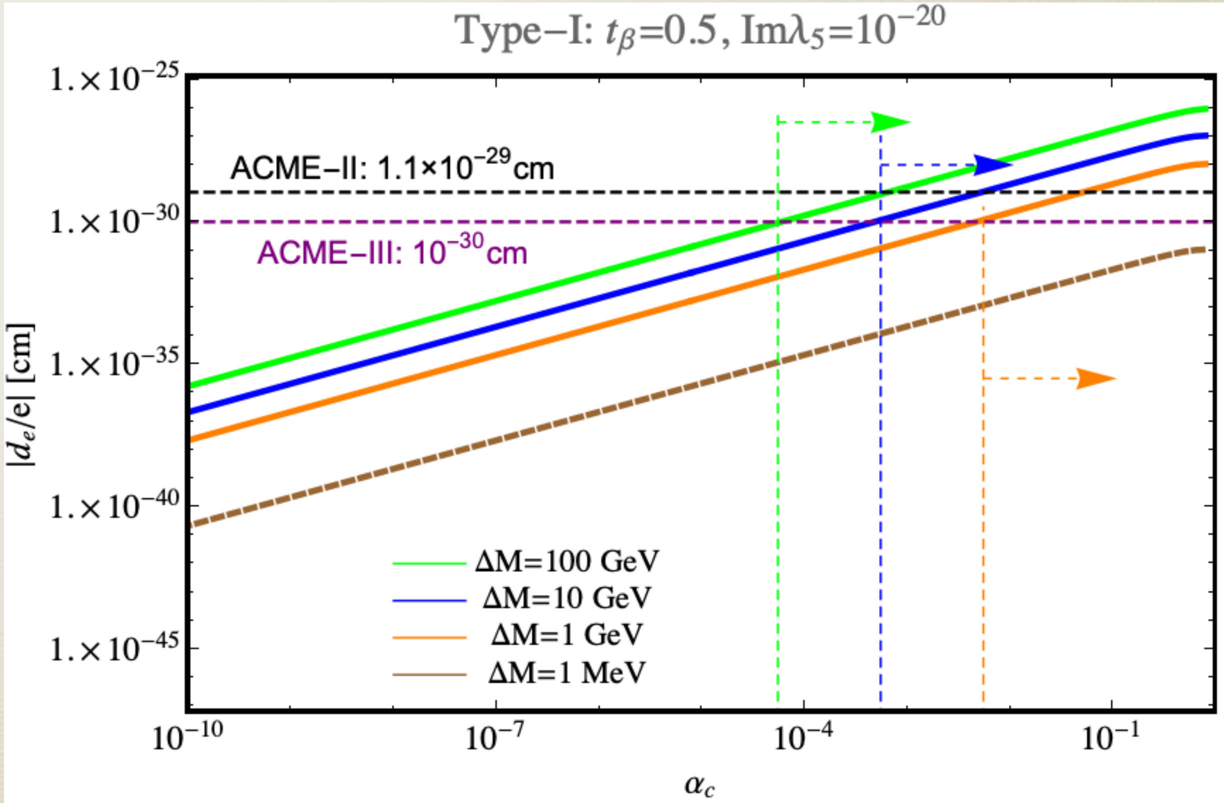
* Contributions in the 2HDM are mainly from Barr-Zee diagrams:



The joint constraints

- The joint eEDM && collapsing domain wall constraints





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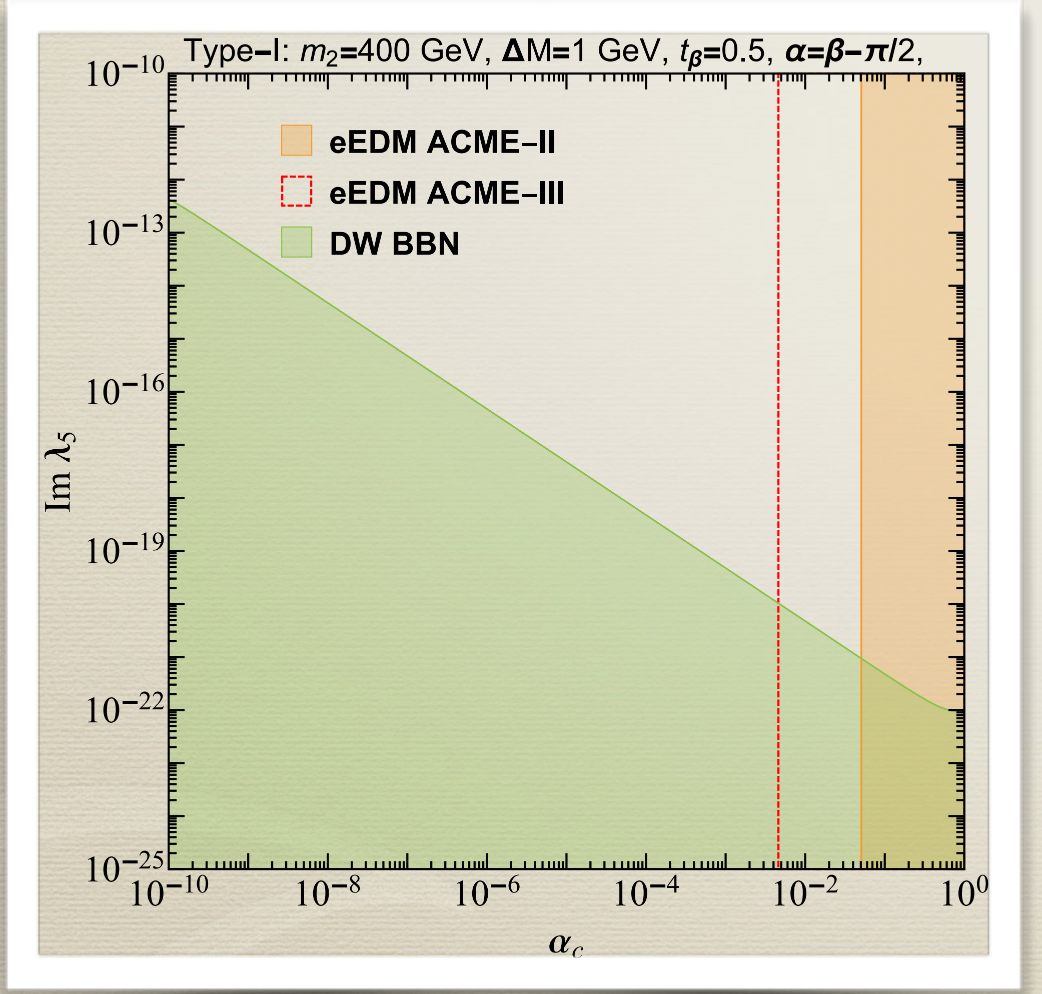
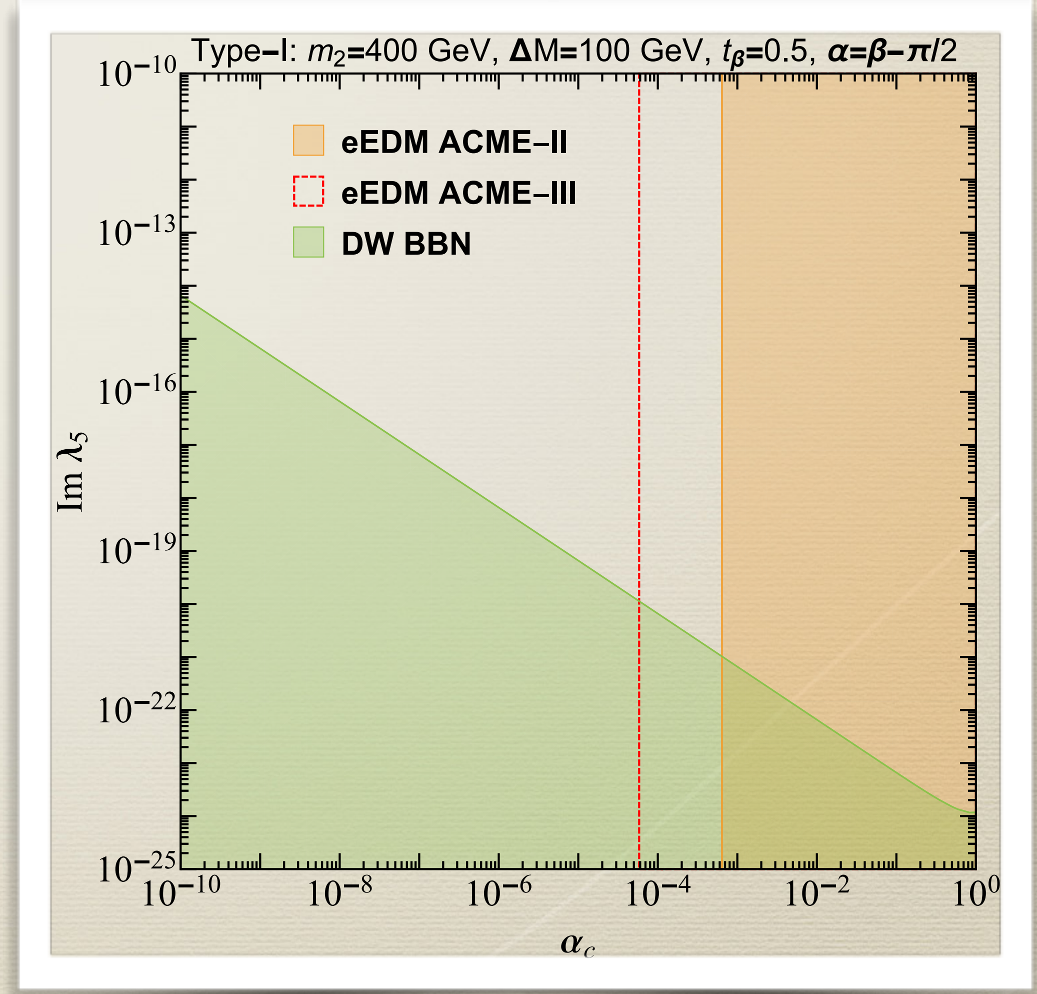




Summary

* DWs (and other topological defects) are possible in the BSM new physics, it is possible that they are unstable with approximate symmetries (subject to the BBN constraints).

* The collapsing DWs due to the CP symmetries are studied.

* The future GW probes at nHz can be useful for very tiny CP phase searches at the $10 - 100$ TeV scale (the cxSM).

* For the first time, we point out the possibility of probing the very small ECPV via the EDM measurements in the 2HDM. This is different from the constraints to the SUSY-breaking scale of $\gtrsim \mathcal{O}(10)\,\mathrm{TeV}$ (c.f. 1810.07736).

Thank you all

Backups

Topological Defects

* Topological defects arise when there is non-trivial homotopy group during the symmetry breaking of $\mathscr{G} \to \mathscr{H}$, i.e., $\pi_n(\mathscr{G}/\mathscr{H}) \neq \mathbf{1}$.

* $\pi_0(\mathscr{G}/\mathscr{H}) \neq \mathbf{1}$: kink/DW,
  $\pi_1(\mathscr{G}/\mathscr{H}) \neq \mathbf{1}$: vortex/cosmic strings,
  $\pi_2(\mathscr{G}/\mathscr{H}) \neq \mathbf{1}$: monopole.

* Topological defects are "objects", where the vacua are described by some space-dependent functions. They contain finite energy.

SCPV+ECPV

- The overall size of the ECPV terms (by re-phasing the Φ_2):
  $V_{\rm ECPV} = -\frac{1}{4}{\rm Im}\lambda_5 v_1^2 v_2^2 s_{2\theta} \Rightarrow \Delta V = \frac{1}{2}|{\rm Im}\lambda_5 s_{2\theta}| v_1^2 v_2^2$

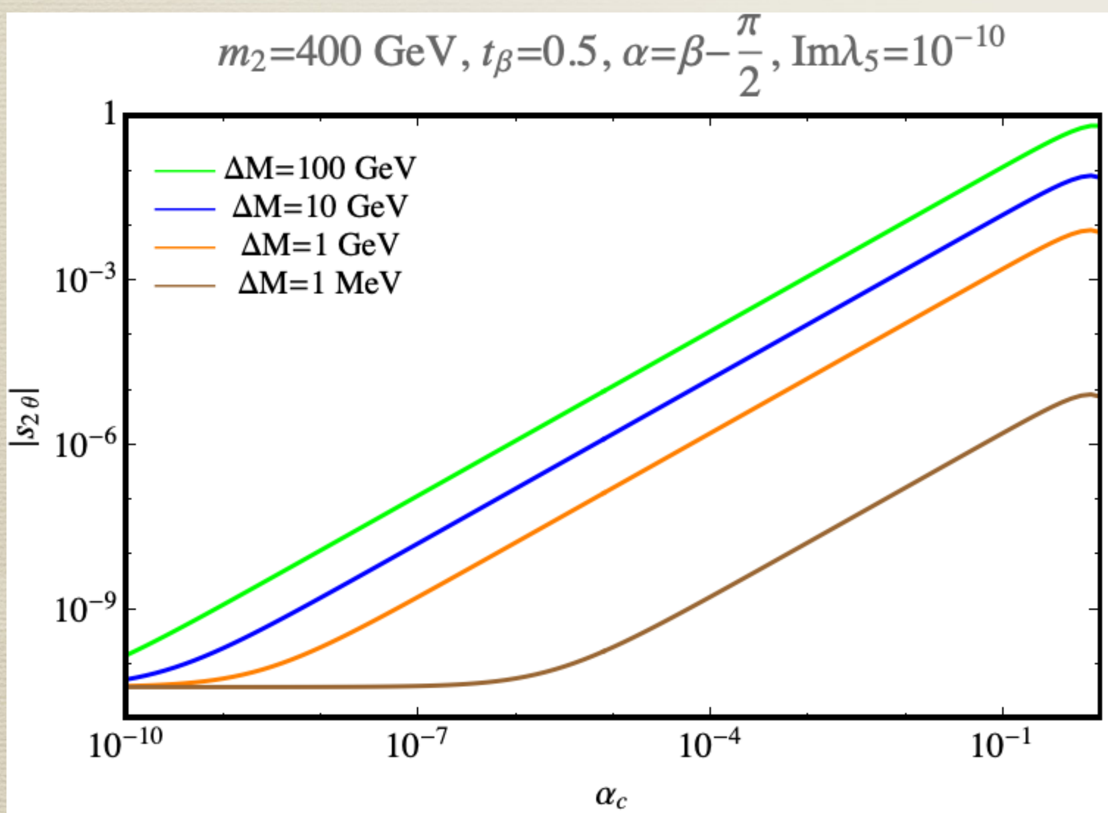
- A simplification for solving the θ:
  $$\left(\frac{2\sum_i m_i^2 \mathscr{R}_{i1}\mathscr{R}_{i3}}{v^2 s_\beta} - {\rm Im}\lambda_5\right) t_\theta^2 + 2\sum_i \frac{m_i^2}{v^2}\mathscr{R}_{i3}^2 t_\theta - {\rm Im}\lambda_5 = 0$$
  with the small α_c and $\alpha = \beta - \frac{\pi}{2}$ limit:
  $$\frac{\sum_i m_i^2 \mathscr{R}_{i1}\mathscr{R}_{i3}}{v^2 s_\beta} \sim \frac{m_2^2 - m_3^2}{v^2 c_{2\beta}}\alpha_c \quad \sum_i \frac{m_i^2}{v^2} \sim \frac{m_3^2}{v^2}$$

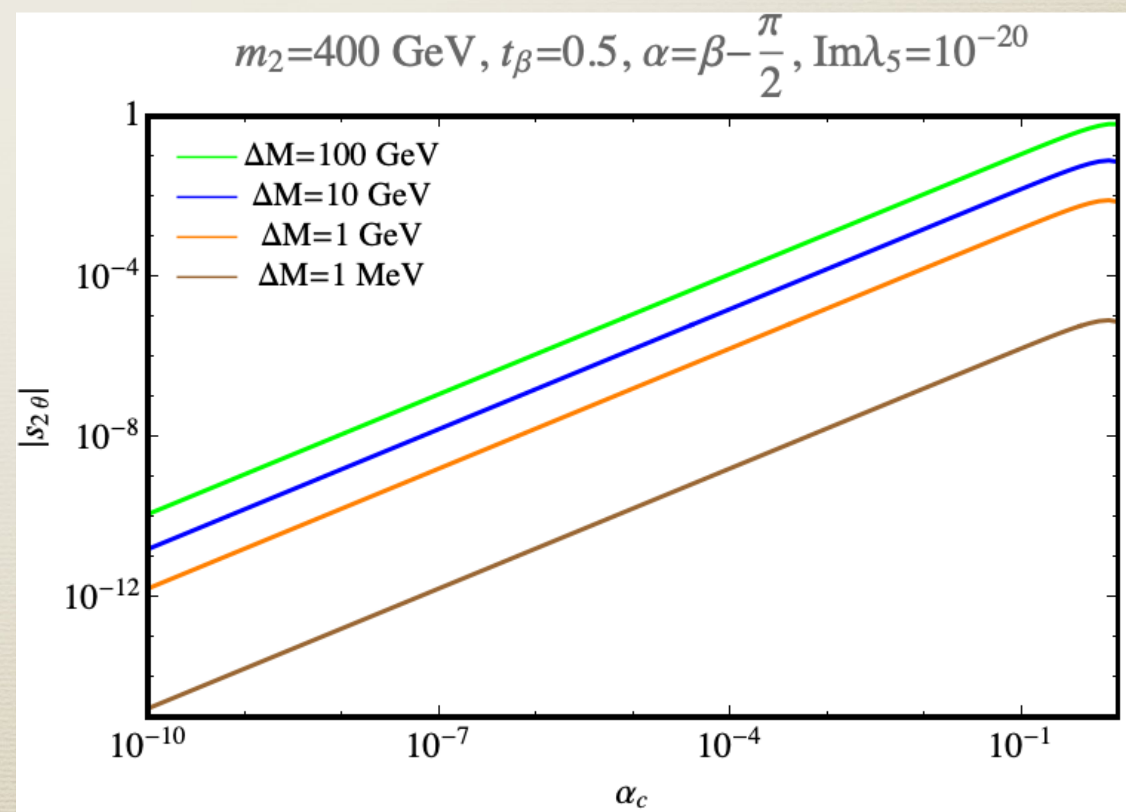
- The relative sizes between ${\rm Im}\lambda_5$ and α_c:
  if $|{\rm Im}\lambda_5| \gg \frac{\sum_i m_i^2 \mathscr{R}_{i1}\mathscr{R}_{i3}}{v^2 s_\beta} \Rightarrow t_\theta \approx \frac{2m_3^2}{v^2 {\rm Im}\lambda_5}$,
  otherwise $|{\rm Im}\lambda_5| \ll \frac{\sum_i m_i^2 \mathscr{R}_{i1}\mathscr{R}_{i3}}{v^2 s_\beta}$, θ varies w.r.t. α_c.

SCPV+ECPV

- The SCPV 2HDM domain walls can collapse with explicit CPV terms: $V_{\rm ECPV} = -\dfrac{1}{4}{\rm Im}\lambda_5 v_1^2 v_2^2 s_{2\theta} \Rightarrow \Delta V = \dfrac{1}{2}|{\rm Im}\lambda_5 s_{2\theta}|\, v_1^2 v_2^2$

- The relative sizes between ${\rm Im}\lambda_5$ and α_c have effects to the solution of the relative phase θ:





The 2HDM: Yukawa

* The Yukawa couplings in the 2HDM (most studied):

$$\mathrm{Type-I}\ :\ -(\frac{c_\alpha}{s_\beta}\frac{m_u}{v})\overline{Q}_L\tilde{\Phi}_2 u_R - (\frac{c_\alpha}{s_\beta}\frac{m_d}{v})\overline{Q}_L\Phi_2 d_R + \mathrm{h.c.}$$

$$\mathrm{Type-II}\ :\ -(\frac{c_\alpha}{s_\beta}\frac{m_u}{v})\overline{Q}_L\tilde{\Phi}_2 u_R + (\frac{s_\alpha}{c_\beta}\frac{m_d}{v})\overline{Q}_L\Phi_1 d_R + \mathrm{h.c.}$$

* The Yukawa couplings are independent of the SCPV or the ECPV scenarios.

* In terms of the mass eigenstates:

$$\mathscr{L}_{\mathrm{Yuk}} = \sum_{i=1}^{3}\left[-m_f\left(c_{f,i}\bar{f}f + \tilde{c}_{f,i}\bar{f}i\gamma_5 f\right) + a_i\left(2m_W^2 W_\mu W^\mu + m_Z^2 Z_\mu Z^\mu\right)\right]\frac{h_i}{v}$$

the existence of both scalar and pseudo-scalar couplings lead to the non-vanishing EDMs

The joint constraints

* The joint eEDM && collapsing domain wall constraints