Domain Wall in Extended Scalar Sectors

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N. Chen, T. Li, YW: 2004.10148
N. Chen, T. Li, Z. Teng, YW: 2006.06913

Related to CP Symmetry

Constraints of Domain Wall in Extended Scalar Sectors

SM + Singlet: cxSM

SM + Doublet: 2HDM

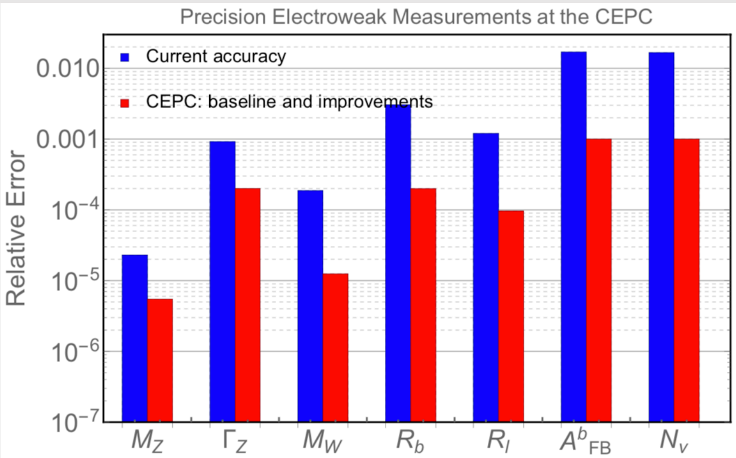
Outline

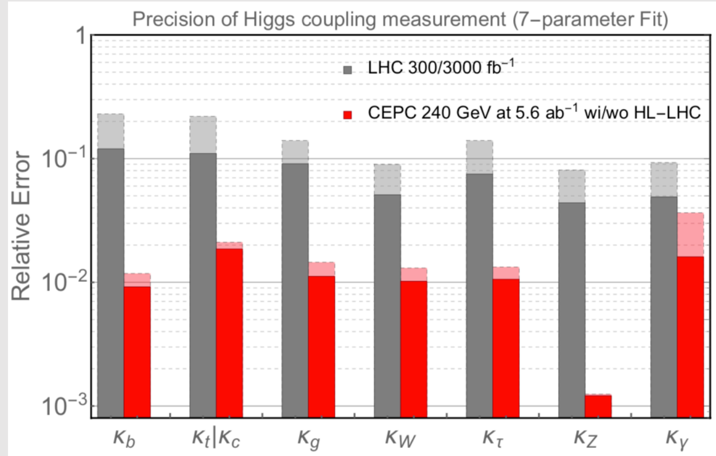
- Introduction
  - Topological Defects
  - Domain Walls
- CP Domain Wall in Extended Scalar Sectors
  - cxSM
  - 2HDM
- Summary

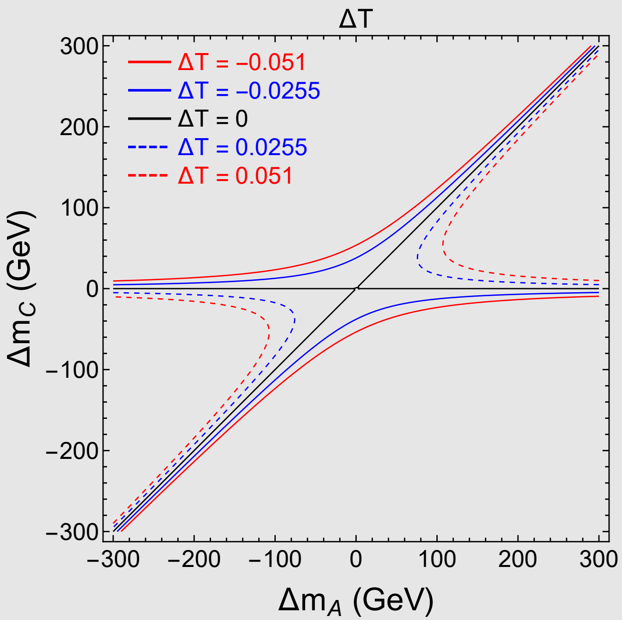
Introduction

- Post-Higgs Era:
  - Higgs Discovery Completes the Standard Model (SM)
  - Unexplained in SM:
    - Dark Matter
    - Baryon Asymmetry in Universe (BAU)
    - Neutrino Masses
    - ……
- Beyond Standard Model
  - SUSY, Composite, ……
  - Extended Scalar Sector

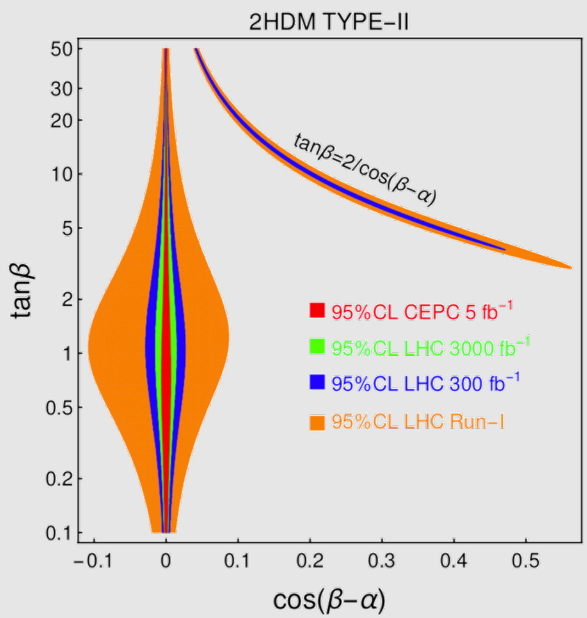
Probes of Extended Scalar Sector



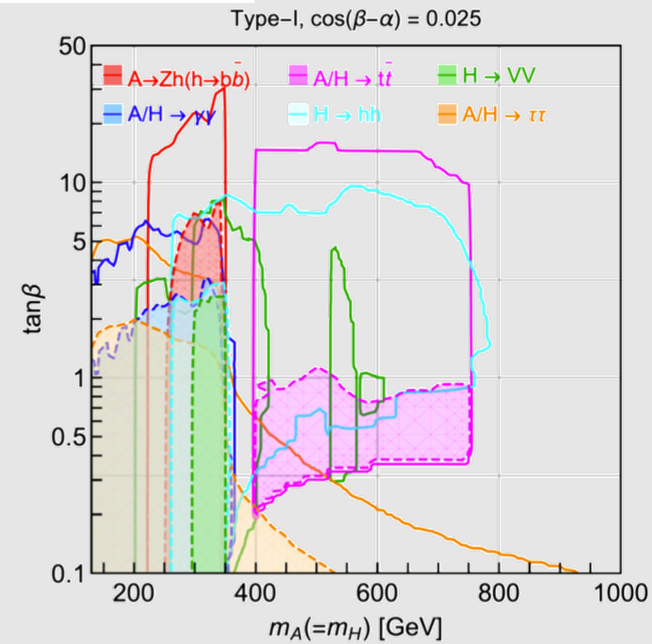




Z-pole (EW)



Higgs Precision



Direct Search

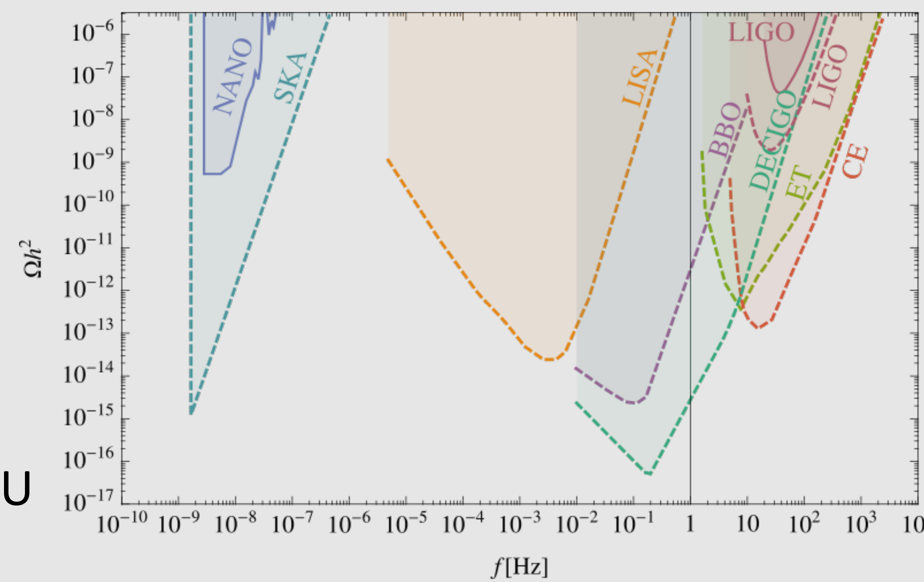
Extended Scalar Sector

- Probes:
  - Z-pole measurements
  - SM Higgs couplings measurements
  - Direct resonance searches

- Connection with Cosmology:
  - Phase transitions:
    - 1st Order Phase transition

    →Gravitational wave (GW)
    - Together with CP violation

    →Electroweak Baryogenesis → BAU
  - Topological Defects



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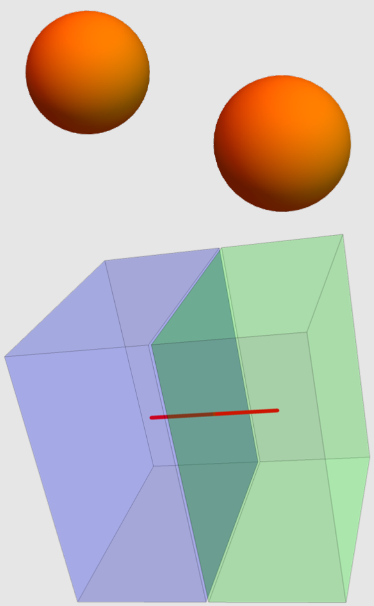
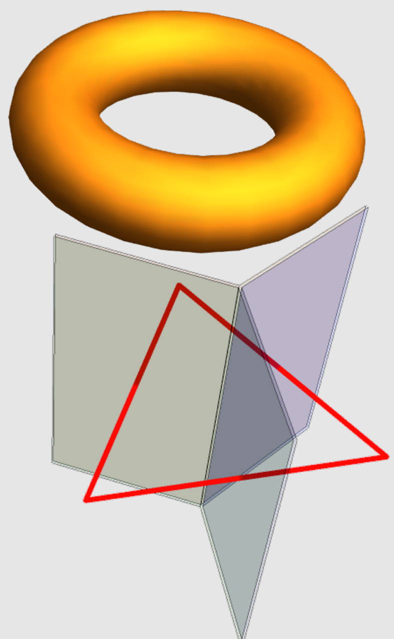
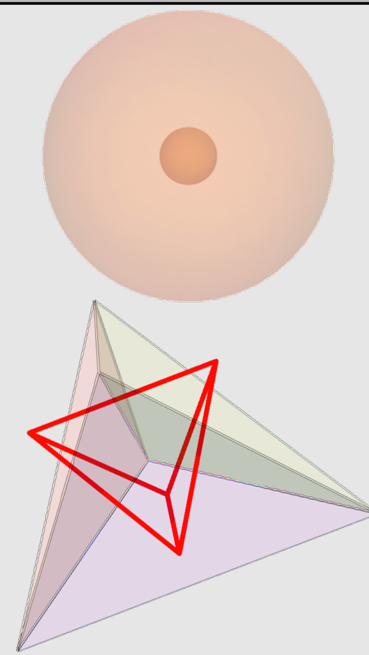
Symmetries & Topological Defects

- Symmetry breaking: $\mathcal{G} \to \mathcal{H},\ \mathcal{M} = \mathcal{G}/\mathcal{H}$
- Vacuum Manifold ($\mathcal{M}$) and Topological Defects:

Topological Defects:	**Requirements:**	
Domain Walls	$\pi_0(\mathcal{M}) \neq I$	Disconnected parts
Cosmic Strings	$\pi_1(\mathcal{M}) \neq I$	Path can't shrink to one point
Monopoles	$\pi_2(\mathcal{M}) \neq I$	Surface can't shrink to one point







T.W.B. Kibble J. Phys. A 9 (1976) 1387

Symmetries & Topological Defects

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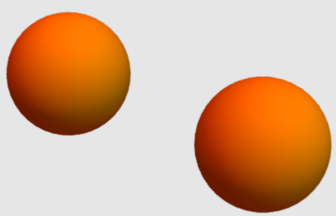

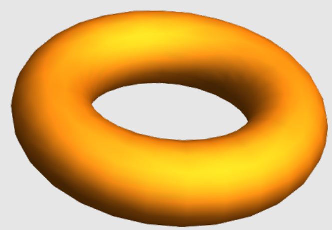

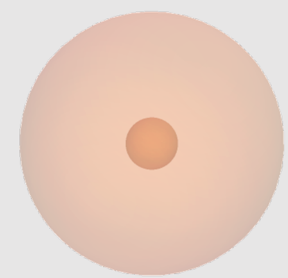

- Simple Examples
  - Domain Walls: Discrete symmetry breaking
  - Cosmic Strings: U(1) Breaking
  - Monopoles: O(3) → O(2),

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Domain Wall

- Discrete Symmetry spontaneously broken
- Main Characteristics of DW:
  - Surface tension/energy: $\sigma \sim \langle\phi\rangle^3$
  - Wall Thickness: $\delta_w \sim m^{-1} \sim \langle\phi\rangle^{-1}$
- Problem with Domain Wall
  - In Scaling region ($R \sim L \sim t$)
    - Energy density: $\rho_w \sim \frac{\sigma R^2}{R^2 L} \sim \frac{\sigma}{t}$
    - Domination time: (Assuming Radiation Era)
      - $\rho_w = \mathcal{A}\frac{\sigma}{t} \simeq \frac{3M_P^2}{4t^2} = \rho_c \Rightarrow t_{dom} \simeq \frac{3M_P^2}{4\mathcal{A}\sigma}$
      - $t_{dom} \simeq 2.93\times10^3 s\, \mathcal{A}^{-1}\left(\frac{\sigma}{TeV^3}\right)^{-1}$
    - Equation of state:
      - $p = \omega\rho,\ \omega = -2/3,\ a \propto t^2$

$\sigma < (10 \sim 100\ MeV)^3$

$\langle\phi\rangle < 10 \sim 100\ MeV$

  - Fluctuation → Excessive anisotropy in CMB (Zeldovich-Kobzarev-Okun Bound)
    - $\langle\phi\rangle < 1$ MeV

Radiation Dominant

$$\rho_M \sim a^{-3} \sim \frac{1}{t^{3/2}}$$

$$\rho_\gamma \sim a^{-4} \sim \frac{1}{t^2}$$

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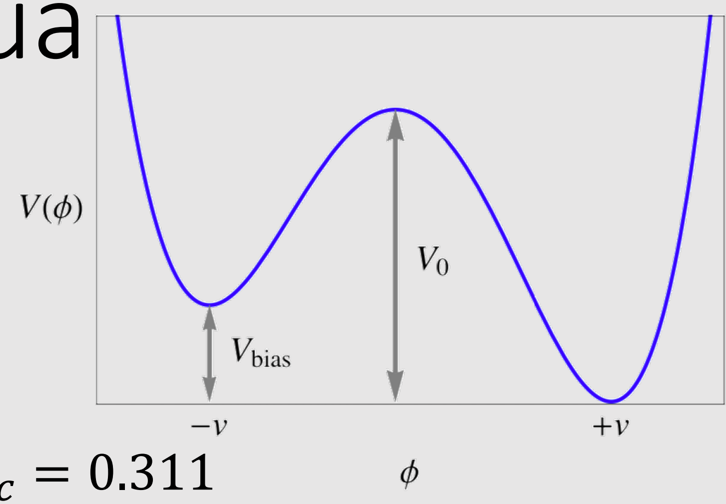
Sov. Phys. JETP 40 (1974) 1

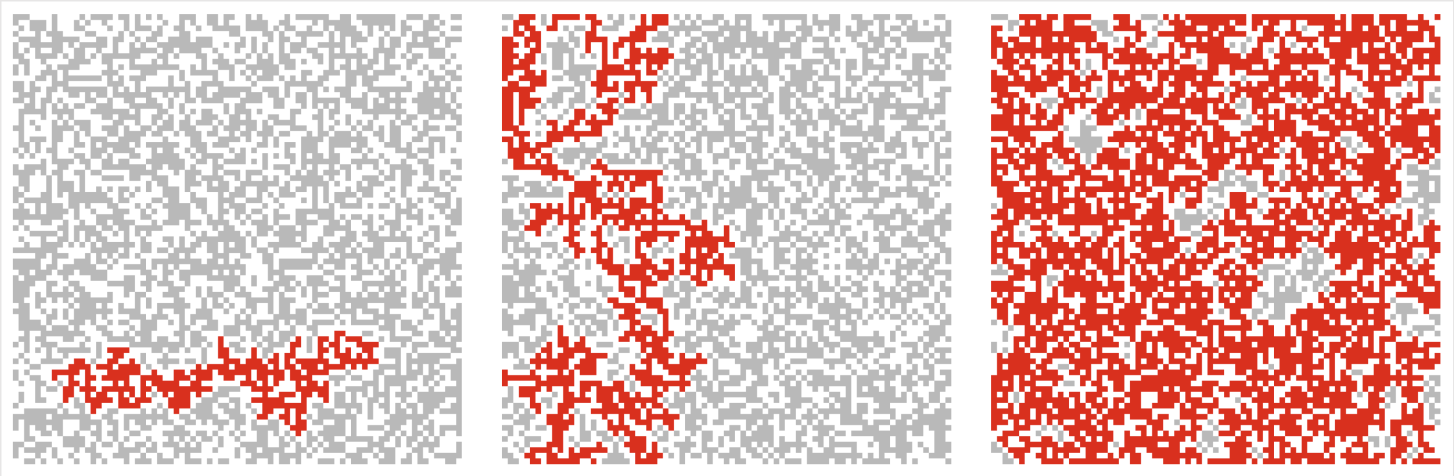
Avoid DW Problem

- Way to avoid DW problem: Phys. Rept. 121 (1985) 263
  - Formation of DW followed by inflation
  - Symmetry restoration
  - Introduce instability
    - Biased term in Potential: ΔV
- Evolution Mainly depends on
  - Tension: σ
    - Tension force: $f_T = \mathcal{A}\frac{\sigma}{R}$
  - Biased Term: ΔV
    - Pressure force: $f_p \sim \Delta V$
- Effects of Biased Term:
  - Bias between two quasi degenerate vacua
  - Pressure force → Collapse of DW

Bias between Two Vacua



- Too large bias, no DW formed
  - $\frac{p_+}{p_-} \simeq \exp\left(-\frac{\Delta V}{V_0}\right)$
  - Percolation Threshold p_c:
    - For 3-d simple cubic lattice system, $p_c = 0.311$
  - $|\Delta V| < 0.795 V_0$ Phys. Rept. 54 (1979) 1



Collapse of DW

- Collapse Time: Universe 3 (2017) 2, 40
  - Tension force on the DW: $f_T \sim \frac{\sigma}{R} \sim \frac{\sigma}{t}$
  - ΔV induce pressure force: $f_p \sim \Delta V$
  - Collapse time: When pressure force dominates
    - $f_V = C_{ann} f_T \Rightarrow t_{ann} = C_{ann} \frac{\mathcal{A}\sigma}{\Delta V}$
    - $t_{ann} \simeq 6.58\times 10^{-4} s\, C_{ann}\mathcal{A}\left(\frac{\sigma}{TeV^3}\right)\left(\frac{\Delta V}{MeV^4}\right)^{-1}$
    - $T_{ann} \simeq 3.41\times 10^{-2}\, GeV\;\; C_{ann}^{-1/2}\mathcal{A}^{-1/2}\left(\frac{g_*}{10}\right)^{-1/4}\left(\frac{\sigma}{TeV^3}\right)^{-1/2}\left(\frac{\Delta V}{MeV^4}\right)^{1/2}$
- Avoid Energy dominant
  - $t_{ann} < t_{dom}$
  - $\Delta V^{1/4} > 2.18\times 10^{-5}\, GeV\, C_{ann}^{1/4}\mathcal{A}^{1/2}\left(\frac{\sigma}{TeV^3}\right)^{1/2}$
- Avoid Ruin BBN:
  - $t_{ann} \lesssim \mathcal{O}(0.01)\, s$
  - $\Delta V^{1/4} > 5.07\times 10^{-4} GeV\, C_{ann}^{1/4}\mathcal{A}^{1/4}\left(\frac{\sigma}{TeV^3}\right)^{1/4}$

GW from DW

- Naïve Estimation: Universe 3 (2017) 2, 40
  - Quadrupole Formula: $P \simeq G\, \dddot{Q}\dddot{Q}$
  - $\dddot{Q} \sim \frac{MR^2}{t^3} \sim \frac{\mathcal{A}\sigma R^2 R^2}{t^3} \sim \mathcal{A}\sigma t$
  - $\rho_{gw} \sim \frac{Pt}{R^3} \sim \frac{P}{t^2} \sim G\mathcal{A}^2\sigma^2$
- Numerical Simulation:
  - $\tilde{\epsilon}_{gw} \equiv \frac{1}{G\mathcal{A}^2\sigma^2}\left(\frac{d\rho_{gw}}{d\ln k}\right)_{peak} \simeq 0.7$

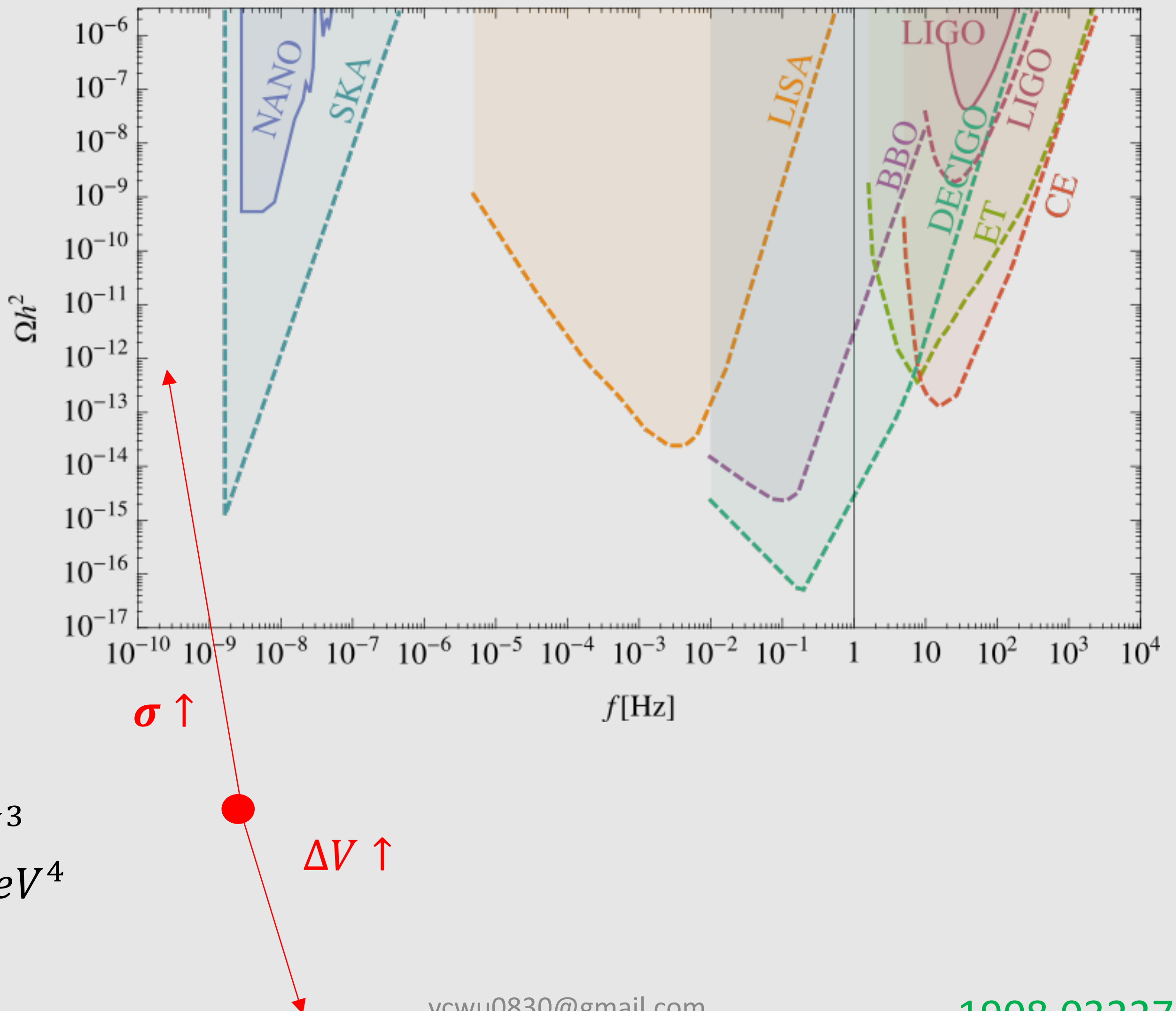
$$\tilde{\epsilon}_{gw} \equiv \frac{1}{G\mathcal{A}^2\sigma^2}\left(\frac{d\rho_{gw}}{d\ln k}\right)_{peak} \simeq 0.7$$

GW from DW

- Peak Amplitude
  - $\left(\Omega_{gw}\right)_{peak} = \frac{1}{\rho_c}\frac{d\rho_{gw}}{d\ln k} \sim \frac{1}{\rho_c}\left(\frac{a(t_{ann})}{a(t_0)}\right)^4\left(\frac{d\rho_{gw}(t_{ann})}{d\ln k}\right)_{peak}$
  - $\left(\Omega_{gw}h^2\right)_{peak} \simeq 7.2\times10^{-18}\tilde{\epsilon}_{gw}\mathcal{A}^2\left(\frac{g_{*s}(T_{ann})}{10}\right)^{-4/3}\left(\frac{\sigma}{TeV^3}\right)^2\left(\frac{T_{ann}}{10^{-2}GeV}\right)^{-4}$
  - $\left(\Omega_{gw}h^2\right)_{peak} \simeq 5.3\times10^{-20}\tilde{\epsilon}_{gw}\mathcal{A}^2C_{ann}^2\left(\frac{g_{*s}(T_{ann})}{10}\right)^{-4/3}\left(\frac{g_{*}(T_{ann})}{10}\right)\left(\frac{\sigma}{TeV^3}\right)^4\left(\frac{\Delta V}{MeV^4}\right)^{-2}$
- Peak Frequency
  - $f_{peak} \simeq \left(\frac{a(t_{ann})}{a(t_0)}\right)H(t_{ann})$
  - $f_{peak} \simeq 1.1\times10^{-9}Hz\left(\frac{g_{*}(T_{ann})}{10}\right)^{1/2}\left(\frac{g_{*s}(T_{ann})}{10}\right)^{-1/3}\left(\frac{T_{ann}}{10^{-2}GeV}\right)$
  - $f_{peak} \simeq 3.75\times10^{-9}Hz\ \mathcal{A}^{-1/2}C_{ann}^{-1/2}\left(\frac{g_{*}(T_{ann})}{10}\right)^{1/4}\left(\frac{g_{*s}(T_{ann})}{10}\right)^{-1/3}\left(\frac{\sigma}{TeV^3}\right)^{-1/2}\left(\frac{\Delta V}{MeV^4}\right)^{1/2}$

Universe 3 (2017) 2, 40

GW from DW



$\sigma \sim TeV^3$
$\Delta V \sim MeV^4$

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Brief Summary of DW Constraints

- Consider in Situation where we do still have DW formation
  - $\Delta V < 0.795 V_0$
- Avoid Energy dominant:
  - $\Delta V^{1/4} > 2.18\times10^{-5}\, GeV\, C_{ann}^{1/4} \mathcal{A}^{1/2} \left(\frac{\sigma}{TeV^3}\right)^{1/2}$
- Avoid Ruin BBN:
  - $\Delta V^{1/4} > 5.07\times10^{-4} GeV\, C_{ann}^{1/4} \mathcal{A}^{1/4} \left(\frac{\sigma}{TeV^3}\right)^{1/4}$
- Possible GW Signals from Collapsing DW
  - High scale

SM + Complex Singlet (cxSM)

- The field Contents:
  - SM Doublet + complex singlet
- Most general Potential:

U(1)

$$V(\Phi,\mathbb{S}) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4$$
$$+ \left(\frac{\delta_1}{4}|\Phi|^2\mathbb{S} + \frac{\delta_3}{4}|\Phi|^2\mathbb{S}^2 + c.c.\right)$$
$$+ \left(a_1\mathbb{S} + \frac{b_1}{4}\mathbb{S}^2 + \frac{c_1}{6}\mathbb{S}^3 + \frac{c_2}{6}\mathbb{S}|\mathbb{S}|^2 + \frac{d_1}{8}\mathbb{S}^4 + \frac{d_3}{8}\mathbb{S}^2|\mathbb{S}|^2 + c.c.\right),$$

Four kinds coupling with different U(1) Charge

At least two terms from different kinds are needed to achieve SCPV

Phys.Rev.D 86 (2012)075007

SCPV and ECPV

- SCPV Potential:

$$V(\Phi, \mathbb{S}) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + \frac{c_1}{6}\mathbb{S}^3 + c.c.\right)$$

  - b_1, c_1 Real for SCPV
  - Symmetries: CP: $\mathbb{S} \to \mathbb{S}^*$
  - Vacuum Manifold:

$$\mathcal{M} = \boxed{S^3} \otimes \boxed{S^0}$$

- ECPV Deviation
  - Imaginary component of b_1, c_1

Spectrum and Parameters

- SCPV Potential:

$$V(\Phi,\mathbb{S}) = \mu^2\,|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}\,|\mathbb{S}|^2 + \frac{d_2}{4}\,|\mathbb{S}|^4 + \left(\frac{b_1}{4}\,\mathbb{S}^2 + \frac{c_1}{6}\,\mathbb{S}^3 + c.c.\right)$$

- $\Phi = (0, v + h)^T, \langle\mathbb{S}\rangle = v_s e^{i\alpha} + S + i\,A = v_s^r + i\,v_s^i + S + i\,A$

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda v^2 & \frac{\delta_2}{2} v v_S & \frac{\delta_2}{2} v v_A \\ \frac{\delta_2}{2} v v_S & \frac{2d_2 v_S^4 + \sqrt{2}c_1(v_S^2 + v_A^2)}{4 v_S} & \frac{d_2 v_S - \sqrt{2}c_1}{2} v_A \\ \frac{\delta_2}{2} v v_A & \frac{d_2 v_S - \sqrt{2}\,c_1}{2} v_A & \frac{d_2}{2} v_A^2 \end{pmatrix}$$

Potential Parameters:

$\mu^2, \lambda, \delta_2, b_2, d_2, b_1, c_1$

$$\mathcal{R}^T \mathcal{M}^2 \mathcal{R} = diag(m_1^2, m_2^2, m_3^2)$$

Physical Parameters:

$v, v_S^r, v_S^i, m_{1,2,3}, \alpha_{1,2,3}$

(v_s, α)

DW Profile

$$\mathcal{M} = S^3 \otimes S^0$$

- Equation of Motion

$$\frac{d^2}{dz^2}\vec{\phi} = \vec{\nabla}_{\phi} V(\vec{\phi}), \qquad \vec{\phi} \equiv (\phi_h, \phi_S, \phi_A)$$

$$V(\phi_h, \phi_S, \phi_A) = \frac{\mu^2}{2}\phi_h^2 + \frac{\lambda}{4}\phi_h^4 + \frac{b_2 + b_1}{4}\phi_S^2 + \frac{b_2 - b_1}{4}\phi_A^2 + \frac{\sqrt{2}c_1}{12}\phi_S(\phi_S^2 - 3\,\phi_A^2) + \frac{d_2}{16}(\phi_S^2 + \phi_A^2)^2 + \frac{\delta_2}{8}\phi_h^2(\phi_S^2 + \phi_A^2)$$

- Boundary condition:

$$\vec{\phi}(z = \pm\infty) = (v, v_s^r, \pm v_s^i)$$

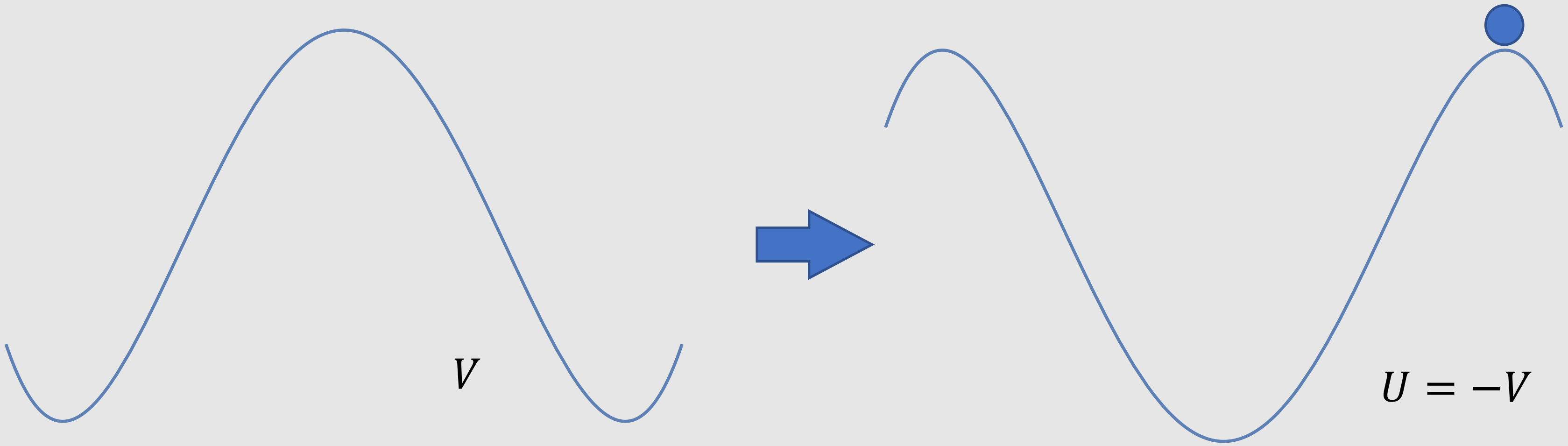
DW Profile

- Equation of Motion

$$\frac{d^2}{dz^2}\vec{\phi} = \vec{\nabla}_\phi V(\vec{\phi})$$

Equivalent to particle rolling in potential well $U = -V$

$$\frac{d^2}{dz^2}\vec{\phi} = \vec{\nabla}_\phi V(\vec{\phi}) \quad \Rightarrow \quad \frac{d^2}{dt^2}\vec{r} = -\vec{\nabla} U \equiv \vec{F}$$



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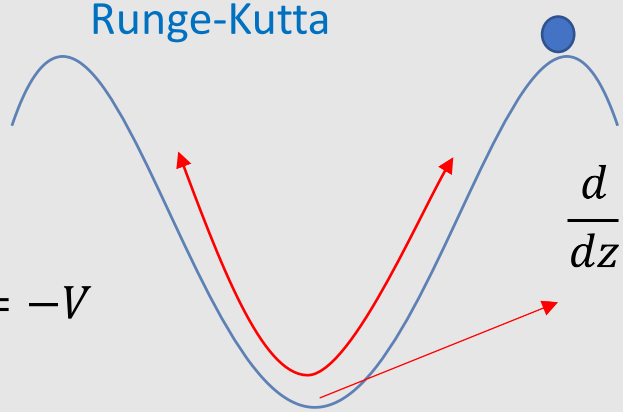
Runge-Kutta

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



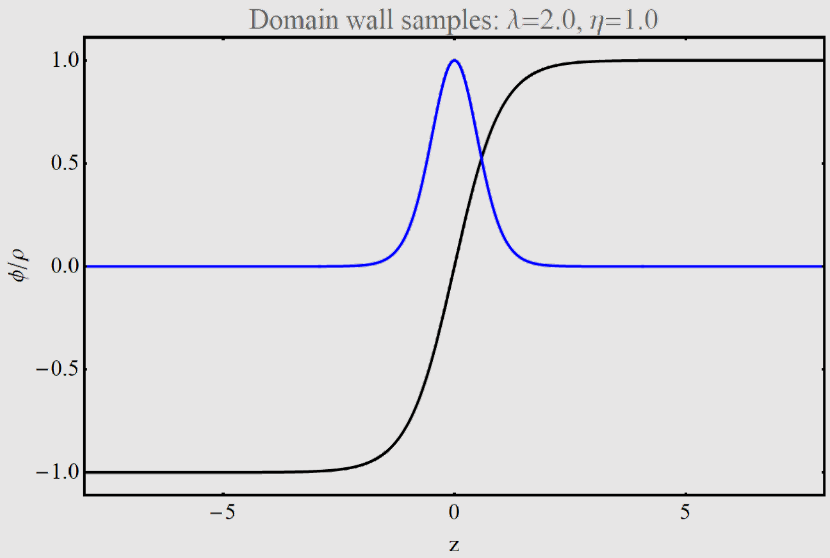
$U = -V$

$$\frac{d}{dz}\phi = \sqrt{2\,|\Delta V|} \quad \sim \quad \frac{1}{2}mv^2 = \Delta U$$

$$\phi(z) = \eta \tanh\left(\frac{z}{\delta}\right)$$

$$\delta = \frac{1}{\sqrt{\lambda}\eta}$$

$$\sigma \sim V_0 \cdot \delta \sim \lambda\eta^4 \cdot \frac{1}{\sqrt{\lambda}\eta} \sim \sqrt{\lambda}\eta^3$$



Path Deformation 1109.4189

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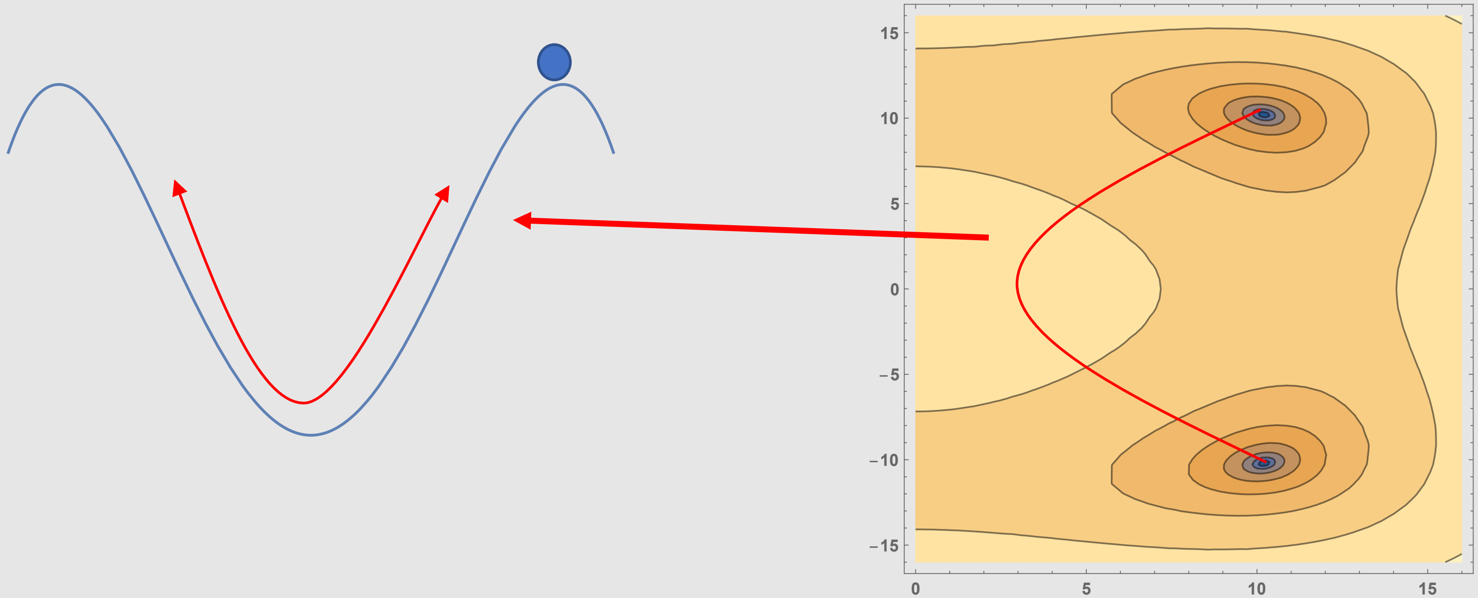
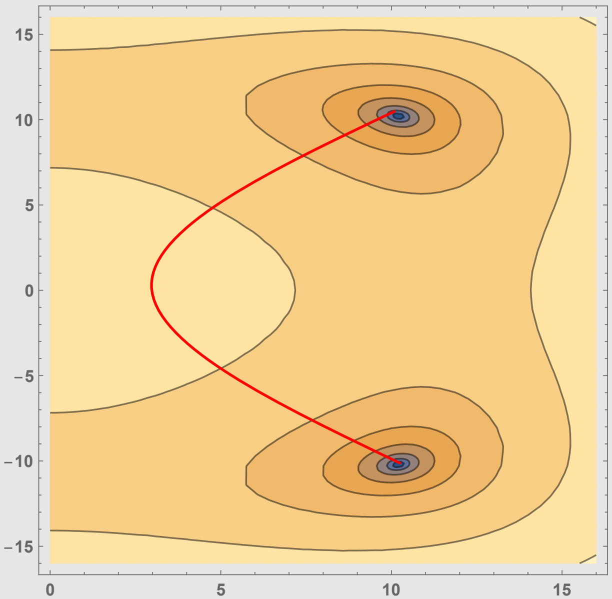


$$N_\perp = \frac{d^2\vec{\phi}}{d\phi_{1D}^2}\left(\frac{d\phi_{1D}}{dz}\right)^2 - \nabla_\phi^\perp V(\vec{\phi})$$

Path Deformation

- Equivalent to particle rolling in potential well $U = -V$

$$\frac{d^2}{dz^2}\vec{\phi} = \vec{\nabla}_{\phi} V(\vec{\phi}) \quad \Rightarrow \quad \frac{d^2}{dt^2}\vec{r} = -\vec{\nabla} U \equiv \vec{F}$$



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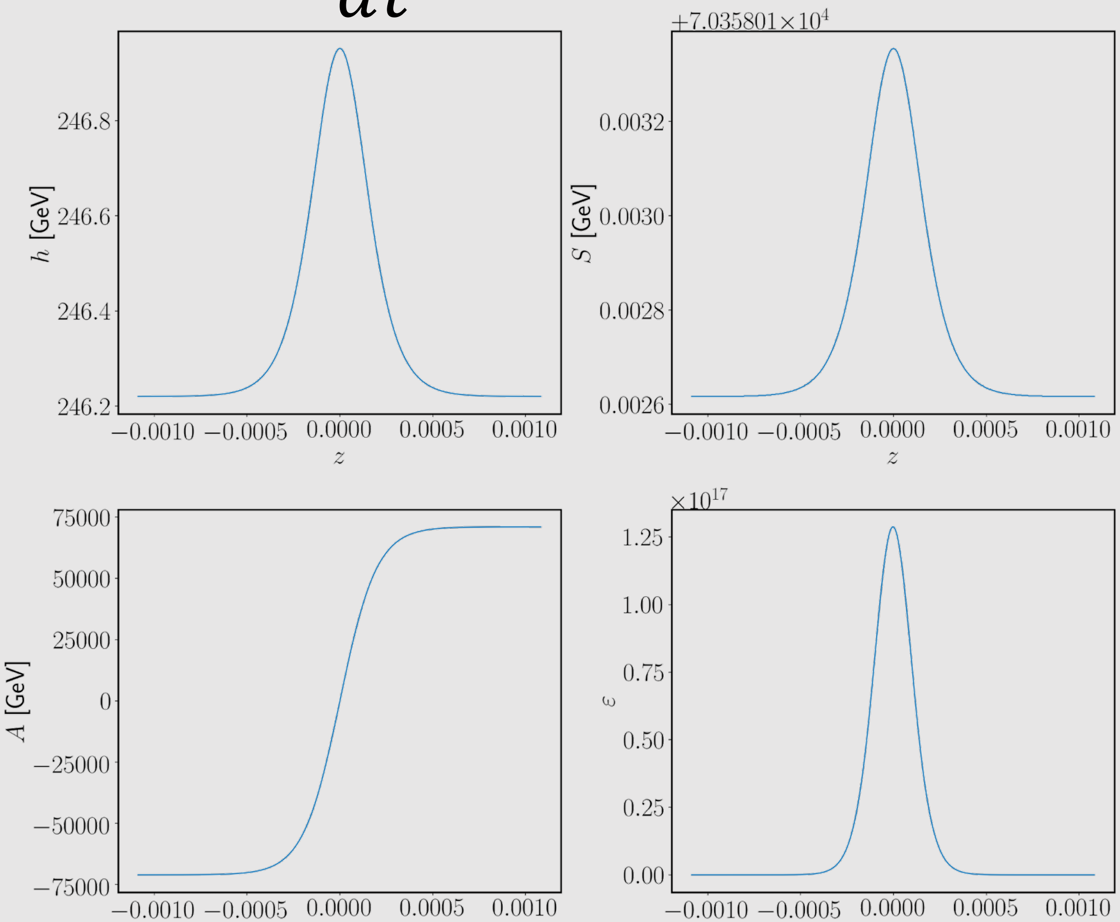


Biased Terms from ECPV

- Potential

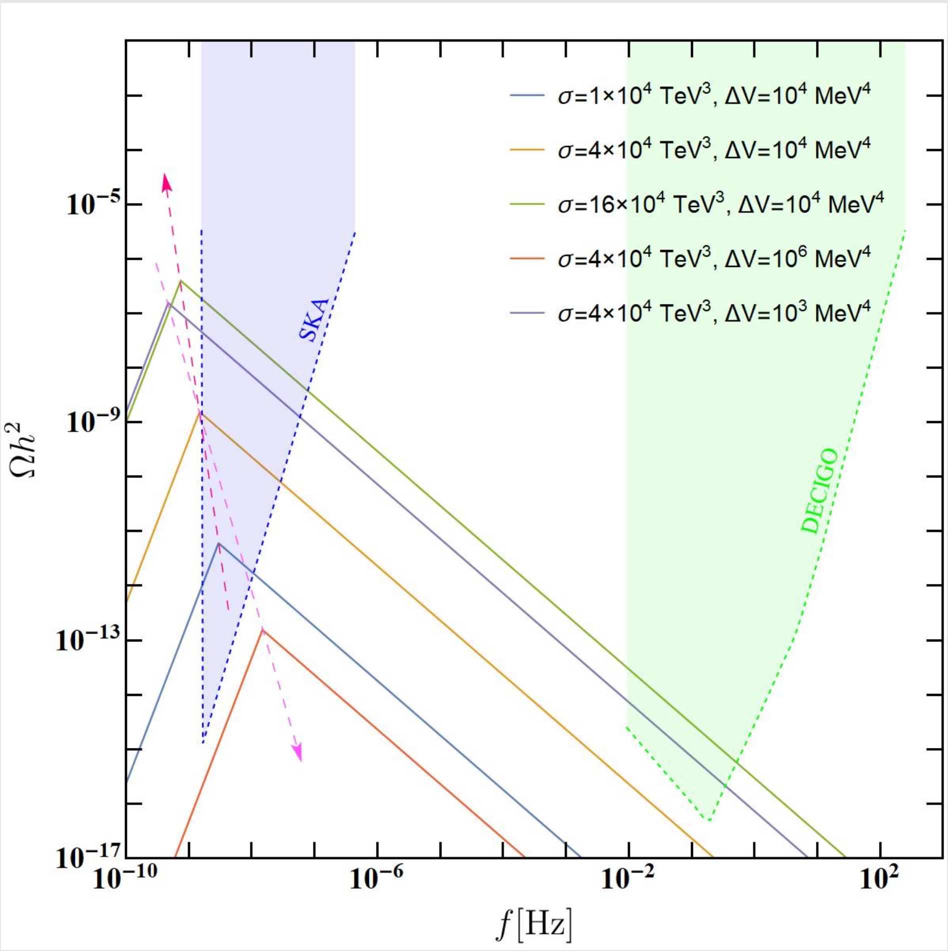
  $$V(\Phi,\mathbb{S}) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + \frac{c_1}{6}\mathbb{S}^3 + c.c.\right)$$

- ECPV
  - Imaginary component of b_1, c_1
- Biased Terms:
  - $V_{bias} = -\frac{1}{12}\phi_A\left(6\,\Im b_1\phi_s + \sqrt{2}\,\Im c_1(3\,\phi_s^2 - \phi_A^2)\right)$

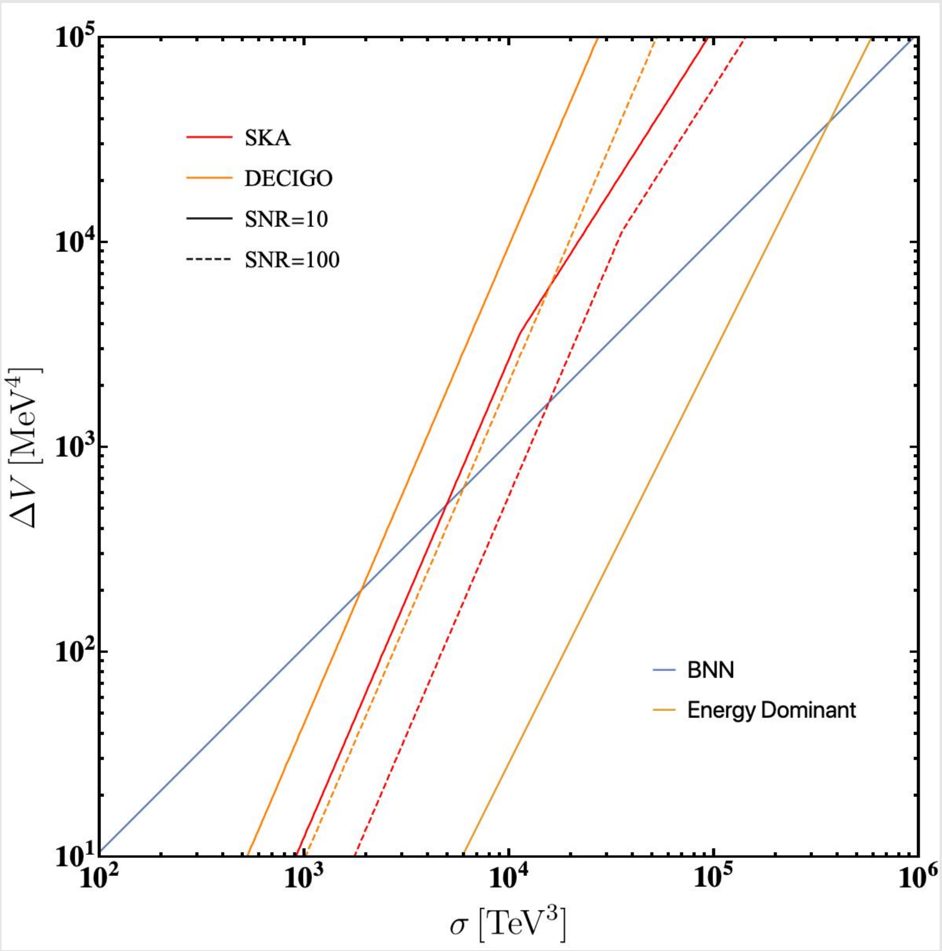
  $$|\Delta \mathrm{V}| \approx \frac{1}{6}v_s^i\left(6\Im b_1 v_s^r + \sqrt{2}\,\Im c_1\left(3(v_s^r)^2 - \left(v_s^i\right)^2\right)\right)$$

Constraints in cxSM

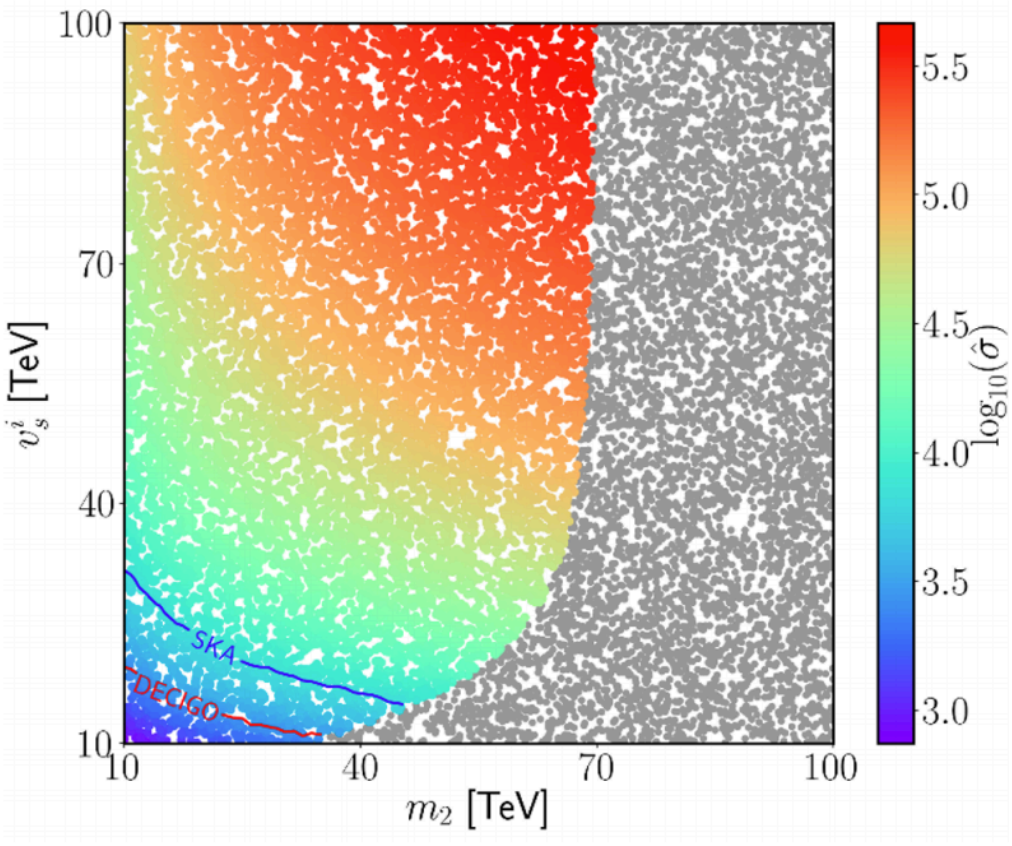
GW from DW

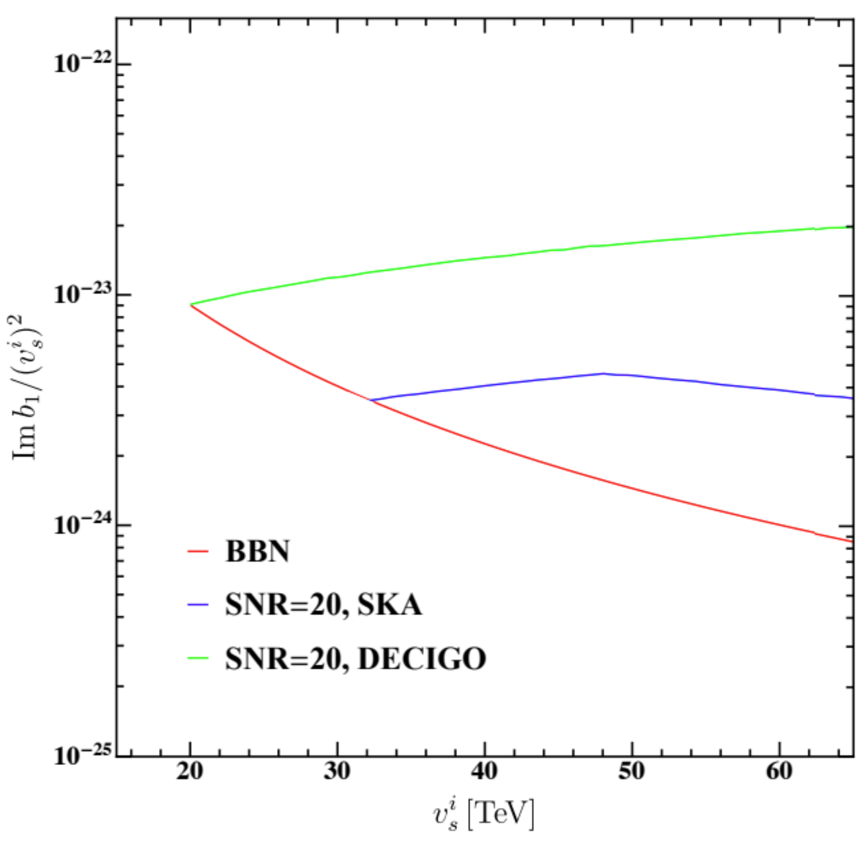


Constraints on Tension and Bias



Constraints in cxSM





SM + Extra Doublet (2HDM)

- Field Content:
  - Two Scalar Doublet

$$\Phi_1 = \begin{pmatrix} H_1^+ \\ \frac{1}{\sqrt{2}}(\varphi_1 + H_1^0 + iA_1^0) \end{pmatrix}, \quad \Phi_2 = e^{i\Theta} \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(\varphi_2 + H_2^0 + iA_2^0) \end{pmatrix}$$

- The potential:

$$\begin{aligned} V(\Phi_1, \Phi_2) = {} & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) \\ & + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 \\ & + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c. \right]. \end{aligned}$$

- SCPV case:
  - Starting with all real parameters
  - Symmetry: CP: $\Phi_1 \to \Phi_1^*, \Phi_2 \to \Phi_2^*$
- ECPV case:
  - Introducing $\Im\lambda_5$ (or $\Im m_{12}^2$)

Mass Eigenstates & Parameters

$$\begin{pmatrix} H_1^\pm \\ H_2^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \cdot \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

$$\begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \cdot \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \mathcal{R} \cdot \begin{pmatrix} H_1 \\ H_2 \\ A^0 \end{pmatrix}$$

$$\text{Tan}\,\beta = \frac{|v_2|}{v_1}$$

$$\mathcal{R} = \mathcal{R}_{23}(\alpha_c) \cdot \mathcal{R}_{13}(\alpha_b) \cdot \mathcal{R}_{12}(\alpha + \frac{\pi}{2})$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\alpha_c} & s_{\alpha_c} \\ 0 & -s_{\alpha_c} & c_{\alpha_c} \end{pmatrix} \cdot \begin{pmatrix} c_{\alpha_b} & 0 & s_{\alpha_b} \\ 0 & 1 & 0 \\ -s_{\alpha_b} & 0 & c_{\alpha_b} \end{pmatrix} \cdot \begin{pmatrix} -s_\alpha & c_\alpha & 0 \\ -c_\alpha & -s_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix}.$$

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, $\mathrm{Re}m_{12}^2$, $\mathrm{Im}m_{12}^2$	α, α_b, α_c, β, θ, $\mathrm{Im}\lambda_5$, $\mathrm{Im}m_{12}^2$

Tension: $\sigma \sim v^3$

$\sigma \sim 10^6\ GeV^3 \sim 10^{-3}\ TeV^3$

$\Omega_{GW} h^2 \sim \mathcal{O}(10^{-23})$ Weak GW

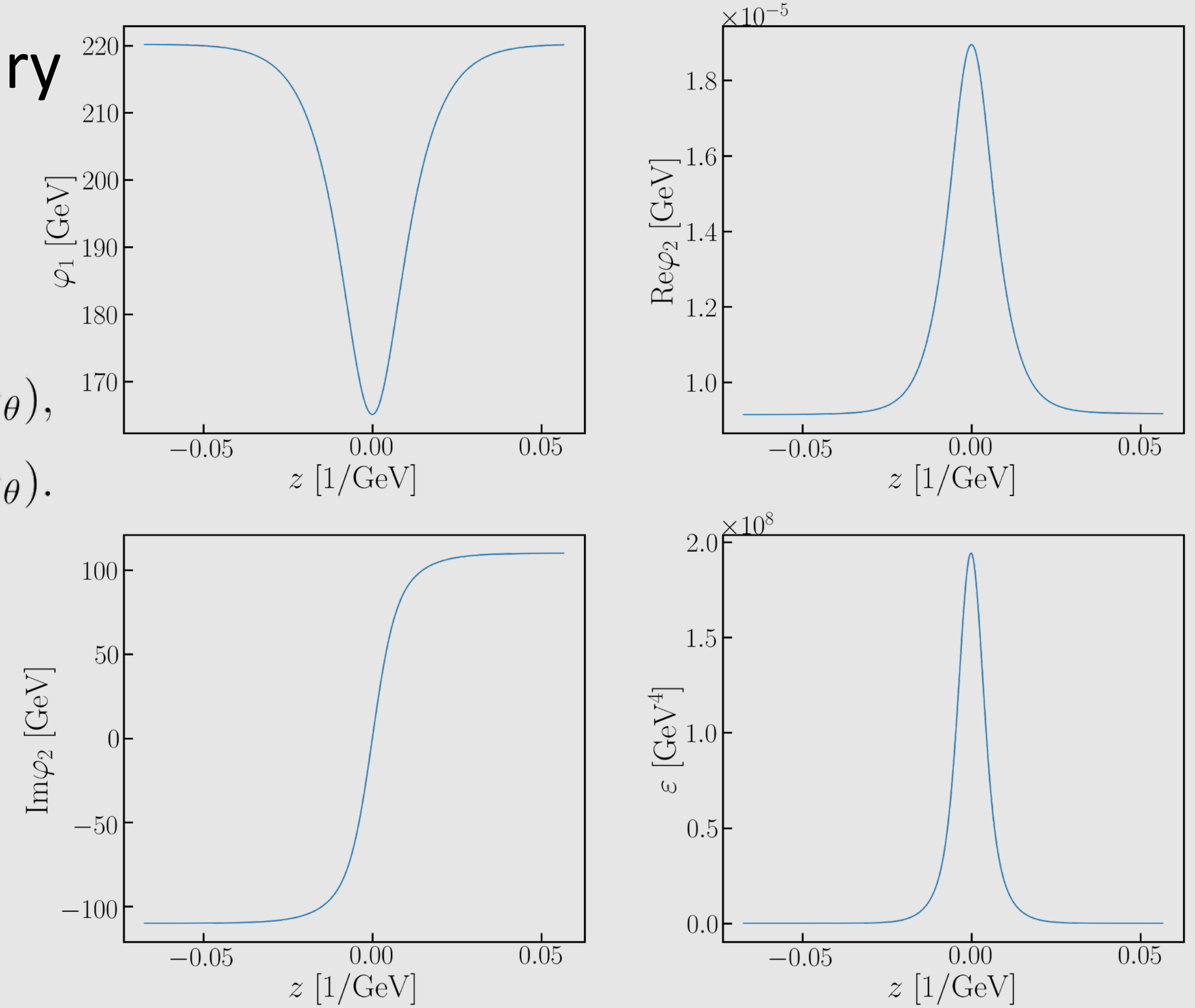
Biased Term: ΔV

DW Profile

- EOM & Boundary

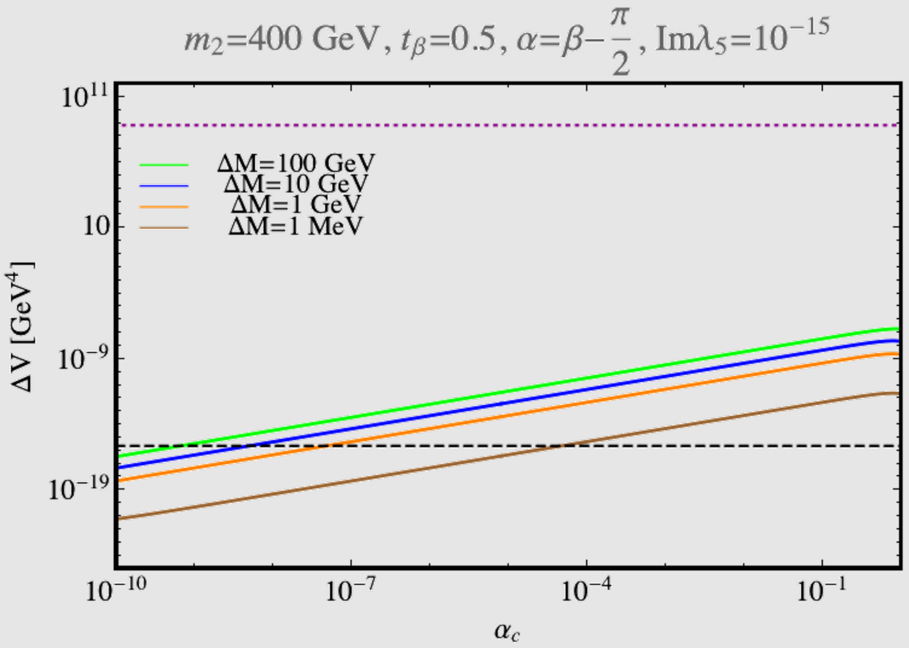
$$\frac{d^2}{dz^2}\vec{\phi} = \vec{\nabla}_\phi V(\vec{\phi})$$

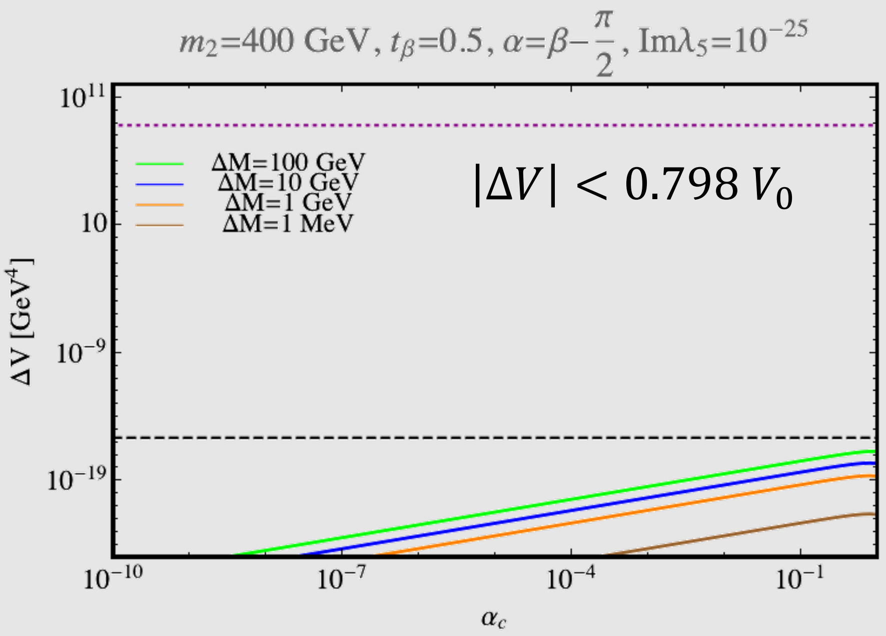
$$\vec{\phi}(z=-\infty) = (v_1\,, v_2 c_\theta\,, -v_2 s_\theta),$$
$$\vec{\phi}(z=+\infty) = (v_1\,, v_2 c_\theta\,, +v_2 s_\theta).$$



Constraints from DW

- To avoid ruin BBN



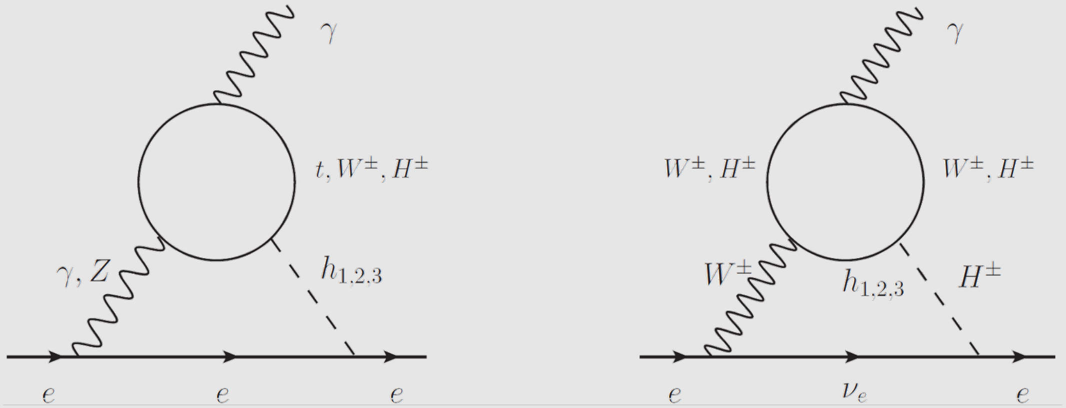


CPV and EDM

- Couplings with CPV

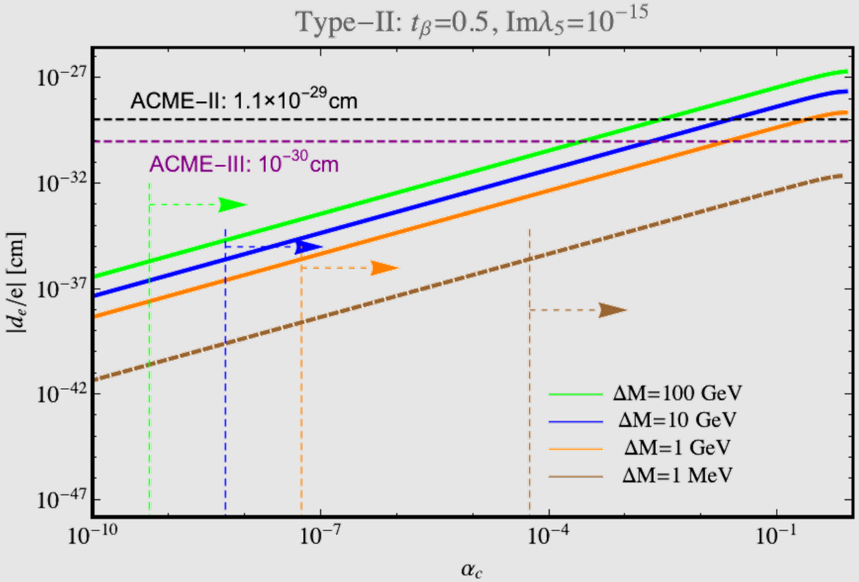
$$\mathcal{L} = \sum_{i=1}^{3} \left[-m_f \left(c_{f,i} \bar{f} f + \tilde{c}_{f,i} \bar{f} i \gamma_5 f \right) + a_i \left(2 m_W^2 W_\mu W^\mu + m_Z^2 Z_\mu Z^\mu \right) \right] \frac{h_i}{v}$$

- Contributions to EDM:

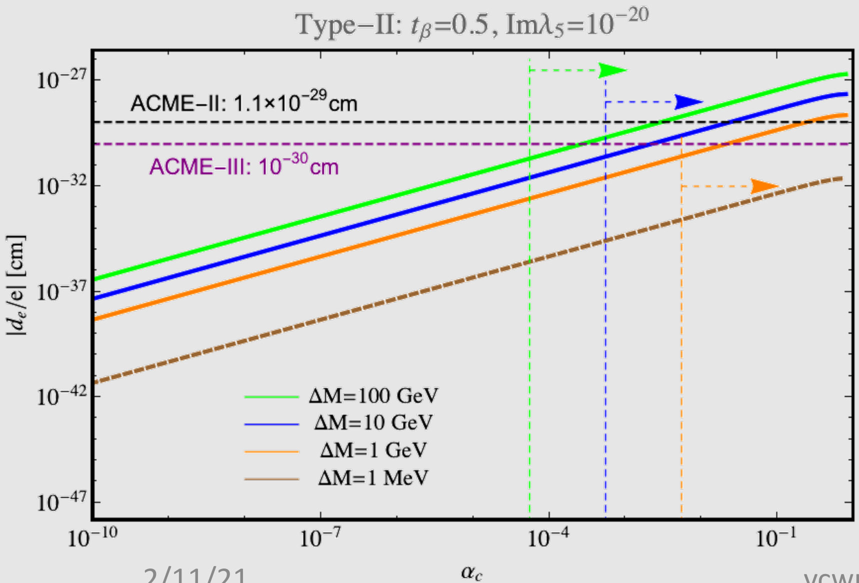


- ACME-II:
  - $\left|\frac{d_e}{e}\right| \leq 1.1 \times 10^{-29}\ cm$
- ACME-III:
  - $\left|\frac{d_e}{e}\right| \leq 1.0 \times 10^{-30} cm$

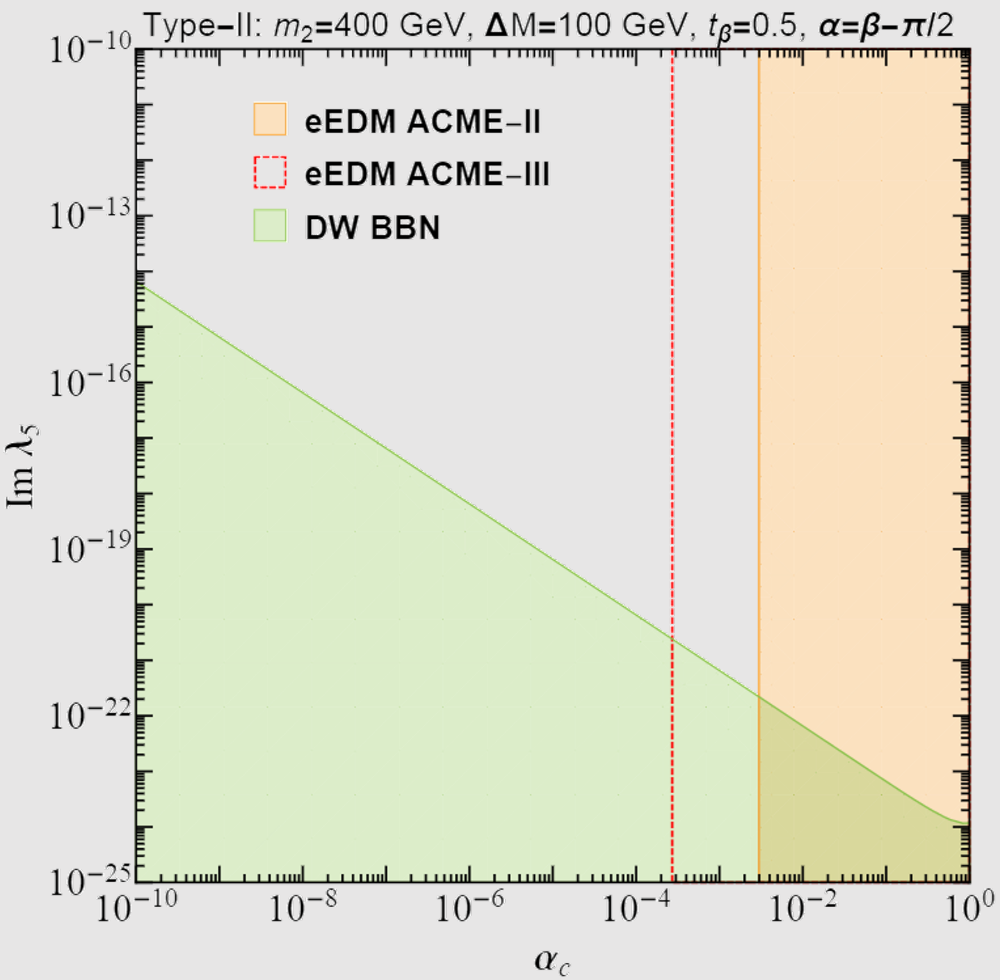
EDM vs. DW



Type−II: t_β=0.5, Imλ_5=10^{-15}
ACME-II: 1.1×10^{-29}cm
ACME-III: 10^{-30}cm
ΔM=100 GeV
ΔM=10 GeV
ΔM=1 GeV
ΔM=1 MeV
$|d_e/e|$ [cm]
α_c



Type−II: t_β=0.5, Imλ_5=10^{-20}
ACME-II: 1.1×10^{-29}cm
ACME-III: 10^{-30}cm
ΔM=100 GeV
ΔM=10 GeV
ΔM=1 GeV
ΔM=1 MeV
$|d_e/e|$ [cm]
α_c



Type-II: m_2=400 GeV, ΔM=100 GeV, t_β=0.5, $\alpha=\beta-\pi/2$
eEDM ACME-II
eEDM ACME-III
DW BBN
Im λ_5
α_c

Summary

- Extended Scalar Sector → Topological Defects
- CP DW is discussed in cxSM and 2HDM
  - cxSM:
    - GW signal from Collapsing DW is sensitive to the tiny CPV parameters, and high scales ($v_s \sim 10\ TeV, m_s \sim 10\ TeV$)
  - 2HDM:
    - GW signal is not detectable due to low scale
    - Constraints from CP DW is complementary with EDM measurement

Thanks!

Happy Chinese New Year!

Backups

Evolution of DW

- No Biased Yet:
  - Two forces:
    - Tension force
      - $f_T \sim \frac{\sigma}{R}$
    - Friction force
      - $f_f \sim \Delta p \cdot n \sim vT^4$
      - Drop dramatically when temperature is less than the mass of other particles
        - Entering Scaling Regime
  - Scaling Regime
    - $R \sim L \sim H^{-1} \sim t$
    - $\rho_w \sim \frac{\sigma R^2}{\mathrm{R^2 L}} \sim \frac{\sigma}{t} \Rightarrow \rho_w = \mathcal{A}\frac{\sigma}{t}$ $\qquad \mathcal{A} \simeq 0.8 \pm 0.1$

Evolution of DW

- $H^2 = \frac{\rho_c}{3M_P^2} \simeq \frac{1}{4t^2} \Rightarrow \rho_c = \frac{3M_P^2}{4t^2}$
- Dominant time:
  - $\rho_w = \mathcal{A}\frac{\sigma}{t} \simeq \frac{3M_P^2}{4t^2} = \rho_c \Rightarrow t_{dom} \simeq \frac{3M_P^2}{4\mathcal{A}\sigma}$
  - $M_P \simeq 2.435\times 10^{18}$ GeV
  - $\mathcal{A} \simeq 0.8$
  - $t_{dom} \simeq 2.93\times 10^3 s\, \mathcal{A}^{-1}\left(\frac{\sigma}{TeV^3}\right)^{-1}$

Evolution of DW

- With Biased Terms:
  - Another force:
    - Pressure force: $f_V \sim \Delta V$
  - Collapse of DW happens when pressure force dominate
    - $f_V \gtrsim f_T = \mathcal{A}\frac{\sigma}{t}$
  - Annihilation time:
    - $f_V = C_{ann} f_T \Rightarrow t_{ann} = C_{ann}\frac{\mathcal{A}\sigma}{\Delta V}$
    - $t_{ann} \simeq 6.58\times 10^{-4} s\ C_{ann}\mathcal{A}\left(\frac{\sigma}{TeV^3}\right)\left(\frac{\Delta V}{MeV^4}\right)^{-1}$
  - Convert to temperature:
    - $T_{ann} \simeq 3.41\times 10^{-2}\ GeV\ \ C_{ann}^{-1/2}\mathcal{A}^{-1/2}\left(\frac{g}{10}\right)^{-1/4}\left(\frac{\sigma}{TeV^3}\right)^{-1/2}\left(\frac{\Delta V}{MeV^4}\right)^{1/2}$

$C_{ann} \simeq 2\ -5$

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Evolution of DW

- Avoid Overclose
  - $t_{ann} < t_{dom}$
  - $\Delta V^{1/4} > 2.18\times10^{-5}\ GeV\ C_{ann}^{1/4}\mathcal{A}^{1/2}\left(\frac{\sigma}{TeV^3}\right)^{1/2}$
  - Or equivalently
  - $T_{ann} > 1.62\times10^{-5}\ GeV\ \mathcal{A}^{1/2}\left(\frac{g_*}{10}\right)^{-1/4}\left(\frac{\sigma}{TeV^3}\right)^{1/2}$

Evolution of DW

- Avoid Ruin BBN:
  - If significant fraction of the energy density of DW is converted into energetic particles:
  - $t_{ann} \lesssim 0.01\ s$
  - Equivalently
  - $\Delta V^{1/4} > 5.07{\times}10^{-4} GeV\ C_{ann}^{1/4} \mathcal{A}^{1/4} \left(\frac{\sigma}{TeV^3}\right)^{1/4}$

GW from DW

- Naïve Estimation:
  - $E_{gw} \simeq G\frac{M^2}{R}$
  - $M \simeq \mathcal{A}\,\sigma R^2$
  - $\rho_{gw} \simeq \frac{E_{gw}}{R^3} \simeq G\mathcal{A}^2\sigma^2$
- Second Estimation:
  - GW radiation power:
    - $P \simeq G\,\dddot{Q}\dddot{Q}$
    - $\dddot{Q} \sim \frac{\mathcal{A}\sigma R^2 R^2}{t^3} \sim \mathcal{A}\sigma t$
    - $\rho_{gw} \simeq \frac{Pt}{R^3} \simeq \frac{P}{t^2} \simeq G\mathcal{A}^2\sigma^2$
- From numerical simulation:
  - $\tilde{\epsilon}_{gw} \equiv \frac{1}{G\mathcal{A}^2\sigma^2}\left(\frac{d\rho_{gw}}{d\ln k}\right)_{peak} \simeq 0.7 \pm 0.4$

GW from DW

$$H^2 = \frac{8\pi G}{3}\rho = \frac{8\pi G}{3}\frac{\pi^2}{30}g_* T^4$$

Entropy Conservation: $sa^3 = Const$

$$s = \frac{2\pi^2}{45}g_{*s}T^3$$

- GW spectrum:
  - $\Omega_{gw}(t,f) = \frac{1}{\rho_c(t)}\frac{d\rho_{gw}(t)}{d\ln k}$
- At annihilation time
  - $\Omega_{gw}(t_{ann})_{peak} = \frac{1}{\rho_c(t_{ann})}\left(\frac{d\rho_{gw}(t_{ann})}{d\ln k}\right)_{peak} = \frac{8\pi G}{3H^2(t_{ann})}\tilde{\epsilon}_{gw}G\mathcal{A}^2\sigma^2 = \frac{8\pi\tilde{\epsilon}_{gw}G^2\mathcal{A}^2\sigma^2}{3H^2(t_{ann})}$
- At current time
  - $$\Omega_{gw}(t_0)h^2(t_0)_{peak} = \frac{\rho_c(t_{ann})}{\rho_c(t_0)}\left(\left(\frac{a(t_{ann})}{a(t_0)}\right)^4\Omega_{gw}(t_{ann})_{peak}\right)h^2(t_0)$$
    $$= \frac{\rho_\gamma(t_0)}{\rho_c(t_0)}h^2\frac{\rho_\gamma(t_{ann})}{\rho_\gamma(t_0)}\left(\frac{g_{*s}(T_0)}{g_{*s}(T_{ann})}\right)^{4/3}\left(\frac{T_0}{T_{ann}}\right)^4\Omega_{gw}(t_{ann})_{peak}$$
    $$= \Omega_{rad}h^2\left(\frac{g_*(T_{ann})}{g_*(T_0)}\right)\left(\frac{g_{*s}(T_0)}{g_{*s}(T_{ann})}\right)^{4/3}\Omega_{gw}(t_{ann})_{peak}$$
  - $\Omega_{gw}h^2(t_0)_{peak} \simeq 7.2\times10^{-18}\tilde{\epsilon}_{gw}\mathcal{A}^2\left(\frac{g_{*s}(T_{ann})}{10}\right)^{-4/3}\left(\frac{\sigma}{TeV^3}\right)^2\left(\frac{T_{ann}}{10^{-2}GeV}\right)^{-4}$

$$H^2 = \frac{8\pi G}{3}\rho = \frac{8\pi G}{3}\frac{\pi^2}{30}g_* T^4$$

Entropy Conservation: $sa^3 = Const$

$$s = \frac{2\pi^2}{45}g_{*s}T^3$$

GW from DW

- The peak frequency:
  - Related to the Hubble parameter and redshifted to today
  - $f_{peak} \simeq \left(\frac{a(t_{ann})}{a(t_0)}\right) H(t_{ann}) = \left(\frac{g_{*s}(T_0)}{g_{*s}(T_{ann})}\right)^{1/3} \left(\frac{T_0}{T_{ann}}\right) \sqrt{\frac{8\pi G}{3}\frac{\pi^2}{30}} g_*^{1/2} T_{ann}^2$
  - $f_{peak} \simeq 1.1\times 10^{-9} Hz \left(\frac{g_*(T_{ann})}{10}\right)^{1/2} \left(\frac{g_{*s}(T_{ann})}{10}\right)^{-1/3} \left(\frac{T_{ann}}{10^{-2} GeV}\right)$
- The cutoff frequency:
  - Related to the width of DW
  - $f_\delta \simeq \left(\frac{a(t_{ann})}{a(t_0)}\right) \delta^{-1} = 2.6\times 10^{16} Hz \left(\frac{g_{*s}(T_{ann})}{10}\right)^{-1} \left(\frac{T_{ann}}{10^{-2} GeV}\right)^{-1} \left(\frac{\delta^{-1}}{1 TeV}\right)$
- From numerical simulations:
  - GW spectrum behave as $\Omega_{gw} \propto f^{-1}$, for $f_{peak} < f < f_\delta$

Mixing angle in 2HDM

- $\alpha_b \approx \frac{m_3^2 - m_2^2}{m_3^2 - m_1^2} t_{2\beta} \alpha_c$
- $t_\theta \approx \frac{m_3^2 c_{2\beta}}{(m_3^2 - m_2^2)\alpha_c}$