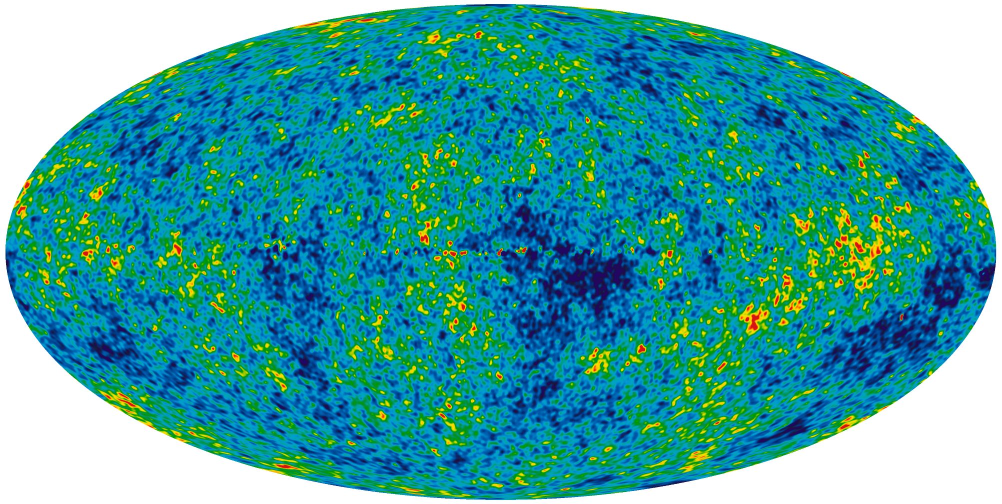
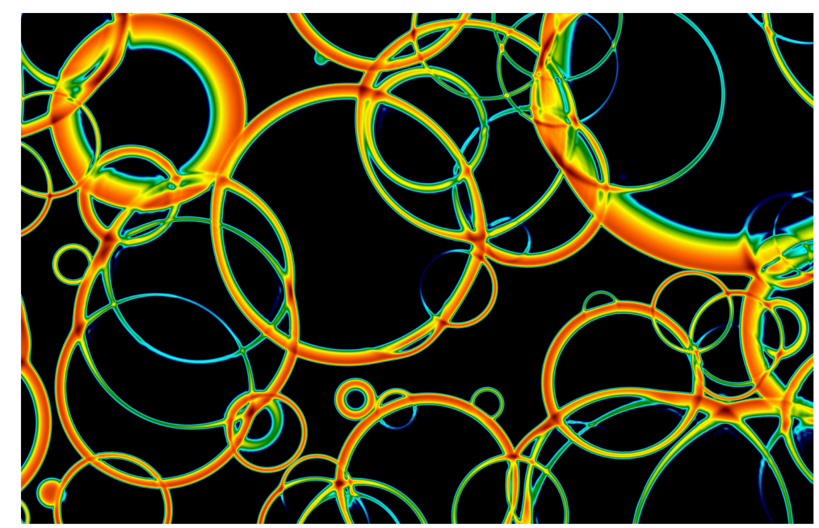


Probing the new physics with Electroweak Phase Transitions

Yikun Wang

yikwang@uchicago.edu



APEC Seminar, Kavli IPMU, 2020

October 14th, Chicago

In Collaboration with: ***Marcela Carena,*** *Zhen Liu, Carlos Wagner, Nausheen Shah, Sebastian Baum, et al*

Outline

1. Introduction

- Higgs potential and the electroweak phase transitions (EWPT)
- Electroweak Baryogenesis and strongly first order EWPT (SFOEWPT)
- Gravitational wave (GW) from a SFOEWPT

2. Extending the Higgs sector: SFOEWPT

- **EWPT with spontaneous Z2 breaking: a singlet extension**

  Enhancing the EWPT and the thermal history, phenomenology and GW

- **EWPT in NMSSM: nucleation is more than critical**

  EWPT in an extended Higgs sector with two doublets and a singlet, nucleation versus critical temperature calculation, collider and DM phenomenology

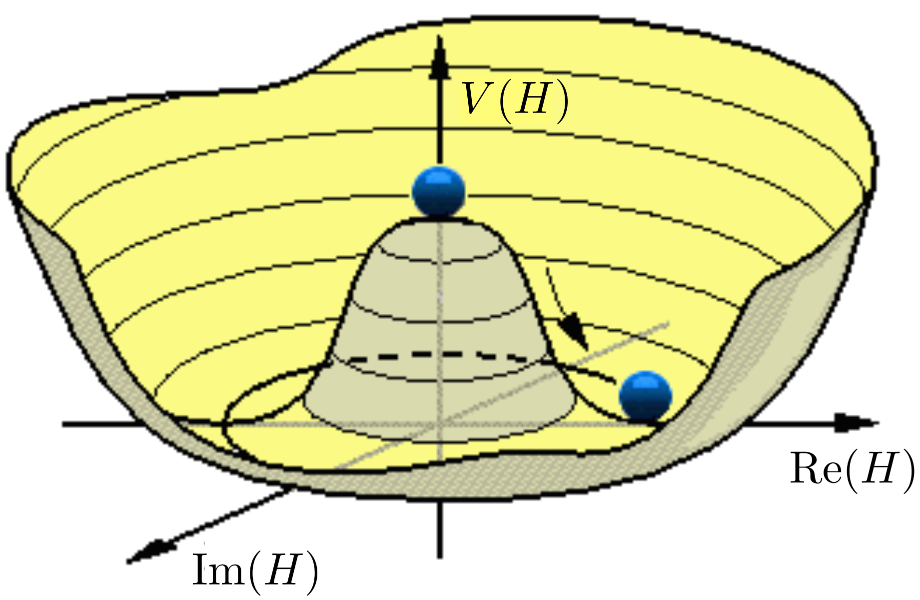
3. Summary

Introduction

- Higgs potential and the electroweak phase transitions (EWPT)
- Electroweak Baryogenesis and strongly first order EWPT (SFOEWPT)
- Gravitational wave (GW) from a SFOEWPT

The Standard Model and Higgs potential

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

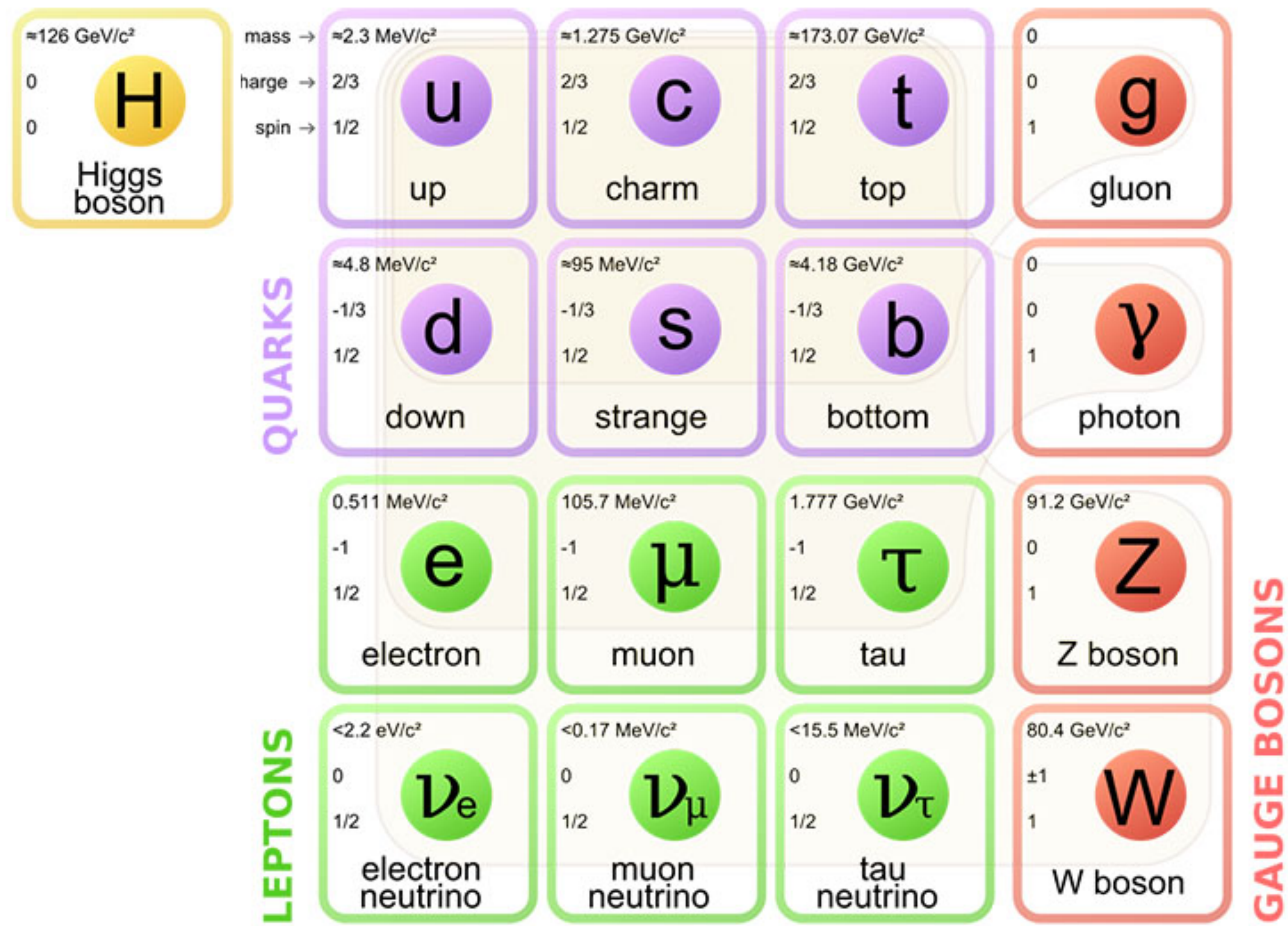


$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

EWSB $\downarrow$ $< H >= \frac{v}{\sqrt{2}}$

$$SU(3)_c \times U(1)_{em}$$

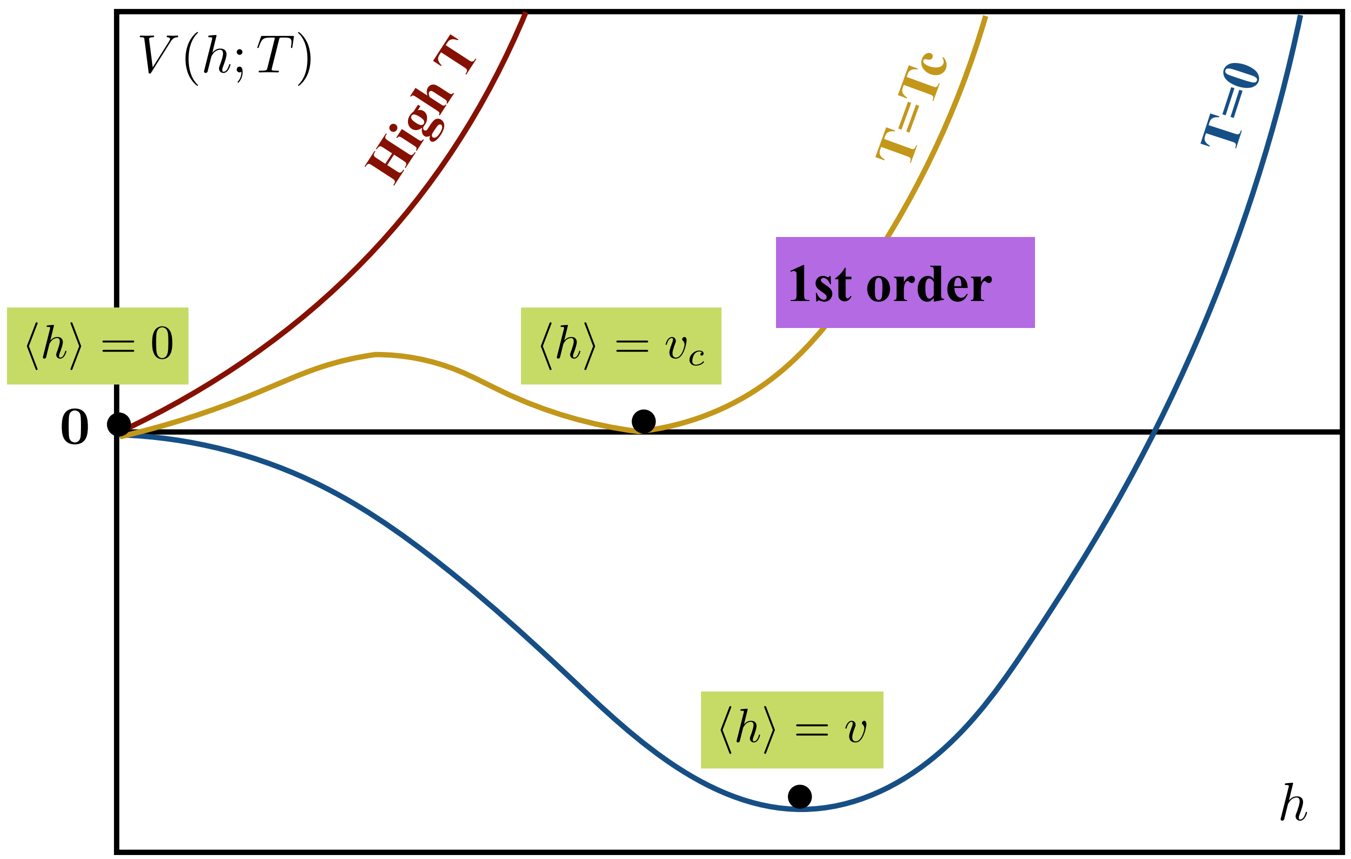
The Standard Model



Electroweak Phase Transitions

Finite temperature QFT

$$V(h,T) \approx D(T^2 - T_0^2)h^2 - ETh^3 + \frac{\lambda(T)}{2}h^4$$



At very high temperatures, the electroweak symmetry is restored.

Electroweak phase transition (EWPT)

The phase transition from the EW preserving phase to the EW broken phase 'happens' at a critical temperature where the two vacua are degenerate:

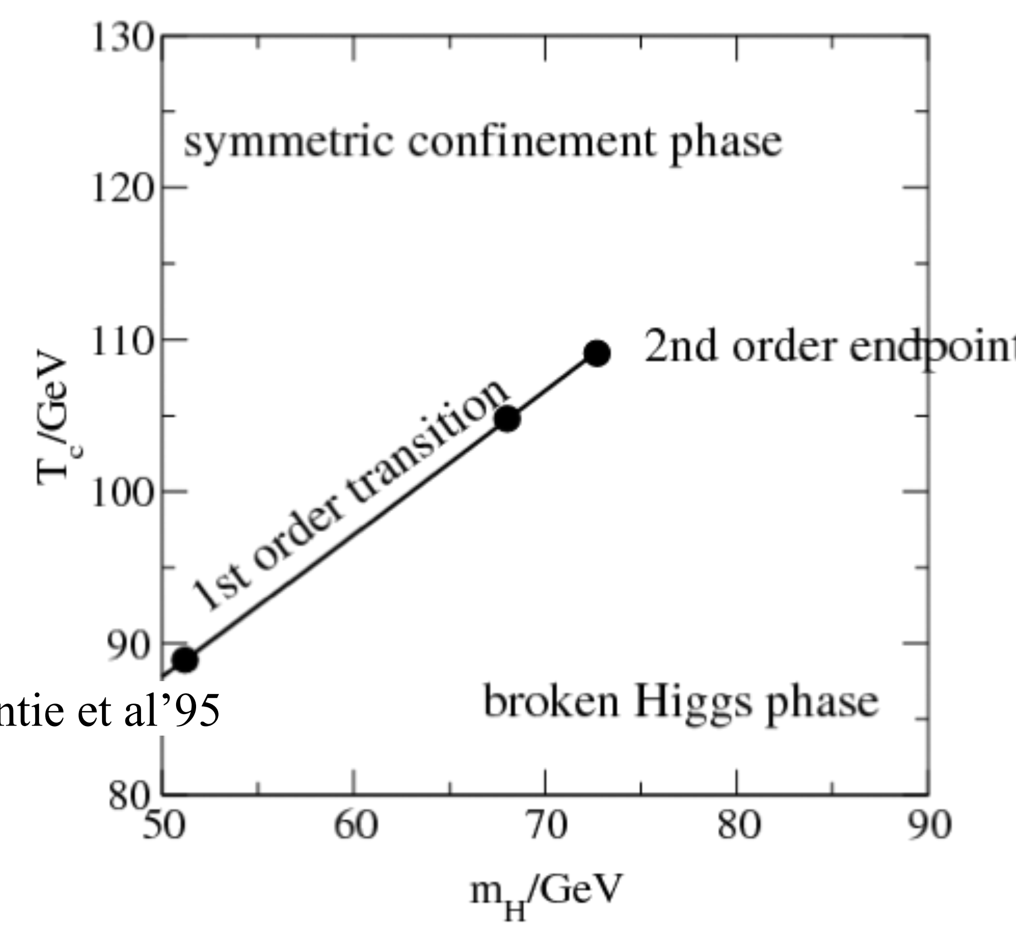
$$V(0;T_c) = V(v_c;T_c)$$

The order parameter typically used for the phase transition is:

$$v_c/T_c$$

where $v_c \equiv v(T = T_c)$

Based on the current measurement of the Higgs mass of 125GeV, lattice calculations show that the EWPT in the SM is a smooth cross over.



Kajantie et al'95

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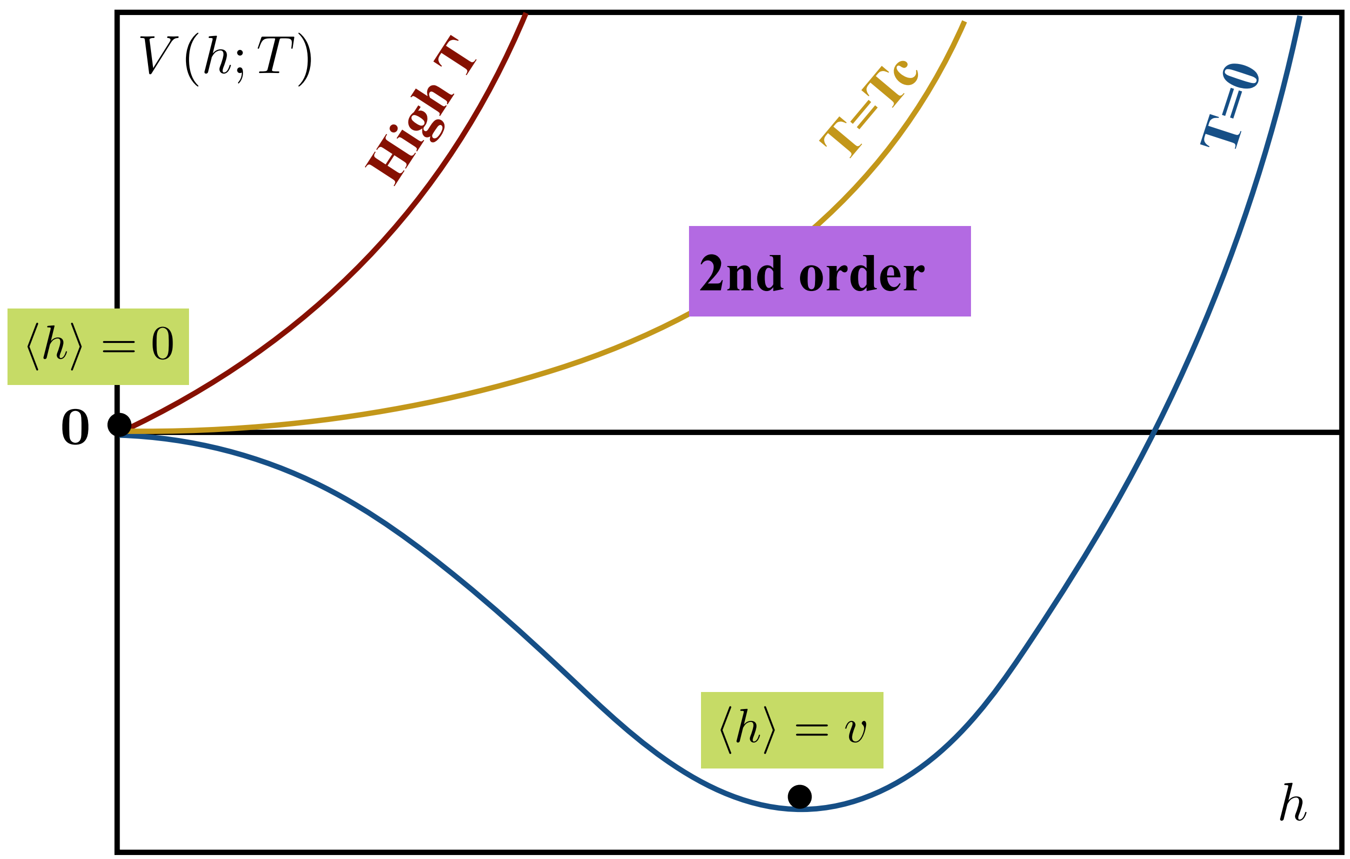

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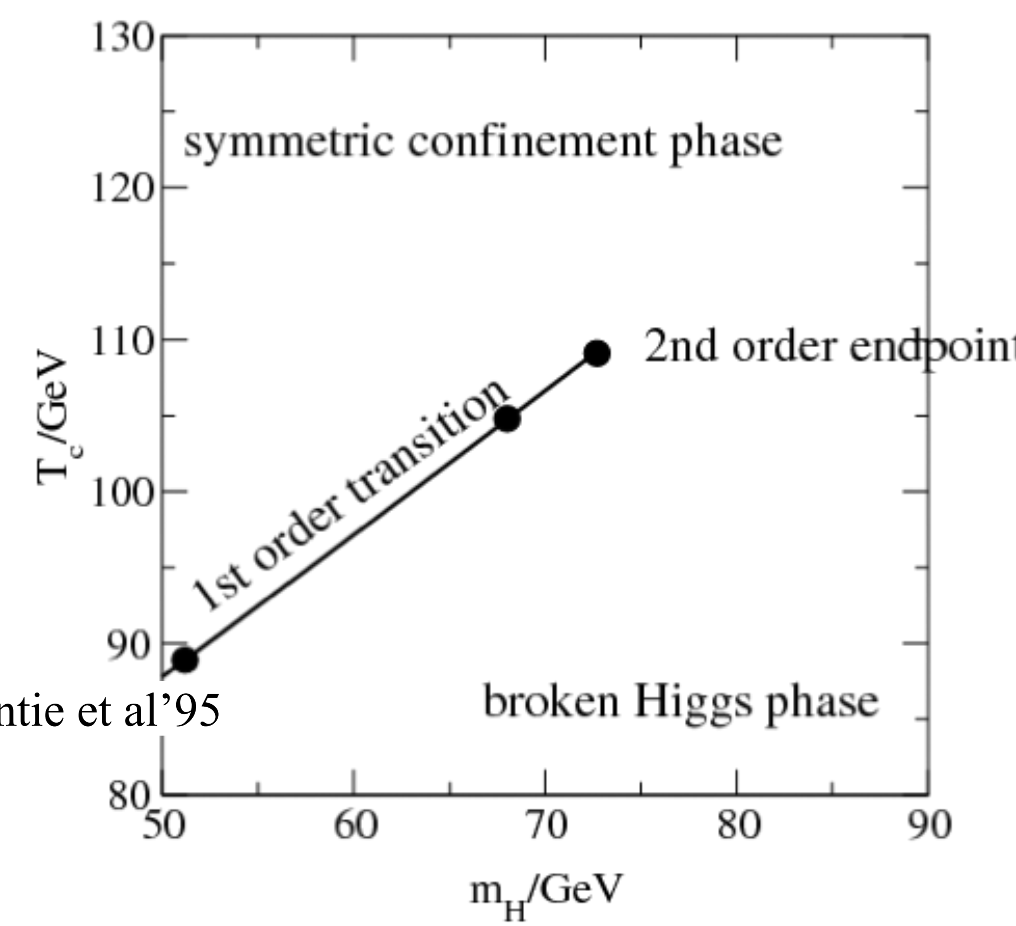
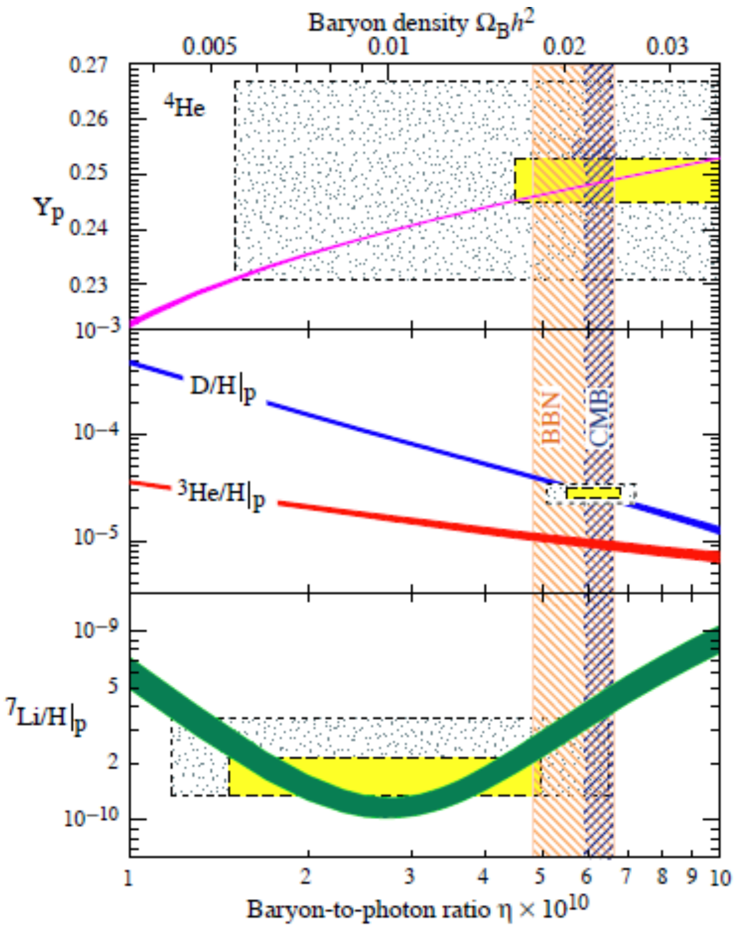
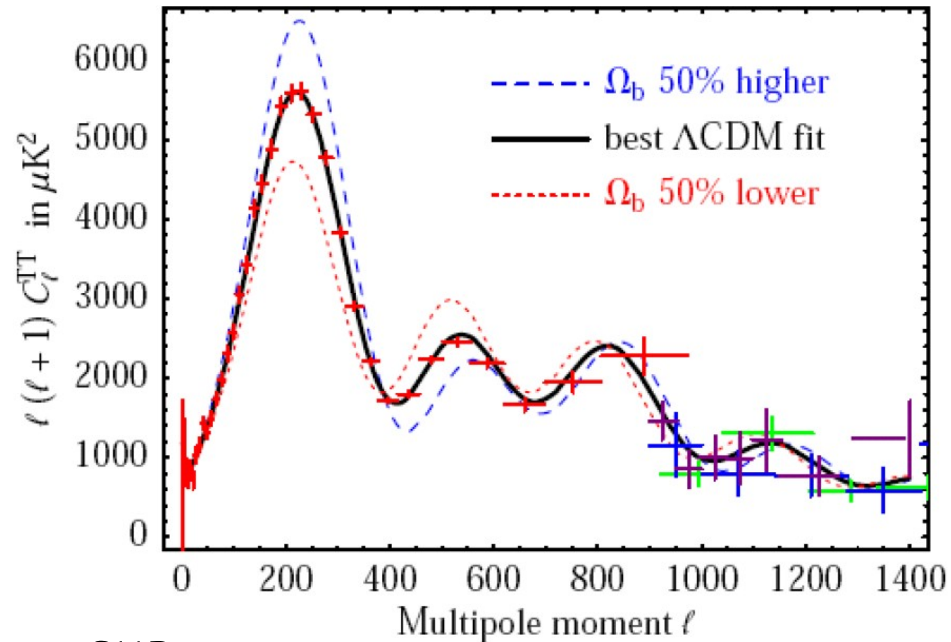


Kajantie et al'95

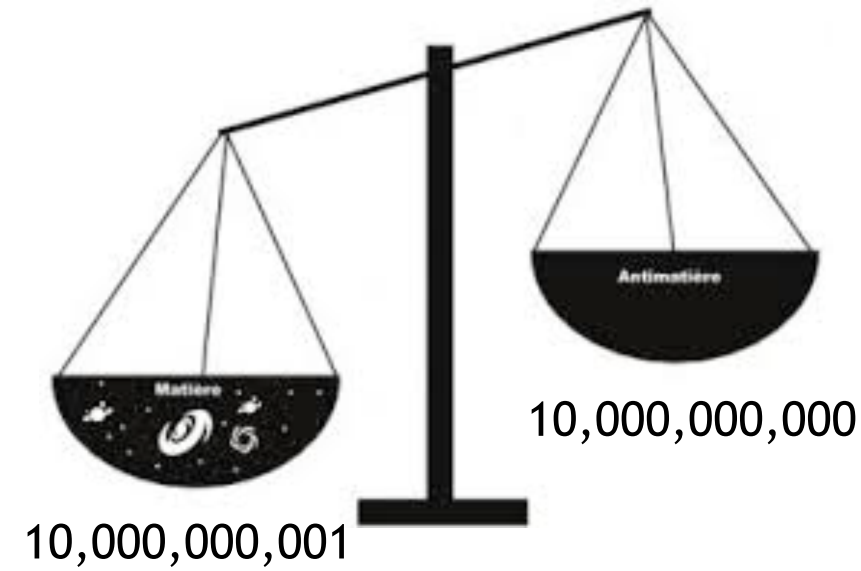
The mystery of our asymmetric universe



Big Bang Nucleosynthesis



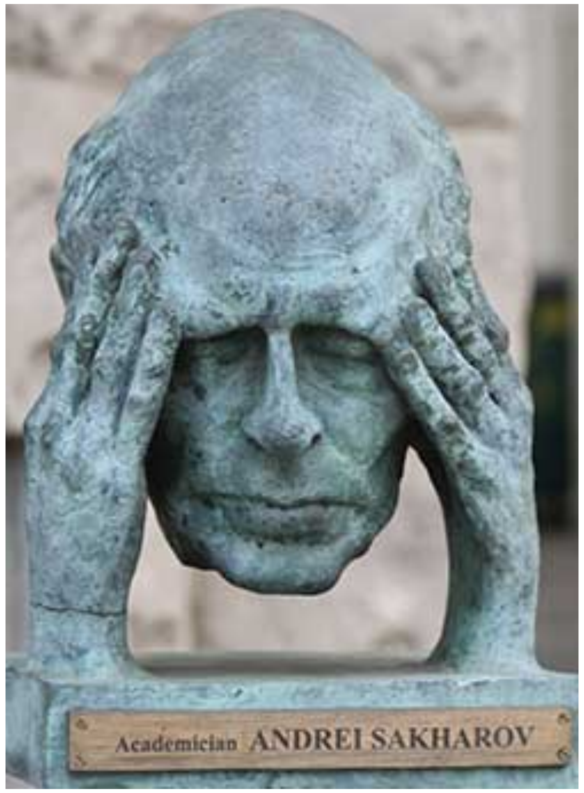
CMB



Matter antimatter asymmetry

$$\eta = \frac{n_B}{n_\gamma} = (6.11 \pm 0.19) \times 10^{-10}$$

Baryons, antibaryons and photons equally abundant in the early universe.
How to generate the observed asymmetry today?



Sakharov's conditions for baryogenesis (Sakharov 1967)

- **Baryon number violation**
- **C and CP violation**
- **Out-of-equilibrium**

Electroweak Baryogenesis

Sakharov's conditions

- **Baryon number violation**
- **C and CP violation**
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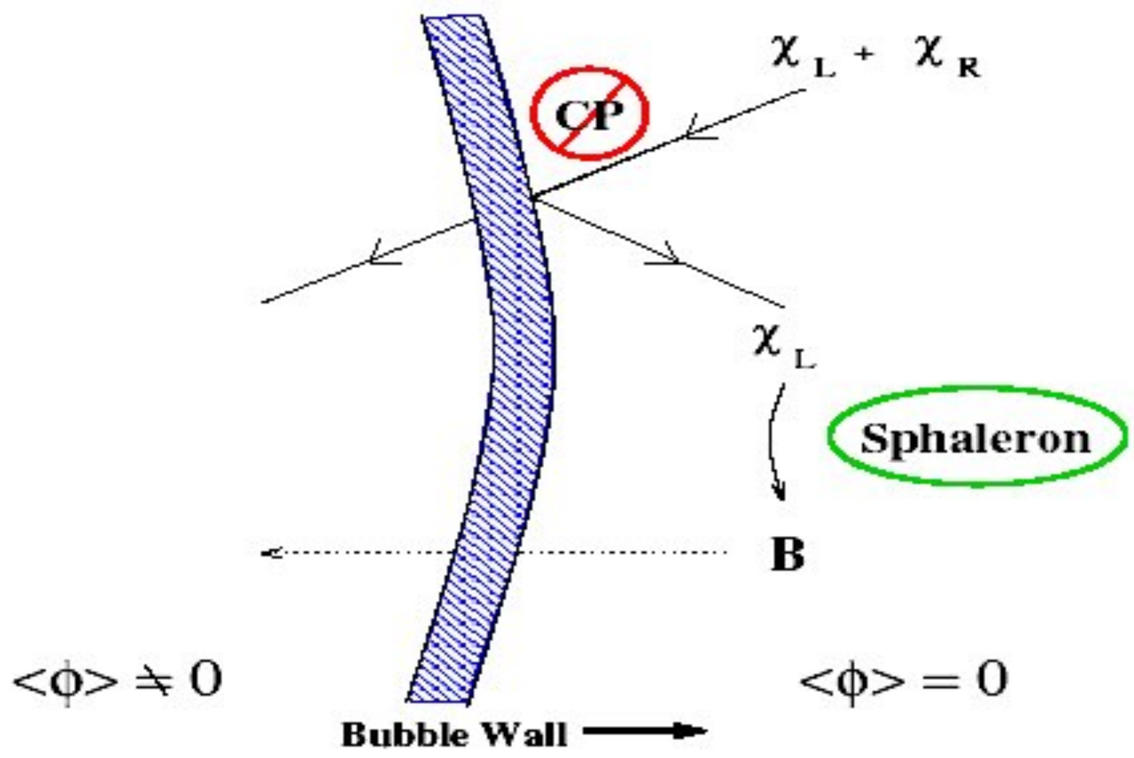
All ingredients exist in the SM around the EW scale.
However, the SM doesn't have enough.



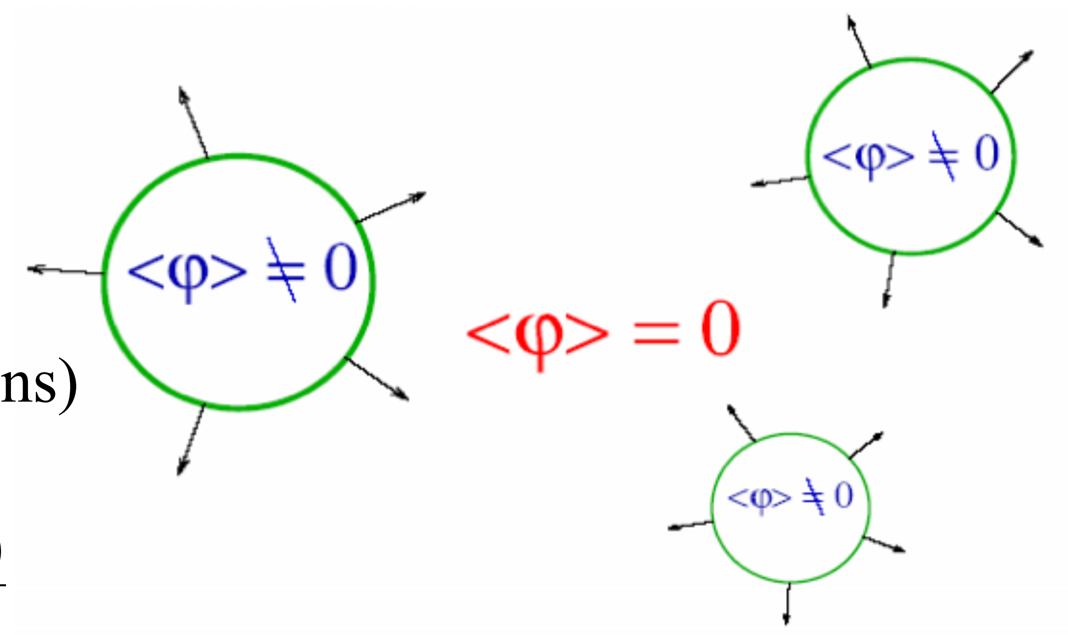
Inputs from the new physics

- more C and CP violation source
- **Strongly first order electroweak phase transition (SFOEWPT)**

$$\frac{v_c}{T_c} \gtrsim 1$$

➡ Provide out-of-thermal equilibrium

➡ Suppress baryon asymmetry washing out (sphalerons)



$$\Gamma_{\Delta B \neq 0} \cong \beta_0 T \exp\left(-\frac{E_{\rm sph}(T)}{T}\right) \qquad \frac{E_{\rm sph}(T)}{T} \cong \frac{8\pi}{g}\frac{v(T)}{T}$$

Electroweak Baryogenesis

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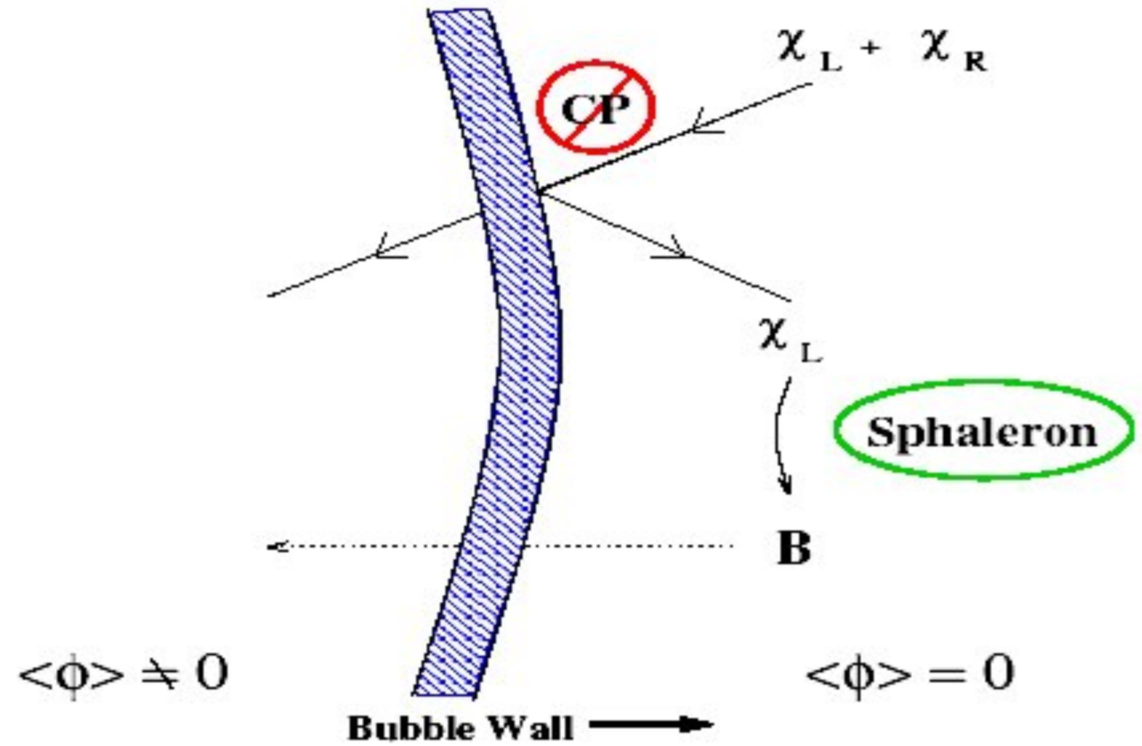

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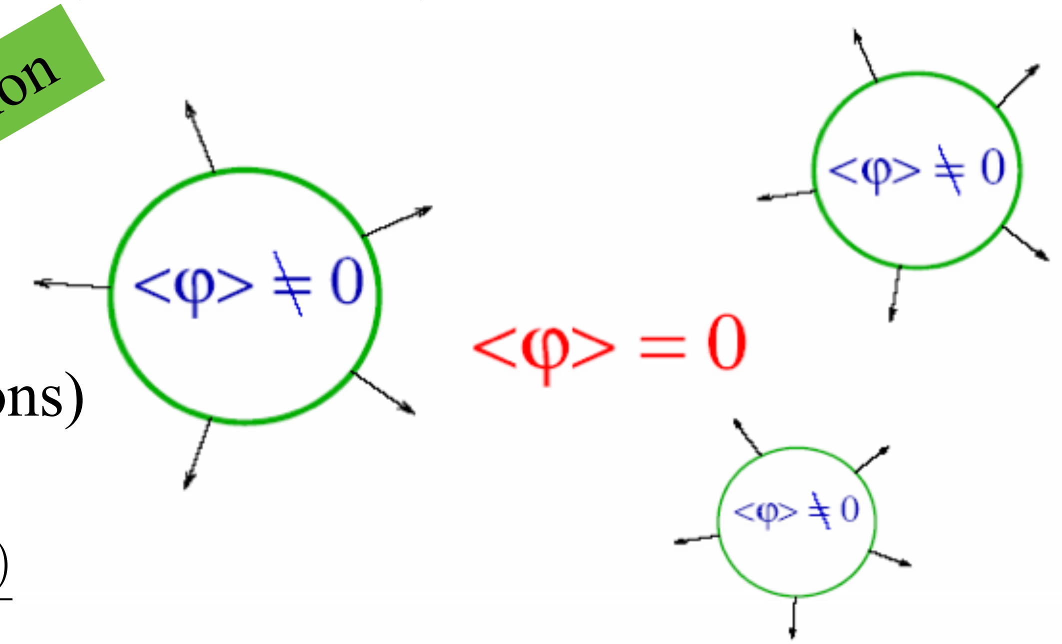
Bubble nucleation

➡ Provide out-of-thermal equilibrium

➡ Suppress baryon asymmetry washing out (sphalerons)



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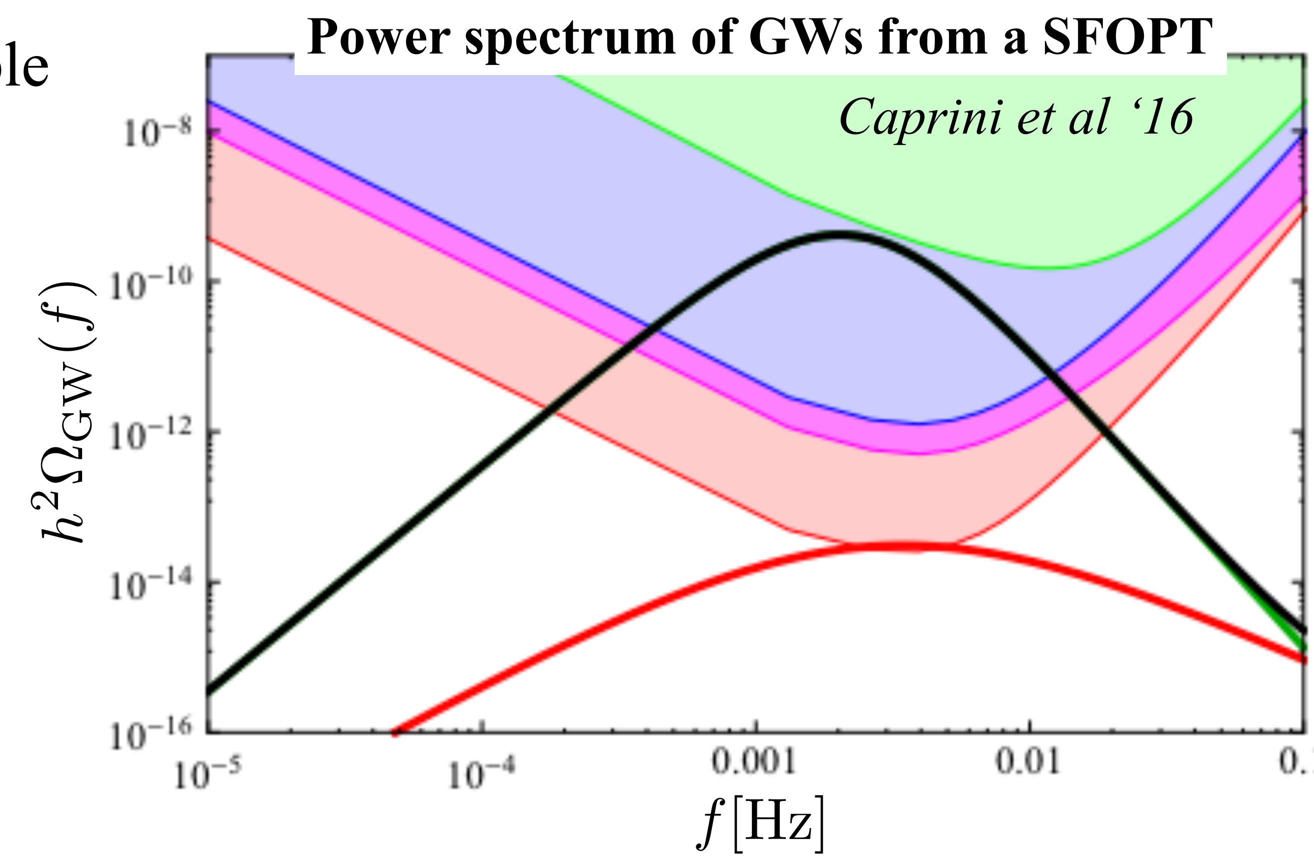
Gravitational wave

A first order phase transition proceeds through bubble nucleation. The expanding bubbles collide and produce **stochastic gravitational waves (GW)**.

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

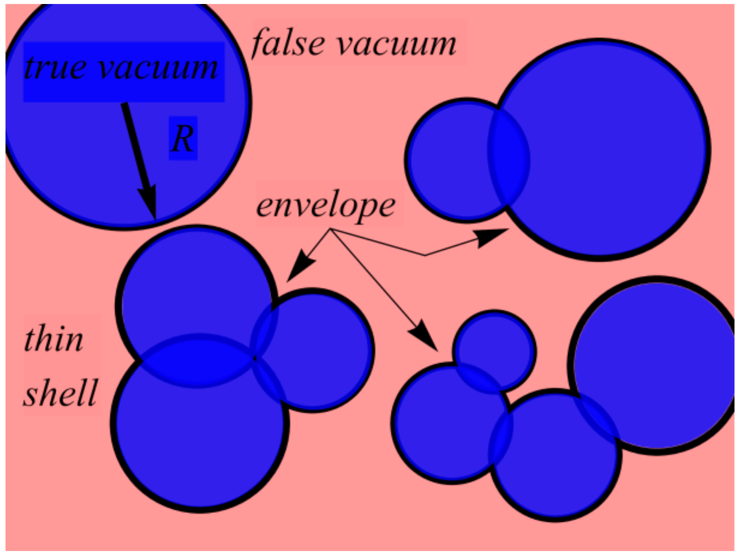


GW sources from bubble nucleation:

- Bubble collisions
- Sound waves
- Turbulent MHD

For example, the power spectrum from bubble collisions can be treated by the 'envelope approximation'

$$h^2\Omega_{\rm env}(f) = 1.67\times10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11v_w^3}{0.42+v_w^2}\right)S_{\rm env}(f)$$



Parameters affecting the power spectrum:

- $\frac{\beta}{H_*} \sim T\,\frac{d(S_3/T)}{dT}\Big|_{T=T_*}$, where β characterizes the **inverse duration of the PT**
- $\alpha = \frac{\rho_{\tilde{v},\tilde{w}} - \rho_{v,w}}{\rho_{rad}}|_{T=T_*}$, fraction of **vacuum energy released** wrt. the radiation bath
- **The bubble wall velocity** v_w

Enhancing the electroweak phase transitions: the general ideas

Finite temperature Higgs potential:

$$V(h,T) \approx D(T^2 - T_0^2)h^2 - ETh^3 + \frac{\lambda(T)}{2}h^4$$

Strength of the phase transition:

$$\frac{v_c}{T_c} \approx \frac{E}{\lambda}$$

Modifying the Higgs potential to enhance the strength:

- **Tree-level Effects**

  New dof, e.g. singlets, doublets etc, modifying the potential at tree level

  $$+V(h, S, H_{\rm BSM}, \cdots)$$

  $\lambda \to \lambda_{\rm eff}$

  $E \to E_{\rm eff}^{\rm tree}$

- **Zero Temperature loop effects**

  Modifying the potential through radiative corrections (from new dof), e.g. CW mechanism $\lambda \to \lambda_{\rm rad}$

- **Thermal effects**

  Modifying the thermal potential through thermal loops (from new dof), e.g. MSSM light stops $E \to E_{\rm BSM} \propto y_t^3$

- **Higher order operators**

Extending the Higgs Sector: SFOEWPT

- [x] EWPT with spontaneous Z2 breaking: a singlet extension
- [ ] EWPT in NMSSM: nucleation is more than critical

The singlet extension of the SM

- **One of the most generic extensions that can enhance the EWPhT**
- **An important benchmark as the most elusive extension**

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

$$+(\text{explicit Z2} - \text{breaking terms})$$

- Generic potential *Espinosa, Quiros '93; Profumo, Musolf, Shaughnessy '07; Choi, Volkas '93 etc*

- Z2 symmetric potential
  - ✤ Z2-preserving $\langle(h,s)\rangle = (v_{\rm EW}, 0)$

    Espinosa, Konstandinc, Riva '11; Curtin, Meade, Yu '15; Barger, Chung, Long, Wang '12 etc

Carena, Liu, Y.W '19

✤ **Z2 spontaneous broken** $\langle(h,s)\rangle = (v_{\rm EW}, w_{\rm EW})$

- **Dark 'Higgs' candidate, Higgs portal**
- **Render SFOPhT: light scalar**
- **Can be probed in various ways due to finite mixing**

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EWPT with spontaneous Z2-breaking: the thermal history

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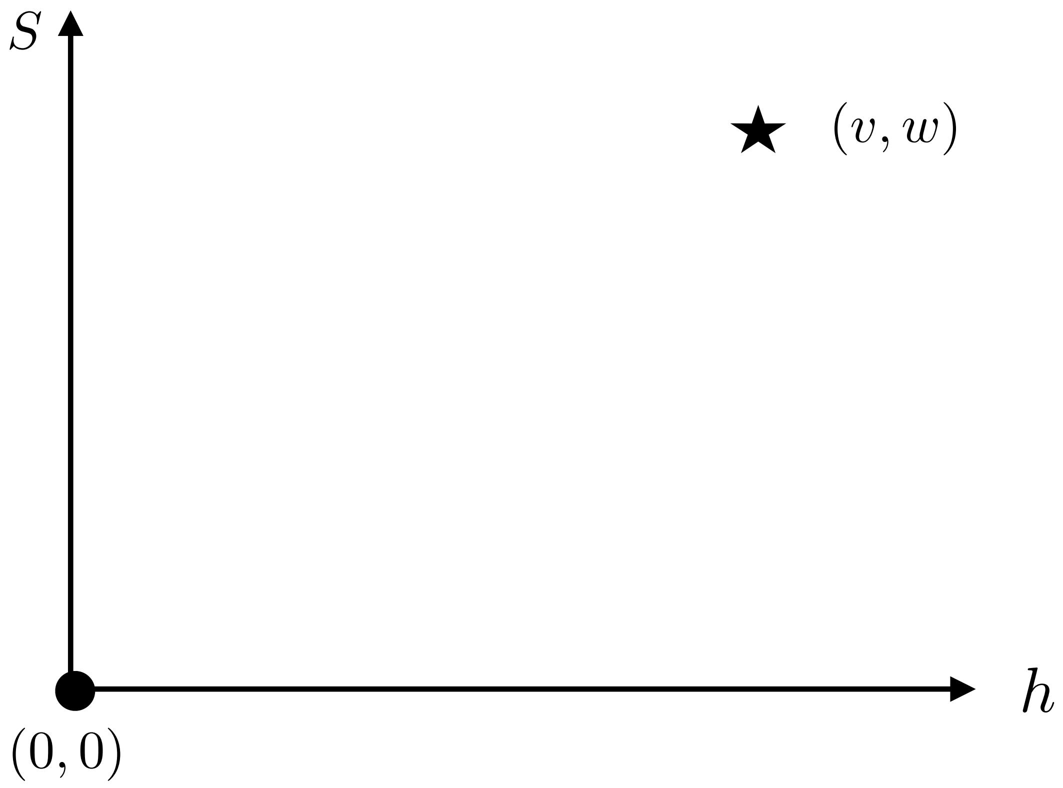

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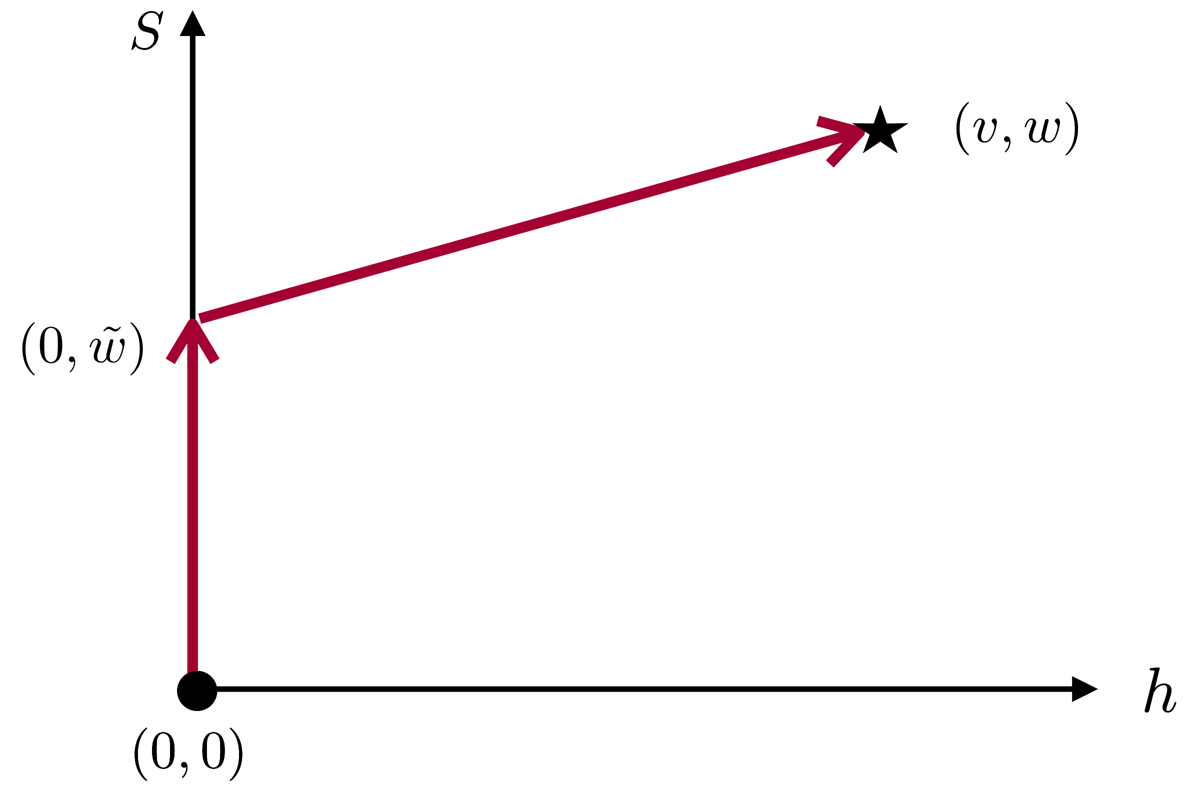

Scenario A: two-step

$$(0,0) \underset{\text{Z2}}{\rightarrow} (0,\tilde{w}) \underset{\text{EW}}{\rightarrow} (v,w)$$

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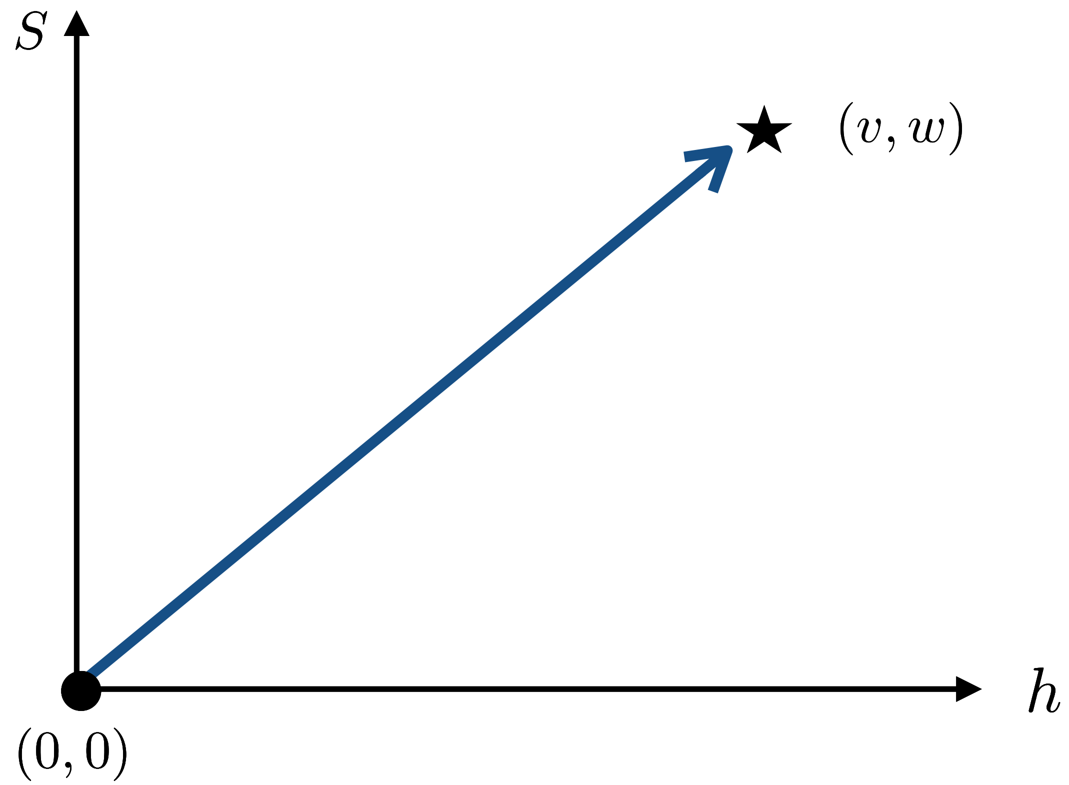

Scenario B: one-step

$$(0,0) \underset{\substack{\text{EW} \\ \text{Z2}}}{\rightarrow} (v,w)$$

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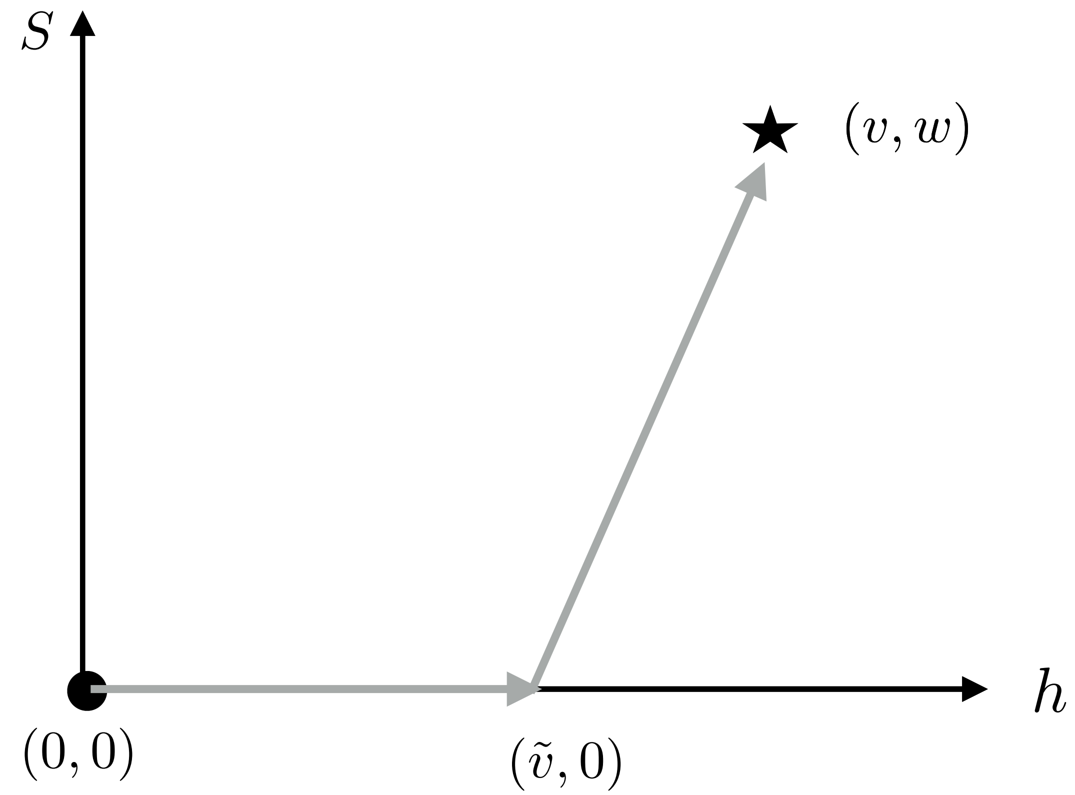
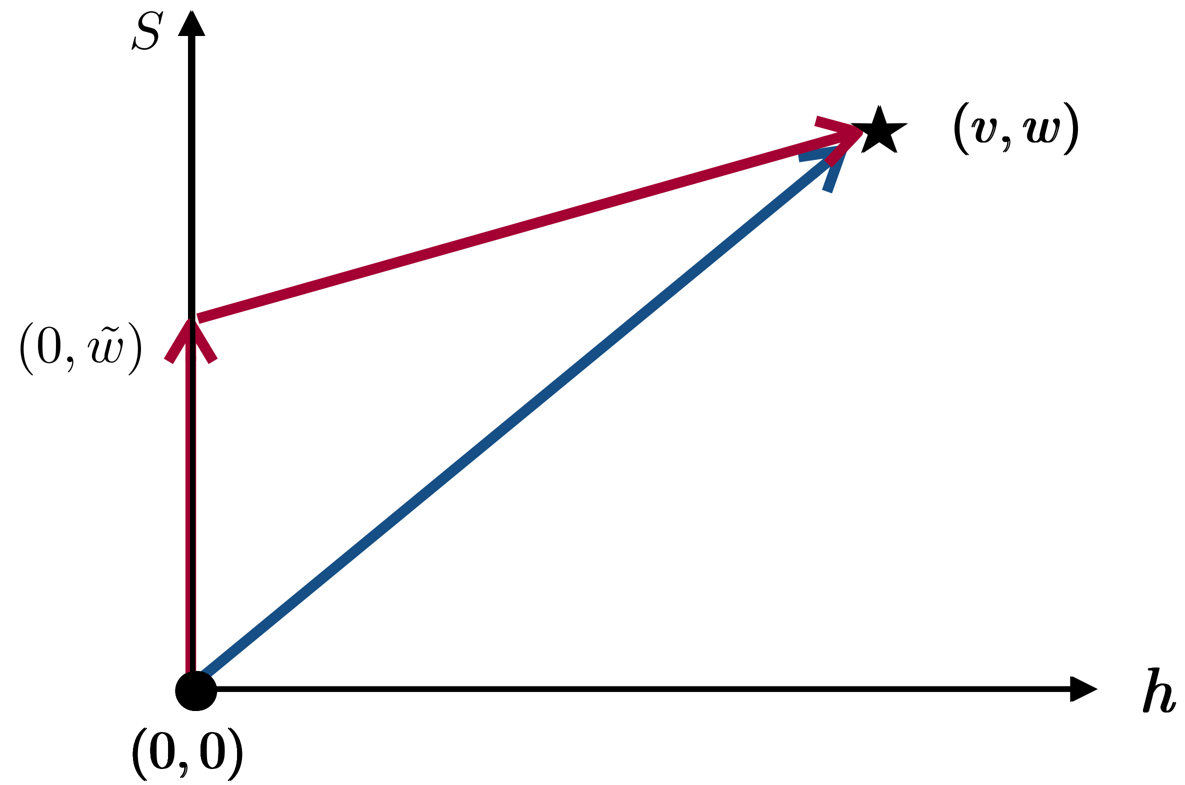


Not for EWBG:

First step is not much enhanced: singlet not yet engaged;

Second step does not onset EWBG: the baryon violation process is already suppressed.

EWPT with spontaneous Z2-breaking: the thermal history



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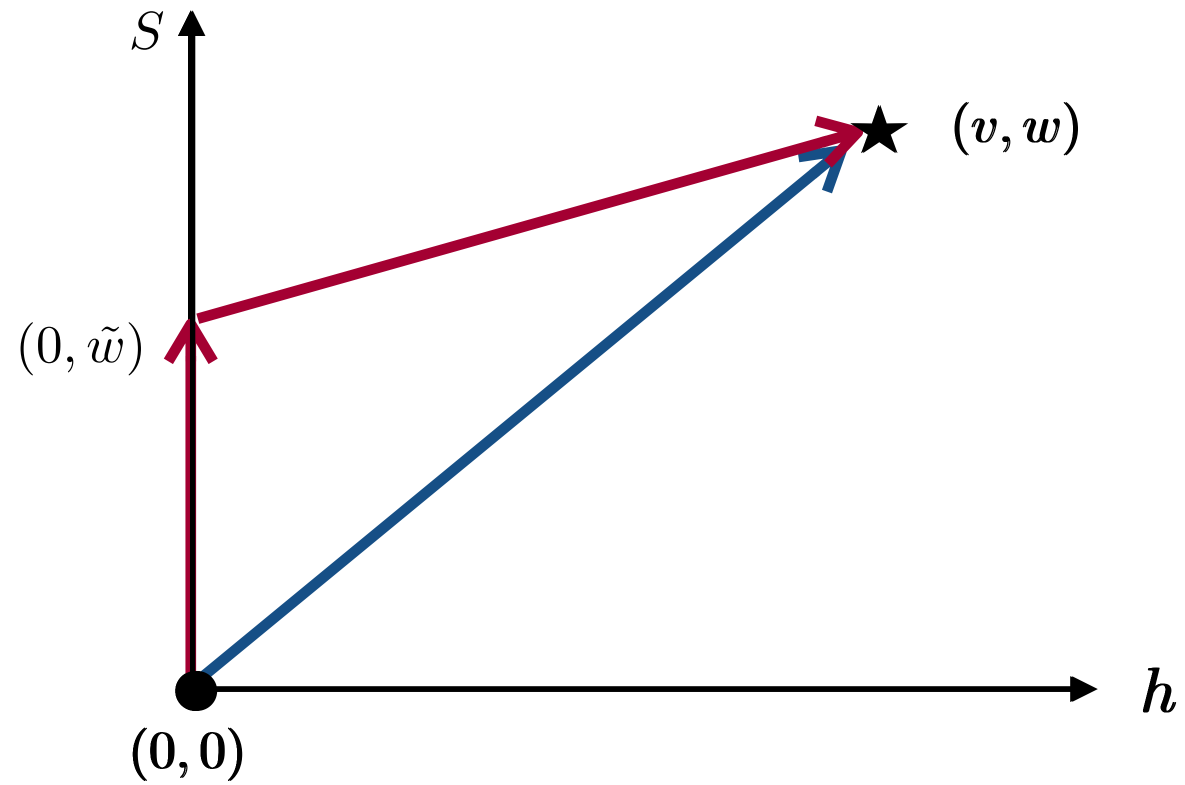

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Is it possible that the EW symmetry or/and the Z2 symmetry is/are Non-Restored ?

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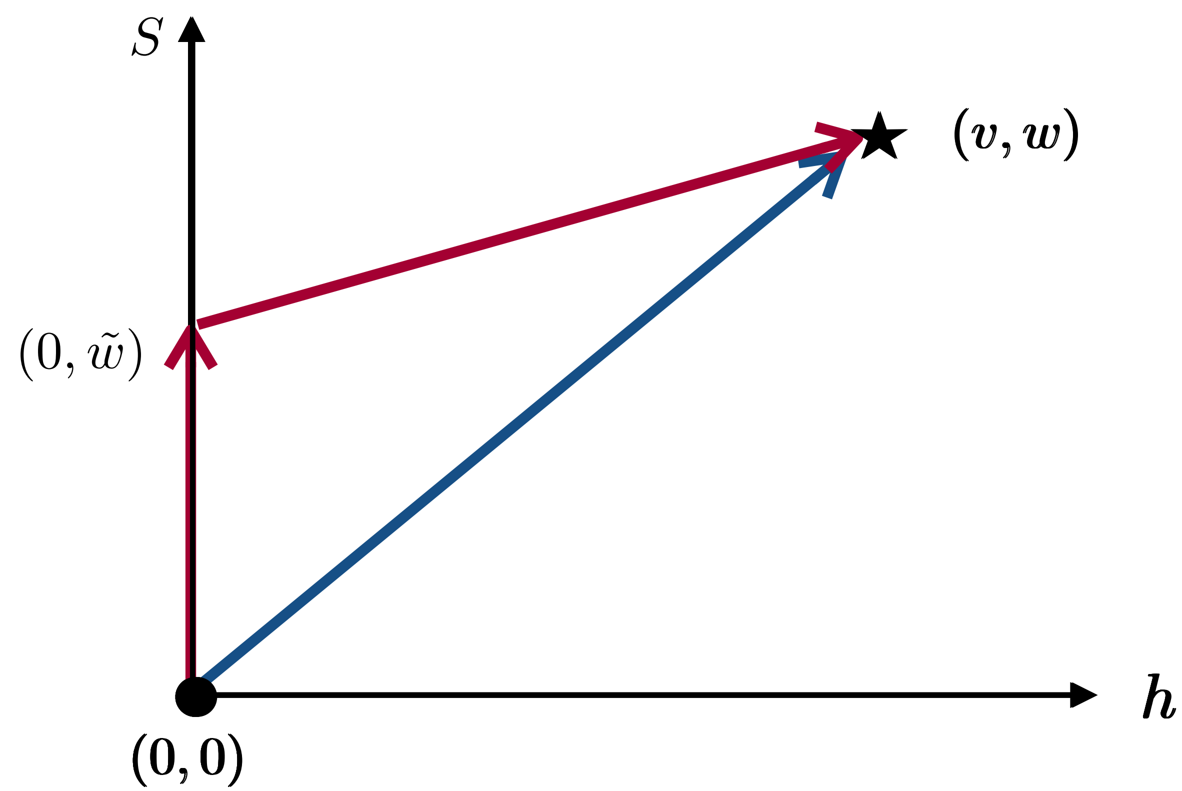

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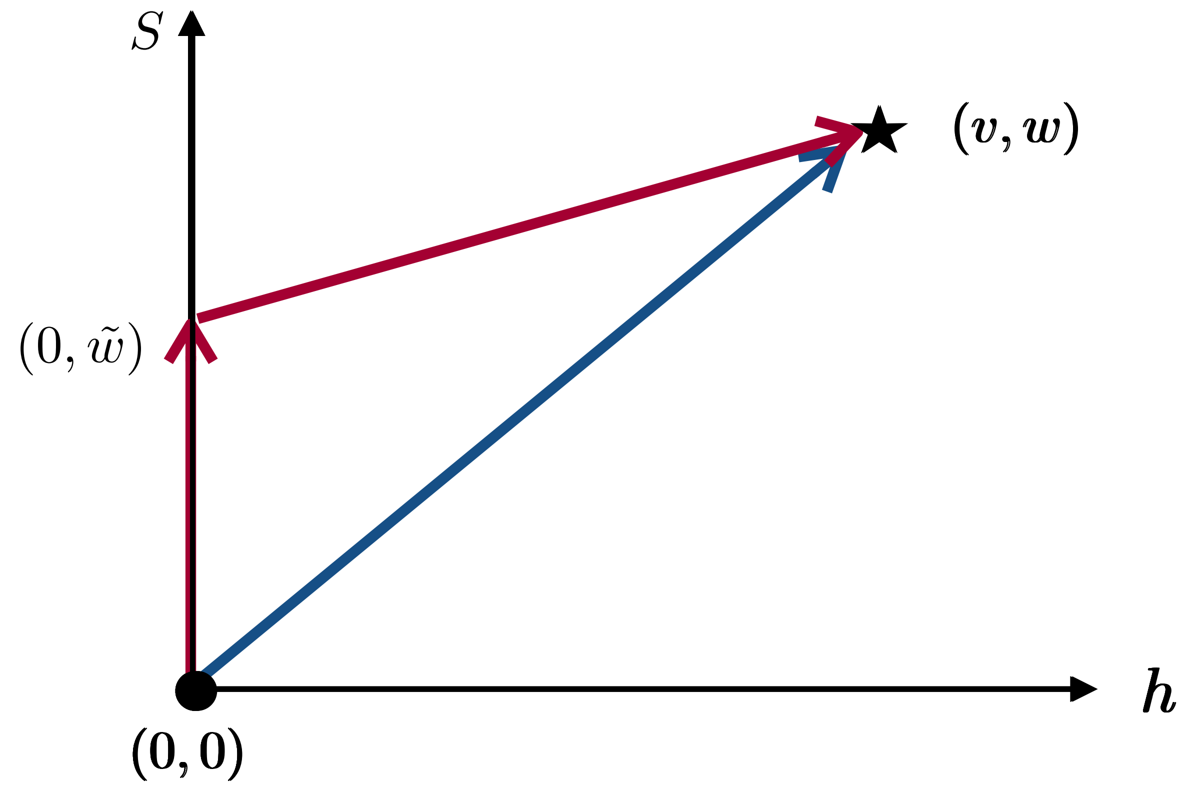

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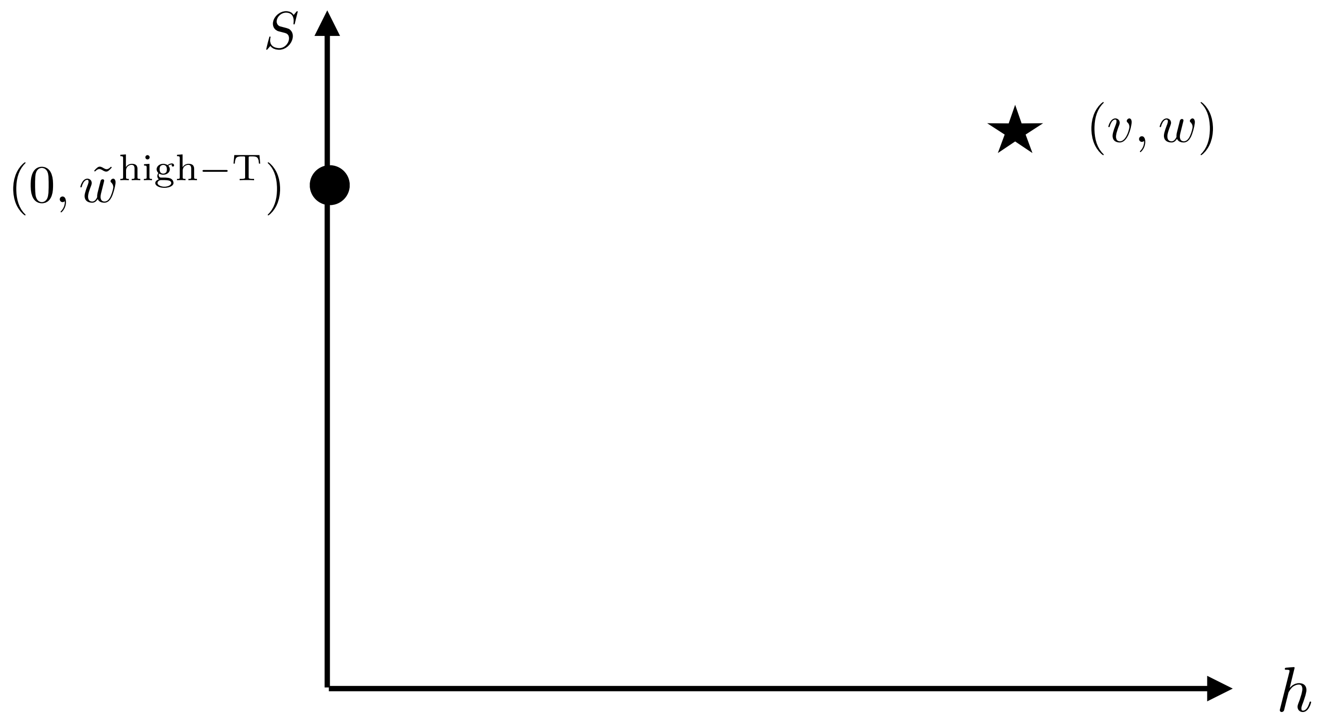

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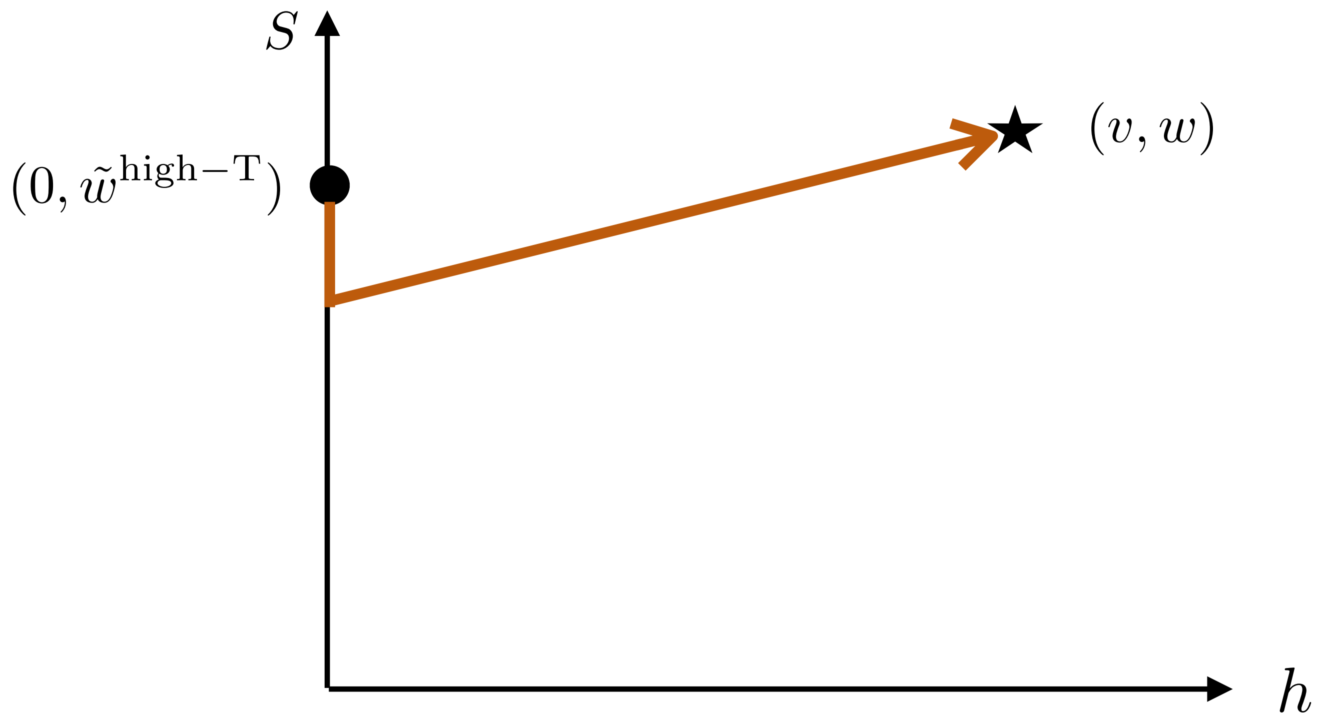

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Scenario A-NR: one-step

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NR stands for non-restoration

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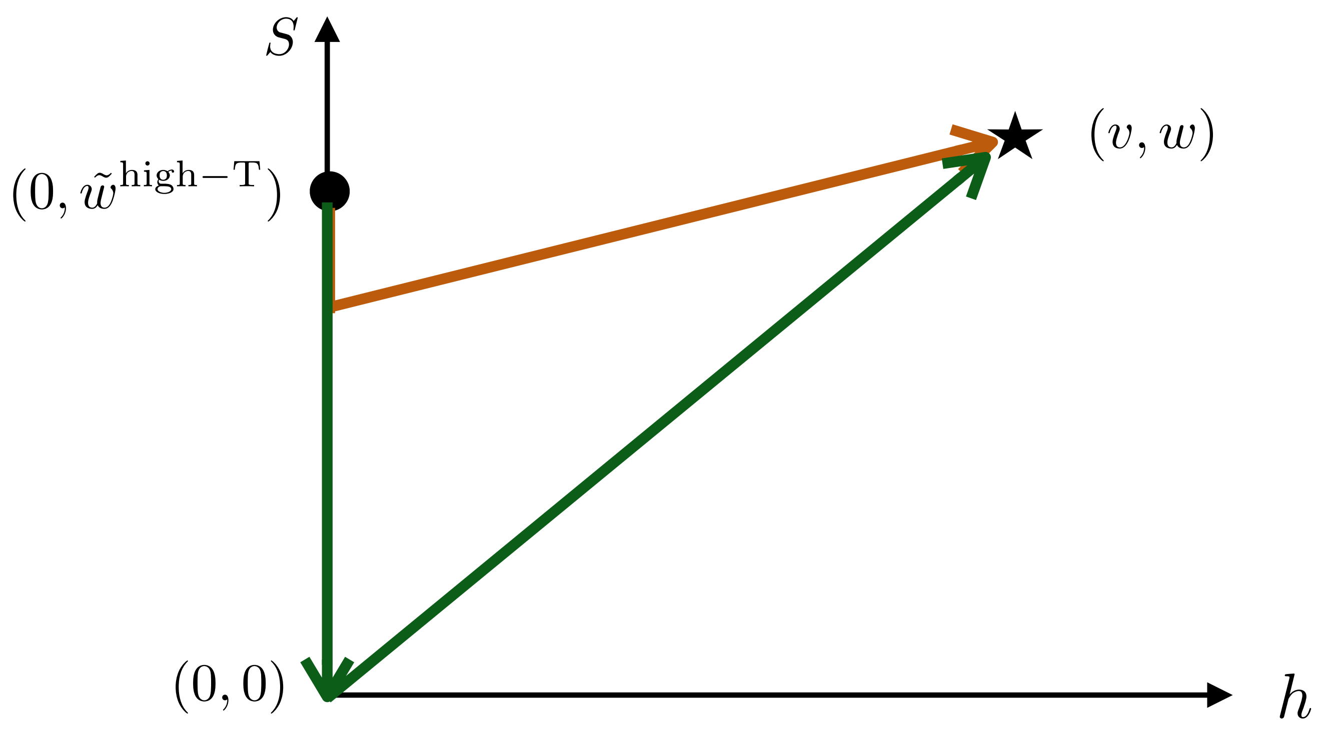

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Scenario B-NR: two-step

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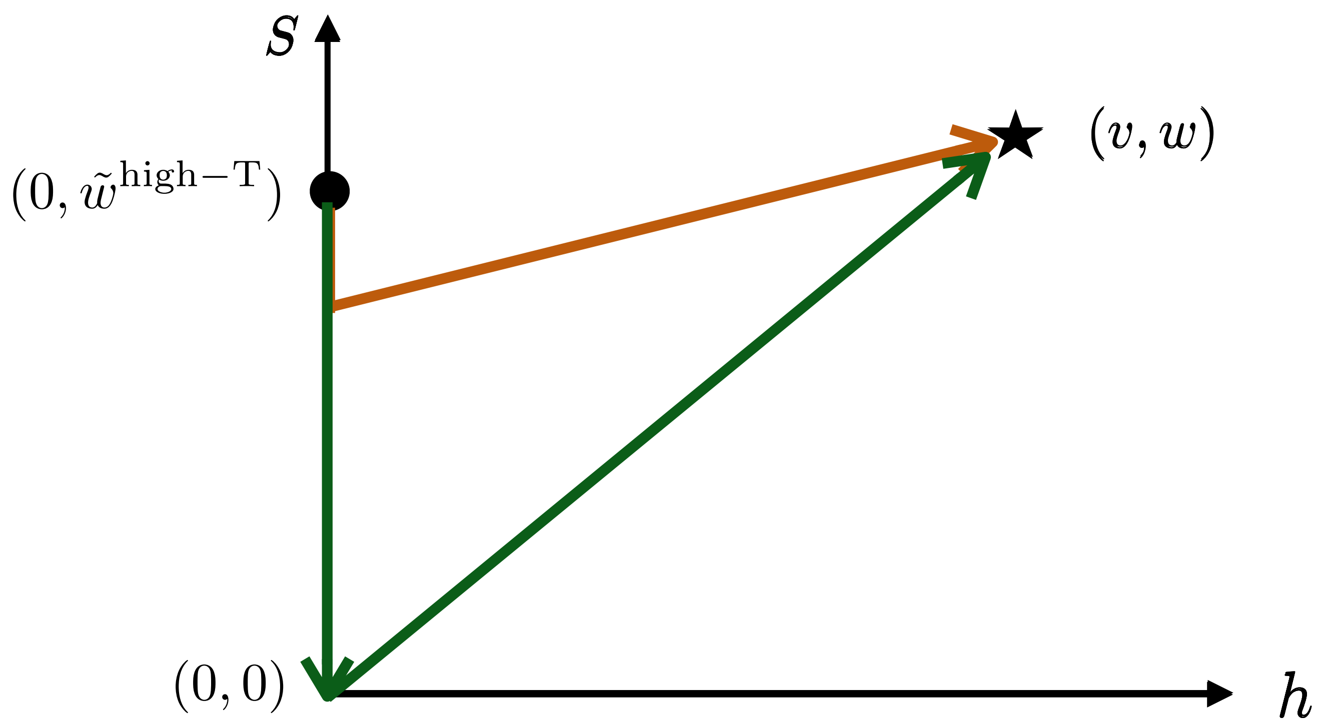

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EWPT with spontaneous Z2-breaking: the finite temperature potential

$$V(h,s,T) = V_0(h,s) + V_{\rm CW}(h,s;T) + V_T(h,s,T)$$

Tree-level Potential

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

Parameters $\{\mu_h^2, \mu_s^2, \lambda_h, \lambda_s, \lambda_m\} \longleftrightarrow \{v_{\rm EW}, m_H, \tan\beta, m_S, \sin\theta\}$

Thermal potential

$$V_T(h,s,T) = \frac{T^4}{2\pi^2}\left[\sum_{i=\{B\}} n_i J_B\left(\frac{m_i^2(h,s)}{T^2}\right) + \sum_{f=\{F\}} n_f J_F\left(\frac{m_f^2(h,s)}{T^2}\right)\right]$$

Treatment

- **Numerically:** CosTransitions *C. L. Wainwright '11*
- **Analytically:** high-T approximation $T^2 \gg m^2$

$$V^{\rm high-T}(h,s,T) \approx \frac{1}{2}(-\mu_h^2 + c_h T^2)h^2 - ETh^3 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}(\mu_s^2 + c_s T^2)s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

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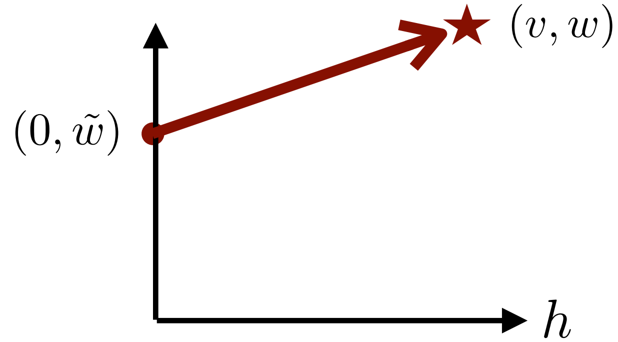
The electroweak phase transition strength

Scenario A (A-NR)



$$\frac{v_c}{T_c} = \frac{2E}{\tilde{\lambda}_h} = \frac{2E}{\lambda_h^{\rm SM}}\left[1 + \sin^2\theta\left(\frac{m_H^2}{m_S^2} - 1\right)\right]$$

- **Bare parameters**

$$\tilde{\lambda}_h \equiv \lambda_h - \frac{\lambda_m^2}{4\lambda_s} \qquad \frac{v_c}{T_c} \propto \tilde{\lambda}_h^{-1}$$

- **Physical parameters**

$\sin\theta \lesssim 0.4$ **bounded by Higgs precision measurements**

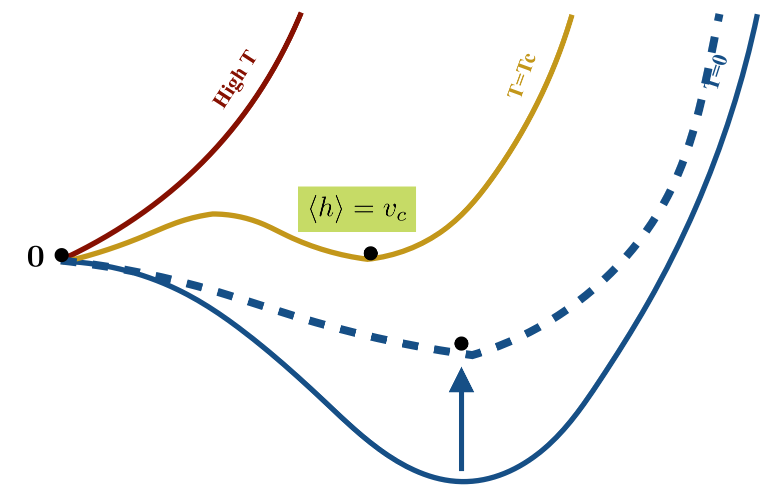
Small m_S renders SFOPhT: light singlet

Similarly for scenario B (B-NR), the transition strength reads

$$\left.\frac{v_c}{T_c}\right|_{00\to vw} = \frac{2E}{\tilde{\lambda}_h + \frac{(\mu_s^2/T_c^2 + c_s)^2}{\lambda_s\left[\frac{v(T_c)}{T_c}\right]^4}}$$

Where the enhancement comes from?

☑ Tree-level Effects ☐ Zero Temperature loop effects ☐ Thermal effects



Potential depth at zero temperature (tree level)

$$\Delta V \equiv V_0(0, \tilde{w}_{T=0}) - V_0(v_{\rm EW}, w_{\rm EW}) = \frac{v^4}{4}\tilde{\lambda}_h$$

Smaller depth, less temperature it takes to be degenerate: lower T_c

$$T_c \approx \frac{v_{\rm EW}}{\sqrt{c_h - \frac{\lambda_m}{2\lambda_s}c_s}}\tilde{\lambda}_h^{\frac{1}{2}}$$

And also larger field value v_c at the critical temperature (closer to $v_{\rm EW}$):

$$v_c \approx v_{\rm EW}\frac{2E}{\sqrt{c_h - \frac{\lambda_m}{2\lambda_s}c_s}}\tilde{\lambda}_h^{-\frac{1}{2}}$$

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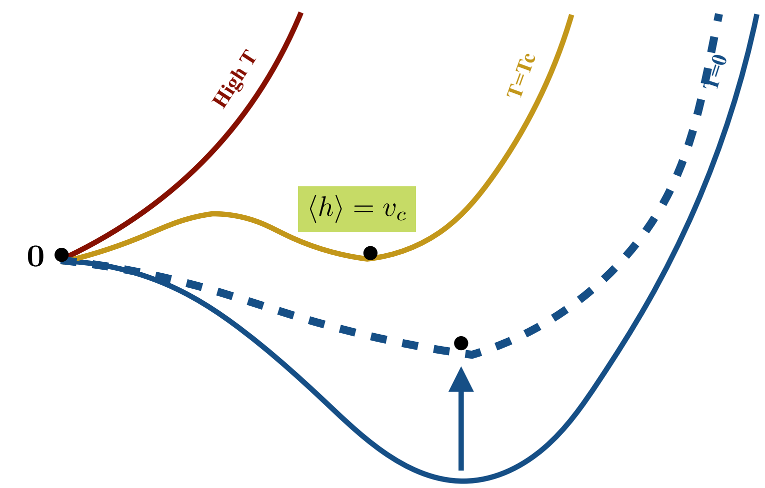

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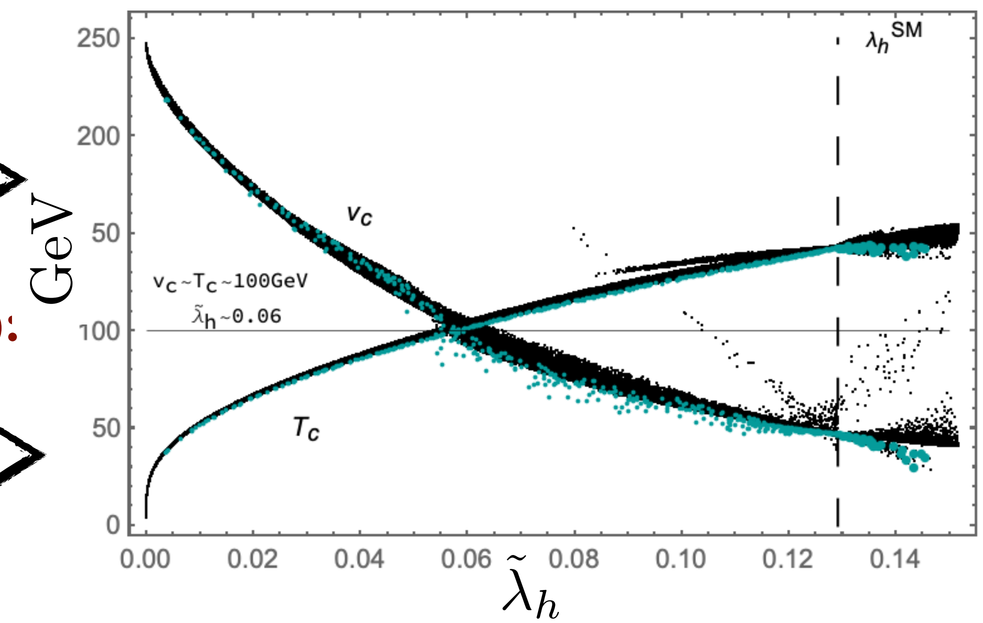

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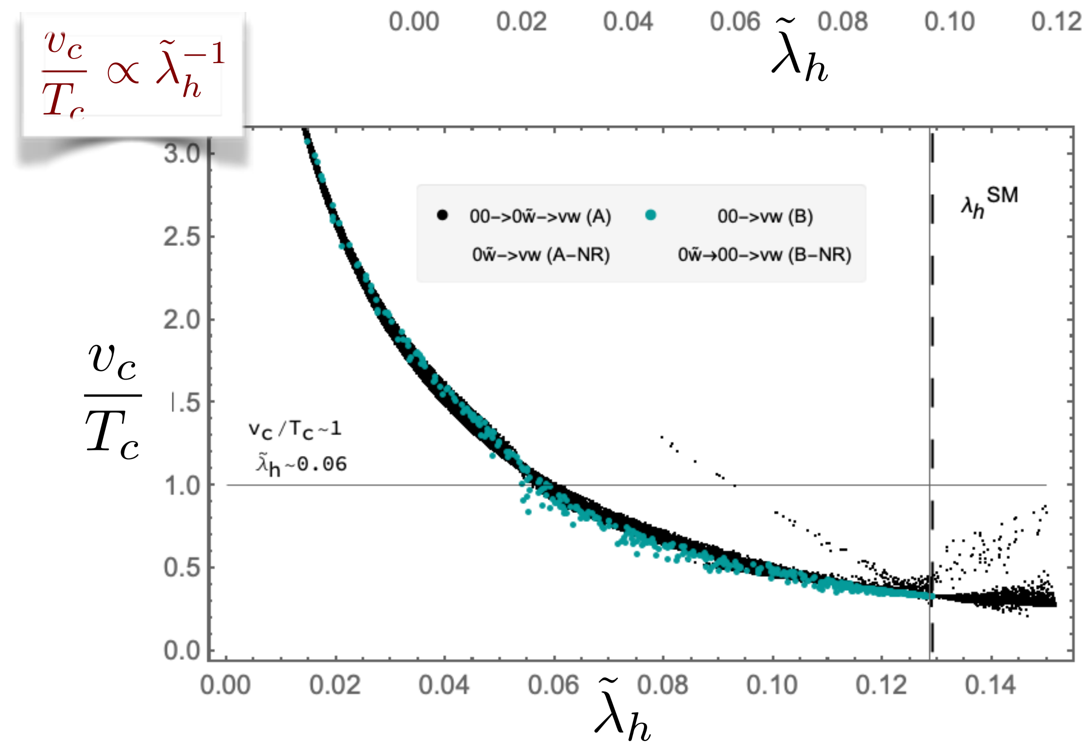
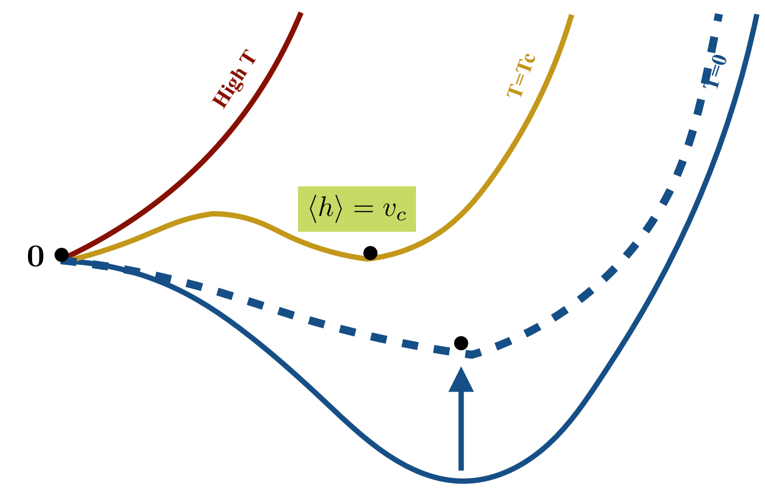


Numerical Scanning with thermal potential fully evaluated

Where the enhancement comes from?

- [x] Tree-level Effects
- [ ] Zero Temperature loop effects
- [ ] Thermal effects



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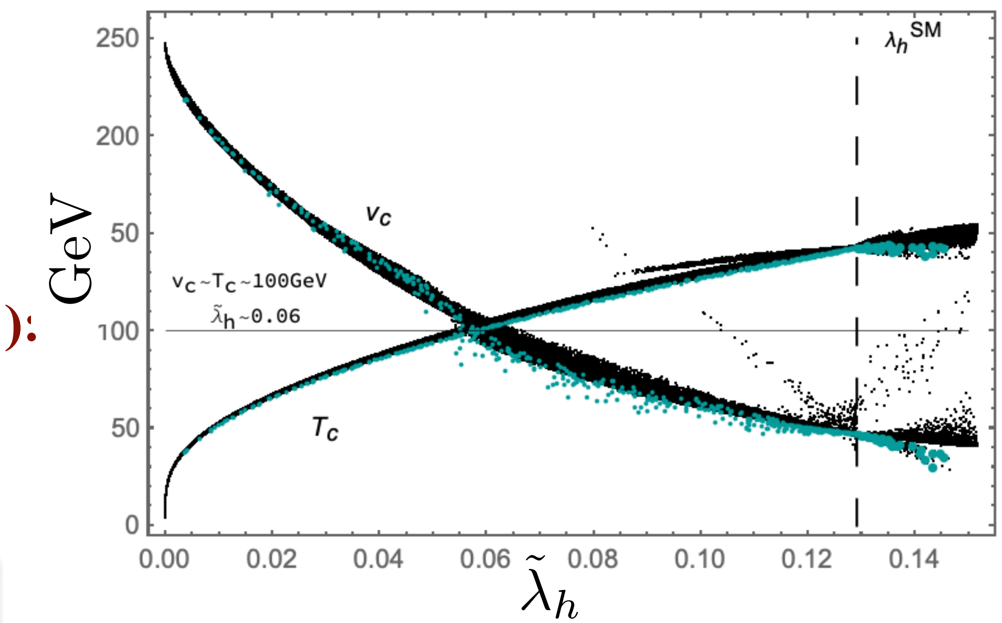
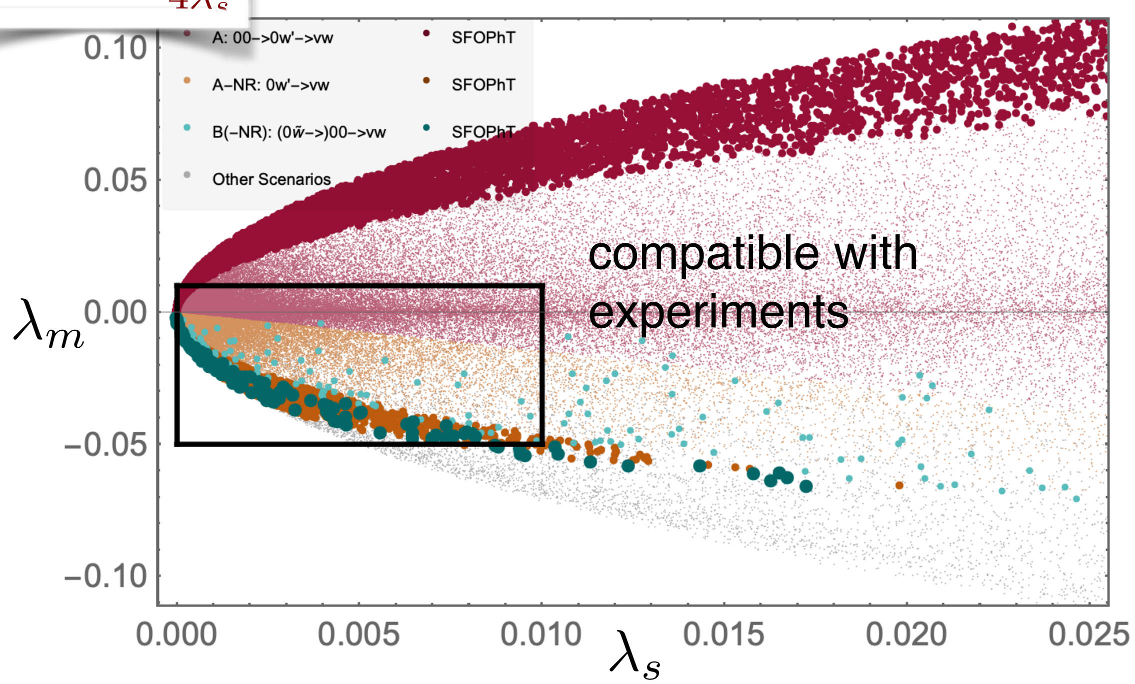
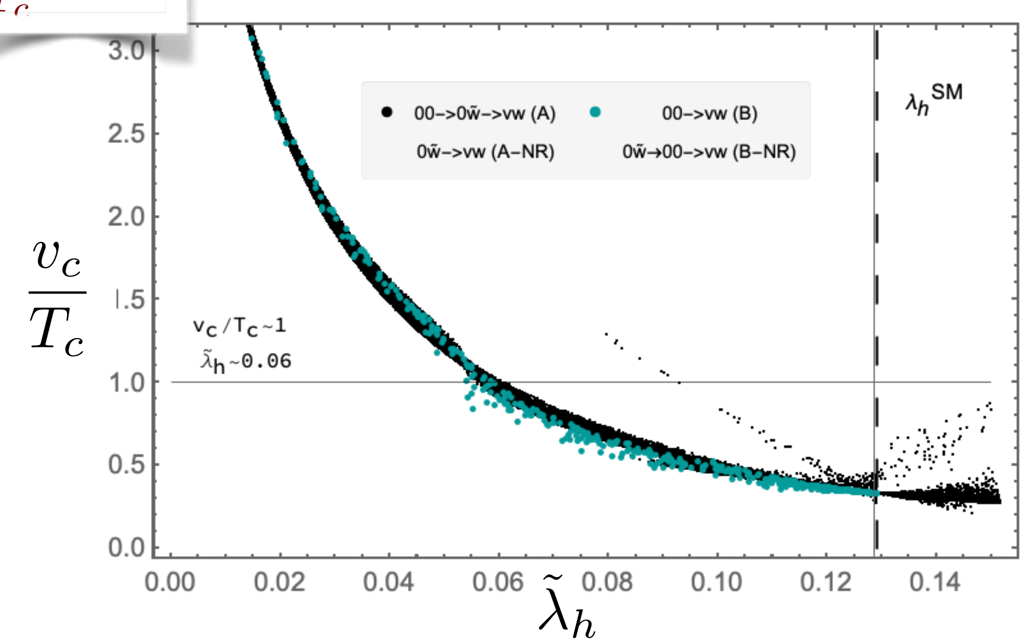


$$\tilde{\lambda}_h \equiv \lambda_h - \frac{\lambda_m^2}{4\lambda_s}$$



$$\frac{v_c}{T_c} \propto \tilde{\lambda}_h^{-1}$$

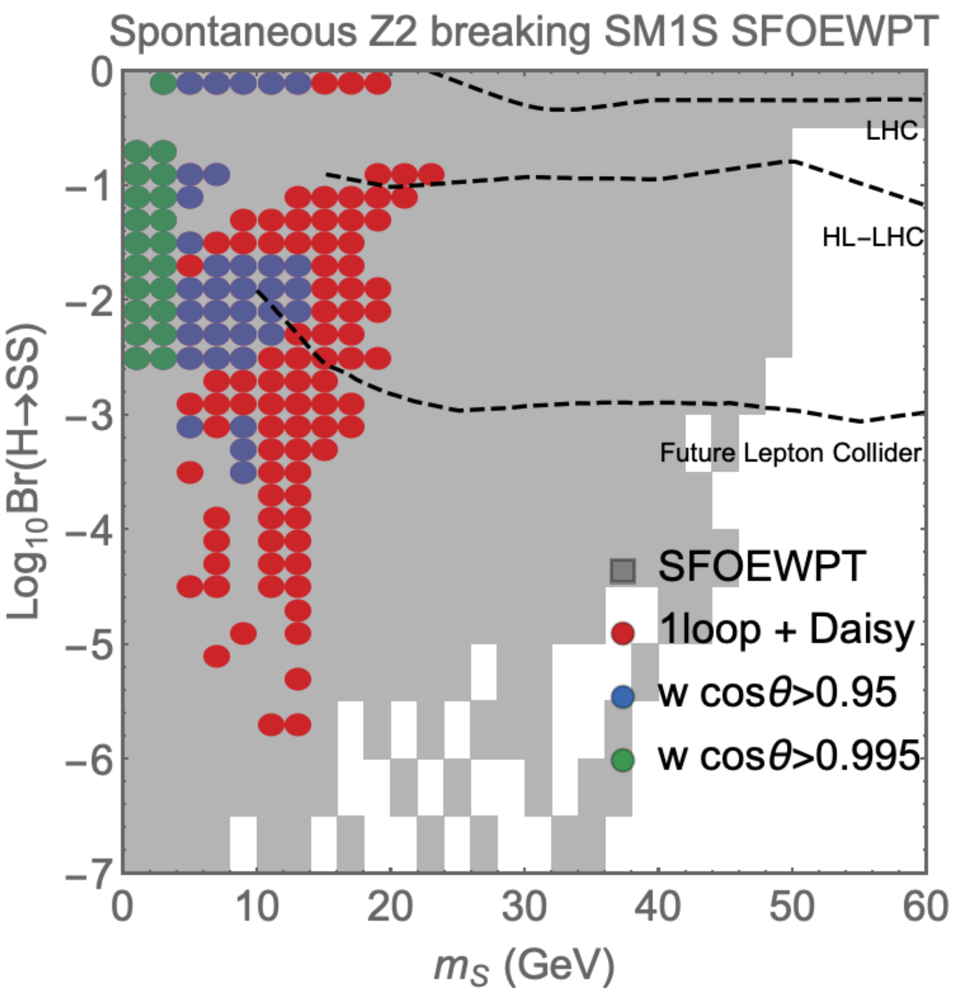


Numerical Scanning with thermal potential fully evaluated

EWPT with spontaneous Z2-breaking: phenomenology

Exciting Phenomenology (important effects of high order corrections to the potential)

Higgs Exotic Decays



- **A firm prediction of a light scalar**
- **Dashed lines: sensitivity to** 4 jets channel
- Further studies of **merged jets** for lighter singlet masses

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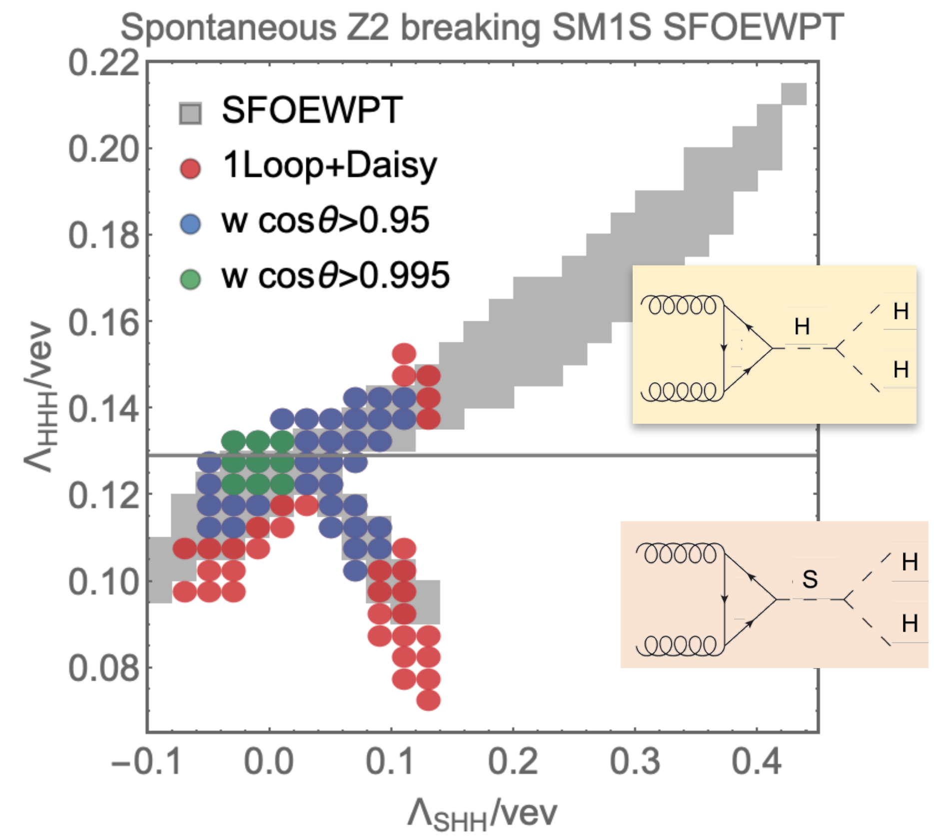
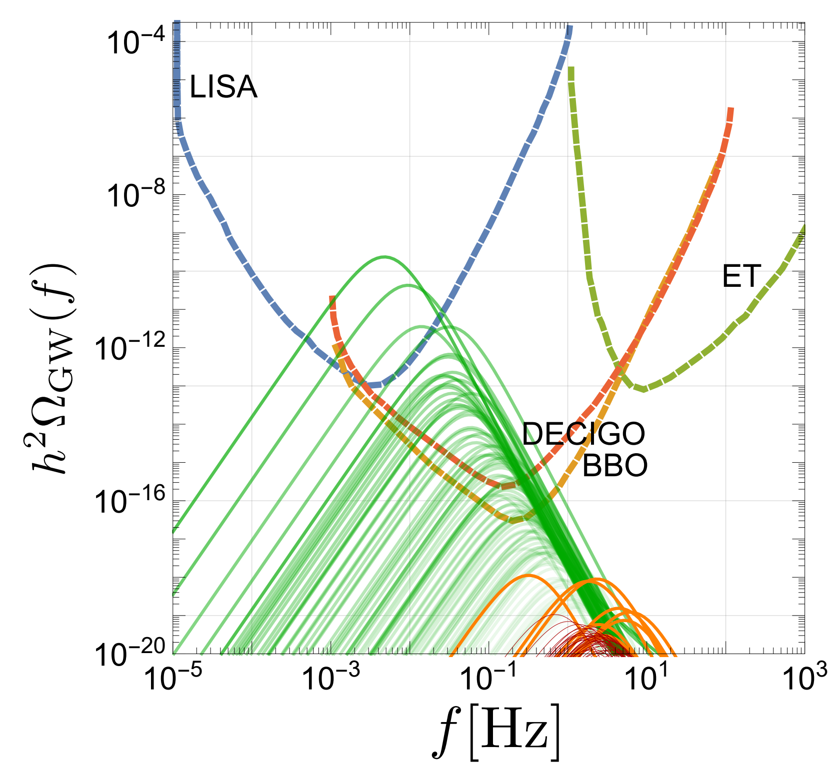
Double Higgs Production



Gravitational wave

- Typically too weak to be probed *after including all relevant corrections (red)*
- Further RG improvement may improve the sensitivity



Extending the Higgs Sector: SFOEWPT

- ☐ EWPT with spontaneous Z2 breaking: a singlet extension
- ☑ EWPT in NMSSM: nucleation is more than critical

EWPT in the NMSSM - the extended Higgs sector

Now let's look at a more extended Higgs sector: two Higgs doublets + a singlet

both charged under the EW gauge group

provide flexibility enhancing the PT strength

A well motivated model with an UV completion for such a Higgs sector is the **Next-to-Minimal Supersymmetry Standard Model (NMSSM).**

$$W = \lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3 + W_{\text{Yuk}} \quad \text{(Z3-NMSSM)}$$

The scalar potential

$$V_0 = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \lambda^2 |S|^2 \left(|H_d|^2 + |H_u|^2\right) + \left|\lambda H_u \cdot H_d + \kappa S^2\right|^2$$
$$+ \left(\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right) + \frac{g_1^2 + g_2^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{g_2^2}{2}\left|H_d^\dagger H_u\right|^2$$

The two Higgs doublets and complex singlet contain 8 new dof, where we consider **3 dynamical dof**

CP even interaction states $\{H^{\text{SM}}, H^{\text{NSM}}, H^S\} \rightarrow$ CP even mass states $\{h_{125}, H, h_S\}$

The EW vacuum $\langle H^{\text{SM}}\rangle = v, \quad \langle H^{\text{NSM}}\rangle = 0, \quad \langle H^{\text{SM}}\rangle = v_S$

Parameters $\left\{ v \equiv \sqrt{v_d^2 + v_u^2}\ ,\ \tan\beta \equiv v_u/v_d\ ,\ \mu \equiv \lambda v_S,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa \right\}$ $\langle H_d\rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \quad \langle H_u\rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}$

What constraints on the parameters before the phase transition calculation?

EWPT in the NMSSM - alignment limits and the parameter space

To be consistent with the current Higgs phenomenology, the mass eigenstate h_{125} needs to be dominantly composed of $H^{\rm SM}$:

$$\left|\mathcal{M}^2_{S,12}\right| \ll \left|\mathcal{M}^2_{S,22} - \mathcal{M}^2_{S,11}\right|, \quad \left|\mathcal{M}^2_{S,13}\right| \ll \left|\mathcal{M}^2_{S,33} - \mathcal{M}^2_{S,11}\right|$$

$$\mathcal{M}^2_{S,12} = 0 \quad \rightarrow \quad \lambda^2 = \frac{m^2_{h_{125}} - m_Z^2 \cos(2\beta)}{2v^2 \sin^2\beta}, \qquad \mathcal{M}^2_{S,13} = 0 \quad \rightarrow \quad A_\lambda = \frac{2\mu}{\sin 2\beta}\left(1 - \frac{\kappa}{\lambda}\sin 2\beta\right)$$

The parameter space $\{v,\ \tan\beta,\ \mu,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa\} \rightarrow \{\mu,\ \tan\beta,\ \kappa,\ A_\kappa\}$ $\left\{\tan\beta\ ,\ \mu\ ,\ \frac{\kappa}{\lambda}\ ,\ \frac{v'_S}{v_S}\right\}$

- 125 GeV mass eigenstate without large radiative corrections $\tan\beta \lesssim 5$
- Avoid Landau poles (GUT) $\sqrt{\lambda^2 + \kappa^2} \lesssim 0.7$
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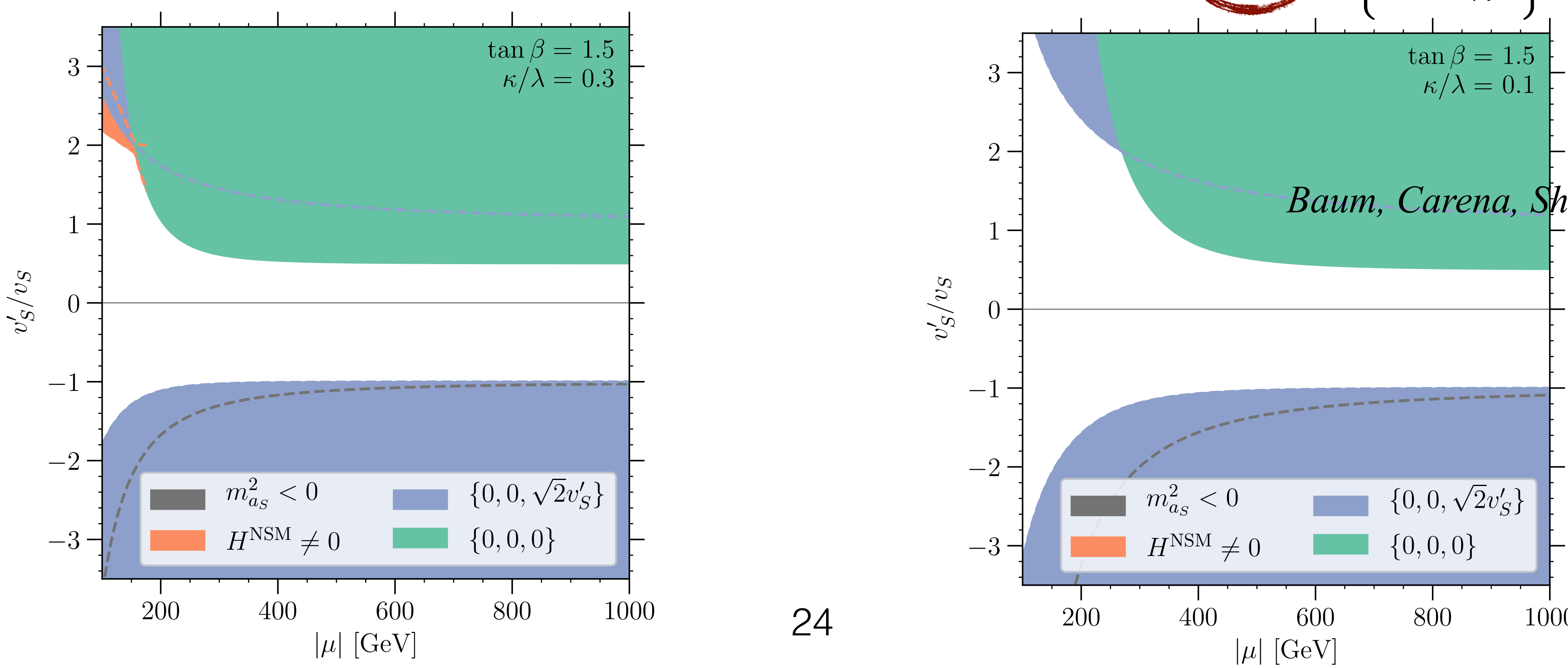

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decoupling limit decoupling limit

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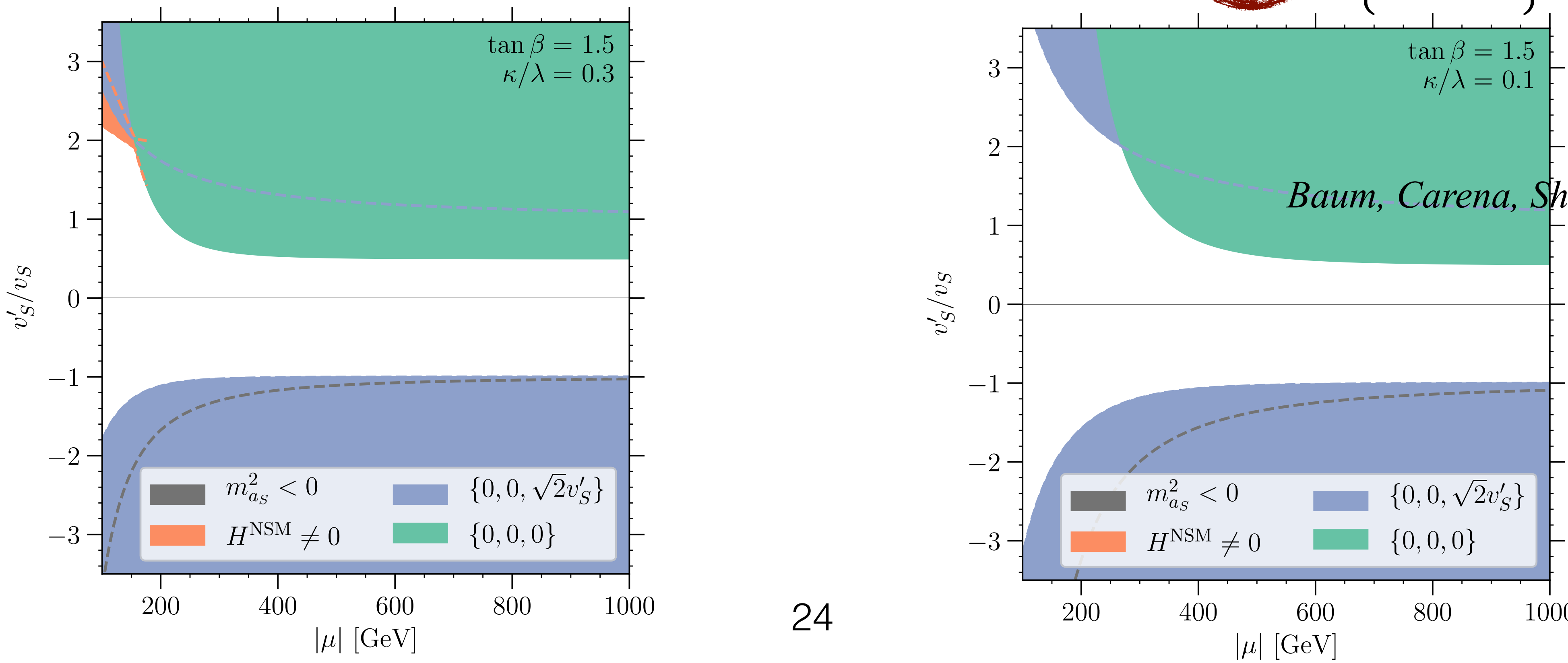

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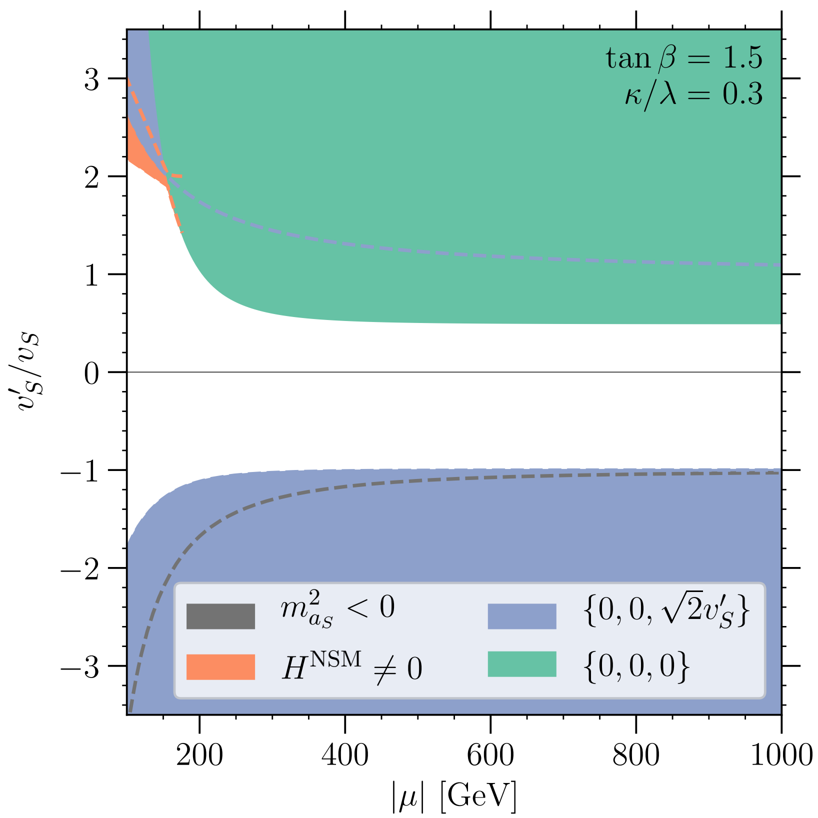

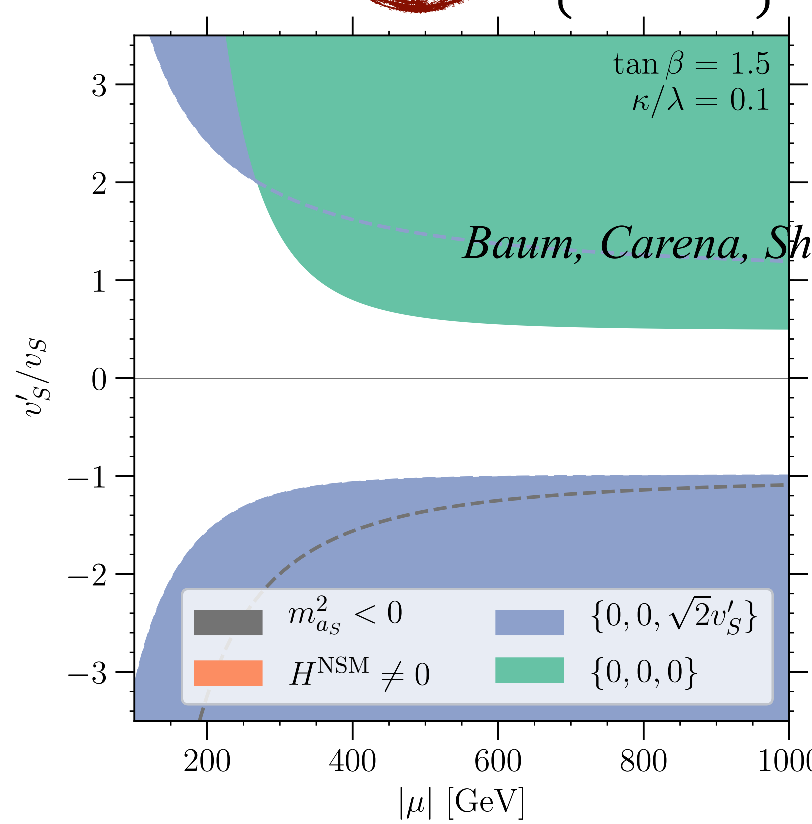

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alignment without decoupling — alignment without decoupling

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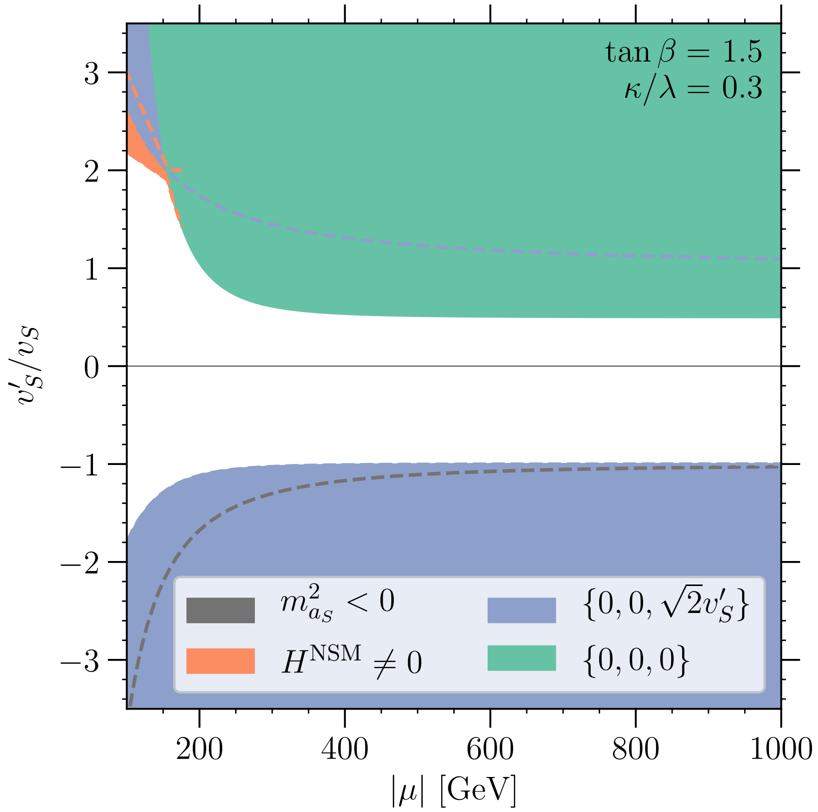

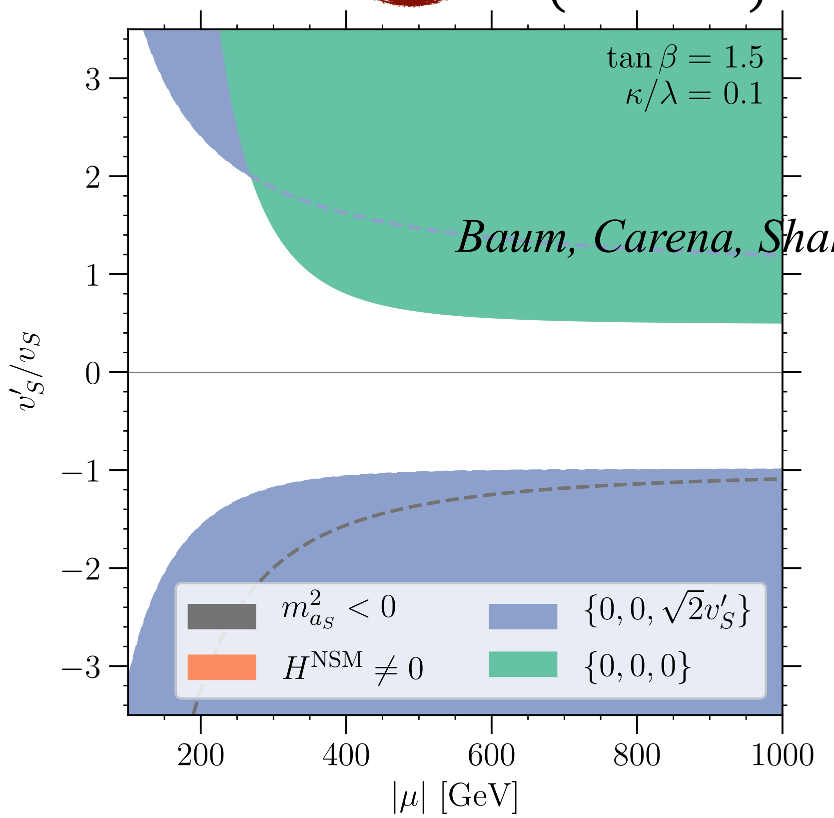

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Alignment (without decoupling) limits

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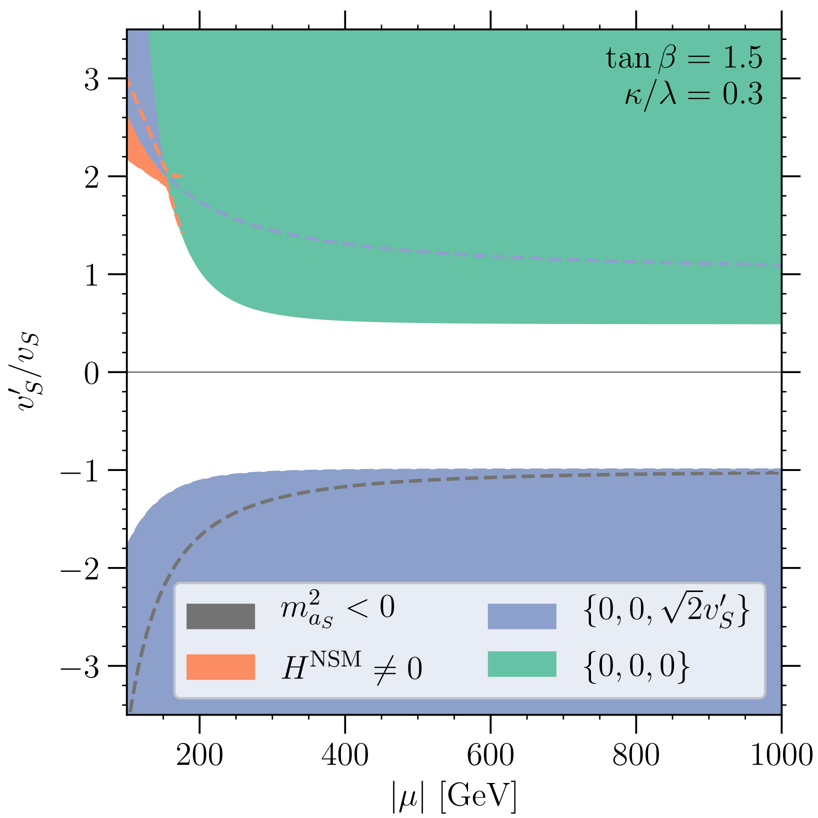

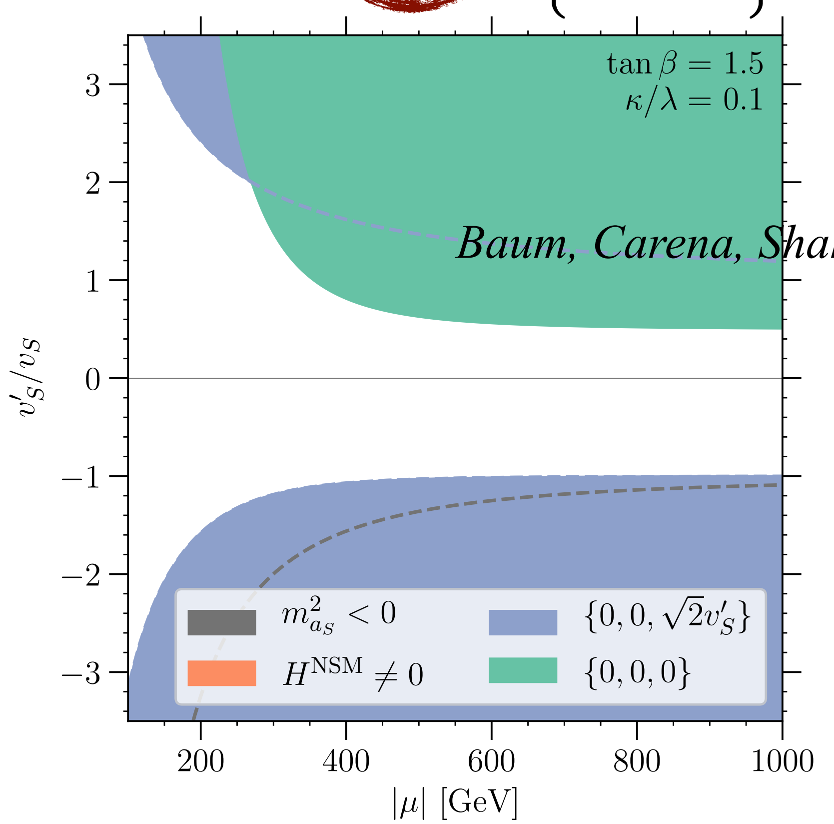

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EWPT in the NMSSM - the effective potential

Radiative corrections (zero temperature)

- **Integrating out heavy degrees of freedom** (sfermions, gluinos etc) are integrated out. A new operator by matching:

$$V_0^{\text{eff}} = V_0 + \frac{\Delta\lambda_2}{2}\left|H_u\right|^4$$

$\Delta\lambda_2$ Fixed by 125 GeV Higgs mass:

$$m^2_{h_{125}} \simeq \mathcal{M}^2_{S,11} = m_Z^2\cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta) + 2\Delta\lambda_2 v^2 \sin^4\beta$$

- **Light degrees of freedom: CW potential**

$$V^{\text{CW}}_{1-\text{loop}} = \frac{1}{64\pi^2}\sum_{i=B,F}(-1)^{F_i} n_i \widehat{m}_i^4\left[\log\left(\frac{\widehat{m}_i^2}{m_t^2}\right) - C_i\right]$$

$$B = \{h_i, a_i, H^\pm, G^0, G^\pm, Z, W^\pm\}$$
$$F = \{\widetilde{\chi}_i^0, \widetilde{\chi}_i^\pm, t\}$$

Introducing counterterms to maintain boundary conditions

$$\delta\mathcal{L} = -\delta_{m^2_{H_d}}\left|H_d\right|^2 - \delta_{m^2_{H_u}}\left|H_u\right|^2 - \delta_{m^2_S}\left|S\right|^2 - \delta_{\lambda A_\lambda}\left(SH_u\cdot H_d + \text{h.c.}\right) - \frac{\delta_{\lambda_2}}{2}\left|H_u\right|^4$$

Finite temperature effective potential

$$V_1(T) = V_0^{\text{eff}} + V^{\text{CW}}_{1-\text{loop}}(\widetilde{m}_i^2) + V^{T\neq 0}_{1-\text{loop}}(\widetilde{m}_i^2)$$

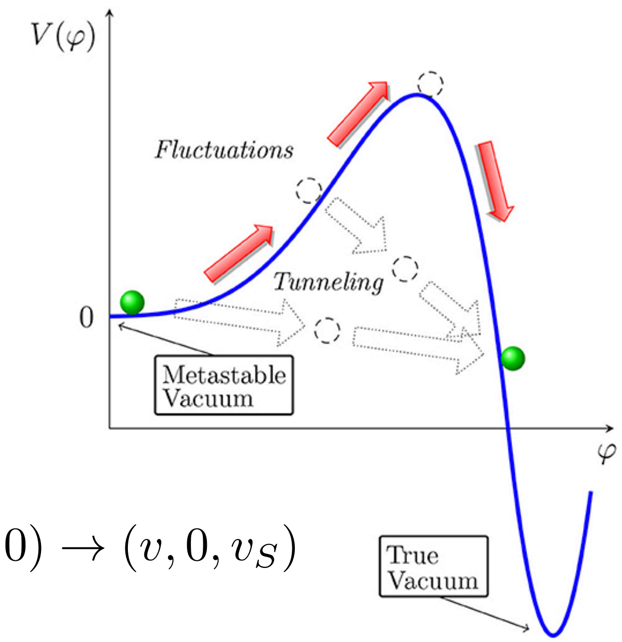
where $V^{T\neq 0}_{1-\text{loop}} = \frac{T^4}{2\pi^2}\sum_{i=B,F}(-1)^{F_i} n_i J_{B/F}\left(\frac{\widetilde{m}_i^2}{T^2}\right)$

EWPT in the NMSSM - nucleation is more than critical

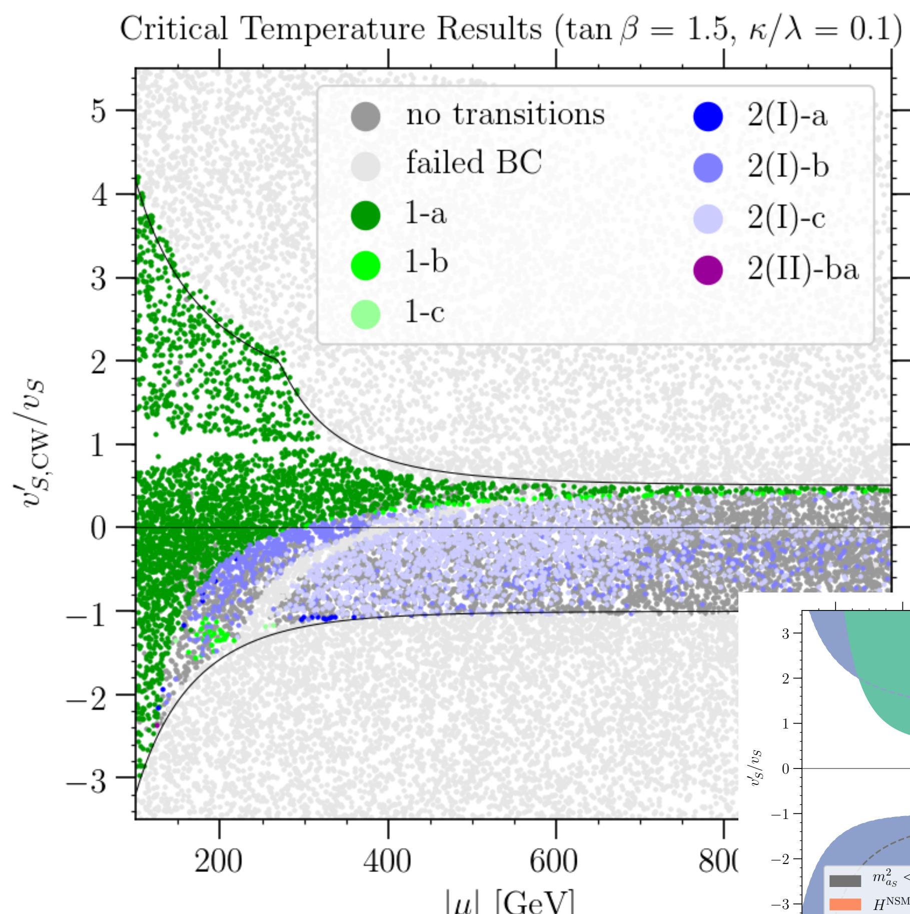
The phase transition proceeds by tunneling through the barrier separating local minima, the so called bubble nucleation.

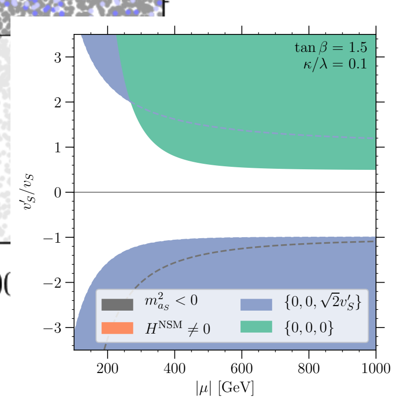
The bubble nucleation rate per unit volume: $\Gamma/V \propto T^4 e^{-S_3/T}$

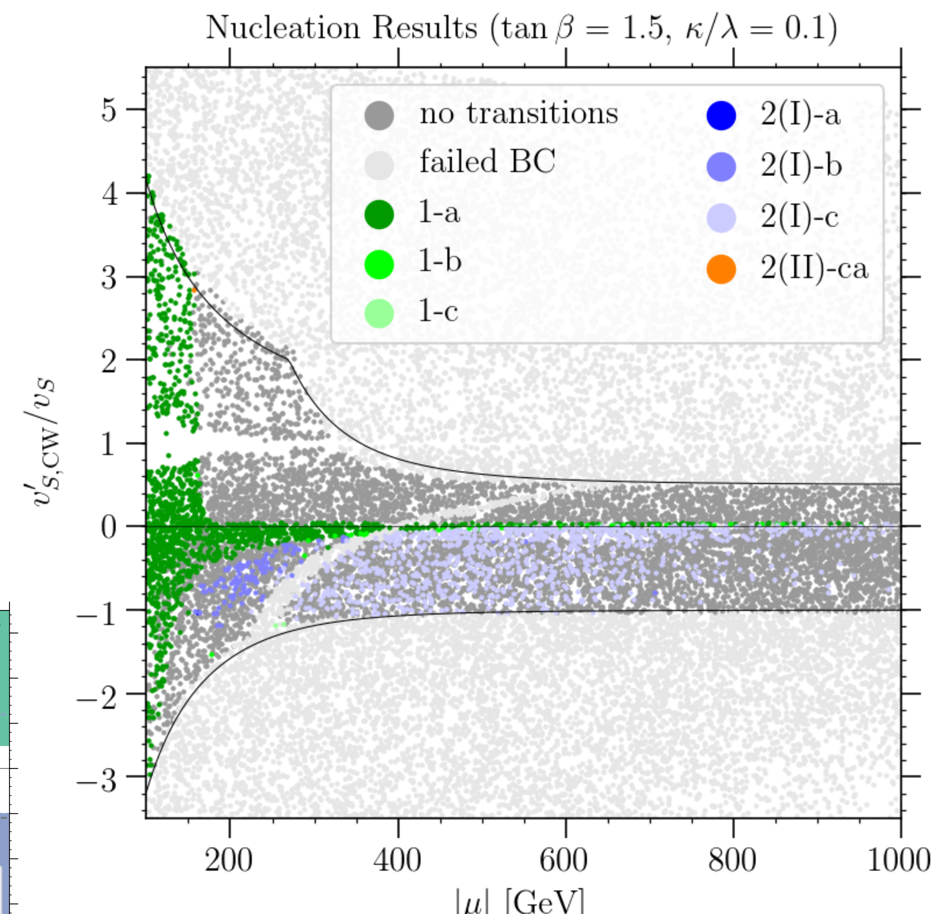
The nucleation happens at a temperature T_n: $\frac{S_3(T_n)}{T_n} \simeq 140$



● $(0,0,0) \to (v,0,v_S)$ ● $(0,0,0) \to (0,0,\tilde{v}_S) \to (v,0,v_S)$ ● $(0,0,0) \to (\tilde{v},\tilde{v}_{\rm NSM},0) \to (v,0,v_S)$







- **Integer: # of steps**
- **Roman number: intermediate phase**
  - (I): singlet-only direction
  - (II): EW symmetry broken phase
- **Lower case letter: strength of the EWPT**
  - a: SFOEWPT
  - b: weakly 1st order
  - c: 2nd order

Single direction barrier: $m_S^2 \equiv \partial_S^2 V\big|_O = 2\frac{\kappa^2}{\lambda^2}\mu^2\frac{v'_S}{v_S}$

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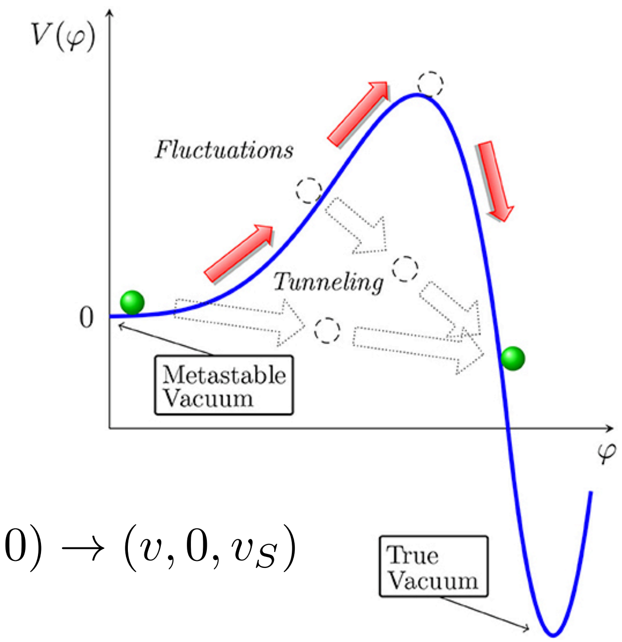
EWPT in the NMSSM - nucleation is more than critical

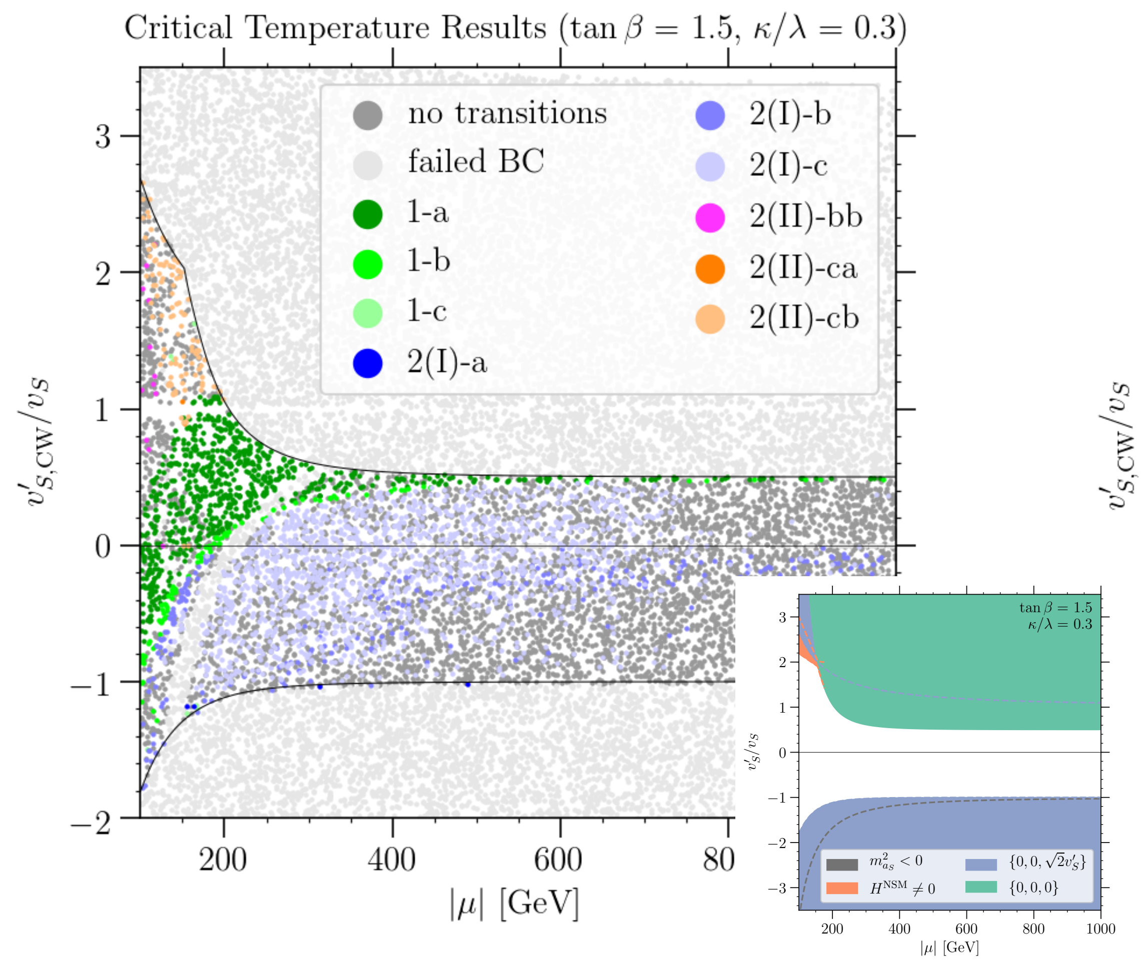
The phase transition proceeds by tunneling through the barrier separating local minima, the so called bubble nucleation.

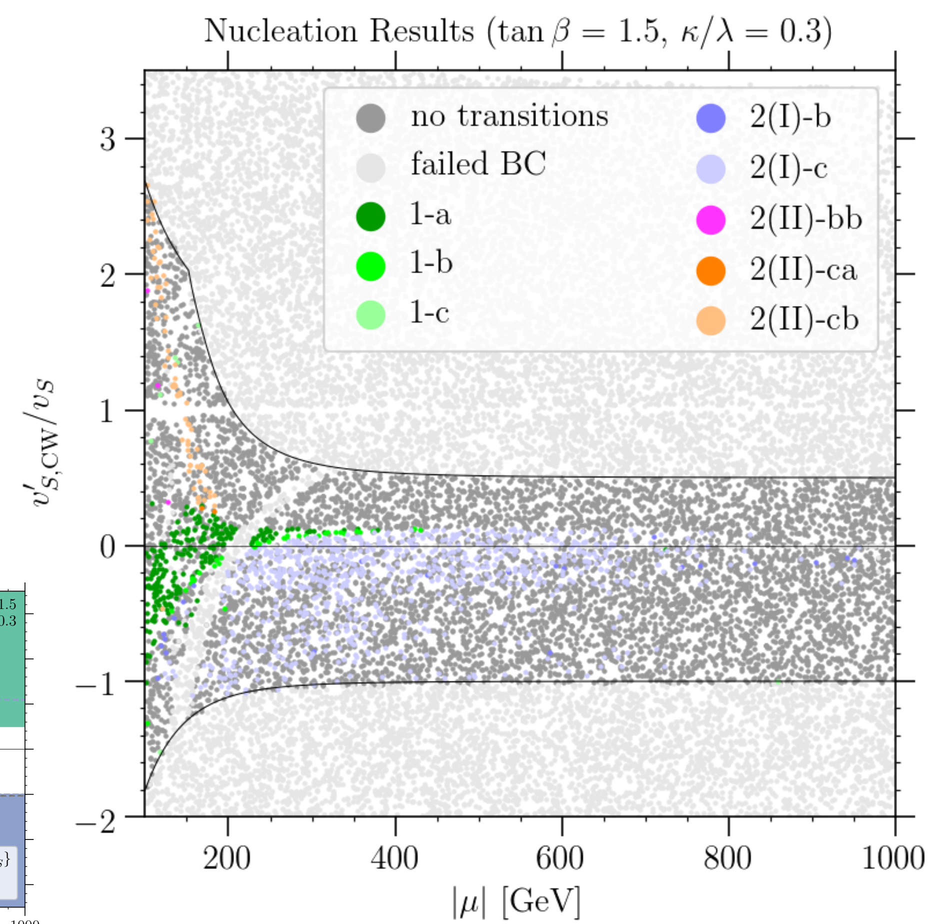
The bubble nucleation rate per unit volume: $\Gamma/V \propto T^4 e^{-S_3/T}$

The nucleation happens at a temperature T_n: $\frac{S_3(T_n)}{T_n} \simeq 140$



● $(0,0,0) \to (v,0,v_S)$ ● $(0,0,0) \to (0,0,\tilde{v}_S) \to (v,0,v_S)$ ● $(0,0,0) \to (\tilde{v},\tilde{v}_{\rm NSM},0) \to (v,0,v_S)$



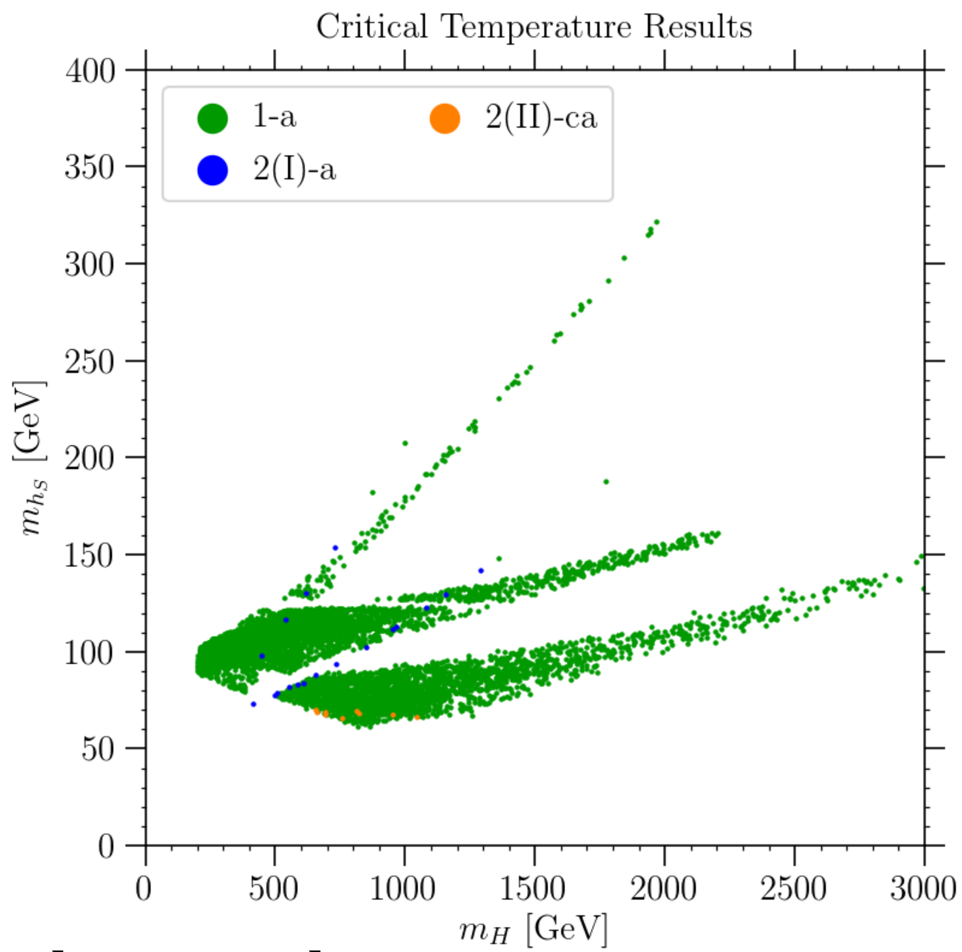


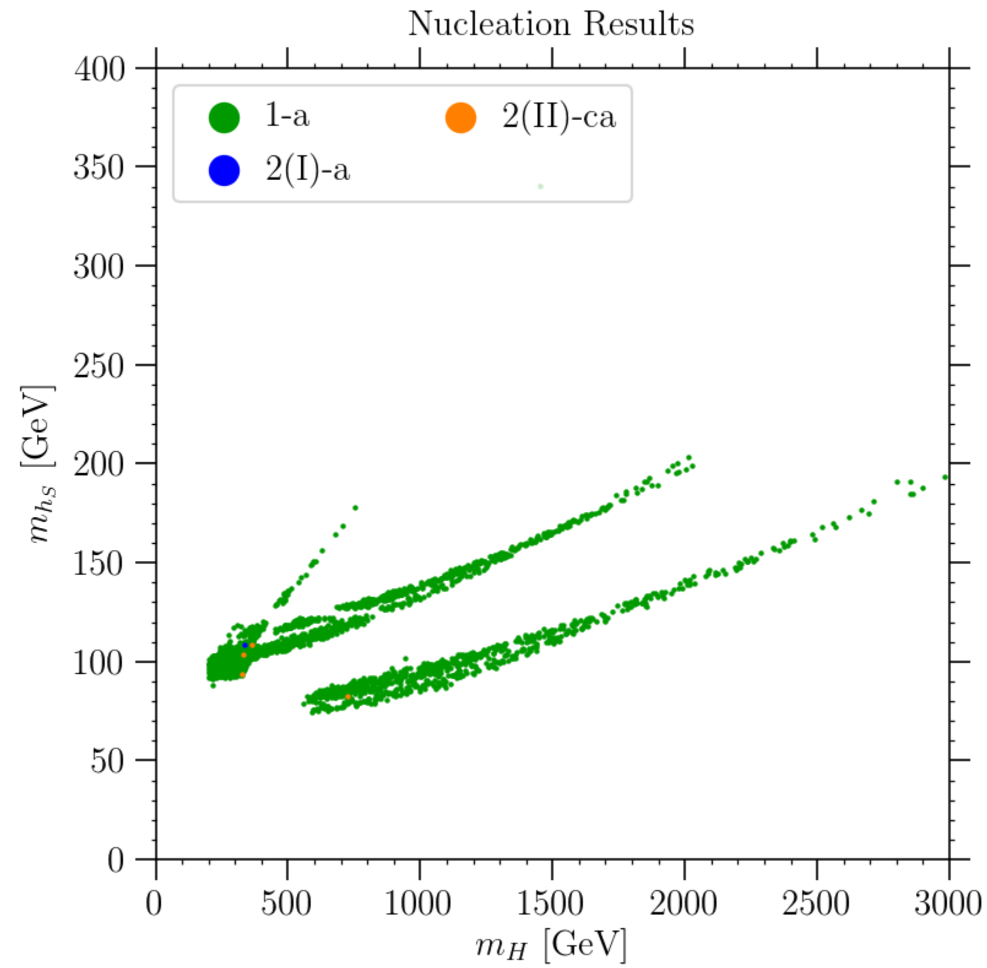
- **Integer: # of steps**
- **Roman number: intermediate phase**
  - (I): singlet-only direction
  - (II): EW symmetry broken phase
- **Lower case letter: strength of the EWPT**
  - a: SFOEWPT
  - b: weakly 1st order
  - c: 2nd order

Doublet direction barrier: $m_{H_u}^2 \approx \frac{\mu^2}{\tan^2\beta}\left(1 - \frac{\kappa}{\lambda}\tan\beta\right) - \frac{m_{h_{125}}^2}{2}$

Baum, Carena, Shah, Wagner, Wang '19

EWPT in the NMSSM - collider and dark matter phenomenology





Collider phenomenology

- **The SFOEWPT consistent with light to heavy non-SM-like Higgs boson and singlet**
- **Despite the light masses, these states are hard to probe in colliders**
  - Production of the singlet-like state suppressed
  - Doublet-like state dominantly decays into neutralinos
  - Promising channels to probe the parameter space are final states containing at least one singlet-like boson

Dark matter

- **The most promising dark matter scenario is a bino-like lightest neutralino**
  - Small interaction cross sections
  - well-tempered scenario for the correct relic density

Summary

- The electroweak phase transition exists in the SM as a smooth cross over;
- Electroweak baryogenesis as an appealing mechanism to explain the matter antimatter asymmetry requires a strongly first order electroweak phase transitions. Gravitational wave experiments can probe the nature of the phase transition;
- We study a singlet extension to the SM to enhance the EWPT, which exhibits rich thermal history and collider phenomenology;
- Studying the electroweak phase transition in the NMSSM indicates a difference between the critical temperature study versus the nucleation temperature study on the EWPT, which is inherited to models with large tree level barriers and multi-dimensional field space.

Thank you