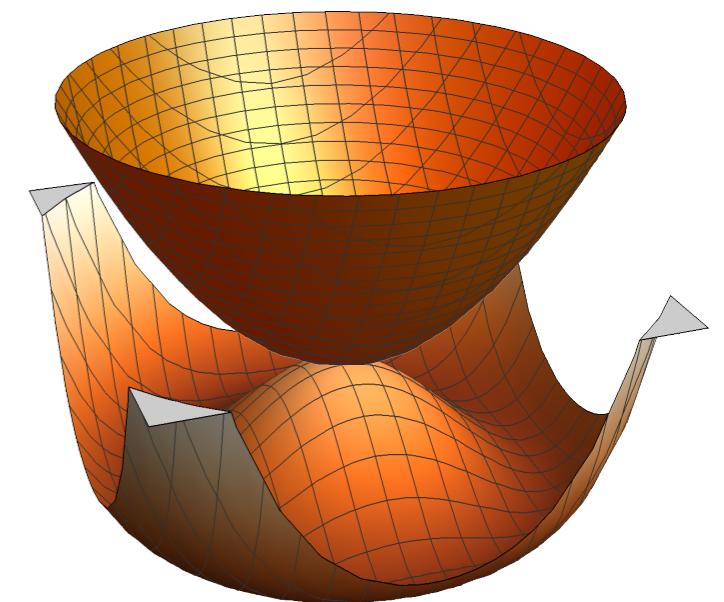


Electroweak Symmetry and the Early Universe

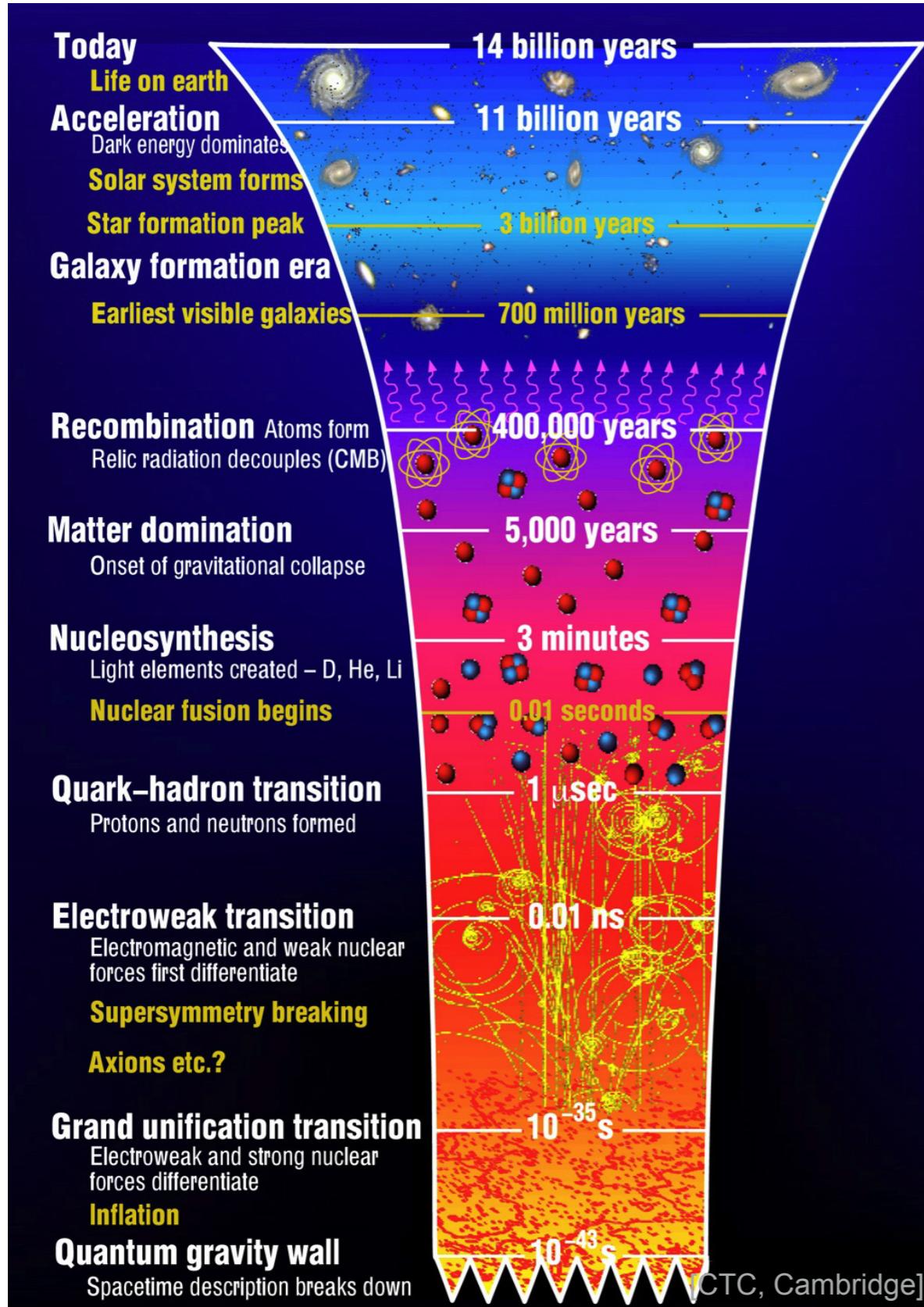


Yikun Wang
Burke Institute, Caltech

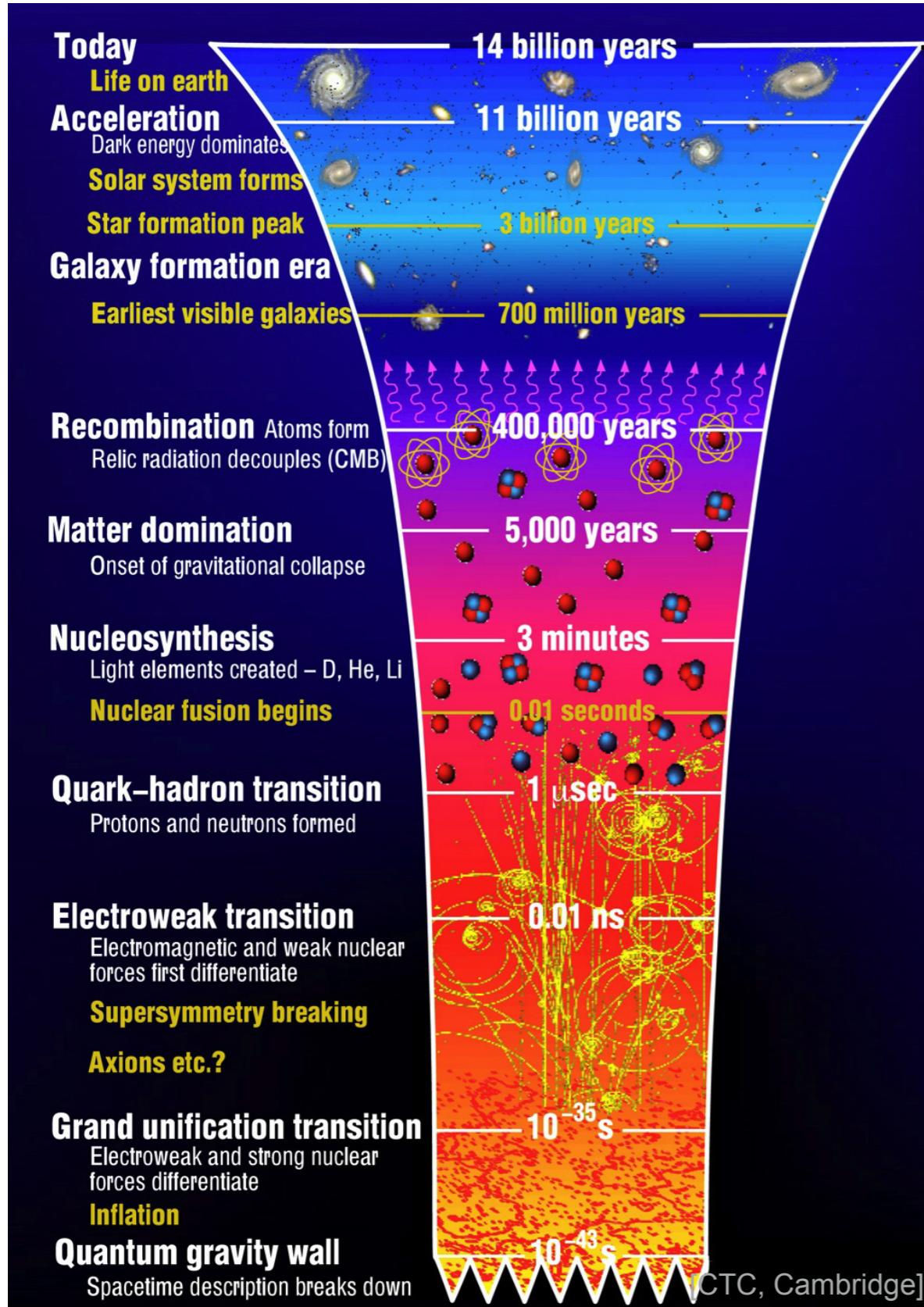


Beyond the SM from Colliders to the Early Universe symposium
May 28, 2023, Chicago

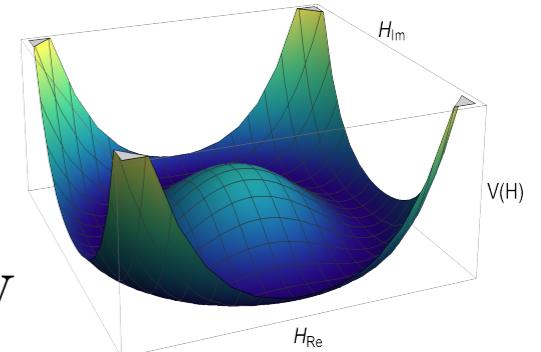
Electroweak symmetry in the early universe and Higgs thermal history



Electroweak symmetry in the early universe and Higgs thermal history



Zero T

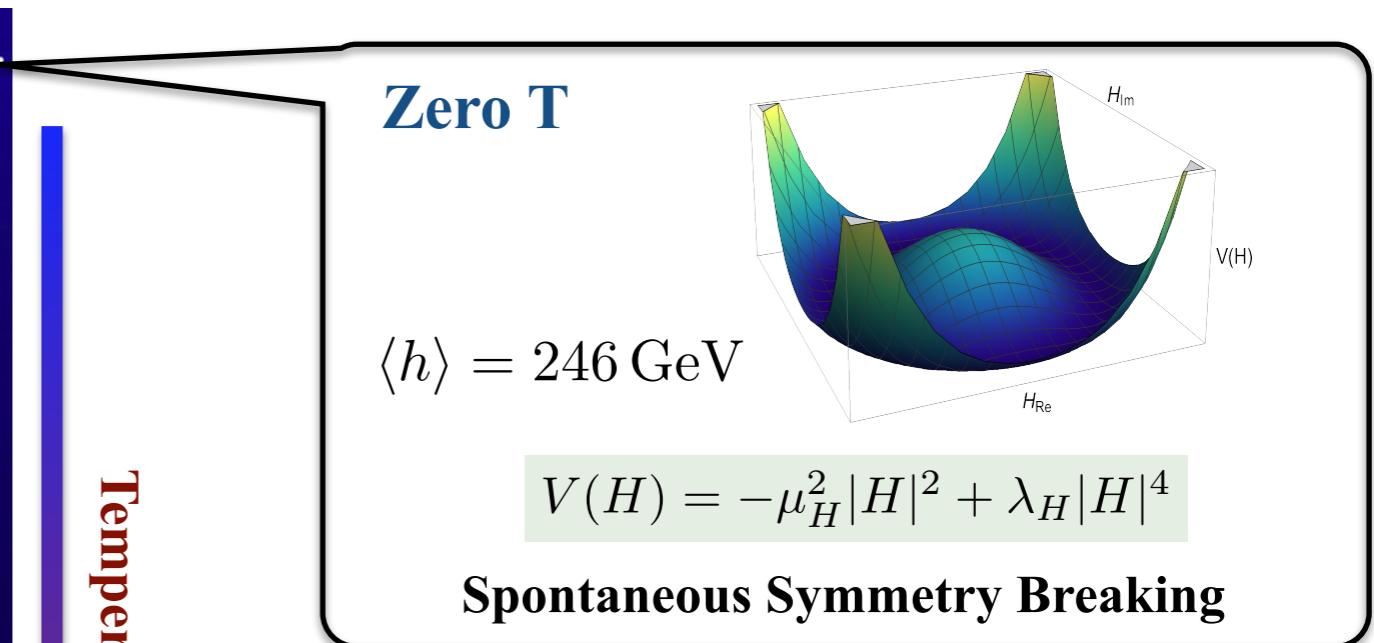
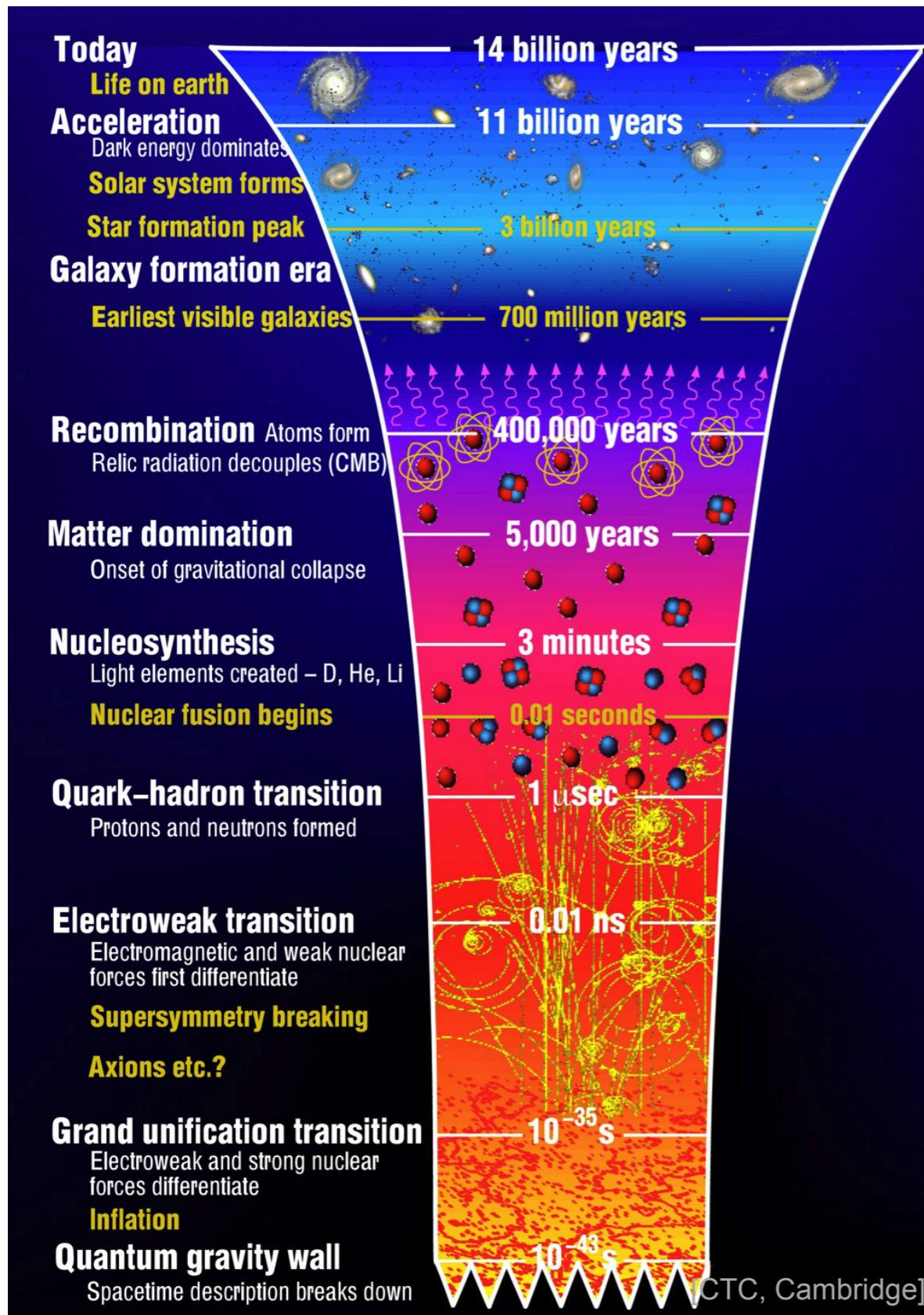


$$\langle h \rangle = 246 \text{ GeV}$$

$$V(H) = -\mu_H^2 |H|^2 + \lambda_H |H|^4$$

Spontaneous Symmetry Breaking

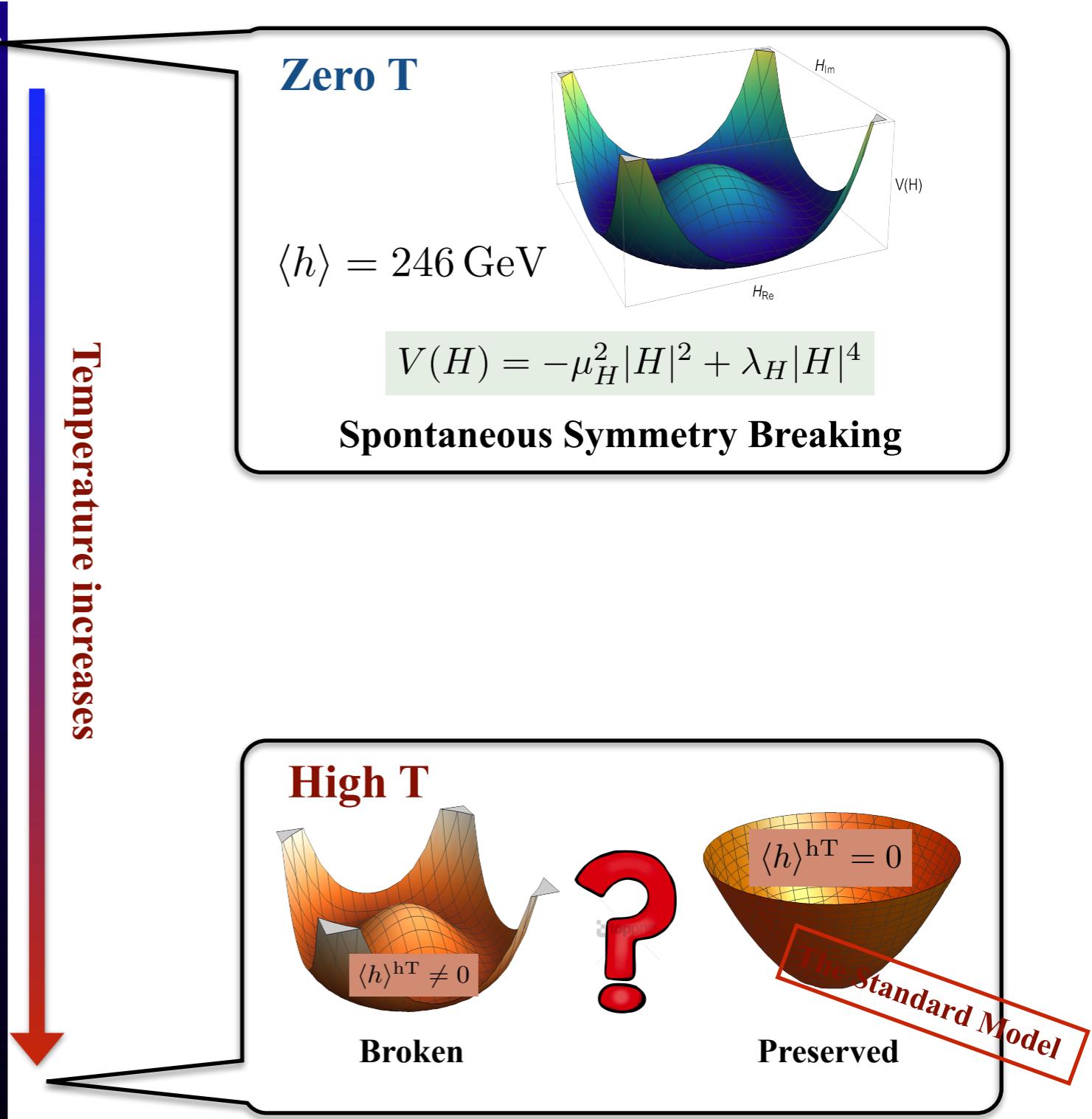
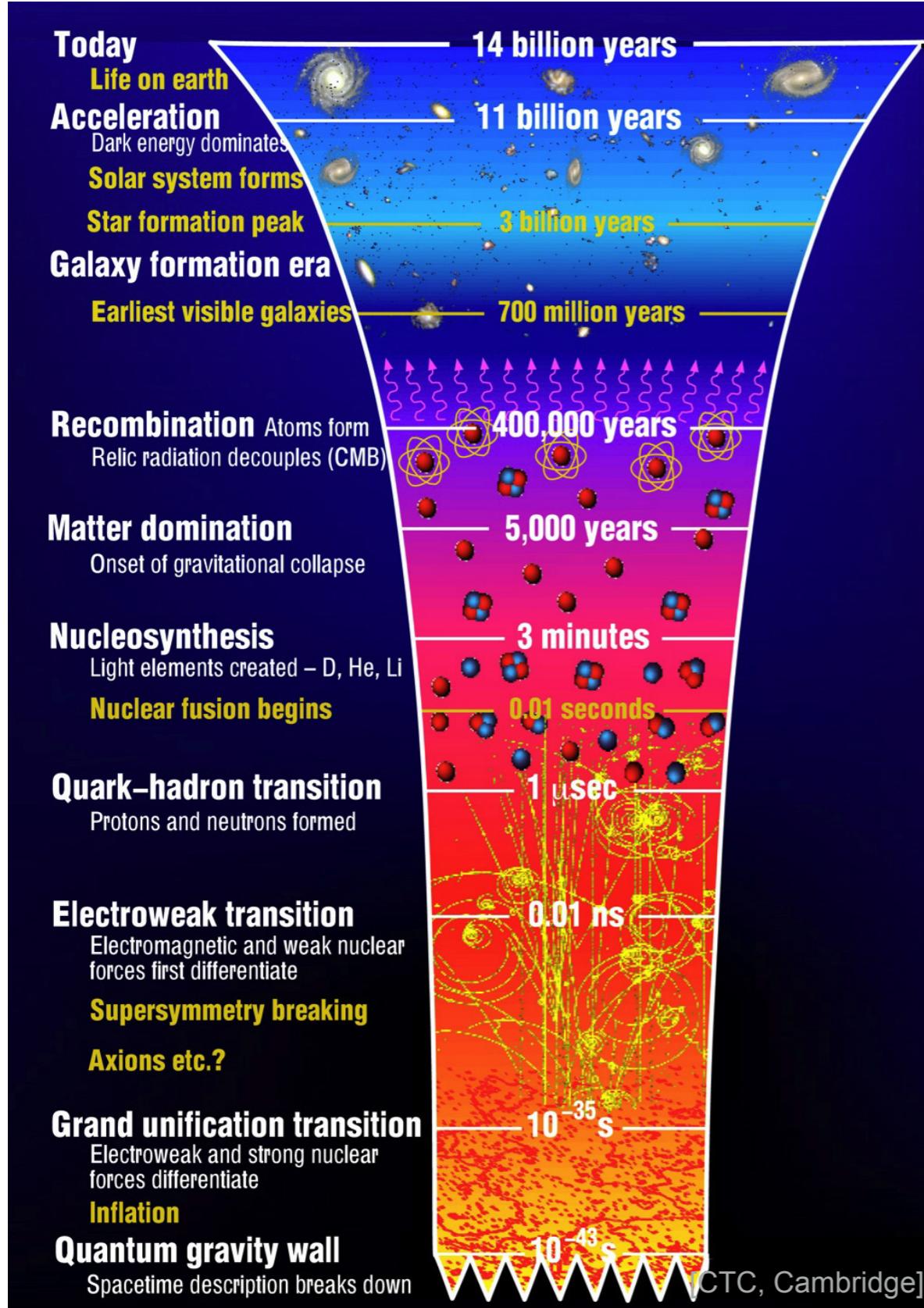
Electroweak symmetry in the early universe and Higgs thermal history



Temperature increases

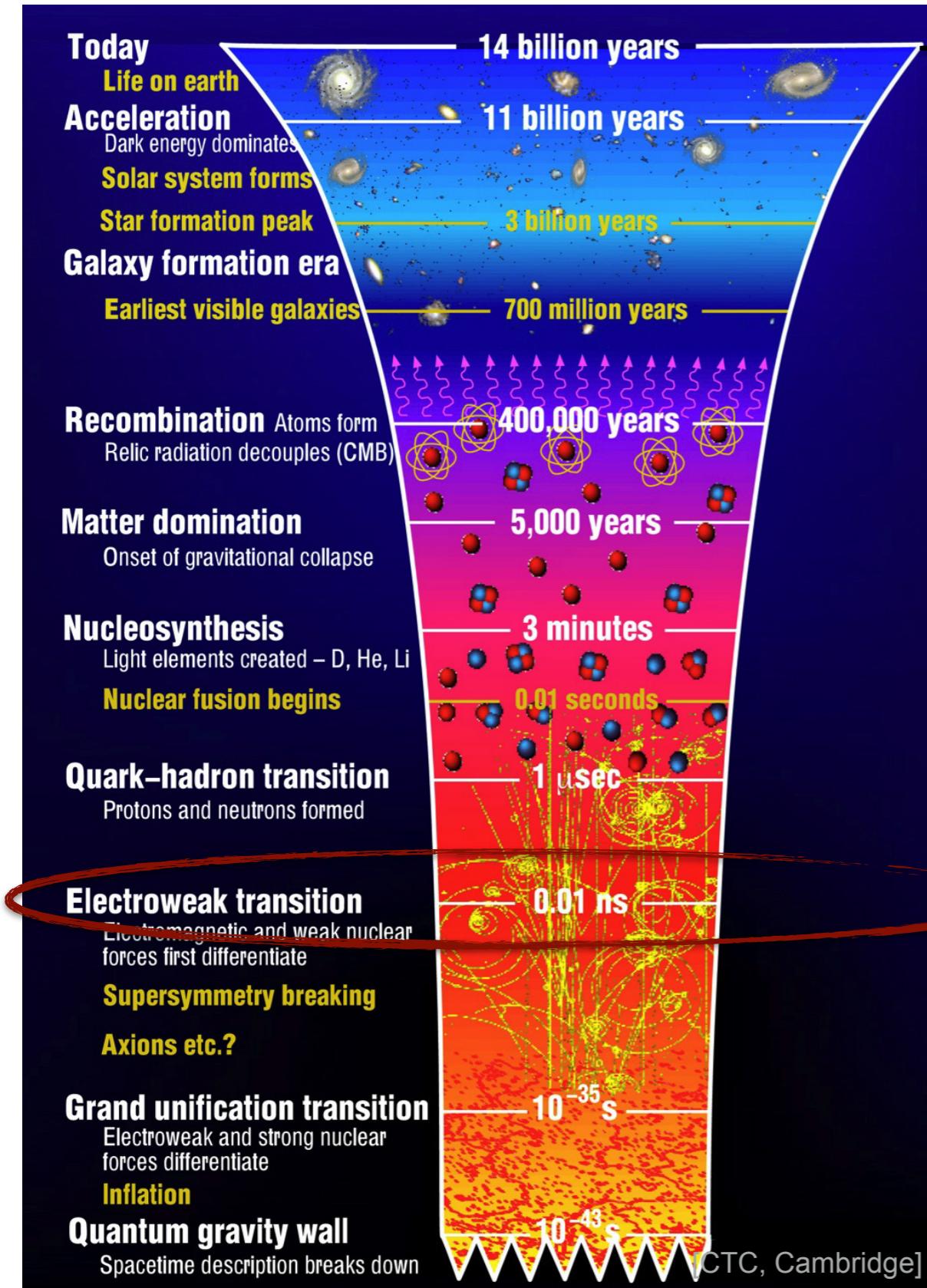
Electroweak Symmetry Thermal History

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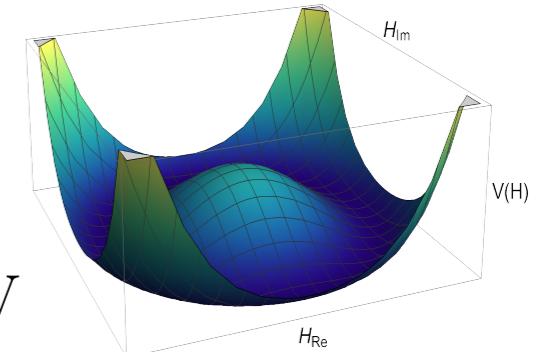
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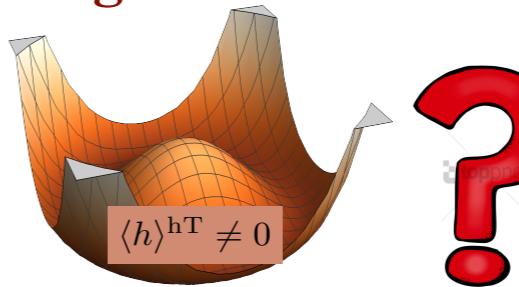
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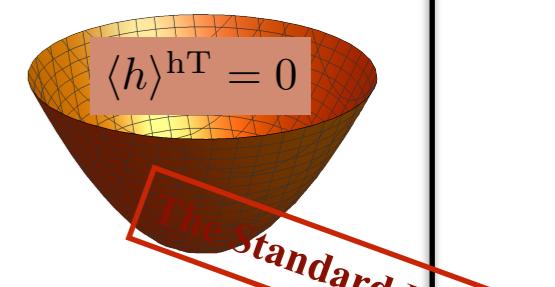
Spontaneous Symmetry Breaking

Electroweak Phase Transition

High T



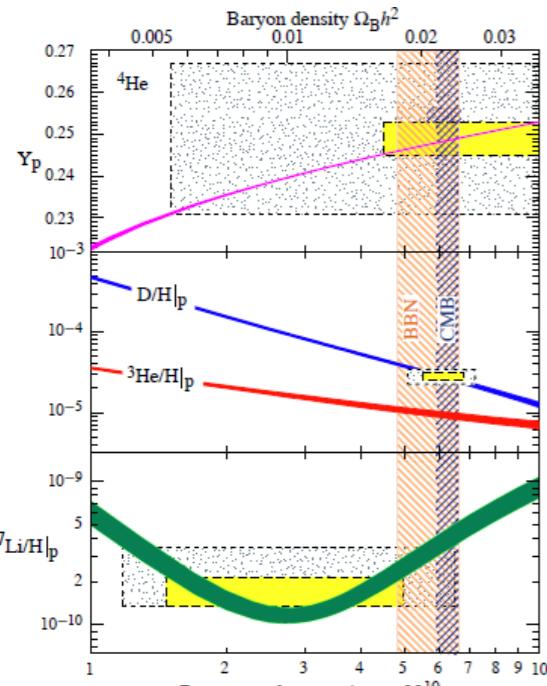
Broken



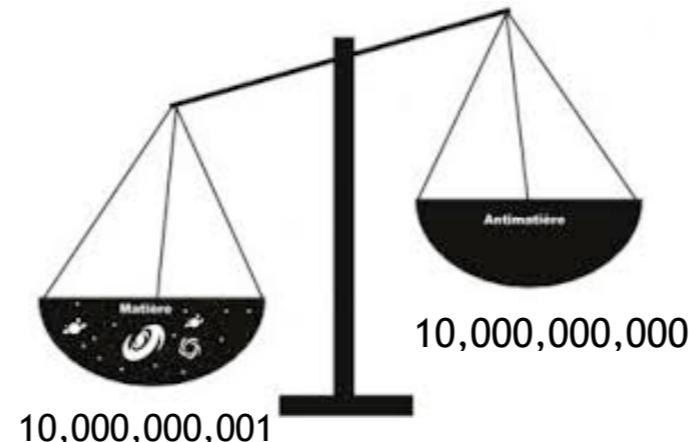
The Standard Model

Electroweak Symmetry Thermal History

Why (strongly first order) electroweak phase transition?

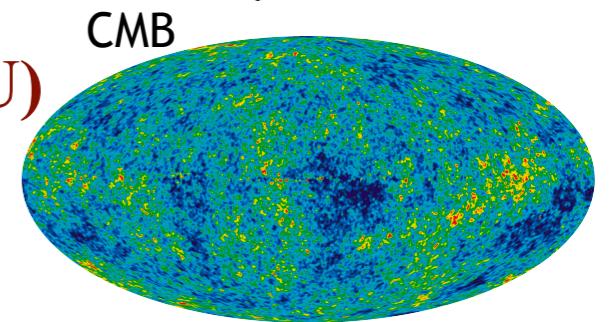
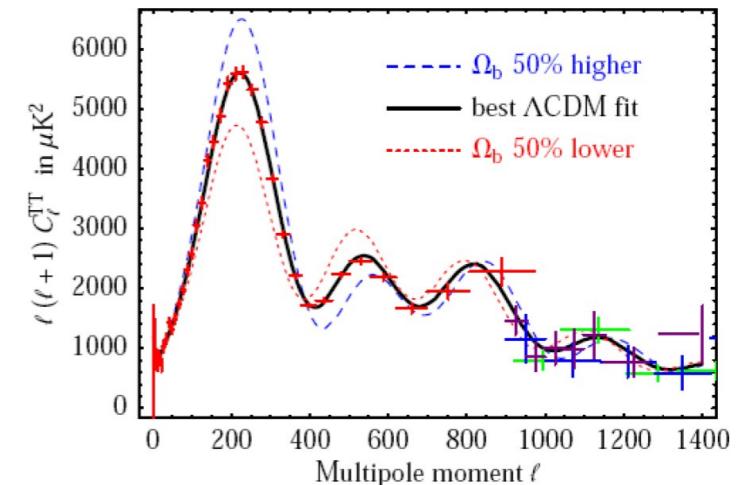


Big Bang Nucleosynthesis

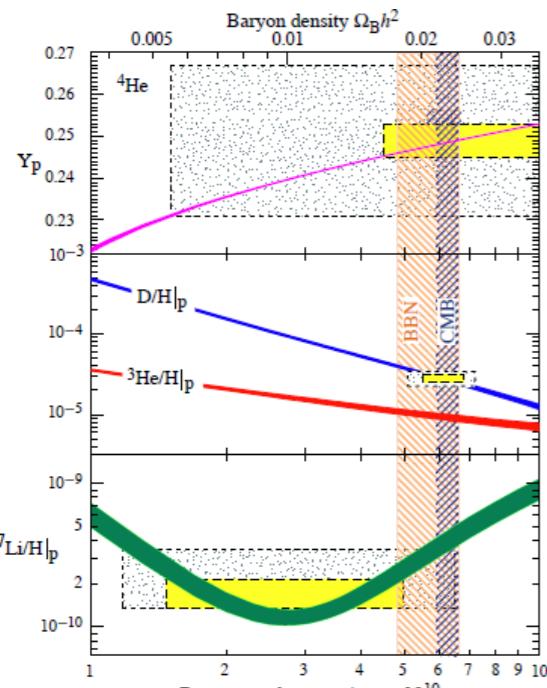


Baryon Asymmetry of the Universe (BAU)

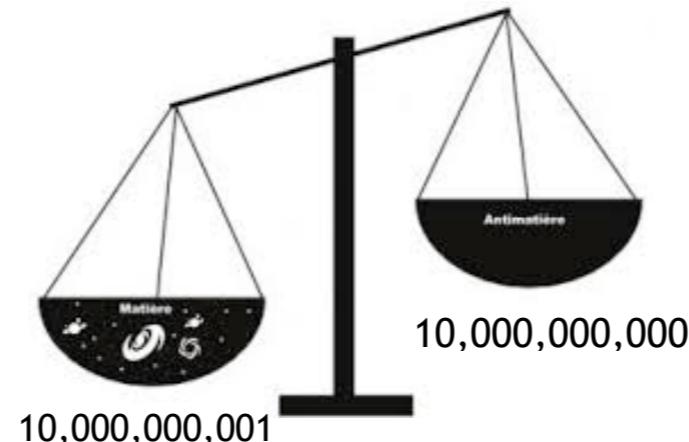
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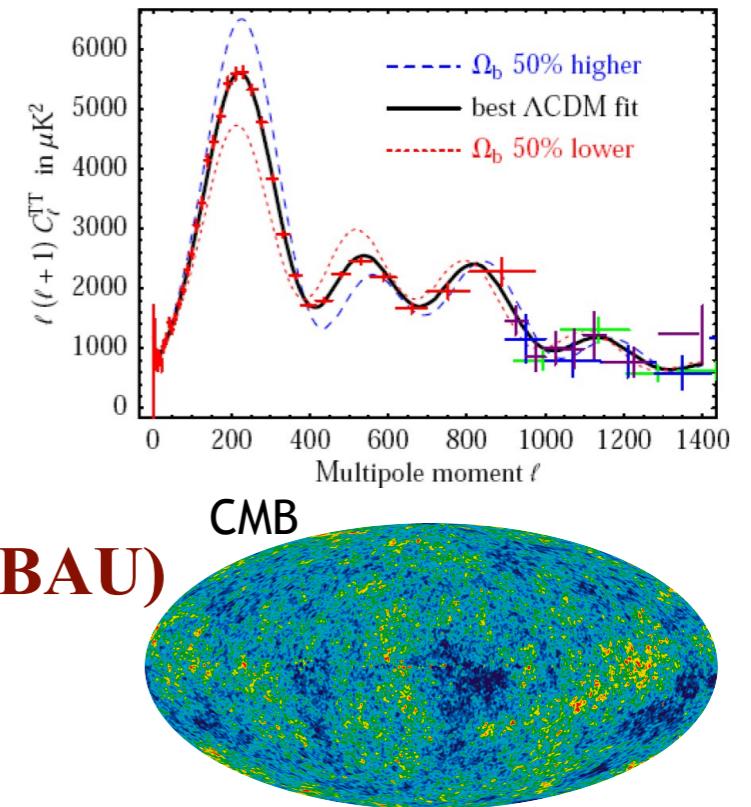


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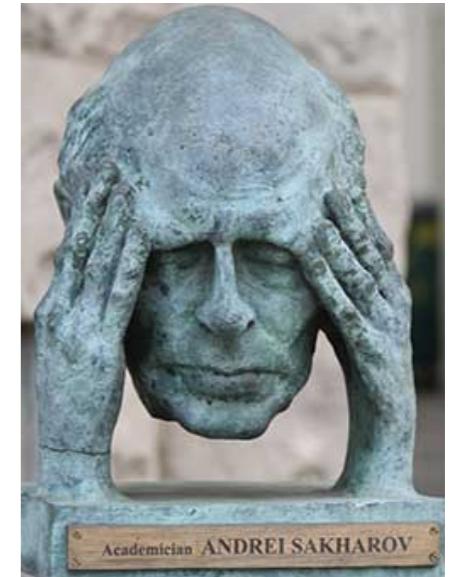
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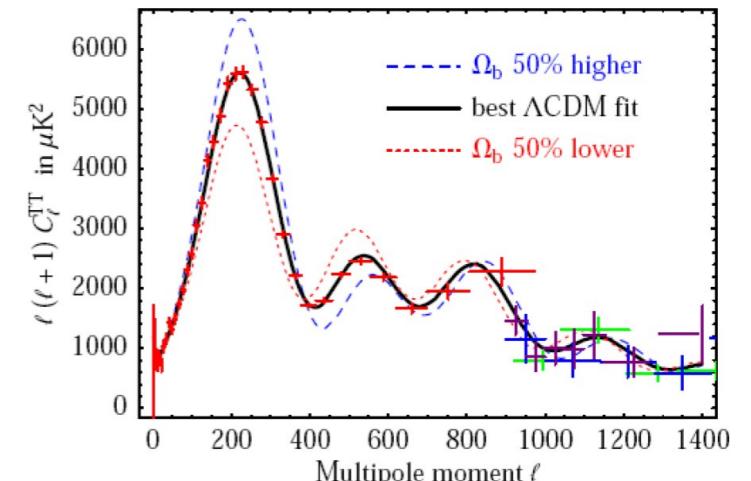
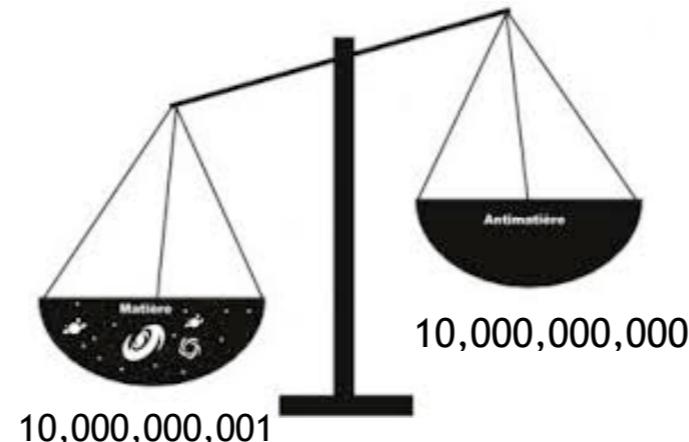
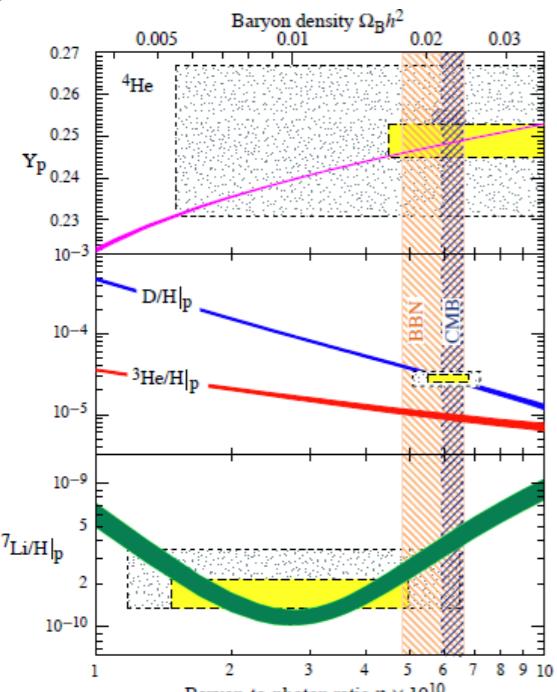


Sakharov's conditions for BAU creation

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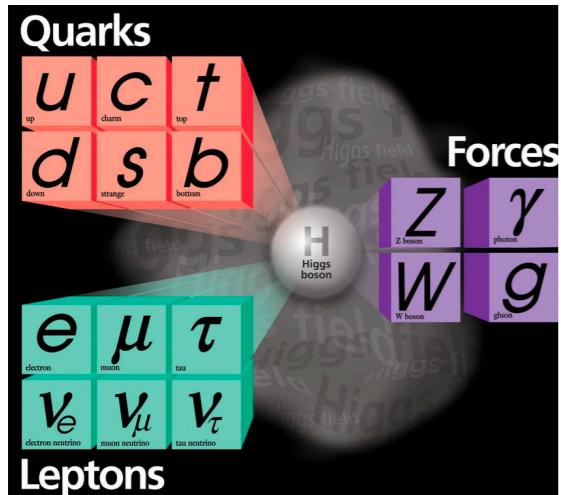


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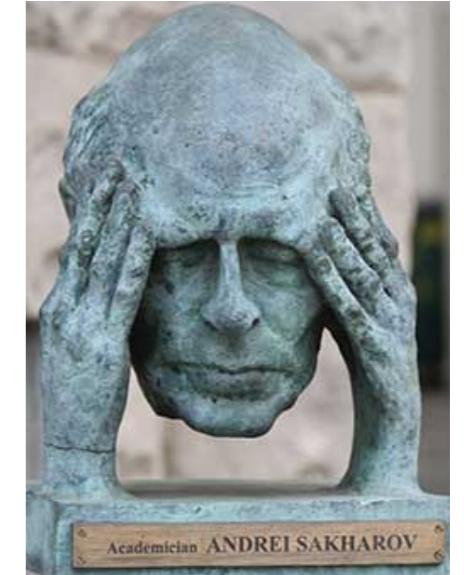
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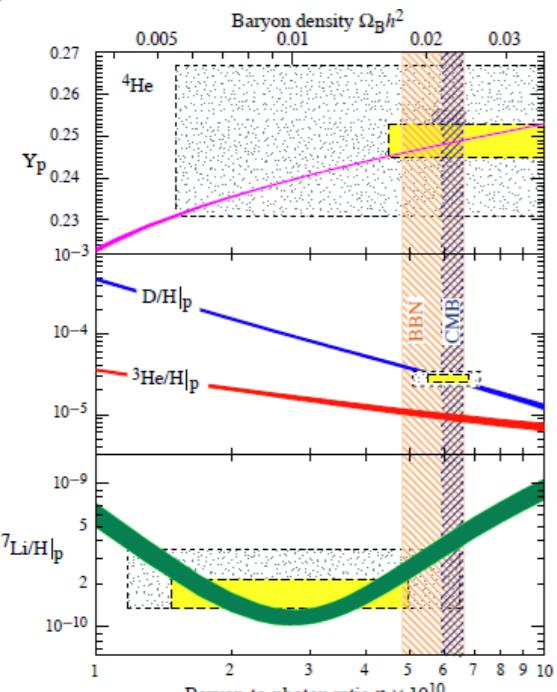
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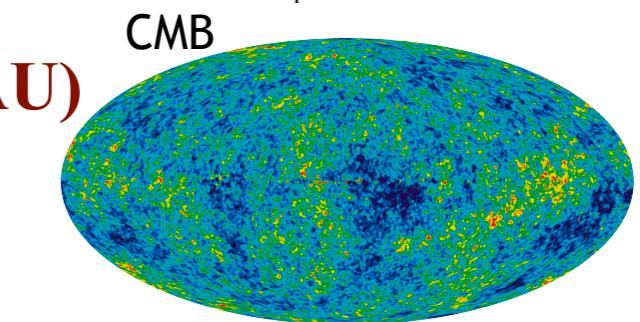
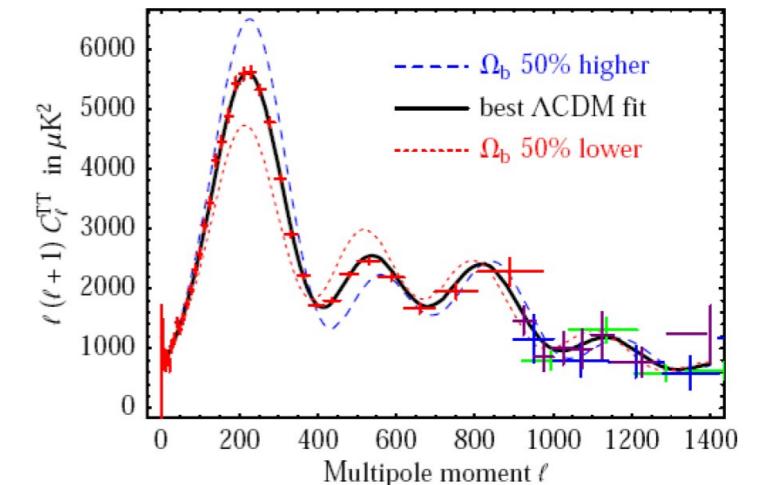
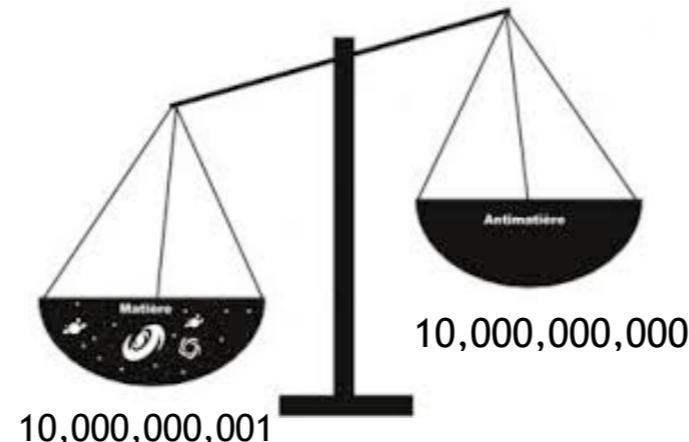


The Standard Model

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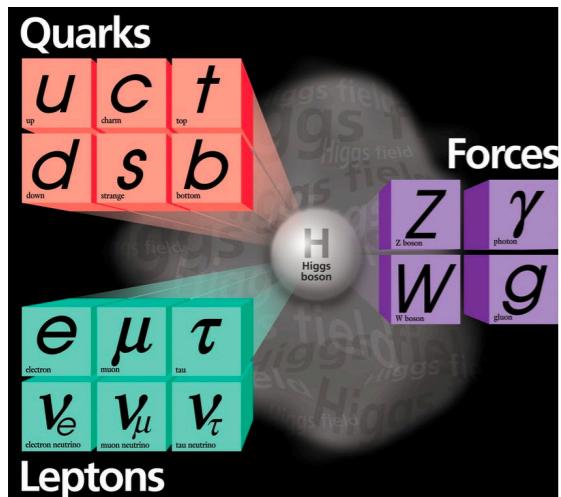


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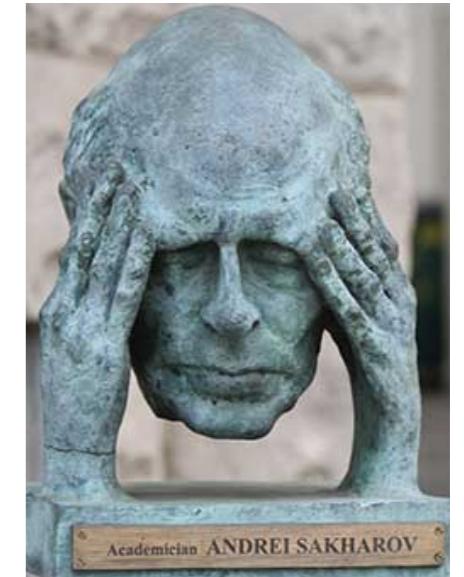
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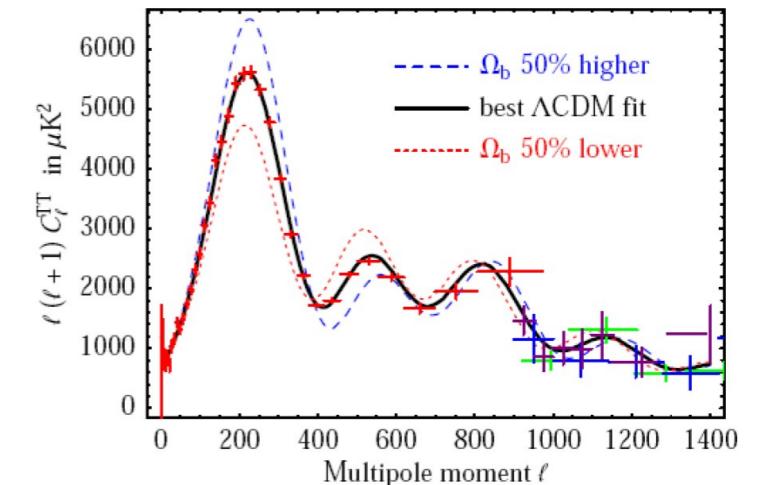
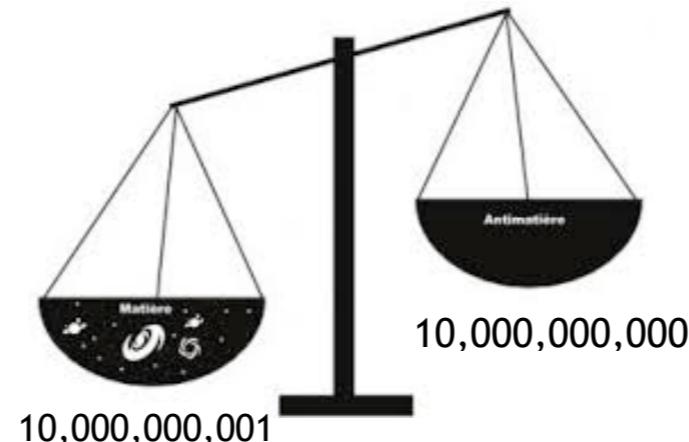
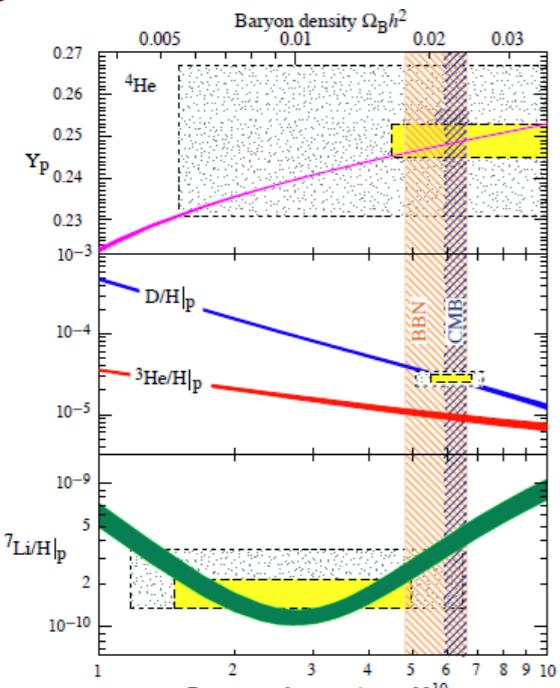
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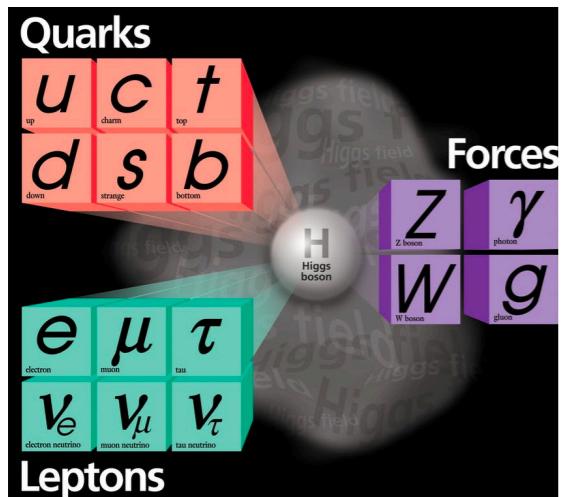
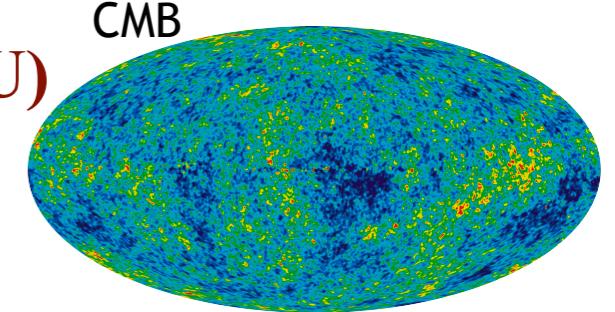
The Standard Model

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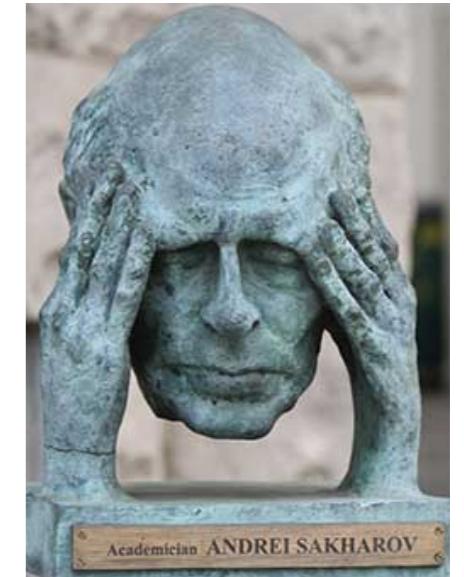
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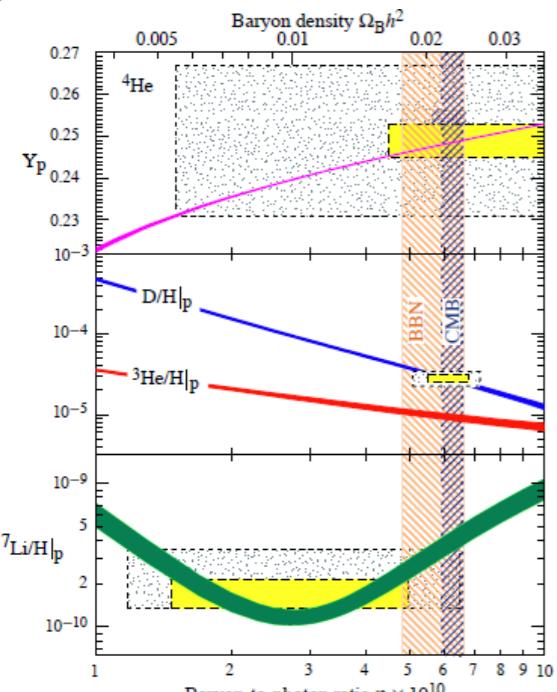
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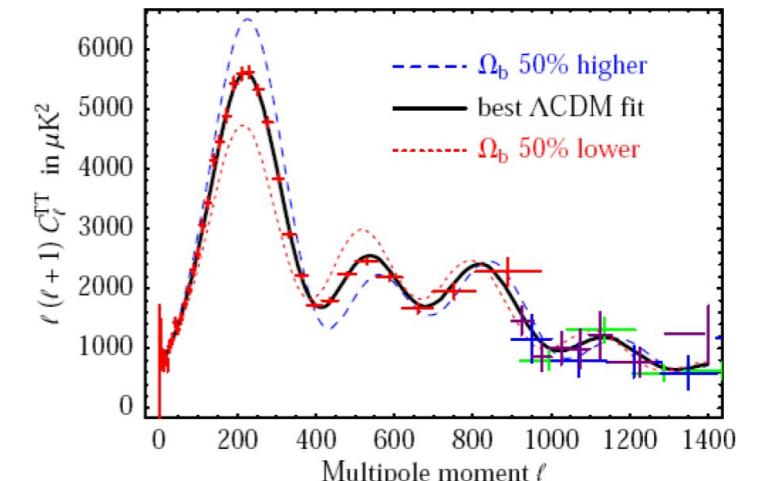
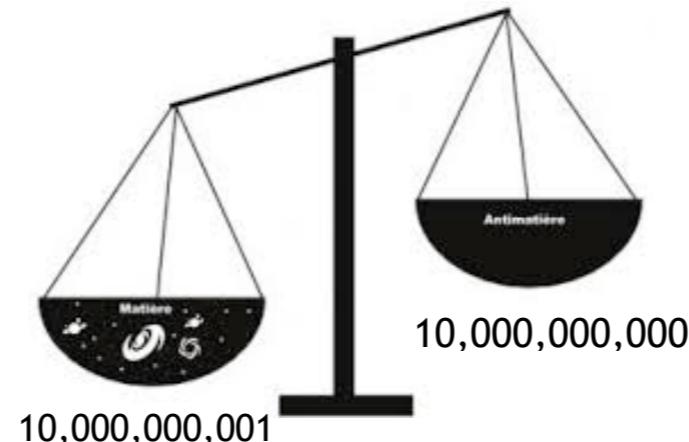


The Standard Model

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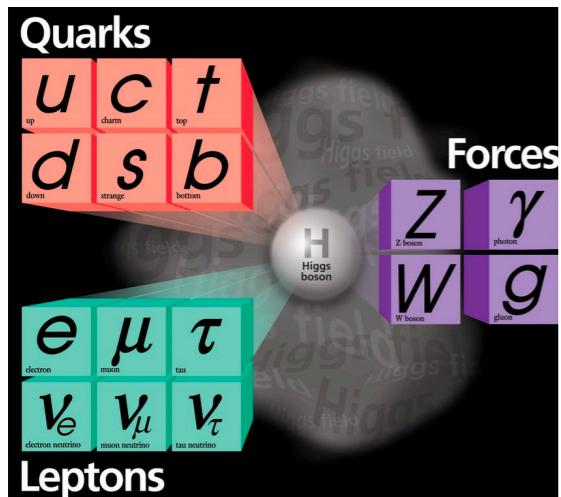


Big Bang Nucleosynthesis



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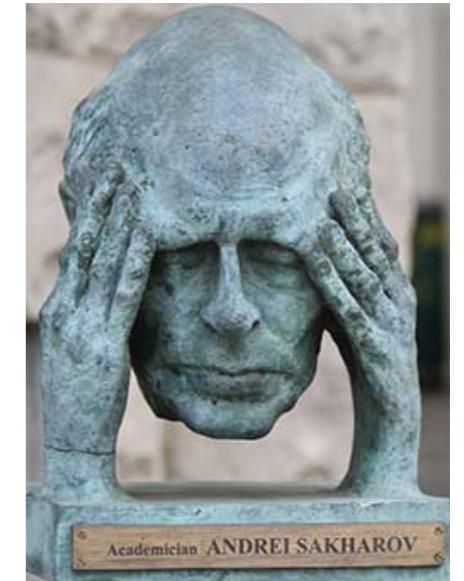
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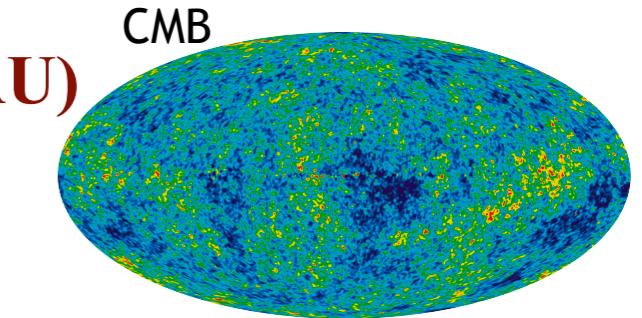
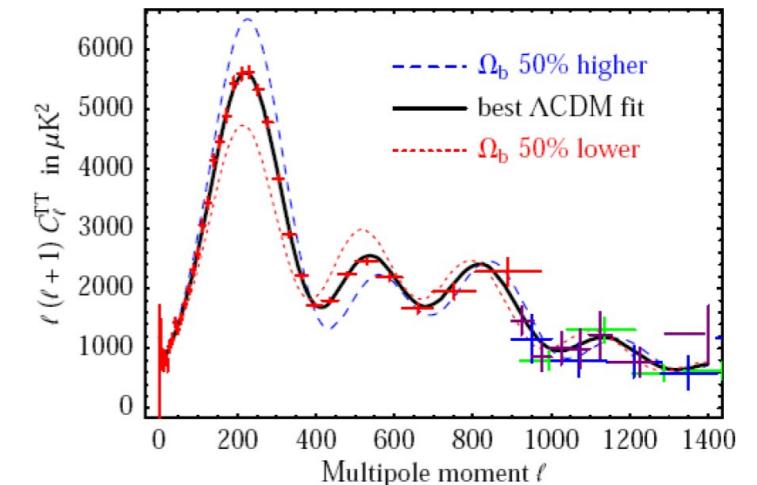
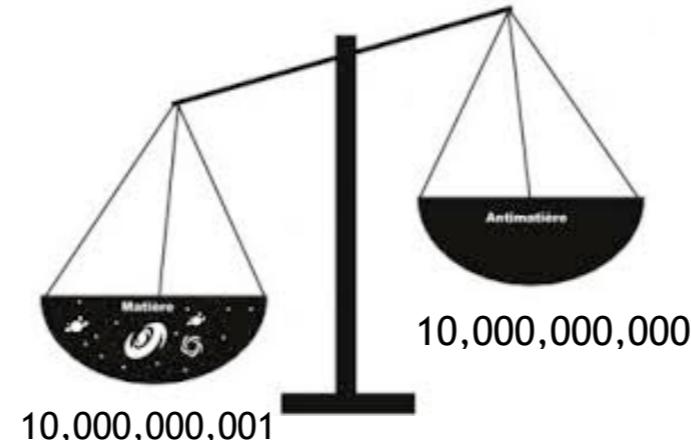
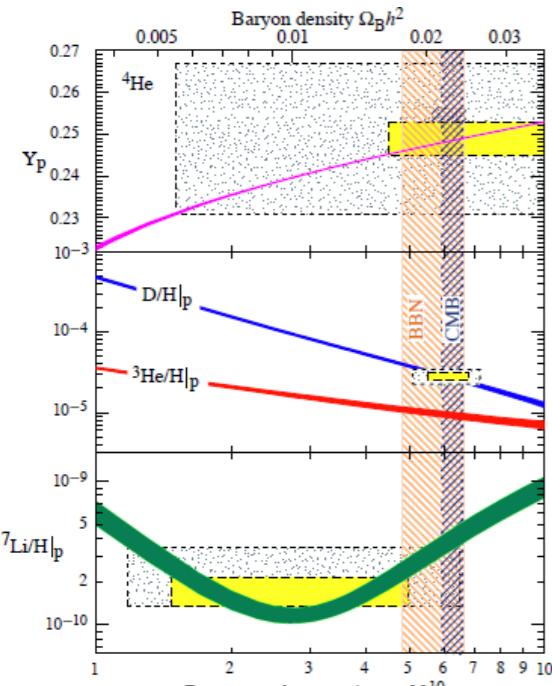
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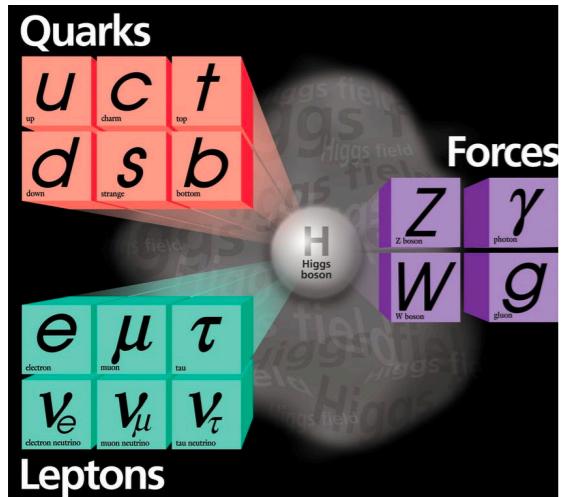


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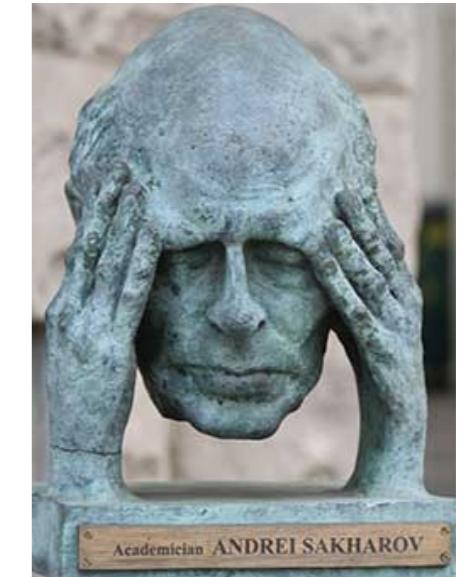
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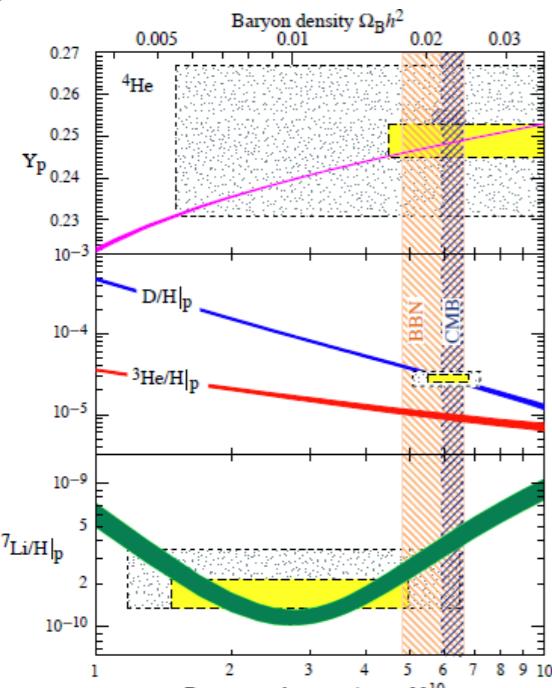
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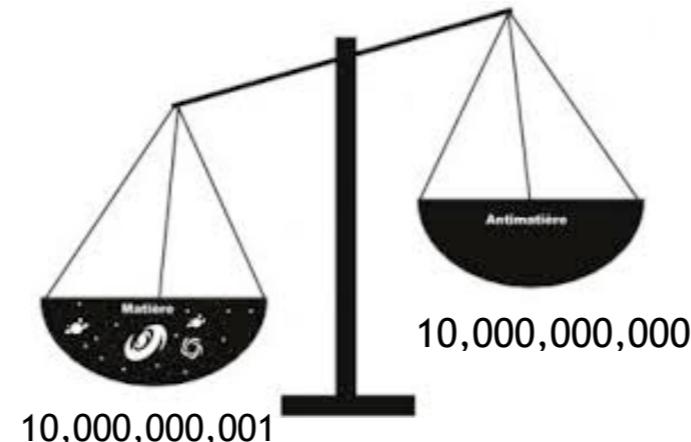
The Standard Model

The Standard Model (SM) could not explain the generation of BAU.

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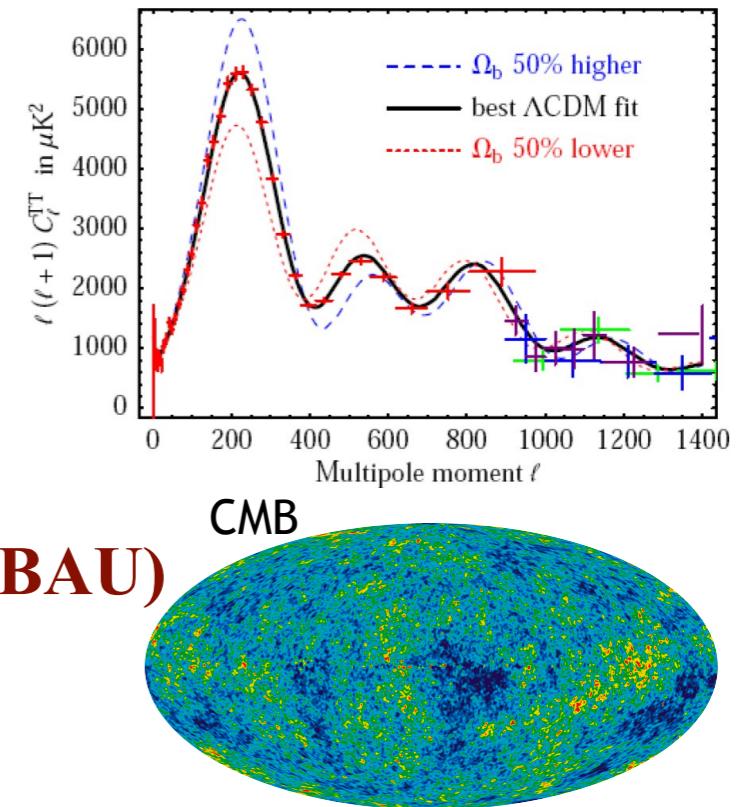


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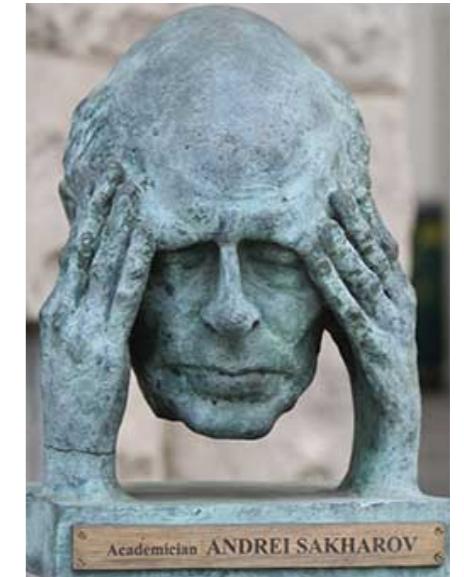
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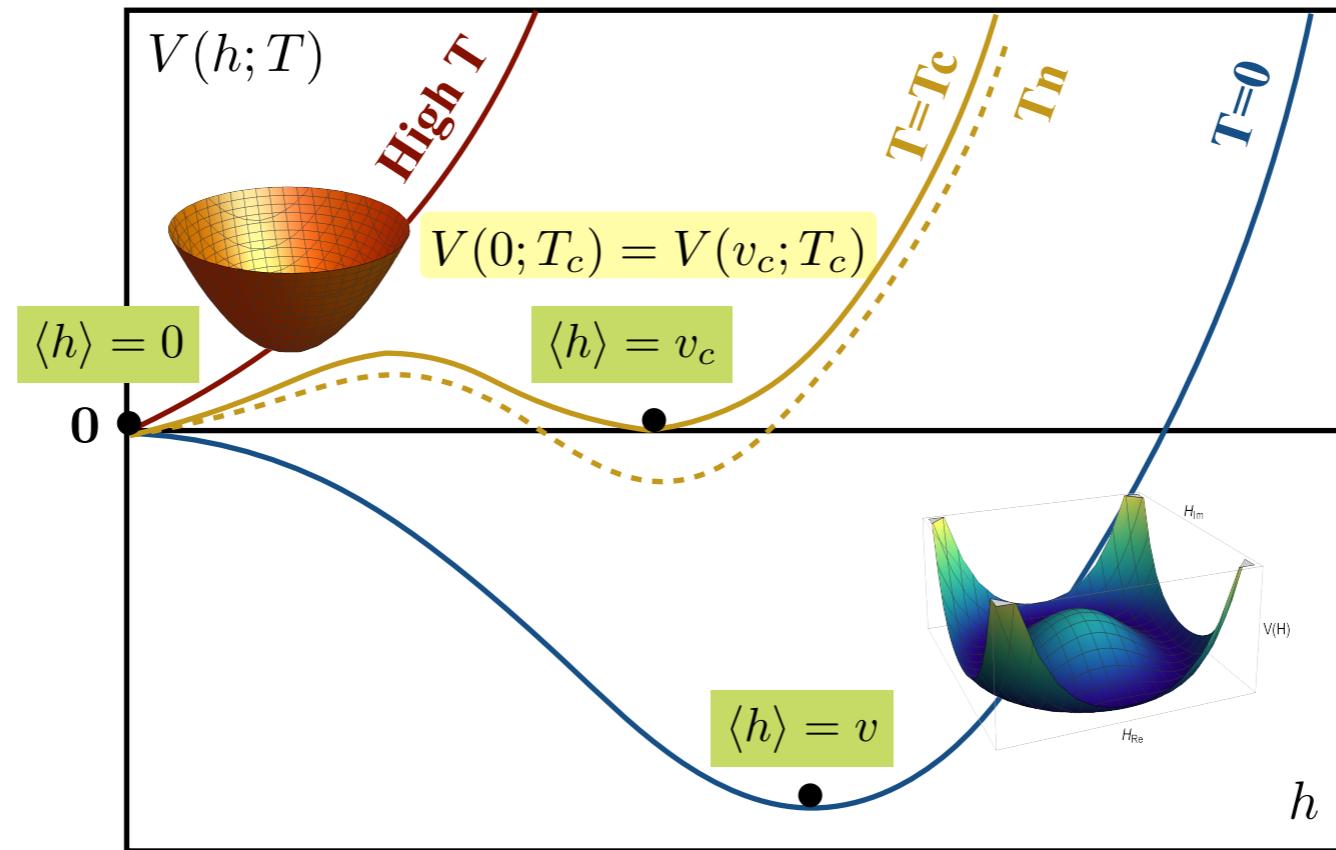


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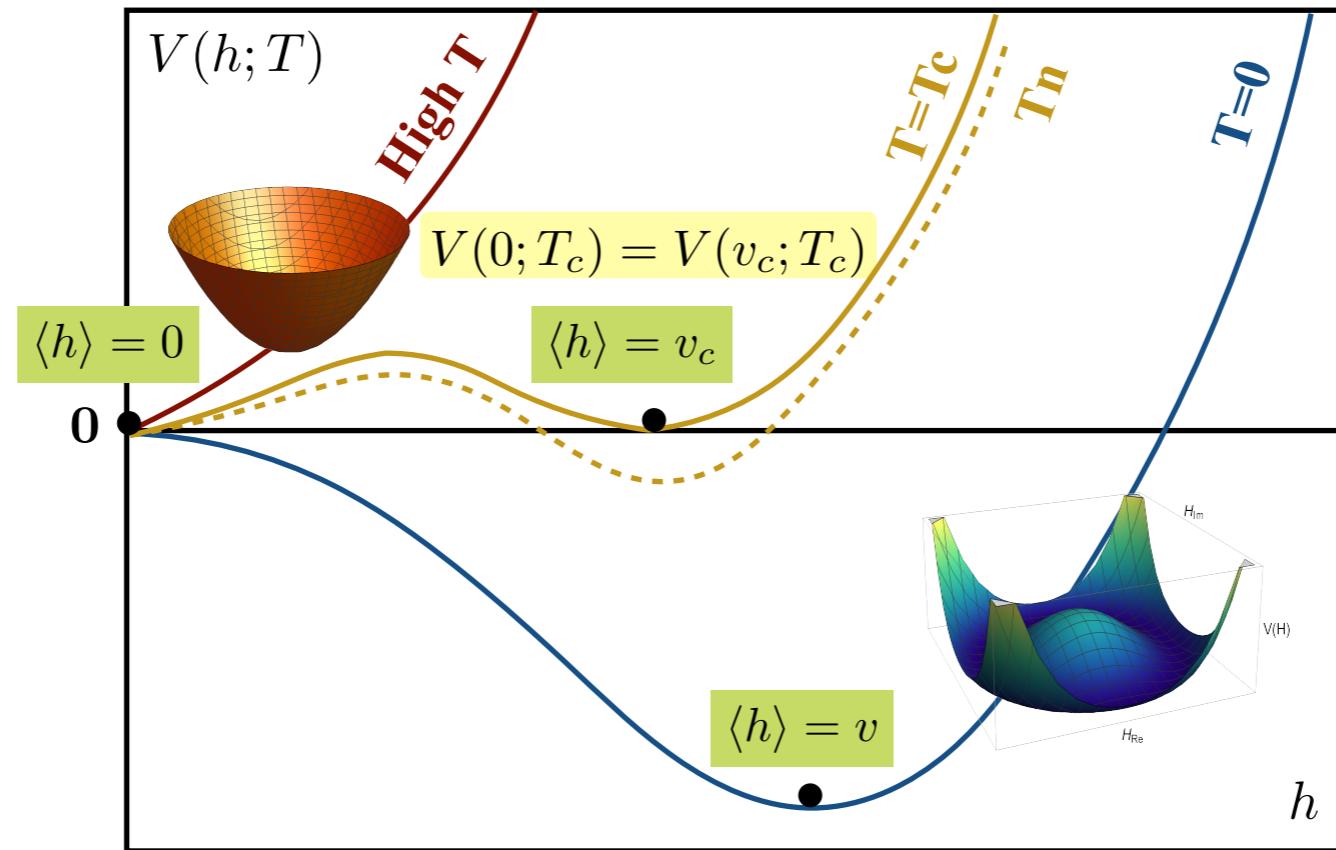
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Strong First Order Electroweak Phase Transition (SFOEWPT)

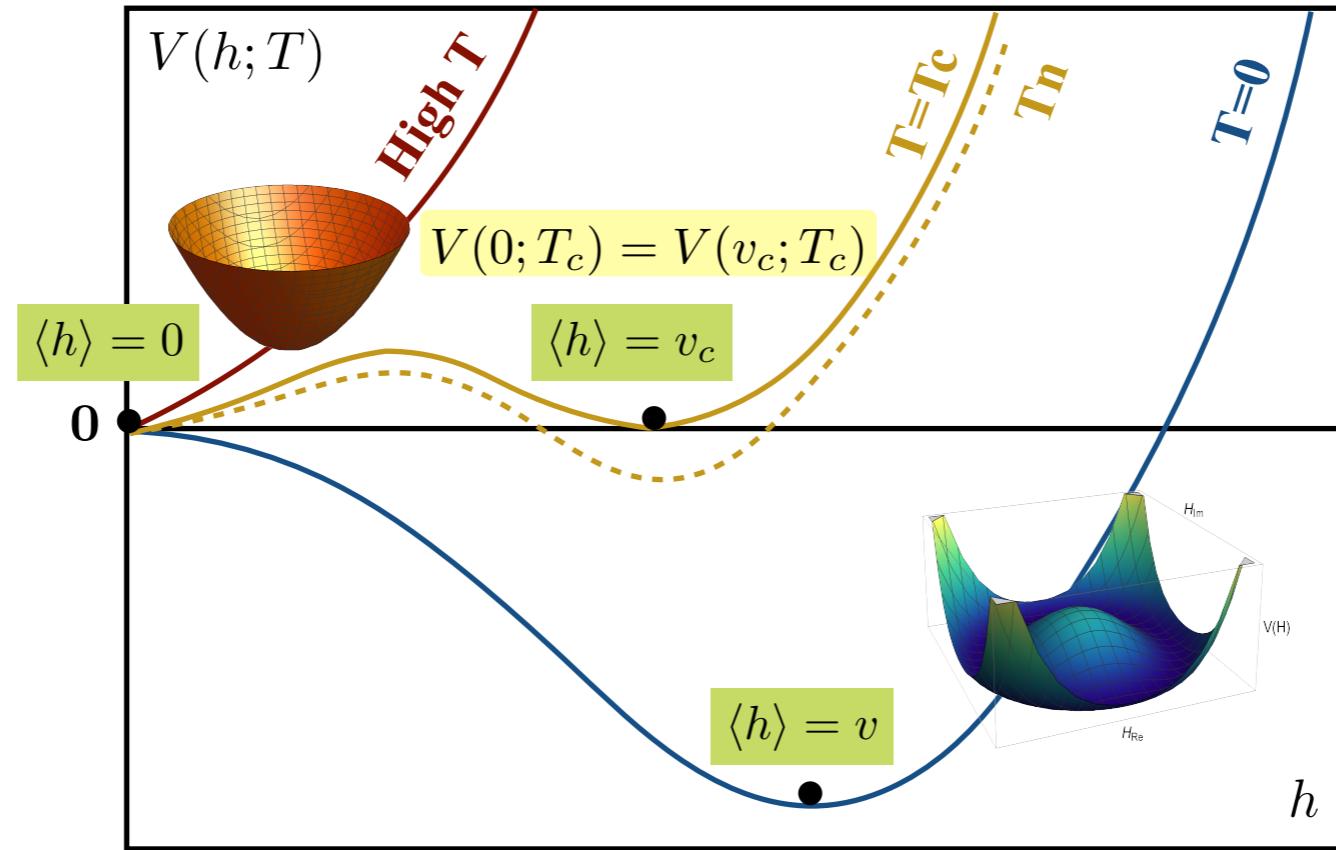


Strong First Order Electroweak Phase Transition (SFOEWPT)



The order parameter $\frac{v_c}{T_c} \gtrsim 1$

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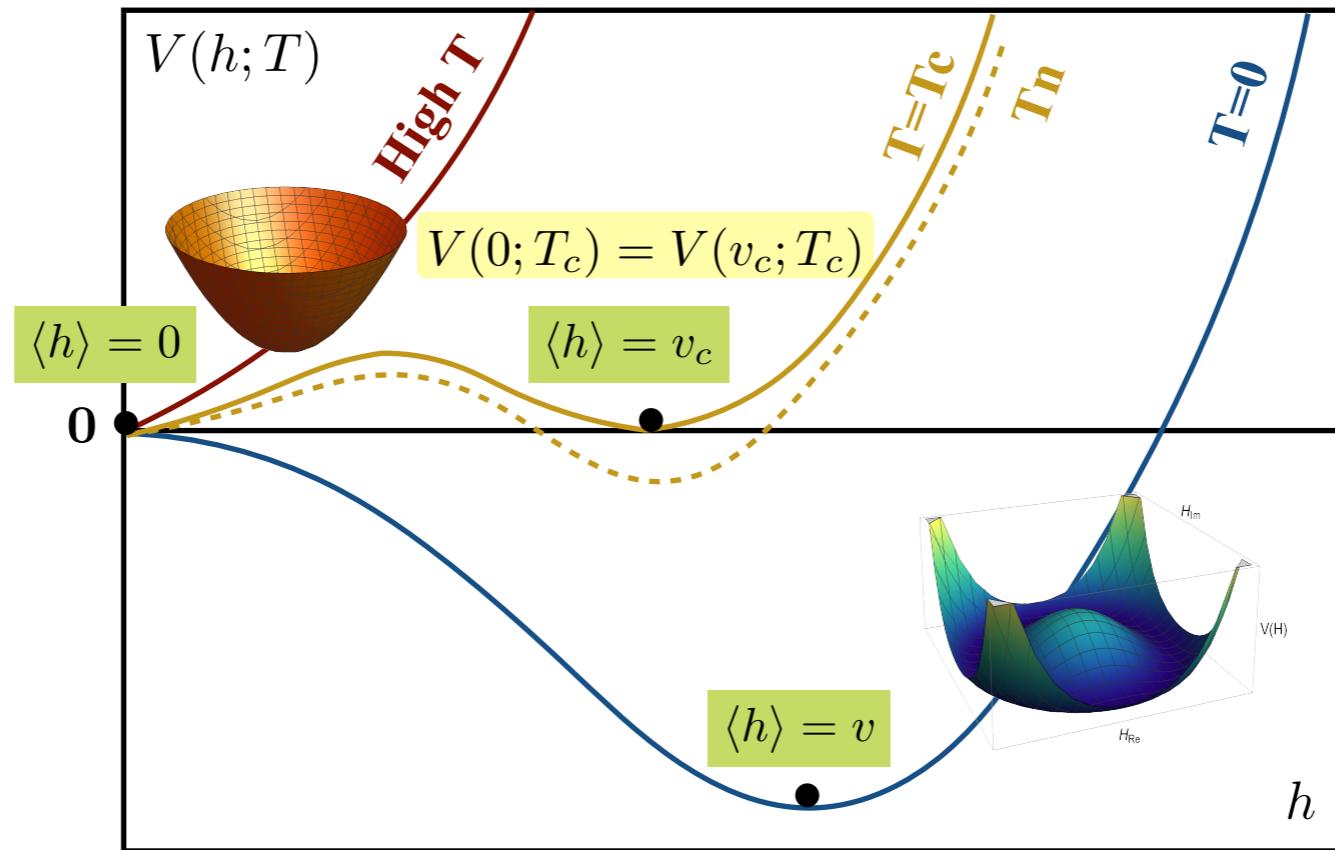
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- Provide out-of-thermal equilibrium
- Suppress baryon asymmetry washing out (sphalerons)

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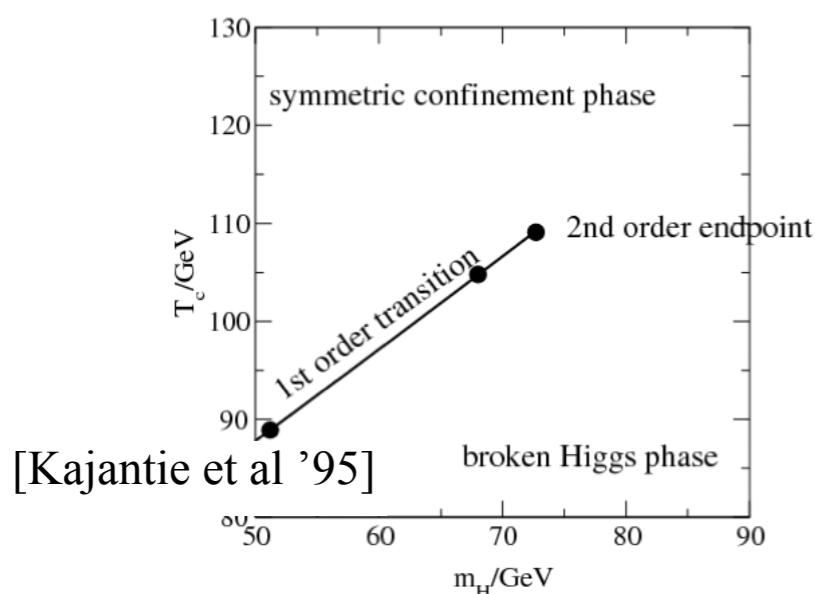
e.g. [V. A. Kuzmin et al '85]

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In the **SM**, the electroweak symmetry broke through a cross over at finite T

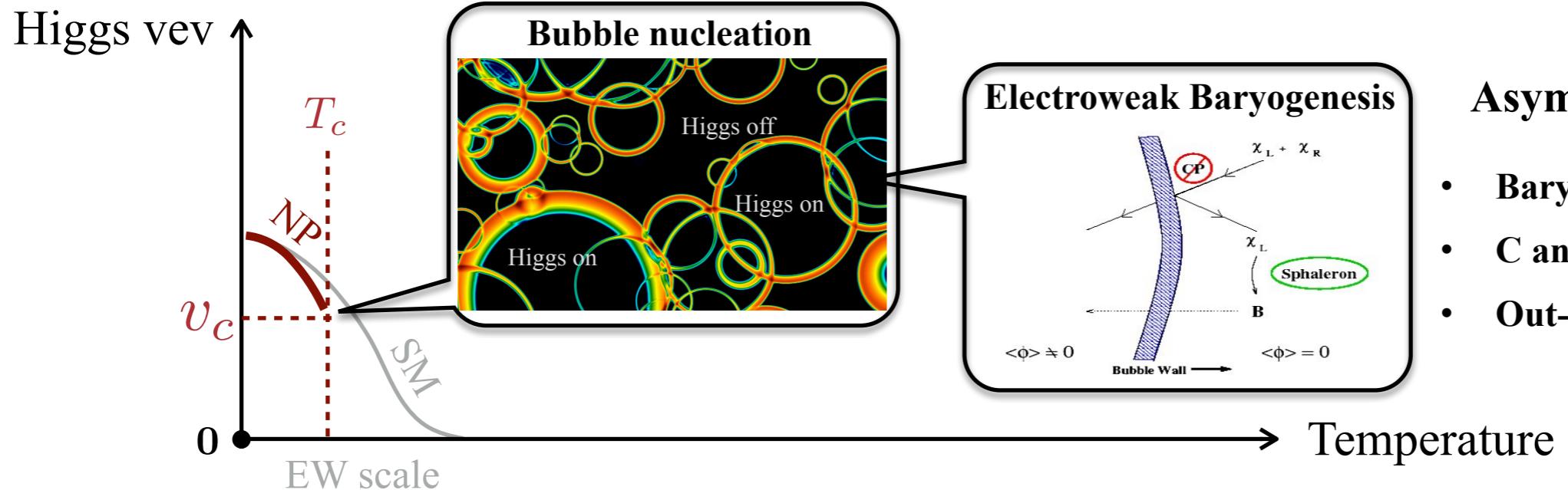
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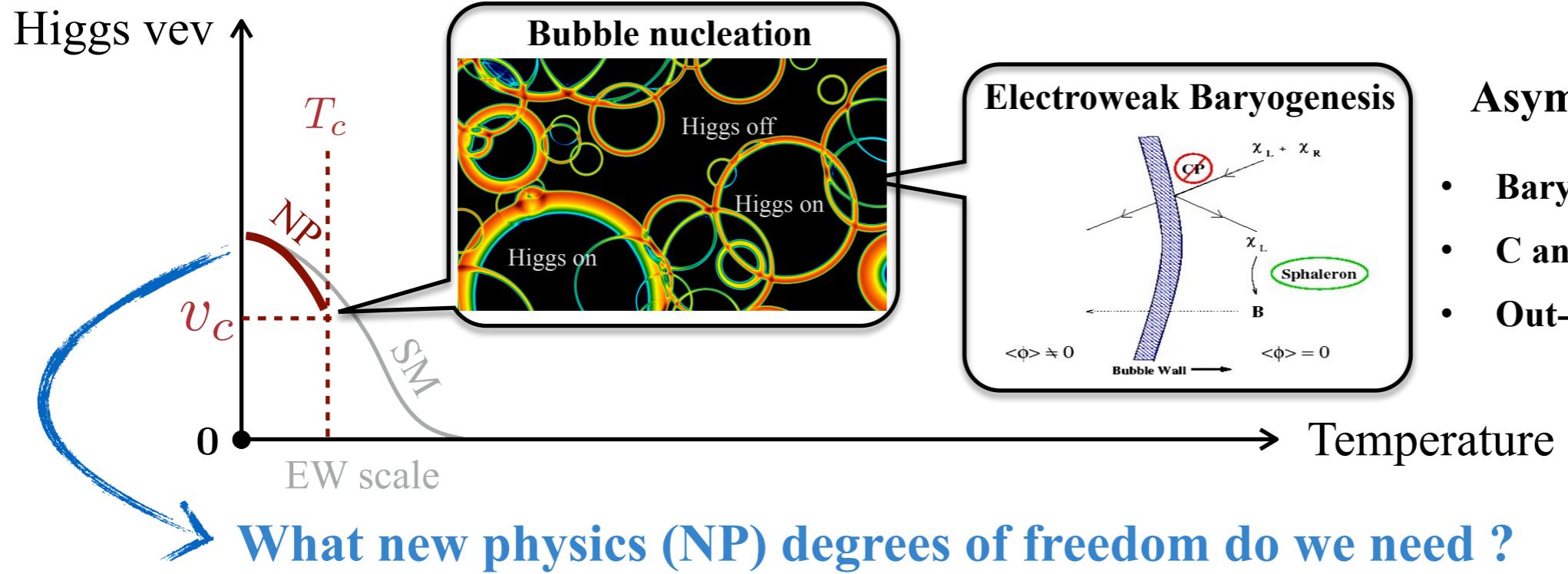
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Asymmetry creation

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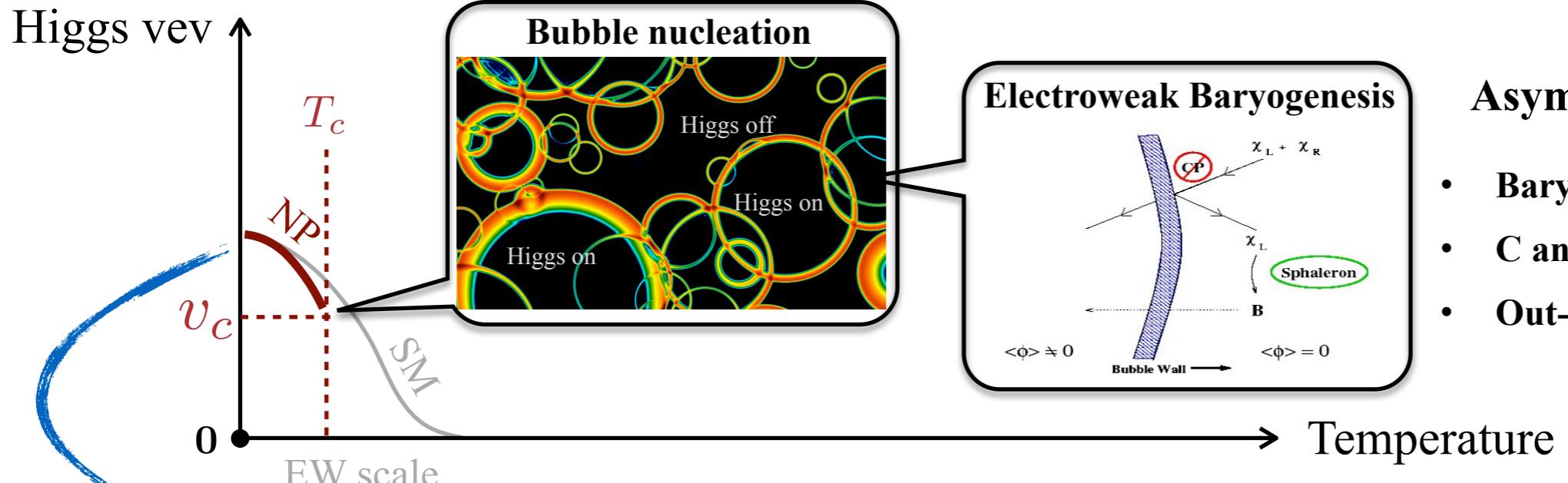
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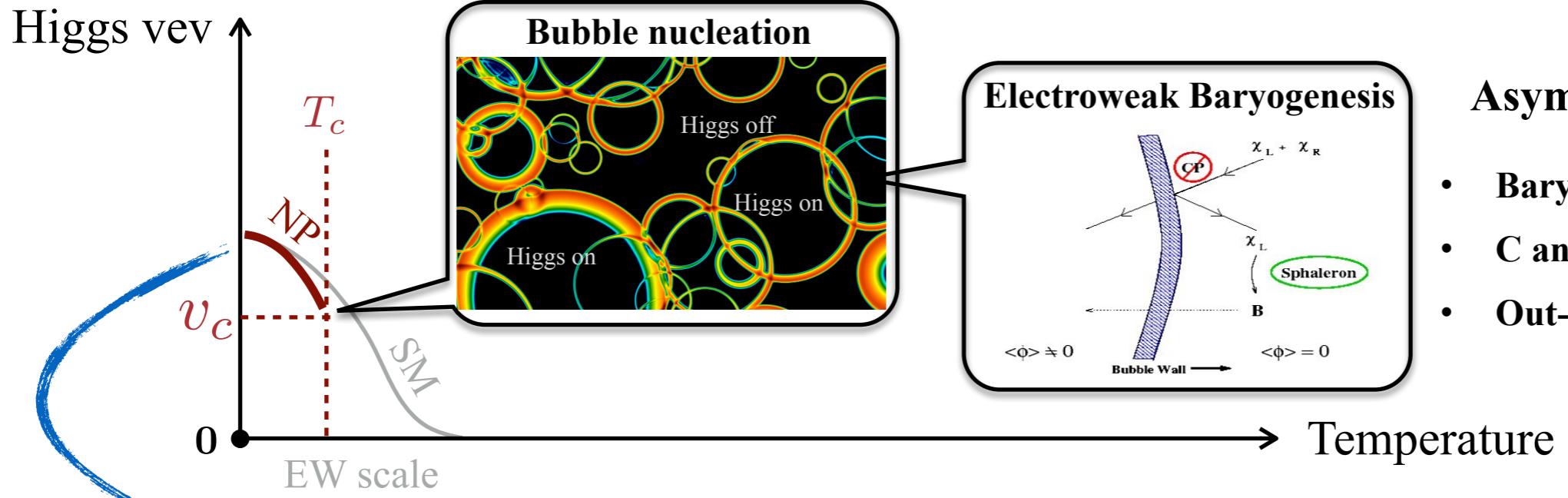
Strong First Order Electroweak Phase Transition (SFOEWPT)



What new physics (NP) degrees of freedom do we need ?

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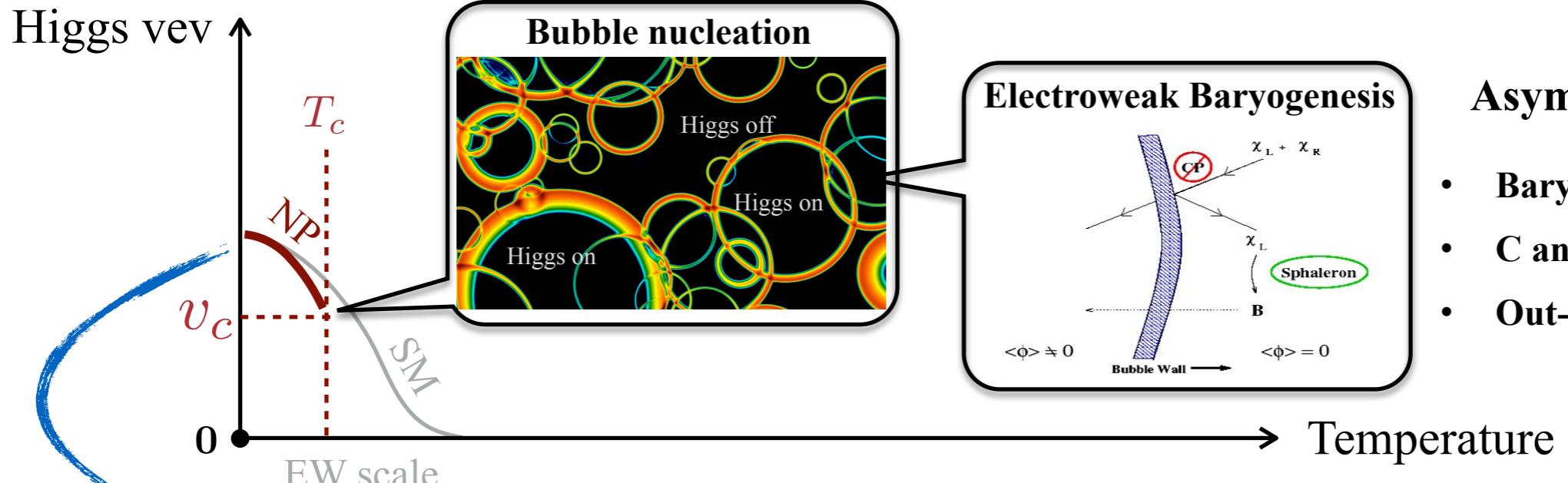
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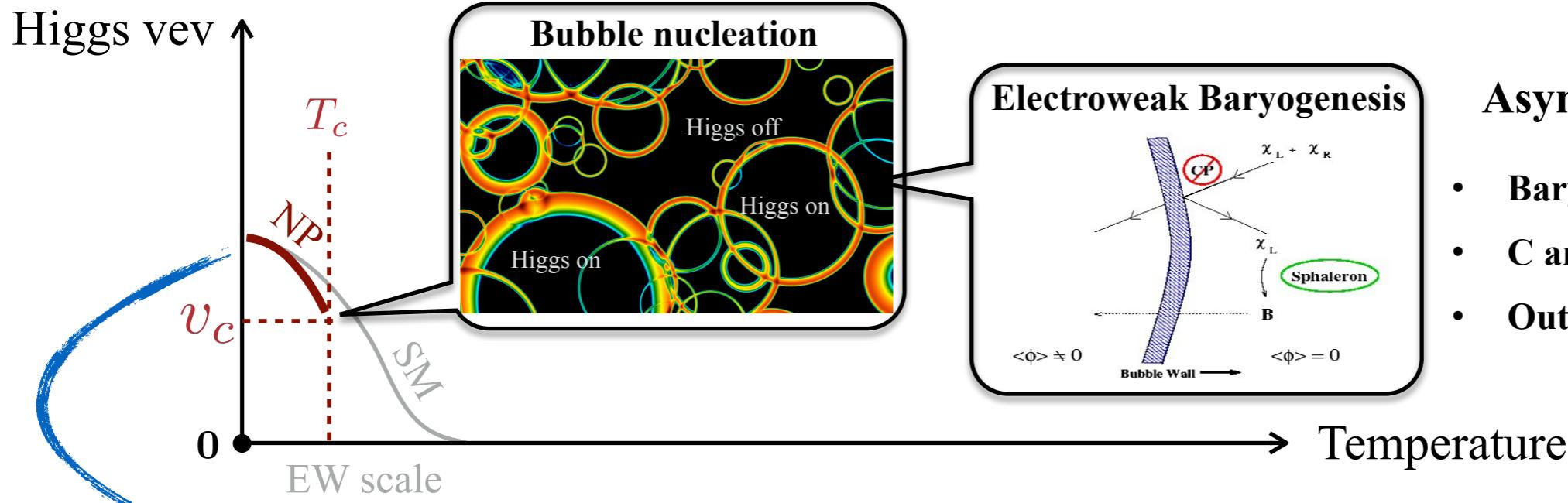
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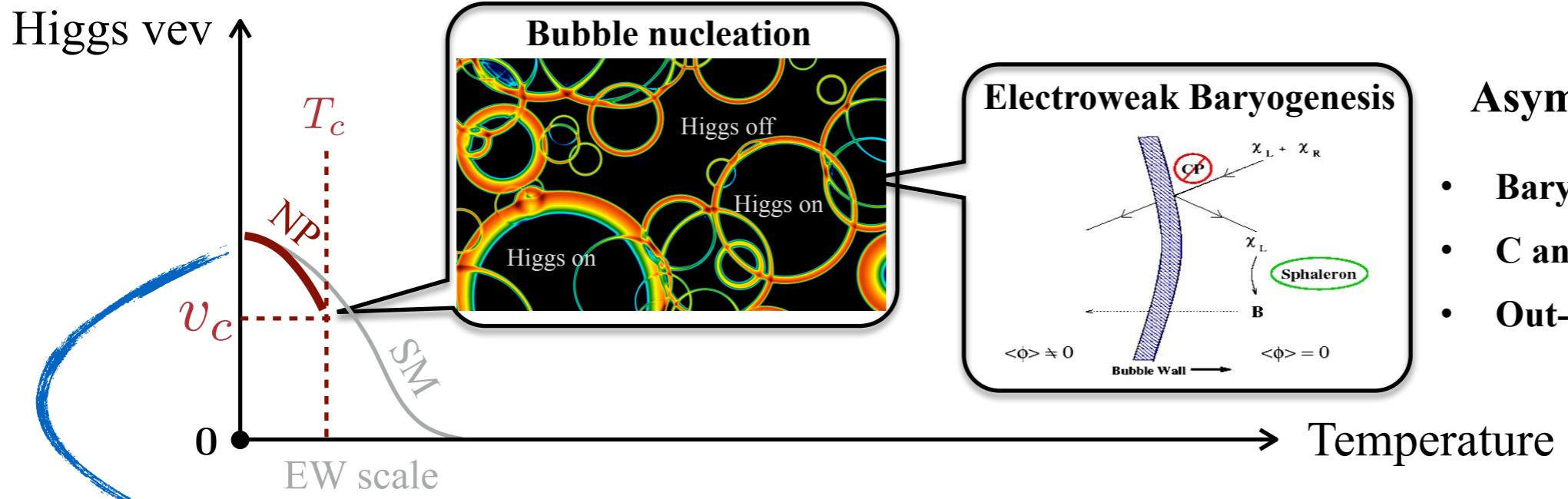
□ Zero Temperature loop effects

□ Thermal effects

□ Tree-level Effects

E.g. [Chung, et al '13]

Strong First Order Electroweak Phase Transition (SFOEWPT)



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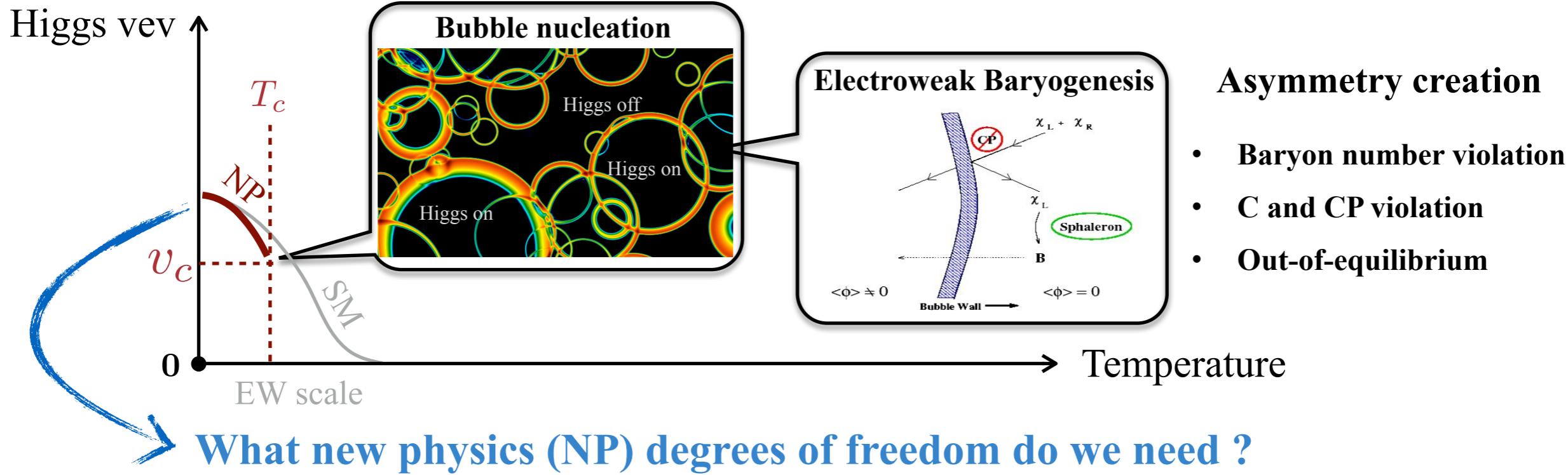
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Strong First Order Electroweak Phase Transition (SFOEWPT)

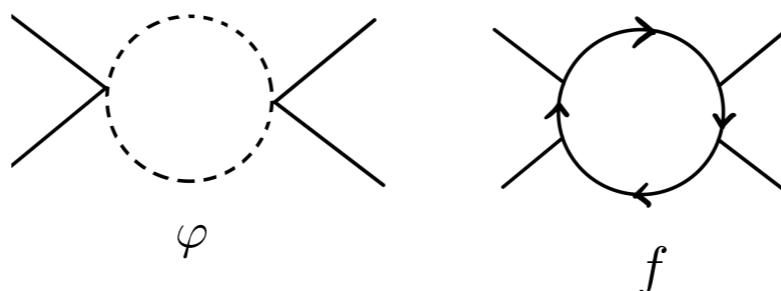


$$V(h, T) \approx c_H(T^2 - T_0^2) h^2 - E T h^3 + \frac{\lambda(T)}{2} h^4 \rightarrow \frac{v_c}{T_c} \approx \frac{E}{\lambda} \gtrsim 1$$

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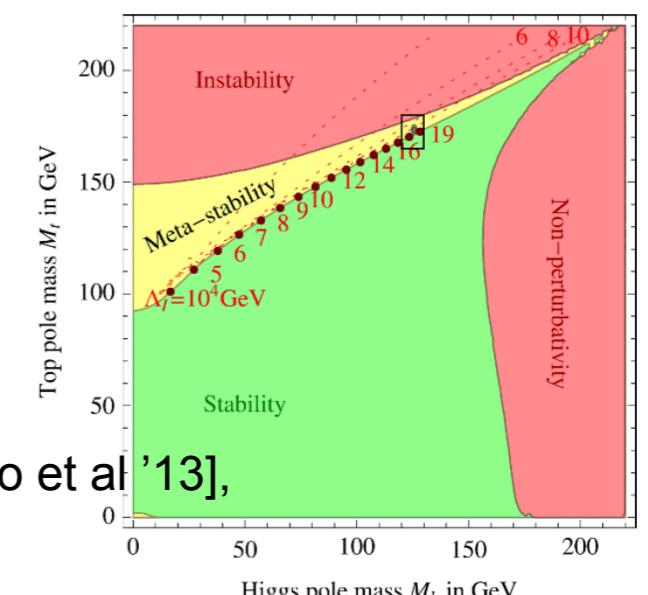
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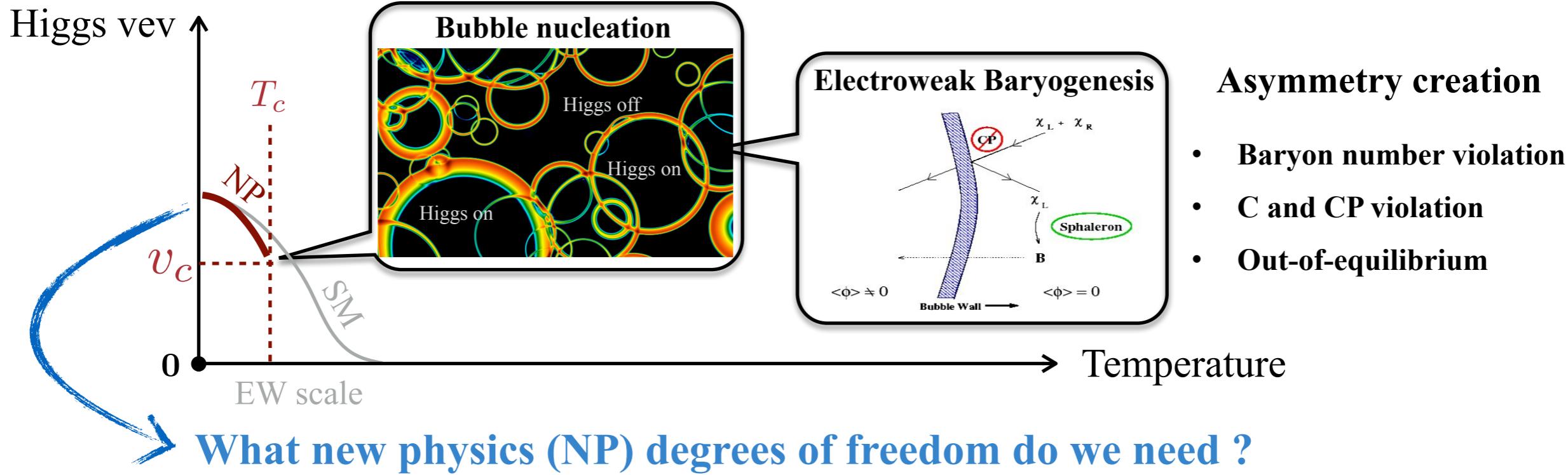
E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], ...

$$V(h, T) = V_0^{\text{eff}} + V_{1-\text{loop}}^{\text{CW}}(\tilde{m}_i^2) + V_{1-\text{loop}}^{T \neq 0}(\tilde{m}_i^2)$$



[Buttazzo et al '13],

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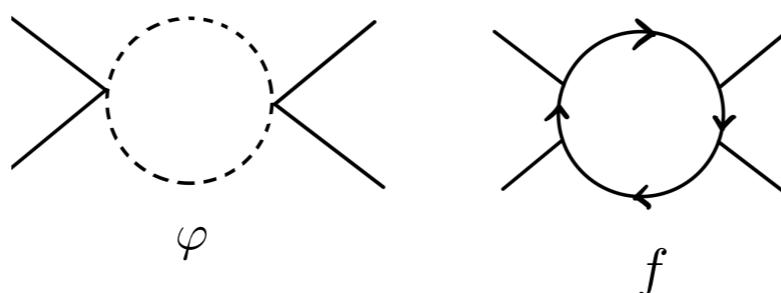


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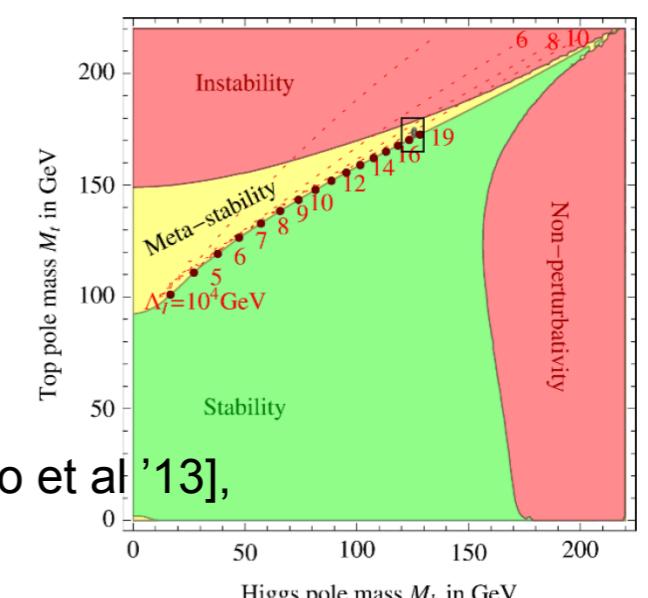
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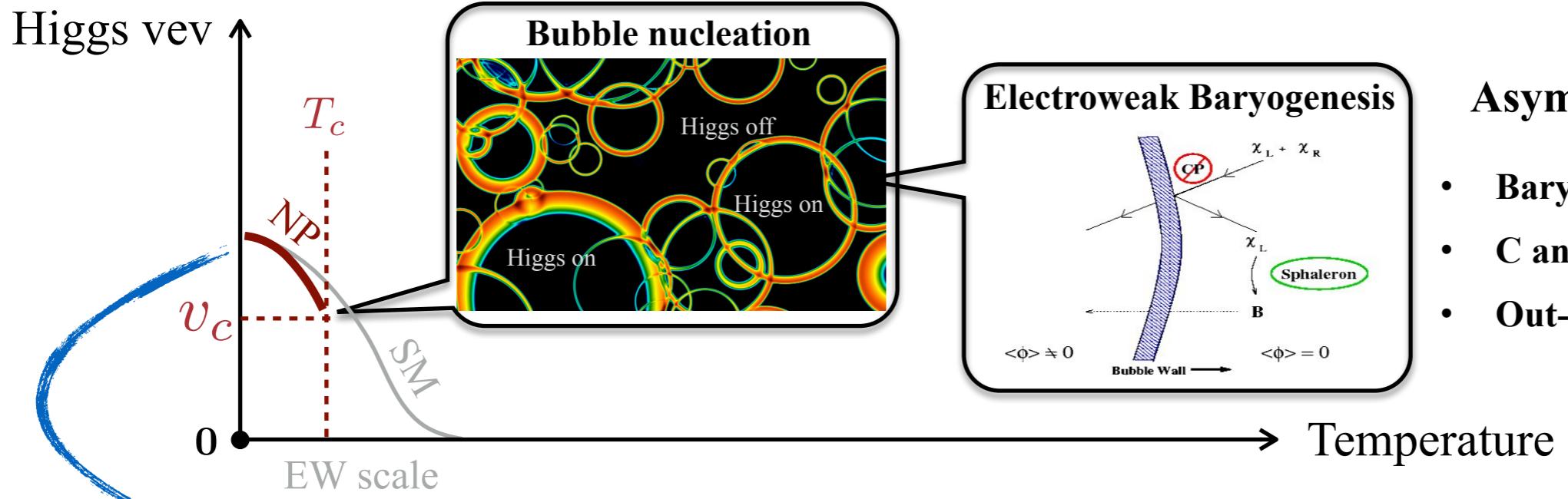


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Strong First Order Electroweak Phase Transition (SFOEWPT)



Asymmetry creation

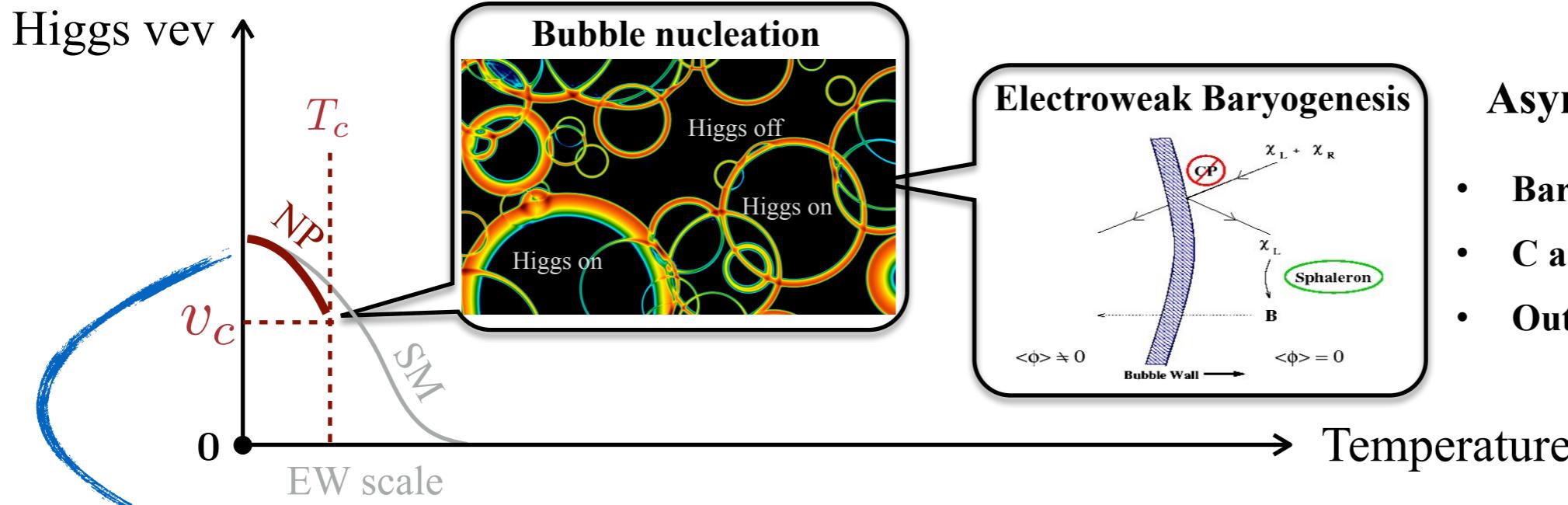
- Baryon number violation
- C and CP violation
- Out-of-equilibrium

What new physics (NP) degrees of freedom do we need ?

$$V(h, T) \approx c_H(T^2 - T_0^2) h^2 - E \Gamma h^3 + \frac{\lambda(T)}{2} h^4 \rightarrow \frac{v_c}{T_c} \approx \frac{E}{\lambda} \gtrsim 1$$

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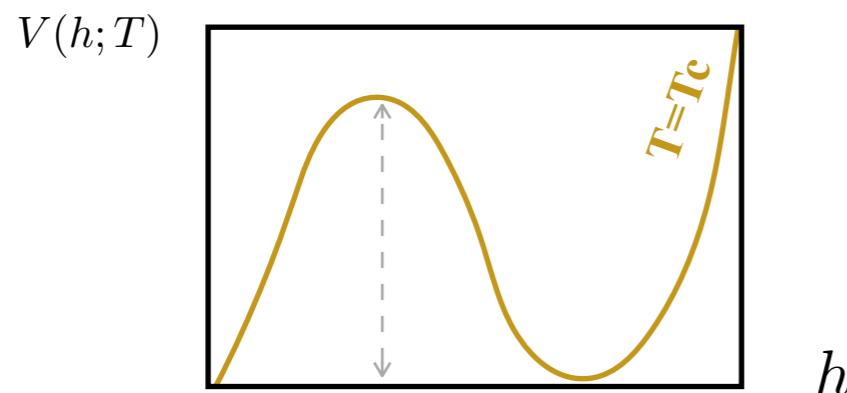


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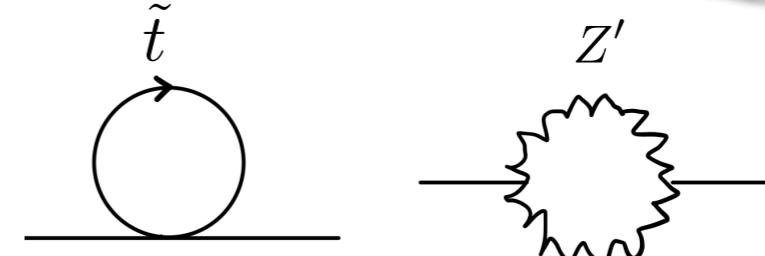


$$Eh^3 \sim (m_{\text{eff}}(h, T_c))^{3/2} \sim \lambda^{3/2} h^3$$

E.g. [Anderson, Hall '92], [Cohen, Morrissey, Pierce '12], [Chowdhury et al '12]

□ Thermal effects

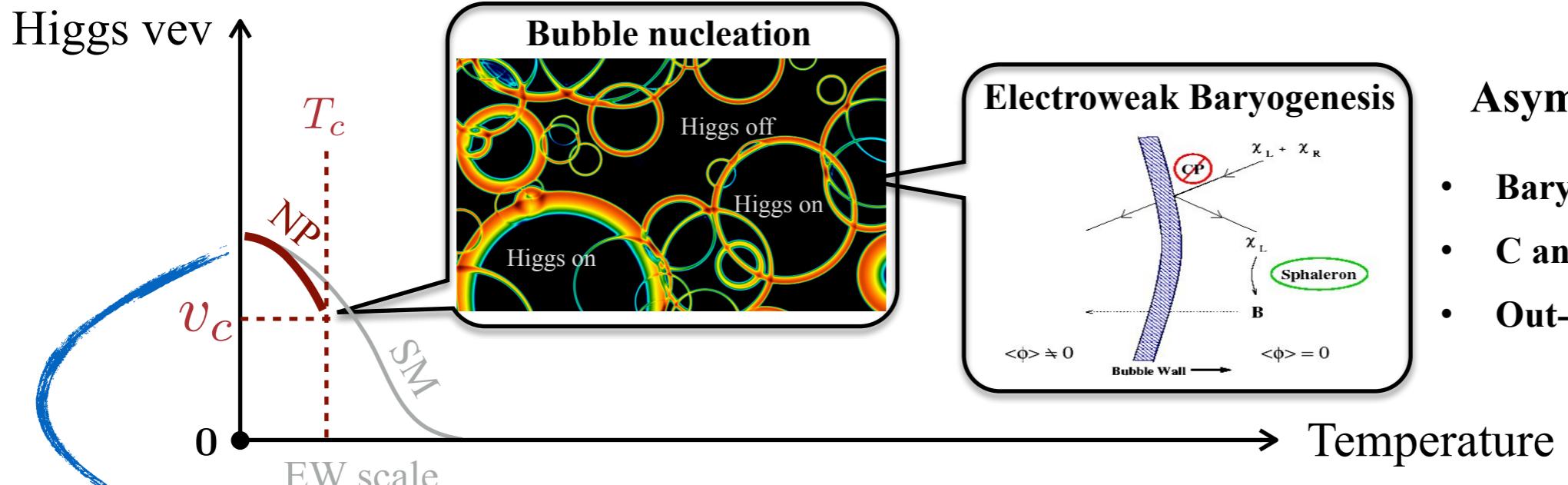
$$V(h, T) = V_0^{\text{eff}} + V_{1-\text{loop}}^{\text{CW}}(\tilde{m}_i^2) + V_{1-\text{loop}}^{T \neq 0}(\tilde{m}_i^2)$$



E.g. Supersymmetry (MSSM) with stop

[Carena, Quiros, Wagner, '96], [Delepine, et al '96]

Strong First Order Electroweak Phase Transition (SFOEWPT)



Asymmetry creation

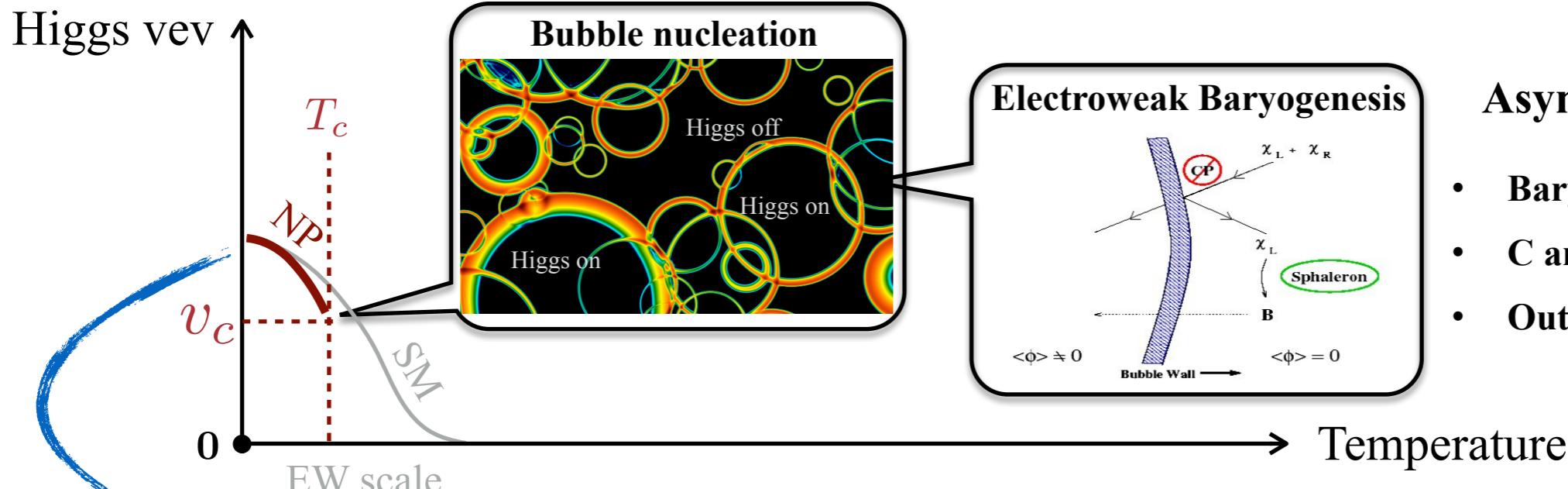
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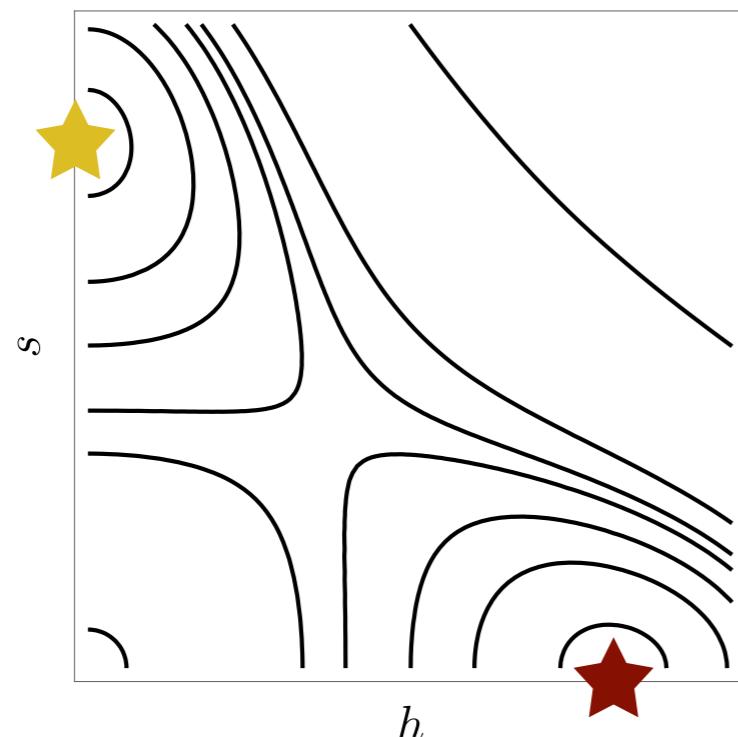


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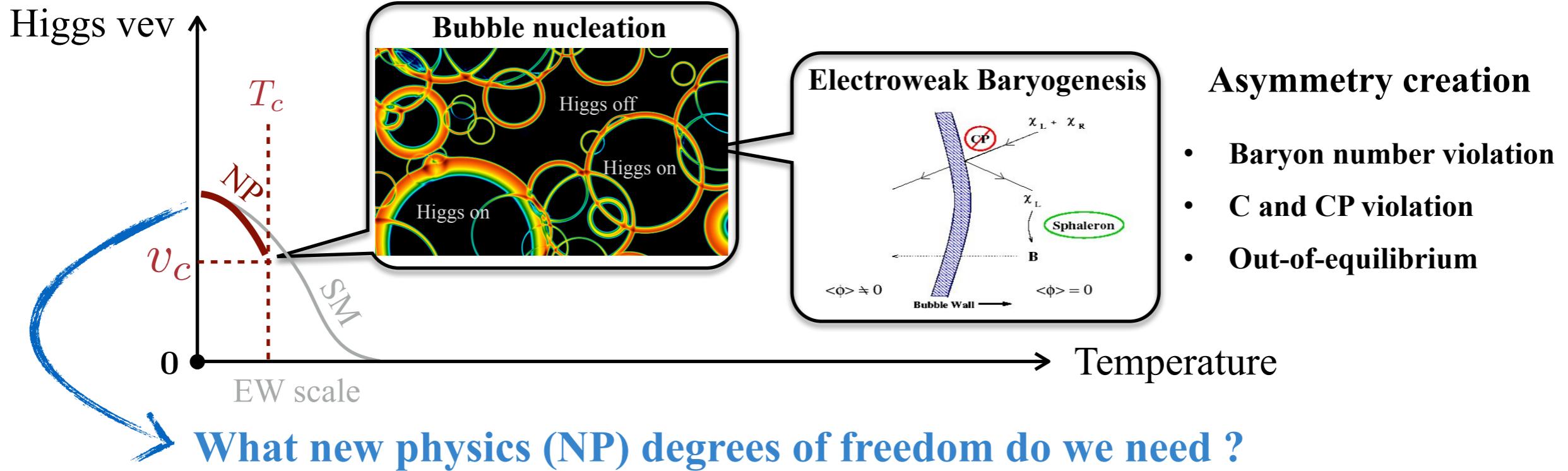


Tree-level Effects

$$V(h, T) = V_0^{\text{eff}} + V_{1-\text{loop}}^{\text{CW}}(\tilde{m}_i^2) + V_{1-\text{loop}}^{T \neq 0}(\tilde{m}_i^2)$$

$$V_0^{\text{eff}}(h) \rightarrow V_0(h, S, H_{\text{BSM}}, \dots)$$

Strong First Order Electroweak Phase Transition (SFOEWPT)



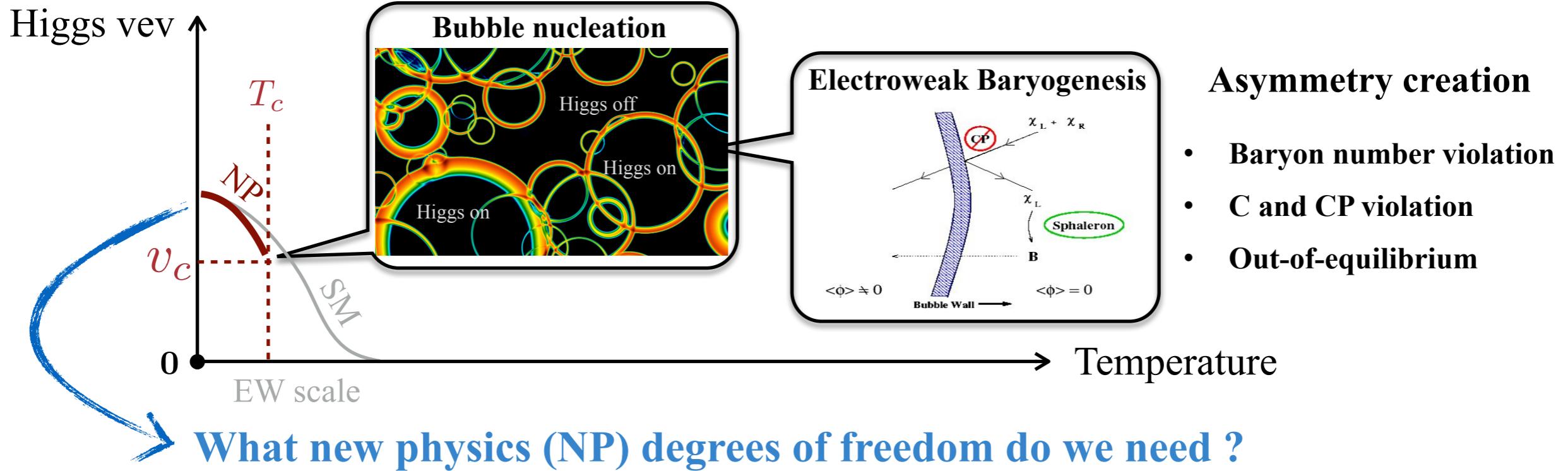
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□ Zero Temperature loop effects

□ Thermal effects

□ Tree-level Effects

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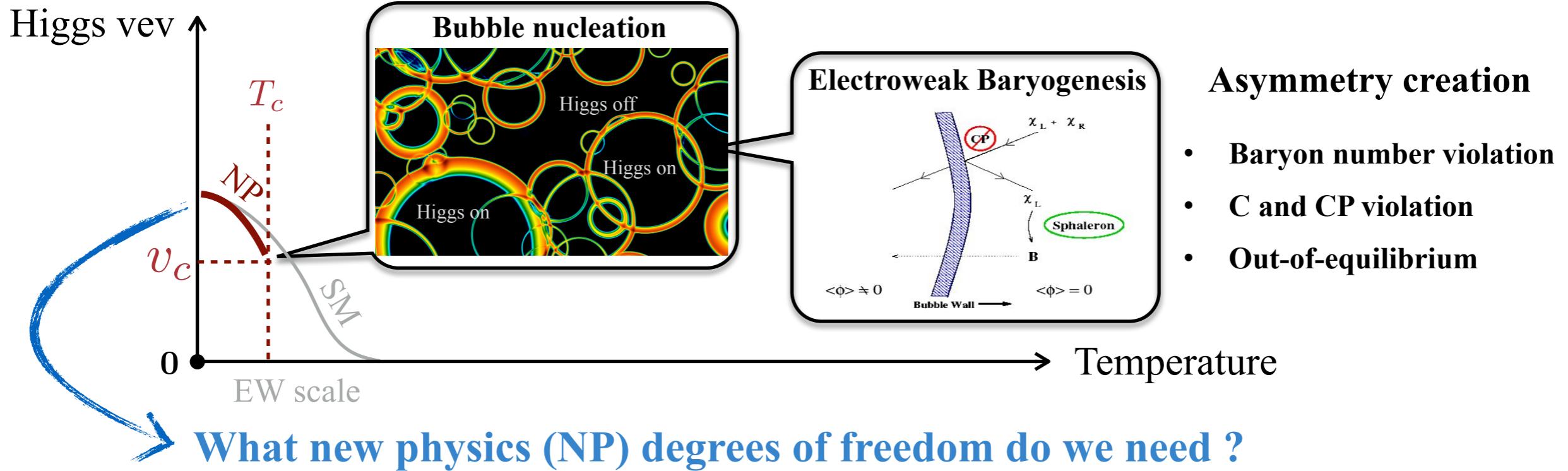
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- Requires departure of Higgs properties from the SM: **Higgs phenomenology**
- Could generate **gravitational wave** signals observable by laboratories

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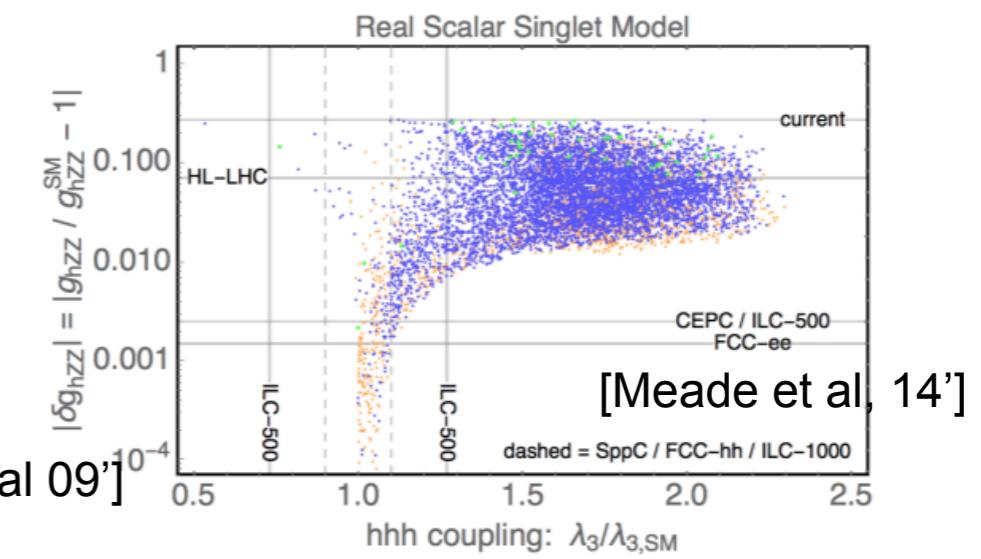
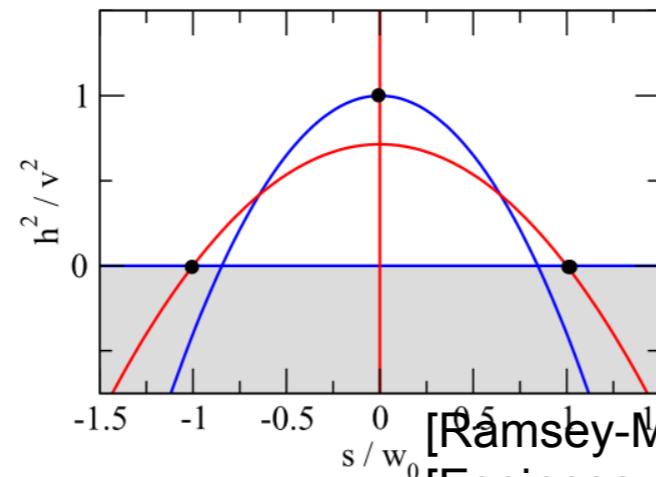
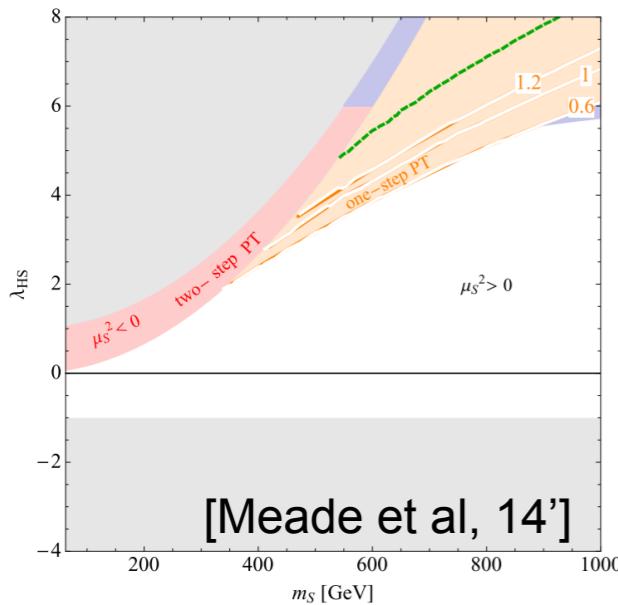
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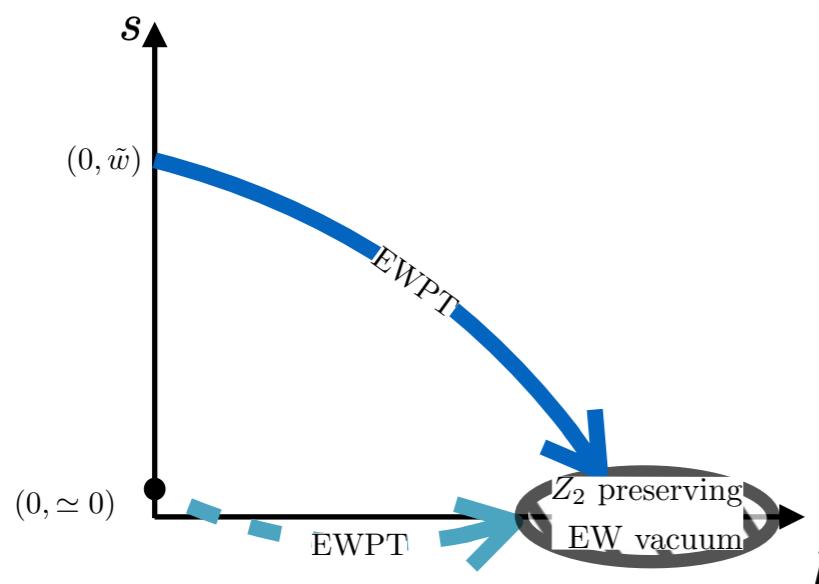
- Requires departure of Higgs properties from the SM: **Higgs phenomenology**
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The singlet extension of the SM

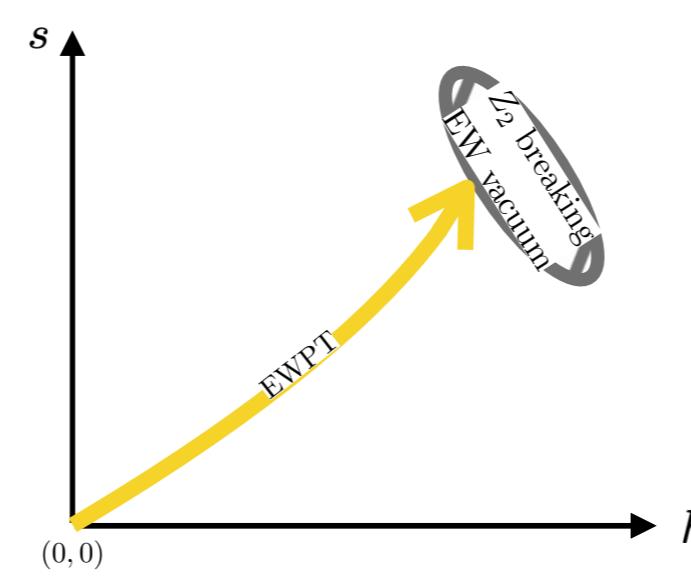
- One of the most generic extensions that can enhance the EWPHT
- An important benchmark as the most elusive extension



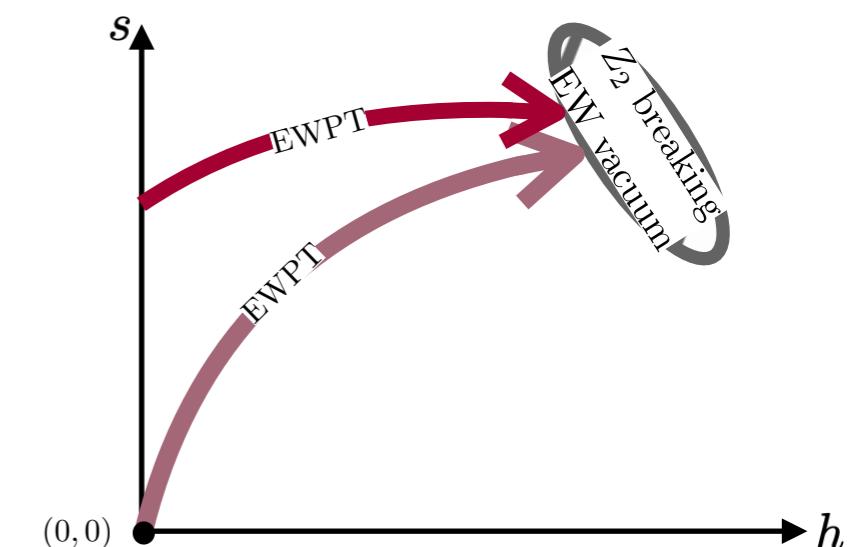
$$V_0(h, s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 + (\text{explicit Z2 - breaking terms})$$



Z₂ preserving
Tree (loop)

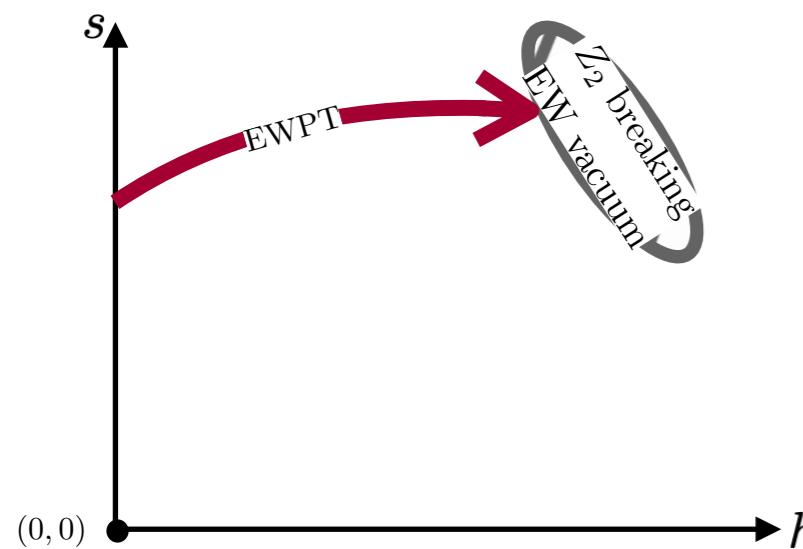


Z₂ breaking (explicit)
Tree



Z₂ breaking (spontaneous)
[Carena, Liu, YW, 19']

EWPT with spontaneous Z2-breaking

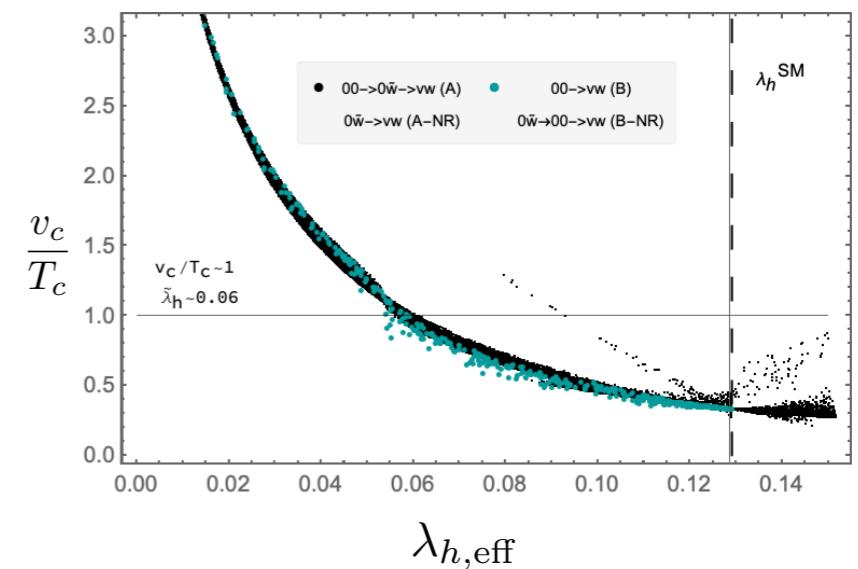


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high-T approximation

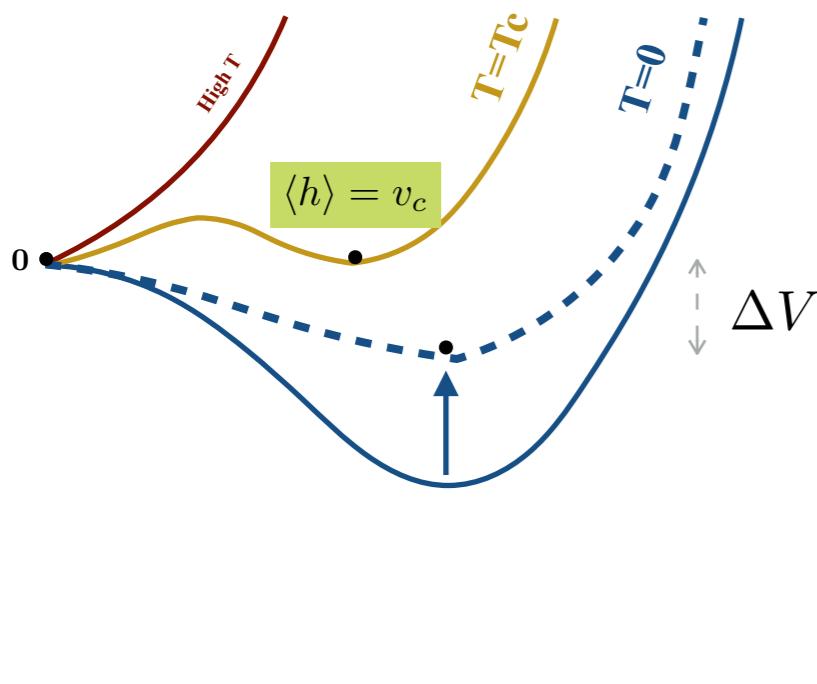
$$\frac{v_c}{T_c} \propto \lambda_{h,\text{eff}}^{-1}$$

with $\lambda_{h,\text{eff}} = \lambda_h - \frac{\lambda_m^2}{4\lambda_s}$



EWPT with spontaneous Z2-breaking

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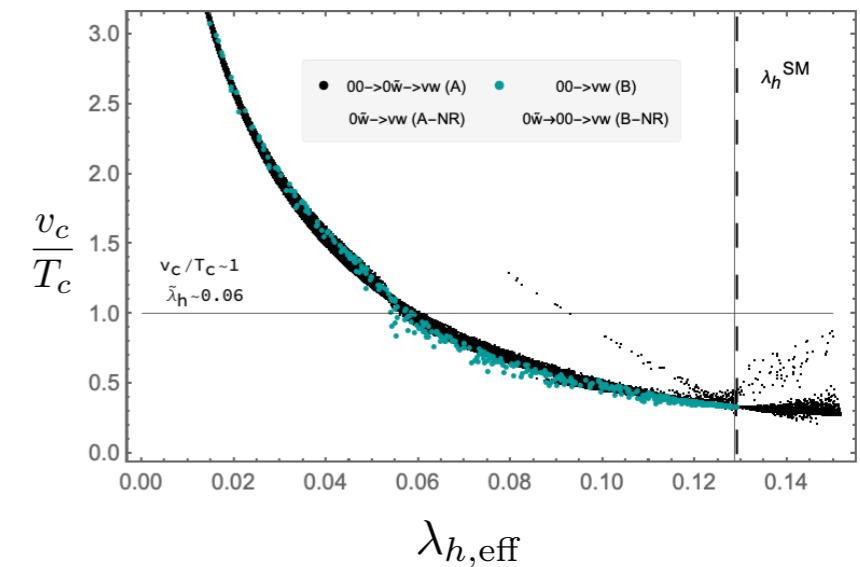


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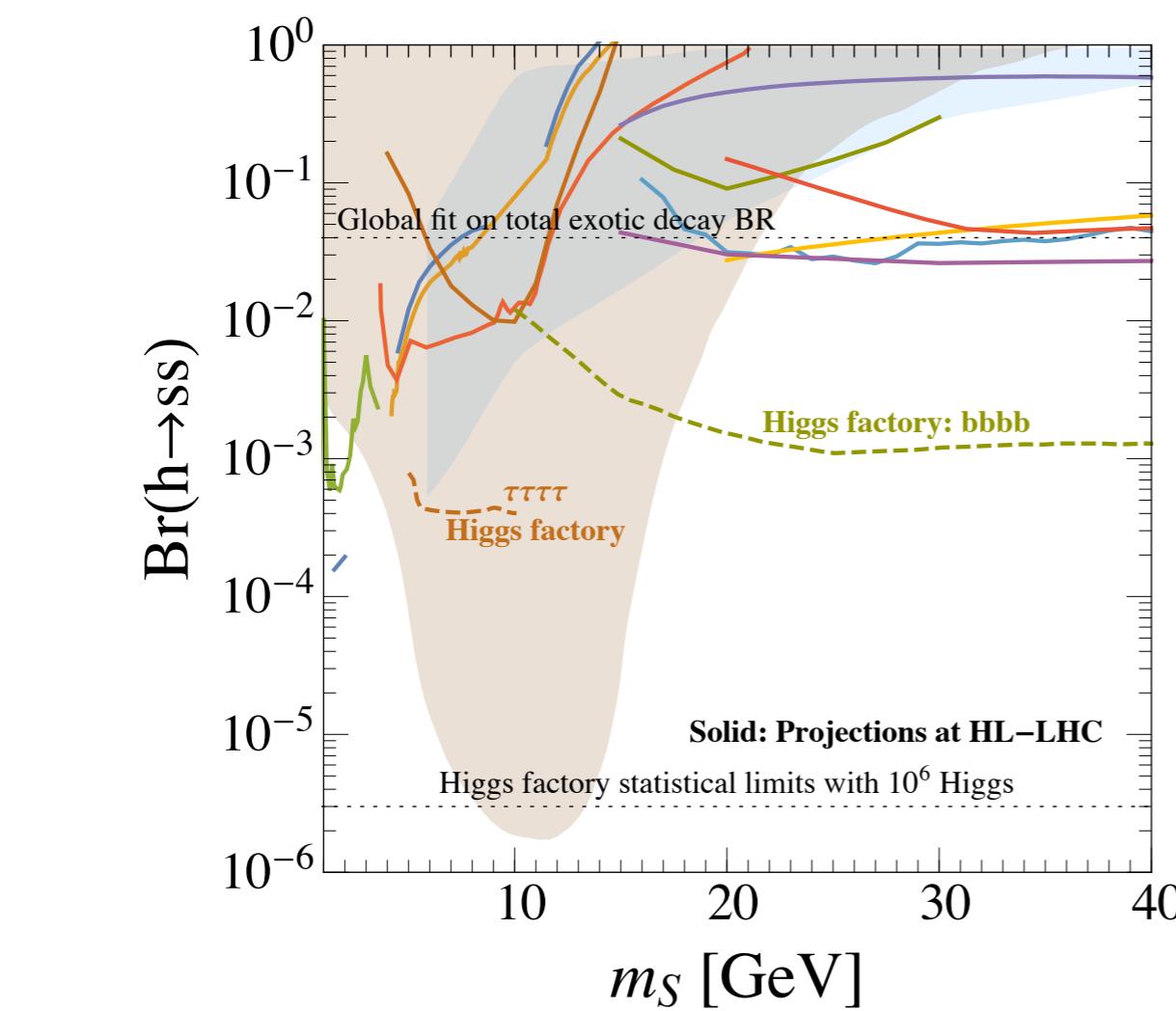
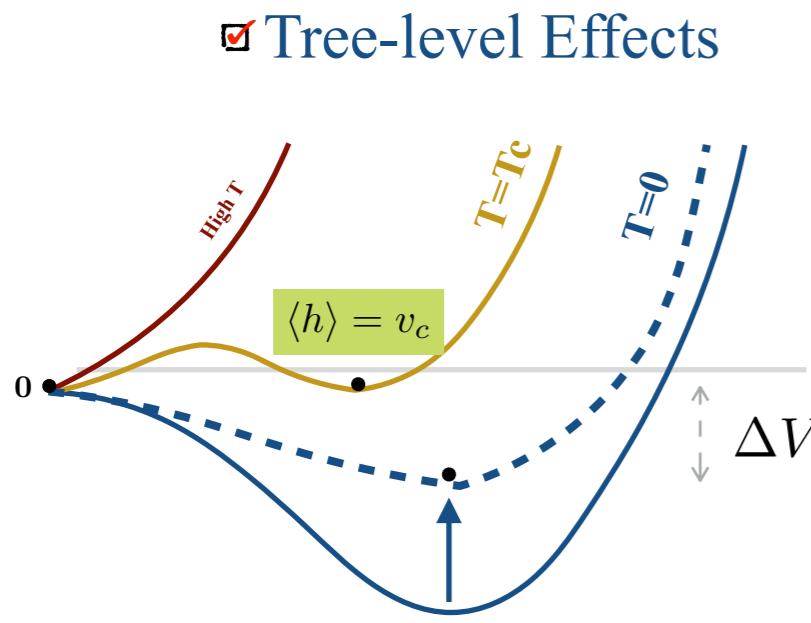
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with $\lambda_{h,\text{eff}} = \lambda_h - \frac{\lambda_m^2}{4\lambda_s}$

$$\frac{v_c}{T_c} \propto 1 + \sin^2 \theta \left(\frac{(125 \text{ GeV})^2}{m_S^2} - 1 \right)$$

- $\sin \theta \lesssim 0.4$ bounded by Higgs precision measurements
- A firm prediction of a light scalar
- $\text{BR}(H \rightarrow SS)$ to be bounded from below

Higgs exotic decays can be strong probes of such models

[Kozaczuk, et al, 19']

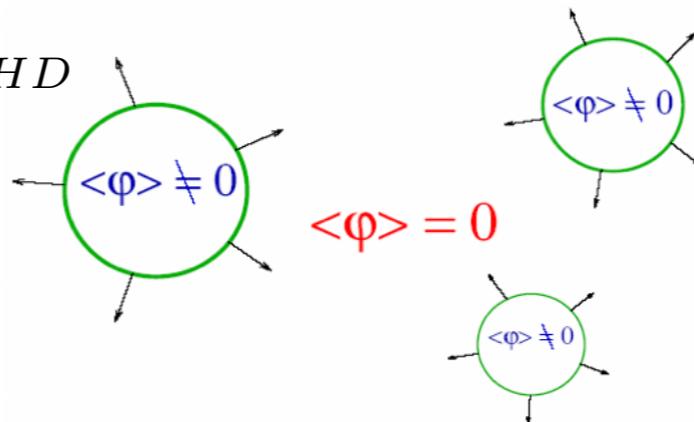
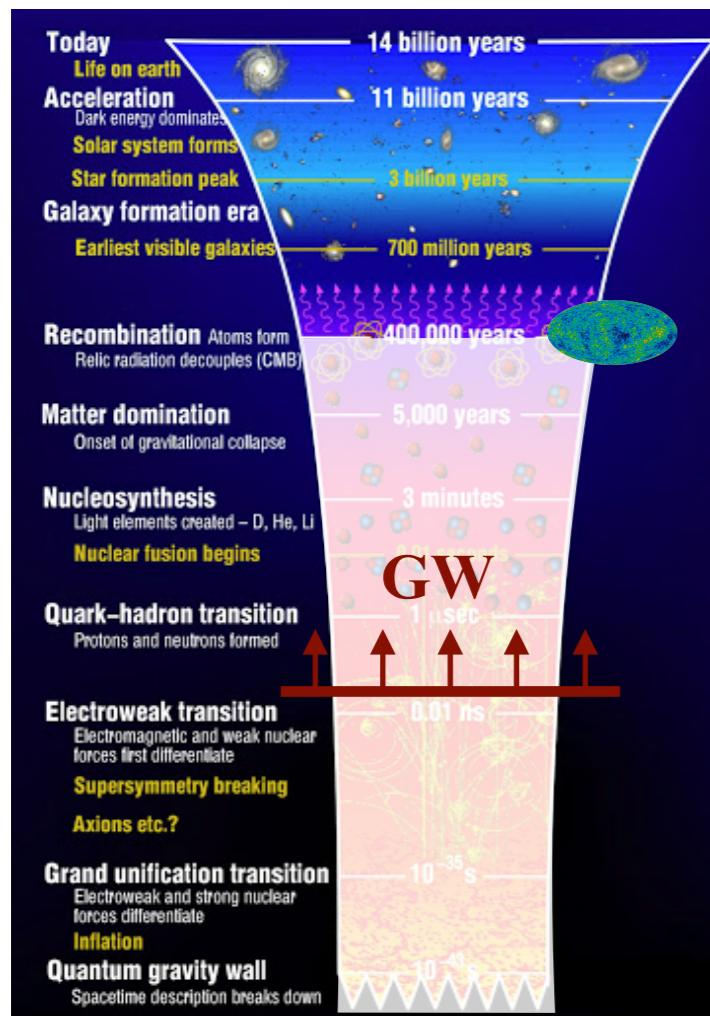
[Carena, et al, 22']

A new probe to SFOEWPT: the gravitational wave signals

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

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

- Bubble collisions
- Sound waves
- Turbulent MHD



Parameters affecting the power spectrum:

- (inverse) duration of the PT

$$\frac{\beta}{H_*} \sim T \left. \frac{d(S_3/T)}{dT} \right|_{T=T_*}$$

- fraction of vacuum energy released w.r.t. the radiation bath

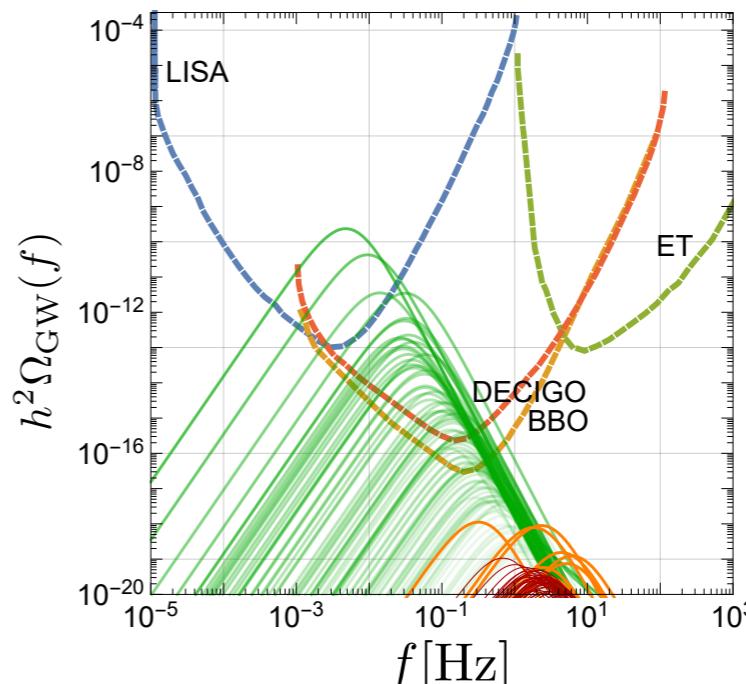
$$\alpha = \frac{\rho_{\tilde{v},\tilde{w}} - \rho_{v,w}}{\rho_{rad}} \Big|_{T=T_*}$$

- The bubble wall velocity v_w

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

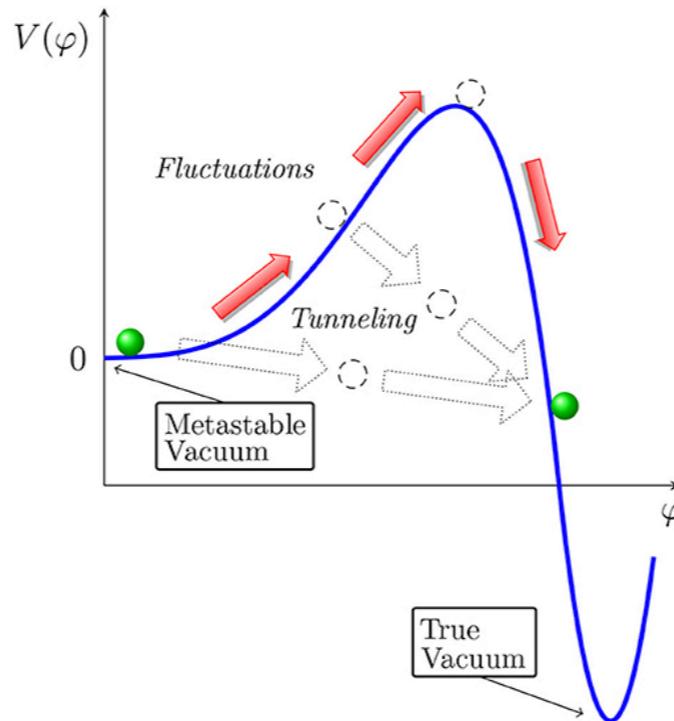
$$h^2 \Omega_{env}(f) = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta} \right)^2 \left(\frac{\kappa \alpha}{1 + \alpha} \right)^2 \left(\frac{100}{g_*} \right)^{\frac{1}{3}} \left(\frac{0.11 v_w^3}{0.42 + v_w^2} \right) S_{env}(f)$$

Power spectrum of GWs from a SFOEWPT

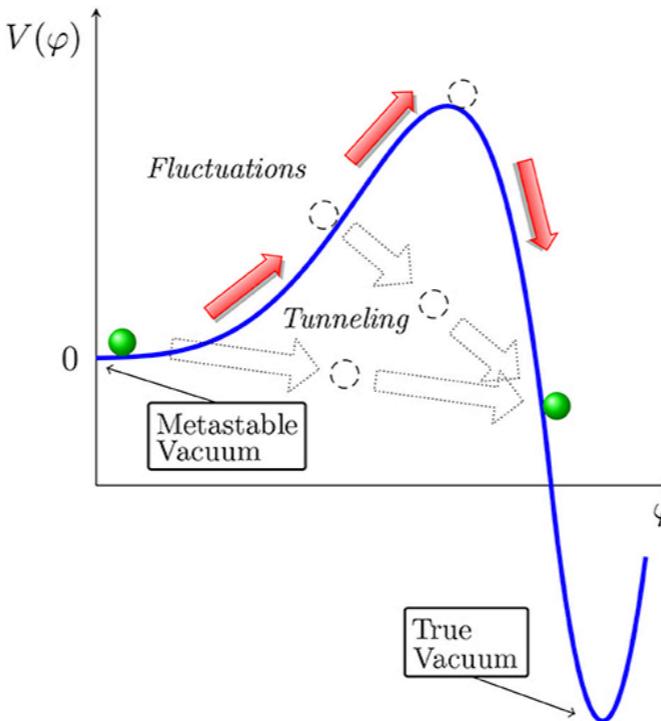


Nucleation is more than critical - NMSSM

Nucleation is more than critical - NMSSM



Nucleation is more than critical - NMSSM



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

both charged under the EW gauge group

The **NMSSM** potential

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

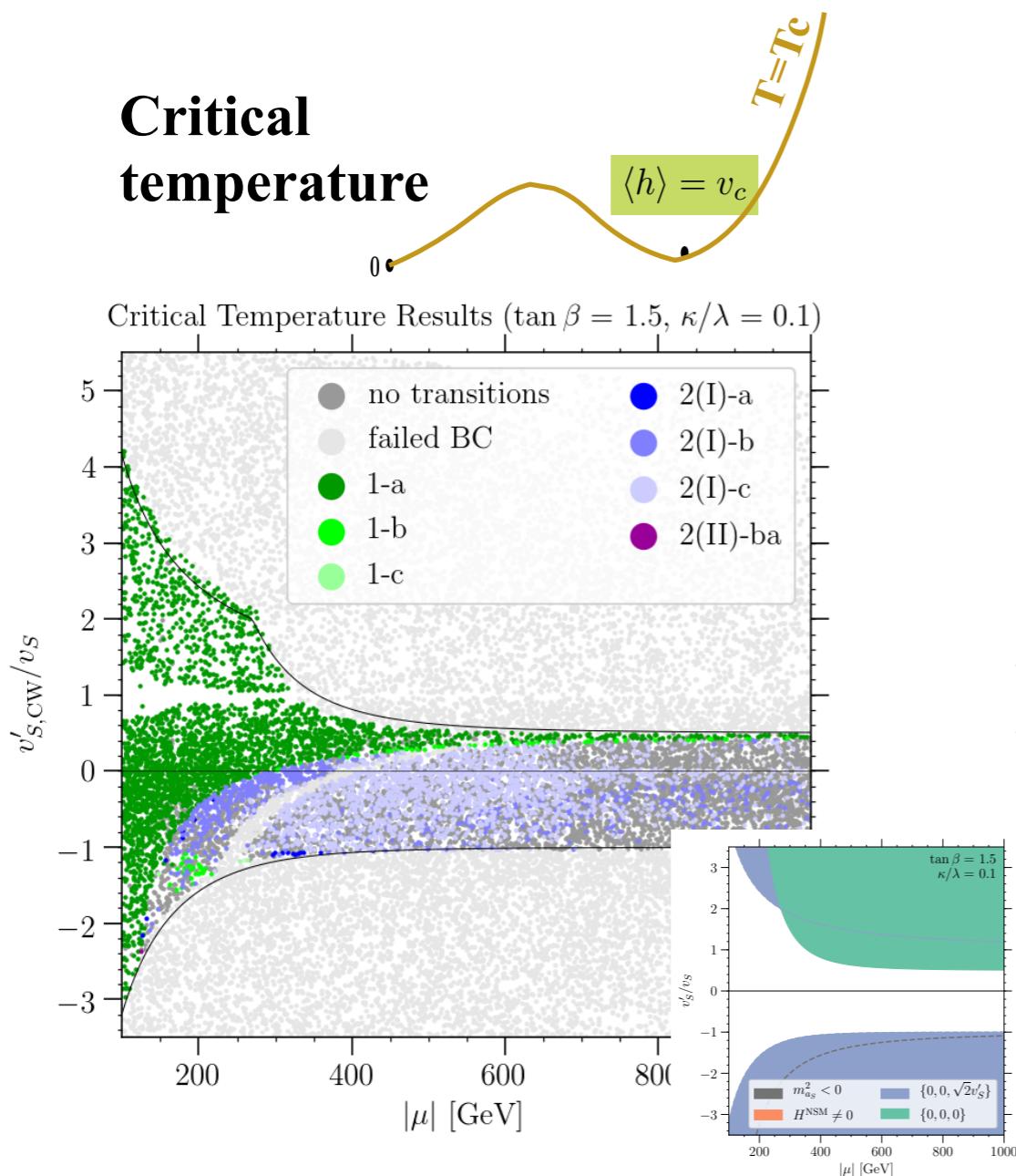
provide flexibility enhancing the PT strength

Nucleation is more than critical - NMSSM

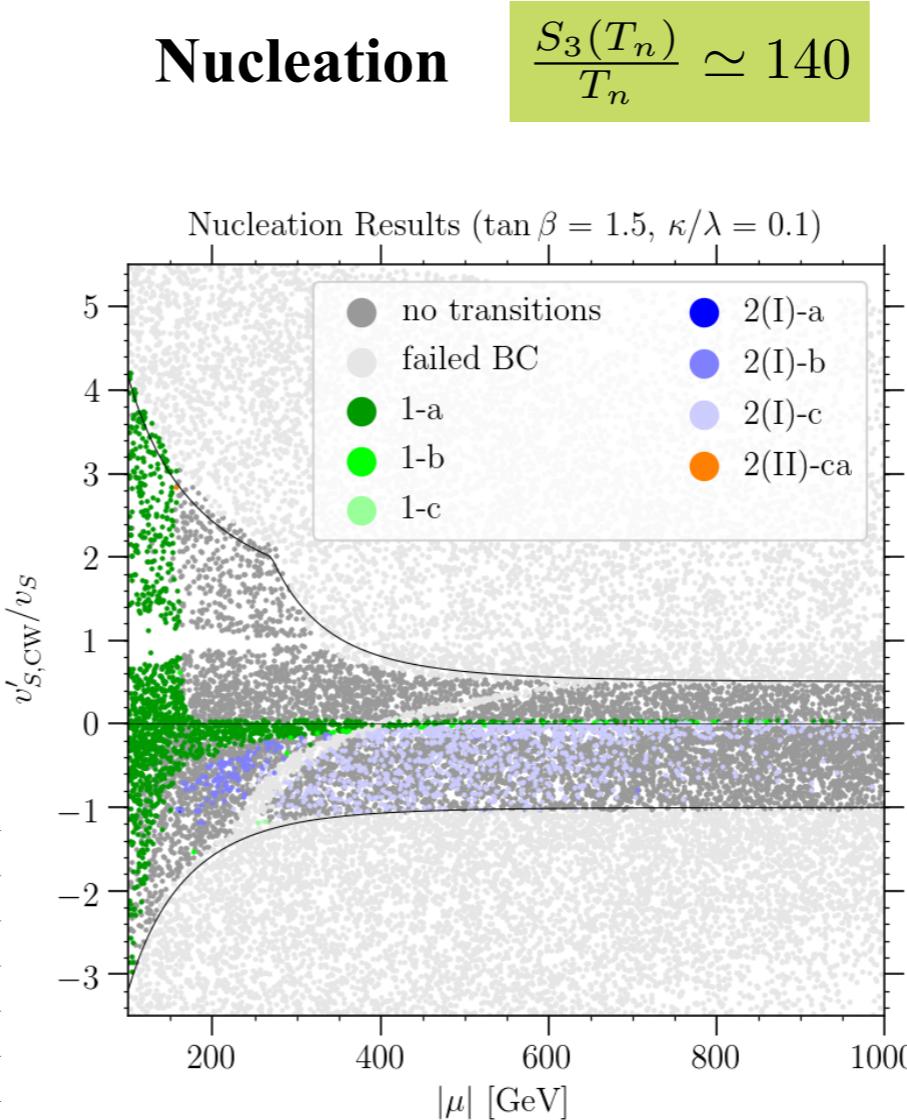
[Baum, Carena, Shah,

Wagner, Y.W '19]

Critical temperature



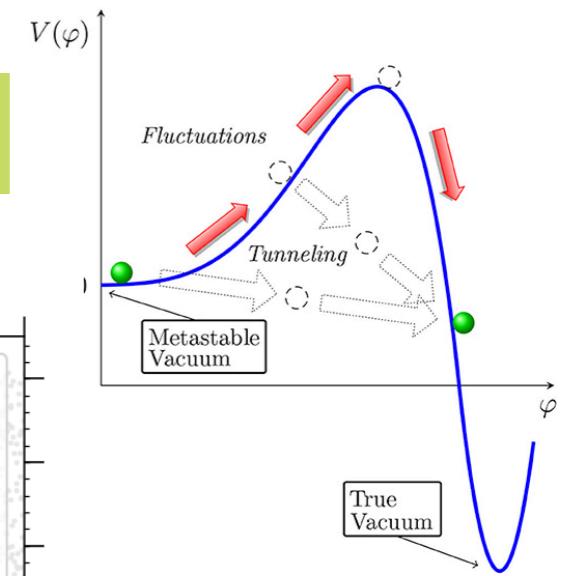
Nucleation



- (Green circle) $(0, 0, 0) \rightarrow (v, 0, v_S)$
- (Blue circle) $(0, 0, 0) \rightarrow (0, 0, \tilde{v}_S) \rightarrow (v, 0, v_S)$
- (Orange circle) $(0, 0, 0) \rightarrow (\tilde{v}, \tilde{v}_{\text{NSM}}, 0) \rightarrow (v, 0, v_S)$

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

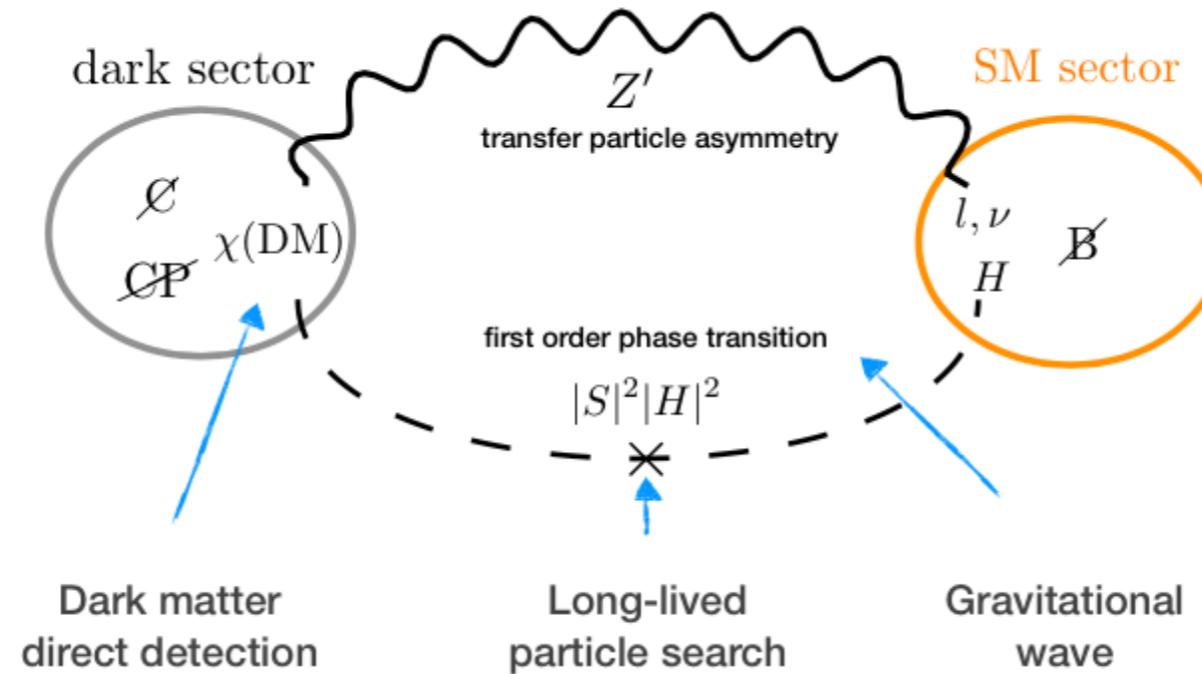
Doublet direction barrier: $m_{H_u}^2 \approx \frac{\mu^2}{\tan^2 \beta} \left(1 - \frac{\kappa}{\lambda} \tan \beta\right) - \frac{m_{h_{125}}^2}{2}$



- 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

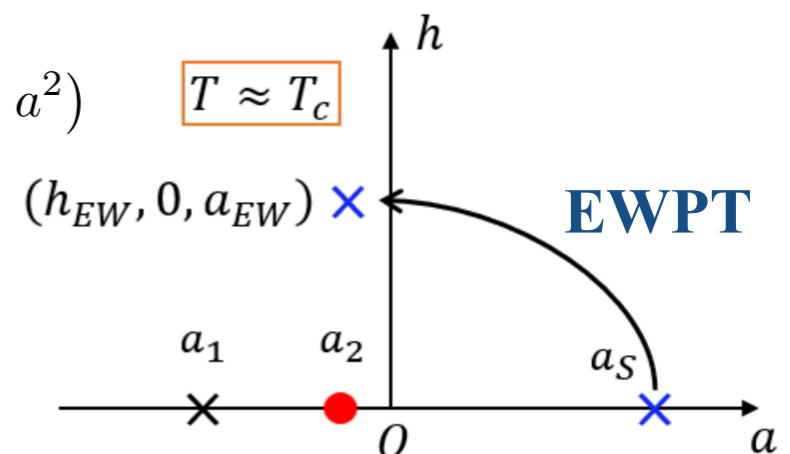
What about CP Violation? Baryogenesis from a dark CPV



[Carena, Quirós, Zhang, '18]
 [Carena, Quirós, Zhang, '19]
 [Carena, Li, Tong, YW, '23]

- **Higgs portal:** sourcing CPV and the phase transition
- **Z' portal:** transfer the particle asymmetry

$$\begin{aligned}
 V(h, s, a, T) = & -\frac{1}{2}\mu_H^2 h^2 + \frac{1}{4}\lambda_H h^4 - \frac{1}{2}\mu_S^2 (s^2 + a^2) + \frac{1}{4}\lambda_S (s^2 + a^2)^2 + \kappa_S^2 (s^2 - a^2) \\
 & + \frac{1}{4}\lambda_{SH} h^2 (s^2 + a^2) \\
 & + \frac{1}{2}T^2 [c_H h^2 + c_S (s^2 + a^2) + A_s s - A_a a]
 \end{aligned}$$

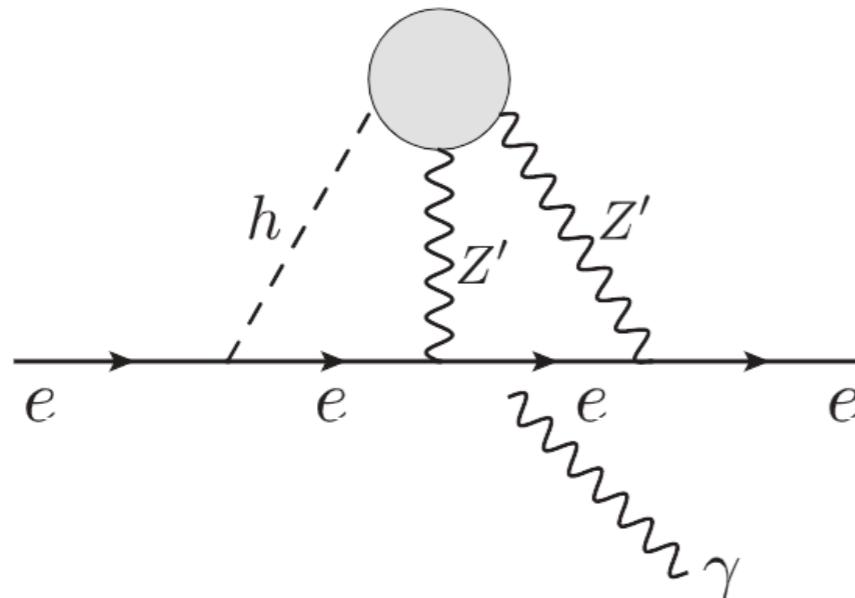


$A_{s,a}$ thermally induced by coupling to a dark fermion χ (dark matter candidate)

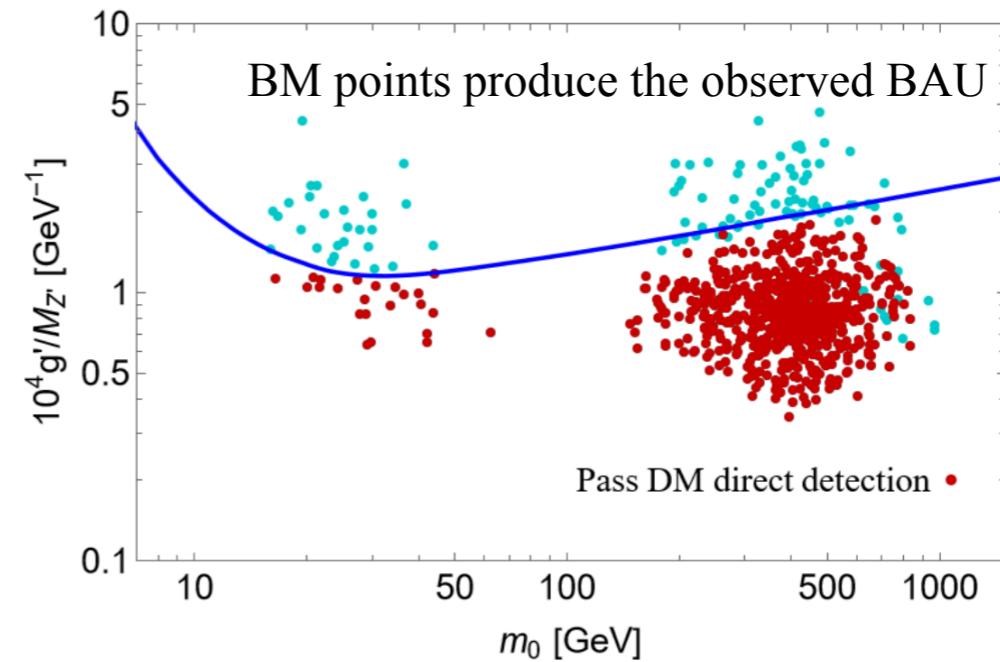
→ $\langle S \rangle \neq 0$ at finite T , that provides an effective barrier

What about CP Violation? Baryogenesis from a dark CPV

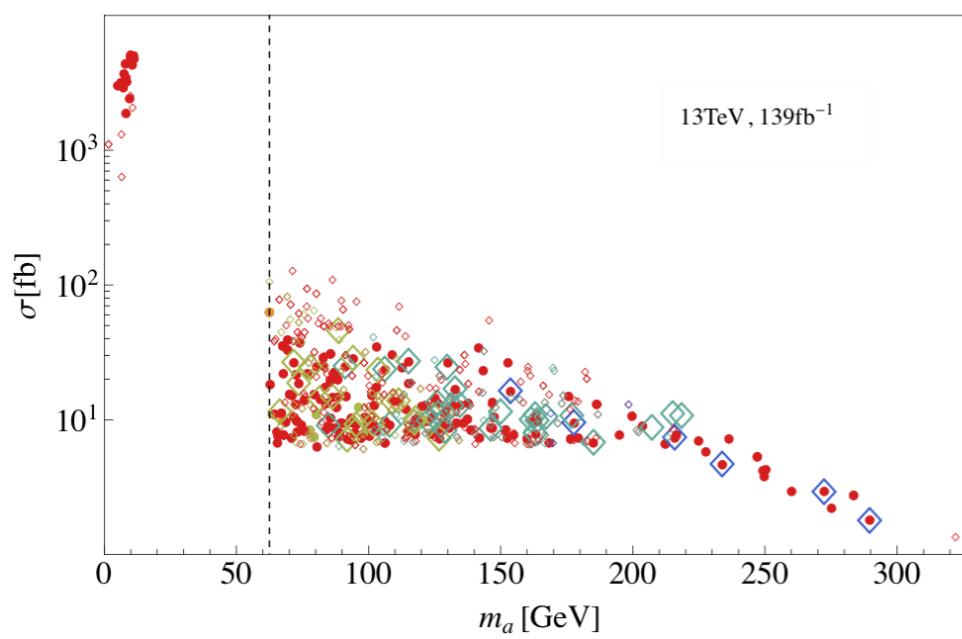
- Loop surprised EDM



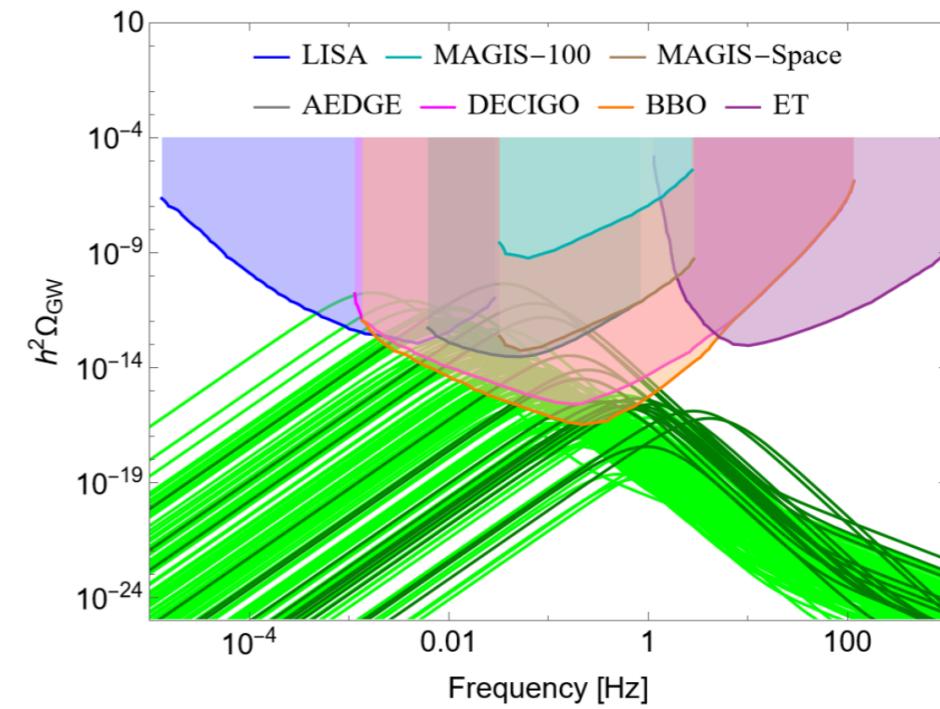
- Dark matter candidate



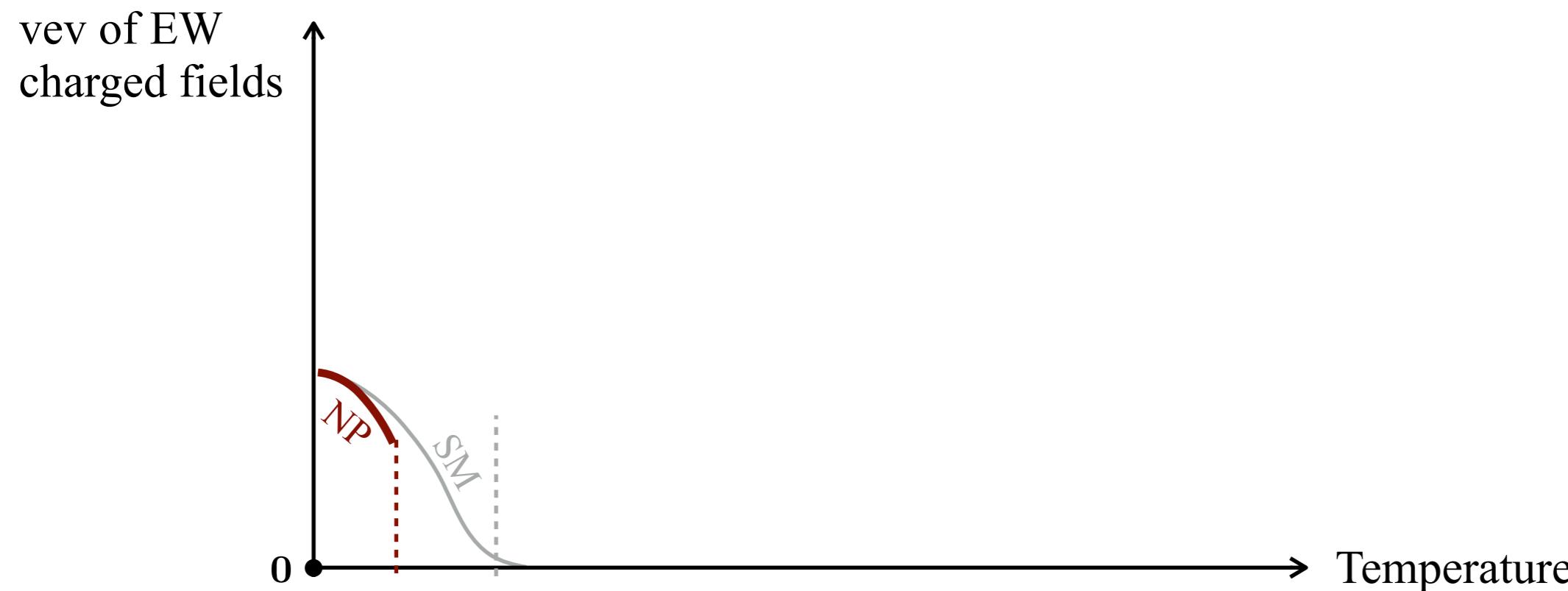
- Singlet search at LHC



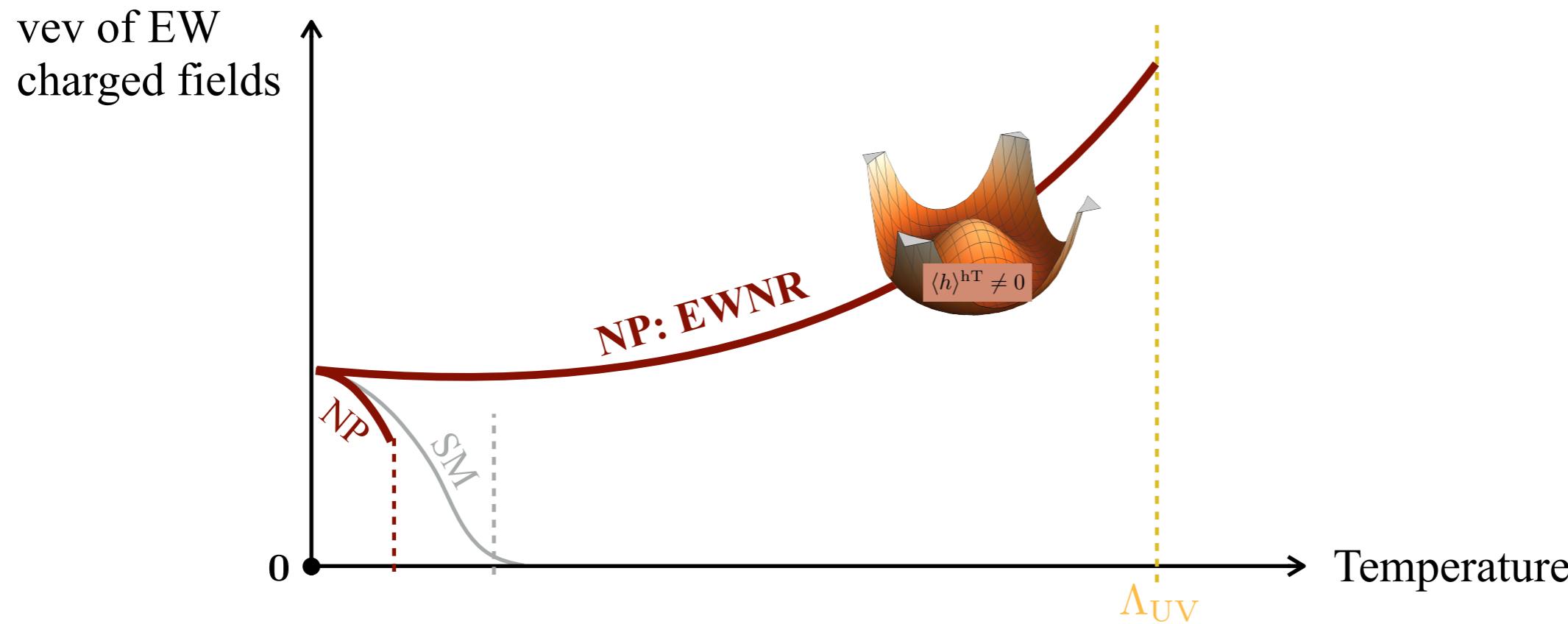
- GW signature



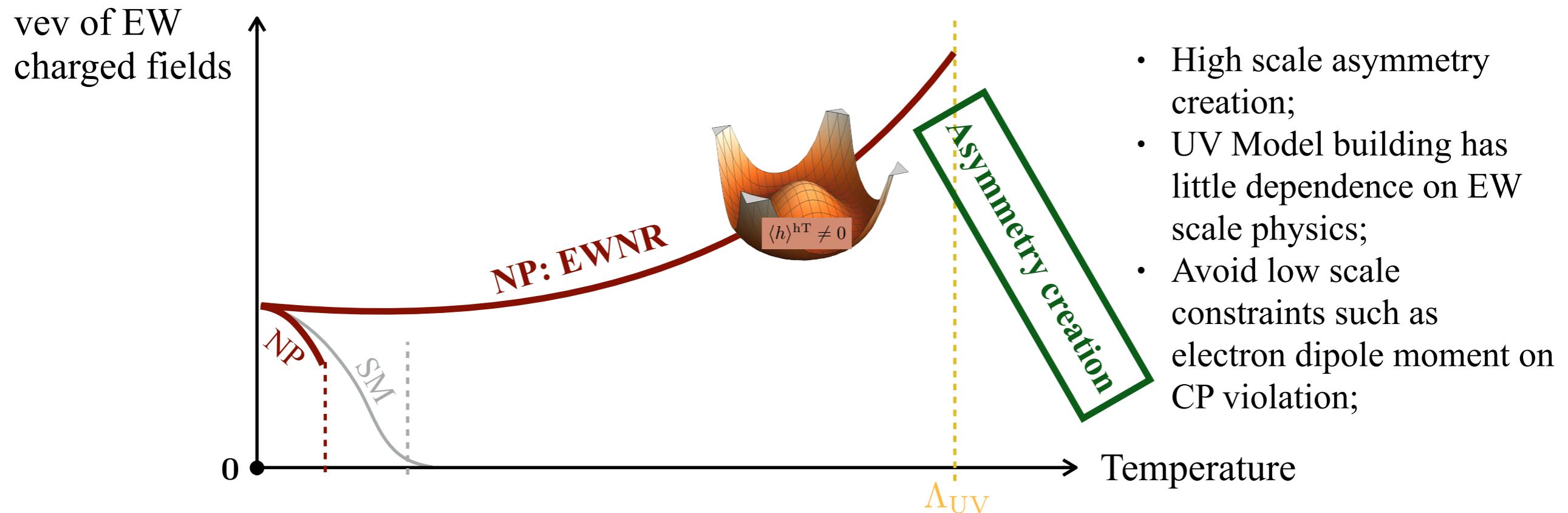
Electroweak symmetry non-restoration



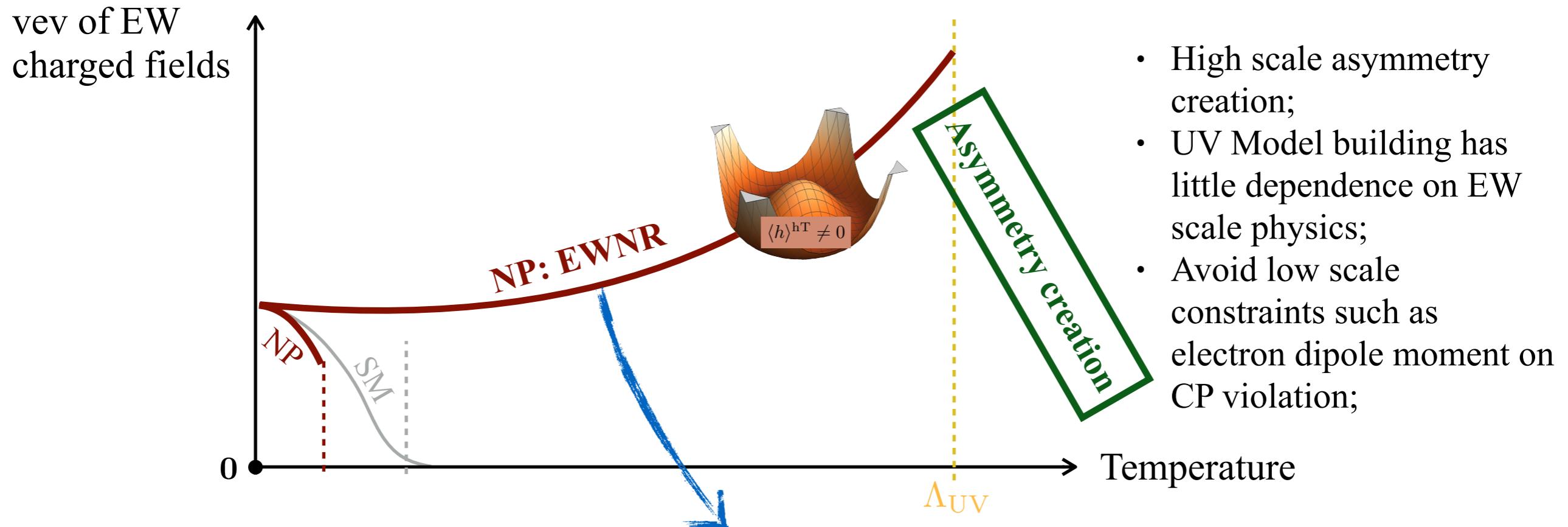
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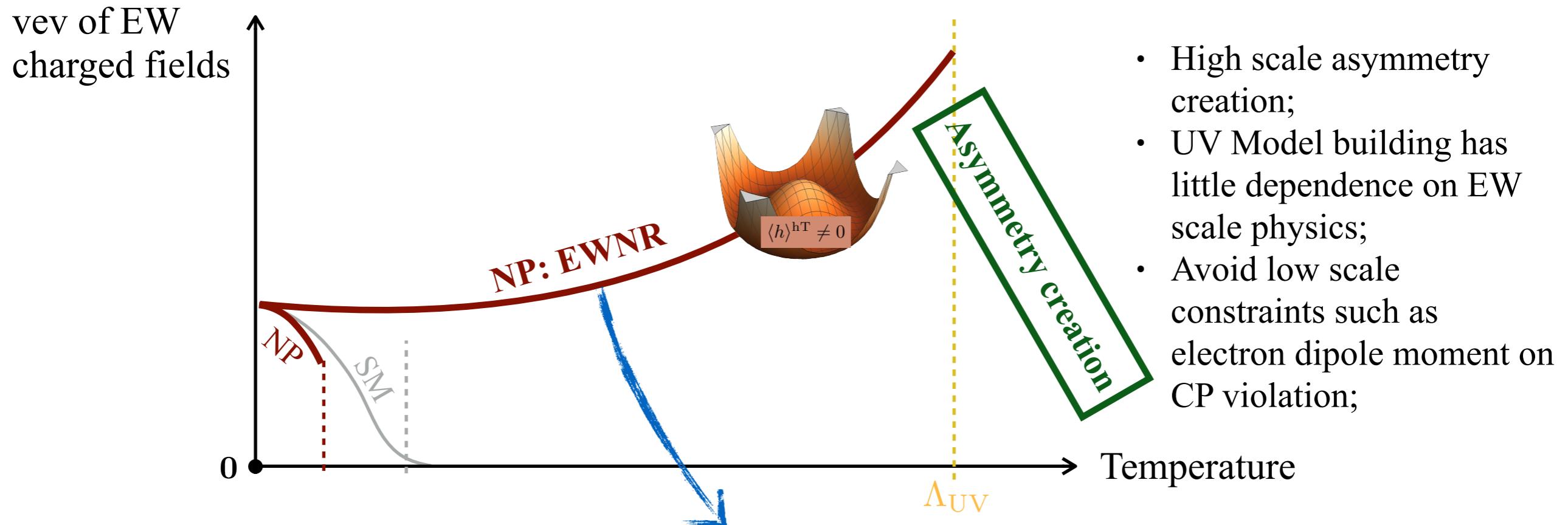
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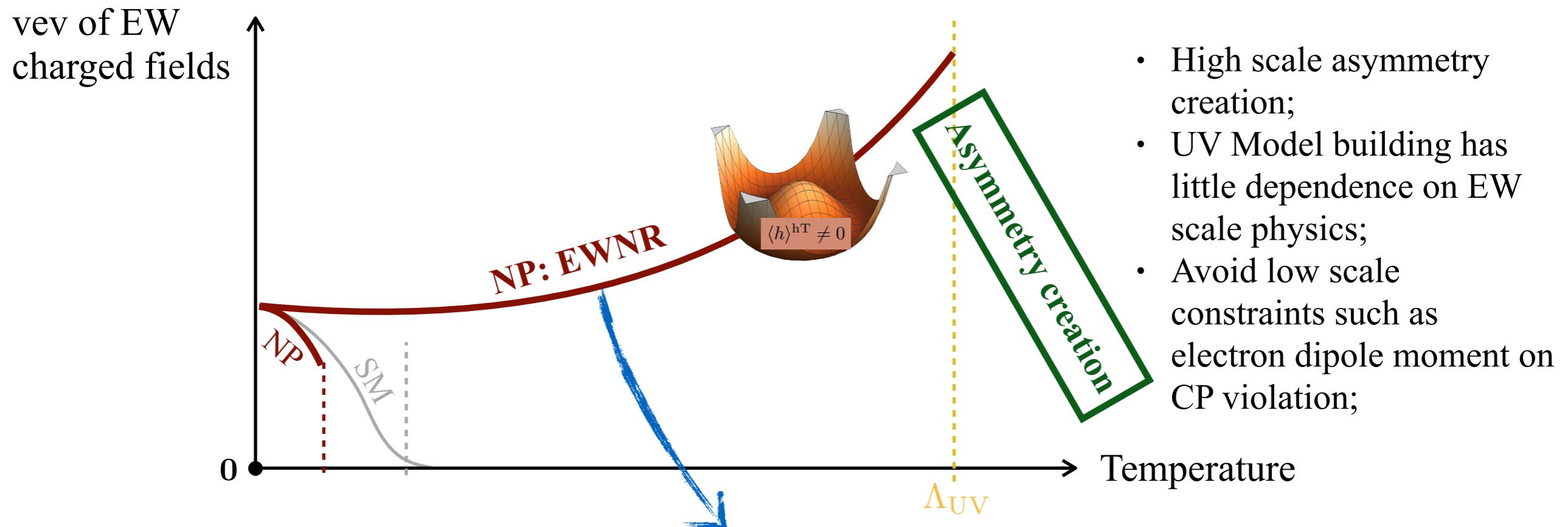
Electroweak symmetry non-restoration



What new physics (NP) degrees of freedom do we need ?

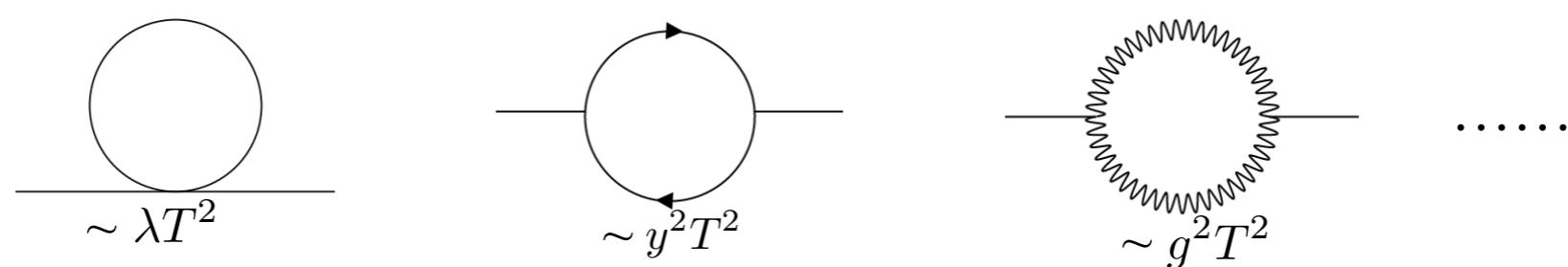
$$V(h, T) \approx c_H (T^2 - T_0^2) h^2 - E T h^3 + \frac{\lambda(T)}{2} h^4 \rightarrow c_H < 0$$

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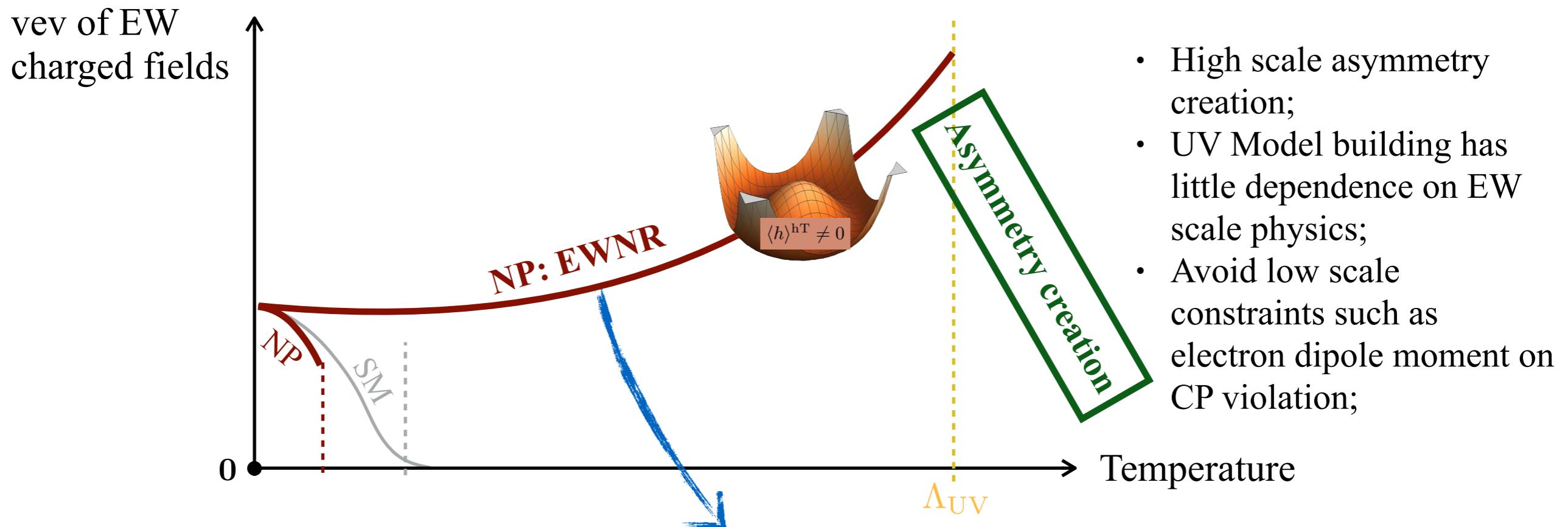


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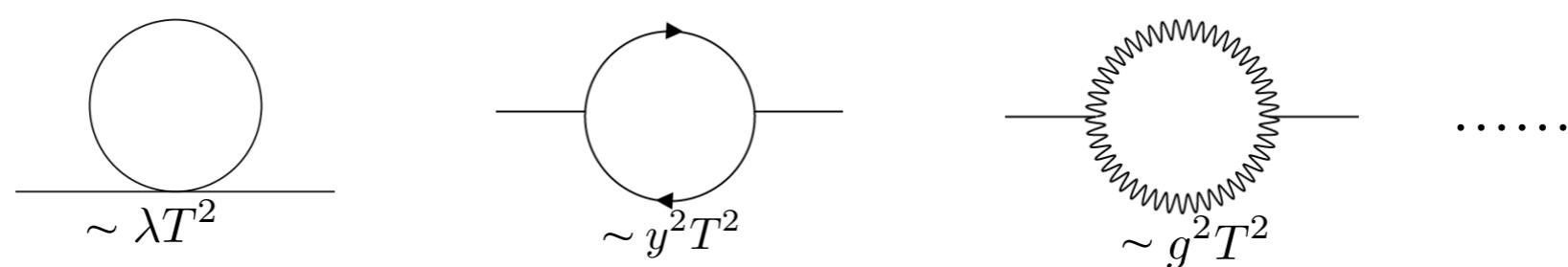


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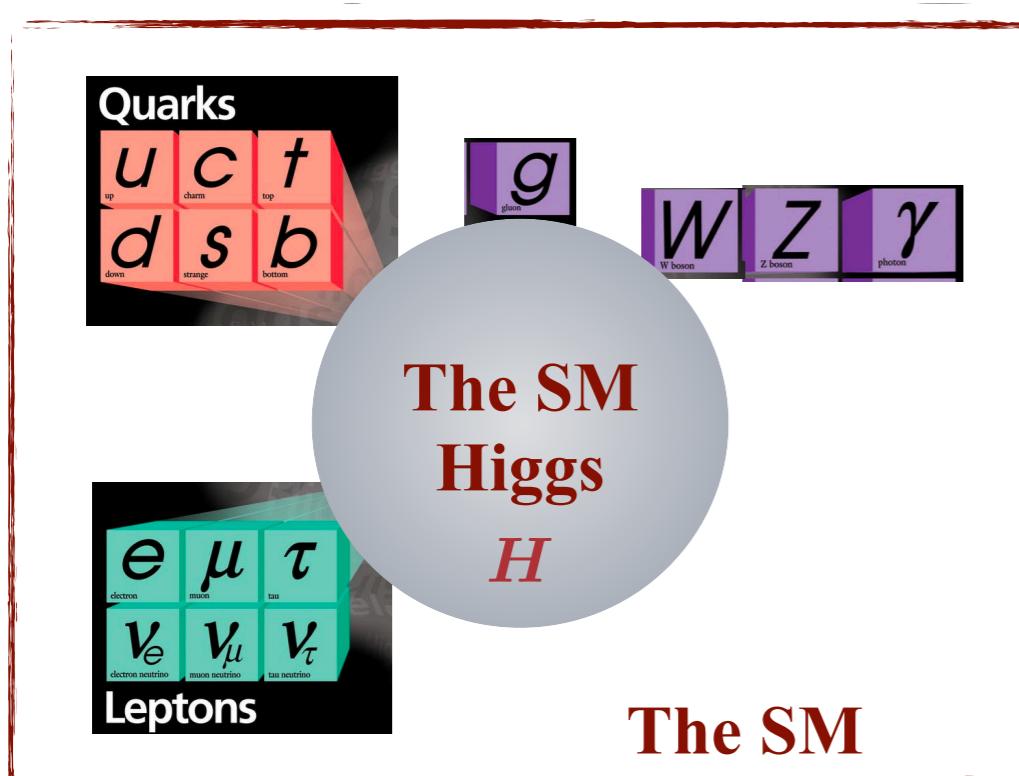
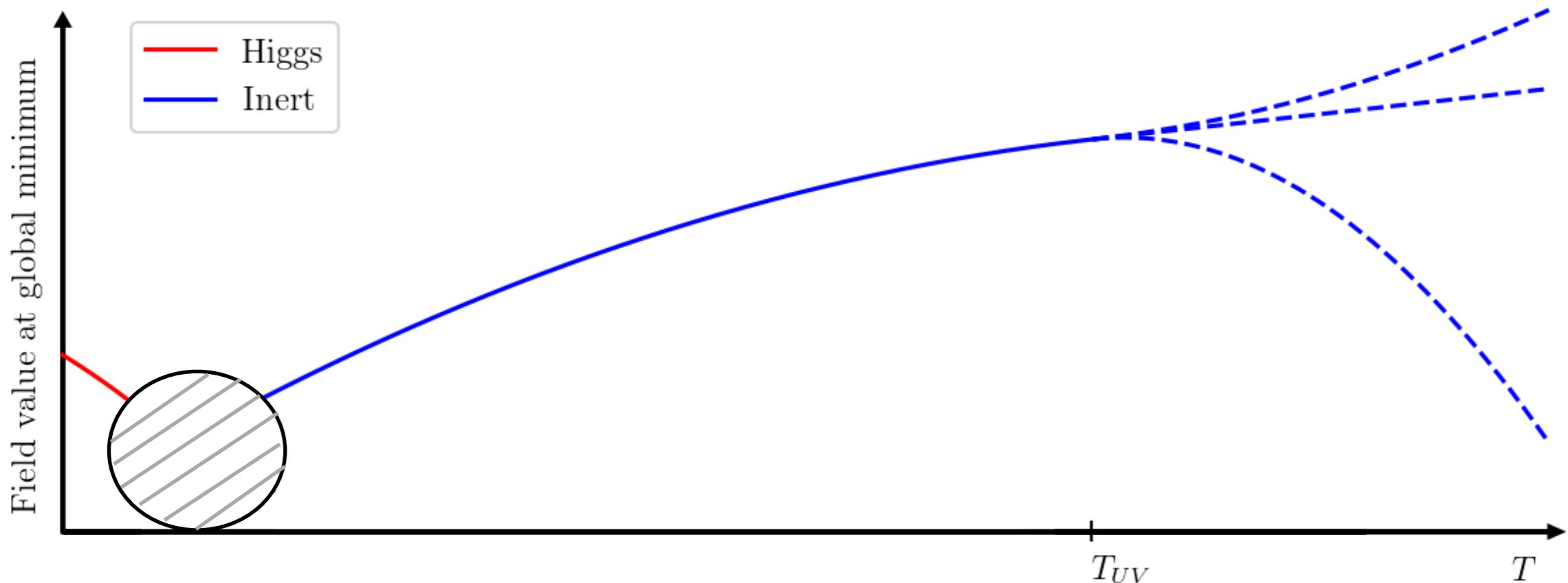
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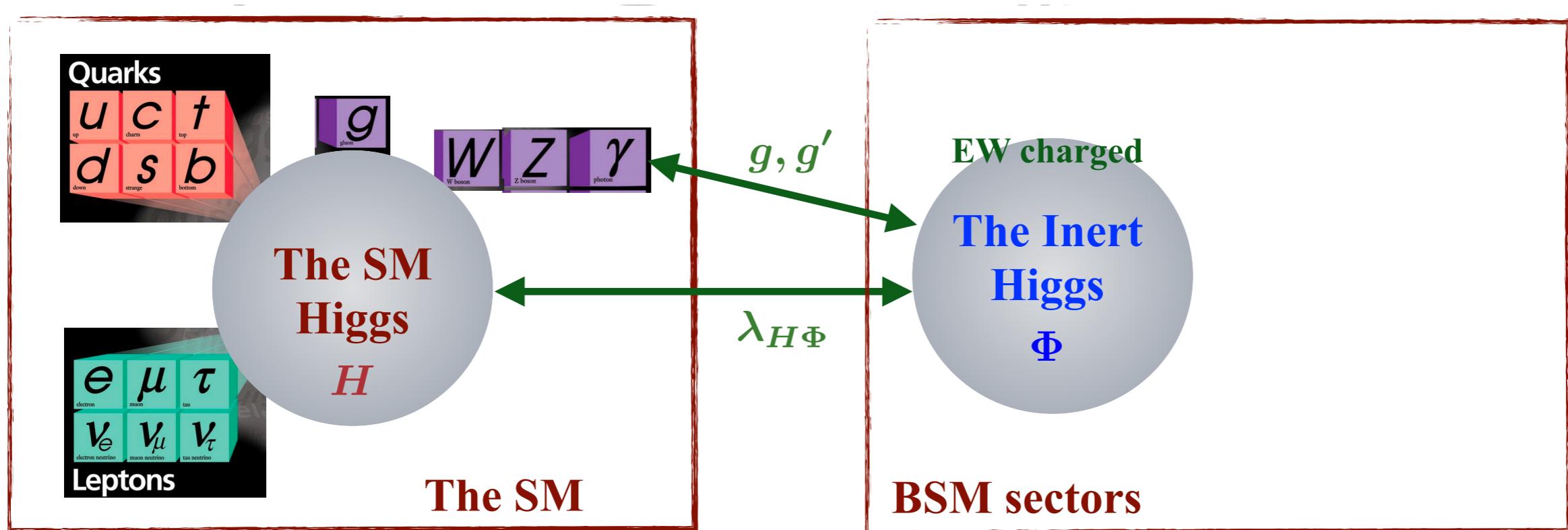
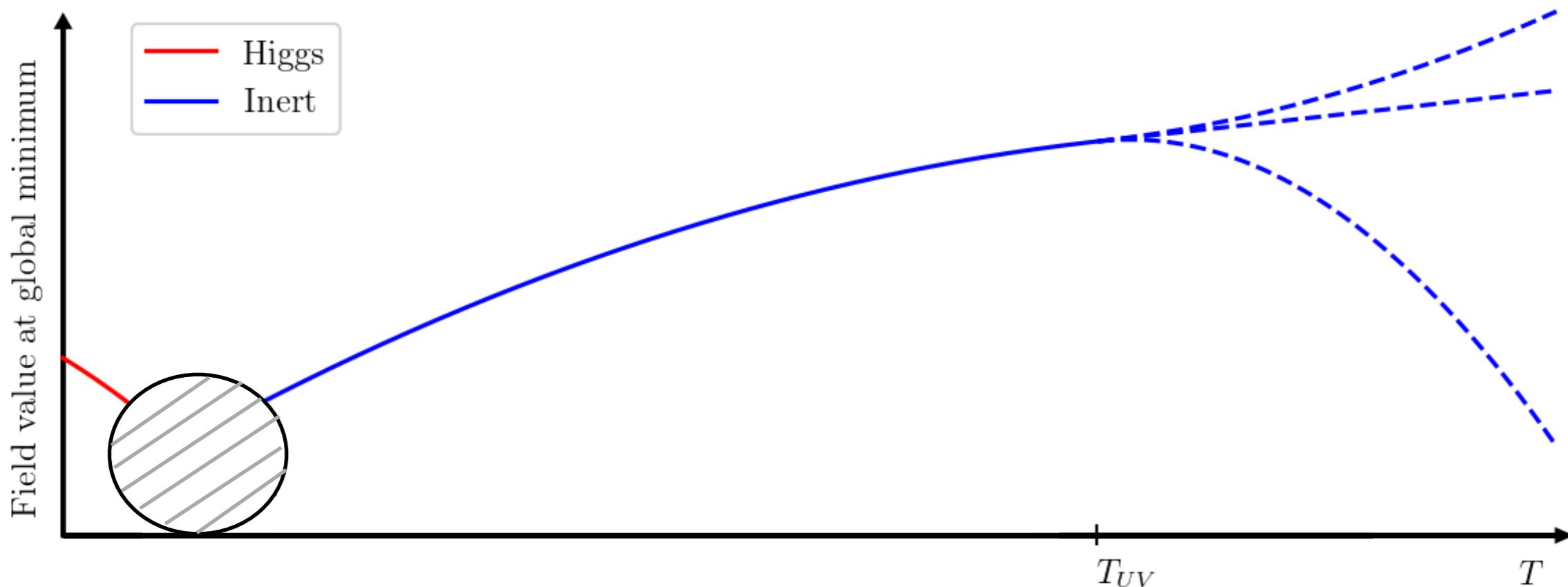
A new approach to EWNR

[Carena, Krause, Liu, YW, '23]



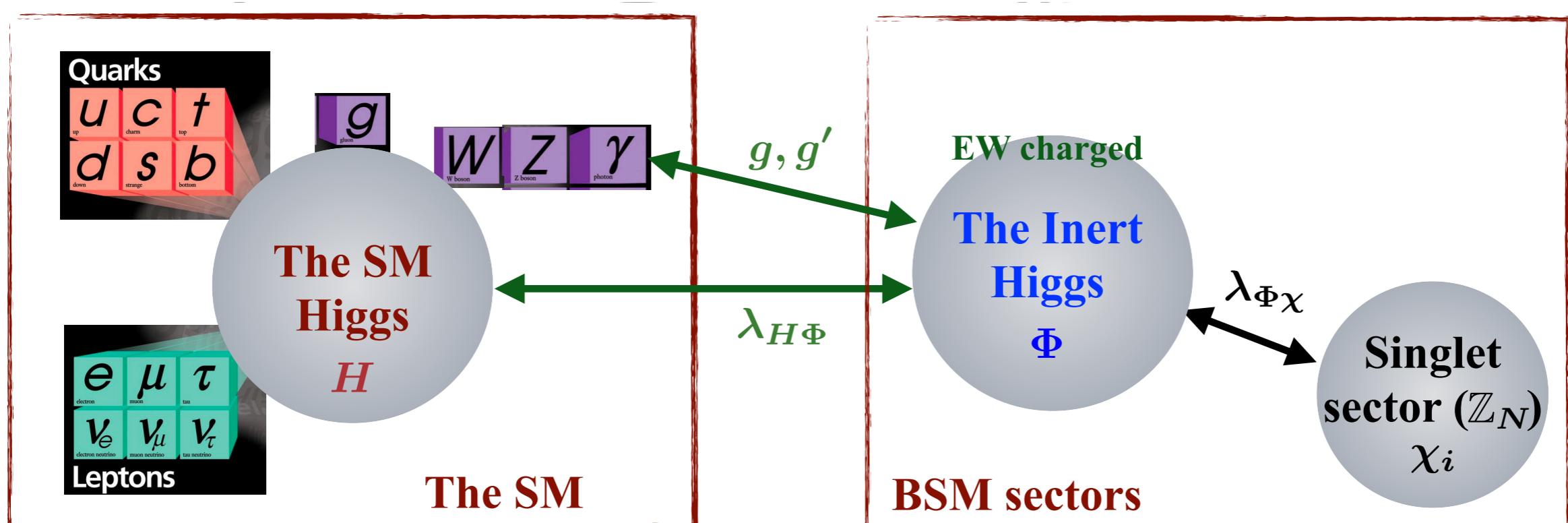
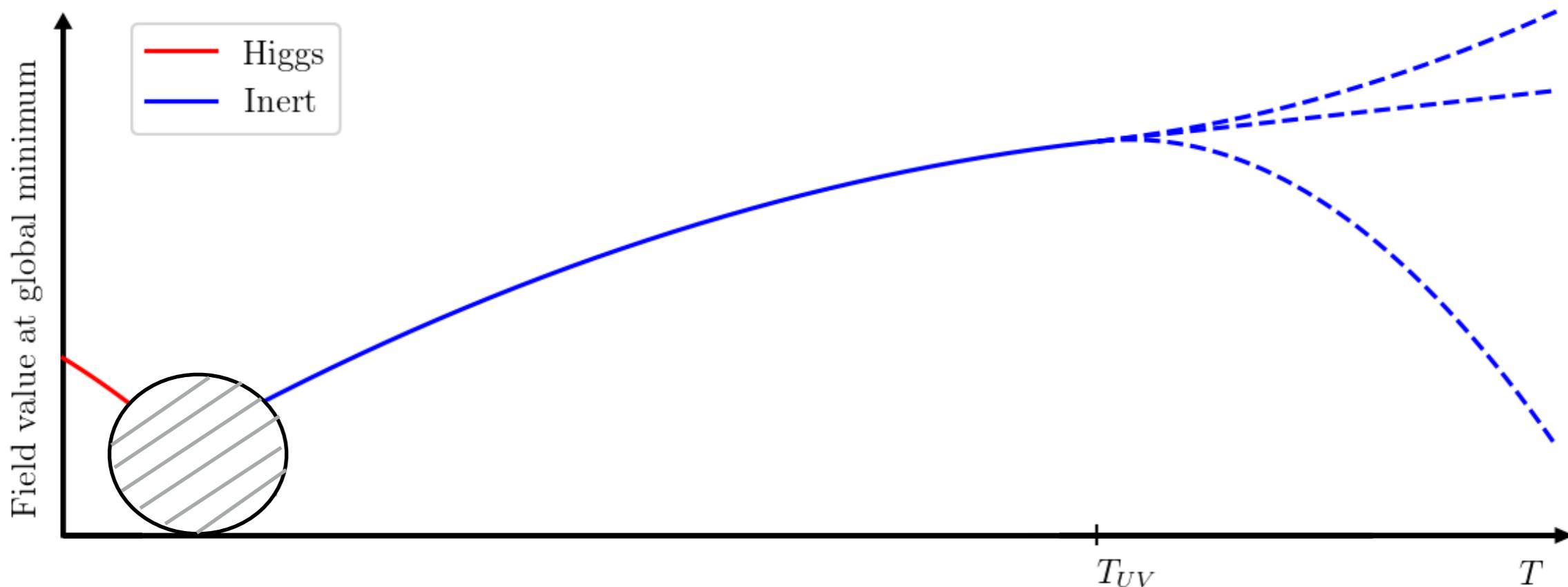
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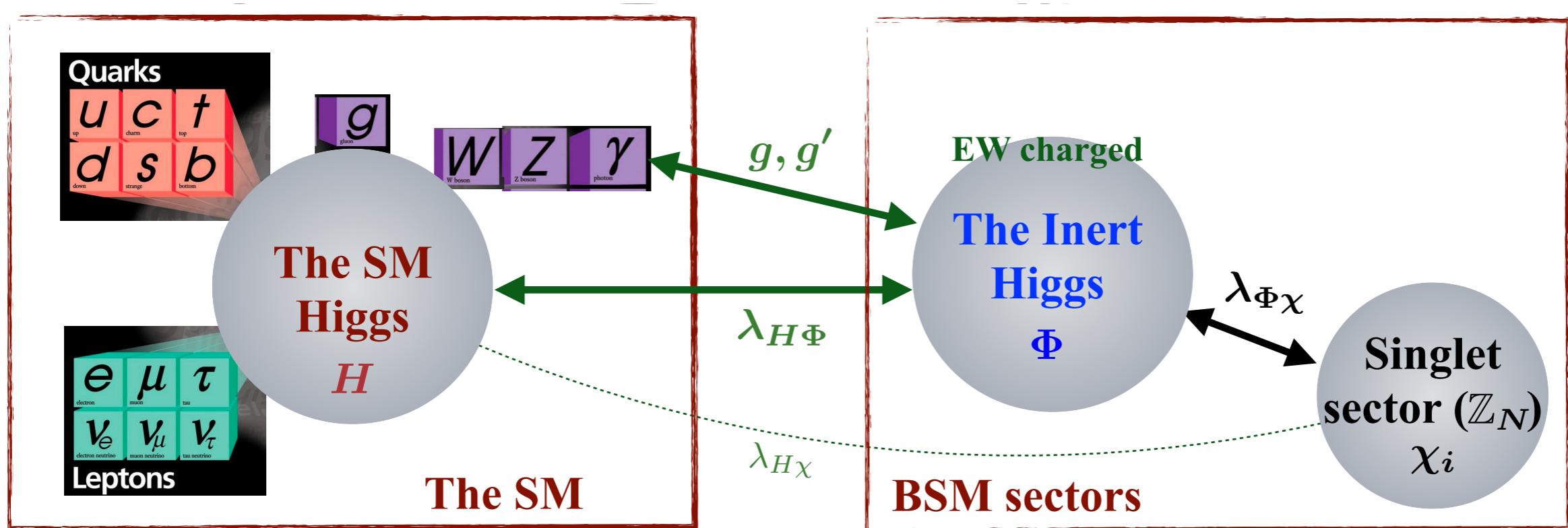
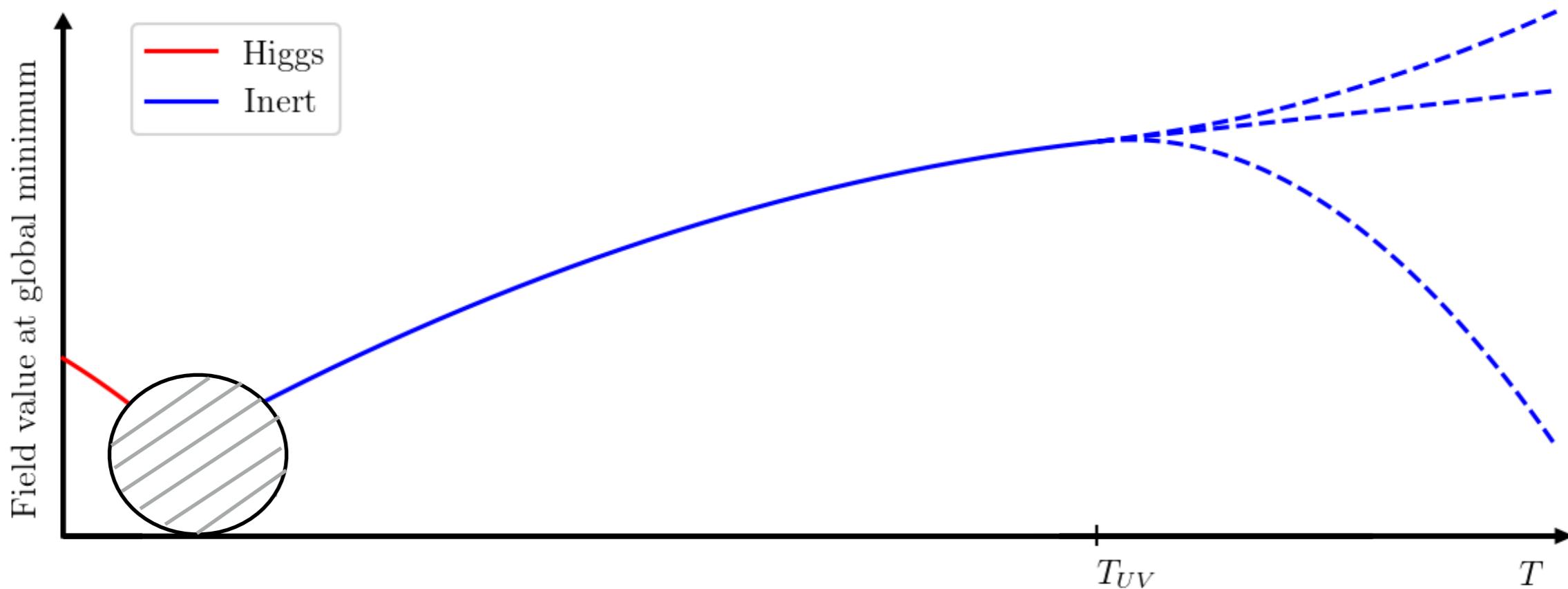
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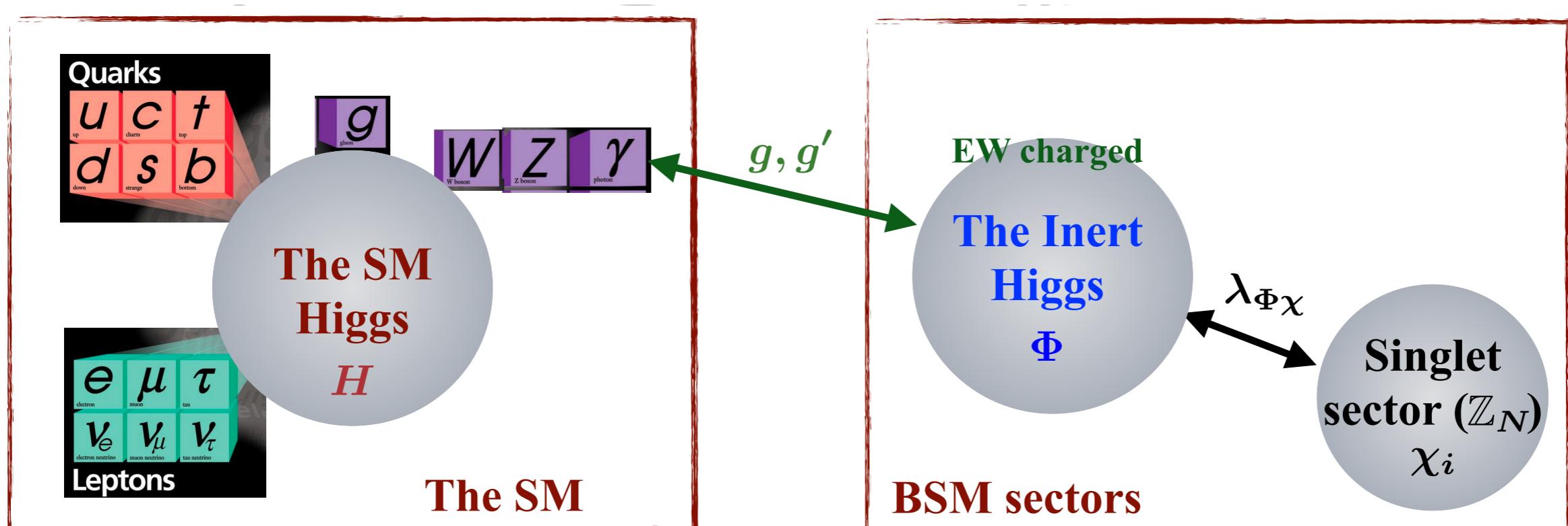
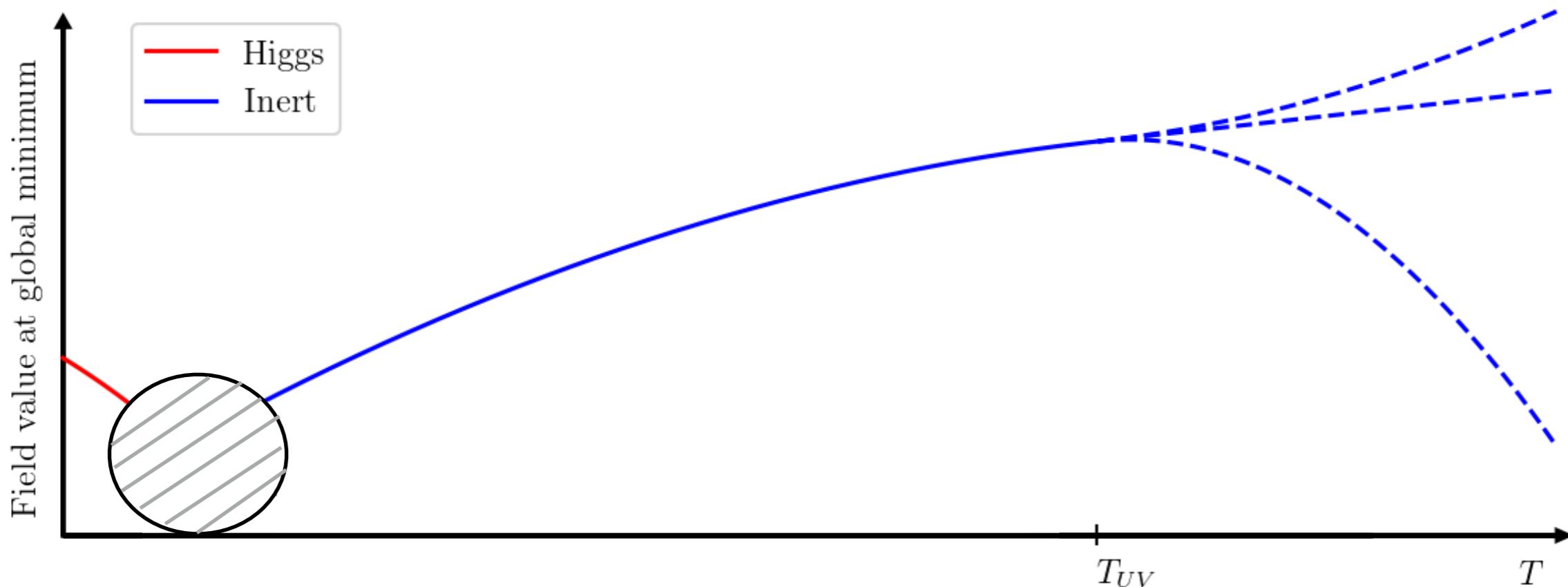
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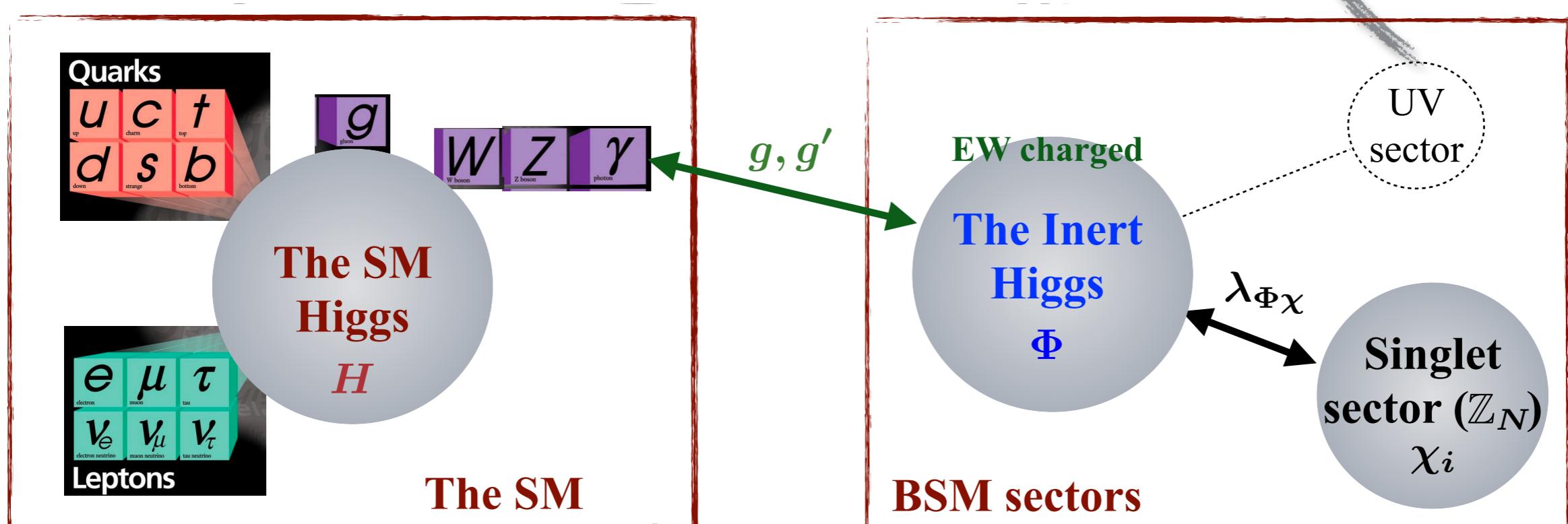
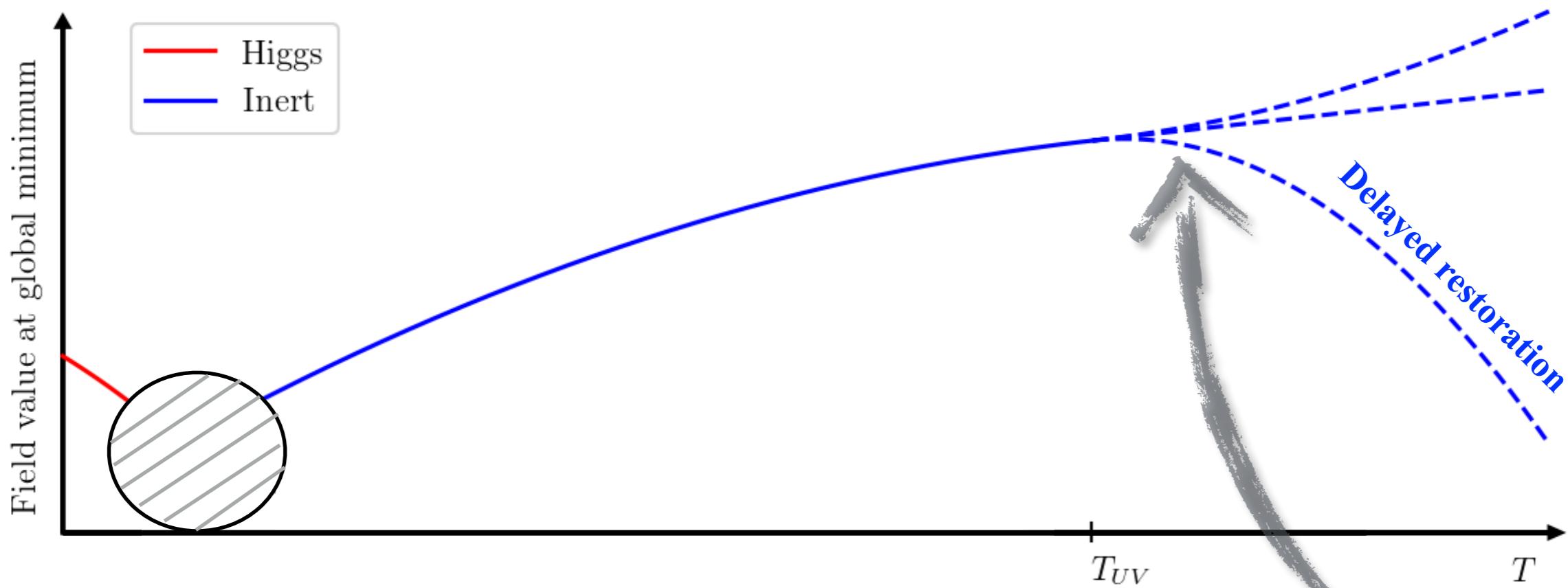
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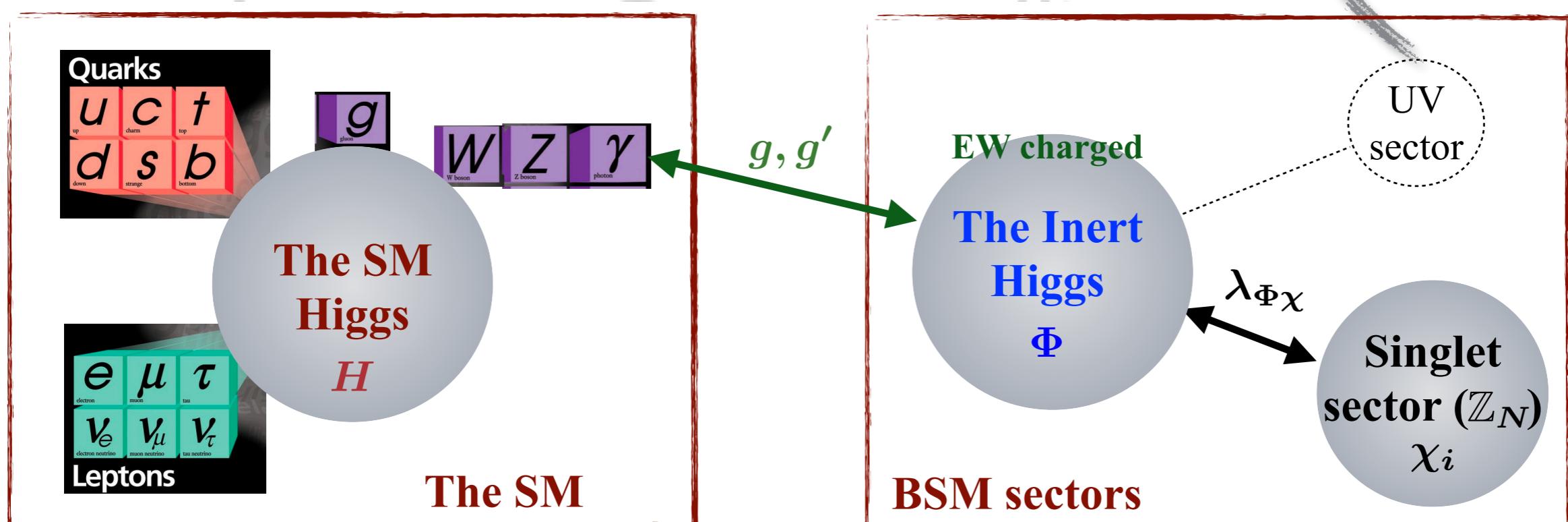
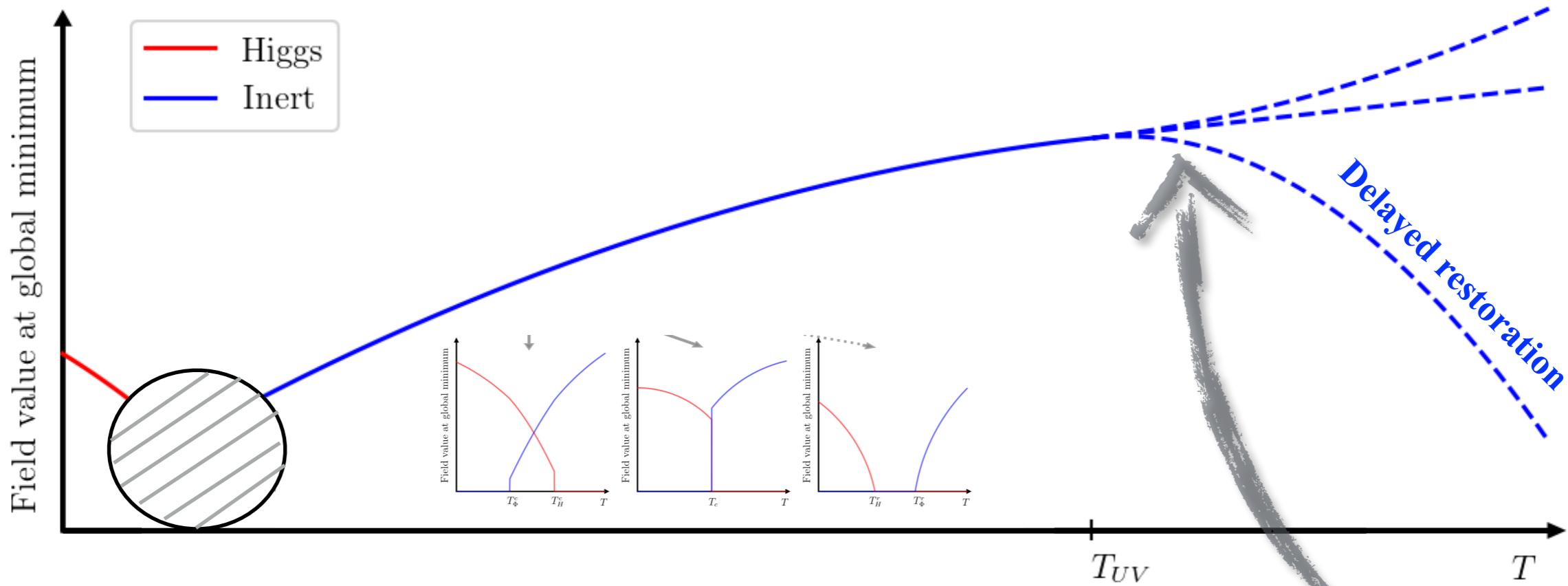
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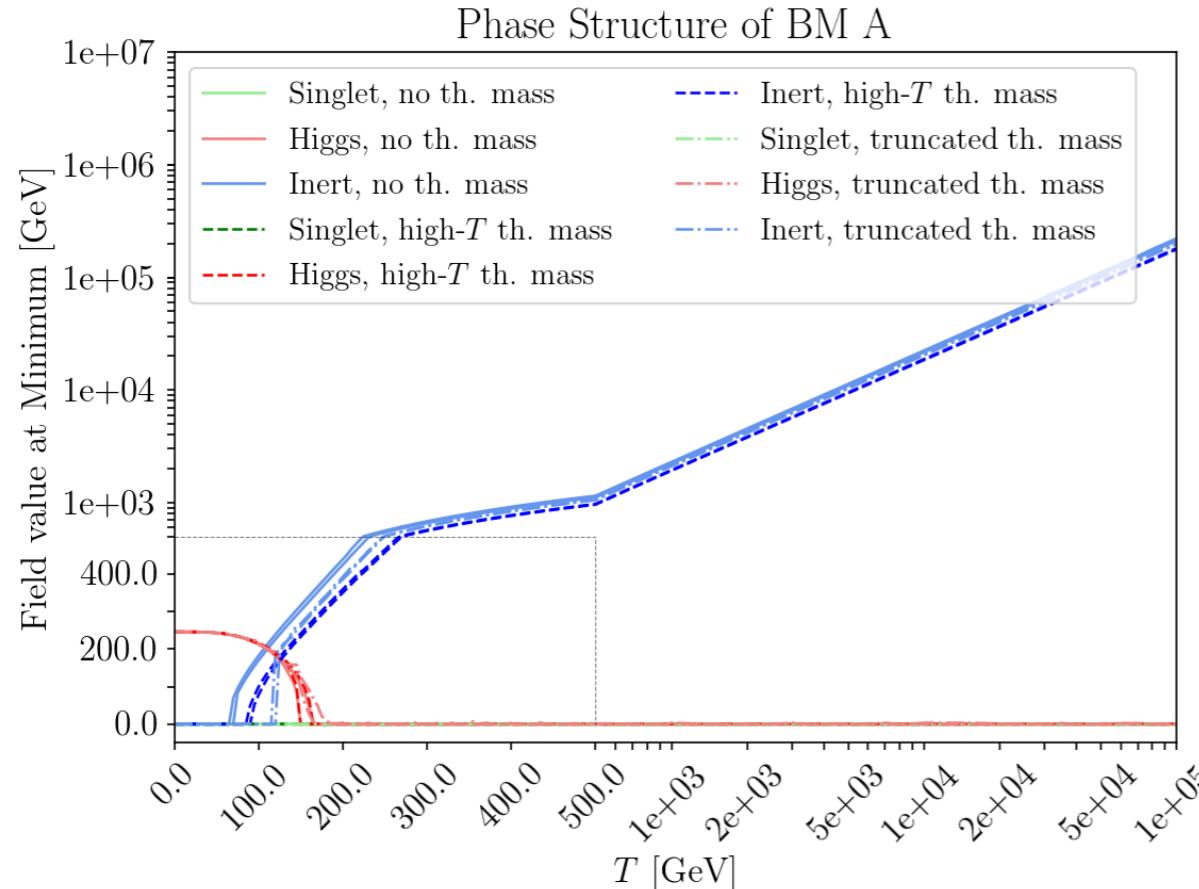


A new approach to EWN

[Carena, Krause, Liu, YW, '23]



Benchmark scenarios: numerical results



	μ_H^2	λ_H	μ_Φ^2	λ_Φ	μ_χ^2	λ_χ	$\lambda_{H\Phi}$	$\tilde{\lambda}_{H\Phi}$
BM A	8994.45	0.119	2500	0.1	100	0.01	-0.001	0
BM B	8991.84	0.119	5800	0.1	5000	0.004	0.01	0

	$\lambda_{\Phi\chi}$	$\tilde{\lambda}_\chi$	$\lambda_{H\chi}$	N	m_h	m_ϕ	m_χ
BM A	-0.06	0	0	250	125	48.47	9.8
BM B	-0.0375	0	0	600	125	84.58	68.87

Higgs invisible decays

$$\Gamma(h \rightarrow ss) = \frac{\lambda_{Hs}^2 v_0^2}{32\pi m_h} \sqrt{1 - \frac{4m_s^2}{m_h^2}}$$

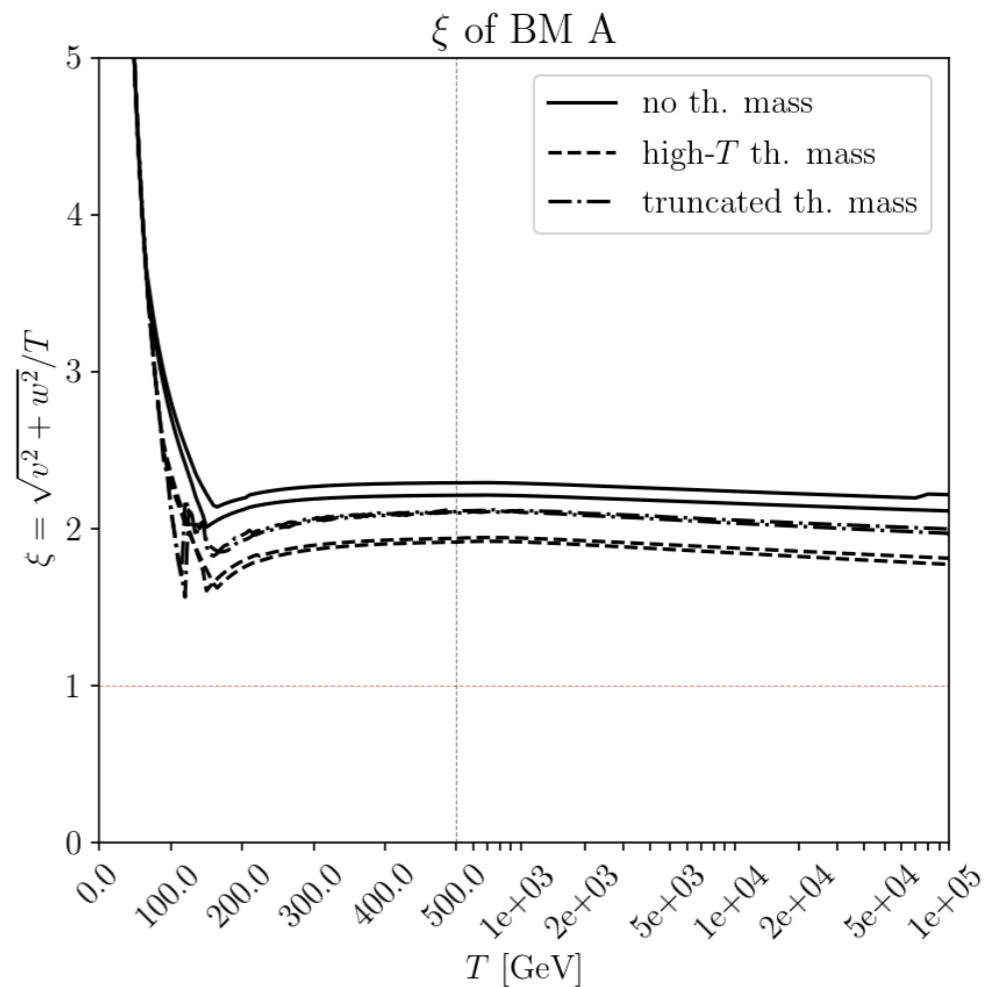
$$\sqrt{N\lambda_{H\chi}^2 + 2(\lambda_{H\Phi} + \tilde{\lambda}_{H\Phi})^2 + 2\lambda_{H\Phi}^2} \leq 0.015 \text{ (0.007)} \text{ for LHC(HL-LHC)}$$

Z boson invisible decays

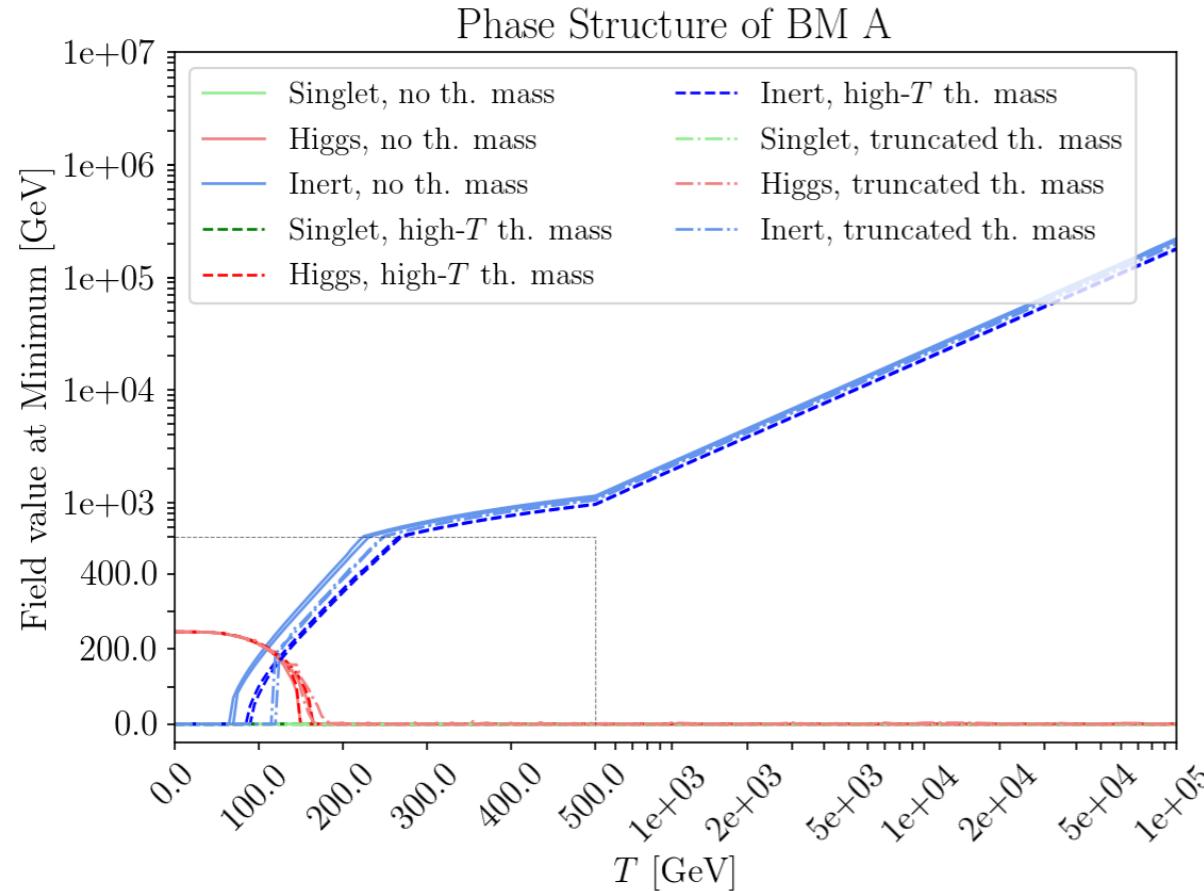
Excludes all inert masses below 45 GeV (LEP II)

Dilution factor $f_{w.o.} = 1 - \frac{n_B(t_{now})}{n_B(0)} = 1 - \exp \left[-\frac{13n_f}{2} \int_0^{T_{high}} dT \frac{\Gamma(T)}{VT^6} M_{Pl} \sqrt{\frac{90}{8\pi^3 g^*}} \right]$

	no th. mass	high-T th. mass	truncated th. mass
BM A	$< 10^{-16} / 10^{-16} / 10^{-14}$	$10^{-11} / 10^{-9} / 10^{-7}$	$8 \cdot 10^{-11} / 8 \cdot 10^{-9} / 8 \cdot 10^{-7}$
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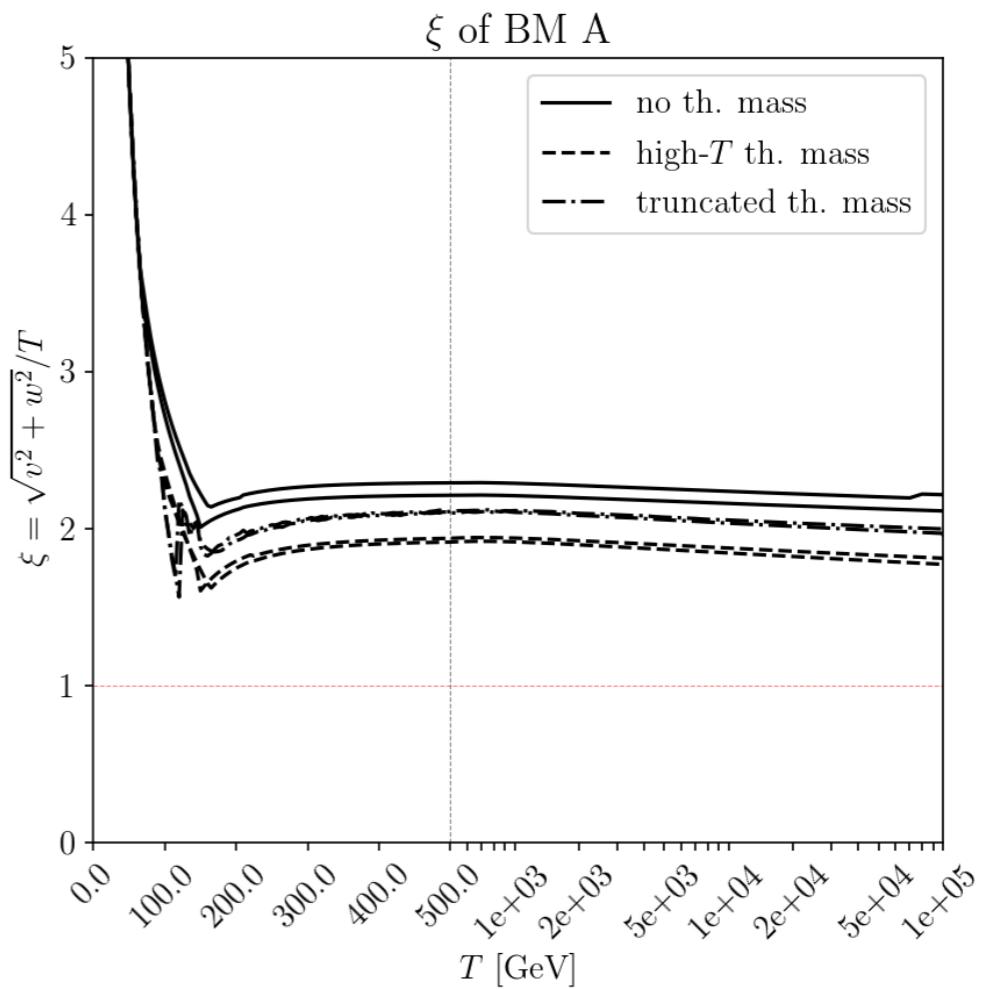
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Summary

- ▶ SFOEWPT occurs with various SM Higgs extensions through tree level, loop and thermal effects
- ▶ Intrinsic connections to Higgs phenomenology and gravitational wave physics are illustrated with an example of singlet extension
- ▶ Symmetry non-restoration can lead us to a bridge between the UV and the IR
- ▶ Be careful with theoretical uncertainties!

Remarks

- ▶ Marcela is my Doktormutter
- ▶ We, and our great collaborators including Carlos, had so much fun together studying the interesting physics of electroweak phase transition, baryogenesis, Higgs, gravitational wave, and so much more
- ▶ Marcela has been a role model and motivated me to be strong as a physicist and a woman

Thank you!

Supplementary

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^{SM} :

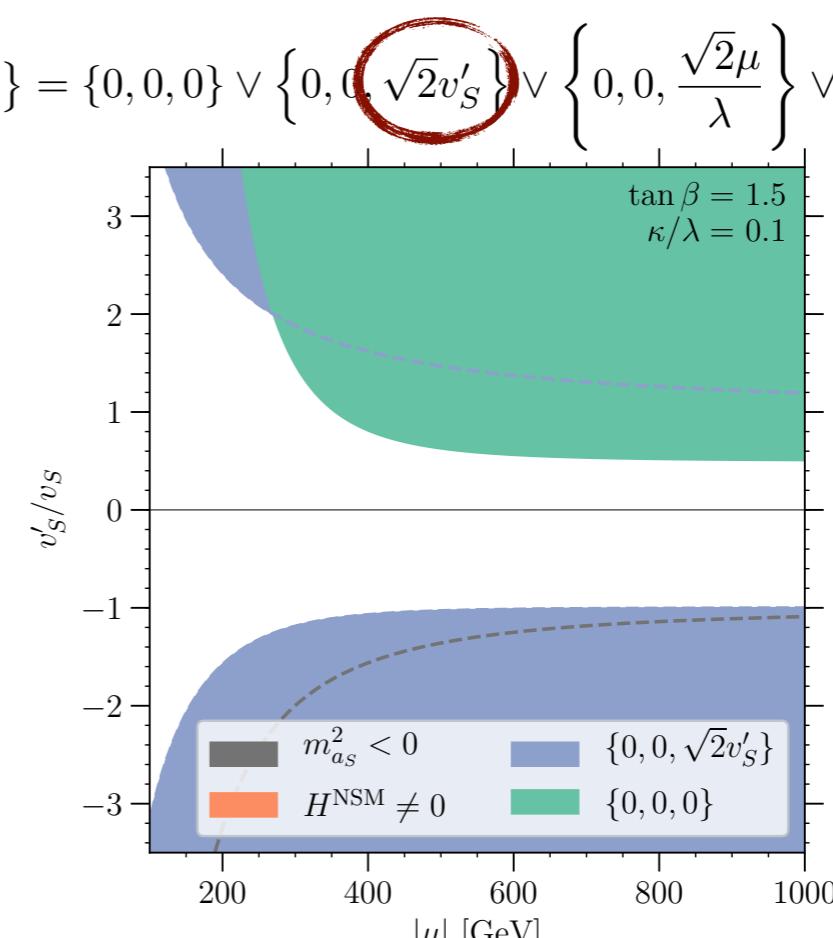
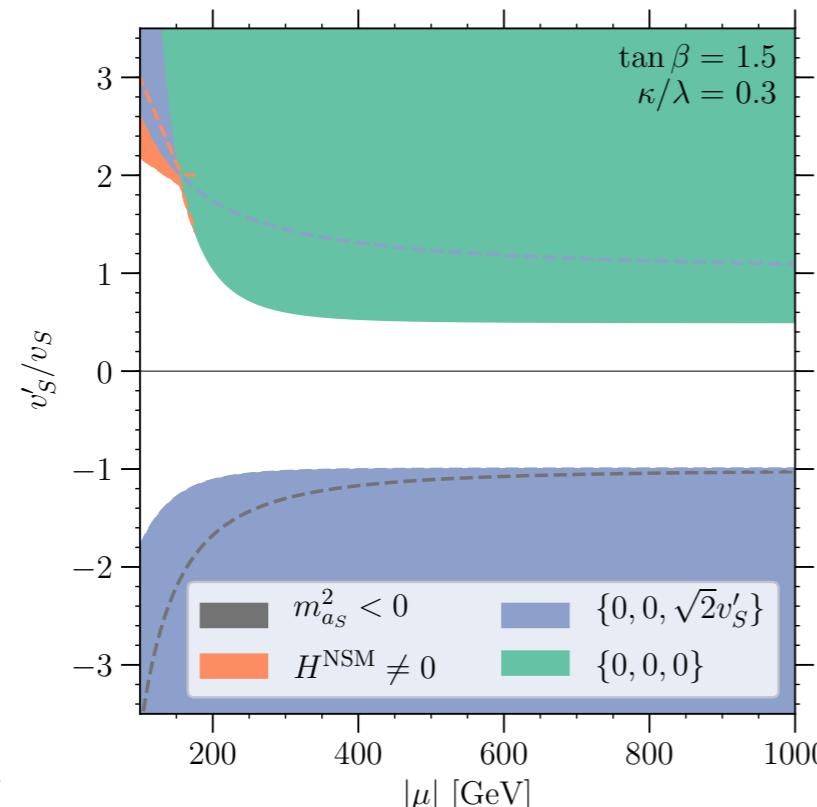
$$|\mathcal{M}_{S,12}^2| \ll |\mathcal{M}_{S,22}^2 - \mathcal{M}_{S,11}^2|, \quad |\mathcal{M}_{S,13}^2| \ll |\mathcal{M}_{S,33}^2 - \mathcal{M}_{S,11}^2|$$

Alignment (without decoupling) limits

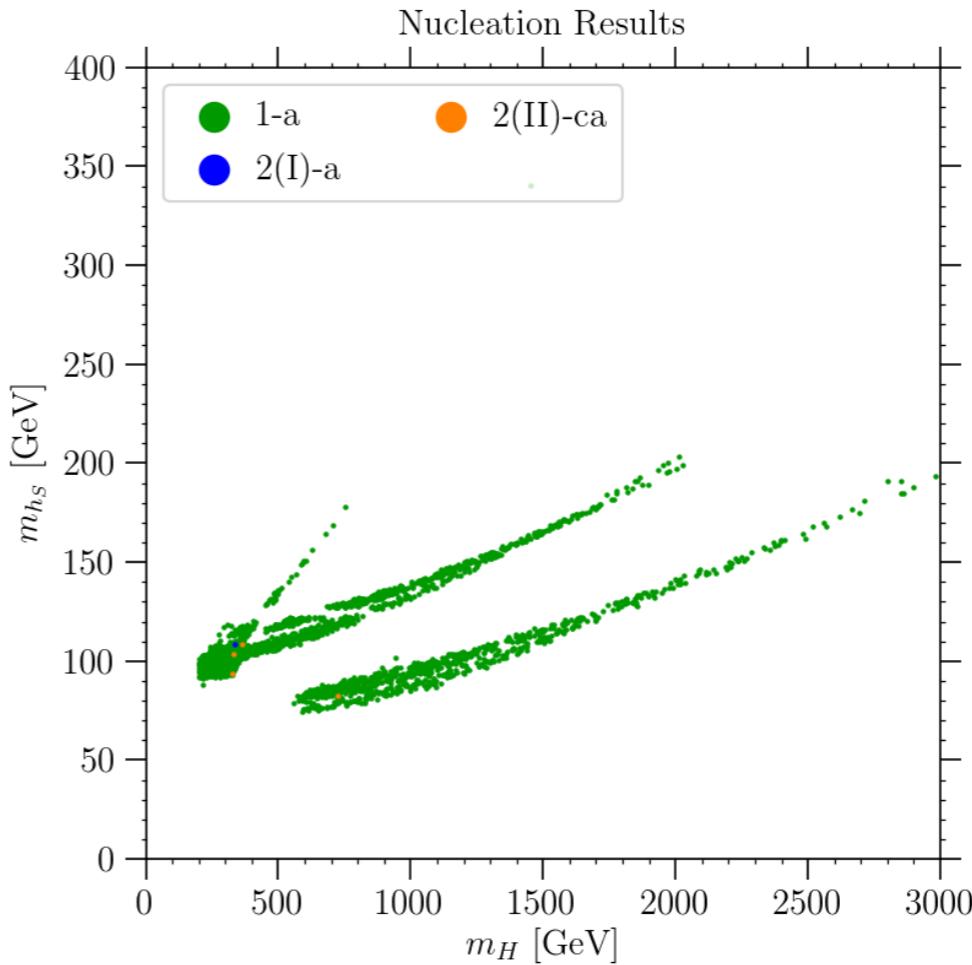
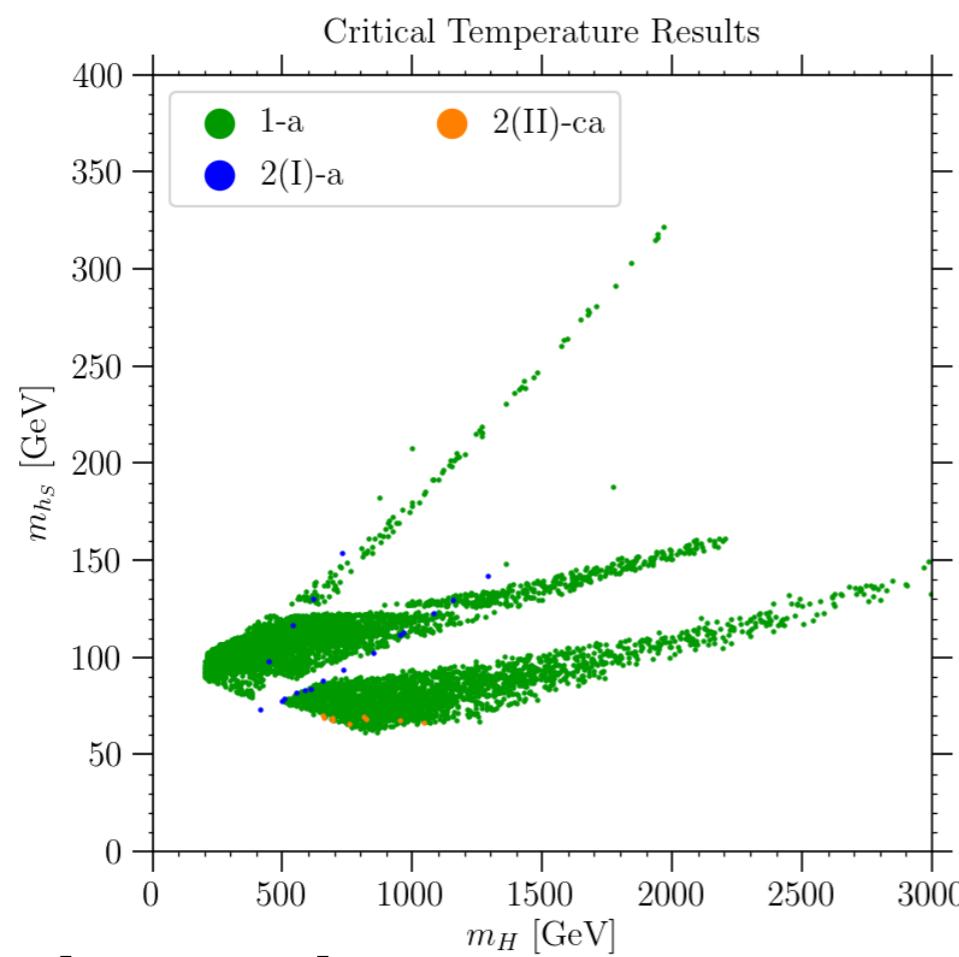
$$\mathcal{M}_{S,12}^2 = 0 \quad \rightarrow \quad \lambda^2 = \frac{m_{h_{125}}^2 - m_Z^2 \cos(2\beta)}{2v^2 \sin^2 \beta}, \quad \mathcal{M}_{S,13}^2 = 0 \quad \rightarrow \quad A_\lambda = \frac{2\mu}{\sin 2\beta} \left(1 - \frac{\kappa}{\lambda} \sin 2\beta\right)$$

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) $\sqrt{\lambda^2 + \kappa^2} \lesssim 0.7$
- Avoid tachyonic masses, e.g. $m_{a_S}^2 \geq 0$
- Correct vacuum structure at zero temperature $\{H^{\text{SM}}, H^{\text{NSM}}, H^S\} = \{0, 0, 0\} \cup \{0, 0, \sqrt{2}v'_S\} \cup \left\{0, 0, \frac{\sqrt{2}\mu}{\lambda}\right\} \cup \left\{\sqrt{2}v, 0, \frac{\sqrt{2}\mu}{\lambda}\right\} \cup \dots$



EWPT in the NMSSM - collider and dark matter phenomenology



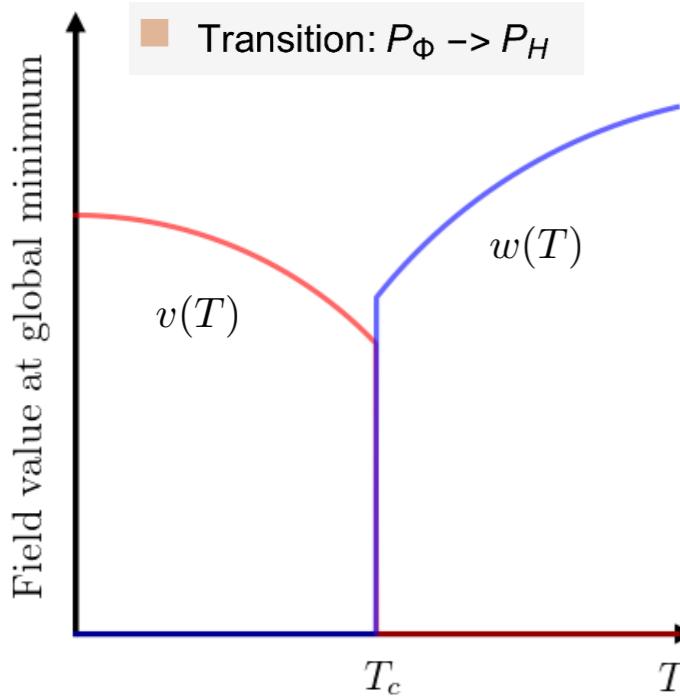
Collider phenomenology

- 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 for light mass
 - 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

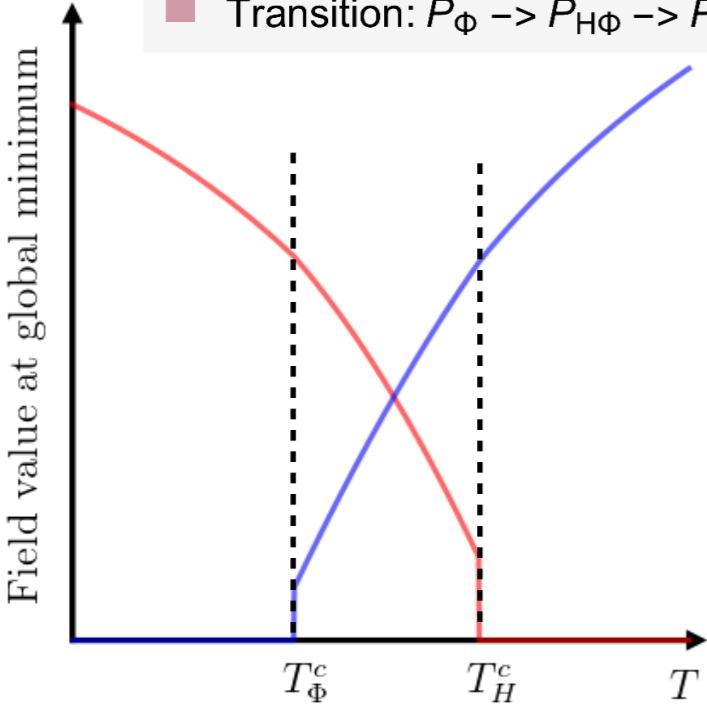
Supplementary - mean field analysis



$$P_\Phi \text{ phase : } w(T) = \sqrt{-\frac{\mu_\Phi^2 + c_\varphi T^2}{\lambda_\Phi}}$$

$$P_H \text{ phase : } v(T) = \sqrt{\frac{\mu_H^2 - c_h T^2}{\lambda_H}}$$

$$\text{The critical temperature : } T_c = \sqrt{\frac{\mu_H^2 + \sqrt{\lambda_H/\lambda_\Phi}\mu_\Phi^2}{c_h - \sqrt{\lambda_H/\lambda_\Phi}c_\varphi}}$$



$$P_{H\Phi} \text{ phase : } \tilde{v}(T) = \sqrt{\frac{\tilde{\mu}_H^2 - \tilde{c}_h T^2}{\tilde{\lambda}_H}}, \quad \tilde{w}(T) = \sqrt{-\frac{\tilde{\mu}_\Phi^2 + \tilde{c}_\varphi T^2}{\tilde{\lambda}_\Phi}}$$

which is the global minimum as long as existing if $4\lambda_\Phi\lambda_H - \lambda_{H\Phi}^2 \geq 0$

$$\text{The critical temperatures : } T_H^c = \sqrt{\frac{\tilde{\mu}_H^2}{\tilde{c}_h}}, \quad T_\Phi^c = \sqrt{\frac{\tilde{\mu}_\Phi^2}{-\tilde{c}_\varphi}}$$

Relevant parameters: $\tilde{\mu}_H^2 \equiv \mu_H^2 + \frac{\Lambda_{H\Phi}}{2\lambda_\Phi}\mu_\Phi^2$, $\tilde{\mu}_\Phi^2 \equiv \mu_\Phi^2 + \frac{\Lambda_{H\Phi}}{2\lambda_H}\mu_H^2$,
 $\tilde{c}_h \equiv c_h - \frac{\Lambda_{H\Phi}}{2\lambda_\Phi}c_\varphi$, $\tilde{c}_\varphi \equiv c_\varphi - \frac{\Lambda_{H\Phi}}{2\lambda_H}c_h$,
 $\tilde{\lambda}_H \equiv \lambda_H - \frac{\Lambda_{H\Phi}^2}{4\lambda_\Phi}$, $\tilde{\lambda}_\Phi \equiv \lambda_\Phi - \frac{\Lambda_{H\Phi}^2}{4\lambda_H}$

Supplementary - sphaleron washout and dilution factor

$$\text{Dilution factor } f_{w.o.} = 1 - \frac{n_B(t_{now})}{n_B(0)} = 1 - \exp \left[-\frac{13n_f}{2} \int_0^{T_{\text{high}}} dT \frac{\Gamma(T)}{VT^6} M_{Pl} \sqrt{\frac{90}{8\pi^3 g^*}} \right]$$

with $\frac{\Gamma}{V} = 4\pi\omega_- \mathcal{N}_{tr} \mathcal{N}_{rot} T^3 \left(\frac{v_{EW}(T)}{T} \right)^6 \kappa \exp [-E_{sph}(T)/T]$

