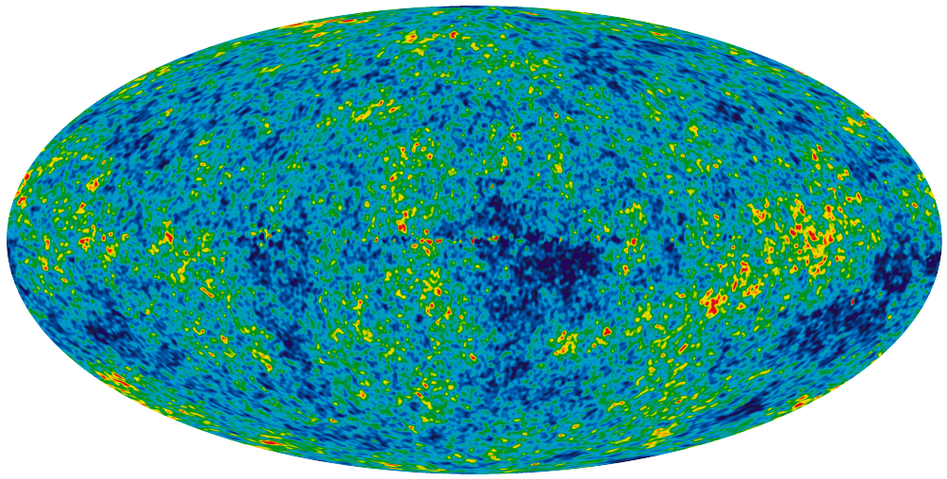
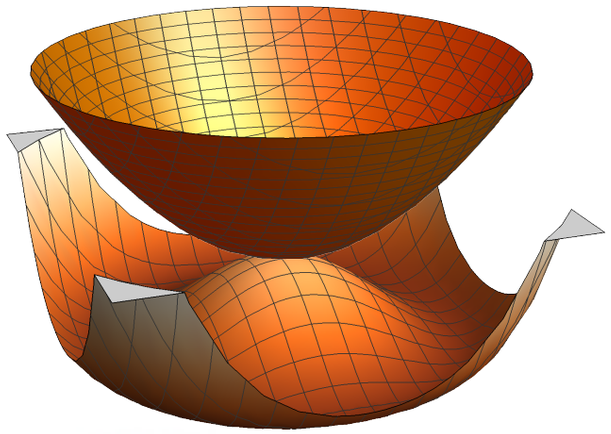


Electroweak Phase Transition and the Higgs Potential

Yikun Wang

California Institute of Technology

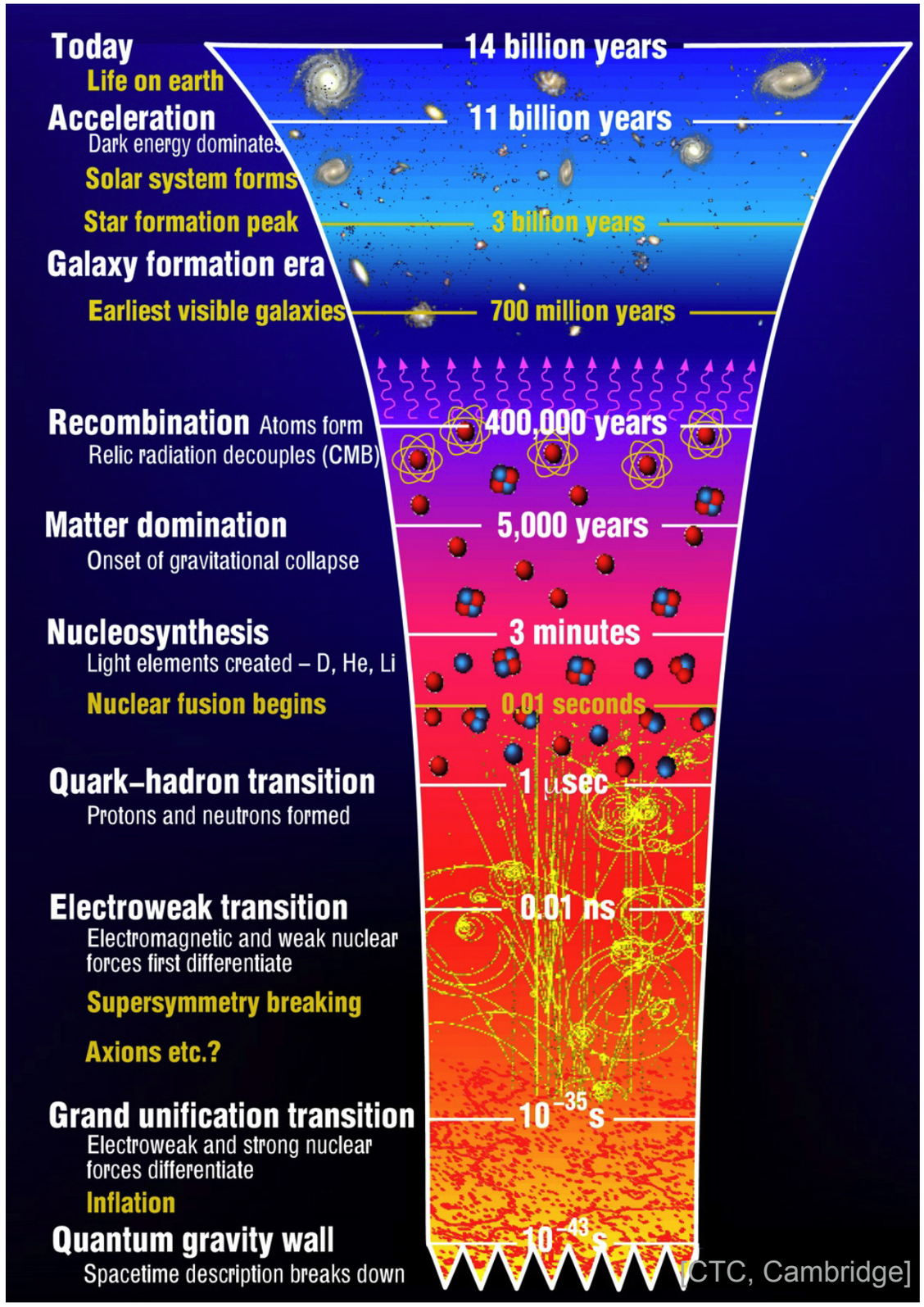


Higgs 2023

November 28th, 2023, IHEP, Beijing

In Collaboration with: Marcela Carena, Claudius Krause, and Zhen Liu.

Electroweak symmetry in the early universe and the Higgs potential



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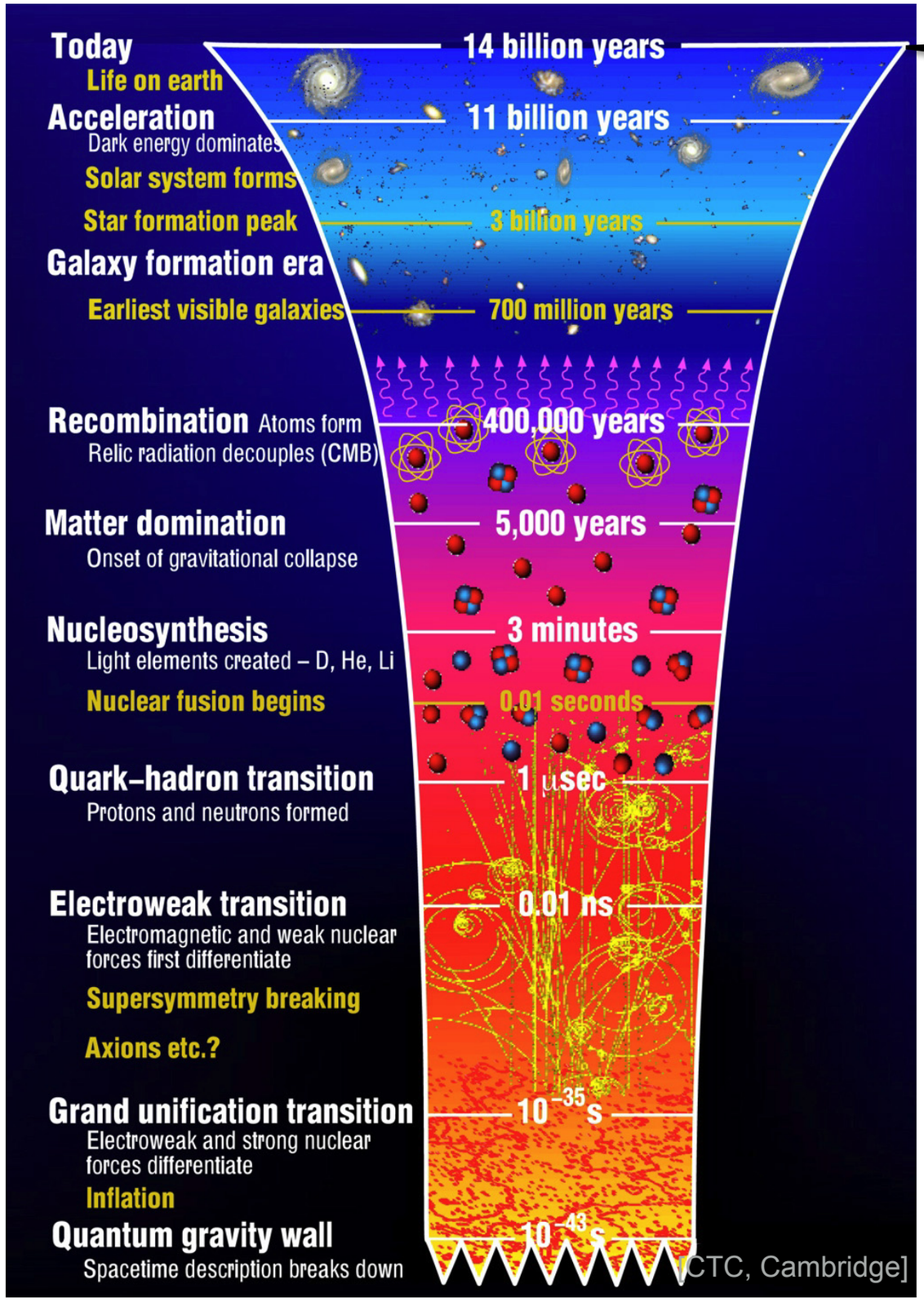
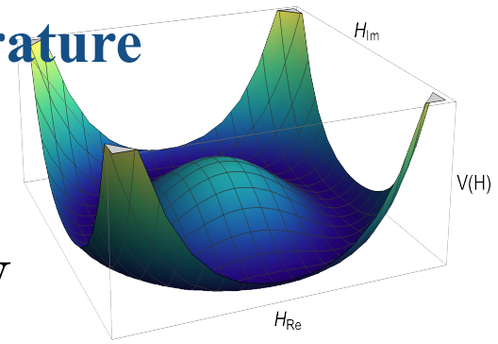


Zero Temperature

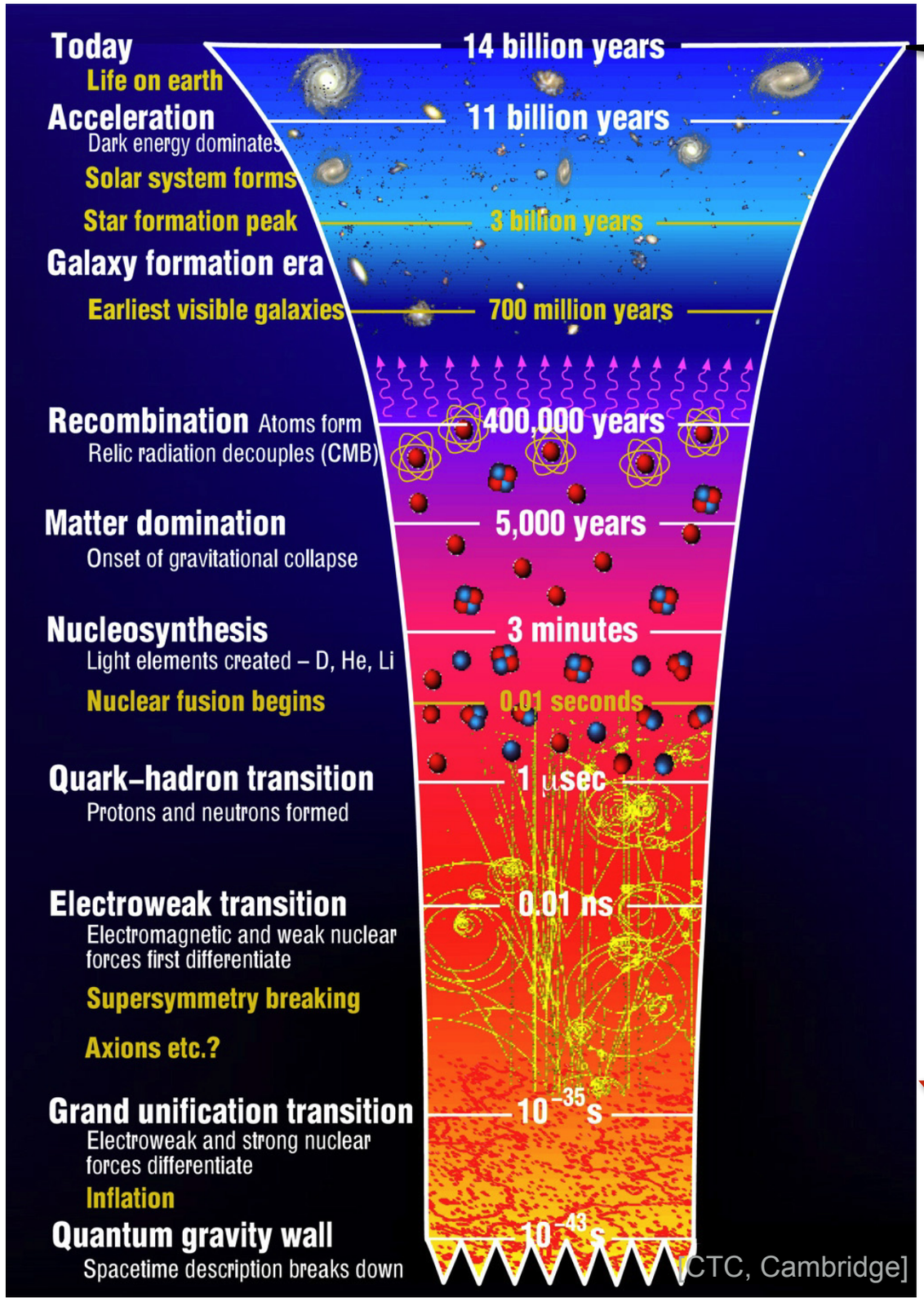


$$\langle h \rangle = 246\,\mathrm{GeV}$$

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

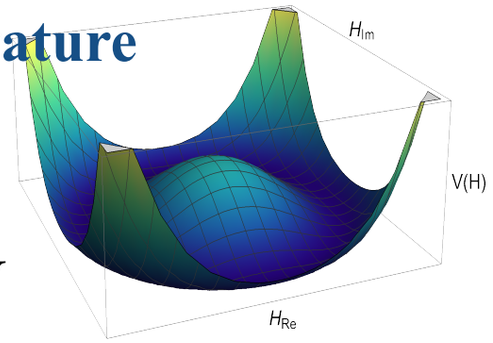
Spontaneous Symmetry Breaking

Electroweak symmetry in the early universe and the Higgs potential



Temperature increases

Zero Temperature



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Electroweak Symmetry Thermal History

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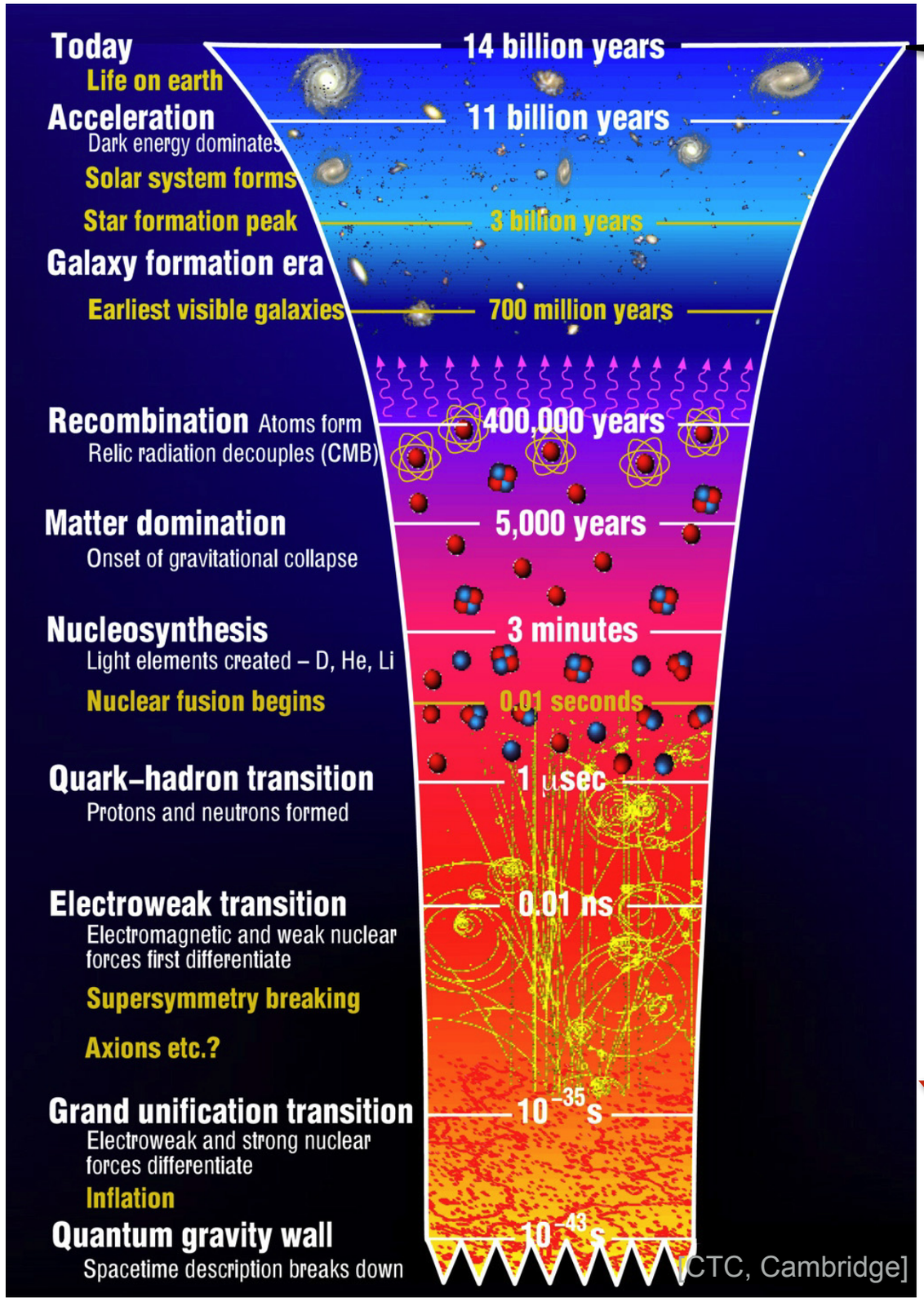

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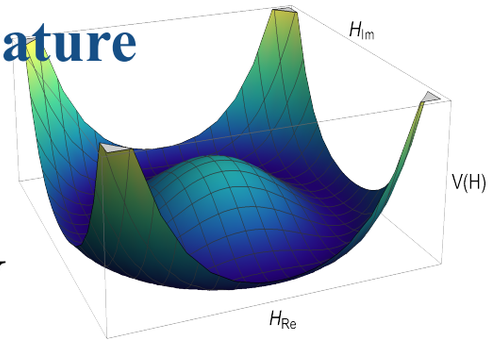

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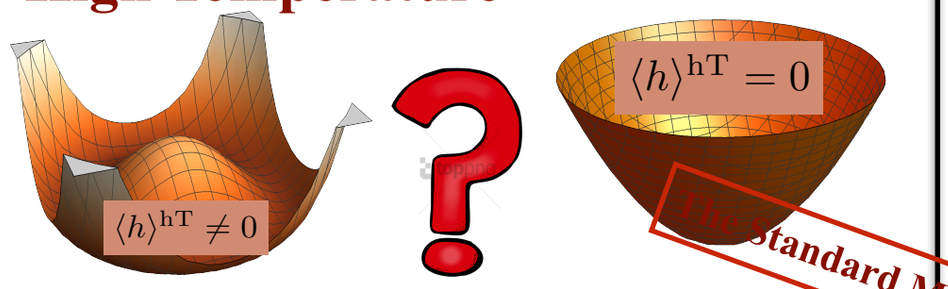

Broken **Preserved**

Electroweak Symmetry Thermal History

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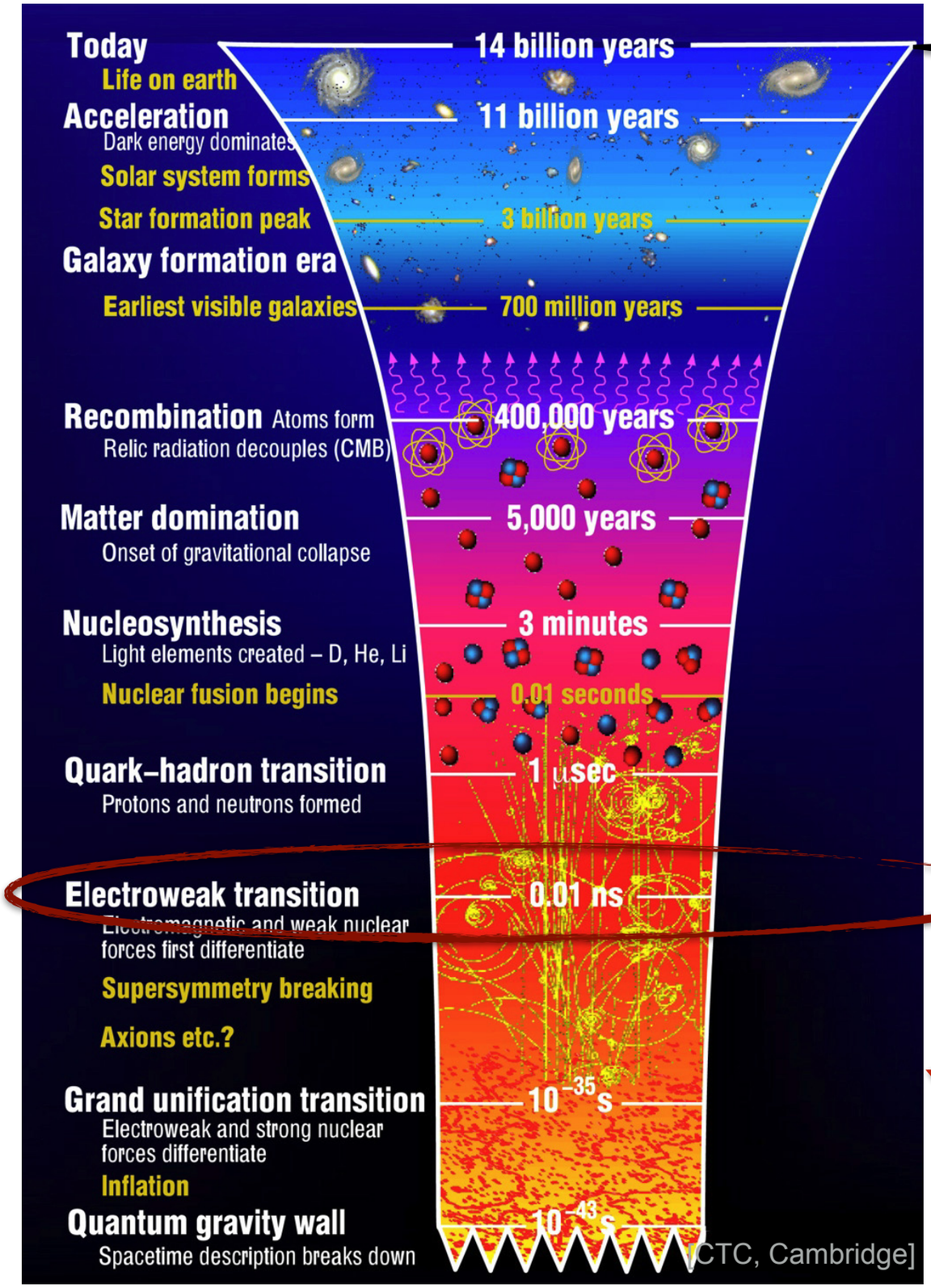

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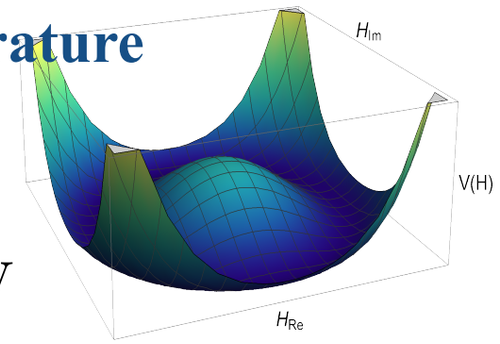

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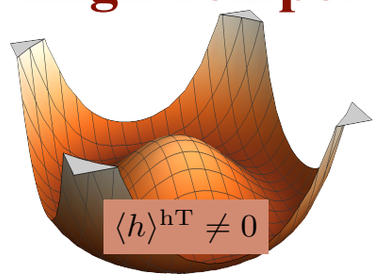

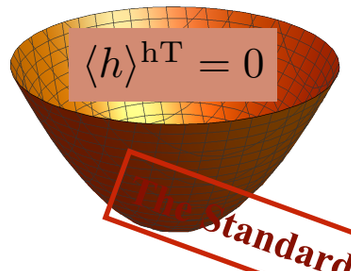

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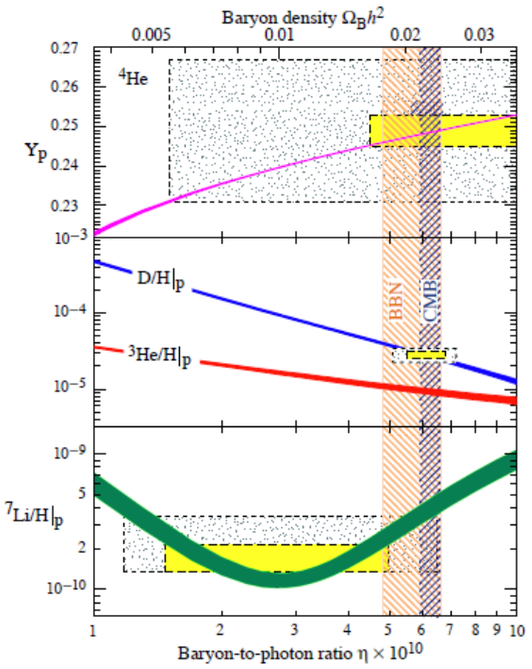
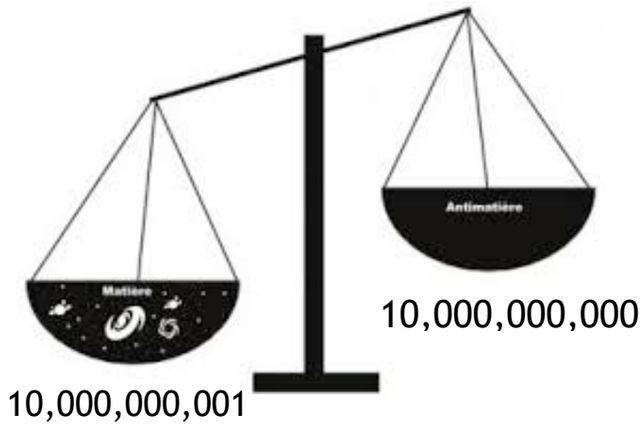
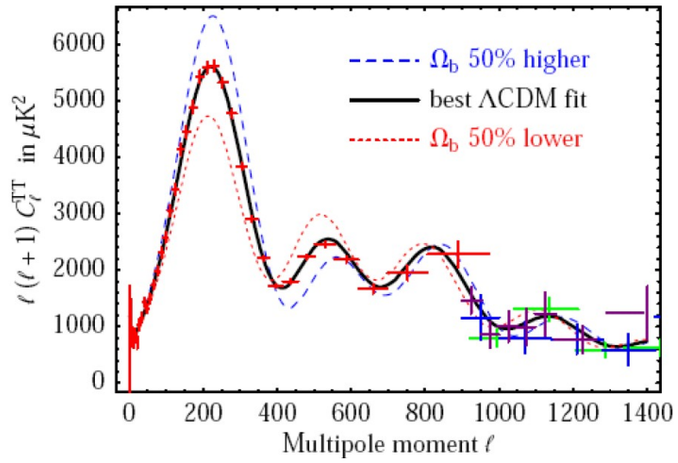
Electroweak Symmetry Thermal History

Why (strongly first order) electroweak phase transition?



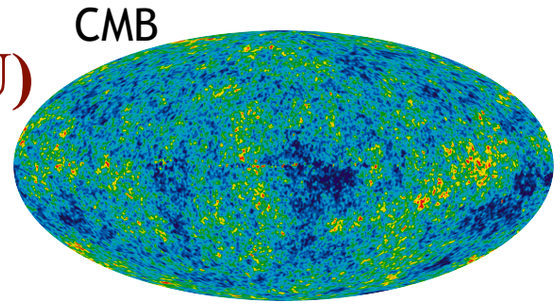
Big Bang Nucleosynthesis





Baryon Asymmetry of the Universe (BAU)

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



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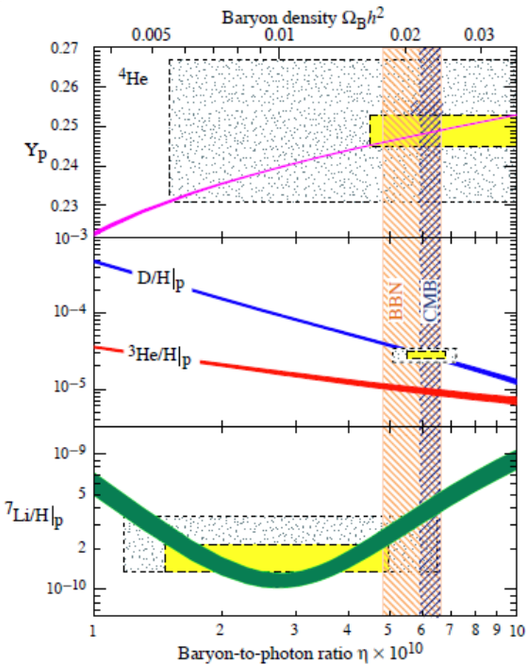

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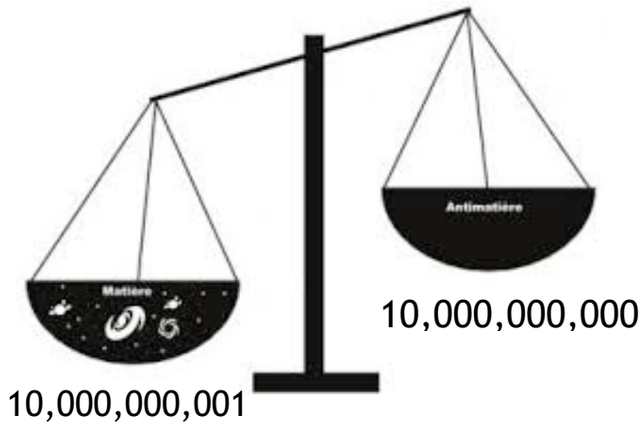

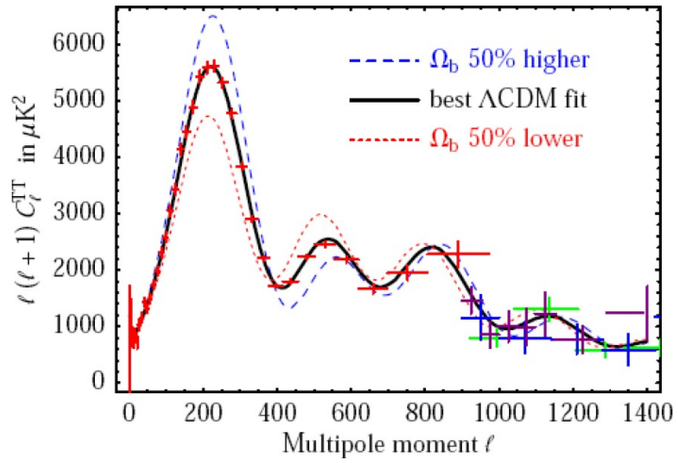

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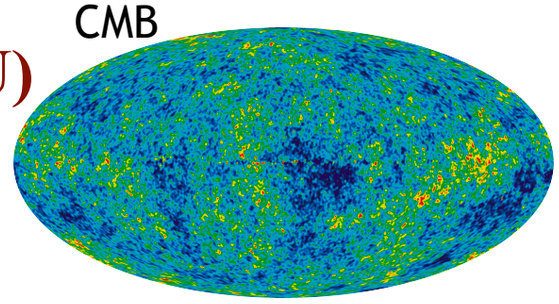
CMB



Sakharov's conditions for BAU creation

- **Baryon number violation**
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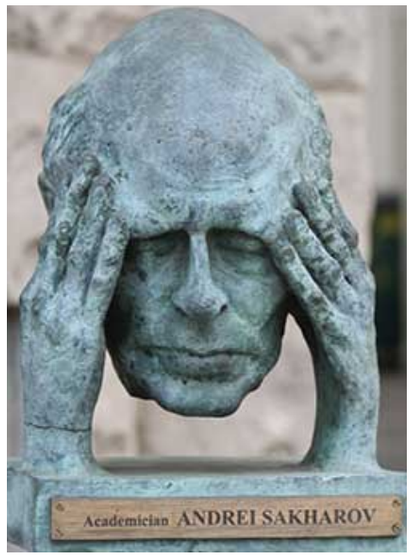

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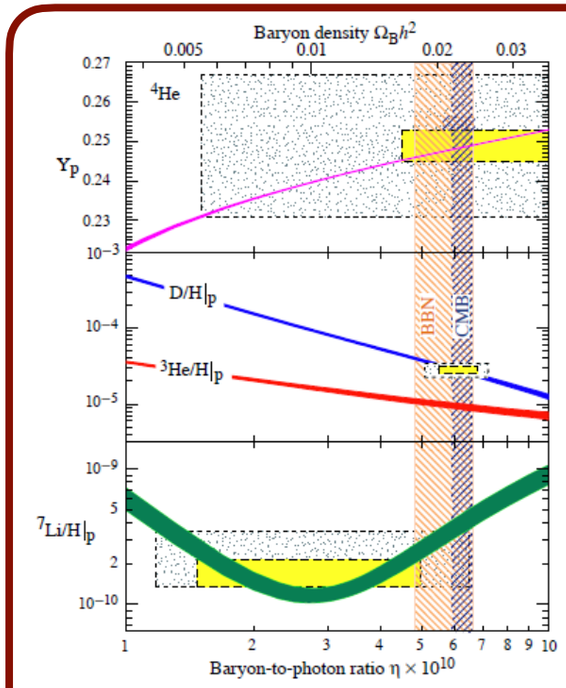

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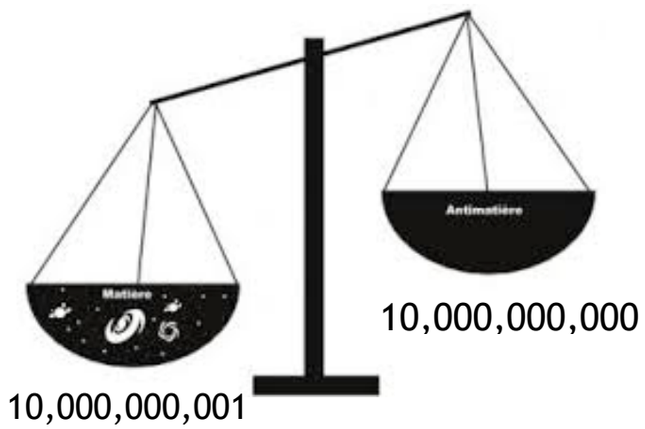

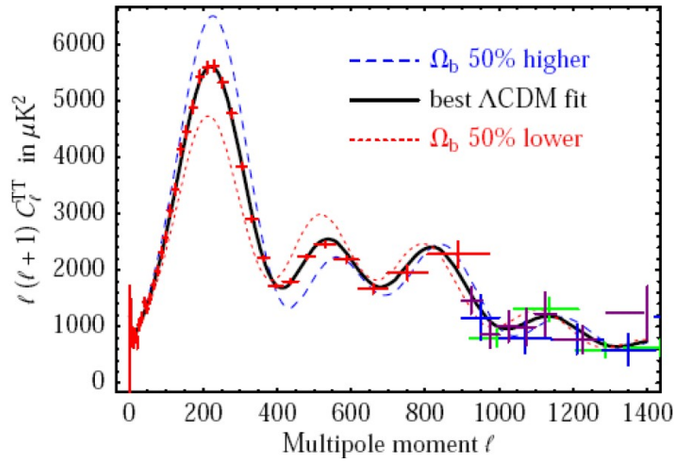

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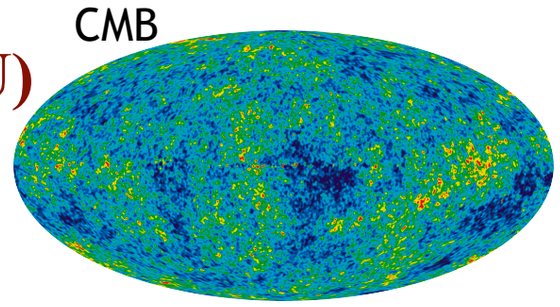

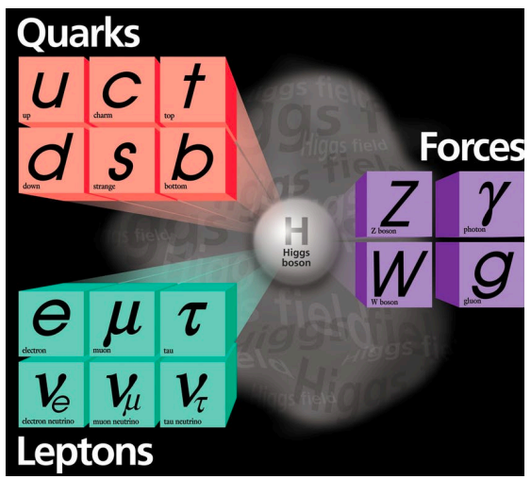

The Standard Model

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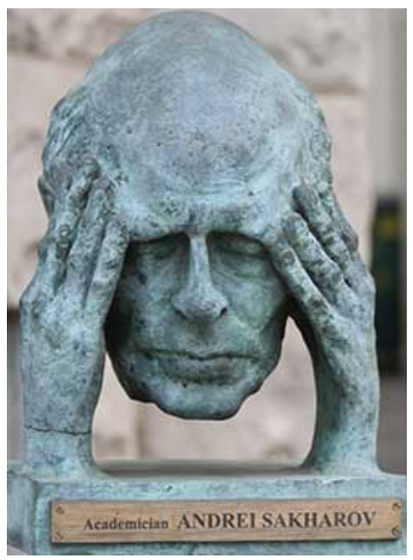

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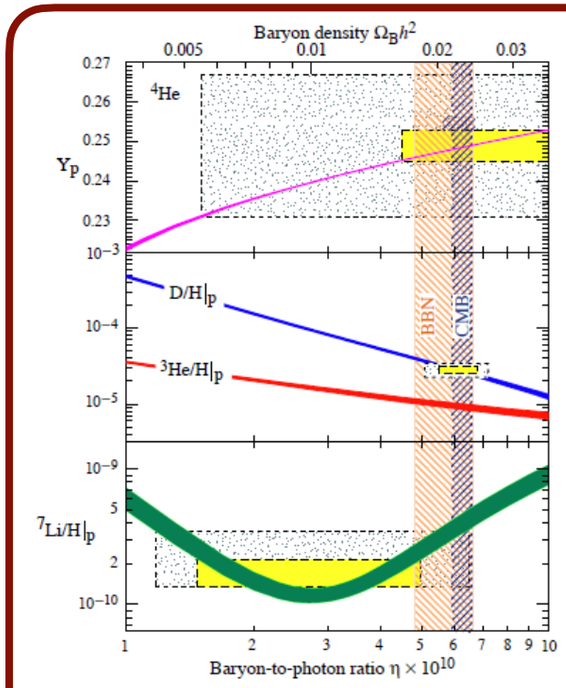

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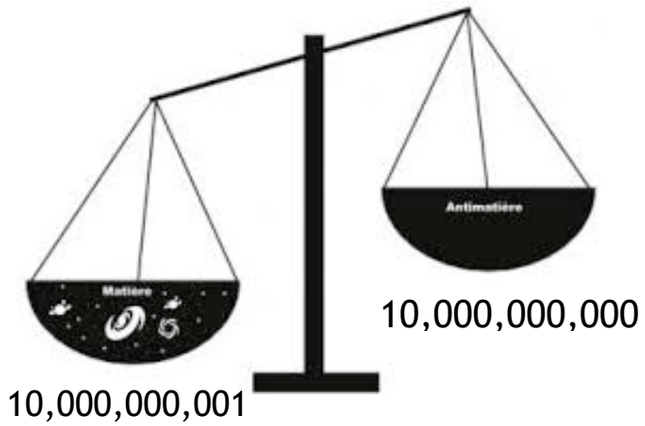

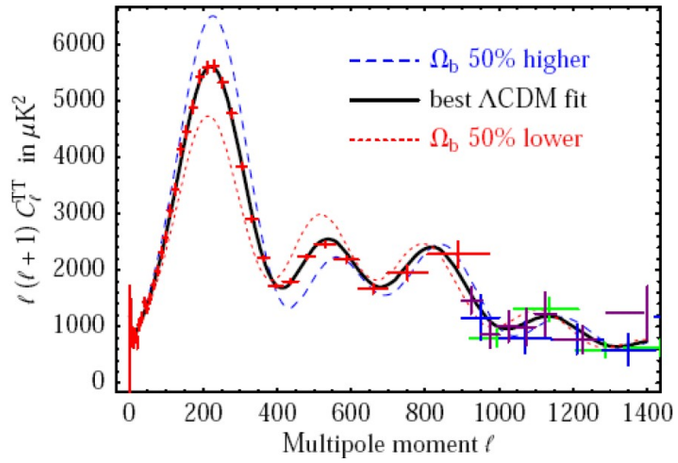

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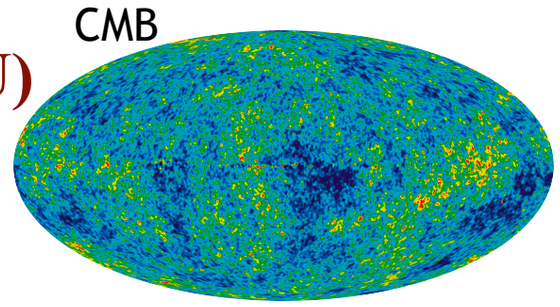

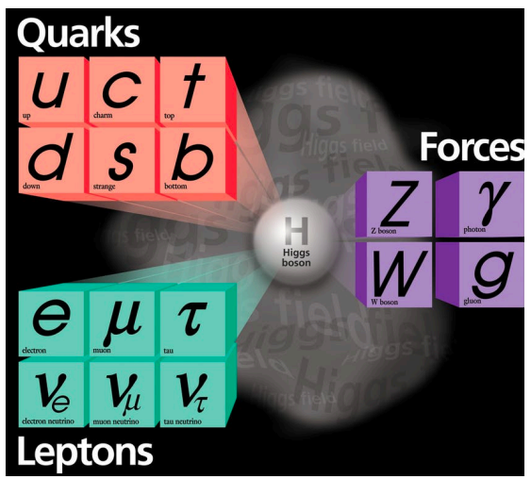

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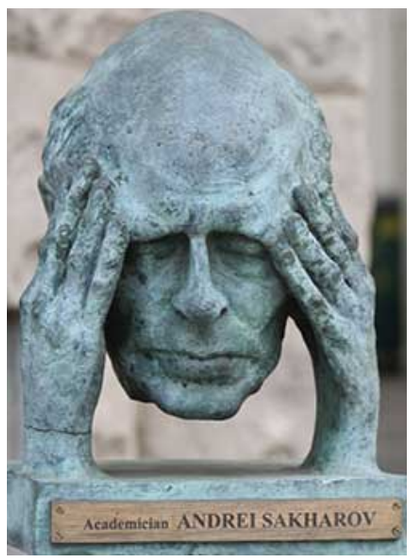

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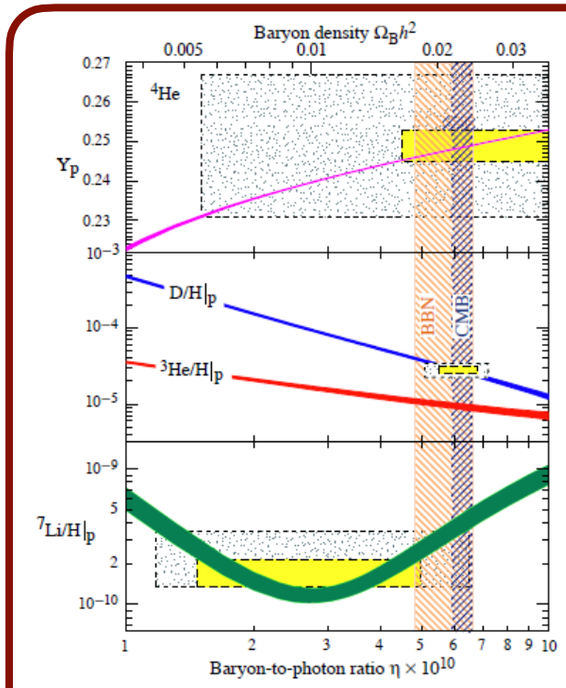

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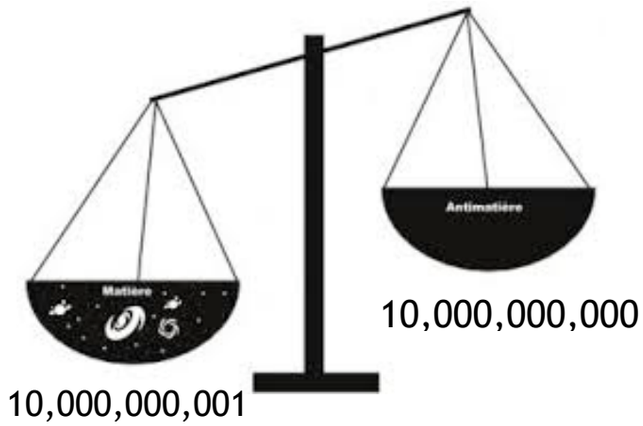

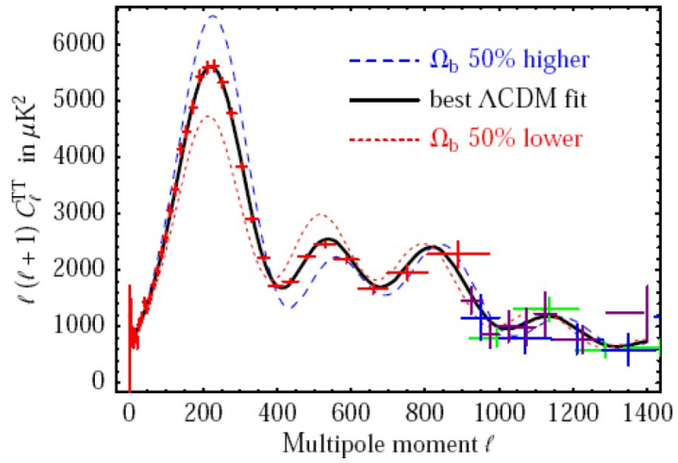

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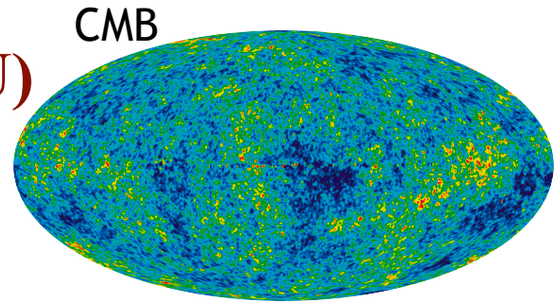

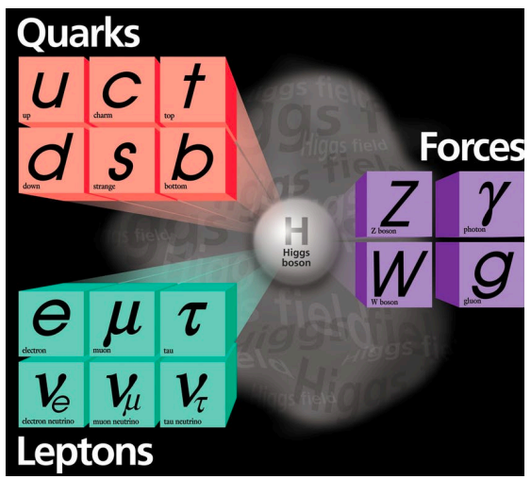

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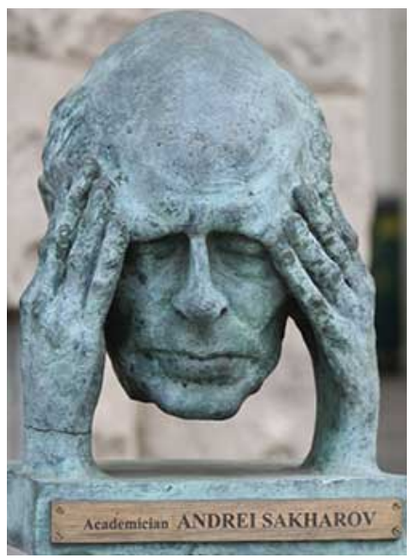

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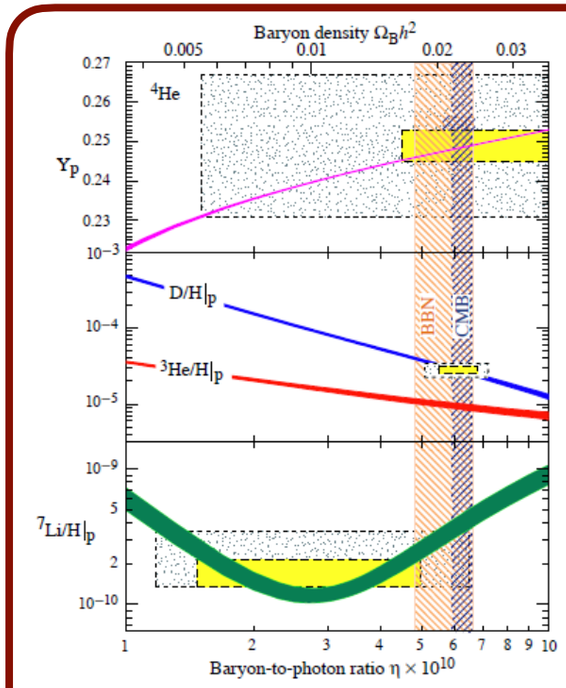

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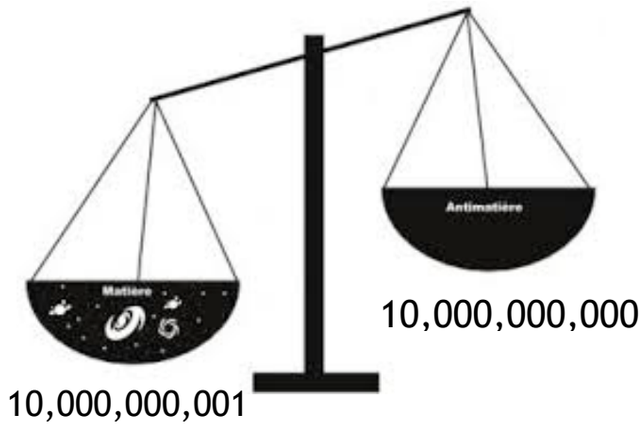

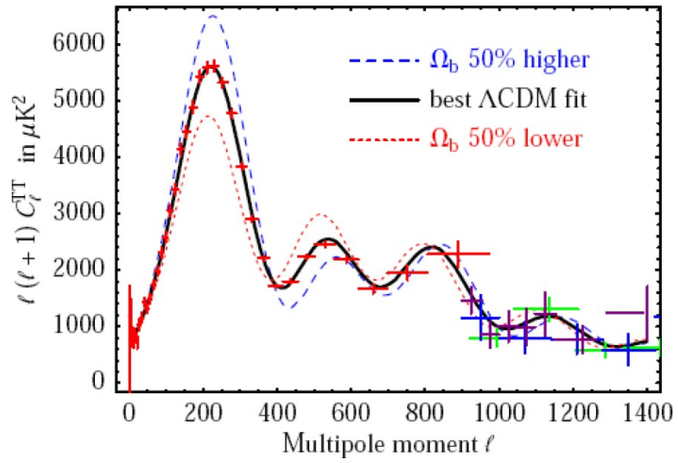

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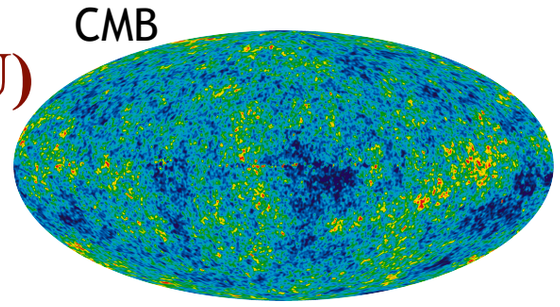

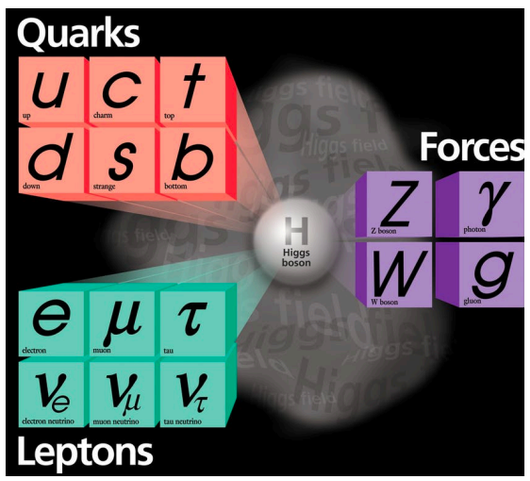

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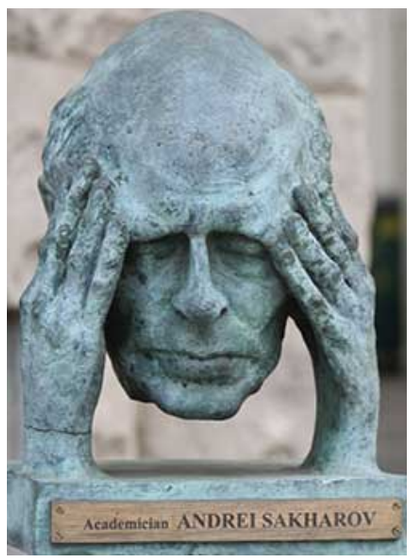

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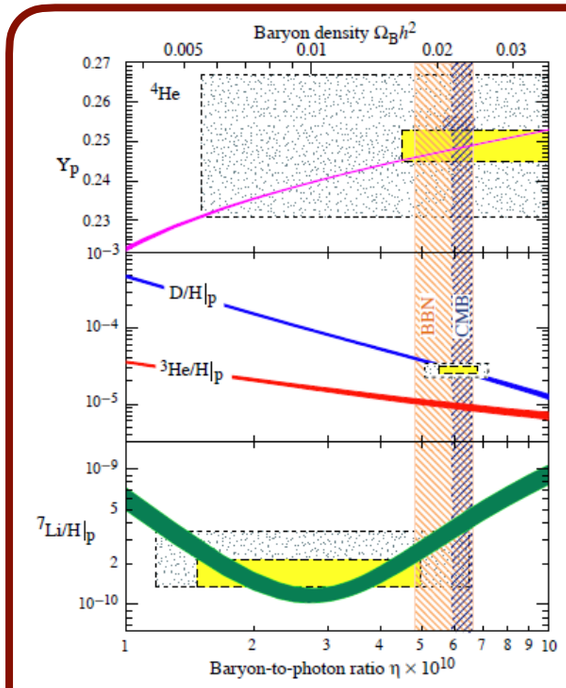

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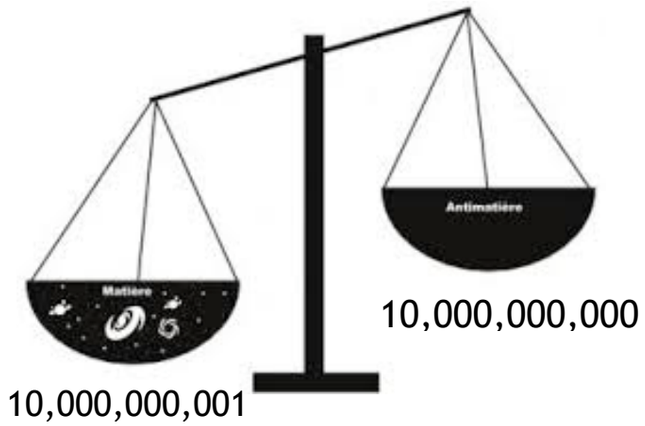

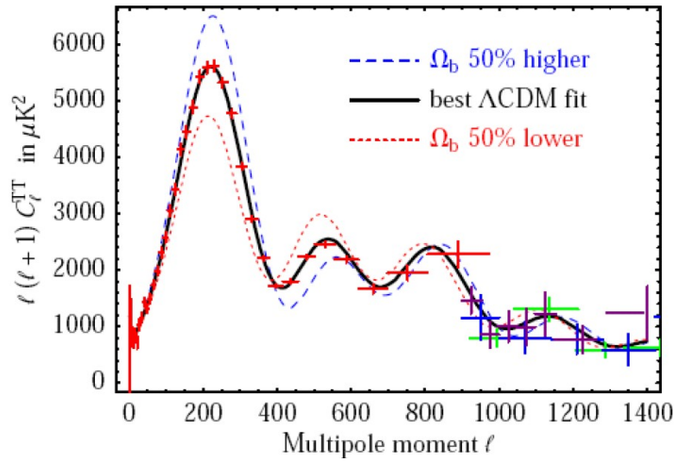

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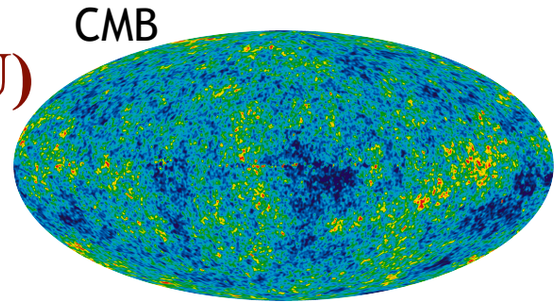

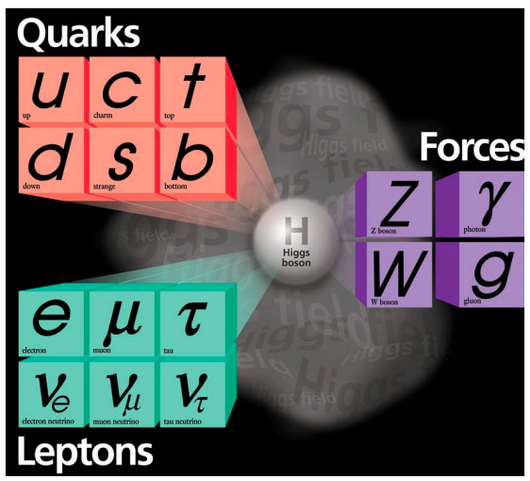

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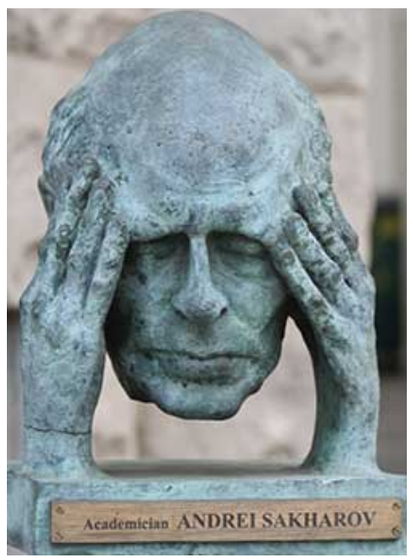
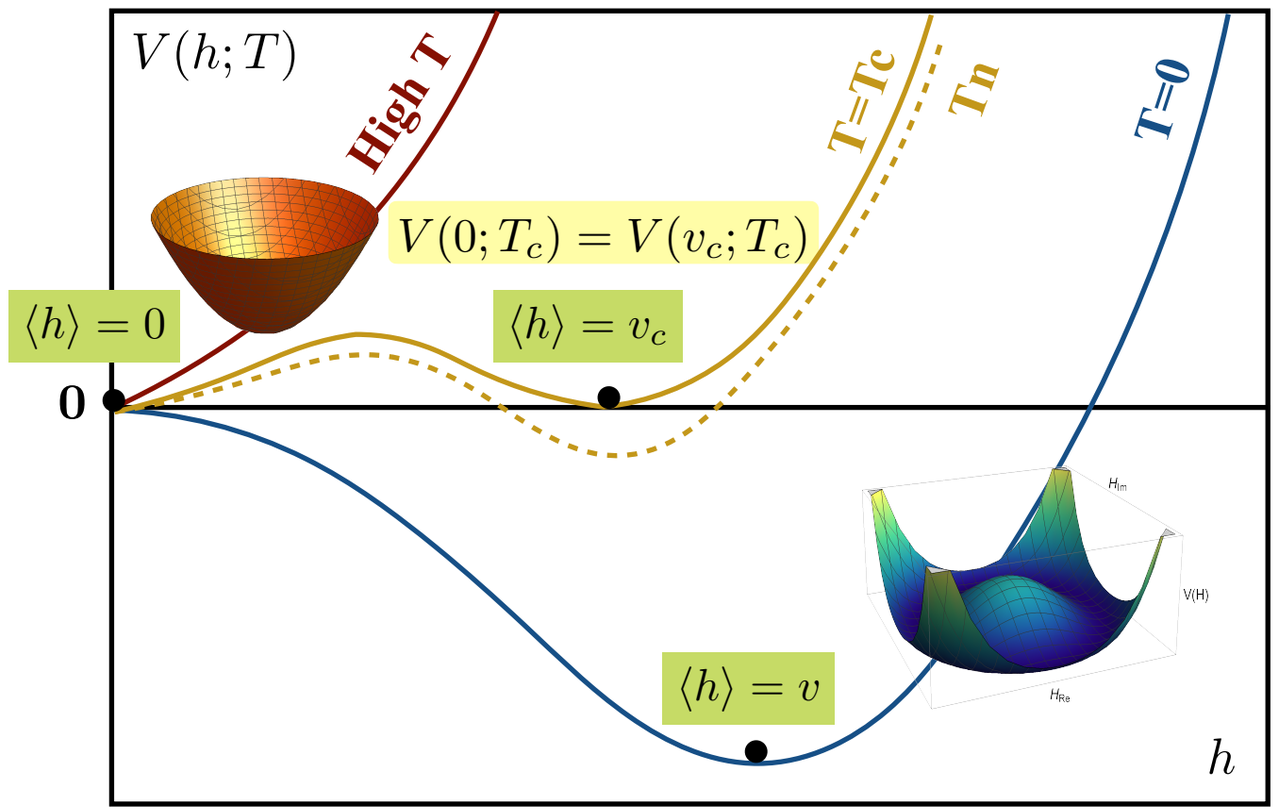


The Standard Model

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

Strong First Order Electroweak Phase Transition (SFOEWPT)



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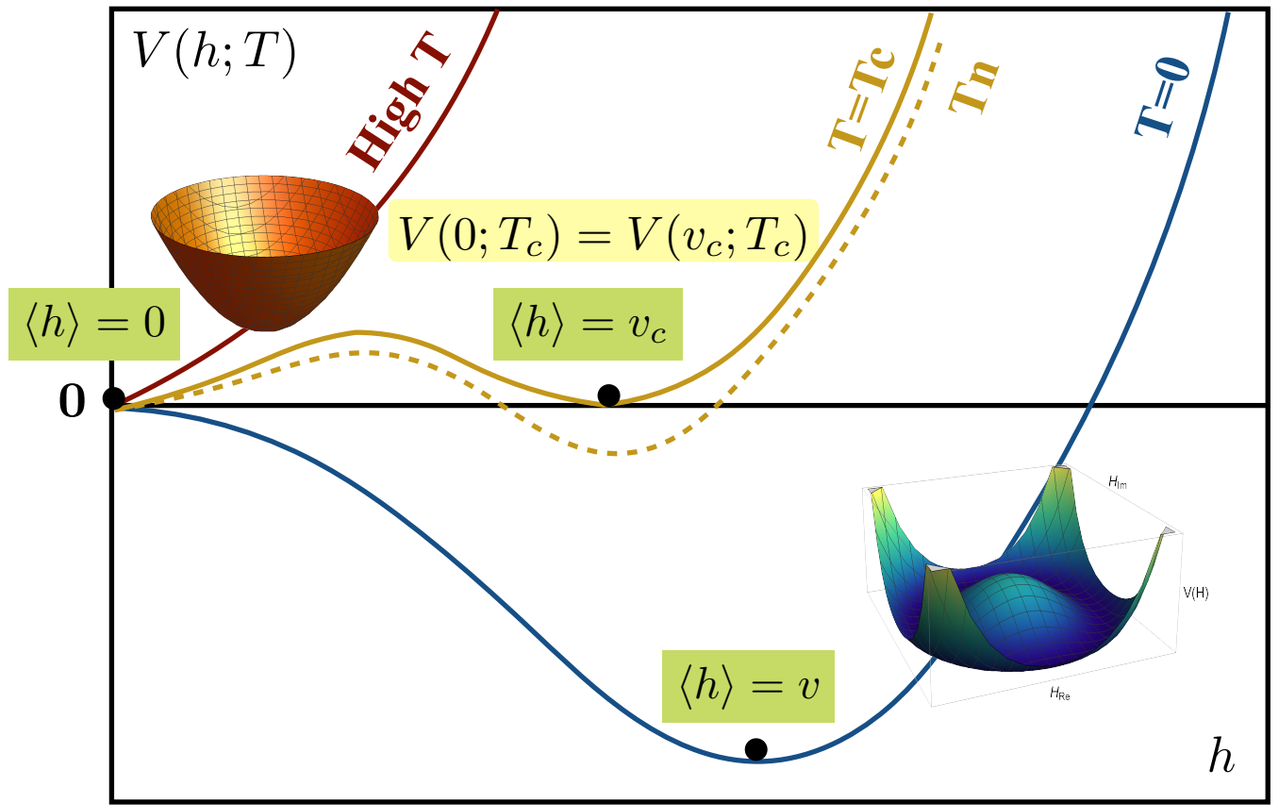

The order parameter $\frac{v_c}{T_c} \gtrsim 1$

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

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

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

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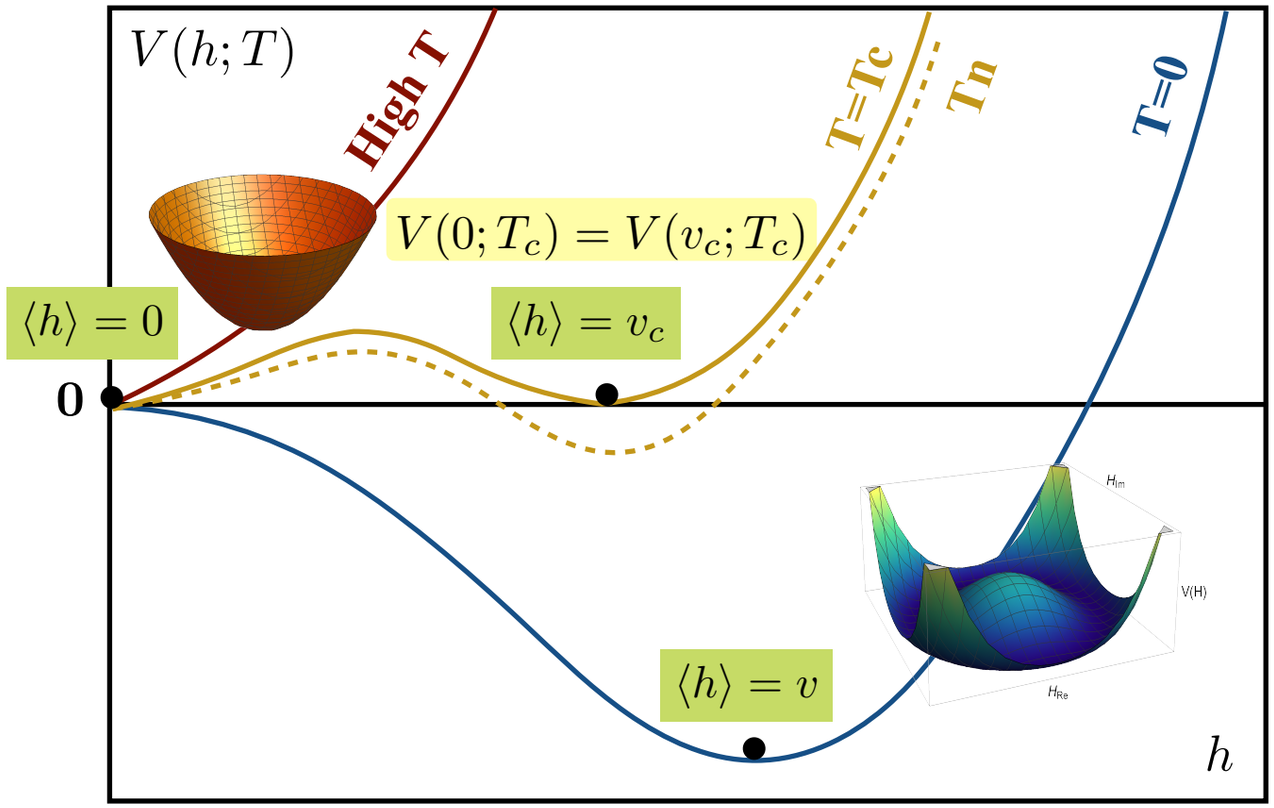

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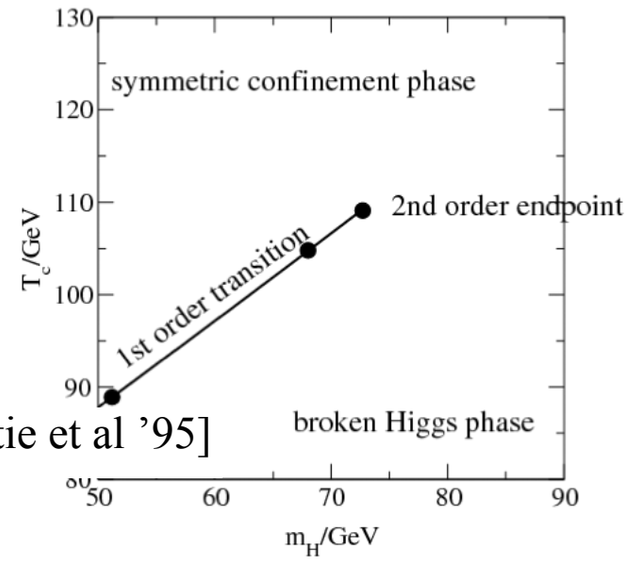

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In the **SM**, the electroweak symmetry broke through a cross over at finite T :' $v_c/T_c = 0'$.

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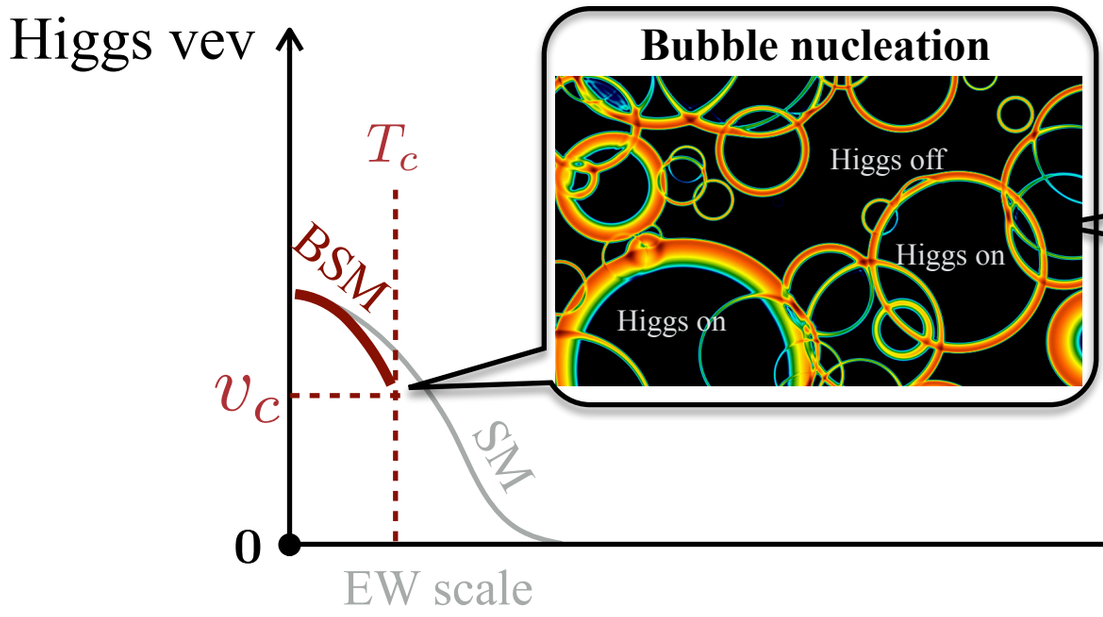

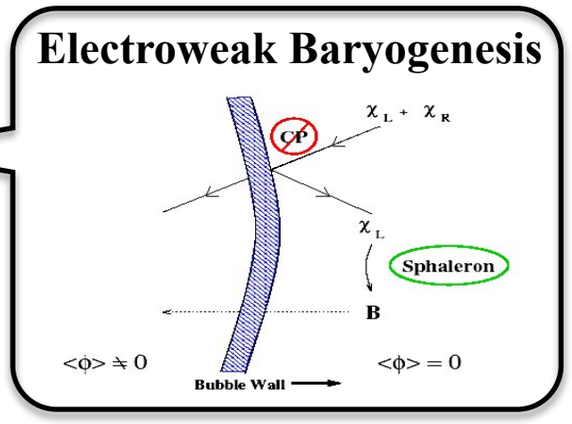

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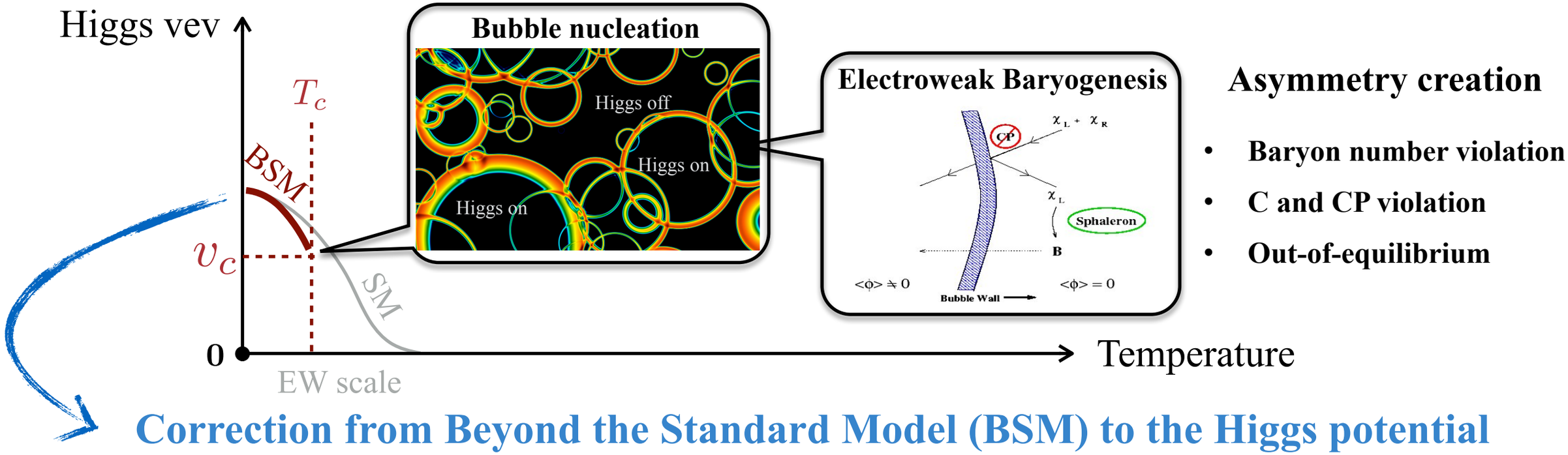

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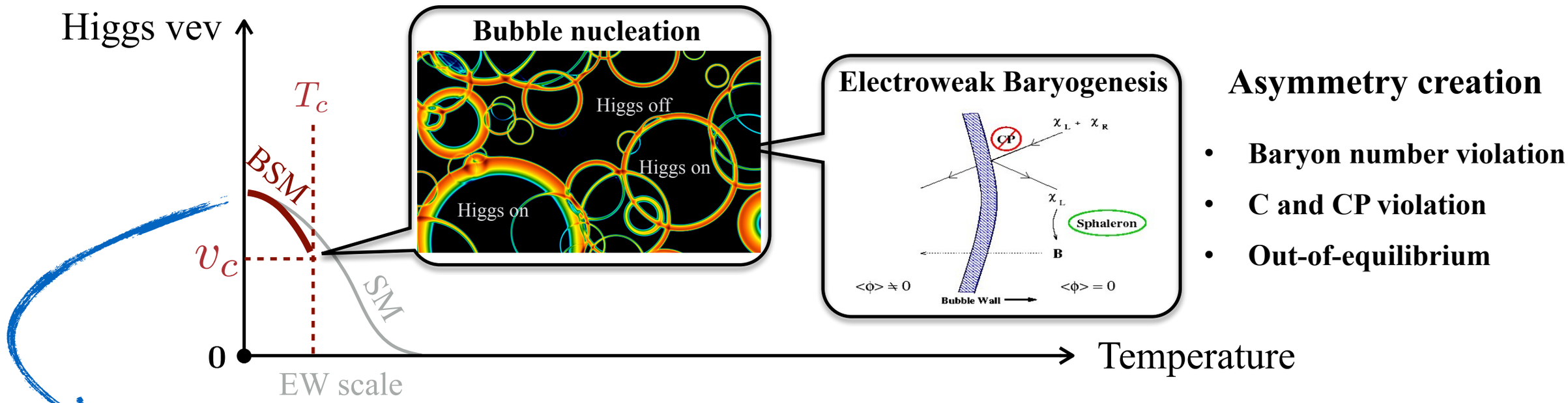

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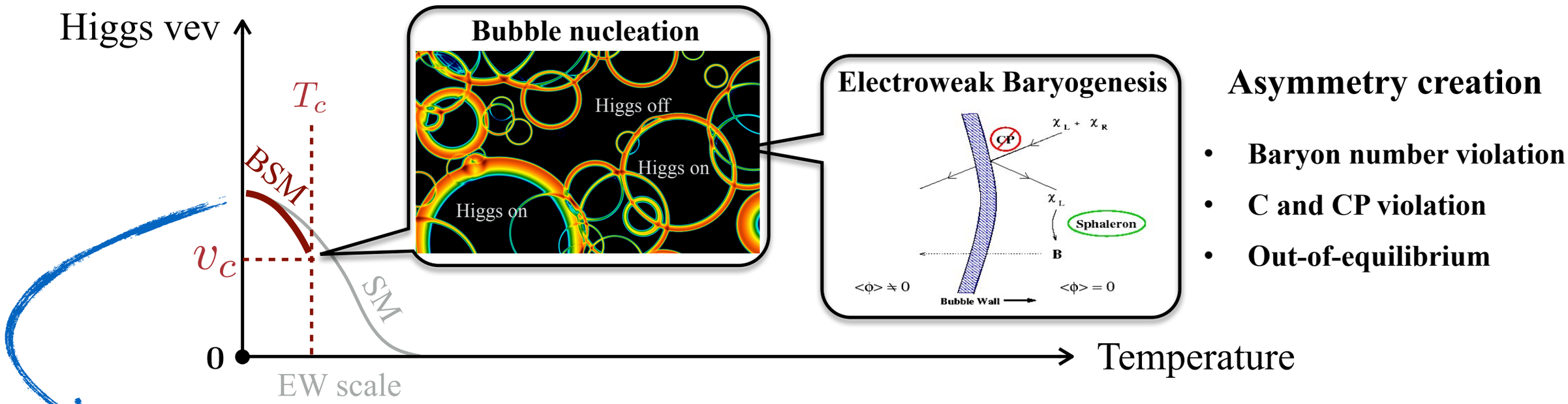

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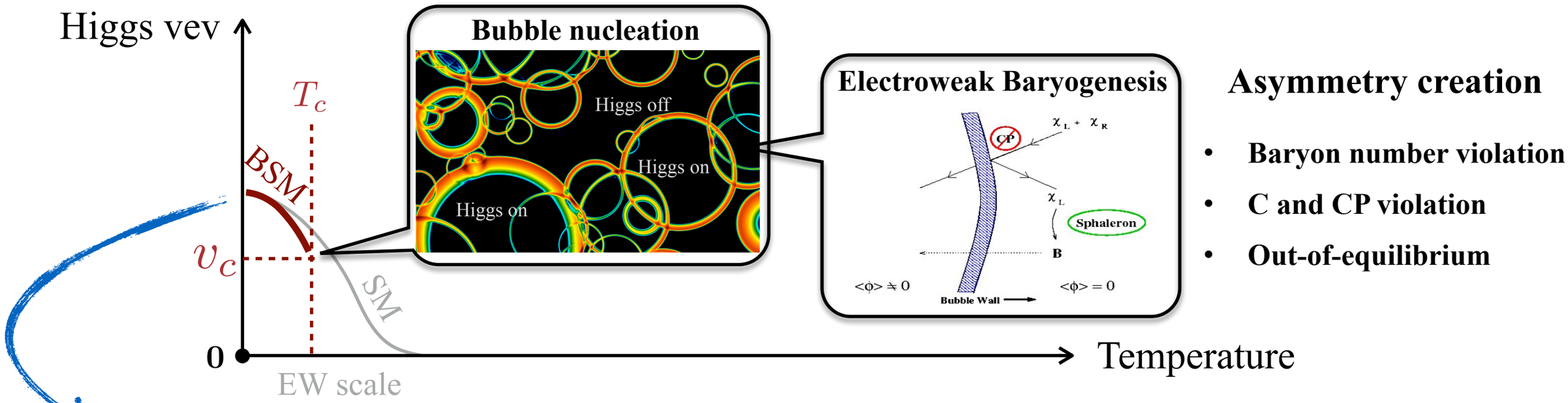

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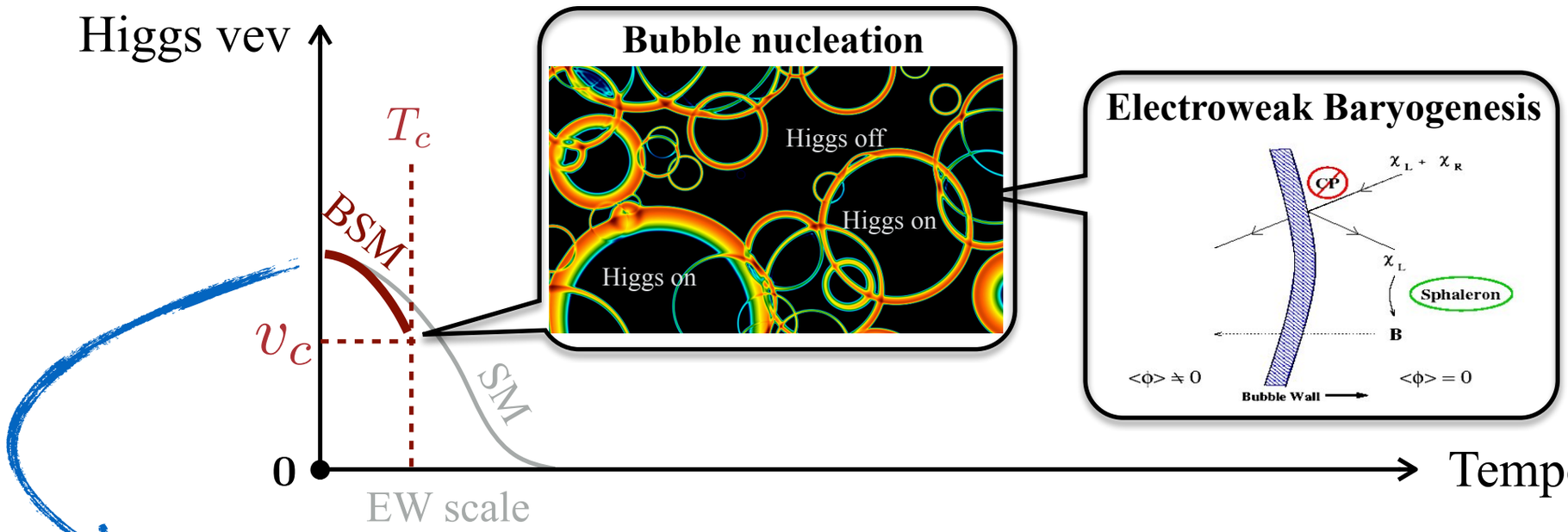

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- **Thermal effects**
- **Tree-level Effects**

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

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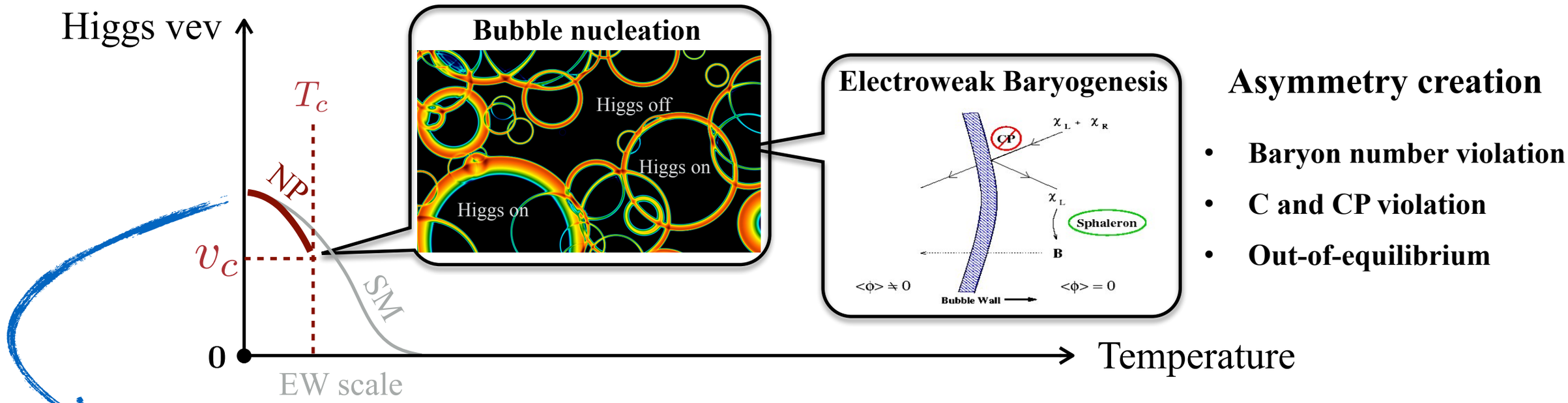

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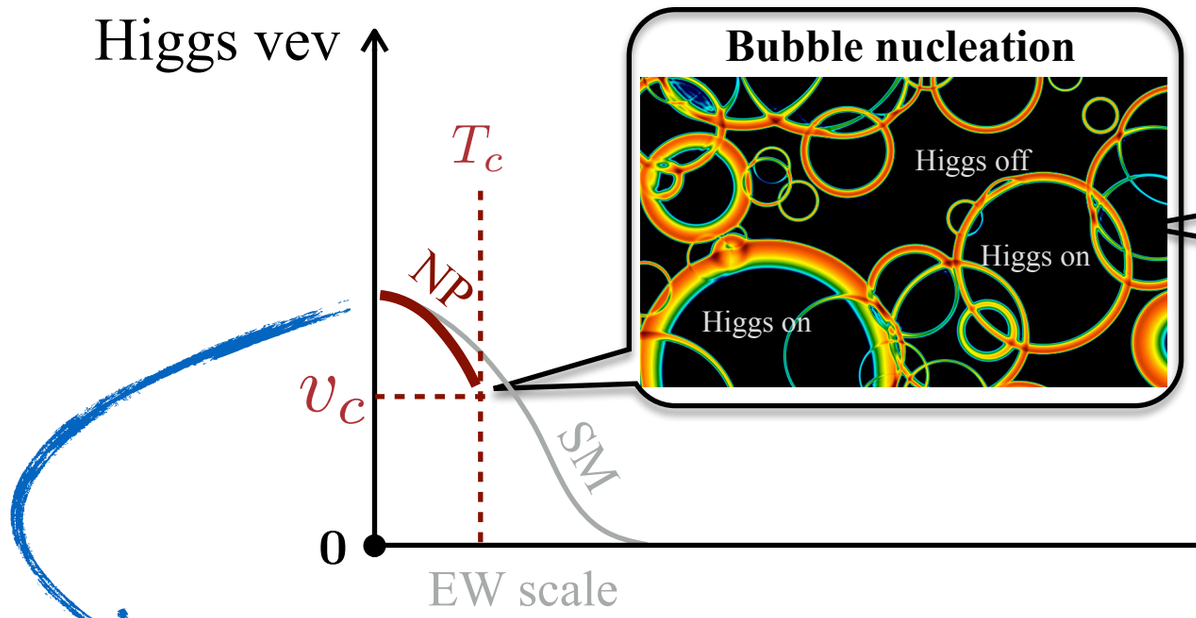

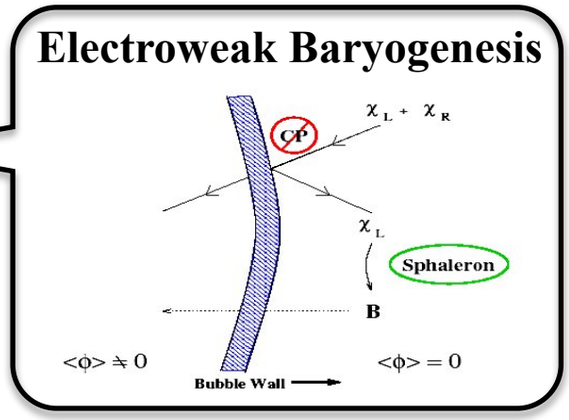

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"Radiative breaking"

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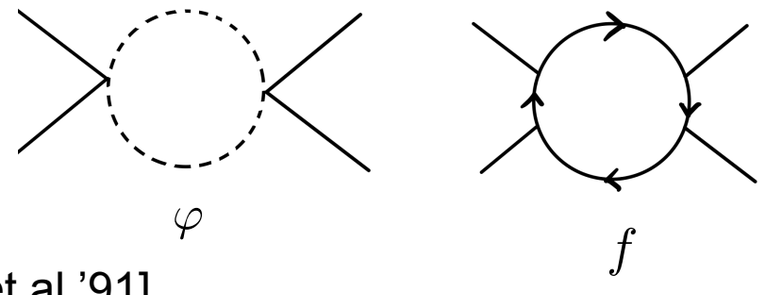
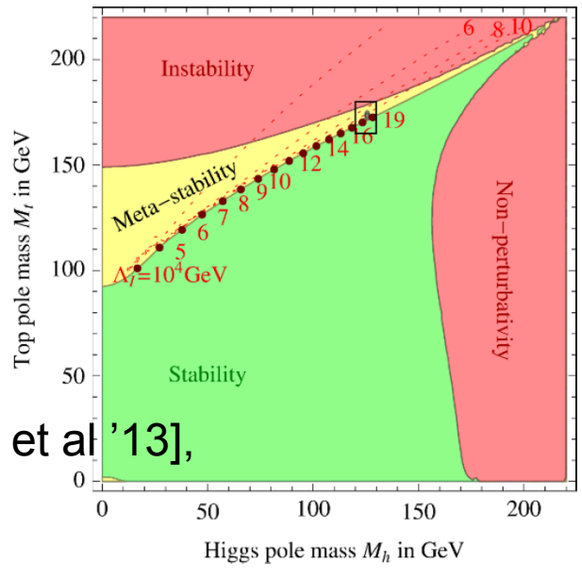


E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …



[Buttazzo et al '13],

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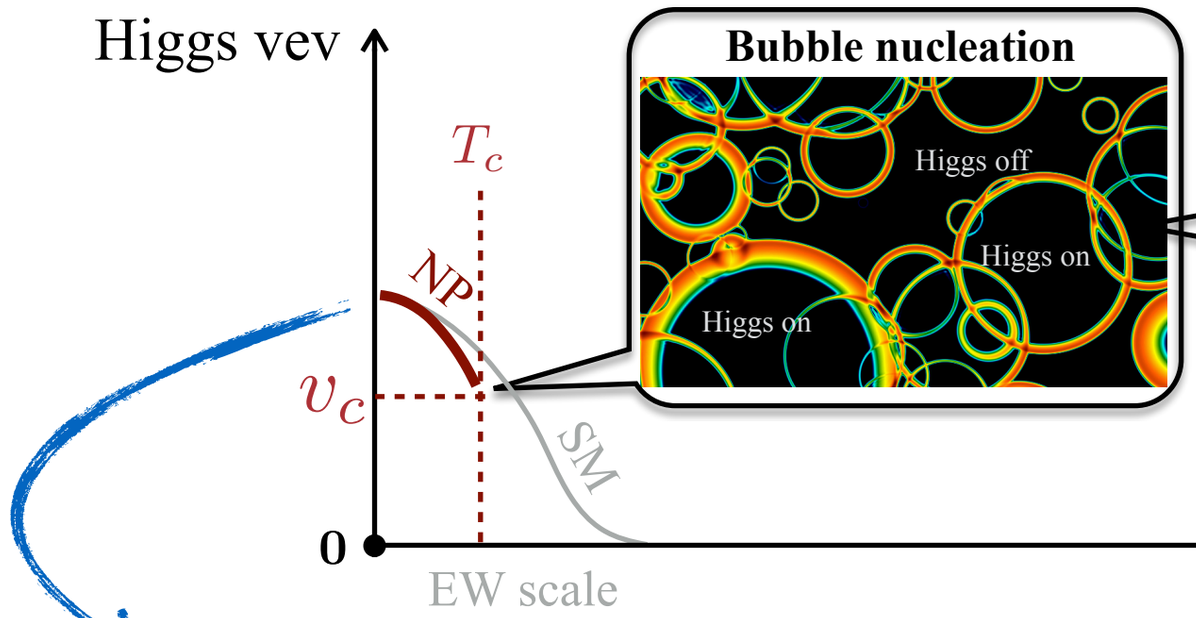

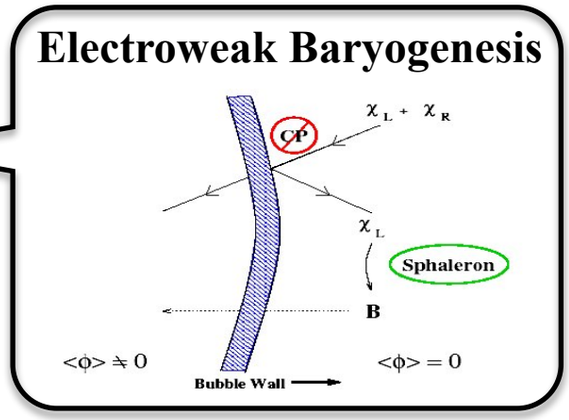

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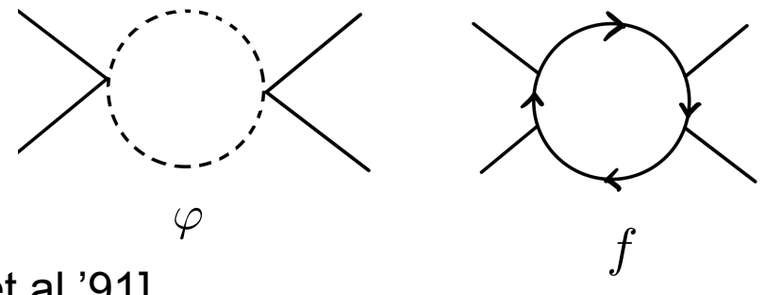

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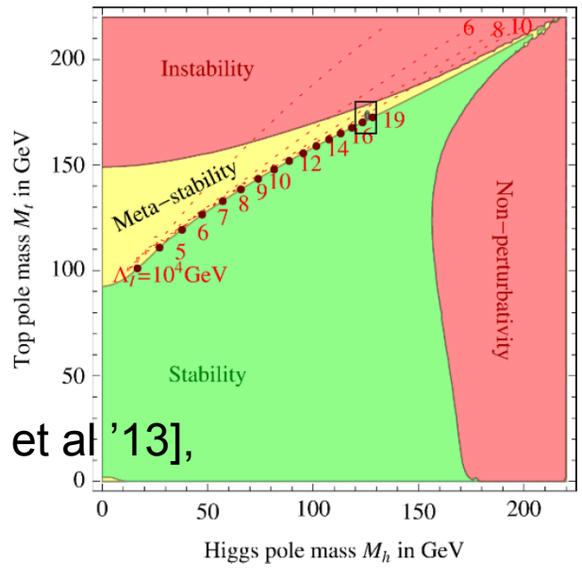

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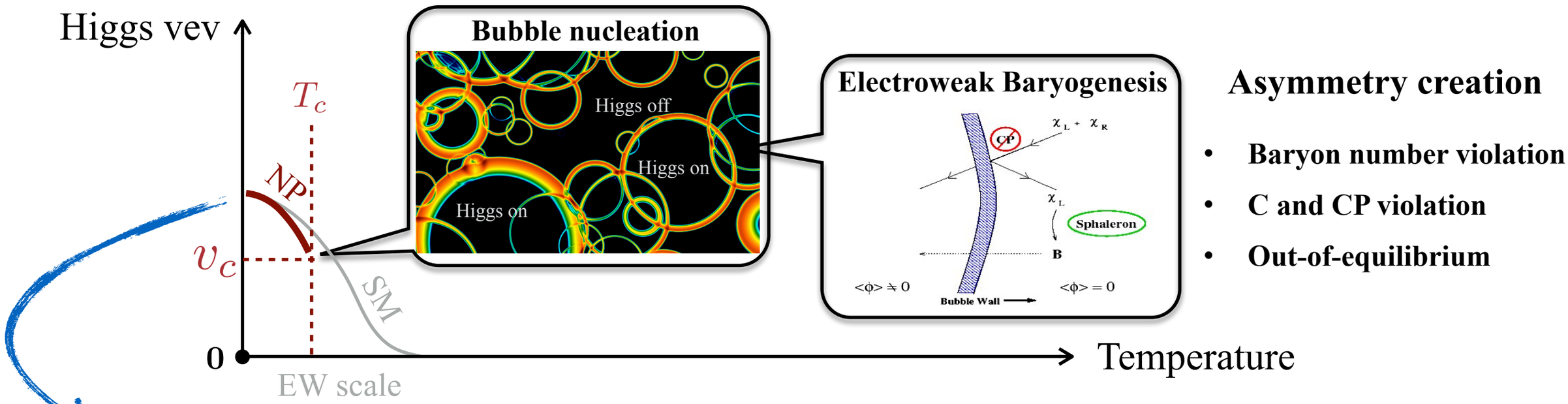

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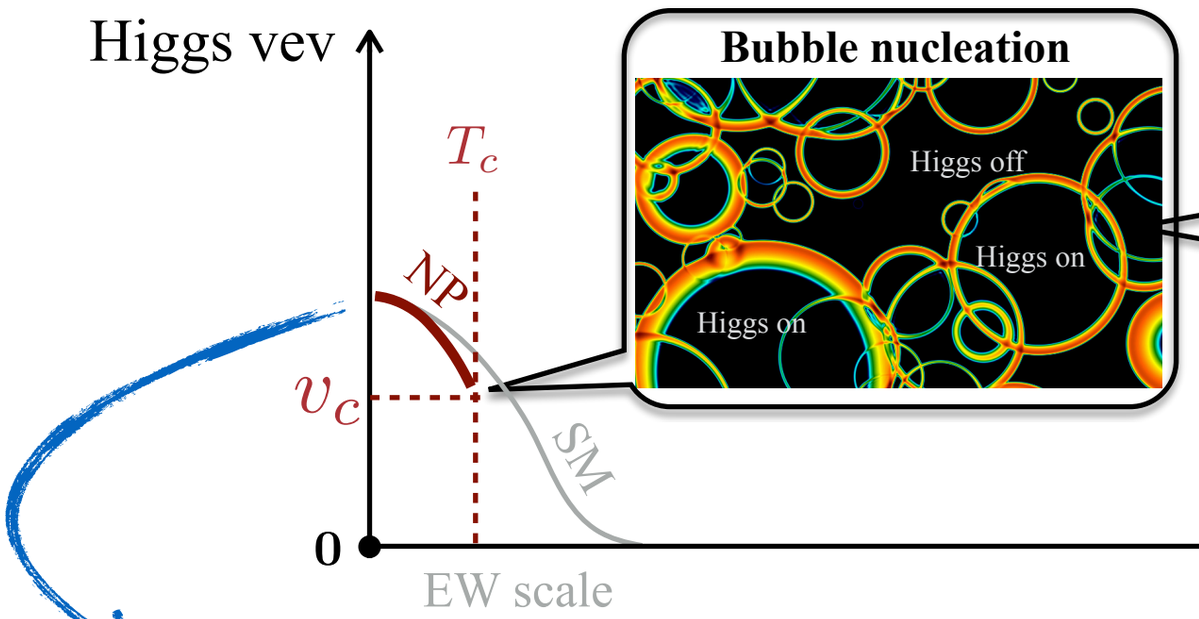

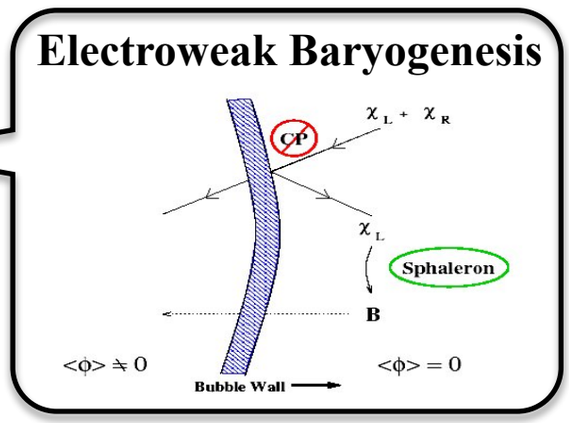

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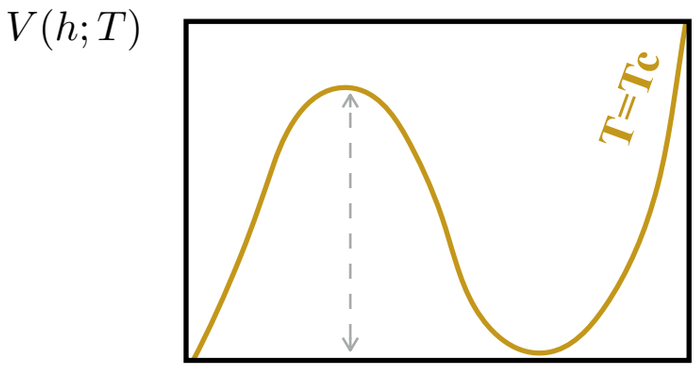

$$Eh^3 \sim \left(m_{\rm eff}(h,T_c)\right)^{3/2} \sim \lambda^{3/2}h^3$$

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

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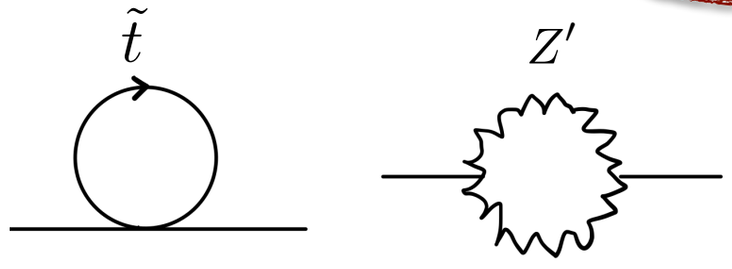

E.g. Supersymmetry (MSSM) with stop

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

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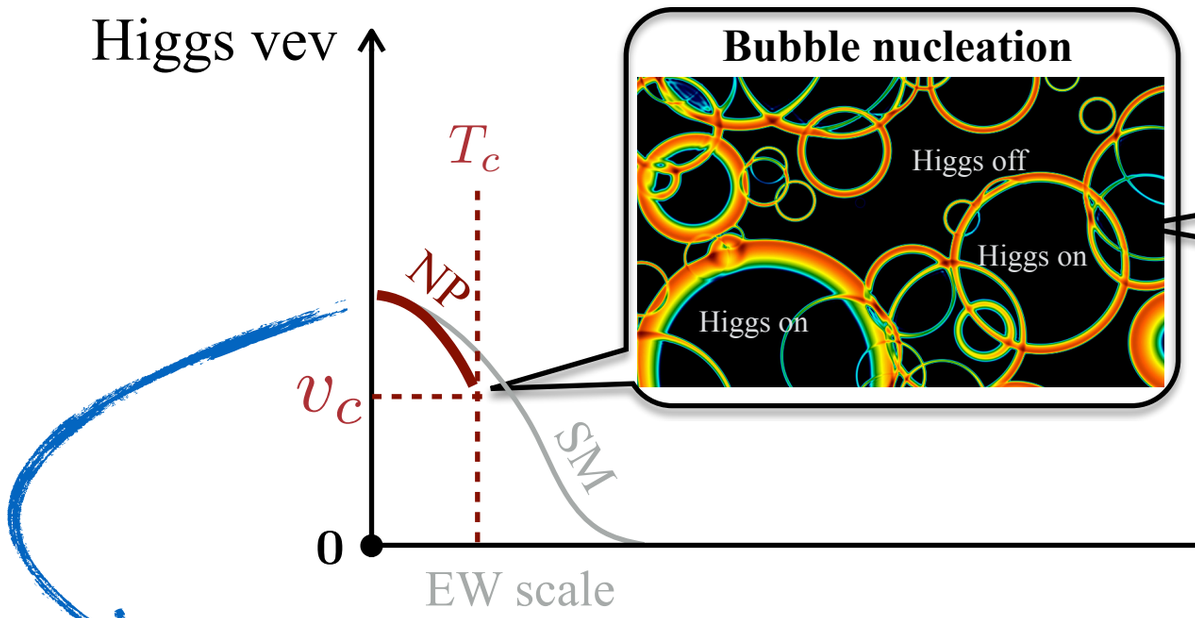

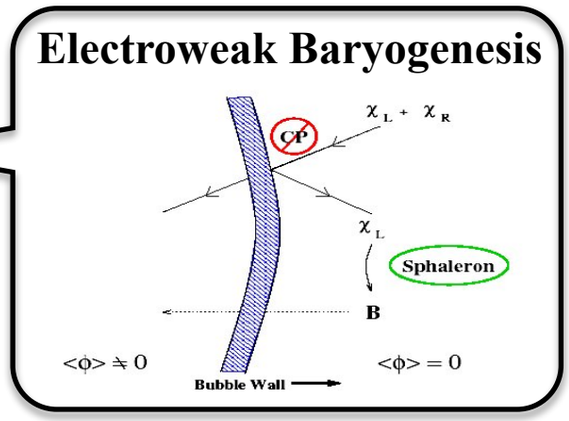

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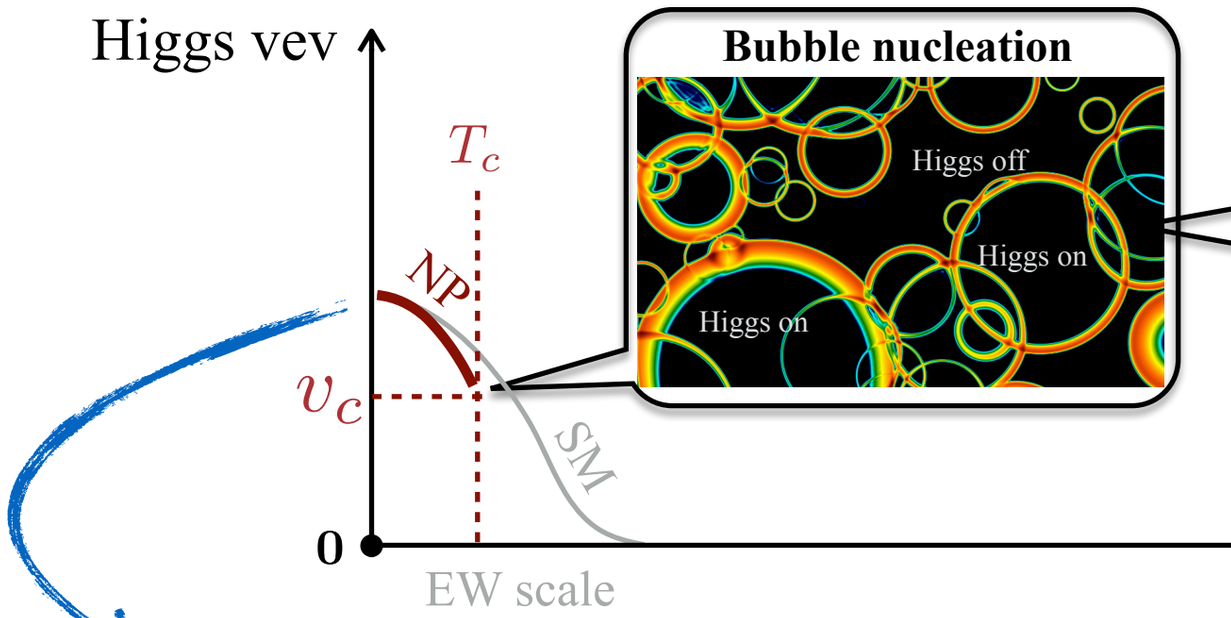

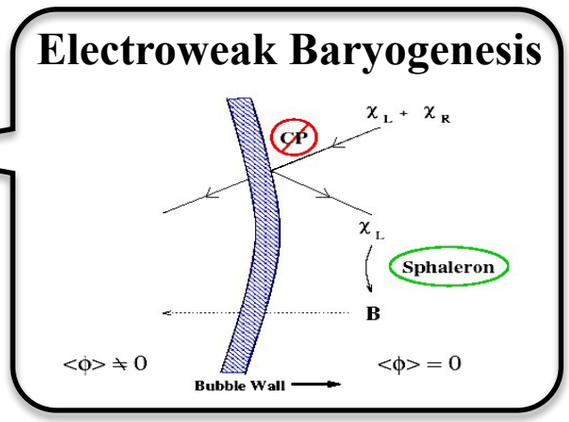

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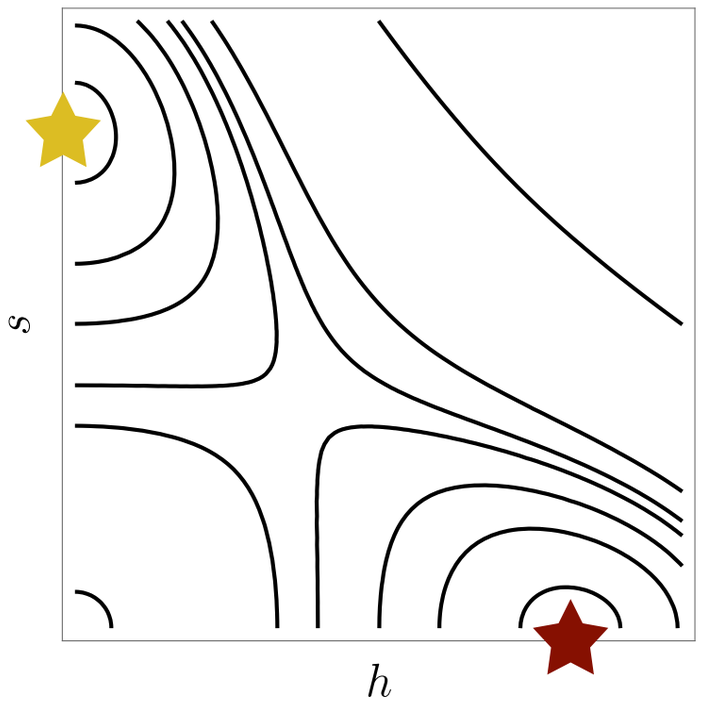

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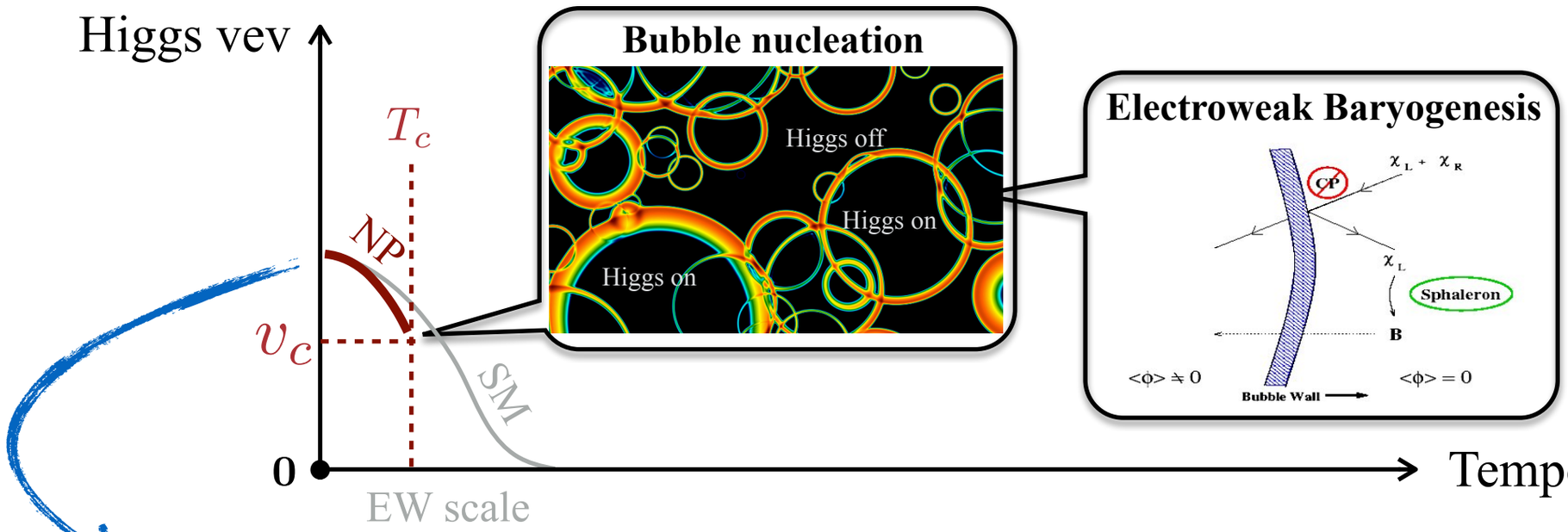

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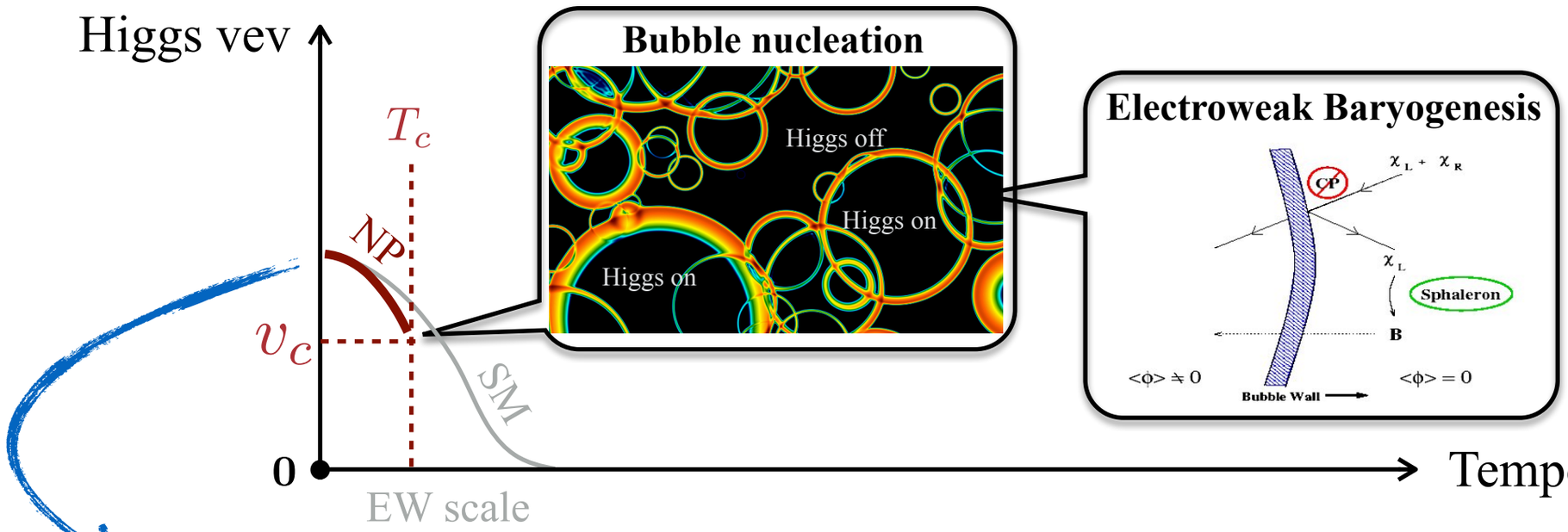

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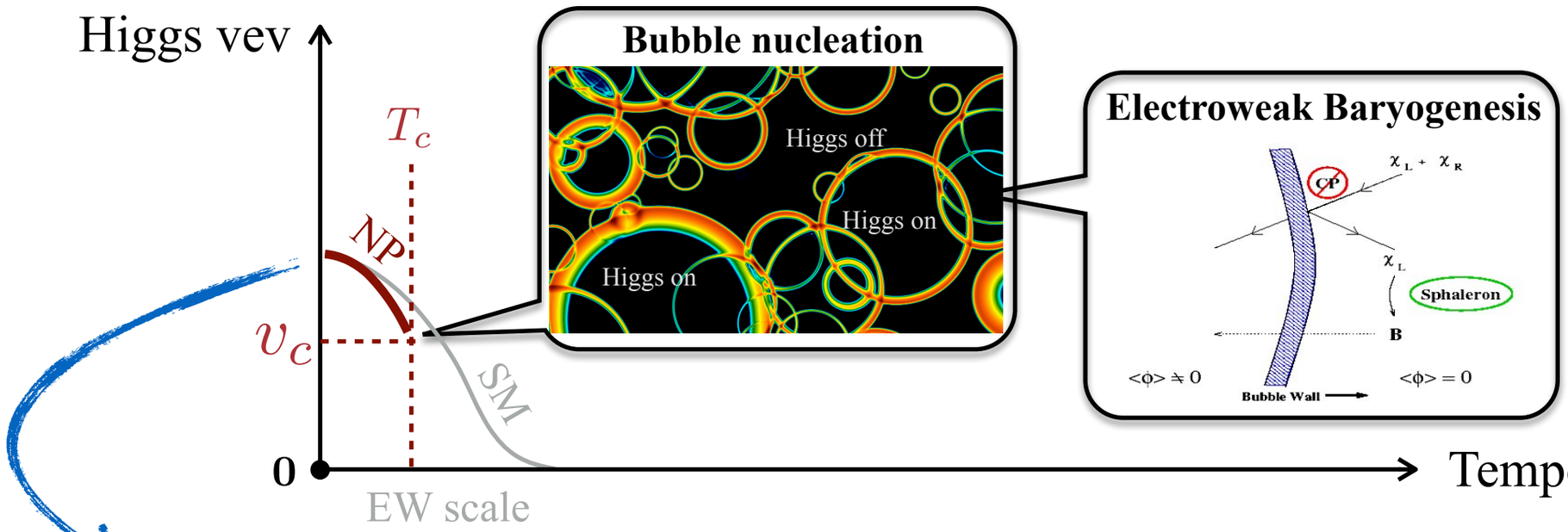

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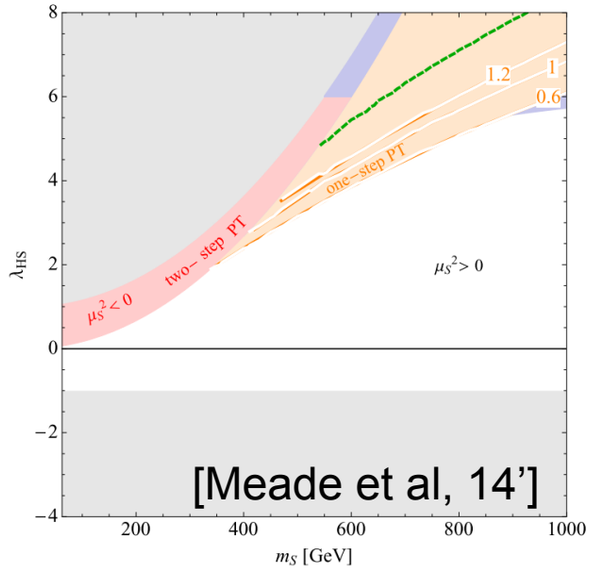
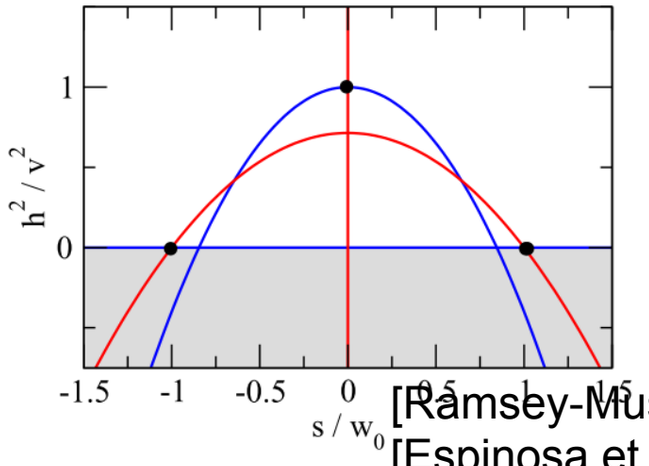
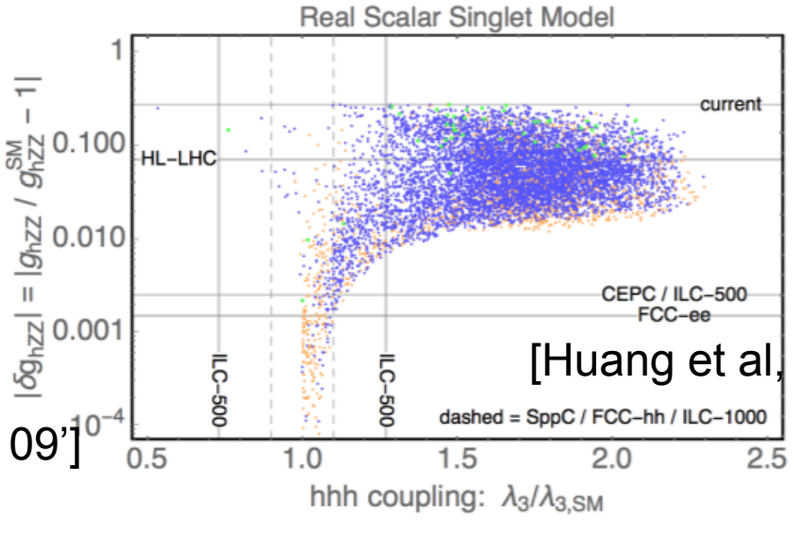


[Meade et al, 14']



[Ramsey-Musolf et al 09']
[Espinosa et al, 11']



[Huang et al, 14']

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

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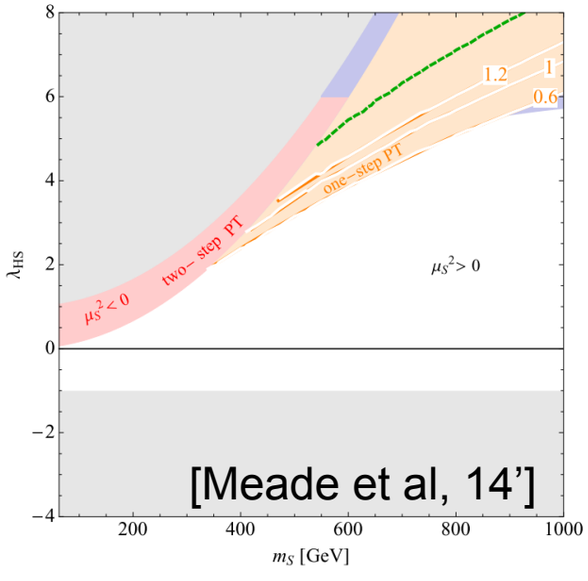
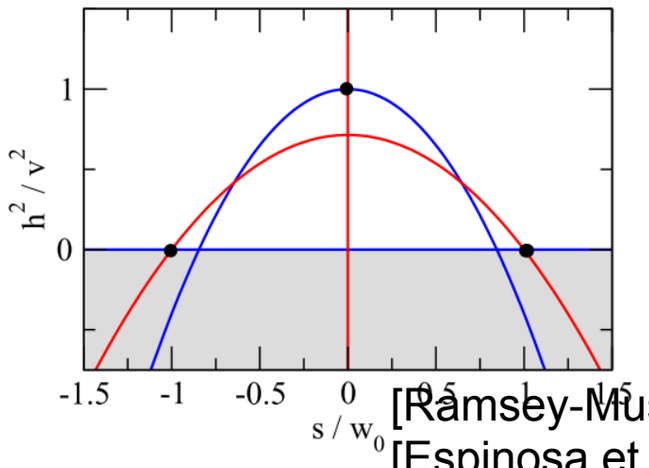


[Meade et al, 14']



[Ramsey-Musolf et al 09']
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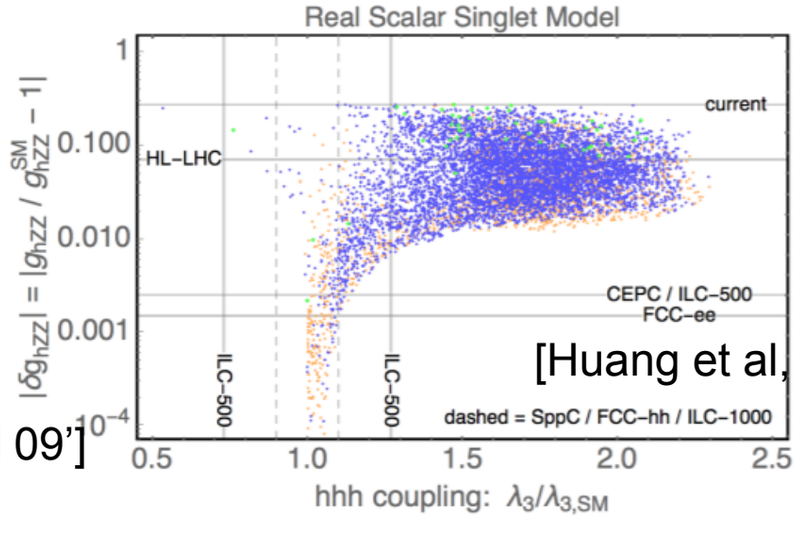

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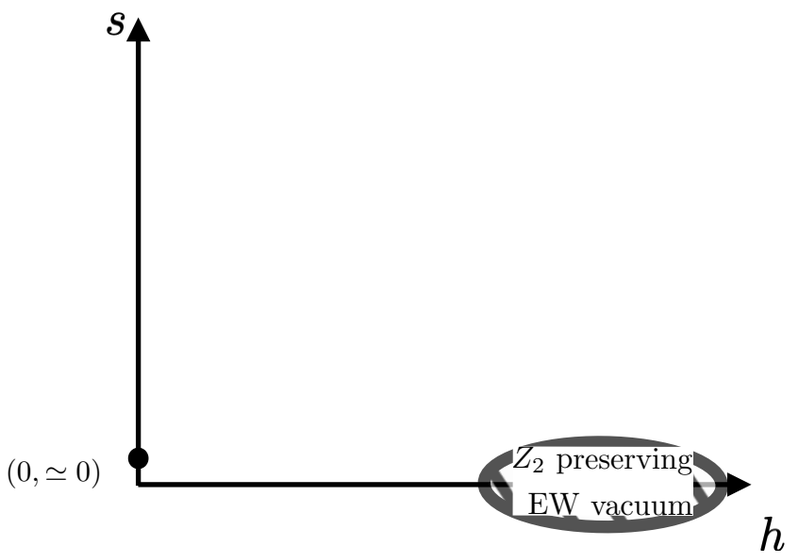
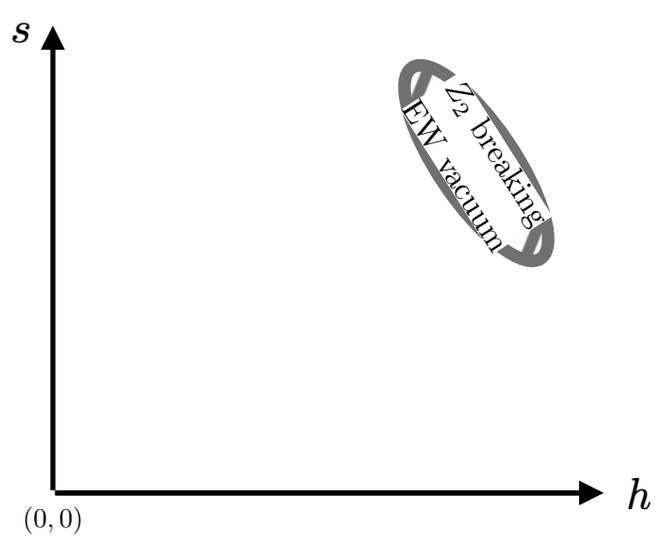


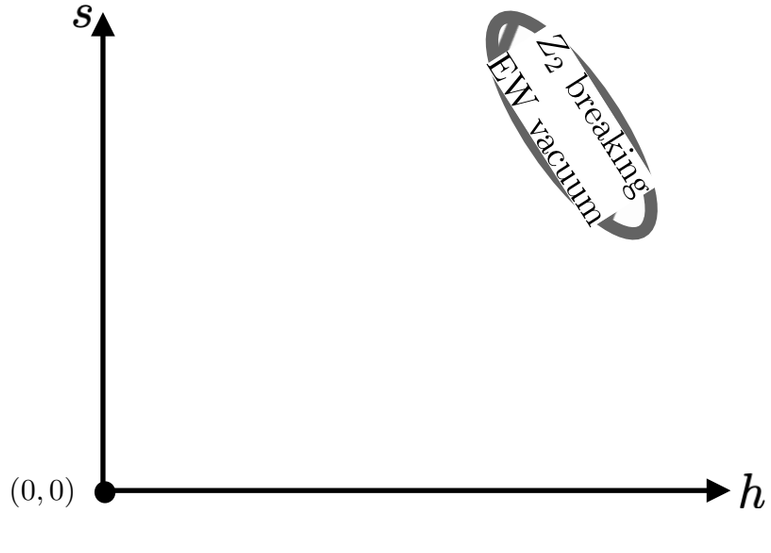
Z_2 preserving

Tree, loop



Z_2 breaking (explicit)

Tree



Z_2 breaking (spontaneous)

Tree

The singlet extension of the SM

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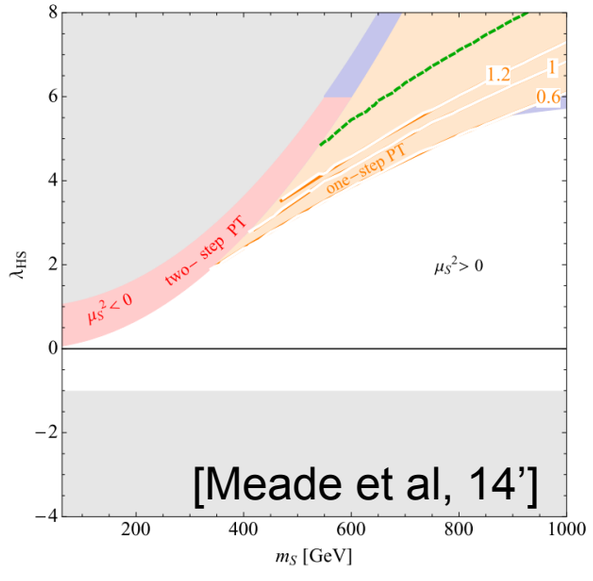

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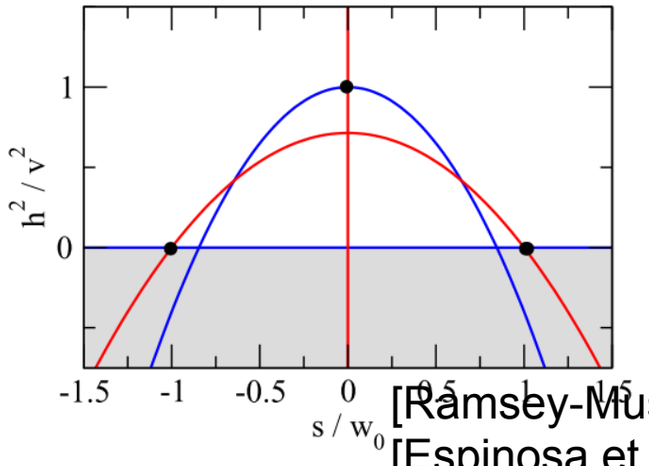

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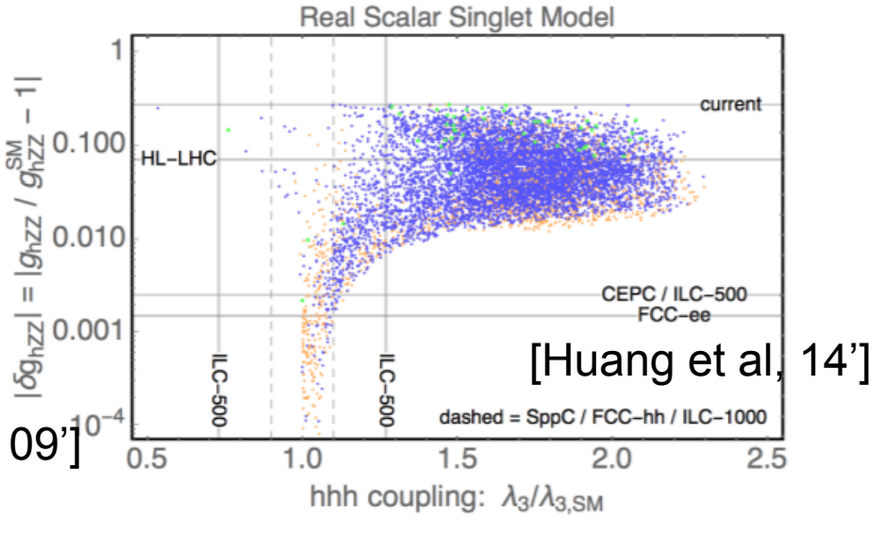

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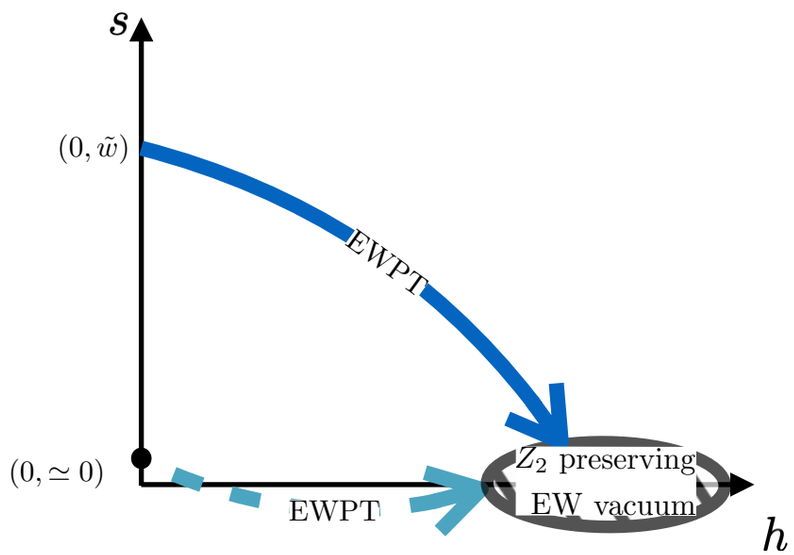

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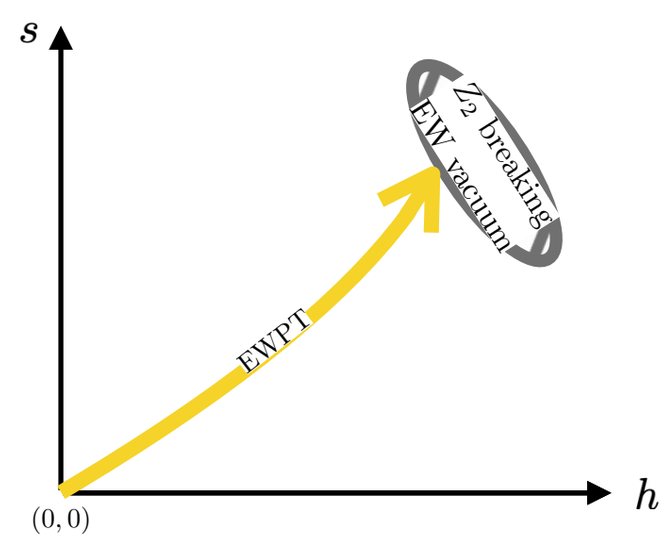
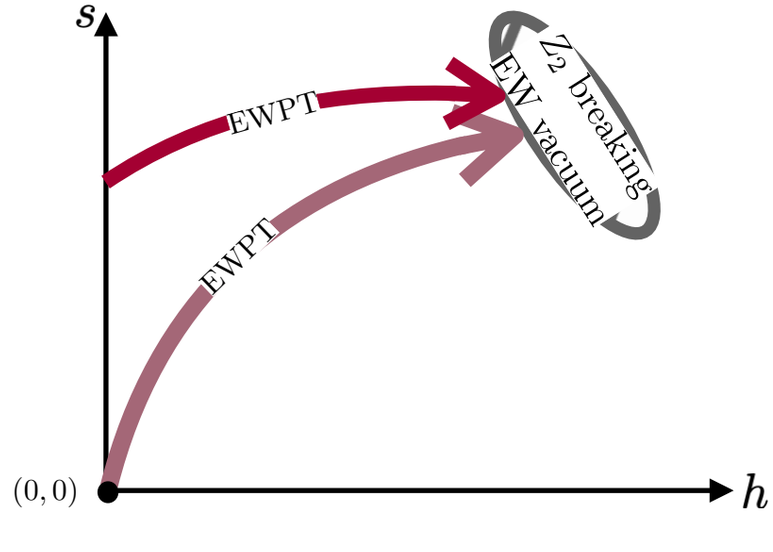


Z_2 breaking (explicit)

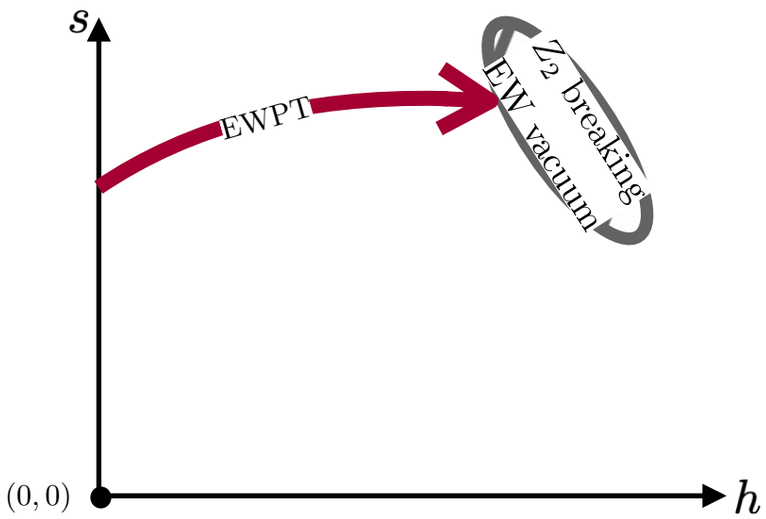
Tree



Z_2 breaking (spontaneous)

Tree

EWPT with spontaneous Z2-breaking [Carena, Liu, Y.W. '19]



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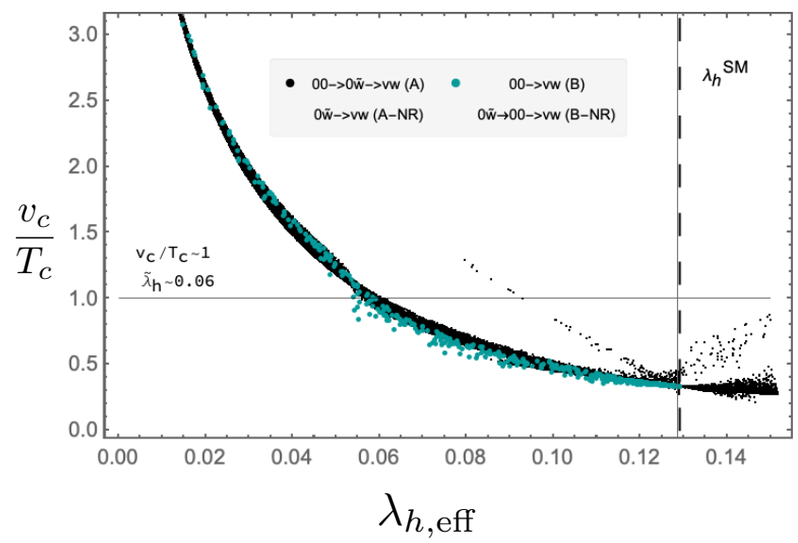

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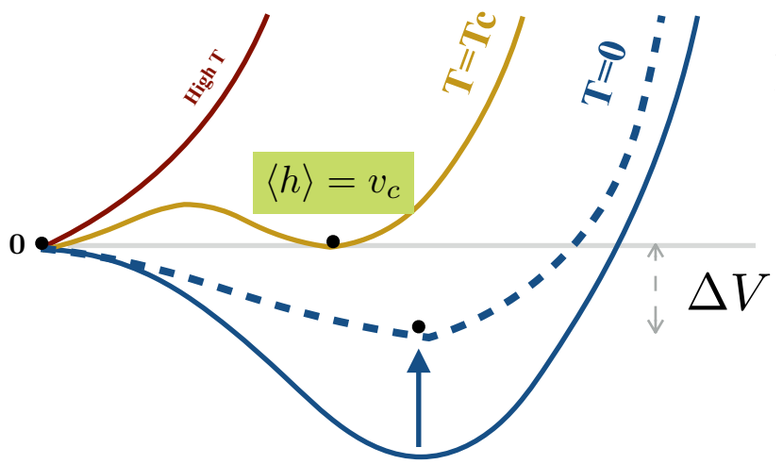

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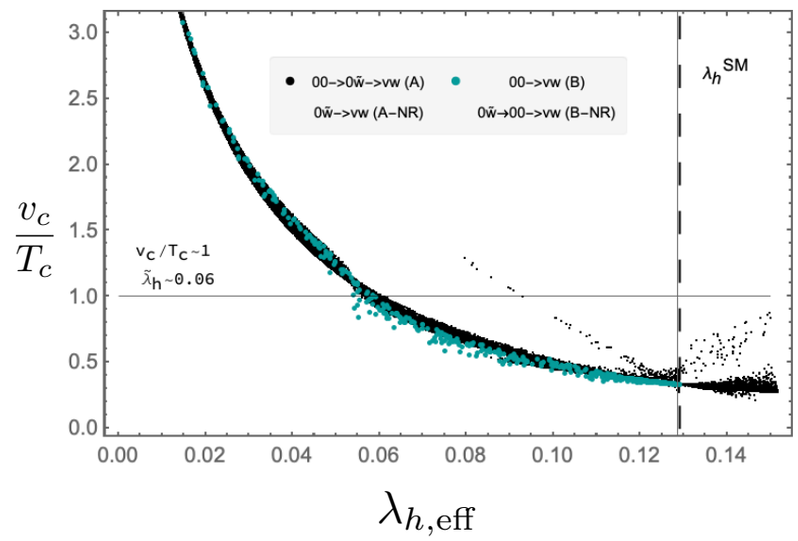

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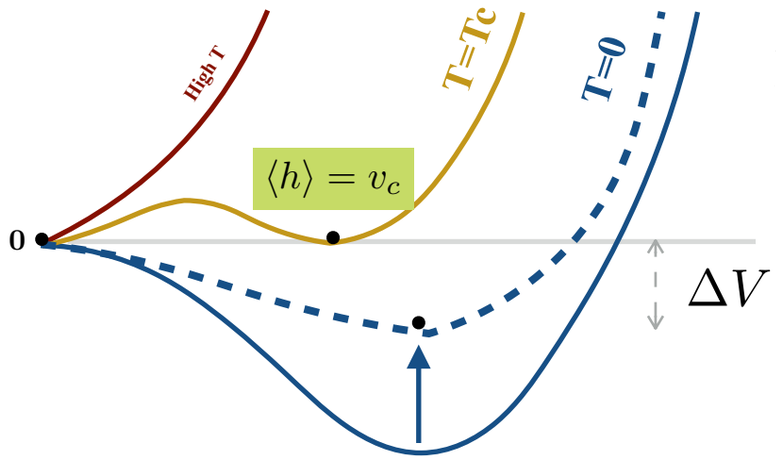

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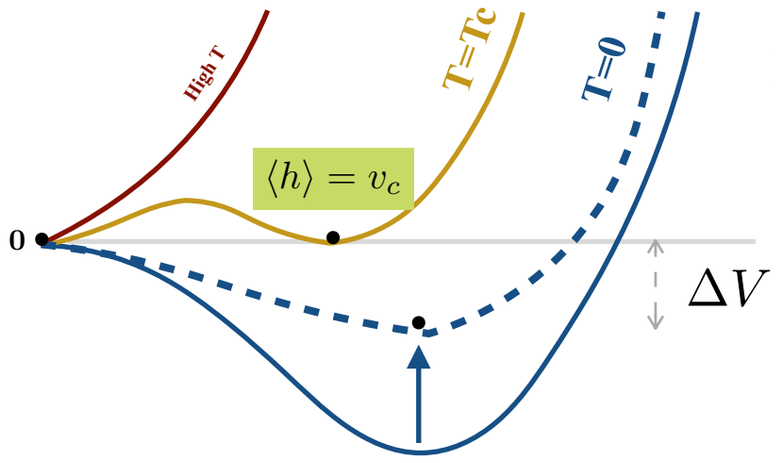

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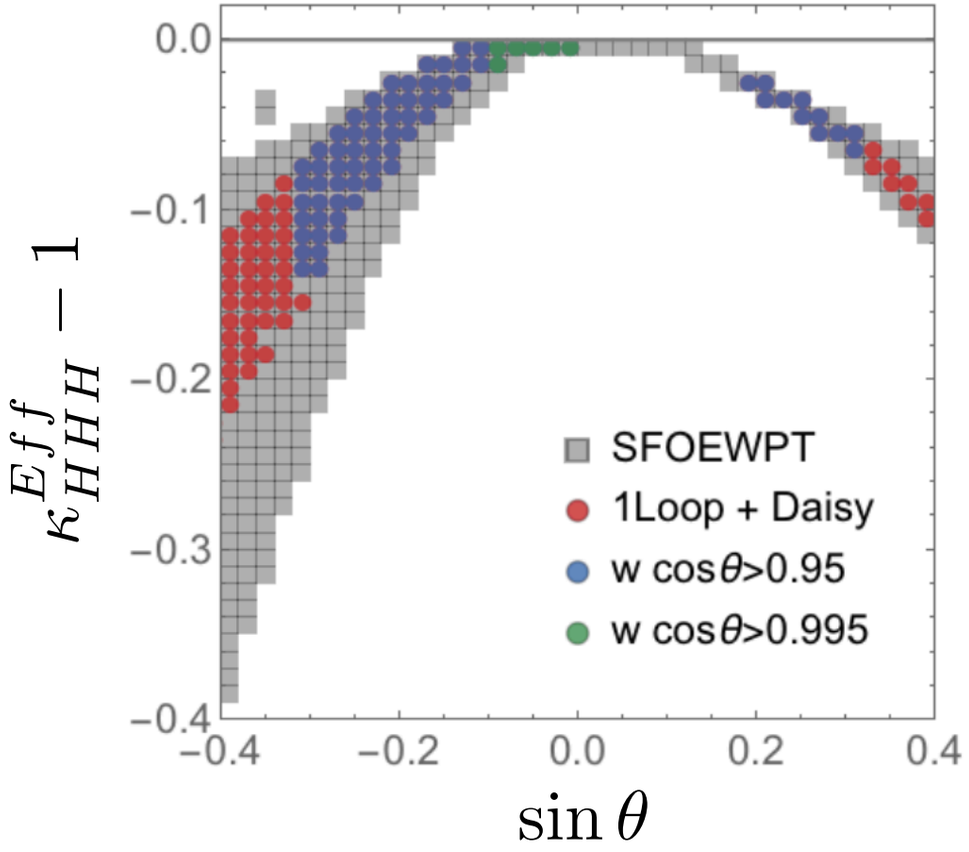
Higgs pair production



$$\Lambda_{HHH} = \frac{m_H^2\left(-\sin^3\theta + \tan\beta\cos^3\theta\right)}{2\tan\beta\ v}$$

$$\Lambda_{SHH} = \frac{(2m_H^2 + m_S^2)(\sin\theta + \tan\beta\cos\theta)\sin 2\theta}{4\tan\beta\ v}$$

$$\kappa_{HHH}^{Eff} \equiv \frac{\Lambda_{HHH}^{Eff}}{\Lambda_{HHH}^{SM}}$$

EWPT with spontaneous Z2-breaking [Carena, Liu, Y.W. '19]

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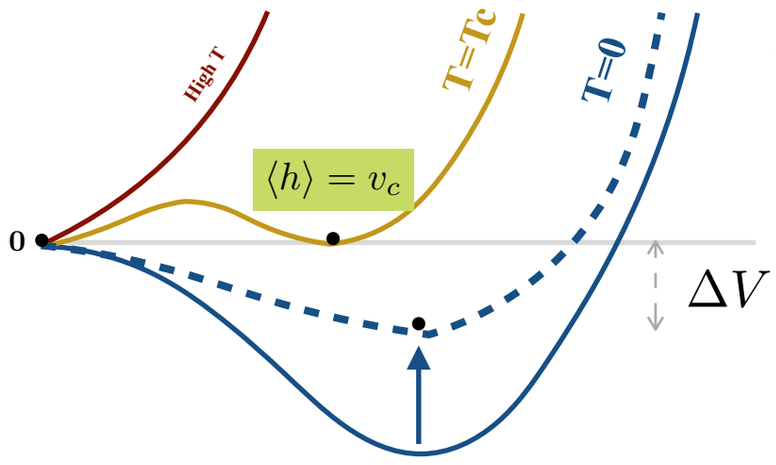

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Probing the EWPT with exotic Higgs decays

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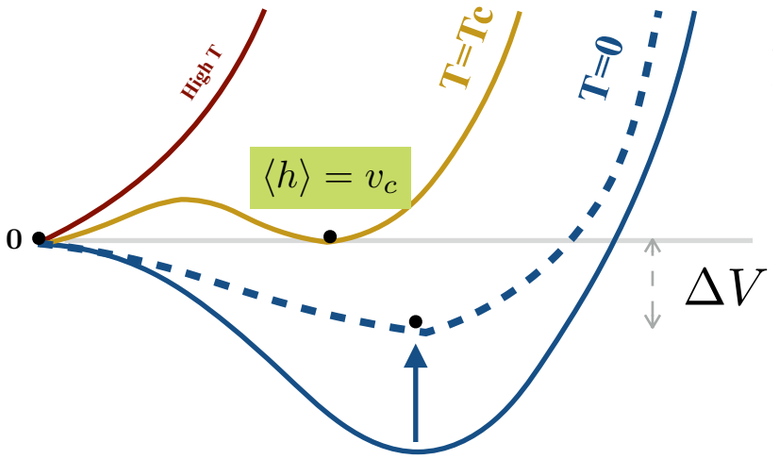

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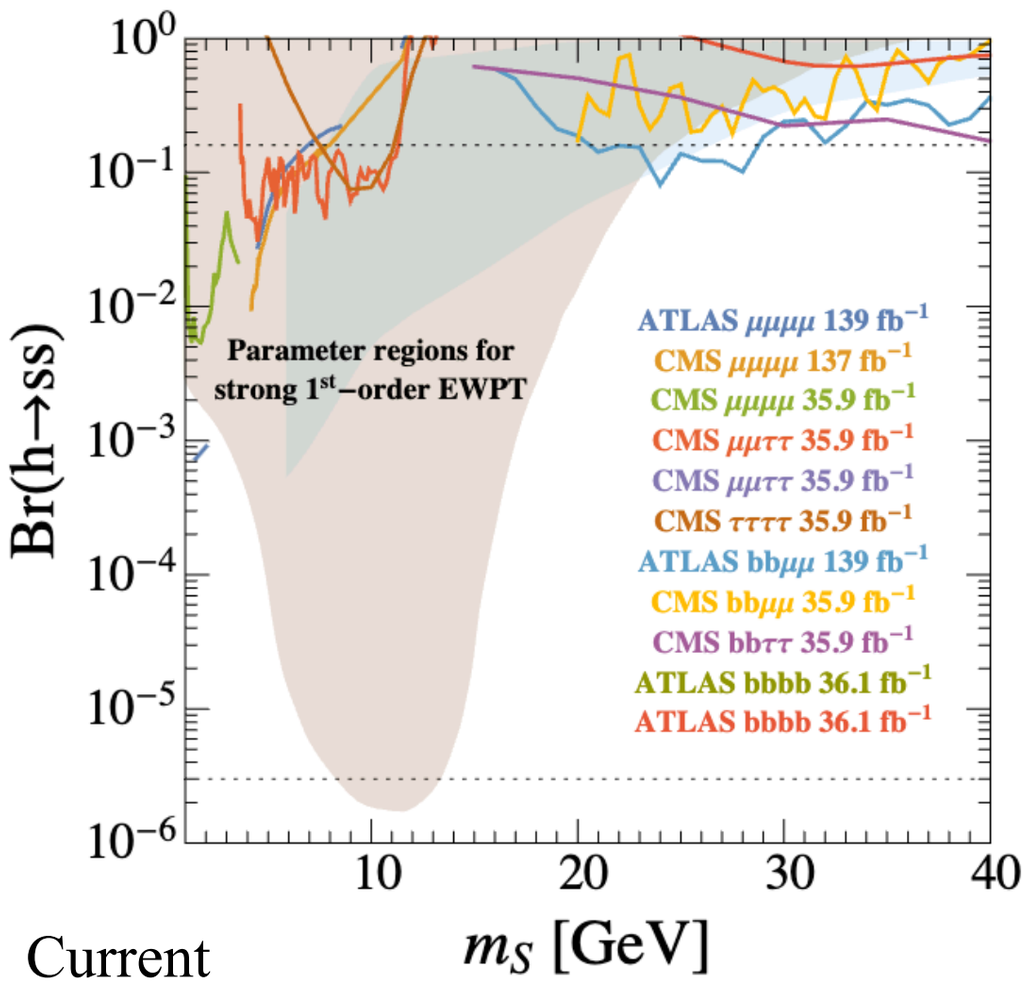

Current

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- **A firm prediction of a light scalar**
- $\text{BR}(H \to SS)$ **to be bounded from below**

Observation window: Higgs exotic decay

[Kozaczuk, et al, 19']

[Carena, et al, 22']

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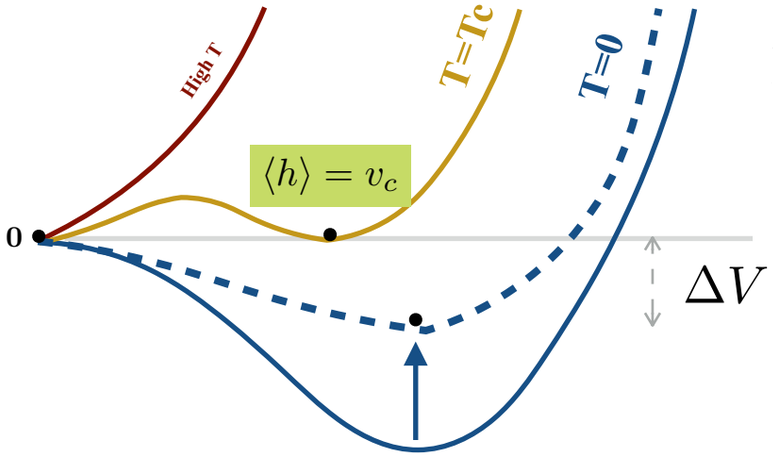

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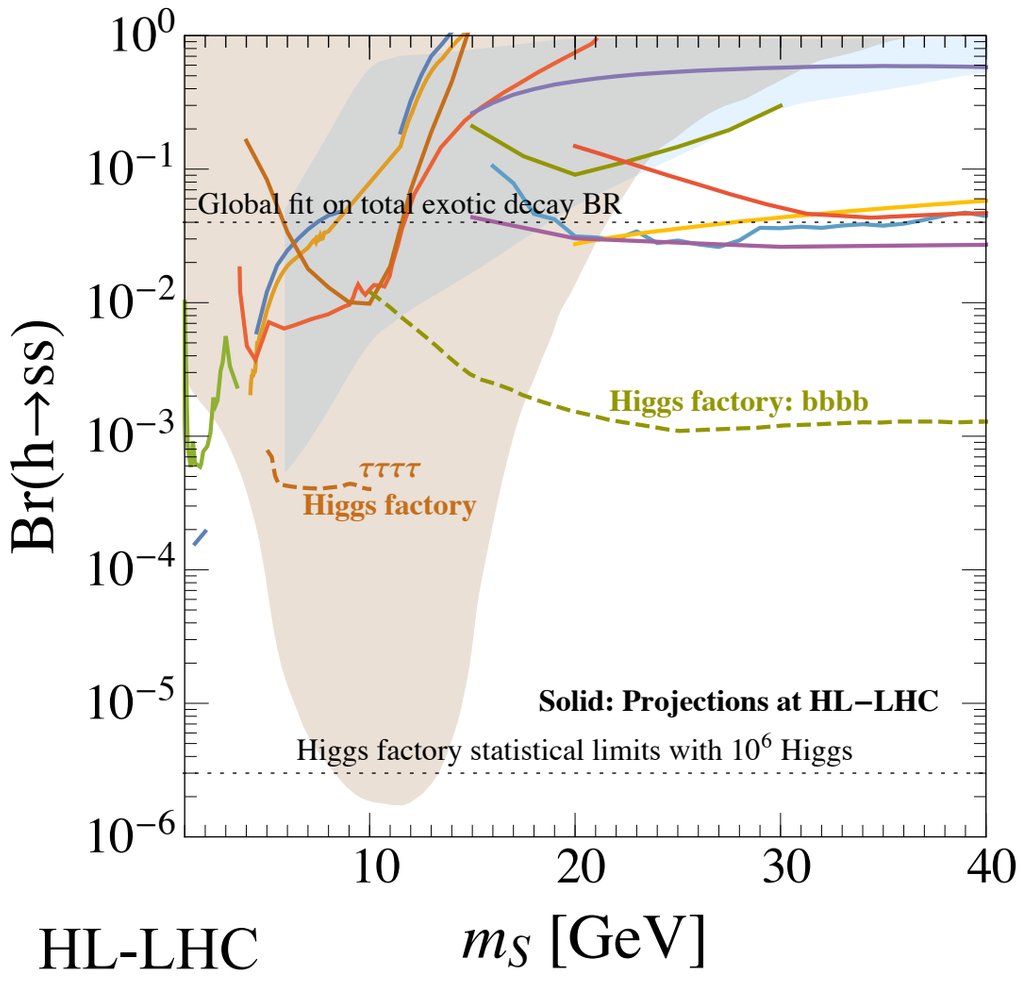

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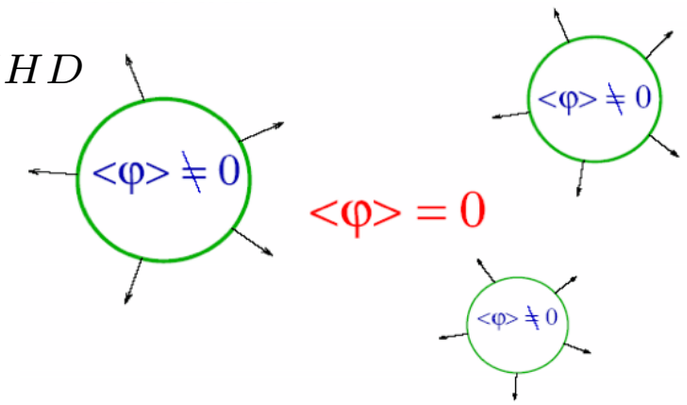
A new probe to SFOEWPT: the gravitational wave signals

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

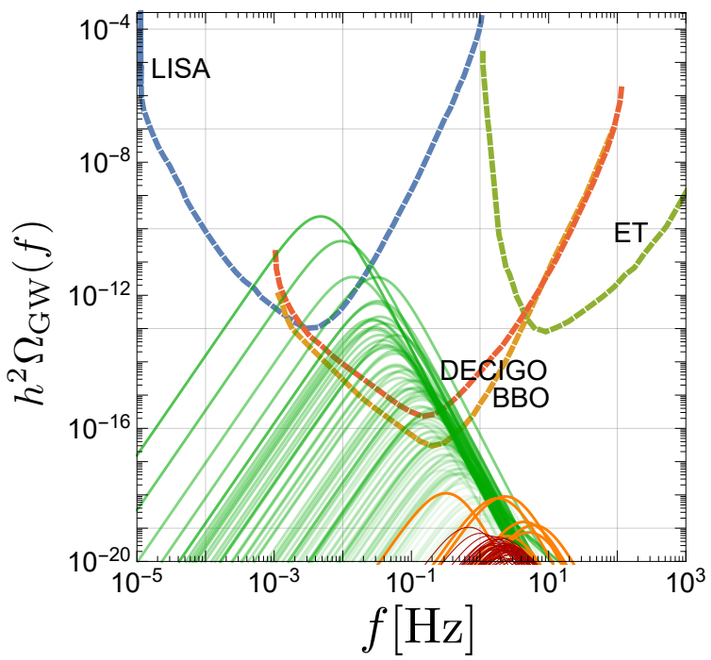
$$\alpha = \left.\frac{\rho_{\tilde{v},\tilde{w}} - \rho_{v,w}}{\rho_{rad}}\right|_{T=T_*}$$

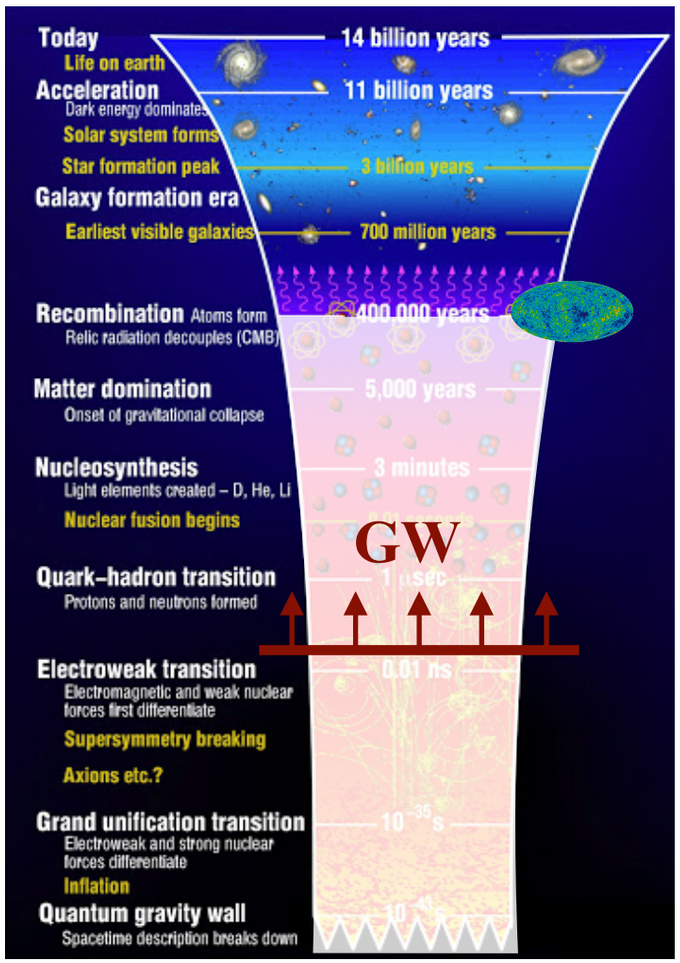
- **The bubble wall velocity** v_w

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

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

Power spectrum of GWs from a SFOEWPT





Electroweak symmetry non-restoration

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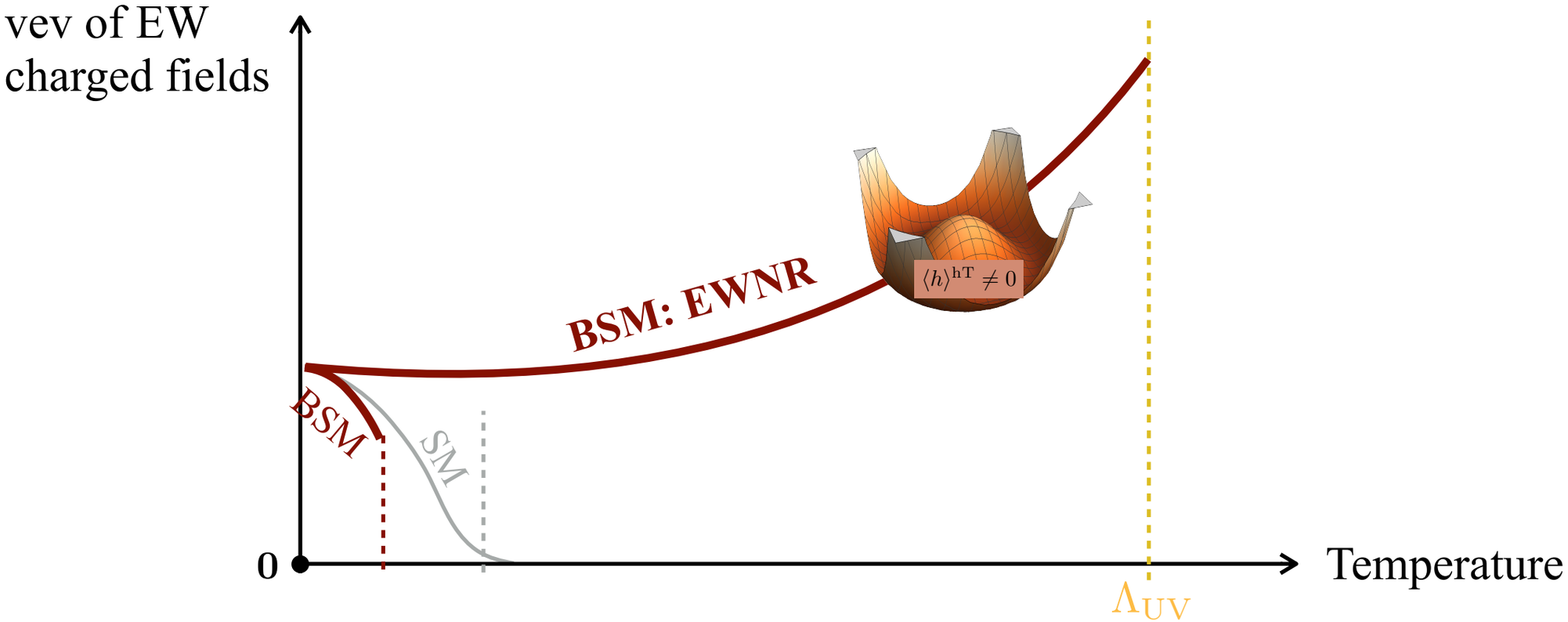

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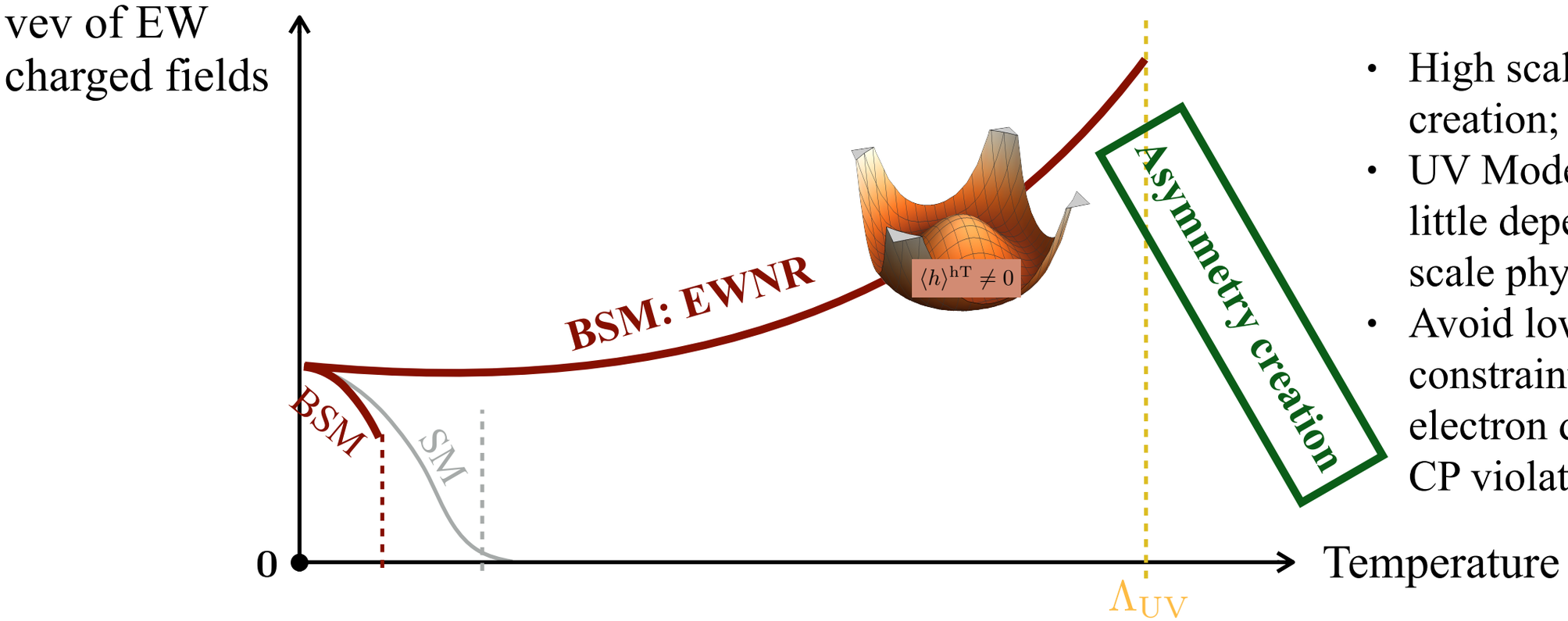

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- UV Model building has little dependence on EW scale physics;
- Avoid low scale constraints such as electron dipole moment on CP violation;

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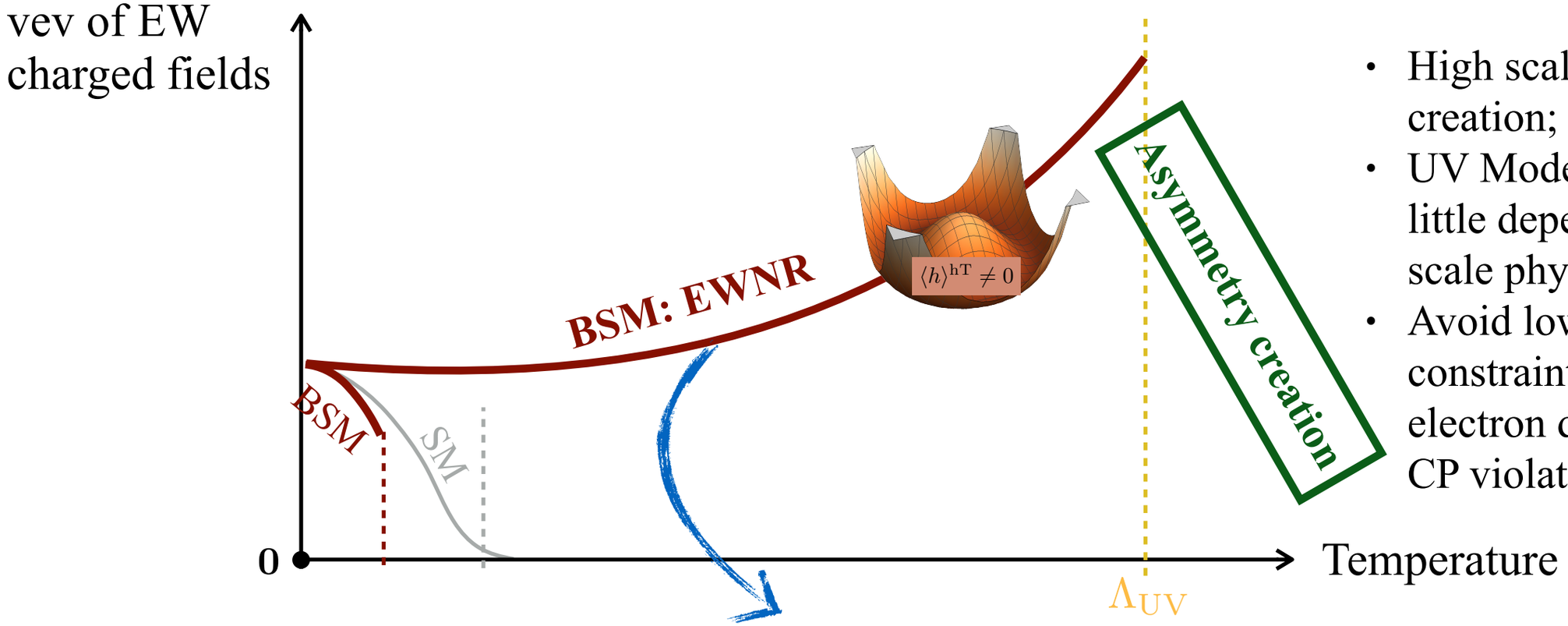

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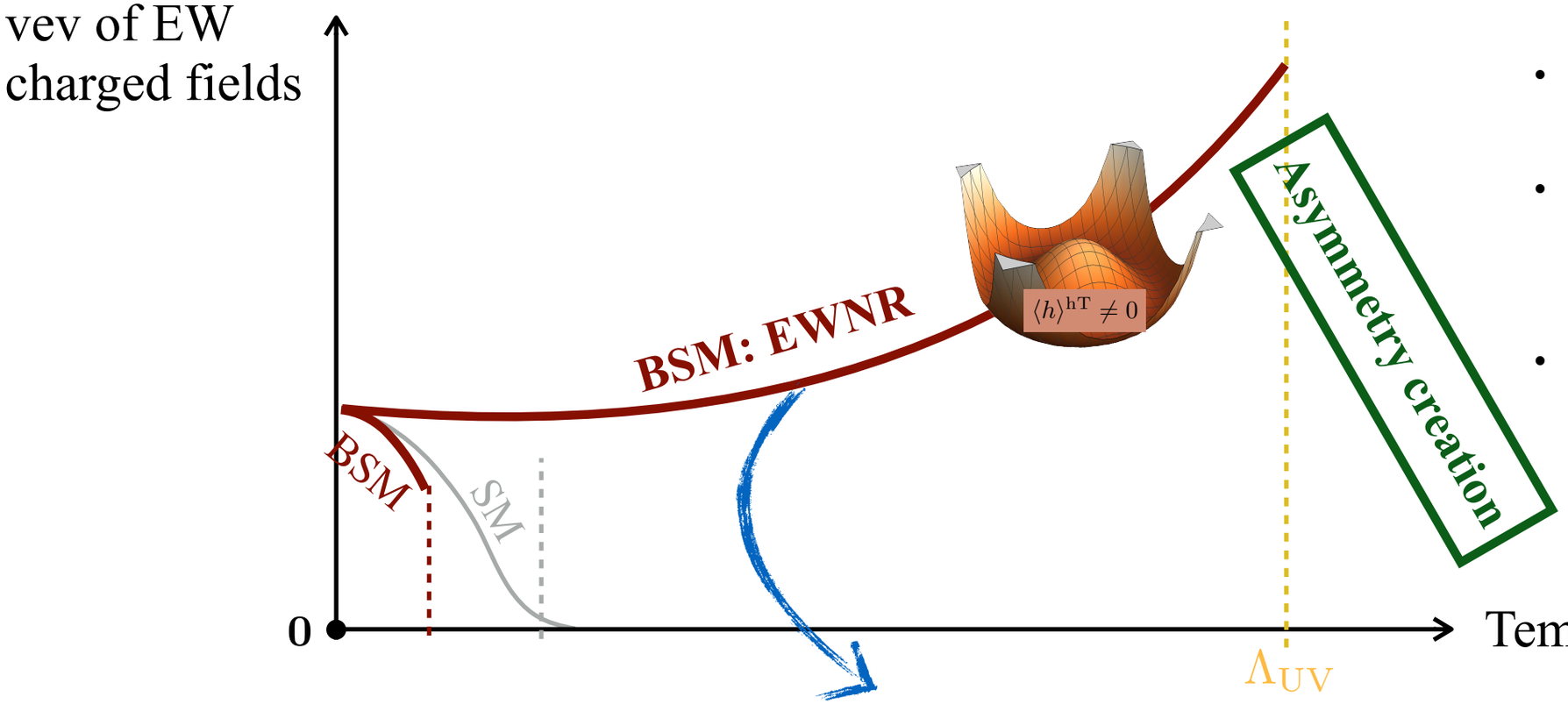

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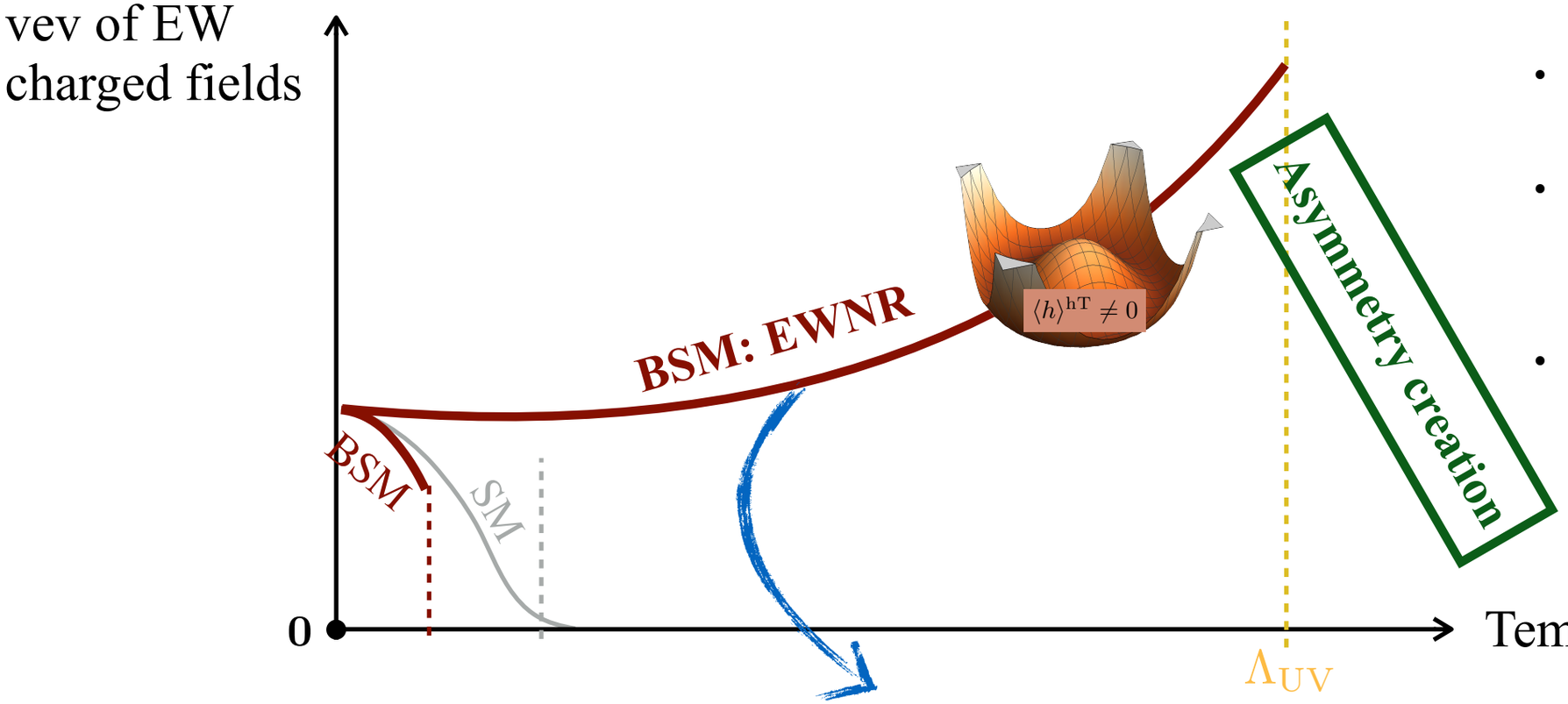

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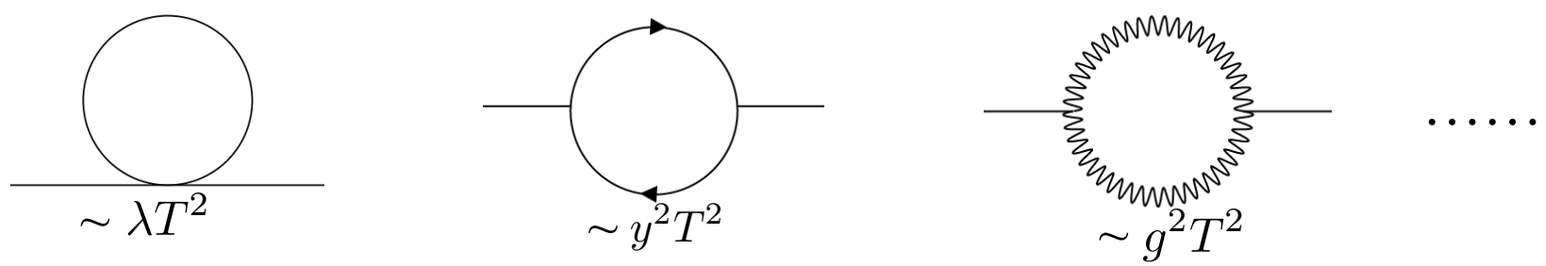

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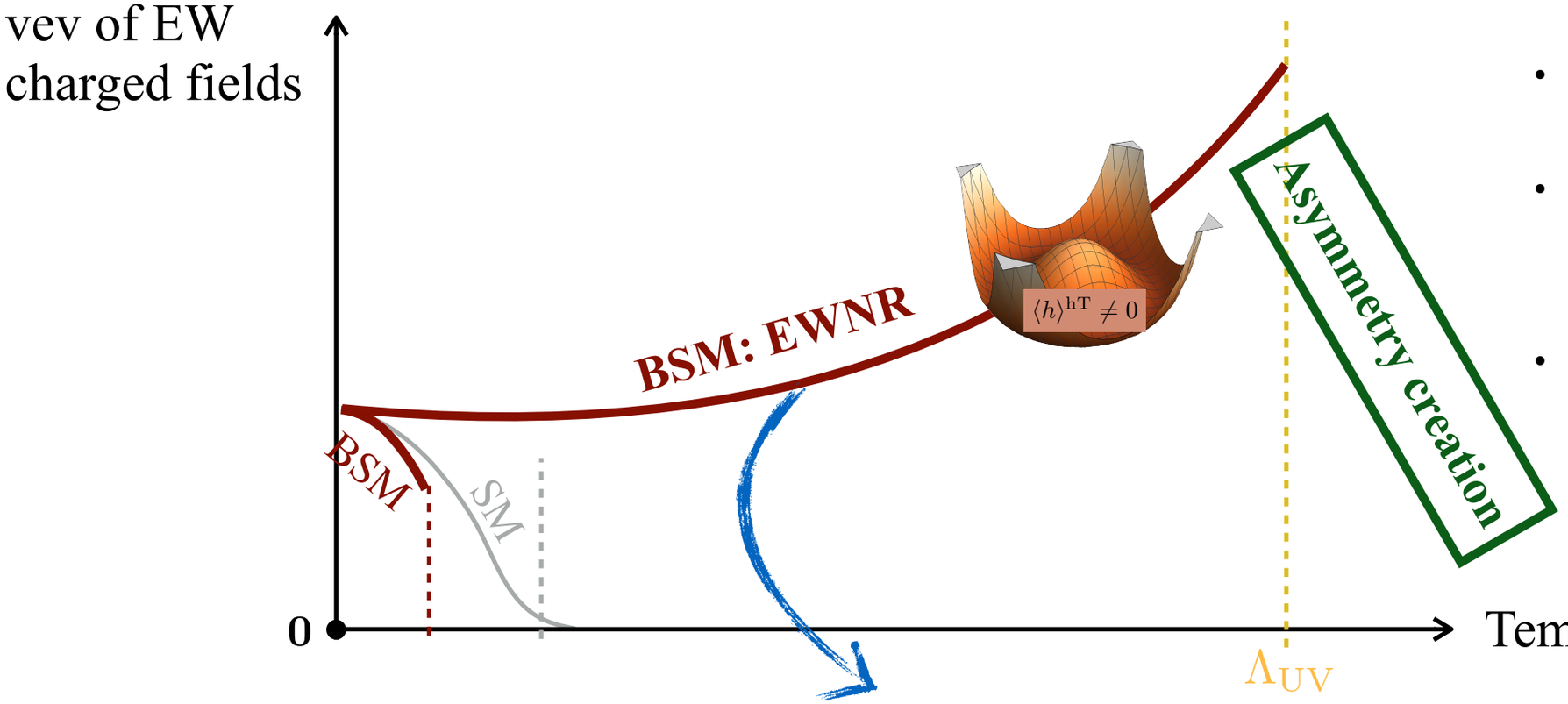

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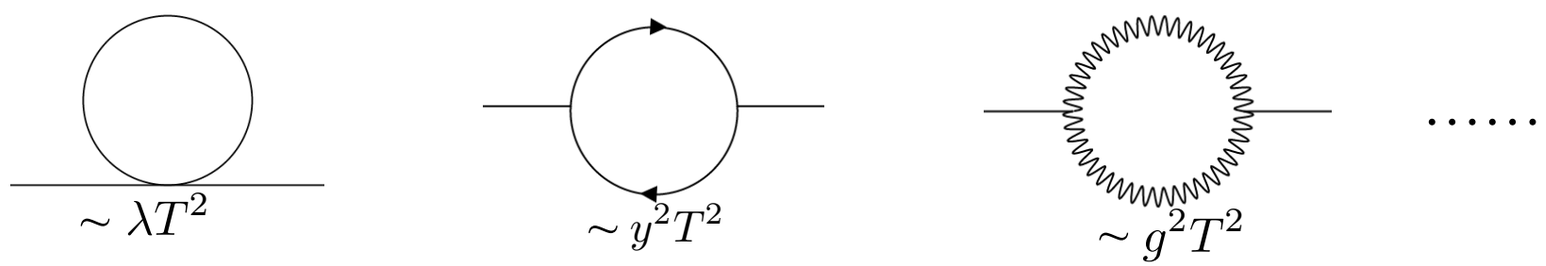
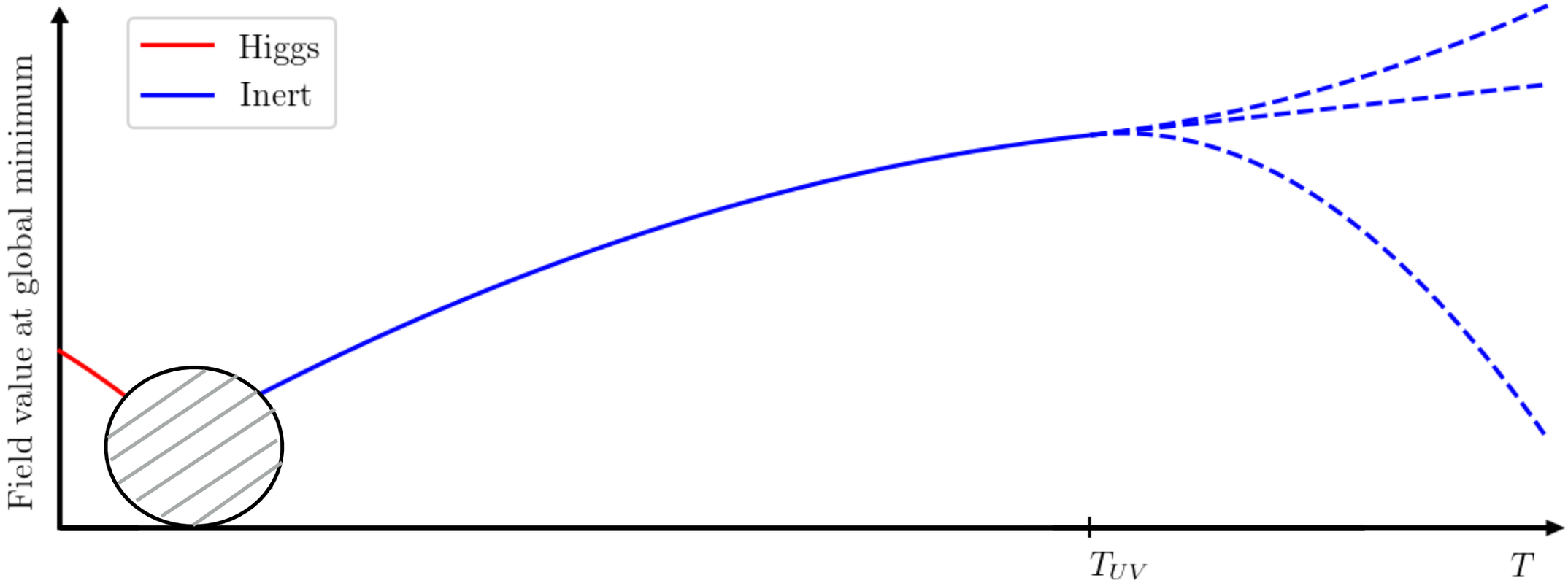
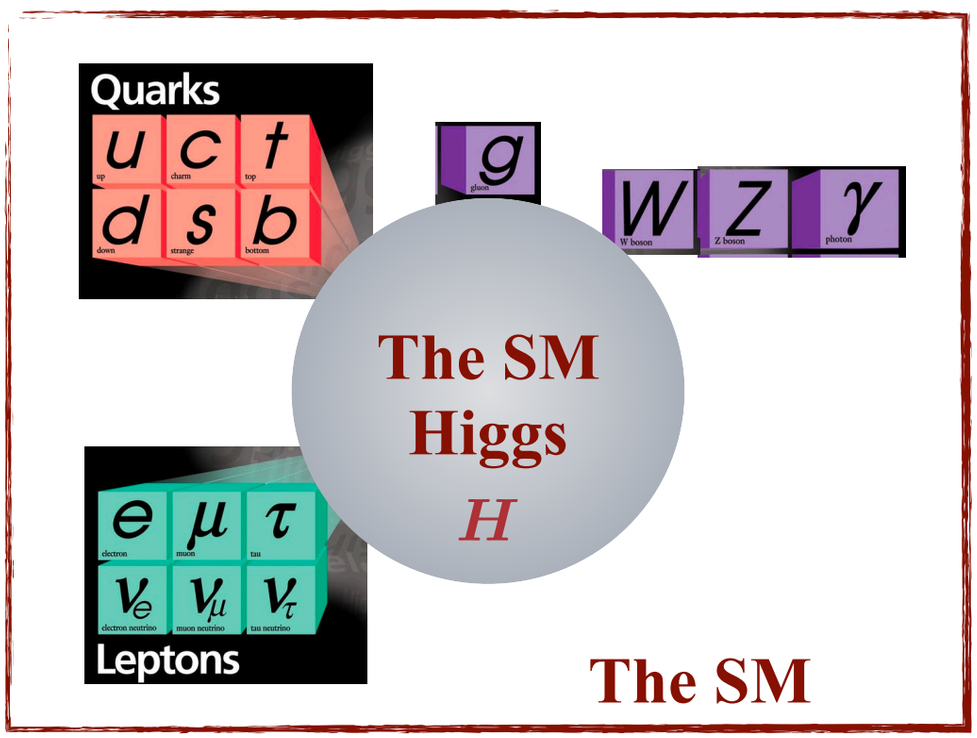


A new approach to EWNR

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





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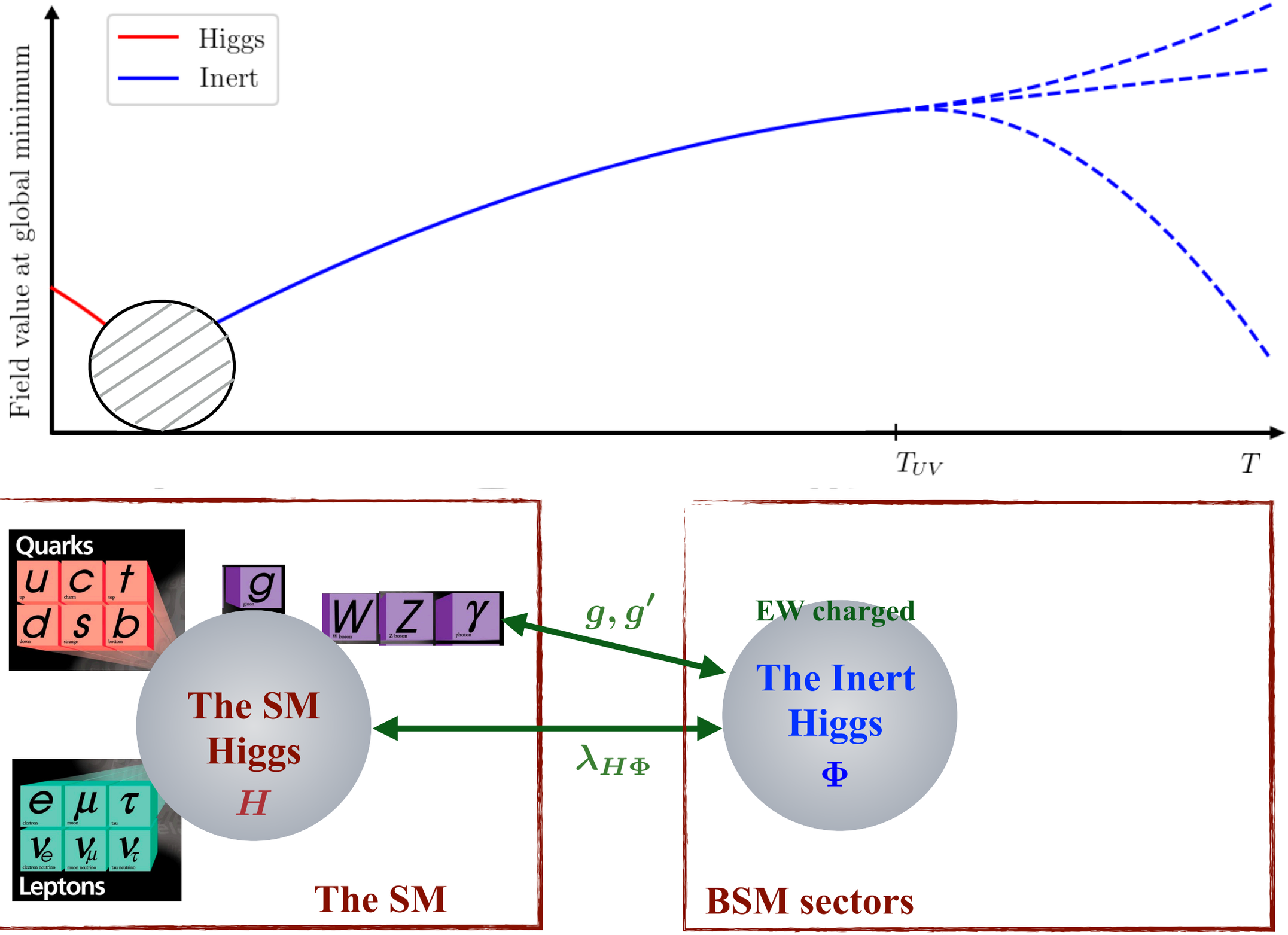

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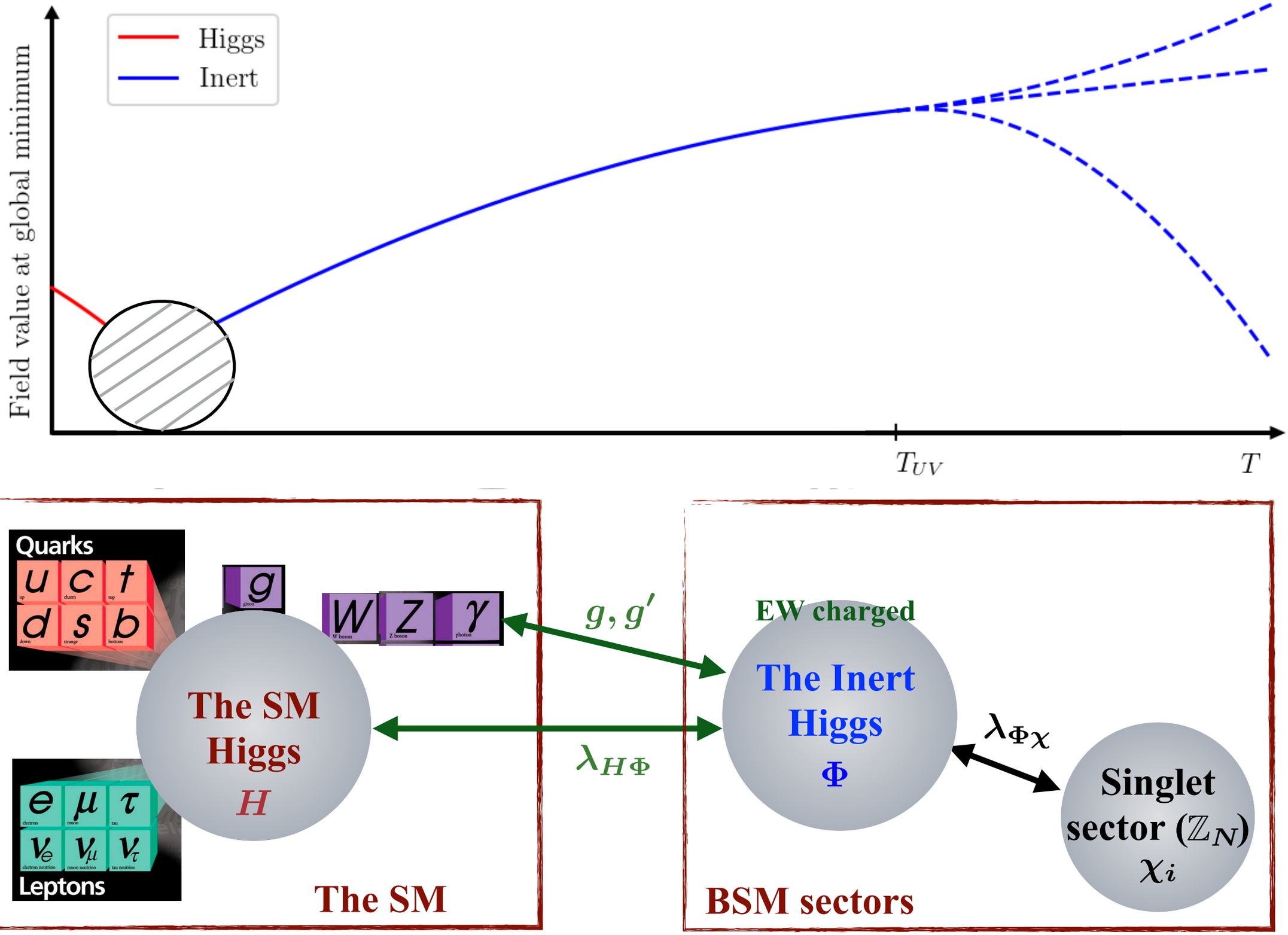

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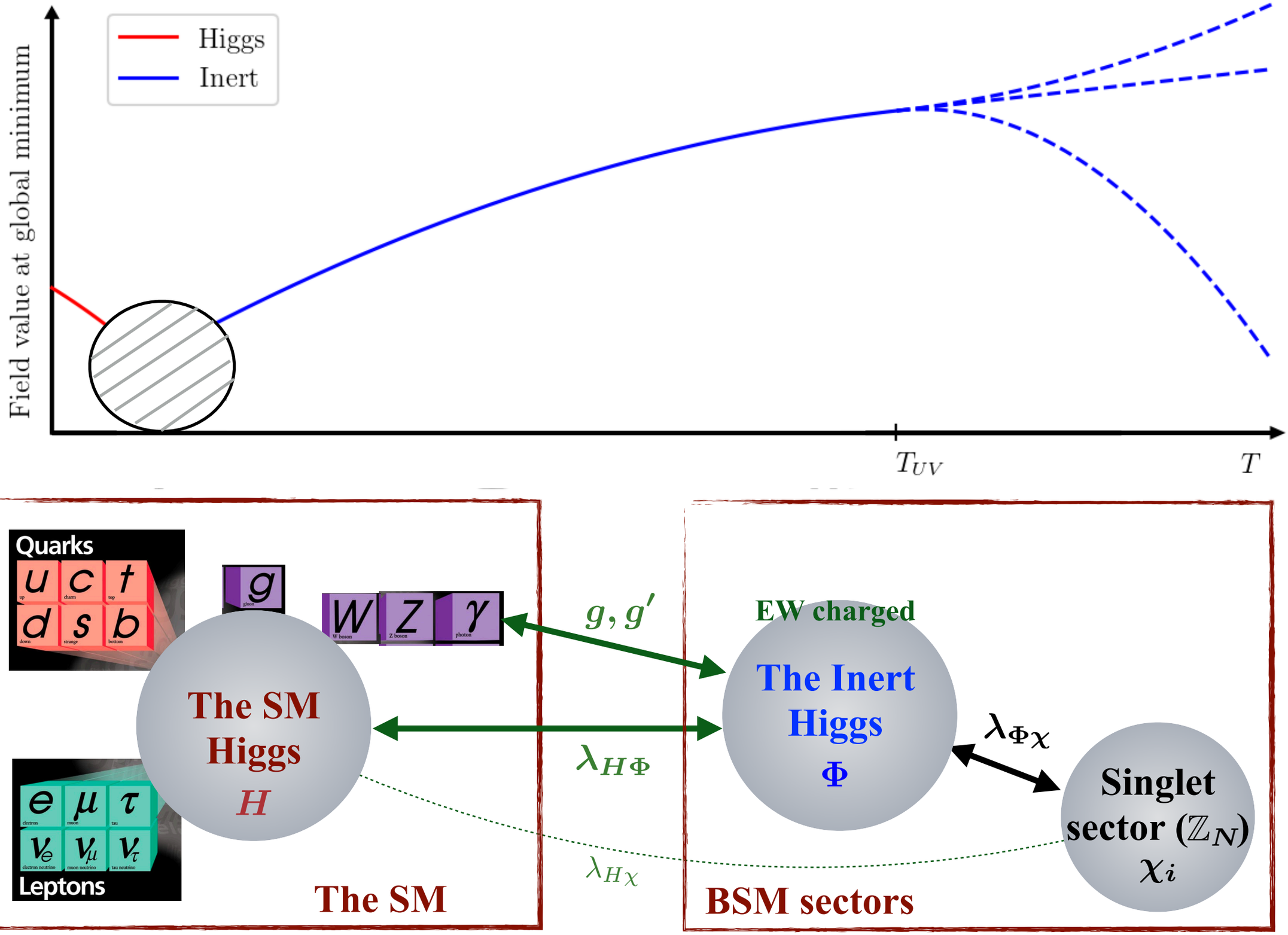

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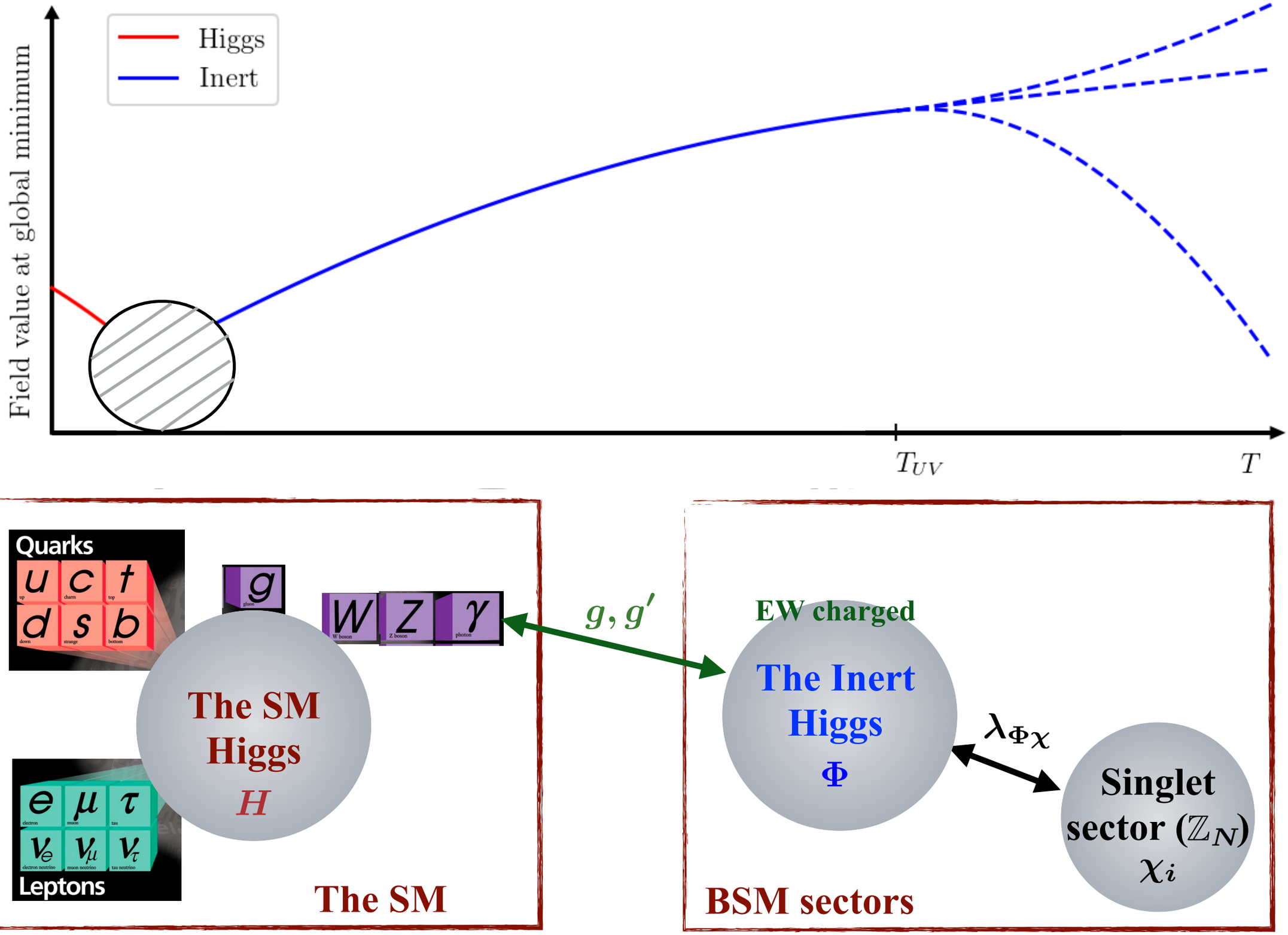

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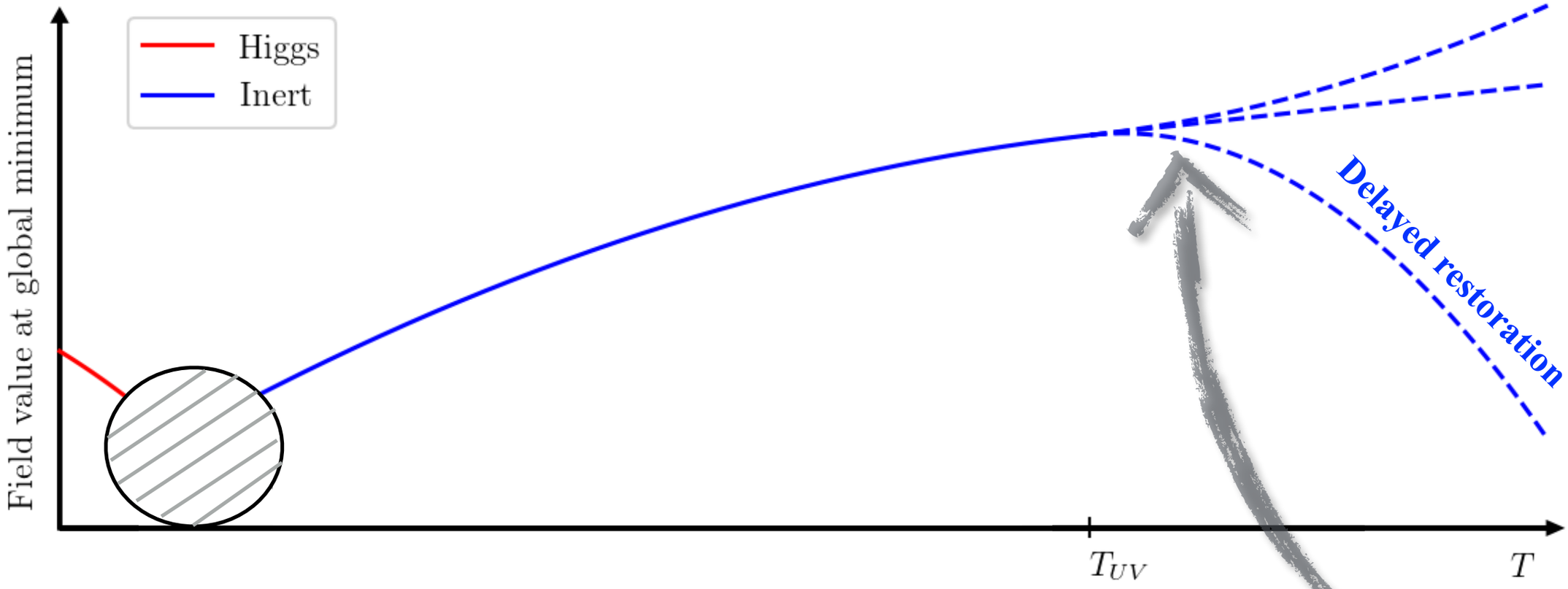

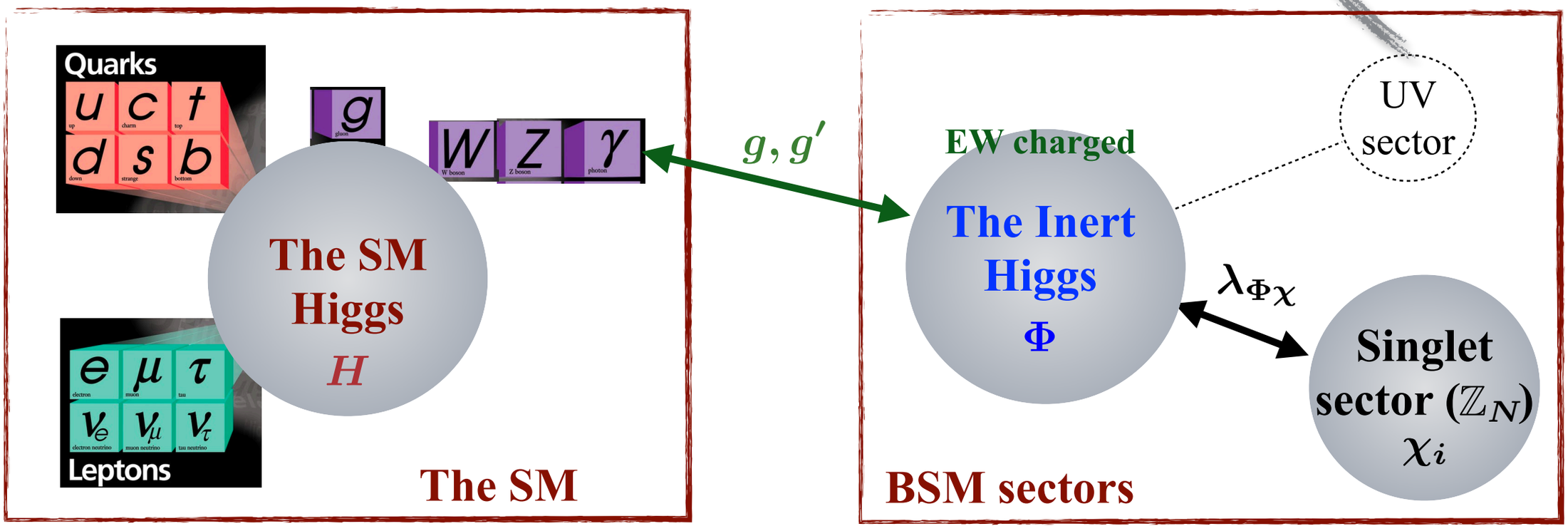

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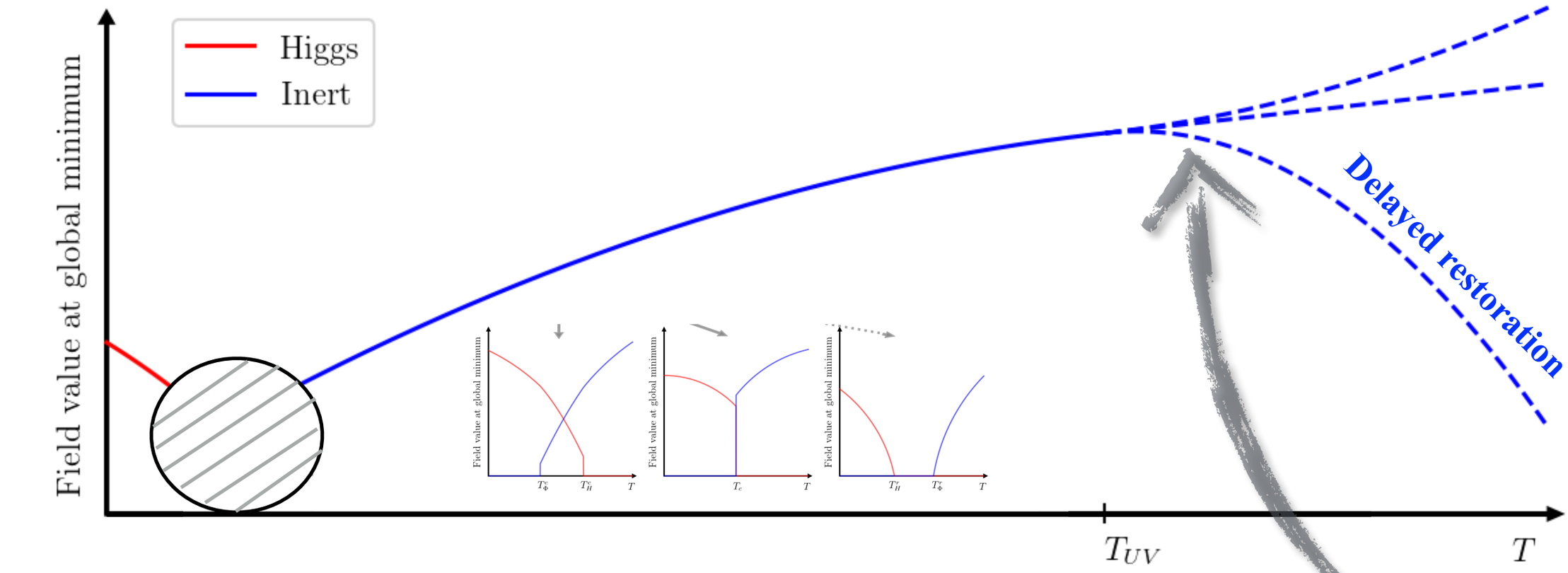
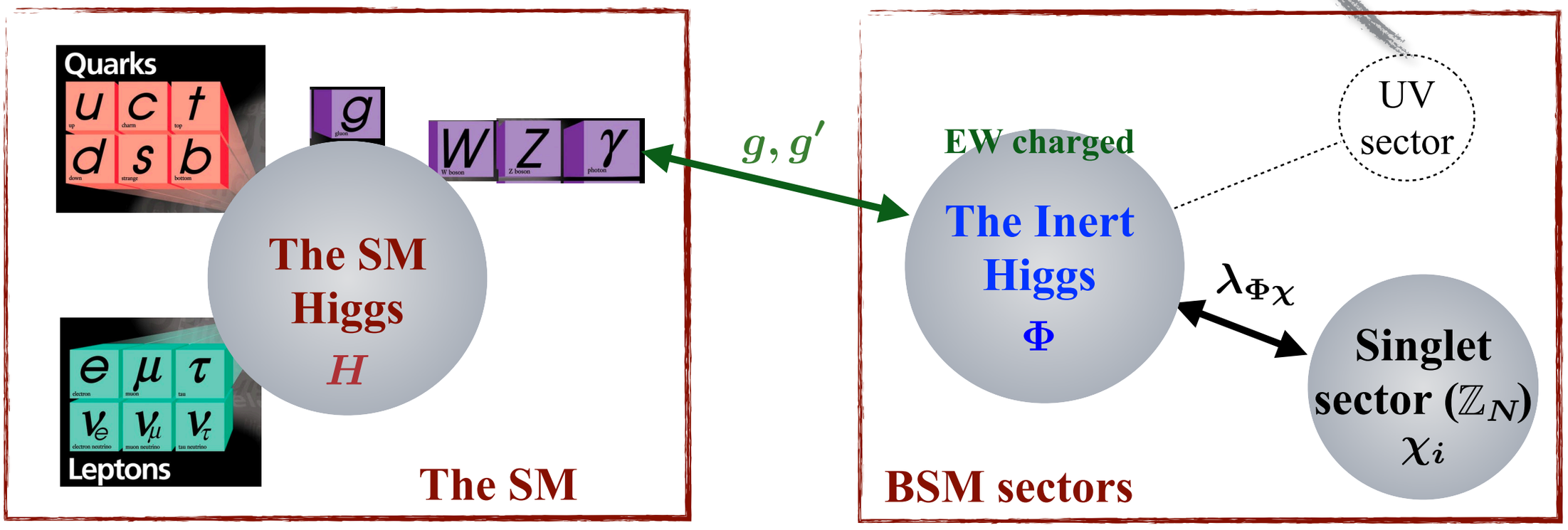
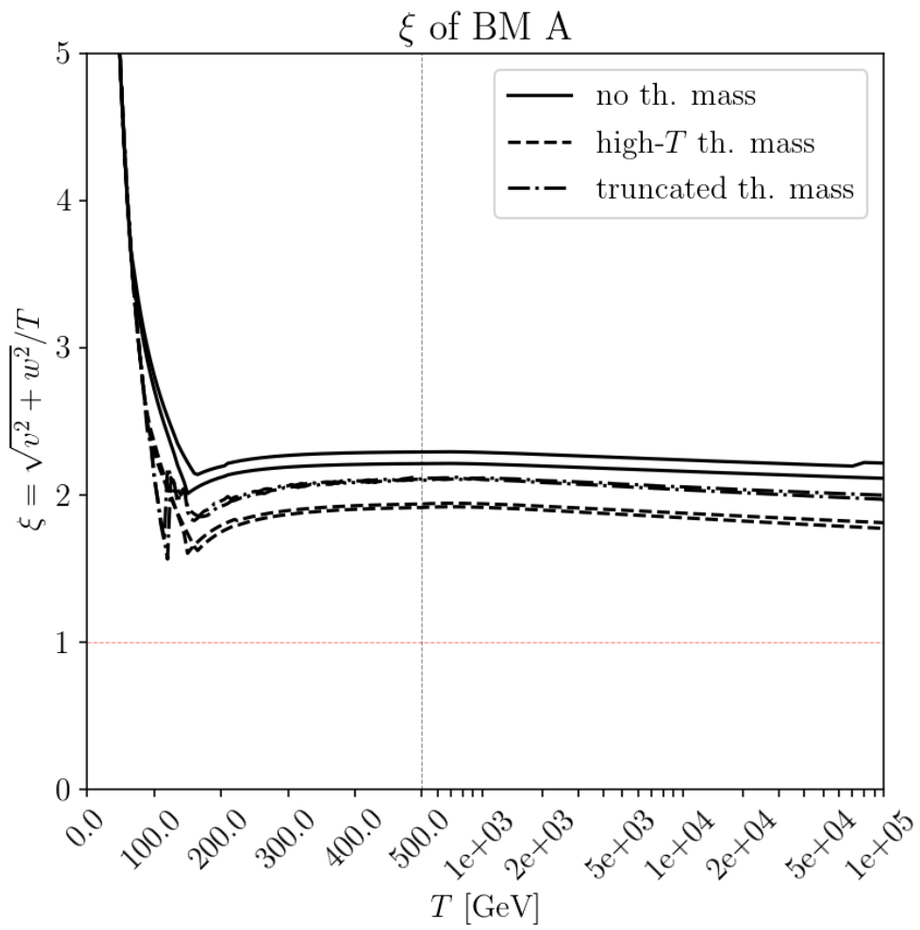




Benchmark scenarios: numerical results



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

	no th. mass	high-T th. mass	truncated th. mass
BM A	$< 10^{-16}$ / $\mathbf{10^{-16}}$ / 10^{-14} $< 10^{-16}$ / $\mathbf{4\cdot 10^{-15}}$ / $4\cdot 10^{-13}$	10^{-11} / $\mathbf{10^{-9}}$ / 10^{-7} $2\cdot 10^{-11}$ / $\mathbf{2\cdot 10^{-9}}$ / $2\cdot 10^{-7}$	$8\cdot 10^{-11}$ / $\mathbf{8\cdot 10^{-9}}$ / $8\cdot 10^{-7}$ 10^{-12} / $\mathbf{10^{-10}}$ / 10^{-8}
BM B	$9\cdot 10^{-10}$ / $\mathbf{9\cdot 10^{-8}}$ / $9\cdot 10^{-6}$ $4\cdot 10^{-12}$ / $\mathbf{4\cdot 10^{-10}}$ / $4\cdot 10^{-8}$	$4\cdot 10^{-5}$ / $\mathbf{4\cdot 10^{-3}}$ / 0.296 $2\cdot 10^{-8}$ / $\mathbf{2\cdot 10^{-6}}$ / $2\cdot 10^{-4}$	$7\cdot 10^{-5}$ / $\mathbf{7\cdot 10^{-3}}$ / 0.498 10^{-4} / $\mathbf{0.012}$ / 0.694

	μ_H^2	λ_H	μ_Φ^2	λ_Φ	μ_χ^2	λ_χ	$\lambda_{H\Phi}$	$\widetilde{\lambda}_{H\Phi}$
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

	$\lambda_{\Phi\chi}$	$\widetilde{\lambda}_\chi$	$\lambda_{H\chi}$	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

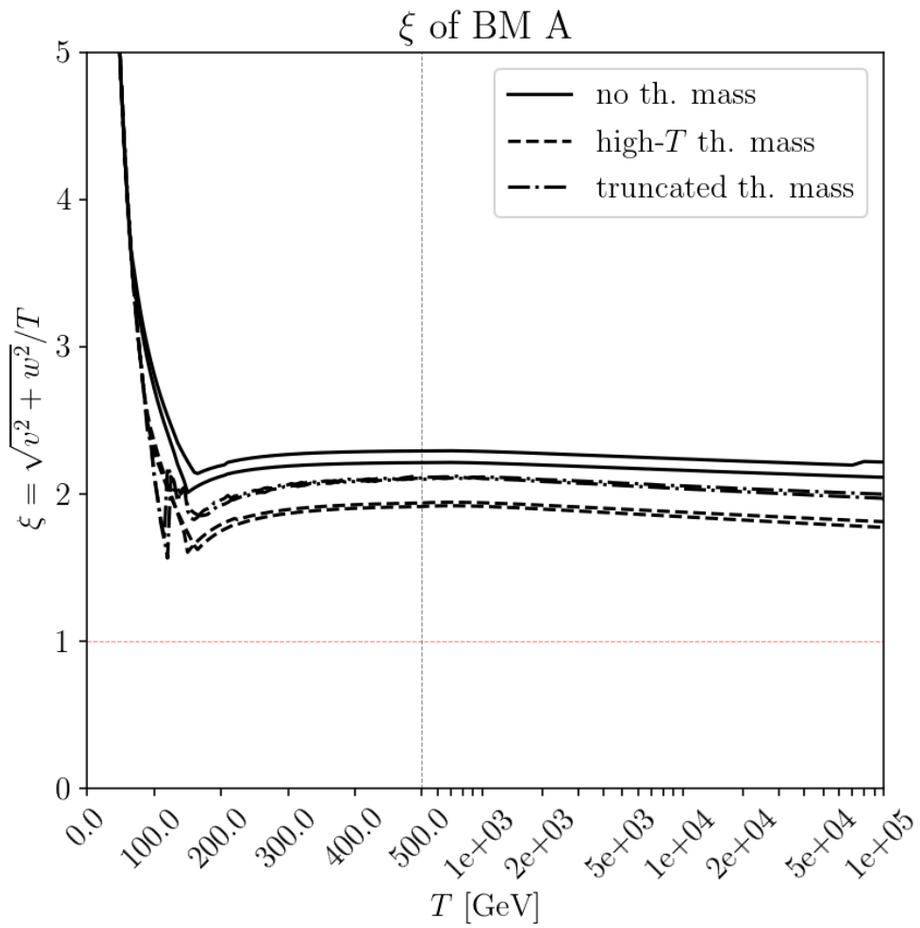
- **Higgs invisible decays** $\Gamma(h \to ss) = \frac{\lambda_{Hs}^2 v_0^2}{32\pi m_h}\sqrt{1 - \frac{4m_s^2}{m_h^2}}$

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

- **Z boson invisible decays**

Excludes all inert masses below 45 GeV (LEP II)

Benchmark scenarios: numerical results



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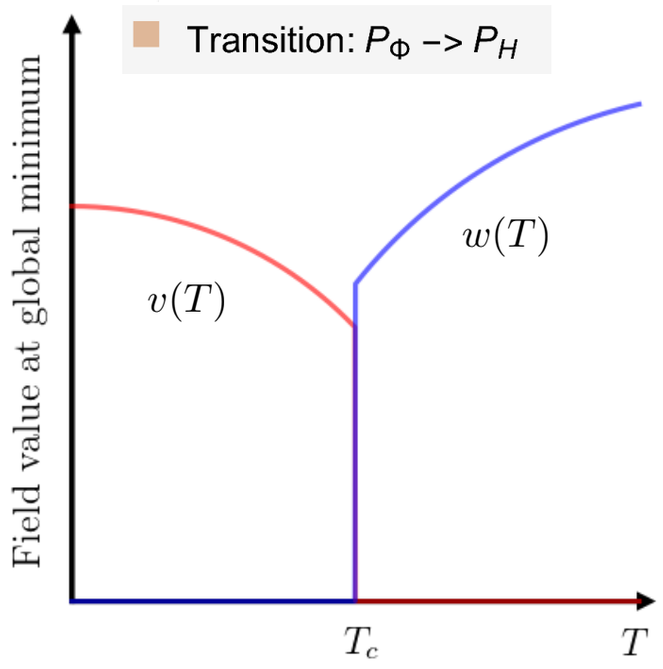
Summary

- A SFOEWPT is a necessary condition for baryogenesis, that can explain the observed baryon asymmetry;
- This finite temperature phenomenology inevitably has an impact on the Higgs potential that we can probe today. The concrete observational channels depend on the model and extension;
- A light scalar is observed to be responsible for a SFOEWPT, that can be searched for with Higgs exotic decays;
- Electroweak symmetry non-restoration is a novel signature to explore for baryogenesis. With a concrete example, it is shown that Higgs invisible decay is a powerful channel to test such a scenario.

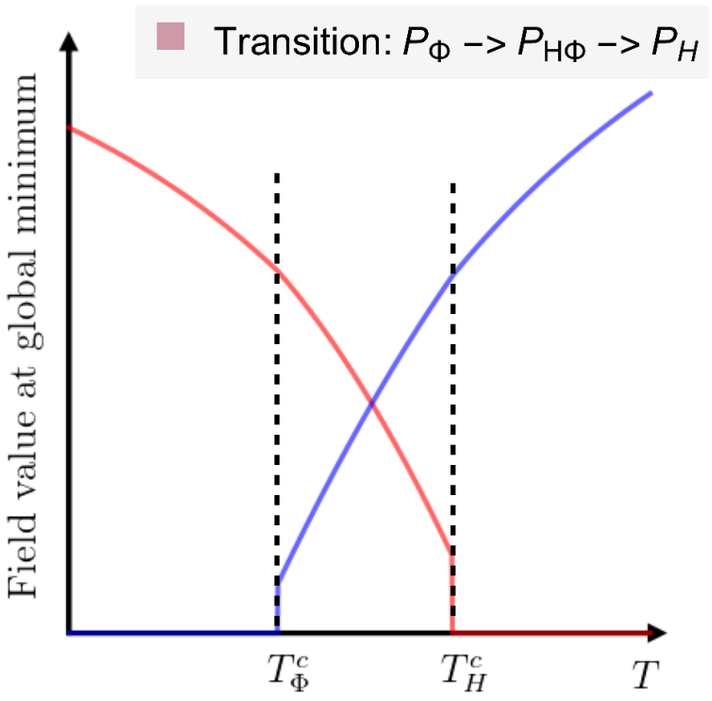
Supplementary

Supplementary - mean field analysis



$$\mathrm{P}_\Phi \text{ phase} : w(T) = \sqrt{-\frac{\mu_\Phi^2 + c_\varphi T^2}{\lambda_\Phi}} \qquad \mathrm{P}_H \text{ phase} : v(T) = \sqrt{\frac{\mu_H^2 - c_h T^2}{\lambda_H}}$$

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



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

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

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

Relevant parameters:

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

Supplementary - sphaleron washout and dilution factor

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

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