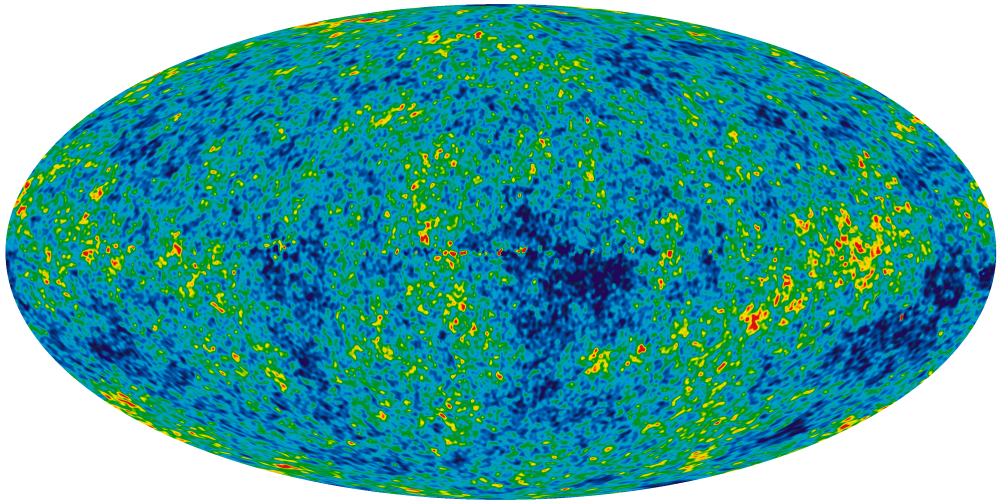

A New Approach to Electroweak Symmetry Non-restoration

arXiv:2104.00638 (PRD)

Yikun Wang
Burke Institute, Caltech
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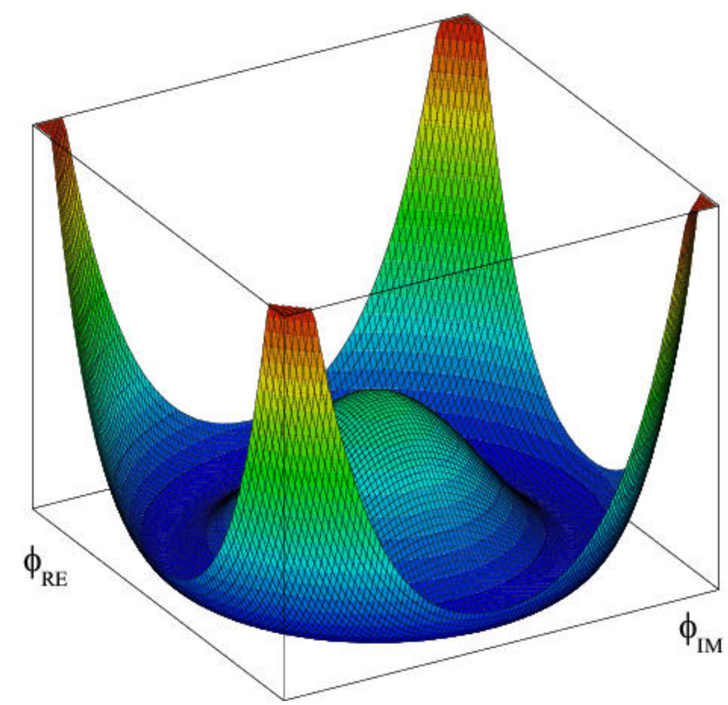


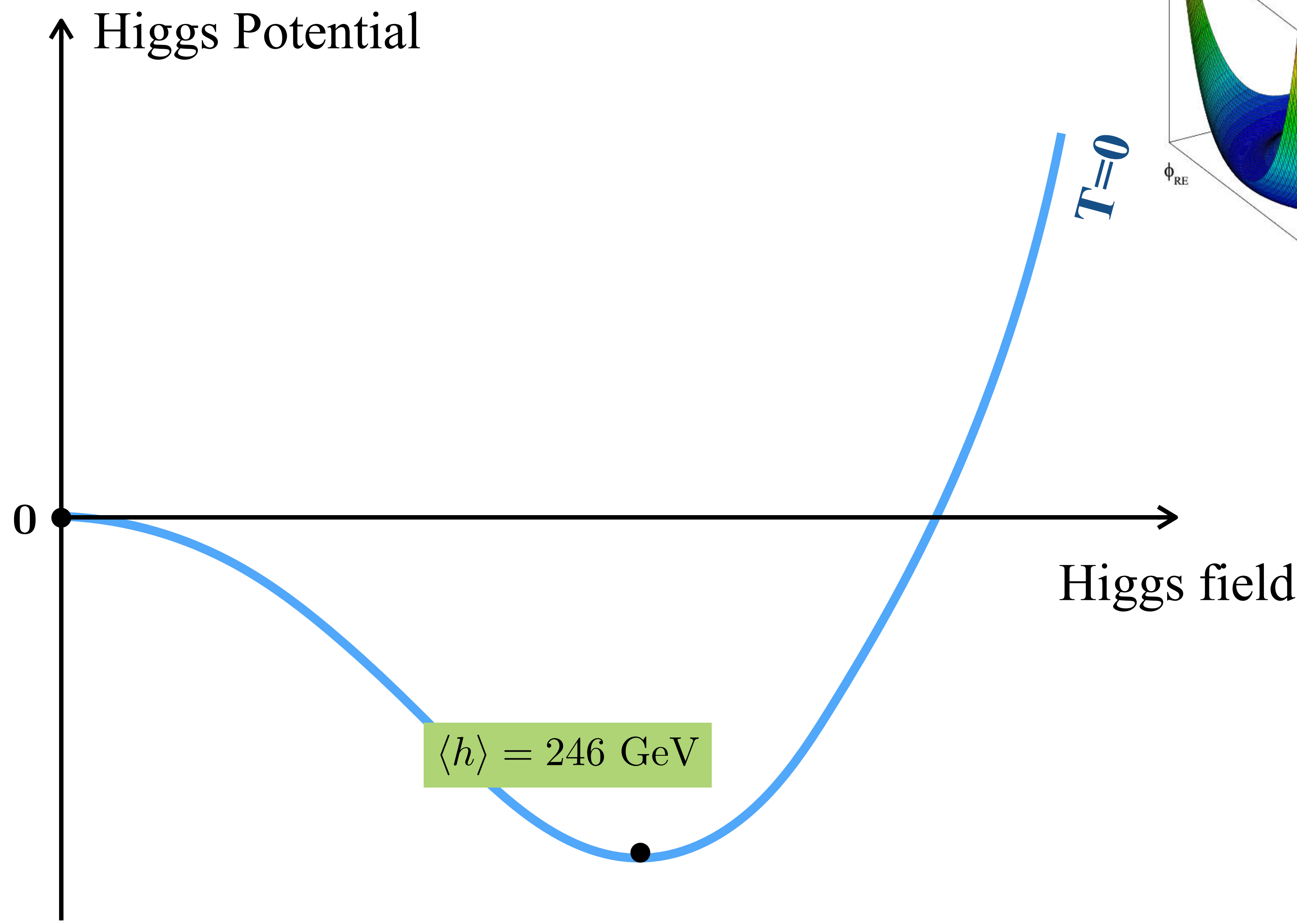
Cambridge High Energy Workshop 2022
August 4, 2022, Cambridge

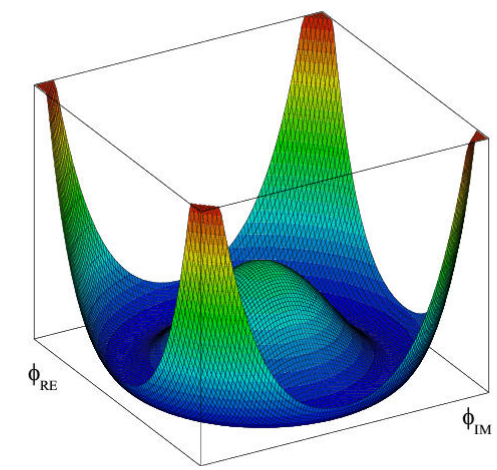
In Collaboration with: Marcela Carena, Claudius Krause and Zhen Liu

Electroweak symmetry in the early universe

Zero temperature: **EWSB**

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



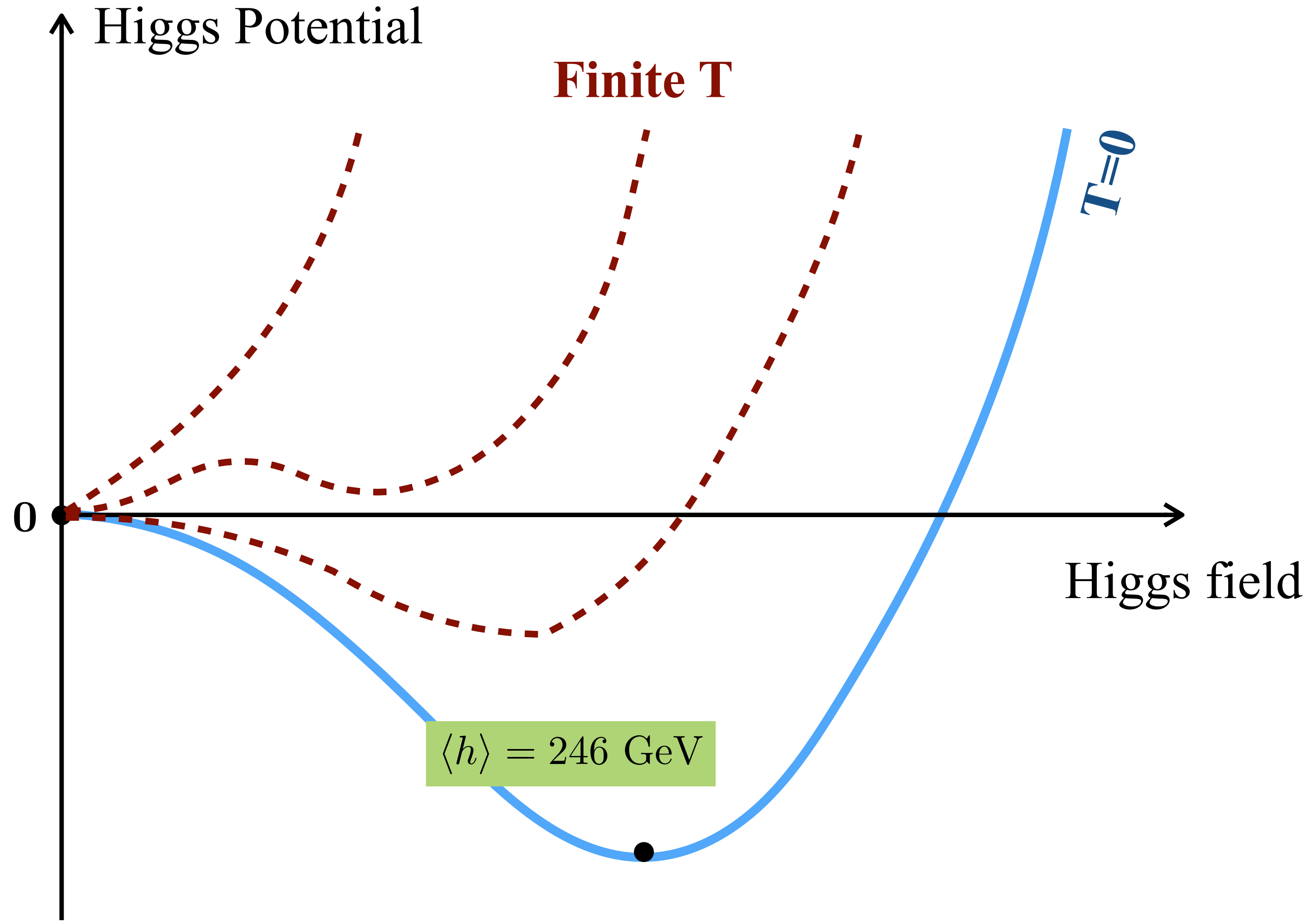


Electroweak symmetry in the early universe

Finite temperatures: thermal corrections from particles coupling to the Higgs

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

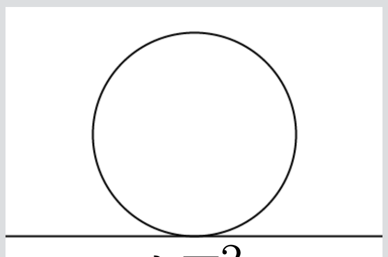
(Leading order in high-T expansion)



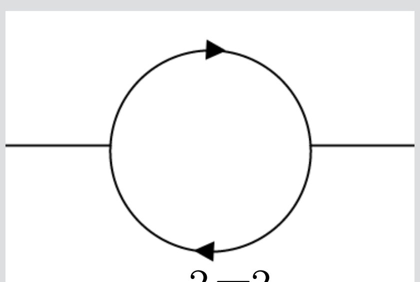
Electroweak symmetry in the early universe

Finite temperatures: thermal corrections from particles coupling to the Higgs

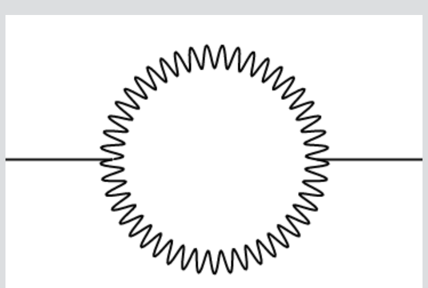
Higgs thermal mass



$\sim \lambda T^2$



$\sim y^2 T^2$



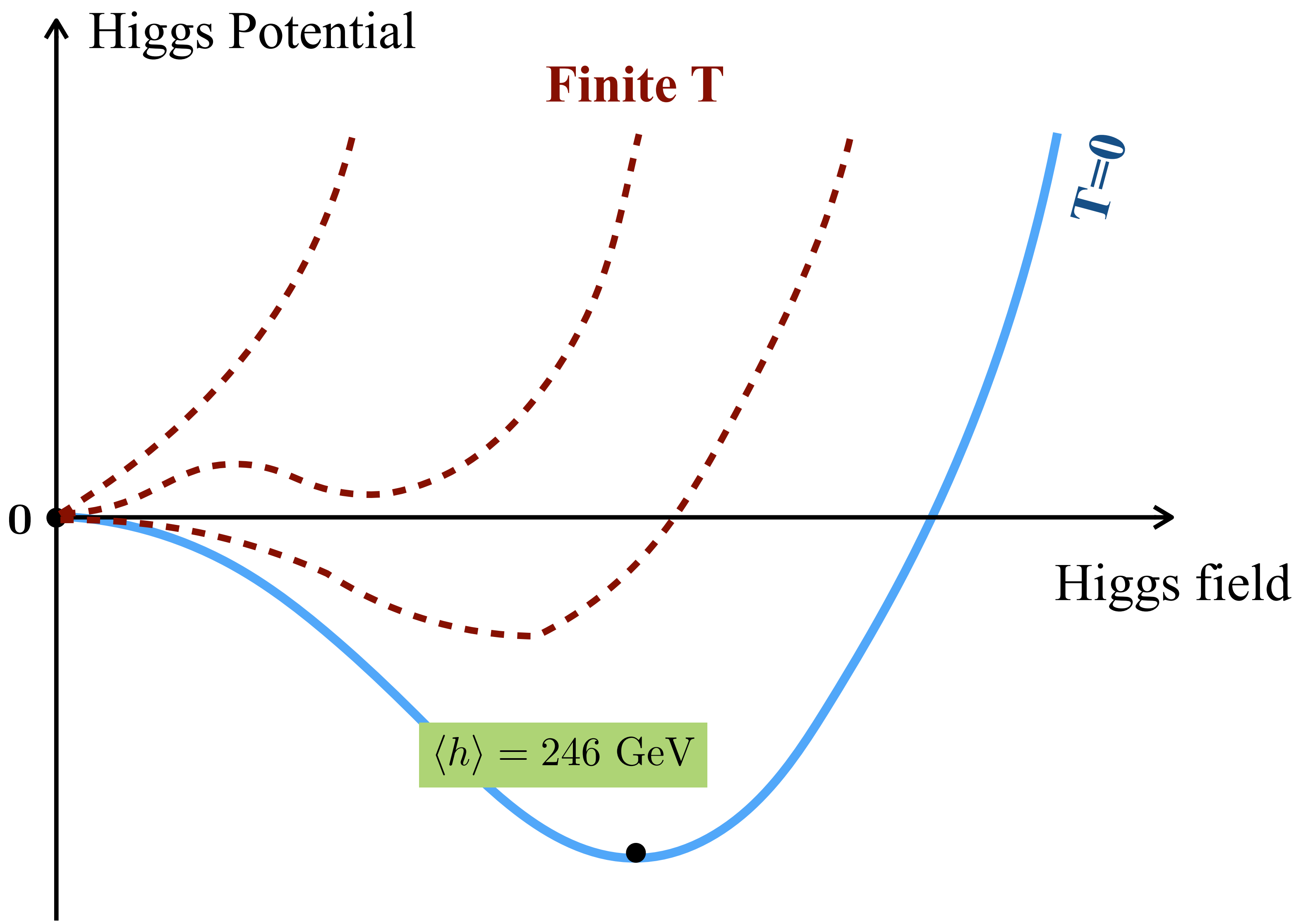
$\sim g^2 T^2$

$\cdots\cdots$

depends on particle content that couples to the Higgs

$$V(H) = -(\mu_H^2 \; -c_H T^2 \;)|H|^2 + \lambda_H |H|^4 + \cdots$$

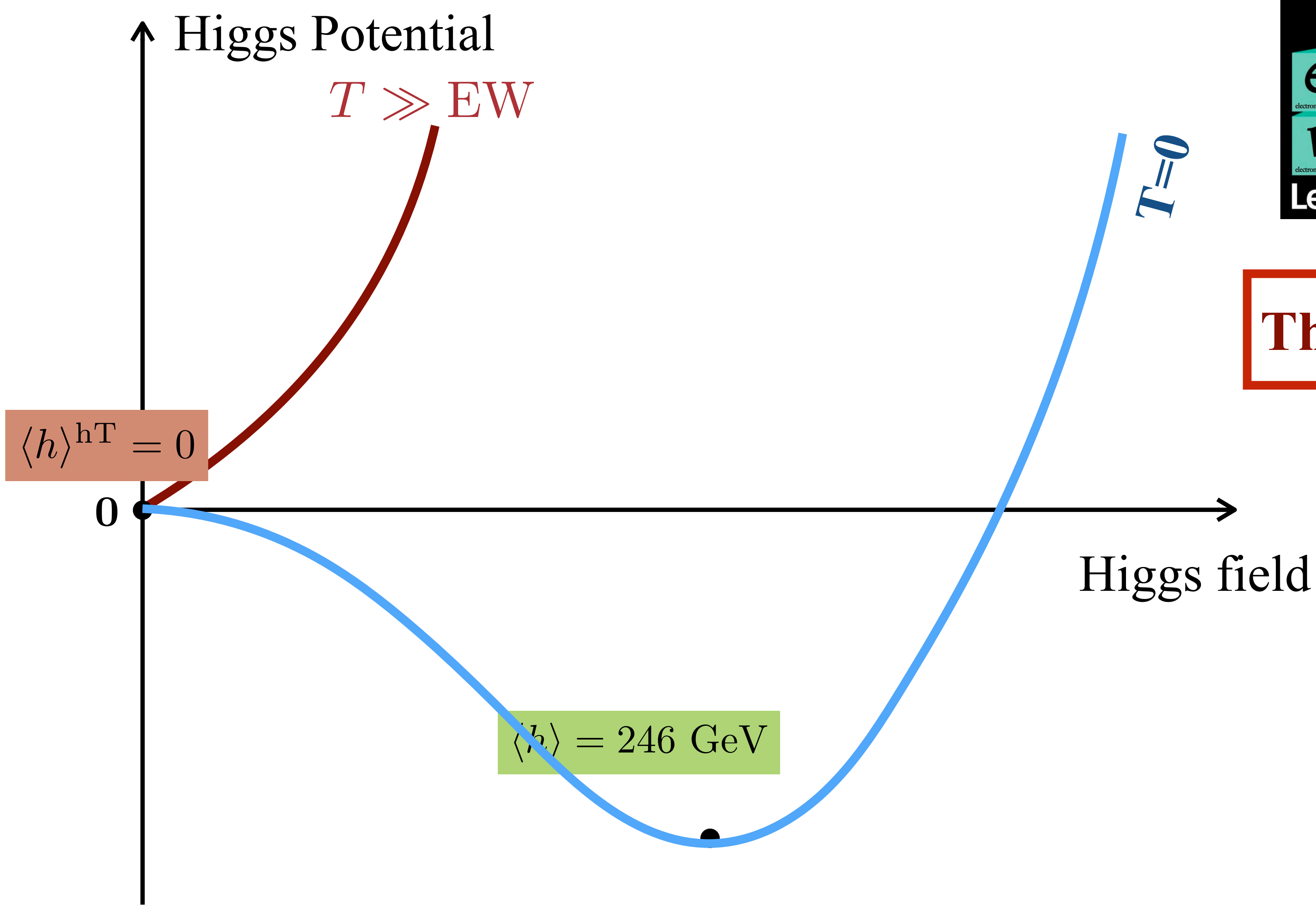
(Leading order in high-T expansion)

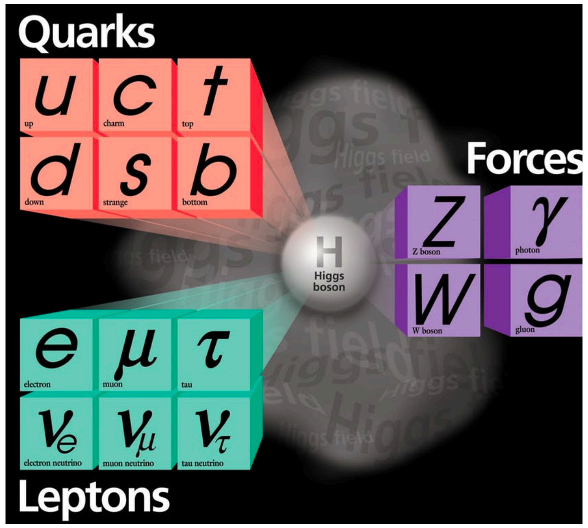


Electroweak symmetry in the early universe: the Standard Model

Finite temperatures: $c_H^{\mathrm{SM}} \geq 0$ **EW symmetry is restored above the EW scale**

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

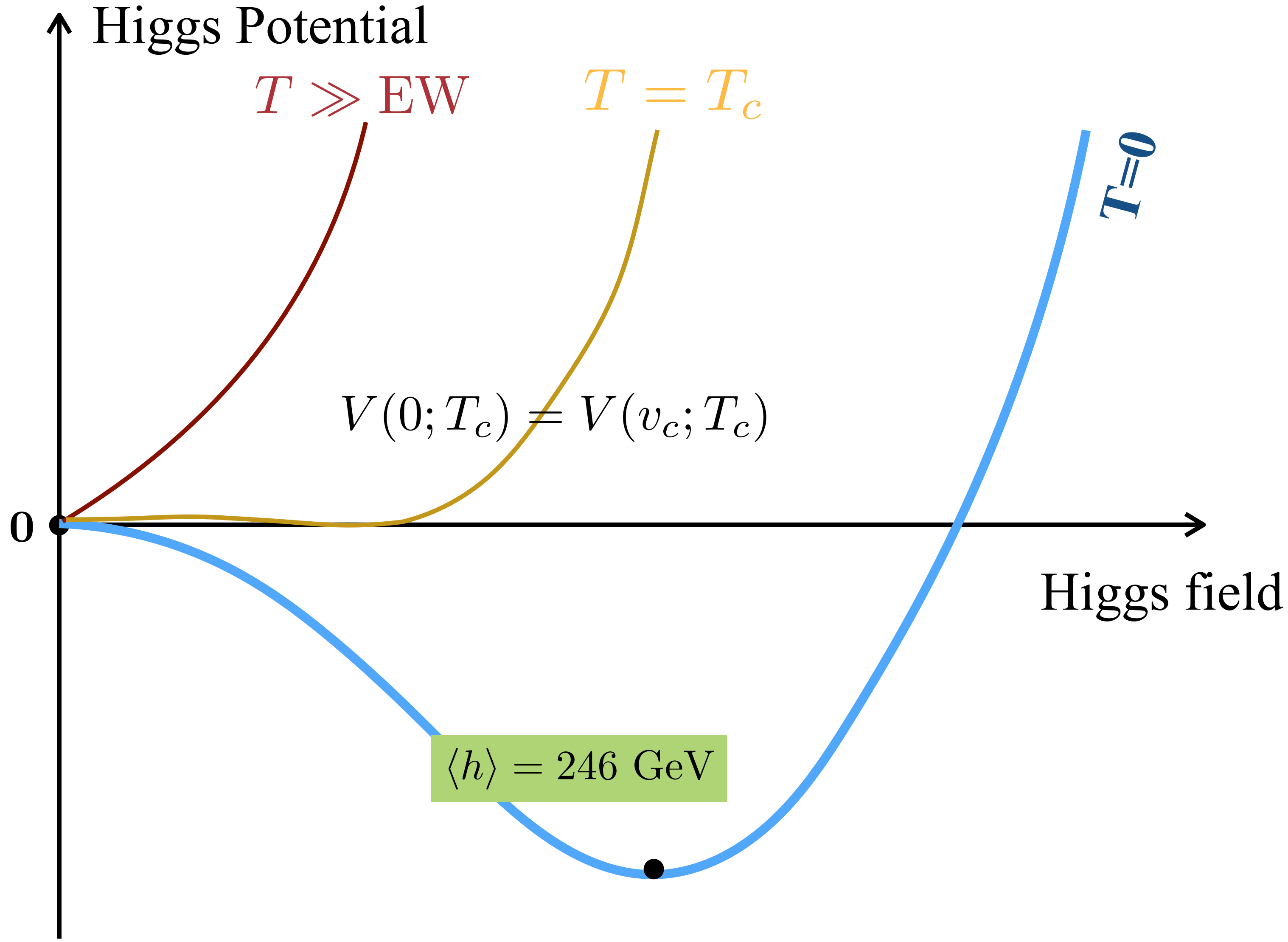




The Standard Model

Electroweak symmetry in the early universe

How symmetry was restored/broken? *Electroweak Phase Transition*



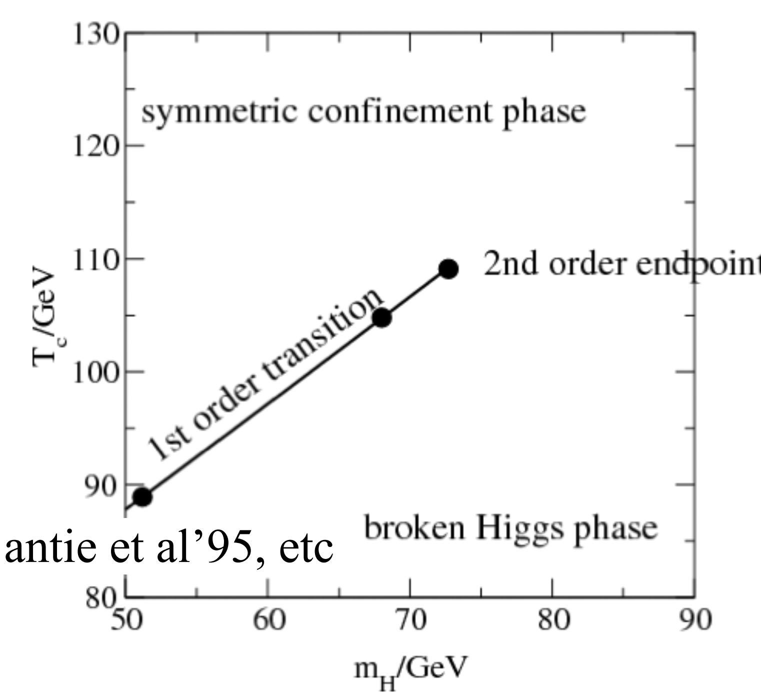
Rich physics at EWPT

Venue for electroweak baryogenesis (EWBG)

Sakharov's conditions

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

Stochastic GW background

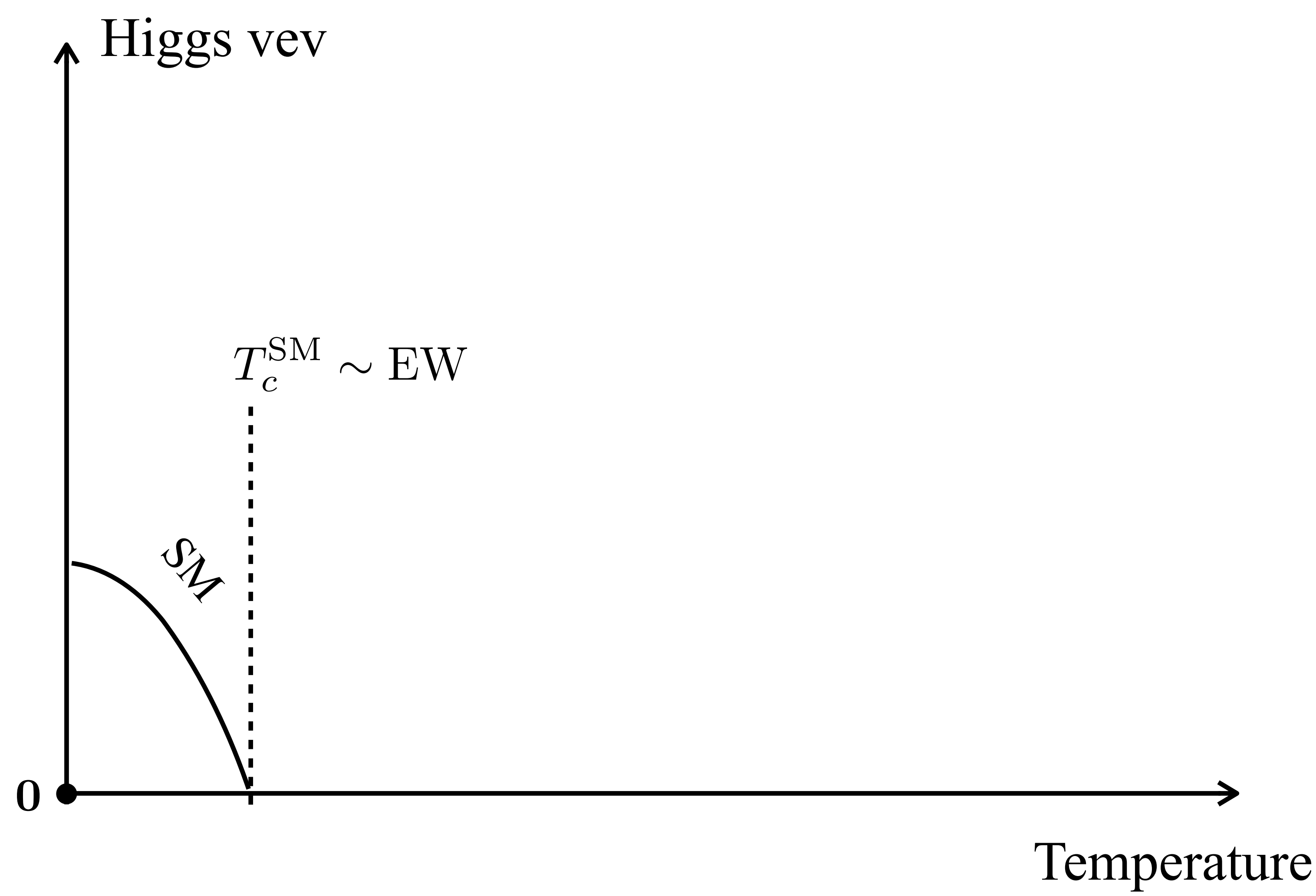


Kajantie et al'95, etc

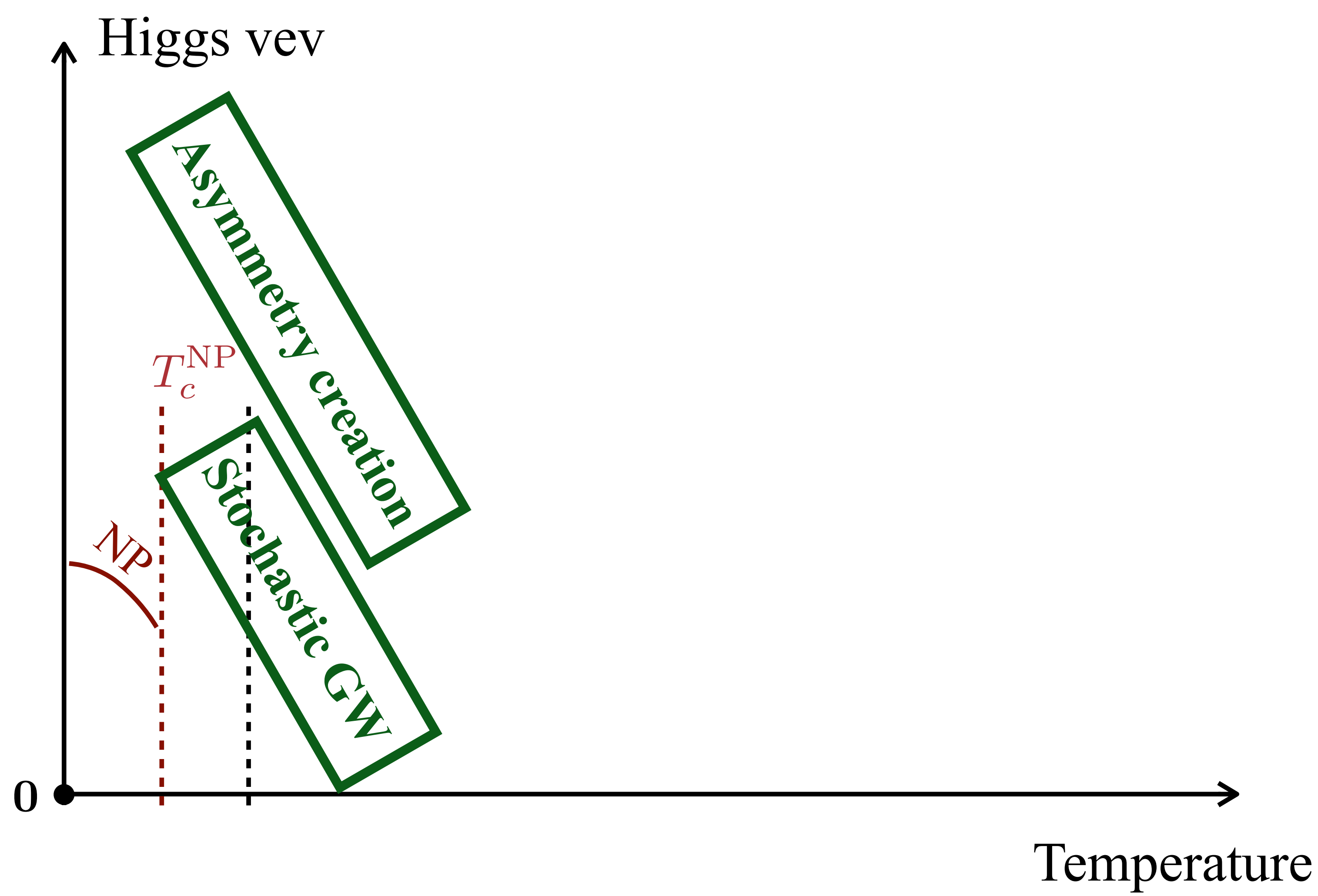
The SM is not compatible with Electroweak baryogenesis (EWBG)

And no Stochastic GW is associated with a cross over

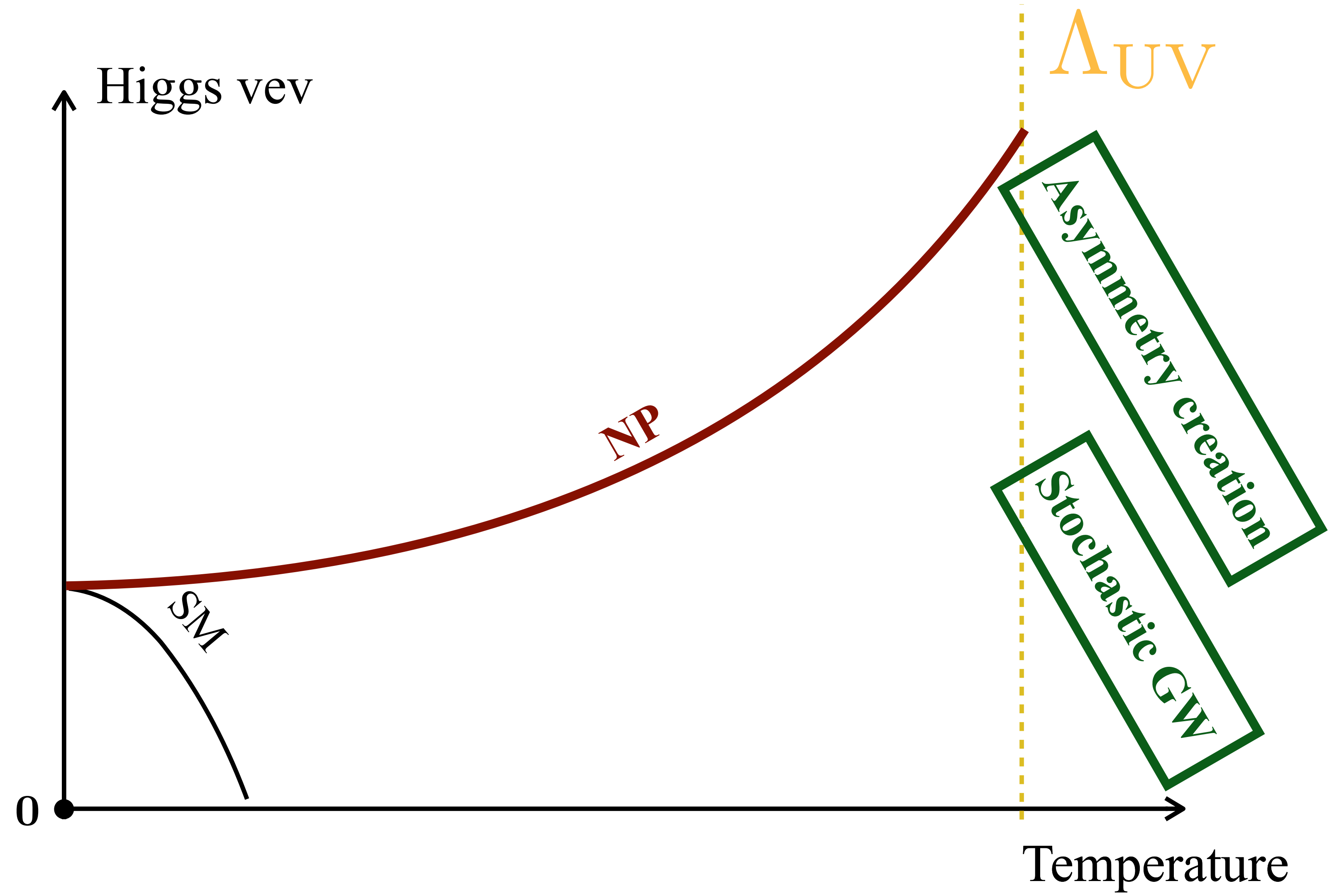
Electroweak symmetry in the early universe



Electroweak symmetry in the early universe: new physics



EWNR: alternative thermal histories



EW Symmetry Non-Restoration (EWNR)

- **High scale baryogenesis model building**

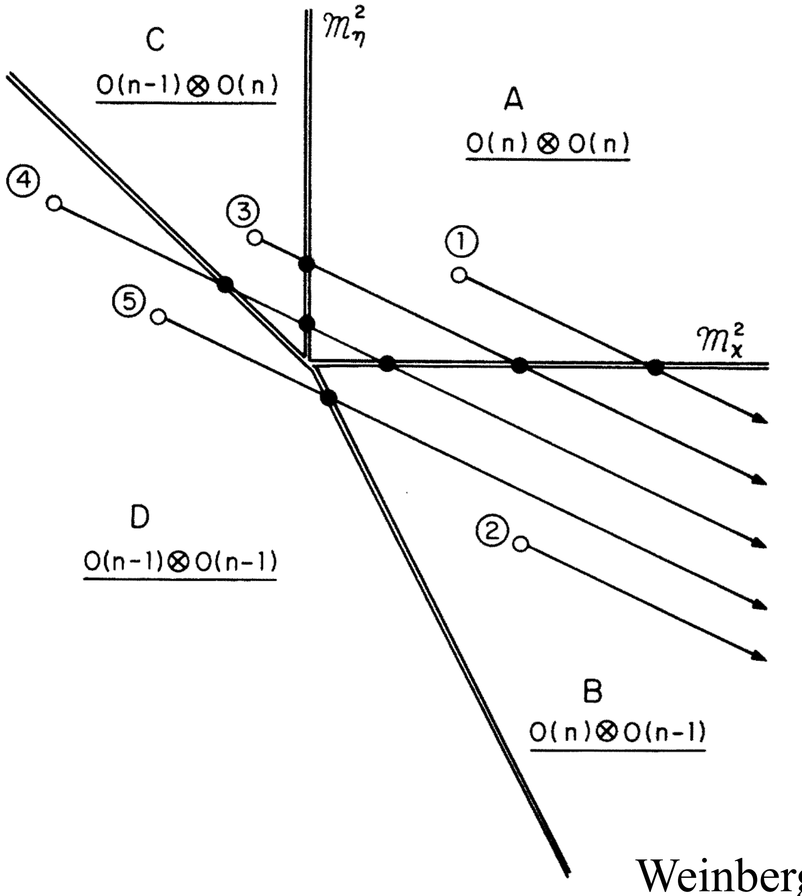
  Dark sector asymmetry creation, evade EDM constraint, etc

- **High frequency stochastic gravitational wave signature**

Symmetry Non-restoration

Weinberg

$$P(\chi, \eta) = \tfrac{1}{2}\mathfrak{M}_\chi{}^2 \chi_A \chi_A + \tfrac{1}{2}\mathfrak{M}_\eta{}^2 \eta_a \eta_a + \tfrac{1}{4} e_{\chi\chi}{}^2 (\chi_A \chi_A)^2$$
$$- \tfrac{1}{2} e_{\chi\eta}{}^2 (\chi_A \chi_A)(\eta_a \eta_a) + \tfrac{1}{4} e_{\eta\eta}{}^2 (\eta_a \eta_a)^2 \ ,$$



Weinberg'74

Symmetry Non-restoration

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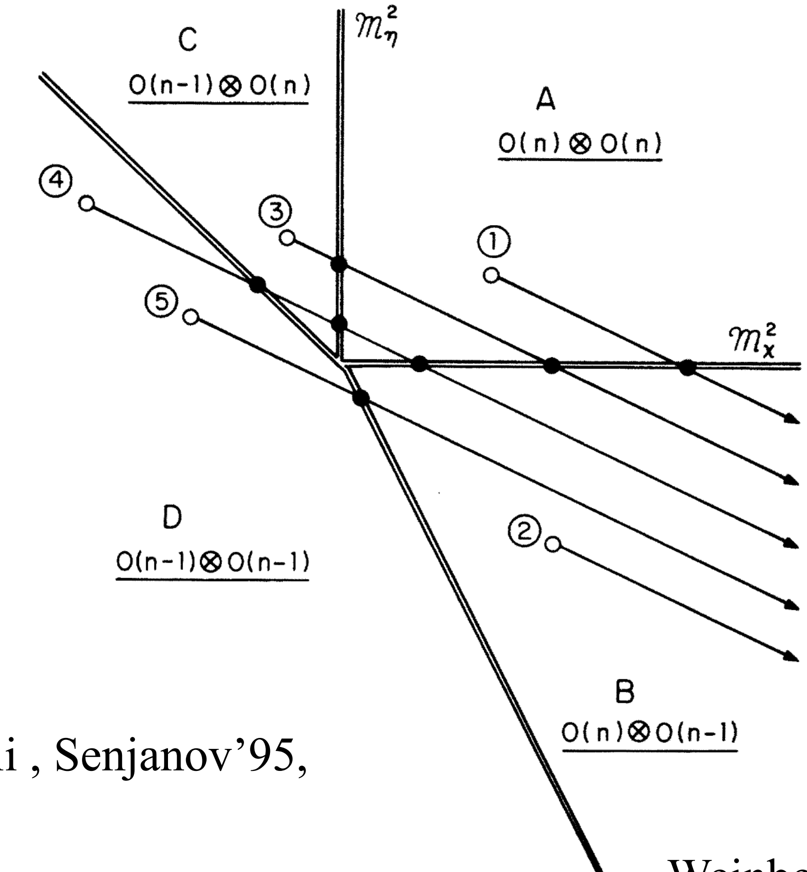
$$P(\chi,\eta)=\tfrac{1}{2}\mathfrak{M}_\chi{}^2\chi_A\chi_A+\tfrac{1}{2}\mathfrak{M}_\eta{}^2\eta_a\eta_a+\tfrac{1}{4}e_{\chi\chi}{}^2(\chi_A\chi_A)^2$$
$$-\tfrac{1}{2}e_{\chi\eta}{}^2(\chi_A\chi_A)(\eta_a\eta_a)+\tfrac{1}{4}e_{\eta\eta}{}^2(\eta_a\eta_a)^2\ ,$$



Weinberg'74

Symmetry non-restoration has be studied to discuss:

- Spontaneous CP violation at high temperature
- Monopole problem (GUT non-restoration)
- Color breaking at finite temperatures
- …

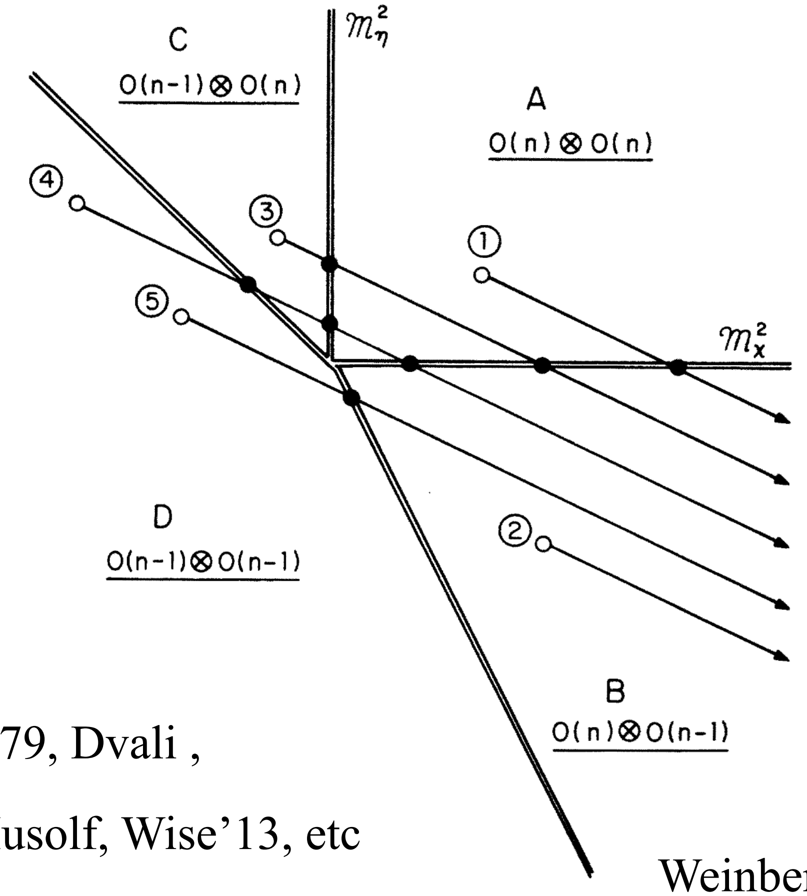
Mohapatra, Senjanov'79, Dvali , Senjanov'95, Patel, Musolf, Wise'13, etc

etc…

Symmetry Non-restoration

Weinberg

$$P(\chi, \eta) = \tfrac{1}{2}\mathfrak{M}_\chi{}^2\chi_A\chi_A + \tfrac{1}{2}\mathfrak{M}_\eta{}^2\eta_a\eta_a + \tfrac{1}{4}e_{\chi\chi}{}^2(\chi_A\chi_A)^2 - \tfrac{1}{2}e_{\chi\eta}{}^2(\chi_A\chi_A)(\eta_a\eta_a) + \tfrac{1}{4}e_{\eta\eta}{}^2(\eta_a\eta_a)^2 ,$$



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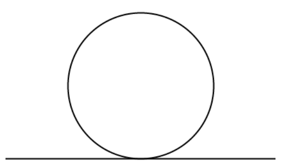
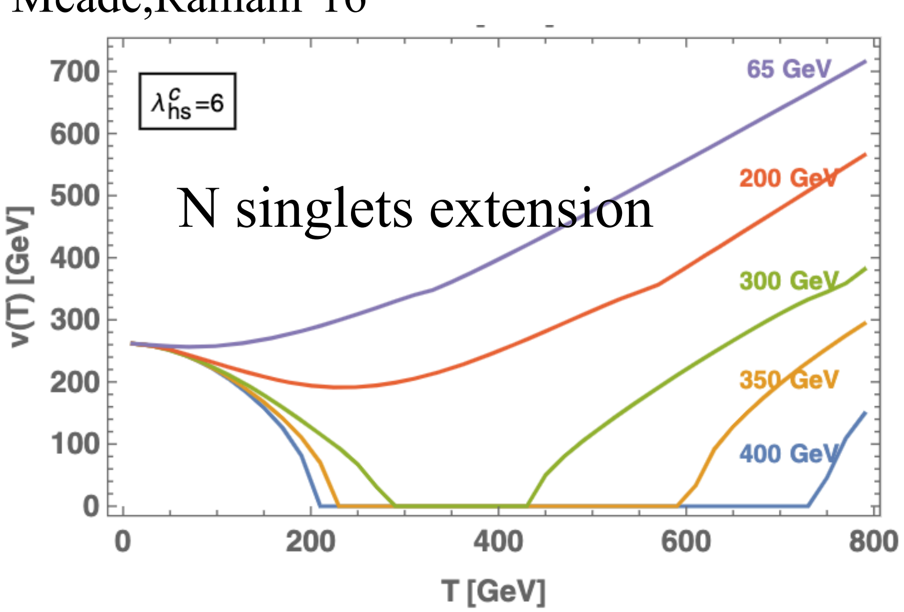
More recent development of EWNR

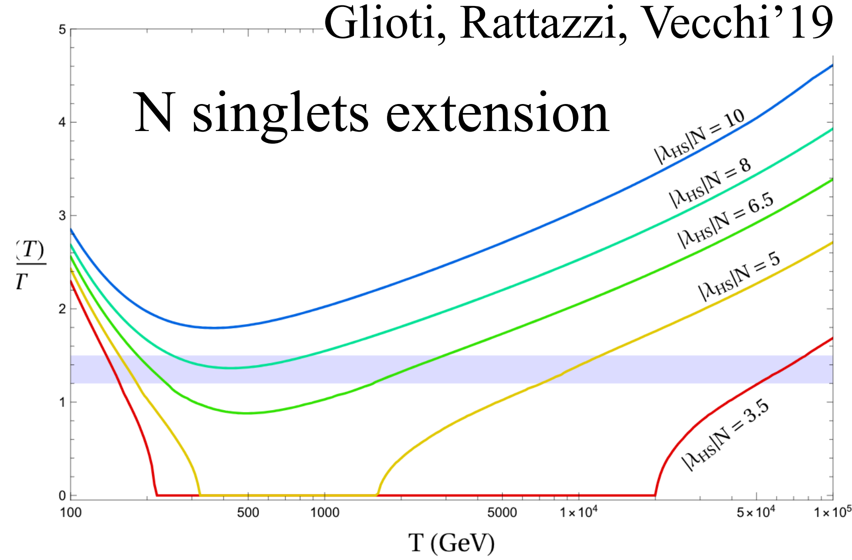


$\sim\lambda T^2$

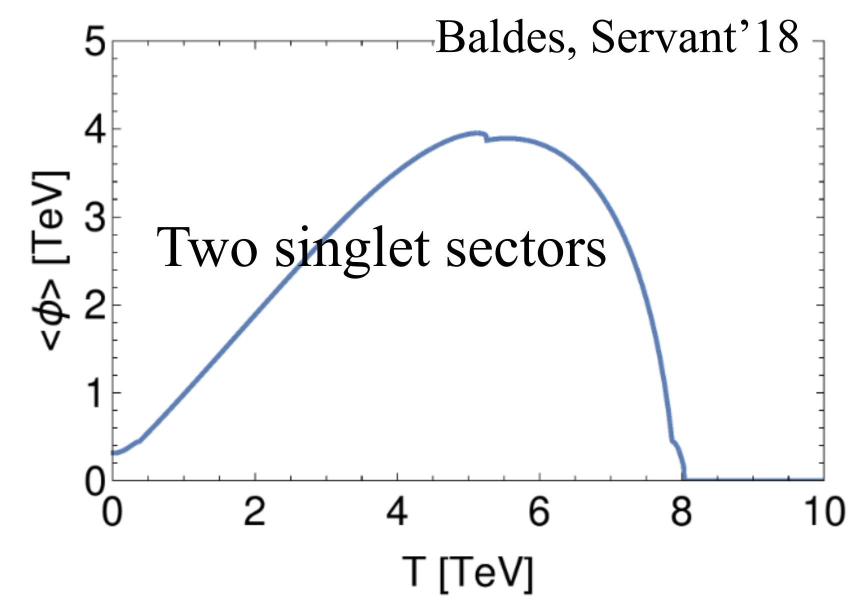
Meade,Ramani’16



Glioti, Rattazzi, Vecchi’19

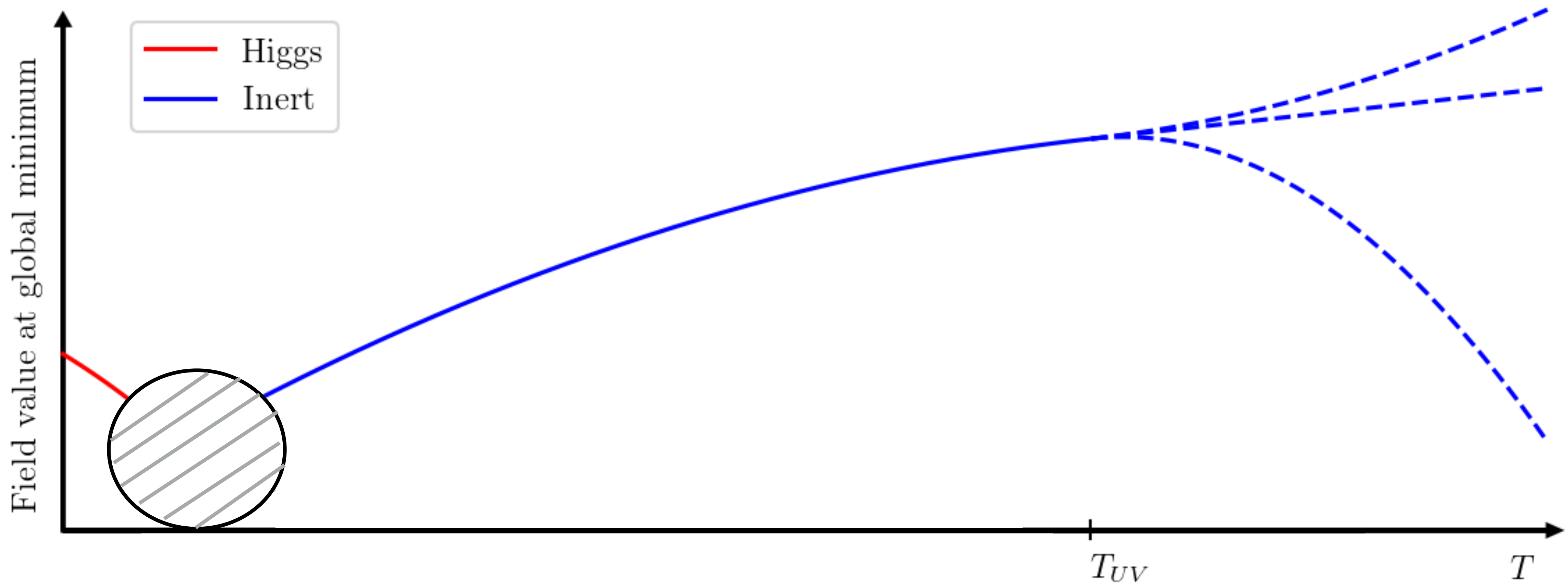


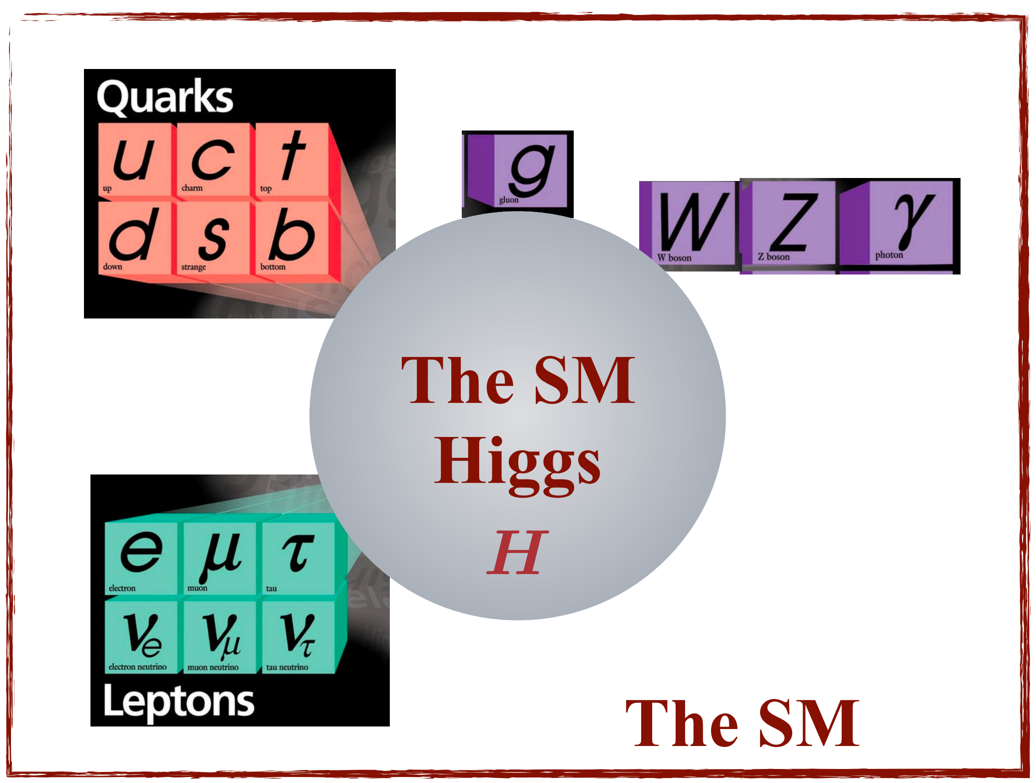
Baldes, Servant’18



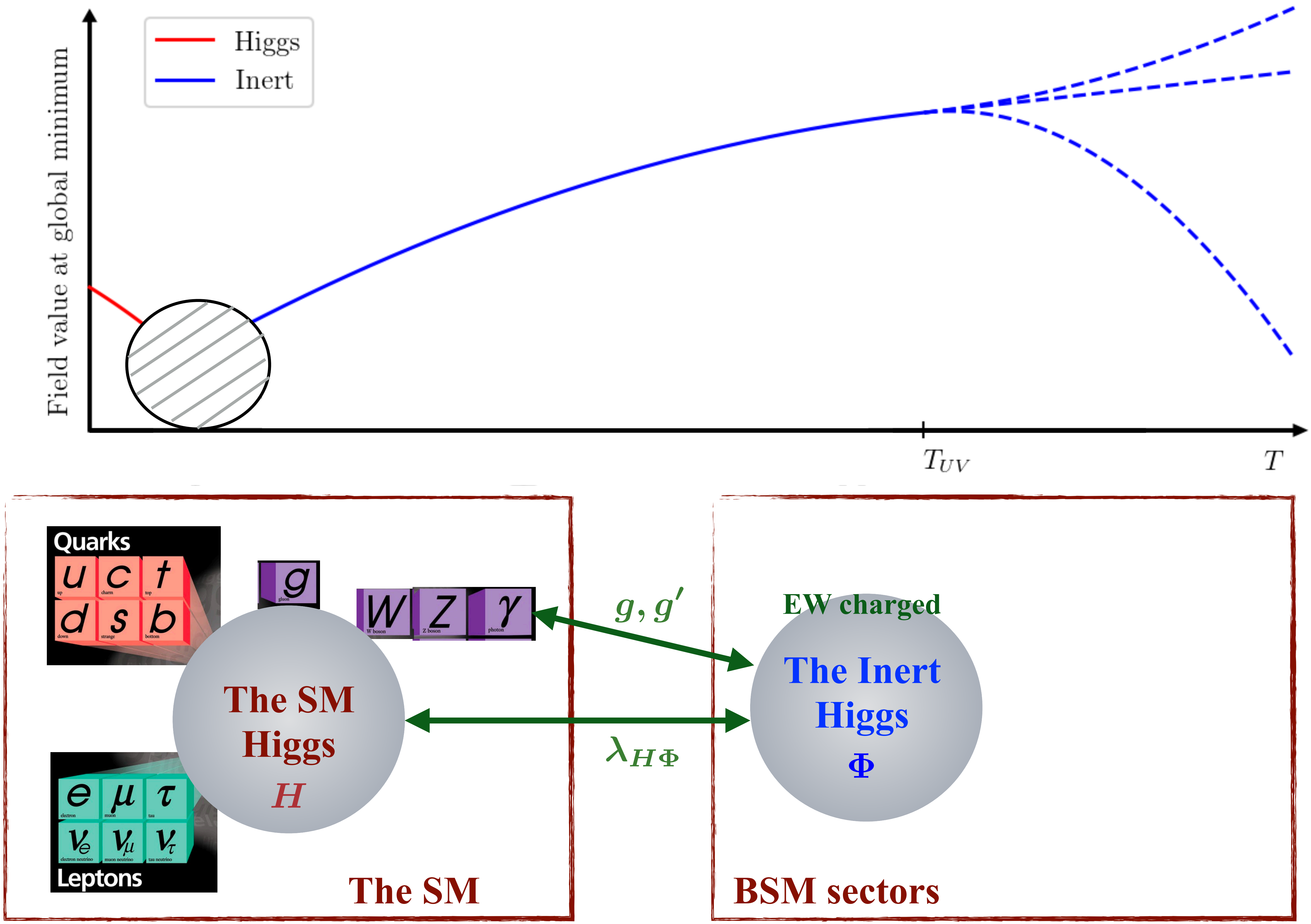
etc…

A new approach to EWNR





A new approach to EWNR



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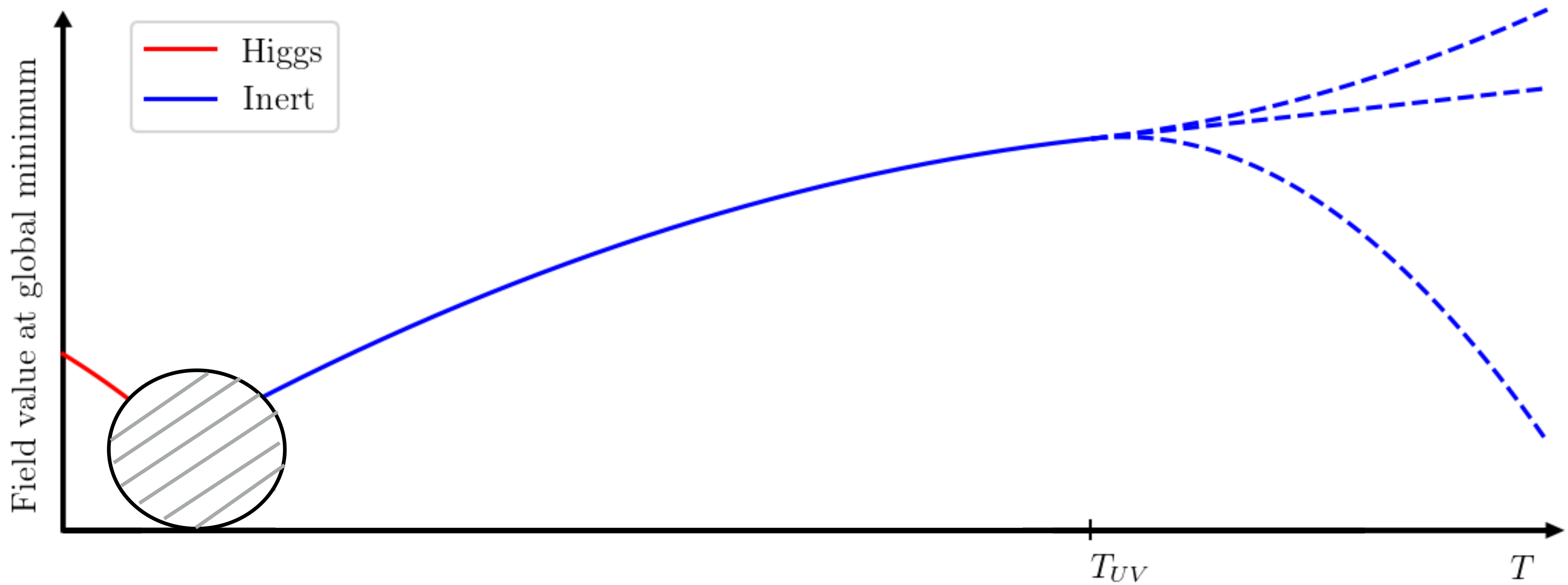

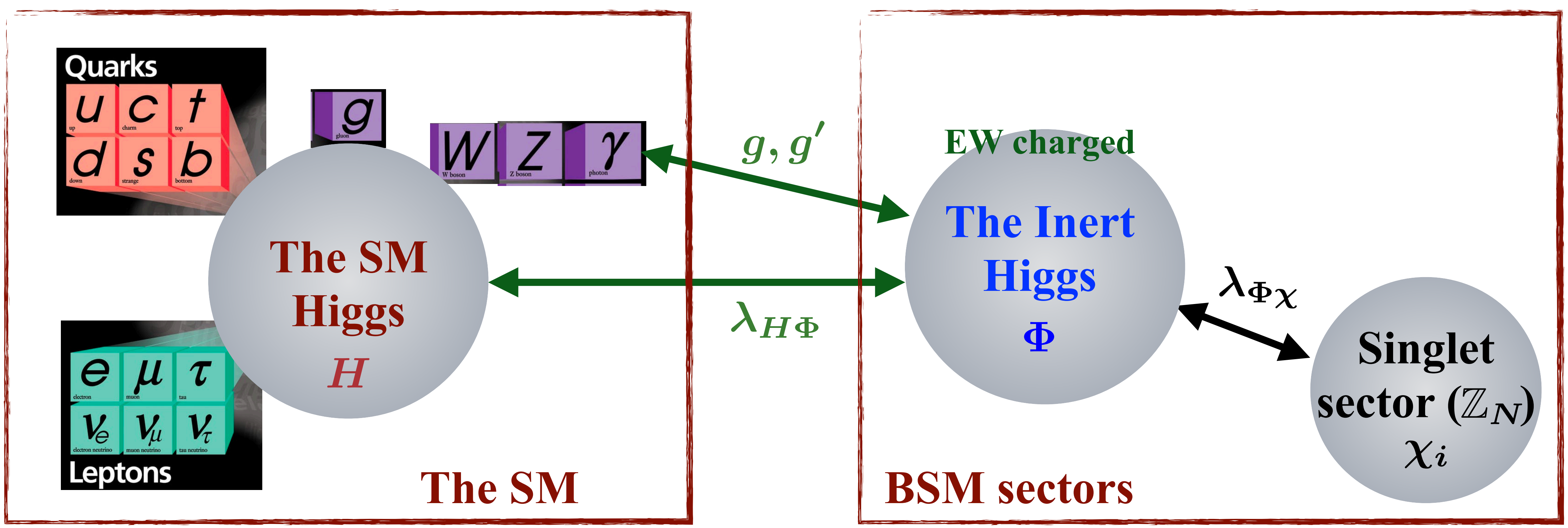

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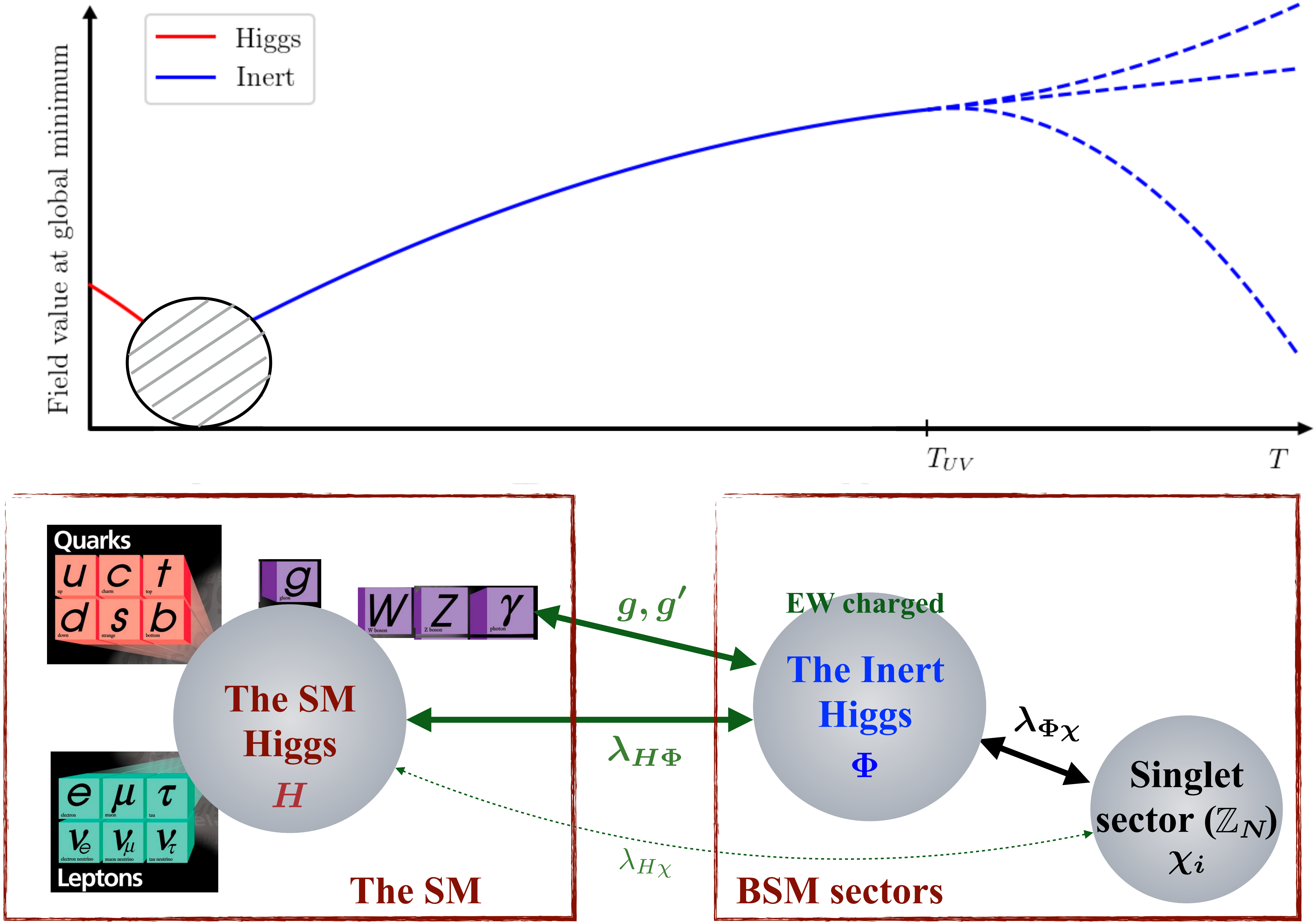
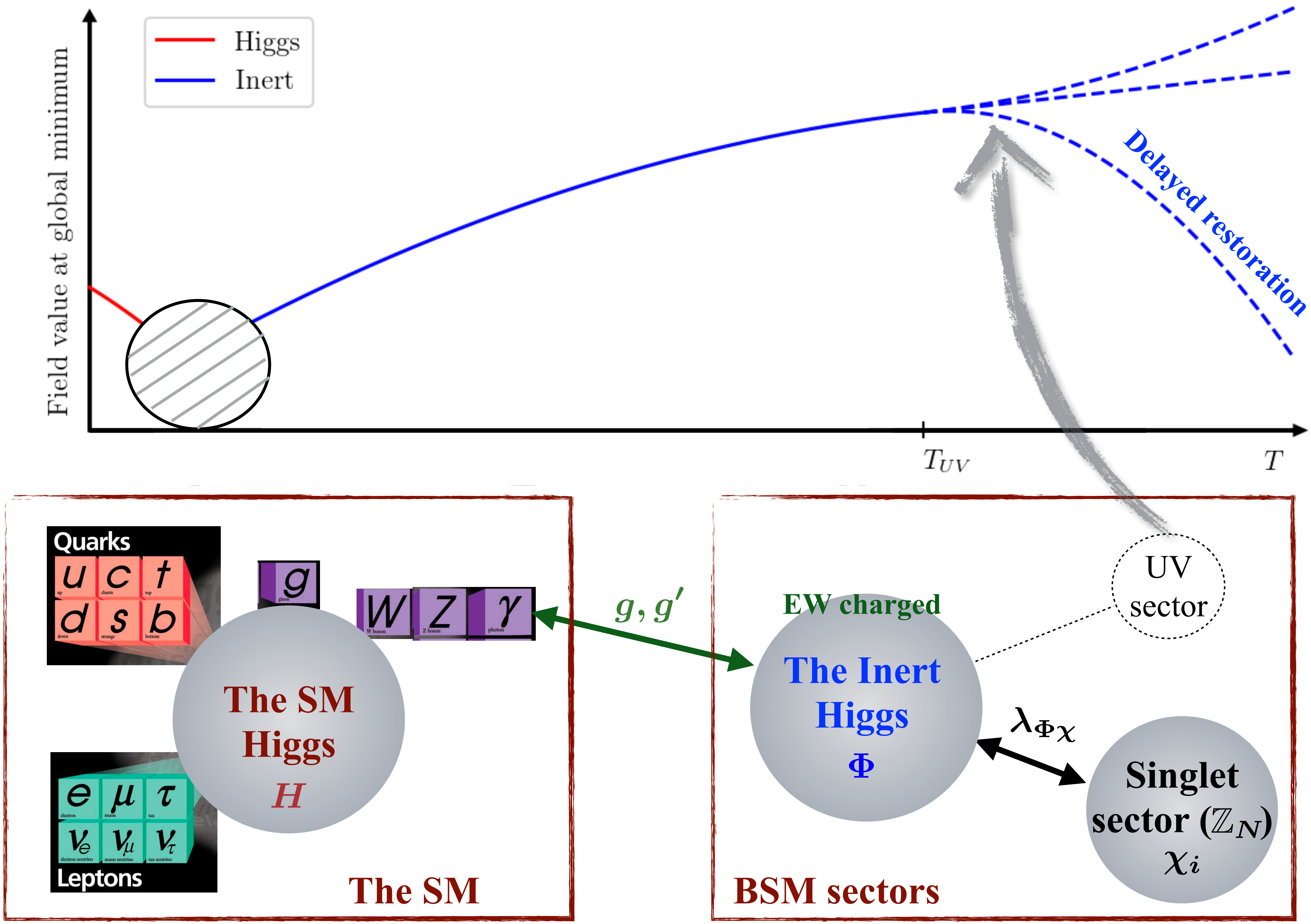
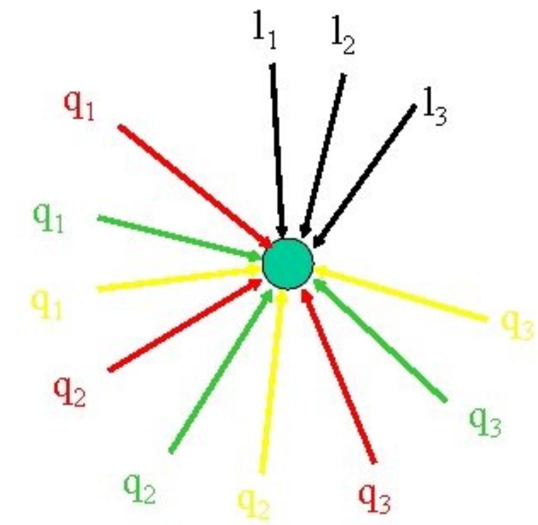


A new approach to EWNR



Asymmetry washout - a model building consideration

The (EW) sphaleron process



Washout B + L; preserve B - L

If the sphalerons become active:

Net B-L generated at **UV**

$$\mathbf{B_{now} = -L_{now} \neq 0}$$ ✓

e.g. leptogenesis

Net B+L generated at **UV**

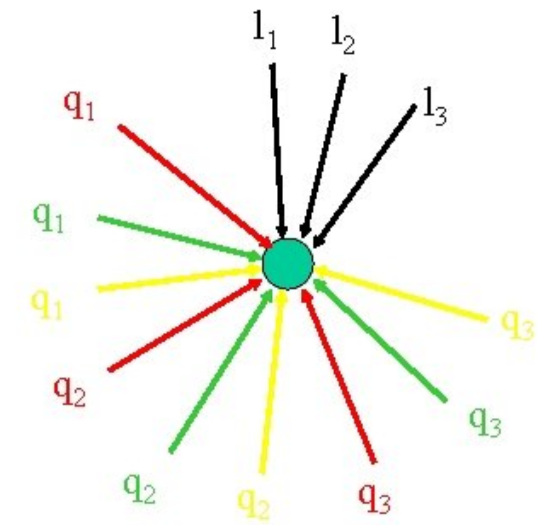
$$\mathbf{B_{now} = L_{now} = 0}$$ ✗

e.g. baryogenesis

Asymmetry washout - a model building consideration

The (EW) sphaleron process

Washout B + L; preserve B - L



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e.g. leptogenesis

Net B+L generated at UV

$$\mathbf{B_{now} = L_{now} = 0}$$

e.g. baryogenesis

The sphaleron rate

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

with

$$\frac{E_{sph}(T)}{T} = \frac{4\pi}{g} B \frac{\sqrt{\langle h\rangle^2 + \langle\varphi\rangle^2}}{T}$$

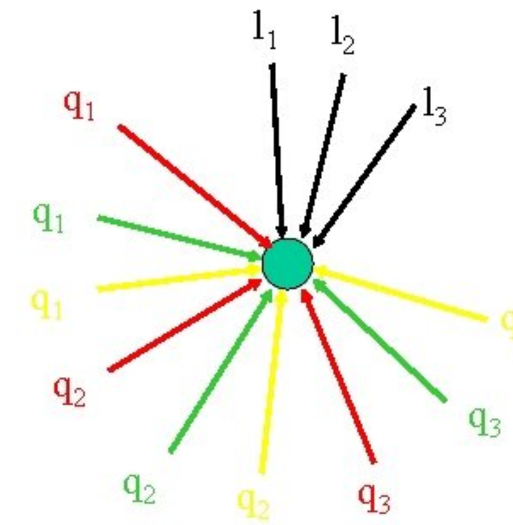
Inactive sphaleron process requires (naively)

$$\frac{\sqrt{\langle h\rangle^2+\langle\varphi\rangle^2}}{T} \gtrsim 1$$

for all temperatures from UV to zero T.

Asymmetry washout - a model building consideration

The (EW) sphaleron process



Washout B + L; preserve B - L

If the sphalerons become active:

Net B-L generated at **UV**	Net B+L generated at **UV**
$\mathbf{B_{now} = -L_{now} \neq 0}$	$\mathbf{B_{now} = L_{now} = 0}$
e.g. leptogenesis	e.g. baryogenesis

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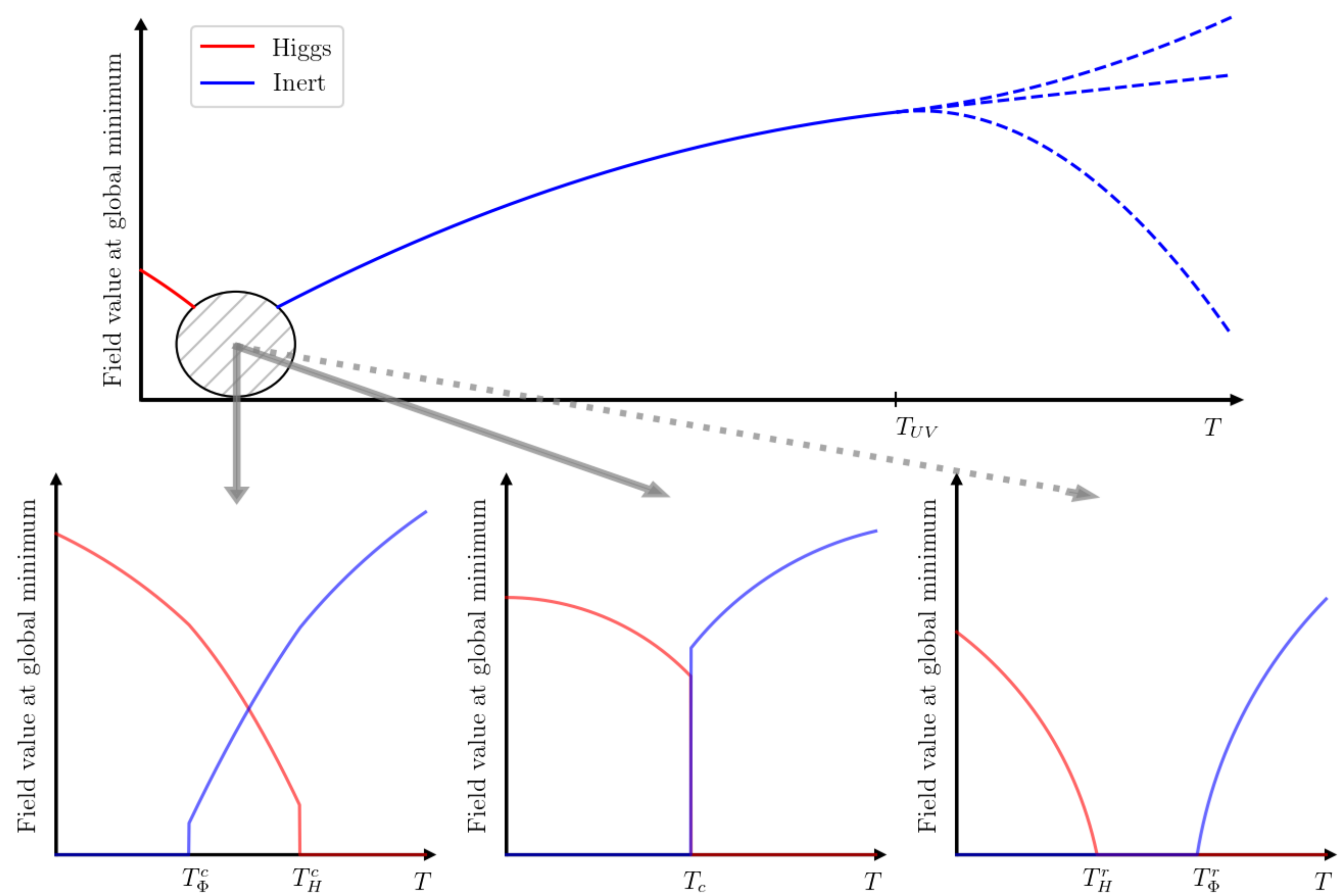


The model and the effective potential

The tree level potential and model parameters

$$V_{\mathbb{Z}_N+\text{I2HDM}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_\Phi^2 (\Phi^\dagger\Phi) + \lambda_\Phi (\Phi^\dagger\Phi)^2 + \lambda_{H\Phi}(H^\dagger H)(\Phi^\dagger\Phi) + \widetilde{\lambda}_{H\Phi}(H^\dagger\Phi)(\Phi^\dagger H)$$
$$+ \frac{\mu_\chi^2}{2}\chi_i^2 + \frac{\widetilde{\lambda}_\chi}{4}\chi_i^4 + \frac{\lambda_\chi}{4}(\chi_i\chi_i)^2 + \frac{\lambda_{\Phi\chi}}{2}\chi_i^2(\Phi^\dagger\Phi) + \frac{\lambda_{H\chi}}{2}\chi_i^2(H^\dagger H)$$

- fixed parameters: $\{\mu_H^2,\ \lambda_H\}$,
- free parameters: $\{\mu_\Phi^2,\ \mu_\chi^2,\ \lambda_\Phi,\ \lambda_\chi,\ \lambda_{\Phi\chi},\ \lambda_{H\Phi},\ N\}$,
- free parameters set to zero: $\{\widetilde{\lambda}_{H\Phi},\ \lambda_{H\chi},\ \widetilde{\lambda}_\chi\}$,

Can be induced by RGE

Zero temperature constraints

Vacuum stability

$$\langle\{h, \varphi, \chi_1, \cdots, \chi_N\}\rangle = \{v_0, 0, 0, \cdots, 0\}$$

Bounded from below (BFB)

$$\lambda_H > 0, \qquad \lambda_\Phi > 0, \qquad \lambda_\chi > 0,$$
$$\lambda_{H\Phi} > -\sqrt{4\lambda_H\lambda_\Phi}, \qquad \lambda_{\Phi\chi} > -\sqrt{4\lambda_\Phi\lambda_\chi}, \qquad \lambda_{H\chi} > -\sqrt{4\lambda_H\lambda_\chi},$$
$$\sqrt{4\lambda_H\lambda_\Phi\lambda_\chi} + \lambda_{H\Phi}\sqrt{\lambda_\chi} + \lambda_{\Phi\chi}\sqrt{\lambda_H} + \lambda_{H\chi}\sqrt{\lambda_\Phi} + \sqrt{\left(\lambda_{H\Phi} + \sqrt{4\lambda_H\lambda_\Phi}\right)\left(\lambda_{\Phi\chi} + \sqrt{4\lambda_\Phi\lambda_\chi}\right)\left(\lambda_{H\chi} + \sqrt{4\lambda_H\lambda_\chi}\right)} > 0$$

(tree level, copositivity of the quadratic potential)

The model and the effective potential

Finite temperature effective potential (one loop)

Zero temperature part (Coleman-Weinberg potential)

$$V_{CW}\left(\{M_i^2(\hat{\Phi})\};\mu_{\rm R}\right)=\frac{1}{64\pi^2}\sum_{i={\rm B,F}}(-1)^{2S_i}n_i M_i^4(\hat{\Phi})\left[\log\frac{M_i^2(\hat{\Phi})}{\mu_{\rm R}^2}-a_i\right]$$

Finite temperature part

$$V_{1-\text{loop}}^T(\{M_k^2(\hat{\Phi})\},T)=\frac{T^4}{2\pi^2}\left[\sum_{i=B}n_iJ_B\left(\frac{M_i^2(\hat{\Phi})}{T^2}\right)-\sum_{i=F}n_iJ_F\left(\frac{M_i^2(\hat{\Phi})}{T^2}\right)\right],$$

$$\text{with}\quad J_{B/F}(y)=\int_0^\infty dx\,x^2\log\left(1\mp e^{-\sqrt{x^2+y}}\right)$$

Degrees for freedom in the plasma: $\{h, G_0, G^\pm, \varphi, \phi_0, \phi^\pm, \chi, \gamma, W^\pm, Z, t\}$

High temperature expansion and the thermal mass

"thermal mass"

$$V^{\rm MF}_{\mathbb{Z}_N+{\rm I2HDM}}=-\frac{1}{2}\left(\mu_H^2-c_hT^2\right)h^2+\frac{1}{2}\left(\mu_\Phi^2+c_\varphi T^2\right)\varphi^2+\frac{1}{2}\left(\mu_\chi^2+c_\chi T^2\right)\chi_i^2$$
$$+\frac{\lambda_H}{4}h^4+\frac{\lambda_\Phi}{4}\varphi^4+\frac{\widetilde{\lambda}_\chi}{4}\chi_i^4+\frac{\lambda_\chi}{4}(\chi_i\chi_i)^2+\frac{\Lambda_{H\Phi}}{4}\varphi^2h^2+\frac{\lambda_{\Phi\chi}}{4}\varphi^2\chi_i^2+\frac{\lambda_{H\chi}}{4}h^2\chi_i^2$$

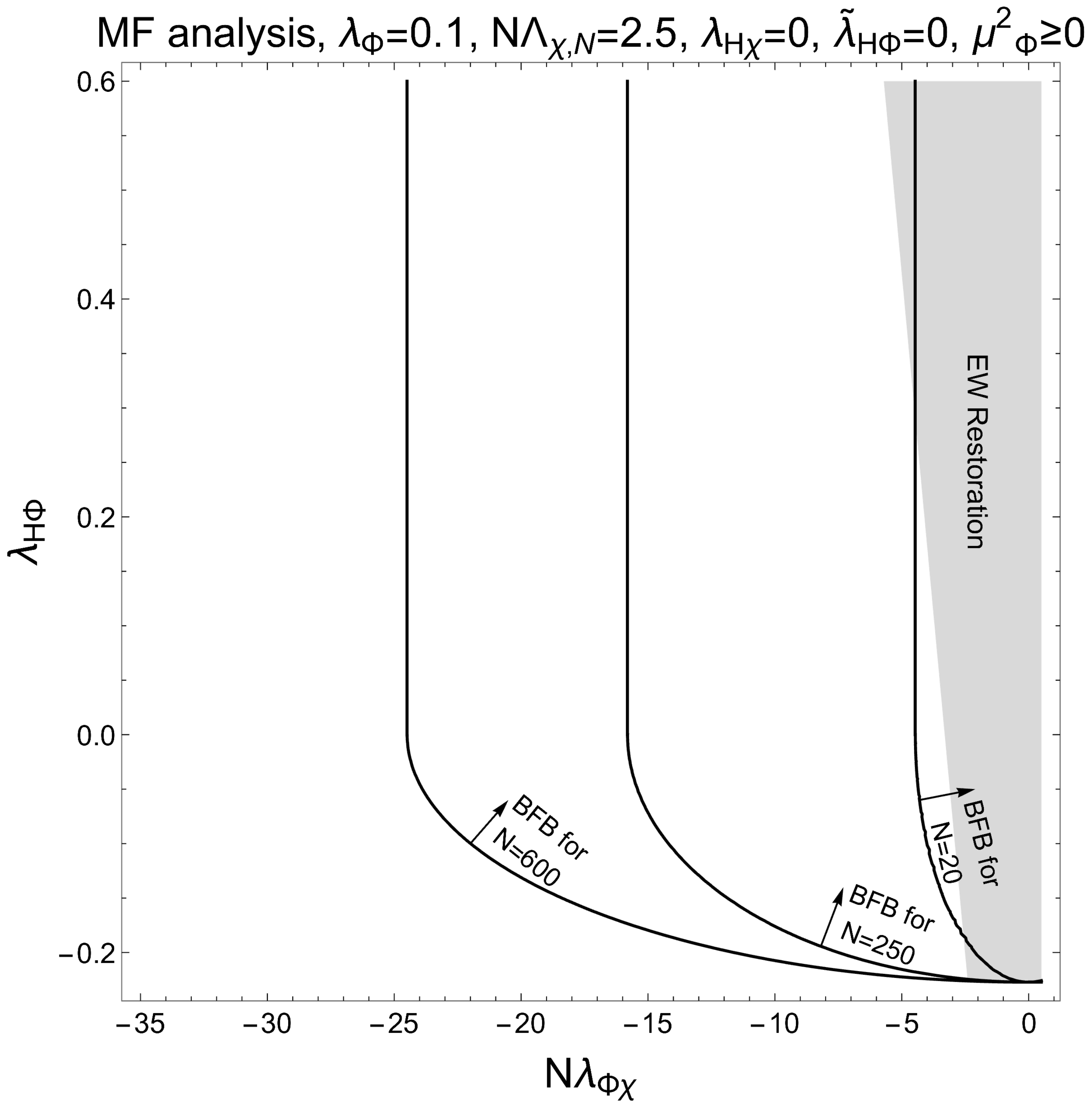
(leading order in the high-T expansion, no CW)

$$\text{e.g.,}\quad c_\varphi=\frac{\lambda_\Phi}{2}+\frac{\lambda_{H\Phi}+\widetilde{\lambda}_{H\Phi}/2}{6}+\frac{3g^2+g'^2}{16}+N\frac{\lambda_{\Phi\chi}}{24}$$

→ **Being negative results in a non-zero inert Higgs vev**

A preliminary look at the parameter space

$$V^{\rm MF}_{\mathbb{Z}_N+{\rm I2HDM}} = -\frac{1}{2}\left(\mu_H^2 - c_h T^2\right)h^2 + \frac{1}{2}\left(\mu_\Phi^2 + c_\varphi T^2\right)\varphi^2 + \frac{1}{2}\left(\mu_\chi^2 + c_\chi T^2\right)\chi_i^2$$
$$+\frac{\lambda_H}{4}h^4 + \frac{\lambda_\Phi}{4}\varphi^4 + \frac{\widetilde{\lambda}_\chi}{4}\chi_i^4 + \frac{\lambda_\chi}{4}(\chi_i\chi_i)^2 + \frac{\Lambda_{H\Phi}}{4}\varphi^2 h^2 + \frac{\lambda_{\Phi\chi}}{4}\varphi^2\chi_i^2 + \frac{\lambda_{H\chi}}{4}h^2\chi_i^2$$



- **Non-restoration**

$$c_\varphi = \frac{\lambda_\Phi}{2} + \frac{\lambda_{H\Phi}+\widetilde{\lambda}_{H\Phi}/2}{6} + \frac{3g^2+g'^2}{16} + N\frac{\lambda_{\Phi\chi}}{24} < 0$$

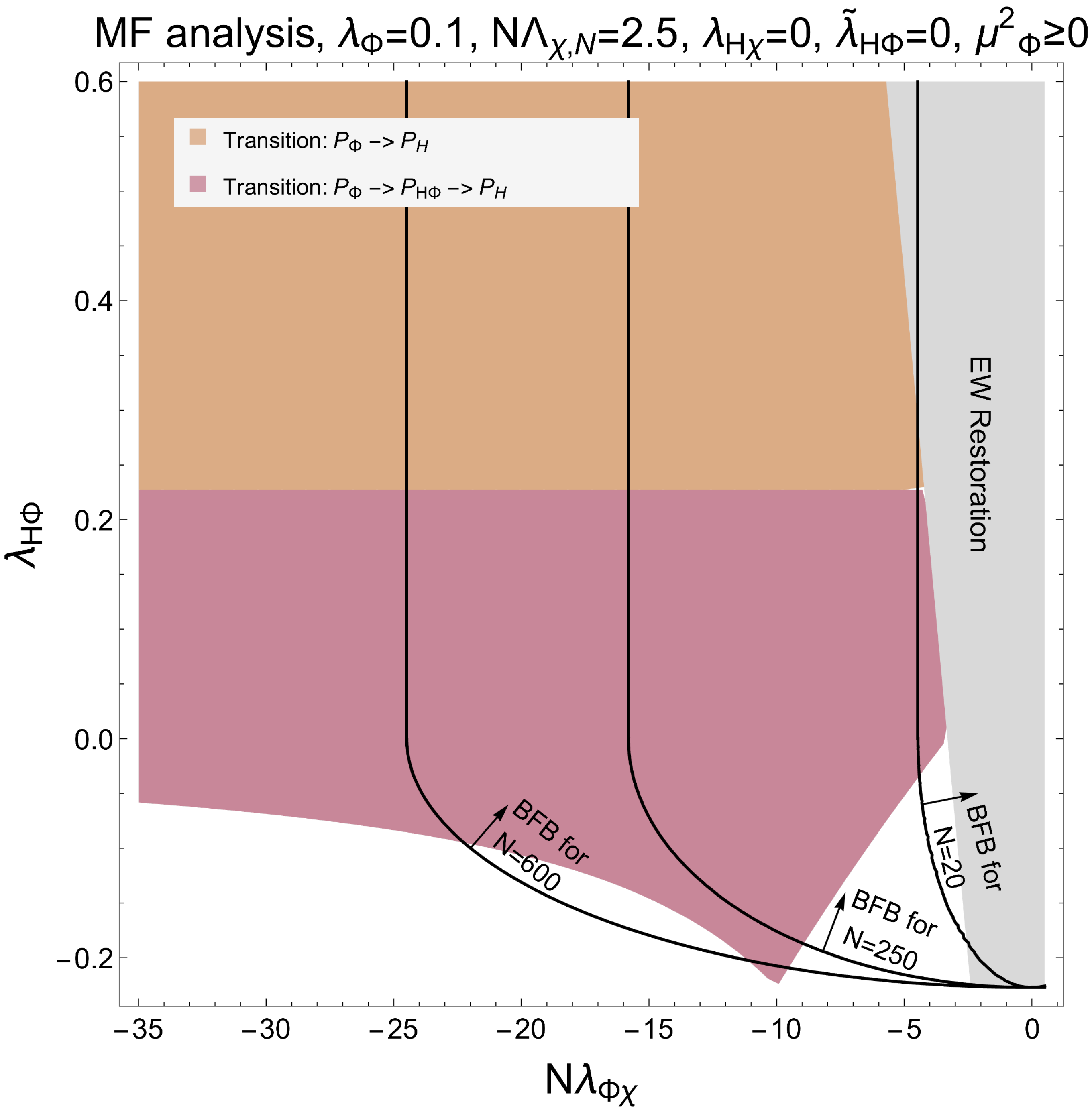
- **Bounded from below**

$$\text{e.g.}\quad \lambda_{\Phi\chi} > -\sqrt{4\lambda_\Phi\lambda_\chi}$$

A preliminary look at the parameter space

$$V^{\rm MF}_{\mathbb{Z}_N+{\rm I2HDM}} = -\frac{1}{2}\left(\mu_H^2 - c_h T^2\right)h^2 + \frac{1}{2}\left(\mu_\Phi^2 + c_\varphi T^2\right)\varphi^2 + \frac{1}{2}\left(\mu_\chi^2 + c_\chi T^2\right)\chi_i^2$$

$$+\frac{\lambda_H}{4}h^4 + \frac{\lambda_\Phi}{4}\varphi^4 + \frac{\widetilde{\lambda}_\chi}{4}\chi_i^4 + \frac{\lambda_\chi}{4}(\chi_i\chi_i)^2 + \frac{\Lambda_{H\Phi}}{4}\varphi^2 h^2 + \frac{\lambda_{\Phi\chi}}{4}\varphi^2\chi_i^2 + \frac{\lambda_{H\chi}}{4}h^2\chi_i^2$$



- **Non-restoration**

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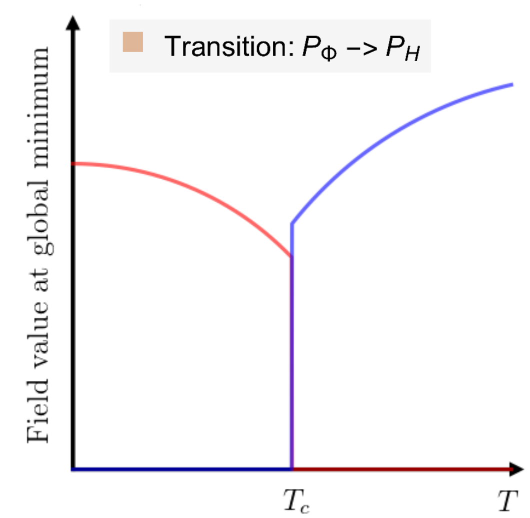
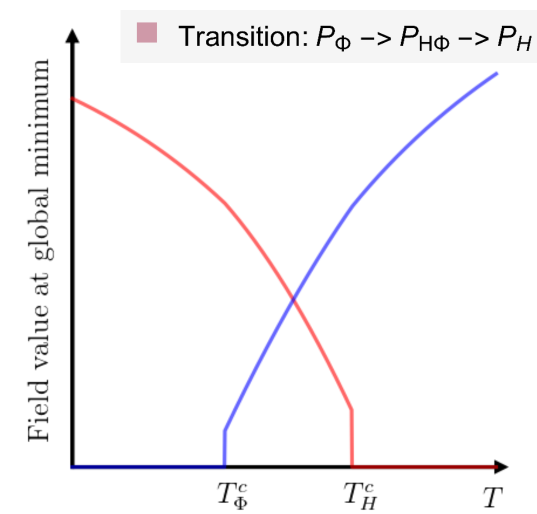
- **Transition**



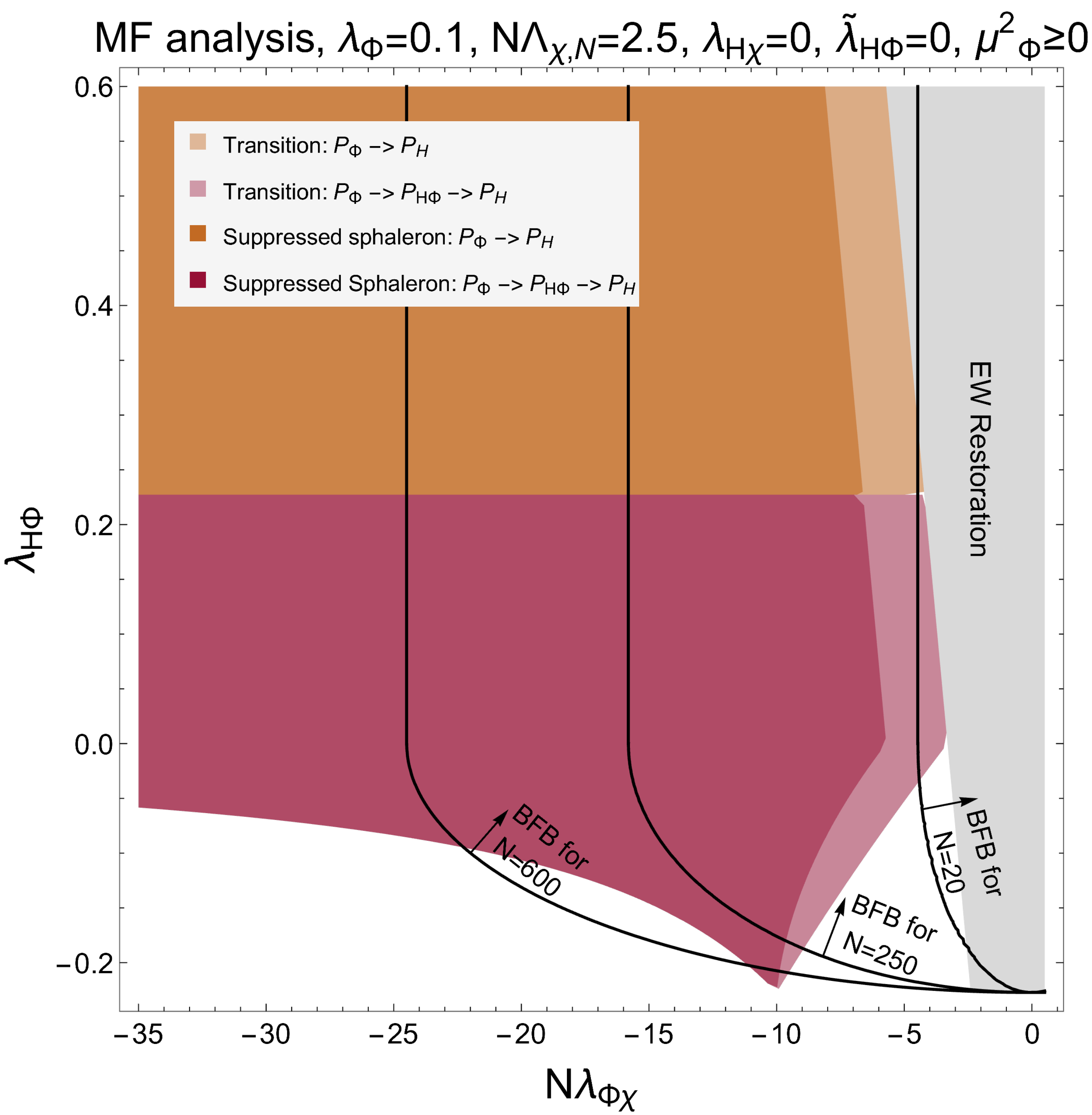


- **Bounded from below**

$$\text{e.g.}\quad \lambda_{\Phi\chi} > -\sqrt{4\lambda_\Phi\lambda_\chi}$$

A preliminary look at the parameter space

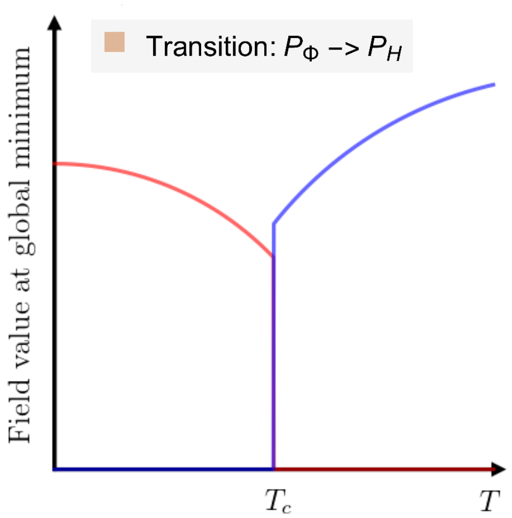
$$V^{\rm MF}_{\mathbb{Z}_N+{\rm I2HDM}} = -\frac{1}{2}\left(\mu_H^2 - c_h T^2\right)h^2 + \frac{1}{2}\left(\mu_\Phi^2 + c_\varphi T^2\right)\varphi^2 + \frac{1}{2}\left(\mu_\chi^2 + c_\chi T^2\right)\chi_i^2$$
$$+\frac{\lambda_H}{4}h^4 + \frac{\lambda_\Phi}{4}\varphi^4 + \frac{\widetilde{\lambda}_\chi}{4}\chi_i^4 + \frac{\lambda_\chi}{4}(\chi_i\chi_i)^2 + \frac{\Lambda_{H\Phi}}{4}\varphi^2 h^2 + \frac{\lambda_{\Phi\chi}}{4}\varphi^2\chi_i^2 + \frac{\lambda_{H\chi}}{4}h^2\chi_i^2$$

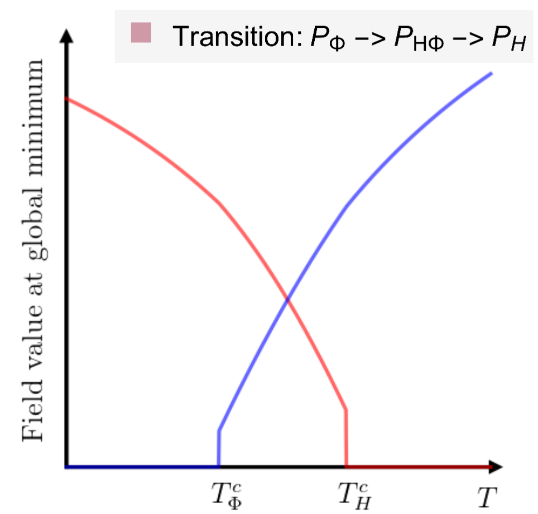


- **Non-restoration**

$$c_\varphi = \frac{\lambda_\Phi}{2} + \frac{\lambda_{H\Phi} + \widetilde{\lambda}_{H\Phi}/2}{6} + \frac{3g^2 + g'^2}{16} + N\frac{\lambda_{\Phi\chi}}{24} < 0$$

- **Transition**





- **Suppressed sphaleron rate**

$$\frac{\sqrt{\langle h\rangle^2 + \langle\varphi\rangle^2}}{T} \gtrsim 1$$

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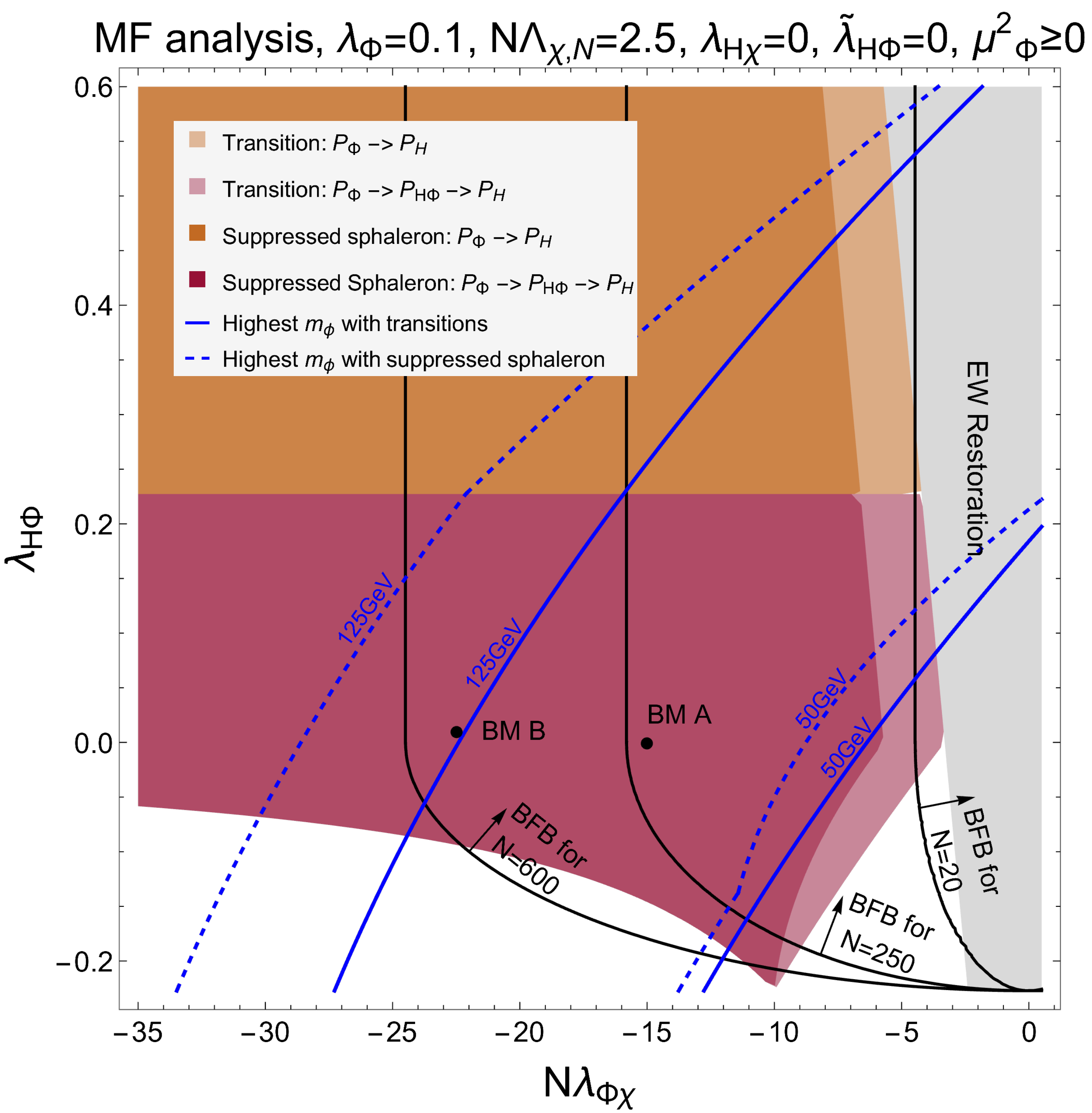

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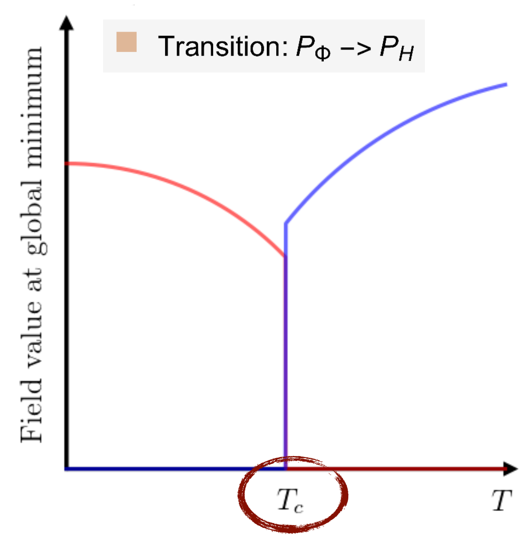

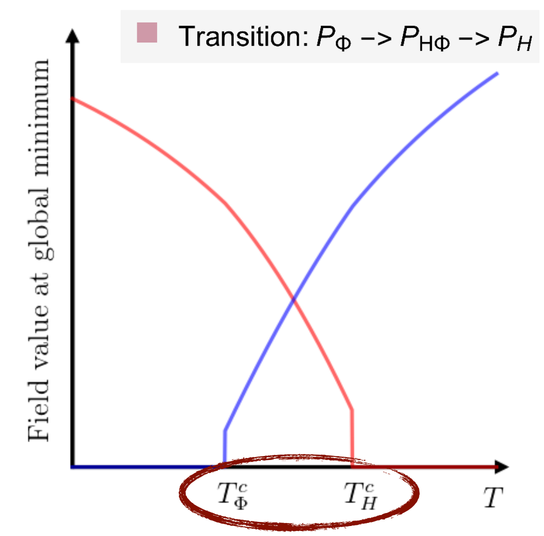

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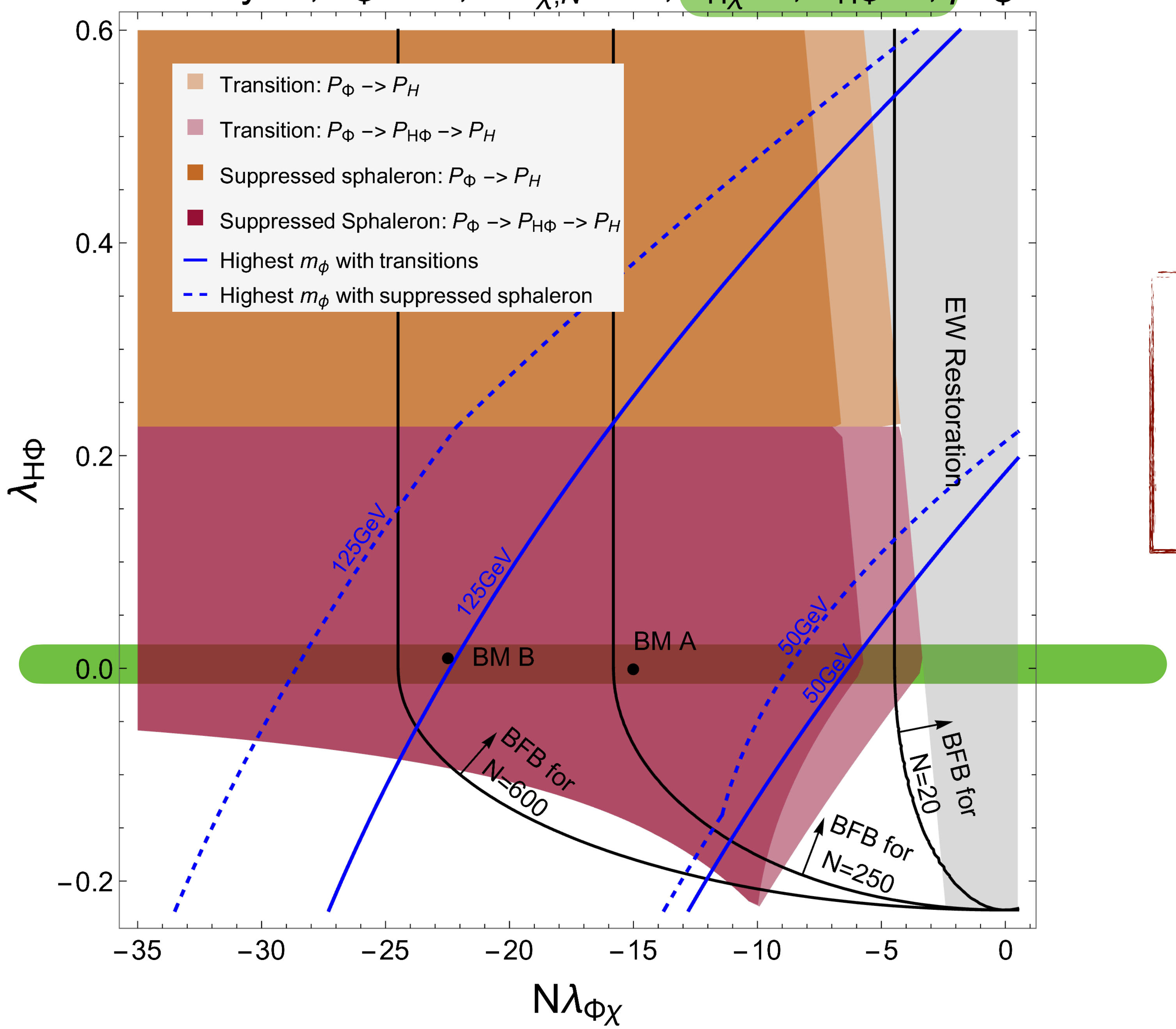
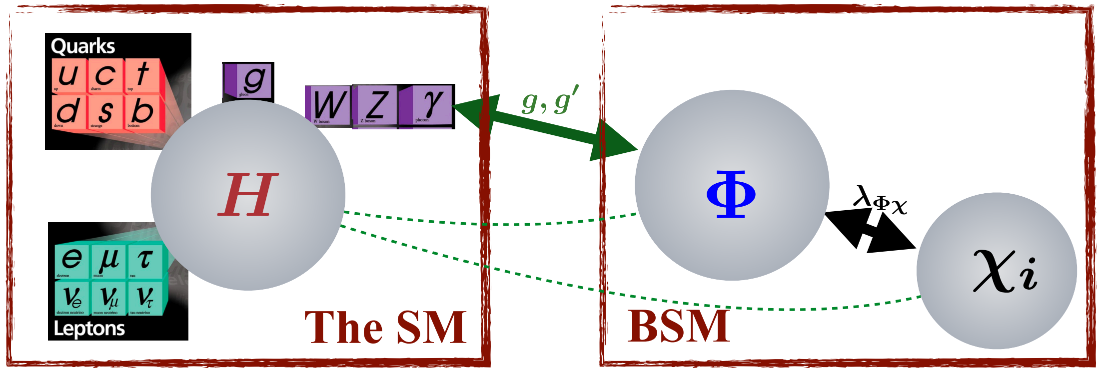
MF analysis, λ_Φ=0.1, $N\Lambda_{\chi,N}$=2.5, $\lambda_{H\chi}$=0, $\tilde{\lambda}_{H\Phi}$=0, $\mu^2_\Phi \geq 0$





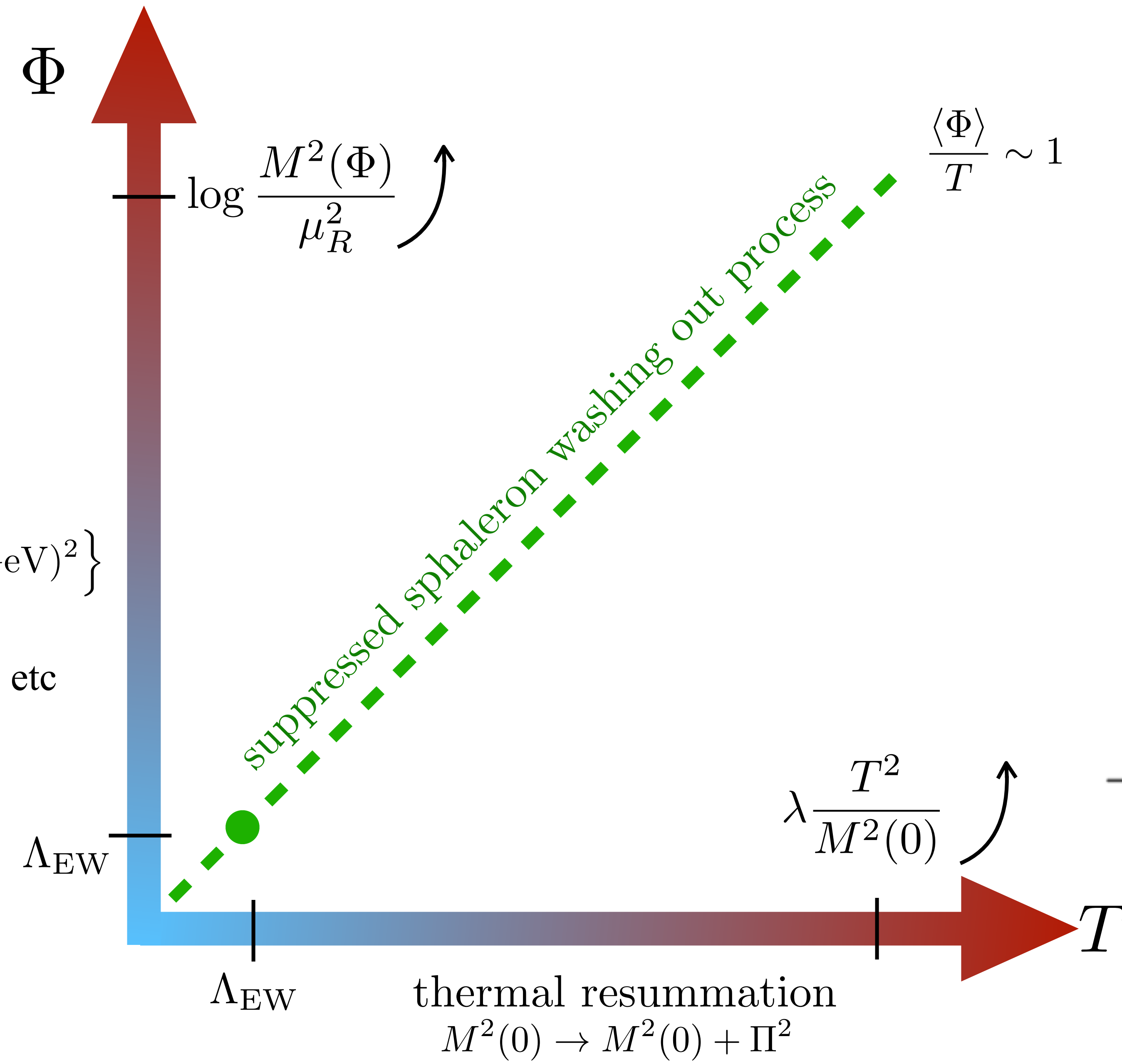
Almost decoupled scenarios

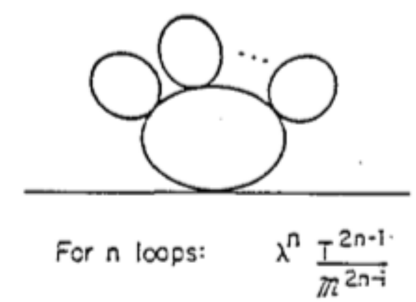
Physics at high scales and temperatures - effective potential improvements

RG – improvement

$$\mu_R^2 = \mathrm{Max}\left\{M_i^2(\hat{\Phi}) + c_i T^2; (246\ \mathrm{GeV})^2\right\}$$

Bando etc'93, etc



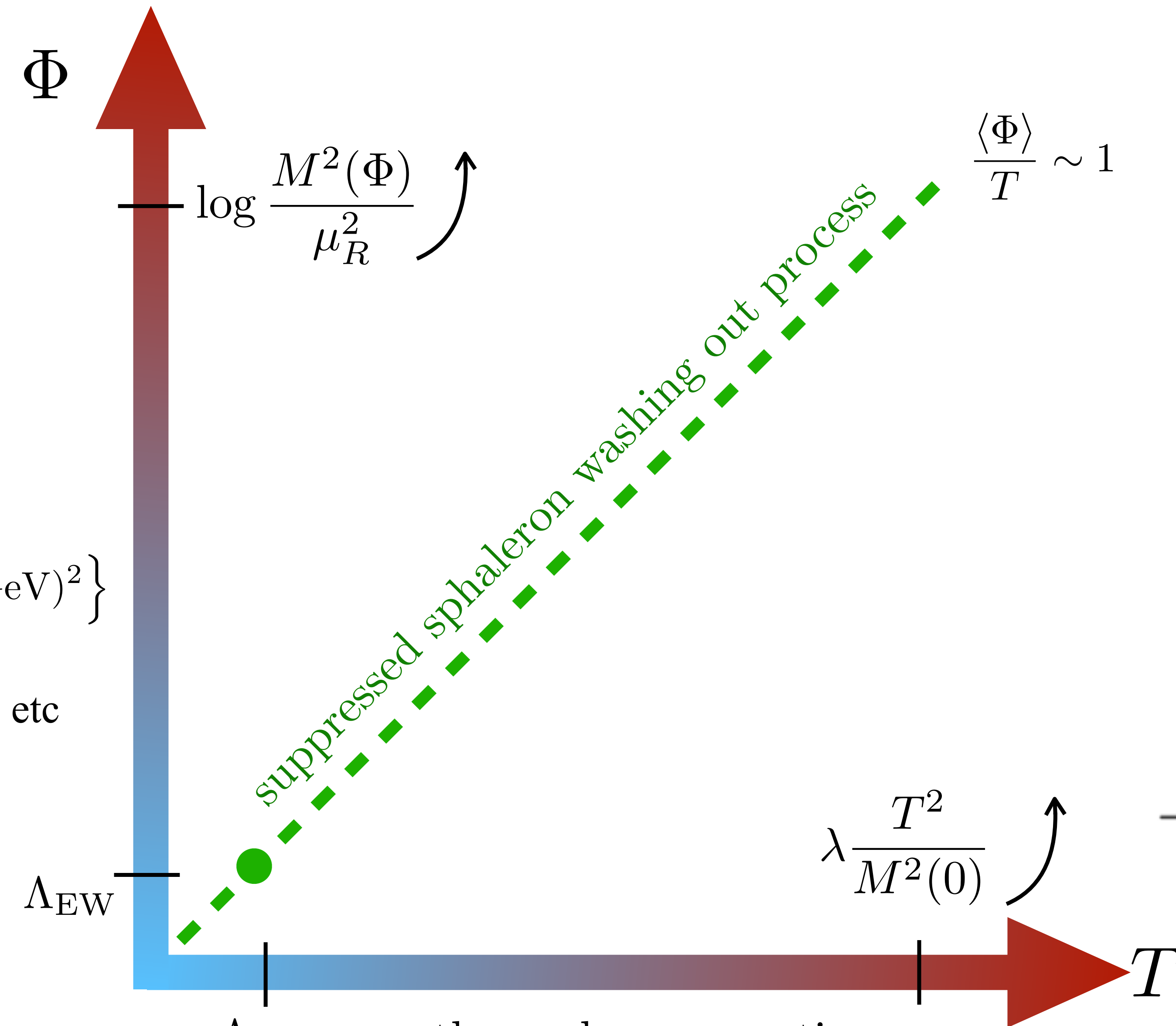


Fendley'87, etc

How to calculate Π^2 ?

$$\Pi_{i,\mathrm{gap}}^2 = \frac{\partial^2}{\partial \hat{\Phi}_i^2} \sum_k V_{1-\mathrm{loop}}^T \left(\{M_k^2(\hat{\Phi}) + \Pi_{k,\mathrm{gap}}^2\}; T\right)$$

Physics at high scales and temperatures - effective potential improvements



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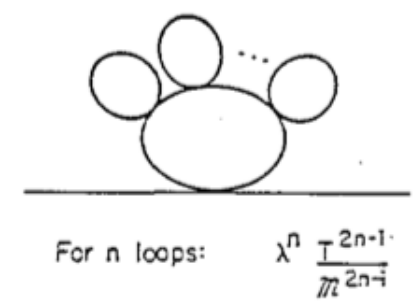


Fendley'87, etc

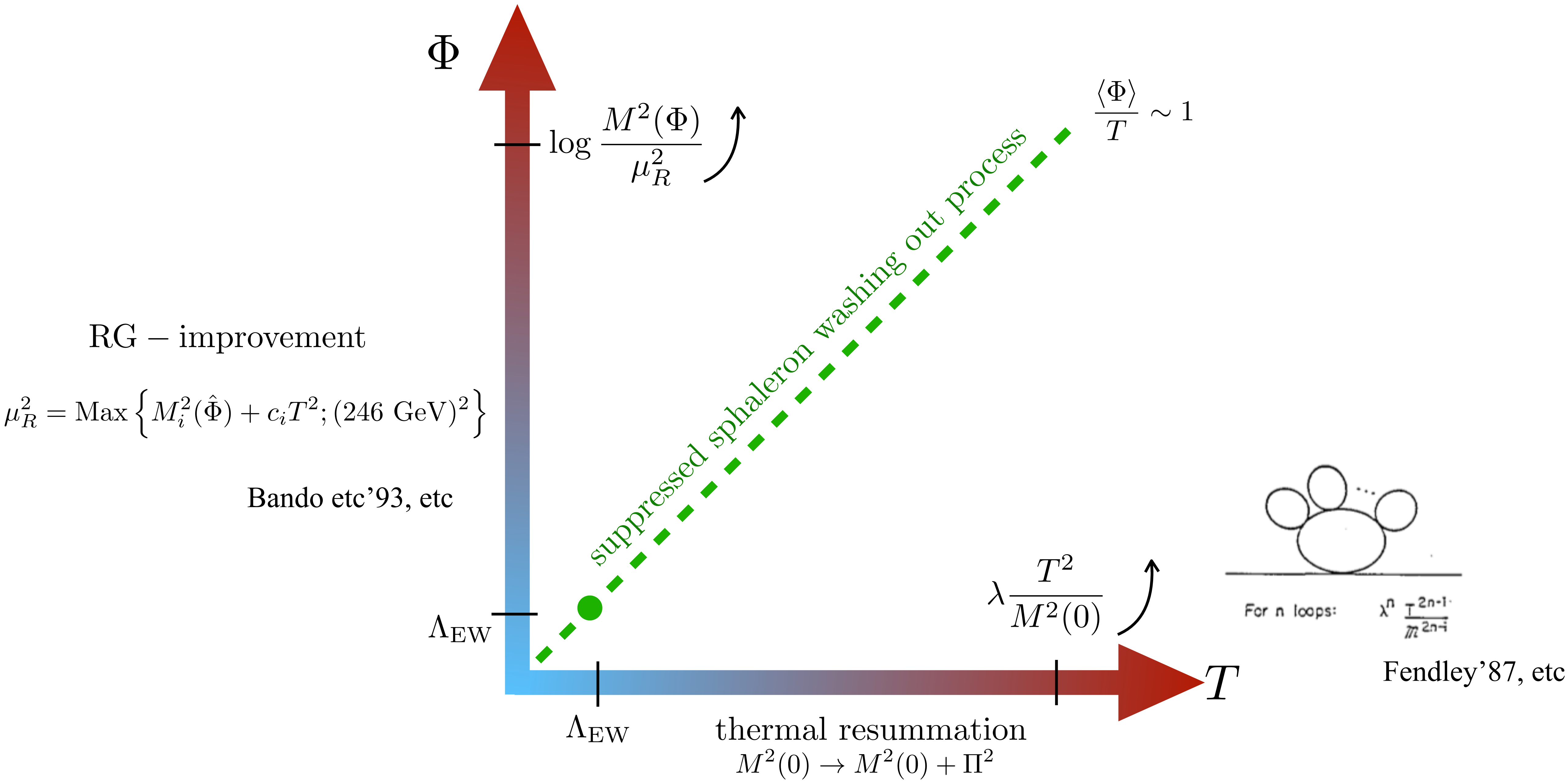
thermal resummation
$M^2(0) \to M^2(0) + \Pi^2$

How to calculate Π^2 ?

truncate (leading order)

$$\Pi^2_{i,\text{gap}} = \frac{\partial^2}{\partial \hat\Phi_i^2} \sum_k V^T_{1-\text{loop}}\left(\{M_k^2(\hat\Phi) + \Pi^2_{k,\text{gap}}\}; T\right)$$

Physics at high scales and temperatures - effective potential improvements



How to calculate Π^2 ?

high T expand (leading order)

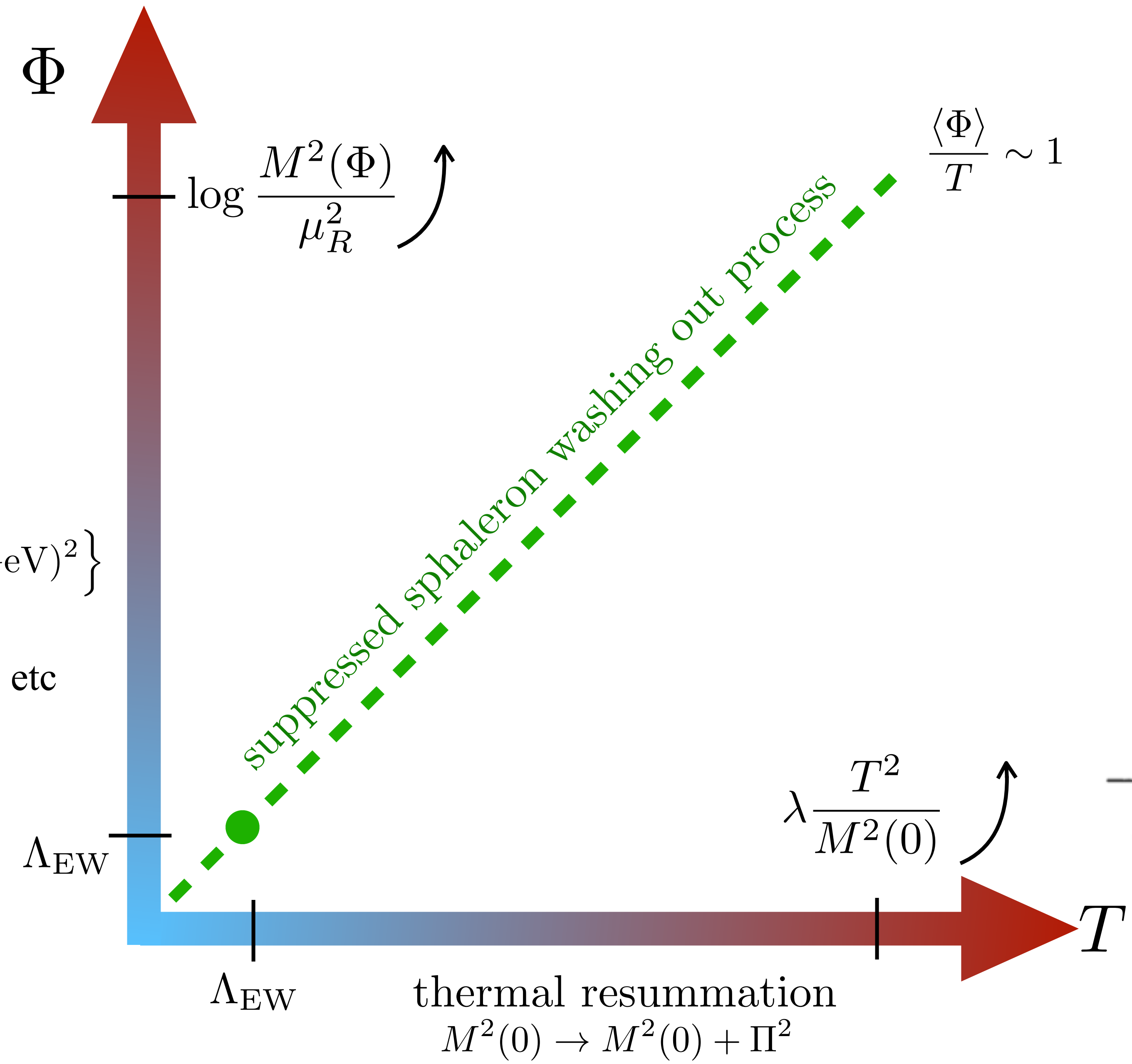
$$\Pi^2_{i,\mathrm{trunc}} = \frac{\partial^2}{\partial \hat{\Phi}_i^2} \sum_k V^T_{1-\mathrm{loop}}\left(\{M_k^2(\hat{\Phi})\}; T\right)$$

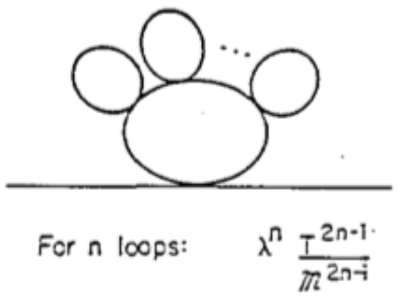
Physics at high scales and temperatures - effective potential improvements

RG – improvement

$$\mu_R^2 = \mathrm{Max}\left\{M_i^2(\hat{\Phi}) + c_i T^2; (246\ \mathrm{GeV})^2\right\}$$

Bando etc'93, etc



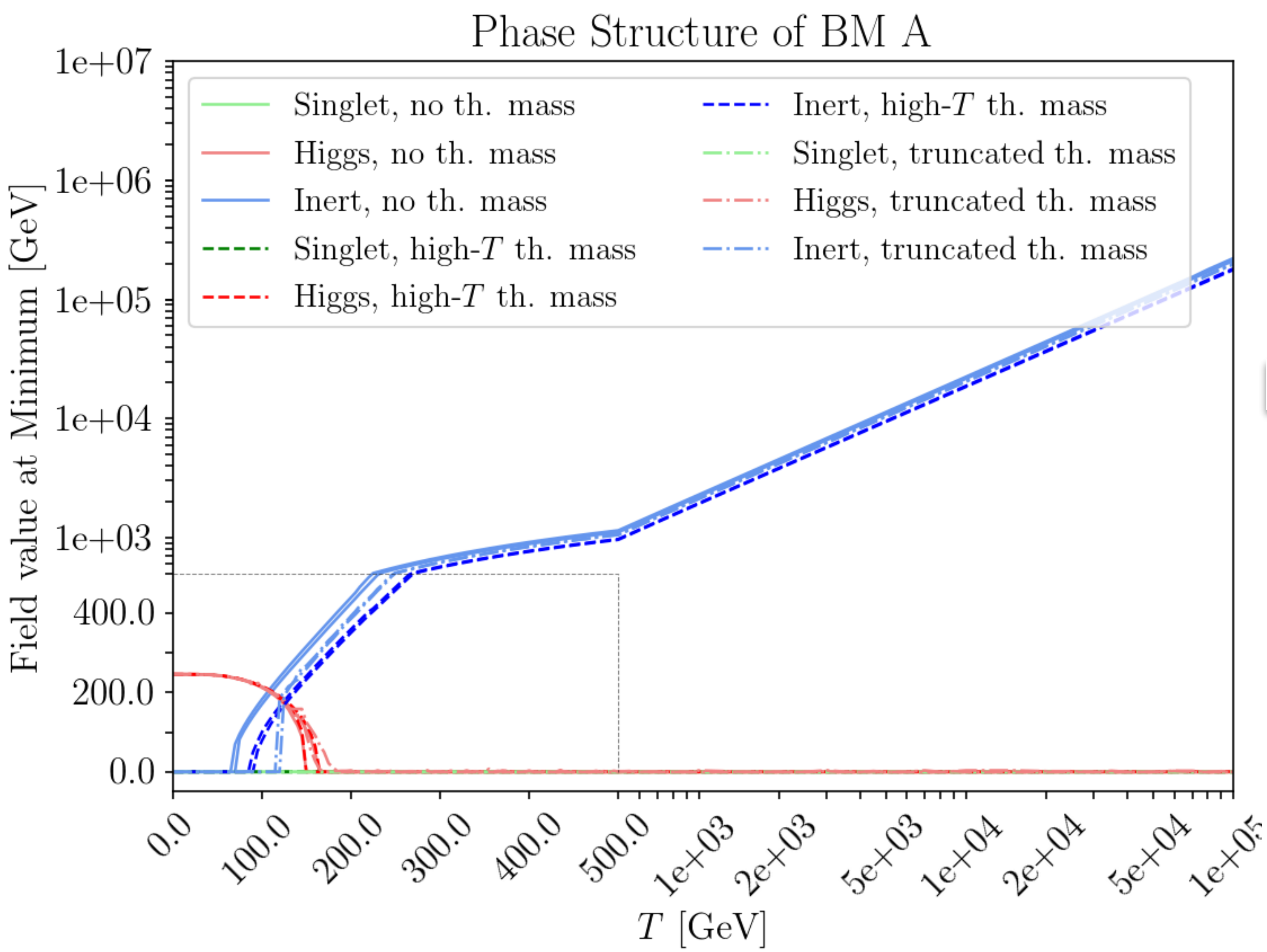


Fendley'87, etc

How to calculate Π^2 ?

$$\Pi_{i,\mathrm{hT}}^2 = c_i T^2$$

Benchmark scenarios: numerical results

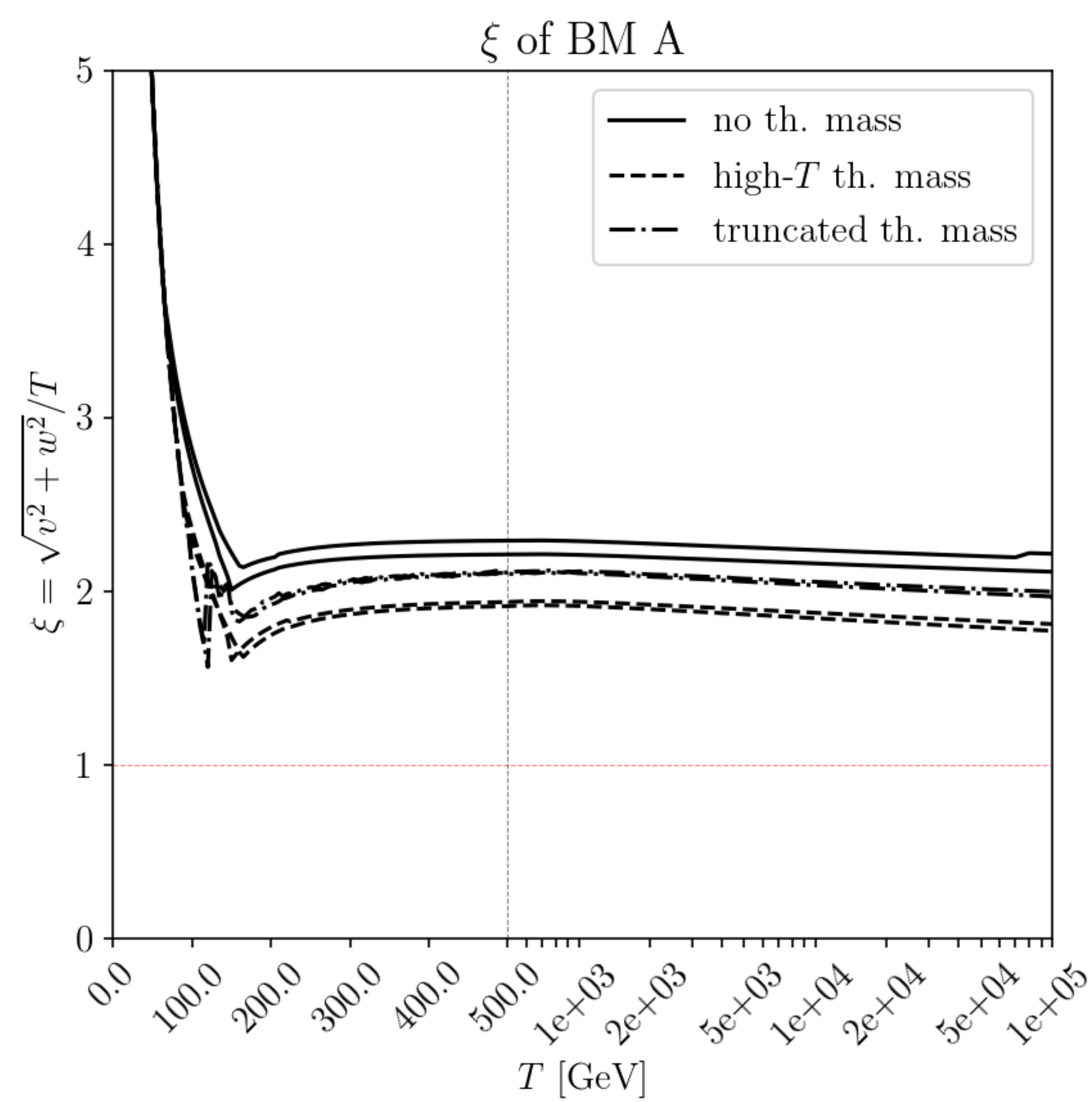


Dilution factor $f_{w.o.} = 1 - \frac{n_B(t_{now})}{n_B(0)} = 1 - \exp\left[-\frac{13 n_f}{2}\int_0^{T_{\rm high}} dT\, \frac{\Gamma(T)}{VT^6} M_{Pl}\sqrt{\frac{90}{8\pi^3 g^*}}\right]$

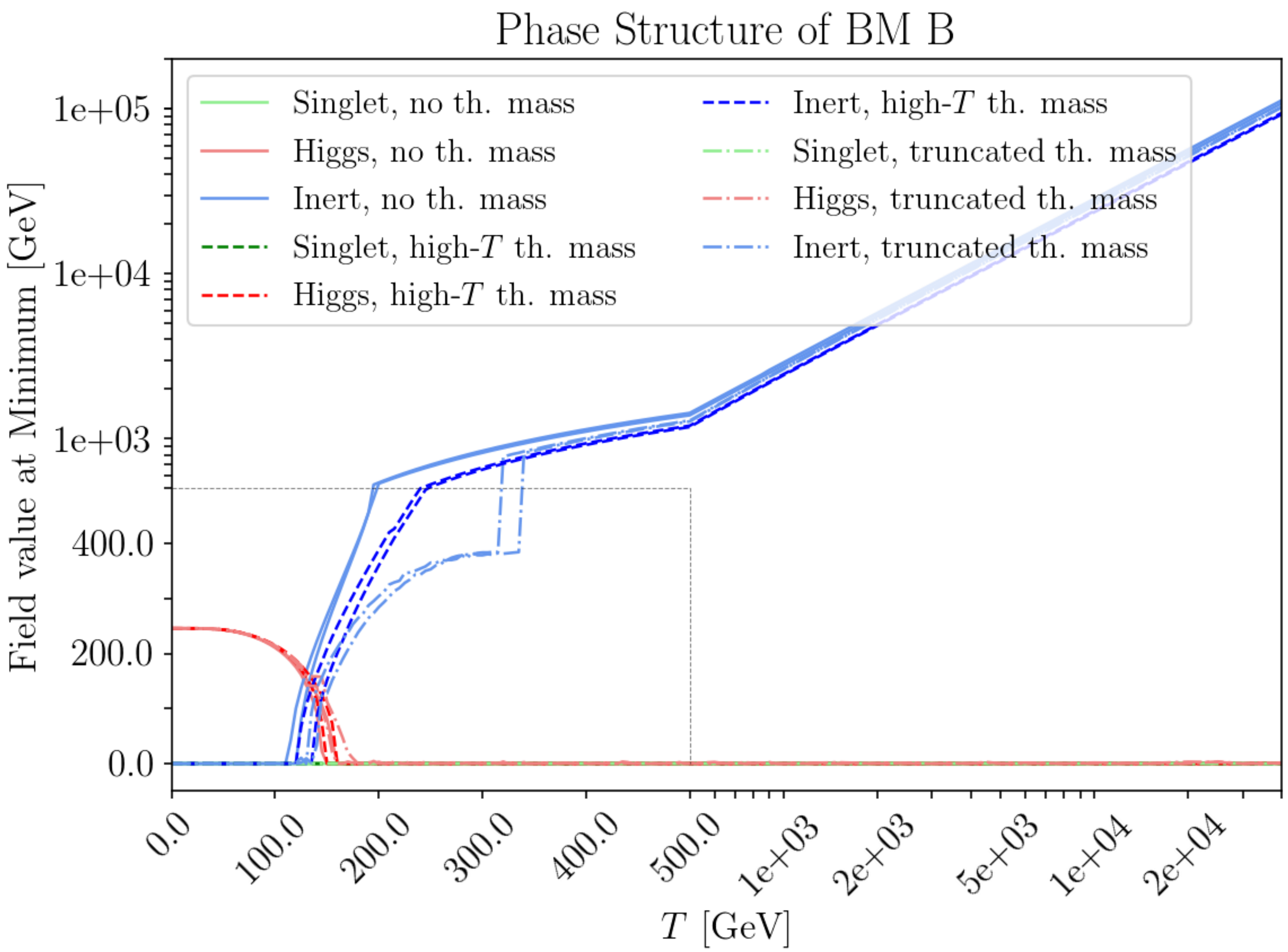
	no th. mass	high-T th. mass	truncated th. mass
BM A	$< 10^{-16}$ / $\mathbf{10^{-16}}$ / 10^{-14}	10^{-11} / $\mathbf{10^{-9}}$ / 10^{-7}	$8 \cdot 10^{-11}$ / $\mathbf{8 \cdot 10^{-9}}$ / $8 \cdot 10^{-7}$
	$< 10^{-16}$ / $\mathbf{4 \cdot 10^{-15}}$ / $4 \cdot 10^{-13}$	$2 \cdot 10^{-11}$ / $\mathbf{2 \cdot 10^{-9}}$ / $2 \cdot 10^{-7}$	10^{-12} / $\mathbf{10^{-10}}$ / 10^{-8}

	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

	$\lambda_{\Phi\chi}$	$\widetilde{\lambda}_\chi$	$\lambda_{H\chi}$	N	m_h	m_ϕ	m_χ
BM A	-0.06	0	0	250	125	48.47	9.8



Benchmark scenarios: numerical results



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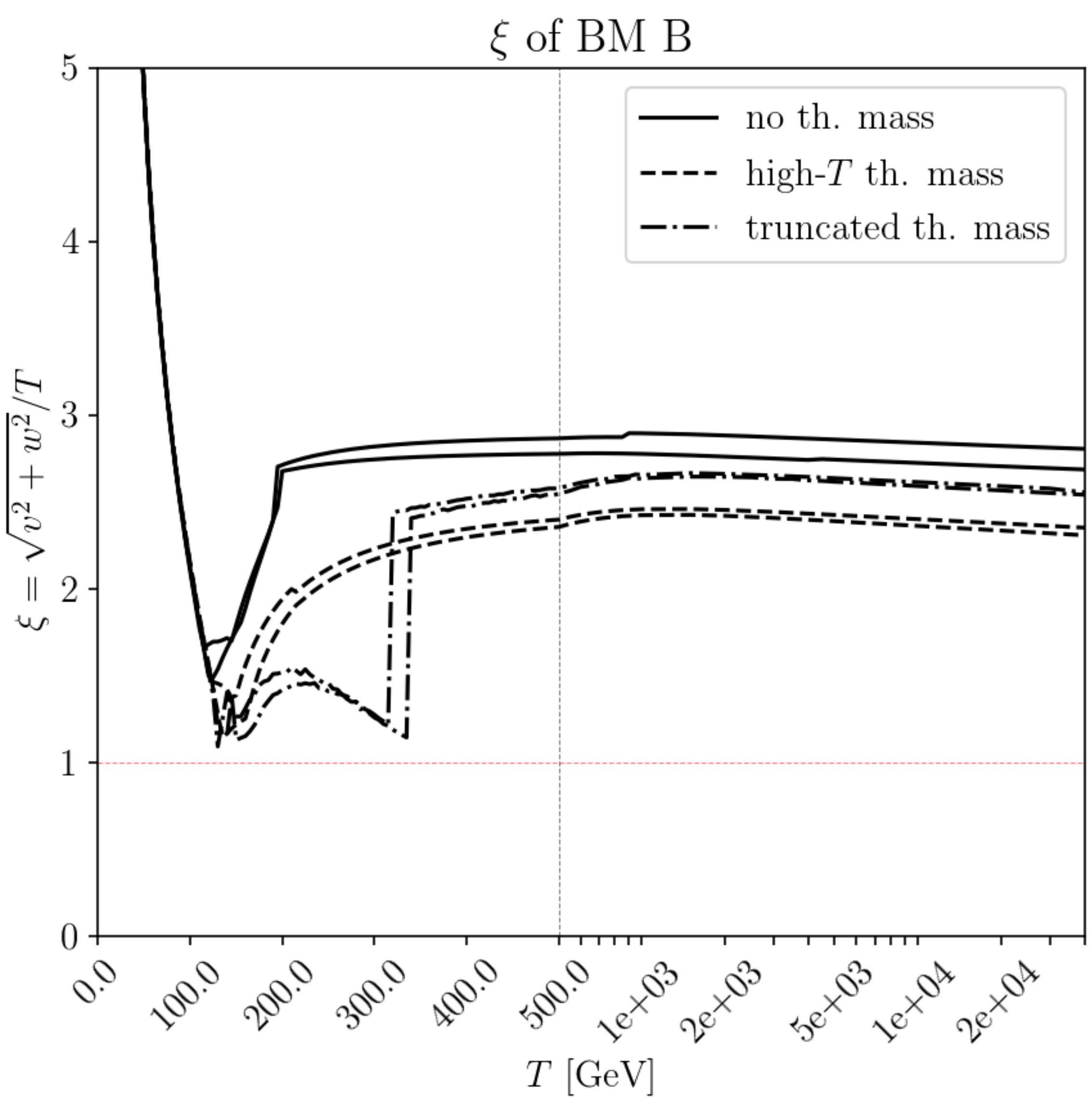
	no th. mass	high-T th. mass	truncated th. mass
BM B	$9\cdot10^{-10}$ / $\mathbf{9\cdot10^{-8}}$ / $9\cdot10^{-6}$ $4\cdot10^{-12}$ / $\mathbf{4\cdot10^{-10}}$ / $4\cdot10^{-8}$	$4\cdot10^{-5}$ / $\mathbf{4\cdot10^{-3}}$ / 0.296 $2\cdot10^{-8}$ / $\mathbf{2\cdot10^{-6}}$ / $2\cdot10^{-4}$	$7\cdot10^{-5}$ / $\mathbf{7\cdot10^{-3}}$ / 0.498 10^{-4} / **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 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 B	-0.0375	0	0	600	125	84.58	68.87

Phenomenology constraints

- **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.

- **Electroweak precision observables (EWPO)**

$$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2, \quad c_T = \frac{\widetilde{\lambda}_{H\Phi}^2}{192\pi^2\mu_\Phi^2} \qquad |\widetilde{\lambda}_{H\Phi}| < 0.36 \text{ at } 95\% \text{ C.L}$$

- **Higgs precision measurements**

Corrections to Higgs couplings, as well as Higgs to gauge boson couplings, are generated via loops. They provide less stringent constraints on Higgs-inert and Higgs-singlets cross quartics, than the Higgs invisible decay searches.

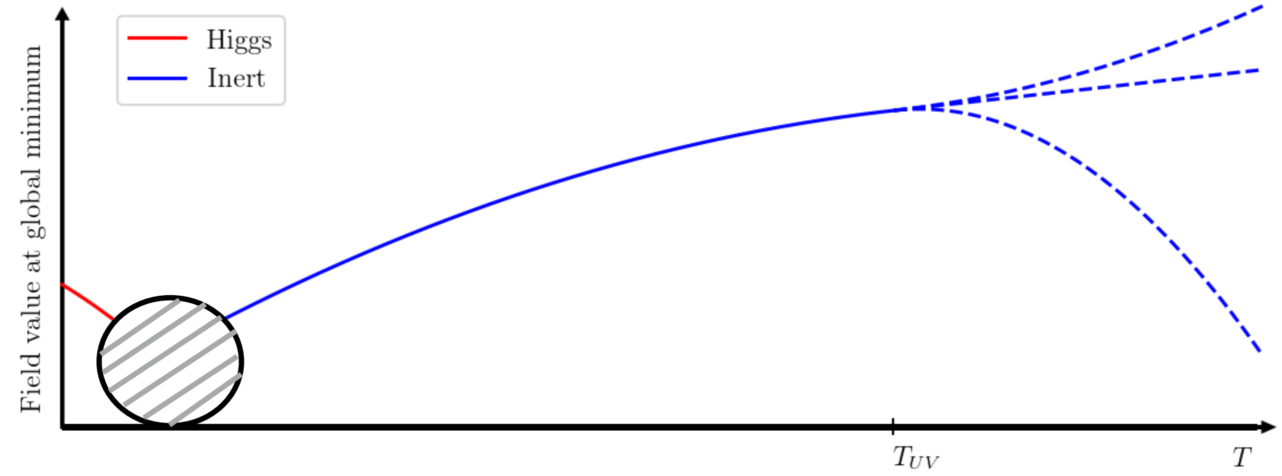
- **Disappearing tracks (charged states)**

Disappearing track searches exclude Higgsinos up to 78 GeV.

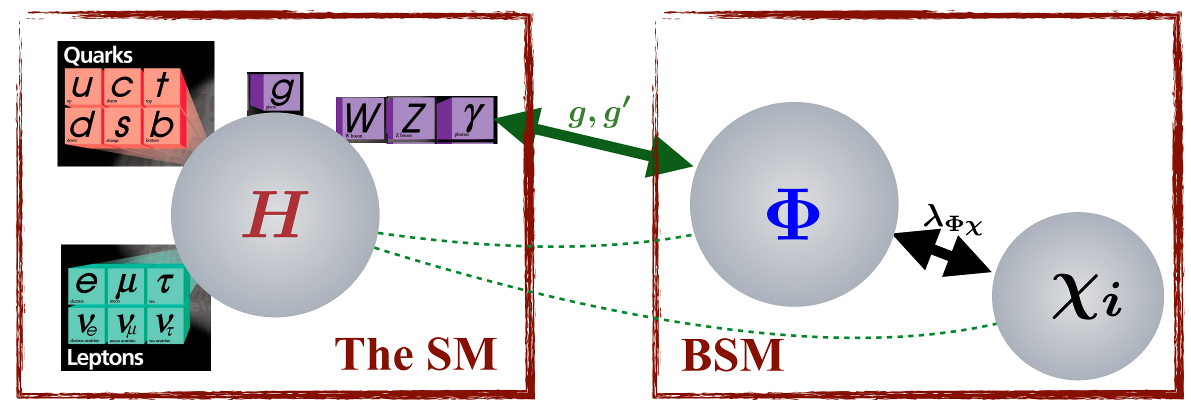
Charged inert Higgs has much smaller (Drell-Yan) production rate compared to Higgsinos. Thus such searches are difficult.

Summary

- Electroweak symmetry non-restoration or delayed restoration provides a playground for rich model building possibilities;



- We provide a method where the EWNR is achieved by transmitting the SM broken electroweak symmetry to an inert Higgs sector up to very high temperatures; Providing a bridge connecting IR and UV physics preserving baryon asymmetry;



Outlook

- Class of possible UV completion from various theoretical motivations
- Stochastic GW signatures
- Effective treatment of high scale thermal field theory convergence
- ….

Thank you

Summary

- Electroweak symmetry non-restoration or delayed restoration provides a playground for rich model building possibilities;

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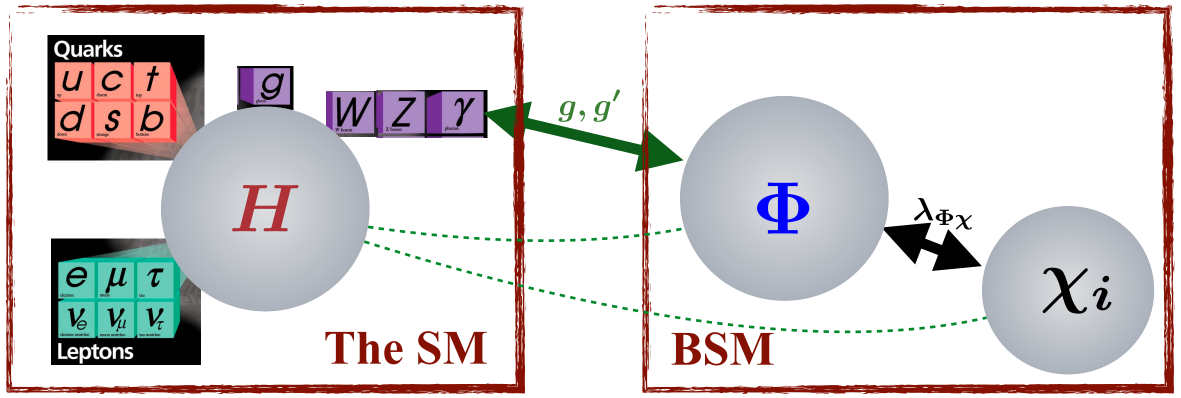
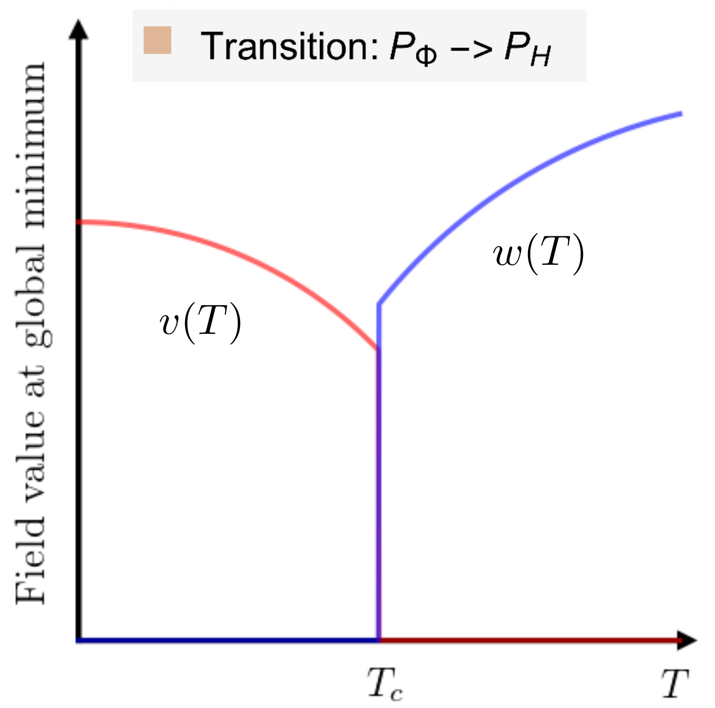


Outlook

- Class of possible UV completion from various theoretical motivations
- Stochastic GW signatures
- Effective treatment of high scale thermal field theory convergence
- ….

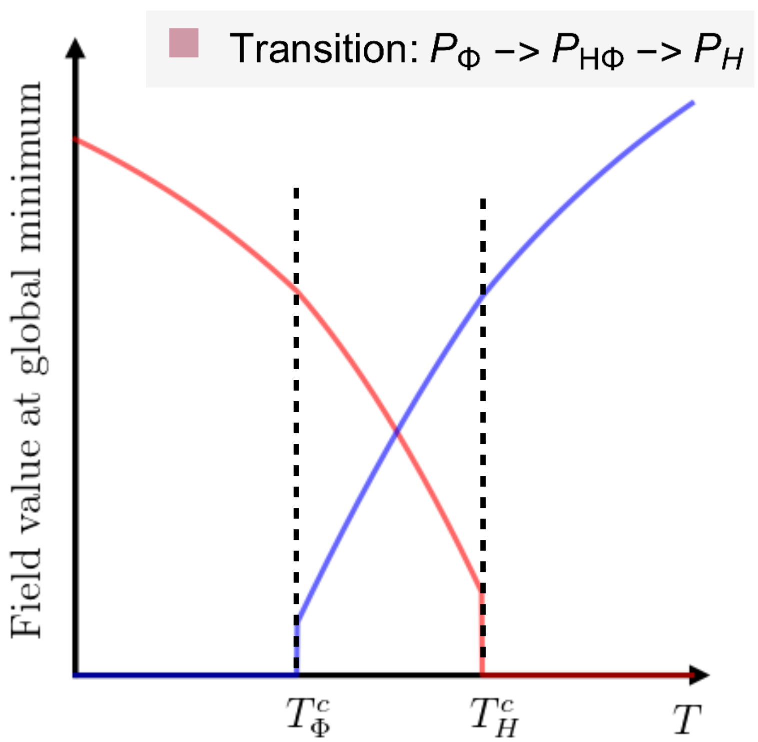
Thank you

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

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