Hot news on...
The phase structure of the SMEFT

XVII CPAN 2025, Valencia

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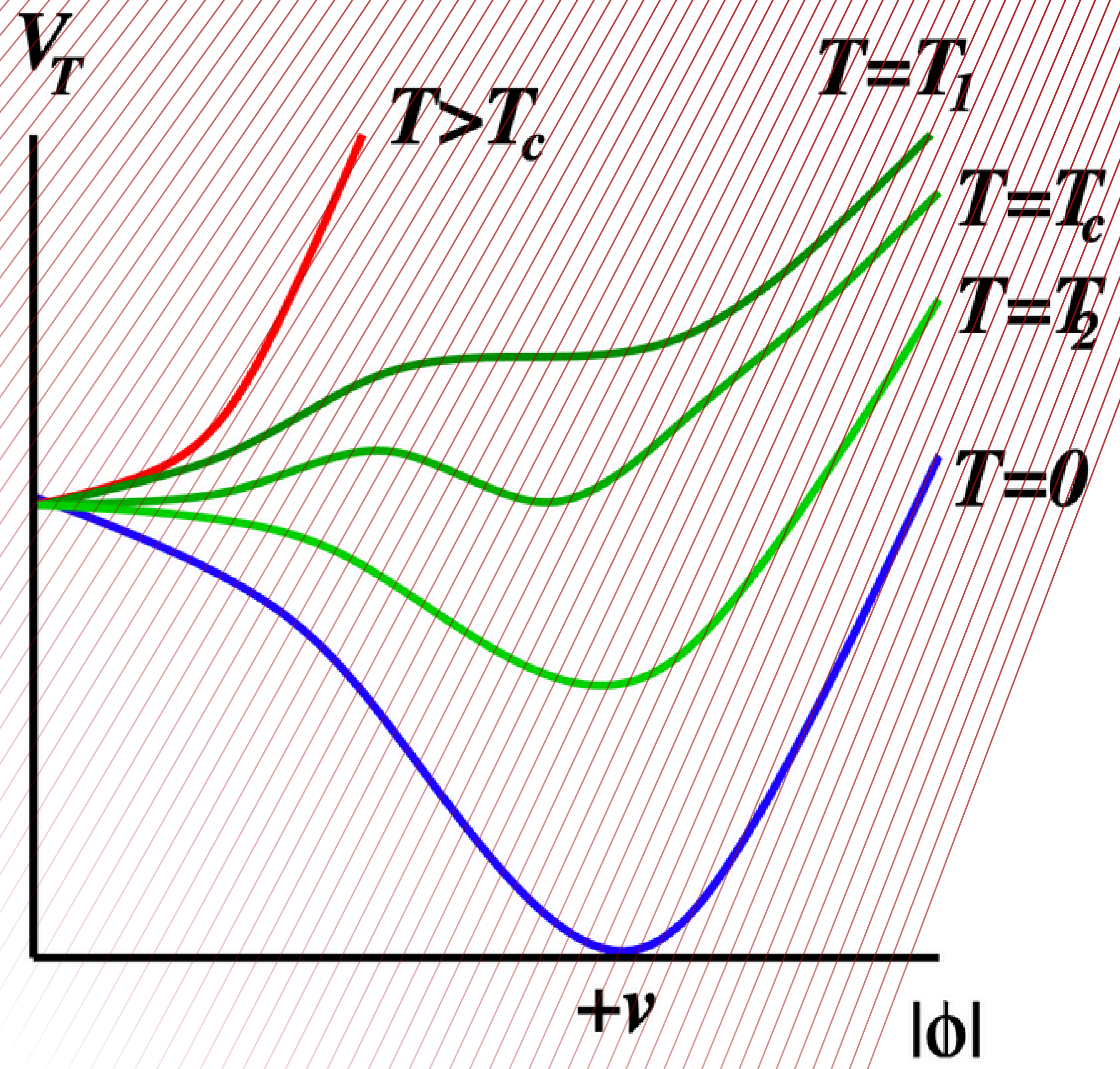
Based on : Mikael Chala, MCF and Luis Gil [2507.16905]

The Universe... was bubbling!

(Let it cook)

What is a First-Order Phase Transition?

- Sudden change, not smooth
- Bubbles appear and grow
- Like boiling water in the early Universe



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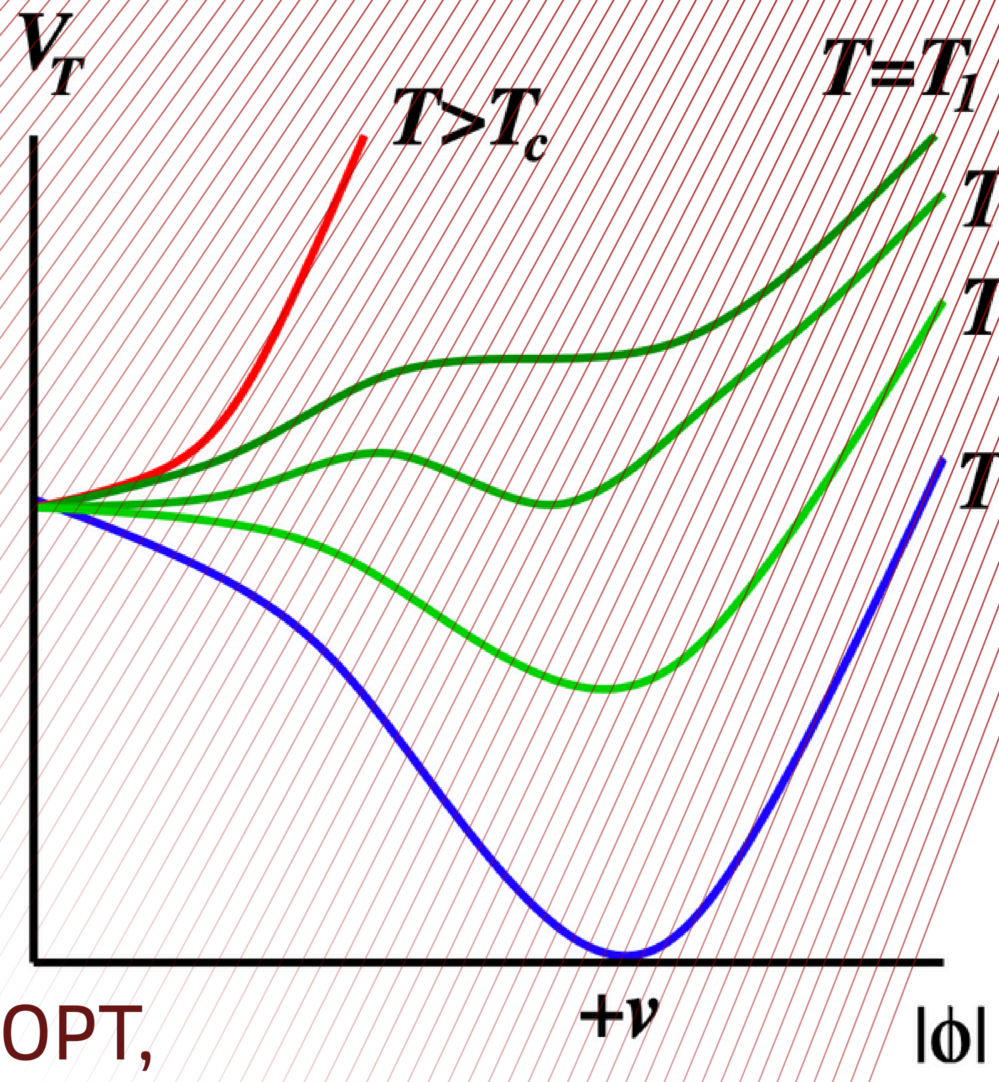


Why they matter (a lot)?

- SM: ~~FOPT~~ ⟶ If we see signs of a FOPT, that's direct evidence of BSM physics
- Fulfillment of Sakharov conditions ⟶ The matter-antimatter asymmetry ✓
- They source GW we might detect soon Caprini et al. [2406.09228]

How do we study BSM physics?

From <u>specific BSM models</u> to Agnosticity

→modify the Higgs potential
→ make the EW phase transition first-order

This type of approach is essential when light degrees of freedom exist beyond those included in the Standard Model

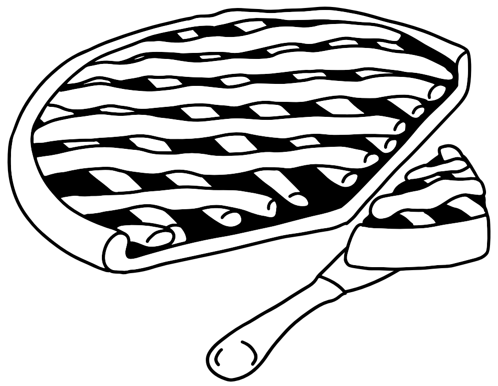
Standard Model Effective Field Theory:

→Captures new physics via higher-dimensional operators suppressed by a cutoff scale

Particularly useful when all new physics degrees of freedom are significantly heavier than those of the Standard Model

Let's you study whole classes of UV completions at once

Exploring: from a Slice to the whole Pie



SMEFT

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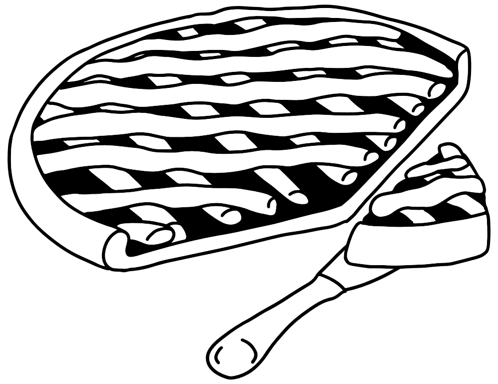

previous works

[e.g. Camargo-Molina et al. 2103.14022; Camargo-Molina et al. 2410.23210]

$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu\phi)^\dagger\phi^\dagger D_\mu\phi$
$\mathcal{O}_{\phi}$	$(\phi^\dagger\phi)^3$

$\longleftarrow$ **SMEFT**

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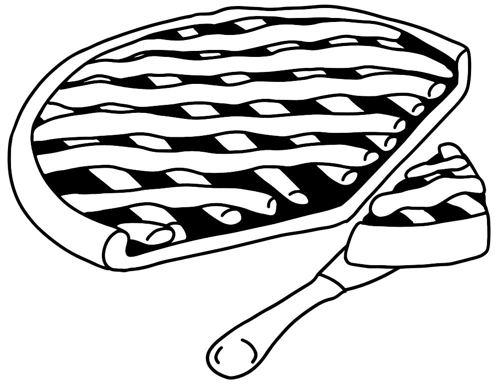

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⟵ **SMEFT** ⟶

so much more to explore

e.g. $\mathcal{O}_{t\phi}$

$\mathcal{O}_{u\phi}$	$\bar{q}\tilde{\phi}u(\phi^\dagger\phi)$

in our work we included all dimension-6 operators

Zooming in on thermal physics

[M. Laine and A. Vuorinen 10.1007/978-3-319-31933-9]

Goal: Determine if a point in SMEFT space leads to a FOPT

Method: Dimensional Reduction (DR)

At finite temperature... time is a circle

- Time becomes **compactified**: Euclidean time $\sim S^1$ of length $1/T$
- Fields acquire **Matsubara modes** → $\omega_n = 2\pi n T$ (bosons); → $\omega'_n = 2\pi\left(n + \frac{1}{2}\right)T$ (fermions)
- **Heavy modes** (with $n \neq 0$) have $M \sim \pi T \Rightarrow$ integrate them out
- What remains: a **3D EFT** for bosonic zero modes

(*temperature dependence is encoded in the parameters of the EFT*)

Matching SMEFT to the 3D EFT

After DR, we get a 3D $SU(2) + Higgs$ model, but:

- In the SM: parameters depend on $g, m_H, T\dots$
- In SMEFT: they also depend on **Wilson coefficients** c_i

Key parameters:

g_3 (thermal gauge coupling)

λ_3 (Higgs quartic coupling)

m_3^2 (thermal Higgs mass)

Control curvature of the effective potential and the **position in the phase diagram**

Why they matter?

- Determine whether the theory undergoes a FOPT or a crossover

From parameters to phases

How do we determine whether a FOPT actually occurs?

→ Use known **lattice results** for the 3D $SU(2) + Higgs$ theory

→ *This combines perturbative SMEFT input with non-perturbative lattice data.*

Phase diagram from lattice

[Gürtler et al.-hep-lat/9704013]

Scan over (x, y) to find FOPT region

Result: clear **phase boundary** between crossover and FOPT

This diagram is universal: it applies to any theory that reduces to SU(2)+Higgs in 3D

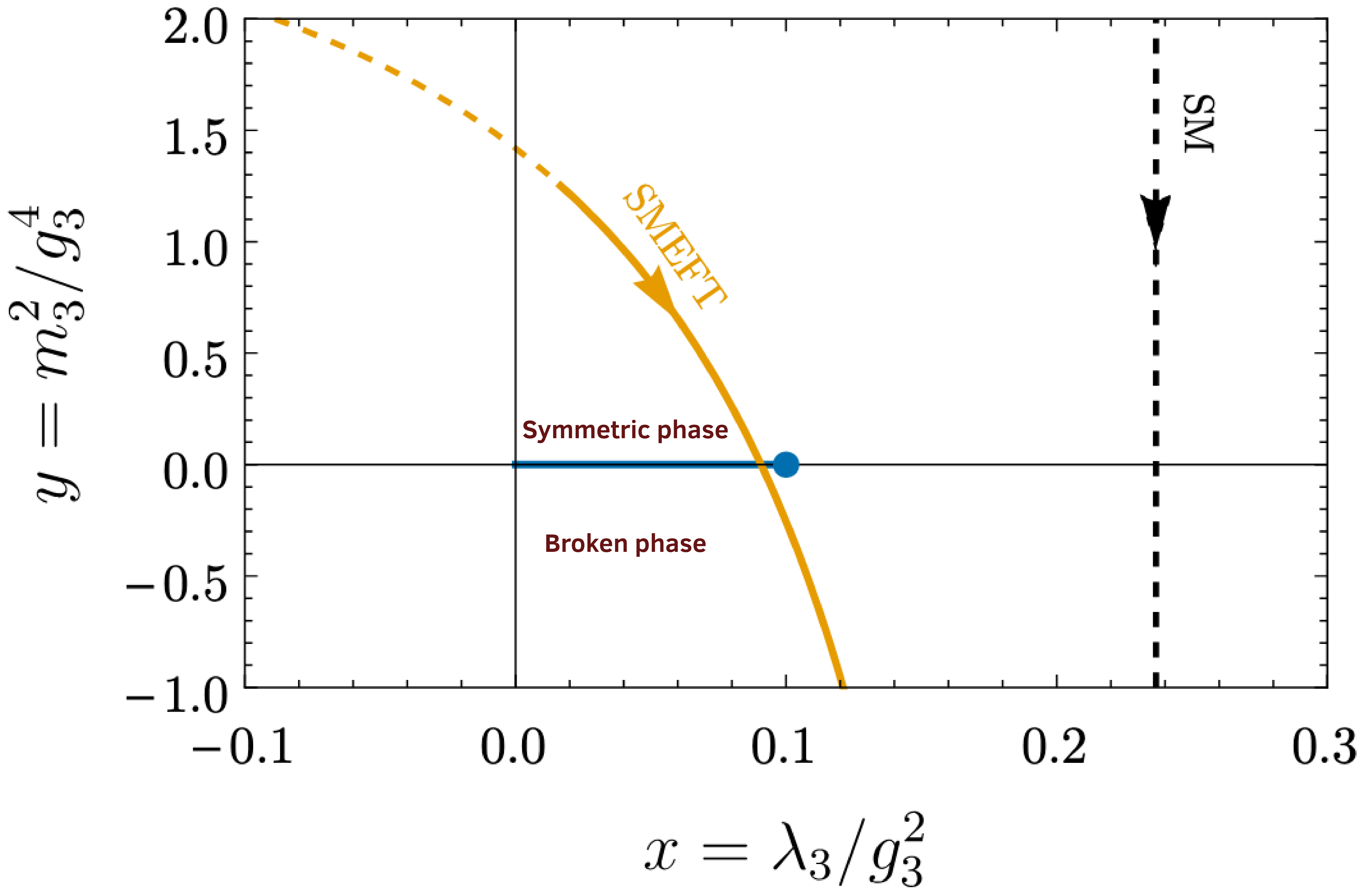

FIG1. Phase diagram of the high temperature limit of the SM and the SMEFT

Which SMEFT operators matter most?

Starting with $O_{t\phi}$:

- Positive $c_{t\phi}$ shifts the thermal trajectory **toward** the FOPT region

But: <u>not enough</u> by itself

Adding $O_{\phi\Box}$:

- A moderate $c_{\phi\Box}$ (within bounds) **pushes the trajectory into the FOPT region**

Result: $c_{t\phi} + c_{\phi\Box} \Rightarrow$ **Successful FOPT**

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What about O_{ϕ} ?

NOT NECESSARY!!

- Small negative c_{ϕ} can compensate a smaller $c_{\phi\Box}$
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Why this is exciting?

- FOPT without explicit ϕ^6 term!
- Consistency with current limits

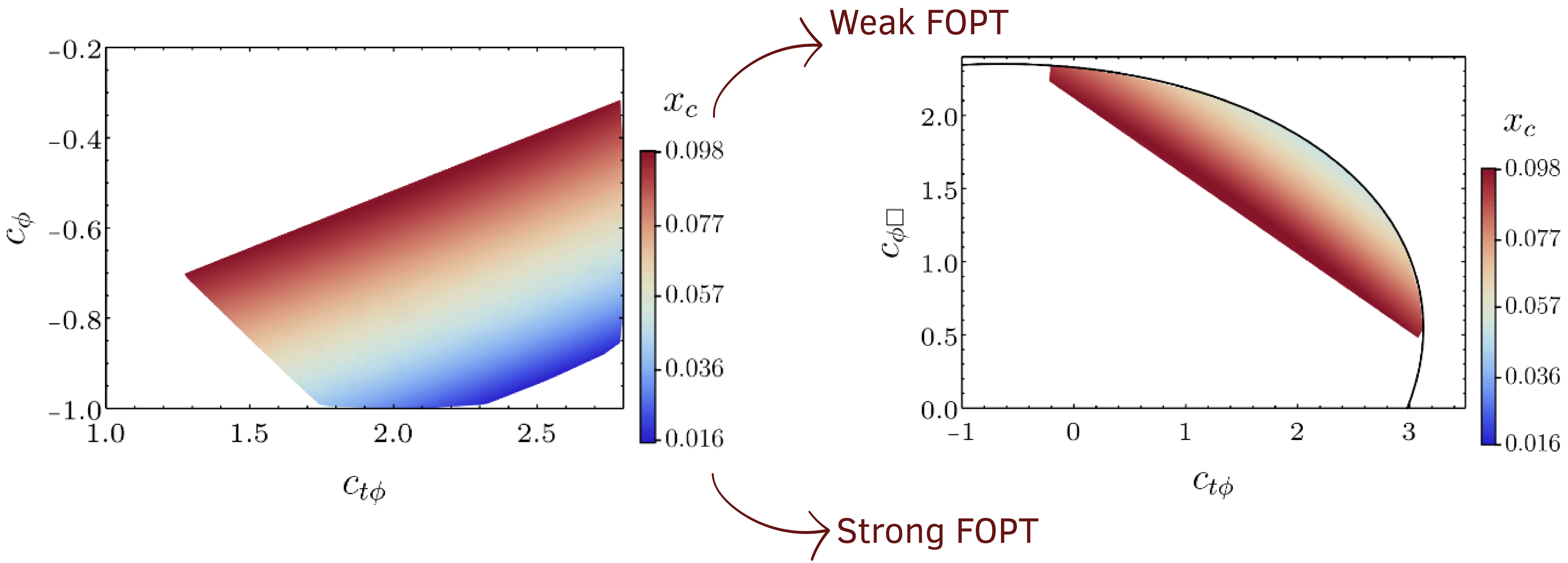


FIG 2.- FIG 3. Region of the parameter space allowed by data that gives rise to FOPT in units of TeV^-2

To conclude:

- We've performed full $\mathcal{O}(g^4)$ dimensional reduction of SMEFT electroweak sector.

- First-order EWPT possible without any T=0 Higgs potential modifications (one- and two-loop matching corrections are essential).

- Expands viable weakly-coupled BSM scenarios; motivates completely new model building and collider searches.

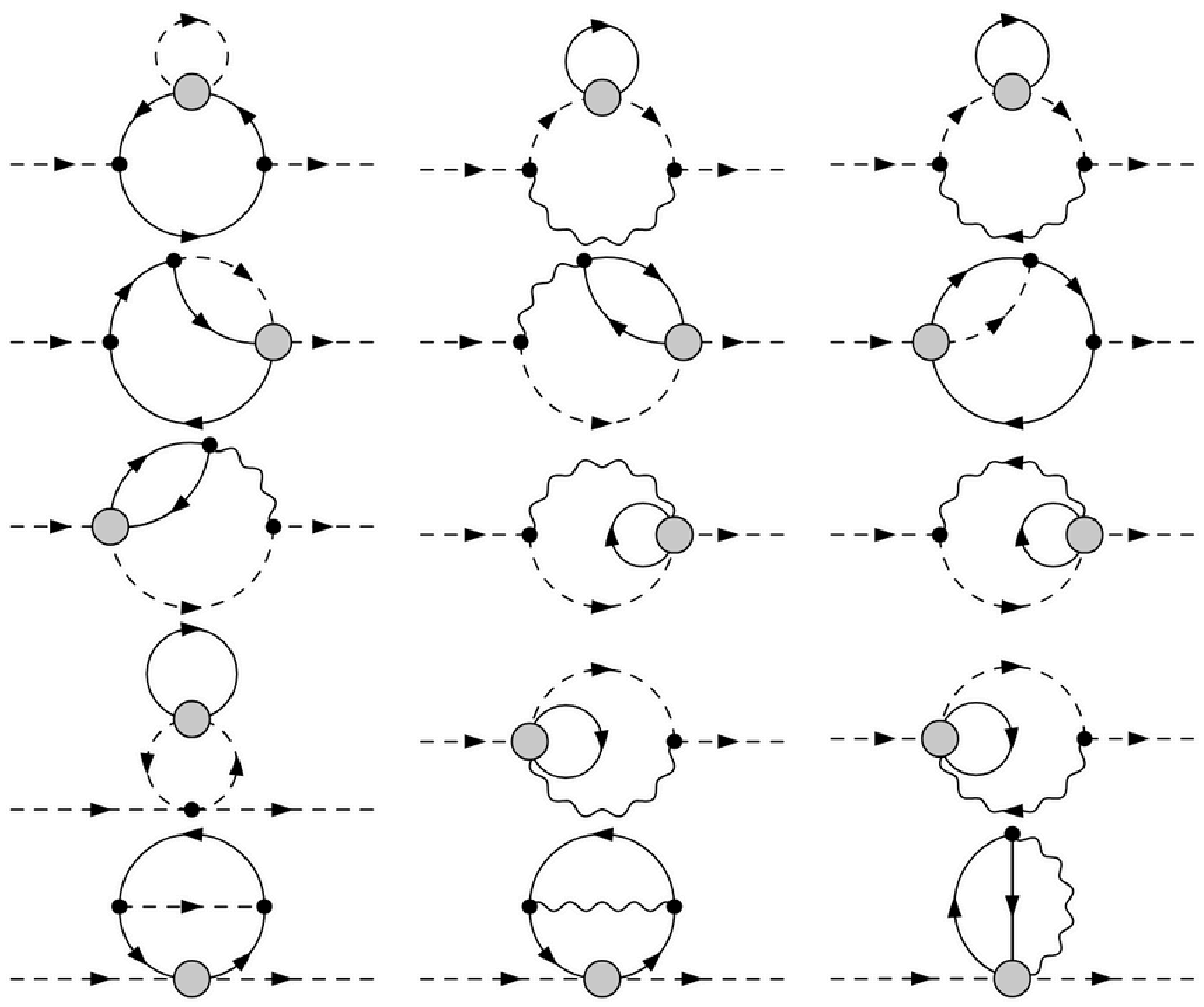
THANK YOU FOR YOUR ATTENTION

ANY QUESTIONS?

Power counting of dimension-six SMEFT operators relevant for thermal matching

$\mathcal{O}(g)$	c_{X^3}
$\mathcal{O}(g^2)$	$c_{X^2\phi^4}, c_{\phi^4 D^2}, c_{\psi^2 X\phi}, c_{\psi^2\phi^2}, c_{\psi^4}$
$\mathcal{O}(g^3)$	$c_{\psi^2\phi^3}$
$\mathcal{O}(g^4)$	c_{ϕ^6}

Two-loops diagrams from SMEFT operators

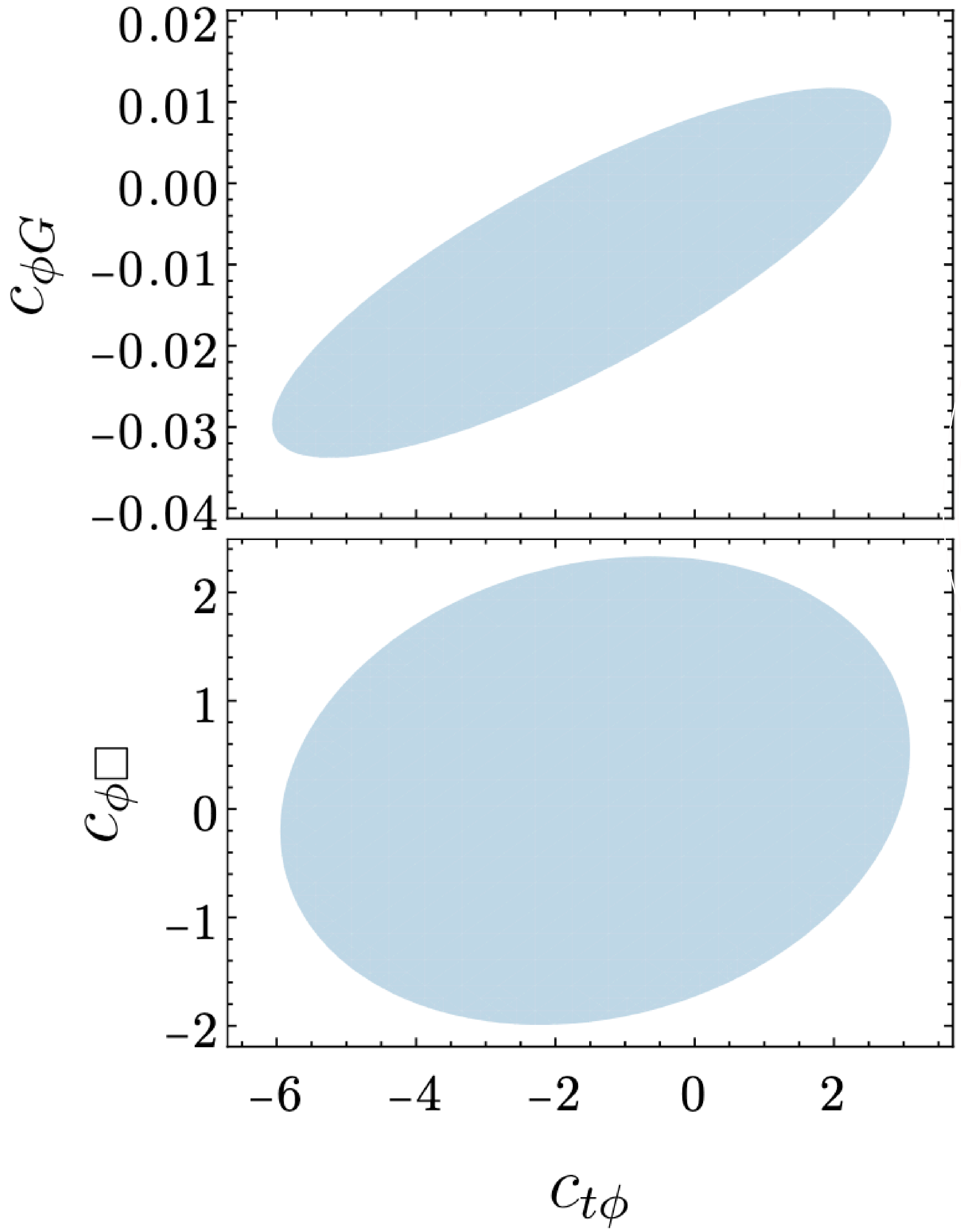


SMEFT vertices are represented as a gray circle

Example of a two-loop matching including all dimension-6 operators

$$m_\phi^2 = \Big[-\frac{1}{4} c_\phi + \frac{47}{3} g_S^2 c_{\phi G} + \frac{1}{576} |Y_u|^2 \big(30 c_{\phi \Box} - 15 c_{\phi D} + 6 c_{\phi u} - 6 c_{\phi q}^{(1)} + 18 c_{\phi q}^{(3)} + 24 c_{qu}^{(1)} + 32 c_{qu}^{(8)} \big) + \frac{3}{64} \big(16 g_S c_{uG} Y_u^* - 3 c_{u\phi} Y_u^* + \mathrm{h.c.} \big) \Big] T^4$$

Experimentally allowed values for $c_{t\phi}, c_{\phi G}, c_{t\phi}, c_{\phi\Box}$ (TeV^{-2}) as derived using **SMEFiT** upon marginalizing over other operators



1. *One-loop results*

At one loop, the non-vanishing SMEFT contributions to the 3D EFT read:

$$k_\phi = \frac{1}{12}(c_{\phi D} - 2c_{\phi\Box})T^2$$

$$k_{B_0} = -\frac{2}{3}c_{\phi B}T^2$$

$$k_{W_0} = -\frac{2}{3}(c_{\phi W} + 3g c_{3W})T^2$$

$$k_B = -\frac{2}{3}c_{\phi B}T^2$$

$$k_W = -\frac{2}{3}(c_{\phi W} + 3g c_{3W})T^2$$

$$m_\phi^2 = \frac{1}{12}\mu^2\left(c_{\phi D} - 2c_{\phi\Box}\right)T^2$$

$$\begin{aligned}\lambda_{\phi^4} = \Big[&-c_\phi + \frac{1}{4}\left(g'^2 c_{\phi B} + g' g c_{\phi WB} + 3g^2 c_{\phi W}\right)\\ &+ \lambda c_{\phi\Box} + \frac{1}{48}\left(3(g'^2 + g^2) - 16\lambda\right)c_{\phi D}\\ &- \frac{1}{12}\left(c_{e\phi}Y_e^* + 3\left(c_{d\phi}Y_d^* + c_{u\phi}Y_u^*\right) + \text{h.c.}\right)\Big]T^3\end{aligned}$$

$$\begin{aligned}\lambda_{\phi^2 B_0^2} =& \frac{1}{48}g'^2\Big(6c_{\phi\Box} + 9c_{\phi D} - 8c_{\phi e} - 8c_{\phi l}^{(1)}\\ &+ 16c_{\phi u} - 8c_{\phi d} + 8c_{\phi q}^{(1)}\Big)T^3\end{aligned}$$

$$\lambda_{\phi^2 W_0^2} = \frac{1}{48}g^2\left(6c_{\phi\Box} + c_{\phi D} + 8c_{\phi l}^{(3)} + 24c_{\phi q}^{(3)}\right)T^3$$

$$\begin{aligned}\lambda_{\phi^2 B_0 W_0} =& \frac{1}{24}g' g\Big(6c_{\phi\Box} + 5c_{\phi D}\\ &- 4c_{\phi e} - 4c_{\phi l}^{(1)} + 4c_{\phi l}^{(3)}\\ &+ 8c_{\phi u} - 4c_{\phi d} + 4c_{\phi q}^{(1)} + 12c_{\phi q}^{(3)}\Big)T^3\end{aligned}$$

Example : Matching m_ϕ^2 by $\mathscr{O}_{\phi e}$

For the sake of clarity, we compute the contribution of $c_{\phi e}$ to m_ϕ^2 in the limit of vanishing g', g and λ and with only one family of fermions. To this aim, we consider the Green's function $\mathscr{G}_{\phi\phi}$ at zero momentum.

$$\begin{aligned}
\mathscr{G}_{\phi\phi} &\sim 4 \sum\!\!\!\!\!\!\!\int_{\{QR\}} \left[\frac{1}{Q^2(Q+R)^2} + \frac{Q\cdot R}{Q^2R^2(Q+R)^2}\right] \\
&= 2 \sum\!\!\!\!\!\!\!\int_{\{QR\}} \left[\frac{1}{Q^2(Q+R)^2} + \frac{1}{Q^2R^2} - \frac{1}{R^2(Q+R)^2}\right] \\
&= 2\left[\sum\!\!\!\!\!\!\!\int_{\{Q\}R} \frac{1}{Q^2R^2} + \sum\!\!\!\!\!\!\!\int_{\{QR\}} \frac{1}{Q^2R^2} - \sum\!\!\!\!\!\!\!\int_{Q\{R\}} \frac{1}{R^2Q^2}\right];
\end{aligned}$$

where $\sim$ indicates that we are ignoring the factor $c_{\phi e}|Y_e|^2$. Substituting the sum-integrals and taking into account that, in the 3D EFT, $\mathscr{G}_{\phi\phi} = m_\phi^2$, we therefore have:

$$\begin{aligned}
m_\phi^2 &= -2c_{\phi e}|Y_e|^2 \left[I^b_{100}I^f_{100} + (I^f_{100})^2 - I^f_{100}I^b_{100}\right] \\
&= -\frac{1}{288}c_{\phi e}|Y_e|^2T^4\,,
\end{aligned}$$