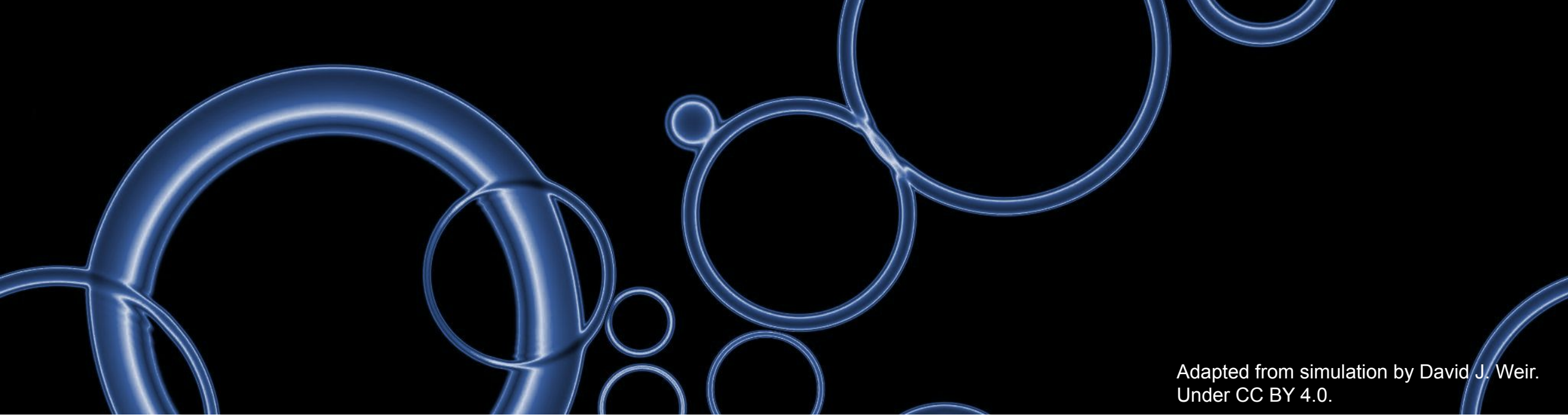


Hot news on the phase structure of the SMEFT

Gravitational Waves and the Early Universe · KMI Nagoya University | March 12th 2026

Luis Gil (Universidad de Granada)

Based on:

M. Chala, M. C. Fiore and **LG** [2505.14335]

Funded by the European Union

European Research Council
Established by the European Commission

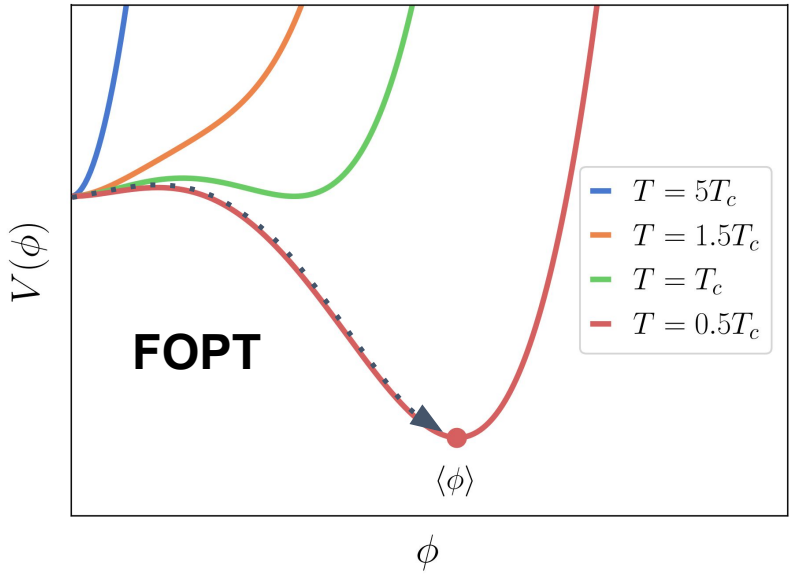
FTAE High Energy Theory

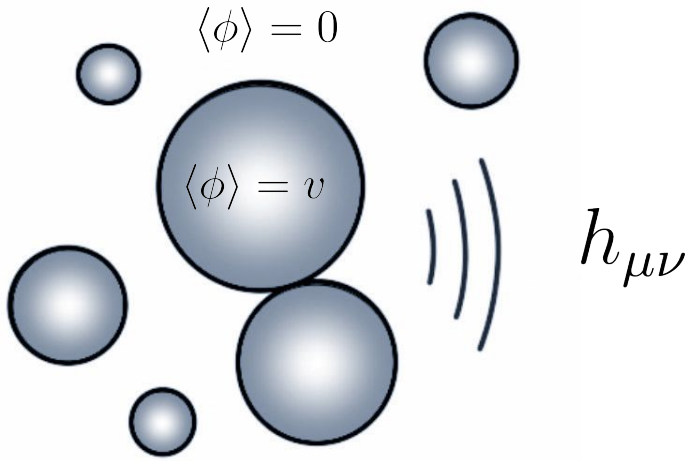
Junta de Andalucía

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Introduction

Cosmological phase transitions



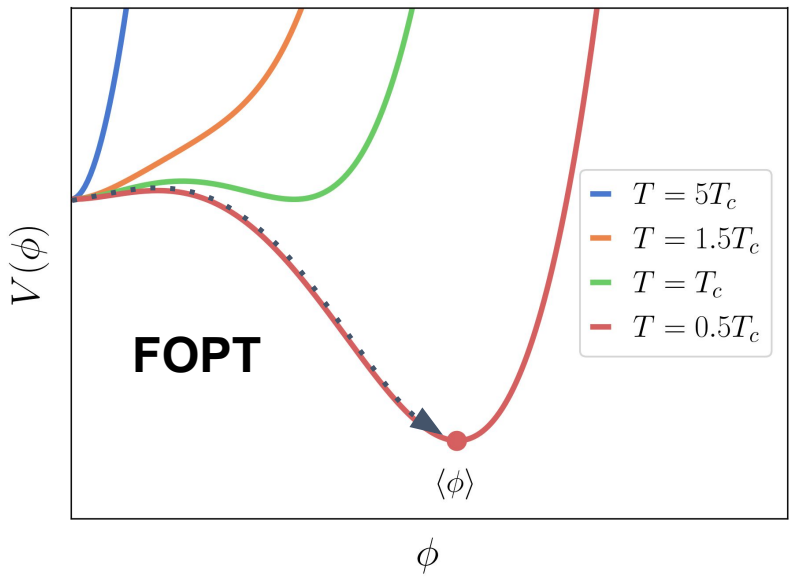


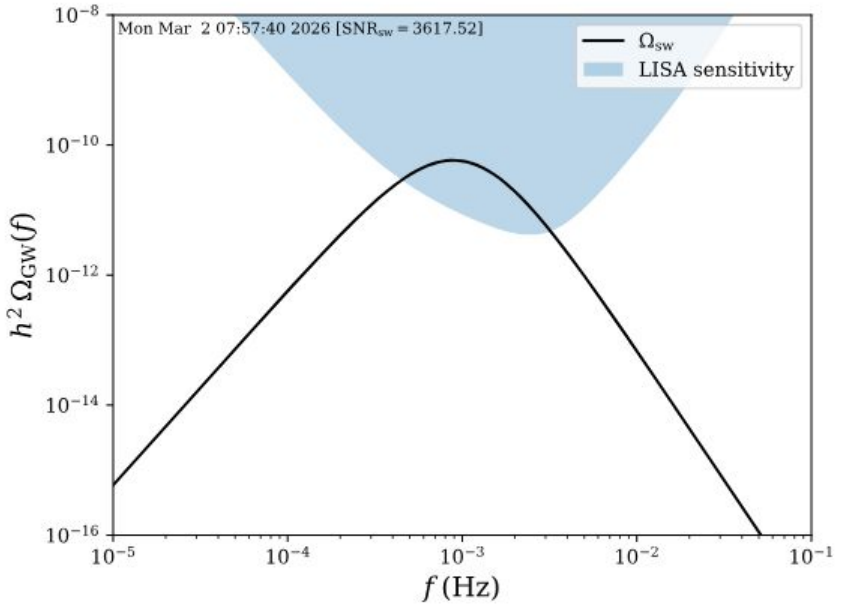
Microscopic scales
Thermal field theory 3D EFT Phase transition (**PT**) parameters

Meso- & macroscopic scales
Cosmological simulations Bubble wall dynamics Particle and GW production

Introduction

Cosmological phase transitions





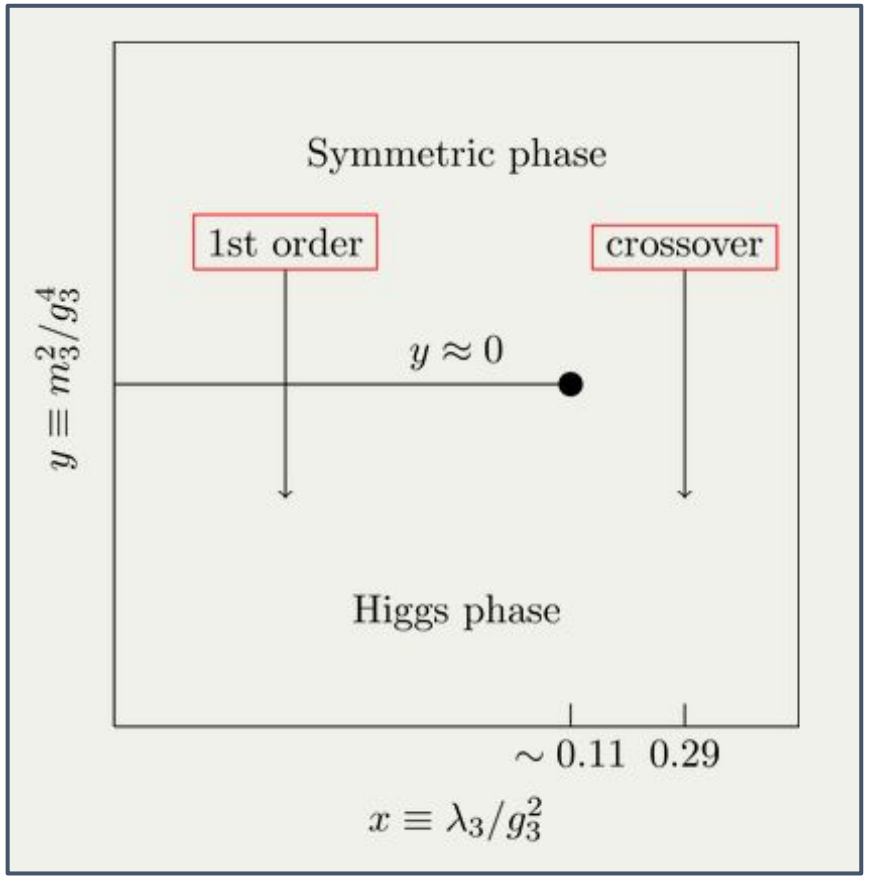
Microscopic scales
Thermal field theory 3D EFT Phase transition (**PT**) parameters

Meso- & macroscopic scales
Cosmological simulations Bubble wall dynamics Particle and GW production

Introduction

Higgs phase diagram

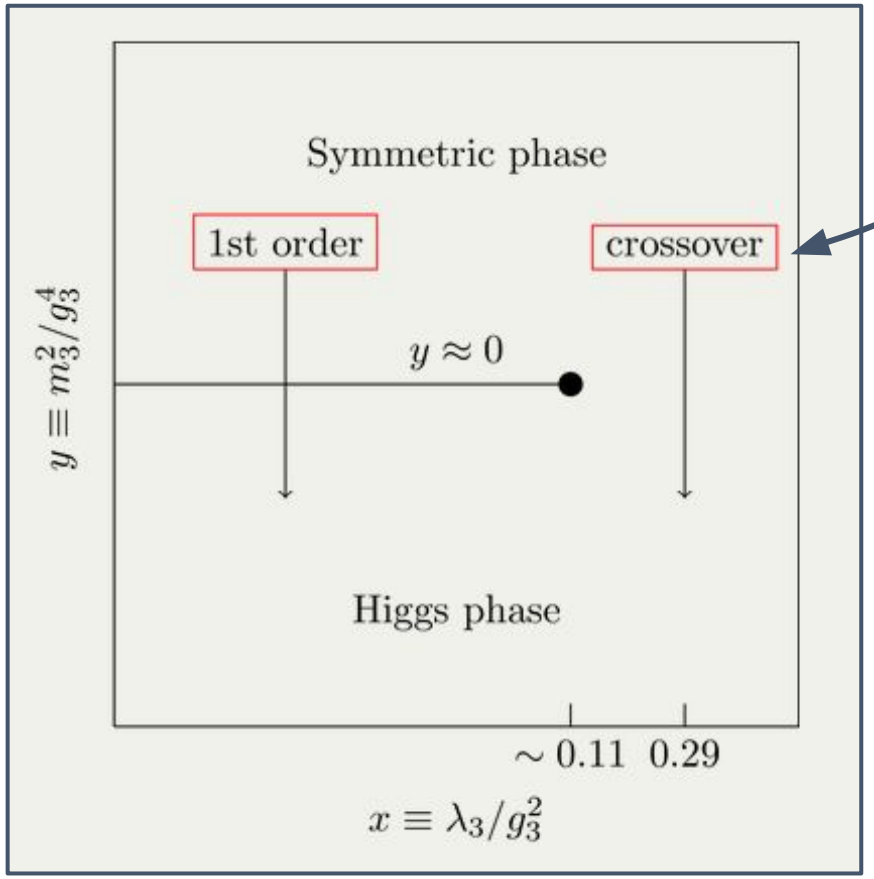
[Kajantie et al. - hep-ph/9605288]
[Gürtler et al. - hep-lat/9704013]
[Csikor et al. - hep-ph/9809291]



Introduction

Higgs phase diagram

[Kajantie et al. - hep-ph/9605288]
[Gürtler et al. - hep-lat/9704013]
[Csikor et al. - hep-ph/9809291]



No electroweak first-order phase transition (FOPT) in **SM** :(

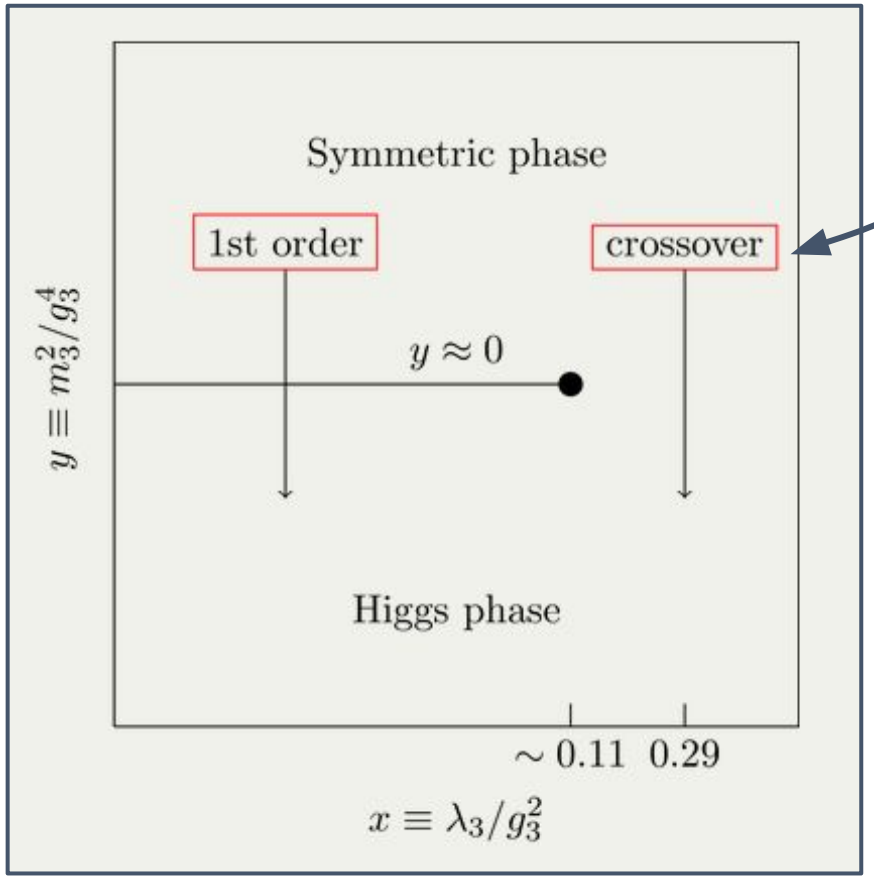
Many unknowns:

- What then caused baryogenesis?
- What BSM physics can trigger a FOPT?
- Can we expect to tell them apart through GWs?

Introduction

Higgs phase diagram

[Kajantie et al. - hep-ph/9605288]
[Gürtler et al. - hep-lat/9704013]
[Csikor et al. - hep-ph/9809291]



No electroweak first-order phase transition (FOPT) in **SM** :(

Many unknowns:

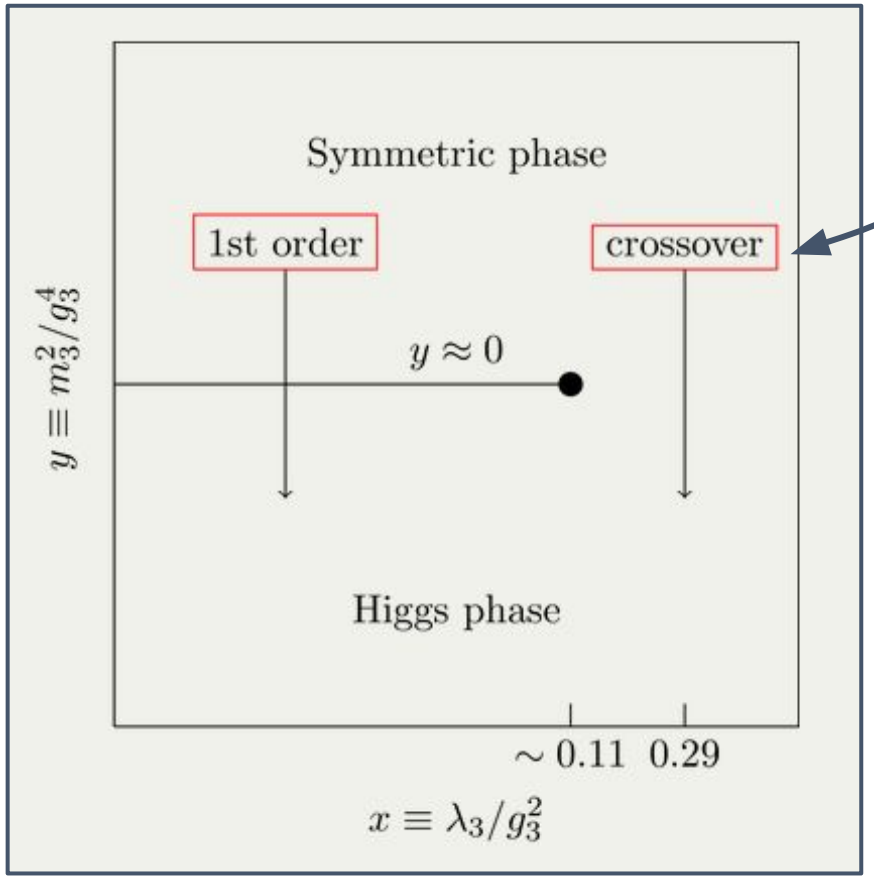
- What then caused baryogenesis?

- What BSM physics can trigger a FOPT?
- Can we expect to tell them apart through GWs?

Introduction

Higgs phase diagram

[Kajantie et al. - hep-ph/9605288]
[Gürtler et al. - hep-lat/9704013]
[Csikor et al. - hep-ph/9809291]



No electroweak first-order phase transition (FOPT) in **SM** :(

Many unknowns:

- What then caused baryogenesis?

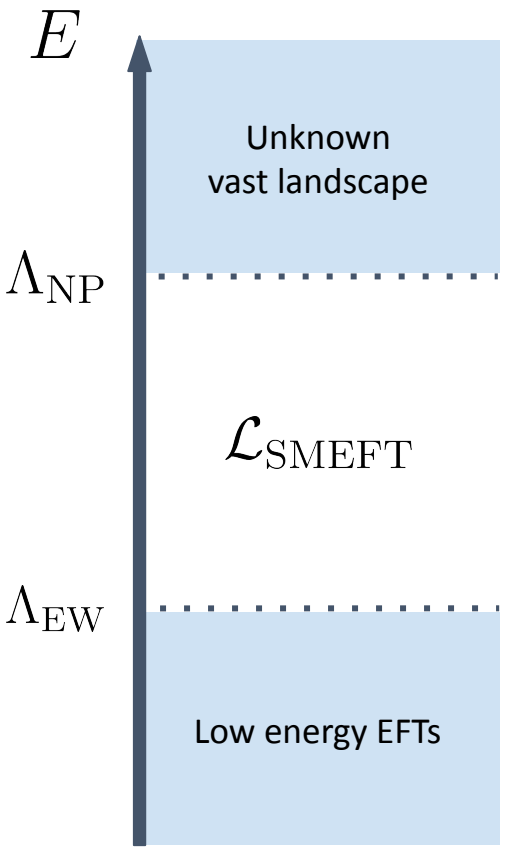
- What BSM physics can trigger a FOPT?
- Can we expect to tell them apart through GWs?

Let's take a look at the SMEFT!

Introduction

What is SMEFT?

[Buchmuller, Wyler - NPB 268 (1986) 621-653]



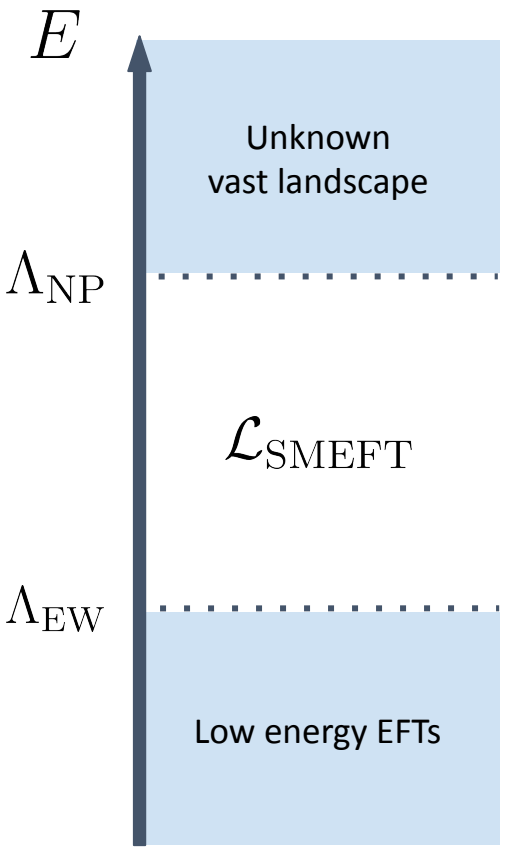
- **SMEFT** captures all heavier-than-$\Lambda_{\rm EW}$ physics as tower of effective operators

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{\ell=0}^{\infty} \sum_{n=5}^{\infty} \sum_{k} \frac{c_{n,k}^{(\ell)}}{(4\pi)^{2\ell} \Lambda^{n-4}} \mathcal{O}_{n,k}$$

Introduction

What is SMEFT?

[Buchmuller, Wyler - NPB 268 (1986) 621-653]



- **SMEFT** captures all heavier-than-$\Lambda_{\rm EW}$ physics as tower of effective operators

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{\ell=0}^{\infty}\sum_{n=5}^{\infty}\sum_{k}\frac{c_{n,k}^{(\ell)}}{(4\pi)^{2\ell}\Lambda^{n-4}}\mathcal{O}_{n,k}$$

PROS

- Whole classes of BSM models at once without new fields
- Universal framework to compare with experiments

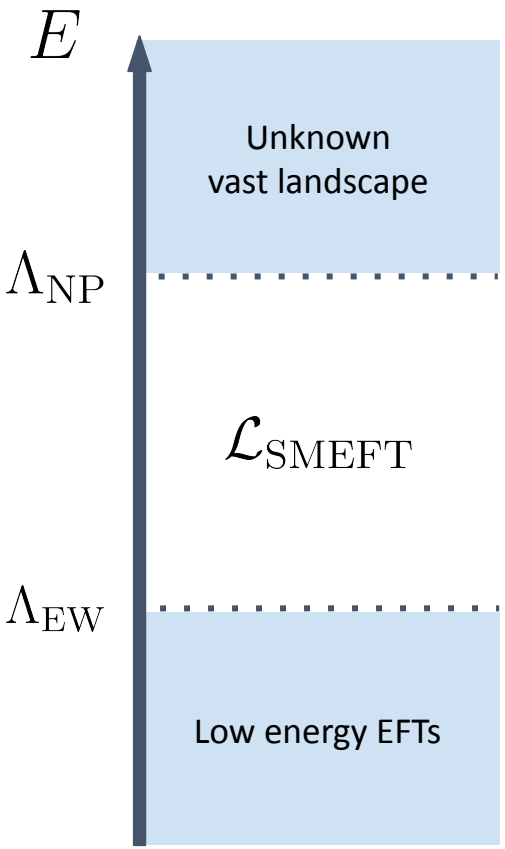
CONS

- No lighter-than-$\Lambda_{\rm EW}$ new physics
- Only Higgs phase transition

Introduction

What is SMEFT?

[Buchmuller, Wyler - NPB 268 (1986) 621-653]



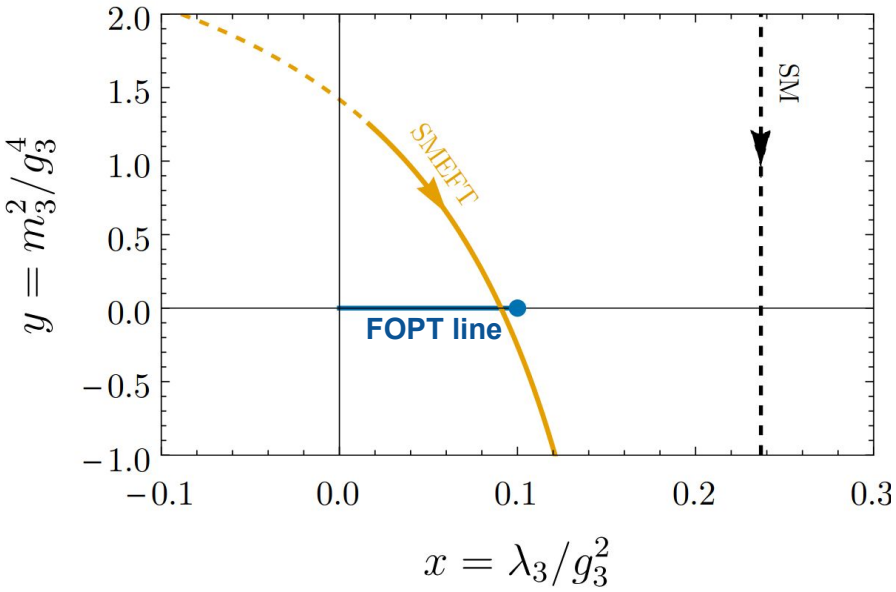
- **SMEFT** captures all heavier-than-$\Lambda_{\rm EW}$ physics as tower of effective operators

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{\ell=0}^{\infty}\sum_{n=5}^{\infty}\sum_{k}\frac{c_{n,k}^{(\ell)}}{(4\pi)^{2\ell}\Lambda^{n-4}}\mathcal{O}_{n,k}$$

$$x, y = f(c_i^{(\rm SM)}; T)$$

$$x', y' = f(c_i^{(\rm SMEFT)}; T)$$

Modify how potential evolves with T



High-T limit of SMEFT

The EFT approach

DIMENSIONAL REDUCTION

At **T ~ 100 GeV,** a hierarchy of thermal scales allows us to construct a **bosonic 3D EFT** for thermal equilibrium.

SM-like theories reduce to:

$$\mathscr{L}_{3\mathrm{D}} = \frac{1}{4} W_{ij}^I W_{ij}^I + (D_i\phi)^\dagger (D_i\phi) + m_3^2 |\phi|^2 + \lambda_3 |\phi|^4$$

where now all couplings are **functions of T.**

High-T limit of SMEFT

The EFT approach

DIMENSIONAL REDUCTION

At **T ~ 100 GeV,** a hierarchy of thermal scales allows us to construct a **bosonic 3D EFT** for thermal equilibrium.

SM-like theories reduce to:

$$\mathscr{L}_{3\mathrm{D}} = \frac{1}{4} W_{ij}^I W_{ij}^I + (D_i\phi)^\dagger (D_i\phi) + m_3^2|\phi|^2 + \lambda_3|\phi|^4$$

where now all couplings are **functions of T.**

1) Assign a **power counting** in powers of gauge coupling **g**
2) **Match** all 3D EFT parameters to $O(g^4)$

$$g_3(T),\ m_3^2(T),\ \lambda_3(T)$$

3) Compute parameters **x** and **y**

$$x \equiv \frac{m_3^2}{g_3^4} \qquad y \equiv \frac{\lambda_3^2}{g_3^2}$$

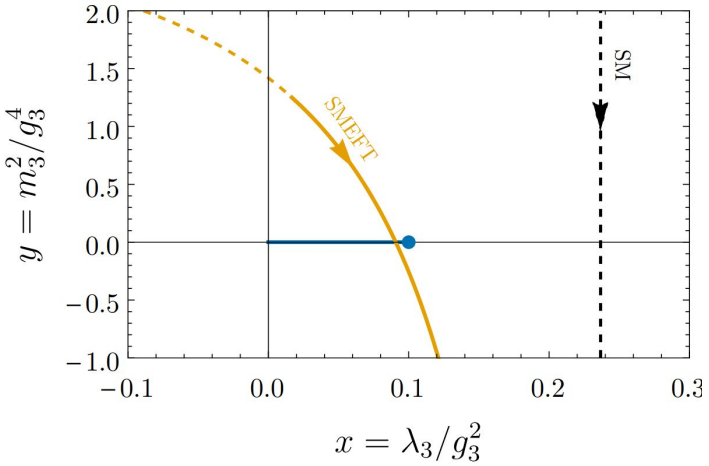
4) **Scan** SMEFT parameter space (compatible with colliders) **[Giani et al. (SMEFiT) - 2302.06660]**

High-T limit of SMEFT

Scanning the SMEFT

- Huge parameter space: **SMEFT @ dim-6** contains **59 independent operators (non B or L violating)**

- Which get us **closer to the FOPT line**?
  - Must make x smaller
  - Must be relatively unconstrained from collider data

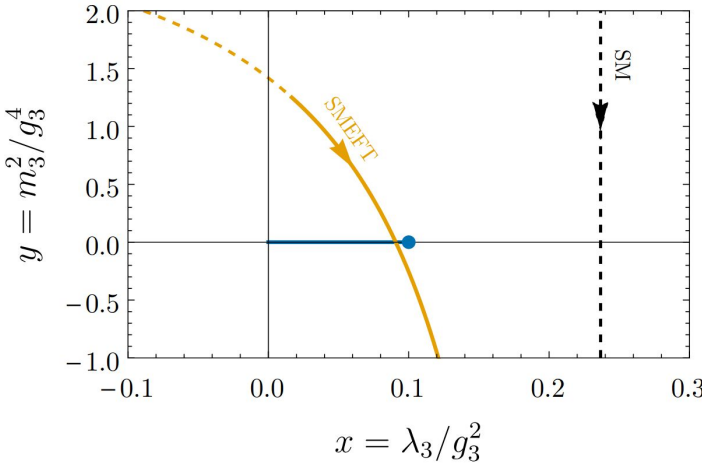


High-T limit of SMEFT

Scanning the SMEFT

- Huge parameter space: **SMEFT @ dim-6** contains **59 independent operators (non B or L violating)**

- Which get us **closer to the FOPT line**?
  - Must make x smaller
  - Must be relatively unconstrained from collider data



- We find the following candidates:

$$\mathcal{O}_\phi \equiv (\phi^\dagger\phi)^3$$

[Camargo-Molina et al. - 2103.14022]

$$\mathcal{O}_{\phi\Box} \equiv (\phi^\dagger\phi)\Box(\phi^\dagger\phi)$$

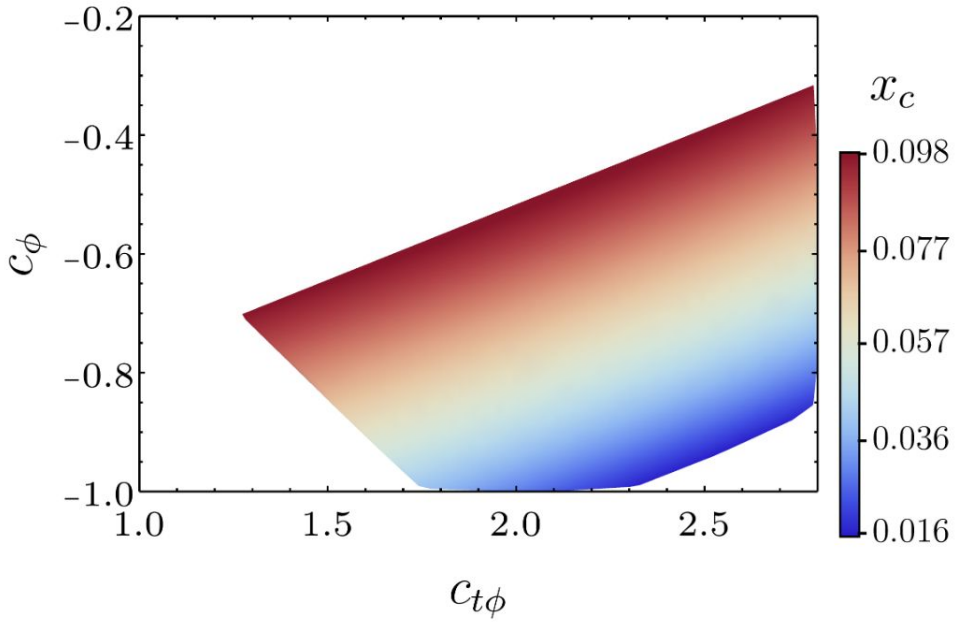
$$\mathcal{O}_{t\phi} \equiv \bar{t}_L\tilde{\phi}t_R(\phi^\dagger\phi)$$

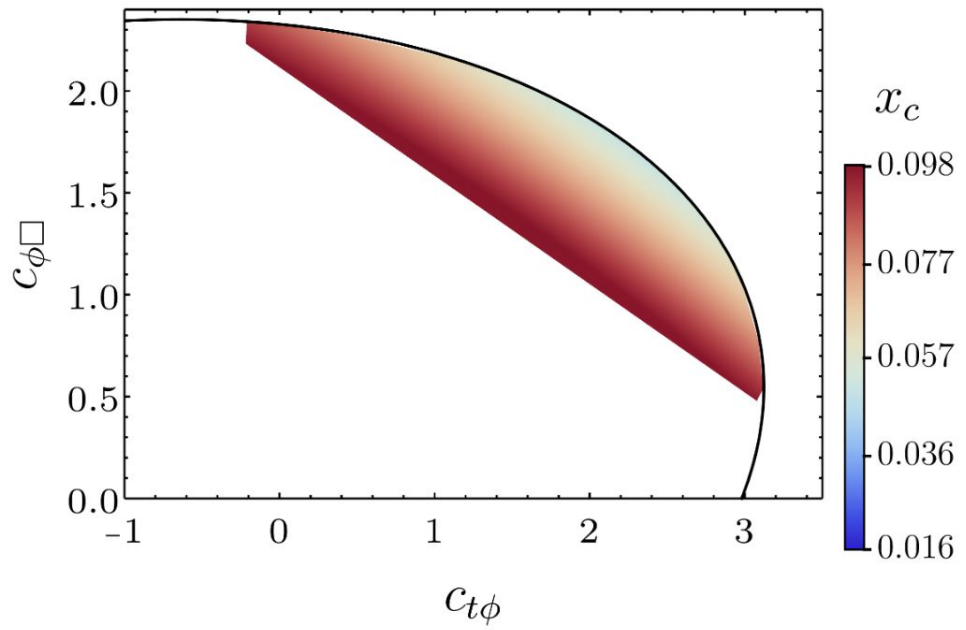
(Hot) new!

Results

Modified phase diagram

[Chala, Fiore, LG - 2507.16905]



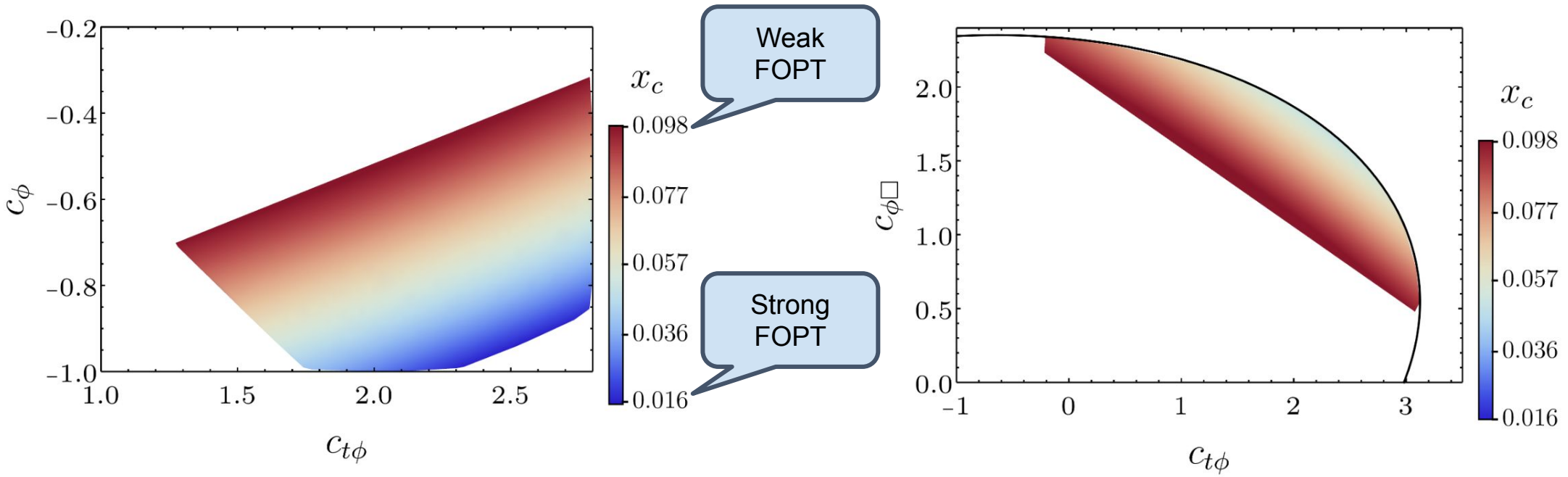


Figures: Regions of the parameter space (in TeV^{-2}) within collider bounds with a FOPT. In both panels, the non-appearing WC is set to zero.

Results

Modified phase diagram

[Chala, Fiore, LG - 2507.16905]

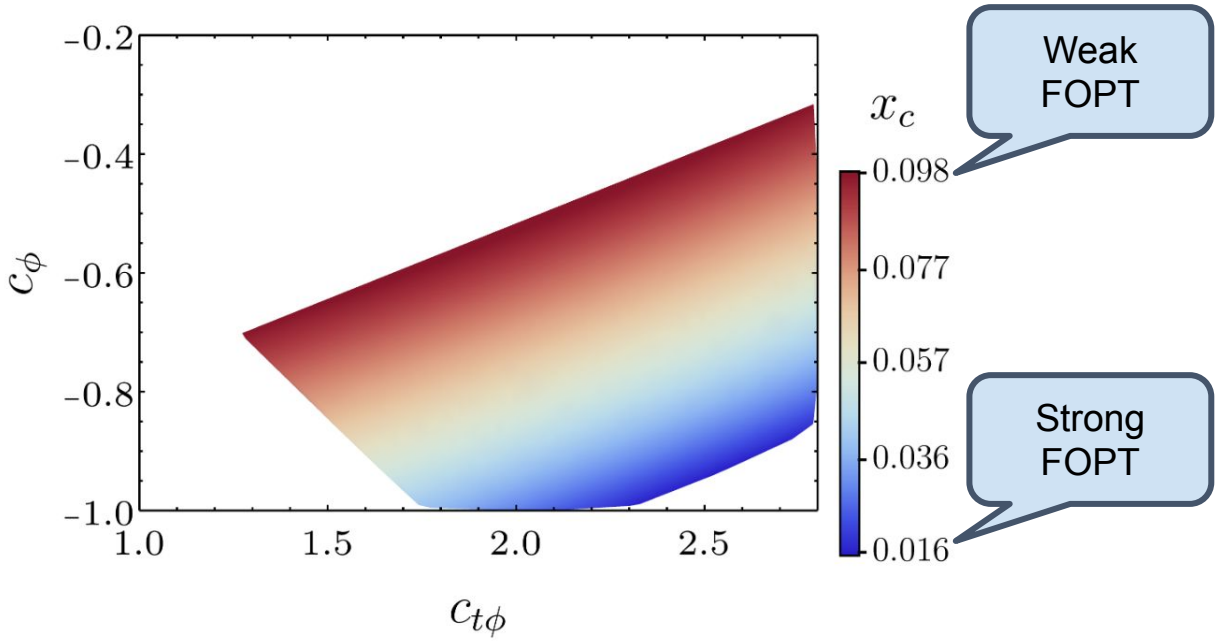


Figures: Regions of the parameter space (in TeV^{-2}) within collider bounds with a FOPT. In both panels, the non-appearing WC is set to zero.

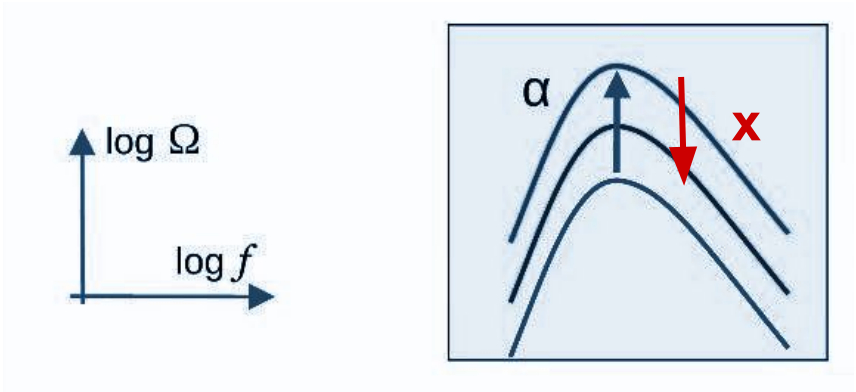
Results

Modified phase diagram

[Chala, Fiore, LG - 2507.16905]



- Small **x** is correlated with stronger transitions, with larger α **(strength parameter)**:



Adapted from K. Rummukainen's talk at CERN August 2025

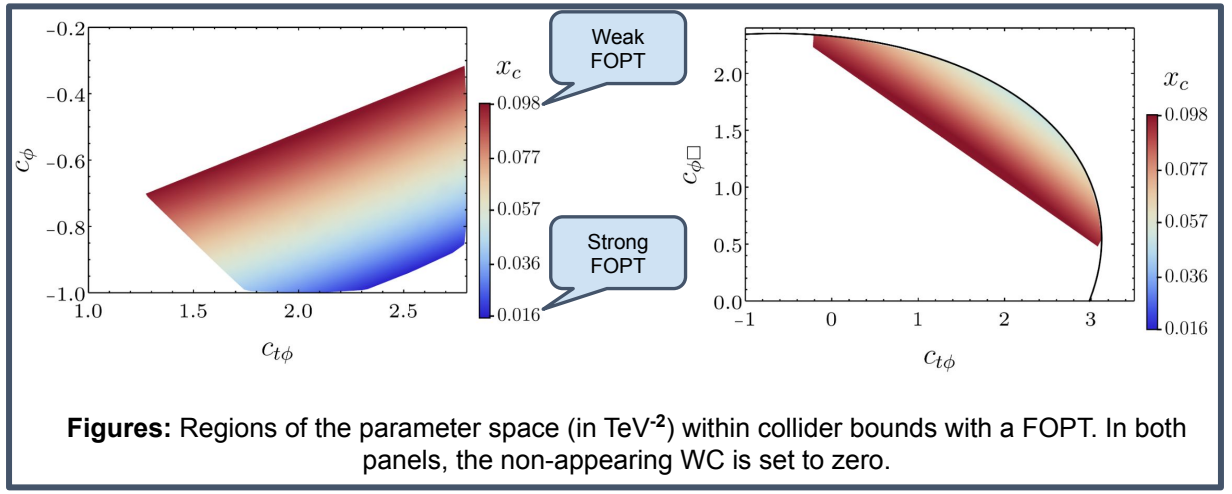
- Strong (observable via GWs) FOPTs require larger SMEFT coefficients.

  Equivalently, **BSM cannot be too heavy or too weakly-coupled** to produce a strong FOPT, but it might still be captured by SMEFT.

Results

Modified phase diagram

[Chala, Fiore, LG - 2507.16905]



Figures: Regions of the parameter space (in TeV^{-2}) within collider bounds with a FOPT. In both panels, the non-appearing WC is set to zero.

- FOPTs possible without direct modification of the Higgs potential **(with $c_\phi = 0$)**.
- Strong FOPTs **with joint contributions** of the three dim-6 operators, with all of them carrying **at most O(1) TeV^{-2} coefficients**, which is within collider bounds.
- Non-observation of GWs can then put upper bounds on these operators

Conclusions

- Computed, for the first time, the full O(g^4) high-temperature limit of the SMEFT.
- Explored new directions in its vast parameter space, constrained by collider bounds.
- Found that FOPTs are possible even without the sextic operator, but it is needed for strong FOPTs

  ⟶ BSM models that generate $\mathcal{O}_{t\phi} \equiv \bar{t}_L \tilde{\phi} t_R (\phi^\dagger \phi)$ at low energies worth checking too!

- Few works have addressed FOPTs in the SMEFT so far:

  [Camargo-Molina et al '22] [Camargo-Molina et al '24] [Chala, Guedes '25] [Chala, Fiore, LG '25]

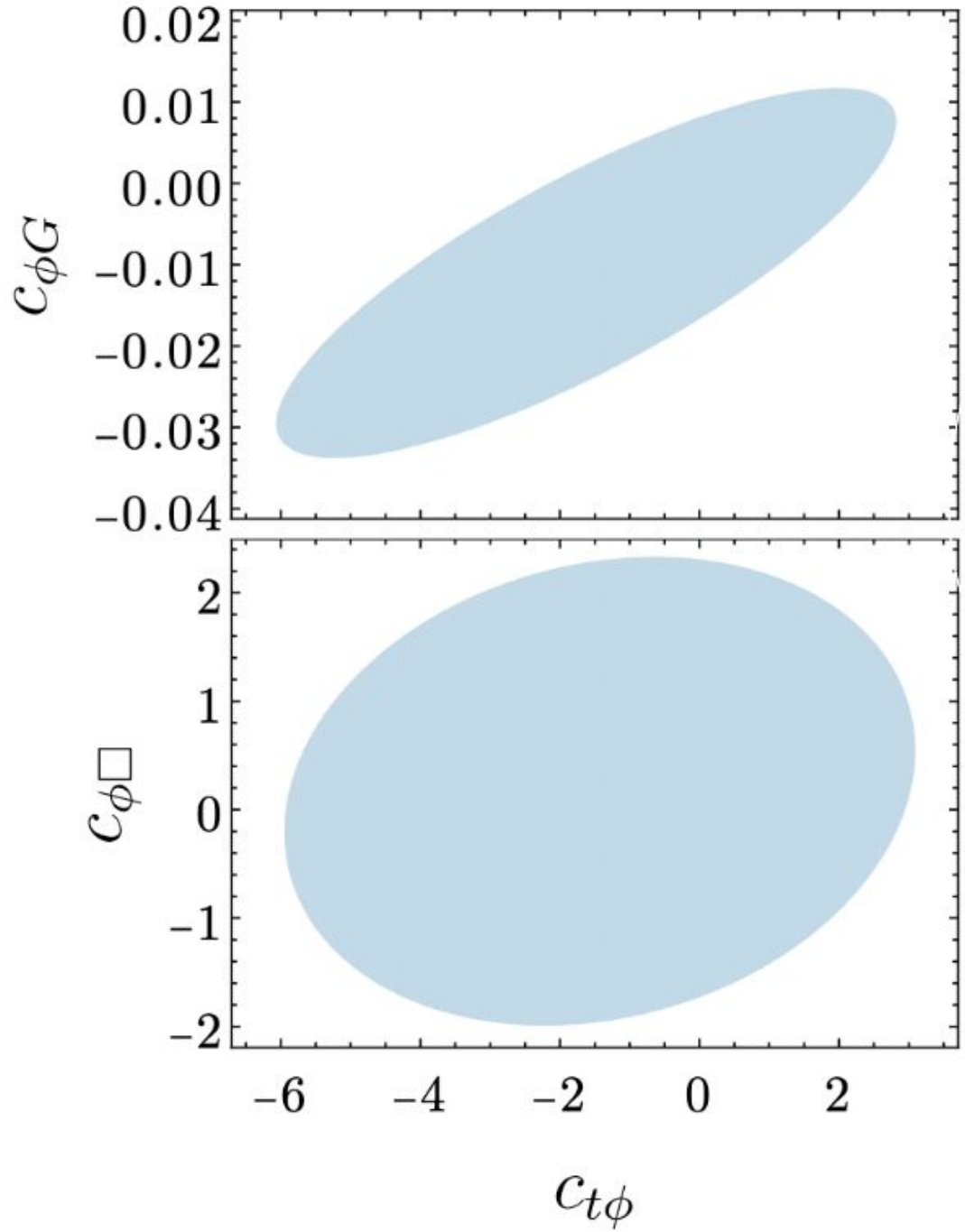
What's left to do? 🔍

Full nucleation study? SMEFT @ dim-8? HEFT? …

Thank you for your attention!

ご清聴ありがとうございました。

$\mathcal{O}(g)$	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}


0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
$c_{\phi G}$
2
1
0
−1
−2
$c_{\phi\Box}$
−6
−4
−2
0
2
$c_{t\phi}$

Thermal field theory in equilibrium

Dimensional reduction

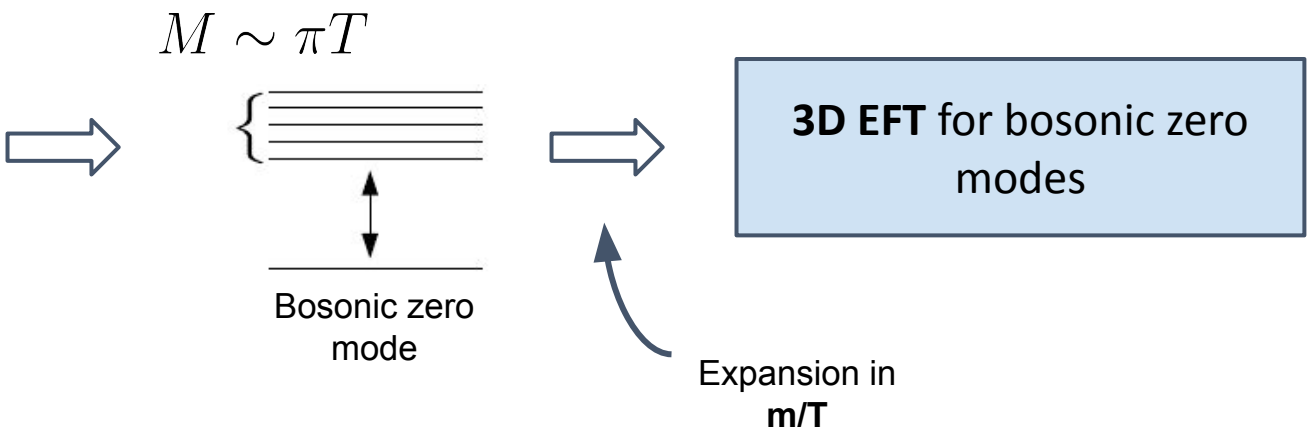
- **Generating functional** in thermal field theory (= Euclidean QFT with periodic time):

$$\mathcal{Z}_{\rm th} = \mathrm{Tr}\left(e^{-\beta\mathcal{H}}\right) = \sum_q \langle q\ 0|e^{-\beta\mathcal{H}}|q\ 0\rangle = \mathcal{N}\int_{q(0)=q(-i\beta)} \mathcal{D}q \exp\left(-S_E\right)$$

- Fields decompose in tower of 3D **Matsubara modes** (~ Kaluza-Klein) with thermal masses:

Bosons: $\omega_n = 2\pi n T$

Fermions: $\omega_n' = 2\pi\left(n+\frac{1}{2}\right)T$



Thermal field theory in equilibrium

[Gould, Tenkanen - 2309.01672]

Thermal hierarchy of scales

$$\underbrace{\pi T}_{\text{hard}} \gg \underbrace{\left(\frac{g}{4\pi}\right)\pi T}_{\text{soft}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{3/2}\pi T}_{\text{softer}}$$

Finite-temperature
4D SMEFT

$$\Lambda_{\rm NP} \gg \pi T$$

Thermal field theory in equilibrium

[Gould, Tenkanen - 2309.01672]

Thermal hierarchy of scales

$$\underbrace{\pi T}_{\text{hard}} \gg \underbrace{\left(\frac{g}{4\pi}\right)\pi T}_{\text{soft}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{3/2}\pi T}_{\text{softer}}$$

Finite-temperature
4D SMEFT

Dimensional reduction

Integrate out heavy Matsubara modes

$$\Lambda_{\rm NP} \gg \pi T \qquad \pi T \gg \mu^2$$

Thermal field theory in equilibrium

[Gould, Tenkanen - 2309.01672]

Thermal hierarchy of scales

$$\underbrace{\pi T}_{\text{hard}} \gg \underbrace{\left(\frac{g}{4\pi}\right)\pi T}_{\text{soft}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{3/2}\pi T}_{\text{softer}}$$

Finite-temperature
4D SMEFT

→ Dimensional reduction

Integrate out heavy Matsubara modes

$$\pi T \gg \mu^2$$

→ 3D matching

Integrate out temporal gauge bosons

$$m_{W_0}^2 \gg m_\phi^2$$

$$\Lambda_{\rm NP} \gg \pi T$$

Thermal field theory in equilibrium

Thermal hierarchy of scales

[Gould, Tenkanen - 2309.01672]

$$\underbrace{\pi T}_{\text{hard}} \gg \underbrace{\left(\frac{g}{4\pi}\right)\pi T}_{\text{soft}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{3/2}\pi T}_{\text{softer}}$$

Finite-temperature **4D SMEFT**

Dimensional reduction

Integrate out heavy Matsubara modes

$\pi T \gg \mu^2$

3D matching

Integrate out temporal gauge bosons

$m_{W_0}^2 \gg m_\phi^2$

Lattice simulation of **3D SU(2) + Higgs**

[Gould et al. - 2205.07238]

$\Lambda_{\rm NP} \gg \pi T$