GOING BEYOND THE SMEFT FOR DI-HIGGS STUDIES

ELIEL CAMARGO-MOLINA

BEYOND THE STANDARD MODELS (BSM)

Particles

Adding extra symmetries and particles to the SM

Many, many different models

Grand Unification of forces

Dark matter candidates

Cosmology

Modified Newtonian Dynamics

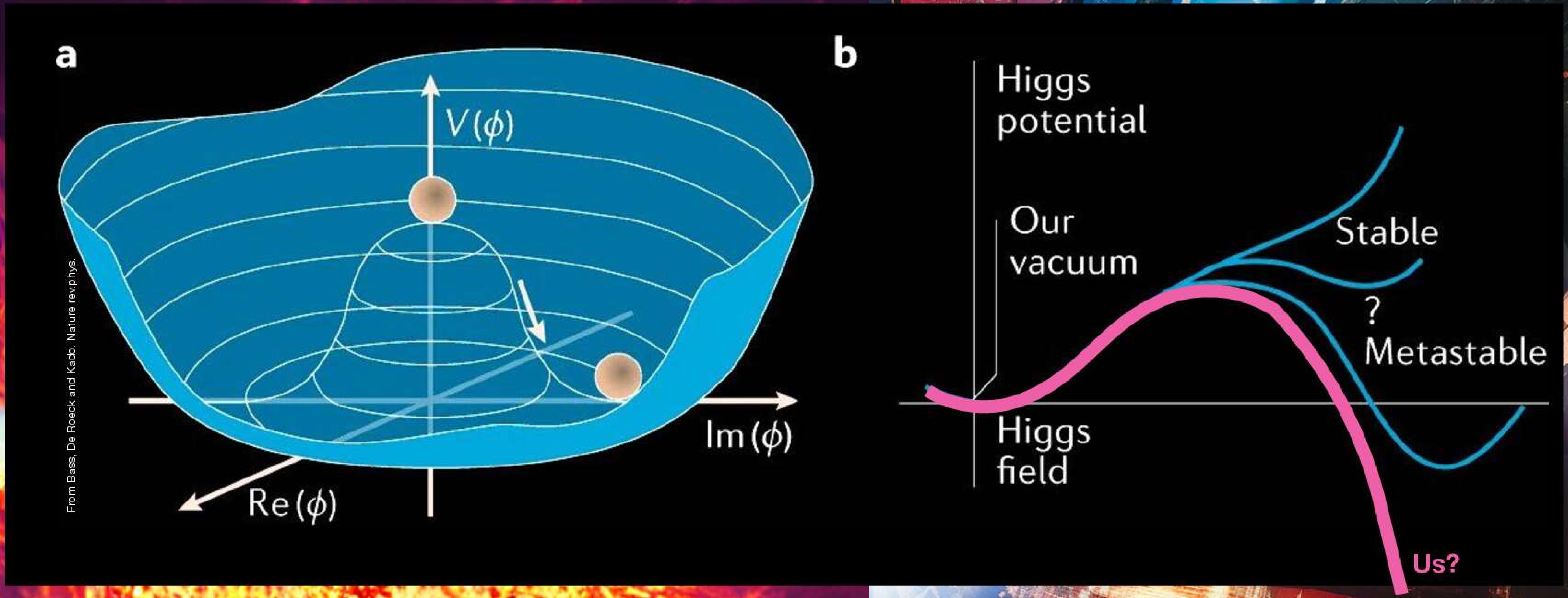
Black holes as dark matter

Many inflationary models

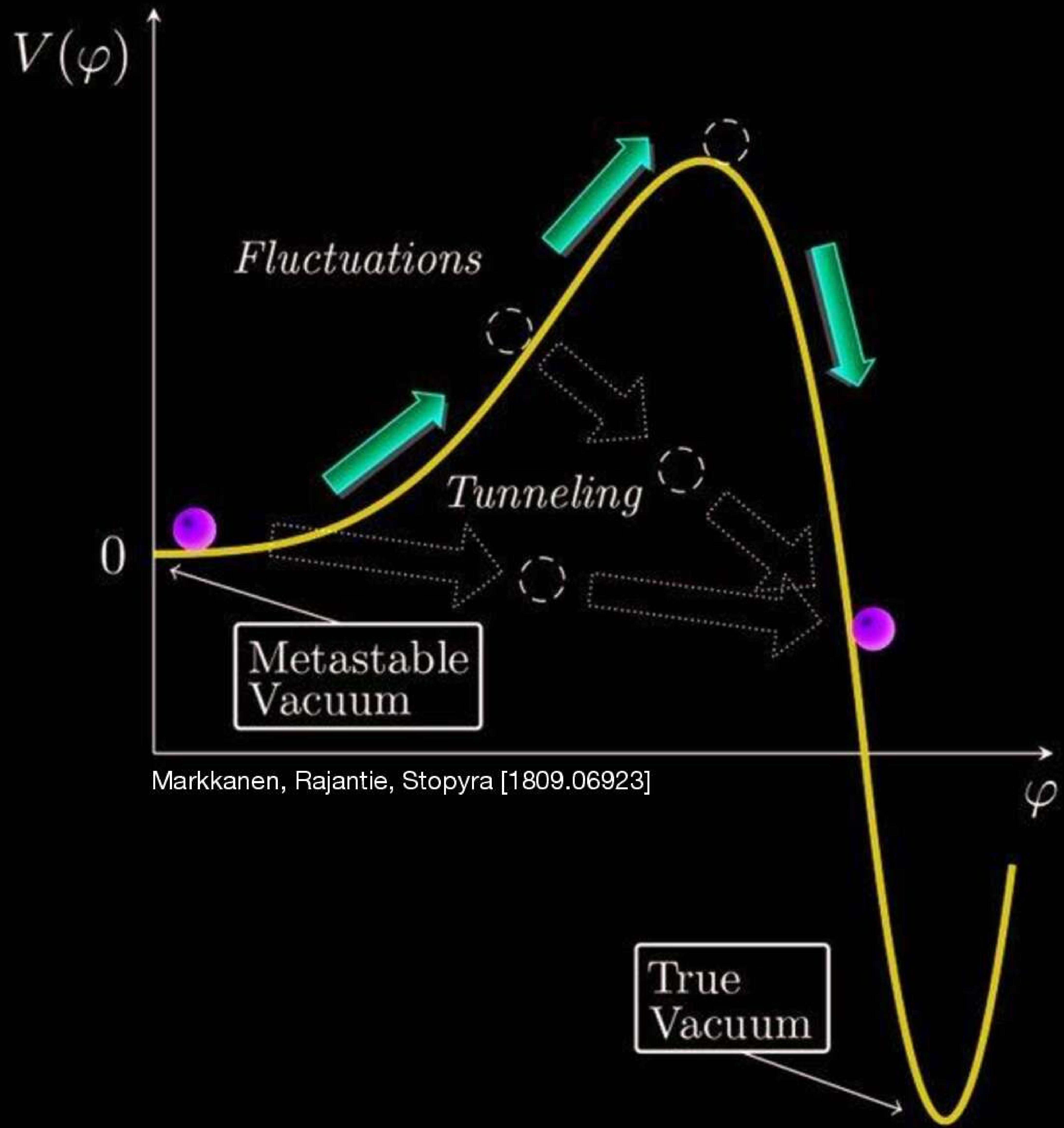
Grand Unification of forces


Adding extra symmetries and
particles to the SM
Grand Unification of forces
Dark matter candidates
The Vacuum and scalar particles
Many inflationary models
Grand Unification of forces

THE HIGGS POTENTIAL: COSMIC FRONTIER PHENOMENOLOGY



VACUUM DECAY



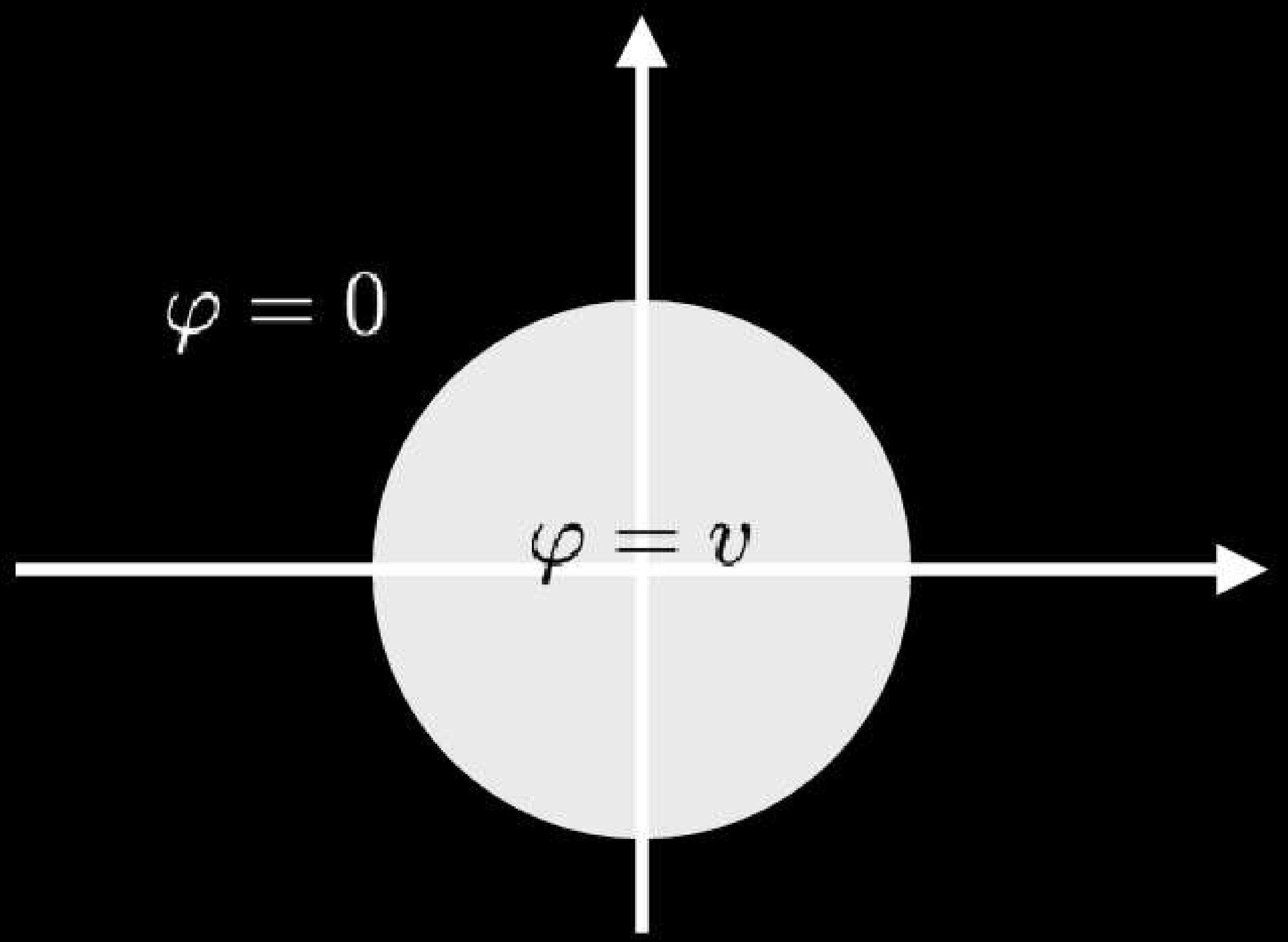
Markkanen, Rajantie, Stopyra [1809.06923]

As we always do, we want to find things that **extremise** an action

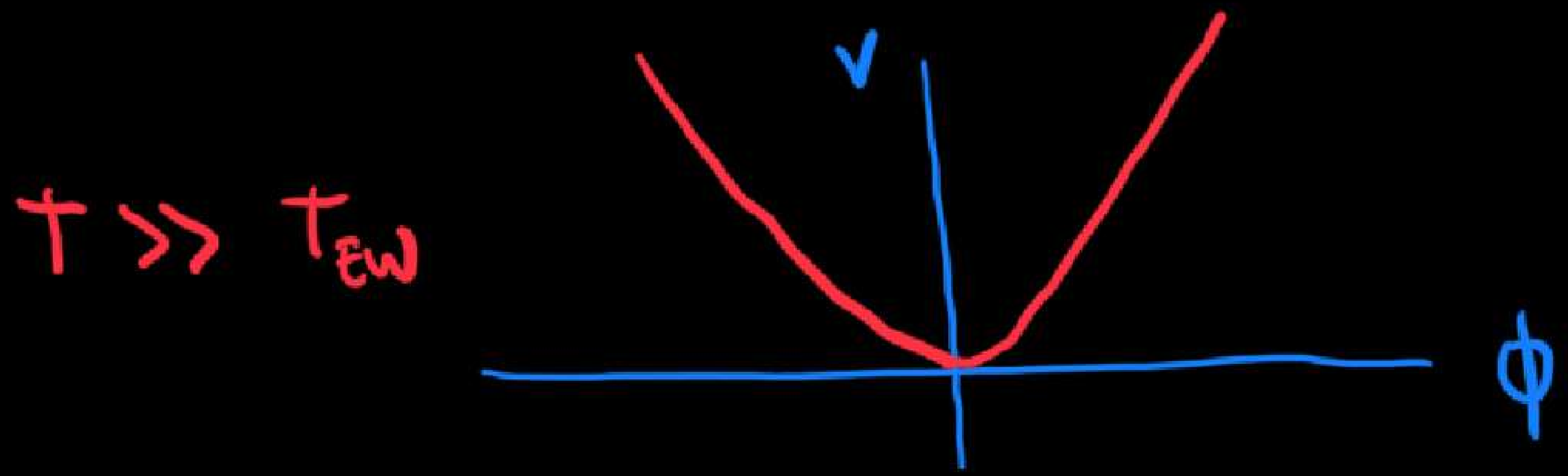
$$S(\phi) = \int d^d x \left(\frac{1}{2}(\partial_\mu \phi)^2 + V(\phi) \right)$$

Which means finding extrema of the corresponding energy functional:

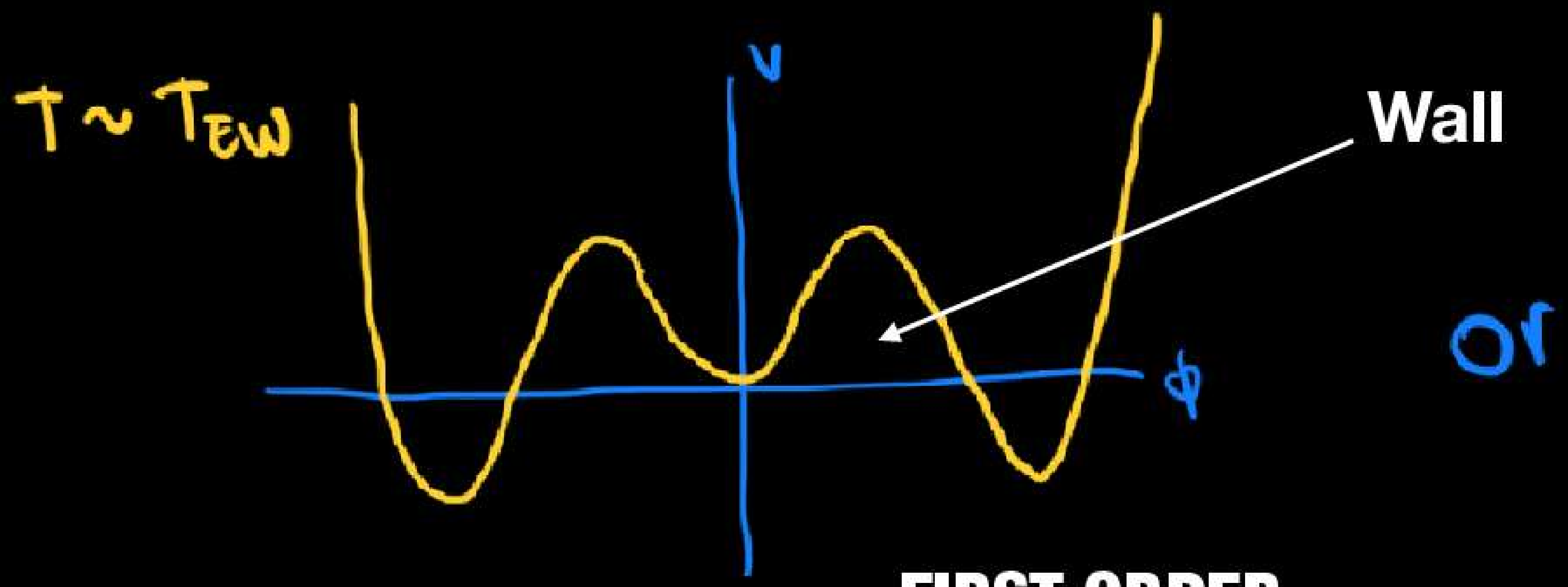
$$U[\phi(x)] = \int d^3 x \left[\frac{1}{2}(\nabla \phi)^2 + V(\phi) \right]$$



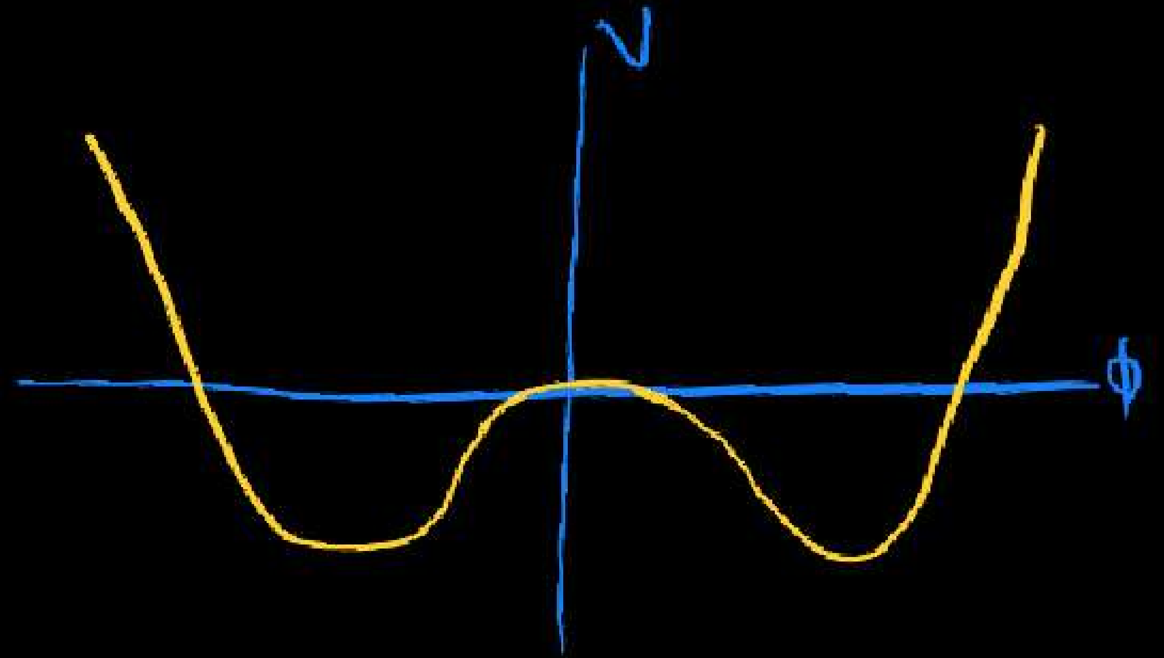
The Electroweak Phase transition, EWPT (schematically)



At high temperatures, the potential is symmetric

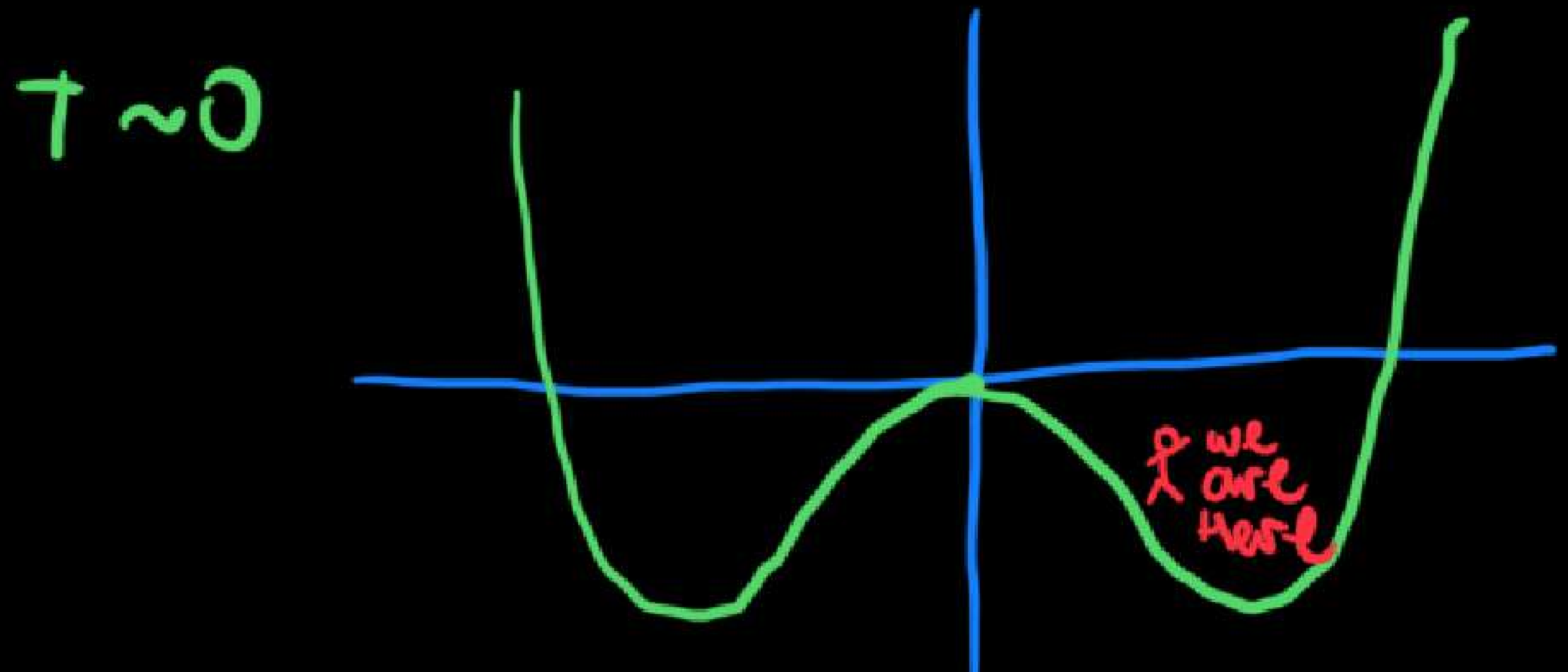


FIRST ORDER



SECOND ORDER

At a certain temperature, a new minimum develops. The transition can happen smoothly (second-order) or strongly (first-order).

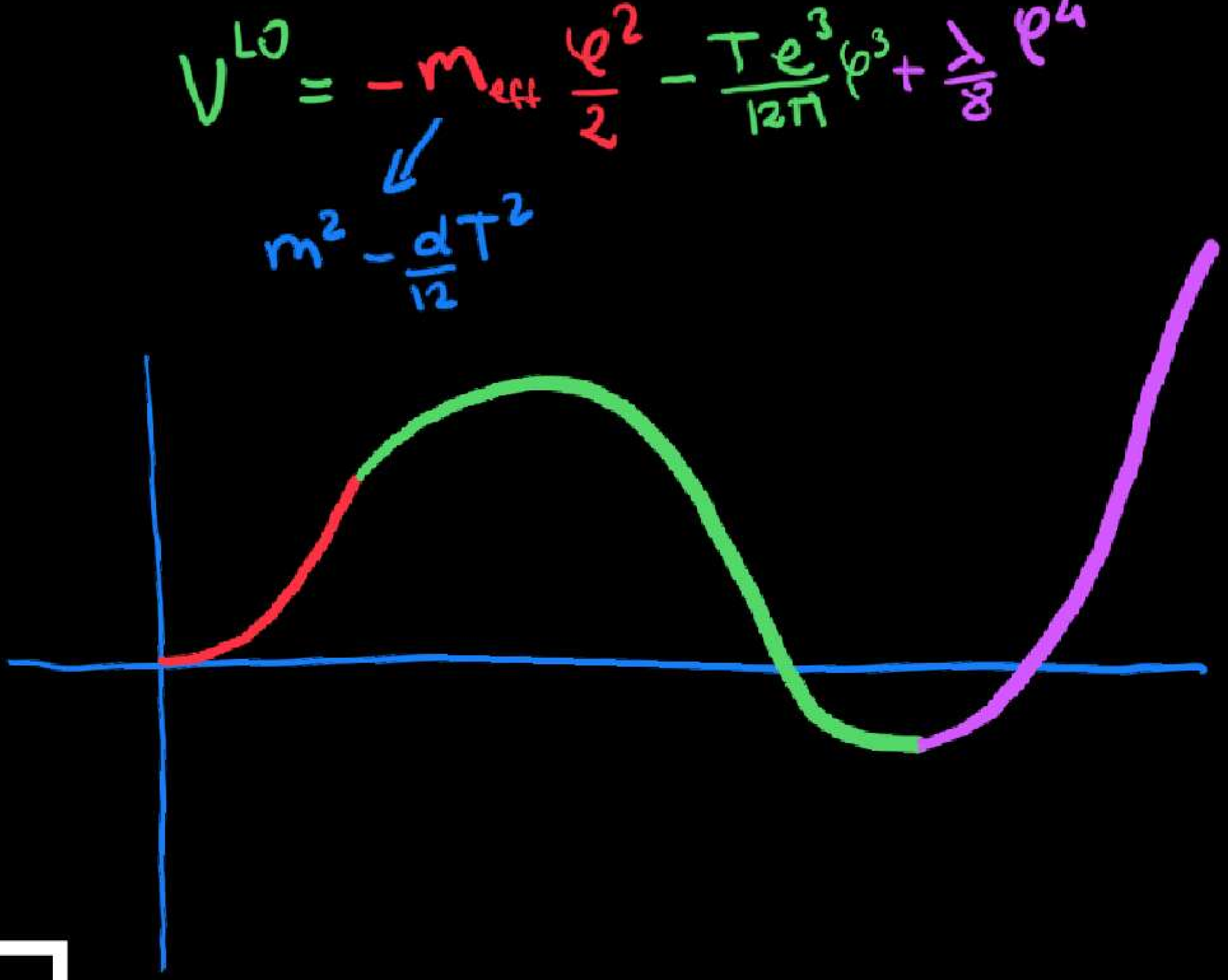


At zero temperature EW symmetry is broken and we do QFT calculations around the broken phase.

A FOPT is the most important ingredient to explain matter antimatter asymmetry with baryogengesis

In the Standard Model….

- At tree-level, there is no barrier
- At leading order (loop + thermal) a radiative barrier is possible
- Lattice calculations settled the matter in the 90s:



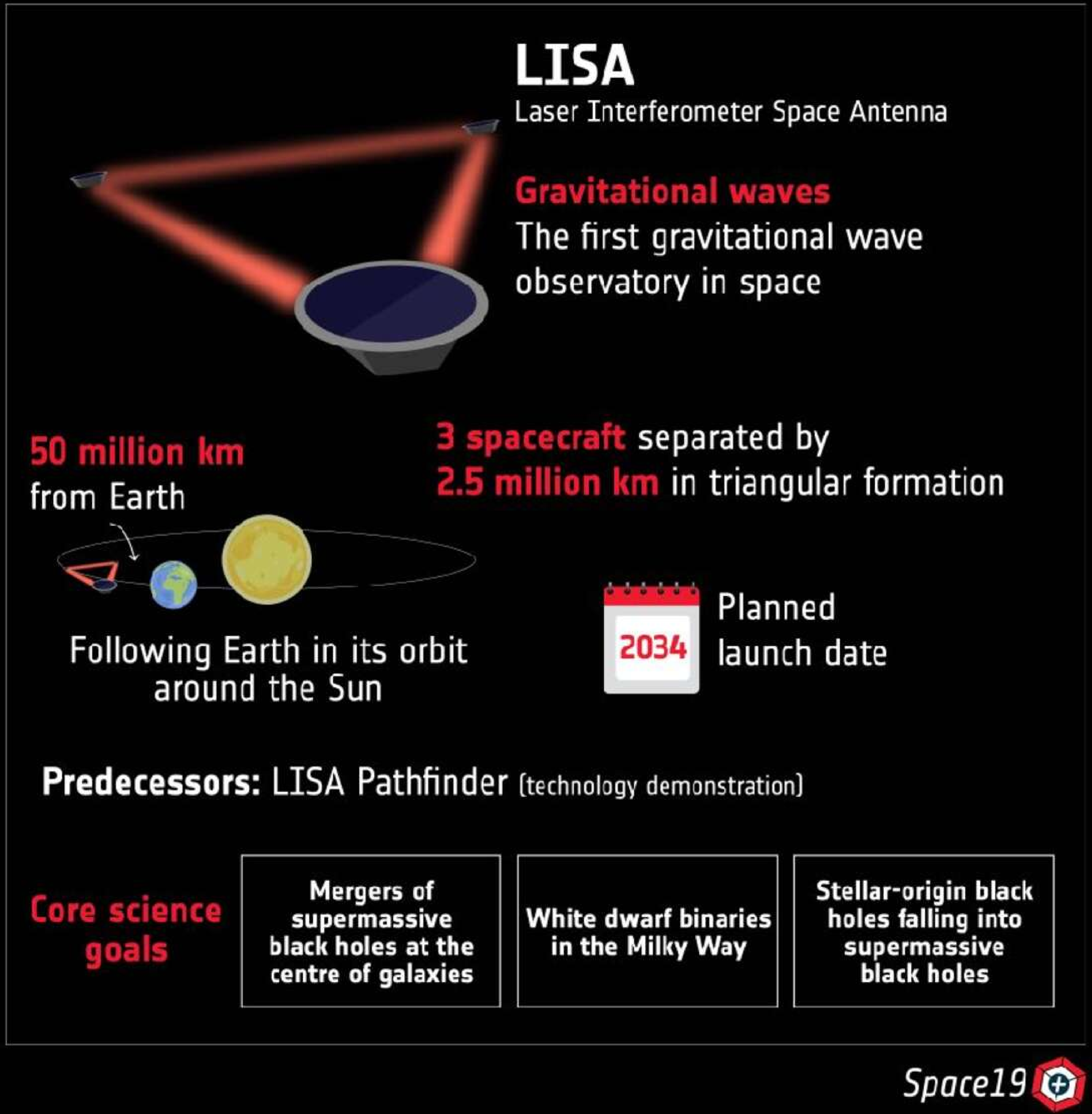
THE ELECTROWEAK PHASE TRANSITION:
A NON-PERTURBATIVE ANALYSIS

K. Kajantie[a,b,1], M. Laine[a,c,2], K. Rummukainen[d,3] and M. Shaposhnikov[b,4]

The Higgs is way to heavy for a first order EWPT!

What if like with neutrino masses the SM is also wrong?

Slide taken from esa



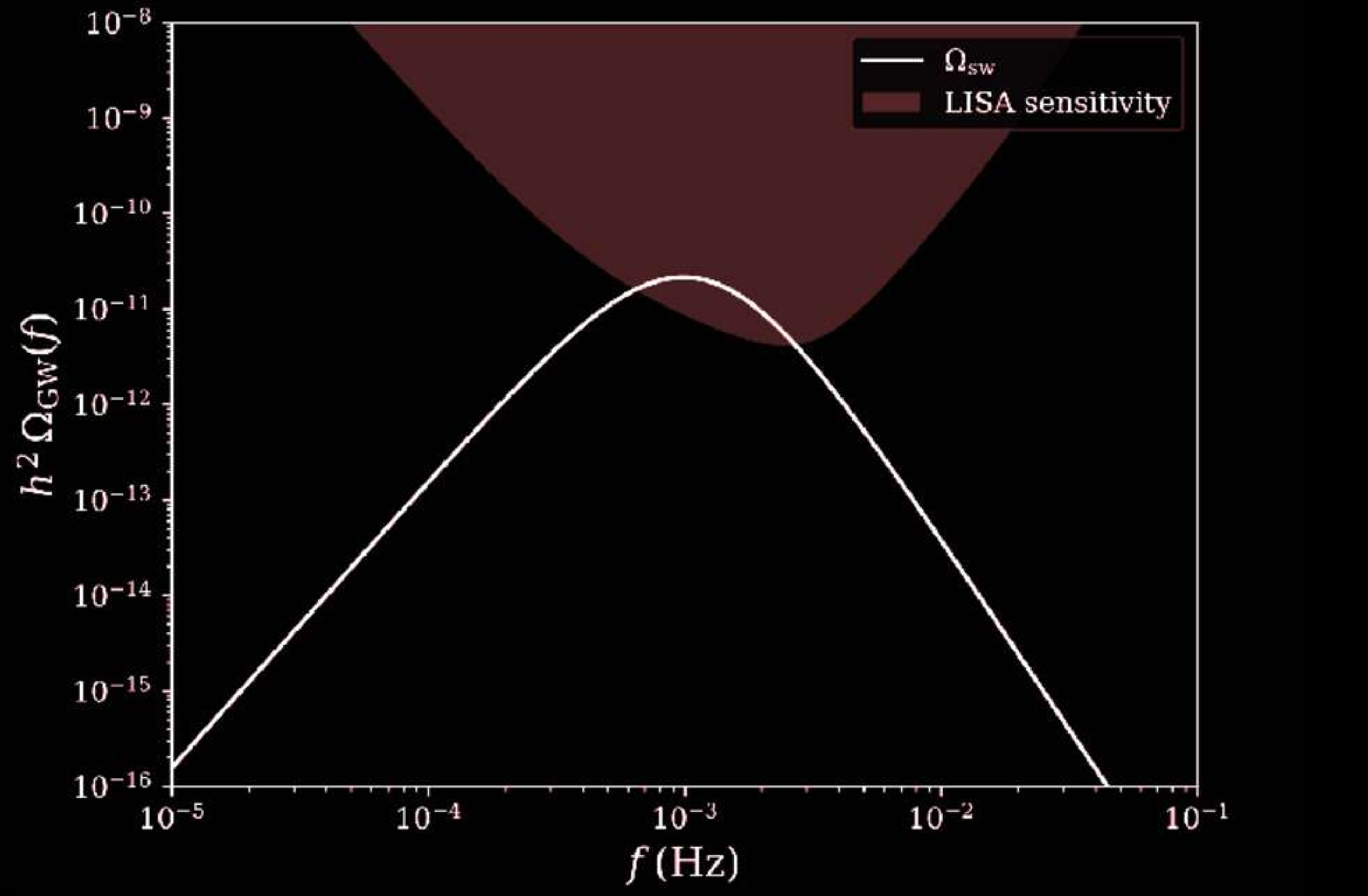
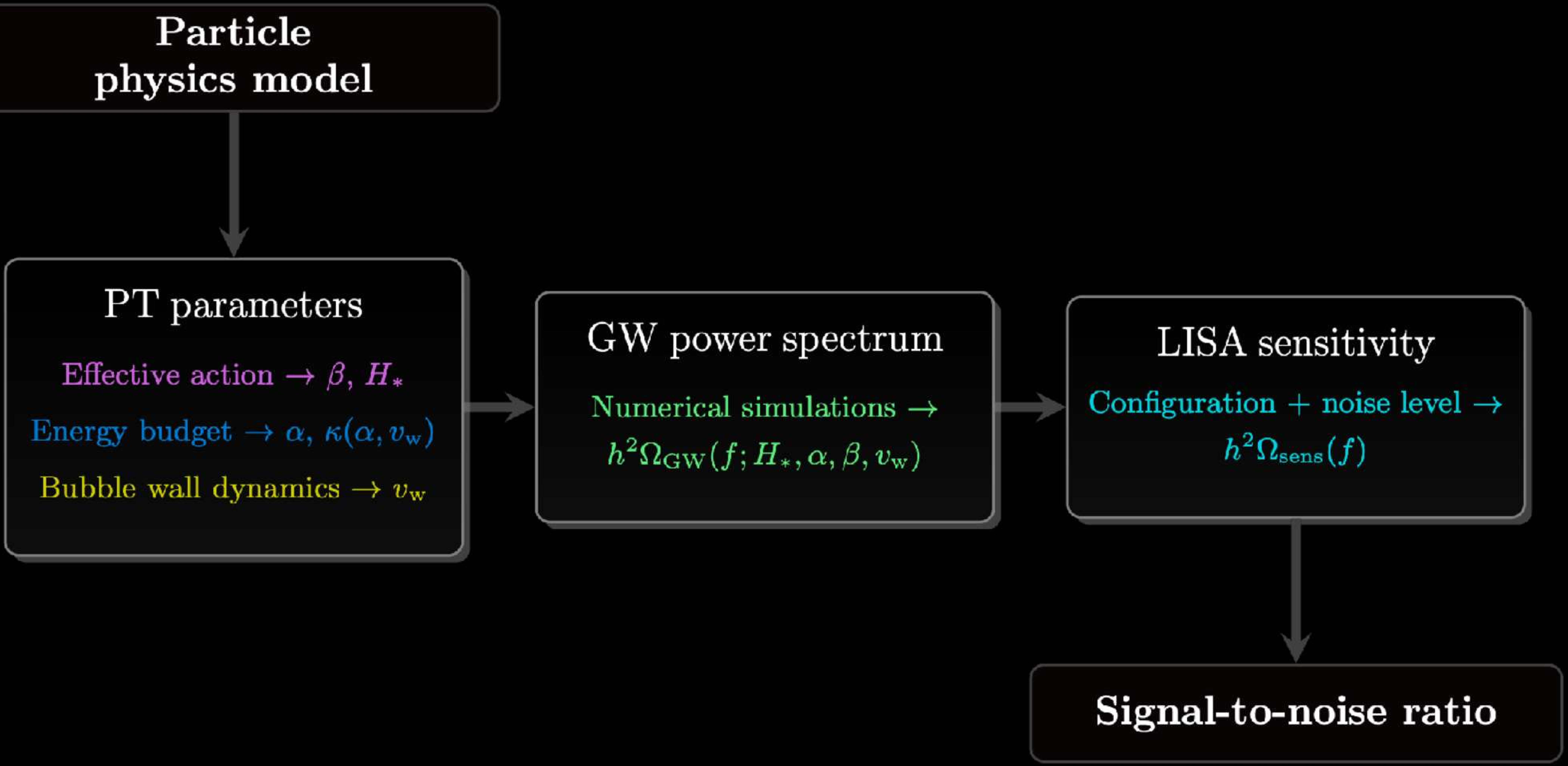


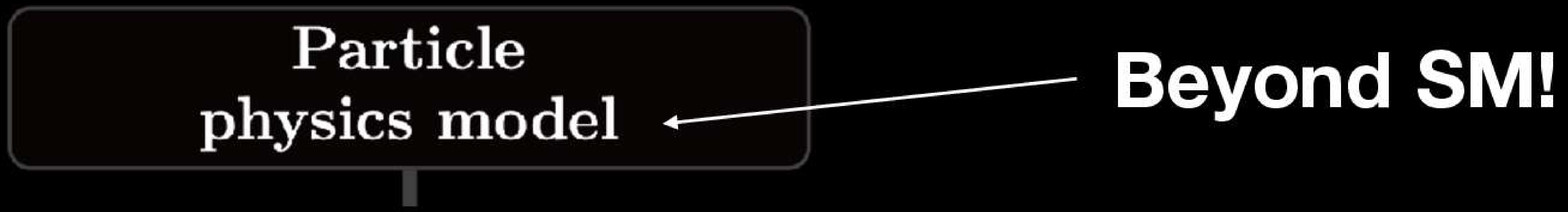
Figure 3: Example output of the PTPlot tool. The plot shows an example of the GW power spectrum from a first-order PT, along with the LISA sensitivity curve ($h^2\Omega_{\rm Sens}(f)$ taken from the LISA Science Requirements Document [65]). The parameters of the example model are $v_w = 0.9$, $\alpha = 0.1$, $\beta/H_* = 50$, $T_* = 200$ GeV, $g_* = 100$.

Detecting gravitational waves from cosmological phase transitions with LISA: an update

Chiara Caprini[a], Mikael Chala[b,c,†], Glauber C. Dorsch[d], Mark Hindmarsh[e,f], Stephan J. Huber[f], Thomas Konstandin[g,‡], Jonathan Kozaczuk[h,i,j,§], Germano Nardini[k], Jose Miguel No[l,m], Kari Rummukainen[e], Pedro Schwaller[n], Geraldine Servant[g,o], Anders Tranberg[k], David J. Weir[e,p,¶]
For the LISA Cosmology Working Group

From LISA cosmology WG





For the EWPT to be first order we need **BSM physics.**

But not every BSM model predicts this, though many do!

Let's say it was first order, then the BSM physics **responsible** is either:

- **At a higher scale (heavy, > 1 TeV)**
- **At a lower scale (light) but very elusive.**

There are so many models though! Can we be a little agnostic?

HEFT (abridged)

Instead of $H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h \quad + iG_0) \end{pmatrix}$

A Higgs centered Effective Field Theory, where the Higgs is parametrized as

$$U = \exp(2i\Phi/v), \qquad \Phi = \varphi^a T^a = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\varphi^0}{\sqrt{2}} & \varphi^+ \\ \varphi^- & -\frac{\varphi^0}{\sqrt{2}} \end{pmatrix}, \quad h$$

$$\mathcal{L}_{\mathrm{HEFT}} \supset \frac{v^2}{4}\mathcal{F}(h)\mathrm{Tr}\left\{D_\mu U^\dagger D_\mu U\right\} + \frac{1}{2}(\partial_\mu h)^2 - V(h),$$

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots, \qquad V(h) = \frac{1}{2}m_h^2 h^2 \left(1 + d_3\frac{h}{v} + \frac{d_4}{4}\frac{h^2}{v^2} + \ldots\right)$$

The SM corresponds to $a = b = d_3 = d_4 = 1$ and the remaining terms with higher powers of h are set to zero.

New physics would then be parametrized by deviations from these values.

Works for new physics that is light or heavy
Easy to define deviations of Higgs self interactions from the SM
Accounts for cases where new physics gets mass from the Higgs vev

Harder to define a good power counting that always works
Other sectors are more flexible which leads to many definitions

Eqs. borrowed from 2305.07689

Particle physics model ← Beyond SM, **heavy**

A consistent prescription to parametrize physics at a higher scale.

Comes with a nice expansion parameter that we can use to keep consistency order by order.

If new physics is at higher scales this is a great tool which exploits a separation of scales

This is formally an expansion in the ratio of the EW scale and the NP scale.

BSM effects → C_i, **SM particles** → O_i

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + C_5 O_5 + \sum_i C_i O_i + O\left(\frac{v^3}{\Lambda^3}\right)$$

C_i: $[\mathrm{GeV}]^{-2}$

$C_i = \frac{\tilde{C}_i}{\Lambda^2}$ if $\tilde{C}_i \sim O(1)$ then from C_i you can get some Λ

Higgs sector Operators

$C^{\varphi}(\phi\phi^{+})^3$

$C^{\varphi\Box}\ \phi\phi^{+}\Box\phi\phi^{+}$

$C^{\varphi D}(\phi D_\mu \phi^{+})(\phi^{+}D^{\mu}\phi)$

A very lively discussion/debate around 2014 on what a ”good” basis for the SMEFT would be.

Finding minimal ”useful” bases of operators is not straightfoward.

CERN-PH-TH/2007–47

The Strongly-Interacting Light Higgs

G. F. Giudice[a], C. Grojean[a,b], A. Pomarol[c], R. Rattazzi[a,d]

[a] *CERN, Theory Division, CH–1211 Geneva 23, Switzerland*
[b] *Service de Physique Théorique, CEA Saclay, F91191 Gif–sur–Yvette, France*
[c] *IFAE, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain*
[d] *Institut de Théorie des Phénomènes Physiques, EPFL, CH–1015 Lausanne, Switzerland*

arXiv:hep-ph/0703164v2 19 Jun 2007

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Prepared for submission to JHEP

Renormalization Group Evolution of the Standard Model Dimension Six Operators I: Formalism and λ Dependence

Elizabeth E. Jenkins,[a] Aneesh V. Manohar,[a] Michael Trott[b,1]

[a] *Department of Physics, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0319, USA*
[b] *Theory Division, Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

E-mail: ejenkins@ucsd.edu, amanohar@ucsd.edu, michael.trott@cern.ch

v:1308.2627v4 [hep-ph] 15 Jul 2020

Abstract: We calculate the order λ, λ^2 and λy^2 terms of the 59×59 one-loop anomalous dimension matrix of dimension-six operators, where λ and y are the Standard Model Higgs self-coupling and a generic Yukawa coupling, respectively. The dimension-six operators modify the running of the Standard Model parameters themselves, and we compute the complete one-loop result for this. We discuss how there is mixing between operators for which no direct one-particle-irreducible diagram exists, due to operator replacements by the equations

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IFT-9/2010
TTP10-35

Dimension-Six Terms in the Standard Model Lagrangian*

B. Grzadkowski[1], M. Iskrzyński[1], M. Misiak[1,2] and J. Rosiek[1]

[1] *Institute of Theoretical Physics, University of Warsaw, Hoża 69, PL-00-681 Warsaw, Poland.*

[2] *Institut für Theoretische Teilchenphysik, Karlsruhe Institute of Technology (KIT), D-76128 Karlsruhe, Germany.*

Xiv:1008.4884v3 [hep-ph] 15 Jan 2017

Abstract

When the Standard Model is considered as an effective low-energy theory, higher dimensional interaction terms appear in the Lagrangian. Dimension-six terms have been enumerated in the

Particle physics model

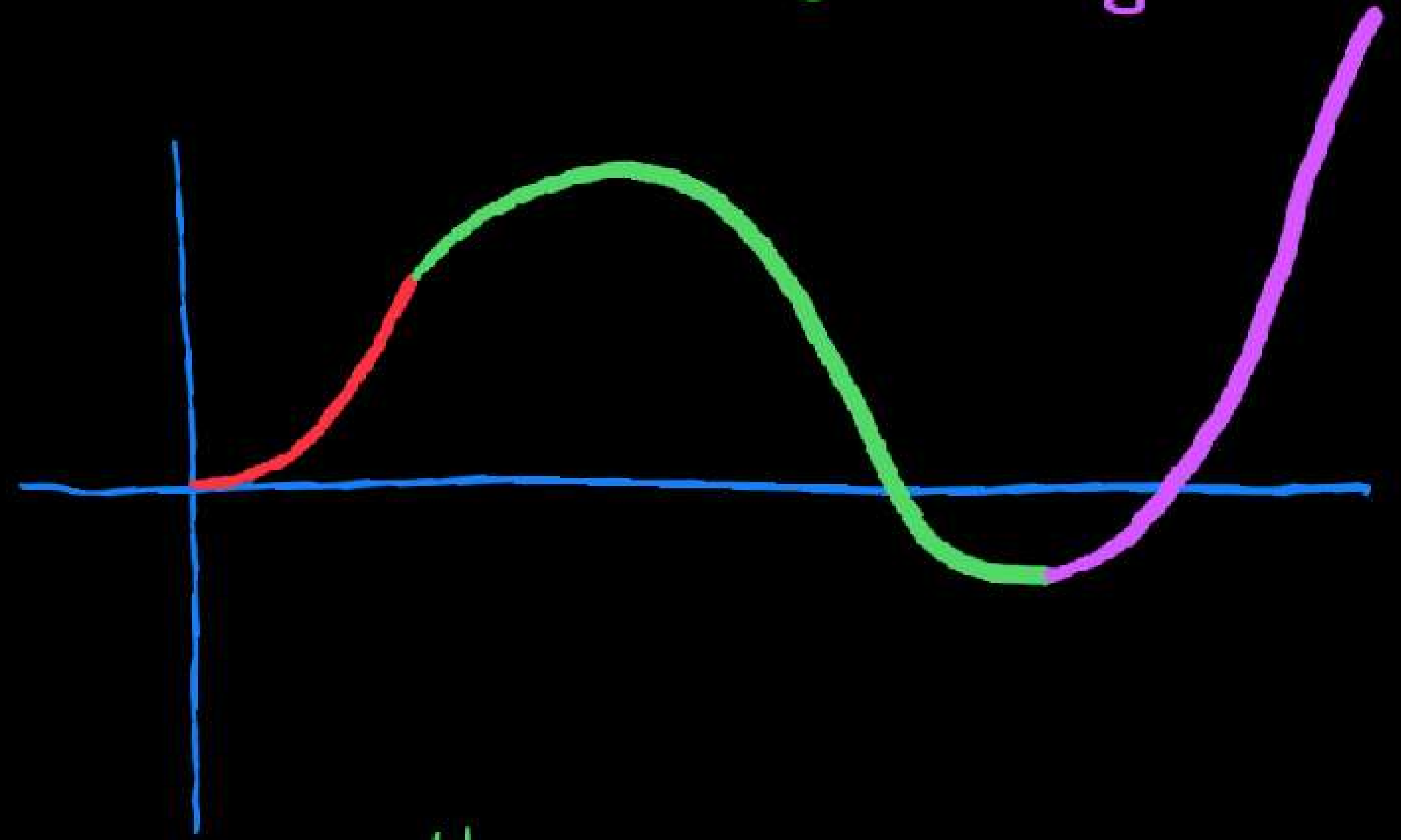
- The new operator allows us to have a barrier already at tree level if

  λ < 0

- A little strange, but nothing in principle against it
- The size of Wilson Coefficients dictates the size of the barrier and the order of the EWPT

$\lambda < 0$, $c^{\varphi} < 0$

$$V_{tree} = -m^2_{eff}(T)\varphi^2 + \frac{\lambda}{8}\varphi^4 - \frac{c^{\varphi}}{8}\varphi^6$$

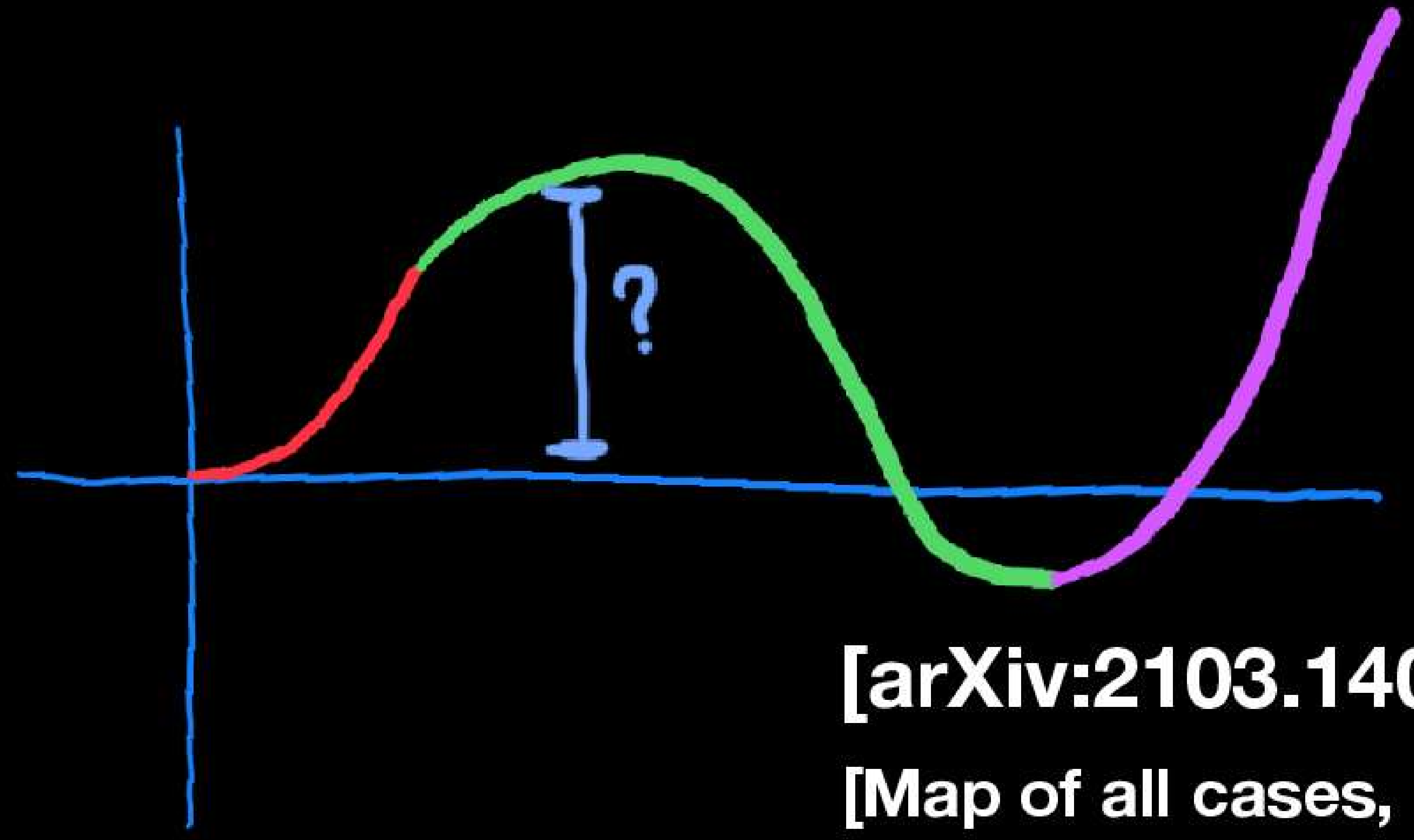


- Large coefficients needed for FOPT
- They suggest a sub-TeV scale of NP
- Or the need to go beyond dim 6
- … unlikely

- λ > 0 and tiny also works!
- The barrier is generated radiatively
- The WC plays a more indirect role (at least at LO)
- Potentially the NP scale can be higher

!!

$$V^{LO} = -m^2_{eff}\frac{\varphi^2}{2} - \frac{Te^3}{12\pi}\varphi^3 + \frac{\lambda}{8}\varphi^4$$



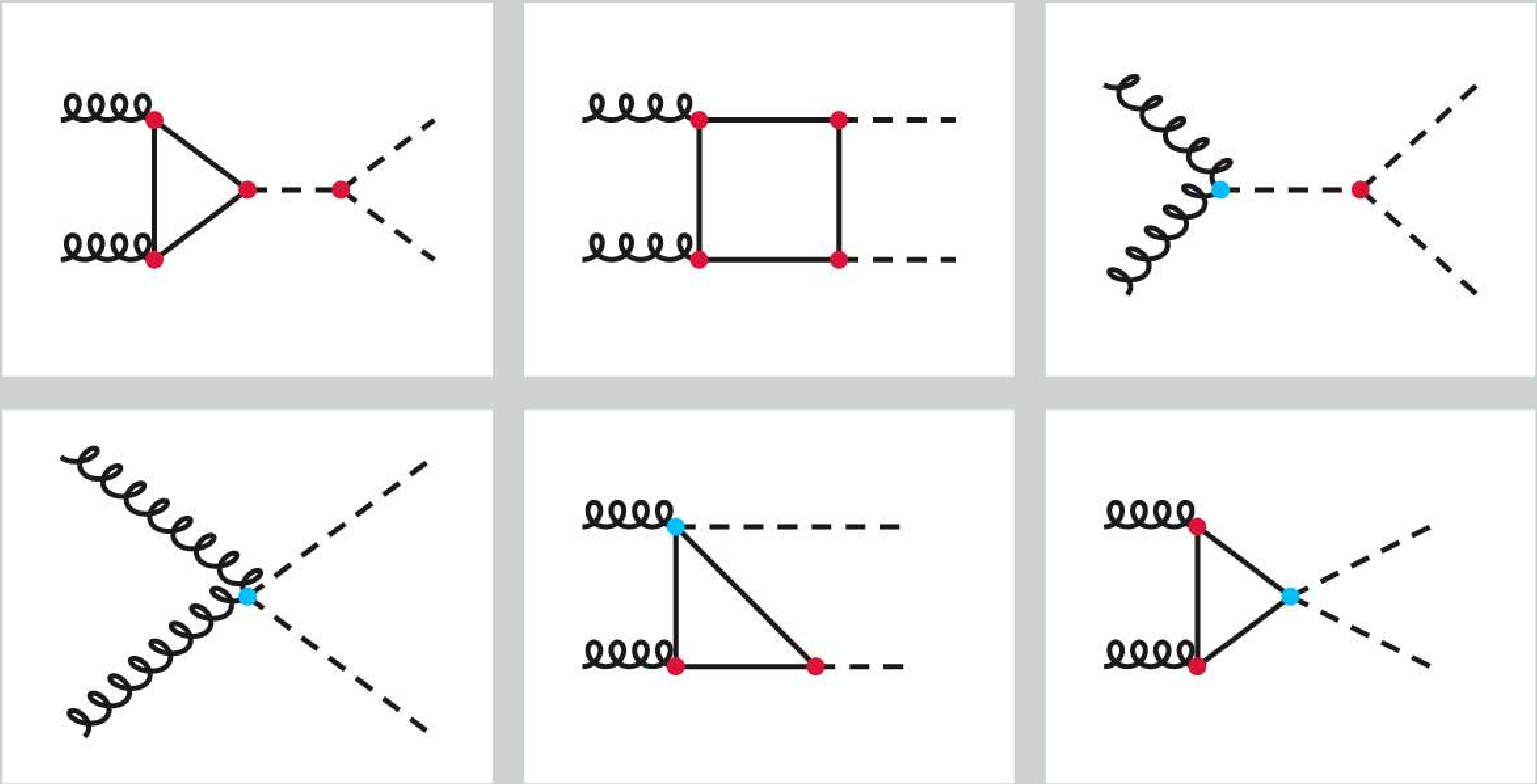
- Smaller coefficients do the trick
- TeV-scale NP
- Testable at future colliders

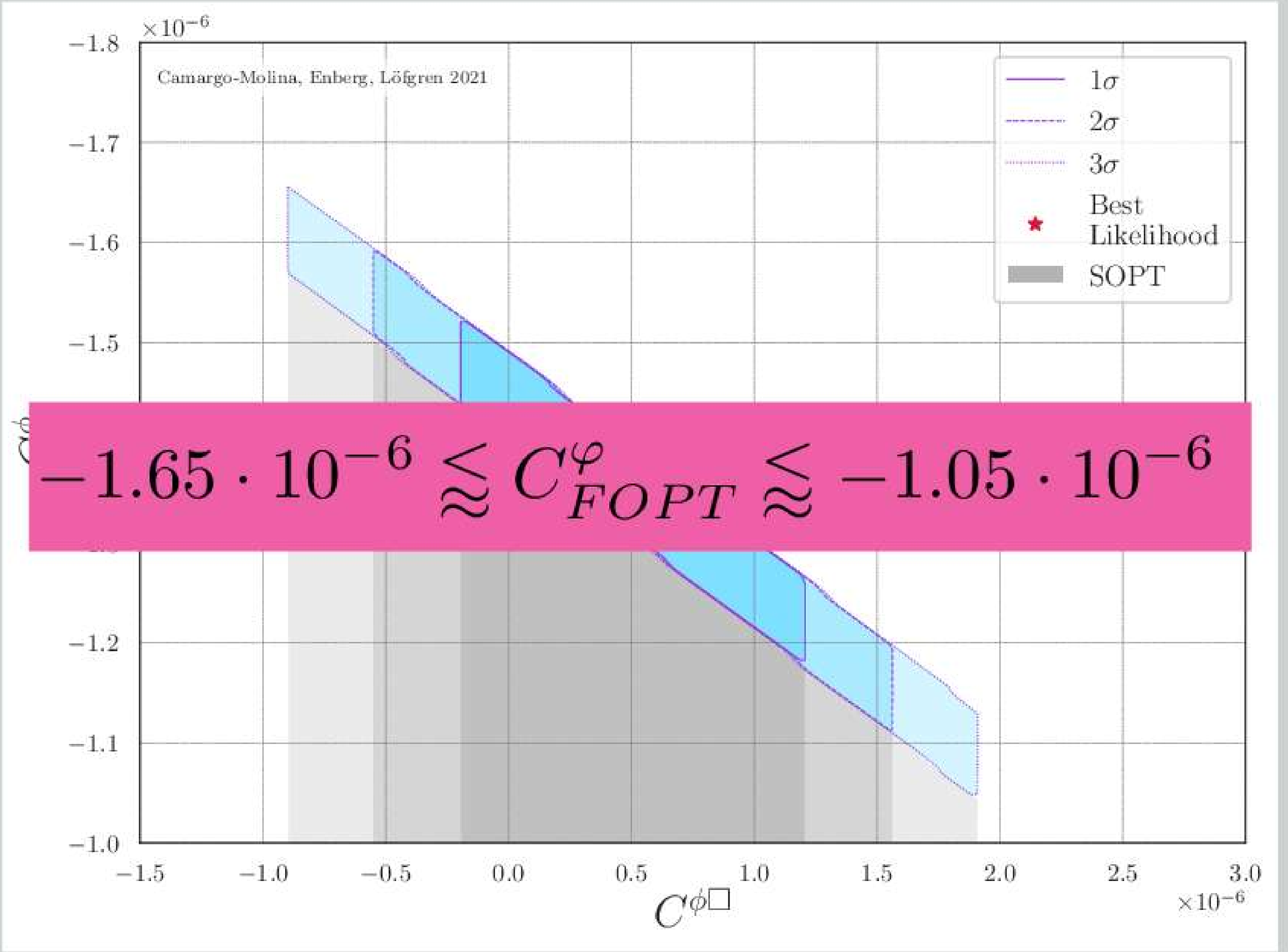
[arXiv:2103.14022 ECM, Enberg, Löfgren]

[Map of all cases, ongoing work ECM, Enberg, Löfgren]

Cosmology at colliders!

[arXiv:2103.14022 ECM, Enberg, Löfgren]





$$-1.65 \cdot 10^{-6} \lessapprox C^{\varphi}_{FOPT} \lessapprox -1.05 \cdot 10^{-6}$$

- Modified vertex (red)
- New vertex (blue)

$$-1.2 \cdot 10^{-5} < C^{\varphi}_{\text{LHC}} < 5.3 \cdot 10^{-6}$$

$$-2.8 \cdot 10^{-6} < C^{\varphi}_{\text{HL-LHC}} < 1.7 \cdot 10^{-6}$$

Kim, Sakaki, Son [1801.06093]

Particle physics model

Beyond SM**EFT**

What if some of the new physics is **light** and does not live at much higher scales?

Let's take that one particle from a BSM theory is light, then we could do the same approach,

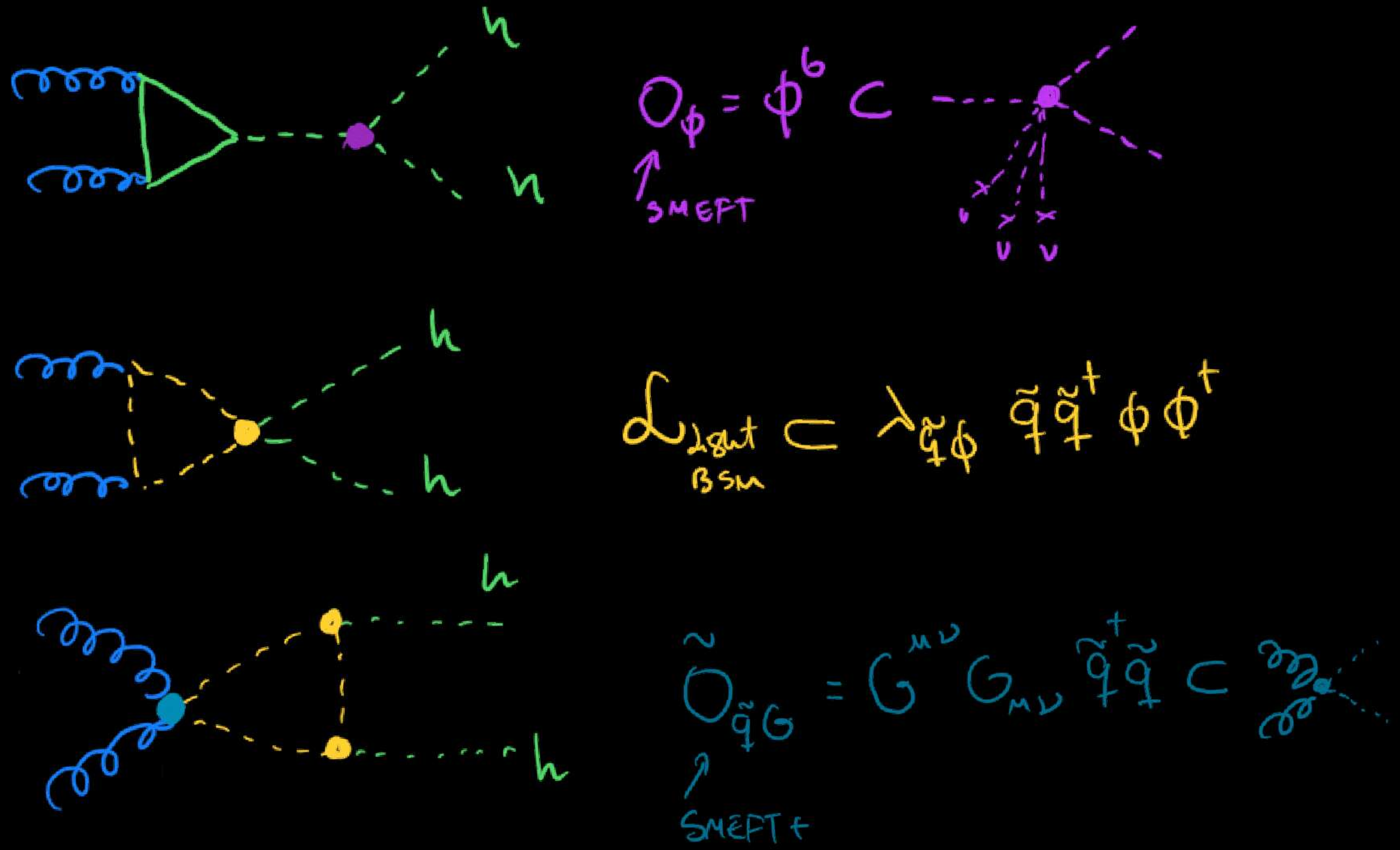
$$\mathcal{L}_{SMEFT^+} = \mathcal{L}_{SM} + \mathcal{L}_{\substack{light \\ BSM}} + \sum_i c_i \tilde{O}_i + O\left(\frac{v^3}{\Lambda^3}\right)$$

Let's say we take a particle, $\tilde{q}$ color carrying scalar

Then we just write a new set of operators $\tilde{O} = O^{SMEFT^+} \cup O^{\substack{light \\ BSM} + SM}$

$$\tilde{O}_{\tilde{q}\phi} = (\phi\phi^\dagger)^2 \tilde{q}\tilde{q}^\dagger$$

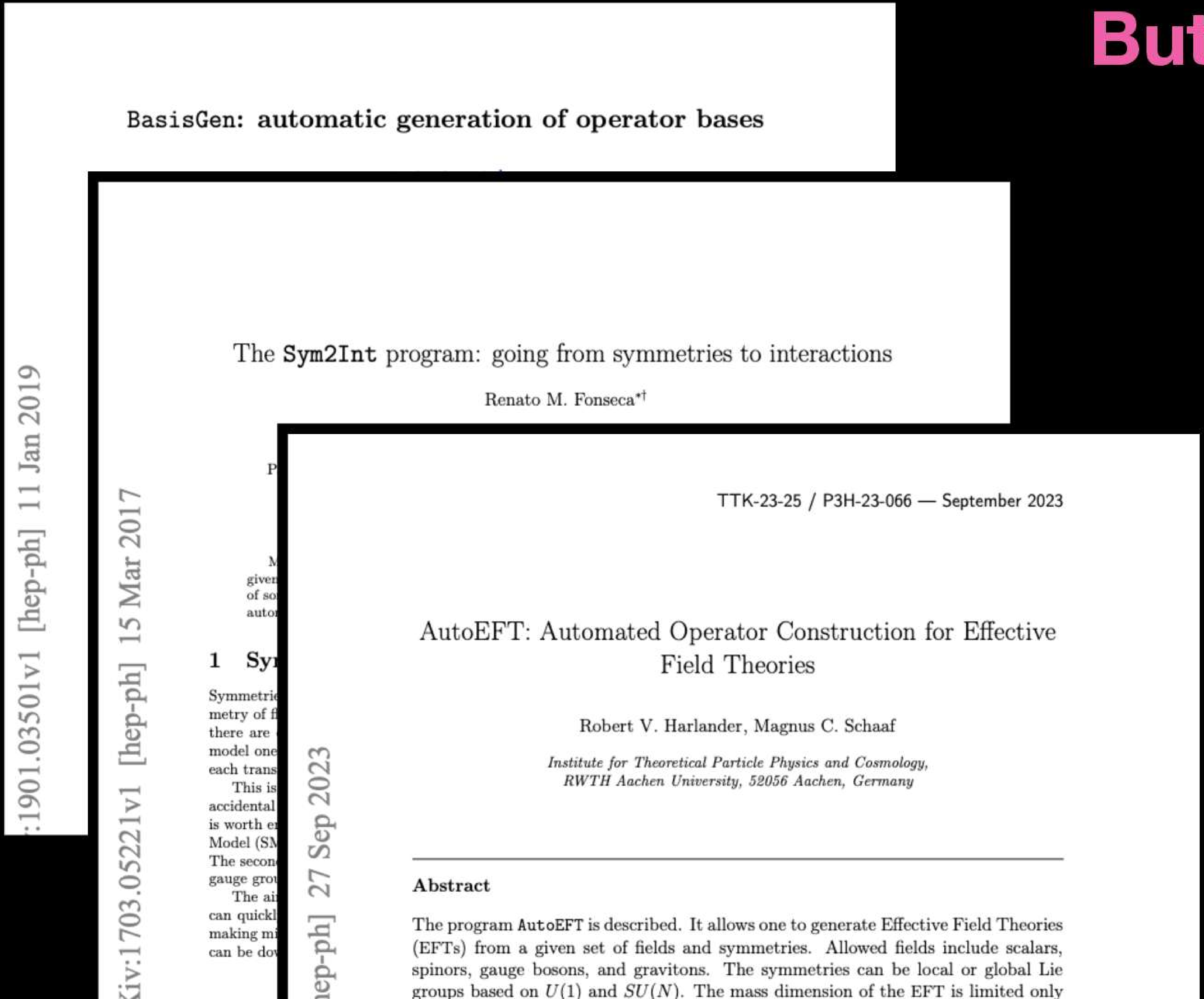
Then we would modify the Higgs interactions



And connect to models with first-order EWPT semi-agnostically

Finding minimal "useful" bases of operators is not straightfoward....

But partly automatable!


BasisGen: automatic generation of operator bases

arXiv:1901.03501v1 [hep-ph] 11 Jan 2019

The Sym2Int program: going from symmetries to interactions

Renato M. Fonseca*†

arXiv:1703.05221v1 [hep-ph] 15 Mar 2017

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TTK-23-25 / P3H-23-066 — September 2023

AutoEFT: Automated Operator Construction for Effective Field Theories

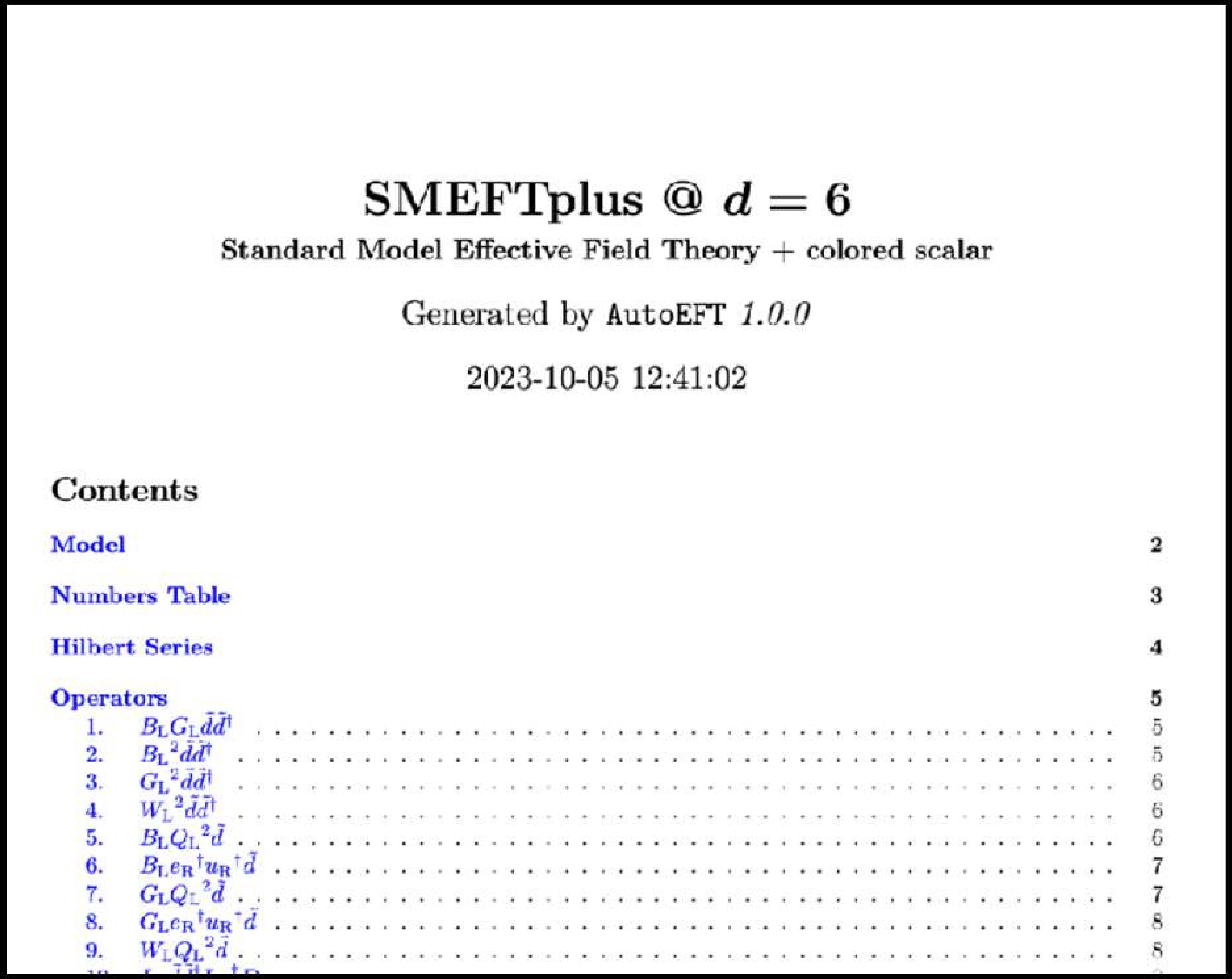
Robert V. Harlander, Magnus C. Schaaf

Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, 52056 Aachen, Germany

arXiv:... [hep-ph] 27 Sep 2023

Abstract

The program AutoEFT is described. It allows one to generate Effective Field Theories (EFTs) from a given set of fields and symmetries. Allowed fields include scalars, spinors, gauge bosons, and gravitons. The symmetries can be local or global Lie groups based on $U(1)$ and $SU(N)$. The mass dimension of the EFT is limited only


SMEFTplus @ $d = 6$

Standard Model Effective Field Theory + colored scalar

Generated by AutoEFT *1.0.0*

2023-10-05 12:41:02

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4. $W_L{}^2 \tilde{d}\tilde{d}^\dagger$	6
5. $B_L Q_L{}^2 \tilde{d}$	6
6. $B_L e_R{}^\dagger u_R{}^\dagger \tilde{d}$	7
7. $G_L Q_L{}^2 \tilde{d}$	7
8. $G_L e_R{}^\dagger u_R{}^\dagger \tilde{d}$	8
9. $W_L Q_L{}^2 \tilde{d}$	8

Beyond SMEFT: A proof of concept

The SM extended with X

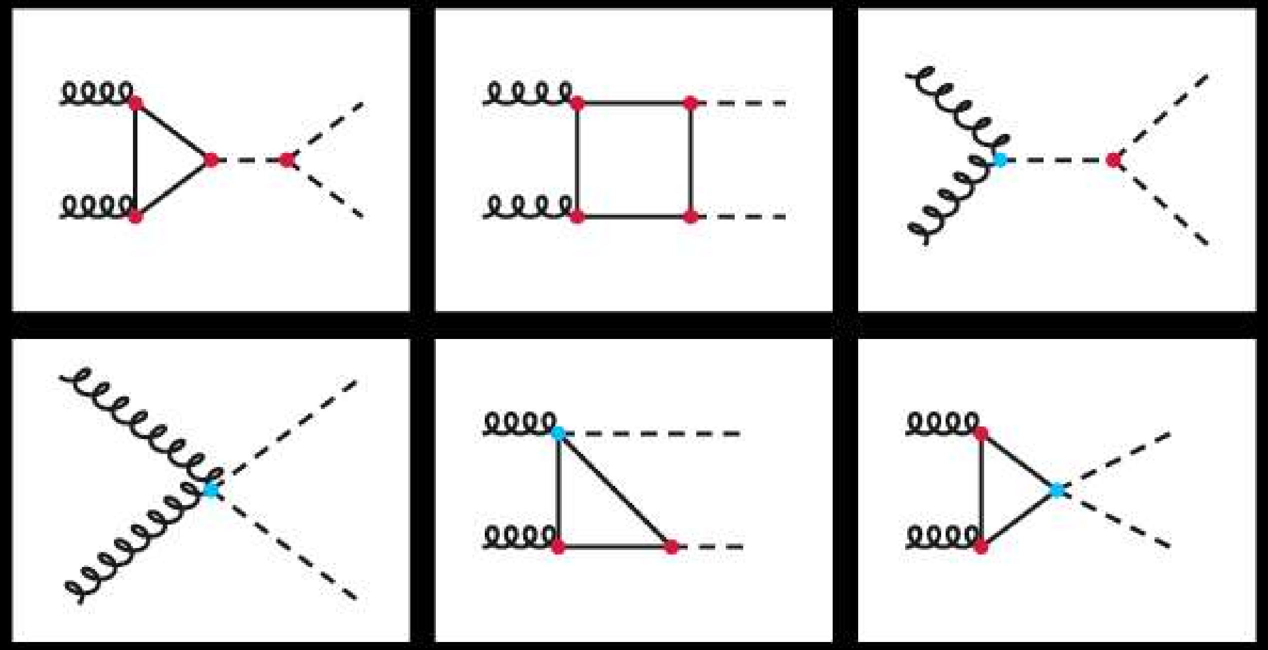
We start with colored scalar, one state. Could be second Higgs, vector boson, etc..

An EFT basis with dim 6 operators + light state

Selection of a subset of relevant operators, including SMEFT + new ones

FeyRules + Feynarts model file

Typically tricky but based on SMEFTsim, open source repository



NLO UFO model file

Borrows from simplified model approach
Thanks for making it open source!

Phenomenology study

ECM, Moretti, Enberg, Waltari … Ongoing work

Conclusions

Understanding the Higgs potential connects particle physics to cosmology.

Limits on Higgs couplings will be useful to understand the Electroweak Phase Transition.

EFTs are a good tool to study BSM (semi) agnostically

Linear EFT (SMEFT, not HEFT) approaches can be used even when some NP states are light

We are working on a proof of concept study for a useful semi-automated implementation


THANKS!