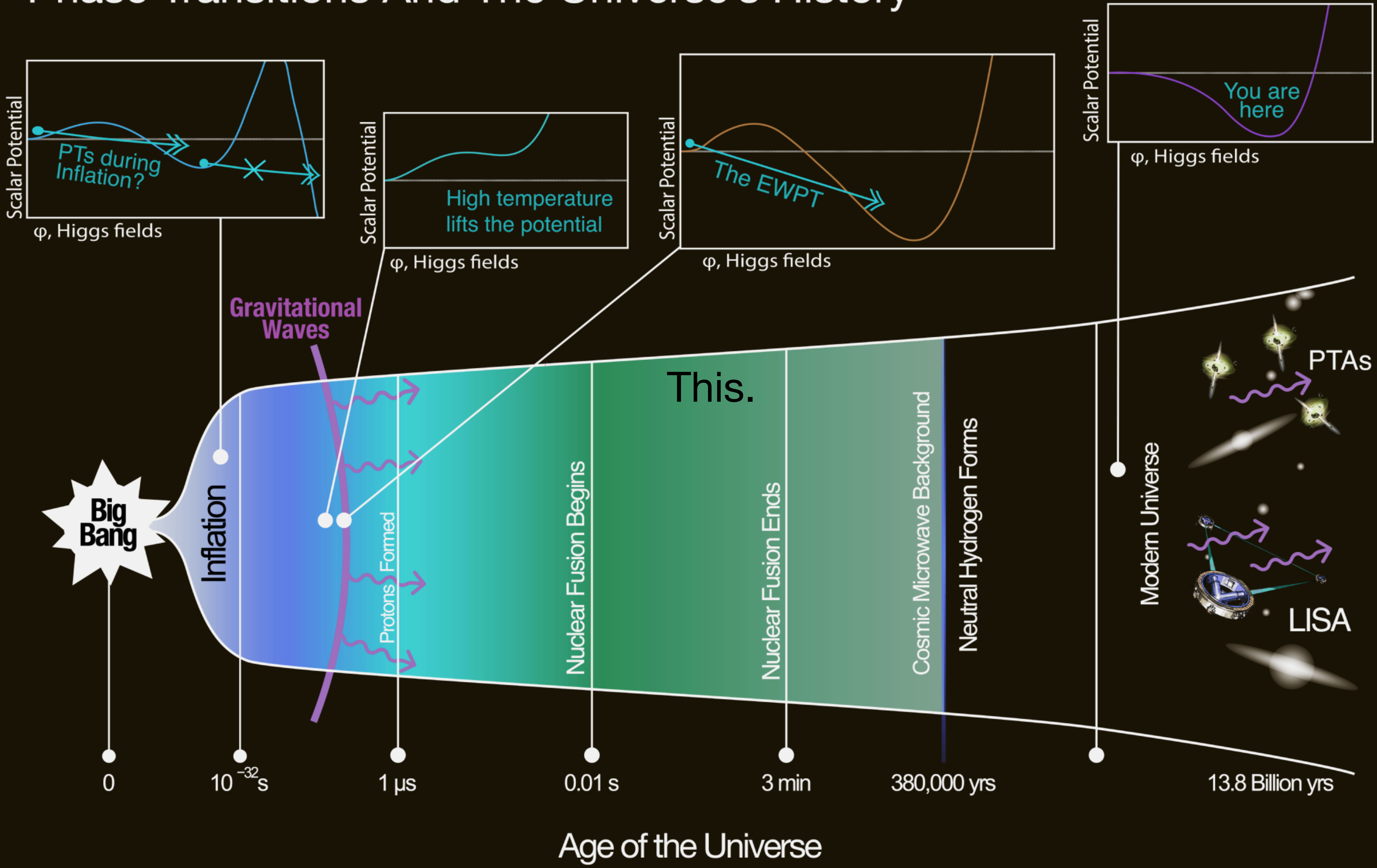
A map of First-Order Electroweak Phase Transitions in the SMEFT

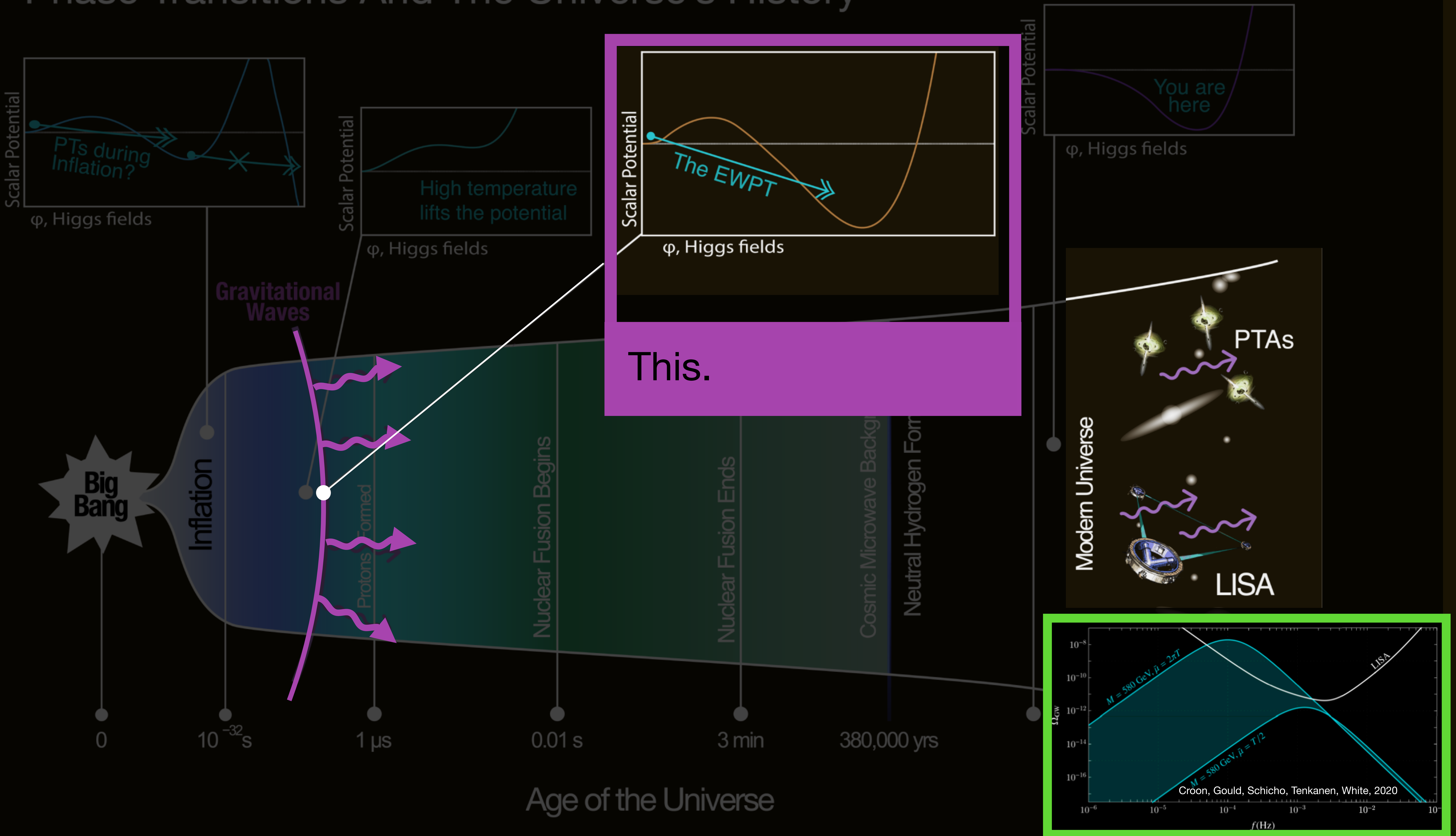
Eliel Camargo-Molina With Rikard Enberg and Johan Löfgren

Phase Transitions And The Universe's History



This.

Phase Transitions And The Universe's History



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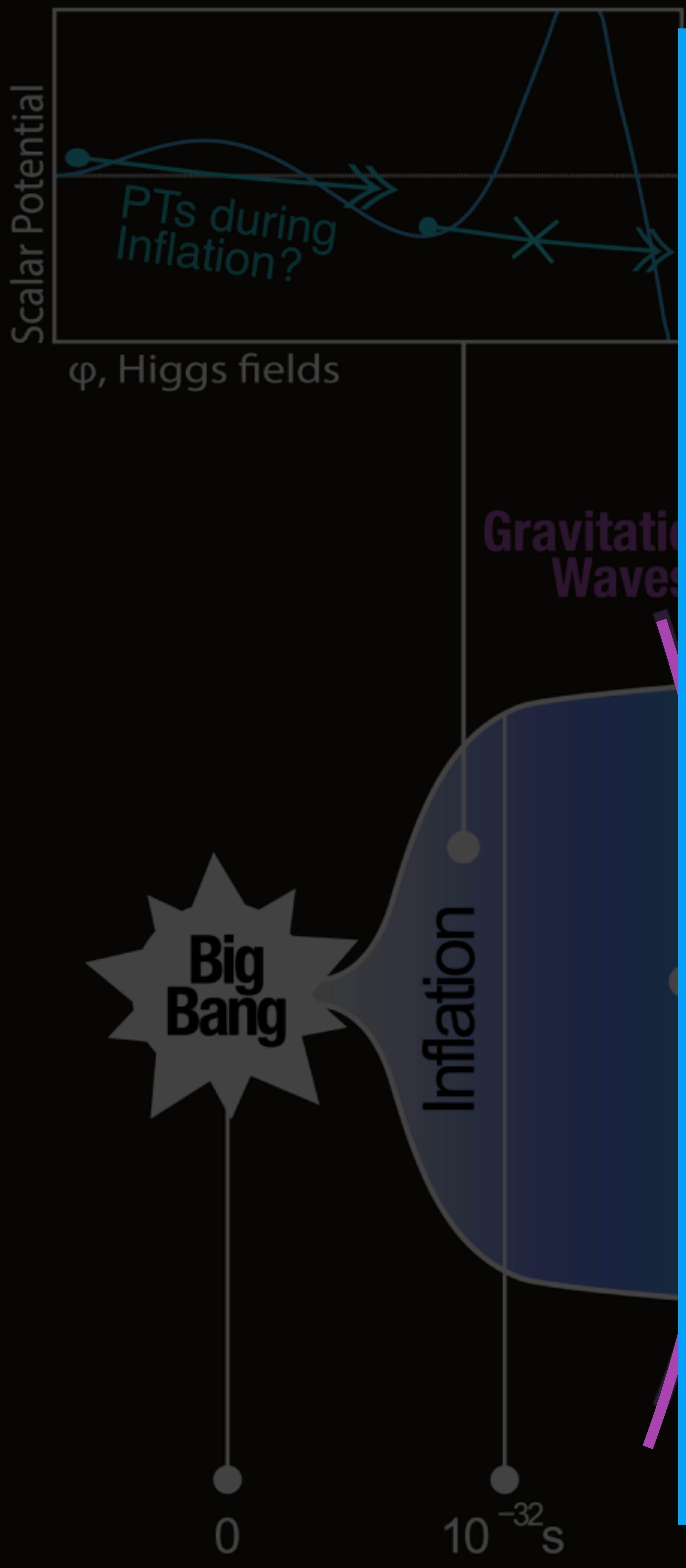
Croon, Gould, Schicho, Tenkanen, White, 2020

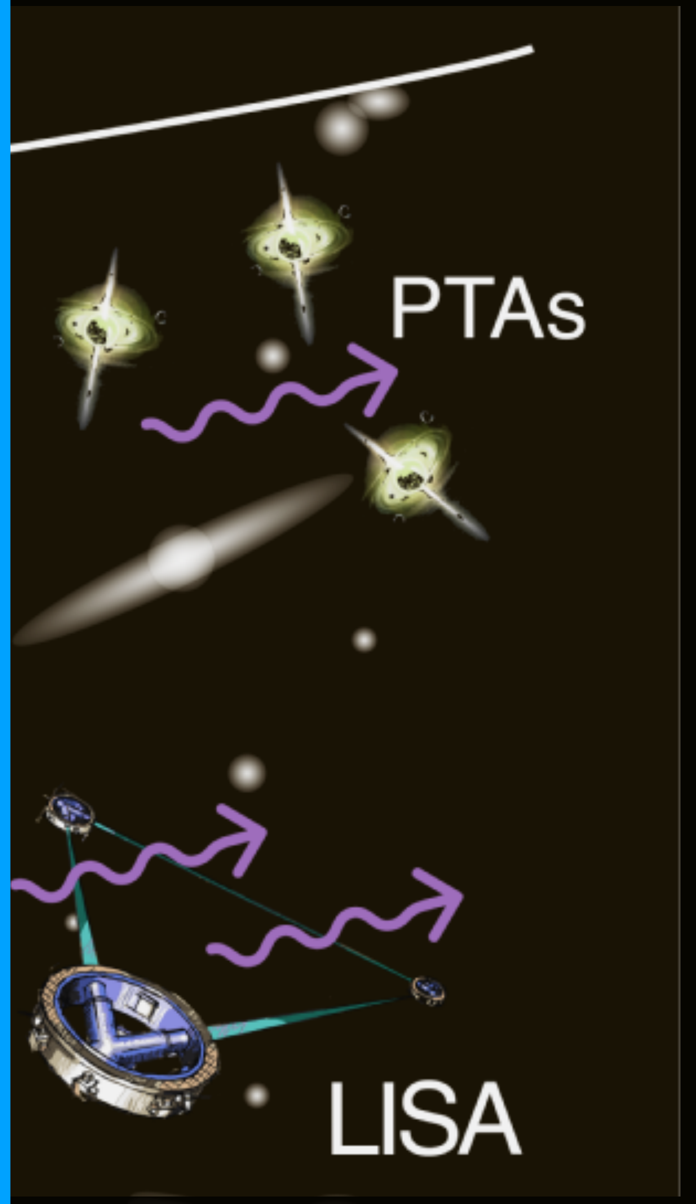
Phase Transitions And The Universe's History

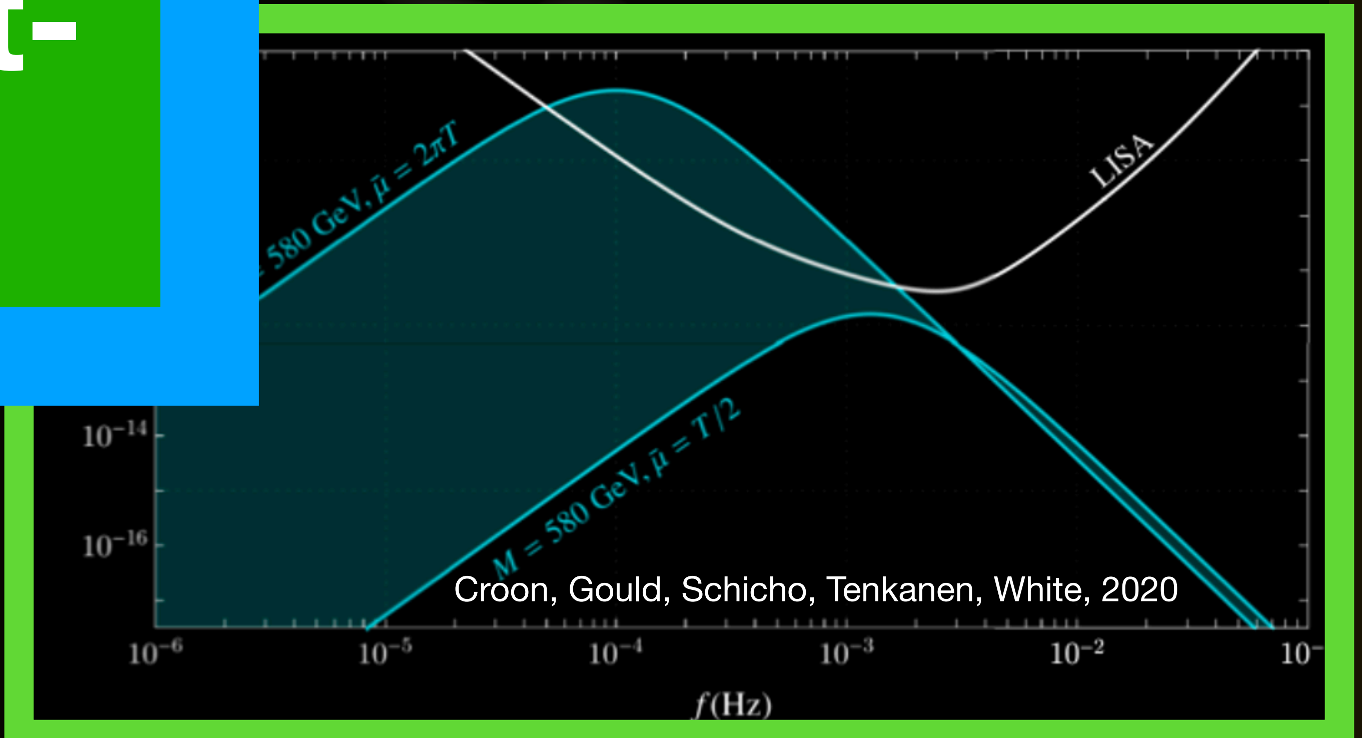
A first order (strong) phase transition is a key ingredient to explain matter-antimatter asymmetry

The Standard Model predicts a second order transition. So no Gravitational Waves.

Many BSM theories predict a first-order transition

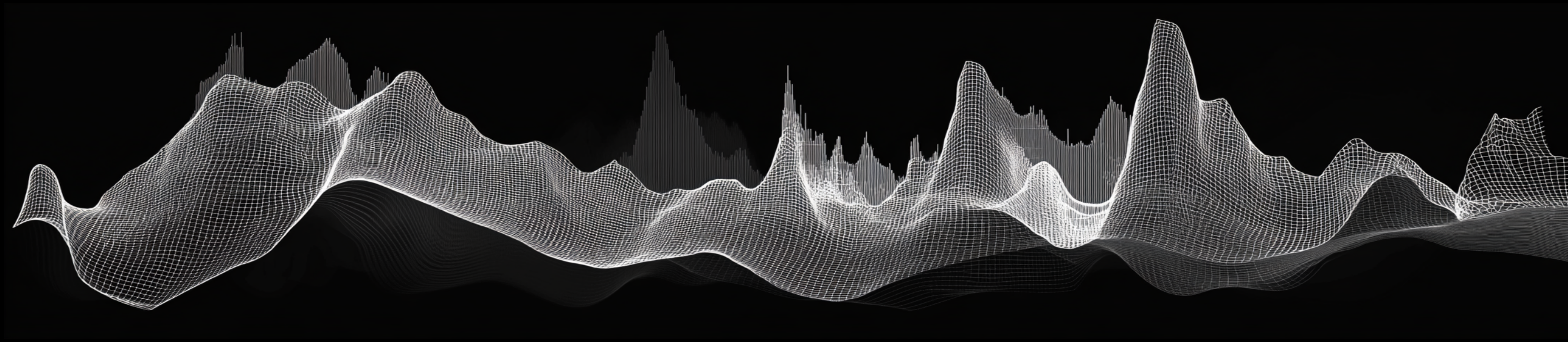






Croon, Gould, Schicho, Tenkanen, White, 2020

The Catalog



What we did:

A comprehensive catalog of potential **first-order EWPT** in the **SMEFT**, including checking for agreement with experimental data.

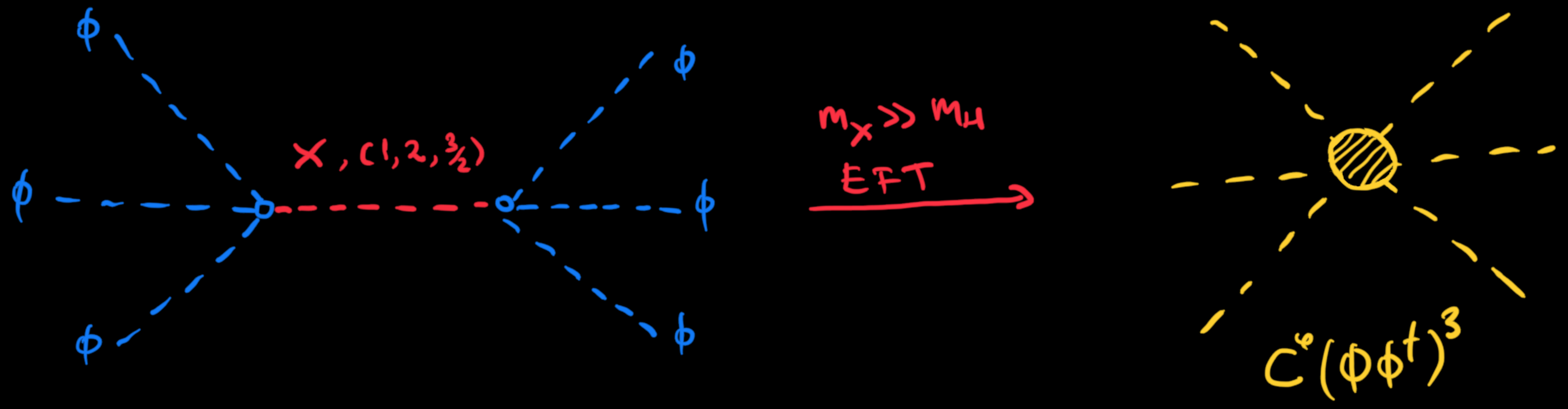
How:

Dimensional reduction + Power-counting techniques.

Why:

Systematically answers the question of whether new physics beyond TeV scale can impact the EWPT, which is typically not considered.
Offers preliminary insights into gravitational wave detection and electroweak baryogenesis possibilities.

The Standard Model Effective Field Theory



A consistent prescription to parametrize physics **at a higher scale.**

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

BSM effects

SM particles

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + C_5 O_5 + \sum_i \underset{\uparrow \, [GeV]^{-2}}{C_i} O_i + O\left(\frac{v^3}{\Lambda^3}\right)$$

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

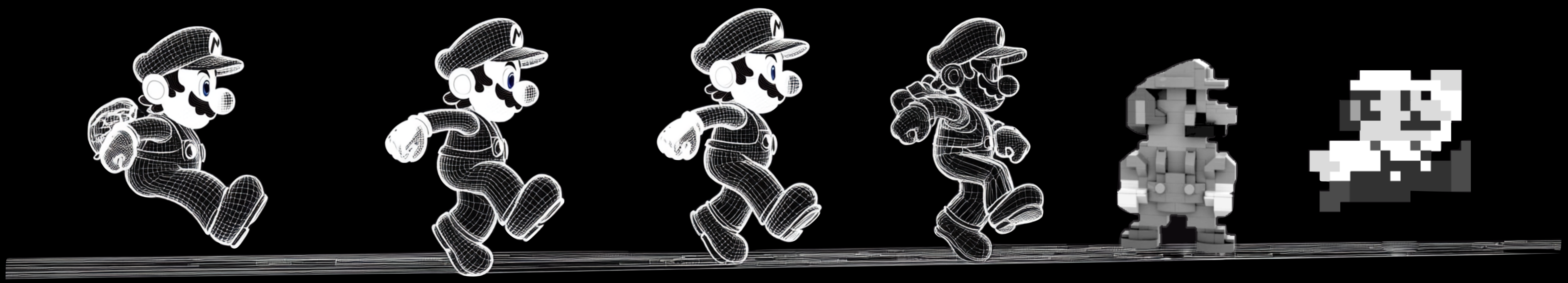
Higgs sector Operators

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

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

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

Dimensional Reduction



Field theory at finite temperature with finite Euclidean time interval $0 < \tau < \beta = \frac{1}{T}$ reduces to a 3D zero-temperature theory with infinitely many d.o.f. At large temperature most can be integrated out.

$$\phi(\tau, \mathbf{x}) = \sum_{n=-\infty}^{\infty} e^{i\omega_n \tau} \phi_n(\mathbf{x}),$$

$$\omega_n = 2n\pi T \;\; \text{(bosons)}, \quad \omega_n = (2n+1)\pi T \;\; \text{(fermions)}, \quad n \in \mathbb{Z}$$

$$M(T)^2 = (2\pi n T)^2 + m^2 \qquad M(T)^2 = ((2n+1)\pi T)^2 + m^2$$

Advantage:

Reduces gauge dependence and theoretical uncertainties in the description of phase transitions, **with a clearer more intuitive understanding of dynamics**

Dimensional Reduction

At non-zero temperature, different physics happens at different energies, there is a **separation of scales**

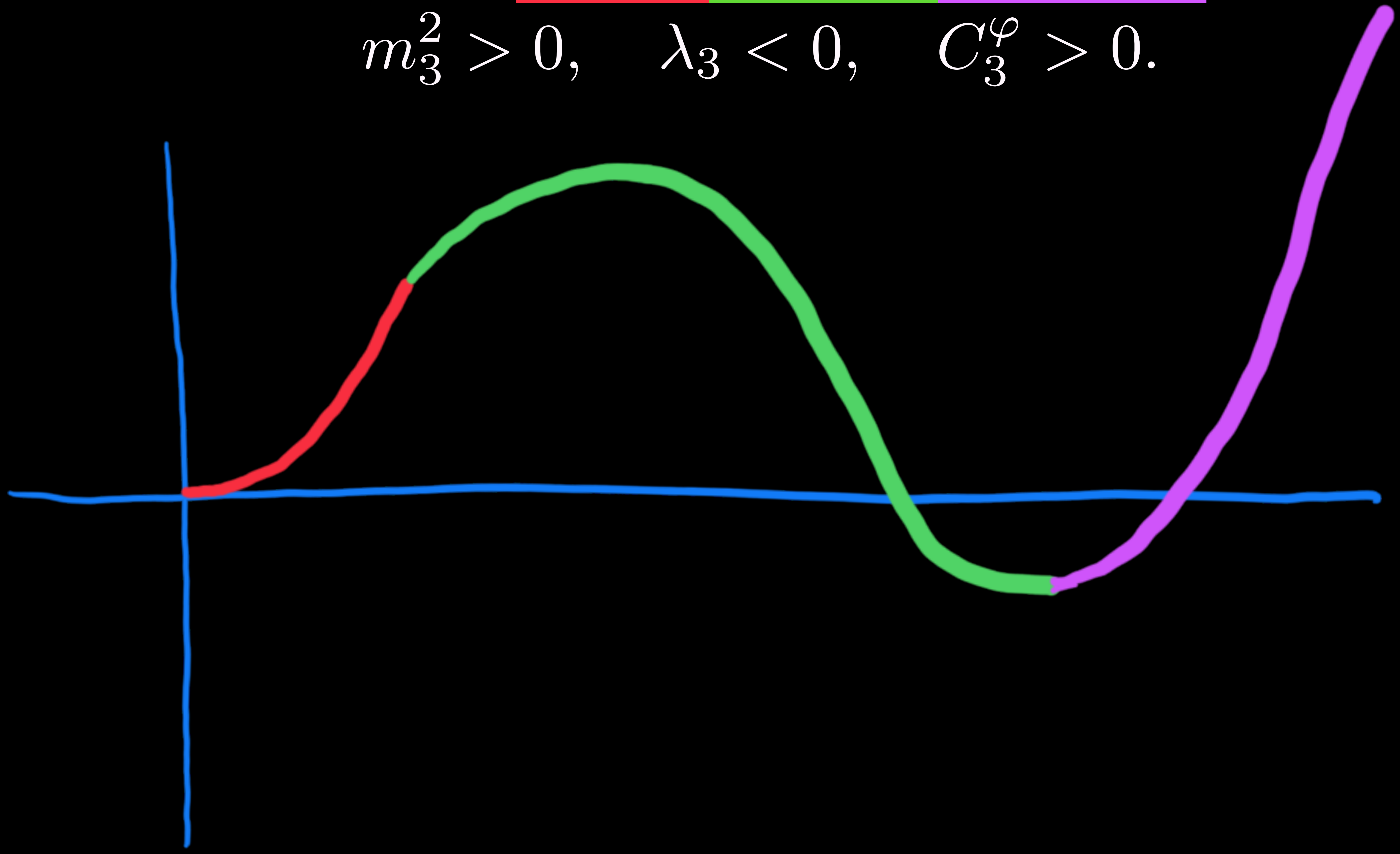
$$\underbrace{\underbrace{\pi T}_{\text{hard scale}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{\frac{1}{2}} \pi T}_{\text{semisoft scale}}}_{\textbf{Other stuff happens here}} \gg \underbrace{\underbrace{\left(\frac{g}{\pi}\right)^{1} \pi T}_{\text{soft scale}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{\frac{3}{2}} \pi T}_{\text{supersoft scale}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{2} \pi T}_{\text{ultrasoft scale}}}_{\textbf{EWPT happens in one of these}} \; .$$

Tree Level Barriers

(the simplest case)

$$V_3(\phi_3) = \boxed{\frac{m_3^2}{2}\phi_3^2} + \boxed{\frac{\lambda_3}{4}\phi_3^4} + \boxed{\frac{C_3^{\varphi}}{8}\phi_3^6},$$

$$m_3^2 > 0, \quad \lambda_3 < 0, \quad C_3^{\varphi} > 0.$$



Studied in detail in literature

For it to happen, C’s needs to be large

Puts into question that the new physics is at a higher scale in the first place

$$\underbrace{\pi T}_{\text{hard scale}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{\frac{1}{2}}\pi T}_{\text{semisoft scale}} \gg \underbrace{\underbrace{\left(\frac{g}{\pi}\right)^{1}\pi T}_{\text{soft scale}}}_{\textbf{PT dynamics}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{\frac{3}{2}}\pi T}_{\text{supersoft scale}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{2}\pi T}_{\text{ultrasoft scale}} .$$

Radiative Barriers

(the SM-like case)

$$V_3(\phi_3) = \boxed{\frac{m_3^2}{2}\phi_3^2}\boxed{-\frac{g_3^3}{16\pi}\phi_3^3}\boxed{+\frac{\lambda_3}{4}\phi_3^4,}$$

$$m_3^2 > 0, \quad \lambda_3 > 0.$$

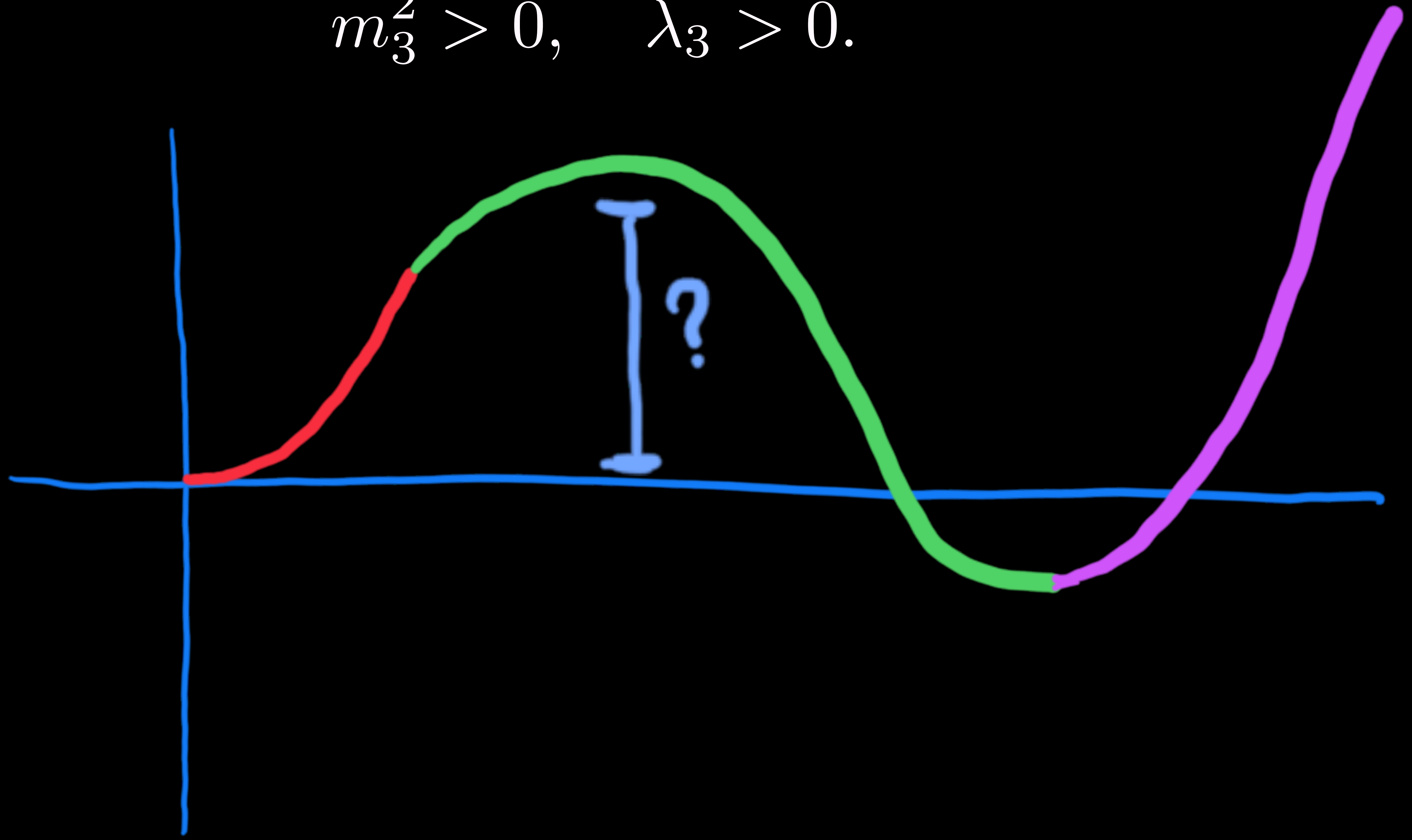
No barrier at tree-level

Loop contributions from gauge bosons are large enough to create a barrier

Just as in the SM, but WC's contribute significantly to the Higgs mass

We studied this in

arXiv:2103.14022
[ECM, Enberg, Löfgren]



$$\underbrace{\pi T}_{\text{hard scale}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{\frac{1}{2}}\pi T}_{\text{semisoft scale}} \gg \underbrace{\underbrace{\left(\frac{g}{\pi}\right)^{1}\pi T}_{\text{soft scale}}}_{\textbf{Gauge bosons}} \gg \underbrace{\underbrace{\left(\frac{g}{\pi}\right)^{\frac{3}{2}}\pi T}_{\text{supersoft scale}}}_{\textbf{Higgs}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{2}\pi T}_{\text{ultrasoft scale}} .$$

Radiative Symmetry Breaking

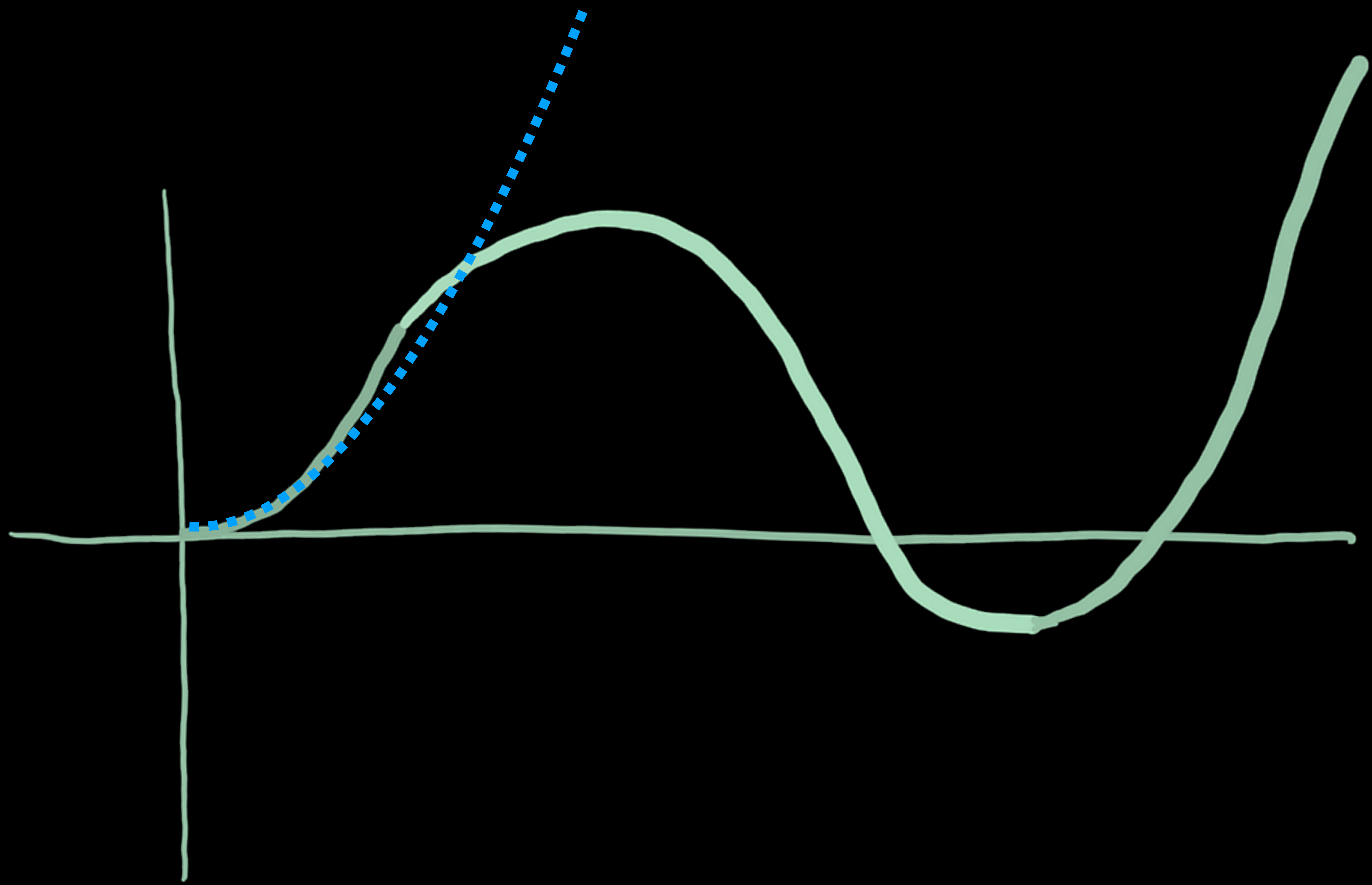
(the wildcard)

Also known as the Coleman-Weinberg mechanism

Here the potential starts totally symmetric

Loop corrections break the symmetry and generate the wall

Gauge bosons don’t fulfill the high-temperature limit as they are too heavy



$$\underbrace{\underbrace{\pi T}_{\text{hard scale}}}_{\textbf{Gauge bosons}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{\frac{1}{2}} \pi T}_{\text{semisoft scale}} \gg \underbrace{\underbrace{\left(\frac{g}{\pi}\right)^{1} \pi T}_{\text{soft scale}}}_{\textbf{Higgs}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{\frac{3}{2}} \pi T}_{\text{supersoft scale}} \gg \underbrace{\left(\frac{g}{\pi}\right)^{2} \pi T}_{\text{ultrasoft scale}} .$$

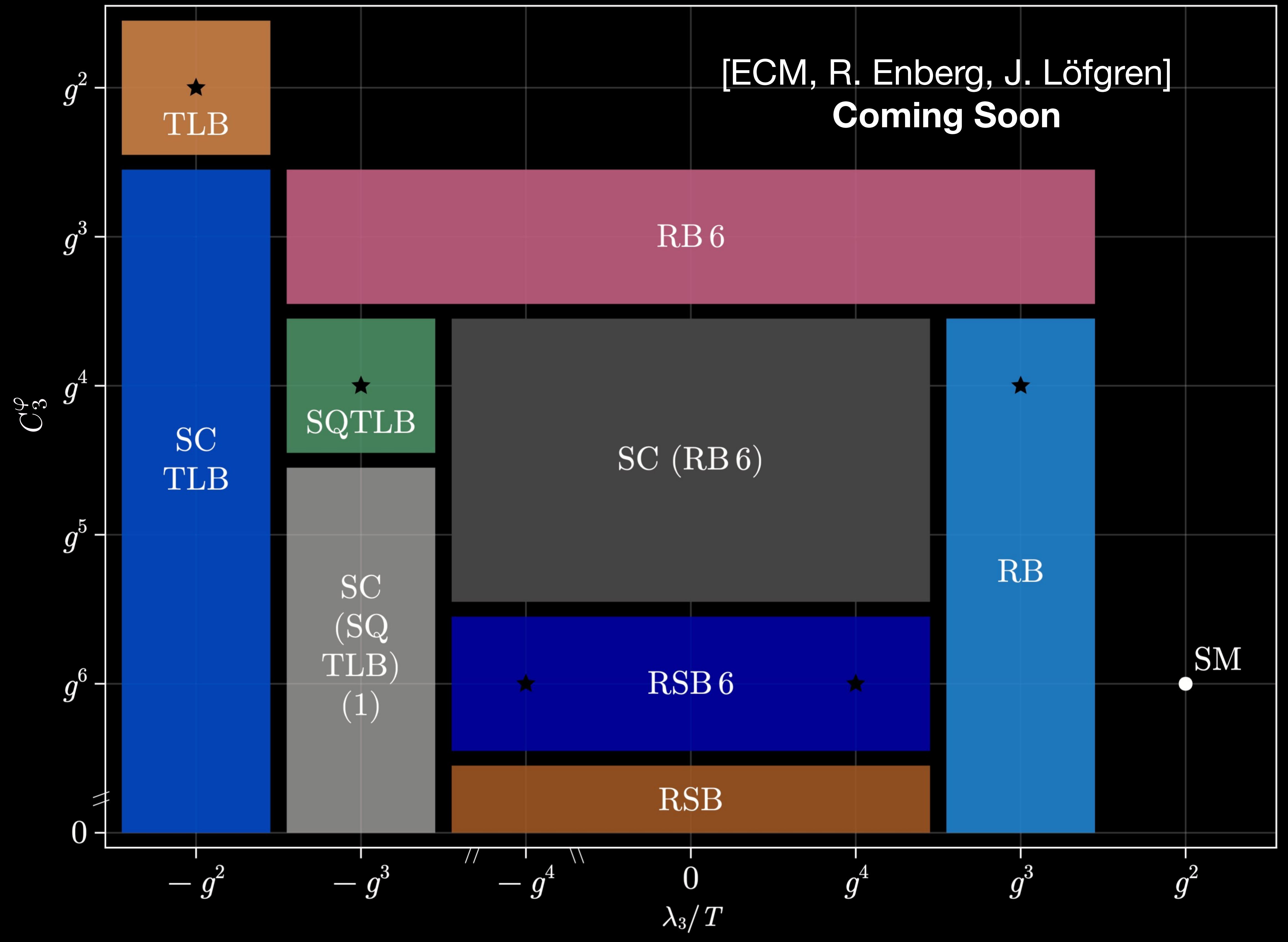
Supercooled Barriers

(the wilder wildcard)

All the options also come with a supercooled variant

Supercooling happens when the nucleation rate is so low that the system stays in the false vacuum “longer than it should”

Physically that means that the PT happens at a much lower temperature than “expected”



[ECM, R. Enberg, J. Löfgren]
Coming Soon

Shorthand	Meaning of acronym	Scale of Higgs dynamics
TLB	tree-level barrier	soft
SQTLB	small quartic TLB	soft
RB	radiative barrier	supersoft
RSB	radiative symmetry breaking	soft
RB 6	RB with dimension-six term ϕ_3^6	supersoft
RSB 6	RSB with dimension-six term ϕ_3^6	soft
SC	supercooled variant	

Ok, but can they really happen?

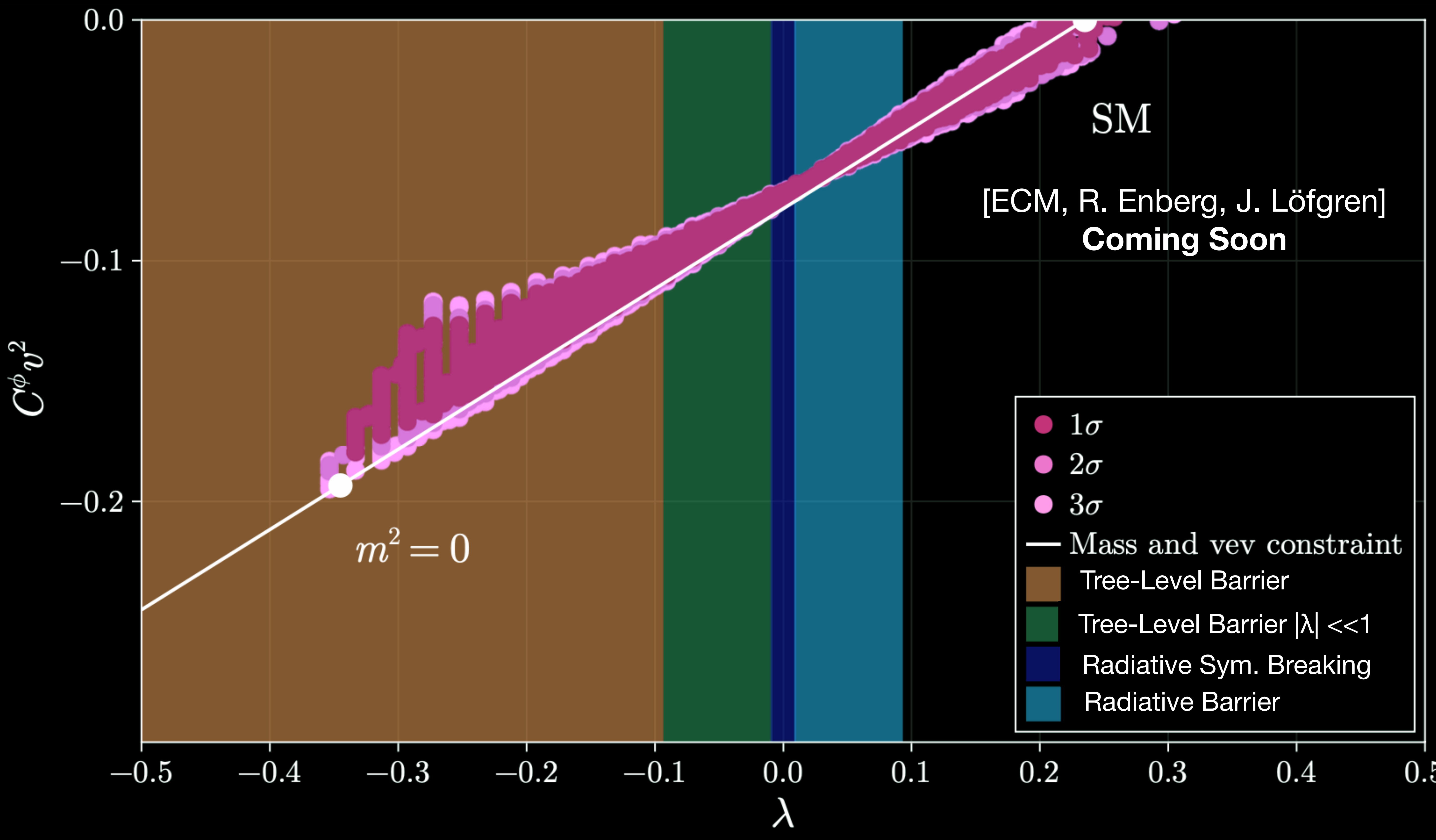
We used Smelli* to get a global Likelihood

We used the soon-to-be-released **lightweight-genetic-algorithm*** package to scan it

We found “good” 4D points that where in agreement with experimental results

We mapped those results to power countings and our 3D results

We can overlay the first-order EWPT scenarios



[ECM, R. Enberg, J. Löfgren]
Coming Soon

*[J. Aebischer, J. Kumar, P. Stangl, and D. M. Straub]

***[ECM, J. Wessén]**

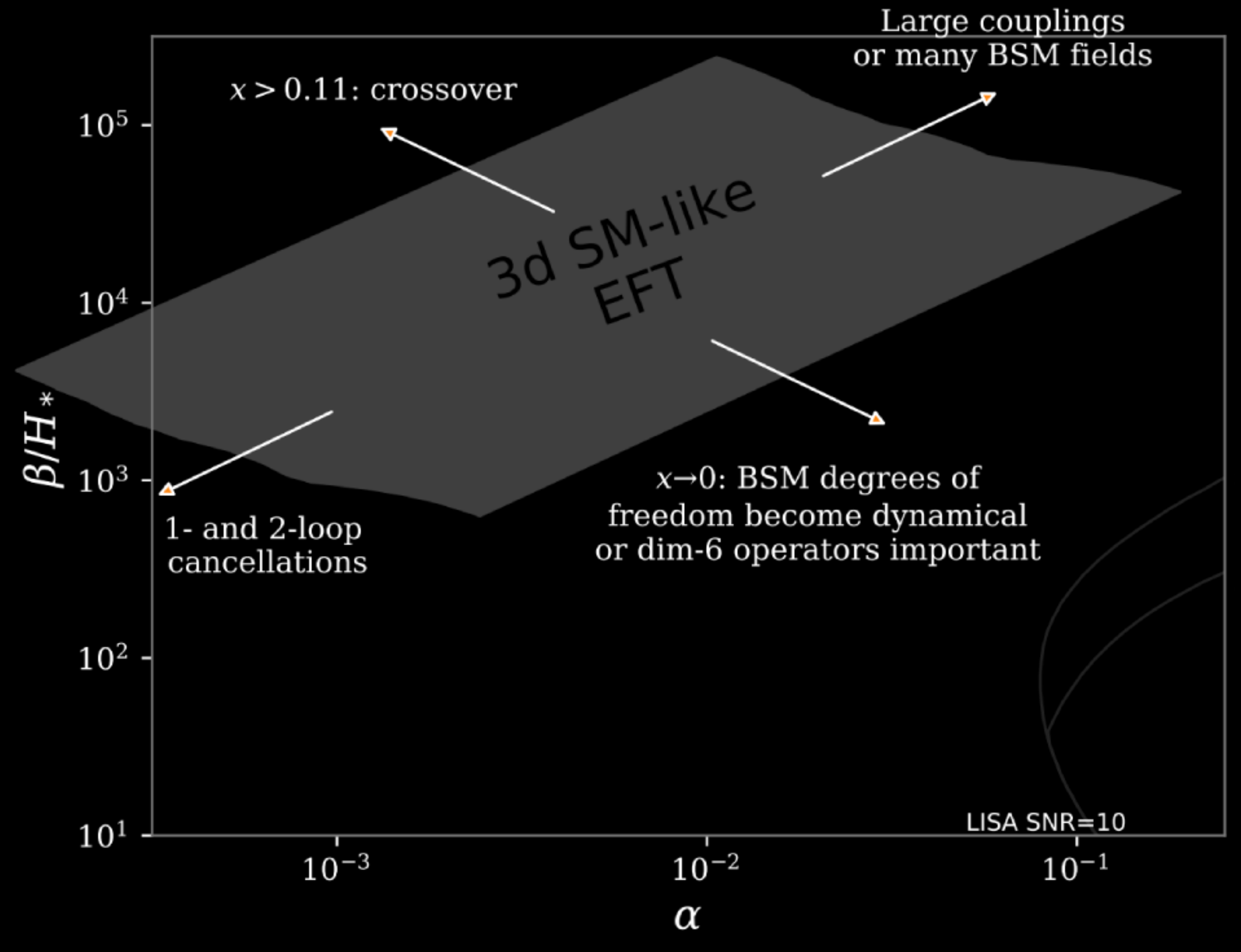
Gravitational Waves

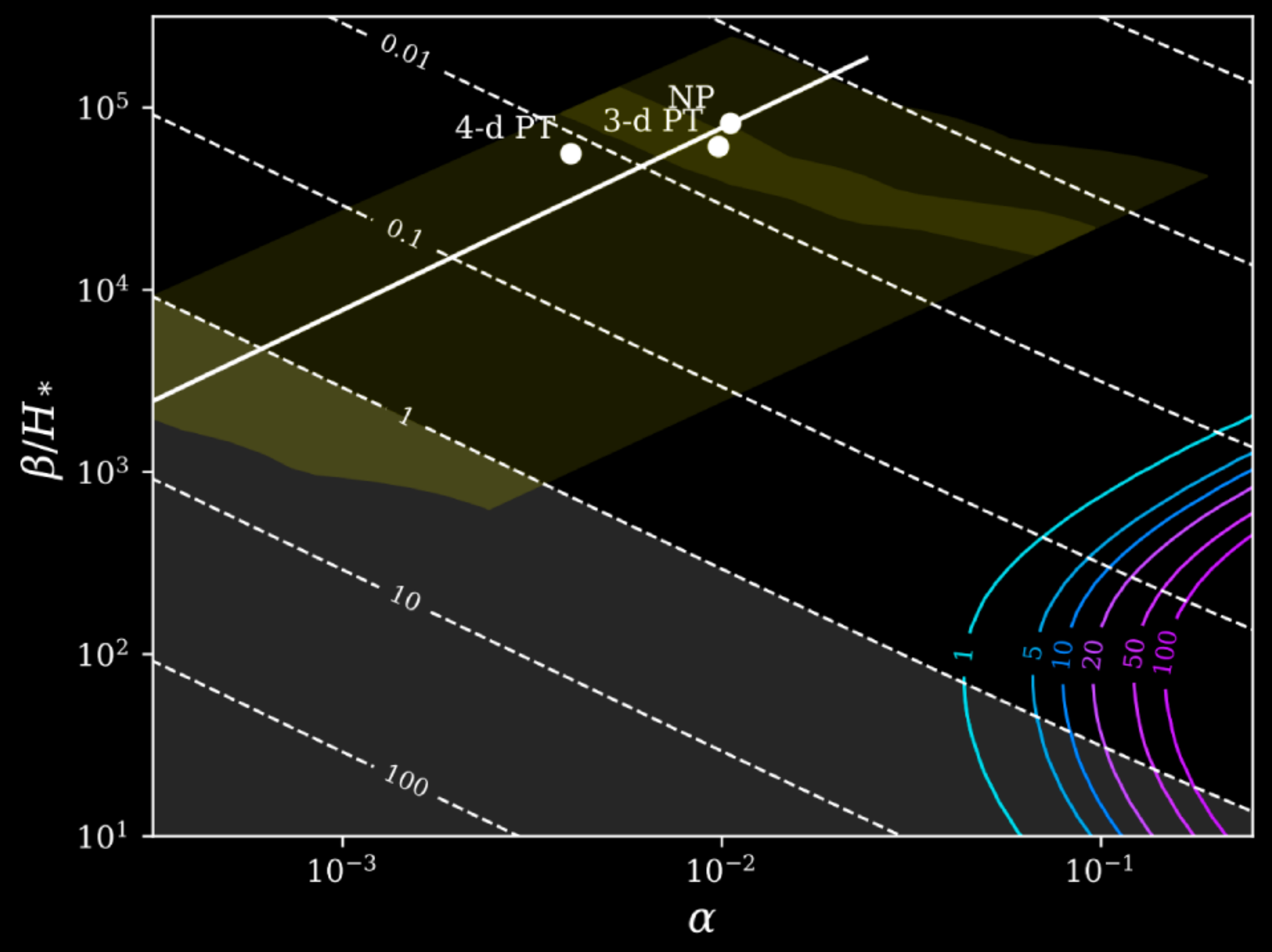
Large latent heat and long phase transitions have the best chance to land on LISA’s eyes.

The usual message is that LISA can’t see GW from a “heavy-physics” first-order EWPT.

But we can estimate this.

We find one promising case the SQTLB.





[1903.11604] Gould et al.

Hierarchy	Shorthand	$\alpha/\alpha_{\rm RB}$	$\beta/H \Big/ (\beta/H)_{\rm RB}$	$-\log\Gamma_{\rm sph}$
$m_3 \sim M \ll \pi T$	TLB	1	$g^{\frac{3}{2}}$	g^{-1}
	SC TLB (1)	1	$g^{\frac{3}{2}}$	g^{-1}
	SC TLB (2)	g^1	g^1	$g^{-\frac{1}{2}}$
$m_3 \ll M \ll \pi T$	SQTLB	g^{-1}	$g^{\frac{1}{2}}$	$g^{-\frac{3}{2}}$
	SC SQTLB (1)	g^{-1}	$g^{\frac{1}{2}}$	$g^{-\frac{3}{2}}$
	SC SQTLB (2)	1	$g^{\frac{1}{4}}$	$g^{-\frac{5}{4}}$
	RB	1	1	g^{-1}
	RB 6	1	1	g^{-1}
	SC RB	g	$g^{\frac{1}{4}}$	$g^{-\frac{1}{2}}$
	SC RSB	g	g	g^{-1}
$m_3 \ll M \sim \pi T$	RSB	g^{-2}	$g^{-\frac{1}{2}}$	—
	RSB 6	g^{-2}	$g^{-\frac{1}{2}}$	—

[ECM, R. Enberg, J. Löfgren]
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