First-order electroweak phase transition in the SMEFT

Rikard Enberg, Uppsala University

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Work with

Eliel Camargo-Molina, Safa Helal, Johan Löfgren, Carlo Tasillo

2103.14022 and 2410.23210, plus forthcoming paper(s)

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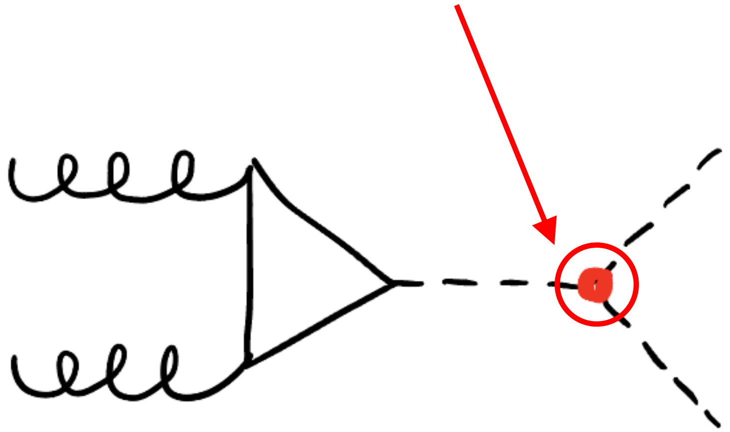
Probing the Higgs potential

$$V_{\rm SM} = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{8}\phi^4$$

Triple Higgs self-coupling



How to test?

- Higgs pair production
- Electroweak phase transition

BSM physics will often affect the Higgs self-coupling and the scalar potential

- New physics can be ***light:*** new bosons at colliders
- Or ***heavy:*** no new visible particles → (bottom up) EFTs → SMEFT

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Standard Model Effective Field Theory (SMEFT)

Effective field theory with SM symmetries and fields:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{\text{dim } 6} \frac{C^i}{\Lambda^2} Q_i$$

Need to define a basis for the operators – the Warsaw basis
[Grzadkowski et al (2010)]

At dim 6 with B&L conservation: 59 operators

In the Higgs sector:

$$\begin{aligned} Q_H &= (H^\dagger H)^3, \\ Q_{H\Box} &= (H^\dagger H)\Box(H^\dagger H), \\ Q_{HD} &= (H^\dagger D_\mu H)^*(H^\dagger D^\mu H) \end{aligned}$$

Looking for possible first order phase transitions

First order PTs are abrupt with energy released in bubbles

The bubbles expand, collide, create sound waves, turbulence

- The bubble dynamics may generate observable ***gravitational waves*** (with space-based expts like LISA)
- Non-perturbative dynamics at the bubble walls may lead to ***electroweak baryogenesis***

We are going to look at gravitational waves – we consider the sound wave contribution and neglect bubbles and turbulence

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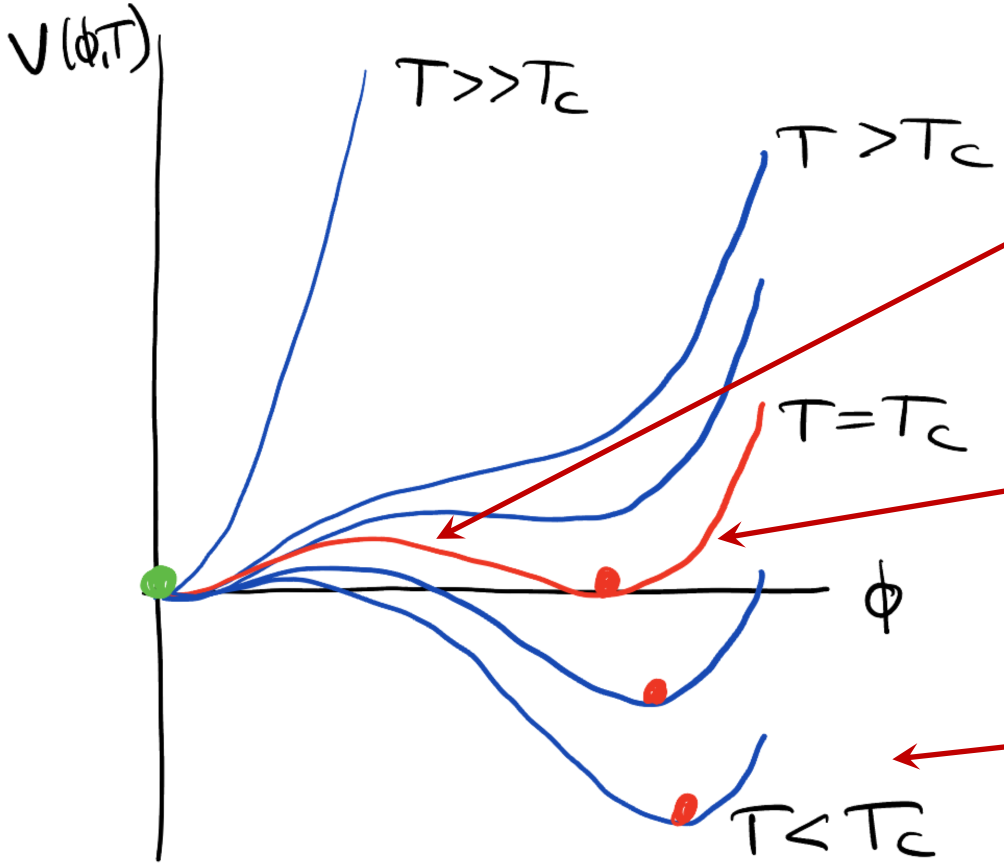
Energy density = effective potential

The effective potential $V_{eff}(\phi, T)$ determines the ground state of the theory

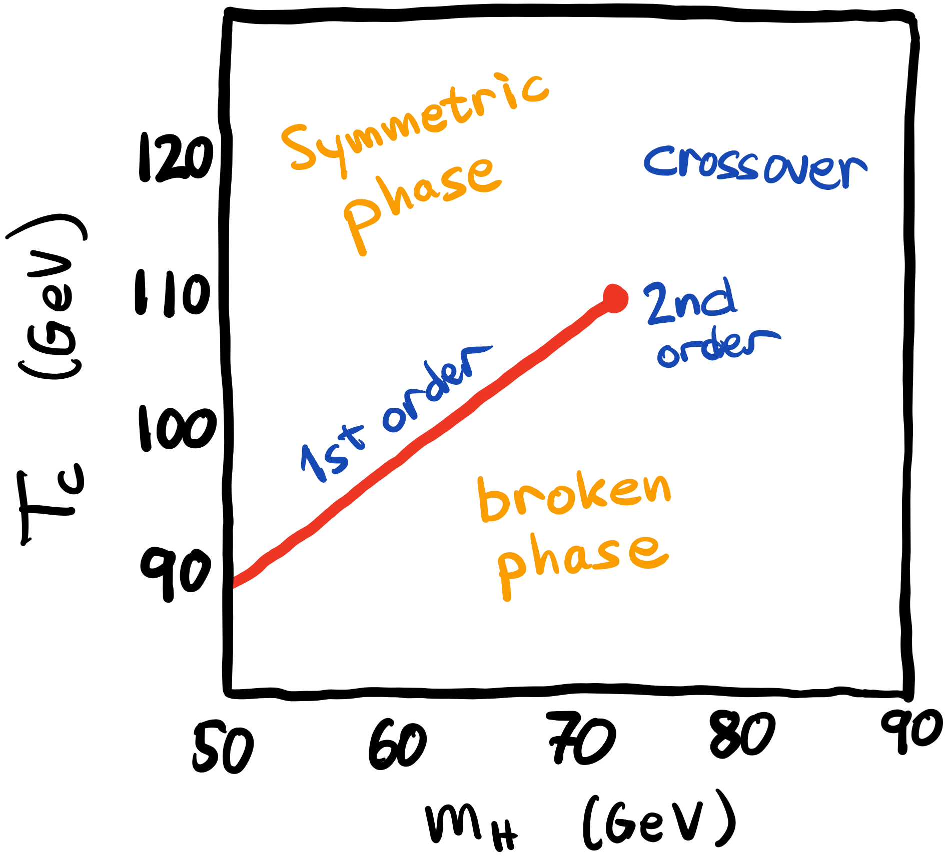


A ***barrier*** is needed for first order transition

Critical temperature, degenerate minimum

Below Tc, a lower minimum exists — bubbles can nucleate and percolate

Electroweak phase diagram of the SM



Plot adapted from Kajantie, Laine Rummukainen, Shaposhnikov (1996 and 1998)

Critical point at
$m_H = m_{Hc} = 72$ GeV
$T = T_c = 109$ GeV

A first order phase transition is only possible if $m_H < 72$ GeV
– in the SM universe, it was a smooth crossover transition

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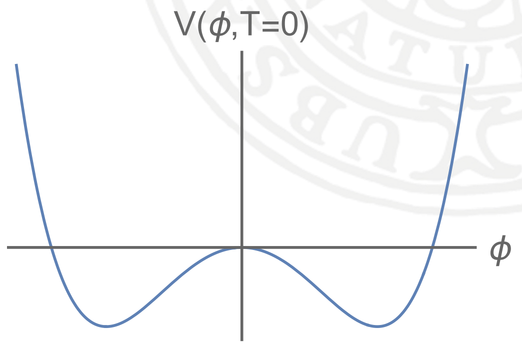
So how do you get a barrier in the SM?

There is no barrier at T=0 so it must be created radiatively:



$$V_0(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{8}\phi^4$$

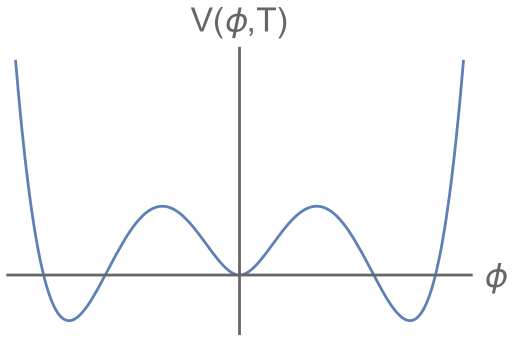
Gauge boson contributions at high T give a cubic term:

$$V_{\rm LO}(\phi) = -\frac{1}{2}\mu_{\rm eff}^2(T)\phi^2 - e^3\frac{T}{12\pi}\phi^3 + \frac{\lambda}{8}\phi^4$$

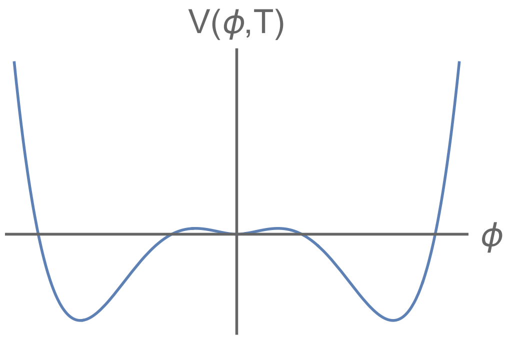
$$\mu_{\rm eff}^2(T) = \mu^2 - \alpha T^2/12$$

$$e^3 = \frac{1}{2}g^3 + \frac{1}{4}(g^2 + g'^2)^{3/2}$$

…but is it large enough to give a substantial barrier?



or



?

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Why does m_H determine the barrier?

To have a large barrier, the cubic term must be about the same size as the other terms:

$$V_{\rm LO}(\phi) = -\frac{1}{2}\mu^2_{\rm eff}(T)\phi^2 - e^3\frac{T}{12\pi}\phi^3 + \frac{\lambda}{8}\phi^4$$

Power counting (Arnold and Espinosa): **we need scaling $\lambda \sim e^3$**, not satisified in the SM: λ is much too large

The Higgs mass is given by $m_H^2 = 2\lambda v^2$:
Thus we need smaller λ and smaller m_H for a 1st order transition

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Use higher dimension operators to do this

- **EWPT with dim-6 operator ϕ^6** – Grojean, Servant, Wells (2004); more recently e.g. Croon et al (2020), Postma & White (2020), Chala et al (2025)
- λ<0 to get barrier at tree-level with ϕ^6 term providing the Mexican Hat
- Requires a rather small cutoff scale

Our take:

I. **Instead consider λ>0 as in SM *but small*.**
Makes FOEWPT possible with correct Higgs mass, because we can get the right Higgs mass from dim-6 operators *(arXiv:2103.14022)*

II. **Catalog all options for barriers that give a FOEWPT in the SMEFT**
Use power counting and 3D EFT for proper calculation, connect to 4D phenomenology *(arXiv:2410.23210)*

III. **Compute detailed gravitational wave properties in 3D and 4D**

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Phase transition in the SMEFT

SMEFT at T=0:

$$V_0(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{8}\phi^4 - \frac{1}{8}\frac{C^H}{\Lambda^2}\phi^6$$

It turns out we can get a radiatively generated barrier like in the SM but for smaller λ with correct Higgs mass because

$$m_h^2 = \lambda v^2 - \left(3C^H - 2\lambda C^{H\Box} + \frac{\lambda}{2}C^{HD}\right)\frac{v^4}{\Lambda^2}$$

Power counting shows that dim-6 term is subleading at the phase transition → can use the same EWPT calculation as in the SM but for smaller λ!

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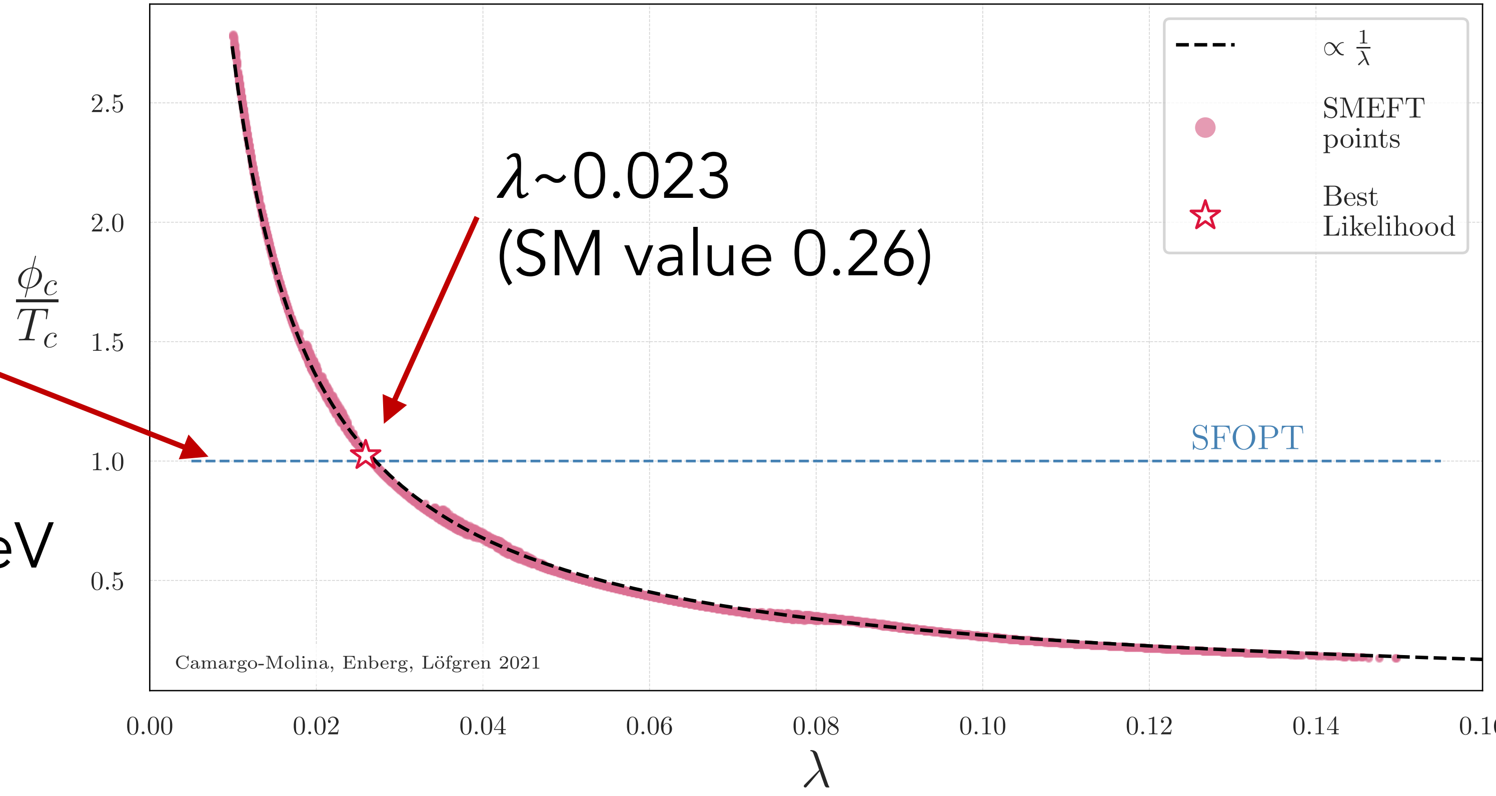
Parameter scan

For small λ we can get a strong 1st order PT

These points have m_H=125 GeV and satisfy all constraints

(The roughly 1/ λ dependence comes from the power counting in the potential)

λ~0.023
(SM value 0.26)



Camargo-Molina, RE, Löfgren, JHEP 10 (2021) 127, arXiv:2103.14022

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But maybe there are more possibilities

- The previous work was done at leading order following the gauge-invariant method of Ekstedt & Löfgren [2006.12614]
- But there are well-known problems with the EWPT calculation:
  - gauge dependence
  - renormalization scale dependence
  - IR divergences
  - perturbative breakdown at high T
  - …
- Basic problem: need to treat perturbation theory right
- Modern idea: don't just resum, use (top-down) EFT

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How to compute?

Stop comparing resummation methods

Johan Löfgren

I argue that the consistency of any resummation method can be established if the method follows a power counting derived from a hierarchy of scales. I.e., whether it encodes a top-down effective field theory. This resolves much confusion over which resummation method to use once an approximation scheme is settled on. And if no hierarchy of scales exists, you should be wary about resumming. I give evidence from the study of phase transitions in thermal field theory, where adopting a consistent power-counting scheme and performing a strict perturbative expansion dissolves many common problems of such studies: gauge dependence, strong renormalization scale dependence, the Goldstone boson catastrophe, IR divergences, imaginary potentials, mirages (illusory barriers), perturbative breakdown, and linear terms.

Johan Löfgren [2301.05197]

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How to compute?

Dimensionally reduced 3D EFT can agree quite well with lattice, and is gauge invariant, if the perturbative expansion is strictly done

– and if there’s a hierarchy of separated scales with the Higgs at an intermediate softer (”supersoft”) scale, above the non-pert scale

Important demonstration in triplet extension example:
Gould & Tenkanen [2309.01672]

See also e.g:

Gould et al [1903.11604]
Ekstedt and Löfgren [2006.12614]
Croon et al [2009.10080]
Ekstedt [2104.11804]
Gould and Hirvonen [2108.04377]
Löfgren et al [2112.05472]
Hirvonen et al [2112.08912]
Ekstedt [2205.05145]
Hirvonen [2205.02687]
Ekstedt, Gould and Löfgren [2205.0724]
Löfgren [2301.05197]
Kierkla et al [2312.12413]

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3D EFT for thermal transitions

- Dimensional reduction: Integrate out non-zero Matsubara modes
- Get Euclidean 3D EFT at "soft scale" with only bosons, and potential

$$V_3(\phi_3) = \frac{1}{2} m_3^2\, \phi_3^2 + \frac{1}{4} \lambda_3\, \phi_3^4 + \frac{1}{6} C_3^H\, \phi_3^6$$

- Wilson coefficients from matching to full theory – contain T-dependence
  Automated by **DRalgo** [Ekstedt, Schicho, Tenkanen 2205.08815]
- Additional ϕ_3^3 term from integrating out gauge bosons
  if the scale hierarchies allow it ($m_H \ll m_{gauge}$) [Gould & Hirvonen 2108.04377]
- This potential determines the properties of phase transitions
- Follow phase as T changes – coefficients depend on 4D parameters

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Scales

$$\underbrace{\pi T}_{\text{hard scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{\frac{1}{2}} \pi T}_{\text{semisoft scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{1} \pi T}_{\text{soft scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{\frac{3}{2}} \pi T}_{\text{supersoft scale}} \gg \underbrace{\left(\frac{g}{4\pi}\right)^{2} \pi T}_{\text{ultrasoft scale}}$$

Non-perturbative

Dimensional reduction

Tree-level barrier: Higgs is here

Radiatively generated barrier: Higgs is here (cancellation in mass between thermal and tree-level contributions)

Catalog of SMEFT phase transitions

Characterize phase transitions with different scale hierarchies in 3D:

- Barriers (tree-level or radiative), or radiative symmetry breaking (CW)
- Supercooled transitions

This must be related to the physical parameters of the 4D theory

➔ Scan parameter space, matching 3D ⟷ 4D

➔ Evaluate prospects for first order transitions

➔ Global fit using EW precision, which scenarios allowed or excluded

➔ Estimate gravitational wave and baryogenesis prospects

Example of power counting & scale hierarchies

3D EFT at "supersoft" scale: $V_{LO} = \frac{1}{2} m_3^2 \phi_3^2 - \frac{1}{8\pi} g_3^3 \phi_3^3 + \frac{1}{4} \lambda_3 \phi_3^4 + \frac{1}{6} C_3^H \phi_3^6$

Scaling:
$$\begin{cases} m_3^2 \sim g^{n_m} T^2 \\ \lambda_3 \sim g^{n_\lambda} T \\ \phi_3 \sim g^{n_\phi} \sqrt{T} \\ C_3^H \sim g^{n_c} \\ g_3 \sim g\sqrt{T} \end{cases}$$

Taking all terms to be important for the barrier, and take perturbativity into account:

$$\begin{cases} n_m = 3 + n_\phi \\ n_\lambda = 3 - n_\phi \\ n_c = 3 - 3n_\phi \end{cases}$$

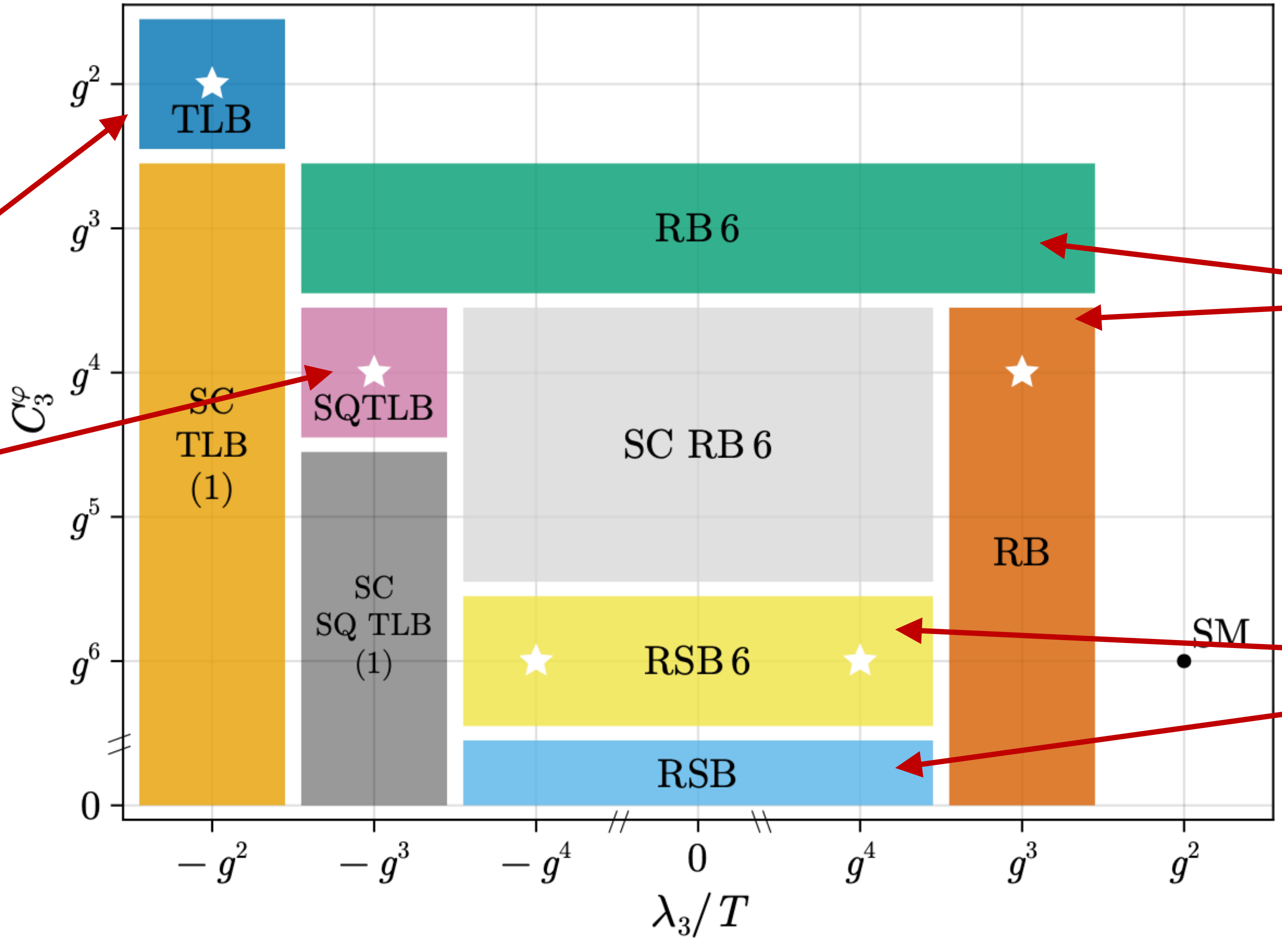
$$\Rightarrow -1 < n_\phi < 1$$

Thus, for a radiative barrier:

$$\begin{cases} m_3^2 \sim g^3 T^2 \\ \lambda_3 \sim g^3 T \\ \phi_3 \sim \sqrt{T} \\ C_3^H \sim g^3 \end{cases}$$

Power counting, schematically

White stars = we can get the correct Higgs mass



TLB=Tree-level barrier

RB=Radiative barrier

RSB=Radiative symmetry breaking (Coleman-Weinberg)

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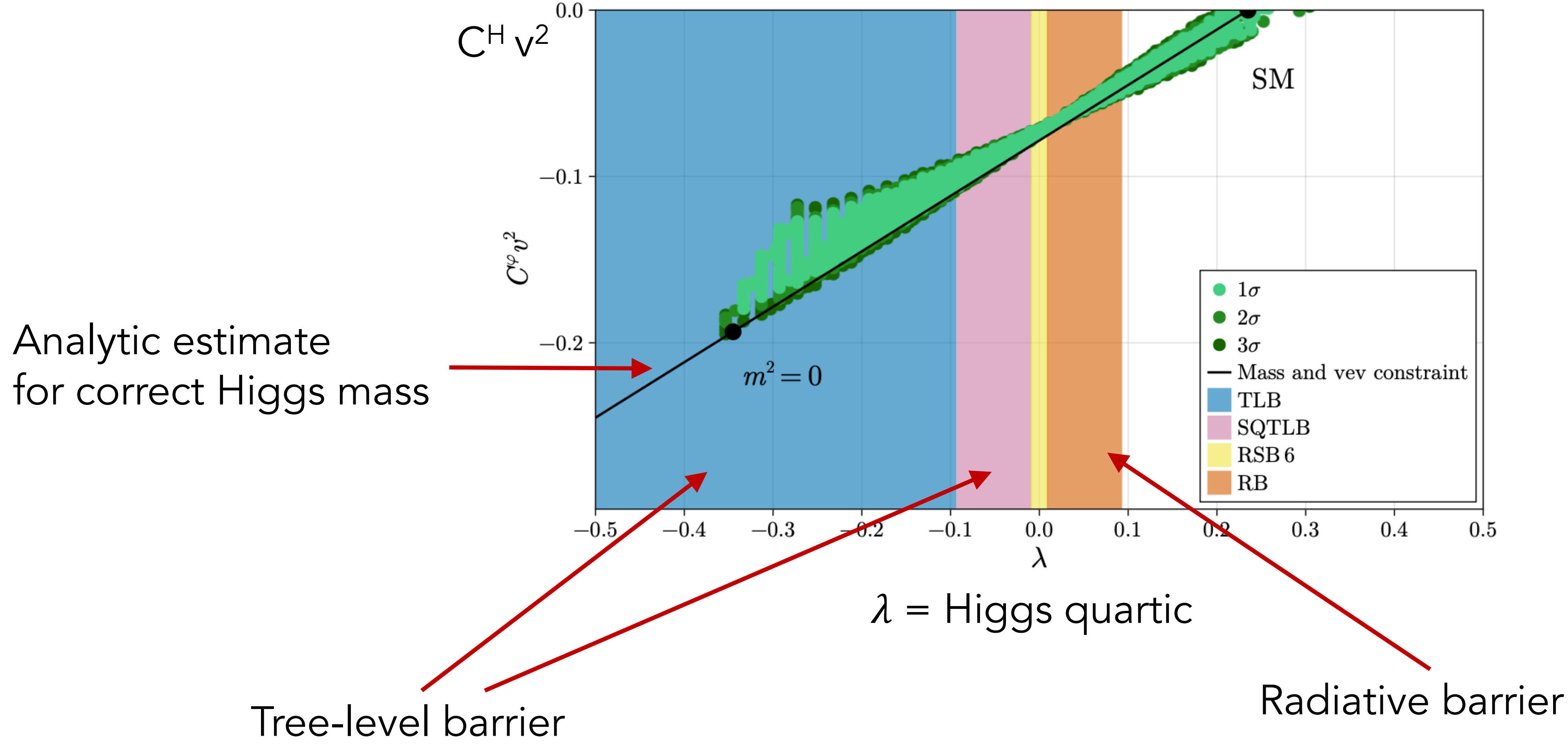
[E. Camargo-Molina, RE, J. Löfgren, arXiv:2410.23210]

Parameter space:

Scanned with genetic algorithm: satisfy particle physics constraints on SMEFT (using smelli) and correct Higgs mass



λ = Higgs quartic

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[E. Camargo-Molina, RE, J. Löfgren, arXiv:2410.23210]

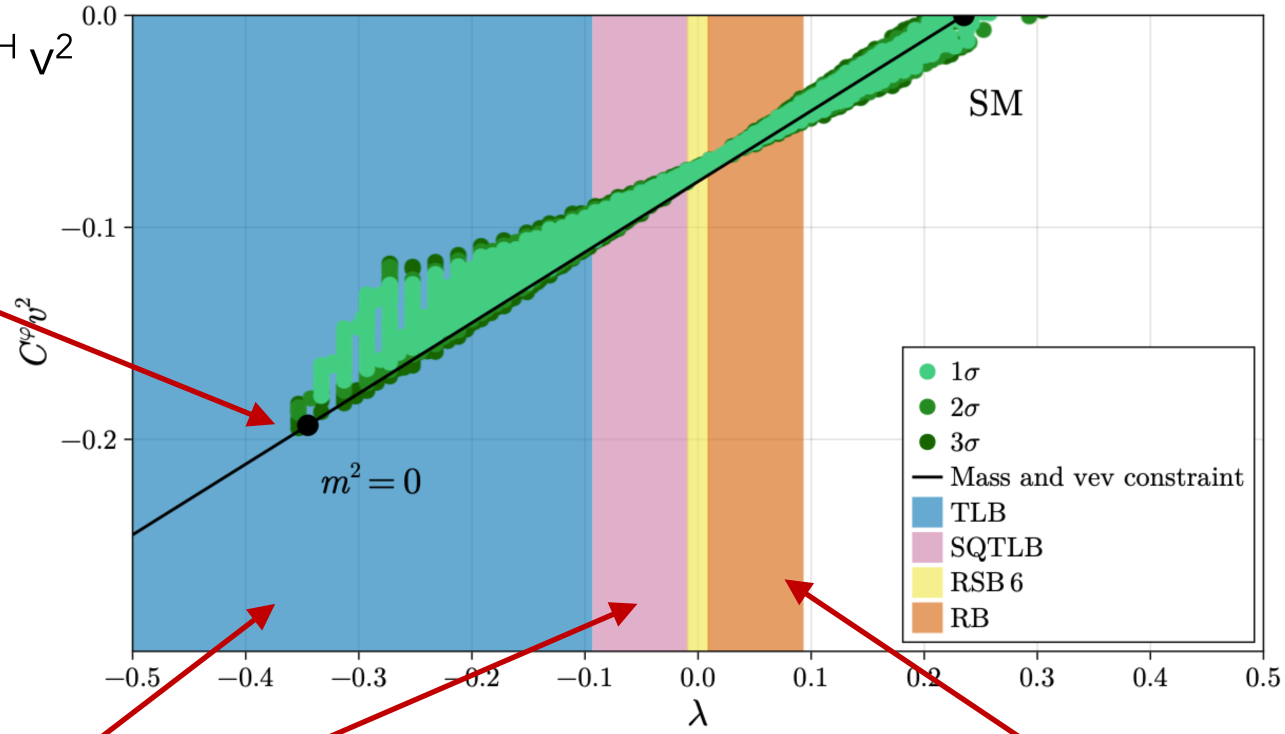
Parameter space:

Scanned with genetic algorithm: satisfy particle physics constraints on SMEFT (using smelli) and correct Higgs mass

Fun fact:
"Effectively conformal" parameter point here: $m^2=0$ so the SMEFT cutoff Λ is the *only* dimensionful scale

However, this point does not have radiative symmetry breaking

$C^H v^2$



λ = Higgs quartic

Tree-level barrier

Radiative barrier

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[E. Camargo-Molina, RE, J. Löfgren, arXiv:2410.23210]

Calculation in 4D

- We want to compare 3D EFT calculations with "ordinary" 4D
- We have done this for the parameter points just shown – using standard methods (one-loop CW, daisy resummation) [with Carlo Tasillo and Safa Helal]
- Additionally: compute gravitational wave properties using the public code ***TransitionListener 2.0*** (soon to be released) by Jonas Matuszak and Carlo Tasillo

Reliable computation of the GW spectra for strong supercooling?

There's currently no public code that can deal with strong supercooling!

The available codes are specific to the Electroweak symmetry breaking

Available codes are specialized on specific sub-tasks like phase tracing, the bounce action, the bubble nucleation rate, …

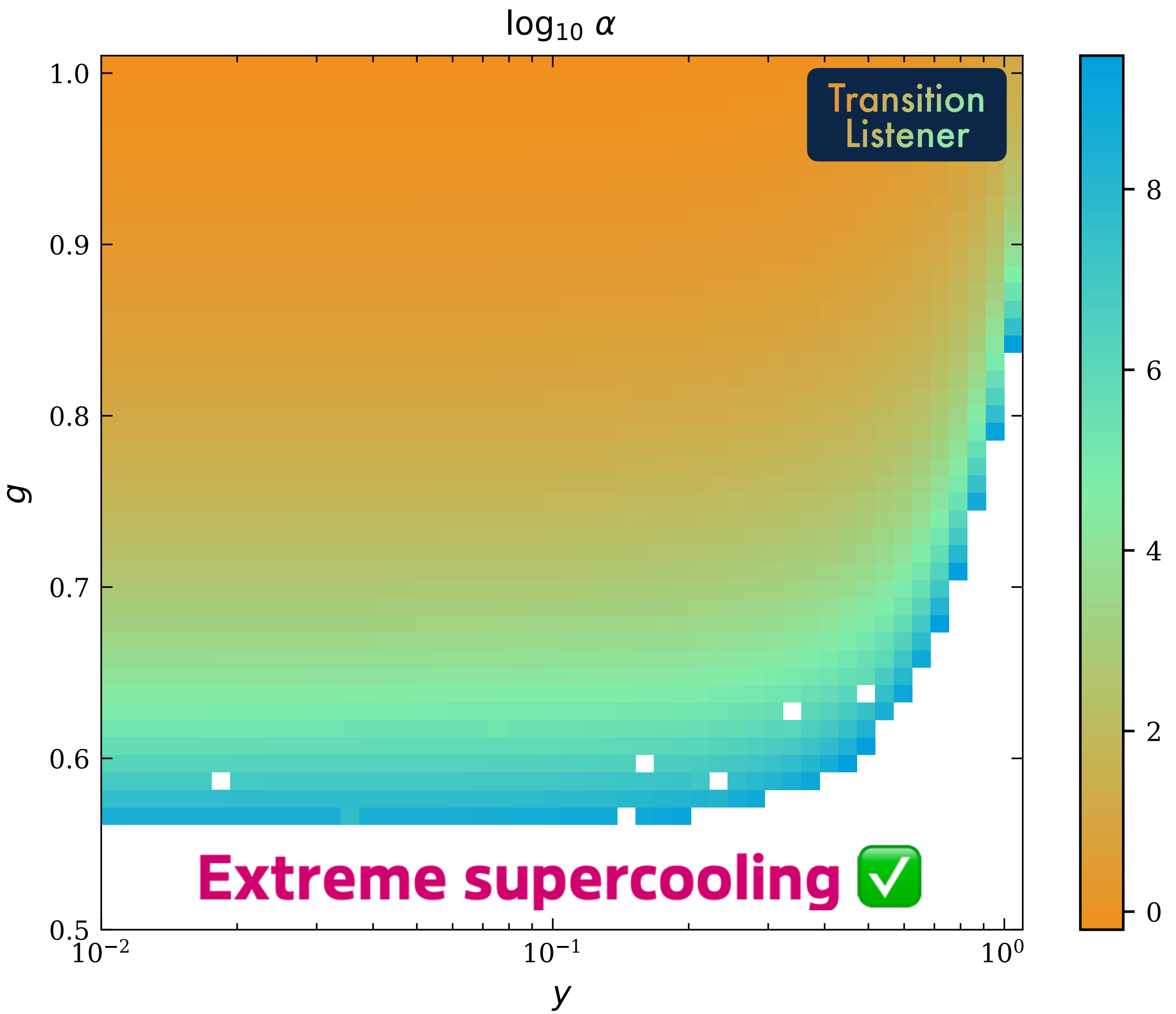
They are not integrated into the ecosystem of global fits, i.e. GAMBIT

Transition Listener 2.0

[Ongoing work Jonas Matuszak]

Slide from Carlo Tasillo

Slide from Carlo Tasillo



- $T_{\rm perc}$
- $T_{\rm reh}$
- $v_{\rm wall}$
- Documentation
- Warnings & error handling
- Quicker than BSMPT
- User-friendly
- Not just EWSB
- PTA likelihoods
- Written in python
- SNR for LISA, ET, ...
- Integration into GAMBIT

See 2502.19478 by Tasillo et al and the talk by Jonas Matuszak in parallel session tomorrow

Abundance and peak frequency of GWs
(contribution from sound waves)

$$h^2\Omega_{\rm GW} \propto \left(\frac{\alpha}{\alpha+1}\right)^2 \left(\frac{\beta}{H}\right)^{-1} \times s\left(\frac{f}{f_{\rm peak}}\right)$$

$$f_{\rm peak} \simeq 0.01\ \text{mHz} \left(\frac{\beta}{H}\right)\left(\frac{T}{100\ \text{GeV}}\right)$$

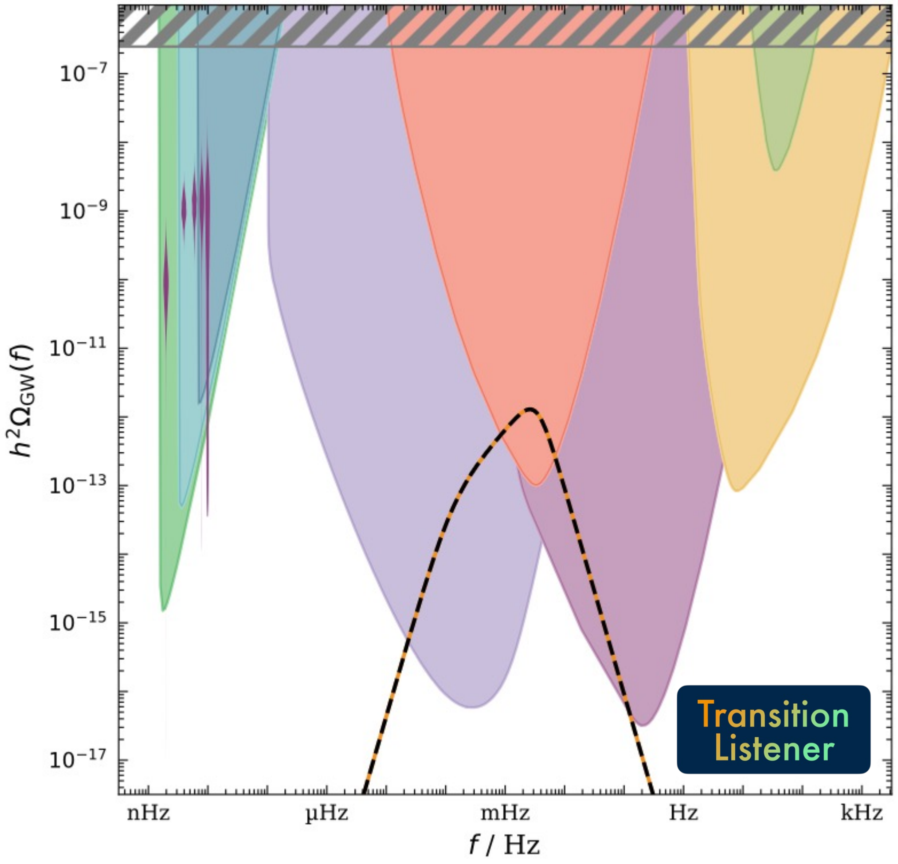
α = strength of phase transition

(proportional to latent heat)

β = inverse duration, or speed, of phase transition

(from T-dependence of nucleation rate)

H = Hubble parameter at phase transition



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(Fig shows one of our results)

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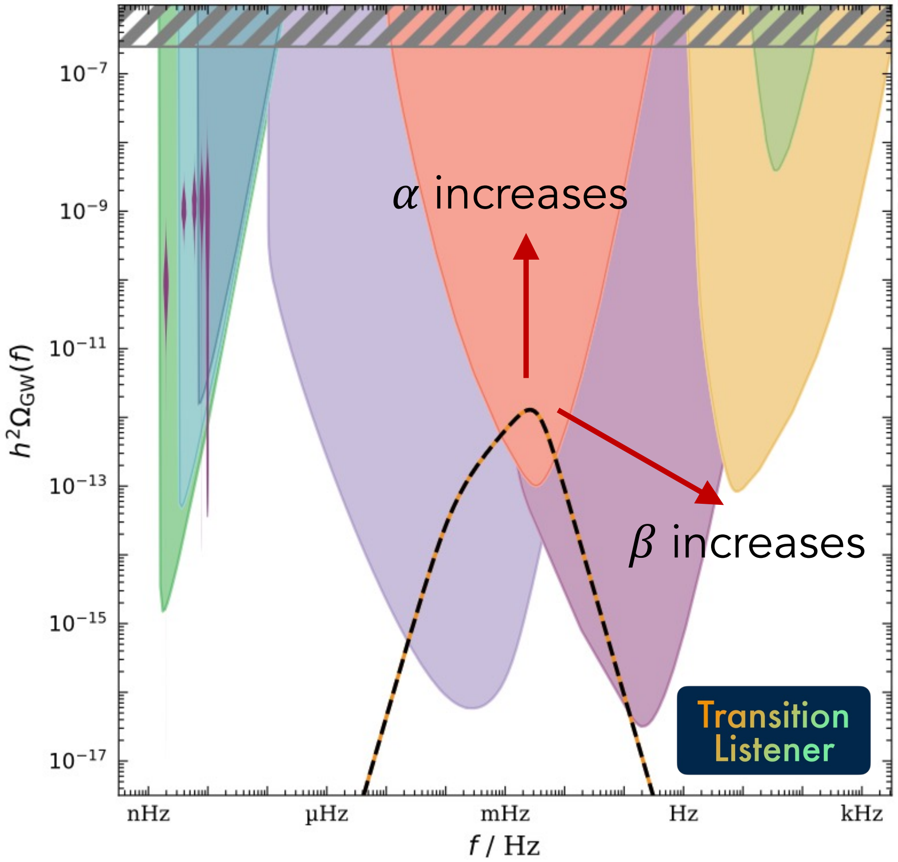
$$f_{\rm peak} \simeq 0.01\ {\rm mHz}\left(\frac{\beta}{H}\right)\left(\frac{T}{100\ {\rm GeV}}\right)$$

α : strong phase transition if $\alpha \gtrsim 1$

β : slow transition if β/H $\lesssim$ 100



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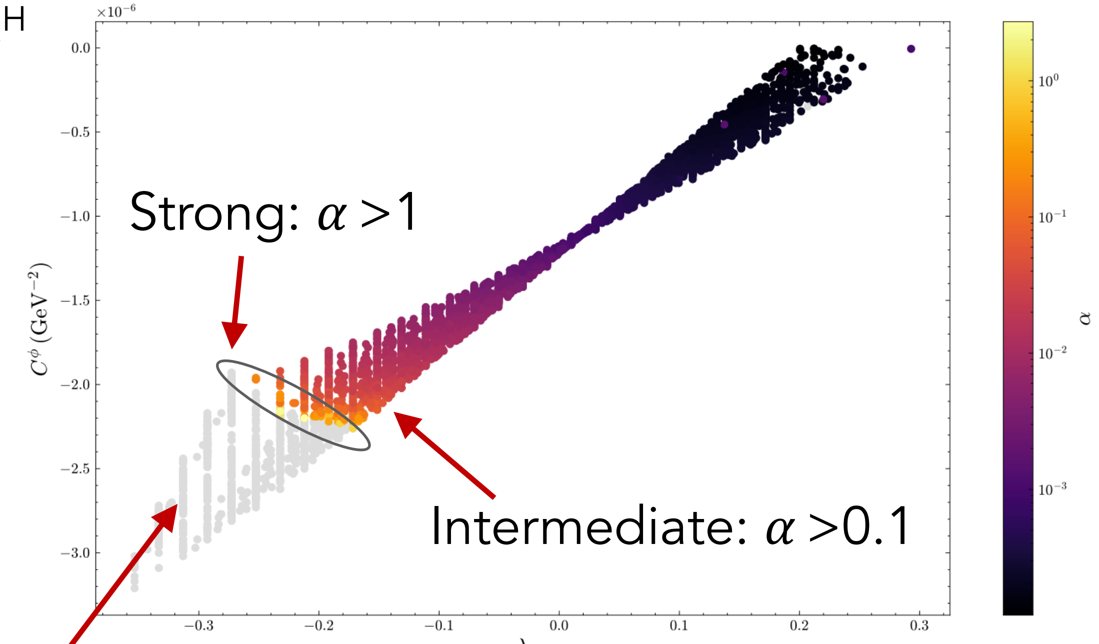
(Fig shows one of our results)

Strength of phase transitions

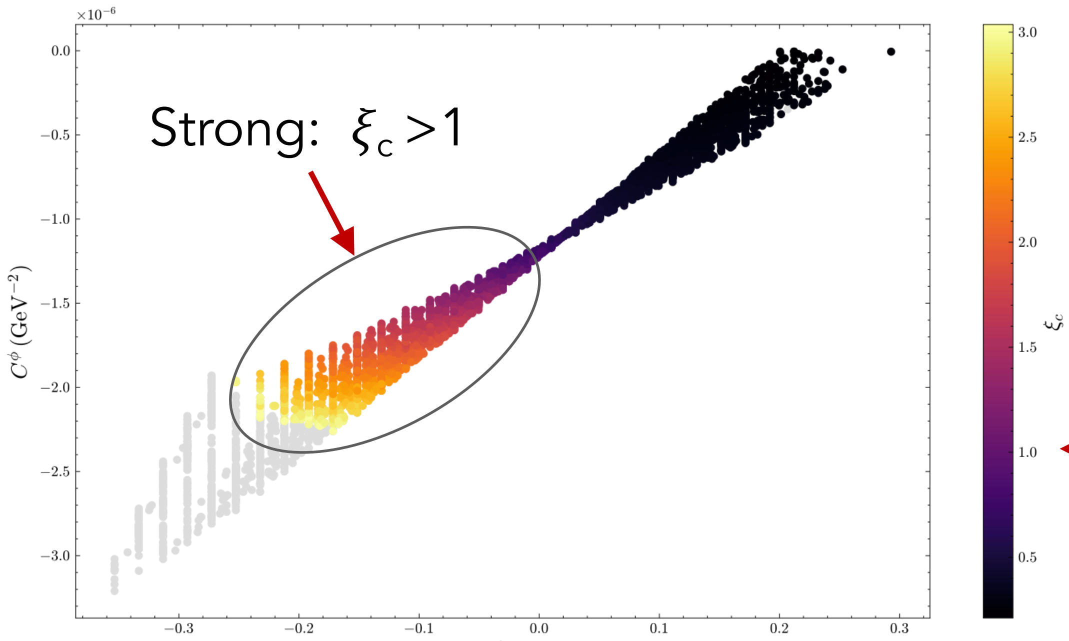
α = GW strength ($\propto$ *latent heat*)

ξ_c = "baryogenesis strength"

C^H



λ = Higgs quartic



λ = Higgs quartic

← 1.0

No transition:
- Symmetric minimum deeper than EW minimum
- or too supercooled to nucleate

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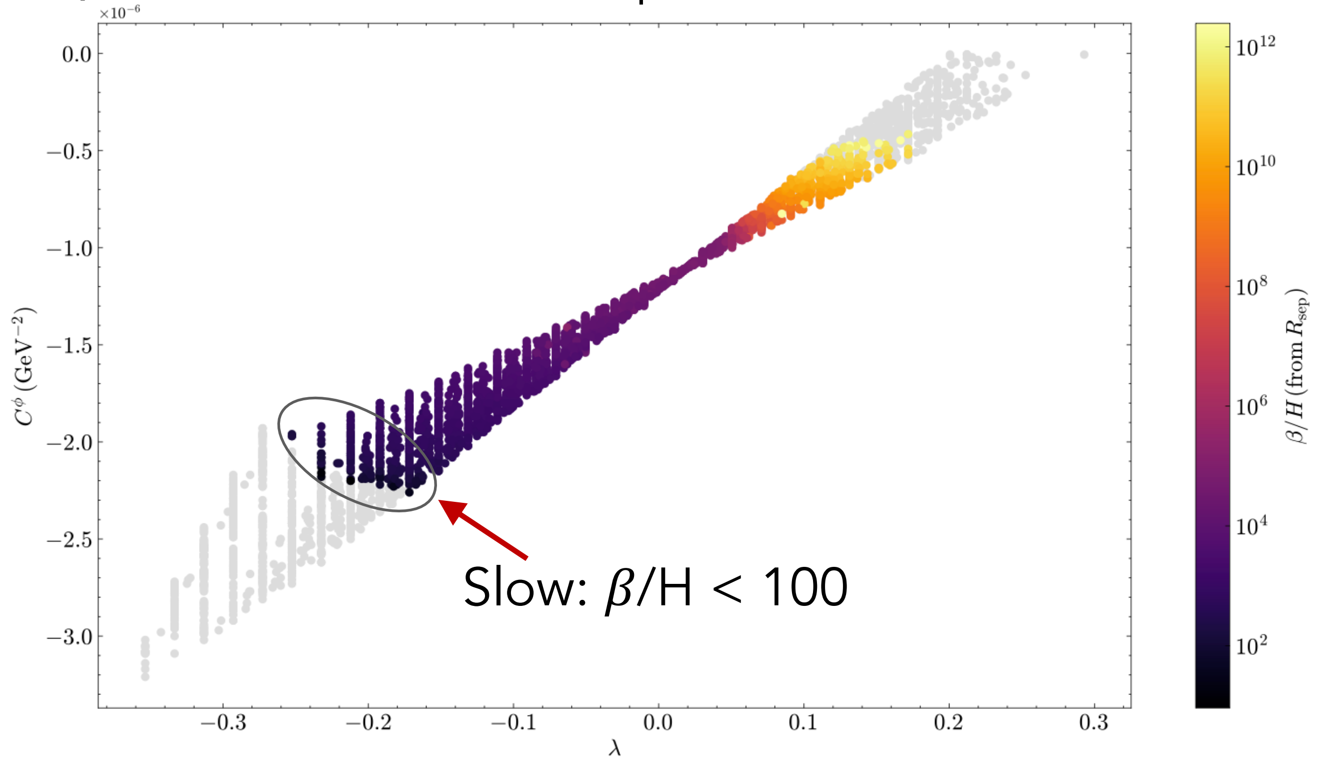
Some strong transitions in GW sense, a lot in baryogenesis sense

Speed of phase transitions

β = inverse duration of phase transition



The ***strong*** and ***slow*** transitions are in the same region, larger negative λ, which is where we get some transitions observable with LISA

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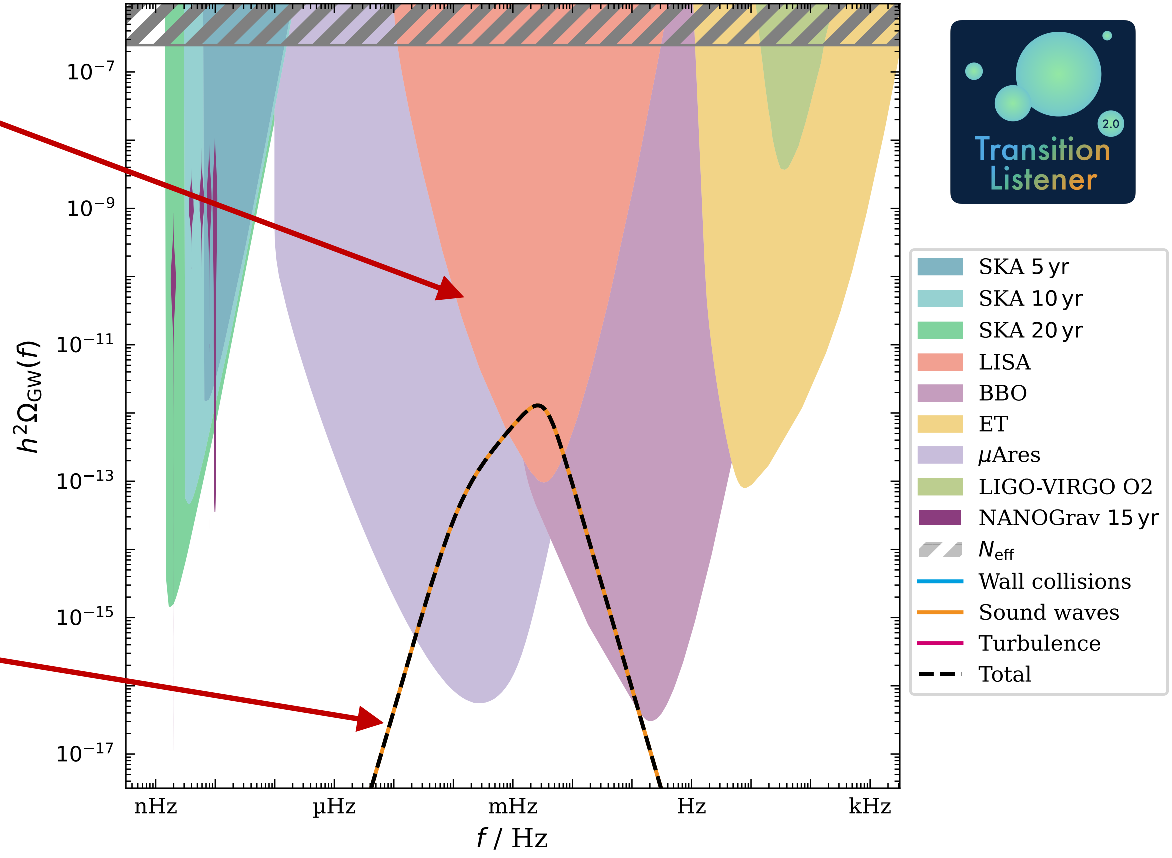
GW spectrum and some experimental sensitivities

LISA sensitivity curve

This work: parameter point with highest SNR at LISA (only includes sound waves)



Plot from Safa Helal's master thesis, Uppsala University, 2025
Made with TransitionListener (Tasillo and Matuszak)

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Conclusions

- SMEFT is a general model-independent approach to heavy BSM physics
- Important to know if a first-order EWPT is allowed in the SMEFT
- It is – and it *may* allow both detectable gravitational waves and electroweak baryogenesis

- To be done: do the full calculation on the 3D side

Backup

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Overview of power counting

Hierarchy	Shorthand	λ_3/T	m_3^2/T^2	$\phi_3/\sqrt{T}$	C_3^φ
$m_3 \sim M \ll \pi T$	TLB	g^2	g^2	g^0	g^2
	SC TLB (1)	g^2	g^2	g^0	$< g^2$
	SC TLB (2)	g^2	g^3	$g^{\frac{1}{2}}$	g^2
$m_3 \ll M \ll \pi T$	SQTLB	g^3	g^2	$g^{-\frac{1}{2}}$	g^4
	SC SQTLB (1)	g^3	g^2	$g^{-\frac{1}{2}}$	$< g^4$
	SC SQTLB (2)	g^3	$g^{\frac{5}{2}}$	$g^{-\frac{1}{4}}$	g^4
	RB	g^3	g^3	g^0	$< g^3$
	RB 6	g^3	g^3	g^0	g^3
	SC RB	g^3	$g^{\frac{7}{2}}$	$g^{\frac{1}{2}}$	$< g^{\frac{3}{2}}$
	SC RSB	g^4	g^3	g^0	$< g^3$
$m_3 \ll M \sim \pi T$	RSB	g^4	g^2	g^{-1}	$< g^6$
	RSB 6	g^4	g^2	g^{-1}	g^6

Tree-level barrier from ϕ^6 term (TLB, SC TLB (1), SC TLB (2))

TLB with small λ (SQTLB, SC SQTLB (1), SC SQTLB (2))

Radiative barrier giving ϕ^3 term (RB, RB 6, SC RB, SC RSB)

Radiative symmetry breaking (CW) (RSB, RSB 6)

[E. Camargo-Molina, RE, J. Löfgren, arXiv:2410.23210]

Gravitational wave prospects from 3D

Hierarchy	Shorthand	$\alpha/\alpha_{\text{RB}}$	$\beta/H \big/ (\beta/H)_{\text{RB}}$
$m_3 \sim M \ll \pi T$	TLB	1	$g^{\frac{3}{2}}$
	SC TLB (1)	1	$g^{\frac{3}{2}}$
	SC TLB (2)	g^1	g^1
$m_3 \ll M \ll \pi T$	SQTLB	g^{-1}	$g^{\frac{1}{2}}$
	SC SQTLB (1)	g^{-1}	$g^{\frac{1}{2}}$
	SC SQTLB (2)	1	$g^{\frac{1}{4}}$
	RB	1	1
	RB 6	1	1
	SC RB	g	$g^{\frac{1}{4}}$
	SC RSB	g	g
$m_3 \ll M \sim \pi T$	RSB	g^{-2}	$g^{-\frac{1}{2}}$
	RSB 6	g^{-2}	$g^{-\frac{1}{2}}$

[E. Camargo-Molina, RE, J. Löfgren, arXiv:2410.23210]

We expect small β here

Larger α and small β here

Large α but large β here

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