

# Refining Gravitational Wave and Collider Physics Dialogue via Singlet Scalar Extension

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*Based on:* [arXiv:2409.17554](https://arxiv.org/abs/2409.17554)

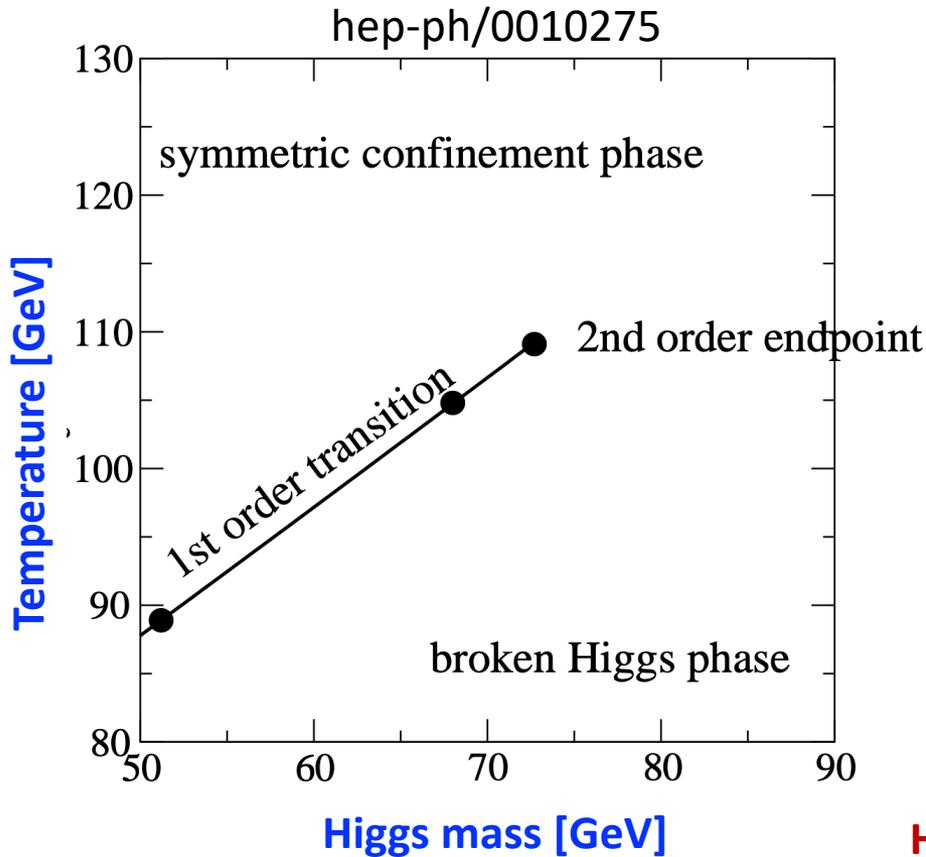
***Gravitational Waves and the Early Universe:  
Accelerated Expansion, Dynamical Inhomogeneity, and Beyond***

@Nagoya, Japan, March. 12-14, 2026

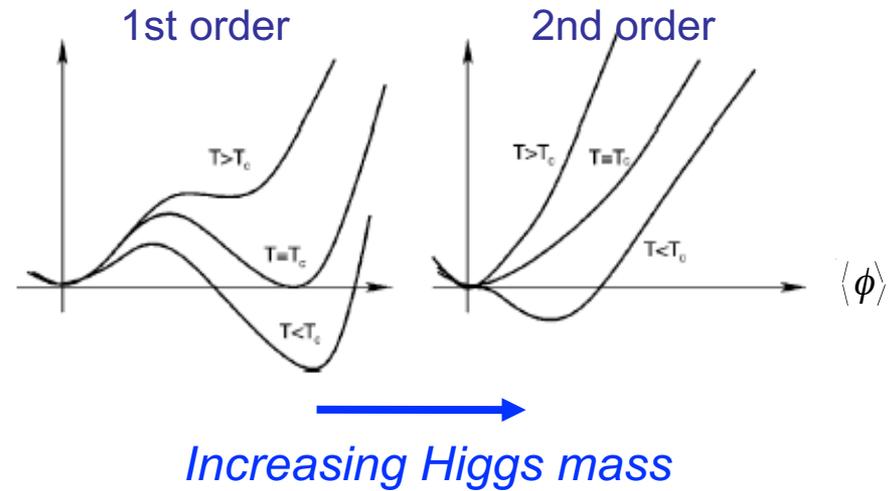


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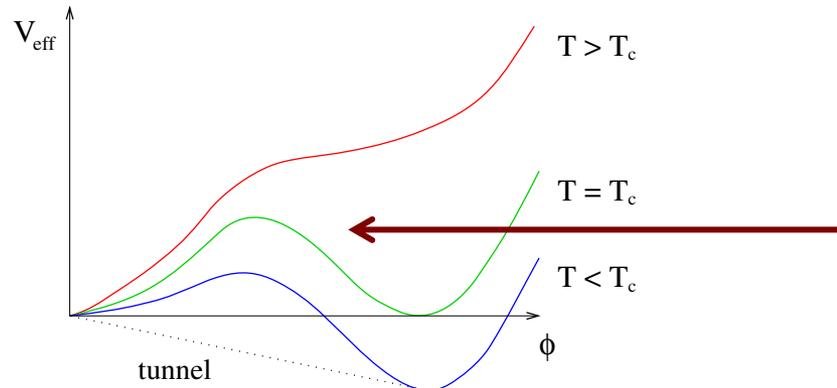


*EW Phase Diagram*

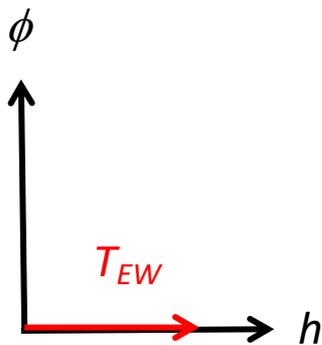


**Higgs mass: 125 GeV**

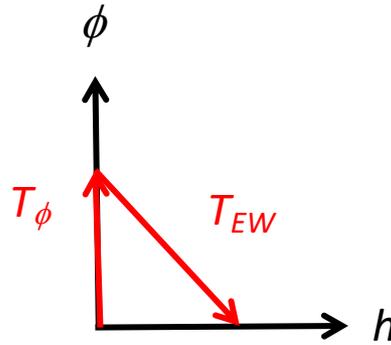
SM EW transition is a **crossover**



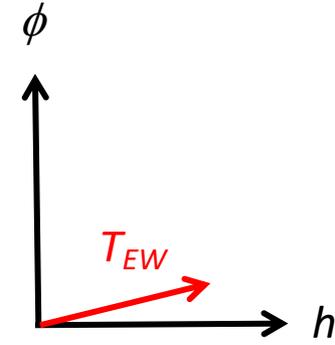
Generate finite- $T$  barrier



$a_2 H^2 \phi^2 : T > 0$   
loop effect



$a_2 H^2 \phi^2 : T = 0$   
tree-level effect



$a_1 H^2 \phi : T = 0$   
tree-level effect

1. It can be indirectly probed by collider
2. It can generate a stochastic background of GW which can be detectable by the next generation of GW detectors such as LISA.
3. It is one of necessary preconditions (Sakharov conditions) for the generation of the observed baryon asymmetry via electroweak baryogenesis



**How reliable are the computations for GW predictions?**

- Temperature  $T_*$ :

➤  $T_* \sim 100 \text{ GeV} \rightarrow \text{mHz today}$

- Latten heat or phase transition strength,  $\alpha$

$$\alpha = \frac{\rho_{\text{vac}}}{\rho_{\text{rad}}^*} = \frac{1}{\rho_{\text{rad}}^*} \left[ \frac{1}{4} T \frac{\partial}{\partial T} \Delta V(T) - \Delta V(T) \right] \Big|_{T_*}$$

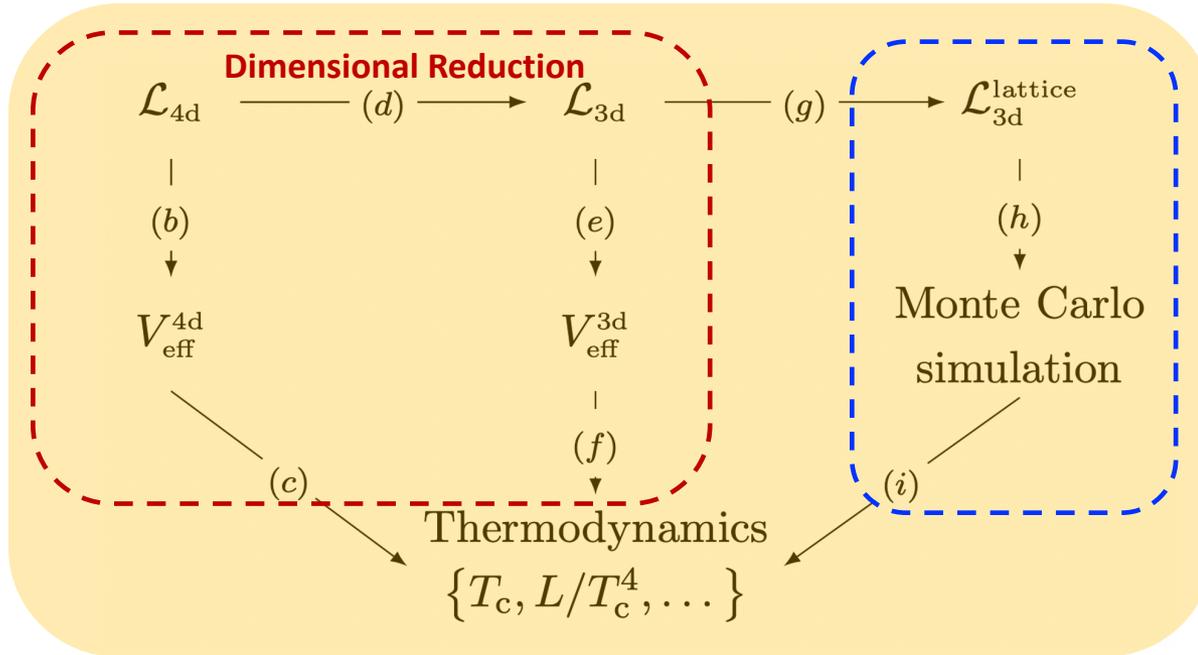
- “Duration”:

$$\frac{\beta}{H_*} = -T \frac{d}{dT} \ln \Gamma \Big|_{T=T_*}$$

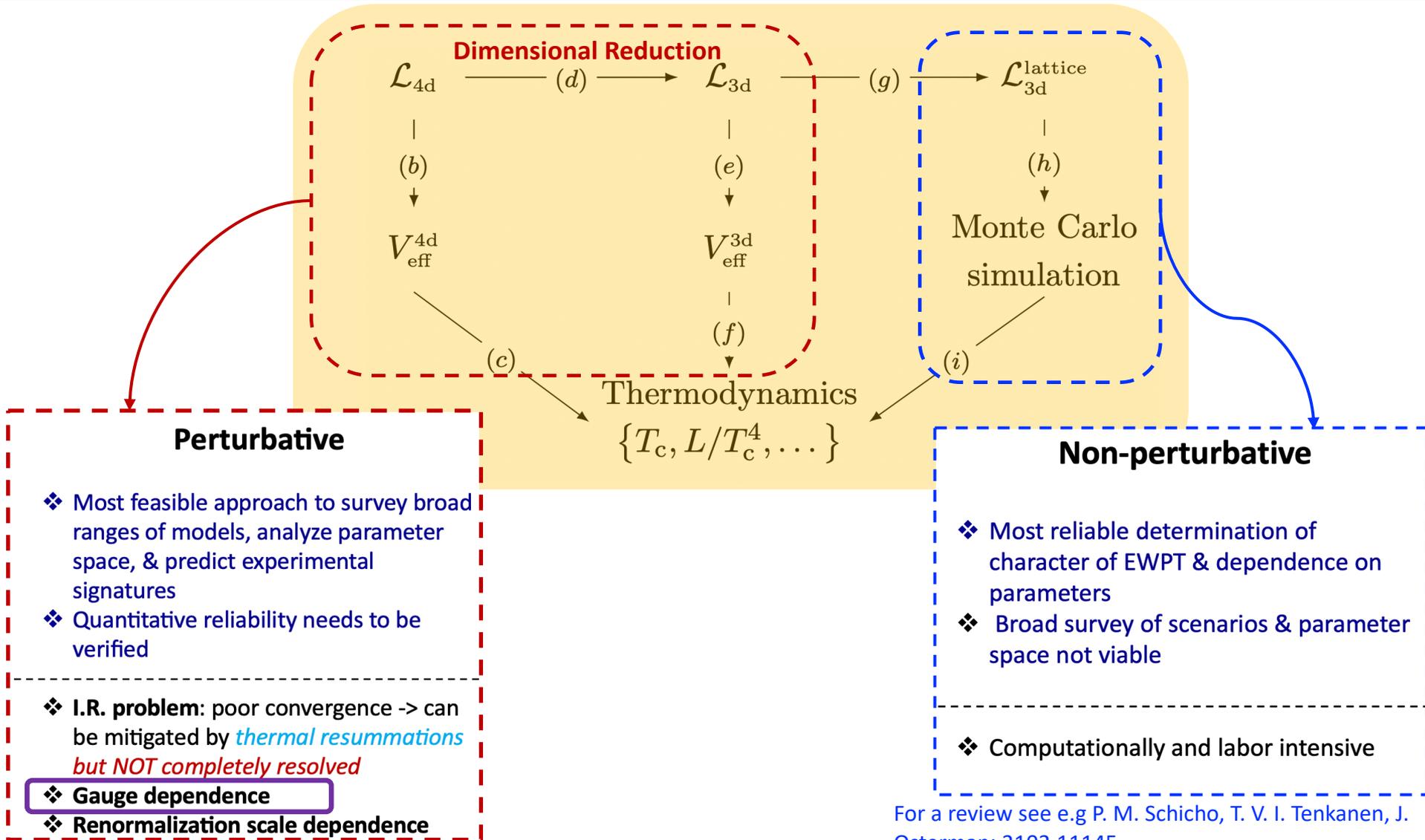
$\beta$ : inverse phase transition duration

$H_*$ : Hubble rate at transition

- $v_w$ : bubble wall velocity



For a review see e.g P. M. Schicho, T. V. I. Tenkanen, J. Osterman: 2102.11145



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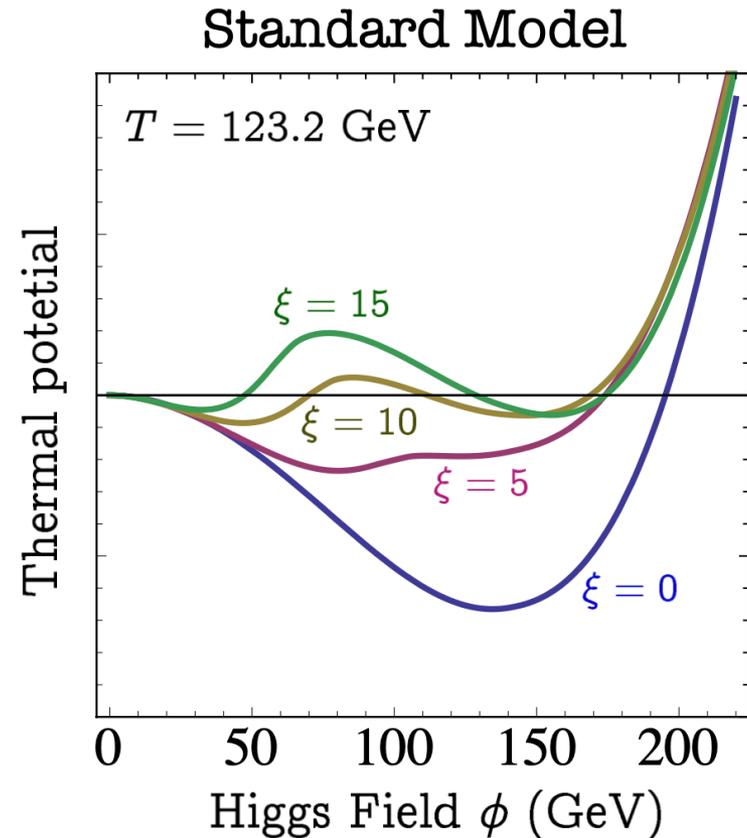


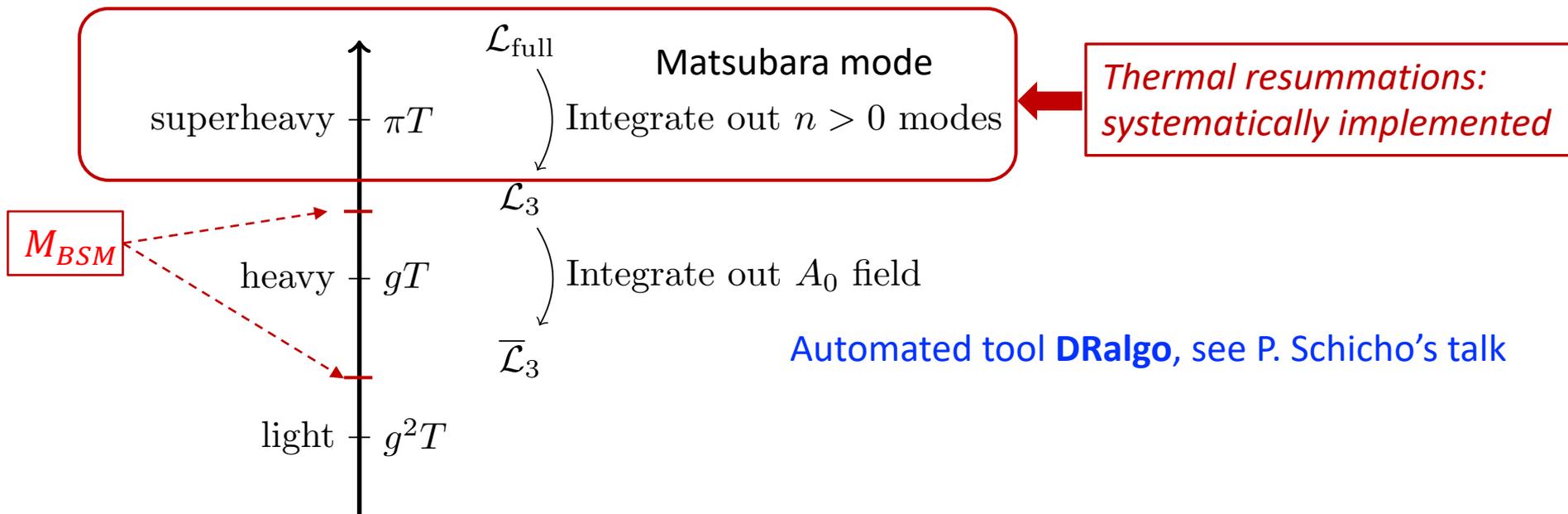
❖ The full effective potential depends on the gauge parameter

❖ Need to use approximations to obtain a gauge independent effective potential:

1. Using high-T expansion
2. Using  $\hbar$  expansion (PRM method)

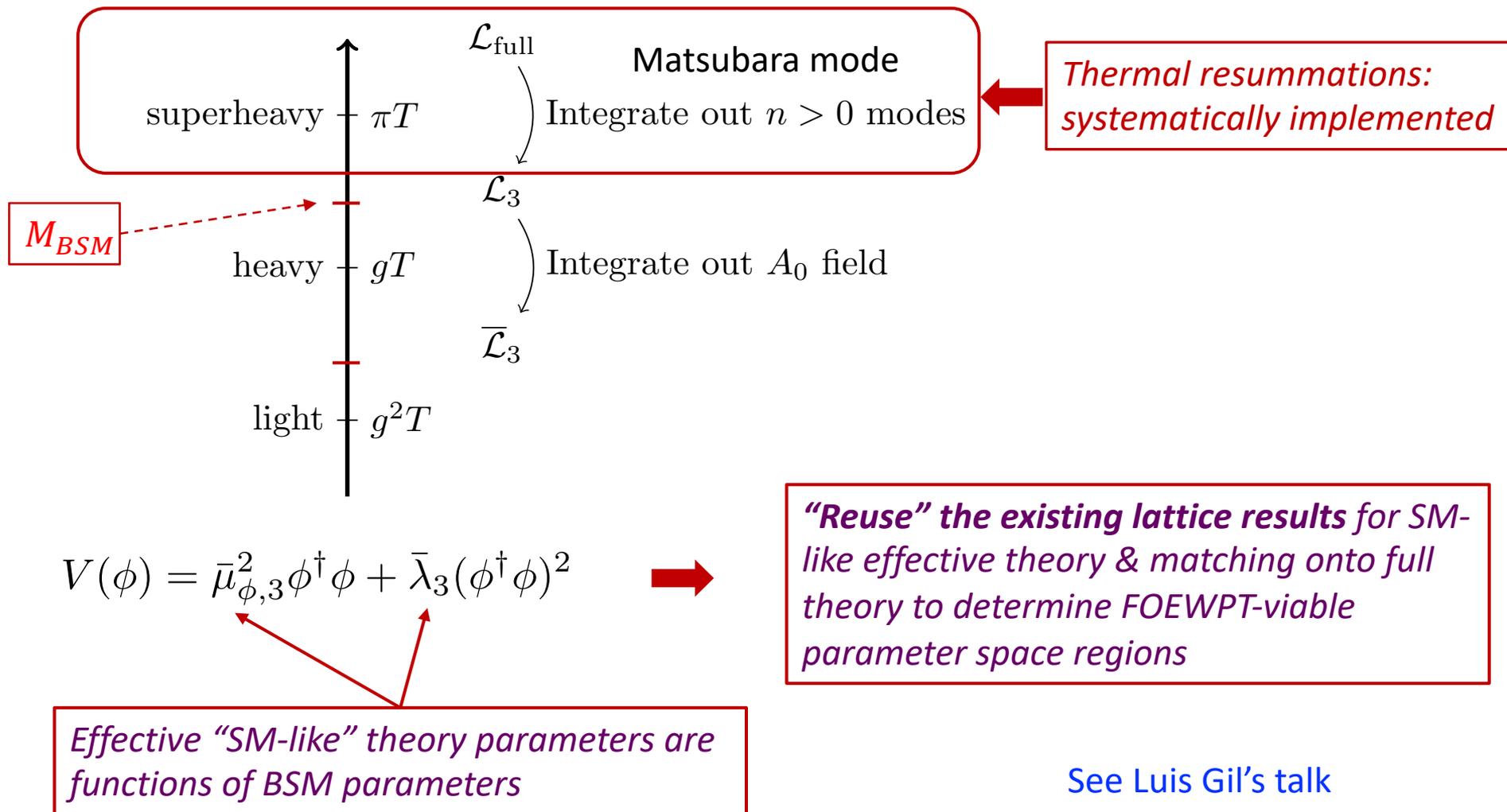
*H.H.Patel and M.J.Ramsey-Musolf JHEP 07 (2011), 029, arXiv:1101.4665*







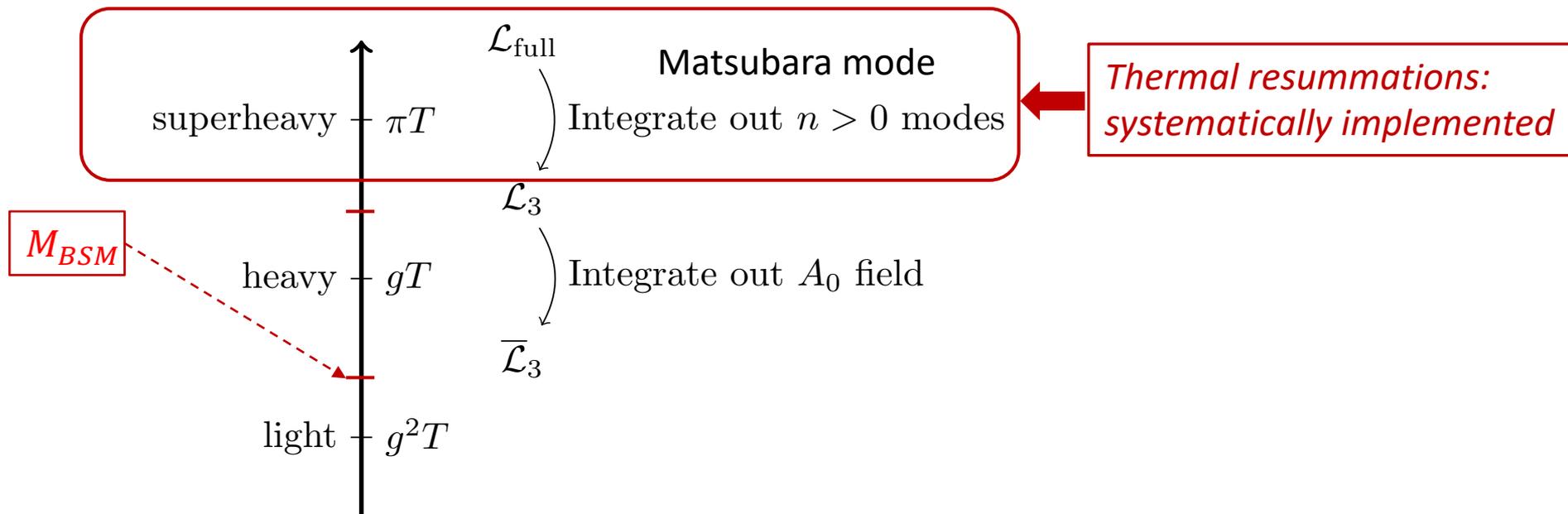
## ❖ Heavy BSM mass



See Luis Gil’s talk



## ❖ Light BSM mass



$$V(\phi) = \bar{\mu}_{\phi,3}^2 \phi^\dagger \phi + \bar{\lambda}_3 (\phi^\dagger \phi)^2 + V_{BSM}$$



*Perform new lattice simulations*

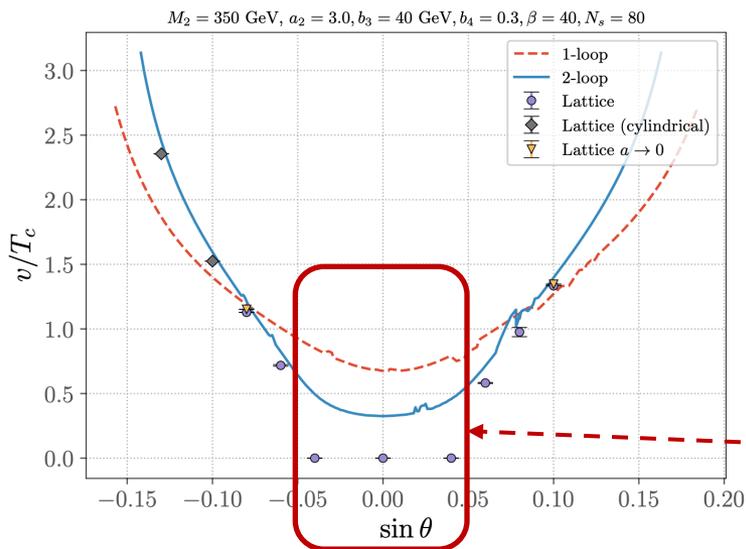
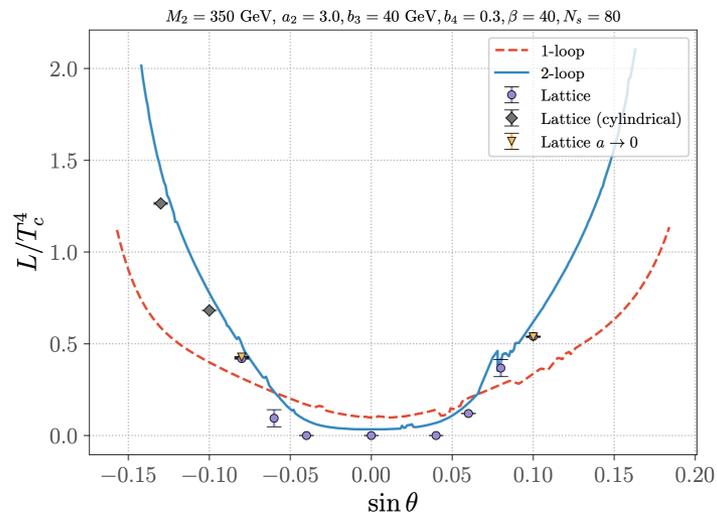
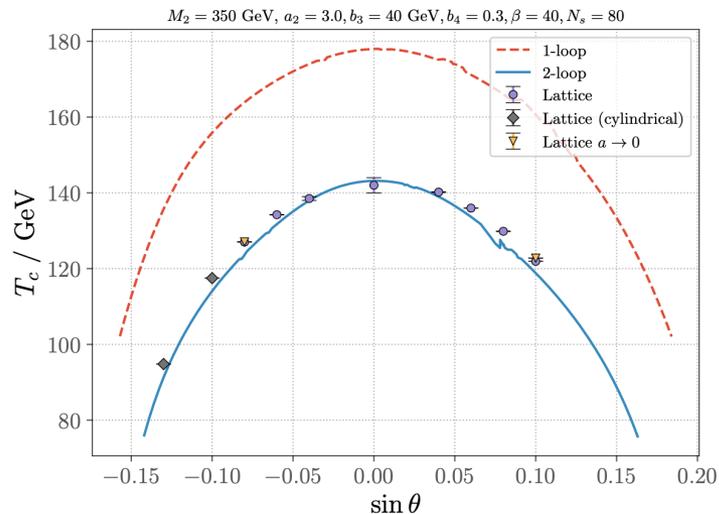
For recent lattice simulations, see

- Niemi, Ramsey-Musolf, Tenkanen, Weir 2005.11332
- L. Niemi, Michael J. Ramsey-Musolf, G. Xia: 2405.01191

*Effective "SM-like" theory parameters are functions of BSM parameters*



# DR 3EFT perturbative vs Lattice: singlet scalar extension



*L. Niemi, M. J. Ramsey-Musolf, G. Xia: 2405.01191*

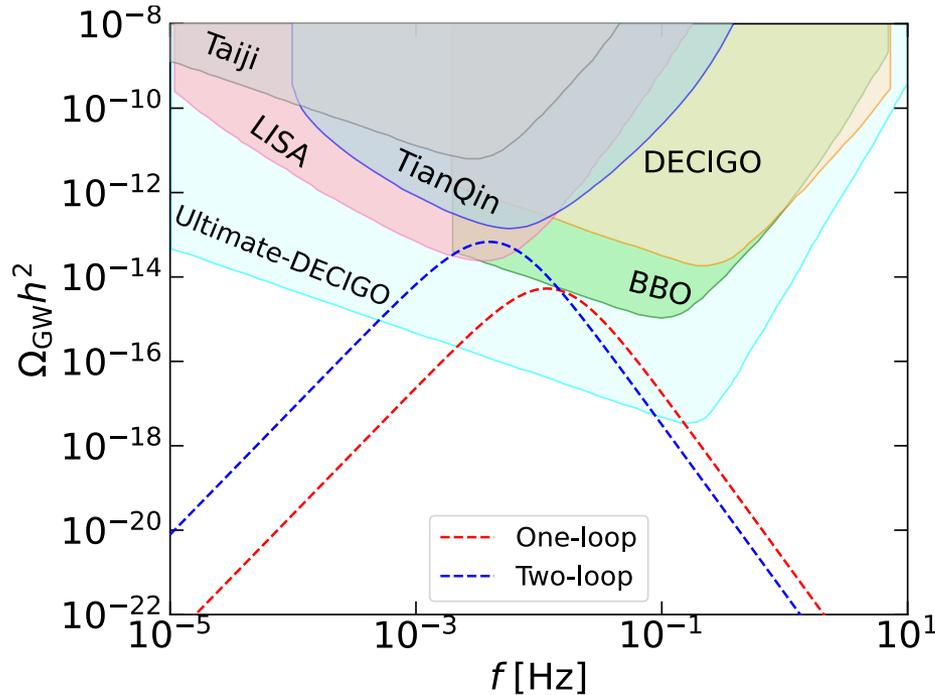
**Transition is crossover**



# DR 3EFT perturbative: GW spectrum

## from 1-loop vs 2-loop corrections

Ramsey-Musolf, Tenkanen, VQT: 2409.17554



Spectrum is obtained using  
**PTPlot** package

BM:  $m_{h_2} = 350$  GeV,  $b_3 = 40$  GeV,  $b_4 = 0.3$ ,  $a_2 = 3.0$ , and  $\sin \theta = 0.1$ .

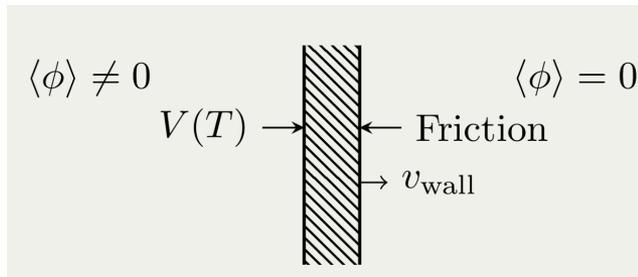
At one-loop order, we find

$$T_* = 82.12 \text{ GeV}, \quad \alpha = 0.065, \quad \frac{\beta}{H_*} = 1102.57, \quad v_w^{\text{LTE}} = 0.70, \quad \text{SNR}_{\text{LISA}} = 0.18.$$

Including two-loop corrections results:

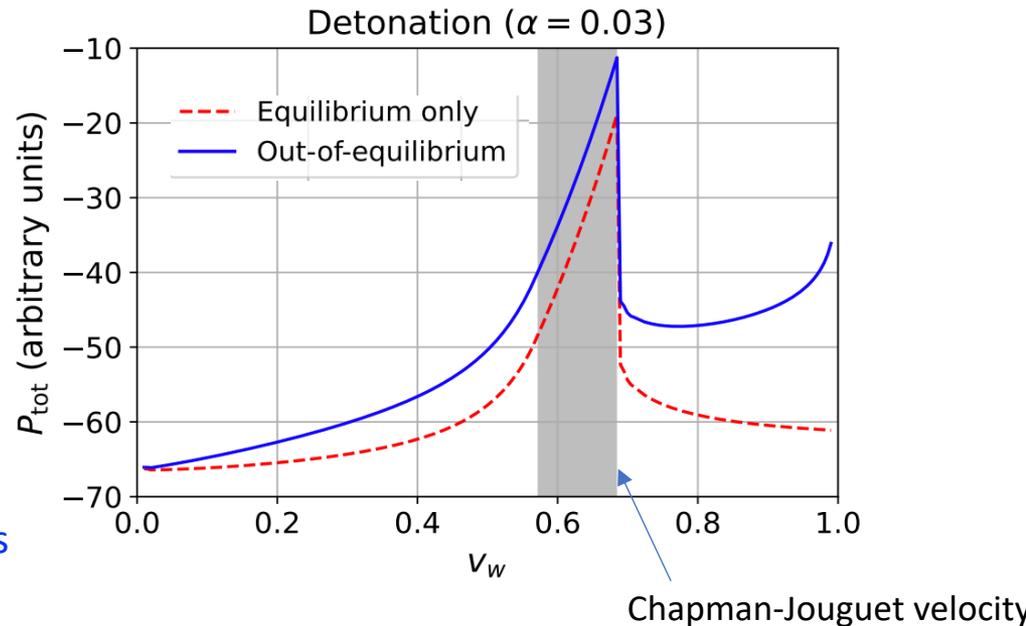
$$T_* = 64.75 \text{ GeV}, \quad \alpha = 0.128, \quad \frac{\beta}{H_*} = 528.4, \quad v_w^{\text{LTE}} = 0.78, \quad \text{SNR}_{\text{LISA}} = 9.3.$$

- ❖ Computing bubble wall velocity is **challenging** especially including **out-of-equilibrium** effects <- *how the **plasma's distribution functions** are represented and calculated?*
- ❖ However, the out-of-equilibrium effects are typically **subdominant** for **some BSMs!**
- The wall velocity can be computed using **Local Thermal Equilibrium approximation\***



see P. Schicho's talk for recent updates and tools

\*all the species in the plasma are in local thermal equilibrium at the same temperature and fluid velocity

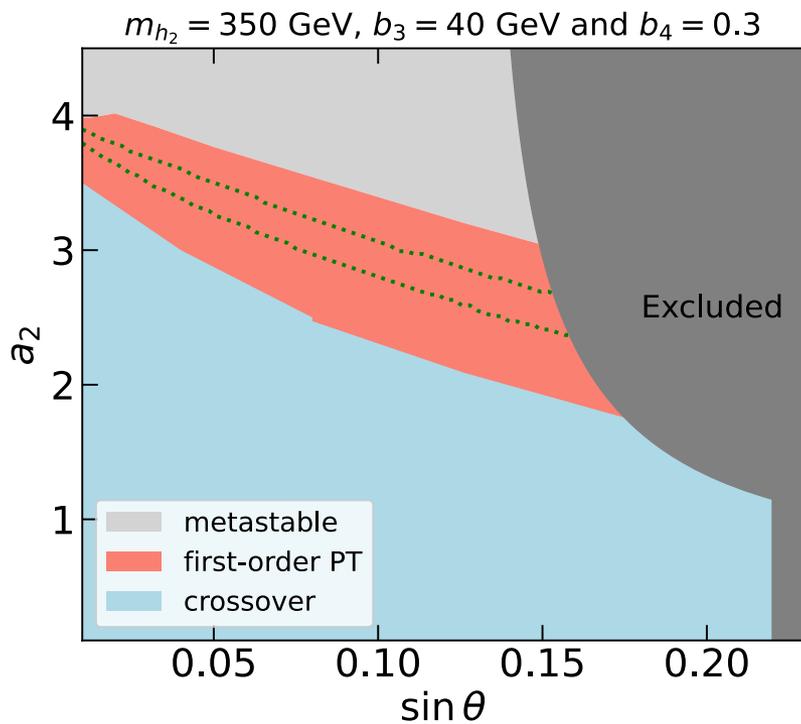


*B. Laurent and J.M. Cline: 2204.13120*

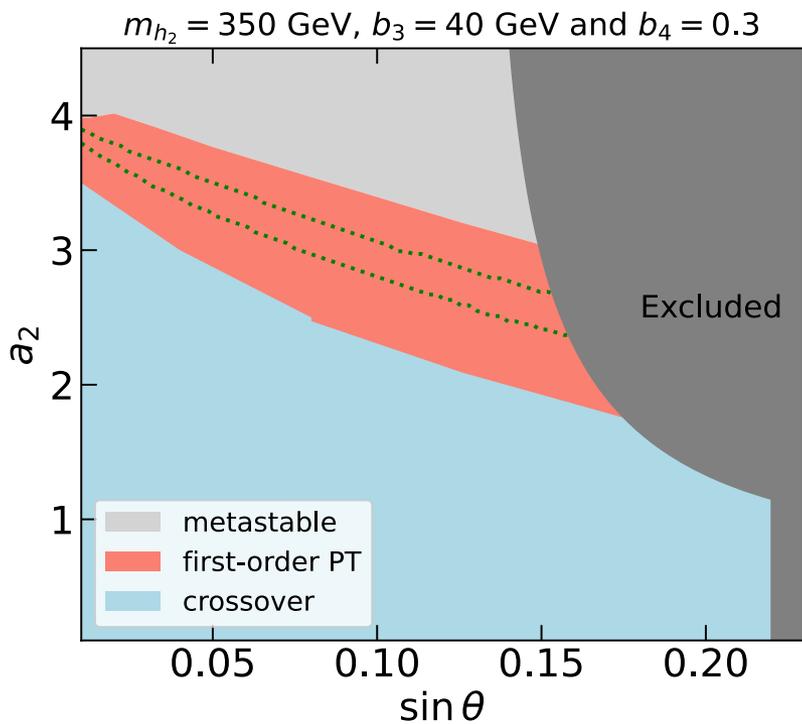
*W-Y. Ai, B. Laurent and J. Vis: 2303.10171*

## Phase structure diagram

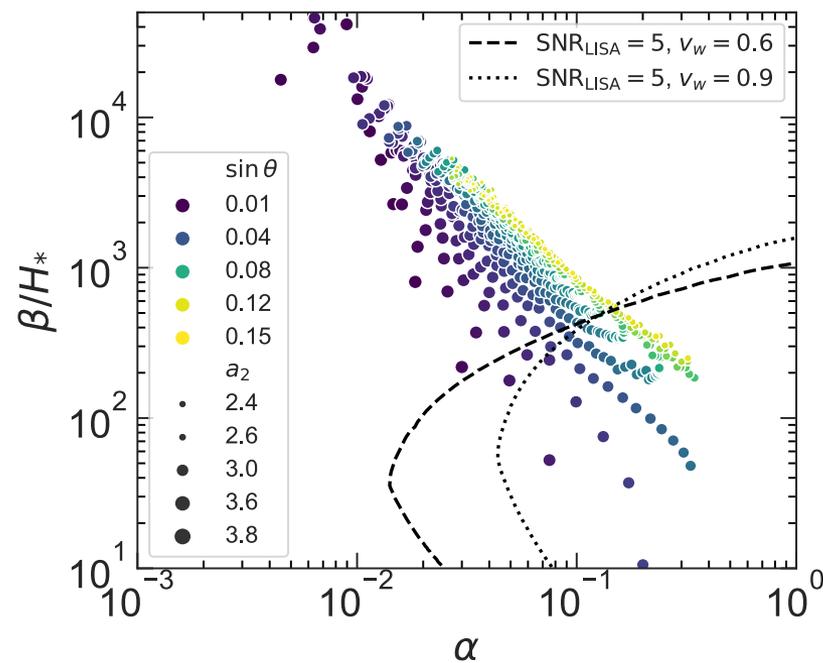
*Ramsey-Musolf, Tenkanen, VQT: 2409.17554*



## Phase structure diagram



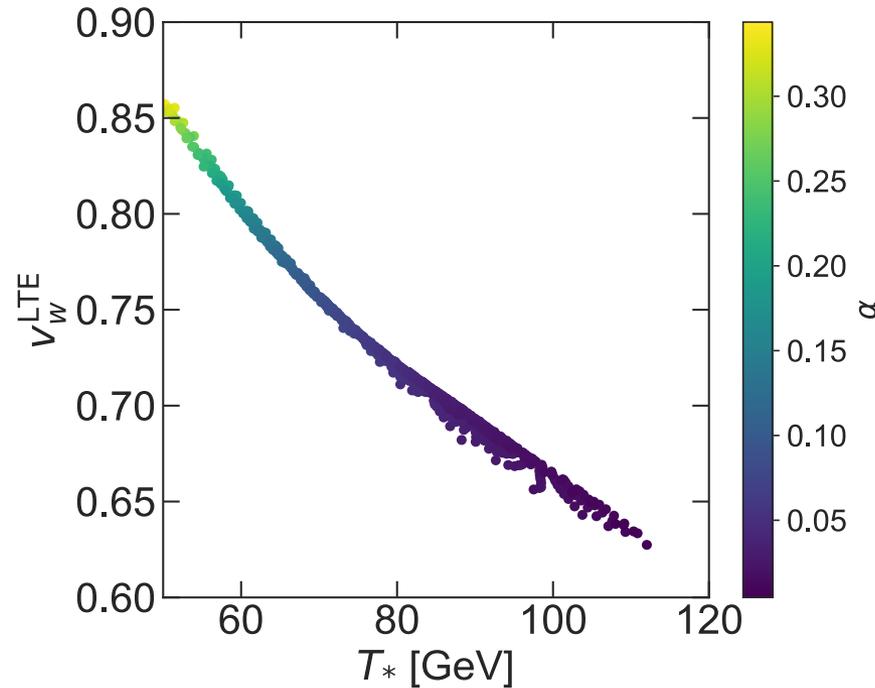
Ramsey-Musolf, Tenkanen, VQT: 2409.17554



The phase transition strength and its duration is sensitive to the coupling  $a_2$ .



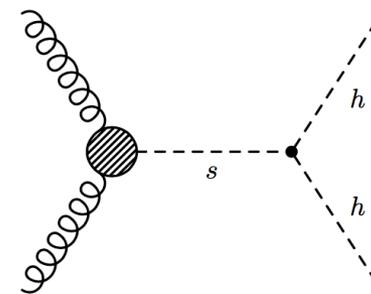
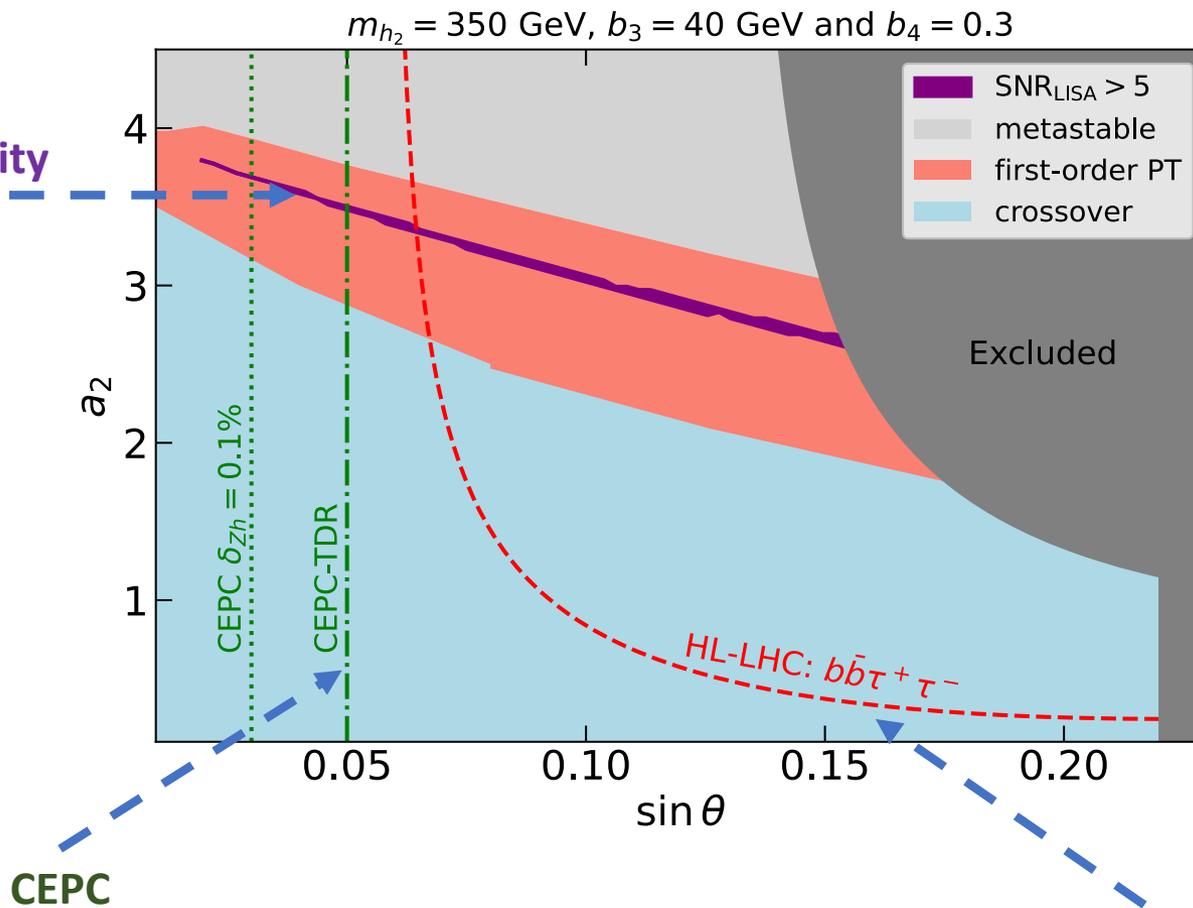
*Ramsey-Musolf, Tenkanen, VQT: 2409.17554*



- **Strong correlation** to nucleation temperature and the latent heat
- Lies in range of **[0.63, 0.85]**



Ramsey-Musolf, Tenkanen, VQT: 2409.17554



**Di-Higgs searches at HL-LHC**

# Summary

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- ❖ The first order electroweak phase transition is interesting and can be probed at future collider and GW detectors.
- ❖ We performed a cutting-edge analysis of GW prediction from the first-order EWPT, combining higher order corrections in perturbative calculations and results from lattice simulation
- ❖ We show a complementary between collider and GW signals in probing parameter space in xSM

*Thank You*