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Addressing the Gravitational Wave – Collider Inverse Problem

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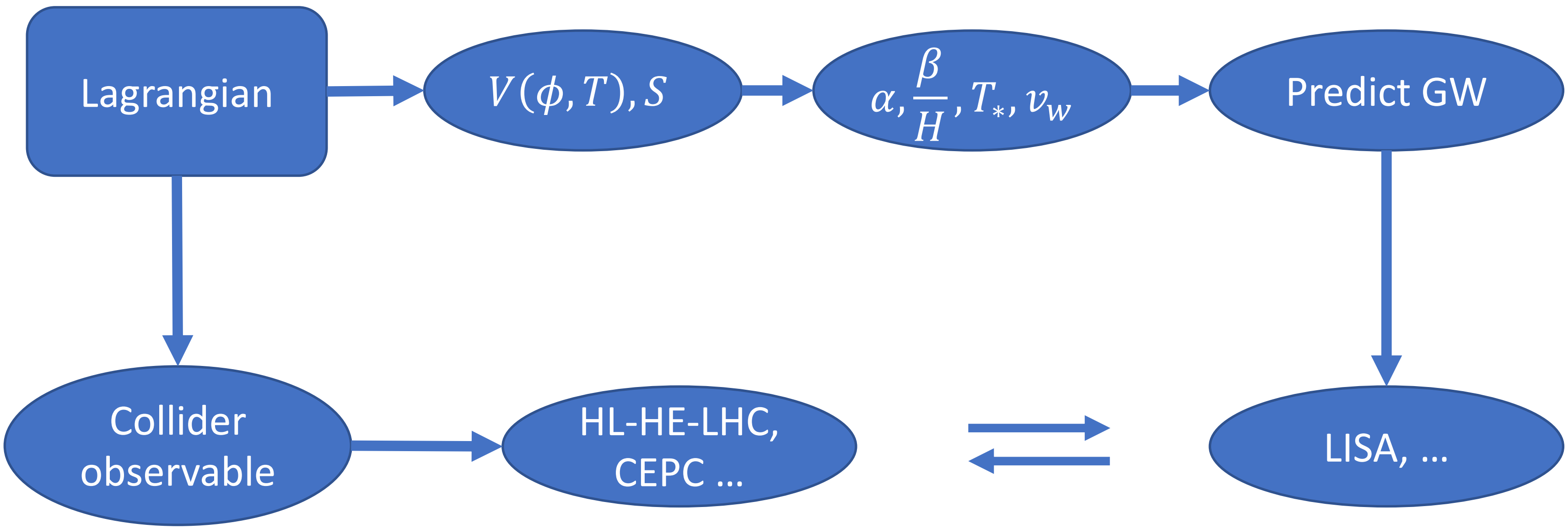
In collaboration with Leon S. Friedrich, Michael J. Ramsey-Musolf, Tuomas V. I. Tenkanen

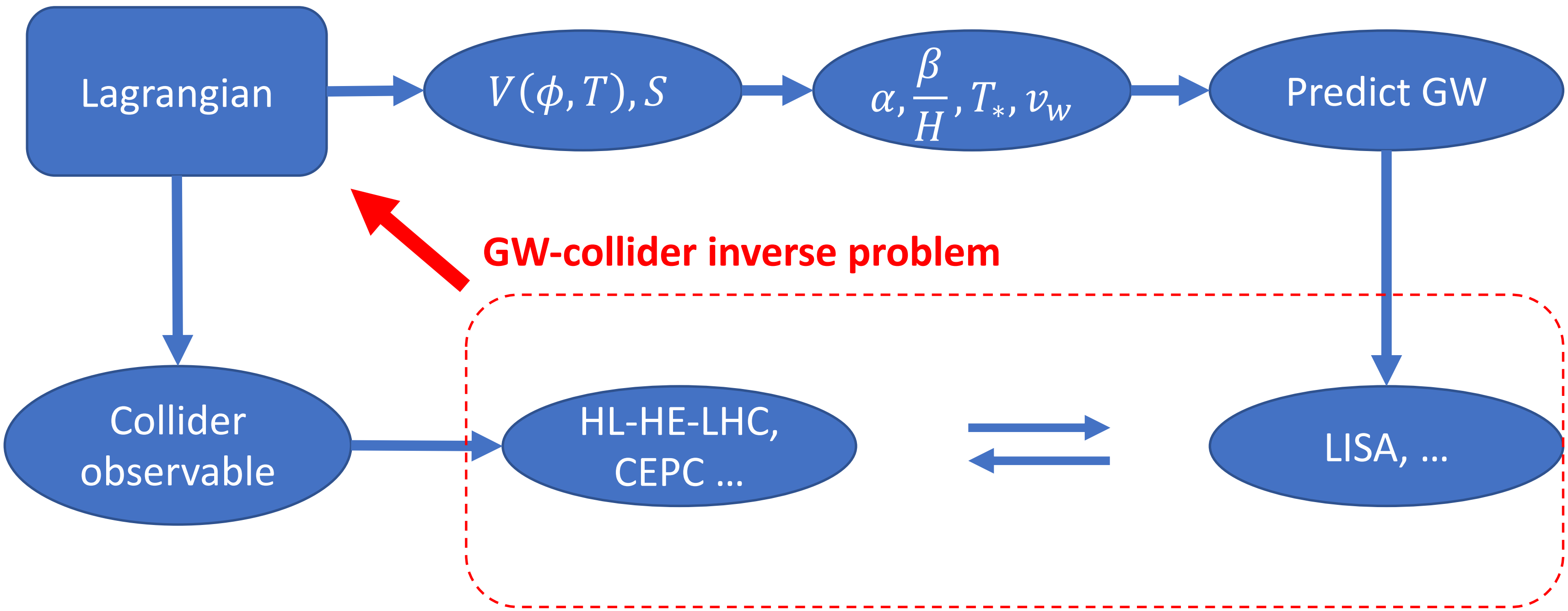
Based on arxiv:[2203.05889](2203.05889)

Joint Workshop of the CEPC Physics, Software and New Detector Concept
May 23-25, 2022

General picture and key questions

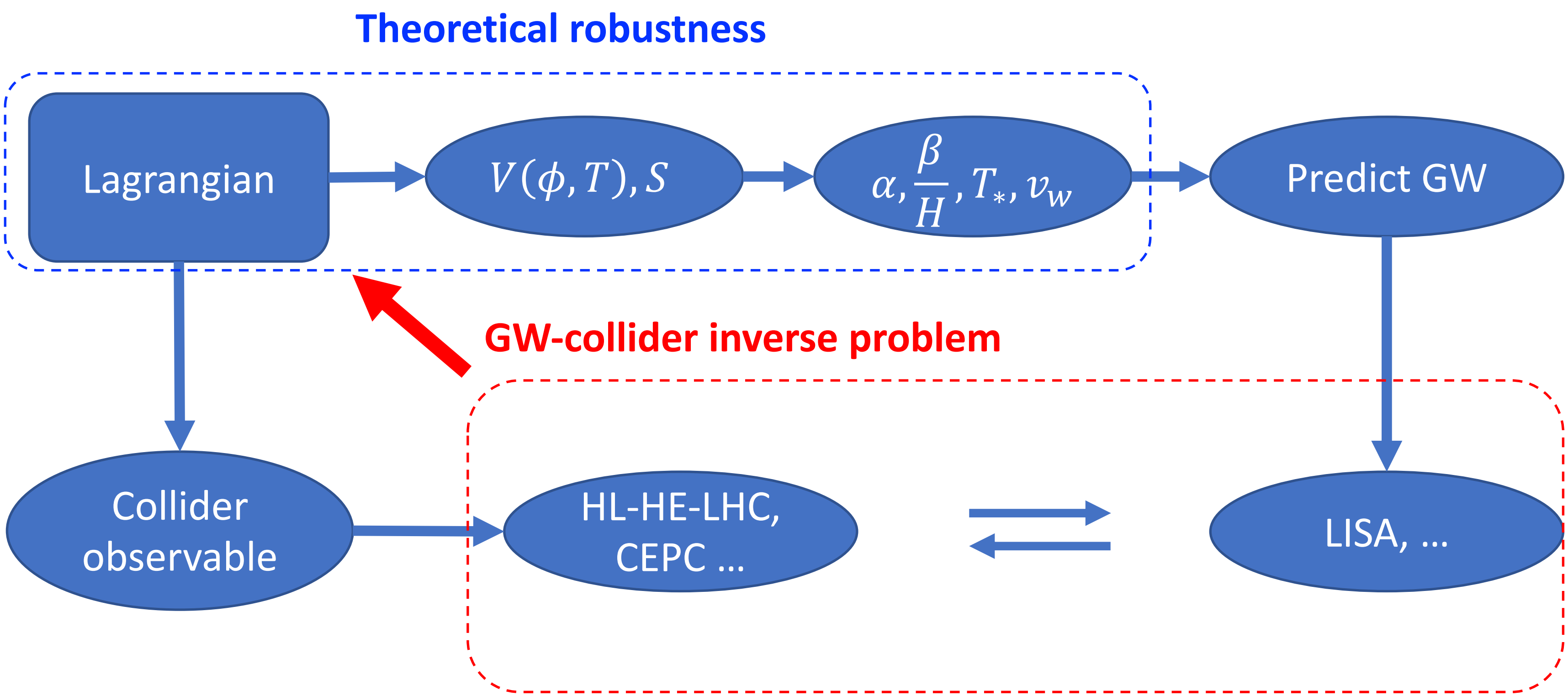


General picture and key questions



❖ Can combination of **collider** and **GW** observations be used to determine the **BSM scenario** responsible for the observed signals?

General picture and key questions



- ❖ Can combination of **collider** and **GW** observations be used to determine the **BSM scenario** responsible for the observed signals?
- ❖ How reliable are the computations that attempt to address the above question?

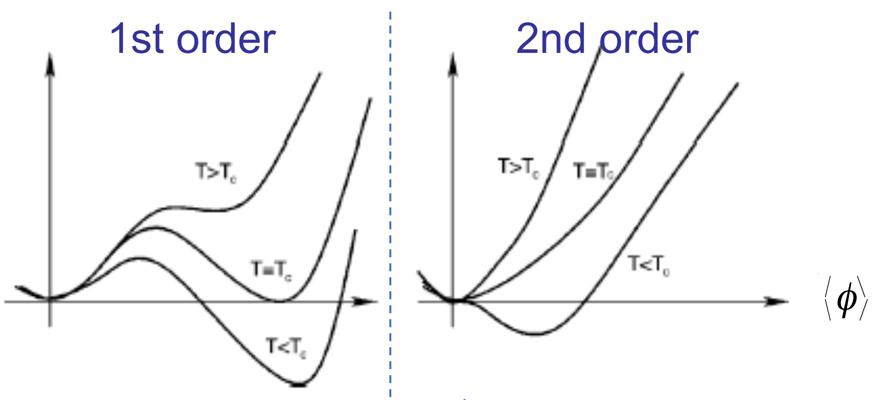
Outline

I. Introduction
II. Theoretical Robustness
III. GW-Collider Inverse Problem: Real Triplet scalar extension
IV. Summary

I. Introduction

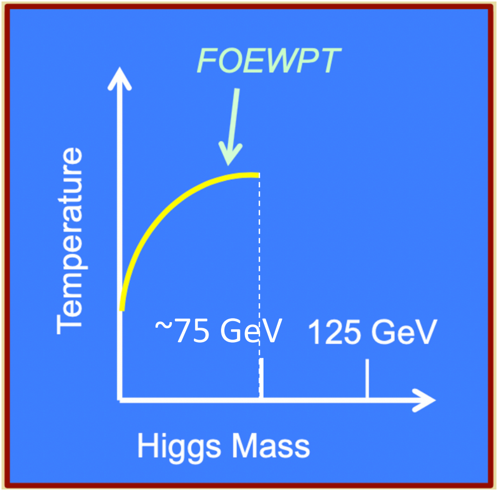
❖ Higgs boson discovery -> what was the nature of EWSB?

- **In SM, the EWPT is a crossover transition**



Increasing Higgs mass

New scalar

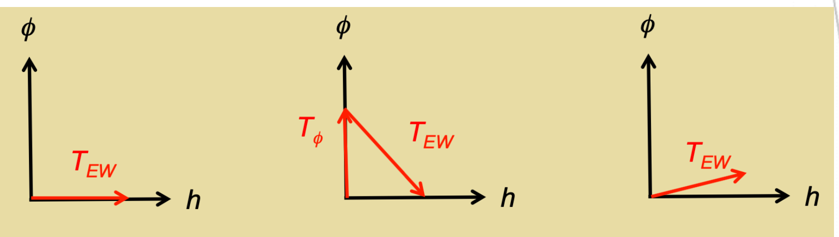


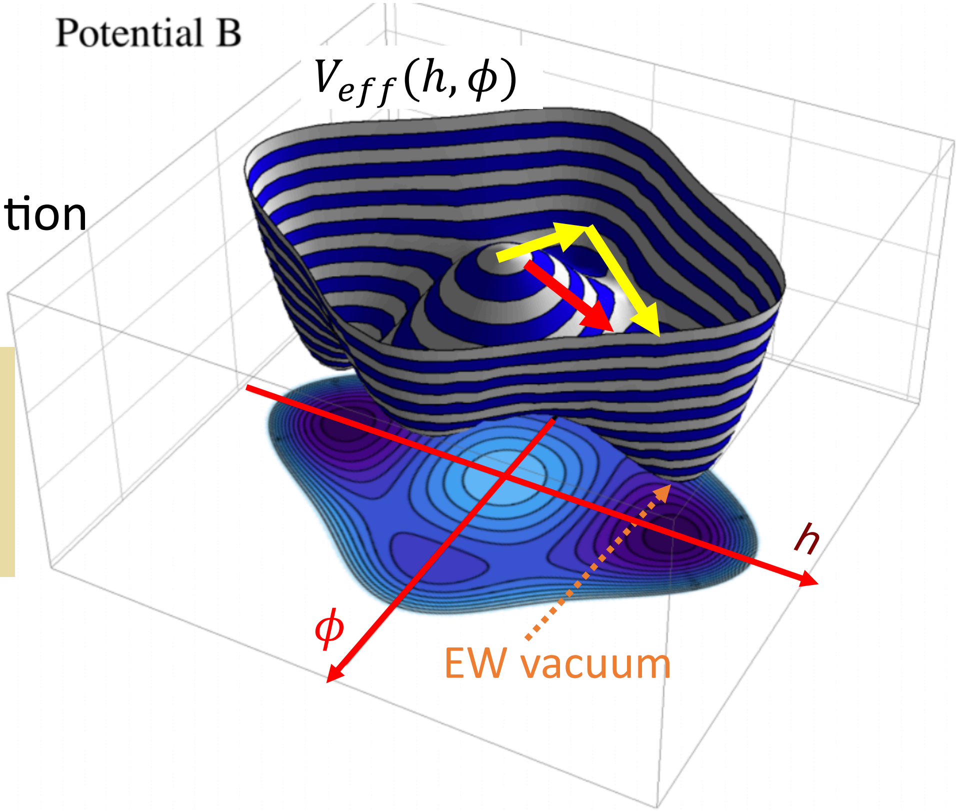
EW Phase Diagram

- **BSM can modify this thermal history!**

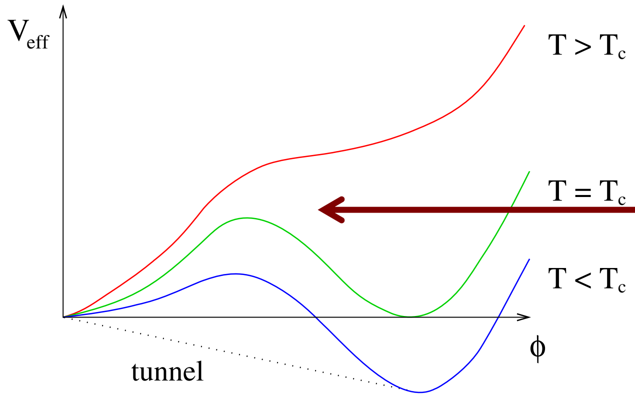
EWSB Transition in BSM

- Effective potential a function of multiple order parameters.
- Possible of multi-step phase transition

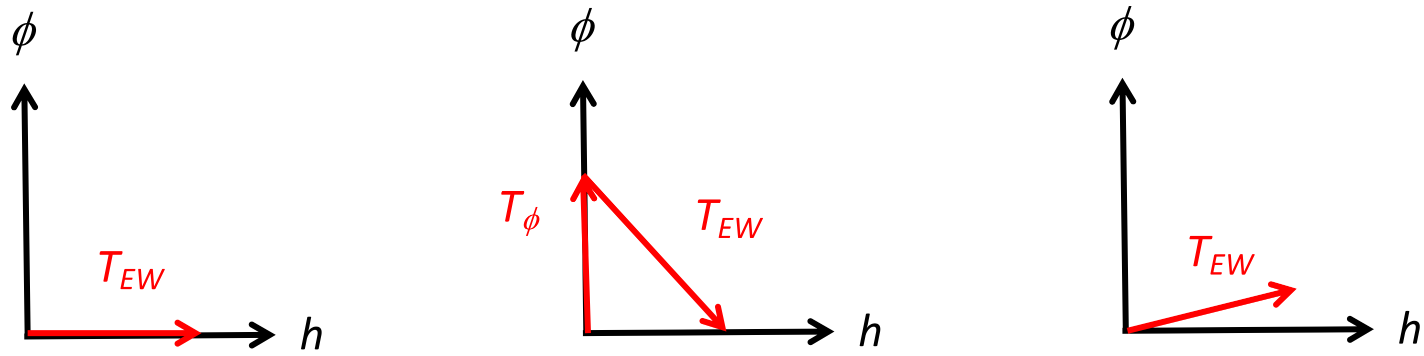




FOEWPT from BSM



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

Taken from Michael

I. Introduction

- Higgs boson discovery -> what was the nature of EWSB?
- FOEWPT could be probed by collider and GW detectors.

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  - FOEWPT occurred at EW scale and new physics couples quite strongly to Higgs -> probed by future collider detectors.

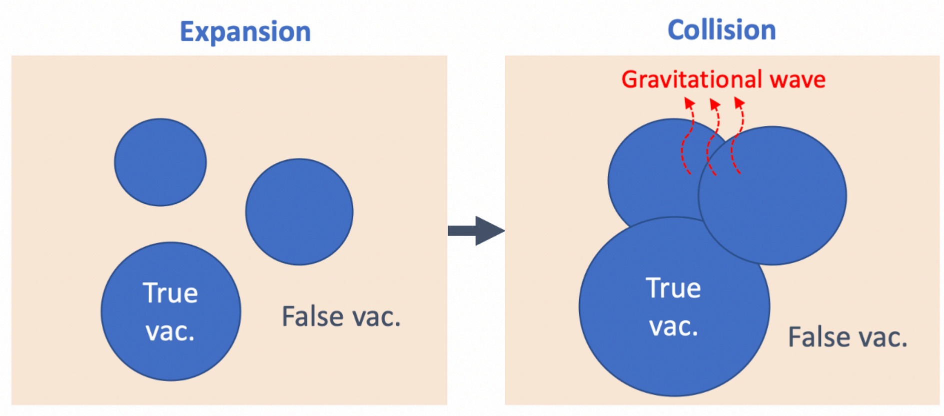
I. Introduction

❖ Higgs boson discovery -> what was the nature of EWSB?

❖ FOEWPT could be probed by collider and GW detectors.

➢ FOEWPT occurred at EW scale and new physics couples quite strongly to Higgs -> probed by future collider detectors.

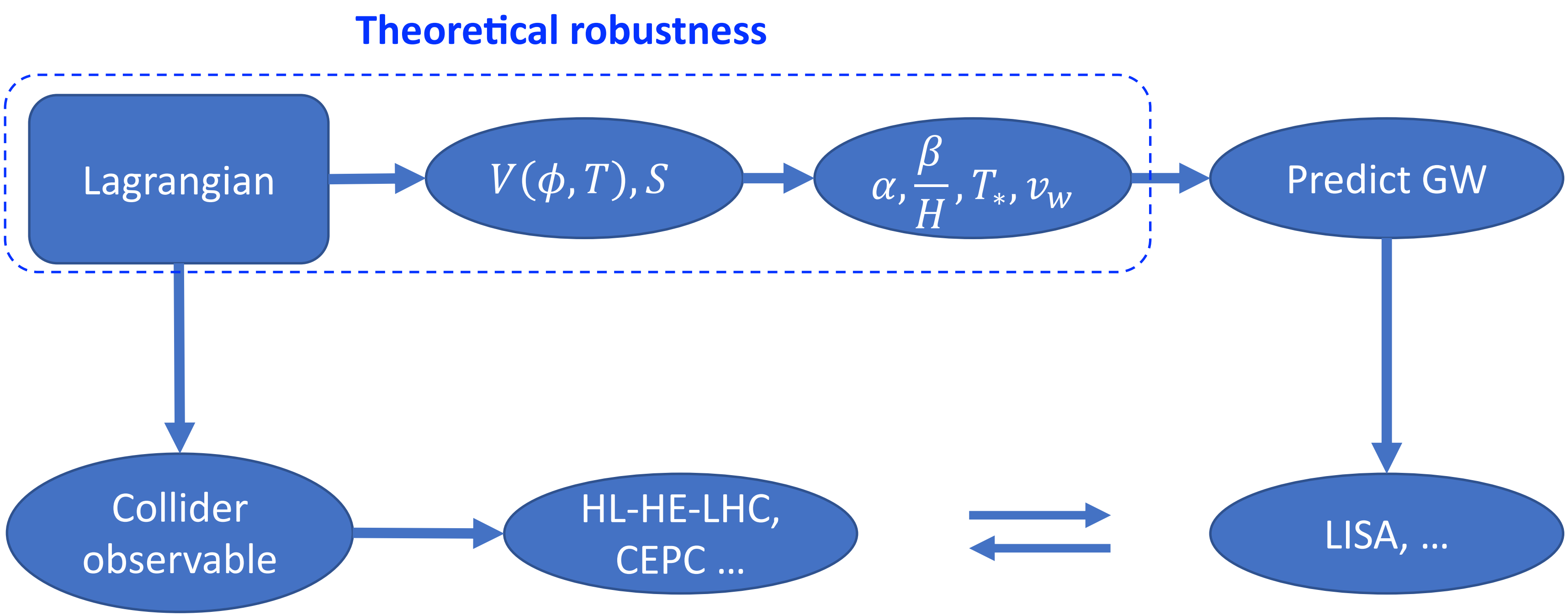
➢ FOEWPT can generates a stochastic background of GW which can be accessible by next-generation GW detector such as LISA



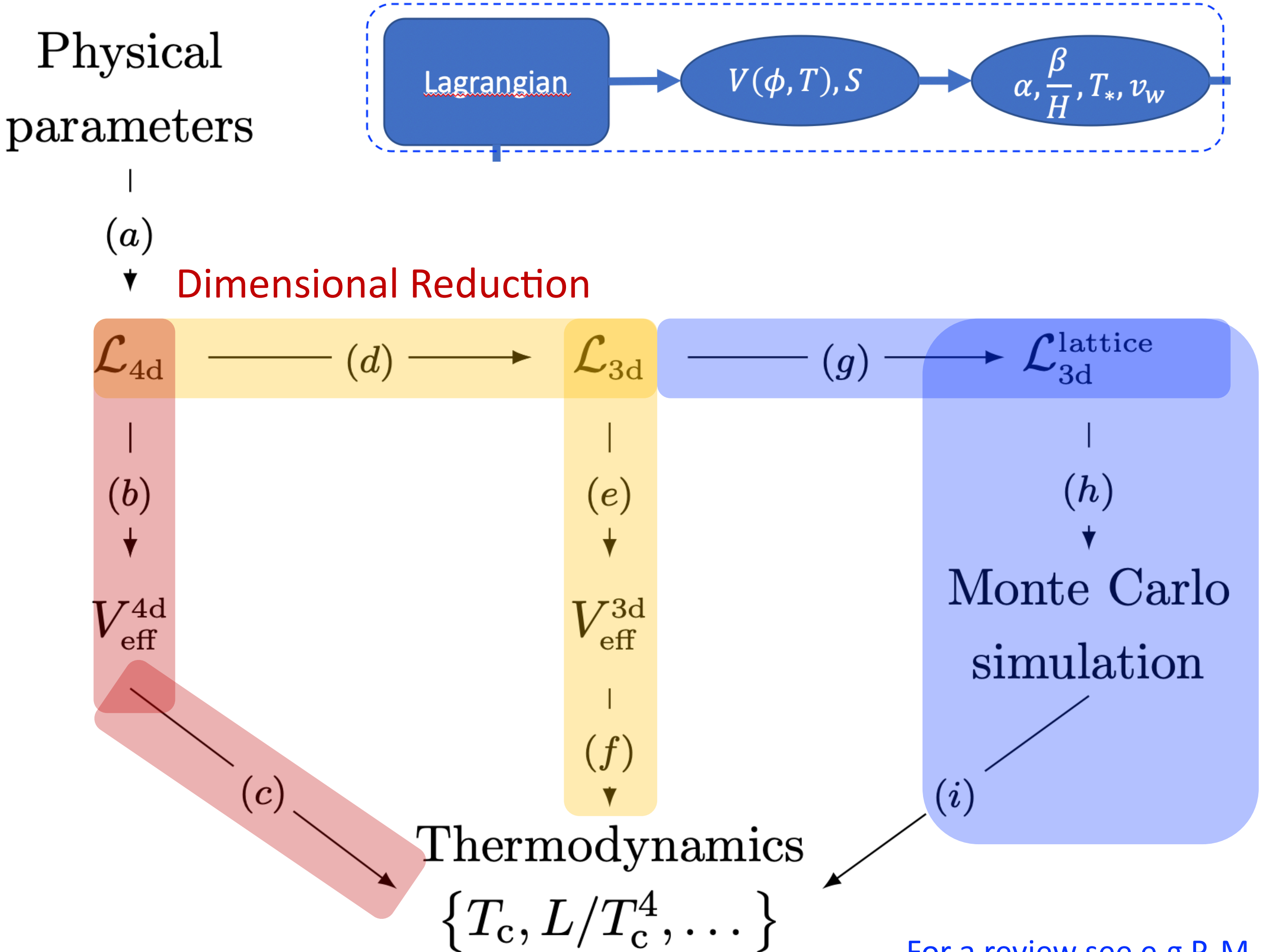
The kinetic energy of bubbles is transferred to GW either by:

- Bubble collisions
- Injection of energy into the plasma fluid

II. Theoretical Robustness



Approach towards thermodynamics



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

Non-perturbative vs Perturbative

A. Non-perturbative

- Most reliable determination of character of EWPT & dependence on parameters
- Broad survey of scenarios & parameter space not viable

B. Perturbative

- Most feasible approach to survey broad ranges of models, analyze parameter space, & predict experimental signatures
- Quantitative reliability needs to be verified

Credit: MRM

Dimensional reduction

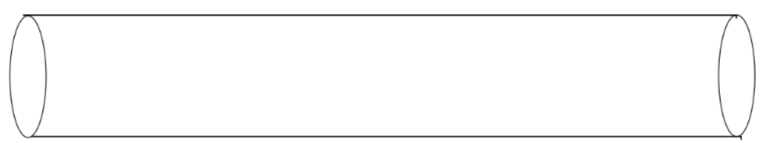
- Matsubara decomposition:

$$\phi(\tau, \mathbf{x}) = T \sum_n \tilde{\phi}(\mathbf{p}) e^{i\omega_n \tau}, \ \omega_n = \begin{cases} 2\pi n T & \text{bosons} \\ (2n+1)\pi T & \text{fermions} \end{cases}$$

- Propagators: $\dfrac{1}{\mathbf{p}^2 + m^2 + \omega_n^2}$

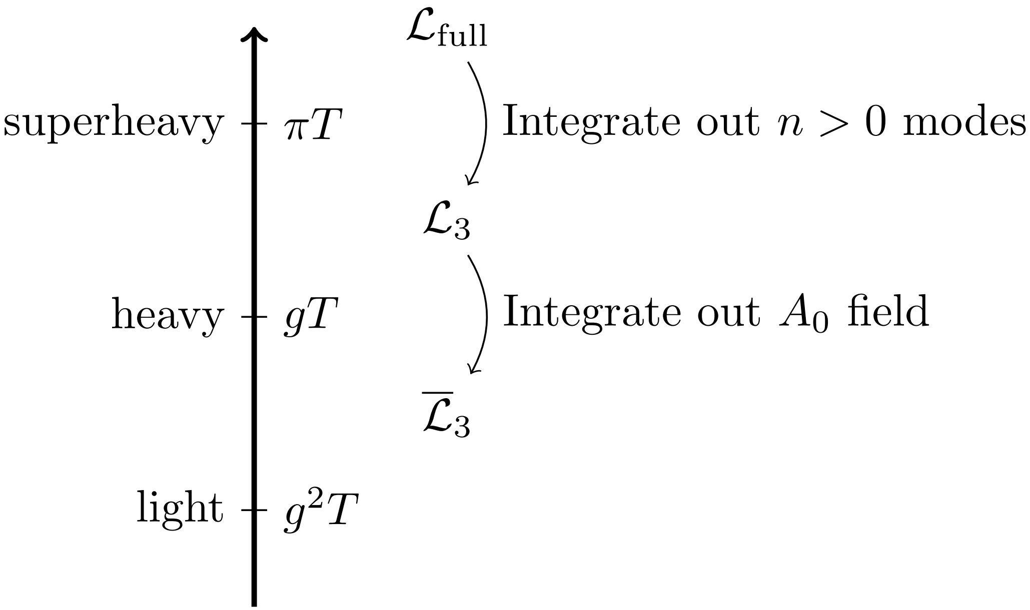
- Modes with $\omega_n \neq 0$ are heavy and decouple at distances $\gg 1/T \rightarrow$ can be integrated out! (dimensional reduction)

1/T



Taken from Tuomas

Dimensional reduction



Dimensional reduction

$\mathcal{L}_{\text{full}}$

superheavy — πT — Integrate out $n > 0$ modes

$\mathcal{L}_3$

heavy — gT — Integrate out A_0 field

$\overline{\mathcal{L}}_3$

light — $g^2 T$

Thermal resummations: systematically implemented

Dimensional reduction

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

Dimensional reduction

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

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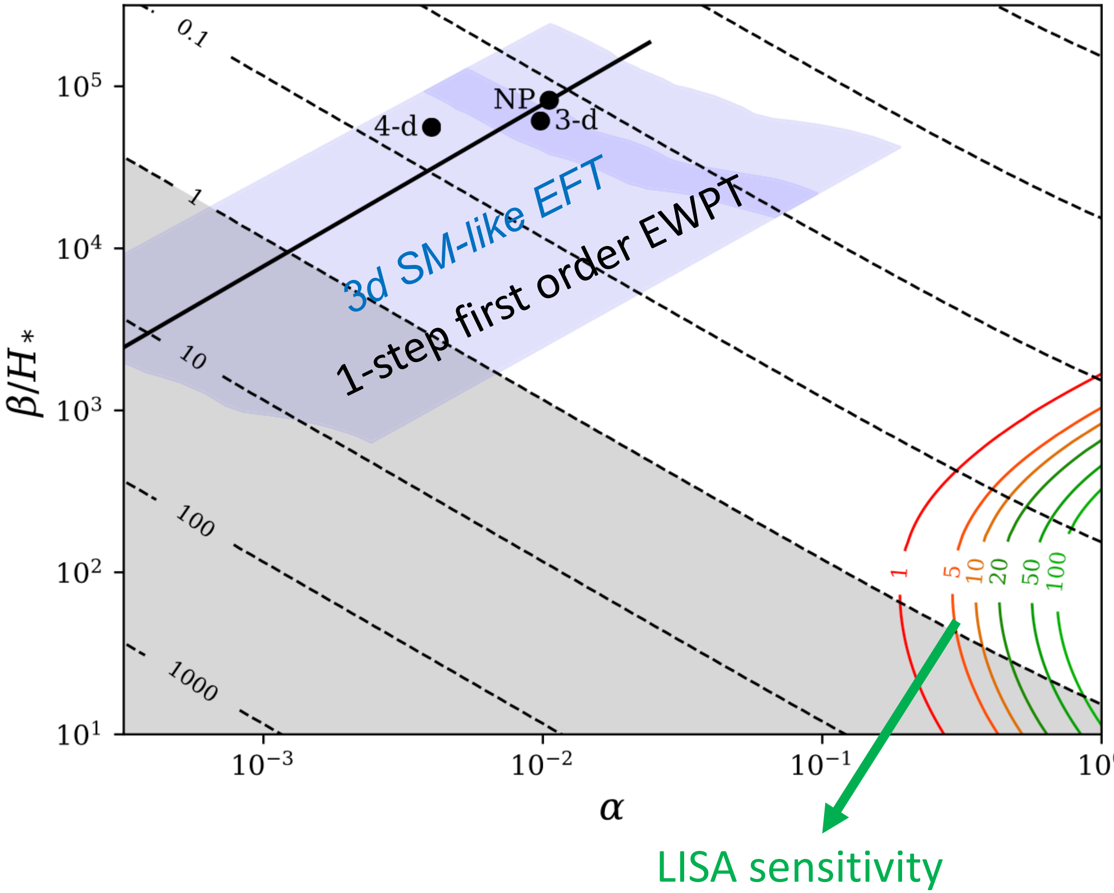
Effective "SM-like" theory parameters are functions of BSM parameters

Use existing lattice computations for SM-like effective theory & matching onto full theory to determine FOEWPT-viable parameter space regions

Lattice simulations exist (e.g., Kajantie et al '95)

Heavy BSM scalar

O. Grould, J.Kozaczuk, L.Niemi, M.J.Ramsey-Musolf, T.V.I Tenkanen, D.J.Weir arXiv:1903.11604



Heavy BSM scalar

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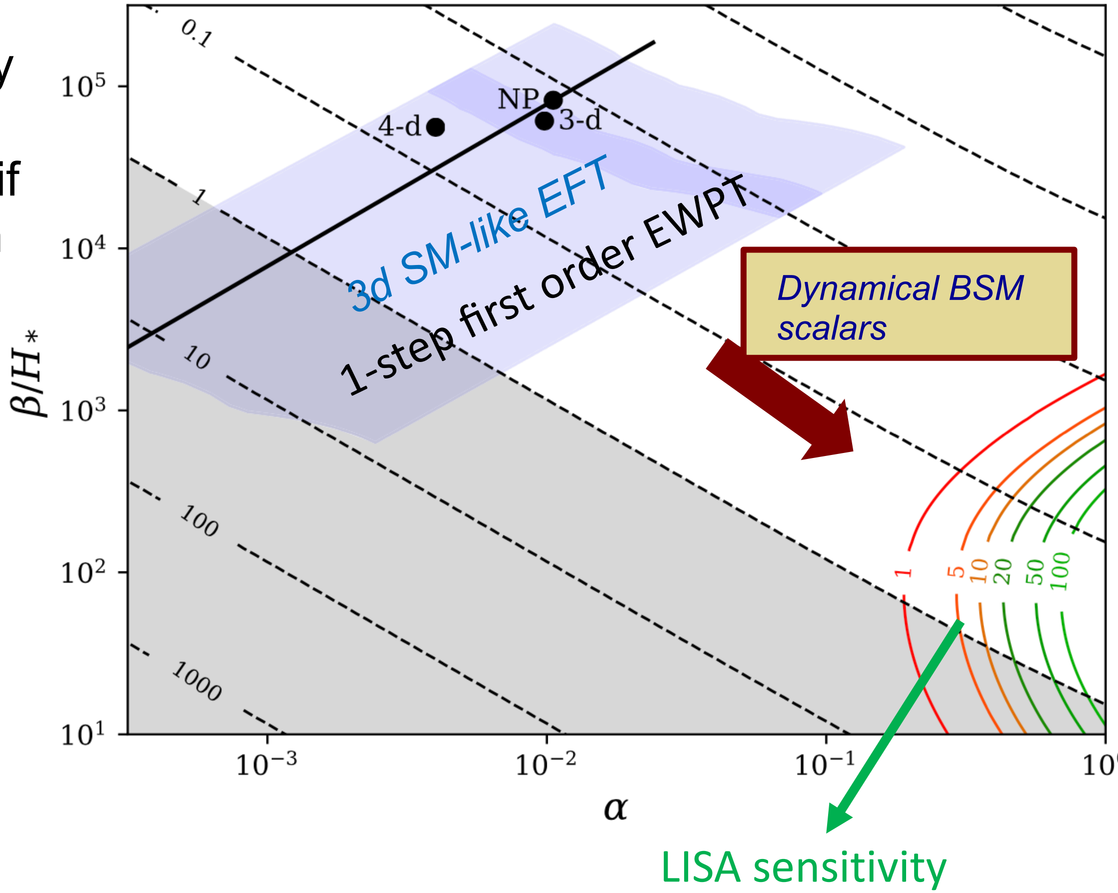
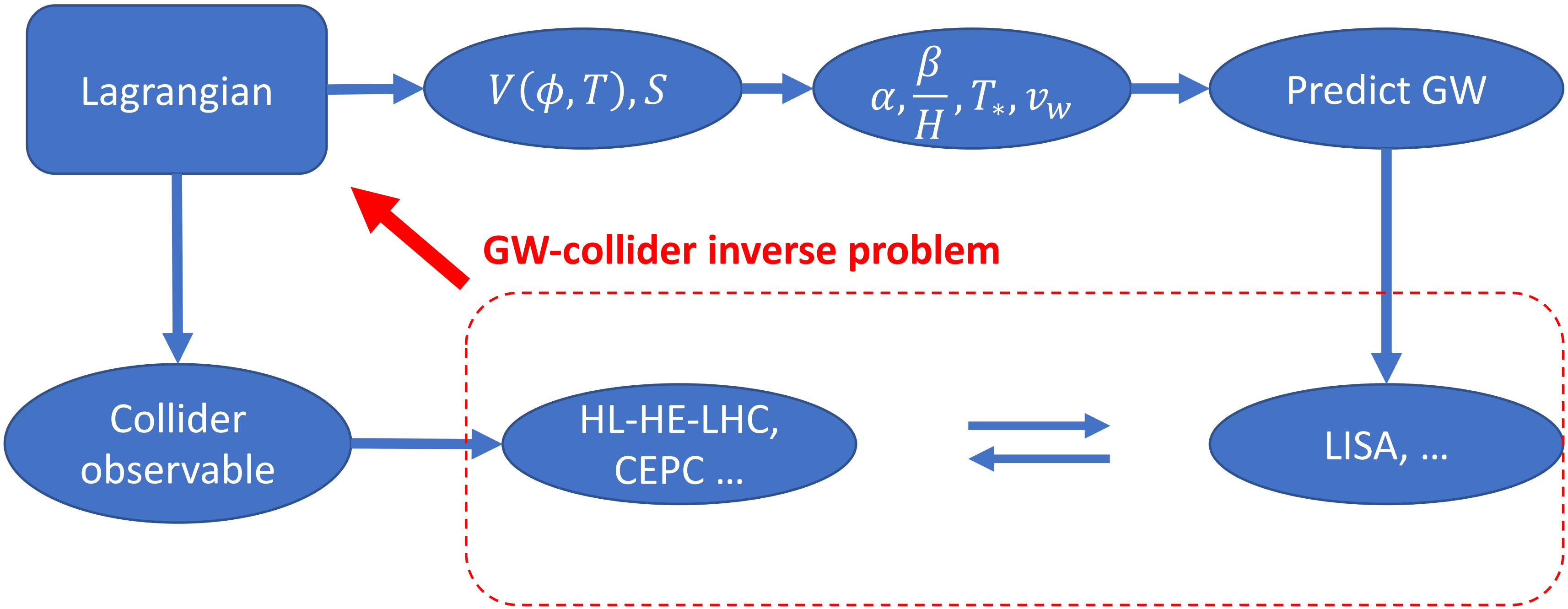
O. Grould, J.Kozaczuk, L.Niemi, M.J.Ramsey-Musolf, T.V.I Tenkanen, D.J.Weir arXiv:1903.11604

- A GW signal detectable by LISA generation experiments is likely only if new scalar is light enough to be dynamical



III. GW-collider inverse problem



Triplet scalar extension model

Scalar field content:

P. Fileviez Pérez, H.Patel, M.J. Ramsey-Musolf, K. Wang. PRD 79 (2009), 055024

$$H = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v_0 + h + i\phi^0) \end{pmatrix}, \qquad \vec{\Sigma} = \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 + x_0 \end{pmatrix},$$

Higgs doublet

SU(2) triplet

$$\Sigma^\pm = (\sigma_1 \mp i\sigma_2)/\sqrt{2} \quad \text{and} \quad \Sigma^0 = \sigma_3,$$

$$\Sigma = (1, \mathbf{3}, 0) = \vec{T} \cdot \vec{\Sigma} = \frac{1}{2} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

Scalar potential:

Standard model

new particle mass + self coupling

Higgs portal interaction

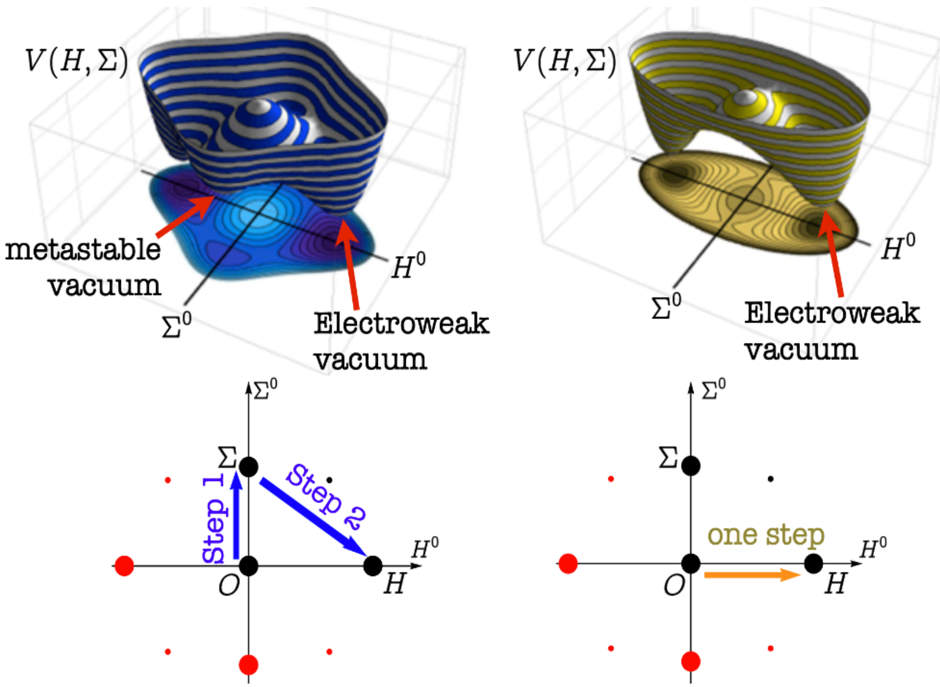
$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^4 \boxed{- \frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2} \boxed{+ a_1 H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2}$$

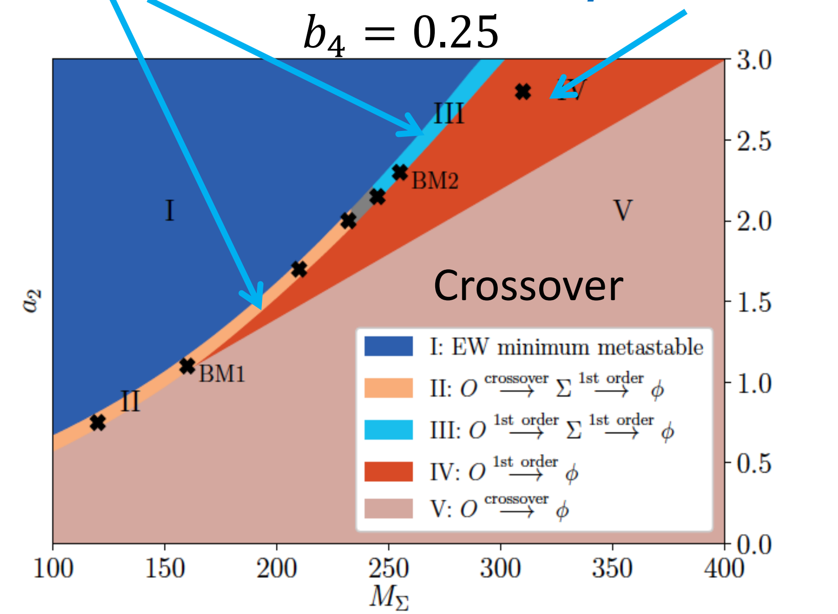
Four unmeasured parameters: $\mu_\Sigma^2, a_1, a_2, b_4$

Breaks Z_2 symmetry

Patterns of phase transition

H.Patel, M.J. Ramsey-Musolf, PRD 88 (2013), 035013





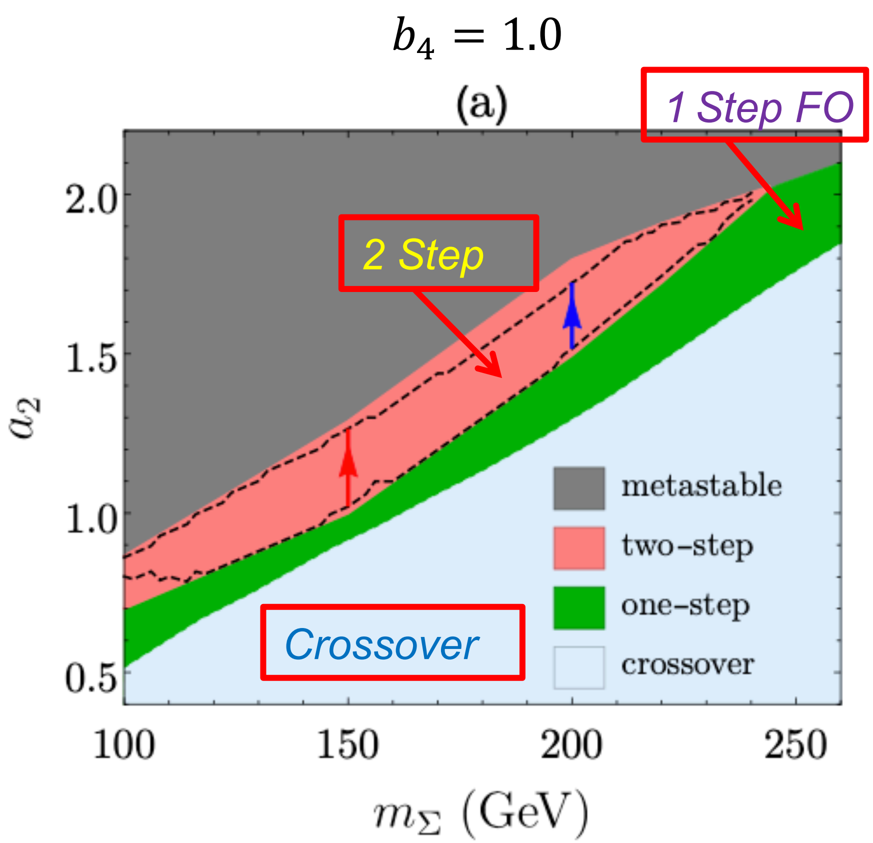
Non-perturbative

- Possibility of multiple step transition has been confirmed by lattice simulation L. Niemi, M. Ramsey-Musolf, T. Tenkanen, D. Weir, PRL 126, 171802 (2021)

Phase structure diagram

EFT+ Non-perturbative

Friedrich, MJRM, Tenkanen, Tran 2203.05889



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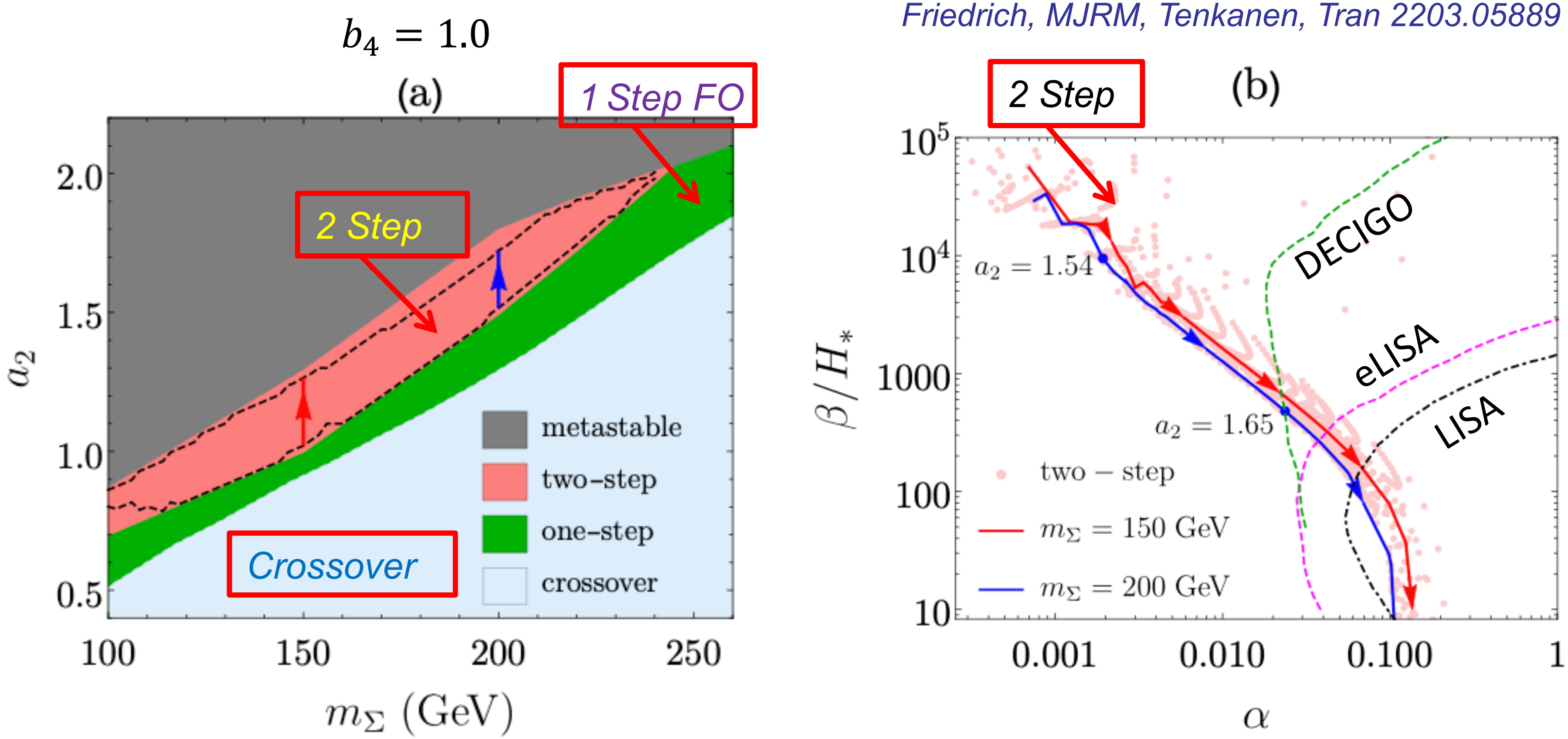
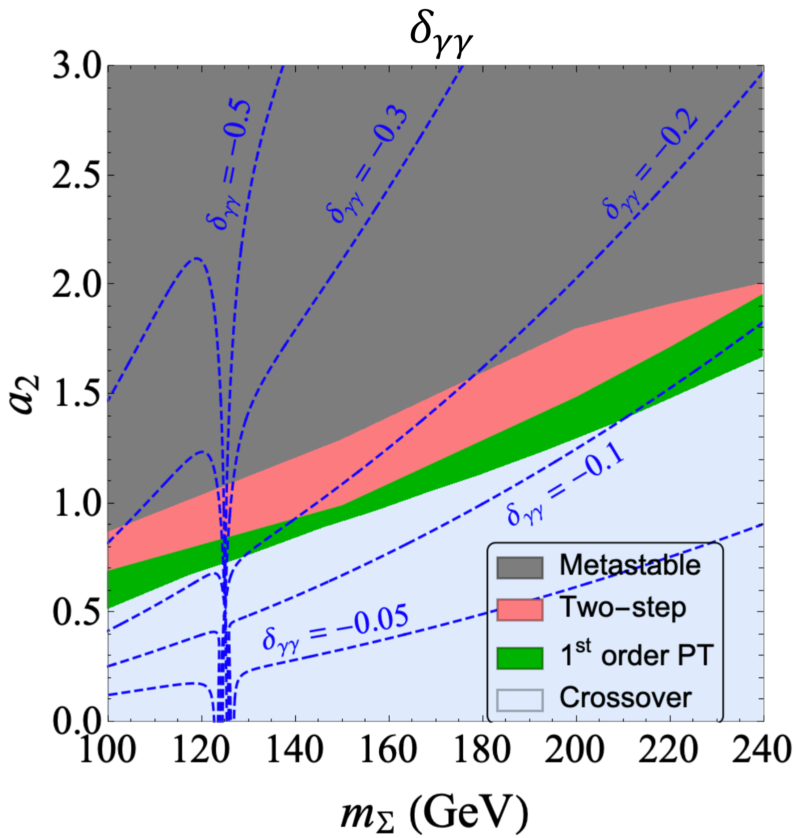
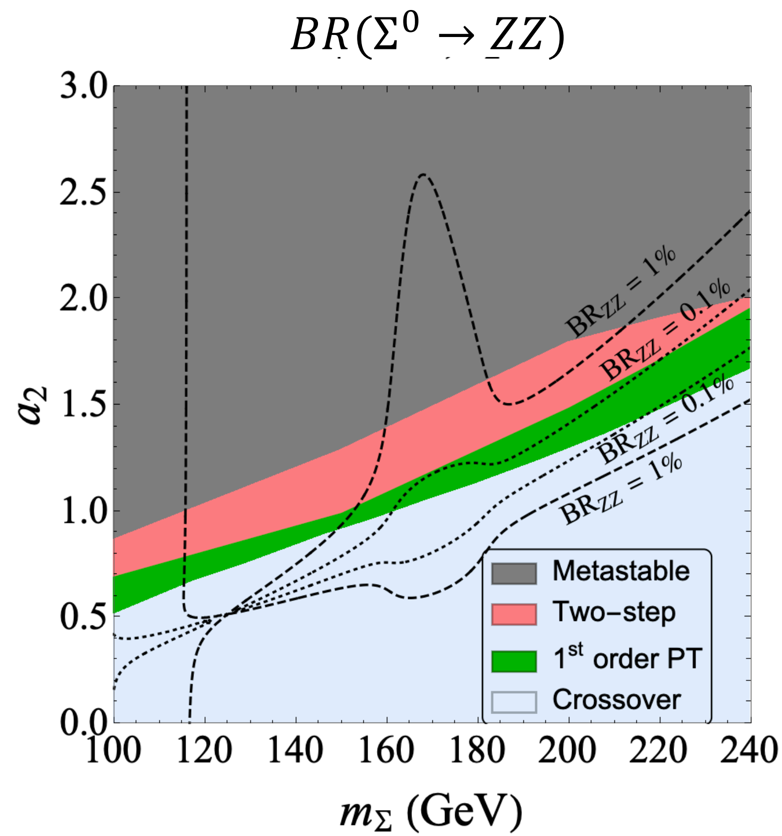
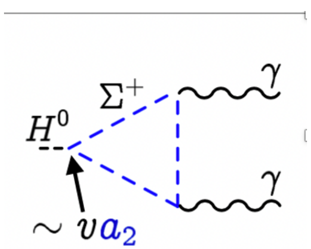


- **Strength and duration of the transition depend strongly on a_2**

Collider search



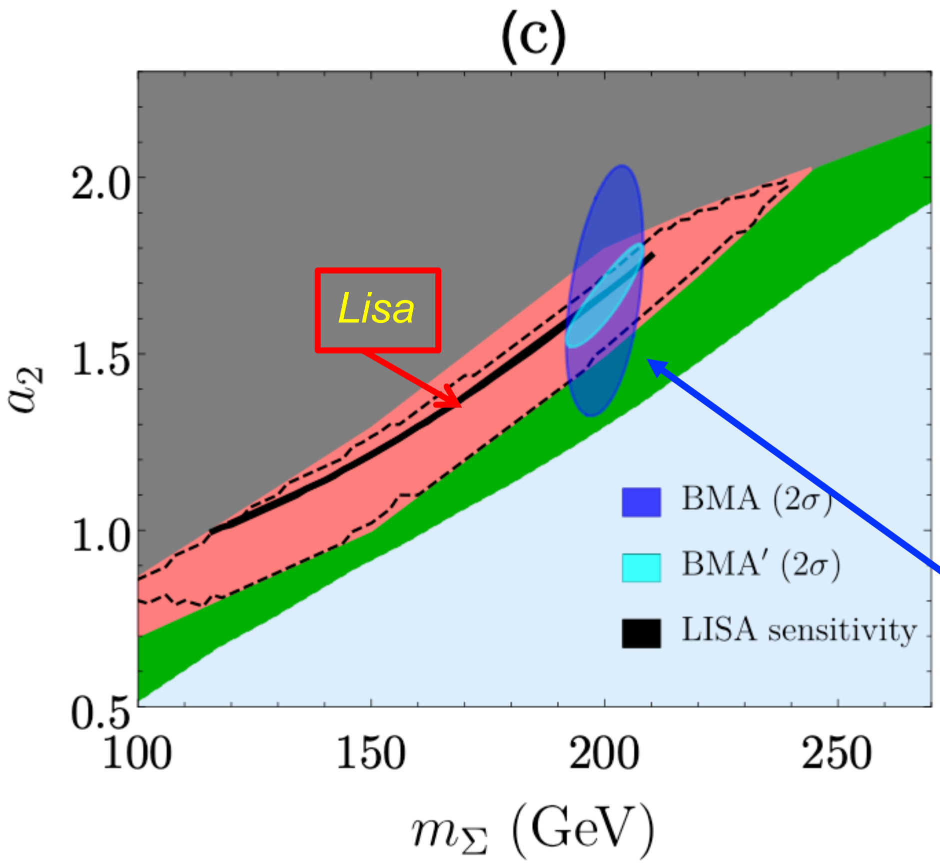




$$\delta_{\gamma\gamma} \equiv \frac{\Gamma^{\Sigma\mathrm{SM}}_{h\to\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{h\to\gamma\gamma}} - 1.$$

These observables can be measured at **future colliders** such as HL-LHC and CEPC

Combination of GW-collider



Hypothetical set of measurements:

$$\delta_{\gamma\gamma} = -0.132 \pm 0.015,$$
$$m_\Sigma = (200 \pm 5)\ \text{GeV}$$
$$\text{BR}(\Sigma^0 \to ZZ) = 0.01 \pm 0.002,$$

FCC-ee

BMA: $m_\Sigma + \delta_{\gamma\gamma}$

BMA' : BMA + $BR(\Sigma^0 \to ZZ)$

- GW-collider overlapped → model is responsible to both GW and collider signals
- If collider observed triplet scalar but the collider regions don't overlap with LISA region → model is not responsible to GW signal → need another BSM

Summary

- Determining the thermal history of EWSB is not only theoretically interesting but also practical importance for GW
- We used the EFT and non-perturbative calculation for determining the nature of EWPT in BSM.
- We provide a roadmap for analyzing the interplay between future collider observations and the detection of a GW signal produced by a 1^{st} OEWPT.
- We show that a combination of collider and GW measurements can determine the parameter space in a real scalar triplet extension.

Thank You

Backup slides

EWPT: collider target

- FOEWPT could be probed by collider and GW detectors.
  - FOEWPT occurred at EW scale and new physics couples quite strongly to Higgs -> probed by future collider detectors.

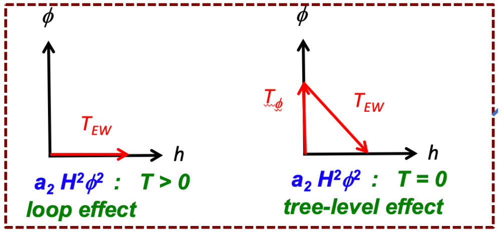
    - Set scale for collider

$$V(h,T)_{\rm SM} = D(T^2 - T_0^2)\, h^2 + \lambda\, h^4$$

$$T_0^2 = (8\lambda + \text{ loops})\left(4\lambda + \frac{3}{2}g^2 + \frac{1}{2}g'^{\,2} + 2y_t^2 + \cdots\right)^{-1} v^2$$

$$\boxed{T_{\rm EW} \equiv T_0 \approx 140\ \text{GeV}}$$

    - New scalar mass should **not be too heavy**



Mass new scalar < 700 GeV

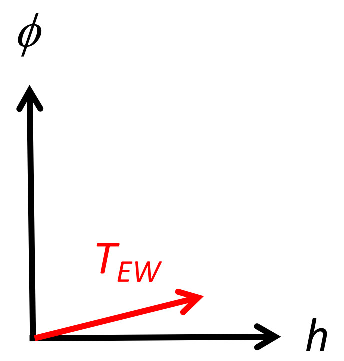
Michael J. Ramsey-Musolf: *1912.07189*

EWPT: collider target

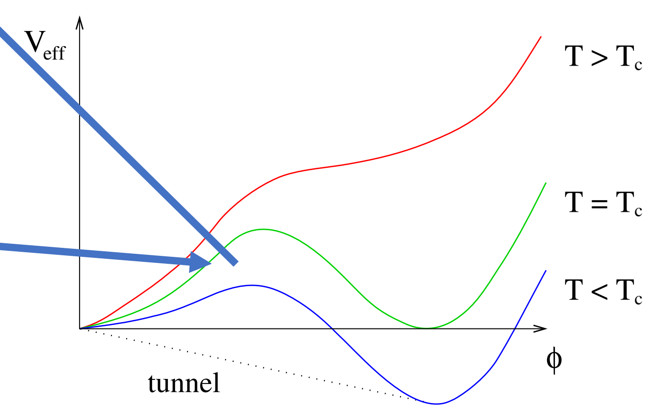
Michael J. Ramsey-Musolf: *1912.07189*

- For a strong 1st OEWPT: prevent baryon number washout

$$\frac{\bar{v}(T_{\rm EW})}{T_{\rm EW}} \gtrsim 1 \longrightarrow \boxed{\frac{|a_1|}{2\lambda T_{\rm EW}} \gtrsim 1} \longrightarrow \boxed{\begin{array}{l} |\sin\theta| \gtrsim 0.01 \\ |\Delta\lambda/\lambda| \gtrsim 0.003 \end{array}}$$

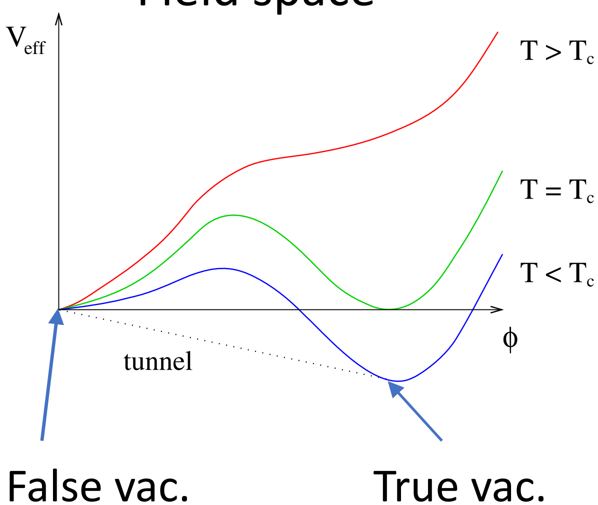


$a_1\, H^2\phi$: $T = 0$
tree-level effect

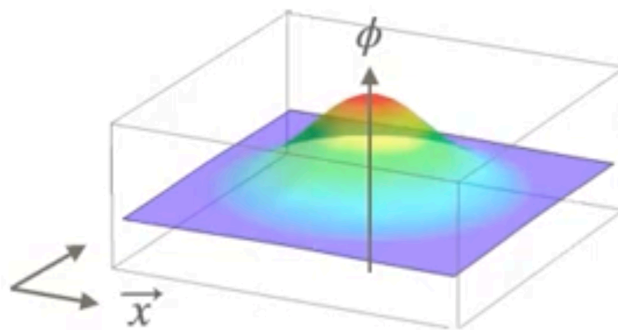


GW from 1st order EWPT

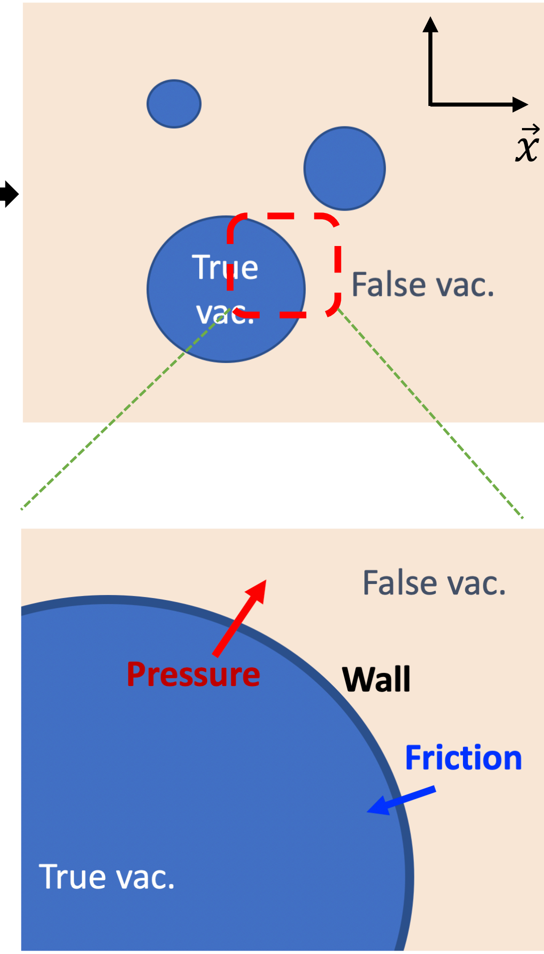
Field space



Position space



Bubble nucleation



- A 1st order phase transition proceeds by nucleation of bubbles.
- The bubble nucleation rate per unit volume per unit time

$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$$

$S_3(T)$: the three dimensional Euclidean action