Was There an Electroweak Phase Transition ?

M.J. Ramsey-Musolf

- T.D. Lee Institute/Shanghai Jiao Tong Univ.
- UMass Amherst
- Caltech

About MJRM:

Science

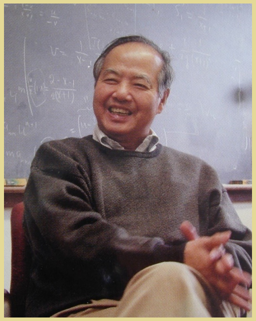
Family

Friends

My pronouns: he/him/his
 # MeToo

Sichuan University Seminar
December 15, 2023

T. D. Lee Institute / Shanghai Jiao Tong U.



A point of convergence of the world's top scientists

A launch pad for the early-career scientists

Director

A world famous source of original innovation

Founded 2016

100+

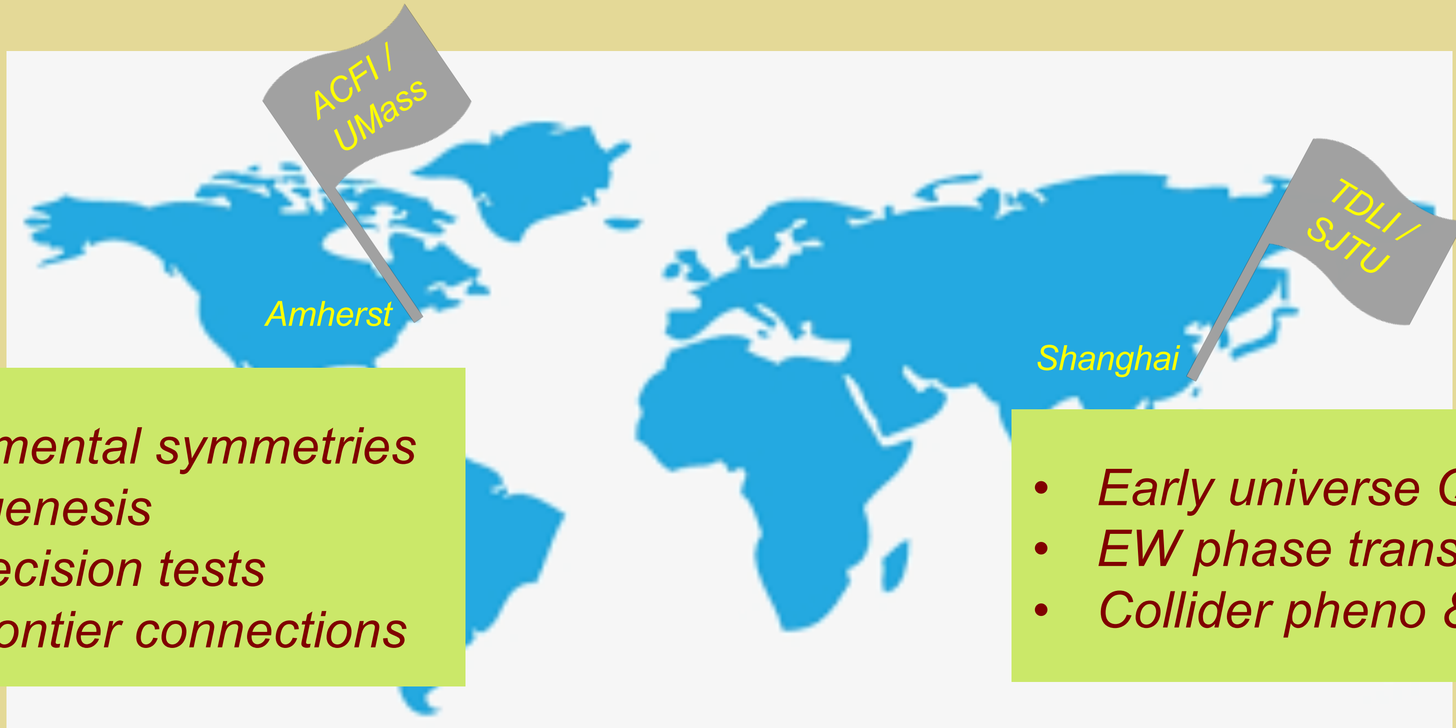
faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

Theory & Experiment

Particle & Nuclear Physics	Astronomy & Astrophysics	Quantum Science
Dark Matter & Neutrino	Laboratory Astrophysics	Topological Quantum Computation

https://tdli.sjtu.edu.cn/EN/

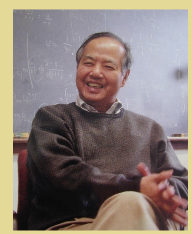
MJRM: Scientist & "Ambassador"



- *Fundamental symmetries*
- *Baryogenesis*
- *EW precision tests*
- *Inter-frontier connections*

- *Early universe QFT*
- *EW phase transition*
- *Collider pheno & Higgs*

- ***Global effort: 18 researchers***
- ***Foster scientific connections***
- ***Science First ! 科学 第一 ！***



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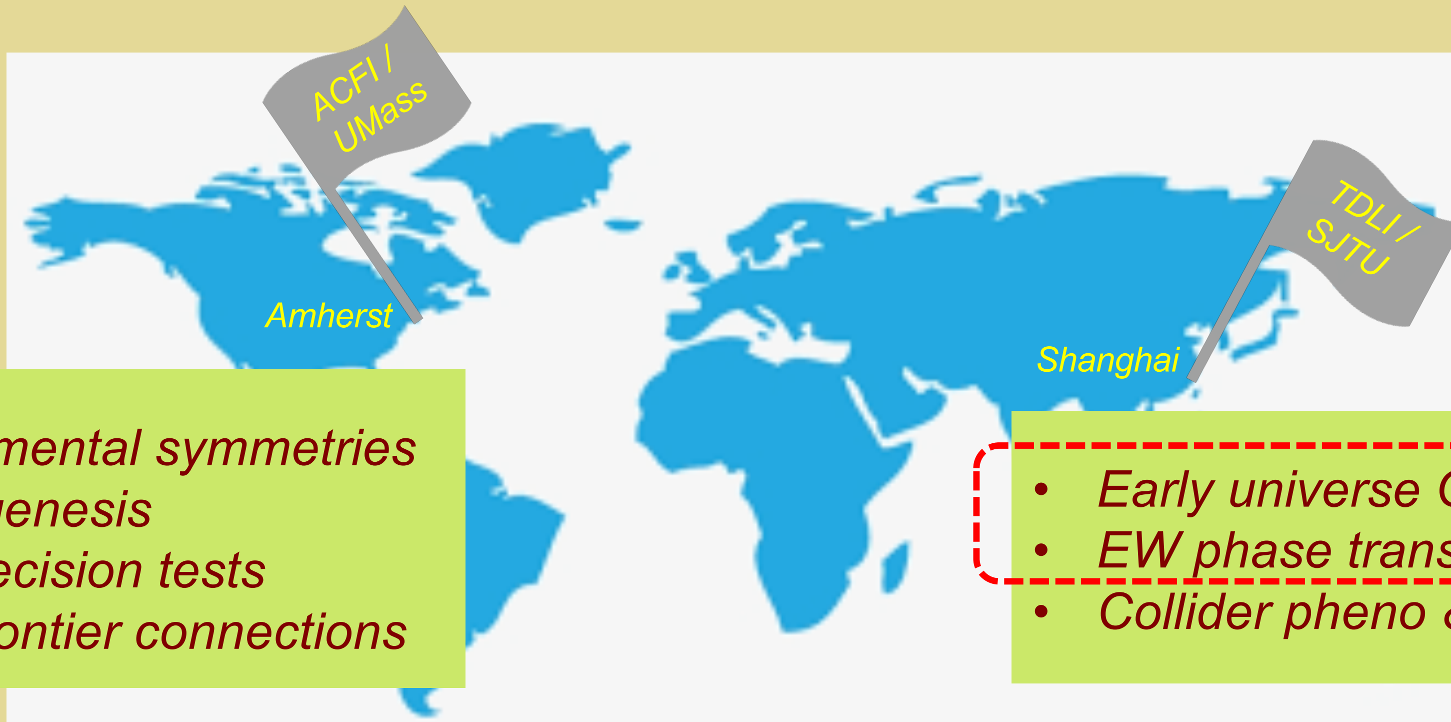

- *Fundamental symmetries*
- *Baryogenesis*
- *EW precision tests*
- *Inter-frontier connections*

Today

- *Early universe QFT*
- *EW phase transition*
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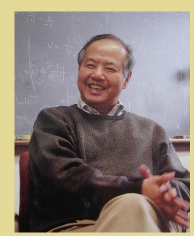
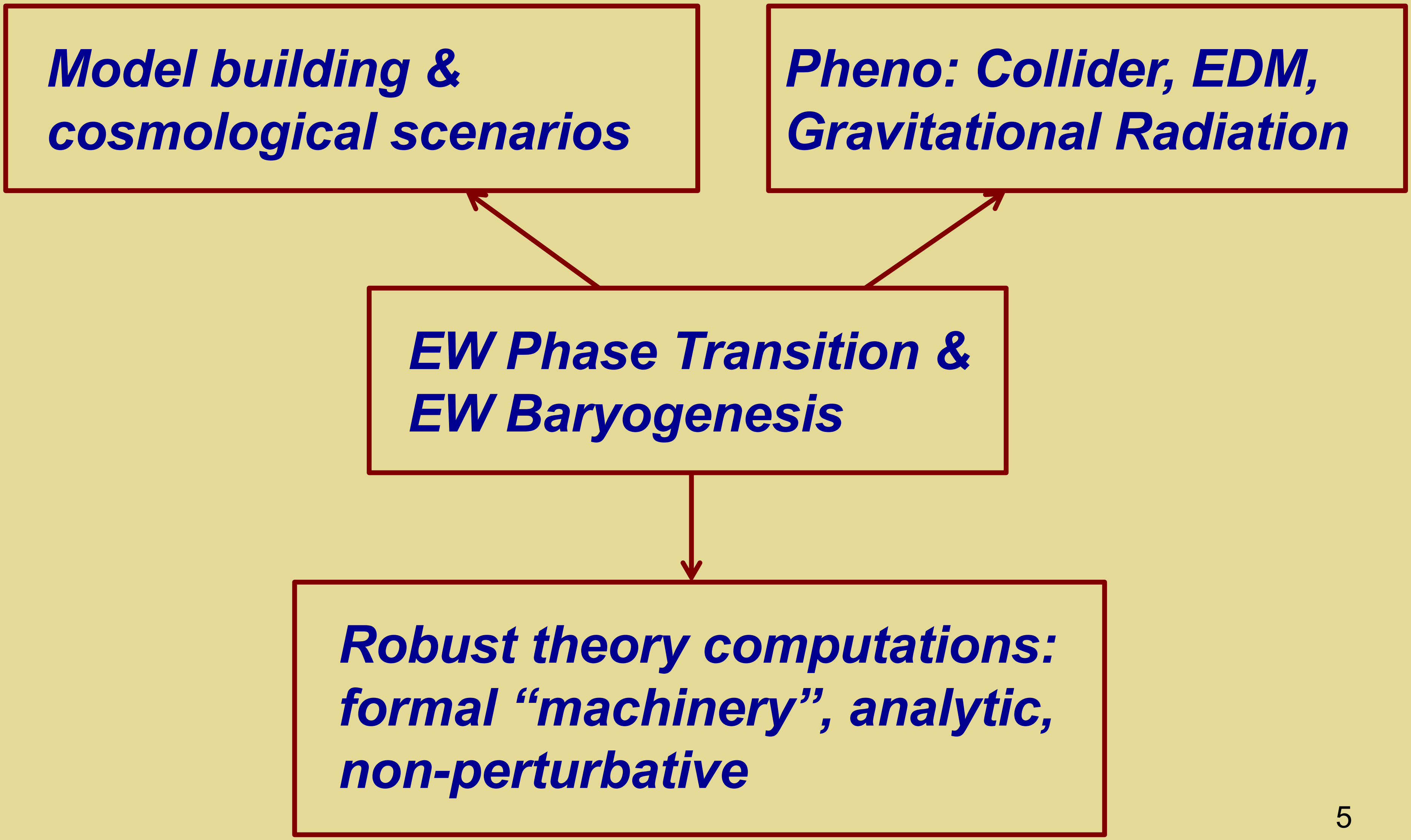


MJRM TDLI/SJTU Program



MJRM TDLI/SJTU Program

Model building & cosmological scenarios

Pheno: Collider, EDM, Gravitational Radiation

EW Phase Transition & EW Baryogenesis

This talk

Robust theory computations: formal "machinery", analytic, non-perturbative

Goals for this Talk

- *Motivate the scientific opportunity associated with a possible EWPT in BSM scenarios*
- *Introduce the EFTs used in studying the thermal history of EW symmetry breaking*
- *Illustrate the interplay with non-perturbative (lattice) computations*
- *Highlight recent results that draw on this interplay*

Key Ideas for this Talk

- The "electroweak temperature" → a scale provided by nature that gives us a clear BSM target for colliders & GW probes
- Simple arguments → BSM physics that changes the thermal history of EWSB cannot be too heavy or too feebly coupled to the SM
- Robust test of theory requires a new era of EFT & non-perturbative computations → new results highlight this theoretical frontier

Key Ideas for this Talk

- ***MJRM: 1912.07189***

- ***Recent EFT + Non-perturbative:***

  - ***L. Niemi, H.H. Patel, MJRM, T.V.I. Tenkanen, D. J. Weir: 1802.10500***
  - ***O. Gould, J. Kozaczuk, L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 1903.11604***
  - ***L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 2005.11332***
  - ***L. Friedrich, MJRM, T.V.I. Tenkanen, V.Q. Tran: 2203.05889***

- ***Nucleation & gauge invariance***

  - ***J. Lofgren, MJRM, P. Schicho, T.V.I. Tenkanen:2112.05472***
  - ***J. Hirvonen, J. Lofgren, MJRM, P. Schicho, T.V.I. Tenkanen: 2112.08912***

Acknowledgments

- Apologies for omissions of references to other important work

- Collaborators (this talk):

  - T. V. I. Tenkanen *
  - L. Niemi *
  - L. Friedrich *
  - V.Q. Tran *
  - G. Xia *
  - D. J. Weir
  - O. Gould
  - J. Kozaczuk
  - P. Schicho
  - J. Hirvonen
  - J. Lofgren
  - H. Patel
  - S. Arunasalam *

* TDLI / SJTU

Outline

I. Context & Questions

II. EWPT: A Collider & GW Target

III. Theoretical Robustness

IV. Gravitational Wave-Collider-Theory Interface

V. Outlook

Time permitting

I. Context & Questions

Electroweak Phase Transition

- *Higgs discovery $\to$ What was the thermal history of EWSB ?*
- *Baryogenesis $\to$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*
- *Gravitational waves $\to$ If a signal observed in LISA, could a cosmological phase transition be responsible ?*

Electroweak Phase Transition

- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*

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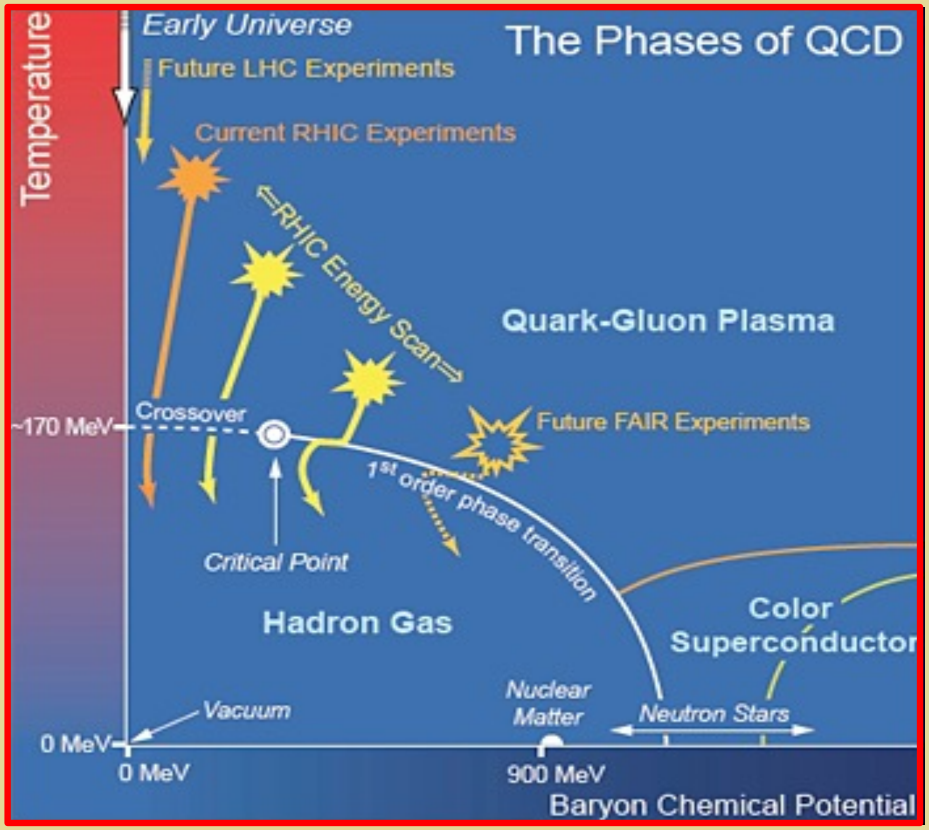
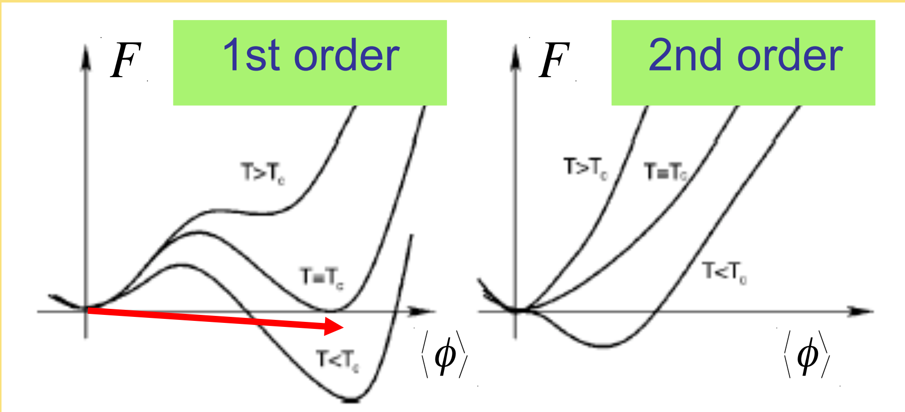
Thermal History of Symmetry Breaking



QCD Phase Diagram → EW Theory Analog?

EWSB Transition: St'd Model



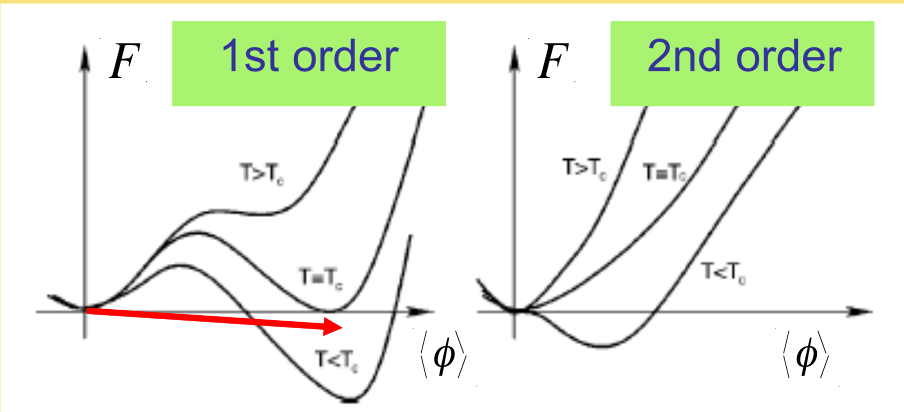
Increasing m_h →

Higgs potential: T=0

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$m_h^2 = 2\lambda v^2$$

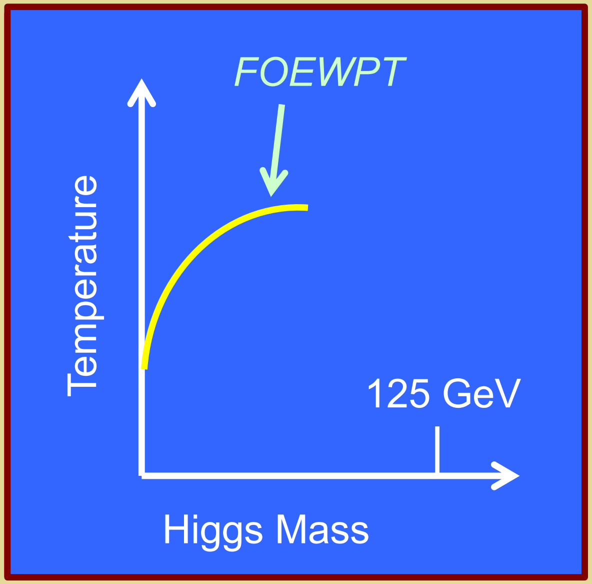
EWSB Transition: St'd Model



Increasing m_h ⟶

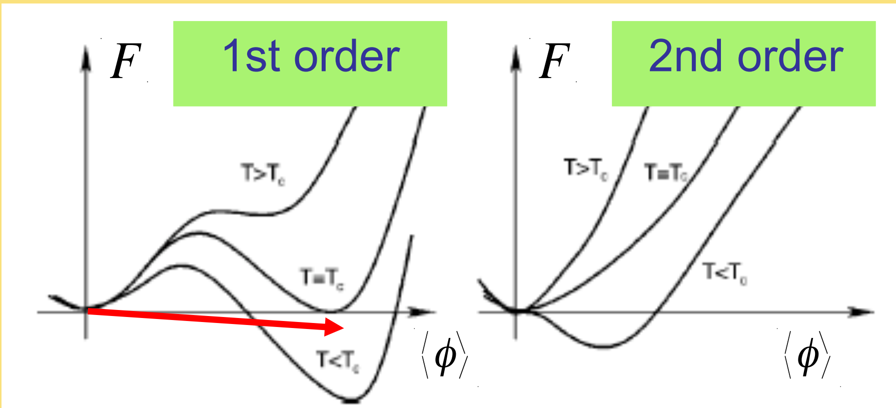
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition

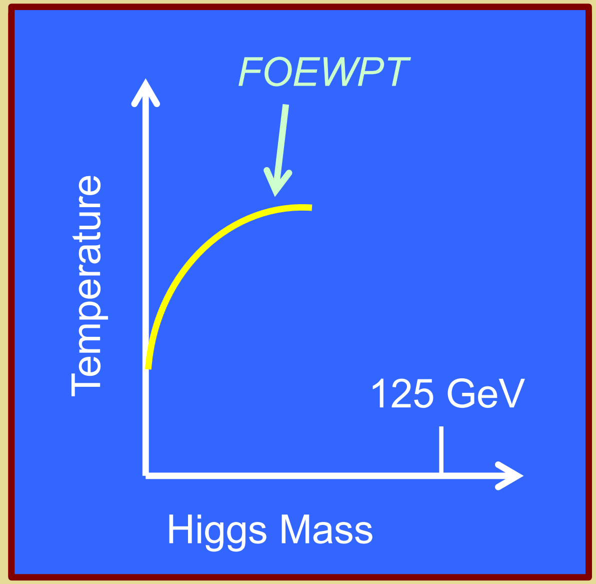


EW Phase Diagram

EWSB Transition: St'd Model



Increasing m_h →



EW Phase Diagram

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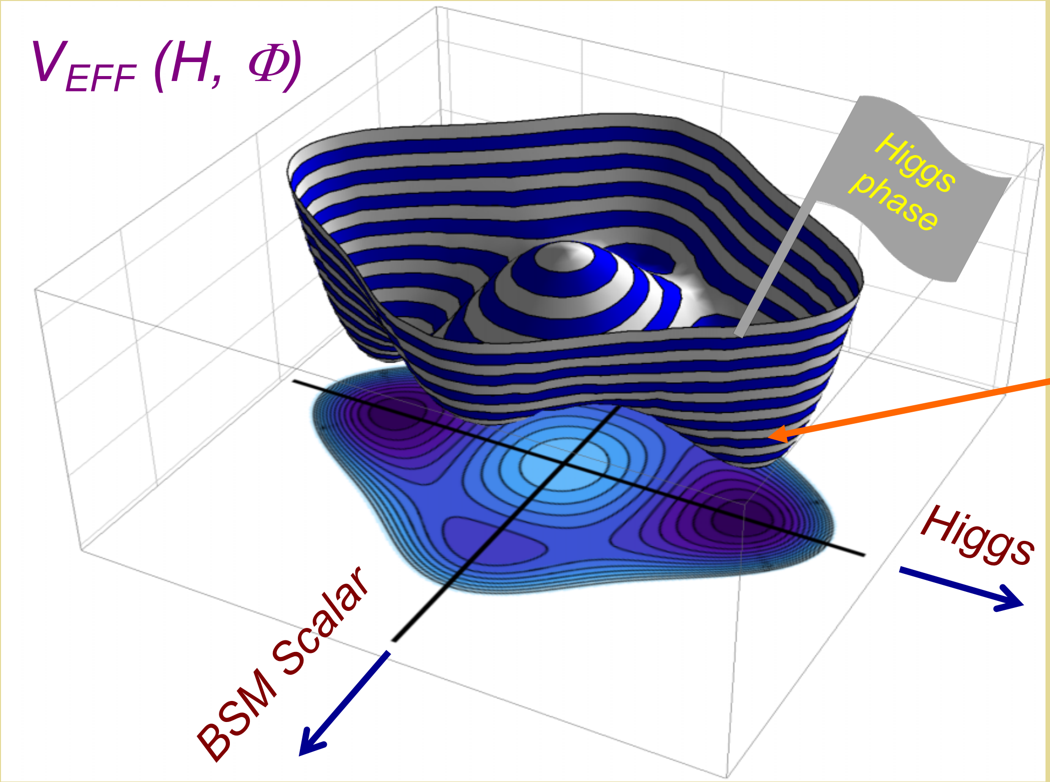
SM EW: Cross over transition

How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

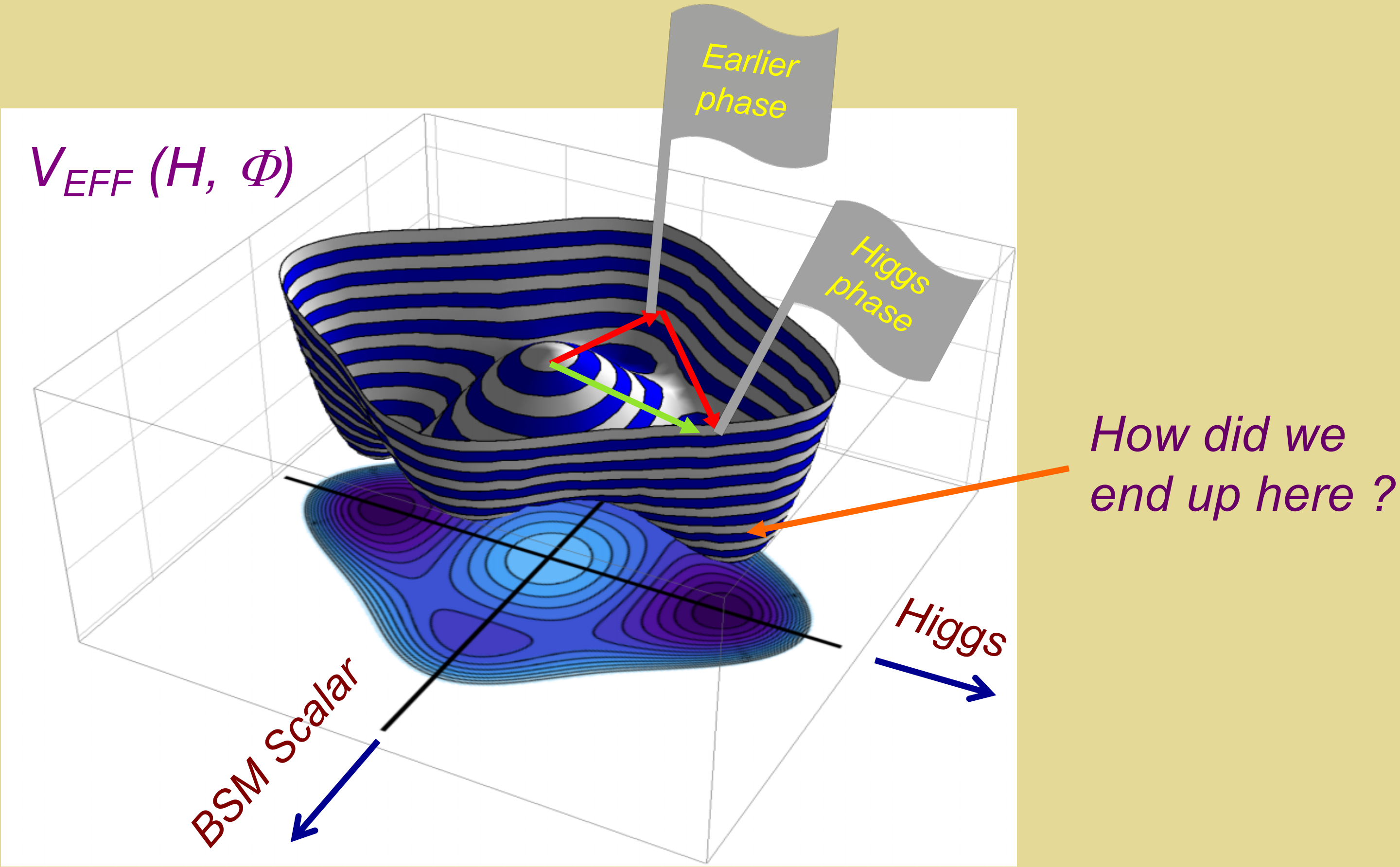
Patterns of Symmetry Breaking



How did we end up here ?

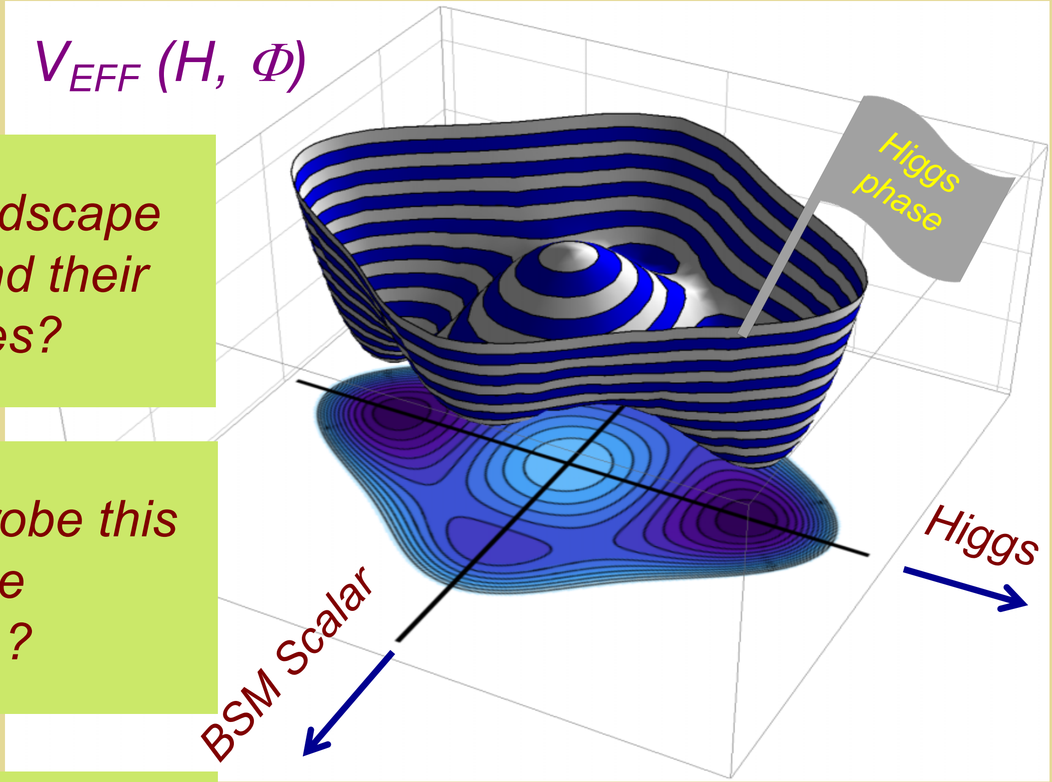
Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

Patterns of Symmetry Breaking



Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

Thermal History of EWSB



- *What is the landscape of potentials and their thermal histories?*
- *How can we probe this T > 0 landscape experimentally ?*
- *How reliably can we compute the thermodynamics ?*

n evolve differently as T evolves →
ilities for symmetry breaking

Electroweak Phase Transition

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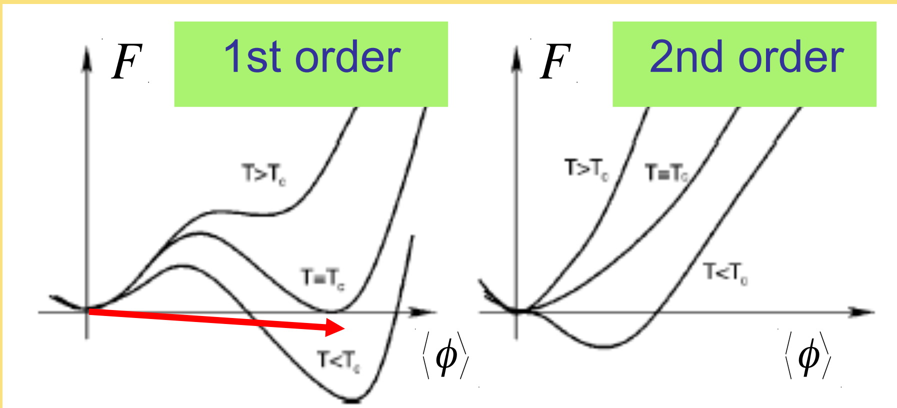
- *Gravitational waves $\rightarrow$ If a signal observed in LISA, could a cosmological phase transition be responsible ?*

EW Phase Transition: Baryogen & GW



Increasing m_h →

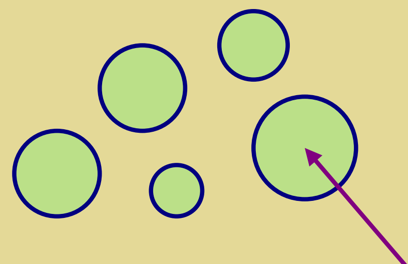
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" | *1st order EWPT*

- *Baryogen**
- *GW*

Bubble nucleation



EWSB

** Need BSM CPV*

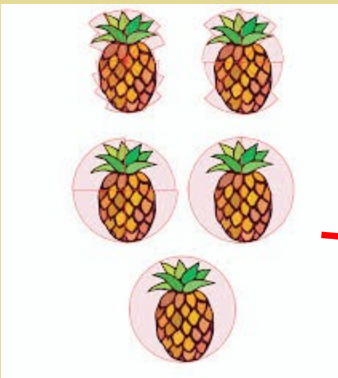
II. EWPT: A Collider Target

MJRM 1912.07189

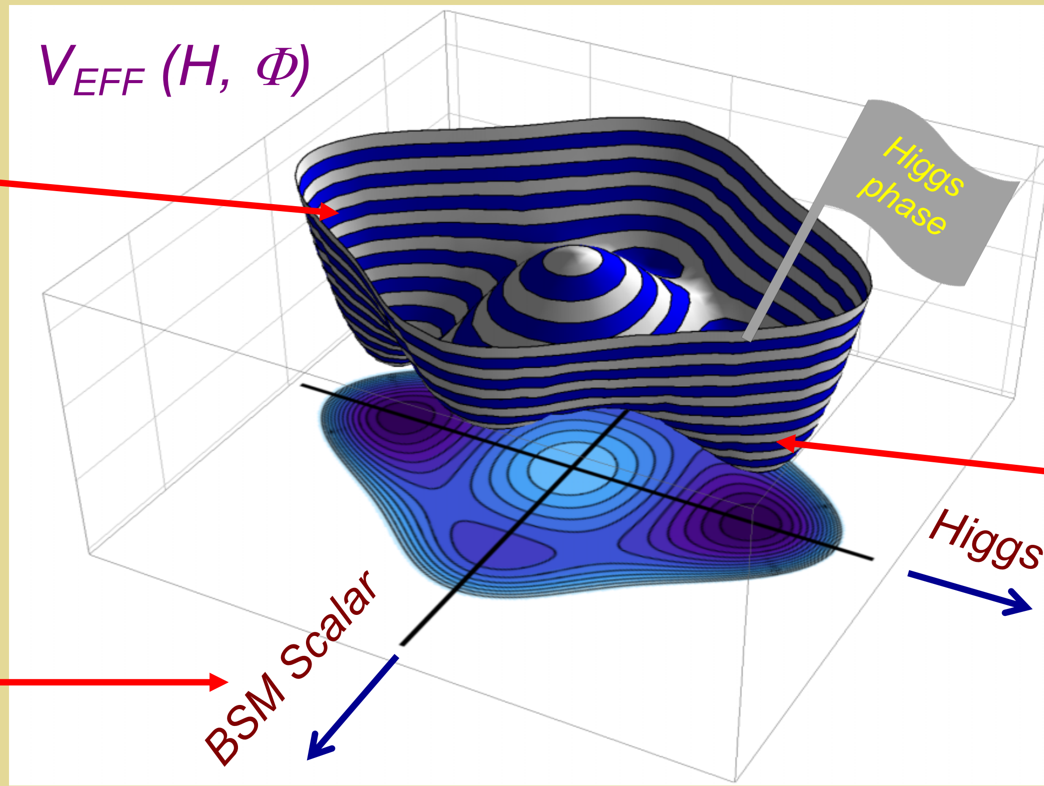
- ***Mass scale***
- ***Precision***

Experimental Probes

Bubble Collisions



Grav Radiation



Higgs precision tests

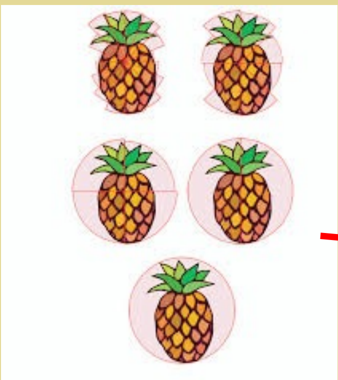
Direct Production

BSM Higgs

Extrema can evolve differently as T evolves → rich possibilities for symmetry breaking

Experimental Probes

Bubble Collisions



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Direct Production

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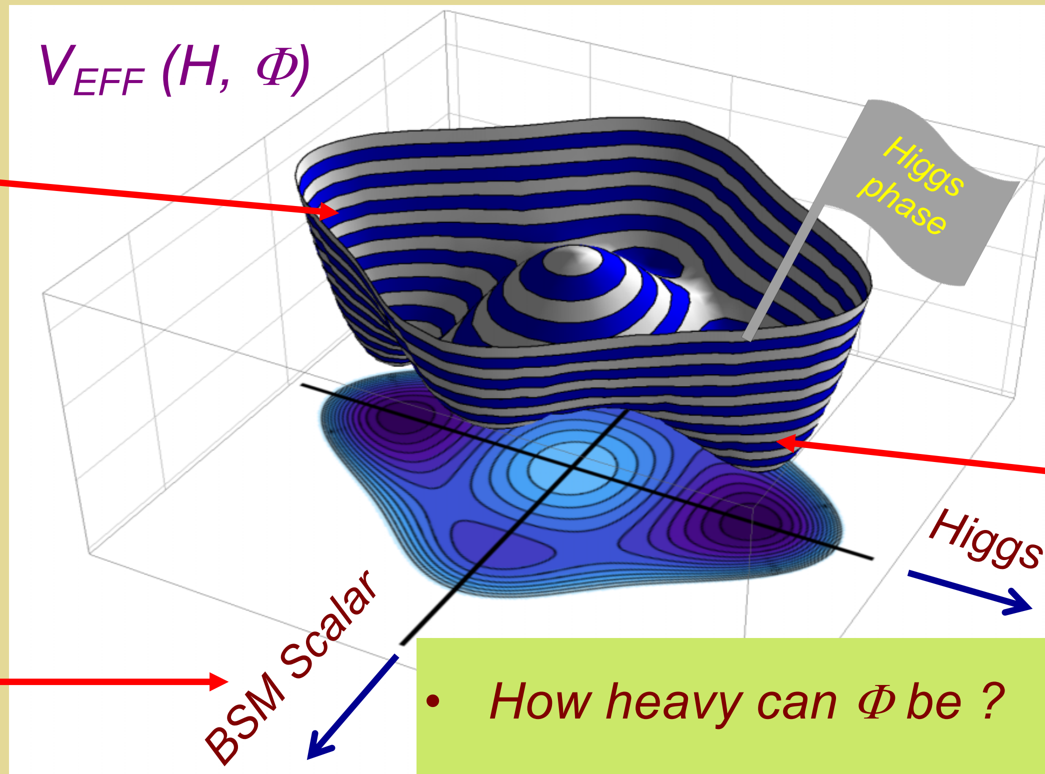


Higgs precision tests

- How heavy can Φ be ?
- How coupled to H ?
- Can it be discovered at the LHC or beyond ?

Extrema can evolv

rich possibilities f

→

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

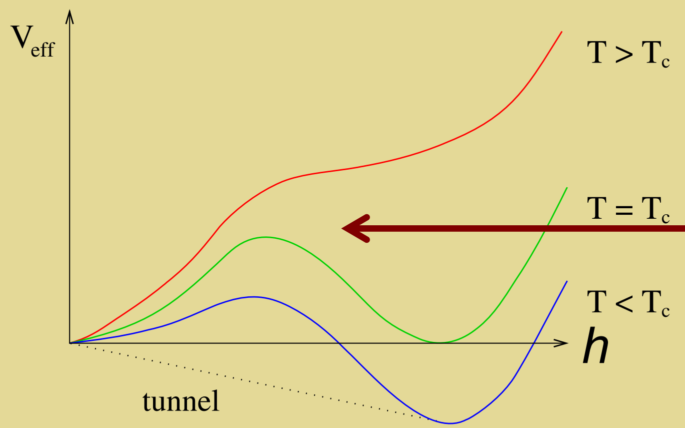
High-T SM Effective Potential

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

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

$T_0 \sim$ 140 GeV $\equiv$ **T_{EW}**

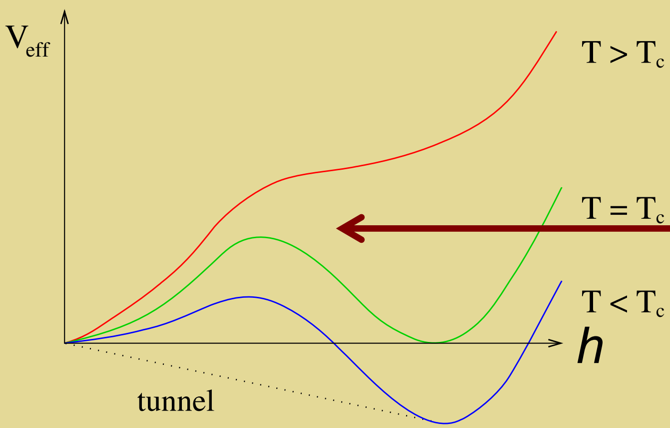
First Order EWPT from BSM Physics



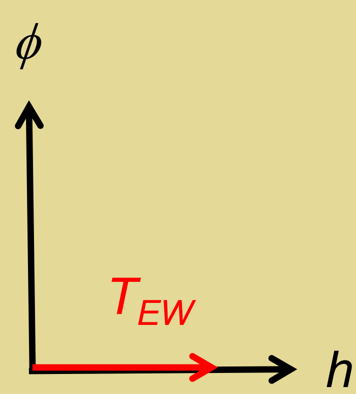
Generate finite-T barrier

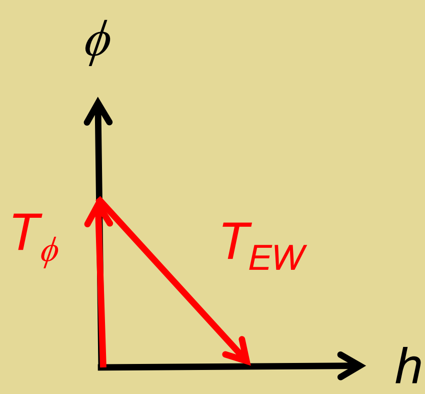
Introduce new scalar ϕ interaction with h via the Higgs Portal

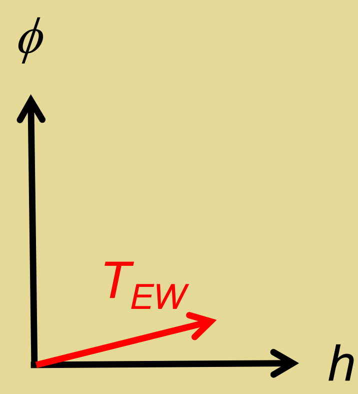
First Order EWPT from BSM Physics



Generate finite-T barrier





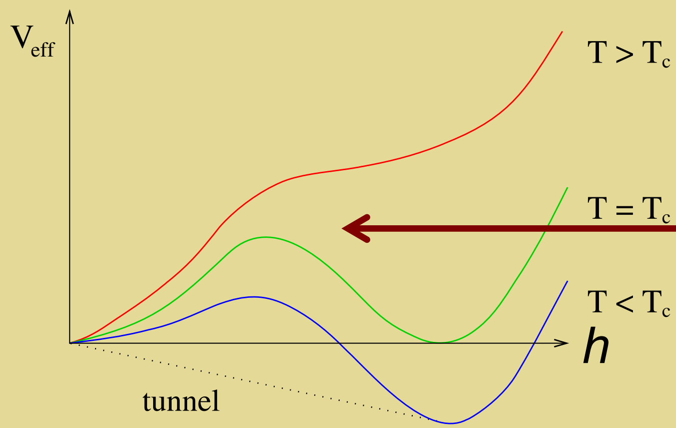


$a_2 H^2\phi^2$: $T > 0$
loop effect

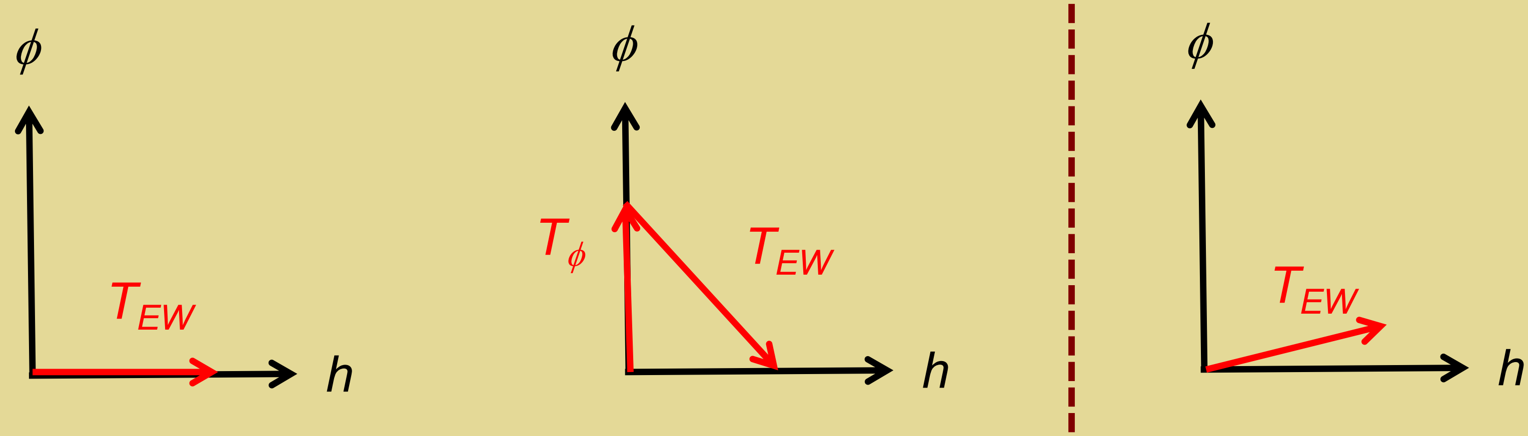
$a_2 H^2\phi^2$: $T = 0$
tree-level effect

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

First Order EWPT from BSM Physics



Simple arguments: T_{EW} + *first order EWPT* → $M_\phi \lesssim 700$ *GeV*



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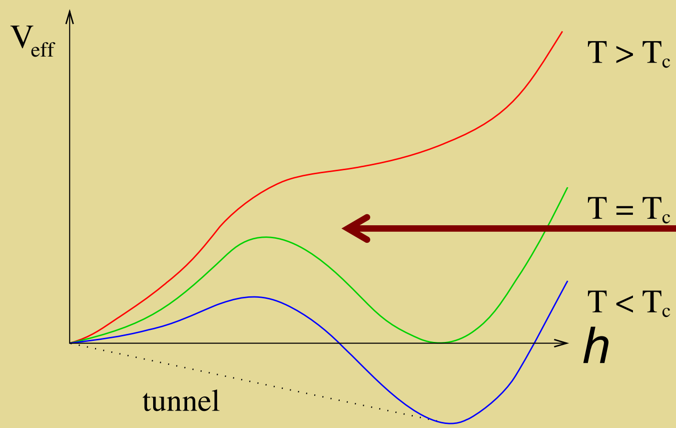
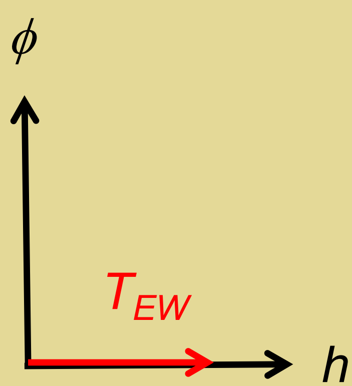
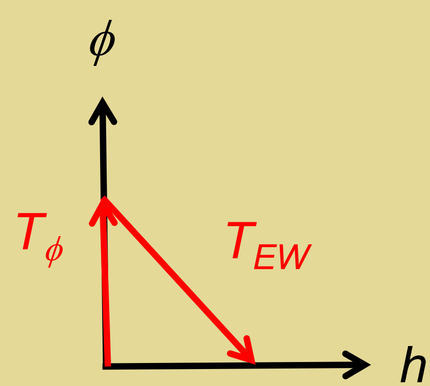


Higgs – ϕ^0 Mixing



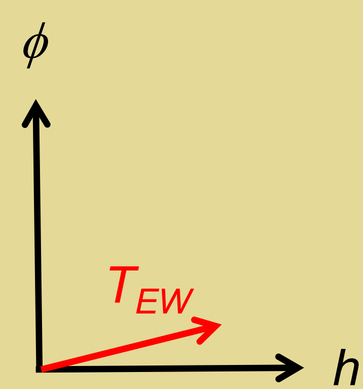
$a_2\, H^2\phi^2$: $T > 0$

loop effect



$a_2\, H^2\phi^2$: $T = 0$

tree-level effect



$a_1\, H^2\phi$: $T = 0$

tree-level effect

Strong First Order EWPT

- **Prevent baryon number washout**
- **Observable GW**

Collider Target: Precision and single ϕ production

$$\frac{|a_1|}{2\lambda T_{\mathrm{EW}}} \gtrsim 1$$

→

$| \sin\theta | \gtrsim 0.01$

$| \Delta\lambda / \lambda | \gtrsim 0.003$

Models & Phenomenology

What BSM Scenarios?

SM + Scalar Singlet

Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17, Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir 19...

SM + Scalar Doublet (2HDM)

Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Fromme, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18...

SM + Scalar Triplet

Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 ...

MSSM

Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14...

NMSSM...

Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15...

Models & pheno: how reliable ?

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

III. Theoretical Robustness

- *L. Niemi, H. Patel, MRM, T. Tenkanen, D. Weir 1802.10500*
- *O. Gould, J. Kozaczuk, L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 1903.11604*
- *L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 2005.11332*

Inputs from Thermal QFT

Thermodynamics

- Phase diagram: first order EWPT?
- Latent heat: GW

Dynamics

- Nucleation rate: transition occurs? T_N ? Transition duration (GW) ?
- EW sphaleron rate: baryon number preserved?

How reliable is the theory ?

EWPT & Perturbation Theory: IR Problem

Bosonic loop at T>0

Bose dist fn

$$I(T) = g^2 \int \frac{d^3p}{(2\pi)^3}\, f_B(E,T)\, \frac{1}{(p^2+m^2)^n}$$

EWPT & Perturbation Theory: IR Problem

Bosonic loop at T>0

Bose dist fn

$$I(T) = g^2 \int \frac{d^3p}{(2\pi)^3} f_B(E,T) \frac{1}{(p^2+m^2)^n} \longrightarrow \boxed{\frac{g^2 T}{m}} \int_{\mathrm{I.R.}} \frac{d^3p}{(2\pi)^3} \frac{1}{(p^2+m^2)^n}$$

Effective expansion parameter

Small p regime

$$f_B(E,T) \longrightarrow \frac{T}{m}$$

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Bosonic loop at T>0

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Effective expansion parameter

Small p regime

$$f_B(E,T) \longrightarrow \frac{T}{m}$$

Field-dependent thermal mass

$$m^2(\varphi, T) \sim C_1\, g^2 \varphi^2 + C_2\, g^2 T^2 \equiv m_T^2(\varphi)$$

- *Near phase transition: $\varphi \sim 0$*
- *$m_T(\varphi) < g\,T$*

EWPT & Perturbation Theory

Expansion parameter

$$g_{\rm eff} \equiv \frac{g^2 T}{\pi m_T(\varphi)}$$

Infrared sensitive near phase trans

SM lattice studies: *g_{eff} ~ 0.8 in vicinity of EWPT for m_H ~ 70 GeV* *

* *Kajantie et al, NPB 466 (1996) 189; hep/lat 9510020 [see sec 10.1]*

Challenges for Theory

Perturbation theory

- I.R. problem: poor convergence
- Thermal resummations
- Gauge Invariance (radiative barriers)
- RG invariance at T>0

Non-perturbative (I.R.)

- Computationally and labor intensive

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BSM proposals

Non-perturbative (I.R.)

- Computationally and labor intensive

Theory Meets Phenomenology

A. Non-perturbative

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

A. Perturbative

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

Theory Meets Phenomenology

A. Non-perturbative

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B. Perturbative

Benchmark pert theory

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BSM proposals

Non-perturbative (I.R.)

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Dimensionally reduced 3D EFT at T > 0

Strategy

- *Employ dimensionally-reduced 3D EFT in two regimes:*
  - *Heavy BSM scalars → integrate out and "repurpose" existing lattice computations*
  - *Light BSM scalars → perform new lattice simulations*
- *Compare with perturbative computations at benchmark parameter points in selected models*

Inputs from Thermal QFT: EFTs

Thermodynamics

- Phase diagram: first order EWPT?
- Latent heat: GW

EFT 1

Dynamics

EFT 2

- Nucleation rate: transition occurs? T_N ? Transition duration (GW) ?

- EW sphaleron rate: baryon number preserved?

EFT 3

High-T EFT: Dimensional Reduction

DR 3dEFT: Scales

• πT	*Non-zero Matsubara modes*
• M_{BSM}	*BSM mass scale: can be > or < πT*
• $g\ T$	*Thermal masses*
• M_{NUC}	*Nucleation scale ~ $1/r_{bubble}$*
• $g^2\ T$	*Light scale*

DR 3dEFT: Scales

- πT — Non-zero Matsubara modes
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EFT 1

DR 3dEFT: Scales

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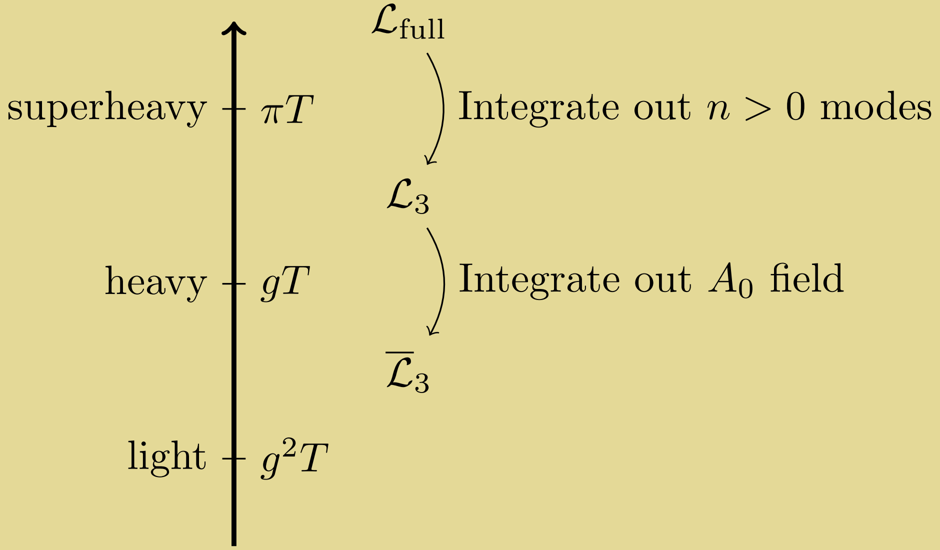
- $g^2\,T$ — Light scale

EFT 2

EFT 1

Thermal Effective Field Theory: EFT 1

Meeting ground: 3-D high-T effective theory



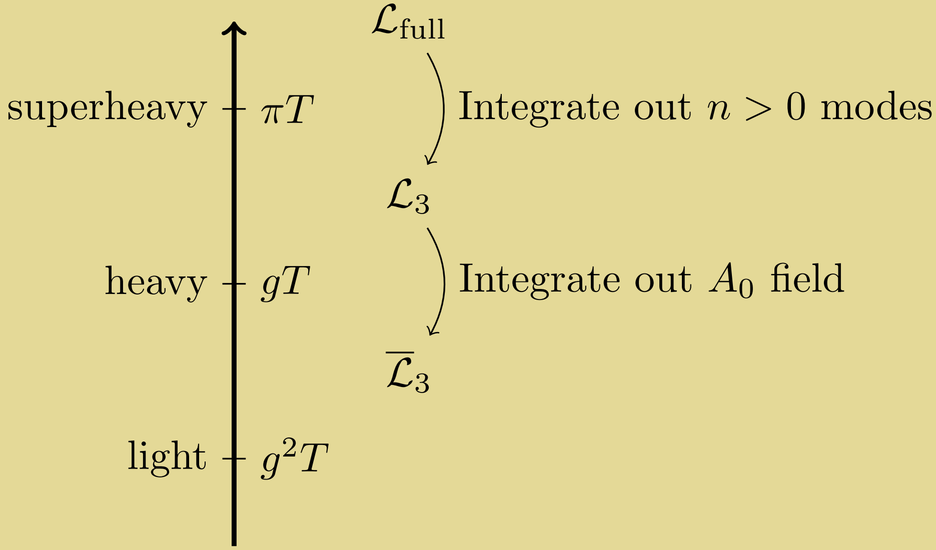
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

$+ V(\Phi) + V(\phi, \Phi)_{portal}$

Non-dynamical BSM scalars ***Dynamical BSM scalars***

EFT 1-A: Integrate Out All BSM Fields

Meeting ground: 3-D high-T effective theory



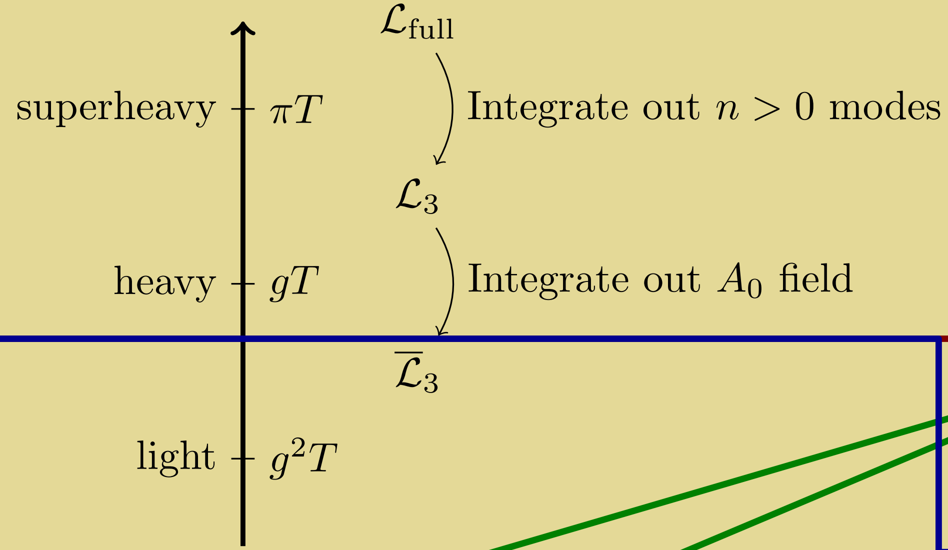
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

- *Assume BSM fields are "heavy" or "supeheavy" : integrate out*
- *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)

EFT 1-A: Integrate Out All BSM Fields

Meeting ground: 3-D high-T effective theory



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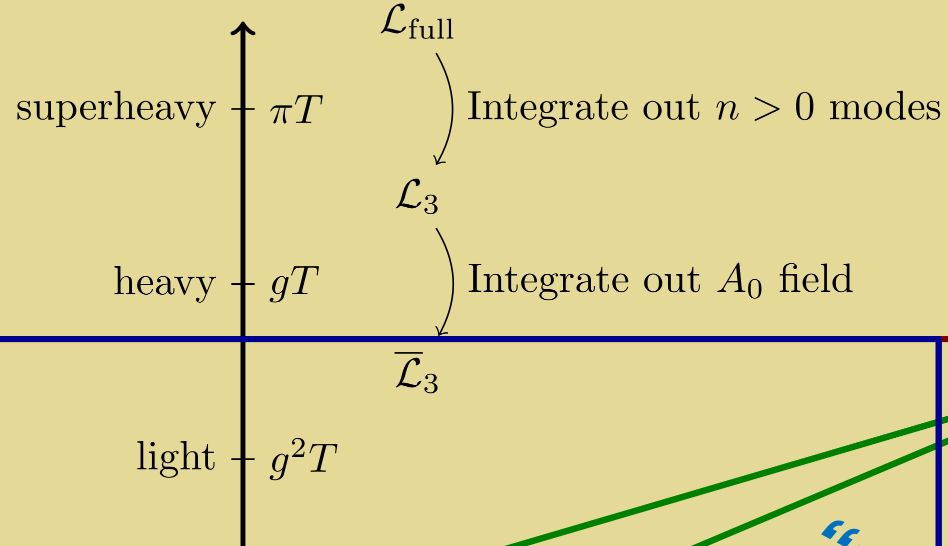

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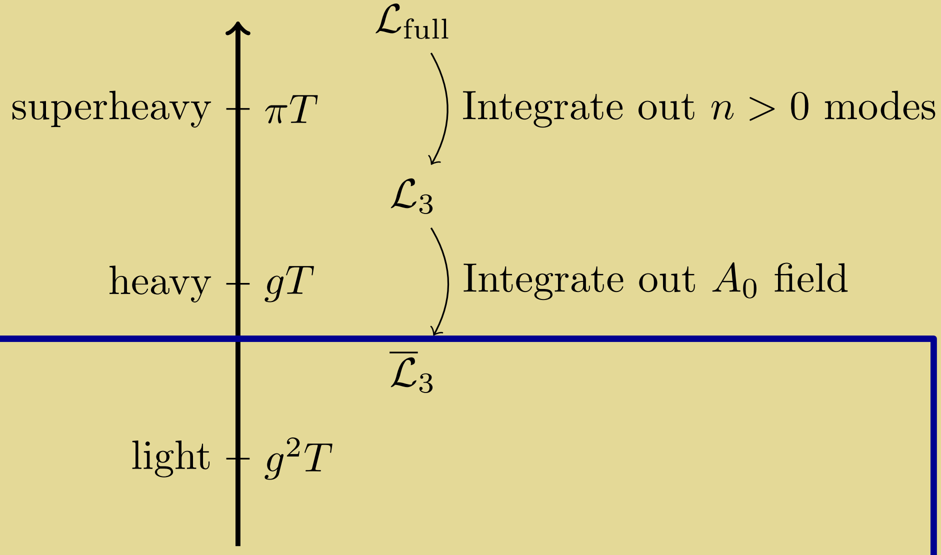
- *Effective "SM-like" theory parameters are functions of BSM parameters*
- *Use existing lattice computations for SM-like effective theory & matching onto full theory to determine FOEWPT-viable parameter space regions*

"Repurpose" lattice results

Lattice simulations exist (e.g., Kajantie et al ʼ95)

EFT 1-A: Integrate all BSM Fields

Meeting ground: 3-D high-T effective theory



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

When $\mathcal{L}_{full}$ contains BSM interactions, λ_3 and $\mu_{\phi,3}$ can accommodate first order EWPT and m_h=125 GeV

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

Model Illustrations

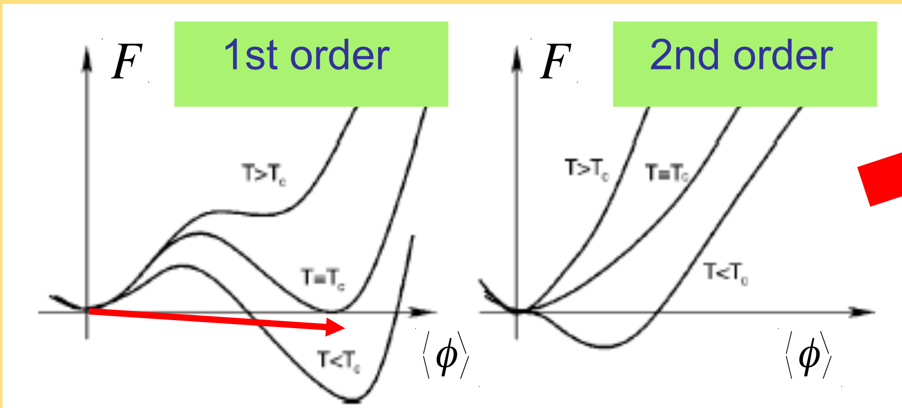
Simple Higgs portal models:

- ***Real gauge singlet (SM + 1)***
- ***Real EW triplet (SM + 3)***

Illustrate with real triplet: $\Sigma \sim (1,3,0)$

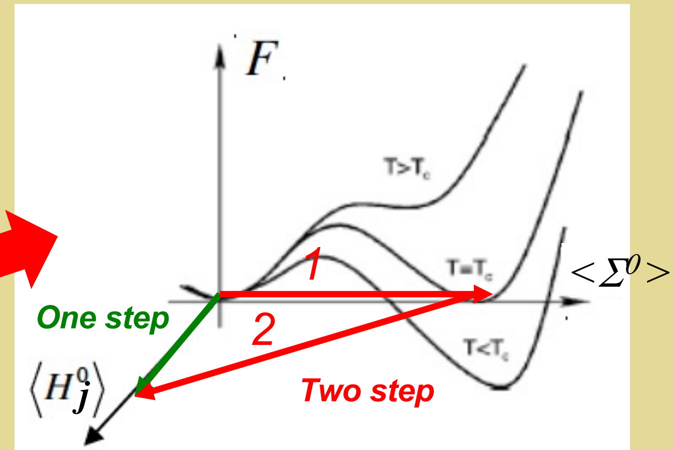
$H^2\phi^2$ **Barrier**

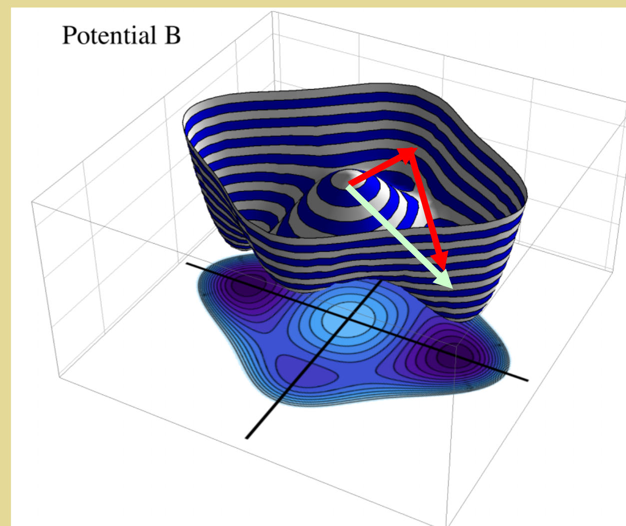
EW Multiplets: Two-Step EWPT



Increasing m_h ⟶

⟵ *New scalars*

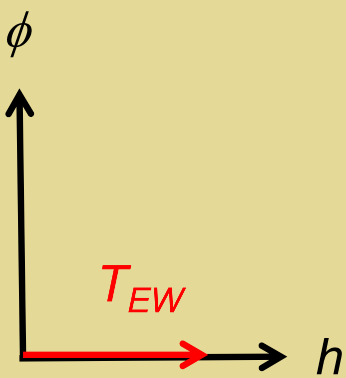




- *One-step: Sym phase → Higgs phase*
- *Two-step: successive EW broken phases*

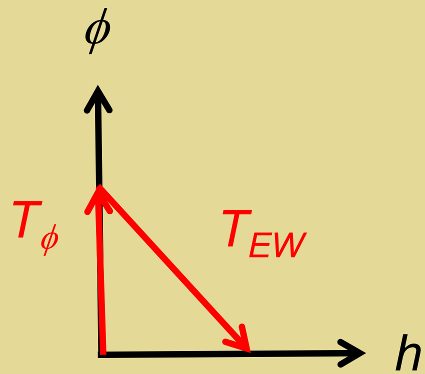
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

Real Triplet: Non-Dynamical Regime



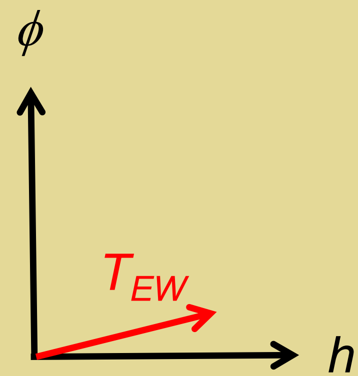
$a_2\, H^2\phi^2$: $T > 0$

loop effect



$a_2\, H^2\phi^2$: $T = 0$

tree-level effect



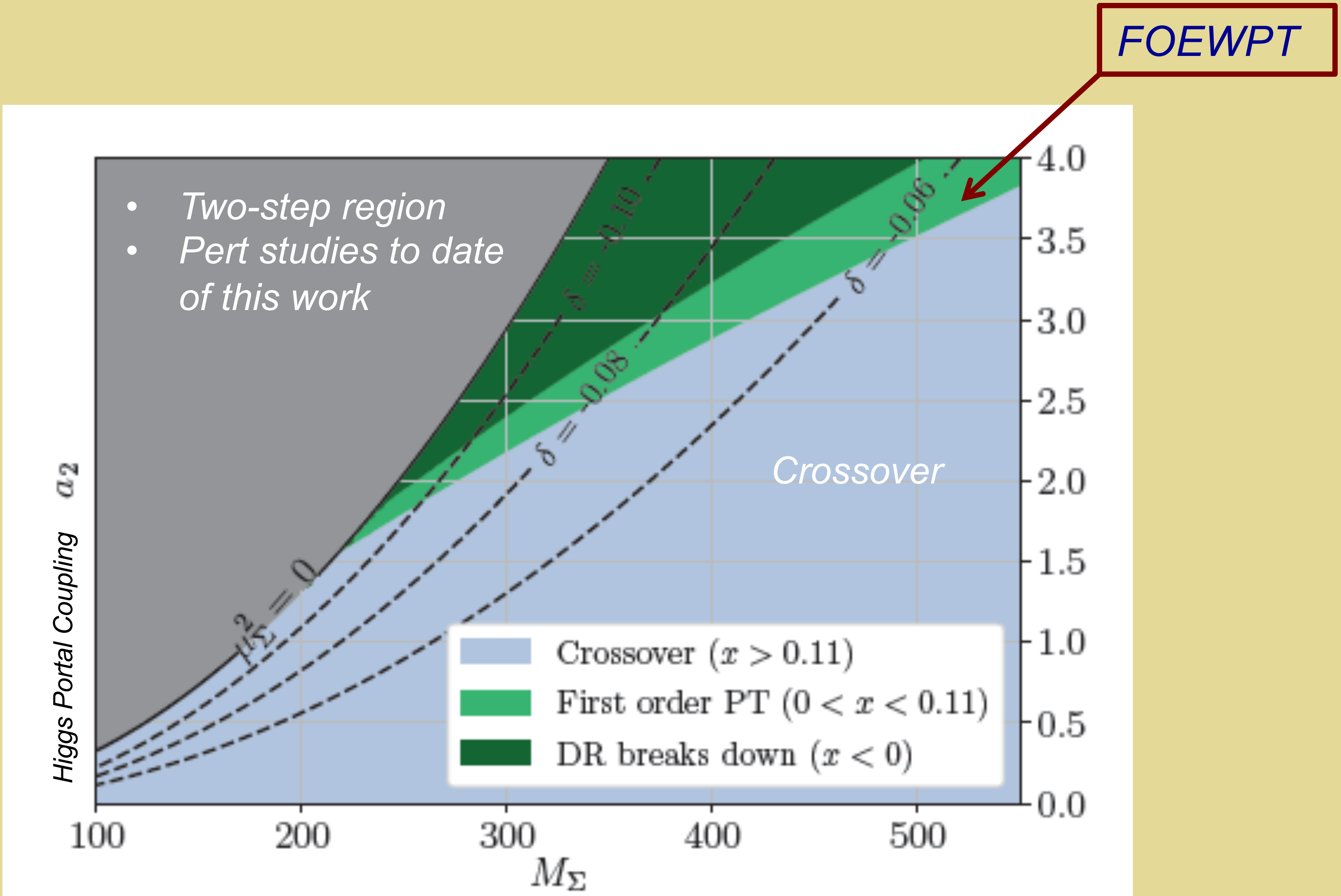
$a_1\, H^2\phi$: $T = 0$

tree-level effect

Non-perturbative results:
Heavy triplet

EW precision tests → too tiny

Non-Dynamical Real Triplet: One-Step EWPT

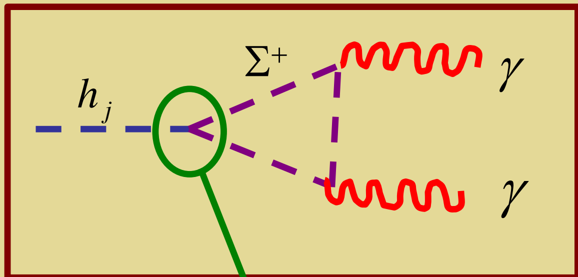


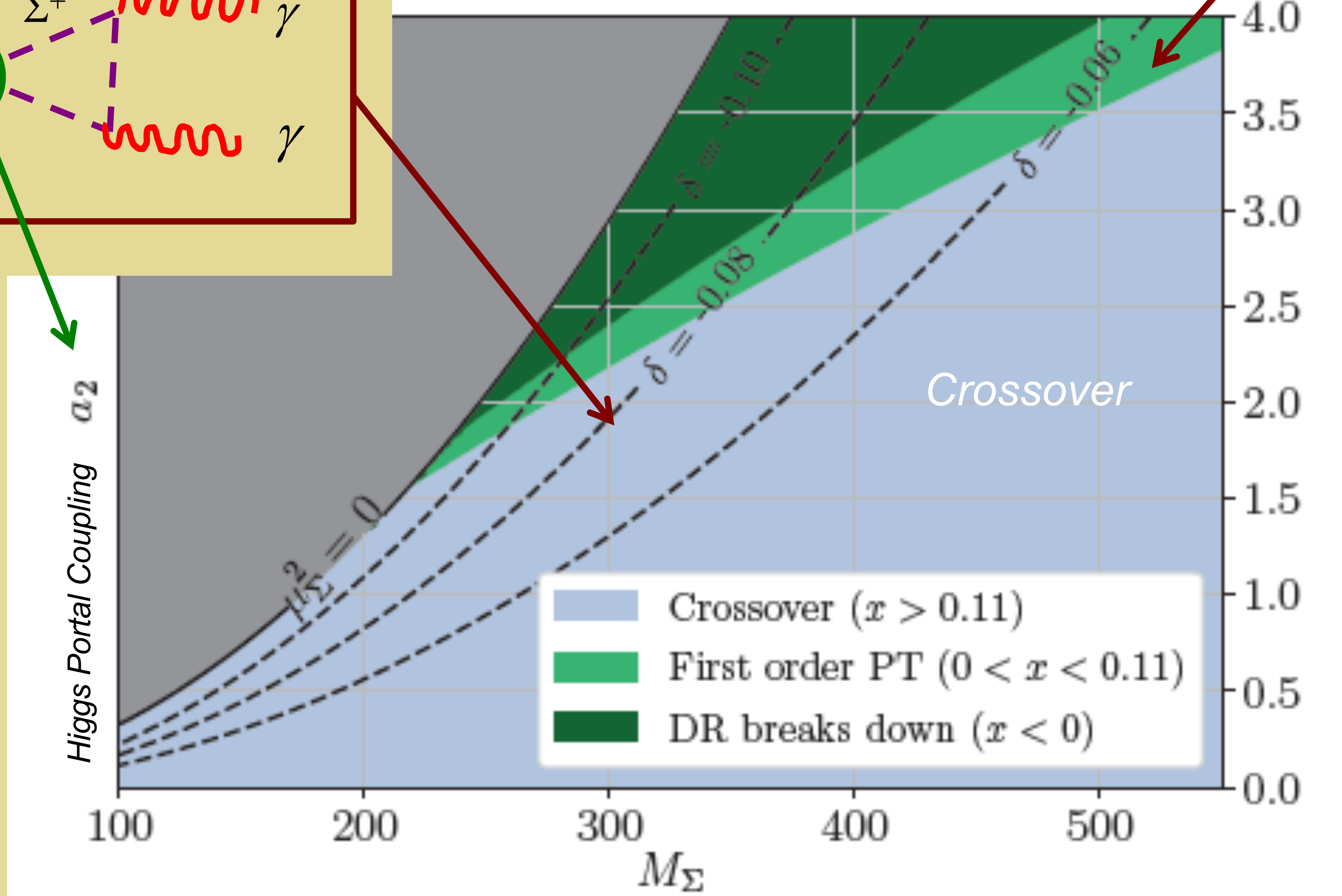
- One-step
- Non-perturbative

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Non-Dynamical Real Triplet: One-Step EWPT

FOEWPT



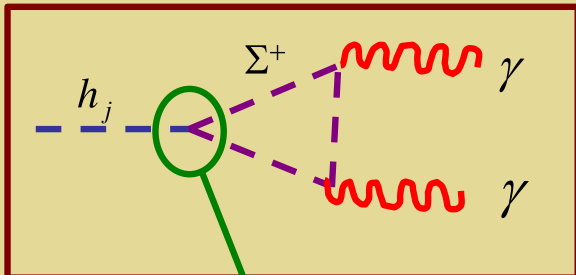


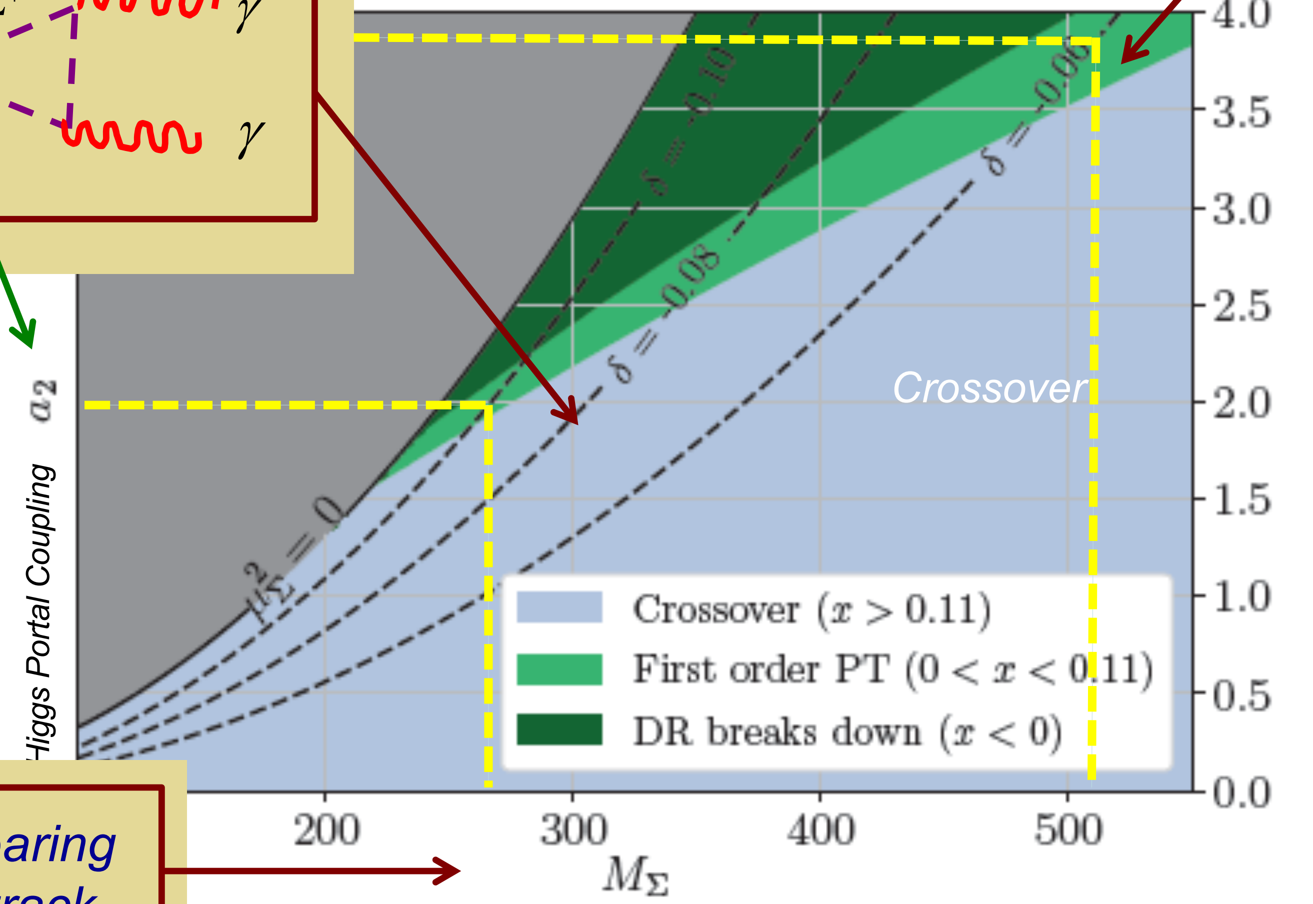
- *One-step*
- *Non-perturbative*

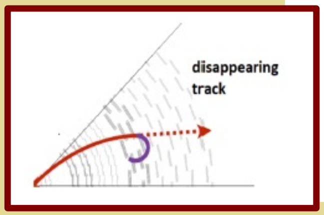
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Non-Dynamical Real Triplet: One-Step EWPT

FOEWPT





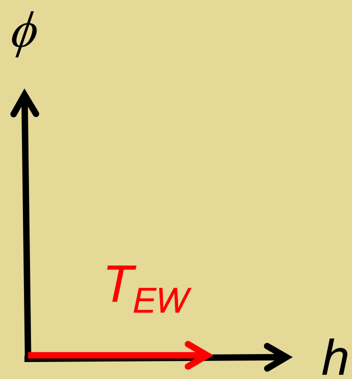


Disappearing charge track

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

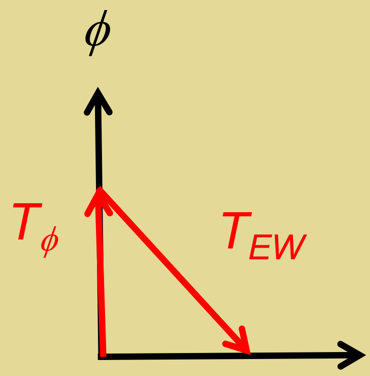
- One-step
- Non-perturbative

Dynamical Real Triplet



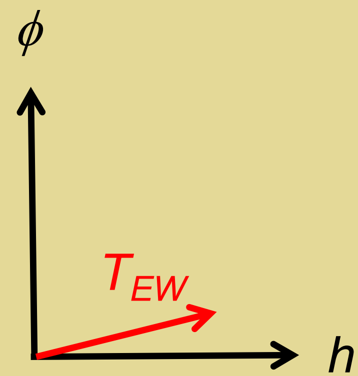
$a_2\, H^2\phi^2$: $T > 0$

loop effect



$a_2\, H^2\phi^2$: $T = 0$

tree-level effect



$a_1\, H^2\phi$: $T = 0$

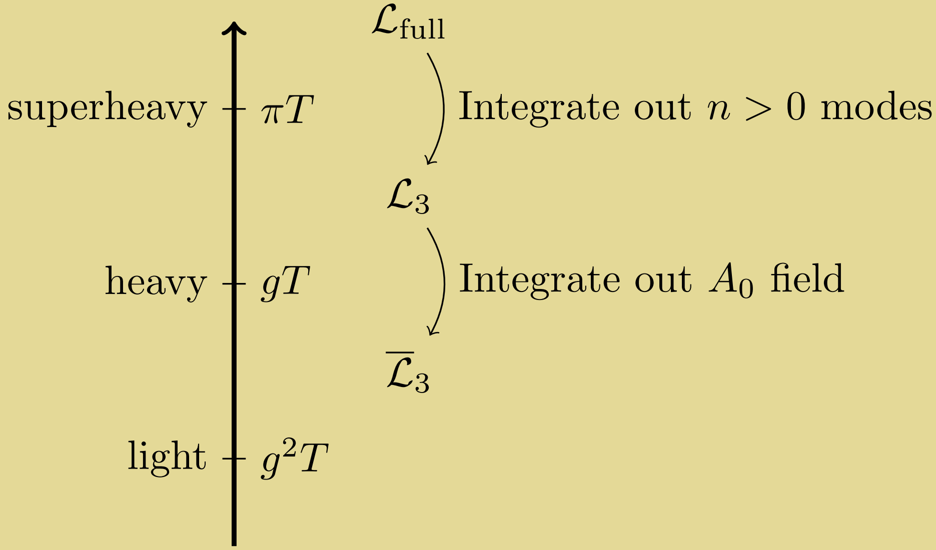
tree-level effect

Non-perturbative results

EW precision tests → too tiny

Thermal Effective Field Theory: EFT 1

Meeting ground: 3-D high-T effective theory

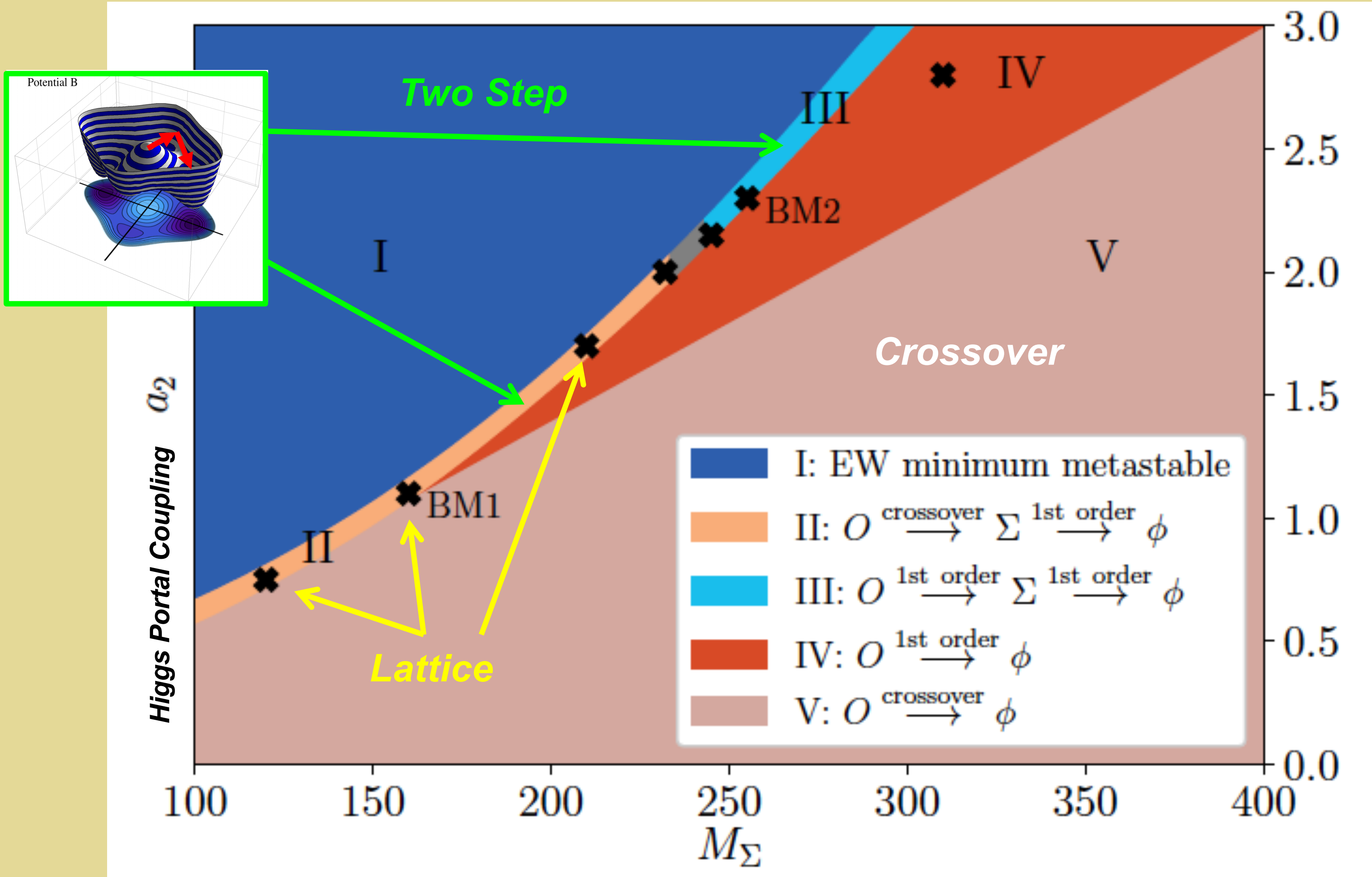


BSM parameters explicit in the light theory EFT used in lattice simulations

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

Non-dynamical BSM scalars ***Dynamical BSM scalars***

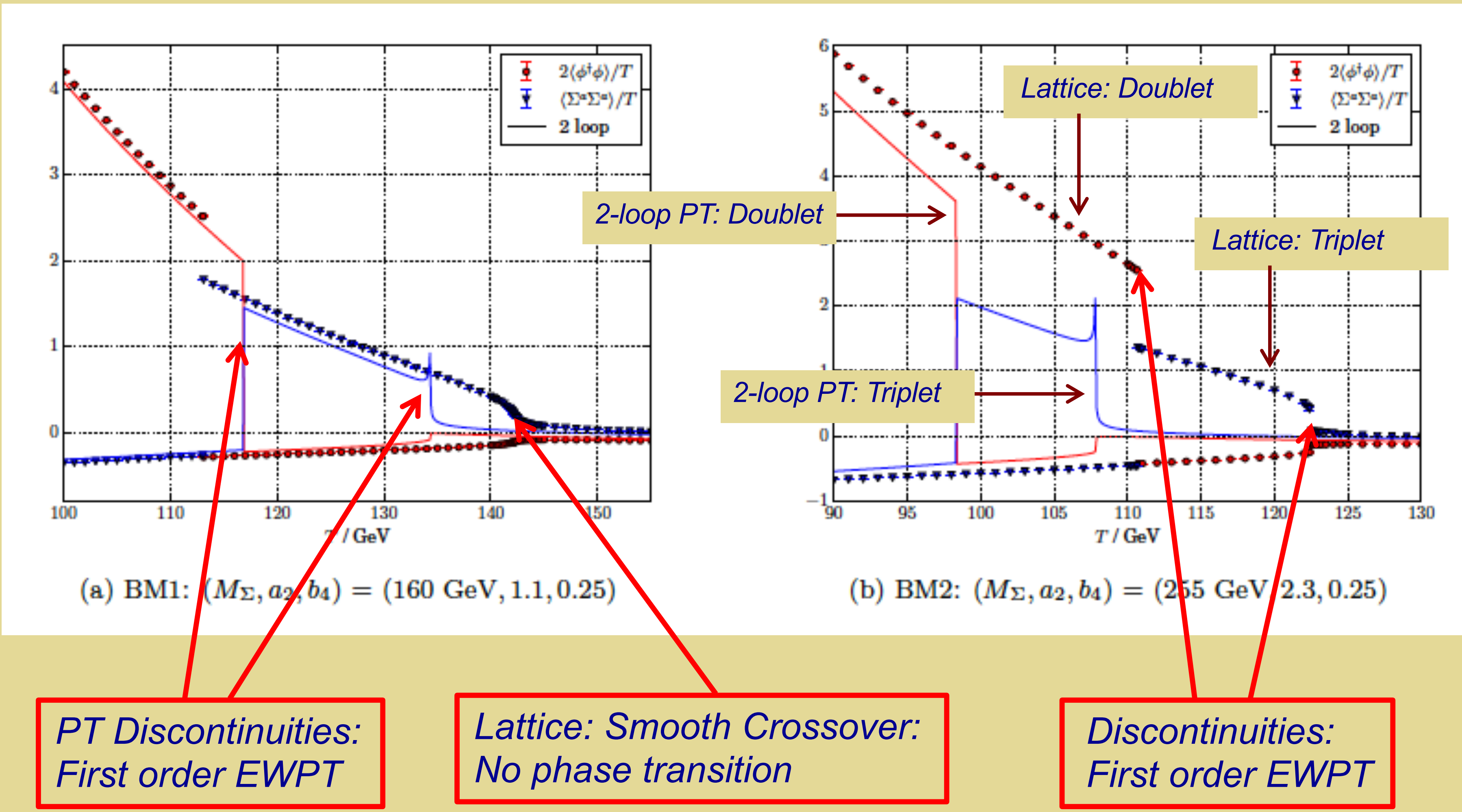
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332

- *1 or 2 step*
- *Non-perturbative*

Real Triplet & EWPT: Benchmark PT



Niemi, R-M, Tenkanen, Weir 2005.11332

IV. GW-Collider Interface: Theory+ Phenomenology

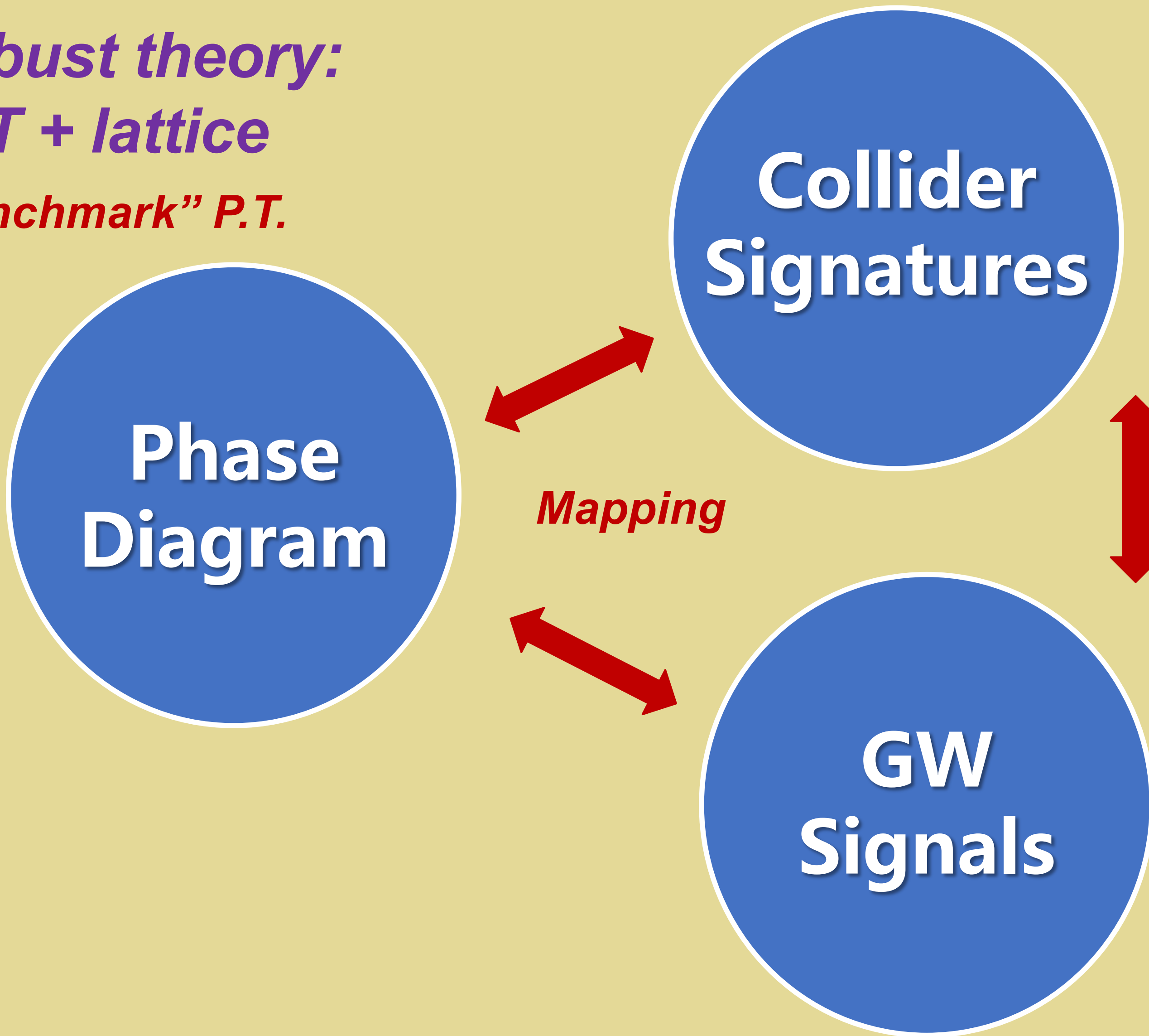
- ***How robustly can we map the phase diagram onto experimental observables ?***

- ***How can we exploit experiment to identify EWPT-viable models & parameters ?***

BSM EWPT: Three Challenges

Robust theory:
EFT + lattice

"Benchmark" P.T.



Observables:
model specific

Combined reach: N_σ vs S/N

Hydro:
$\alpha\,,\ \beta / H_*$

Tunneling @ T>0: Gravitational Waves

Amplitude & frequency: latent heat & intrinsic time scale

Normalized latent heat

$$\Delta Q = \Delta F + T\Delta S$$
$$S = -\partial F/\partial T$$
$$F \approx V$$

$$\Delta Q \approx \Delta V - T\partial\Delta V/\partial T$$

$$\alpha = \frac{30\Delta q}{\pi^2 g_* T^4}$$

Time scale

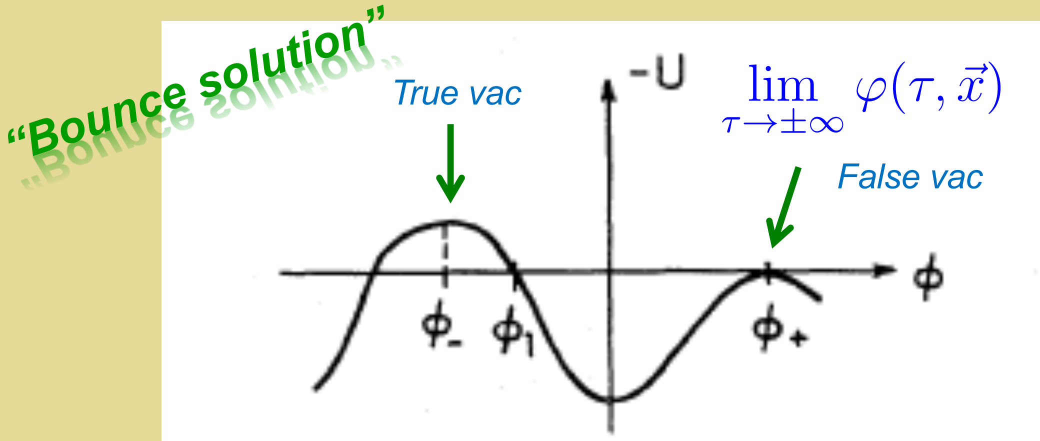
$$\frac{\beta}{H_*} = T\frac{d}{dT}\frac{S_3}{T}$$

How Reliable?

S. Coleman, PRD 15 (1977) 2929

Tunneling @ T=0: Coleman

Scalar Quantum Field Theory



Rotational symmetry

$$\rho^2 \equiv \tau^2 + |\vec{x}|^2$$

$$\frac{d^2\varphi}{d\rho^2} + \frac{3}{\rho}\frac{d\varphi}{d\rho} = U'(\varphi)$$

Path: minimize S_E

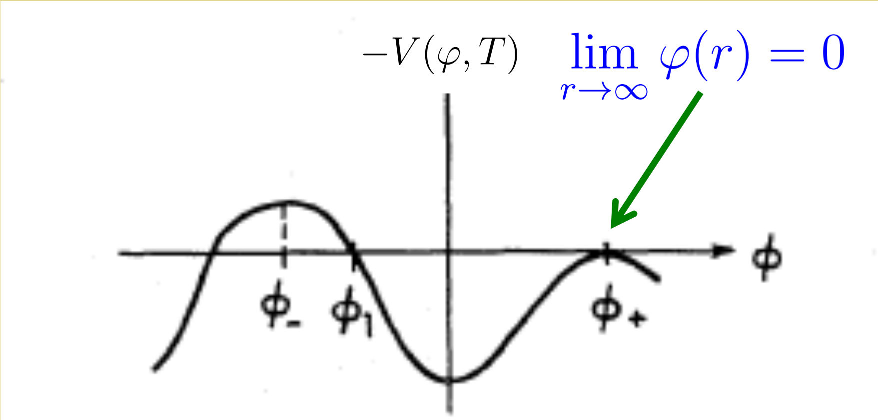
Friction term

Ln Γ

$$S_E = \int d\tau d^3x \left\{ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2}(\vec{\nabla}\varphi)^2 + U(\varphi) \right\}$$

Tunneling @ T>0

Scalar Quantum Field Theory



Tunneling rate / unit volume:

$$\Gamma = A e^{-\beta S_3/\hbar}\left[1 + \mathcal{O}(\hbar)\right]$$

$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} = V'(\varphi, T)$$

Friction term

Exponent in Γ

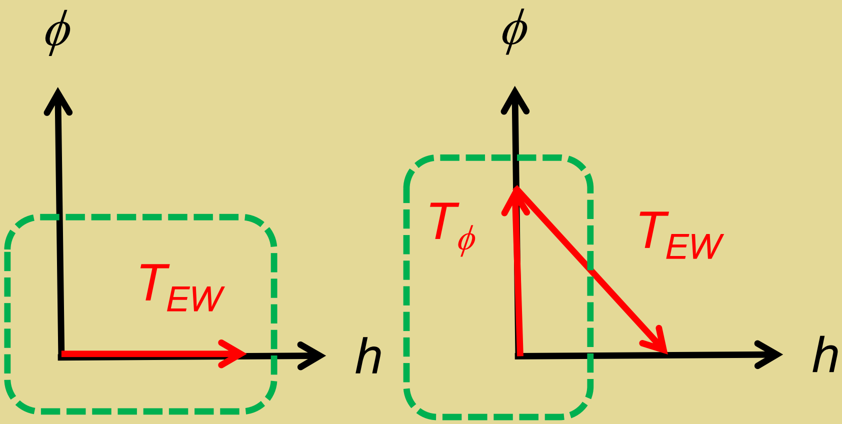
Path: minimize S_E

$$S_3 = \int d^3x \left\{ \frac{1}{2}(\vec{\nabla}\varphi)^2 + V(\varphi, T) \right\}$$

$$A \sim \mathcal{O}(1) \times T^4$$

Tunneling @ T>0

Radiative barriers → st'd method gauge-dependent



Tunneling rate / unit volume:

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Path: minimize S_E

Friction term

Exponent in Γ

$$S_3=\int d^3x\left\{\frac{1}{2}(\vec{\nabla}\varphi)^2+V(\varphi,T)\right\}$$

$$A\sim\mathcal{O}(1)\times T^4$$

Tunneling @ T>0

Theoretical issues:

- *Radiatively-induced barrier (St'd Model) → gauge dependence*
  - *$T = 0$ Abelian Higgs: E. Weinberg & D. Metaxas: hep-ph/9507381*
  - *$T=0$ St'd Model: A. Andreassen, W. Frost, M. Schwartz 1408.0287*
  - *$T > 0$ Gauge theories:* ***recently solved in 2112.07452 (→ PRL) and 2112.08912***
- *Multi-field problem (still gauge invar issue)*
  - *Cosmotransitions: C. Wainwright 1109.4189*
  - *Espinosa method: J. R. Espinosa 1805.03680*

(Re) Organize the Perturbative Expansion

Illustrate w/ Abelian Higgs

$$\mathcal{L} = \frac{1}{4} F_{\mu\nu} F_{\mu\nu} + (D_\mu \Phi)^* (D_\mu \Phi) + \mu^2 \Phi^* \Phi + \lambda (\Phi^* \Phi)^2 + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm FP}$$

- *Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL*
- *Hirvonen, Lofgren, MRM, Tenkanen, Schicho 2112.08912*

Full 3D effective action

$$S_3 = \int \mathrm{d}^3 x \left[V^{\rm eff}(\phi, T) + \frac{1}{2} Z(\phi, T) \, (\partial_i \phi)^2 + \ldots \right]$$

Adopt appropriate power-counting in couplings

$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

(Re) Organize the Perturbative Expansion

Illustrate w/ Abelian Higgs

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G.I. pertubative expansion only valid up to NLO → Δ: higher order contributions only via other methods

G.I. pertubative expansion

(Re) Organize the Perturbative Expansion

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Details: back up slides

Full 3D effective action

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Adopt appropriate power-counting in couplings

$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

G.I. pertubative expansion only valid up to NLO → Δ: higher order contributions only via other methods

G.I. pertubative expansion

Tunneling @ T>0: Take Aways

- *For a radiatively-induced barrier, a gauge-invariant perturbative computation of nucleation rate can be performed for S_3 to $\mathcal{O}(g^{-1/2})$ by adopting an appropriate power counting for T in the vicinity of T_{nuc}*

- *Abelian Higgs example generalizes to non-Abelian theories as well as other early universe phase transitions*

- *Remaining contributions to Γ_{nuc} beyond $\mathcal{O}(g^{-1/2})$ in S_3 and including long-distance (nucleation scale) contributions require other methods*

- *Assessing numerical reliability will require benchmarking with non-perturbative computations*

GW-Collider Inverse Problem

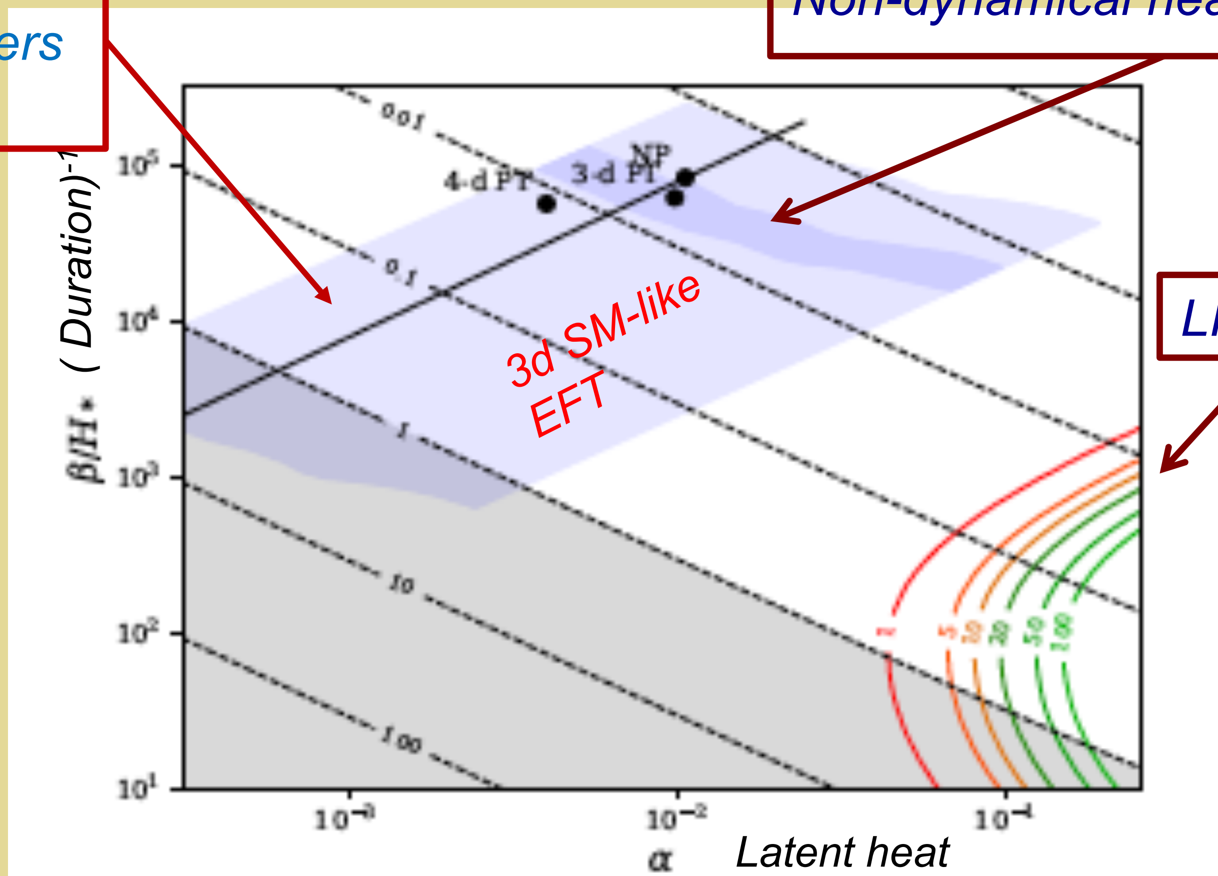
How can a combination of collider and GW measurements identify a given model and determine the Lagrangian parameters ?

- ***O. Gould, J. Kozaczuk, L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 1903.11604***
- ***L. Friedrich, MJRM, T.V.I. Tenkanen, V.Q. Tran: 2203.05889***

Heavy BSM Scalar: EWPT & GW

Collider probes of BSM parameters in $\mathcal{L}_{full}$?

Non-dynamical heavy BSM scalars



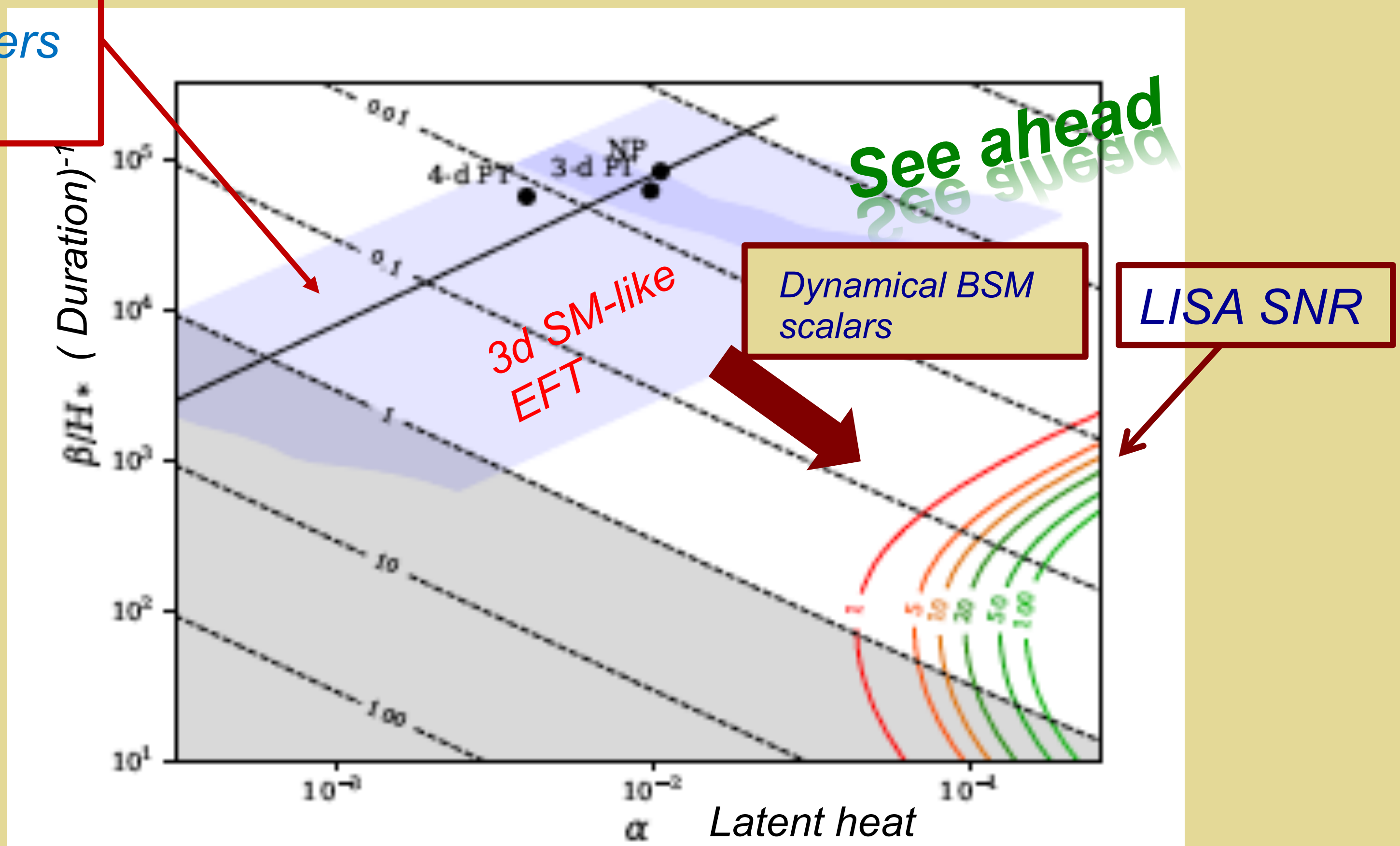
LISA SNR

- One-step
- Non-perturbative

Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

Heavy BSM Scalar: EWPT & GW

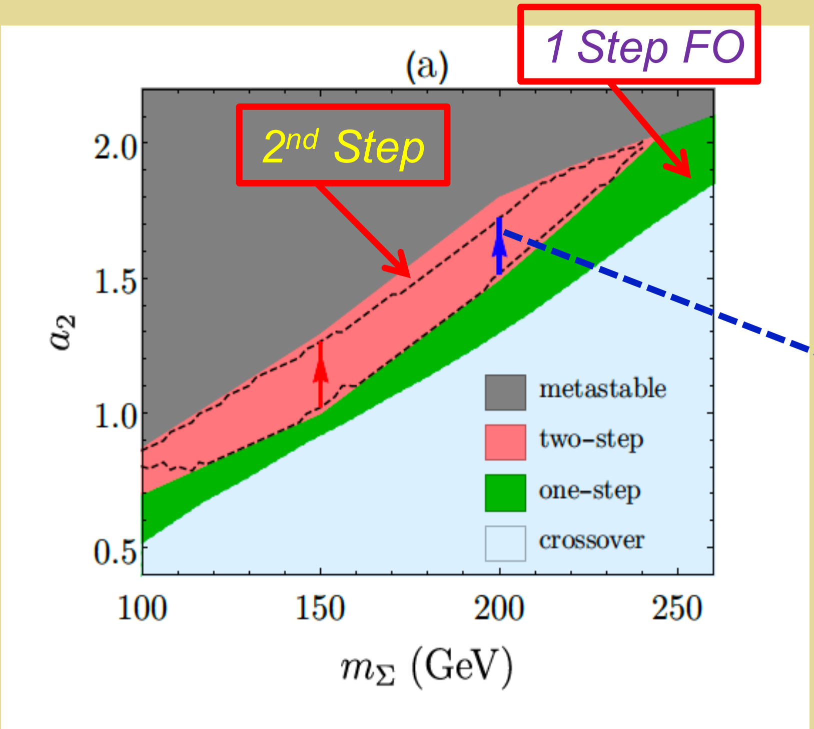
Collider probes of BSM parameters in $\mathcal{L}_{full}$?

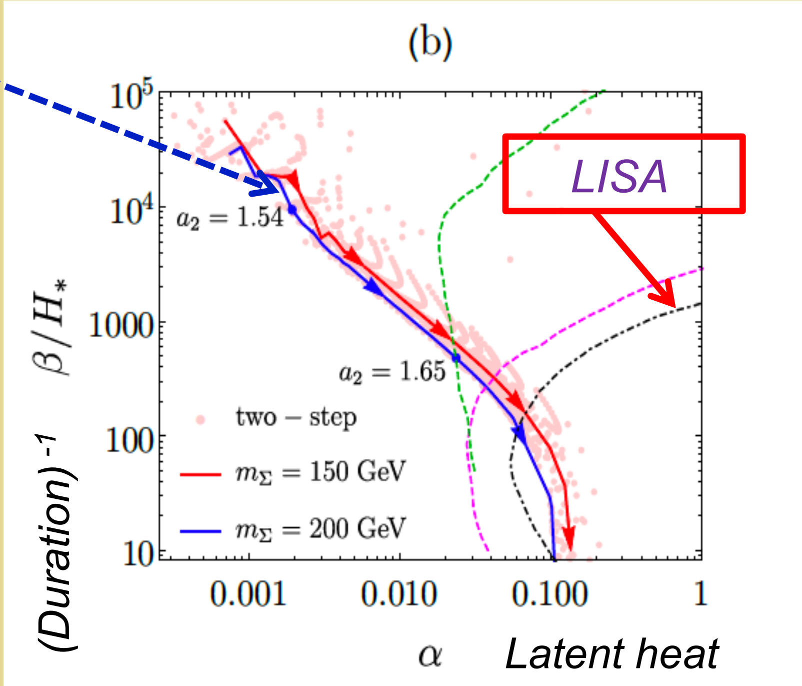


- One-step
- Non-perturbative

Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

GW, Collider & EWPT Phase Diagram

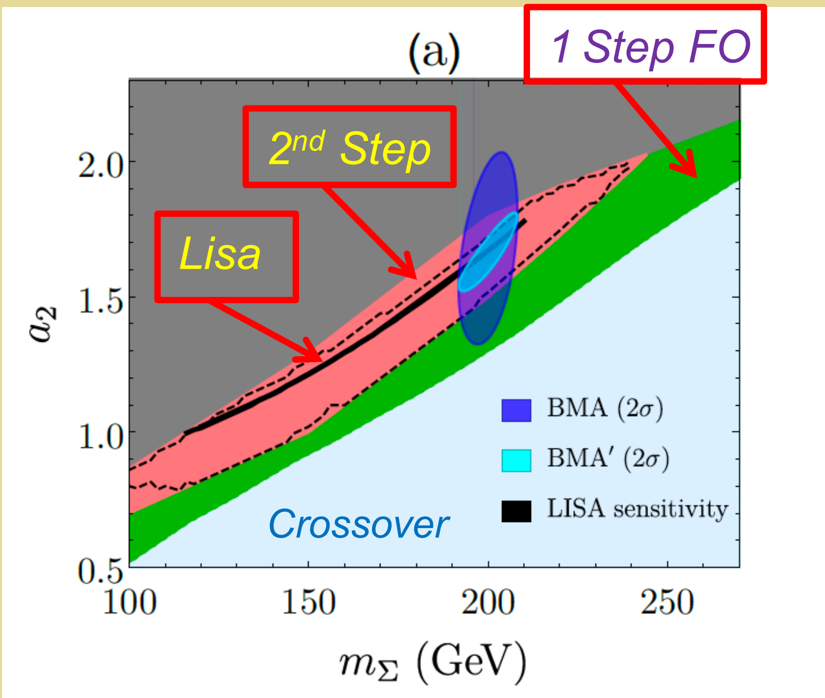


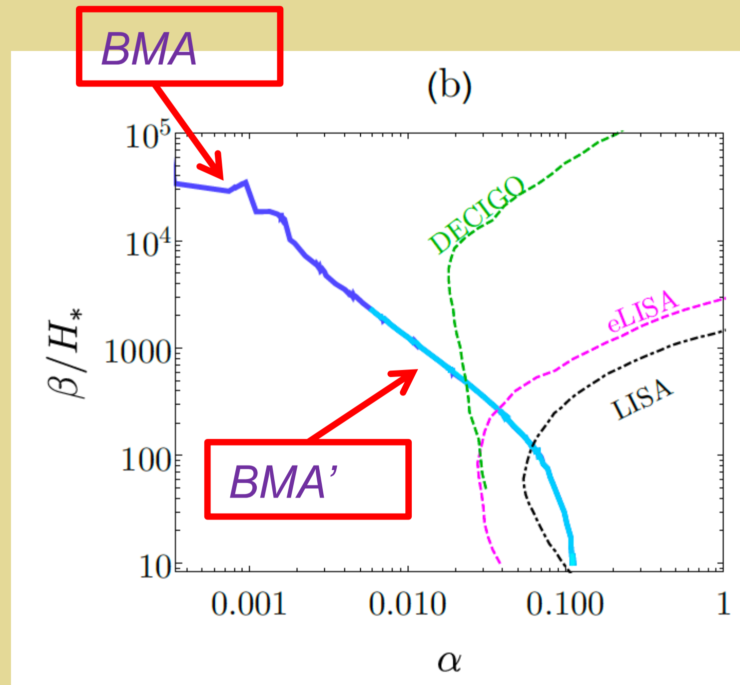


- ***Single step transition: GW well outside LISA sensitivity***
- ***Second step of 2-step transition can be observable***

Friedrich, MJRM, Tenkanen, Tran 2203.05889

Dynamical BSM Scalar: EWPT & GW





BMA: m_Σ + $h \to \gamma\gamma$

BMA' : BMA + $\Sigma^0 \to ZZ$

- *Two-step*
- *EFT+ Non-perturbative*

Friedrich, MJRM, Tenkanen, Tran 2203.05889

Other Selected Recent Work

- *Gauge invariance in Γ_N (EFT2) : radiative barriers*
  - *Arunasalam, MJRM: 2105.07588*
  - *Lofgren, MJRM, Schicho, Tenkanen 2112.05472*
  - *Hirvonen, Lofgren, MJRM, Schicho, Tenkanen 2112.08912*

- *RGE at T> 0*
  - *Gould, Tenkanen 2104.04399*

- *Nucleation: EFT2*
  - *Gould, Hirvonen 2108.04377*

V. Outlook - 1

- *Determining the thermal history of EWSB is field theoretically interesting in its own right and of practical importance for baryogenesis and GW*

- *The scale T_{EW} → any new physics that modifies the SM crossover transition to a first order transition must live at M < 1 TeV and couple with sufficient strength to yield (in principle) observable shifts in Higgs boson properties*

- *Searches for new scalars and precision Higgs measurements at the LHC and prospective next generation colliders could conclusively determine the nature of the EWSB transition*

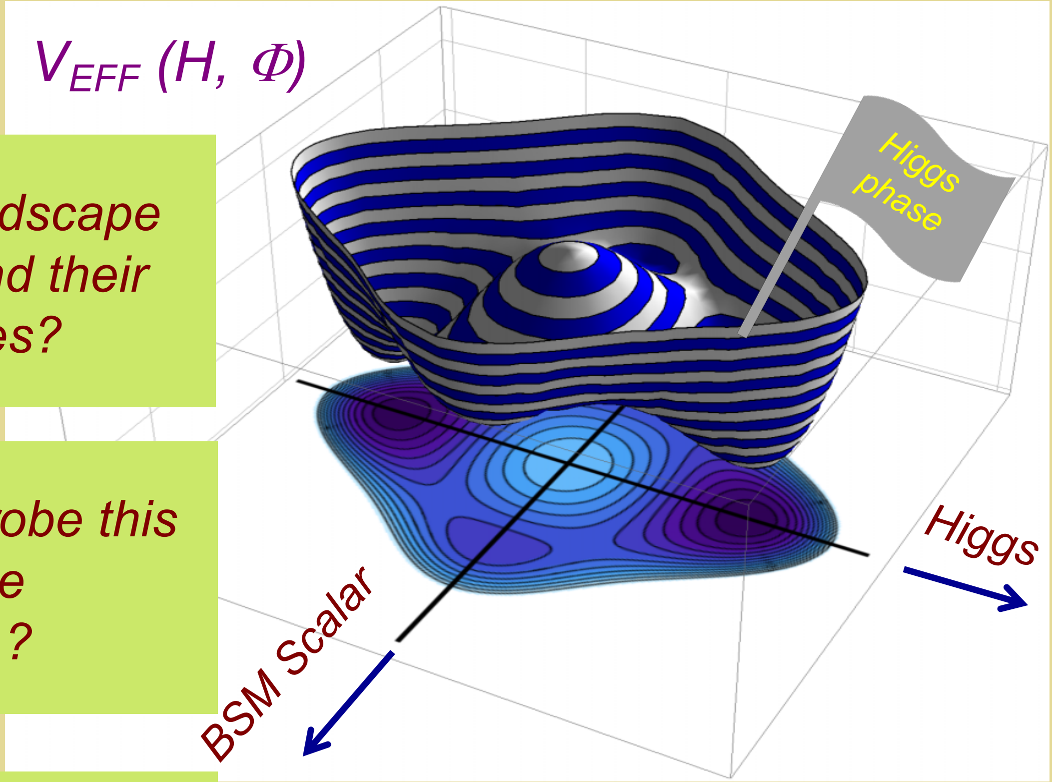
V. Outlook - 2

- *Realizing this opportunity requires meeting several theoretical challenges:*

    - *Performing a new generation of robust theoretical computations, using EFT & non-perturbative methods, to benchmark perturbative calculations*

    - *Mapping out the full landscape of EWPT-viable BSM scenarios and making robust connections with exp't*

Thermal History of EWSB



- *What is the landscape of potentials and their thermal histories?*

- *How can we probe this T > 0 landscape experimentally ?*

- *How reliably can we compute the thermodynamics ?*

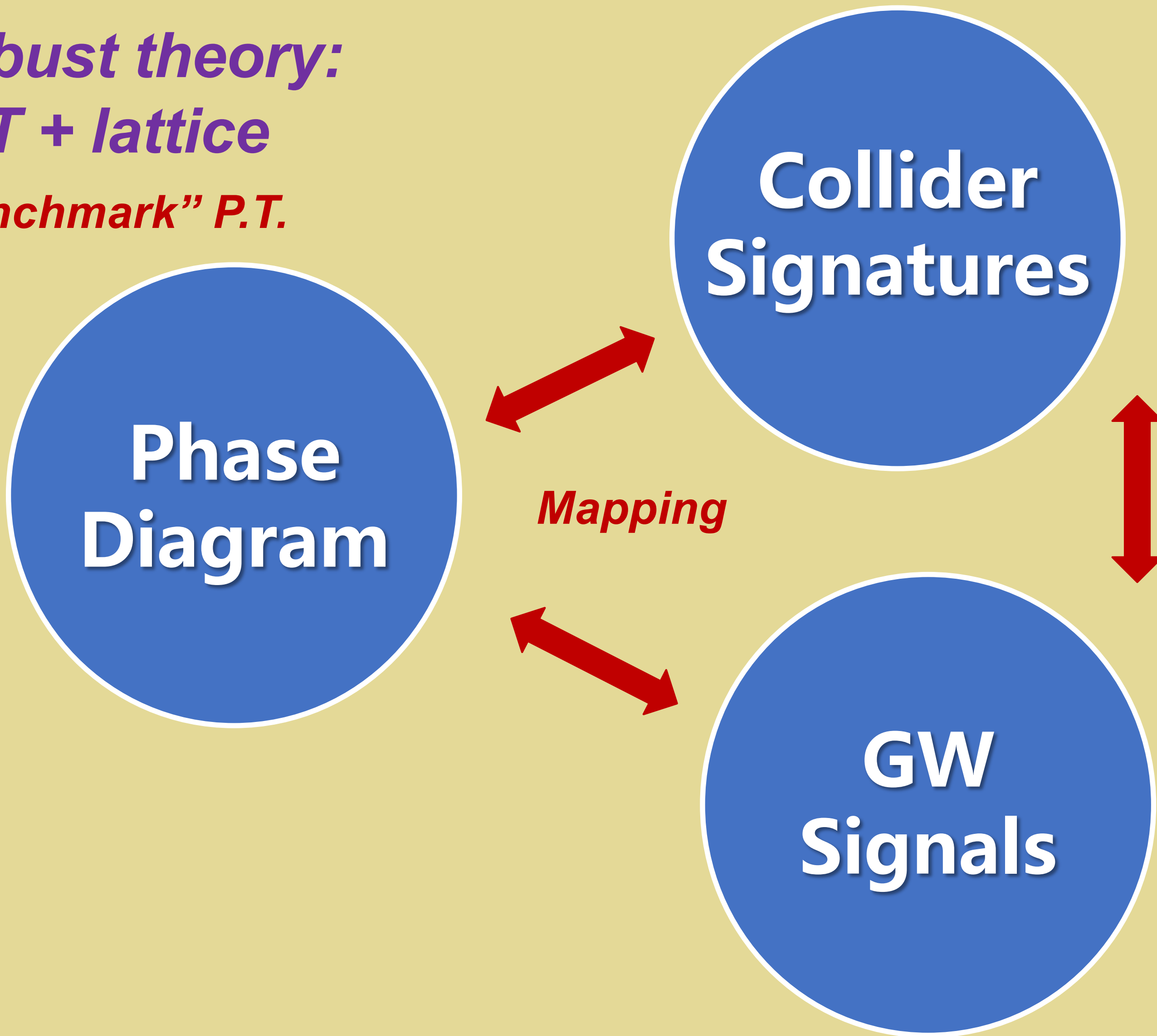
n evolve differently as T evolves →
ilities for symmetry breaking

BSM EWPT: Three Challenges

Robust theory:
EFT + lattice

"Benchmark" P.T.

Observables:
model specific



Combined reach: N_σ vs S/N

Hydro:
$\alpha\,,\ \beta\,/\,H_*$

V. Outlook - 3

- *Realizing this opportunity requires meeting several theoretical challenges:*

  - *Performing a new generation of robust theoretical computations, using EFT & non-perturbative methods, to benchmark perturbative calculations*

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TDLI theory program

V. Outlook - 3

- *Realizing this opportunity requires meeting several theoretical challenges:*
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TDLI theory program

- *There are exciting opportunities for talented and ambitious theorists to make significant contributions to this growing frontier*

谢谢