Was There an Electroweak Phase Transition ?

M.J. Ramsey-Musolf

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

About MJRM:

Science

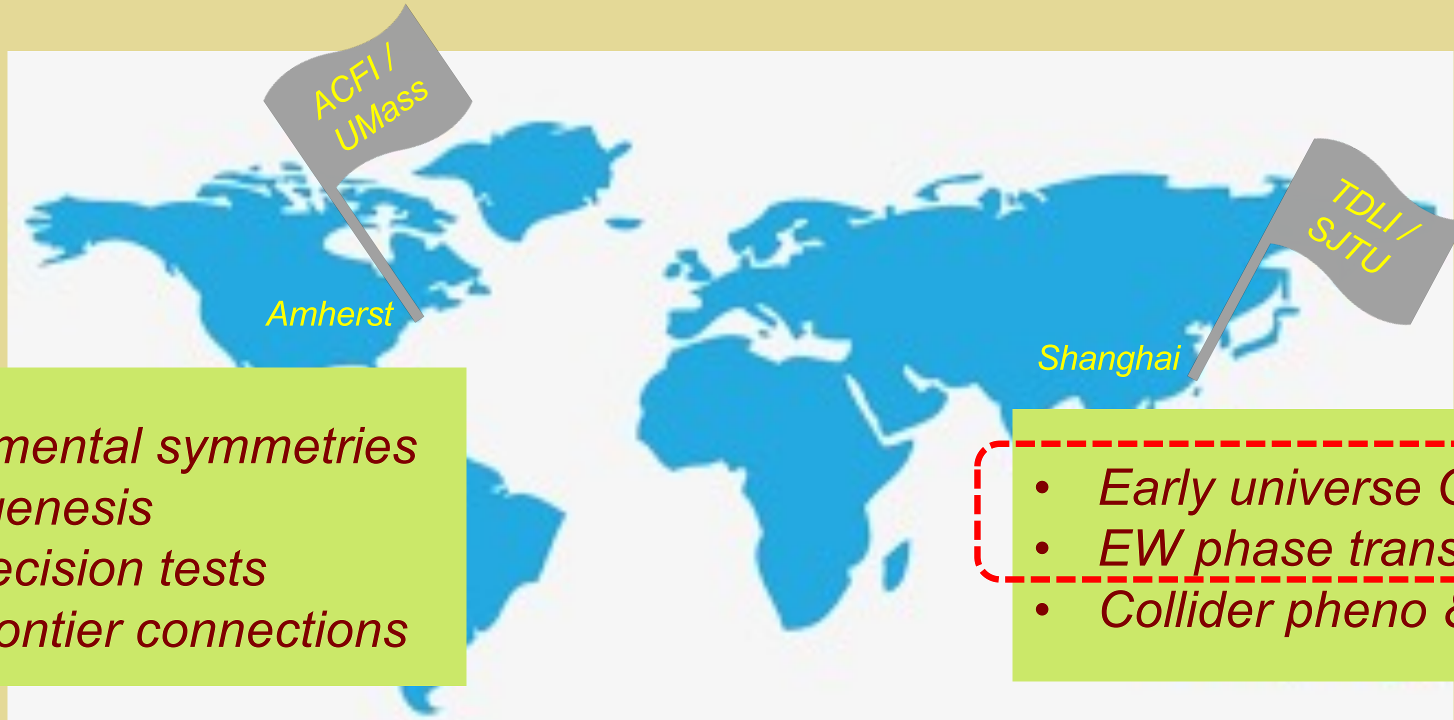
Family

Friends

My pronouns: he/him/his
 # MeToo

IPMU Seminar March 3-4, 2022

MJRM: Scientist & "Ambassador"

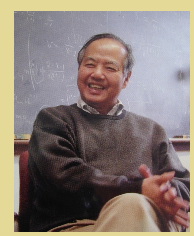


- *Fundamental symmetries*
- *Baryogenesis*
- *EW precision tests*
- *Inter-frontier connections*

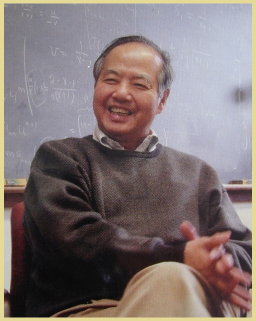
Today

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

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



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



Director

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

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

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

Theory & Experiment

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

TDLI/SJTU: Particle & Nuclear Physics

Underground Experimental Group

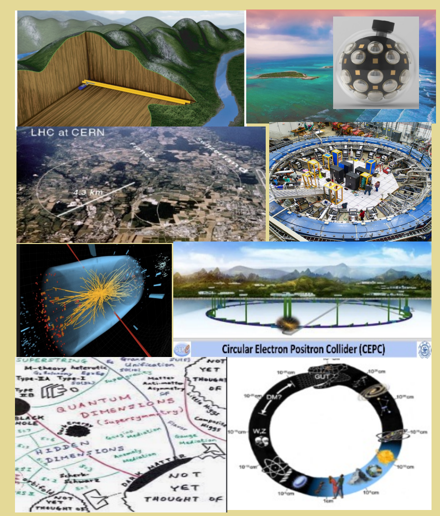
1. Dark Matter and Axion (PandaX).
2. Neutrinoless Double Beta Decay (PandaX).
3. Neutrino mass, Reactor and Cosmic Experiments (JUNO, ICECUBE, Hai-Ling Neutrino Telescope).

Collider Experiment Group

1. LHC Physics. 2. CEPC R&D. 3. Muon g-2. 4. Dark photon.

Theory Group

1. Dark Matter, Dark Energy, Inflation, Phase Transition In the Early Universe, Gravitational Waves, and Unification of Different Interactions.
2. Lattice QCD Calculations, Higgs, Neutrino and Flavor Physics, New Physics and Collider Phenomenology.



Amherst Center for Fundamental Interactions

- *Experimental & theoretical research at the energy, intensity, and cosmic frontiers*
- *Targeted topical workshop program*

https://www.physics.umass.edu/acfi/

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***

Acknowledgments

- ***Apologies for omissions of references to other important work***

- ***Collaborators (this talk):***

  - *T. V. I. Tenkanen* *
  - *L. Niemi* *
  - *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. Outlook

I. Context & Questions

Electroweak Phase Transition

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

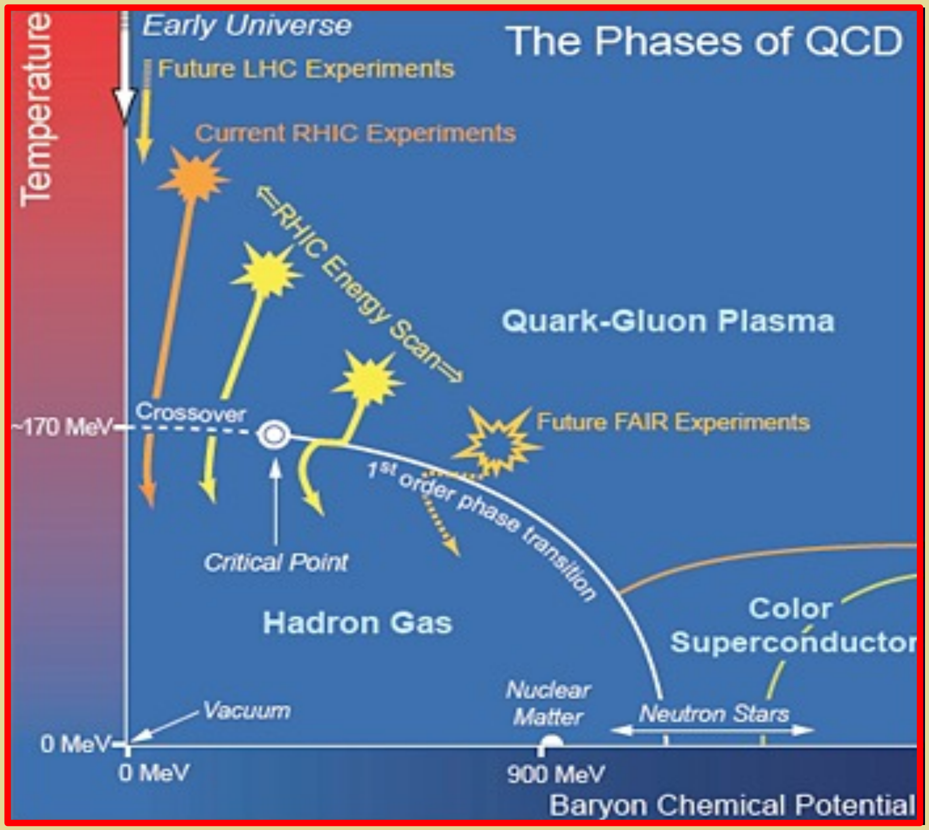
Electroweak Phase Transition

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

- *Baryogenesis $\to$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*

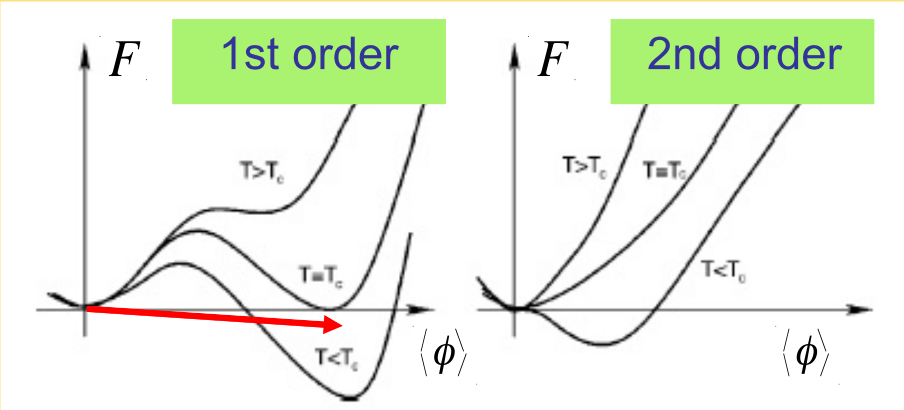
- *Gravitational waves $\to$ If a signal observed in LISA, could a cosmological phase transition be responsible ?*

Thermal History of Symmetry Breaking



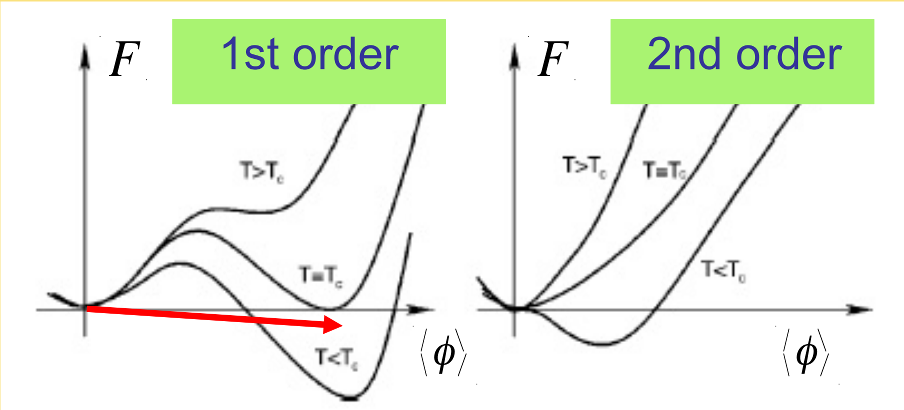
QCD Phase Diagram → EW Theory Analog?

EWSB Transition: St'd Model

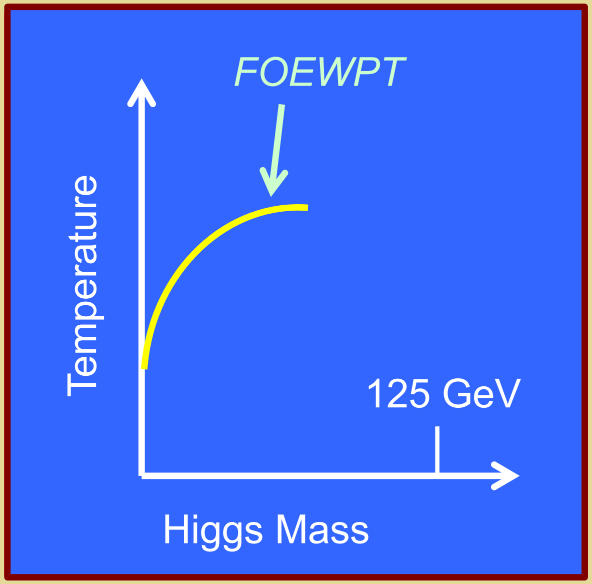


Increasing m_h →

EWSB Transition: St'd Model



Increasing m_h ⟶



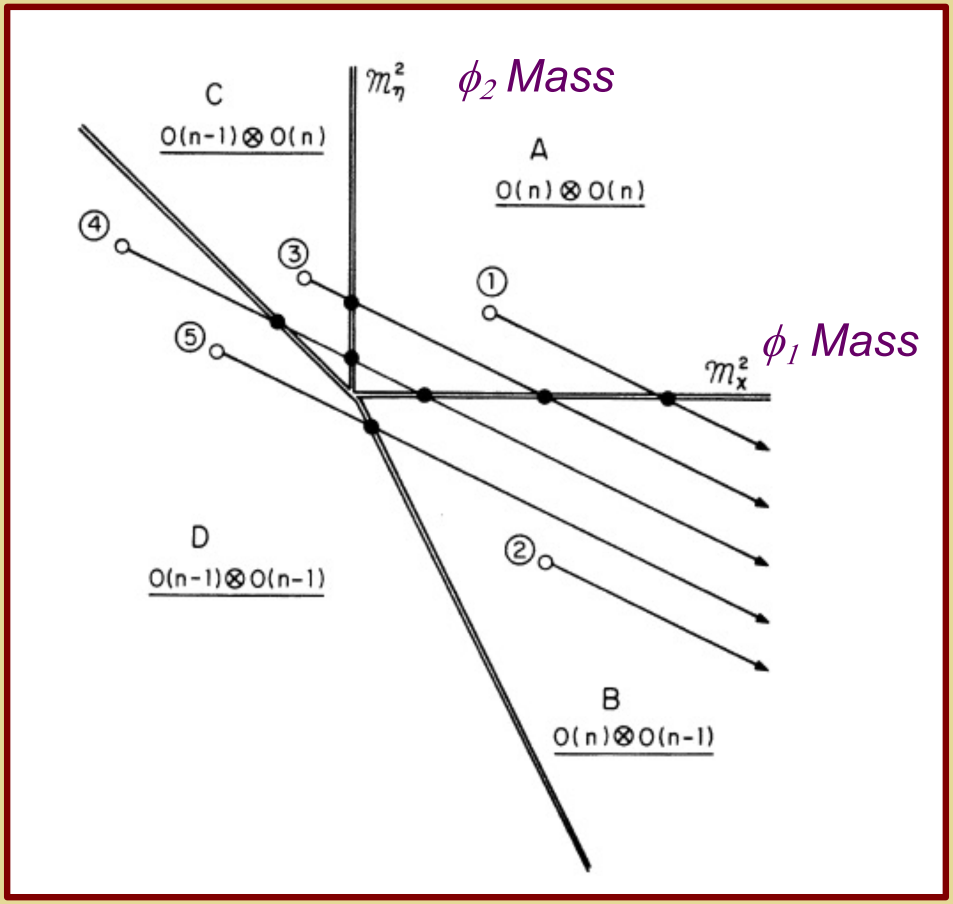
EW Phase Diagram

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

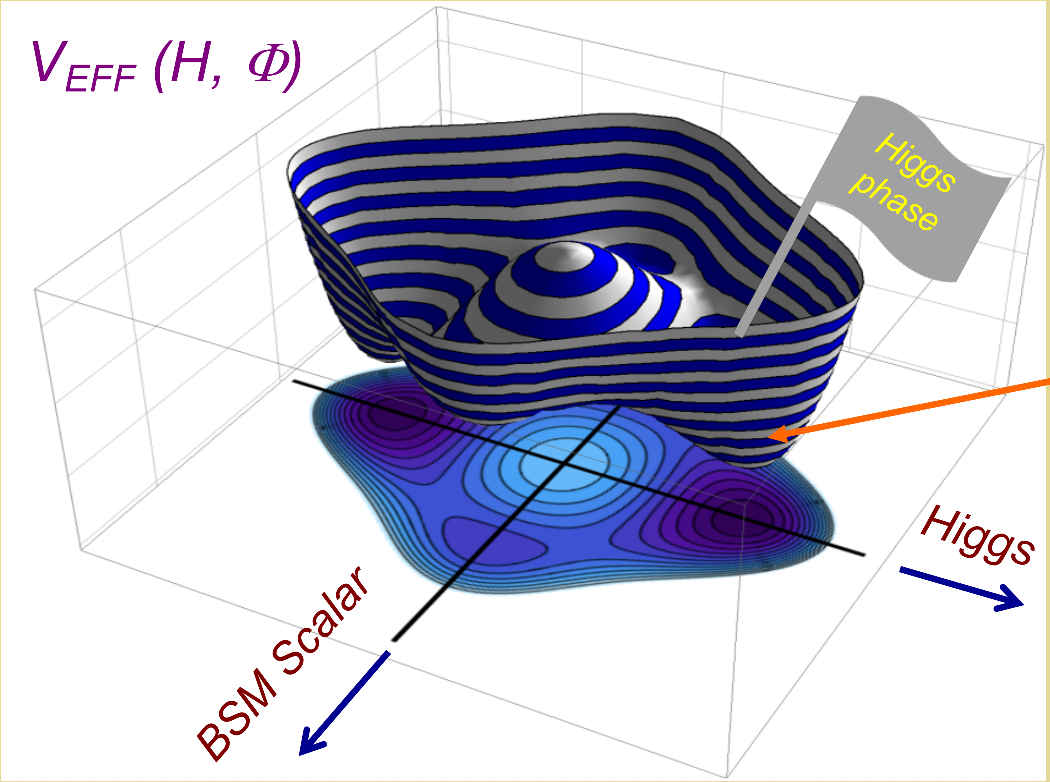
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

Patterns of Symmetry Breaking



S. Weinberg, PRD 9 (1974) 3357

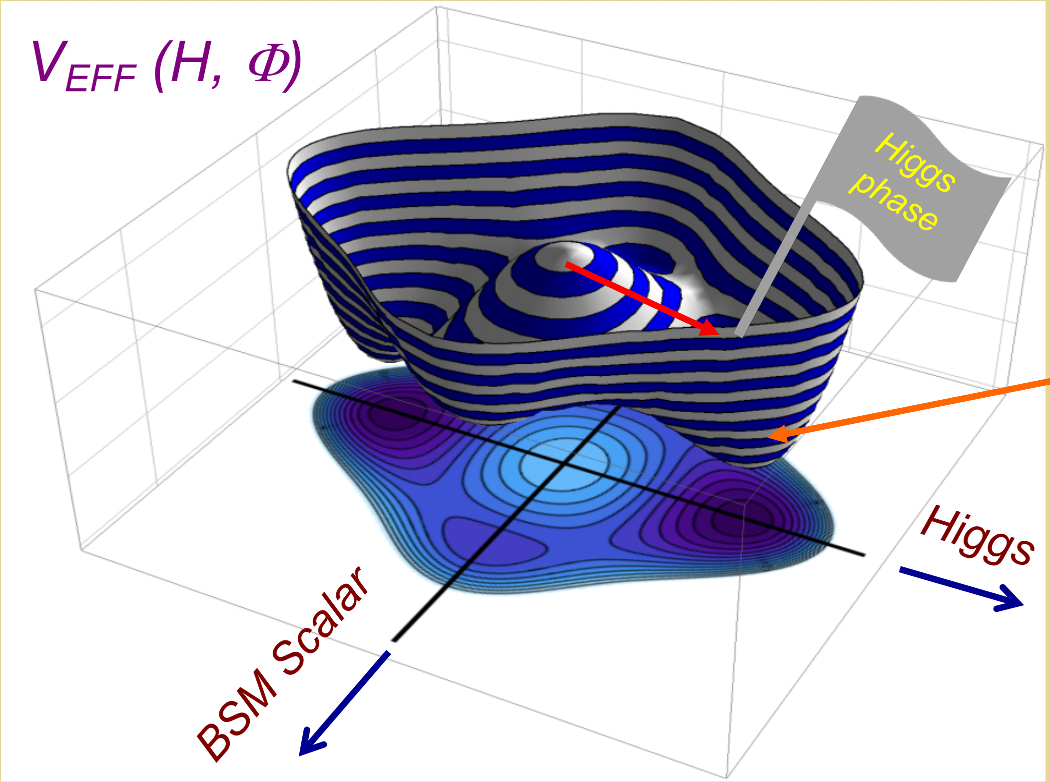
Patterns of Symmetry Breaking



How did we end up here ?

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

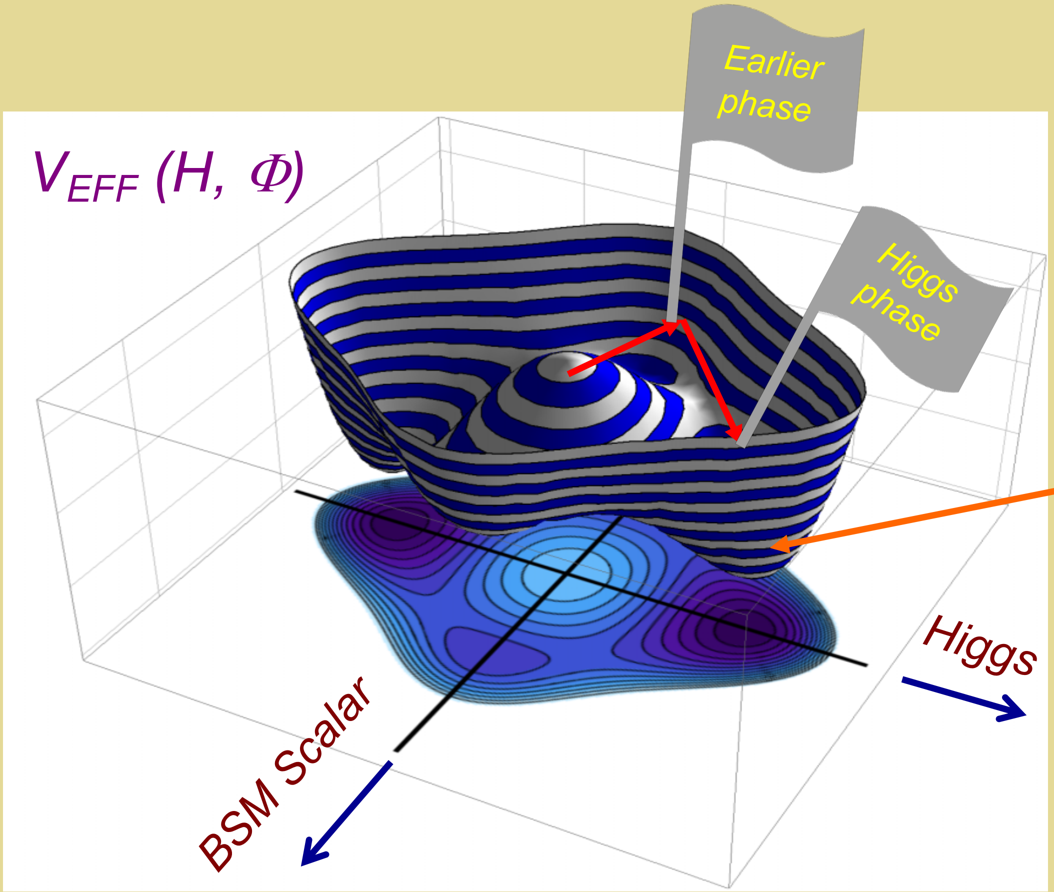
Patterns of Symmetry Breaking



How did we end up here ?

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

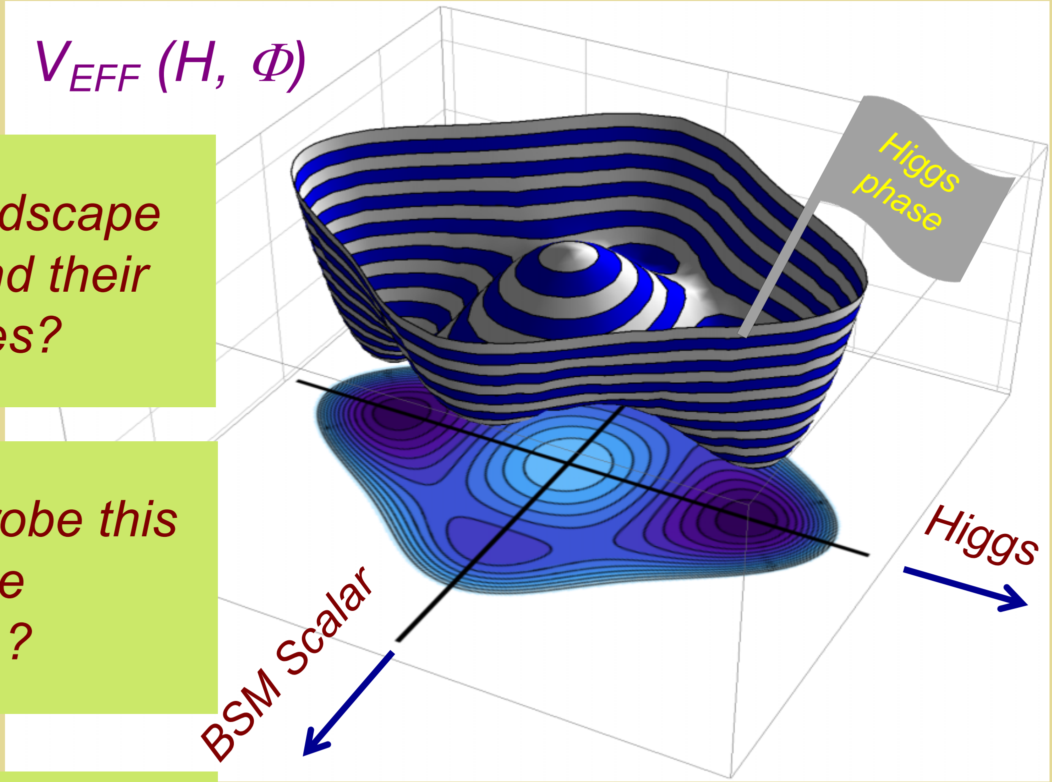
Patterns of Symmetry Breaking



How did we end up here ?

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

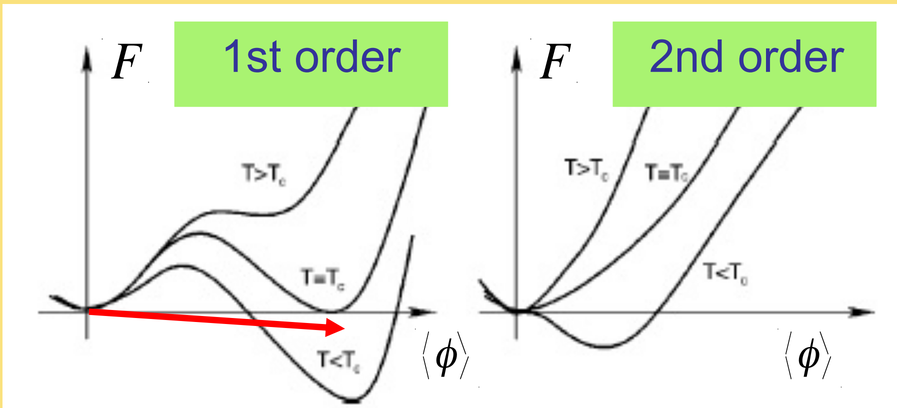
Electroweak Phase Transition

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

- *Baryogenesis $\rightarrow$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*

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

EW Phase Transition: Baryogen & GW



Increasing m_h →

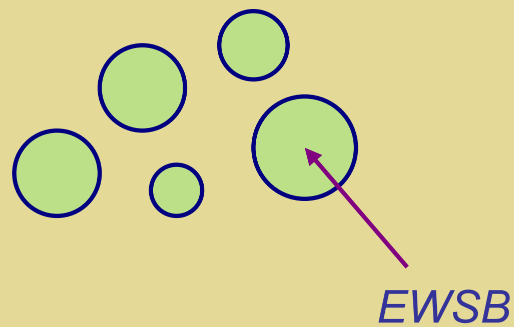
← *New scalars*

Baryogenesis *Gravity Waves* *Scalar DM* *LHC Searches*

"Strong" | *1^{st} order EWPT*

- *Baryogen**
- *GW*

Bubble nucleation



* *Need BSM CPV*

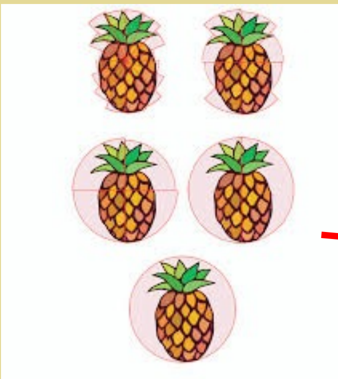
II. EWPT: A Collider Target

MJRM 1912.07189

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

Experimental Probes

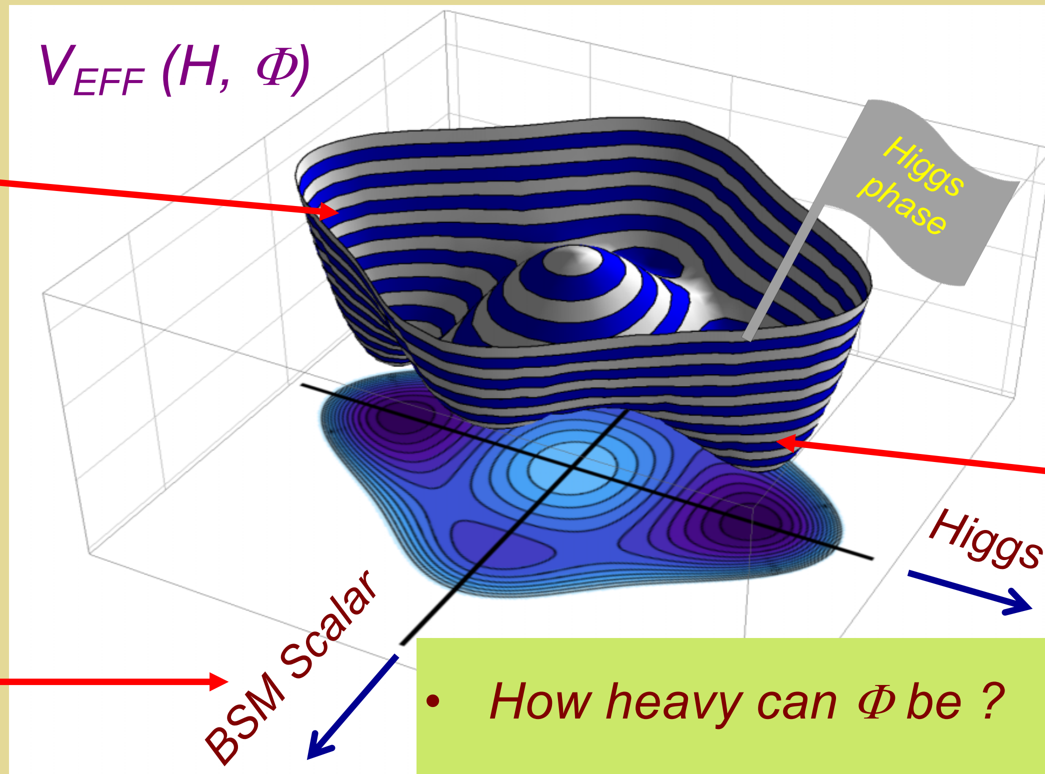
Bubble Collisions



Grav Radiation

Direct Production

BSM Higgs



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 fo

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

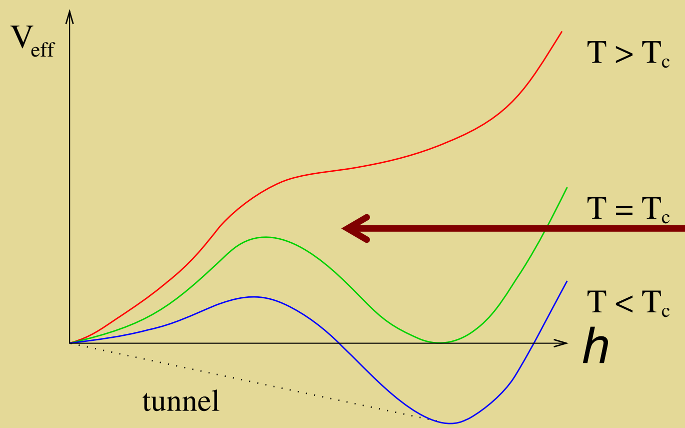
High-T SM Effective Potential

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

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

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

First Order EWPT from BSM Physics

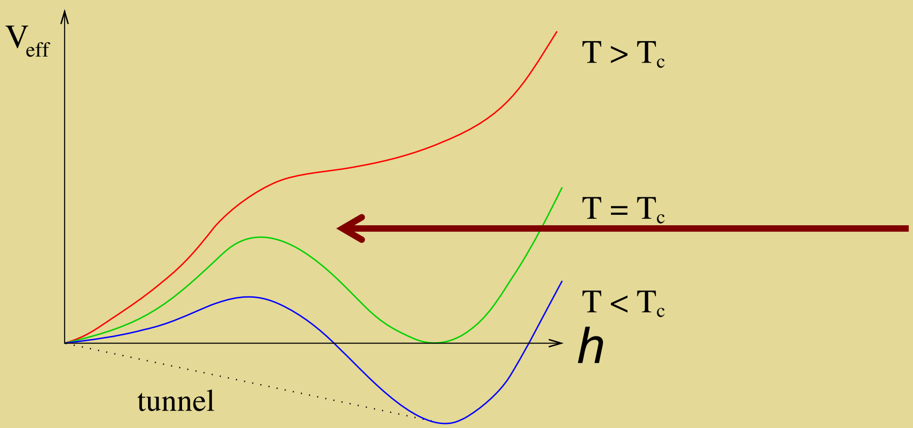


Generate finite-T barrier

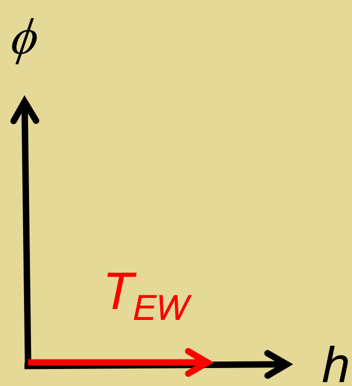
Introduce new scalar ϕ interaction with h via the Higgs Portal

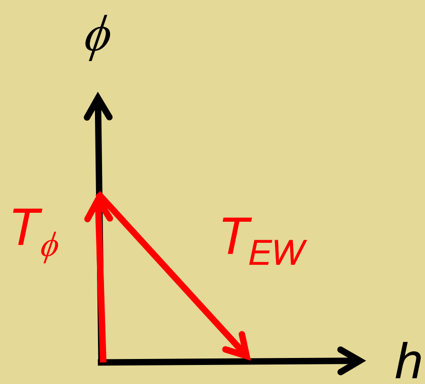
MJRM: 1912.07189

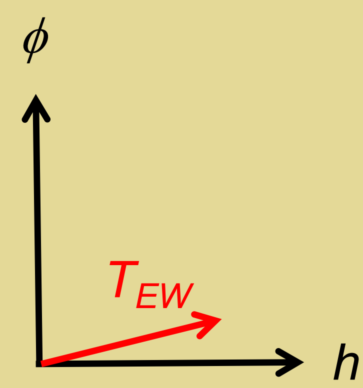
First Order EWPT from BSM Physics



Generate finite-T barrier





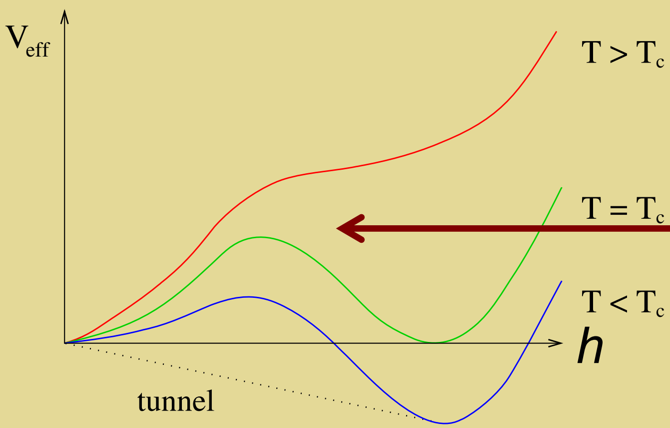


$a_2 H^2\phi^2$: $T > 0$
loop effect

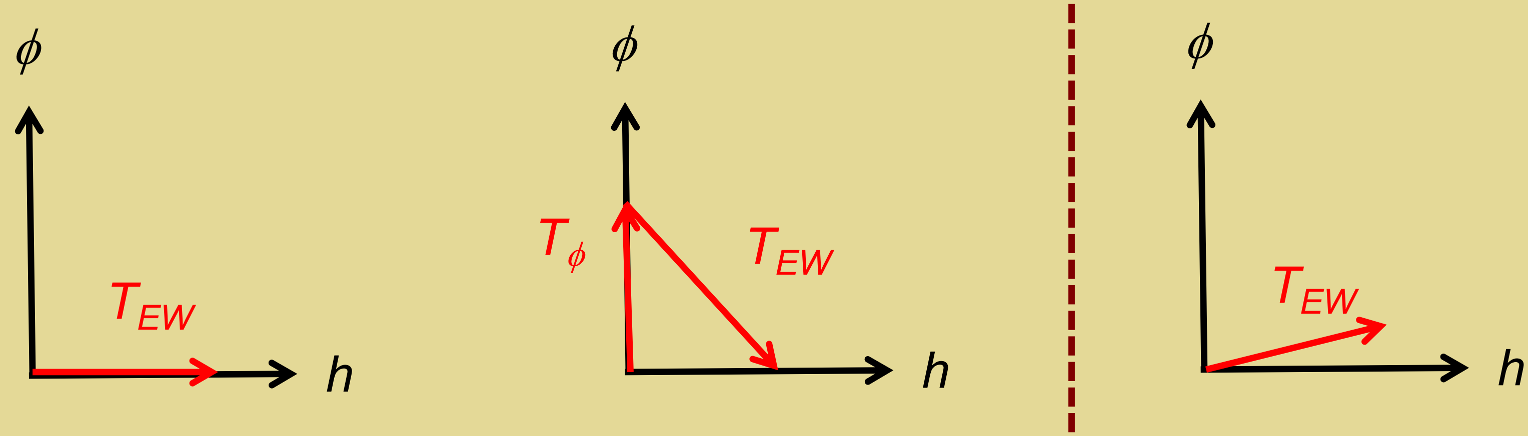
$a_2 H^2\phi^2$: $T = 0$
tree-level effect

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

First Order EWPT from BSM Physics



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



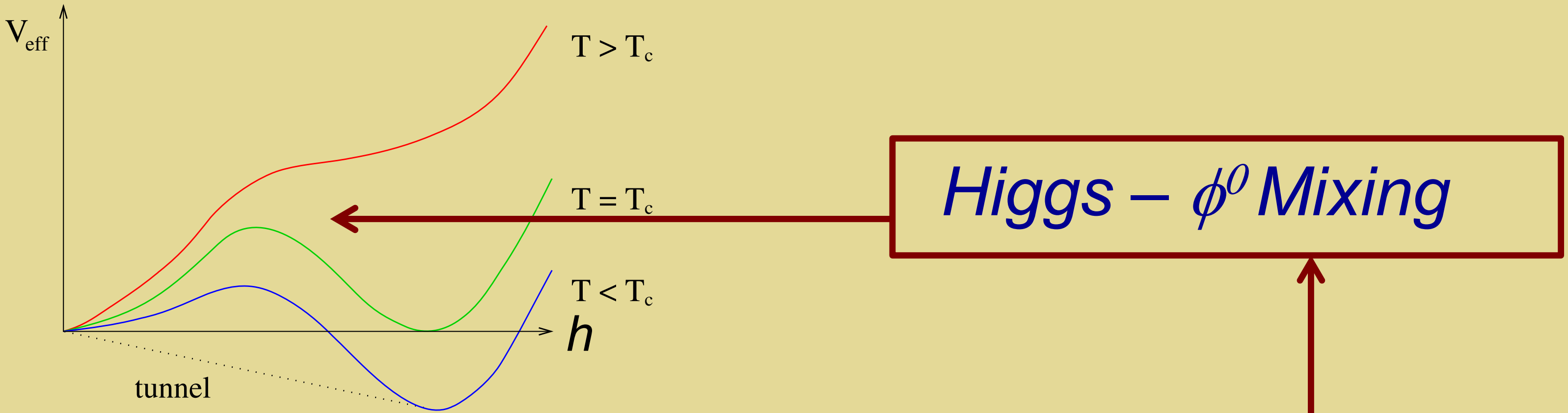
$a_2 H^2\phi^2$: $T > 0$
loop effect

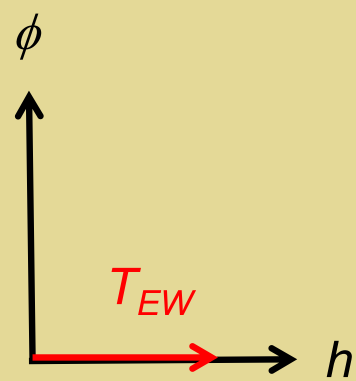
$a_2 H^2\phi^2$: $T = 0$
tree-level effect

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

MJRM: 1912.07189

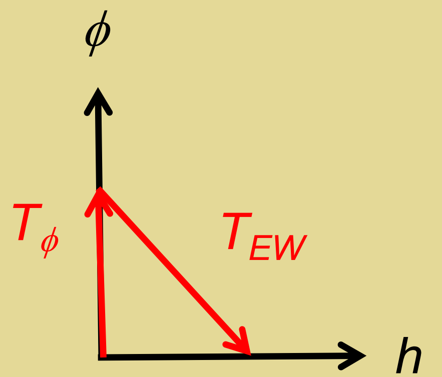
First Order EWPT from BSM Physics





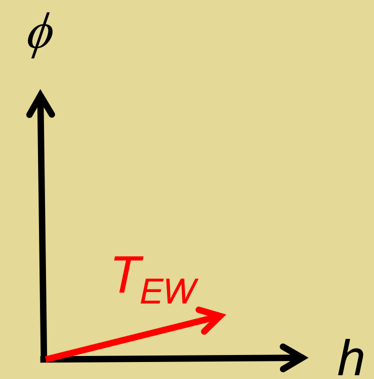
$a_2 H^2\phi^2$: T > 0

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

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

$$|\sin\theta| \gtrsim 0.01$$

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

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, Froome, 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...

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*

Models & Phenomenology

What BSM Scenarios?

Models & pheno: how reliable ?

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...

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

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

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

Effective expansion parameter

Small p regime

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

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

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

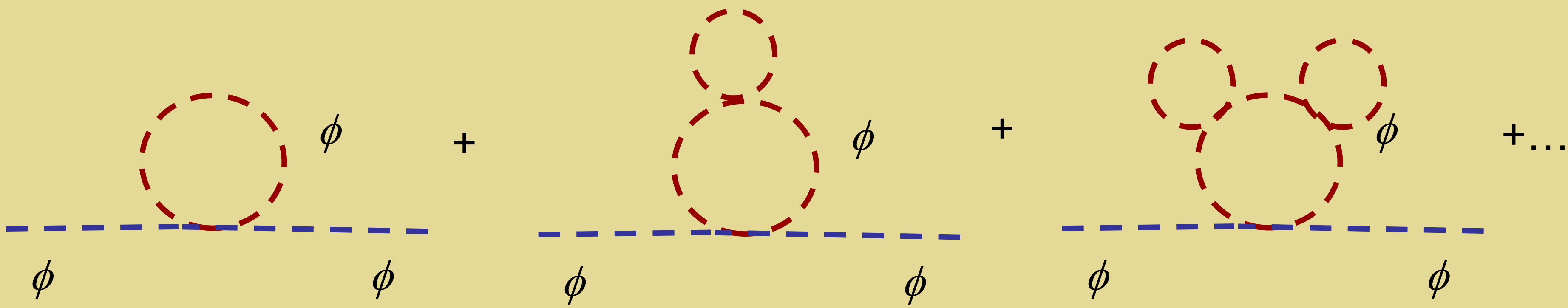
Infrared sensitive near phase trans

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]*

Power Counting & Resummations

Thermal masses $\Delta m^2\,(T)$:



$$\frac{\lambda T^2}{24} \qquad \sim \frac{\lambda T^2}{24} \times \zeta \qquad \sim \frac{\lambda T^2}{24} \times \zeta^2$$

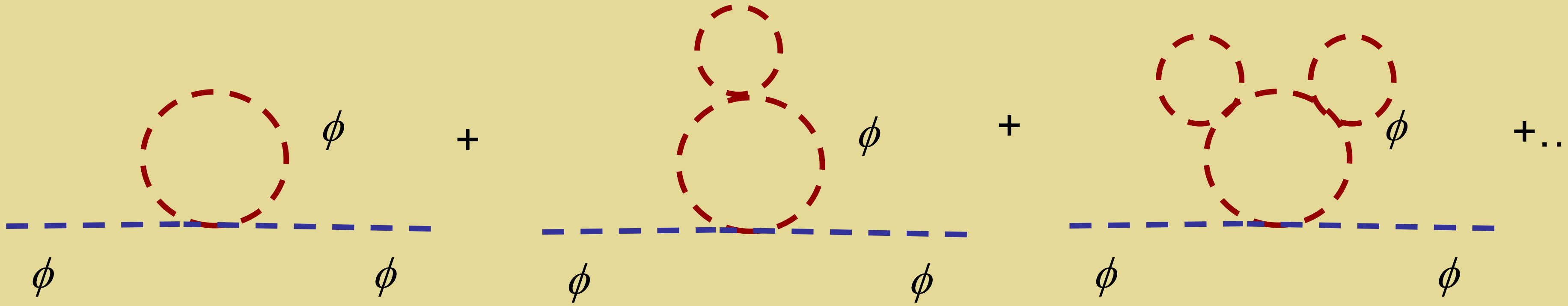
$$\zeta = \frac{T^2}{m^2[\phi_c]}$$

Can be O(1) near phase transition

Resum !

Power Counting & Resummations

"Daisy" or "ring" resummation



$$V_1(\phi_c, T) \longrightarrow V_1(\phi_c, T) + \Delta V_{\text{ring}}(\phi_c, T)$$

$$\Delta V_{\text{ring}}(\phi_c, T) = -\frac{T}{12\pi} \sum_k n_k \left\{ \left[m_k^2(\phi_c, T) \right]^{3/2} - \left[m_k^2(\phi_c) \right]^{3/2} \right\}$$

Ad hoc…

Systematic resummation: dimensional reduced 3D EFT

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

Challenges for Theory

Perturbation theory

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

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

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

Benchmark pert theory

B. Perturbative

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

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

Dimensionally reduced 3D EFT at T > 0

BSM proposals

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

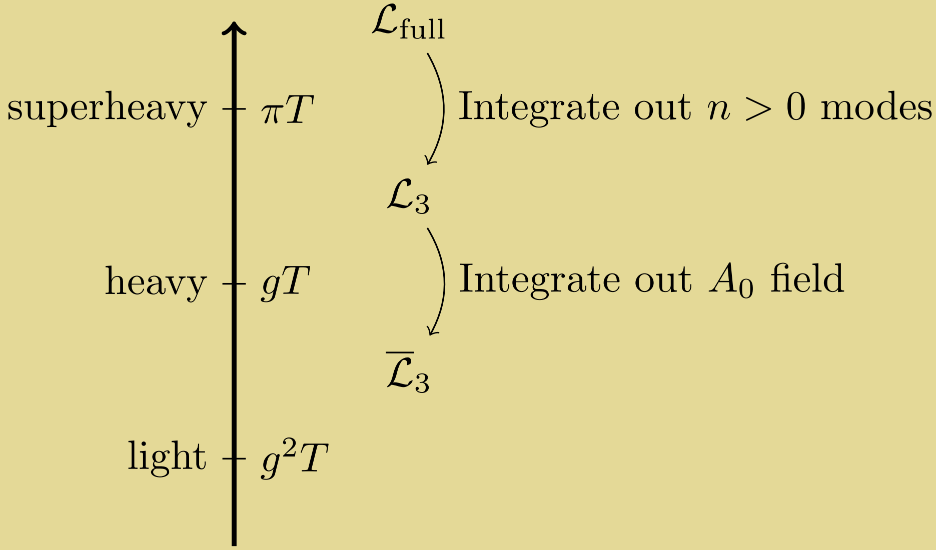
- πT — *Non-zero Matsubara modes*
- M_{BSM} — *BSM mass scale: can be > or < πT*
- $g\,T$ — *Thermal masses*
- M_{NUC} — *Nucleation scale ~ $1/r_{bubble}$*
- $g^2\,T$ — *Light scale*

EFT 2

EFT 1

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



EFT 1: Thermodynamics

Matching: Two Elements

Dimensional Reduction

All integrals are 3D with prefactor T → Rescale fields, couplings…

$$\int \frac{d^4k}{(2\pi)^4} \longrightarrow \frac{1}{\beta}\sum_n \int \frac{d^3k}{(2\pi)^3}$$

- $\varphi^2_{4d} = T\,\varphi^2_{3d}$
- $T\,\lambda_{4d} = \lambda_{3d}$

Thermal Loops

Equate Greens functions

$$\phi^2_{3\mathrm{d}} = \frac{1}{T}\left[1 + \hat{\Pi}'_\phi(0,0)\right]\phi^2$$

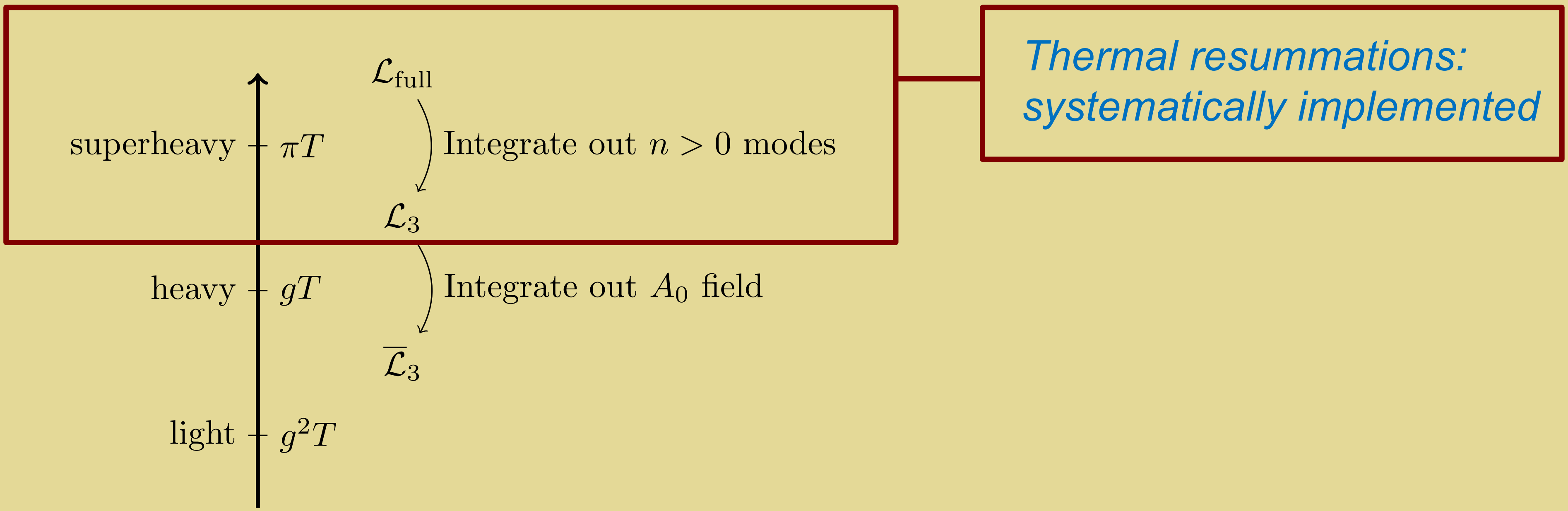
Field

$$a_{2,3} = T\left[a_2 - a_2(\hat{\Pi}'_H(0) + \hat{\Pi}'_\Sigma(0)) + \hat{\Gamma}(0)\right]$$

Quartic coupling

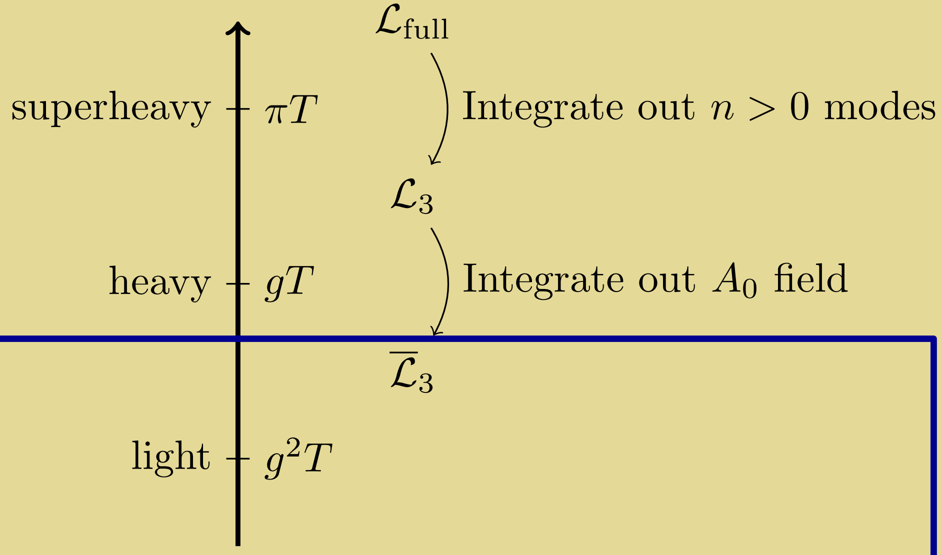
EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



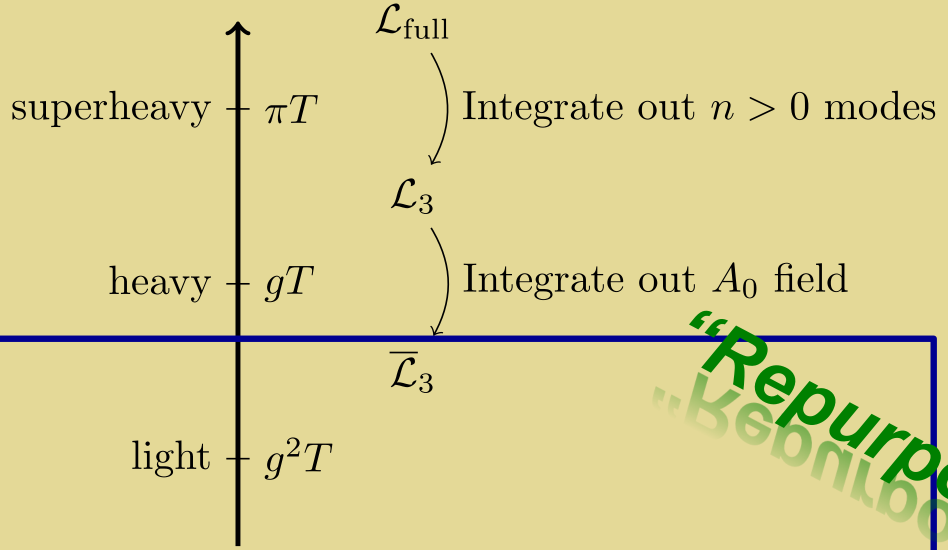
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

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

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



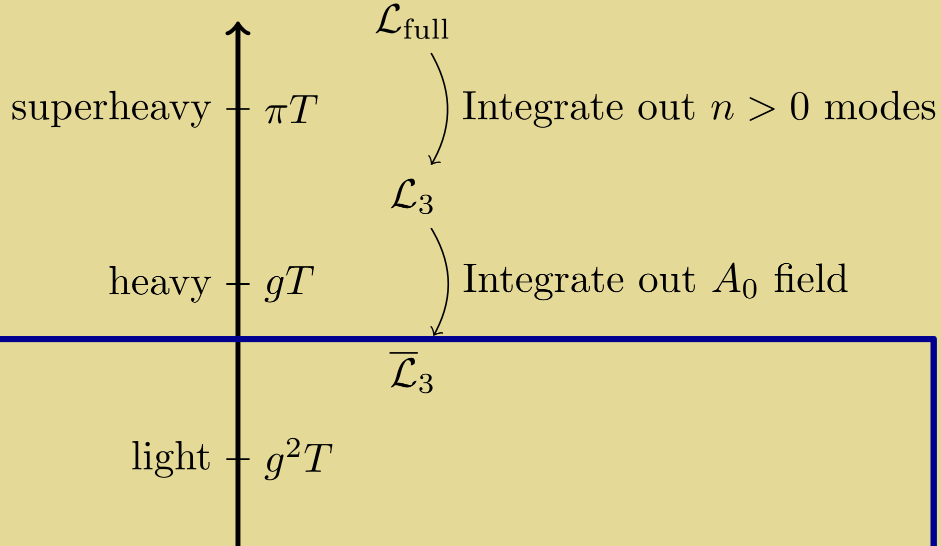
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

"Repurpose" lattice results

Lattice simulations exist

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



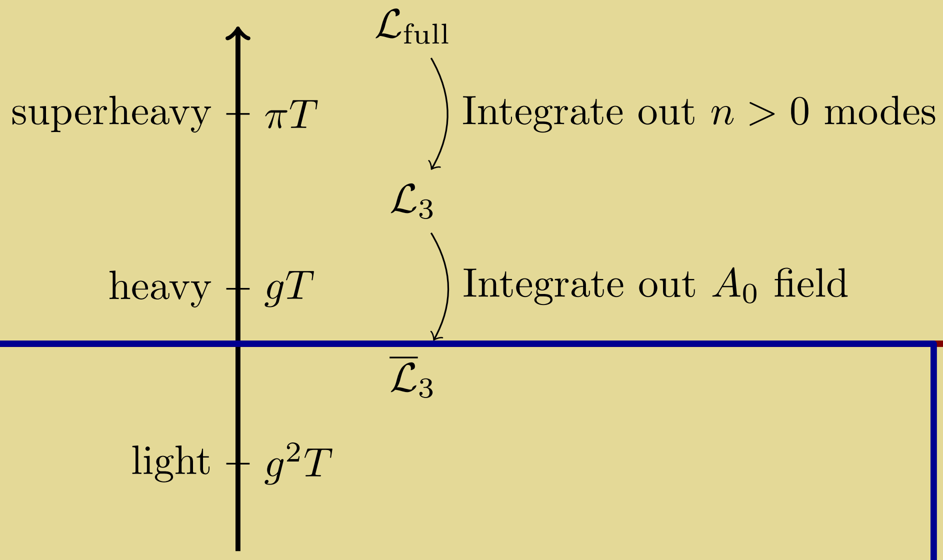
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

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

- *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*

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



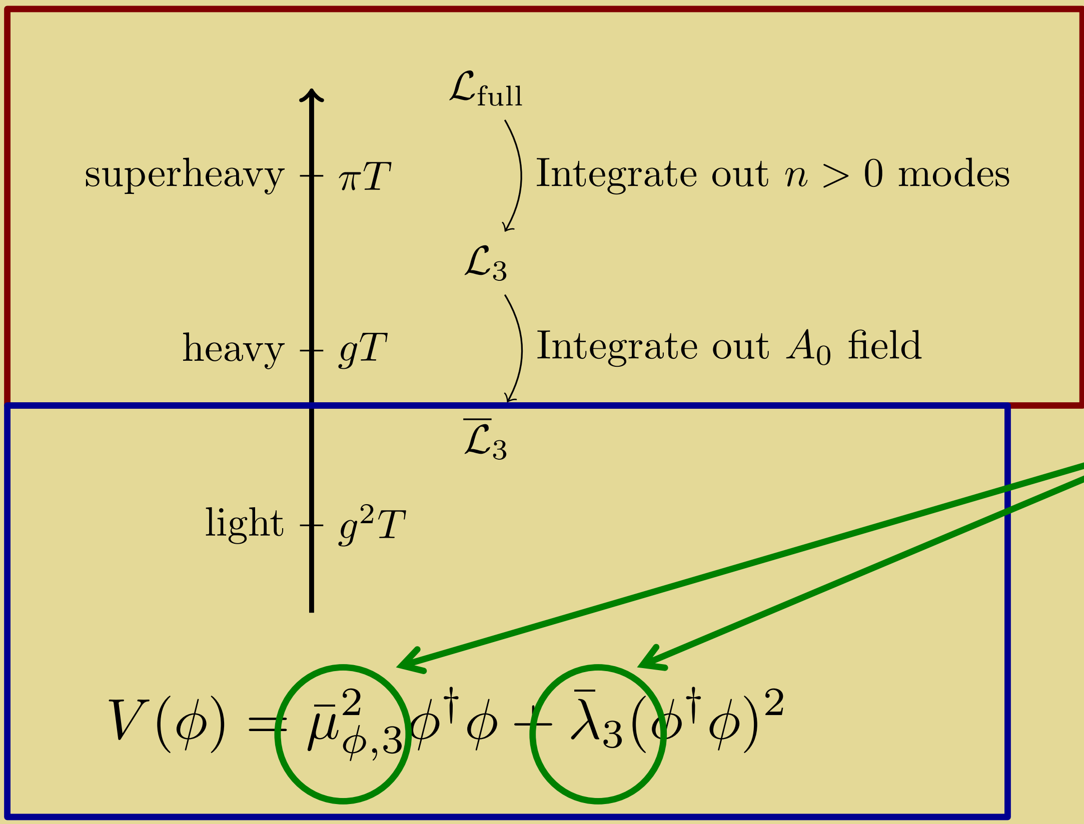
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

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

- *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*

Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory



- *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)

Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory

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

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

$\mathcal{L}_3$

heavy — gT — Integrate out A_0 field

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

light — $g^2 T$

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

- *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*

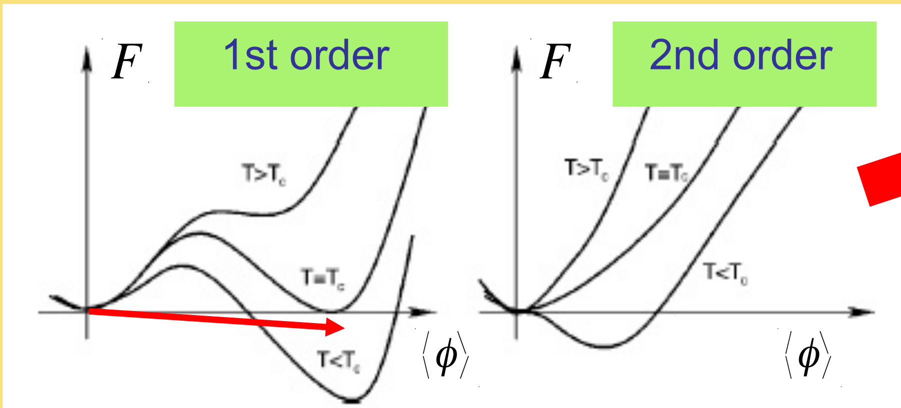
Lattice simulations exist (e.g., Kajantie et al ʼ95)

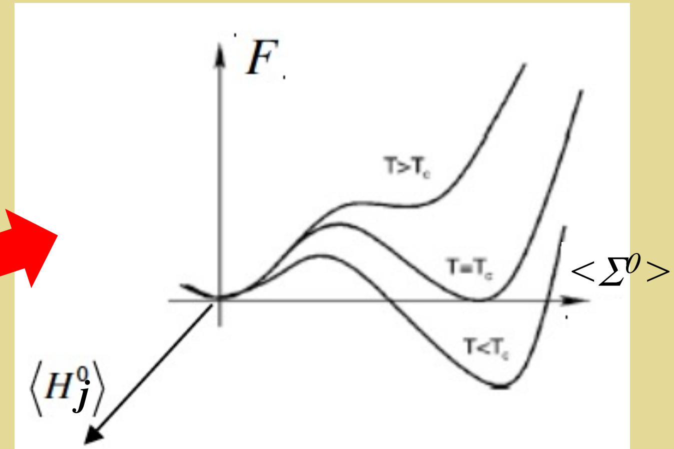
Model Illustrations

Simple Higgs portal models:

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

EW Multiplets: EWPT





Increasing m_h ⟶

⟵ *New scalars*

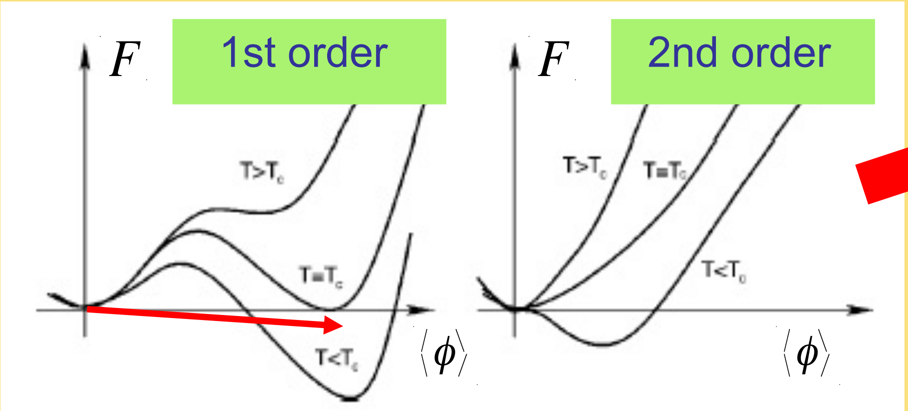
- *Thermal loops*
- *Tree-level barrier*

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

$H^2\phi^2$ Barrier ?

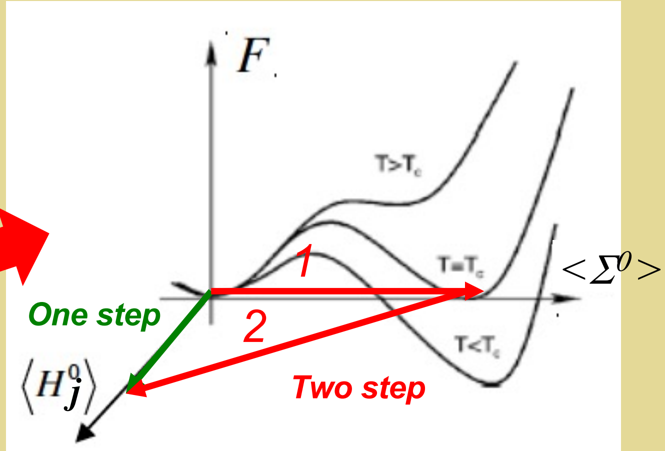
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

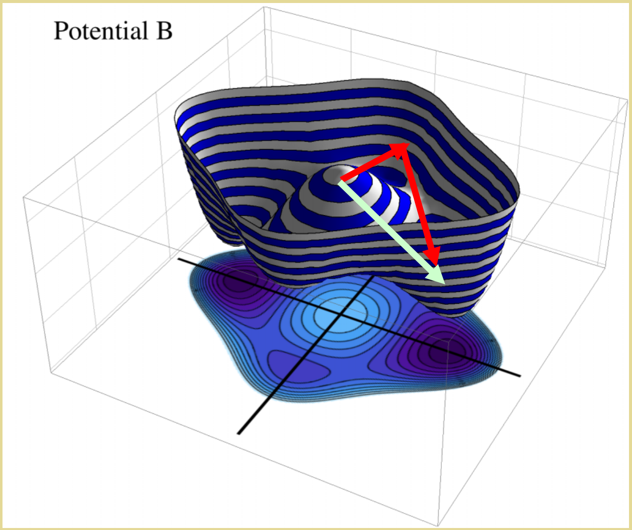
EW Multiplets: Two-Step EWPT



Increasing m_h →

← *New scalars*

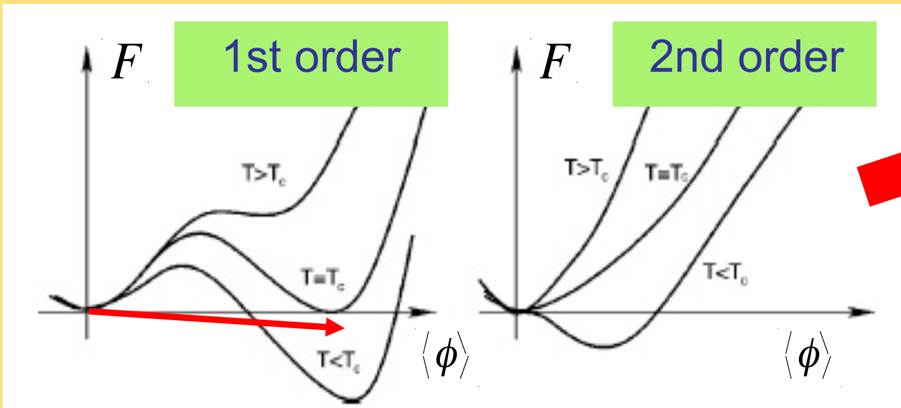




- *One-step: Sym phase → Higgs phase*
- *Two-step: successive EW broken phases*

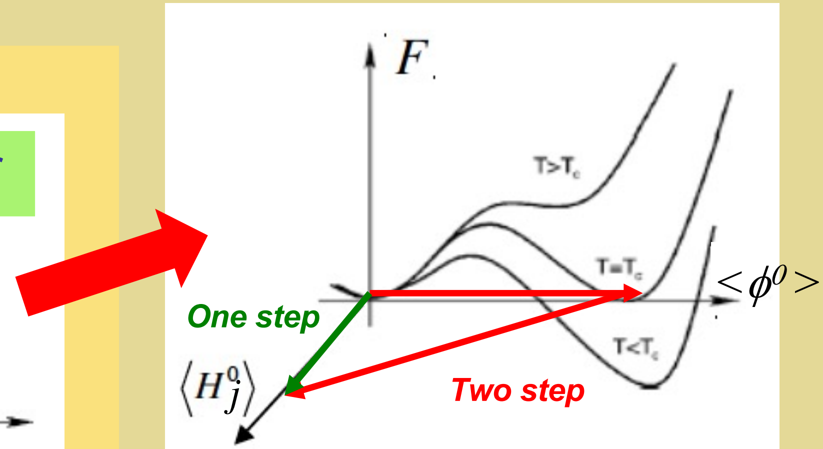
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: Two-Step EWPT

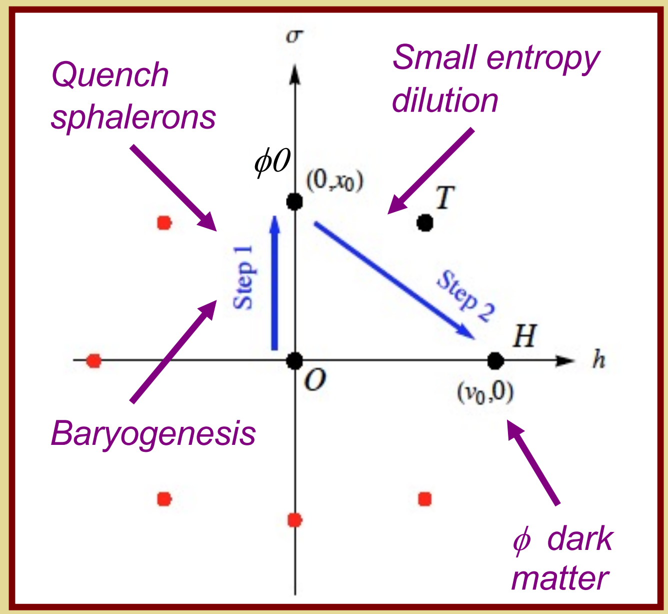


Increasing m_h ⟶

⟵ *New scalars*

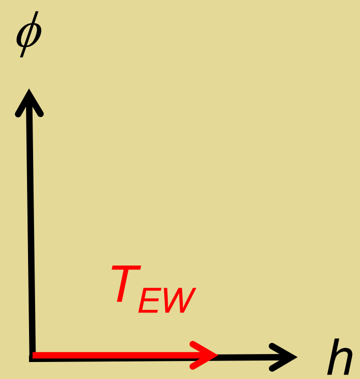


- *One-step: thermal loops*
- *Two-Step 1: thermal loops*
- *Two-Step 2: tree-level barrier*



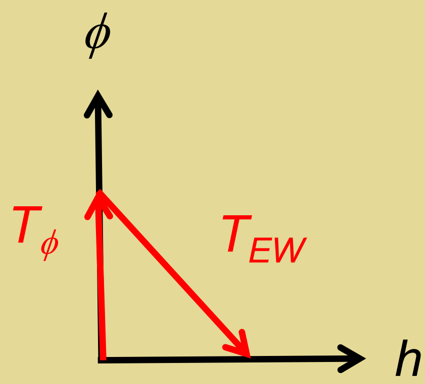
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

Real Triplet



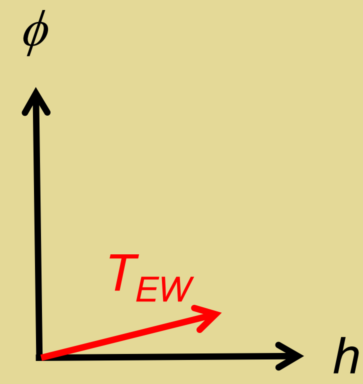
$a_2\, H^2\phi^2$: $T > 0$

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:
Heavy triplet

EW precision tests → too tiny

Super Heavy Triplet: EFT 1

$$V(\phi,\Sigma) = -\mu_\phi^2\phi^\dagger\phi - \frac{1}{2}\mu_\Sigma^2\Sigma^a\Sigma^a + \lambda(\phi^\dagger\phi)^2 + \frac{b_4}{4}(\Sigma^a\Sigma^a)^2 + \frac{a_2}{2}\phi^\dagger\phi\Sigma^a\Sigma^a,$$

Full theory potential

$$\lambda_3 = T\left\{\lambda(\Lambda) + \frac{1}{(4\pi)^2}\left[\frac{1}{8}\left(3g^4 + g'^4 + 2g^2g'^2\right) + 3L_f\left(y_t^4 - 2\lambda y_t^2\right) - L_b\left(\frac{3}{16}\left(3g^4 + g'^4 + 2g^2g'^2\right) - \frac{3}{2}\left(3g^2 + g'^2 - 8\lambda\right)\lambda + \frac{3}{4}a_2^2\right)\right]\right\},$$

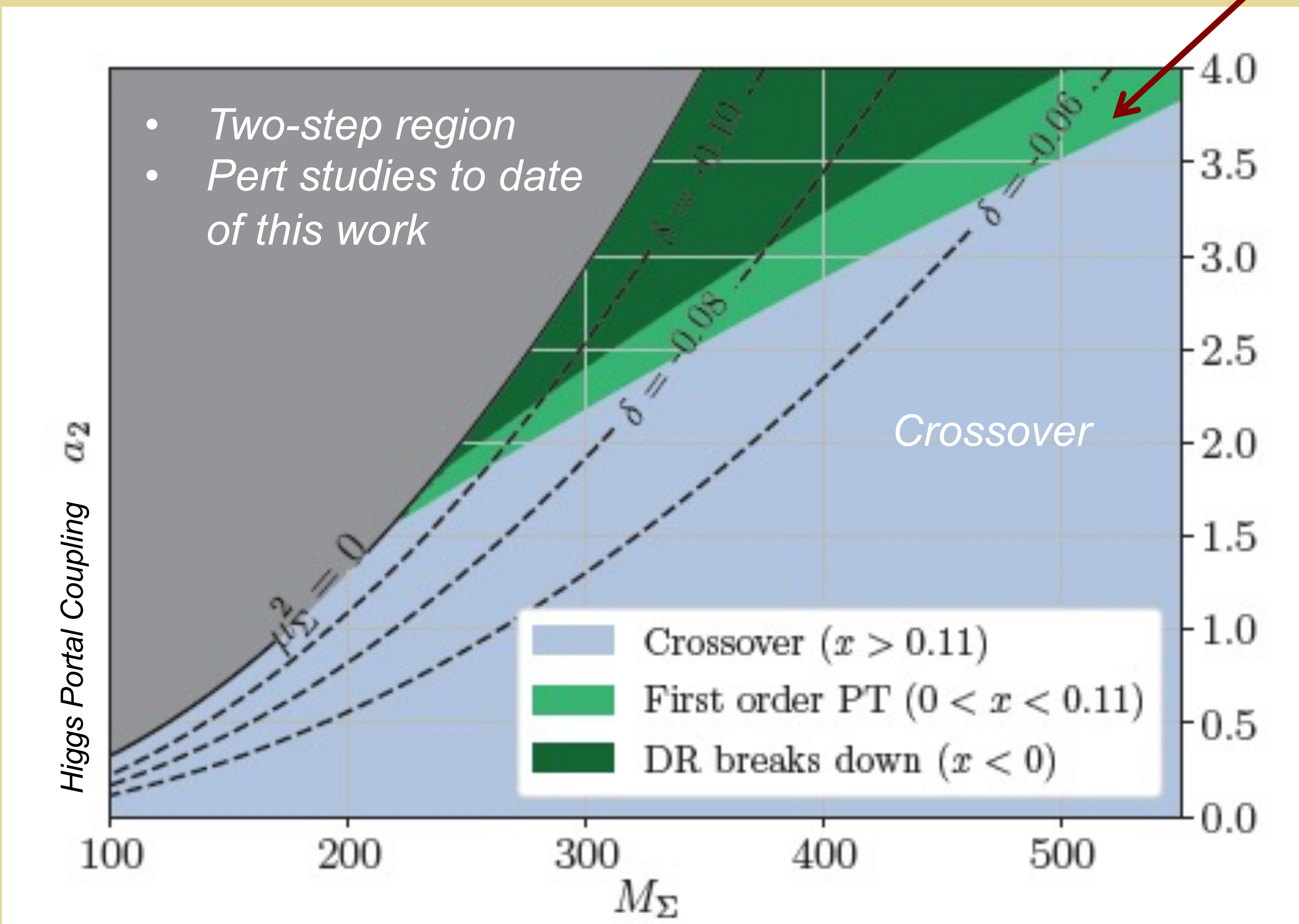
Matching: heavy theory

Allows for first order EWPT with $\lambda(\Lambda)$ consistent with $m_h = 125$ GeV

Niemi, R-M, Tenkanen, Weir 2005.11332

Real Triplet: One-Step EWPT

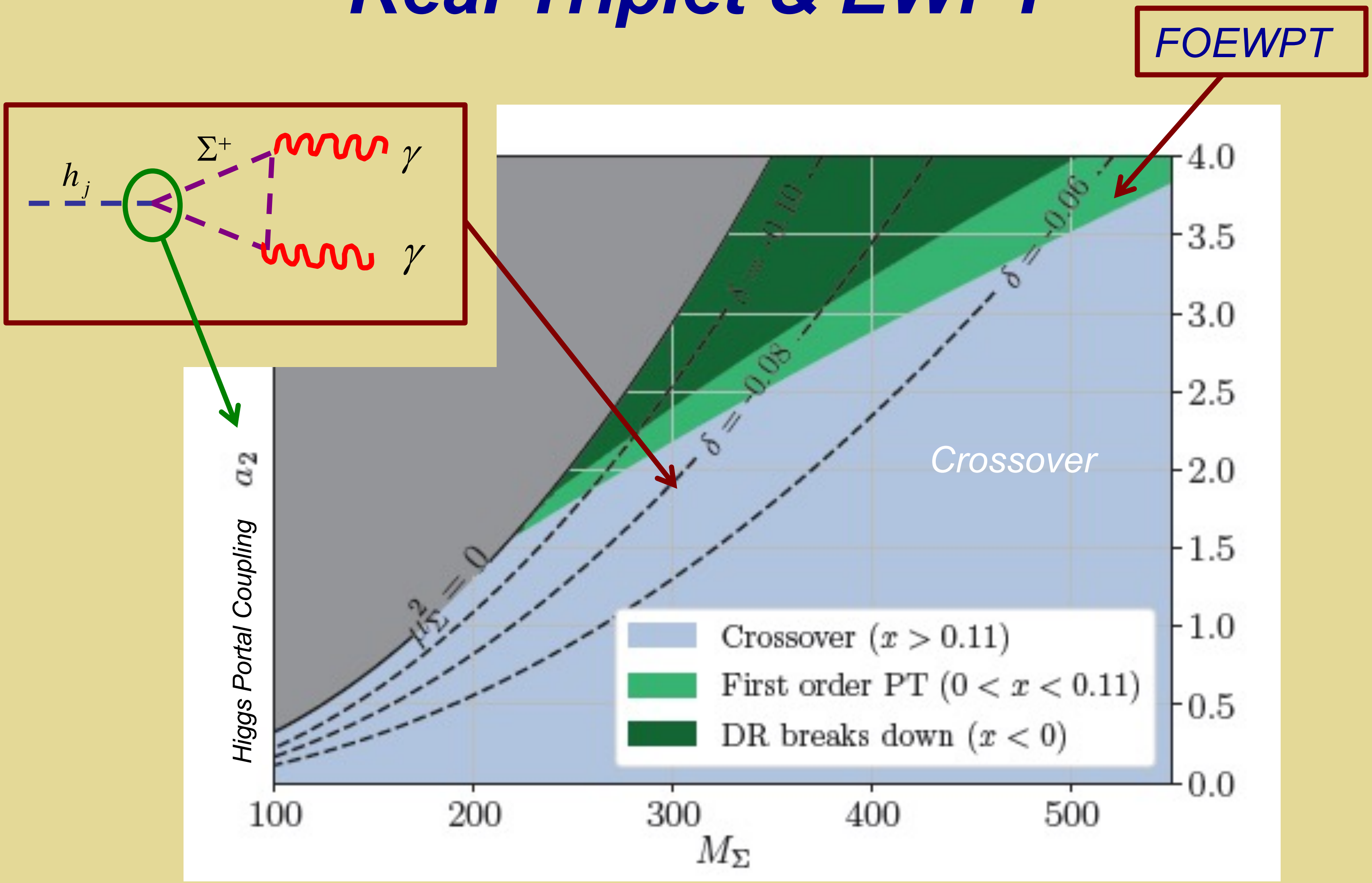
FOEWPT



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

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

Real Triplet & EWPT

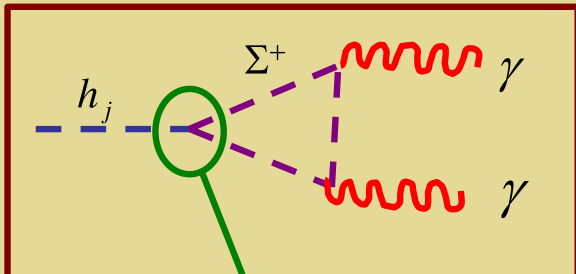


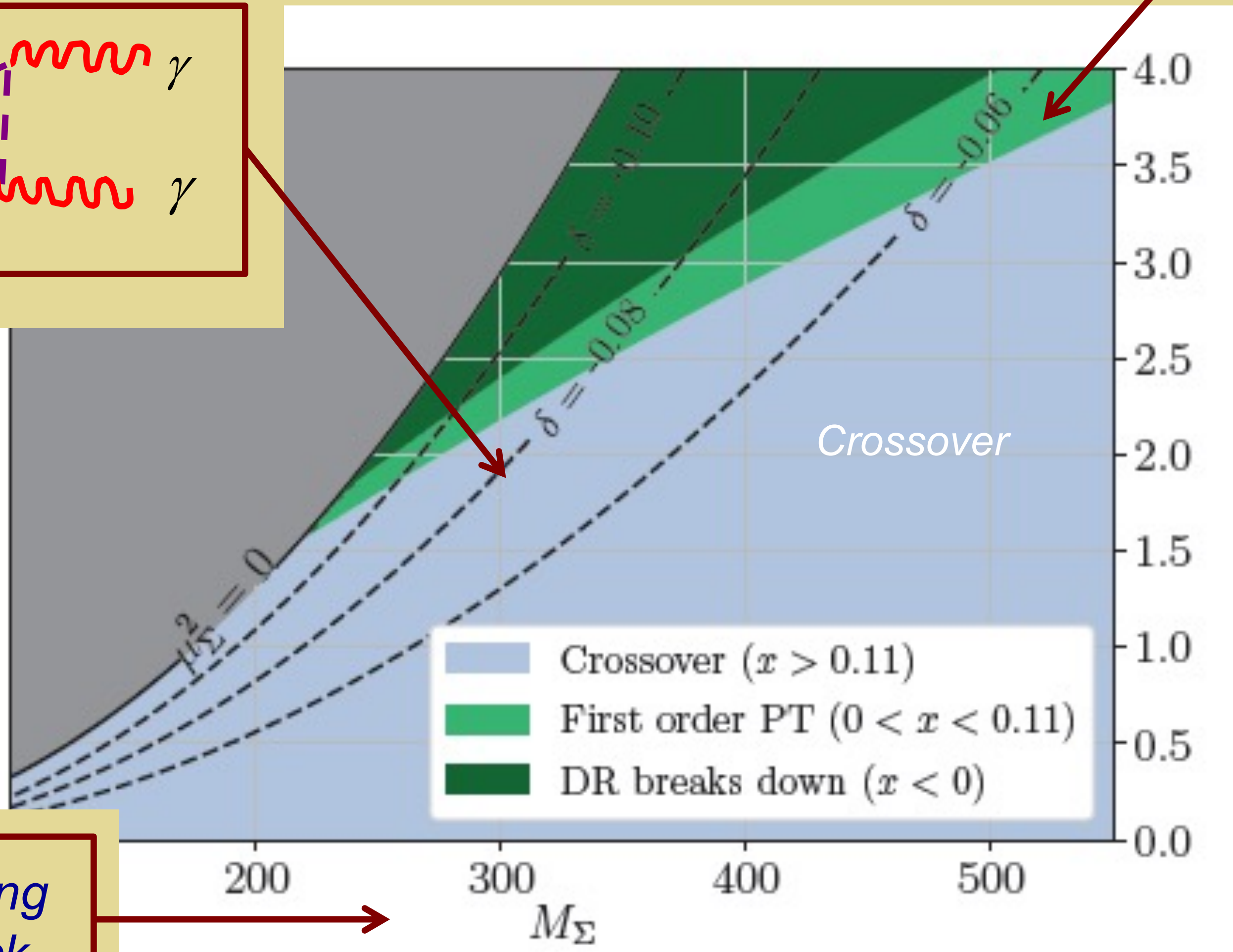
- *One-step*
- *Non-perturbative*

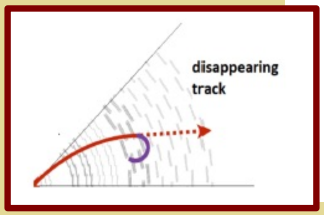
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

FOEWPT







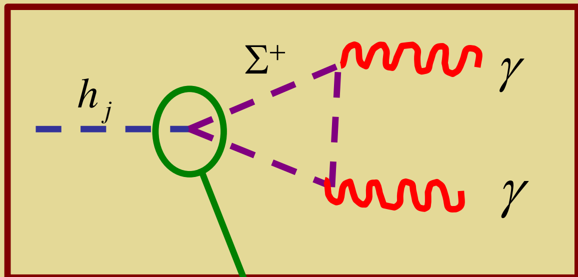
Disappearing charge track

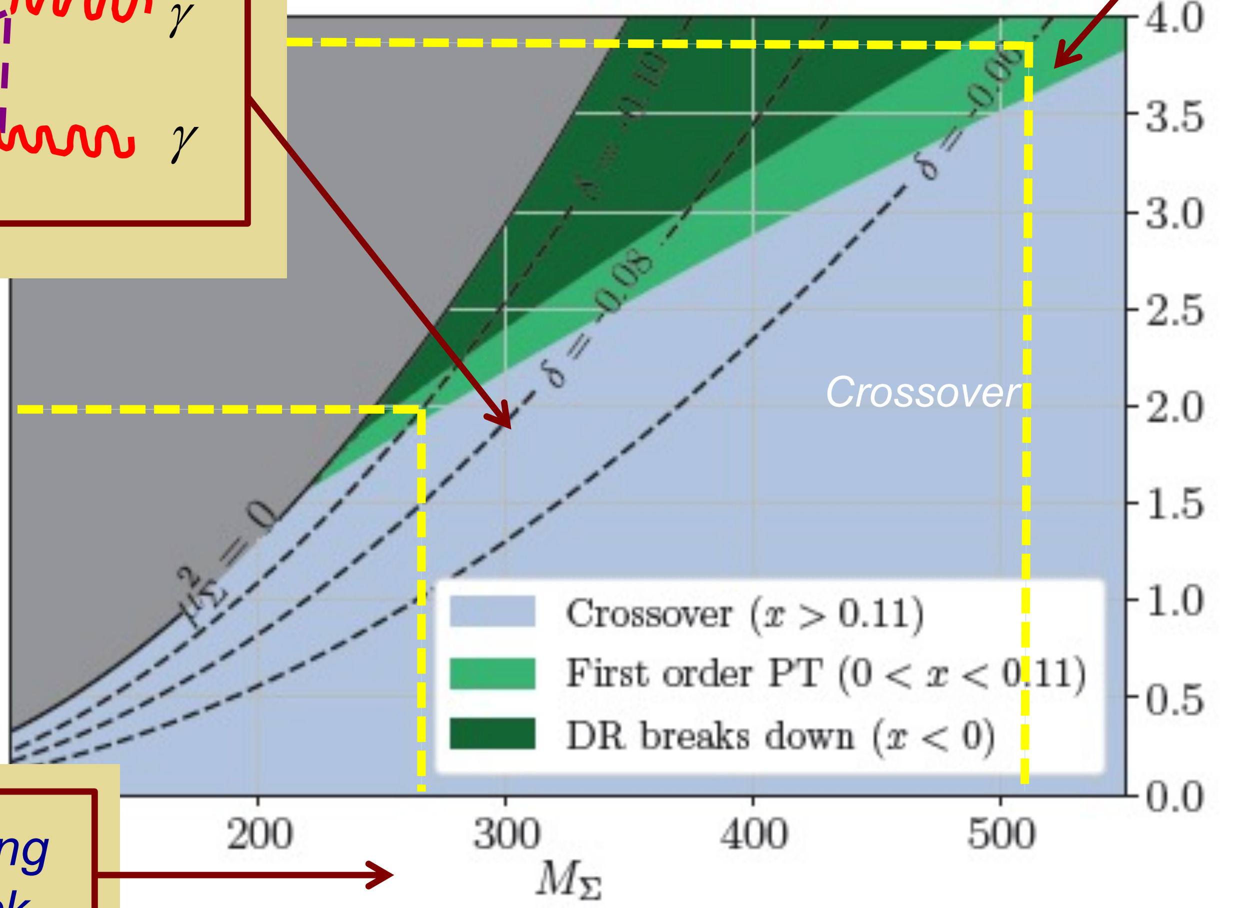
- *One-step*
- *Non-perturbative*

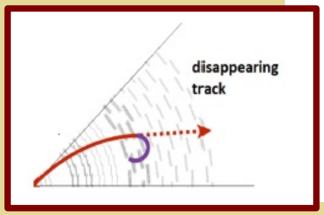
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

FOEWPT





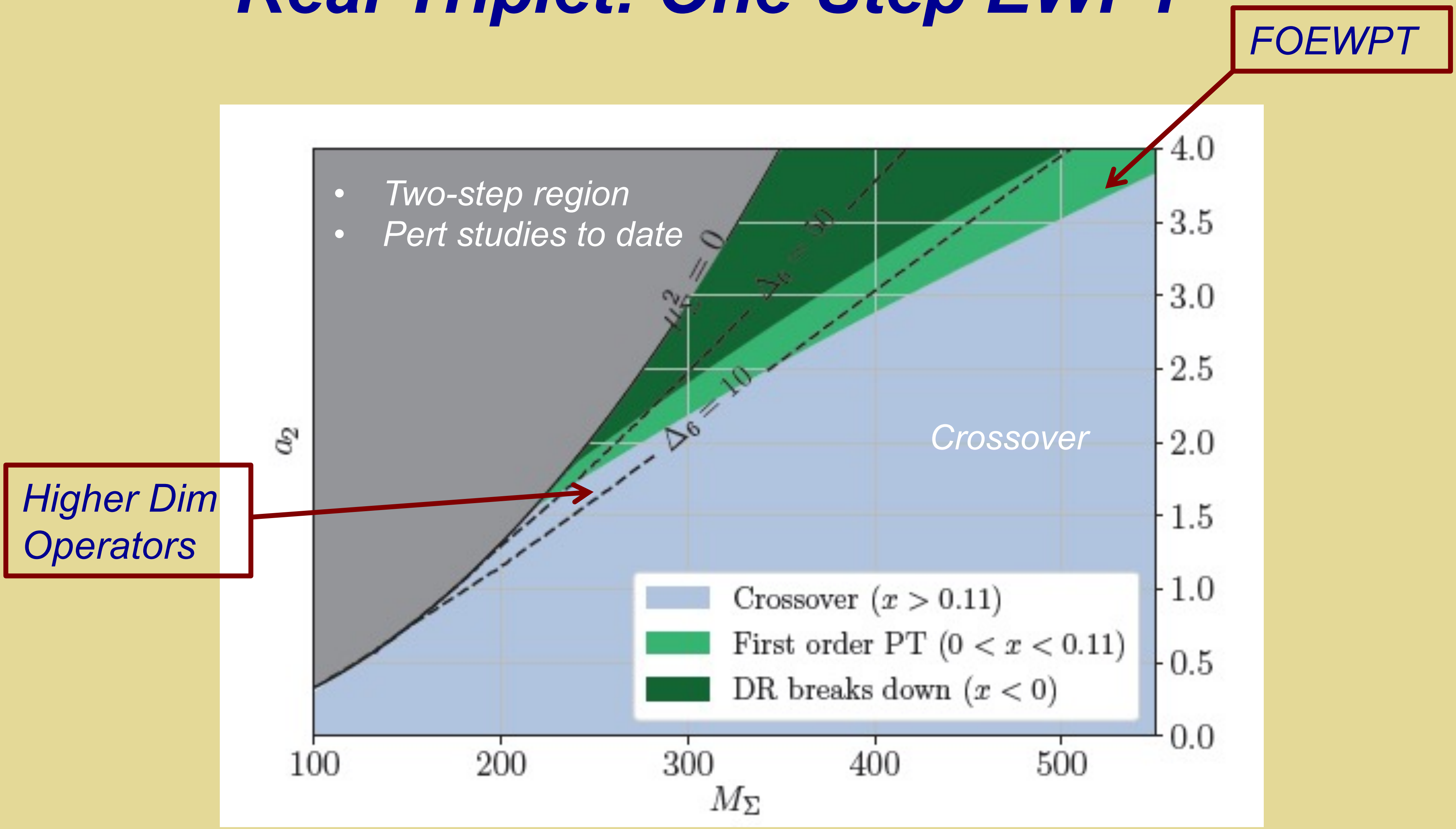


Disappearing charge track

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

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

Real Triplet: One-Step EWPT



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

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

Dynamical Real Triplet: EFT 1

$$V(\phi,\Sigma) = -\mu_\phi^2\phi^\dagger\phi - \frac{1}{2}\mu_\Sigma^2\Sigma^a\Sigma^a + \lambda(\phi^\dagger\phi)^2 + \frac{b_4}{4}(\Sigma^a\Sigma^a)^2 + \frac{a_2}{2}\phi^\dagger\phi\Sigma^a\Sigma^a,$$

Full theory potential

$$\lambda_3 = T\Big\{\lambda(\Lambda) + \frac{1}{(4\pi)^2}\Big[\frac{1}{8}\Big(3g^4 + g'^4 + 2g^2g'^2\Big) + 3L_f\Big(y_t^4 - 2\lambda y_t^2\Big) - L_b\Big(\frac{3}{16}\Big(3g^4 + g'^4 + 2g^2g'^2\Big) - \frac{3}{2}\Big(3g^2 + g'^2 - 8\lambda\Big)\lambda + \frac{3}{4}a_2^2\Big)\Big]\Big\}.$$

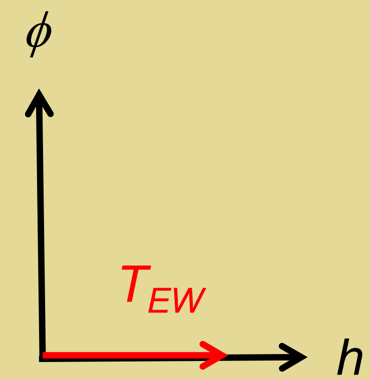
Matching: heavy theory

$$\mathcal{L}_{3\text{d}} = \frac{1}{4}(F_{ij}^a)^2 + |D_i\phi|^2 + \frac{1}{2}(D_i\Sigma^a)^2 + \bar{\mu}_\phi^2\phi^\dagger\phi + \bar{\lambda}(\phi^\dagger\phi)^2 + \frac{\bar{\mu}_\Sigma^2}{2}\Sigma^a\Sigma^a + \frac{\bar{b}_4}{4}(\Sigma^a\Sigma^a)^2 + \frac{\bar{a}_2}{2}\phi^\dagger\phi\Sigma^a\Sigma^a. \quad (2)$$

Light theory

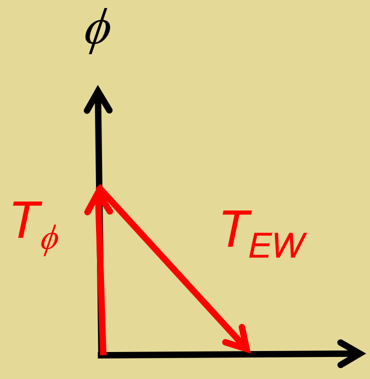
Niemi, R-M, Tenkanen, Weir 2005.11332

Real Triplet



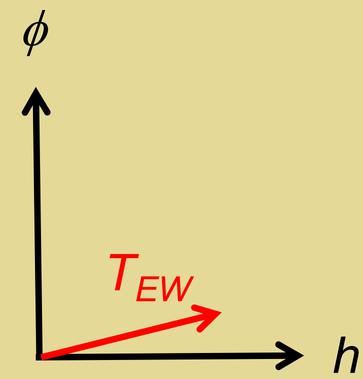
$a_2\, H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



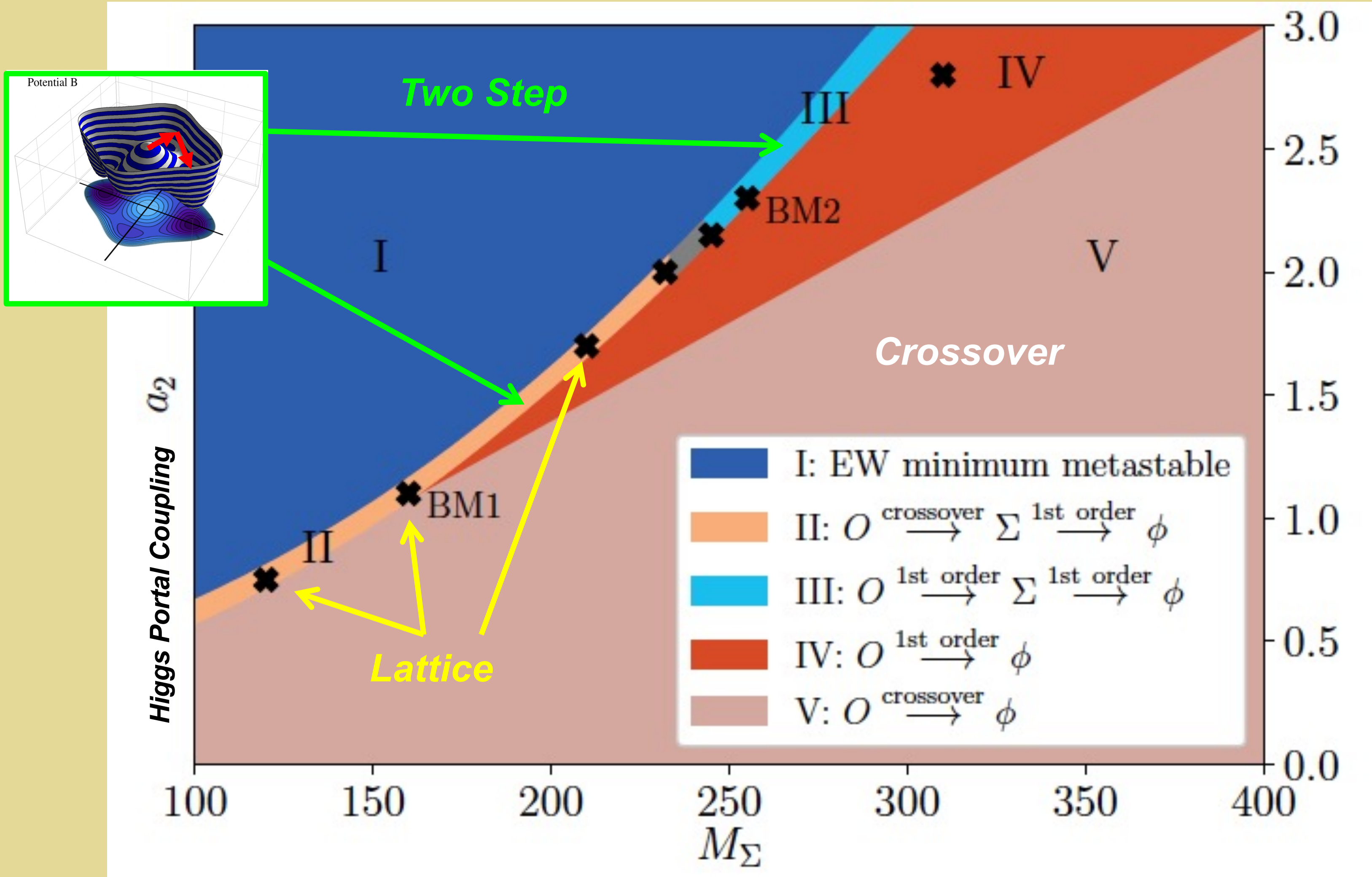
$a_1\, H^2\phi$: $T = 0$

tree-level effect

Non-perturbative results

EW precision tests → too tiny

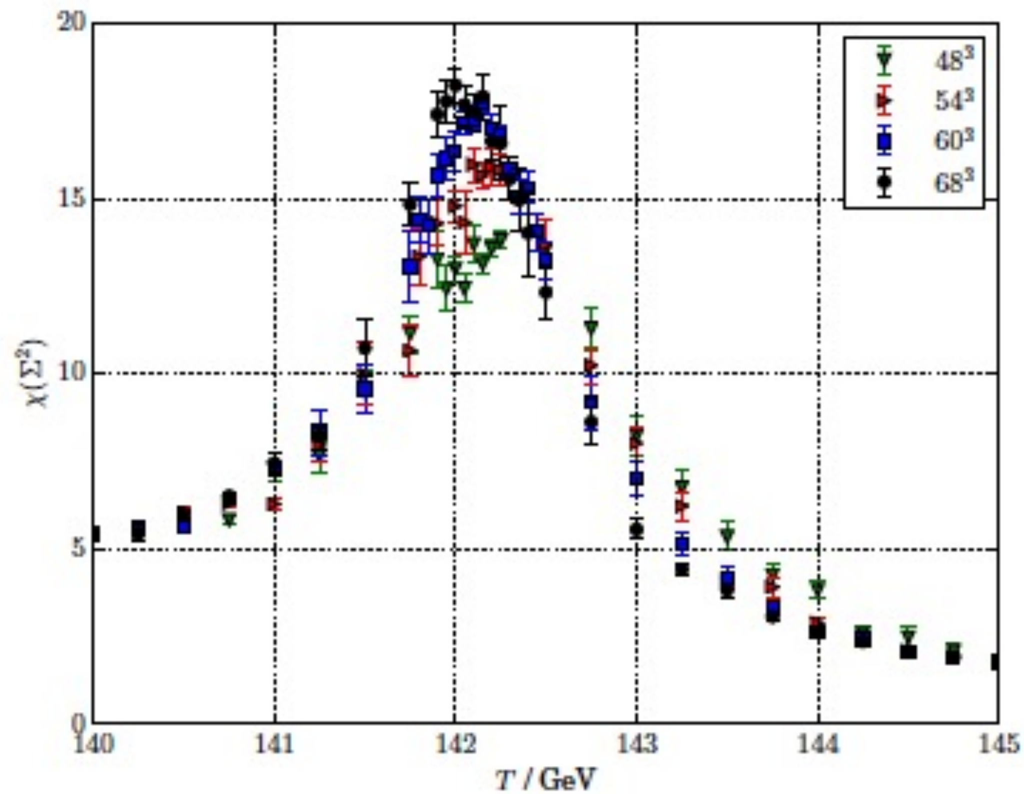
Real Triplet & EWPT: Novel EWSB



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

Niemi, R-M, Tenkanen, Weir 2005.11332

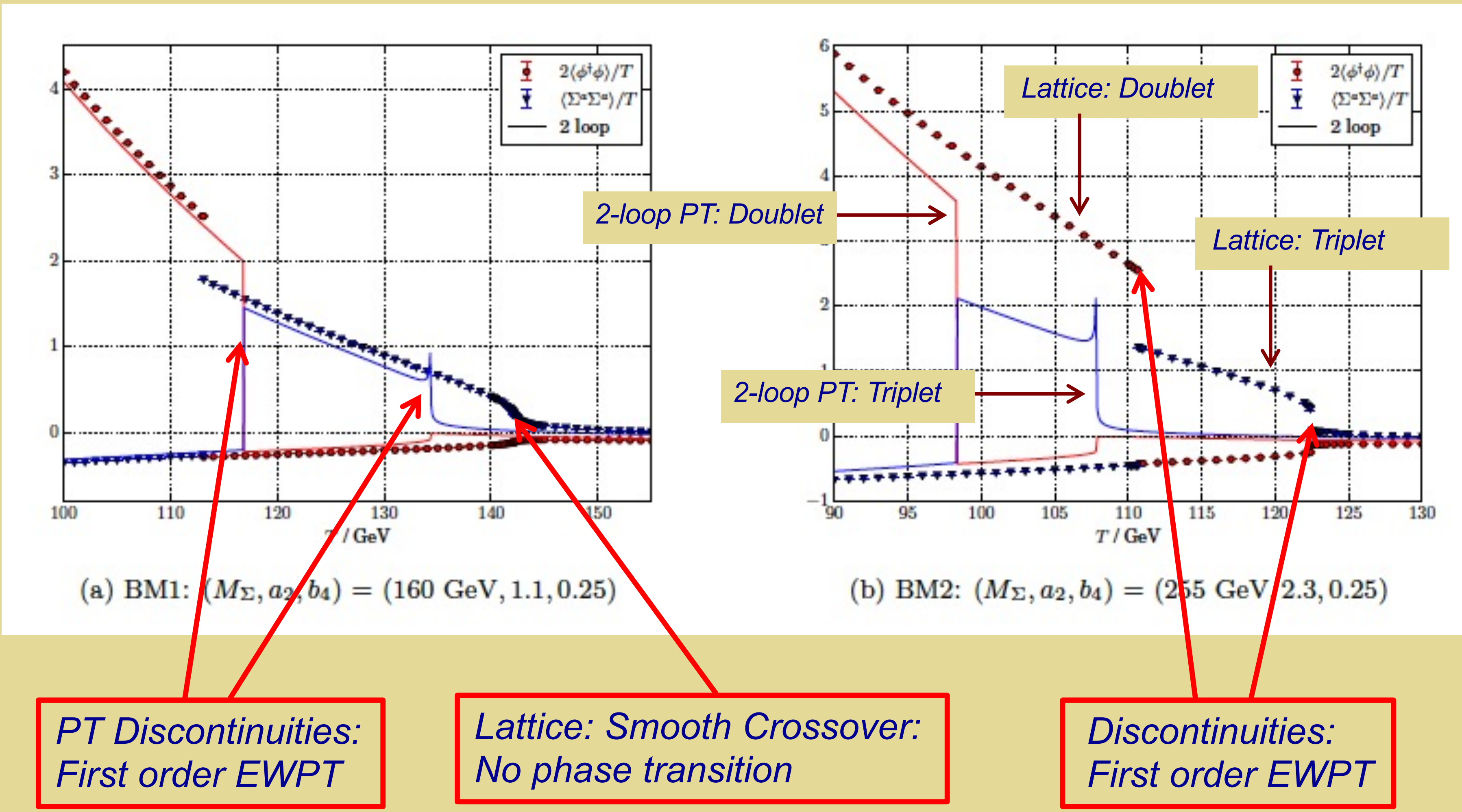
Real Triplet: Crossover vs 2nd Order



$$\chi(\Sigma^2) = \frac{1}{4} VT \left[\langle (\Sigma^a \Sigma^a)_V^2 \rangle - \langle (\Sigma^a \Sigma^a)_V \rangle^2 \right]$$

Niemi, R-M, Tenkanen, Weir 2005.11332

Real Triplet & EWPT: Benchmark PT



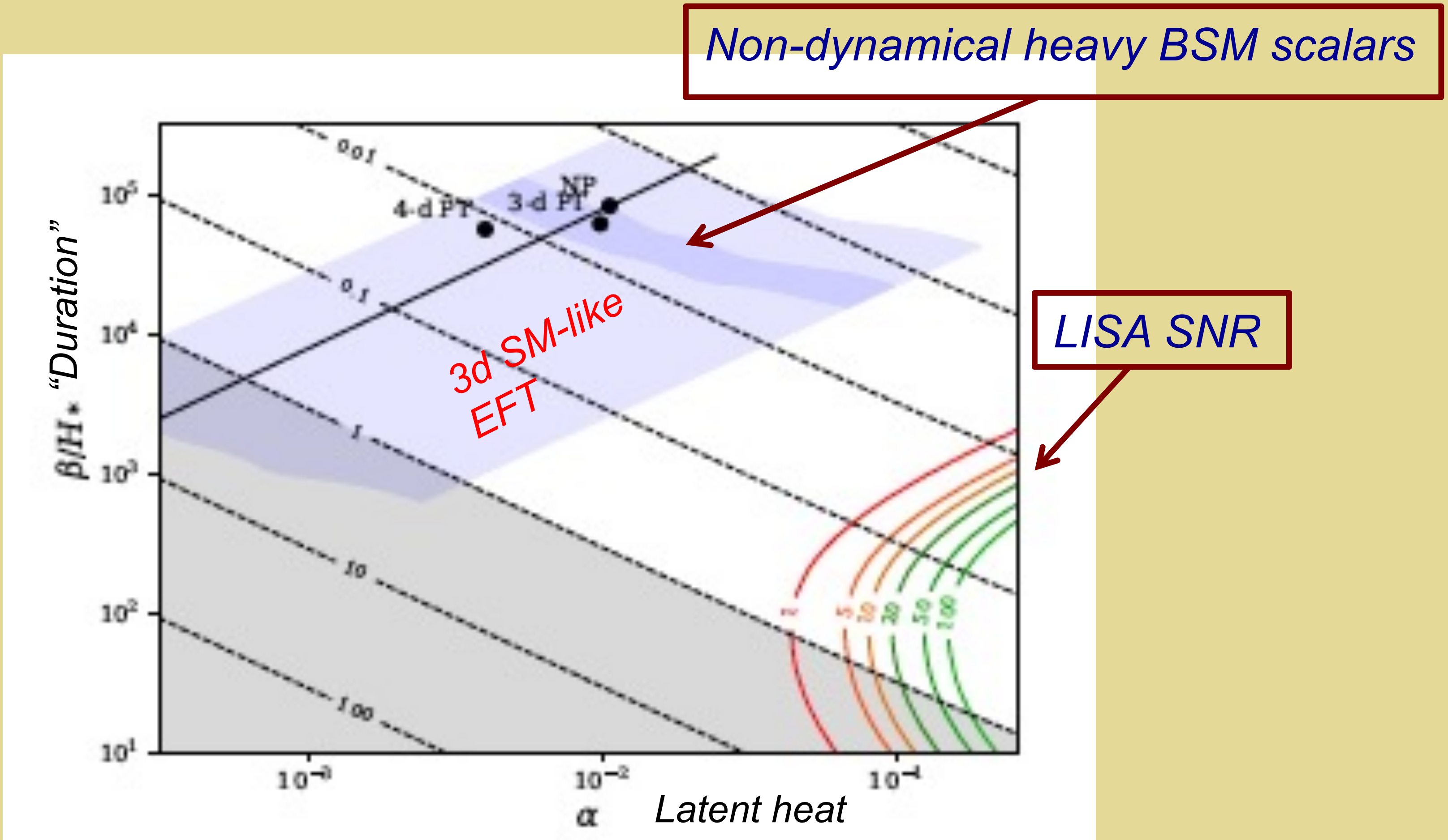
Niemi, R-M, Tenkanen, Weir 2005.11332

Model Illustrations

Simple Higgs portal models:

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

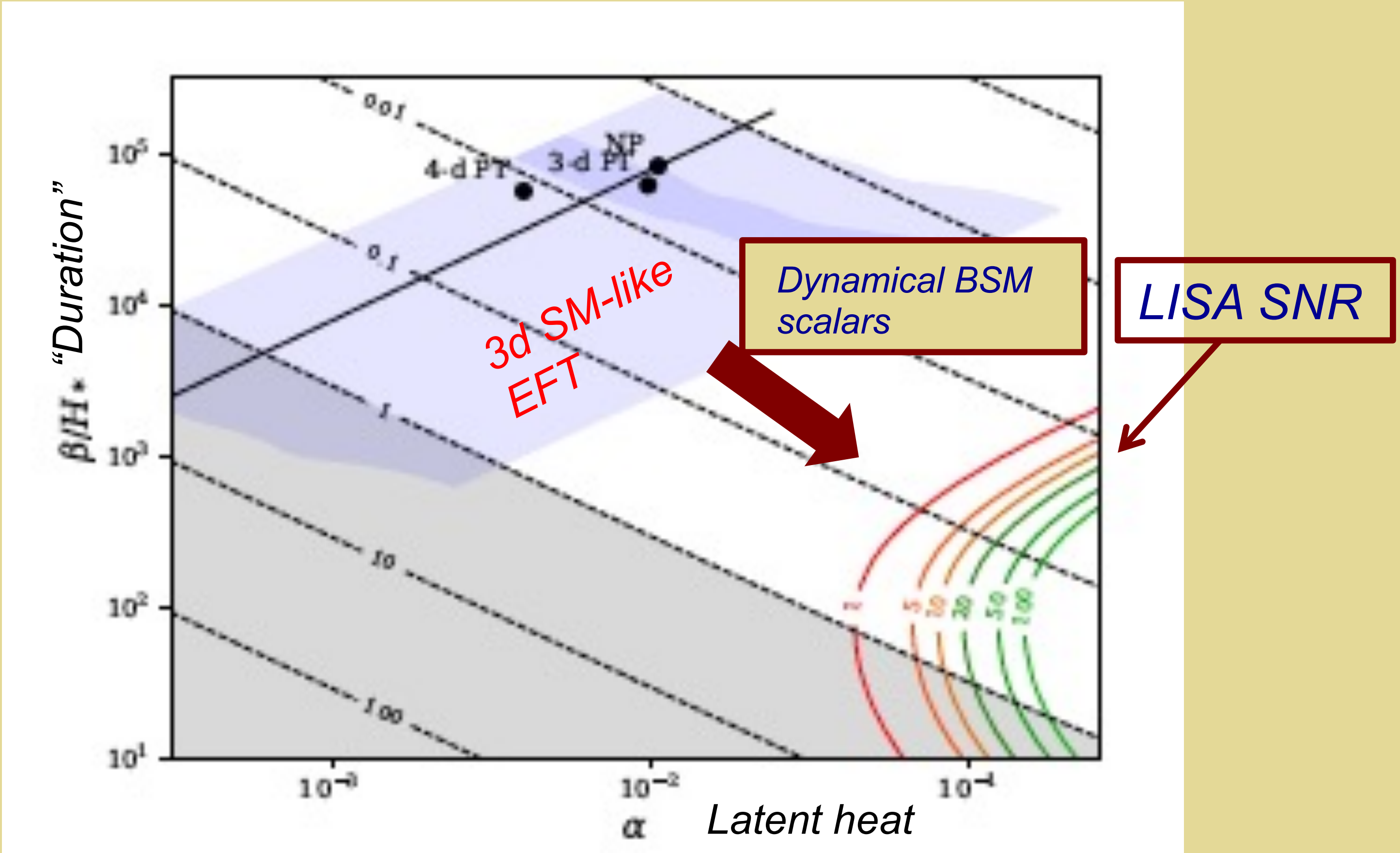
Heavy Real Singlet: EWPT & GW



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

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

Heavy Real Singlet: EWPT & GW



- One-step
- Non-perturbative

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

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*

IV. 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*

IV. Outlook - 2

- *Realizing this opportunity requires a new generation of robust theoretical computations, using EFT & non-perturbative methods, to benchmark perturbative calculations*

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

谢谢

Back Up Slides

Temperature Dependence of V(ϕ)

"Imaginary time":

$$t \longrightarrow i\tau$$

Im time Greens functions:

$$\mathcal{G}_\beta(\tau; \vec{x} - \vec{x'}) \equiv G(0, i\tau; \vec{x} - \vec{x'})_\beta$$

KMS:

$$\mathcal{G}_\beta(\tau; \vec{r}) = \mathcal{G}_\beta(\tau + \beta; \vec{r})$$

Temperature Dependence of V(ϕ)

$$\left(\frac{\partial^2}{\partial\tau^2} + \nabla^2 - m^2\right)\mathcal{G}_\beta(\tau;\vec{r}) = -\delta^3(r)\delta(\tau)$$

$$\mathcal{G}_\beta(\tau;\vec{r}) = \mathcal{G}_\beta(\tau+\beta;\vec{r})$$

Solutions:

$$\mathcal{G}_\beta(\tau;\vec{r}) = \frac{1}{\beta}\sum_n \int \frac{d^3k}{(2\pi)^3} e^{-i(\omega_n\tau - \vec{k}\cdot\vec{r})}\,\mathcal{G}_\beta(\vec{k},\omega_n)$$

$$\mathcal{G}_\beta(\vec{k},\omega_n) = \frac{1}{\omega_n^2 + \vec{k}^2 + m^2}$$

Temperature Dependence of V(ϕ)

$$\mathcal{G}_\beta(\tau;\vec{r}) = \frac{1}{\beta}\sum_n \int \frac{d^3k}{(2\pi)^3} e^{-i(\omega_n\tau - \vec{k}\cdot\vec{r})}\,\mathcal{G}_\beta(\vec{k},\omega_n)$$

$$\mathcal{G}_\beta(\vec{k},\omega_n) = \frac{1}{\omega_n^2 + \vec{k}^2 + m^2}$$

"Matsubara frequencies"

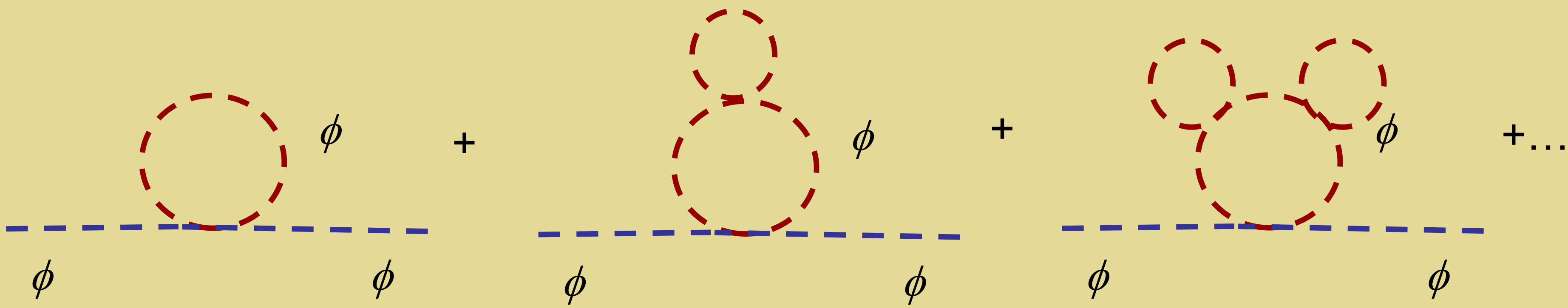
$$\omega_n = \begin{cases} \frac{2n\pi}{\beta}\,, & \text{bosons} \\ \frac{(2n+1)\pi}{\beta}\,, & \text{fermions} \end{cases}$$

bosons ← *Periodic BC's*

fermions ← *Antiperiodic BC's*

Power Counting & Resummations

"Daisy" or "ring" resummation



$$J_B(y) \approx -\frac{\pi^4}{45} + \frac{\pi^2}{12} y^2 - \frac{\pi}{6} y^3 - \frac{y^4}{32} \ln\left(\frac{y^2}{a_B}\right)$$

$$J_F(y) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24} y^2 - \frac{y^4}{32} \ln\left(\frac{y^2}{a_F}\right) \quad ,$$

- *Nonanalytic in ϕ_c*
- *Origin of barrier in V_{EFF}*
- *Susceptible to higher order ring diagrams: "screening"*