BSM EWPT: The Theory-Collider-Gravitational Wave Interface

M.J. Ramsey-Musolf

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

About MJRM:

Science

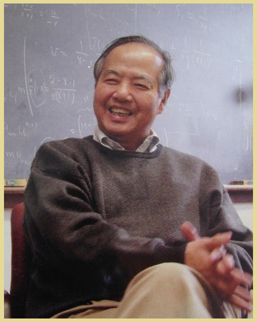
Family

Friends

My pronouns: he/him/his
 # MeToo

FCC Pheno Workshop
July 6, 2022

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

Was There an EW Phase Transition ?

- *Promising prospects exist for answering this question with a combination of theory + collider & gravitational wave searches: T_{EW} sets the scale & makes this question experimentally accessible*
- *Early universe (T>0) QFT has advanced considerably beyond the conventional one-loop perturbative framework: appropriate "meeting ground" for theory & exp't is BSM phase diagram from EFT+ lattice*
- *Mapping between experimental observables & phase diagram require continuing advances in QFT, benchmarking perturbative studies, and model-specific phenomenology*

Outline

I. Context & Questions

II. Theoretical Robustness -1: Lattice vs. P.T.

- *Collider pheno implications*
- *GW probe implications*

III. Theoretical Robustness – 2: Nucleation & Gauge Invariance ***Time Permitting***

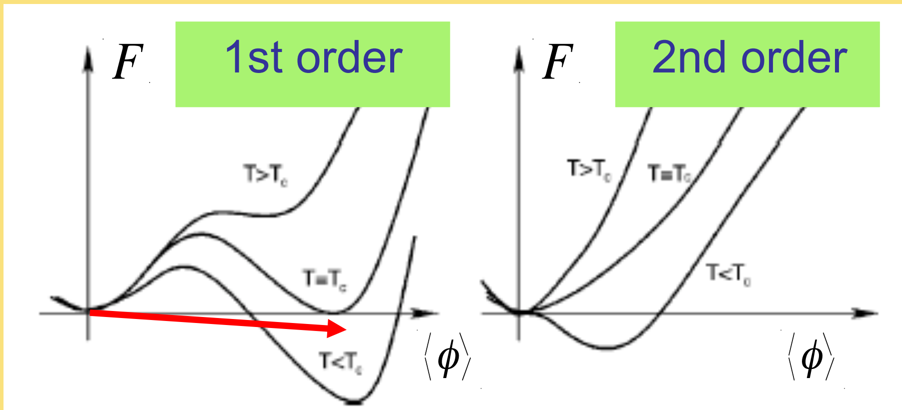
IV. Outlook

I. Context & Questions

Was There an Electroweak Phase Transition ?

- *Interesting in its own right*
- *Key ingredient for EW baryogenesis*
- *Source of gravitational radiation*

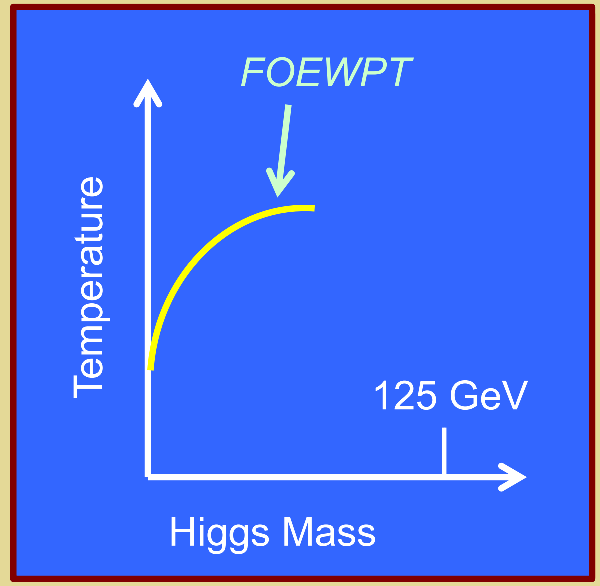
Was There an EW Phase Transition?



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

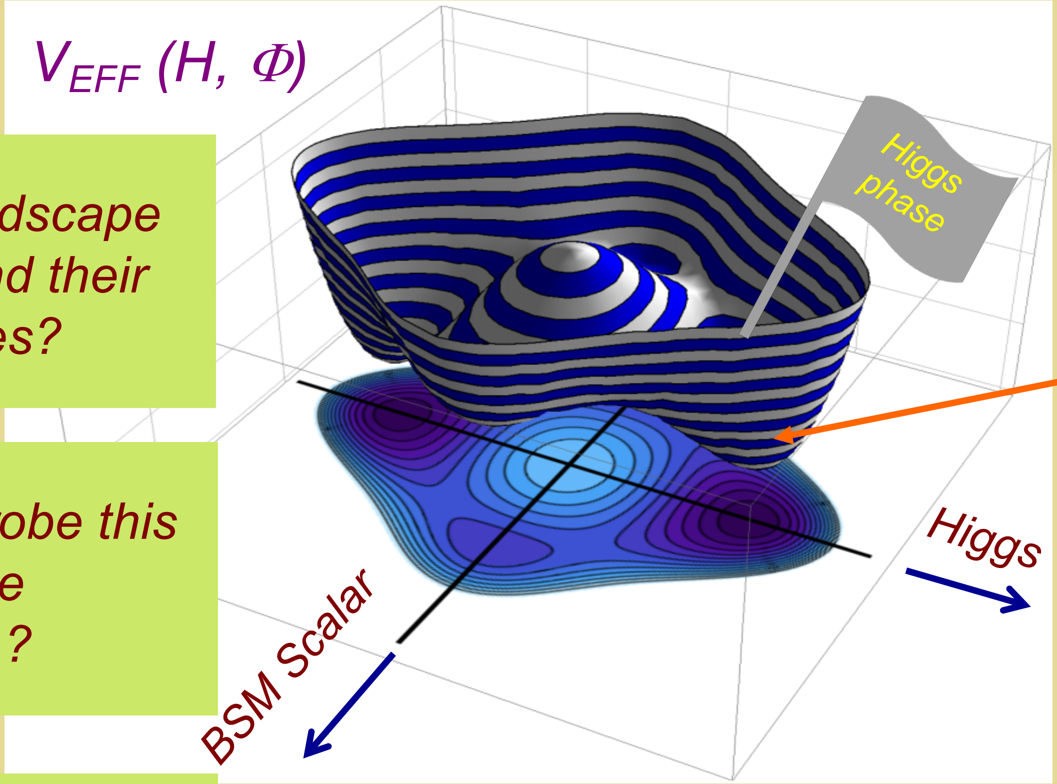
SM EW: Cross over transition



EW Phase Diagram

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

Was There an EW Phase Transition?

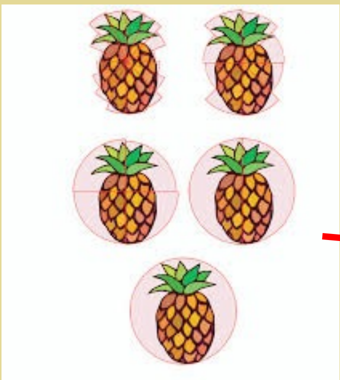


- What is the landscape of potentials and their thermal histories?
- How can we probe this T > 0 landscape experimentally ?
- How reliably can we compute the thermodynamics ?

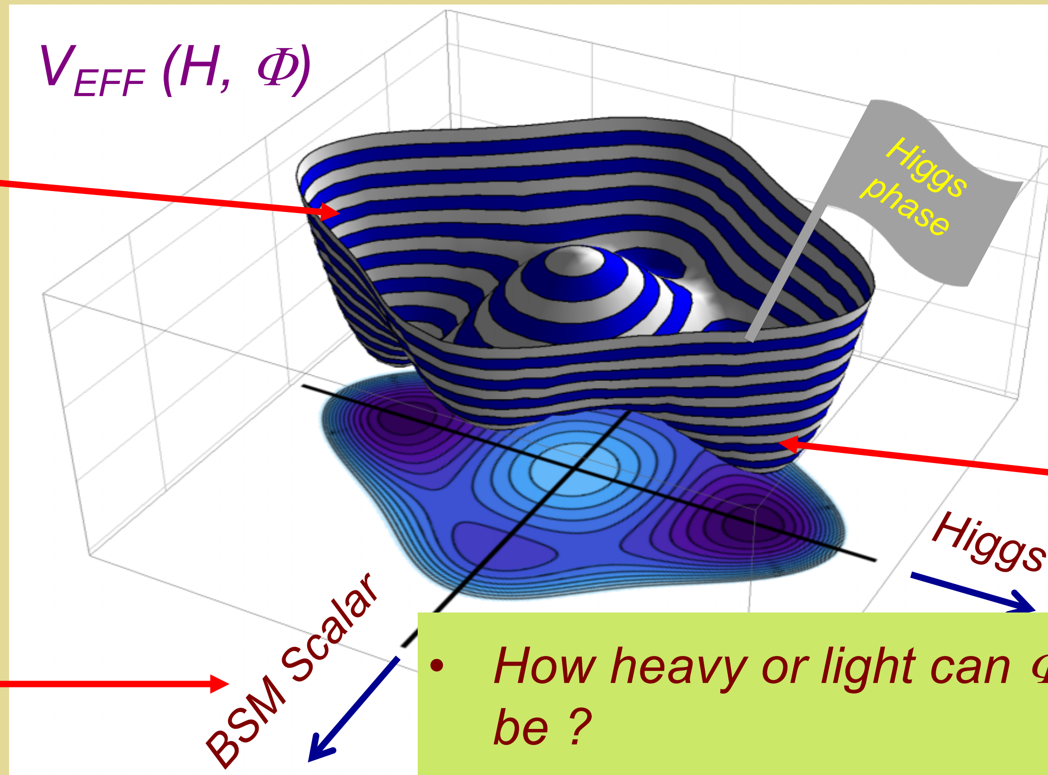
n evolve differently as T evolves →
ilities for symmetry breaking

Was There an EW Phase Transition?

Bubble Collisions

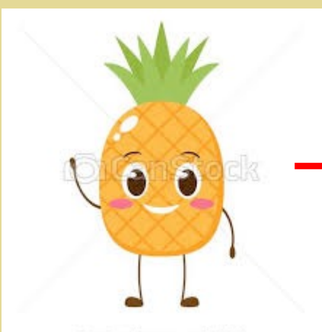


Grav Radiation



Higgs precision tests

Direct Production



BSM Higgs

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

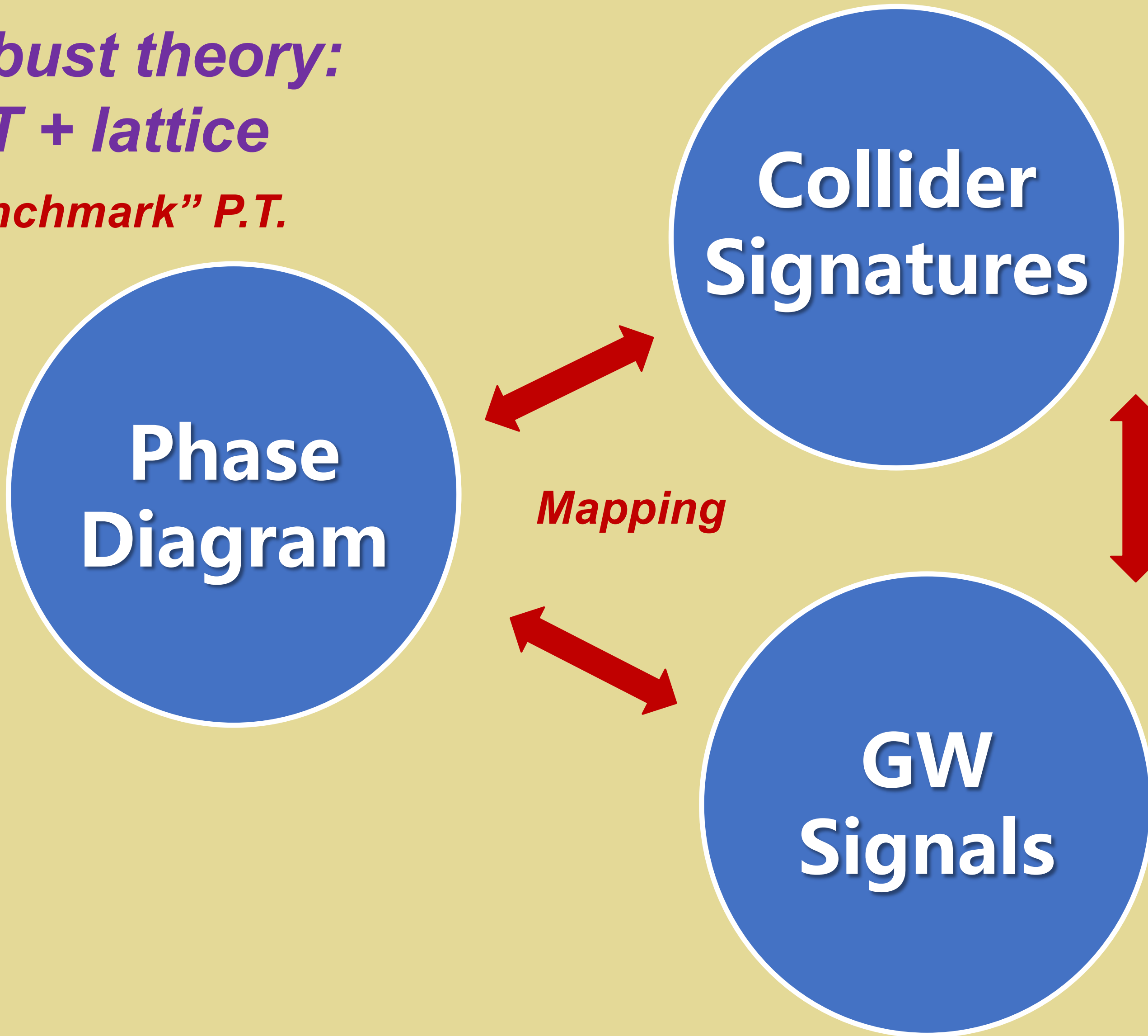
Extrema can evolv →
rich possibilities fo

BSM EWPT: Three Challenges

Robust theory:
EFT + lattice

"Benchmark" P.T.

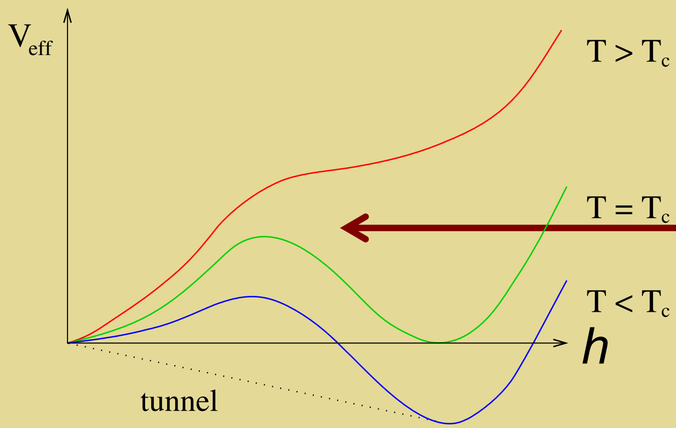
Observables:
model specific



Combined reach: N_σ vs S/N

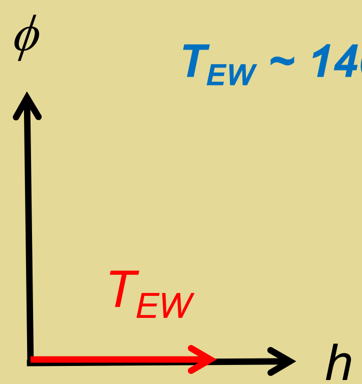
Hydro:
α , β / H_*

First Order EWPT from BSM Physics



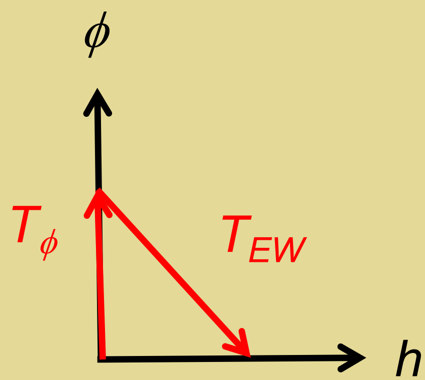
Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV

T_{EW} ~ 140 GeV



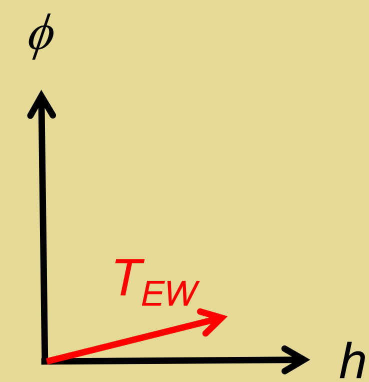
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

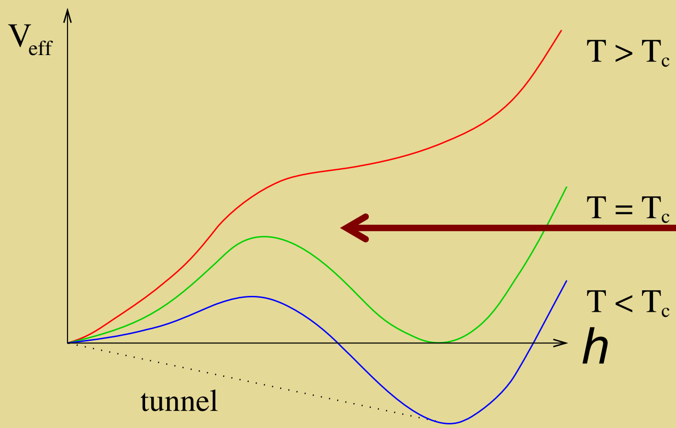
tree-level effect



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

tree-level effect

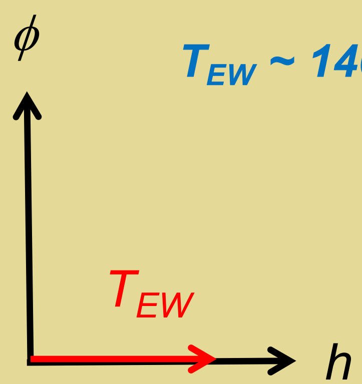
First Order EWPT from BSM Physics



$|\sin\theta| \gtrsim 0.01$ $\quad |\Delta\lambda/\lambda| \gtrsim 0.003$

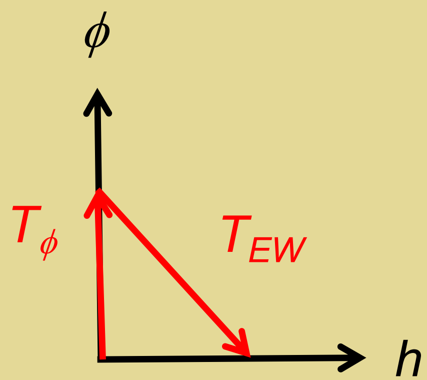
Higgs – ϕ^0 Mixing

$T_{EW} \sim 140$ GeV



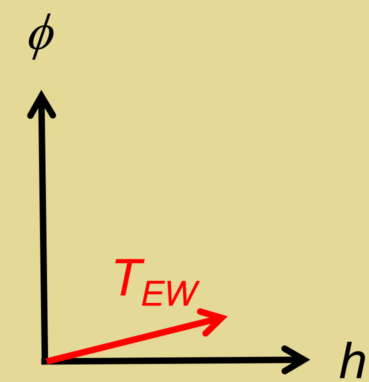
$a_2\, H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



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

tree-level effect

II. Theoretical Robustness - 1

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 ?

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*

Dimensionally reduced 3D EFT at T > 0

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*

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

DR 3dEFT: Scales

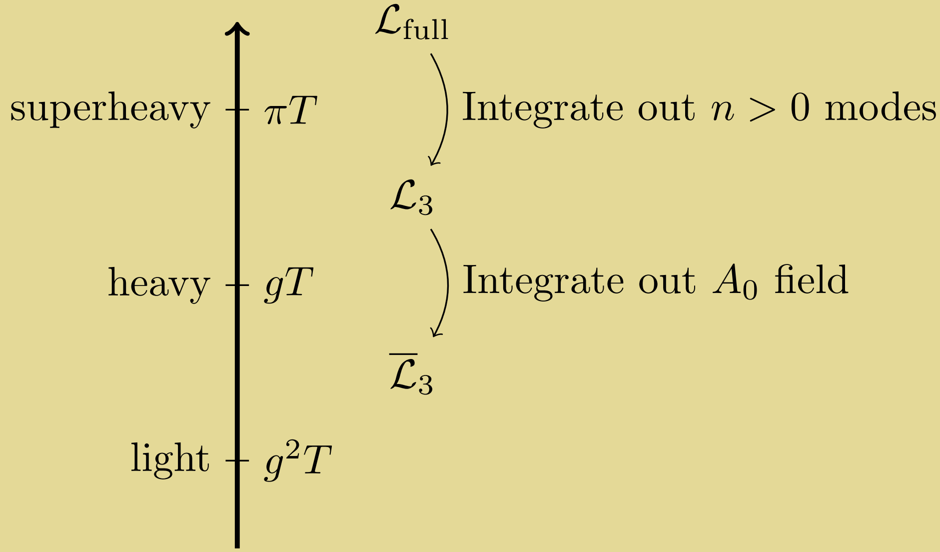
• πT	*Non-zero Matsubara modes*
• M_{BSM}	*BSM mass scale: can be > or < πT*
• $g T$	*Thermal masses*
• M_{NUC}	*Nucleation scale ~ $1/r_{bubble}$*
• $g^2 T$	*Light scale*

EFT 2

EFT 1

Thermal Effective Field Theory: EFT 1

Meeting ground: 3-D high-T effective theory



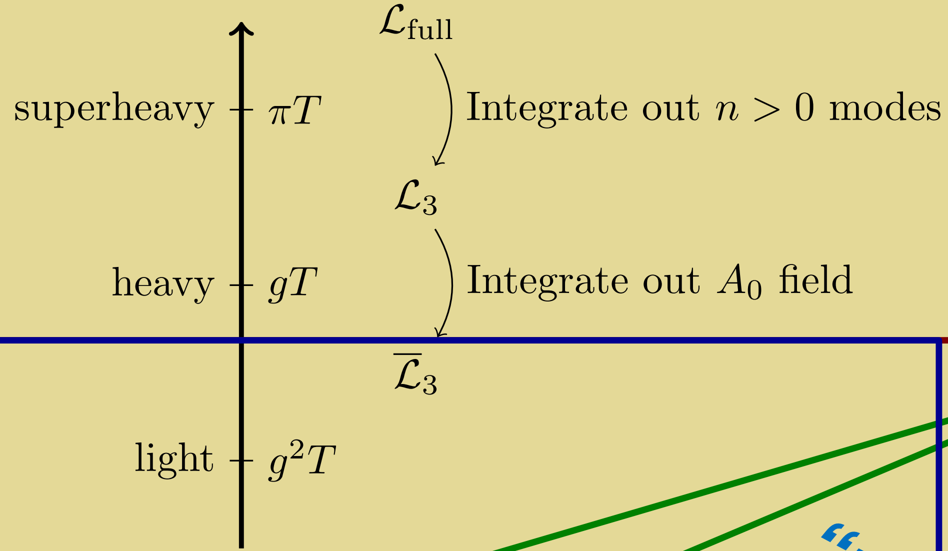
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

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

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*

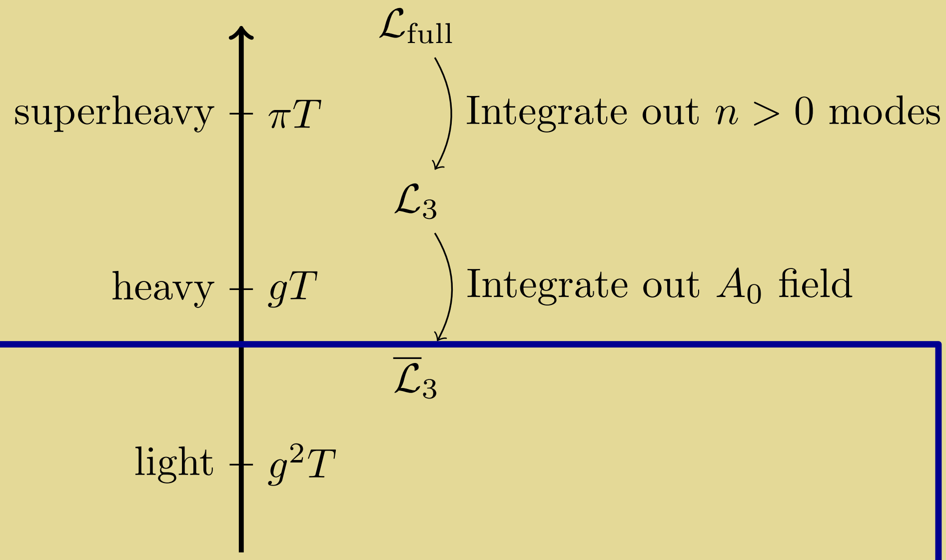
- *Use existing lattice computations for SM-like effective theory & matching onto full theory to determine FOEWPT-viable parameter space regions*

"Repurpose" lattice results

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



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

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)

Tunneling @ T>0: Gravitational Waves

Amplitude & frequency: latent heat & intrinsic time scale

Normalized latent heat

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

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

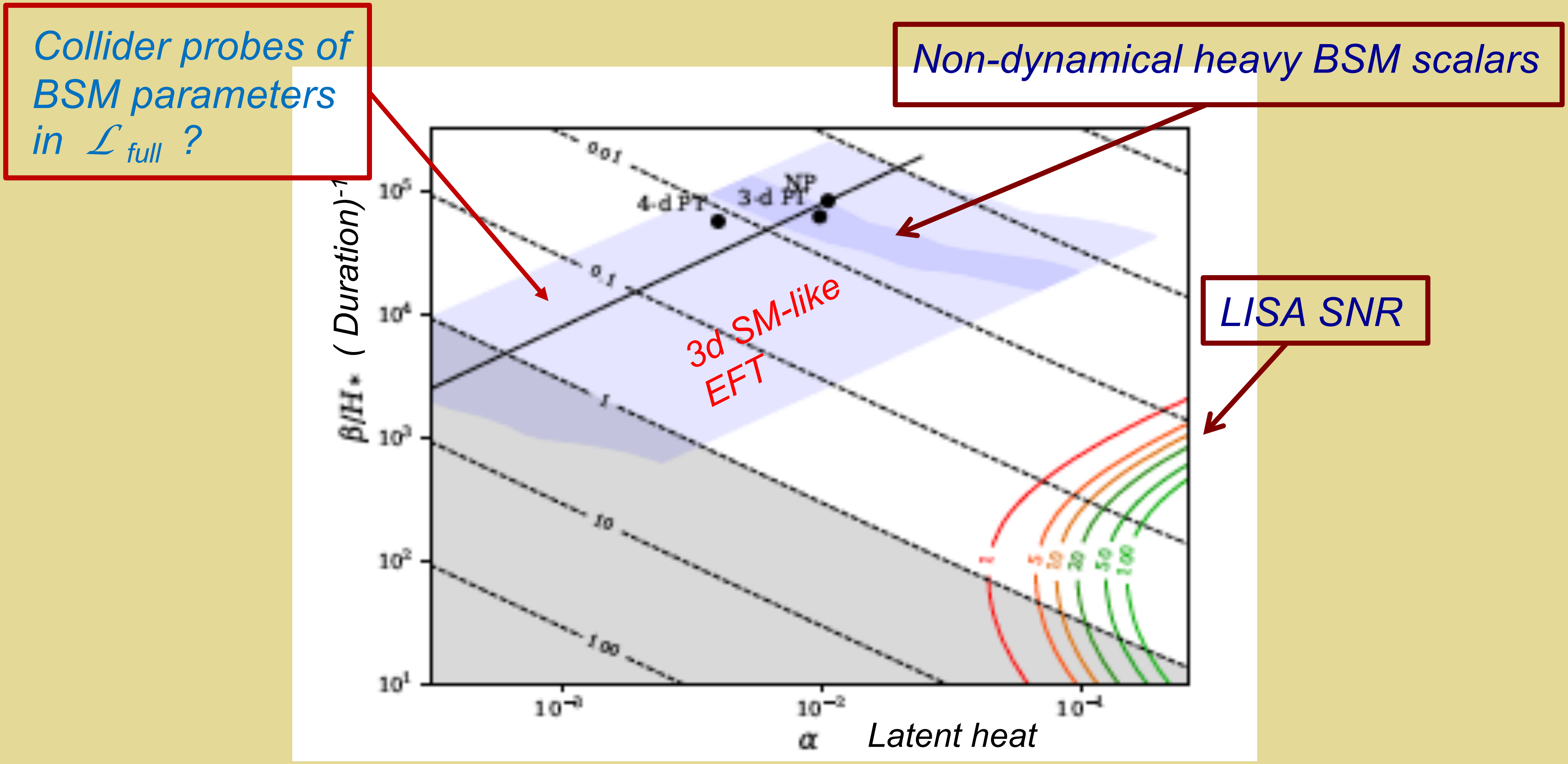
$$\alpha = \frac{30\Delta q}{\pi^2 g_* T^4}$$

Time scale

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

How Reliable?

Heavy BSM Scalar: EWPT & GW

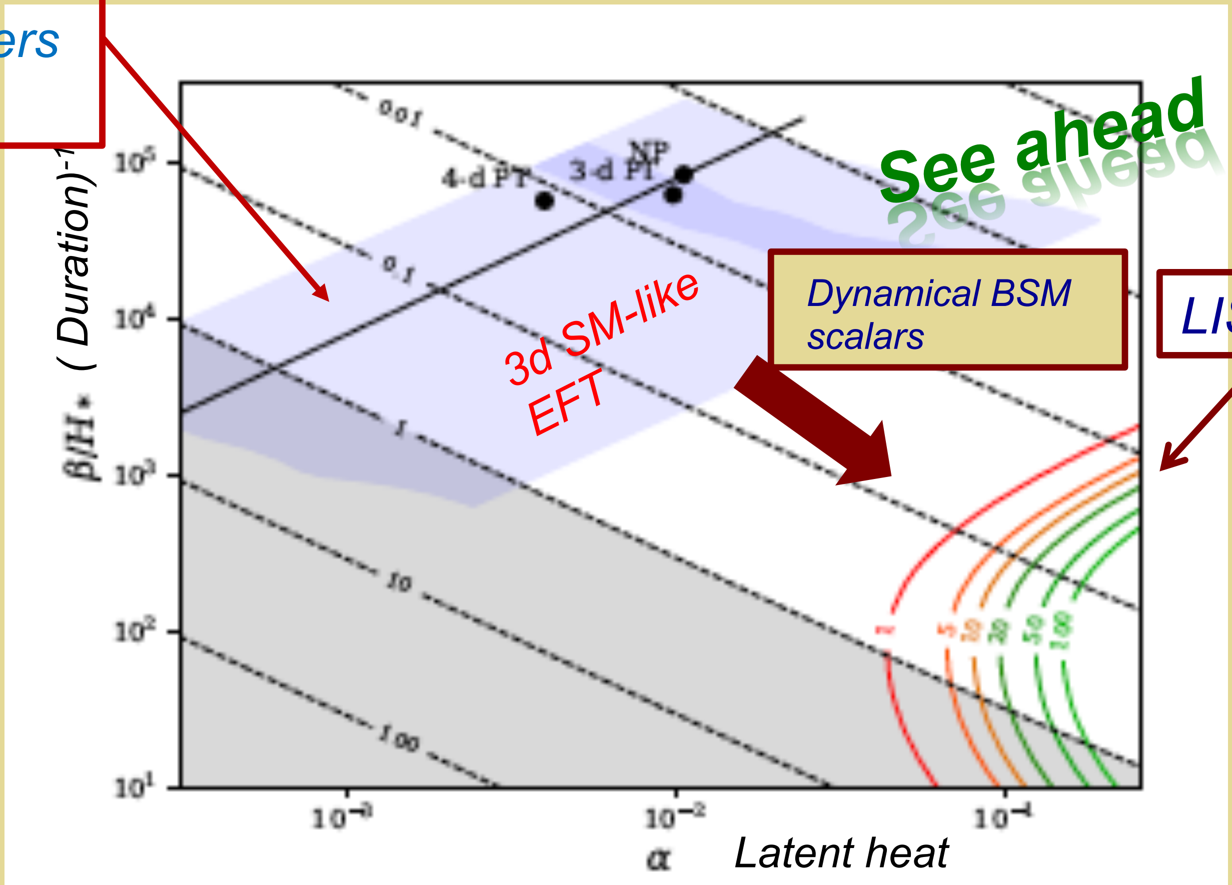


- One-step
- Non-perturbative

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

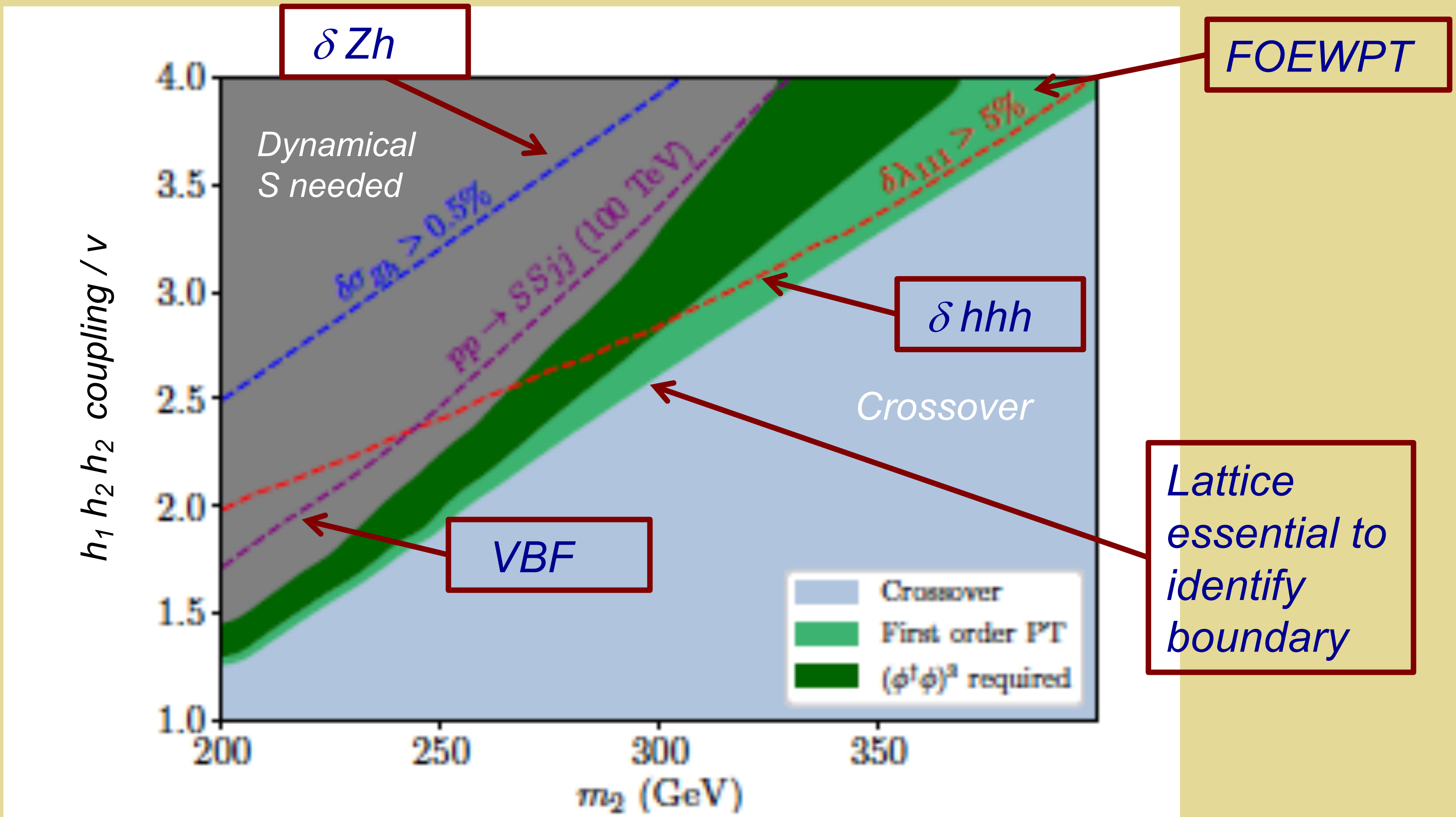
II. Model Illustrations

Simple Higgs portal models:

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

- ***Non-dynamical real singlet: LISA inaccessible, collider accessible***
- ***Dynamical real singlet: LISA + collider accessible***

Non-Dynamcial Real Singlet & EWPT: Probes



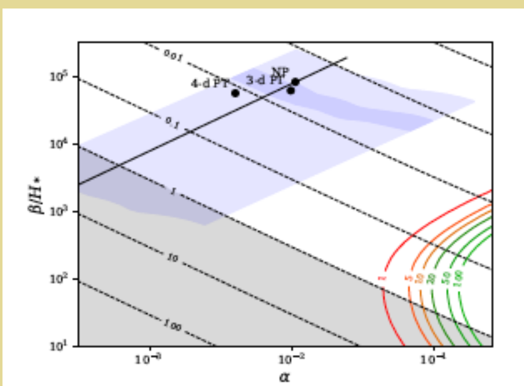
Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

- One-step
- Non-perturbative

Non-Dynamical Real Singlet: Lattice vs PT

Benchmark pert theory

	T_c/GeV	T_n/GeV	$\alpha(T_c)$	β/H_*
NP	140.4	140.2	0.011	8.20×10^4
3-d PT	140.4	140.0	0.010	6.11×10^4
4-d PT	131.0	130.7	0.004	5.59×10^4

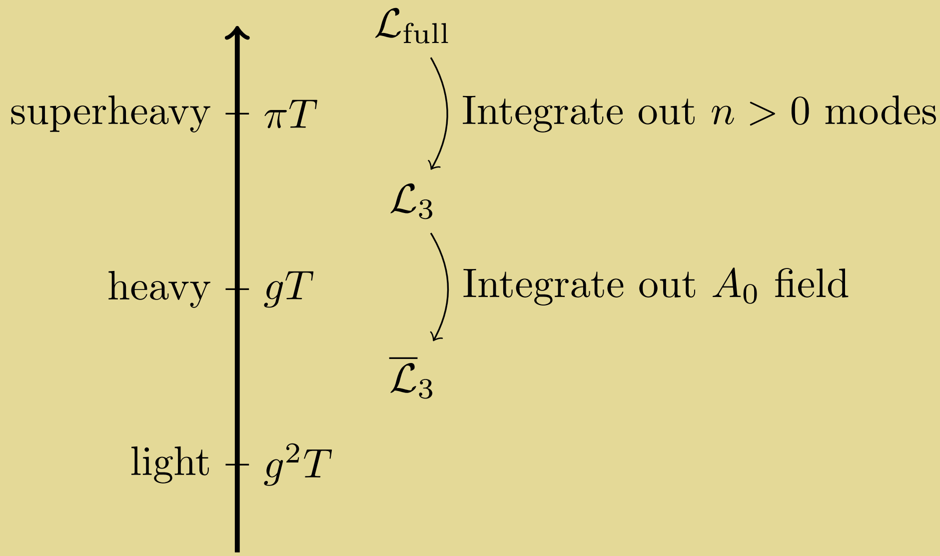


- *One-step*
- *Non-perturbative*

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

Dynamical Real Singlet

Meeting ground: 3-D high-T effective theory

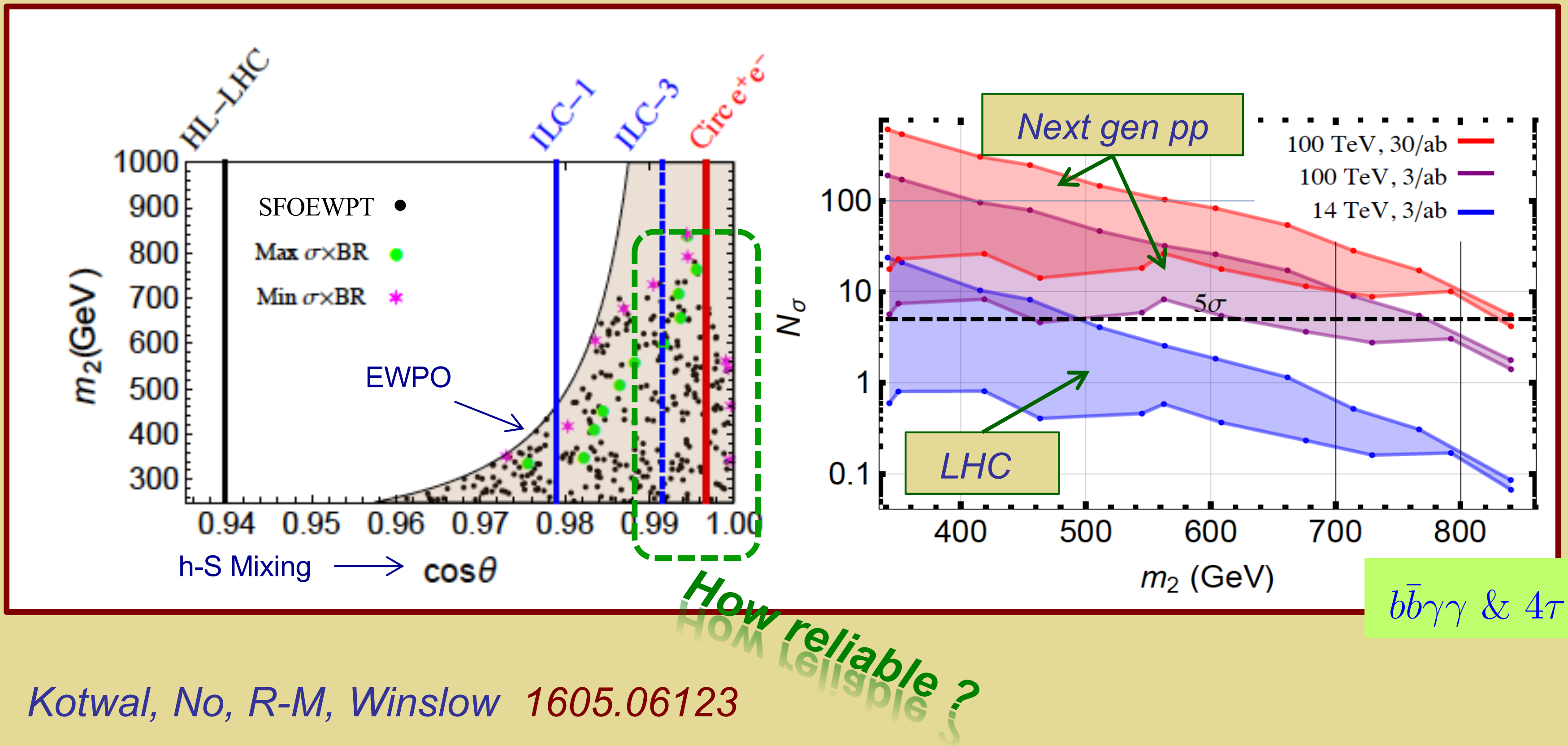


$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2 \qquad + V(\Phi) + V(\phi, \Phi)_{portal}$$

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

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

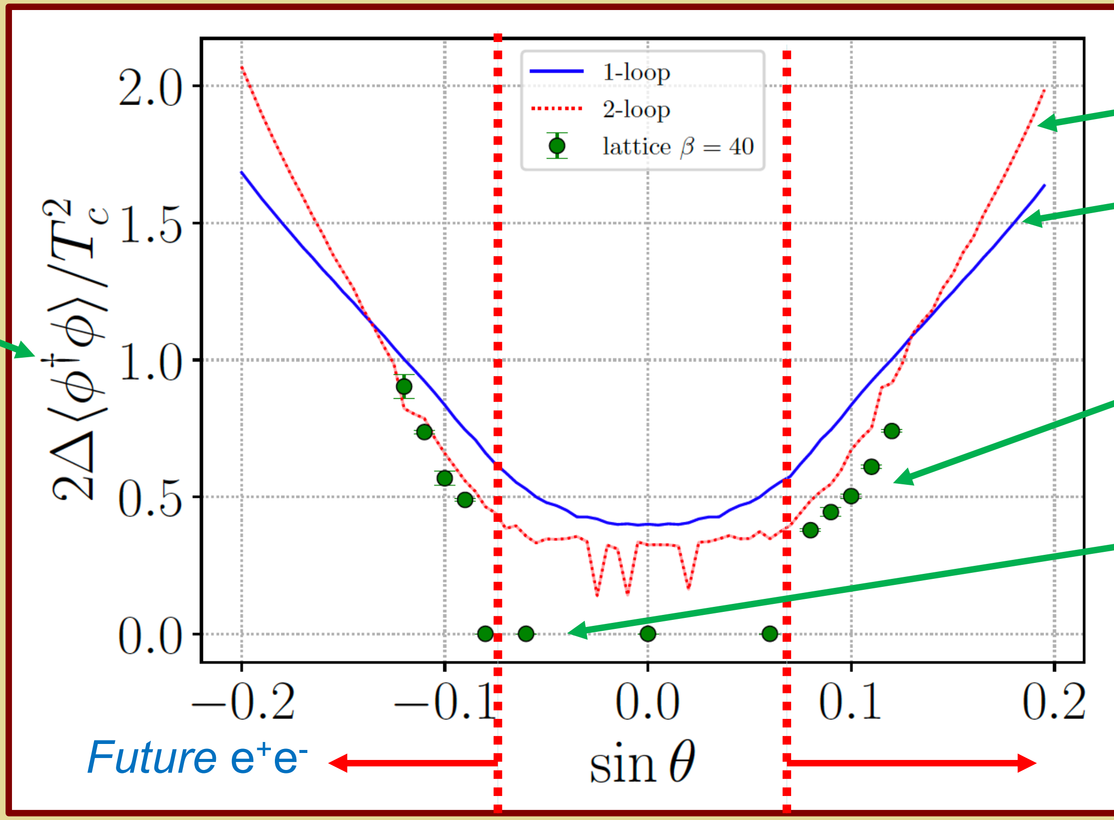


Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442;
Li et al, 1906.05289

Dynamical Singlet: Lattice Benchmarking

L. Niemi, MRM, G. Xia in prog



- *When a FOEWPT occurs, 2 loop PT gives a good description*
- *Lattice needed to determine when onset of FOEWPT occurs*
- *Future precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized*

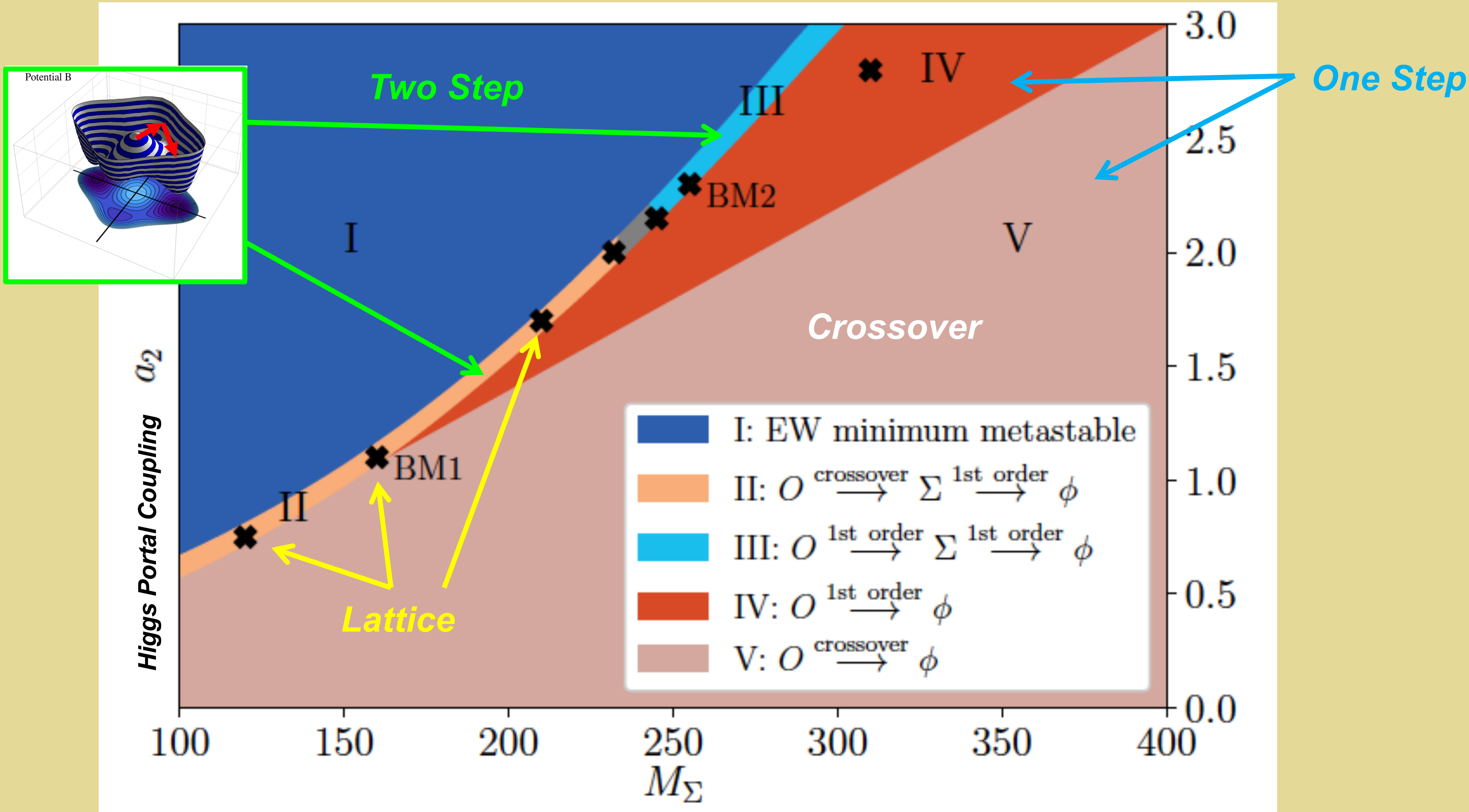
Model Illustrations

Simple Higgs portal models:

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

Dynamical BSM scalars

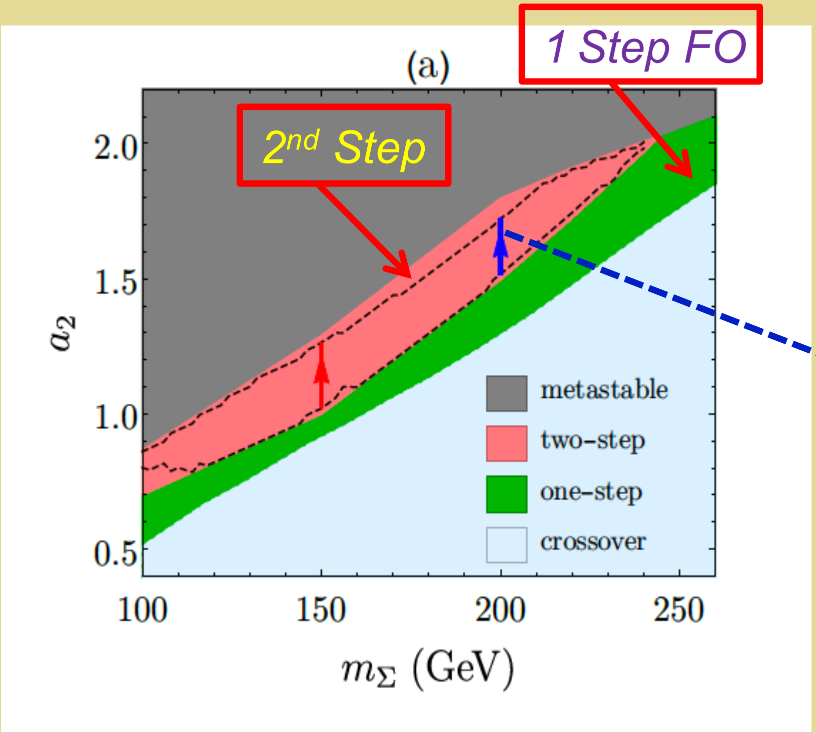
Real Triplet & EWPT: Novel EWSB

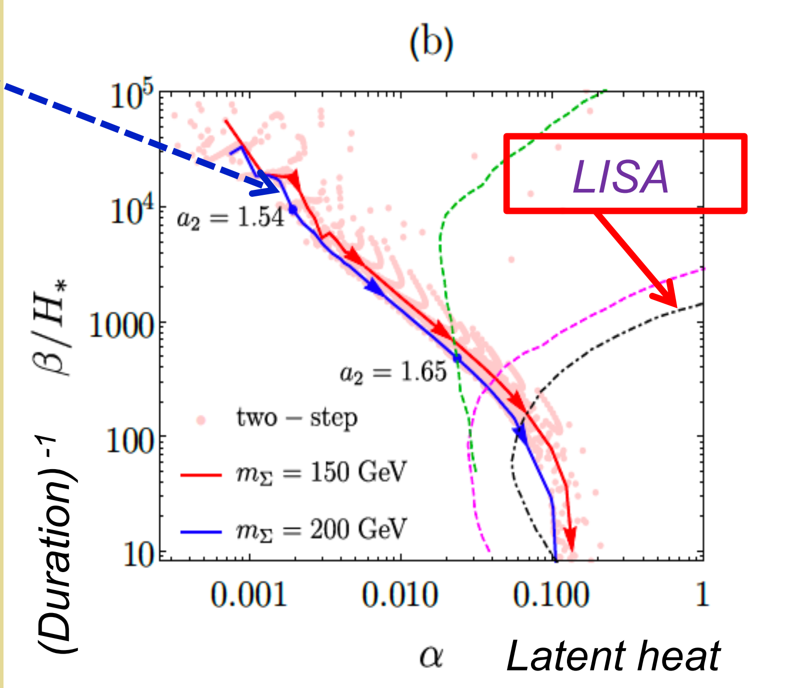


- *1 or 2 step*
- *Non-perturbative*

Niemi, R-M, Tenkanen, Weir 2005.11332

GW, Collider & EWPT Phase Diagram

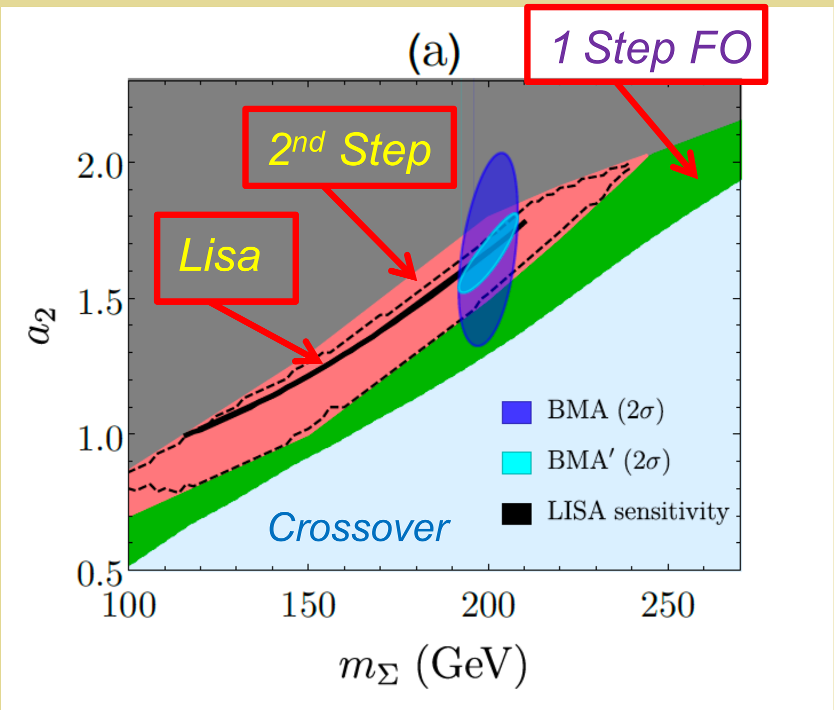


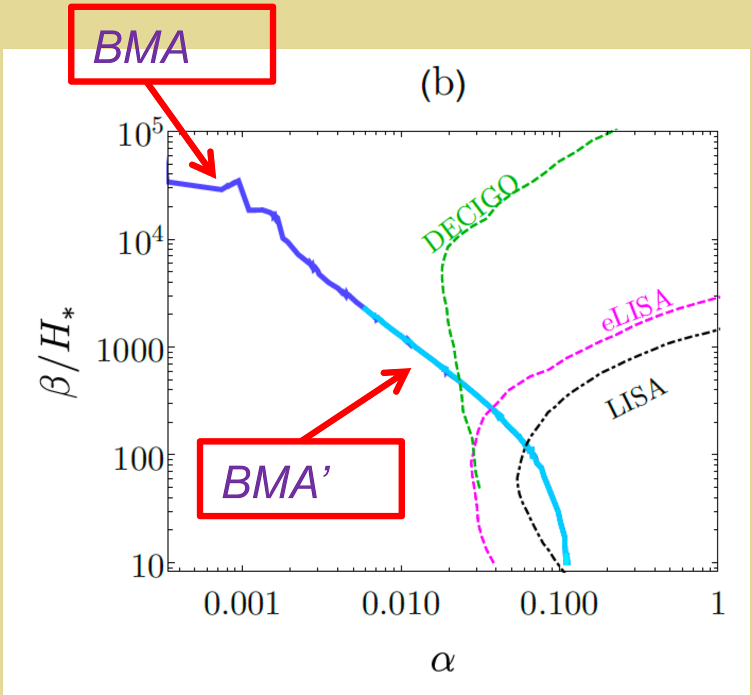


- ***Single step transition: GW well outside LISA sensitivity***
- ***Second step of 2-step transition can be observable***

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW, Collider & EWPT Phase Diagram





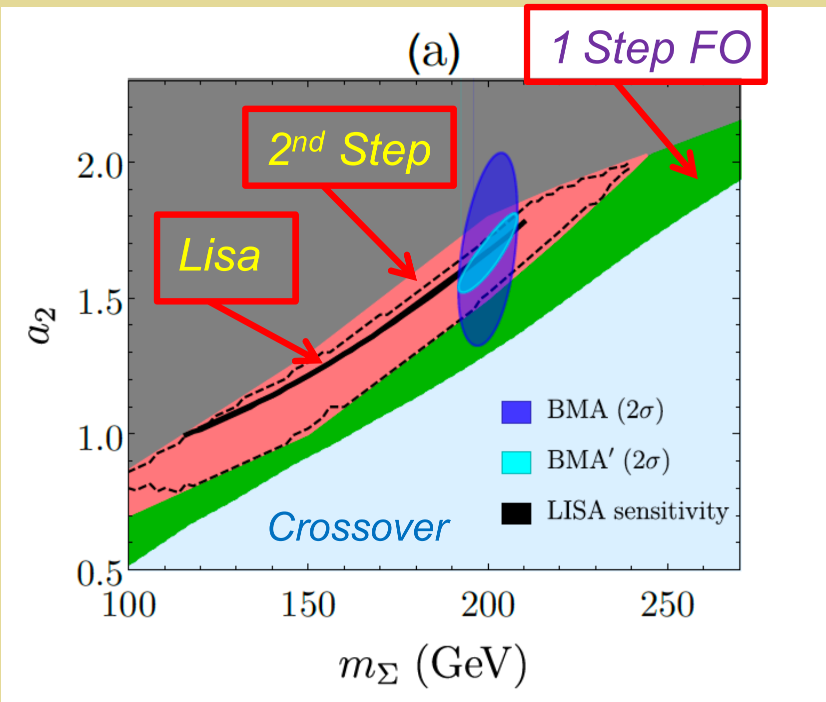
BMA: m_Σ + h → $\gamma\gamma$

BMA' : BMA + Σ^0 → ZZ

Friedrich, MJRM, Tenkanen, Tran 2203.05889

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

GW, Collider & EWPT Phase Diagram



How combine sensitivities ?

$$\mathrm{SNR} = \left\{ \mathcal{T} \int_{f_{\min}}^{f_{\max}} df \left[\frac{\Omega_{\rm GW}(f)}{\Omega_{\rm sens}(f)} \right]^2 \right\}^{1/2}$$

- *Gaussian significance (N_σ)*

BMA: m_Σ + h → $\gamma\gamma$

BMA' : BMA + Σ^0 → ZZ

Friedrich, MJRM, Tenkanen, Tran 2203.05889

Collider Signatures (Model-Dep)

- ***Thermal*** Γ ***(h → $\gamma\gamma$)***
- ***Higgs signal strengths***
- $\delta\sigma$ ***(e+e- → Zh)***
- ***Higgs self-coupling***
- ***Exotic Decays***
- ***Single*** ϕ ***production***

III. Theoretical Robustness – 2: Nucleation

Computing

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

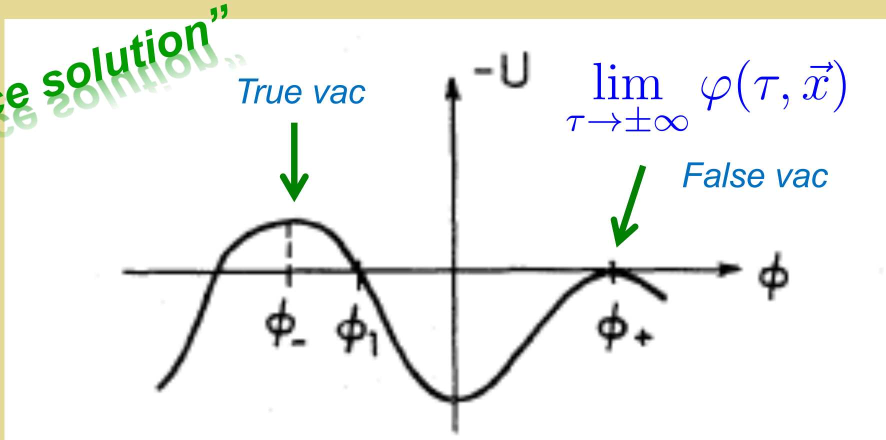
+ T_N

S. Coleman, PRD 15 (1977) 2929

Tunneling @ T=0: Coleman

Scalar Quantum Field Theory

"Bounce solution"



Rotational symmetry

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

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

Friction term

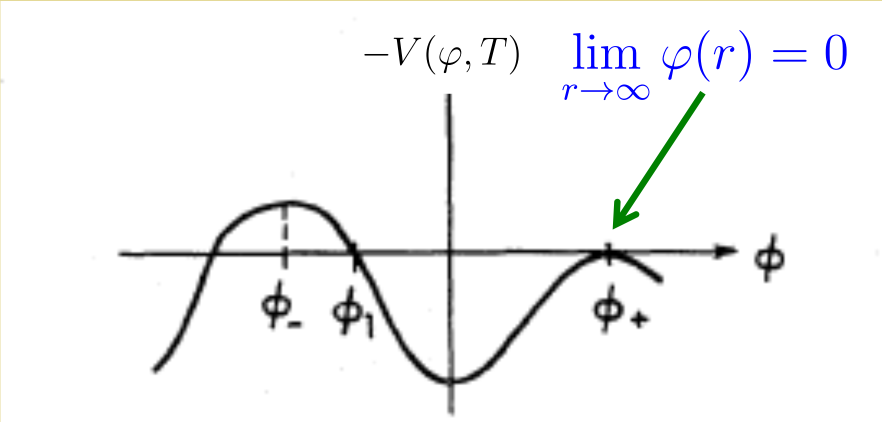
Ln Γ

Path: minimize S_E

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

Tunneling @ T>0

Scalar Quantum Field Theory



Tunneling rate / unit volume:

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

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

Exponent in Γ

Path: minimize S_E

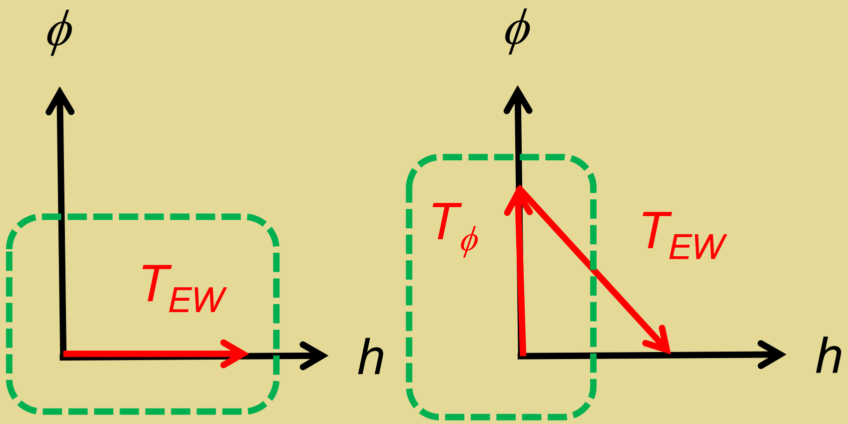
Friction term

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

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

Tunneling @ T>0

Radiative barriers → st'd method gauge-dependent



Tunneling rate / unit volume:

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

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

Exponent in Γ

Path: minimize S_E

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

Friction term

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

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*

Details: back up slides

Full 3D effective action

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

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*

IV. Outlook

Future Discussion @ TDLI: SPCS 2023

The 2023 Shanghai Symposium on Particle Physics and Cosmology: Phase Transitions, Gravitational Waves, and Colliders (SPCS 2023)

Sep 22 – 24, 2023
Tsung-Dao Lee Institute
Asia/Shanghai timezone

Enter your search term

- Overview
- Registration
- Call for Abstracts
- Accommodation
- Transportation
- Participant List

Contact

wang.wen@sjtu.edu.cn

The 2023 Shanghai Symposium on Particle Physics and Cosmology: Phase Transitions, Gravitational Waves, and Colliders (SPCS 2023) will be held September 22-24 at the Tsung Dao Lee Institute/Shanghai Jiao Tong University. The focus will be on the possibilities for phase transitions in the early universe, including but not limited to an electroweak phase transition; the prospective signatures in next generation gravitational wave probes, the Large Hadron Collider, and future lepton and hadron colliders as well as their interplay; and the related theory and phenomenology.

The Symposium seeks to introduce the latest theoretical developments and experimental progress and to promote scientific exchanges and cooperation in related fields in China.

With the discovery of the Higgs boson in 2012, the possibility of an extended Higgs sector leading to a first order electroweak phase transition has become a key science driver for future collider studies, including the LHC and prospective lepton colliders, as well as next generation gravitational wave probes, such as LISA, Taiji and Tianqin. The possible synergies and complementary of these astrophysical and terrestrial probes constitute an exciting forefront in particle physics and cosmology, stimulating considerable advances theory as well. Phase transitions may also occur in other context, such as in the dark sector or the post-recombination era relevant to neutrino physics. The symposium will provide opportunities to discuss the latest developments in these directions and foster new ideas and collaborations.

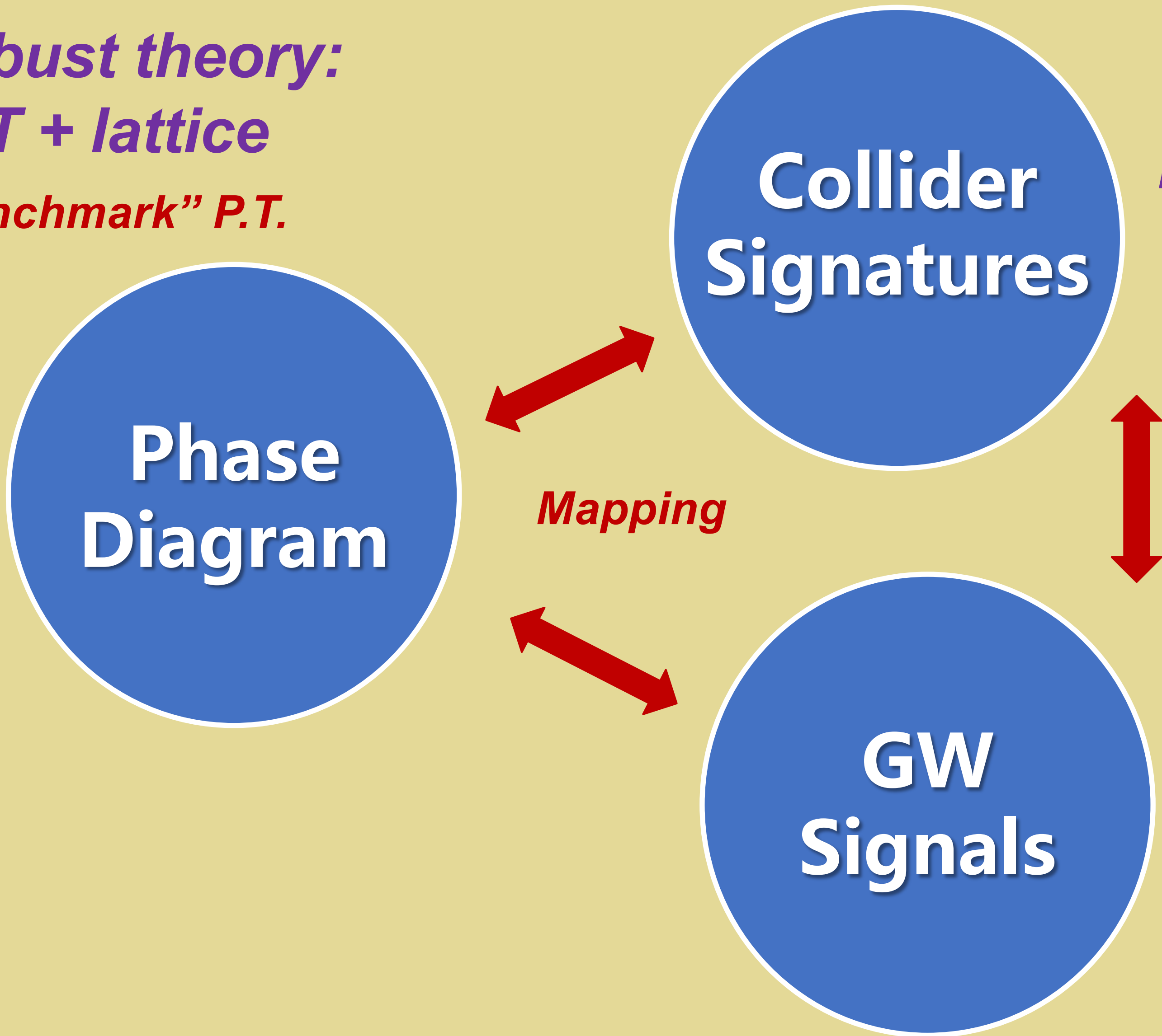
The symposium plan adopts an offline-based, online-offline combination method, and everyone is welcome to register and participate. In addition to invited reports, this symposium will also open report applications, and some time slots will be reserved for students and postdoctoral fellows. Young scholars are welcome to apply. Participants are requested to complete the registration before **September 10, 2023**; students and postdoctoral students who apply for reports are requested to submit report information (title, abstract, and article information if they have been submitted to arXiv or published publicly). The meeting report will be in English.

BSM EWPT: Three Challenges

Robust theory:
EFT + lattice

"Benchmark" P.T.

Observables:
model specific



Combined reach: N_σ vs S/N

Hydro:
α , β / H_*

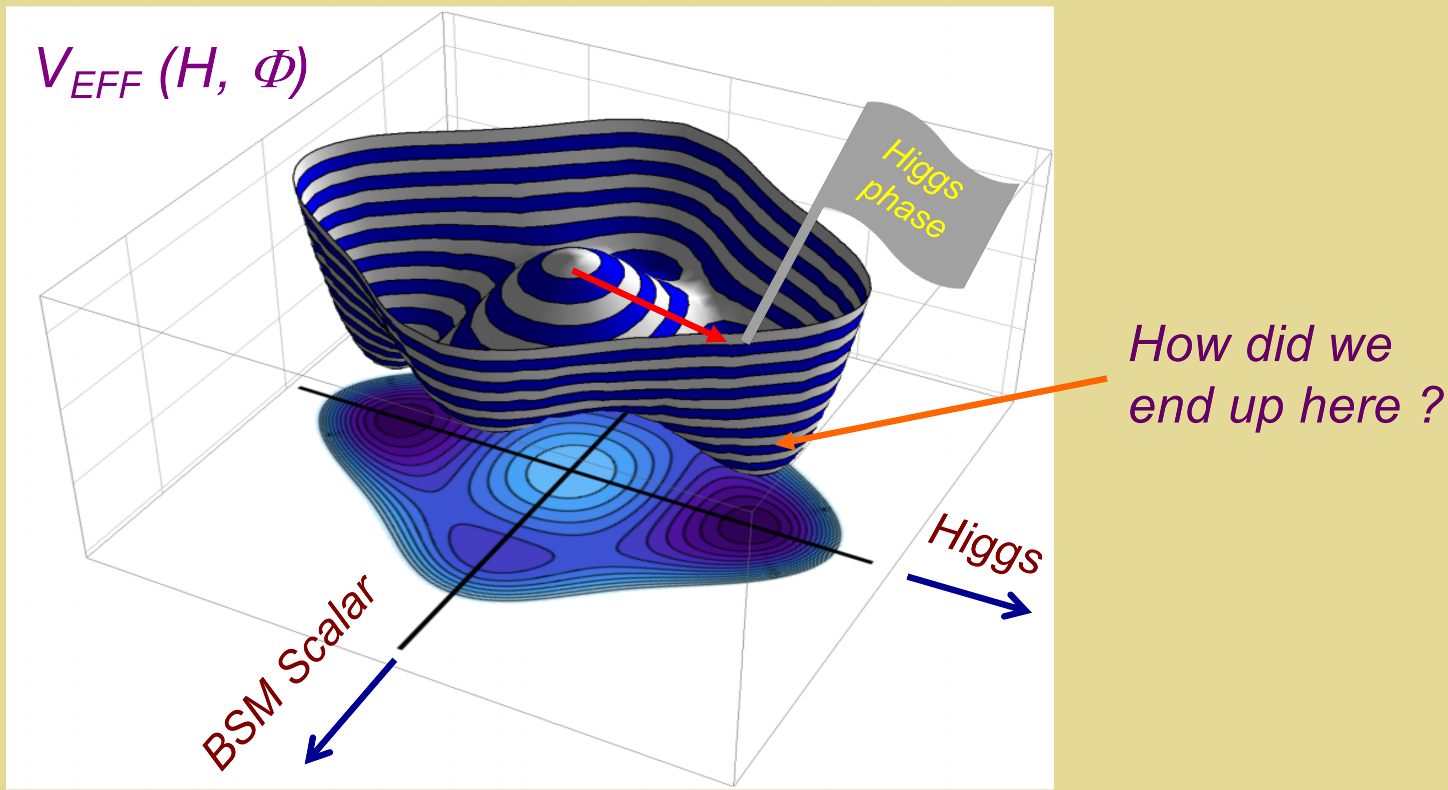
Was There an EW Phase Transition ?

- *Promising prospects exist for answering this question with a combination of theory + collider & gravitational wave searches: T_{EW} sets the scale & makes this question experimentally accessible*
- *Early universe (T>0) QFT has advanced considerably beyond the conventional one-loop perturbative framework: appropriate "meeting ground" for theory & exp't is BSM phase diagram from EFT+ lattice*
- *Mapping between experimental observables & phase diagram require continuing advances in QFT, benchmarking perturbative studies, and model-specific phenomenology*

谢谢！

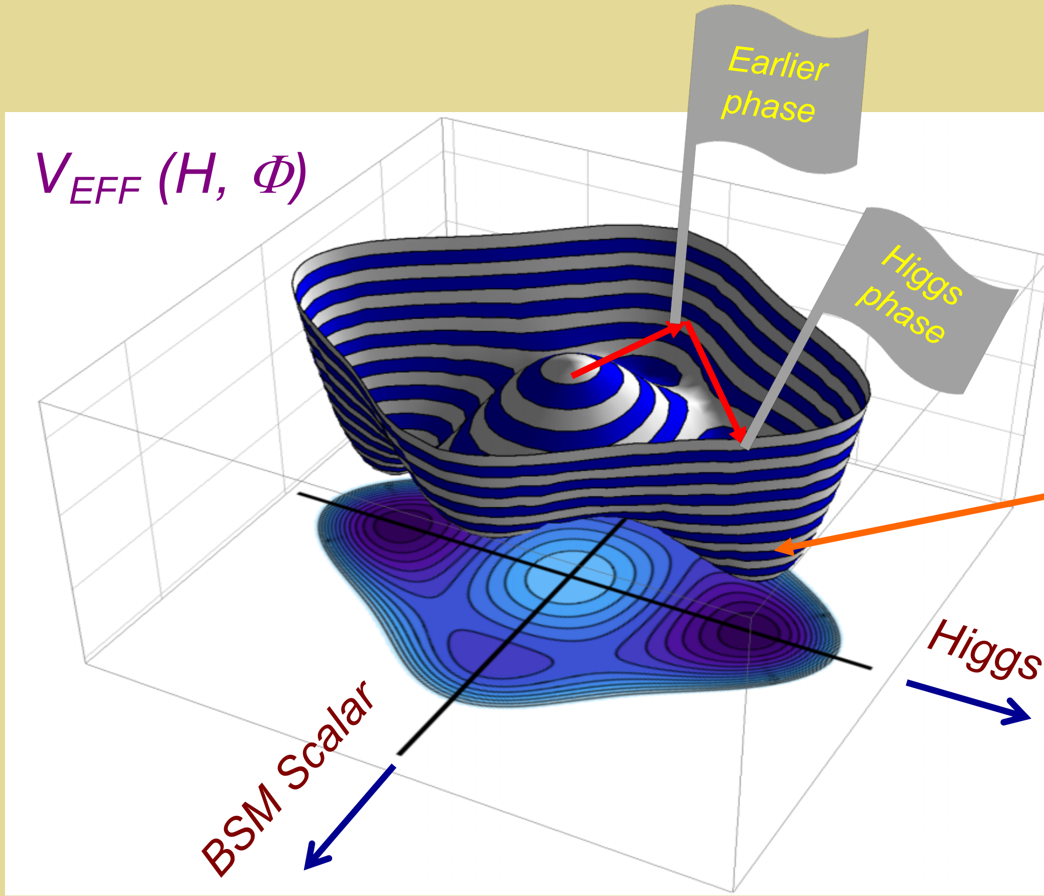
Back Up Slides

Patterns of Symmetry Breaking



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

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

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

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

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

SSB @ T>0 : Power Counting

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

$$\mu^2_{\rm eff} \equiv \mu^2 + (4\lambda + 3g^2)\frac{T^2}{12}$$

T=0 parameter < 0

Thermal corrections > 0

Near cancellation for $T \sim T_C$

For a range of $T \sim T_{nuc}$: N = 1

$$\mu^2_{\rm eff} \sim \mathcal{O}(g^{2+N}\, T^2) < \mathcal{O}(g^2\, T^2)$$

Power Counting

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

ϕ	~	T
λ	~	g^3
μ^2	~	$g^2 T^2$
$\mu_{\mathrm{eff}}{}^2$	~	$g^3 T^2$

$$V_{\mathrm{LO}}^{\mathrm{eff}} = \frac{1}{2}\mu_{\mathrm{eff}}^2\phi^2 + \frac{1}{4}\lambda\phi^4 - \frac{g^3 T}{12\pi}\left[2\phi^3 + \left(\frac{1}{3}T^2 + \phi^2\right)^{\frac{3}{2}}\right]$$

Radiative barrier: ξ-independent

Tunneling @ T>0: G.I. & Nielsen Identities

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

Adopt appropriate power-counting in couplings

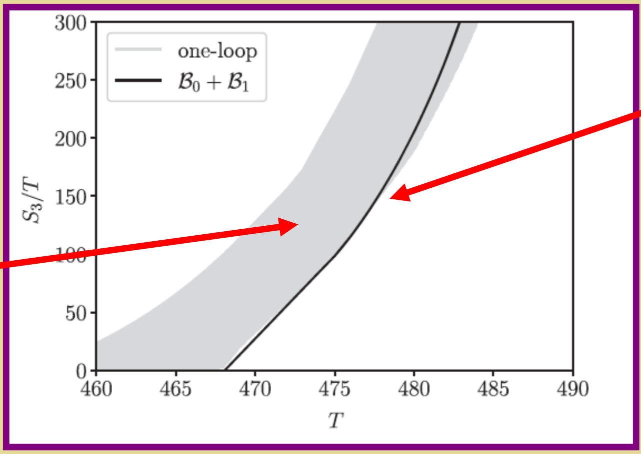
$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

Order-by-order consistent with Nielsen Identities

$$\xi \frac{\partial S^{\text{eff}}}{\partial \xi} = -\int \mathrm{d}^d\mathbf{x} \frac{\delta S^{\text{eff}}}{\delta \phi(x)} \mathcal{C}(x)$$

$$\mathcal{C}(x) = \frac{ig}{2} \int \mathrm{d}^d\mathbf{y} \Big\langle \chi(x) c(x) \bar{c}(y) \times \Big[\partial_i B_i(y) + \sqrt{2} g \xi \phi \chi(y) \Big] \Big\rangle$$

Numerical comparison with conventional approach



Conventional: $0 < \xi < 4$

S_3 to $\mathcal{O}(g^{-1/2})$: $0 < \xi < 4$

First Order EWPT from BSM Physics

- $\Gamma(h \rightarrow \gamma\gamma)$
- *Higgs signal strengths*
- *Higgs self-coupling*
- *Exotic Decays*

Back up slides

First Order EWPT from BSM Physics

- Thermal $\Gamma(h \rightarrow \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

$H^2\phi$ Barrier ?

First Order EWPT from BSM Physics

- Thermal $\Gamma(h \rightarrow \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

$H^2\phi$ Barrier ?

H-ϕ Mixing

First Order EWPT from BSM Physics

- Thermal $\Gamma(h \rightarrow \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays
- Single ϕ production

$H^2\phi$ Barrier ?

H-ϕ Mixing

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

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

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

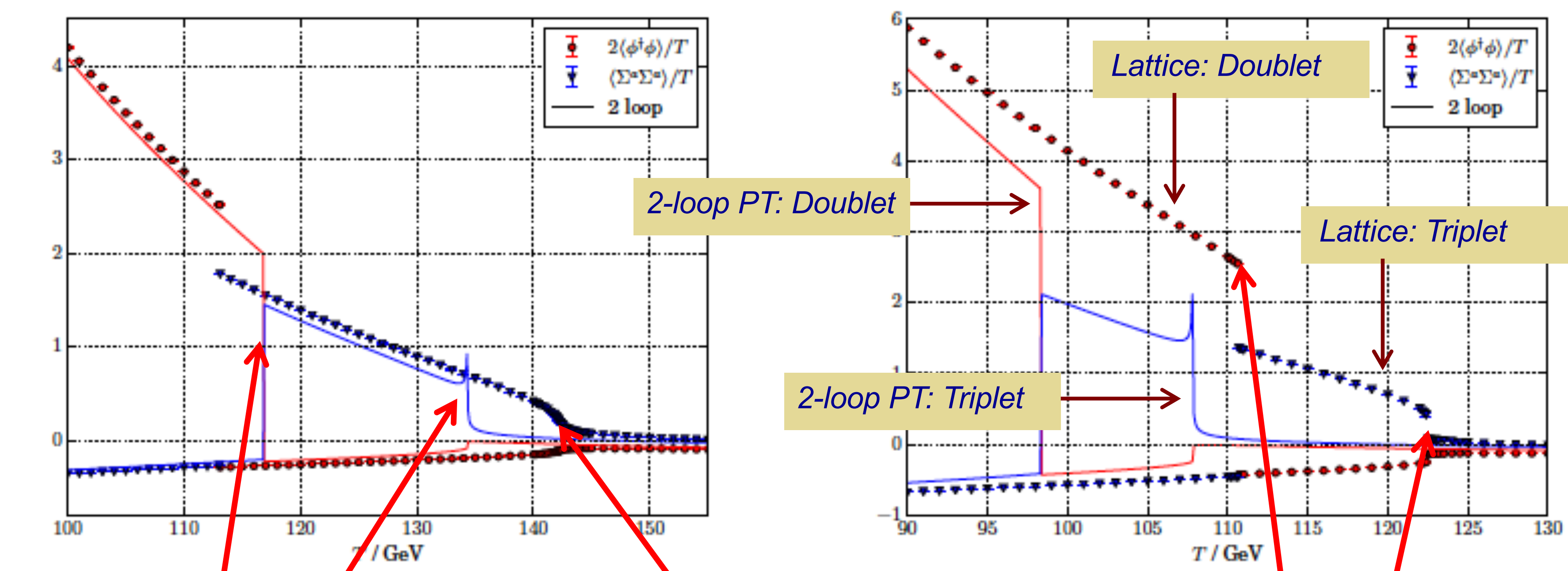
$$g_{\mathrm{eff}} \equiv \frac{g^2 T}{\pi m_T(\varphi)}$$

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]*

Real Triplet & EWPT: Benchmark PT



(a) BM1: $(M_\Sigma, a_2, b_4) = (160\ \text{GeV}, 1.1, 0.25)$

(b) BM2: $(M_\Sigma, a_2, b_4) = (255\ \text{GeV}, 2.3, 0.25)$

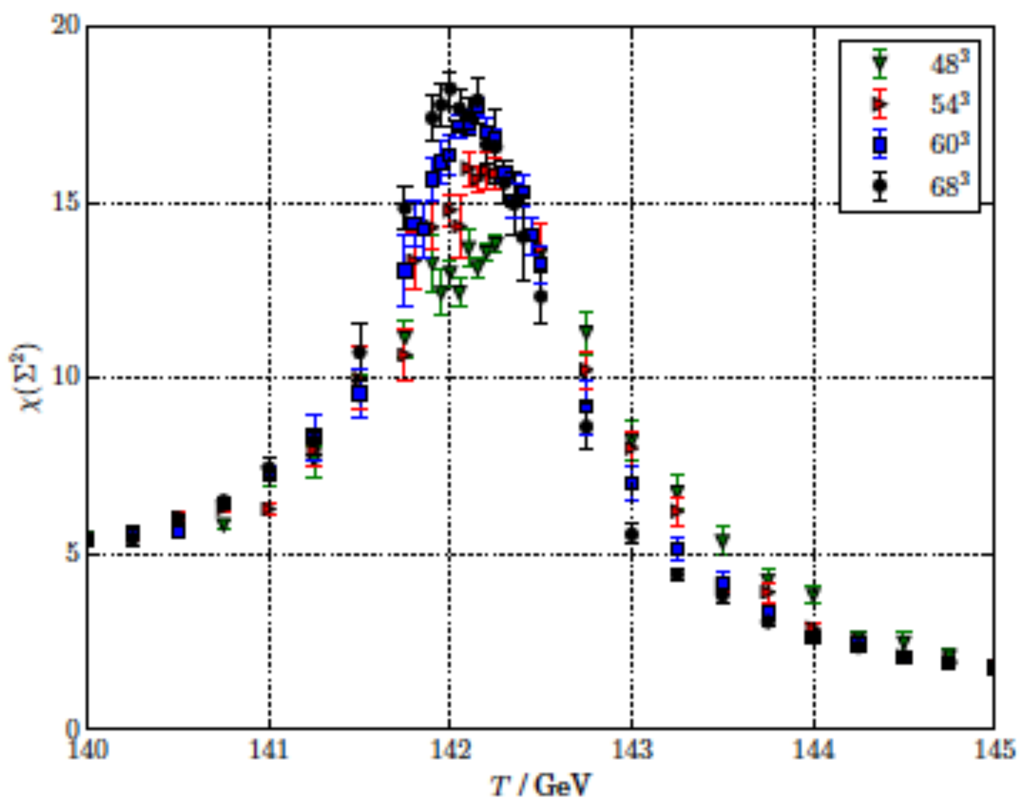
PT Discontinuities: First order EWPT

Lattice: Smooth Crossover: No phase transition

Discontinuities: First order EWPT

Niemi, R-M, Tenkanen, Weir 2005.11332

Real Triplet: Crossover vs 2nd Order



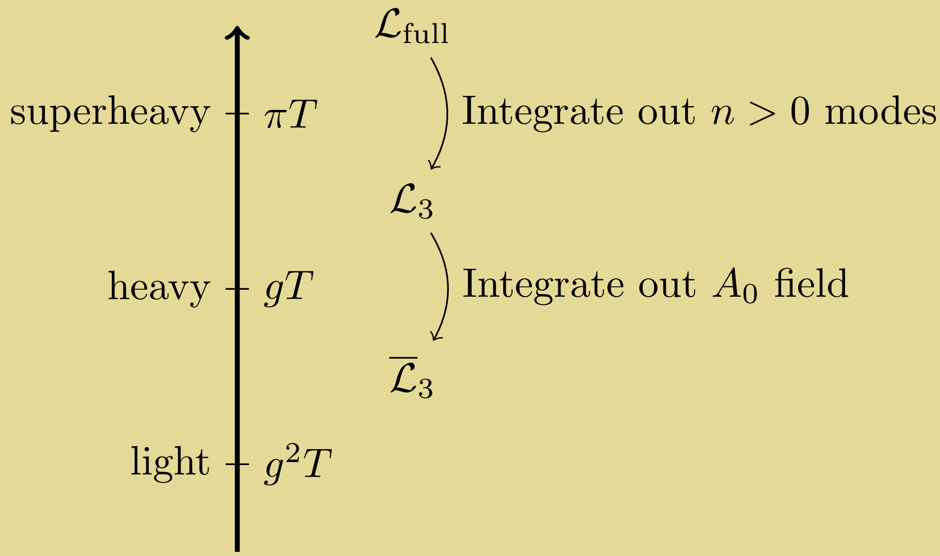
$$\chi(\Sigma^2) = \frac{1}{4} VT \left[\langle (\Sigma^a \Sigma^a)_V^2 \rangle - \langle (\Sigma^a \Sigma^a)_V \rangle^2 \right]$$

Niemi, R-M, Tenkanen, Weir 2005.11332

High-T EFT: Dimensional Reduction

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

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

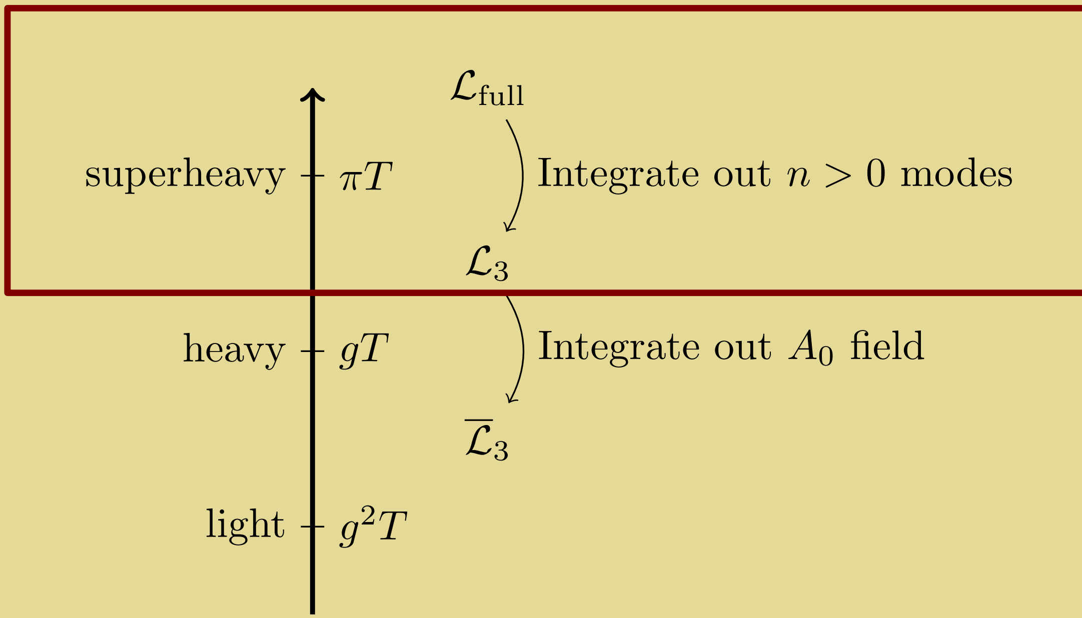
Field

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

Quartic coupling

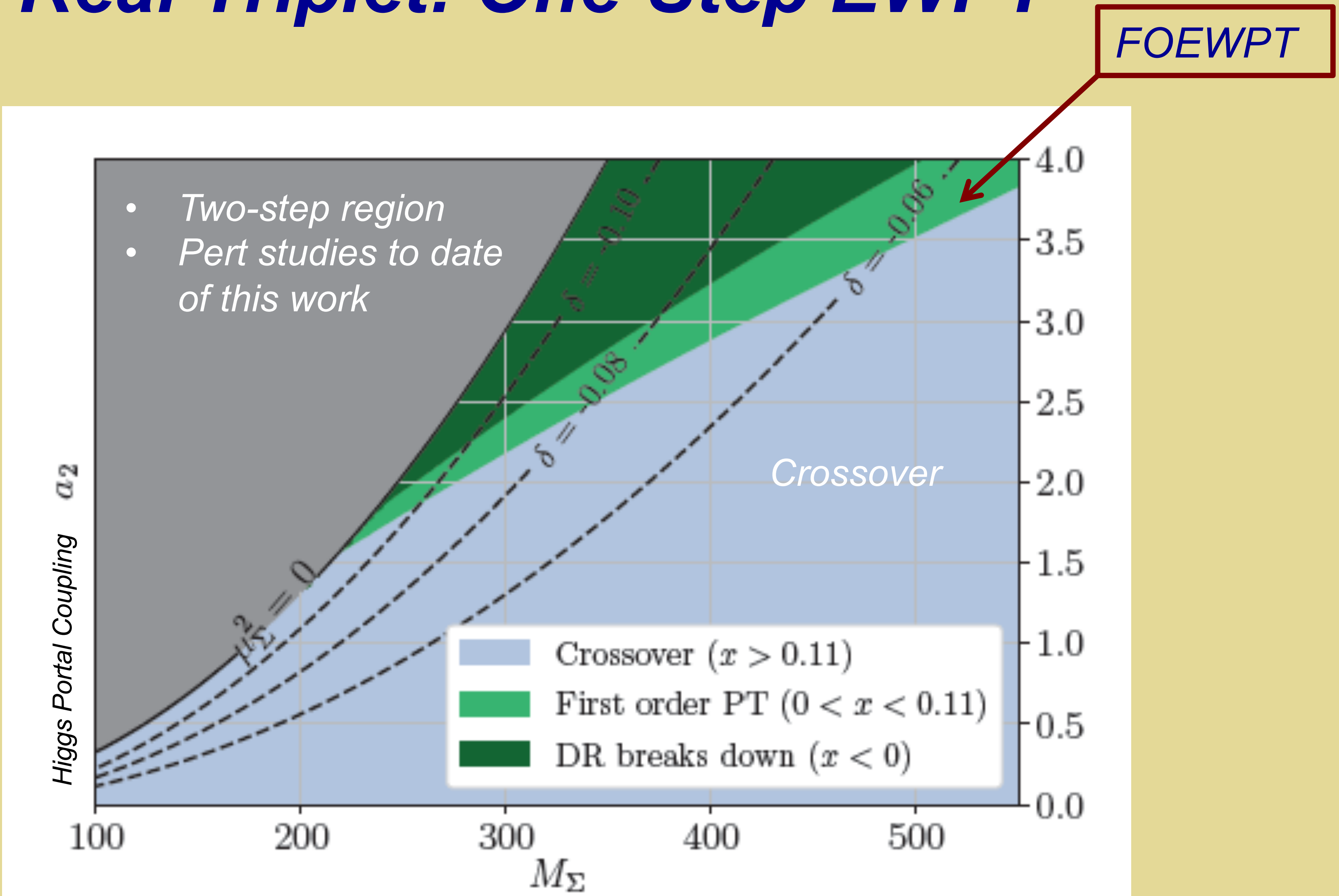
EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



Thermal resummations: systematically implemented

Real Triplet: One-Step EWPT

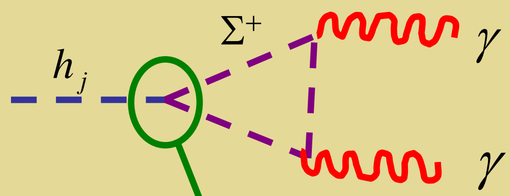


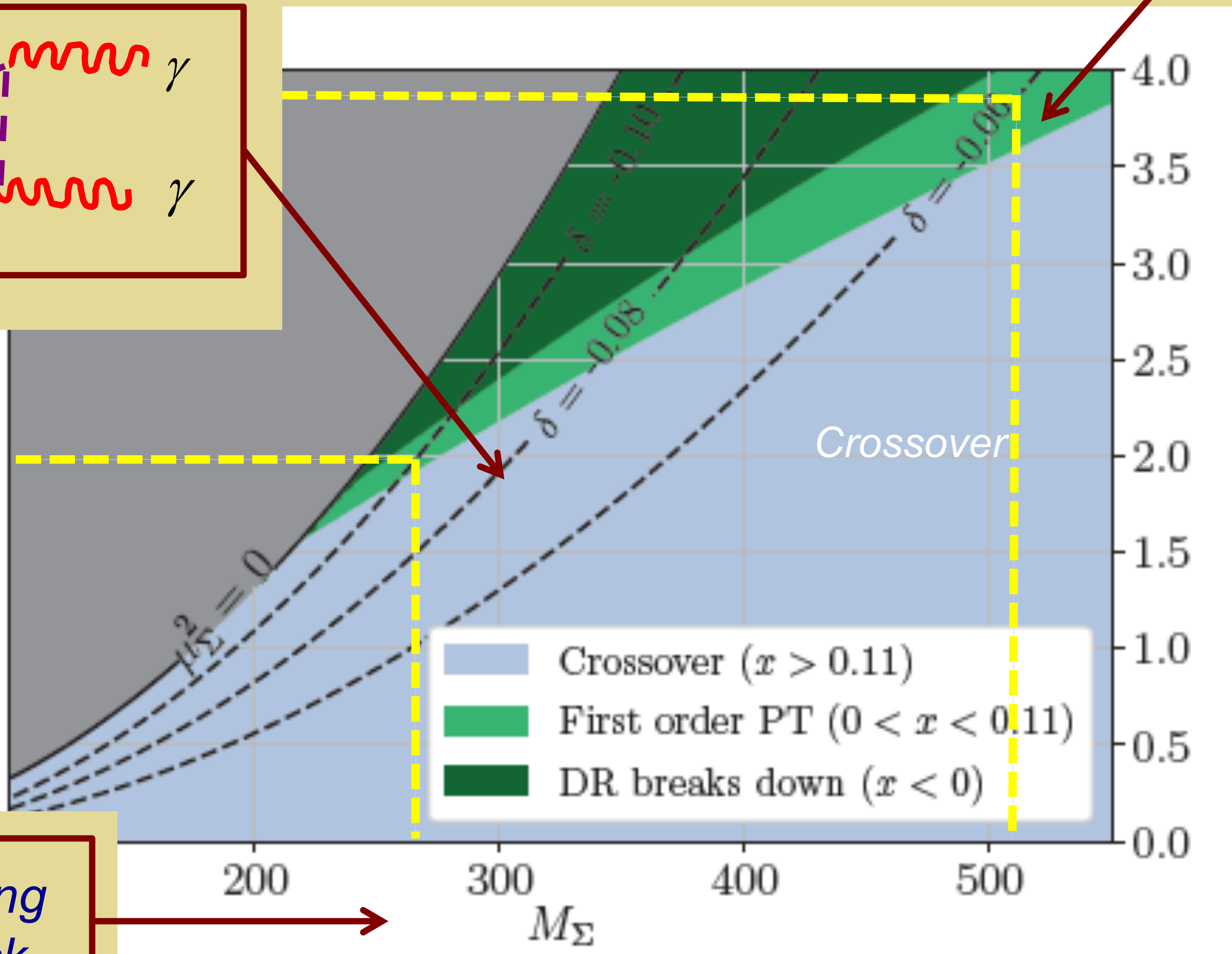
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

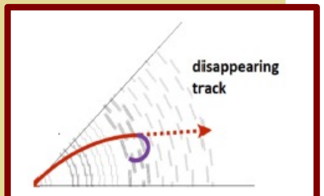
- One-step
- Non-perturbative

Real Triplet & EWPT

FOEWPT







Disappearing charge track

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

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