BSM Higgs & EW Phase Transition: Recent Developments

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- *Caltech*

About MJRM:

Science

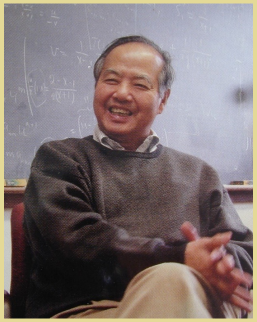
Family

Friends

My pronouns: he/him/his
 # MeToo

HPNP Osaka, June 7, 2022

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/

Outline

I. Context & Questions

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

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

III. Nucleation & Gauge Invariance

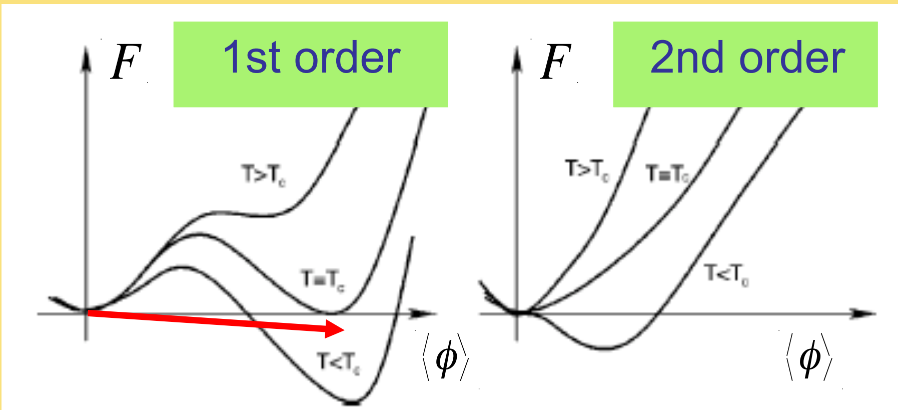
IV. Outlook

I. Context & Questions

Was There an Electroweak Phase Transition ?

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

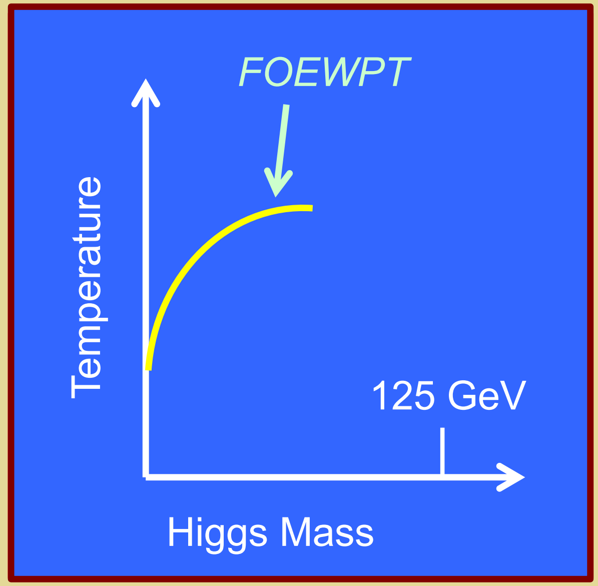
Was There an EW Phase Transition?



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

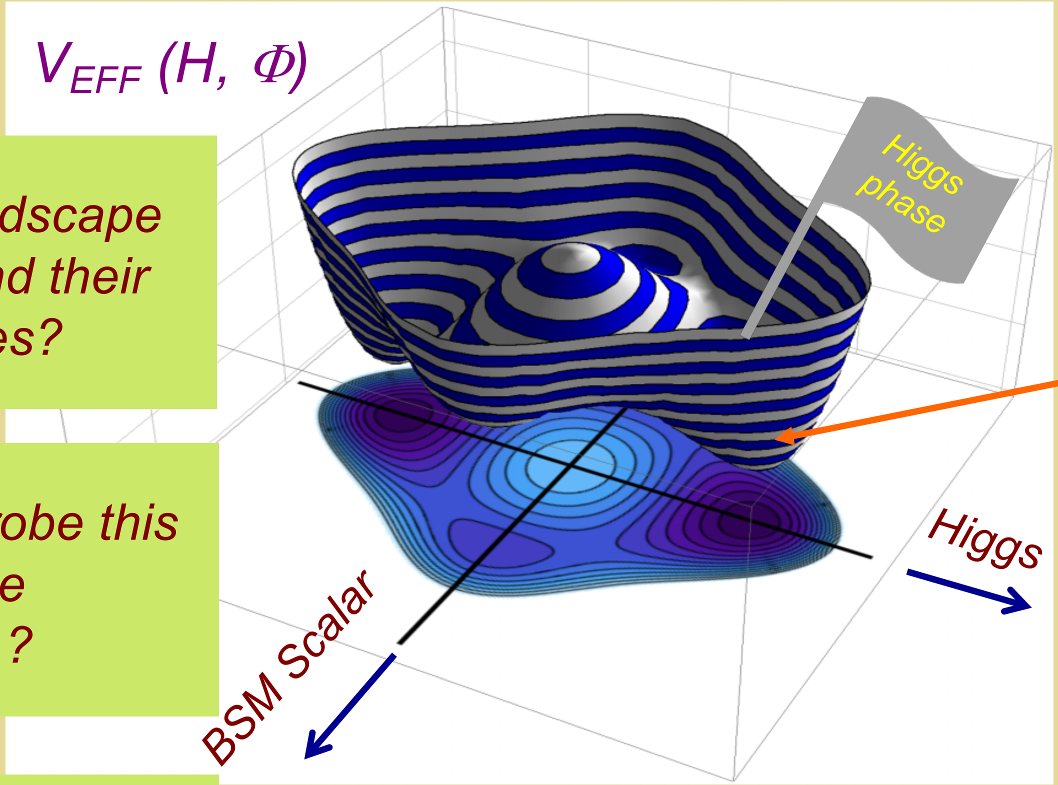
SM EW: Cross over transition



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?



How did we end up here ?

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

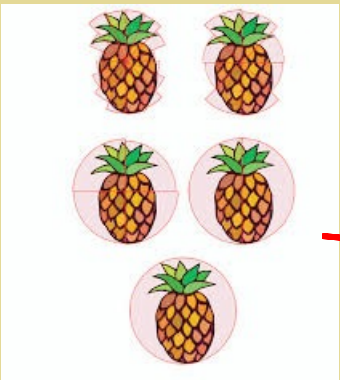
- How can we probe this T > 0 landscape experimentally ?

- How reliably can we compute the thermodynamics ?

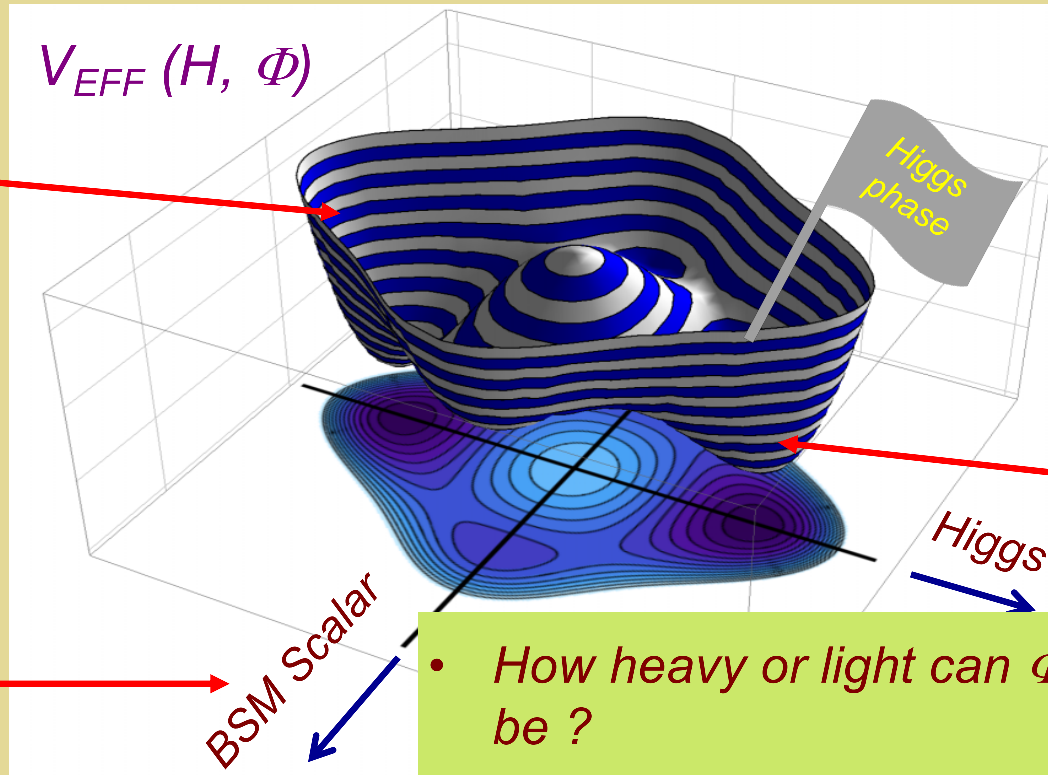
n evolve differently as T evolves →
ilities for symmetry breaking

Was There an EW Phase Transition?

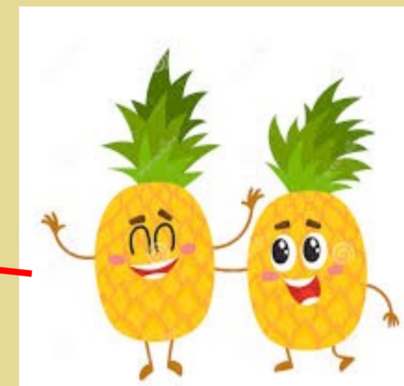
Bubble Collisions



Grav Radiation

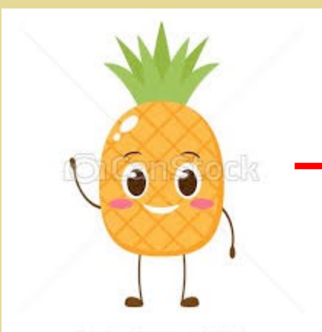


Higgs precision tests



SM Higgs **BSM Higgs**

Direct Production



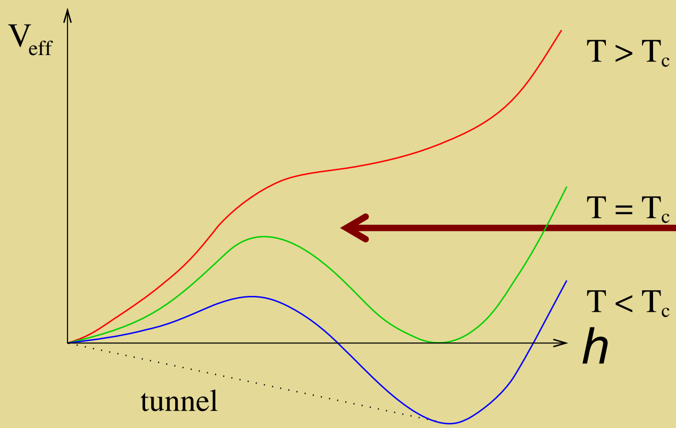
BSM Higgs

- *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

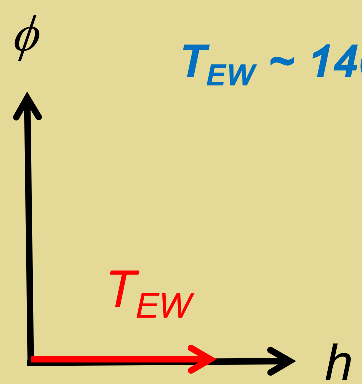
MJRM: 1912.07189

First Order EWPT from BSM Physics



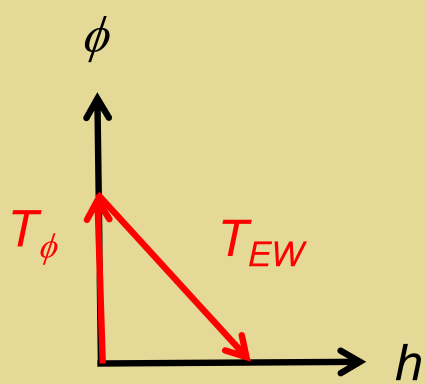
Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV

$T_{EW} \sim 140$ GeV



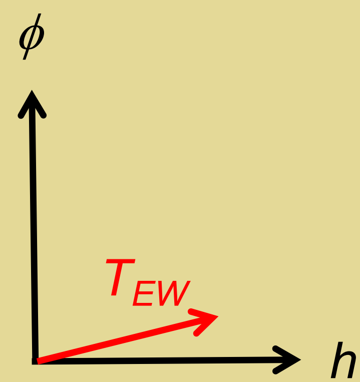
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

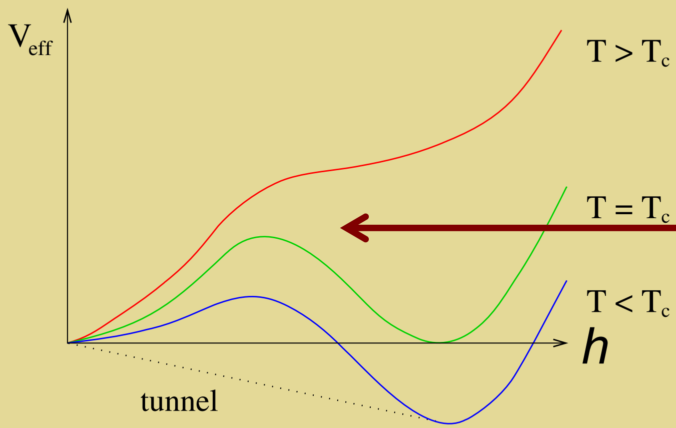
tree-level effect



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

tree-level effect

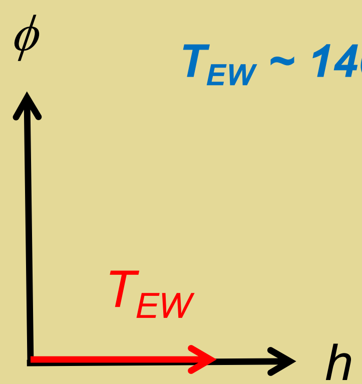
First Order EWPT from BSM Physics



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

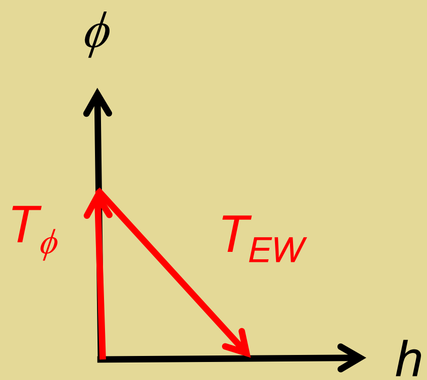
Higgs – ϕ^0 Mixing

T_{EW} ~ 140 GeV



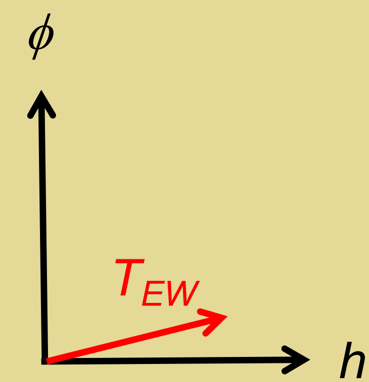
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



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

tree-level effect

II. Theoretical Robustness

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

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

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

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

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*

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

B. Perturbative

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

Benchmark pert theory

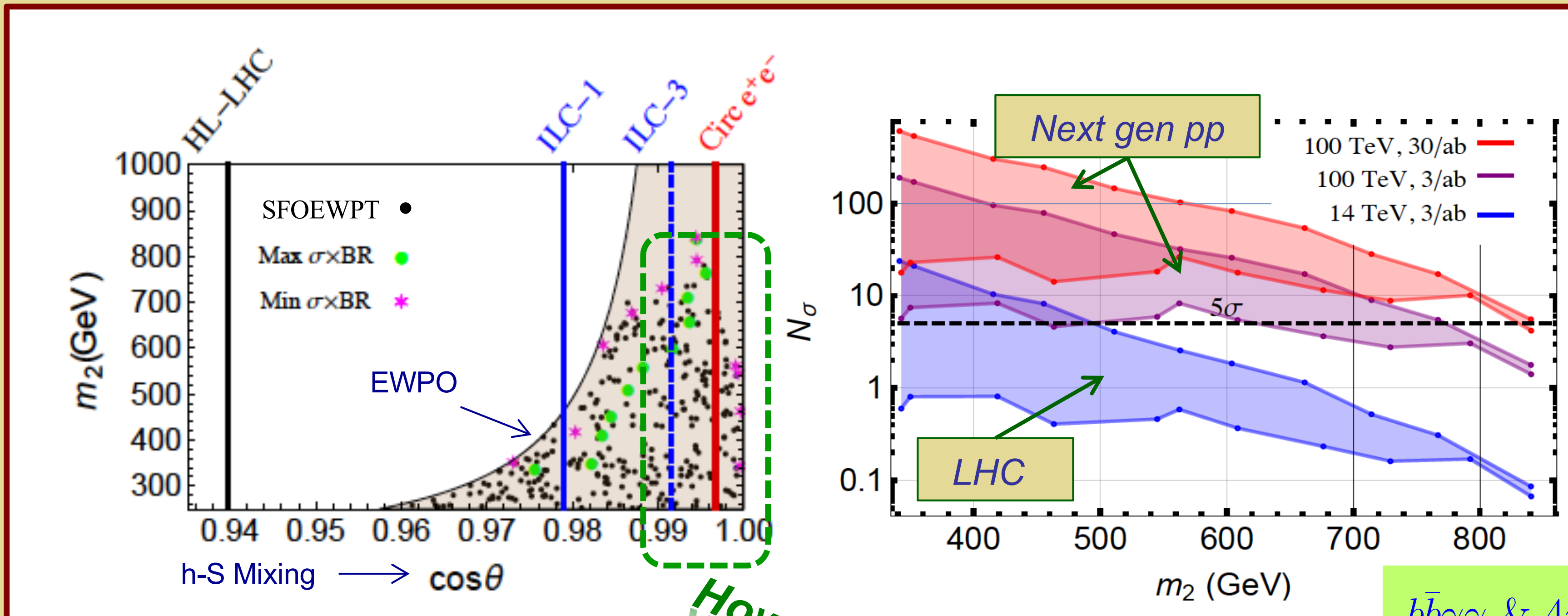
Model Illustrations

Simple Higgs portal models:

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

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



$b\bar{b}\gamma\gamma$ & 4τ

How reliable ?

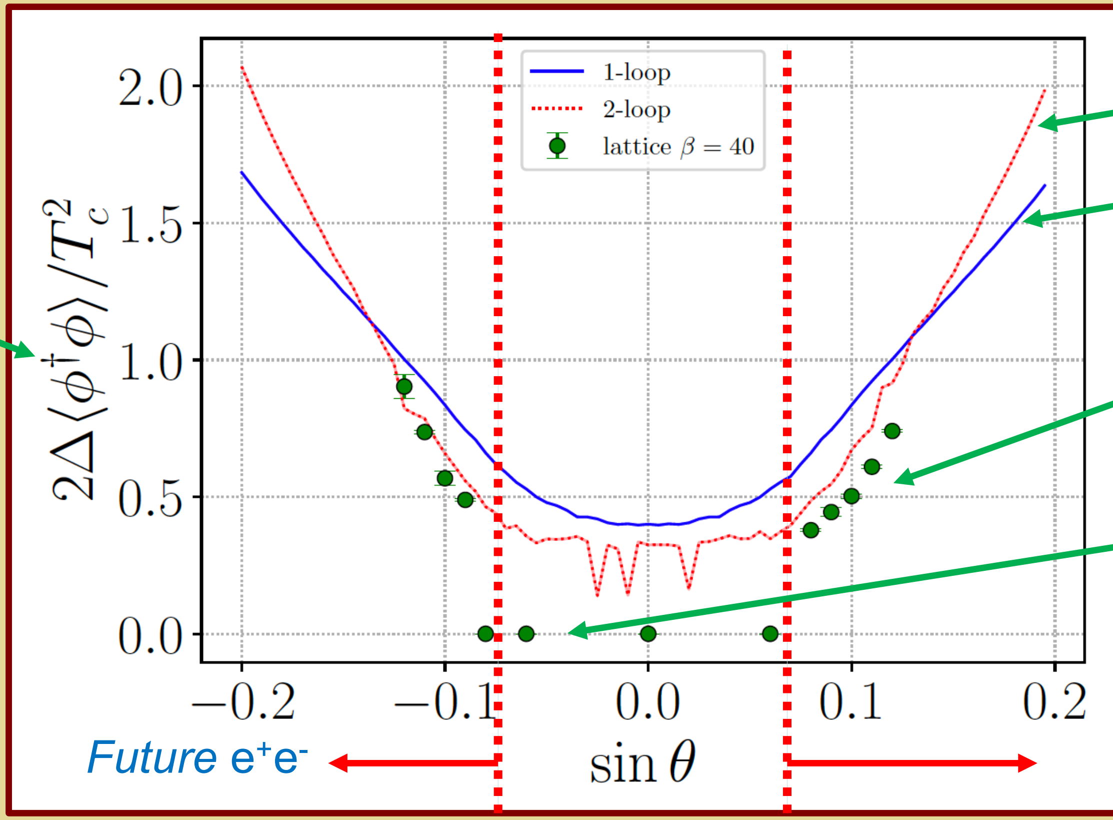
Kotwal, No, R-M, Winslow 1605.06123

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

Lattice Benchmarking

L. Niemi, MRM, G. Xia in prog

M_{h2} = 350 GeV



Change in condensate at T_C

2 loop PT

1 loop PT

Lattice: FOEWPT

Lattice: Crossover

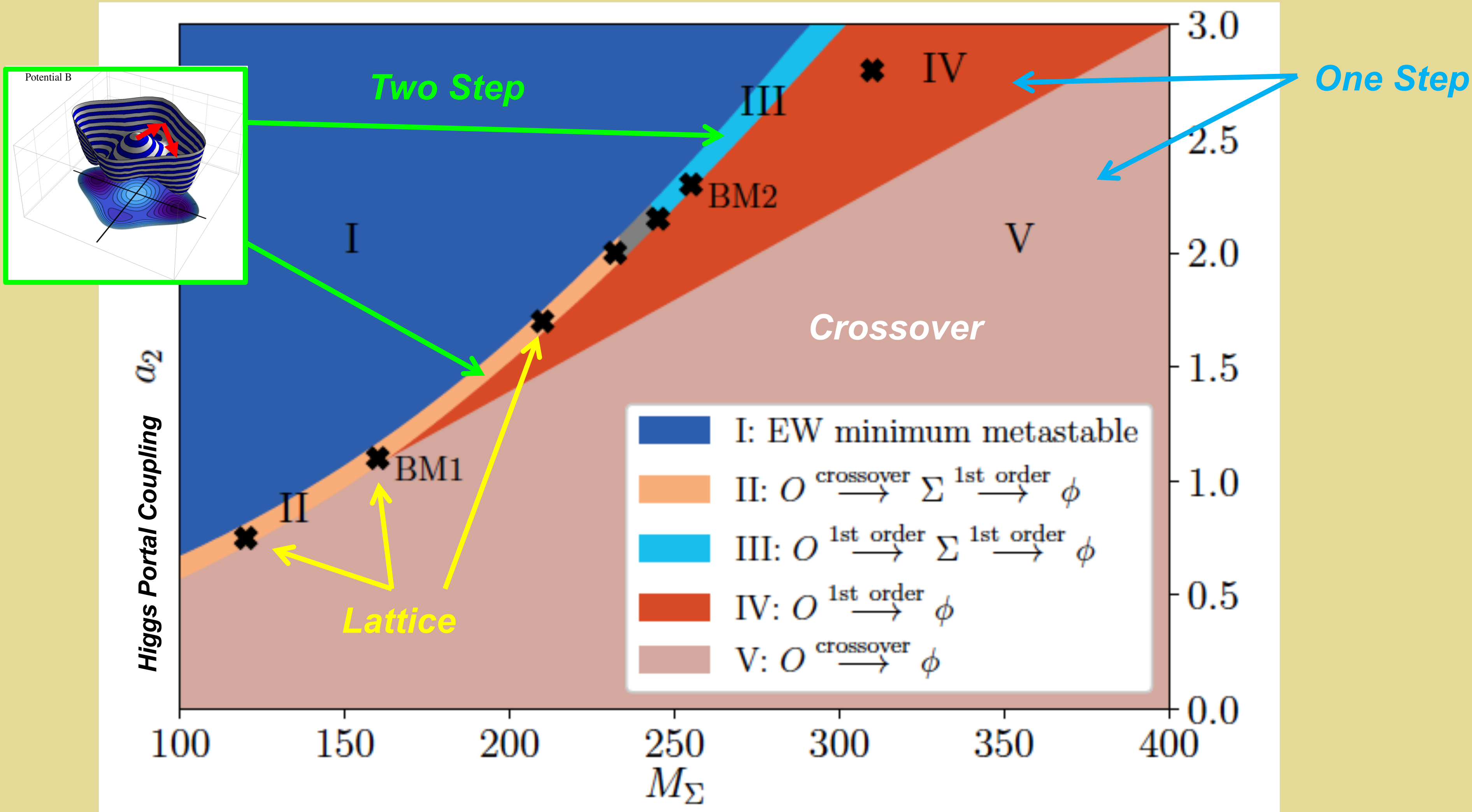
- *When a FOEWPT occurs, 2 loop PT gives a good description*
- *Lattice needed to determine when onset of FOEWPT occurs*
- *Future precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized*

Model Illustrations

Simple Higgs portal models:

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

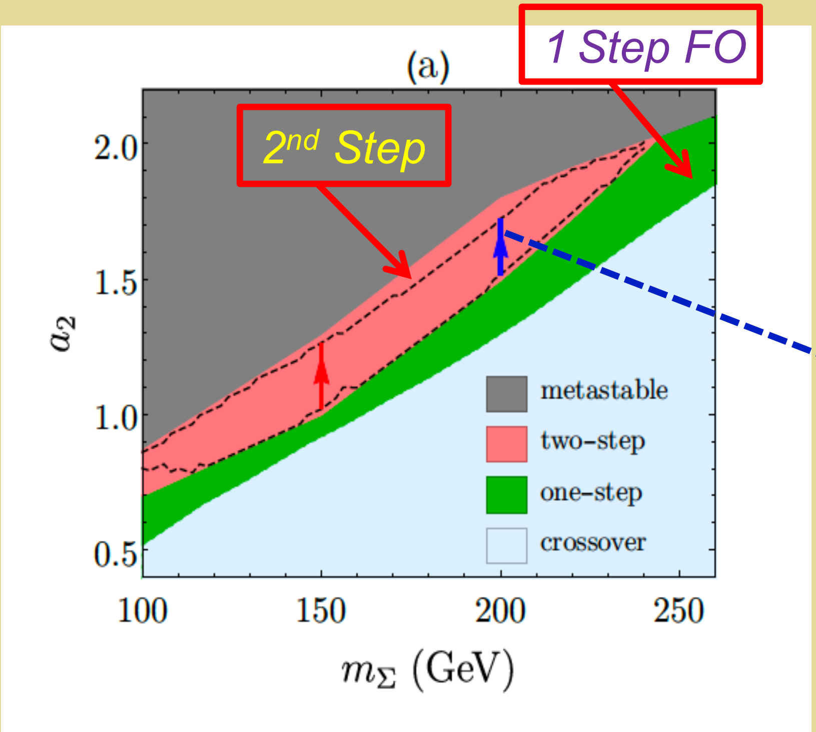
Real Triplet & EWPT: Novel EWSB

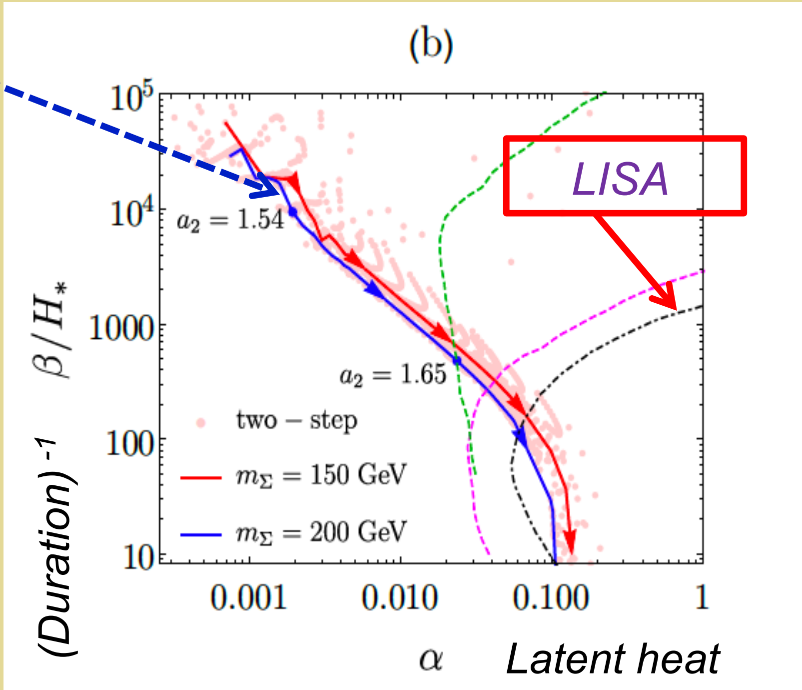


- *1 or 2 step*
- *Non-perturbative*

Niemi, R-M, Tenkanen, Weir 2005.11332

GW & EWPT Phase Diagram

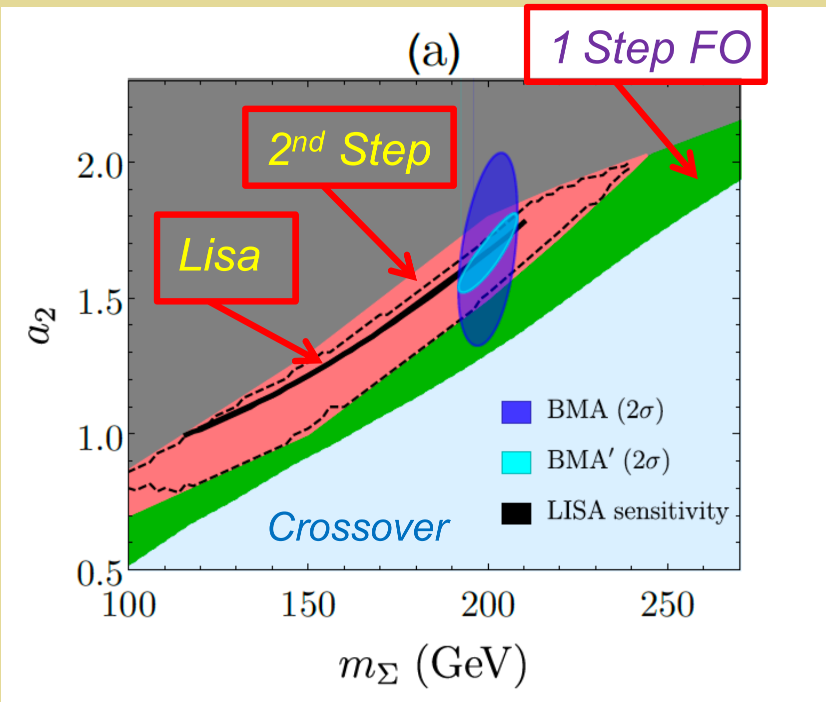


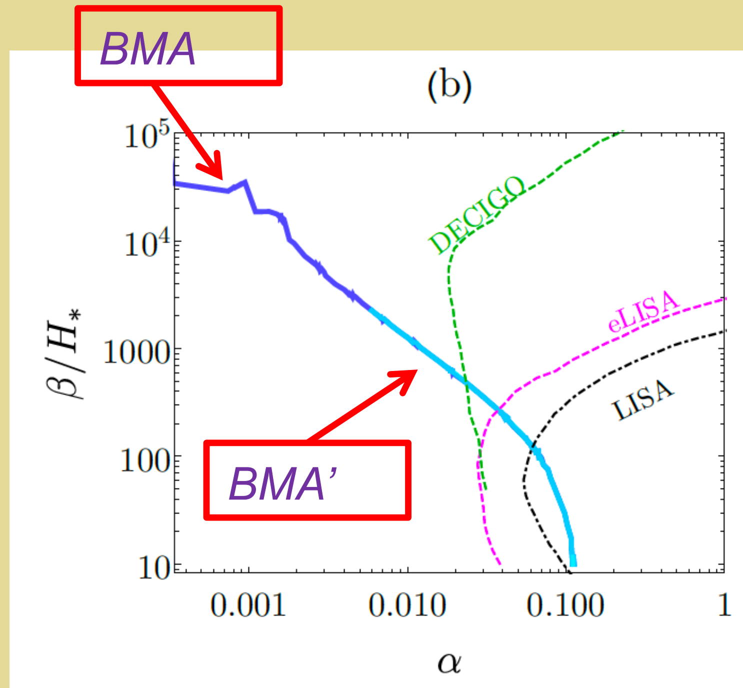


- ***Single step transition: GW well outside LISA sensitivity***
- ***Second step of 2-step transition can be observable***

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW & EWPT Phase Diagram





BMA: m_Σ + h → $\gamma\gamma$

BMA' : BMA + Σ^0 → ZZ

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

Friedrich, MJRM, Tenkanen, Tran 2203.05889

III. Nucleation

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

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

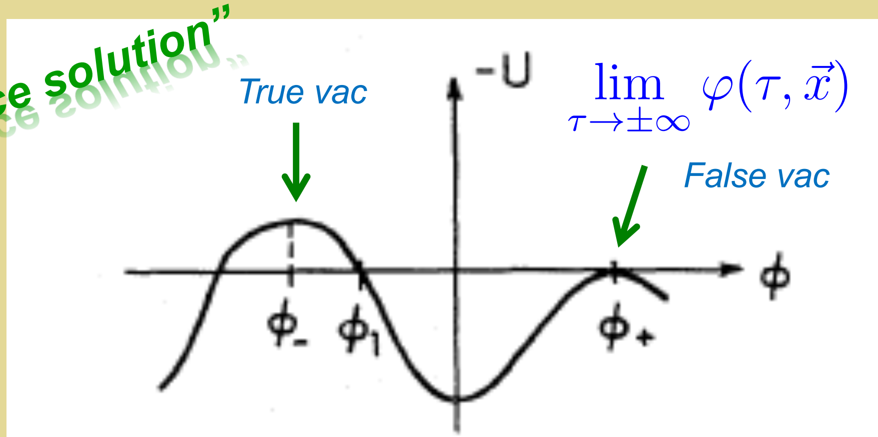
How Reliable?

S. Coleman, PRD 15 (1977) 2929

Tunneling @ T=0: Coleman

Scalar Quantum Field Theory

"Bounce solution"



$$\lim_{\tau \to \pm\infty} \varphi(\tau, \vec{x})$$

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

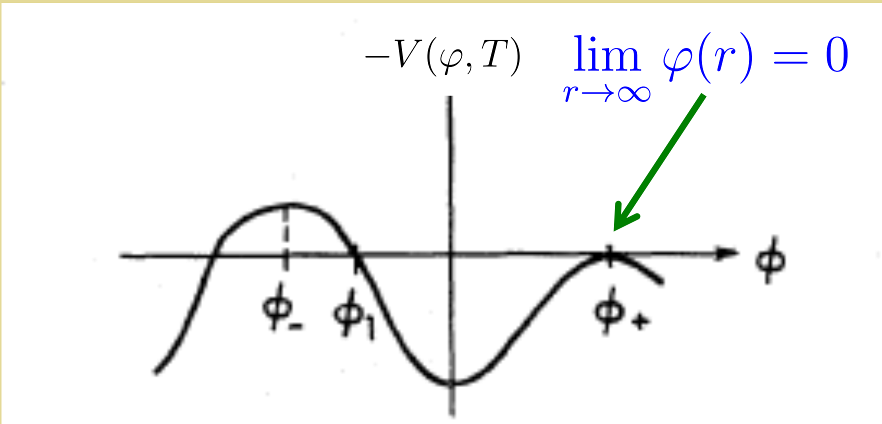
Ln Γ

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:

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

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

Exponent in Γ

Path: minimize S_E

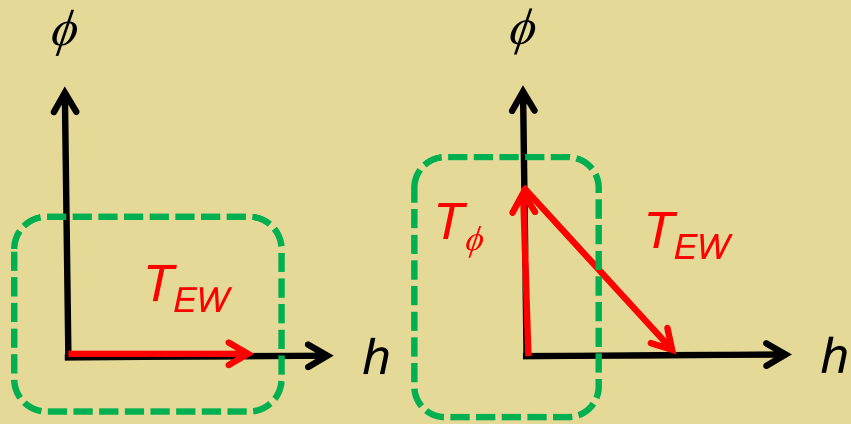
Friction term

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

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

Tunneling @ T>0

Radiative barriers → st'd method gauge-dependent



Tunneling rate / unit volume:

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

Exponent in Γ

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

Path: minimize S_E

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

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

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

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

Full 3D effective action

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

Adopt appropriate power-counting in couplings

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

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

SSB @ T>0 : Power Counting

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

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

T=0 parameter < 0

Thermal corrections > 0

Near cancellation for $T \sim T_C$

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

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

Power Counting

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

ϕ	~	T
λ	~	g^3
μ^2	~	$g^2 T^2$
μ_{eff}^2	~	$g^3 T^2$

→

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

Radiative barrier: ξ-independent

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

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

Adopt appropriate power-counting in couplings

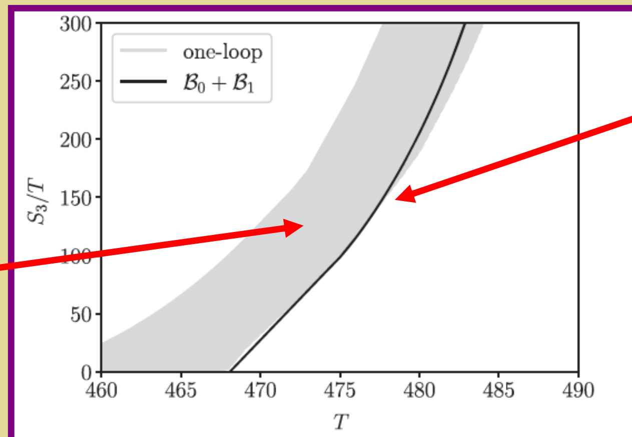
$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

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

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

Was There an Electroweak Phase Transition ?

- *Answering this question is an important and exciting challenge for Higgs Physics as New Physics*
- *The relevant scale T_{EW} makes this physics a prime target for collider and gravitational wave probes*
- *The EWPT question entails a rich interplay of model building, phenomenology, and thermal QFT*
- *Achieving the most robust possible treatment of EWPT dynamics and thermodynamics – through a combination of lattice, thermal EFT, and refined QFT – is an essential foundation for this quest with compelling opportunities for more theoretical work*

谢谢!

Back Up Slides

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

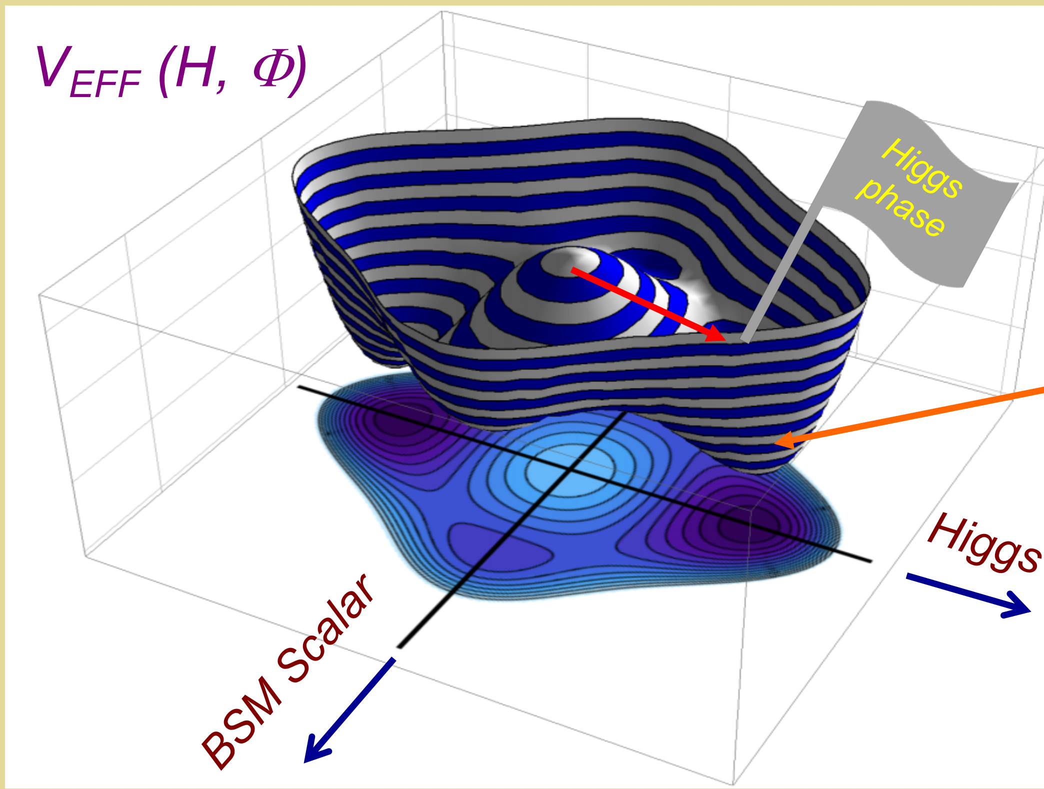
High-T SM Effective Potential

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

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

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

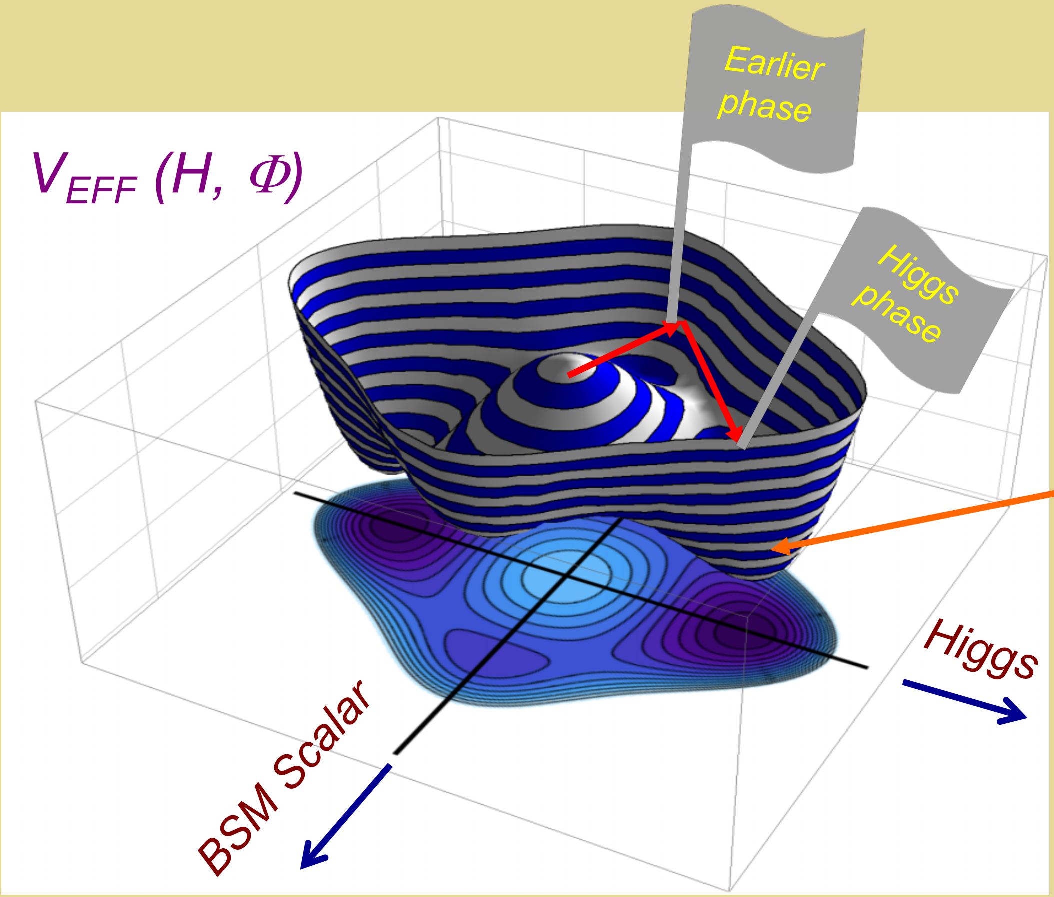
Patterns of Symmetry Breaking



How did we end up here ?

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

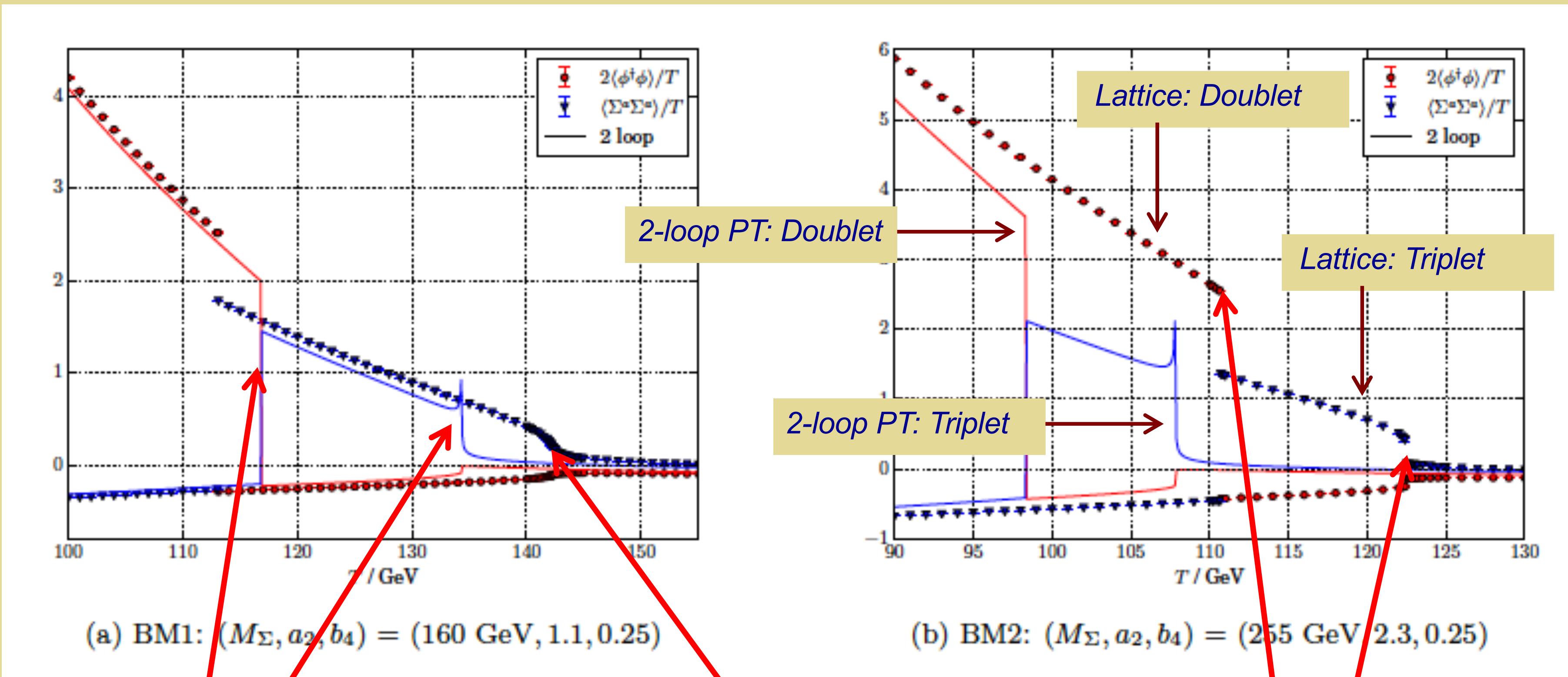
Patterns of Symmetry Breaking



How did we end up here ?

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

Real Triplet & EWPT: Benchmark PT



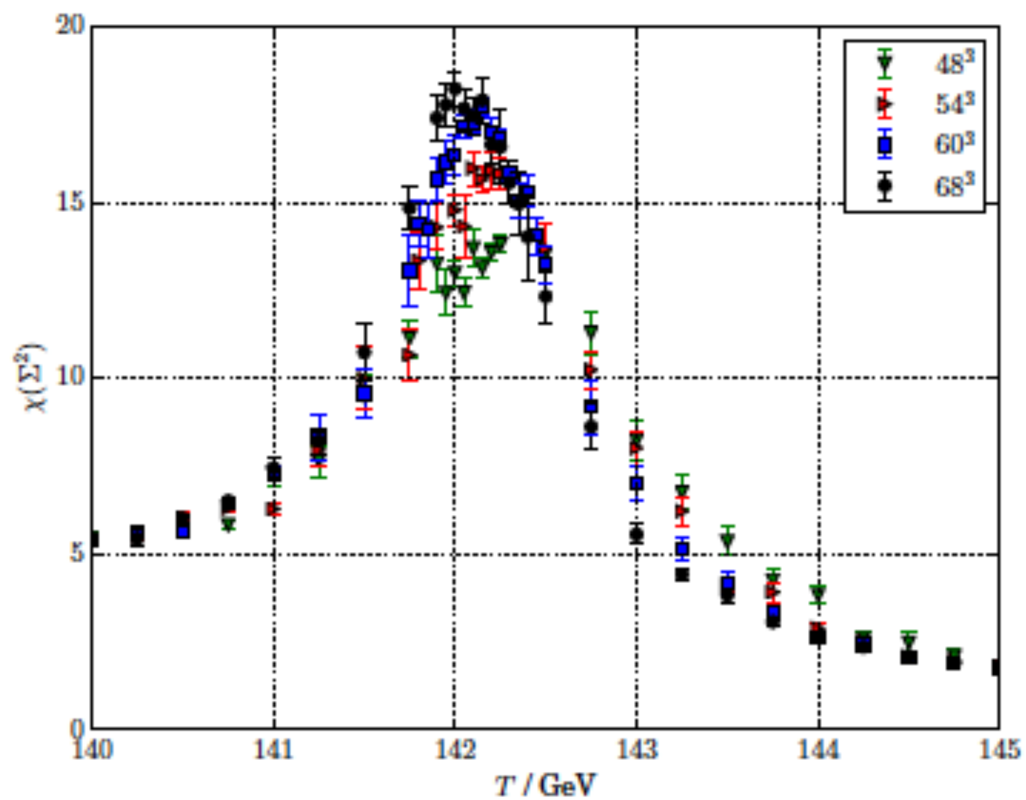
PT Discontinuities:
First order EWPT

Lattice: Smooth Crossover:
No phase transition

Discontinuities:
First order EWPT

Niemi, R-M, Tenkanen, Weir 2005.11332

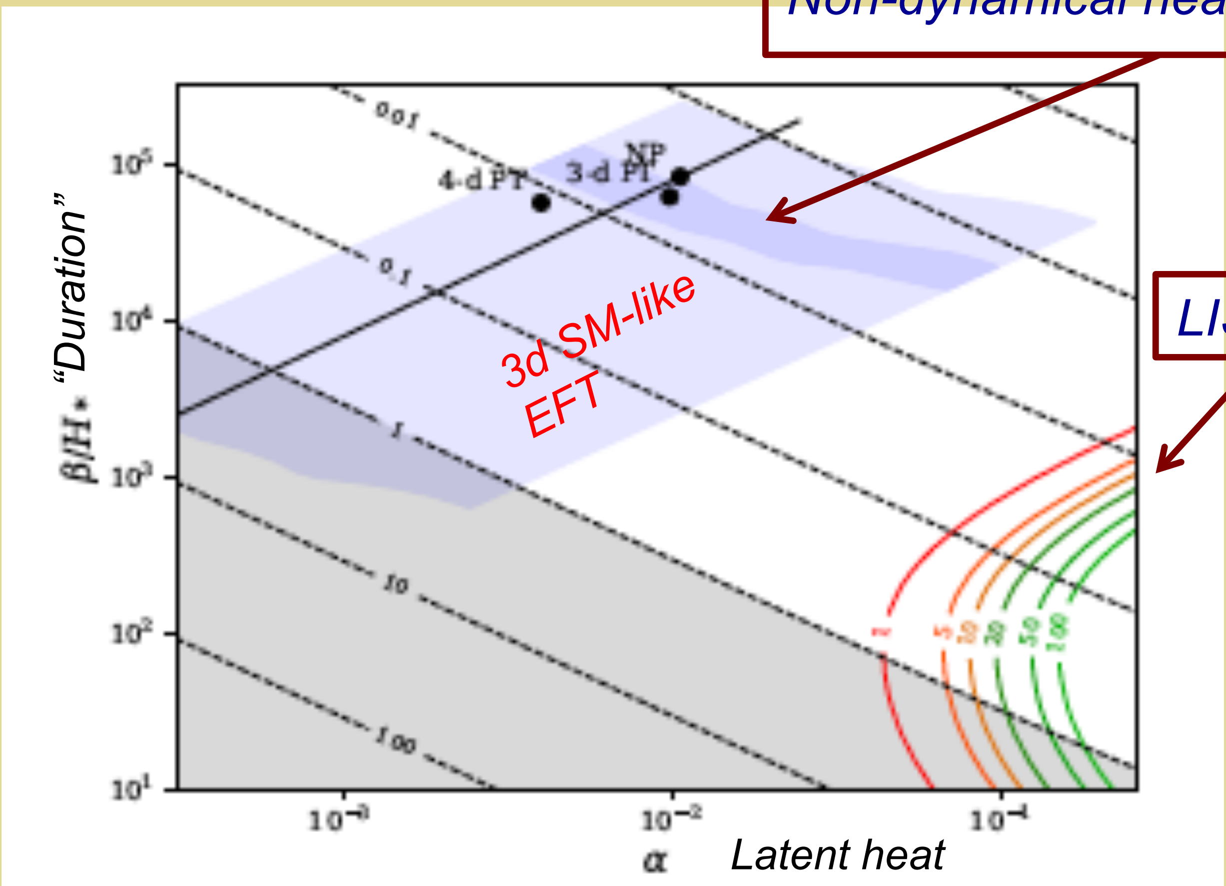
Real Triplet: Crossover vs 2nd Order



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

Niemi, R-M, Tenkanen, Weir 2005.11332

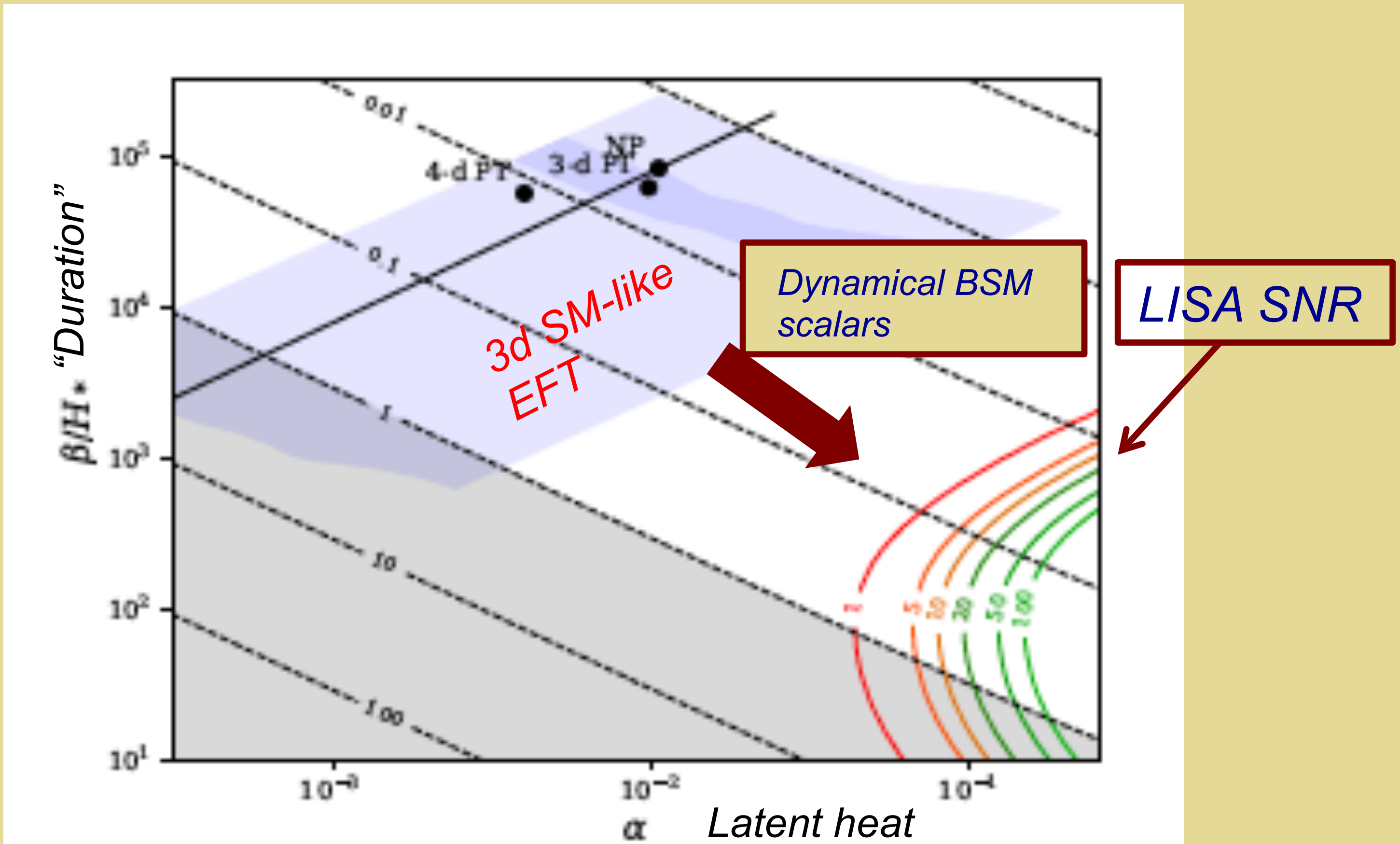
Heavy BSM Scalar: EWPT & GW



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

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

Heavy BSM Scalar: EWPT & GW



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

- One-step
- Non-perturbative

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

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

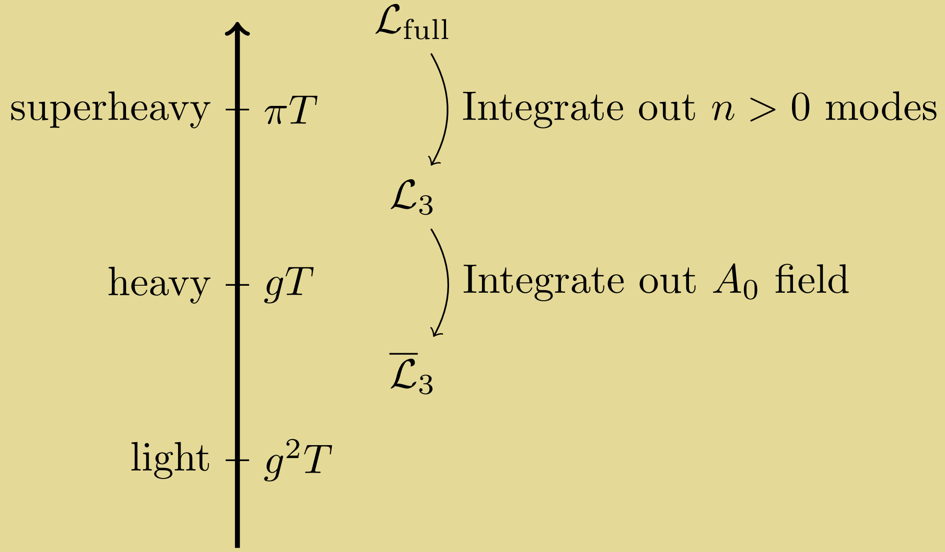
• πT	*Non-zero Matsubara modes*
• M_{BSM}	*BSM mass scale: can be > or < πT*
• $g\, T$	*Thermal masses*
• M_{NUC}	*Nucleation scale ~ $1/r_{bubble}$*
• $g^2\, T$	*Light scale*

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

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

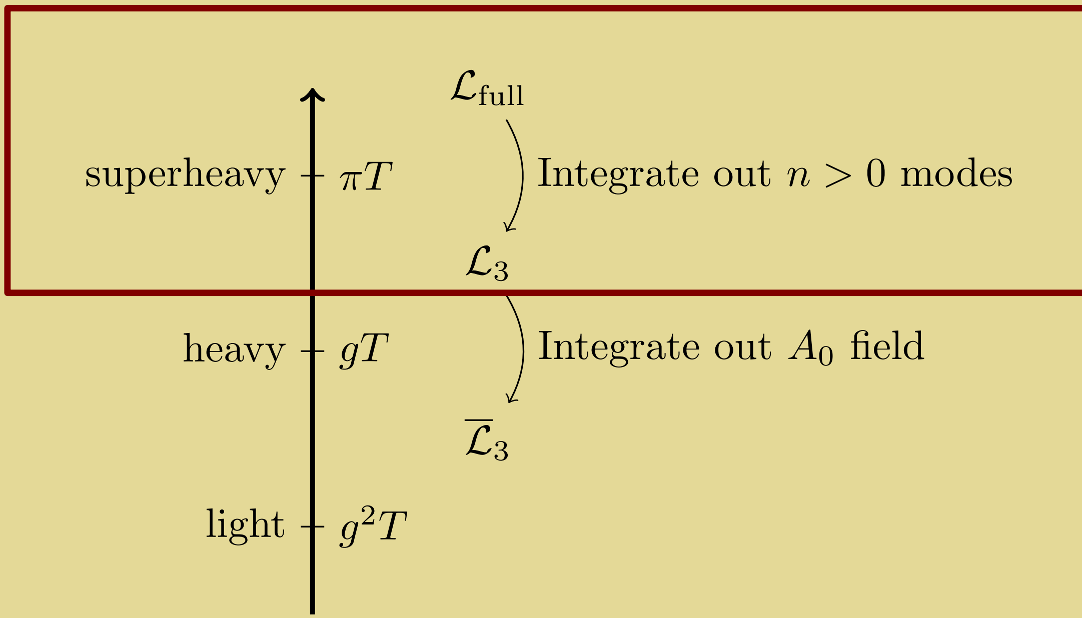
Field

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

Quartic coupling

EFT 1: Thermodynamics

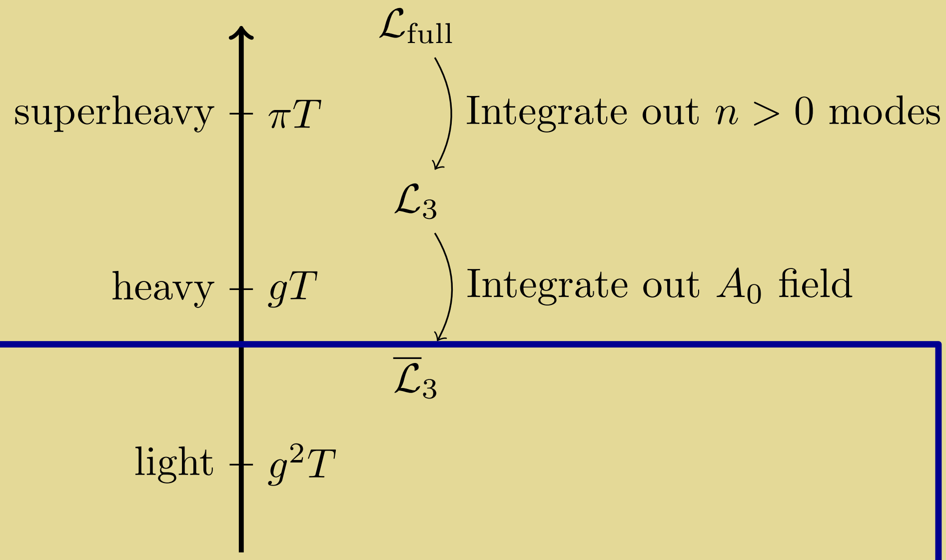
Meeting ground: 3-D high-T effective theory



Thermal resummations: systematically implemented

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



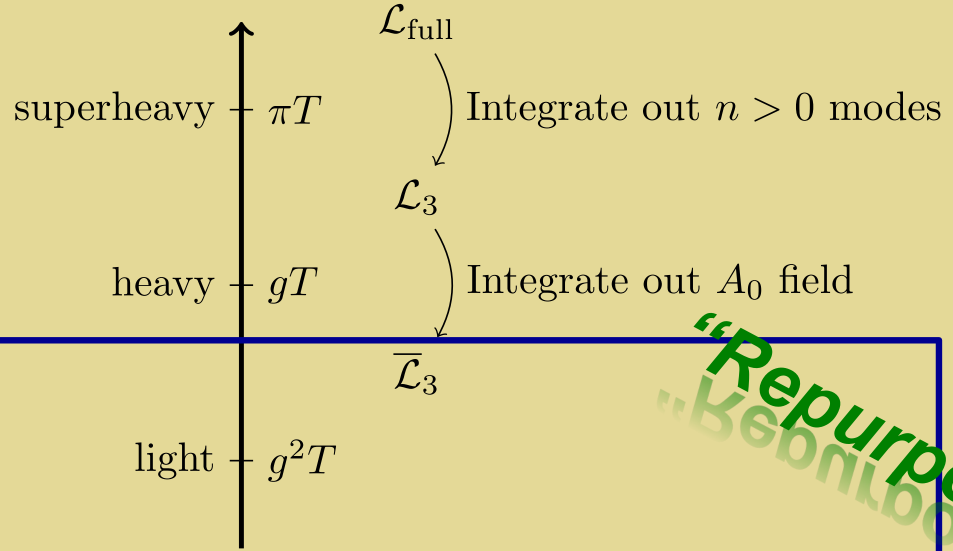
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

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



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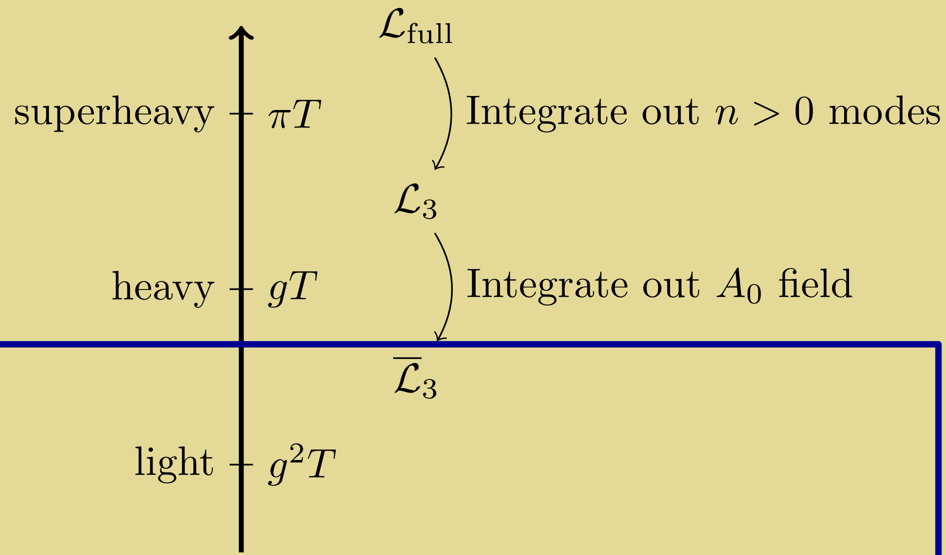
"Repurpose" lattice results

Lattice simulations exist

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



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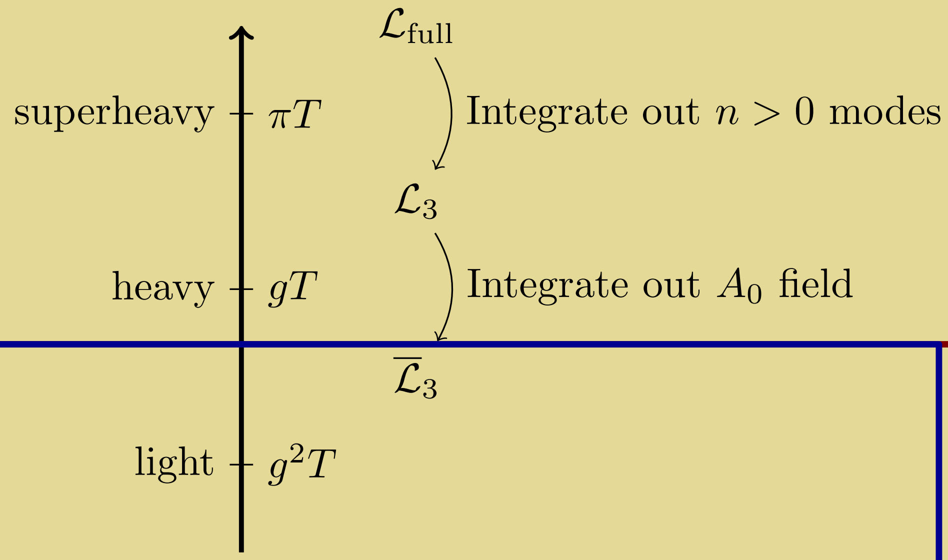
Lattice simulations exist (e.g., Kajantie et al '95)

- *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



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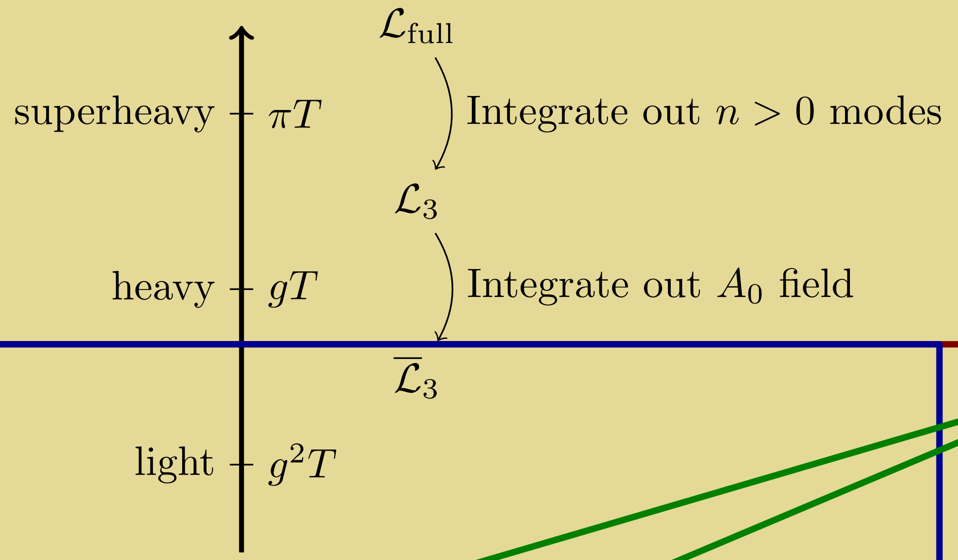
Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory



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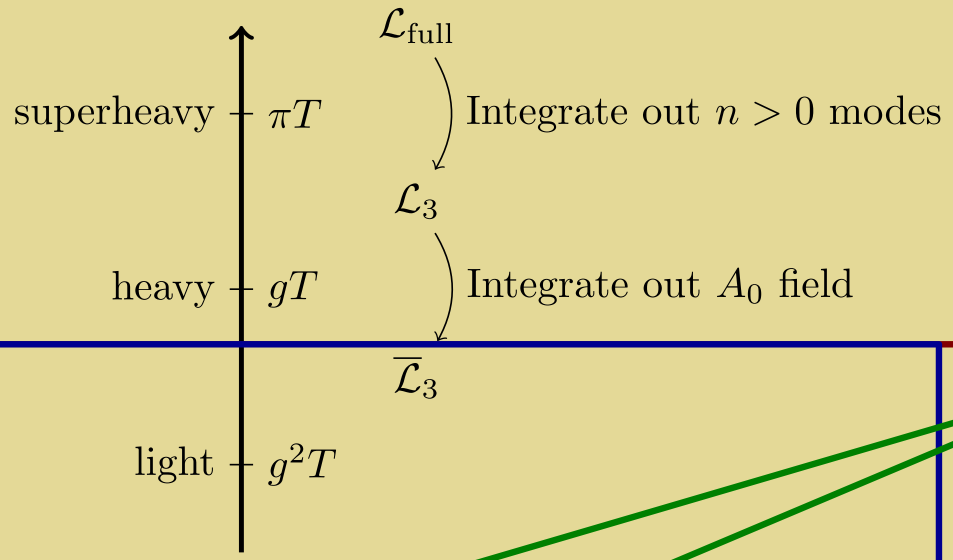

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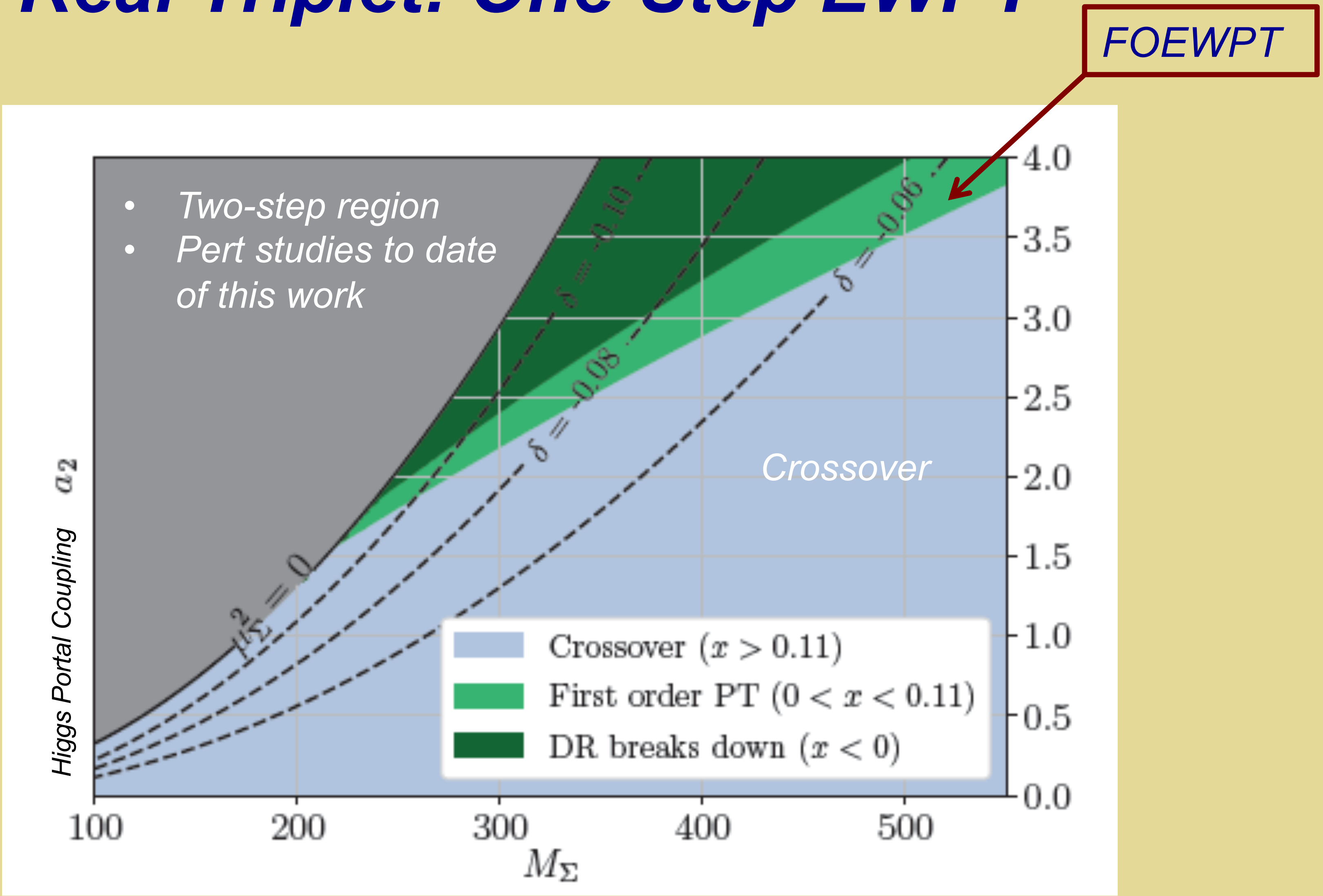
Real Triplet: One-Step EWPT

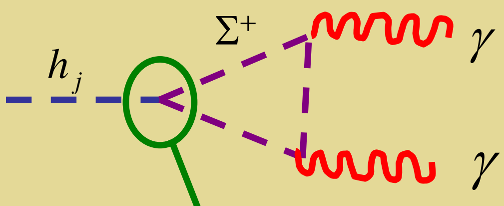


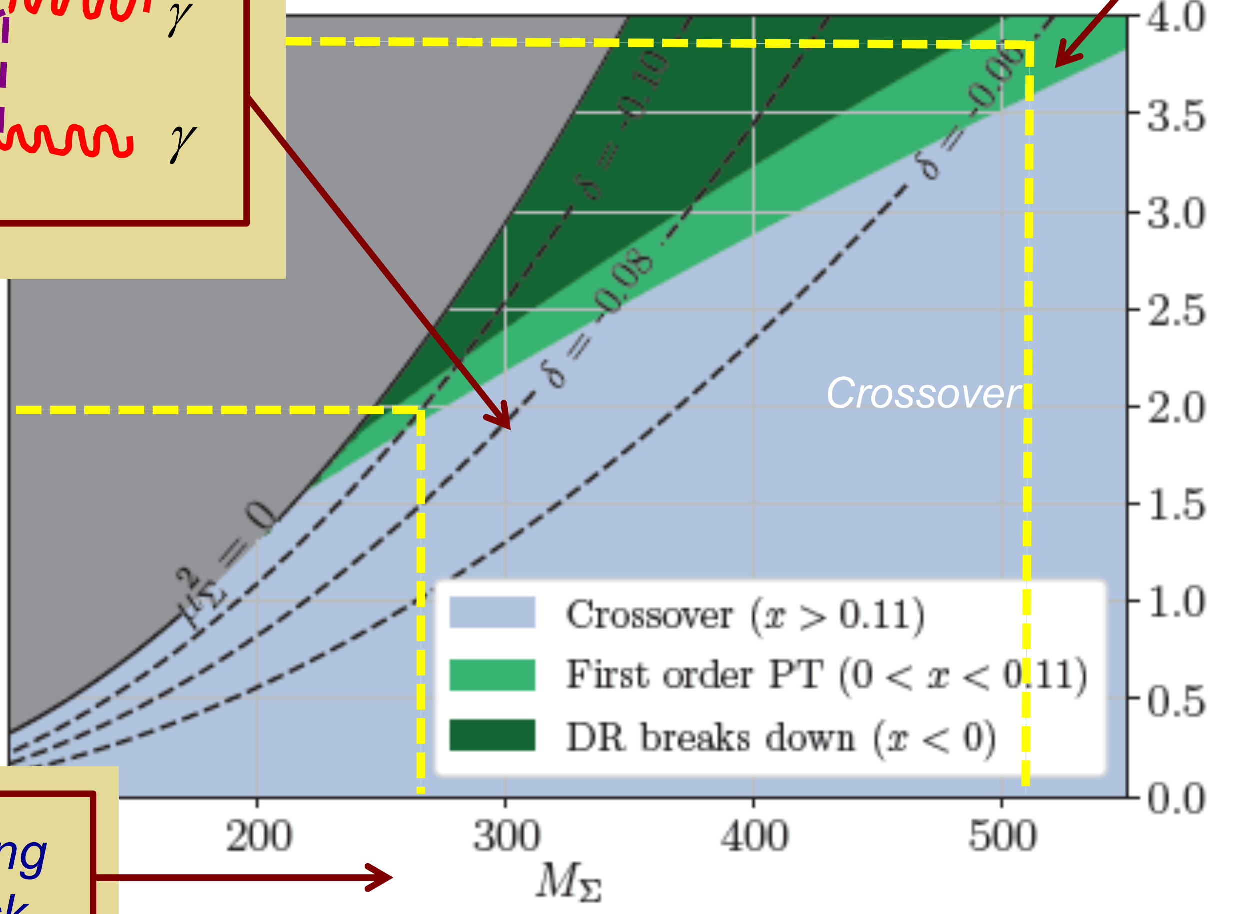
- *One-step*
- *Non-perturbative*

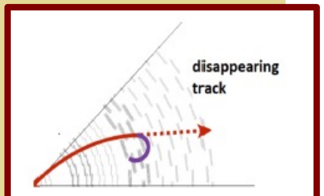
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

FOEWPT







Disappearing charge track

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

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