EW Scalars: Cosmological Implications & Terrestrial Probes

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My pronouns: he/him/his

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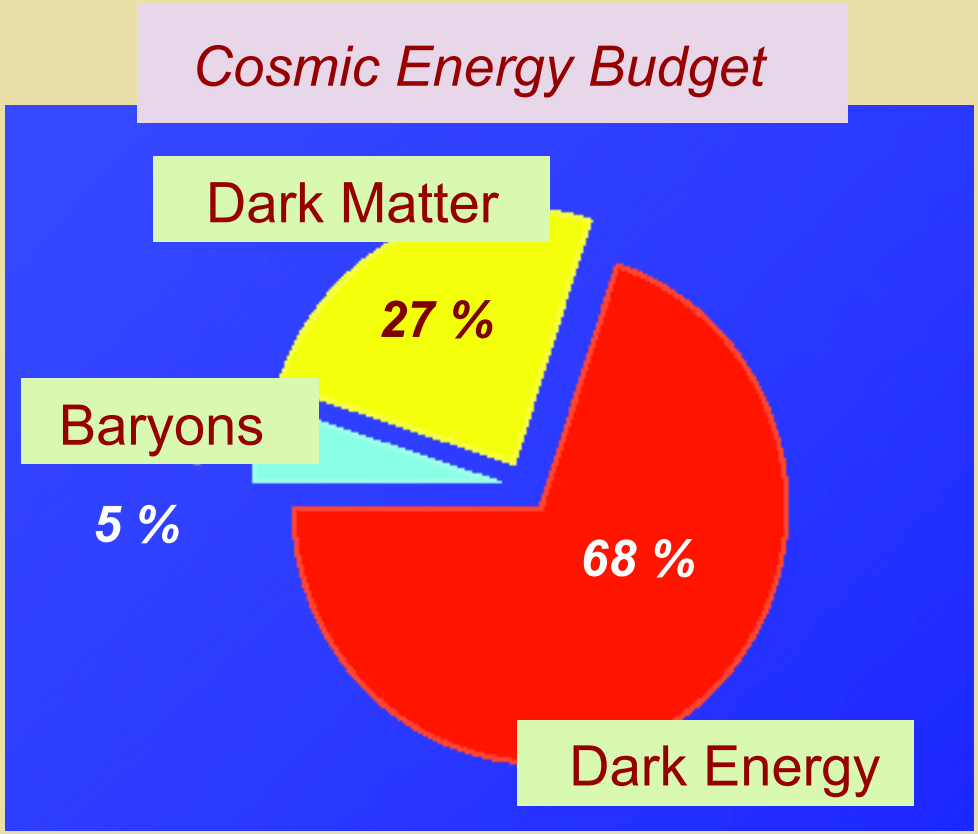
Particle Physics-Cosmology Interface



Can extensions of the SM scalar sector with EW multiplets address open problems in cosmology ?

This talk: baryogenesis & dark matter

Goals for This Talk

- *Discuss the implications of extended scalar sectors w/ electroweak multiplets for the thermal history of electroweak symmetry breaking & illustrate collider probes*
- *Highlight the importance of carrying out non-perturbative studies of the EW symmetry-breaking transition & report on our recent work*
- *Illustrate the interplay between EW mutliplets, dark matter, and the electroweak phase transition*

Outline

I. Electroweak Phase Transition

II. EWPT: Theoretical Robustness

III. General EW Multiplets & Dark Matter

IV. Outlook

I. Electroweak Phase Transition

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 ?*

EWPT: Theory & Phenomenology

- *What models can lead to a (strong) first order electroweak phase transition ?*
- *Can they also yield contributions to Ω_{DM} ?*
- *How can they be tested experimentally ?*
- *How reliably can we compute phase transition properties & make the connection with phenomenology ?*

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: ~~Z_2~~	1	✔	✖
Real singlet: Z_2	1	✔	✔
Complex Singlet	2	✔	✔
EW Multiplets	3+	✔	✔

May be low-energy remnants of UV complete theory & illustrative of generic features

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This talk

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Real Triplet

$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]

$$V_{H\Sigma} = \frac{a_1}{2} H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

EWPT: $a_{1,2} \neq 0$ & $\langle \Sigma^0 \rangle \neq 0$

DM & EWPT: $a_1 = 0$ & $\langle \Sigma^0 \rangle = 0$

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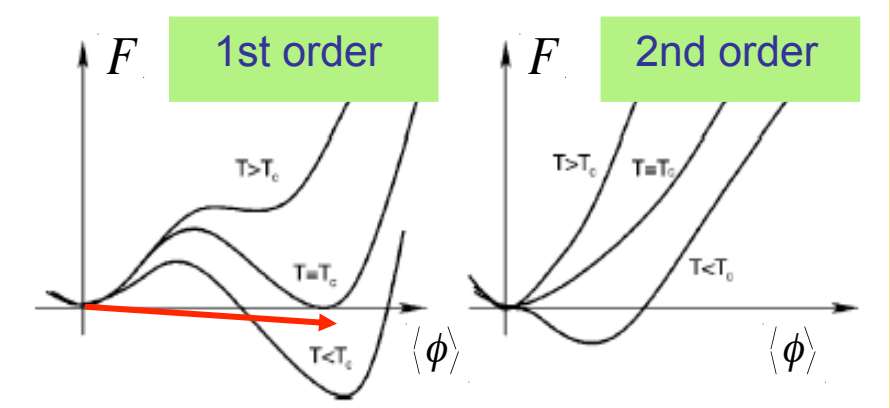
DM Stability

EW Multiplets: EWPT



Increasing m_h →

← *New scalars*

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

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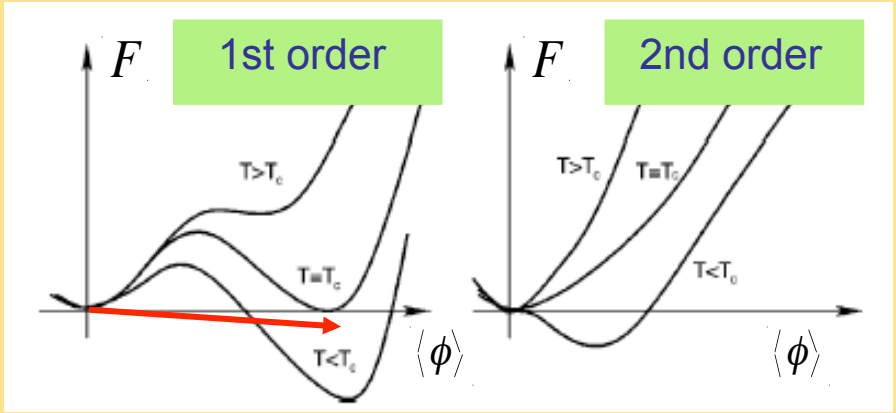

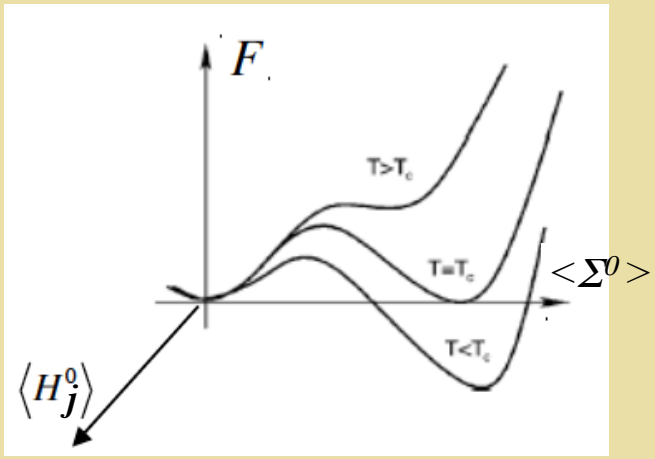

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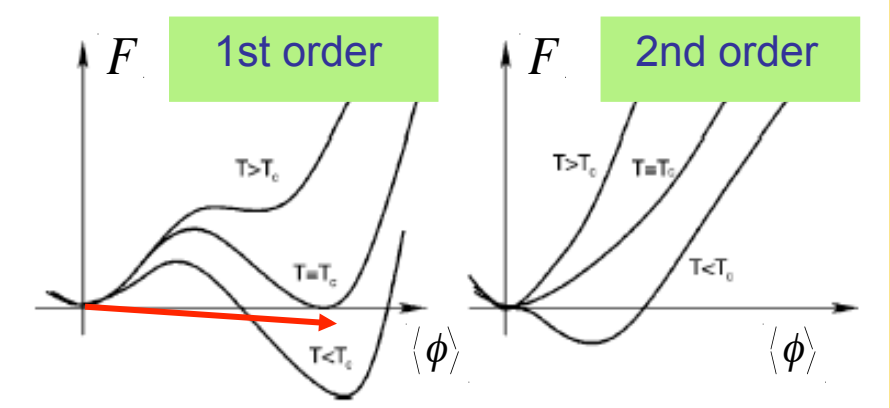

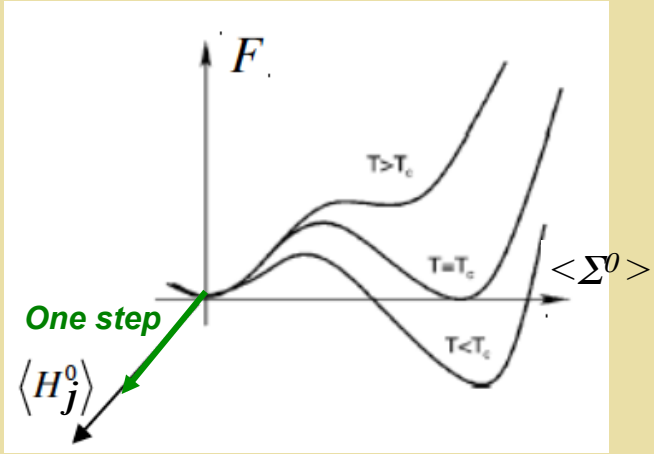

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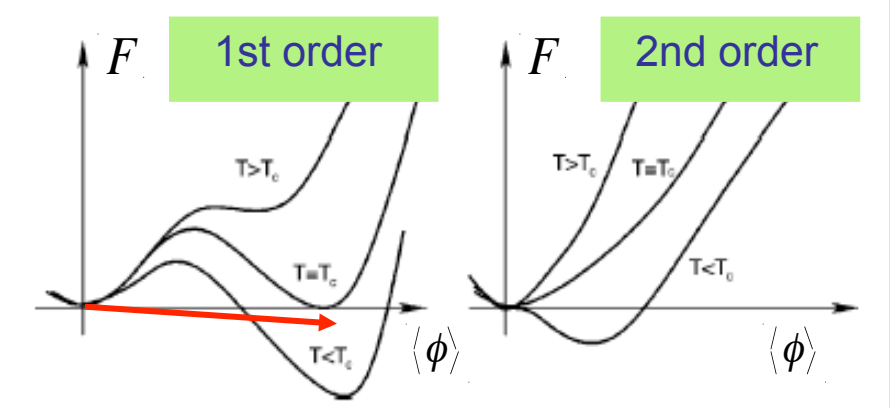

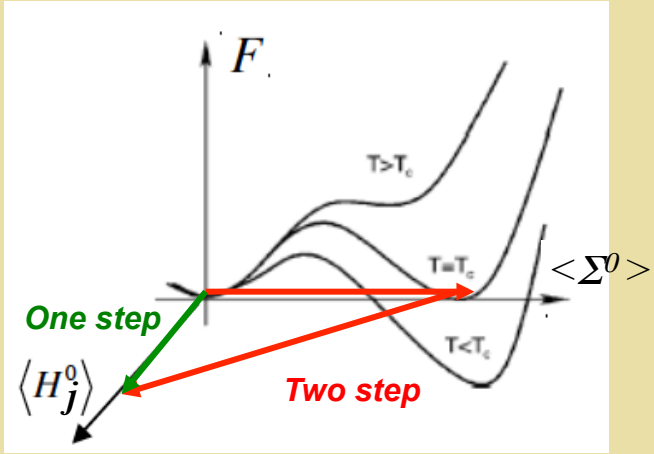

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- *One-step: Sym pase → Higgs phase*
- *Two-step: successive EW broken phases*

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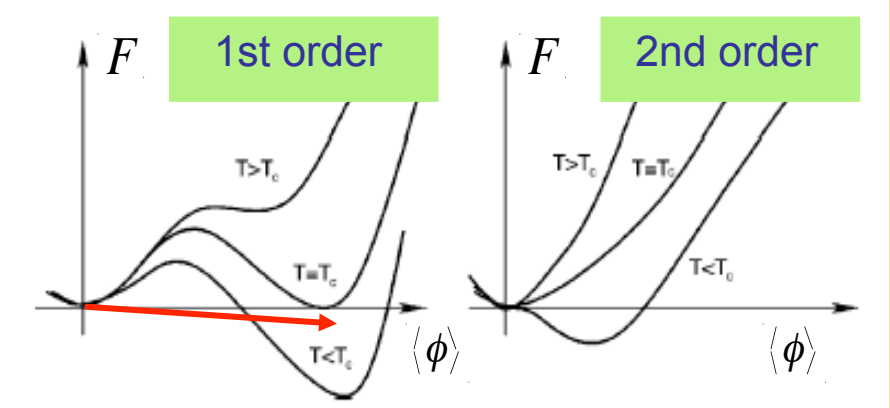

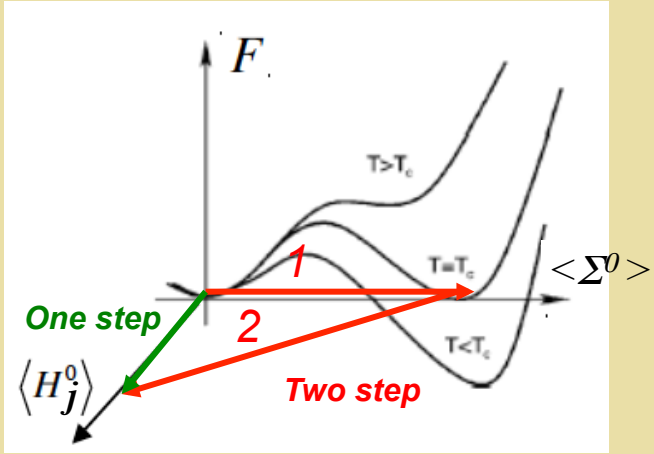

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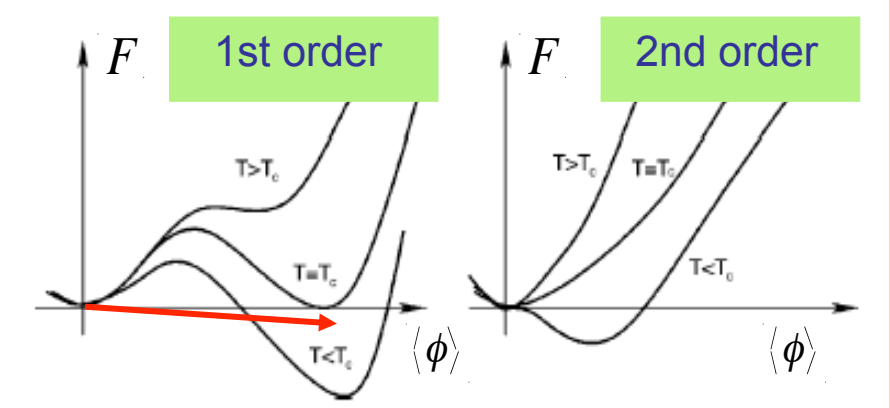

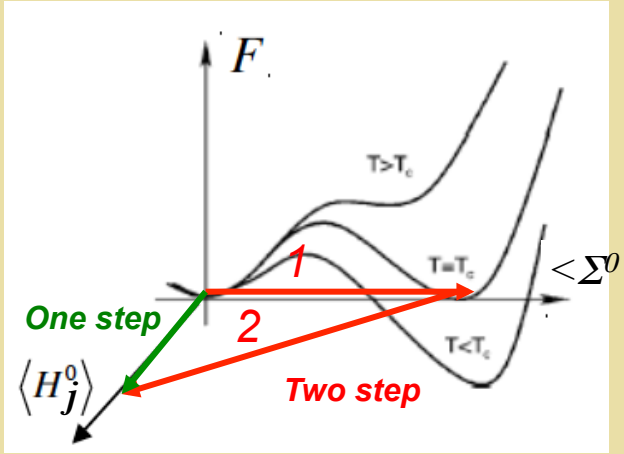

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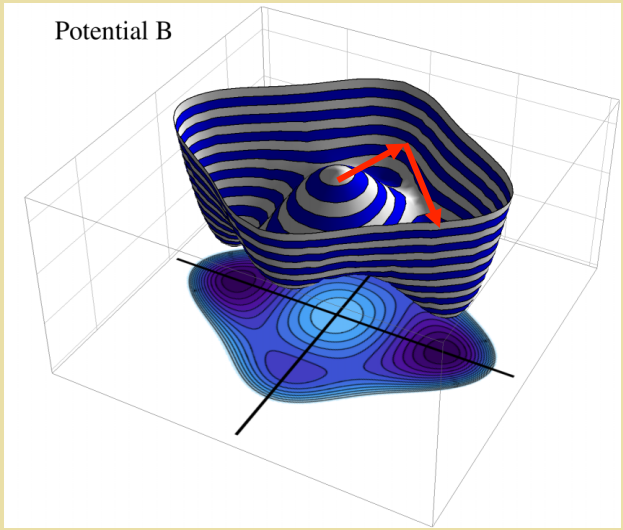

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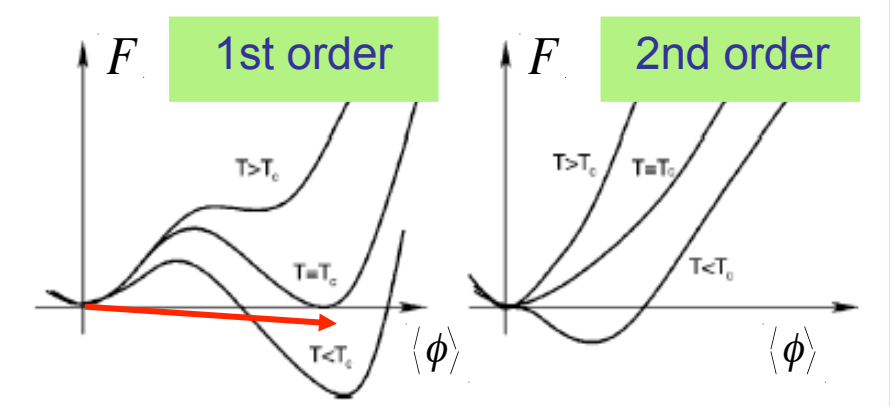

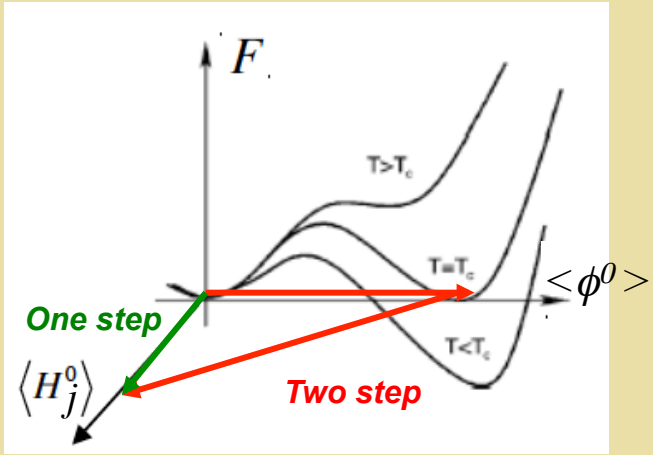

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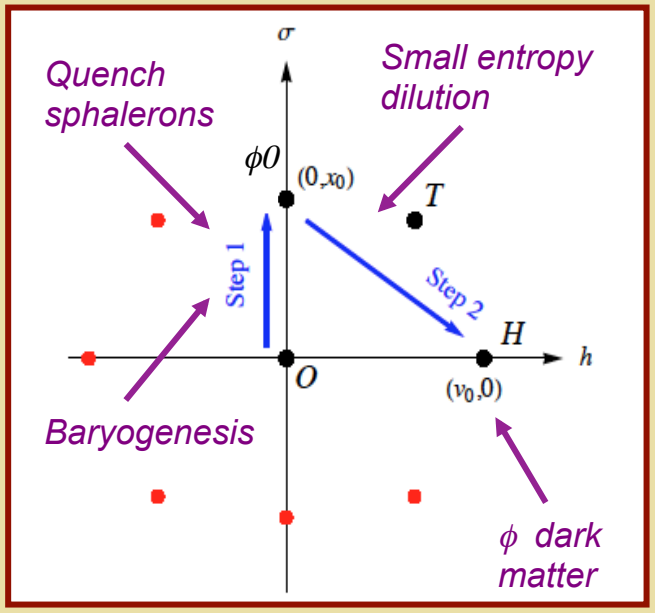

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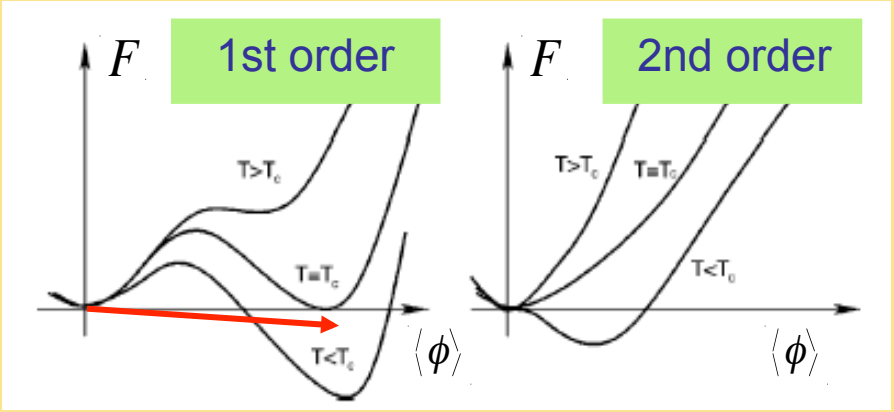

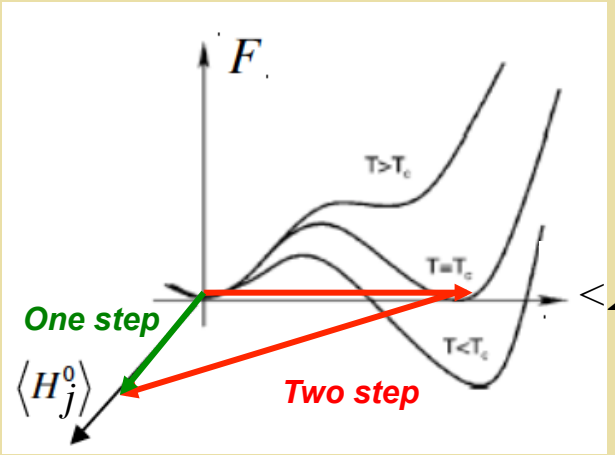

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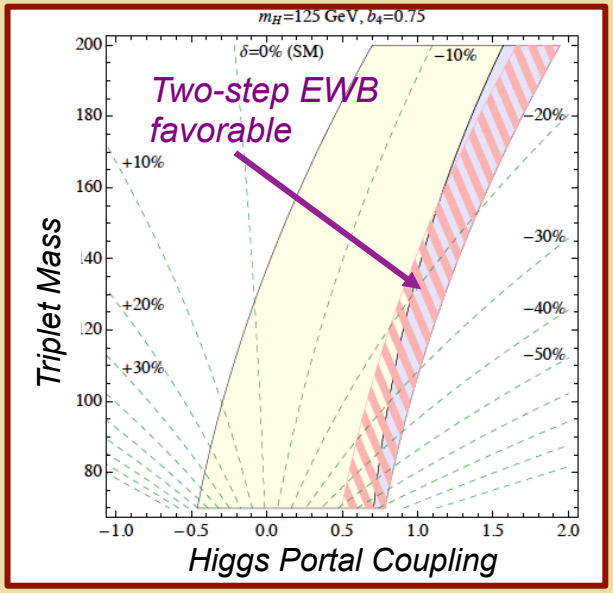
$$\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger\phi\ H^\dagger H$$



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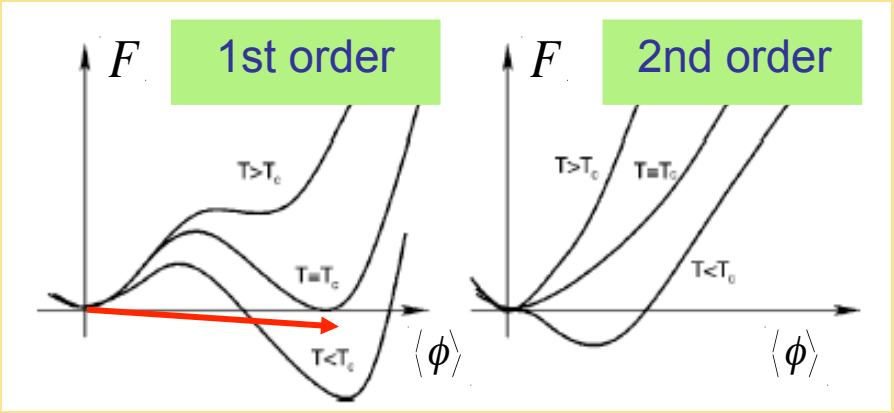

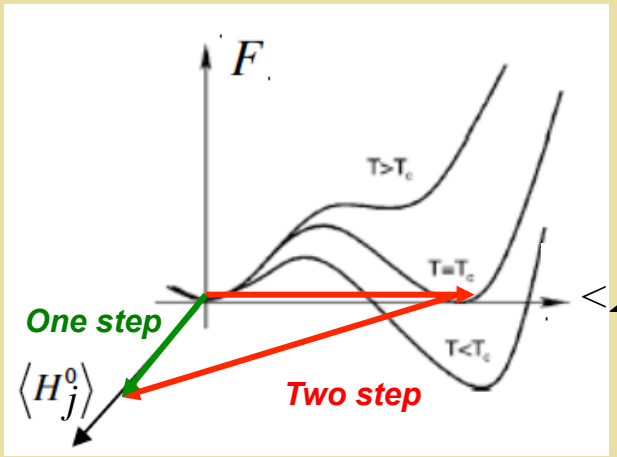

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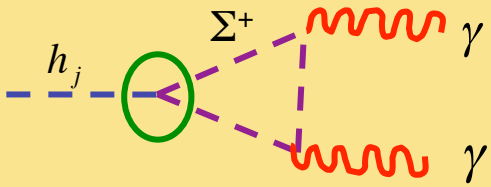

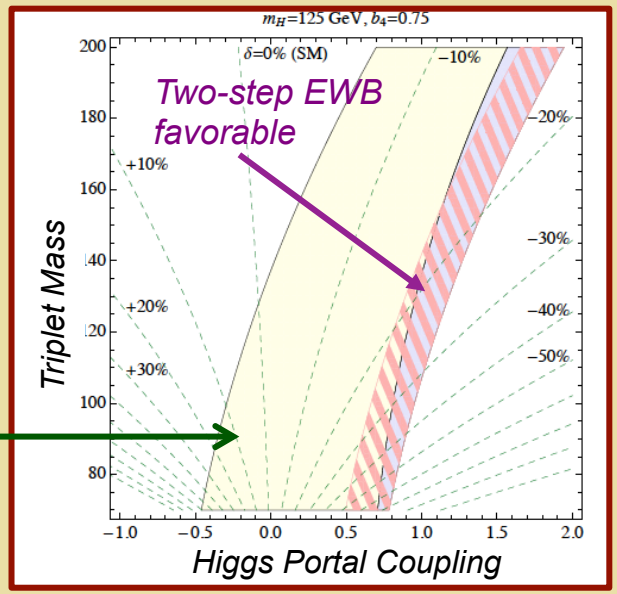

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EW Multiplets: Two-Step EWPT

Using BR(H→ZZ*) from FCC-ee (known at ~0.3% from δg_{HZZ}~0.15%), production ratios σ(H→XY)/σ(H→ZZ*) for p_T>100 GeV return the following stat precision on the **absolute value** of rare BRs

	γγ	Zγ	μμ
δ BR	~0.5%	~1%	~1%

M. Mangano

FCC-ee: < 2% on $\delta_{H\gamma\gamma}$

Increasing m_h →

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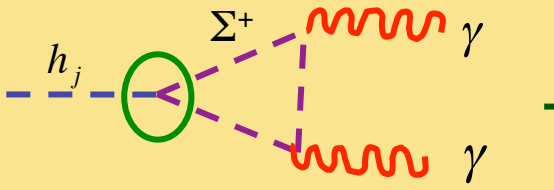

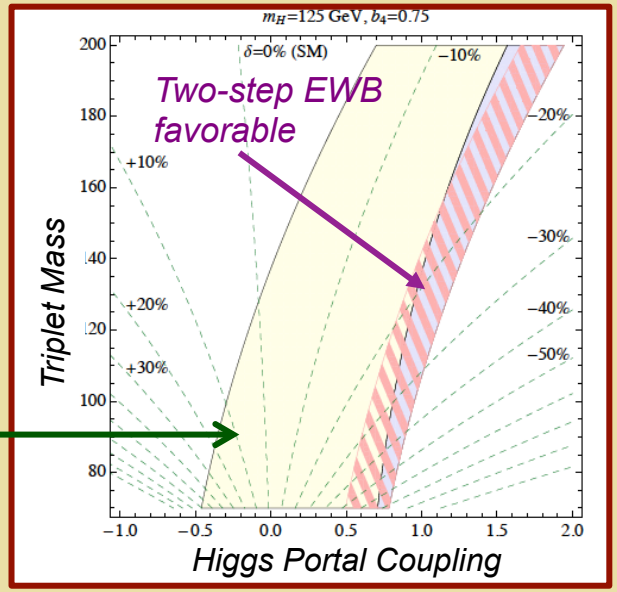

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II. EWPT: Theoretical Robustness

- *L. Niemi, H. Patel, MRM, T. Tenkanen, D. Weir 1802.10500*
- *New work in progress*

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*

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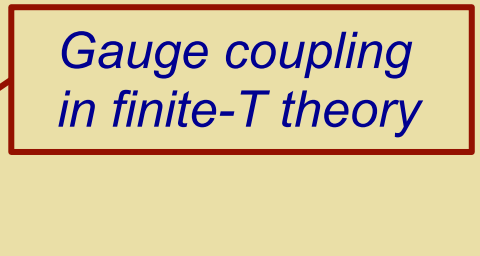
Benchmark pert theory

EWPT & Perturbation Theory

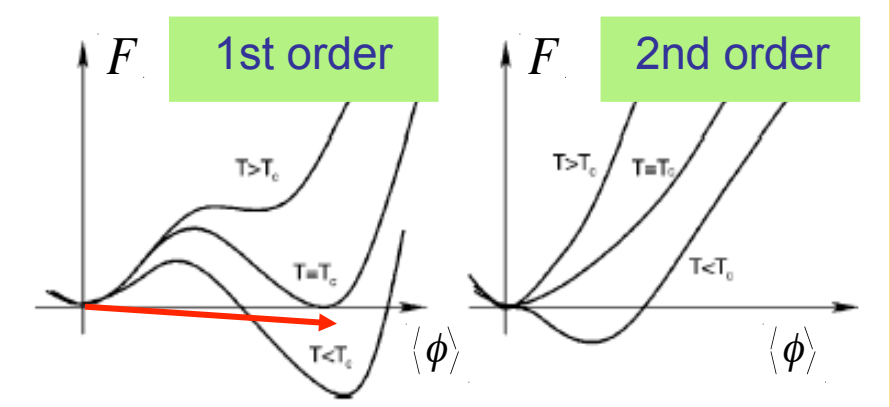
Expansion parameter

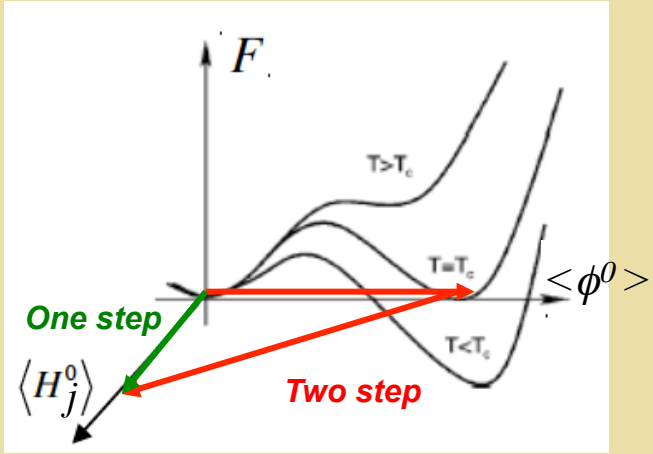


$$g_{\rm eff} \equiv \frac{g_3^2}{\pi m_T(\varphi)}$$

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

EW Multiplets: One-Step EWPT ?





Increasing m_h →

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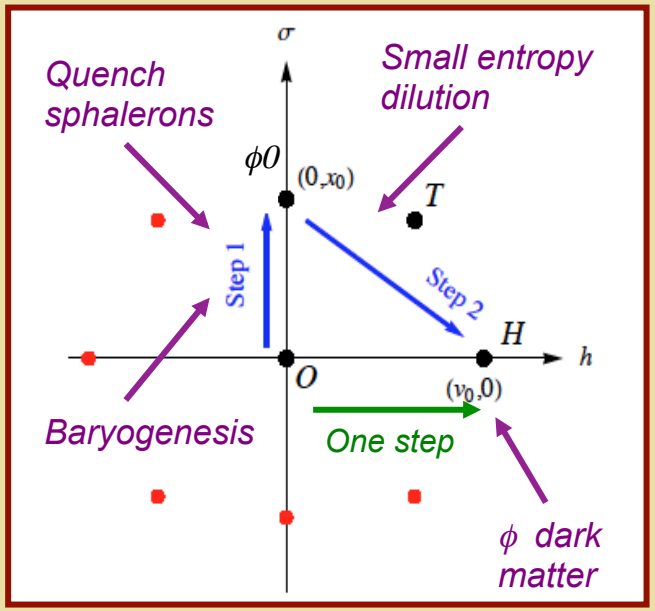
- *One-step: thermal loops*



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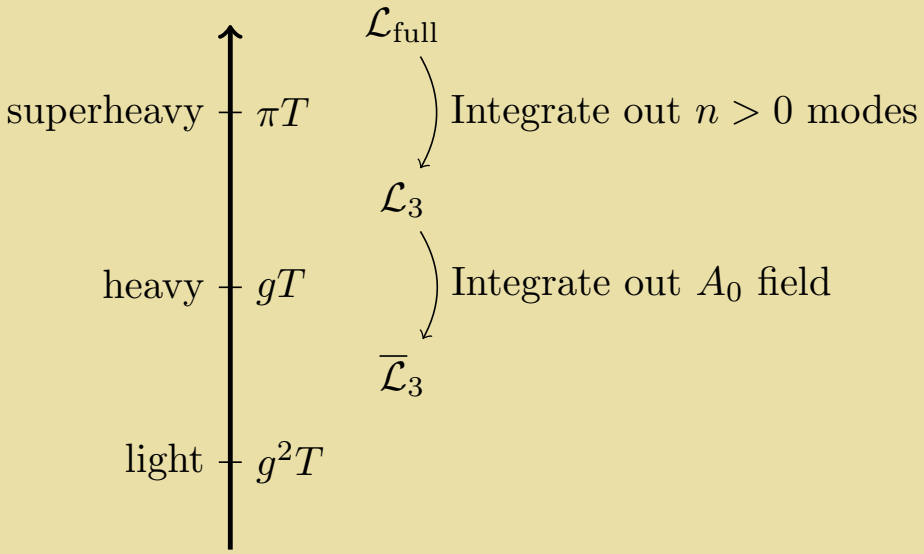
Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory



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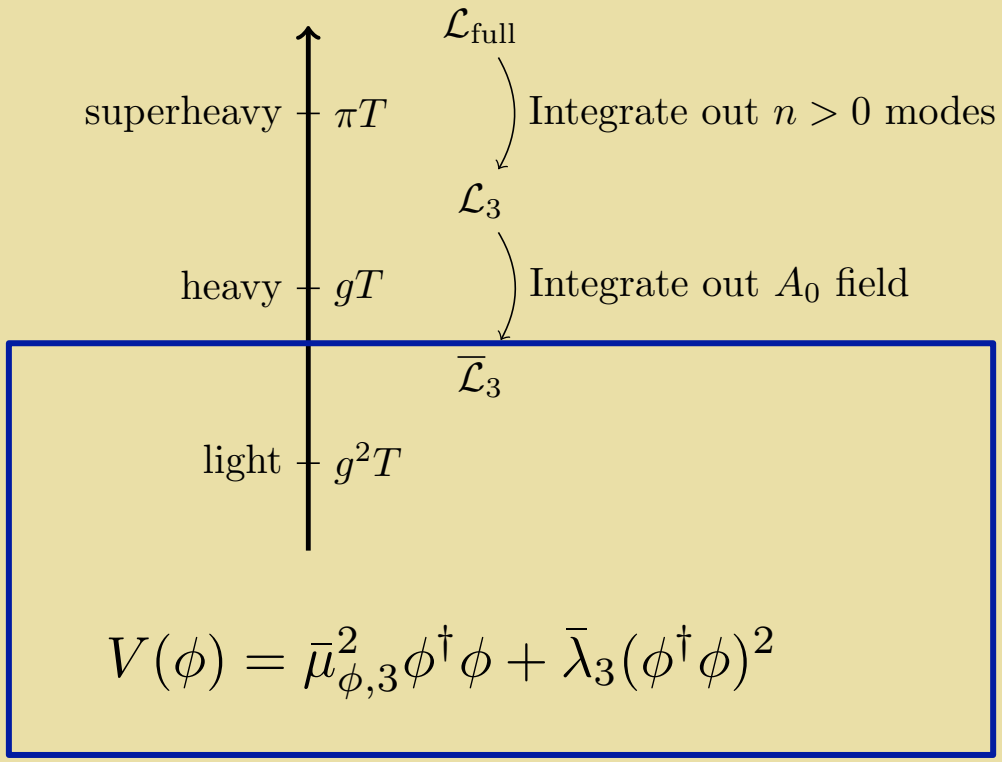

Lattice simulations exist

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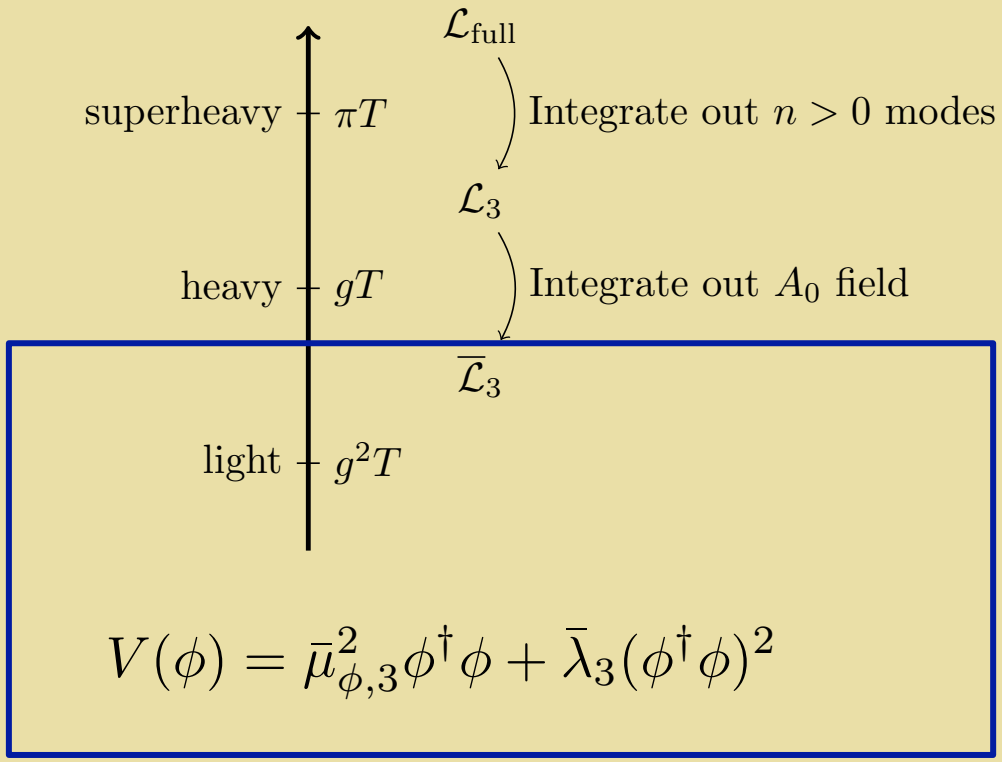

Lattice simulations exist (e.g., Kajantie et al '95)

- *Assume BSM fields are "heavy" or "supeheavy" : integrate out*
- *Effective "SM-like" theory parameters are functions of BSM parameters*
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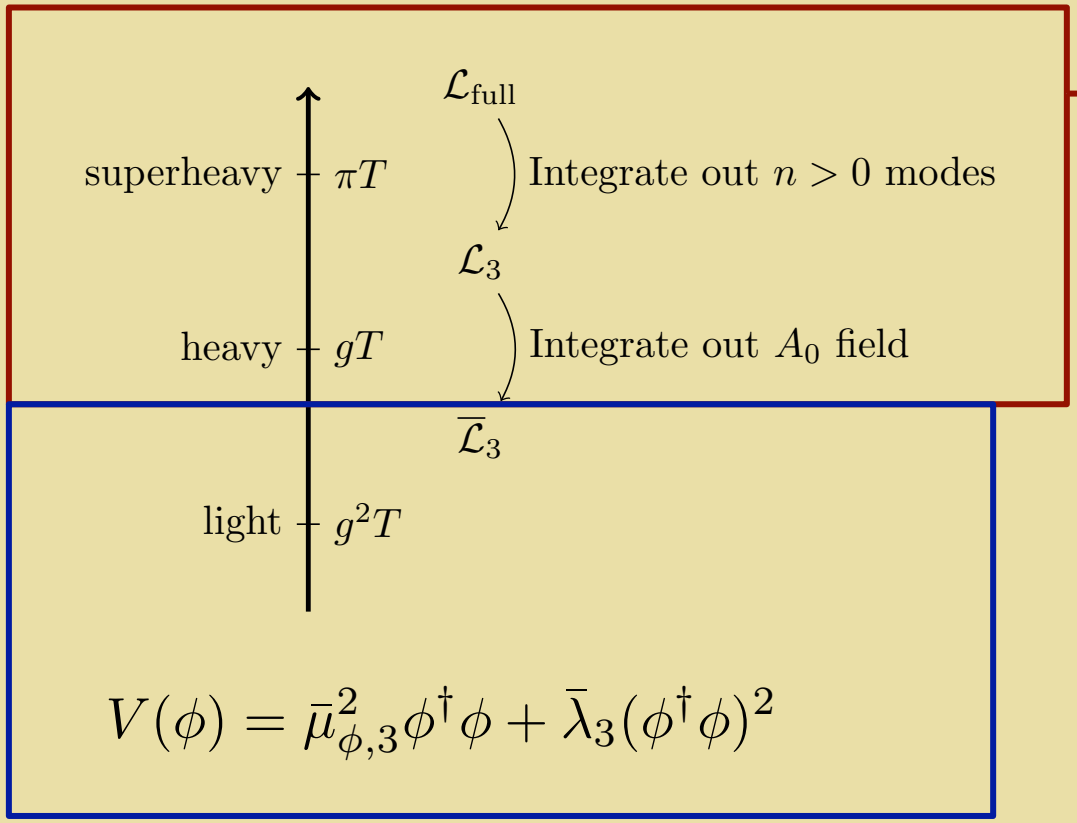

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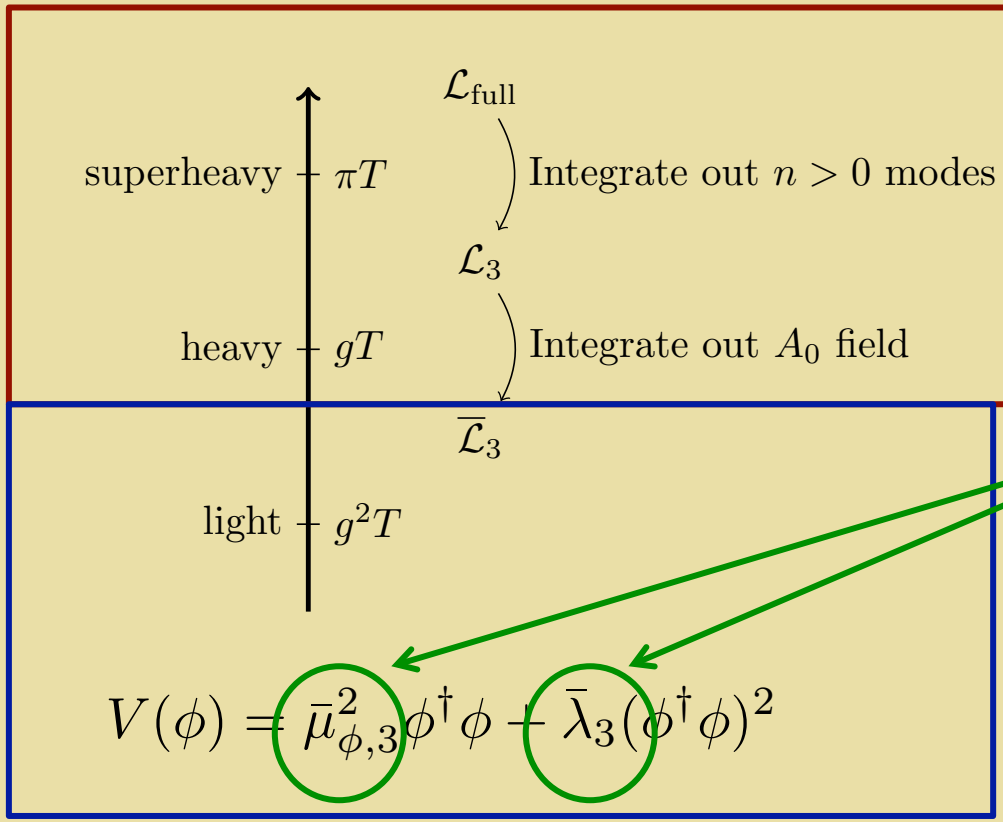

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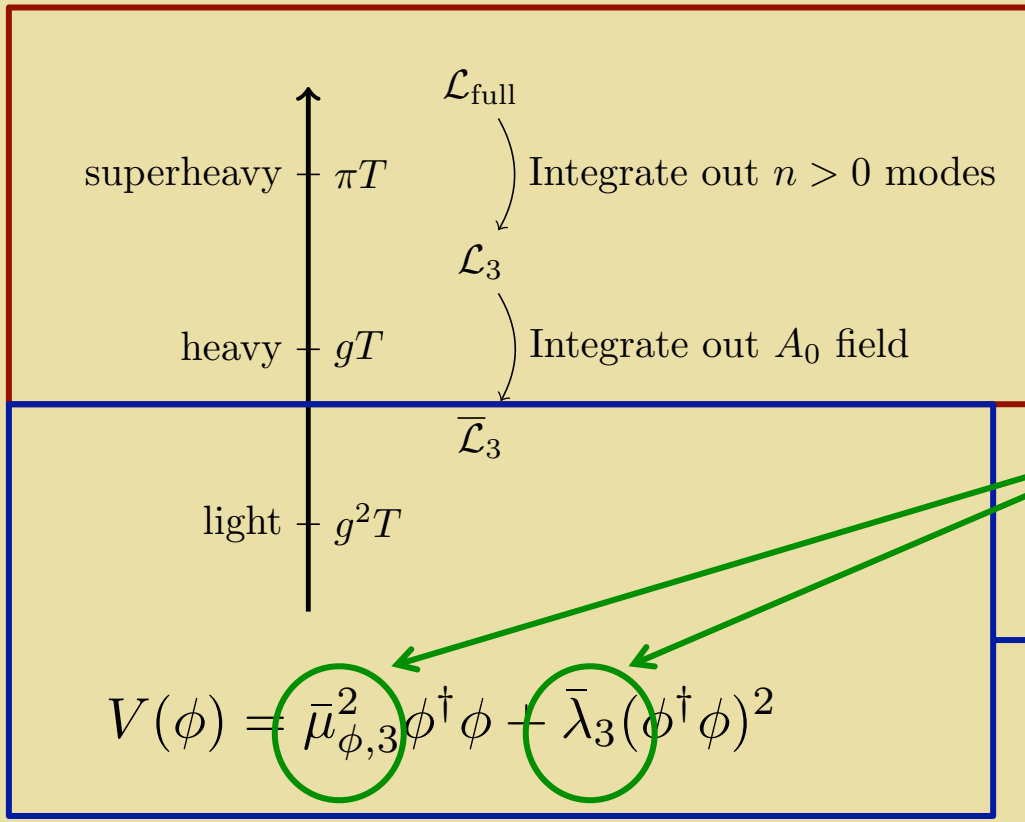

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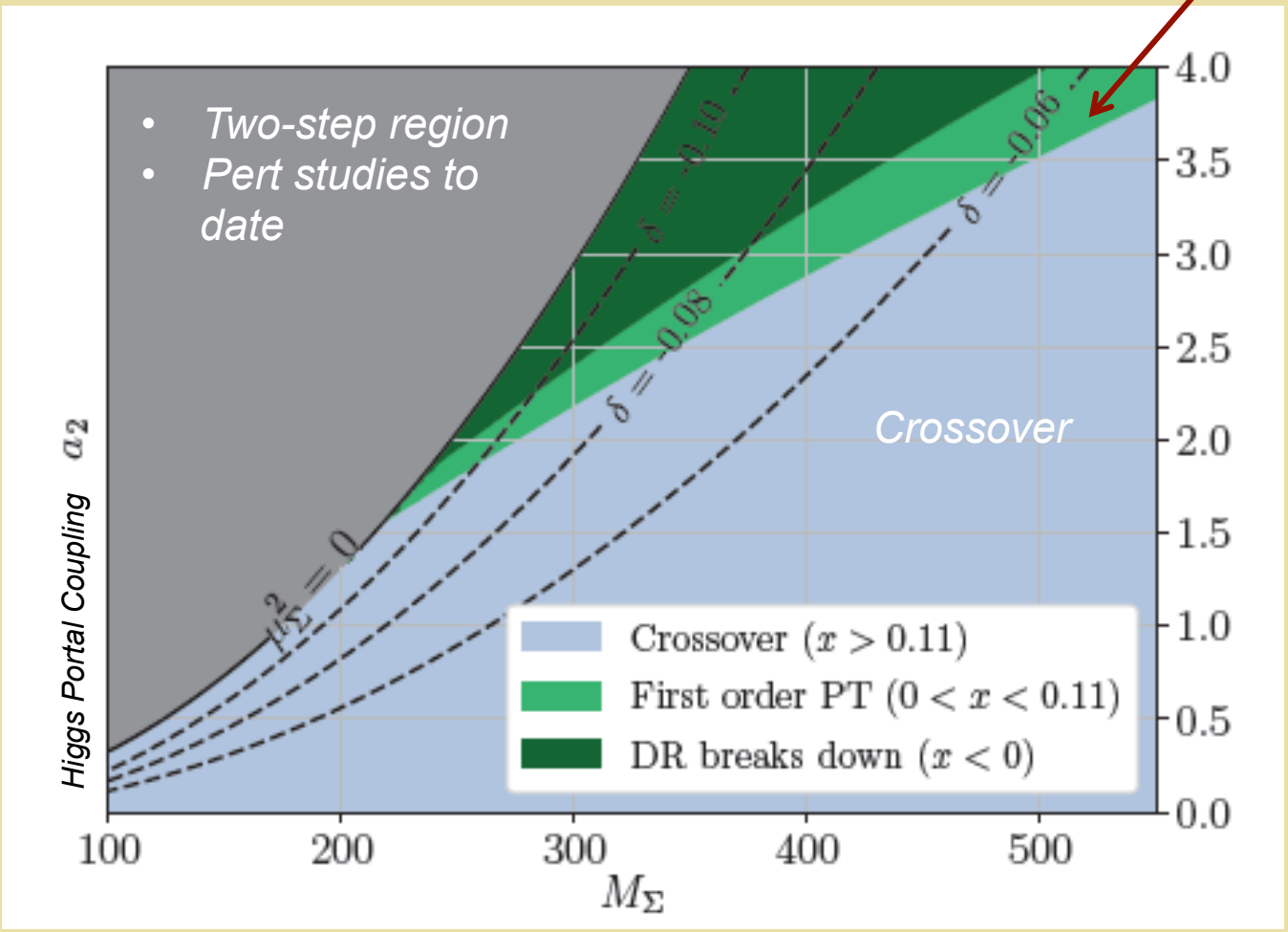
Real Triplet & EWPT

FOEWPT



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- *Non-perturbative*

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

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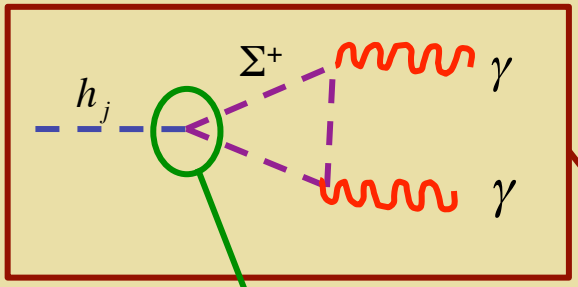

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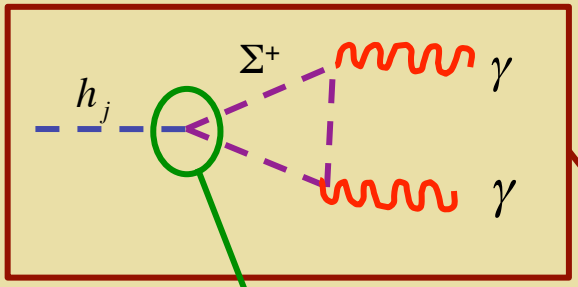

FOEWPT

Disappearing charge track

- One-step
- Non-perturbative

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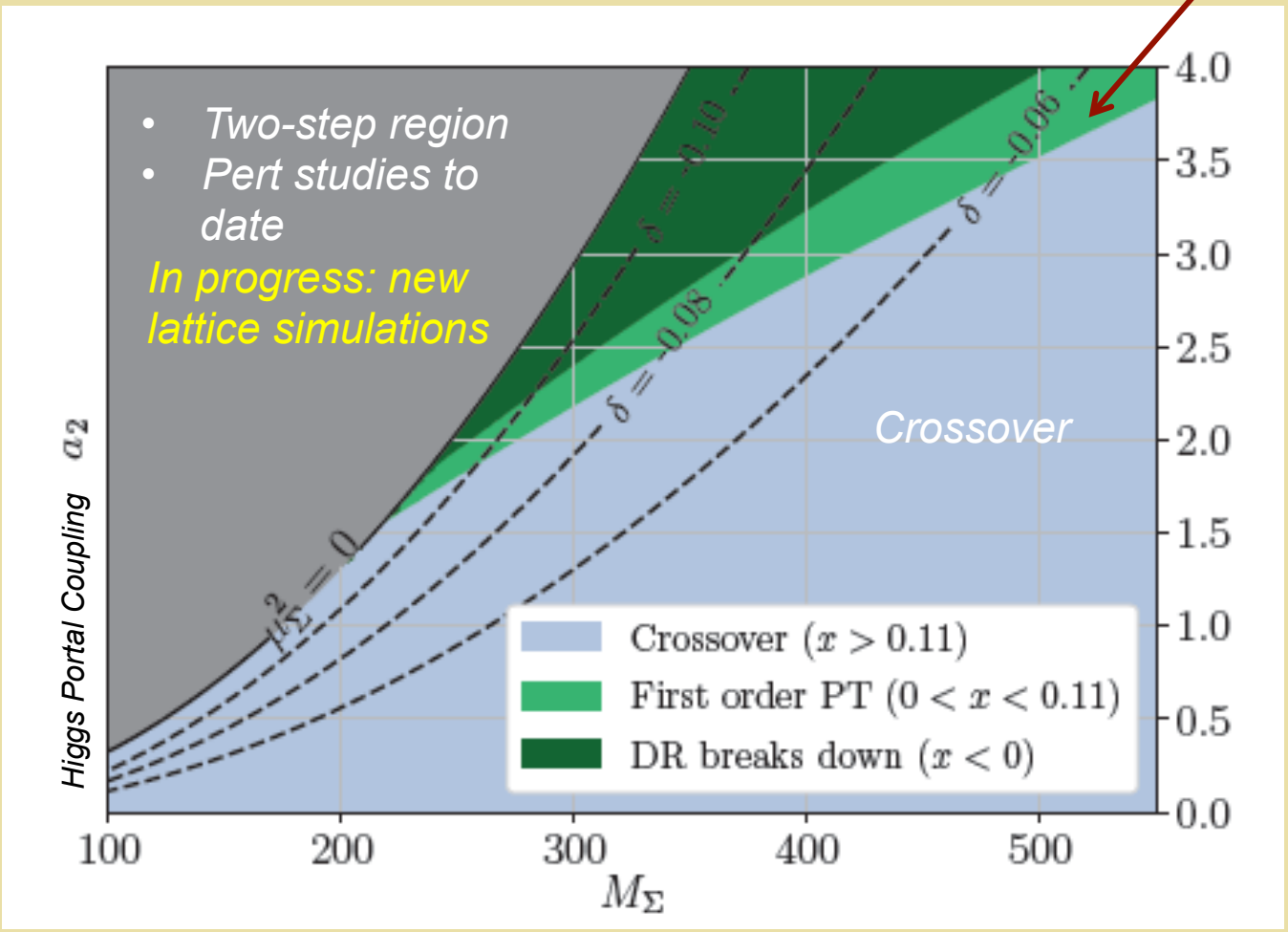
Real Triplet & EWPT

FOEWPT



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Real Triplet Example: Lessons

- *Initial non-perturbative studies using 3d EFT reveals regions of FOEWPT & crossover transition not evident in PT*
- *Next generation circular e+e- and pp colliders likely necessary to access these region: a first order transition $\rightarrow$ Observable shift in $h \rightarrow \gamma\gamma$ rate* ***
- *Next generation colliders will have needed sensitivity*

**** Higgs self coupling not so important in this case***

III. General EW Multiplets & DM

- *W. Chao, G.-J. Ding, X.-G. He, MJRM 1812.07829*

EWPT & Dark Sector: EW Multiplets

- ***To what extent can EW multiplets catalyze a strong 1st order EWPT and contribute to Ω_{DM} ?***
- ***What is interplay between DM mass, Higgs portal coupling, dimension of the representation, Ω_{DM} , and bounds on σ_{SI} ?***

EWPT & Dark Sector: EW Multiplets

Cirelli & Strumia '05

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\,dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

EWPT & Dark Sector: EW Multiplets

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EWPT & Dark Sector: EW Multiplets

Septuplet case (n=5 similar)

$$
\begin{aligned}
V = & +M_A^2(\Phi^\dagger\Phi) + \left\{M_B^2(\Phi\Phi)_0 + \text{h.c.}\right\} - \mu^2 H^\dagger H \\
& +\lambda(H^\dagger H)^2 + \lambda_1(H^\dagger H)(\Phi^\dagger\Phi) \\
& +\lambda_2[(\overline{H}H)_1(\overline{\Phi}\Phi)_1]_0 + [\lambda_3(\overline{H}H)_0(\Phi\Phi)_0 + \text{h.c.}]
\end{aligned}
$$

EWPT & Dark Sector: EW Multiplets

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Three portal couplings in general

EWPT & Dark Sector: EW Multiplets

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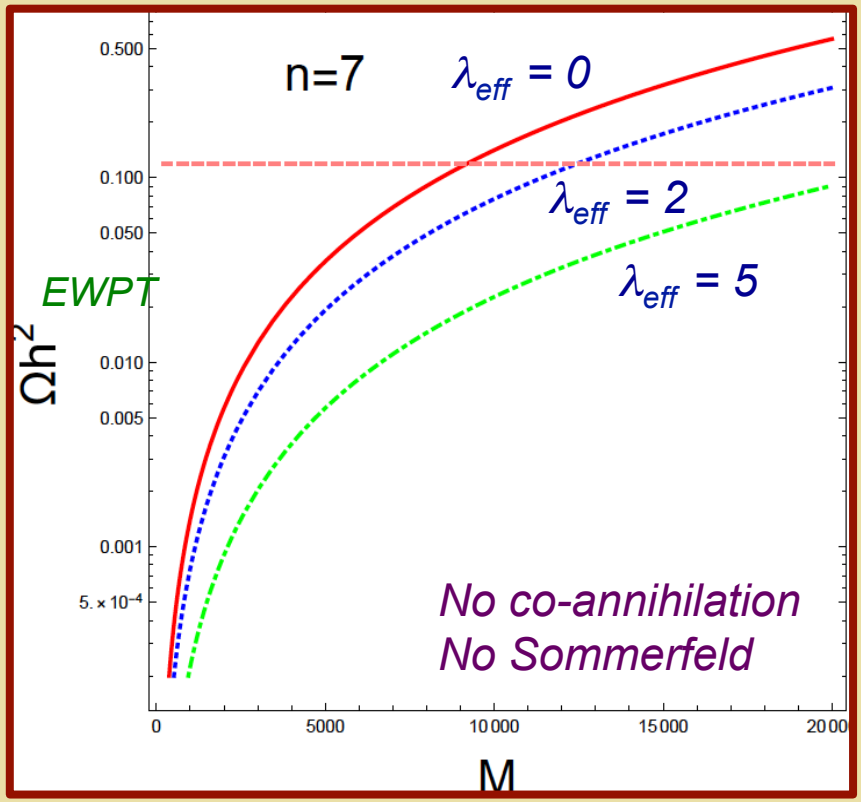
\end{aligned}
$$

Three portal couplings in general

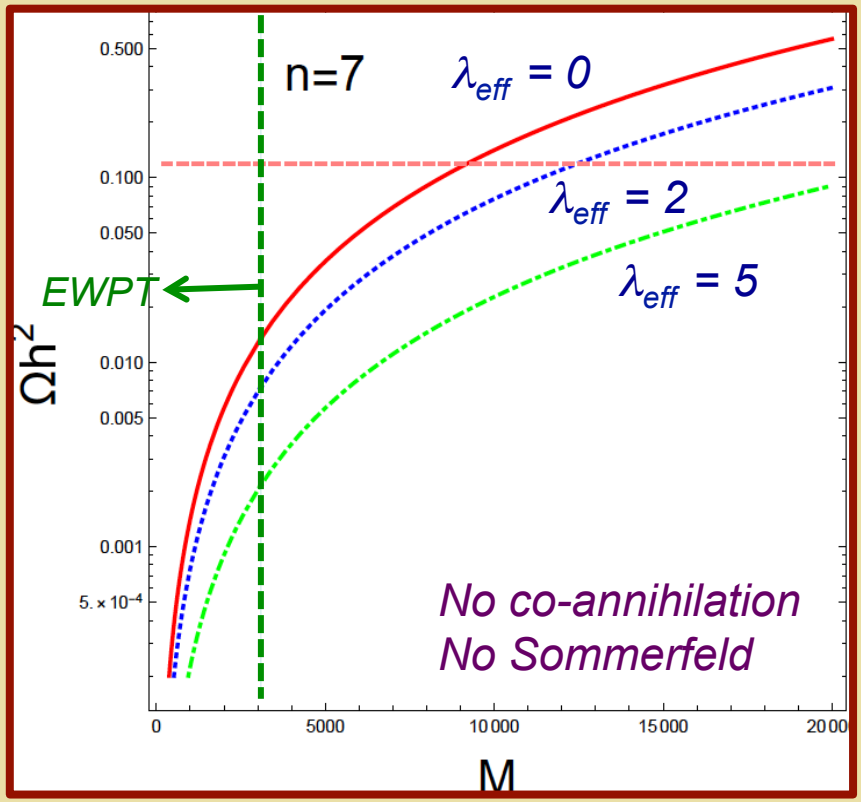
- *Set $\lambda_2 = 0$ for DM stability*
- *All dynamics affected by λ_{eff}*

$$
\lambda_{\text{eff}} = \begin{cases} \lambda_1 \pm \sqrt{\frac{2}{7}}\lambda_3 \ , & \text{septuplet} \\ \lambda_1 \mp \sqrt{\frac{2}{5}}\lambda_3 \ , & \text{quintuplet} \end{cases}
$$

EWPT & Dark Sector: EW Multiplets

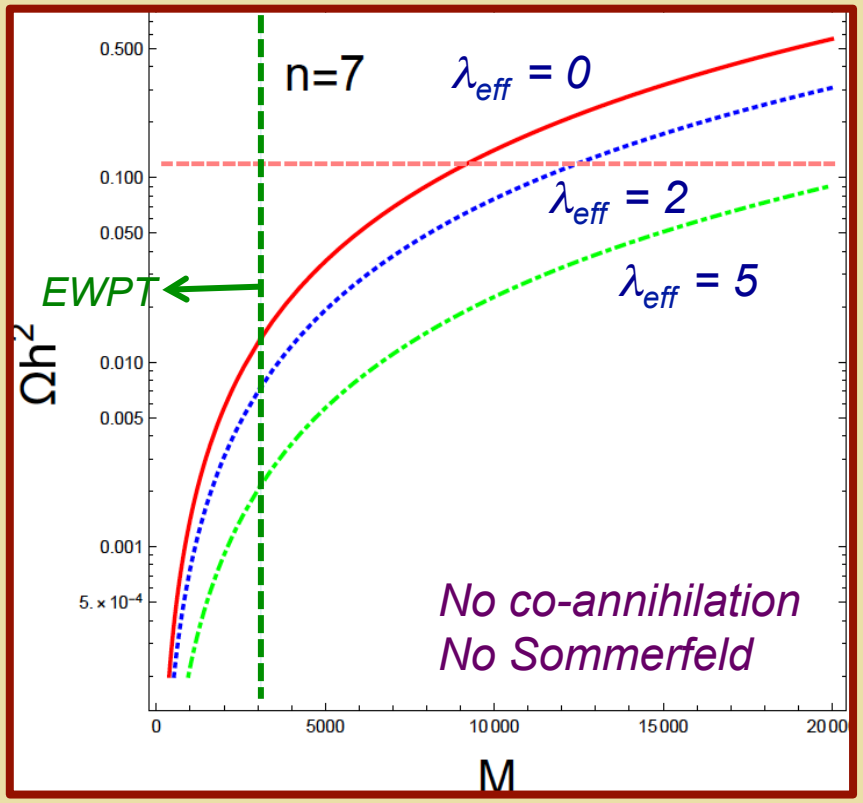


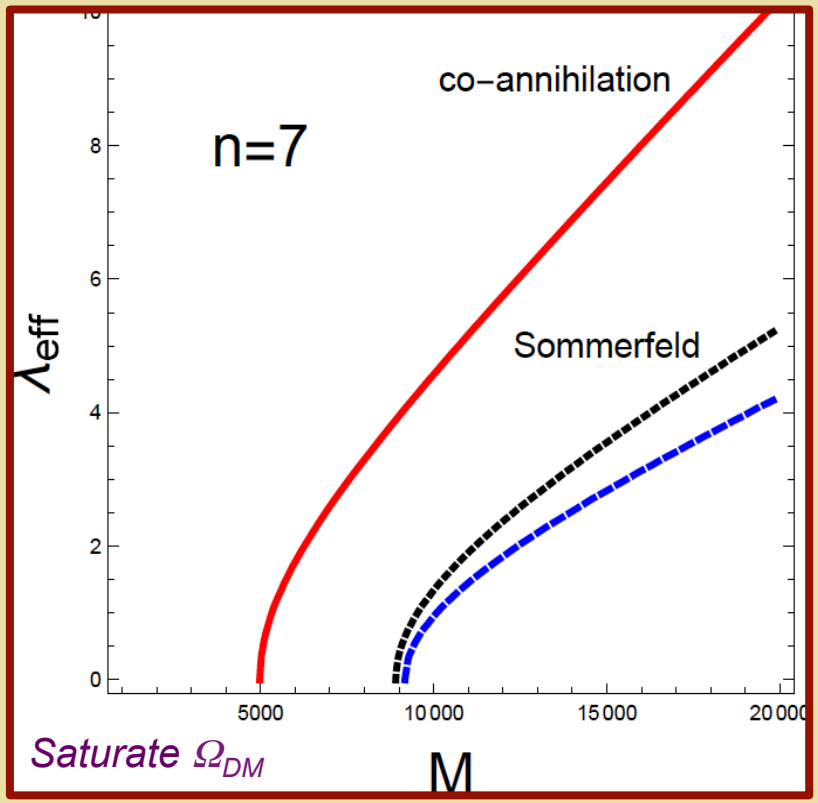
EWPT & Dark Sector: EW Multiplets



EWPT viable region → χ [n=5] a subdominant component of Ω_{DM}

EWPT & Dark Sector: EW Multiplets

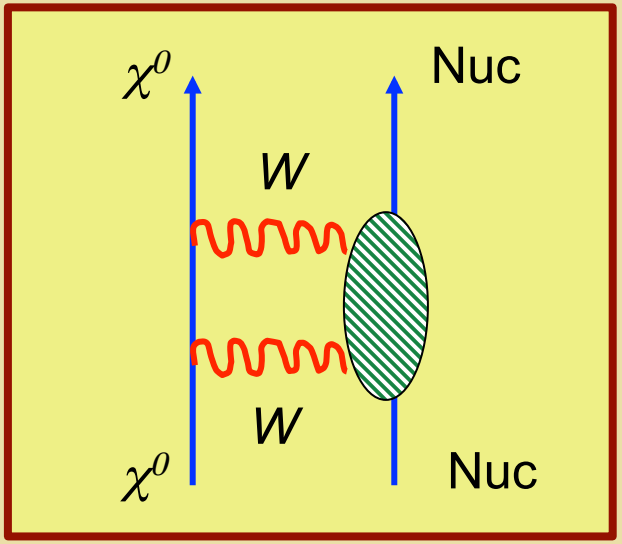




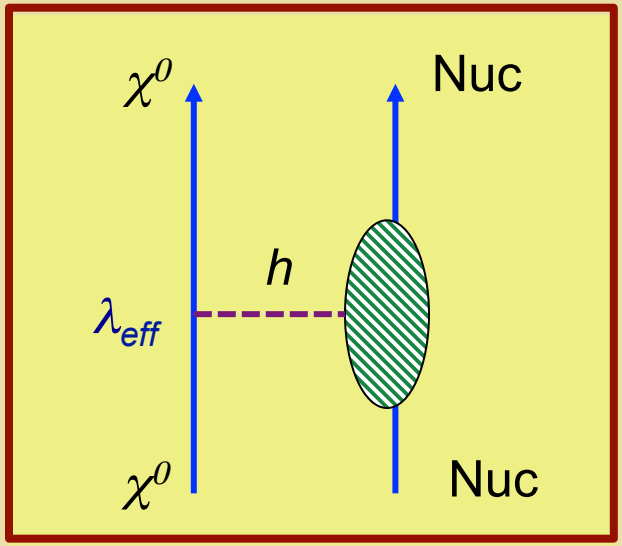
EWPT viable region → χ [n=5] a subdominant component of Ω_{DM}

EW Multiplet DM: Direct Detection

Gauge interactions

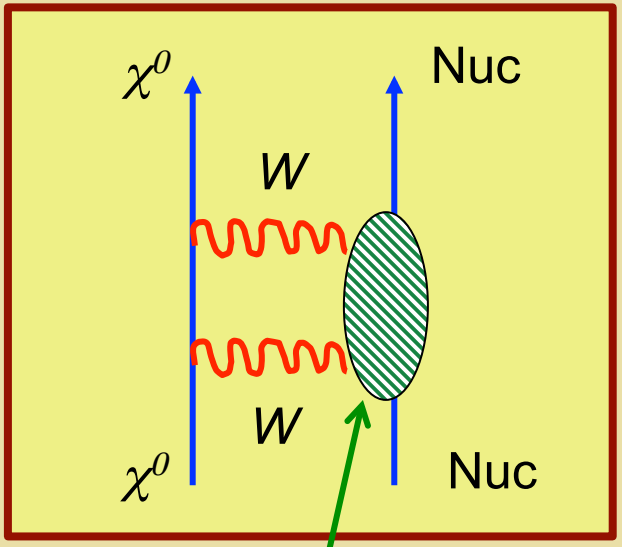


Higgs portal interactions

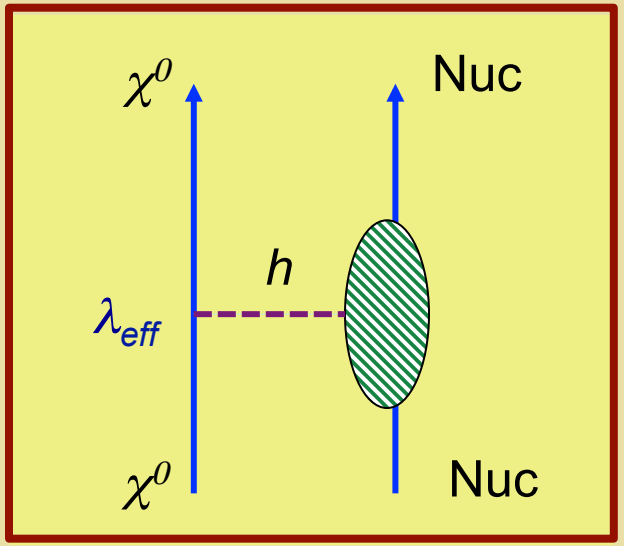


EW Multiplet DM: Direct Detection

Gauge interactions

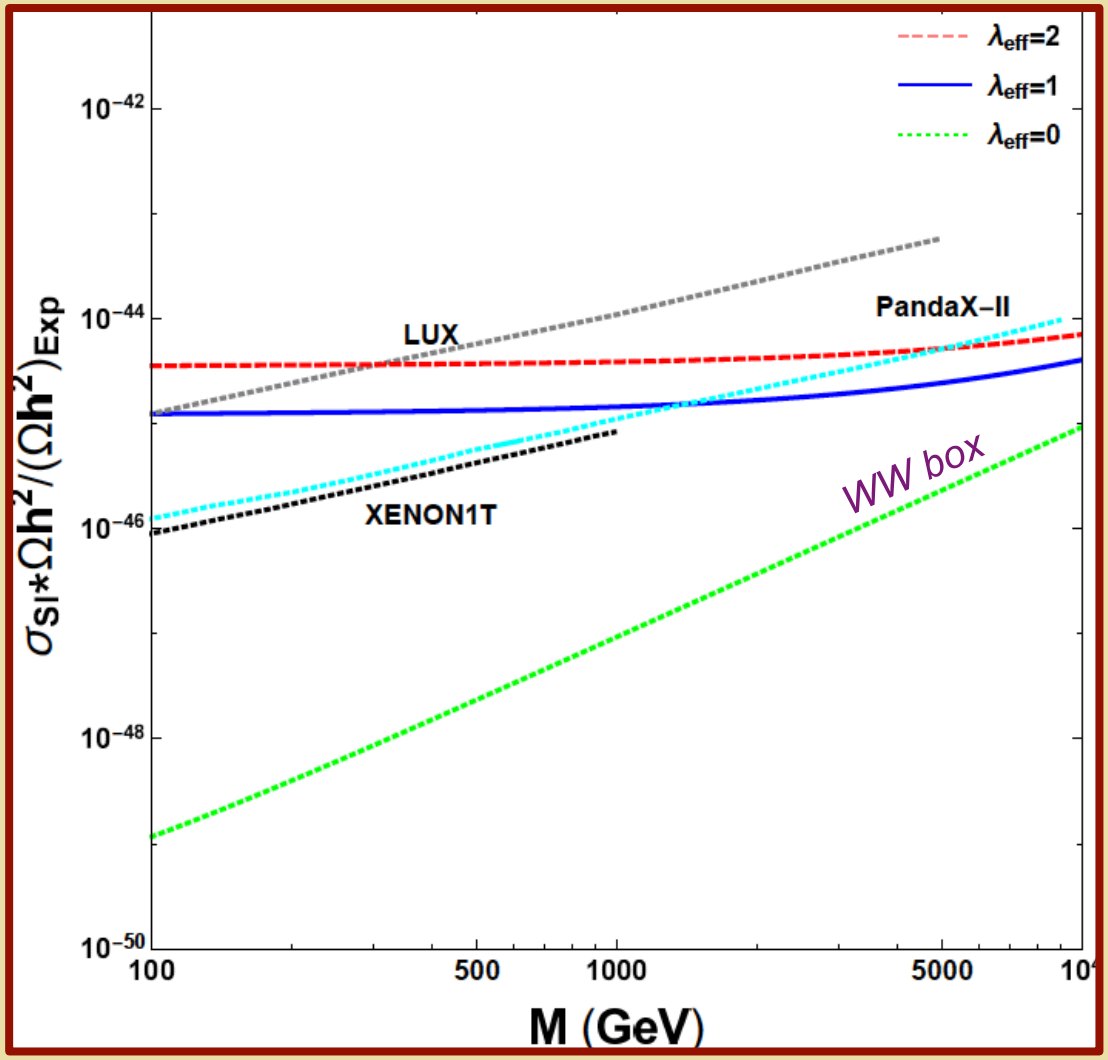


Higgs portal interactions

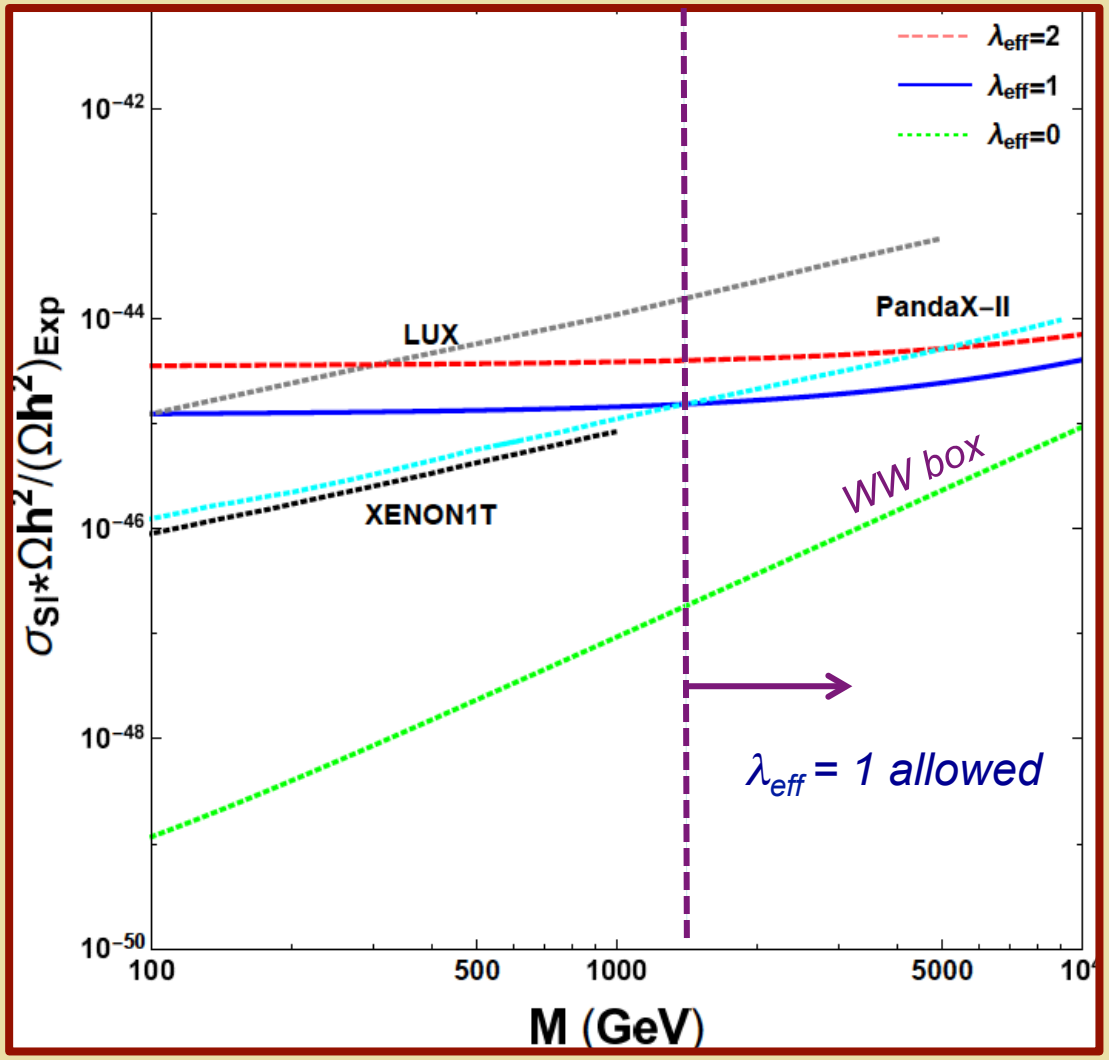


Dominant: twist-two

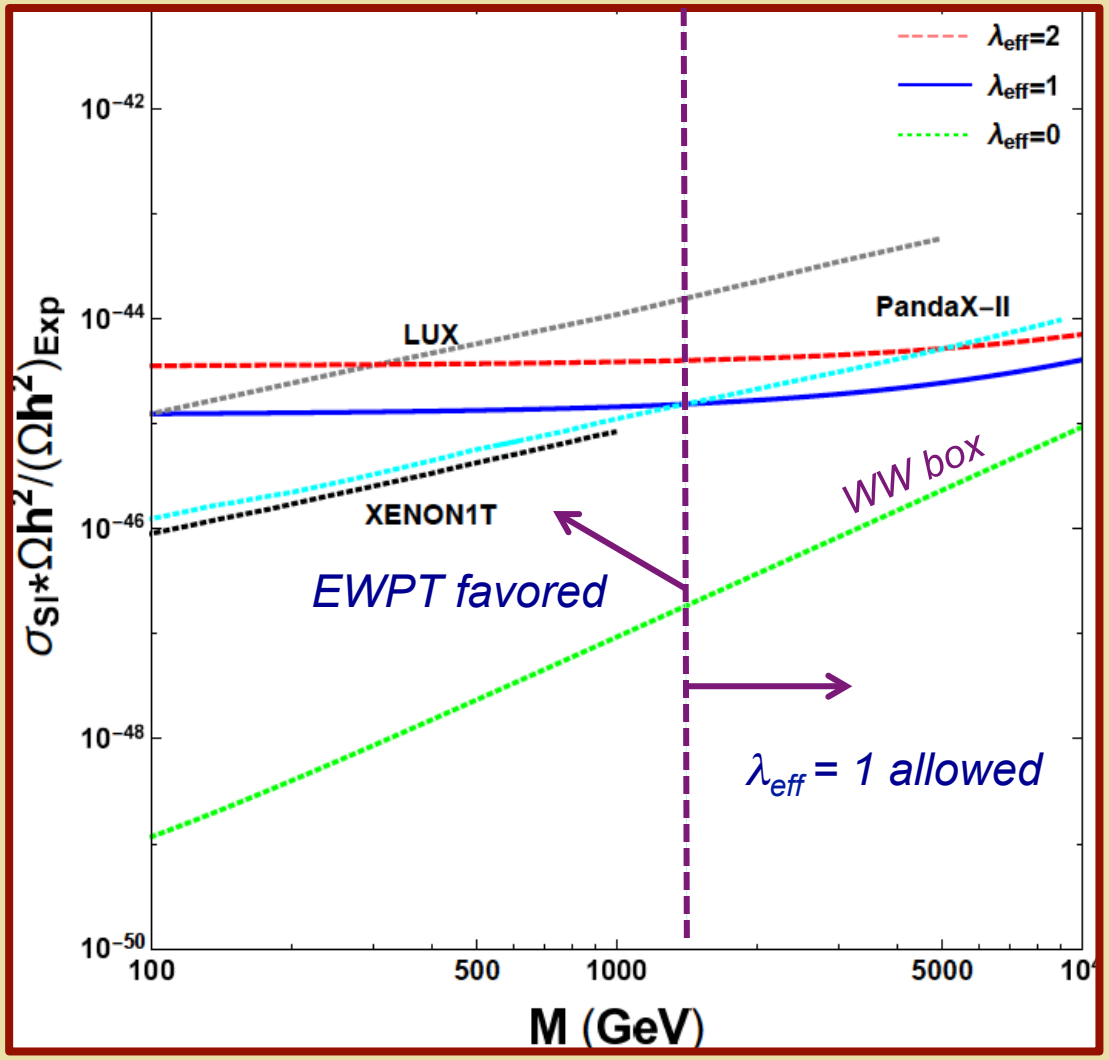
EW Multiplet DM: Direct Detection



EW Multiplet DM: Direct Detection



EW Multiplet DM: Direct Detection



IV. Outlook

- *Extended scalar sectors w/ electroweak multiplets admit a rich array of patterns of EWSB at finite temperature and new paths to a SFOEWPT as needed for successful EWBG*
- *Direct searches for new states + precision tests of Higgs properties at the LHC and beyond may yield definitive tests of this general scenario*
- *A robust analysis of the EWPT dynamics requires non-perturbative computations that can reveal properties not accessible with perturbation theory and that are needed for phenomenological guidance*
- *The existence of a SFOEWT in this class of scenarios → EW mutliplets would be a subdominant component of the DM relic density*

Back Up Slides

EWPT & Perturbation Theory (PT)

Takeaways

- *Perturbative studies of EWPT properties may yield qualitatively realistic results but are not unlikely to be quantitatively reliable*

- *Non-perturbative studies also face limitations: challenging to study broad range of models & parameters, and (so far) limited information on whether or not FOEWPT is sufficiently strong for EWBG* **

- *Future theoretical work: interfacing PT w/ non-pert studies ("benchmarking") & improving PT*

** *However, see G. Moore '99 for non-pert SM sphaleron rate calc*

Real Singlet Higgs Portal

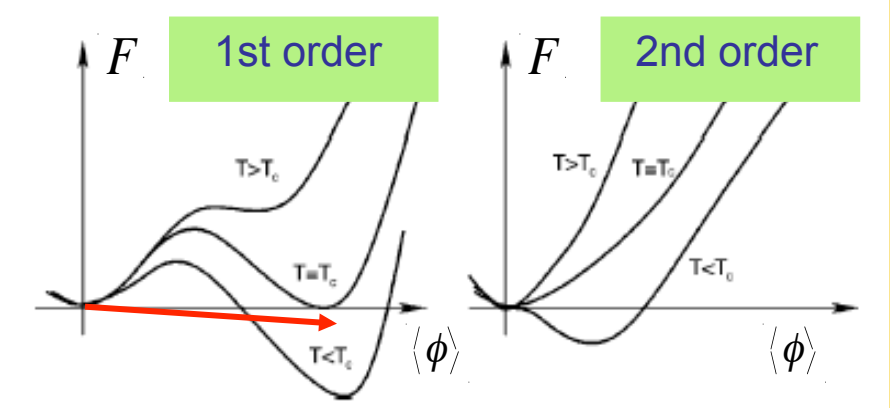
Standard Model + real singlet scalar

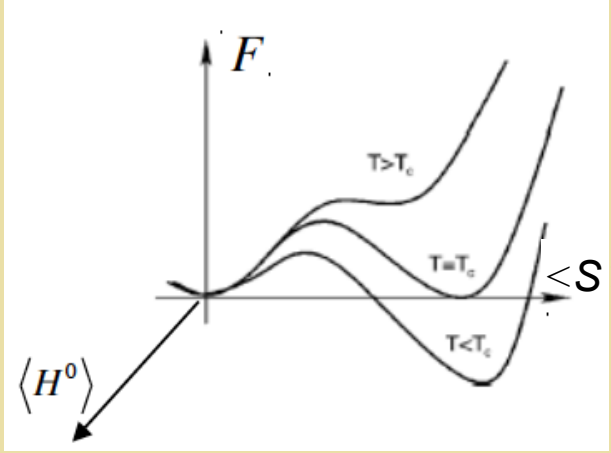
$$V_{\rm HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

- *Strong first order EWPT*
- *Two mixed singlet-doublet states*

$h_1 = h\cos\theta + S\sin\theta$, $h_2 = S\cos\theta - h\sin\theta$

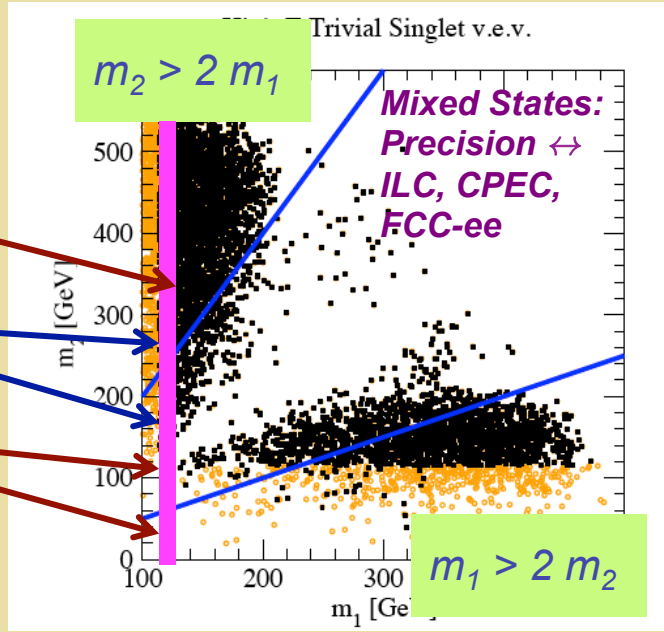
EW Phase Transition: Singlet Scalars





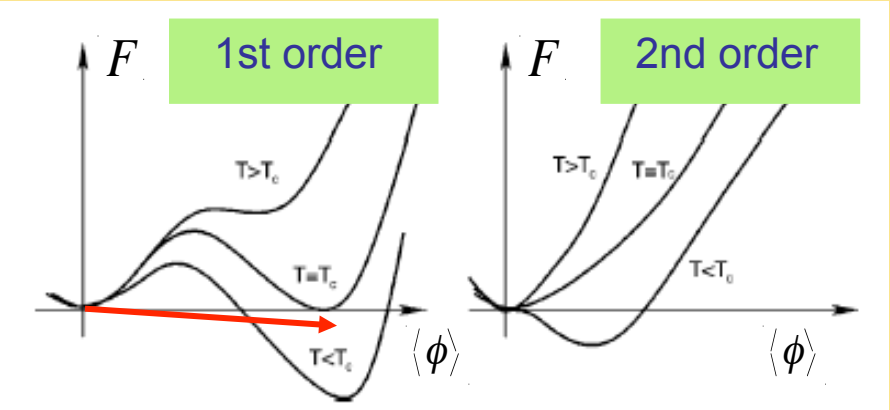
Collider probes

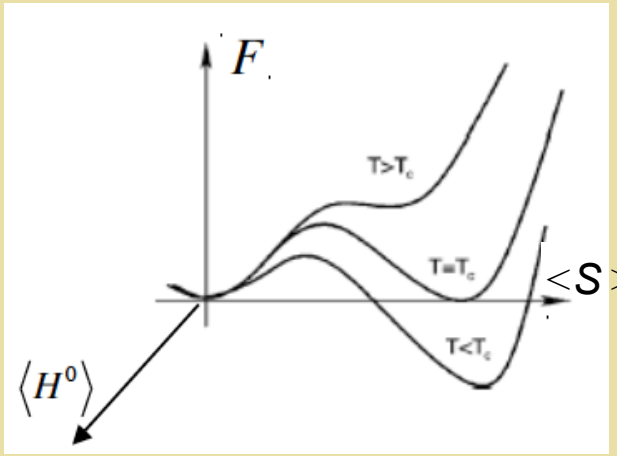
- *Resonant di-Higgs production*
- *Precision Higgs measurements*
- *Non-resonant di-Higgs & exotic Higgs decays*



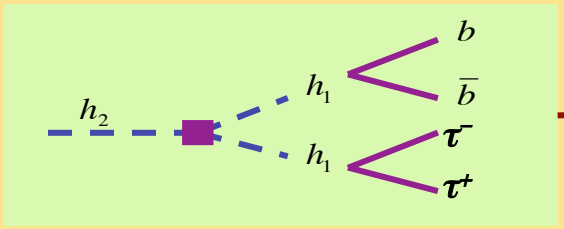
Profumo, MJRM, Shaugnessy '07

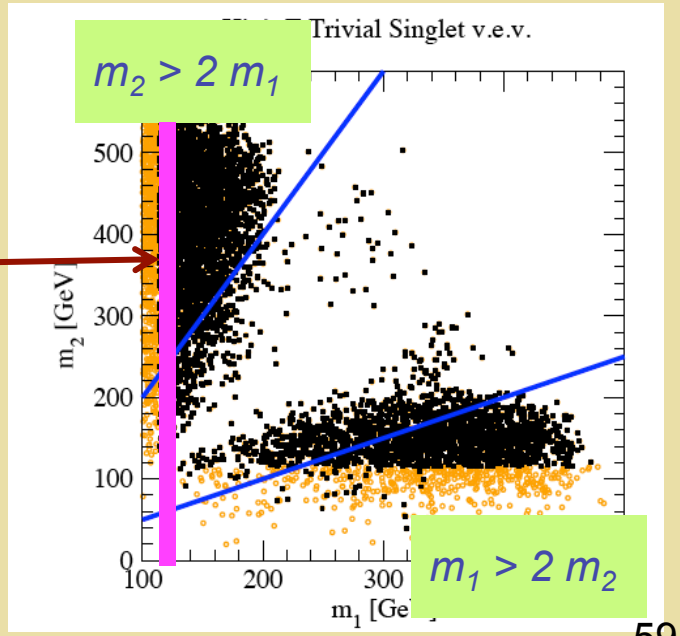
EW Phase Transition: Singlet Scalars





Resonant Di-Higgs Production

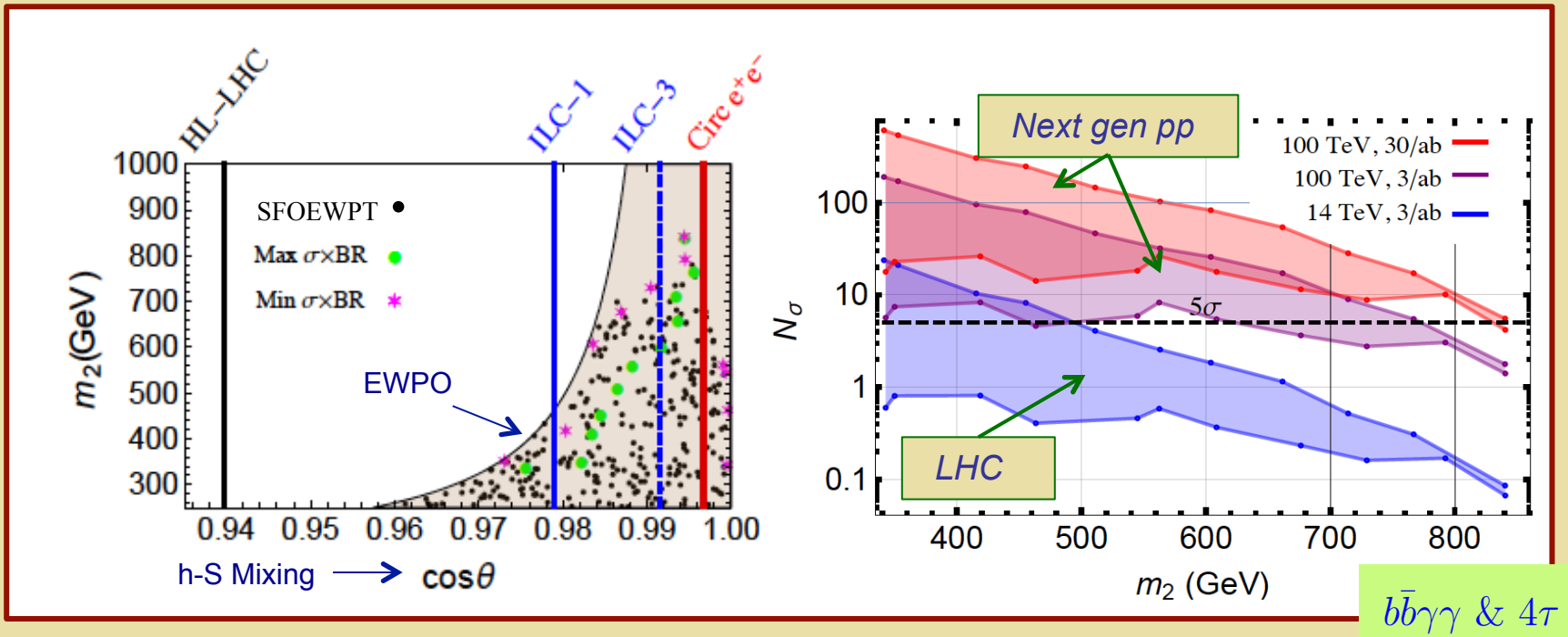




Profumo, MJRM, Shaugnessy '07

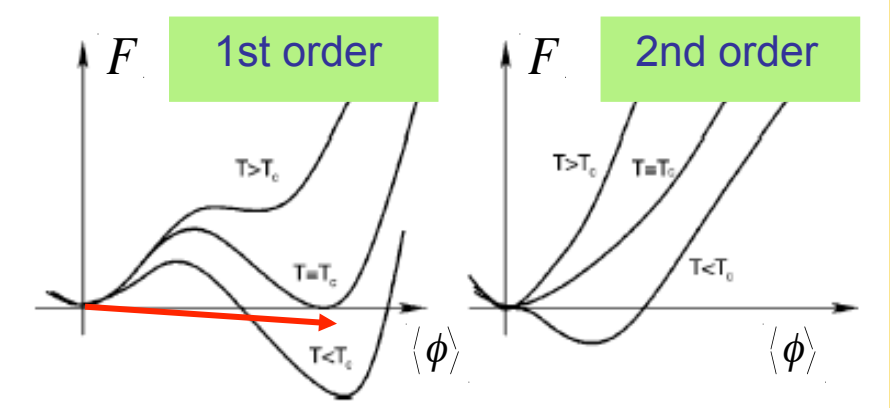
EW Phase Transition: Singlet Scalars

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

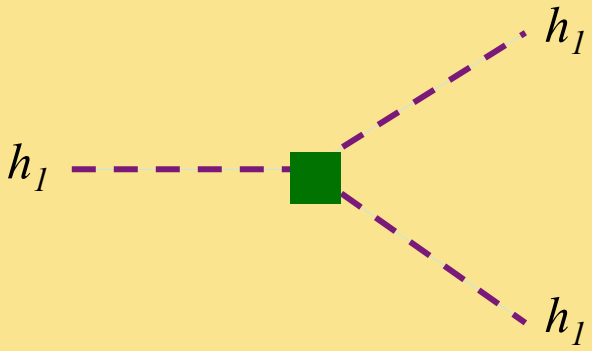


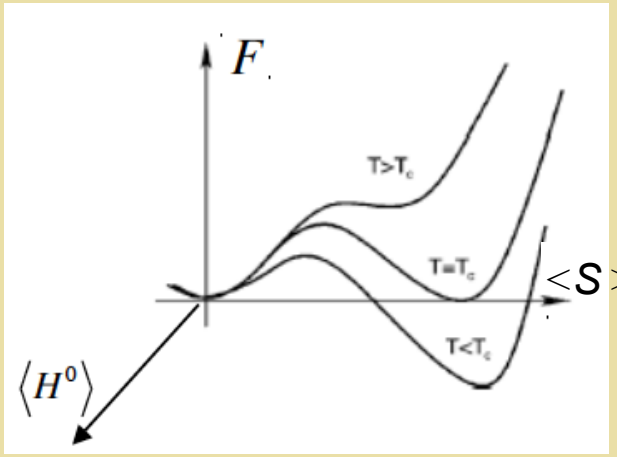
Next gen pp: Kotwal, No, R-M, Winslow 1605.06123

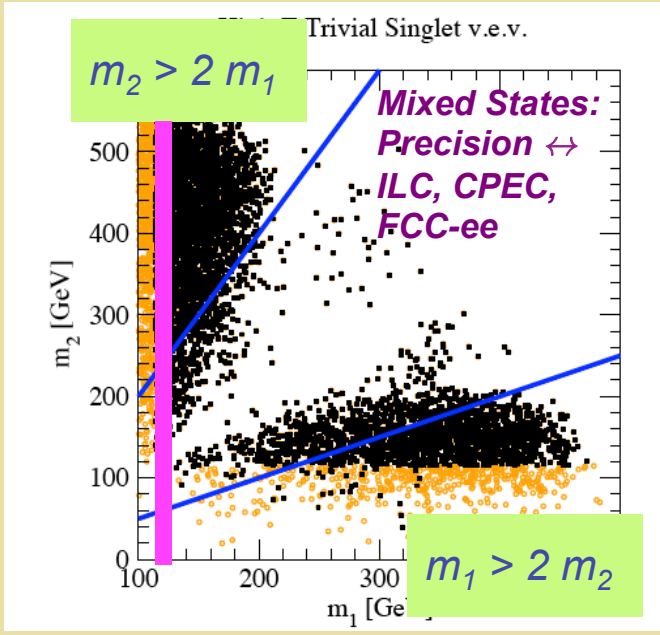
EW Phase Transition: New Scalars



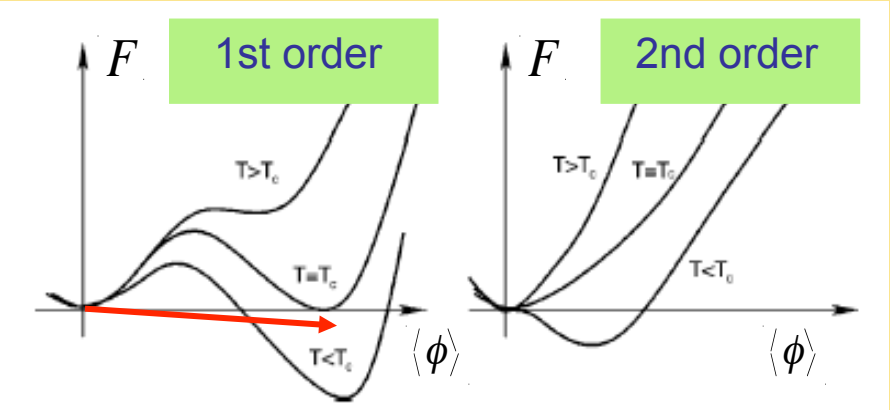
Modified Higgs Self-Coupling

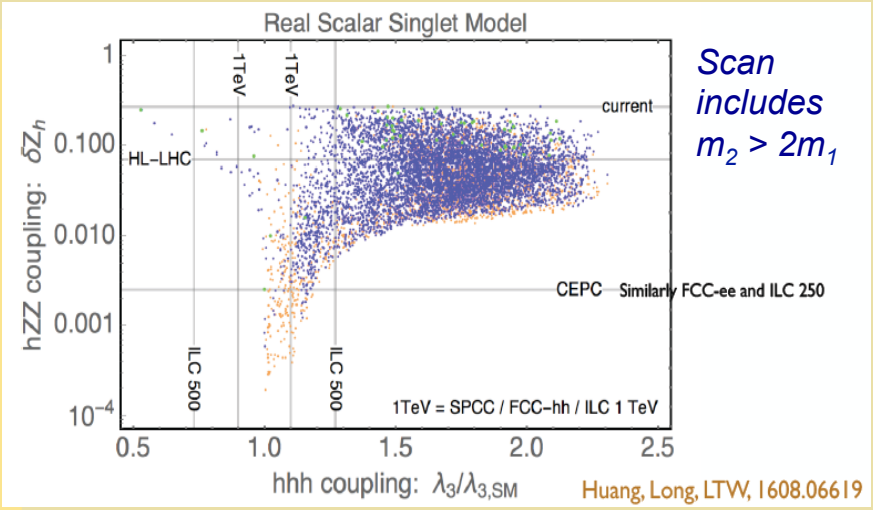






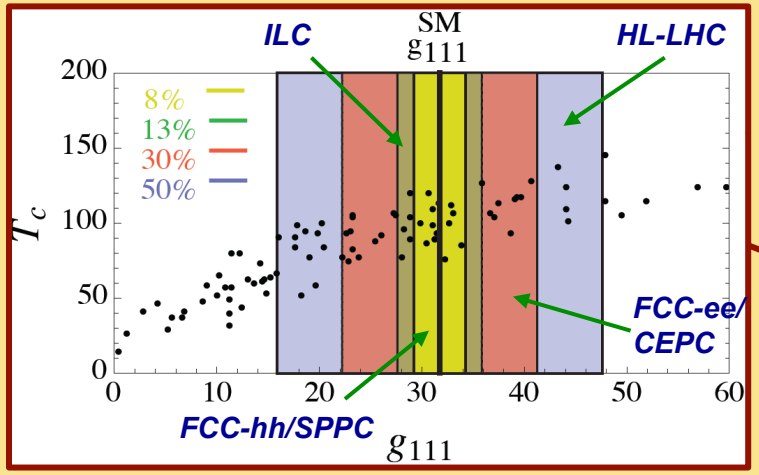
EW Phase Transition: Singlet Scalars

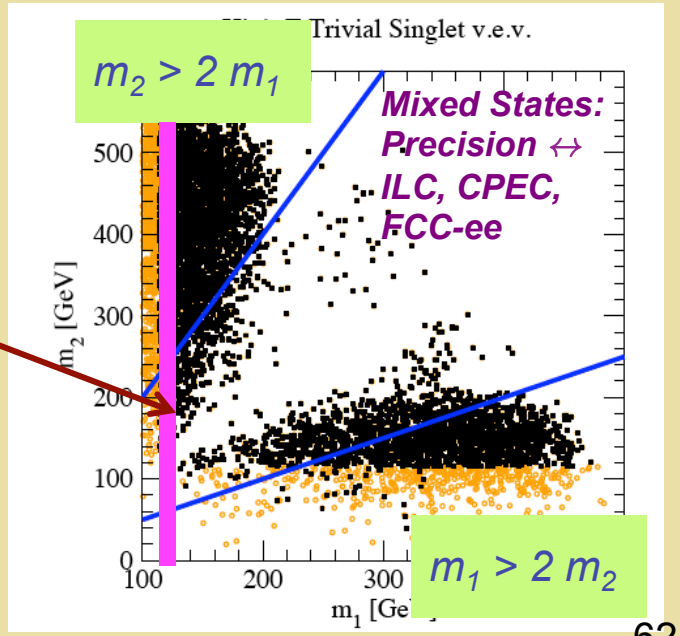




Scan includes $m_2 > 2m_1$

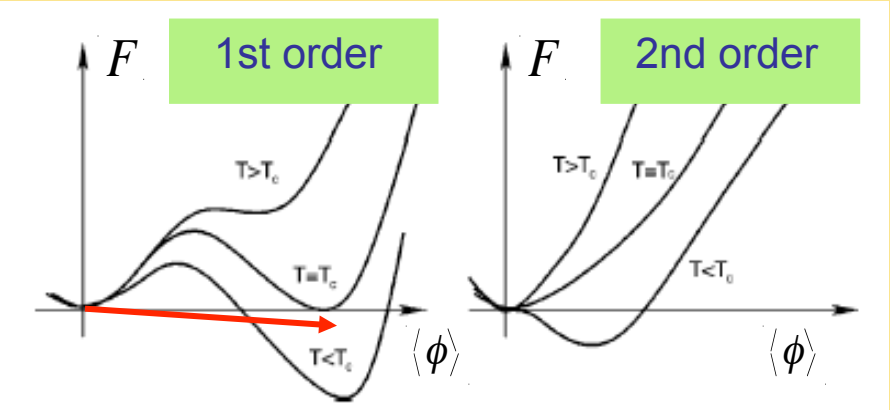
Modified Higgs Self-Coupling

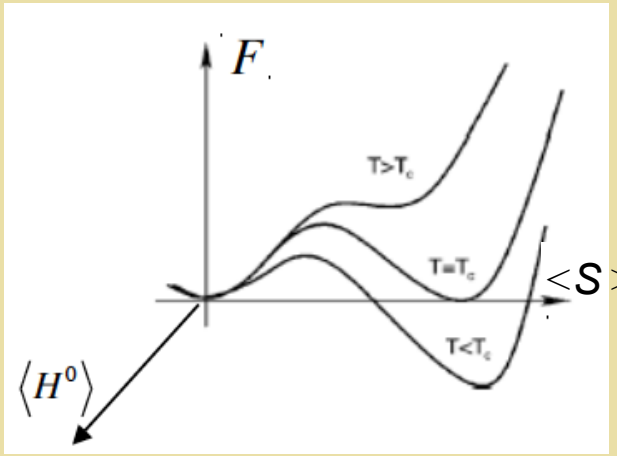




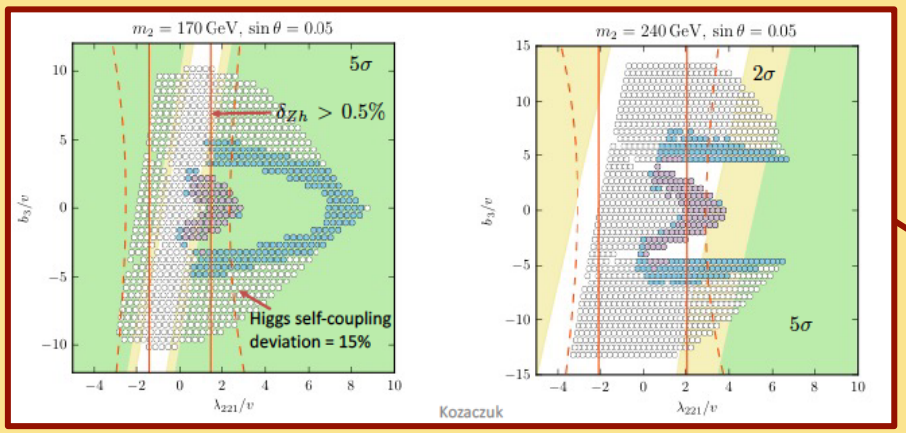
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

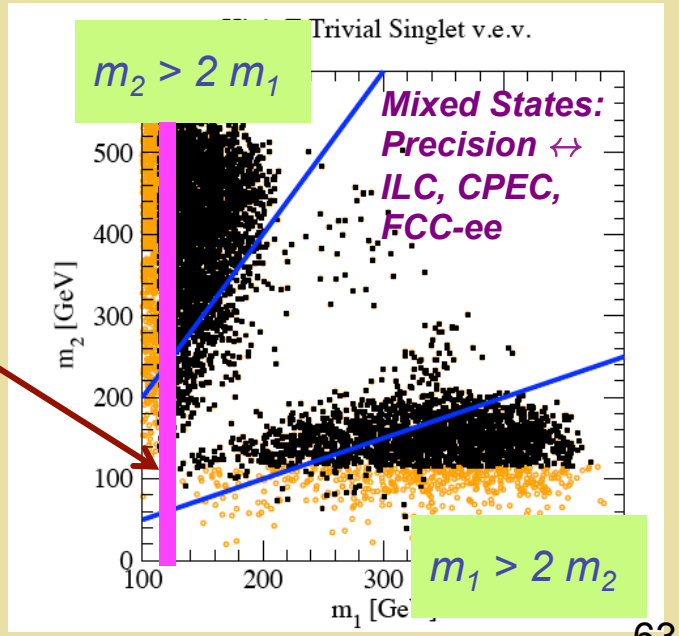
EW Phase Transition: Singlet Scalars





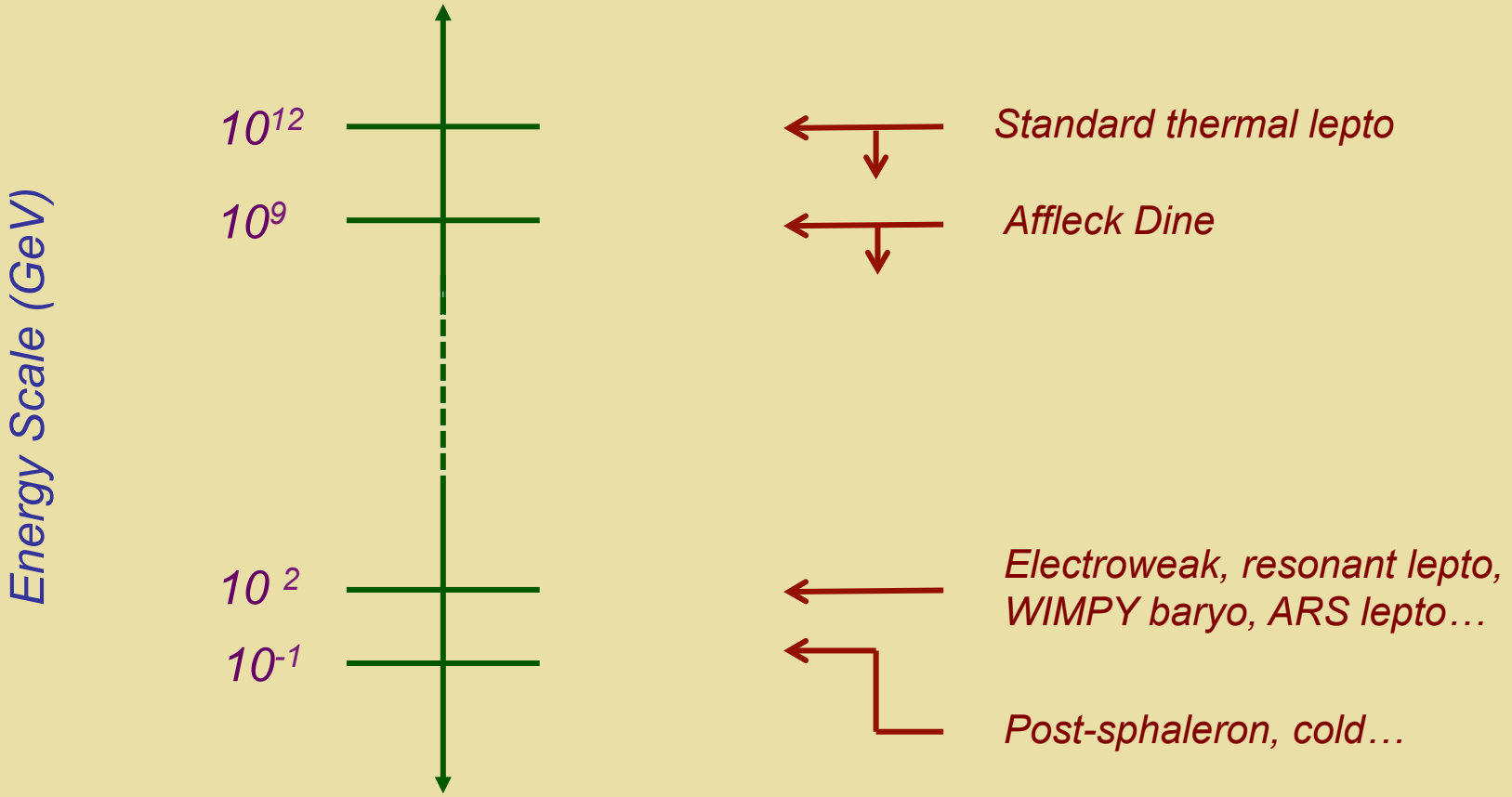
Non-resonant Di-Higgs



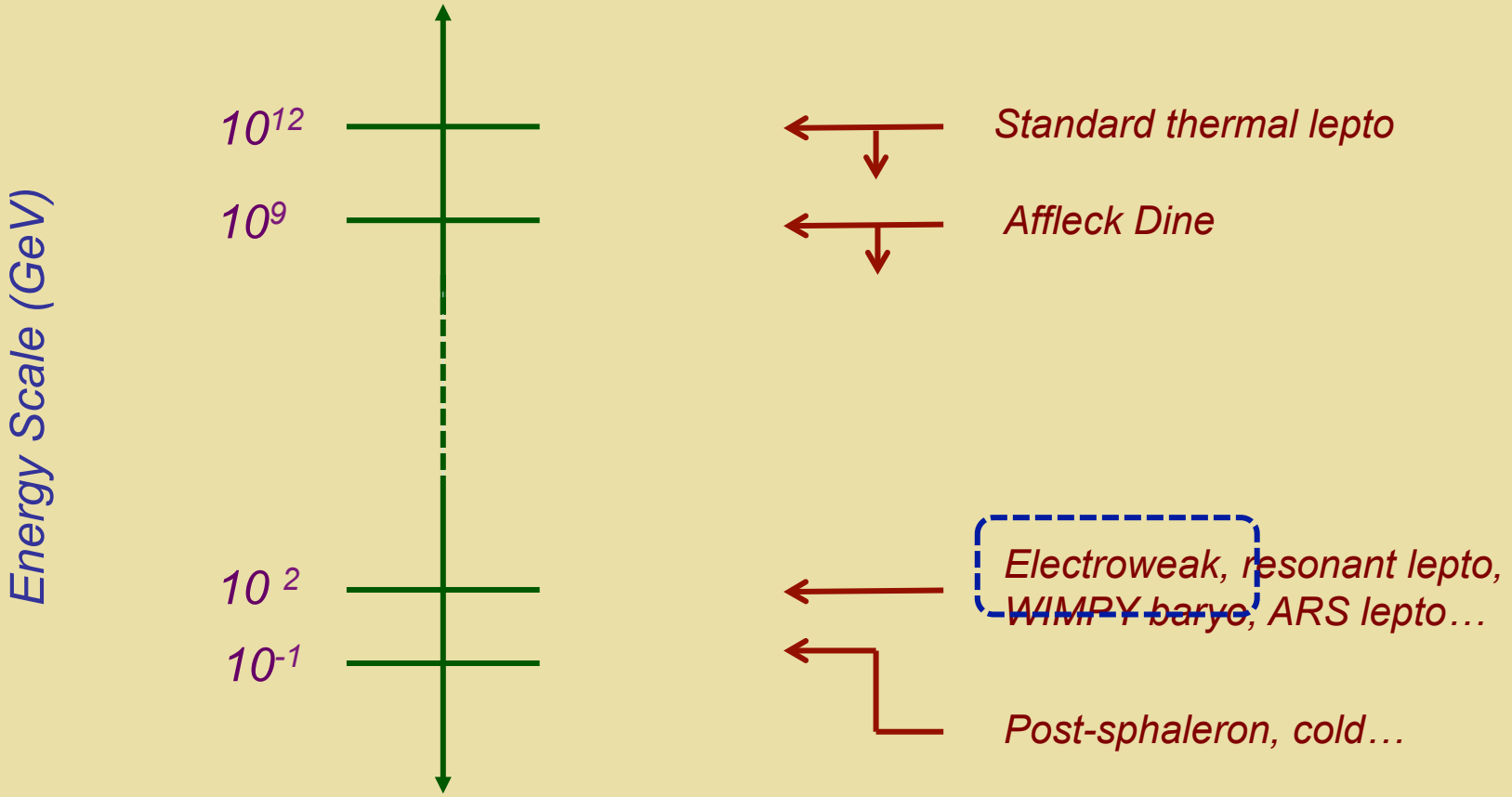


Chen, Kozaczuk, Lewis 2017

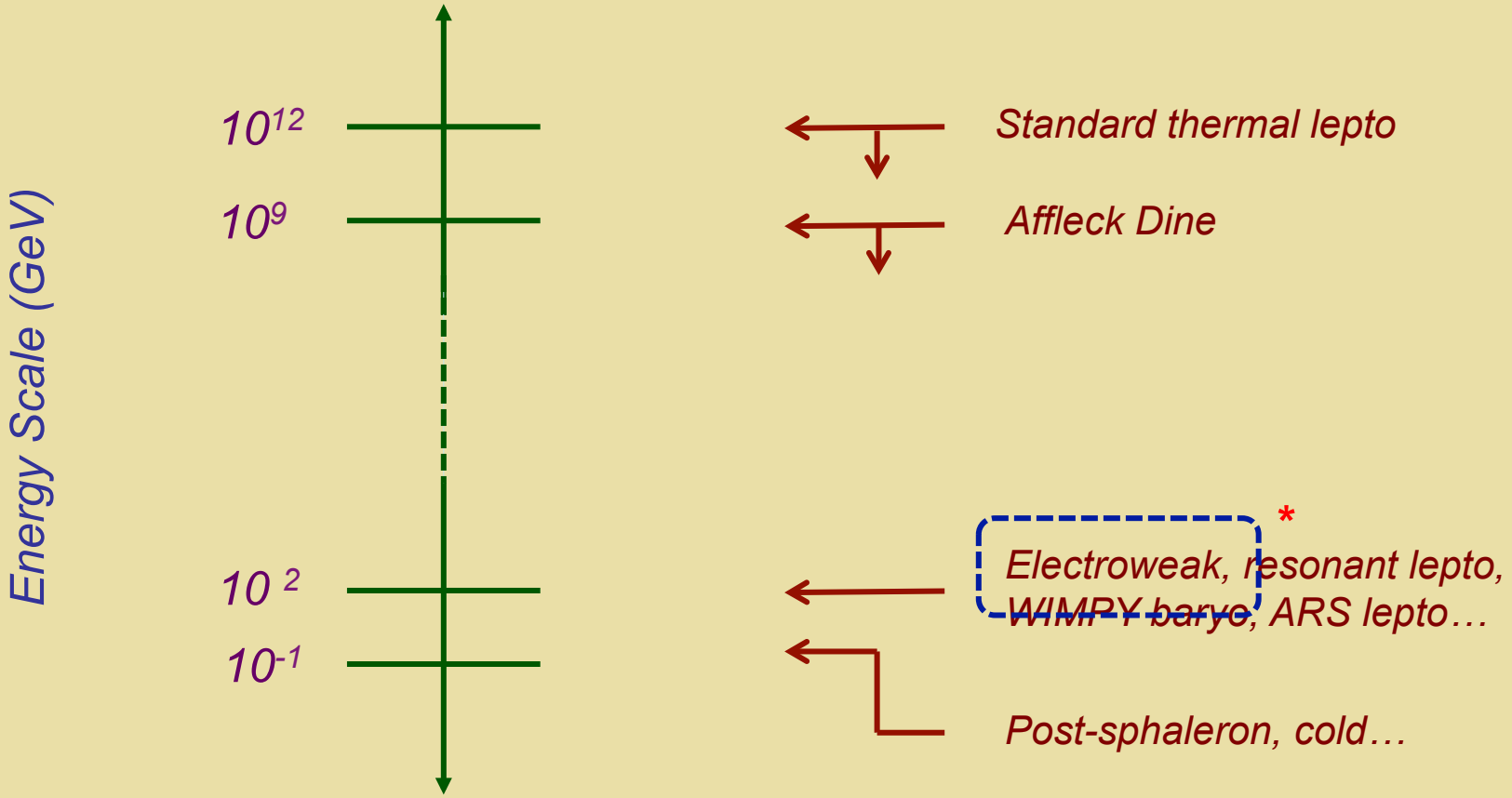
Baryogenesis Scenarios



Baryogenesis Scenarios



Baryogenesis Scenarios



*** Necessary conditions: Strong 1st order EWPT**