Collider-Cosmology Interface: EW Phase Transition

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My pronouns: he/him/his

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Tsung-Dao Lee Institute
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

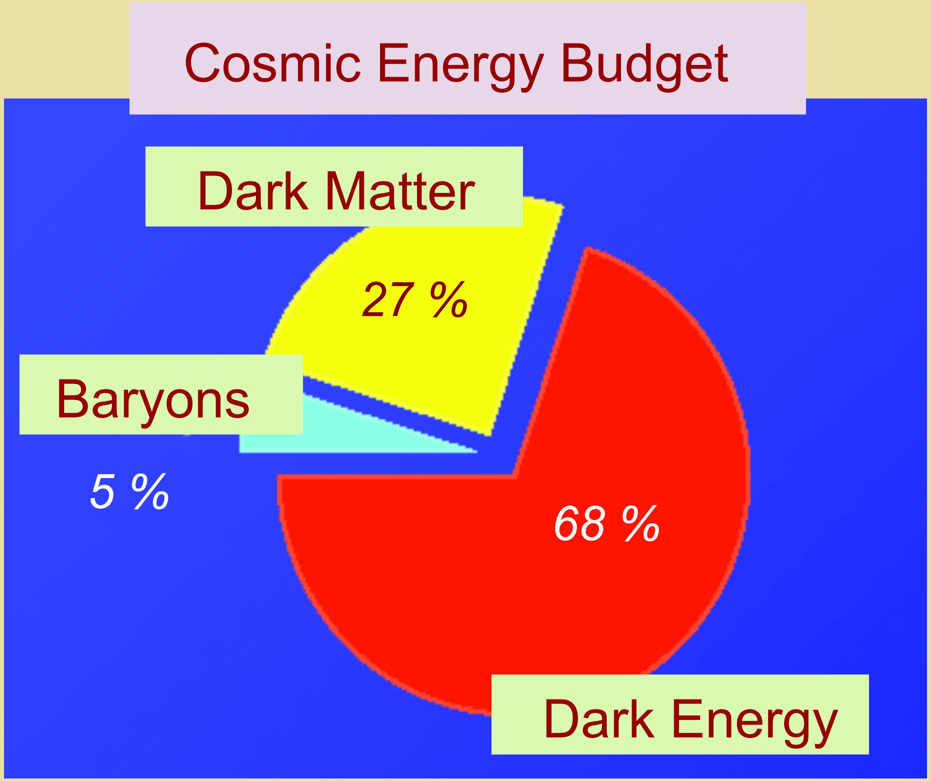
http://www.physics.umass.edu/acfi/

http://tdli.sjtu.edu.cn/web/yjxy/5130001.htm

US ATLAS Workshop
UMass Amherst, August 6, 2019

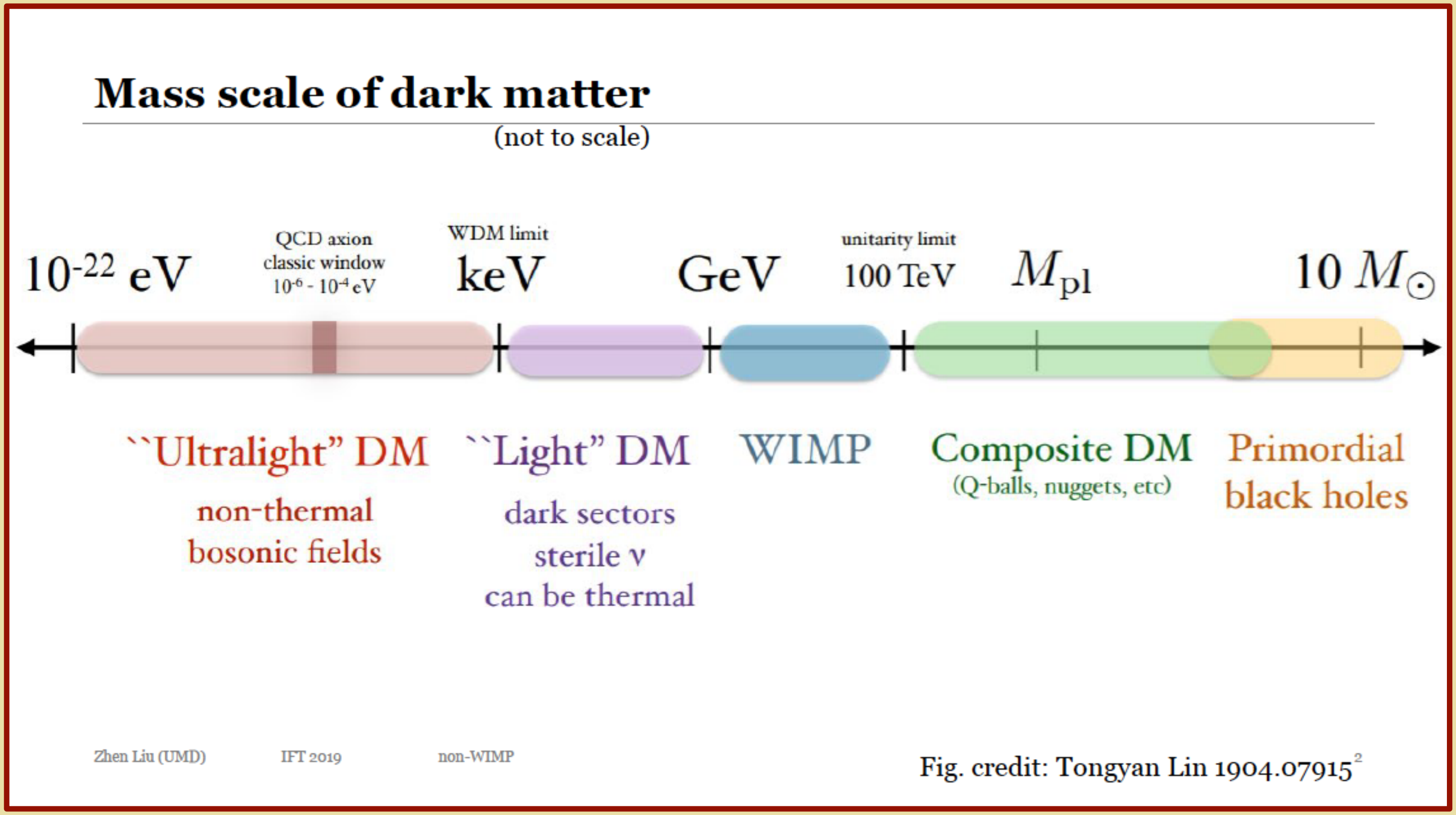
Ann E. Nelson

The Origin of Matter



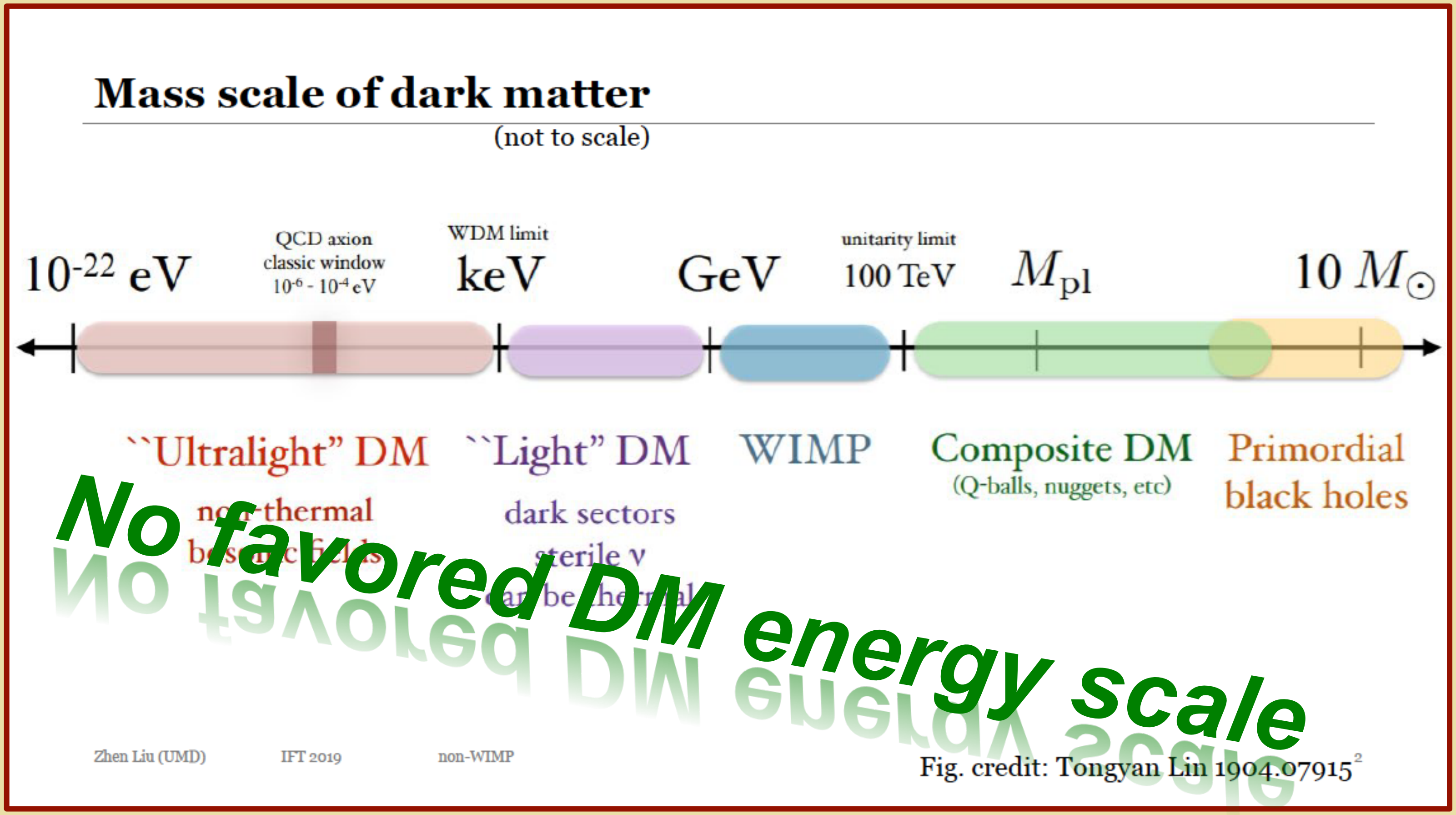
What can the LHC & future colliders teach us about open questions in cosmology ?

Dark Matter



Thanks: Z. Liu

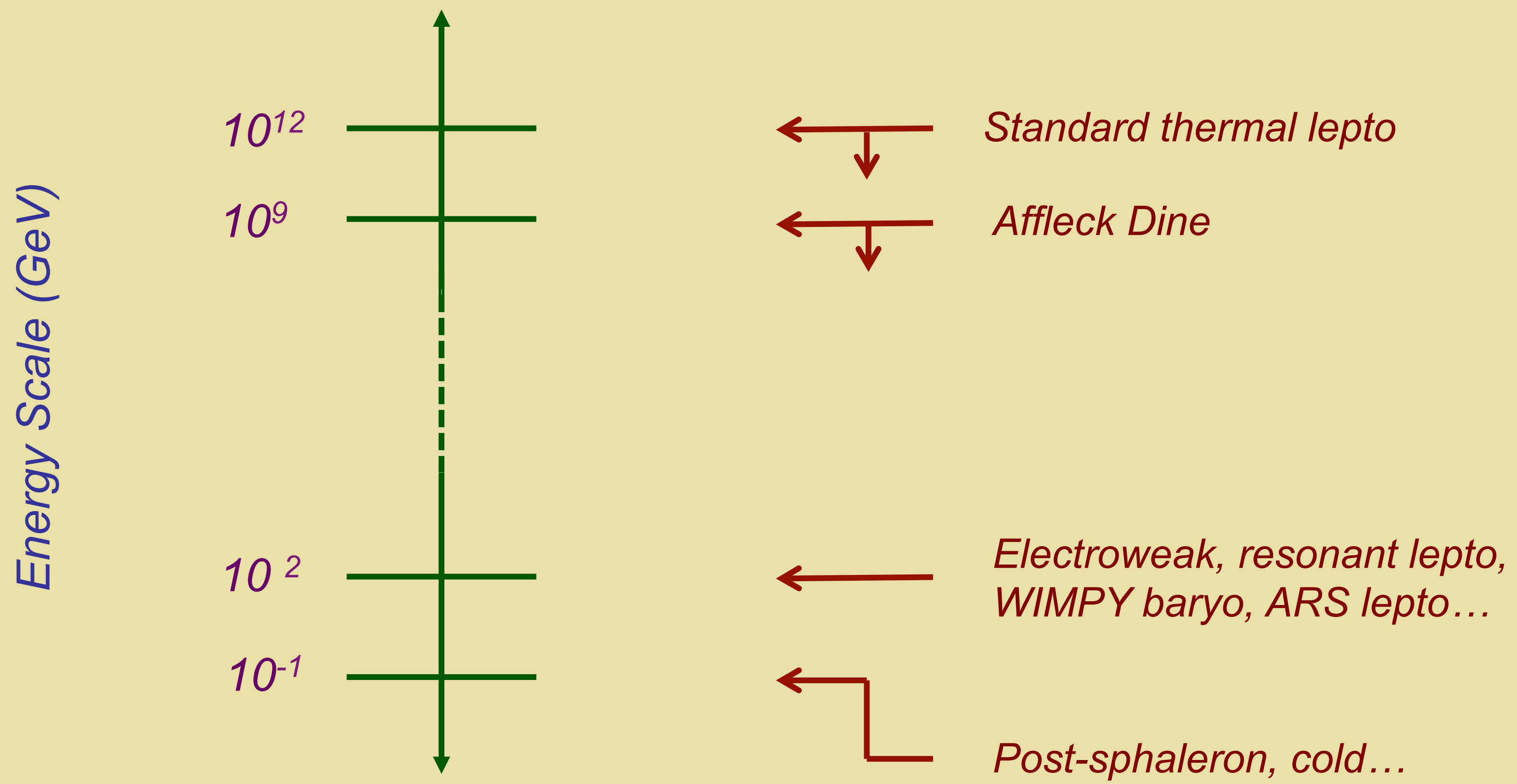
Dark Matter



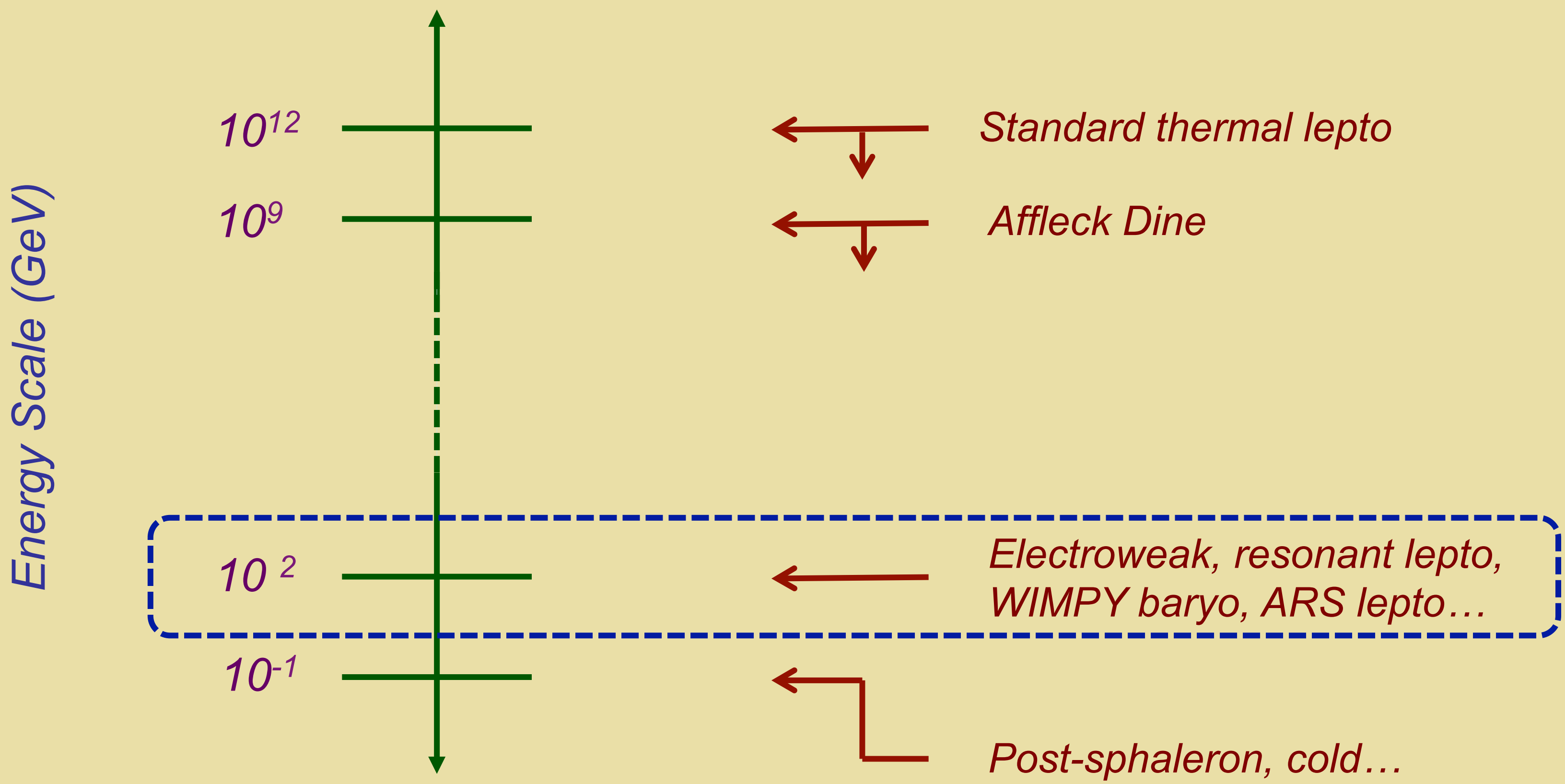
No favored DM energy scale

Thanks: Z. Liu

Baryogenesis Scenarios

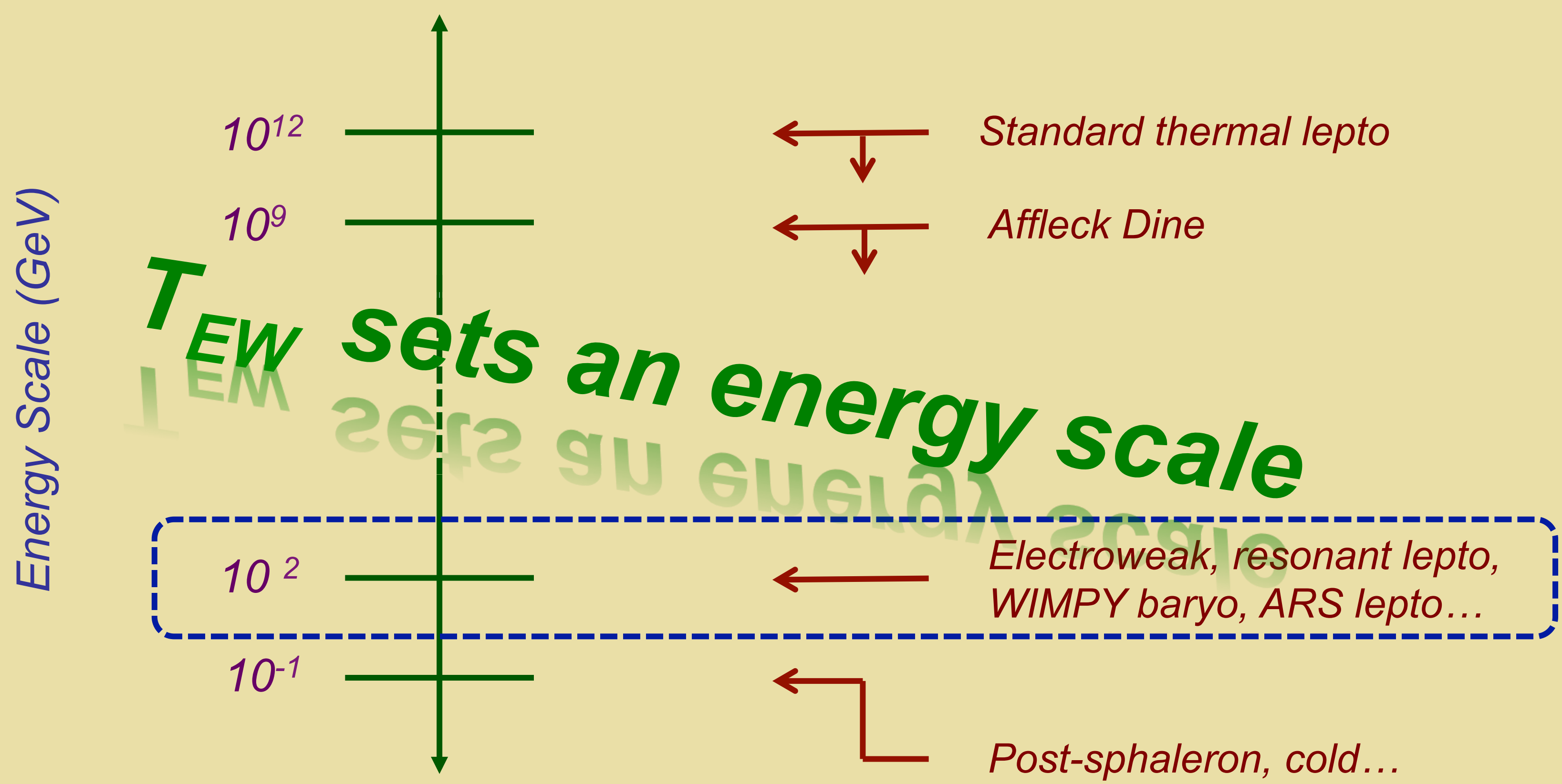


Baryogenesis Scenarios



Era of EWSB: t_{univ} ~ 10 ps

Baryogenesis Scenarios



Era of EWSB: t_{univ} ~ 10 ps

Main Theme for This Talk

T_{EW} → EW phase transition is a target for the LHC & beyond

Outline

I. Context & Questions

II. EWPT: A Collider Target

III. Models & Phenomenology

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

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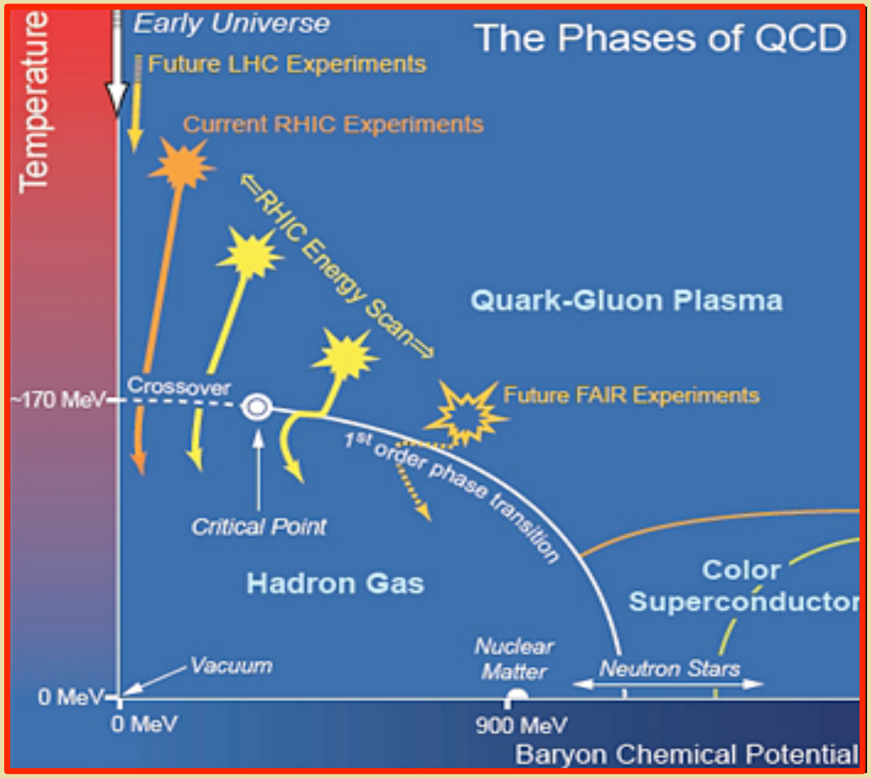
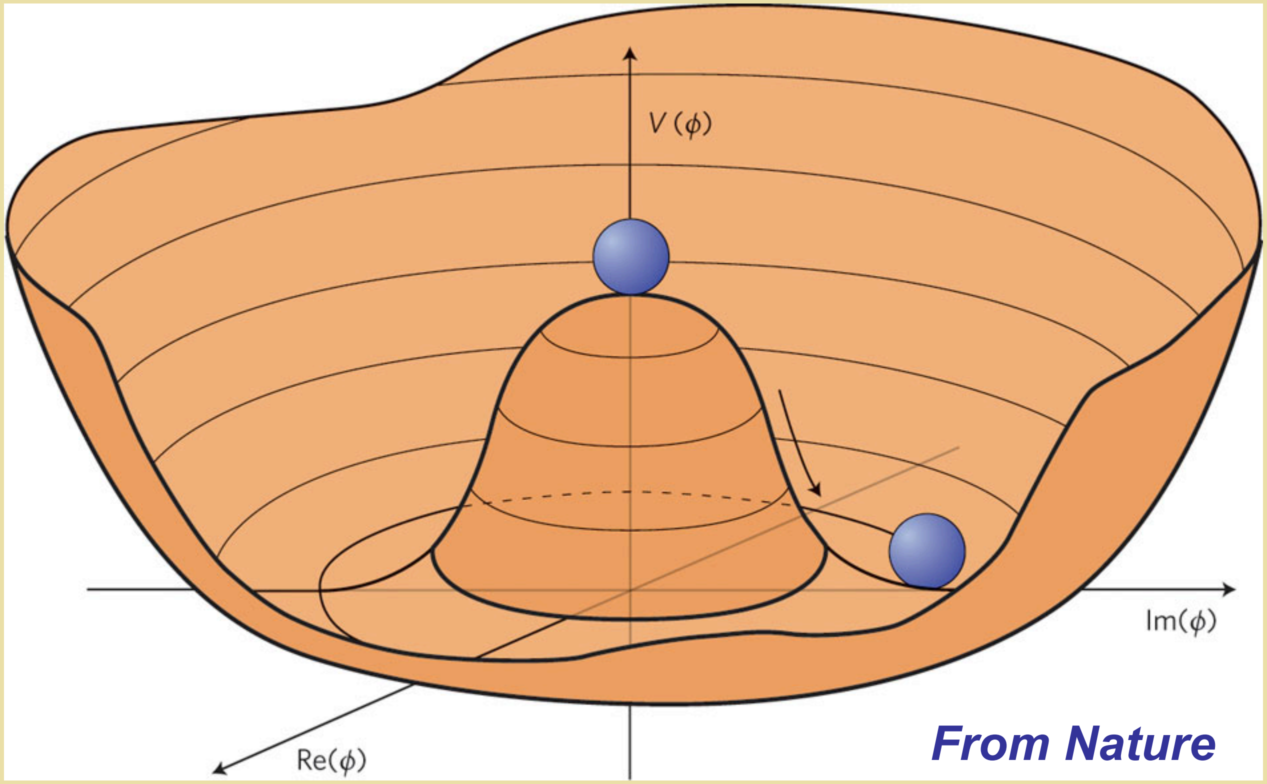
Thermal History of Symmetry Breaking



QCD Phase Diagram → EW Theory Analog?

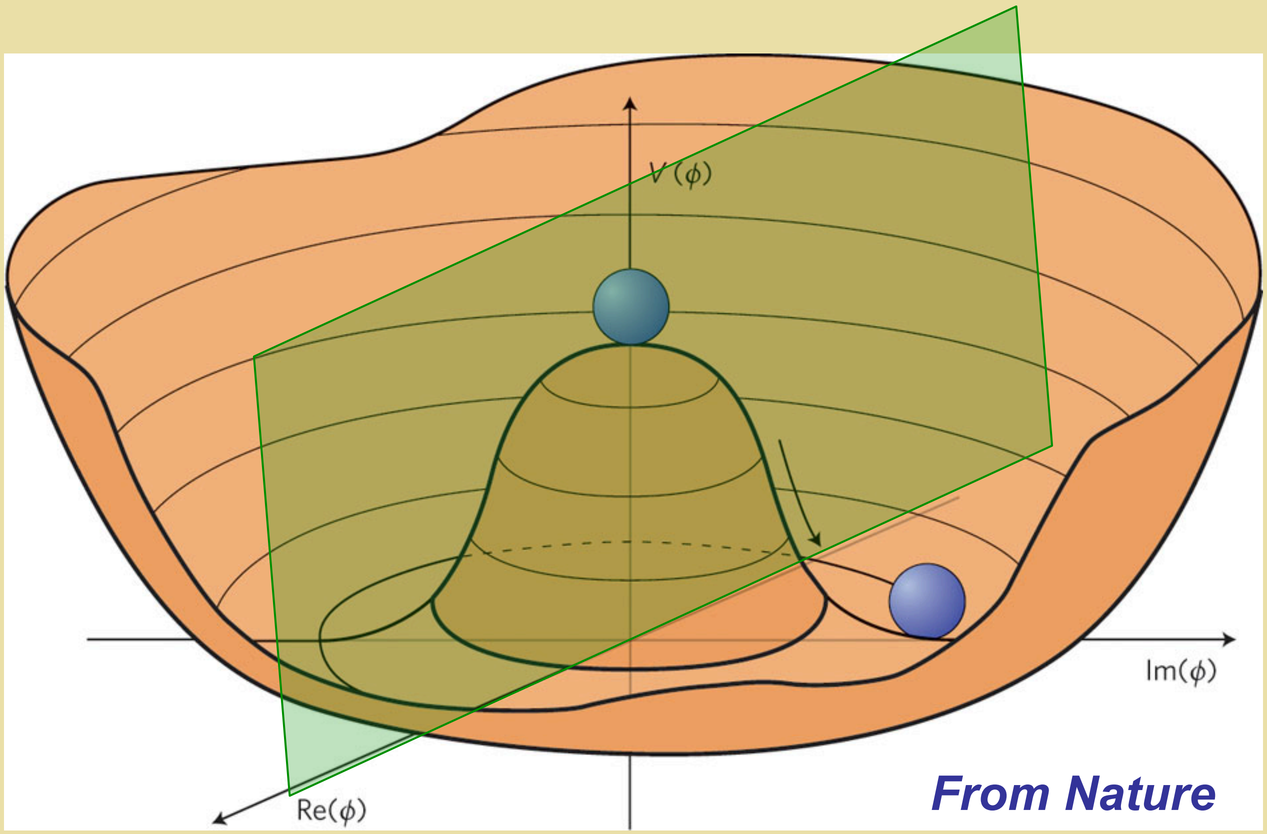
EWSB: The Scalar Potential



From Nature

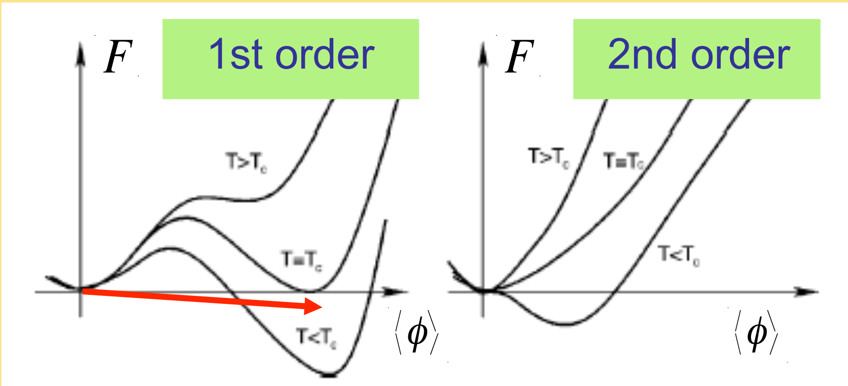
What was the thermal history of EWSB ?

EWSB: The Scalar Potential



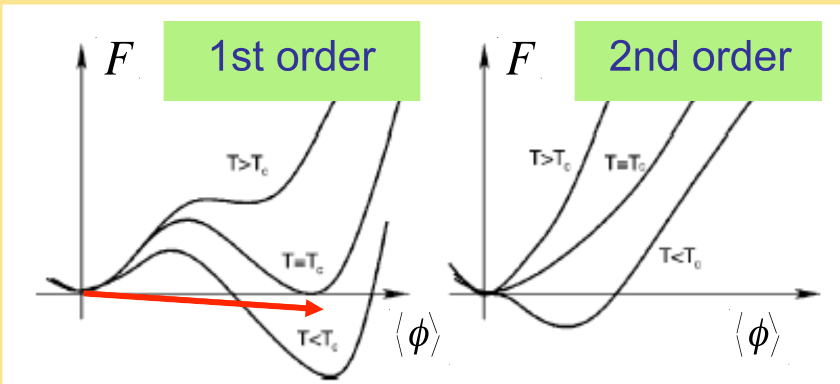
What was the thermal history of EWSB ?

EW Phase Transition: St'd Model



Increasing m_h →

EW Phase Transition: St'd Model



Increasing m_h →

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
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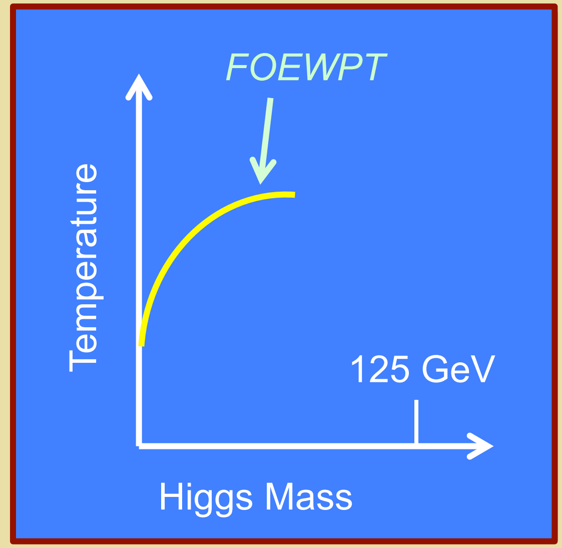
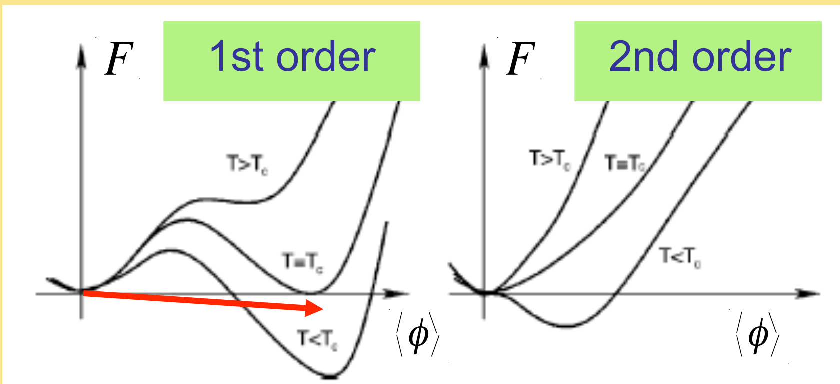
SM EW: Cross over transition



EW Phase Diagram

EW Phase Transition: St'd Model



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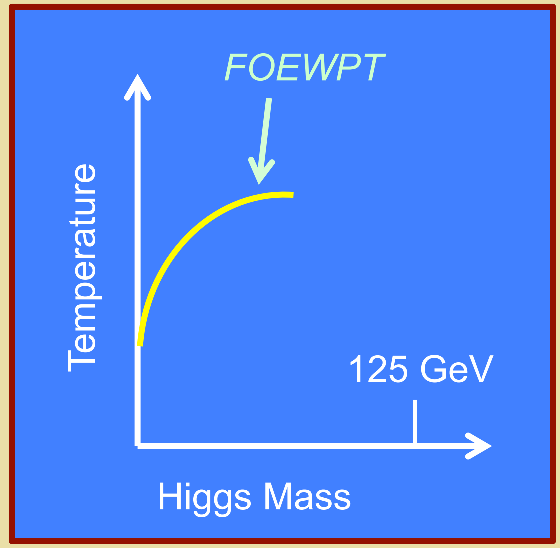

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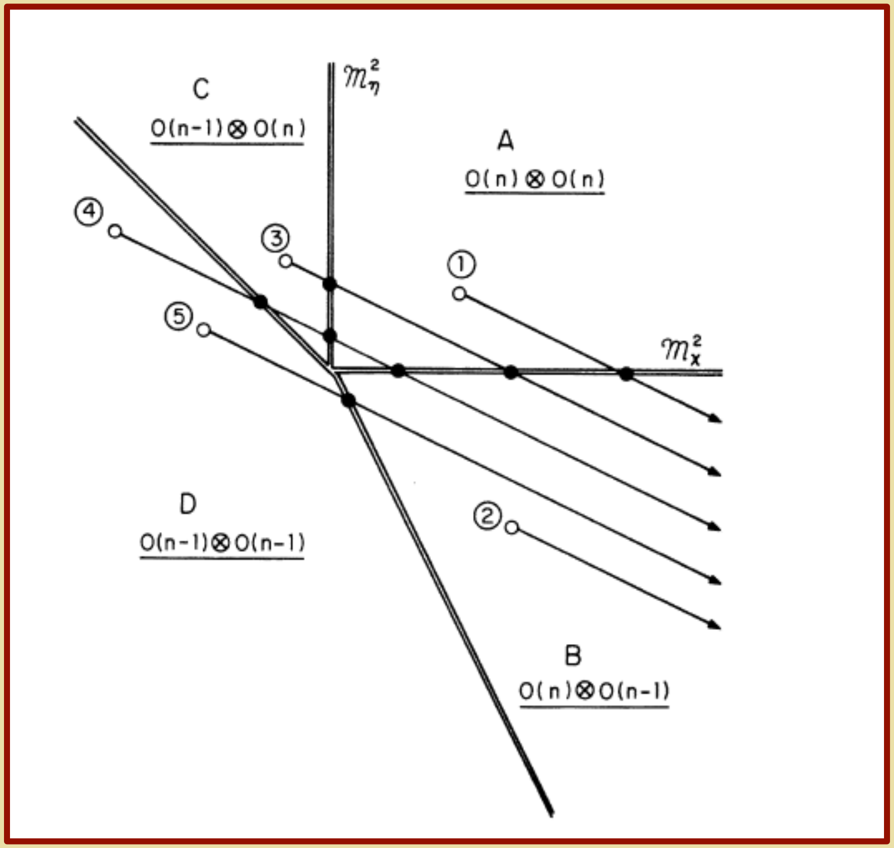
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

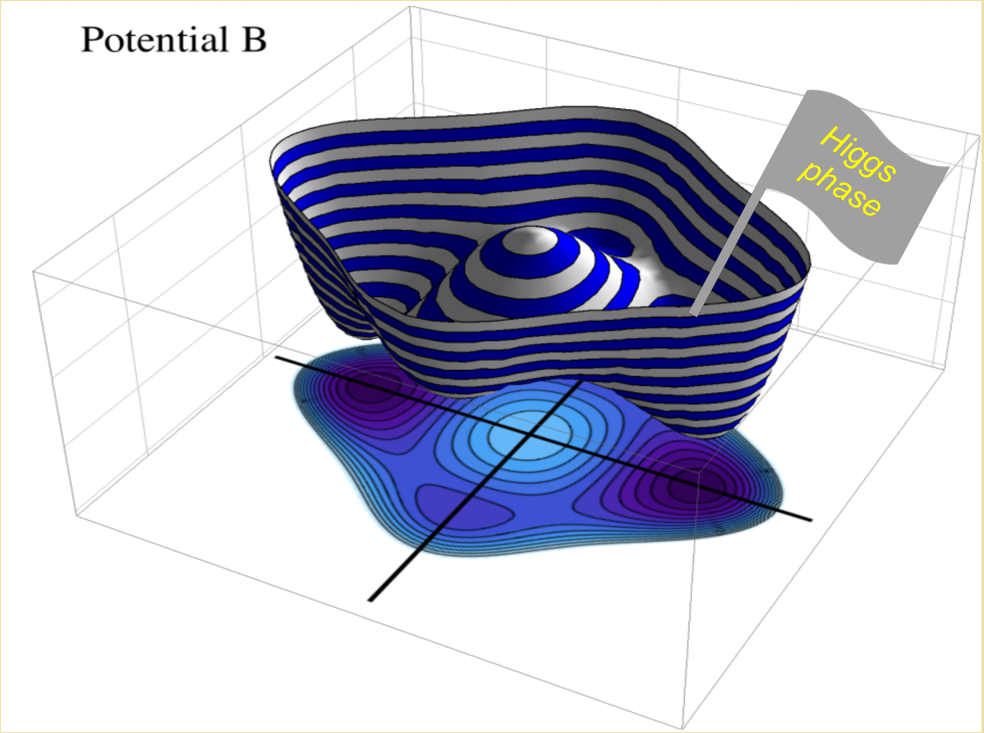
SM EW: Cross over transition

Patterns of Symmetry Breaking



S. Weinberg, PRD 9 (1974) 3357

Patterns of Symmetry Breaking



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

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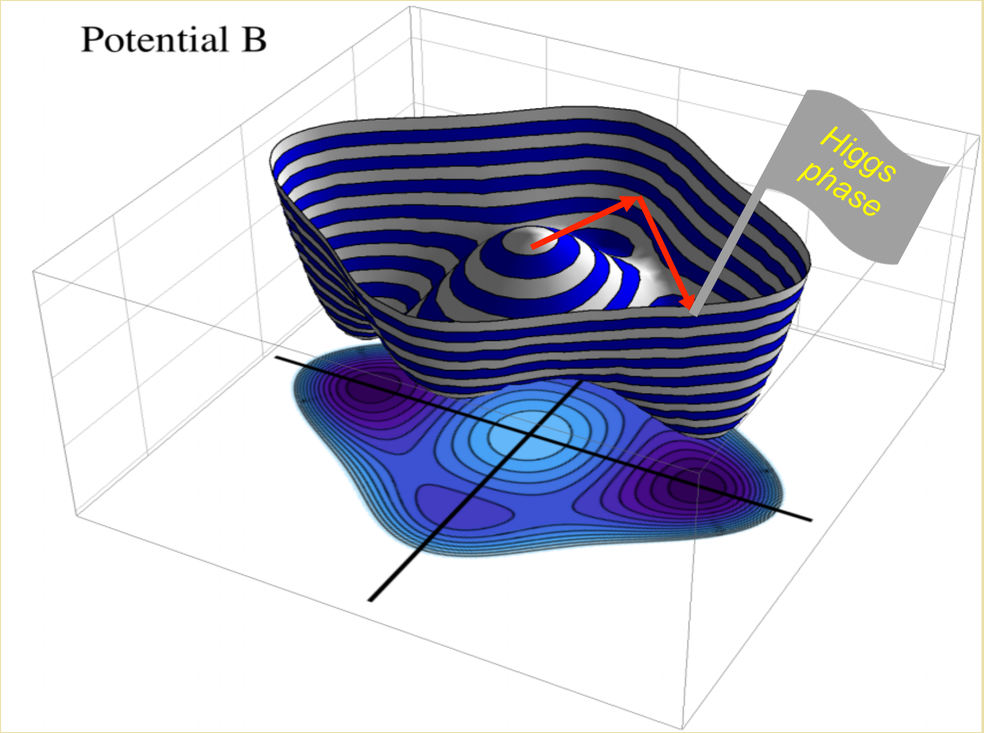

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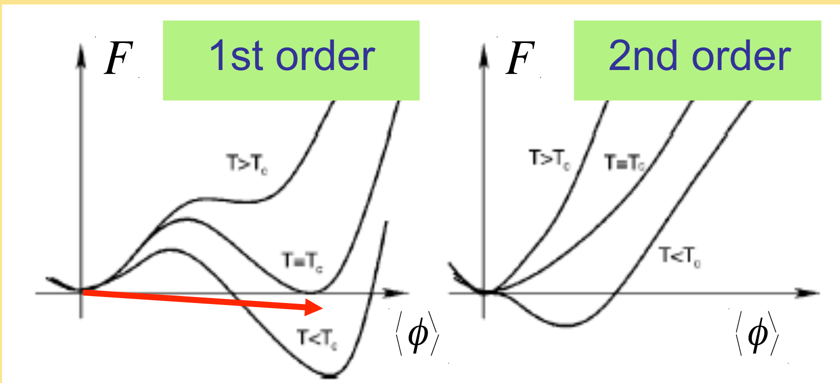
EW Phase Transition: Baryogen & GW



Increasing m_h →

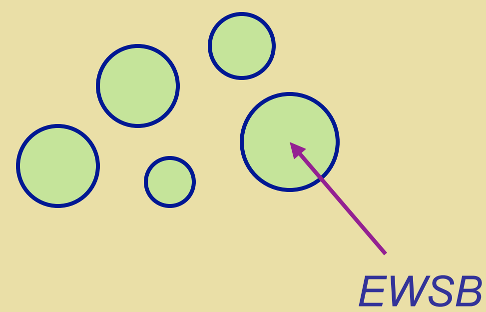
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

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

↓

Bubble nucleation



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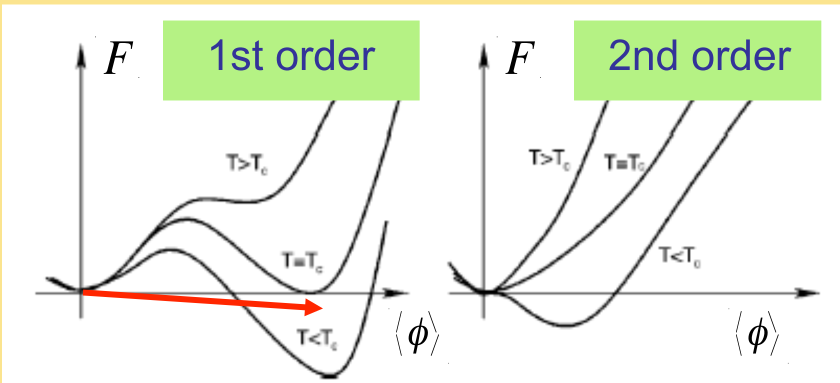

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Baryogenesis
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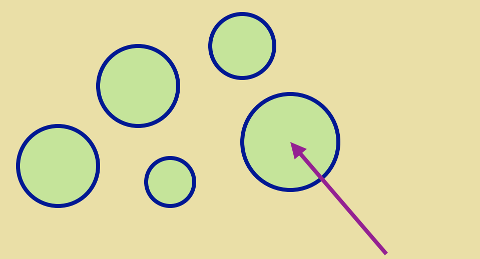
"Strong" 1st order EWPT

- *Baryogen**
- *GW*

Bubble nucleation



* *Need BSM CPV*

II. EWPT: A Collider Target

MJRM 1908.NNNNN

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

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

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

$T_0 \sim$ 140 GeV

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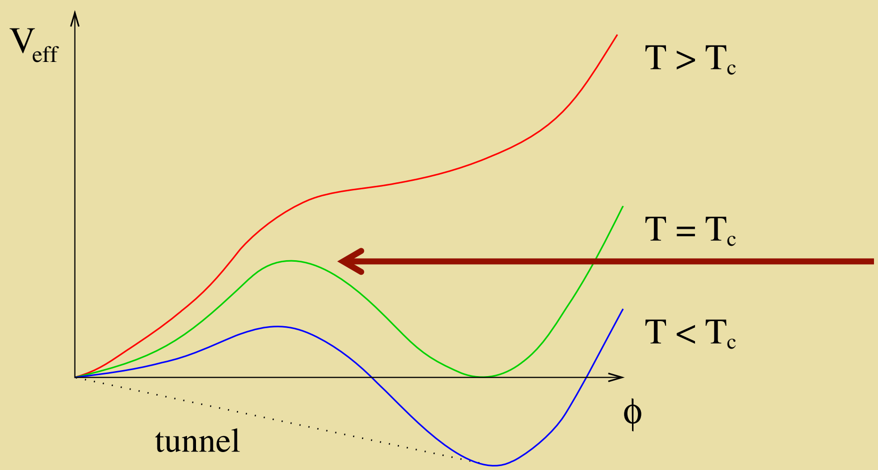
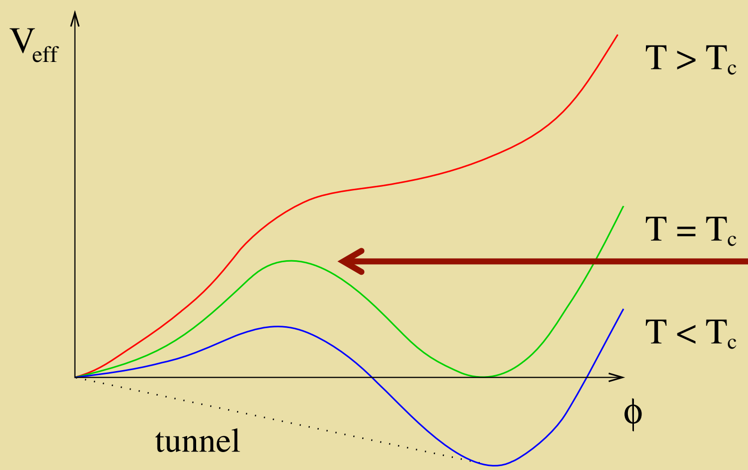
$T_0 \sim$ 140 GeV $\equiv$ **T_{EW}**

First Order EWPT from BSM Physics



Generate finite-T barrier

First Order EWPT from BSM Physics



Generate finite-T barrier

$$V(H,\phi)_{T=0} = V(H) + \frac{a_2}{2}\phi^\dagger \phi H^\dagger H + V(\phi)$$

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

$$V(\phi) = \frac{b_2}{2}\phi^\dagger \phi + \frac{b_4}{4!}(\phi^\dagger \phi)^2$$

First Order EWPT from BSM Physics

- ***Thermal loops involving new bosons***
- ***T=0 loops (CW Potential)***
- ***Change tree-level vacuum structure***

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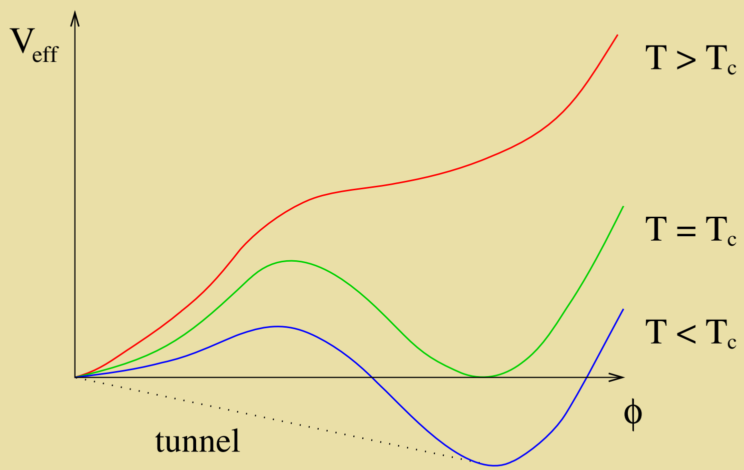
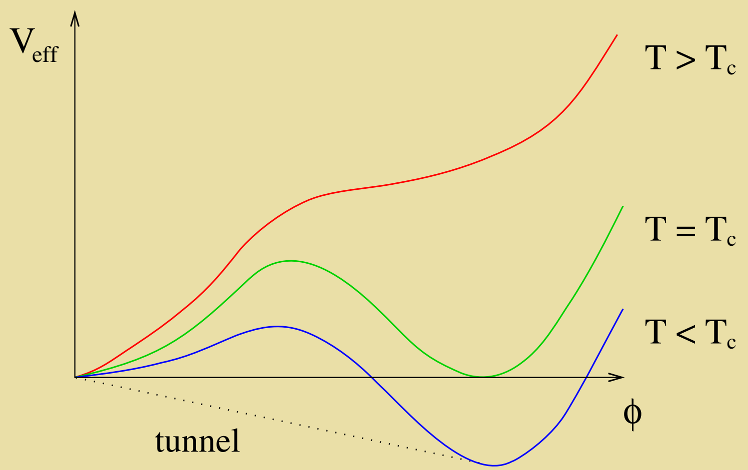


$$\Delta V(h,T) \supset -\frac{T}{12\pi} M_\phi(h,T)^3$$

$$M_\phi(h,T)^3 = \left[\frac{a_2}{12}T^2 + b_2 + \frac{a_2}{4}h^2\right]^{3/2}$$

First Order EWPT from BSM Physics



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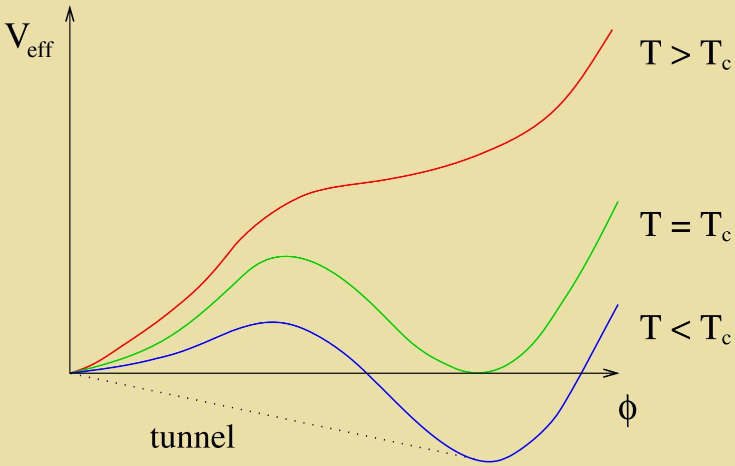
Choose b_2 , a_2 to cancel at $T \sim T_{EW}$

First Order EWPT from BSM Physics



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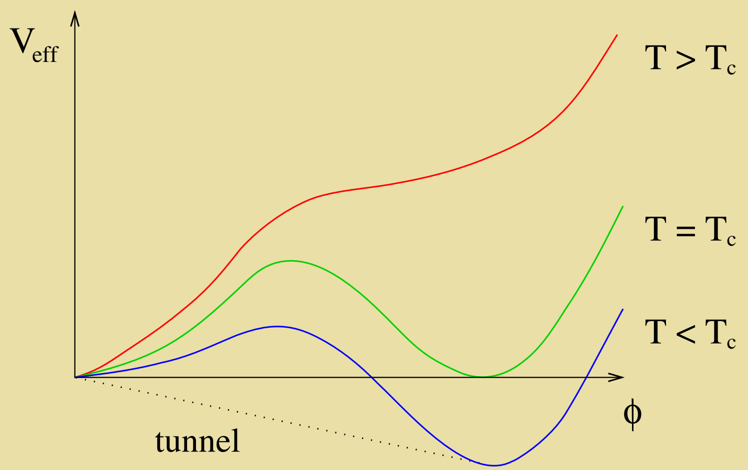
Choose b_2 , a_2 to cancel at $T \sim T_{EW}$

$$M_\phi(T=0) = \frac{a_2}{4}\left(v^2 - T_{\rm EW}^2/3\right)$$

First Order EWPT from BSM Physics



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M_ϕ < 350 GeV for perturbative a_2

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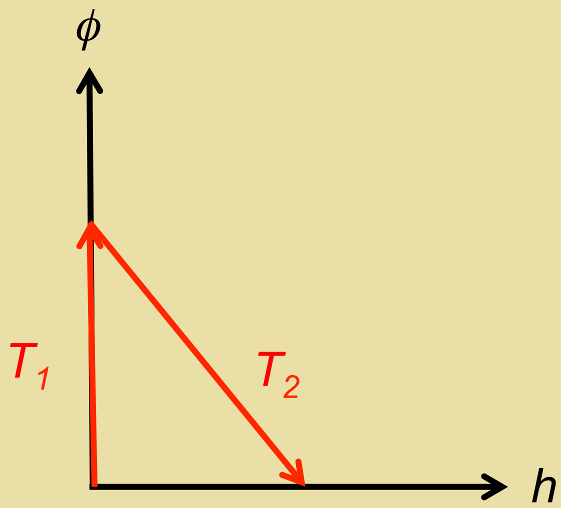

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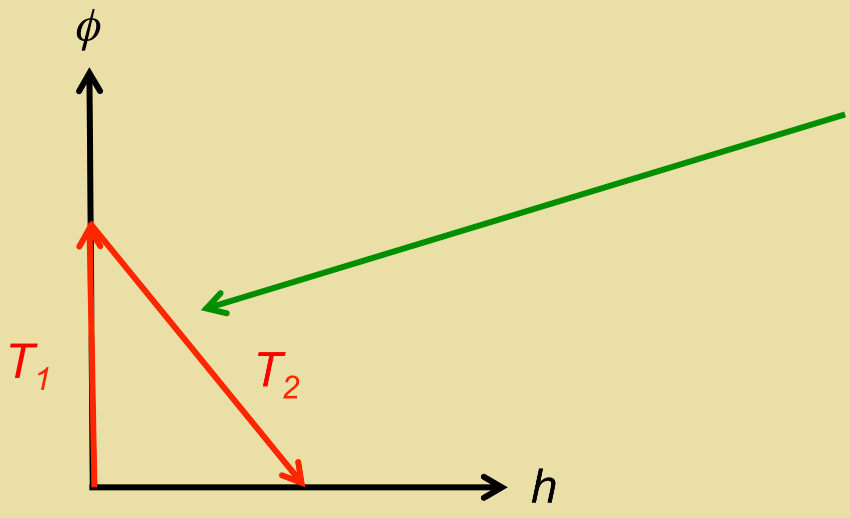
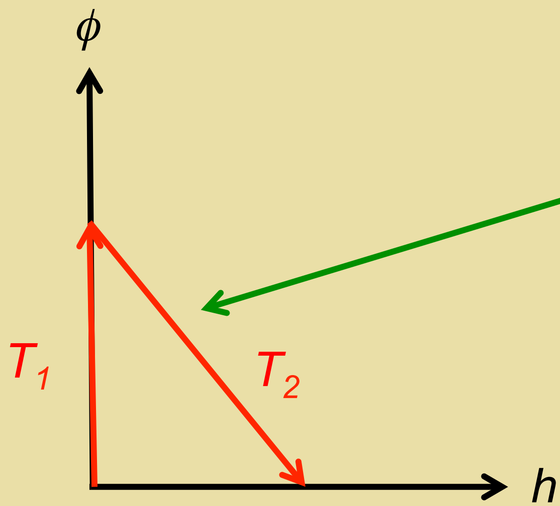


- *Tree-level barrier:* $a_2\, \phi^+\phi\, H^+H$
- *Want* $T_1 > T_2 \sim T_{EW}$

First Order EWPT from BSM Physics



- Tree-level barrier: $a_2\, \phi^+ \phi\, H^+ H$
- Want $T_1 > T_2 \sim T_{EW}$

$$M_\phi(T=0) < \left[\frac{a_2}{4} v^2 - \frac{T_{\rm EW}^2}{6}\left(a_2 + \frac{3}{2} b_4\right)\right]^{1/2}$$

M_ϕ < 350 GeV for perturbative a_2 , b_4

T_{EW} : A Scale for Collider Discovery

- *Foregoing arguments: good up to factor of ~ 2 → M_{ϕ} < 800 GeV (-ish)*
- *QCD production: LHC exclusion → ϕ is colorless*
- *Electroweak or Higgs portal (h-ϕ mixing…) production → σ_{PROD} ~ (1- 500) fb (LHC) and (0.1-25) pb (100 TeV pp)*
- *Precision Higgs studies: see ahead*

III. Models & Phenomenology

Models & Phenomenology

What BSM Scenarios?

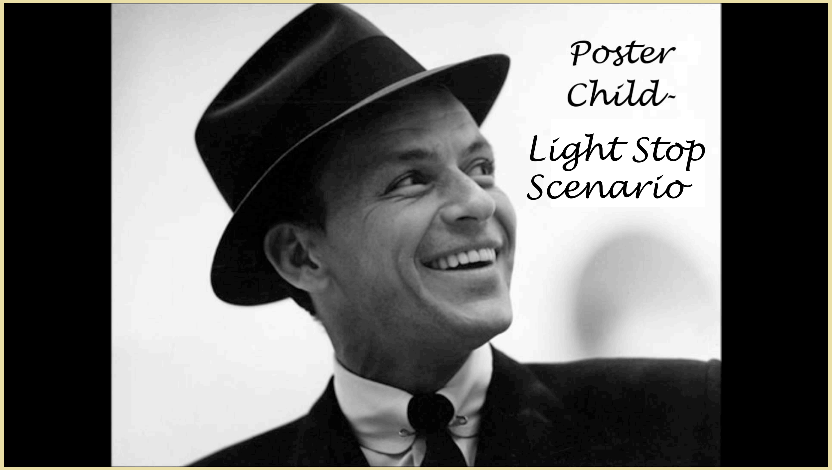
SM + Scalar Singlet	Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, 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

EWPT: Theory & Phenomenology

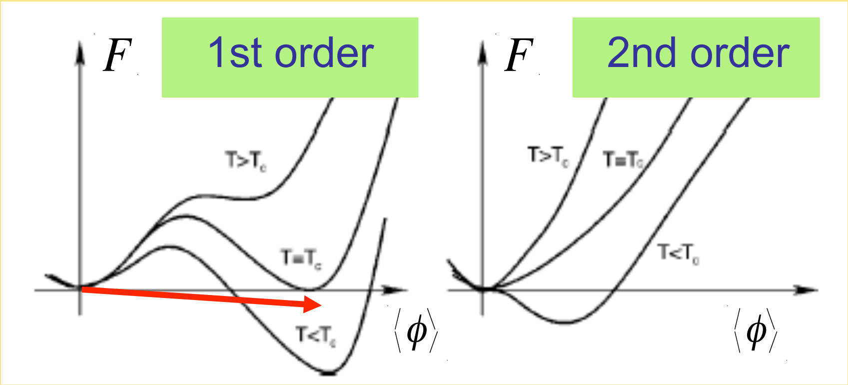
- *What models can lead to a (strong) first order electroweak phase transition (EW baryogenesis & gravitational waves) ?*
- *Can they also yield contributions to Ω_{DM} ?*
- *How can they be tested experimentally ?*
- *How reliably can we compute phase transition properties & make the connection with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

EWPT "Poster Child": MSSM Light Stop Scenario



Thermal loops

EW Phase Transition: SUSY



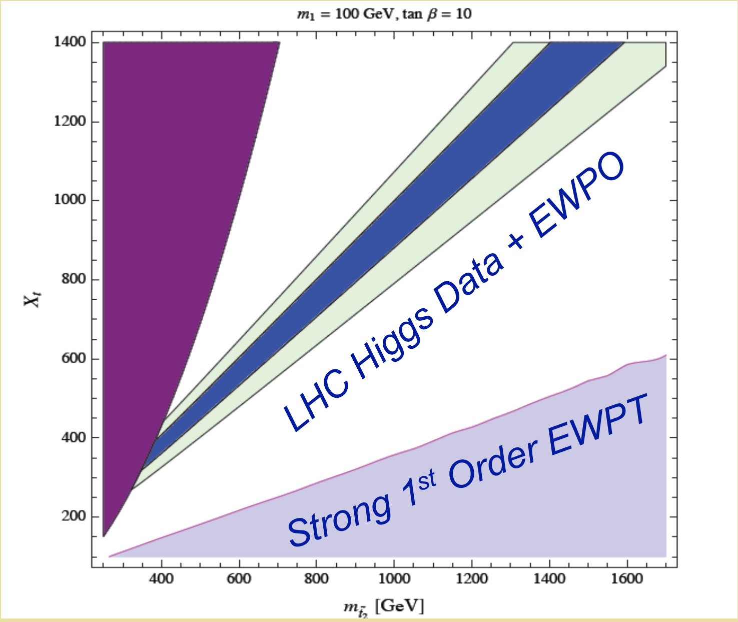
Increasing m_h →

← *New scalars*

Light RH stops also affect Higgs properties

Curtin, Jaiswal, Meade 1203.2932

MSSM + $\delta\lambda_4 (H_u^\dagger H_u)^2$



Katz, Perelstein, R-M, Winslow 1509.02934

Strong 1st Order EWPT

Definitive probe of the possibilities →
LHC + next generation colliders

The Higgs Portal

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

Simplest Extension

Standard Model + real singlet scalar

Singlet Driven EW Phase Transition

(lots of) Motivation

⇒ Neutral Naturalness

⇒ Higgs Portal (Dark Sectors)

⇒ Non-minimal SUSY (e.g. NMSSM)

⇒ Warped Extra Dim (dilaton...)

...

Thanks: J. M. No

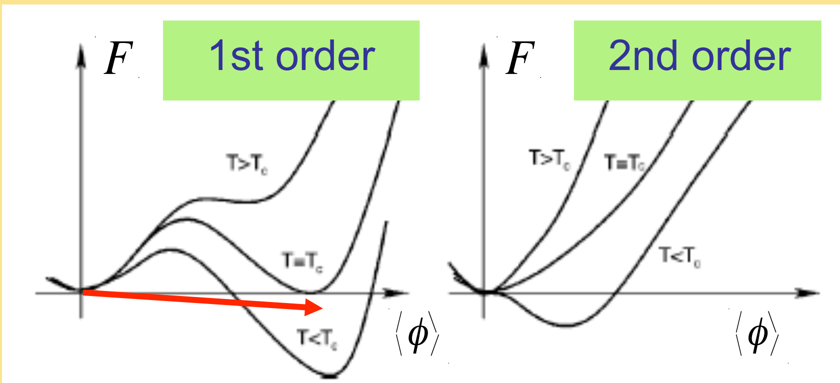
Simplest Extension

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*

EW Phase Transition: New Scalars

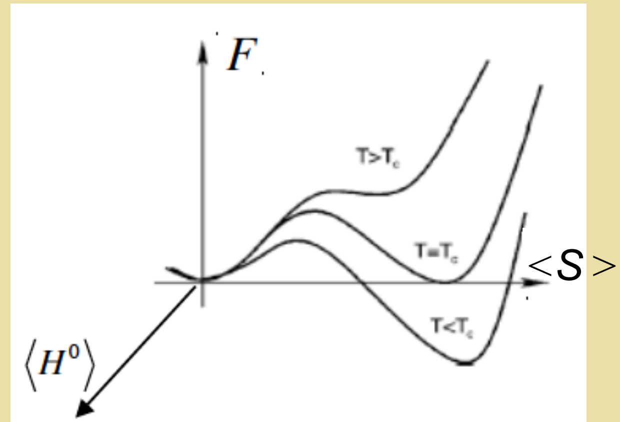


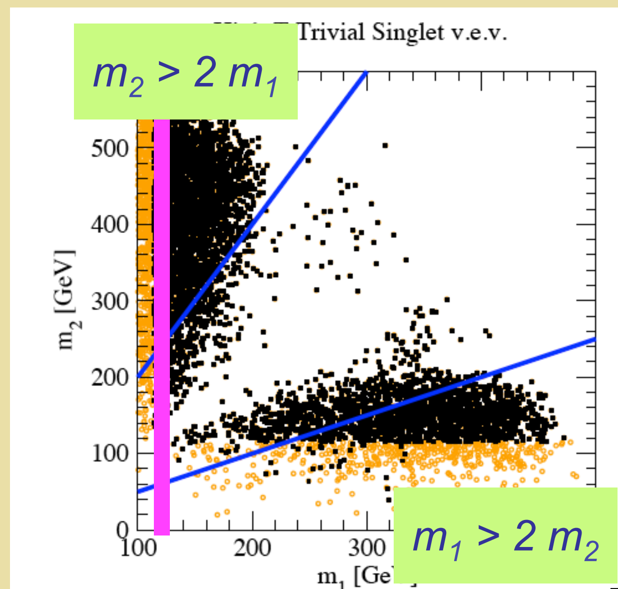
Increasing m_h →

← *New scalars*

Real Singlet: $\phi \to S$

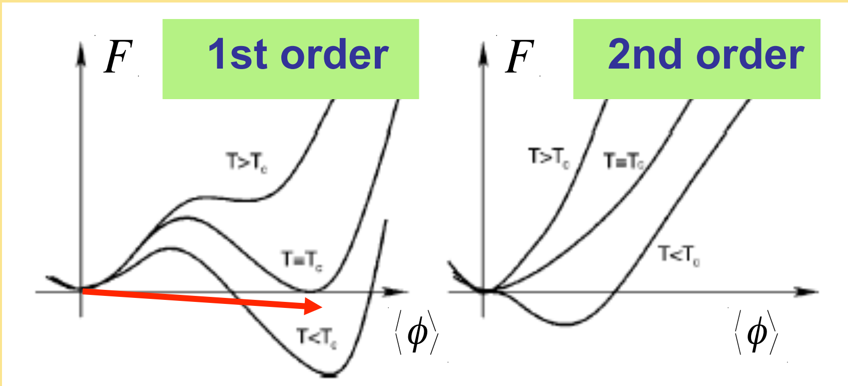
Simplest Extension:
two states h_1 & h_2





Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010
Espinosa, Konstandin, Riva NPB 854 (2012) 592

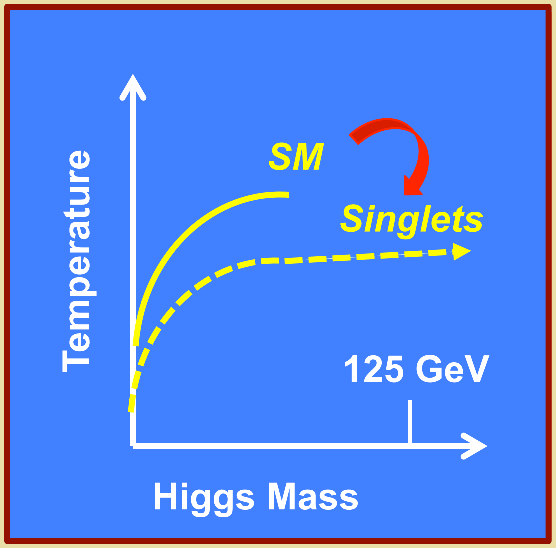
EW Phase Transition: Singlet Scalars



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

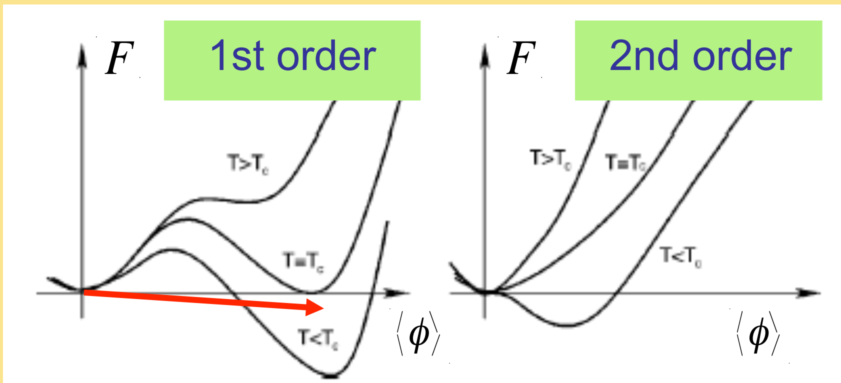
SM EW: Cross over transition



EW Phase Diagram

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

EW Phase Transition: Singlet Scalars

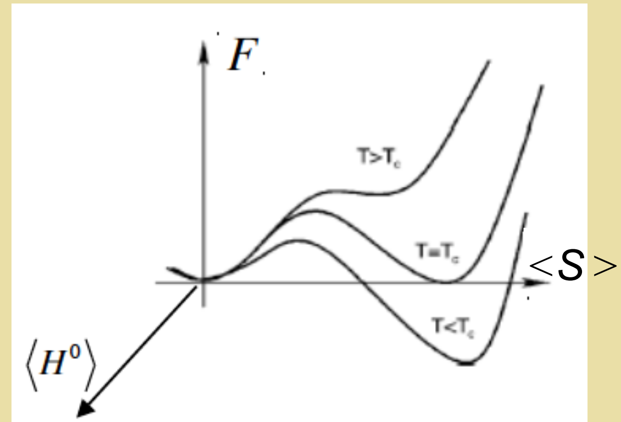


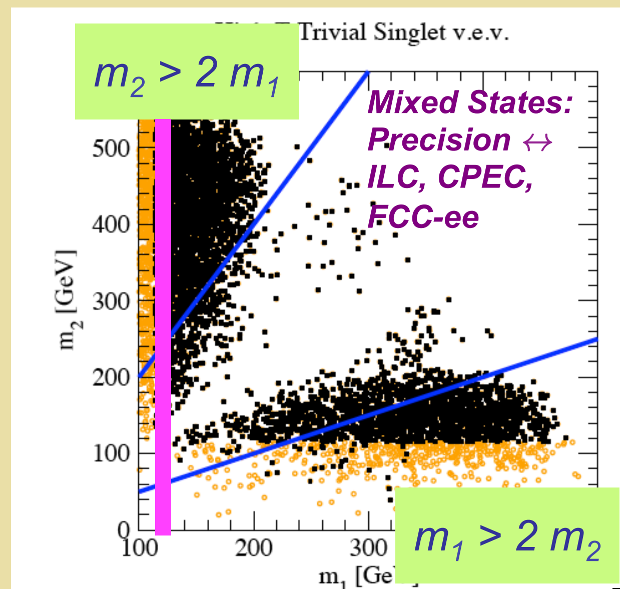
Increasing m_h →

← *New scalars*

Real Singlet: $\phi \to S$

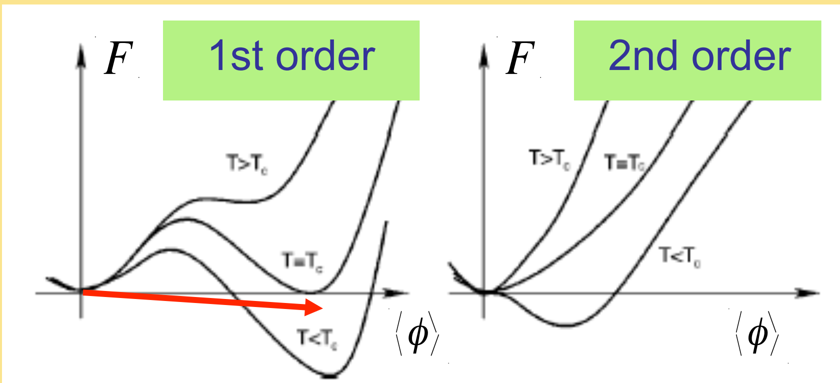
Simplest Extension: two states h_1 & h_2 – h,S mixtures

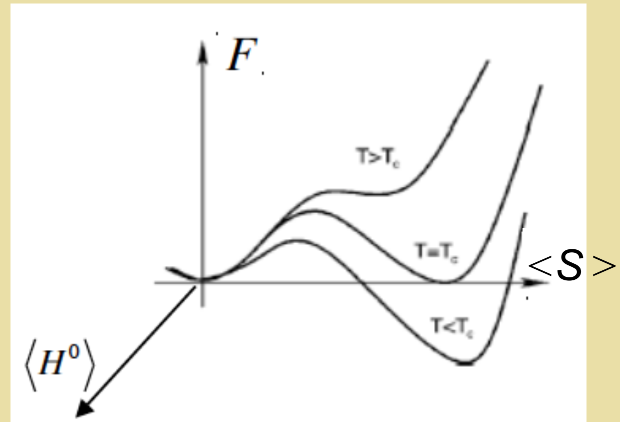




Profumo, MJRM, Shaugnessy '07

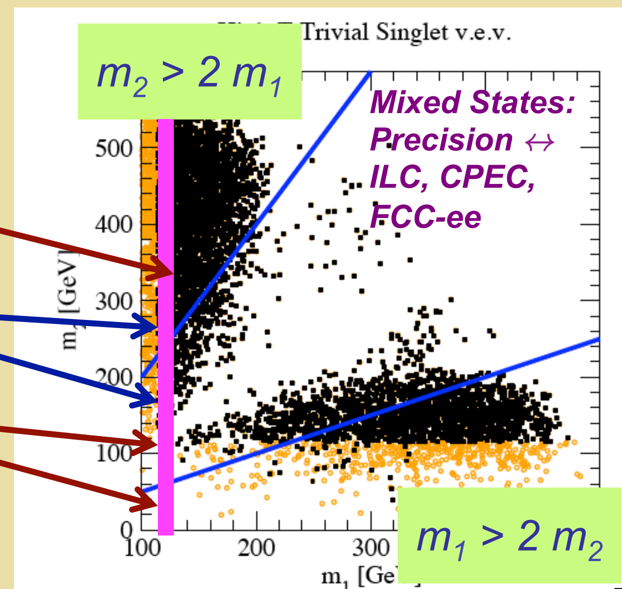
EW Phase Transition: Singlet Scalars





Collider probes

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



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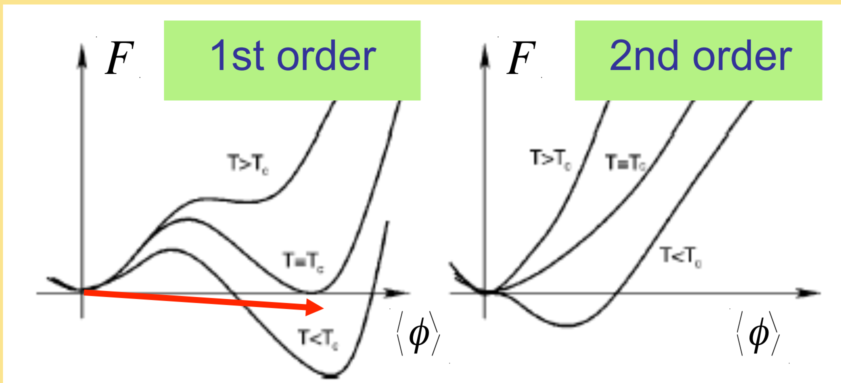
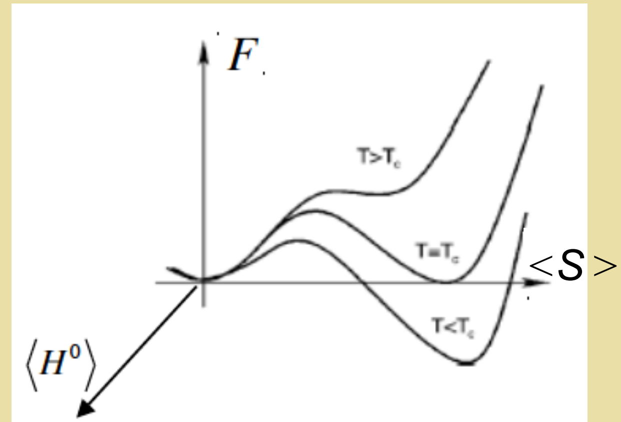
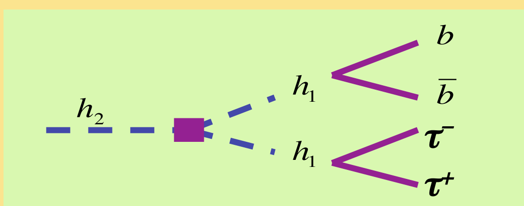
EW Phase Transition: New Scalars

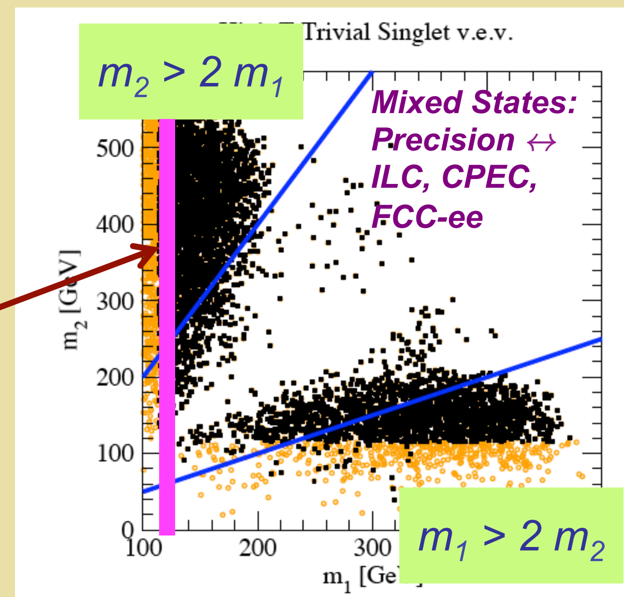




Increasing m_h ⟶

Resonant di-Higgs production

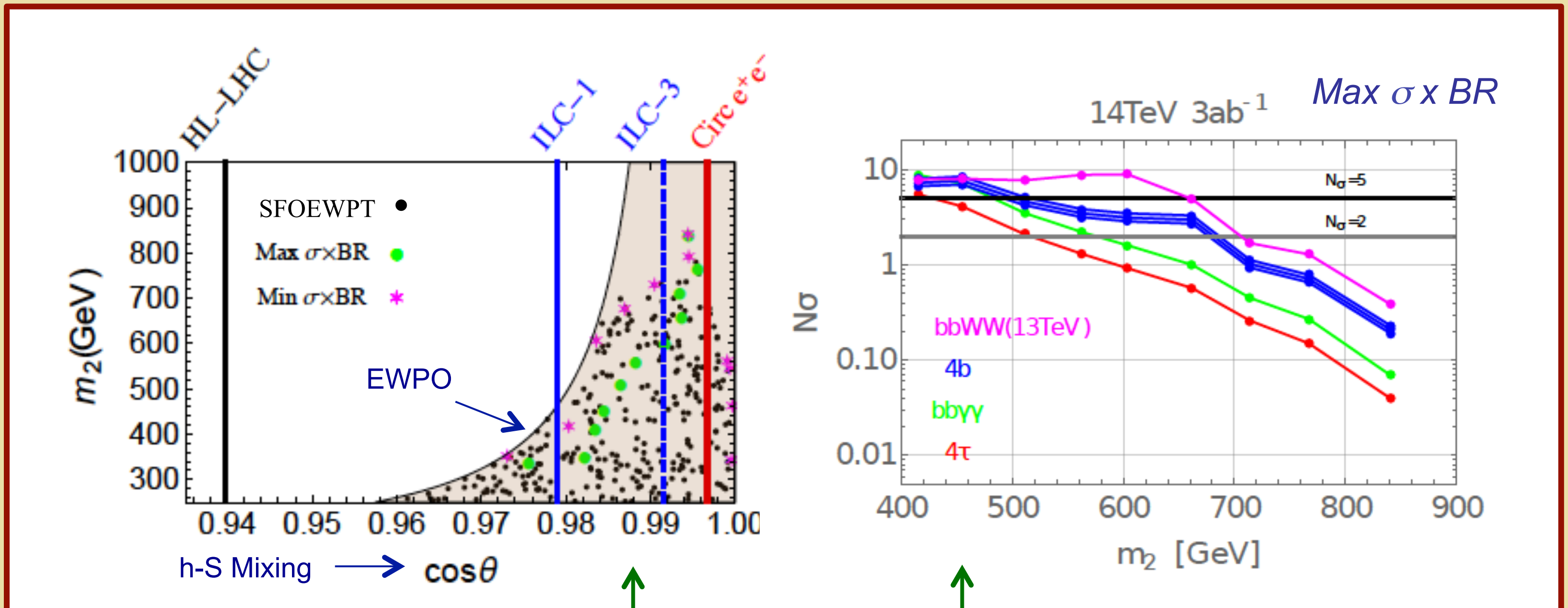




No & RM, arXiv:1310.6035 : **LHC Discovery w/ 100 fb^{-1}**

EWPT & Singlets: Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

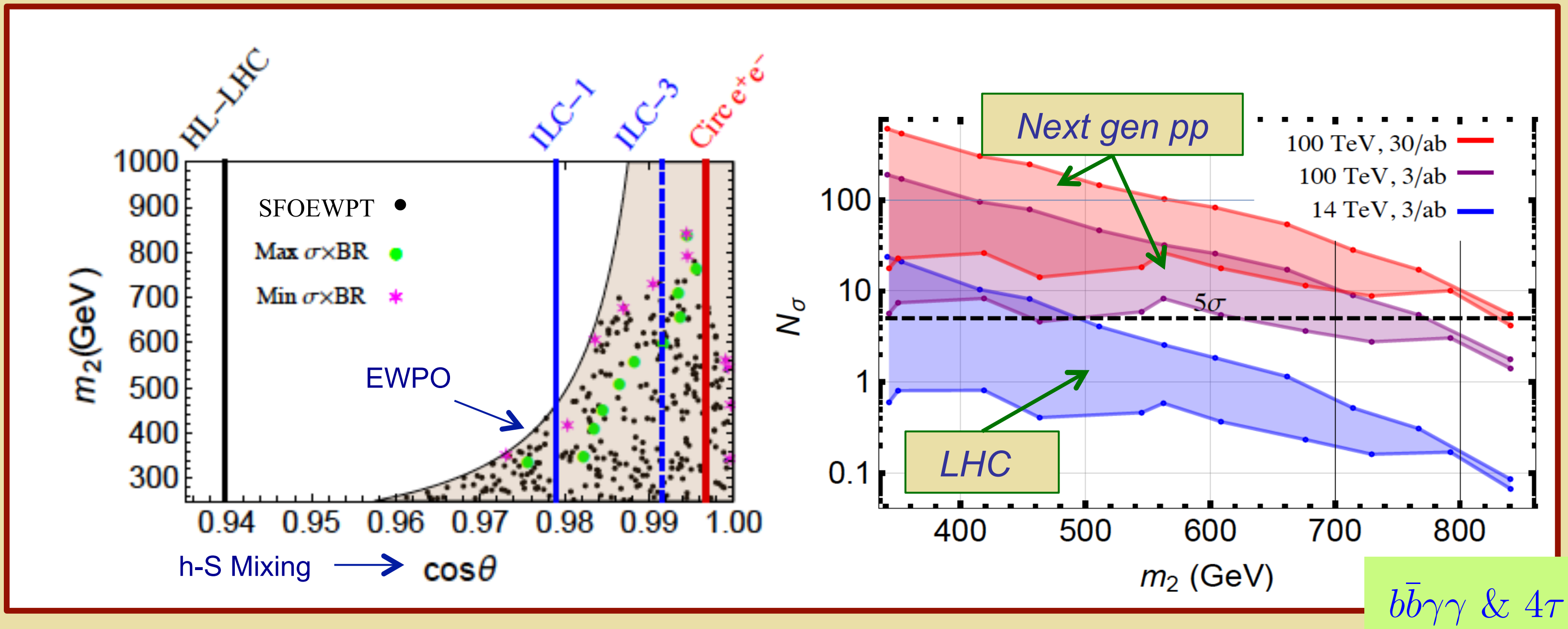


Kotwal, No, R-M, Winslow 1605.06123

Li, R-M, Willocq 1906.05289
See also: Huang et al, 1701.04442

EWPT & Singlets: Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



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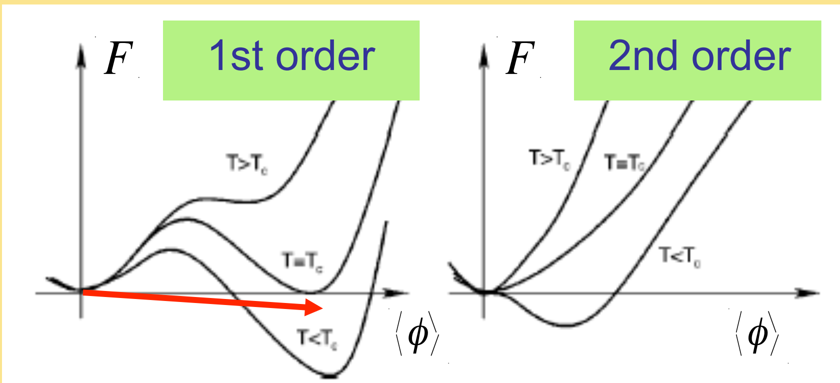
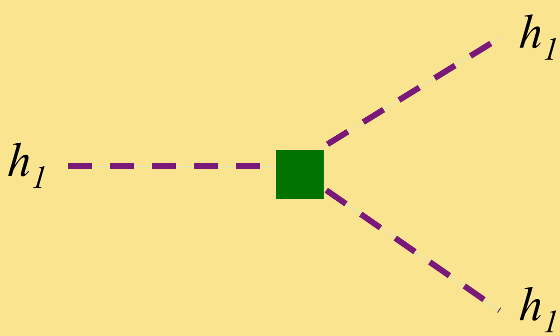
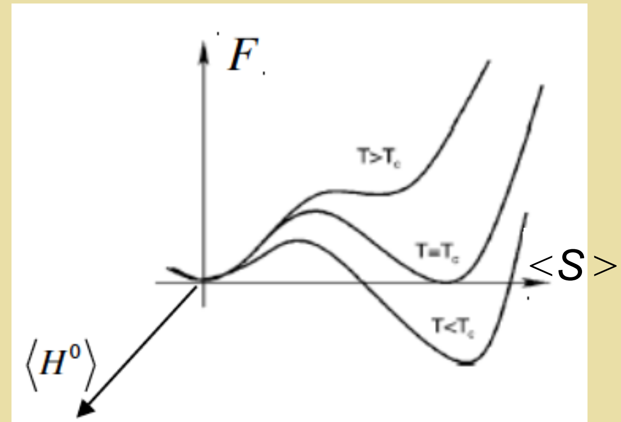
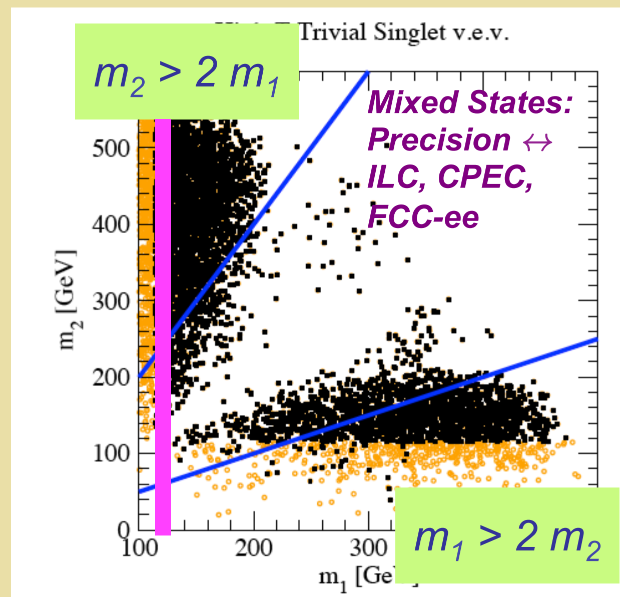
EW Phase Transition: New Scalars



Modified Higgs Self-Coupling







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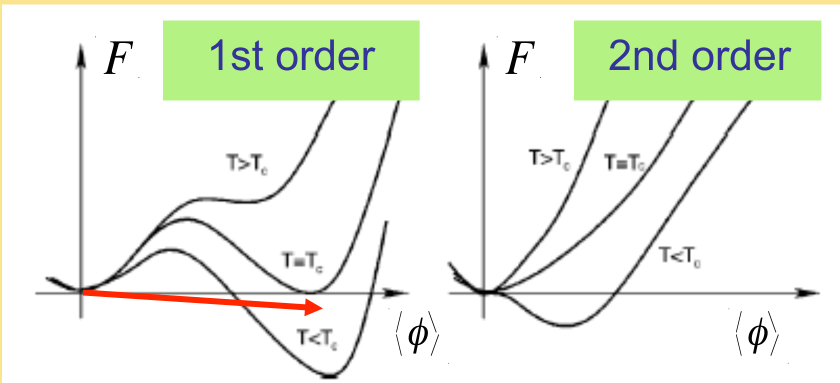

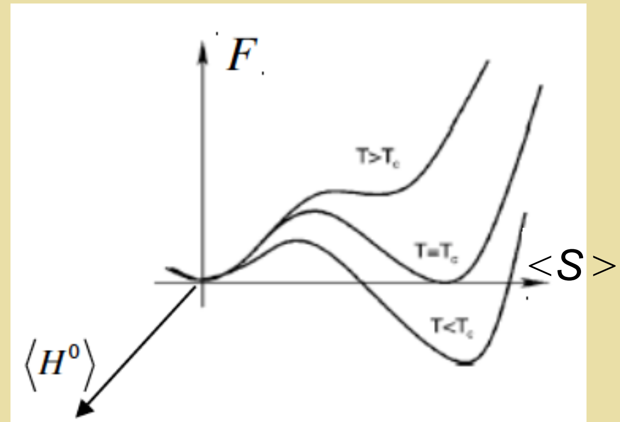

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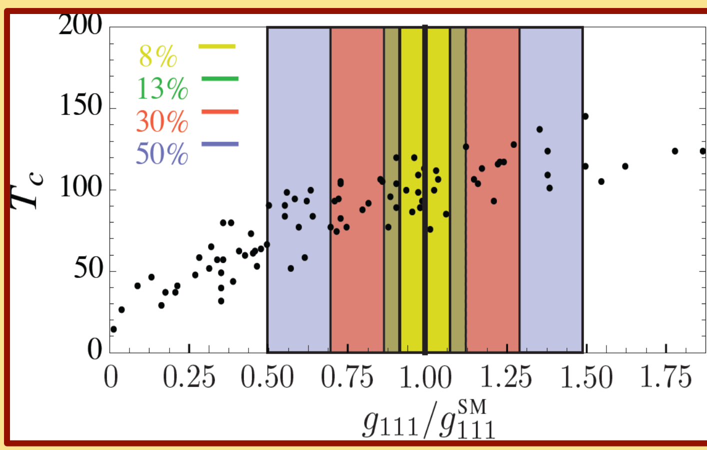
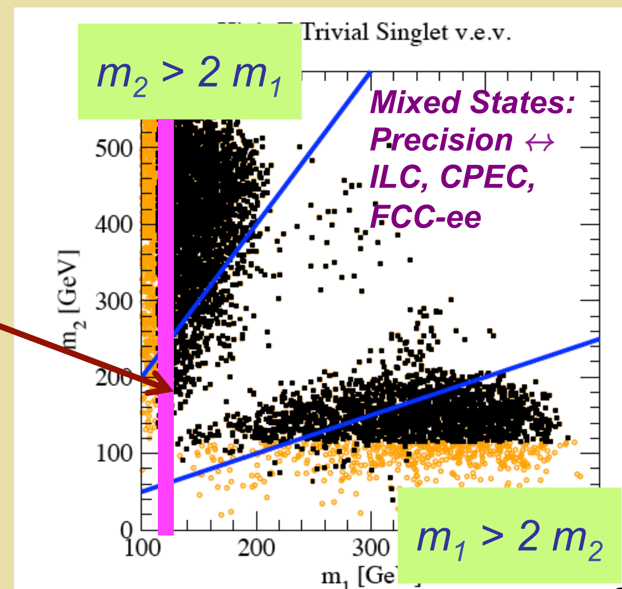
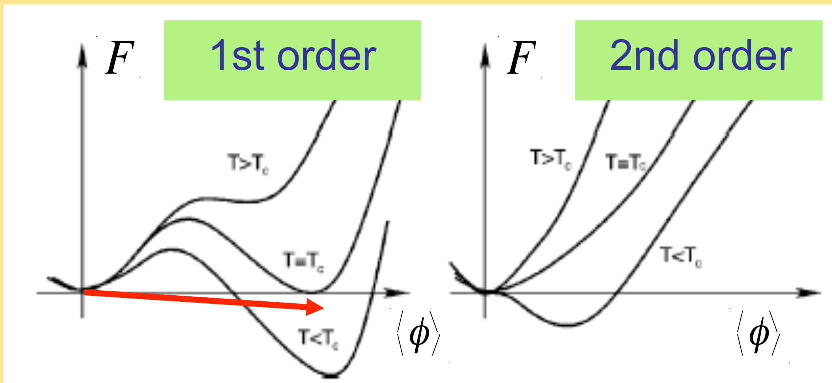
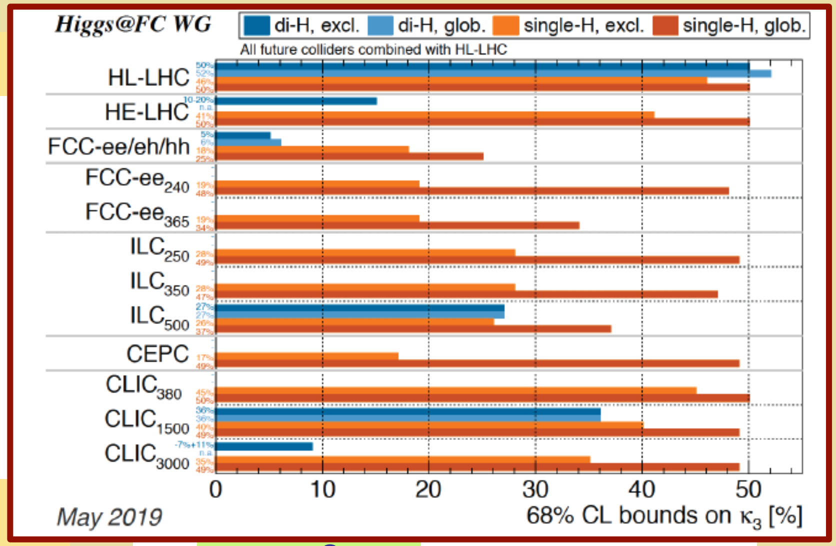




Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

EW Phase Transition: Singlet Scalars





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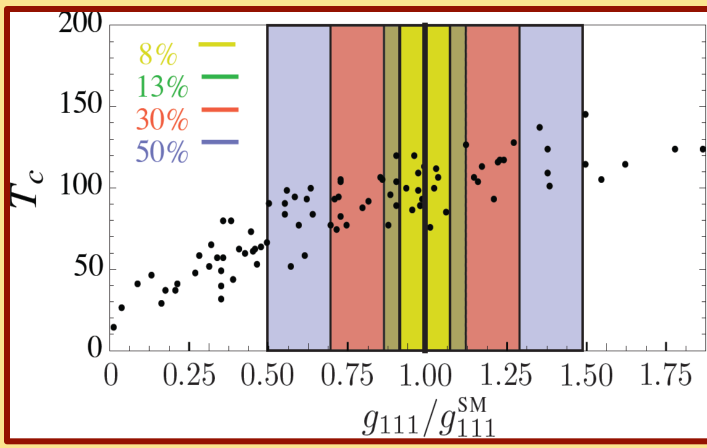

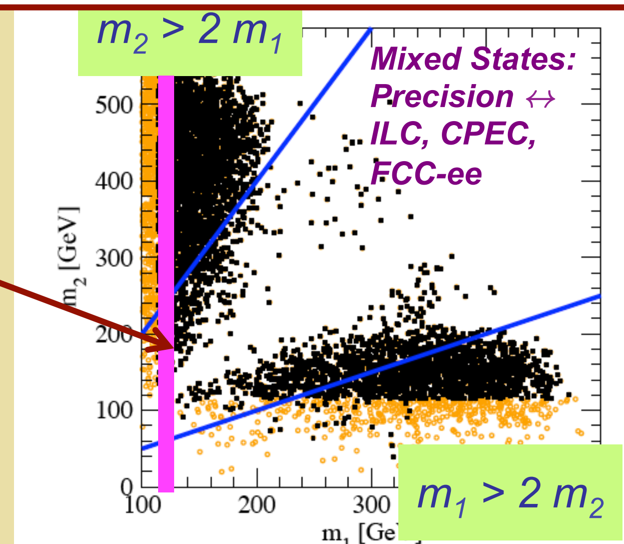

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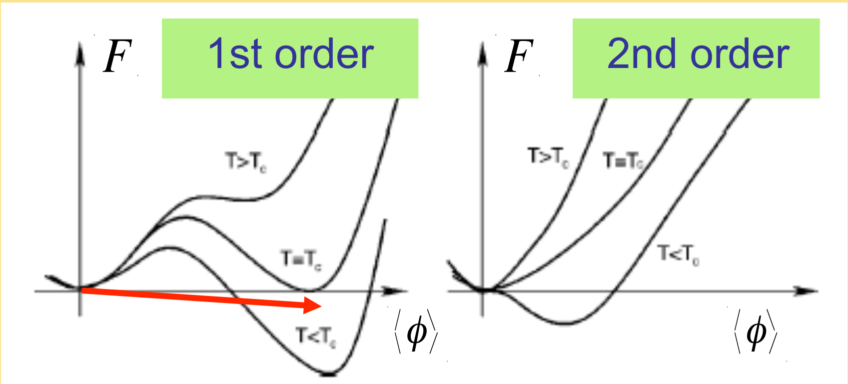
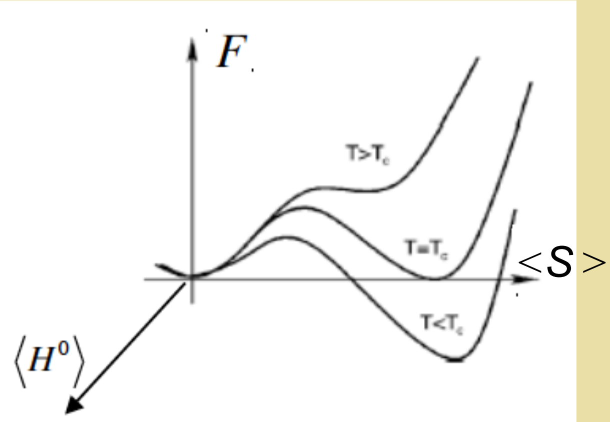
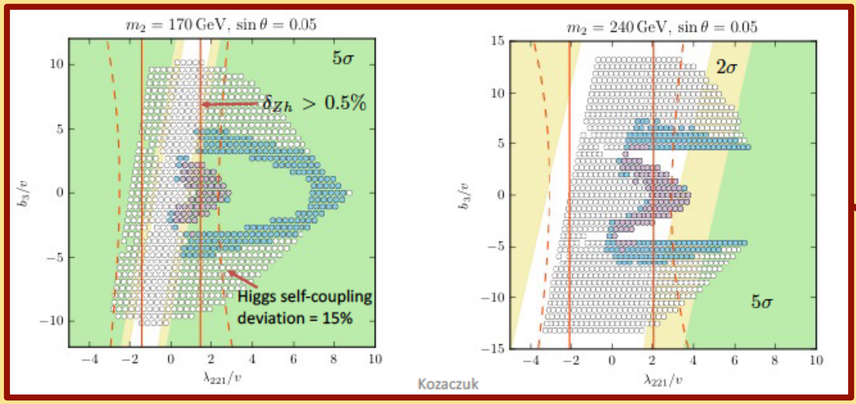
Thanks: M. Cepeda

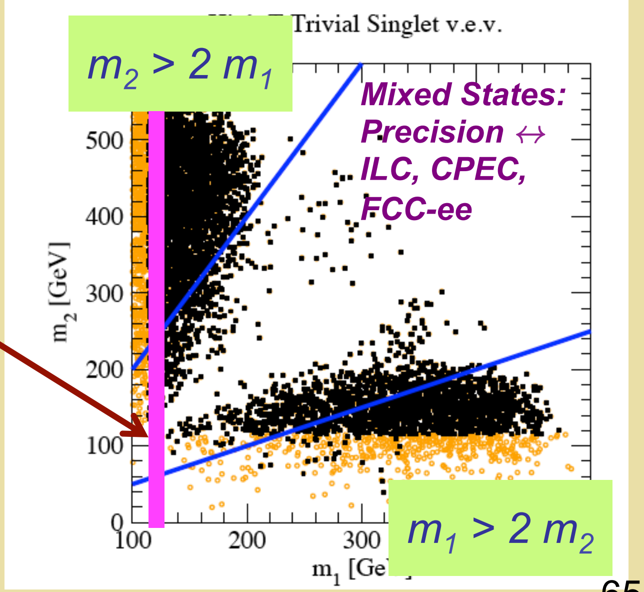
EW Phase Transition: Singlet Scalars





Singlet-like pair production (off shell)





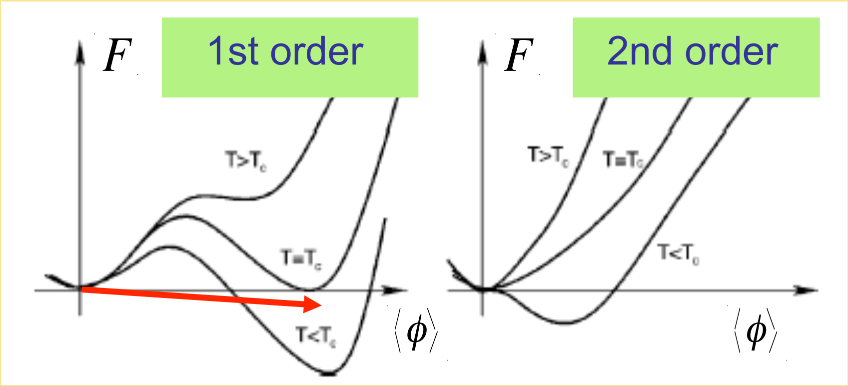
Chen, Kozaczuk, Lewis 2017

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

EW Multiplets: EWPT

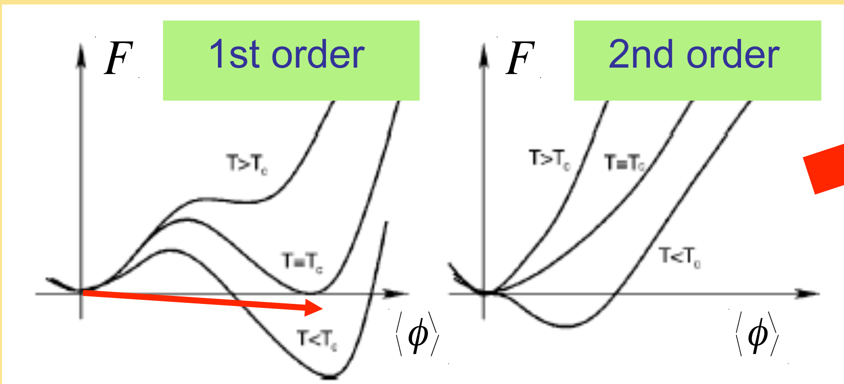


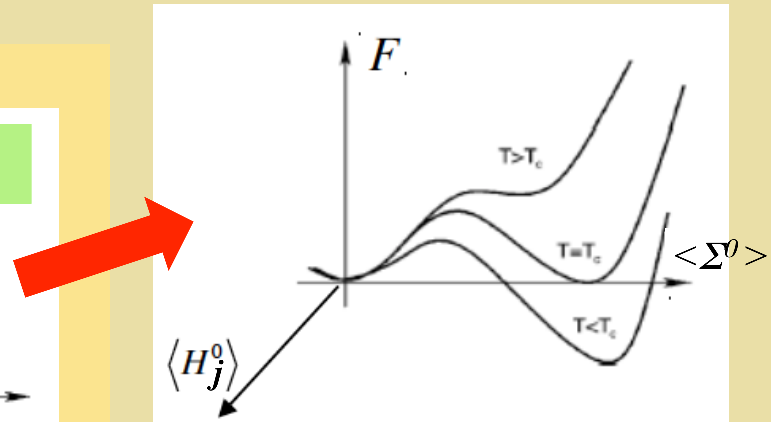
Increasing m_h →

← *New scalars*

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

EW Multiplets: EWPT





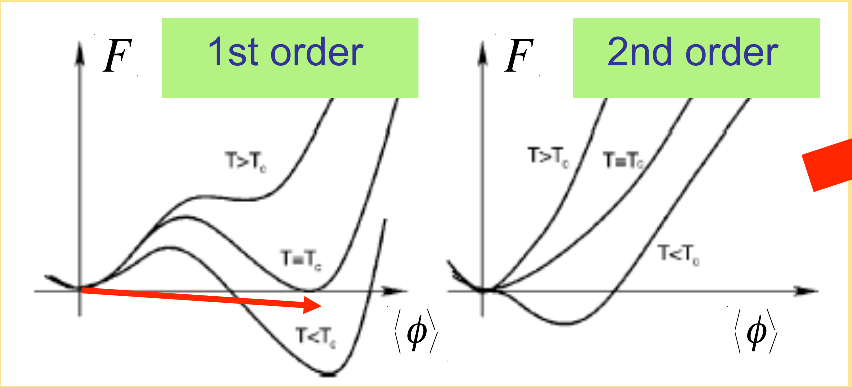
Increasing m_h →

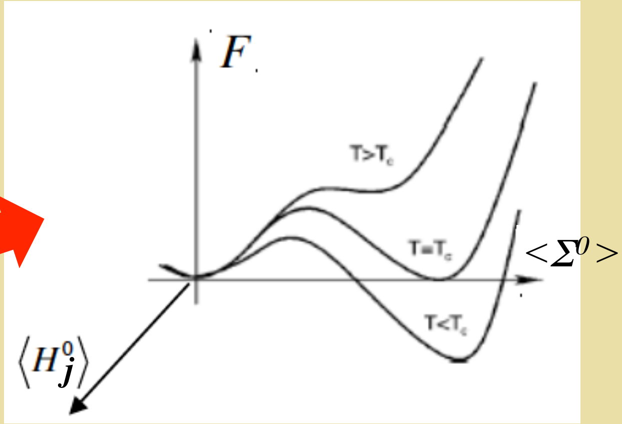
← *New scalars*

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

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

EW Multiplets: EWPT





Increasing m_h →

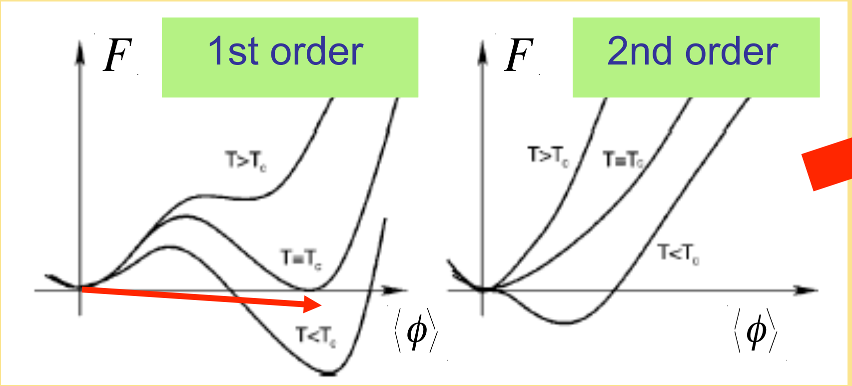
← *New scalars*

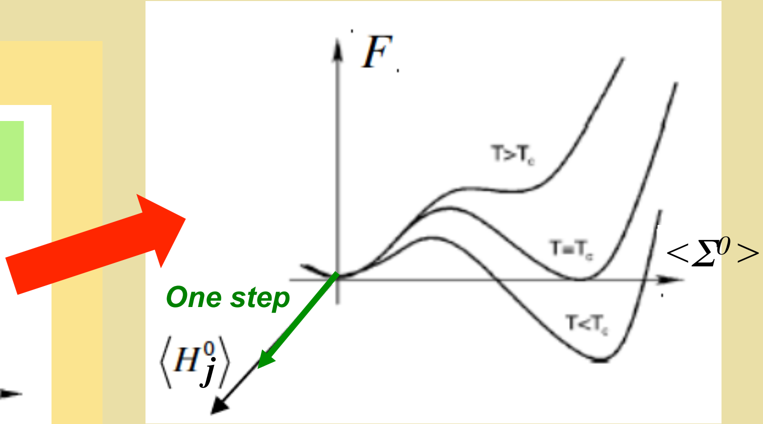
- *Thermal loops*
- *Tree-level barrier*

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

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

EW Multiplets: One-Step EWPT





Increasing m_h →

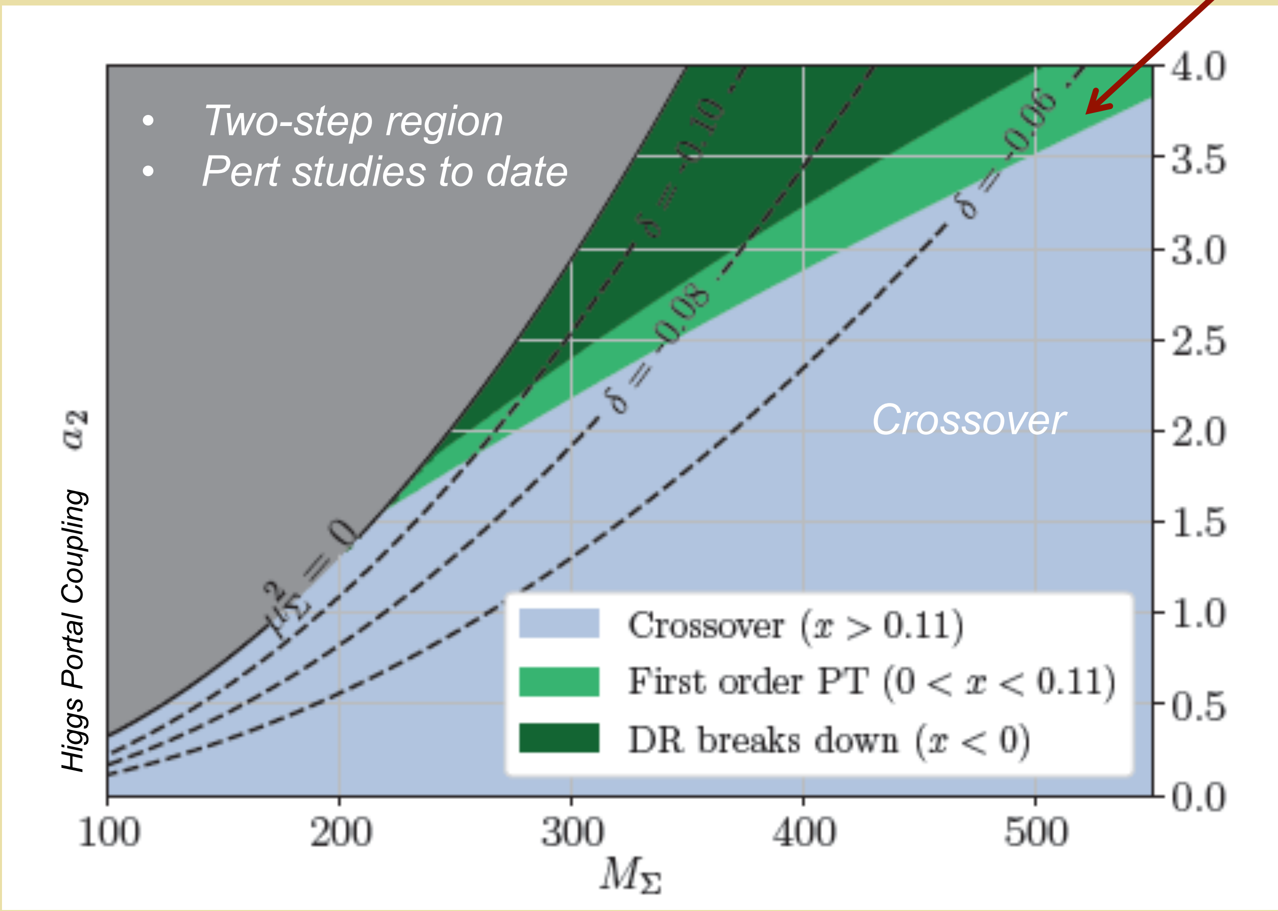
← *New scalars*

- *One-step: Sym phase → Higgs phase*

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

Real Triplet: One-Step EWPT

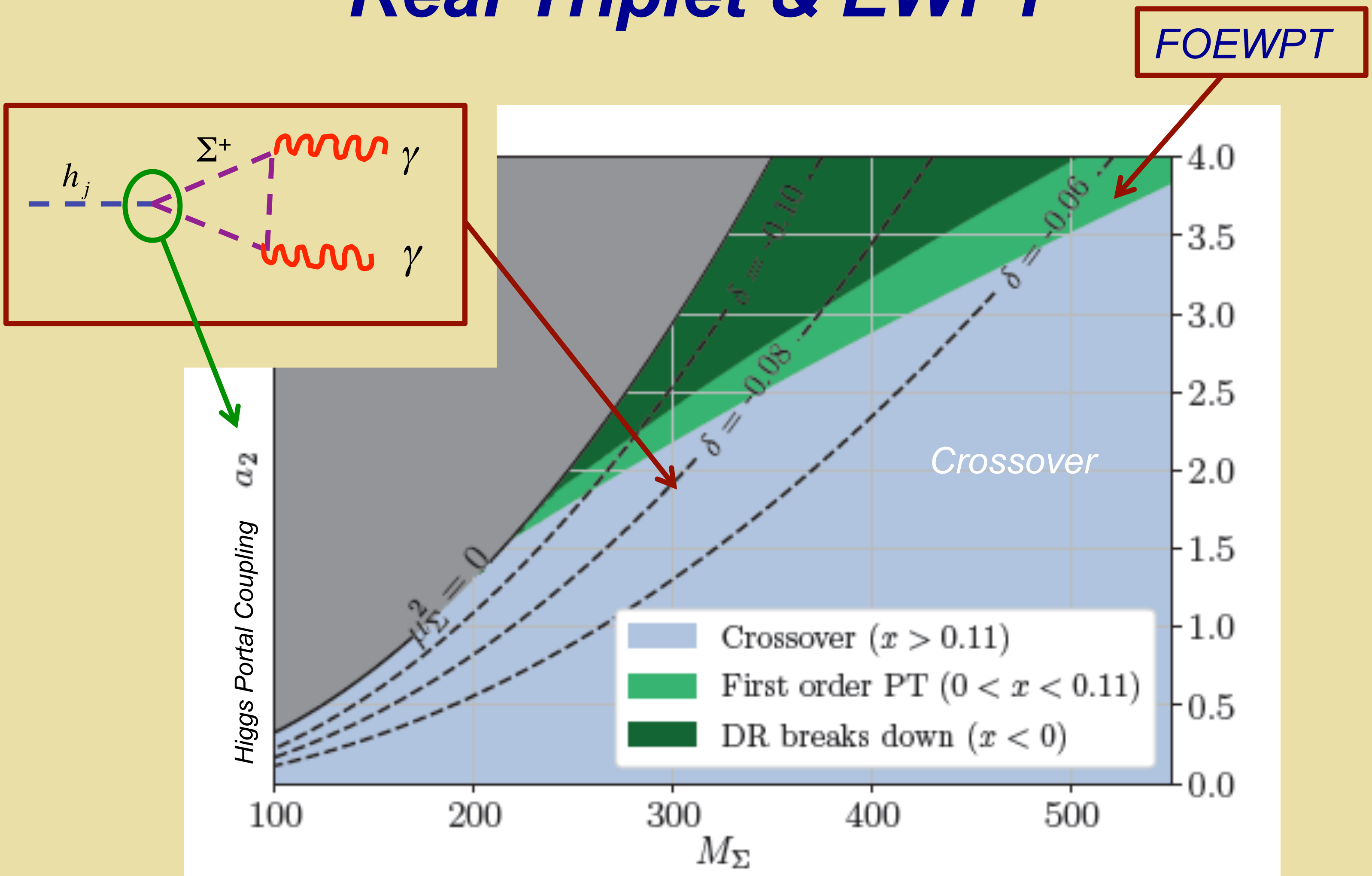
FOEWPT



- One-step
- Non-perturbative

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

Real Triplet & EWPT



- *One-step*
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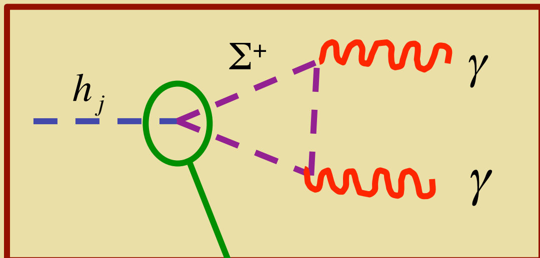
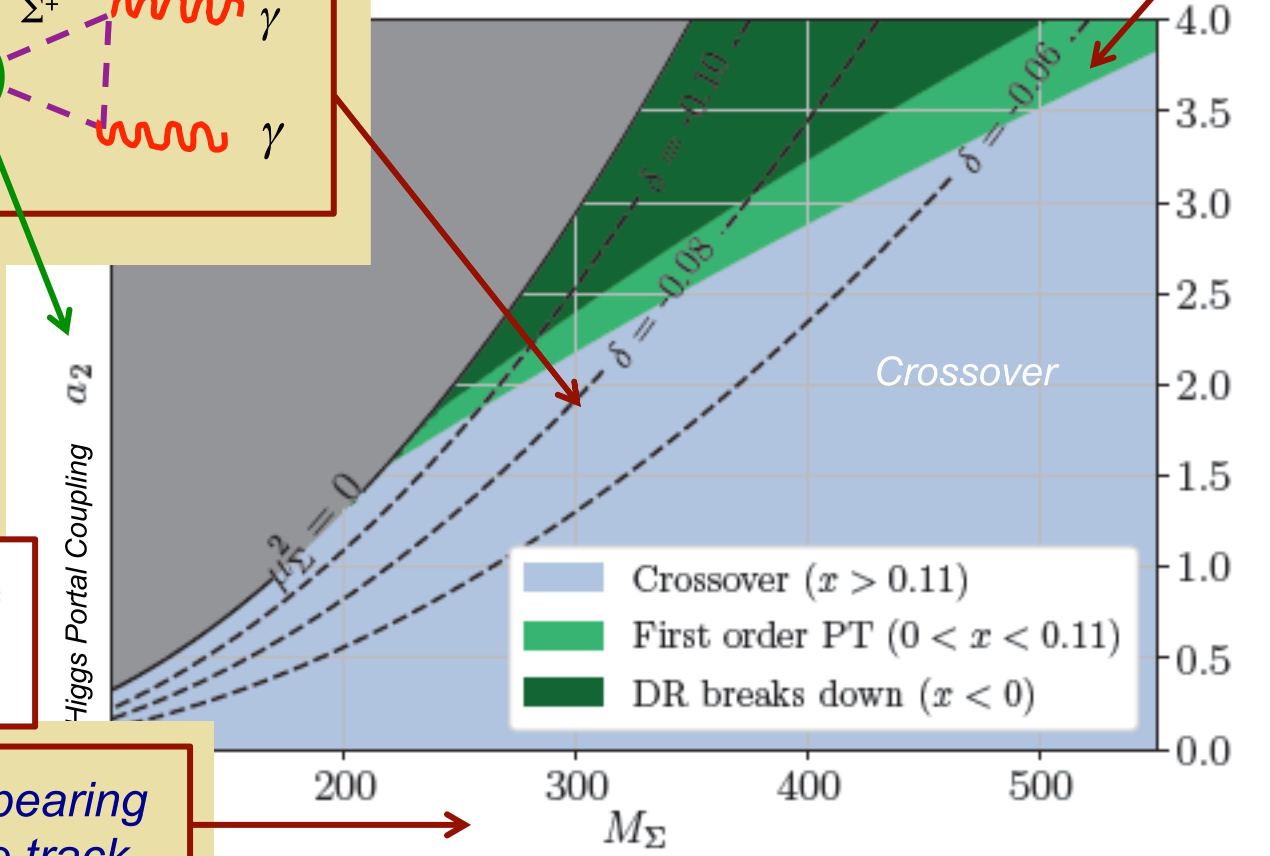




FOEWPT

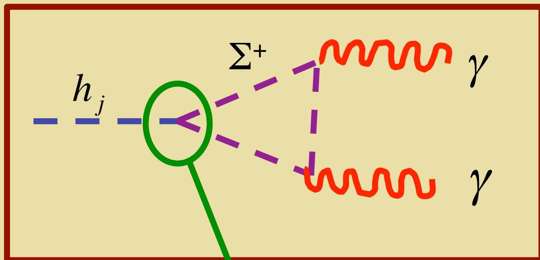
Disappearing charge track

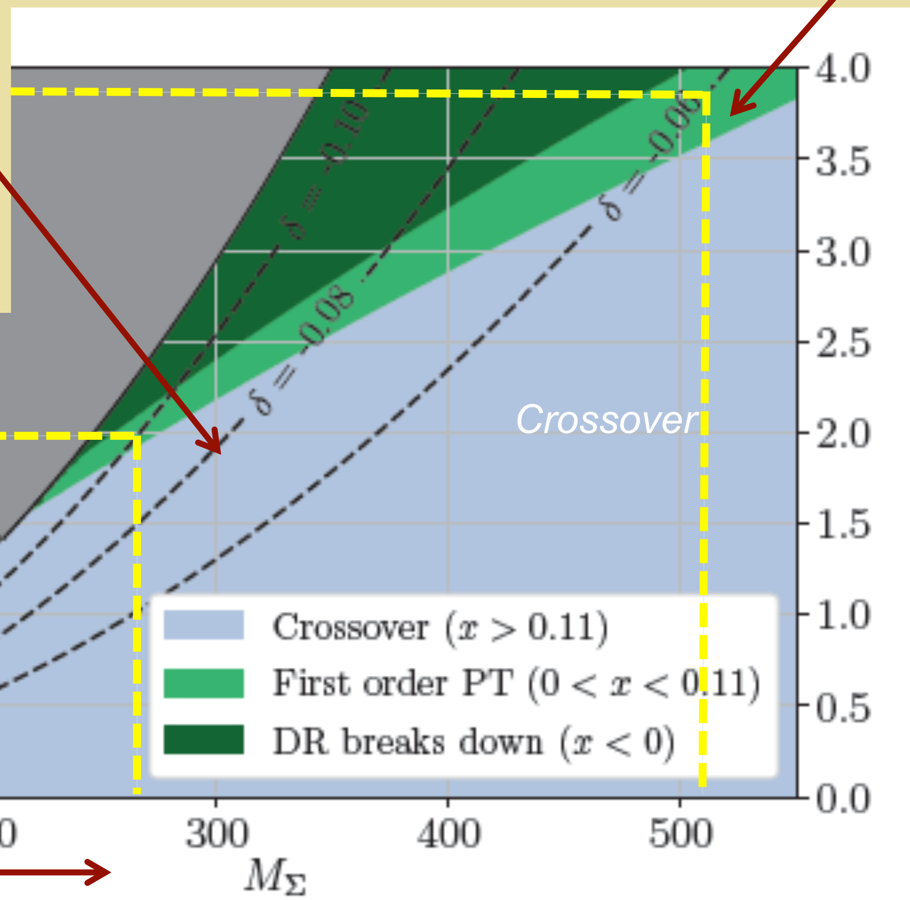
- *One-step*
- *Non-perturbative*

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

Real Triplet & EWPT

FOEWPT



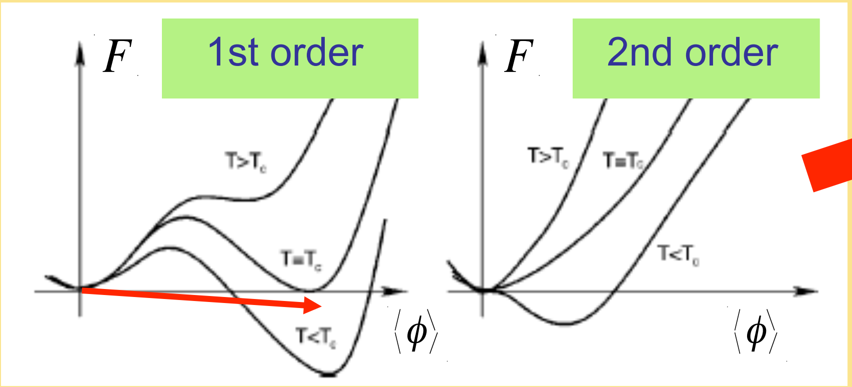


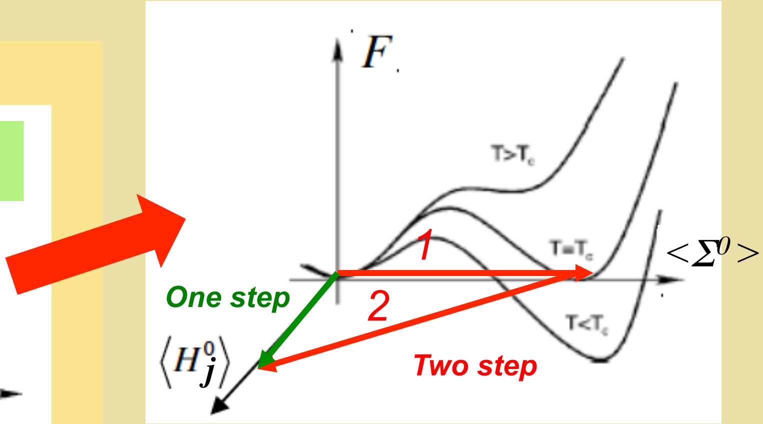
Disappearing charge track

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

- One-step
- Non-perturbative

EW Multiplets: Two-Step EWPT





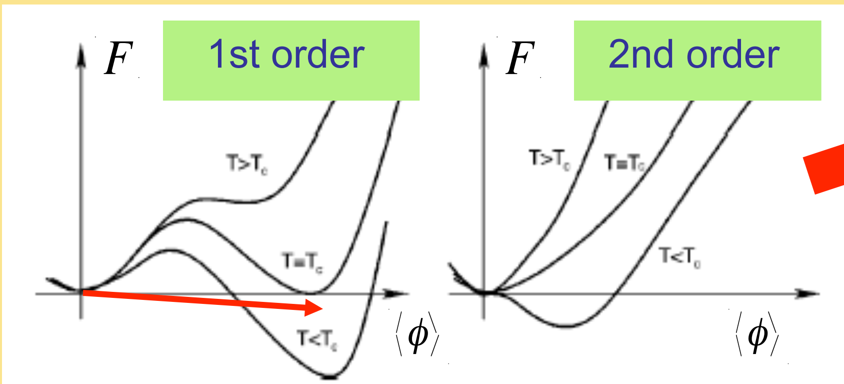
Increasing m_h ⟶

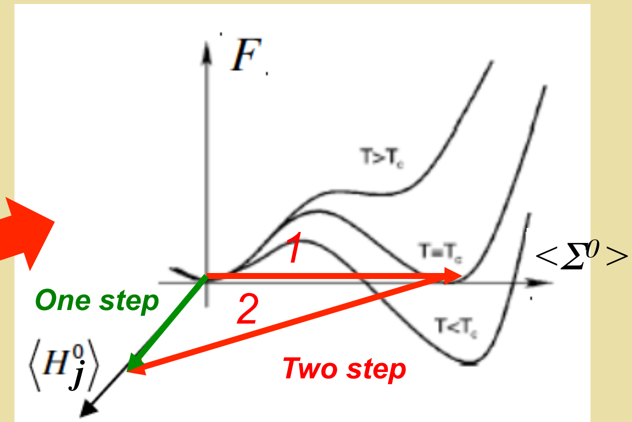
⟵ *New scalars*

- *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





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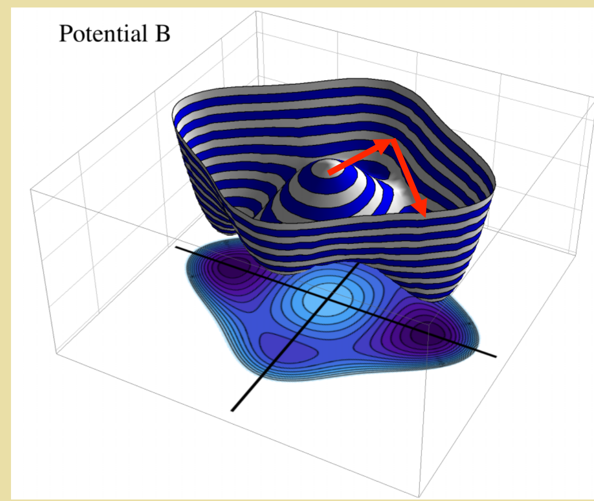

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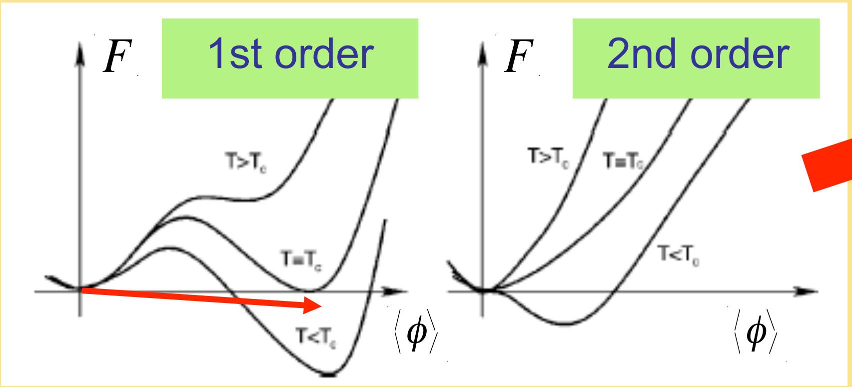

Increasing m_h ⟶

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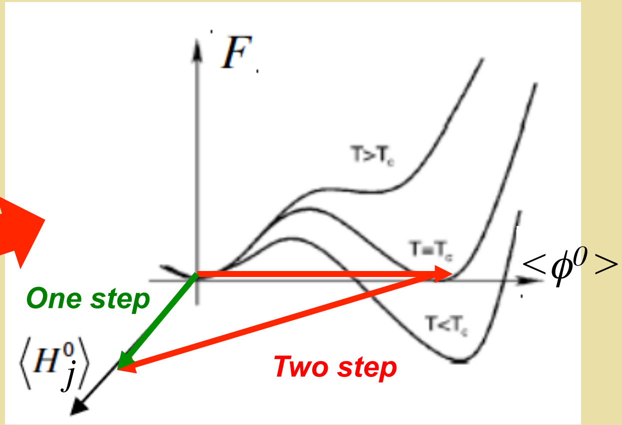
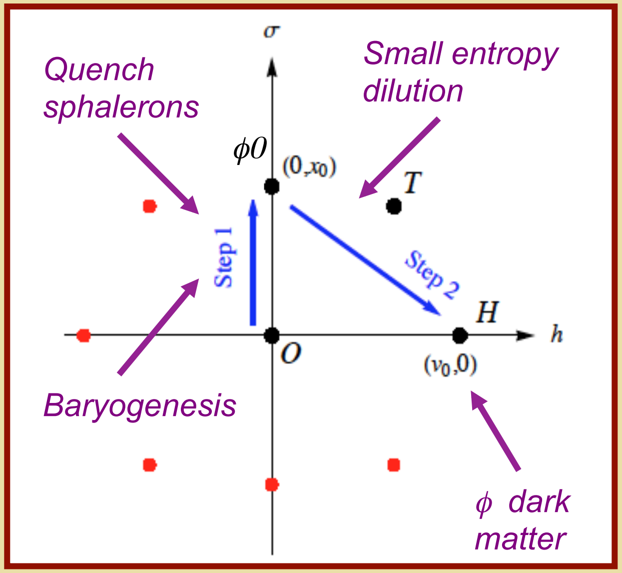


- *Step 1: thermal loops*
- *Step 2: tree-level barrier*



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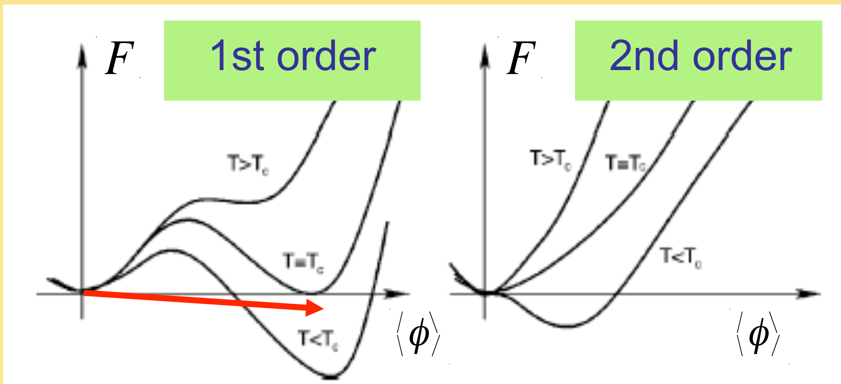
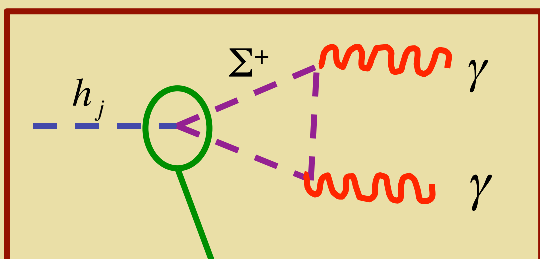
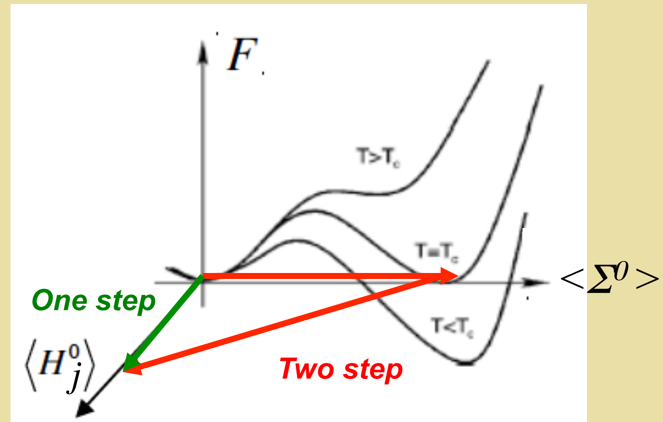
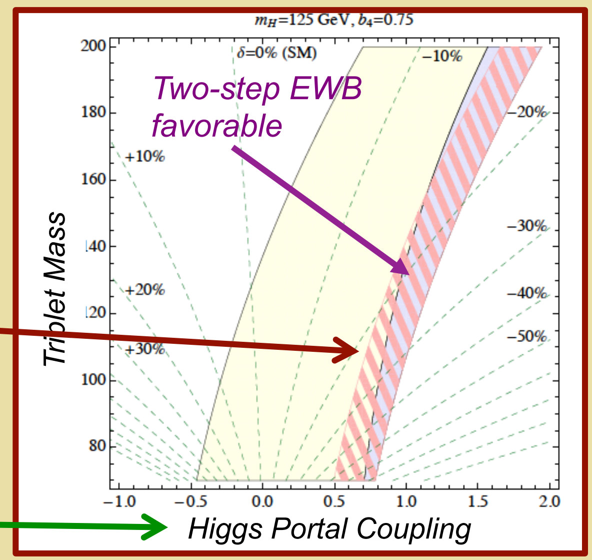


Increasing m_h







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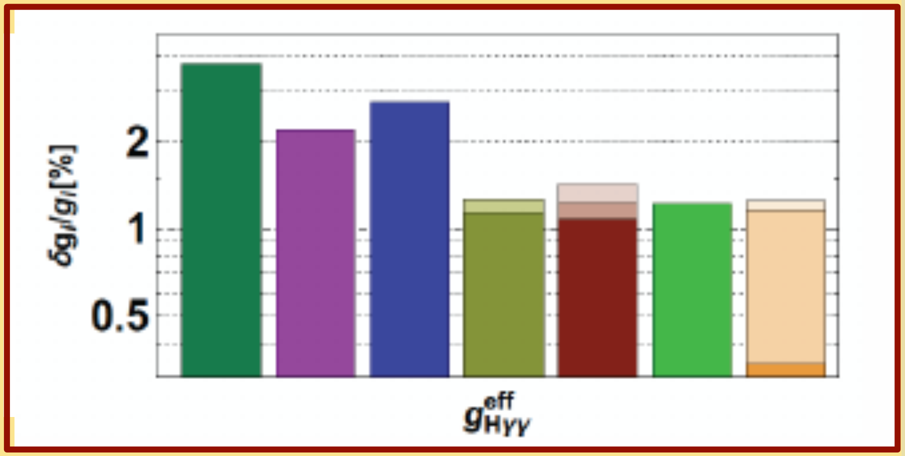

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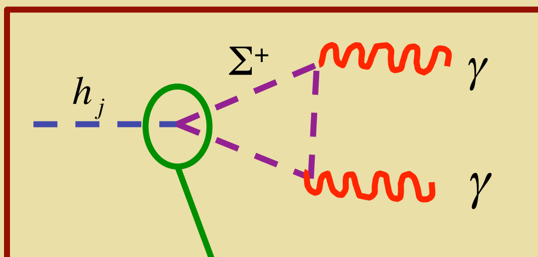

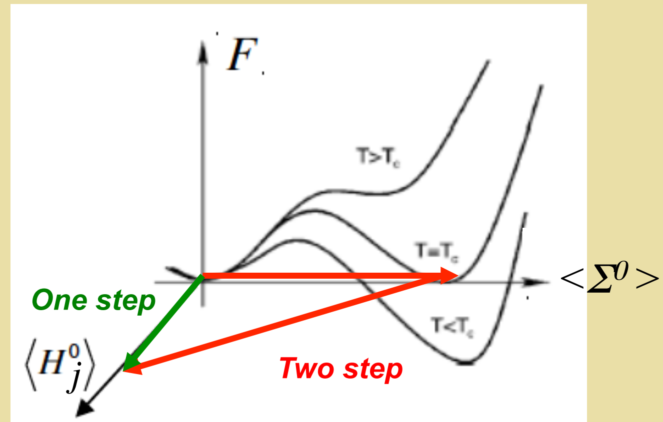

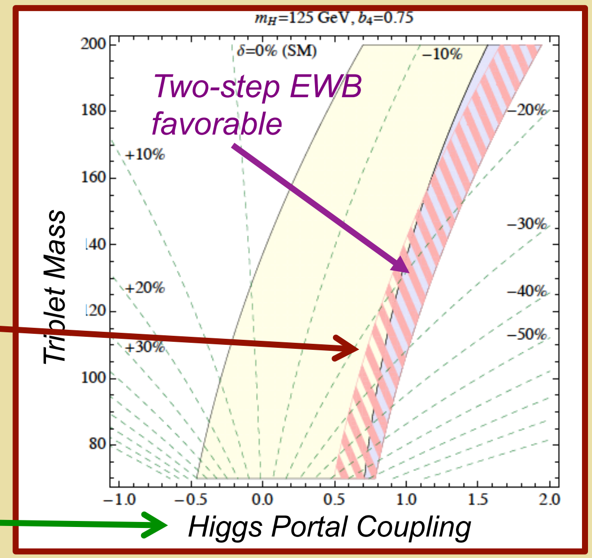

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Thanks: M. Cepeda

IV. Outlook

- *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*

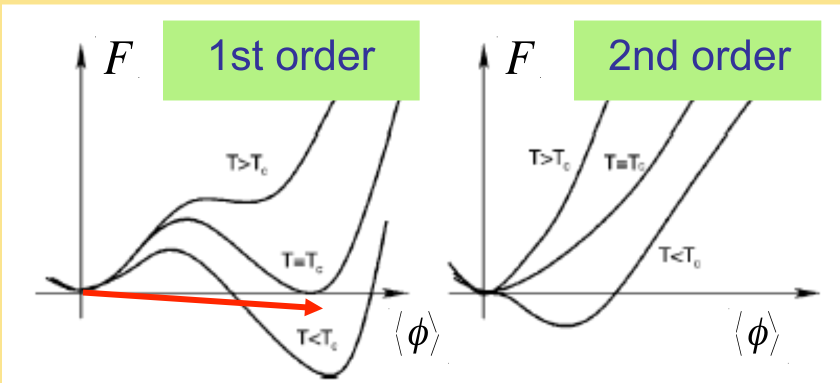
- *Searches for new scalars and precision Higgs measurements at the LHC and prospective next gen colliders could conclusively determine the nature of the EWSB transition*

Main Theme for This Talk

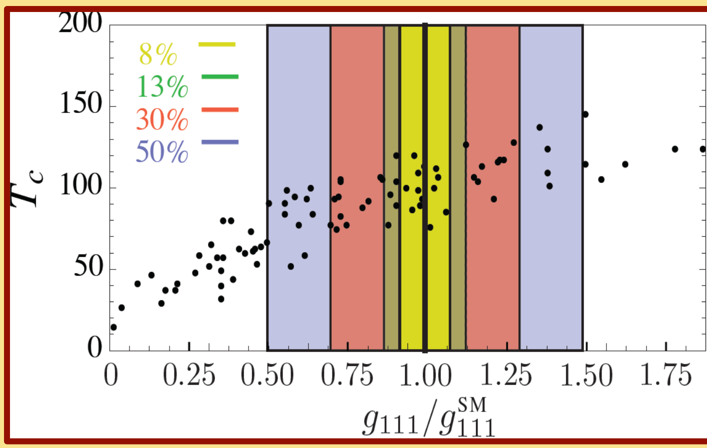
T_{EW} → EW phase transition is a target for the LHC & beyond

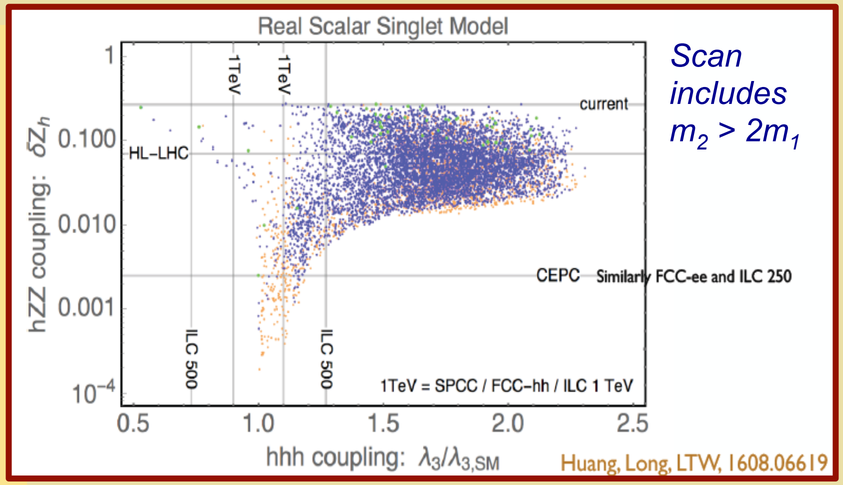
Back Up Slides

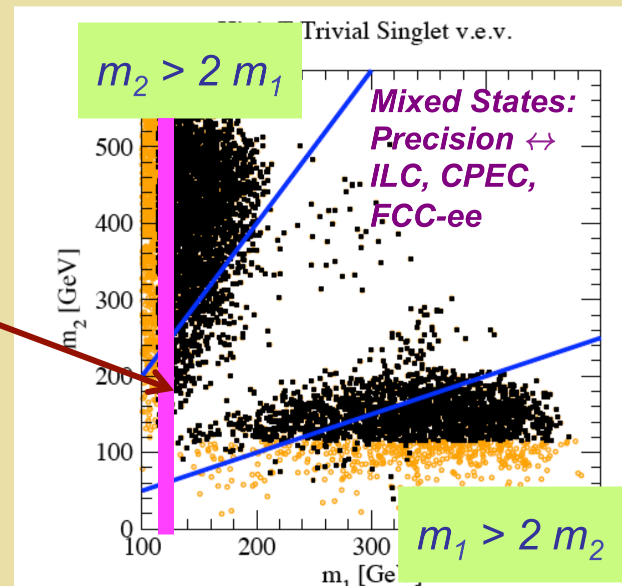
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling





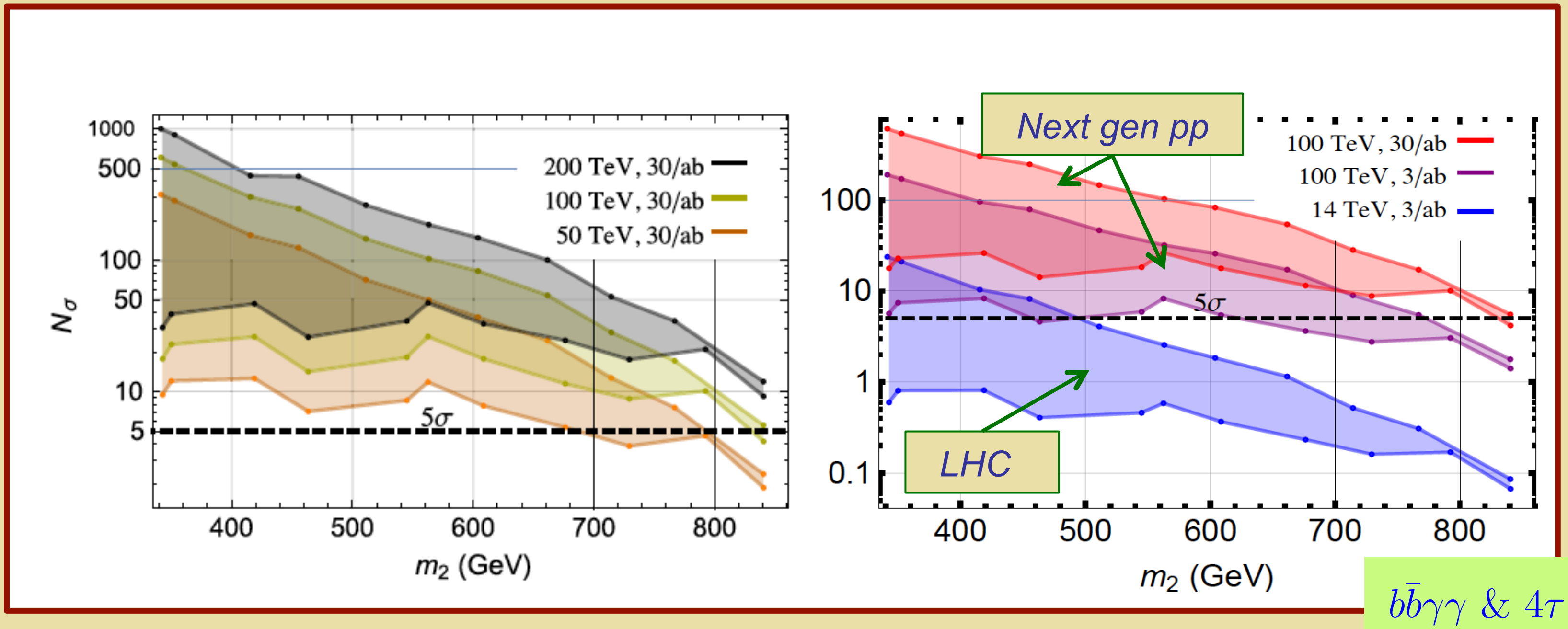


Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

Thanks: M. Cepeda

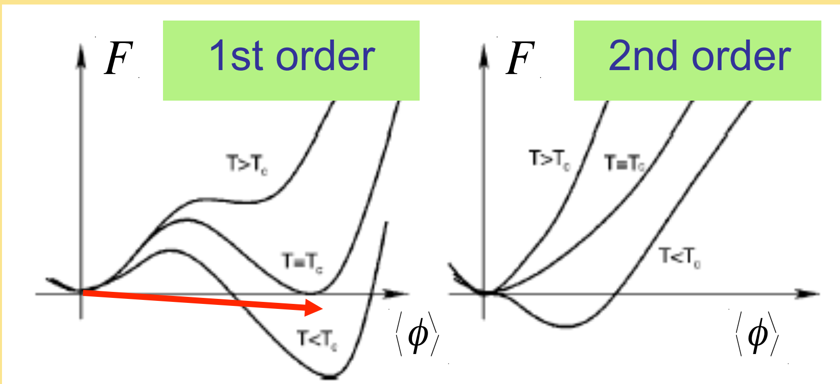
EW Phase Transition: Singlet Scalars

SFOEWPT Benchmarks: Resonant di-Higgs

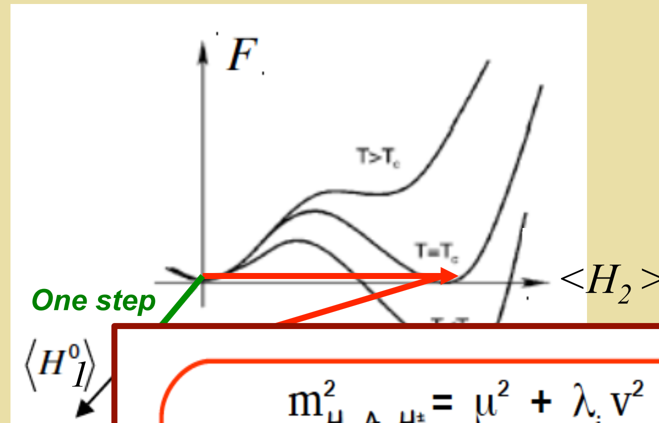


Kotwal, No, R-M, Winslow 1605.06123

EW Multiplets: 2HDM



Increasing m_h →



$$m^2_{H_0,A_0,H^\pm} = \mu^2 + \lambda_i v^2$$

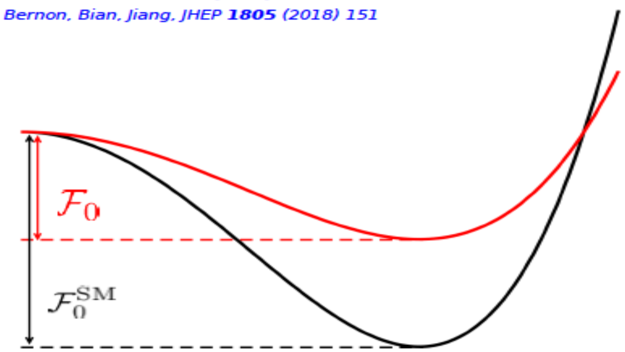
Difference between Symmetric - Broken phase in CW piece guaranteed for large BSM mass splitting!

$m_{A_0} - m_{H_0}$

Nature of EWPT dominantly controlled by T=0 Vacuum energy difference

*Dorsch, Huber, Mimasu, JMN, JHEP **1712** (2017) 086*

*Bernon, Bian, Jiang, JHEP **1805** (2018) 151*



$$\Delta \mathcal{F} \equiv \mathcal{F}_0 - \mathcal{F}_0^{SM} = -\frac{v^2}{8}\cos(\beta-\alpha)^2(m_{H_0}^2 - m_h^2) + \left[\sum_s \frac{m_s^4}{64\pi^2}\left(\log\frac{|m_s^2|}{Q^2}-\frac{1}{2}\right)\right]\Bigg|_v - \left[\sum_s \frac{m_s^4}{64\pi^2}\left(\log\frac{|m_s^2|}{Q^2}-\frac{1}{2}\right)\right]\Bigg|_0$$

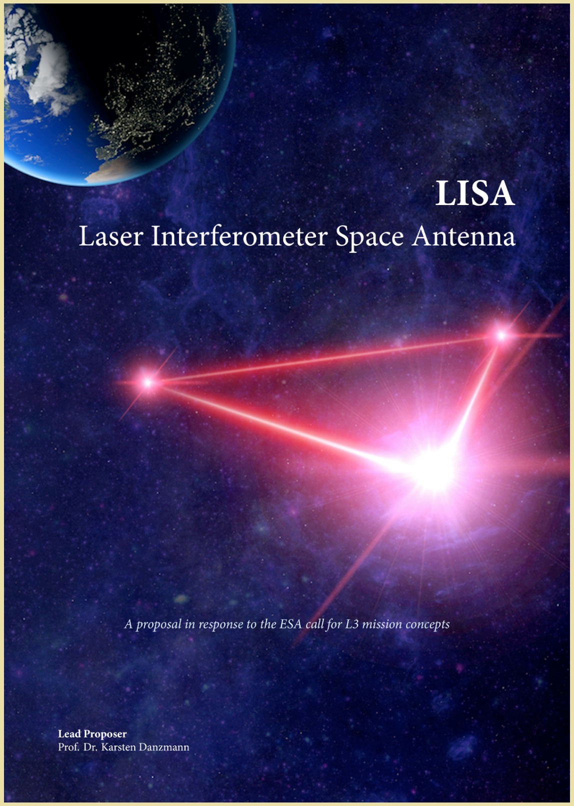
Broken Symmetric

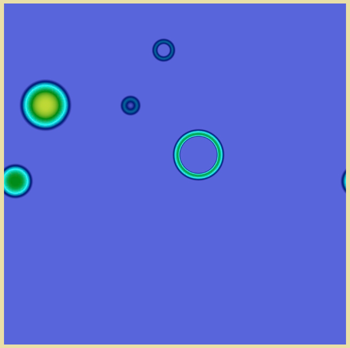
1-loop (Coleman-Weinberg)

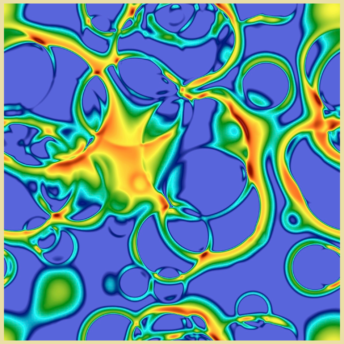
Thanks: J. M. No

See S. Huber Talk

Gravitational Radiation







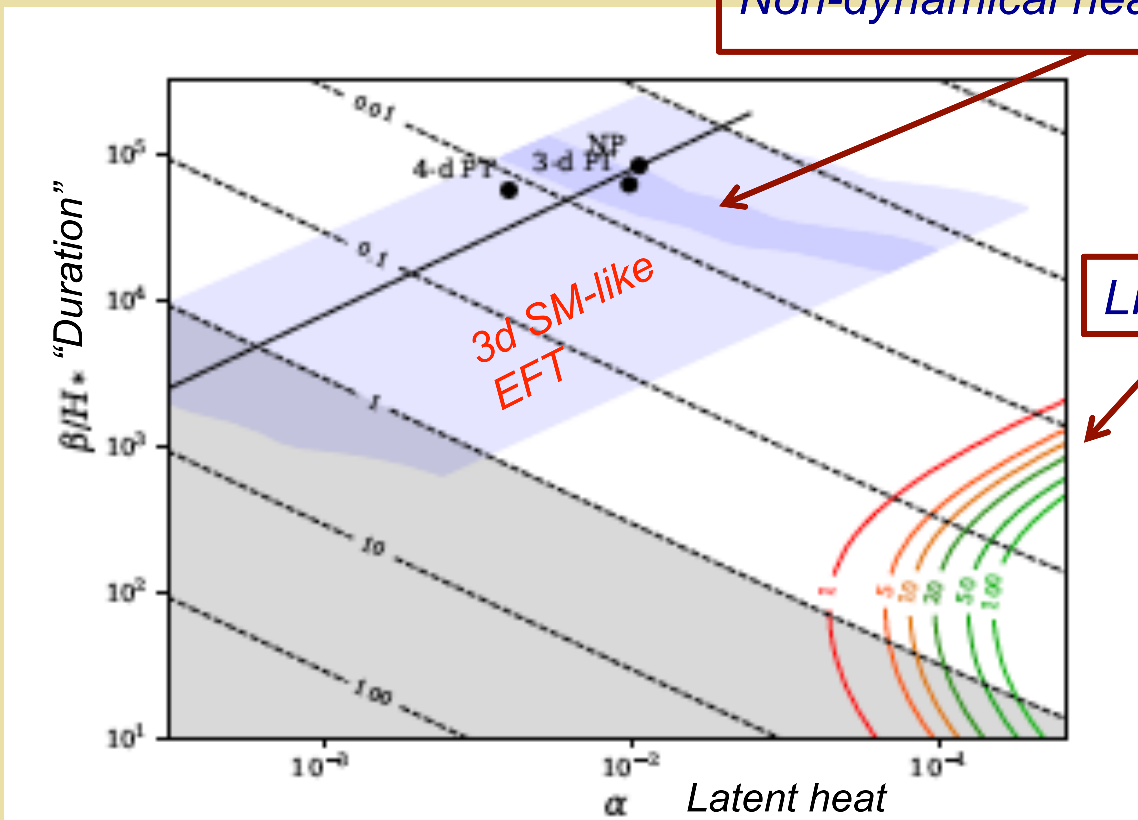
1. Bubbles nucleate and grow
2. Expand in a plasma - create reaction fronts
3. Bubbles + fronts collide - violent process
4. Sound waves left behind in plasma
5. Turbulence; damping

Thanks: D. Weir

Heavy Real Singlet: EWPT & GW

Non-dynamical heavy BSM scalars

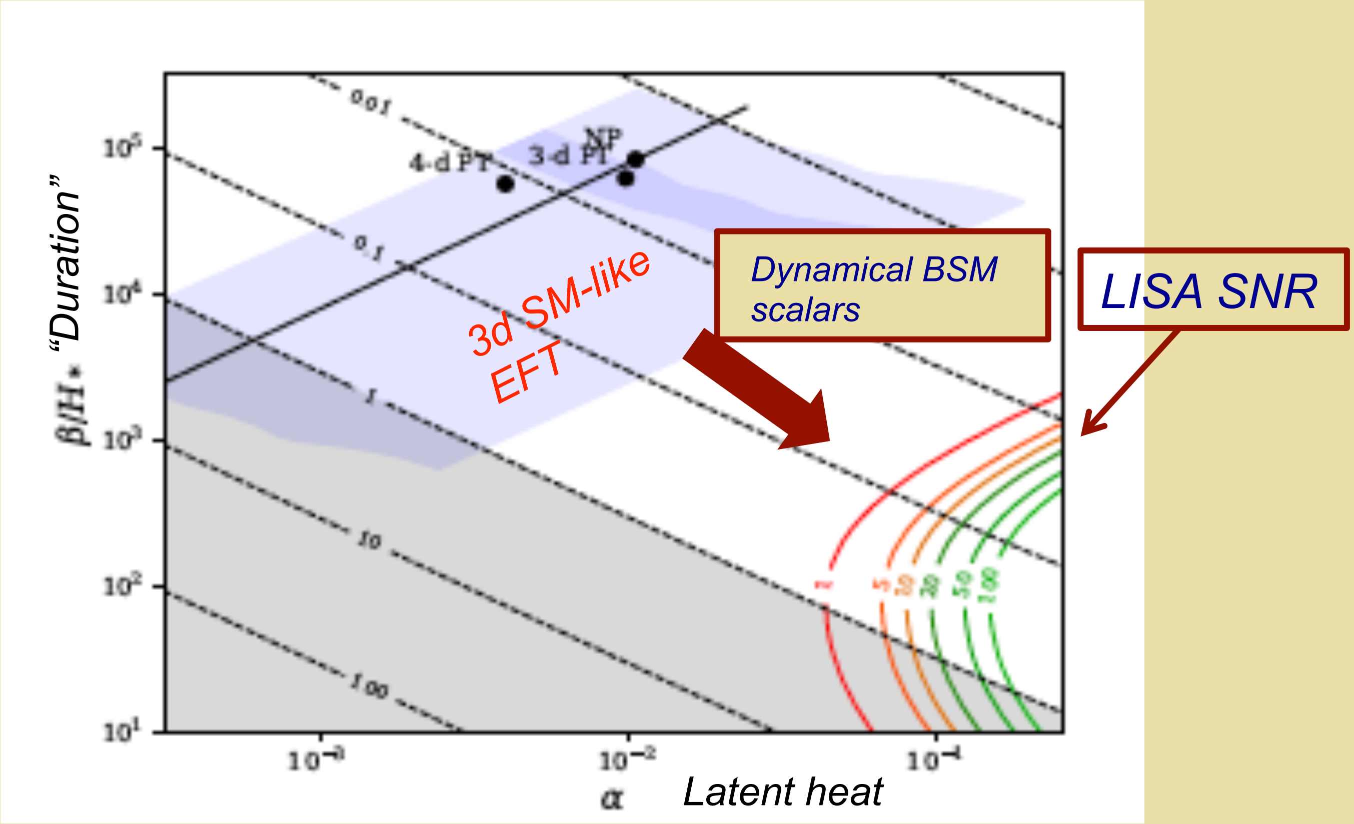
LISA SNR



- One-step
- Non-perturbative

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

Heavy Real Singlet: EWPT & GW



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

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