EDMs & Baryogenesis

M.J. Ramsey-Musolf

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

About MJRM:

Science

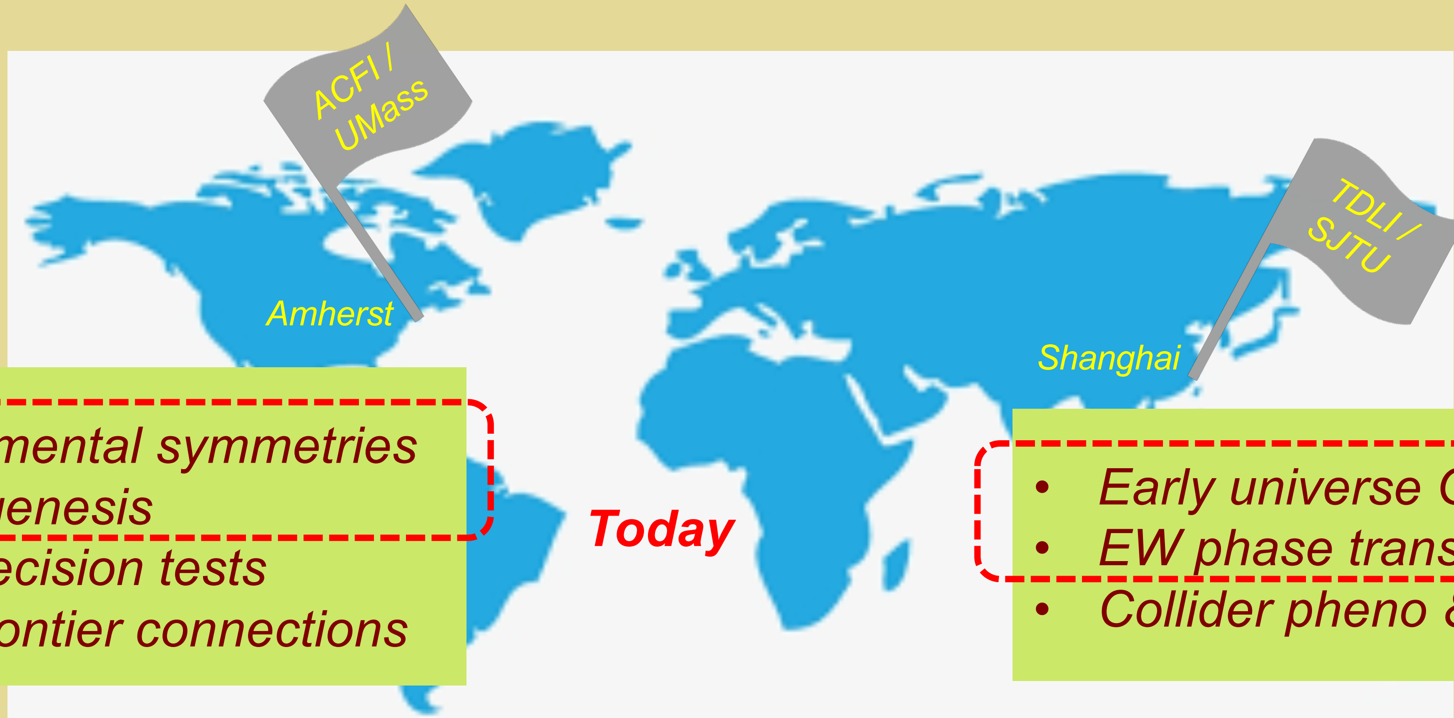
Family

Friends

My pronouns: he/him/his
 # MeToo

Neutron EDM Workshop
ECT* Trento   August 2, 2022

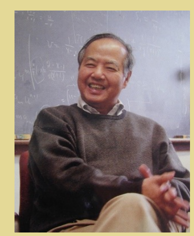
MJRM: Scientist & "Ambassador"



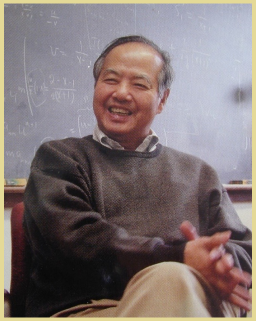
- *Fundamental symmetries*
- *Baryogenesis*
- *EW precision tests*
- *Inter-frontier connections*

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

- ***Global effort: 20 researchers***
- ***Foster scientific connections***
- ***Science First ! 科学 第一 ！***



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/

TDLI/SJTU: Particle & Nuclear Physics

Underground Experimental Group

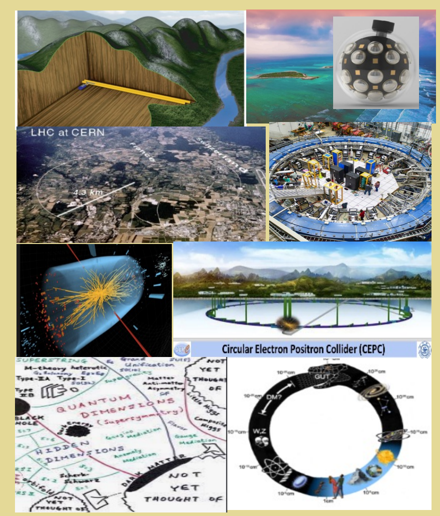
1. Dark Matter and Axion (PandaX).
2. Neutrinoless Double Beta Decay (PandaX).
3. Neutrino mass, Reactor and Cosmic Experiments (JUNO, ICECUBE, Hai-Ling Neutrino Telescope).

Collider Experiment Group

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

Theory Group

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



Amherst Center for Fundamental Interactions

Founded 2013

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

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

EDM's & Fundamental Questions

- *Do the fundamental laws of nature violate CP beyond the known CKM CPV ?*
- *Why does the Universe contain more matter than anti-matter ?*
- *What is the mass scale associated with Beyond the Standard Model Physics ?*
- *Is BSM physics perturbative or strongly coupled ?*

Goals for This Talk

- *Provide a context for drawing implications of EDM measurements for the cosmic baryon asymmetry*
- *Explain how electroweak baryogenesis works*
- *Review recent theoretical developments in EWBG and corresponding phenomenological implications*
- *Catalyze questions/discussion*

Themes for This Talk

- *Electroweak baryogenesis remains a theoretically attractive, phenomenologically viable, and experimentally testable scenario*
- *Collider & gravitational wave searches probe the “pre-conditions” for successful EWBG*
- *EDMs remain the most powerful probe of the necessary CPV for EWBG*
- *Considerable challenges remain at the “theory frontier” to achieve the most robust confrontation of EWBG with experiment*

Outline

I. EDM Basics & the BSM context

II. Baryogenesis Scenarios

III. Electroweak Baryogenesis Overview

IV. Electroweak Phase Transition

V. CPV for EWBG

VI. Outlook

I. EDM Basics & The BSM Context

EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ \ x\ \ \theta_{QCD} + \ d_n^{CKM}$$

EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ \times\ \theta_{QCD} + d_n^{CKM}$$

$$d_n^{CKM} = (1 - 6) \times 10^{-32}\ e\ cm$$

C. Seng arXiv: 1411.1476

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ x\ \ \sin\phi\ \ x\ y_f\, F$$

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ x\ \boxed{\sin\phi}\ x\ y_f\ F$$

CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f\, F$$

BSM mass scale: TeV ? Much higher ?

υ = 246 GeV Higgs vacuum expectation value
Λ > 246 GeV Mass scale of BSM physics

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f F$$

BSM dynamics: perturbative? Strongly coupled?

y_f	Fermion f Yukawa coupling
F	Function of the dynamics

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ \boxed{(\upsilon / \Lambda)^2}\ \times\ \boxed{\sin\phi}\ \times\ \boxed{y_f F}$$

Need information from at least three "frontiers"

- *Baryon asymmetry* — *Cosmic Frontier*
- *High energy collisions* — *Energy Frontier*
- *EDMs* — *Intensity Frontier*

II. Baryogenesis Scenarios

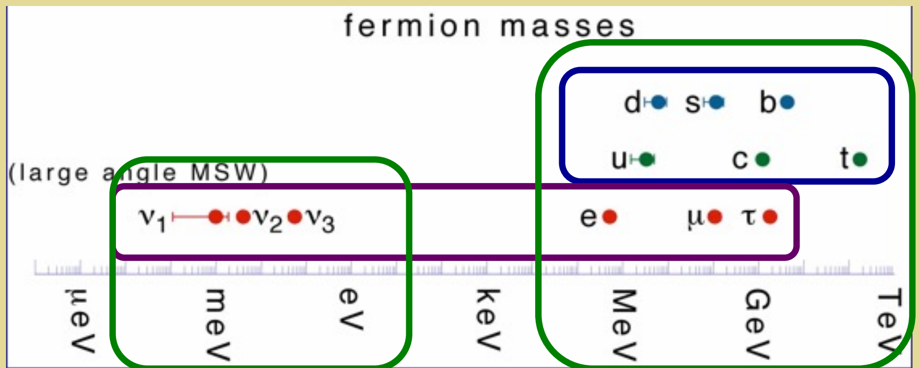
Ingredients for Baryogenesis

This talk

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	*BSM*
• *B violation (sphalerons)*	✓	✓
• *C & CP violation*	✗	✓
• *Out-of-equilibrium or CPT violation*	✗	✓

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

Higgs Mechanism

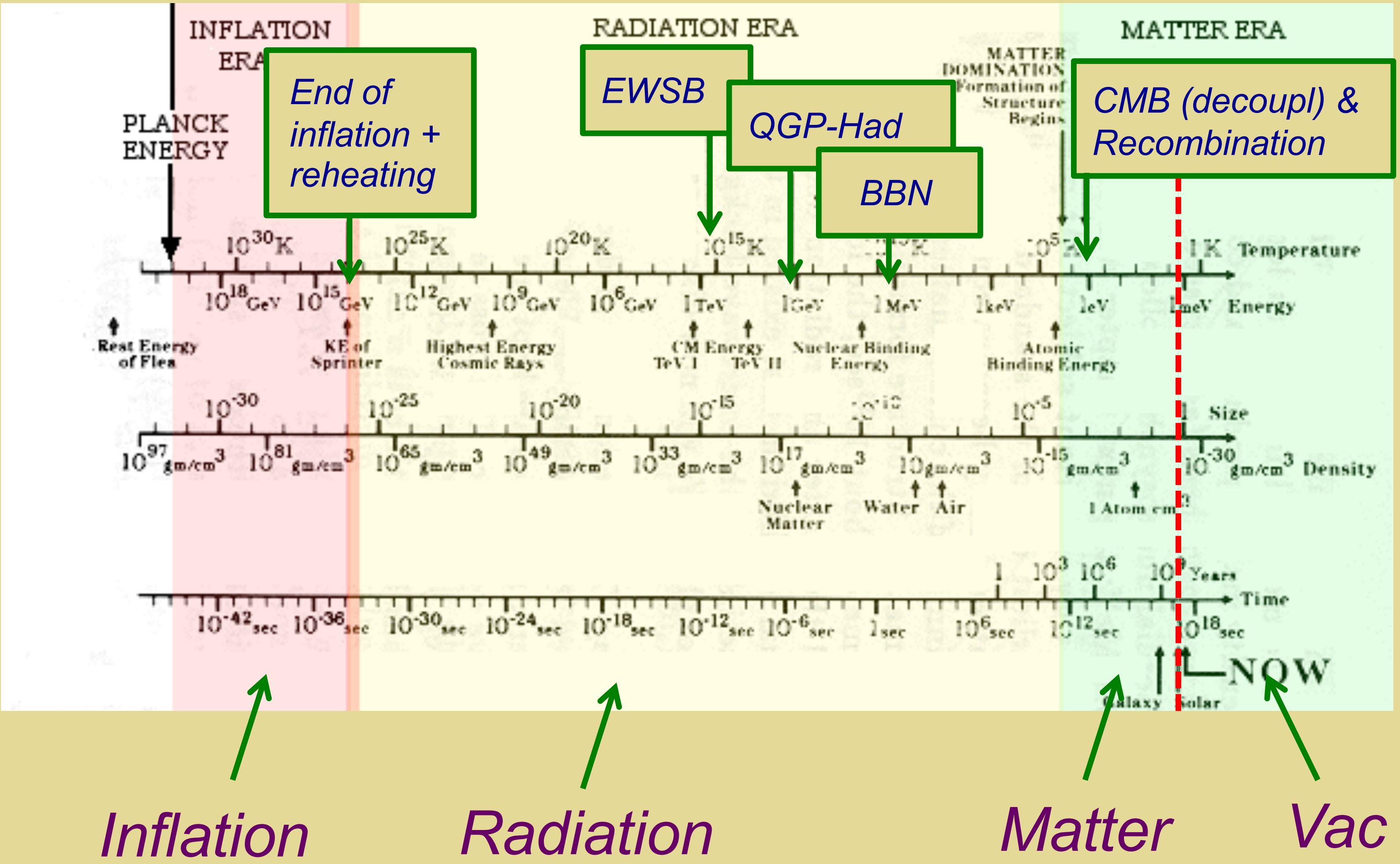
Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

Fukugita & Yanagida '86

Kuzmin, Rubakov, & Shaposhnikov '85

Thermal History



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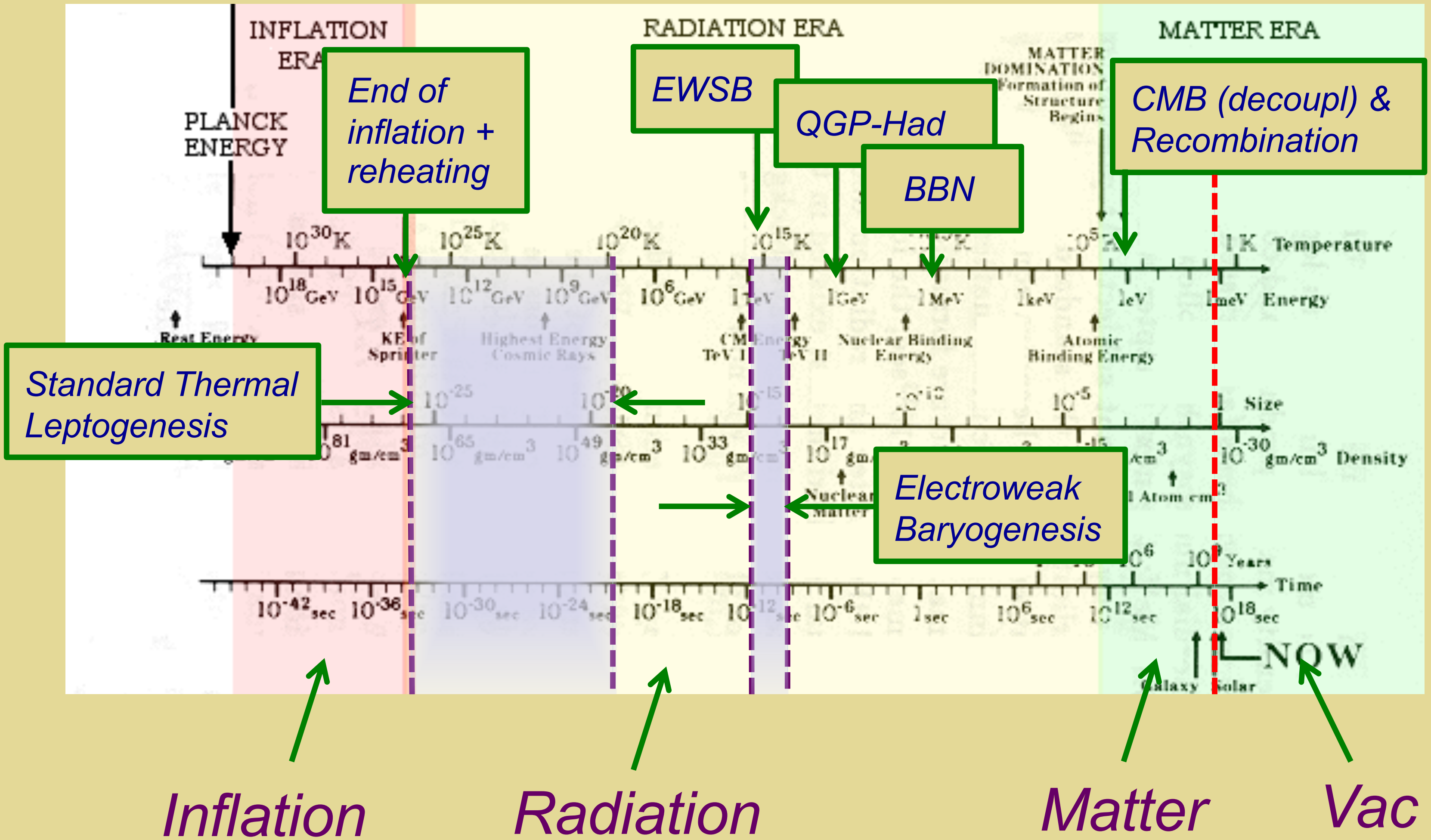

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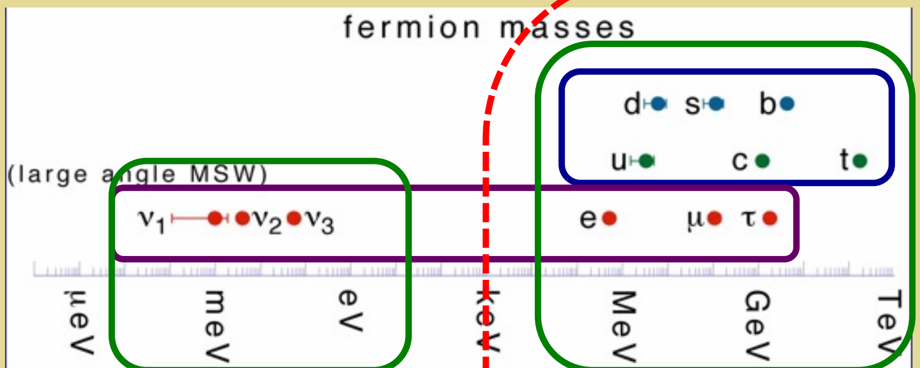

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Something else ?

Higgs Mechanism

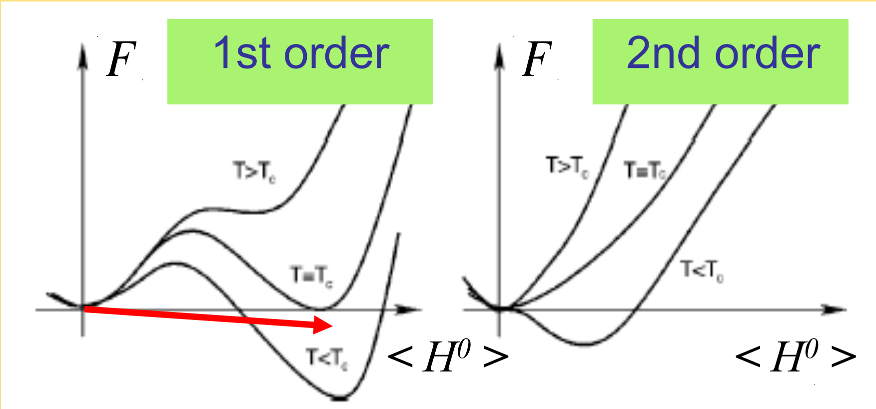
Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

This lecture

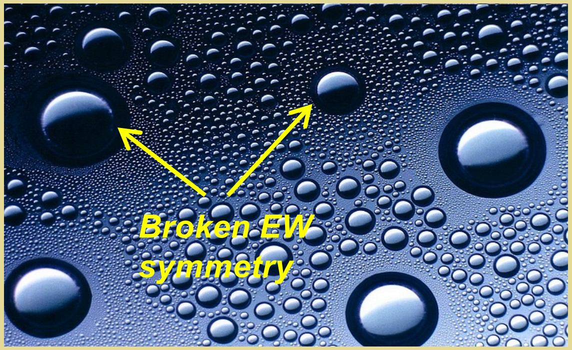
III. Electroweak Baryogenesis Overview

EW Baryogenesis: BSM Scalars & CPV



How Higgs potential energy evolves with T

Increasing m_h →

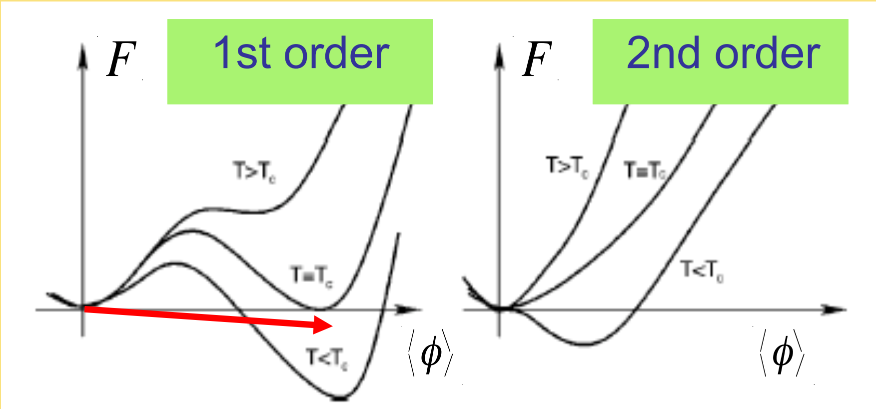


SM: 1st order EWPT endpoint

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

Maximum Higgs mass for a first order transition

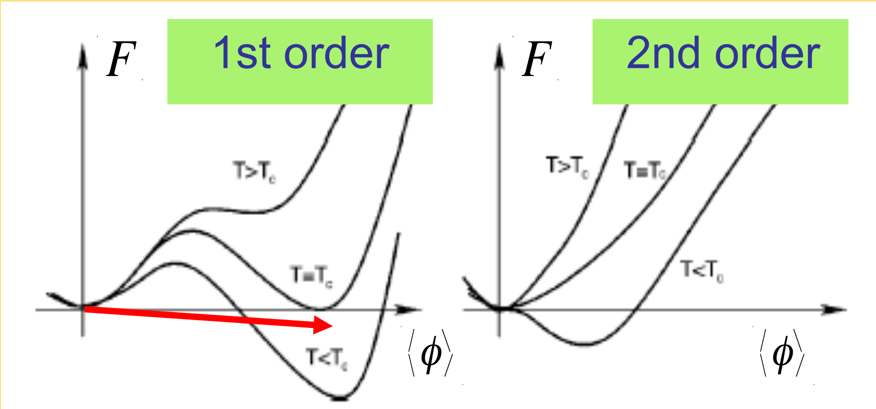
EW Baryogenesis: BSM Scalars & CPV



Increasing m_h →

← *New scalars*

EW Baryogenesis: BSM Scalars & CPV

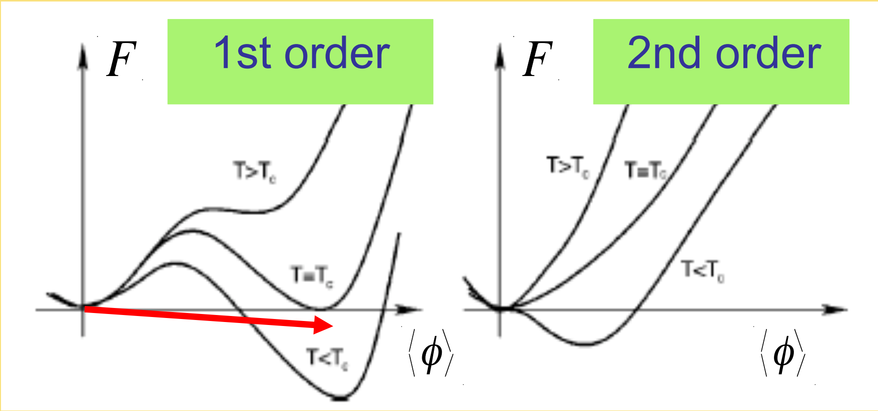


Increasing m_h →

← *New scalars*

- *Loop effects*
- *Tree-level barrier*

EW Baryogenesis: BSM Scalars & CPV



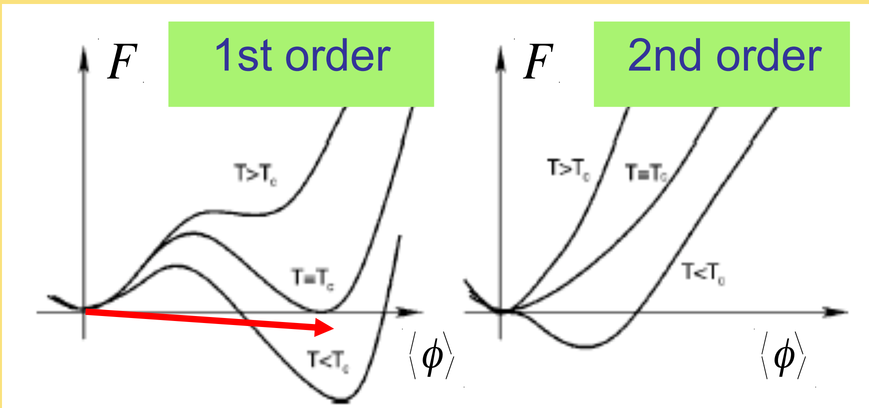
Increasing m_h →

← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

EW Baryogenesis: BSM Scalars & CPV



Increasing m_h →

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Baryogenesis
Gravity Waves
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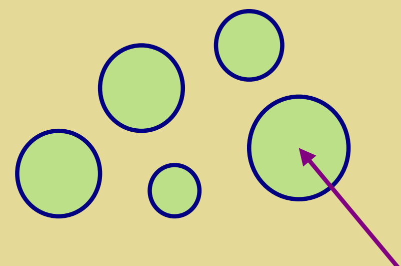
"Strong" 1st order EWPT

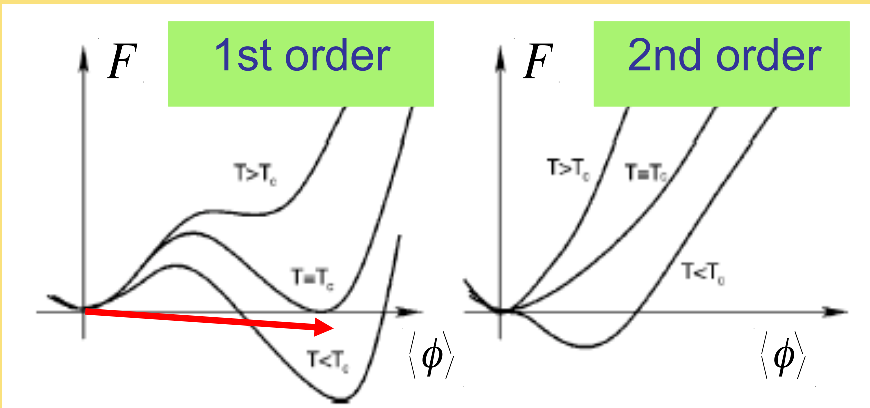
↓

Bubble nucleation



EWSB

EW Baryogenesis: BSM Scalars & CPV



Increasing m_h →

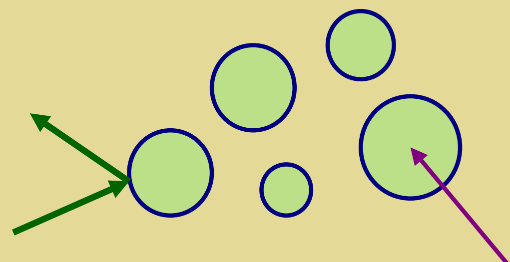
← *New Higgses*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" *1st order EWPT*

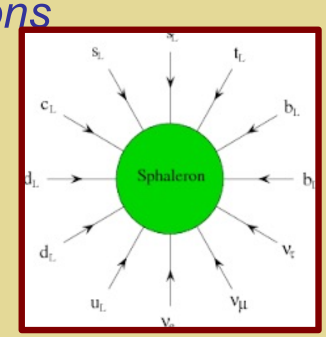
↓

Bubble nucleation

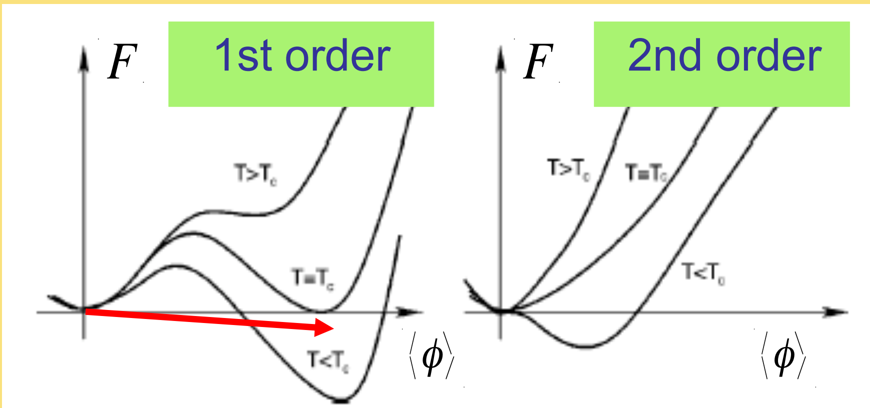


Y_B : CPV & EW sphalerons

EWSB



EW Baryogenesis: BSM Scalars & CPV



Increasing m_h →

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- *LHC Searches*

"Strong" 1st order EWPT

↓

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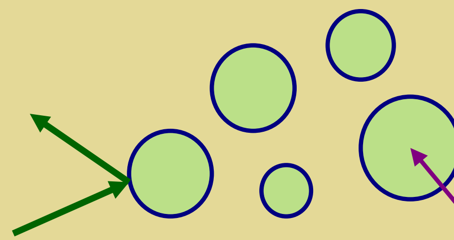
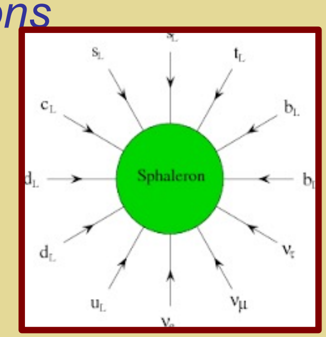


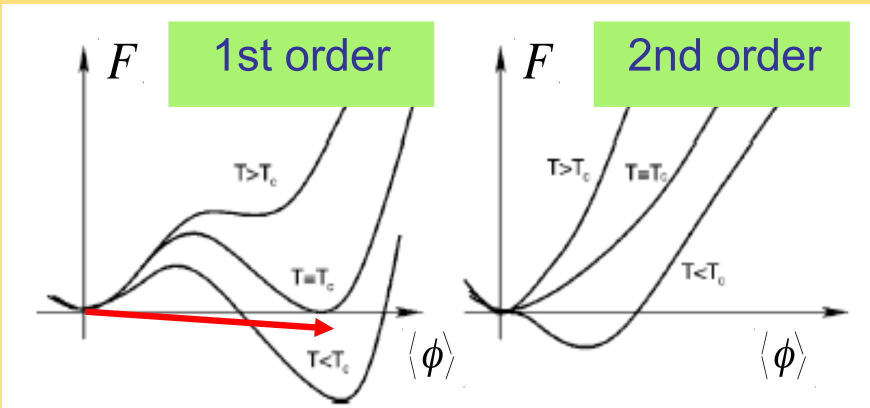
Y_B : CPV & EW sphalerons

EWSB

BSM



EW Baryogenesis: BSM Scalars & CPV



Increasing m_h →

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Baryogenesis
Gravity Waves
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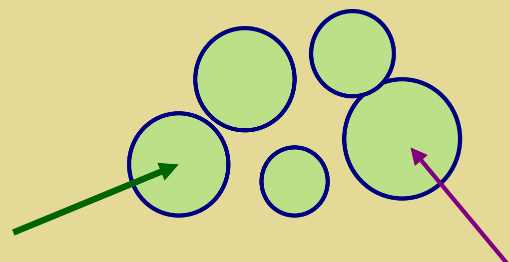
"Strong" 1st order EWPT

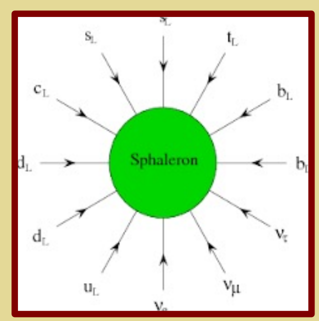
↓

Bubble nucleation

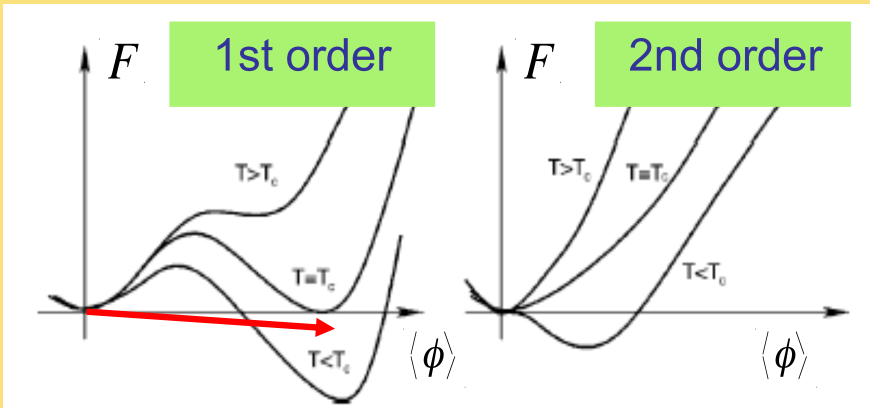


Y_B : diffuses into interiors

EWSB



EW Baryogenesis: BSM Scalars & CPV



Increasing m_h ⟶

⟵ New scalars

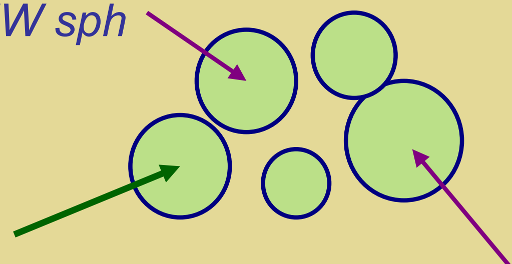
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

Preserve $Y_B^{initial}$

Bubble nucleation

Quench EW sph



Y_B : diffuses into interiors

EWSB

IV. Electroweak Phase Transition

- ***Did the necessary preconditions for EWBG occur in the early universe ?***
- ***How can we address this question experimentally ?***
- ***How reliably can we compute the EWPT (thermo) dynamics ?***

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 ?*

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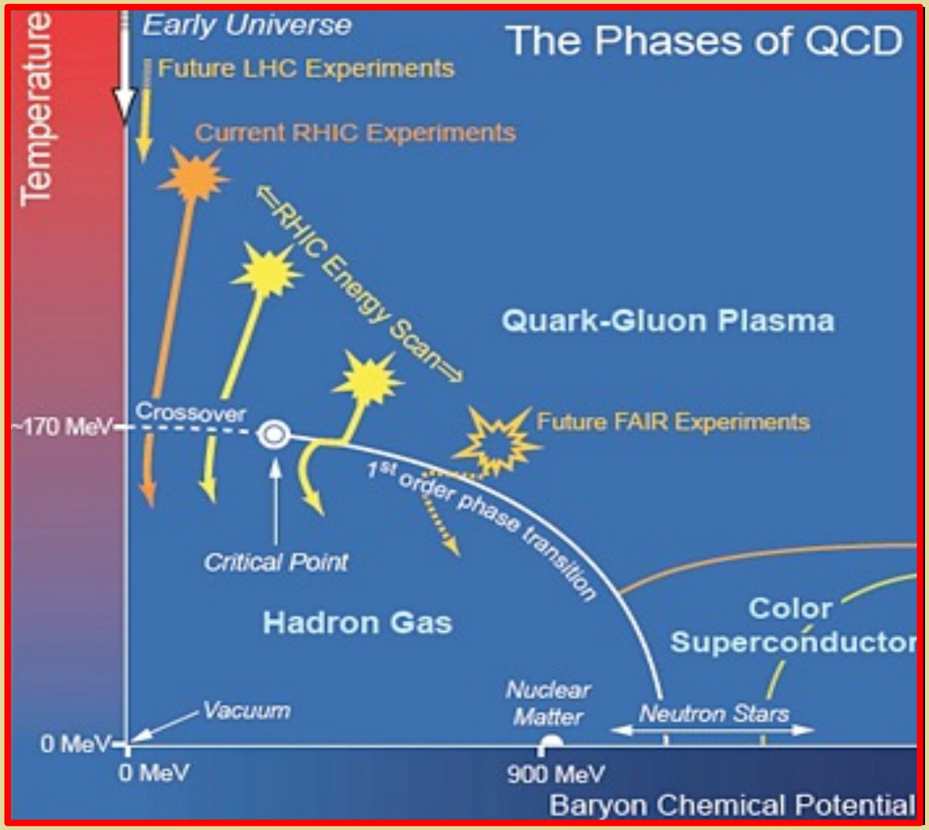
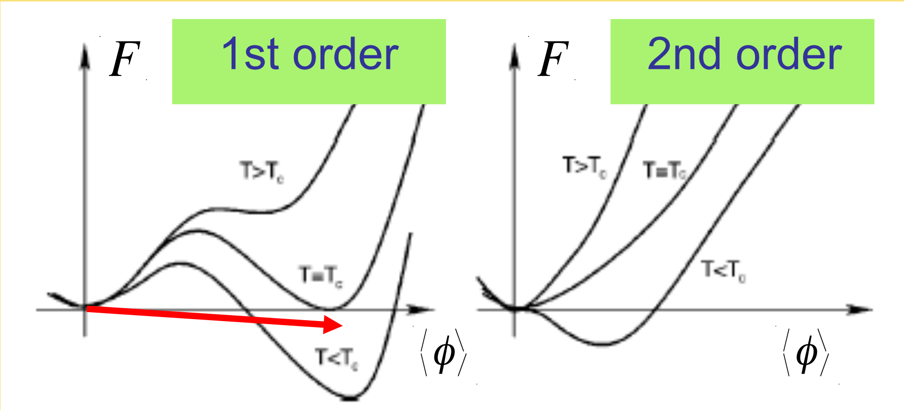
Thermal History of Symmetry Breaking



QCD Phase Diagram → EW Theory Analog?

EWSB Transition: St'd Model



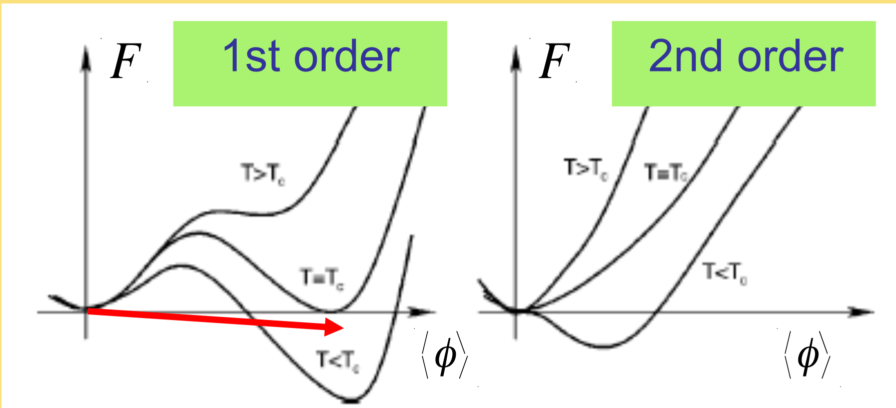
Increasing m_h →

Higgs potential: T=0

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

$$m_h^2 = 2\lambda\, v^2$$

EWSB Transition: St'd Model



Increasing m_h →

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3D Isotropic	[72]	72.3 ± 0.7
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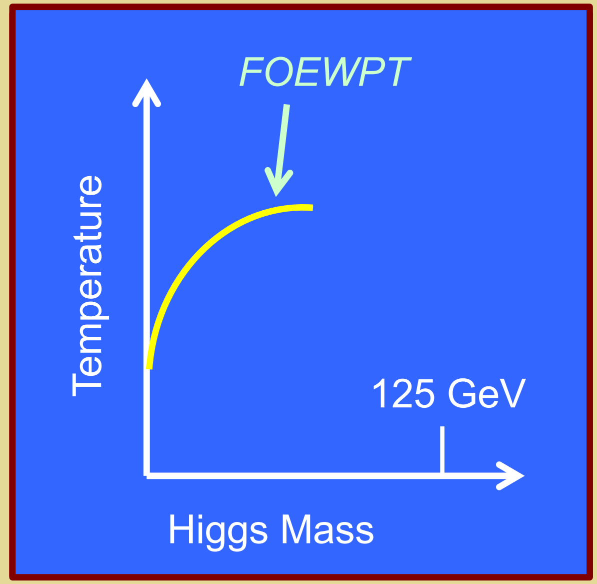
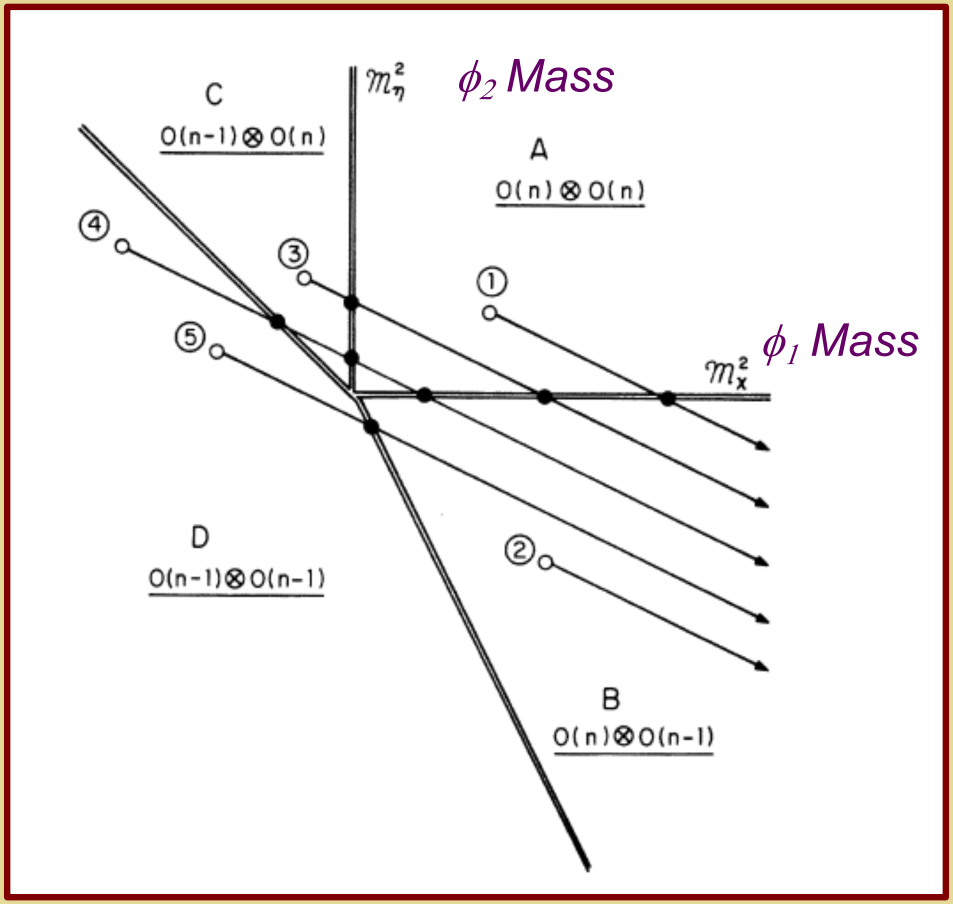
SM EW: Cross over transition



EW Phase Diagram

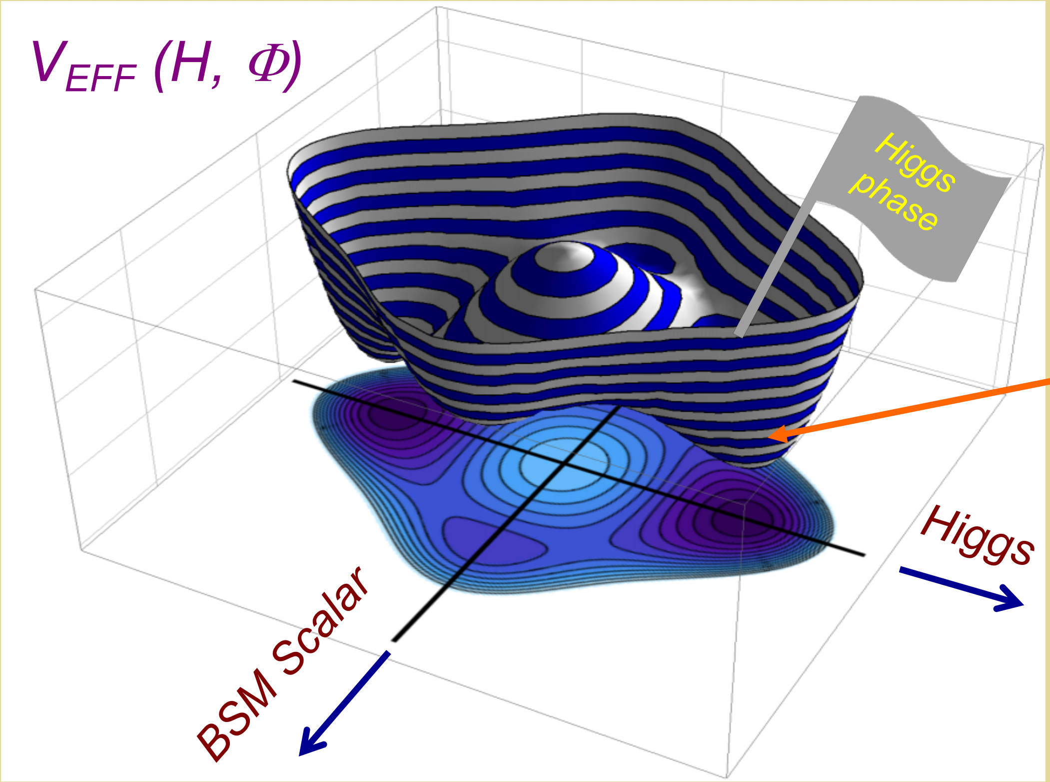
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

Patterns of Symmetry Breaking



S. Weinberg, PRD 9 (1974) 3357

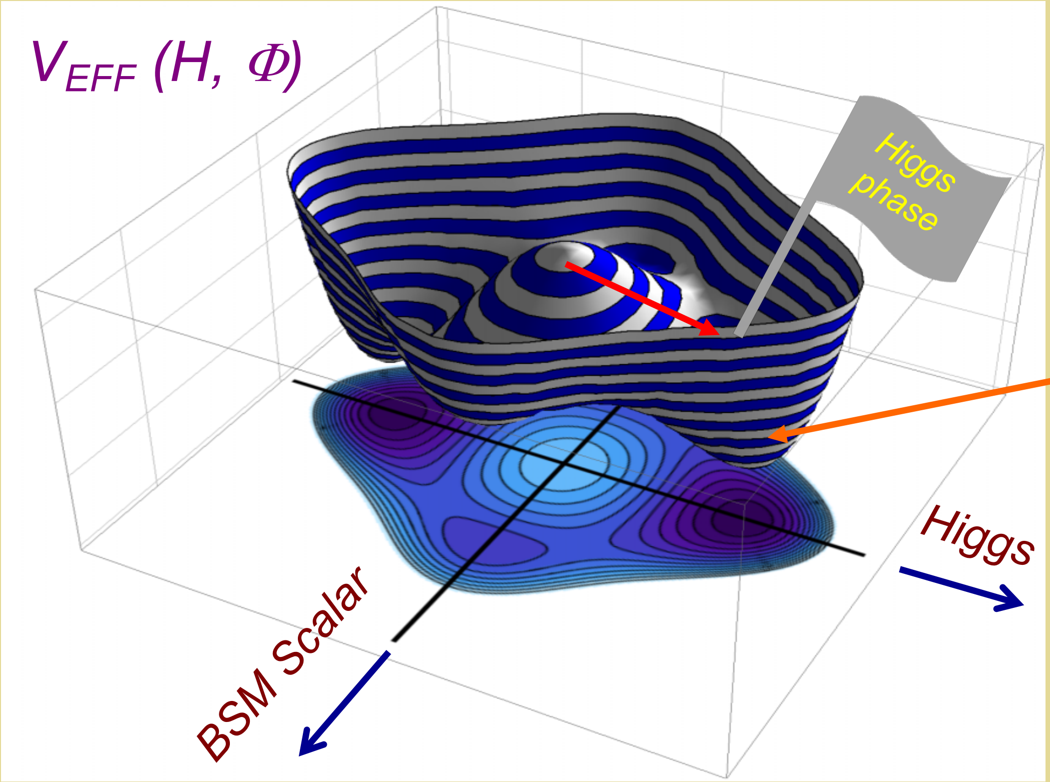
Patterns of Symmetry Breaking



How did we end up here ?

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

Patterns of Symmetry Breaking



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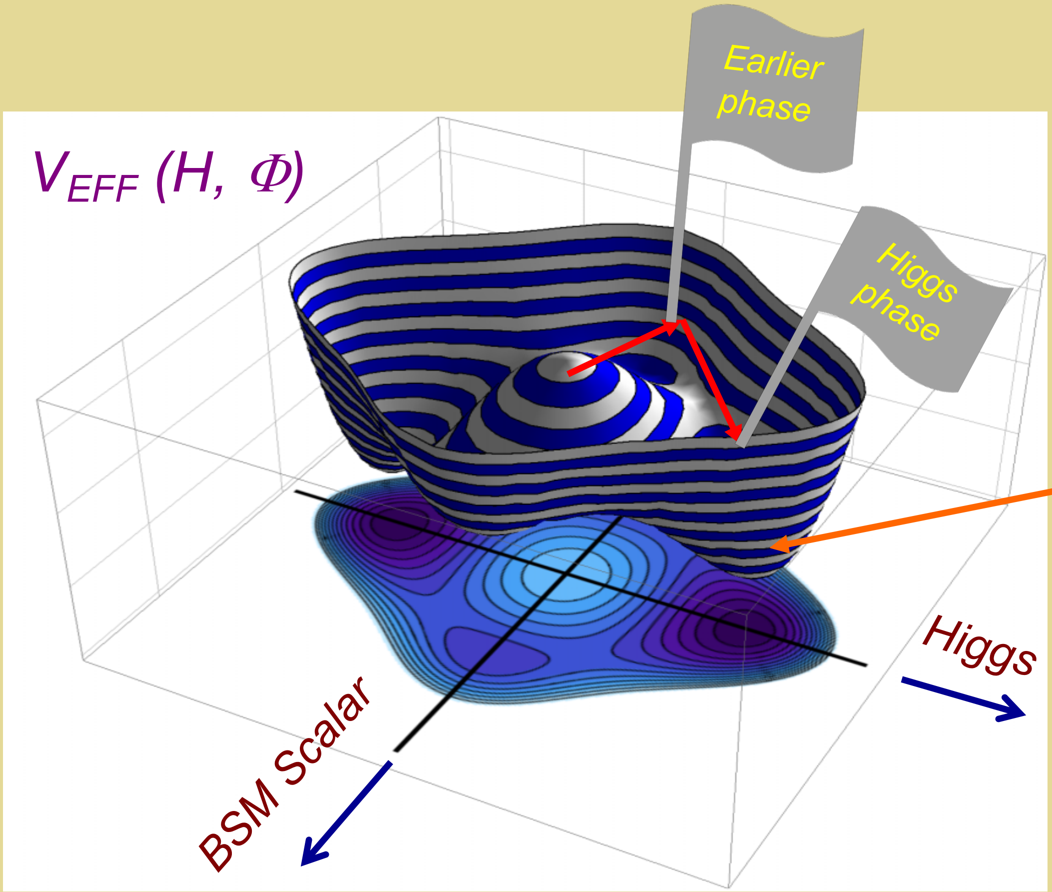
Patterns of Symmetry Breaking



How did we end up here ?

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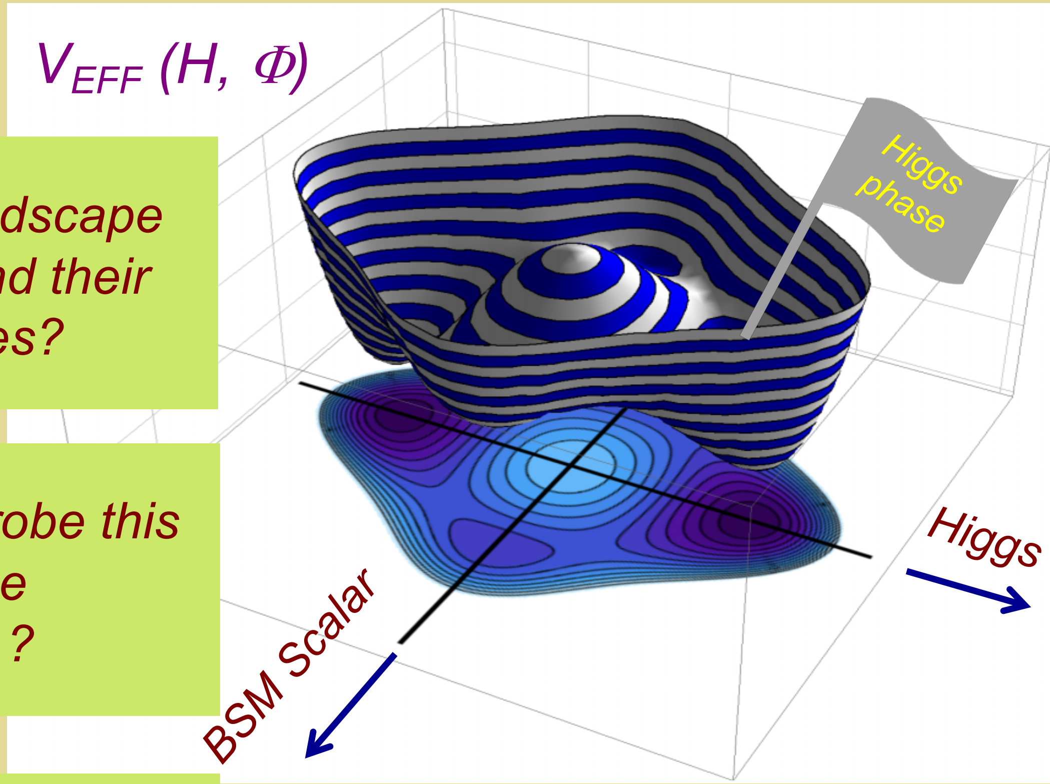
Thermal History of EWSB



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

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

- *How reliably can we compute the thermodynamics ?*

n evolve differently as T evolves →
ilities for symmetry breaking

Electroweak Phase Transition

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

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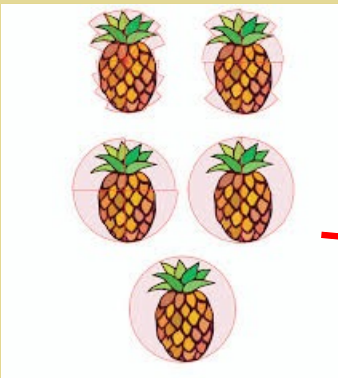
Experimental Probes

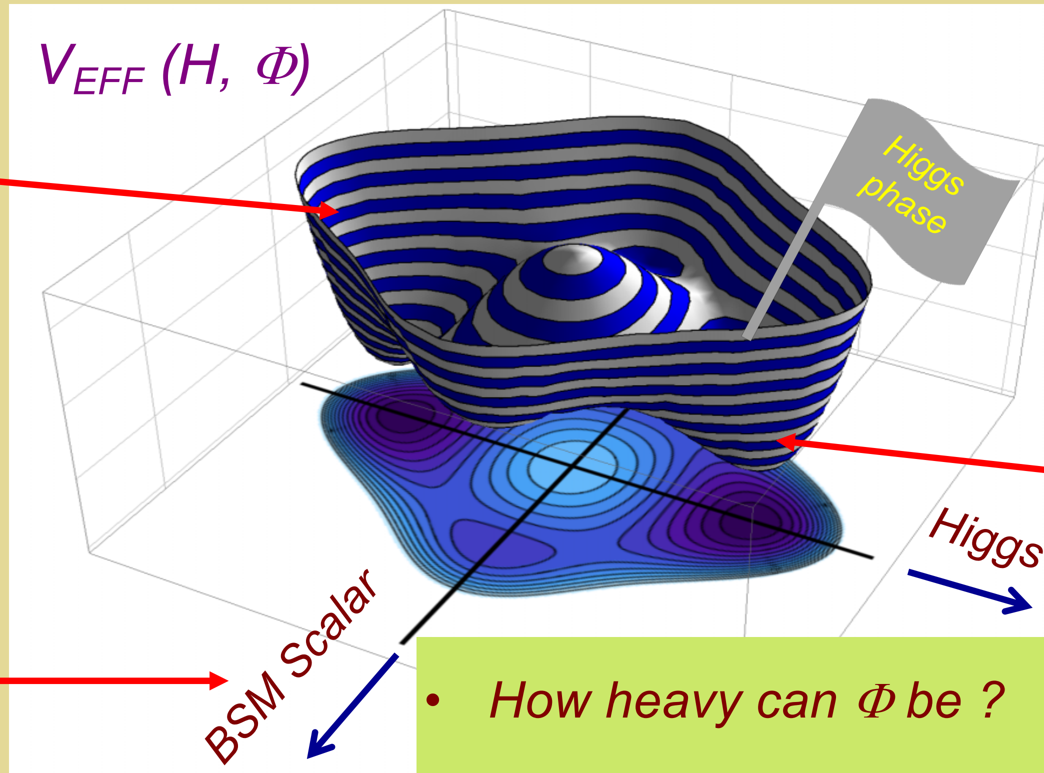
Bubble Collisions



Grav Radiation

Direct Production

BSM Higgs



Higgs precision tests

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

Extrema can evolv … →

rich possibilities f …

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

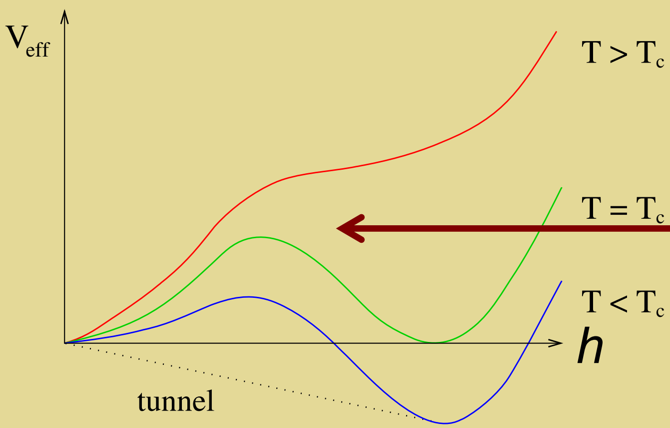
$$V(h,T)_{\mathrm{SM}} = D(T^2 - T_0^2)\, h^2 + \lambda\, h^4 \;\; + \ldots$$

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

$T_0 \sim$ 140 GeV

$\equiv \; T_{EW}$

First Order EWPT from BSM Physics

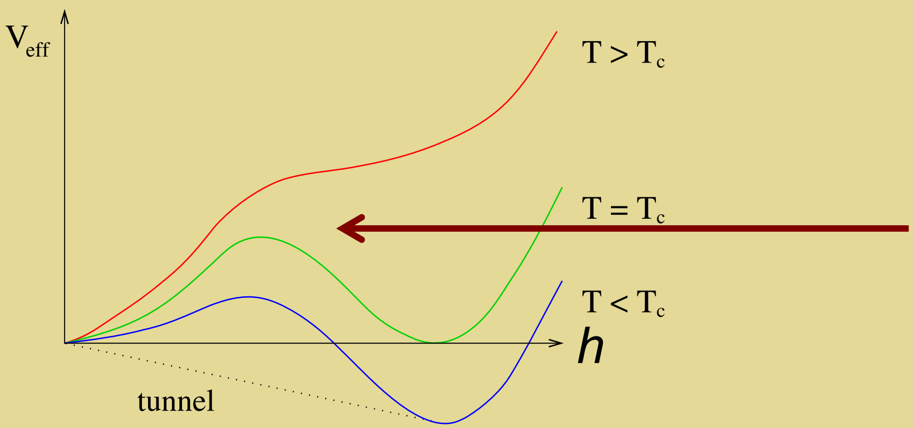


Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

MJRM: 1912.07189

First Order EWPT from BSM Physics



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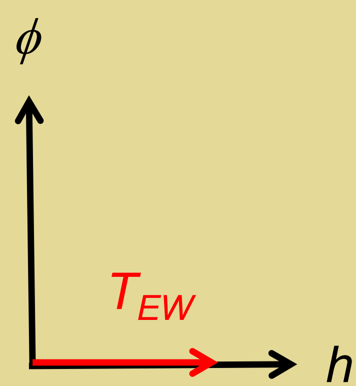
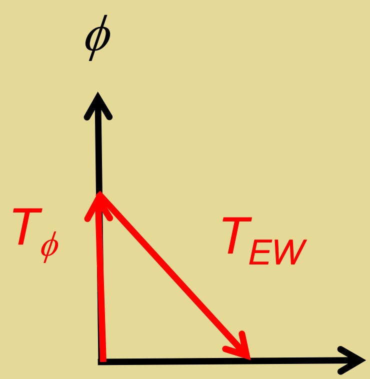
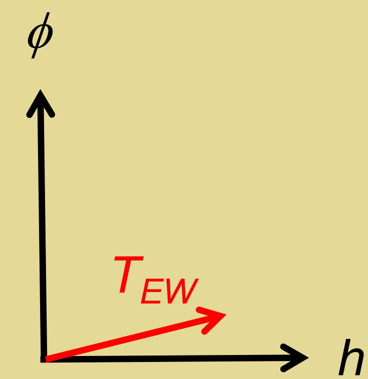


$a_2\, H^2\phi^2$: $T > 0$
loop effect

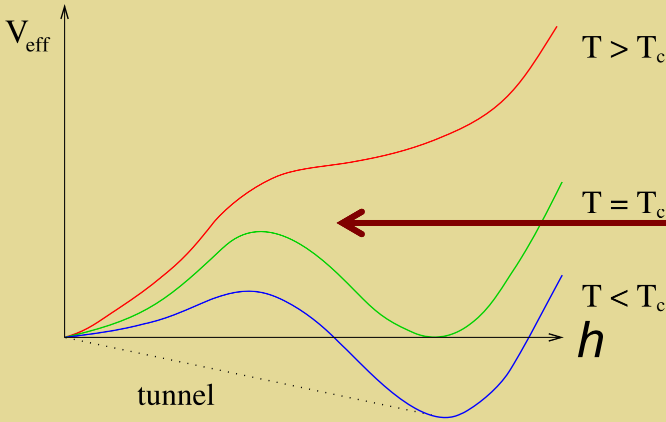


$a_2\, H^2\phi^2$: $T = 0$
tree-level effect

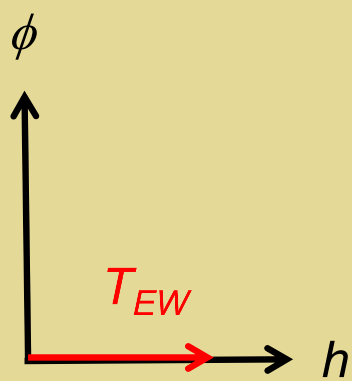


$a_1\, H^2\phi$: $T = 0$
tree-level effect

First Order EWPT from BSM Physics

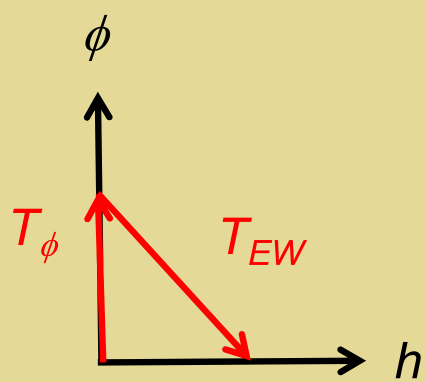


Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV



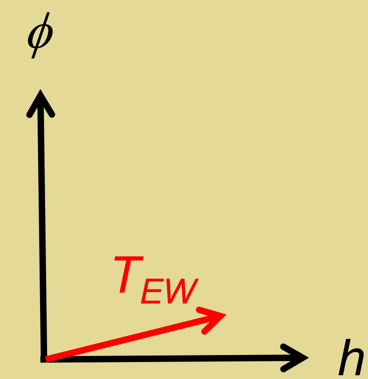
$a_2\, H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect

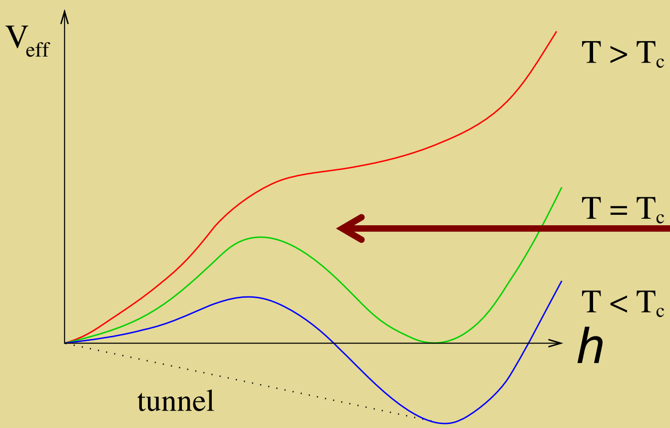


$a_1\, H^2\phi$: $T = 0$

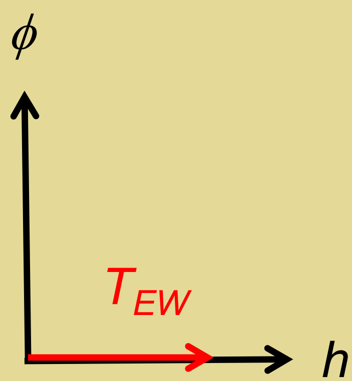
tree-level effect

MJRM: 1912.07189

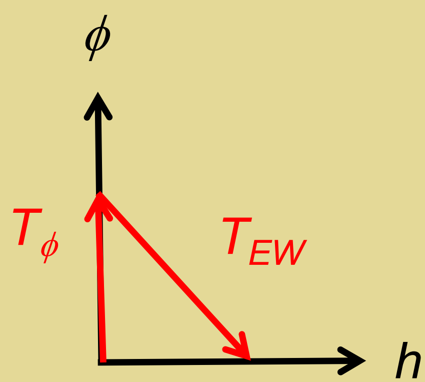
First Order EWPT from BSM Physics



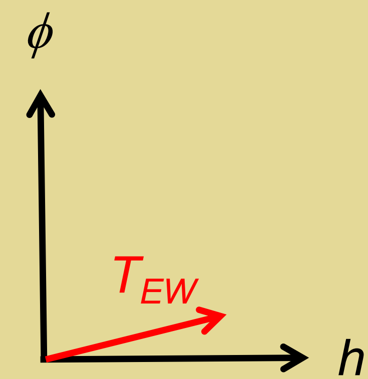
Higgs – ϕ^0 Mixing



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



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



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

MJRM: 1912.07189

Strong First Order EWPT

- ***Prevent baryon number washout***
- ***Observable GW***

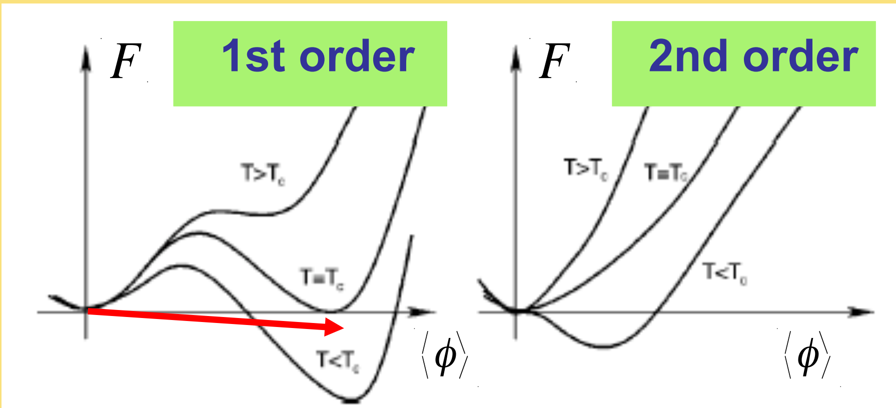
Collider Target: Precision and single ϕ production

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

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

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

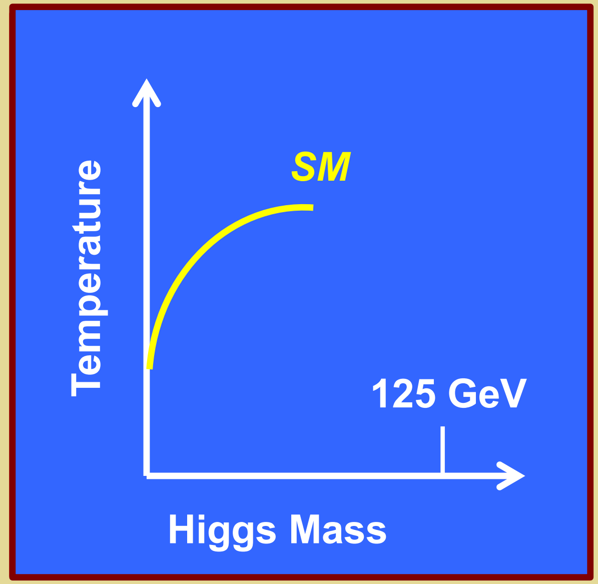
EW Phase Transition: Singlet Scalars



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

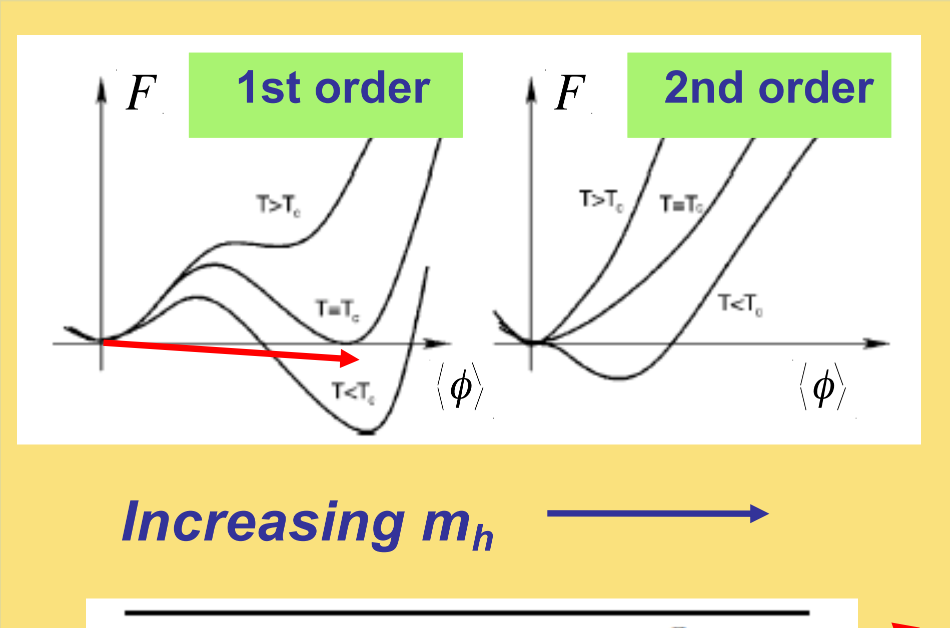
SM EW: Cross over transition



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



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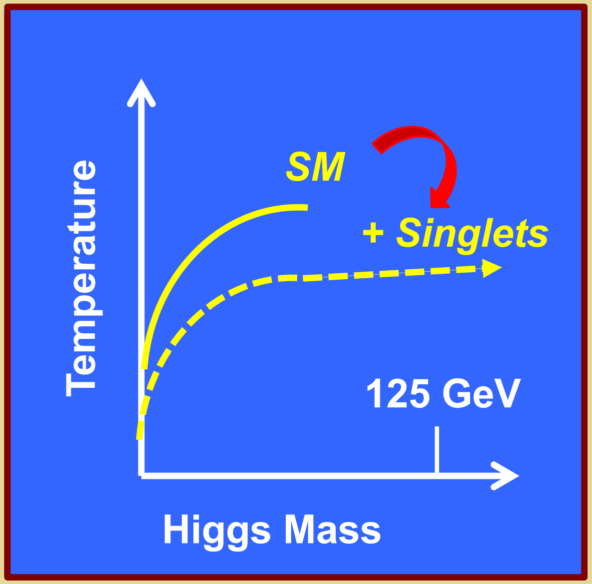
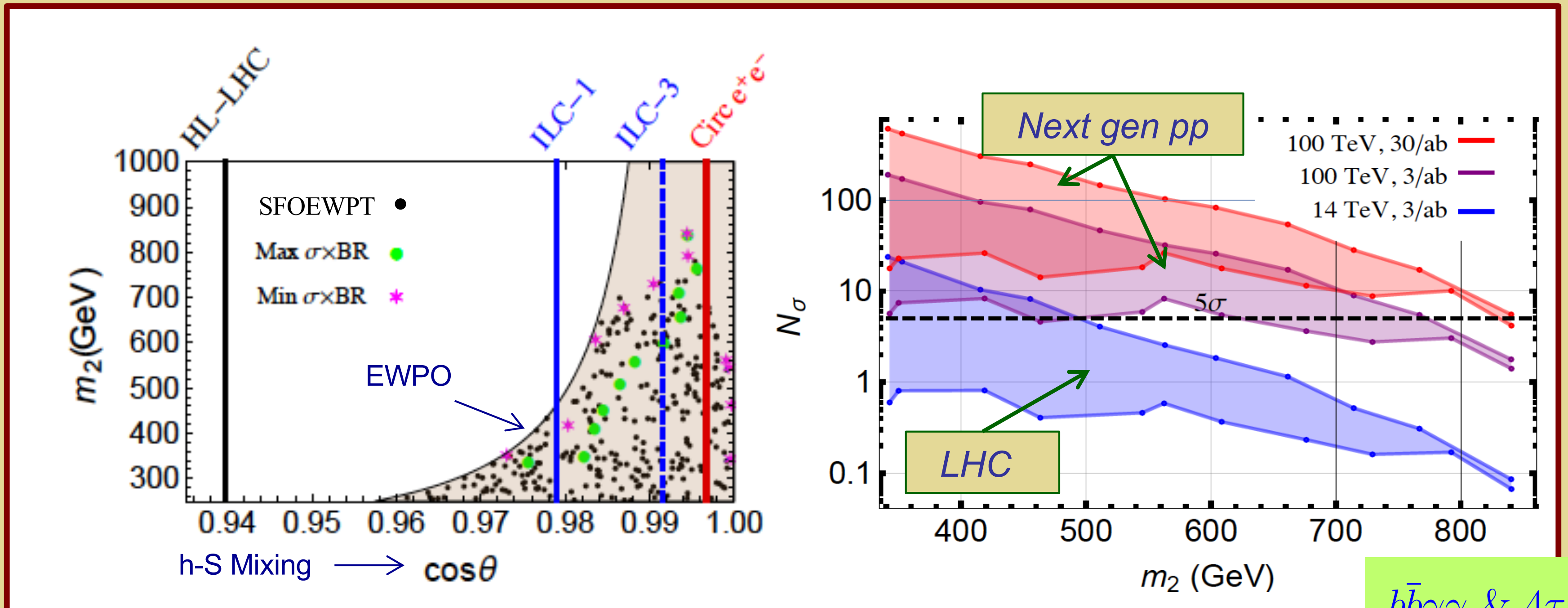


EW Phase Diagram

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

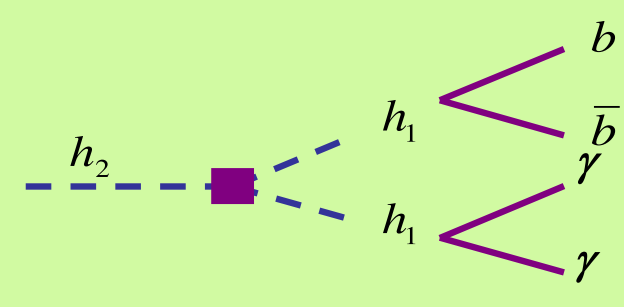
Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



$b\bar{b}\gamma\gamma$ & 4τ

Kotwal, No, R-M, Winslow 1605.06123



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

Models & Phenomenology

What BSM Scenarios?

SM + Scalar Singlet	Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17, Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir 19…
SM + Scalar Doublet (2HDM)	Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18…
SM + Scalar Triplet	Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 …
MSSM	Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14…
NMSSM…	Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15…

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

Models & Phenomenology

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Models & pheno: how reliable ?

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

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

Theory Meets Phenomenology

A. Non-perturbative

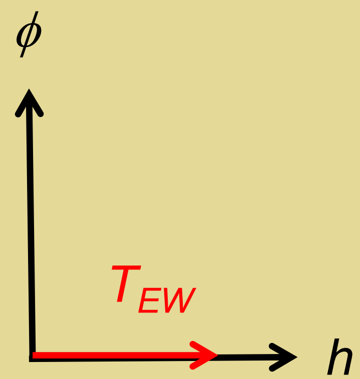
- *Most reliable determination of character of EWPT & dependence on parameters*
- *Broad survey of scenarios & parameter space not viable*

B. Perturbative

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

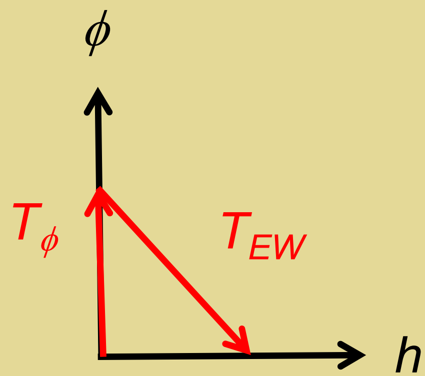
Benchmark pert theory

Real Triplet



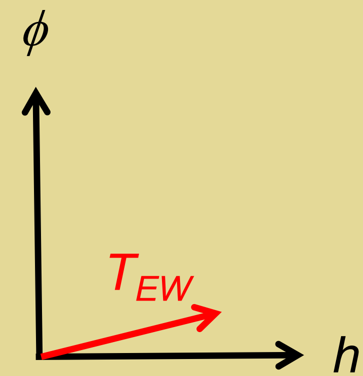
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



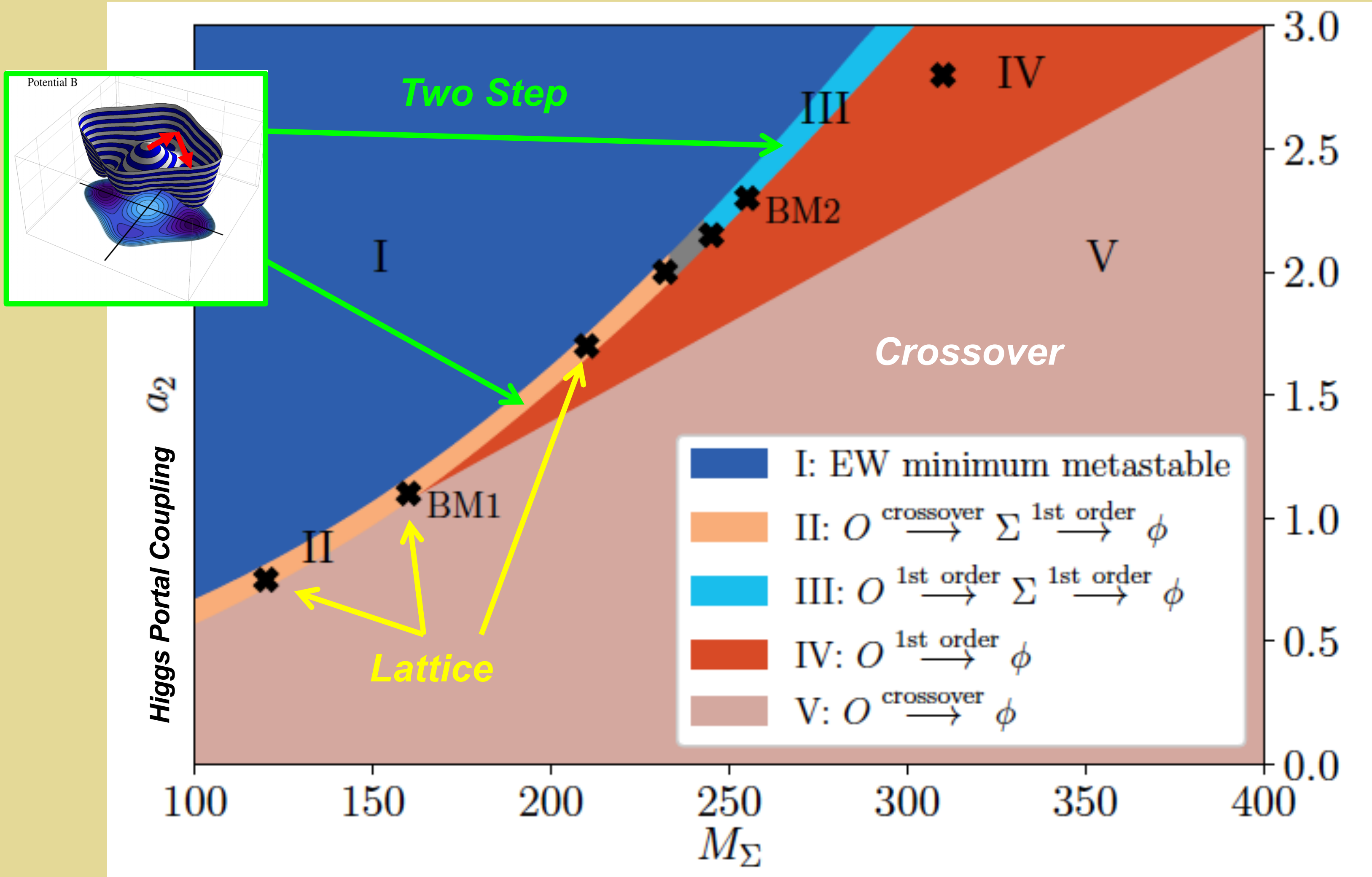
$a_1 H^2\phi$: $T = 0$

tree-level effect

EFT + Non-perturbative results

EW precision tests → too tiny

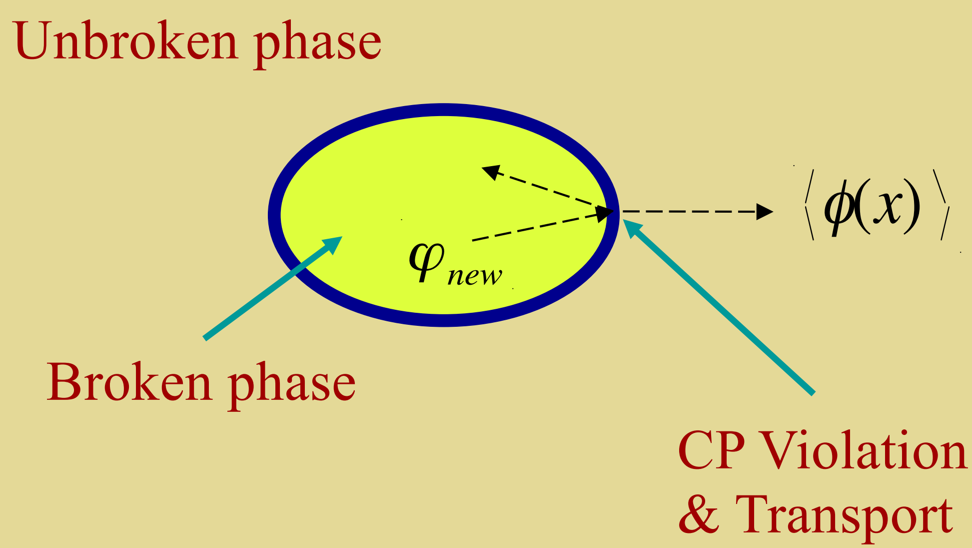
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332

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

V. CPV for EWBG



Particle propagation in spacetime varying background: masses are functions of spacetime

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

CTP or Schwinger-Keldysh Green's functions

$$\tilde{G}(x,y) = \left\langle P \varphi_a(x)\varphi_b^*(y)\right\rangle \boldsymbol{\tau}_{ab} = \begin{bmatrix} G^t(x,y) & -G^<(x,y) \\ G^>(x,y) & -G^{\bar{t}}(x,y) \end{bmatrix}$$

- *Appropriate for evolution of "in-in" matrix elements*
- *Contain full info on number densities: $n_{\alpha\beta}$*
- *Matrices in flavor space: (e,μ,τ) , $(\tilde{t}_L, \tilde{t}_R)$, …*

See C. Lee, V. Cirigliano, MJRM, PRD 71 (2005) 075010 [hep-ph/0412345]; V. Cirigliano et al PRD 81 (2010) 103503 [0912.3523/hep-ph]; V. Cirigliano et al PRD 84 (2011) 056006 [1106.0747/hep-ph]

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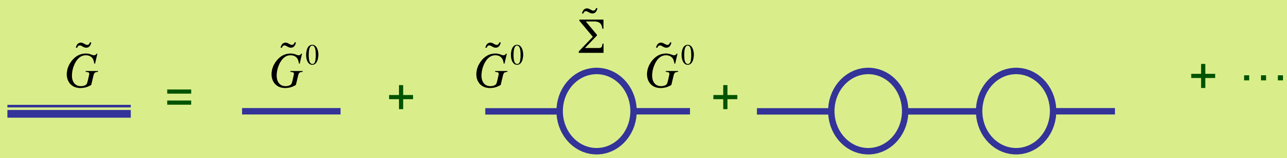

Systematic Baryogenesis:

Scale Hierarchies $\rightarrow$ *power counting*

<u>*EW Baryogenesis*</u>	<u>*Leptogenesis*</u>
Gradient expansion	*Gradient expansion*
$\varepsilon_w = v_w (k_w / \omega) << 1$	$\varepsilon_{LNV} = \Gamma_{LNV} / \Gamma_H < 1$
Quasiparticle description	*Quasiparticle description*
$\varepsilon_p = \Gamma_p / \omega << 1$	$\varepsilon_p = \Gamma_p / \omega << 1$
Thermal, but not too dissipative	*Thermal, but not too dissipative*
$\varepsilon_{coll} = \Gamma_{coll} / \omega << 1$	$\varepsilon_{coll} = \Gamma_{coll} / \omega << 1$
Plural, but not too flavored	
$\varepsilon_{osc} = \Delta\omega / T << 1$	

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

Lowest non-trivial order in grad's

$$2k \cdot \partial_X \, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k \cdot \Sigma, G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

Systematic Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

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Diagonal after rotation to local mass basis:

$$M^2(X) = U^+\, m^2(X)\, U$$

$$\Sigma_\mu(X) = U^+\, \partial_\mu U$$

$(\tilde{t}_L, \tilde{t}_R) \rightarrow (\tilde{t}_1, \tilde{t}_2)$

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

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Flavor oscillations: flavor off-diag densities

Systematic Baryogenesis:

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CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields

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CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields

How large is CPV source ? Riotto; Carena et al; Prokopec et al; Cline et al; Konstandin et al; Cirigliano et al; Kainulainen….

Systematic Baryogenesis:

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CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields

Earlier EDM-EWBG phenomenology: use of "vev insertion approximation": under or over estimate ?

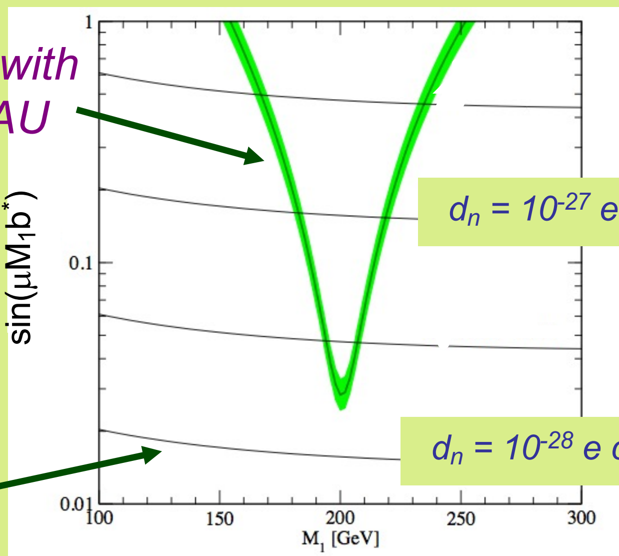
Systematic Baryogenesis:

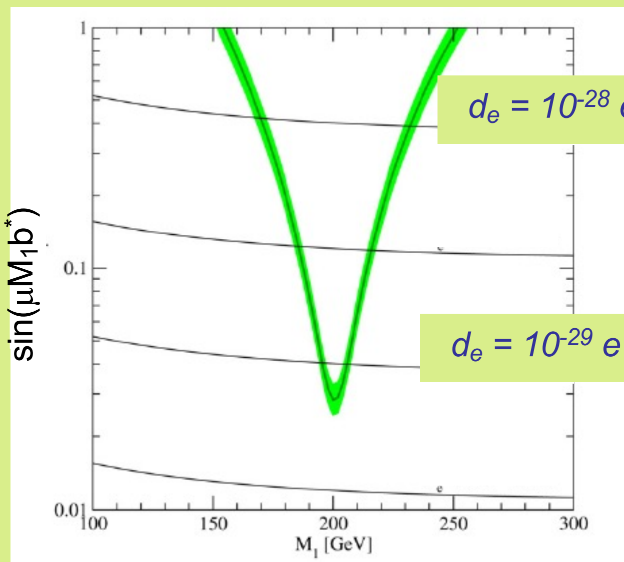
Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2k\cdot\partial_X\, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k\cdot\Sigma, G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

Compatible with observed BAU





ACME: ThO

Next gen d_n

Li, Profumo, RM '09-'10

BAU in MSSM computed using VIA: how reliable?

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2k\cdot\partial_X\, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k\cdot\Sigma, G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields

Resonant enhancement of CPV sources for small ε_{osc}

Cirigliano et al

Systematic Baryogenesis:

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$$2k\cdot\partial_X\, G^{<}(k,X) = -i\left[M^2(X), G^{<}(k,X)\right] - 2\left[k\cdot\Sigma, G^{<}(k,X)\right] + \boxed{\Lambda\left[G(k,X)\right]}$$

Collision term: scattering, decays, thermal masses, particle species changing reactions…

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2k\cdot\partial_X\, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k\cdot\Sigma, G^<(k,X)\right] + \boxed{\Lambda\left[G(k,X)\right]}$$

Open challenges:

- *Application to realistic models for scalar theories*
- *Full formulation for fermions*

Systematic Baryogenesis:

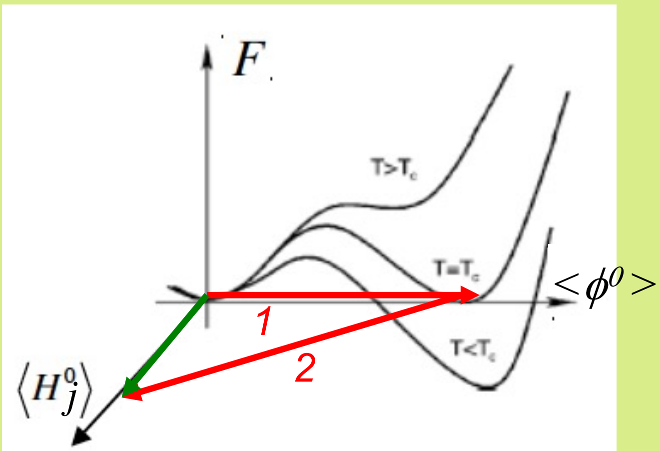
Illustrative Results: work in progress

Kinetic eq (approx) in Wigner space:

$$2k\cdot\partial_X\, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k\cdot\Sigma, G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

Two-step EWBG: 1508.05404

BAU generated in step 1 → passed to Higgs phase in step 2



H_j	*Two Higgs doublets*
ϕ	*Two BSM Scalar Sectors: one $SU(2)_L$ real triplet plus gauge singlets ("partially secluded sector"), both get vevs in step 1*

Yuan-Zhen Li, Jiang-Hao Yu, MJRM

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Illustrative Results: work in progress

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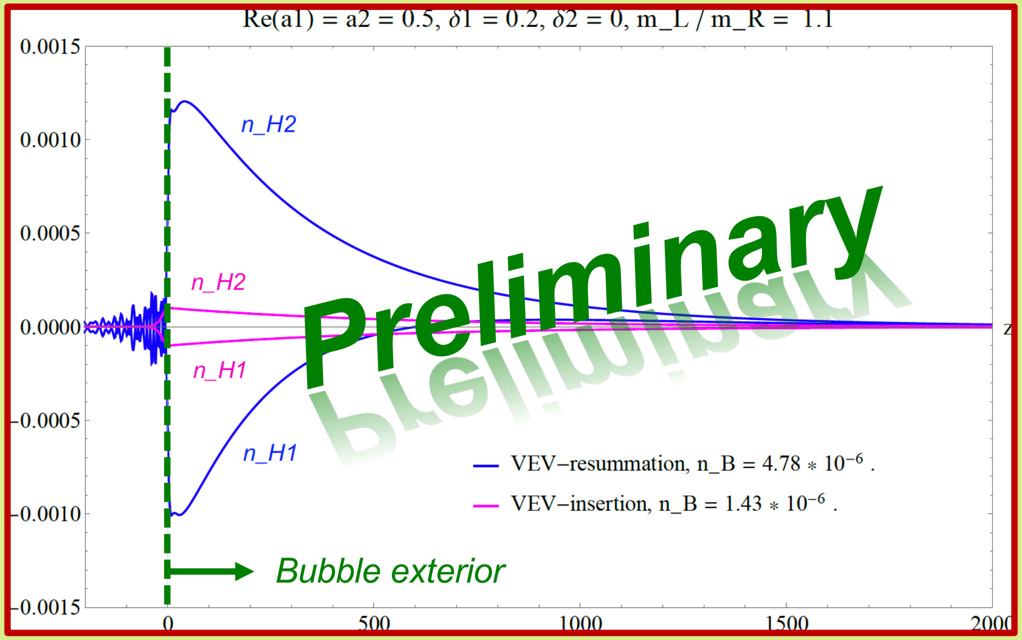

Yuan-Zhen Li, Jiang-Hao Yu, MJRM

VI. Outlook

- *Electroweak baryogenesis remains a theoretically attractive, phenomenologically viable, and experimentally testable scenario*
- *Collider & gravitational wave searches probe the "pre-conditions" for successful EWBG*
- *EDMs remain the most powerful probe of the necessary CPV for EWBG*
- *Considerable challenges remain at the "theory frontier" to achieve the most robust confrontation of EWBG with experiment*