How Viable Is Electroweak Baryogenesis ?

M.J. Ramsey-Musolf

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

- *mjrm@umass.edu*
- *mjrm@sjtu.edu.cn*
- *微信：mjrm-china*
- *https://michaelramseymusolf.com/*

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

Catch22+2 Conference
Dublin May 3, 2024

Electroweak Baryogenesis

Motivation

- *BAU $\leftrightarrow$ Higgs mechanism*
- *Experimentally testable*

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- *Consistent w/ experiment*

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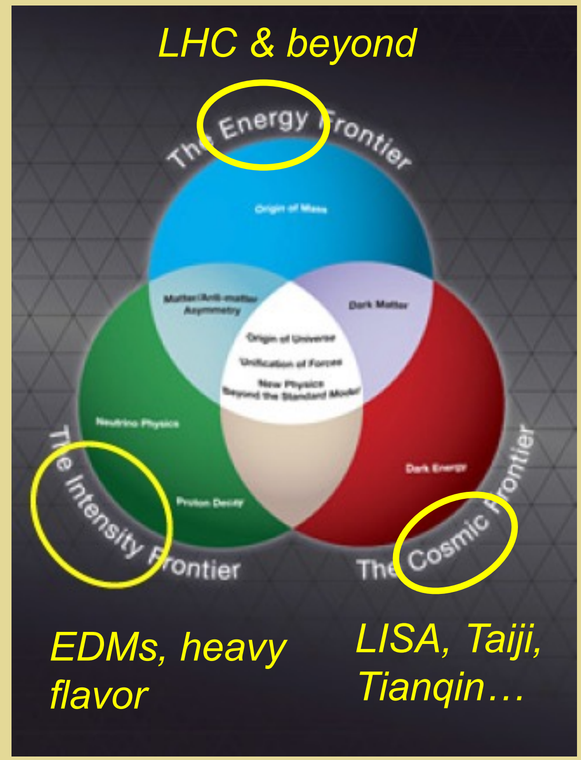

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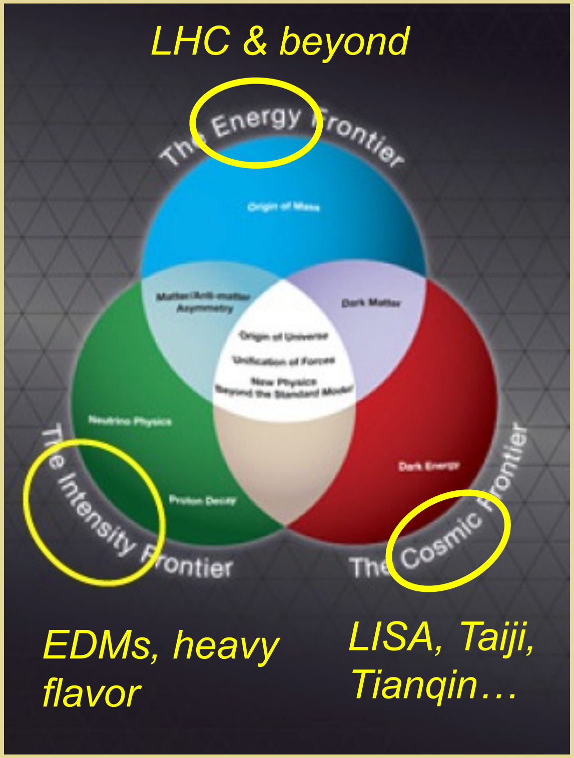
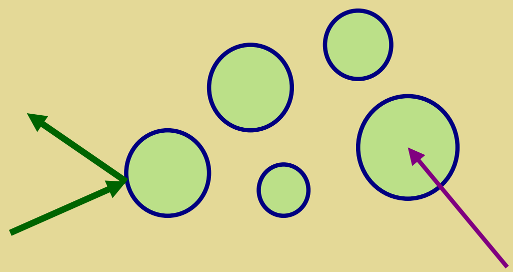
This talk



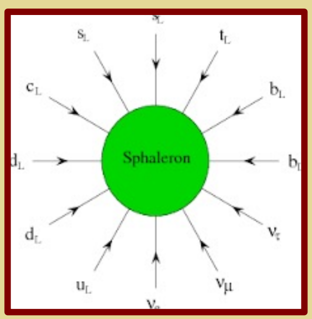
Electroweak Baryogenesis

1st order EWPT



Y_B : CPV &
EW sphalerons

EWSB



Electroweak Baryogenesis

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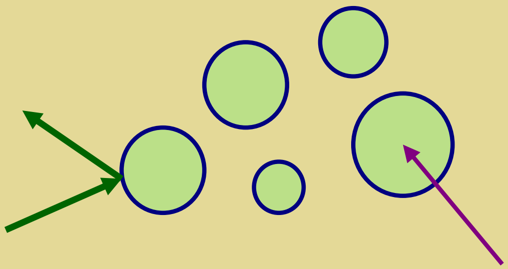

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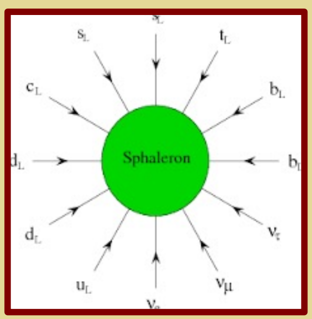
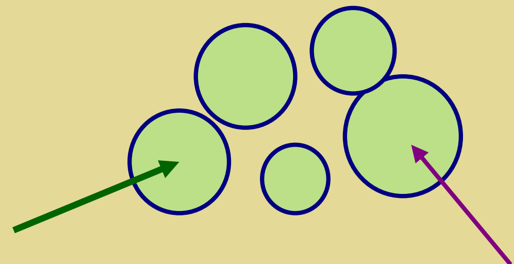


1^{st} order EWPT →
"strong" to preserve Y_B



Y_B : diffuses
into interiors

EWSB

EWBG Ingredients

- *EW Sphalerons*
- *Strong 1st Order EW Phase Transition*
- *Left-handed number density*

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- *Strong 1st Order EW Phase Transition* ➡ *BSM Higgs*
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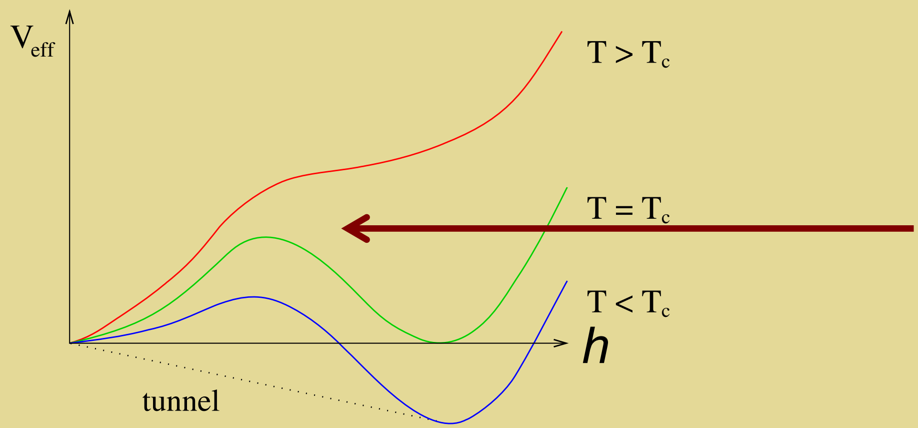
First Order EWPT from BSM Higgs



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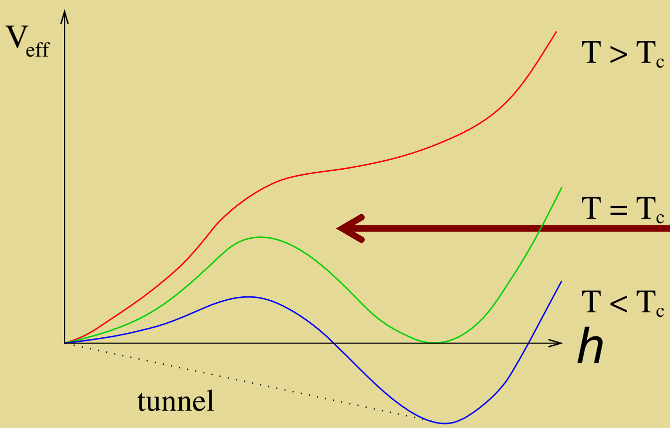
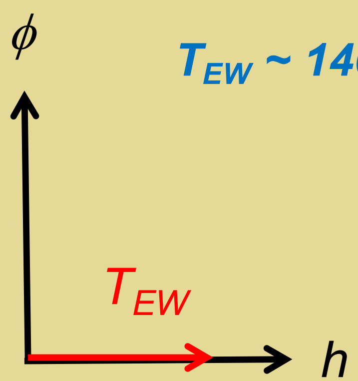
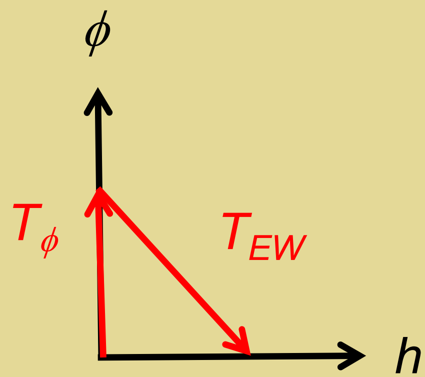
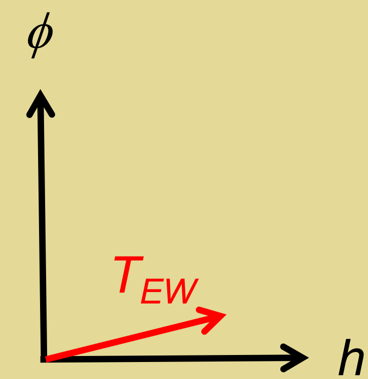


Representative thermal histories → barrier for SFOEWPT

T_{EW} ~ 140 GeV







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

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

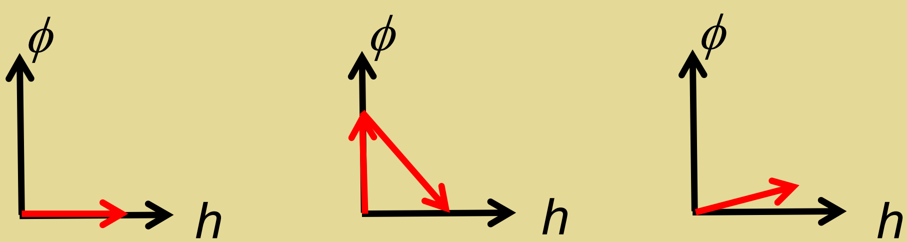
$a_1 H^2 \phi$: $T = 0$
tree-level effect

Theory-Pheno Interface

Simple Higgs portal models:

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

$$V \subset a_1 H^2\phi + a_2 H^2\phi^2$$



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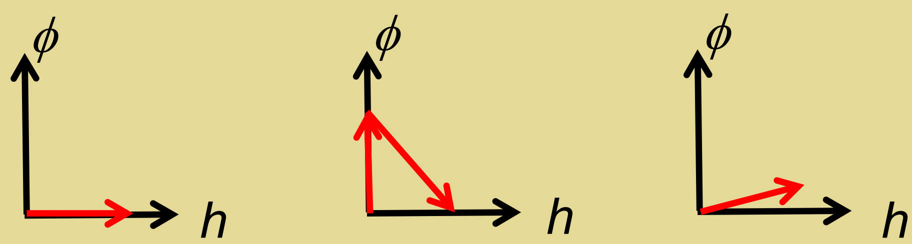

Phenomenology

$$h_1 = \sin\theta \; s + \cos\theta \; h$$
$$h_2 = \cos\theta \; s - \sin\theta \; h$$

$m_{1,2}$; θ ; $h_i\, h_j\, h_k$ couplings

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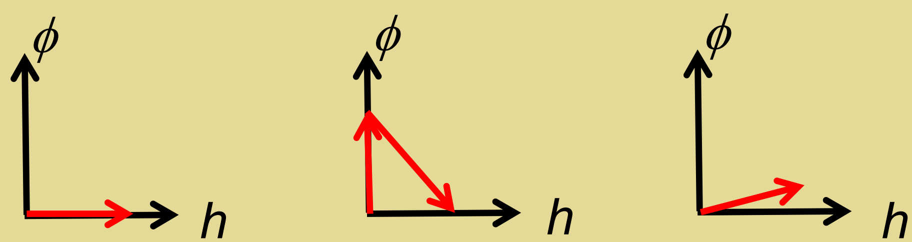

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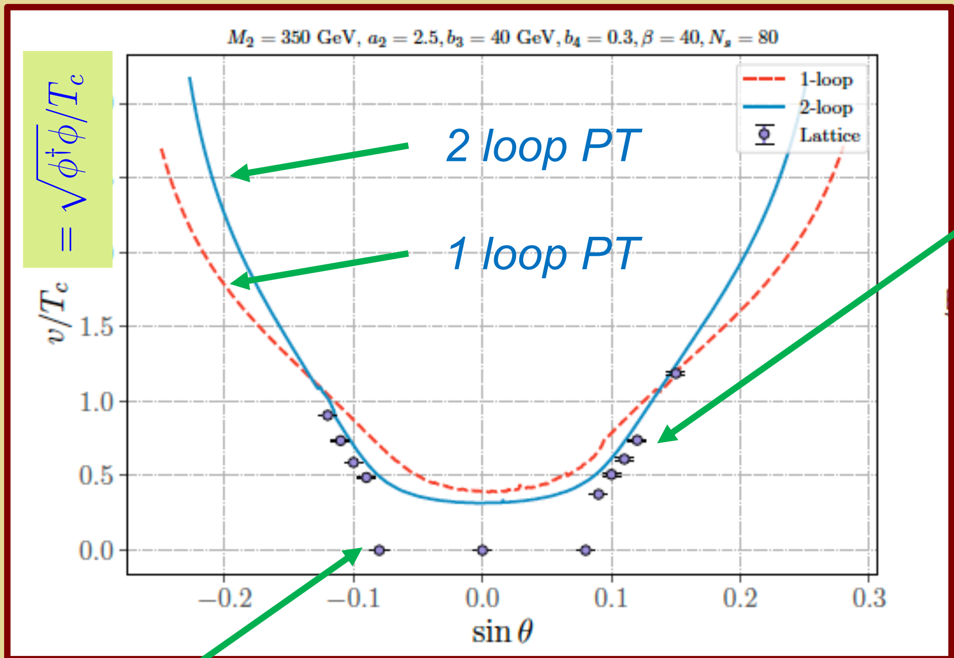
Lauri Niemi, MJRM, Gutao Xia, 2405.01191 (today!)

Singlets: Lattice vs. Pert Theory



Lattice:
FOEWPT

Lattice:
Crossover

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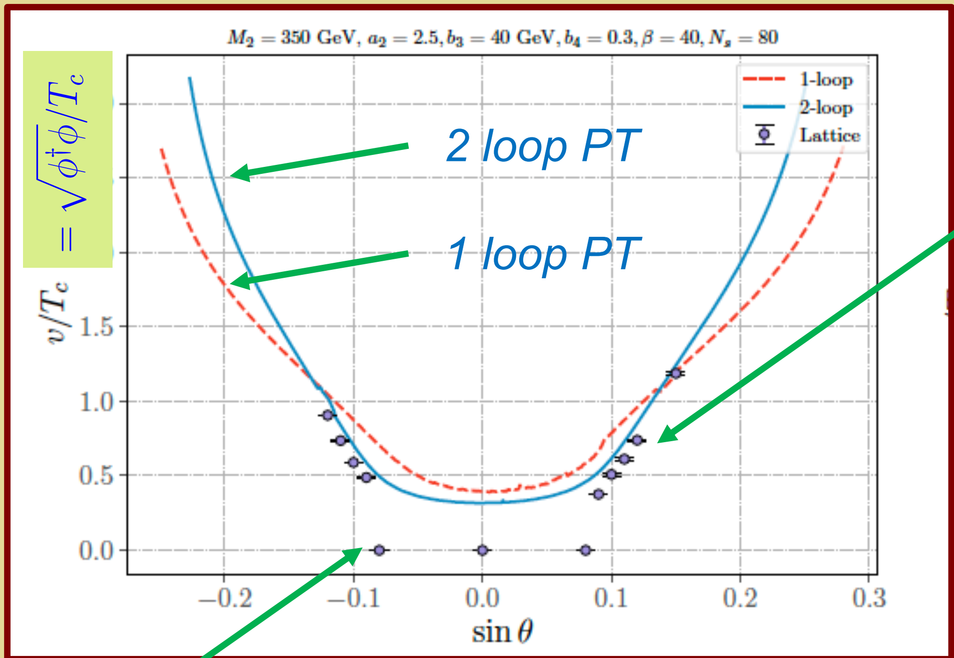
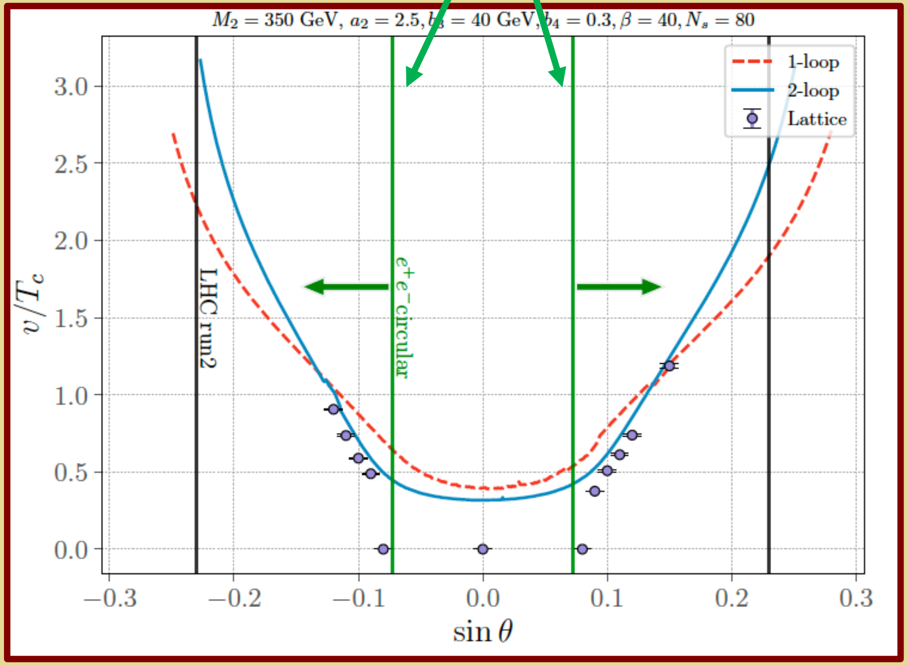


Lattice:
FOEWPT

Future e^+e^-



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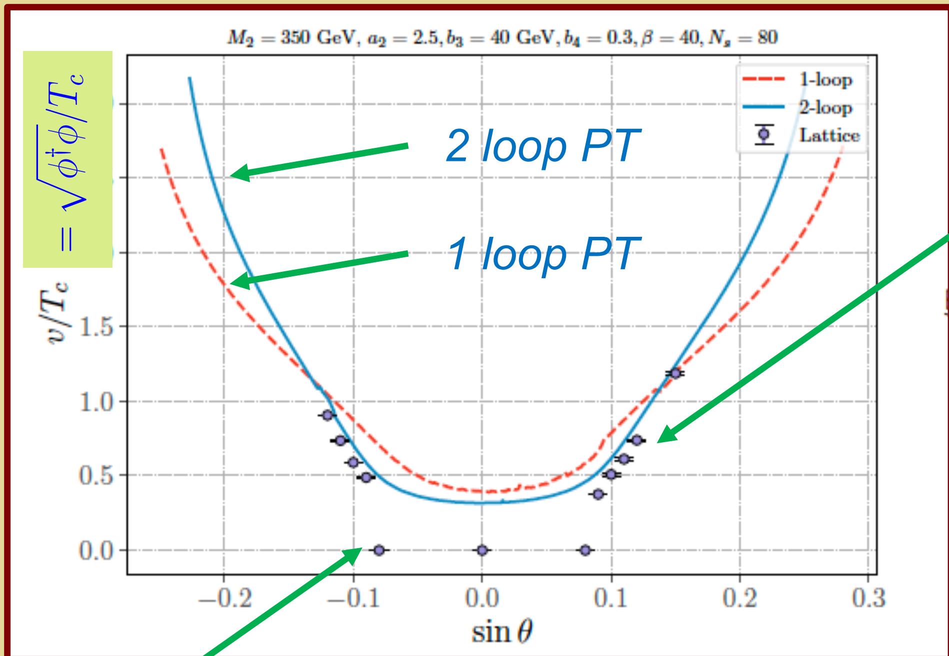

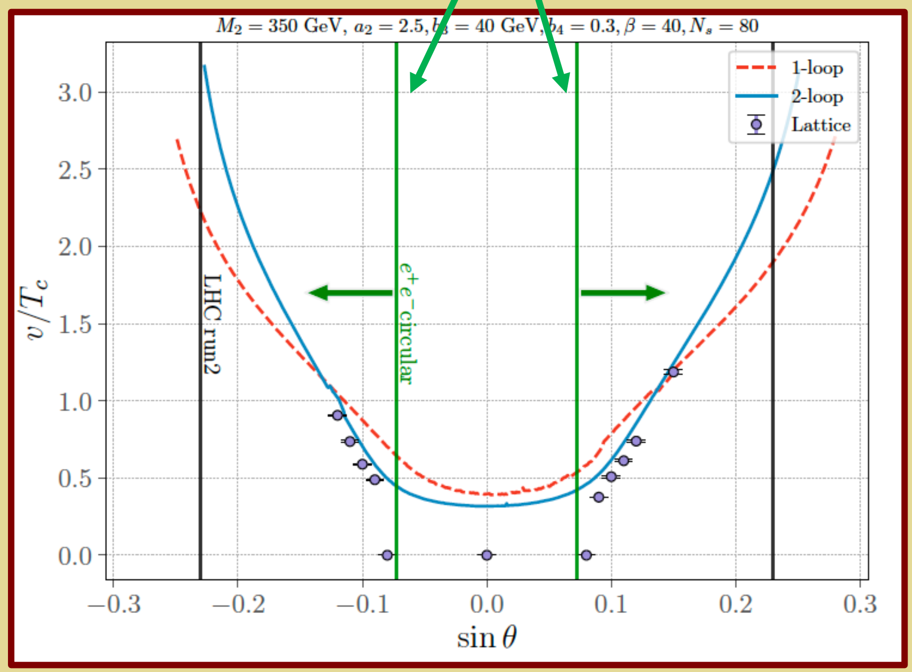

- *Lattice: crossover-FOEWPT boundary*
- *FOEWPT region: PT-lattice agreement*
- *Pheno: precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized*

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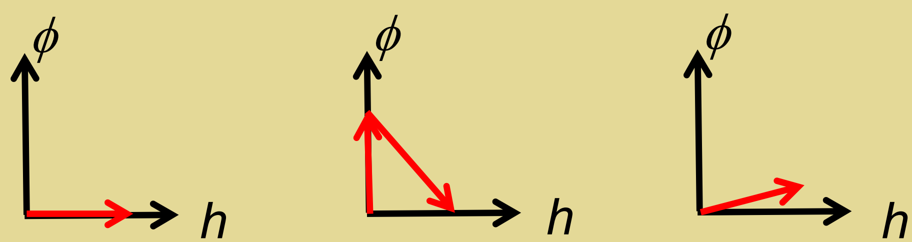

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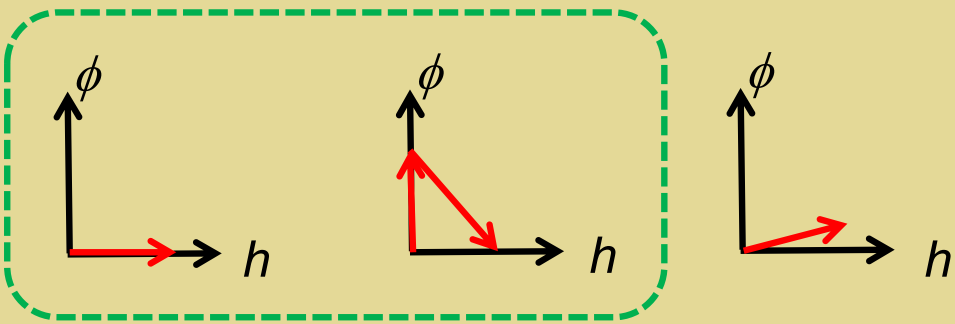

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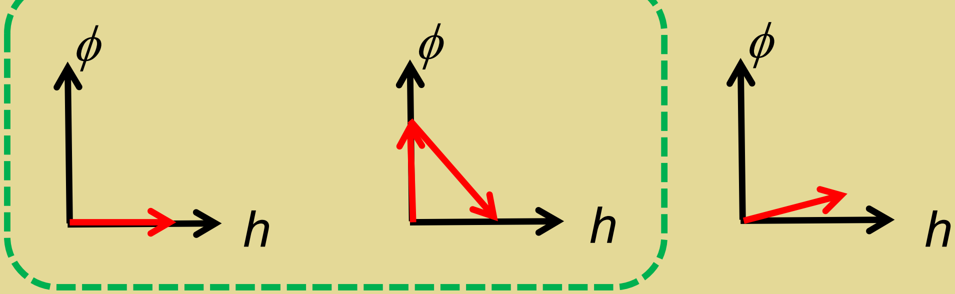
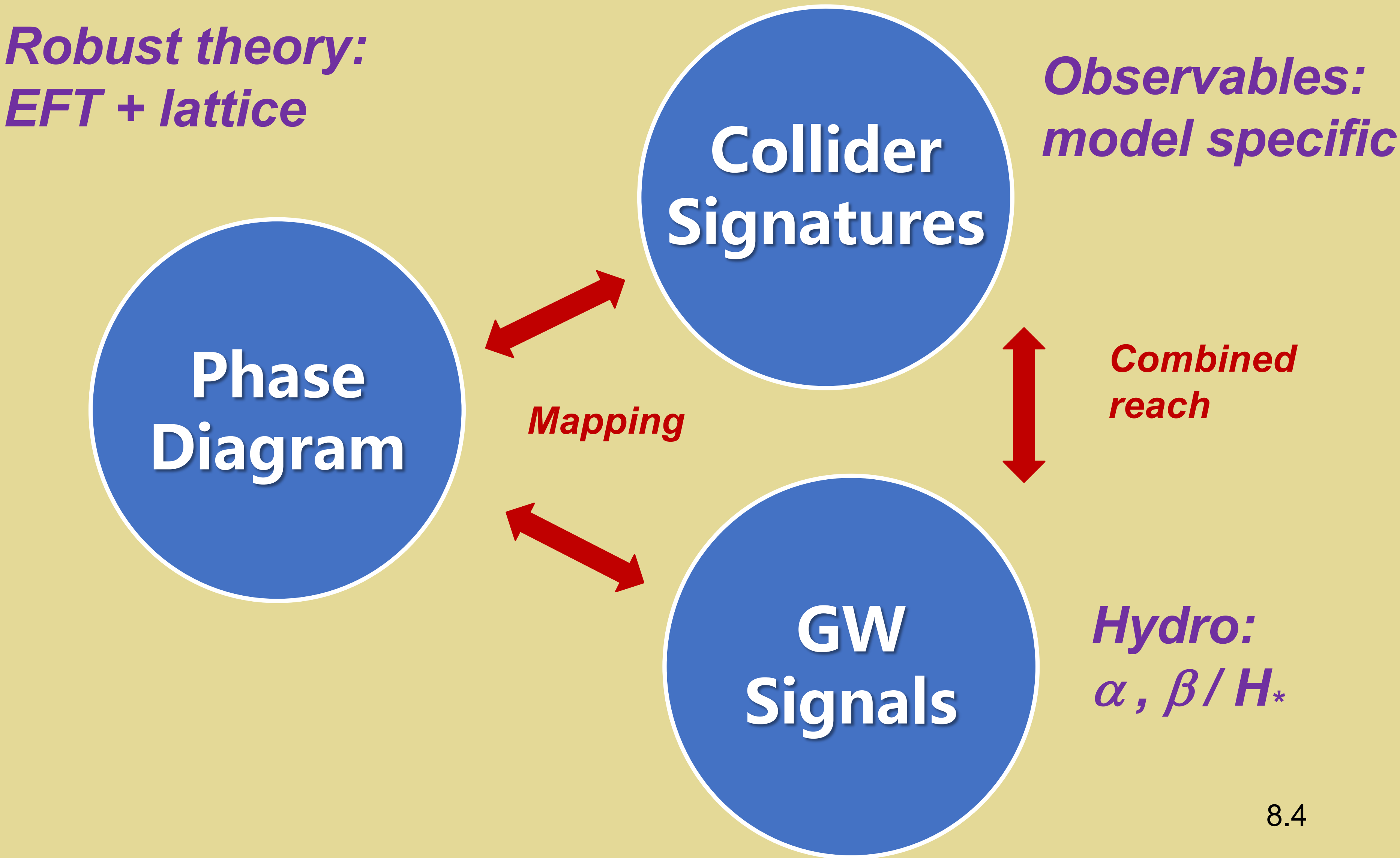


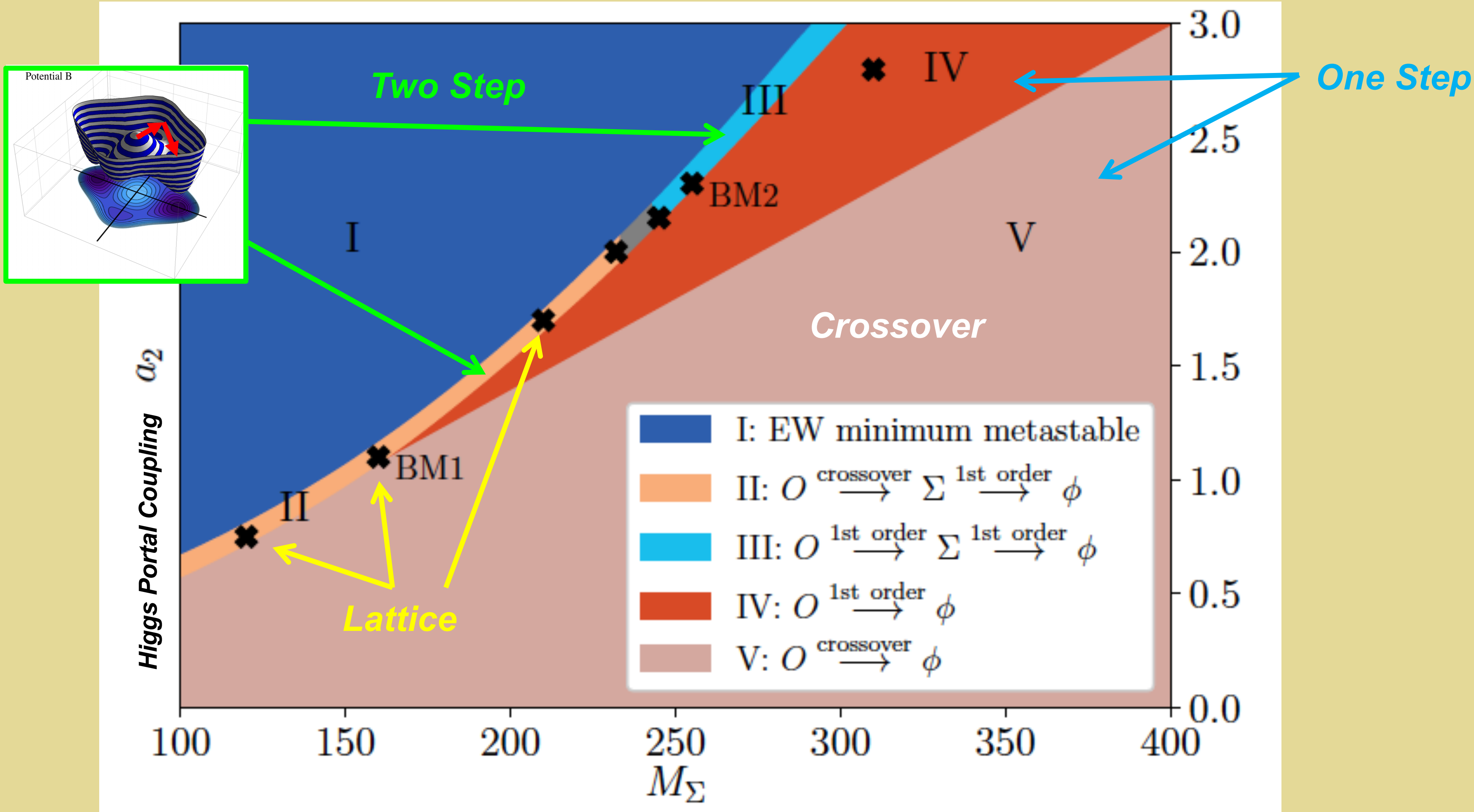
Phenomenology

- *Gravitational waves*
- *Collider: $h \to \gamma\gamma$, dis charged track, NLO $e^+e^- \to Zh$…*

BSM EWPT: Inter-frontier Connections



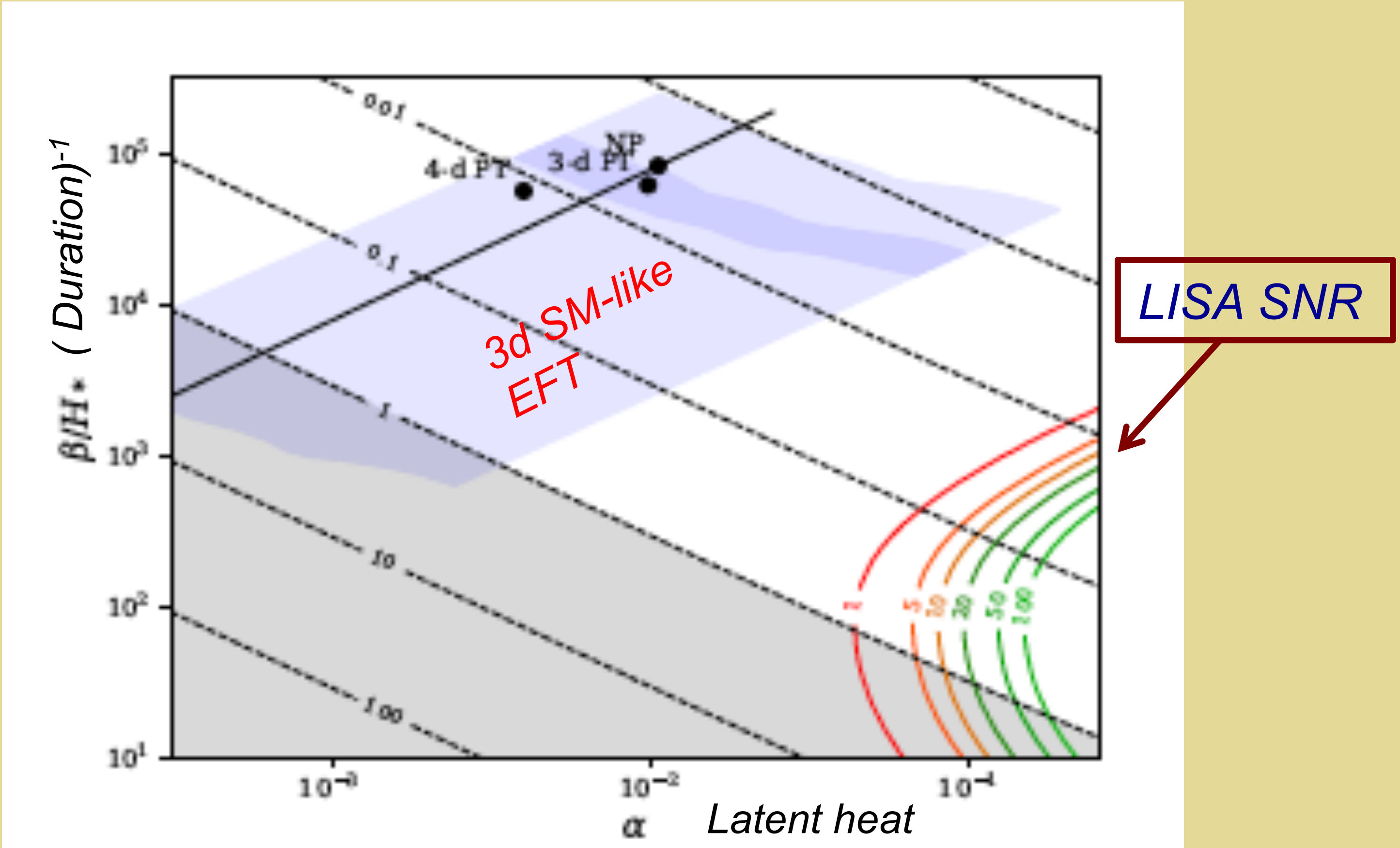
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332
→ PRL 126 (2021) 17

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

BSM Scalar: EWPT & GW



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

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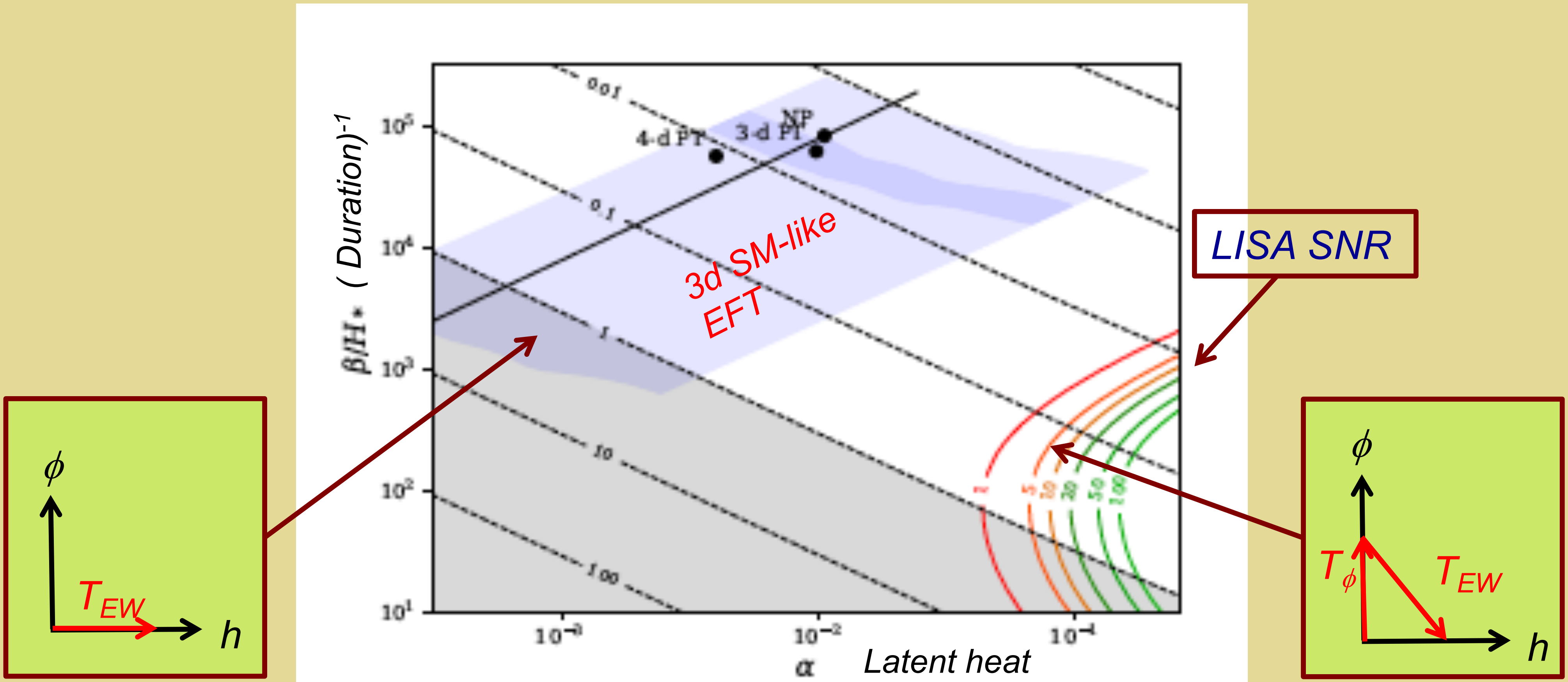
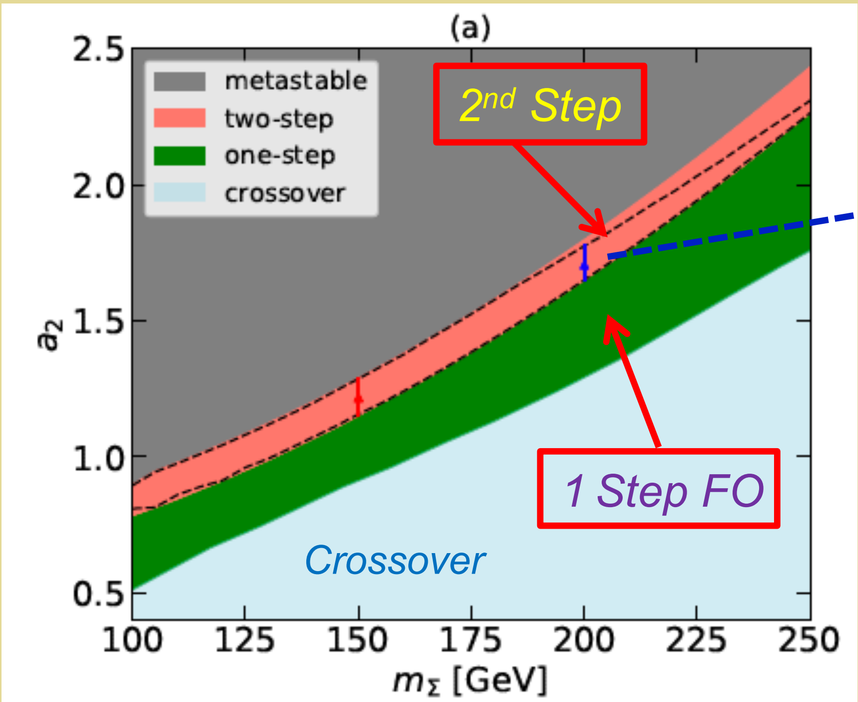
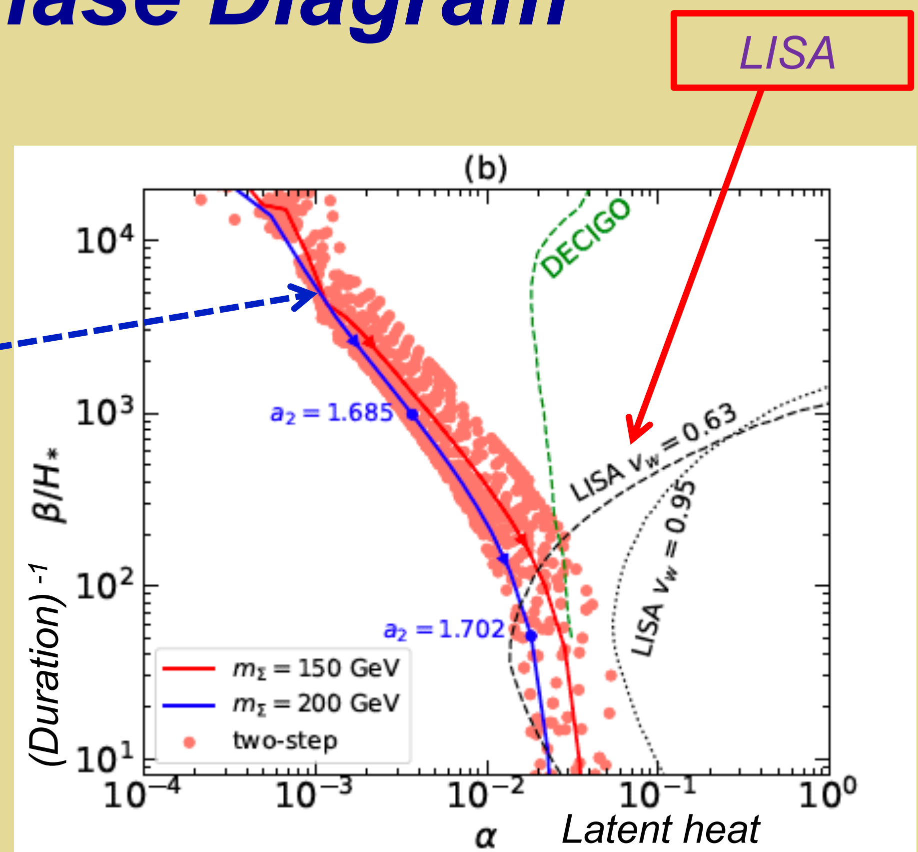


Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

GW & EWPT Phase Diagram

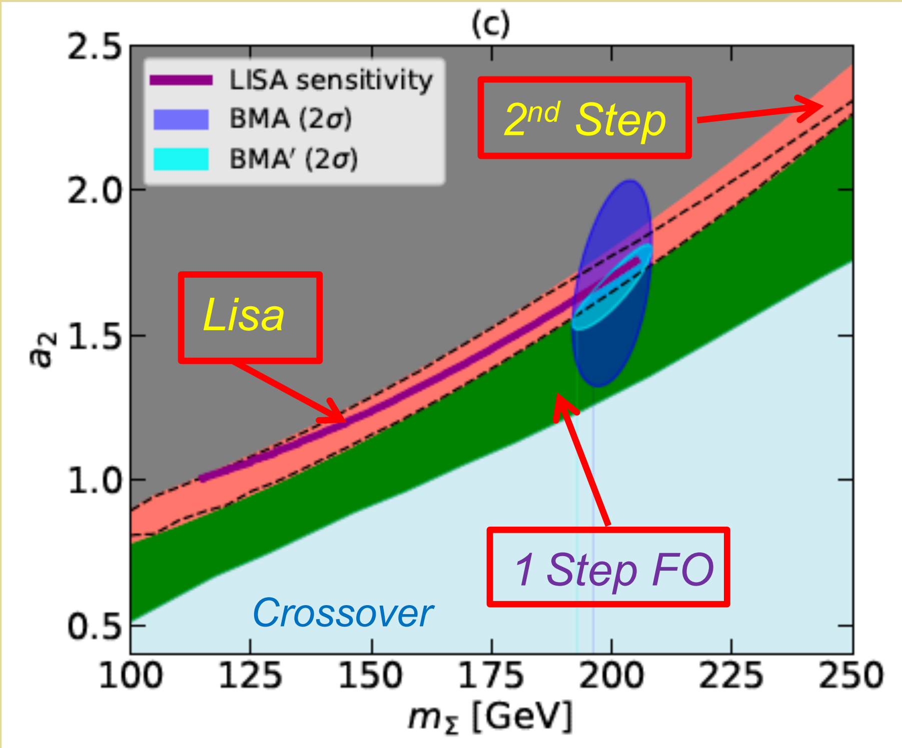


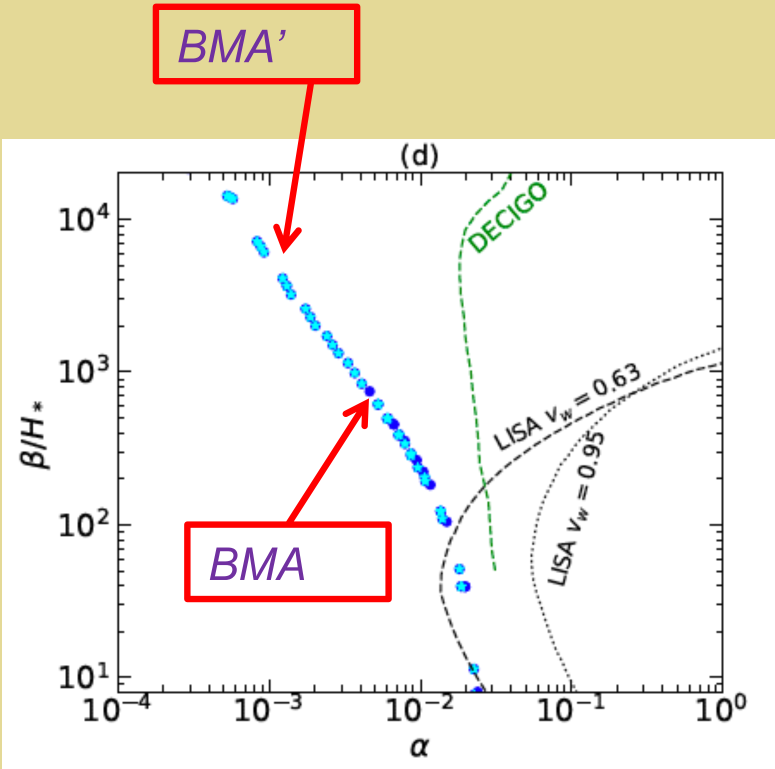


- *Single step transition: GW well outside LISA sensitivity*
- *Second step of 2-step transition can be observable*
- *Significant GW sensitivity to portal coupling*

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW & EWPT Phase Diagram





BMA: $m_\Sigma + h \rightarrow \gamma\gamma$

BMA' : BMA + $\Sigma^0 \rightarrow ZZ$

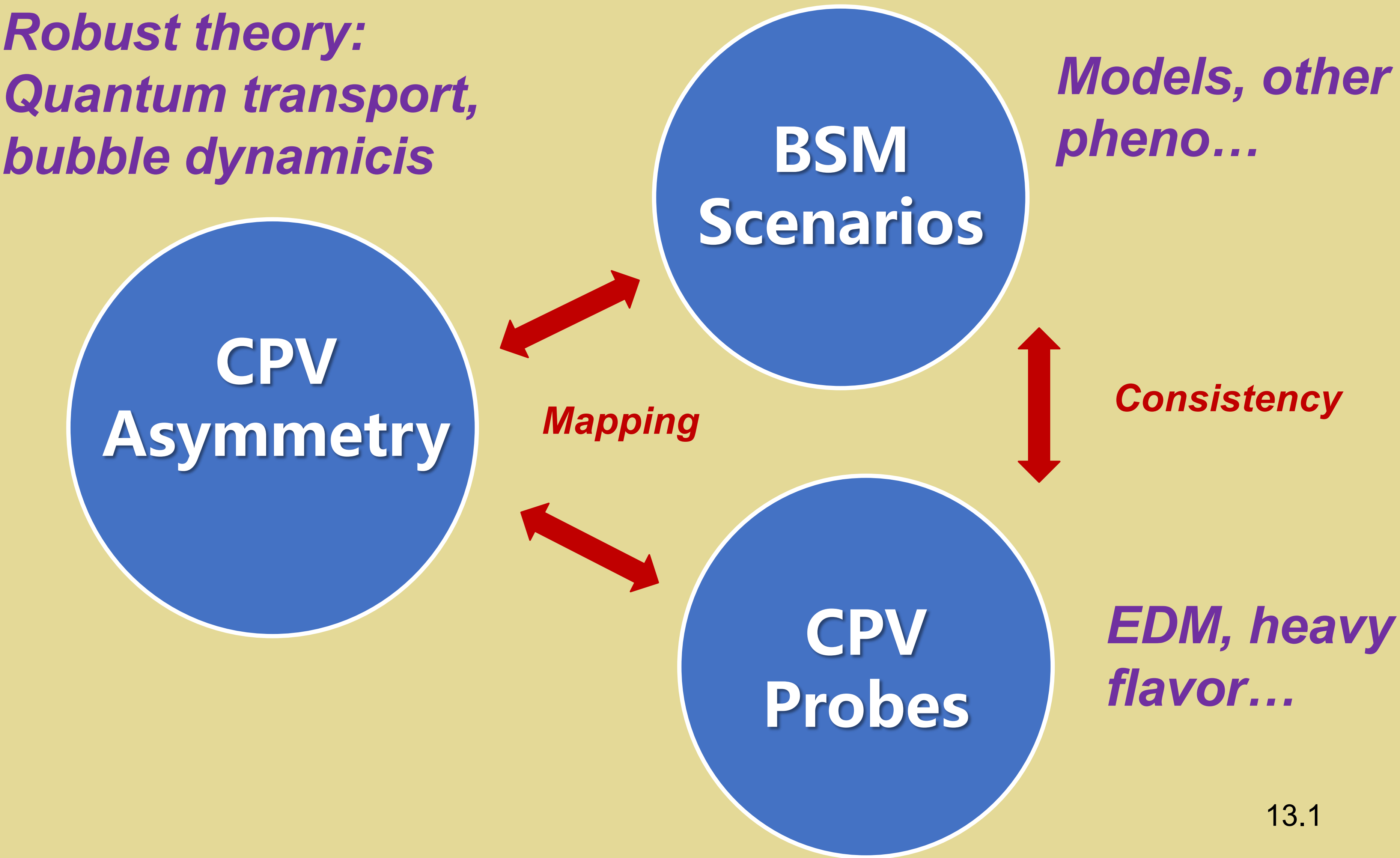
- Two-step
- EFT+ Non-perturbative

Friedrich, MJRM, Tenkanen, Tran 2203.05889

EWBG Ingredients

- EW Sphalerons ✔
- Strong 1st Order EW Phase Transition → BSM Higgs
- Left-handed number density → BSM CPV

BSM CPV: Inter-frontier Connections



EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-35}	10^{-30}
HfF^{+}	4.1×10^{-30} **	10^{-38}	10^{-29}
n	1.8×10^{-26}	10^{-31}	10^{-26}

* 95% CL   ** e^{-} equivalent

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

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Challenge for EWBG

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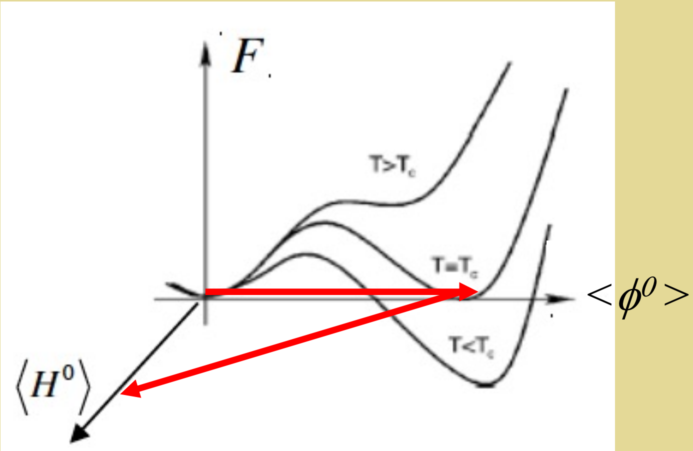
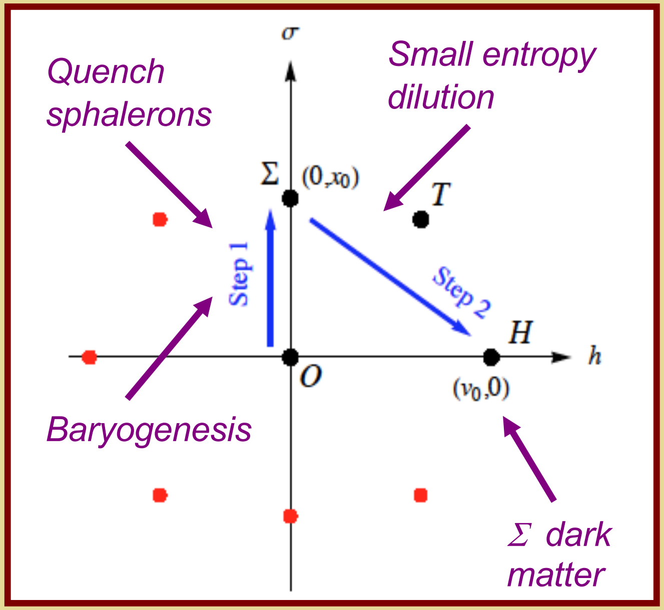
Two-Step EW Baryogenesis





Inoue, Ovanesyan, R-M: 1508.05404

Illustrative Model:

New sector: "Real Triplet" Σ
Gauge singlet S

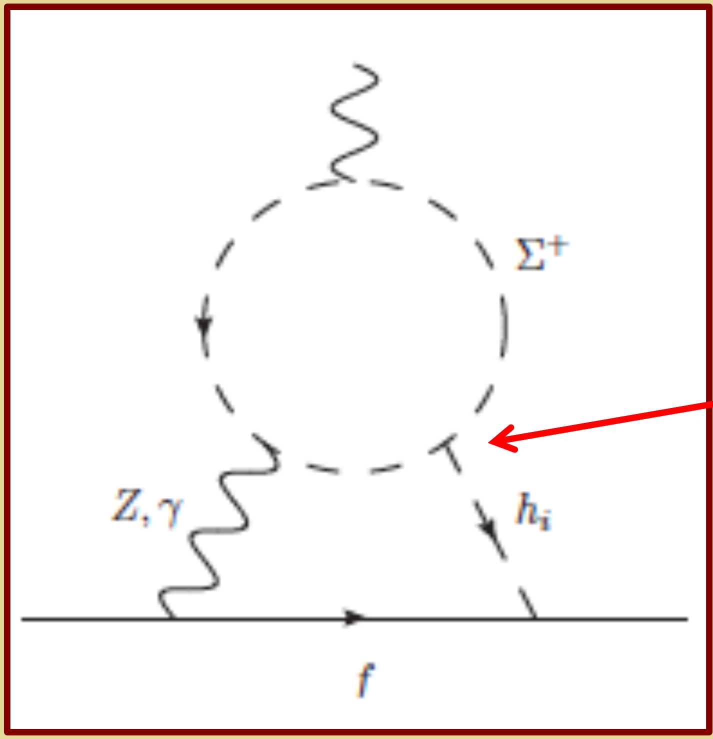
H $\rightarrow$ *Set of "SM" fields: 2 HDM*

(SUSY: "TNMSSM", Coriano…)

Two CPV Phases:

δ_Σ : *Triplet phase*
δ_S : *Singlet phase*

Two-Step EW Baryogenesis & EDMs



EDMs are Two Loop

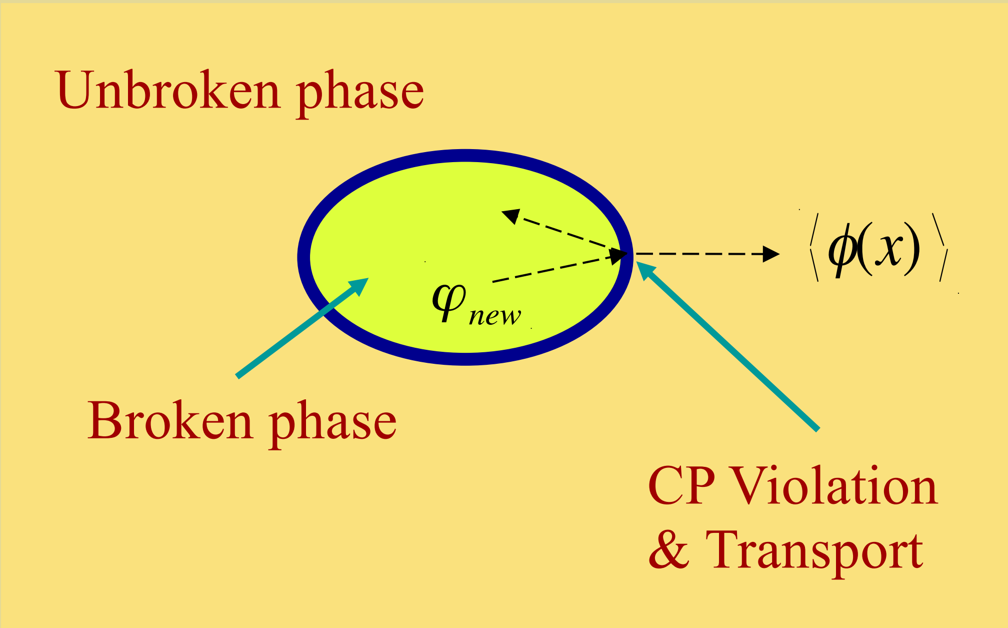
Two CPV Phases:

δ_Σ : Triplet phase
δ_S : Singlet phase

Insensitive to δ_S : electrically neutral $\rightarrow$ "partially secluded"

Inoue, Ovanesyan, R-M: 1508.05404

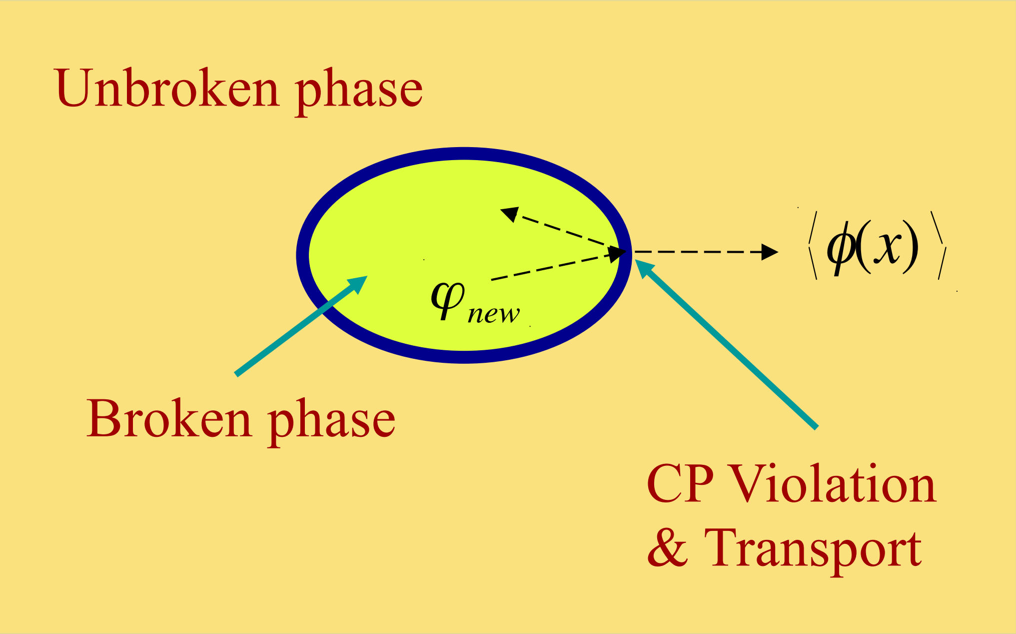
Transport Theory



Transport Problem:

- ***Particle masses depend on spacetime → CPV sources***
- ***Include CPC effects in thermal plasma***

Transport Theory



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- ***Bubble dynamics***
- ***CPV Sources***
- ***Chemical & thermal equilibration, diffusion…***

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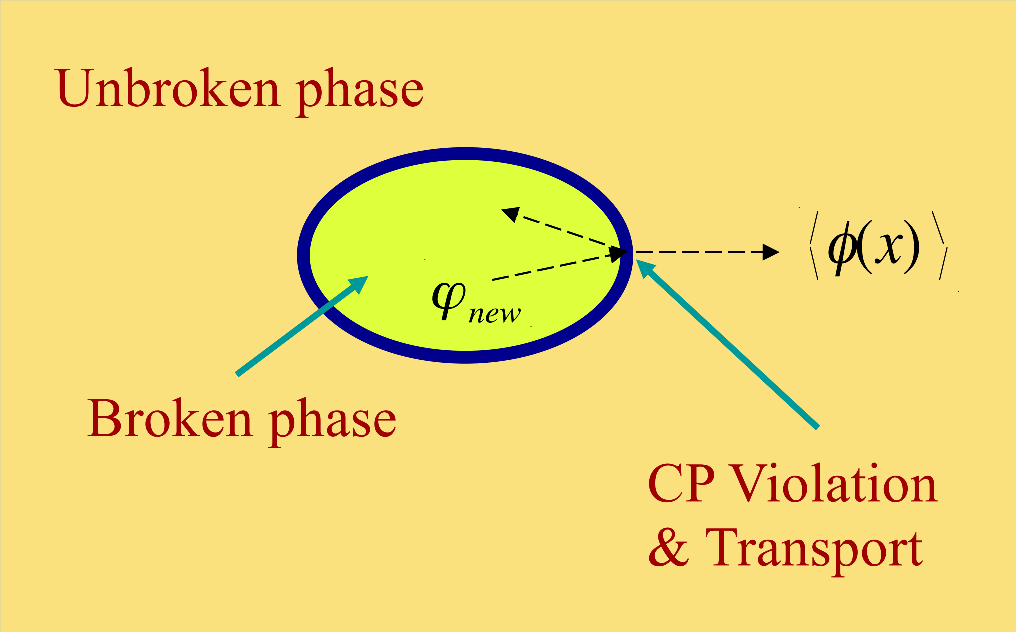

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→ ***Quantum Kinetic Eqs***

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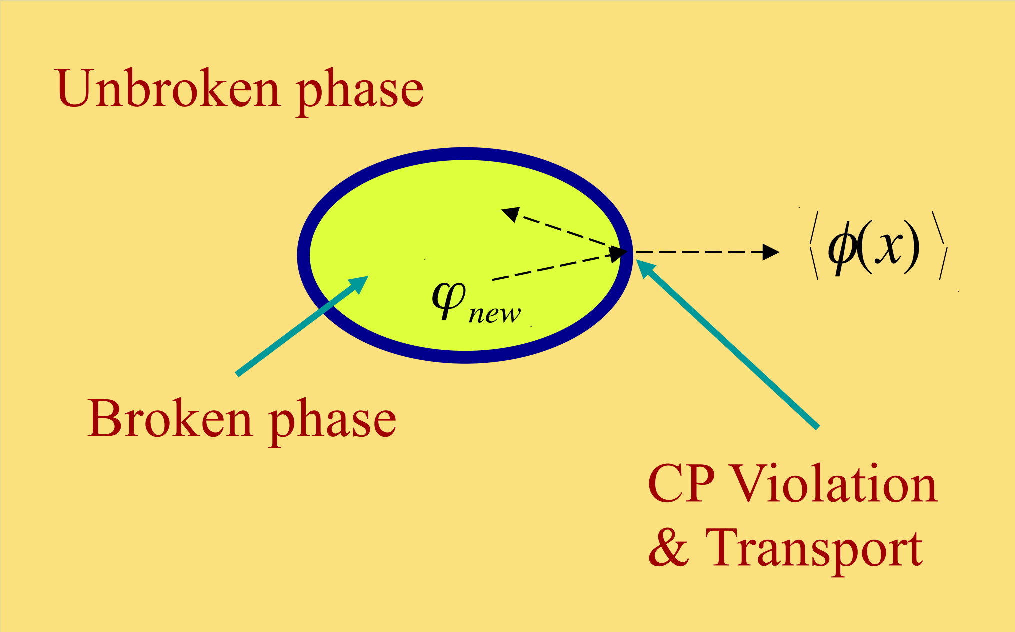

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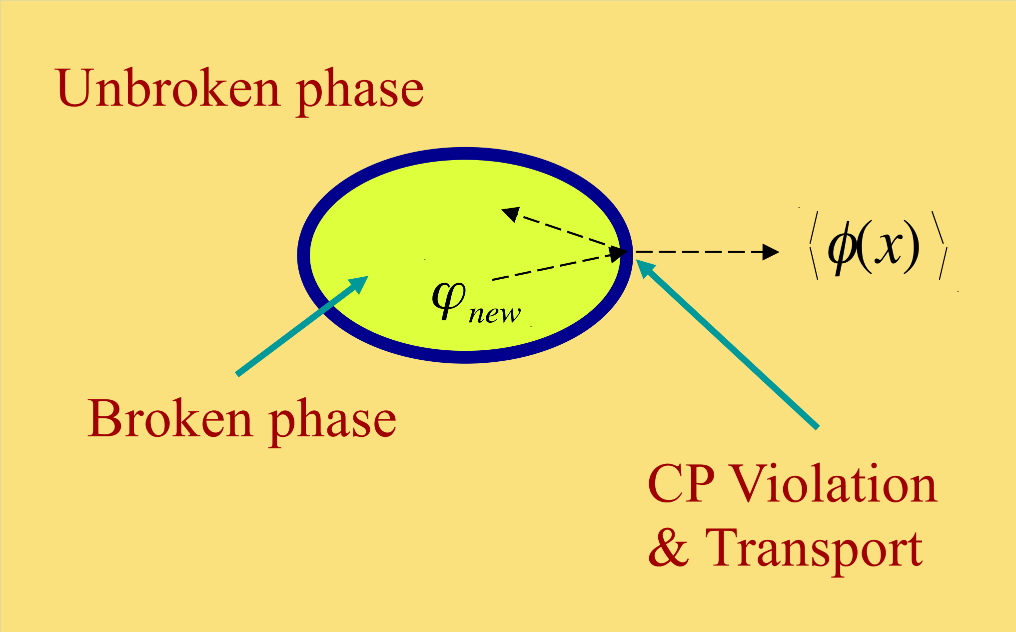
- *Vev insertion approx (VIA) : "perturbative" expansion in v(x) → CPV 1st order in v'(x) but theoretically fraught*
- *WKB/Semiclassical: re-sum v(x) → CPV 2nd order in v'(x)*
- *Vev resummation (VR): re-sum v(x) → CPV 1st order in v'(x) for flavor mixing & realistic inclusion of CPC plasma interactions*

Closed Time Path

Quantum Kinetic Eqs

16.4

Transport Theory



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Closed Time Path

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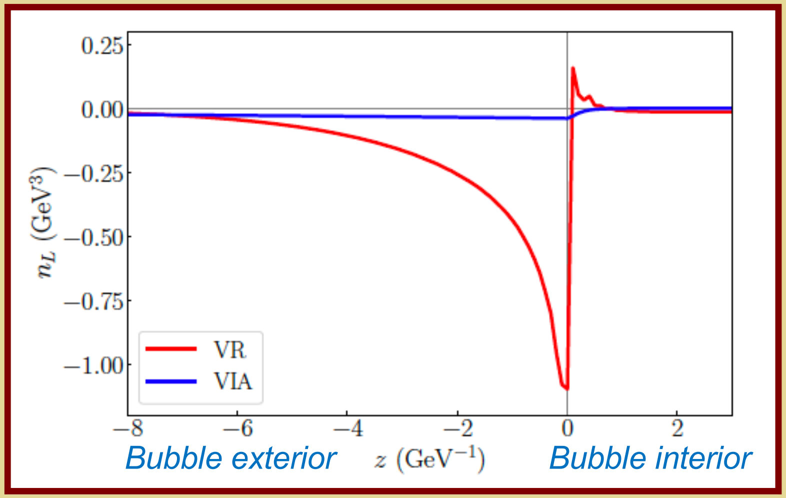
Cirlgliano, Lee, MJRM, Tulin 1912.3523; Clrigliano, Lee, Tulin 1106.0747

16.4

Yuan-Zhen Li, MJRM, Jiang-Hao Yu 2404.19197

Two-Step EWBG: Transport Theory & EDMS



Yuan-Zhen Li, MJRM, Jiang-Hao Yu 2404.19197

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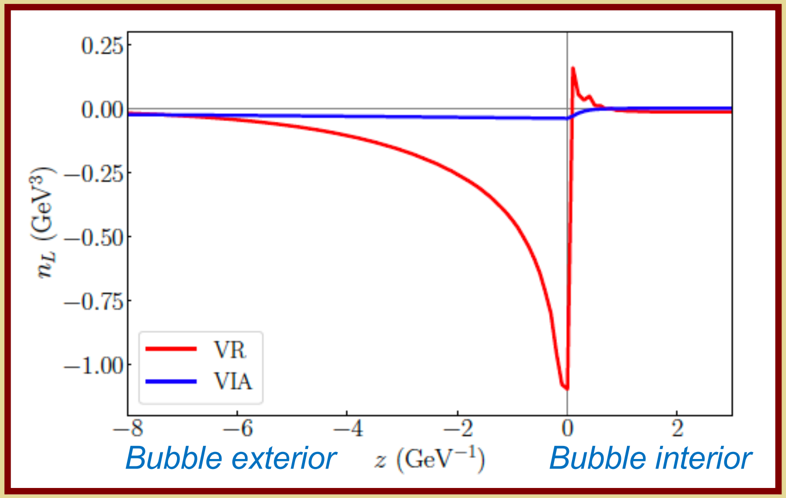

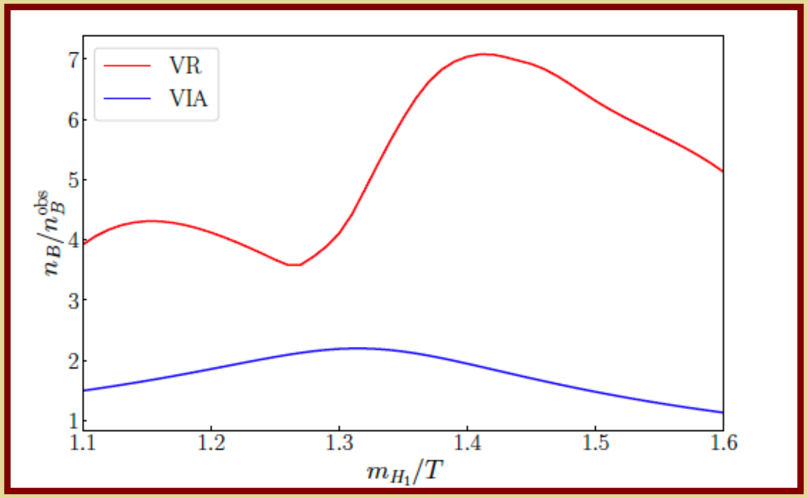

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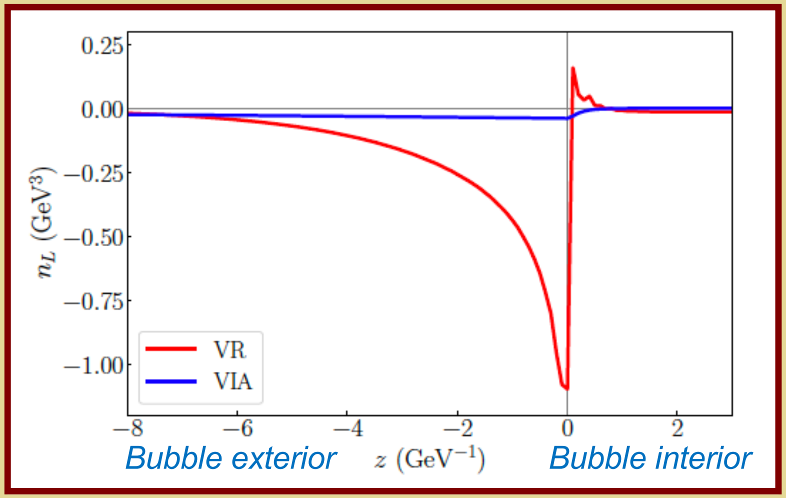

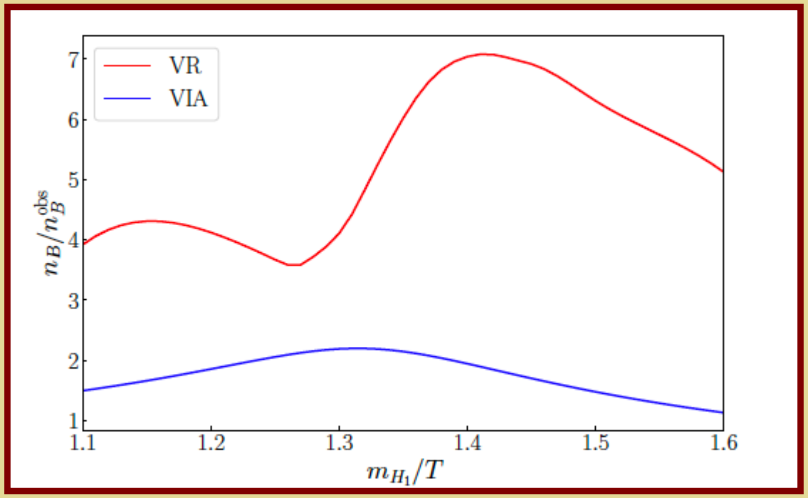

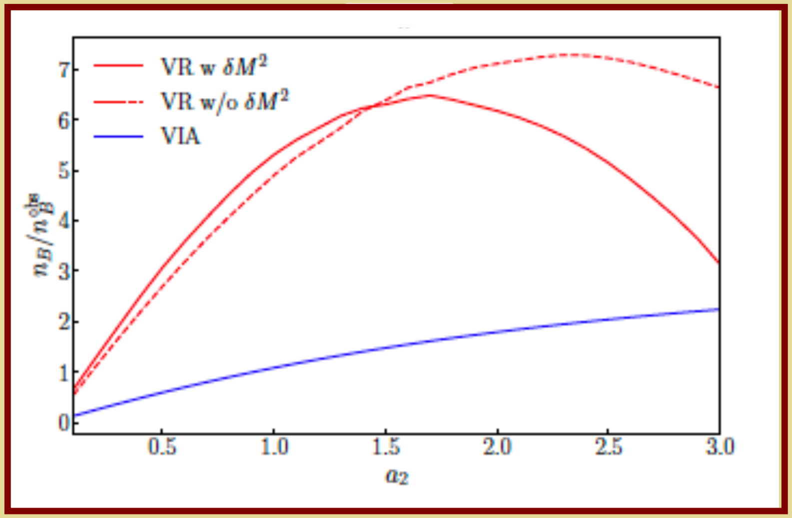

$a_2\, H_1^*\, H_2\, \Sigma^2$ + c.c.

Yuan-Zhen Li, MJRM, Jiang-Hao Yu 2404.19197

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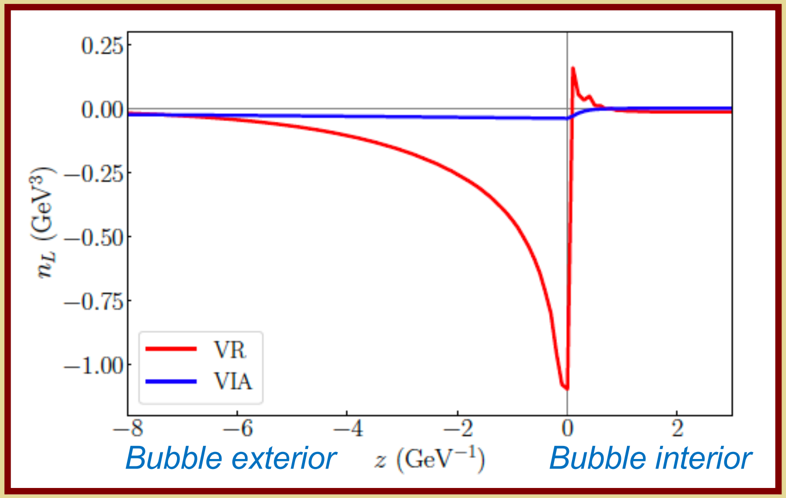
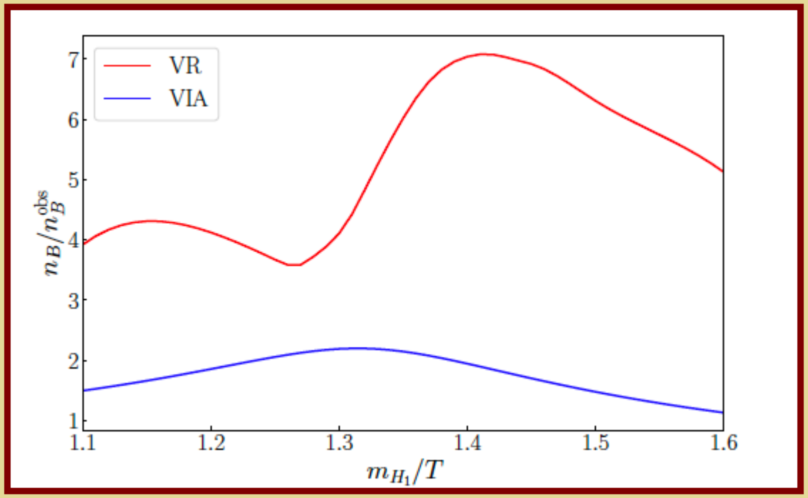
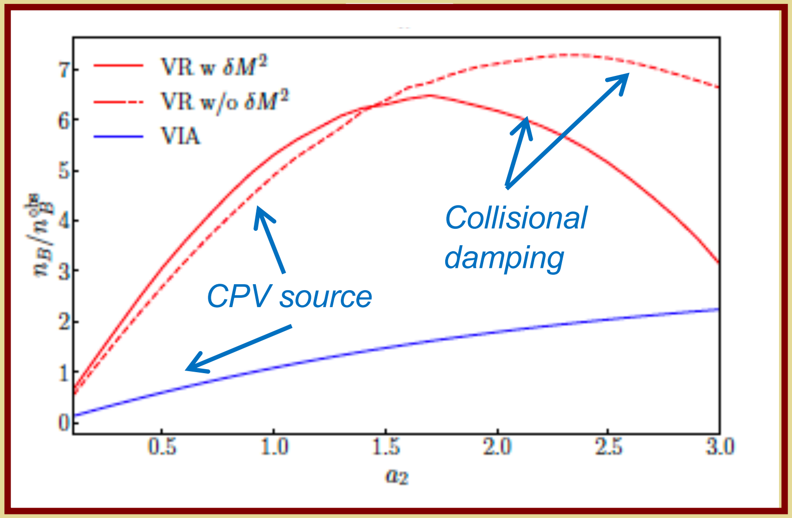


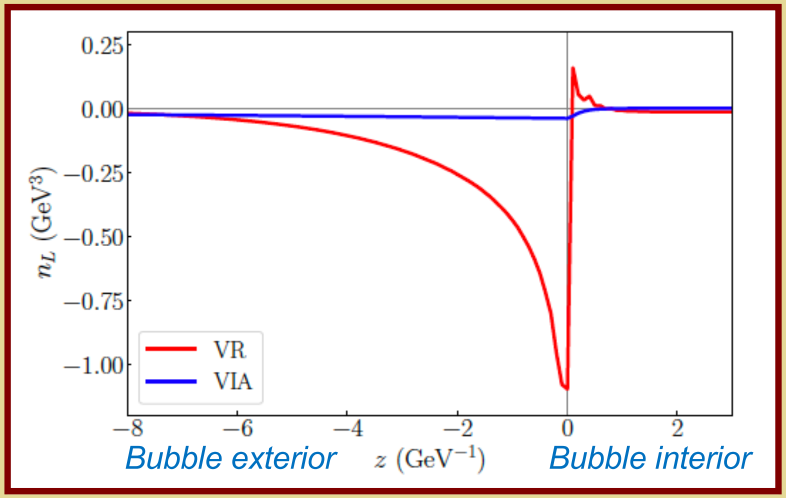


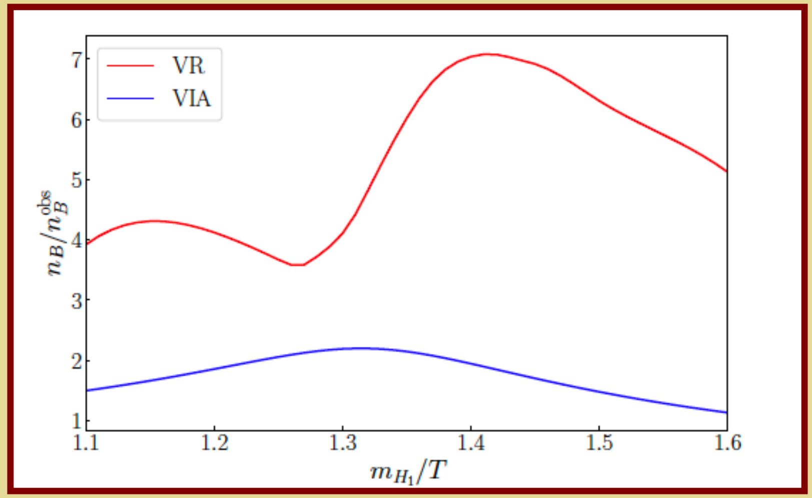


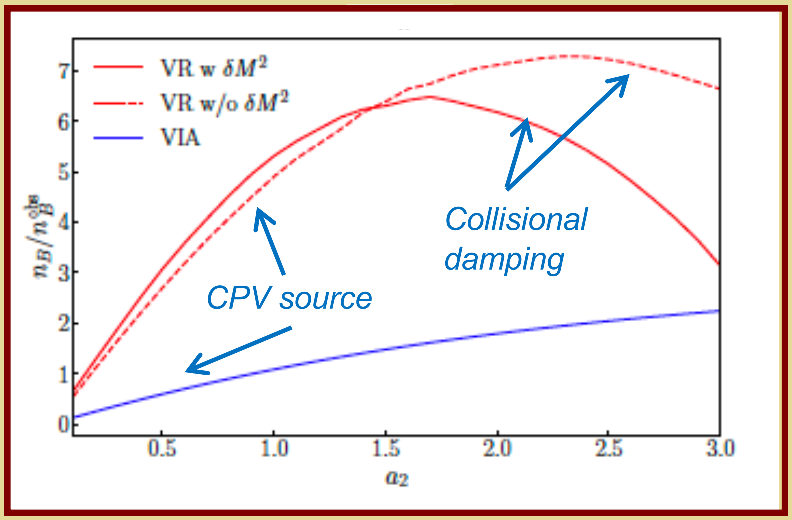
$a_2 H_1^* H_2 \Sigma^2$ + c.c.

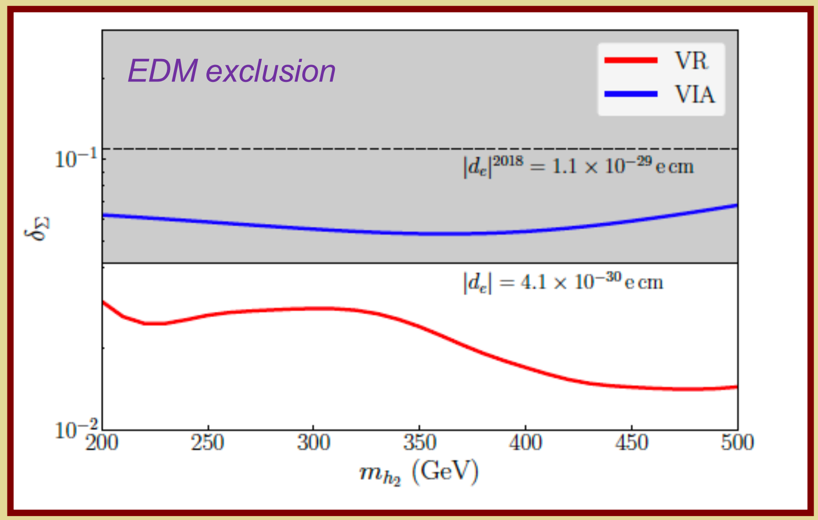
Yuan-Zhen Li, MJRM, Jiang-Hao Yu 2404.19197

Two-Step EWBG: Transport Theory & EDMS









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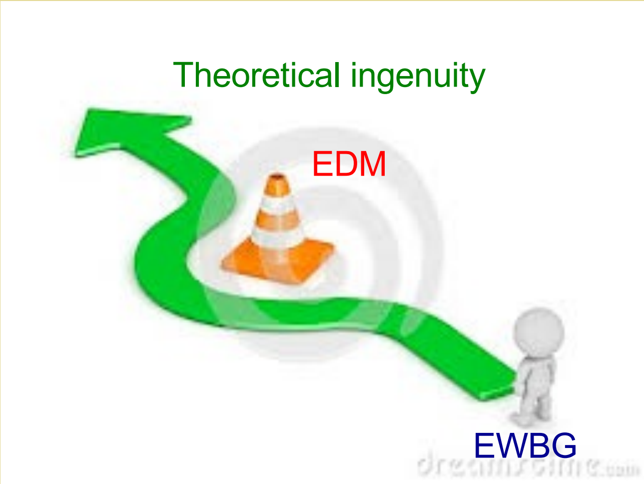
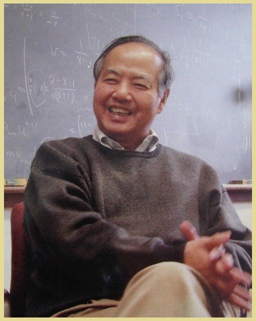
CPV for EWBG



How Viable is EWBG ?

- ***Electroweak baryogenesis remains a theoretically compelling and experimentally testable scenario***
- ***Experimental information from the cosmic, energy, and intensity frontiers provides essential input for assessing EWBG viability***
- ***A robust confrontation of theory and experiment relies on continual improvements in theoretical tools, from high-T EFT and lattice thermodynamics through quantum transport theory and more***

T. D. Lee Institute / Shanghai Jiao Tong U.



Director

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

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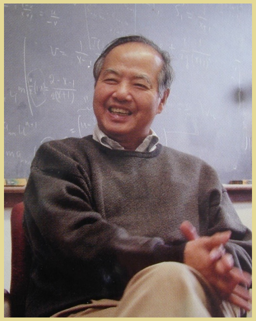

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谢谢！

Back Up Slides

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

Lowest non-trivial order in grad's

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

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Spacetime evolution of densities

Systematic Systematic Baryogenesis:

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Diagonal after rotation to local mass basis:

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

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

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

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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

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

→ ***First order in v' (x)***

Systematic Baryogenesis:

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Collision term: CP conserving interactions leading to thermalization, chemical equilibration, diffusion, damping,…

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

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

$$(u\cdot\partial_X + \vec{F}\cdot\nabla_k) f_m(\vec{k},X) = -\left[i\omega_k + u\cdot\Sigma, f_m(\vec{k},X)\right] + \mathcal{C}_m[f_m,\bar{f}_m](\vec{k},X) \qquad \text{(2a)}$$

$$(u\cdot\partial_X + \vec{F}\cdot\nabla_k) \bar{f}_m(\vec{k},X) = +\left[i\omega_k - u\cdot\Sigma, \bar{f}_m(\vec{k},X)\right] + \mathcal{C}_m[\bar{f}_m,f_m](\vec{k},X) \quad , \quad \text{(2b)}$$

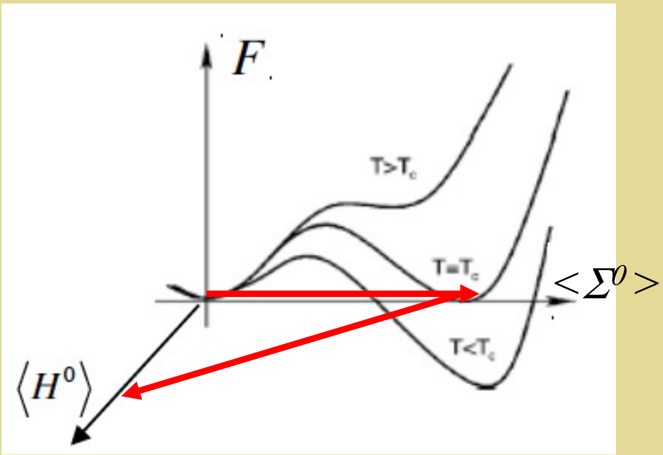
Effective $\Delta\omega$ between particle & antiparticle flavor oscillations

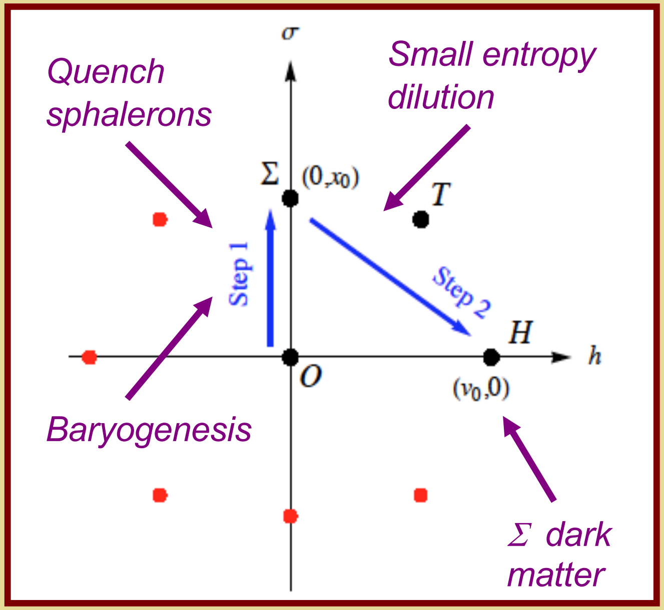
Phase in m^2 (x)

$$\Sigma^\mu(x) \equiv U^\dagger(x)\,\partial^\mu U(x) = \begin{pmatrix} 0 & -e^{-i\alpha} \\ e^{i\alpha} & 0 \end{pmatrix}\partial^\mu\theta + \begin{pmatrix} i\sin^2\theta & \frac{i}{2}\sin 2\theta e^{-i\alpha} \\ \frac{i}{2}\sin 2\theta e^{i\alpha} & -i\sin^2\theta \end{pmatrix}\partial^\mu\alpha\,.$$

Rotation to mass basis: θ

General Considerations



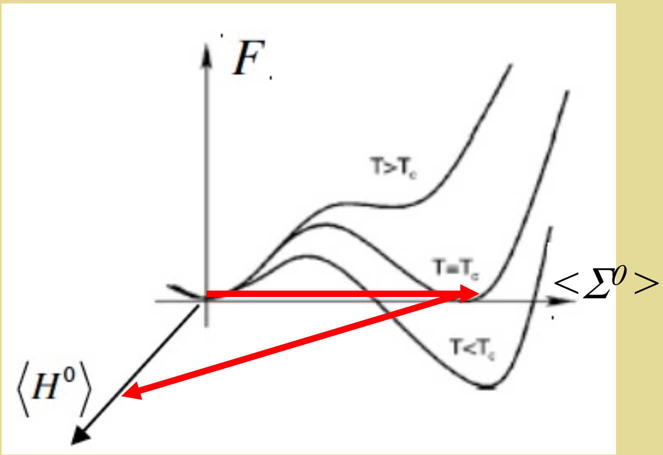


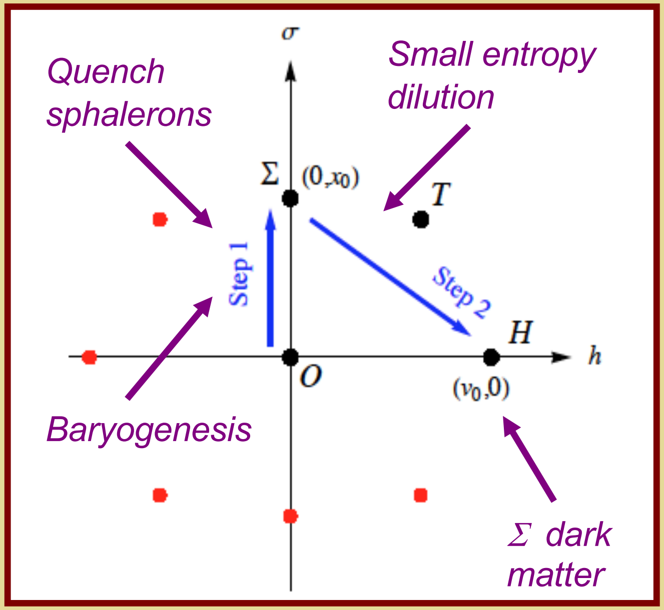
$\Sigma \rightarrow$ New sector: set of BSM fields ϕ_j, including at least one that breaks EWSB at $T > 0$ during first step

$H \rightarrow$ Set of "SM" fields, including at least one that breaks EWSB at during second step & persists to $T = 0$ (e.g., single H, 2HDM…)

What are possibilities for generating CPV asymmetries needed for baryogenesis during the first step ?

2-Step EWBG: Rich Array of Scenarios





$\Sigma \to$ New sector: set of BSM fields ϕ_j, including at least one that breaks EWSB at $T > 0$ during first step

- *New sector contains additional LH fermions that contribute to the B+L anomaly: CPV interactions with $\phi_j \to n_L$*
- *CPV asymmetry generated for subset of ϕ_j, then transferred to SM sector*
- *CPV asymmetry generated in SM sector via interactions with the ϕ_j*

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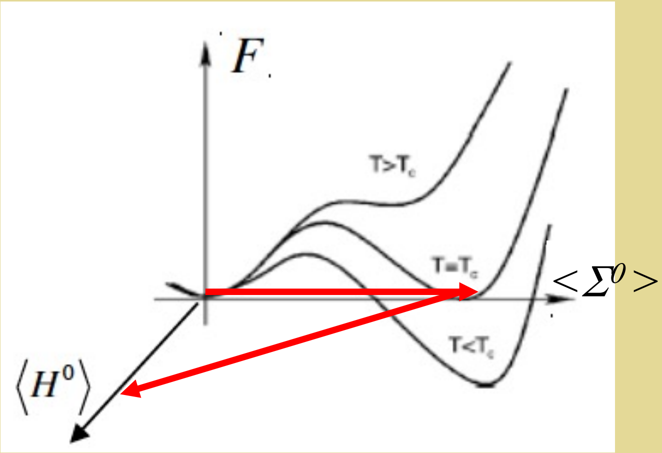

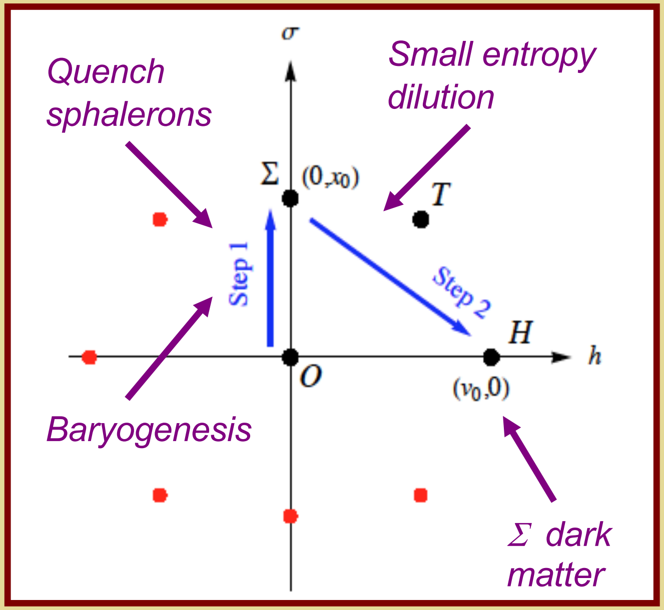

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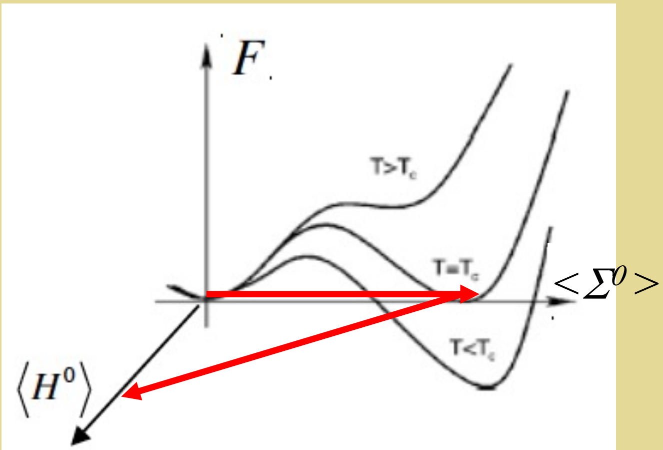
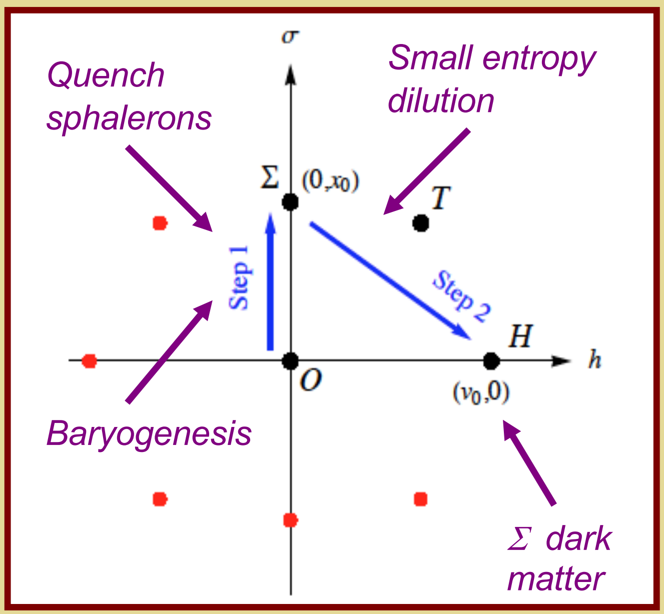
Illustrative Study





CPV asymmetry generated in SM sector via interactions with the ϕ_j

Considerations:

- *Renormalizable interactions in scalar sector*
- *At least two new sector fields get spacetime varying vevs $v_{NEW}(x)$ during step 1, at least one of which is EWSB*
- *At least two scalar fields mix due to $v_{NEW}(x)$, at least one of which is in SM sector*

MJRM: 1912.07189

T_{EW} → Scale for Colliders & GW probes

High-T SM Effective Potential

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

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

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High-T SM Effective Potential

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FO EWPT → Collider target: $M_{BSM} \lesssim 700$ GeV, $\delta\kappa_H \gtrsim 0.01$

Challenges for Theory

Perturbation theory

- I.R. problem: poor convergence
- Thermal resummations
- Gauge Invariance (radiative barriers)
- RG invariance at T>0

BSM proposals

Non-perturbative (I.R.)

- Computationally and labor intensive

EFT 1: Thermodynamics

Matching: Two Elements

Dimensional Reduction

All integrals are 3D with prefactor T → Rescale fields, couplings…

$$\int \frac{d^4k}{(2\pi)^4} \longrightarrow \frac{1}{\beta}\sum_n \int \frac{d^3k}{(2\pi)^3}$$

- $\varphi^2_{4d} = T\,\varphi^2_{3d}$
- $T\,\lambda_{4d} = \lambda_{3d}$

Thermal Loops

Equate Greens functions

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

Field

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

Quartic coupling