How Viable is Electroweak Baryogenesis ?

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About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

Caltech-TDLI EDM Workshop
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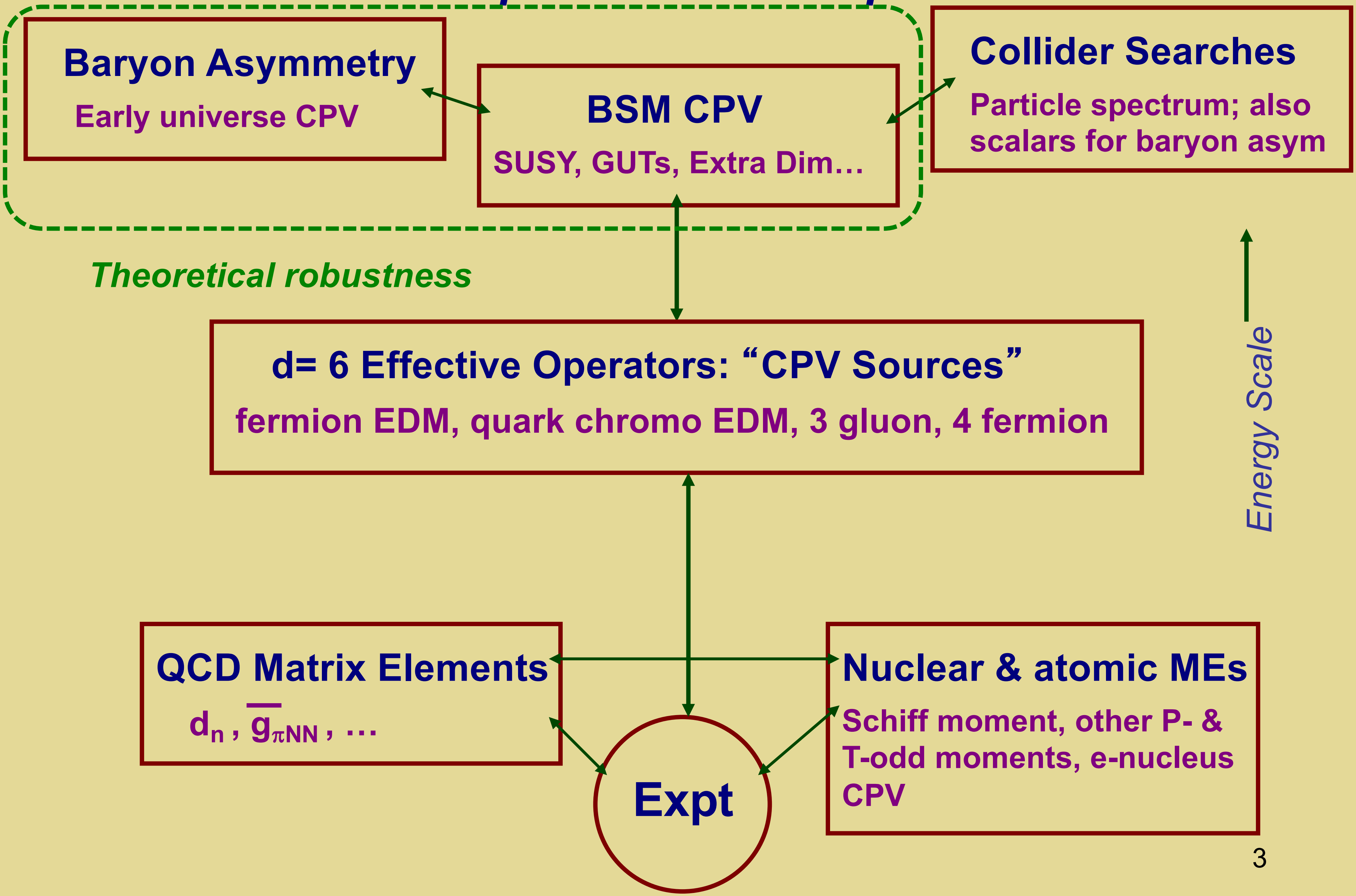
Key Ideas for this Talk

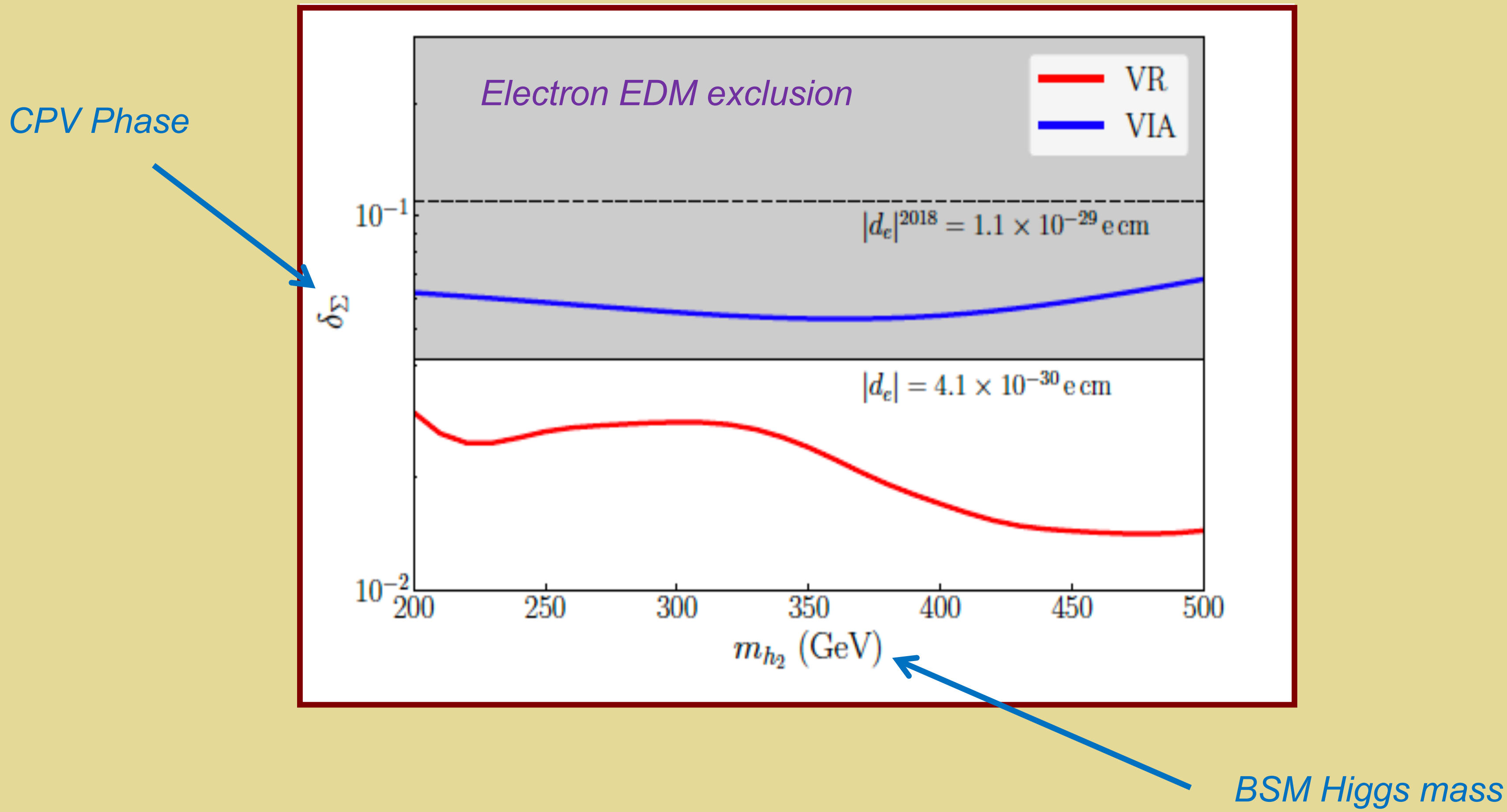
- ***EW baryogenesis (EWBG) is a theoretically well-motivated and experimentally testable baryogenesis scenario***
- ***EDM searches provide most powerful probes of BSM CPV needed for EWBG***
- ***Robust assessment of EWBG viability in light of EDMs requires development of early universe quantum transport theory → recent progress implies EWBG remains viable but the experimental target is within reach***

EDM Interpretation & Multiple Scales



Electron EDM & BAU

Illustrative model:



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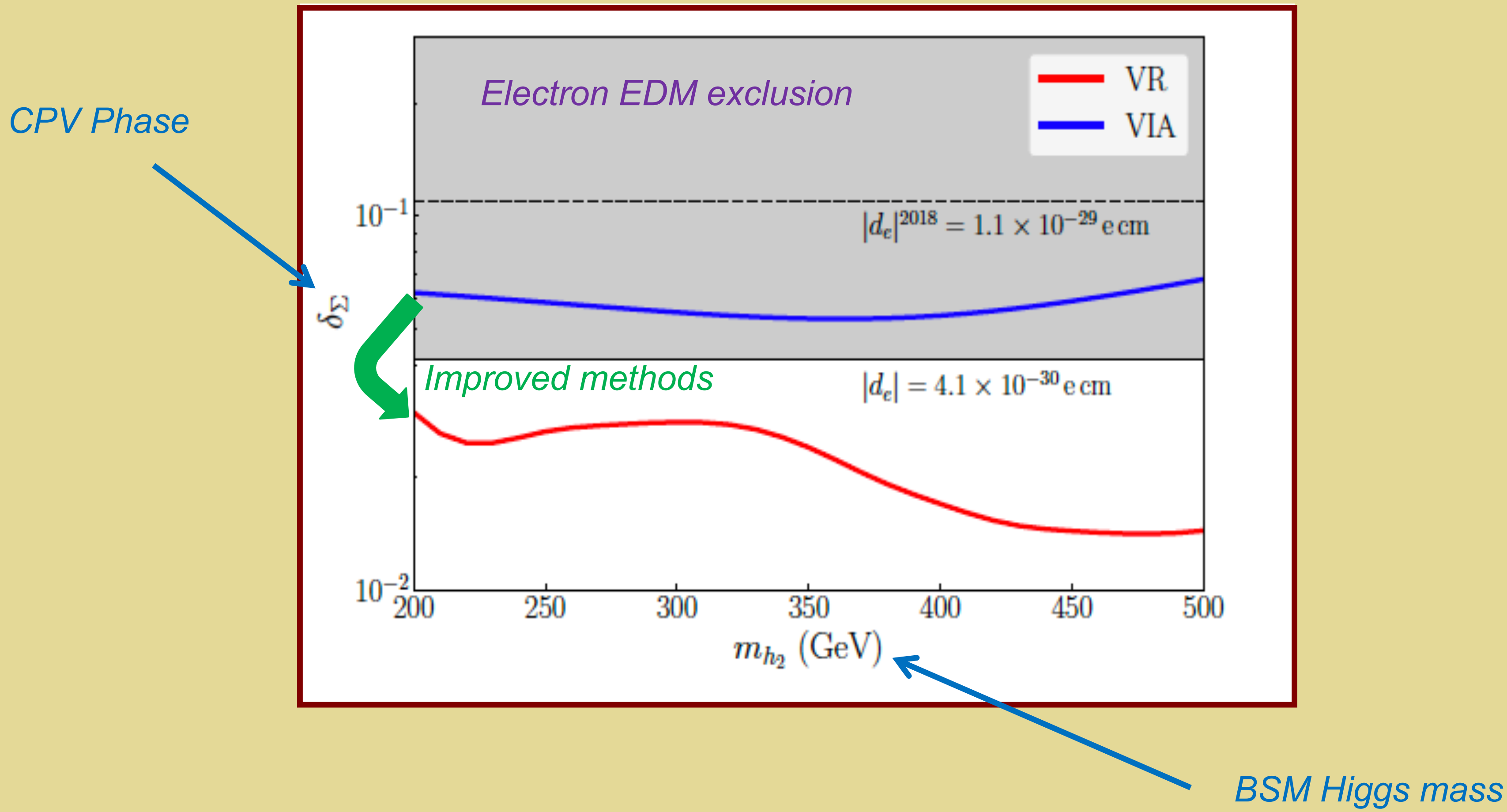

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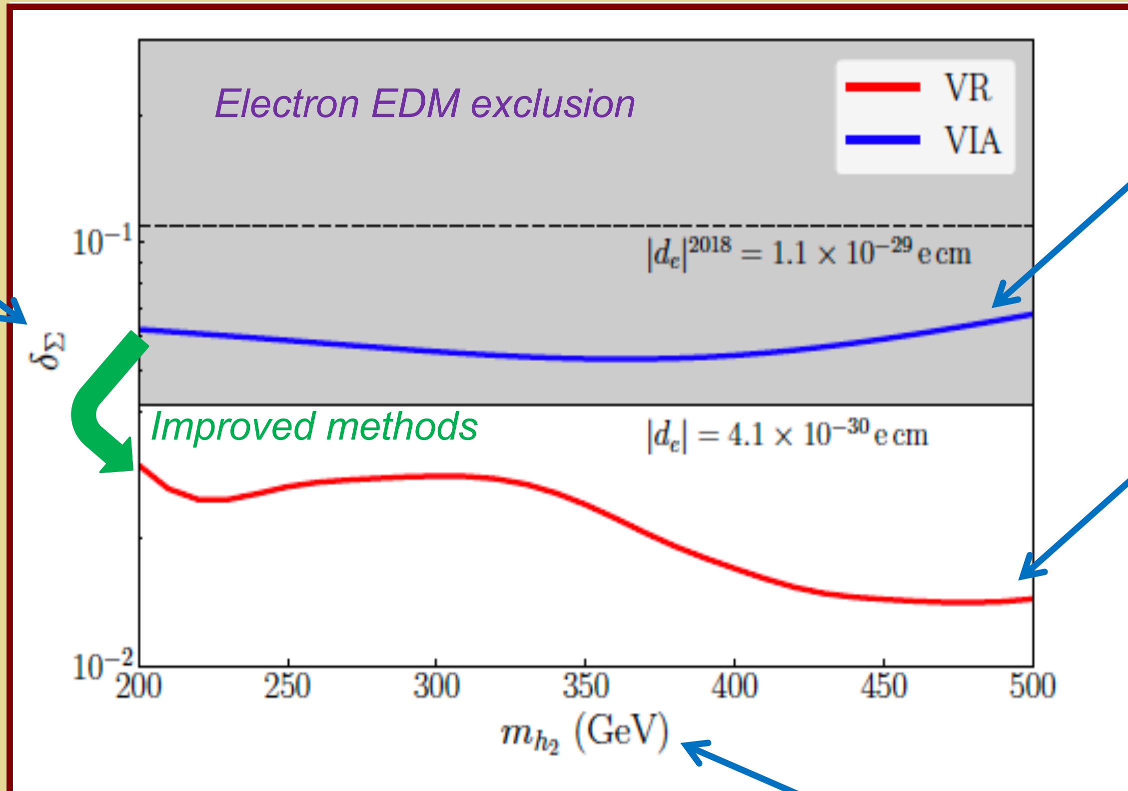
Electron EDM & BAU

Illustrative model:

CPV Phase



BAU: Previous "VIA" method

BAU: current "VR" method

BSM Higgs mass

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

Implications

Other EDM searches & measurements of CPV observables in other systems (B mesons, Higgs decays) provide complementary probes of BSM CPV →

electron EDM – EWBG confrontation is a key arena for assessing the early universe QFT framework for analyzing implications of these other CPV probes for baryogenesis

Outline

I. *Context for EWBG*

II. *Theoretical Theoretical Challenge & Progress*

III. *Illustrative Application: Scalar sector CPV*

IV. *Outlook*

I. Context

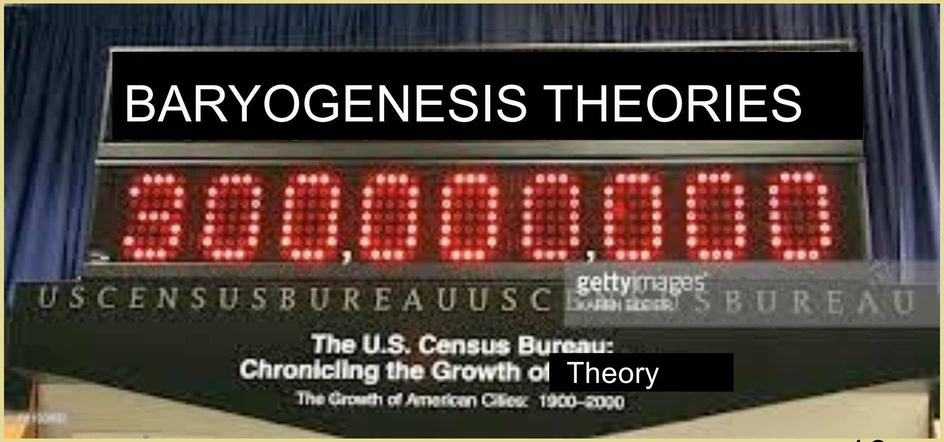
Cosmic Baryon Asymmetry

$$Y_B = \frac{n_B}{s} = (8.66 \pm 0.04) \times 10^{-11}$$

One number $\rightarrow$ ~~||||~~ ~~||||~~ ~~||||~~ … Explanations

Experiment can help:

- *Discover ingredients*
- *Falsify candidates*

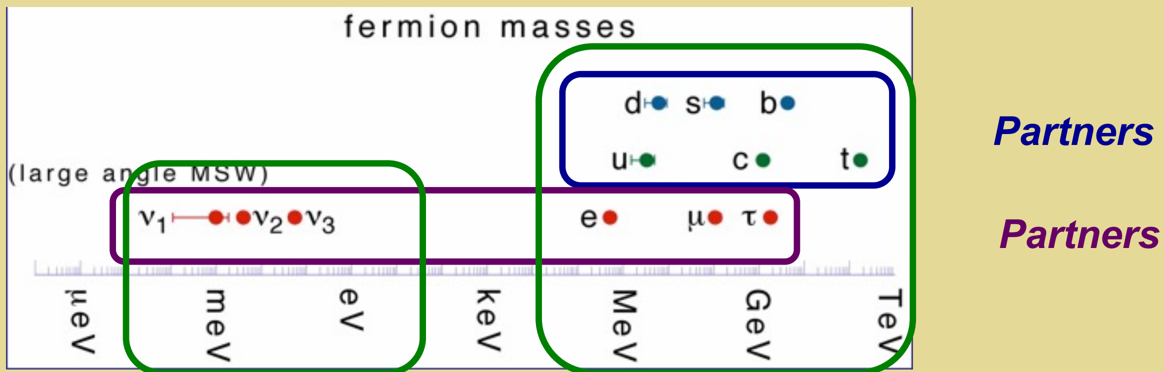


Ingredients for Baryogenesis

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



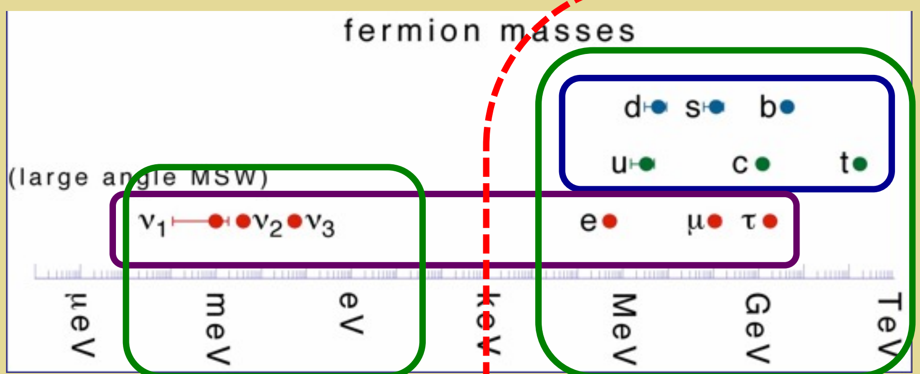
Seesaw Mech ?

Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

Fermion Masses & Baryon Asymmetry



Partners

Partners

Seesaw Mech ?

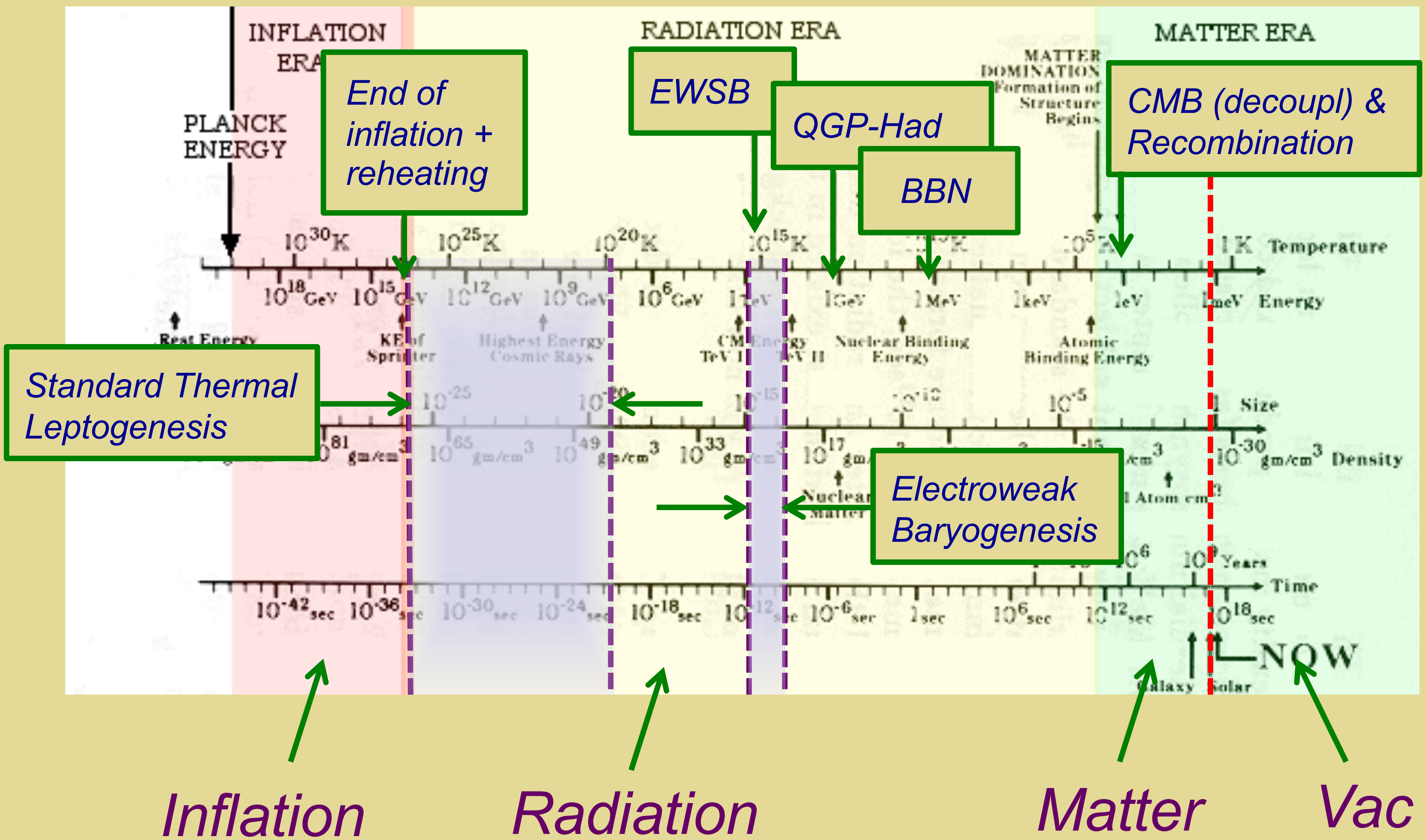
Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

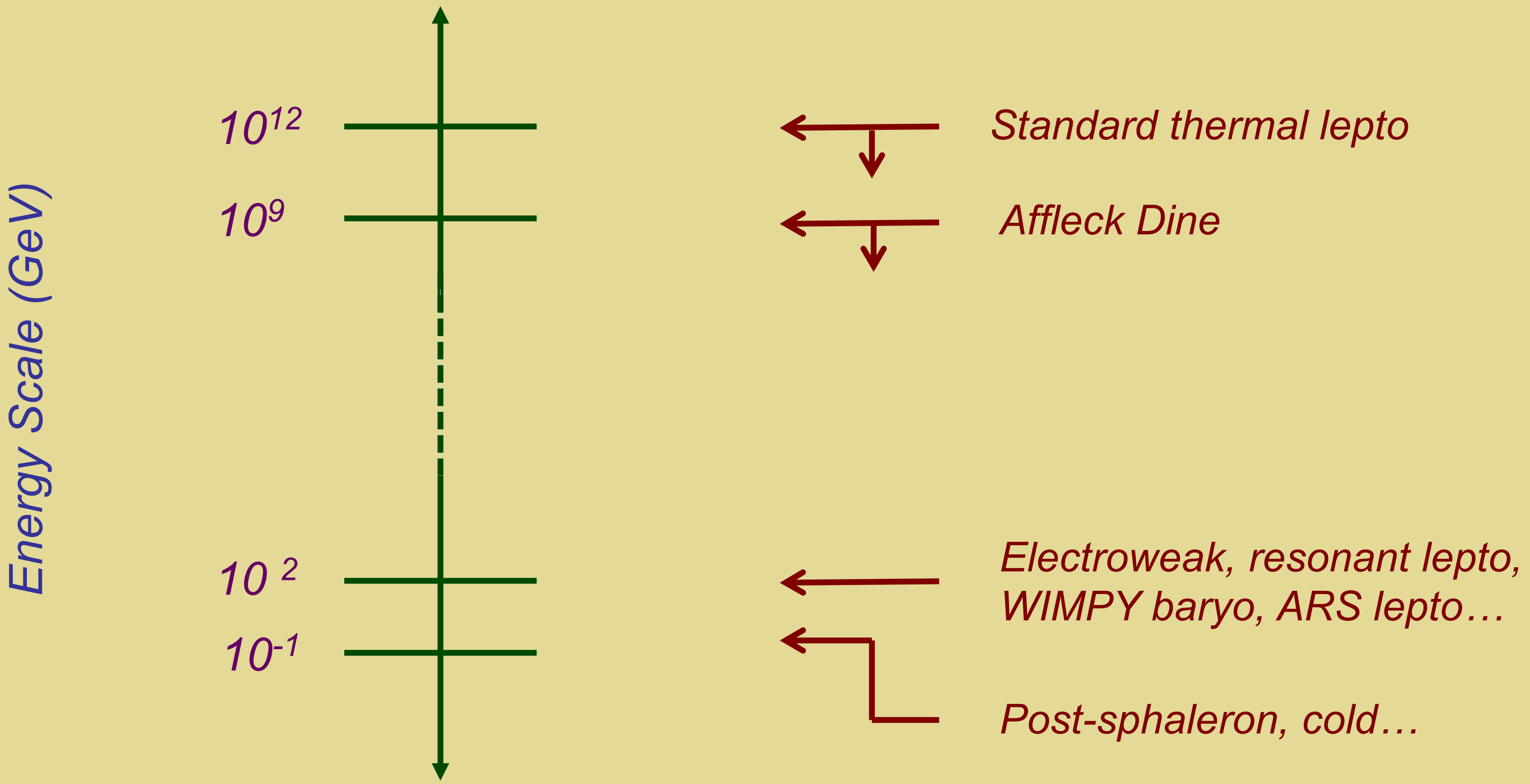
Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

This talk

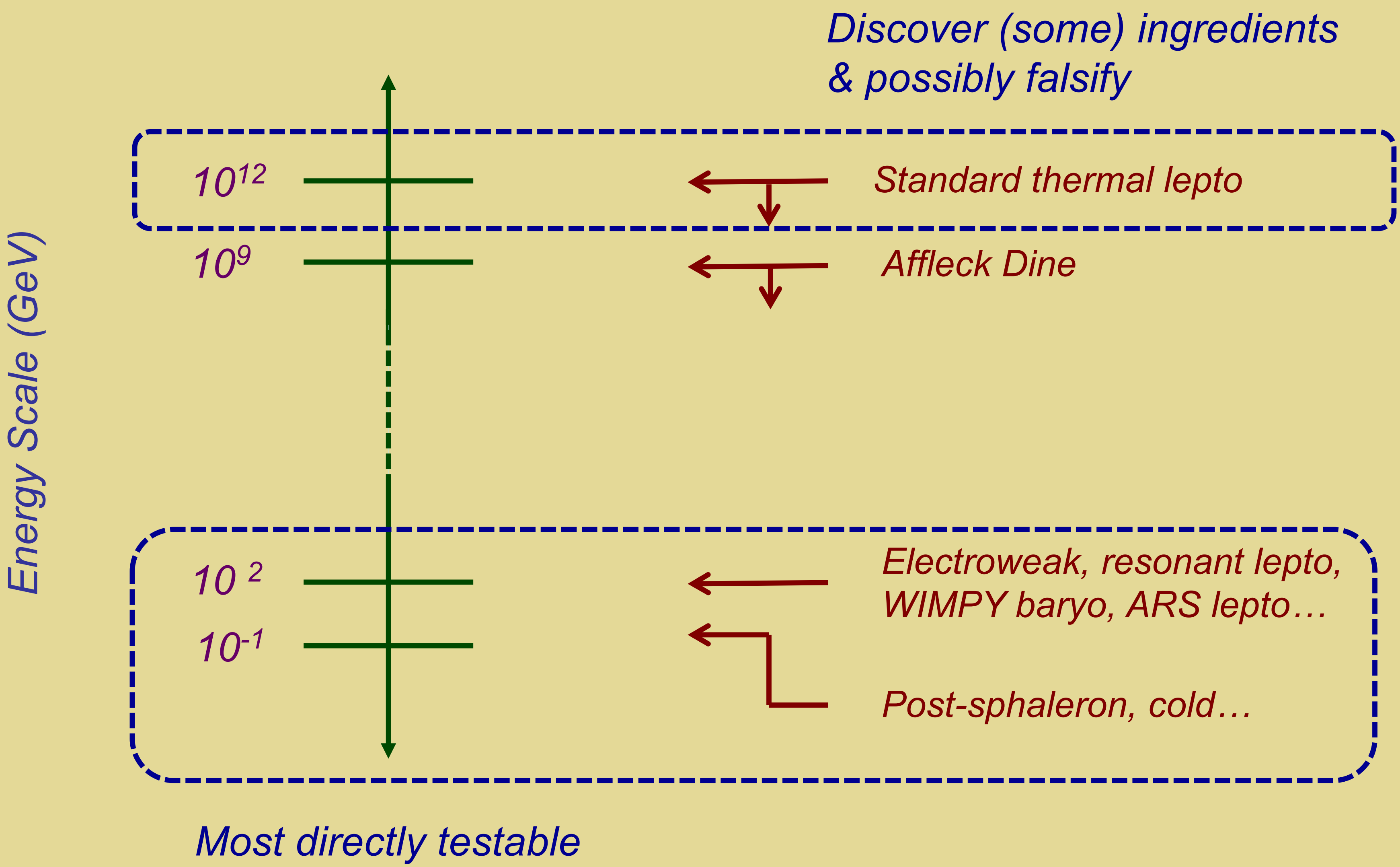
Cosmic History



Baryogenesis Scenarios



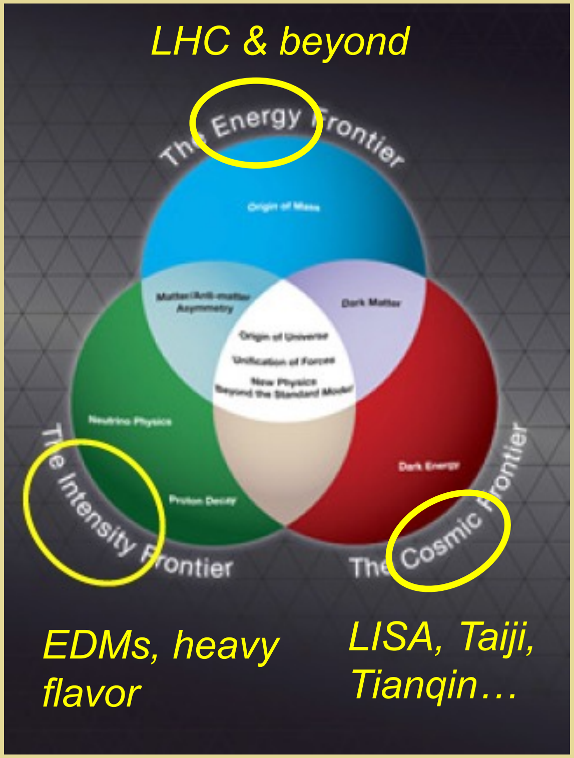
Baryogenesis Scenarios



Electroweak Baryogenesis

Motivation

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



Viability

- *Well motivated BSM scenarios*
- *Robust theory*
- *Consistent w/ experiment*

Electroweak Baryogenesis

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Viability

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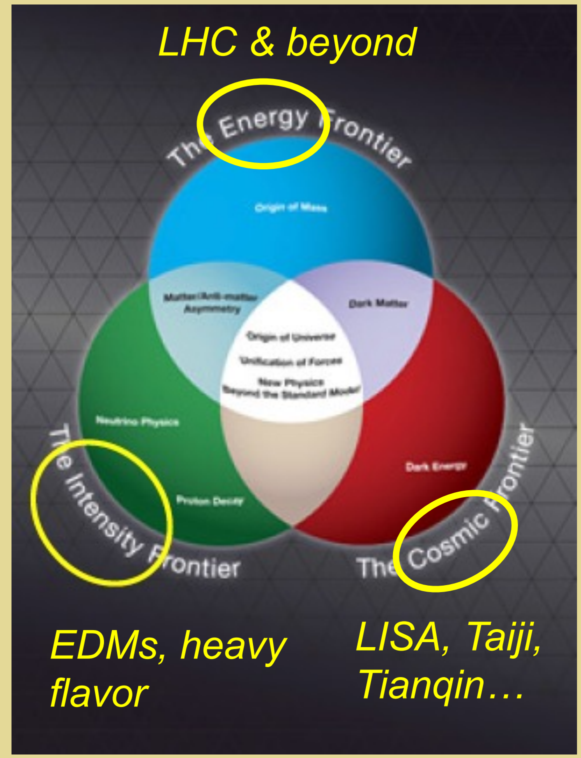
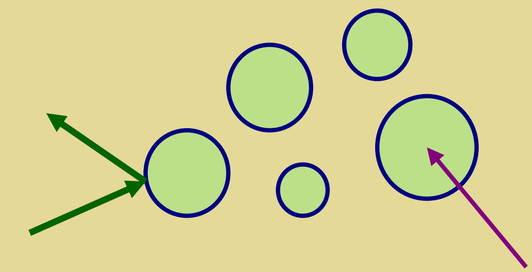
This talk



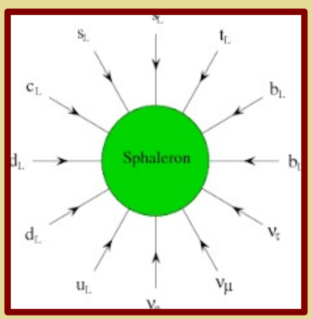
Electroweak Baryogenesis

1^{st} order EWPT

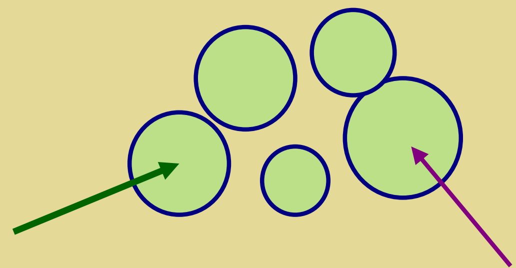


Y_B : CPV &
EW sphalerons

EWSB



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



Y_B : diffuses
into interiors

EWSB

EWBG Ingredients

- *EW Sphalerons* ✔ *St'd Model*
- *Strong 1st Order EW Phase Transition* → *BSM Higgs*
- *Left-handed number density* → *BSM CPV*

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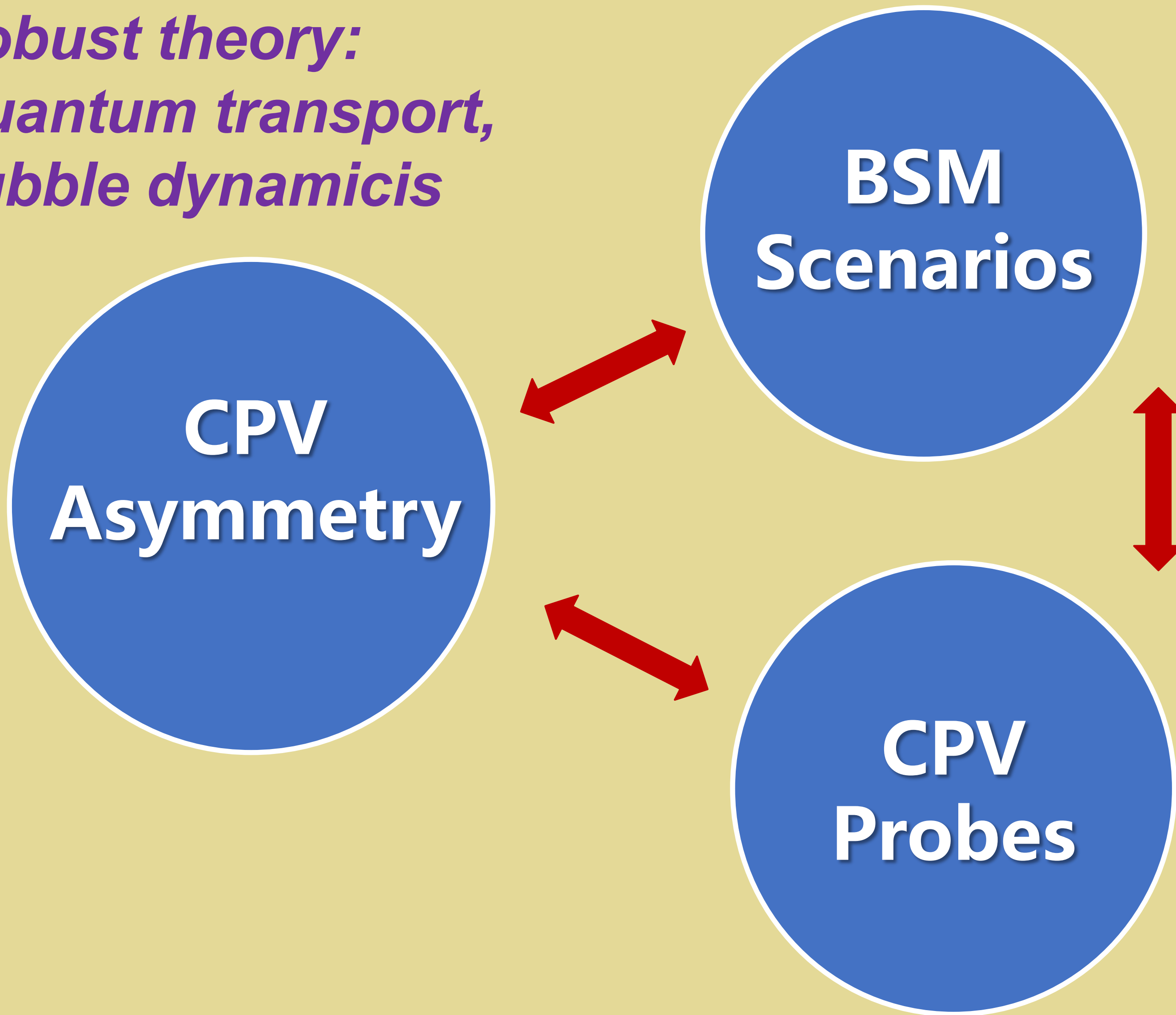
BSM CPV: Theory-Exp't Interplay

Robust theory: Quantum transport, bubble dynamicis

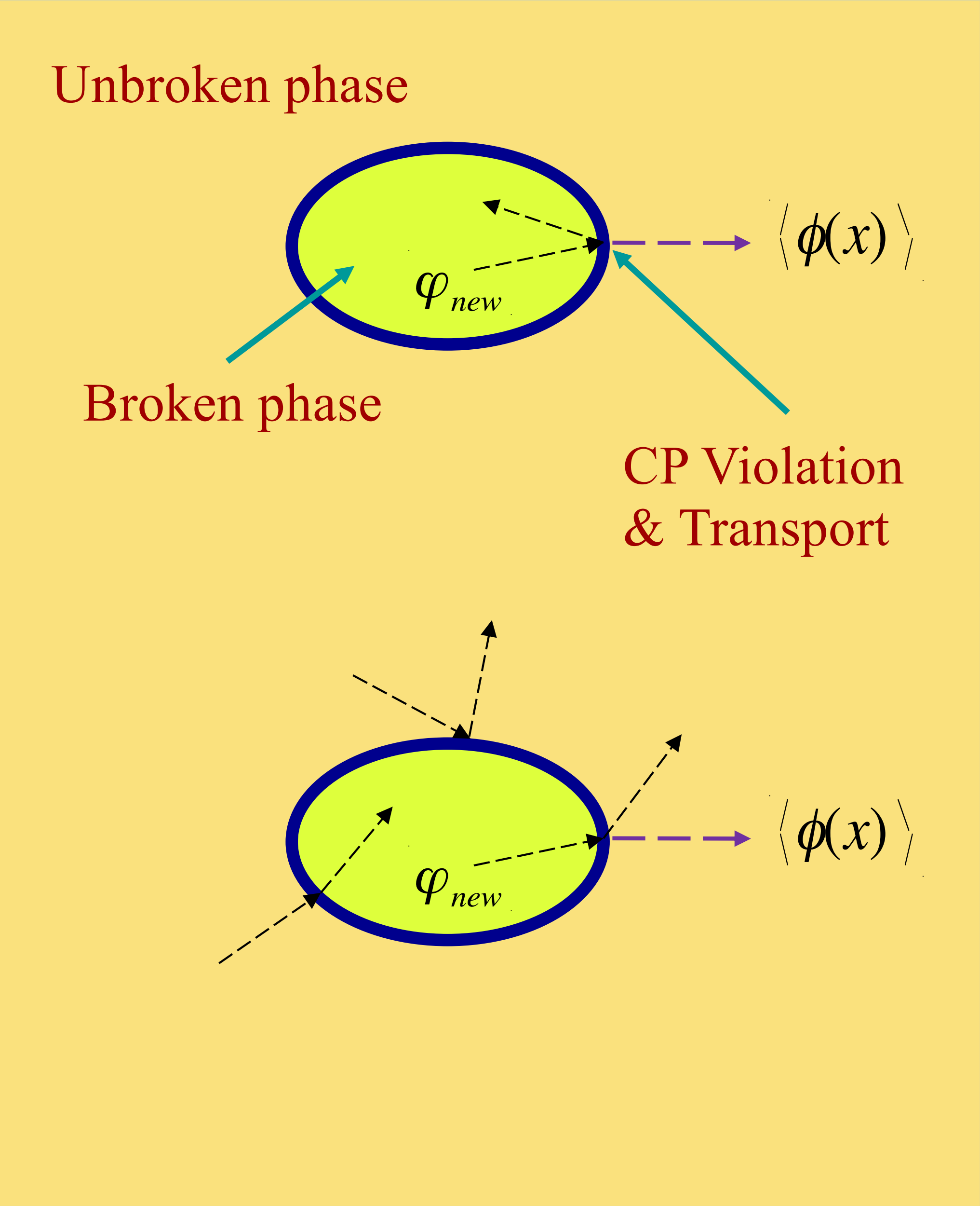
Models, other pheno…



EDM, heavy flavor…

II. Theoretical Challenge & Progress

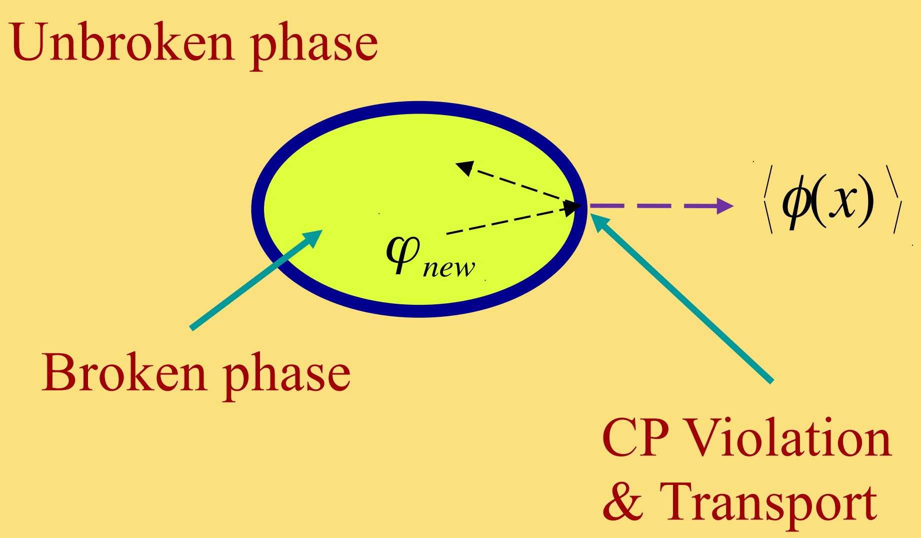
Transport Theory



Transport Problem:

- ***CPV → left-handed fermion density n_L (x)***
- ***Include diffusion, CP-cons thermalizing & particle number changing reactions***

Transport Theory



Transport Problem:

- ***CPV → left-handed fermion density n_L (x)***
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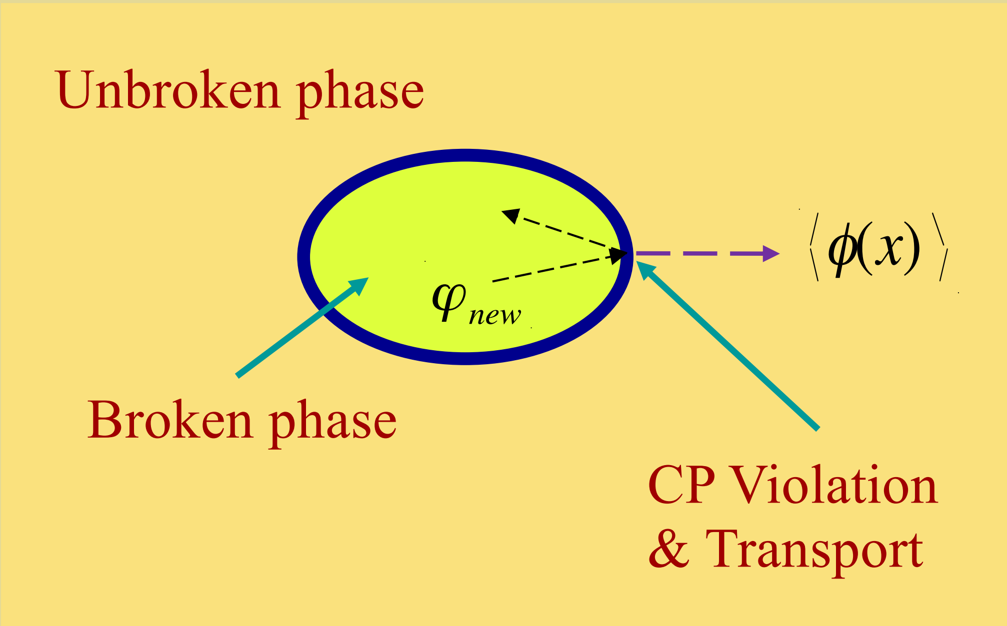
$\Gamma_{WS} << \Gamma_{other}$

$$\partial_\mu j_B^\mu = -\frac{N_f}{2}\left[k_{ws}^{(1)}(T,x)n_B(x) + k_{ws}^{(2)}(T,x)n_L(x)\right]$$

Transport Theory



Transport Problem:

- ***CPV → left-handed fermion density n_L (x)***
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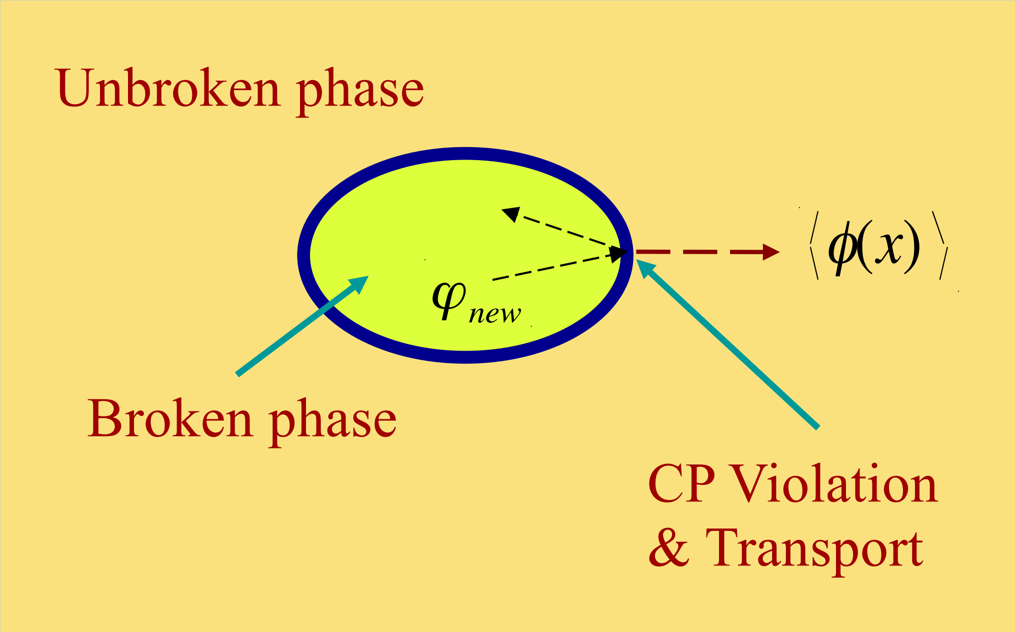
$\Gamma_{WS} << \Gamma_{other}$

Source

$$\partial_\mu j^\mu_B = -\frac{N_f}{2}\left[k^{(1)}_{ws}(T,x)n_B(x) + k^{(2)}_{ws}(T,x)n_L(x)\right]$$

Relaxation

Transport Theory



Transport Problem:

- ***CPV → left-handed fermion density $n_L(x)$***
- ***Include diffusion, CP-cons thermalizing & particle number changing reactions***

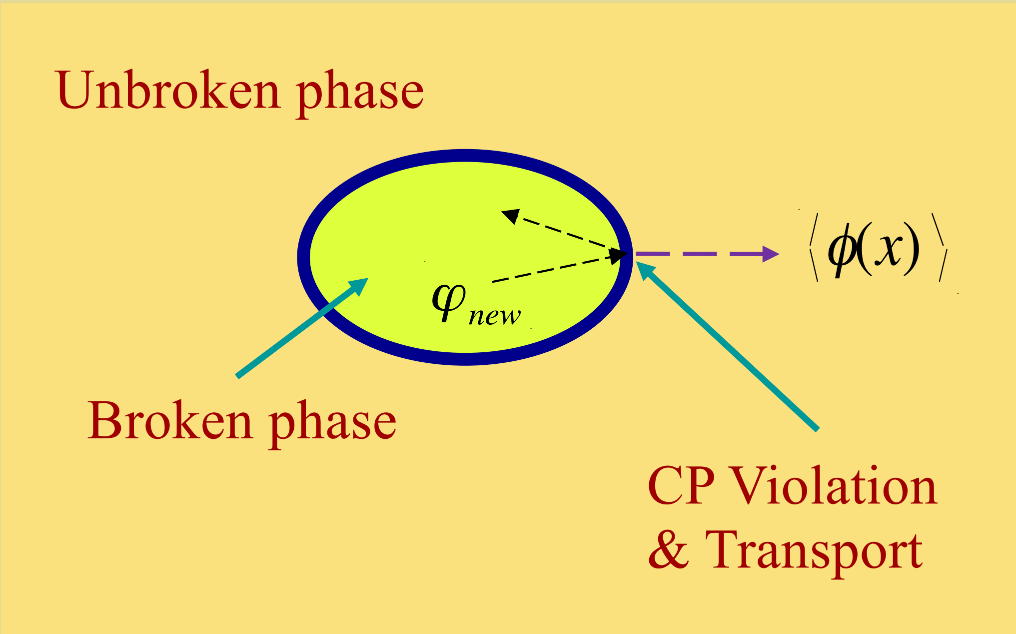
$\Gamma_{WS} \ll \Gamma_{other}$

Weak sph rates — *Source*

$$\partial_\mu j_B^\mu = -\frac{N_f}{2}\left[k_{ws}^{(1)}(T,x)n_B(x) + k_{ws}^{(2)}(T,x)n_L(x)\right]$$

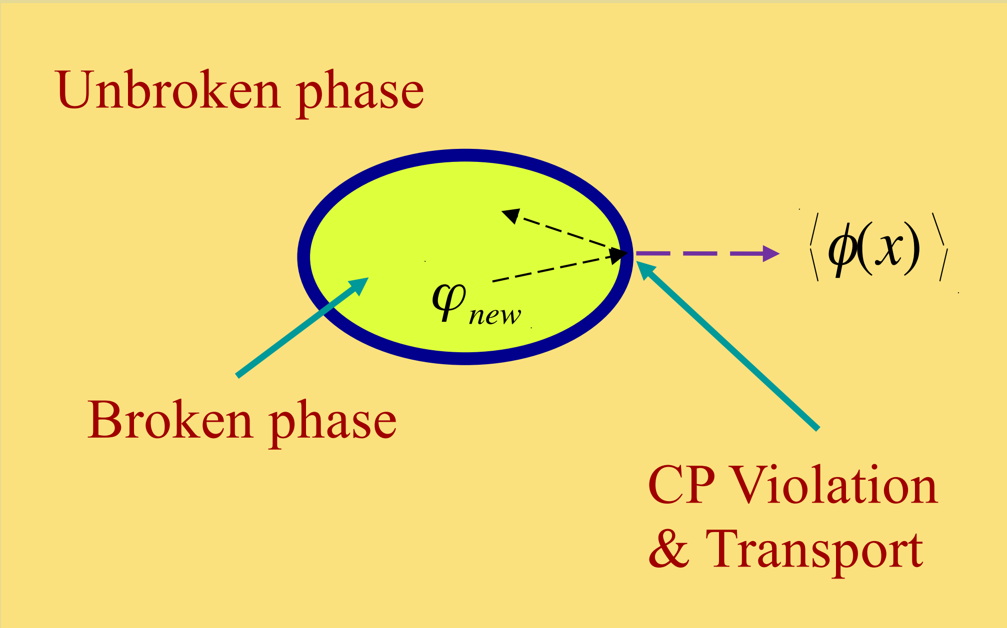
Relaxation

Transport Theory



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

Transport Theory



Transport Problem:

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

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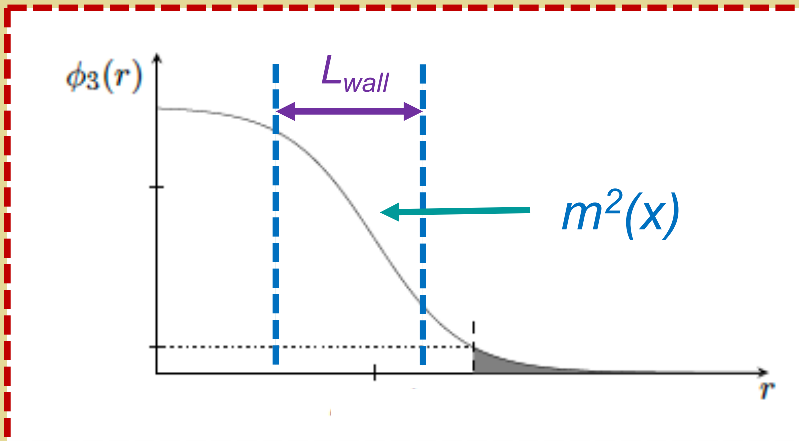

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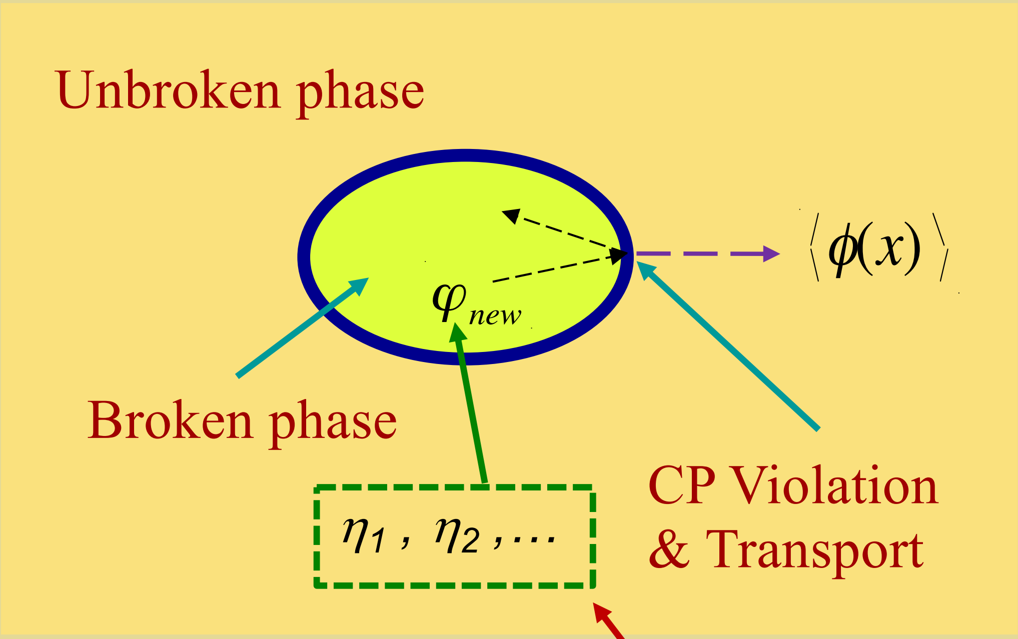

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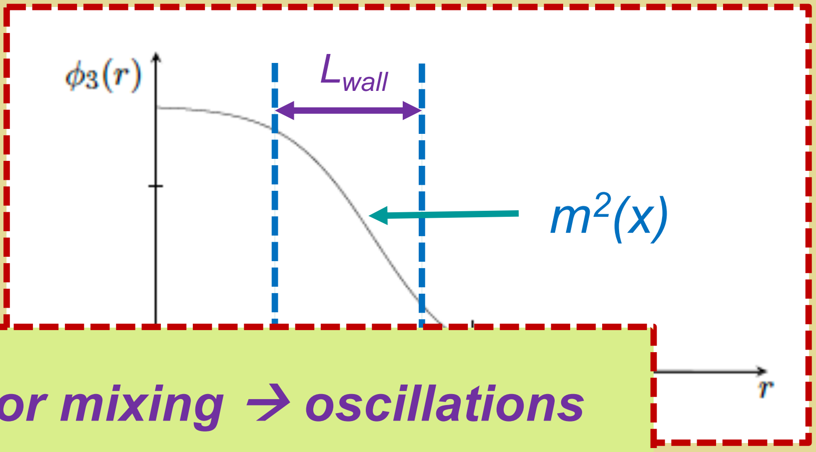

- ***Bubble dynamics***
- ***CPV Sources***
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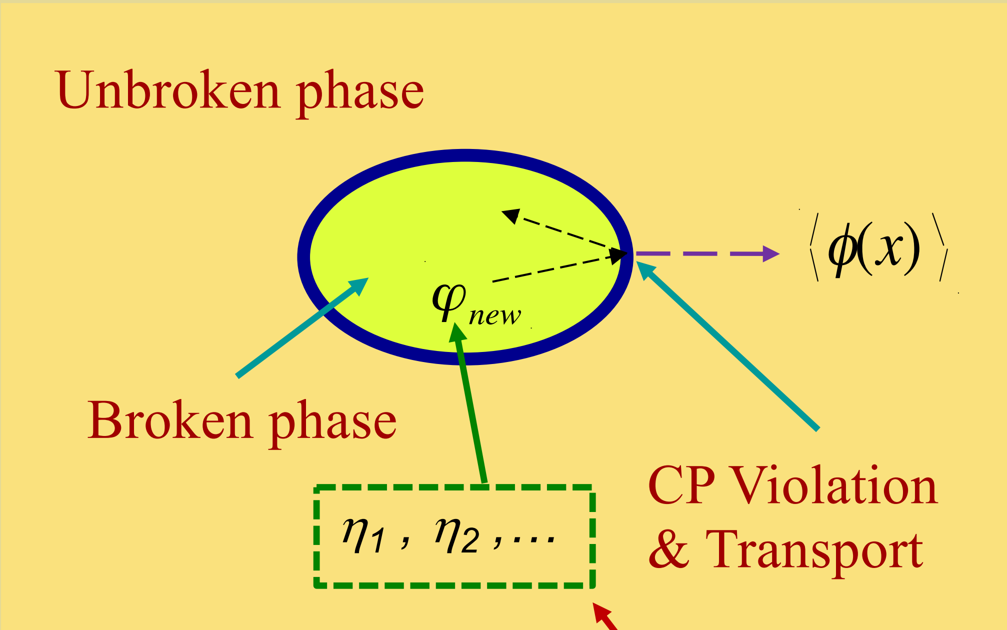
Flavor mixing → oscillations

Consider two (or more) fields η_j interacting with $\phi(x)$

Transport Theory



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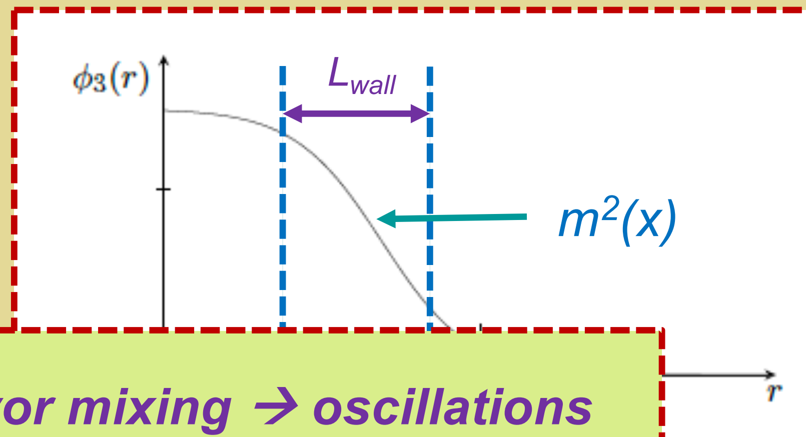

- ***Bubble dynamics***
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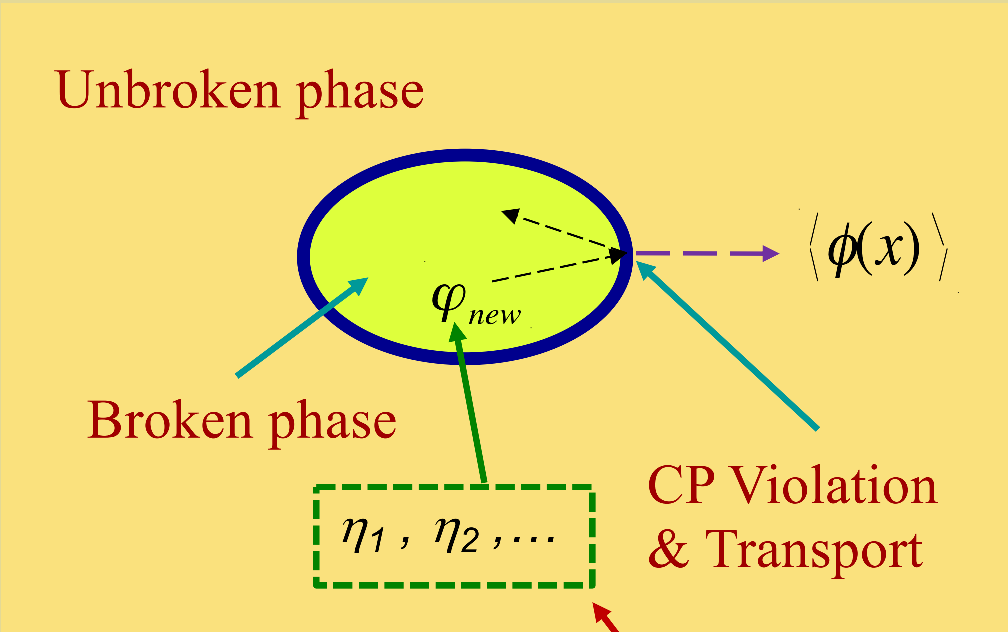
Flavor mixing → oscillations

$$M_\eta^2(x) = \begin{pmatrix} M_1^2(x) & R(x)\, e^{-i\,\alpha(x)} \\ R(x)\, e^{i\,\alpha(x)} & M_2^2(x) \end{pmatrix}$$

Transport Theory



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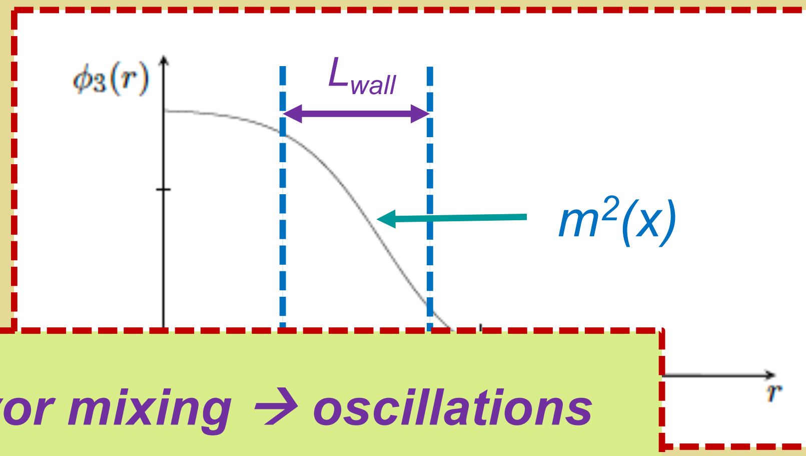

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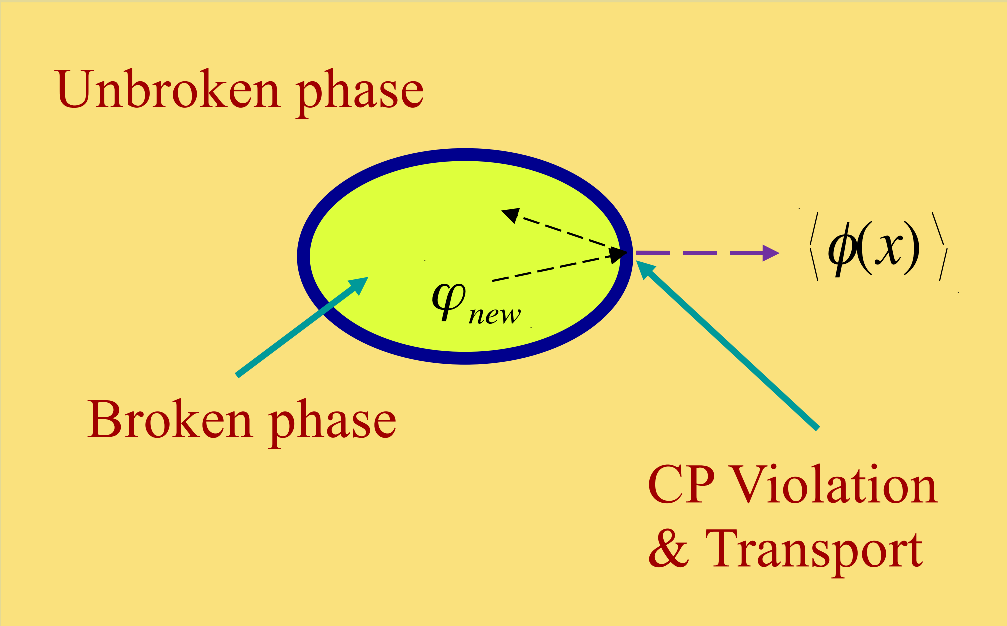

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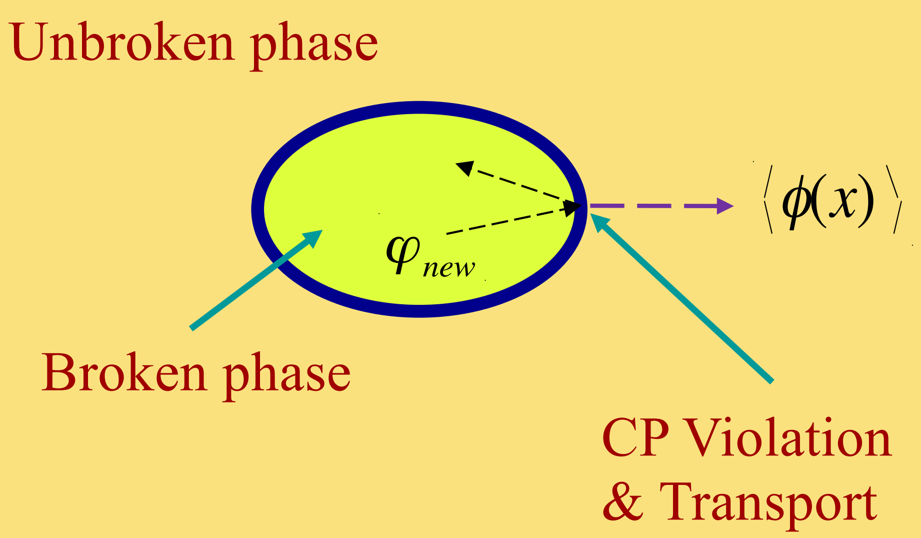
→ ***Quantum Kinetic Eqs***

Transport Theory



Transport Problem:

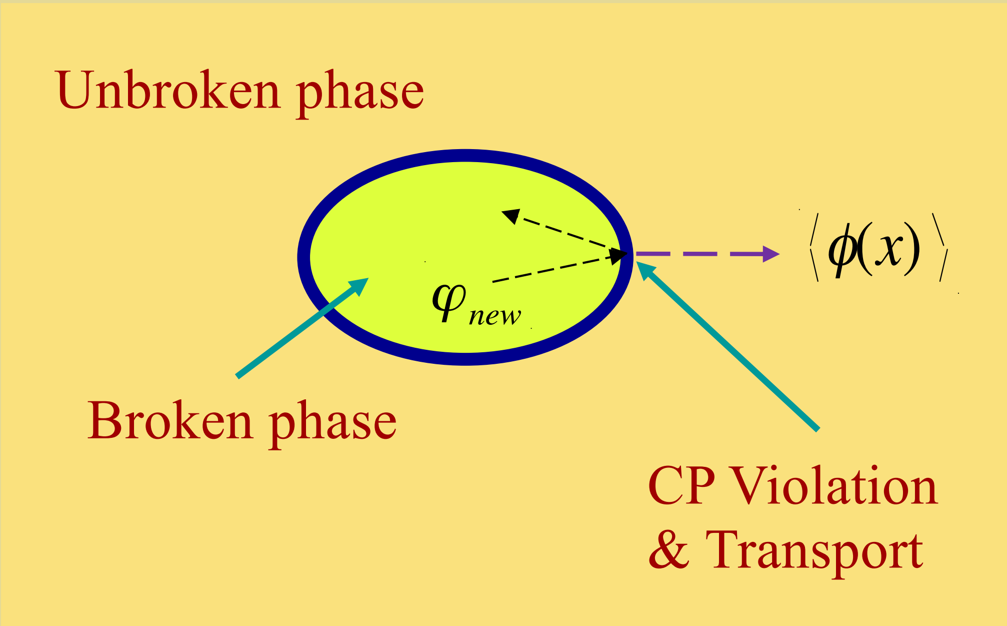
- ***Particle masses depend on spacetime → CPV sources***
- ***Include CPC effects in thermal plasma***

- ***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

Transport Theory



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Closed Time Path

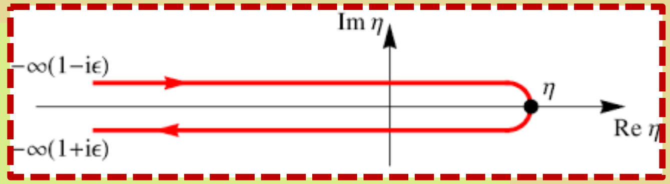
Quantum Kinetic Eqs

Cirlgliano, Lee, MJRM, Tulin 1012.3523; Clrigliano, Lee, Tulin 1106.0747

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

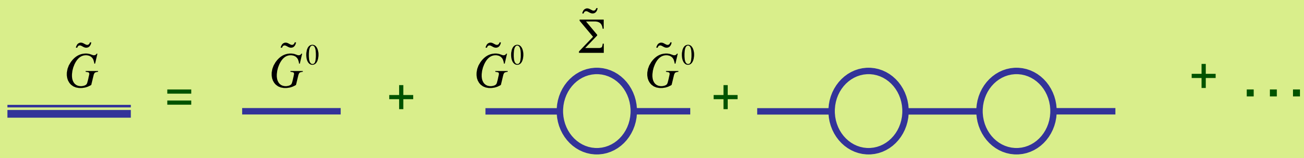
closed time path (CTP)



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) , $(\tilde{t}_L, \tilde{t}_R)$, …*



Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

$$\left(2k^2 - \frac{\partial_x^2}{2}\right) G^{\gtrless}(k,x) = e^{-i\diamond}\Big(\{ m^2(x) - 2i\,k\cdot\Sigma(x) + \Sigma(x)^2,\ G^{\gtrless}(k,x)\} + i\,\{\Pi^h(k,x), G^{\gtrless}(k,x)\} + i\,\{\Pi^{\gtrless}(k,x), G^h(k,x)\} + \frac{i}{2}\left[\Pi^>(k,x), G^<(k,x)\right] + \frac{i}{2}\left[G^>(k,x), \Pi^<(k,x)\right]\Big)$$

Wigner transformed Wightman functions

Constraint eq → dispersion relation

$$2k\cdot\partial_x G^{\gtrless}(k,x) = e^{-i\diamond}\Big(-i\left[m^2(x) - 2i\,k\cdot\Sigma(x) + \Sigma(x)^2,\ G^{\gtrless}(k,x)\right] + \left[\Pi^h(k,x), G^{\gtrless}(k,x)\right] + \left[\Pi^{\gtrless}(k,x), G^h(k,x)\right] + \frac{1}{2}\{\Pi^>(k,x), G^<(k,x)\} - \frac{1}{2}\{\Pi^<(k,x), G^>(k,x)\}\Big)$$

Kinetic eq → dynamics for number densities

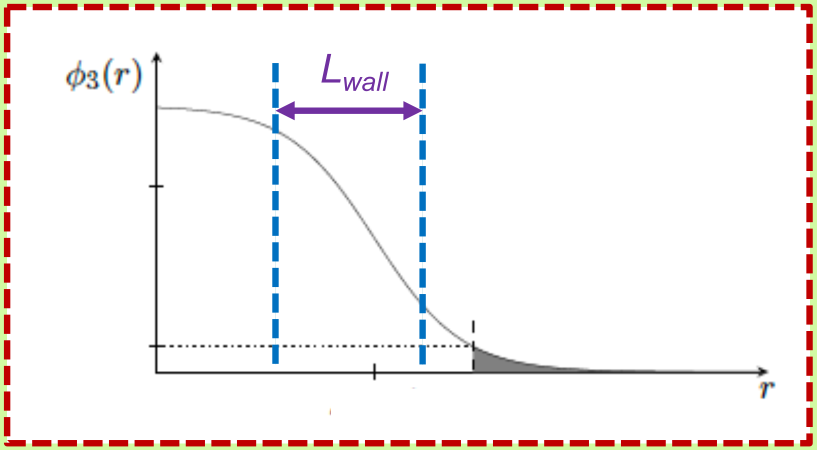
$$\diamond\Big(A(k,x)B(k,x)\Big) = \frac{1}{2}\left(\frac{\partial A}{\partial x^\mu}\frac{\partial B}{\partial k_\mu} - \frac{\partial A}{\partial k_\mu}\frac{\partial B}{\partial x^\mu}\right)$$

"Diamond operator"

Systematic Baryo/leptogenesis:

Scale Hierarchies $\rightarrow$ *power counting*

EW Baryogenesis



Gradient expansion

$\varepsilon_w = L_{int} / L_{wall} \ll 1$

Quasiparticle description

$\varepsilon_p = \Gamma_p / \omega \ll 1$

Thermal, but not too dissipative

$\varepsilon_{coll} = \Gamma_{coll} / \omega \ll 1$

Plural, but not too flavored

$\varepsilon_{osc} = \Delta\omega / T \ll 1$

$L_{int} \sim \lambda \sim T^{-1}$

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

Lowest non-trivial order in grad's

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

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Spacetime evolution of densities

Systematic Systematic Baryogenesis:

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Diagonal after rotation to local mass basis:

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

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

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

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

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

Flavor oscillations: flavor off-diag densities

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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,…

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Kinetic eq (approx) in Wigner space:

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

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

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

Distribution functions

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

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Distribution functions

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

Phase in m^2 (x)

Rotation to mass basis: θ

Systematic Baryogenesis:

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$$\left(u\cdot\partial_X + \vec{F}\cdot\vec{\nabla}\right) f_{11} \supset -\left[\, i(\omega_k + \sin^2\theta\, u\cdot\partial\alpha), f\,\right]_{11} + \cdots$$

$$\left(u\cdot\partial_X + \vec{F}\cdot\vec{\nabla}\right) \bar{f}_{11} \supset \left[\, i(\omega_k - \sin^2\theta\, u\cdot\partial\alpha), \bar{f}\,\right]_{11} + \cdots$$

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

Systematic Baryogenesis:

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Source of CPV asymmetry

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

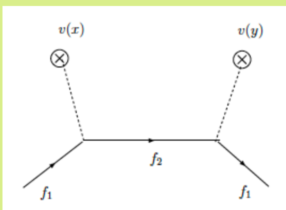
$$\left(u\cdot\partial_X + \vec{F}\cdot\vec{\nabla}\right) f_{11} \supset -\left[\, i(\omega_k + \sin^2\theta\, u\cdot\partial\alpha), f\,\right]_{11} + \cdots$$

$$\left(u\cdot\partial_X + \vec{F}\cdot\vec{\nabla}\right) \bar{f}_{11} \supset \left[\, i(\omega_k - \sin^2\theta\, u\cdot\partial\alpha), \bar{f}\,\right]_{11} + \cdots$$

Systematic Baryogenesis:

Comparison with other approaches

VEV insertion approximation



- *Perturbative in v(x)*
- *Flavor-mixing CPV*
- *Work in flavor basis*

VEV resummation

$$M_\eta^2(x) = \begin{pmatrix} M_1^2(x) & R(x)\, e^{-i\,\alpha(x)} \\ R(x)\, e^{i\,\alpha(x)} & M_2^2(x) \end{pmatrix}$$

- *Local $M^2(x)$ diagonalization*
- *Flavor-mixing CPV*
- *Work in local mass basis*

WKB / Semi-classical

$$S_{WKB} \sim \frac{1}{2E^2}(m^* m' - m^{*\prime} m)'$$

- *CPV source: second order in gradients from constraint eq*

VEV resummation

$$S_{VR} \sim -\left[\, i(\omega_k + \sin^2\theta\, u \cdot \partial\alpha), f\,\right]_{11}$$

- *CPV source: first order in gradients*

III. Illustrative Application

Scalar Field BSM CPV

Similar set up for BSM CPV in fermion sector (e.g., Yukawa interactions in 2HDM) but avoid complications due to multiple spin d.o.f.

“Two-Step EW Baryogenesis” & EDMs

Illustrative Model:

New sector: “Real Triplet” Σ
Gauge singlet S

$H \to$ Set of “SM” fields: 2 HDM

(SUSY: “TNMSSM”, Coriano…)

EDMs are Two Loop

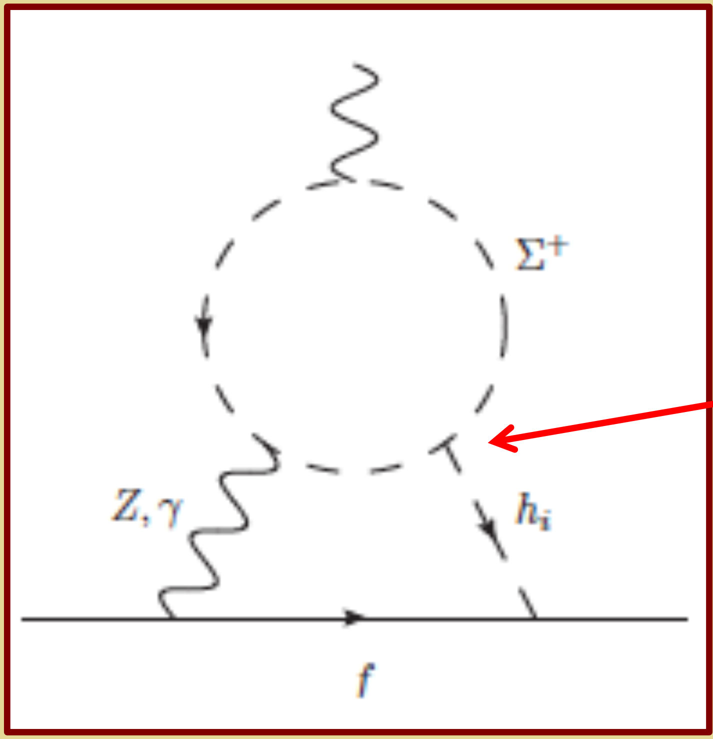
Two CPV Phases:

δ_Σ : Triplet phase
δ_S : Singlet phase

Insensitive to δ_S : electrically neutral $\to$ “partially secluded”

Inoue, Ovanesyan, R-M: 1508.05404

"Two-Step EW Baryogenesis" & EDMs



EDMs are Two Loop

Two CPV Phases:

δ_Σ : Triplet phase

δ_S : Singlet phase

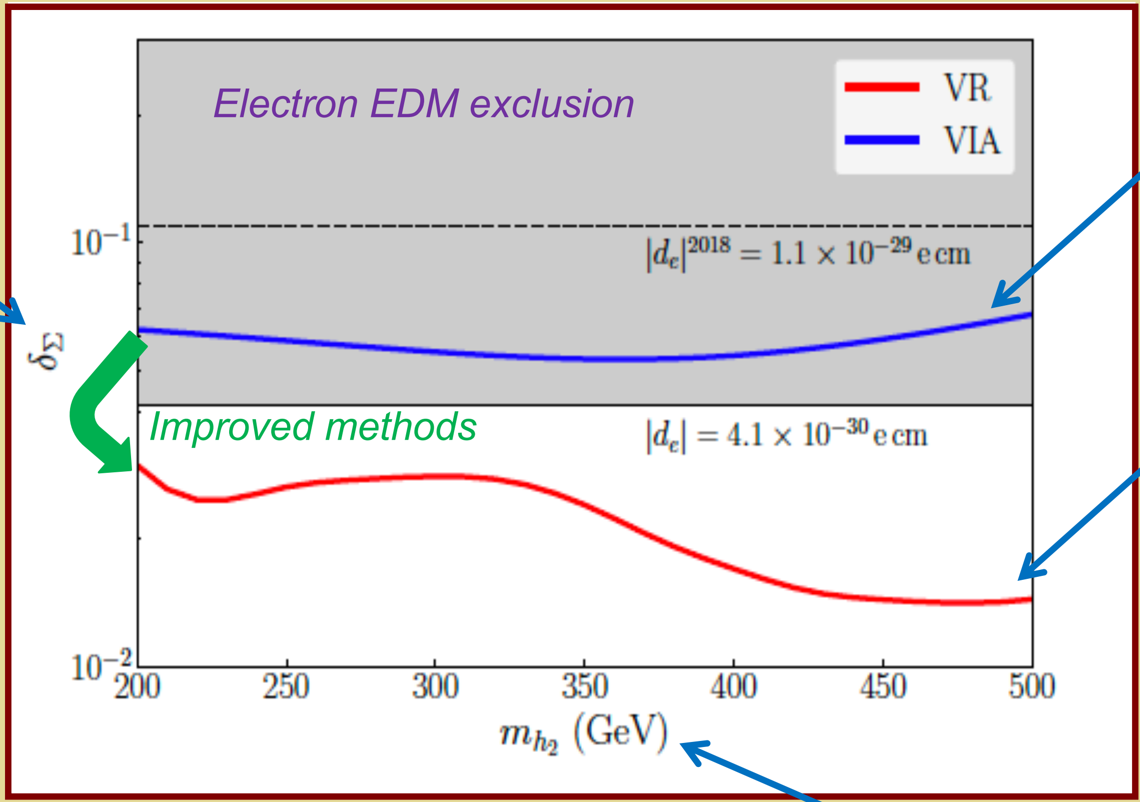
Insensitive to δ_S : electrically neutral $\rightarrow$ "partially secluded"

Consider nonzero δ_Σ , < Σ^0 >(x) , < S >(x) → α(x)

Inoue, Ovanesyan, R-M: 1508.05404

Electron EDM & BAU

Illustrative model: two-step EWBG w/ scalar sector CPV



CPV Phase

BAU: Previous "VIA" method

BAU: current "VR" method

BSM Higgs mass

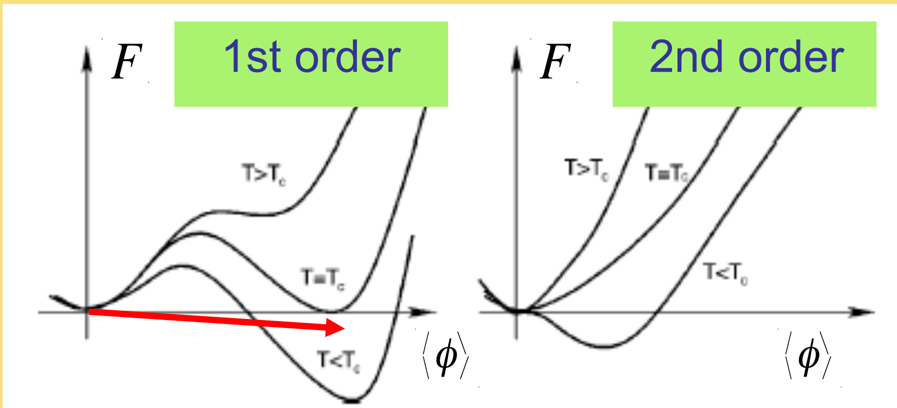
Yuan-Zhen Li, MJRM, Jiang-Hao Yu 2404.19197

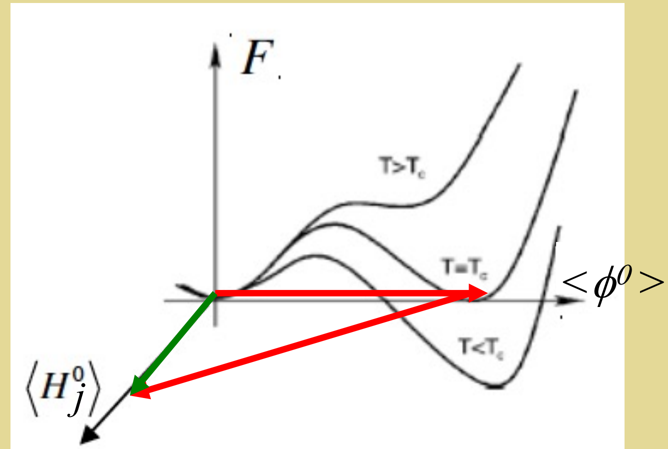
IV. Outlook: How Viable is EWBG ?

- *EW baryogenesis (EWBG) is a theoretically well-motivated and experimentally testable baryogenesis scenario*
- *EDM searches provide most powerful probes of BSM CPV needed for EWBG*
- *Robust assessment of EWBG viability in light of EDMs requires development of early universe quantum transport theory → recent progress implies EWBG remains viable but the experimental target is within reach*

Back Up Slides

Two-Step EW Baryogenesis

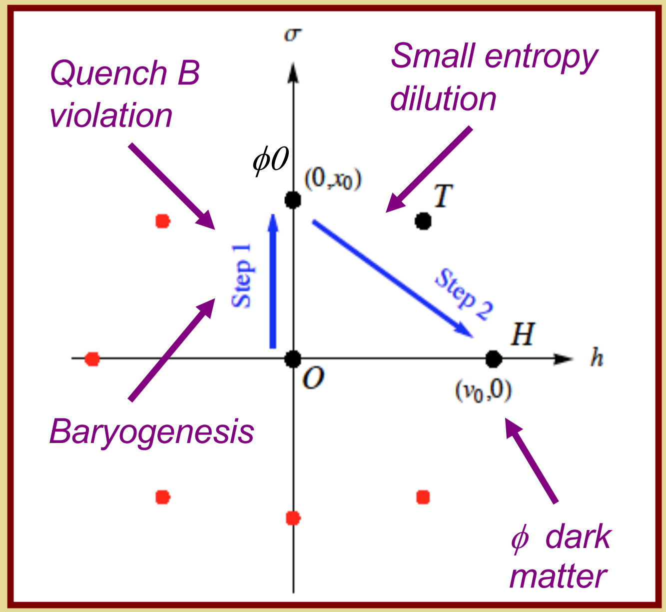




Increasing m_h →

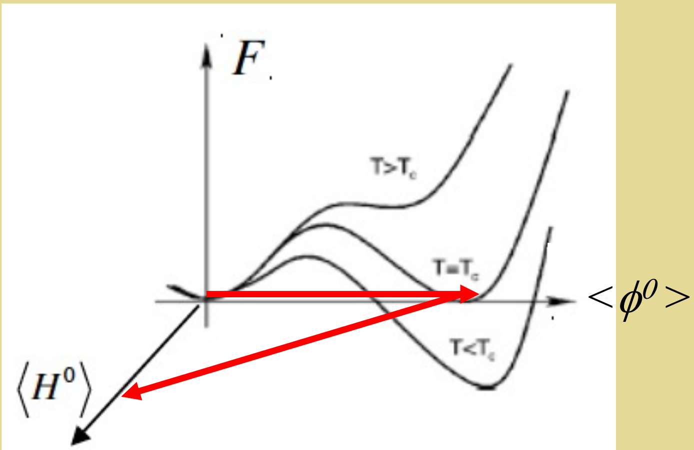
← *New scalars*

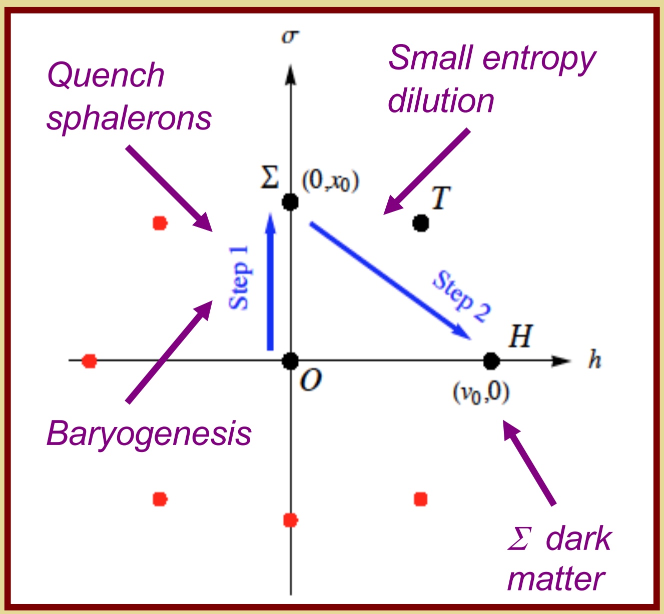
$$\mathcal{O}_4 = \lambda_{\phi H} \, \phi^\dagger \phi \, H^\dagger H$$ **+…**



Real Triplet $\phi \rightarrow \Sigma^+ , \Sigma^- , \Sigma^0$

Two-Step EW Baryogenesis





Inoue, Ovanesyan, R-M: 1508.05404

Illustrative Model:

New sector: "Real Triplet" Σ
Gauge singlet S

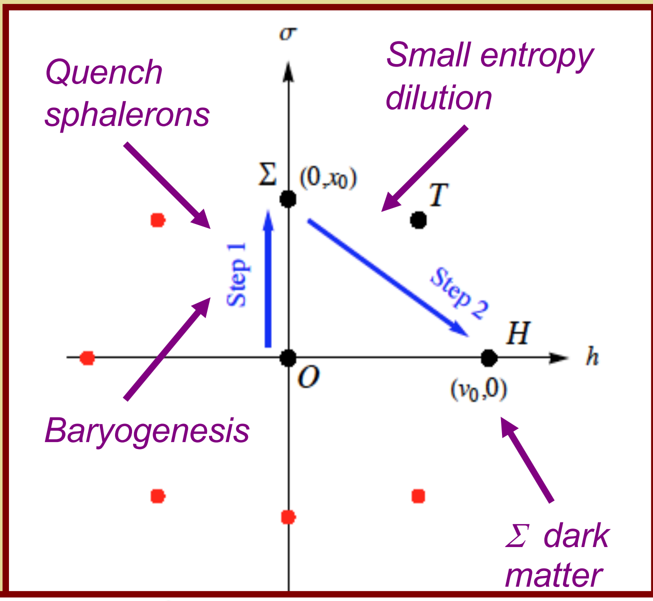
$H \rightarrow$ Set of "SM" fields: 2 HDM

(SUSY: "TNMSSM", Coriano…)

Two CPV Phases:

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

Two-Step EW Baryogenesis



$$V_{H\phi} \supset \frac{1}{2} H_1^\dagger H_2 \left(a_1 S^2 + a_2 \Sigma^2 \right) + \text{h.c.}$$
$$+ \sum_{i=1,2} \left[y_1^{ii} S^2 + y_2^{ii} \Sigma^2 + y_3^{ii} A^2 \right] H_i^\dagger H_i \quad .$$

$\delta_\Sigma = Arg\ (a_2^* v_1 v_2^*)$

$\delta_S = Arg\ (a_1^* v_1 v_2^*)$

Illustrative Model:

New sector: "Real Triplet" Σ
Gauge singlet S

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

(SUSY: "TNMSSM", Coriano…)

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δ_Σ : Triplet phase

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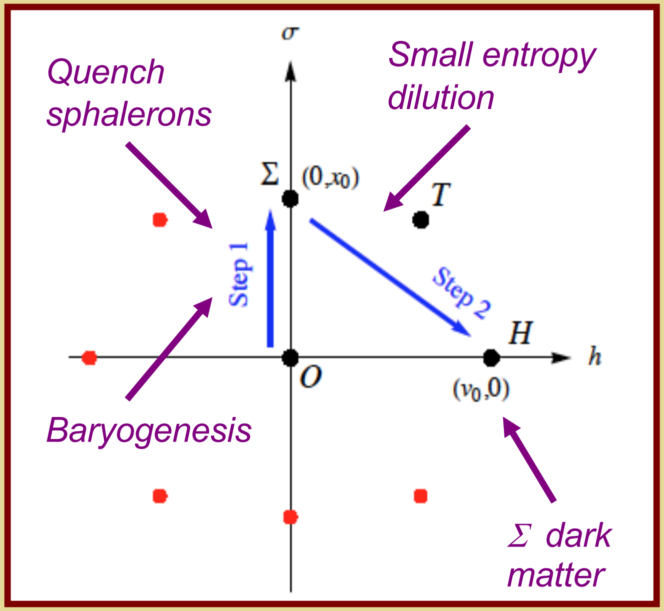
Two Step EWBG

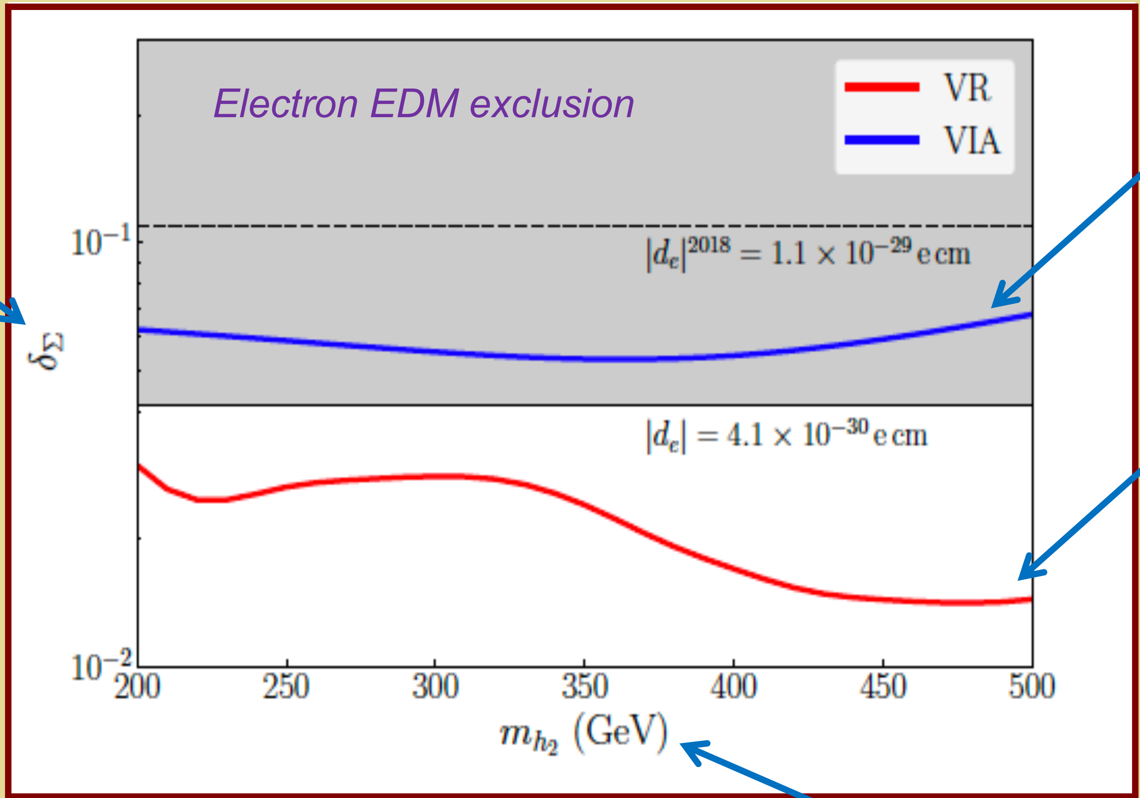


$$V_{H\phi} \supset \frac{1}{2} H_1^\dagger H_2 \left(a_1 S^2 + a_2 \Sigma^2\right) + \text{h.c.} + \sum_{i=1,2} \left[y_1^{ii} S^2 + y_2^{ii} \Sigma^2 + y_3^{ii} A^2\right] H_i^\dagger H_i \quad .$$

- ***BAU produced in step 1:***
  - ***Nonzero δ_Σ , < Σ^0 >(x) , < S >(x) → α(x)***
  - ***Flavor mixing during step 1: (H_1, H_2) → (H_A , H_B)***
  - ***$H_{A,B}$ densities → f_L densities via Yukawa interactions***
- ***BAU transferred to present Higgs phase in step 2***

Electron EDM & BAU

CPV Phase



BAU: Previous "VIA" method

BAU: current "VR" method

BSM Higgs mass

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

Experimental Situation: EDMs

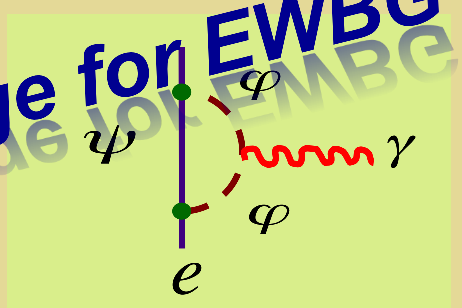
EDMs: New CPV?

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^{-30}
n	1.8×10^{-26}	10^{-31}	10^{-26}

* 95% CL   ** e^- equivalent

Mass Scale Sensitivity

Challenge for EWBG



$\sin\phi_{CP} \sim 1 \rightarrow$ M > 5000 GeV

M < 500 GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
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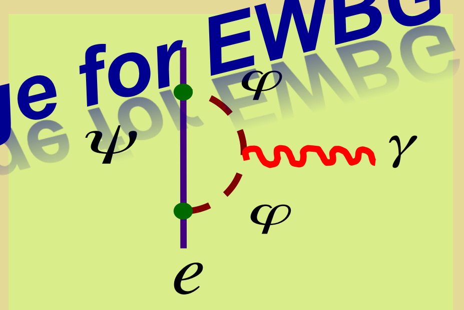
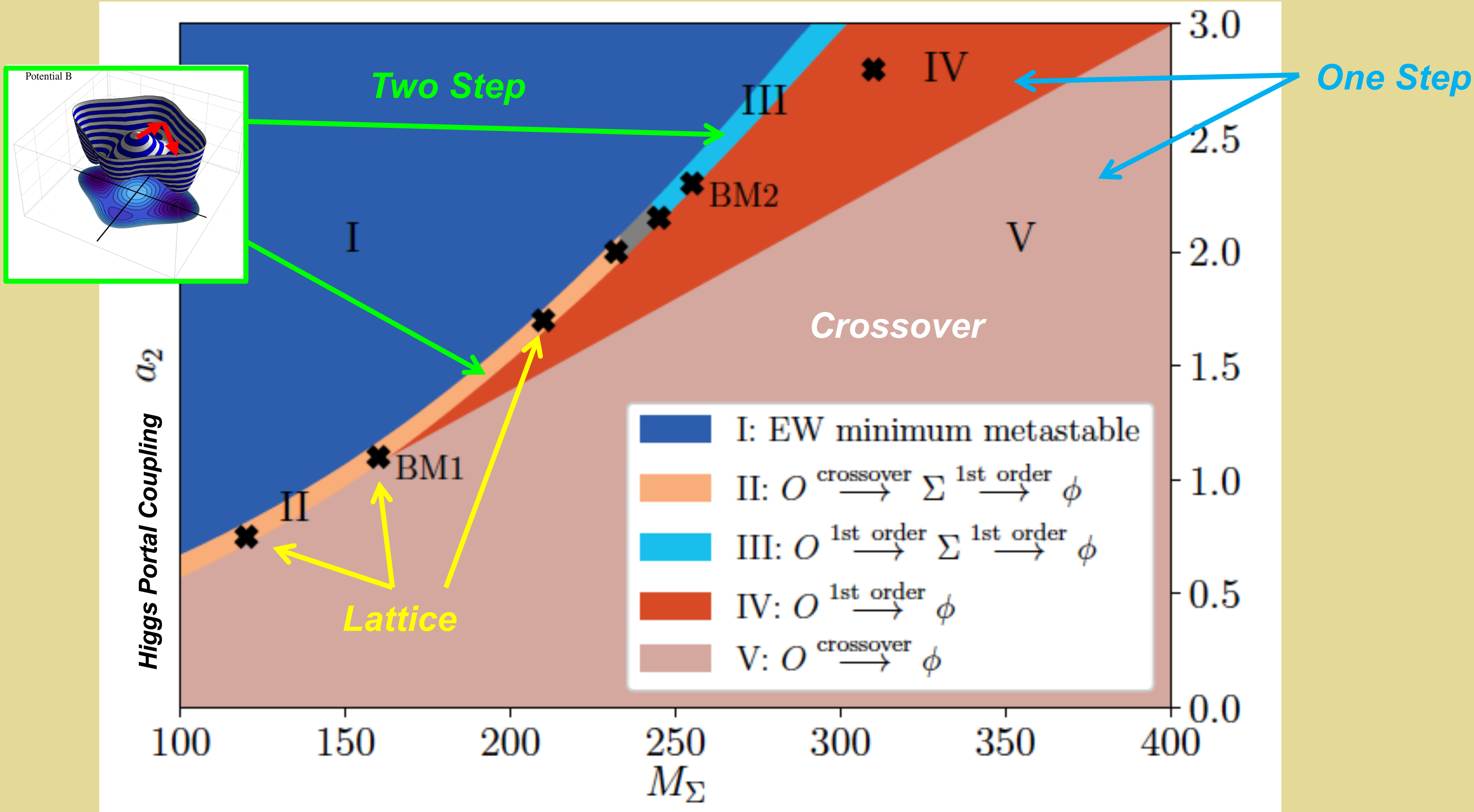


- ***EDMs arise at > 1 loop***
- ***CPV is flavor non-diagonal***
- ***CPV is "partially secluded"***

Two-Step EWSB: SM + Real Triplet



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

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

Some Details

Systematic Baryogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

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

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Distribution functions

Source of CPV asymmetry

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

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Rotation to mass basis: θ

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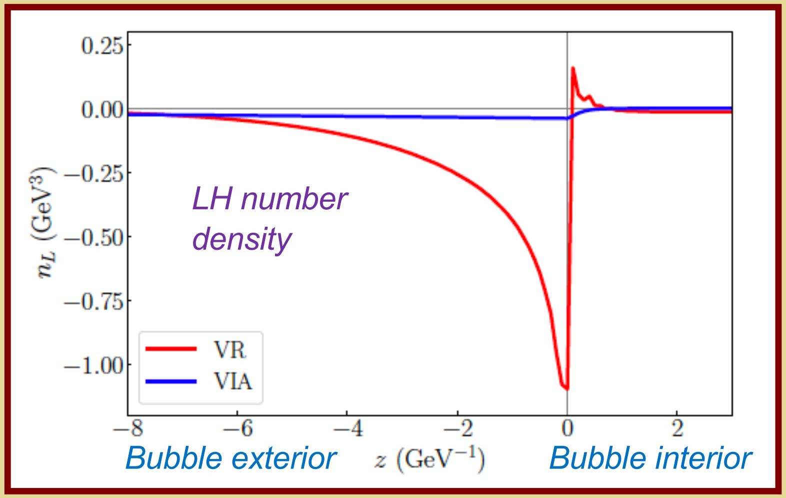
Two-Step EWBG: Transport Theory & EDMS



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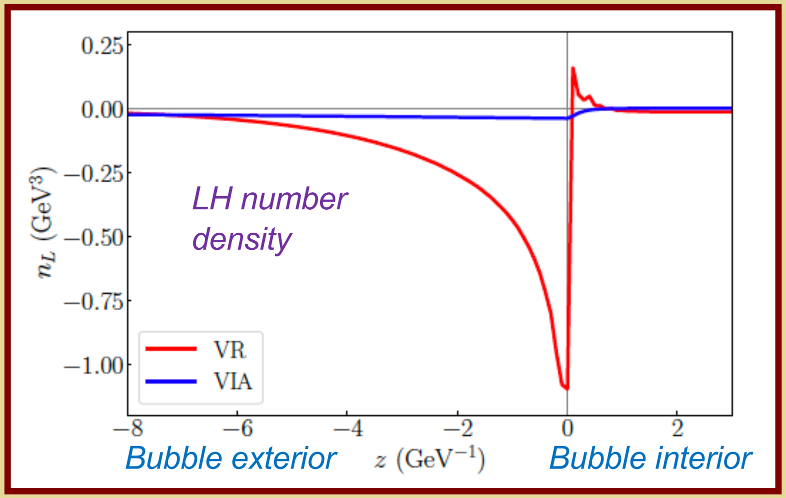

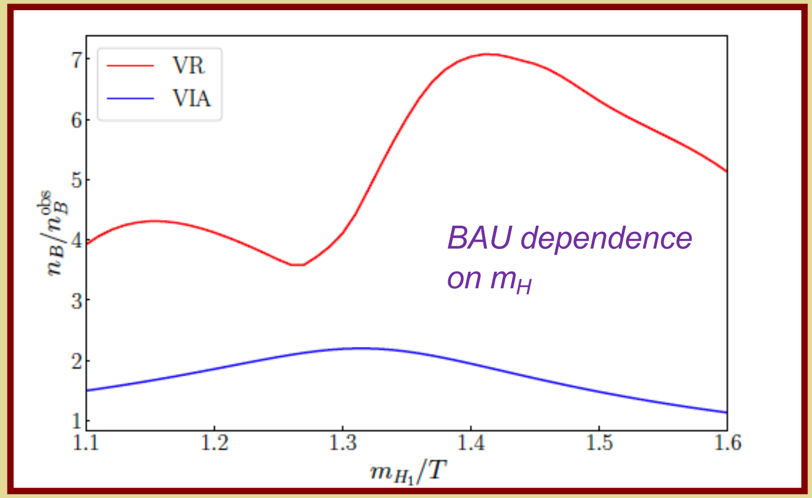

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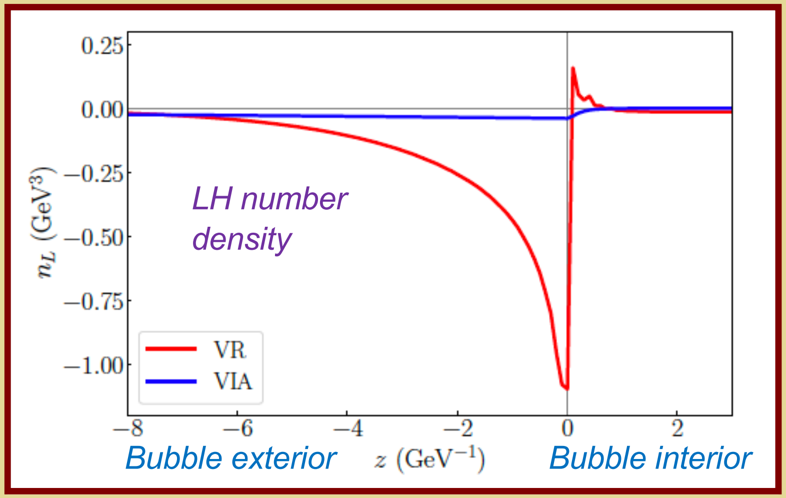

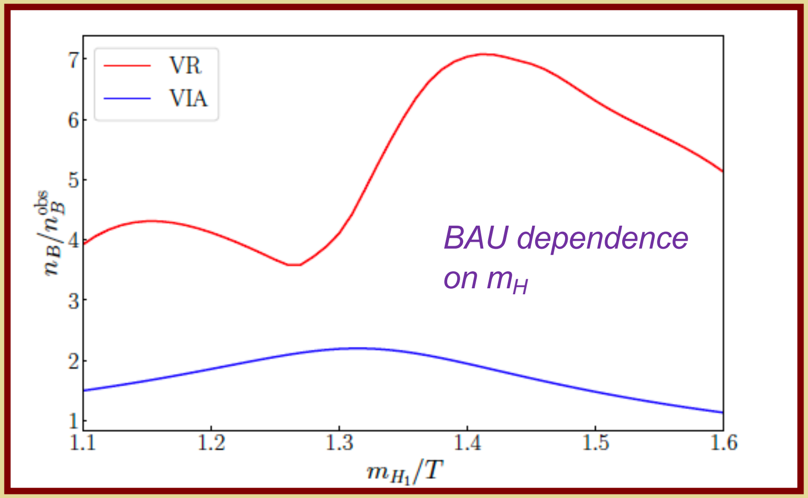

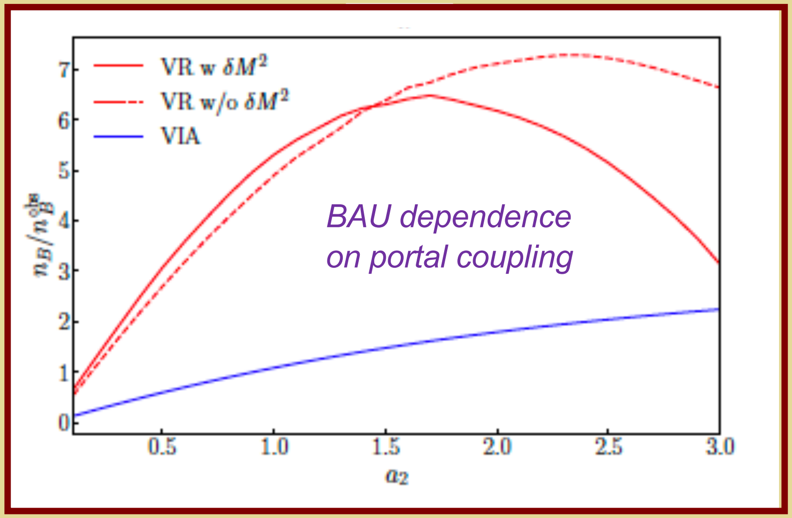

$a_2 H_1^* H_2 \Sigma^2 + c.c.$

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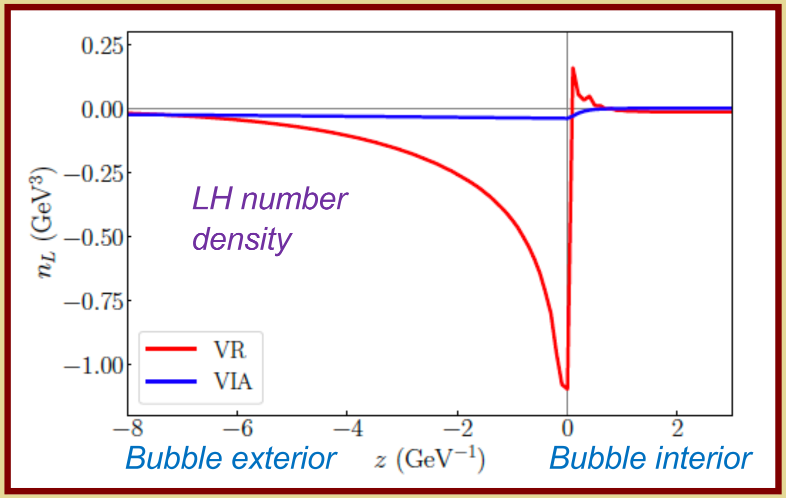
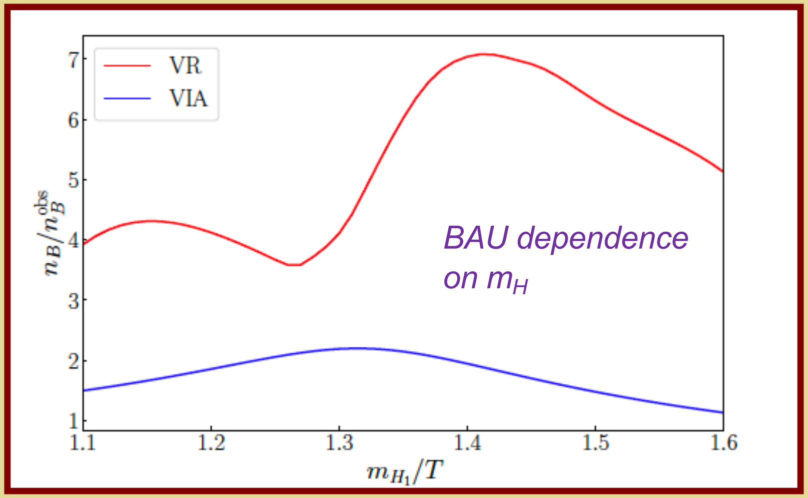
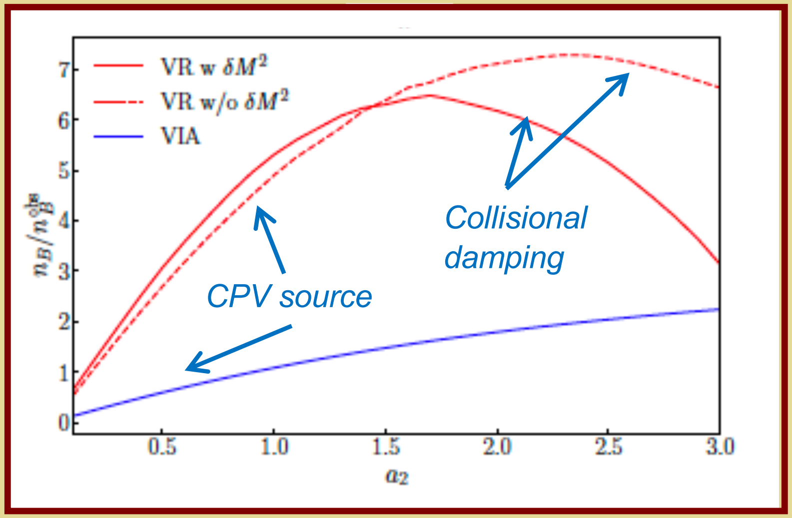
Two-Step EWBG: Transport Theory & EDMS







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

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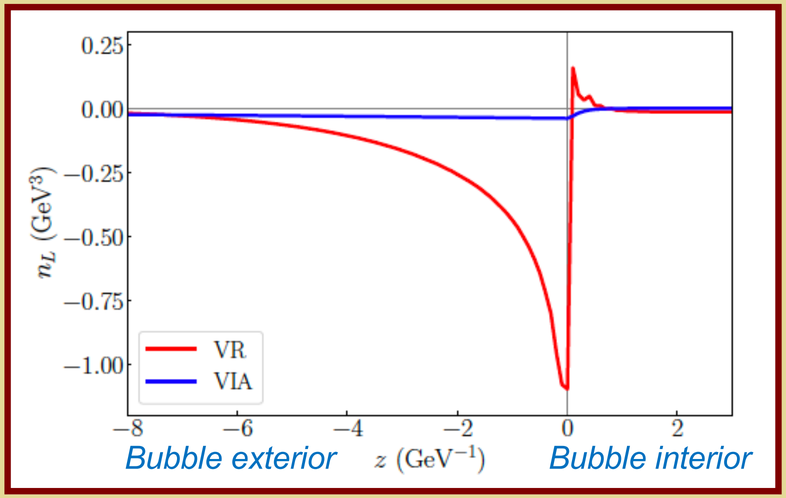
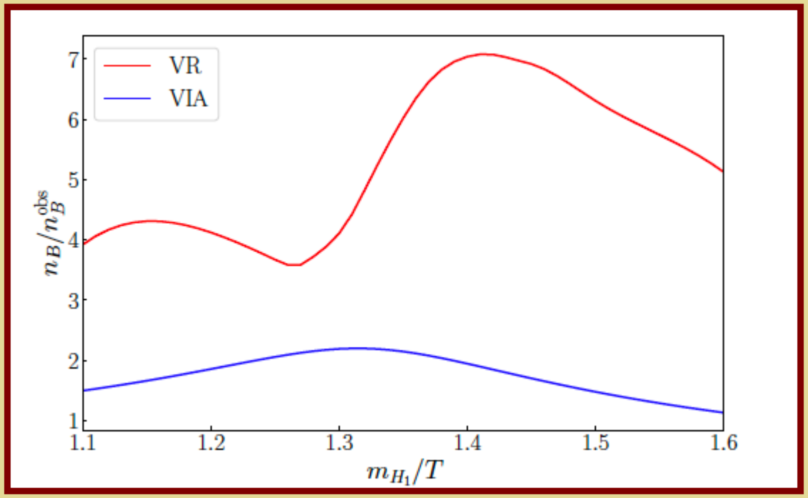
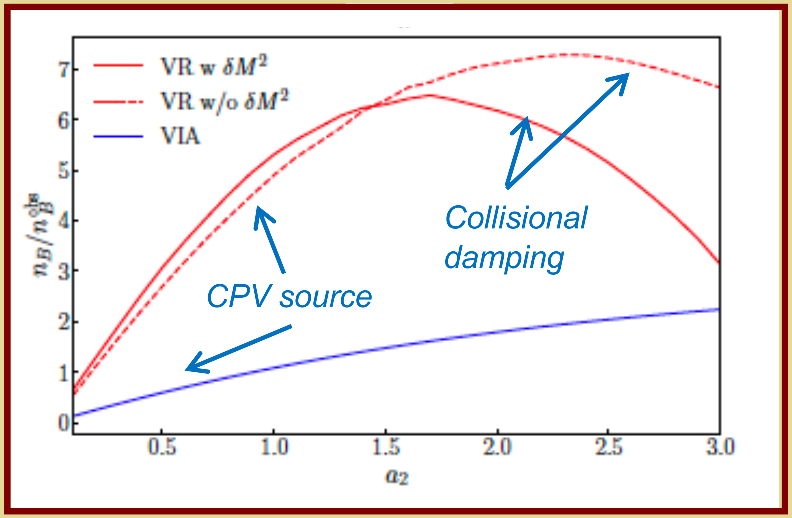
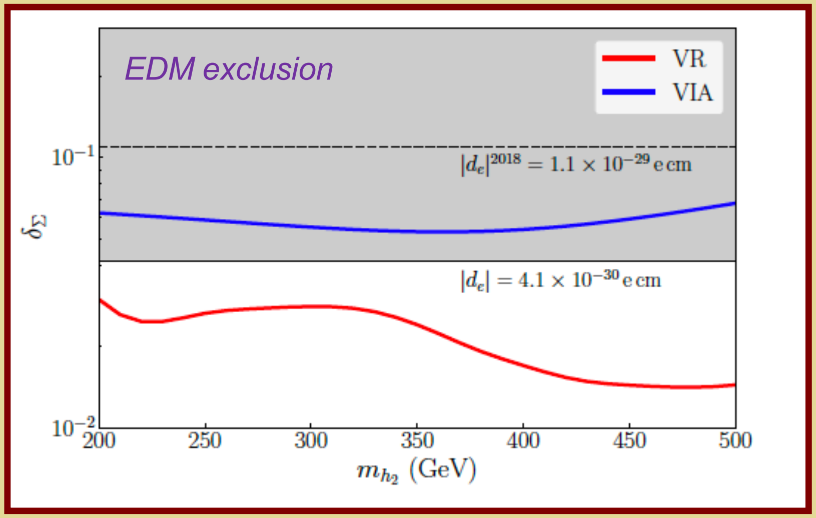
Two-Step EWBG: Transport Theory & EDMS







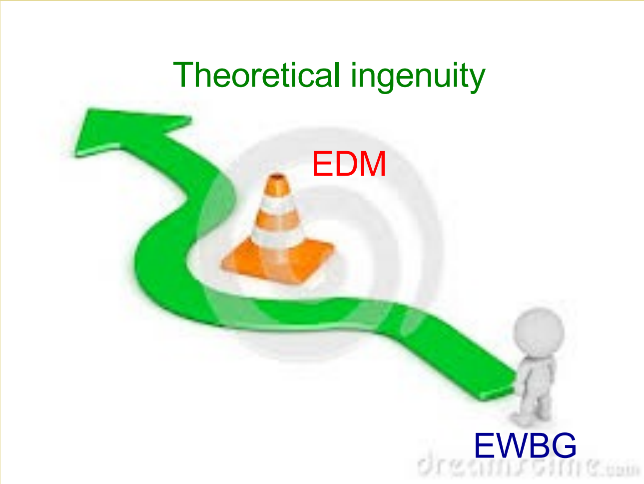


$a_2 H_1^* H_2 \Sigma^2 + c.c.$

Lessons

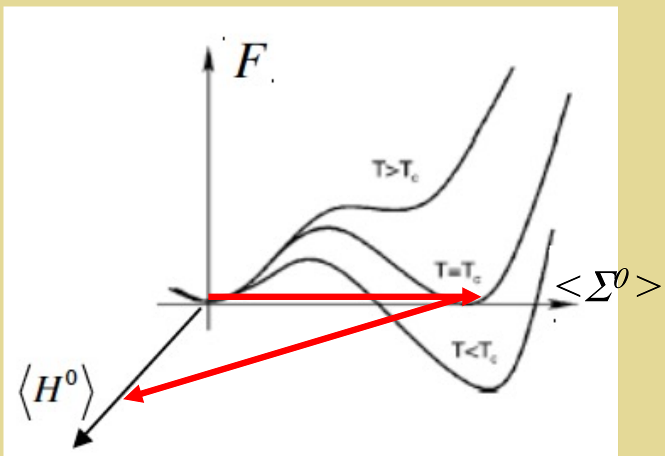
- For a given set of model parameters can get larger BAU with full resummation in presence of CPV flavor mixing → more "relaxed" EDM constraints
- BAU is larger than in WKB / semiclassical framework: 1st order vs 2nd order in gradients
- Realistic accounting for CP-conserving interactions in collision terms

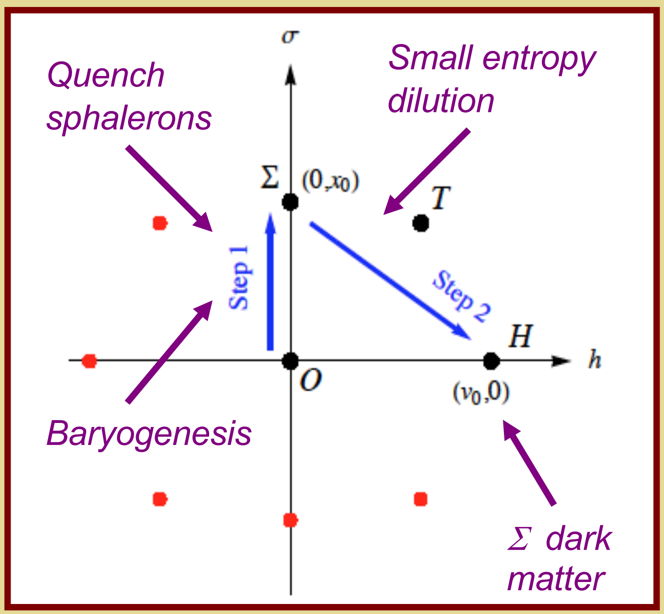
CPV for EWBG



Now apply to other models, e.g., 2HDM, NMSSM,…

CPV: General Considerations



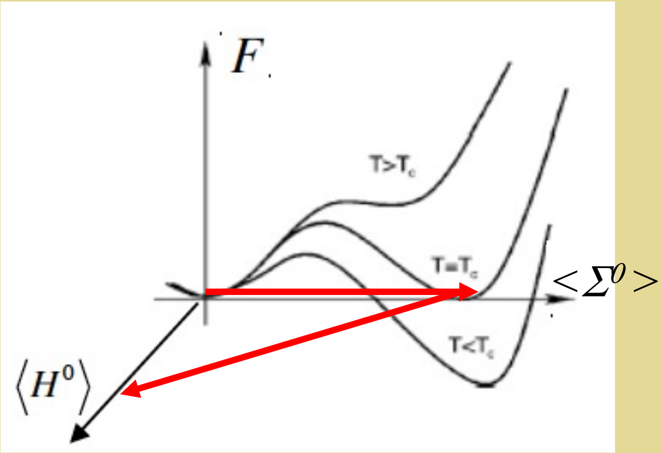


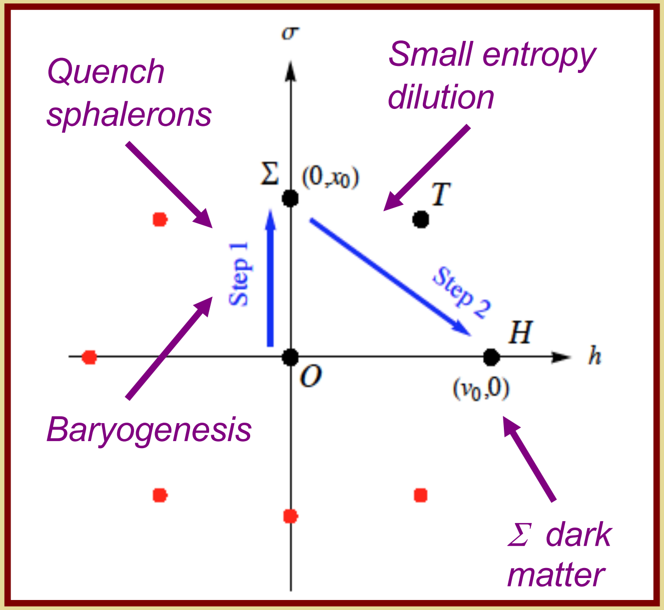
$\Sigma \to$ New sector: set of BSM fields ϕ_j, including at least one that breaks EWSB at $T > 0$ during first step

$H \to$ 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





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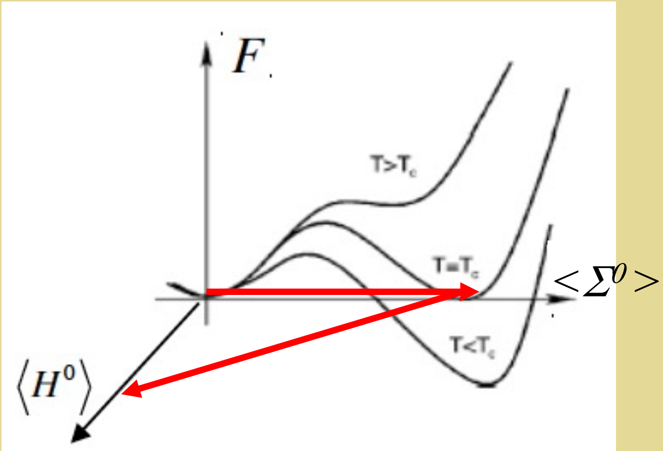

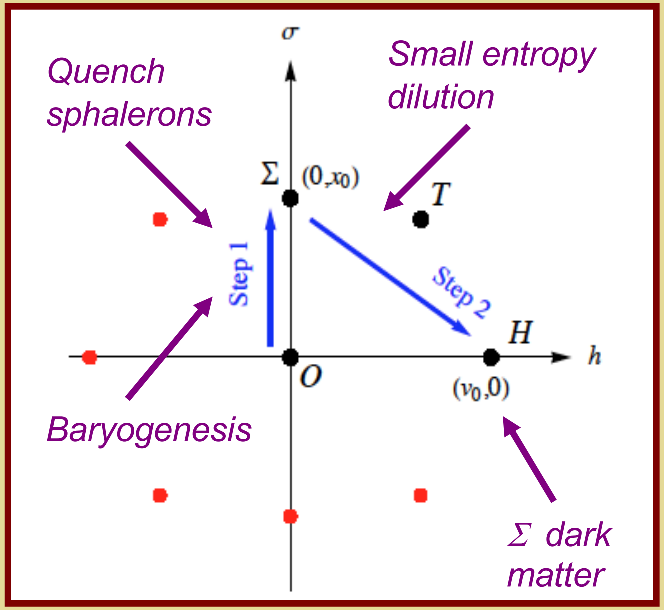

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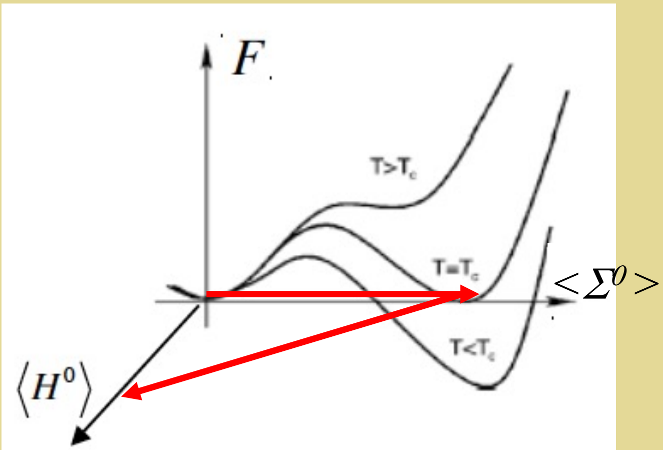
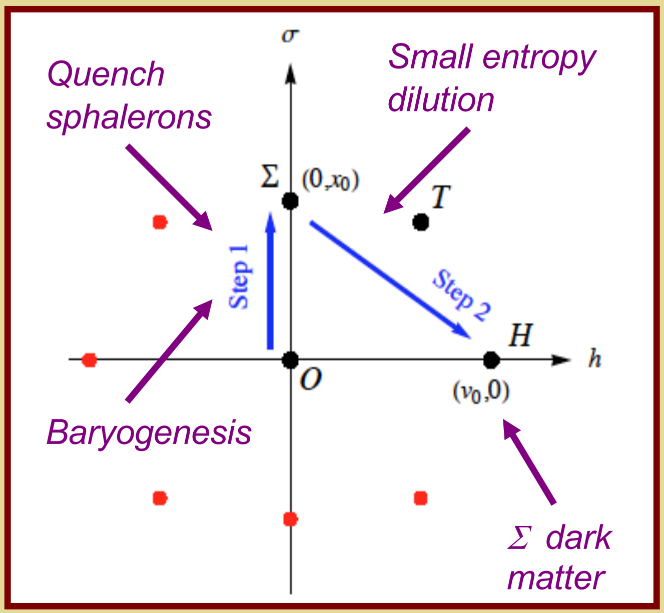
Illustrative Study





CPV asymmetry generated in SM sector via interactions with the ϕ_j

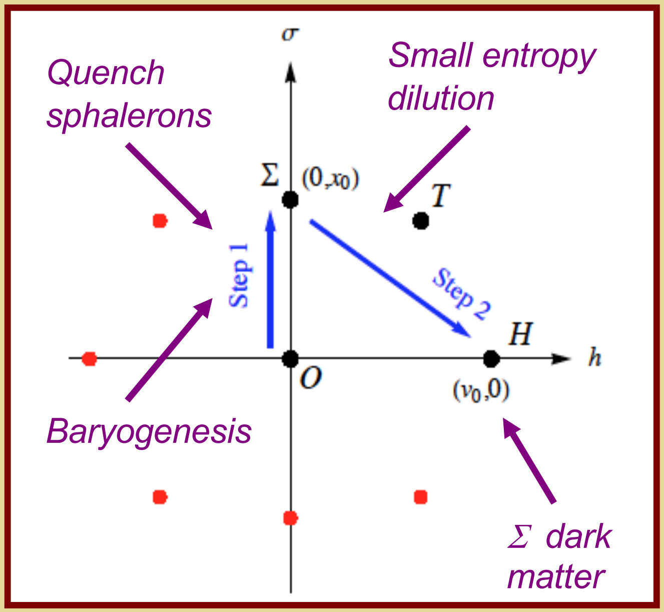
Considerations:

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

Two-Step EW Baryogenesis

$$V_{H\phi} \supset \frac{1}{2} H_1^\dagger H_2 \left(a_1 S^2 + a_2 \Sigma^2\right) + \text{h.c.}$$
$$+ \sum_{i=1,2} \left[y_1^{ii} S^2 + y_2^{ii} \Sigma^2 + y_3^{ii} A^2\right] H_i^\dagger H_i \quad .$$

Step 1: *Σ, S vevs → non-zero $H_{1,2}$ densities → $t_{L,R}$ via Yukawa interactions → BAU in "σ" phase (Σ, S vevs)*



Inoue, Ovanesyan, R-M: 1508.05404

Illustrative Model:

New sector: "Real Triplet" Σ
Gauge singlet S

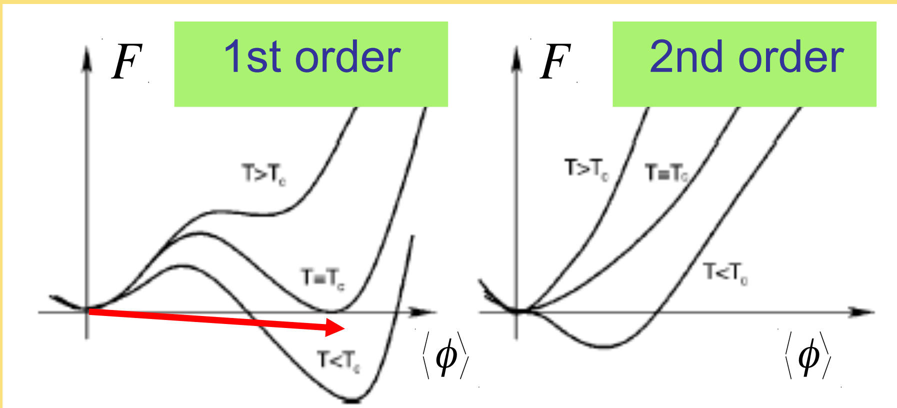
H → Set of "SM" fields: 2 HDM

(SUSY: "TNMSSM", Coriano…)

Two CPV Phases:

δ_Σ : Triplet phase
δ_S : Singlet phase

Concrete Realization: Real Triplet

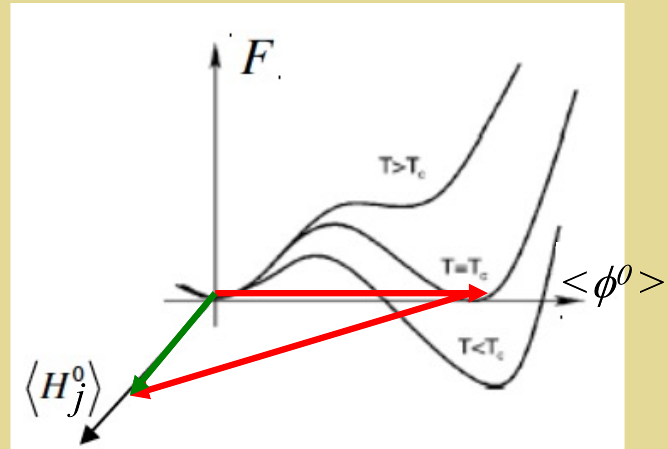


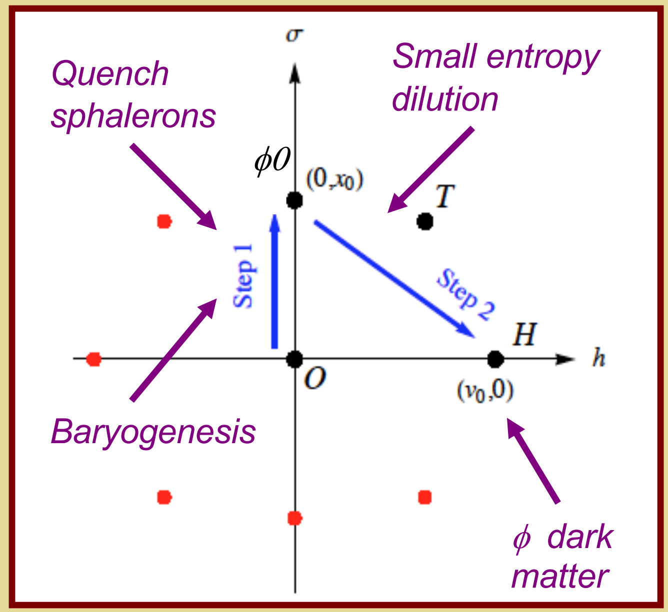
Increasing m_h ⟶

⟵ New scalars

Real Triplet $\Sigma^+, \Sigma^-, \Sigma^0$

Two-step EWPT &
dark matter





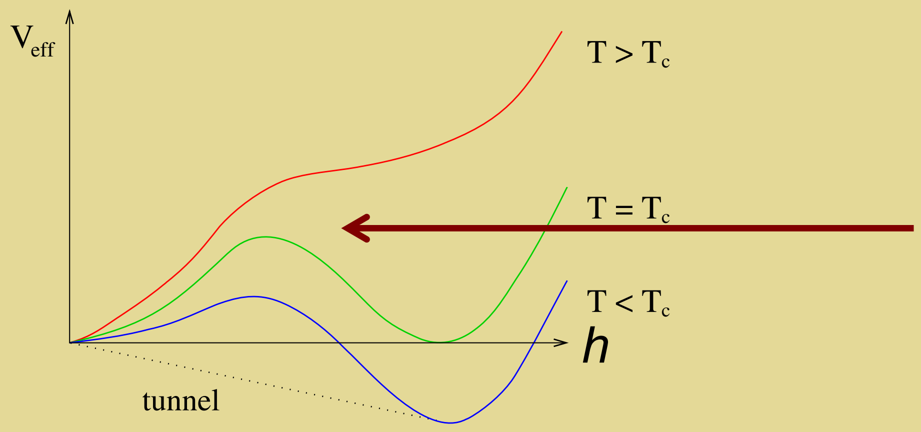
Patel, R-M, PRD 88 (2013) 035013 ; Fileviez-Perez, Patel, RM, Wang, PRD 79 (2009) 055024

EWBG Ingredients

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

MJRM: 1912.07189

First Order EWPT from BSM Higgs



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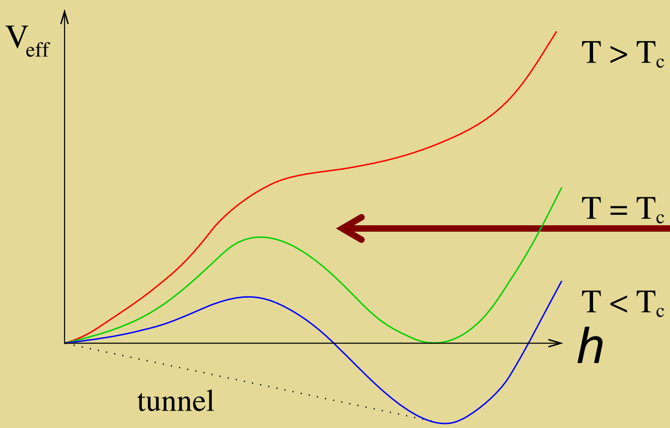
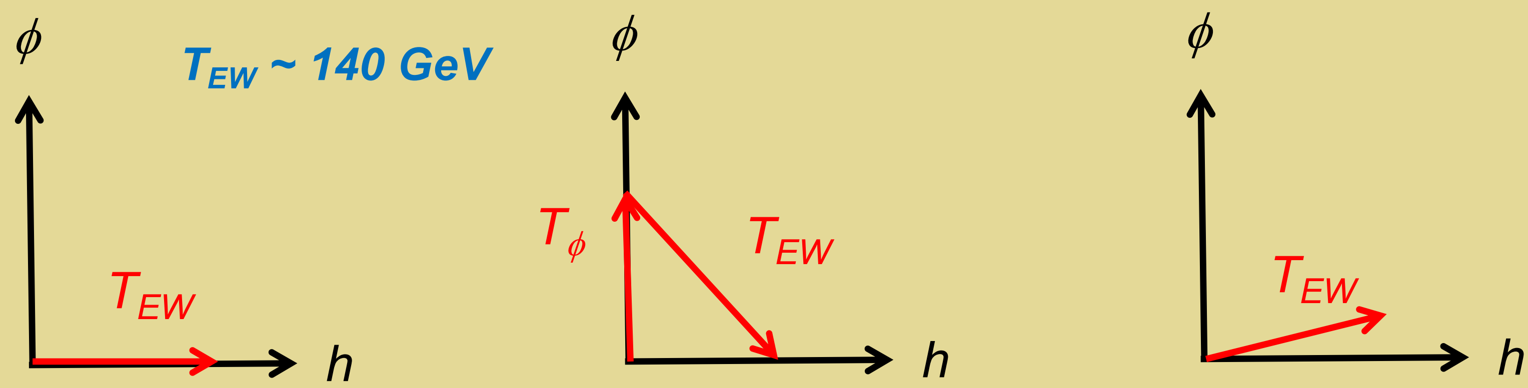


Representative thermal histories → barrier for SFOEWPT



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

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

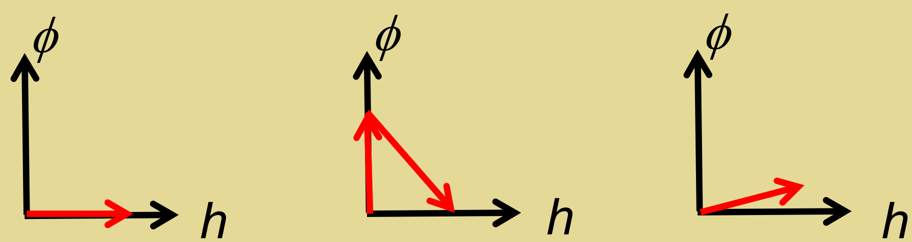
$a_1 H^2\phi$: $T = 0$
tree-level effect

Theory-Pheno Interface

Simple Higgs portal models:

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

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



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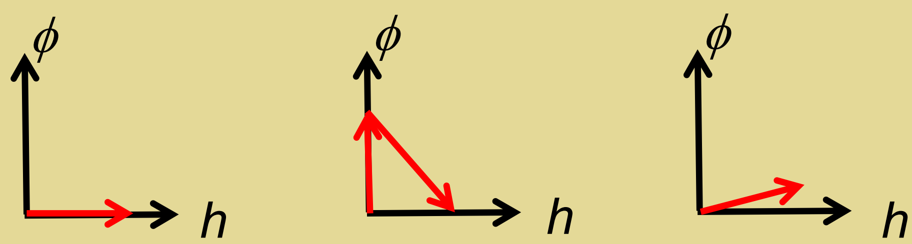

Phenomenology

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

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

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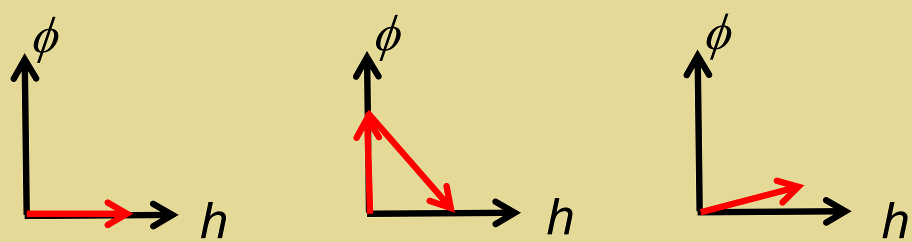

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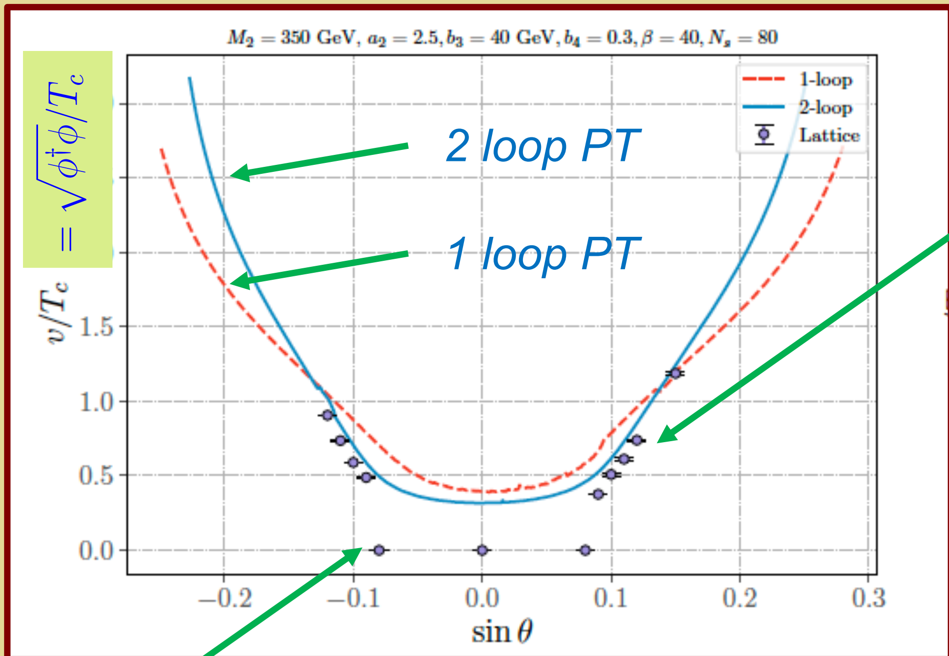
Lauri Niemi, MJRM, Gutao Xia, 2405.01191 (today!)

Singlets: Lattice vs. Pert Theory



Lattice: FOEWPT

Lattice: Crossover

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

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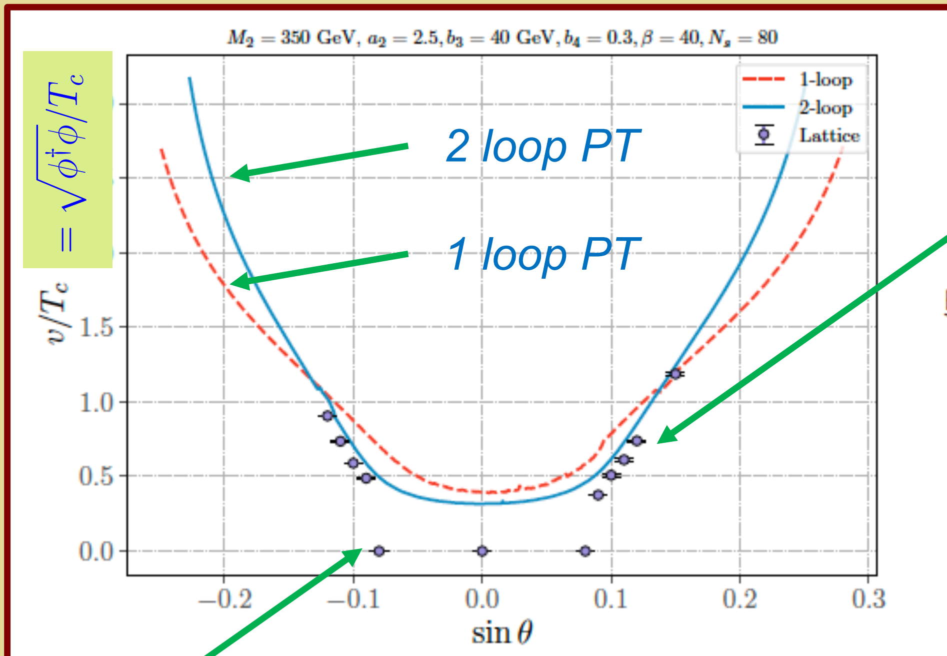
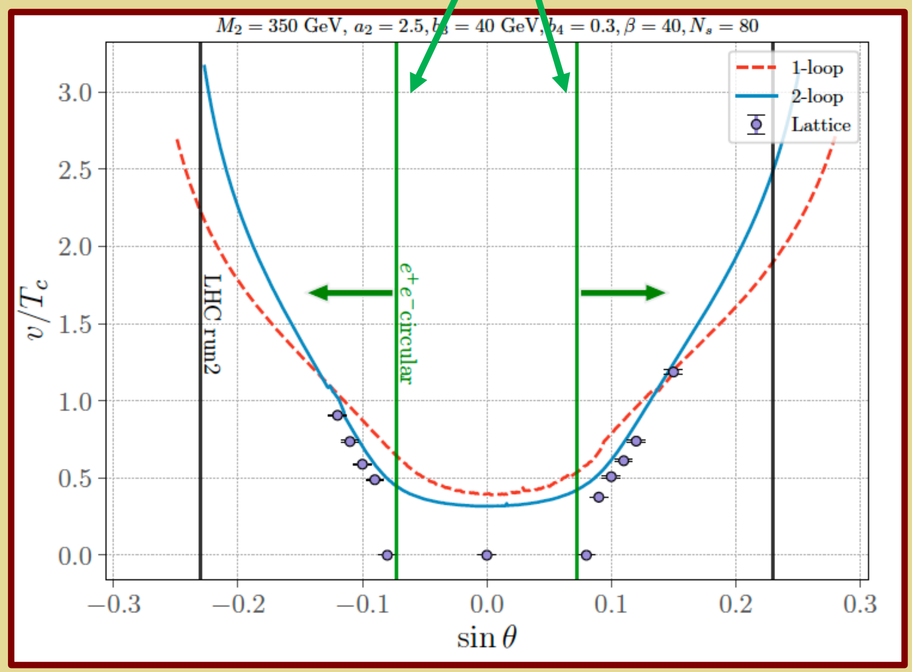


Lattice:
FOEWPT

Future e⁺e⁻

Lattice:
Crossover



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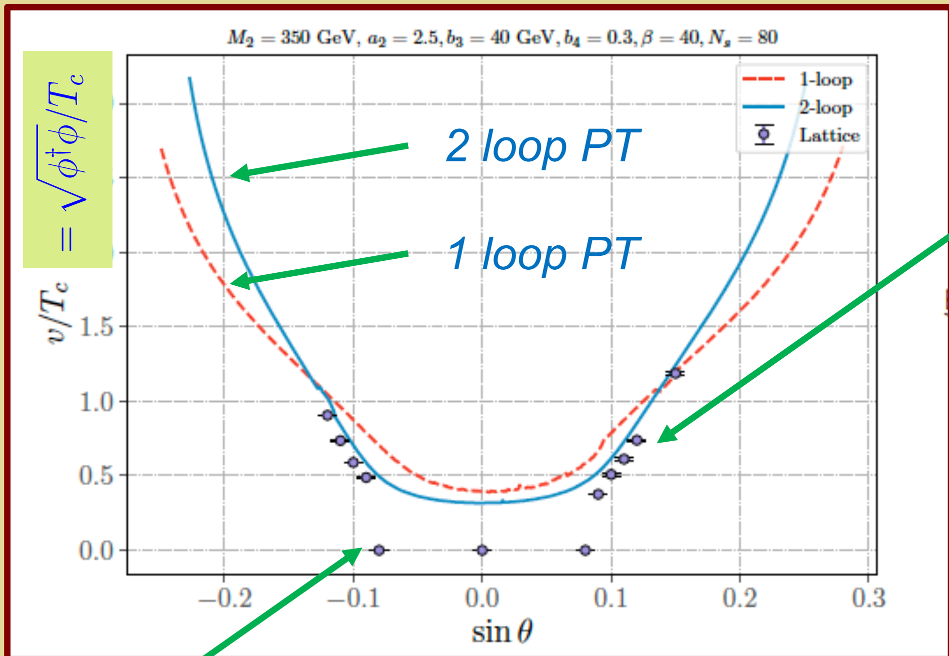
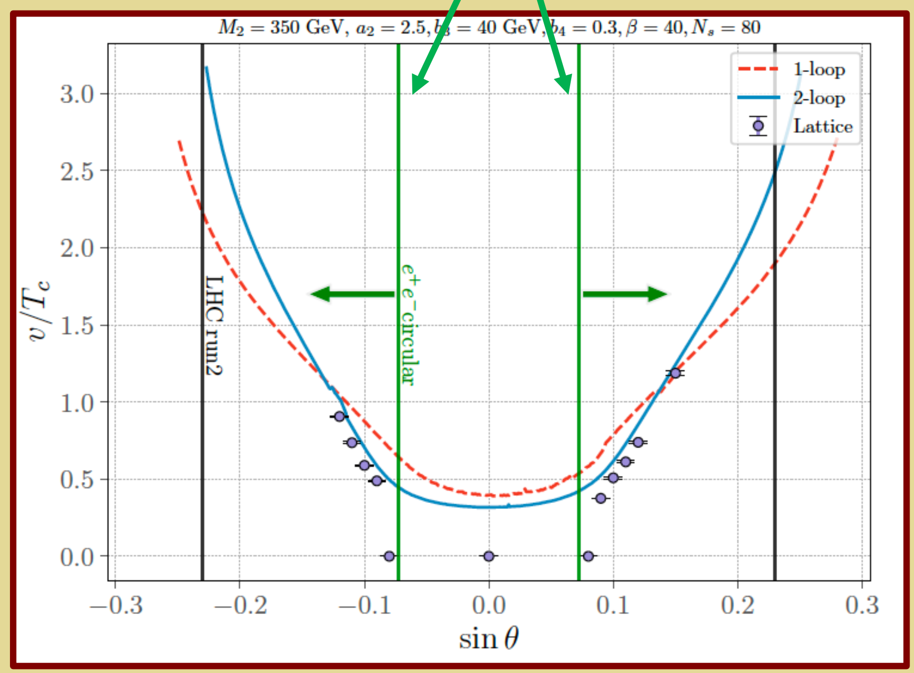


Lattice: FOEWPT

Future e^+e^-



Lattice: Crossover

- *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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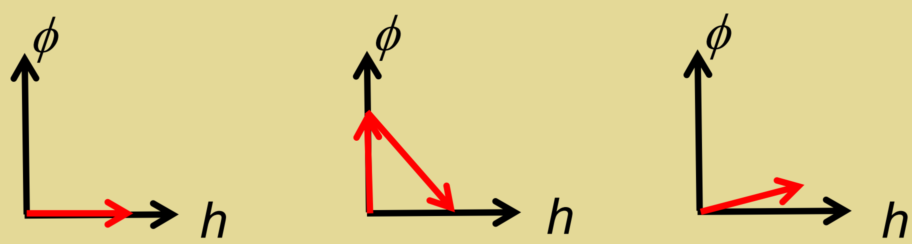

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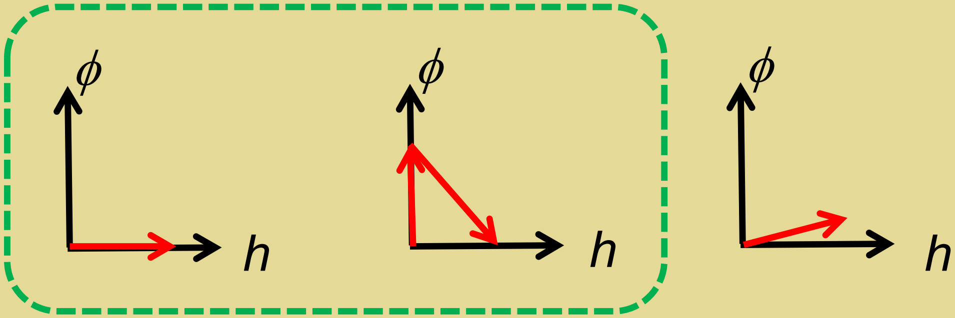

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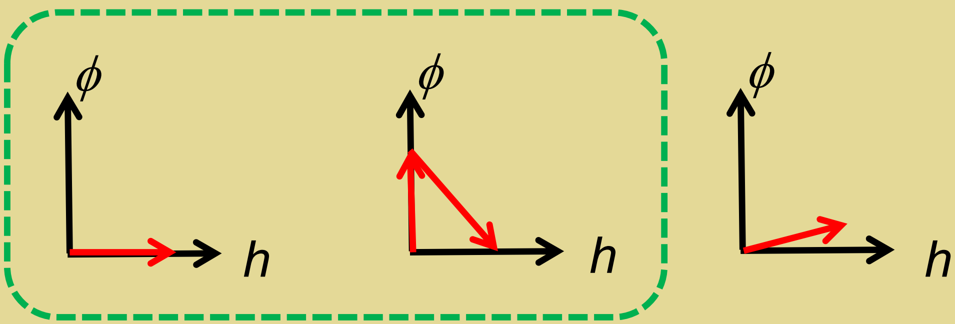


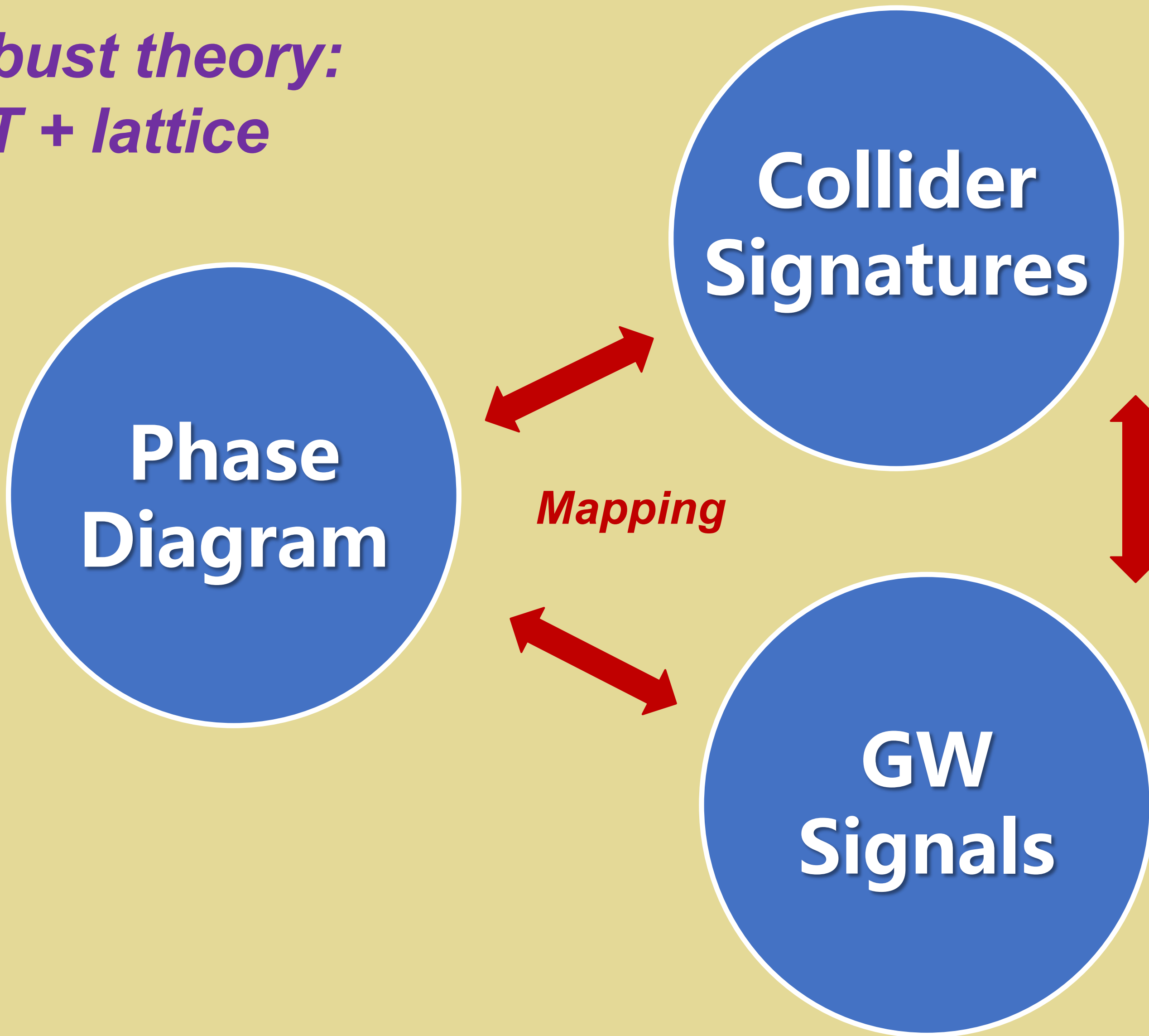
Phenomenology

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

BSM EWPT: Inter-frontier Connections

Robust theory:
EFT + lattice

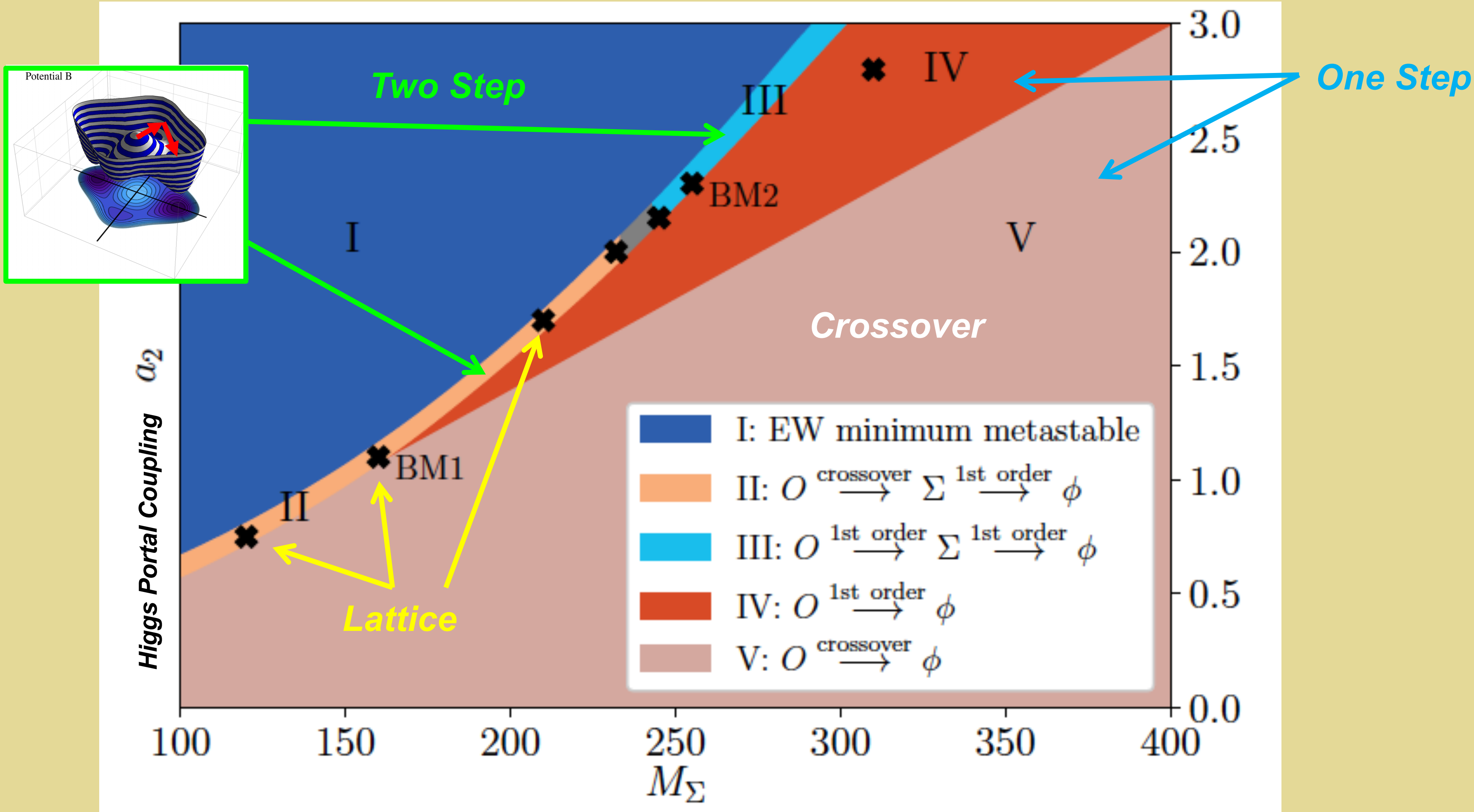
Observables:
model specific



Combined
reach

Hydro:
α , β / H_*

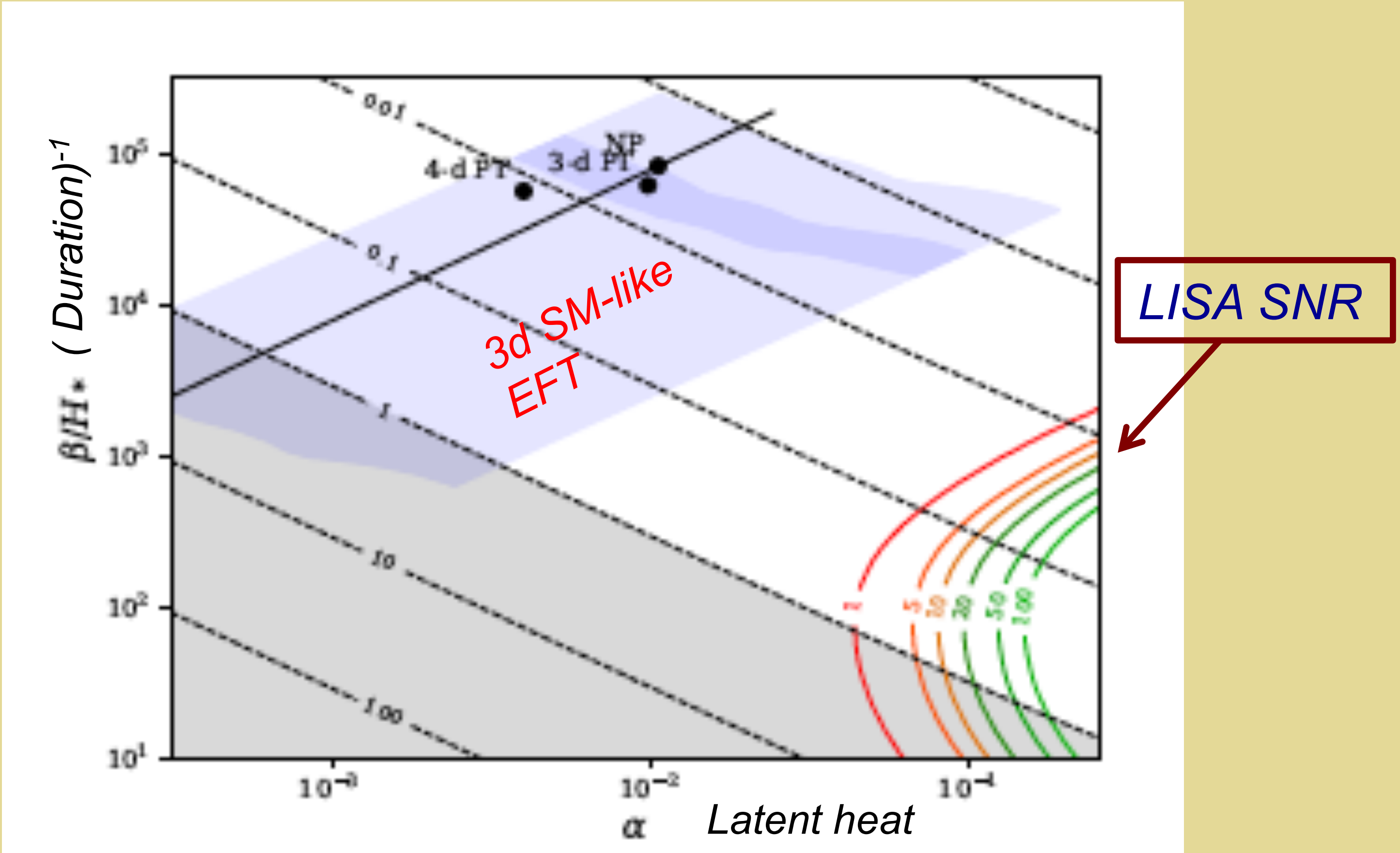
Real Triplet & EWPT: Novel EWSB



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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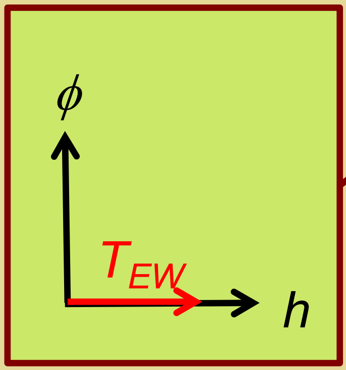
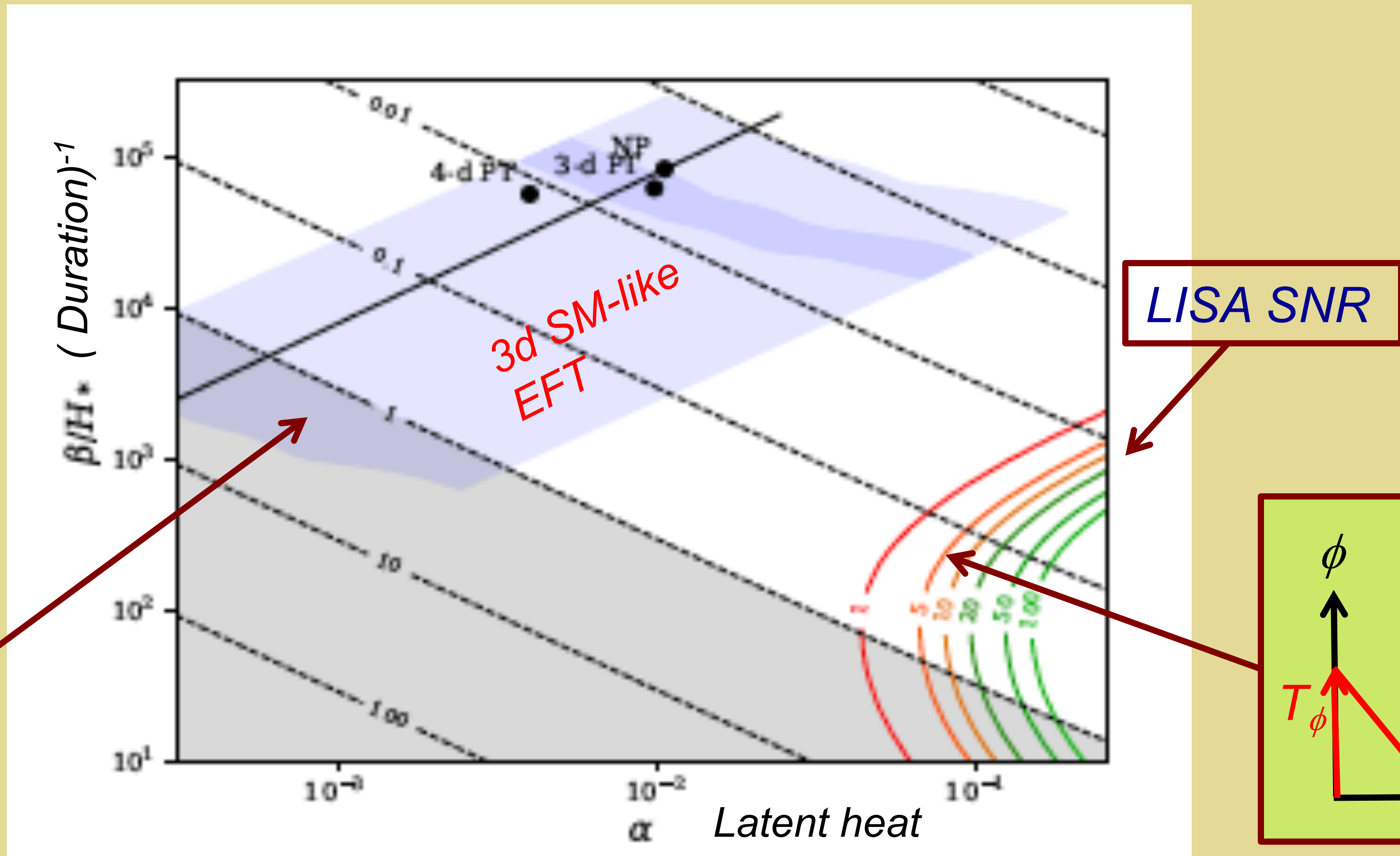
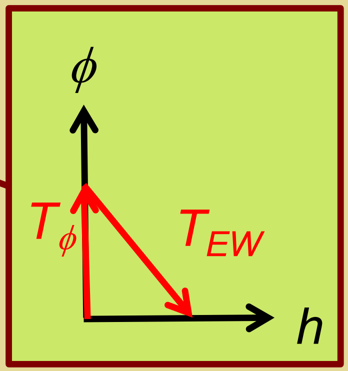


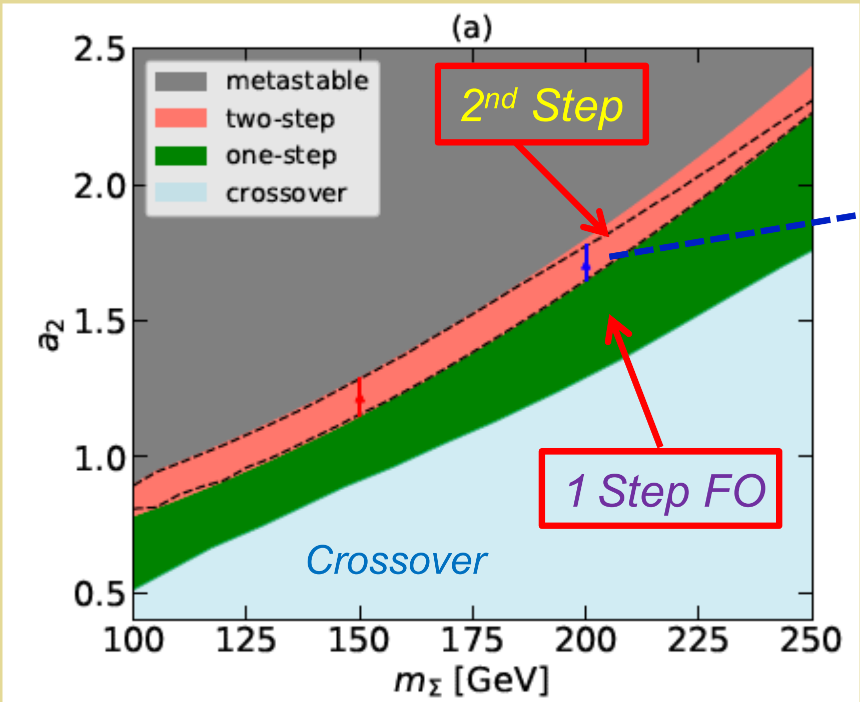


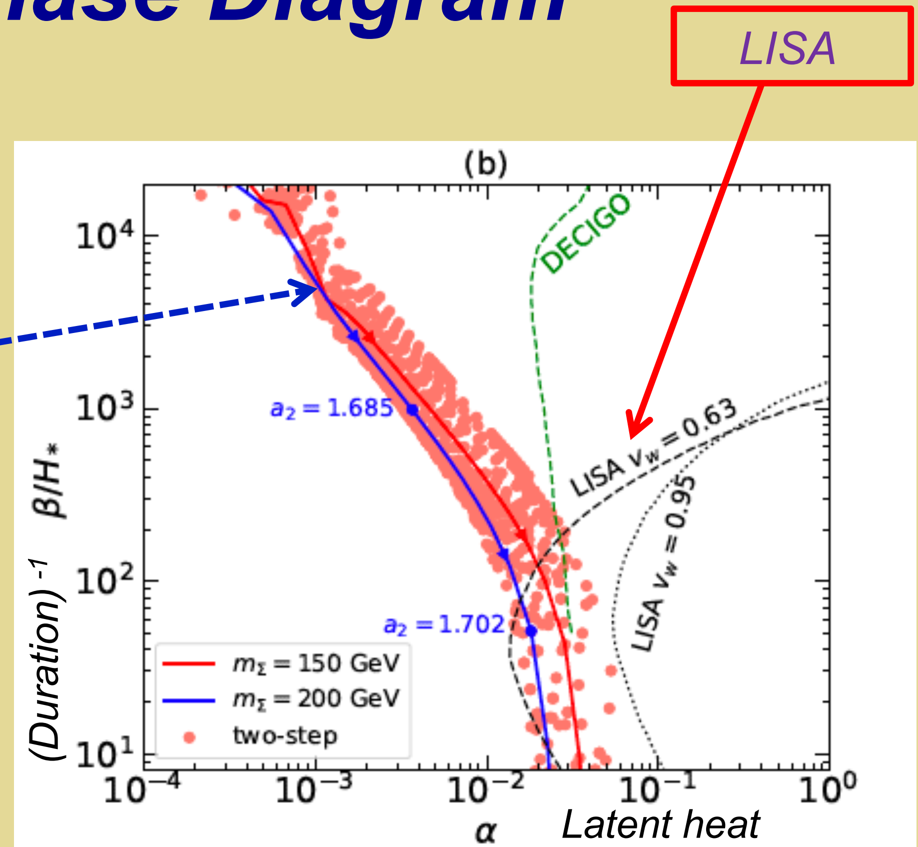


10.2

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

GW & EWPT Phase Diagram

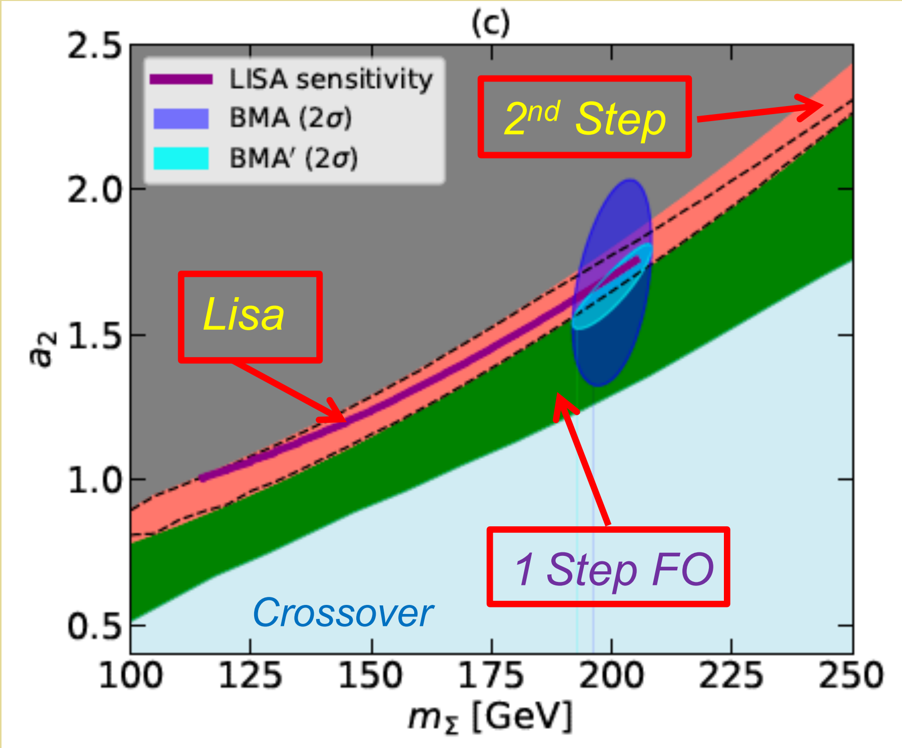


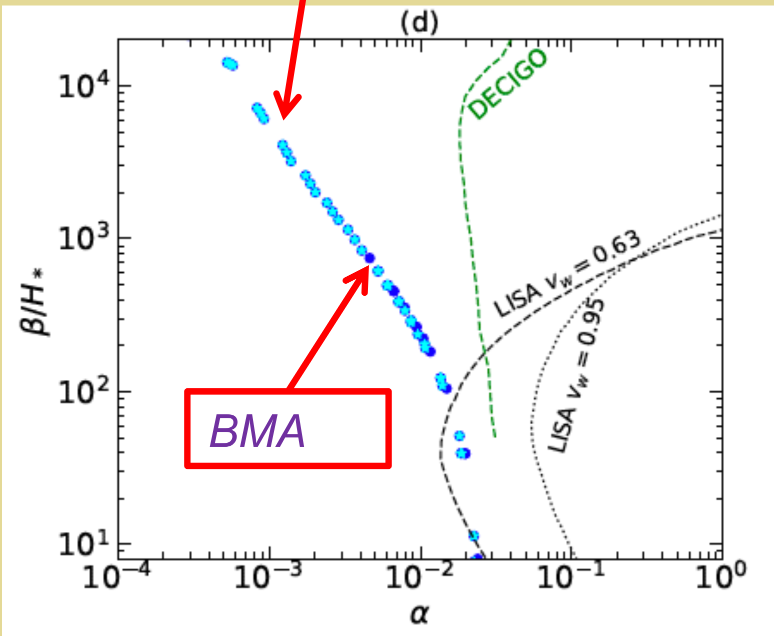


- ***Single step transition: GW well outside LISA sensitivity***
- ***Second step of 2-step transition can be observable***
- ***Significant GW sensitivity to portal coupling***

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW & EWPT Phase Diagram





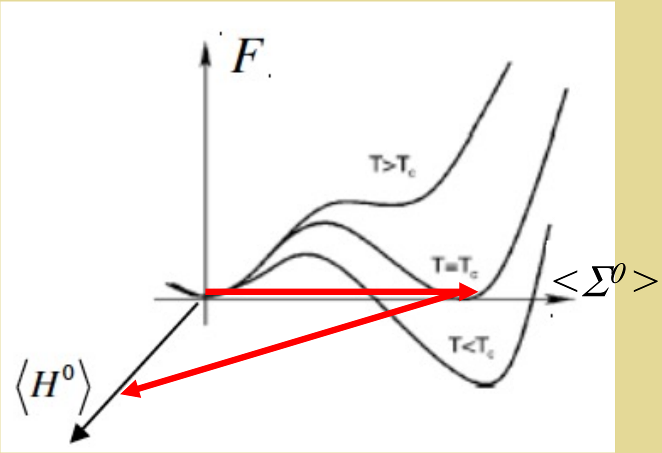
BMA: m_Σ + h → $\gamma\gamma$

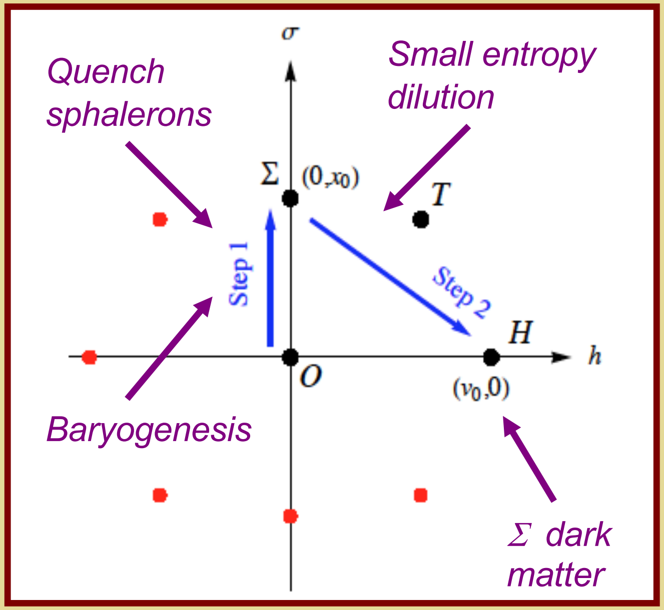
BMA' : BMA + Σ^0 → ZZ

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

Friedrich, MJRM, Tenkanen, Tran 2203.05889

General Considerations





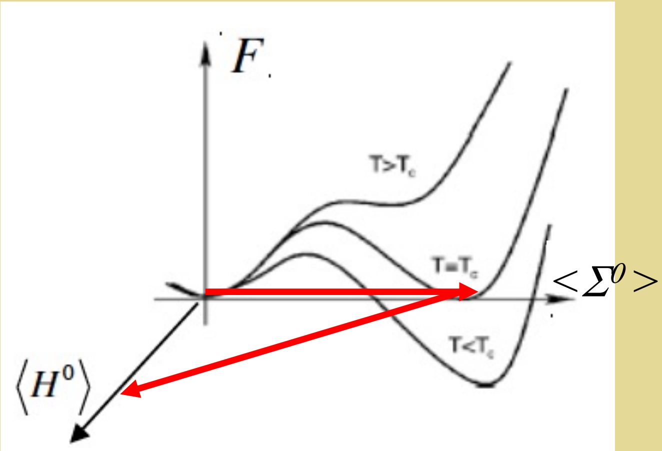
$\Sigma \rightarrow$ New sector: set of BSM fields ϕ_j, including at least one that breaks EWSB at T > 0 during first step

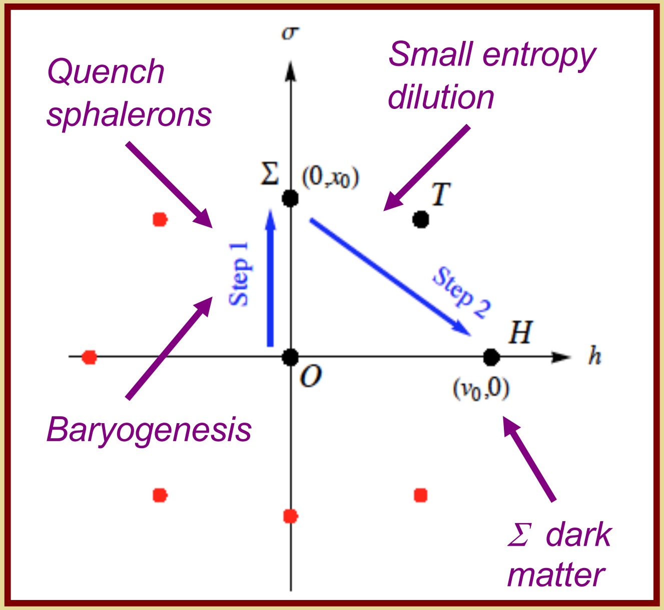
$H \rightarrow$ Set of "SM" fields, including at least one that breaks EWSB at during second step & persists to T = 0 (e.g., single H, 2HDM…)

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

B6.1

2-Step EWBG: Rich Array of Scenarios





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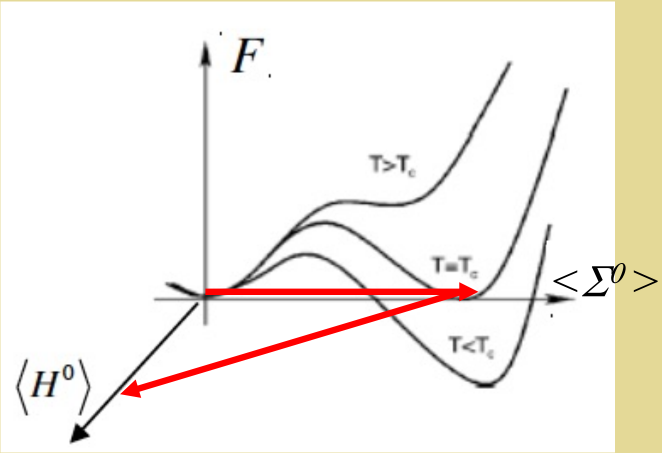

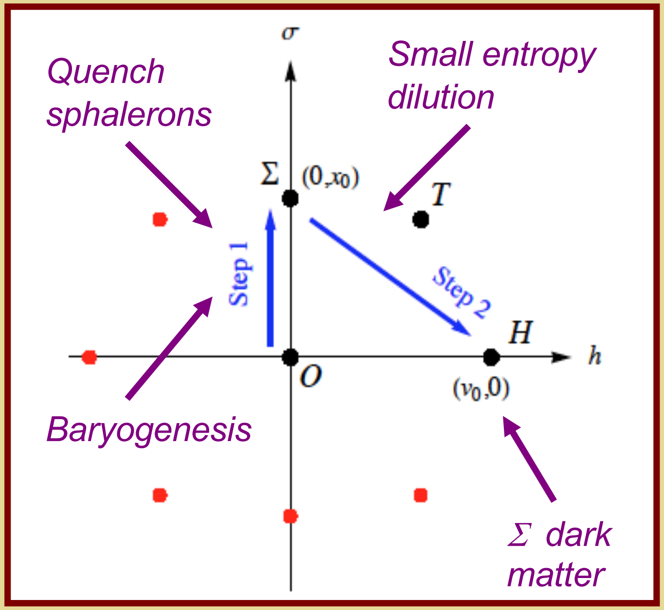

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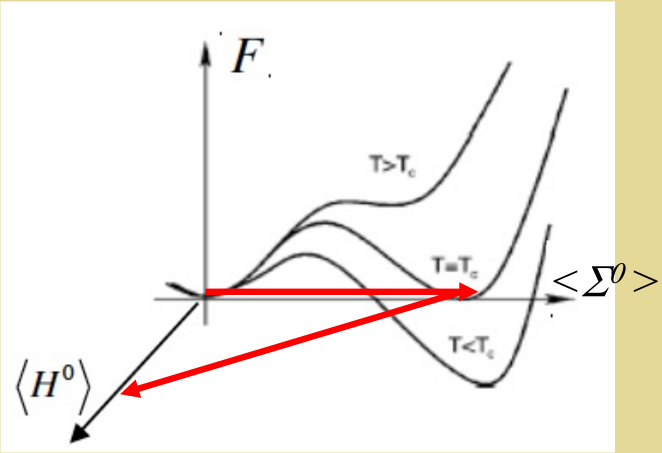

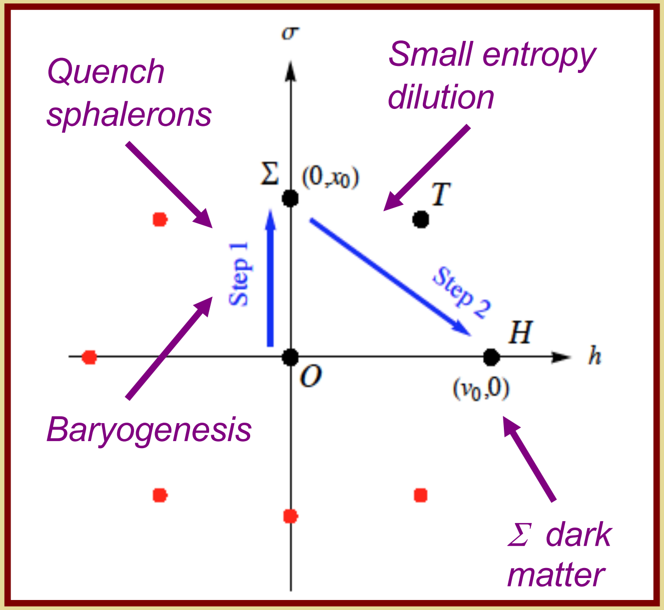

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MJRM: 1912.07189

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 ~ 140 GeV ≡ T_{EW}

MJRM: 1912.07189

T_{EW} → Scale for Colliders & GW probes

High-T SM Effective Potential

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

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

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

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

Field

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

Quartic coupling