CPV & Electroweak Baryogensis

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

FIND Workshop USTC, August 26, 2023

Key Themes

- *The experimental discovery of BSM CPV at the EW → TeV scale could hold the key to explaining the cosmic matter-antimatter asymmetry*
- *Electroweak baryogenesis (EWBG) connects this CPV to the origin of elementary particle masses through EW symmetry breaking*
- *The ingredients for EWBG are experimentally accessible through a combination of low-energy symmetry tests, collider searches, and GW probes*
- *An exciting opportunity exists for inter-frontier synergy in the quest to pursue this quest*

Outline

I. Context

II. EWBG in a nutshell

III. EWBG in detail

- *EW phase transition (brief)*
- *CPV & EDMs*

IV. Outlook

I. Context & Questions

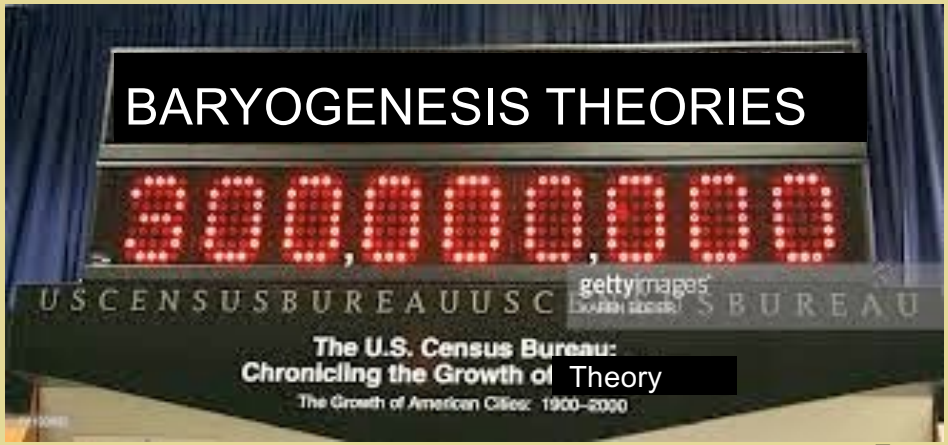
Cosmic Baryon Asymmetry

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

One number → ~~N N N~~ … Explanations

Experiment can help:

- *Discover ingredients*
- *Falsify candidates*



Ingredients for Baryogenesis

Andrei Sakharov

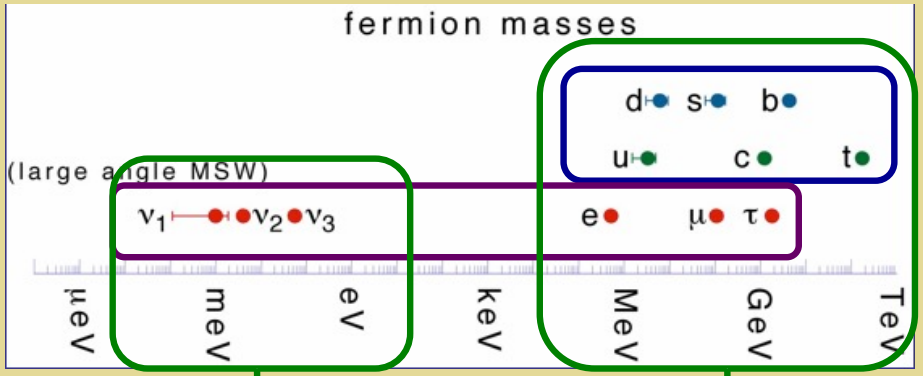
- *Russian theoretical physicist*
- *Nobel Peace Prize recipient*
- *1921-1989*

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



Partners

Partners

Something else ?

Higgs Mechanism

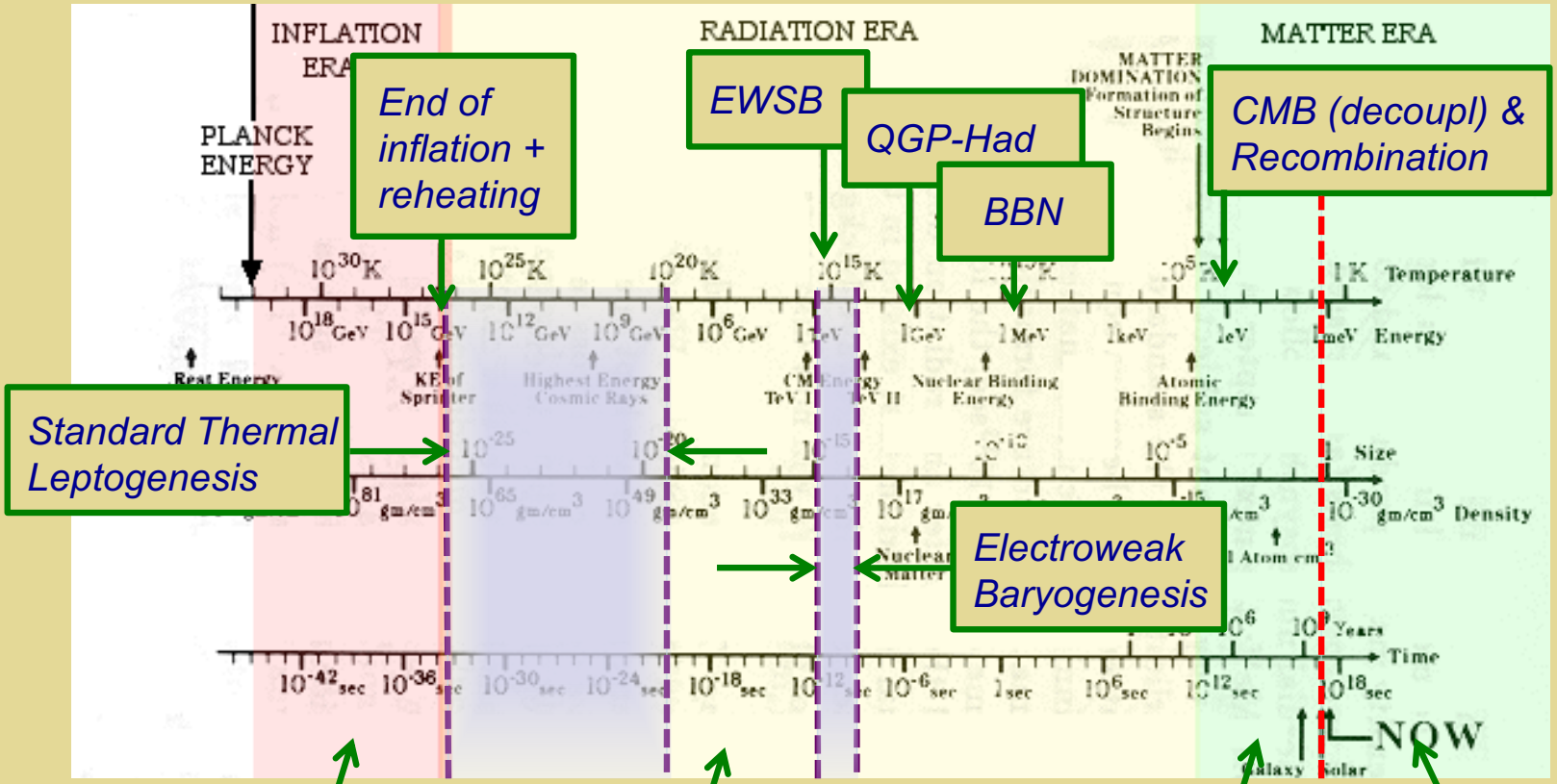
Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

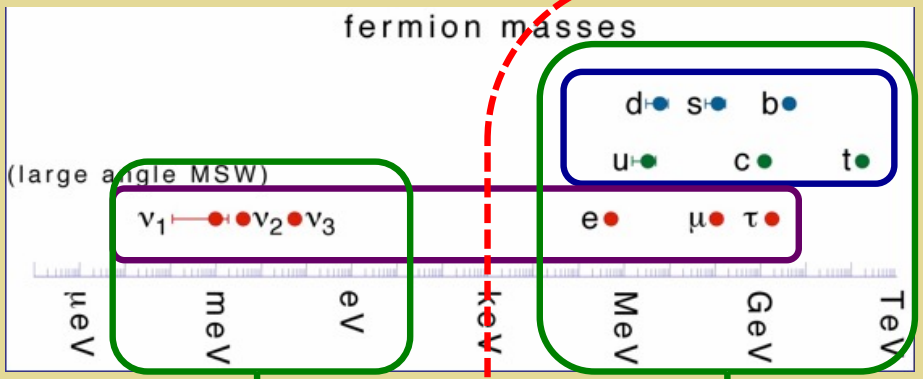
Fukugita & Yanagida '86

Kuzmin, Rubakov, & Shaposhnikov '85

Thermal History



Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

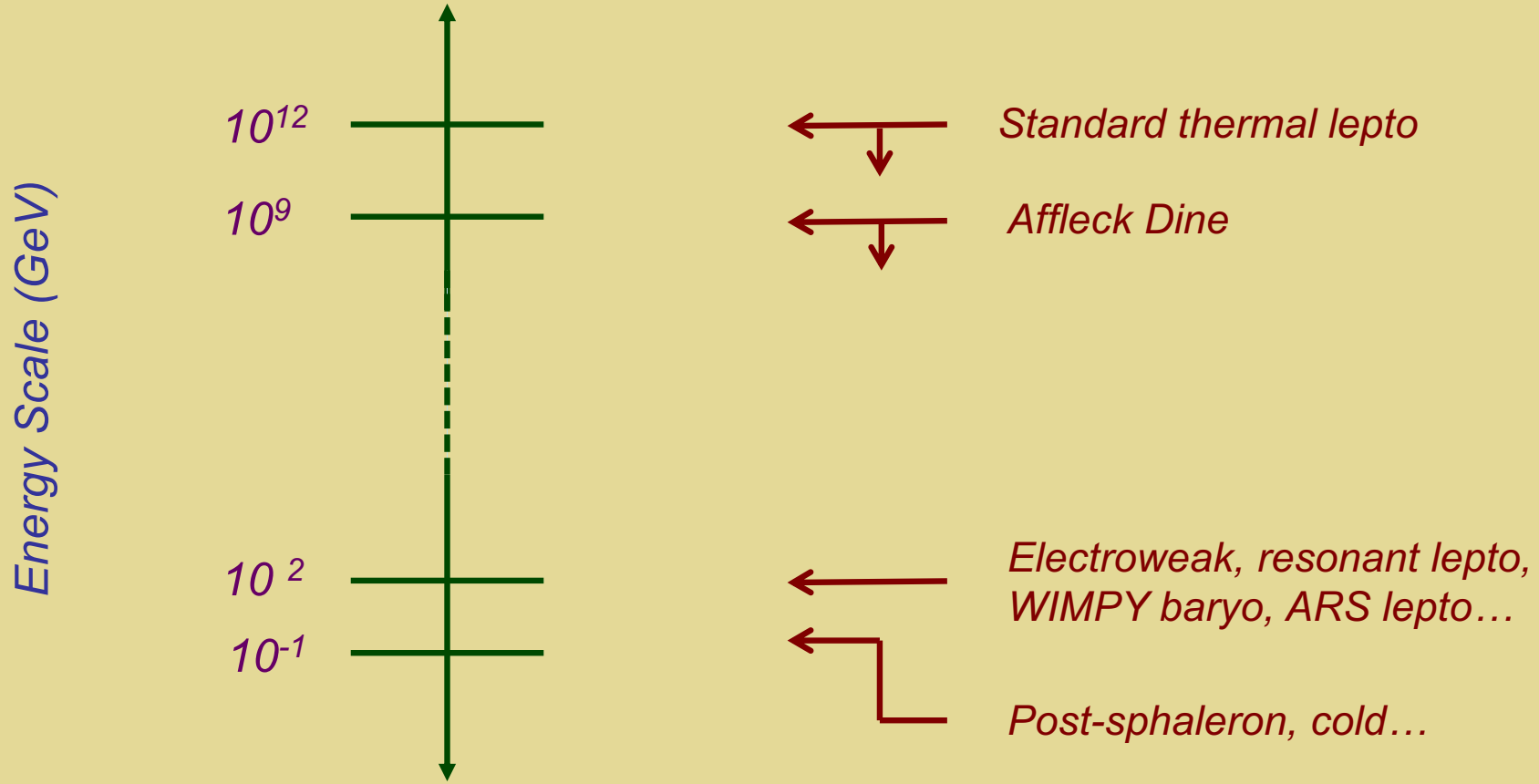
Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

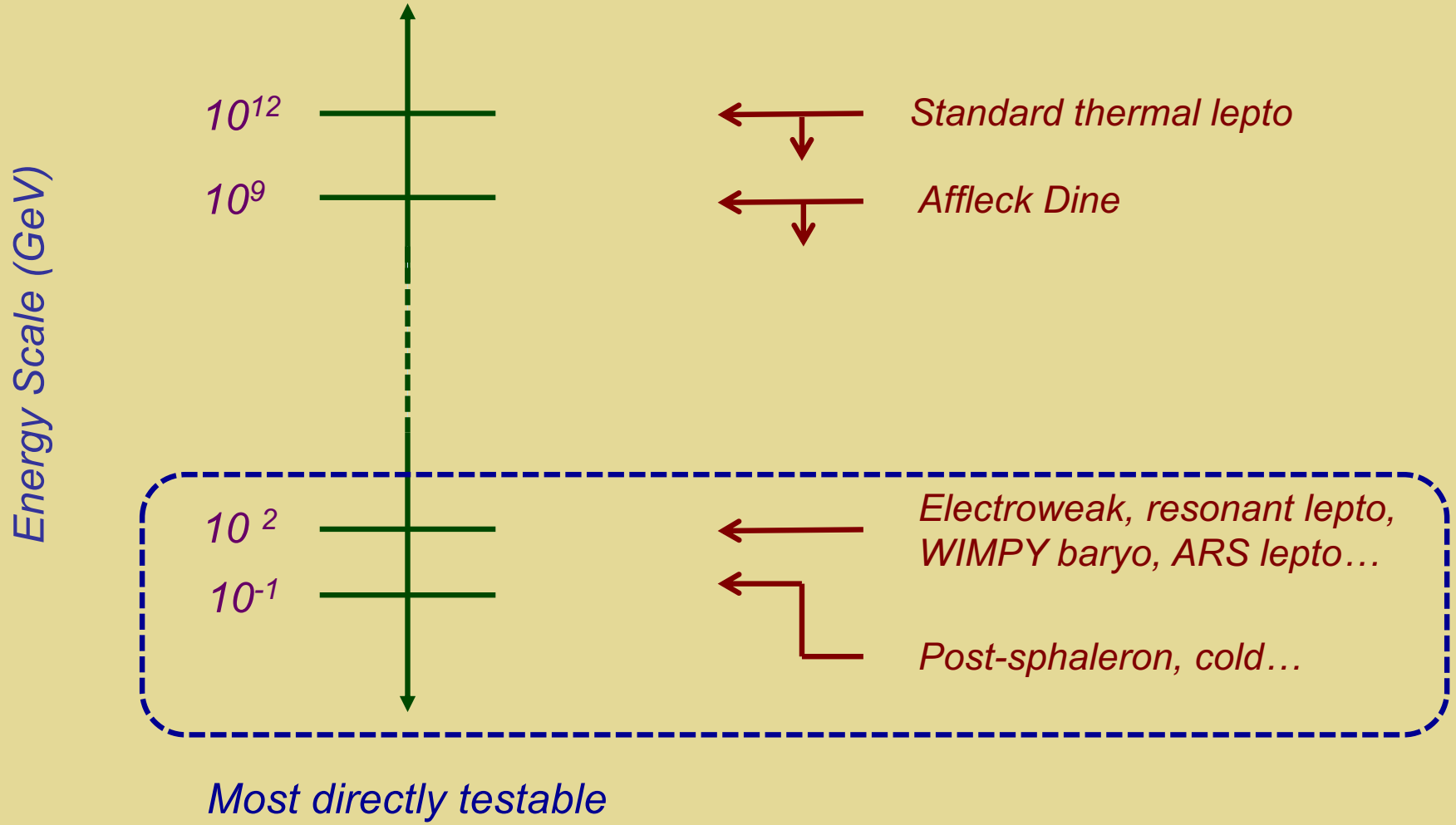
Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

This talk

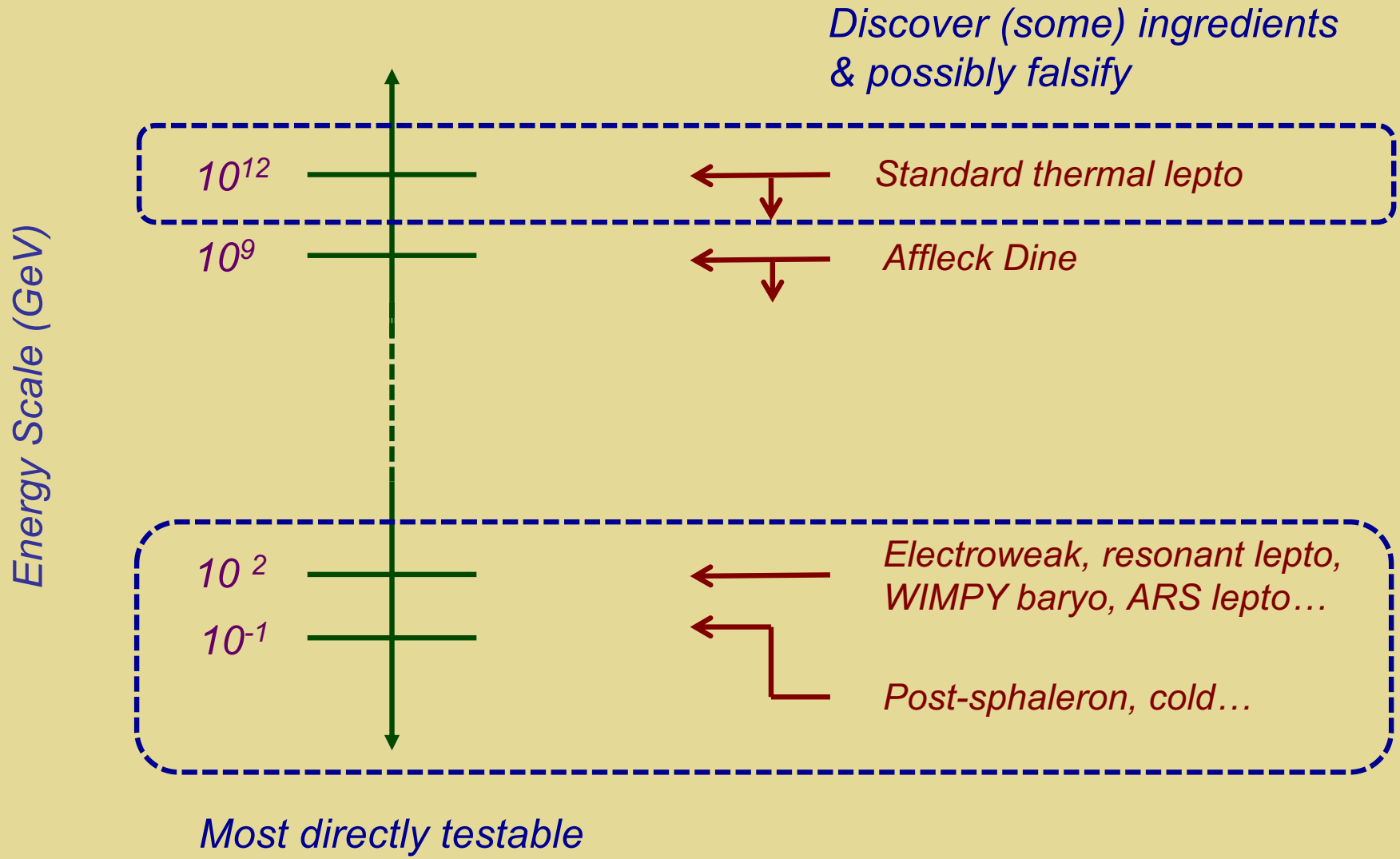
Baryogenesis Scenarios



Baryogenesis Scenarios



Baryogenesis Scenarios



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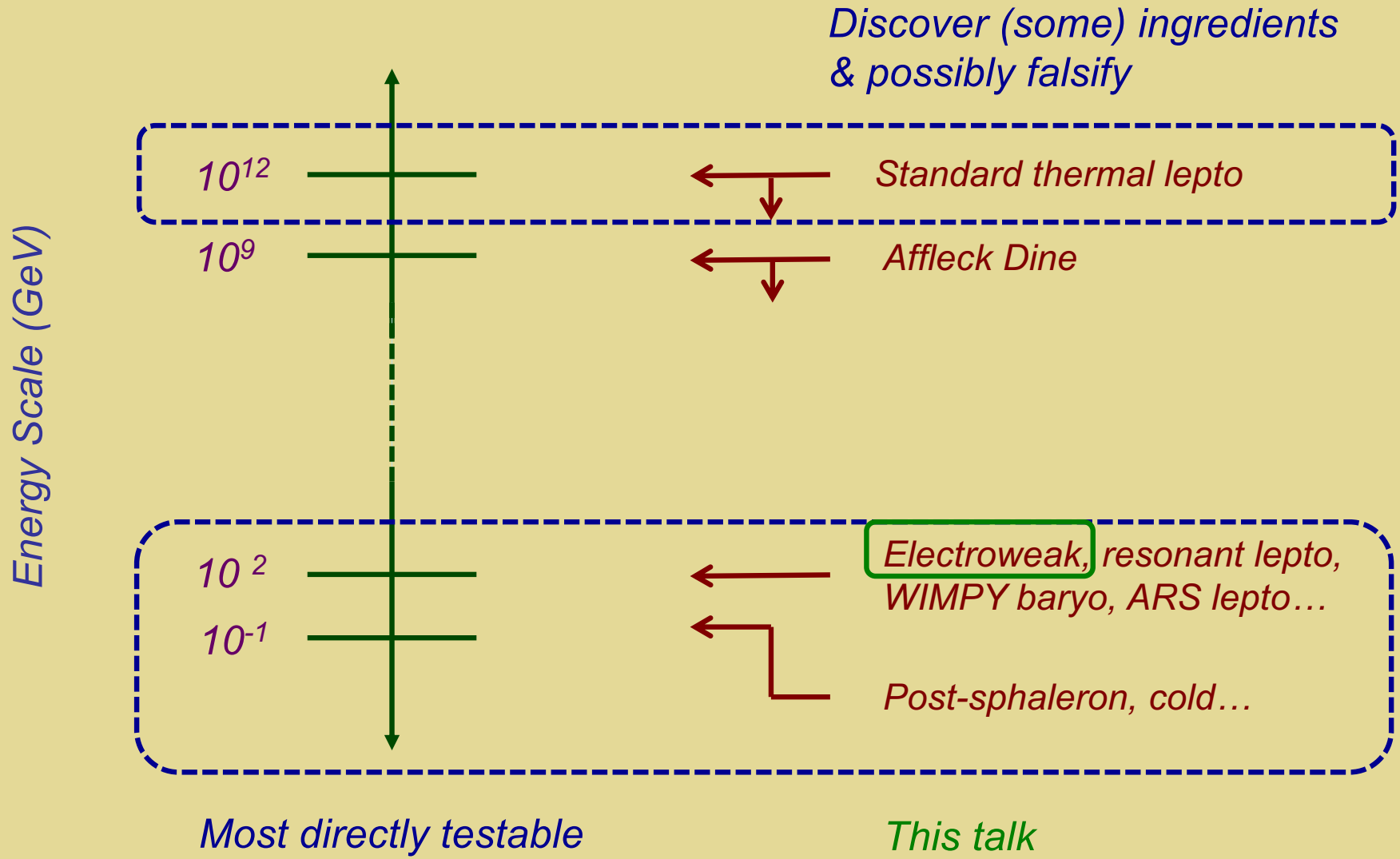
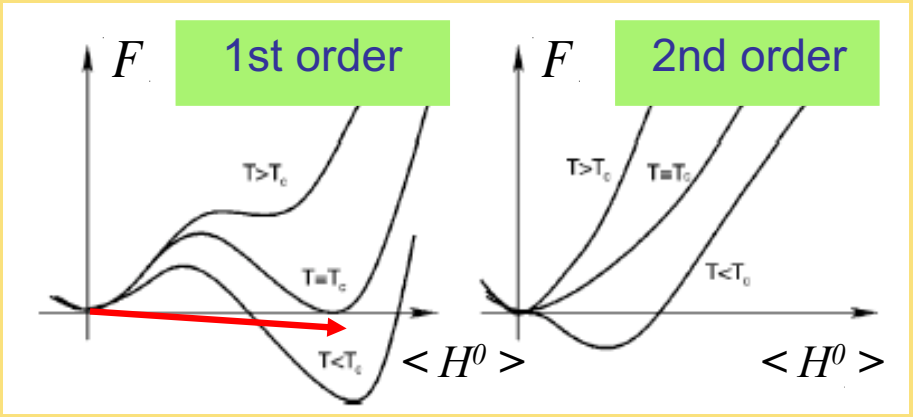


Electroweak Baryogenesis

Was Y_B generated in conjunction with electroweak symmetry-breaking?

II. EWB in a Nutshell

EW Phase Transition: More Higgses



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
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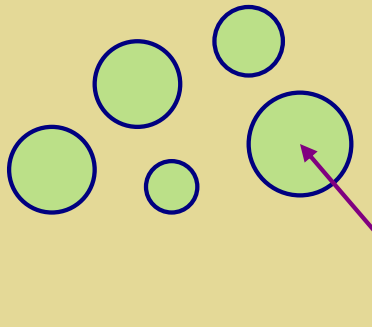
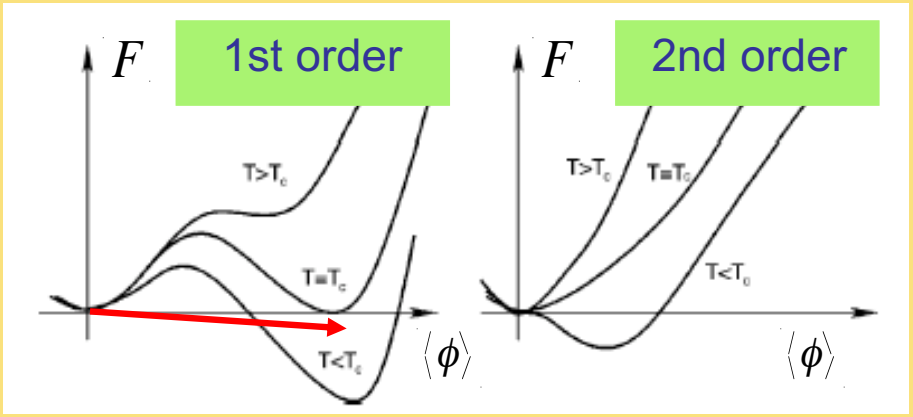
"Strong" *1st order EWPT*

Bubble nucleation



Cannot occur in the St'd Model: Higgs too heavy

EW Phase Transition: More Higgses & CPV

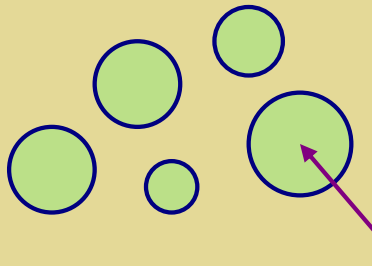


Increasing m_h →

← *New Higgses*

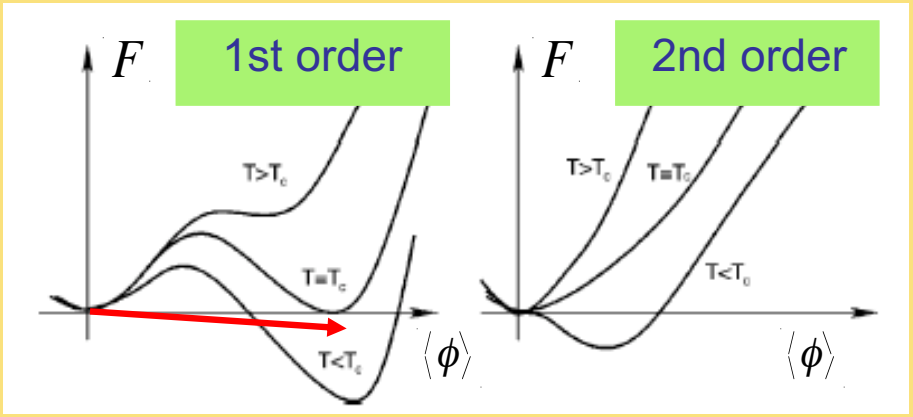
"Strong" **1st order EWPT**

Bubble nucleation



EWSB

EW Phase Transition: More Higgses & CPV



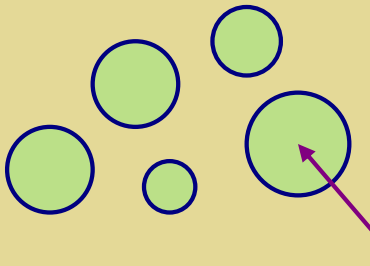
Increasing m_h →

← *New Higgses*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" **1st order EWPT**

Bubble nucleation



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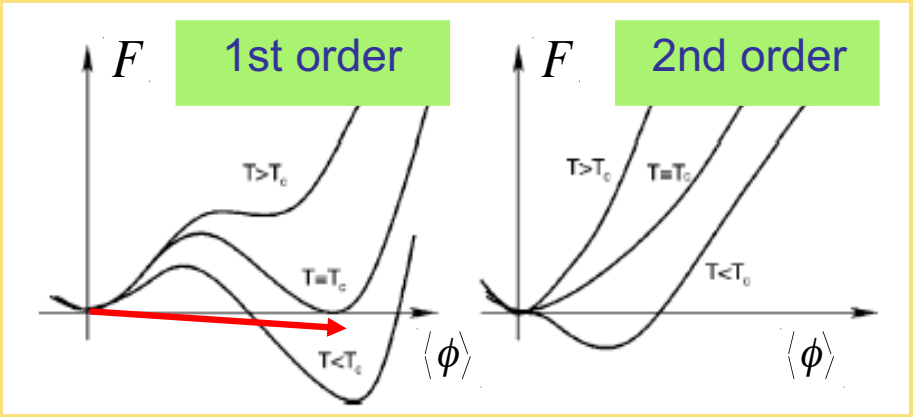

Increasing m_h →

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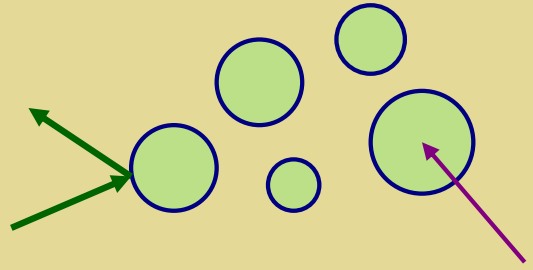
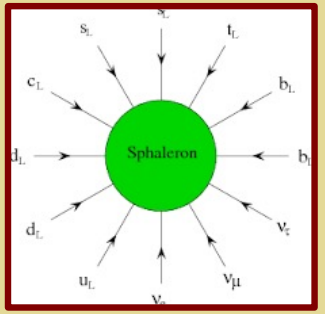
"Strong" **1st order EWPT** → *Bubble nucleation*



Y_B : CPV & EW sphalerons

EWSB



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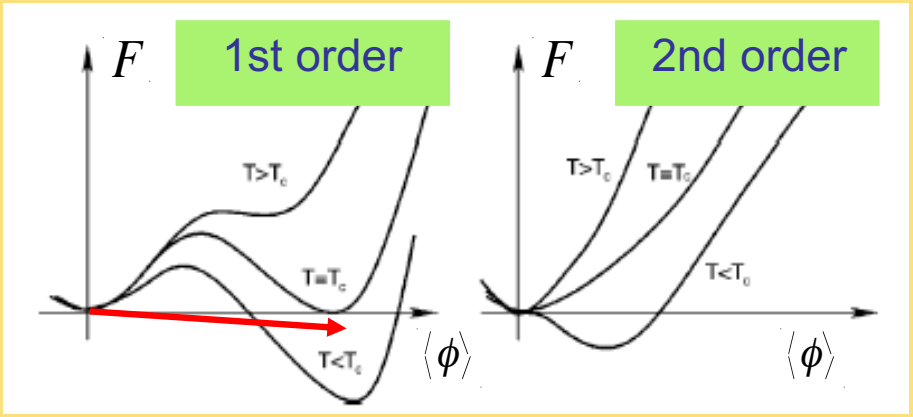

Increasing m_h →

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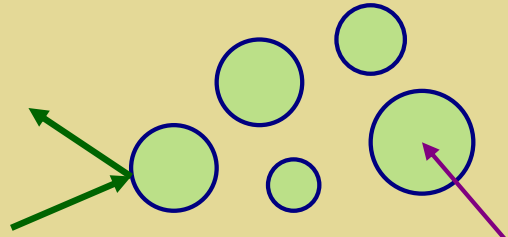
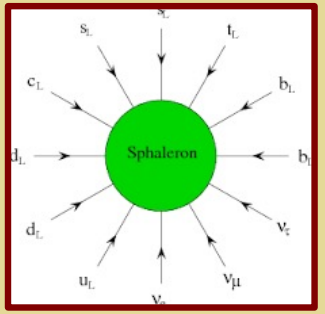
"Strong" **1st order EWPT** → *Bubble nucleation*

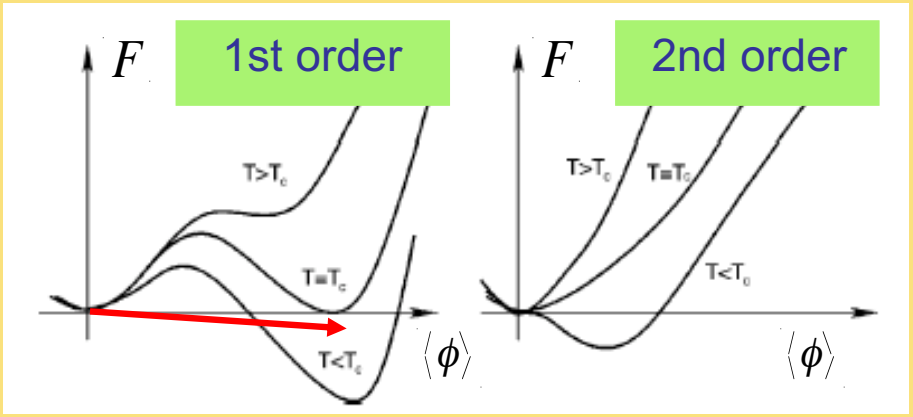


Y_B : CPV & EW sphalerons → **BSM**

EWSB



EW Phase Transition: New Scalars & CPV



Increasing m_h →

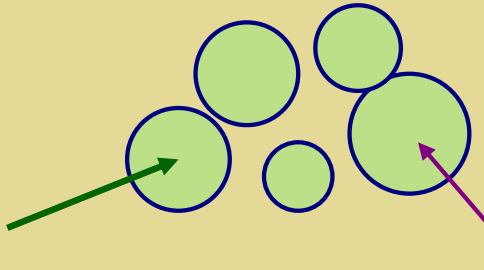
← *New Higgses*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" **1st order EWPT**

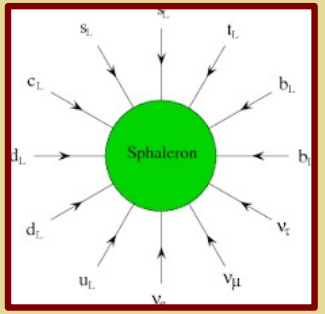
↓

Bubble nucleation

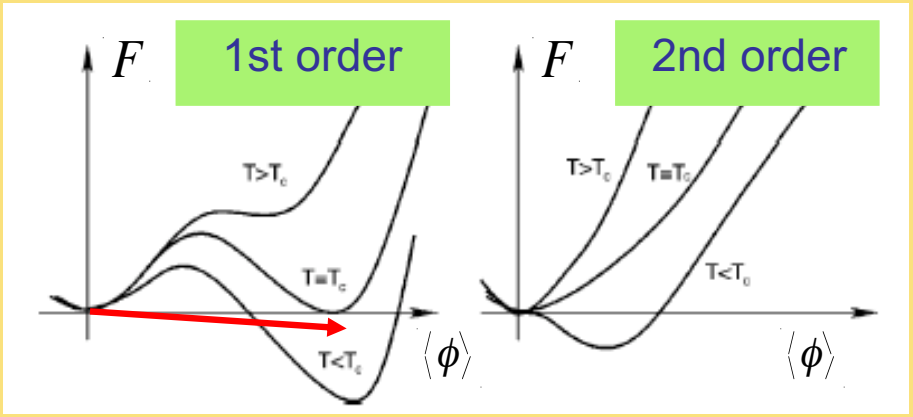


Y_B : diffuses into interiors

EWSB



EW Phase Transition: More Higgses & CPV



Increasing m_h →

← *New Higgses*

Baryogenesis
Gravity Waves
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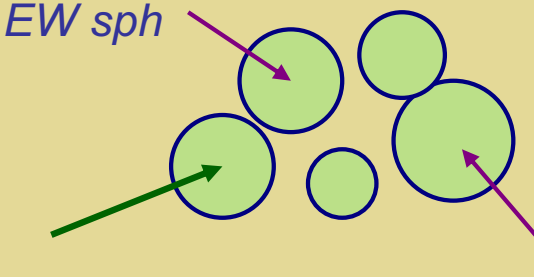
LHC Searches

"Strong" | *1st order EWPT*

Preserve $Y_B^{initial}$

Bubble nucleation

Quench EW sph



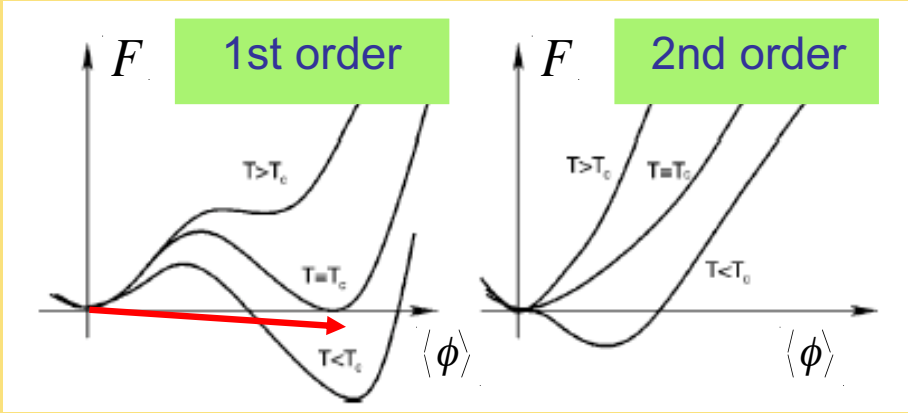
Y_B *: diffuses into interiors*

EWSB

IIIA. Electroweak Phase Transition

Conditions for Electroweak Baryogenesis ?

EW Phase Transition: St'd Model



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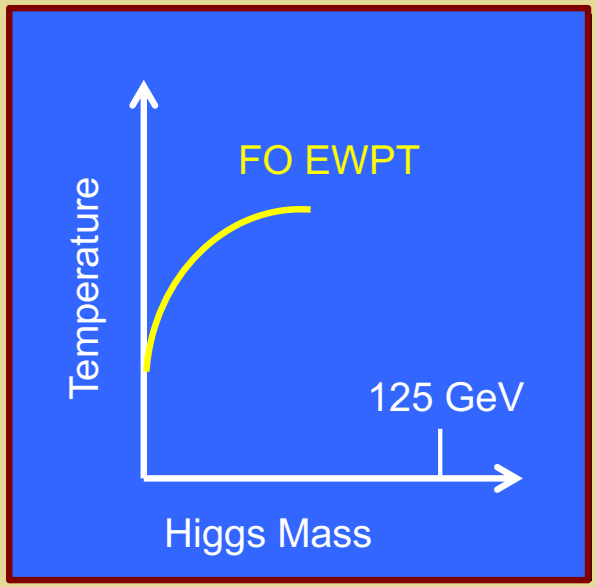
SM EW: Cross over transition

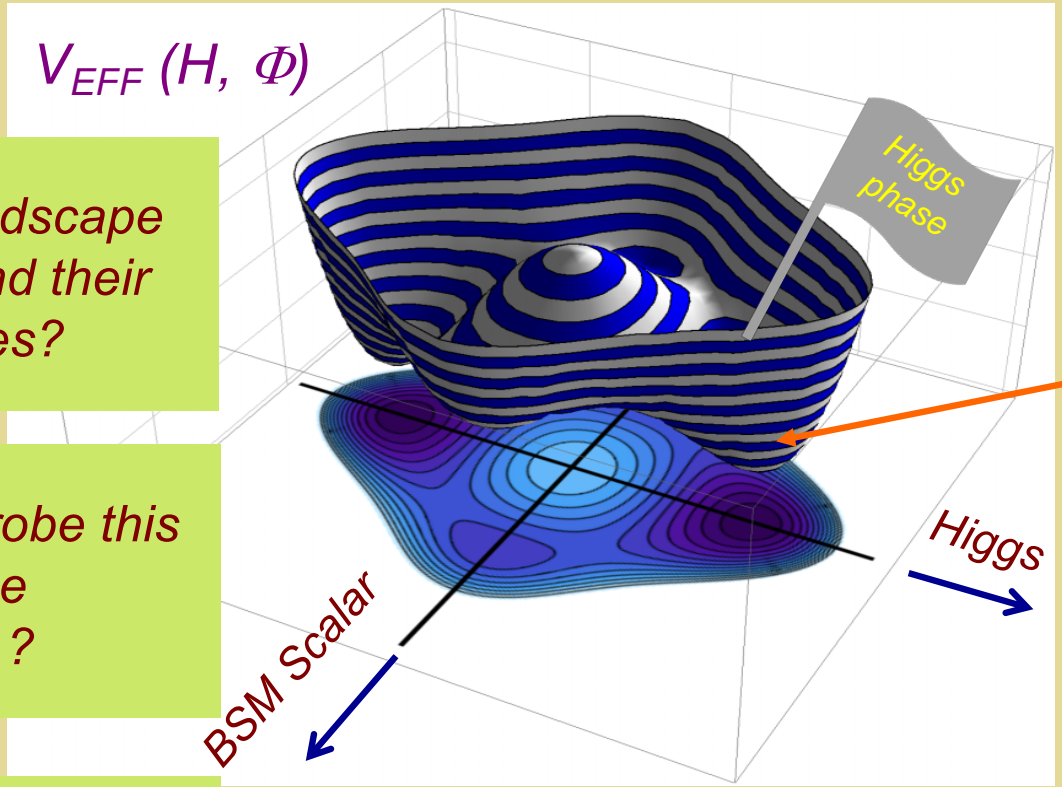


EW Phase Diagram

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

Was There an EW Phase Transition?

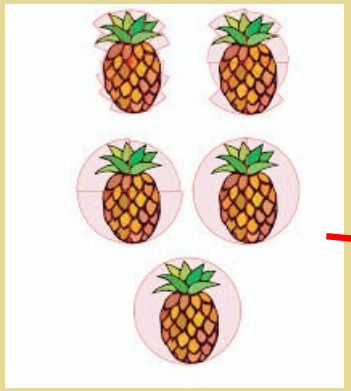
- *What is the landscape of potentials and their thermal histories?*
- *How can we probe this T > 0 landscape experimentally ?*
- *How reliably can we compute the thermodynamics ?*



n evolve differently as T evolves → ilities for symmetry breaking

Was There an EW Phase Transition?

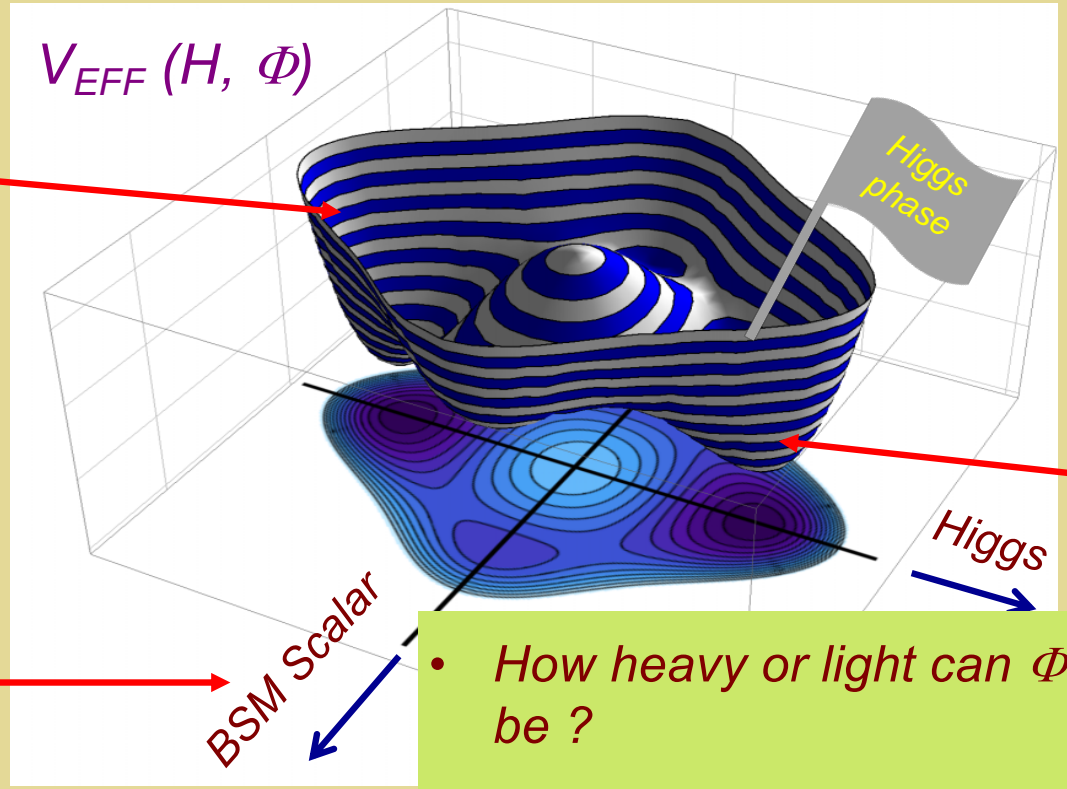
Bubble Collisions



Grav Radiation

Direct Production

BSM Higgs



Higgs precision tests

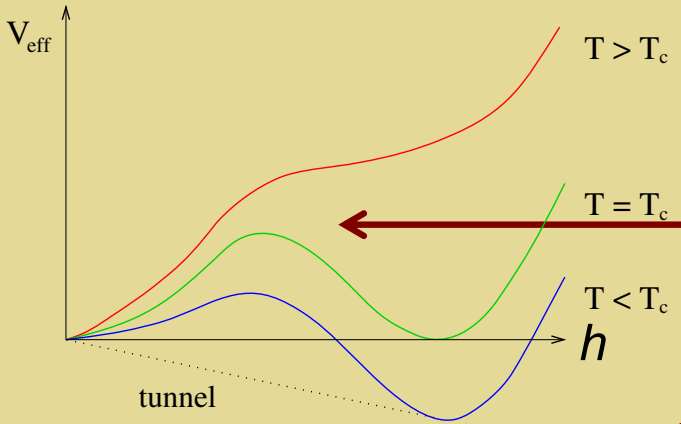
SM Higgs BSM Higgs

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

Extrema can evolv… rich possibilities fo… →

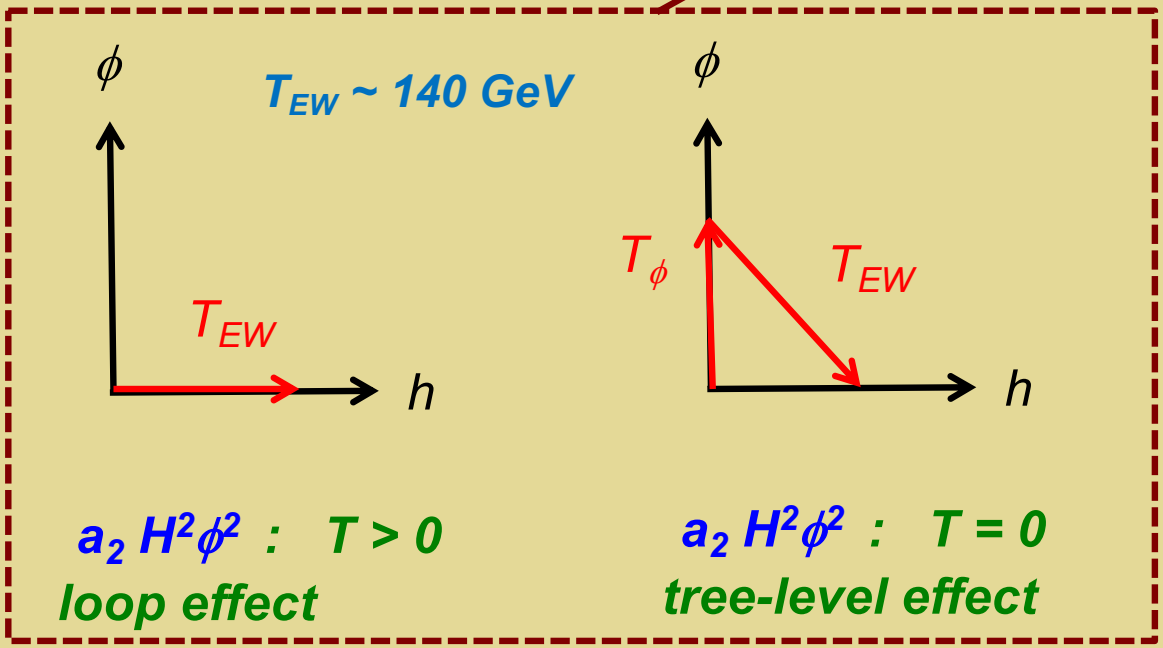
MJRM: 1912.07189

First Order EWPT from BSM Physics



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

Collider Target



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

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

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

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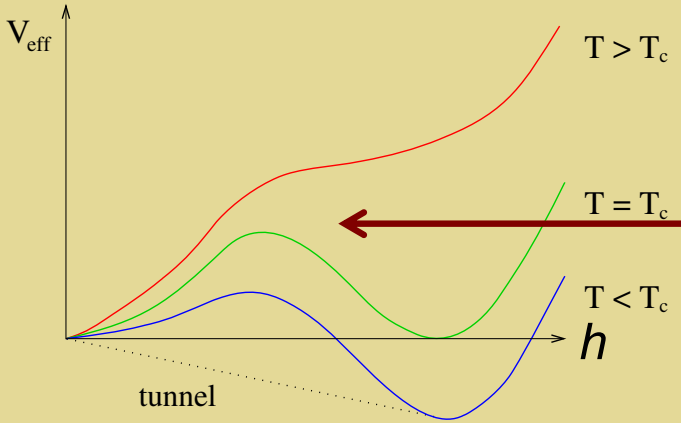
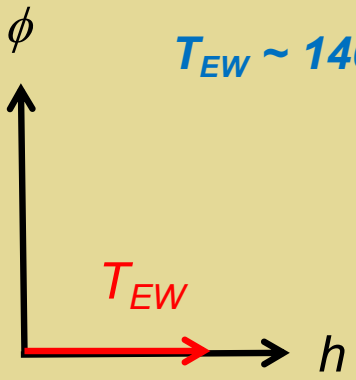
First Order EWPT from BSM Physics



$|\sin\theta| \gtrsim 0.01$ $|\Delta\lambda/\lambda| \gtrsim 0.003$

Higgs – ϕ^0 Mixing

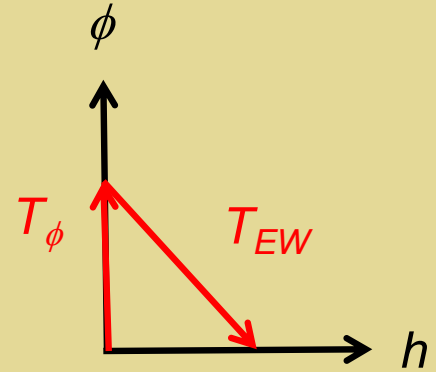
Collider Target



T_{EW} ~ 140 GeV

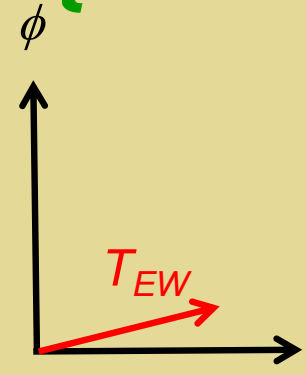
$a_2 H^2\phi^2$: T > 0

loop effect



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

tree-level effect

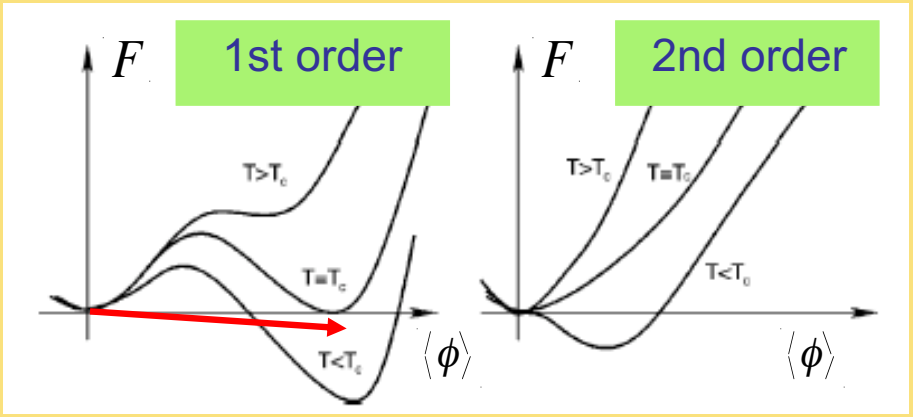


$a_1 H^2\phi$: T = 0

tree-level effect

IIIB. CPV: Baryon Asymmetry & EDMs

EW Phase Transition: New Scalars & CPV

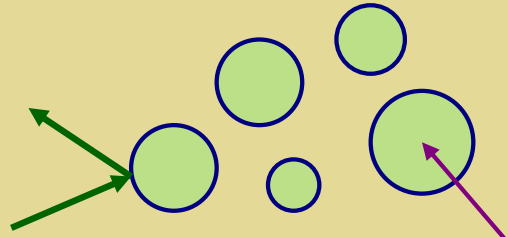


Increasing m_h →

← *New scalars*

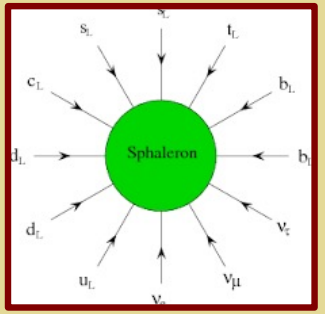
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" **1st order EWPT** → *Bubble nucleation*



Y_B : CPV & EW sphalerons → **BSM**

EWSB



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

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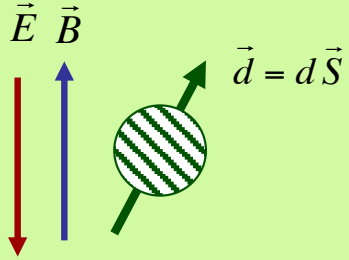
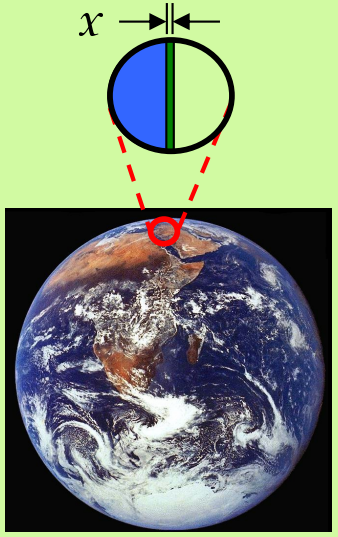


$$\nu_{EDM} = -\frac{d\vec{S}\cdot(-\vec{E})}{h}$$

T-odd , CP-odd by CPT theorem



d_n: $x < 0.25$ mm

C-Y Liu

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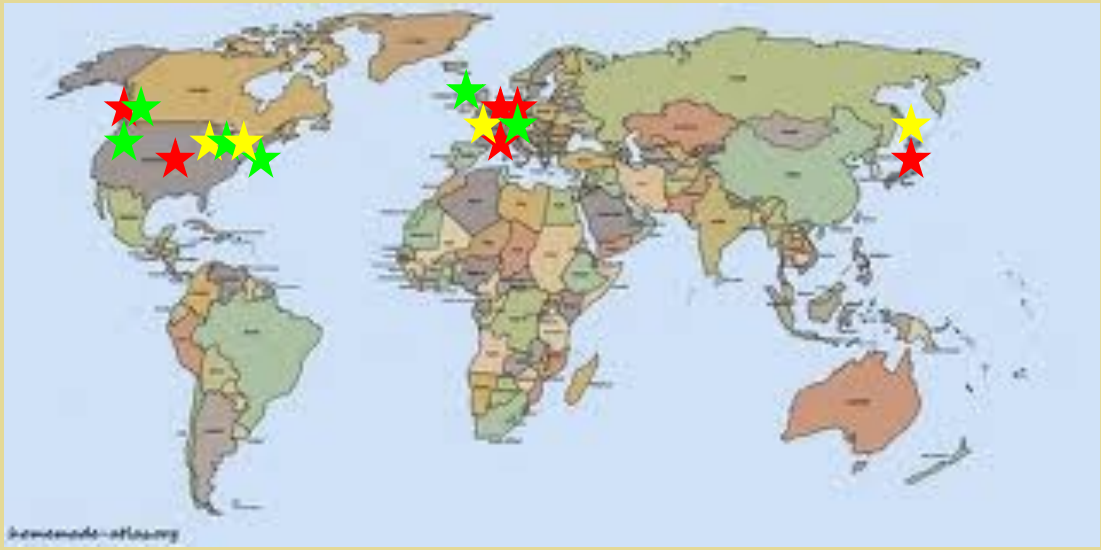

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

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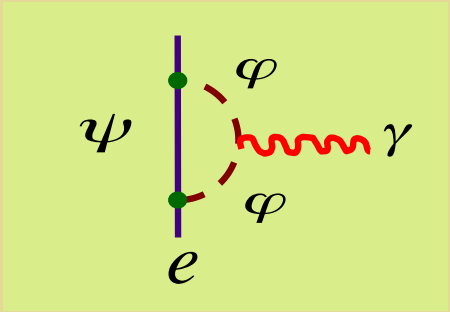
Mass Scale Sensitivity



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

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

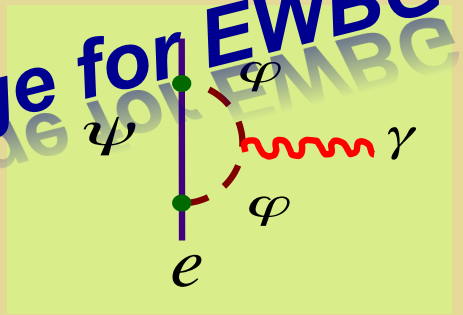
EDMs: New CPV?

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

Mass Scale Sensitivity

Challenge for EWBG



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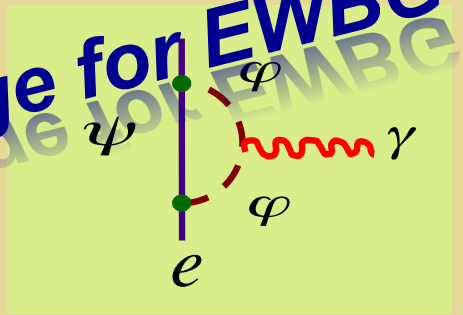
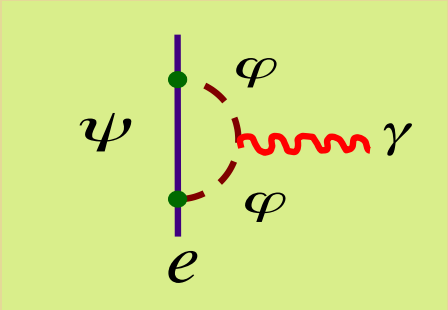
Mass Scale Sensitivity

Challenge for EWBG



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

EDMs & EWBG: MSSM & Beyond



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

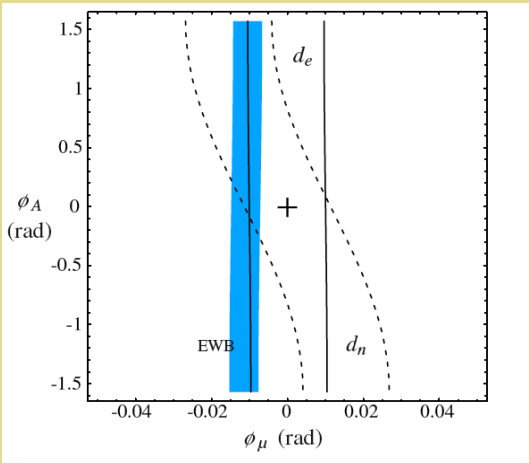
$M < 500$ GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

15+ years ago…

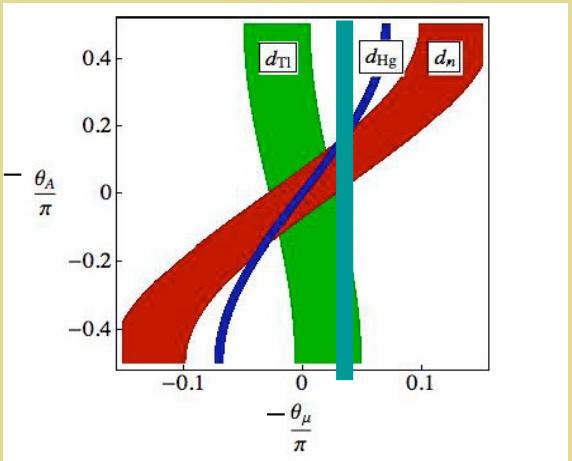
Universal gaugino phases

$Arg(\mu M_i b^*) =$

$Arg(\mu M_j b^*)$



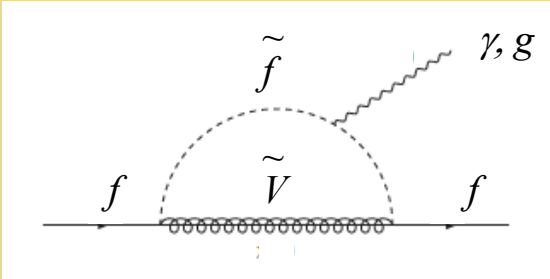
Cirigliano, R-M, Tulin, Lee '06



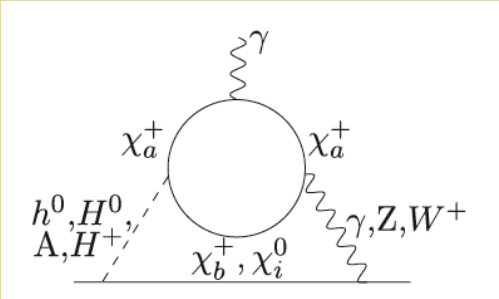
Ritz CIPANP 09 +

Cirigliano, R-M, Tulin, Lee '06

EDMs & EWBG: MSSM & Beyond

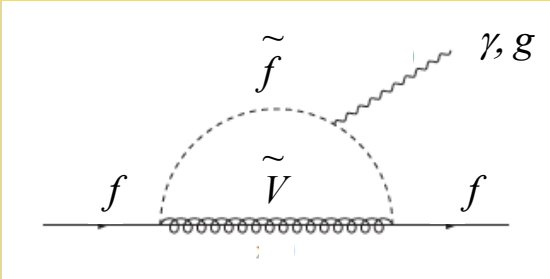


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

EDMs & EWBG: MSSM & Beyond



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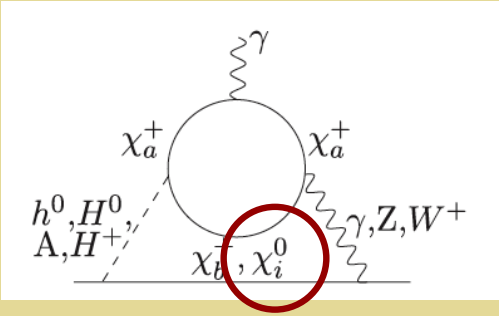
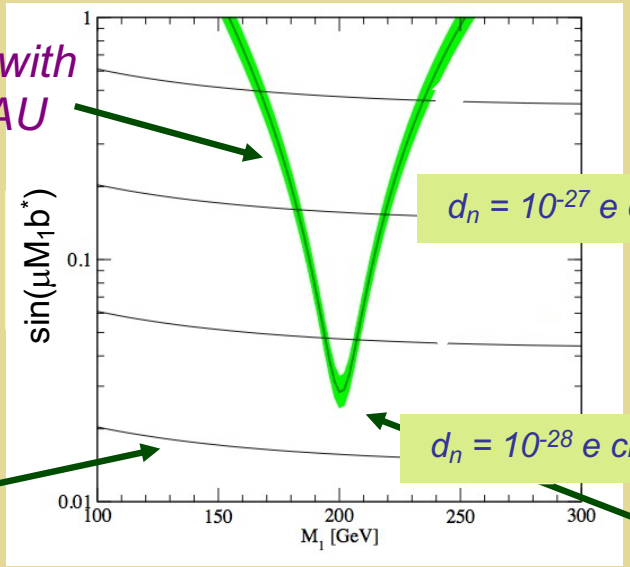


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU

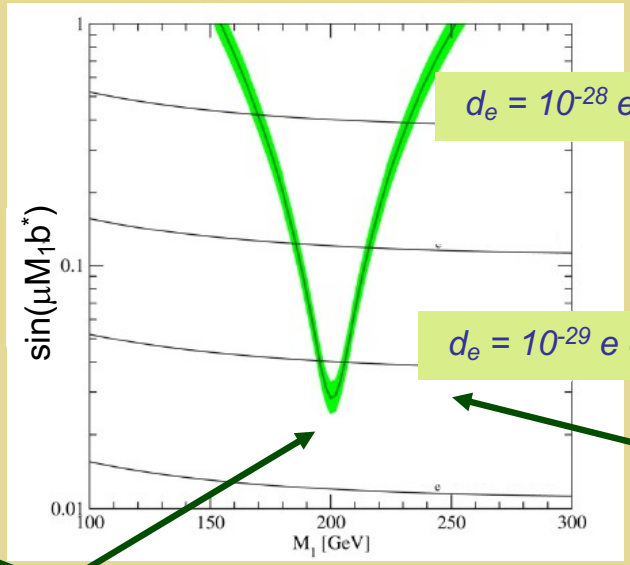


d_n = 10^{-27} e cm

d_n = 10^{-28} e cm

Next gen d_n

Li, Profumo, RM '09-'10



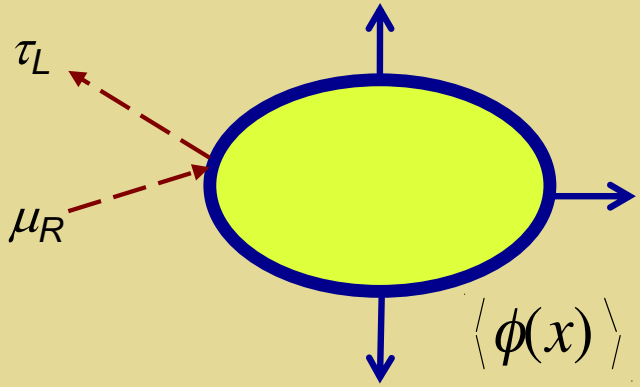
d_e = 10^{-28} e cm

d_e = 10^{-29} e cm

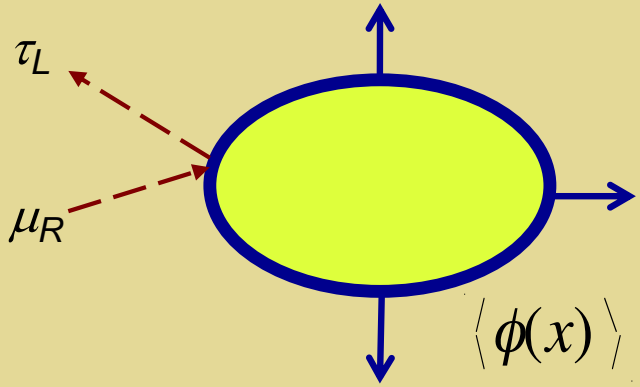
HfF^+ d_e

Compressed spectrum

Flavored EW Baryogenesis



Flavored EW Baryogenesis



Flavor basis (high T)

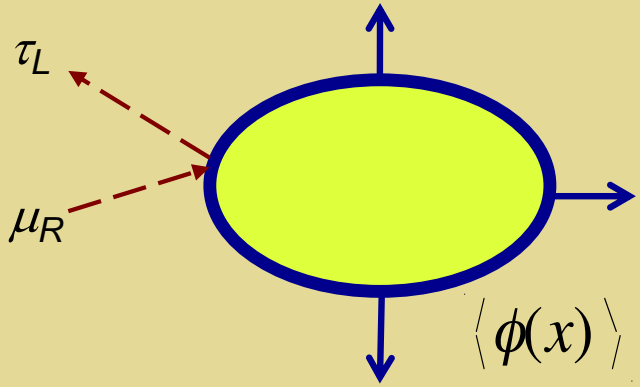
$$\mathscr{L}^{\text{Lepton}}_{\text{Yukawa}} = -\overline{E^i_L}\left[(Y^E_1)_{ij}\Phi_1 + (Y^E_2)_{ij}\Phi_2\right] e^j_R + h.c.$$

Mass basis (T=0)

$$\frac{m_f}{v}\kappa_\tau\left(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau\right)h$$

Guo, Li, Liu, R-M, Shu 1609.09849

Flavored EW Baryogenesis



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Guo, Li, Liu, R-M, Shu 1609.09849

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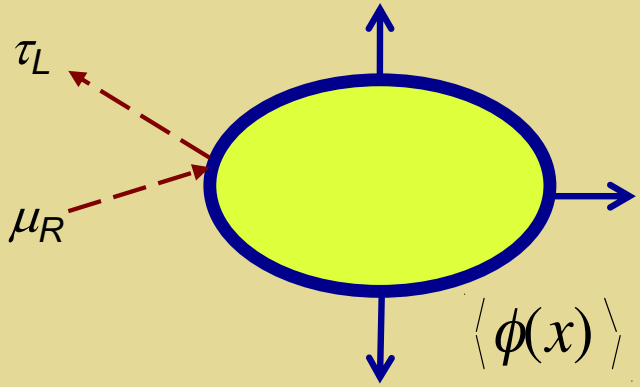

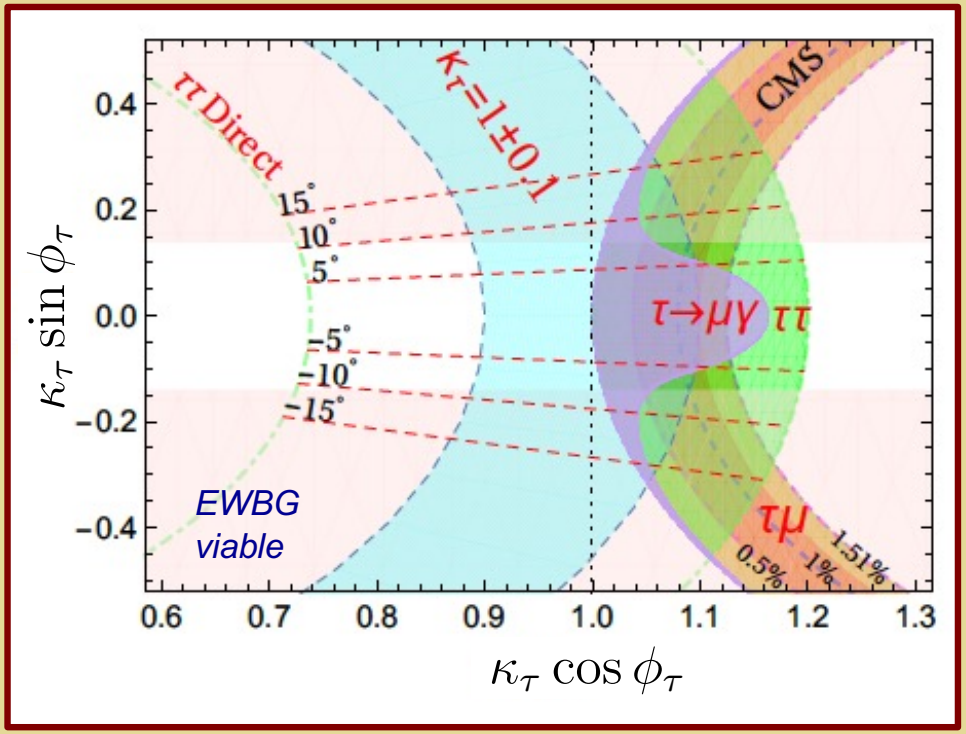

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Guo, Li, Liu, R-M, Shu 1609.09849

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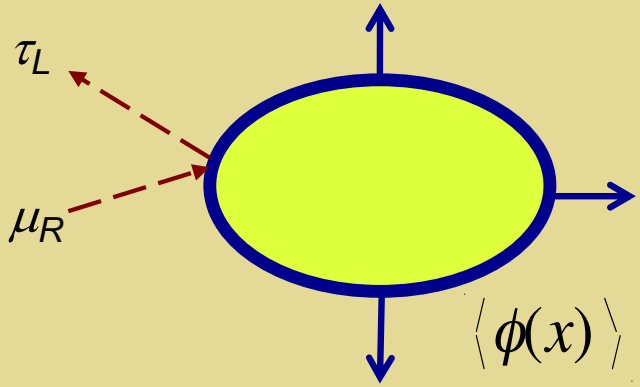

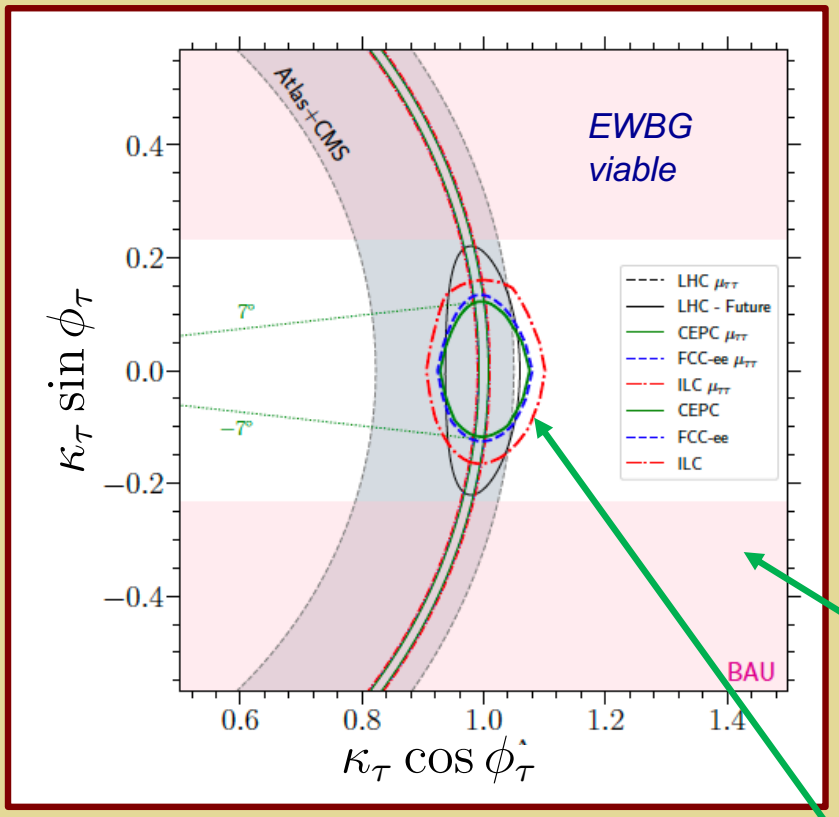

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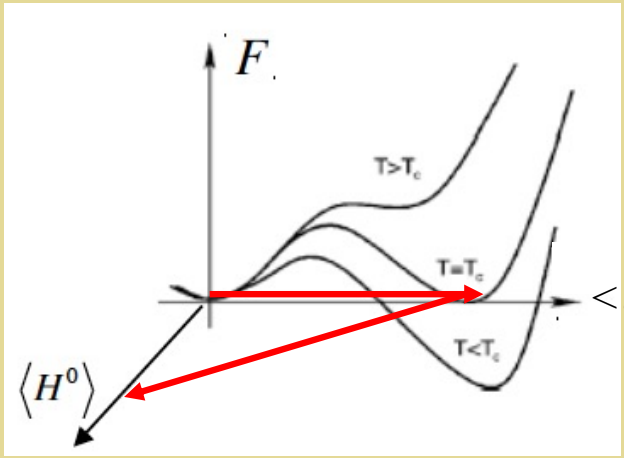
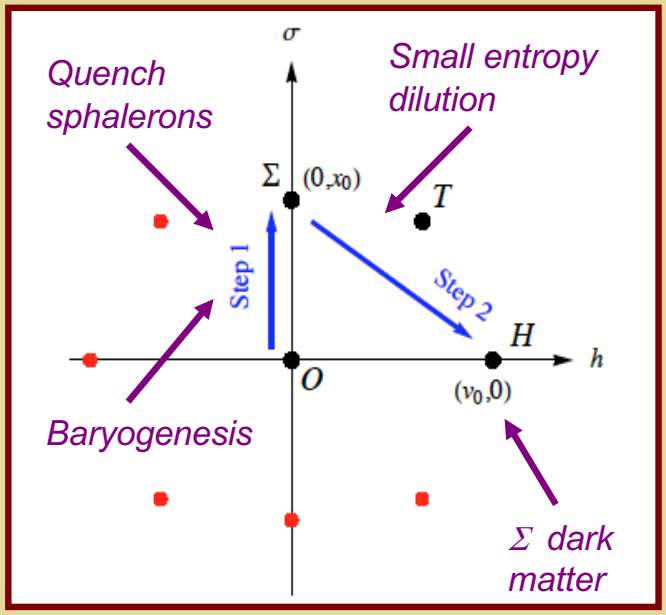
Guo, Li, Liu, R-M, Shu 1609.09849

Ge, Li, Pasquini, R-M, Shu 2012.13922

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*

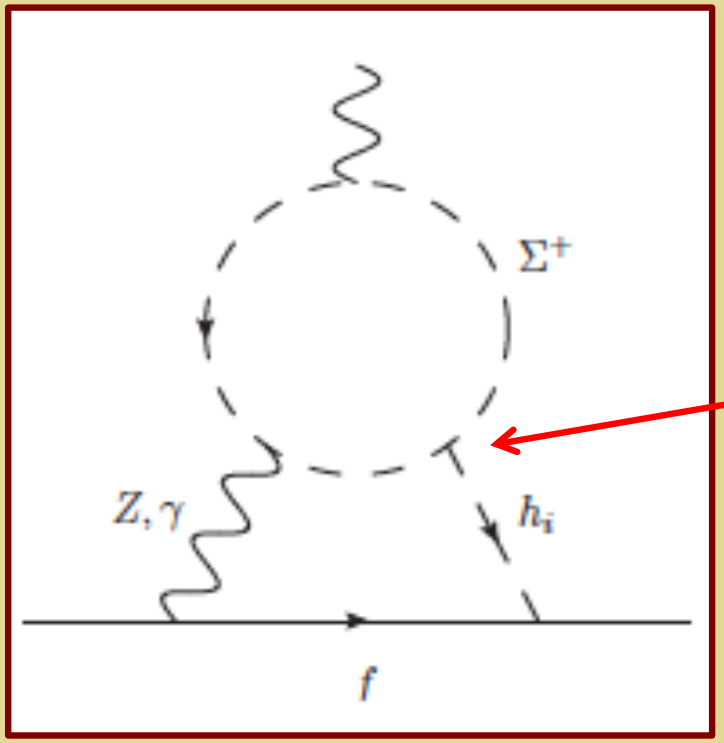
(SUSY: "TNMSSM", Coriano…)

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*

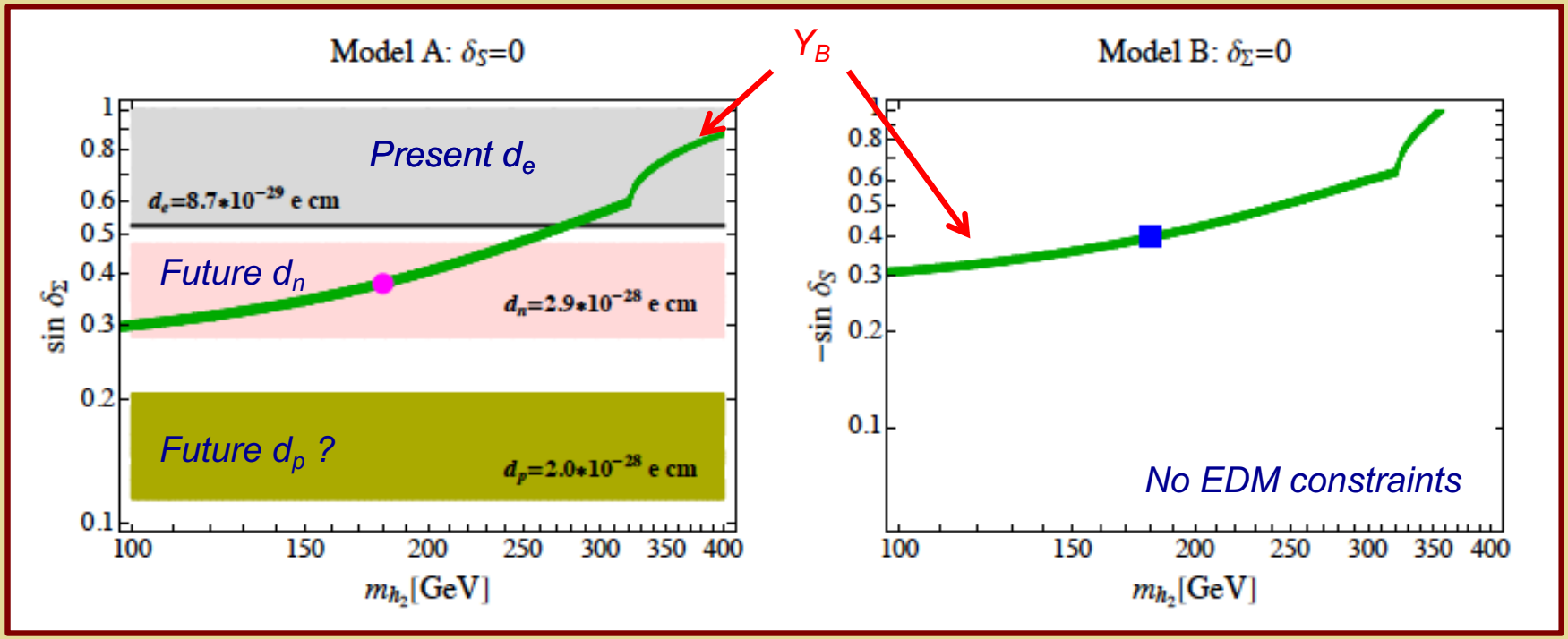
δ_S : *Singlet phase*

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

Inoue, Ovanesyan, R-M: 1508.05404

Two-Step EW Baryogenesis & EDMs

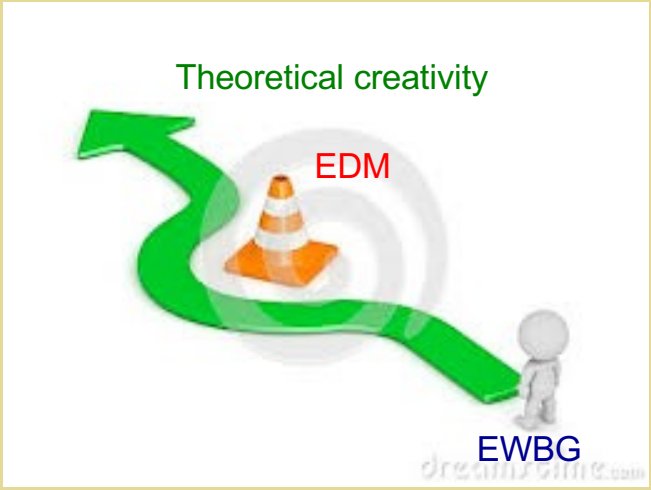
Two cases: (A) $\delta_S = 0$ (B) $\delta_\Sigma = 0$



Triplet phase **Singlet phase**

Inoue, Ovanesyan, R-M: 1508.05404

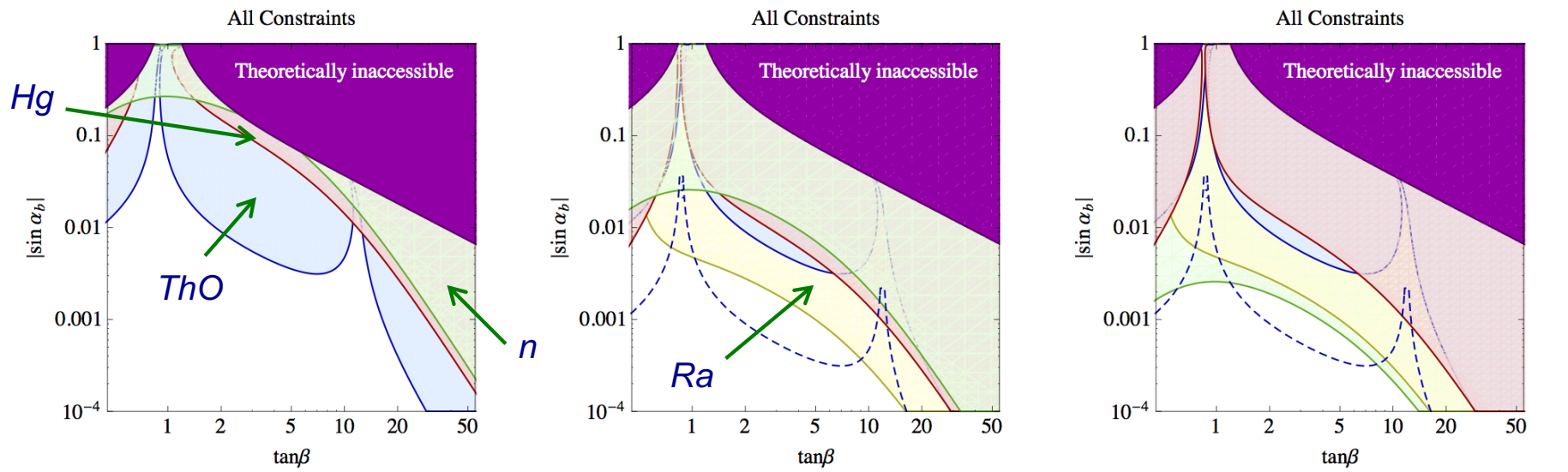
CPV for EWBG



2HDM CPV : EDMs

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ *= 0 for simplicity*



2014

New HfF+

Present & Future:

- d_n x 0.1
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra) [10^{-27} e cm]

Future:

- d_n x 0.01
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra)

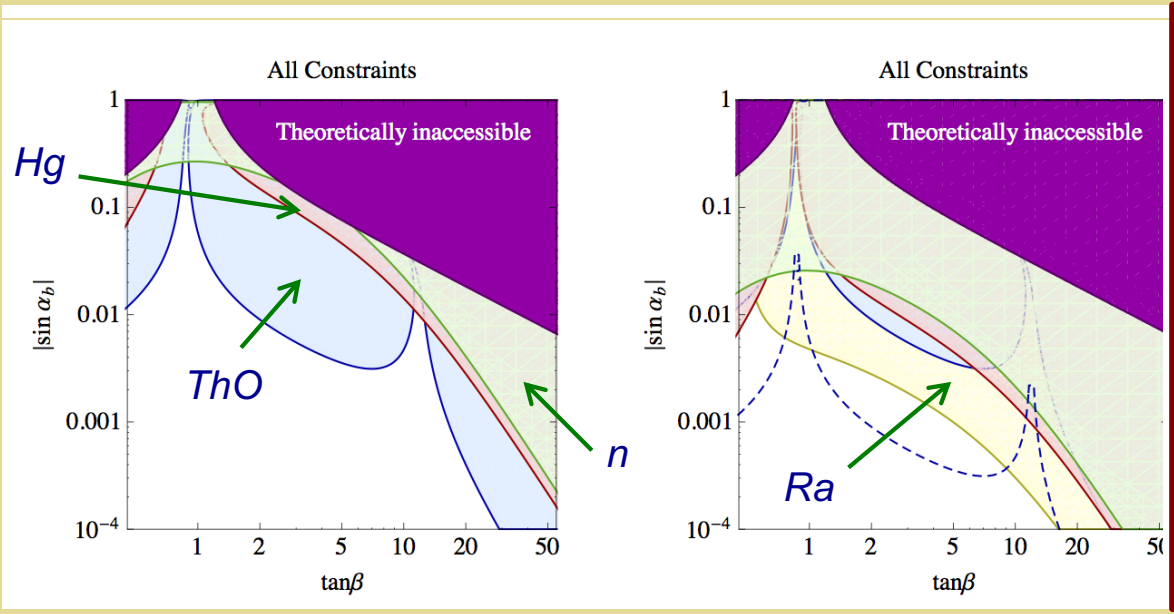
sin α_b : CPV scalar mixing

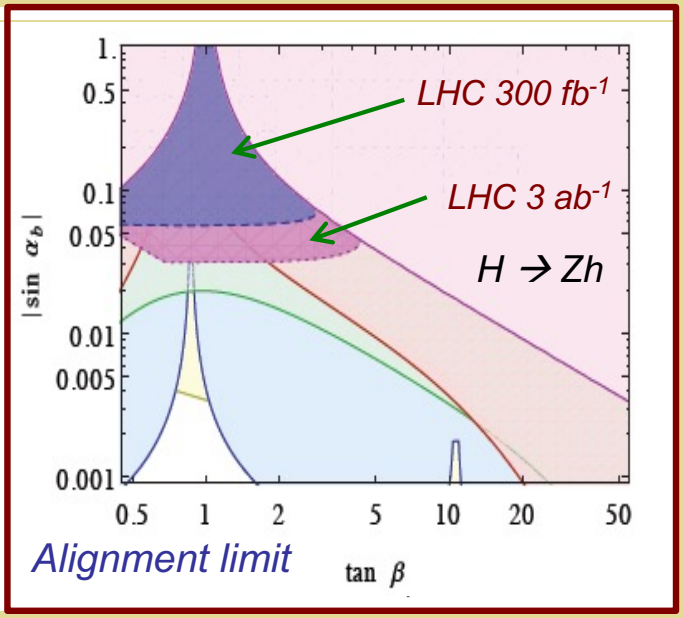
Inoue, R-M, Zhang: 1403.4257

2HDM CPV : EDMs & LHC

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity





Chen, Li, R-M: 1708.00435

Present → *New HfF+*

sin α_b : CPV scalar mixing

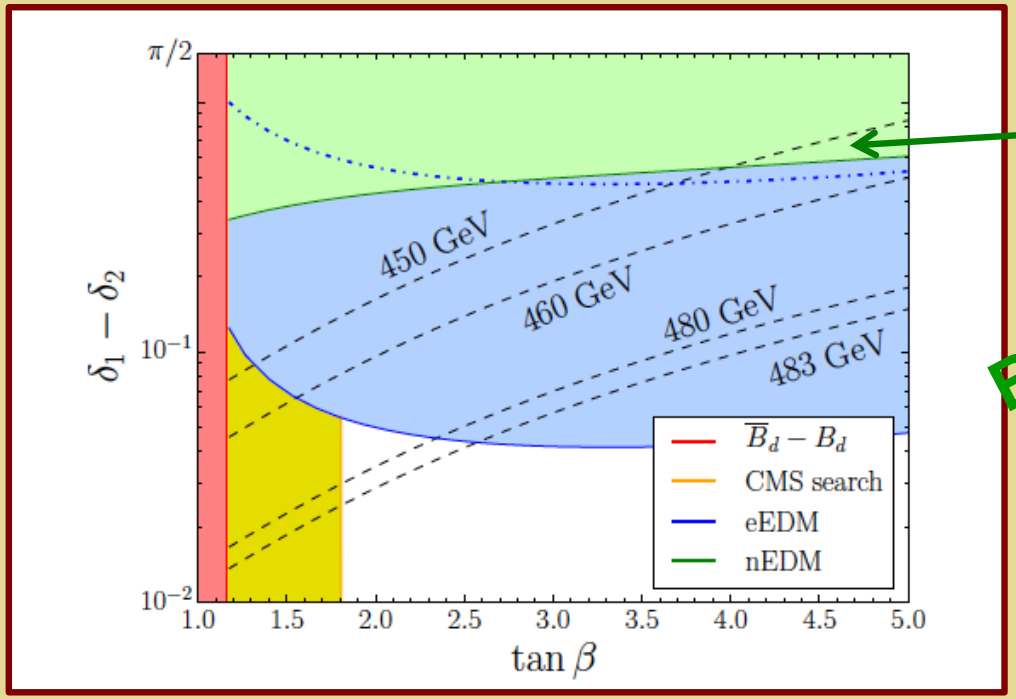
Present & Future:	*Future:*
d_n x 0.1	d_n x 0.01
d_A(Hg) x 0.1	d_A(Hg) x 0.1
d_{ThO} x 0.1	d_{ThO} x 0.1
d_A(Ra) [10^{-27} e cm]	d_A(Ra)

Inoue, R-M, Zhang: 1403.4257

2HDM CPV & EWBG

2HDM CPV: Source for EWBG?

Dorsch et al, 1611.05874



EWBG viable

But new transport theory → stay tuned…

$\alpha_b \propto \delta_1 - \delta_2$

IV. Outlook

Questions for this Workshop

- *What are the most interesting probes of BSM CPV for the LHC and beyond ?*
- *How do these collider probes complement EDM searches ?*
- *Which probes provide tests of BSM CPV needed for electroweak baryogenesis and other EW → TeV scale baryogenesis scenarios ?*

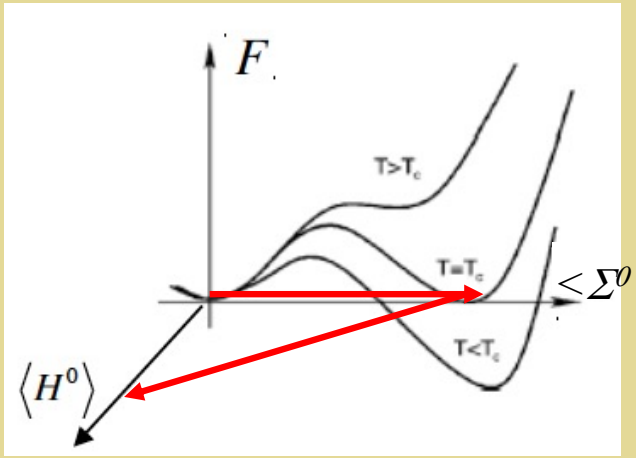
Key Themes

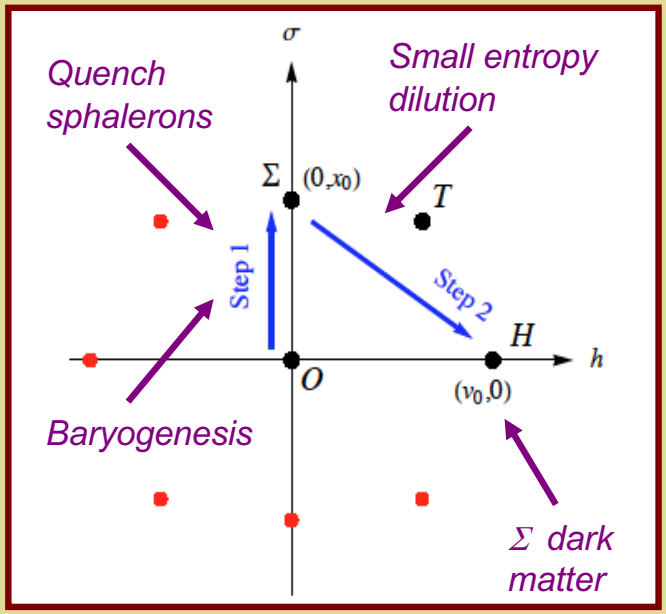
- *The experimental discovery of BSM CPV at the EW → TeV scale could hold the key to explaining the cosmic matter-antimatter asymmetry*
- *Electroweak baryogenesis (EWBG) connects this CPV to the origin of elementary particle masses through EW symmetry breaking*
- *The ingredients for EWBG are experimentally accessible through a combination of low-energy symmetry tests, collider searches, and GW probes*
- *An exciting opportunity exists for inter-frontier synergy in the quest to pursue this quest*

谢谢！

Back Up Slides

General Considerations

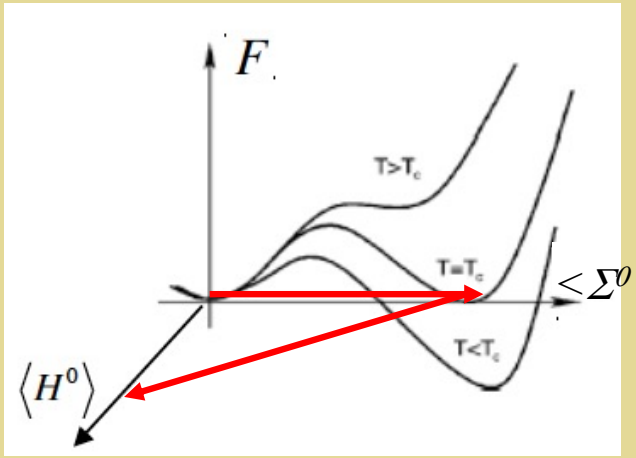


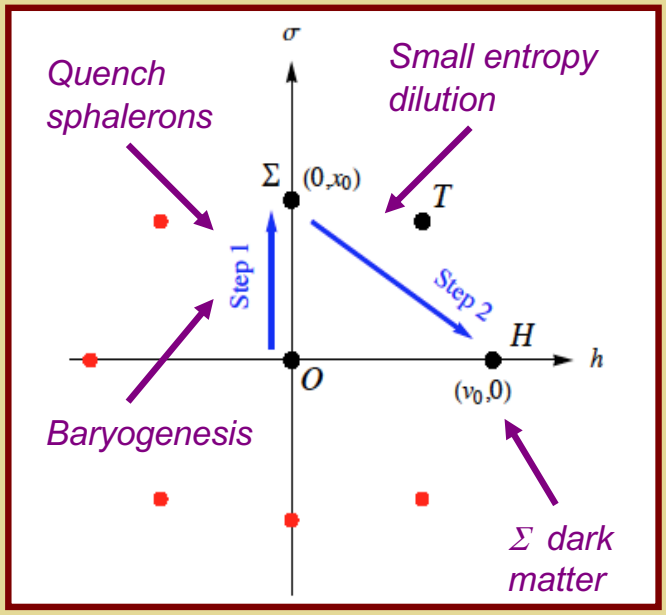


$\Sigma \rightarrow$ New sector: set of BSM fields ϕ_j, including at least one that breaks EWSB at T > 0 during first step

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

General Considerations





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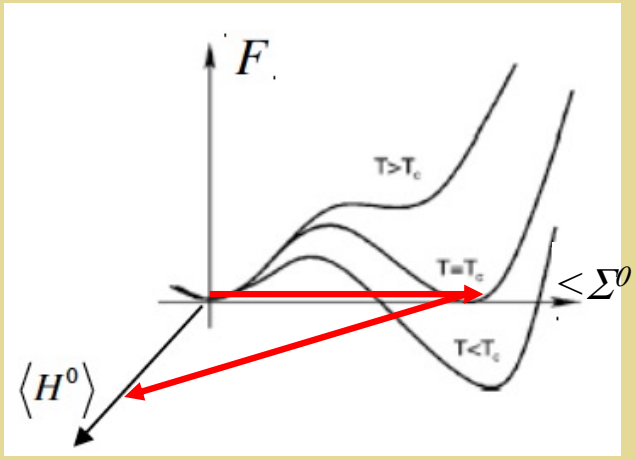
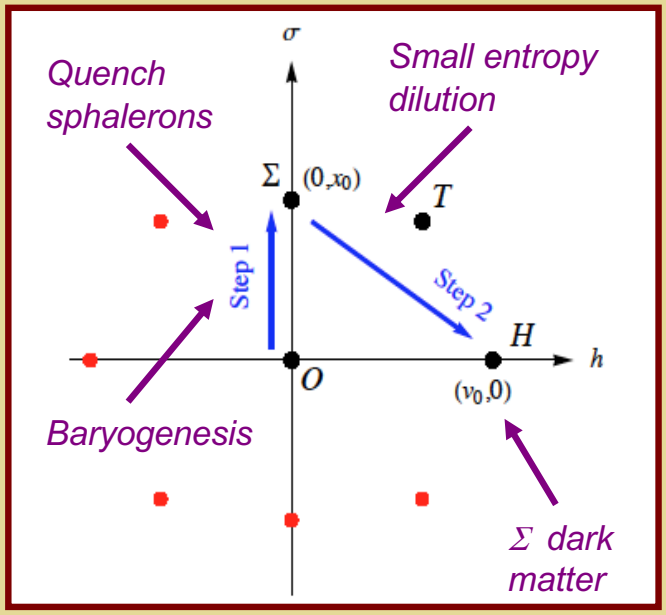
H → Set of "SM" fields, including at least one that breaks EWSB at during second step & persists to T = 0 (e.g., single H, 2HDM…)

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

General Considerations

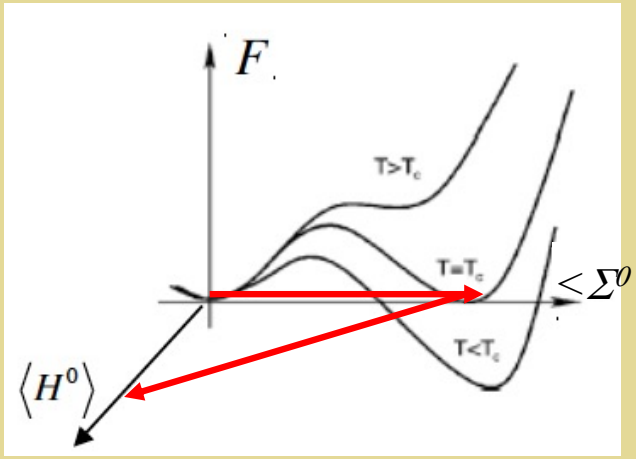


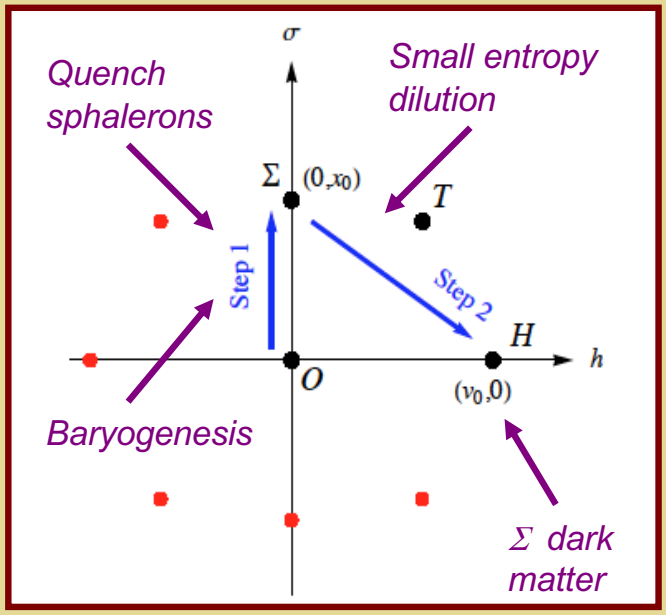


$\Sigma \rightarrow$ New sector: set of BSM fields ϕ_j, including at least one that breaks EWSB at T > 0 during first step

- *New sector contains additional LH fermions that contribute to the B+L anomaly: CPV interactions with $\phi_j \rightarrow n_L$*

General Considerations





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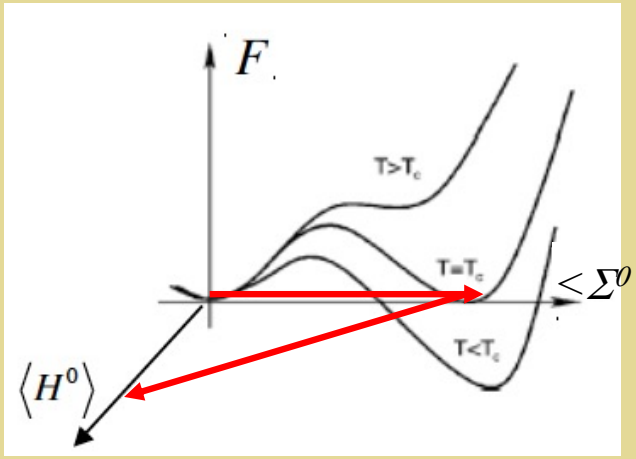

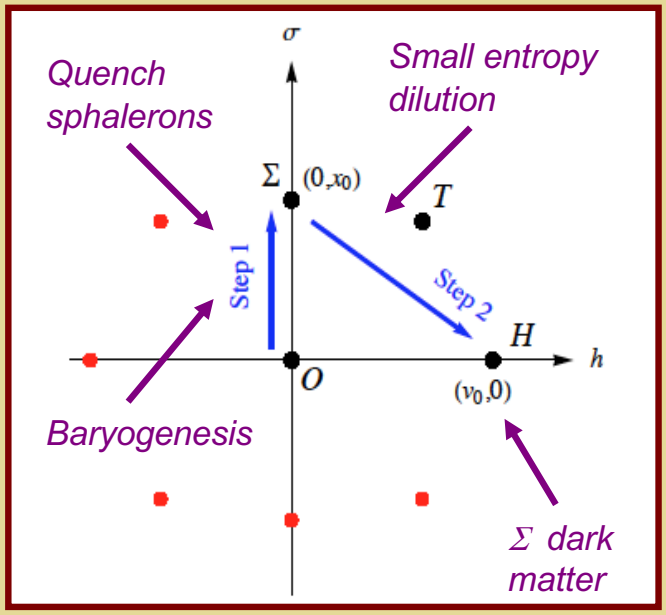

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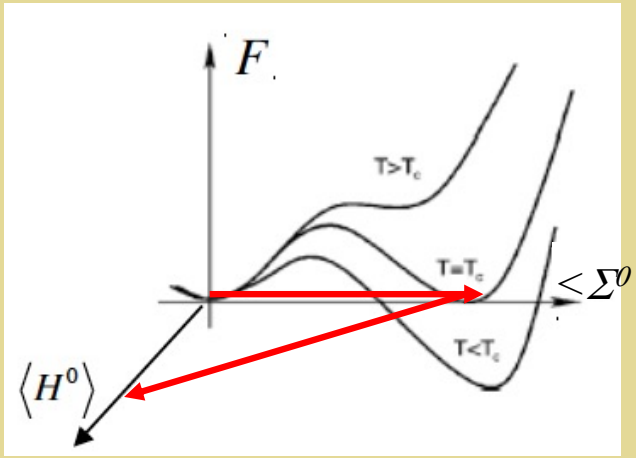

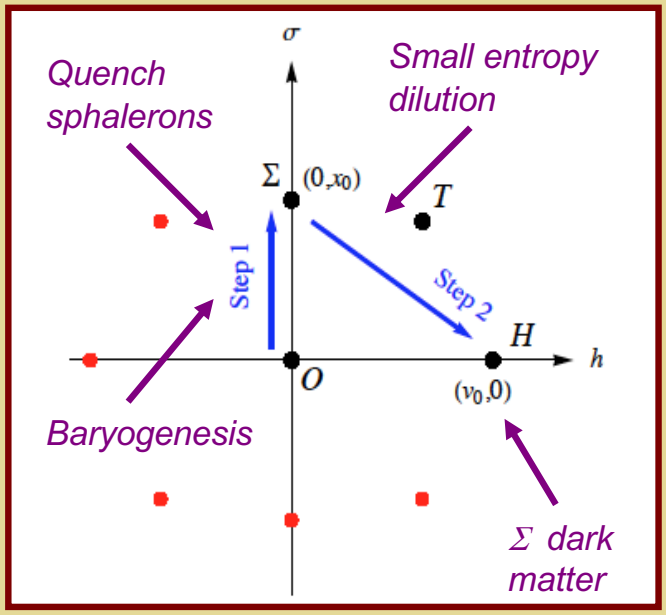

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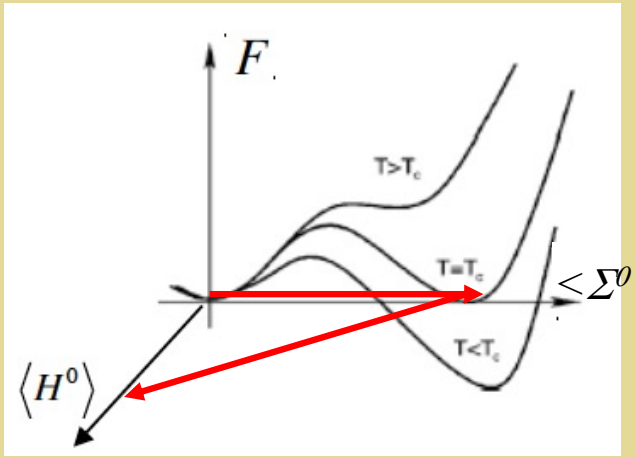
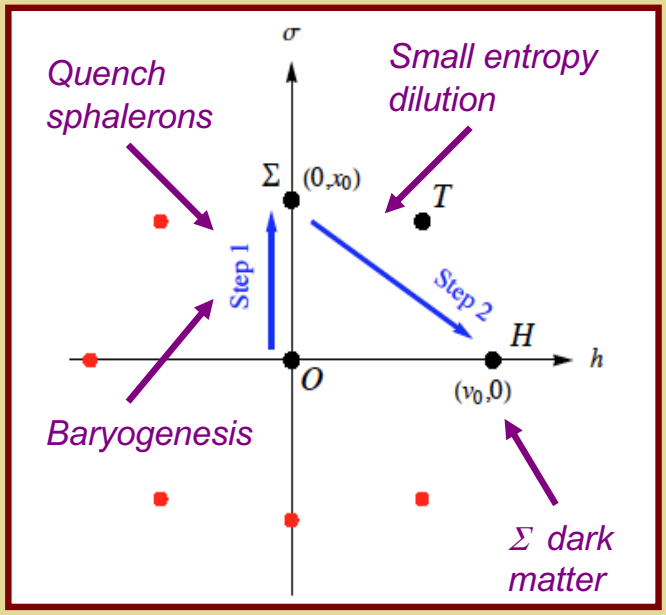
- *CPV asymmetry generated in SM sector via interactions with the ϕ_j*

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*

Illustrative Study: Model

$$\mathbf{M}^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 \\ m_{12}^{2*} & m_{22}^2 \end{pmatrix}$$

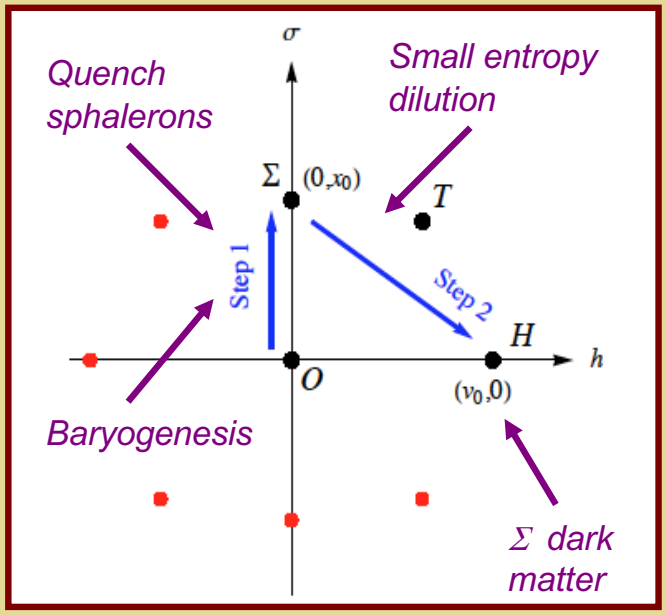
CPV: $\theta = Arg\,(m_{12}^2) = \theta(x)$

$m_{12}^2 = a\, v_1(x) + b\, v_2(x)$

CPV asymmetry generated in SM sector via interactions with the ϕ_j

- *New sector: real triplet (Σ) & real singlet (S)*
- *SM Sector: Z_2 symmetric 2HDM*

EW Singlet: "partially secluded sector"



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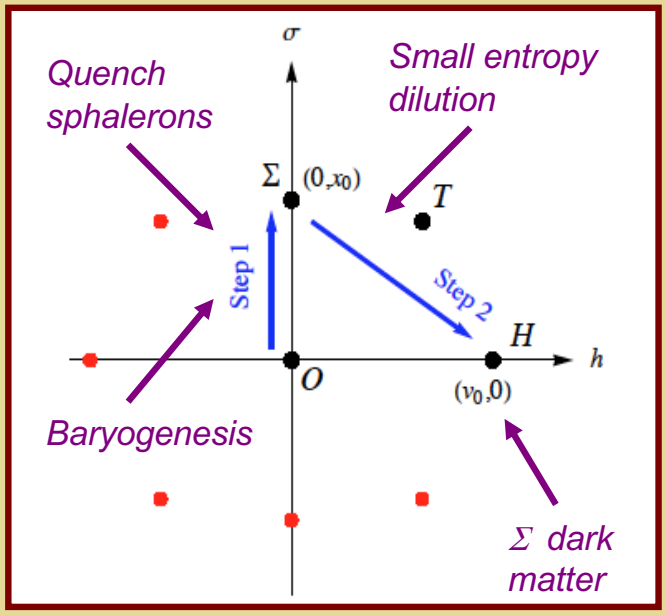

$$V(H_1, H_2, \Sigma, S)$$
$$= -\frac{\mu_\Sigma^2}{2}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right) + \frac{b_{4\Sigma}}{4}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right)^2 + \frac{b_{2S}}{2}S^2 + \frac{b_{4S}}{4}S^4$$
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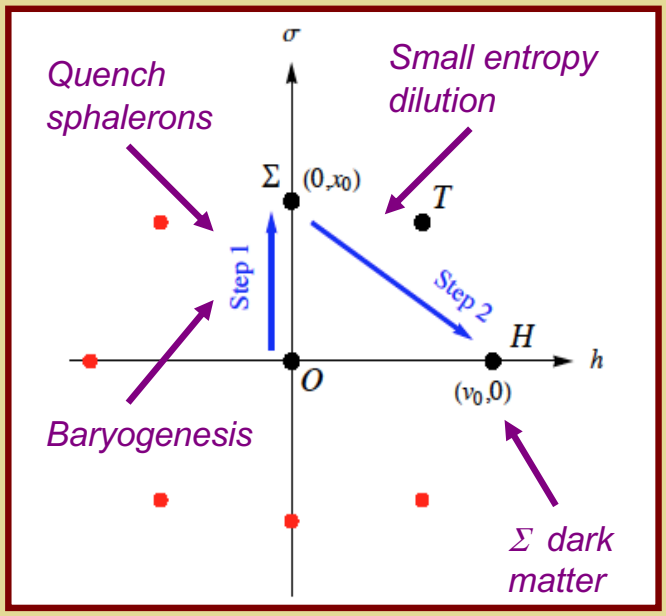

$$V(H_1, H_2, \Sigma, S) \qquad \text{CPV}$$
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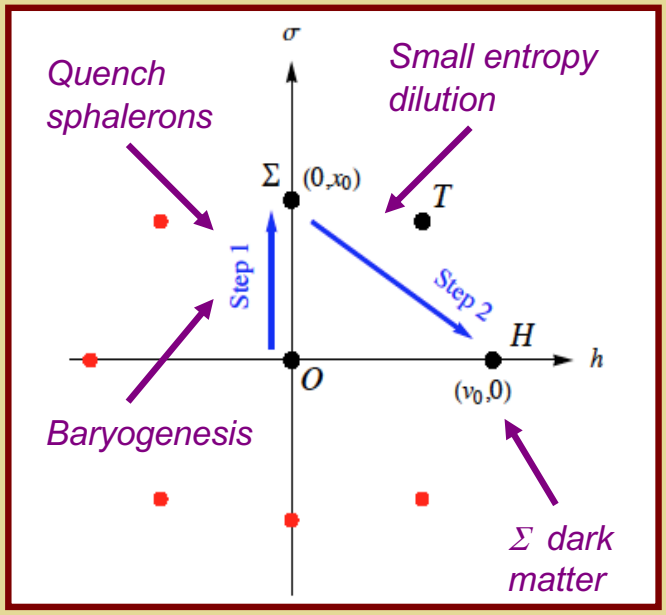

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Set to zero for simplicity

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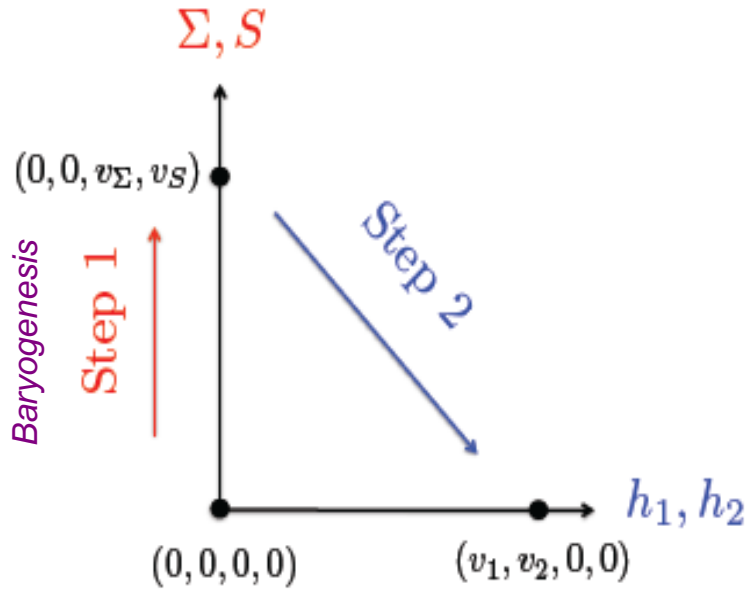

Rephasing invariants

$$\begin{aligned} \delta_\Sigma &= \arg\left[a_{2\Sigma}^*\, v_1 v_2^*\right], \\ \delta_S &= \arg\left[a_{2S}^*\, v_1 v_2^*\right], \\ \delta_{\lambda_5} &= \arg\left[\lambda_5^*\, (v_1 v_2^*)^2\right] \end{aligned}$$

Illustrative Study: Y_B

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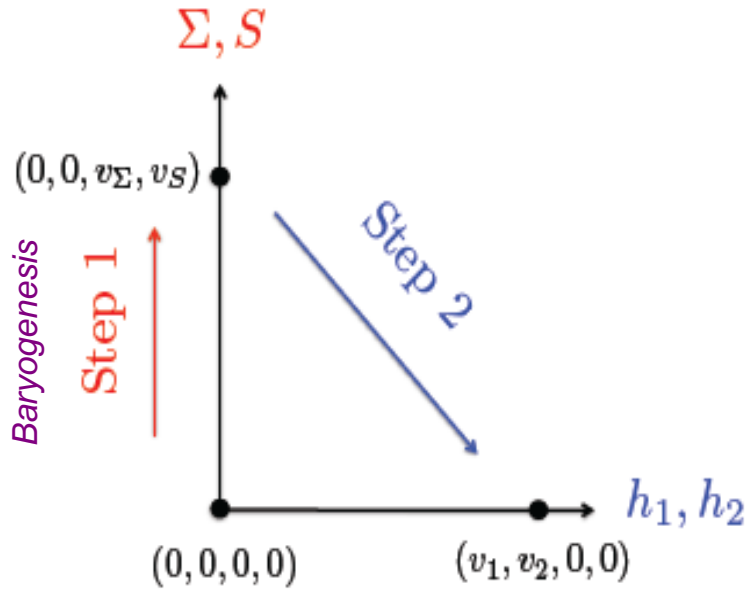

CPV sources

Transport equations

$$\partial_\lambda j_k^\lambda = -\sum_A \Gamma_A\left(\mu_k - \mu_\ell - \cdots\right) + S_k^{\not{CP}}$$

Particle # changing reactions:

Transfer asymmetry from H to fermions

Illustrative Study: Constraints

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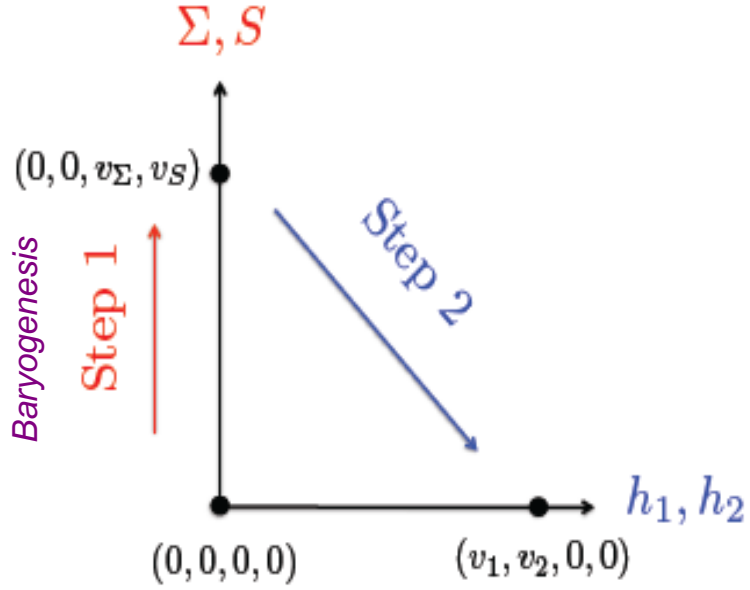

EDMs

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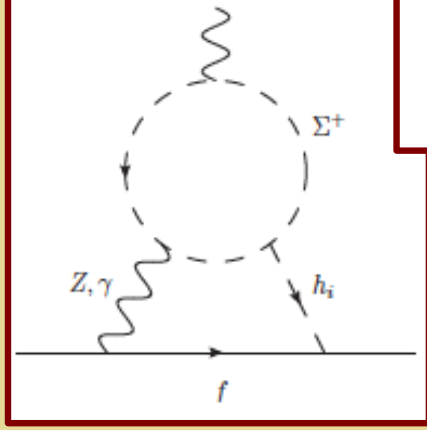

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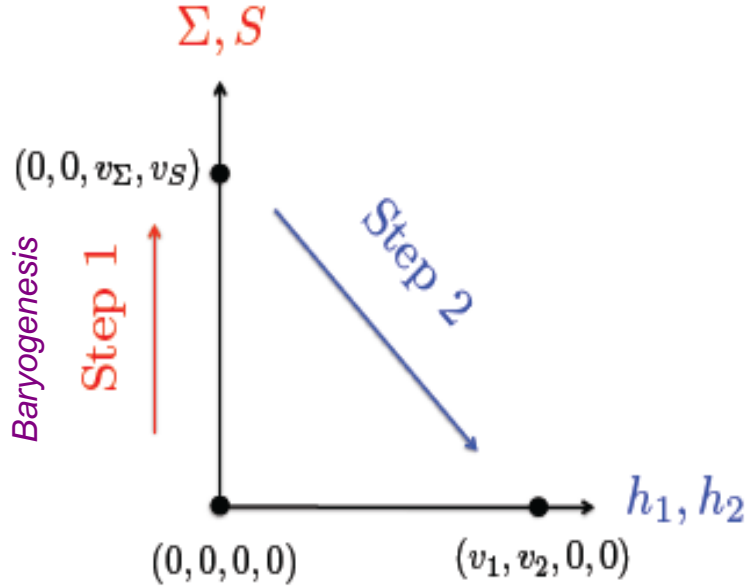

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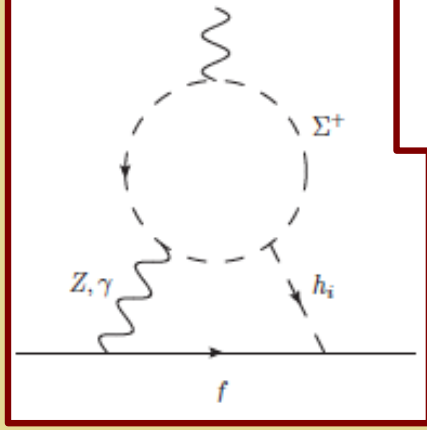

No δ_S *sensitivity*

Illustrative Study: Lessons

- ***Two-step electroweak baryogenesis is viable***
- ***No fine tuning of parameters necessary (yet)***
- ***CPV from a partially secluded sector can evade EDM constraints: direct CPV probes are sensitive to non-singlet sector***
- ***LHC & beyond may discover the new light states***
- ***Rich variety of scenarios yet to be explored***