Electric Dipole Moments: A Look Beyond the Standard Model

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My pronouns: he/him/his

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Goals for This Talk

- *Give a brief update on the experimental status & outlook for EDM searches*
- *Discuss the implications for explaining the cosmic matter-antimatter asymmetry*
- *Illustrate the interplay of EDM searches with collider searches*
- *Highlight the range of BSM mass scales EDM searches access*

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-35}	10^{-30}
ThO	1.1×10^{-29} **	10^{-38}	10^{-29}
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* 95% CL ** e^- equivalent

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Diamagnetic

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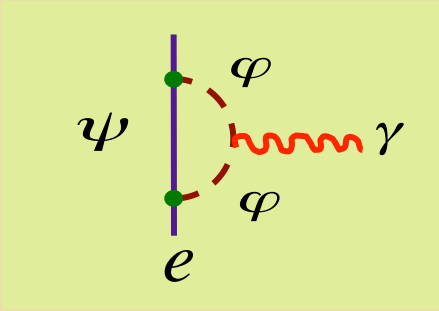
Mass Scale Sensitivity



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

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

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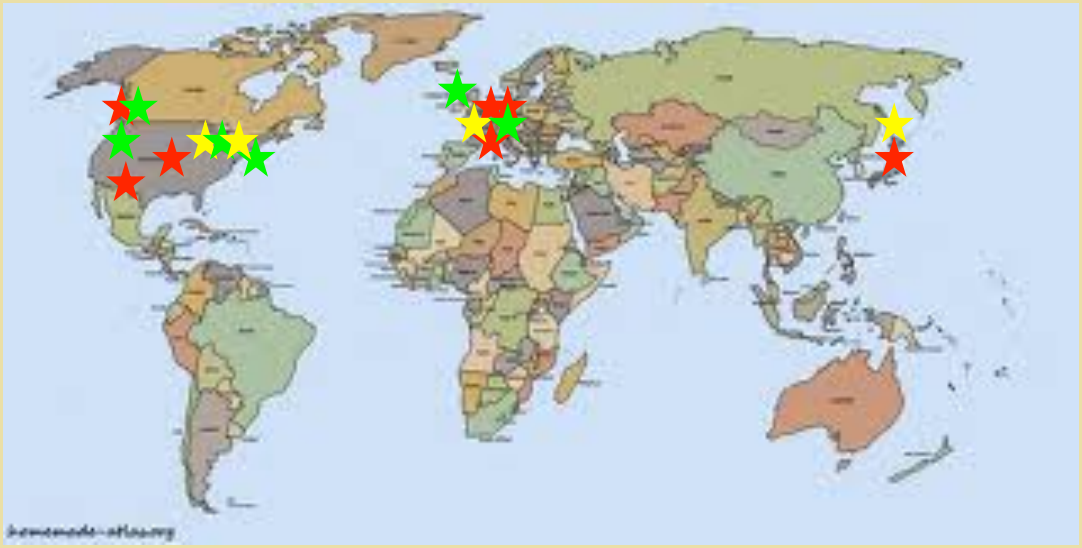

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

Outline

I. *EDM Interpretation: The SM & BSM context*

II. *The Cosmic Matter-Antimatter Asymmetry*

III. *The Higgs Boson & Top Quark Portals*

IV. *EDM Complementarity*

V. *Outlook*

I. Interpretation: The SM & BSM Context

EDMs & SM Physics

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

EDMs & SM Physics

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

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

C. Seng arXiv: 1411.1476

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

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* $3.3 \times 10^{-33}\ e\ cm < d_p < 3.3 \times 10^{-32}\ e\ cm$

EDMs & BSM Physics

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

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CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

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

BSM mass scale: TeV ? Much higher ?

EDMs & BSM Physics

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

BSM dynamics: perturbative? Strongly coupled?
Dependence on other parameters ?

EDMs & BSM Physics

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

Need information from at least three "frontiers"

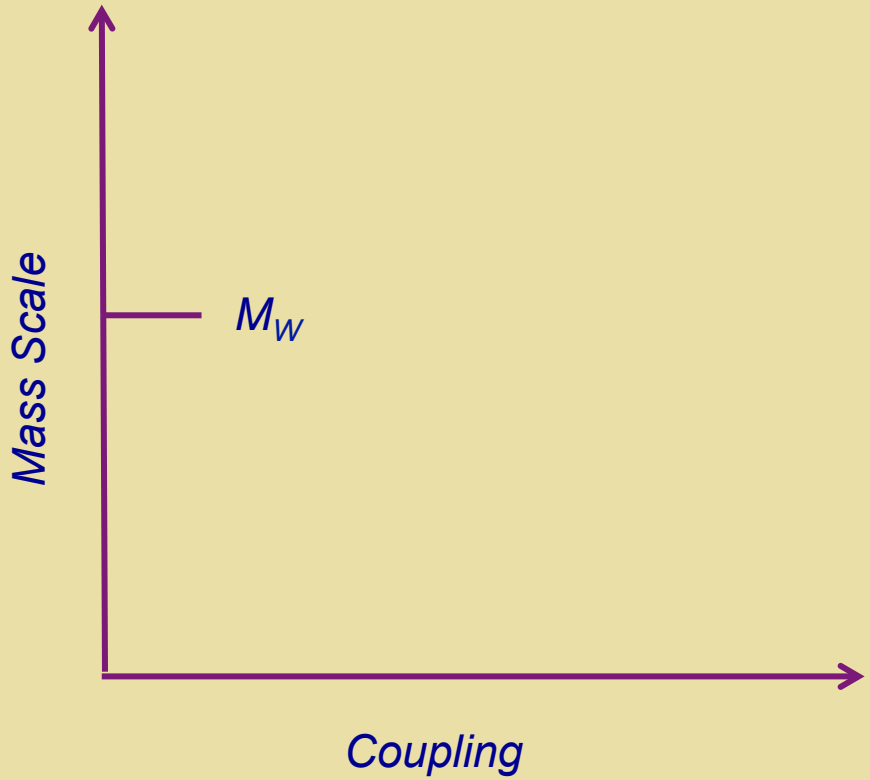
EDMs & BSM Physics

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

Need information from at least three "frontiers"

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

BSM Physics: Where Does it Live ?



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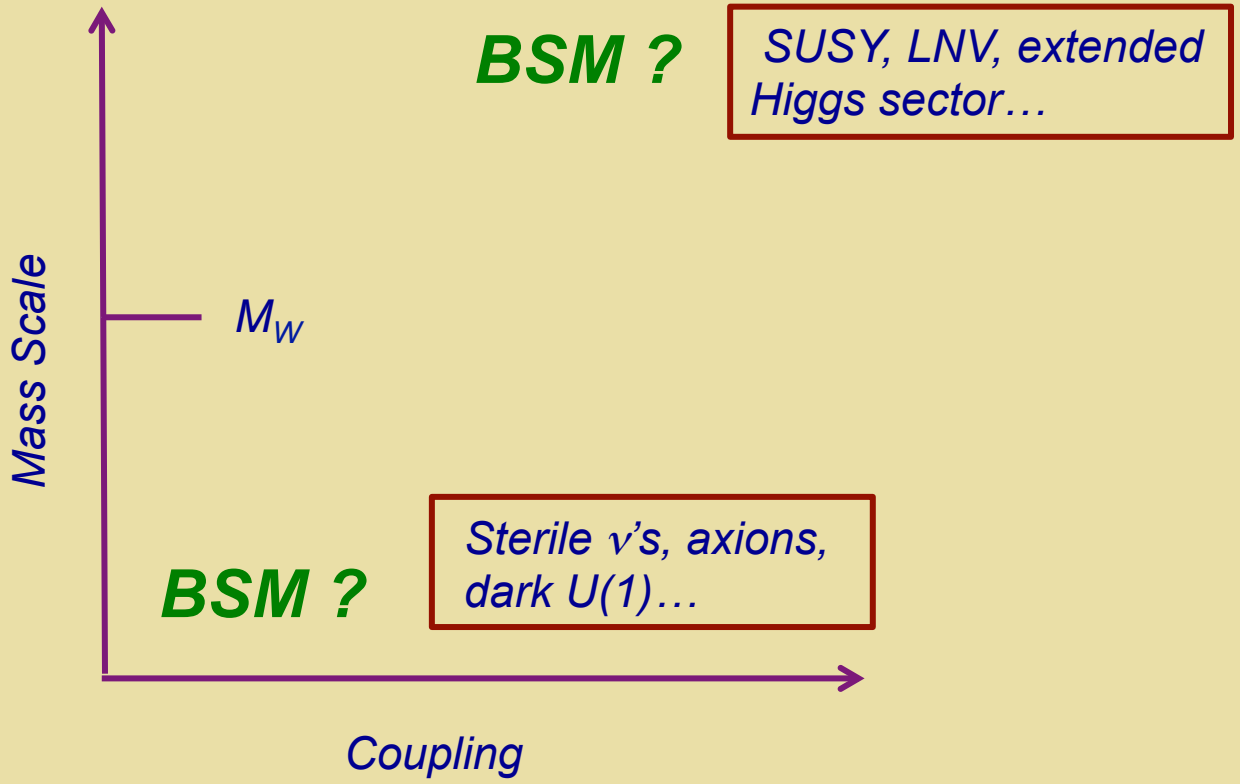

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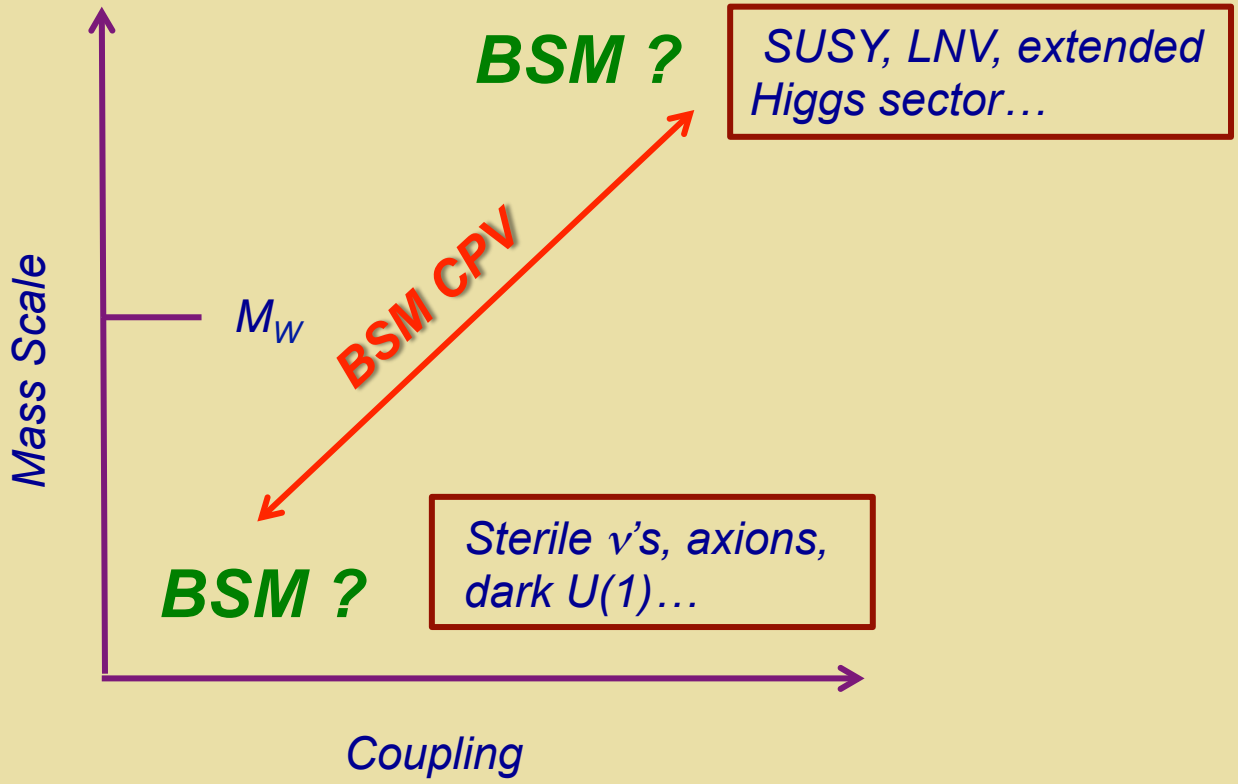
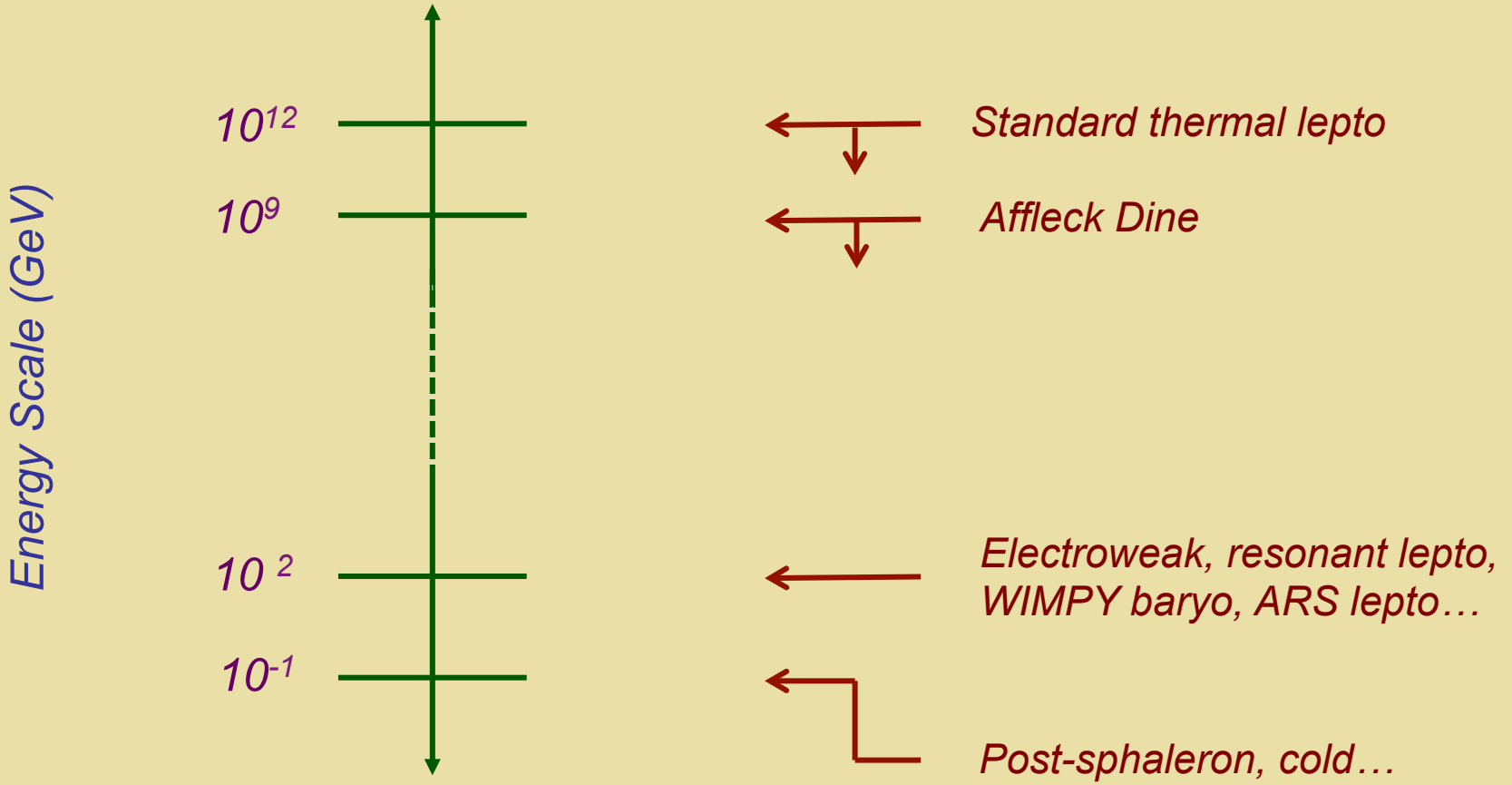


BSM Physics: T (CP) Invariant ?

II. The Matter-Antimatter Asymmetry

Baryogenesis Scenarios



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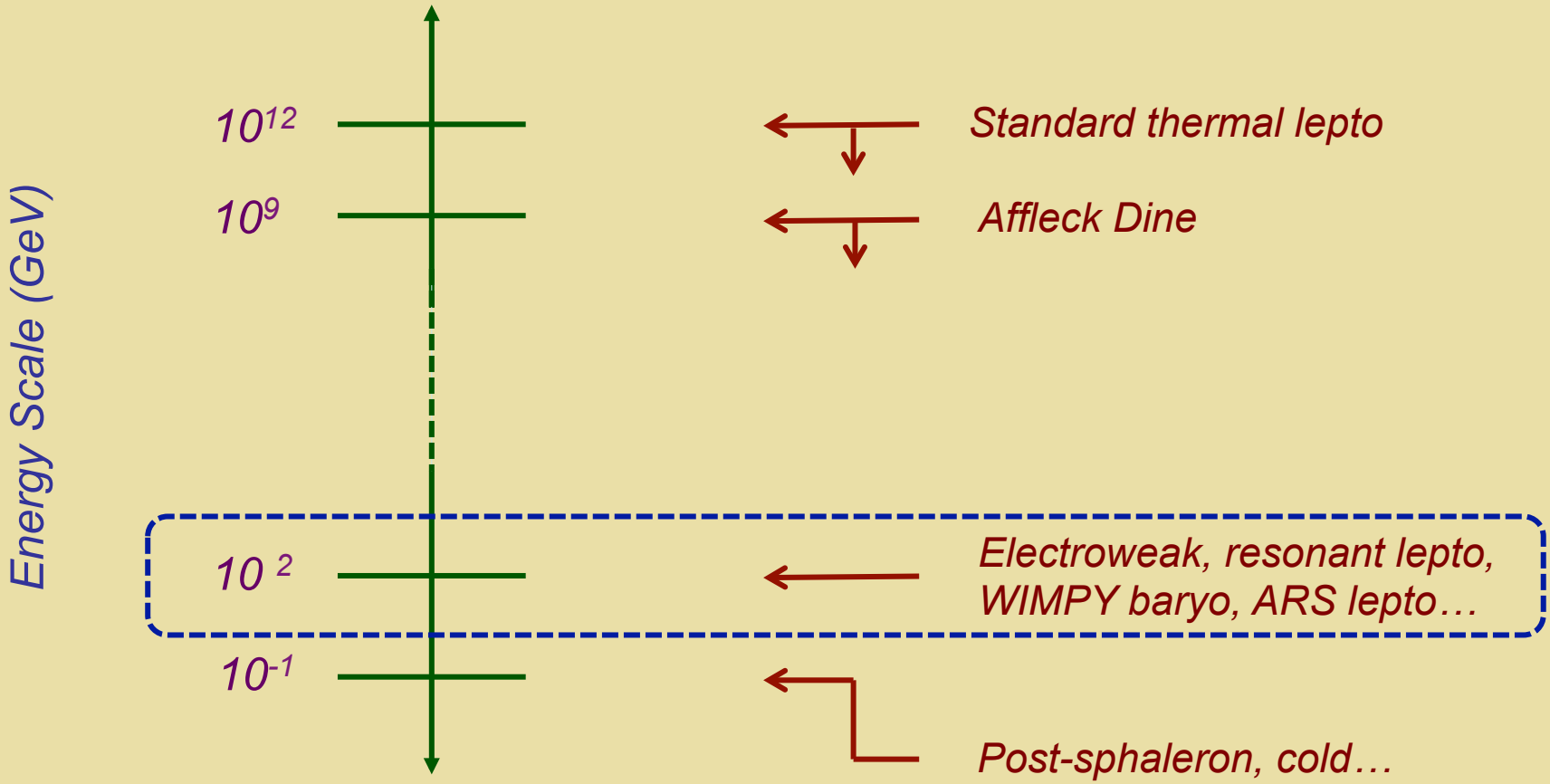


Era of EWSB: t_{univ} ~ 10 ps

Electroweak Baryogenesis

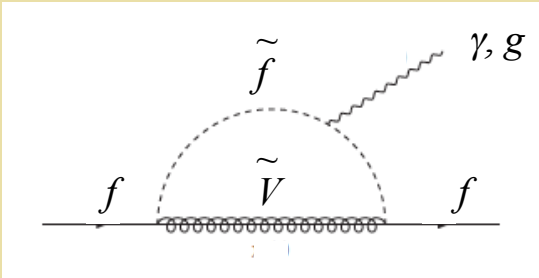
Was Y_B generated in conjunction with electroweak symmetry-breaking?

EWBG: MSSM & Beyond

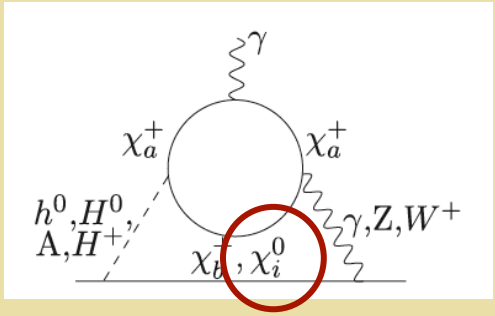
- ***Strong first order EWPT:*** *LHC $\rightarrow$ Excluded for the MSSM $\rightarrow$ Possible w/ extensions (e.g., NMSSM)*

- ***CPV:*** *Sources same as in MSSM + possible additional*

EDMs & EWBG: MSSM & Beyond

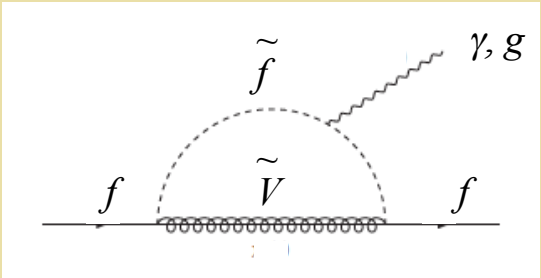


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

EDMs & EWBG: MSSM & Beyond



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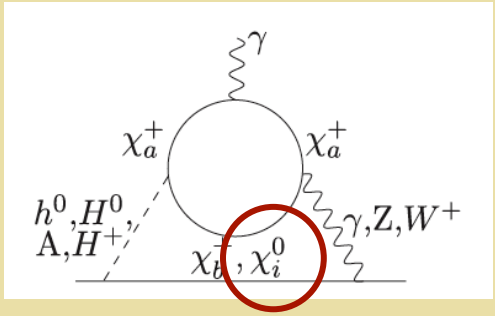

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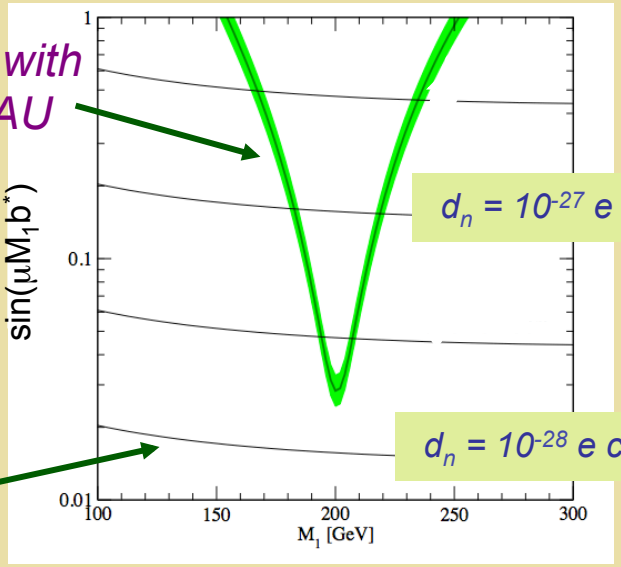
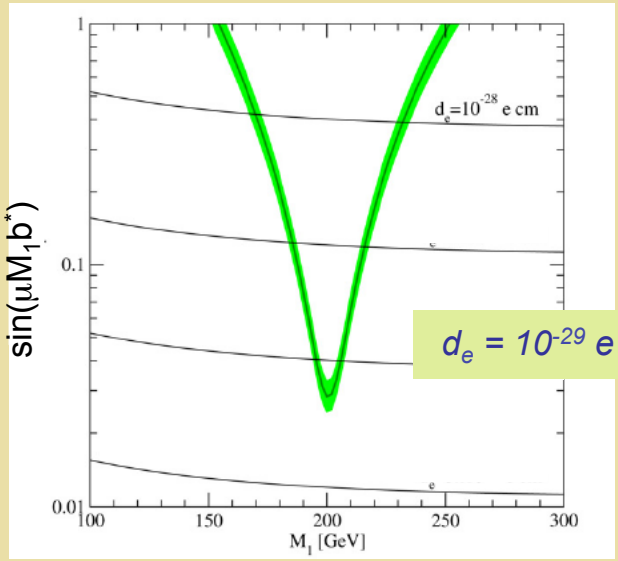
Compatible with observed BAU



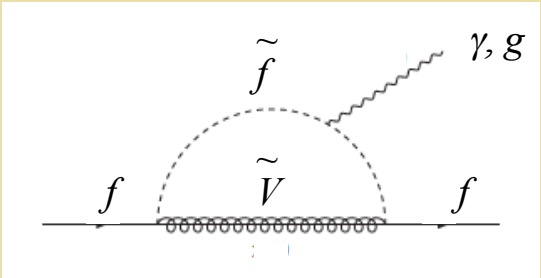
Next gen d_n



ACME: ThO

Li, Profumo, RM '09-'10

EDMs & EWBG: MSSM & Beyond



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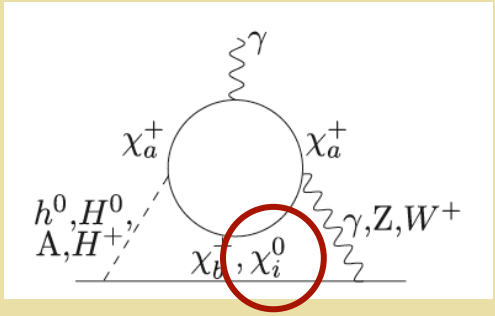

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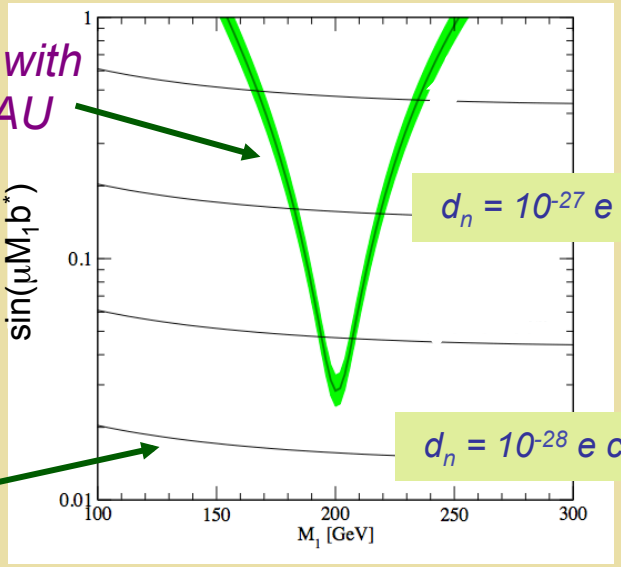

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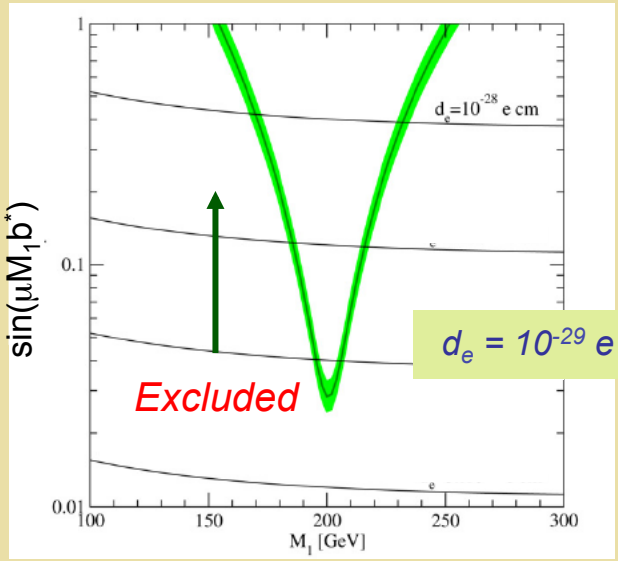

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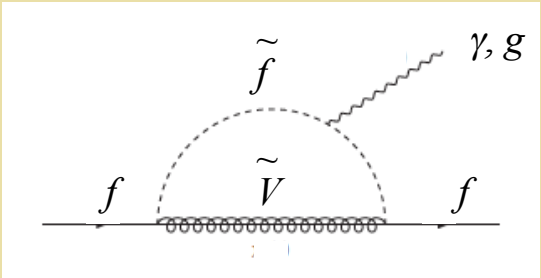

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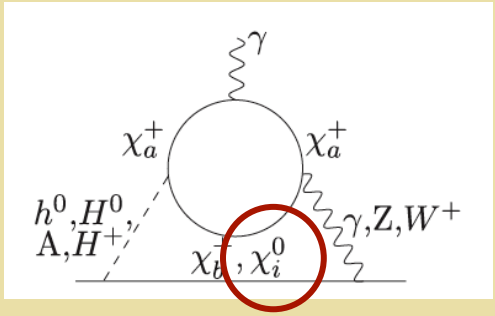

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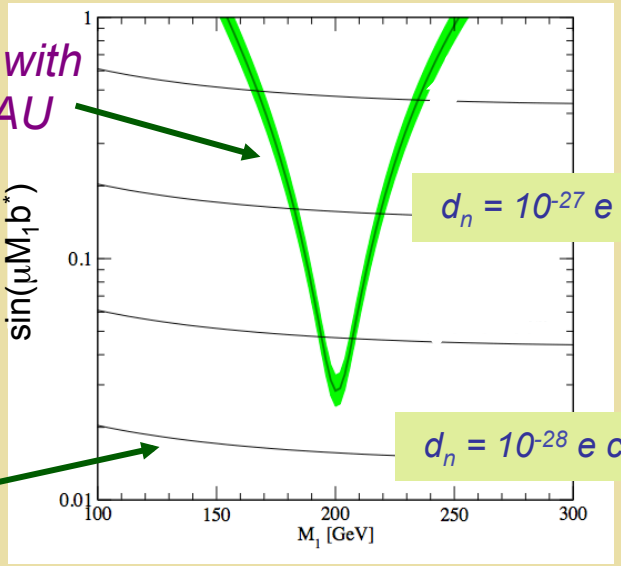

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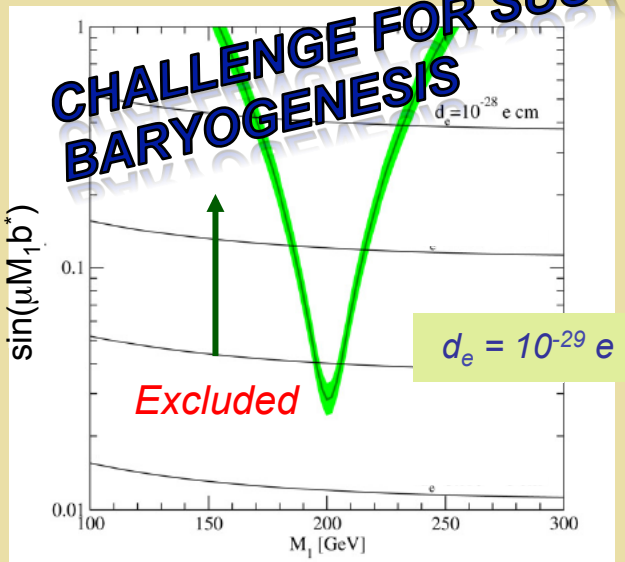

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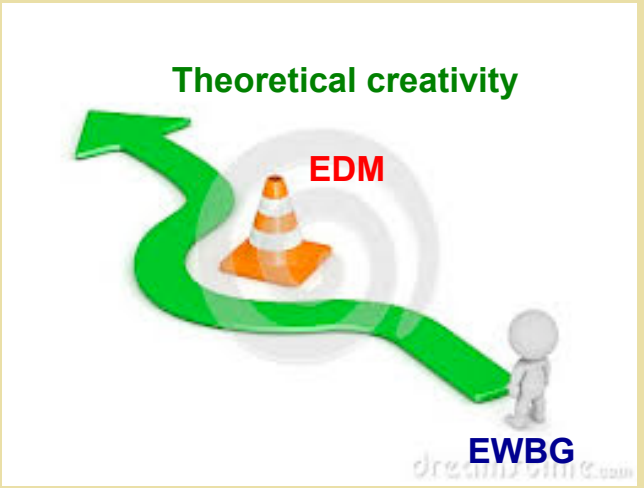
CPV for EWBG



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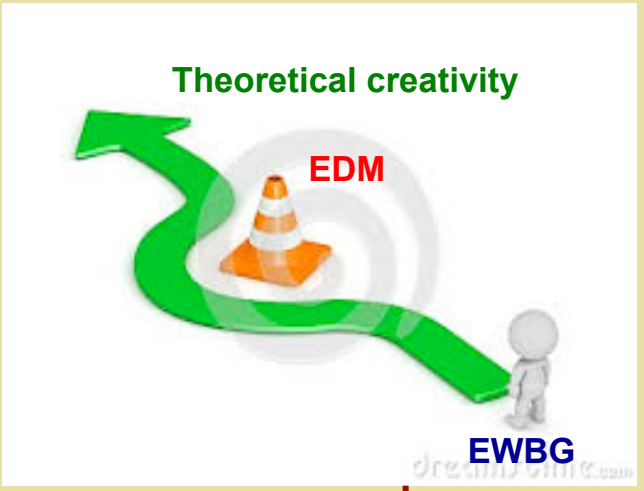
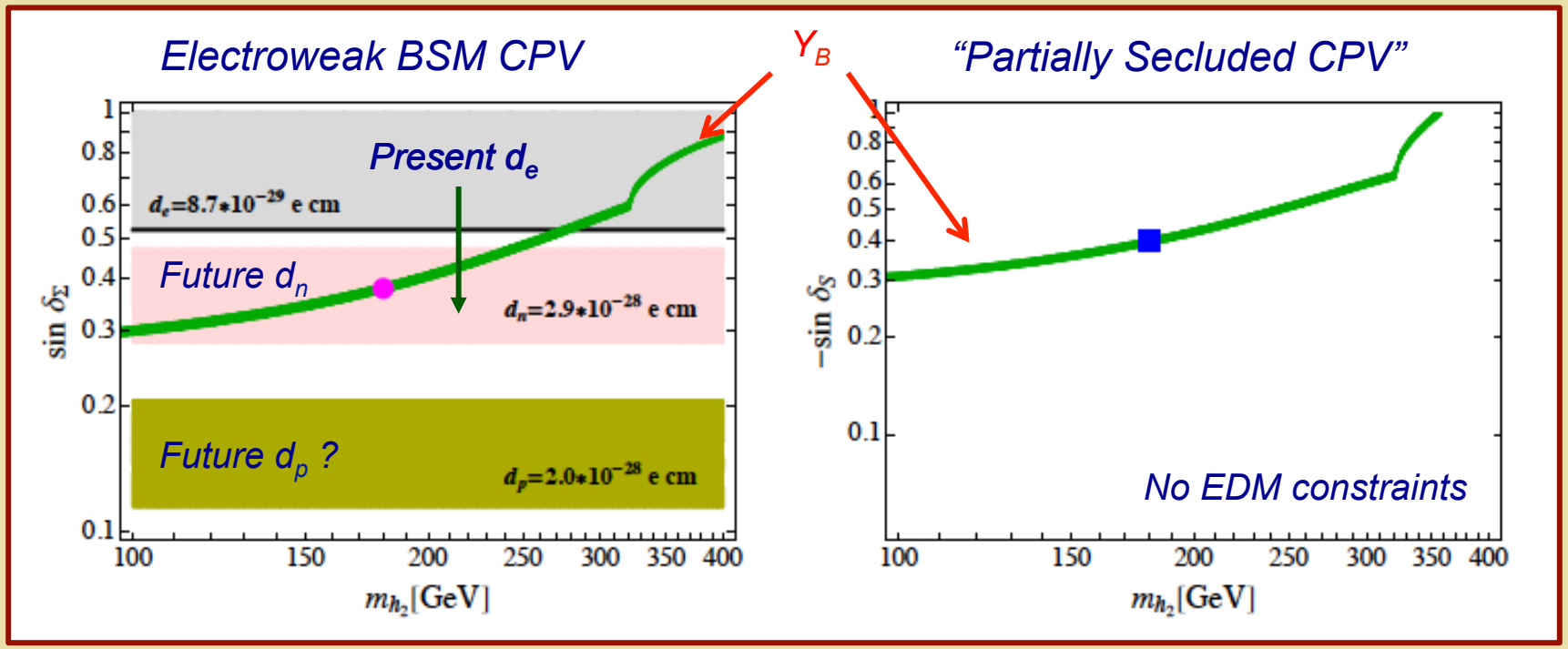


- *Flavored CPV*
- *"Partially secluded" CPV*
- *CPV w/ vector-like fermions*
- *…*

"Two-Step EW Baryogenesis"

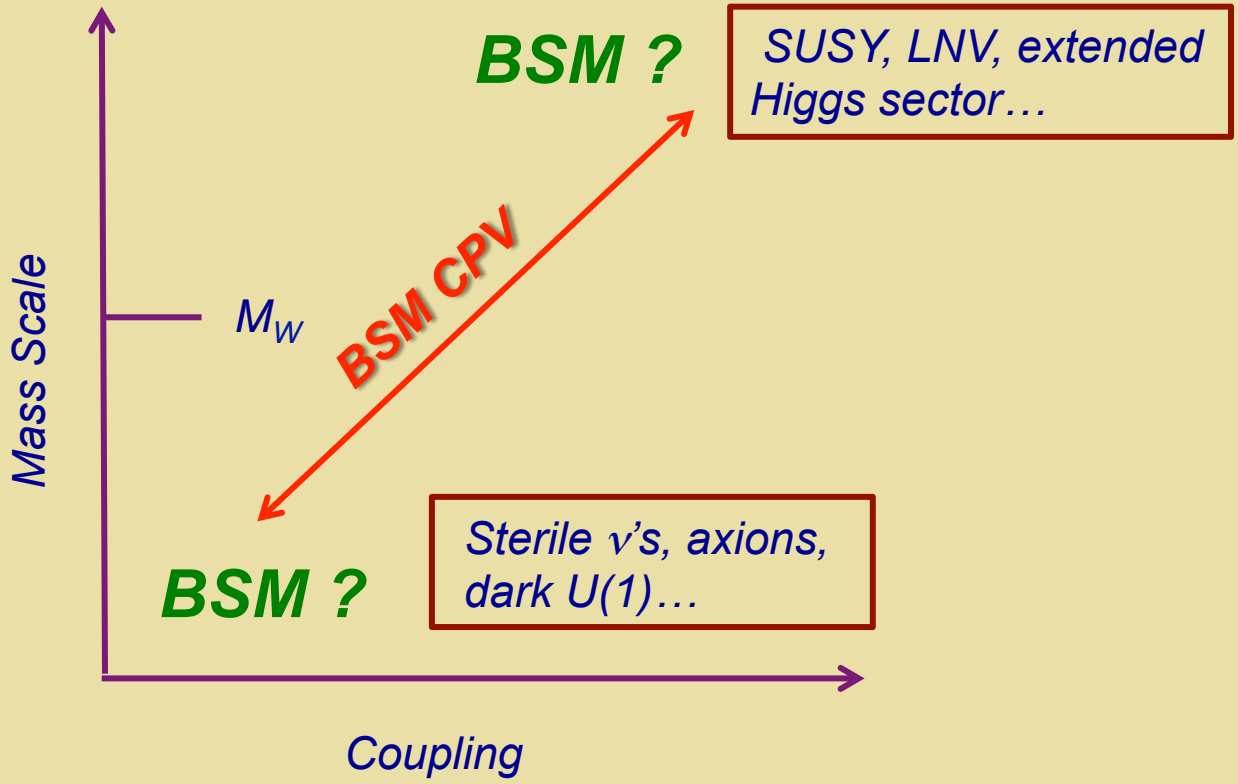
Two CPV sources for baryon asymmetry



Inoue, Ovanesyan, R-M: 1508.05404

III. Portals: The BSM Mass Scale & CP

BSM Physics: Where Does it Live ?



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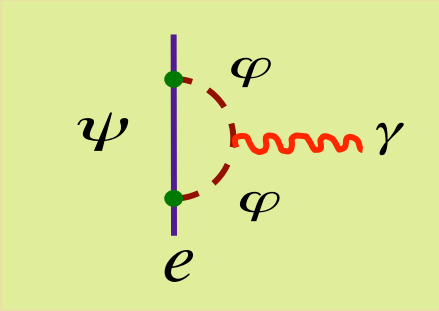
Mass Scale Sensitivity



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

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

EDMs: New Light CPV?

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Ultralight Mass Scale Sensitivity

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

Limits on d_n & d_A (^{199}Hg) $\rightarrow$ $\theta < 10^{-10}$
Suggests Peccei-Quinn symmetry & existence of axion (ultralight)

Specific Illustrations: "Portals"

- *Higgs boson*
- *Top quark*
- *Dark photon*

Where is BSM CPV hiding ?

The Higgs Portal

What is the CP Nature of the Higgs Boson ?

- *Interesting possibilities if part of an extended scalar sector*
- *Two Higgs doublets ?*

$$H \rightarrow H_1 , H_2$$

- *New parameters:*

$\tan \beta = \langle H_1 \rangle / \langle H_2 \rangle$
$\sin \alpha_b$

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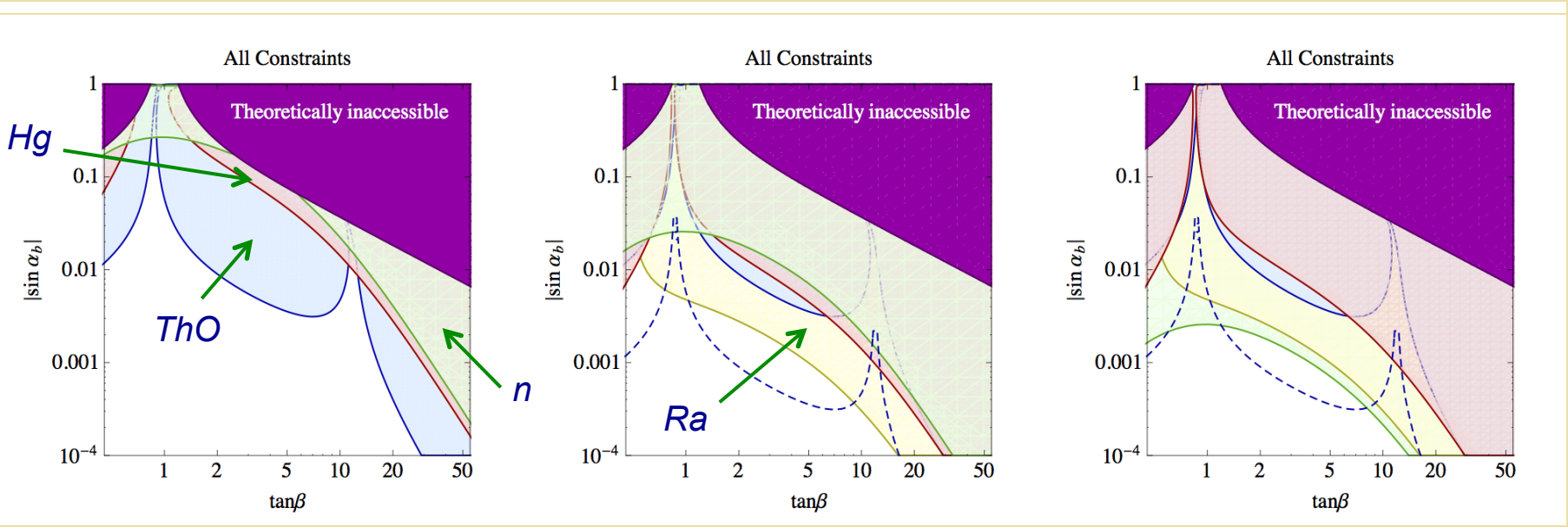
$\sin\alpha_b$

CPV : scalar-pseudoscalar mixing from $V(H_1, H_2)$

Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

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



Present → *New ThO: ACME*

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

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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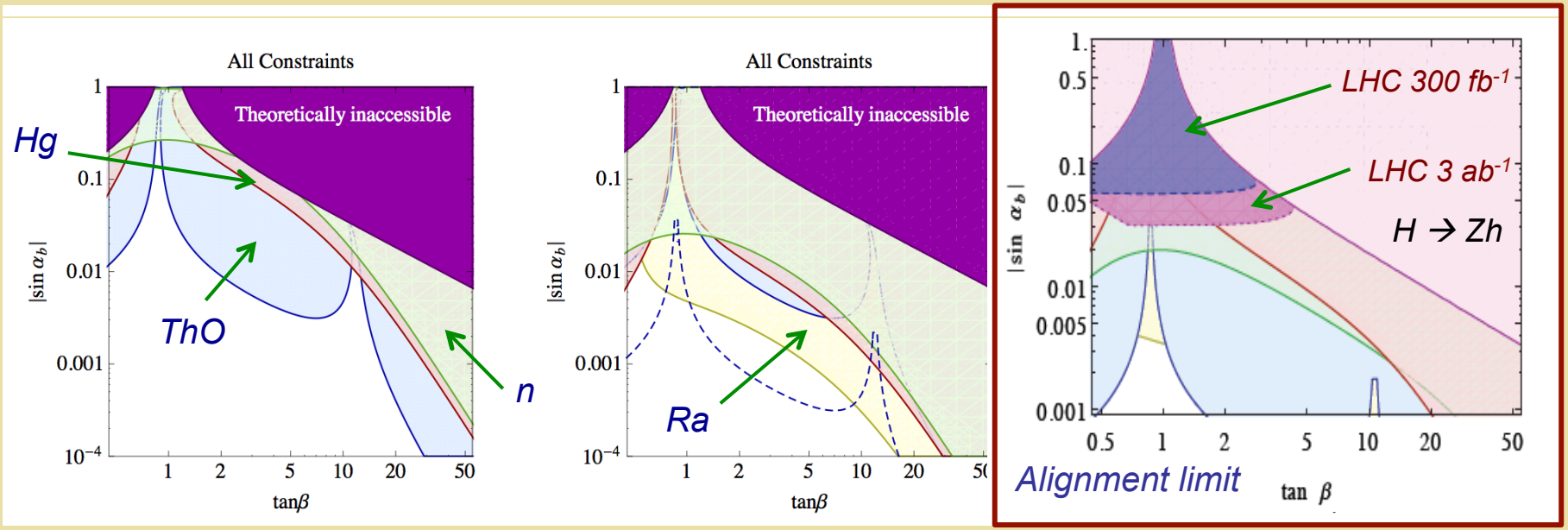

Chen, Li, R-M: 1708.00435

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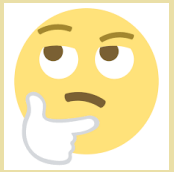
The Top Quark Portal

CPV Top Quark Interactions?

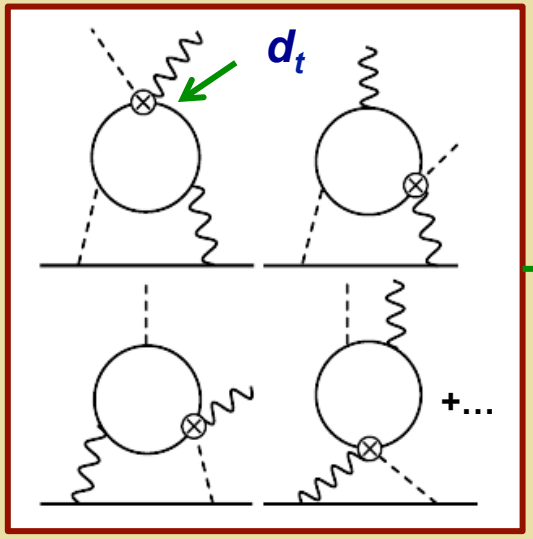
- *3rd generation quarks often have a special role in BSM scenarios, given m_t >> all other m_f*
- *If BSM CPV exists, d_t may be enhanced*
- *Top EDMs difficult to probe experimentally*
- *Light fermion EDMs to the rescue !*

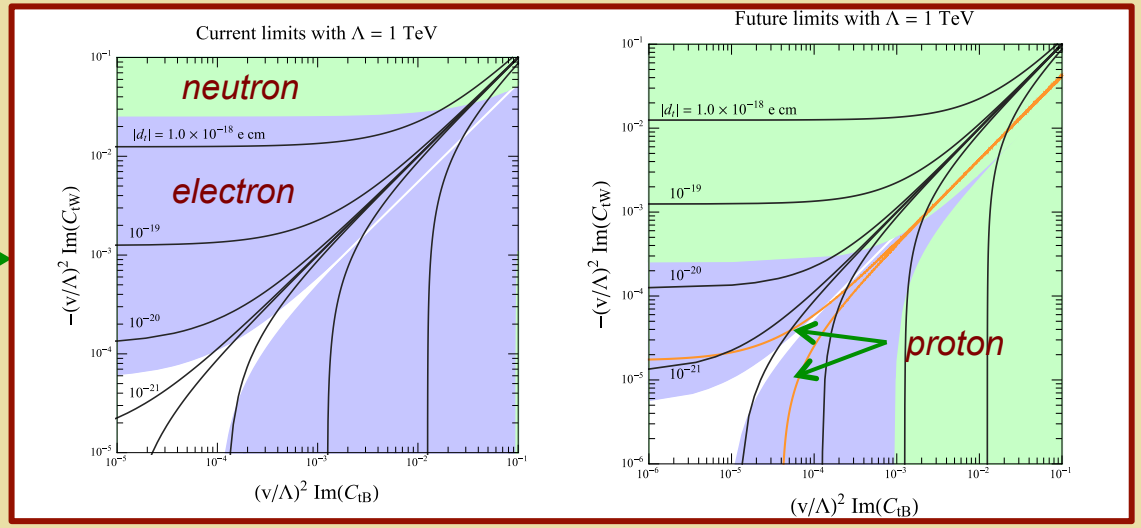


CPV Top Quark Interactions?

Cordero-Cid et al '08, Kamenik et al '12, Cirigliano et al '16, Fuyuto & MRM in 1706.08548

Model-indep: independent $SU(2)_L$ & $U(1)_Y$ dipole operators: C_{tB} , C_{tW} → Tree level d_t & loop level d_e , $d_{light\ q}$





Induced d_e , $d_{light\ quark}$

Fuyuto & MRM '17
Fuyuto '19: Updated for new ThO

Dark Photon Portal

Dark Photon Portal

Standard Model ⟷ ***Hidden Sector***

New CPV ?

Dark Photon Portal

SM	Mediator	Dark
SU(2) Triplet	X	Sector

Thanks: K. Fuyuto

CPV Dark Photon

$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

CP-conserving CP-violating

Thanks: K. Fuyuto

K. Fuyuto, X.-G. He, G. Li, MJRM 1902.XXXXX

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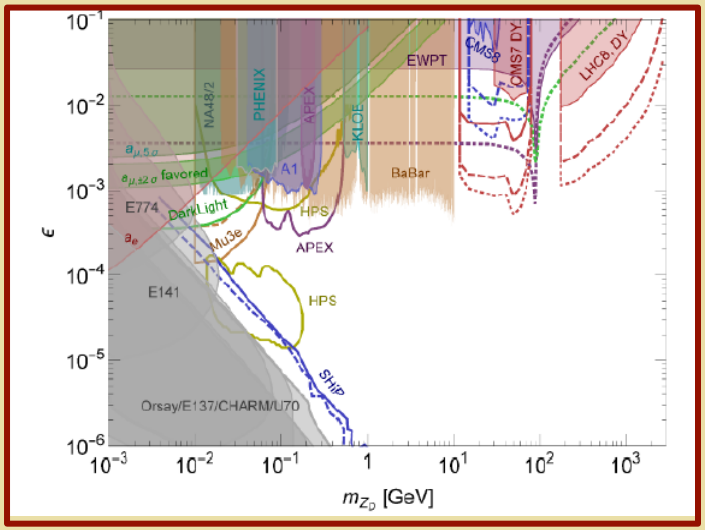
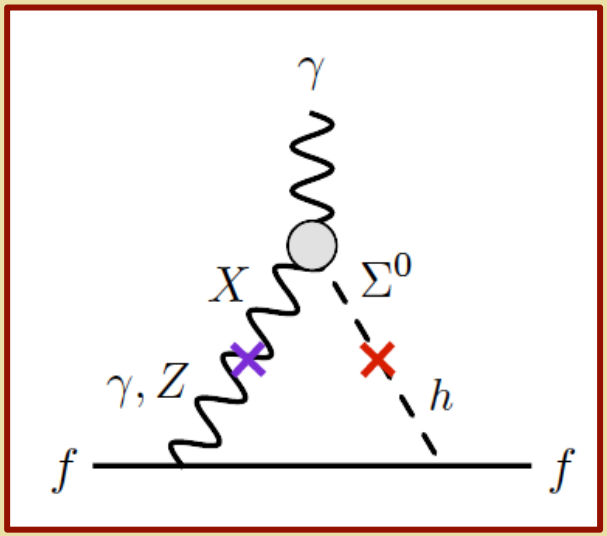
X − γ Mixing



EDM



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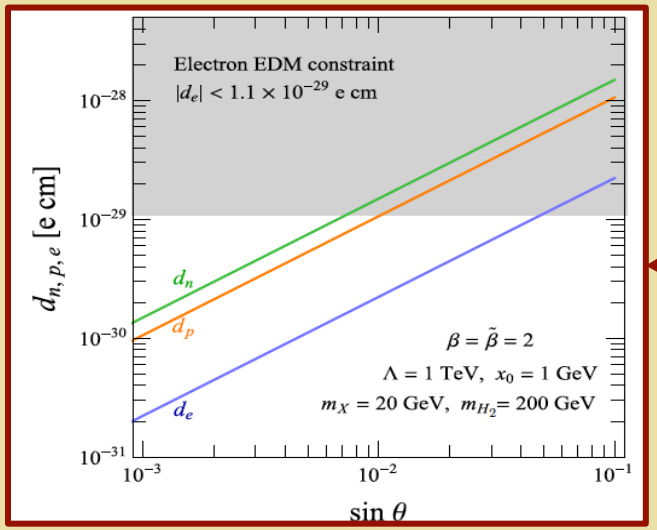
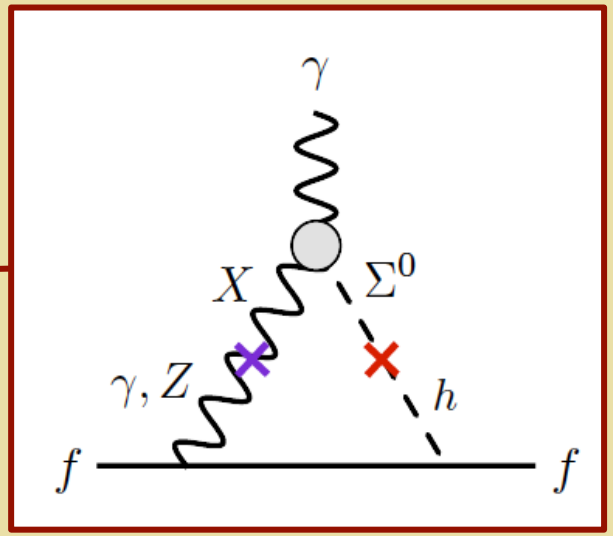
$X-\gamma$ Mixing

EDM





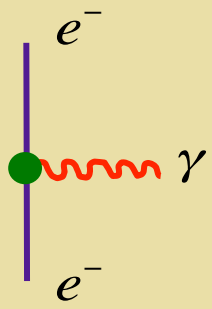
IV. EDM Complementarity

Why Multiple Systems ?

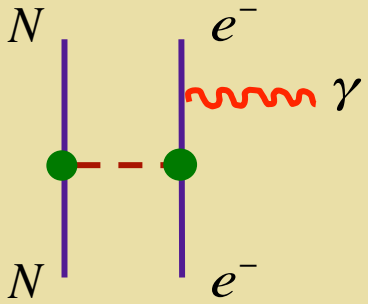
Multiple sources & multiple scales

Paramagnetic Systems: Two Sources

Electron EDM



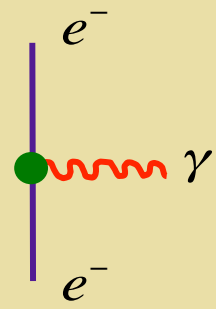
(Scalar q) x (PS e^-)



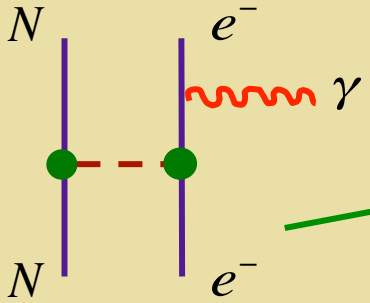
Tl, YbF, ThO…

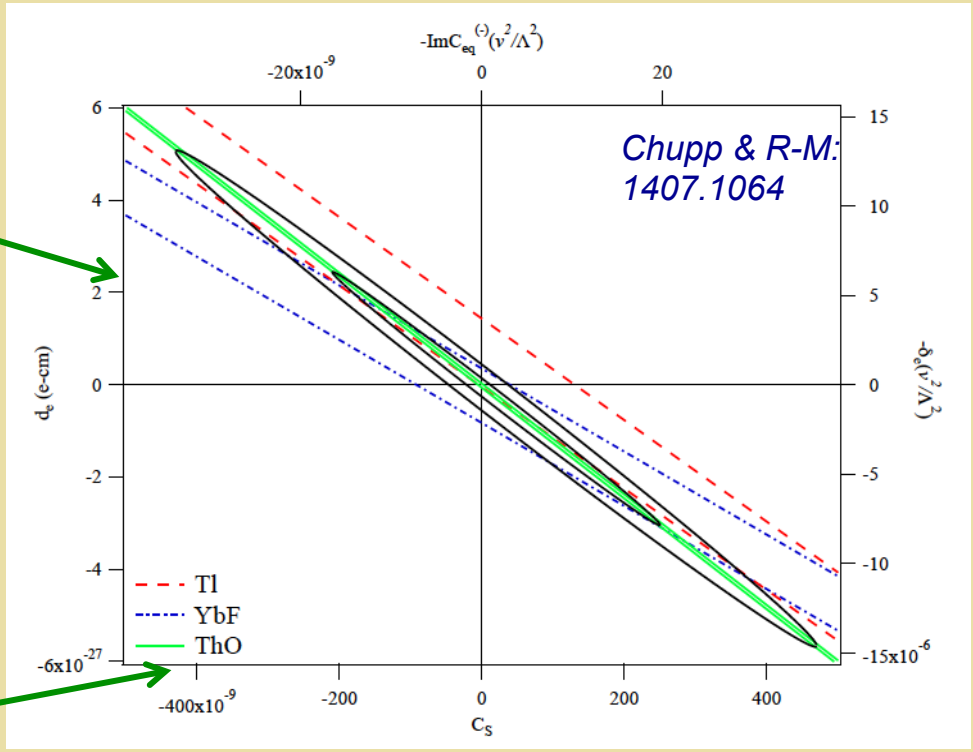
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e⁻)

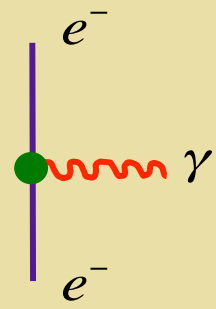




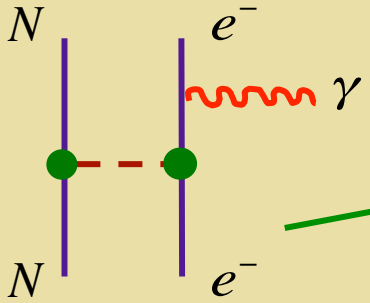
Tl, YbF, ThO…

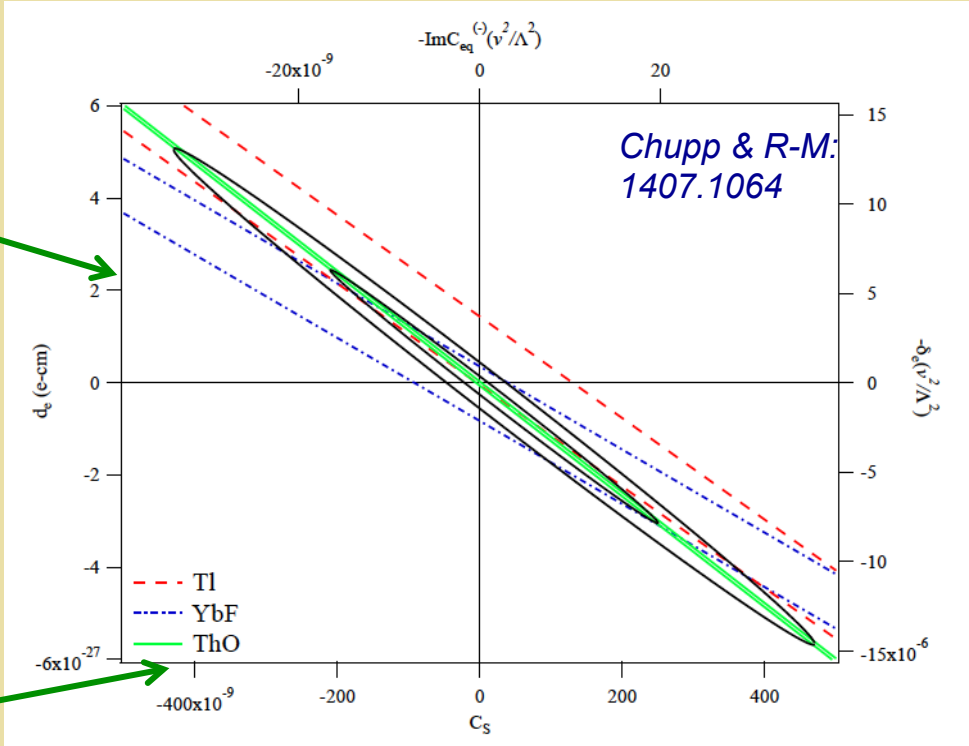
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





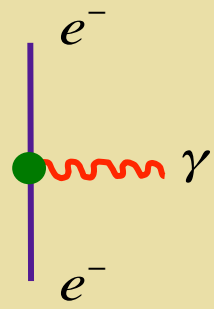
$$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}} \qquad \text{Electron EDM (global)}$$

$$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}} \qquad C_S\ \text{(global)}$$

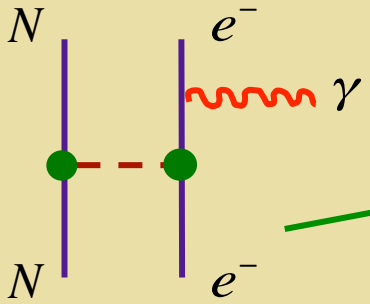
Tl, YbF, ThO…

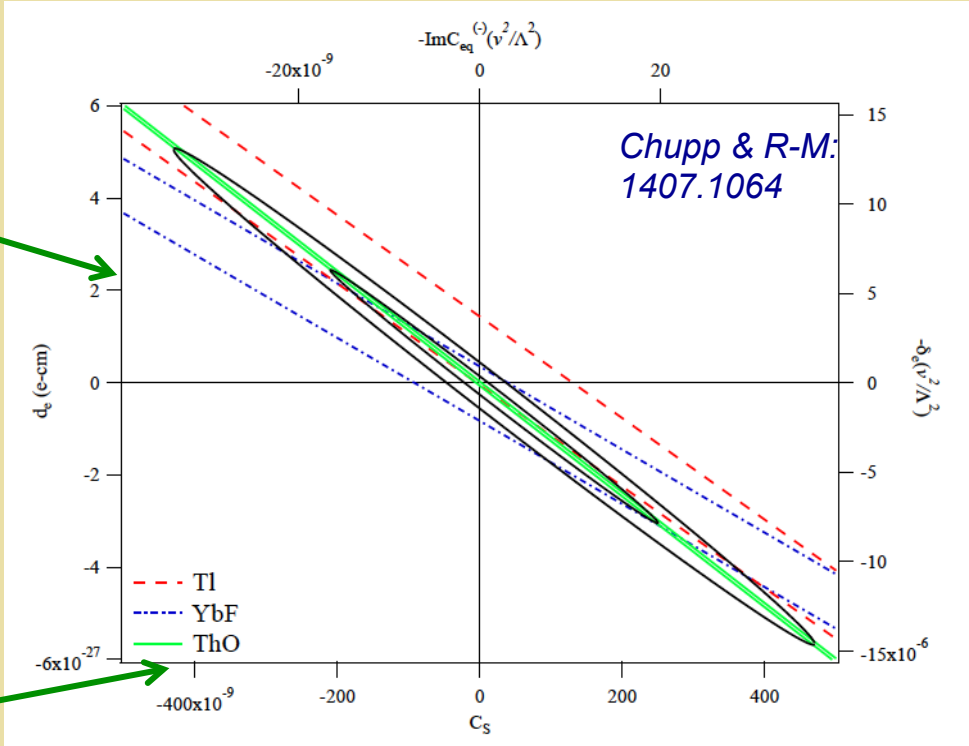
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ Electron EDM (global)

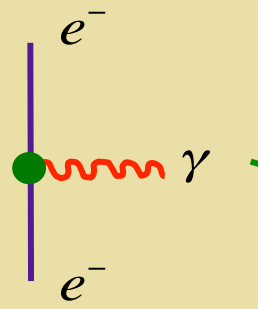
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ C_S (global)

LHC inaccessible

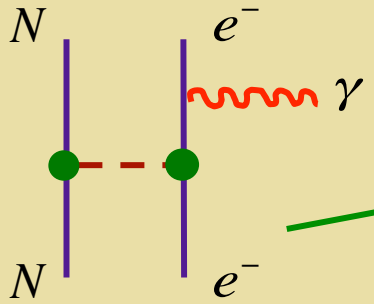
Tl, YbF, ThO…

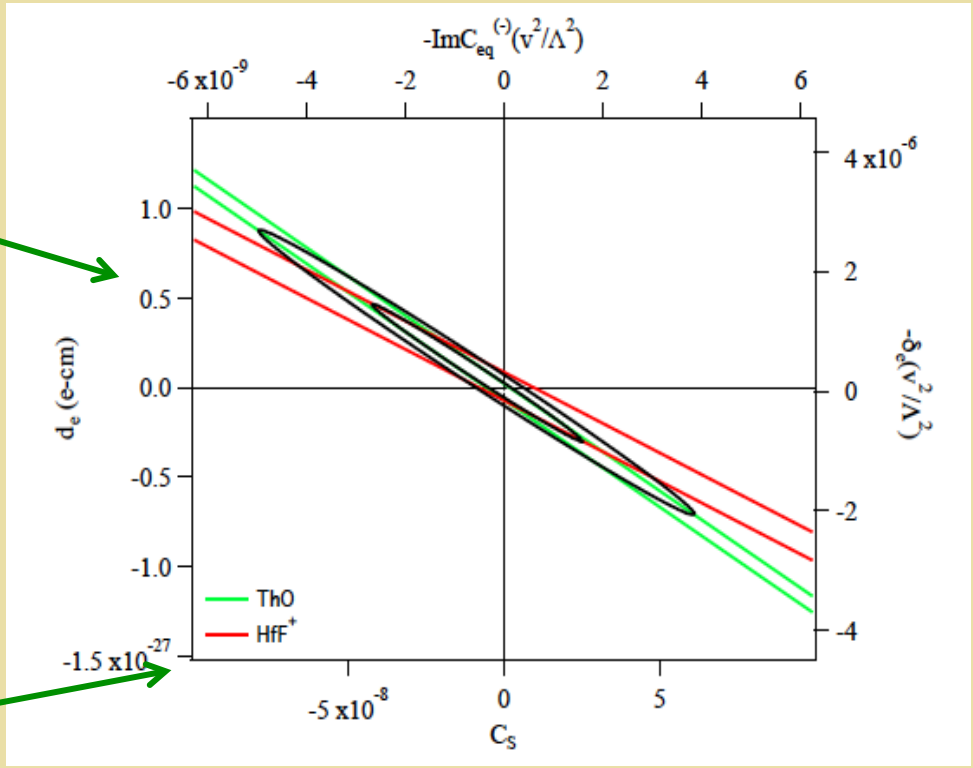
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





Chupp, Fierlinger, R-M, Singh 1710.02504; Fleig & Jung 1802.02171

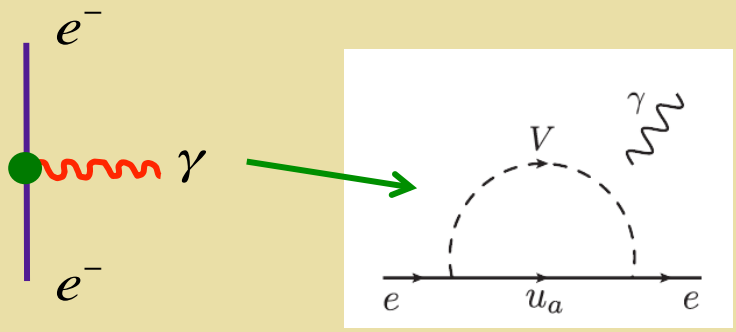
Inclusion of HfF+ : ~ 6 times stronger bounds on d_e & C_S → 2.5 higher on Λ

New ThO → even stronger !

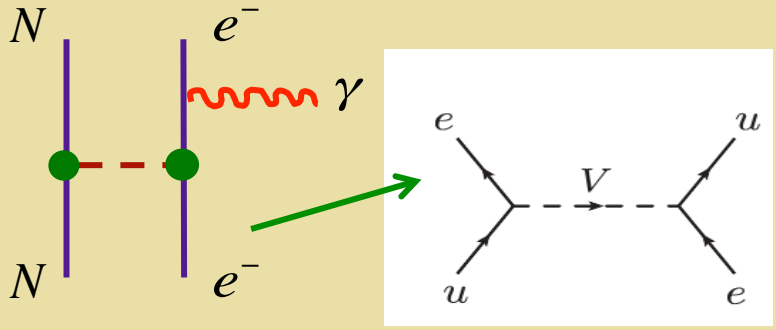
Tl, YbF, ThO, HfF+

Illustrative Example: Leptoquark Model

Electron EDM



(Scalar q) x (PS e^-)

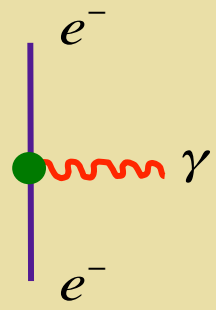


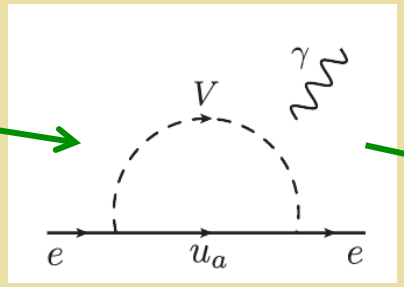
(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab} \bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab} \bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

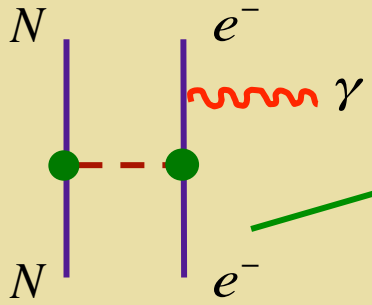
Illustrative Example: Leptoquark Model

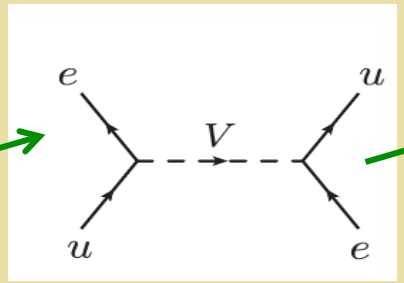
Electron EDM

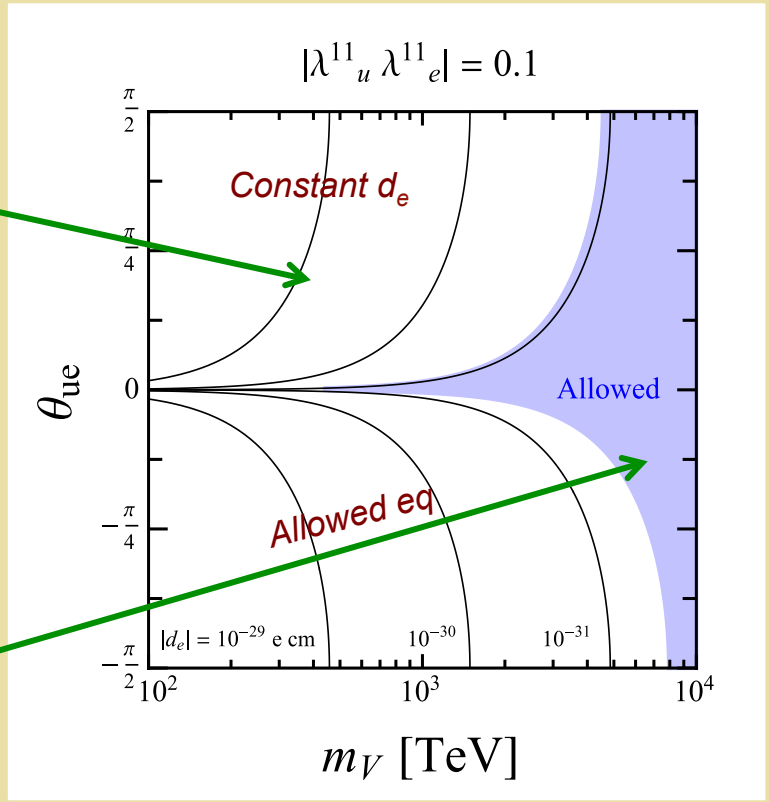




(Scalar q) x (PS e^-)







Fuyuto, R-M, Shen 1804.01137

(3, 2, 7/6)

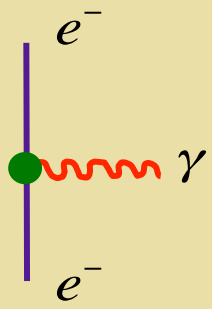
$$\mathcal{L} \ni -\lambda_u^{ab}\bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab}\bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

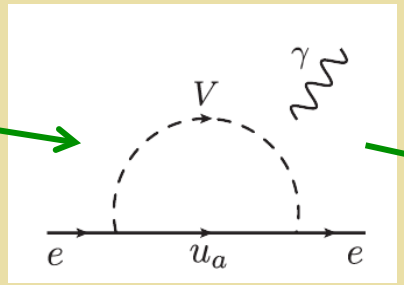
Illustrative Example: Leptoquark Model

Orange: $|d_p| = 10^{-30}, 10^{-31}, 10^{-32}$ e cm

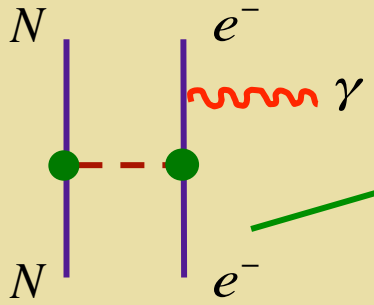
Green: $|d_n| = 10^{-30}, 10^{-31}, 10^{-32}$ e cm

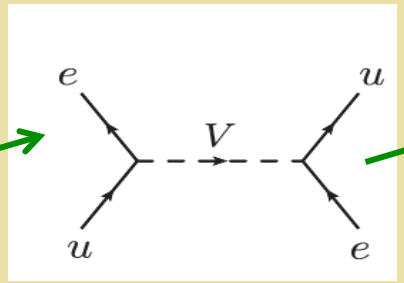
Electron EDM

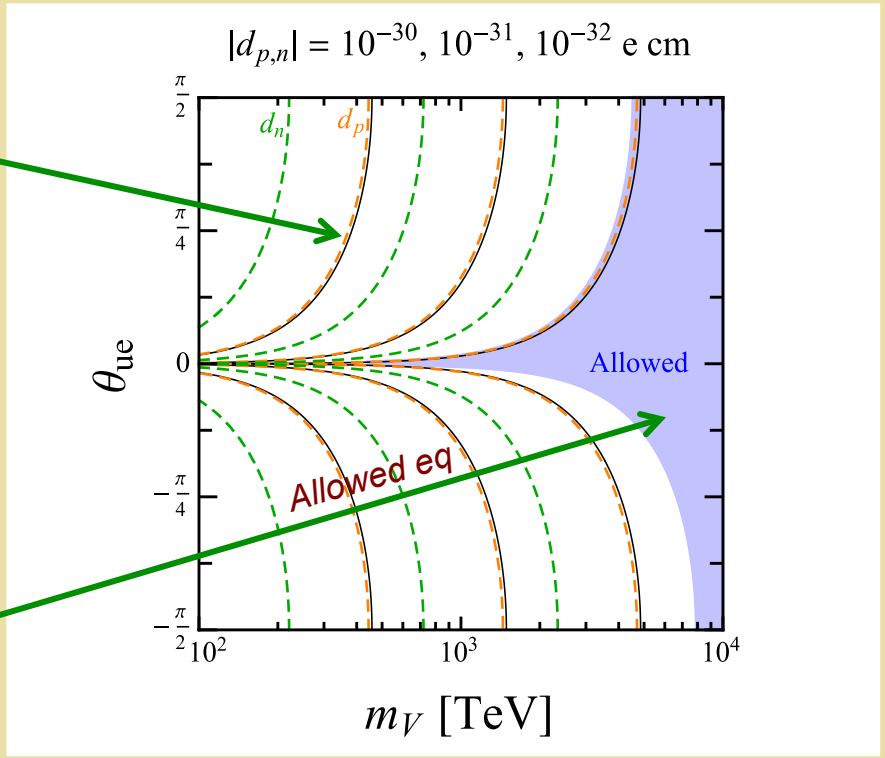




(Scalar q) x (PS e^-)







Fuyuto, R-M, Shen 1804.01137

(3, 2, 7/6)

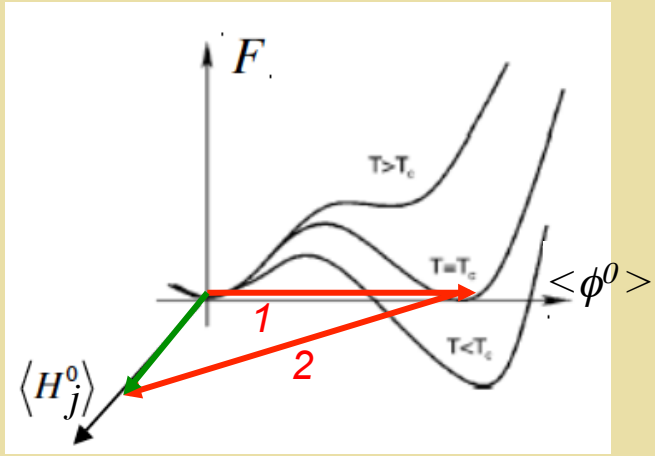
$$\mathcal{L} \ni -\lambda_u^{ab} \bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab} \bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

IV. Outlook

- *Searches for permanent EDMs of atoms, molecules, hadrons and nuclei provide powerful probes of BSM physics at a range of mass scales and constitute important tests of weak scale baryogenesis*
- *Studies on complementary systems is essential for first finding and then disentangling new CPV*
- *There exists a rich interplay between EDM searches and the quest to discover BSM physics at the Energy and Cosmic frontiers*
- *The next decade could yield exciting discoveries that provide a new window on some of the most compelling open questions in science* $\rightarrow$ *Stay tuned !*

Back Up Slides

Two-Step EW Baryogenesis



H_j *St'd Model Scalar Sector*

ϕ *BSM Scalar Sector: at least one $SU(2)_L$ non-singlet plus possibly gauge singlets ("partially secluded sector")*

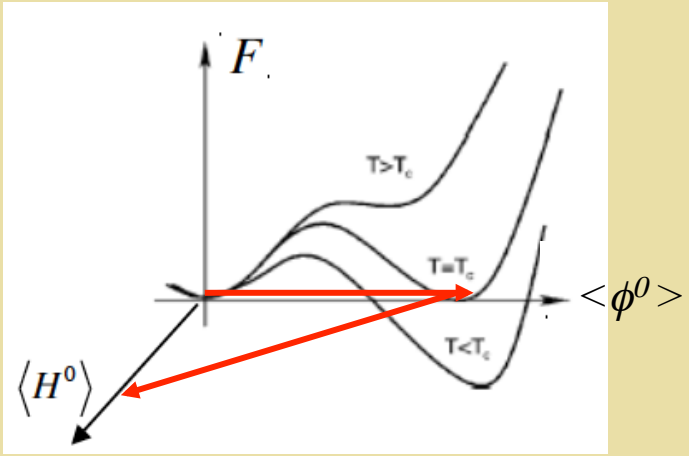
→ *Conventional one step EWSB*

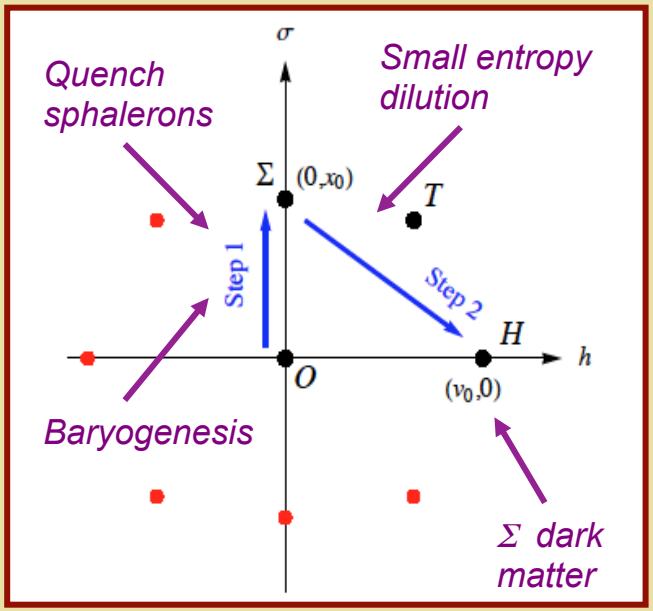
→ *Two step EWSB*

BSM CPV in ϕ H interactions: baryogenesis during step 1

Inoue, Ovanesyan, R-M: 1508.05404; Patel & R-M: 1212.5652; Blinov, Kozaczuk, Morrissey: 1504.05195

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*

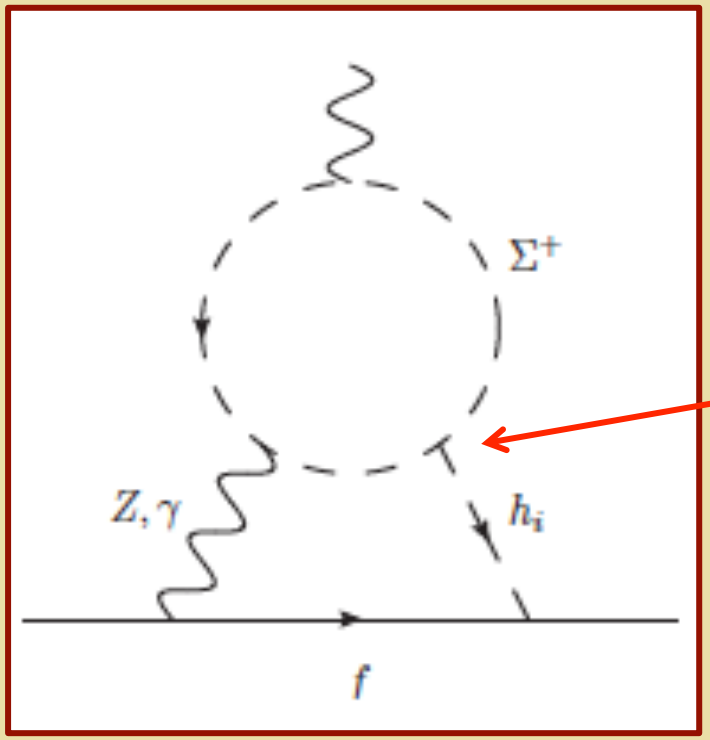
(SUSY: "TNMSSM", Coriano…)

Two CPV Phases:

δ_Σ : *Triplet phase*

δ_S : *Singlet phase*

Two-Step EW Baryogenesis & EDMs



EDMs are Two Loop

Two CPV Phases:

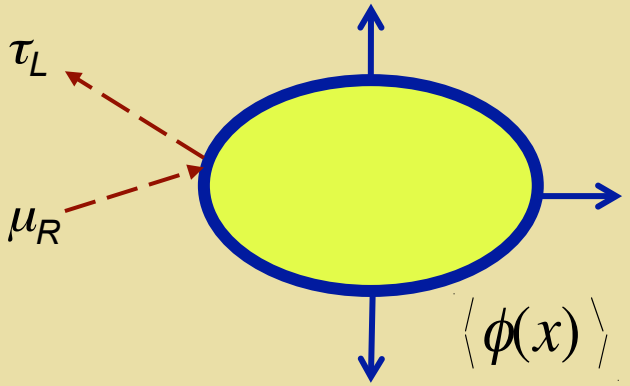
δ_Σ : *Triplet phase*

δ_S : *Singlet phase*

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

Inoue, Ovanesyan, R-M: 1508.05404

Flavored EW Baryogenesis



Flavor basis (high T)

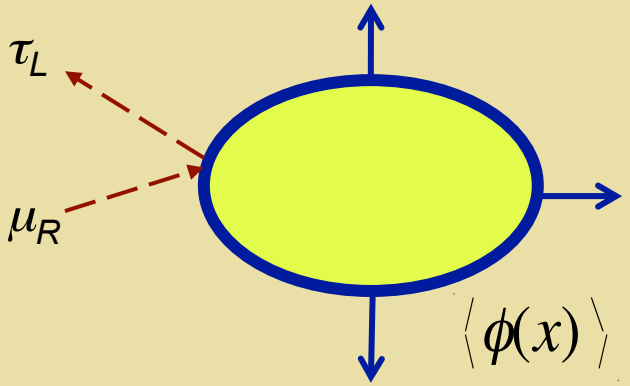
$$\mathscr{L}^{\text{Lepton}}_{\text{Yukawa}} = -\overline{E^i_L}\left[(Y^E_1)_{ij}\Phi_1 + (Y^E_2)_{ij}\Phi_2\right] e^j_R + h.c.$$

Mass basis (T=0)

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

Guo, Li, Liu, R-M, Shu 1609.09849
Chiang, Fuyuto, Senaha 1607.07316

Flavored EW Baryogenesis



Jarlskog invariant

$$J_A = \frac{1}{v^2 \mu_{12}^{\rm HB}} \sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc} {\rm Tr}\left[Y_c Y_a^\dagger\right]$$

T=0 Higgs couplings

Im (y_τ) ~ Im (J_A)

EWBG CPV Source

S^{CPV} ~ Im (J_A)

Flavor basis (high T)

$$\mathscr{L}^{\rm Lepton}_{\rm Yukawa} = -\overline{E_L^i}\left[(Y_1^E)_{ij}\Phi_1 + (Y_2^E)_{ij}\Phi_2\right] e_R^j + h.c.$$

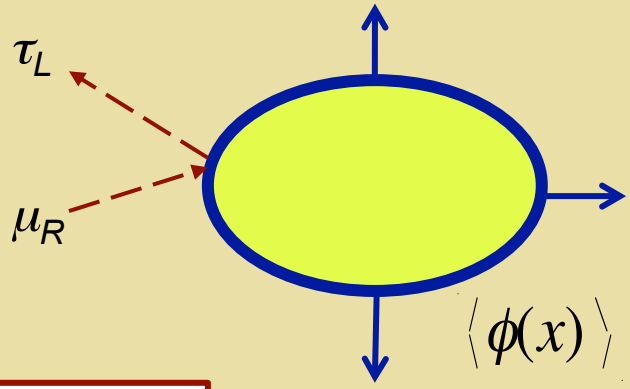
Mass basis (T=0)

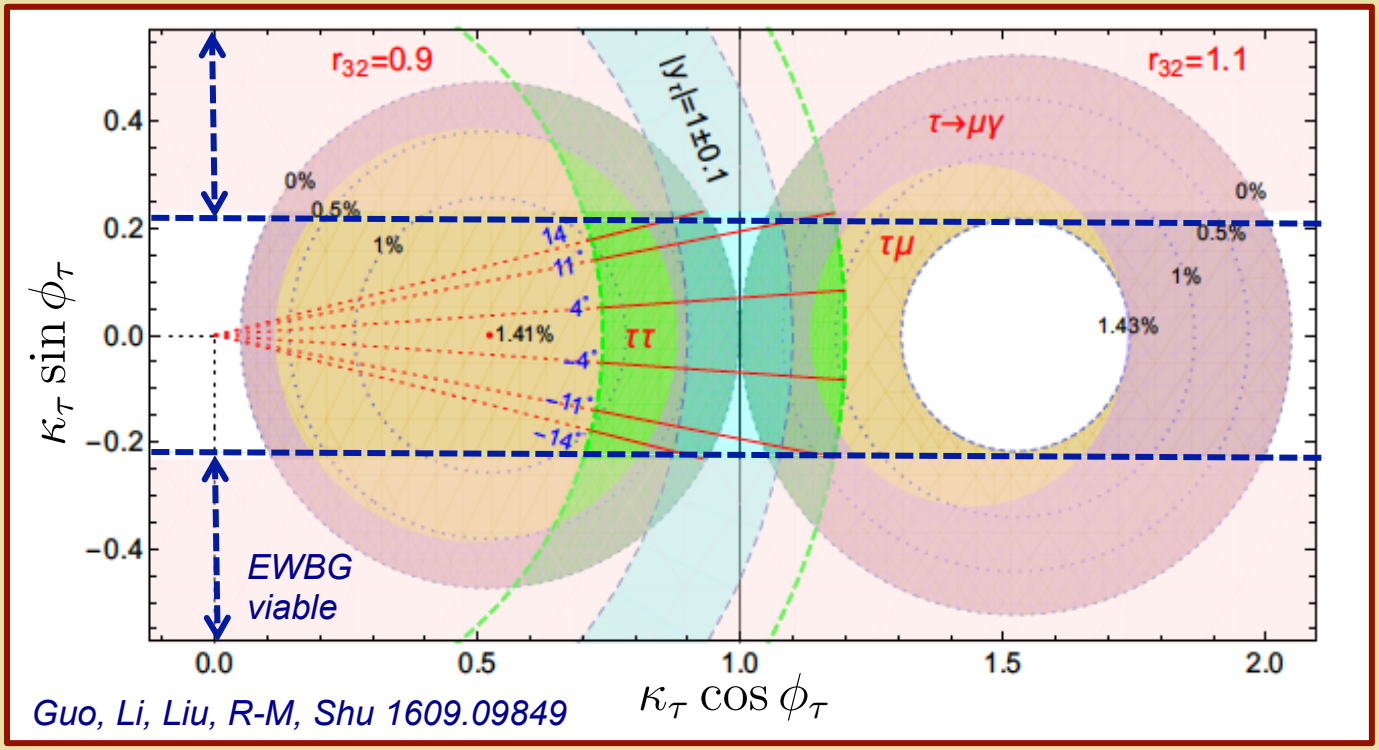
CPV $h \to \tau\tau$

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

Guo, Li, Liu, R-M, Shu 1609.09849
Chiang, Fuyuto, Senaha 1607.07316

Flavored EW Baryogenesis





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

$\Delta\phi_\tau \sim 10^o$:

3 ab^{-1} @ LHC 14

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

$$
\begin{aligned}
V &= \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] \\
&\quad -\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.
\end{aligned}
$$

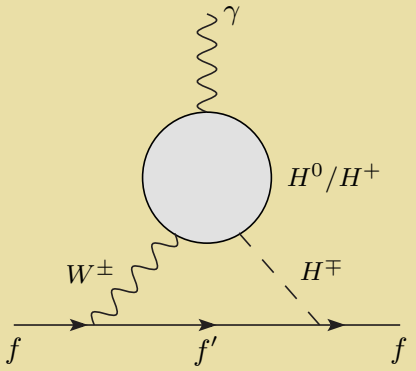
$$
\begin{aligned}
\delta_1 &= \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] , \\
\delta_2 &= \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]
\end{aligned}
$$

EWSB

$$
\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1
$$

$h, H^0, A^0 \rightarrow h_{1,2,3}$

$$
\begin{pmatrix}
-s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\
s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\
s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c}
\end{pmatrix}
$$



Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

$$
\begin{aligned}
V &= \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] \\
&\quad -\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.
\end{aligned}
$$

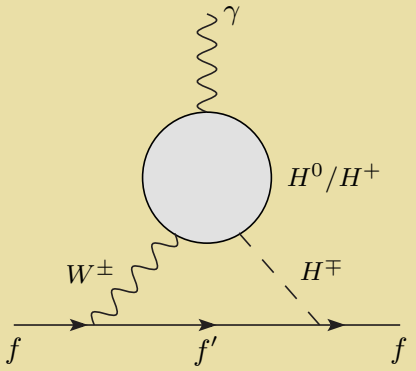
$$
\begin{aligned}
\delta_1 &= \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] , \\
\delta_2 &= \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]
\end{aligned}
$$

EWSB

$$
\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1
$$

$h, H^0, A^0 \rightarrow h_{1,2,3}$

$$
\begin{pmatrix}
-s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\
s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\
s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c}
\end{pmatrix}
$$

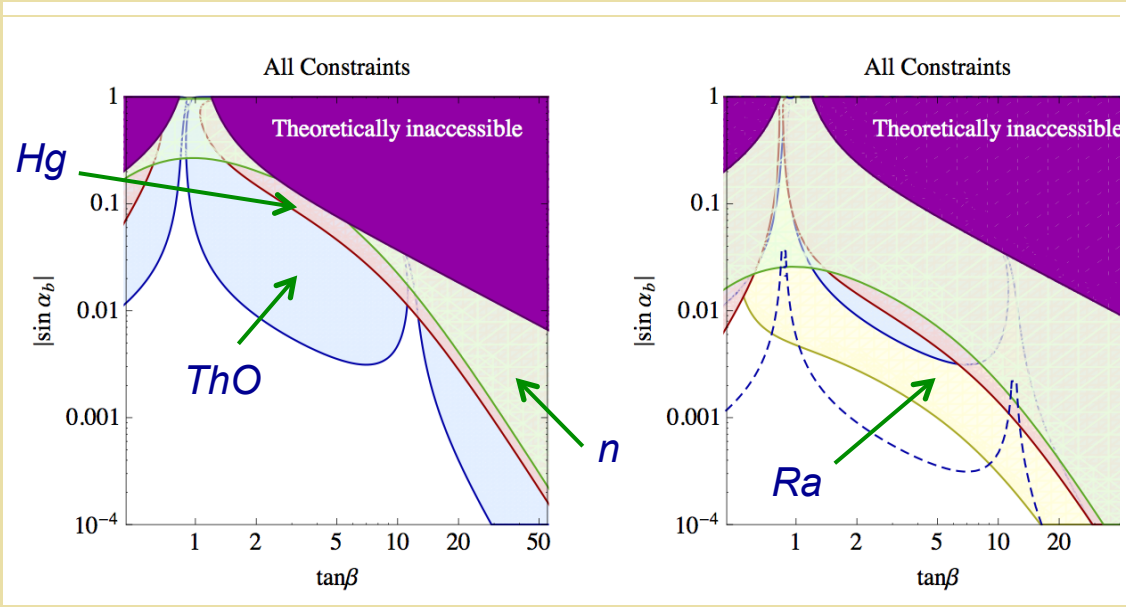


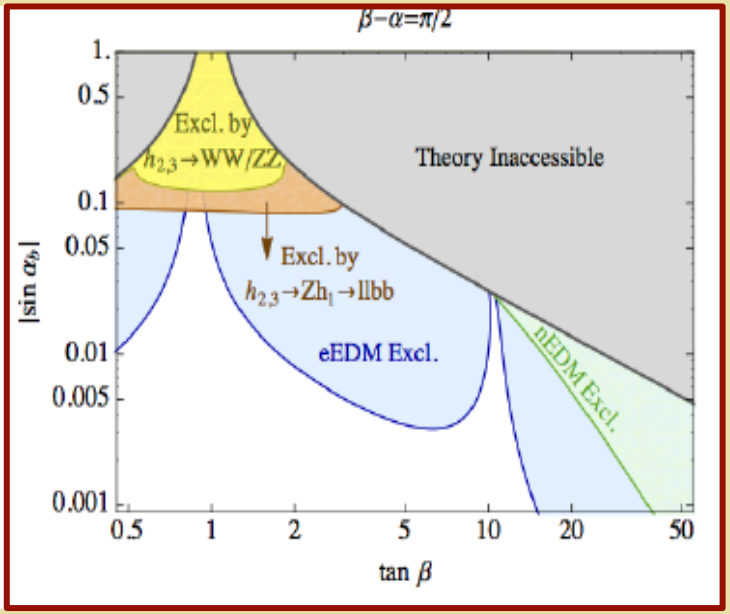
CP mixing: α_b & α_c not independent

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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





Chen, Lewis, Dawson: 1503.01114

Present → *New ThO: ACME*

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)

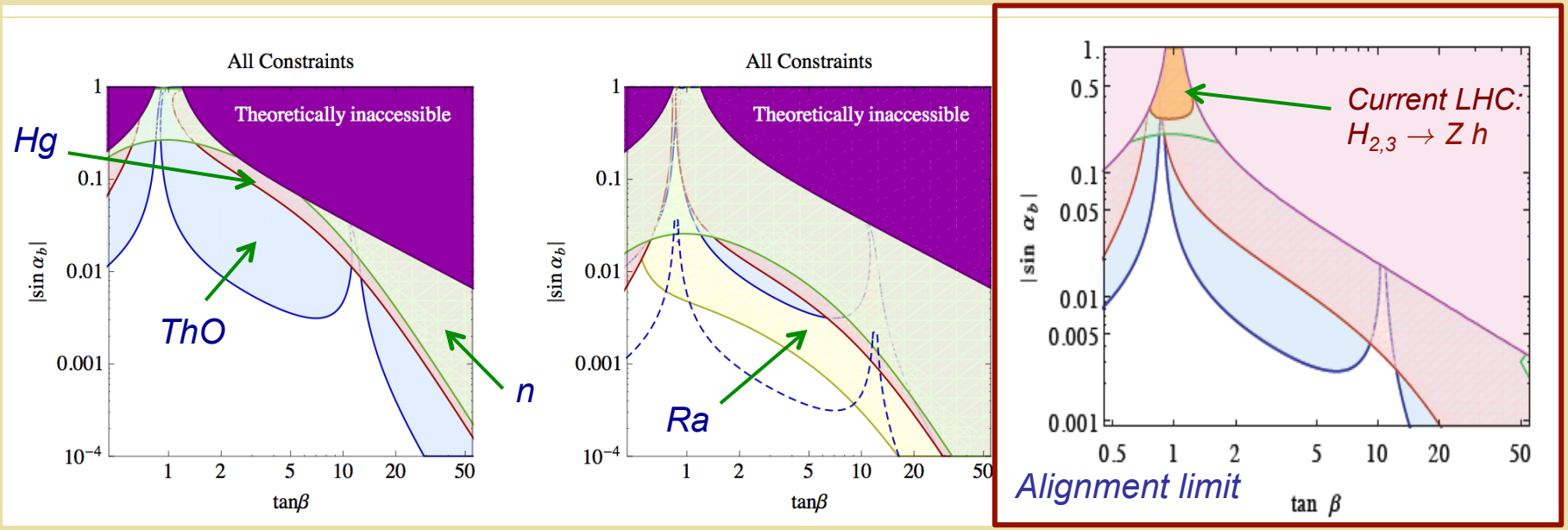
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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



Chen, Li, R-M: 1708.00435

Present → *New ThO: ACME*

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
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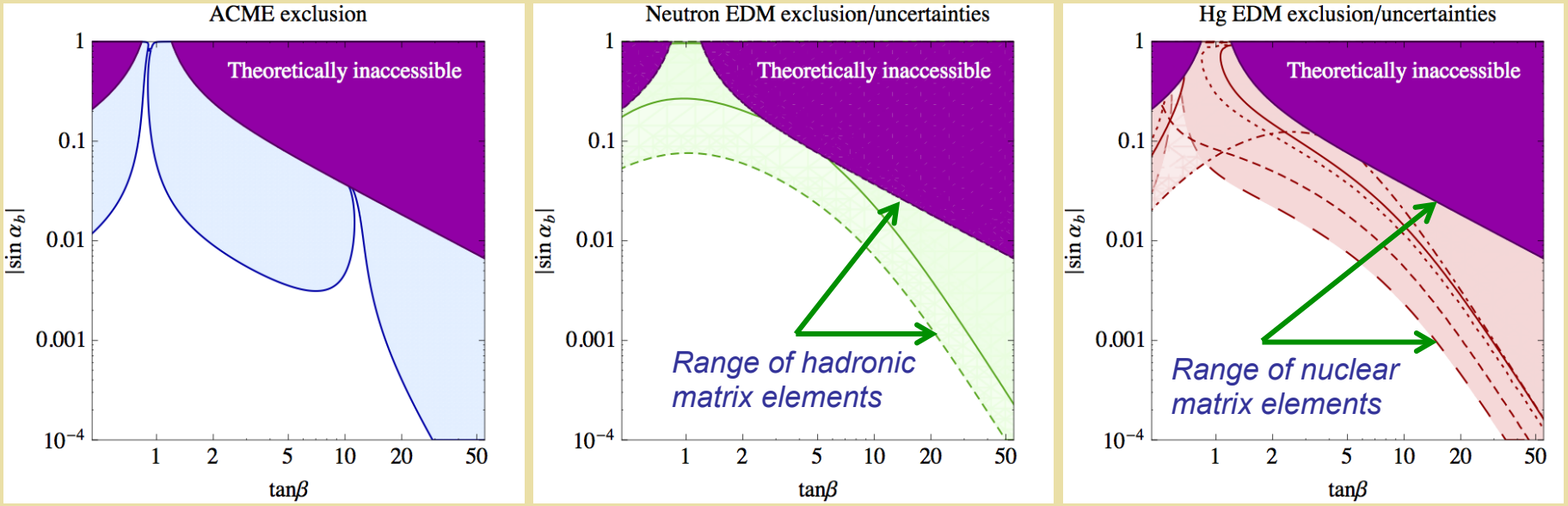
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



Present

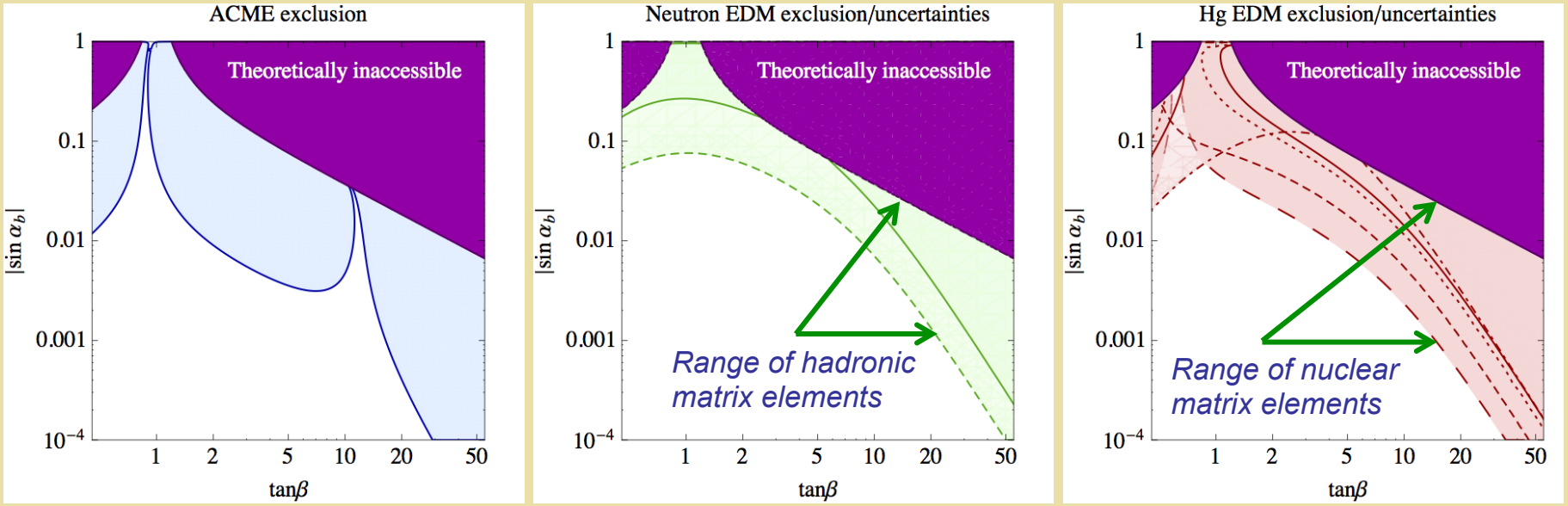
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



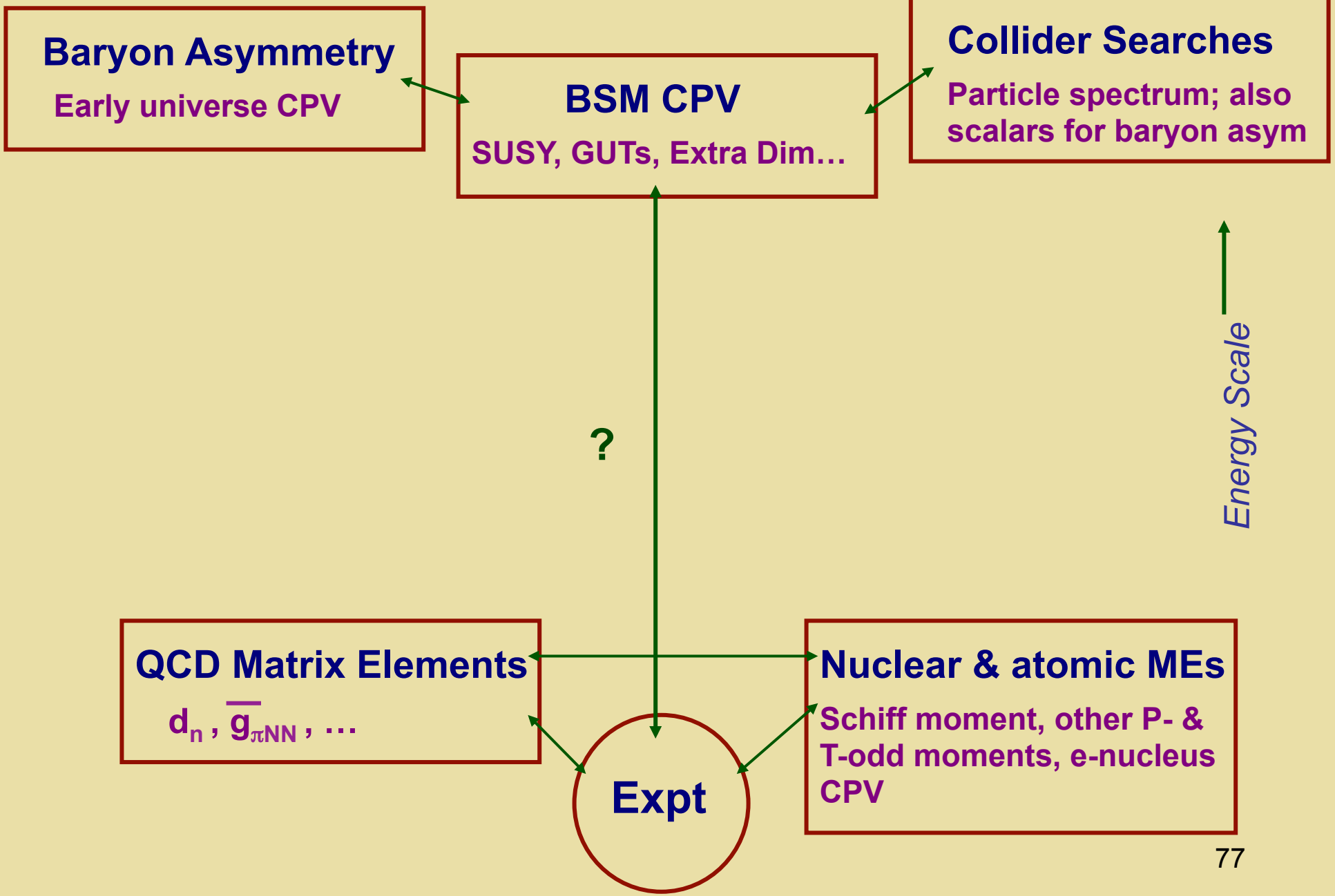
Present

Challenge

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

EDM Interpretation & Multiple Scales



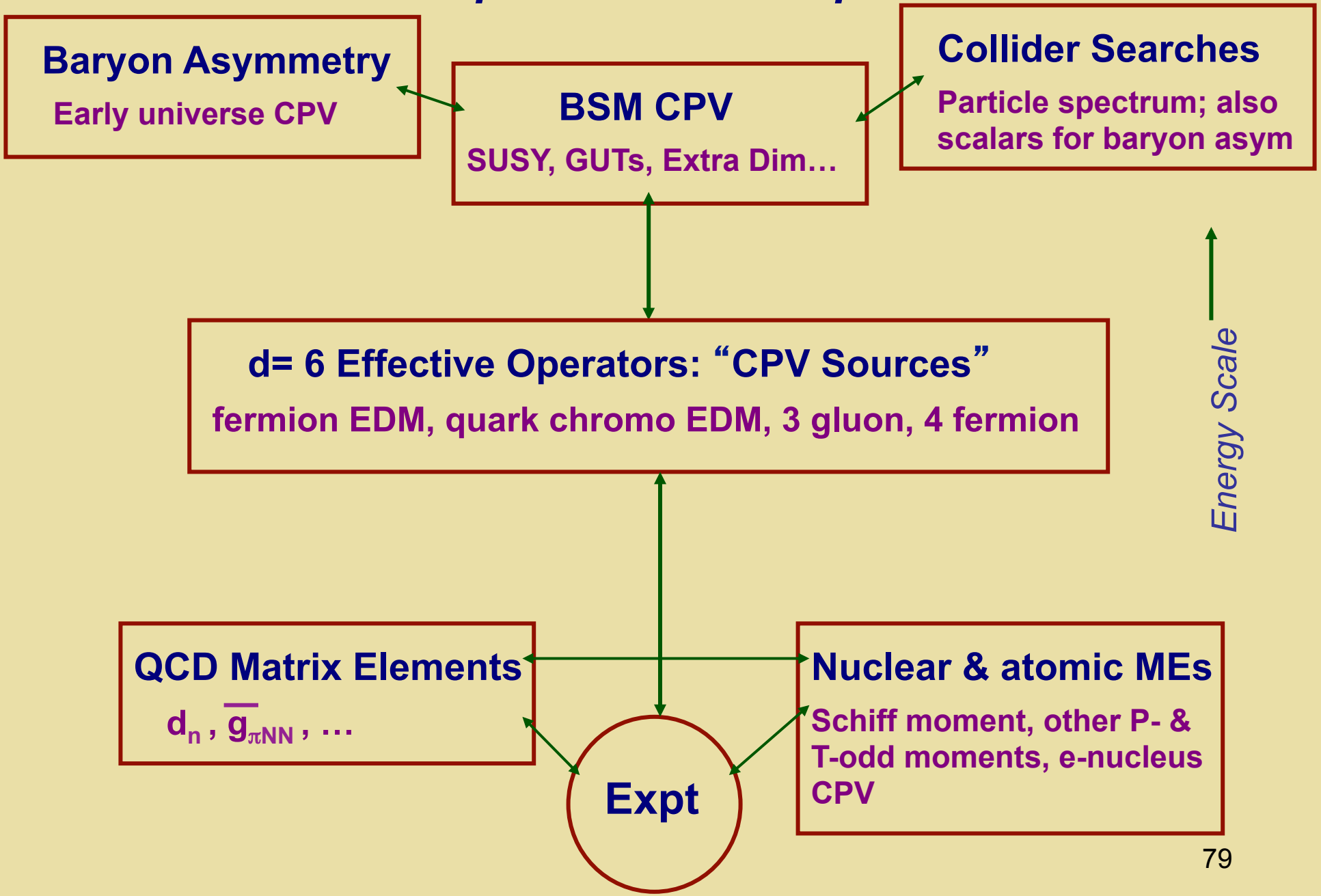
Effective Operators: The Bridge

$$\mathcal{L}_{\rm CPV} = \mathcal{L}_{\rm CKM} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}^{\rm eff}_{\rm BSM}$$

$$\mathcal{L}^{\rm eff}_{\rm BSM} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)}$$

+…

EDM Interpretation & Multiple Scales



Wilson Coefficients: Summary

δ_f	fermion EDM (3)	
$\tilde{\delta}_q$	quark CEDM (2)	
$C_{\tilde{G}}$	3 gluon	(1)
C_{quqd}	non-leptonic	(2)
$C_{lequ,\ ledq}$	semi-leptonic (3)	
$C_{\varphi ud}$	induced 4f	(1)

12 total + $\overline{\theta}$

light flavors only (e,u,d)

Complementary searches needed