

Electric Dipole Moments: A Look Beyond the Standard Model

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

<http://www.physics.umass.edu/acfi/>

PSI Symmetries Workshop
October 2016

Outline

- I. The BSM context*
- II. Electric dipole moments*
- III. EDM complementarity*
- IV. Outlook*
- V. Back up slides: challenges for hadronic & nuclear structure theory*

I. The BSM Context

EDMs & SM Physics

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

C. Seng arXiv: 1411.1476

EDMs & BSM Physics

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

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CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

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BSM mass scale: TeV ? Much higher ?

EDMs & BSM Physics

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BSM dynamics: perturbative? Strongly coupled?

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BSM dynamics: perturbative? Strongly coupled?

Hadronic & atomic systems: reliable SM calc's?

EDMs & BSM Physics

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

Need information from at least three “frontiers”

EDMs & BSM Physics

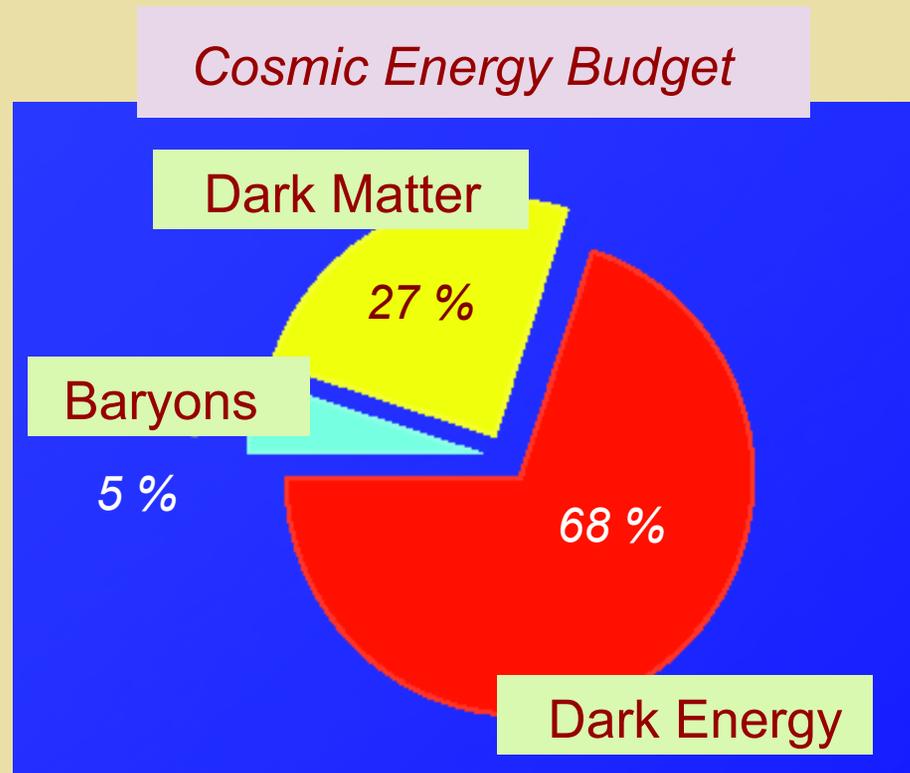
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Need information from at least three “frontiers”

- *Baryon asymmetry*
- *High energy collisions*
- *EDMs*

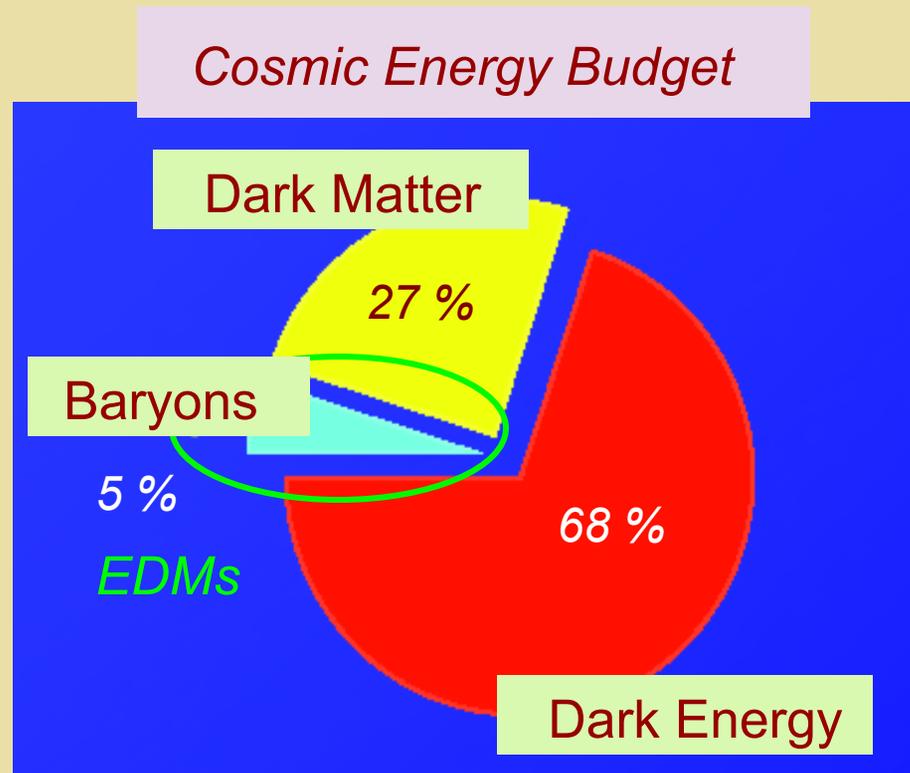
Cosmic Frontier
Energy Frontier
Intensity Frontier

The Origin of Matter



Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model

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Ingredients for Baryogenesis



Scenarios: leptogenesis, EW baryogenesis, Affleck-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis...

Testable

Standard Model

BSM

- B violation (sphalerons)
- C & CP violation
- Out-of-equilibrium or CPT violation

✓

✓

✗

EDM

✓

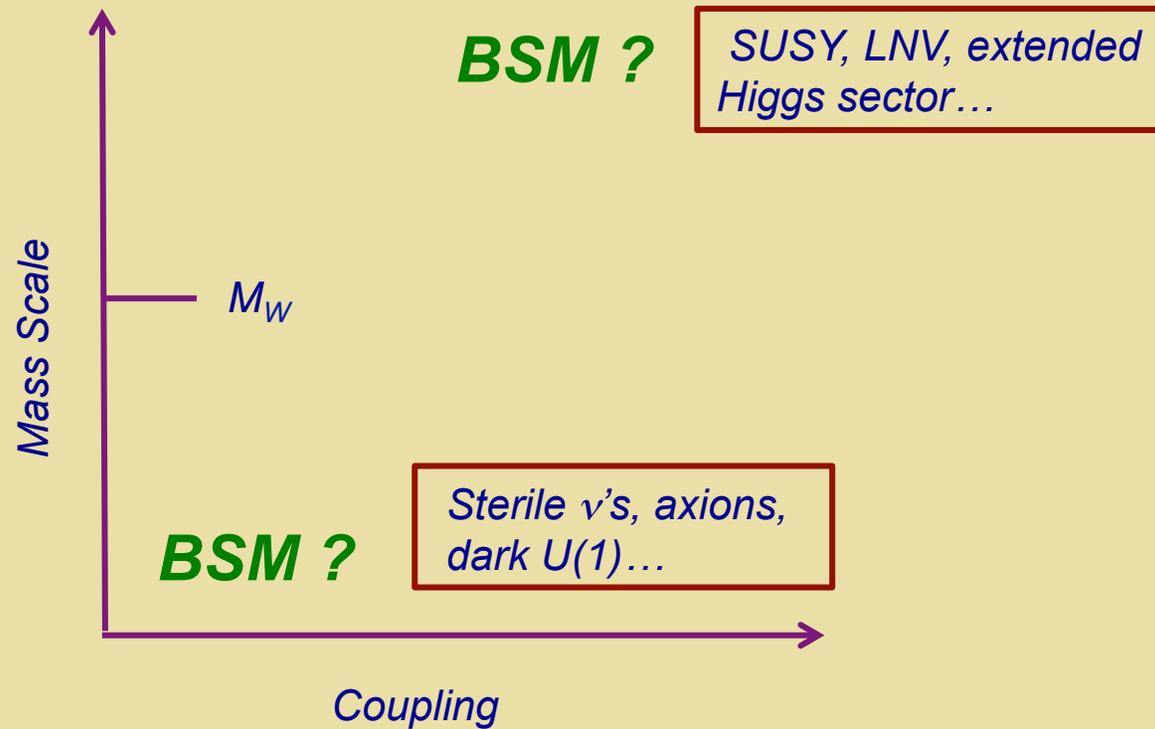
✗

✓

Electroweak Baryogenesis

Was Y_B generated in conjunction with electroweak symmetry-breaking?

BSM Physics: Where Does it Live ?



Low-Energy / High-Energy Interplay

Discovery



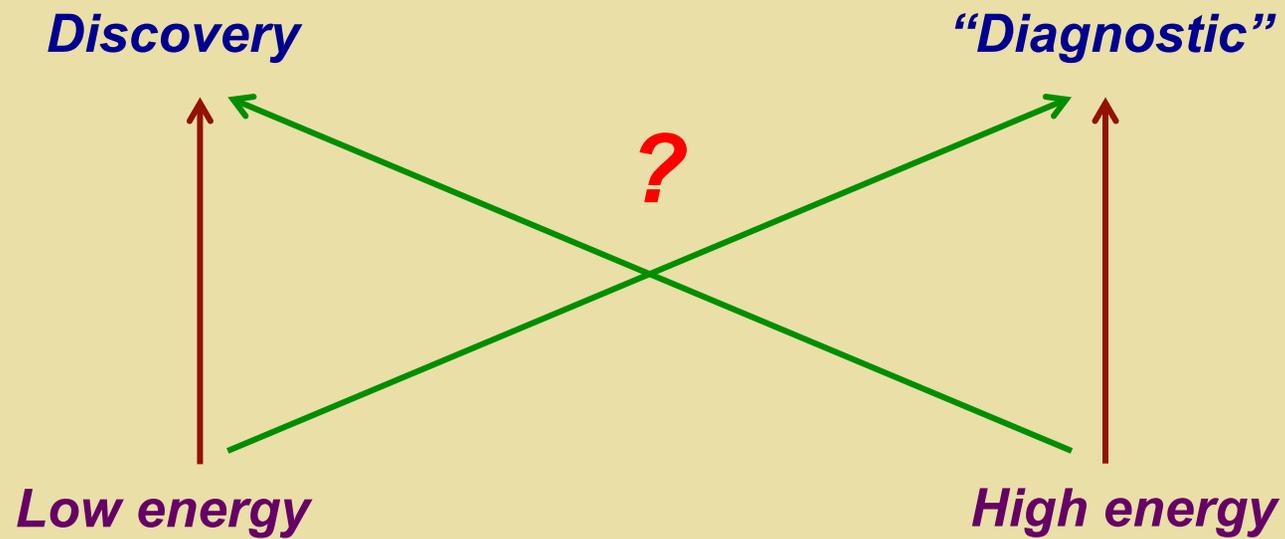
Low energy

“Diagnostic”



High energy

Low-Energy / High-Energy Interplay



II. EDMs

EDMs: New CPV?

System	Limit (e cm)[*]	SM CKM CPV	BSM CPV
¹⁹⁹Hg	7.4×10^{-30}	10^{-33}	10^{-30}
ThO	8.7×10^{-29} **	10^{-38}	10^{-29}
n	3.3×10^{-26}	10^{-31}	10^{-26}

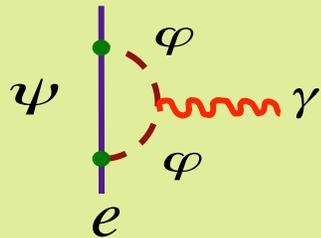
*** 95% CL ** e⁻ equivalent**

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Mass Scale Sensitivity



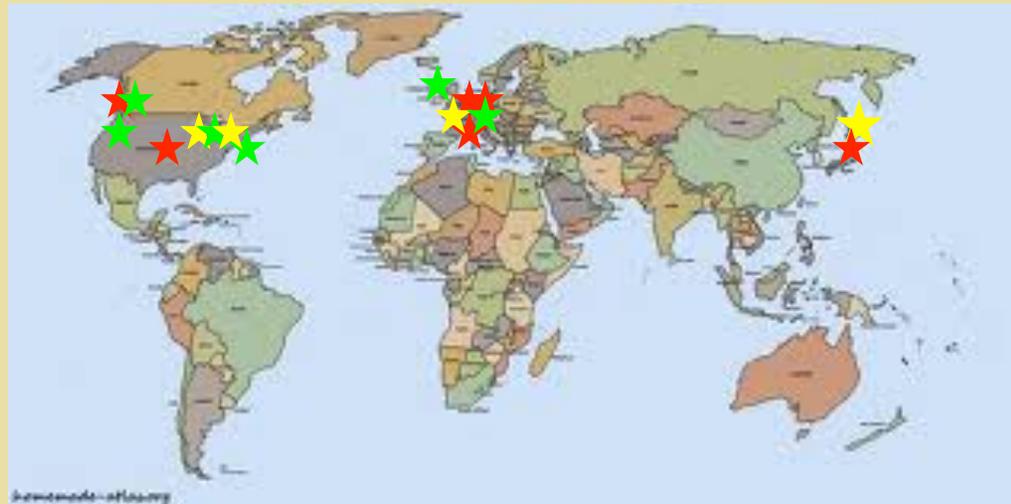
$$\sin\phi_{\text{CP}} \sim 1 \rightarrow M > 5000 \text{ GeV}$$

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

EDMs: New CPV?

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* 95% CL ** e⁻ equivalent



- ★ neutron
- ★ proton & nuclei
- ★ atoms

~ 100 x better sensitivity

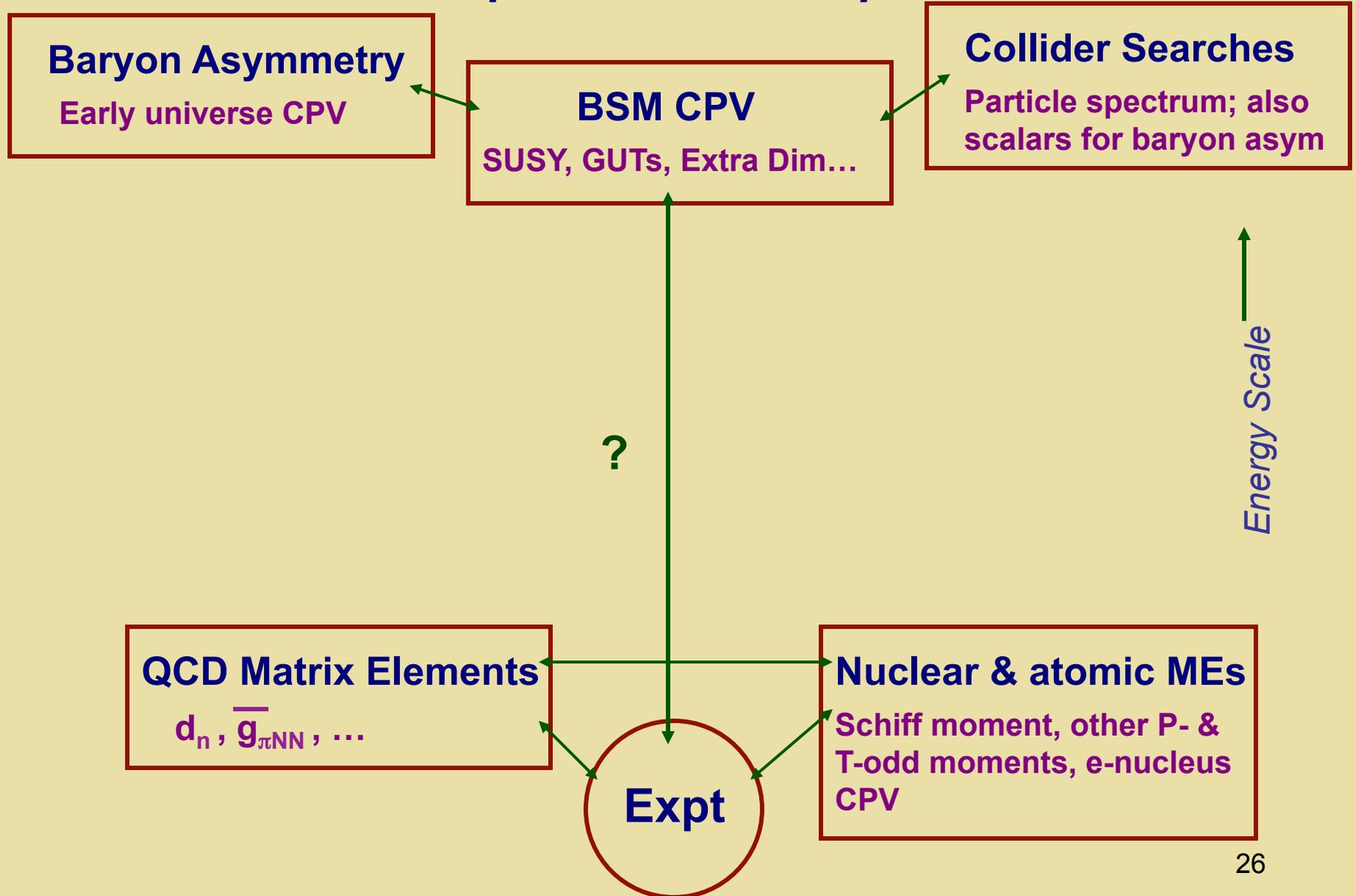
Not shown:
muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales

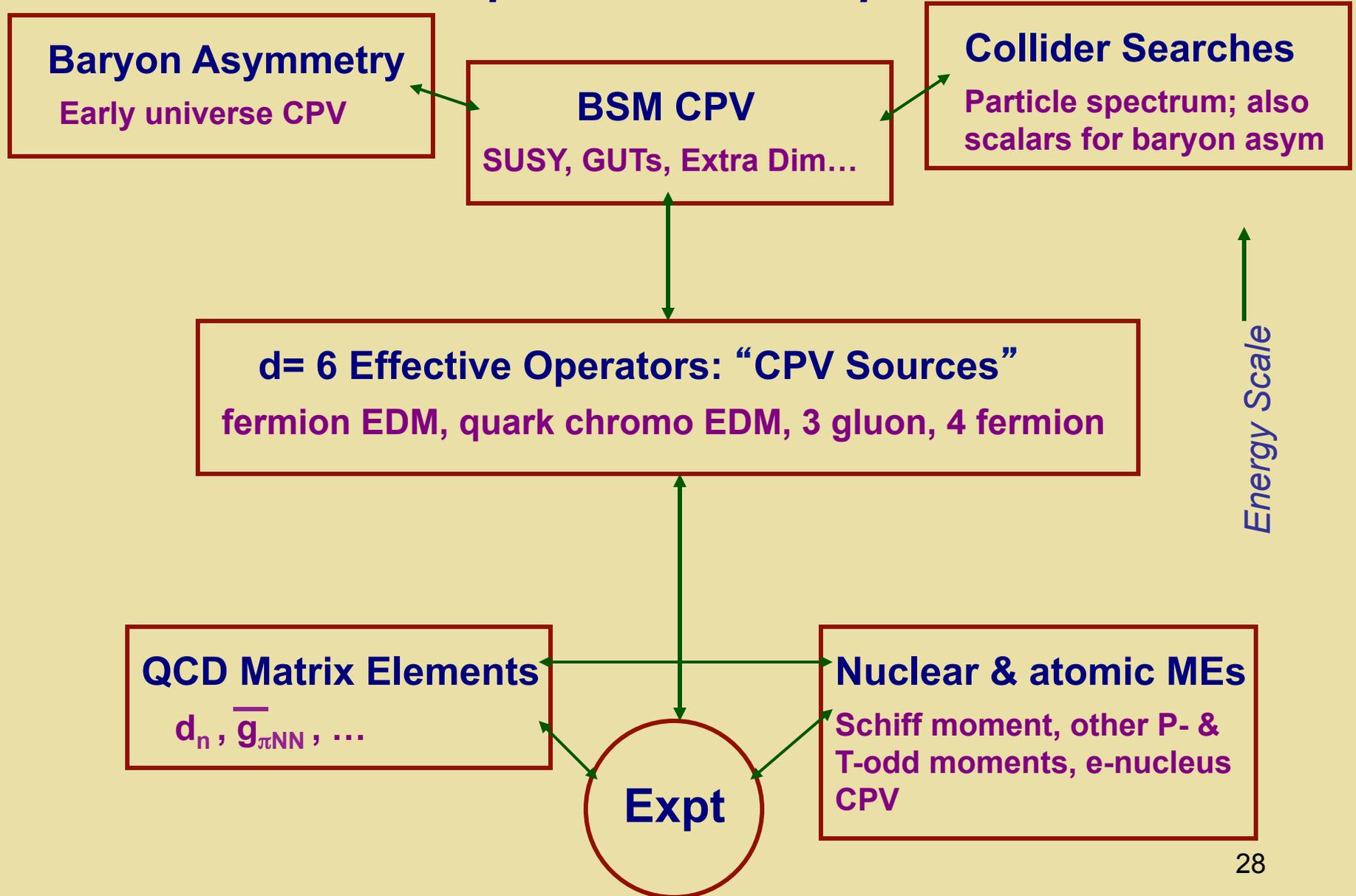


Effective Operators: The Bridge

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

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

EDM Interpretation & Multiple Scales



Wilson Coefficients: Summary

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

12 total + $\overline{\theta}$

light flavors only (e,u,d)

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Complementary searches needed

BSM Origins

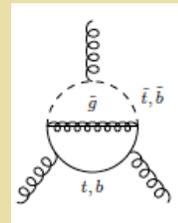
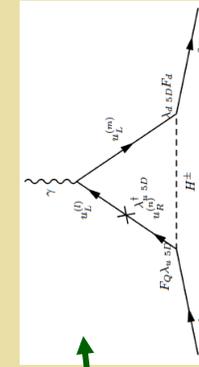
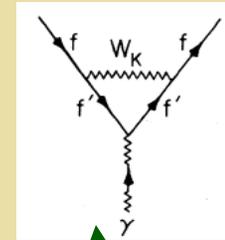
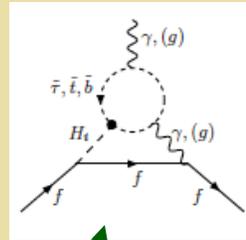
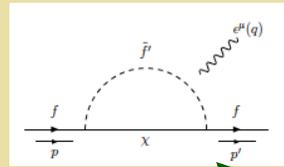
EDM: γff

CEDM: gff

Weinberg ggg :

Four fermion

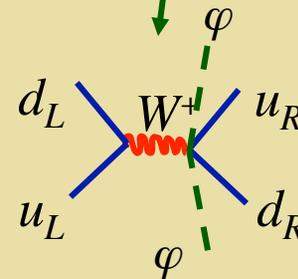
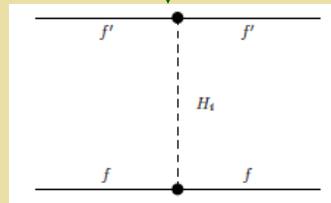
$udHH$



MSSM

LRSM

RS



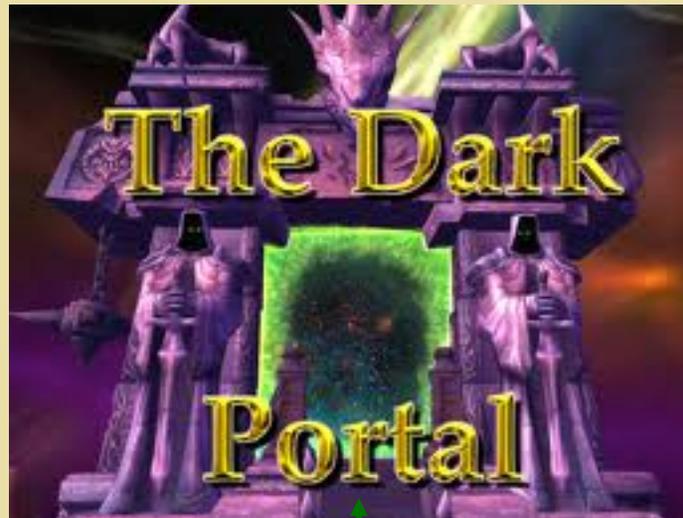
III. EDM Complementarity

- *CPV in an extended scalar sector (2HDM): “Higgs portal CPV”*
- *Weak scale baryogenesis (MSSM)*
- *Model-independent*

The Higgs Portal

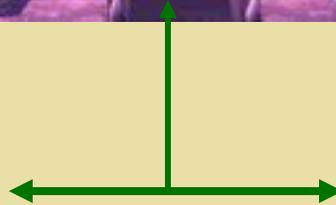


Portals & Early Universe



Standard Model

Hidden Sector



New CPV ?

Higgs Portal CPV

Inoue, R-M, Zhang:
1403.4257

CPV & 2HDM: Type I & II

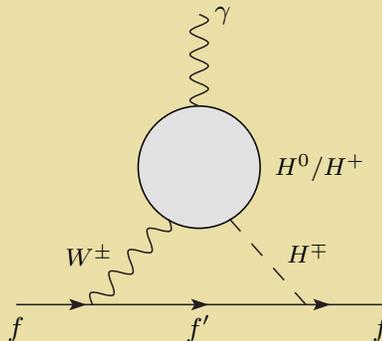
$\lambda_{6,7} = 0$ for simplicity

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

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

EWSB

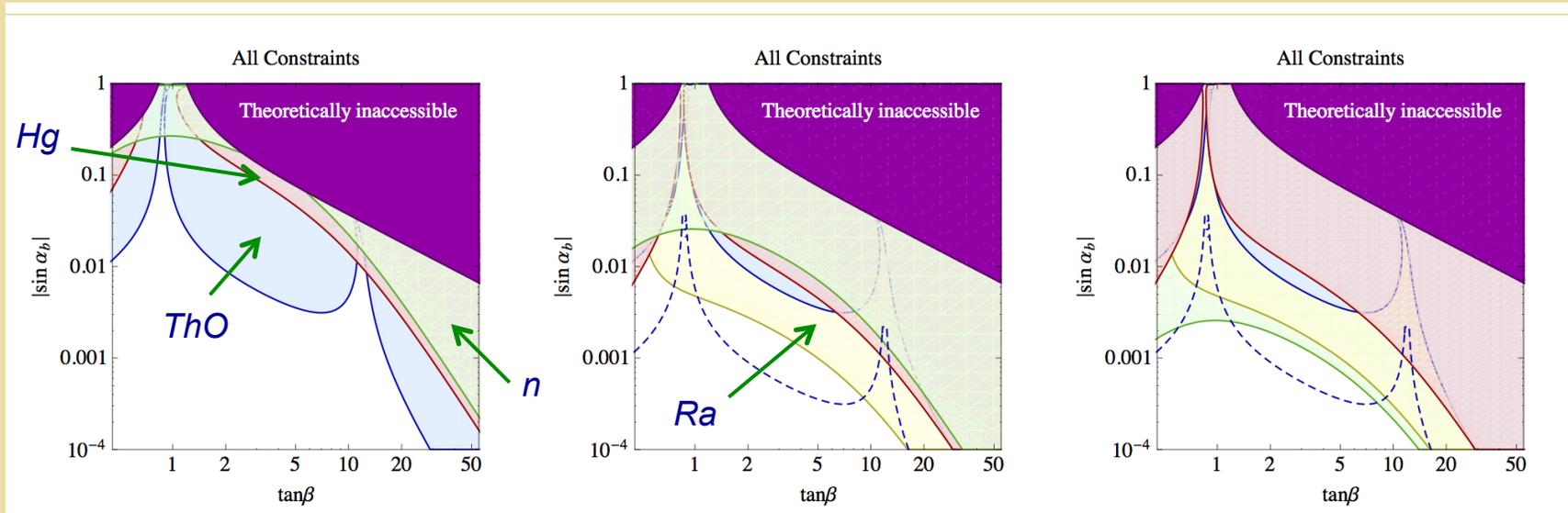
$$\delta_2 \approx \frac{1 - \left| \frac{\lambda_5 v_1 v_2}{m_{12}^2} \right|}{1 - 2 \left| \frac{\lambda_5 v_1 v_2}{m_{12}^2} \right|} \delta_1$$



Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

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



Present

$\sin \alpha_b$: CPV
scalar mixing

Future:

$d_n \times 0.1$
 $d_A(Hg) \times 0.1$
 $d_{ThO} \times 0.1$
 $d_A(Ra) [10^{-27} \text{ e cm}]$

Future:

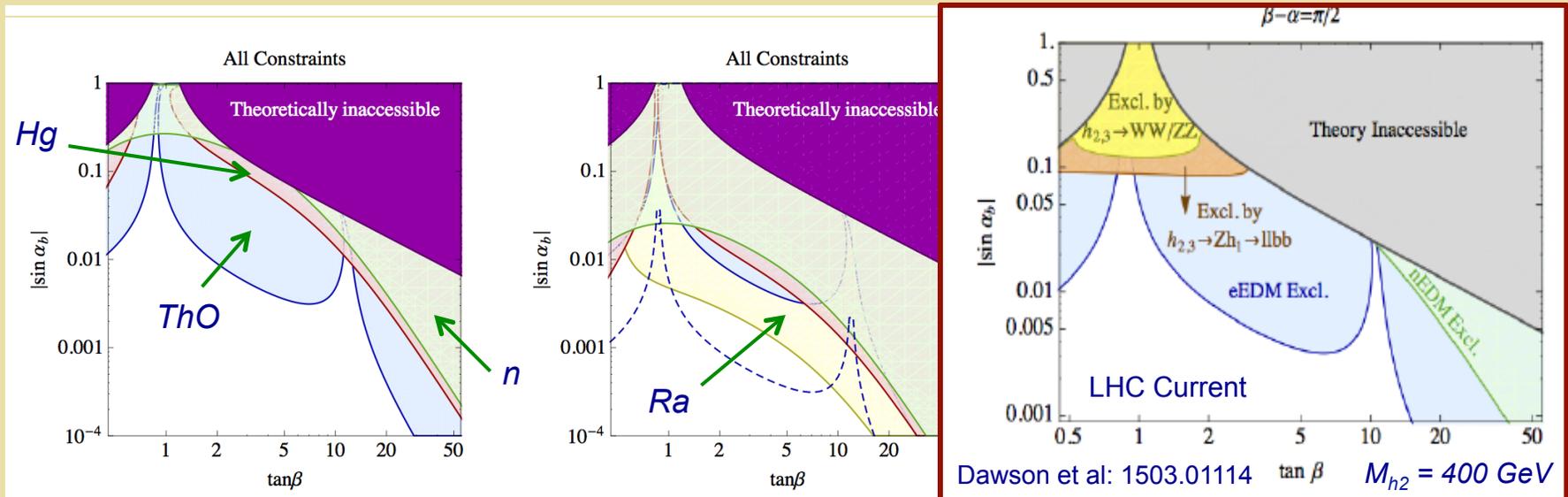
$d_n \times 0.01$
 $d_A(Hg) \times 0.1$
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Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

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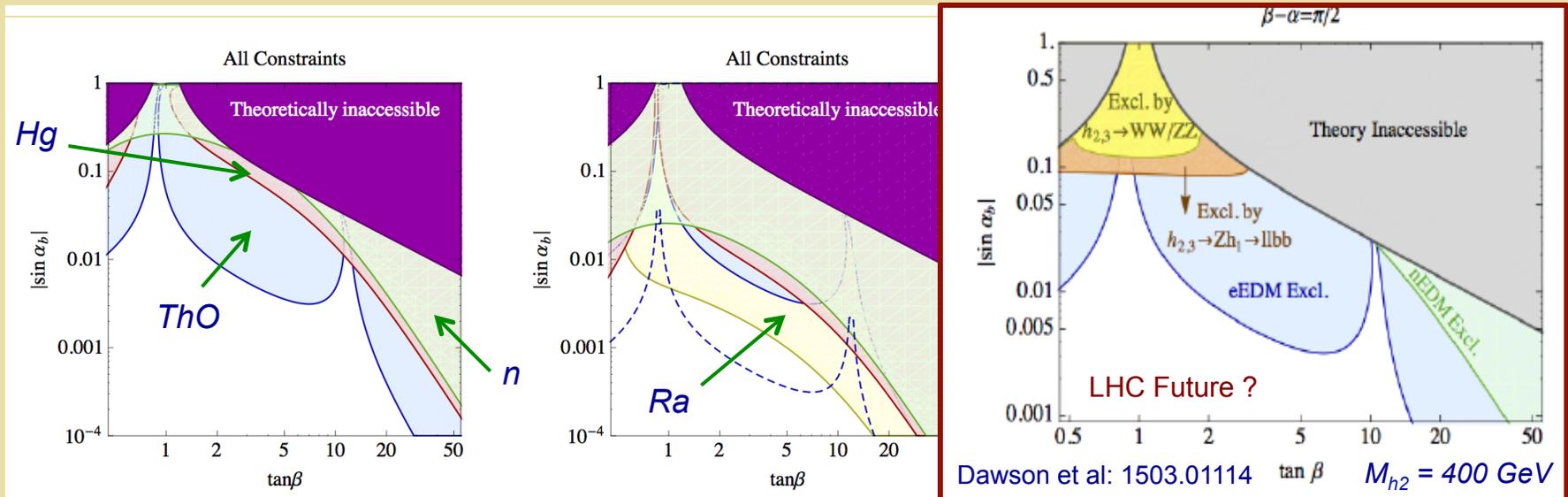
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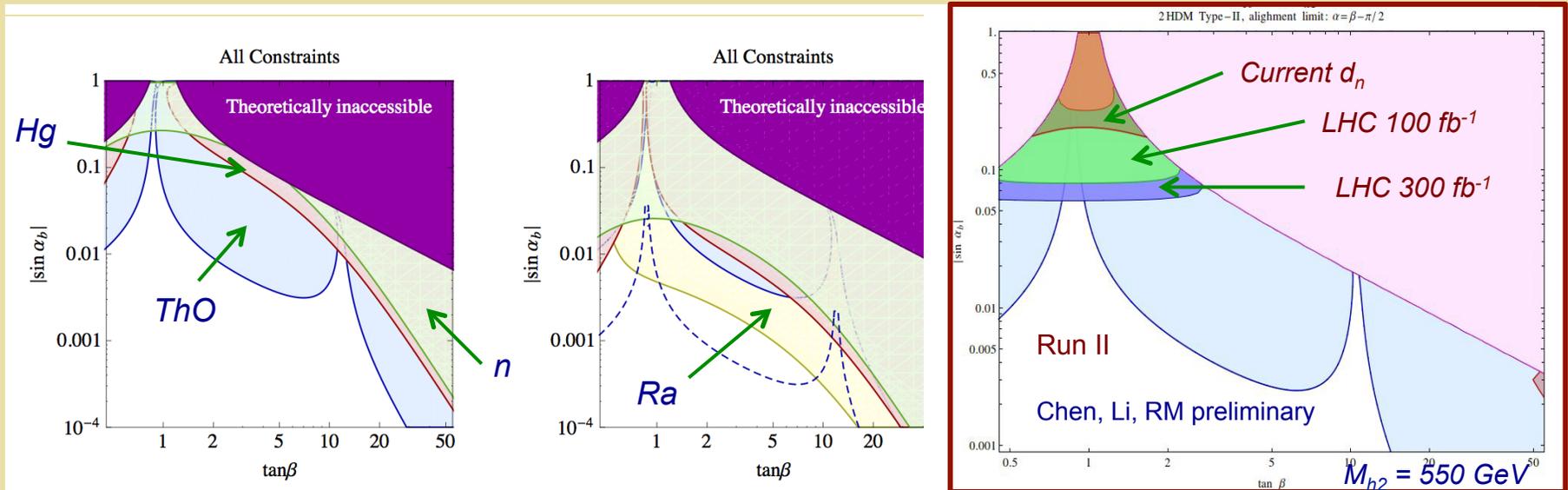
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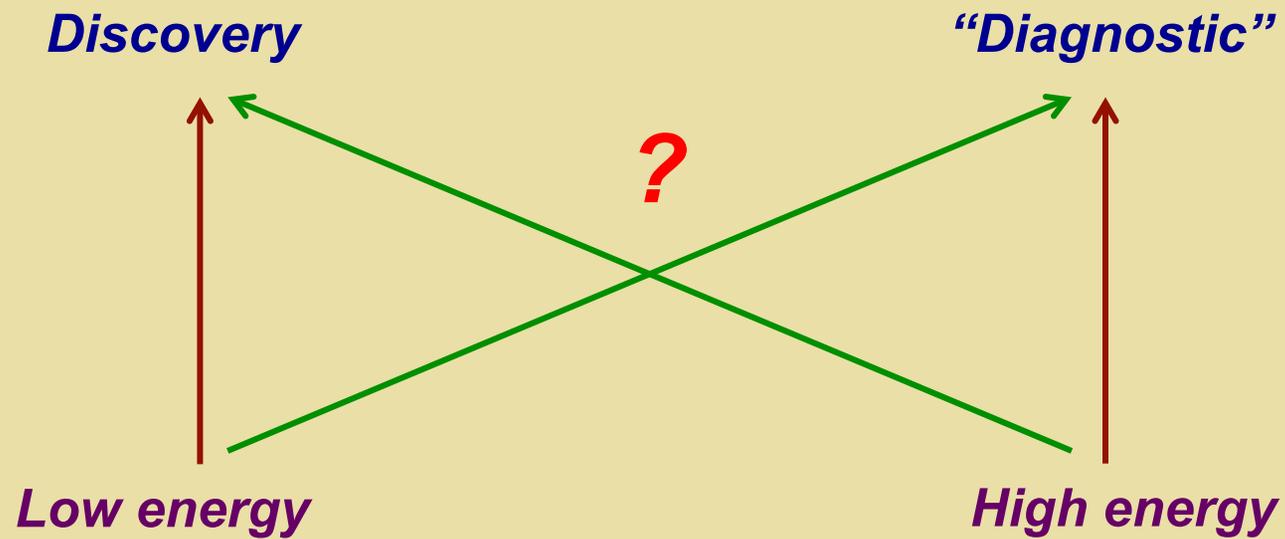
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Low-Energy / High-Energy Interplay

Higgs Portal CPV

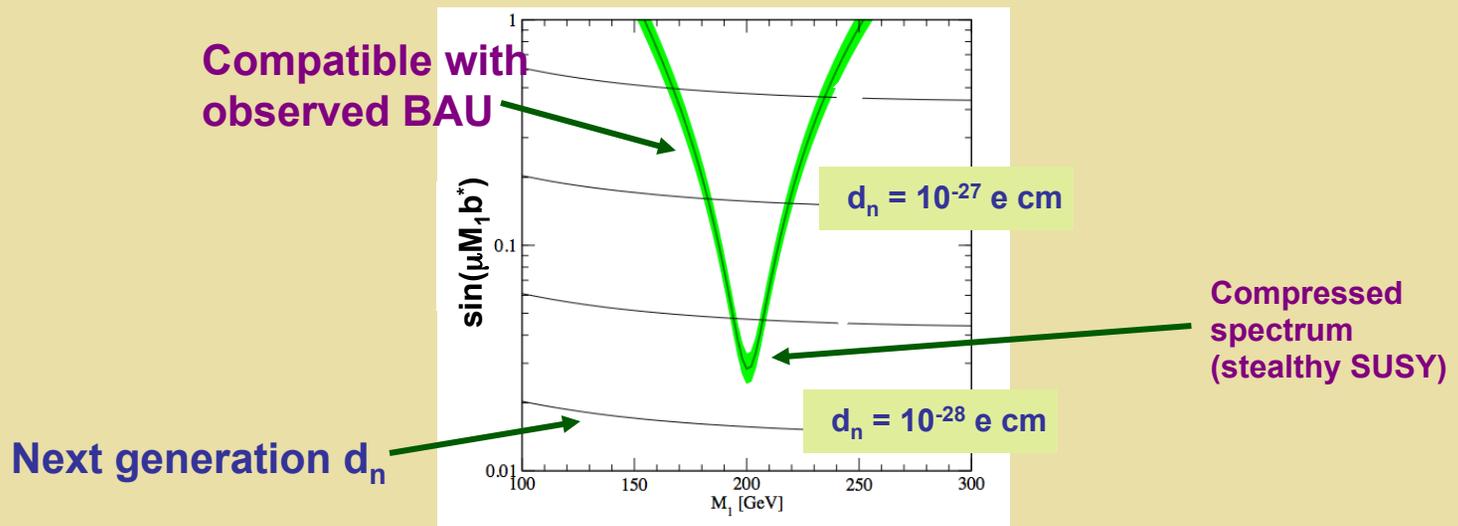


Was the baryon asymmetry produced during electroweak symmetry-breaking ?

- *EDMs provide most powerful probe of CPV*
- *Phase transition → Separate talk*

EDMs & EW Baryogenesis: MSSM

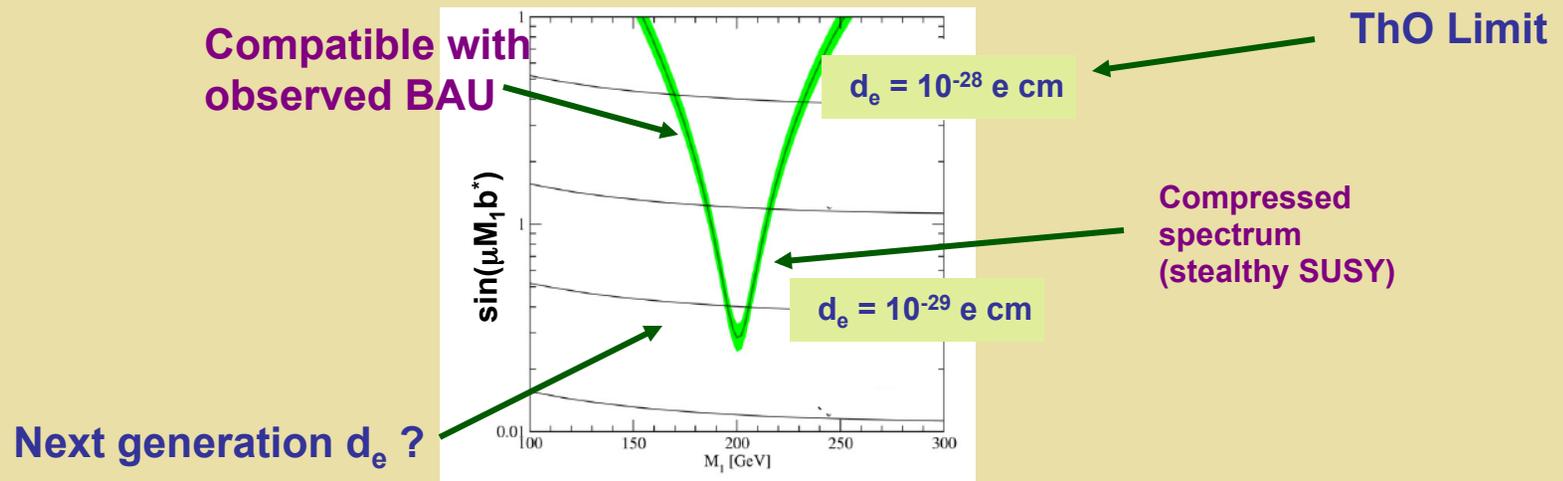
Neutron EDM



Li, Profumo, RM '09-' 10

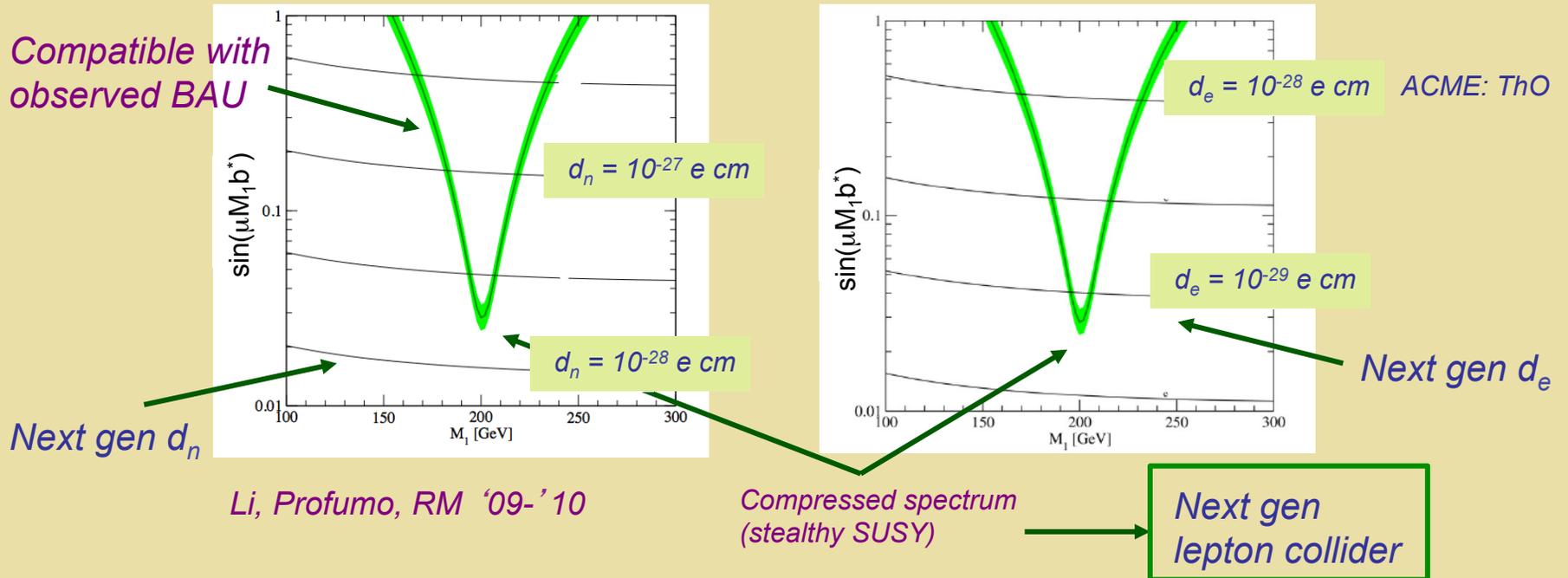
EDMs & EW Baryogenesis: MSSM

Electron EDM



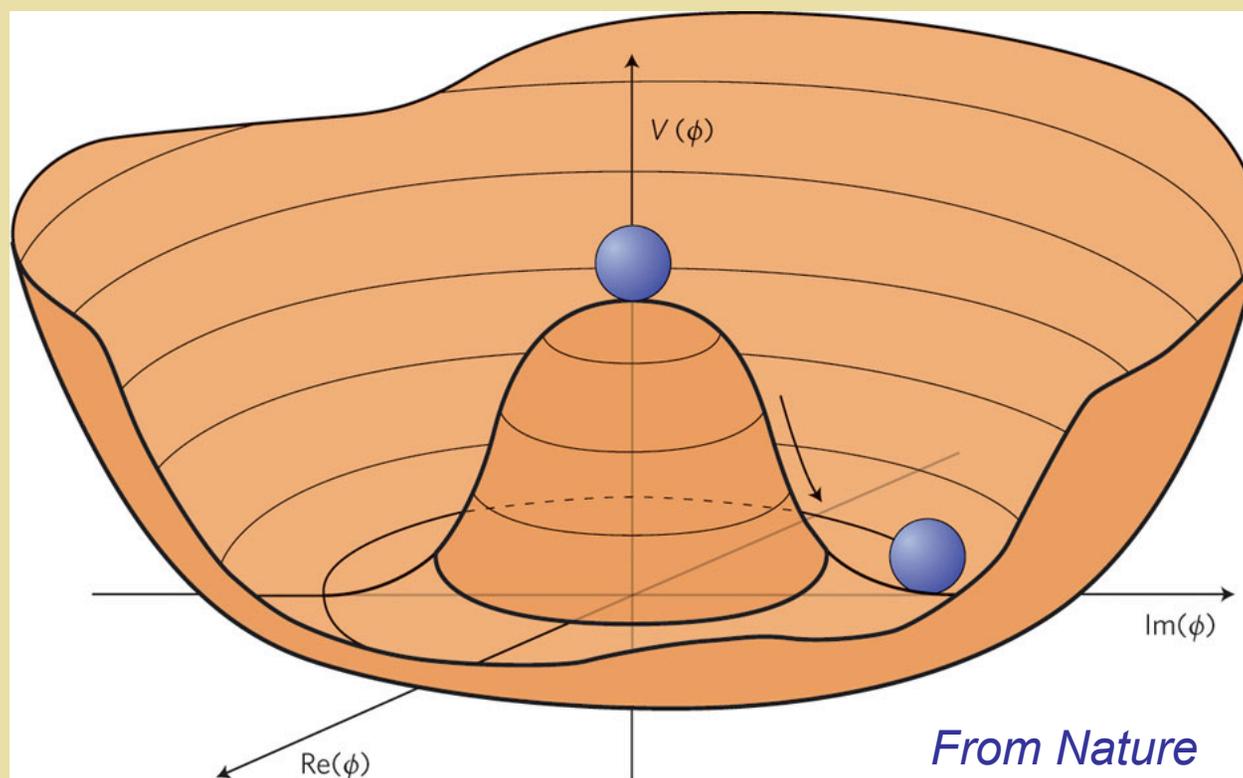
Li, Profumo, RM '09-' 10

EDMs & EW Baryogenesis: MSSM



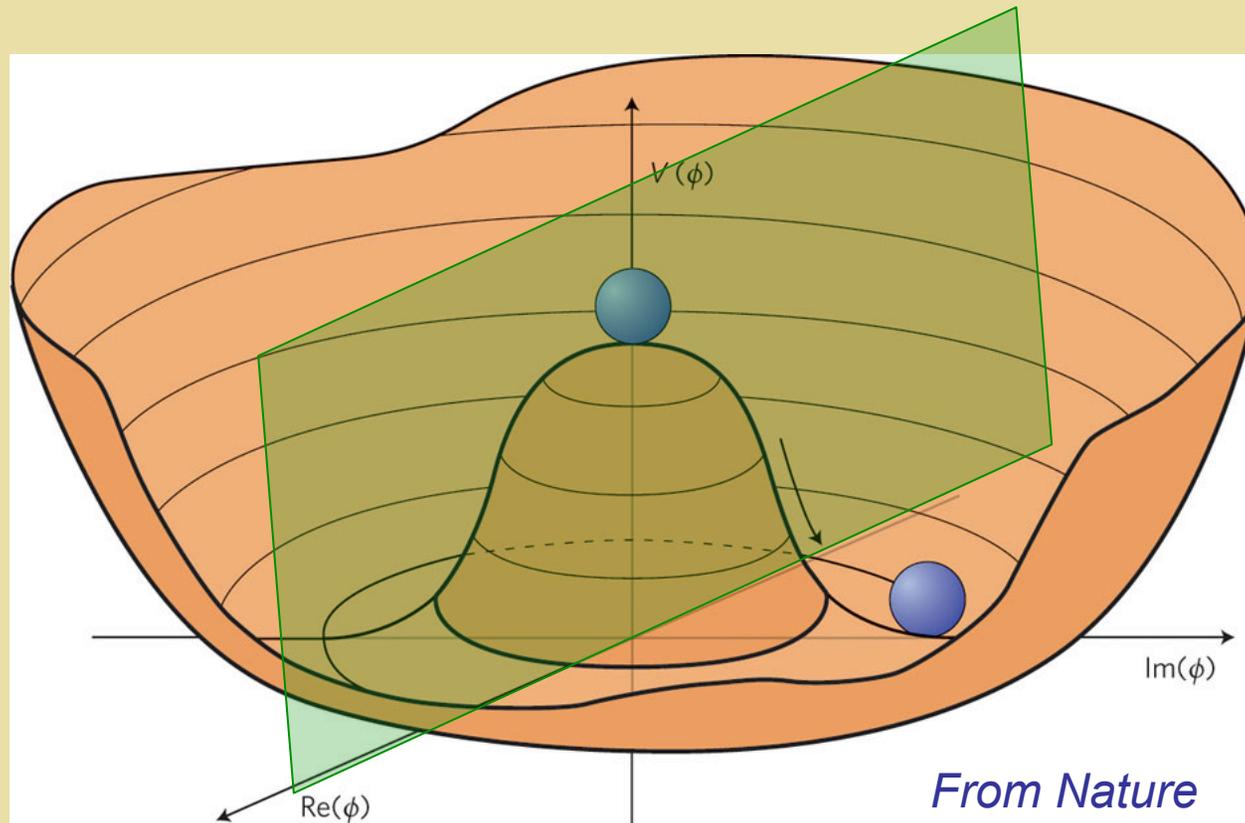
Two-Step EW Baryogenesis

EWSB: The Scalar Potential



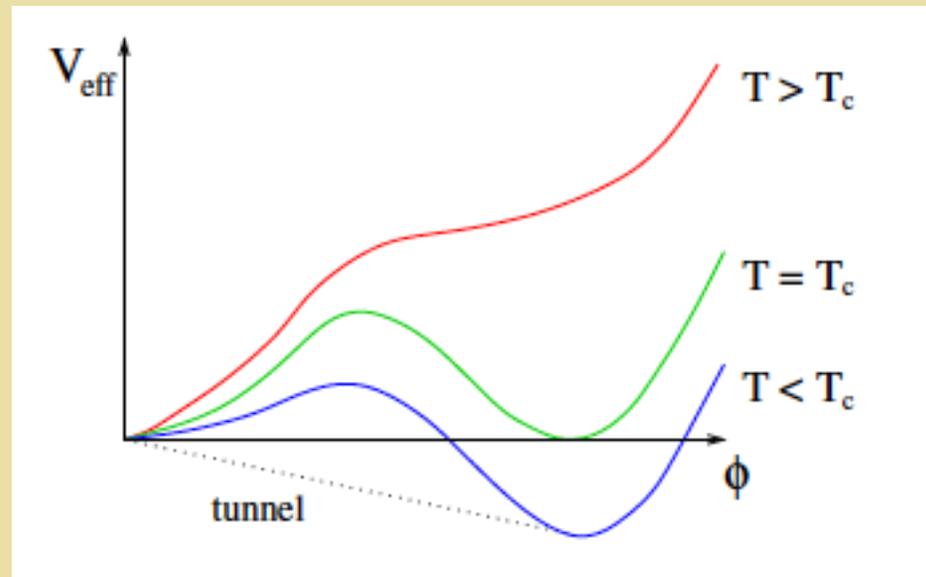
What was the thermal history of EWSB ?

EWSB: The Scalar Potential



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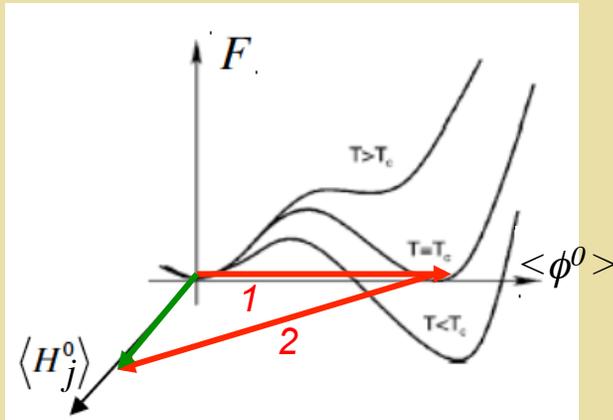
Scalar Potential: Thermal History



Single-Step EWSB

Constrained by experiment, but not the only possibility

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



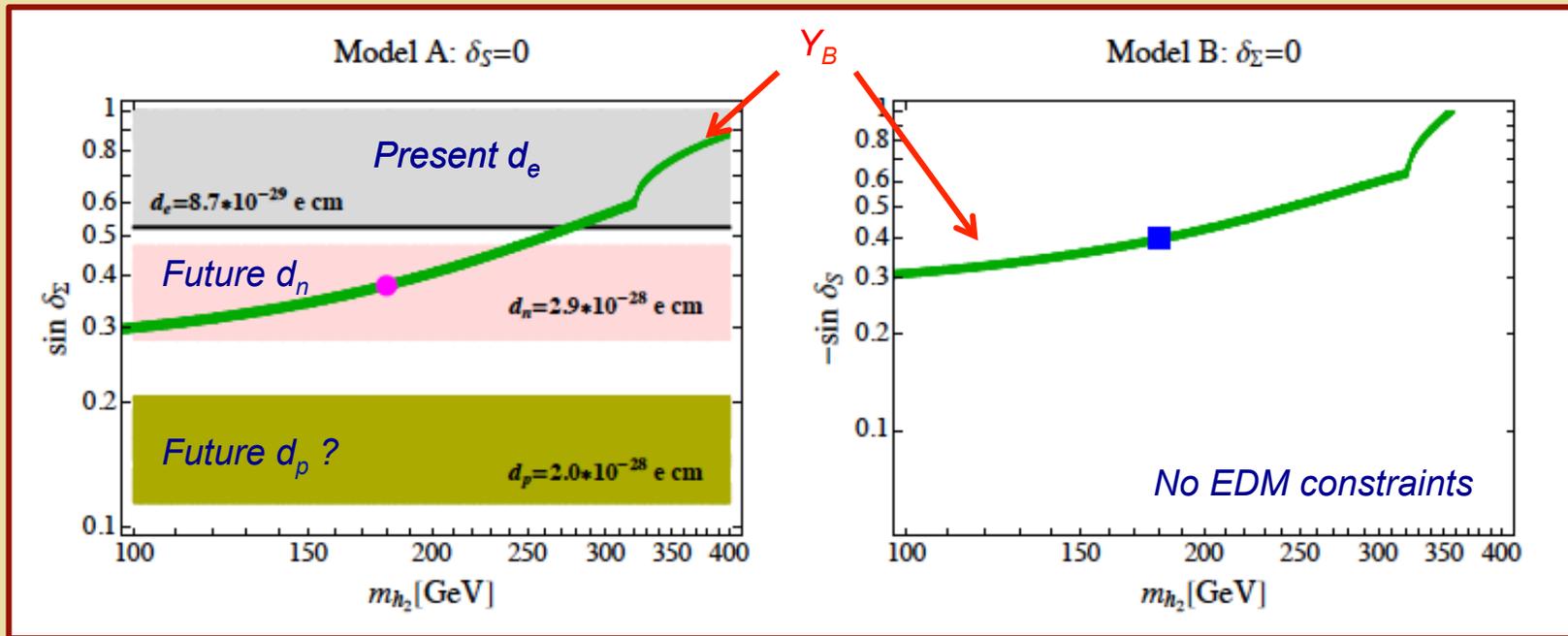
Two step EWSB

BSM CPV in ϕH interactions: baryogenesis during step 1

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

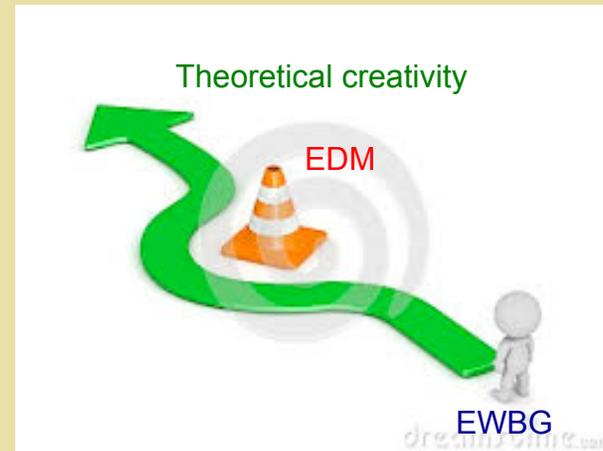
Two-Step EW Baryogenesis

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



Inoue, Ovanesyan, R-M: 1508.05404

CPV for EWBG



Wilson Coefficients: Model Independent

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12 total + $\overline{\theta}$

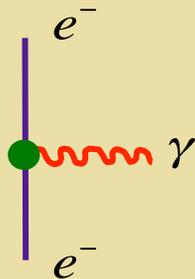
light flavors only (e,u,d)

Global Analysis: Input

System	Year/ref	Result
Paramagnetic systems		
Cs	1989 [37]	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ e cm $d_e = (-1.5 \pm 5.6) \times 10^{-26}$ e cm
Tl	2002 [9]	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ e cm $d_e = (-6.9 \pm 7.4) \times 10^{-28}$ e cm
YbF	2011 [8]	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$ e cm
ThO	2014 [7]	$\omega^{NE} = 2.6 \pm 5.8$ mrad/s $d_e = (-2.1 \pm 4.5) \times 10^{-29}$ e cm $C_S = (-1.3 \pm 3.0) \times 10^{-9}$
Diamagnetic systems		
¹⁹⁹ Hg	2009 [5]	$d_A = (0.49 \pm 1.5) \times 10^{-29}$ e cm
¹²⁹ Xe	2001 [38]	$d_A = (0.7 \pm 3) \times 10^{-27}$ e cm
TlF	2000 [39]	$d = (-1.7 \pm 2.9) \times 10^{-23}$ e cm
neutron	2006 [4]	$d_n = (0.2 \pm 1.7) \times 10^{-26}$ e cm

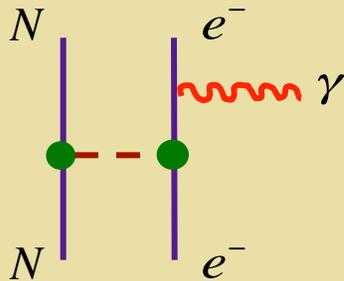
Paramagnetic Systems: Two Sources

Electron
EDM



$$d_f = -(1.13 \times 10^{-3} \text{ e fm}) \left(\frac{v}{\Lambda}\right)^2 Y_f \delta_f$$

(Scalar q)
 \times (PS e^-)

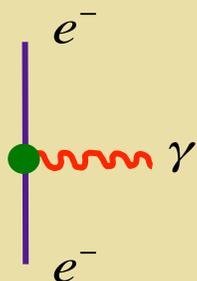


$$C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \text{Im } C_{eq}^{(-)}$$

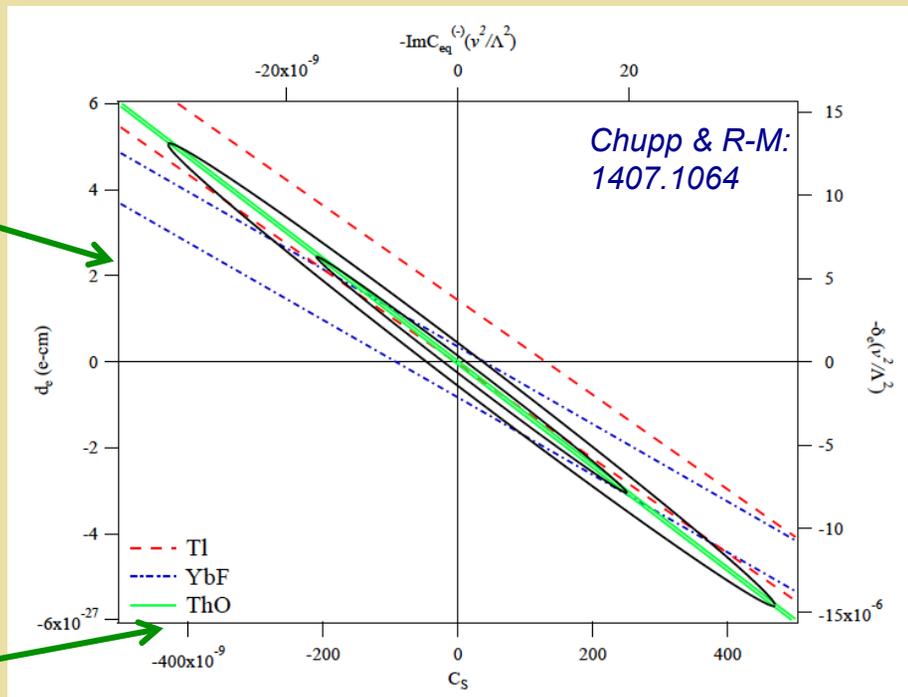
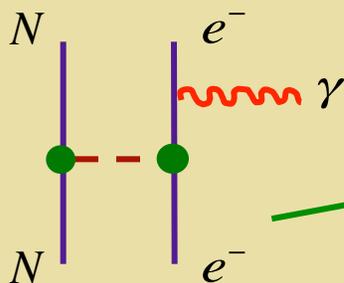
Tl, YbF, ThO...

Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q)
 \times (PS e^-)



$$\Lambda \gtrsim (1.5 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}}$$

Electron EDM (global)

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

C_S (global)

TI, YbF, ThO...

LHC accessible?

IV. Outlook

- *Searches for permanent EDMs of atoms, molecules, hadrons and nuclei provide powerful probes of BSM physics at the TeV scale and above 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 advancing experimental sensitivity challenges hadronic structure theory to aim for an unprecedented level of reliability & model building to envision new pathways for baryogenesis*

V. Theoretical Challenges

Hadronic Matrix Elements

$$d_N = \boxed{\alpha_N} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \boxed{\beta_N^{(k)}} \text{Im } C_k,$$

$$\bar{g}_\pi^{(i)} = \boxed{\lambda_{(i)}} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \boxed{\gamma_{(i)}^{(k)}} \text{Im } C_k,$$



Hadronic Matrix Elements

Hadronic Matrix Elements

Param	Coeff	Best value ^a	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\text{Im } C_{qG}$	β_n^{uG}	4×10^{-4}	$(1 - 10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2 - 18) \times 10^{-4}$
\tilde{d}_q	$e\tilde{\rho}_n^u$	-0.35	-(0.09 - 0.9)
	$e\tilde{\rho}_n^d$	-0.7	-(0.2 - 1.8)
$\tilde{\delta}_q$ (CEDM)	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4 - 40) \times 10^{-9}$
$\text{Im } C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2 - 0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8 - 2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)-0.52
	ρ_n^d	1.4	0.7-2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4 - 12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16 - 50) \times 10^{-9}$
$C_{\bar{G}}$	$\beta_n^{\bar{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$
$\text{Im } C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$
$\text{Im } C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$
$\text{Im } C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11-14.5
$\text{Im } C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6-1.2

Nuclear Matrix Elements

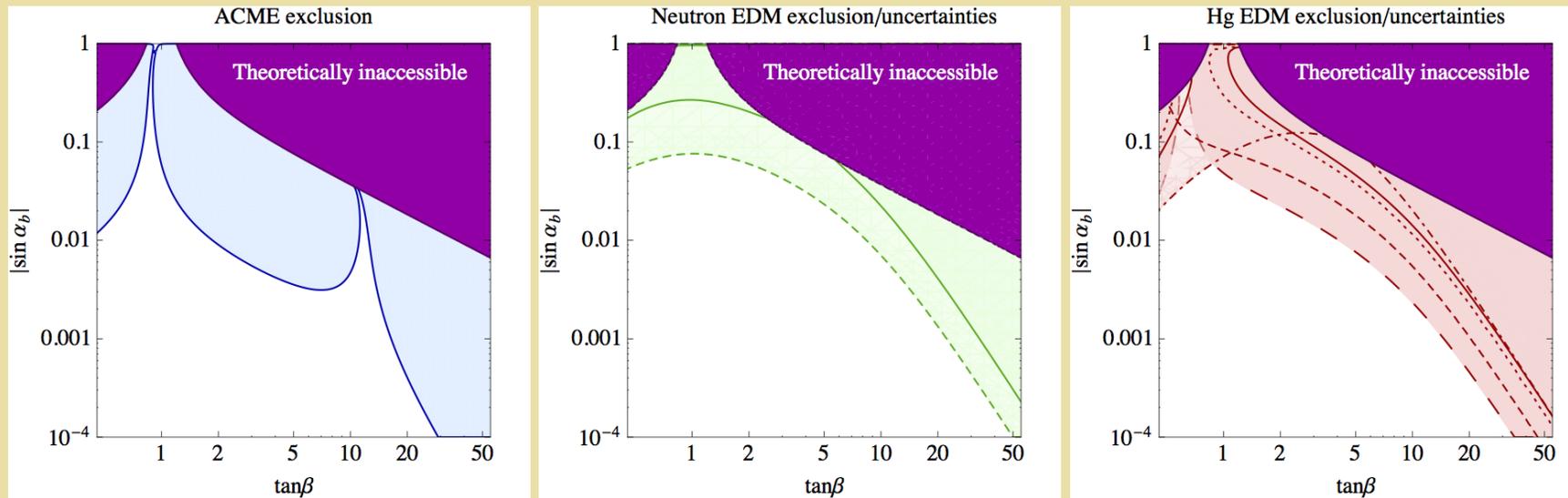
$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

Nucl.	Best value		
	a_0	a_1	a_2
¹⁹⁹ Hg	0.01	± 0.02	0.02
¹²⁹ Xe	-0.008	-0.006	-0.009
²²⁵ Ra	-1.5	6.0	-4.0
Range			
	a_0	a_1	a_2
	0.005-0.05	-0.03-(+0.09)	0.01-0.06
	-0.005-(-0.05)	-0.003-(-0.05)	-0.005-(-0.1)
	-1-(-6)	4-24	-3-(-15)

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



Present

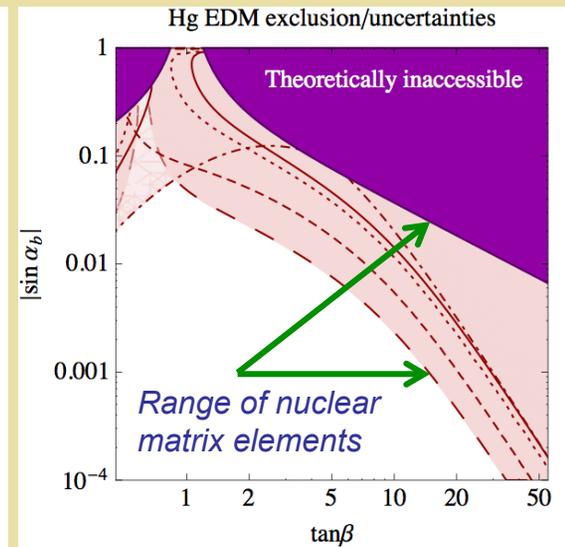
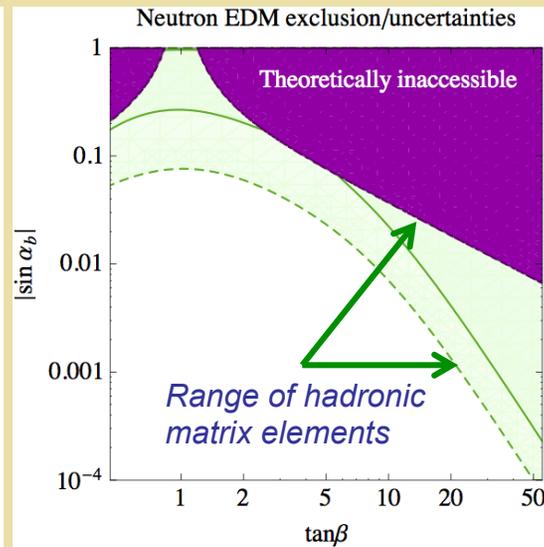
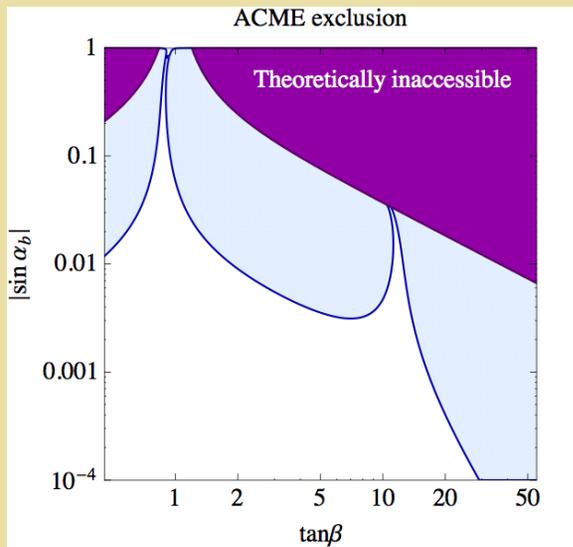
$\sin\alpha_b$: CPV
scalar mixing

Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



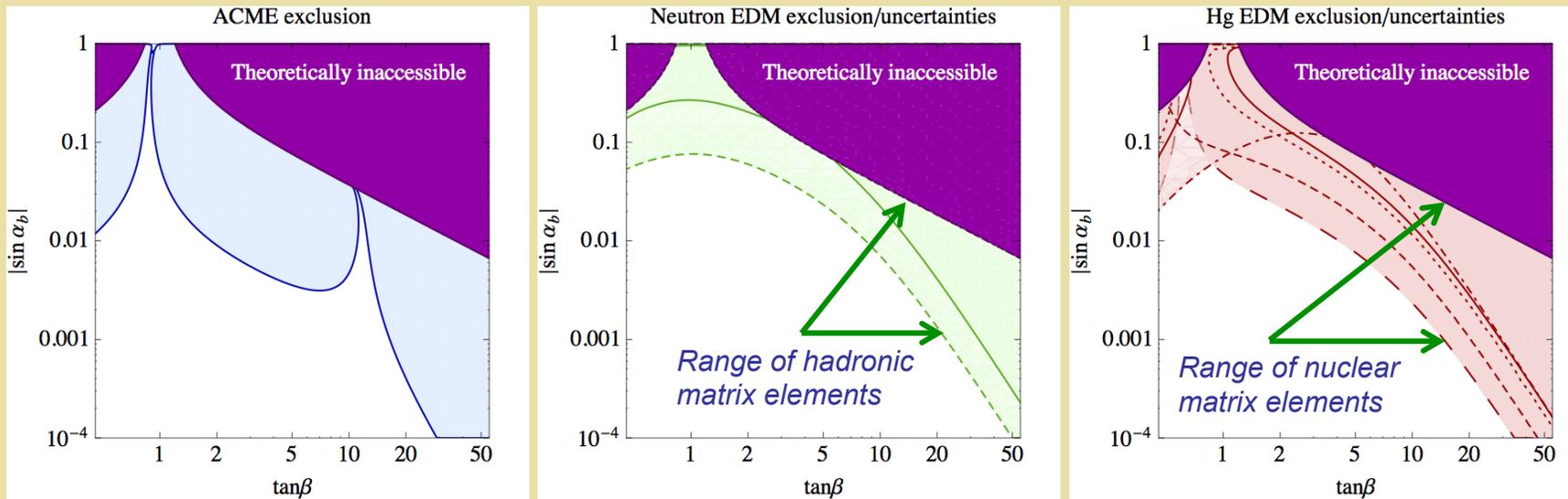
Present

$\sin \alpha_b$: CPV
scalar mixing

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



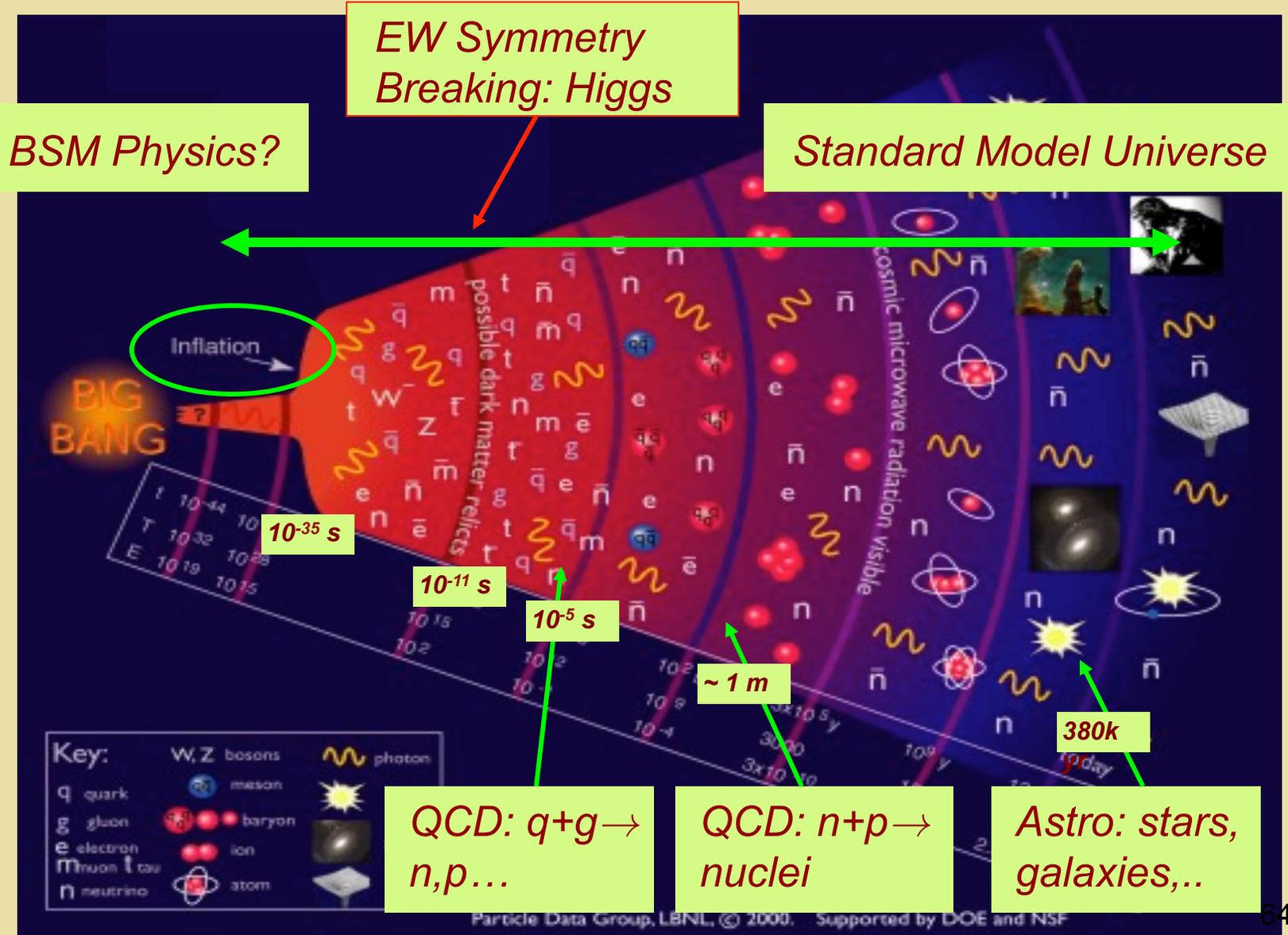
Present

Challenge for Theory

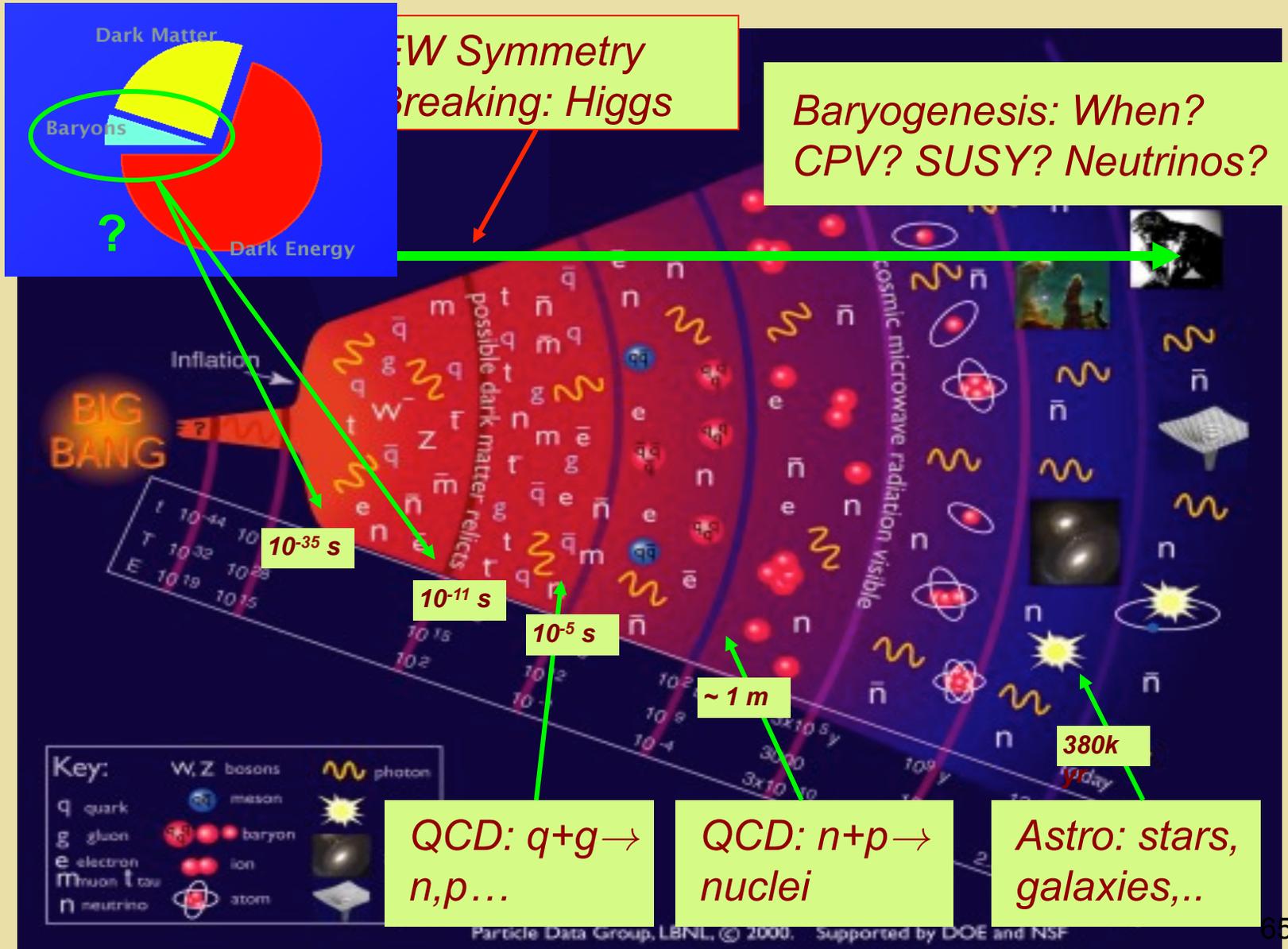
$\sin\alpha_b$: CPV
scalar mixing

Inoue, R-M, Zhang: 1403.4257

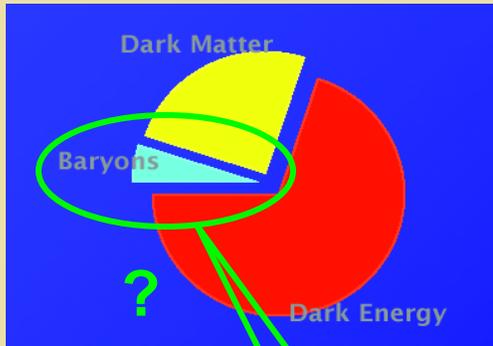
Symmetries & Cosmic History



Symmetries & Cosmic History



Symmetries & Cosmic History



EW Symmetry Breaking: Higgs

*Baryogenesis: When?
CPV? SUSY? Neutrinos?*

*Leptogenesis:
look for ingred's
w/ ν s: DBD, ν osc*

*EW Baryogenesis:
testable w/ EDMs +
colliders*

