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/

Mainz UCN Workshop
April 2016

Goals for this talk

- *Set a context for the workshop*
- *Illustrate the broader implications of present & prospective EDM searches*
- *Introduce some terminology & notation*
- *Illustrate present theoretical landscape*
- *Pose challenges for hadronic & nuclear structure theory*

Outline

I. The BSM context

II. Electric dipole moments

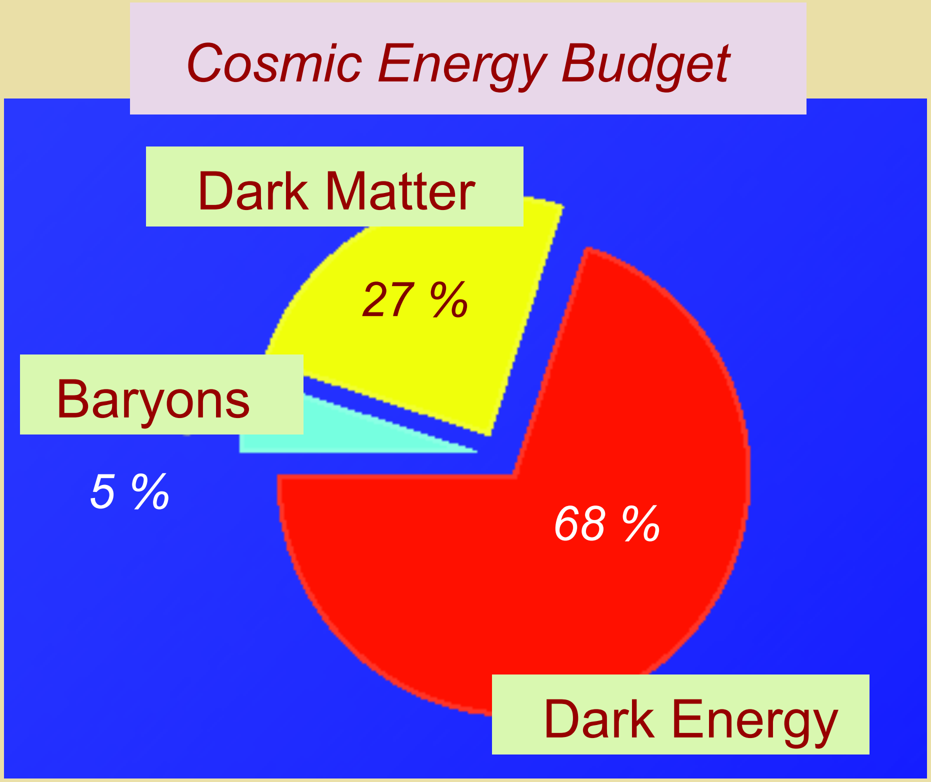
III. EDM complementarity

IV. Challenges for hadronic & nuclear structure theory

V. Outlook

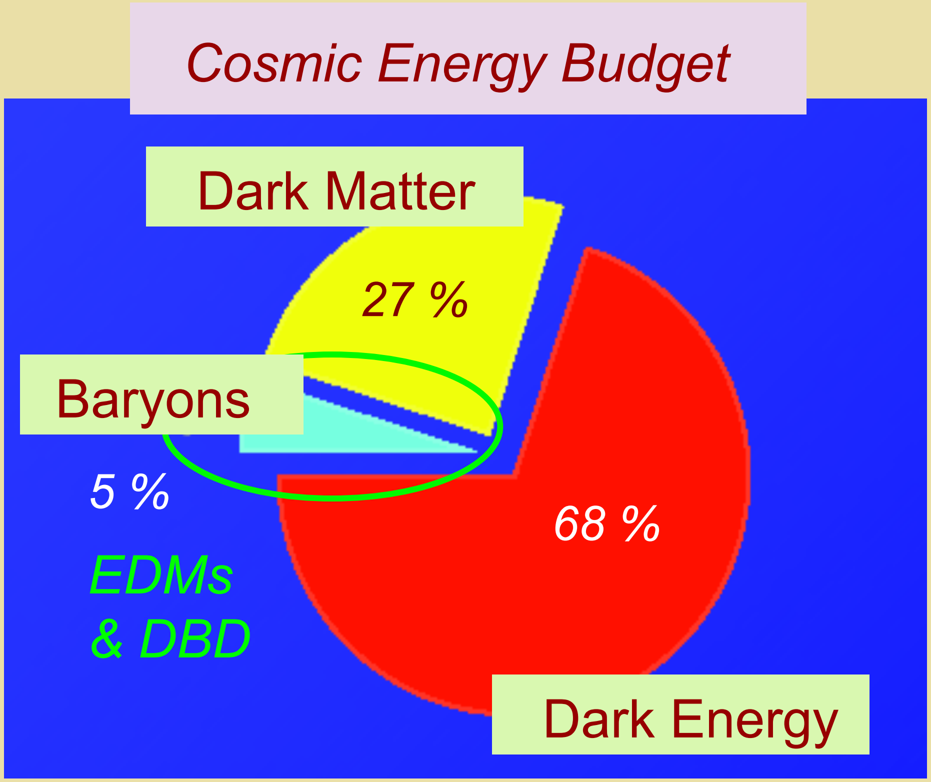
I. The BSM Context

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

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

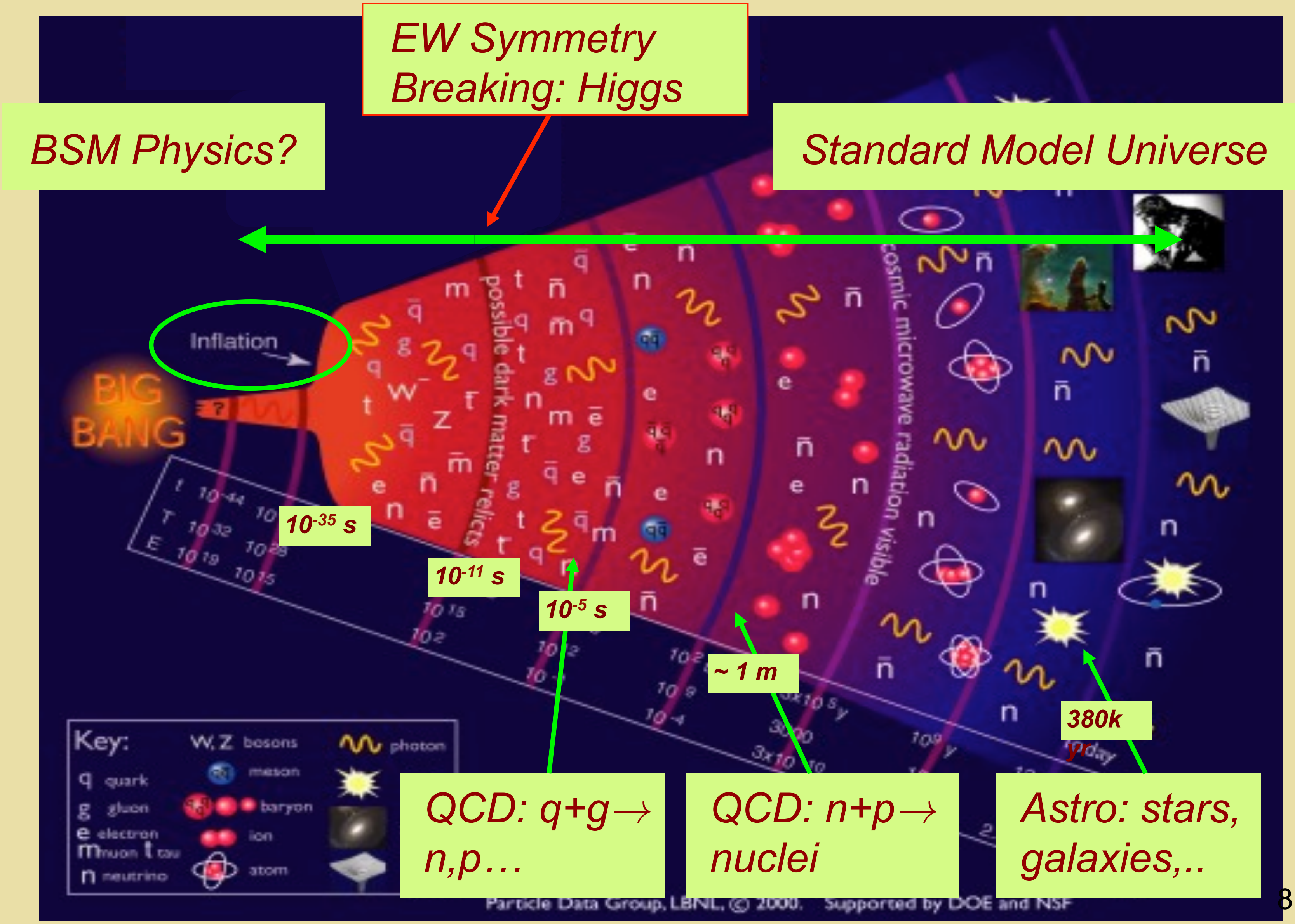
Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

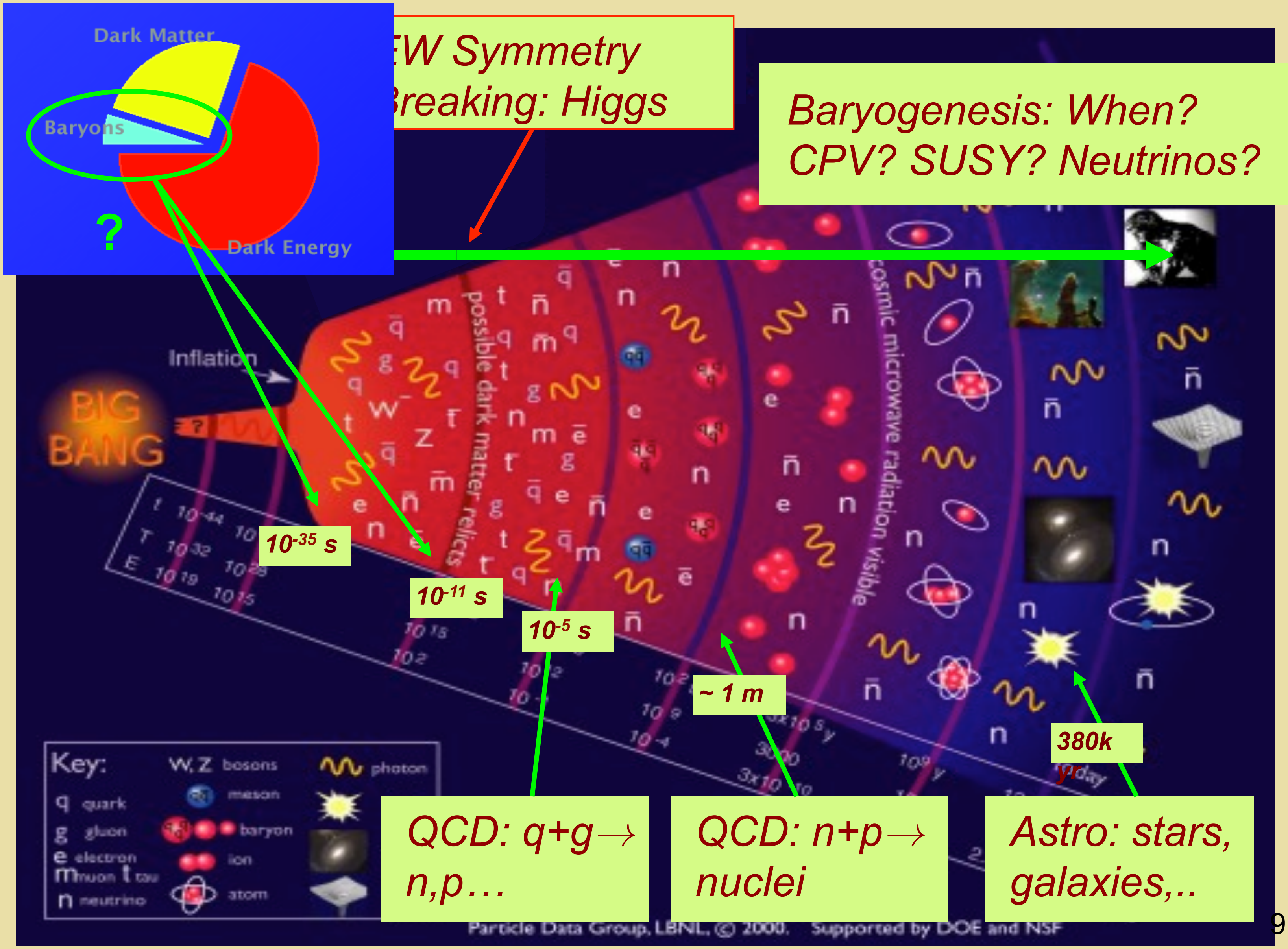
Testable

	Standard Model		BSM
• B violation (sphalerons)	✔		✔
• C & CP violation	✖	EDM	✔
• Out-of-equilibrium or CPT violation	✖		✔

Symmetries & Cosmic History



Symmetries & Cosmic History



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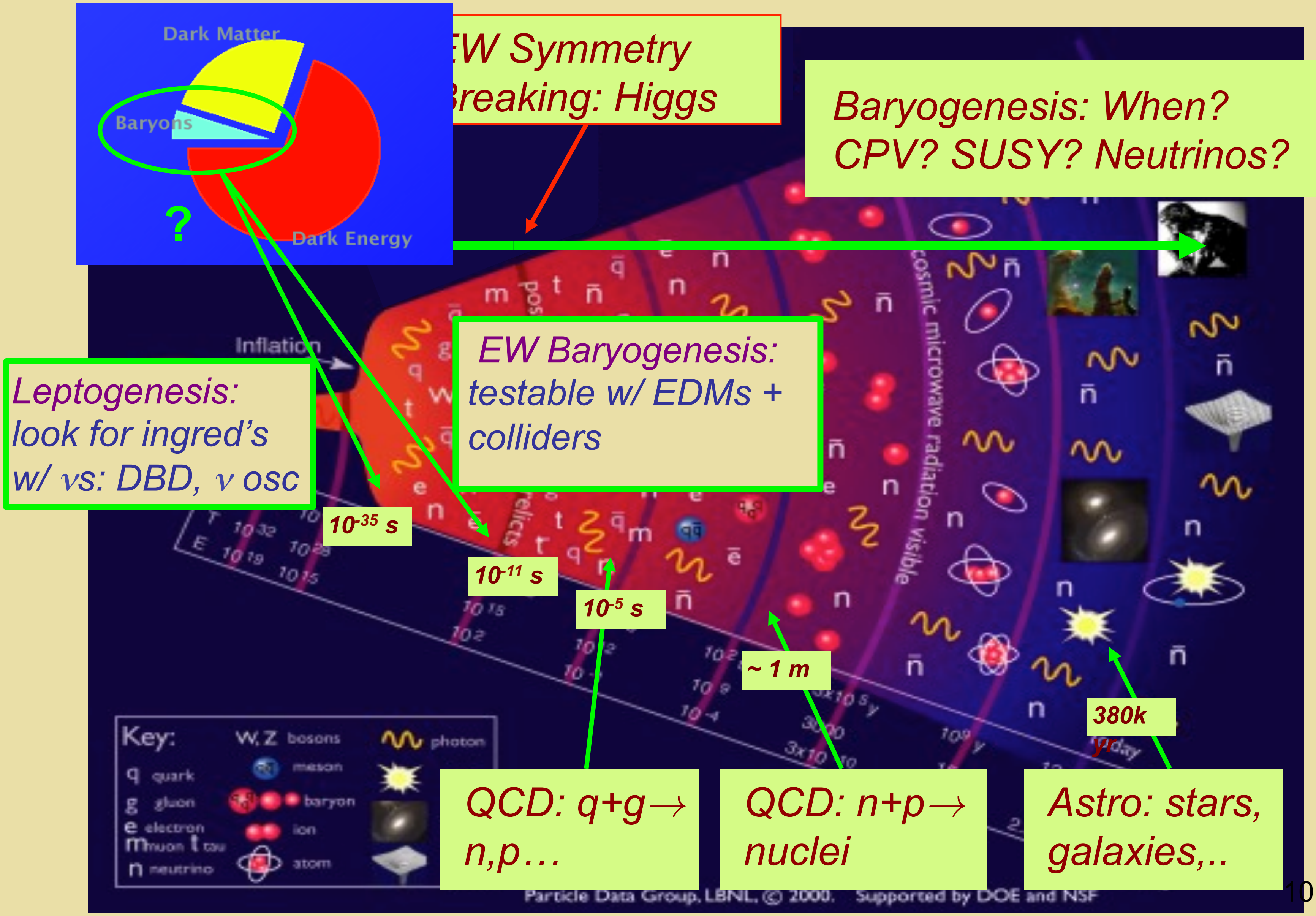
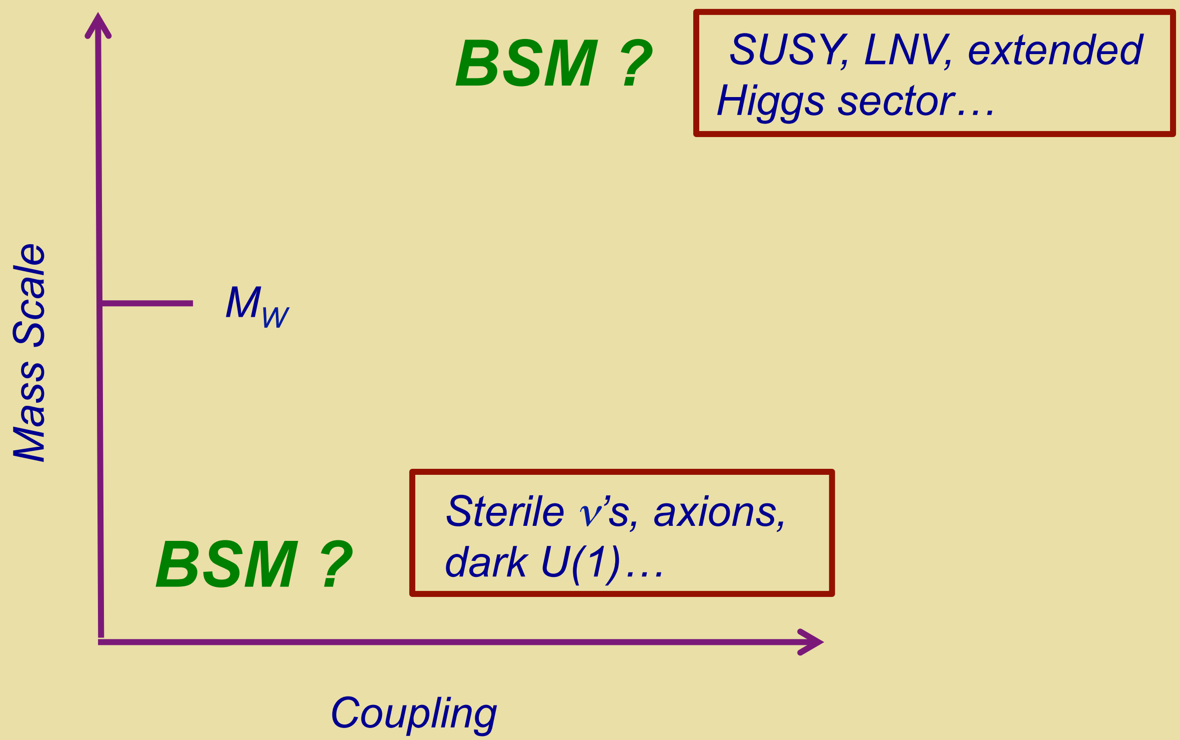


BSM Physics: Where Does it Live ?



Low-Energy / High-Energy Interplay

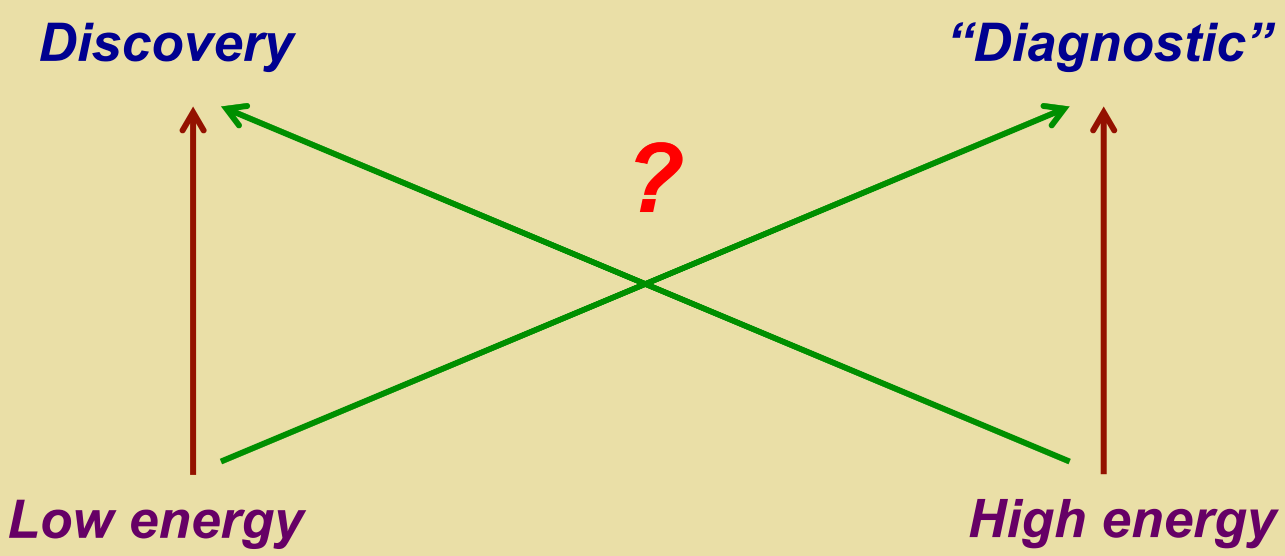
Discovery

Low energy

"Diagnostic"

High energy

Low-Energy / High-Energy Interplay



II. EDMs

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL   ** e^- equivalent

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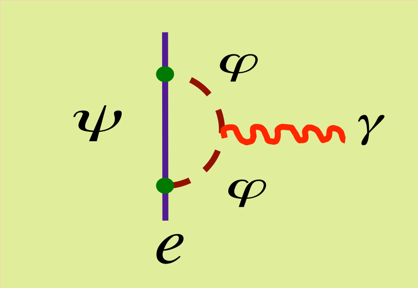
Mass Scale Sensitivity



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

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

EDMs: New CPV?

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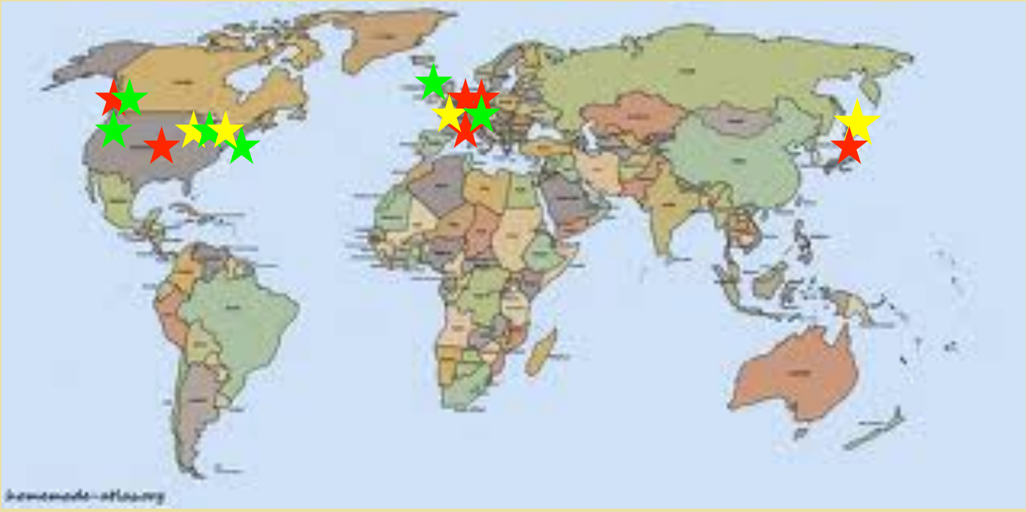


neutron

proton & nuclei

atoms

~ 100 x better sensitivity

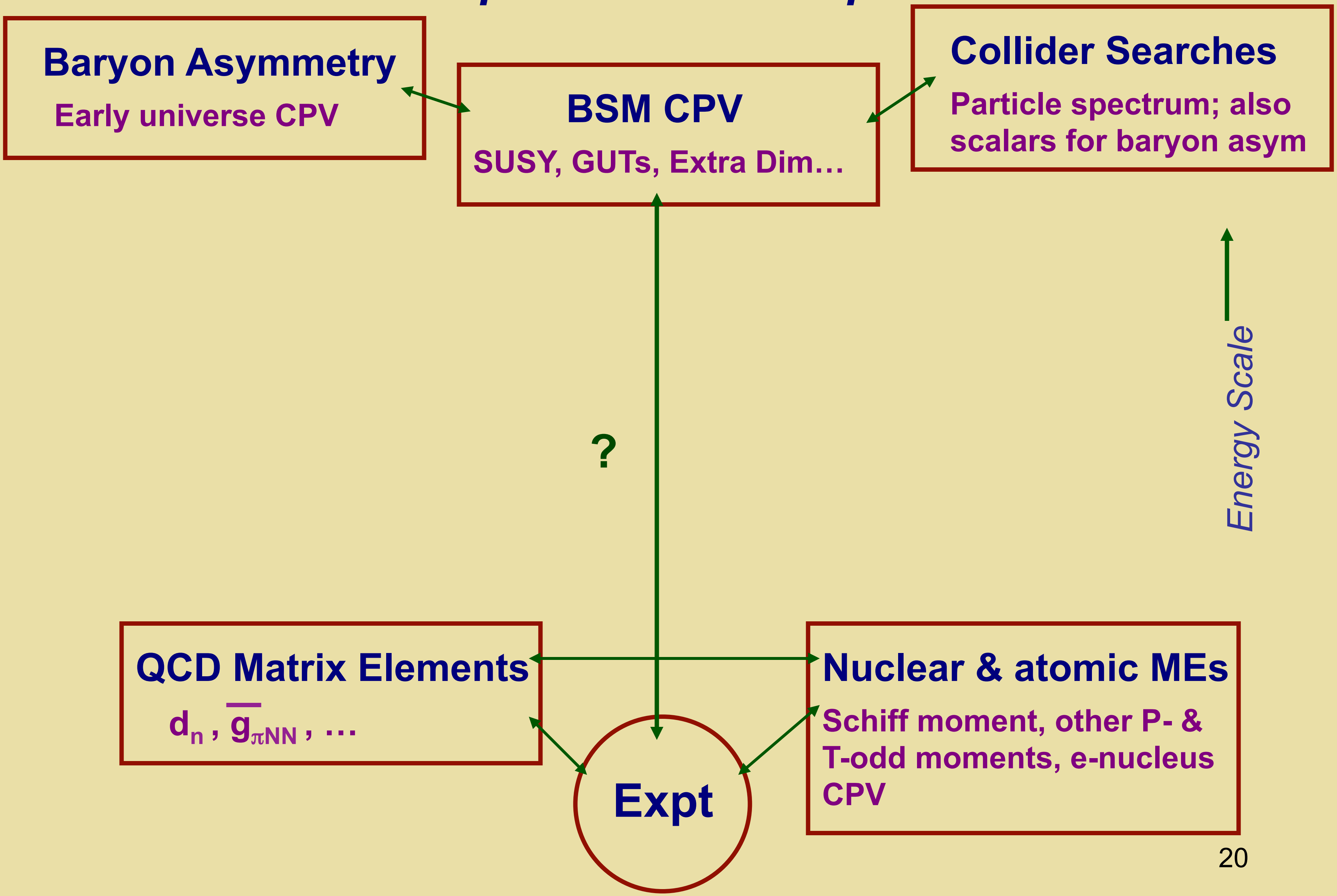
Not shown: muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales

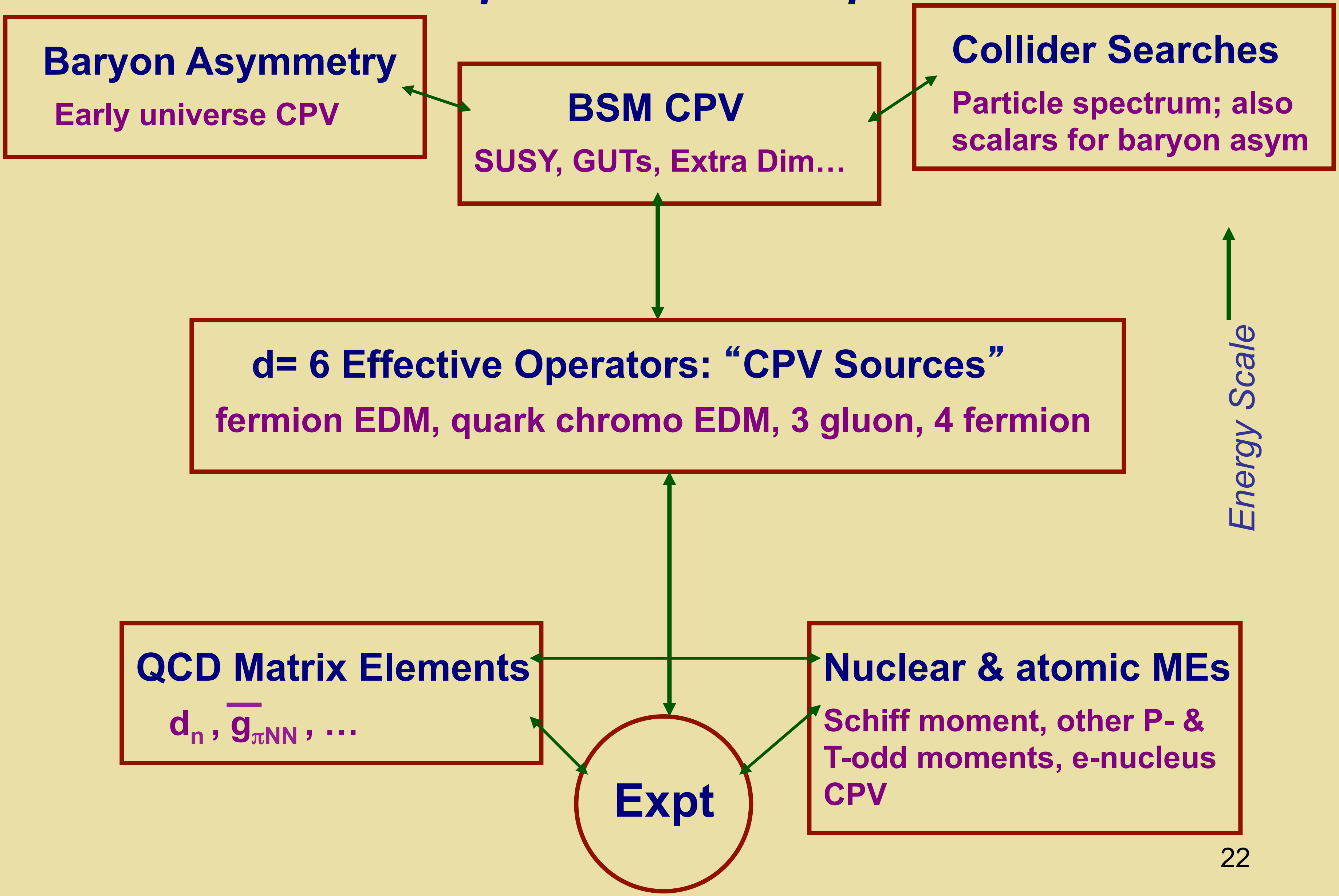


Effective Operators: The Bridge

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

$$\boxed{\mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)}} \quad + \ldots$$

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 + $\bar{\theta}$

light flavors only (e,u,d)

Wilson Coefficients: Summary

δ_f	*fermion EDM*	*(3)*
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$C_{\tilde{G}}$	*3 gluon*	*(1)*
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$C_{\varphi ud}$	*induced 4f*	*(1)*

12 total + $\bar{\theta}$

light flavors only (e,u,d)

Complementary searches needed

BSM Origins

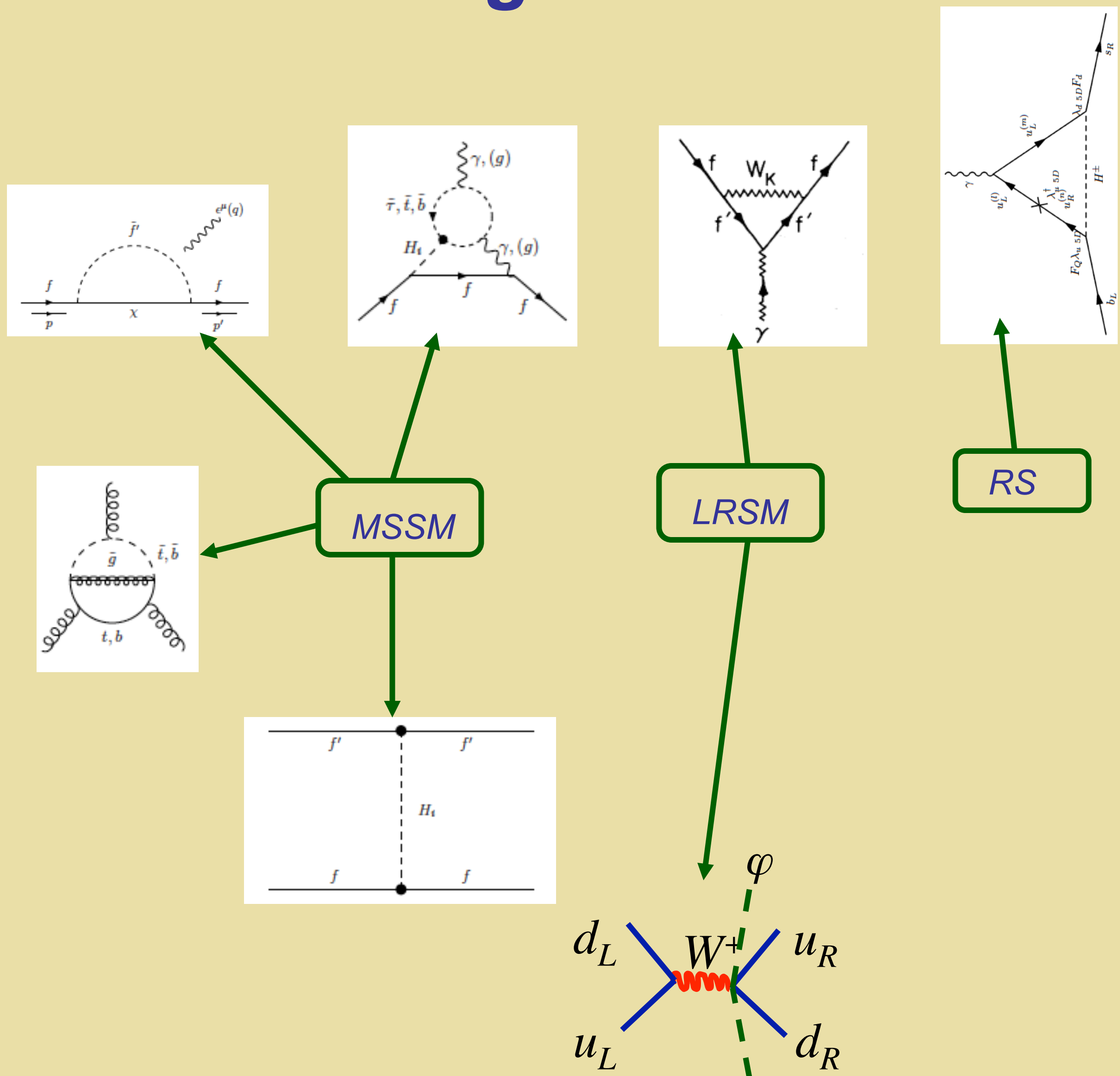
EDM: γff

CEDM: gff

Weinberg ggg:

Four fermion

udHH



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

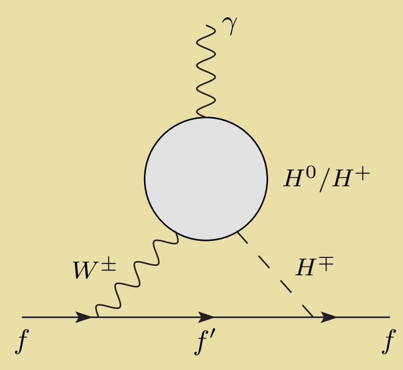
$\lambda_{6,7}$ = 0 for simplicity

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

$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] ,$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right]$$

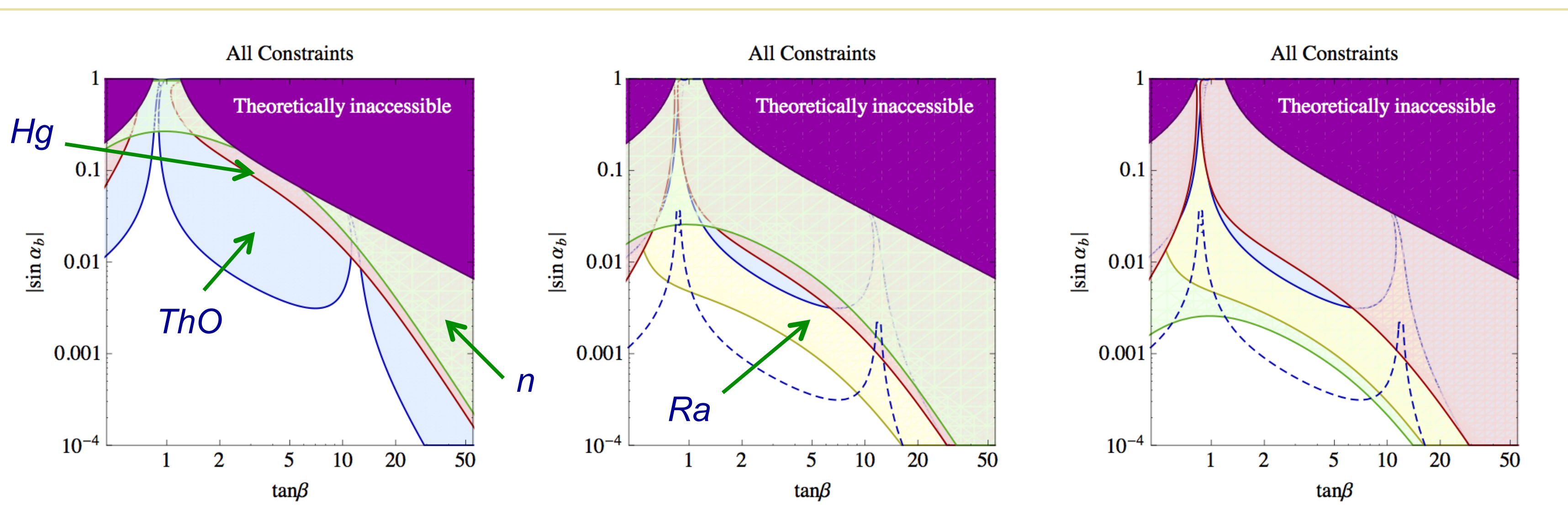
$\xrightarrow{\text{EWSB}}$

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



Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



Present	*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)

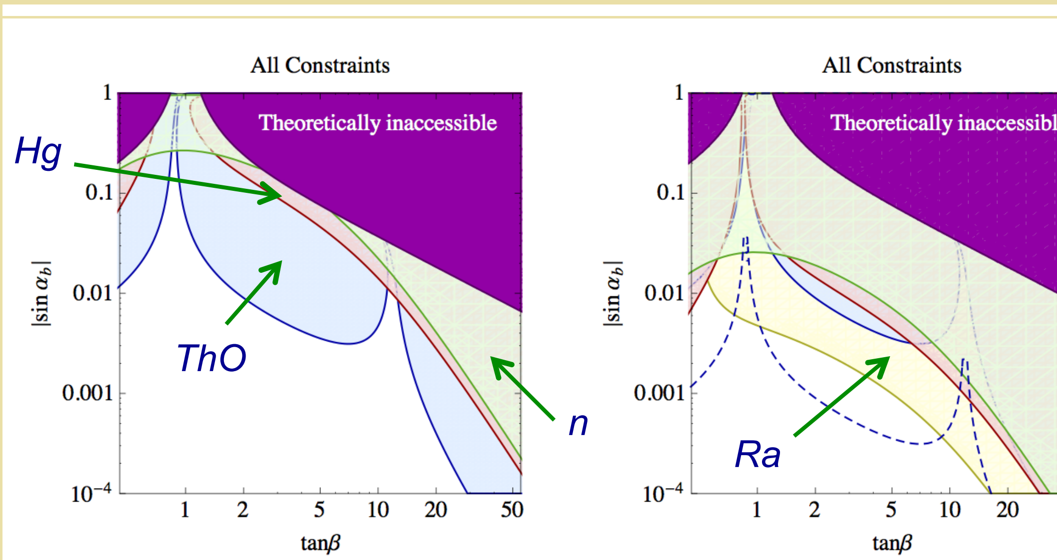
$\sin\alpha_b$: CPV scalar mixing

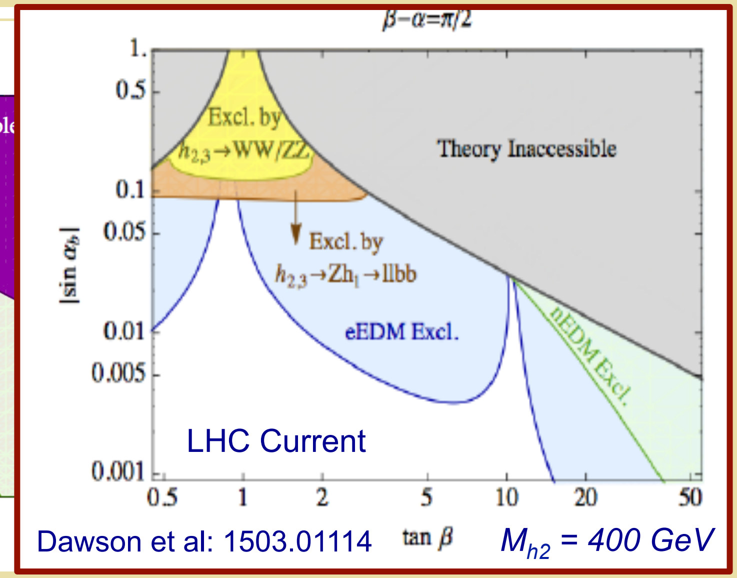
Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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





Present

$\sin \alpha_b$: CPV scalar mixing

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

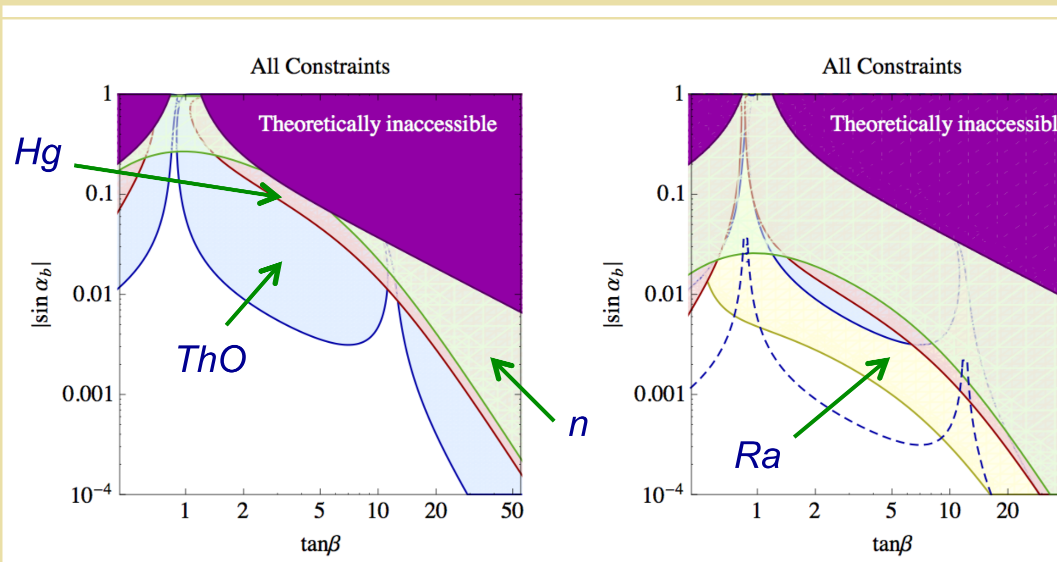
d_{ThO} x 0.1

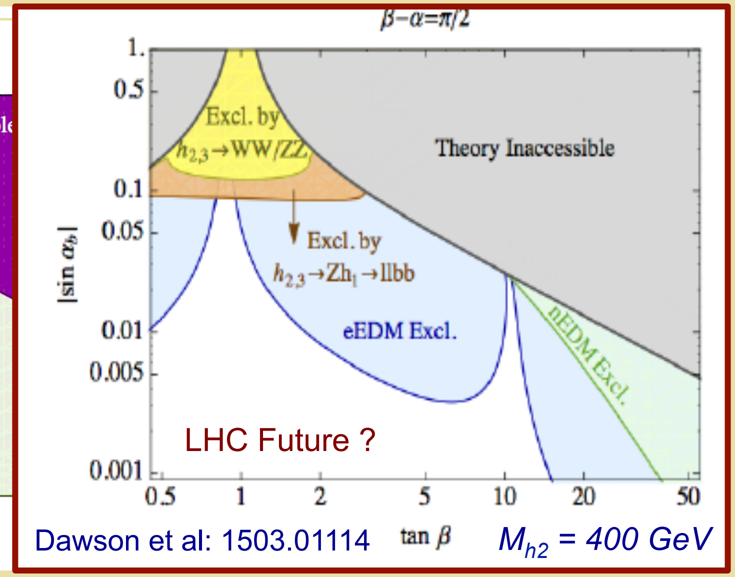
$d_A(Ra)$

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



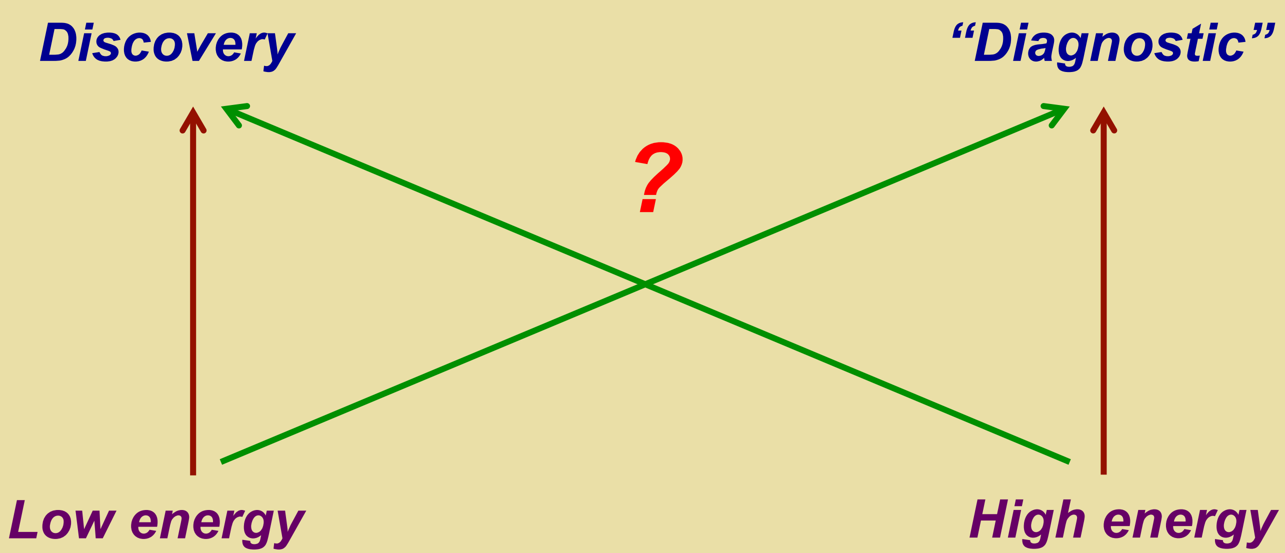


Present	*Future:*	*Future:*
	d_n x 0.1	d_n x 0.01
	$d_A(Hg)$ x 0.1	$d_A(Hg)$ x 0.1
sin α_b : CPV scalar mixing	d_{ThO} x 0.1	d_{ThO} x 0.1
	$d_A(Ra)$ [10^{-27} e cm]	$d_A(Ra)$

Inoue, R-M, Zhang: 1403.4257

Low-Energy / High-Energy Interplay

Higgs Portal CPV



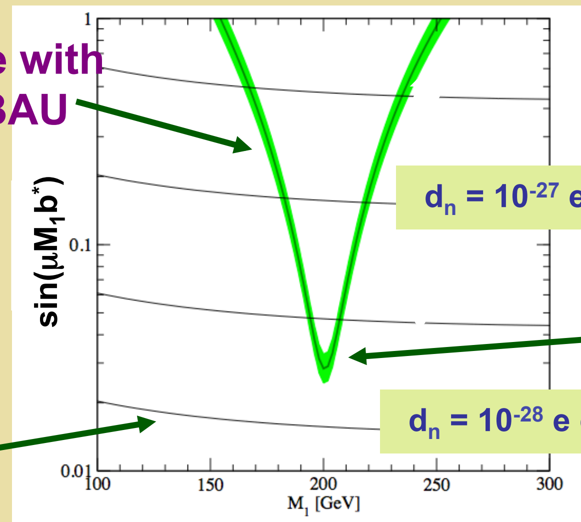
Was the baryon asymmetry produced during electroweak symmetry-breaking ?

- *EDMs provide most powerful probe of CPV*
- *Phase transition $\rightarrow$ Separate talk*

EDMs & EW Baryogenesis: MSSM

Neutron EDM

Compatible with observed BAU



$d_n = 10^{-27}$ e cm

Compressed spectrum (stealthy SUSY)

$d_n = 10^{-28}$ e cm

Next generation d_n

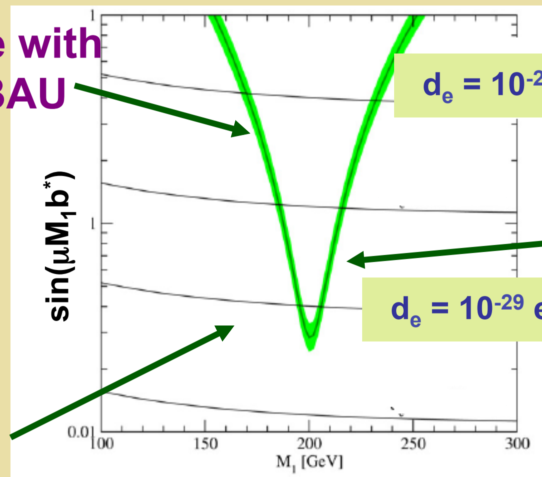
Li, Profumo, RM '09-' 10

EDMs & EW Baryogenesis: MSSM

Electron EDM

ThO Limit

Compatible with observed BAU



$d_e = 10^{-28}$ e cm

Compressed spectrum (stealthy SUSY)

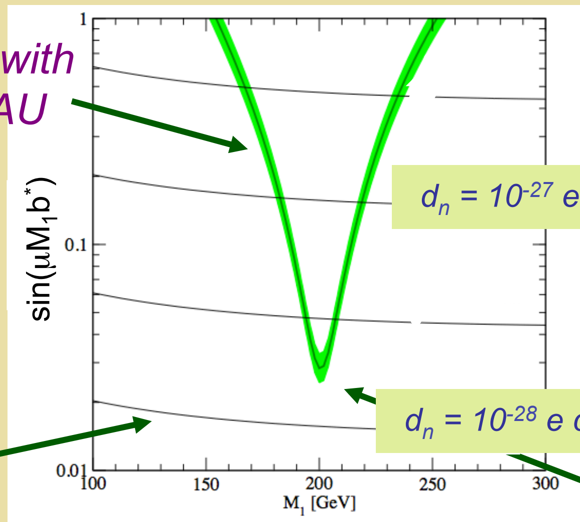
$d_e = 10^{-29}$ e cm

Next generation d_e ?

Li, Profumo, RM '09-'10

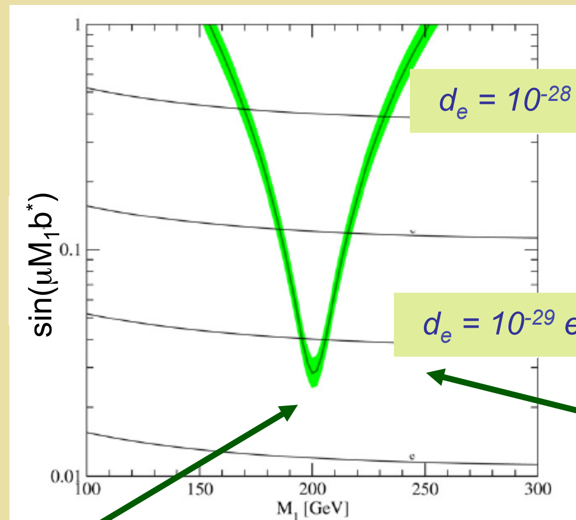
EDMs & EW Baryogenesis: MSSM

Compatible with observed BAU



Next gen d_n

Li, Profumo, RM '09-'10



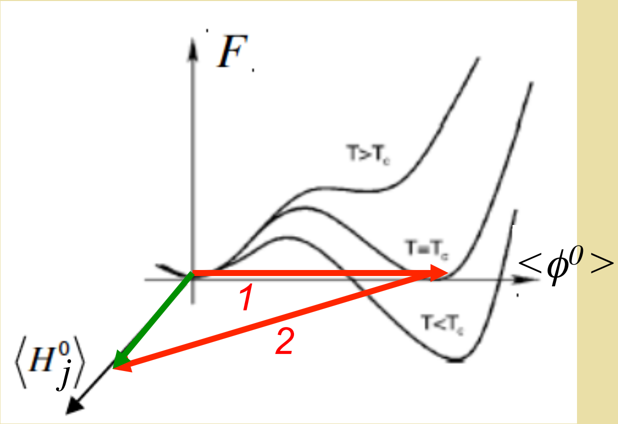
ACME: ThO

Next gen d_e

Compressed spectrum (stealthy SUSY)

Next gen lepton collider

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

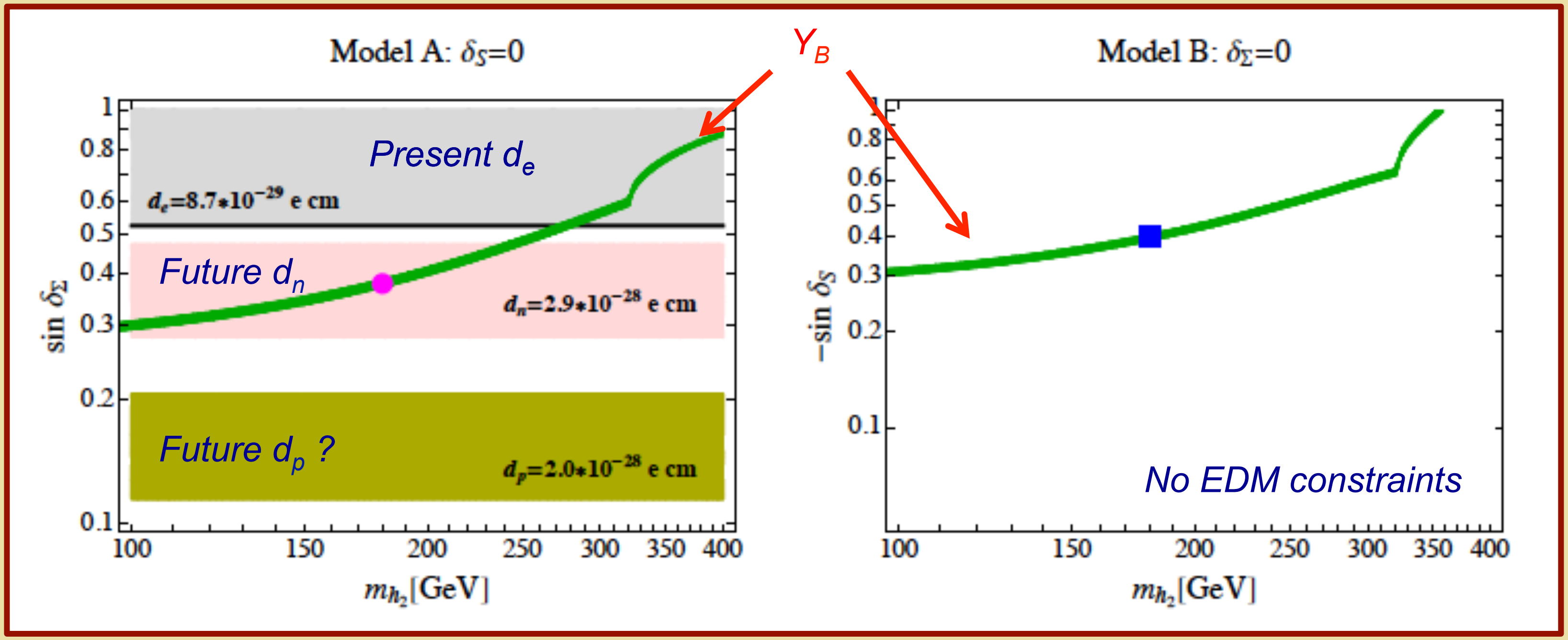
Two step EWSB

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

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



Inoue, Ovanesyan, R-M: 1508.05404

Wilson Coefficients: Model Independent

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 + $\bar{\theta}$

light flavors only (e,u,d)

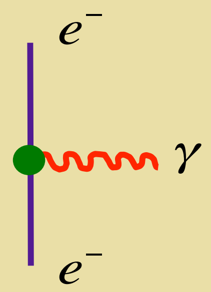
Global Analysis: Input

System	Year/ref	Result	
Paramagnetic systemss			
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]	$\omega^{\mathcal{N}E} = 2.6 \pm 5.8$	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

Chupp & R-M:
1407.1064

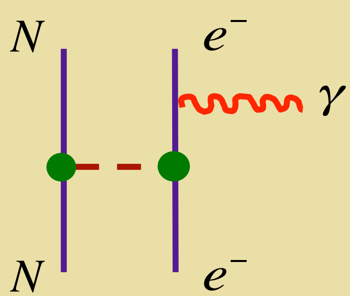
Paramagnetic Systems: Two Sources

Electron EDM



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

(Scalar q) x (PS e$^-$)

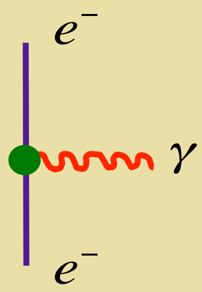


$$\boxed{C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\, C_{eq}^{(-)}}$$

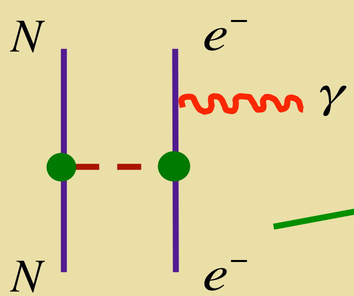
Tl, YbF, ThO…

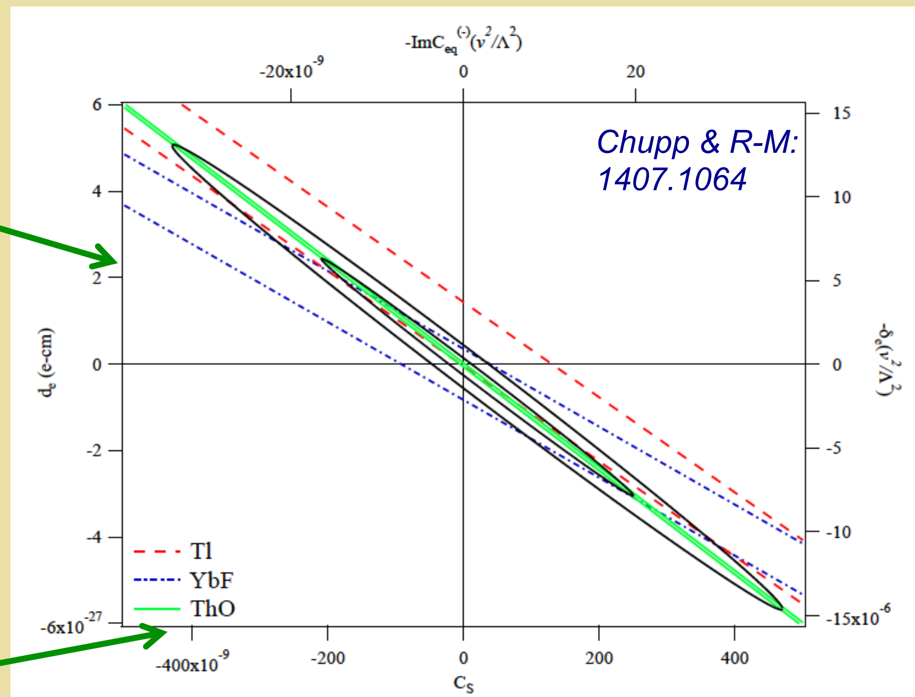
Paramagnetic Systems: Two Sources

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 accessible?

Tl, YbF, ThO…

IV. Theoretical Challenges

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)
$\mathrm{Im}\, C_{qG}$	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	$-(0.2 - 1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4 - 40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	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}	$-(16 - 50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Engel, R-M, van Kolck ‘13

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)
$\mathrm{Im}\, C_{qG}$	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}	$(4 - 40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	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}	$-(16 - 50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Engel, R-M, van Kolck '13

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	$\pm$ 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)

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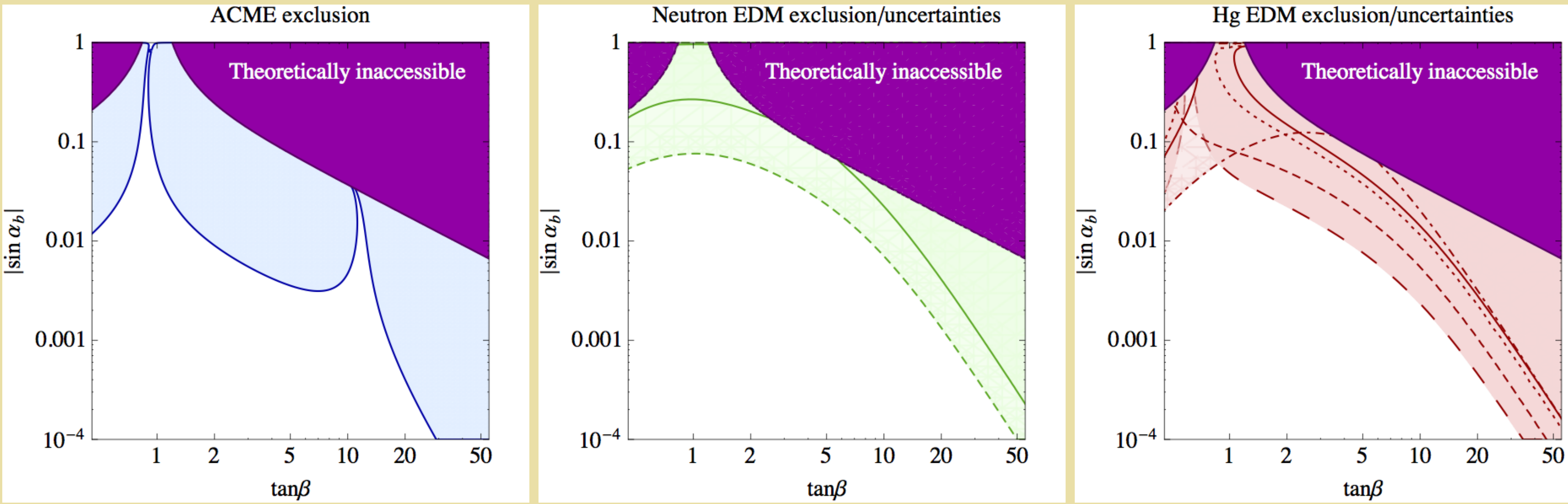
Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



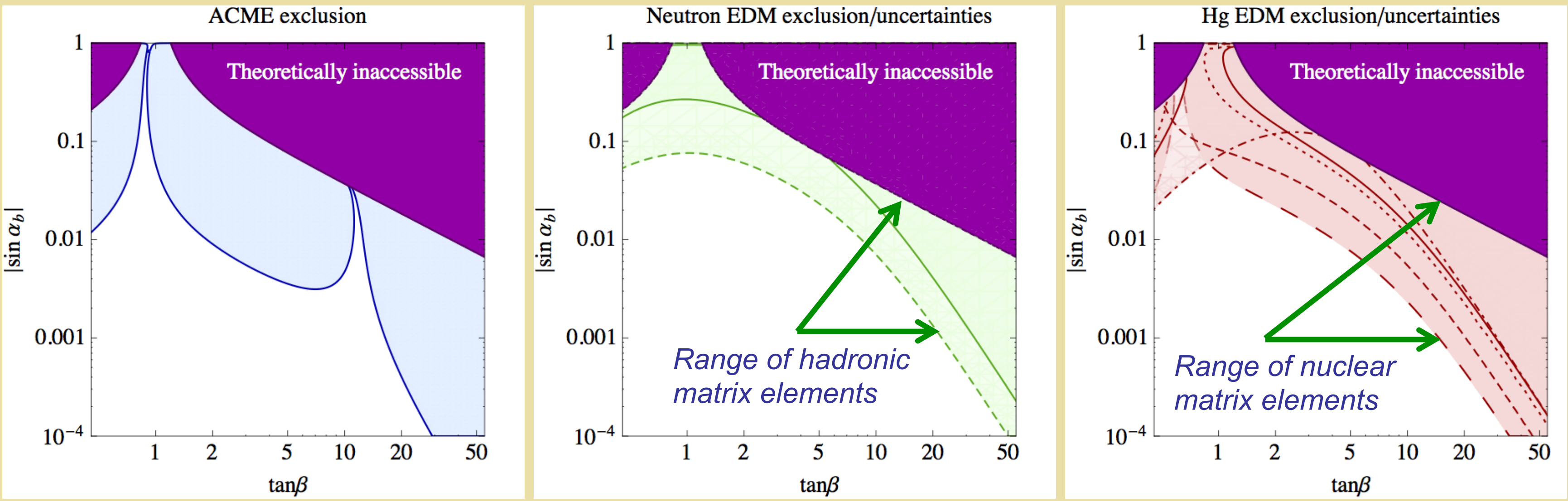
Present

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*



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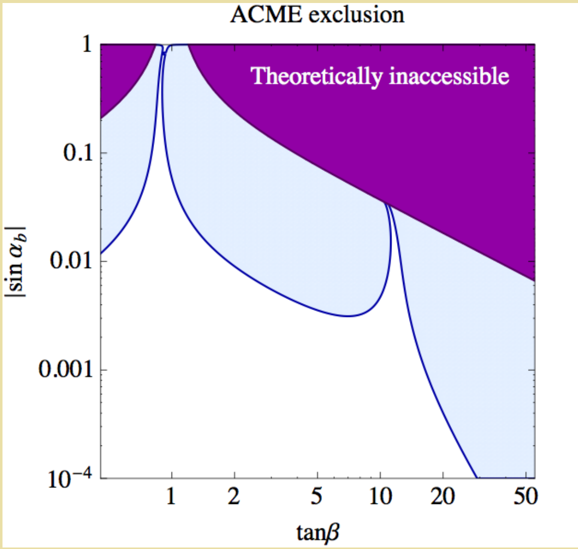

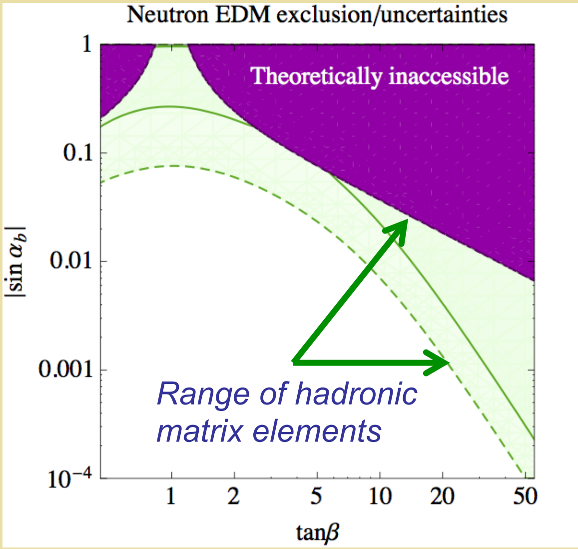

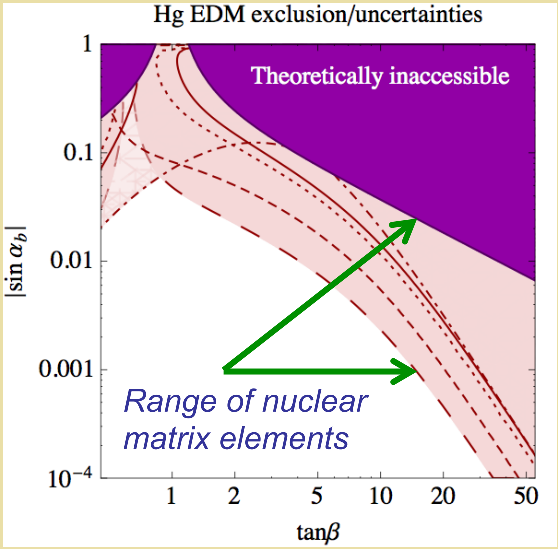

Present

Challenge for Theory

$\sin\alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

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*
- *The interpretation of diamagnetic system EDMs (including the nucleon) is challenged by substantial hadronic and nuclear many-body uncertainties*
- *The advancing experimental sensitivity challenges hadronic structure theory to aim for an unprecedented level of reliability & model building to envision new pathways for baryogenesis*