Electric Dipole Moments: Phenomenology & Implications

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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/

ACFI Workshop, Amherst January 2015

Goals for this talk

- *Set the context for the workshop: What are key scientific questions & how do they fit in the broader context ?*
- *Illustrate the broader implications of present & prospective EDM searches*
- *Introduce terminology & notation*
- *Pose questions for hadronic structure theory*

Outline

I. The BSM & NP context

II. Electric dipole moments

III. Questions for hadronic structure theory

IV. Outlook

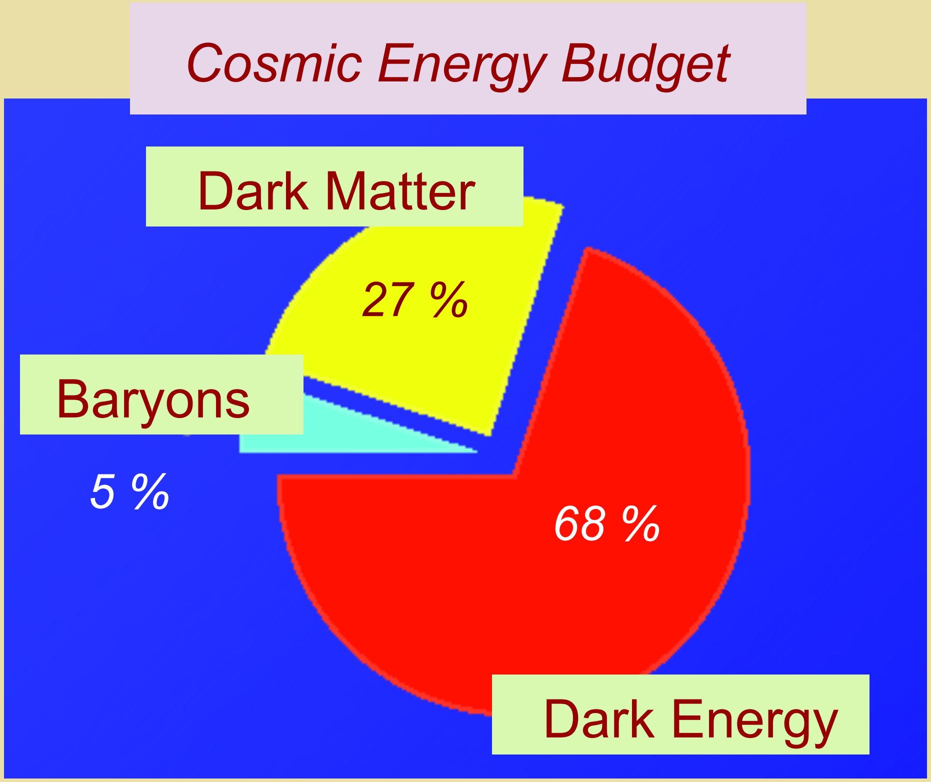
I. The BSM & NP Context

Scientific Questions

2007 NSAC LRP:

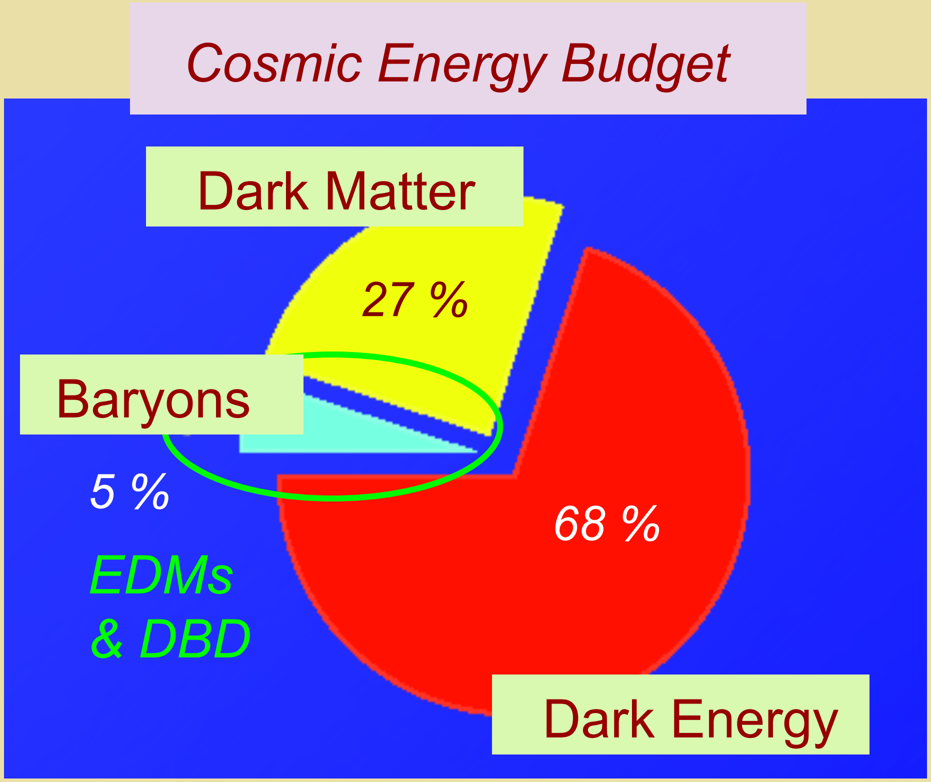
- *What are the masses of neutrinos and how have they shaped the evolution of the universe?*
- *Why is there more matter than antimatter in the present universe?*
- *What are the unseen forces that disappeared from view as the universe cooled?*

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

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

Ingredients for Baryogenesis

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

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	✖	✔
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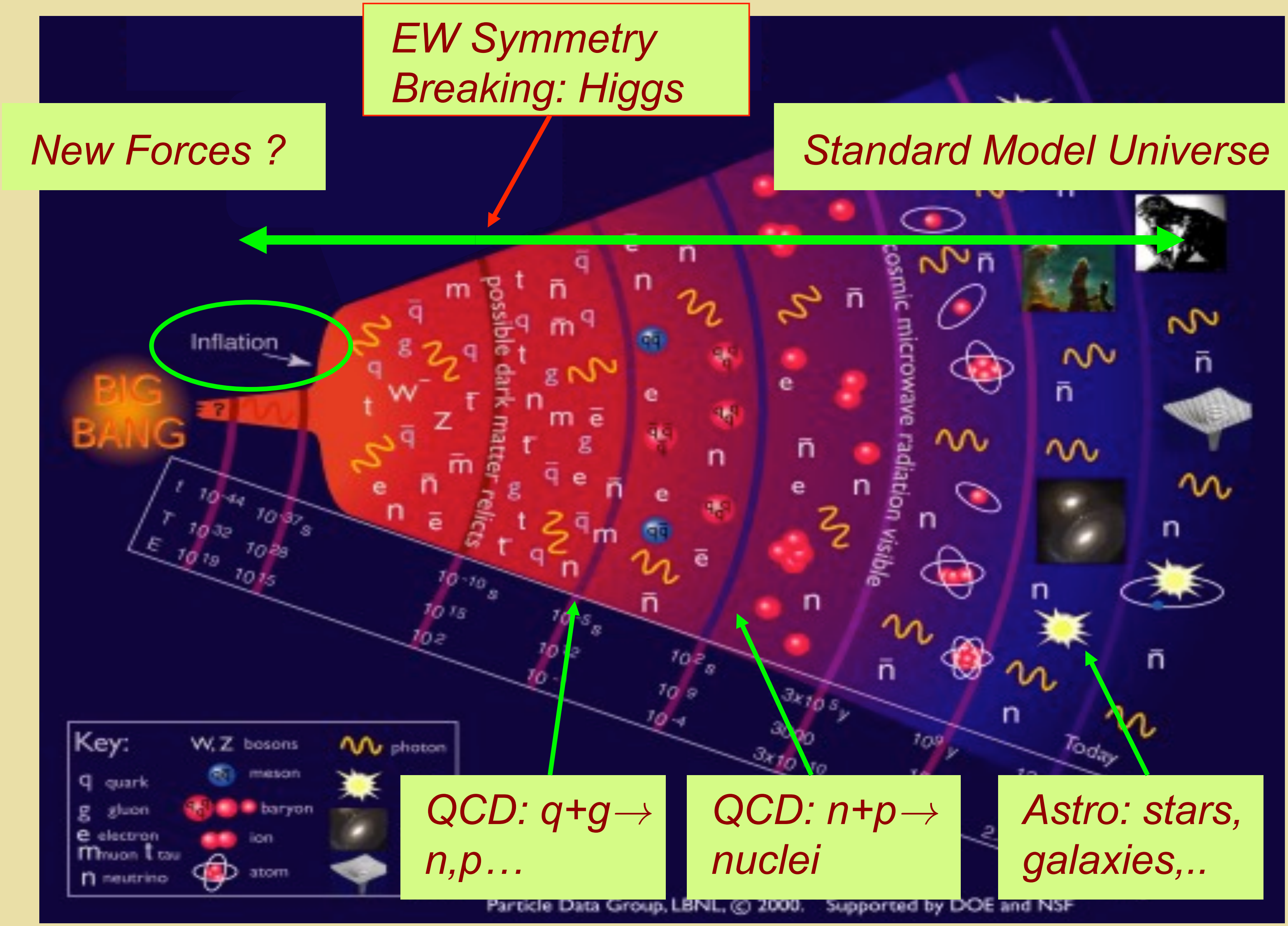
Ingredients for Baryogenesis

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

Testable

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

Symmetries & Cosmic History



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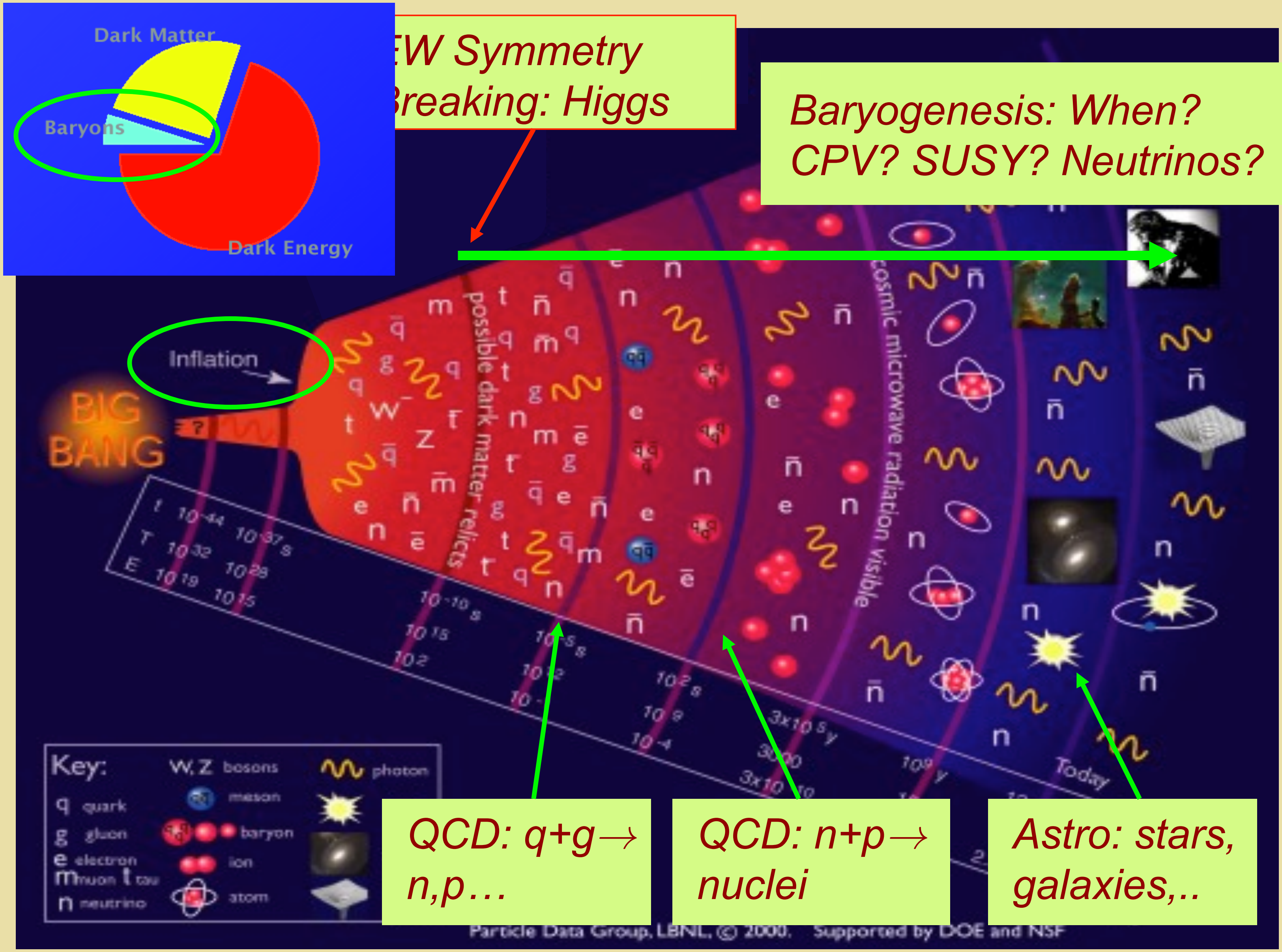

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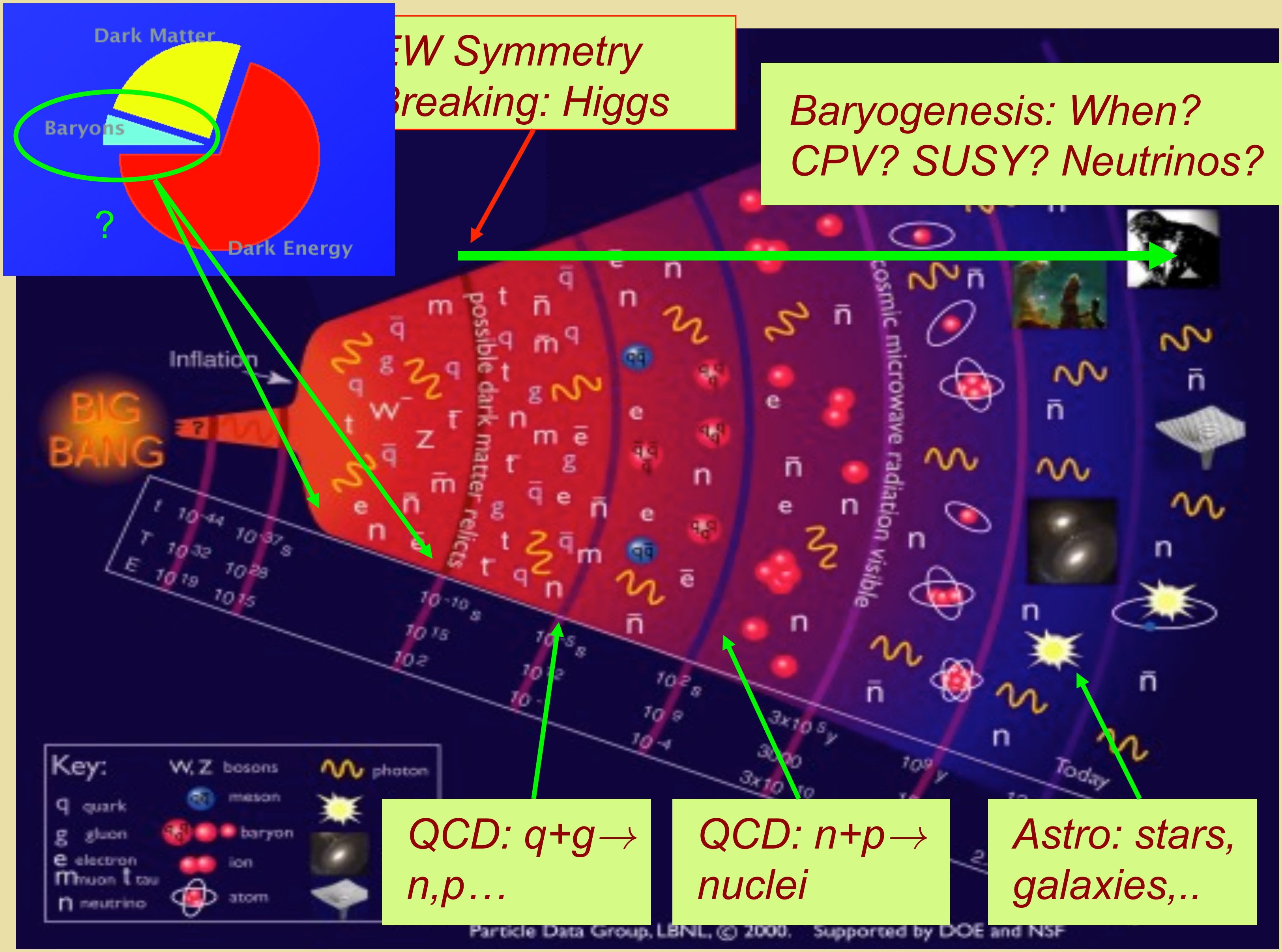

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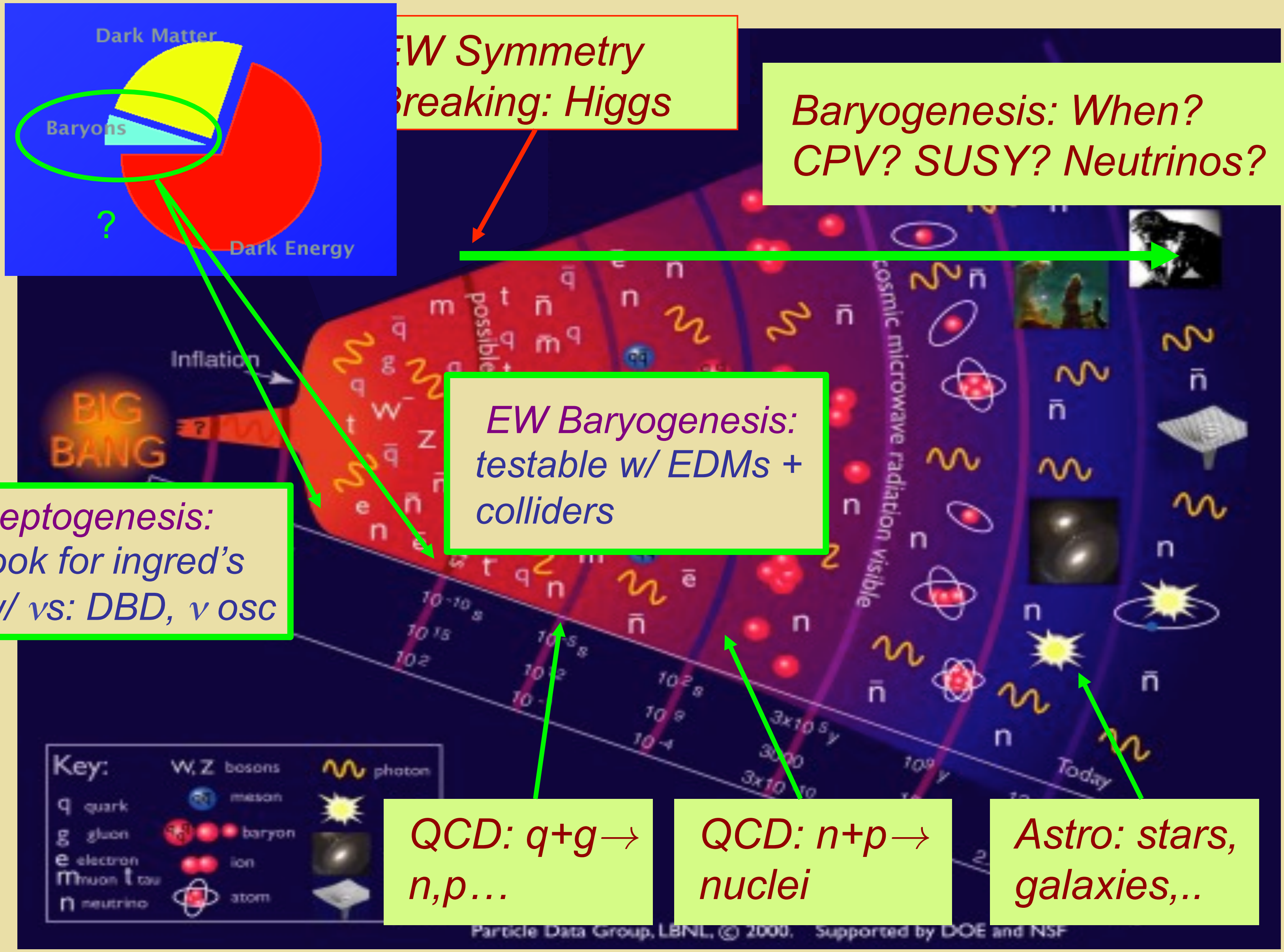

Recent Results

- *Discovery of BEH-like scalar at the LHC*

- *Non-observation (so far) of sub-TeV particles at LHC*

- *New stringent limits on EDMs*

Recent Results

- Discovery of BEH-like scalar at the LHC
  - Idea of ϕ-driven spontaneous EW symmetry breaking is likely correct
- Non-observation (so far) of sub-TeV particles at LHC
  - Sub-TeV BSM spectrum is compressed
  - Sub-TeV BSM is purely EW or Higgs portal
  - BSM physics lies at very different mass scale
- New stringent limits on EDMs
  - BSM CPV lies at high mass scale
  - BSM CPV doesn't talk directly to SM fermions
  - BSM CPV is flavor non-diagonal

II. Electric Dipole Moments

- *Discovery potential & interpretation: need for searches in multiple systems*
- *Benchmark sensitivities: three examples*
- *Challenges & opportunities for hadronic & many-body theory*

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	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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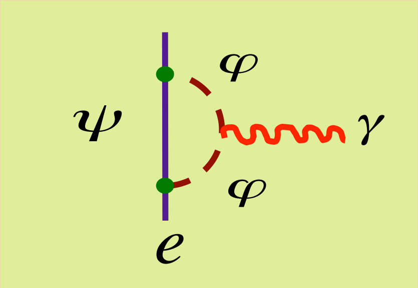
Mass Scale Sensitivity



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

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

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* 95% CL ** e^- equivalent

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

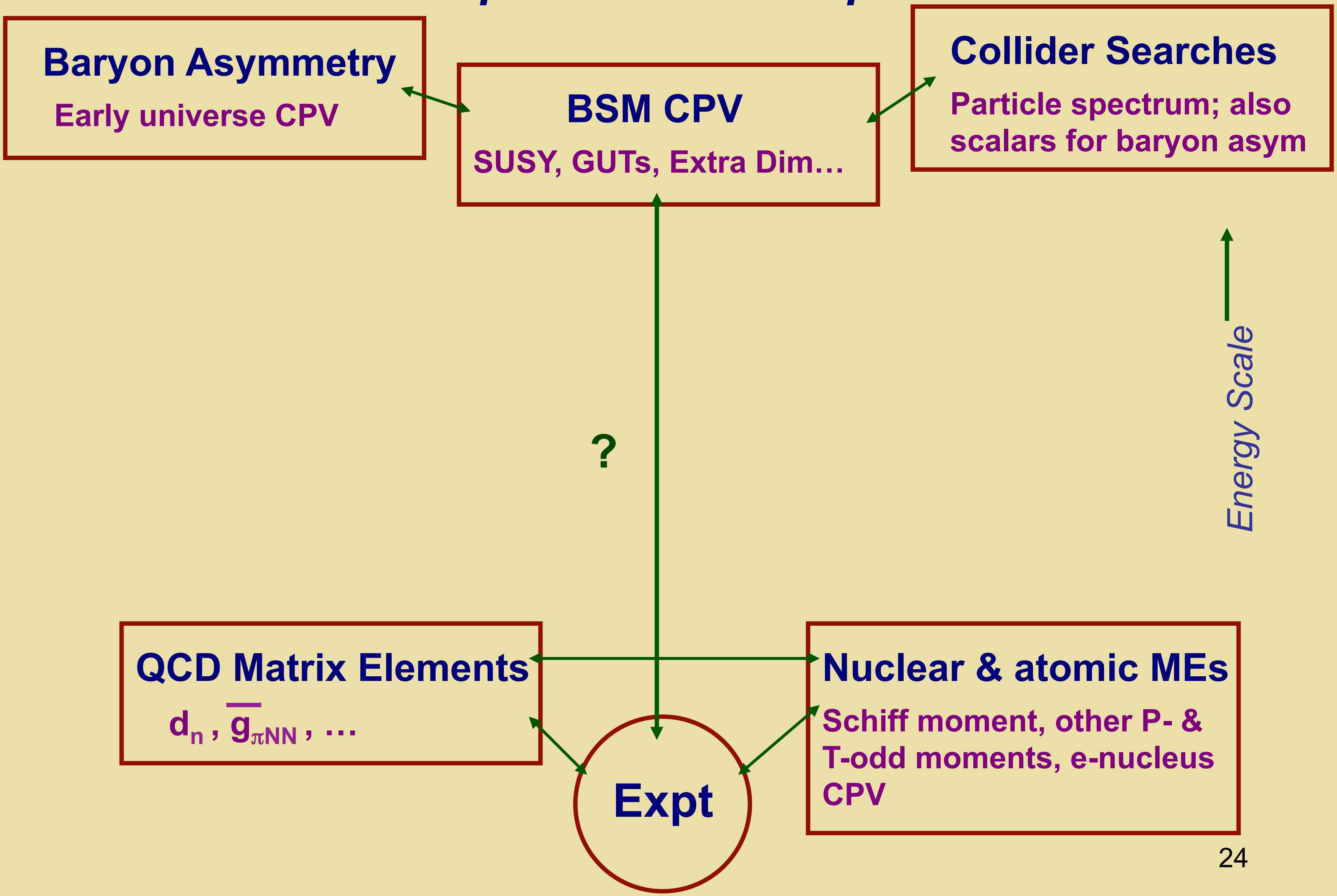
Not shown: muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales

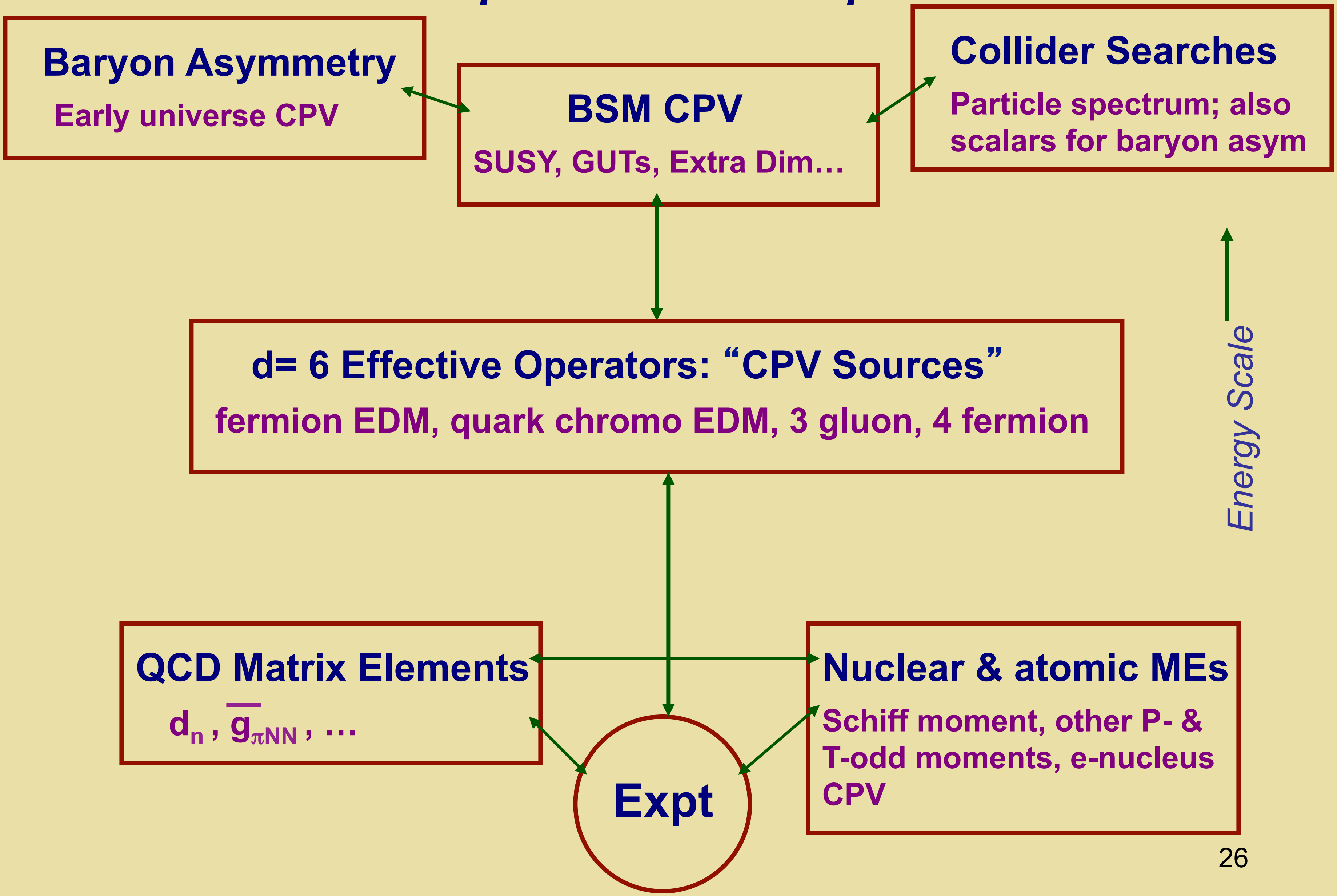


Effective Operators: The Bridge

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

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

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)

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12 total + $\bar{\theta}$

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Complementary searches needed

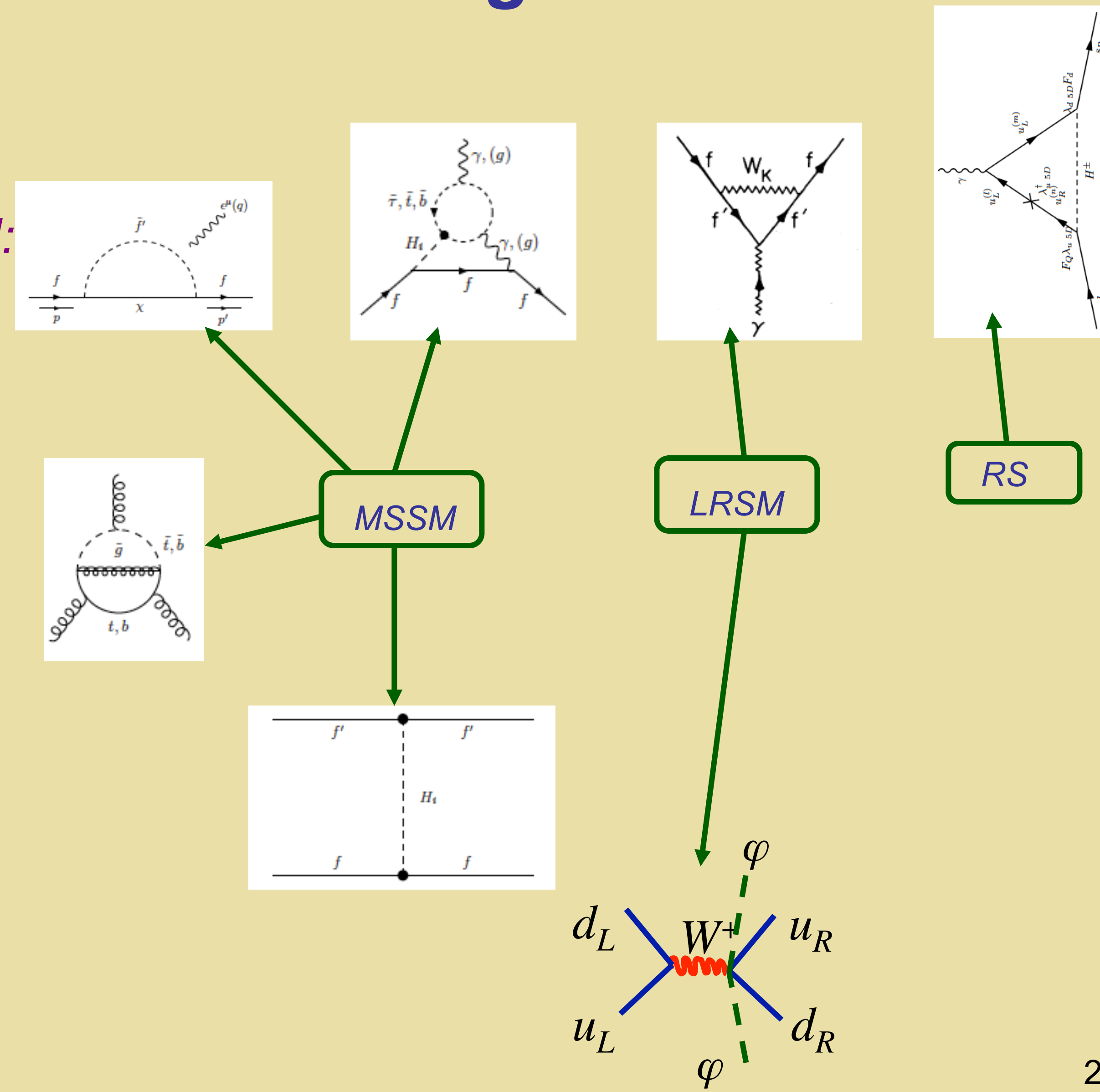
BSM Origins

EDM: γff CEDM: gff

Weinberg ggg:

Four fermion

udHH



Complementarity: Three Illustrations

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

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

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

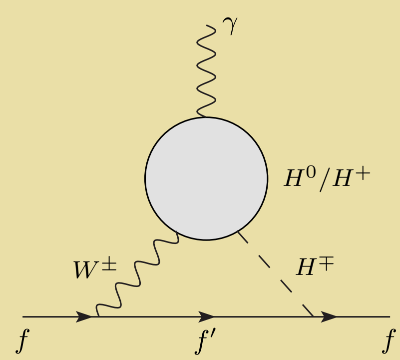
$$
\begin{aligned}
\delta_1 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] \;, \\
\delta_2 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]
\end{aligned}
$$

EWSB →

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

Viable EWB & CPV:

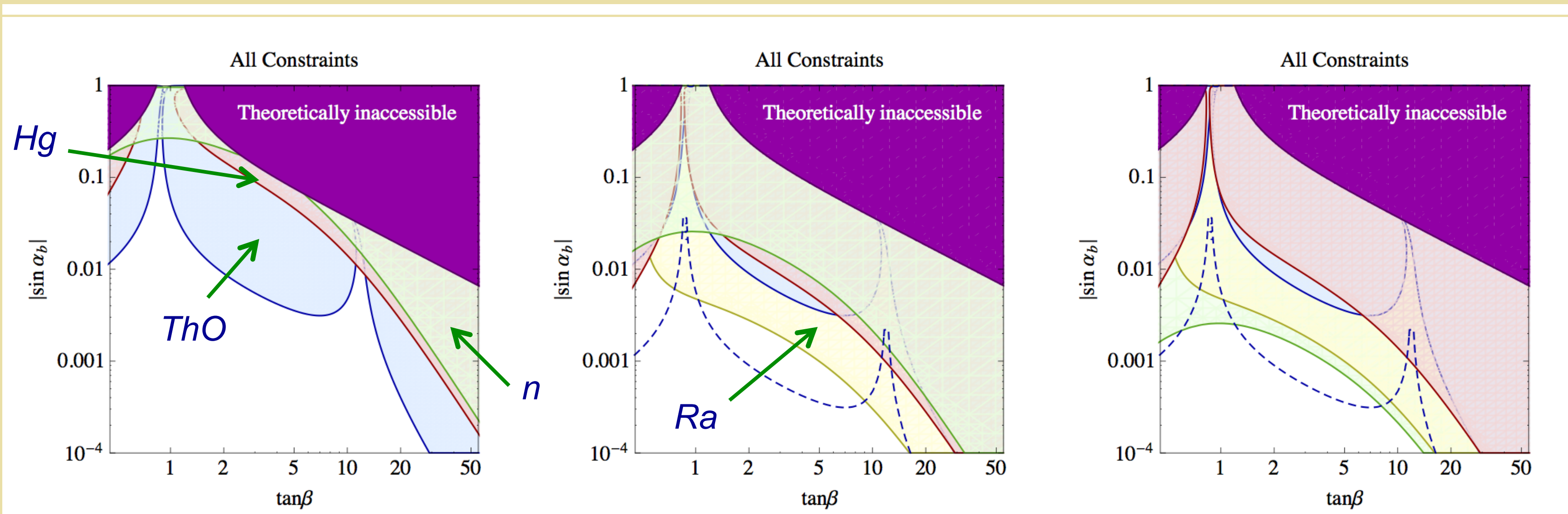
- EDMs are 2-loop
- CPV is flavor non-diag



Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

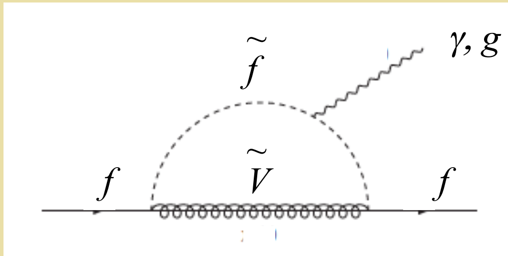
$\lambda_{6,7}$ = 0 for simplicity



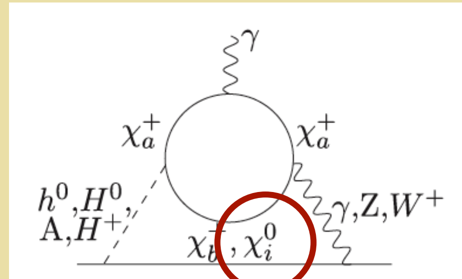
Present	*Future:*	*Future:*
	d_n x 0.1	*d_n x 0.01*
	d_A(Hg) x 0.1	*d_A(Hg) x 0.1*
sin α_b : CPV scalar mixing	*d_{ThO} x 0.1*	*d_{ThO} x 0.1*
	d_A(Ra)	*d_A(Ra)*

Inoue, R-M, Zhang: 1403.4257

EDMs & EW Baryogenesis: MSSM

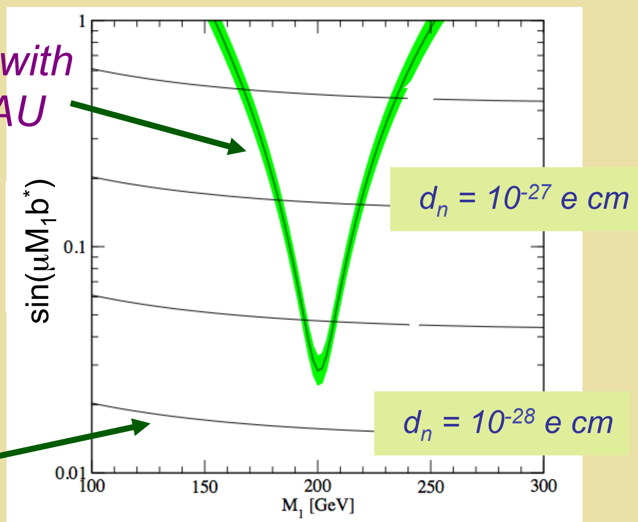


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

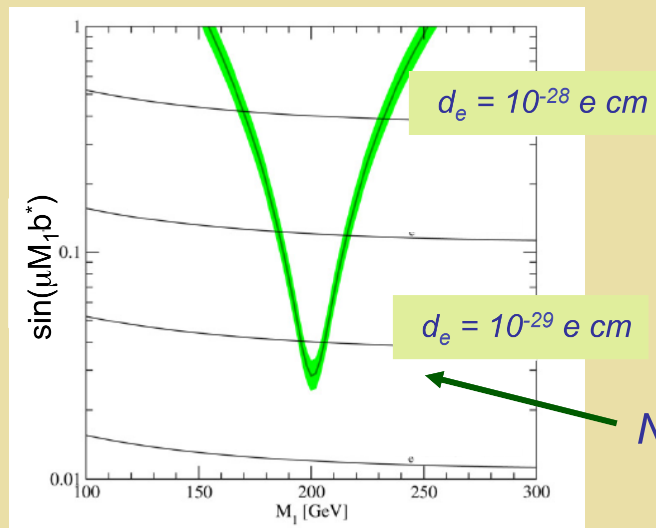


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



Next gen d_n

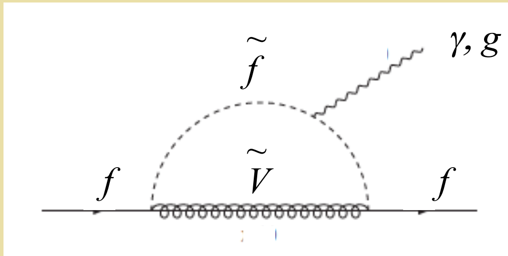


ACME: ThO

Next gen d_e

Li, Profumo, RM '09-'10

EDMs & EW Baryogenesis: MSSM



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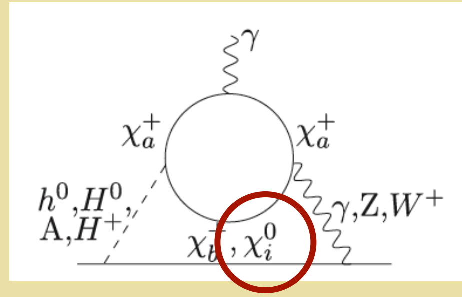

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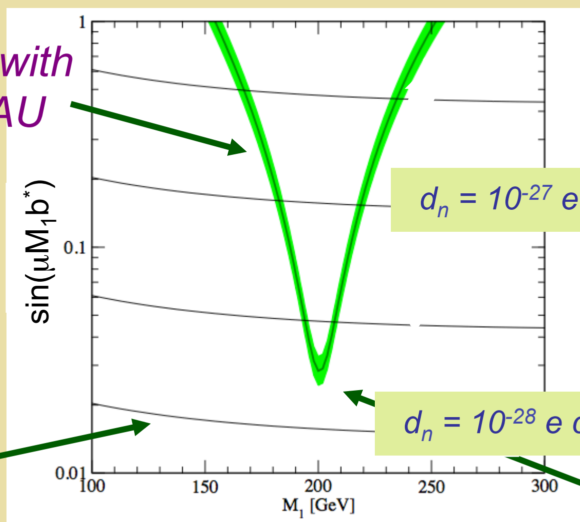
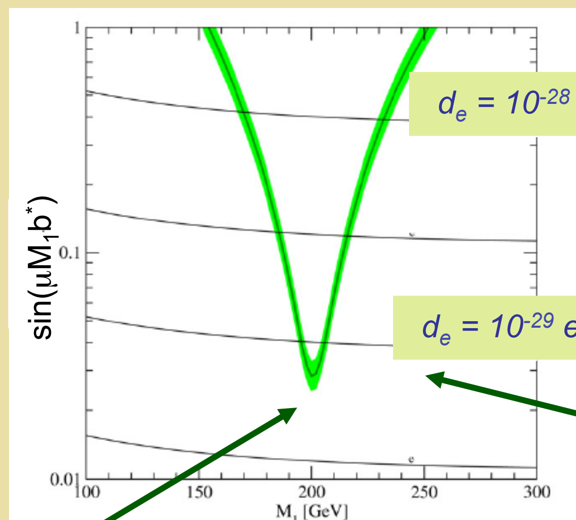


$d_n = 10^{-27}$ e cm

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

Next gen d_n



$d_e = 10^{-28}$ e cm *ACME: ThO*

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

Next gen d_e

Li, Profumo, RM '09-'10

Compressed spectrum (stealthy SUSY)

Wilson Coefficients: Model Independent

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$\tilde{\delta}_q$	quark CEDM	(2)
$C_{\tilde{G}}$	3 gluon	(1)
C_{quqd}	non-leptonic	(2)
$C_{lequ,\, ledq}$	semi-leptonic	(3)
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12 total + $\bar{\theta}$

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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
		$d_e = (\quad 6.9 \pm 7.4) \times 10^{-28}$	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
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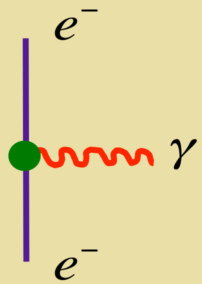
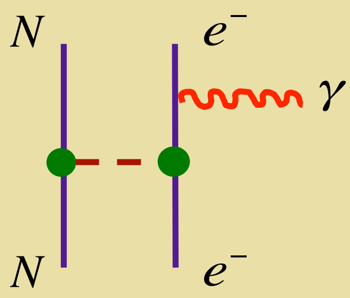
Chupp & R-M: 1407.1064

Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)



Tl, YbF, ThO…

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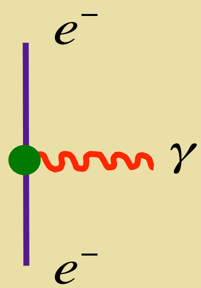
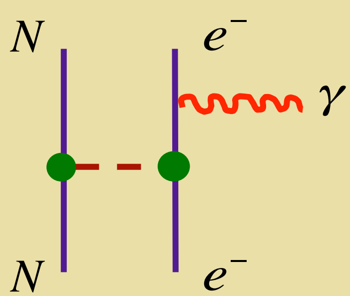


$$d_f = -(1.13 \times 10^{-3}\, e\,\mathrm{fm}) \left(\frac{v}{\Lambda}\right)^2 \; Y_f\, \delta_f$$

(Scalar q)
x (PS e-)

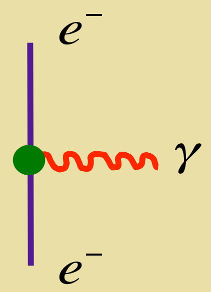


$$C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\, C_{eq}^{(-)}$$

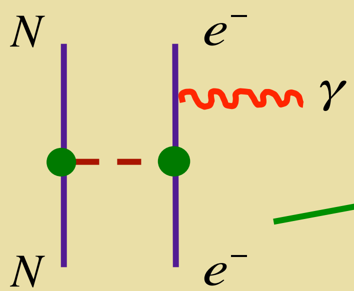
Tl, YbF, ThO…

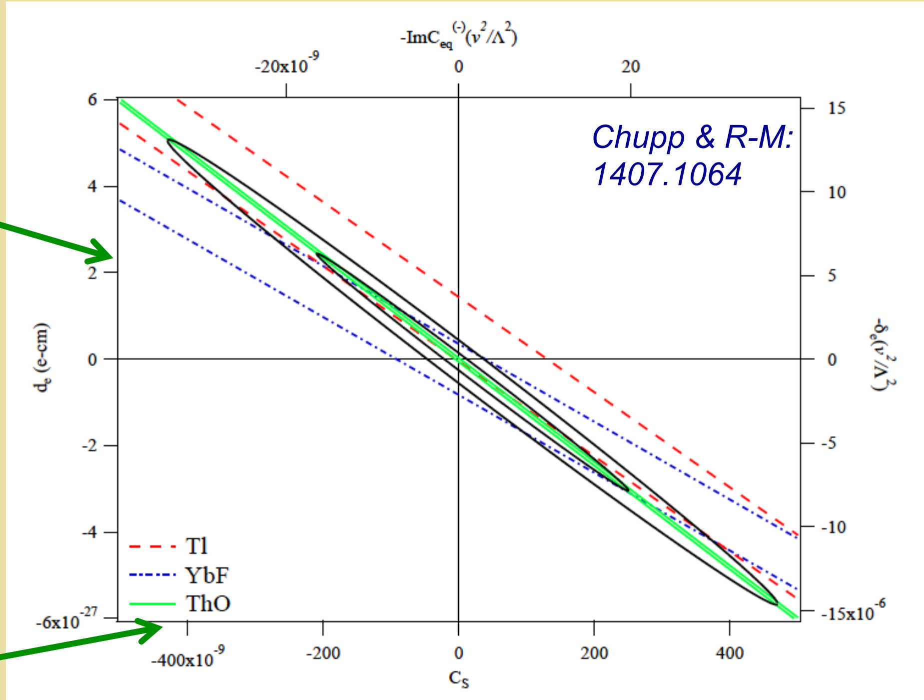
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e⁻)





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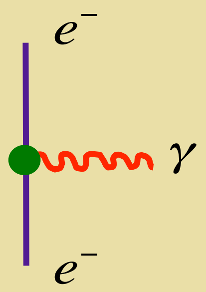
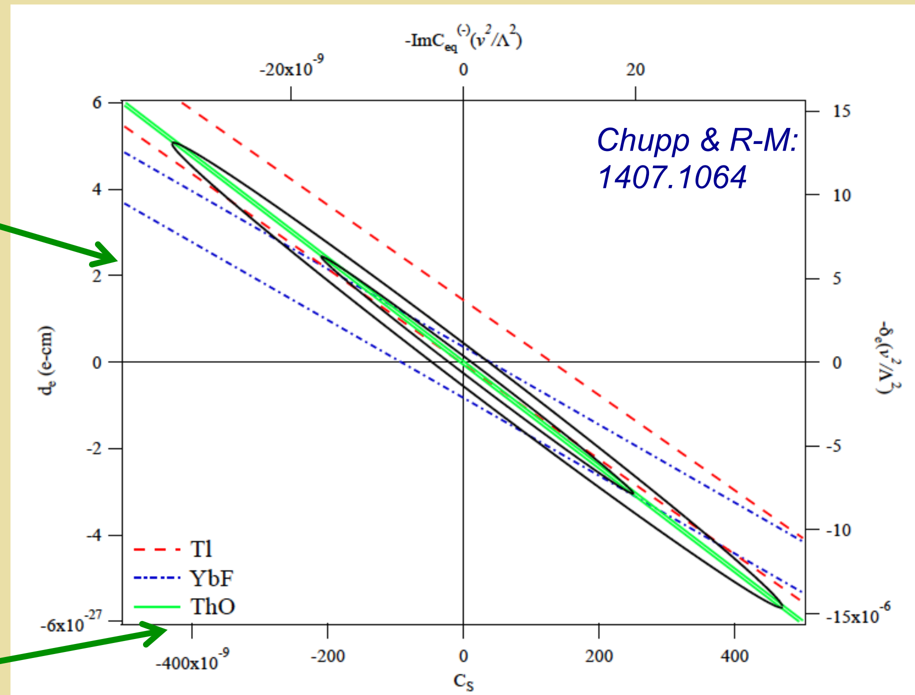
Paramagnetic Systems: Two Sources

Electron EDM





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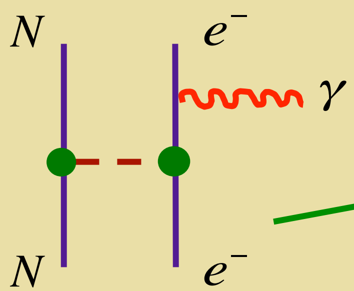

$$\Lambda \gtrsim (1.5\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}} \qquad \text{Electron EDM (global)}$$

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

Tl, YbF, ThO…

Global Analysis: Diamagnetic Systems

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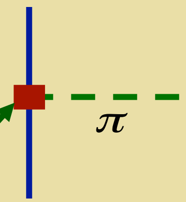
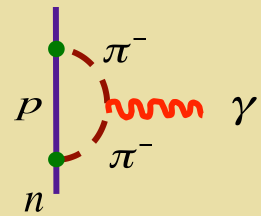
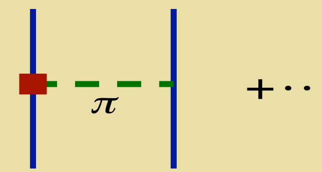
Chupp & R-M: 1407.1064

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction







- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

Nucleon EDM

+ quark EDM

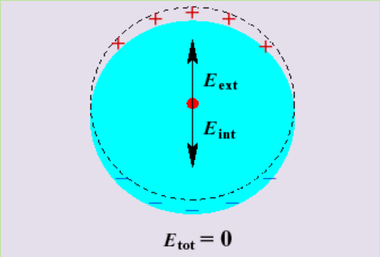
Nuclear EDM & Schiff moment

+ ~~quark EDM~~

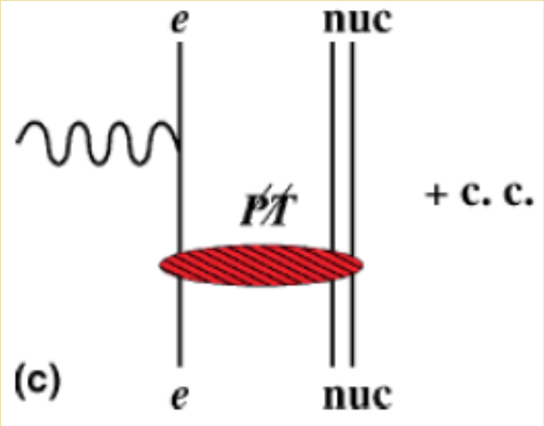
Neutron, proton & light nuclei (future), diamagnetic atoms

Diamagnetic Systems: P- & T-Odd Moments

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems

Nuclear Moments

	$P\,T$	$\not P\,T$	$P\,\not T$	$\not P\,\not T$	
C_J	E	✖	✖	O	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	E	*MQM….*
$T^E{}_J$	✖	O	E	✖	*Anapole…*

Diamagnetic Systems

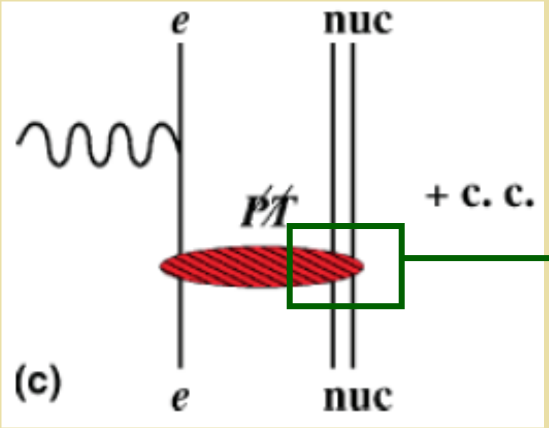
Nuclear Moments

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	O	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	E	*MQM….*
$T^E{}_J$	✖	O	E	✖	*Anapole…*

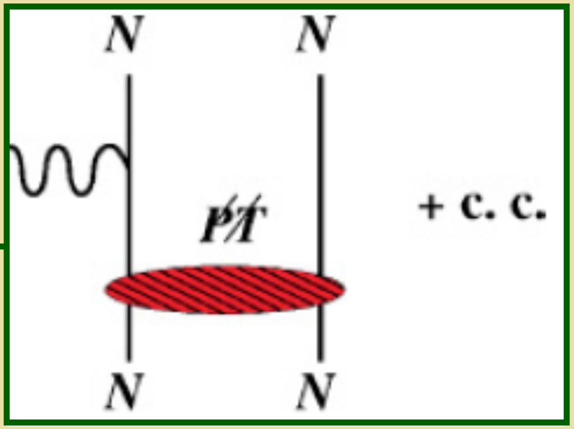
Nuclear Enhancements

Nuclear Schiff Moment

Nuclear Enhancements



Schiff moment, MQM,…

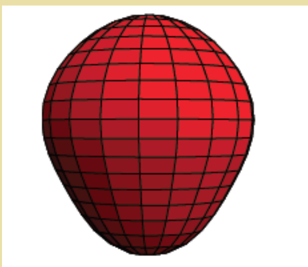


Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

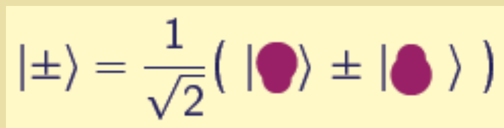
EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

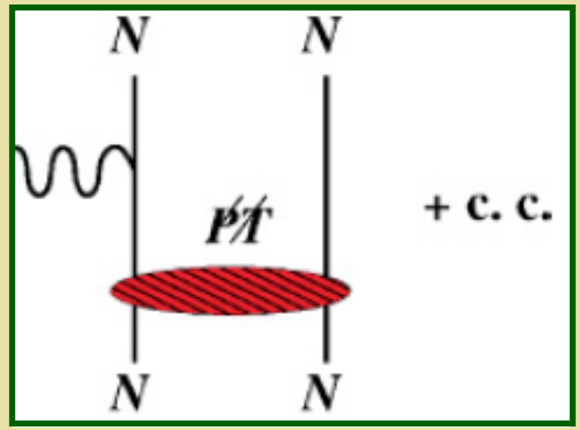
Nuclear Enhancements:
Octupole Deformation



Calculated ^{225}Ra density



Opposite parity states mixed by H^{TVPV}



"Nuclear amplifier"

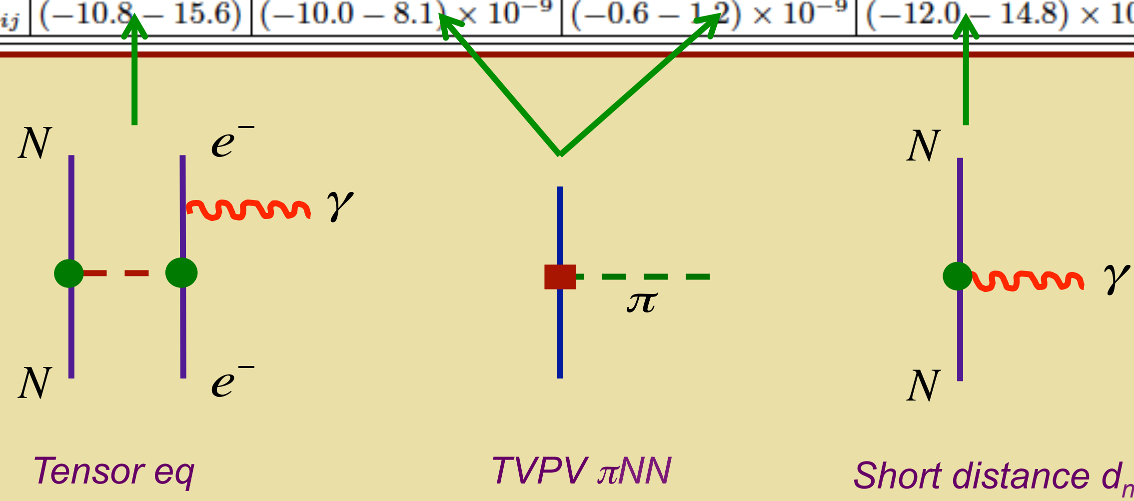
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{225}Ra)

Thanks: J. Engel

Diamagnetic Global Fit

	$C_T \times 10^7$	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n$ (e-cm)
Exact solution	1.265	-6.687×10^{-10}	1.4308×10^{-10}	9.878×10^{-24}
Range from best values of α_{ij}	$(-7.6 - 9.5)$	$(-5.0 - 4.0) \times 10^{-9}$	$(-0.2 - 0.4) \times 10^{-9}$	$(-5.9 - 7.4) \times 10^{-23}$
Range from best values with $\alpha_{g^1_\pi}(\text{Hg}) = -4.9 \times 10^{-17}$	$(-7.6 - 8.4)$	$(-7.0 - 4.0) \times 10^{-9}$	$(0 - 0.2) \times 10^{-9}$	$(5.9 - 10.4) \times 10^{-23}$
Range from best values with $\alpha_{g^1_\pi}(\text{Hg}) = +1.6 \times 10^{-17}$	$(-9.2 - 12.4)$	$(-4.0 - 4.0) \times 10^{-9}$	$(-0.4 - 0.8) \times 10^{-9}$	$(-5.9 - 5.9) \times 10^{-23}$
Range from full variation of α_{ij}	$(-10.8 - 15.6)$	$(-10.0 - 8.1) \times 10^{-9}$	$(-0.6 - 1.2) \times 10^{-9}$	$(-12.0 - 14.8) \times 10^{-23}$



Chupp & R-M: 1407.1064

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Isoscalar CEDM

$$\tilde{\delta}_q^{(+)} \left(\frac{v}{\Lambda}\right)^2 \lesssim 0.01 \qquad \Lambda \gtrsim (2\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}}$$

Caveat: Large hadronic uncertainty

Chupp & R-M: 1407.1064

Hadronic Matrix Elements

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

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

$$\bar C_i = \kappa_i\,\bar\theta + \left(\frac{v}{\Lambda}\right)^2 \sum_k \delta_i^{(k)}\,\mathrm{Im}\,C_k,$$

$$\left(\frac{v}{\Lambda}\right)^2 \left[\beta_N^{qG}\,\mathrm{Im}\,C_{qG} + \beta_N^{q\gamma}\,\mathrm{Im}\,C_{q\gamma}\right] = e\,\tilde\rho_N^q\,\tilde d_q + \rho_N^q\,d_q = \left(\frac{v}{\Lambda}\right)^2 \left[e\,\tilde\zeta_N^q\,\tilde\delta_q + e\,\zeta_N^q\,\delta_q\right],$$

$$\left(\frac{v}{\Lambda}\right)^2 \left[\gamma_{(i)}^{qG}\,\mathrm{Im}\,C_{qG} + \gamma_{(i)}^{q\gamma}\,\mathrm{Im}\,C_{q\gamma}\right] = \tilde\omega_{(i)}^q\,\tilde d_q + \omega_{(i)}^q\,d_q = \left(\frac{v}{\Lambda}\right)^2 \left[\tilde\eta_{(i)}^q\,\tilde\delta_q + \eta_{(i)}^q\,\delta_q\right].$$

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	$-(0.2 - 1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	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

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$\tilde{\delta}_q$ (CEDM)	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$
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$\text{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	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	±0.02	0.02
^{129}Xe	−0.008	−0.006	−0.009
^{225}Ra	−1.5	6.0	−4.0

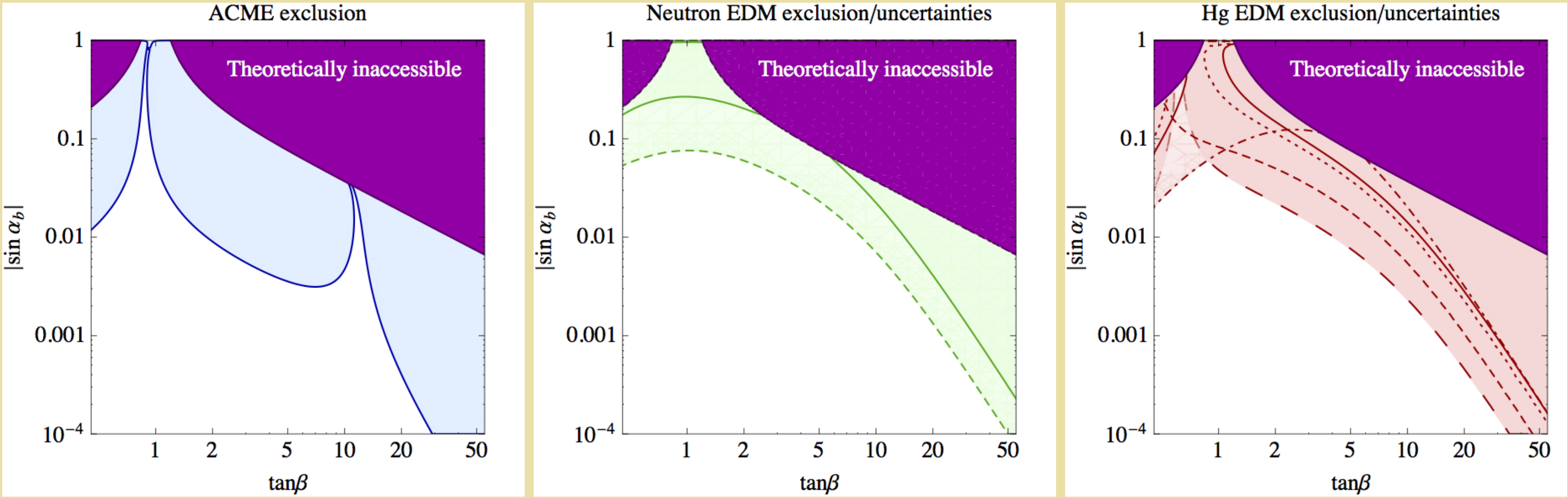
Range		
a_0	a_1	a_2
0.005–0.05	−0.03–(+0.09)	0.01–0.06
−0.005–(−0.05)	−0.003–(−0.05)	−0.005–(−0.1)
−1–(−6)	4–24	−3–(−15)

Engel, R-M, van Kolck ‘13

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

III. Questions

- *What is the roadmap for reducing hadronic theory uncertainties for EDMs?*
- *What progress can be achieved through different approaches (lattice, DSE, EFT…)? Are they complementary ? If so, how ?*
- *What are the key conceptual and/or technical challenges that must be addressed make progress?*
- *Are there emerging new directions that call for further theoretical progress (e.g., few-body nuclear EDMs) ?*

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 plagued by substantial hadronic and nuclear many-body uncertainties*
- *The advancing experimental sensitivity challenges hadronic structure theory to aim for an unprecedented level of reliability*