

# *Fundamental Symmetries & Neutrinos in Nuclear Science*



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## NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

<http://www.physics.wisc.edu/groups/particle-theory/>

DOE , May 2010

# *Outline*

1. *Context: Fundamental Symmetries & Neutrinos in Nuclear Physics*
  2. *Challenges for the new Standard Model*
  3. *The role of the “precision frontier”*
  4. *CPV & the origin of baryonic matter*
  5. *CP & T: EDMs*
- 
- *Supersymmetry as an illustration*

# *Low Energy Precision Tests : the Standard Model*



*Observation of parity-violation in  $^{60}\text{Co}$   $\beta$ -decay: LH nature of weak int*



*Measurement of PV asymmetry in eD scattering:  $SU(2)_L \times U(1)_Y$  prediction for neutral currents*



*Searches for neutron EDM: tiny QCD  $\theta$  parameter: axions?*

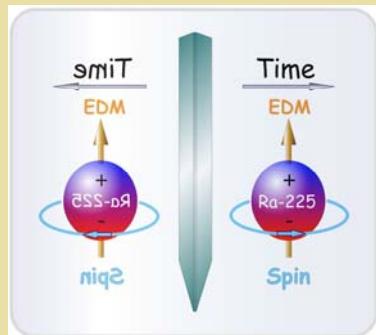


*Measurements of superallowed nuclear  $\beta$ -decay: most precise determination of quark mixing parameter*

*What are the symmetries of the “new Standard Model” ?*

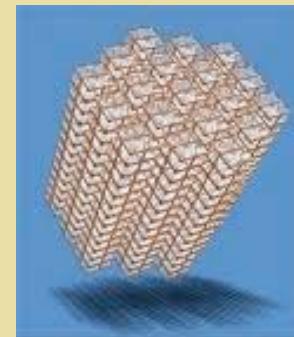
# Rare Processes: Experiments

## EDM Searches



- nucleon
- atoms
- leptons

## $0\nu\beta\beta$ Searches



- Cuore
- Exo
- Majorana
- SNO +

## CLFV Searches



- mu2e
- PRIME
- EIC

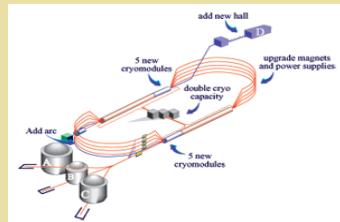
## Dark Matter Searches



- CLEAN
- WARP

# Precision Tests: Experiments

## PV Electron Scattering



- Q-Weak
- 12 GeV Moller
- PV DIS

## Weak Decays



- $n$  decay correlations
- nuclear  $\beta$  decay
- pion decays
- muon decays

## Torsion Balances



- Equiv Prin Tests
- Non-grav forces

## Muons



- $g_\mu - 2$
- $\mu A \rightarrow e A$

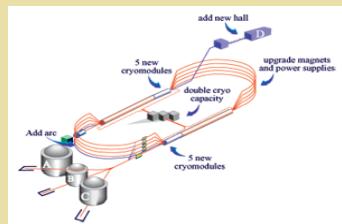
## Neutrinos



- oscillations
- $\beta$  &  $\beta\beta$  decay

# *EW Probes of QCD: Experiments*

## *PV Electron Scattering*



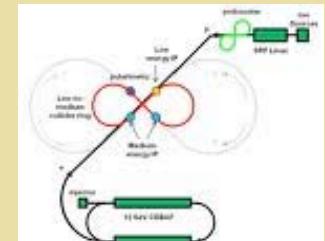
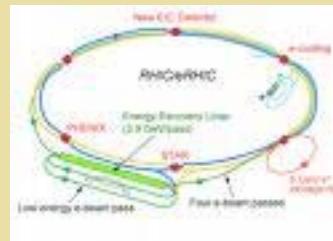
- SAMPLE, G0,  
HAPPEX, PVA4
- PREX
- PV DIS

## *Hadronic PV*



- FNPB/SNS
- NIST

## *EIC*



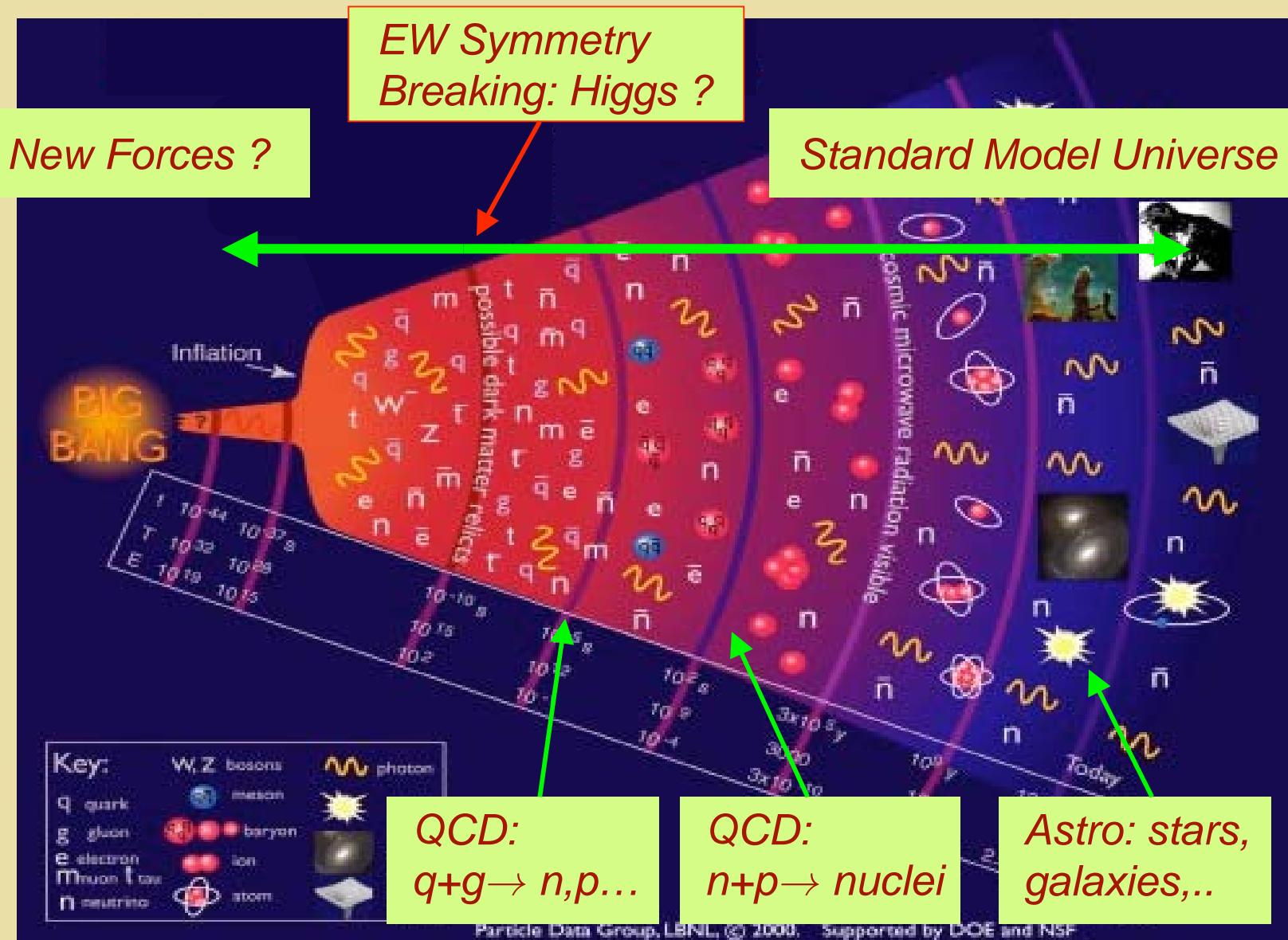
- PVDIS
- CC DIS

## *Scientific Questions*

- *Why is there now more visible matter than antimatter in the universe?*
- *What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the cosmos ?*
- *What are the unseen forces that were present at the dawn of the universe but disappeared from view as it evolved ?*

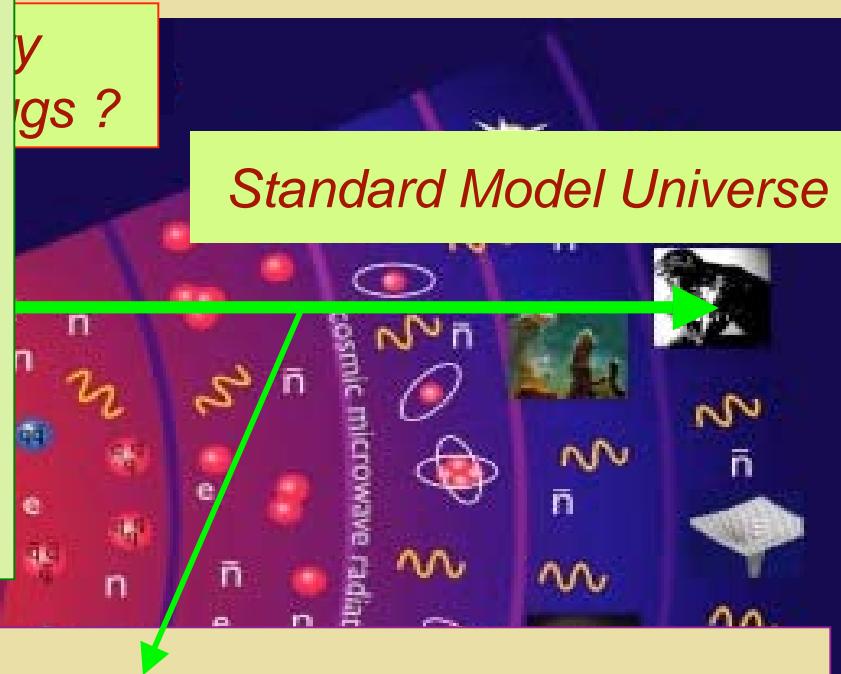
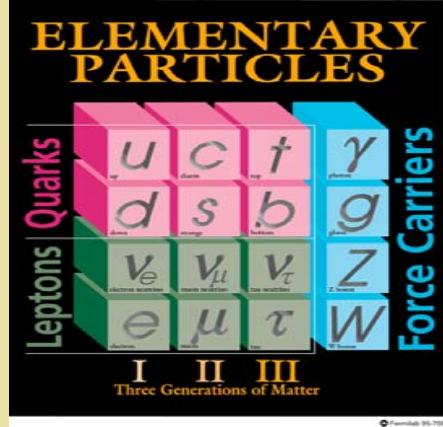
## *Challenges for the New Standard Model*

# Symmetries & Cosmic History



# Symmetries & Cosmic History

- Big Bang Nucleosynthesis (BBN) & light element abundances
- Weak interactions in stars & solar burning
- Supernovae & neutron stars

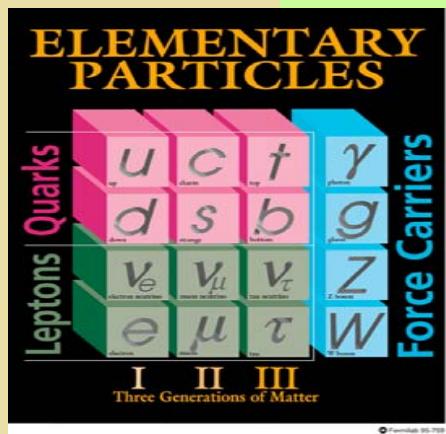
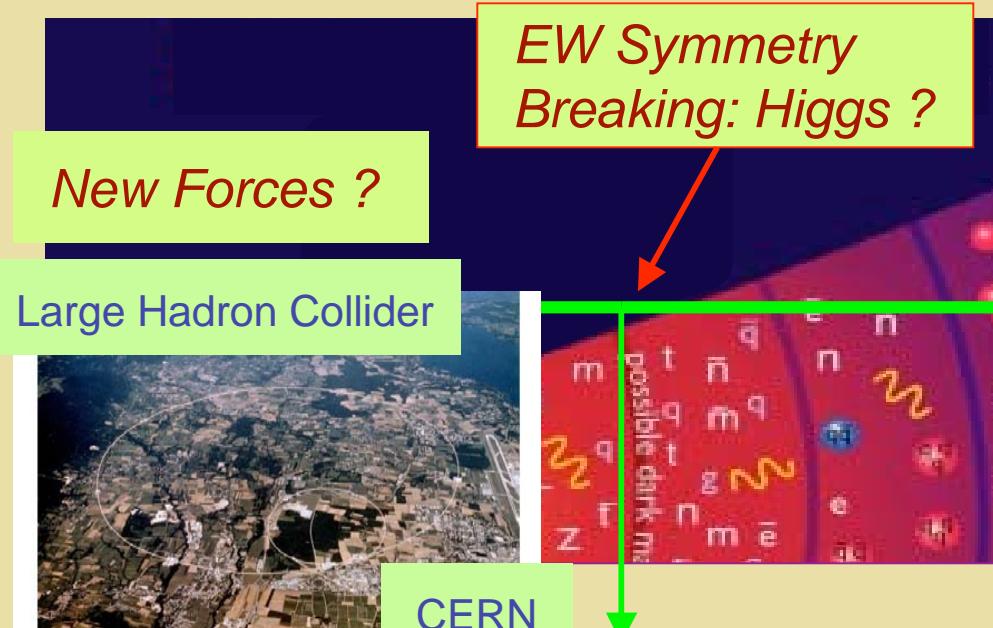


*It utilizes a simple and elegant symmetry principle*

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

*to explain the microphysics of the present universe*

# Symmetries & Cos



- Non-zero vacuum expectation value of neutral Higgs breaks electroweak sym and gives mass:

$$m_e = \lambda_e \langle H^0 \rangle$$

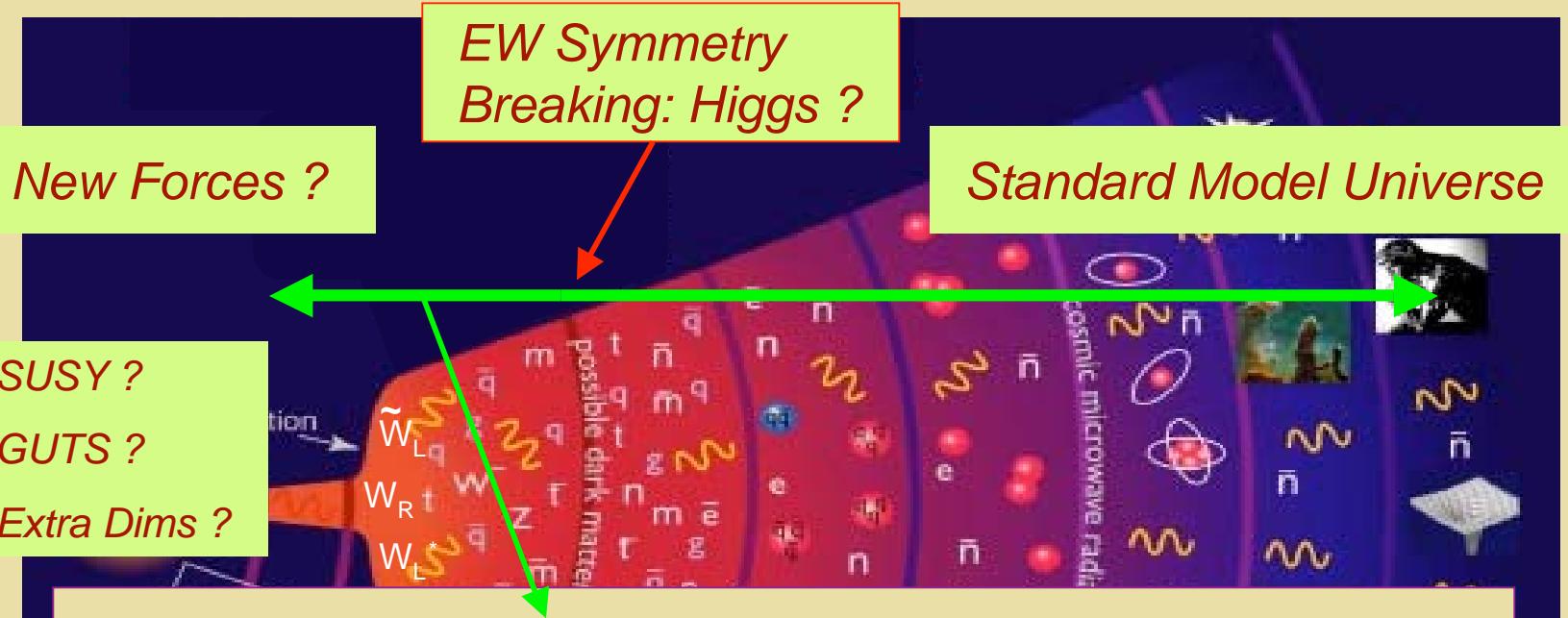
- Where is the Higgs particle?
- Is there more than one?

Puzzles the St'd Model may or may not solve:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

How is electroweak symmetry broken?  
How do elementary particles get mass ?

# Symmetries & Cosmic History



Puzzles the Standard Model can't solve

1. **Origin of matter**
2. **Unification & gravity**
3. **Weak scale stability**
4. **Neutrinos**

What are the symmetries (forces) of the early universe beyond those of the SM?

## *The Role of the Precision Frontier*

# Searching for Symmetries of the New SM:

*Unique role for low energy studies in the LHC era*

## Two frontiers in the search

Collider experiments  
( $p\bar{p}$ ,  $e^+e^-$ , etc) at higher  
energies ( $E \gg M_Z$ )

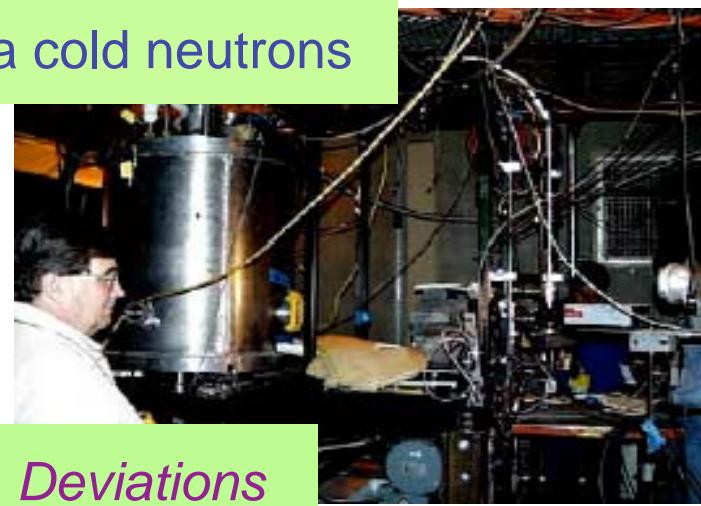
Indirect searches at  
lower energies ( $E < M_Z$ )  
but high precision

Large Hadron Collider



Bumps

Ultra cold neutrons



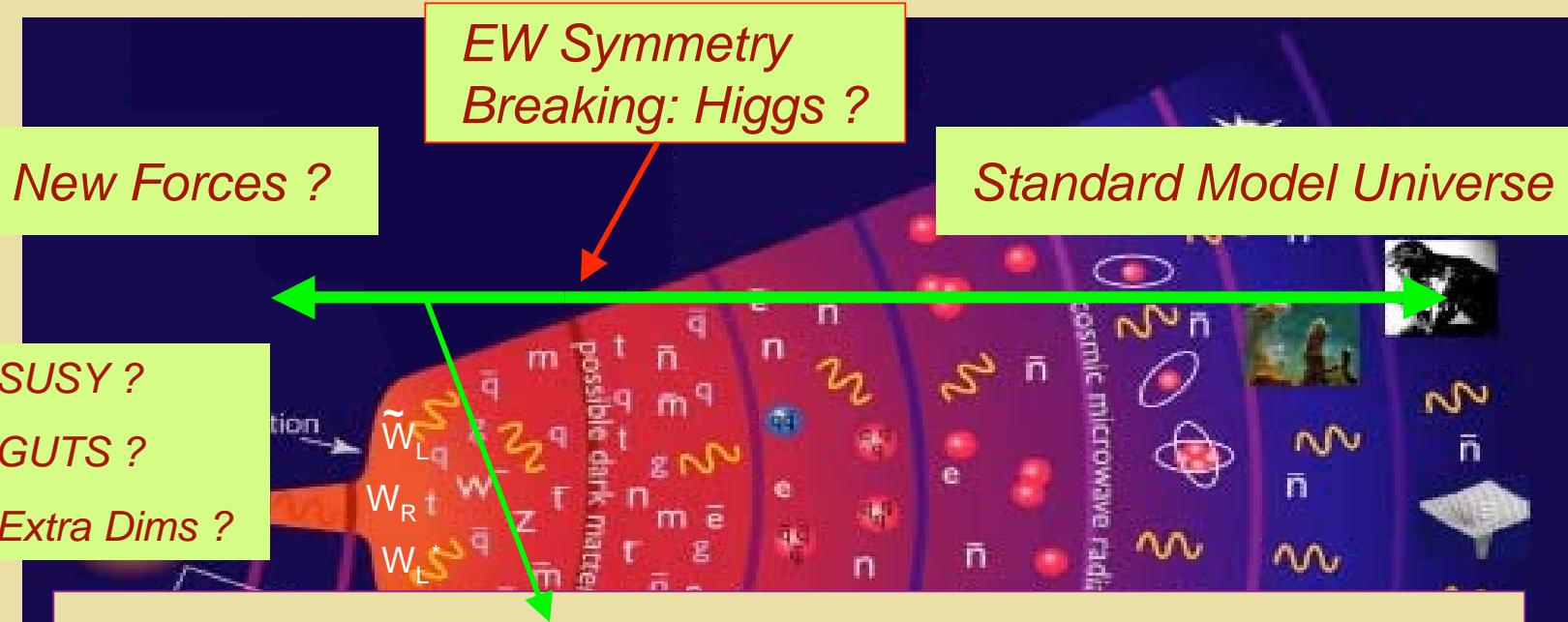
Deviations

High energy  
physics

Particle, nuclear  
& atomic physics

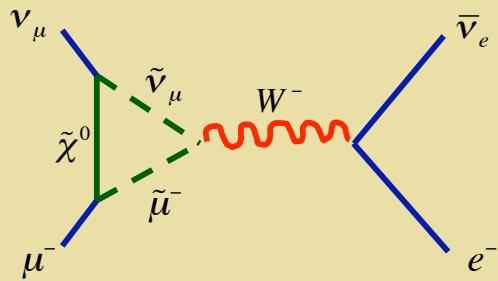
CERN

# Precision Probes of New Symmetries

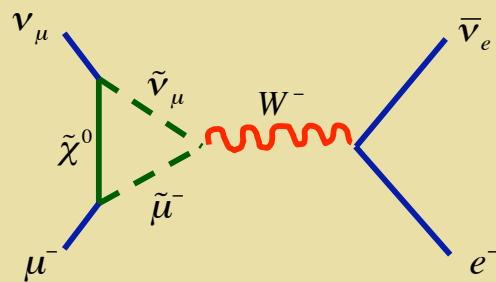


Puzzles the Standard Model can't solve

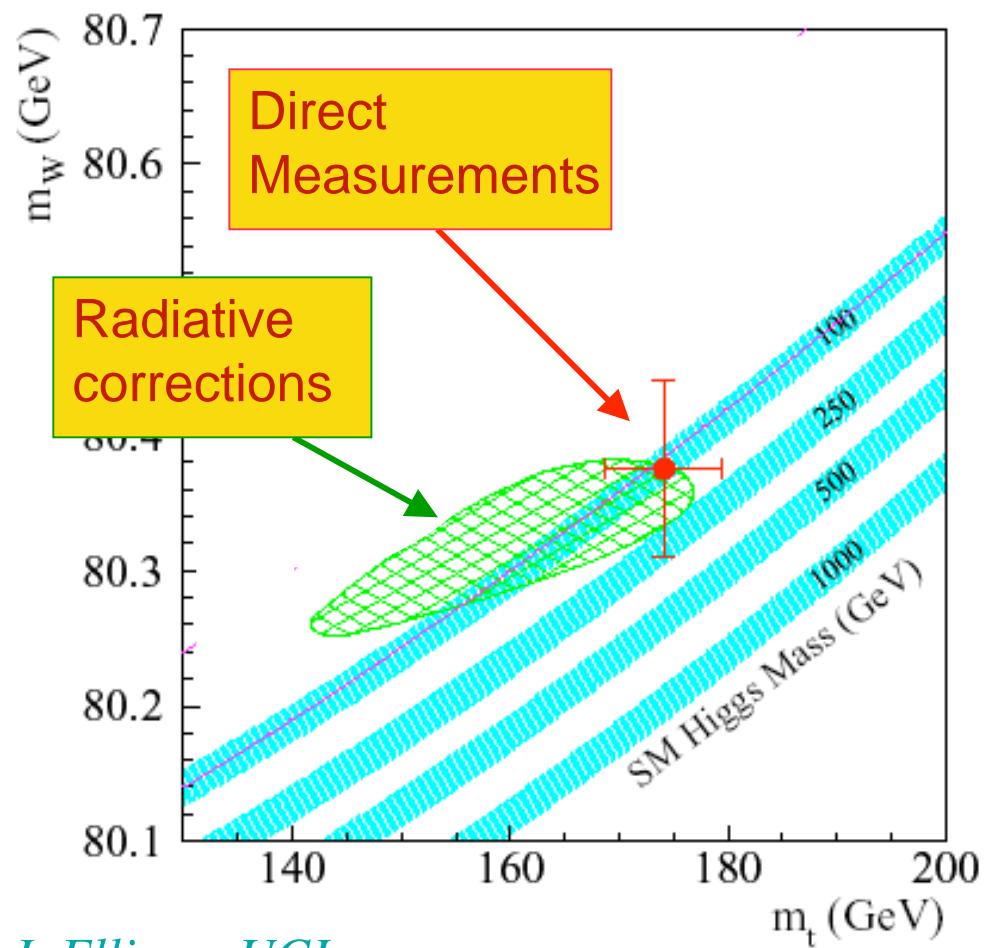
1. Origin of matter
2. Unification & gravity
3. Weak scale stability
4. Neutrinos



# Precision Probes of New Symmetries



# Precision & Energy Frontiers

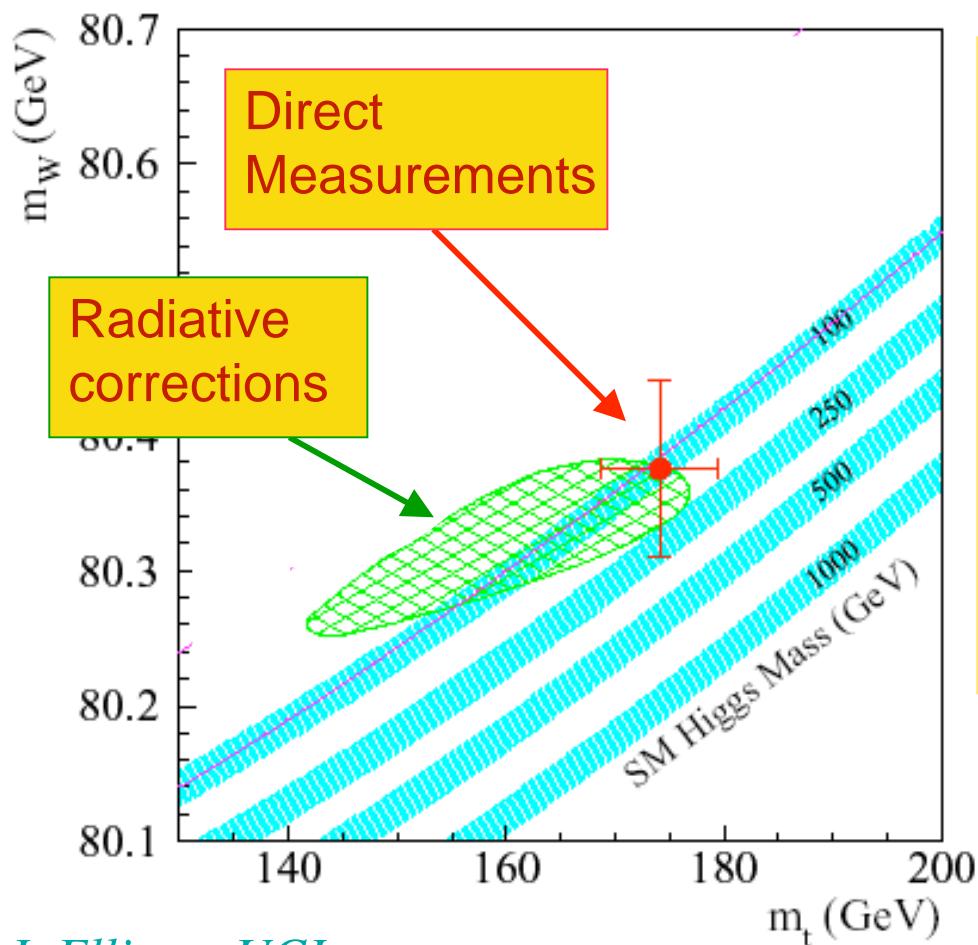


$$\frac{G_F^Z}{G_F^\mu} \approx (1 + \Delta r_Z - \Delta r_\mu)$$

Feynman diagrams illustrating Z boson decays. The left diagram shows a Z boson (red wavy line) decaying into a top quark ( $t$ , green loop) and an anti-top quark ( $\bar{t}$ ). The right diagram shows a Z boson (red wavy line) decaying into a bottom quark ( $b$ , green loop) and an anti-bottom quark ( $\bar{b}$ ). Red arrows indicate the direction of particle flow.

J. Ellison, UCI

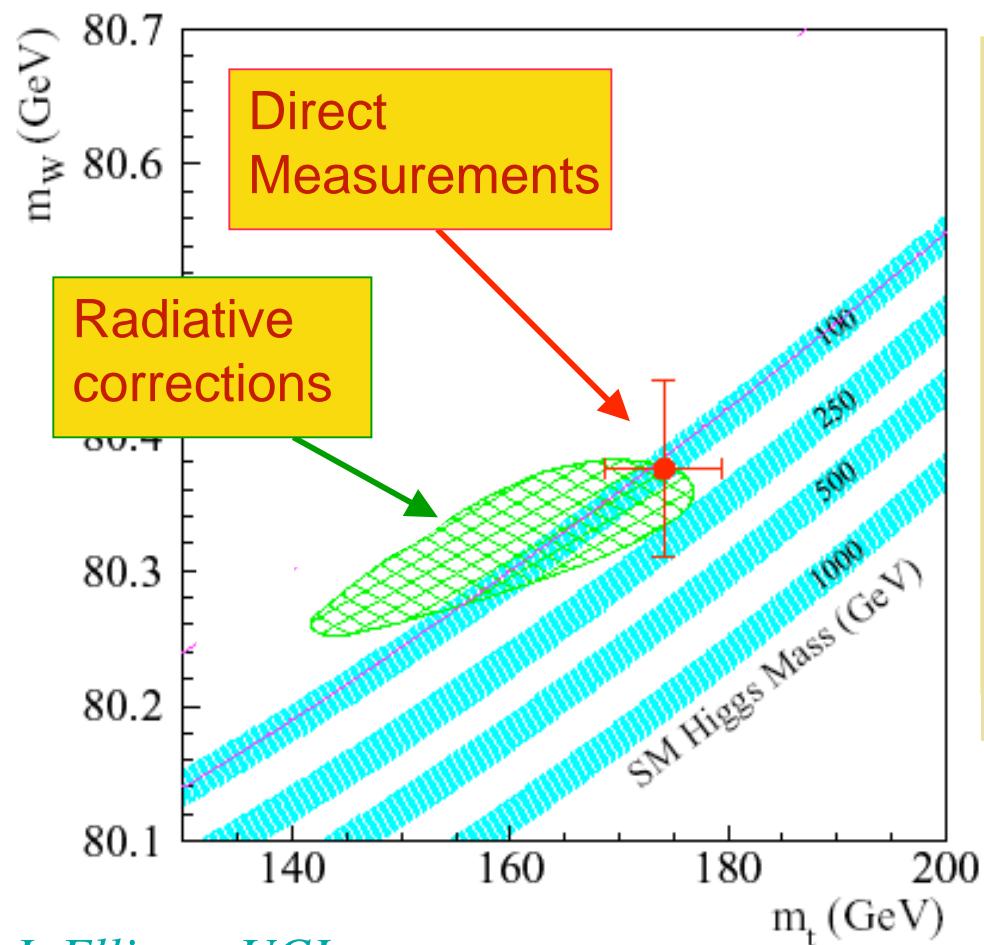
# Precision & Energy Frontiers



- Precision measurements predicted a range for  $m_t$  before top quark discovery
- $m_t \gg m_b$ !
- $m_t$  is consistent with that range
- It didn't have to be that way

Stunning SM Success

# Precision & Energy Frontiers



J. Ellison, UCI

*Probing Fundamental Symmetries beyond the SM:*

*Use precision low-energy measurements to probe virtual effects of new symmetries & compare with collider results*

**Stunning SM Success**

# *Precision Probes of the New SM*

*Precision ~ Mass Scale*

$$\delta_{NEW} = \frac{\Delta O^{NEW}}{O^{SM}} \approx \frac{\alpha}{\pi} \left( \frac{M}{\tilde{M}} \right)^2$$

$$M=m_\mu \quad \delta \sim 2 \times 10^{-9}$$

$$M=M_W \quad \delta \sim 1 \times 10^{-9}$$

$$M=M_Z \quad \delta \sim 10^{-3}$$

*Interpretability*

- Precise, reliable SM predictions
- Comparison of a variety of observables
- Special cases: SM-forbidden or suppressed processes

*Discovery*

# Precision Probes of the New SM

Precision ~ Mass Scale

$$\delta_{NEW} = \frac{\Delta O^{NEW}}{O^{SM}} \approx \frac{\alpha}{\pi} \left( \frac{M}{\tilde{M}} \right)^2$$

$$M=m_\mu$$

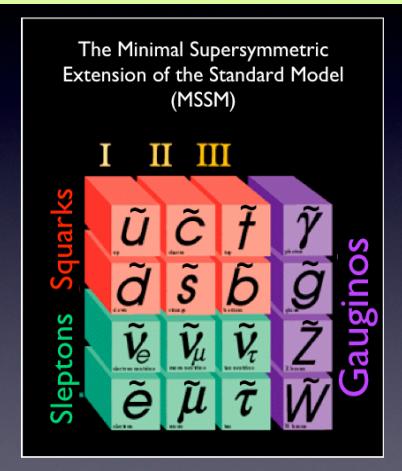
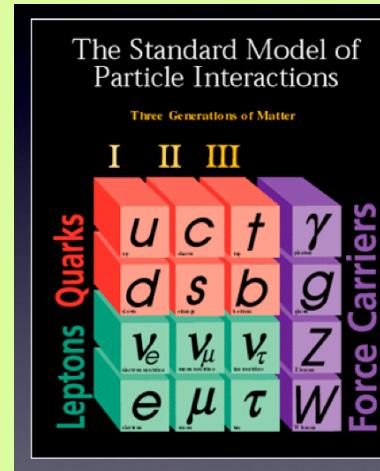
$$\delta \sim 2 \times 10^{-9}$$

$$M=M_W$$

$$\delta^{\text{exp}} \sim 1 \times 10^{-9}$$

$$\delta \sim 10^{-3}$$

Illustrate ideas, physics reach,  
& developing theoretical  
methods with Minimal  
Supersymmetric SM (MSSM)  
but more generally applicable



# *EDMs & the Origin of Baryonic Matter*

# What is the Origin of Matter



Leptogenesis:  
less testable,  
look for  
ingredients w/  $\nu s$

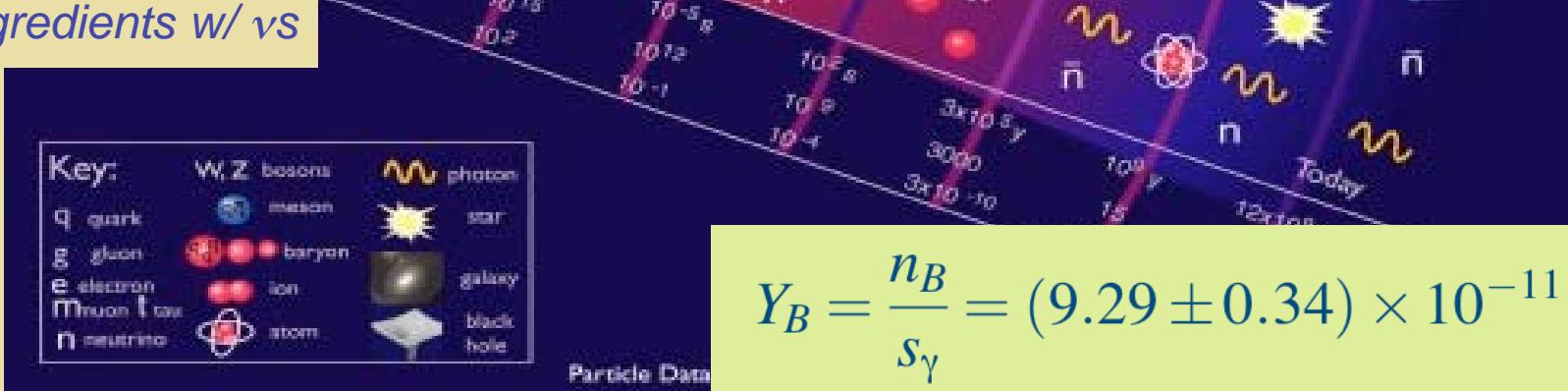
*EW Baryogenesis:*  
testable w/ EDMs +  
colliders

Baryogenesis: When?  
CPV? SUSY? Neutrinos?

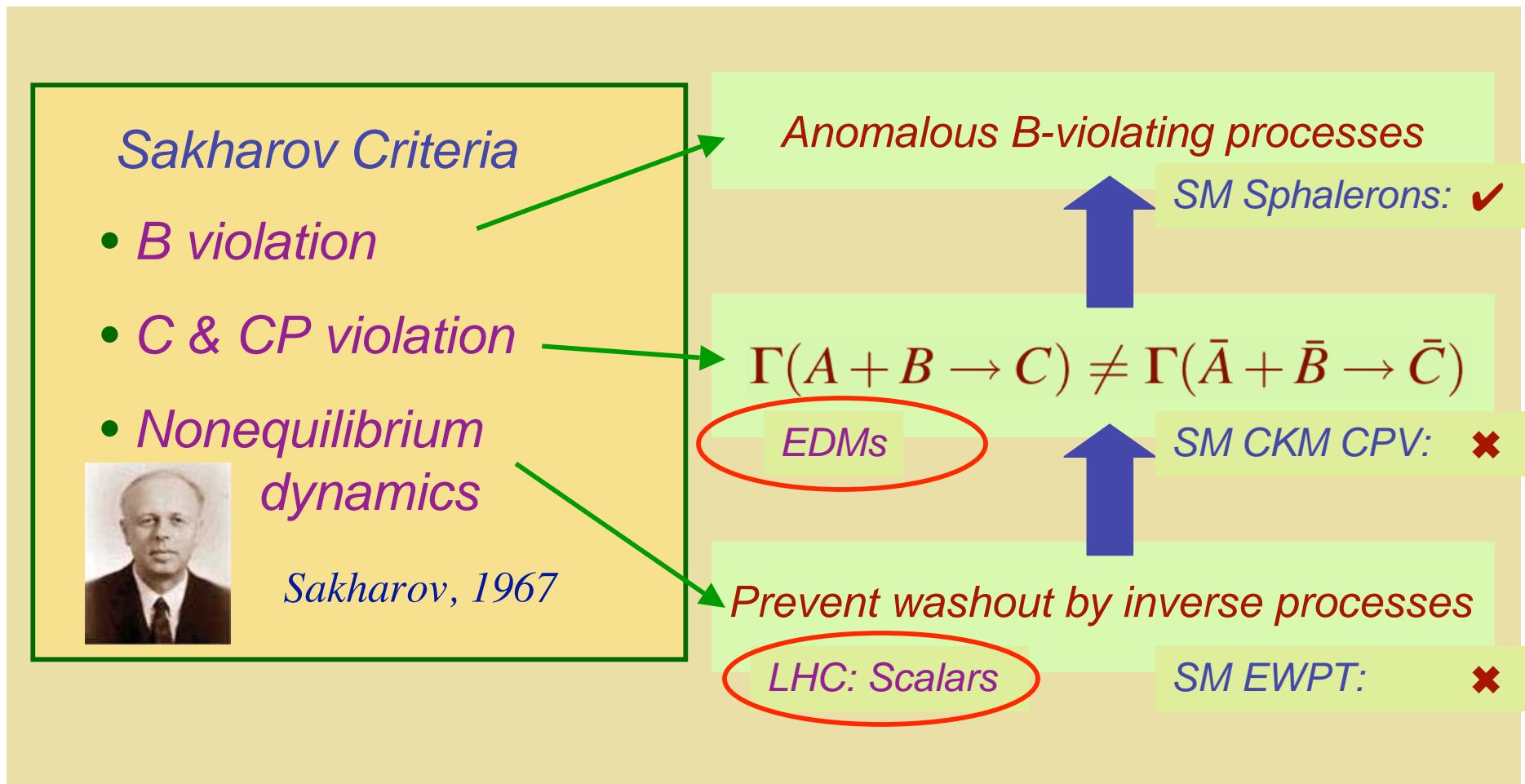


Can new TeV scale  
physics explain the  
abundance of matter ?

If so, how will we  
know ?



# Baryogenesis: Ingredients



# Baryogenesis: New Electroweak Physics

## Weak Scale Baryogenesis

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*



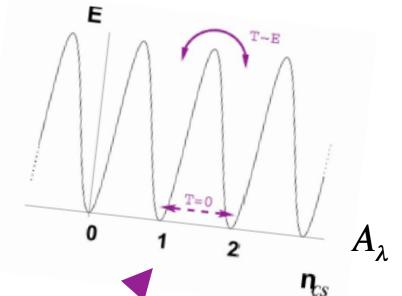
Sakharov, 1967

Unbroken phase

Topological transitions

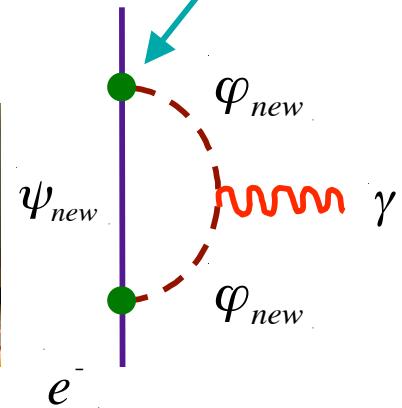
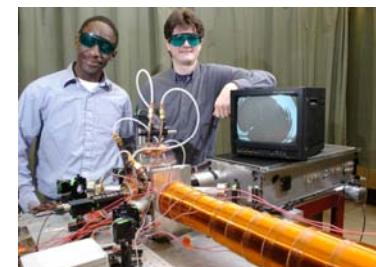
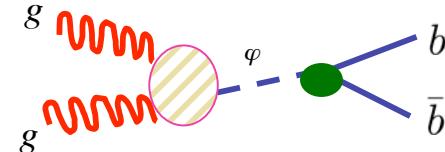
Broken phase

1st order phase transition



$$\langle \phi(x) \rangle$$

CP Violation



# Baryogenesis: New Electroweak Physics

## Weak Scale Baryogenesis

- $B$  violation
- $C$  &  $CP$  violation
- Nonequilibrium dynamics



Topological transitions

1st order phase transition

Unbroken phase

Broken phase

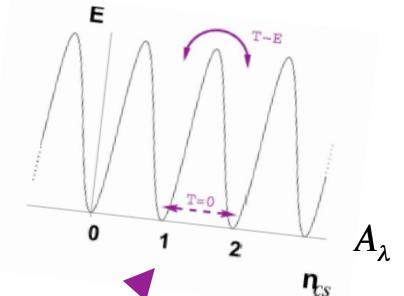
Theoretical Issues:

Strength of phase transition (Higgs sector)

Bubble dynamics (numerical)

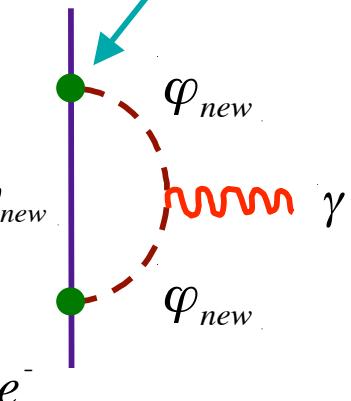
Transport at phase boundary (non-eq QFT)

EDMs: many-body physics & QCD



$$\langle \phi(x) \rangle$$

CP Violation



# Baryogenesis: EW Phase Transition

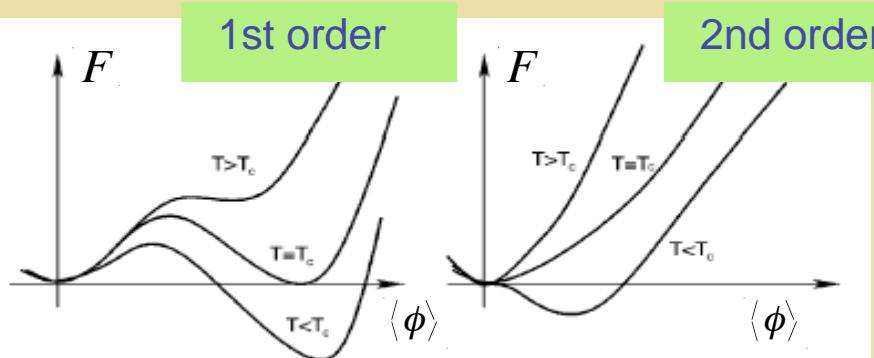
## Weak Scale Baryogenesis

- $B$  violation
- $C$  &  $CP$  violation
- None



Scalar Dark Matter?

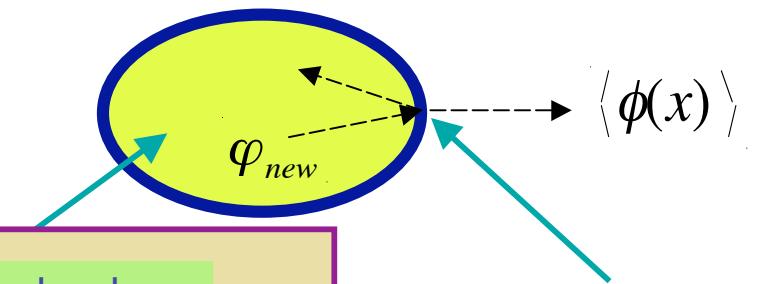
...Gonderinger,  
Li, Patel, R-M



Increasing  $m_h$

Profumo, Shaugnessy, MR-M, Patel...

Unbroken phase



CP Violation  
& Transport



Adding new  
scalar particles  
to the SM

Barger, Fileviez-Perez,  
Langacker, McCaskey,  
O'Connell, Patel, Profumo, R-M,  
Shaugnessy, Wang, Wise

# Baryogenesis: CPV & Transport

Weak Scale Baryogenesis

- $B$  violation
- $C$  &  $CP$  violation
- Nonequilibrium dynamics

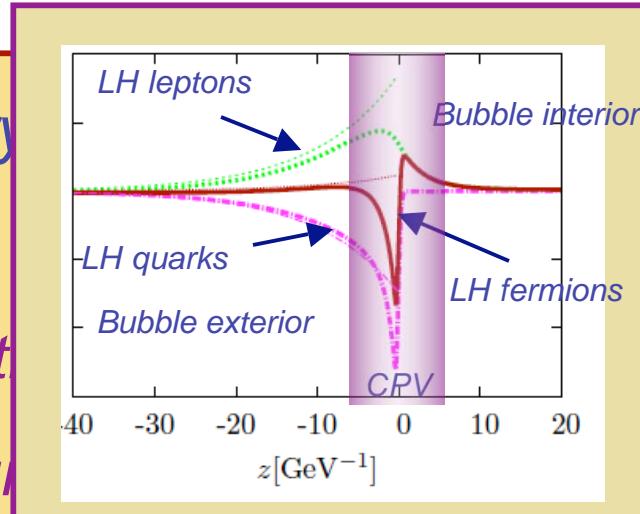


Sakharov, 1967

Coupled set of ( $\sim 30$ ) quantum Boltzmann equations

$$\partial_\mu \tilde{t}^\mu = -\Gamma_Y^{(\bar{t}, \bar{q}, H_1)} \left( \frac{\tilde{t}}{k_{\bar{t}}} - \frac{\tilde{q}}{k_{\bar{q}}} - \frac{H_1}{k_{H_1}} \right) - \Gamma_Y^{(\bar{t}, \bar{q}, H_2)} \left( \frac{\tilde{t}}{k_{\bar{t}}} - \frac{\tilde{q}}{k_{\bar{q}}} - \frac{H_2}{k_{H_2}} \right) + S_t^{\text{CPV}}$$

$$- \Gamma_Y^{(\bar{t}, q, \bar{H})} \left( \frac{\tilde{t}}{k_{\bar{t}}} - \frac{q}{k_q} - \frac{\bar{H}}{k_{\bar{H}}} \right) - \Gamma_V^{(t, \bar{t})} \left( \frac{\tilde{t}}{k_{\bar{t}}} - \frac{t}{k_t} \right) - \Gamma_M^{(\bar{t}, \bar{q})} \left( \frac{\tilde{t}}{k_{\bar{t}}} - \frac{\tilde{q}}{k_{\bar{q}}} \right)$$

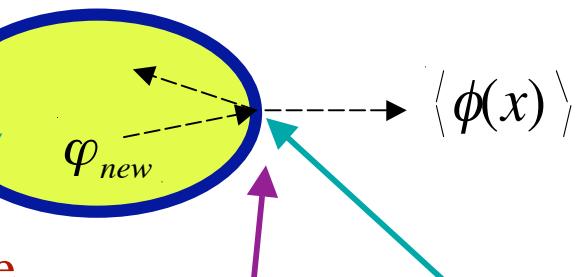


MSSM: Chung, Garbrecht, R-M, Tulin '09

Also Cirigliano,  
Lee, R-M, Tulin

phase

phase



CP Violation  
& Transport

Transport: A Competition    R-M et al

$$\Gamma(A + B \rightarrow C) \neq \Gamma(\bar{A} + \bar{B} \rightarrow \bar{C}) \quad \text{CPV}$$

$$\Gamma(A + B \leftrightarrow C) \quad \text{Chem Eq}$$

$$\Gamma(A + B \leftrightarrow A + B) \quad \text{Diffusion}$$

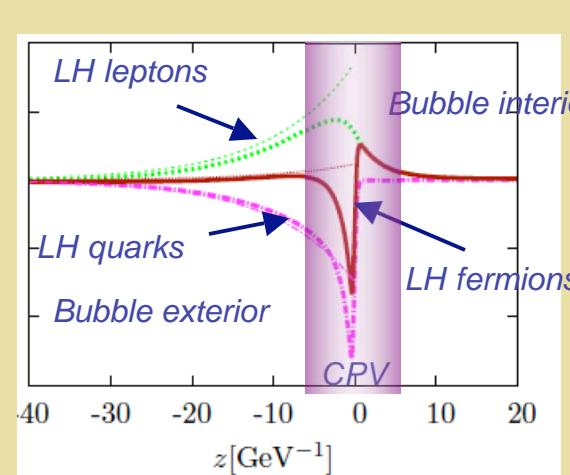
# Baryogenesis: CPV & Transport

Weak Scale Baryogenesis

- $B$  violation
- $C$  &  $CP$  violation
- Nonequilibrium dynamics



Sakharov, 1967



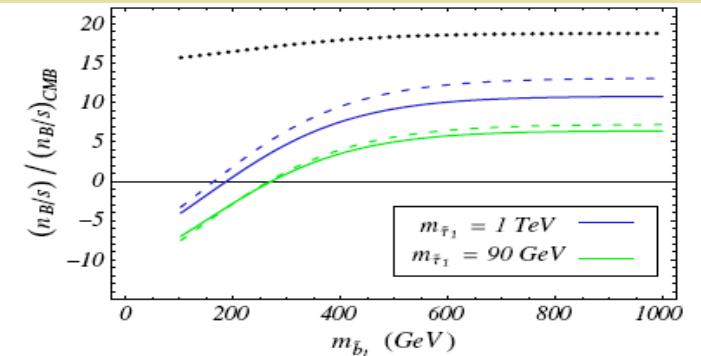
MSSM: Chung, Garbrecht, R-M, Tulin '08

Also Cirigliano,  
Lee, R-M, Tulin

phase

phase

Details of spectrum impt: LHC !



Chung, Garbrecht, R-M, Tulin '08

EDM searches:

How strong was the CPV “kick” ?

# *Probing CP & T: Electric Dipole Moments*

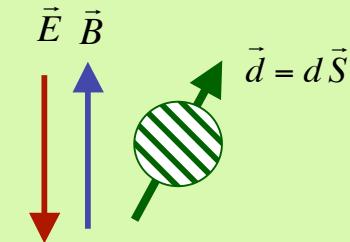
# EDMs: New CPV?

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction	New Physics
e	$1.9 \times 10^{-27}$	Tl atom	$10^{-38}$	$10^{-27}$
$\mu$	$1.1 \times 10^{-19}$	rest frame $E$	$10^{-35}$	$10^{-22}$
$\tau$	$3.1 \times 10^{-16}$	$e^+e^- \rightarrow \tau^+\tau^-\gamma$	$10^{-34}$	$10^{-20}$
p	$6.5 \times 10^{-23}$	TIF molecule	$10^{-31}$	$10^{-26}$
n	$2.9 \times 10^{-26}$	UCN	$10^{-31}$	$10^{-26}$
$^{199}\text{Hg}$	$3.1 \times 10^{-29}$	atom cell	$10^{-33}$	$10^{-28}$

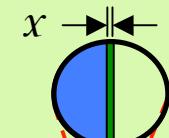
- SM “background” well below new CPV expectations

C-Y Liu



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

T-odd, CP-odd  
by CPT theorem

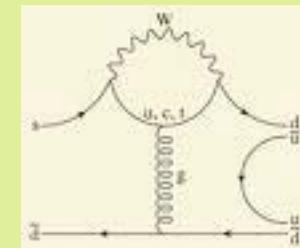


$d_n$ :  $x < 0.5 \text{ mm}$

# EDMs: Standard Model CKM

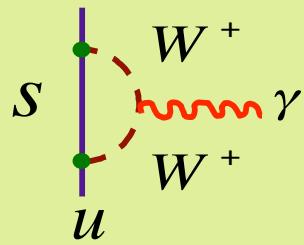
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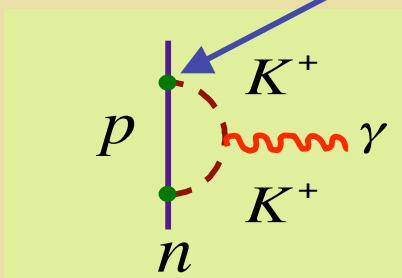


Penguin:  $\Delta S = 1$

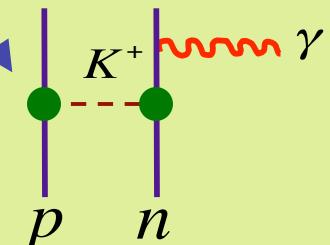
## CKM CPV



- 1 loop vanishes ( $\sim V_{us} V_{us}^*$ )
- 2 loop shown to vanish explicitly



- Khriplovich et al; McKellar...



- Donoghue, Holstein, RM; Khriplovich et al

# EDMs: Standard Model $\theta$ -term

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction
e	$1.9 \times 10^{-27}$	Tl atom	$10^{-38}$
$\mu$	$1.1 \times 10^{-19}$	rest frame $E$	$10^{-35}$
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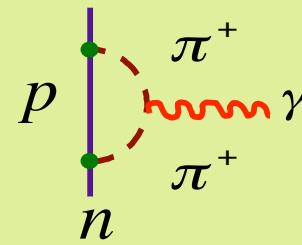
$d_n$  &  $d_A$  ( $^{199}\text{Hg}$ ):

$$\bar{\theta} < 10^{-10}$$

Peccei -Quinn Sym?

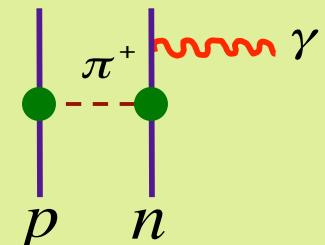
$$\mathcal{L}_{QCD}^\theta$$

$$\frac{\alpha_s \bar{\theta}}{4\pi} \text{Tr } \tilde{G}_{\mu\nu} G^{\mu\nu}$$



- vanishes for any  $m_q=0$
- “bar”: absorb quark field redefinition

- Crewther et al; van Kolck et al ; Herczeg



- Haxton & Henley; Engel;

# EDMs: Peccei-Quinn & Axions I

*θ-term*

$$\frac{\alpha_s \bar{\theta}}{4\pi} \text{Tr } \tilde{G}_{\mu\nu} G^{\mu\nu}$$

*Axion Field: GB of Spont Broken  $U(1)_{PQ}$*

$$\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a + \frac{a(x)}{f_a} \frac{\alpha_s}{8\pi} G \tilde{G},$$

$$\bar{\theta} \rightarrow \bar{\theta} + \frac{a}{f_a}$$

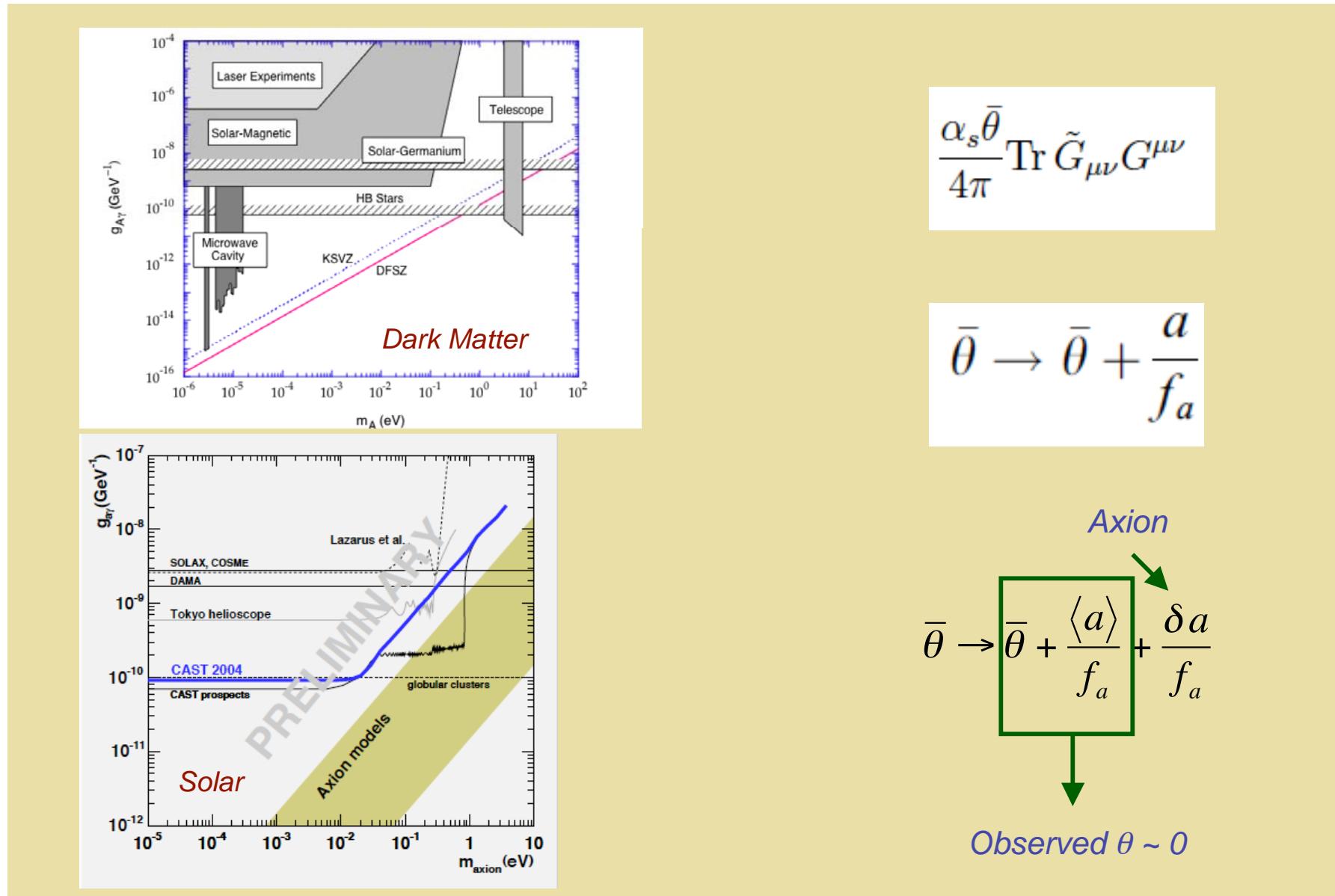
*Chiral Anomaly:*

$$a \rightarrow \langle a \rangle + \delta a$$

$$\bar{\theta} \rightarrow \boxed{\bar{\theta} + \frac{\langle a \rangle}{f_a}} + \frac{\delta a}{f_a}$$

*Axion*   
*Observed  $\theta \sim 0$*  

# EDMs: Peccei-Quinn & Axions II



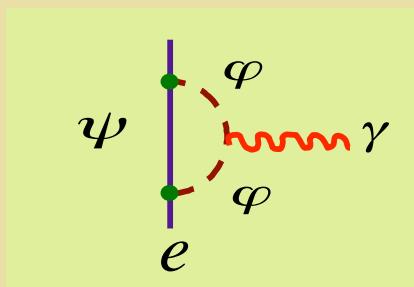
# EDMs: New CPV?

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction	New Physics
e	$1.9 \times 10^{-27}$	Tl atom	$10^{-38}$	$10^{-27}$
$\mu$	$1.1 \times 10^{-19}$	rest frame $E$	$10^{-35}$	$10^{-22}$
$\tau$	$3.1 \times 10^{-16}$	$e^+e^- \rightarrow \tau^+\tau^-\gamma$	$10^{-34}$	$10^{-20}$
p	$6.5 \times 10^{-23}$	TIF molecule	$10^{-31}$	$10^{-26}$
n	$2.9 \times 10^{-26}$	UCN	$10^{-31}$	$10^{-26}$
$^{199}\text{Hg}$	$3.1 \times 10^{-29}$	atom cell	$10^{-33}$	$10^{-28}$

- SM “background” well below new CPV expectations
- New expts:  $10^2$  to  $10^3$  more sensitive
- CPV needed for BAU?

## Mass Scale Sensitivity



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

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

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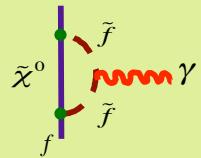
- SM “background” well below new CPV expectations
- New expts:  $10^2$  to  $10^3$  more sensitive
- CPV needed for BAU?

A non-exhaustive list:

Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	$^{199}\text{Hg}$ (cell)	Seattle
HBr <sup>+</sup> (trapped)	JILA	$^{129}\text{Xe}$ (liquid)	Princeton
PbF (trapped)	Oklahoma	$^{225}\text{Ra}$ (trapped)	Argonne
GdIG (solid)	Amherst	$^{213,225}\text{Ra}$ (trapped)	KVI
GGG (solid)	Yale/Indiana	$^{223}\text{Rn}$ (trapped)	TRIUMF
muon (ring)	J-PARC	deuteron (ring)	BNL?

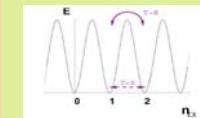
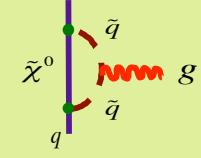
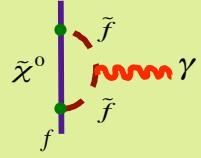
# *EDMs: Complementary Searches I*

*Electron*



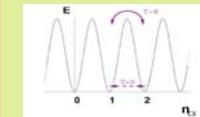
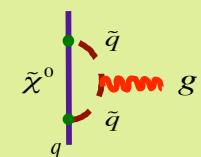
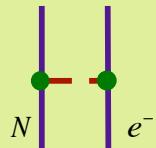
*Improvements  
of  $10^2$  to  $10^3$*

*Neutron*



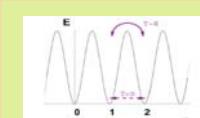
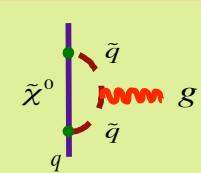
*QCD*

*Neutral  
Atoms*



*QCD*

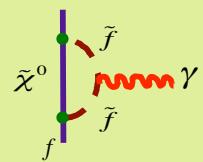
*Deuteron*



*QCD*

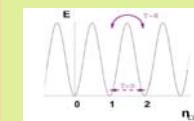
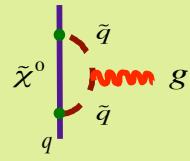
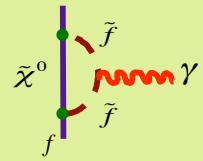
# EDMs: Complementary Searches II

*Electron*



*Improvements  
of  $10^2$  to  $10^3$*

*Neutron*



*Neutral  
Atoms*

*Nuclear Moments*

	$P_T$	$\not{P}_T$	$P_T$	$\not{P}_T$
$C_J$	E	✗	✗	O
$T^M_J$	O	✗	✗	E
$T^E_J$	✗	O	E	✗

*EDM, Schiff...*

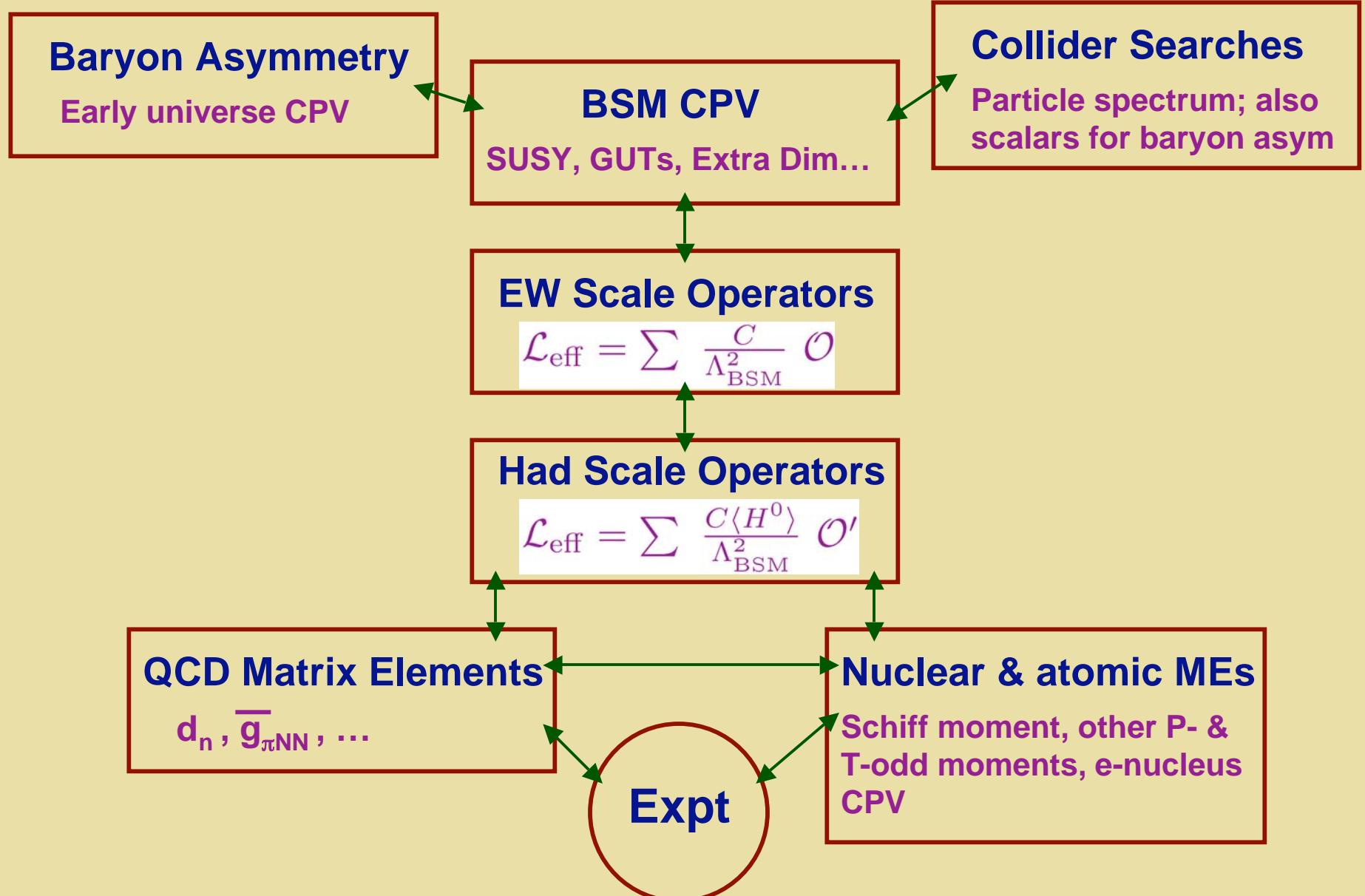
*Nuclear  
Enhancements*

*MQM....*

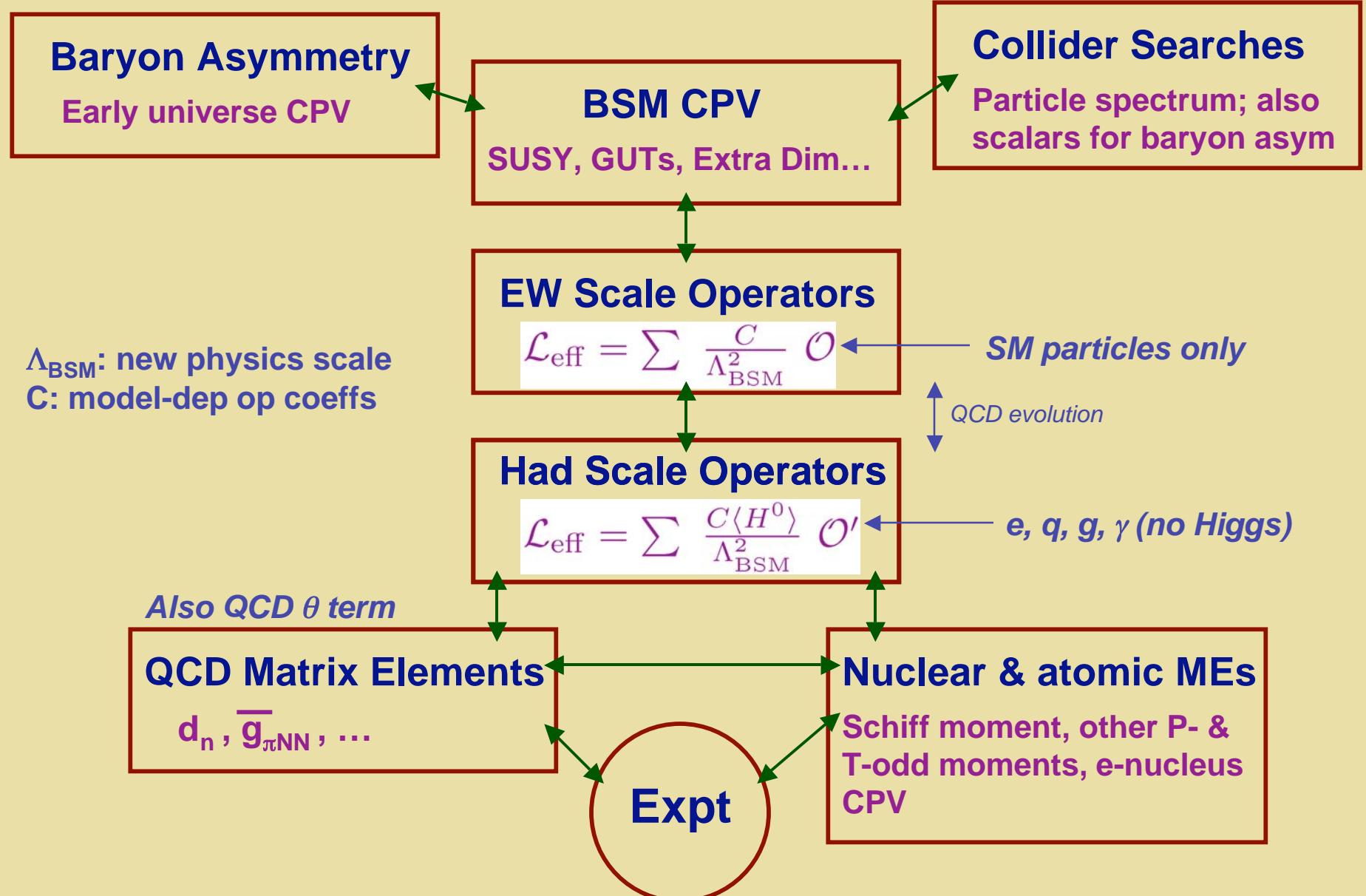
*Deuteron*

*Anapole...*

# *EDM Interpretation & Multiple Scales*

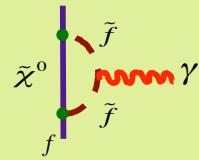


# EDM Interpretation & Multiple Scales



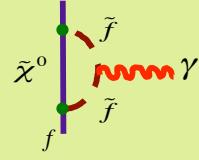
# *EDMs: QCD & Many-Body Theory I*

*Electron*

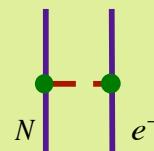


*Improvements  
of  $10^2$  to  $10^3$*

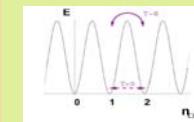
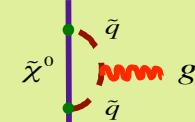
*Neutron*



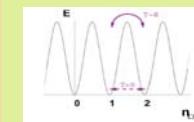
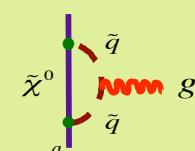
*Neutral  
Atoms*



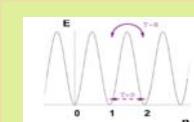
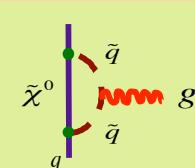
*Deuteron*



*QCD*



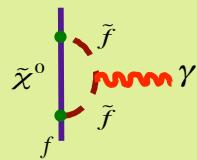
*QCD*



*QCD*

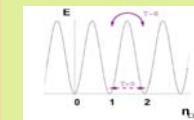
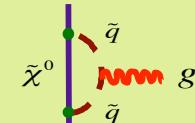
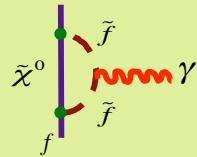
# EDMs: QCD & Many-Body Theory I

Electron



*Improvements  
of  $10^2$  to  $10^3$*

Neutron



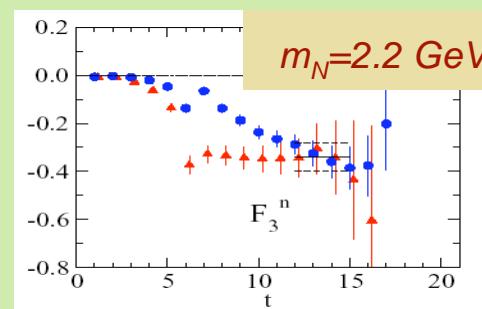
QCD

Neutron EDM from LQCD:

$$S_\theta = \frac{g^2 \bar{\theta}}{32\pi^2} \int d^4x \text{Tr}(G\tilde{G})$$

Two approaches:

- Expand in  $\theta$  & average over topological sectors (Blum et al, Shintani et al)
- Compute  $\Delta E$  for spin up/down nucleon in background  $E$  field (Shintani et al)



$$d_n^\theta / \bar{\theta} = -1.83(60) \times 10^{-15} e\text{-cm}$$

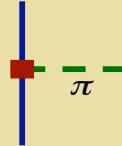
QCD SR (Pospelov et al)

$$d_n^\theta / \bar{\theta} = (2.5 \pm 1.2) \times 10^{-16} e\text{-cm}$$

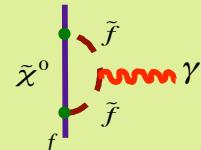
# EDMs: QCD & Many-Body Theory

ChPT for  $d_n$ : van Kolck et al

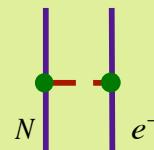
$P-, T\text{-odd } \pi NN$



$\bar{g}_{\pi NN}^I$   
 $I = 0, 1, 2$



Neutral  
Atoms



Deuteron

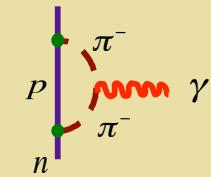
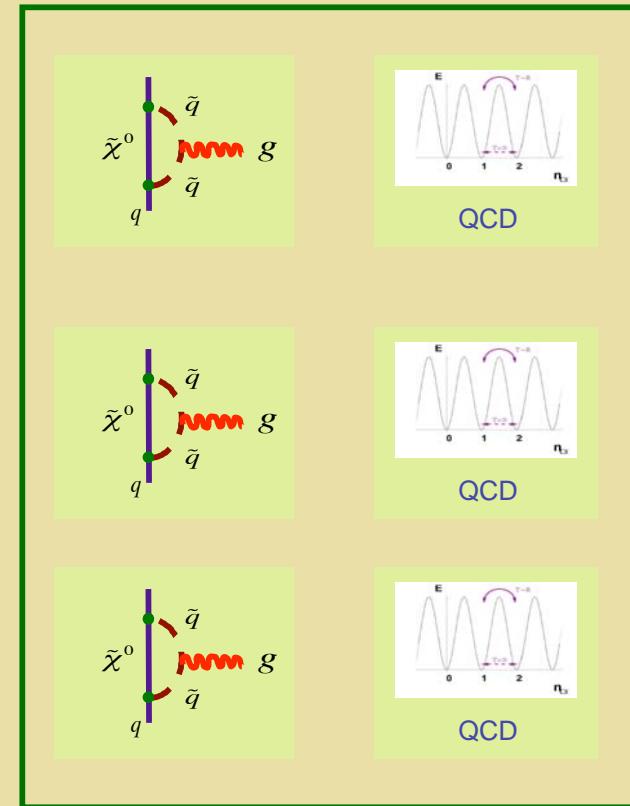
Improvements  
of  $10^2$  to  $10^3$

Hadronic couplings

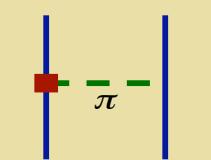
Pospelov, Ji et al:

$$\bar{g}_{\pi NN}^I$$

PCAC + had  
models & QCD SR



+ ...



+ ...

# EDMs: QCD & Many-Body Theory

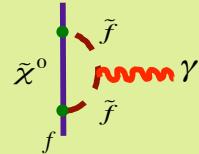
*Nuclear Schiff Moment*

$$S \sim \int d^3x x^2 \vec{x} \rho(\vec{x})^{\text{CPV}}$$

*Nuclear EDM: Screened in atoms*

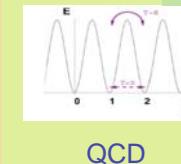
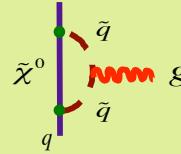
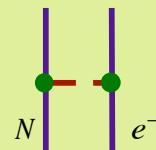
$$d_{\text{nuc}} \sim \int d^3x \vec{x} \rho(\vec{x})^{\text{CPV}}$$

*Neutron*

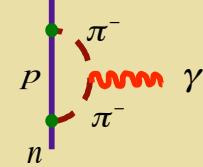


*Improvements  
of  $10^2$  to  $10^3$*

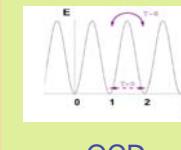
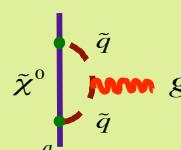
*Neutral  
Atoms*



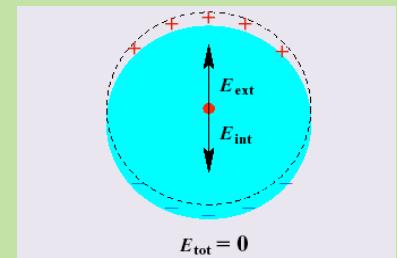
*Atomic effect from  
nuclear finite size:  
Schiff moment*



*Deuteron*



*Schiff Screening*



# EDMs: QCD & Many-Body Theory

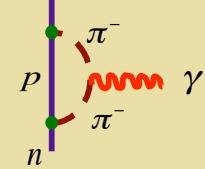
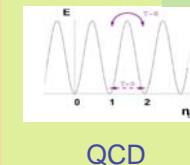
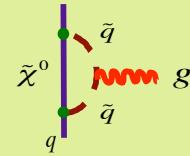
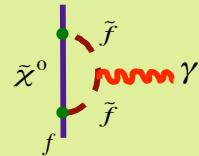
Nuclear Schiff Moment

$$S \sim \int d^3x x^2 \vec{x} \rho(\vec{x})^{\text{CPV}}$$

Nuclear EDM: Screened in atoms

$$d_{\text{nuc}} \sim \int d^3x \vec{x} \rho(\vec{x})^{\text{CPV}}$$

Neutron

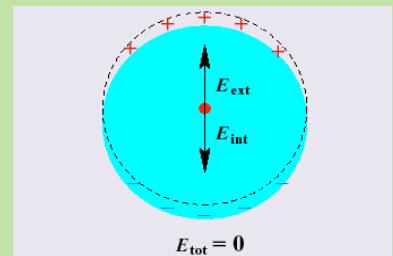


Liu et al: New formulation of Schiff operator

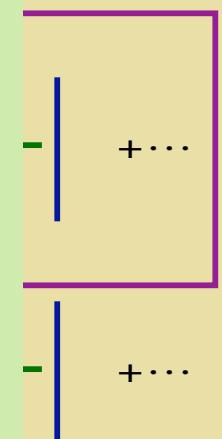
$$\hat{S}^\lambda = \frac{1}{10} \int d^3y \hat{\rho}(y) y^2 \left\{ y^\lambda - \frac{5}{3Z} \left( \hat{d}_N^\lambda - \frac{4\sqrt{2\pi}}{5} [\hat{d}_N \otimes Y_2(\hat{y})]_1^\lambda \right) \right\} + \dots$$

Role of nuclear correlations

Schiff Screening

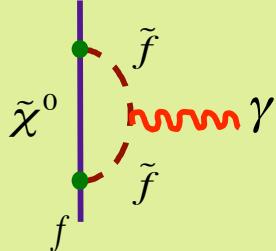


Atomic effect from nuclear finite size: Schiff moment

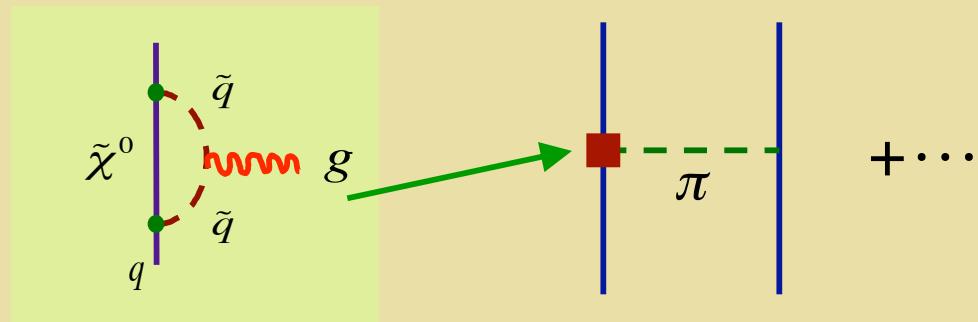


# ***EDMs & Schiff Moments***

*One-loop*



*EDM:  $q, l, n\dots$*



*Chromo-EDM:  $q, n\dots$*

*Dominant in  
nuclei & atoms*

*Schiff Moment in  $^{199}\text{Hg}$*

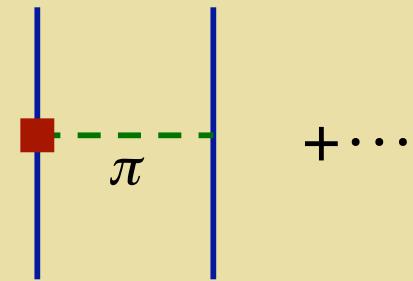
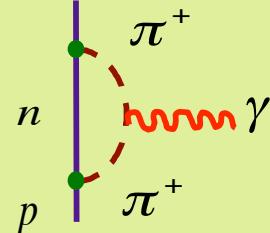
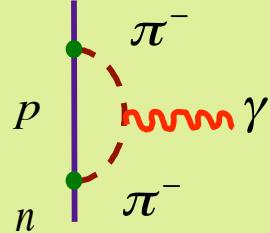
*Nuclear & hadron structure*

$$S_{^{199}\text{Hg}}^{\text{ave}} = 0.007g\bar{g}_0 + 0.071g\bar{g}_1 + 0.018g\bar{g}_2 [e\text{ fm}^3]$$

*Engel & de Jesus: Enhanced isoscalar sensitivity (  $\theta_{QCD}$  )*

# ***EDMs & Isospin Filter: n, p, A***

*Chiral limit:*



*Nucleons*

$$d_n - d_p \sim \bar{g}_0$$

$$d_n + d_p \sim \bar{g}_1$$

$$\begin{aligned} d_N^{I=1} &\simeq 0.87(d_u - d_d) + 0.27e(d_u^c - d_d^c) \\ d_N^{I=0} &\simeq 0.5(d_u + d_d) + 0.83e(d_u^c + d_d^c) \end{aligned}$$

*Schiff Moments*

*Schiff Moment in  $^{199}\text{Hg}$*

$$S_{^{199}\text{Hg}}^{\text{ave}} = 0.007g\bar{g}_0 + 0.071g\bar{g}_1 + 0.018g\bar{g}_2 [e\text{ fm}^3]$$

## EDMs BSM: MSSM

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{\ell} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_{\bar{u}}^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_{\bar{d}}^2 \tilde{d}^\dagger - \tilde{\ell} \mathbf{m}_{\bar{e}}^2 \tilde{\ell}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & - (b H_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

$$\phi_A = \arg(A_f M_j)$$

*Universality Assumption*

$$\phi_1 = \phi_2 = \phi_3$$

*Common  $\phi_A$*

## EDMs BSM: MSSM

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{u}\mathbf{a}_u \tilde{Q}H_u - \tilde{d}\mathbf{a}_d \tilde{Q}H_d - \tilde{\epsilon}\mathbf{a}_e \tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u}\bar{\mathbf{m}}_{\bar{u}}^2 \tilde{u}^\dagger - \tilde{d}\bar{\mathbf{m}}_{\bar{d}}^2 \tilde{d}^\dagger - \tilde{\epsilon}\bar{\mathbf{m}}_{\bar{e}}^2 \tilde{e}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & -(bH_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

$$\phi_A = \arg(A_f M_j)$$

$$\begin{aligned} \mathcal{L}_{(6)}^{\text{CPV}} = & \left[ \frac{i g_1 d_u^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} \tilde{H} U + \frac{i g_1 d_d^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H D + \frac{i g_1 d_e^B}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H E \right. \\ & + \left. \frac{i g_2 d_u^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} \tilde{H} U + \frac{i g_2 d_d^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H D + \frac{i g_2 d_e^W}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H E \right] \\ & + \frac{i g_3 d_u^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} \tilde{H} U + \frac{i g_3 d_d^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} H D \\ & + \frac{w}{\Lambda^2} \text{Tr} \left( G^{\mu\nu} G_{\nu\alpha} \tilde{G}_\mu^\alpha \right) + \sum_{ab} \frac{C_{abcd}}{\Lambda^2} \epsilon_{ij} \bar{Q}_i^a d^c \bar{Q}_j^b i \gamma_5 u^d + \dots , \end{aligned} \quad (5)$$

Quark & Lepton EDMs

EWSB

$$\mathcal{L}_{\text{EDM}} = -\frac{i e d_u^\gamma}{2\Lambda} \bar{U}_L \sigma_{\mu\nu} F^{\mu\nu} U_R - \frac{i e d_d^\gamma}{2\Lambda} \bar{D}_L \sigma_{\mu\nu} F^{\mu\nu} D_R - \frac{i e d_\ell^\gamma}{2\Lambda} \bar{\ell}_L \sigma_{\mu\nu} F^{\mu\nu} \ell_R$$

## EDMs BSM: MSSM

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{\ell} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_{\bar{u}}^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_{\bar{d}}^2 \tilde{d}^\dagger - \tilde{\ell} \mathbf{m}_{\bar{e}}^2 \tilde{\ell}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & - (b H_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

$$\phi_A = \arg(A_f M_j)$$

$$\begin{aligned} \mathcal{L}_{(6)}^{\text{CPV}} = & \frac{i g_1 d_u^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} \tilde{H} U + \frac{i g_1 d_d^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H D + \frac{i g_1 d_e^B}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H E \quad (5) \\ & + \frac{i g_2 d_u^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} \tilde{H} U + \frac{i g_2 d_d^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H D + \frac{i g_2 d_e^W}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H E \\ & + \boxed{\frac{i g_3 d_u^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} \tilde{H} U + \frac{i g_3 d_d^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} H D} \\ & + \frac{w}{\Lambda^2} \text{Tr} \left( G^{\mu\nu} G_{\nu\alpha} \tilde{G}_\mu^\alpha \right) + \sum_{ab} \frac{C_{abcd}}{\Lambda^2} \epsilon_{ij} \bar{Q}_i^a d^c \bar{Q}_j^b i \gamma_5 u^d + \dots , \end{aligned}$$

Quark Chromo-EDMs

$$\mathcal{L}_{\text{EDM}} = -\frac{i e d_u^\gamma}{2\Lambda} \bar{U}_L \sigma_{\mu\nu} F^{\mu\nu} U_R - \frac{i e d_d^\gamma}{2\Lambda} \bar{D}_L \sigma_{\mu\nu} F^{\mu\nu} D_R - \frac{i e d_\ell^\gamma}{2\Lambda} \bar{\ell}_L \sigma_{\mu\nu} F^{\mu\nu} \ell_R$$

## EDMs BSM: MSSM

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{u}\mathbf{a}_u \tilde{Q}H_u - \tilde{d}\mathbf{a}_d \tilde{Q}H_d - \tilde{e}\mathbf{a}_e \tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u}\bar{\mathbf{m}}_{\bar{u}}^2 \tilde{u}^\dagger - \tilde{d}\bar{\mathbf{m}}_{\bar{d}}^2 \tilde{d}^\dagger - \tilde{e}\bar{\mathbf{m}}_{\bar{e}}^2 \tilde{e}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & -(bH_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg (\mu M_j b^*)$$

$$\phi_A = \arg (A_f M_j)$$

$$\begin{aligned} \mathcal{L}_{(6)}^{\text{CPV}} = & \frac{i g_1 d_u^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} \tilde{H} U + \frac{i g_1 d_d^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H D + \frac{i g_1 d_e^B}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H E \quad (5) \\ & + \frac{i g_2 d_u^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} \tilde{H} U + \frac{i g_2 d_d^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H D + \frac{i g_2 d_e^W}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H E \\ & + \frac{i g_3 d_u^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} \tilde{H} U + \frac{i g_3 d_d^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} H D \\ & + \boxed{\frac{w}{\Lambda^2} \text{Tr} (G^{\mu\nu} G_{\nu\alpha} \tilde{G}_\mu^\alpha)} + \sum_{ab} \frac{C_{abcd}}{\Lambda^2} \epsilon_{ij} \bar{Q}_i^a d^c \bar{Q}_j^b i \gamma_5 u^d + \dots , \quad \text{Weinberg 3 gluon Op} \end{aligned}$$

$$\mathcal{L}_{EDM} = -\frac{i e d_u^\gamma}{2\Lambda} \bar{U}_L \sigma_{\mu\nu} F^{\mu\nu} U_R - \frac{i e d_d^\gamma}{2\Lambda} \bar{D}_L \sigma_{\mu\nu} F^{\mu\nu} D_R - \frac{i e d_\ell^\gamma}{2\Lambda} \bar{\ell}_L \sigma_{\mu\nu} F^{\mu\nu} \ell_R$$

## EDMs BSM: MSSM

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{u}\mathbf{a}_u \tilde{Q}H_u - \tilde{d}\mathbf{a}_d \tilde{Q}H_d - \tilde{\ell}\mathbf{a}_e \tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u}\bar{\mathbf{m}}_{\bar{u}}^2 \tilde{u}^\dagger - \tilde{d}\bar{\mathbf{m}}_{\bar{d}}^2 \tilde{d}^\dagger - \tilde{\ell}\bar{\mathbf{m}}_{\bar{e}}^2 \tilde{e}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & -(bH_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg (\mu M_j b^*)$$

$$\phi_A = \arg (A_f M_j)$$

$$\begin{aligned} \mathcal{L}_{(6)}^{\text{CPV}} = & \frac{i g_1 d_u^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} \tilde{H} U + \frac{i g_1 d_d^B}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H D + \frac{i g_1 d_e^B}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 B^{\mu\nu} H E \quad (5) \\ & + \frac{i g_2 d_u^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} \tilde{H} U + \frac{i g_2 d_d^W}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H D + \frac{i g_2 d_e^W}{\Lambda^2} \bar{L} \sigma_{\mu\nu} \gamma_5 \tau^A W^{\mu\nu A} H E \\ & + \frac{i g_3 d_u^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} \tilde{H} U + \frac{i g_3 d_d^G}{\Lambda^2} \bar{Q} \sigma_{\mu\nu} \gamma_5 \lambda^A G^{\mu\nu A} H D \\ & + \frac{w}{\Lambda^2} \text{Tr} \left( G^{\mu\nu} G_{\nu\alpha} \tilde{G}_\mu^\alpha \right) + \boxed{\sum_{ab} \frac{C_{abcd}}{\Lambda^2} \epsilon_{ij} \bar{Q}_i^a d^c \bar{Q}_j^b i \gamma_5 u^d} + \dots , \quad \text{Four fermion Ops} \end{aligned}$$

$$\mathcal{L}_{EDM} = -\frac{i e d_u^\gamma}{2\Lambda} \bar{U}_L \sigma_{\mu\nu} F^{\mu\nu} U_R - \frac{i e d_d^\gamma}{2\Lambda} \bar{D}_L \sigma_{\mu\nu} F^{\mu\nu} D_R - \frac{i e d_\ell^\gamma}{2\Lambda} \bar{\ell}_L \sigma_{\mu\nu} F^{\mu\nu} \ell_R$$

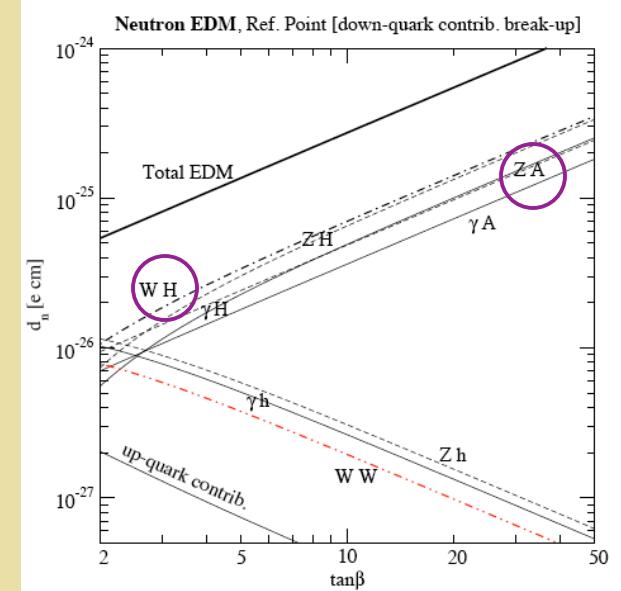
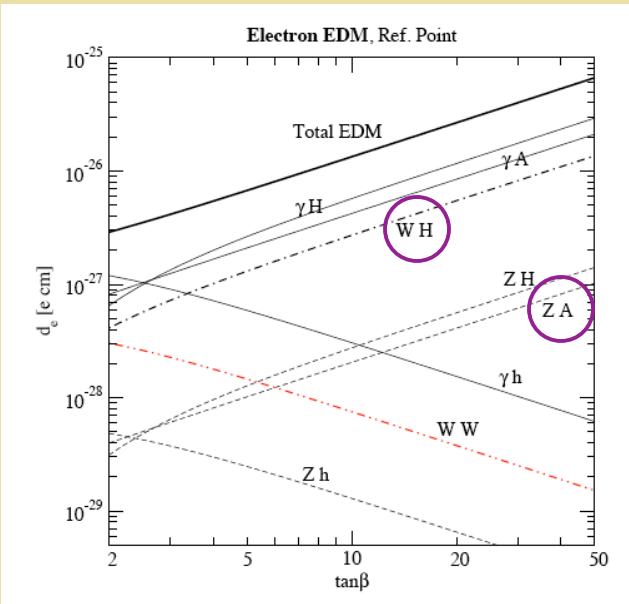
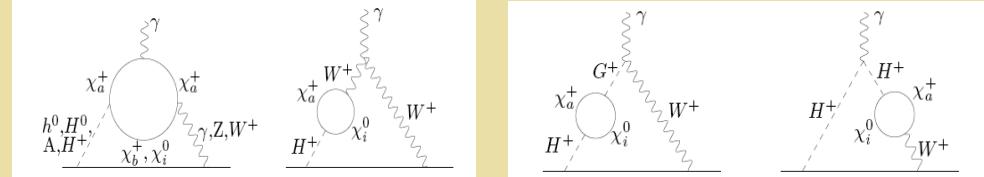
# MSSM EDMs: Leading Contributions

	$q, l$ EDM	Chromo-EDM	Weinberg 3 gluon
Electron			
Neutron			
Neutral Atoms			
Deuteron			

# Heavy Sfermions: Two-loop EDMs

*One loop EDMs suppressed in heavy sfermion regime*

Li, Profumo, R-M: PRD 78:075009  
(2008)



$$m_A=300 \text{ GeV}, \mu=300 \text{ GeV}, M_2=2M_i=290 \text{ GeV}$$

$$d_n = \sum_K H_k(g_i, M_i) \sin \phi_k$$



*WH Loops dominate for neutron & comparable to  $\gamma H$ ,  $\gamma A$  for electron*

# EDM Interpretation: MSSM

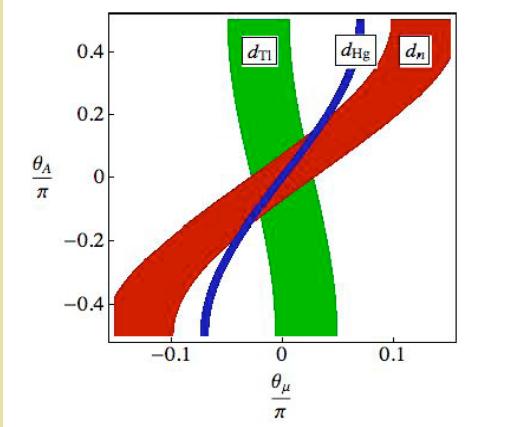
$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{\epsilon} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \bar{\mathbf{m}}_{\bar{u}}^2 \tilde{u}^\dagger - \tilde{d} \bar{\mathbf{m}}_{\bar{d}}^2 \tilde{d}^\dagger - \\ & - (b H_u H_d + c.c.) \end{aligned}$$

*Universality Assumption*

$$\phi_1 = \phi_2 = \phi_3$$

*Common  $\phi_A$*



1-loop: Universal Phases

Ritz CIPANP 09

# EDM Interpretation: MSSM

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

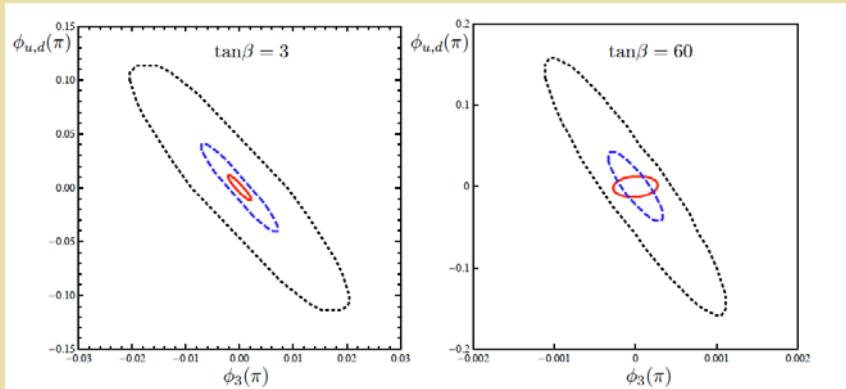
$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_{\bar{u}}^2 \tilde{\bar{u}}^\dagger - \tilde{d} \mathbf{m}_{\bar{d}}^2 \tilde{\bar{d}}^\dagger - \tilde{e} \mathbf{m}_{\bar{e}}^2 \tilde{\bar{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & - (b H_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

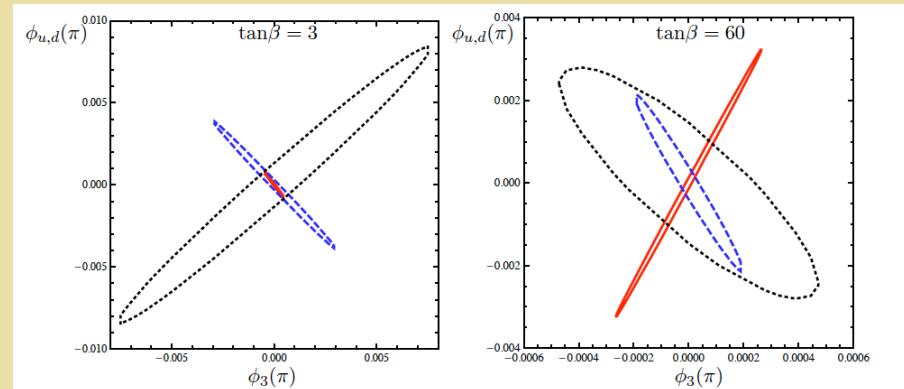
$$\phi_A = \arg(A_f M_j)$$

## Correlated Constraints

*Li, Profumo, R-M '10*



Present



Future  $d_n$ :  $100 \times$   
present sensitivity

# EDM Interpretation: MSSM

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

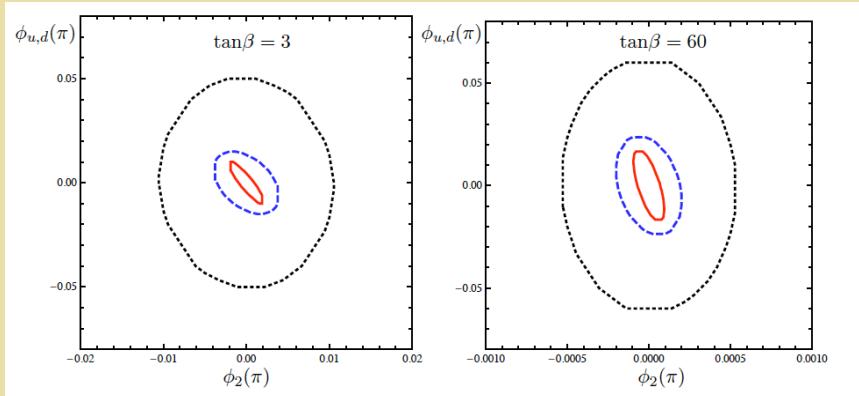
$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_{\bar{u}}^2 \tilde{\bar{u}}^\dagger - \tilde{d} \mathbf{m}_{\bar{d}}^2 \tilde{\bar{d}}^\dagger - \tilde{e} \mathbf{m}_{\bar{e}}^2 \tilde{\bar{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & - (b H_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

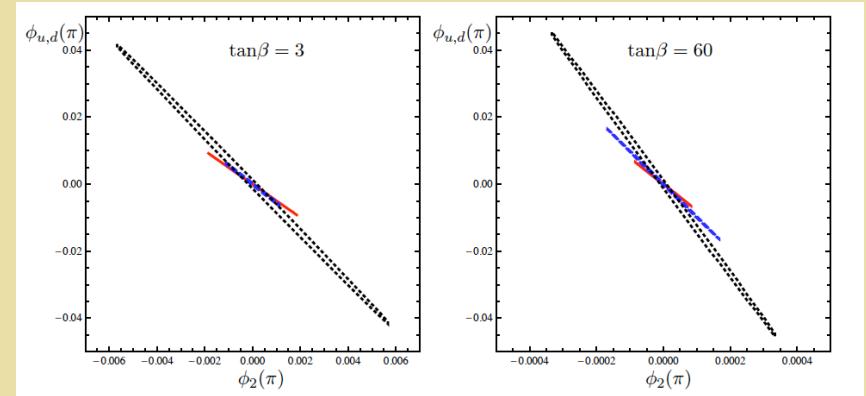
$$\phi_A = \arg(A_f M_j)$$

## Correlated Constraints

*Li, Profumo, R-M '10*



Present



Future  $d_n$ :  $100 \times$   
present sensitivity

# EDM Interpretation: MSSM at 2 Loop

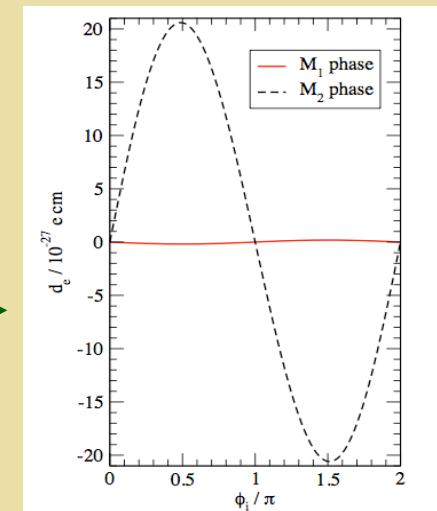
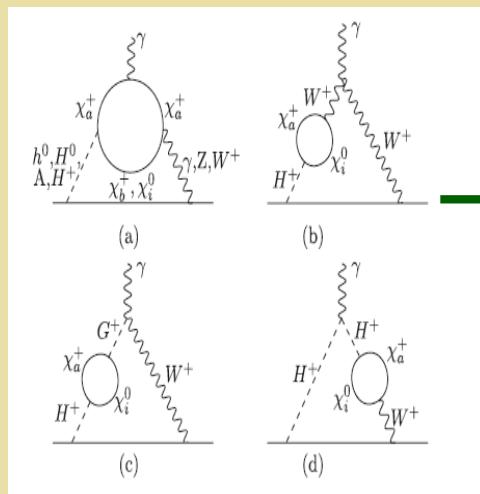
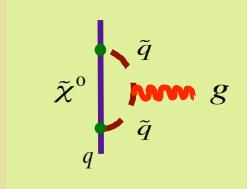
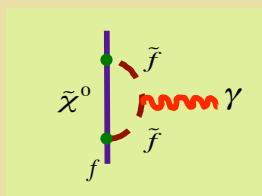
$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{u}\mathbf{a}_u \tilde{Q}H_u - \tilde{d}\mathbf{a}_d \tilde{Q}H_d - \tilde{e}\mathbf{a}_e \tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u}\mathbf{m}_{\bar{u}}^2 \tilde{u}^\dagger - \tilde{d}\mathbf{m}_{\bar{d}}^2 \tilde{d}^\dagger - \tilde{e}\mathbf{m}_{\bar{e}}^2 \tilde{e}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & -(bH_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

$$\phi_A = \arg(A_f M_j)$$

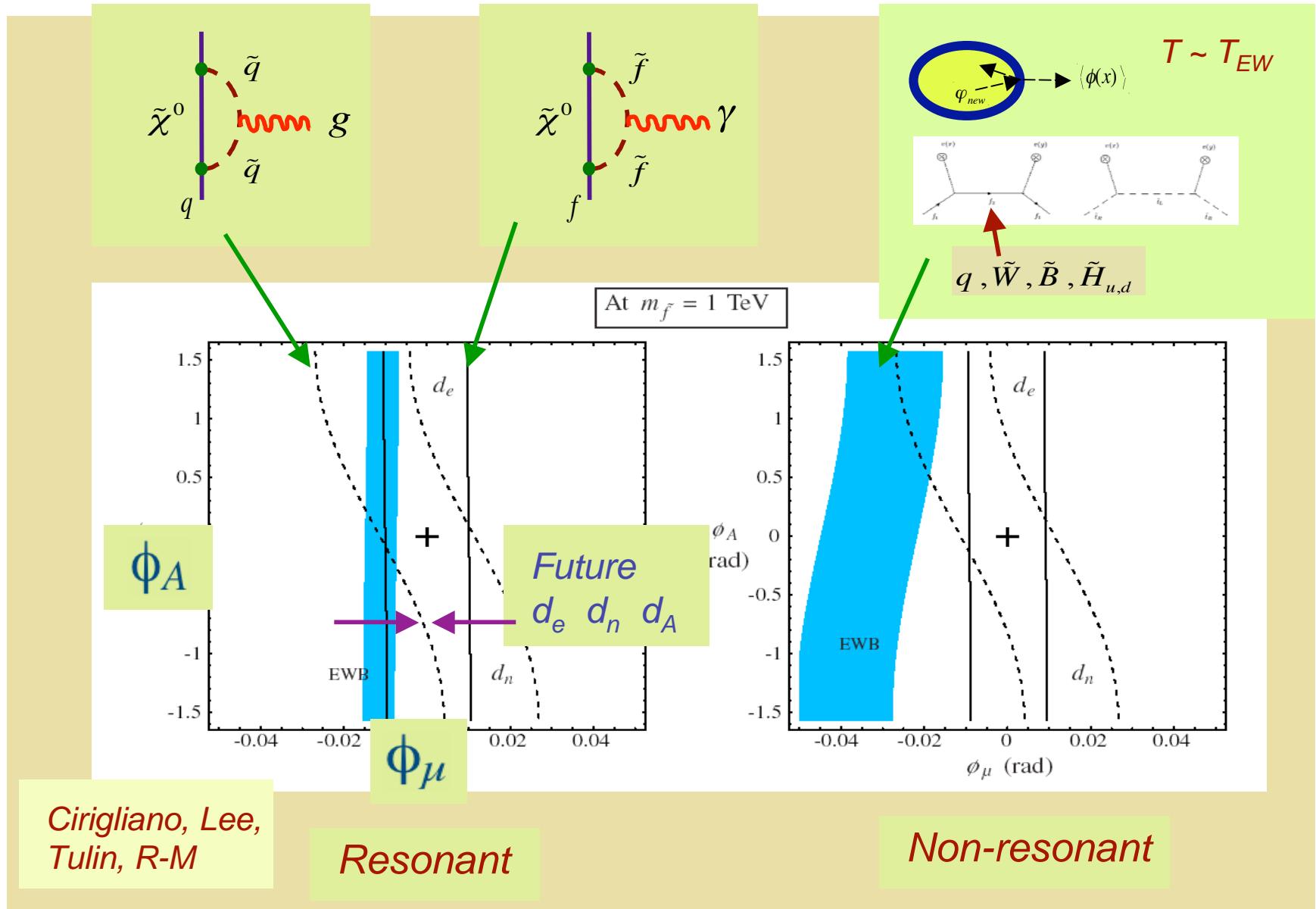
Decouple in heavy sfermion regime



2-loop: Non-universal Phases

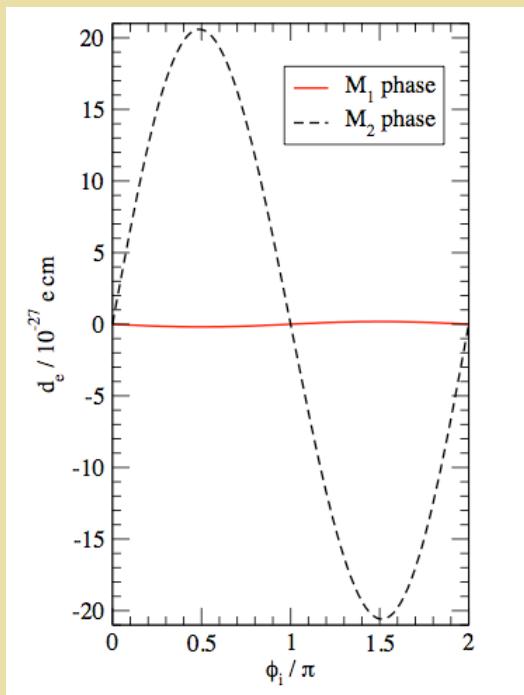
Li, Profumo, R-M 09

# One Loop EDMs & Baryogenesis

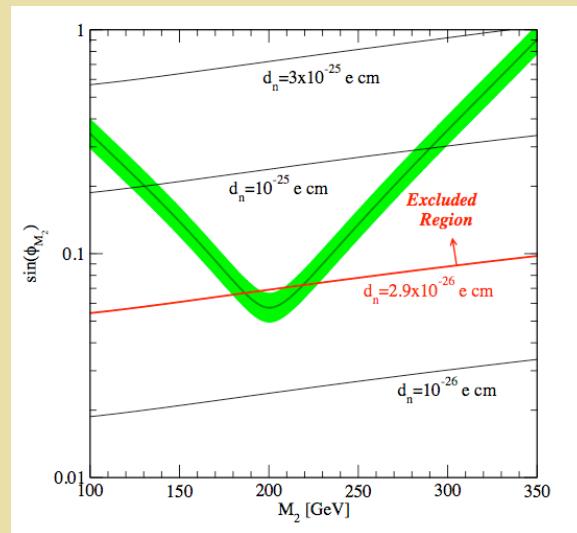


# EDMs & EWB: 2 Loop Regime

$\text{Arg}(\mu M_1 b^*) \neq \text{Arg}(\mu M_2 b^*)$

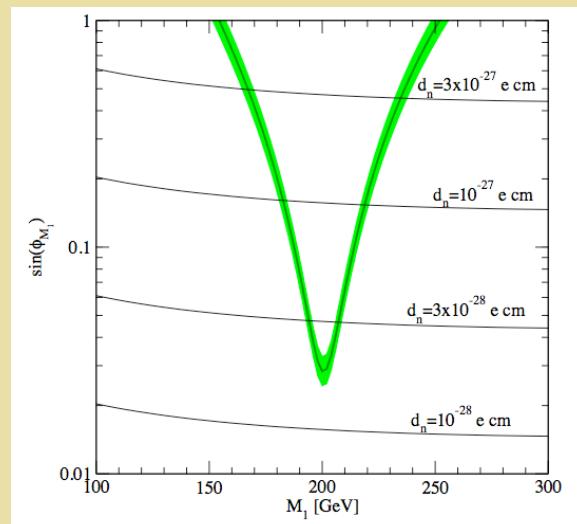


Weak dependence of  $d_e, d_n$  on  $\text{Arg}(\mu M_1 b^*)$



Li, Profumo, R-M: PLB 673:95 (2009)

Res  $\chi^+$  EWB not compatible with  $d_n$



Res & non-res  $\chi^0$  EWB compatible with future  $d_n$ , light  $m_A$ , & moderate  $\tan\beta$

# EDM Interpretation & Multiple Scales

Baryon Asymmetry

Early universe CPV

*EW Baryogenesis  
Quantum transport  
theory*

BSM CPV

SUSY, GUTs, Extra Dim...

Collider Searches

Particle spectrum; also  
scalars for baryon asym

EW Scale Operators

$$\mathcal{L}_{\text{eff}} = \sum \frac{C}{\Lambda_{\text{BSM}}^2} \mathcal{O}$$

*LHC phenomenology  
B Physics  
Dark Matter*

Had Scale Operators

$$\mathcal{L}_{\text{eff}} = \sum \frac{C \langle H^0 \rangle}{\Lambda_{\text{BSM}}^2} \mathcal{O}'$$

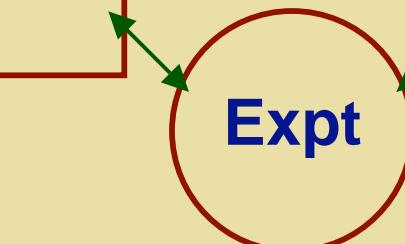
QCD Matrix Elements

$$d_n, \bar{g}_{\pi NN}, \dots$$

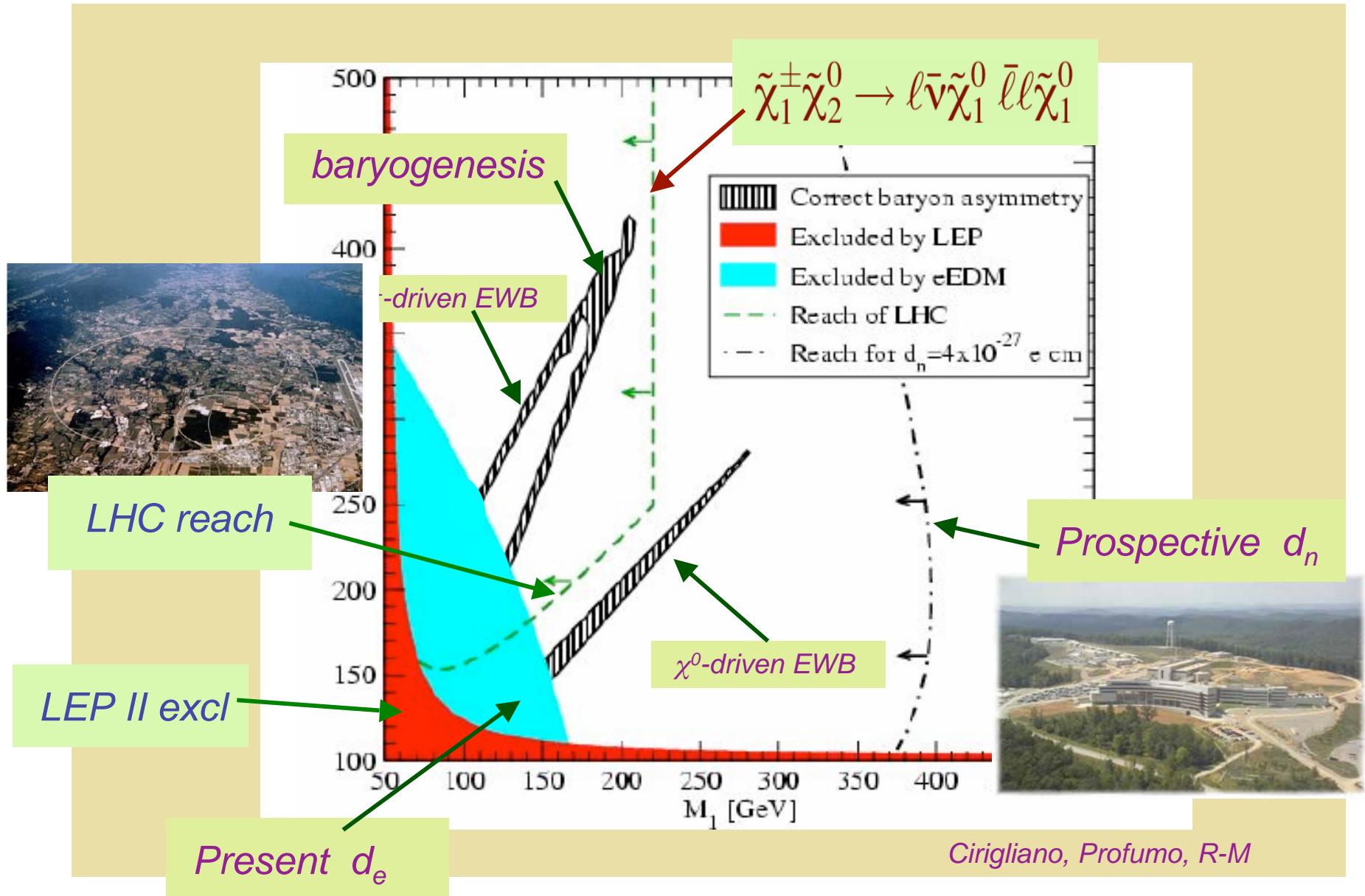
Nuclear & atomic MEs

Schiff moment, other P- &  
T-odd moments, e-nucleus  
CPV

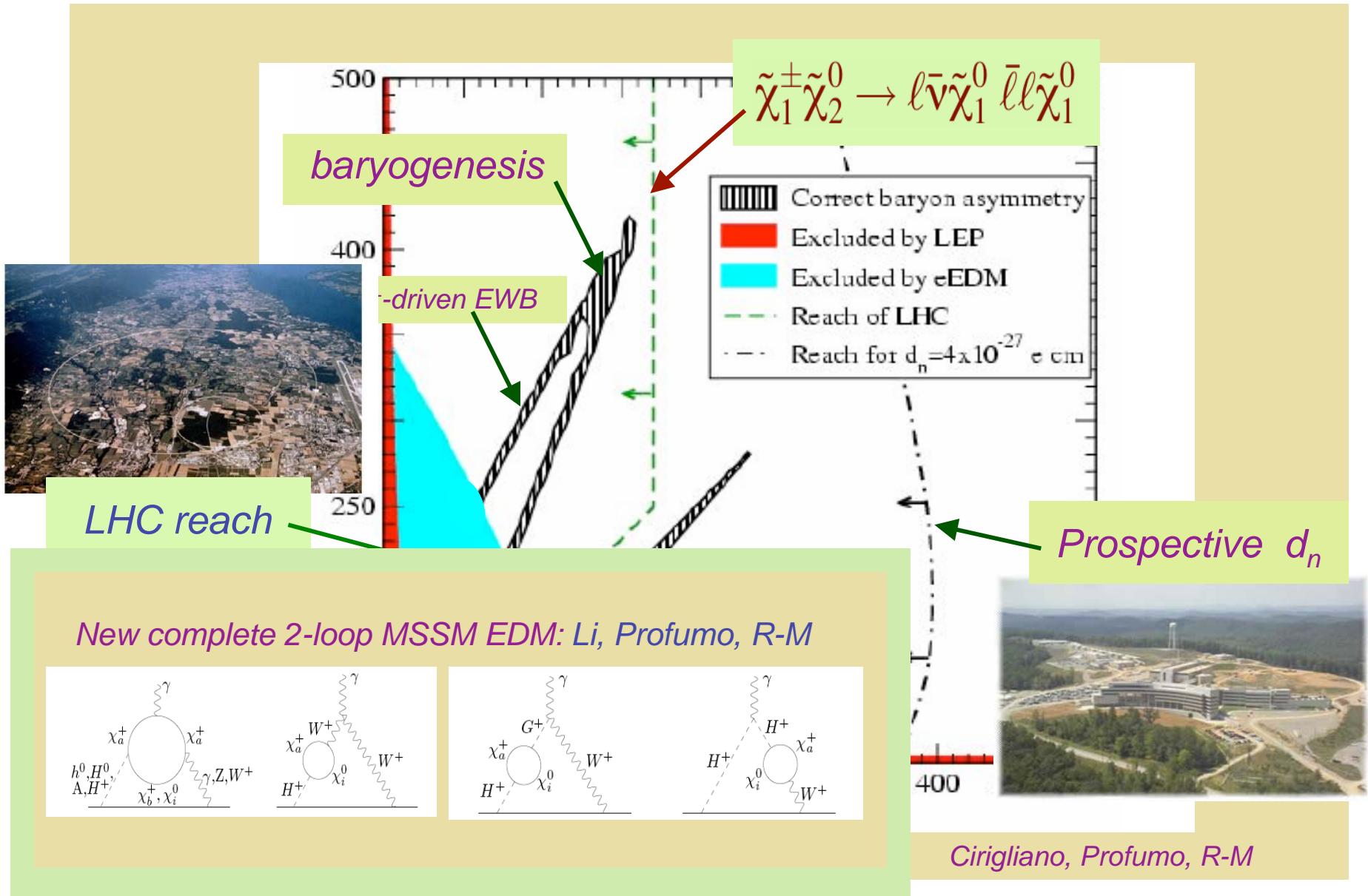
Expt



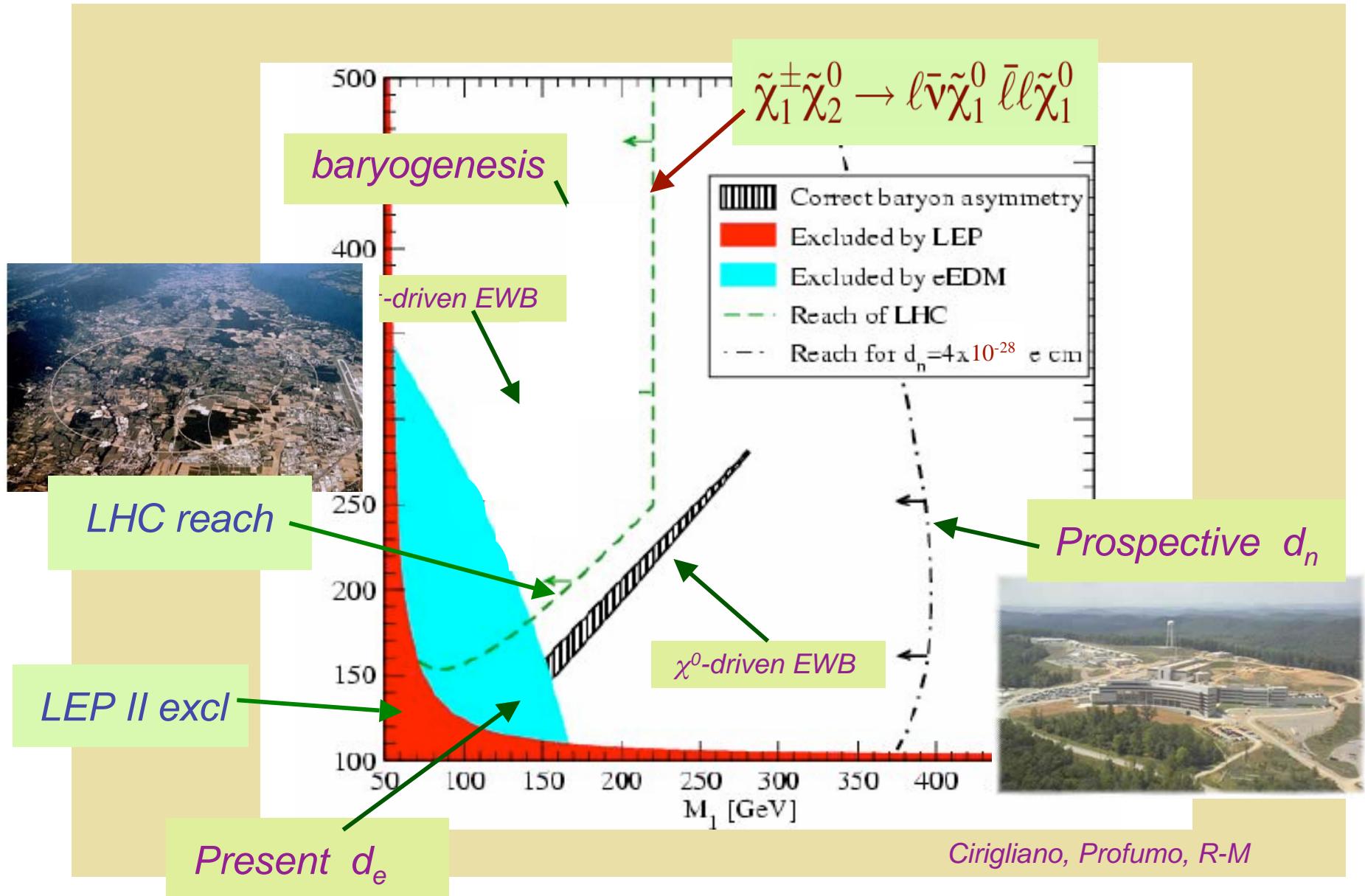
# MSSM Baryogenesis: EDMs & LHC



# MSSM Baryogenesis: EDMs & LHC



# MSSM Baryogenesis: EDMs & LHC



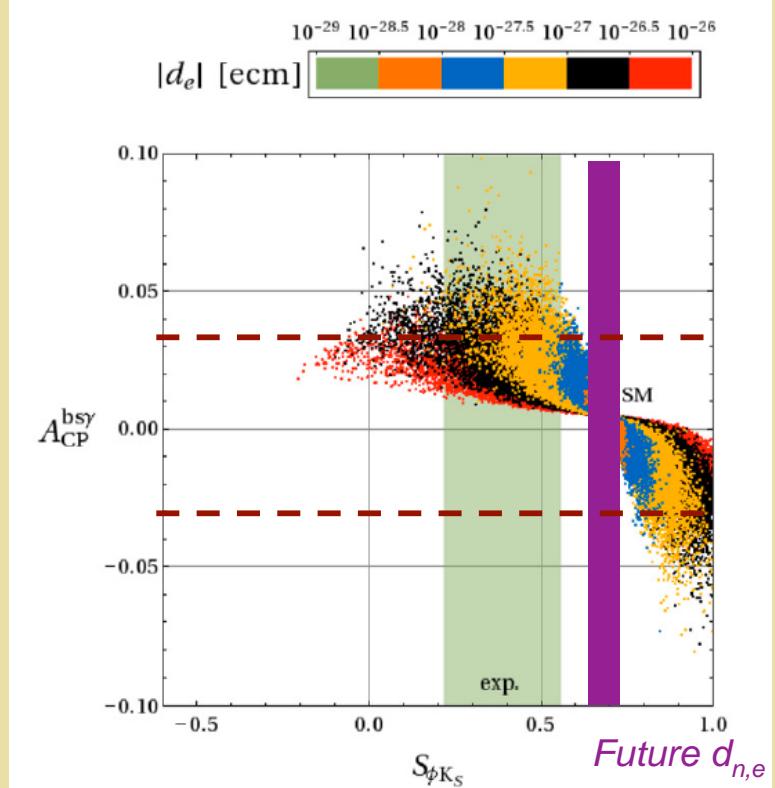
# B Physics

*FBMSSM: only  $\phi_A$*

Table 1: Observables for our analysis

Observable	SM theory	Exp. current	Exp. future
$S_{\phi K_S}$	$\sin 2\beta + 0.02 \pm 0.01$ [19]	$0.39 \pm 0.17$ [3]	(2–3)% [20]
$S_{\eta' K_S}$	$\sin 2\beta + 0.01 \pm 0.01$ [19]	$0.61 \pm 0.07$ [3]	(1–2)% [20]
$A_{CP}(b \rightarrow s\gamma)$	$(0.44^{+0.24}_{-0.14})\%$ [24]	$(0.4 \pm 3.6)\%$ [3]	(0.4–0.5)% [20]
$ d_e $ [e cm]	$\approx 10^{-38}$ [15]	$< 1.6 \times 10^{-27}$ [18]	$\approx 10^{-31}$ [15]
$ d_n $ [e cm]	$\approx 10^{-32}$ [15]	$< 2.9 \times 10^{-26}$ [16]	$\approx 10^{-28}$ [15]

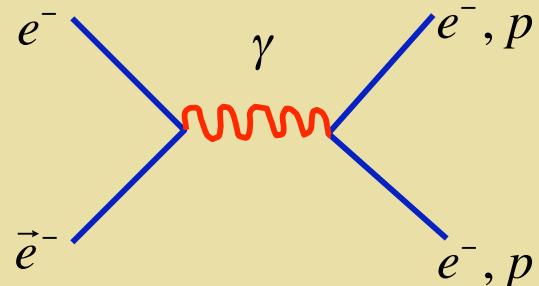
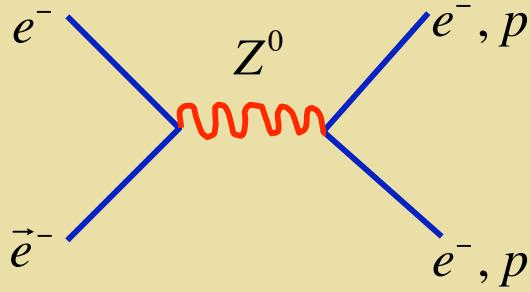
$$A_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$



Altmannshofer et al, PLB 669, 239 (2008)

# Relationship to JLab PVES

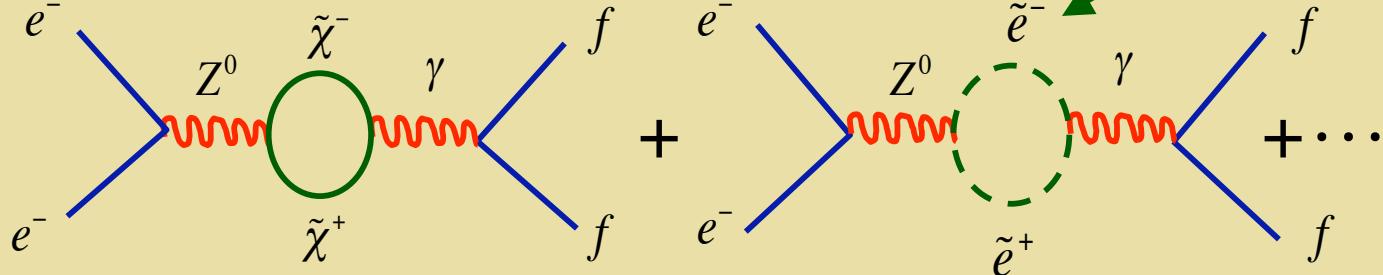
J Lab PVES: Insensitive to CPV but probes mass scale



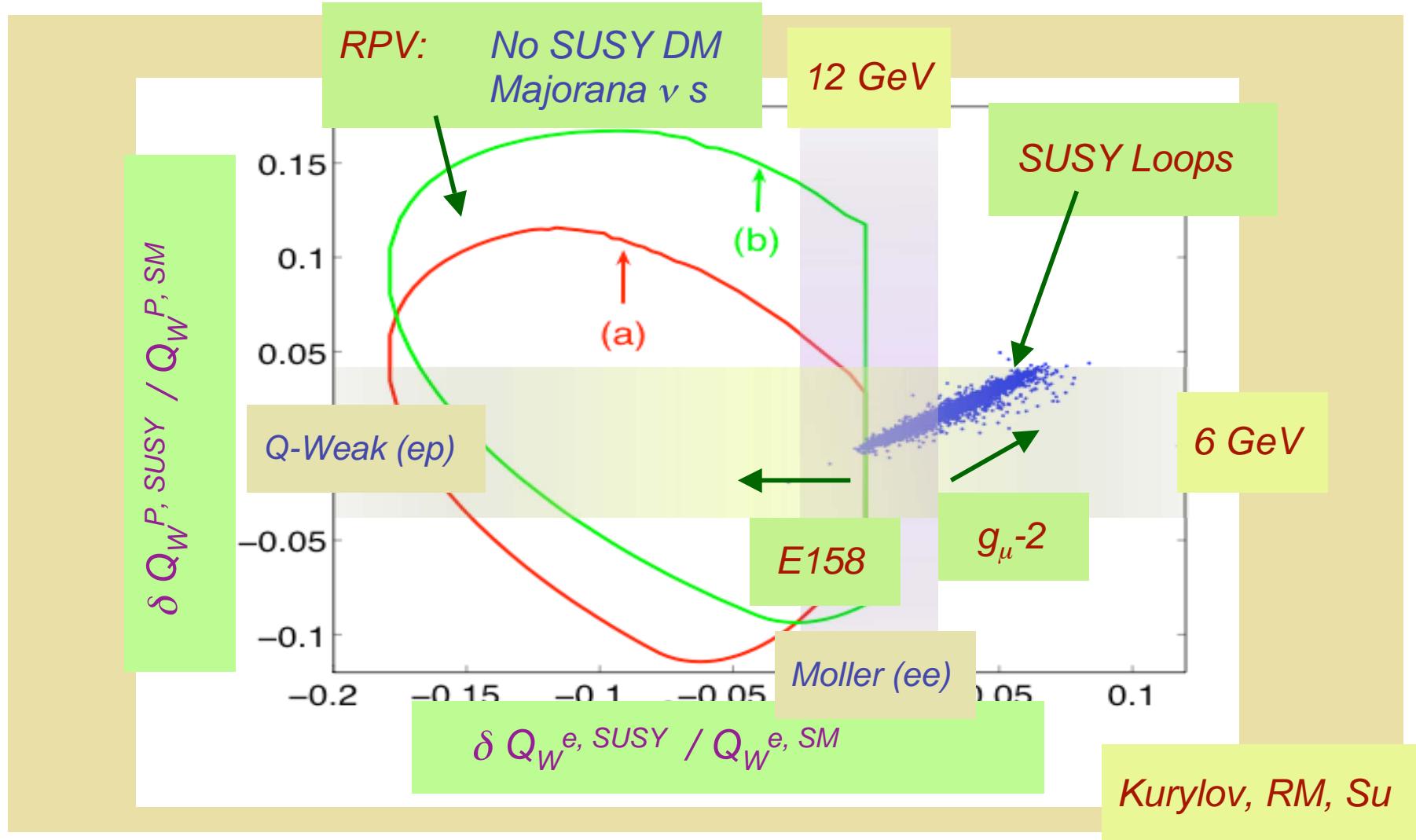
$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} [Q_W - F(Q^2, \theta)]$$

SUSY Loops: Kurylov, SU, MR-M

How heavy are the sfermions?

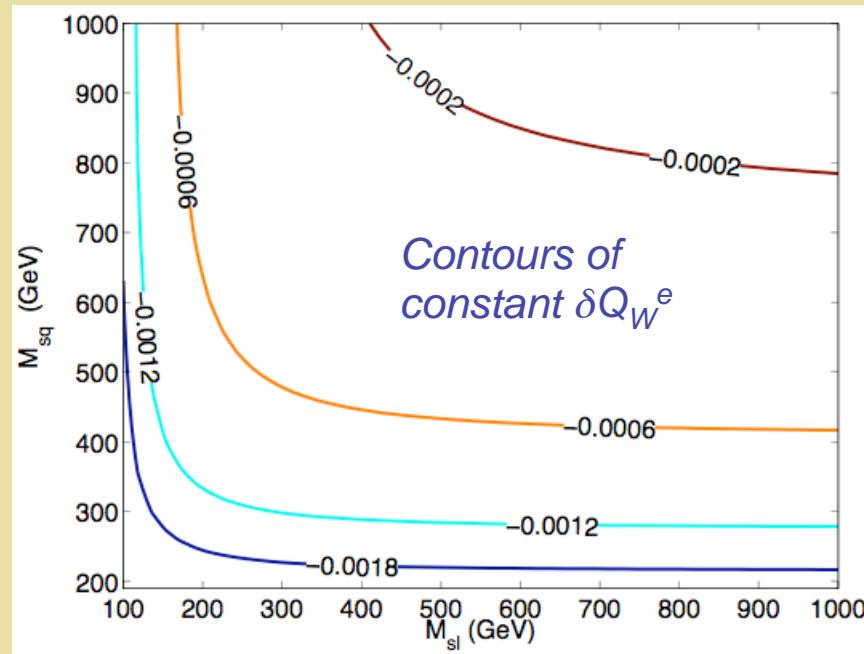
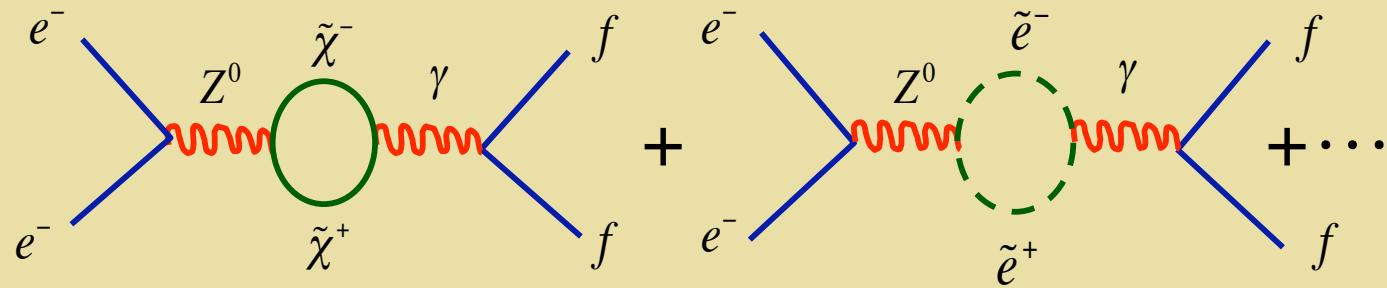


# Probing SUSY with PV Electron Scattering



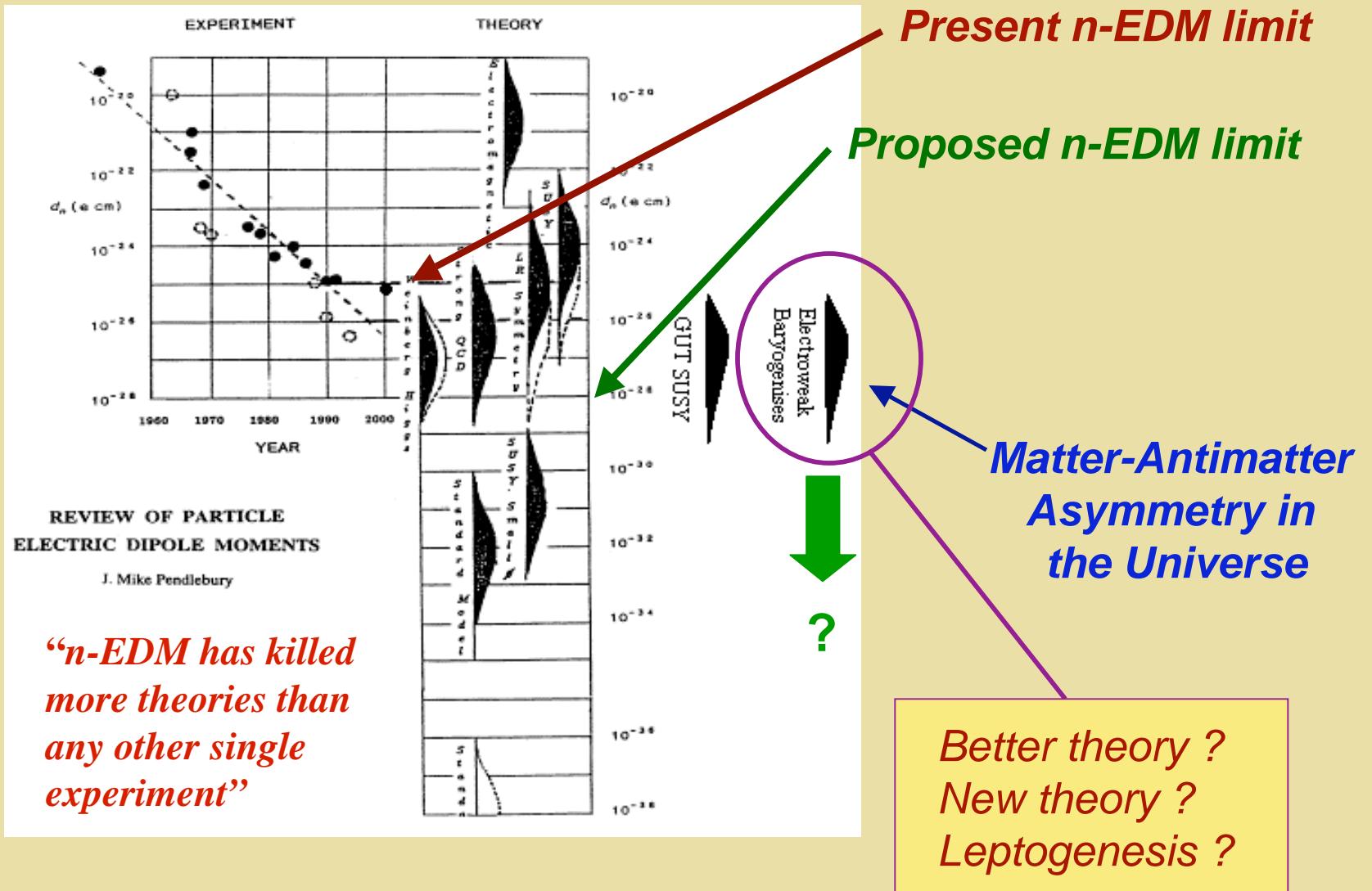
# Probing Sfermion Mass Scale

SUSY Loops: Kurylov, SU, MR-M



Su, R-M  
Preliminary

# EDMs: What We May Learn



## *Summary & Outlook I*

1. *NP studies of FS &  $\nu$ 's are poised to provide key ingredients of the new Standard Model*
2. *EDM searches may discover the CPV needed to explain the origin of baryonic matter*
3. *Sensitivity of EDMs exceeds that of LHC & B-physics program, but HEP experiments provide complementarity information*
4. *Comprehensive search strategy involving a variety of systems is crucial*
5. *Ongoing theory work essential to guide the EDM program, properly interpret results in terms of the new Standard Model, and delineate broader implications*

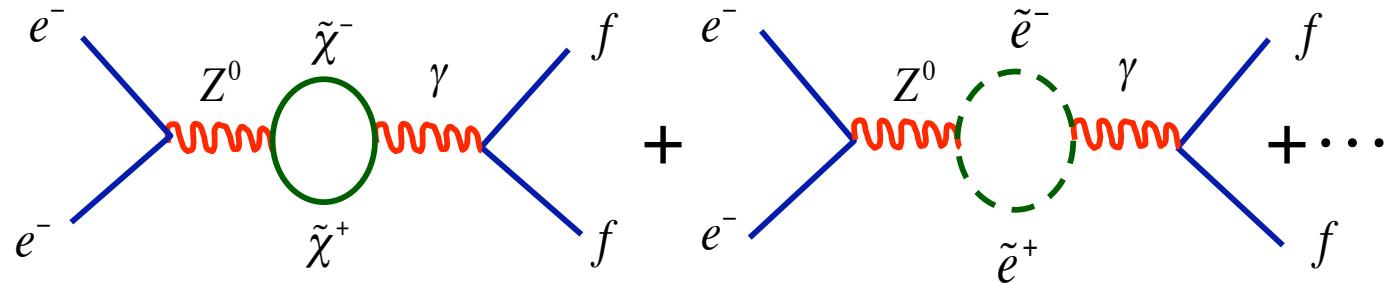
## *Summary & Outlook II*

1. *Nucleon & lepton EDM searches with a sensitivity of  $\sim 10^{-28}$  e-cm needed to conclusively probe MSSM baryogenesis*
2. *Theoretical tasks include:*
  - *Complete development of tools for robust baryogenesis calculations (transport, EWPT)*
  - *Up-dated calculations of nuclear Schiff moments and other P,T-odd moments*
  - *Refined hadronic computations of  $d_{n,p}$  and P,T-odd pion-nucleon couplings*
  - *Apply to other BSM scenarios*
  - *Delineate comprehensively relation with future B-physics and LHC studies*

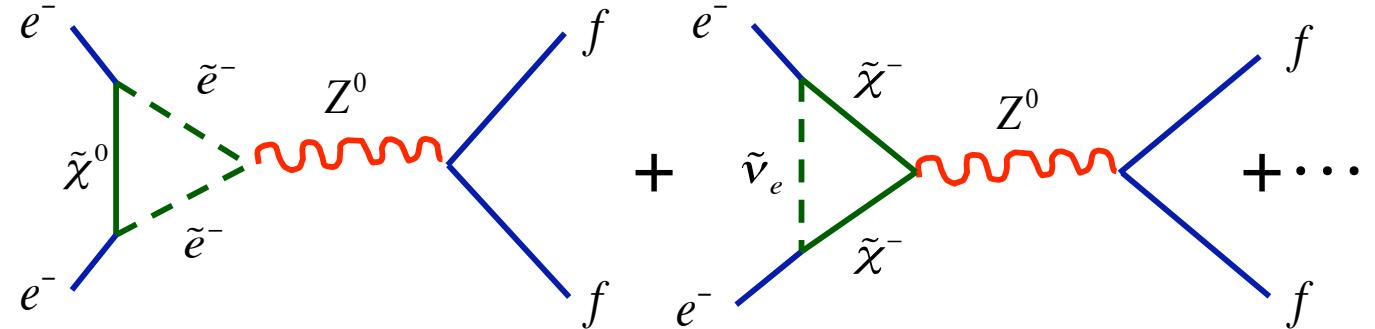
# *Back Matter*

# SUSY Radiative Corrections

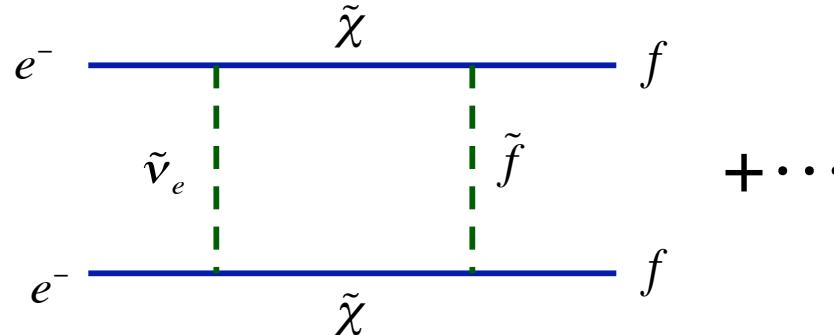
Propagator



Vertex & External leg

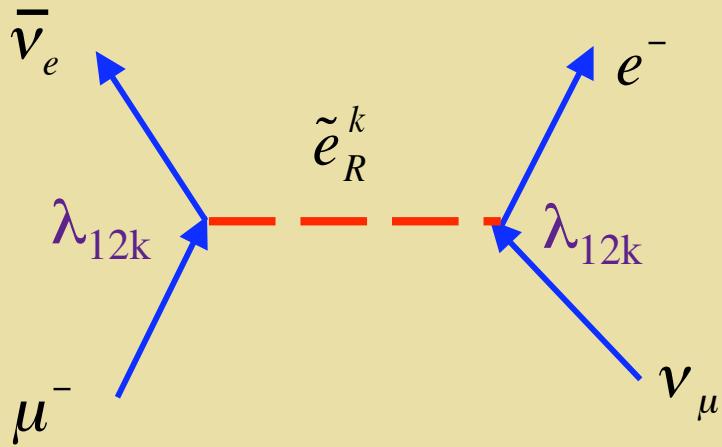


Box

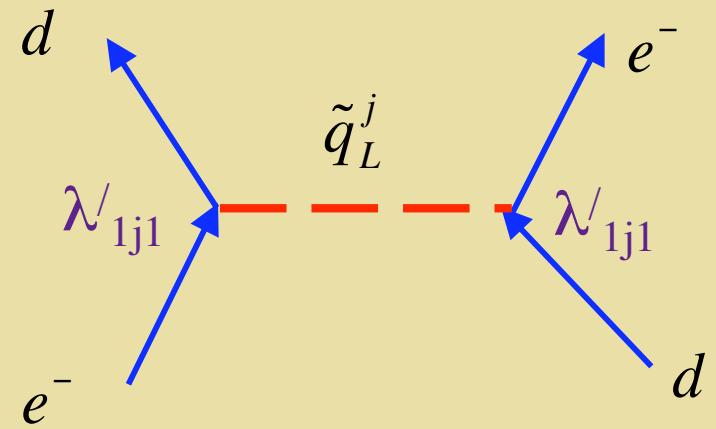


Kurylov, RM, Su

# SUSY: R Parity-Violation



$\Delta L=1$



$\Delta L=1$

$$\Delta_{12k} = \frac{|\lambda_{12k}|^2}{4\sqrt{2}G_F M_{\tilde{e}_R^k}^2}$$

$$\Delta'_{1j1} = \frac{|\lambda'_{1j1}|^2}{4\sqrt{2}G_F M_{\tilde{q}_L^j}^2}$$