EDM School

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Doyle group 11/9/16

Based partly on material from
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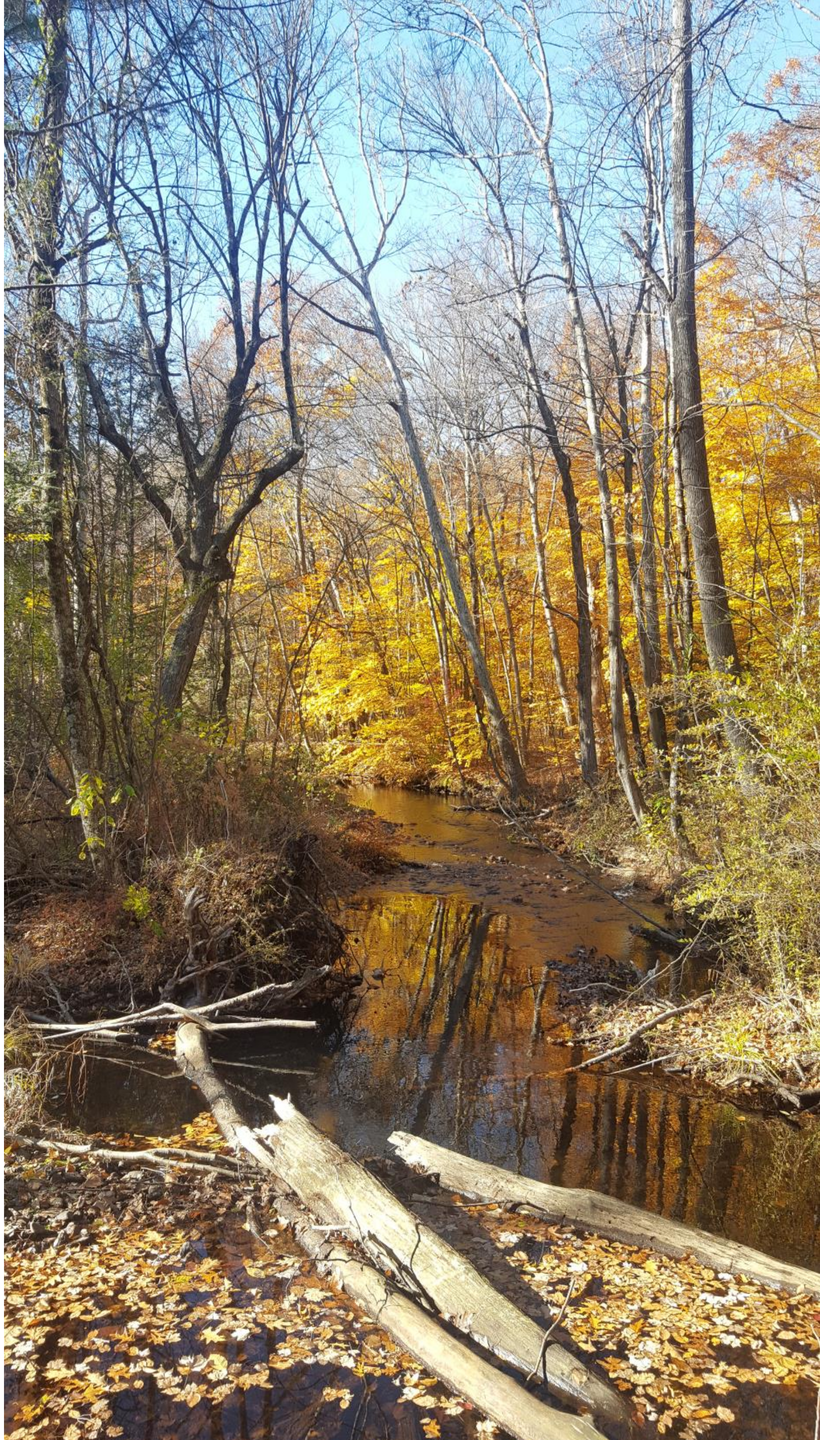


Overview

- "Basic" EDM physics
  - EDM Hamiltonian
  - Symmetry properties
  - Baryogenesis
- EDMs in the eyes of a quantum field theorist
- Getting EDMs from BSM
  - Effective field theory
- Constraining BSM parameter space

Introduction to EDM physics

We are looking for a term in the Hamiltonian

$$H_d = -\vec{d} \cdot \vec{E}$$

- Less exciting characterization: "Linear Stark shift at $|E| = 0$"
- Admits classical electric dipole moment interpretation
- But classical interpretation of $\vec{d}$ can be misleading:
  - Ideal classical dipole: infinite charges separated infinitesimally
  - "Normal" classical dipole: finite charge separated finite distance
  - Does this make sense for a point particle/quantal object?
  - More importantly: $\vec{\mathrm{d}} \propto \vec{S}$

Why is the EDM along $\vec{S}^*$?

- Example with Wigner-Eckart explanation:

$$\langle J, m = J | \vec{d} \cdot \vec{E} | J, m = J \rangle = \langle J, J | \vec{d} | J, J \rangle \cdot \vec{E}$$
$$= \langle J, J | T^{rank-1} | J, J \rangle \cdot \vec{E}$$
$$= \langle J, J \left| T^{k=1}{}_{q=0} \right| J, J \rangle \; E_z$$

Expectation value of EDM interaction in state with $\vec{S}||\hat{z}$ is only from $\vec{d}||\hat{z}$ part of the operator

Classical picture: The projection of the dipole moment perpendicular to the spin averages out as it "whips around" the electron

*Up to a sign (can be aligned or anti-aligned), which comes out of our measurement

Why is the EDM along $\vec{S}$*?

- More general explanation: we know electrons are spin-1/2 from spectroscopy (i.e., have 2 internal states)
  - E.g., degeneracy=2 in atomic 1s shell due to spin degree of freedom
- A particle is an "irreducible representation of the Lorentz group" with precisely specified transformation properties under rotations
  - Transformation depends on spin—e.g., spin-0 unchanged under rotations
- If a distinct vector were associated with the particle, then the particle's transformation under rotations would be different!
  - Applies even to a distinct "vector operator" built from components of $\vec{S}$
  - E.g., the expectation value of $S_x^2\hat{x} + S_y^2\hat{y} + S_z^2\hat{z}$ for spin-1/2 is always $(\hat{x} + \hat{y} + \hat{z})/2$ – doesn't transform under rotations, so not a true vector!

*Up to a sign (can be aligned or anti-aligned), which comes out of our measurement

Why is the EDM along $\vec{S}^*$?

- Loophole that we don't think about: if the electron is a composite system (experimentally constrained!), its EDM not necessarily along its angular momentum
  - E.g., symmetric top molecules have a linear Stark shift at $|E| = 0$, neglecting some high-order corrections, but dipole moment not necessarily along total angular momentum
- Another subtlety: $\vec{S}$ is a vector *operator*. For $|S| \geq 1$, can't even always picture the spin as having a definite orientation in space. The "alignment" of the dipole with spin means that for

$$\vec{S}^{op.} = S_x^{op.}\hat{x} + S_y^{op.}\hat{y} + S_y^{op.}\hat{y},$$

the dipole operator is

$$\vec{d}^{op.} = d(S_x^{op.}\hat{x} + S_y^{op.}\hat{y} + S_y^{op.}\hat{y})$$

*Up to a sign (can be aligned or anti-aligned), which comes out of our measurement

EDM symmetries

$$H = -d\,\vec{S}\cdot\vec{E}$$
$$T:\ \vec{S} \rightarrow -\vec{S}, \vec{E} \rightarrow +\vec{E}$$
$$P: \vec{S} \rightarrow +\vec{S}, \vec{E} \rightarrow -\vec{E}$$

$$T: H \rightarrow -H$$
$$P: H \rightarrow -H$$

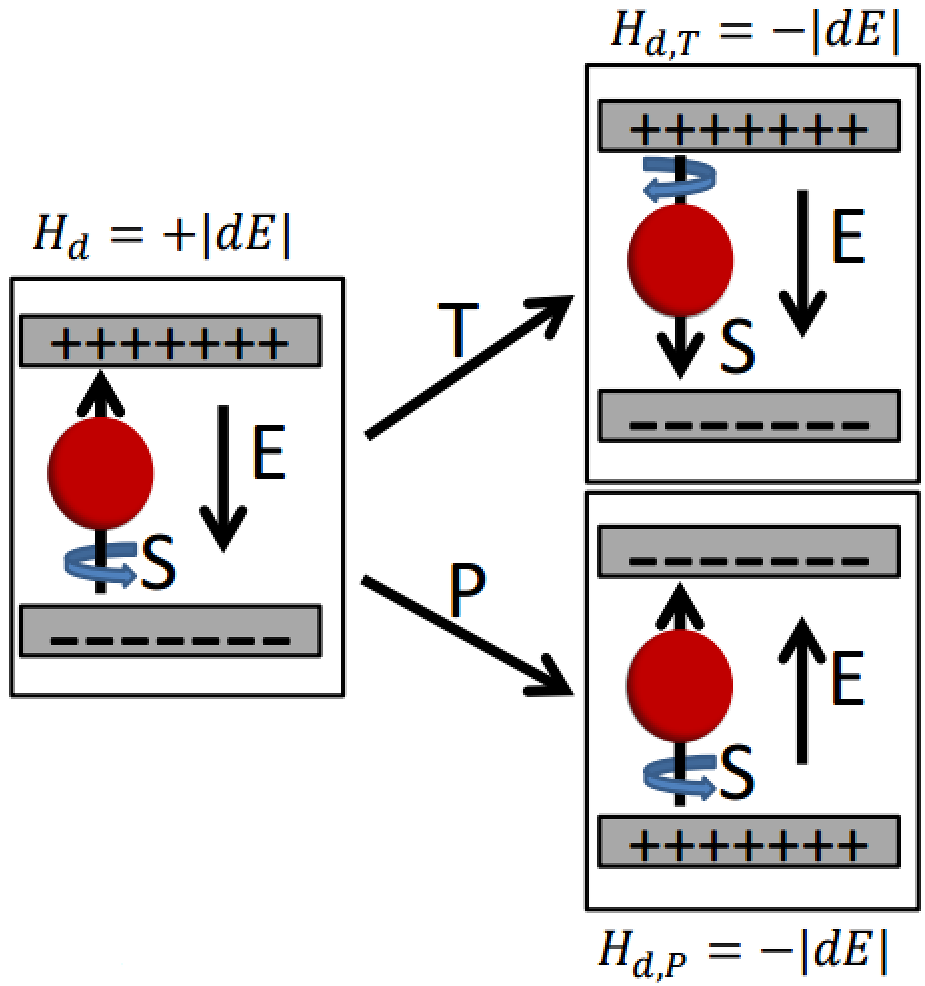
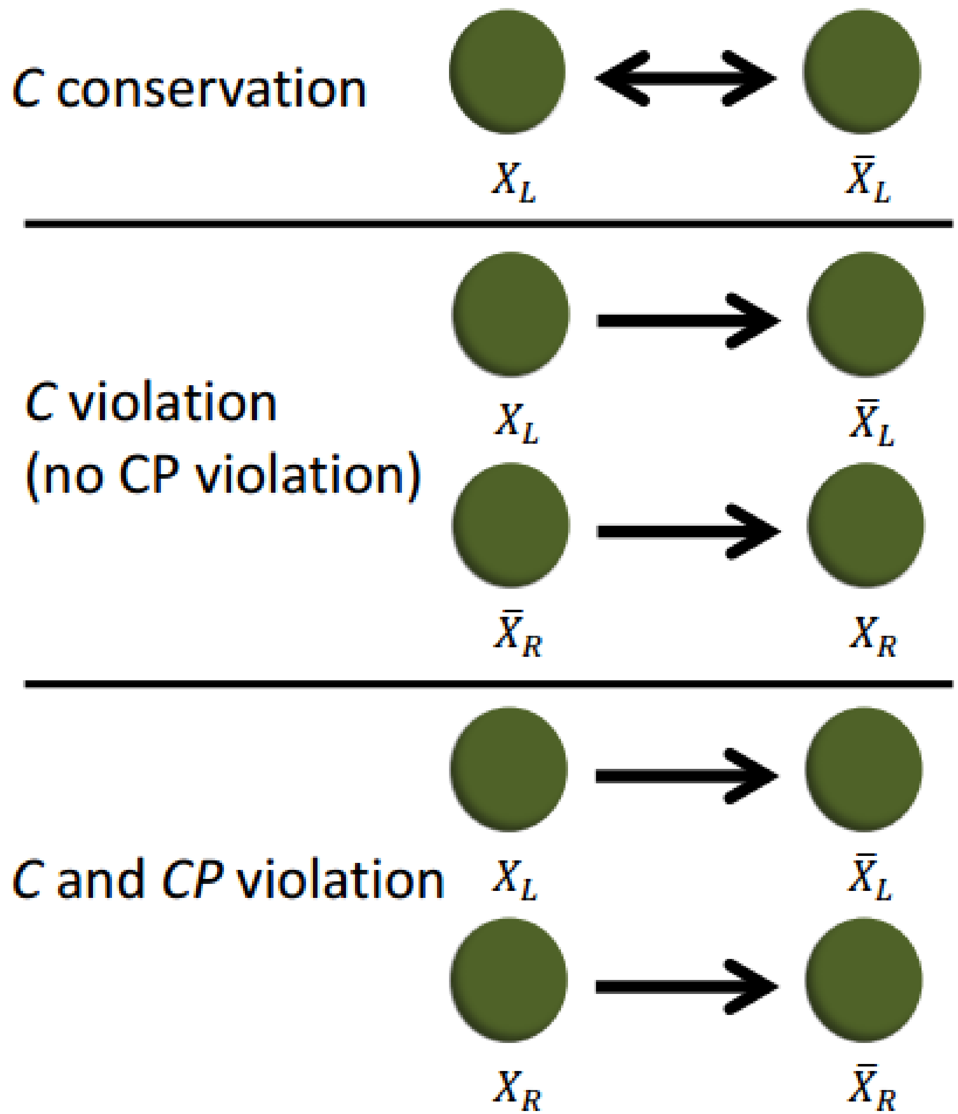


*Diagram energy labels assume $d = |d|$

Matter/antimatter asymmetry

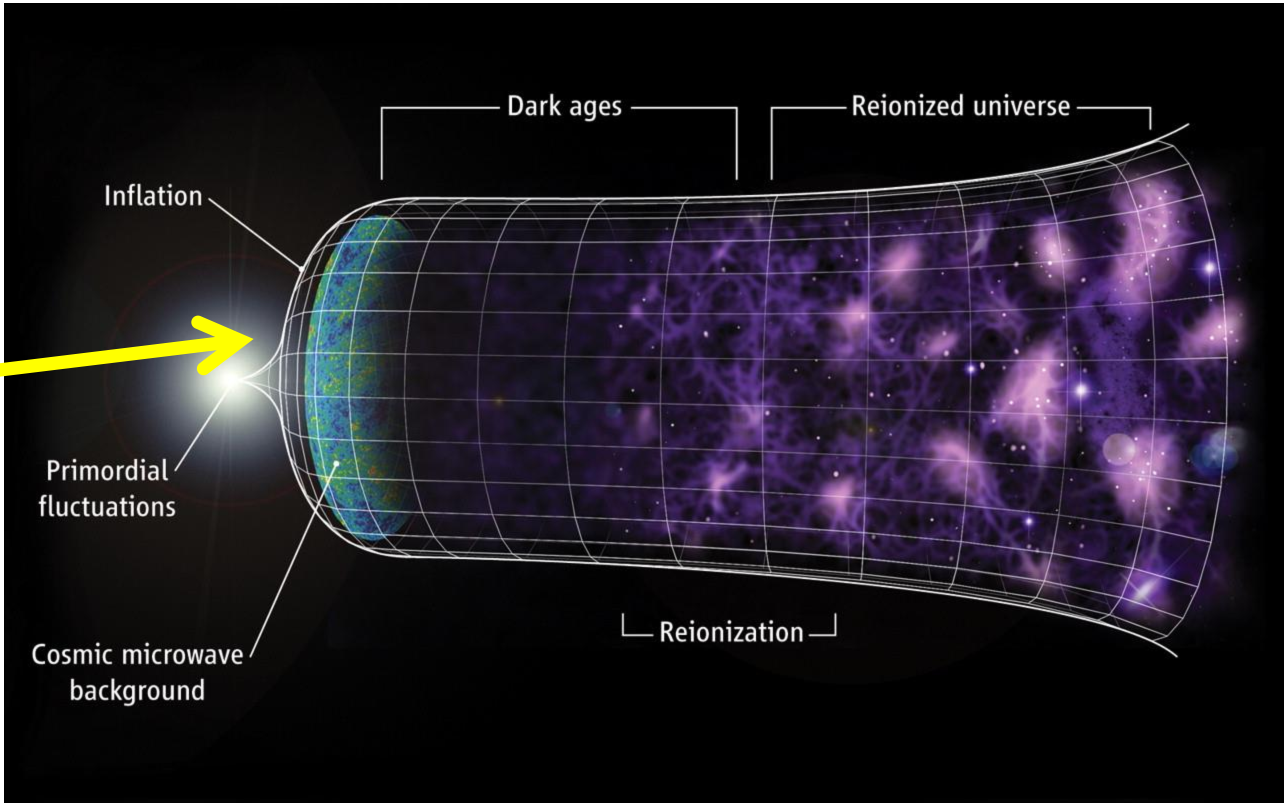
- Sakharov argues CP violation necessary for matter/antimatter asymmetry
- CPT theorem (basic assumptions like Lorentz invariance) gives $T = CP$
- EDMs potentially generated from same models as baryogenesis



Baryogenesis at $t = 0$?

Obvious question: Why can't excess baryon number be an initial condition?
Answer: because inflation (10^{60} e-folds) would wash it out
If baryon excess large enough to *not* wash out, then inflation couldn't occur

Here be dragons
but not baryon excess



EDMs in QFT language

- $H = -\vec{d} \cdot \vec{E}$ is non-relativistic
- Most general couplings of a fermion to electromagnetic field, consistent with EW gauge symmetry: (from R-M)

$$\boxed{\langle p'|\, J_\mu^{\mathrm{EM}}\, |p\rangle = \bar{U}(p')\left[F_1\gamma_\mu + \frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu + \frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu + \frac{F_A}{M^2}(q^2\gamma_\mu - \not{q}q_\mu)\gamma_5\right]U(p)}$$

F_1 :	Dirac (charge) form factor	P, T Conserving
F_2 :	Pauli (magnetic) ff	P, T Conserving
F_3 :	Electric Dipole ff	P, T Violating
F_A :	Anapole ff	P Violating

Ramsey-Musolf, Lecture VI

Electromagnetic couplings

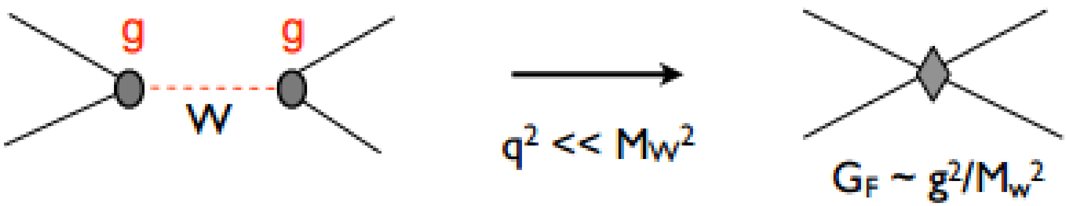
$$\langle p'|\, J_\mu^{\mathrm{EM}}\, |p\rangle = \bar{U}(p')\left[F_1\gamma_\mu + \frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu + \frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu + \frac{F_A}{M^2}(q^2\gamma_\mu - \not{q}q_\mu)\gamma_5\right]U(p)$$

F_1 :	*Dirac (charge) form factor*	*P, T Conserving*
F_2 :	*Pauli (magnetic) ff*	*P, T Conserving*
F_3 :	*Electric Dipole ff*	*P, T Violating*
F_A :	*Anapole ff*	*P Violating*

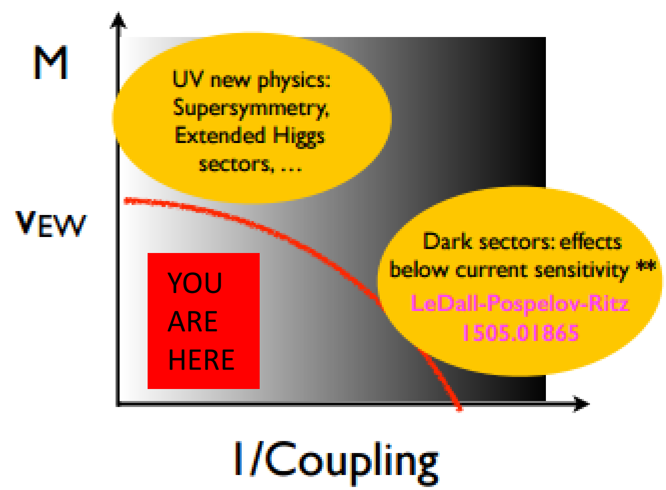
- Obviously, charge and magnetic dipole moment well-known
- We're looking for F_3, the electric dipole moment
- For a fundamental fermion, the anapole moment depends on EW gauge (not physically meaningful)
- Recover non-relativistic EDM interaction from F_3 term by plugging in low-p spinors, expanding σ, γ matrices, and using $L_{int} \propto J_\mu A^\mu$
  - Derivation not too enlightening to me…

EDM term from high-energy models

- How do our low-energy experiments talk to high-energy particles in BSM theories?
- Effective field theory: can “integrate out” virtual particles with masses larger than experimental energy scale



Fermi successfully modeled a “four-fermion” interaction before knowing about the W boson!



- Generate operators with only SM particles, scale with BSM coupling constants and suppressed by new particle masses
- Not applicable if BSM is low-mass, weak-coupling

Cirigliano, Lecture III

EFT operator dimension

- QFT typically expressed in terms of "Lagrangian density": $S = \int d^3x\, dt\, \mathrm{L}$
- In natural units $[\hbar] = [c] = 1$:

$$[S] = [1]$$
$$[x] = [t] = [m]^{-1}$$
$$\rightarrow [L] = [m]^4$$

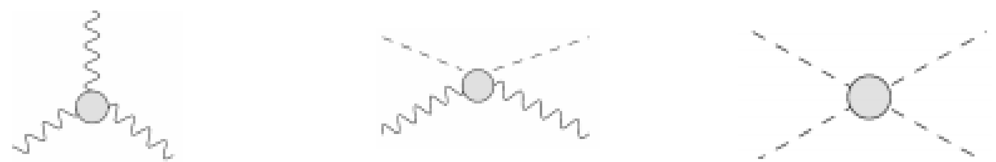
- All SM operators have four dimensions of mass
- E.g., $[\phi] = m, [\psi] = m^{3/2}$. Spin-1/2 mass term:

$$g\langle h\rangle_{vacuum}\bar{\psi}_L\psi_R$$
$$m \equiv g\langle h\rangle_{vacuum}$$

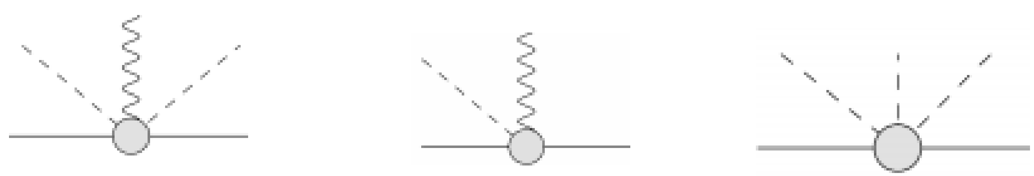
EFT operator dimension

- EFT can have mass-dim-(5+) operator structure!
- Extra dimensions of mass compensated by new-particle mass in denominator
- There is a single dim-5 operator
  - Not CP-violating, so we don't care!
- There are 59 EFT "structures" with dim-6
  - Many more if flavor included

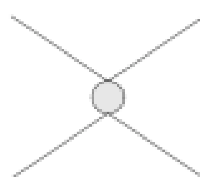
No fermions



Two fermions



Four fermions

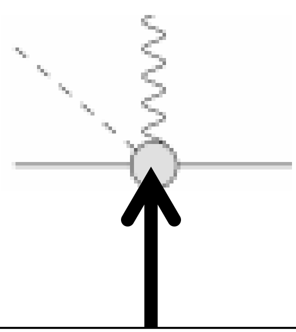


Cirigliano, Lecture III

CPV EFT*

- When including flavor, there are 2499 dim-6 operators
  - 1149 are CP violating
  - Many (not all) CP-violating operators can contribute to EDMs

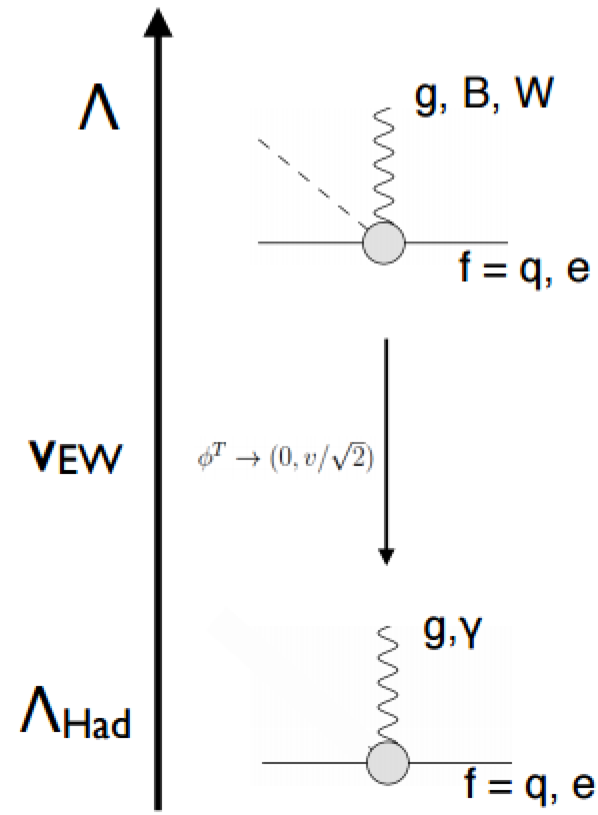
“Direct” EDM operator



Here be dragons
and baryon excess?

<u>Right:</u>
High-energy diagram with no photons can become a diagram with photons in the low-energy limit

“By the magic of quantum mechanics”
–Vicenzo Cirigliano

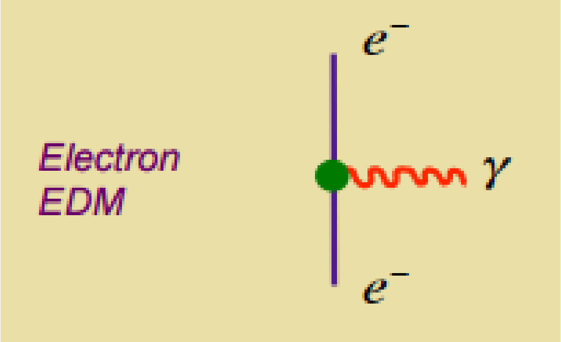


*My favorite slide title from the school: “EDMs BSM: MSSM”

Cirigliano, Lecture III

Other CPV effects

- We measure CPV effects in ThO:
  - eEDM
  - "scalar-pseudoscalar electron-nucleon coupling" C_S



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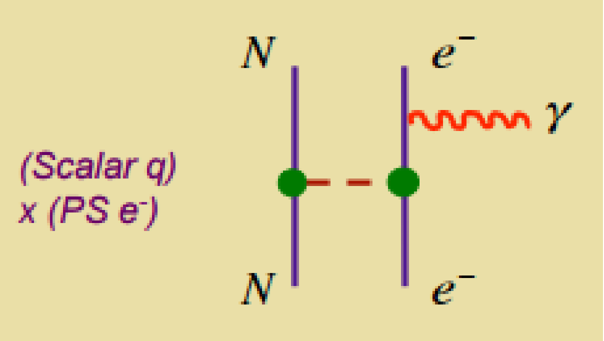
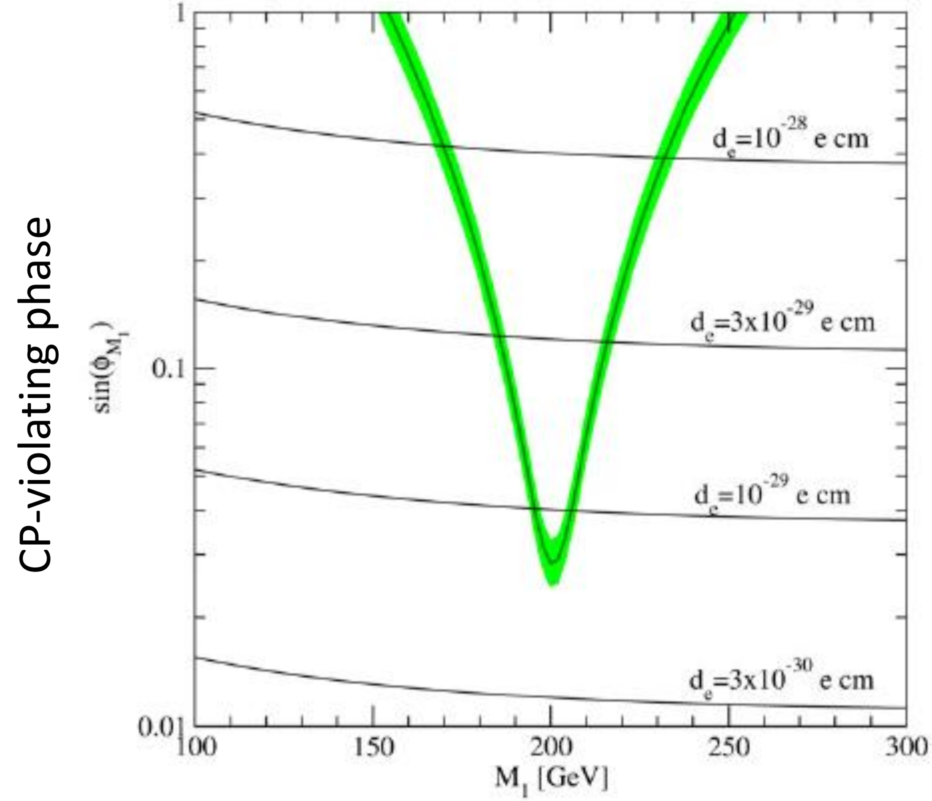


- Some linear combination contributes to any eEDM result
- If non-zero EDM measured, could use experiments in different systems to disentangle which term dominates

“The Money Plot”

- Example: eEDM limiting parameter space BSM
- If model not “asked” to solve baryogenesis, can always live with smaller CPV phases
- Tying EDMs to baryogenesis places much stricter constraints on theory viability

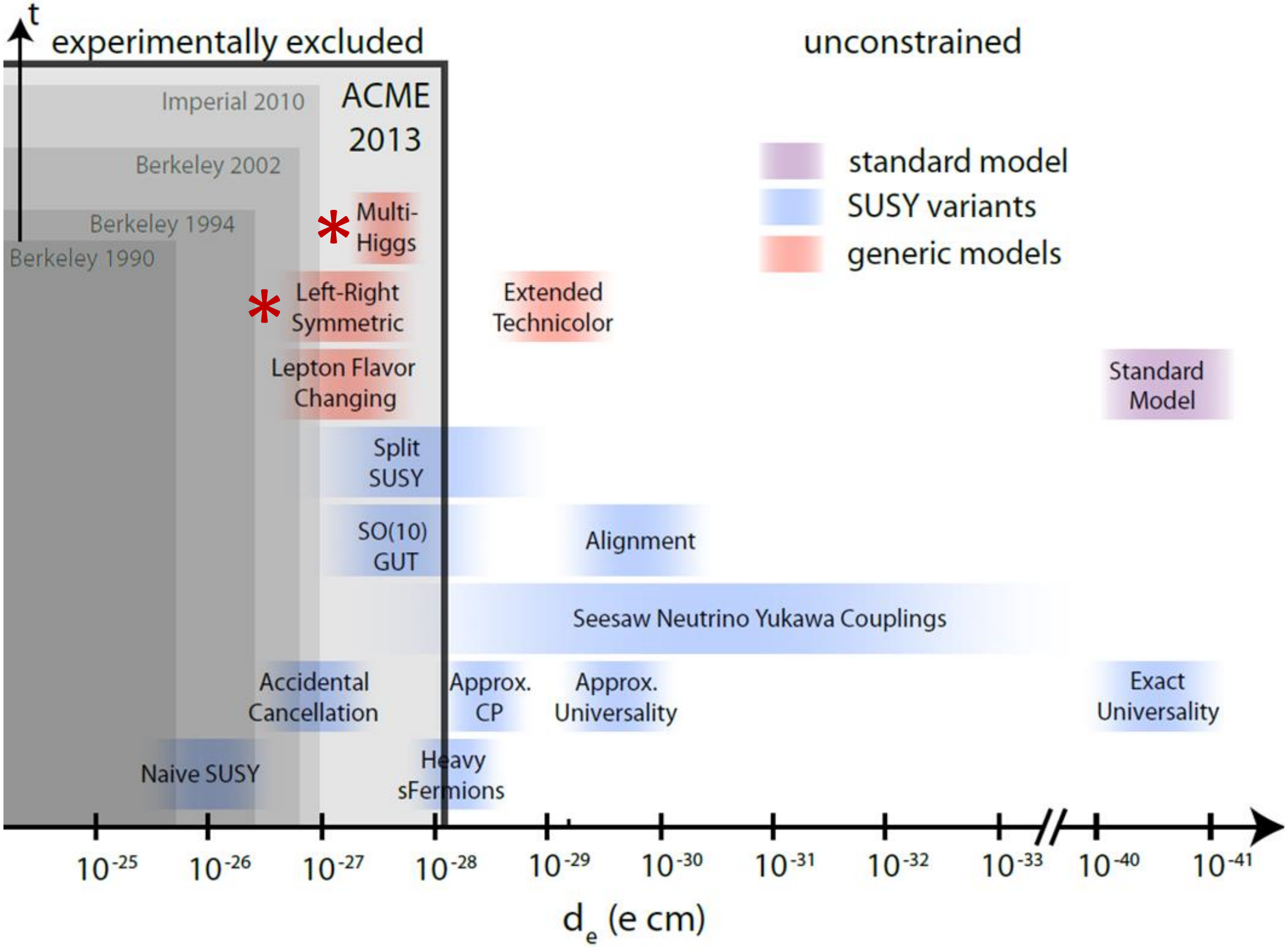
(M+)SSM Baryogenesis



Mass of supersymmetric particle

Li, Profumo, and Ramsey-Musolf, Phys.Lett.B673:95-100,2009

The money plot?



*Theories we talked about (in some form)

- Not dead? These plots might not be the way to go…

Other lessons

- All lecture slides from the school available at

http://www.physics.umass.edu/acfi/seminars-and-workshops/school-on-the-physics-of-electric-dipole-moments

- More detail on much of this material
- Diamagnetic vs. paramagnetic systems
- Naturalness problem in SM / BSM solutions
- Baryon/lepton number violation in SM ("sphalerons")
- Overview of specific theories (SUSY, EW baryogenesis, …)
- Calculation machinery (lattice QCD, chiral perturbation theory*, mean-field theory + Skyrme interactions, …)
- Lots of nEDM/hadronic sector content: θ_{QCD}, axions/Peccei-Quinn mechanism, CKM matrix contribution to SM EDMs
- Theorists are sad when you use their plots without citations

*I still have no idea what this is

Contemplative path through the woods to inspire your questions