Searches for new physics in precision atomic experiments

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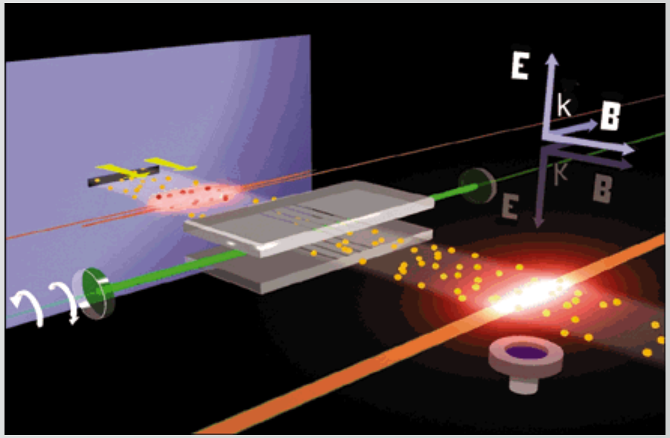


Canberra International Physics Summer School 2023 “Fields and Particles”

Plan

Lecture 1. How can atoms be used to test the SM and search for new physics?

- Atomic parity violation

Lecture 2. Time-reversal violating electric dipole moments

- Atomic EDMs, enhancement mechanisms

Lecture 3. Precision atomic theory

- Many-body methods, relativistic Hartree-Fock, QED in many-electron atoms

Lecture 4. Adventures at the intersection of atomic and nuclear physics

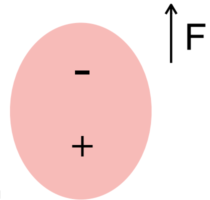
- Case study in the hyperfine structure

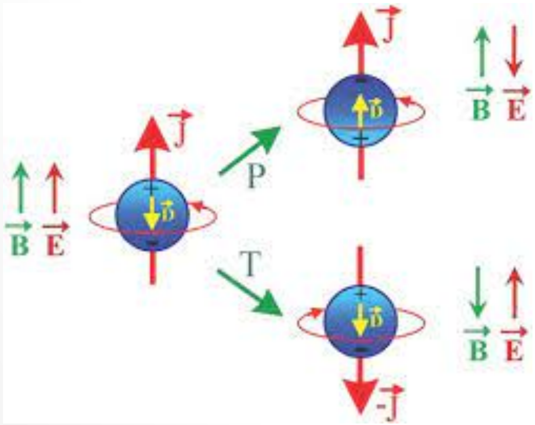
Lecture 2.
Time-reversal violating electric dipole moments

Electric dipole moments (EDMs)

Intrinsic EDMs of quantum systems (e.g., elementary particle, neutron, atom) violate parity P and time-reversal T

- EDM $\mathbf{d} = d(\mathbf{F}/F)$, where **F** is the total angular momentum of the system (e.g., atom)
- Probed through interaction with electric field **E**, $h_d = -\mathbf{d}\cdot\mathbf{E}$. Leads to *Stark shift* that is first-order in the electric field
- P,T-odd nature seen from $\mathbf{d} \propto \mathbf{F}$ or from form of interaction h_d . Note the parity operation $\mathrm{P}(\mathbf{E}) = -\mathbf{E}$





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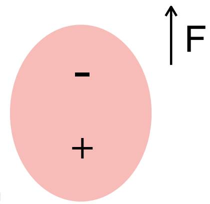

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- T-violation ≡ CP-violation (CPT theorem)
- Standard model CP-violation:
    - single phase in Cabibbo-Kabayashi-Maskawa matrix, $\delta \sim 1$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$, 3 angles, 1 phase

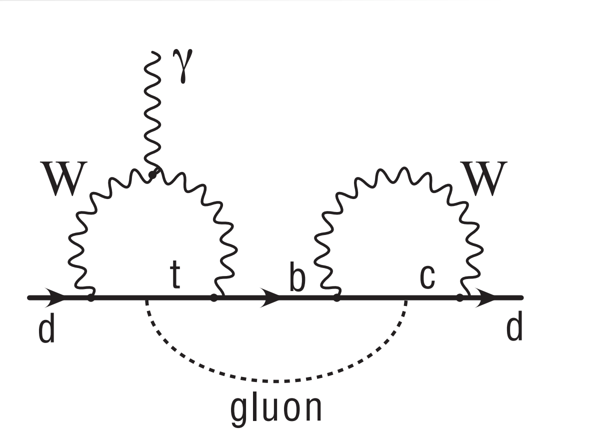
    - theta term in strong interaction, $-\bar{\theta}(g_s^2/16\pi^2)G^{\mu\nu}\tilde{G}_{\mu\nu}$, $\bar{\theta} \lesssim 10^{-10}$. Led to proposal for *axions.* Interaction analogous to $F^{\mu\nu}\tilde{F}_{\mu\nu} \propto \mathbf{E}\cdot\mathbf{B}$, which in EM has no observable effects

- <u>Not enough CP-violation in SM to explain matter-antimatter asymmetry of universe!</u>

EDMs — SM and BSM

Standard model EDMs appear in *high-order loops*

- Quark EDMs appear at 3-loop level



- Electron EDM appears at 4-loop level
- Introduction of new CP-violation phases induces EDMs orders of magnitude larger

Phenomenology

Phenomenological description, effective operators

- Fermion EDMs $\mathcal{L}_{\mathrm{EDM}} = -i\frac{d}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$

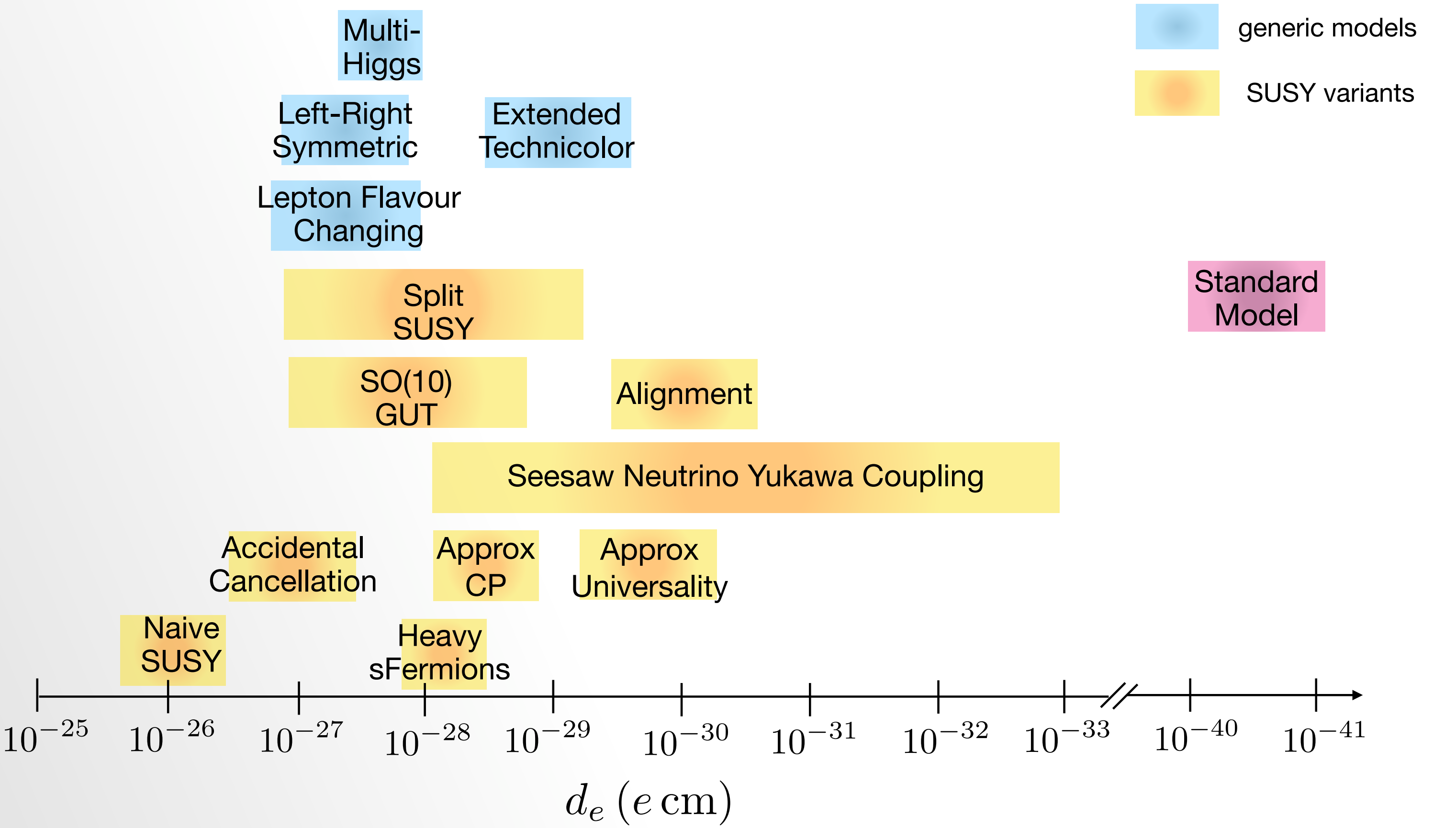
  - non-relativistic limit $\Rightarrow -d\langle\boldsymbol{\sigma}\rangle \cdot \mathbf{E}$

- Chromo EDMs $\tilde{d}_q$, interaction with gluon field $G_{\mu\nu}$
- Three-gluon term $GG\tilde{G}$
- Four-fermion interactions:

$$\underbrace{\bar{\psi}_1\psi_1\bar{\psi}_2 i\gamma_5\psi_2}_{\text{scalar}} \quad , \quad \underbrace{\bar{\psi}_1 i\gamma_5\psi_1\,\bar{\psi}_2\psi_2}_{\text{pseudoscalar}} \quad ,$$

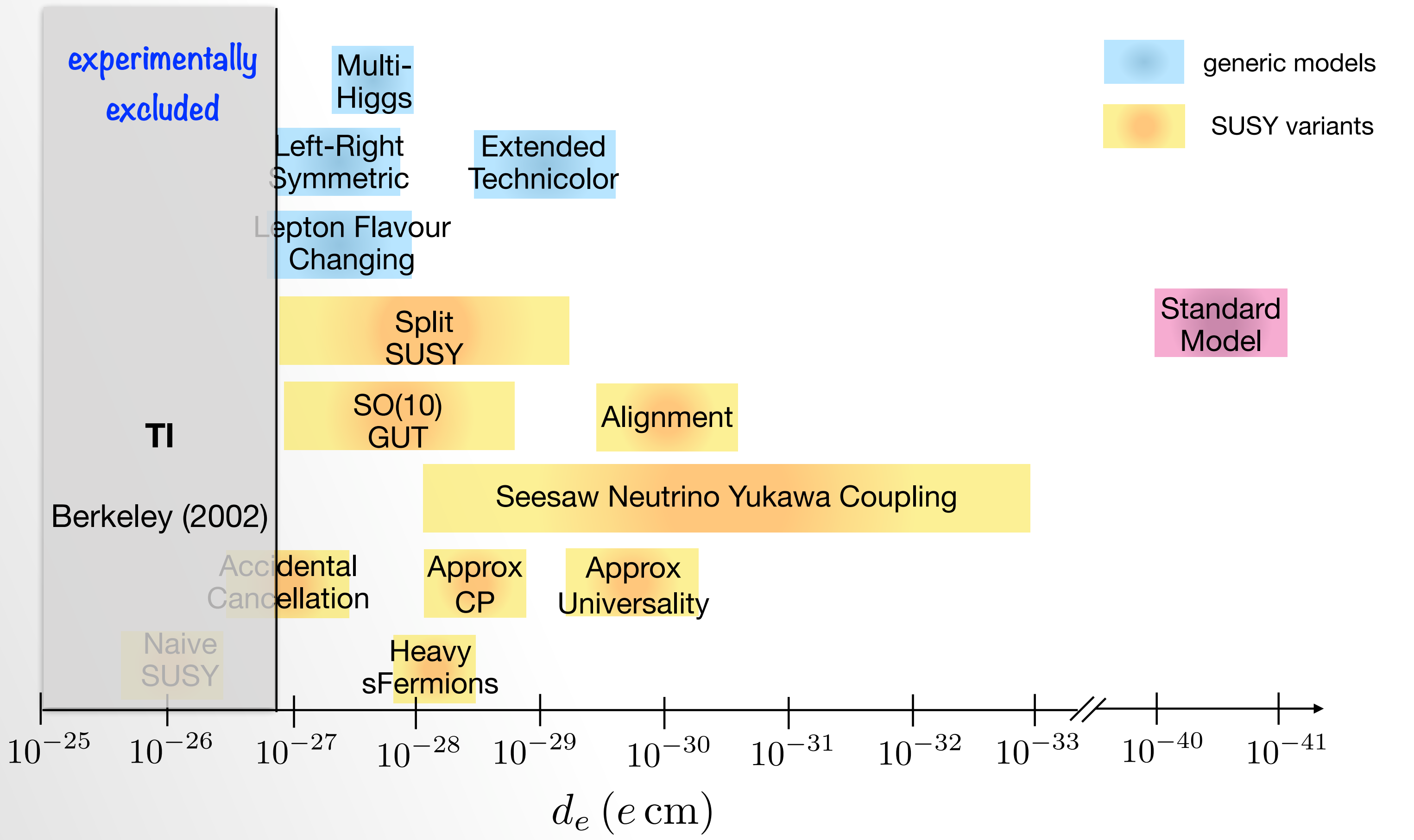
$$\underbrace{\epsilon_{\mu\nu\alpha\beta}\,\bar{\psi}_1\sigma^{\mu\nu}\psi_1\,\bar{\psi}_2\sigma^{\alpha\beta}\psi_2}_{\text{tensor}}$$

Predictions and bounds — electron EDM



B. E. Sauer *et al.*, New J. Phys. (2017)

Predictions and bounds — electron EDM



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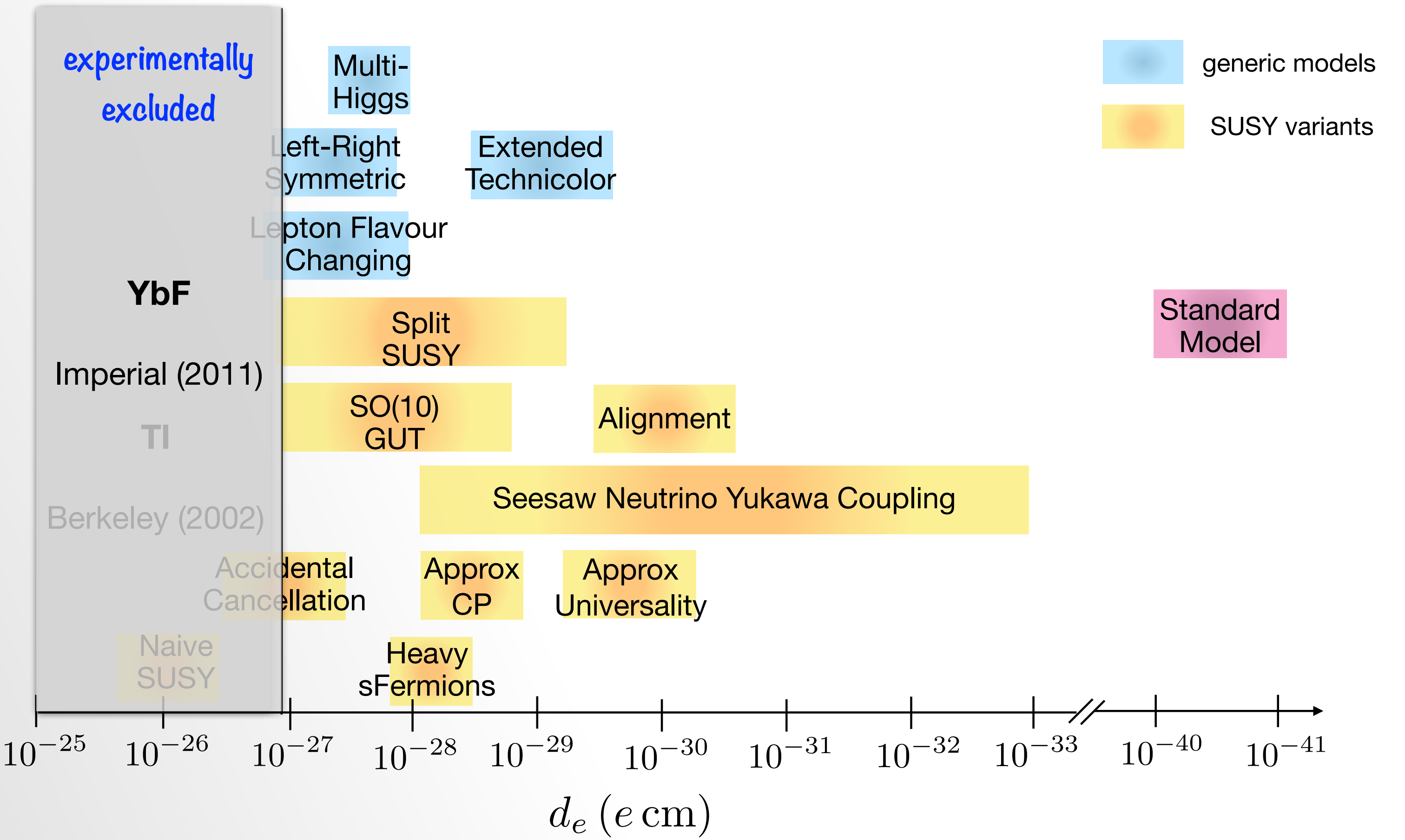

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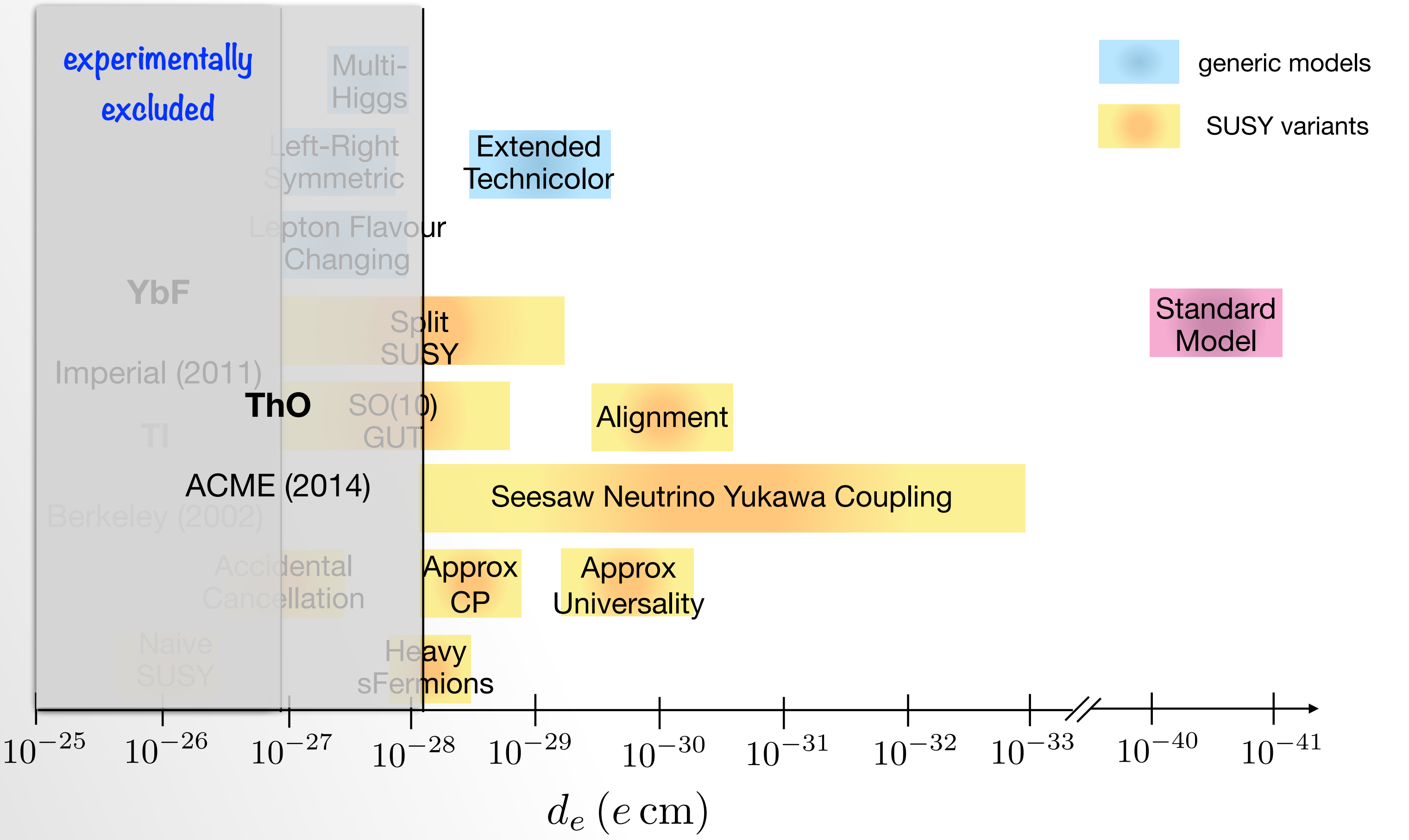

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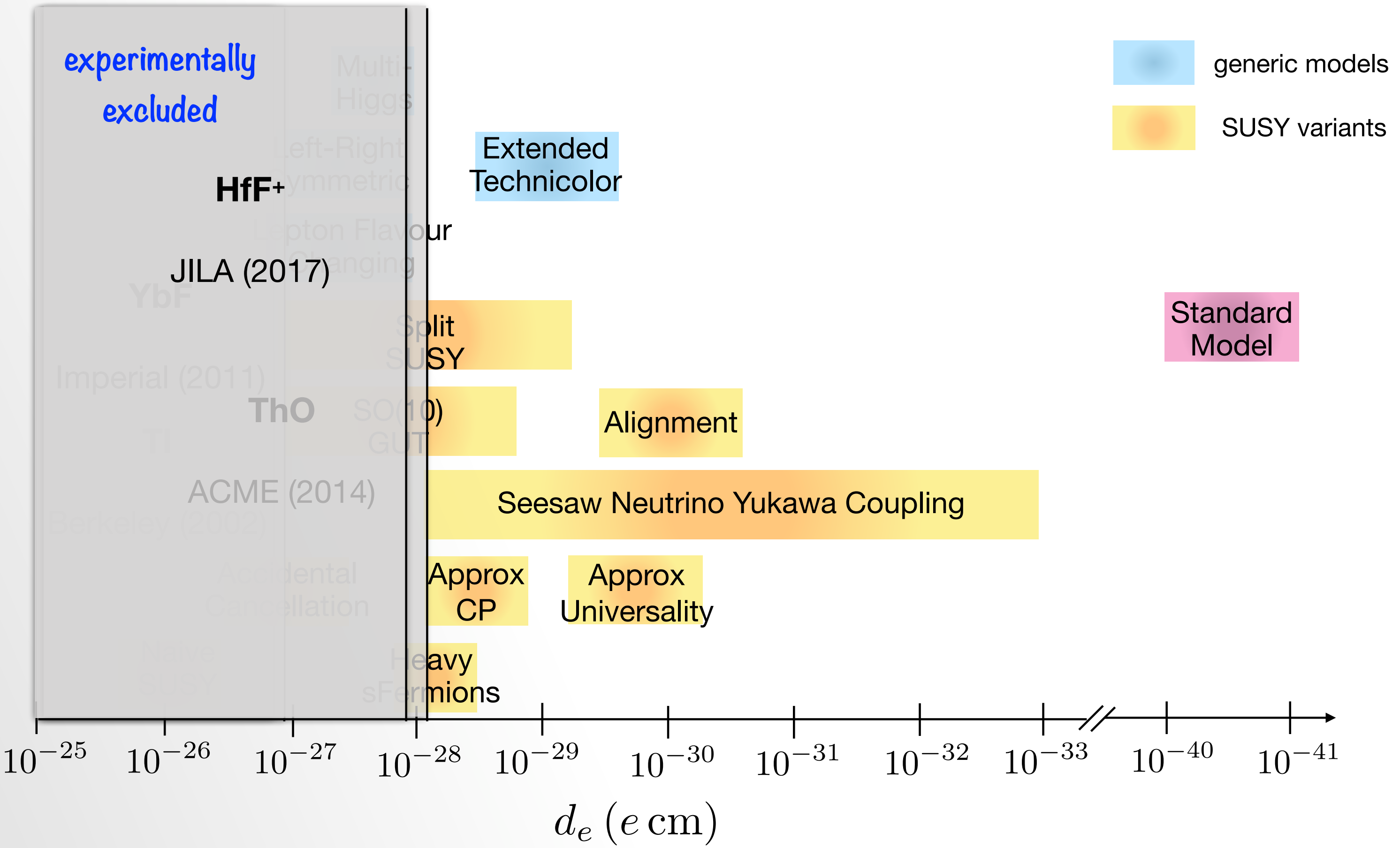

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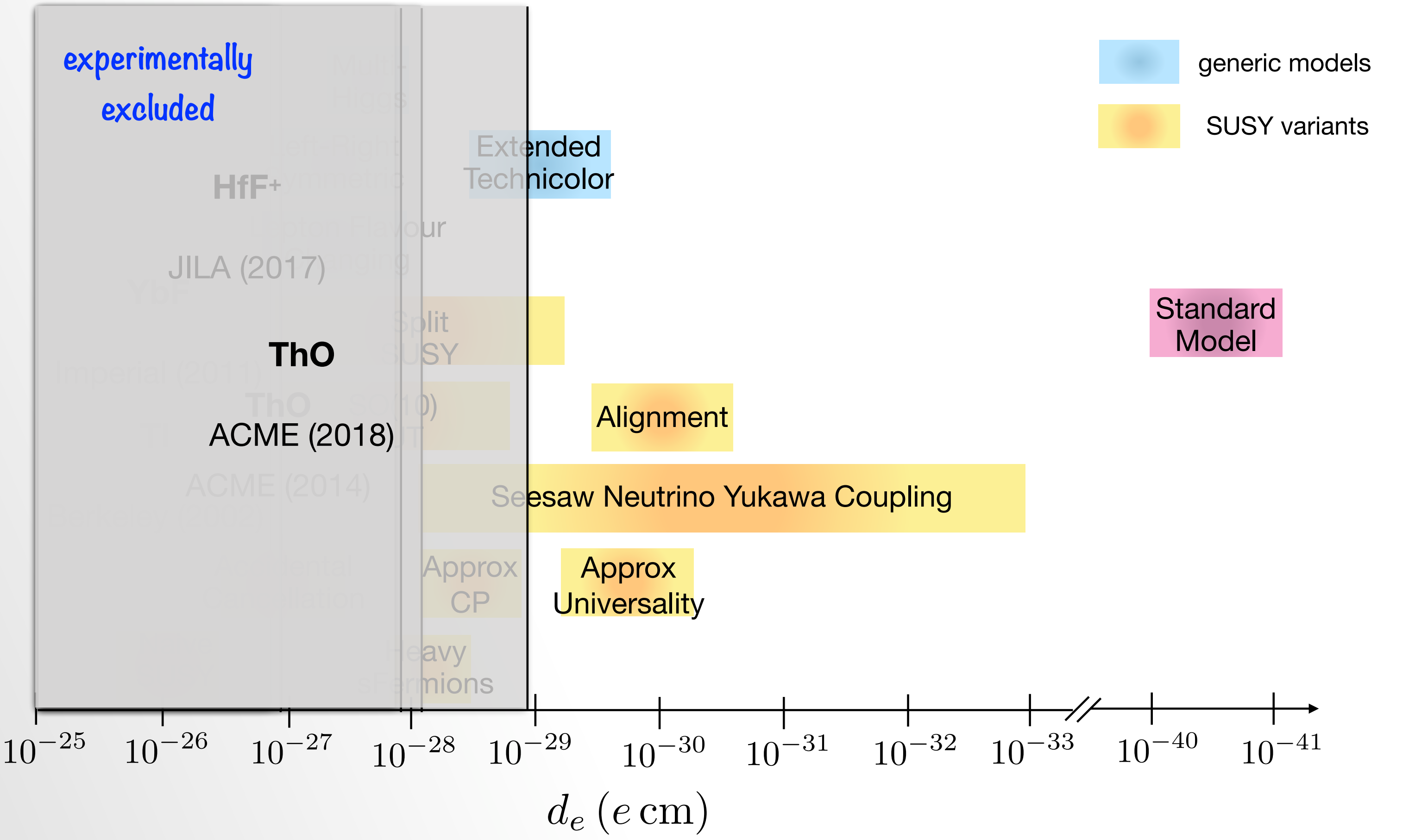

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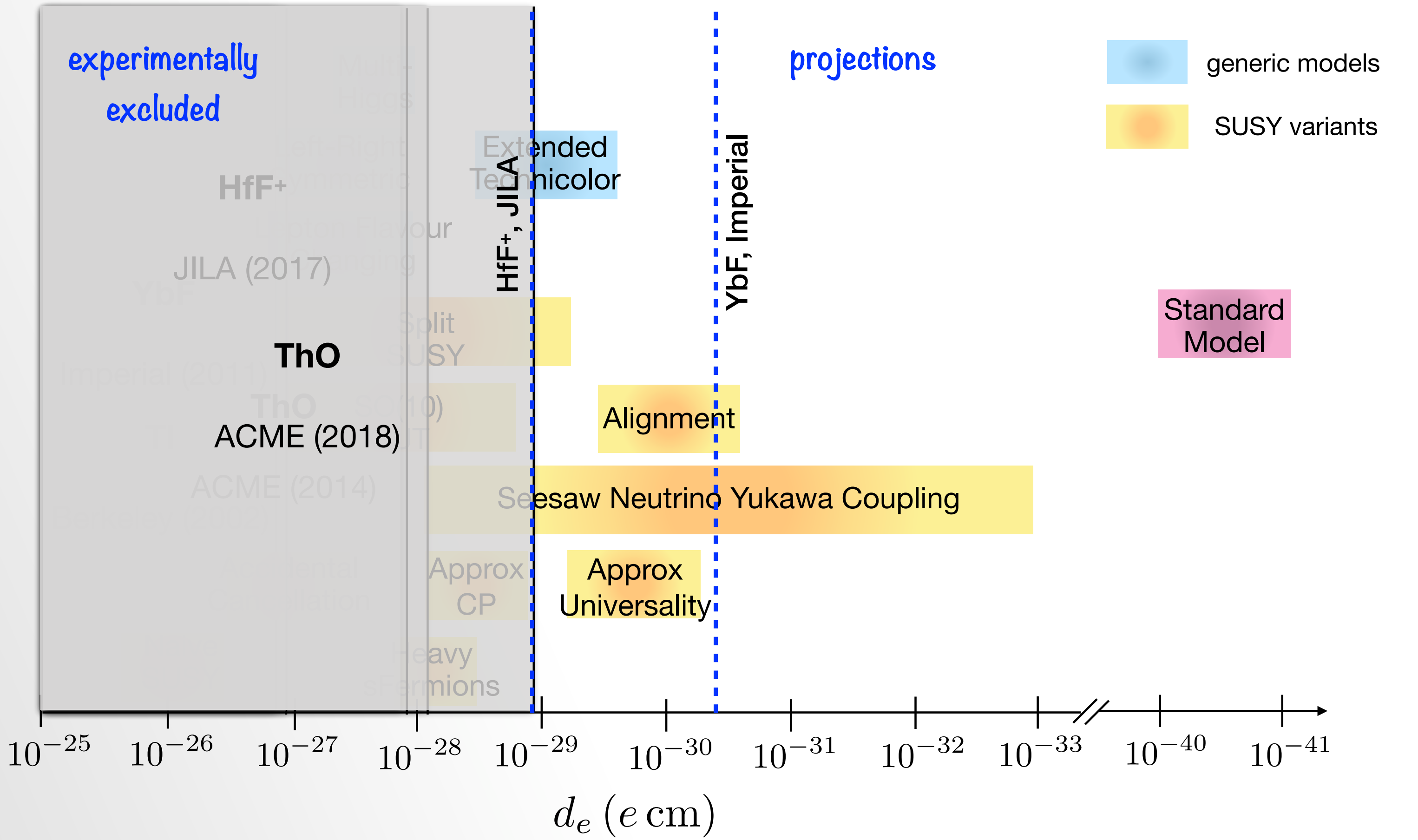

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ACME collaboration — Harvard, Yale, Northwestern, Caltech

Scale of precision

Q. A 10^{-29} cm limit on deviation from sphericity of the electron is equivalent to measuring the diameter of the solar system with an accuracy of:

A. The size of the sun.
B. The size of Earth.
C. The size of a football field.
D. A fraction of the width of a human hair.

Energy reach

- EDM of fermion of mass *m* arising due to new heavy particle of mass Λ and phase ϕ_{CP} in diagram with *n* loops:

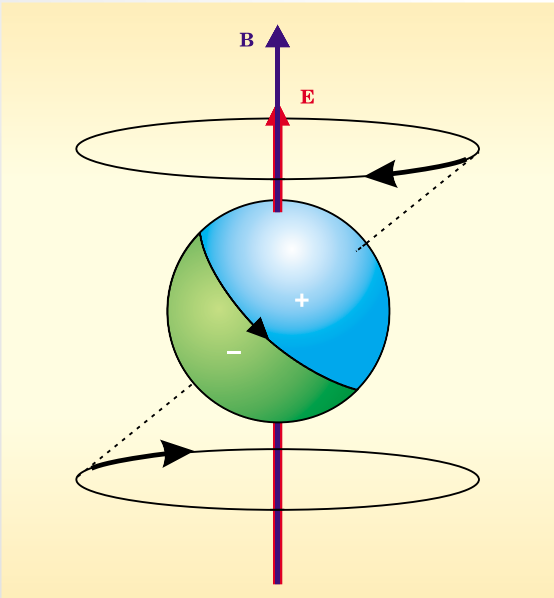
$$d \sim \mu \, \sin\phi_{\mathrm{CP}} \, (g^2/2\pi)^n \, (m/\Lambda)^2$$

- Current bounds from atomic and molecular experiments give

$$\Lambda \gtrsim (1 - 1000 \, \mathrm{TeV}) \sqrt{\sin\phi_{\mathrm{CP}}}$$

Basics of an EDM measurement

- Measure difference in precession frequencies in parallel and antiparallel electric and magnetic fields



$$H = -\mu \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$$

$$\Rightarrow \hbar \Delta\omega = 4 d_{\mathrm{Hg}} E$$

Atomic EDMs

- P,T-violating interactions induce EDMs in atoms

$$\mathbf{d}_{\mathrm{atom}} = \langle \tilde{N} | \mathbf{D} | \tilde{N} \rangle = 2 \sum_M \frac{\langle N|\mathbf{D}|M\rangle \langle M|H_{PT}|N\rangle}{E_N - E_M} = d_{\mathrm{atom}}\, \mathbf{F}/F$$

- Effects increase with nuclear charge Z,

$$d_{\mathrm{atom}} \propto Z^2,\ Z^3$$

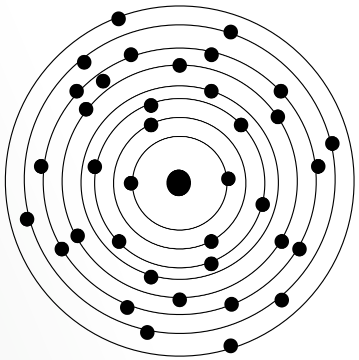
- Molecules — projection of spin on internuclear axis

Diamagnetic systems:
hadronic and semi-leptonic mechanisms

Paramagnetic systems:
leptonic and semi-leptonic mechanisms

Schiff screening

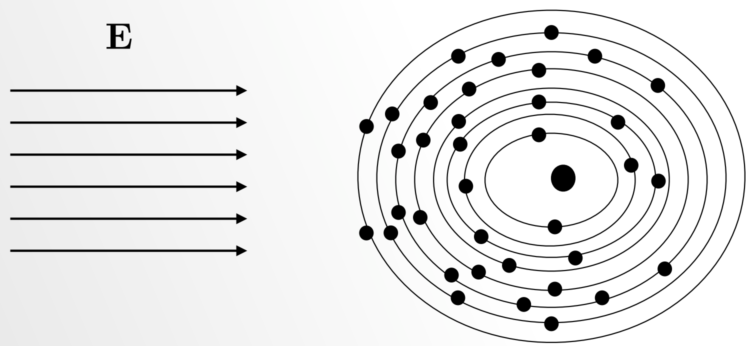
Schiff theorem



Neutral system comprised of
non-relativistic point-particles
interacting via
Coulomb force

Schiff screening

Schiff theorem



Neutral system comprised of
non-relativistic point-particles
interacting via
Coulomb force

Internal electric field produced
s.t. at each particle

$$\mathbf{d} \cdot \langle \mathbf{E} \rangle = 0$$

Schiff screening derivation

Consider atom made of point charges with electric dipole moments and experiencing Coulomb interaction only. Treat non-relativistically.

The total EDM of the atom consists of:

- bare EDM contribution
- induced EDM contribution

Bare EDM: $\sum_i \mathbf{d}_i$

Induced EDM: $\langle \tilde{N} | \mathbf{D} | \tilde{N} \rangle = \langle \tilde{N} | \sum_i e_i \mathbf{r}_i | \tilde{N} \rangle$,

where $|\tilde{N}\rangle$ is state of the atom perturbed by the P,T-odd EDM interaction,

$$|\tilde{N}\rangle = |N\rangle + \sum_M \frac{\langle M | H_d | N \rangle}{E_N - E_M} |M\rangle \quad .$$

The P,T-odd interaction Hamiltonian,

$$H_d = -\sum_i \mathbf{d}_i \cdot \mathbf{E}(\mathbf{r}_i) = \sum_i \frac{1}{e_i} \mathbf{d}_i \cdot \nabla_i U(\mathbf{r}) \ ,$$

where U(**r**) is the potential energy.

This may be expressed in terms of the unperturbed Hamiltonian,

$$H_d = i \sum_i \frac{1}{e_i} [\mathbf{d}_i \cdot \mathbf{p}_i, H_0] \ .$$

Therefore, the perturbed atomic wave function:

$$|\tilde{N}\rangle = |N\rangle + i \sum_M \frac{\langle M | \sum_i (1/e_i) [\mathbf{d}_i \cdot \mathbf{p}_i, H_0] | N \rangle}{E_N - E_M} |M\rangle$$

$$\Rightarrow |\tilde{N}\rangle = |N\rangle + i \sum_M \frac{\langle M | \sum_i (1/e_i) \mathbf{d}_i \cdot \mathbf{p}_i (E_N - E_M) | N \rangle}{E_N - E_M} |M\rangle$$

$$\Rightarrow |\tilde{N}\rangle = \left(1 + i \sum_i (1/e_i) \mathbf{d}_i \cdot \mathbf{p}_i\right) |N\rangle$$

Therefore, induced atomic EDM:

$$\langle \tilde{N} | \sum_i e_i \mathbf{r}_i | \tilde{N} \rangle = \langle N | \left(1 - i \sum_i (1/e_i) \mathbf{d}_i \cdot \mathbf{p}_i \right) \sum_j e_j \mathbf{r}_j \left(1 + i \sum_k (1/e_k) \mathbf{d}_k \cdot \mathbf{p}_k \right) | N \rangle$$

$$= \langle N | i \left[\sum_i e_i \mathbf{r}_i , \sum_j (1/e_j) \mathbf{d}_j \cdot \mathbf{p}_j \right] | N \rangle$$

$$= - \langle N | \sum_i \mathbf{d}_i | N \rangle = - \sum_i \mathbf{d}_i$$

This *exactly* cancels the bare EDM, so total atomic EDM is zero!

Violation of Schiff theorem?

Yes!

Finite nuclear size $\Rightarrow$ nuclear Schiff moment! $d_{\text{atom}} = \eta\, S$, $\mathbf{S} = S\mathbf{I}/I = \frac{e}{10}\left[\langle r^2 \mathbf{r} \rangle - \frac{5}{3Z} \langle r^2 \rangle \langle \mathbf{r} \rangle \right]$

Relativistic effects $\Rightarrow$ electron EDM, with enhancement! $d_{\text{atom}} = K\, d_e$, $|K(\text{Tl})| \approx 600$

Leading mechanisms

neutron EDM

diamagnetic (Hg,TlF,…)

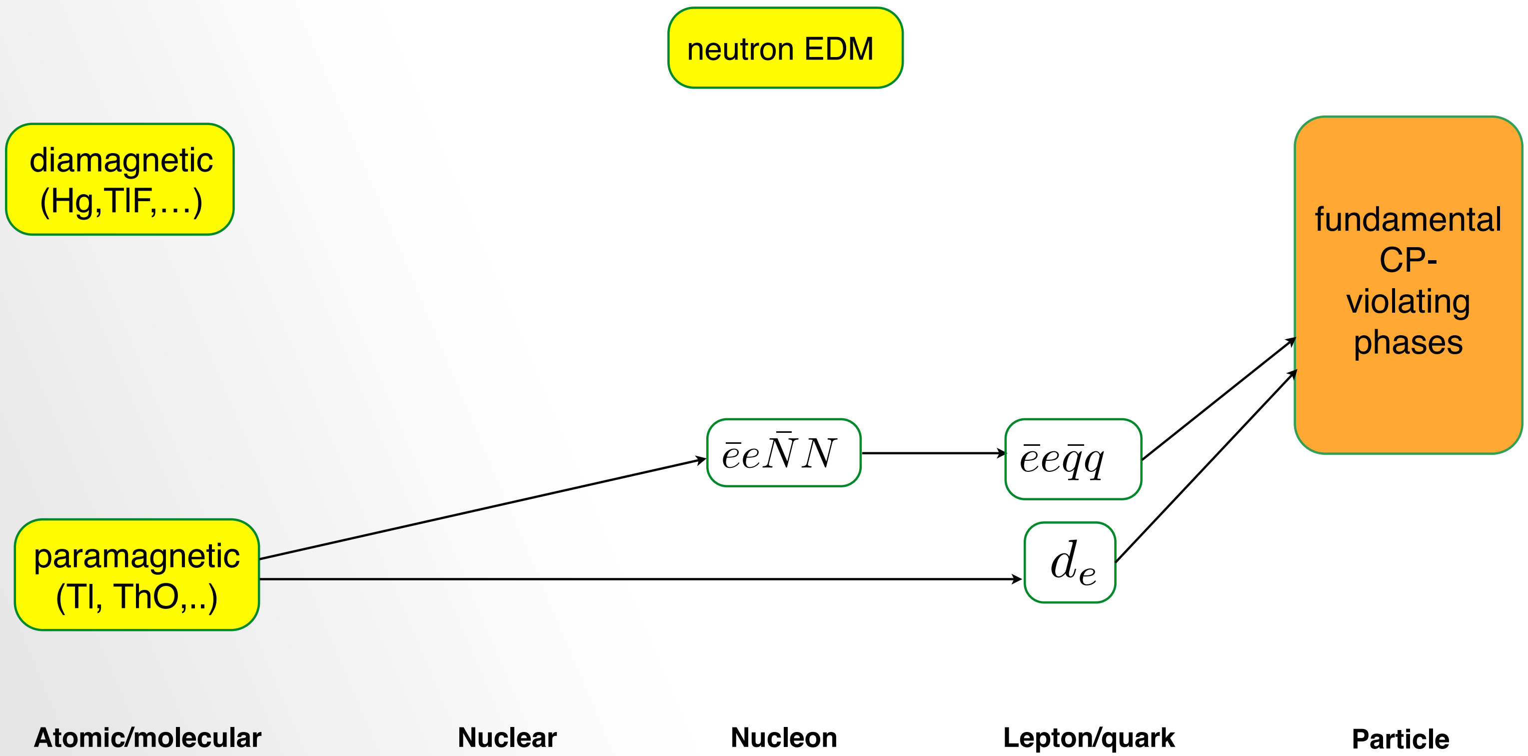
fundamental CP-violating phases

Measurements

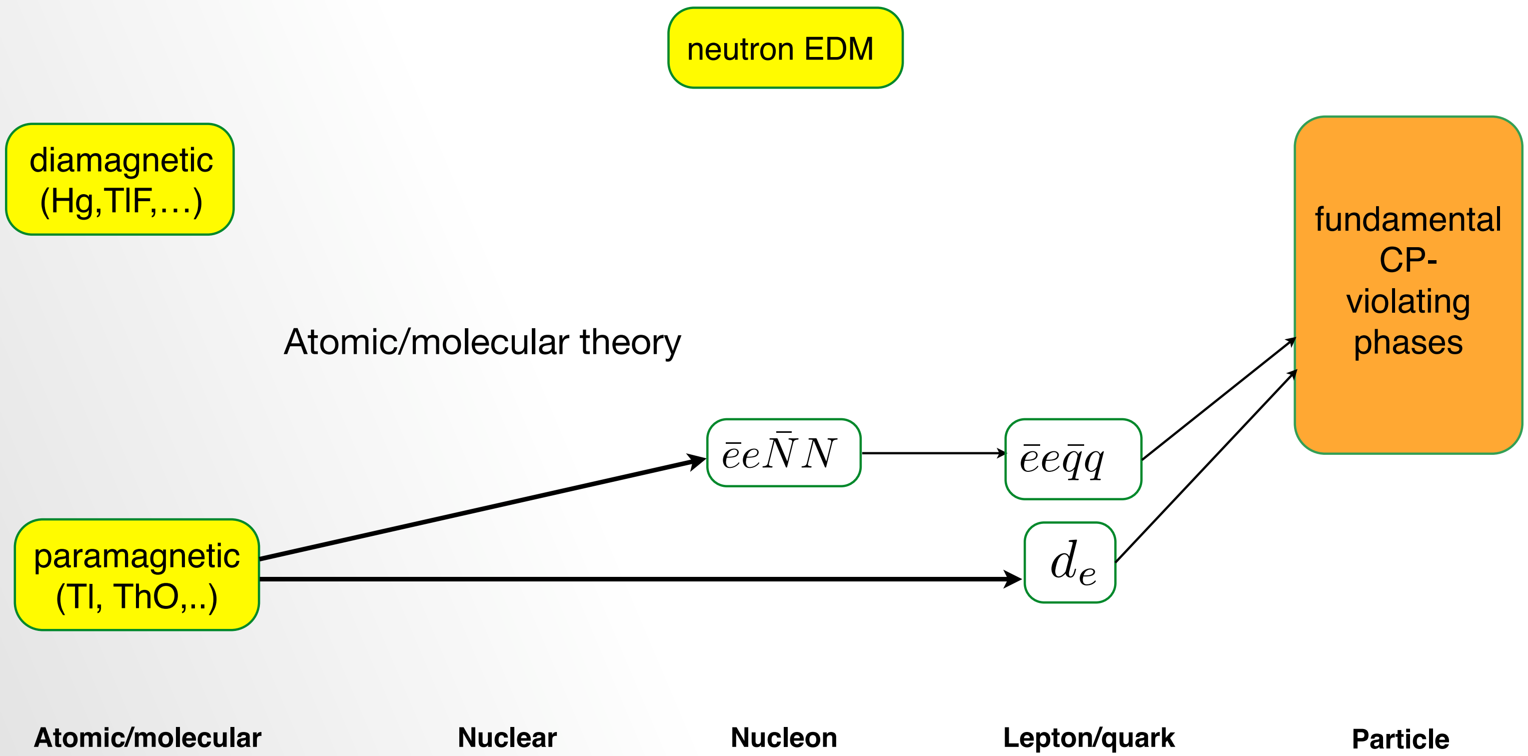
paramagnetic (Tl, ThO,..)

Atomic/molecular **Nuclear** **Nucleon** **Lepton/quark** **Particle**

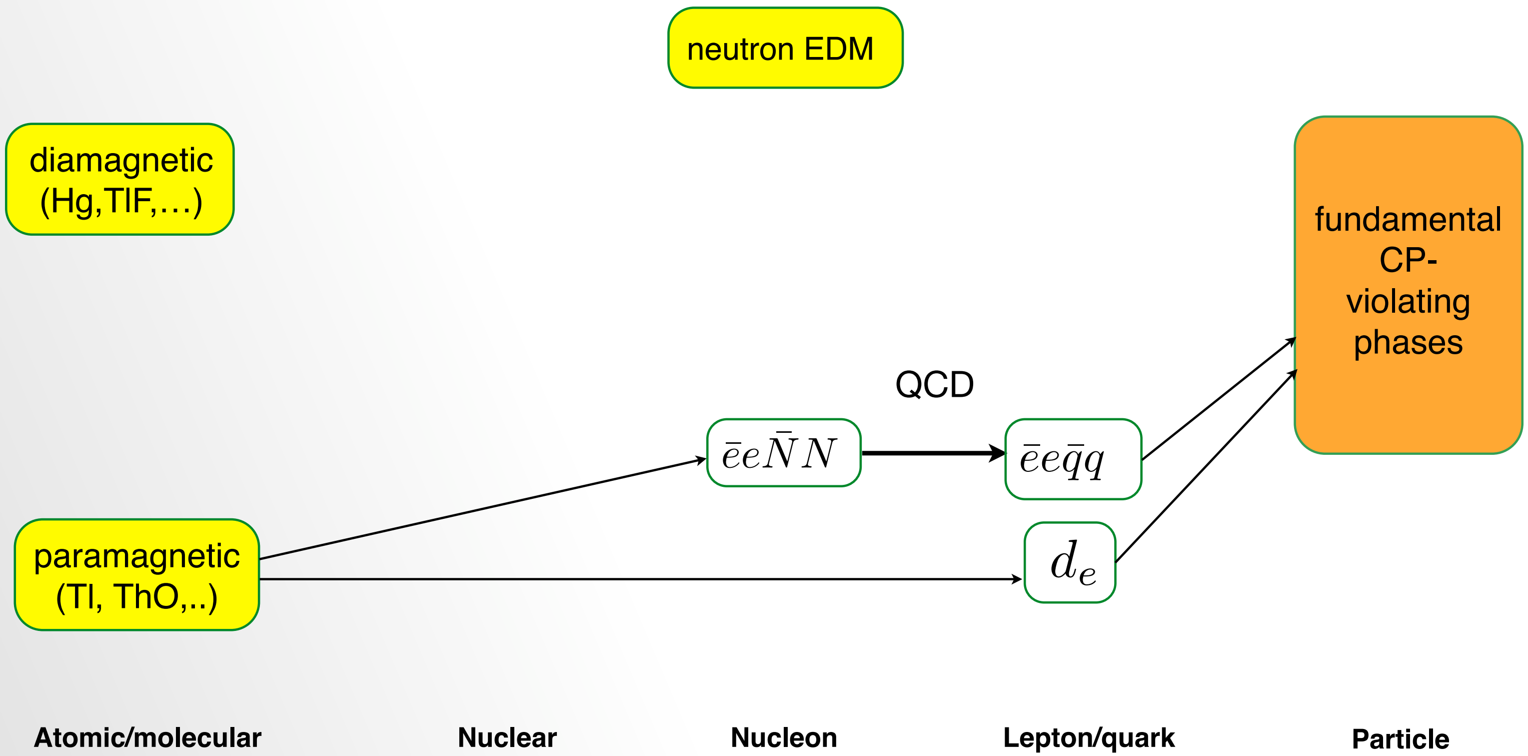
Leading mechanisms



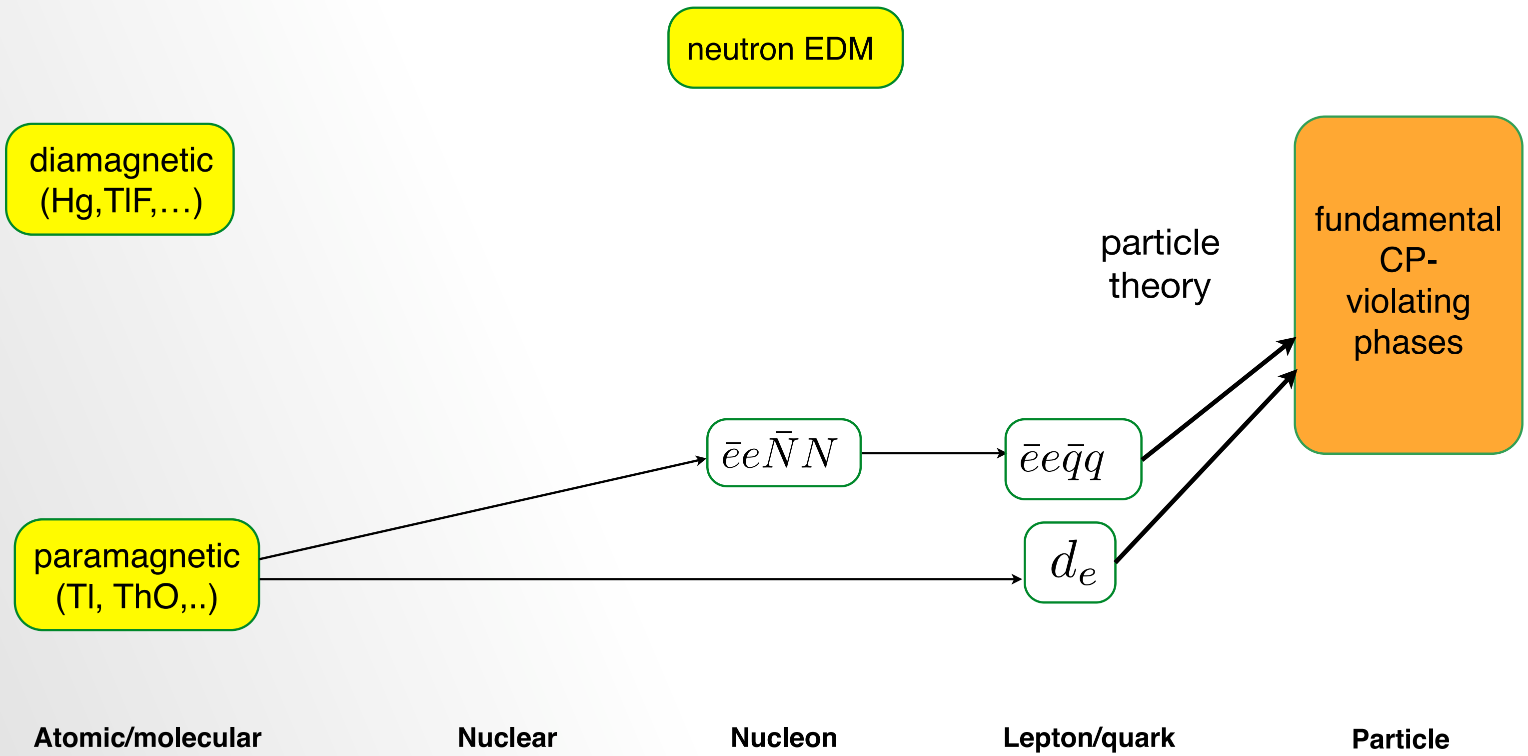
Leading mechanisms



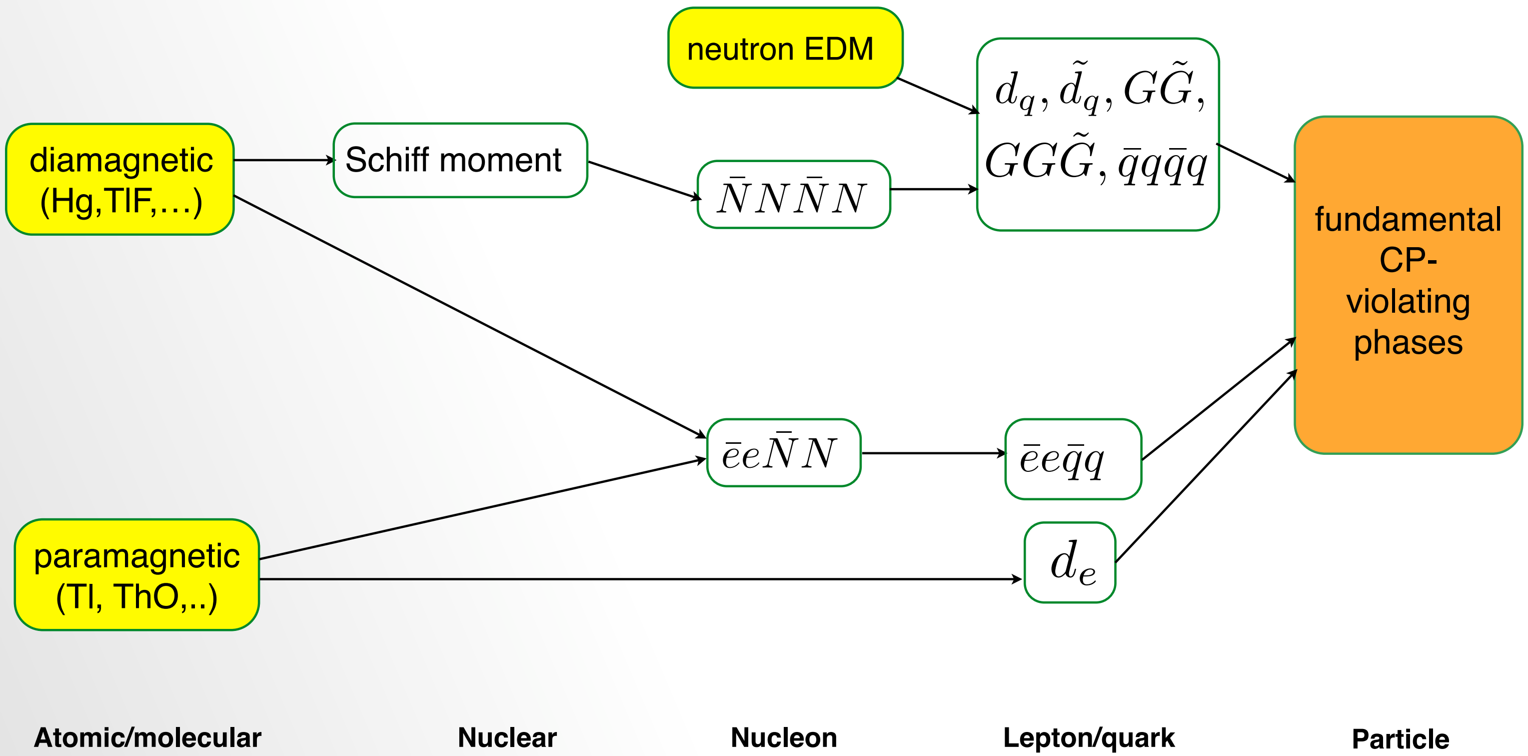
Leading mechanisms



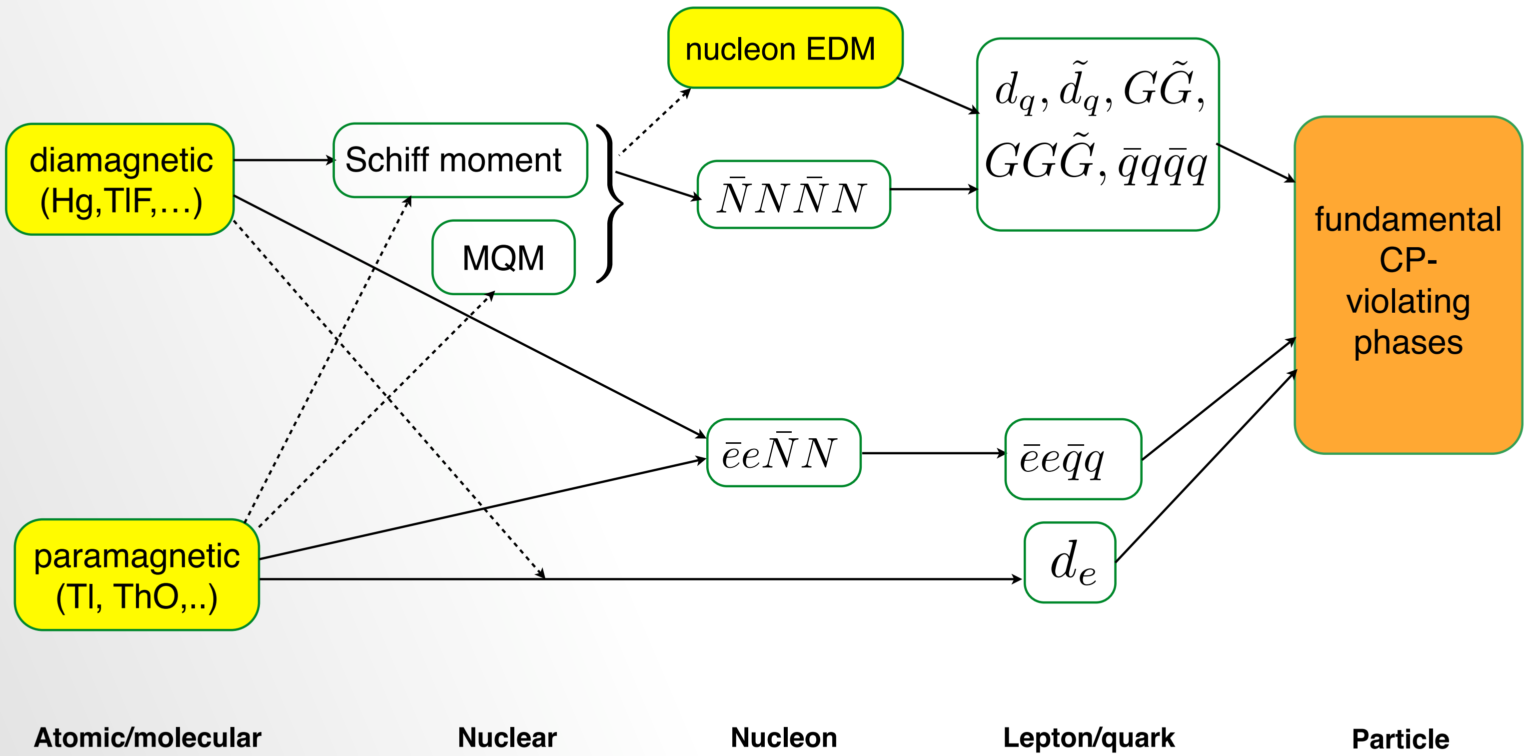
Leading mechanisms



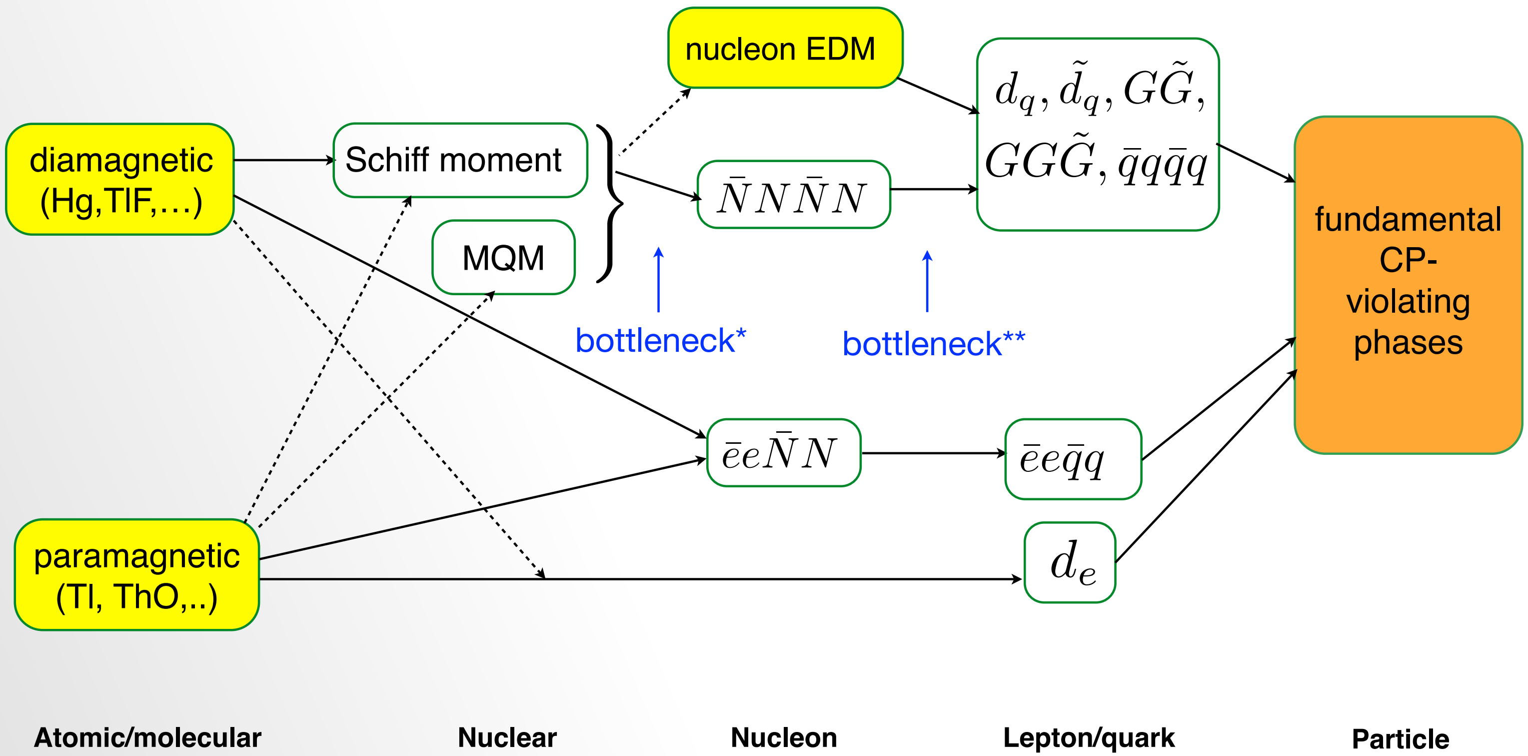
Leading mechanisms



Leading mechanisms



Leading mechanisms

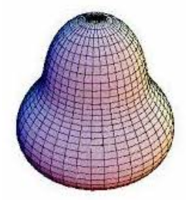


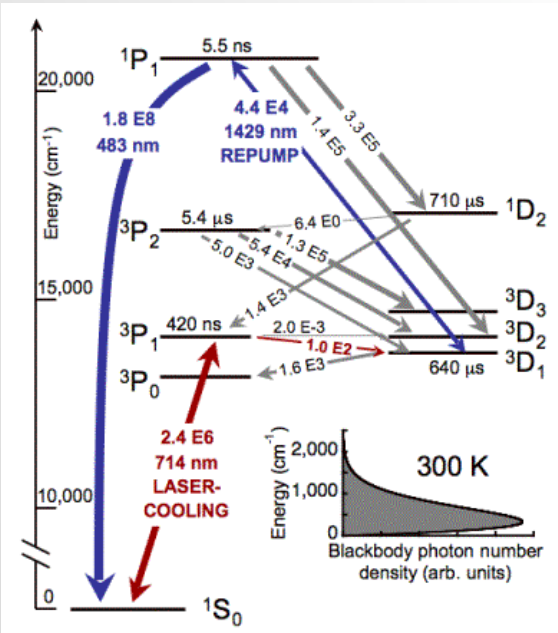
* uncertainties up to 500%   ** uncertainties ~100%

Enhancement mechanisms

P,T-violating effects are *tiny*. It's important to consider systems where effects are enhanced

- Nuclear mechanism — octuple deformed nuclei, e.g., radium, radon

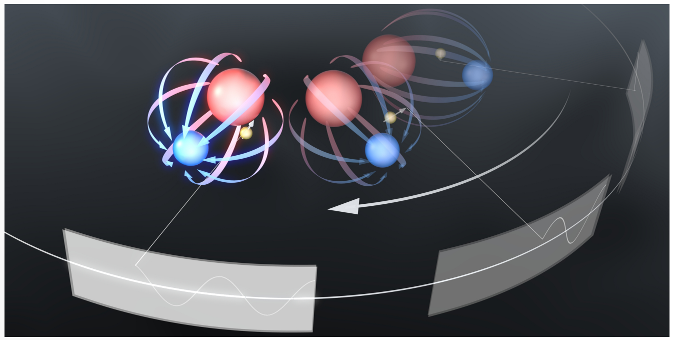




Argonne National Lab

- Electronic mechanism — close atomic levels of opposite parity, e.g., rare earth atoms, metastable state of radium,…

- Molecules — huge intramolecular electric field



Cornell group

- Other — solids, oscillating electric field, …

Nuclear Schiff moment

Previous form for electrostatic potential of nuclear Schiff moment, valid only for non-relativistic electrons:

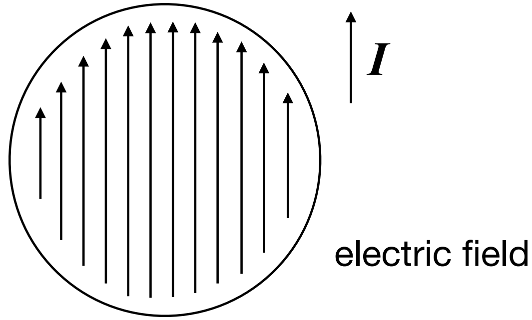
$$H_{P,T} = -e\varphi = -4\pi e\mathbf{S}\cdot\nabla\delta(\mathbf{R})$$

$$\langle s| - e\varphi|p\rangle = 4\pi e\mathbf{S}\cdot(\nabla\psi_s^\dagger\psi_p)_{R=0} = \text{constant}$$

Though electrons near the nucleus are relativistic! Introduced finite nuclear size form:

$$\varphi = -\frac{3\mathbf{S}\cdot\mathbf{R}}{B}\rho(R)$$

$$B = \int \rho(R)R^4 dR \approx R_N^5/5$$



Flambaum, Ginges (2002)

Induced atomic EDMs

Atomic calculations for Xe, Hg, Rn, Ra

$$d_{\rm atom} = 2\sum_M \frac{\langle N|H_{P,T}|M\rangle\langle M|D_z|N\rangle}{E_N - E_M}$$

Use V^N approximation (TDHF) and V^{N-2} approximation (CI+MBPT).

	$d_{\rm atom}\,[10^{-17}\,S/(e\,{\rm fm}^3)\,e\,{\rm cm}]$			Polarizability α (a.u.)		
	HF	TDHF	CI+MBPT	TDHF	CI+MBPT	Expt.
^{129}Xe	0.289	0.378		26.97		27.34
^{223}Rn	2.47	3.33		35.00		
^{199}Hg	-1.19	-2.97	-2.70	44.92	32.99	33.75
^{225}Ra	-1.85	-8.23	-8.70	297.0	229.9	

Calculations accurate to 20%

Dzuba, Flambaum, Ginges, Kozlov (2002)

Best limits and recent measurements

	$\lvert d_{atom} \rvert$, 95% c.l.	Constraints, 95% c.l.	Group
Paramagnetic			
^{205}Tl	1.1×10^{-24} *e* cm	$\lvert d_e \rvert < 1.9 \times 10^{-27}$ *e* cm	Berkeley, 2002
ThO		$\lvert d_e \rvert < 1.2 \times 10^{-29}$ *e* cm	ACME, 2018
HfF^+		$\lvert d_e \rvert < 16 \times 10^{-29}$ *e* cm	JILA, 2017
Diamagnetic			
^{199}Hg	7.4×10^{-30} *e* cm	$\lvert d_n \rvert < 1.6 \times 10^{-26}$ *e* cm	Seattle, 2016
		$\lvert \theta_{QCD} \rvert < 1.5 \times 10^{-10}$	
^{225}Ra	1.4×10^{-23} *e* cm		Argonne, 2015
^{129}Xe	1.5×10^{-27} *e* cm		Juelich, 2019
^{129}Xe	4.8×10^{-27} *e* cm		HeXeEDM, 2019
n		$\lvert d_n \rvert < 3.6 \times 10^{-26}$ *e* cm	Grenoble, 2015

Other ongoing experiments

Paramagnetic: YbF (Imperial), ThF (JILA), Cs (Penn State), Fr (Tokyo), BaF (Groningen)

Diamagnetic: ^{223}Rn (TRIUMF), ^{129}Xe (Tokyo), TlF (CeNTREX)

Summary

Lecture 2. Time-reversal violating electric dipole moments

- Atomic EDMs, enhancement mechanisms

Next. Precision atomic theory

- Many-body methods, relativistic Hartree-Fock, QED in many-electron atoms