

The search for electric dipole moments: an overview

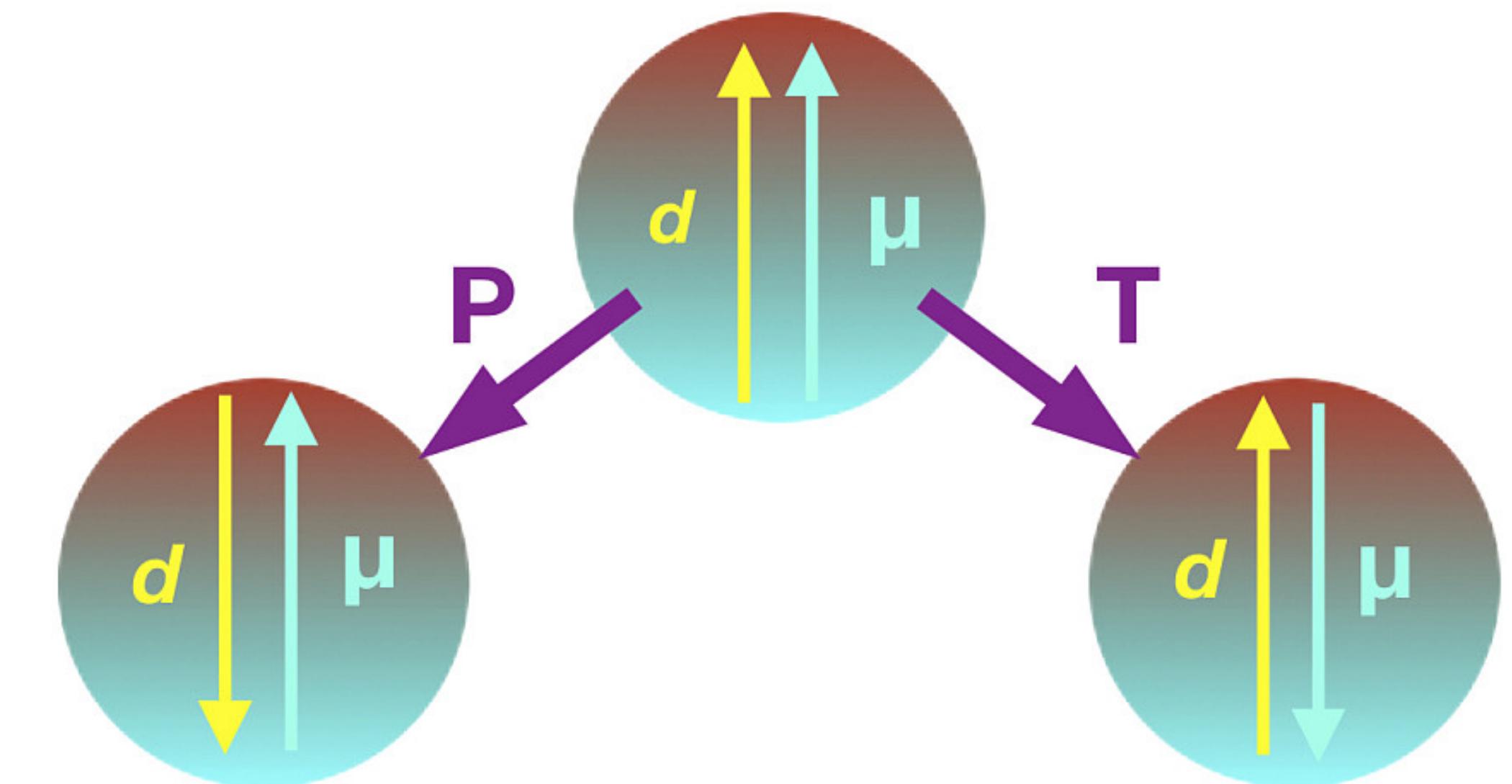
Jacinda Ginges



THE UNIVERSITY
OF QUEENSLAND
AUSTRALIA



Australian Government
Australian Research Council



Motivation

- Search for beyond Standard Model physics
- Probe mass scales far beyond direct collider experiments
- Shed light on origin of matter-antimatter asymmetry of Universe



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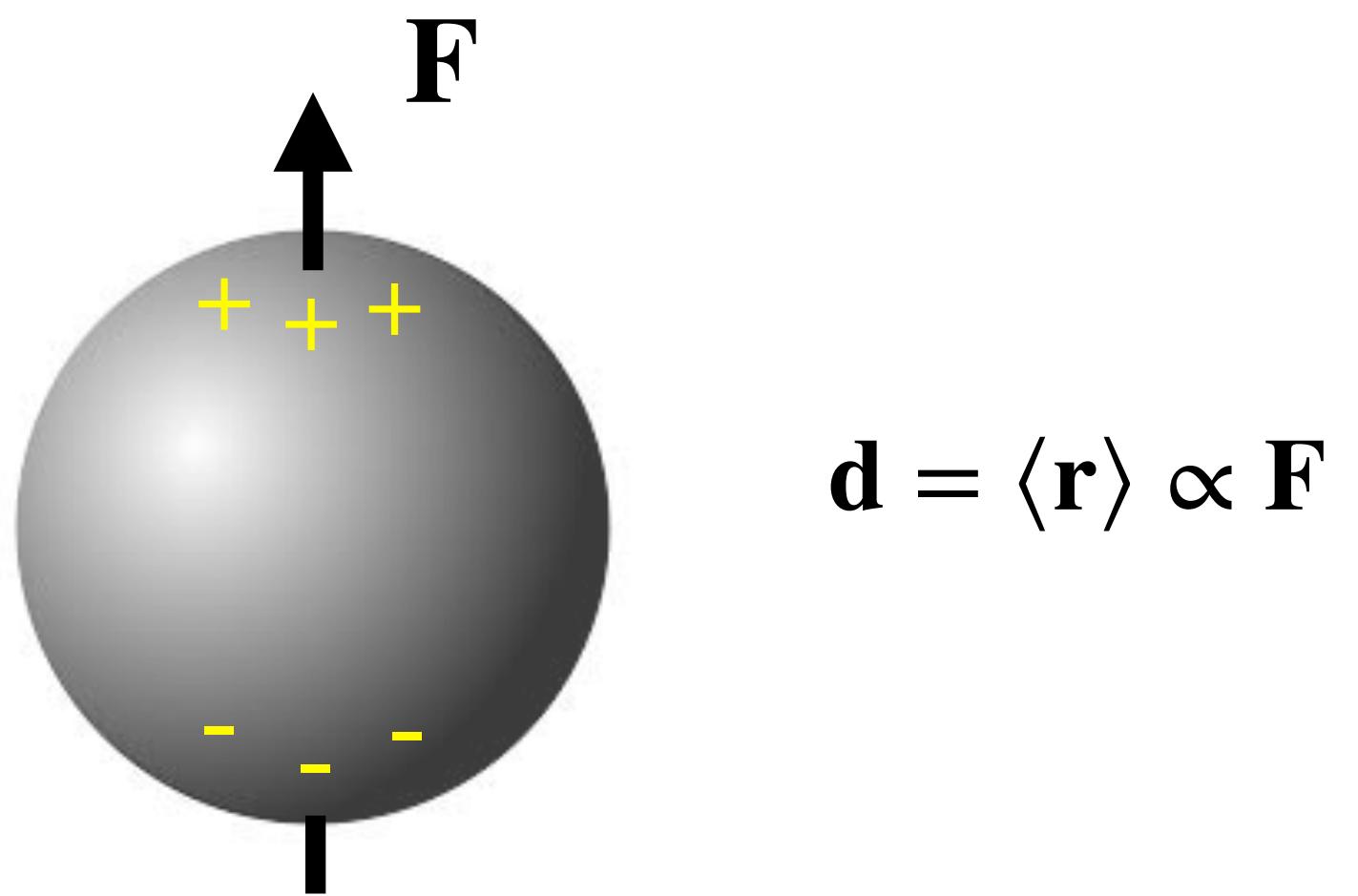
Overview

- What is an electric dipole moment?
- Scale of experimental precision and energy reach
- Schiff screening and CP-violating mechanisms
- Best limits and upcoming experiments

What is meant by electric dipole moment (EDM)?

Intrinsic EDM of quantum system (elementary particle, neutron, atom,...)
violates parity P and time-reversal T

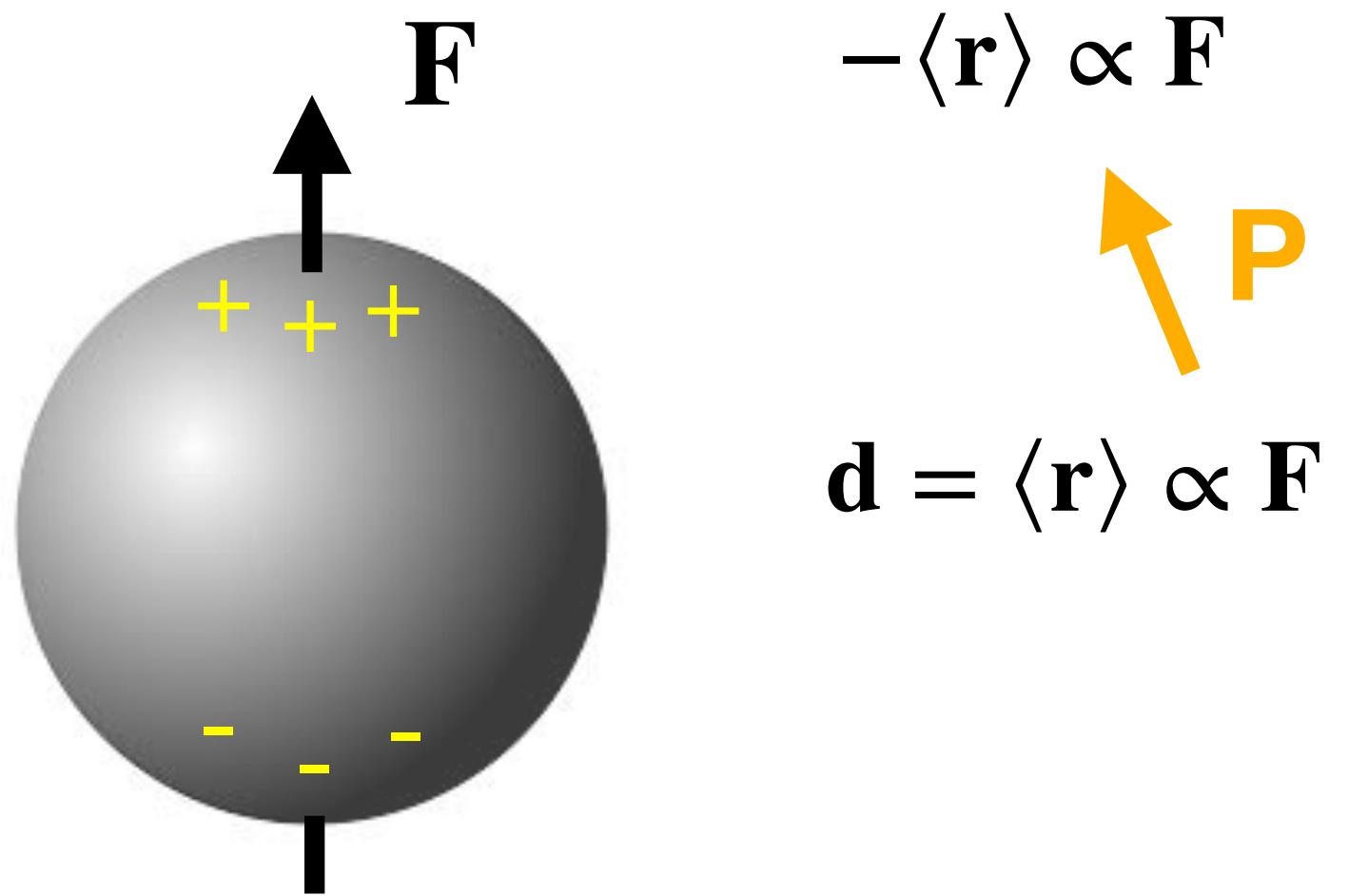
- Directed along angular momentum of system \mathbf{F}
- Probed through interaction with electric field \mathbf{E} , $h_d = - \mathbf{d} \cdot \mathbf{E}$
- T-violation \equiv CP-violation (CPT theorem)



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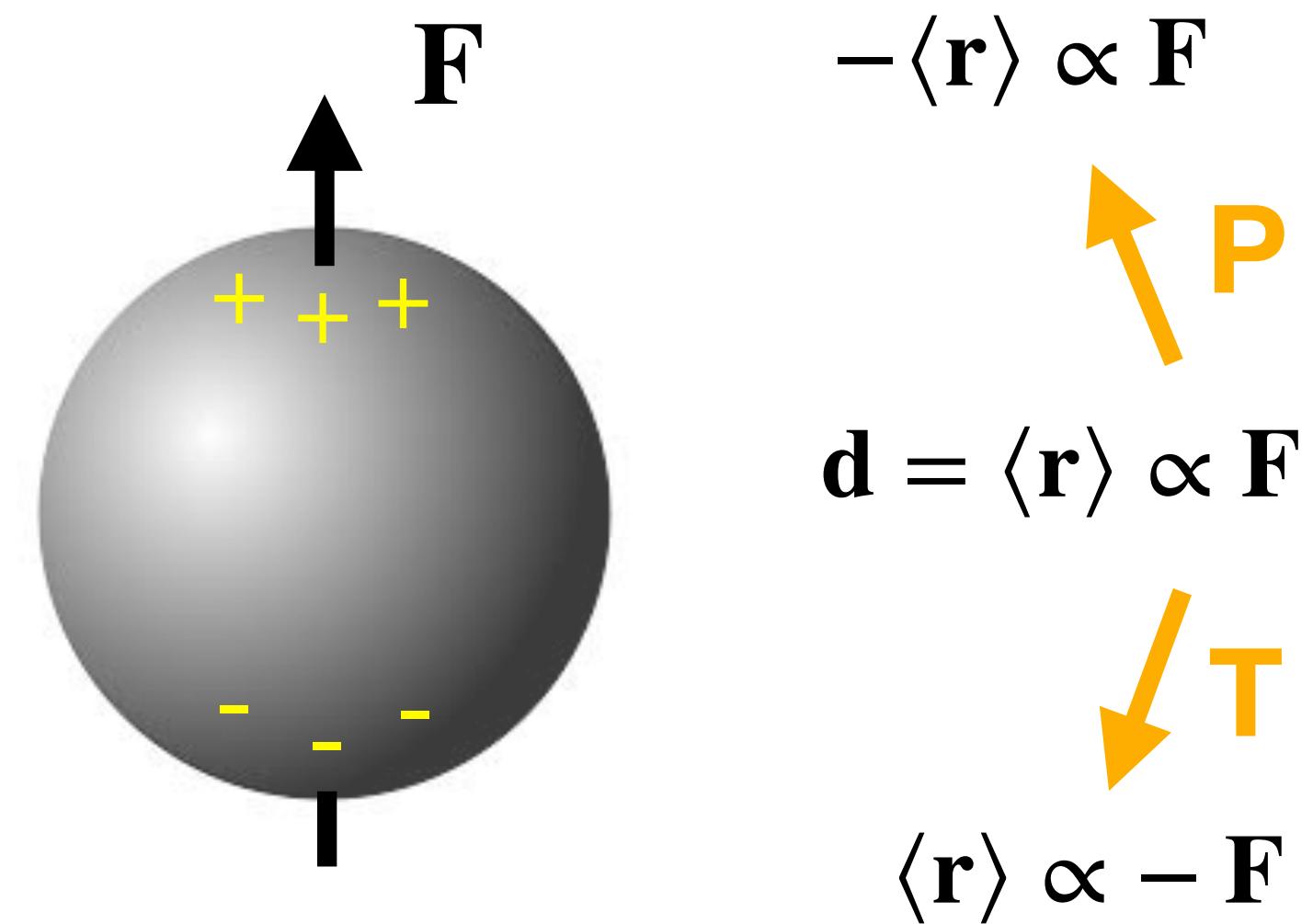
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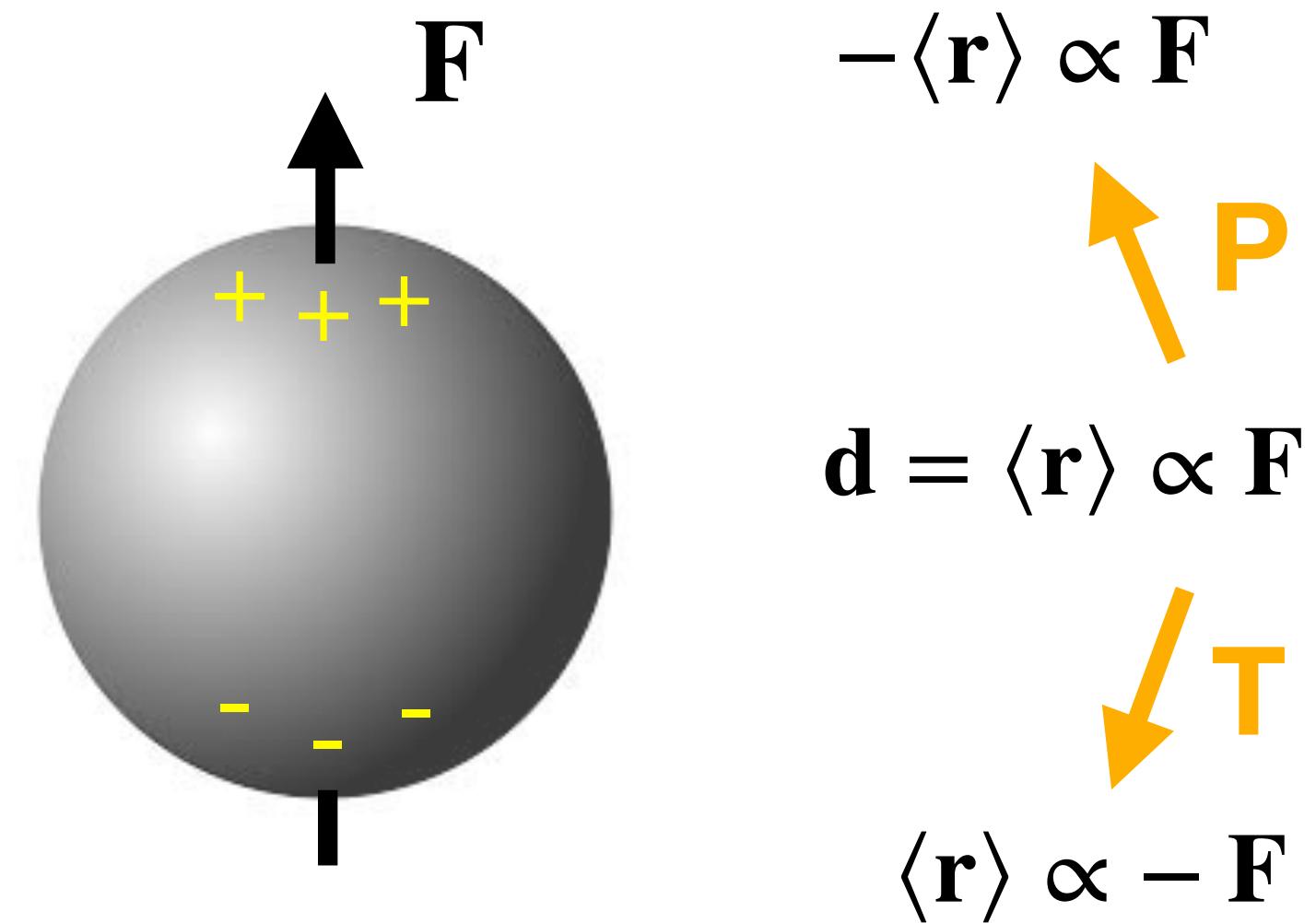
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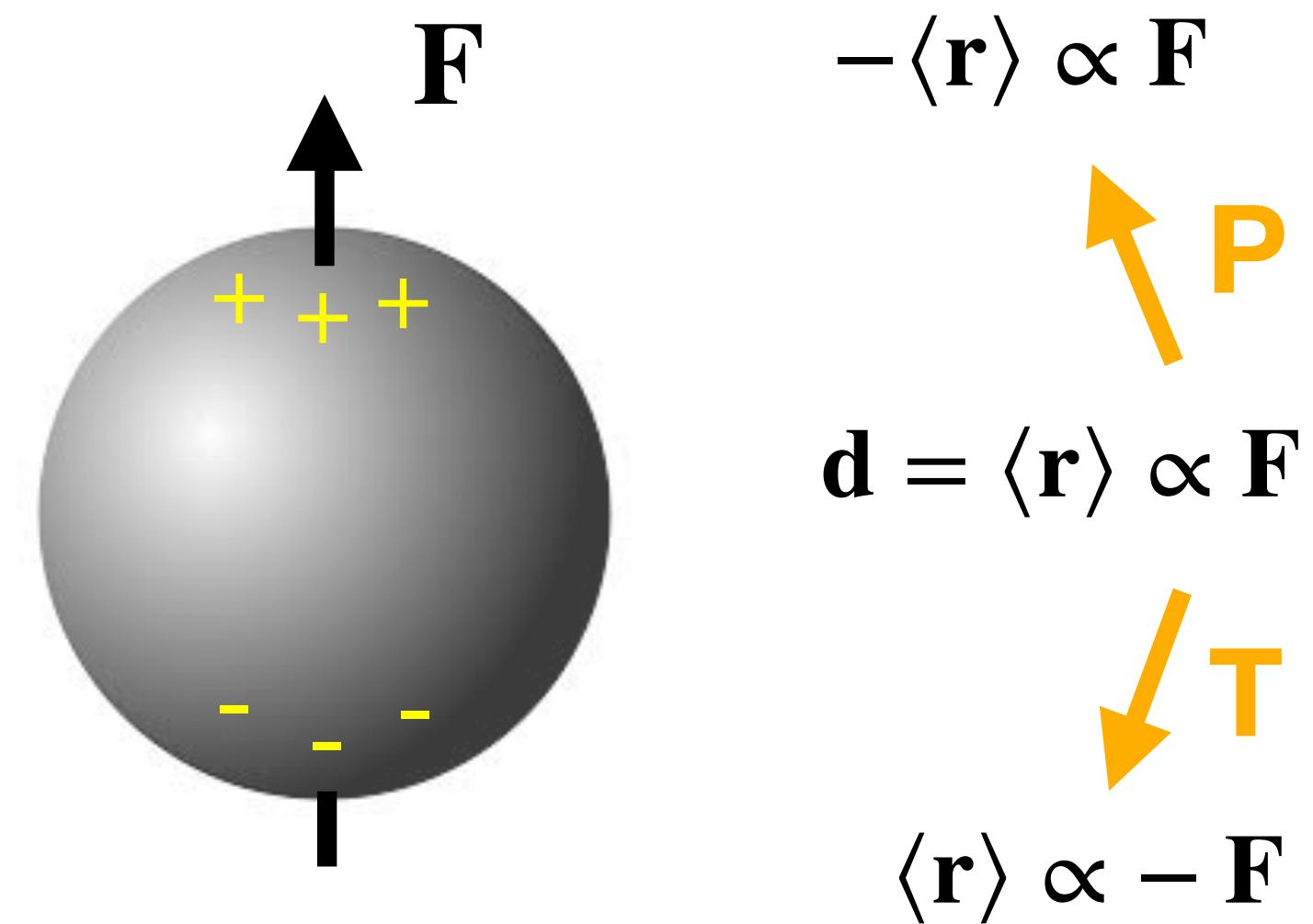
Standard Model CP-violation

- single phase in quark-mixing matrix, $\delta \sim 1$
- theta term in strong interaction, $-\bar{\theta}(g_s^2/16\pi^2)G^{\mu\nu}\tilde{G}_{\mu\nu}$, $\bar{\theta} \lesssim 10^{-10}$

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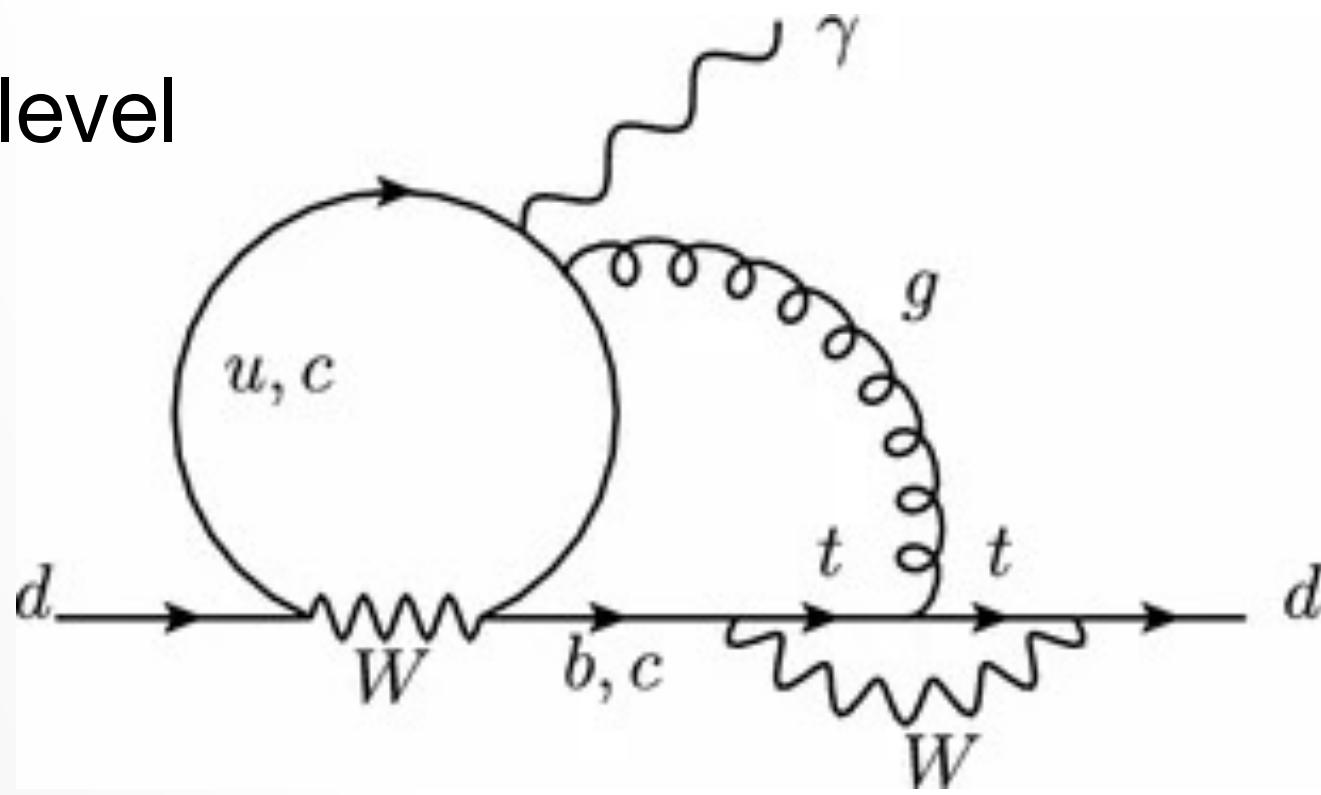
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strong CP problem, and proposal for axions

Suppression of EDMs in the Standard Model

Standard Model EDMs appear in *high-order loops*

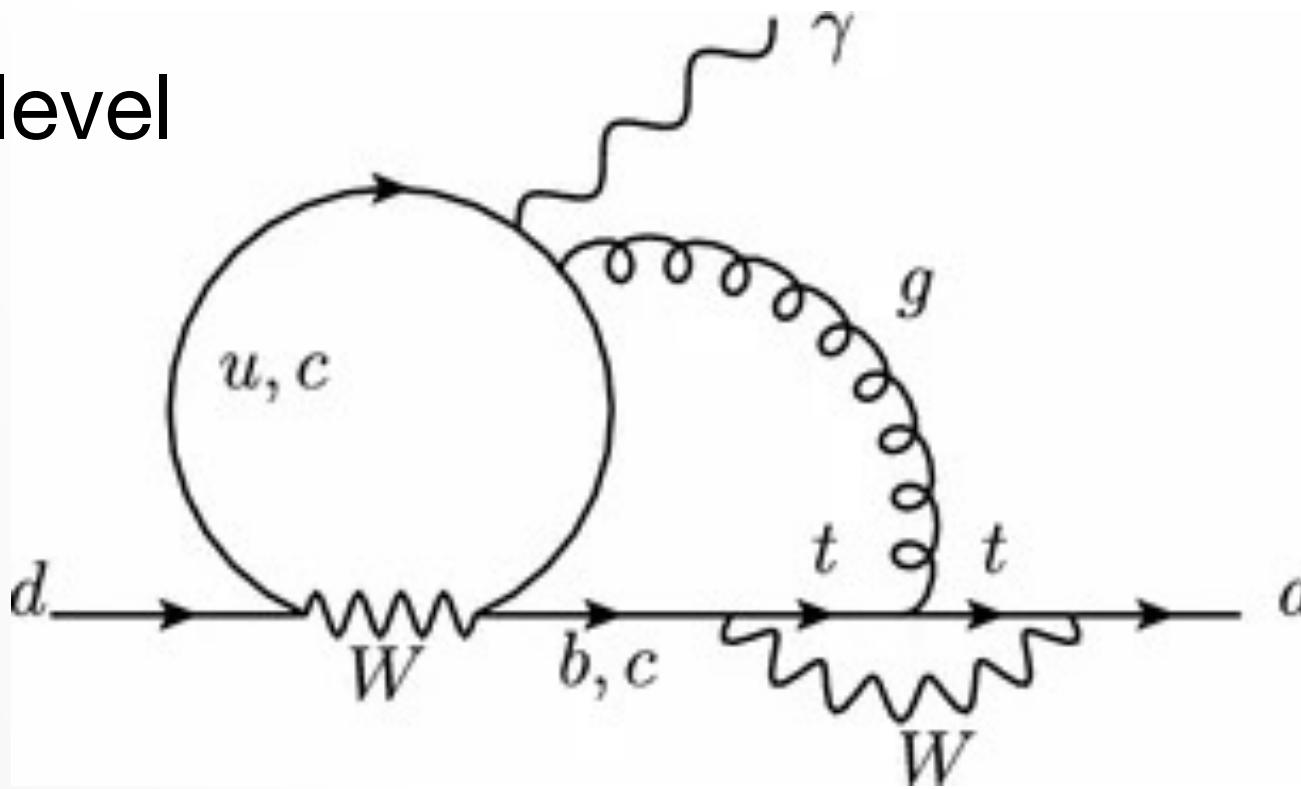
- Quark EDMs appear at 3-loop level



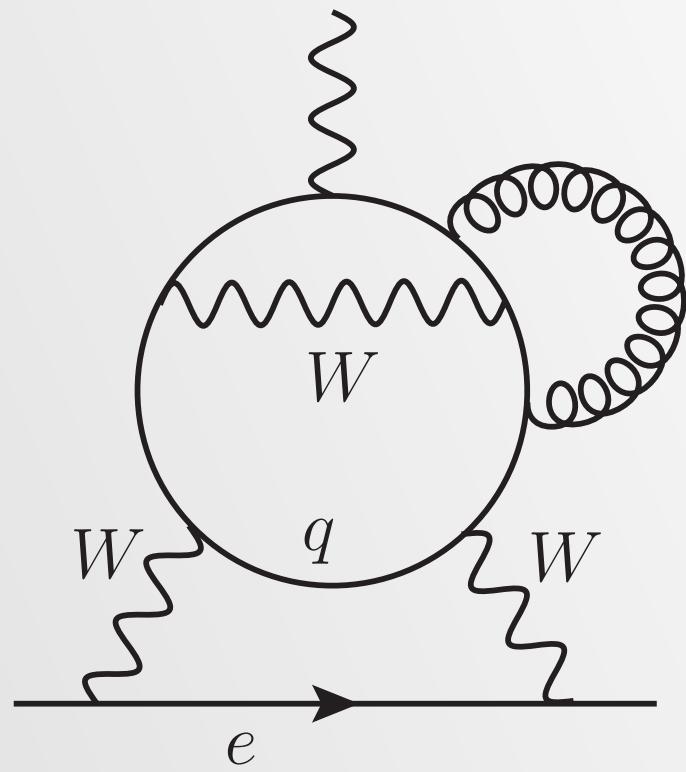
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- Electron EDM appears at 4-loop level

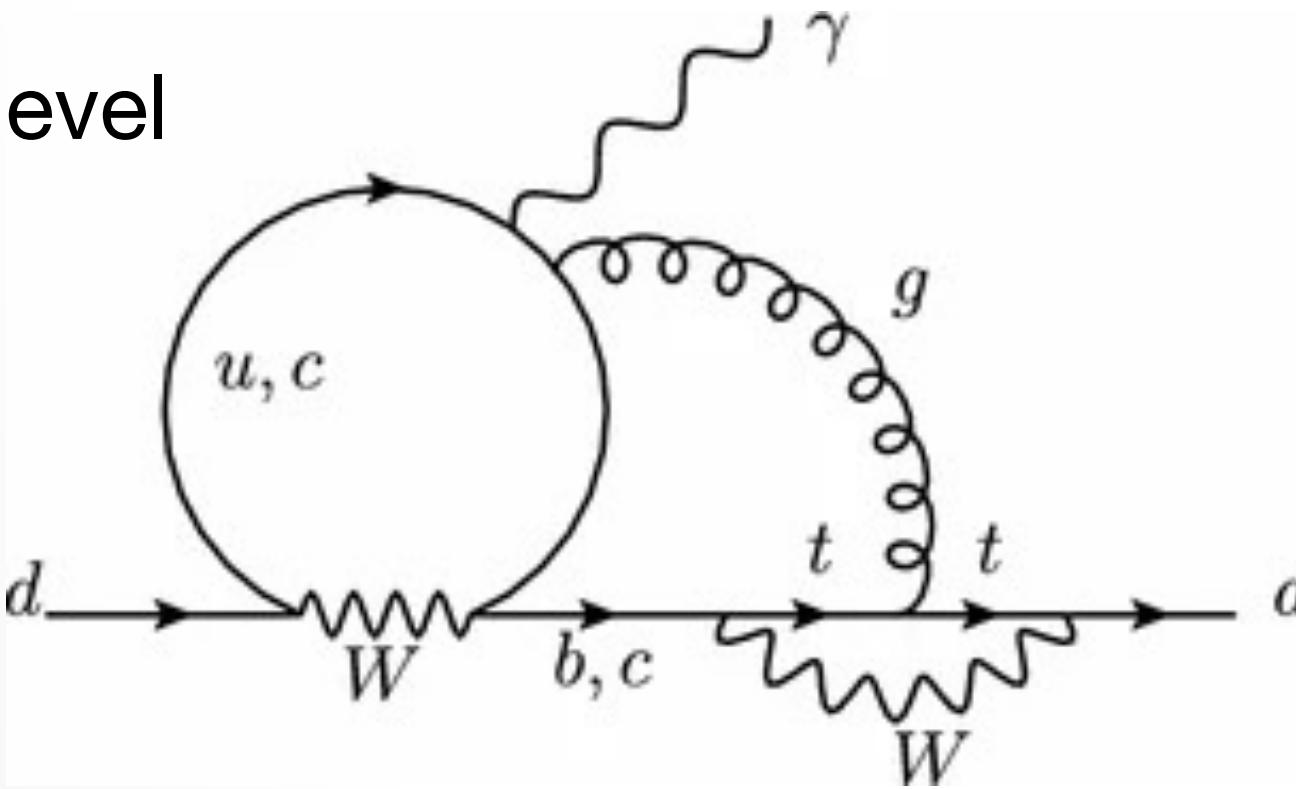


Czarnecki and Krause, PRL (1997); Yamanaka (2013);
Pospelov and Ritz, PRD (2014)

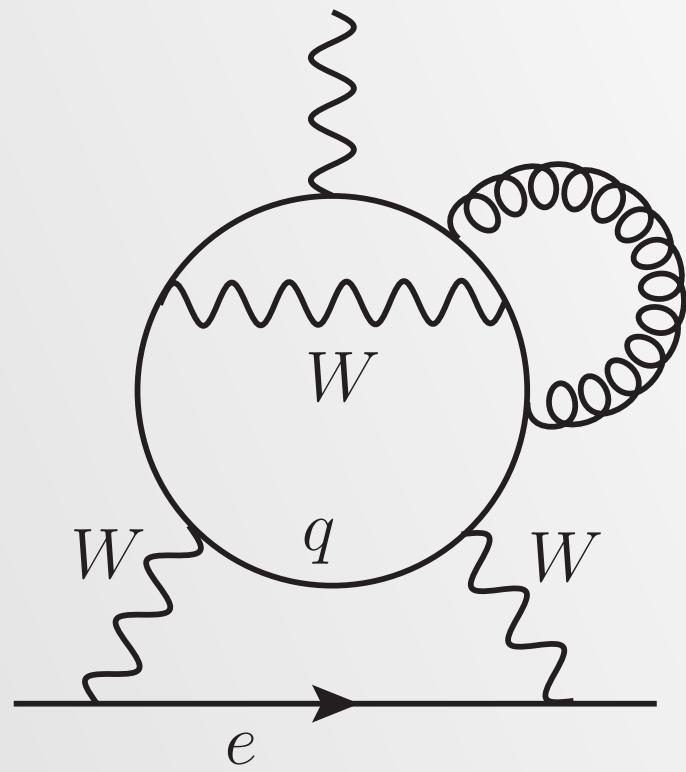
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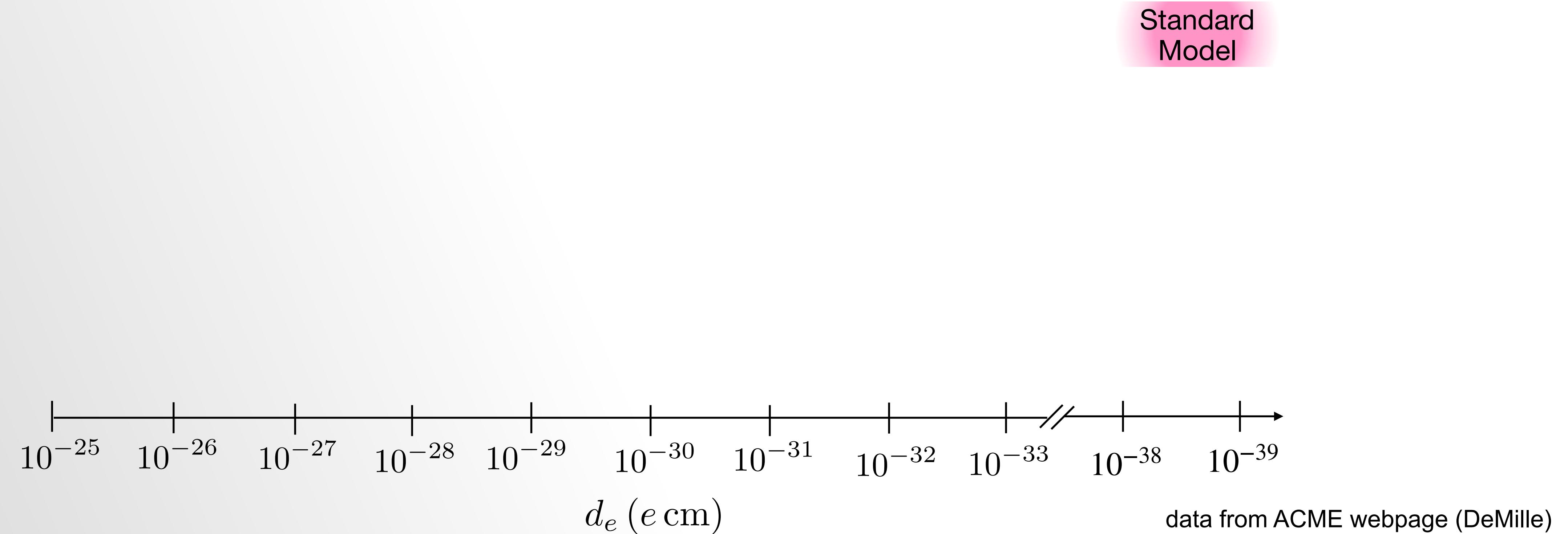
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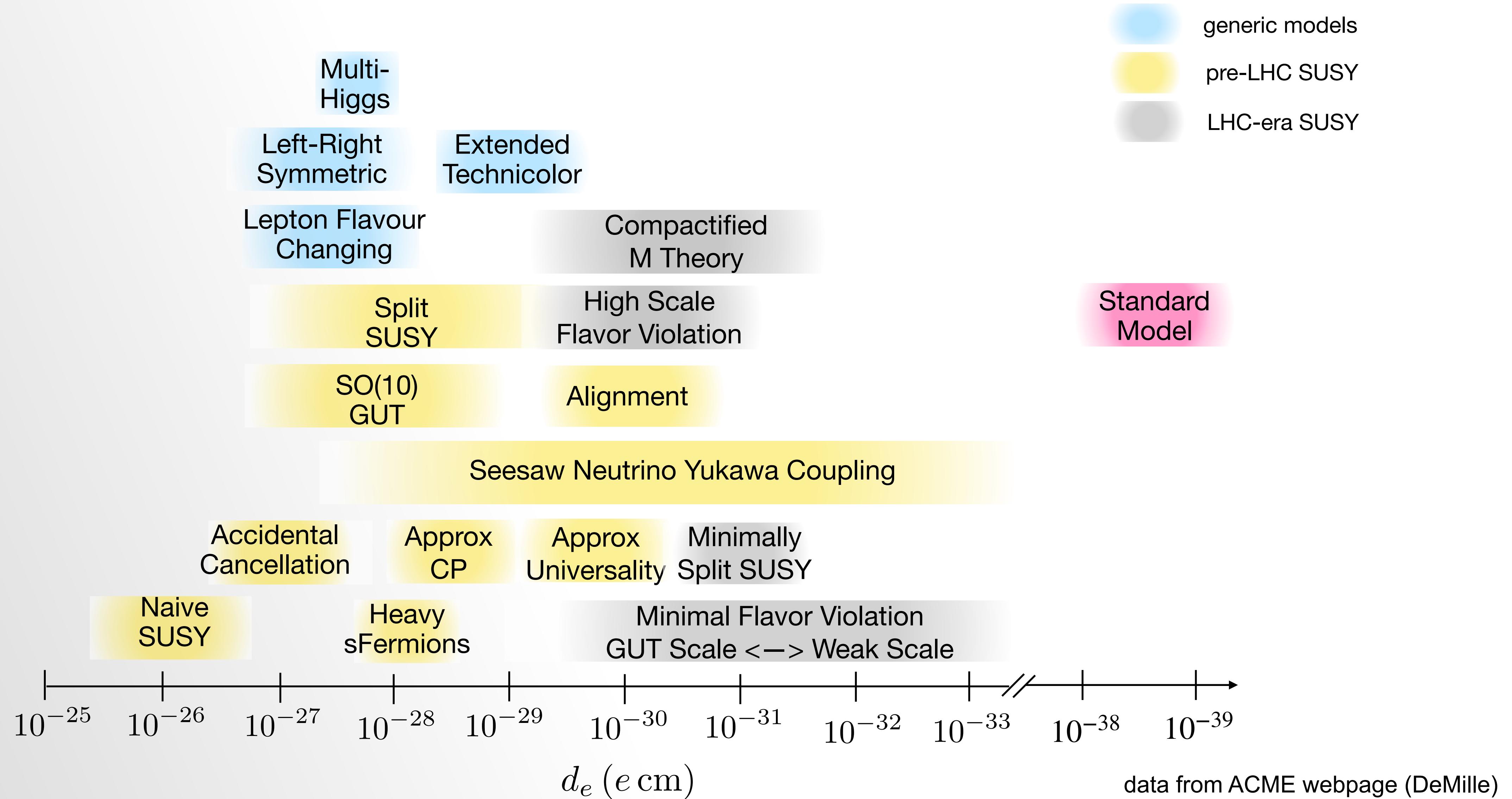
☞ Introduction of new CP-violating phases
induces EDMs *orders of magnitude larger*

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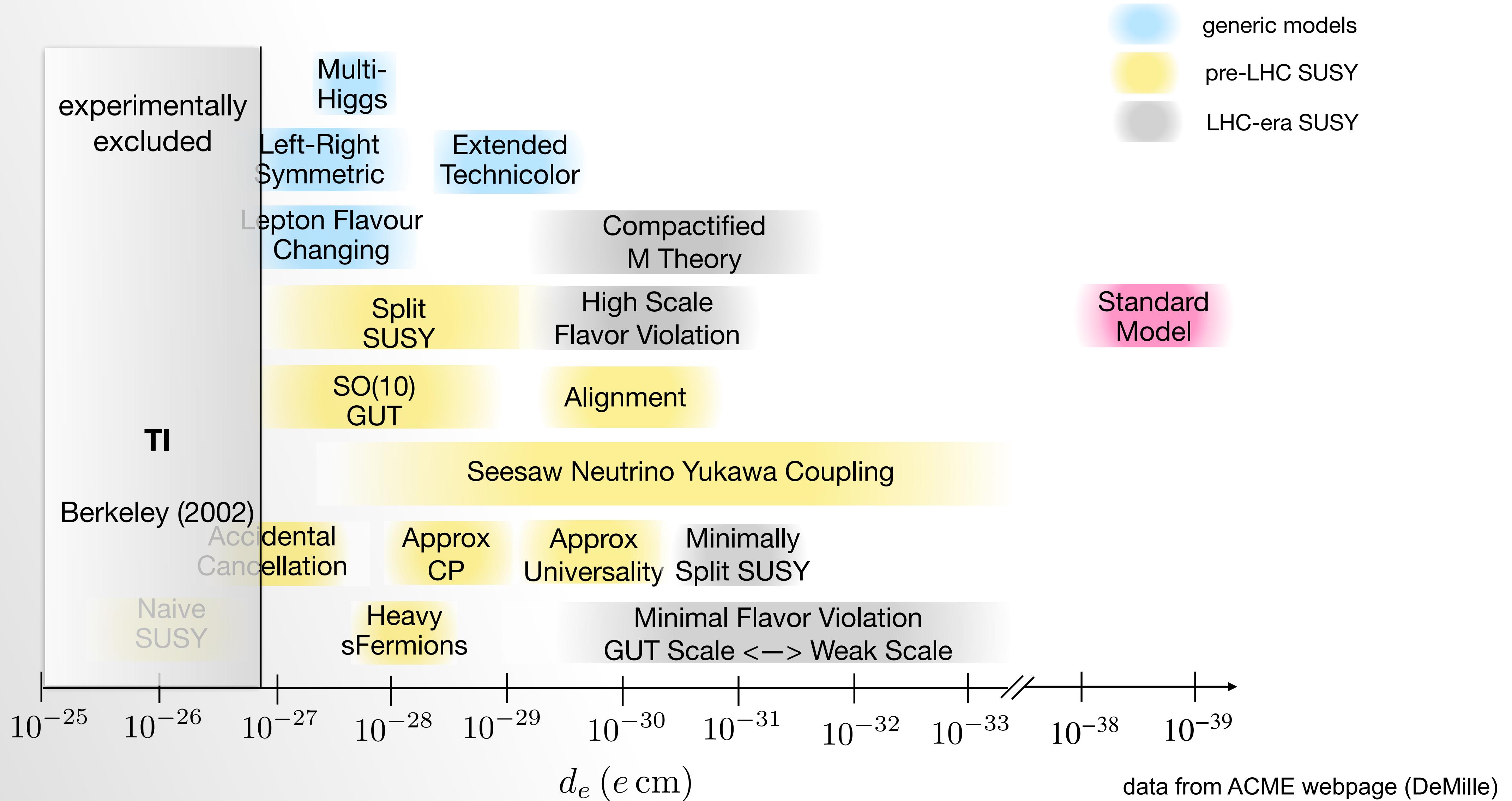
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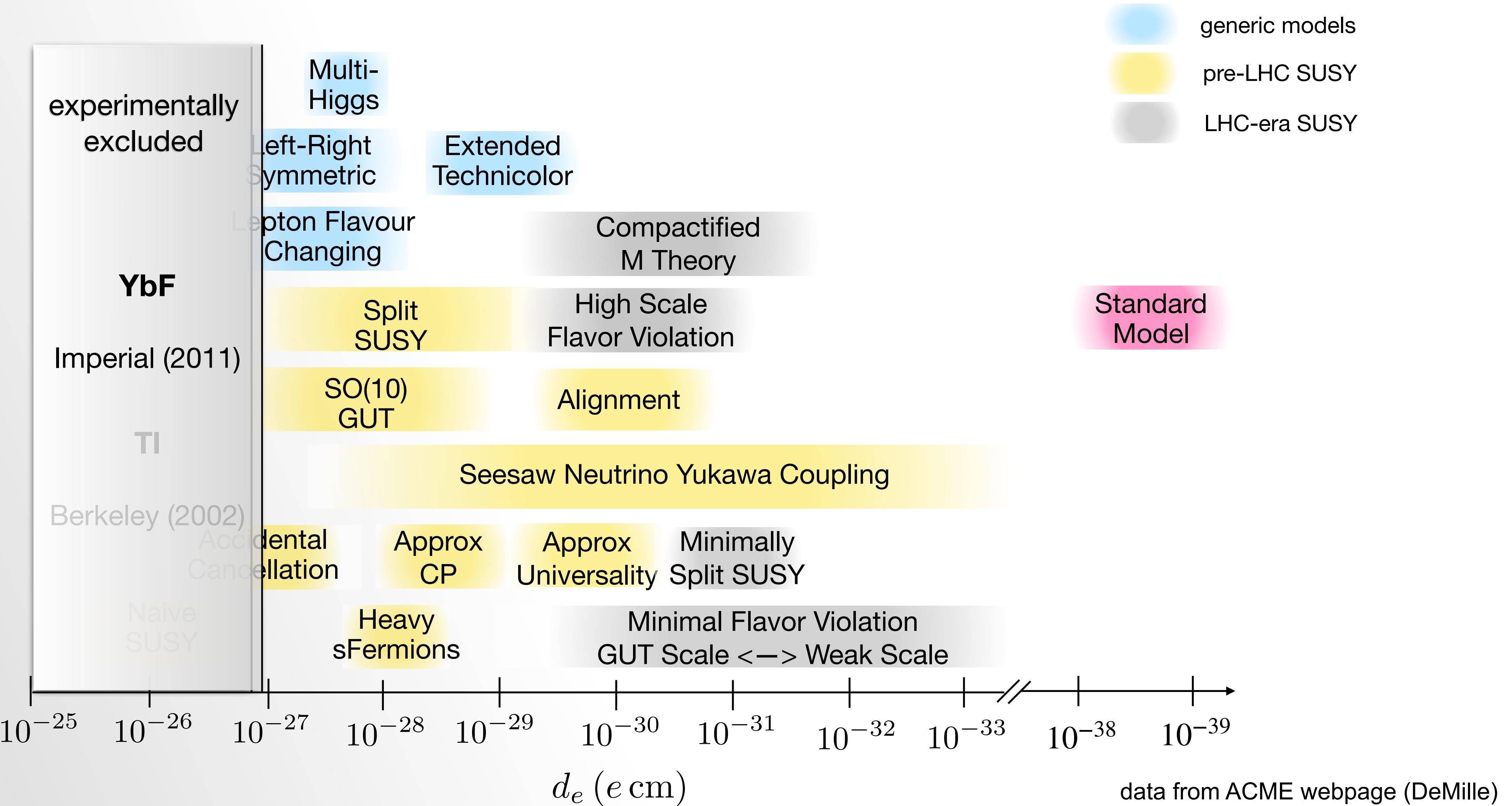
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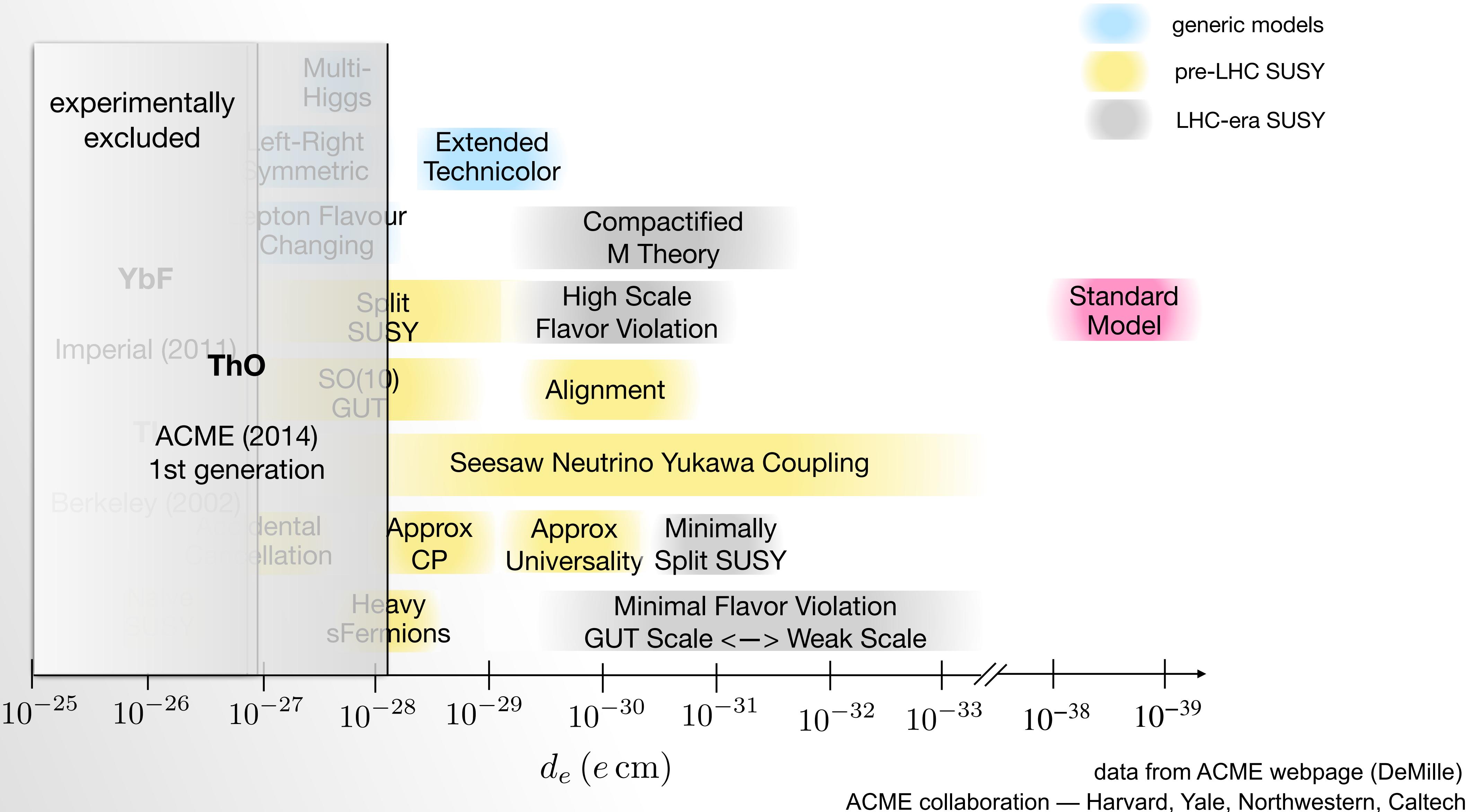
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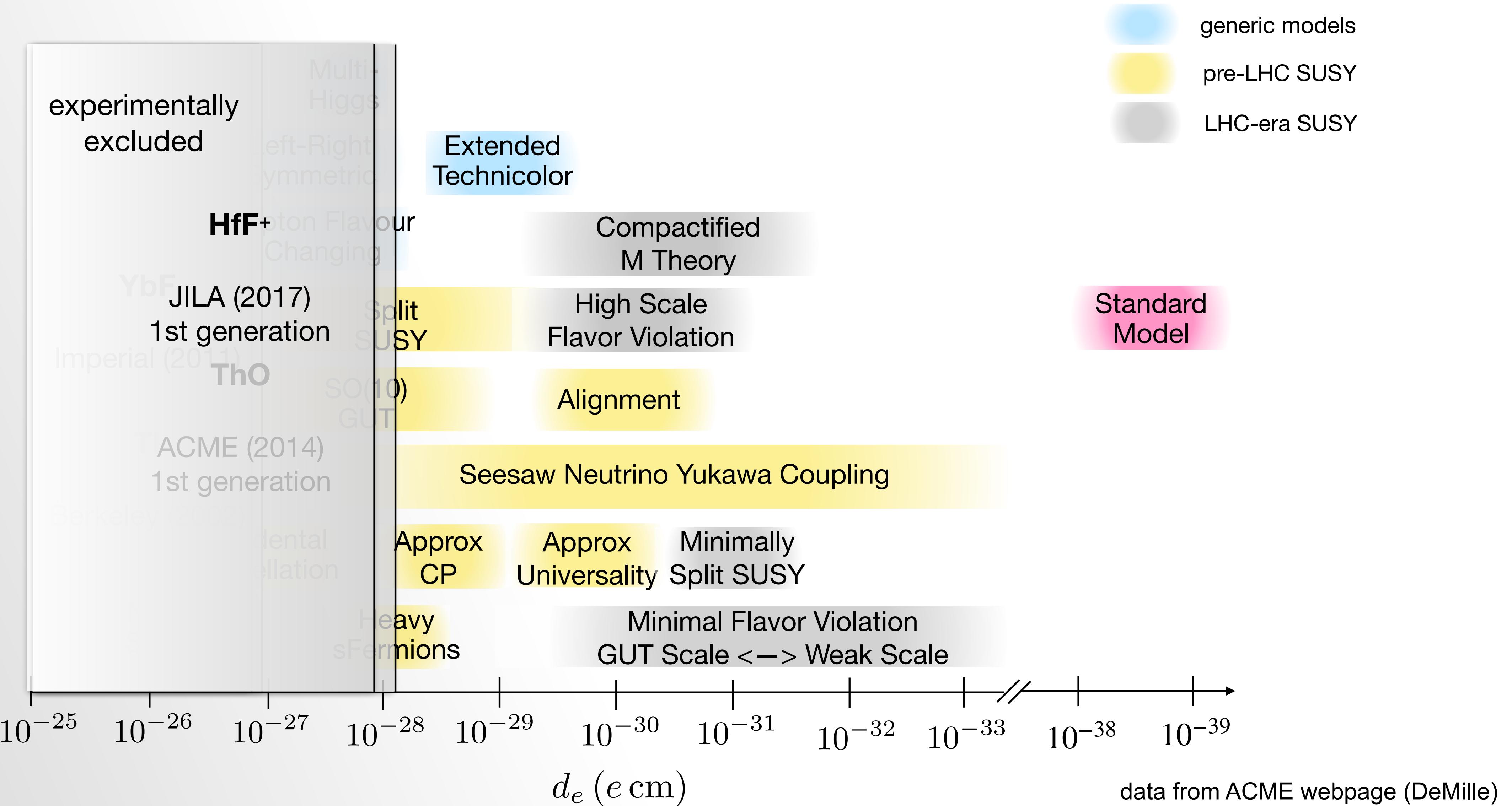
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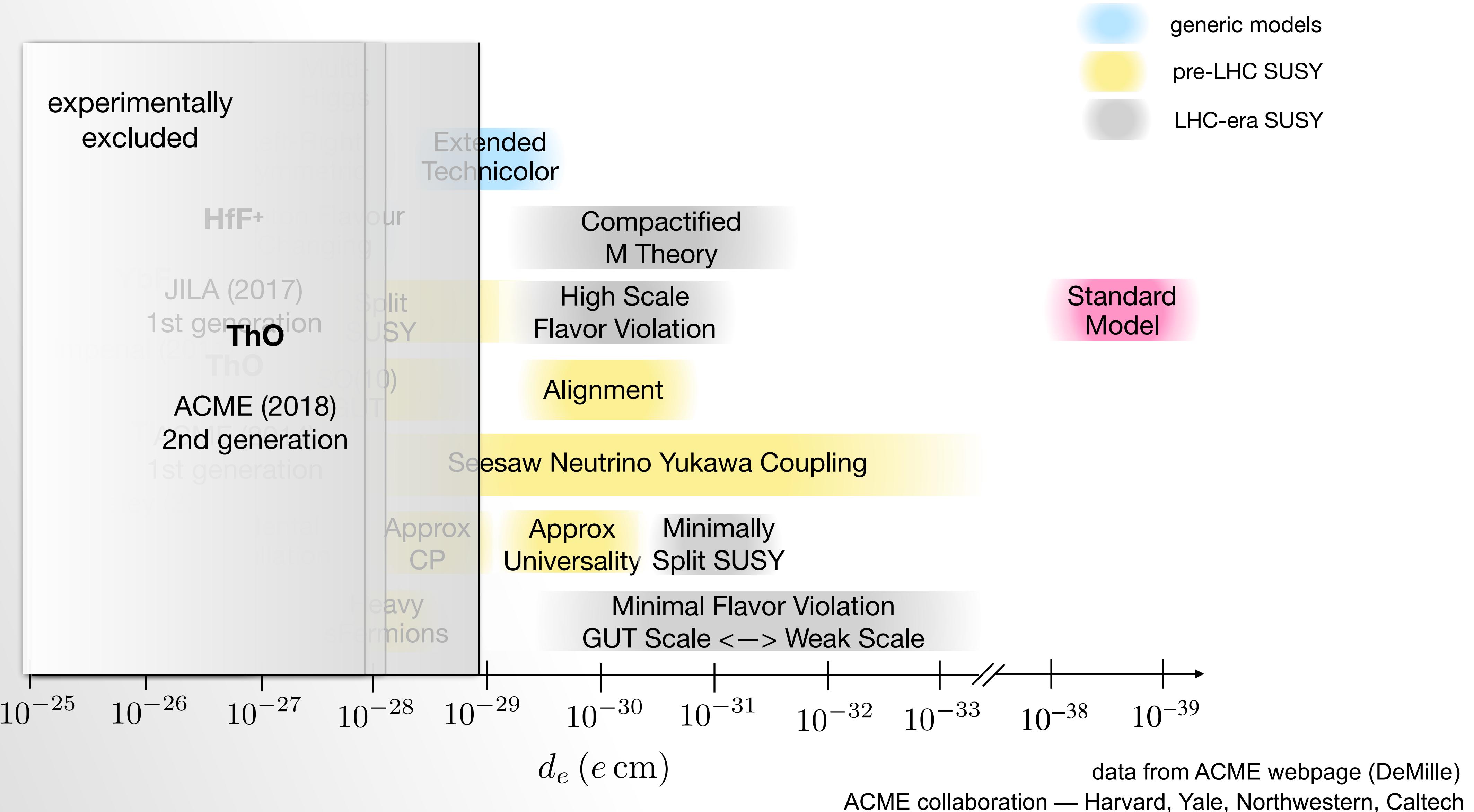
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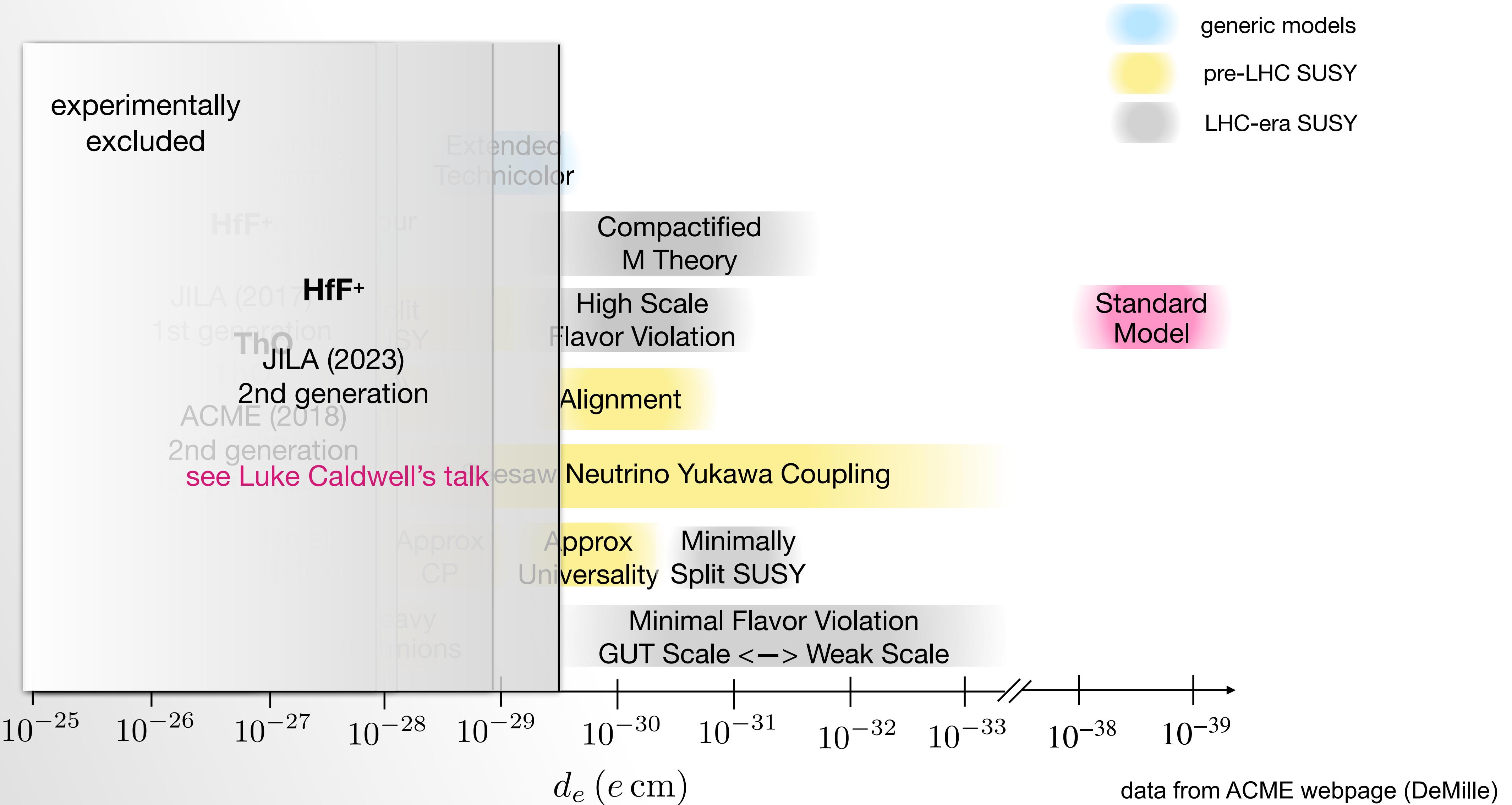
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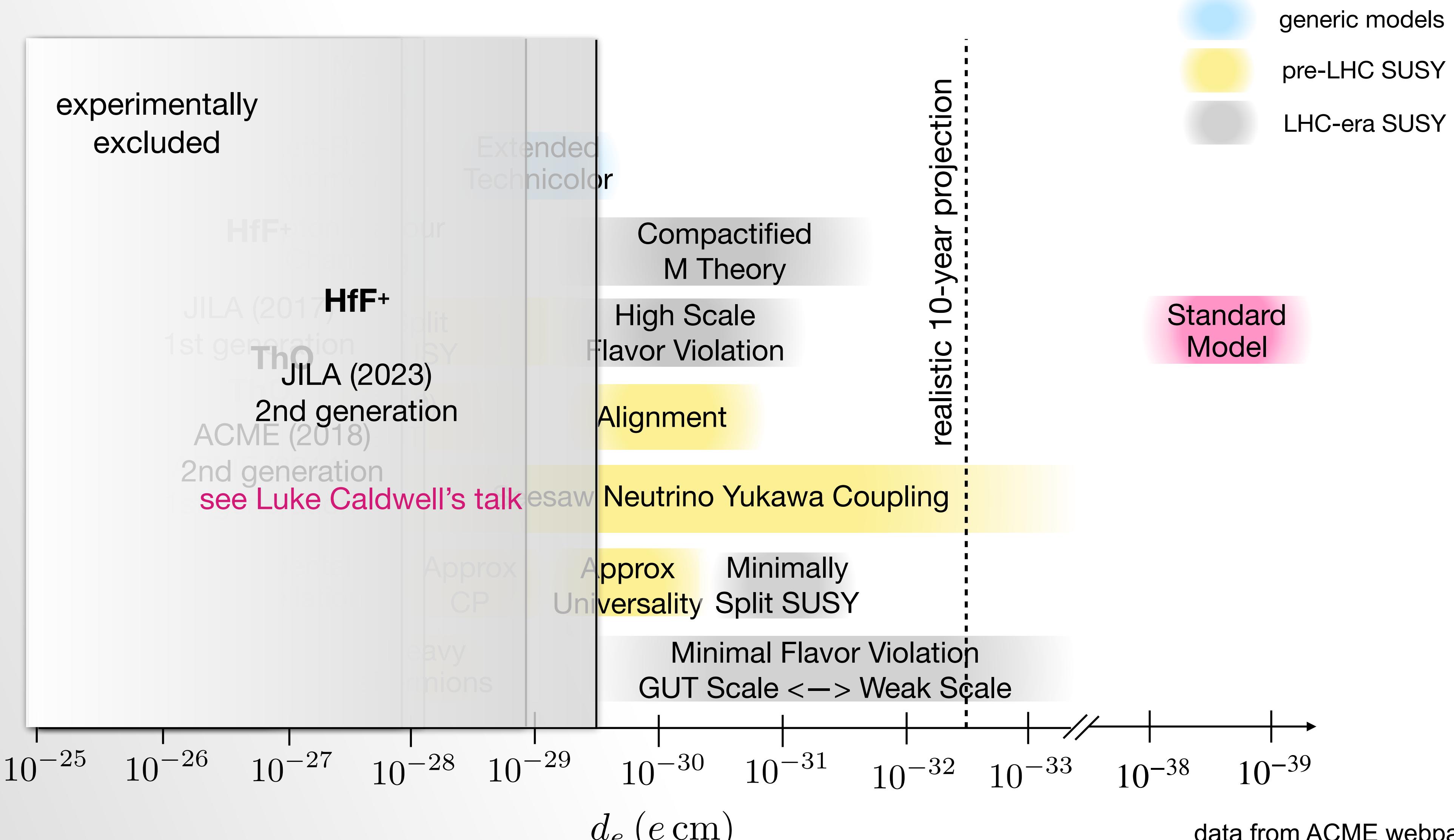
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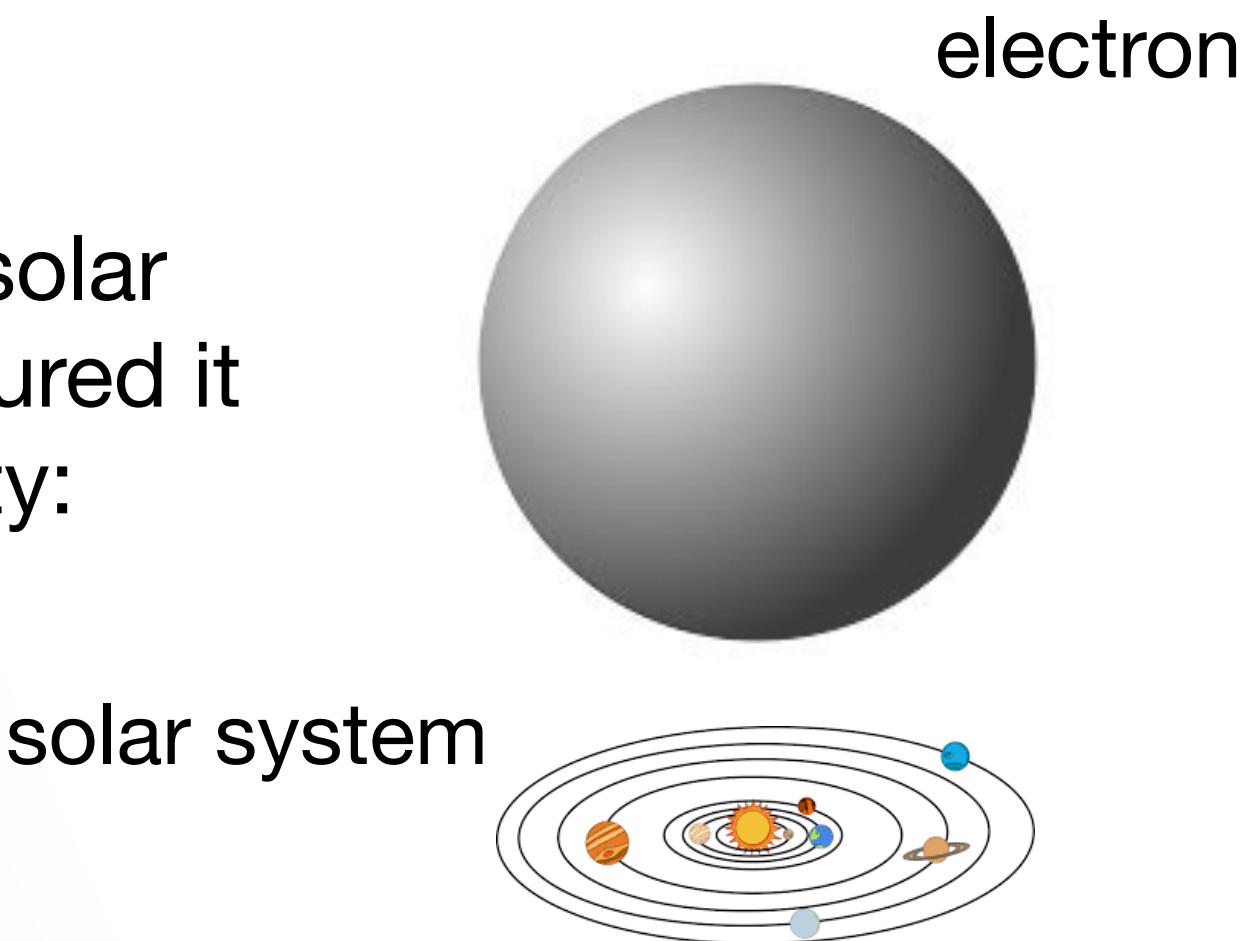
Predictions and bounds – electron EDM



data from ACME webpage (DeMille);
white paper on EDMs, arXiv:2203.08103

Scale of precision

Q. If the electron were the size of the solar system, EDM experiments have measured it to be perfectly “round” with uncertainty:

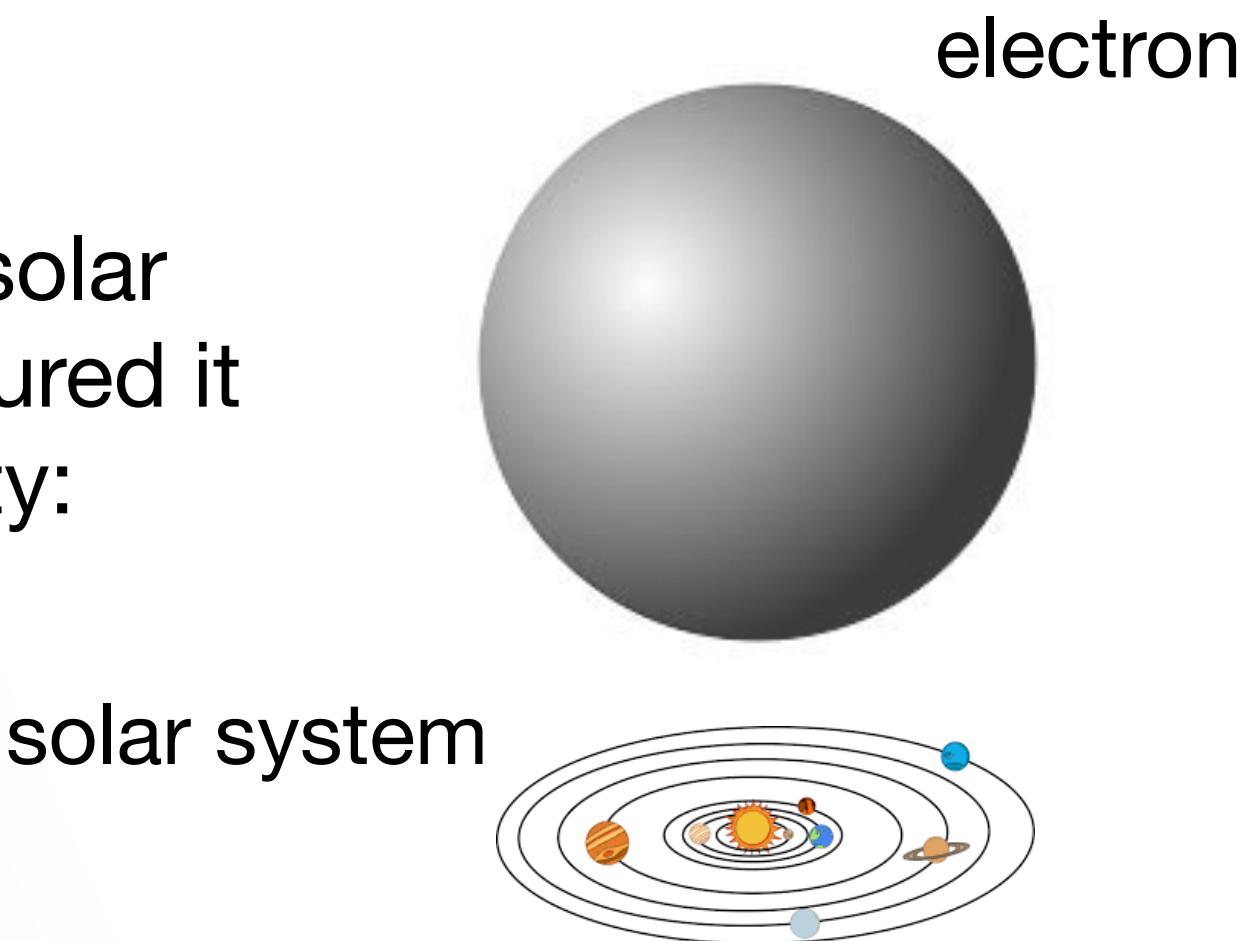


- A. The size of the sun.
- B. The size of Earth.
- C. The size of a football field.
- D. A fraction of the width of a human hair.

comparison from Ed Hinds, Imperial College

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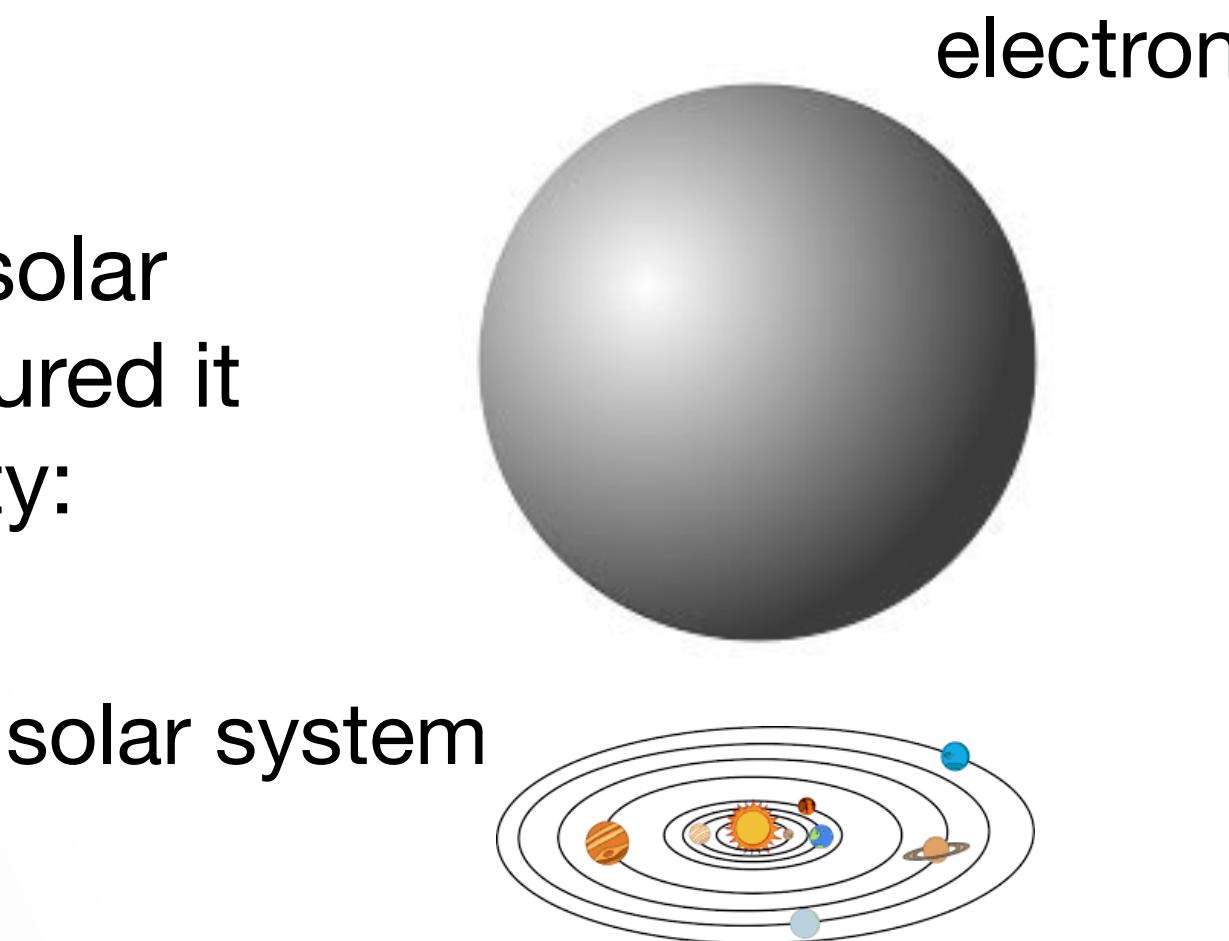


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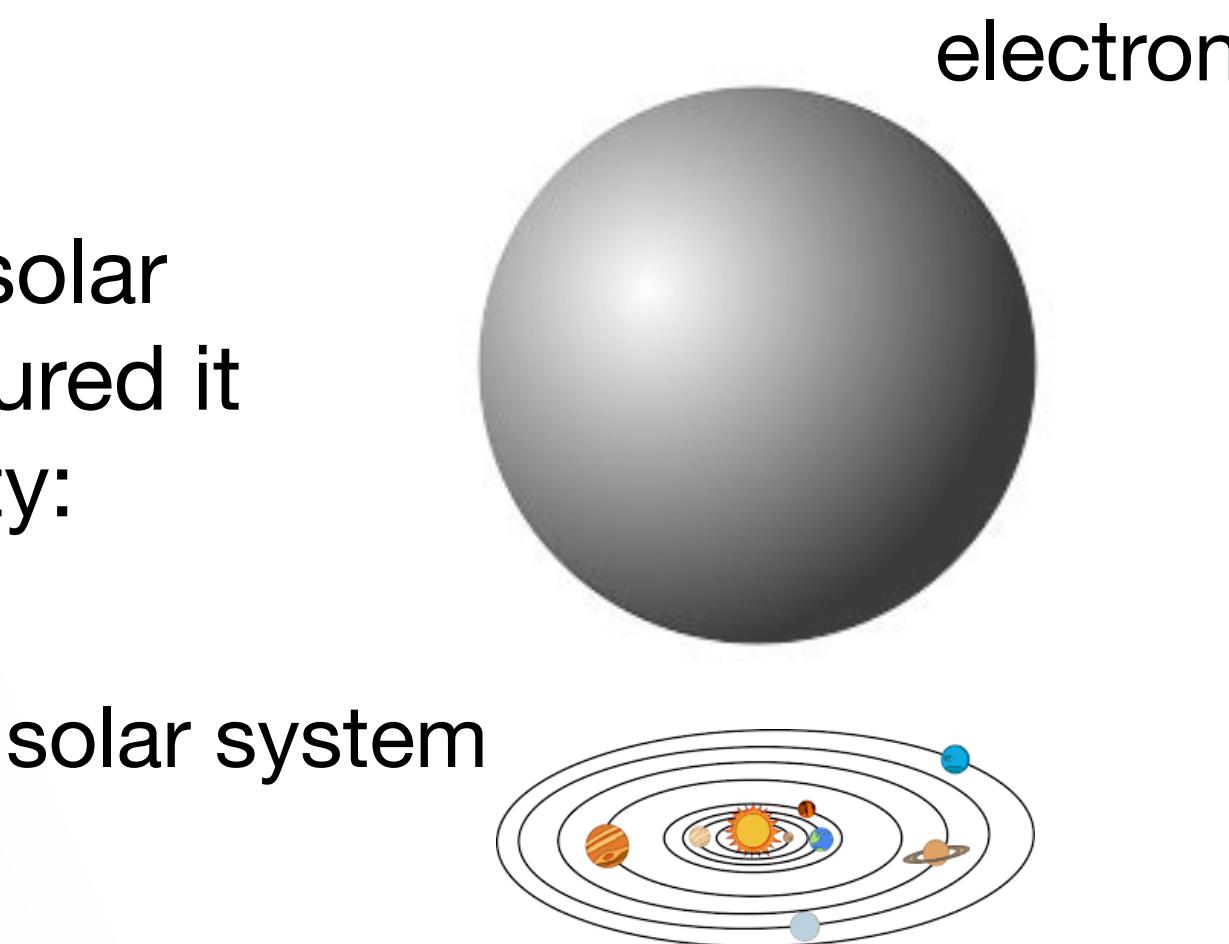
Energy reach

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

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

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- Current bounds from atomic and molecular experiments give

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

Safronova *et al.*, Rev. Mod. Phys. (2018);
Chupp, Ramsey-Musolf, PRC (2015)

Atomic EDMs

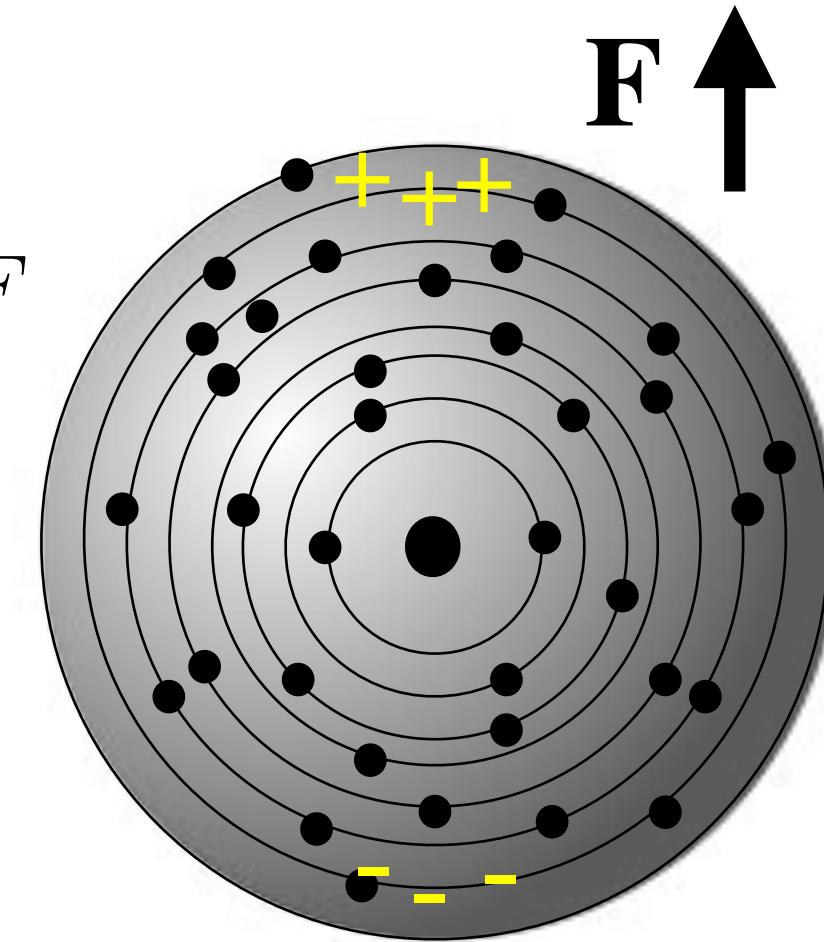
- P,T-violating interactions induce EDMs in atoms

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

- Effects increase with nuclear charge Z ,

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

- Molecules – projection of spin on internuclear axis



Sandars, Phys. Lett. (1965);
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Atomic EDMs

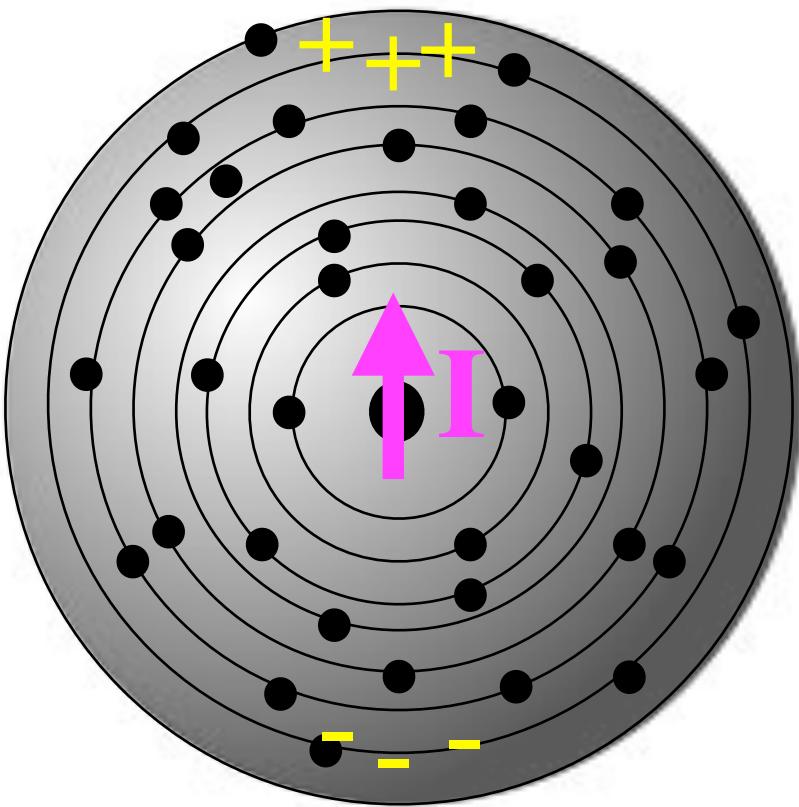
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Diamagnetic systems (closed electron shells):
hadronic and semi-leptonic mechanisms

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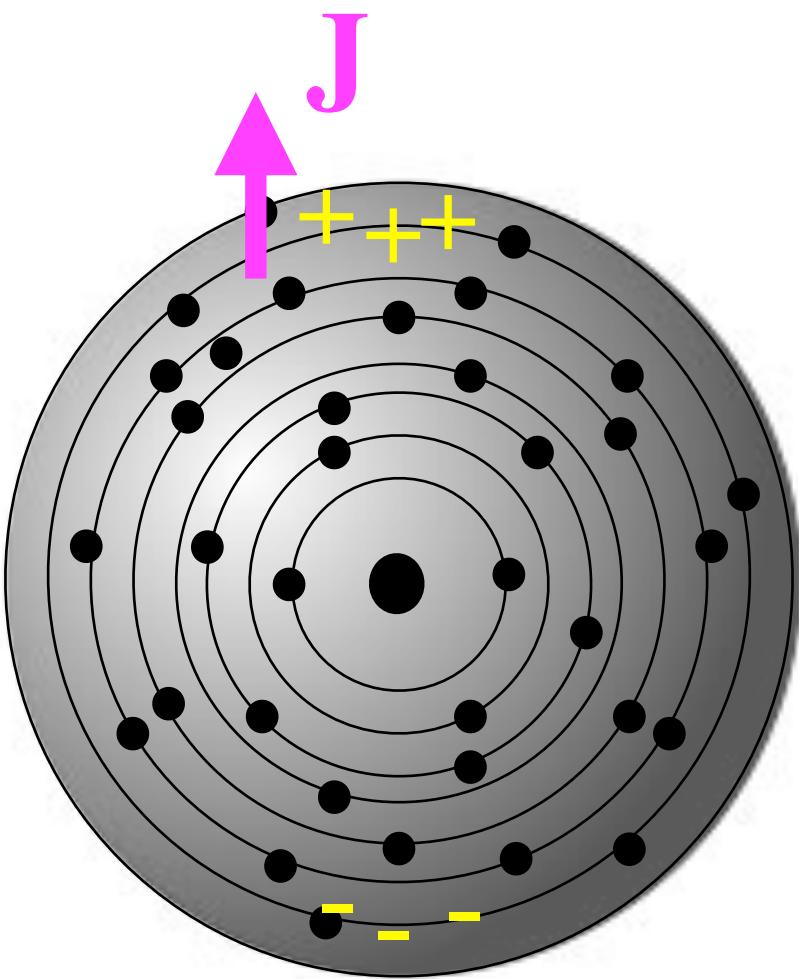
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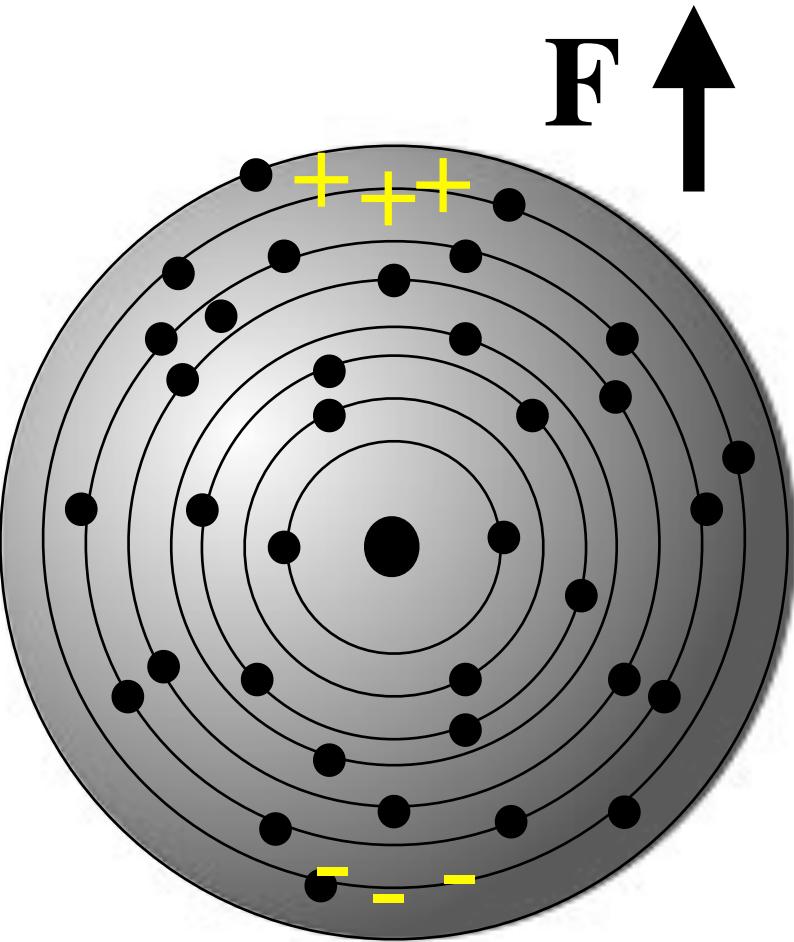
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Phenomenology

Effective operators

- Fermion EDMs

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

- non-relativistic limit, Hamiltonian

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

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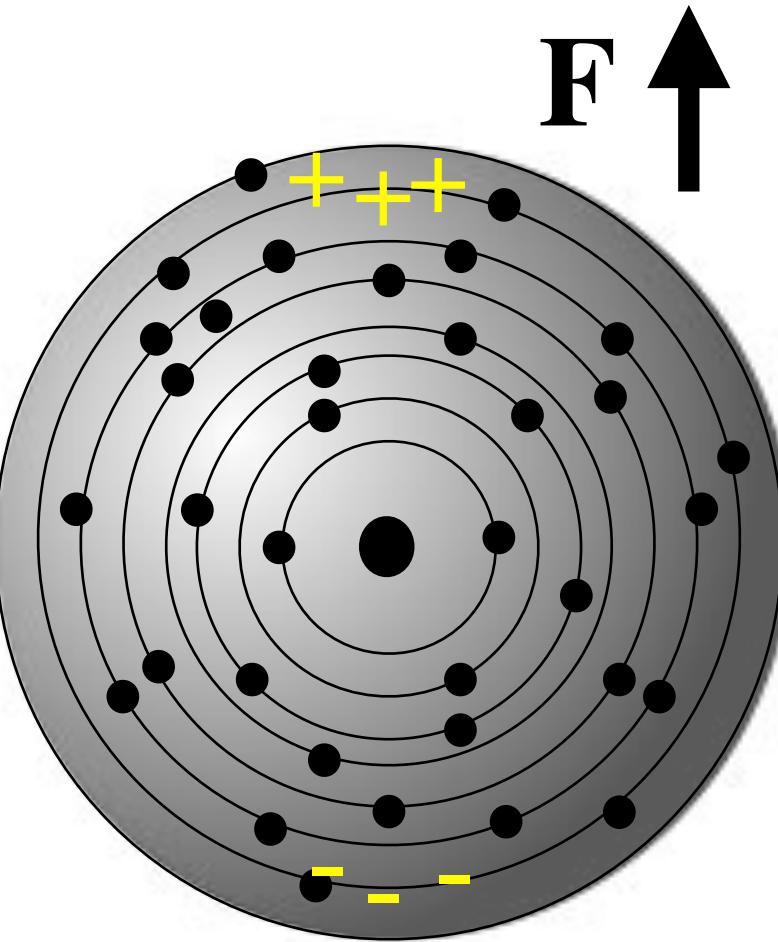
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- Chromo EDMs \tilde{d}_q , interaction with gluon field $G_{\mu\nu}$

- Three-gluon term $GG\tilde{G}$

- Four-fermion interactions: $\bar{\psi}_1 \psi_1 \bar{\psi}_2 i\gamma_5 \psi_2$,

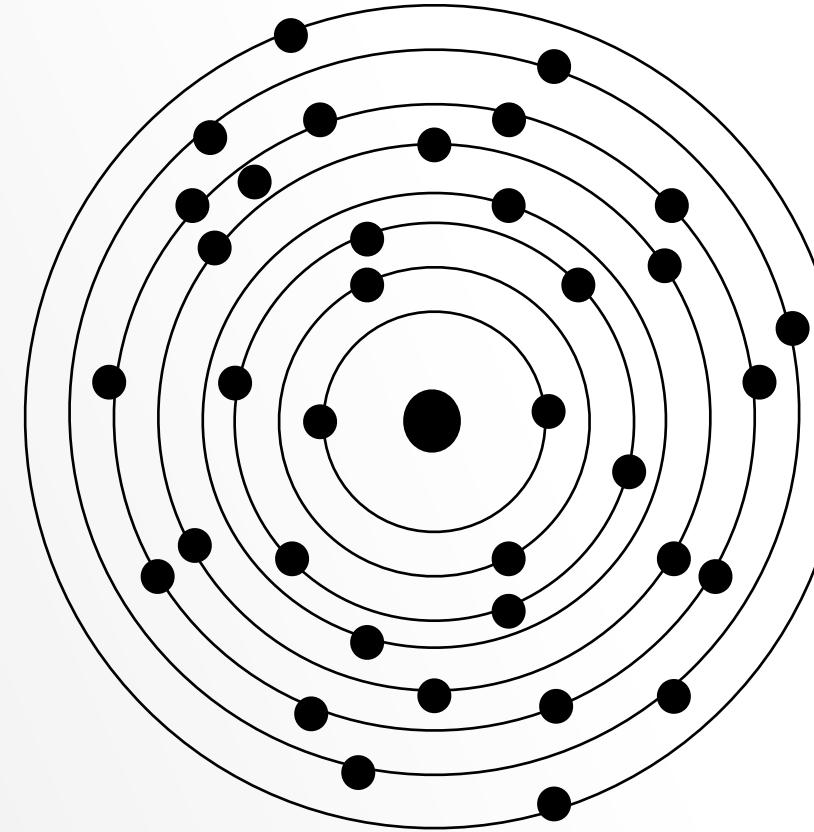
$$\bar{\psi}_1 i\gamma_5 \psi_1 \bar{\psi}_2 \psi_2, \epsilon_{\mu\nu\alpha\beta} \bar{\psi}_1 \sigma^{\mu\nu} \psi_1 \bar{\psi}_2 \sigma^{\alpha\beta} \psi_2$$

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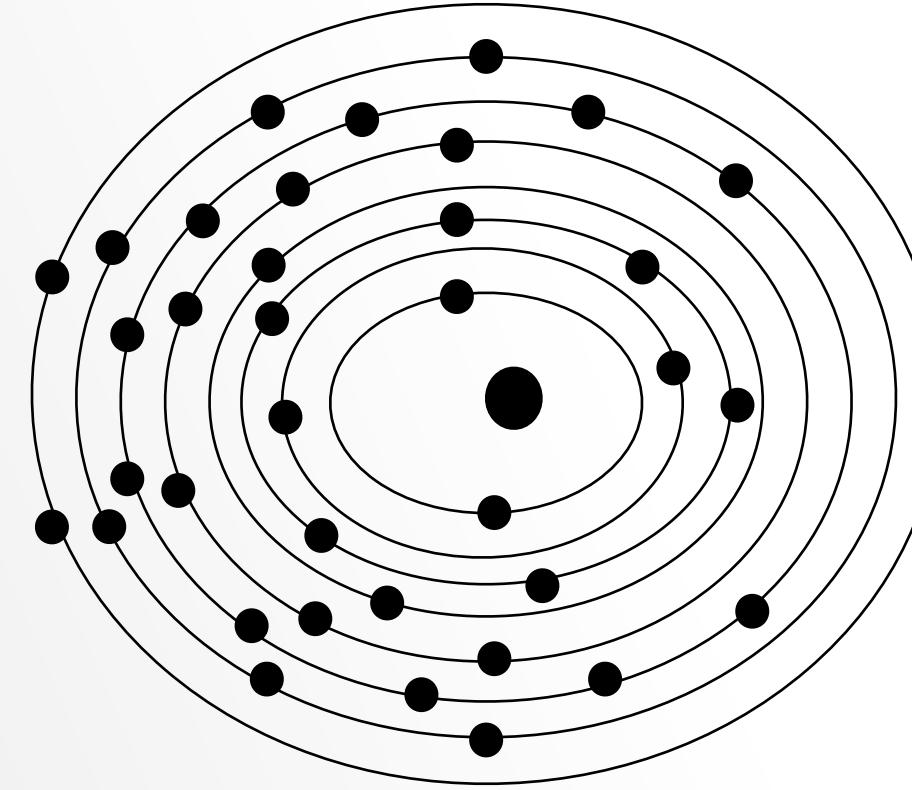
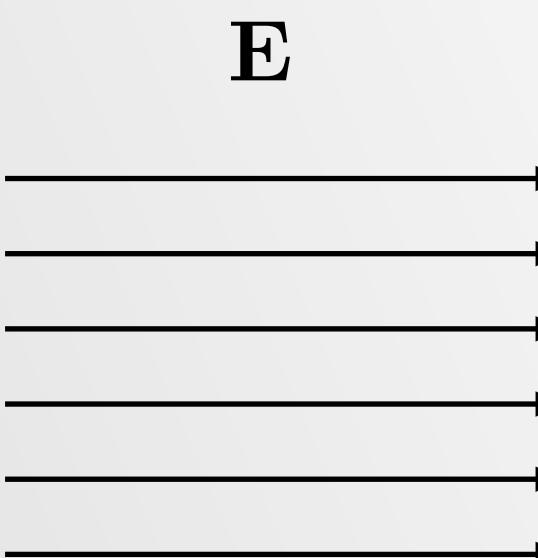
Pospelov and Ritz, Annals of Physics (2005)

Schiff screening



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

Schiff screening

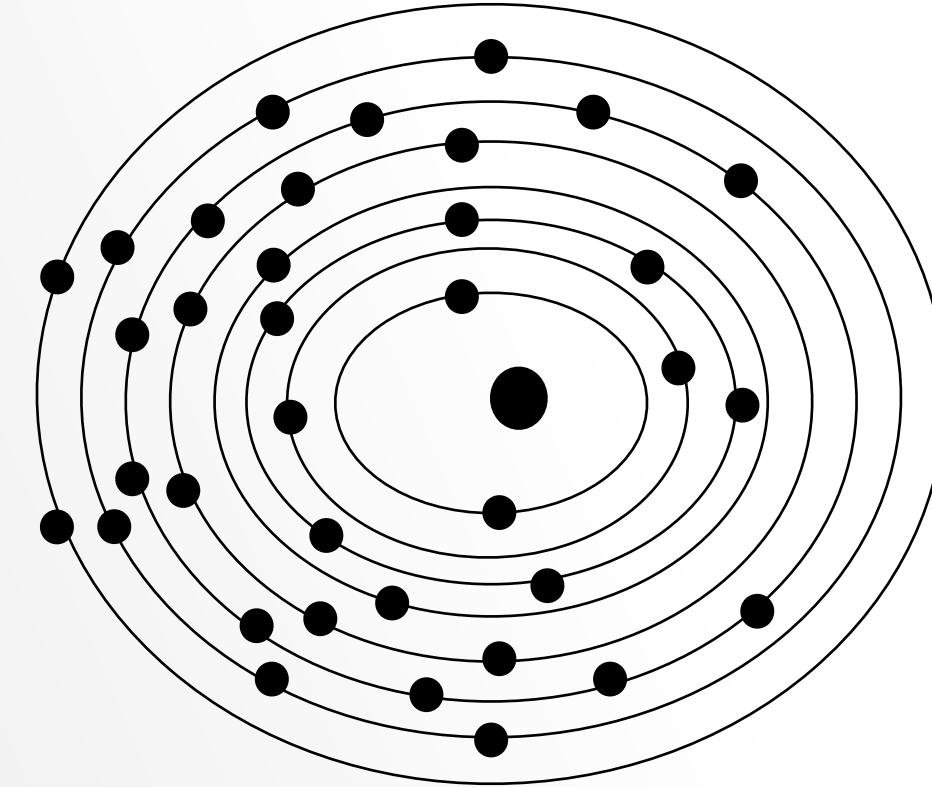
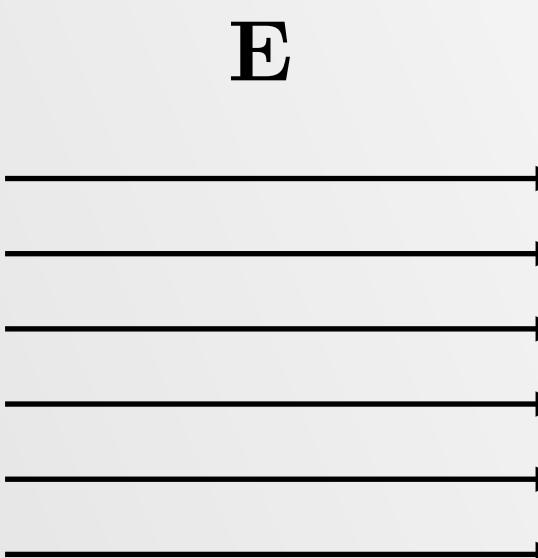


Neutral system comprised of non-relativistic point-particles interacting via Coulomb force

Internal electric field produced
s.t. at each particle

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

Schiff screening



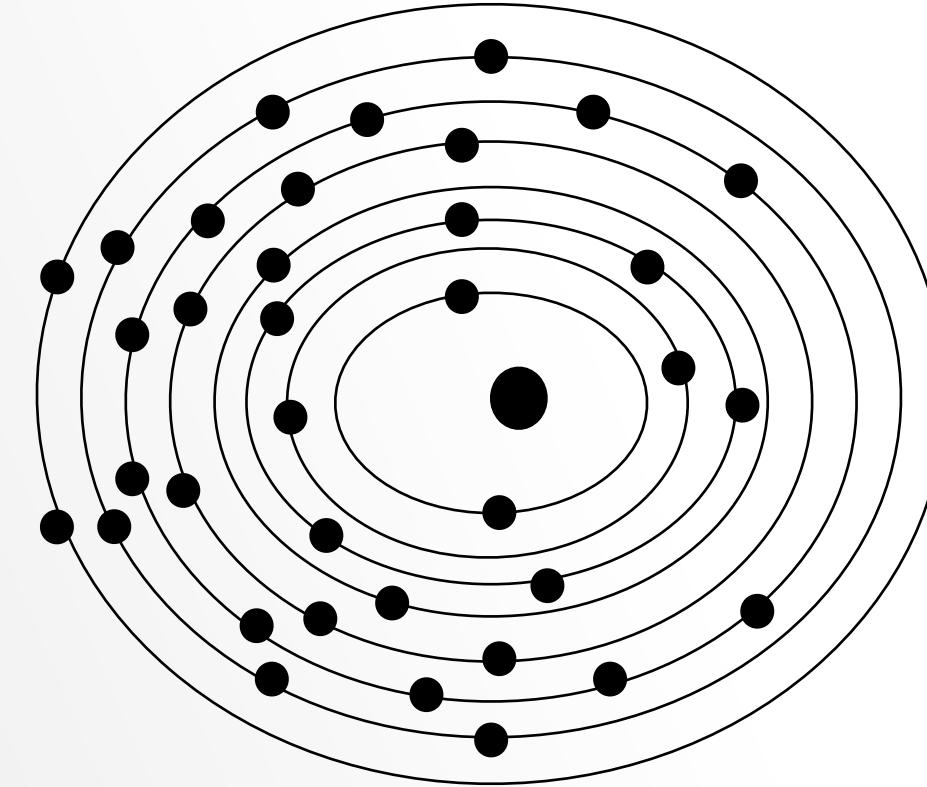
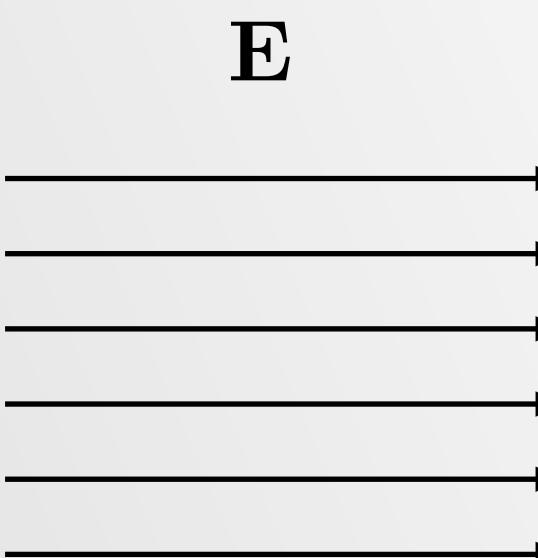
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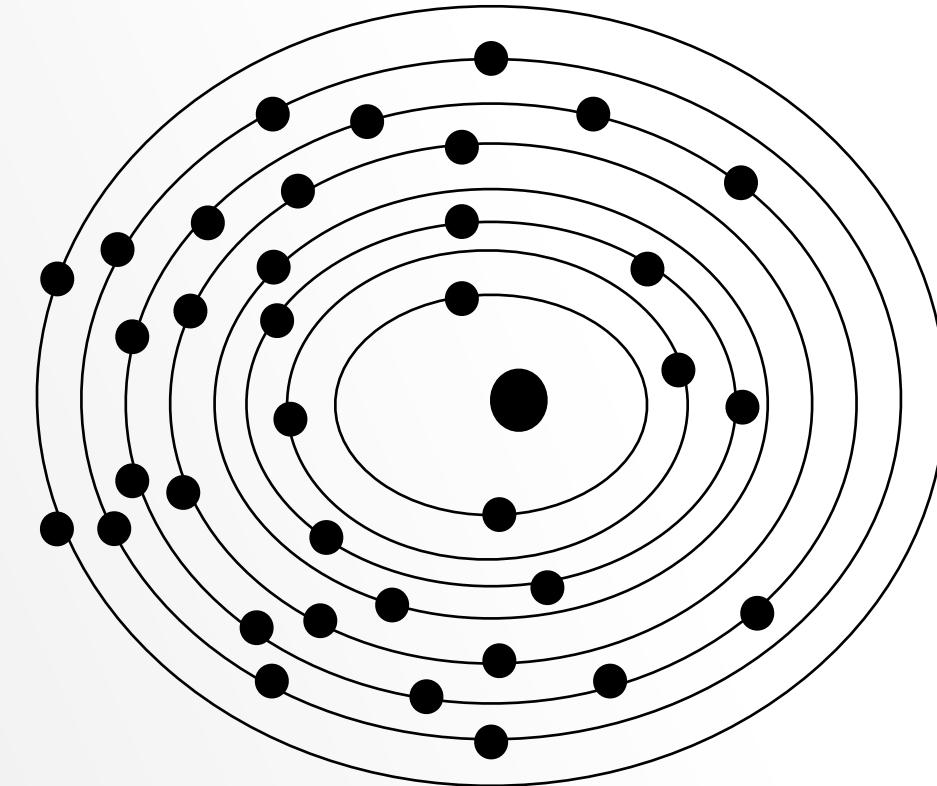
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Schiff screening

$$\mathbf{E}$$

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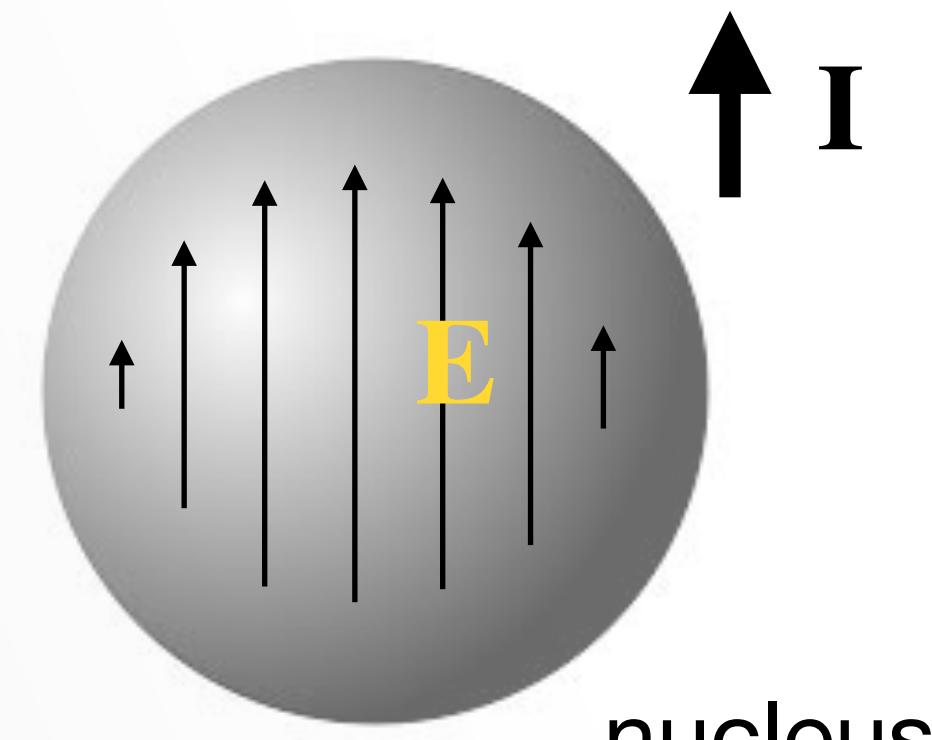
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Finite nuclear size

Nuclear Schiff moment!

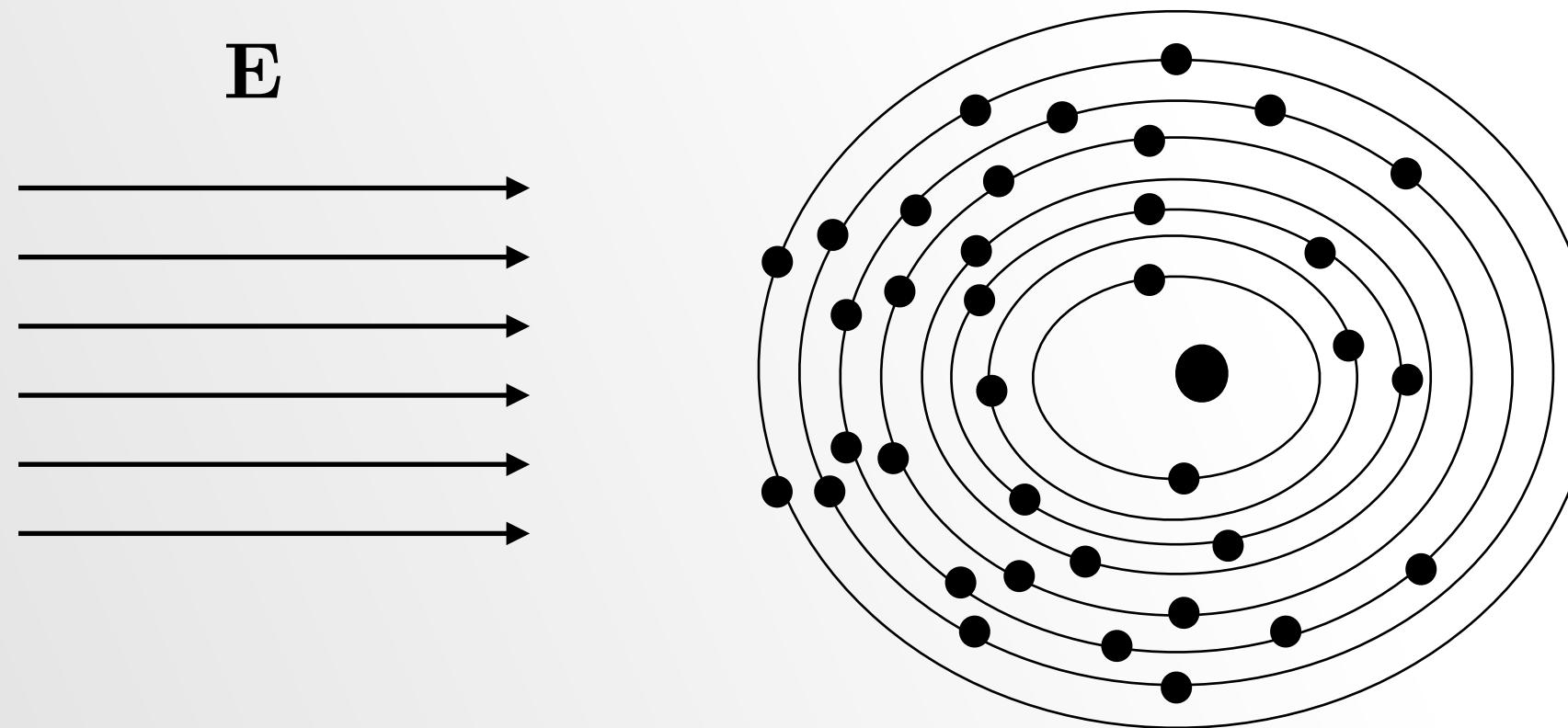
$$d_{\text{atom}} = \eta S$$

$$\mathbf{S} = S\mathbf{I}/I = \frac{e}{10} \left[\langle r^2 \mathbf{r} \rangle - \frac{5}{3Z} \langle r^2 \rangle \langle \mathbf{r} \rangle \right]$$



Schiff, Phys. Rev. (1963); Sandars, Phys. Lett. (1965);
Sushkov, Flambaum, Khriplovich, ZhETF (1984);
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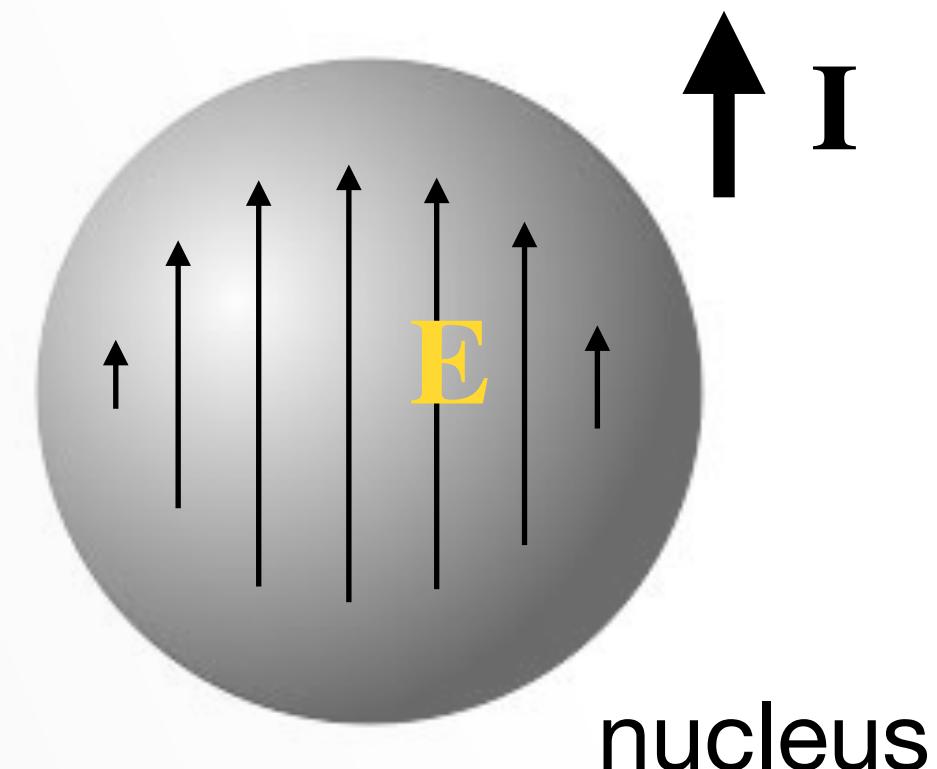
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Relativistic effects

Electron EDM, with enhancement!

$$d_{\text{atom}} = K d_e$$

$$\text{e.g., } |K(\text{Tl})| \approx 600$$

Schiff, Phys. Rev. (1963); Sandars, Phys. Lett. (1965);
Sushkov, Flambaum, Khriplovich, ZhETF (1984);
Flambaum and Ginges, PRA (2002)

Leading mechanisms

diamagnetic
(Hg, TlF,...)

neutron EDM

fundamental
CP-
violating
phases

paramagnetic
(Tl, ThO,...)

Atomic/molecular

Nuclear

Nucleon

Lepton/quark

Particle

See, e.g., Ginges and Flambaum, Phys. Rep. (2004)

Leading mechanisms

diamagnetic
(Hg, TlF,...)

paramagnetic
(Tl, ThO,...)

Atomic/molecular

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Measurements



Nuclear

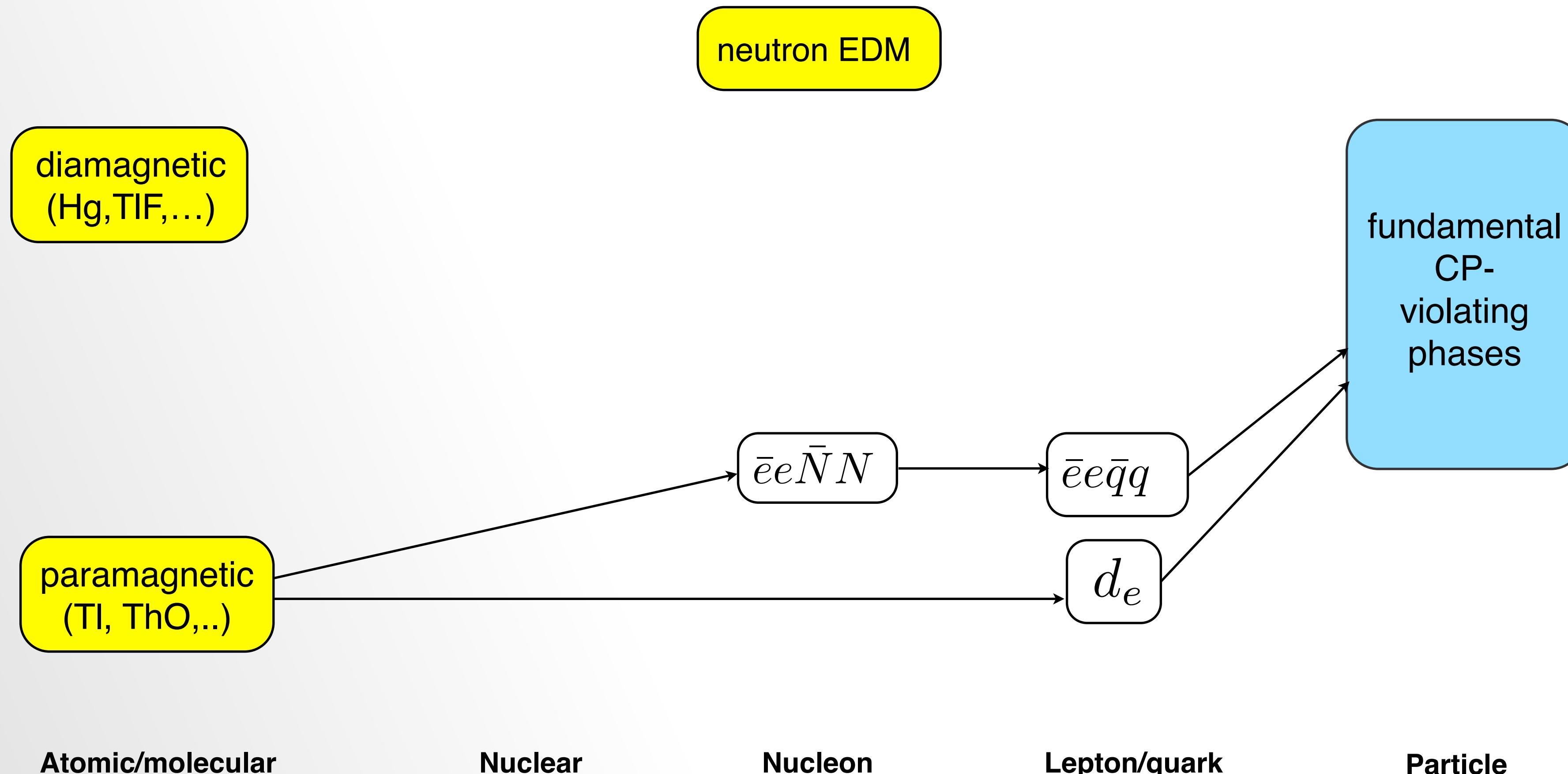
Nucleon

Lepton/quark

Particle

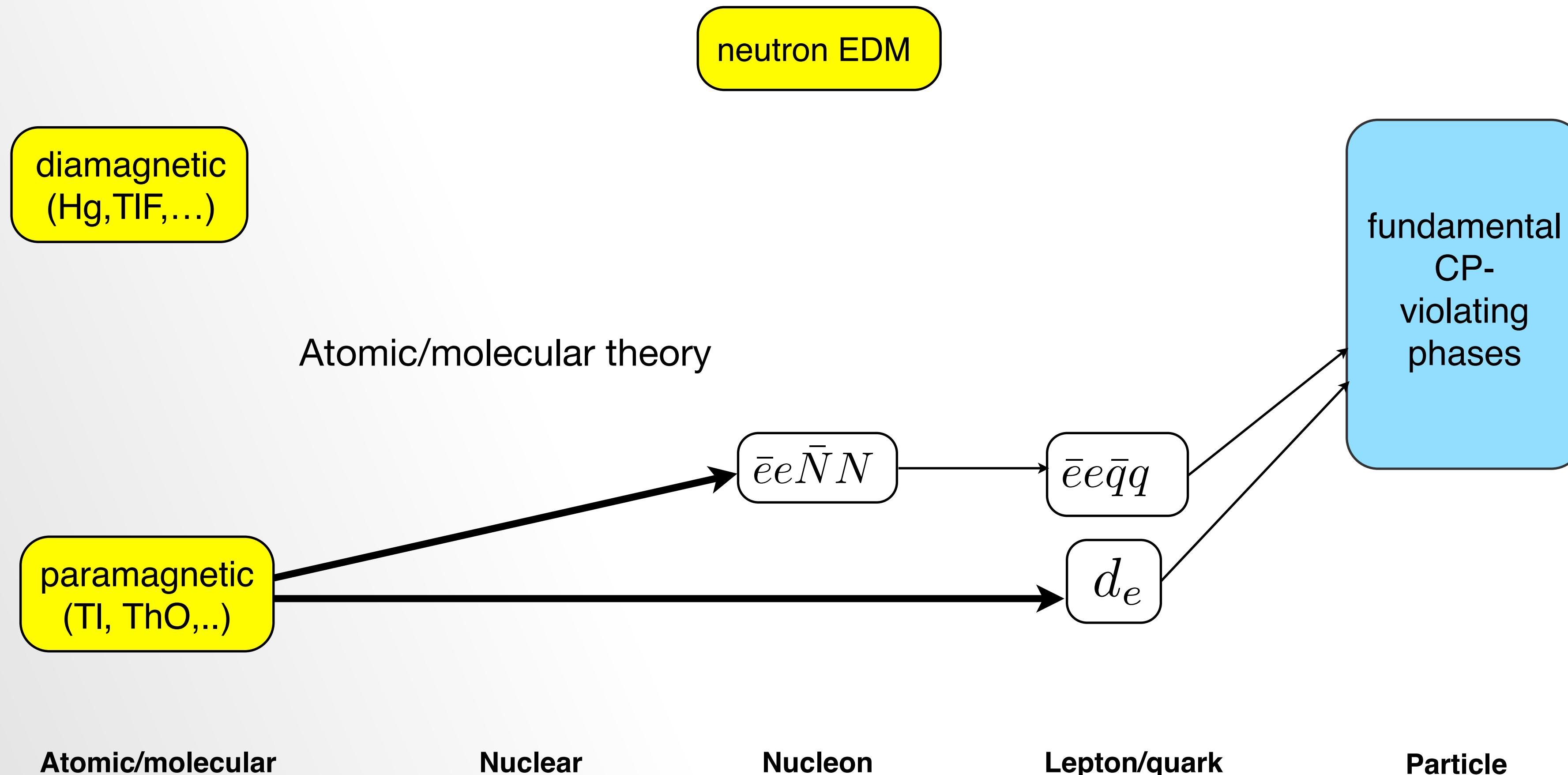
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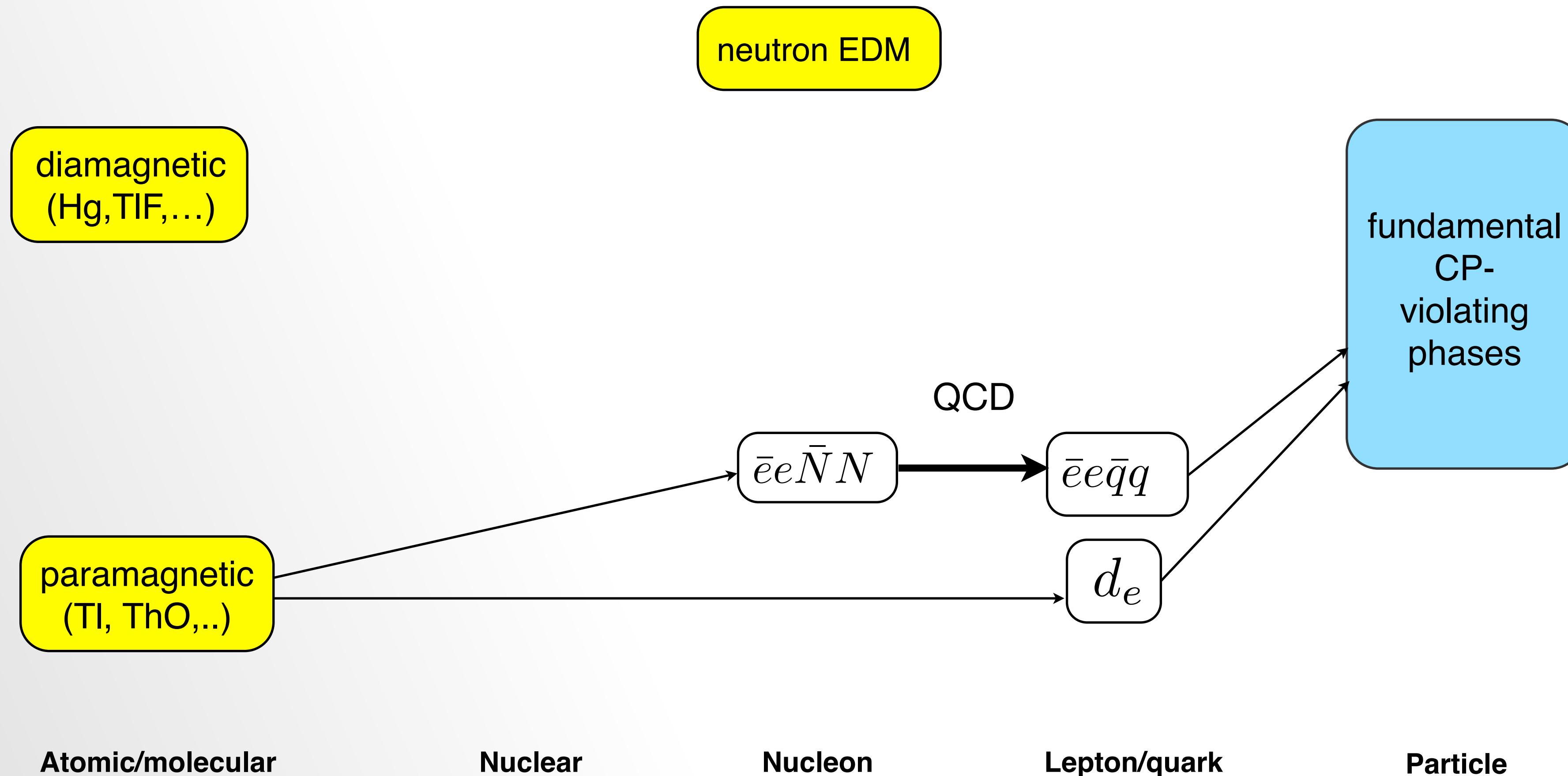
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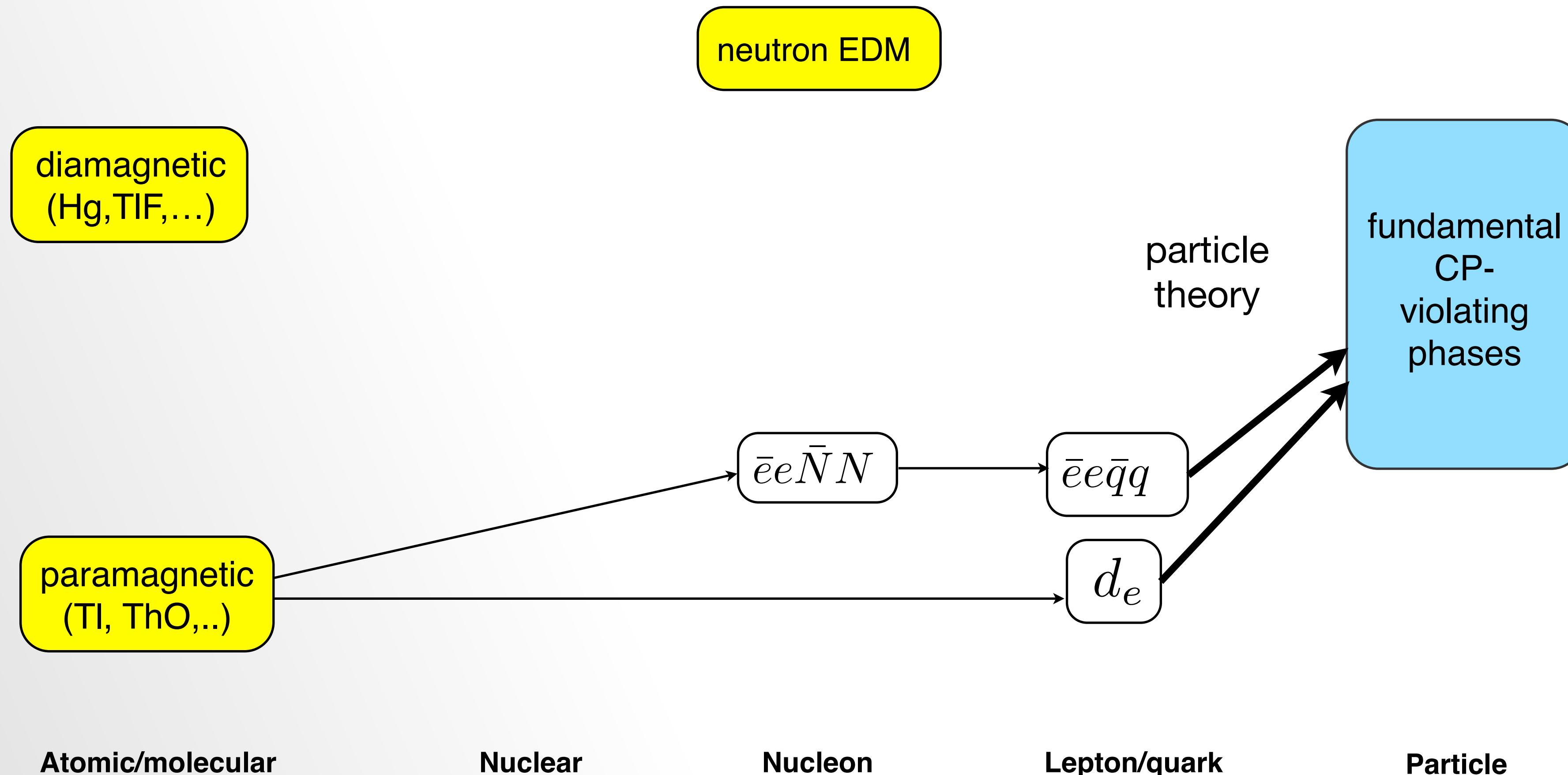
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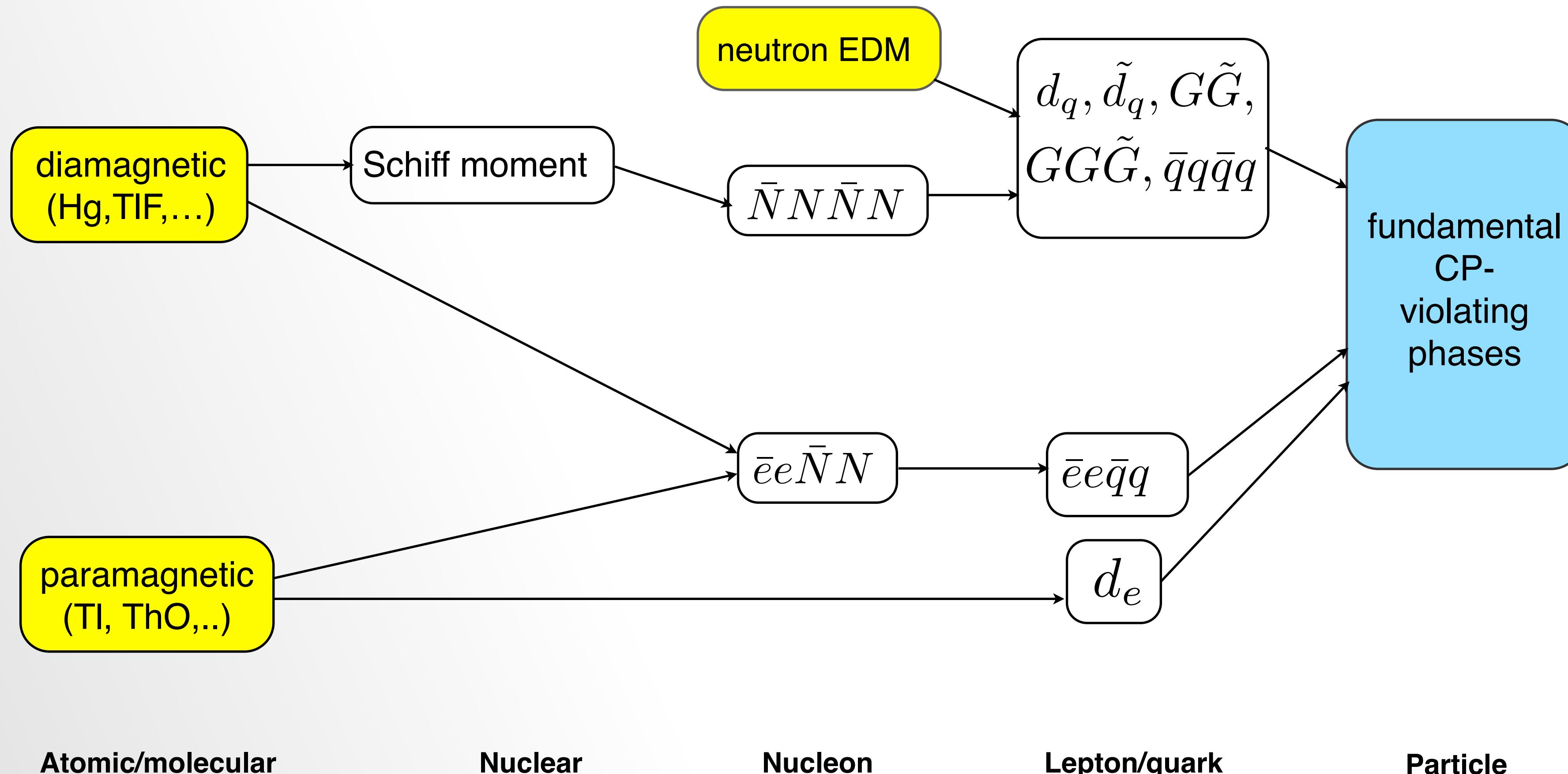
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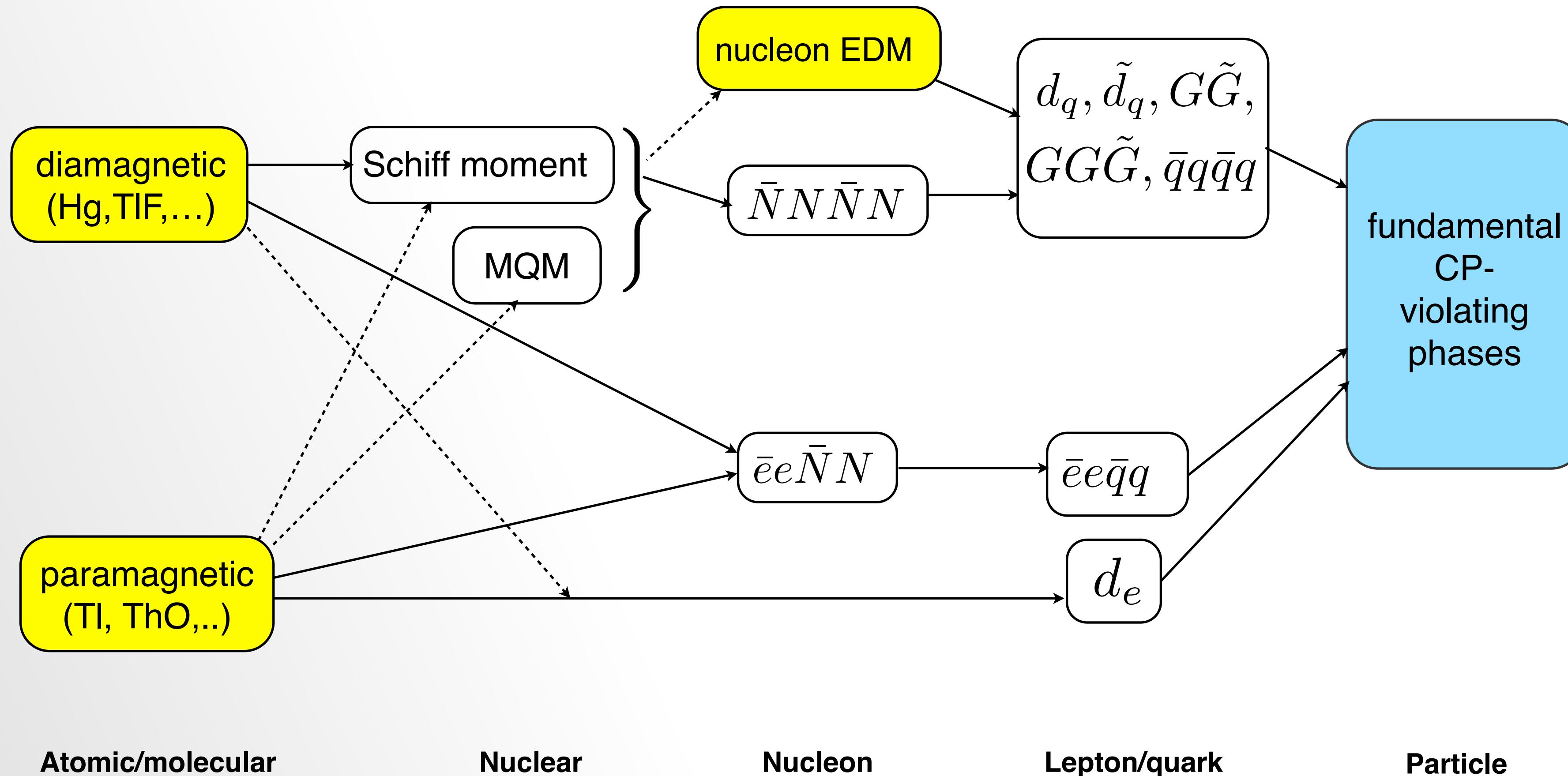
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Leading mechanisms



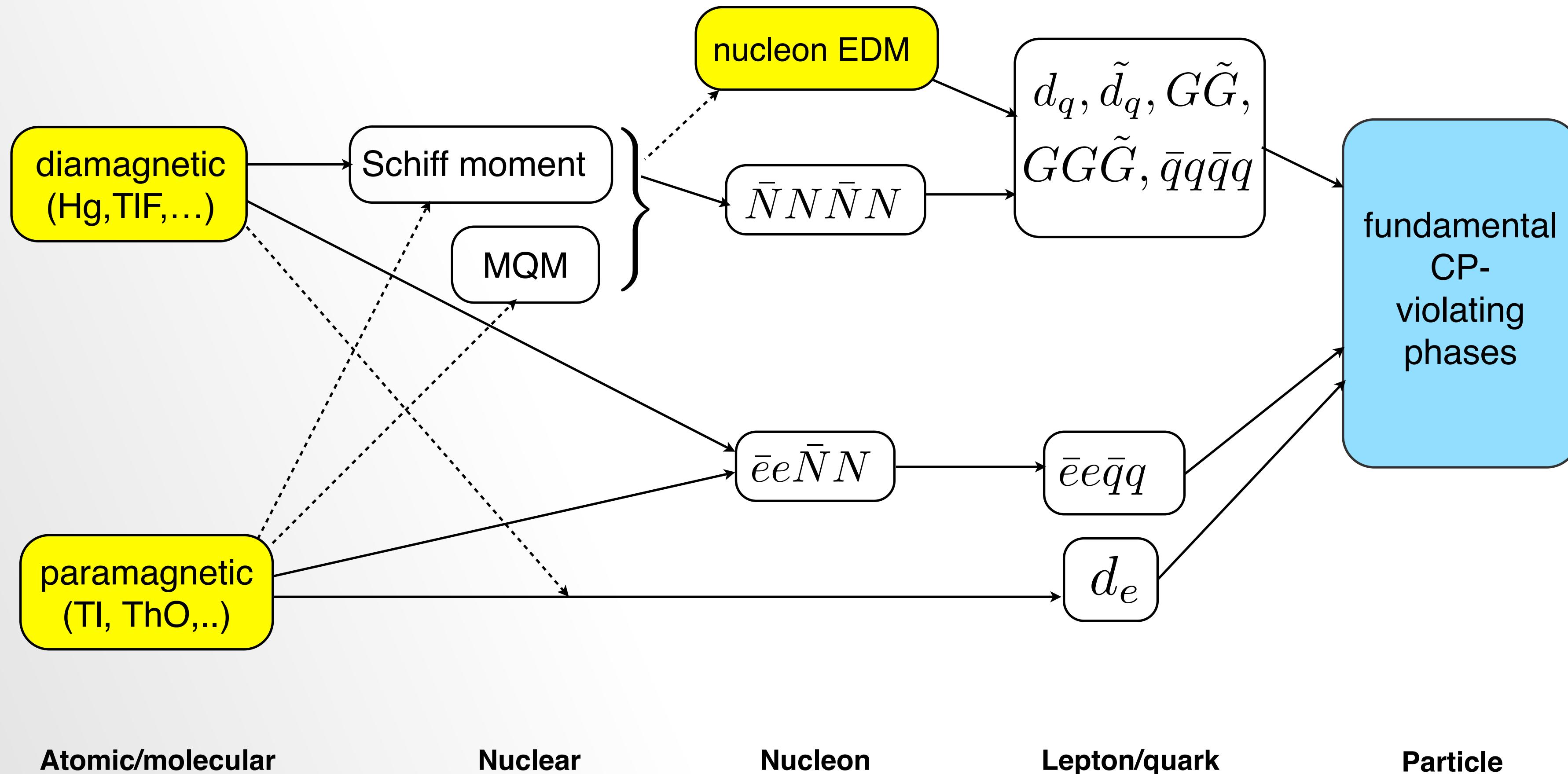
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Leading mechanisms



Atomic/molecular

Nuclear

Nucleon

Lepton/quark

Particle

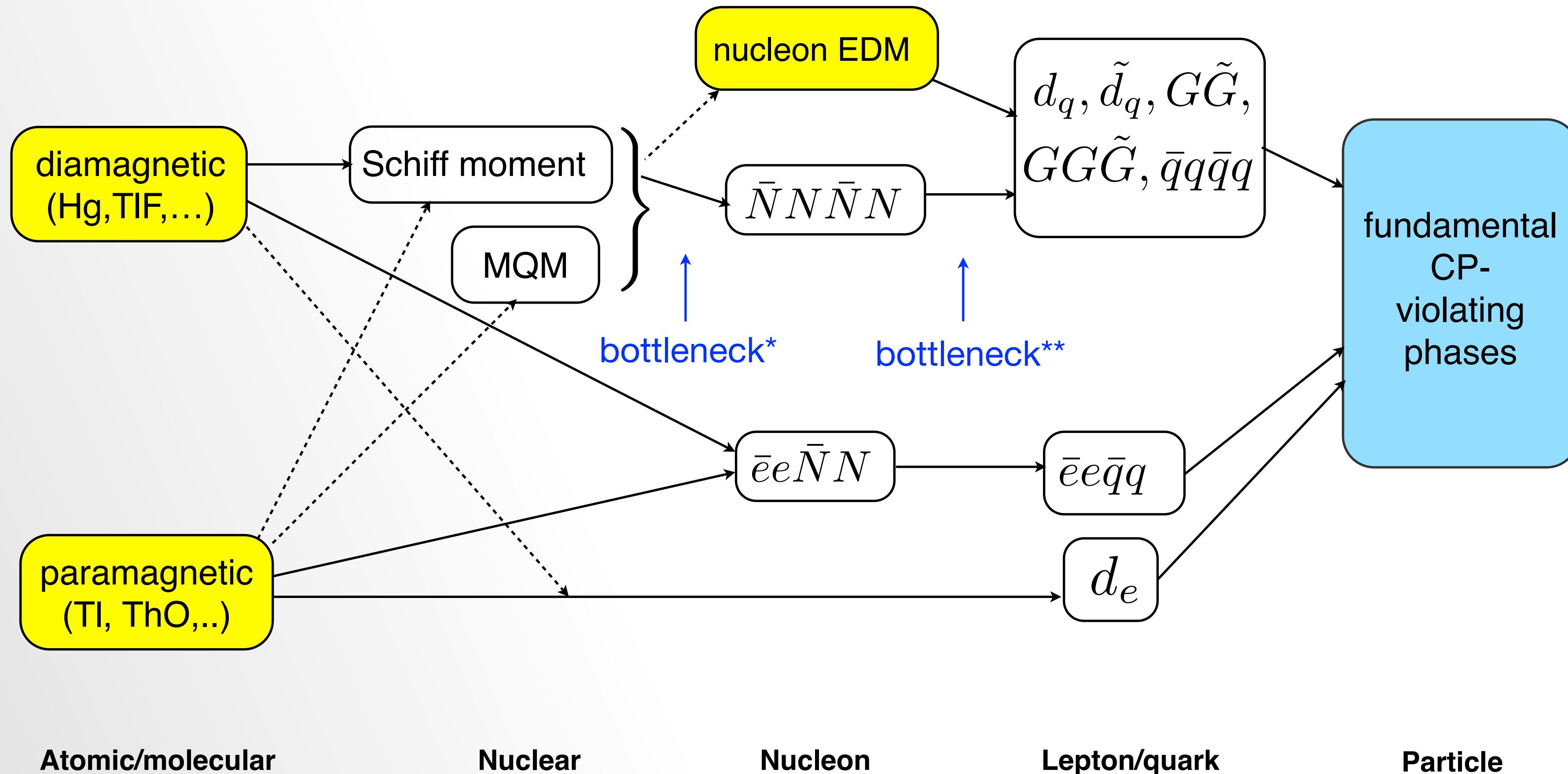
Atomic theory precision.

One-valence electron: $\lesssim 1\%$; closed electron shells: $\lesssim 10\%$

Molecular theory precision: $\lesssim 10\%$

See, e.g., Ginges and Flambaum, Phys. Rep. (2004);
Safranova et al., Rev. Mod. Phys. (2018);
Engel, Ramsey-Musolf, Kolck, Prog. Part. Nucl. Phys. (2013)

Leading mechanisms



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* uncertainties up to 500%

** uncertainties ~100%

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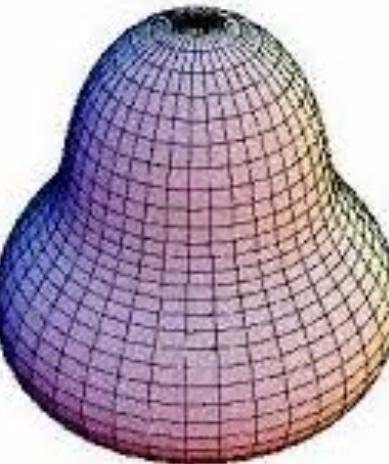
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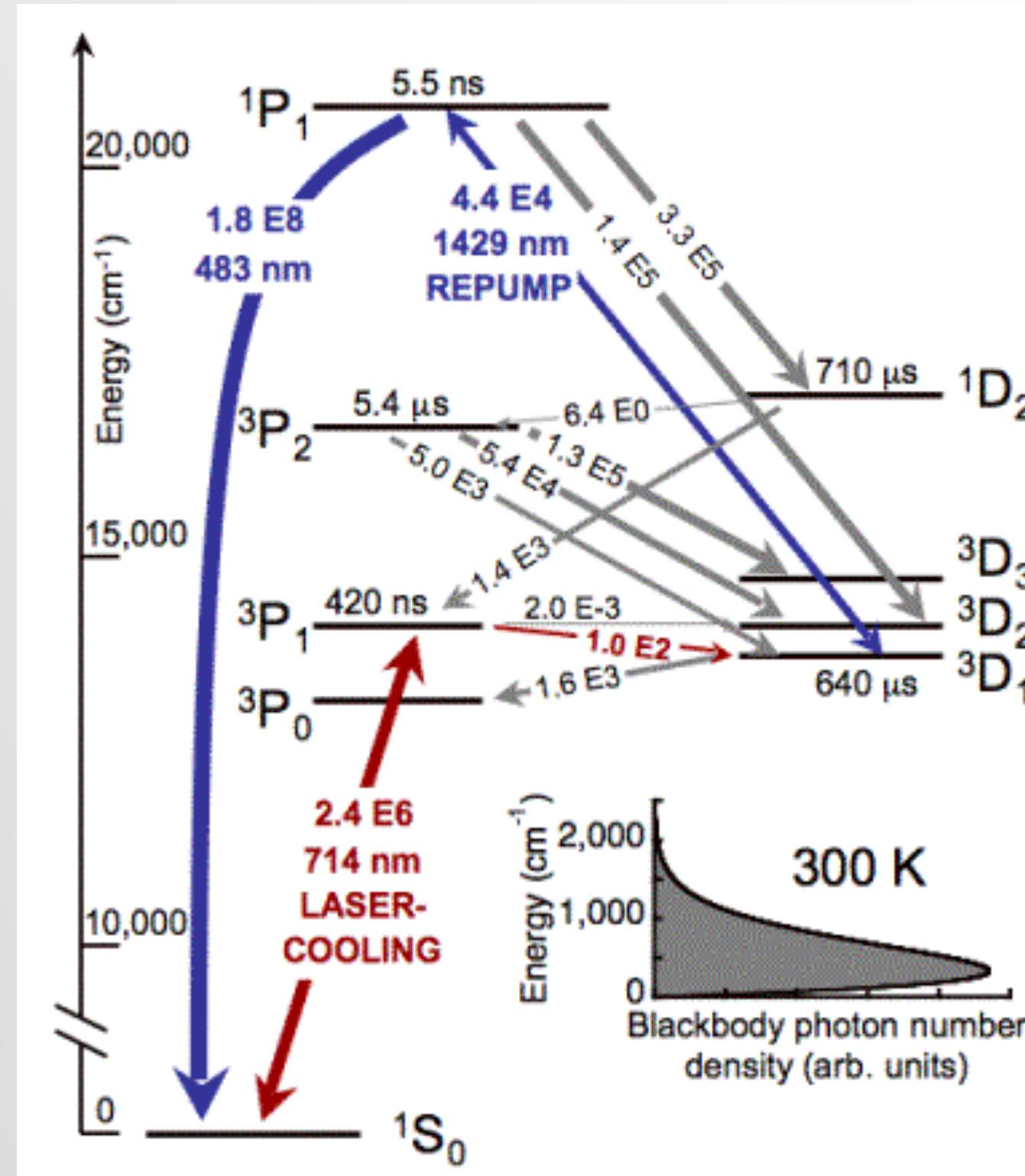


Auerbach, Flambaum, Spevak, PRL (1996);

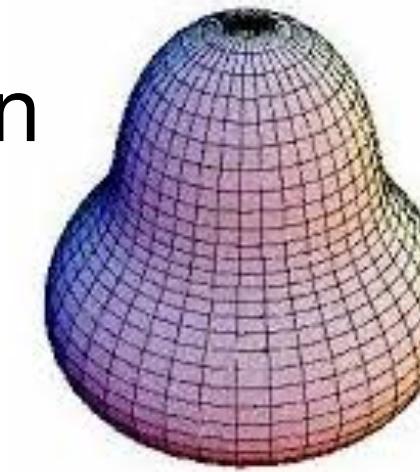
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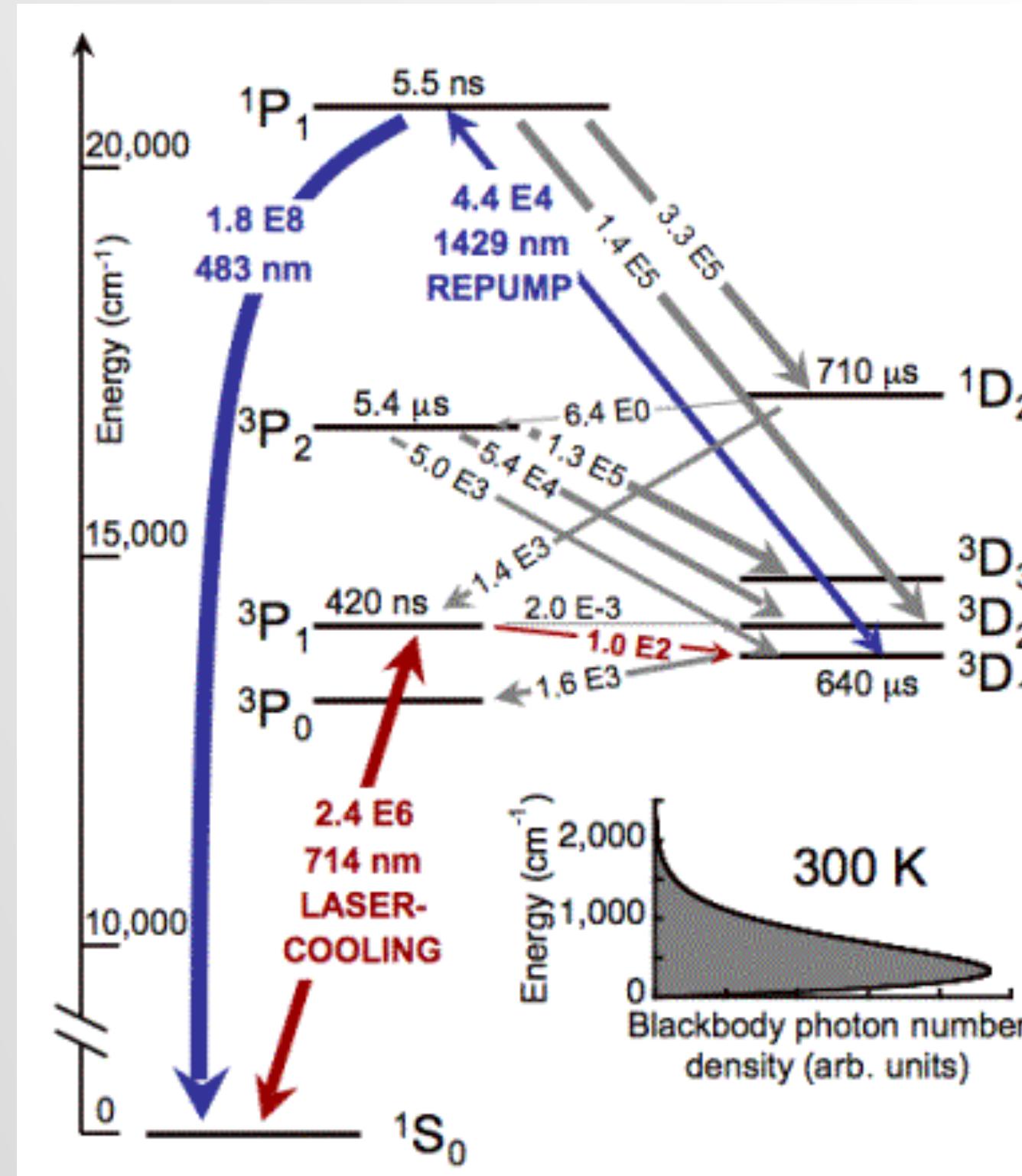
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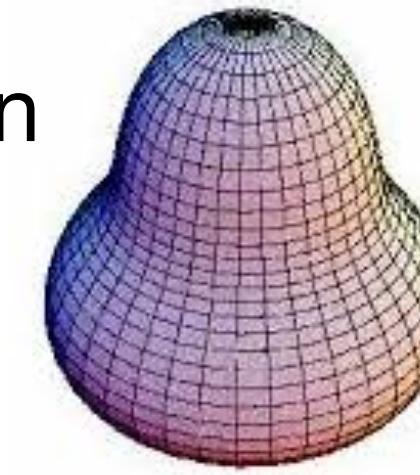
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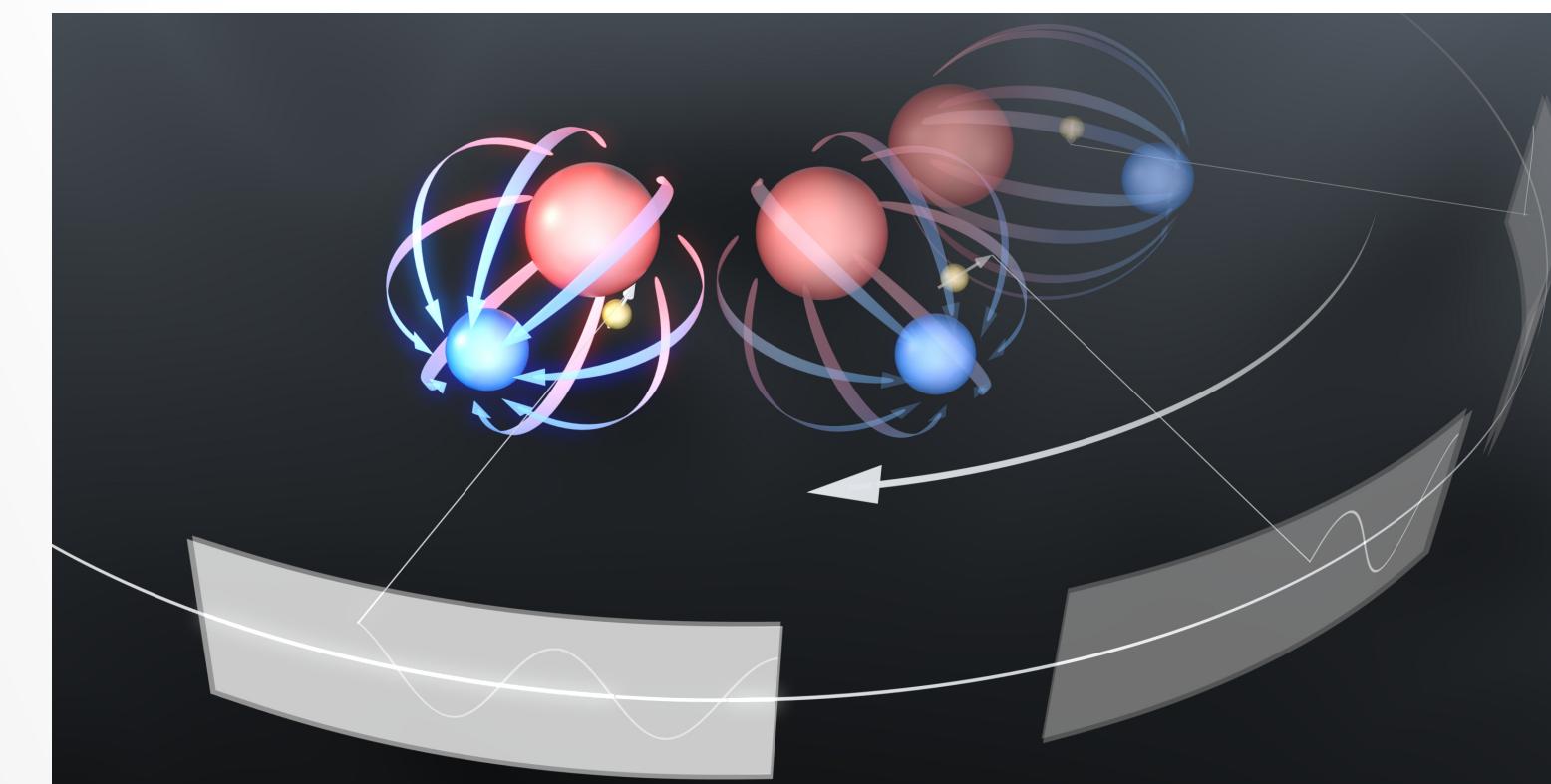
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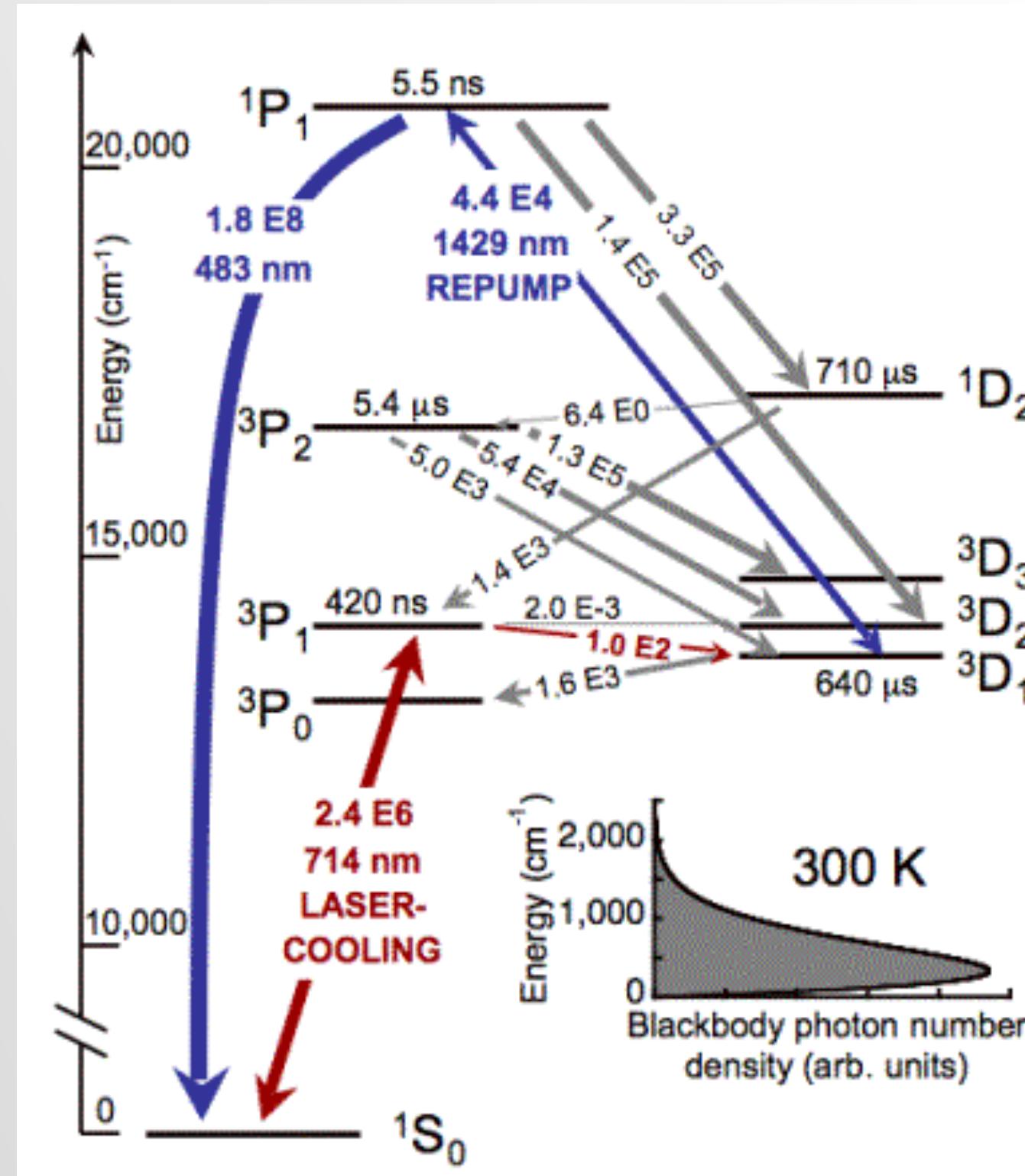
Eric Cornell group

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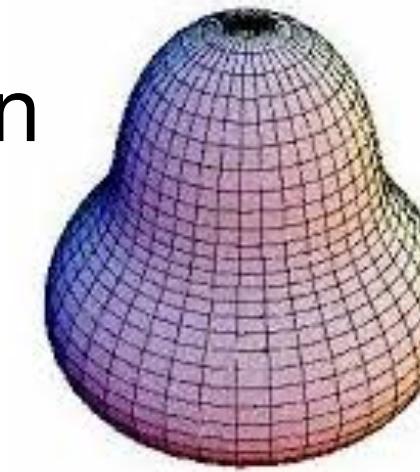
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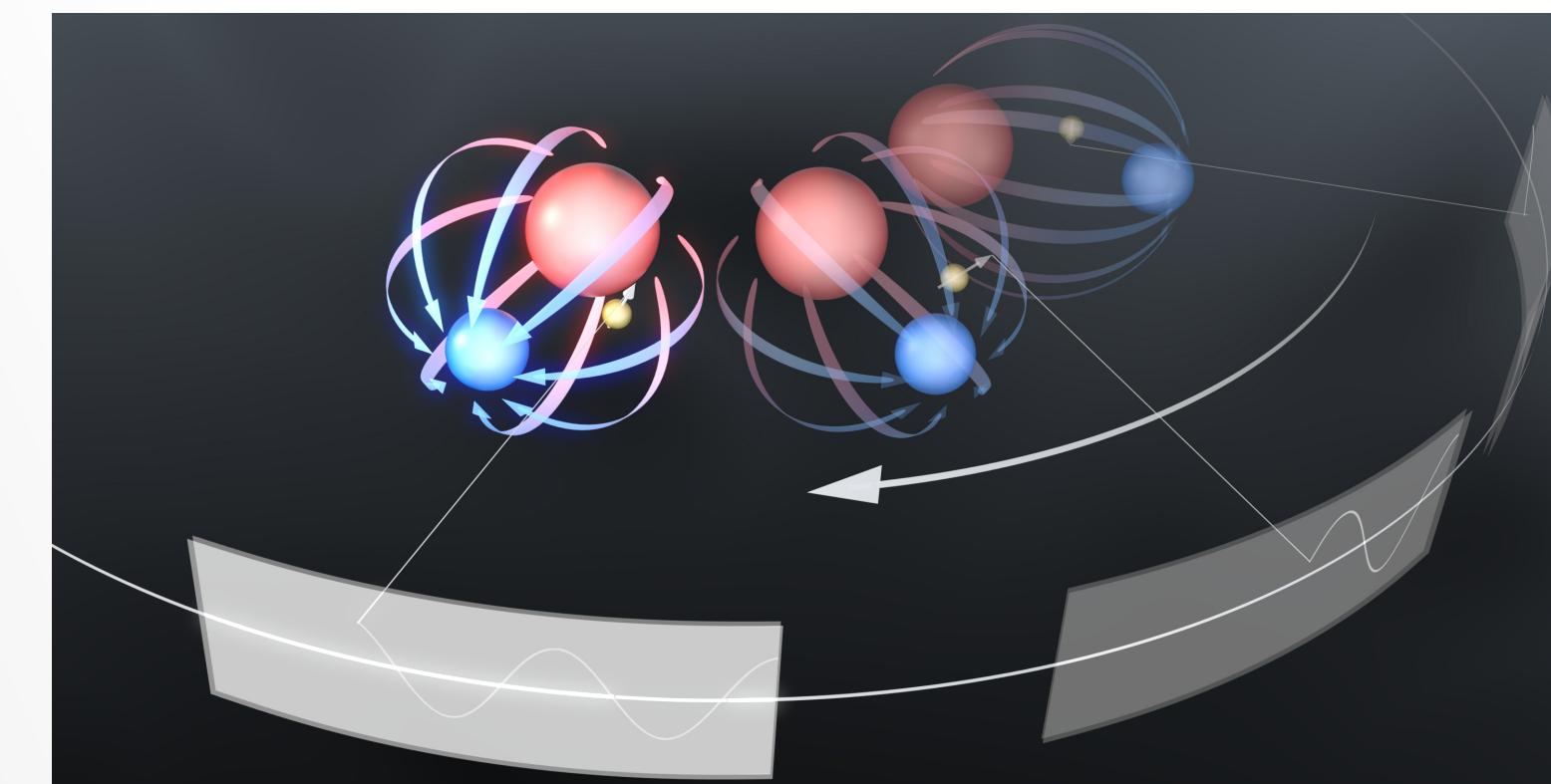
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- Other – solids, oscillating electric field, ...

Auerbach, Flambaum, Spevak, PRL (1996);
Dzuba, Flambaum, Khriplovich, Z. Phys. D (1986);
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Best limits and recent measurements

	$ d_{\text{atom}} , 95\% \text{ c.l.}$	Constraints, 95% c.l.	Group
Paramagnetic			
^{205}Tl	$1.1 \times 10^{-24} e \text{ cm}$	$ d_e < 1.9 \times 10^{-27} e \text{ cm}$	Berkeley, 2002
ThO		$ d_e < 1.2 \times 10^{-29} e \text{ cm}$	ACME, 2018
HfF^+		$ d_e < 5.4 \times 10^{-30} e \text{ cm}$	JILA, 2023
Diamagnetic			
^{199}Hg	$7.4 \times 10^{-30} e \text{ cm}$	$ d_n < 1.6 \times 10^{-26} e \text{ cm}$ $ \theta_{\text{QCD}} < 1.5 \times 10^{-10}$	Seattle, 2016
^{225}Ra	$1.4 \times 10^{-23} e \text{ cm}$		Argonne, 2015
^{129}Xe	$1.5 \times 10^{-27} e \text{ cm}$		Juelich, 2019
^{129}Xe	$4.8 \times 10^{-27} e \text{ cm}$		HeXeEDM, 2019
n		$ d_n < 2.2 \times 10^{-26} e \text{ cm}$	PSI, 2020

Other ongoing experiments:
 Paramagnetic: YbF (Imperial), ThF (JILA), Cs (Penn State), Fr (Tokyo, LBNL/TRIUMF), BaF (Groningen)
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Also: Measurements of *oscillating* EDMs to search for axionlike particles (JILA); experiments with μ , d , p ,...

Summary

- Rapid gains in EDM measurements with atoms, molecules, neutrons, other systems
- *Orders of magnitude* improvement in sensitivity anticipated within decade
- Observation or lack of observation of EDM will have a profound effect on our understanding of new physics
- If unambiguous detection, measurements in multiple systems needed to determine CP-violation source(s)
- Calculations at the nuclear and QCD scales pose the most limiting theory constraints