KITP Santa Barbara - September 2016

Precision Symmetry Tests and Electric Dipole Moments

Adam Ritz
University of Victoria

with Matthias Le Dall and Maxim Pospelov

[e.g. 1505.01865, Review - hep-ph/0504231]

Plan

Brief summary, further talks this week…

- Part 1 - EDMs & precision tests
- Part 2 - Implications for New Physics

History + Sensitivity to (light) new physics in a hidden sector

EDMs as precision probes

Motivations for new CP-odd sources

- Required for baryogenesis (Sakharov conditions)
- Quite generic with extra degrees of freedom (e.g. potential for CP-violation in lepton sector with massive neutrinos)
- Mysterious suppression of θ_{QCD}

EDMs are powerful (amplitude-level) probes for new CP/T violation

$$H = -d\vec{E}\cdot\frac{\vec{S}}{S}$$

- Best current limits from neutrons, para- and dia-magnetic atoms and molecules.
- Negligible SM (CKM) background

Paramagnetic EDMs

Harvard/Yale (ThO)
[Baron et al. '13]

Imperial (YbF)
[Hudson et al. '11]

Berkeley (Tl)
[Regan et al. '02]

Diamagnetic EDMs

U Washington (Hg)
[Graner et al '16]

U Michigan (Xe)
[Rosenberry & Chupp '01]

Argonne (Ra)
[Bishof et al '16]

Neutron EDM

Sussex/RAL/ILL
[Baker et al. '06, Pendlebury et al '15]

(and many others in development around the world)

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$$|d_e^{\text{equiv}}| < 8.7 \times 10^{-29}\, e\text{cm}$$

Diamagnetic EDMs

U Washington (Hg)
[Graner et al '16]

$$|d_{\text{Hg}}| < 7.4 \times 10^{-30}\, e\text{cm}$$

Neutron EDM

Sussex/RAL/ILL
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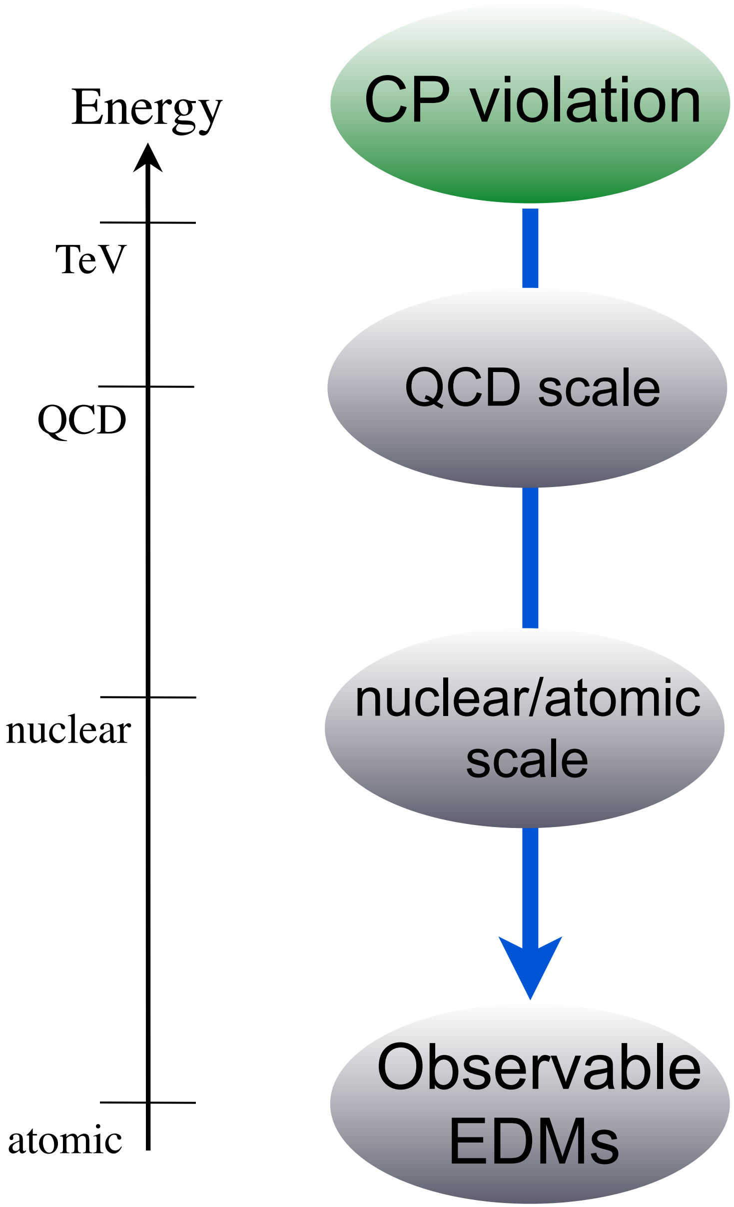
$$|d_n| < 3 \times 10^{-26} e\text{cm}$$

[→Talks by J. Doyle, E. Cornell, B. Heckel, M. Dietrich, B. Filippone, P. Fierlinger]

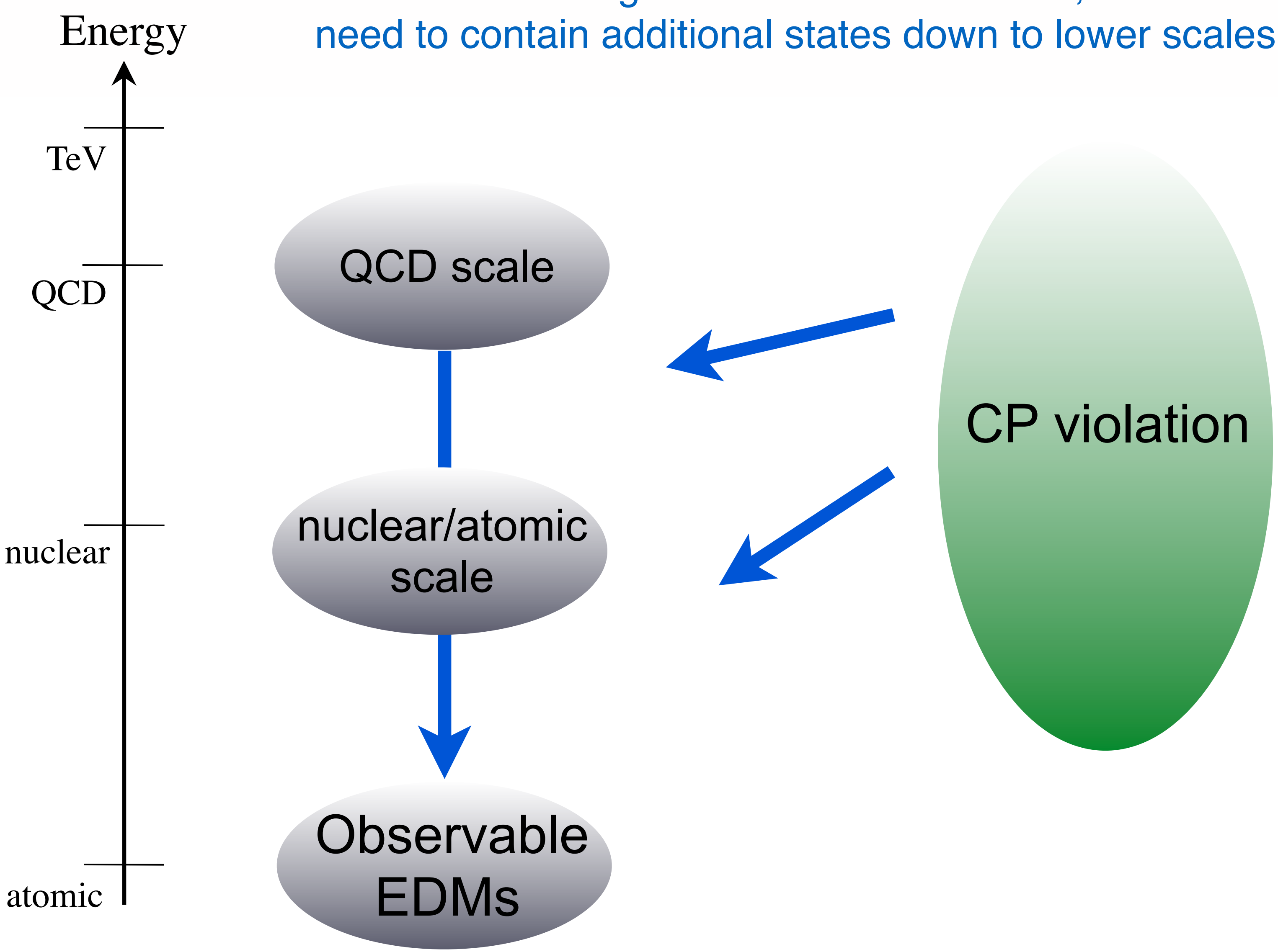
CP-odd EFT



Energy
TeV
QCD
nuclear
atomic
CP violation
QCD scale
nuclear/atomic scale
Observable EDMs

CP-odd EFT

If CP violation originates in a hidden sector, the EFT may need to contain additional states down to lower scales…



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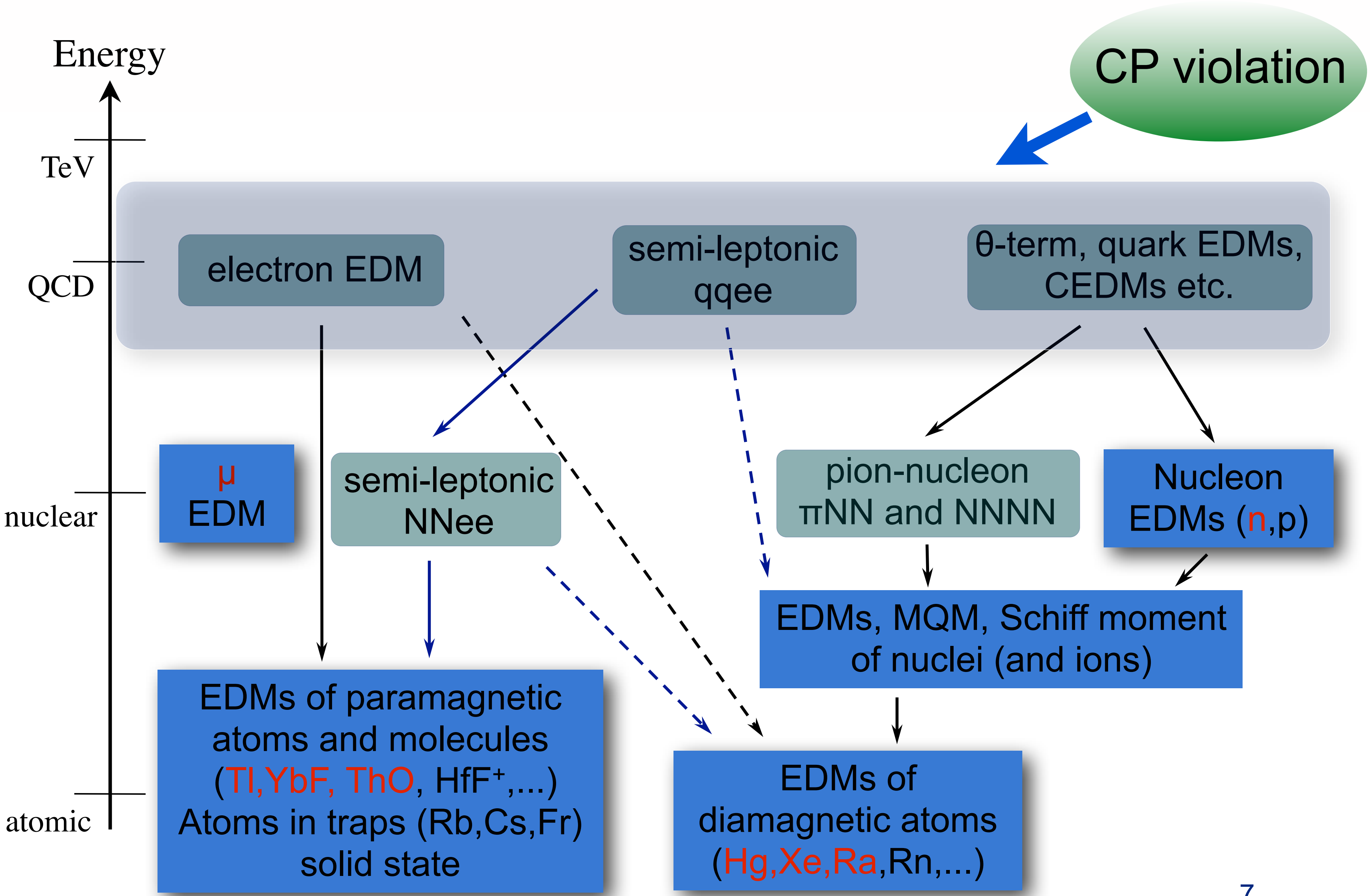


Energy
TeV
QCD
nuclear
atomic
CP violation
electron EDM
semi-leptonic qqee
θ-term, quark EDMs, CEDMs etc.
μ EDM
semi-leptonic NNee
pion-nucleon πNN and NNNN
Nucleon EDMs (n,p)
EDMs, MQM, Schiff moment of nuclei (and ions)
EDMs of paramagnetic atoms and molecules (Tl,YbF, ThO, HfF+,...) Atoms in traps (Rb,Cs,Fr) solid state
EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn,...)

CP-odd EFT

CP-odd (flavor-diagonal) operator expansion (at ~ 1GeV)

$$\mathcal{L}_{\rm eff} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

CP violation

Energy

TeV

QCD

nuclear

atomic

electron EDM

semi-leptonic qqee

θ-term, quark EDMs, CEDMs etc.

$$\mathcal{L}_{\rm dim\,4} \supset \bar\theta \alpha_s G\tilde G$$

$$d_i \sim c Y_i \frac{v}{\Lambda^2}$$

$$\mathcal{L}_{\text{``dim 6''}} \supset \sum_{q=u,d,s} \left(d_q \bar q F\sigma\gamma_5 q + \tilde d_q \bar q G\sigma\gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar l F\sigma\gamma_5 l$$

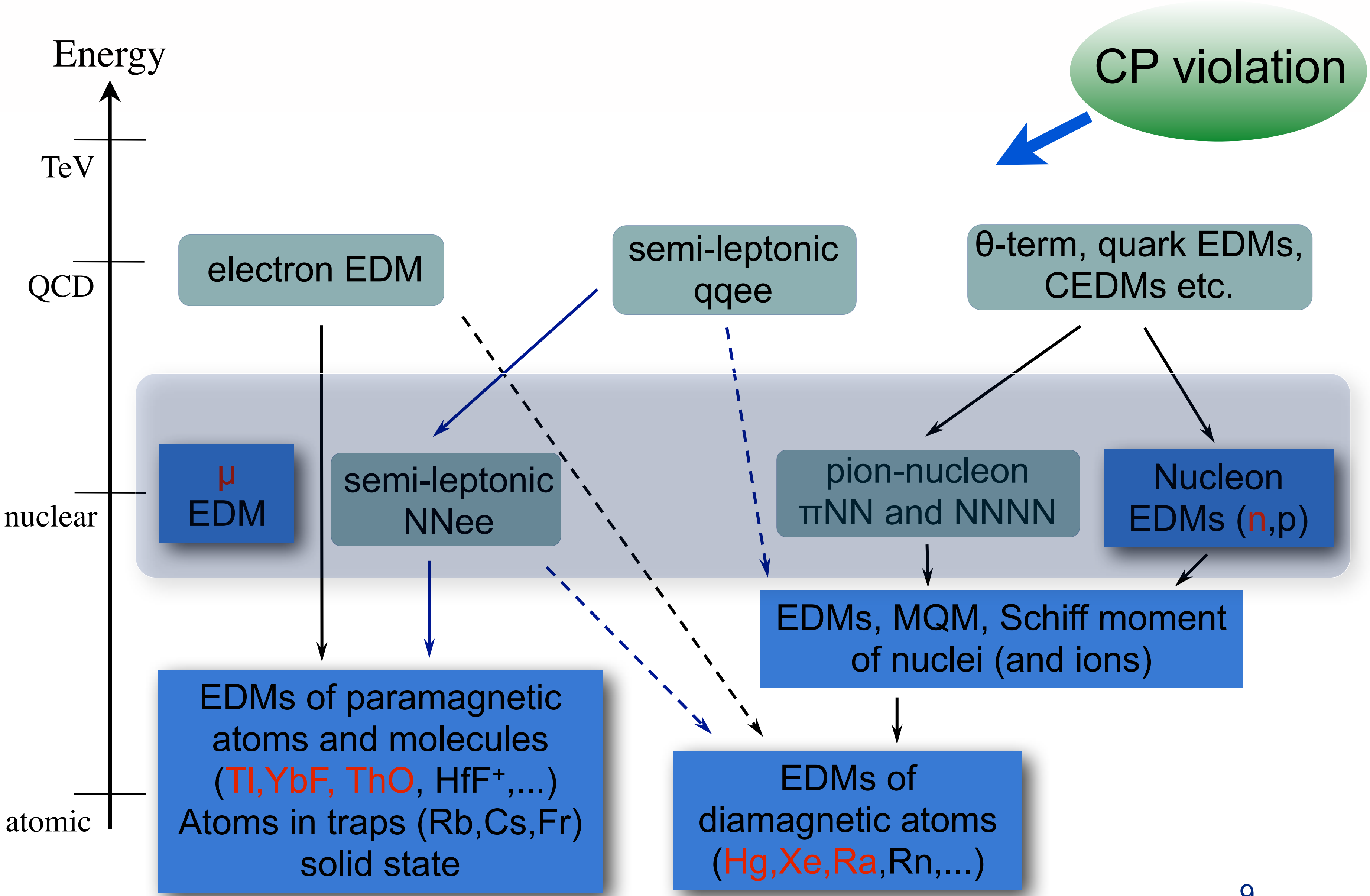
$$\mathcal{L}_{\rm dim\,6} \supset w g_s^3 G G\tilde G + \sum_{f,f',\Gamma} C'_{ff'} (\bar f \Gamma f')_{LL} (\bar f \Gamma f')_{RR}$$

$$\mathcal{L}_{\text{``dim 8''}} \supset \sum_{q,\Gamma} C_{qq} \bar q \Gamma q \bar q \Gamma i\gamma_5 q + C_{qe} \bar q \Gamma q \bar e \Gamma i\gamma_5 e + \cdots$$

$$C_{ij} \sim c Y_i Y_j \frac{v^2}{\Lambda^4}$$

[→Talk by V. Cirigliano]

CP-odd EFT



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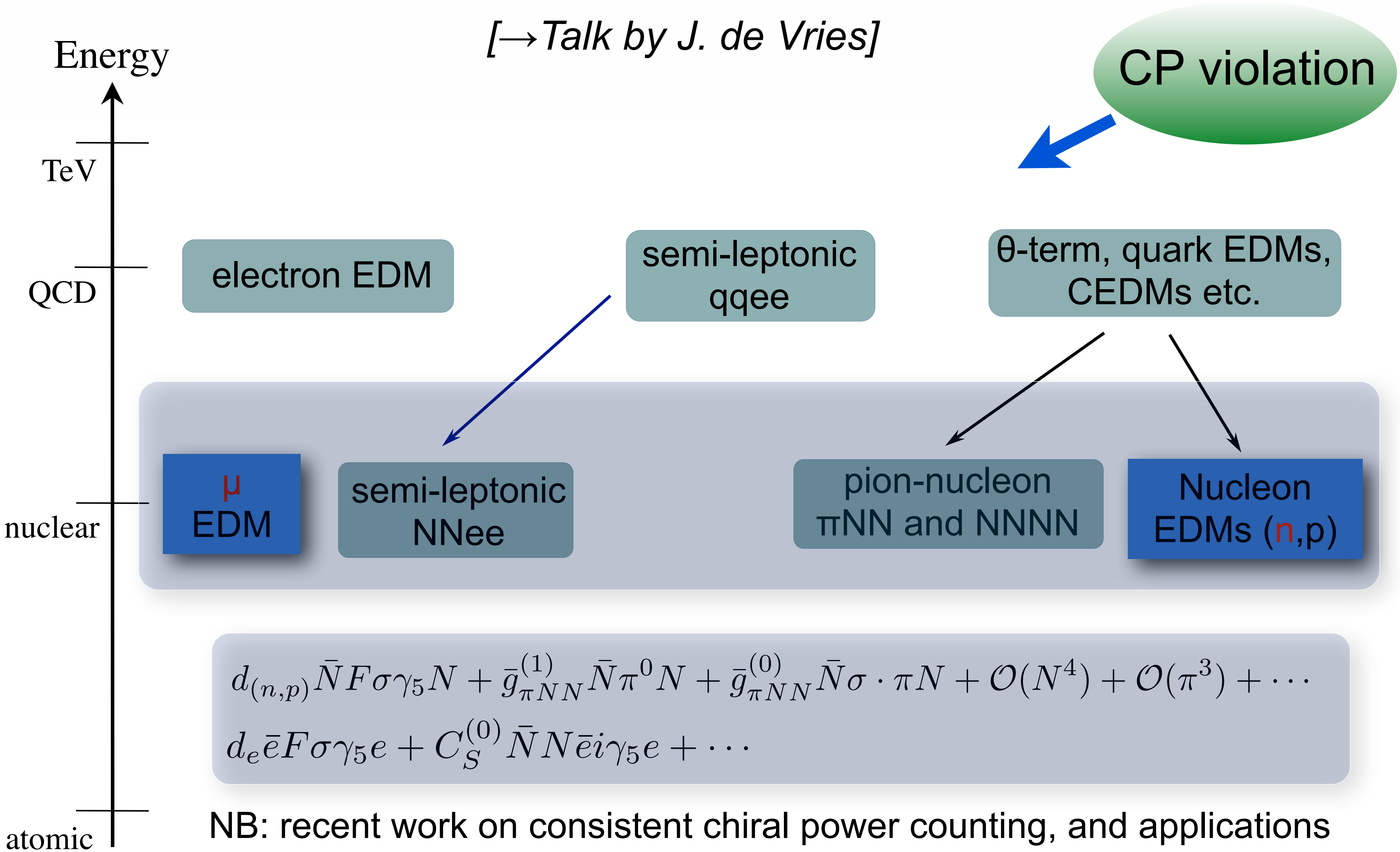
CP-odd EFT

[→Talk by J. de Vries]

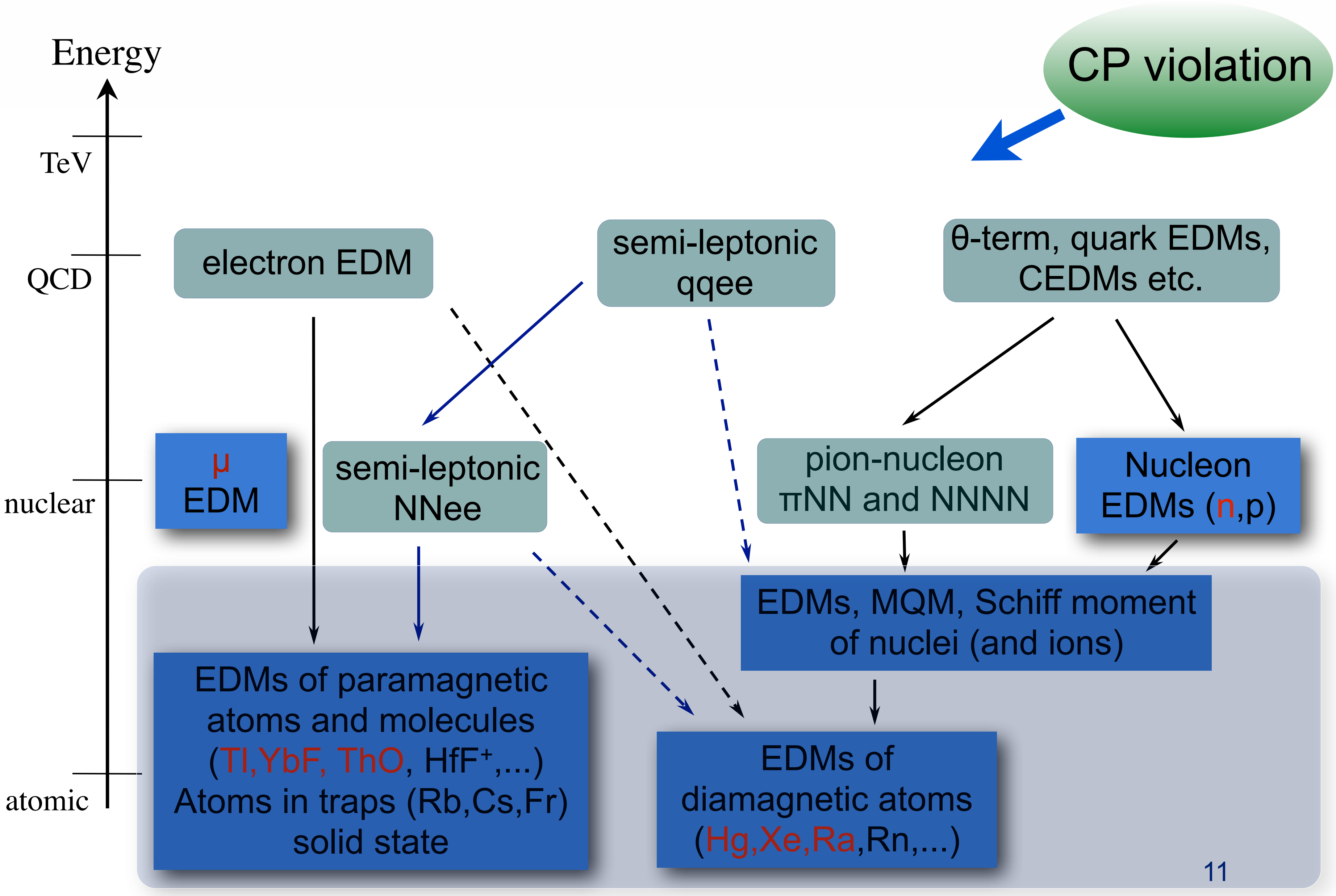


$$d_{(n,p)} \bar{N} F \sigma \gamma_5 N + \bar{g}^{(1)}_{\pi NN} \bar{N} \pi^0 N + \bar{g}^{(0)}_{\pi NN} \bar{N} \sigma \cdot \pi N + \mathcal{O}(N^4) + \mathcal{O}(\pi^3) + \cdots$$

$$d_e \bar{e} F \sigma \gamma_5 e + C^{(0)}_S \bar{N} N \bar{e} i \gamma_5 e + \cdots$$

NB: recent work on consistent chiral power counting, and applications [Stetcu et al ’08, de Vries et al. ‘11,12; Guo & Meissner ’12, Dekens et al ’14, Bsaisou et al ’15]

CP-odd EFT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EDMs of paramagnetic atoms and molecules (Tl,YbF, ThO, HfF⁺,...) Atoms in traps (Rb,Cs,Fr) solid state
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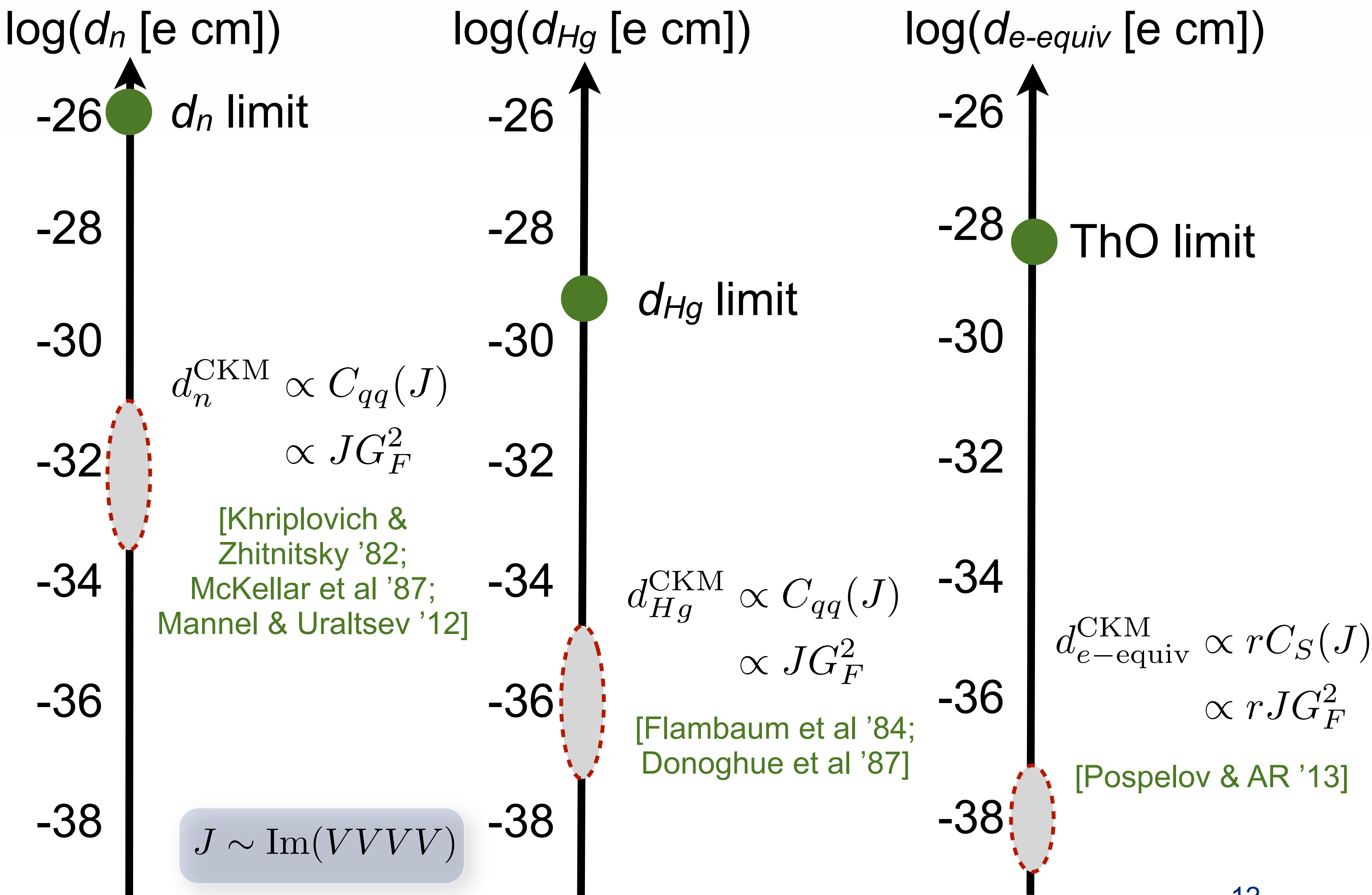
EDMs in the Standard Model (CKM phase)



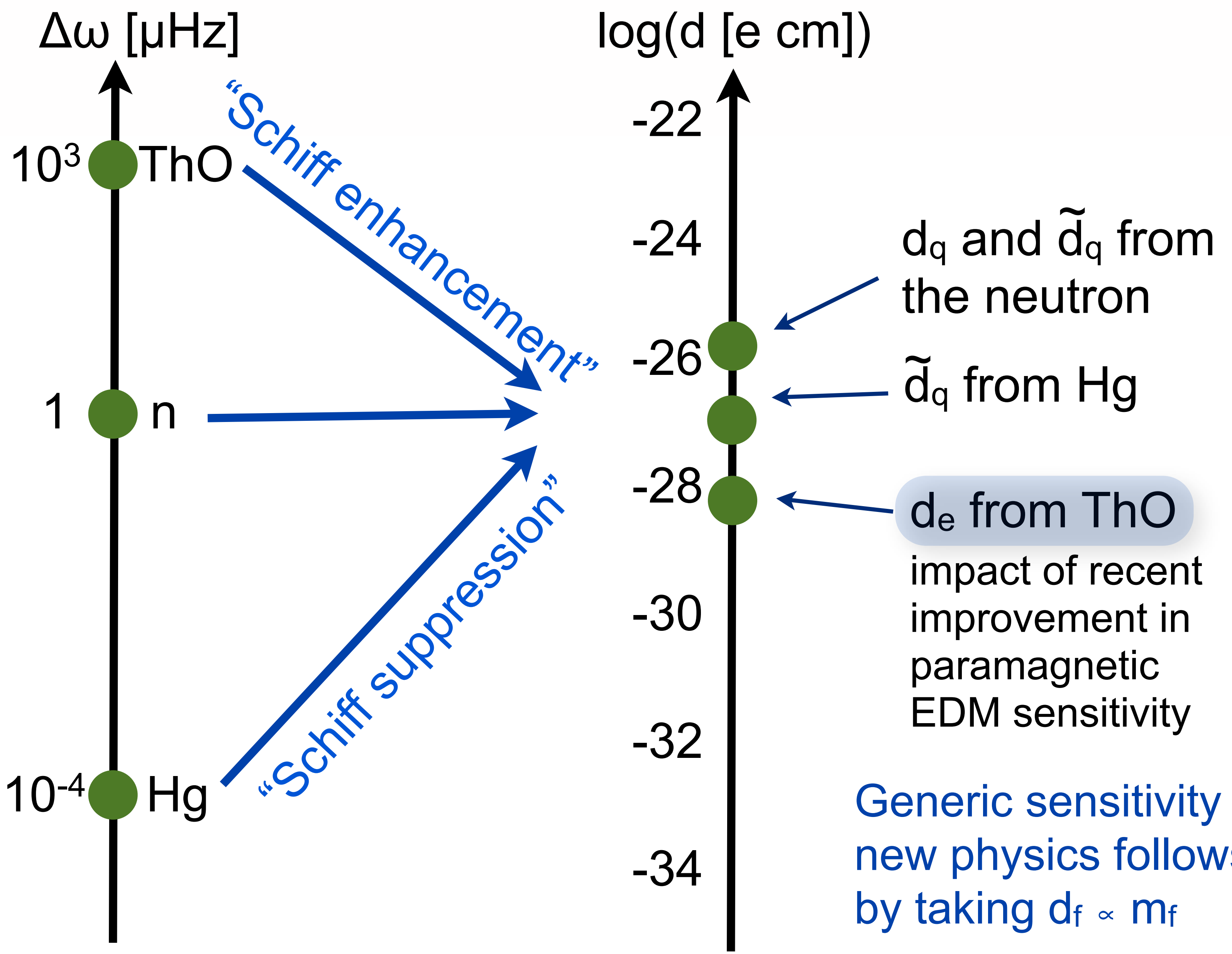
Resulting Bounds on fermion EDMs & CEDMs

ThO	$\left\| d_e + e(26\,\mathrm{MeV})^2 \left(3\frac{C_{ed}}{m_d} + 11\frac{C_{es}}{m_s} + 5\frac{C_{eb}}{m_b}\right)\right\| < 8.7\times 10^{-29} e\,cm$ (precision ~ 30%) [Koslov et al '94-98, Meyer & Bonn '08, Skripnikov et al '13]
n	$\|e(\tilde{d}_d^{(0.9\mathrm{GeV})} + 0.5\tilde{d}_u^{(0.9\mathrm{GeV})}) + 1.3(d_d^{(0.9\mathrm{GeV})} - 0.25 d_u^{(0.9\mathrm{GeV})}) + \mathcal{O}(\tilde{d}_s, w, C_{qq})\| < 2\times 10^{-26} e\,\mathrm{cm}$ (using QCDSR - NB: LQCD-inferred nucleon coupling reduces this by factor of 1.5-2, which brings q-EDM contribution into line with recent lattice tensor charge calculations) (precision ~ 50%) [Pospelov & AR '99-01, Hisano et al '12]
Hg	$\|\tilde{d}_d^{(0.9\mathrm{GeV})} - \tilde{d}_u^{(0.9\mathrm{GeV})} + \mathcal{O}(d_e, \tilde{d}_s, w, C_{qq}, C_{qe})\| < 6\times 10^{-27}\mathrm{cm}$ (using QCDSR + "best value" for $S(g^1)$ from Engel et al '13) (precision ~ ??%) [Dzuba et al '02, Ban et al '10, Pospelov '01]

See also recent compilation of limits: [Engel, Ramsey-Musolf, van Kolck '13]

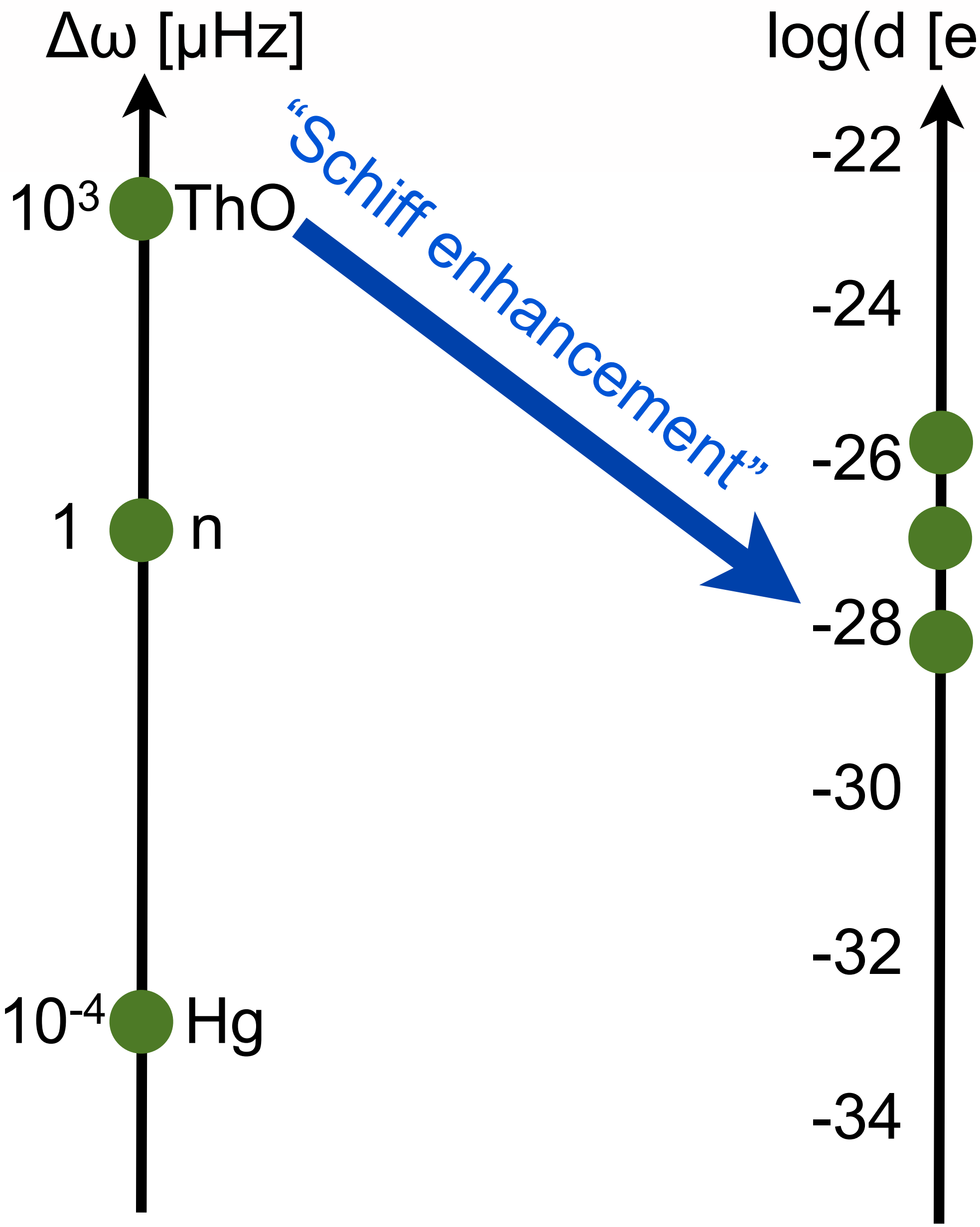
NB: PQ relaxation of θ assumed. BUT, with current precision, a nonzero neutron and/or Hg EDMs couldn't unambiguously point to a source other than θ.

Summary of the bounds



Generic sensitivity to new physics follows by taking $d_f \propto m_f$

Summary of the bounds

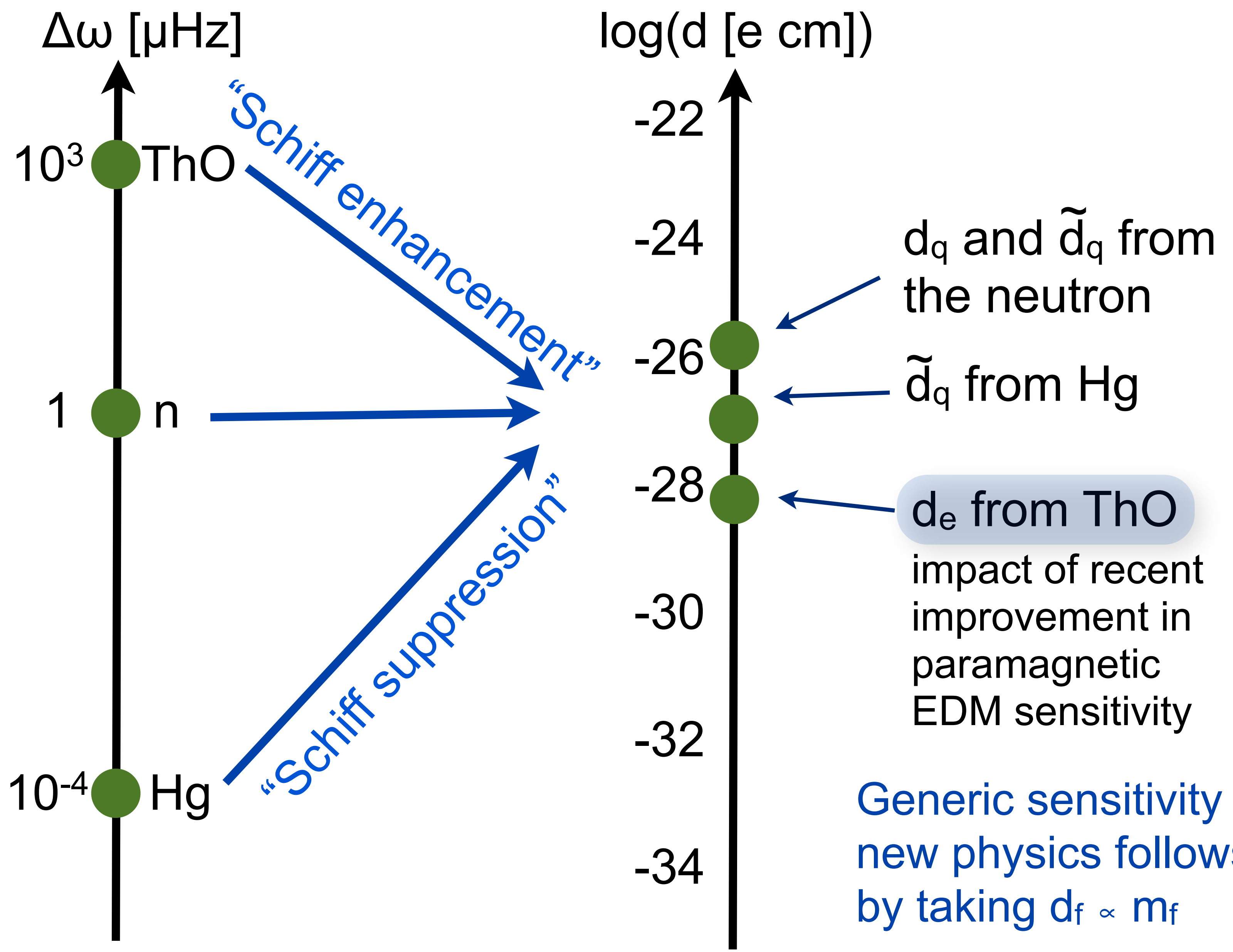


Contributions from d_e and C_S, so this can also be read as sensitivity to $(d_e)^{equiv} = r\,C_S$

d_e from ThO

~30% precision, but for Tl, YbF, and ThO, the relative coefficient between d_e and C_S is similar, so this sensitivity assumes minimal cancelation.

Summary of the bounds



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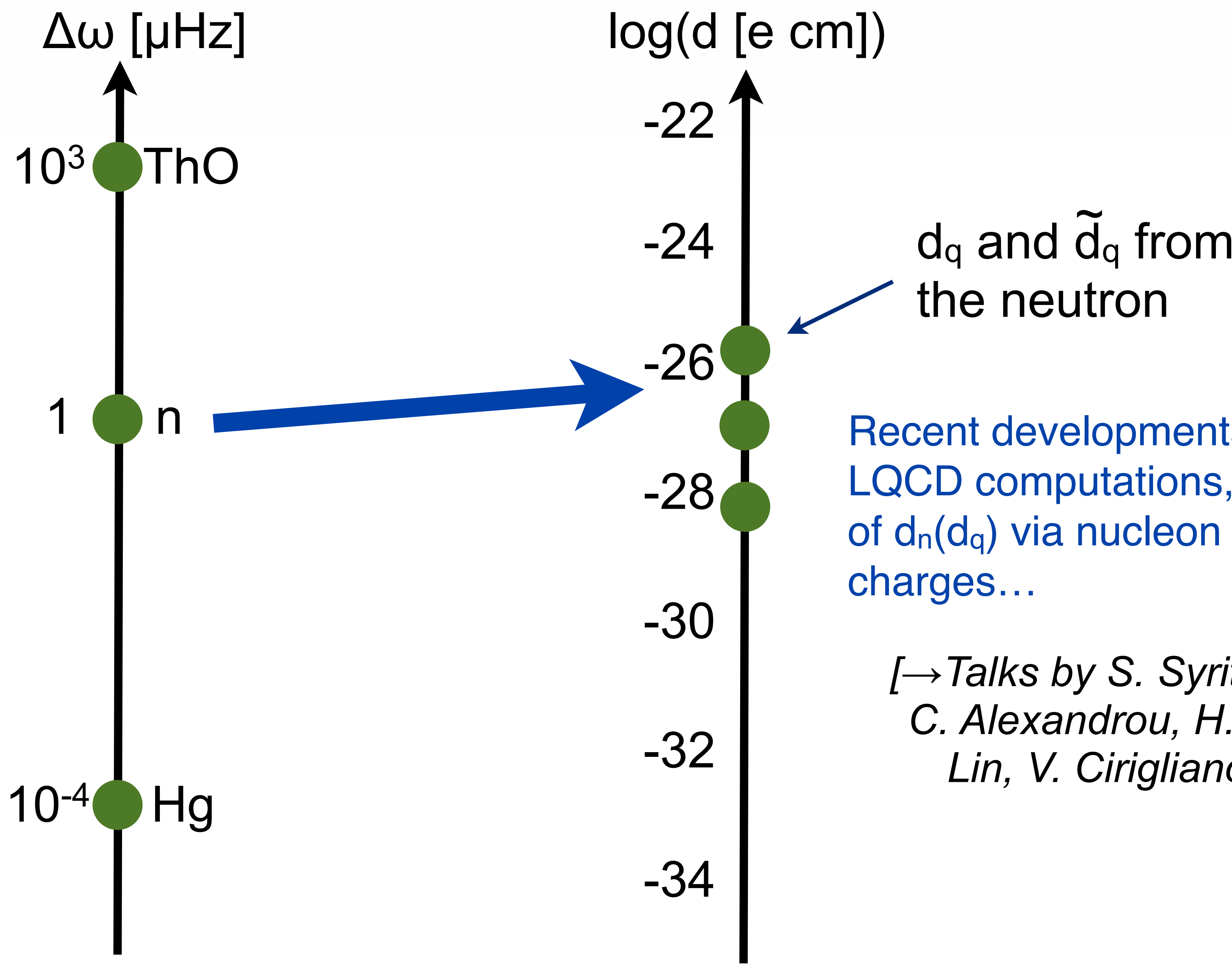
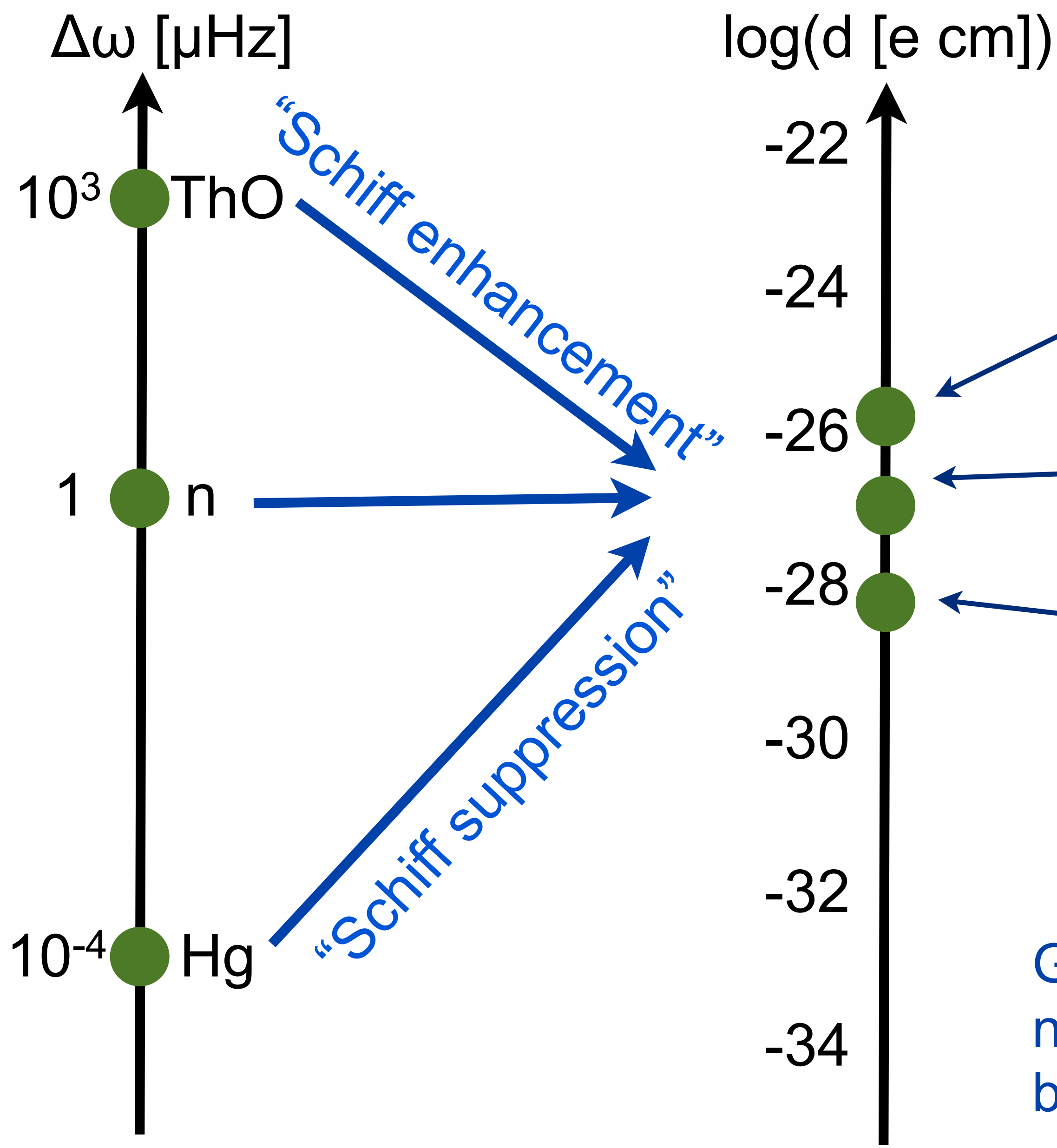


Recent developments in LQCD computations, e.g. of $d_n(d_q)$ via nucleon tensor charges…

[→Talks by S. Syritsyn, C. Alexandrou, H.-W. Lin, V. Cirigliano]

Summary of the bounds



d_q and $\tilde{d}_q$ from the neutron

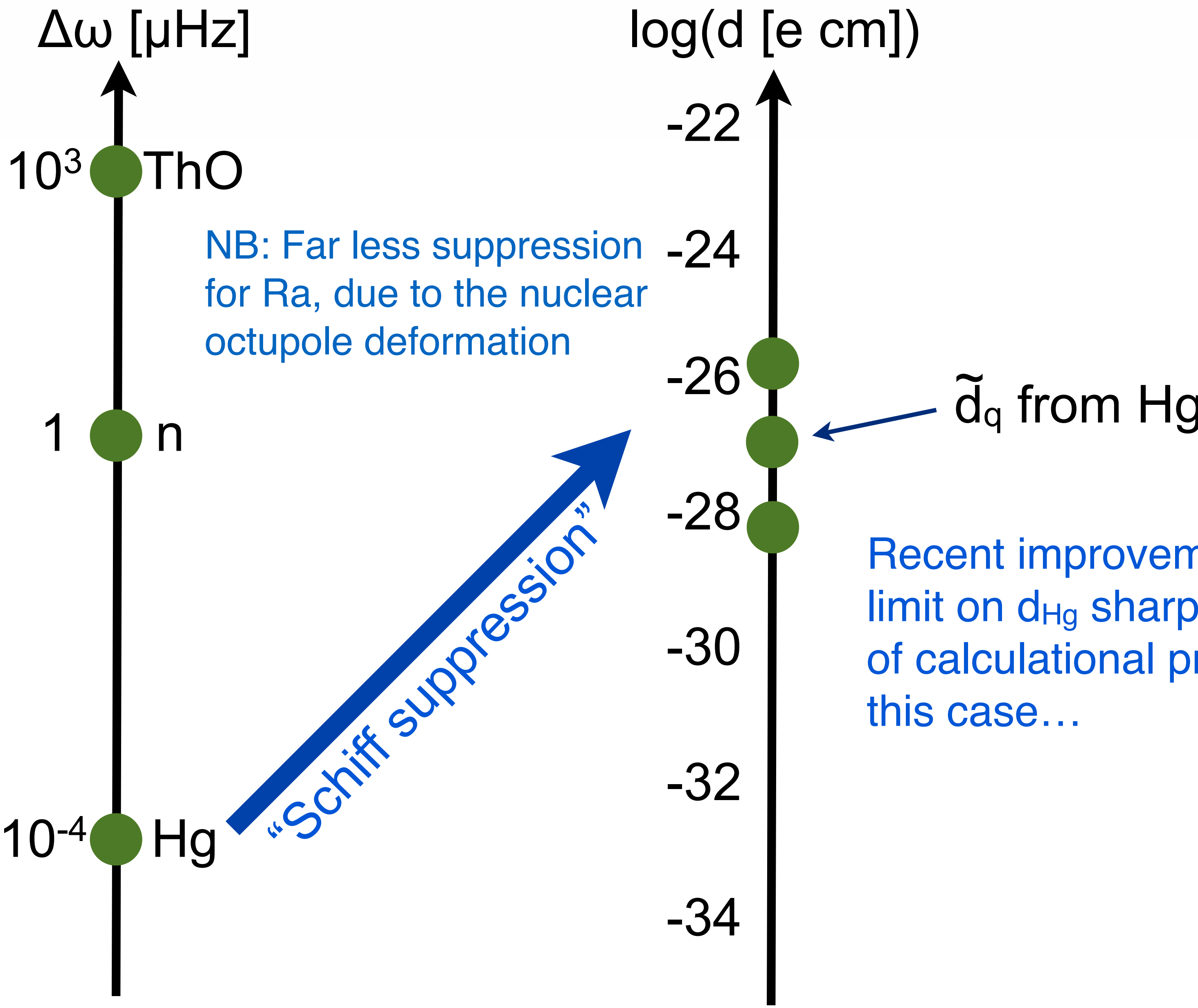
$\tilde{d}_q$ from Hg

d_e from ThO

impact of recent improvement in paramagnetic EDM sensitivity

Generic sensitivity to new physics follows by taking $d_f \propto m_f$

Summary of the bounds



NB: Far less suppression for Ra, due to the nuclear octupole deformation

Recent improvement in the limit on d_{Hg} sharpens the issue of calculational precision in this case…

Diamagnetic EDMs - precision

"Schiff Suppression" $d_{Hg} \sim 10Z^2(R_N/R_A)^2 d_{\rm nuc} \sim \mathcal{O}(10^{-3}) d_{\rm nuc}$

$$d_{\rm Hg} \sim -3\times 10^{-17}\left(\frac{S(^{199}{\rm Hg})}{e\,{\rm fm}^3}\right) e\,{\rm cm} + \mathcal{O}(d_e, C_{qe}, C_{qq})$$

Schiff moment
[Schiff '63]

[Flambaum et al '86;
Dzuba et al. '02]

$$\vec{S} = S\frac{\vec{I}}{I} = \frac{1}{10}\left[\int e\rho(\vec{r})\vec{r}r^2 d^3r - \frac{5}{3Z}\vec{d}\int \rho(\vec{r})r^2 d^3r\right]$$

Require <0|S_z|0>, and the original calculation [Flambaum et al '86] considered a mean-field nuclear potential, and accounted for interactions of the valence nucleon with the core

$$H_{CP}^{\rm nucleon-core} = \xi\vec{\sigma}\cdot\vec{\nabla}U, \qquad \xi = \eta(\bar{g}_i)\frac{G}{2\sqrt{2}m}\frac{\rho(0)}{U(0)} \sim -0.12(g\bar{g}^0 + g\bar{g}^1 + \cdots)\,{\rm fm}$$

$$S(^{199}{\rm Hg}) \sim \frac{e}{10}\xi R_{\rm nuc}^2$$

[Flambaum et al '86]

$$\approx -0.09 g(\bar{g}^0 + \bar{g}^1 + \cdots)\, e\cdot {\rm fm}^3$$

Later calculations suggest collective multi-particle effects may be significant...

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$$S = (a_0 + b) g\bar{g}^0 + a_1 g\bar{g}^1 + \cdots$$

[Flambaum et al '86, Dmitriev & Sen'kov '03; de Jesus & Engel '05; Ban et al. '10]

	$E_{\rm gs}$	β	$E_{\rm exc.}$	a_0	a_1	a_2	b
SLy4	-1561.42	-0.13	0.97	0.013	-0.006	0.022	0.003
SIII	-1562.63	-0.11	0	0.012	0.005	0.016	0.004
SV	-1556.43	-0.11	0.68	0.009	-0.0001	0.016	0.002
SLy4	-1560.21	-0.10	0.83	0.013	-0.006	0.024	0.007
SkM*	-1564.03	0	0.82	0.041	-0.027	0.069	0.013
Ref. [6]	—	—	—	0.0004	0.055	0.009	—
Ref. [8]	—	—	—	0.007	0.071	0.018	—

Suggests potentially large suppression of a_0 and/or a_1 relative to "natural" scale ~ 0.09

[Ban et al. '10]

$g^{0,1}$ primarily sensitive to quark CEDMs

coupling	preferred range
$\bar{g}^{(1)}_{\pi NN} \times 10^{12}$	$(1 \text{ to } 6)\ d_{-,26}$
$\bar{g}^{(0)}_{\pi NN} \times 10^{12}$	$(-0.5 \text{ to } 1.5)\ d_{+,26}$

[Pospelov '01]

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[Ban et al. '10]

Nucleon EDMs also contribute [Dmitriev & Sen'kov '03], and the new Hg EDM limit nominally provides sensitivity to d_n comparable to the direct measurement…

Diamagnetic EDMs - precision

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Further prospects for accessing CP-odd χEFT couplings

- Ra EDM has an enhanced Schiff moment (octupole deformation), and may be computationally more tractable. *[→Talk by M. Dietrich]*
- Schiff moment is dominant for large atoms (Hg, Xe, Ra). MQM is dominant for smaller nuclei and classes of molecules of recent interest (^{229}ThO, TaN) [Flambaum, DeMille, Kozlov '14]
- Storage rings could allow direct measurement of light *nuclear EDMs*, avoiding Schiff suppression, e.g. for p, and light nuclei tractable with χEFT [Stetcu et al '08, de Vries et al. '11,12; Dekens et al '14, Bsaisou et al '15]

[→Talks by Y.-I. Kim, F. Rathmann, N.N. Nikolaev]

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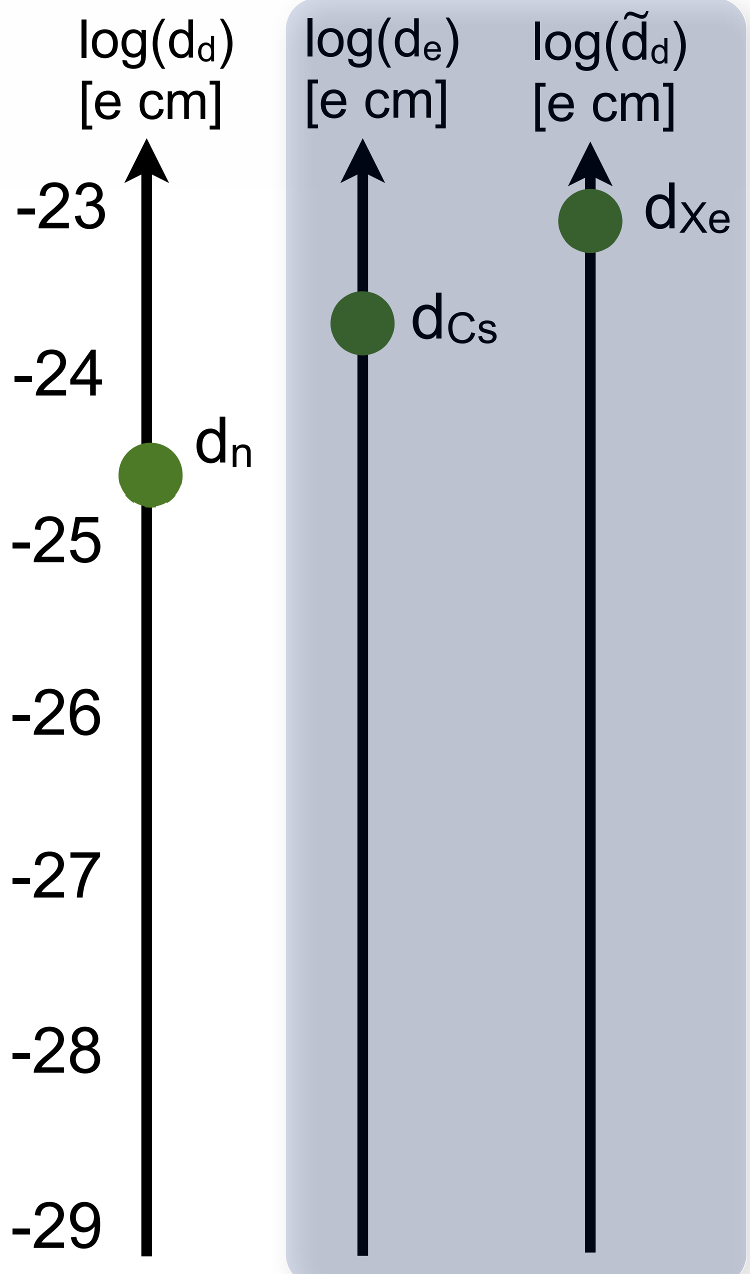
History + Sensitivity to (light) new physics in a hidden sector

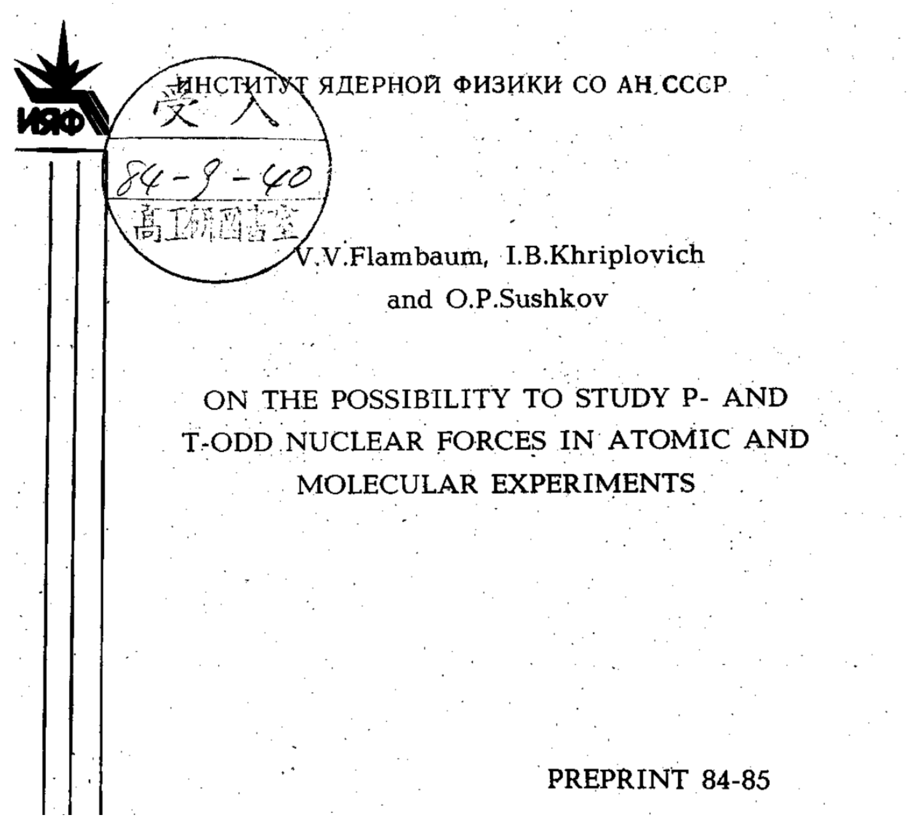
[→Talk by V. Cirigliano]

Looking back…

Looking back 30 years (~1985)…



EDM sensitivity through para- and diamagnetic atoms circa 1985…



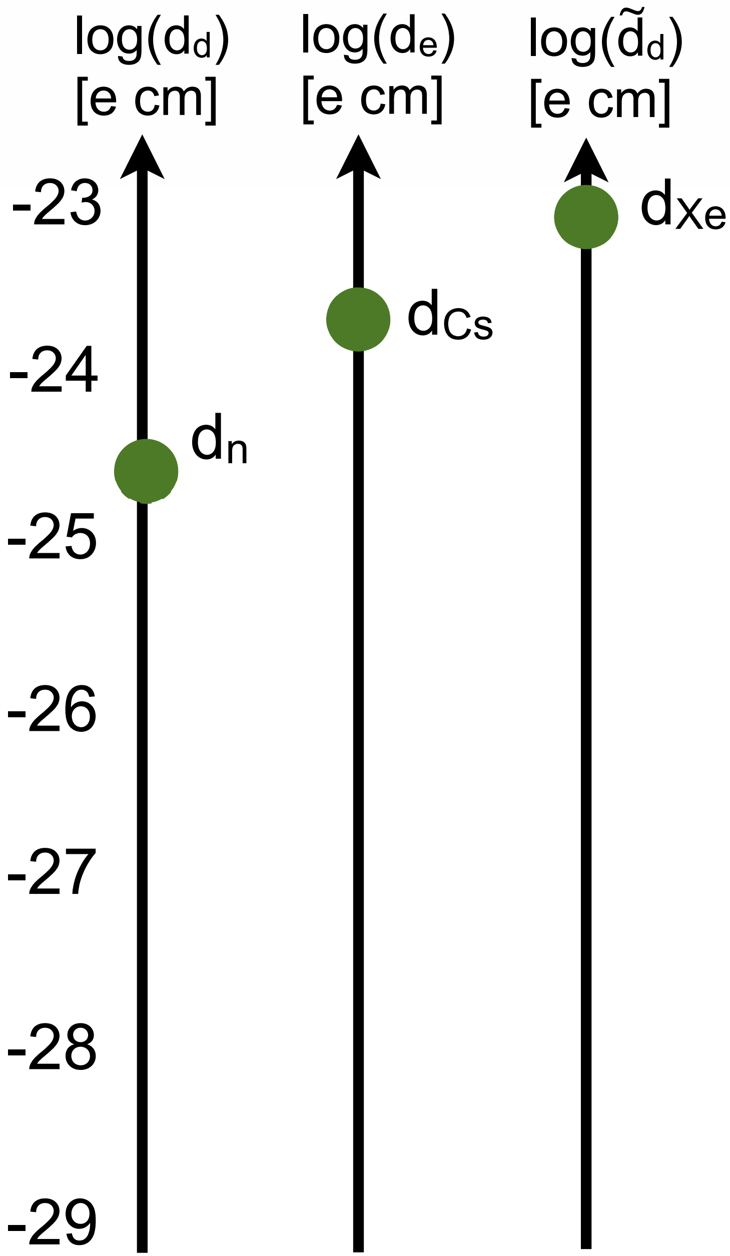
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

V.V.Flambaum, I.B.Khriplovich and O.P.Sushkov

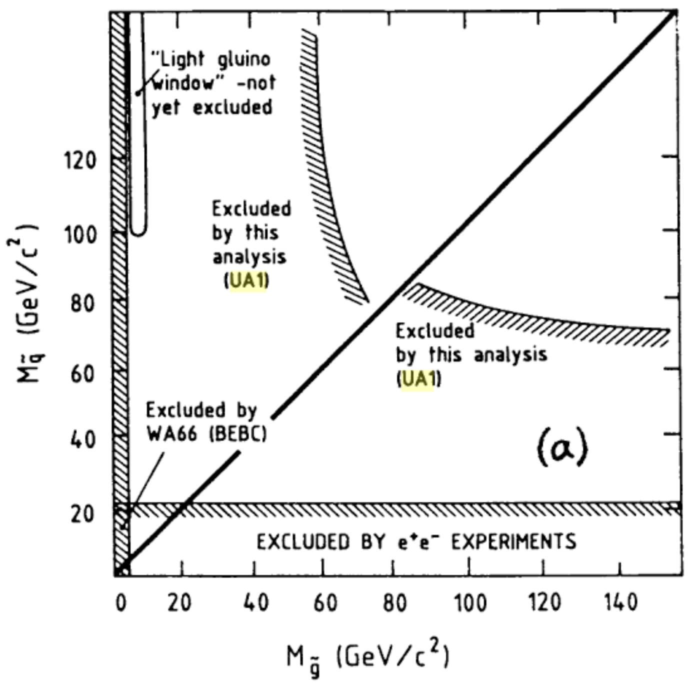
ON THE POSSIBILITY TO STUDY P- AND T-ODD NUCLEAR FORCES IN ATOMIC AND MOLECULAR EXPERIMENTS

PREPRINT 84-85

Looking back 30 years (~1985)…



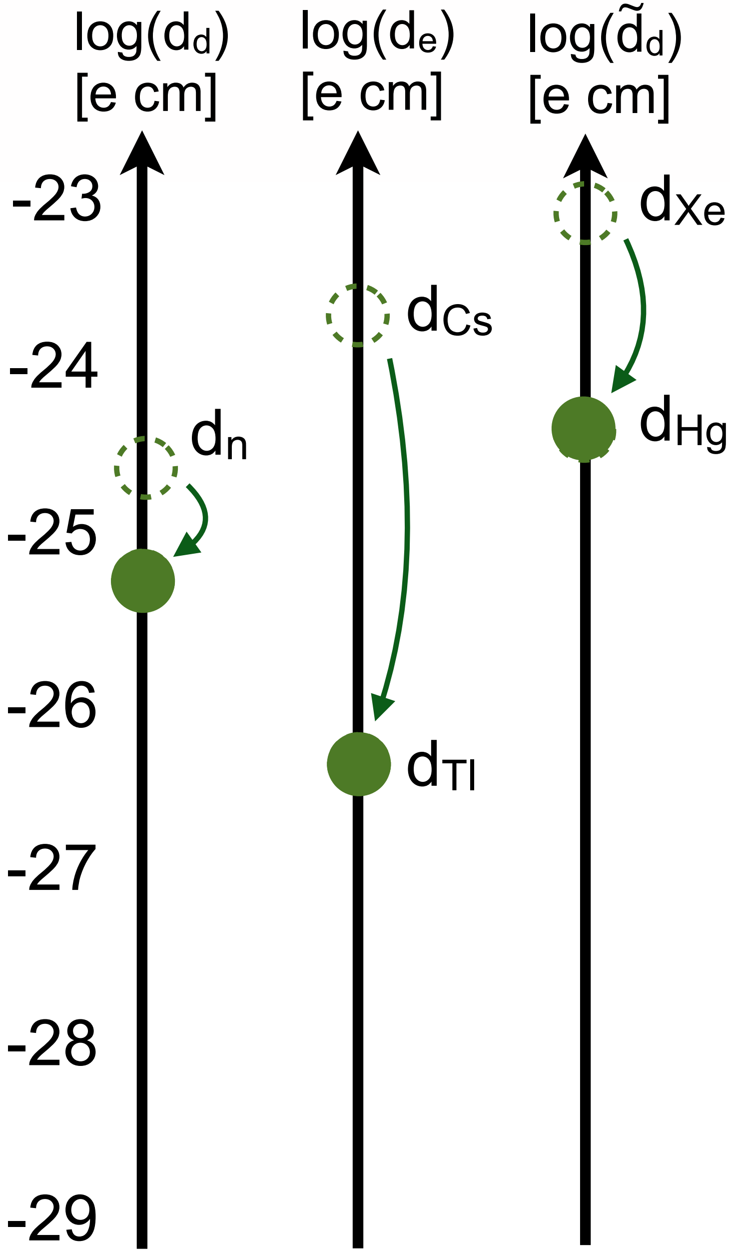
Comparison with direct mass limits on new (strongly-interacting) particles…



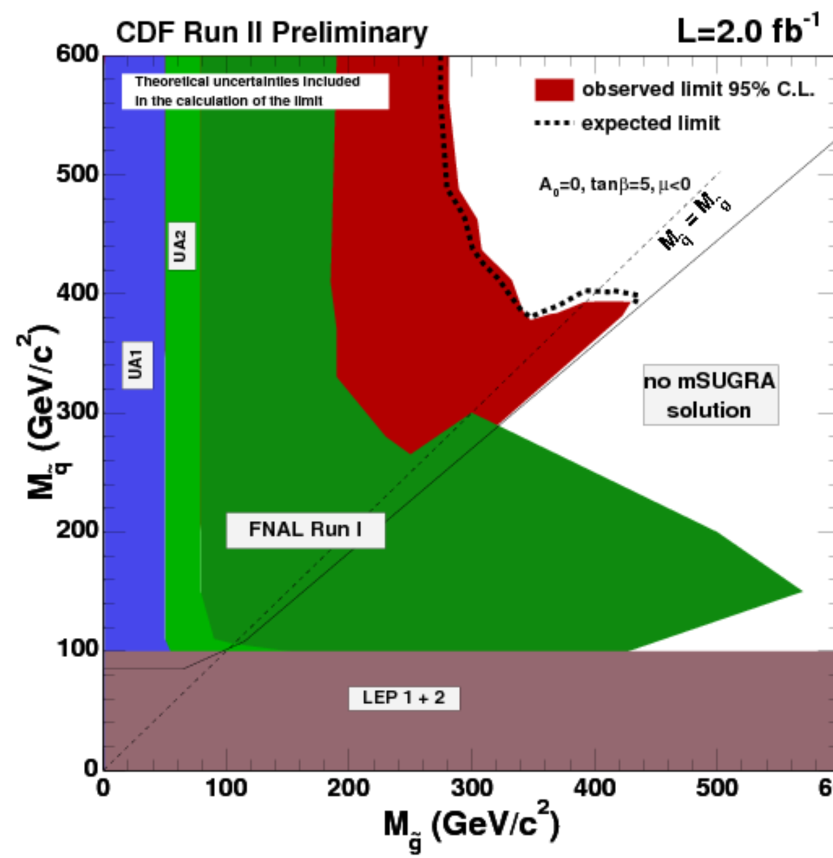
$$d \sim (\text{loop}) \times \frac{m_f}{\Lambda^2} \sim 10^{-25} e\text{cm} \left(\frac{1\,\text{TeV}}{\Lambda}\right)^2$$

(assuming O(1) CP phases)

Looking back 15 years (~2000)…



Comparison with direct mass limits on new (strongly-interacting) particles [NB: red exclusions from Run II came after 2001]



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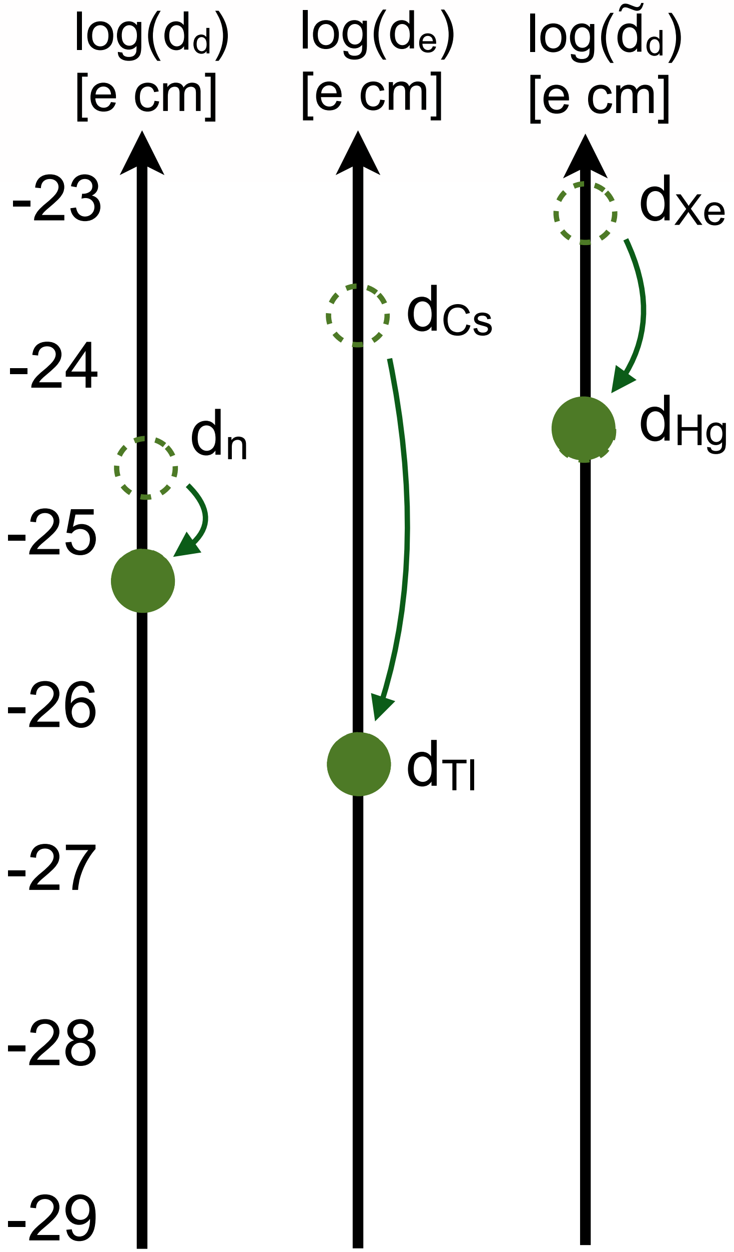
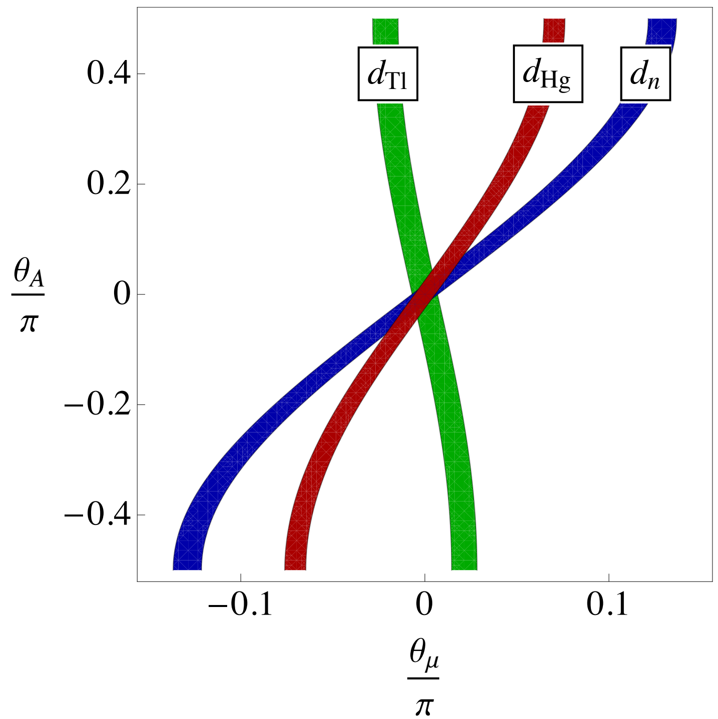


M_{susy} = 500 GeV



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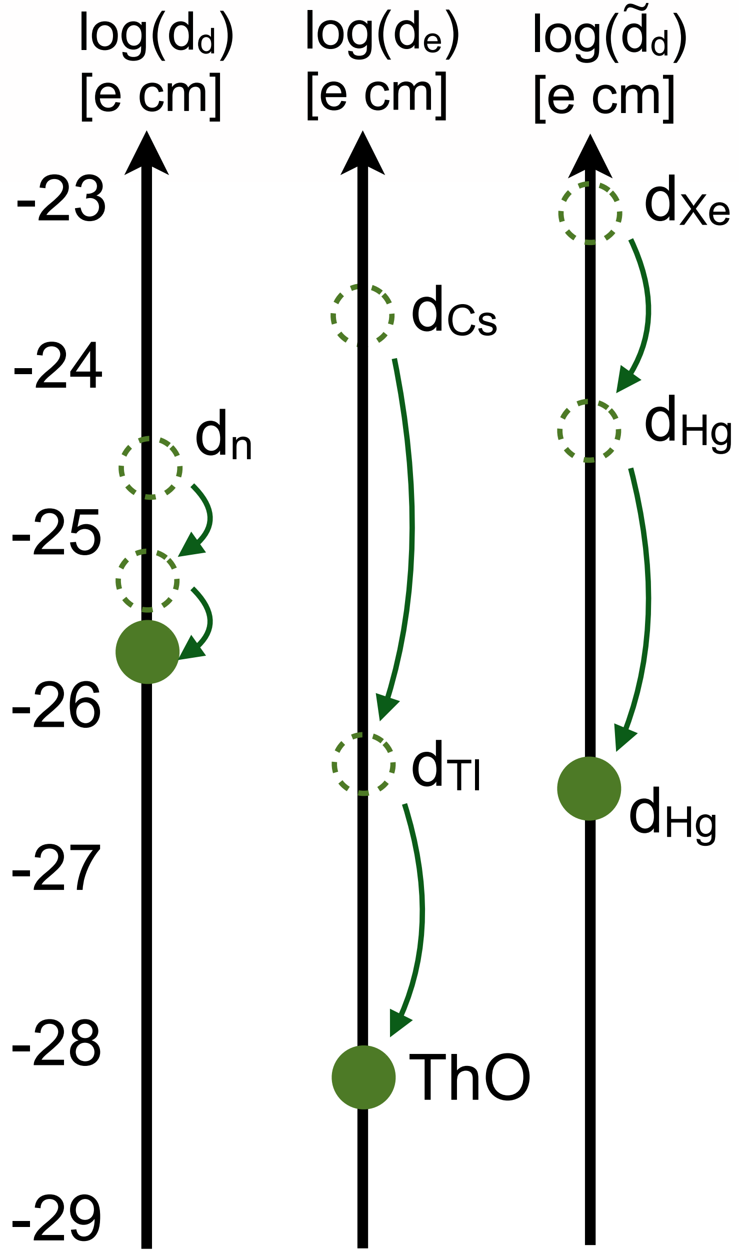
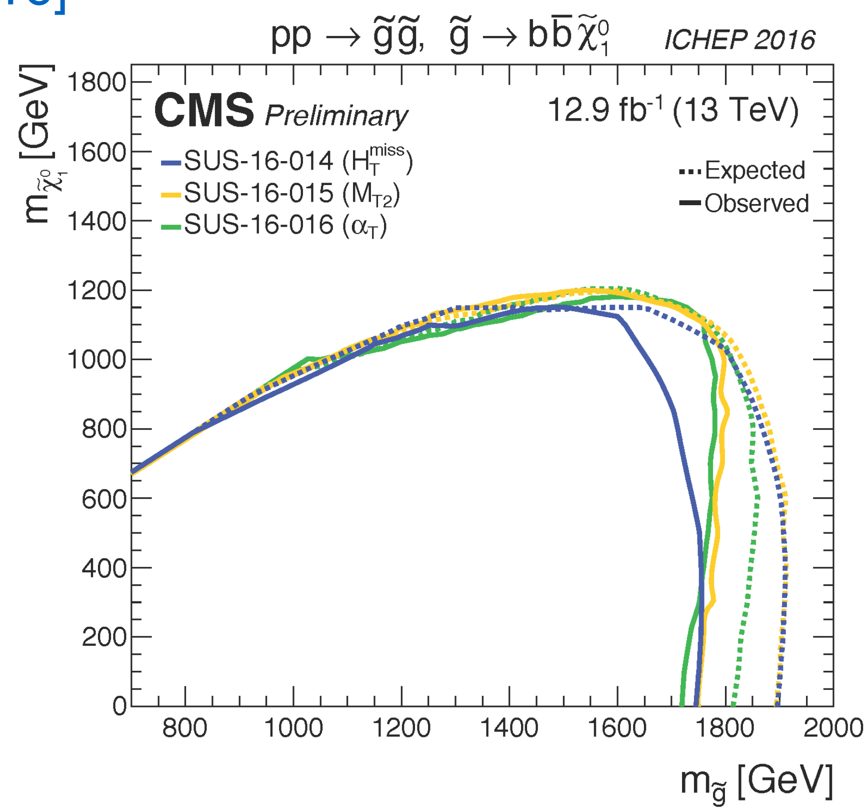
Looking back 0 years…



Comparison with direct mass limits on new (strongly-interacting) particles [from ICHEP 2016]



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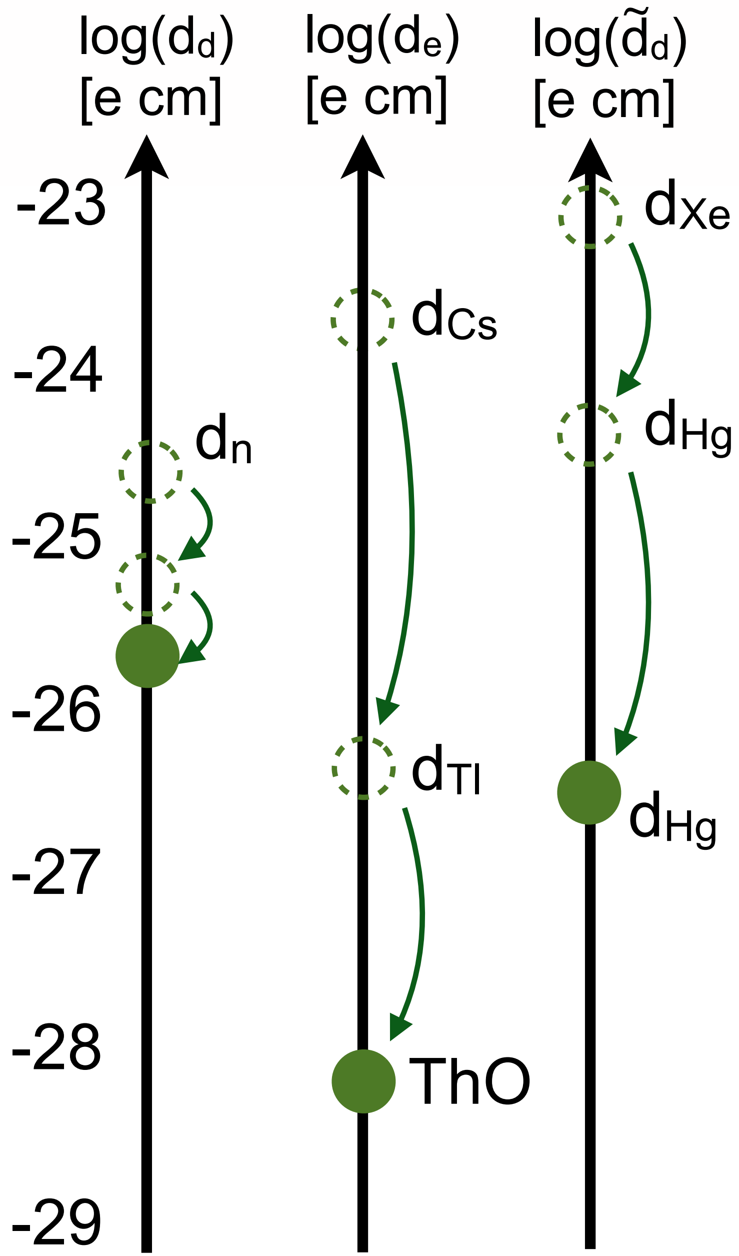

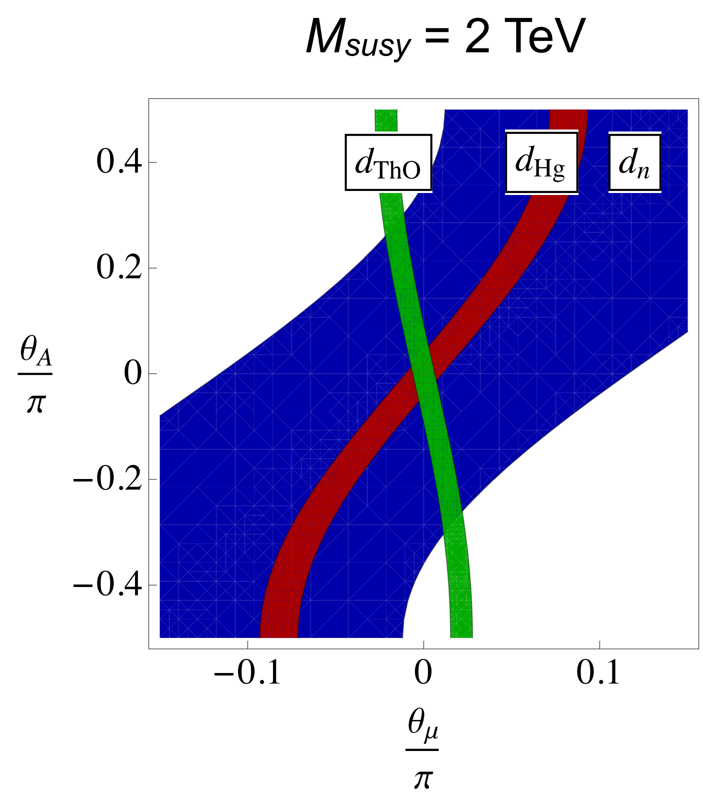

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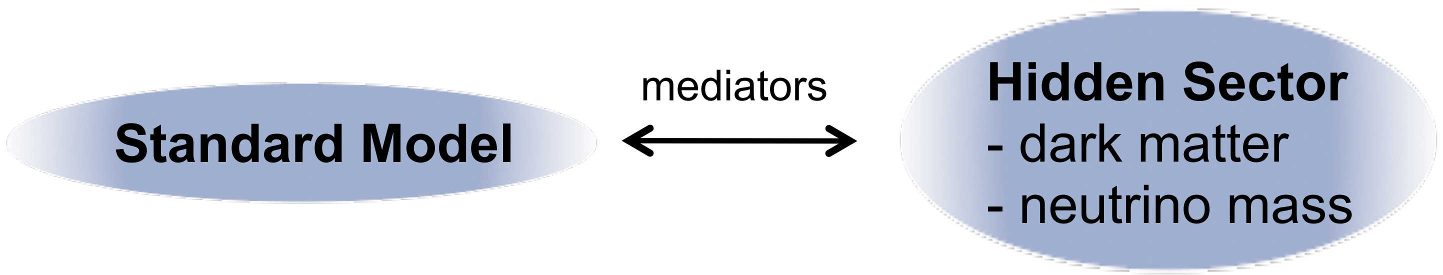
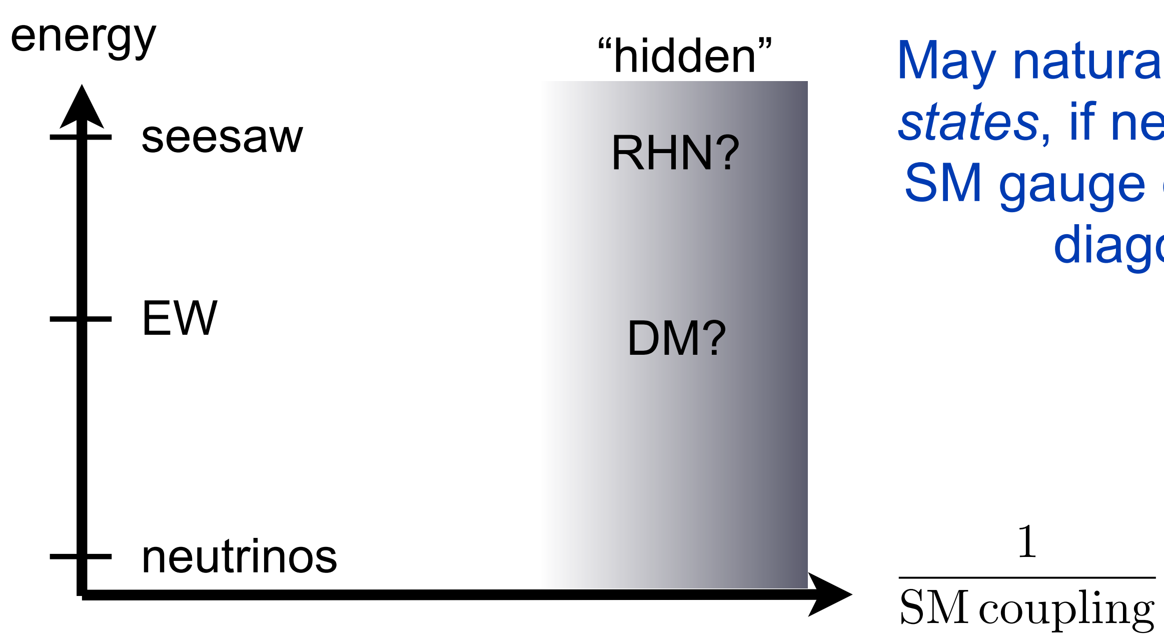
Precision probes of a hidden sector

- Empirical evidence for new physics (neutrino oscillations, dark matter, baryon asymmetry) doesn't a priori point to a specific mass scale





May naturally contain *light states*, if neutral under the SM gauge group, flavour-diagonal, etc

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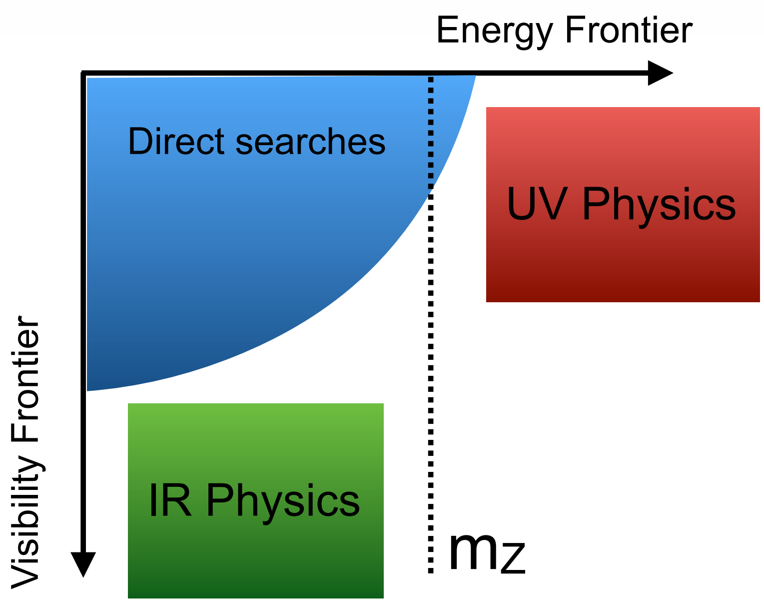


- Precision observables that vanish (or are suppressed) by **symmetry** in the SM allow for broad new physics searches, with indirect reach in both mass scale *and* weak coupling (visibility)

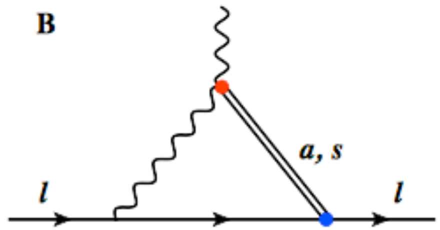
What do EDMs imply for (light) new physics….?

Precision Tests and IR New Physics

In general, EDMs already provide stringent constraints on light dofs with CP-odd couplings, e.g. a light (< 1 GeV) CP-odd scalar

$$\mathcal{L} = \frac{\tilde{g}_{\Phi\gamma\gamma}}{4}\Phi F\tilde{F} + \frac{g_{\Phi\gamma\gamma}}{4}\Phi F^2 + \left(y_{\Phi\psi}\Phi\bar{\psi}P_L\psi + h.c.\right)$$

B

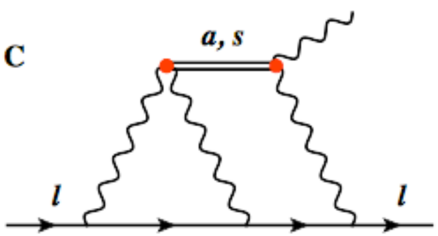


Using ACME limit on d_e

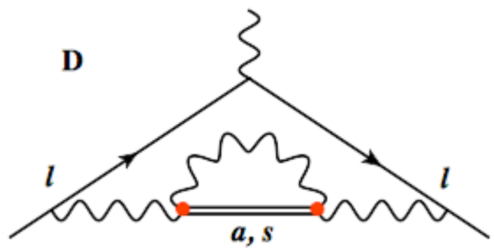
$$|g_{\Phi\gamma\gamma}\,\mathrm{Im}(y_{\Phi e})|, |\tilde{g}_{\Phi\gamma\gamma}\,\mathrm{Re}(y_{\Phi e})| \lesssim 5\times 10^{-14}\,\mathrm{GeV}^{-1}$$

$$\sqrt{|g_{\Phi\gamma\gamma}\,\tilde{g}_{\Phi\gamma\gamma}|} \lesssim 6\times 10^{-5}\,\mathrm{GeV}^{-1}$$

C



D



[Marciano et al '16]

BUT, these models are not UV-complete $g_{\Phi\gamma\gamma} \sim \alpha/\Lambda$ ... EFT arguments point to a special class of interactions, unsuppressed by a heavy mass scale Λ

EFT for a (neutral) hidden sector

Standard Model ⟷ mediators ⟷ **Hidden Sector**

$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)} \mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Generic interactions are irrelevant (dimension > 4), but there are three *UV-complete* relevant or marginal "portals" to a neutral hidden sector, unsuppressed by the (possibly large) NP scale Λ

- Vector portal: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu}$ [Okun; Holdom; Foot et al]
- Higgs portal: $\mathcal{L} = -H^\dagger H (AS + \lambda S^2)$ [Patt & Wilczek]
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$

Many more UV-sensitive interactions at dim ≥ 5

EFT for a (neutral) hidden sector

Standard Model ⟷ (mediators) **Hidden Sector**

$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)}\mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Generic interactions are irrelevant (dimension > 4), but there are three *UV-complete* relevant or marginal “portals” to a neutral hidden sector, unsuppressed by the (possibly large) NP scale Λ

- Vector portal: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu} \longrightarrow \kappa V_\mu J^\mu_{\mathrm{EM}}$
- Higgs portal: $\mathcal{L} = -ASH^\dagger H \longrightarrow \frac{Av^2}{m_h^2} S J_S$
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j \longrightarrow v Y_N^{ij} \bar{\nu}_i N_j$

Universal couplings to EM/scalar currents at low energy, so hidden sector models have correlated observable effects

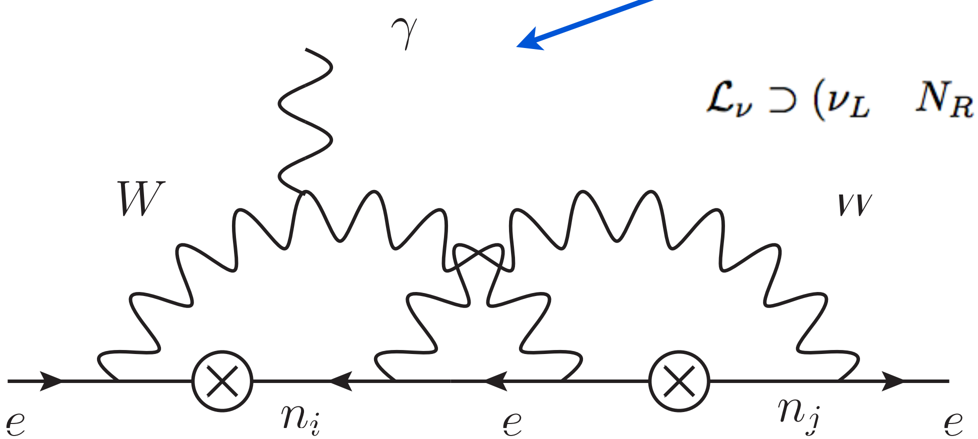
EDM Sensitivity to light (UV-complete) hidden sectors

Standard Model ⟷ Hidden Sector

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portals}(\mathcal{O}_3, \mathcal{O}_4) + \mathcal{L}_{\rm hid}$$

UV complete neutrino portal

$$\mathcal{L}_\nu \supset (\nu_L \quad N_R \quad N_S) \begin{pmatrix} 0 & m_{D_1} & m_{D_2} \\ m_{D_1} & M_R & \epsilon \\ m_{D_2} & \epsilon & M_S \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \\ N_S \end{pmatrix}$$



$$d_e \sim (3 \times 10^{-35} e{\rm cm}) \frac{m_{D_1}^2 m_{D_2}^2}{M^4} \frac{M_S^2 - M_R^2}{\rm GeV^2} \sin(2\eta)$$

➠ EDMs suppressed by constraints on light neutrino spectrum

$$d_e(\text{“}\theta_{\rm mixing}\text{”}) \lesssim 10^{-33} e \cdot cm$$

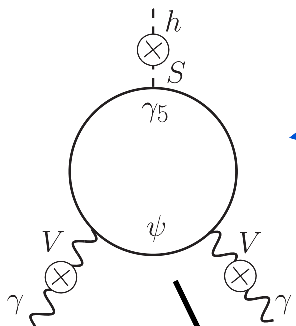
[Archambault et al ’04, Le Dall, Pospelov & AR ’15]]

EDM Sensitivity to light (UV-complete) hidden sectors

Standard Model ⟷ Hidden Sector

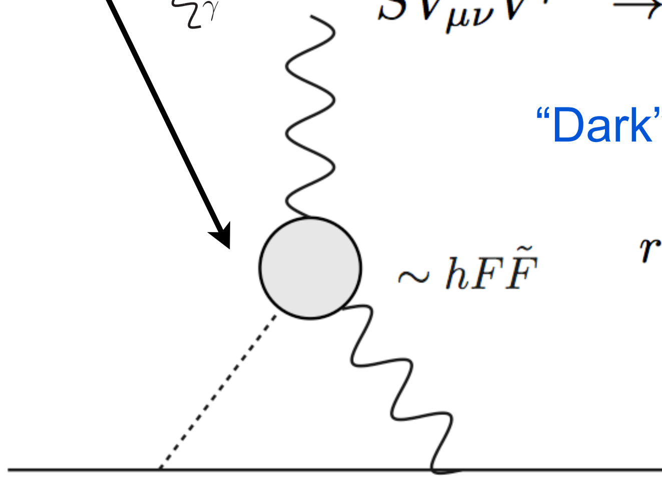
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portals}(\underbrace{\mathcal{O}_3, \mathcal{O}_4}) + \mathcal{L}_{\rm hid}$$

UV complete Higgs and vector portals



$$S V_{\mu\nu}\tilde{V}^{\mu\nu} \to \frac{i}{2}\bar{\psi}_e \sigma^{\mu\nu}\gamma_5 \psi_e V_{\mu\nu} \to \frac{i}{2}\bar{\psi}_e \sigma^{\mu\nu}\gamma_5 \psi_e \frac{\Box F_{\mu\nu}}{m_V^2}$$

“Dark” EDM generates an “EDM radius” operator



$$r_{d_f}^2 = -\frac{|e|\alpha' \tilde{Y}_S m_f}{16\pi^3 v m_\psi m_V^2} \times \kappa^2 \theta \ln(m_\psi^2/m_S^2)$$

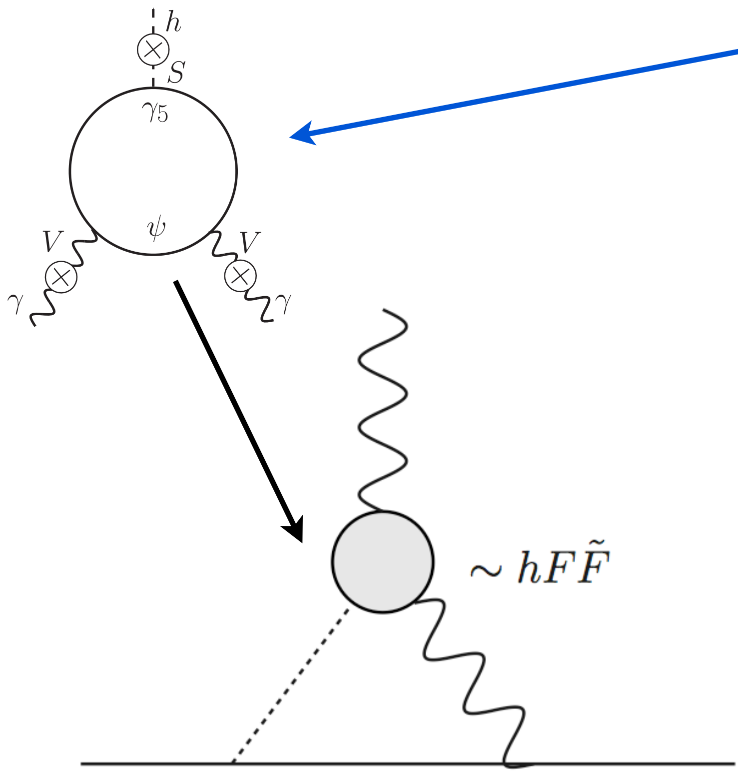
$$d_e \sim (Z\alpha m_e)^2 r_{d_e}^2$$

[Le Dall, Pospelov & AR ’15]

EDM Sensitivity to light (UV-complete) hidden sectors

Standard Model ⟷ Hidden Sector

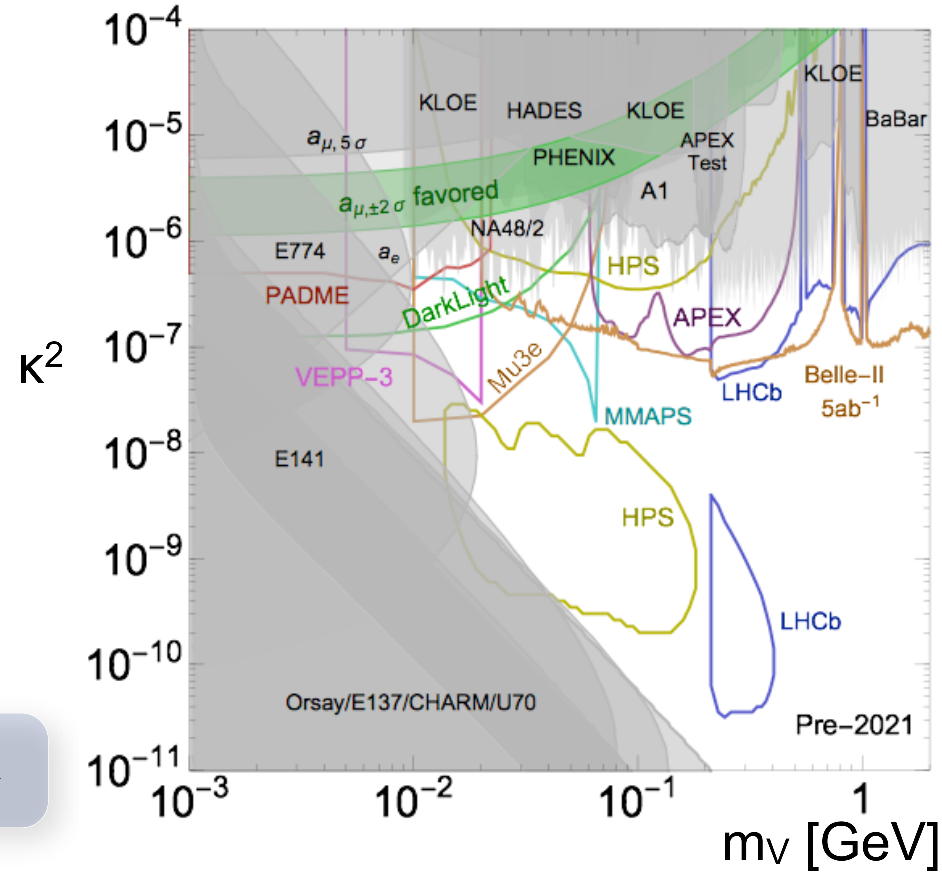
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portals}(\mathcal{O}_3, \mathcal{O}_4) + \mathcal{L}_{\rm hid}$$



$$d_e(\text{“}\theta_{\rm mixing}\text{”}) \lesssim 10^{-32} e \cdot cm$$

[Le Dall, Pospelov & AR '15]

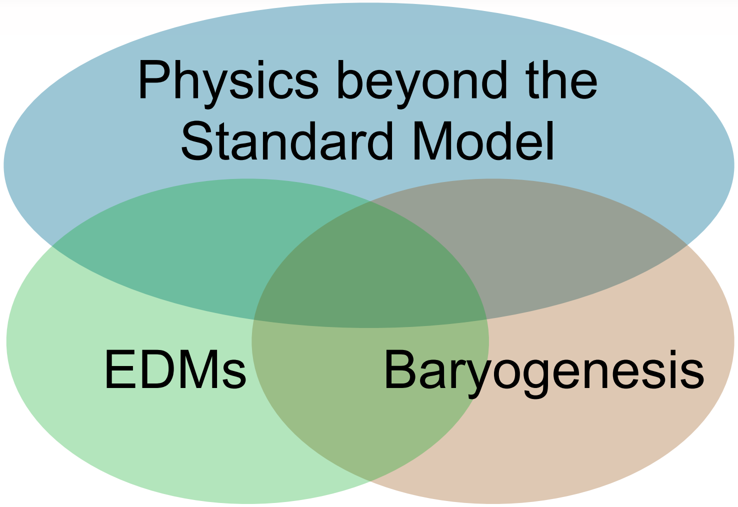
[Dark Sectors 2016, Alexander et al '16]



➟ EDM suppressed by limit on 1-loop (“dark photon”) correction to $(g-2)_e$

Summary/Outlook

EDMs remain powerful probes of new flavour-diagonal CP-violation



- Progress with χEFT for light nuclei motivates the SR EDM program, but *experimental results* in AMO physics (e.g. new limit on Hg EDM) motivate further efforts to quantify calculational precision for diamagnetic EDMs

- A nonzero EDM near the current level of sensitivity would point to new UV physics, rather than *UV-complete* light hidden sectors (distinct from many other precision leptonic observables, e.g. LFV, LNV, muon g-2, that can be induced in either scenario)
  - *Given recent results from the 13 TeV LHC run, precision tests including EDMs remain crucial to the search for new physics*