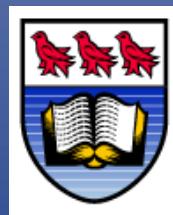


KITP - August 2015

Electric Dipole Moments

(and other ways LQCD could help constrain new physics)

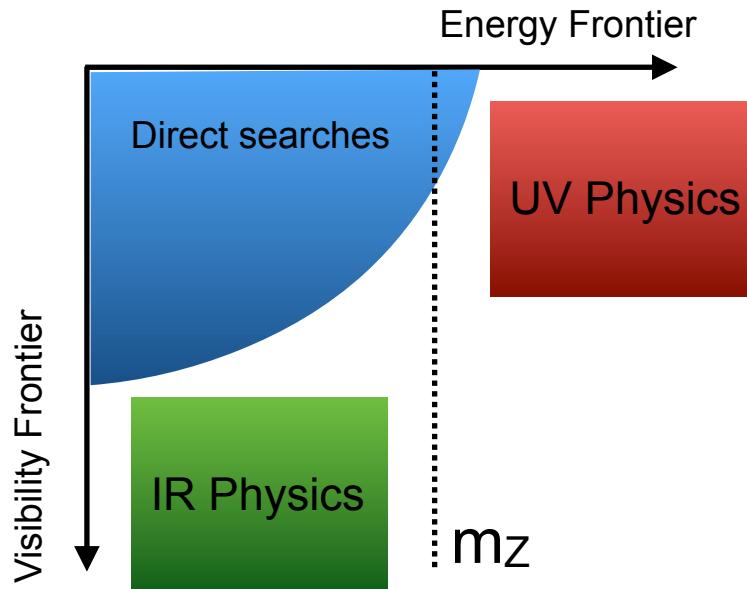
Adam Ritz
University of Victoria



with Matthias Le Dall and Maxim Pospelov
[e.g. 1505.01865, Review - hep-ph/0504231]

Precision searches for new physics

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

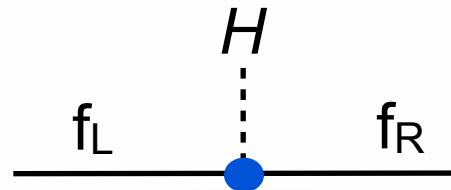


- Precision observables that vanish (or are suppressed) by **symmetry** in the SM allow for broad new physics searches, with indirect reach in both energy scale *and* weak coupling (visibility)
 - Low energy observables often involve hadronic physics, so control of QCD can be important

Plan

- Part 1 - EDMs & precision tests
- Part 2 - Precision tests & EDMs

CP (or T) Violation in the Standard Model



“known”

$$m_f \sim Y_f^{\text{diag}} \langle H \rangle$$

“unknown”

$$\sin(\delta_{\text{KM}}) \propto \text{Arg Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$$\delta_{\text{KM}} \sim \mathcal{O}(1)$$

Explains CP-violation in K and B meson mixing and decays

$$\sin(\bar{\theta} - \theta_0) \sim \text{ArgDet}[Y_u Y_d]$$

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

Constrained experimentally
(strong CP problem)

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 (TI)
[Regan et al. '02]

Diamagnetic EDMs

U Washington (Hg)
[Griffith et al '09]

U Michigan (Xe)
[Rosenberry & Chupp '01]
Argonne (Ra)
[Parker et al '15]

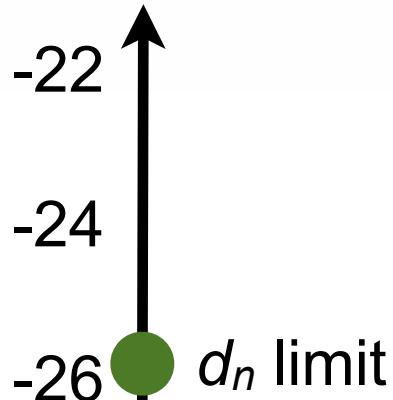
Neutron EDM

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

(and many others
in development
around the world)

EDMs in the Standard Model (CKM phase)

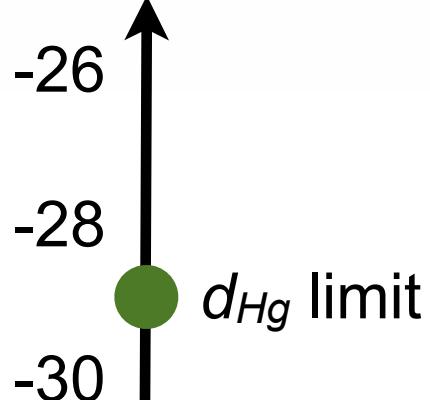
$\log(d_n [\text{e cm}])$



$$d_n^{\text{CKM}} \propto C_{qq}(J) \propto J G_F^2$$

[Khriplovich & Zhitnitsky '82;
McKellar et al '87;
Mannel & Uraltsev '12]

$\log(d_{Hg} [\text{e cm}])$

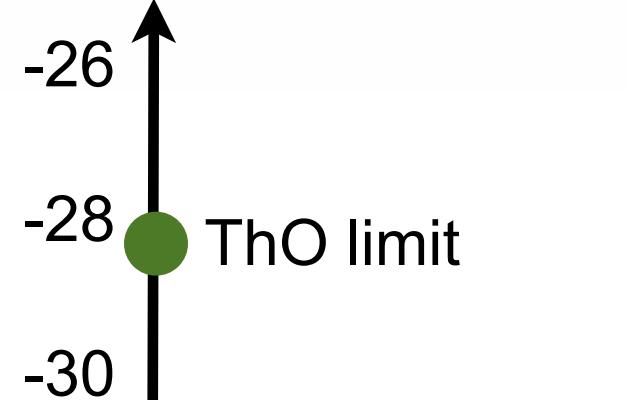


$$d_{Hg}^{\text{CKM}} \propto C_{qq}(J) \propto J G_F^2$$

[Flambaum et al '84;
Donoghue et al '87]

$$J \sim \text{Im}(VVVV)$$

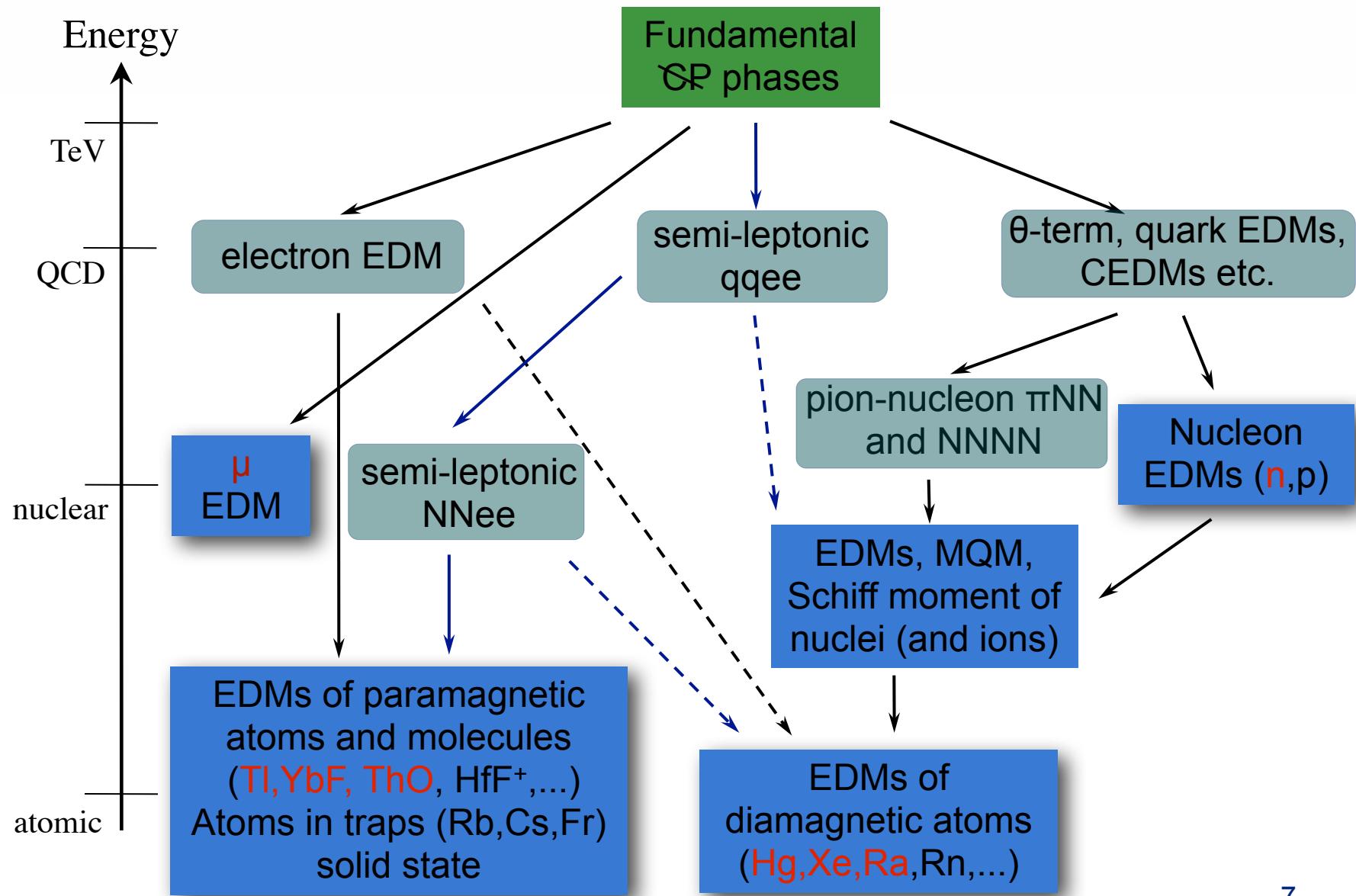
$\log(d_{e\text{-equiv}} [\text{e cm}])$



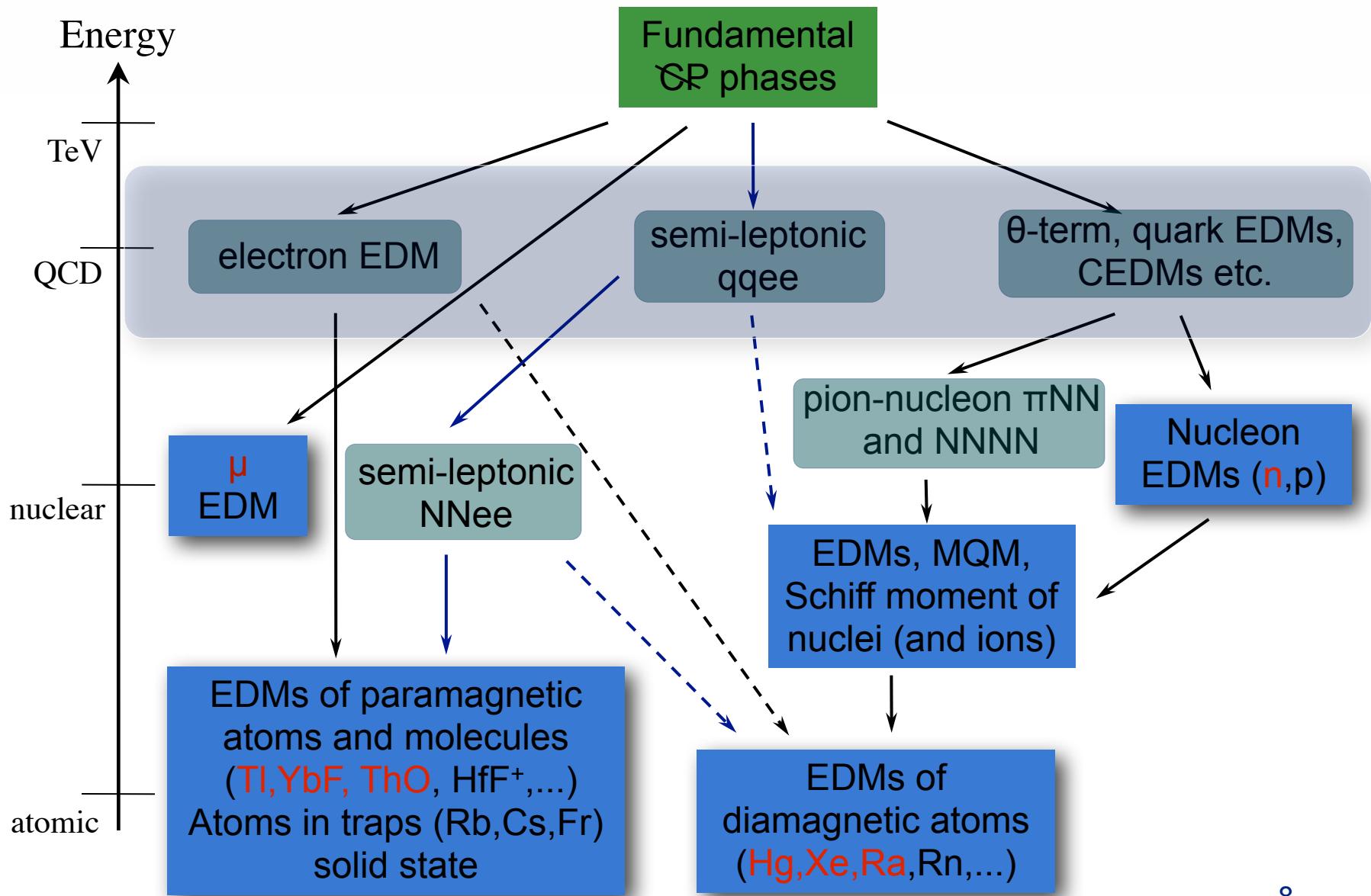
$$d_{e\text{-equiv}}^{\text{CKM}} \propto r C_S(J) \propto r J G_F^2$$

[Pospelov & AR '13]

EDM Sensitivity to (short distance) CP-violation



EDM Sensitivity to (short distance) CP-violation



CP-odd operator expansion (at $\sim 1\text{GeV}$)

(Flavor-diagonal) CP-violating operator expansion at $\sim 1\text{GeV}$

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

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

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

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

$$\mathcal{L}^{\text{"dim 8"}} \supset \sum_{q,\Gamma} C_{qq} \bar{q} \Gamma q \bar{q} \Gamma i \gamma_5 q + C_{qe} \bar{q} \Gamma q \bar{e} \Gamma i \gamma_5 e + \dots$$

NB: Basis at $\sim 1\text{ GeV}$ simpler than at EW scale, useful starting point *if* new physics is heavier than $\sim 1\text{ GeV}$. (Still assume Standard Model L-R chirality.)

CP-odd operator expansion (at $\sim 1\text{GeV}$)

(Flavor-diagonal) CP-violating operator expansion at $\sim 1\text{GeV}$

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

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

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

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

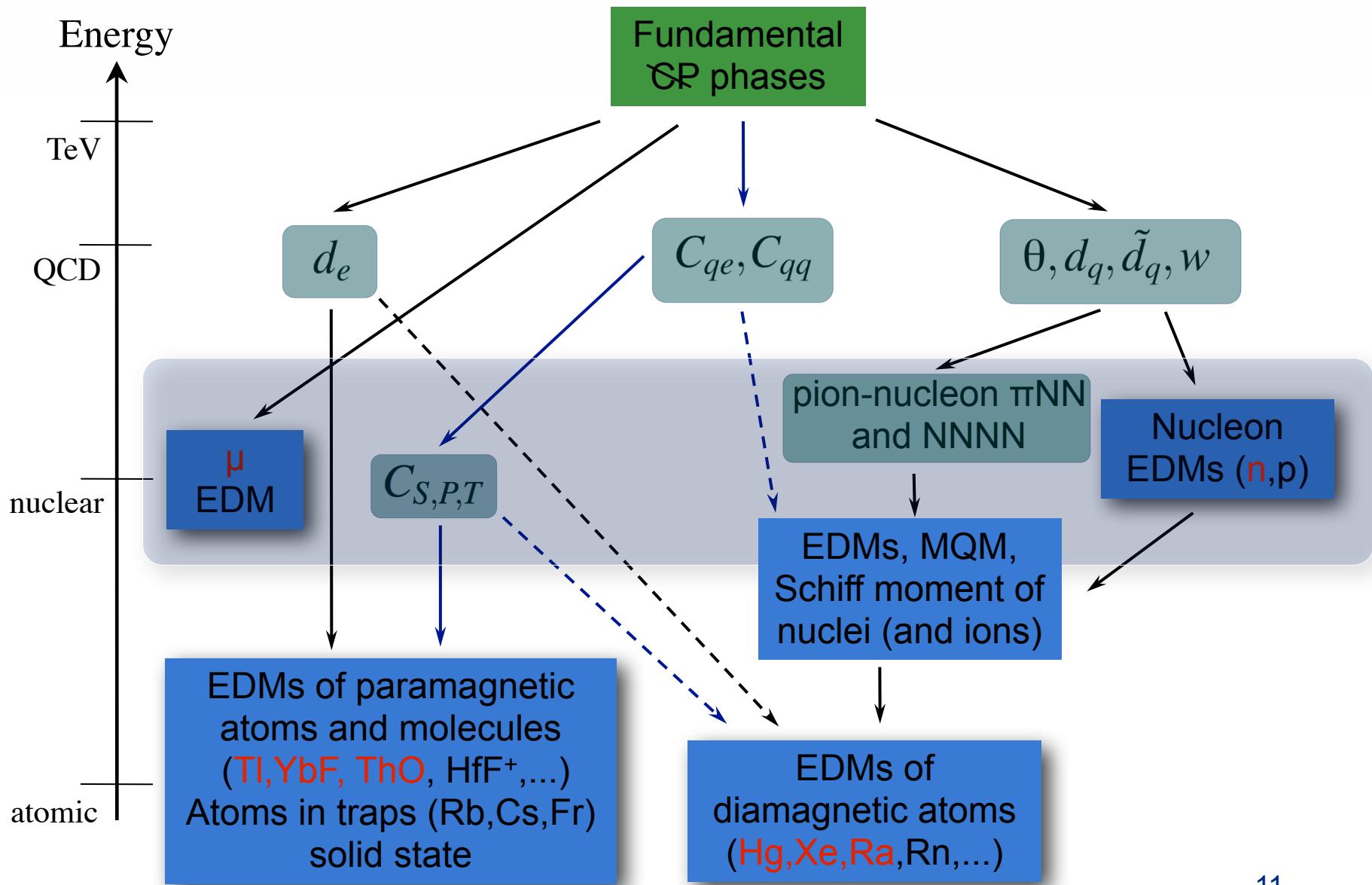
$$\mathcal{L}_{\text{dim 6}} \supset w g_s^3 G G \tilde{G} + \sum_{f,f',\Gamma} C'_{f f'} (\bar{f} \Gamma f')_{LL} (\bar{f} \Gamma f')_{RR}$$

$\xrightarrow{\quad \text{Requires new LR-mixing} \quad}$

$$\mathcal{L}^{\text{"dim 8"}} \supset \sum_{q,\Gamma} C_{qq} \bar{q} \Gamma q \bar{q} \Gamma i \gamma_5 q + C_{qe} \bar{q} \Gamma q \bar{e} \Gamma i \gamma_5 e + \dots$$

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

EDM Sensitivity to (short distance) CP-violation



CP-odd operator expansion (nuclear scales)

(Flavor-diagonal) CP-violating operator expansion at $\sim 1\text{GeV}$

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

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

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

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

$$\mathcal{L}^{\text{"dim 8"}} \supset \sum_{q,\Gamma} C_{qq} \bar{q} \Gamma q \bar{q} \Gamma i \gamma_5 q + C_{qe} \bar{q} \Gamma q \bar{e} \Gamma i \gamma_5 e + \dots$$

NB: recent work on consistent chiral power counting

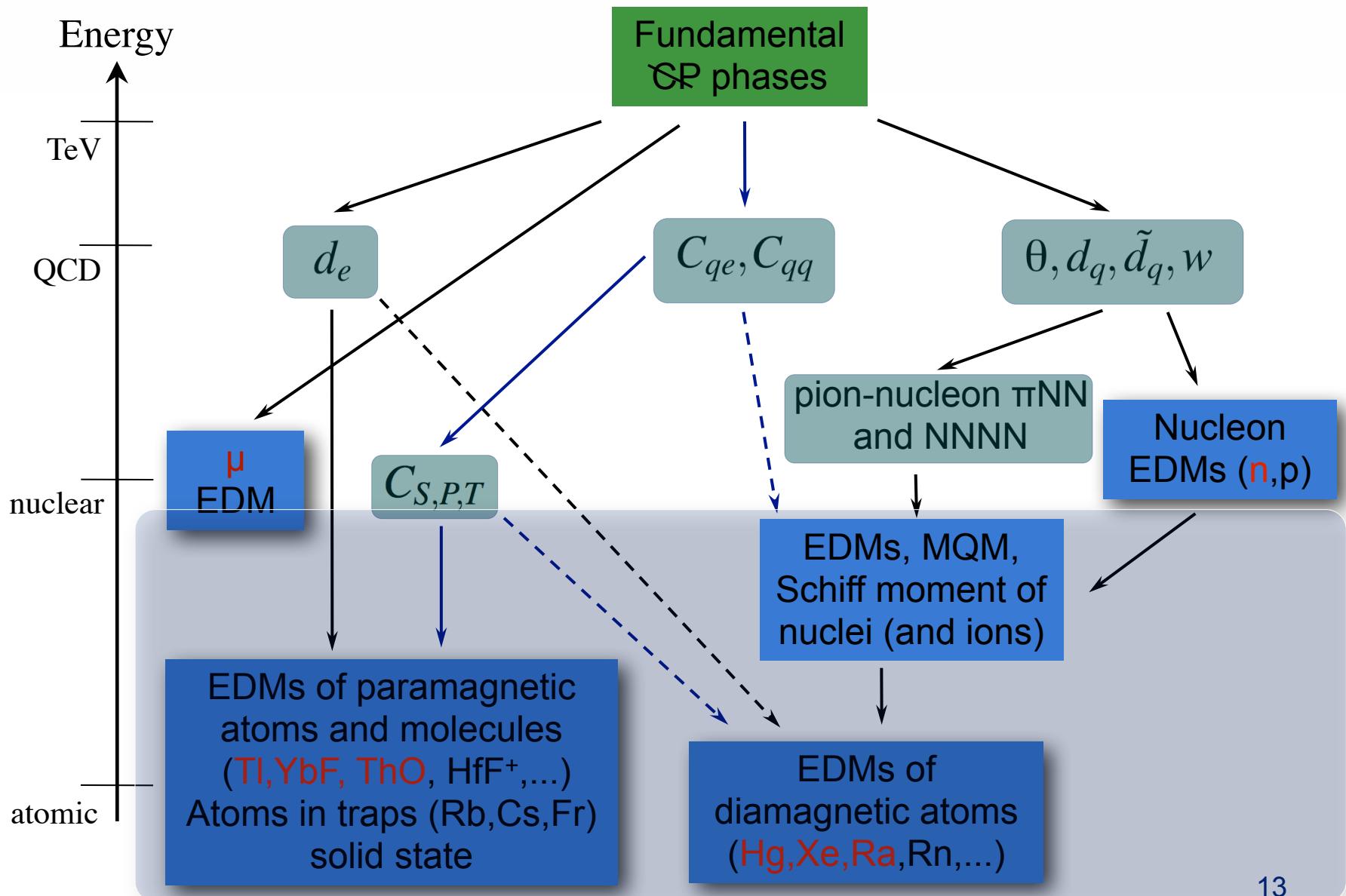
 nuclear scales

[Stetcu et al '08, de Vries et al. '11, '12; Guo & Meissner '12, Dekker et al '14]

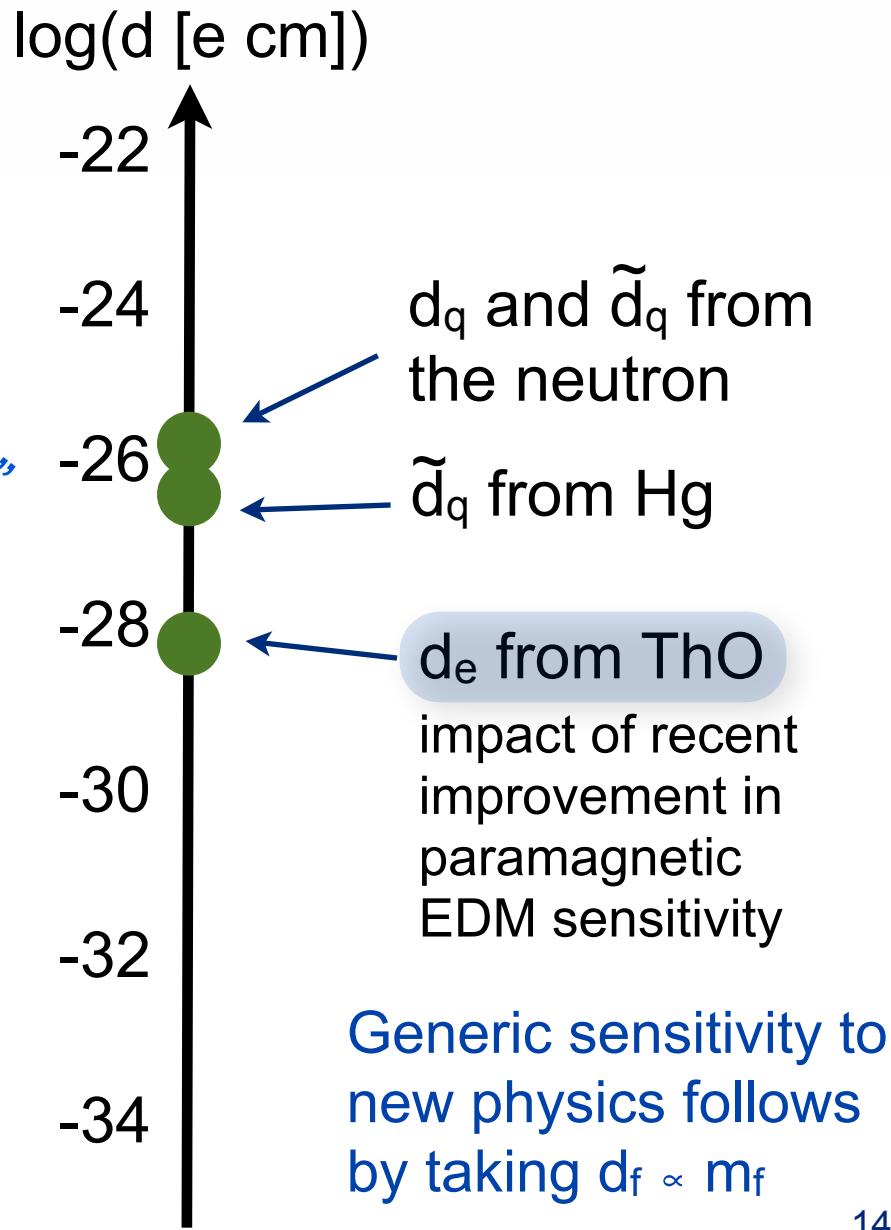
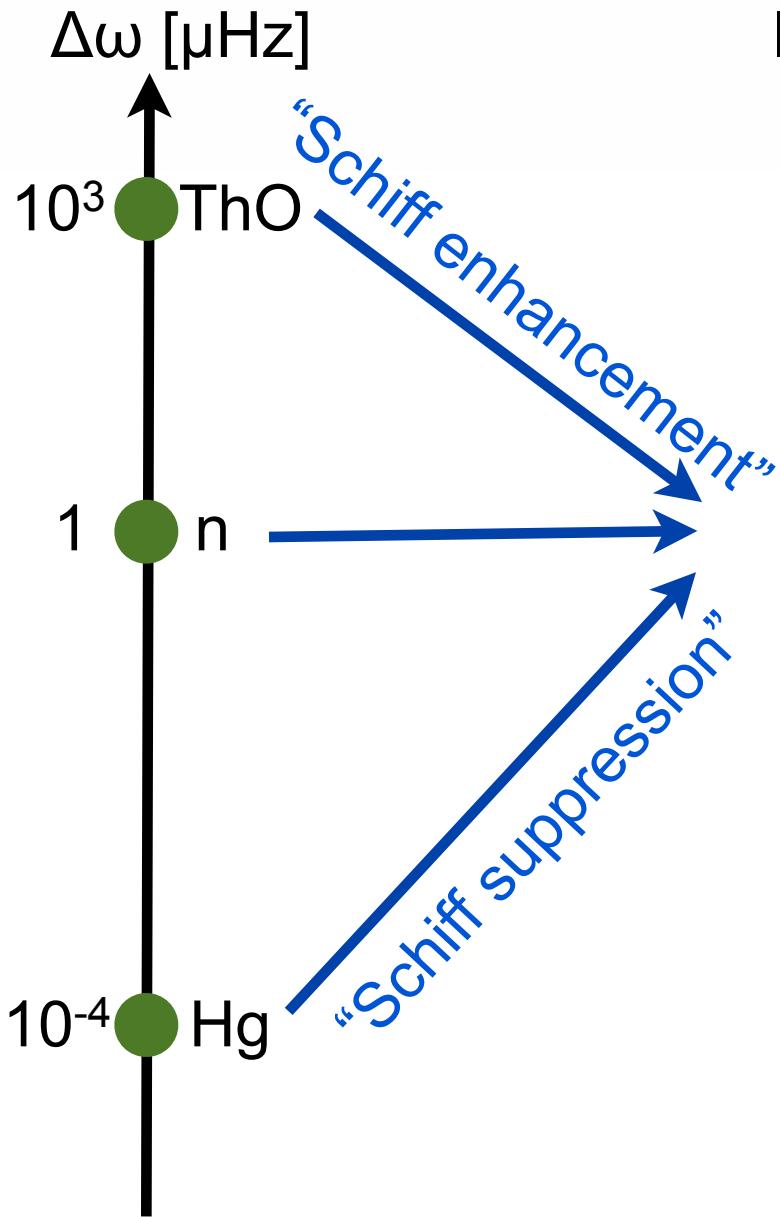
$$d_{(n,p)} \bar{N} F \sigma \gamma_5 N + \bar{g}_{\pi NN}^{(1)} \bar{N} \pi^0 N + \bar{g}_{\pi NN}^{(0)} \bar{N} \sigma \cdot \pi N + \mathcal{O}(N^4) + \mathcal{O}(\pi^3) + \dots$$

$$d_e \bar{e} F \sigma \gamma_5 e + C_S^{(0)} \bar{N} N \bar{e} i \gamma_5 e + \dots$$

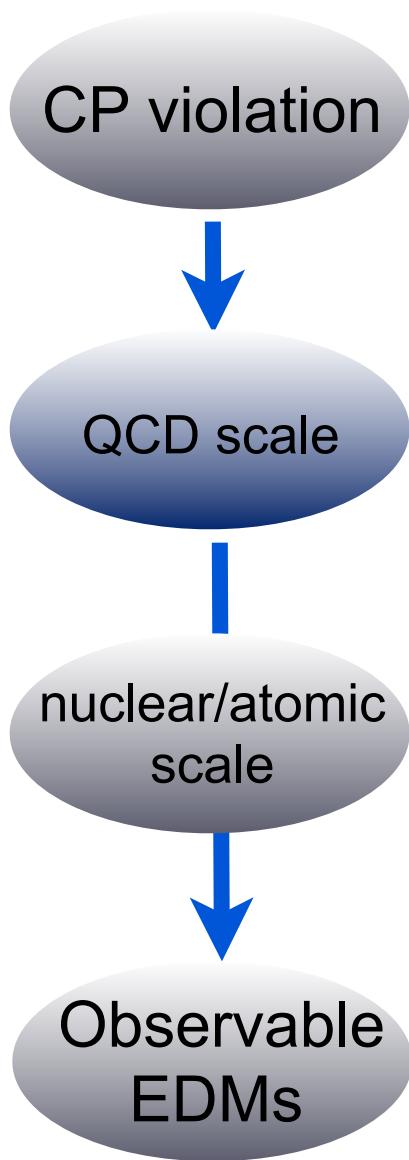
EDM Sensitivity to (short distance) CP-violation



Summary of the bounds



Multi-scale calculational scheme

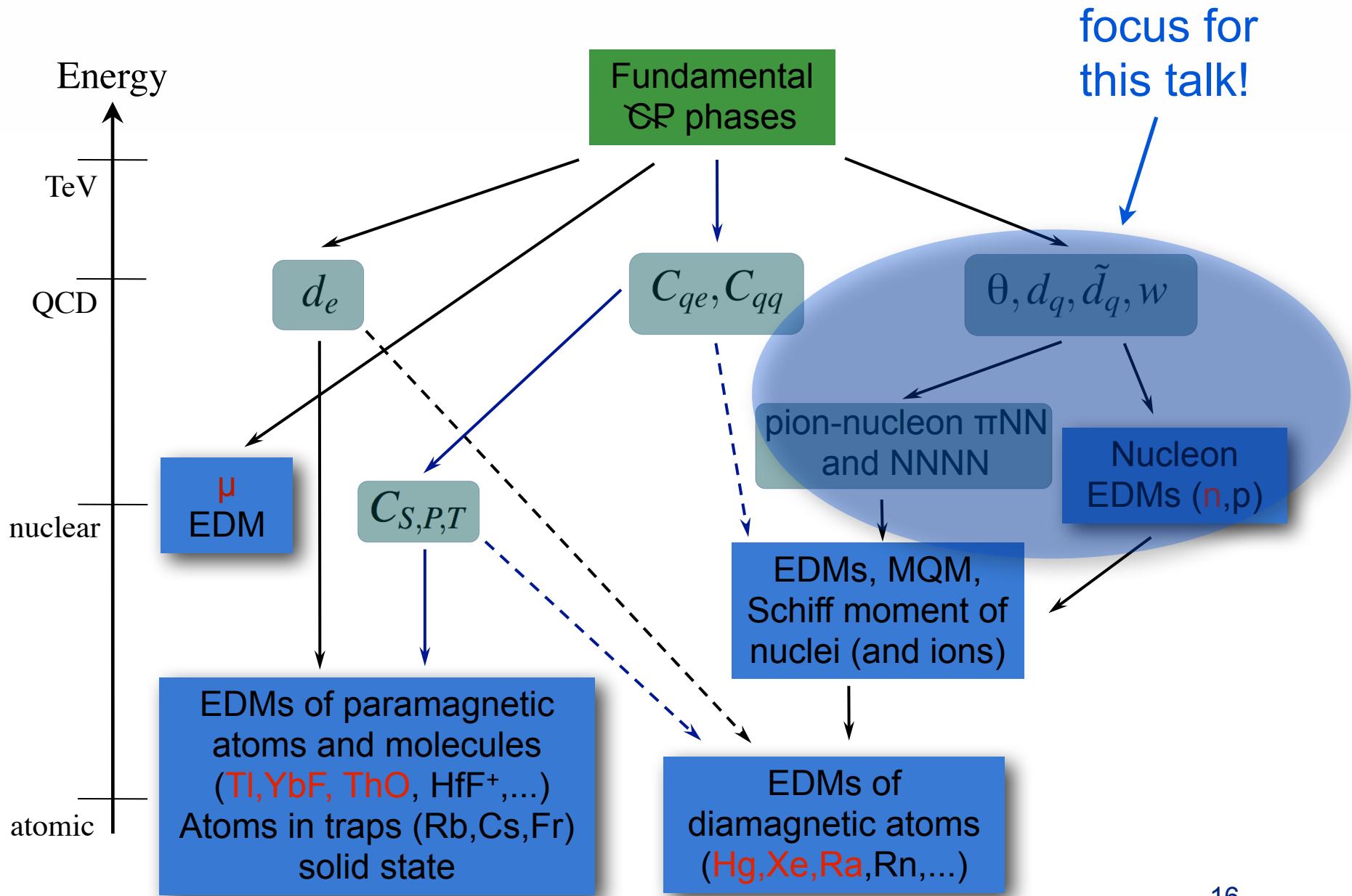


- Model-dependent (e.g. perturbative)

Significant uncertainties
for nucleon, nuclear and
diamagnetic EDMs

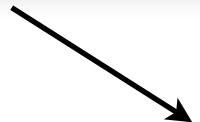
- Nucleon matrix elements, nucleon EDMs, pion-nucleon, nucleon-nucleon couplings
- Nuclear scale, e.g. Schiff moment, magnetic quadrupole
- Atomic/Molecular EDM

EDM Sensitivity to (short distance) CP-violation



The QCD scale

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


 low energy
 constants $\left\{ \begin{array}{l} d_N(\bar{\theta}, d_q, \tilde{d}_q, w, C_{ij}, \dots) \\ \bar{g}_{\pi NN}^{(0,1)}(\bar{\theta}, \tilde{d}_q, C_{ij}, \dots) \end{array} \right.$

- LEC's related by IR loops (chiral logs), but still need input to fix UV counterterms
- Simplest option is **NDA** - $\Lambda_{\text{had}}/f_\pi \sim g_s(\mu) \sim 4\pi$ $m_{q, \text{av}} \sim m_\pi^2/\Lambda_{\text{had}}$

	θ_q	d_q	\tilde{d}_q
d_n	$\frac{em_q}{\Lambda_{\text{had}}^2}$	$\mathcal{O}(1)$	$\frac{eg_s}{4\pi}$
$\bar{g}_{\pi NN}^{(0)}$	$\frac{m_q}{f_\pi}$	$\sim \mathcal{O}(\alpha)$	$\frac{\Lambda_{\text{had}}^2}{f_\pi}$

Why do better than NDA?

- Some current (and some prehistoric) motivations...
 - precision is not crucial for detecting new physics, given the negligible SM background, but would be required for interpretation (to disentangle CP-violating sources).
 - NB: In the 1990's, when SUSY was “just around the corner”, the same goal arose due to the focus on combining multiple EDM contributions to constrain the MSSM parameter space
 - to indicate possible enhancement/suppression factors (cf. NDA)
 - requires a systematic procedure able to handle multiple CP-odd sources. We used QCD sum rules, but LQCD can in principle improve the precision significantly.

CP-odd nucleon correlators & QCD Sum Rules

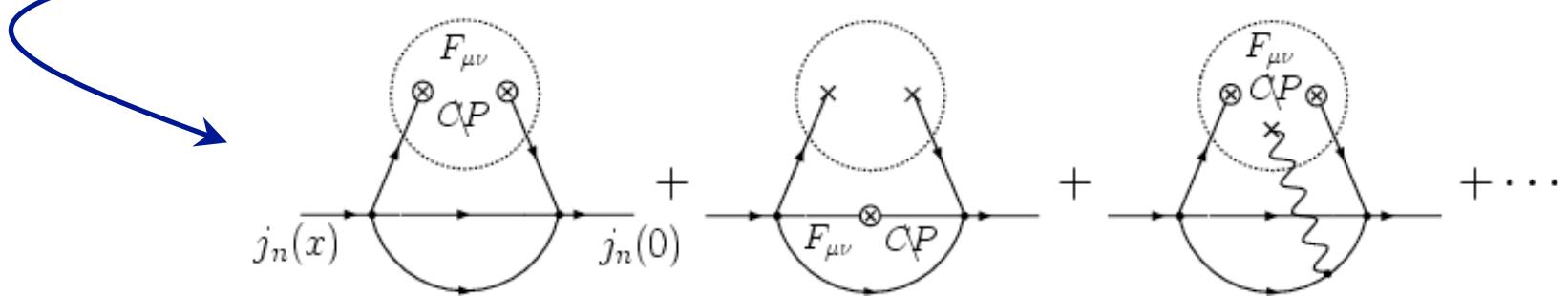
- OPE for nucleon 2-pt correlator

[Pospelov & AR '99-'00]

$$\int d^4x e^{ip \cdot x} \langle \bar{j}_n(x), j_n(0) \rangle_{CP,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p) F_{\mu\nu} + \dots$$



$$\Pi_1(p) \cdot F \sim \{F \sigma \gamma_5, \not{p}\} \left(\frac{d_n \lambda^2 m_n}{(p^2 - m_n^2)^2} + \frac{A}{p^2 - m_n^2} + \dots \right) + \dots$$



- Isolate EDM from unique chirally-invariant structure in off-shell dipole form-factor ($\langle 0 | j_n | n \rangle = (\lambda_1 + \beta \lambda_2) e^{i\alpha \gamma_5/2} v$)
- Account for mixing with CP-conjugate currents
- Perform a self-consistent fit for the EDM, using other CP-even nucleon sum rules (mass, σ_N , etc) to determine $\{m_n, \lambda, A\}$

Neutron EDM

$$d_n = (0.4 \pm 0.2) \left[\chi m_* (4e_d - e_u) \bar{\theta} + (4d_d - d_u) + \frac{1}{8} (4\tilde{d}_d e_d \alpha^+ - \tilde{d}_u e_u \alpha^-) \right. \\ \left. + \frac{1}{2} \chi m_0^2 (\tilde{d}_d - \tilde{d}_u) \frac{4e_d m_d + e_u m_u}{m_u + m_d} - \frac{1}{2} \chi m_0^2 (4e_d - e_u) \tilde{d}_s \frac{m_*}{m_s} \right]$$

- Depends on vacuum condensates

$$\langle \bar{q} \sigma_{\mu\nu} q \rangle_F \equiv \chi e_q F_{\mu\nu} \langle \bar{q} q \rangle$$

$$g \langle \bar{q} G \sigma q \rangle \equiv -m_0^2$$

$$2g \langle \bar{q} (G_{\mu\nu} \mp i\gamma_5 \tilde{G}_{\mu\nu}) q \rangle_F \equiv \alpha^\pm e_q F_{\mu\nu} \langle \bar{q} q \rangle$$

- Coefficient is proportional to $\left(\frac{\langle \bar{q} q \rangle}{(225 \text{ MeV})^3} \right) \left(\frac{1.1/(2\pi)^4}{\lambda^2} \right)$
- Proton EDM follows by sending $u \leftrightarrow d$
- NB: Calculation repeated by Hisano et al (2012), with same answer up to replacing $\alpha^{+/-} \rightarrow 4\alpha^{-/+}$ (and inserting a numerically larger lattice result for λ)

Neutron EDM

- Results:

$$d_n(\bar{\theta}) = (1 \pm 0.5) \frac{|\langle \bar{q}q \rangle|}{(225 \text{ MeV})^3} \bar{\theta} \times 2.5 \times 10^{-16} e \text{ cm}$$

- If the axion relaxes θ , the CEDM sources shift the minimum of the axion potential $V(\theta)$ away from zero [Bigi & Uraltsev]

$$\theta_{ind} = \frac{1}{2} m_0^2 \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q}$$

$$d_n^{\text{PQ}} = (0.4 \pm 0.2) \frac{|\langle \bar{q}q \rangle|}{(225 \text{ MeV})^3} \left[4d_d - d_u + 2.7e(\tilde{d}_d + 0.5\tilde{d}_u) + \dots \right] + \mathcal{O}(d_s, w, C_{qq})$$

[Pospelov & AR '99,'00;
Hisano et al '12]

Sensitive only to ratios of light quark masses
(via GMOR relation, given $d_q \sim m_q$ etc.)

- at this order, s-quark CEDM contribution cancels under axion relaxation (appears accidental)

Neutron EDM

- Precision?
 - numerical coefficients are consistent with NDA, NQM (for d_q), and the chiral log (for θ)
 - another test for $d_n(d_q)$ via (LQCD) nucleon tensor charge [e.g. Falk et al '99]

$$\langle N | \frac{1}{2} d_q \bar{q} \tilde{F} \sigma q | N \rangle = \frac{1}{2} d_q \tilde{F}^{\mu\nu} \langle N | \sigma_{\mu\nu} | N \rangle = \frac{1}{2} g_T^q d_q \bar{N} \tilde{F} \sigma N$$

$$\implies d_n(d_q) = g_T^u d_d + g_T^d d_u \sim 0.8d_d - 0.25d_u$$



In the isospin-symmetric limit,
inserting (connected) LQCD results
[Hagler '09; Bhattacharya et al '11, '13]

$$\left[d_n^{(\text{SR})} = \left(\frac{\langle \bar{q}q \rangle}{(225 \text{ MeV})^3} \right) \left(\frac{1.1/(2\pi)^4}{\lambda^2} \right) \times (1.6(8)d_d(0.9 \text{ GeV}) - 0.4(2)d_u(0.9 \text{ GeV})) \right]$$

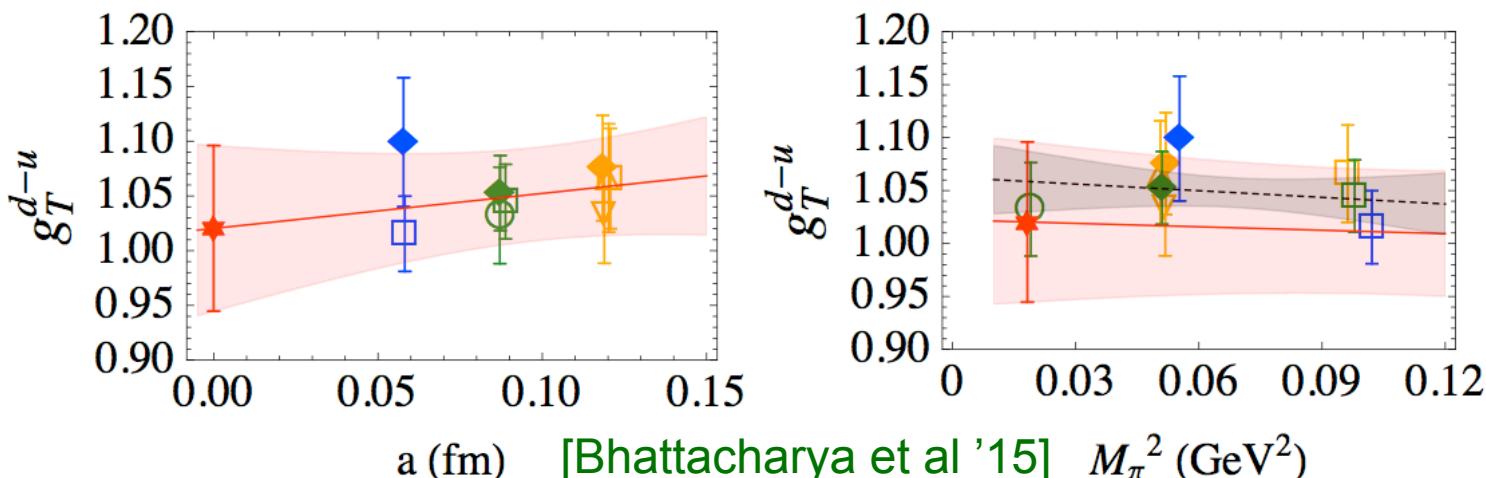
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Recent improvement, including disconnected diagrams, and improved statistical precision

$$d_n = 0.774(66)d_d(2 \text{ GeV}) - 0.233(28)d_u(2 \text{ GeV}) + 0.008(9)d_s(2 \text{ GeV})$$



Neutron EDM

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$$\implies d_n(d_q) = g_T^u d_d + g_T^d d_u \sim 0.8d_d - 0.25d_u$$
 - sum-rules fixes ($d_n \sim \langle qq \rangle / \lambda^2$), so the normalization of the nucleon coupling matters

$$\lambda \sim 0.025 \text{ GeV}^3$$

from analysis of CP-even sum rules for m_n , σ_N , etc (or lattice result for tensor charge above)

[Pospelov & AR '99,'00]

$$\lambda \sim 0.044 \pm 0.01 \text{ GeV}^3$$

from LQCD [Y. Aoki et al '08] run down from 2 GeV, *BUT* $\langle qq \rangle$ is also larger with LQCD values for m_q and final effect on $d_n(d_q)$ is a reduction by a factor of 2, consistent with the LQCD tensor charge... [Hisano et al '12, Fuyuto et al '12]

Neutron EDM

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 - May be useful to consider normalized ratios, e.g. d/μ , d/σ_N to remove dependence on nucleon coupling

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 - NB: recent exploratory lattice study of $d_n(\theta)$ using $\theta \rightarrow i\theta$,
$$d_n = -3.9(2)(9) \times 10^{-16} \theta e \text{ cm} \quad [\text{e.g. Guo et al '15}]$$

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$$d_n = -3.9(2)(9) \times 10^{-16} \theta e \text{ cm} \quad [\text{e.g. Guo et al '15}]$$
 - Would be useful to clarify dependence on s-quark EDM

Pion-nucleon couplings

- Can follow a similar approach for the pion-nucleon couplings
 - focus on the isovector coupling [Pospelov '01]

(a)

$$\bar{g}_{\pi NN}^{(1)}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2f_\pi} \left\langle N \left| \sum_{q=u,d} \bar{q} g_s G \sigma q \right| N \right\rangle + \dots$$

Pion-nucleon couplings

- Can follow a similar approach for the pion-nucleon couplings
 - focus on the isovector coupling [Pospelov '01]

The figure shows two Feynman diagrams labeled (a) and (b). Diagram (a) illustrates a nucleon (N) interacting with a pion (π) through a contact interaction operator \mathcal{O}_{CP} . A blue arrow points from this diagram to the corresponding mathematical expression below. Diagram (b) shows a similar process but with a different contact interaction operator, involving a dot product between the pion and nucleon momenta.

$$\bar{g}_{\pi NN}^{(1)}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2f_\pi} \left\langle N \left| \sum_{q=u,d} \bar{q} g_s G \sigma q - m_0^2 \bar{q} q \right| N \right\rangle + \dots$$

cancelation in vacuum

Pion-nucleon couplings

- Using QCD sum rules

$$\int d^4x e^{ip \cdot x} \langle \bar{j}_n(x), j_n(0) \rangle_{\tilde{d}_q H_q} \sim p \left(\frac{2\lambda^2 \bar{g}_{\pi NN} m_N}{(p^2 - m_N^2)^2} + \frac{A}{p^2 - m_N^2} + \dots \right) + \dots$$

↓
isolate chirally invt structure

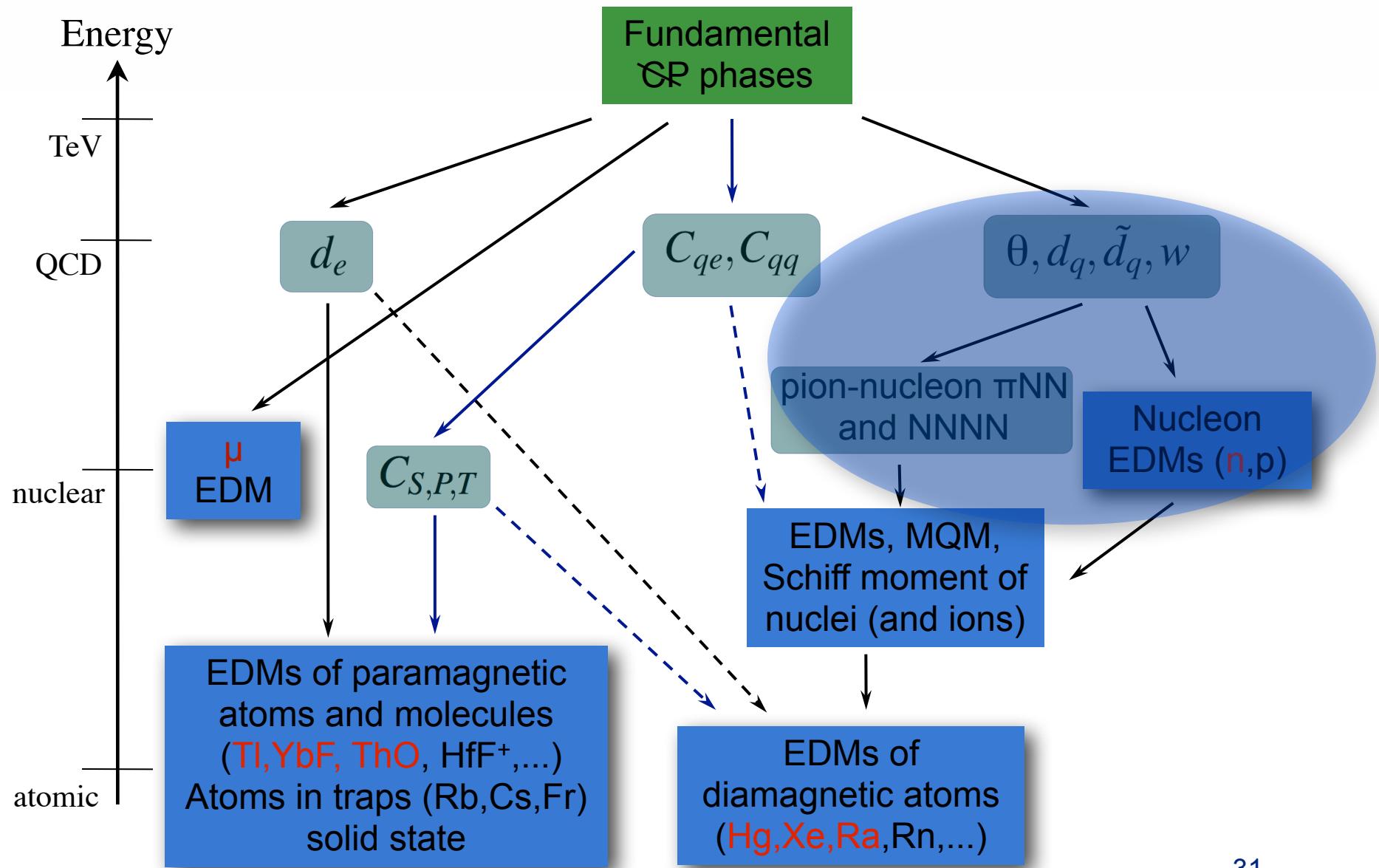
$$\bar{g}_{\pi NN}^{(1)}(\tilde{d}_q) \sim (2 \leftrightarrow 12) \text{GeV} \frac{|\langle \bar{q}q \rangle|}{(225 \text{ MeV})^3} (\tilde{d}_u - \tilde{d}_d) + \mathcal{O}(\tilde{d}_s, w)$$

$$\bar{g}_{\pi NN}^{(0)}(\tilde{d}_q) \sim (-1 \leftrightarrow 3) \text{GeV} \frac{|\langle \bar{q}q \rangle|}{(225 \text{ MeV})^3} (\tilde{d}_u + \tilde{d}_d) + \mathcal{O}(\tilde{d}_s, w)$$

[Pospelov '01]

- normalization again consistent with NDA, but larger errors due to cancelations between direct & rescattering terms
[result slightly smaller than estimates using LETs: Falk et al '99; Hisano & Shimizu '04]
- dependence of $g^{(0)}$ on θ determined by chiral techniques, but dependence on quark EDMs suppressed by α_{em}

EDM Sensitivity to (short distance) CP-violation



Resulting Bounds on fermion EDMs & CEDMs

ThO [Baron et al '13]	$\left d_e + e(26 \text{ MeV})^2 \left(3\frac{C_{ed}}{m_d} + 11\frac{C_{es}}{m_s} + 5\frac{C_{eb}}{m_b} \right) \right < 8.7 \times 10^{-29} e \text{ cm}$	[±20%]
neutron [Baker et al '06]	$ e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25d_u) + \mathcal{O}(\tilde{d}_s, w, C_{qq}) < 2 \times 10^{-26} e \text{ cm}$	[±50%?]
Hg [Griffith et al '09]	$e \tilde{d}_d - \tilde{d}_u + \mathcal{O}(d_e, \tilde{d}_s, C_{qq}, C_{qe}) < 6 \times 10^{-27} e \text{ cm}$	[±300%?]

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

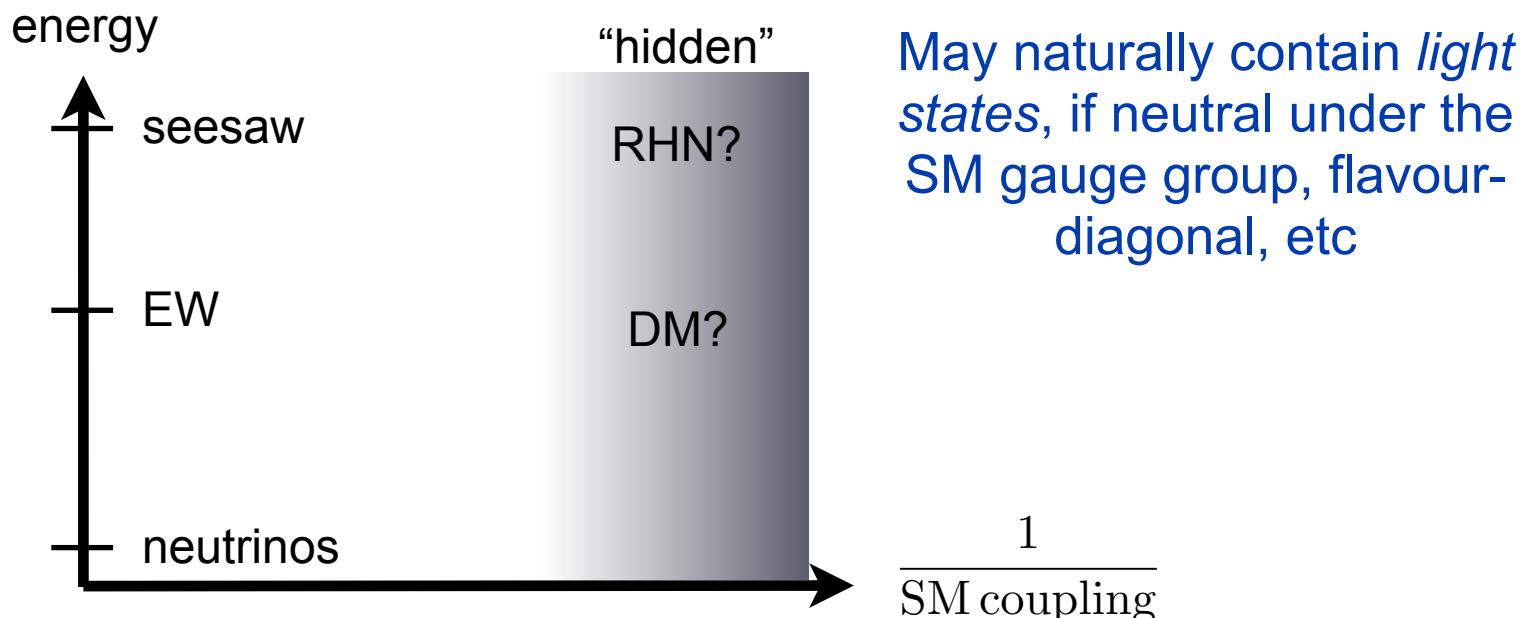
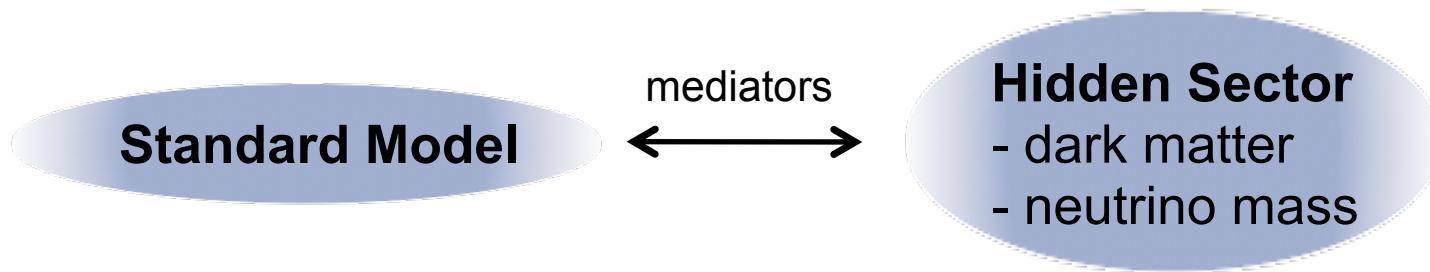
NB: Results assume PQ relaxation but, with current precision limits, nonzero n and/or Hg EDMs could not unambiguously point to a source other than θ .

Plan

- Part 1 - EDMs & precision tests
- Part 2 - Precision tests & EDMs

New physics in a hidden sector

Arguably, most *empirical* evidence for physics beyond the Standard Model does not point to a specific mass scale, but rather to a hidden (or dark) sector



Precision Tests and IR New Physics

- The results of precision (e.g. EDM) experiments are commonly interpreted within an EFT, assuming all new physics is “heavy” compared to the SM, at or above the weak scale.
- However, the empirical evidence for new physics (neutrino mass, DM), plus the lack thus far of beyond-SM discoveries at the LHC, motivates a more comprehensive strategy, parametrizing UV *and* IR new physics scenarios



IR new physics is often best probed at low energy (either in precision tests or with high-intensity sources). This tends to introduce low energy QCD (for the SM background and sometimes the *signal* as well).

- Even (clean) observables testing SM symmetries, e.g. $0\nu\beta\beta$, LFV, EDMs, that are less reliant on calculational precision for discovery of NP, still need it to disentangle potential NP contributions.

EFT for a (neutral) 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 $\text{dim} \geq 5$

EFT for a (neutral) hidden sector



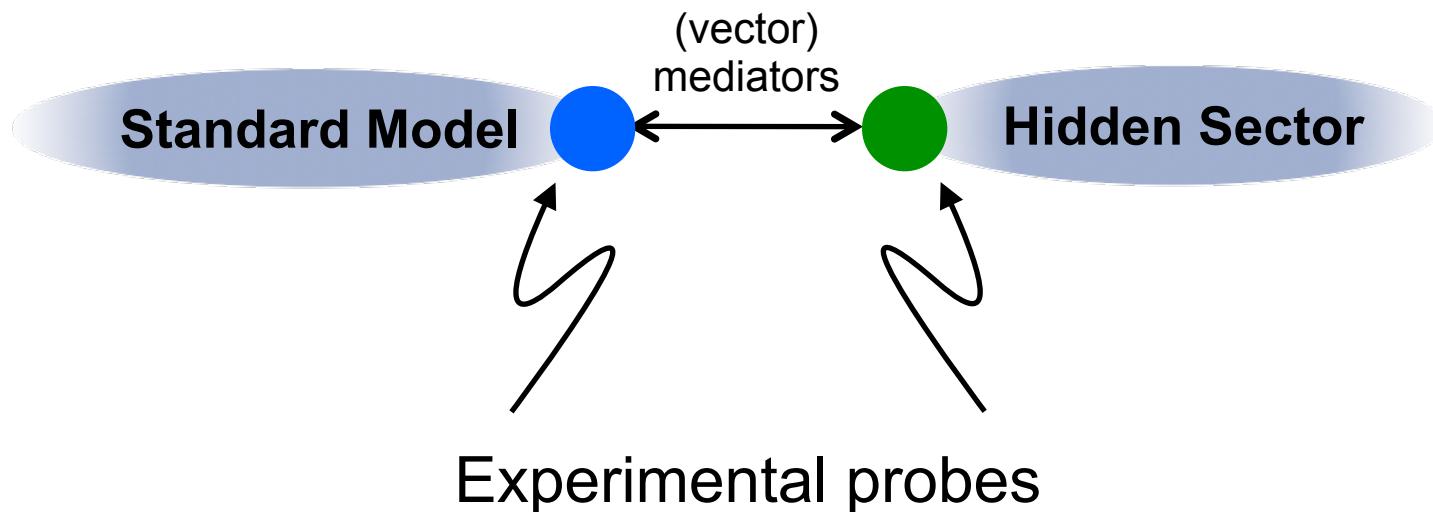
$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)} \mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

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: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu} \rightarrow \kappa V_\mu J_\text{EM}^\mu$
- Higgs portal: $\mathcal{L} = -A S H^\dagger H \rightarrow \frac{Av^2}{m_h^2} S J_S$
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$

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

E.G. probes of the vector portal

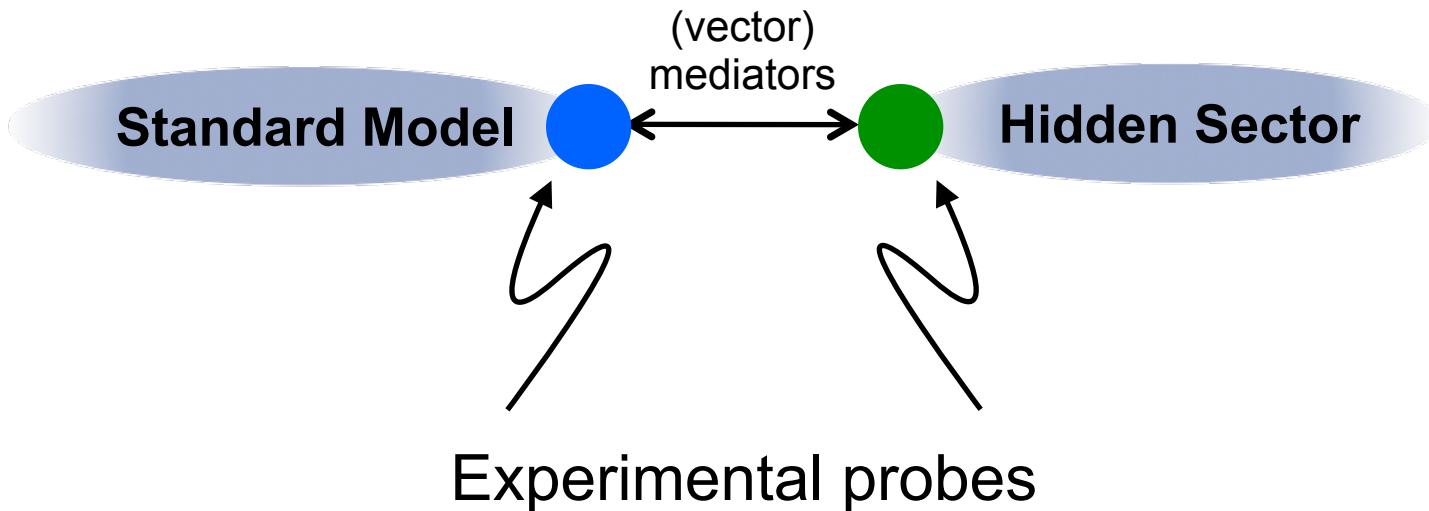


- Precision corrections
 - e.g. lepton g-2, EDMs
- rare (visible) decays
 - e.g. collider/fixed target production plus e.g. leptonic A' decays, $O(\kappa^2) \times Br(SM)$

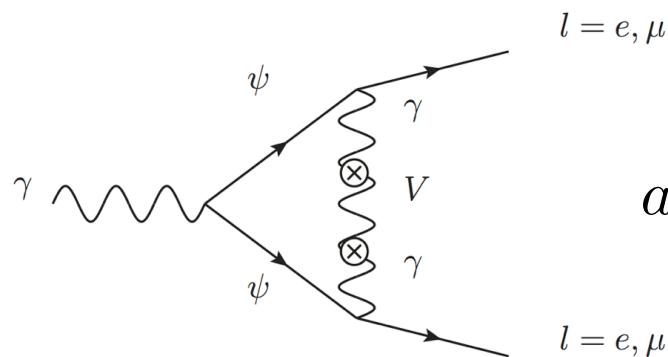
- rare (invisible) decays
 - e.g. collider production plus missing energy in decays and scattering, $O(\kappa^2) \times Br(Hid)$
- anomalous NC-like scattering
 - Fixed target production plus anomalous NC-like scattering, $O(\kappa^2 \times \kappa^2 \alpha')$

(also astrophysics & cosmology)

E.G. probes of the vector portal



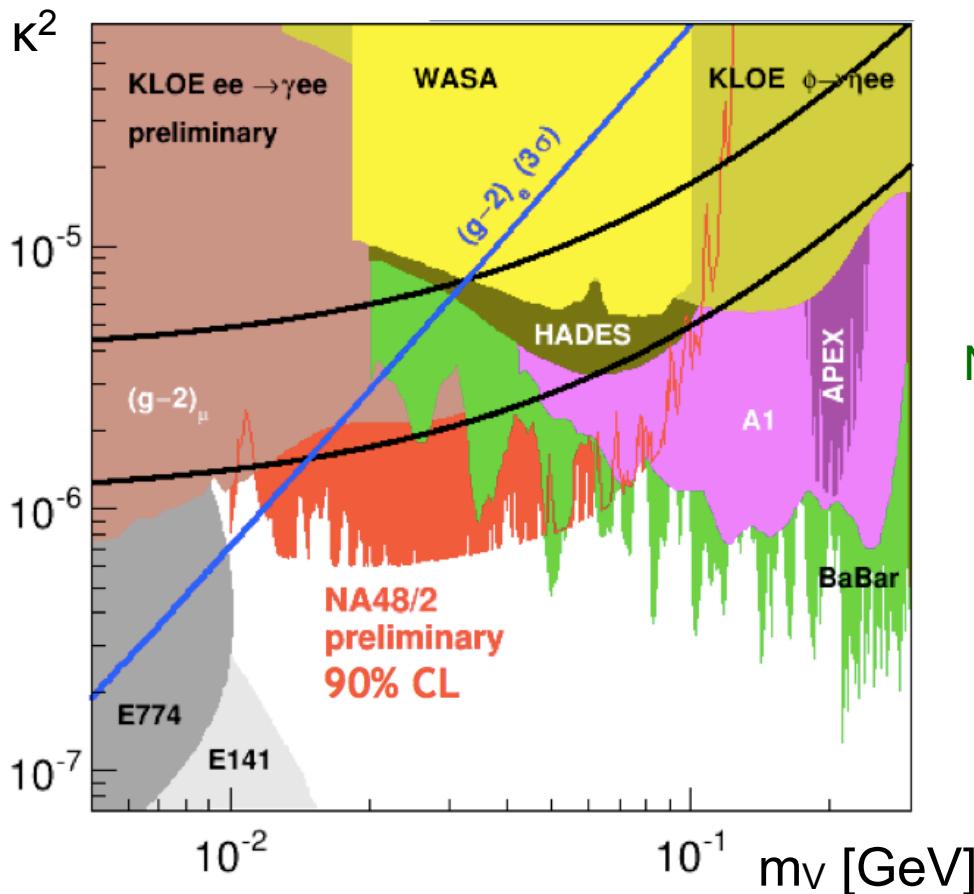
- Precision corrections
 - e.g. lepton g-2



$$a_l^V = \frac{\alpha \kappa^2}{2\pi} \times \begin{cases} 1 & m_l \gg m_V \\ 2m_l^2/(3m_V^2) & m_l \ll m_V \end{cases}$$

E.G. probes of the vector portal

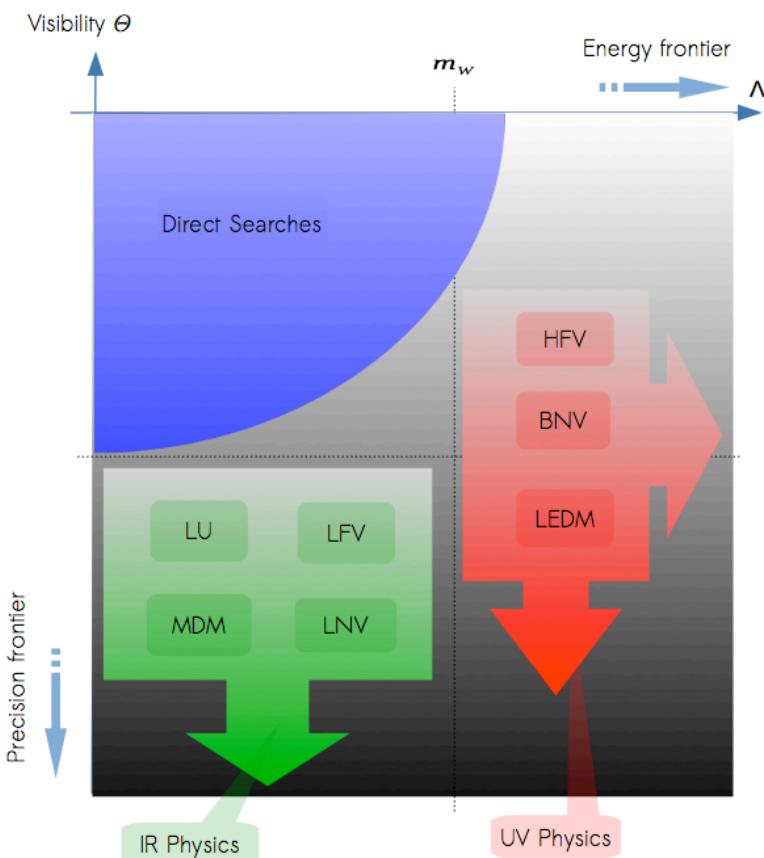
$\text{Br}(V \rightarrow \text{leptons}) \sim 1$



[Snowmass
NLWCP WG, Essig,
Jaros, Wester et al
'13; BaBar '14;
NA48/2 '14]

An explanation of the muon g-2 discrepancy is still possible with models that allow hidden decays, but there has been impressive recent progress in testing this portal. A number of new experiments are in development.

Precision sensitivity to general IR new physics



[Le Dall, Pospelov & AR '15]

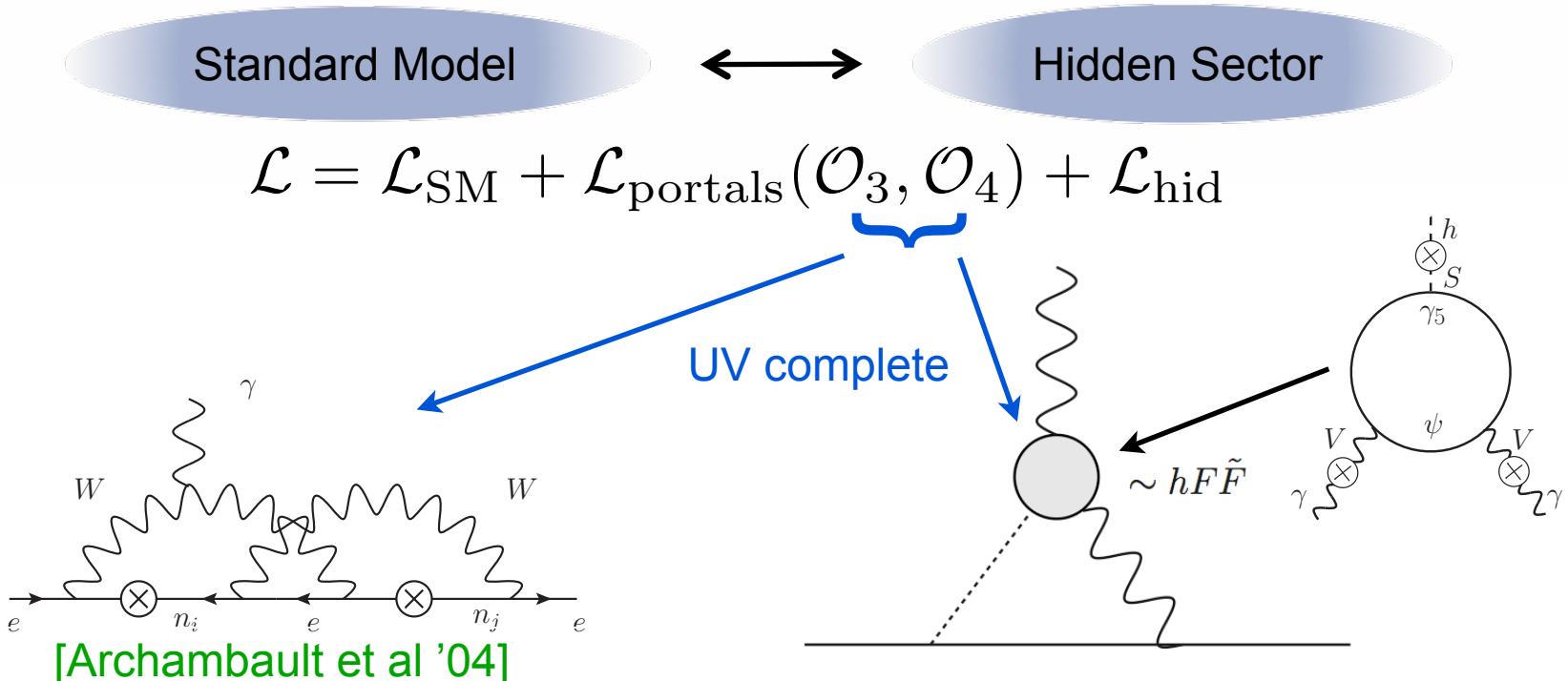
Light NP coupled through any of the portals, or gauged B-L, L_i - L_j , which are **UV-insensitive**

More general light NP that is **UV-incomplete**

Observable	(A,B) Portals	(C,D) UV-incomplete
LFV	✓	✓
LU	✓	✓
$(g - 2)_l$	✓	✓
LNV	✓	✓
LEDMs		✓
HFV		✓
BNV		✓

Precision observables which cannot (currently) distinguish UV from IR new physics

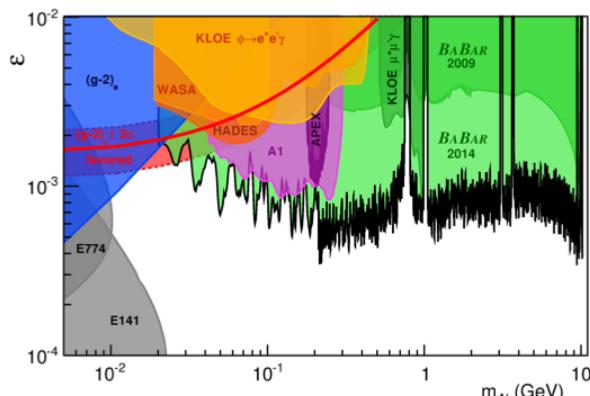
EDM Sensitivity to light hidden sectors



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

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

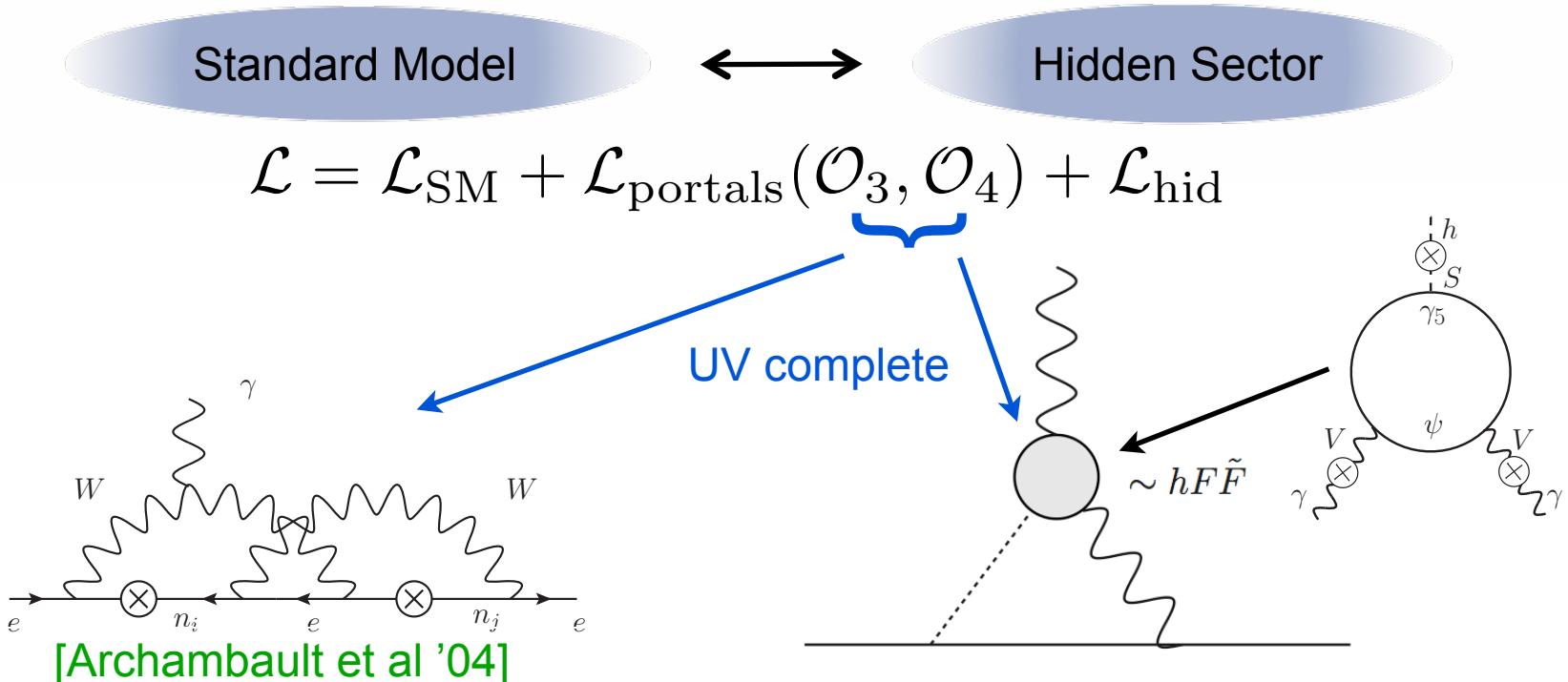
➡ EDMs suppressed by constraints on light neutrino spectrum



➡ EDMs suppressed by limit on associated 1-loop ("dark photon") correction to $(g-2)_e$

[Le Dall, Pospelov & AR '15]

EDM Sensitivity to light hidden sectors



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

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

- • At current sensitivity levels, lepton EDMs primarily probe NP with new UV dofs, unlike other precision probes such as LFV, LNV, muon g-2, etc.
- Similar statements apply to hadronic EDMs (n , Hg), except that both could also be interpreted in terms of θ_{QCD} , given current theoretical precision

[Le Dall, Pospelov & AR '15]

Summary

EDMs are a powerful probe of new flavour-diagonal CP-violation
(motivated by the need for baryogenesis)

- EDM computations require a multi-scale approach:

$$d_{\text{exp}}(C_{\text{atomic}}(C_{\text{nuclear}}(C_{\text{QCD}}(C_{\text{new physics}}))))$$

- Improving precision (with QCD sum rules) is hard without input on (i) excited state mixing, and (ii) interpolating current ambiguity
 - Cannot currently disentangle sources other than θ , given a detection of either the n or Hg EDM
 - Examples where LQCD input would be valuable:
 - $d_N(\langle N | \bar{q} F \sigma \gamma_5 q | N \rangle)$ ✓ via tensor charges
 - $d_N(\langle N | G\tilde{G} | N \rangle), d_N(\langle N | \bar{q} G \sigma \gamma_5 q | N \rangle), \bar{g}_{\pi NN} (\langle N | \bar{q} g_s G \sigma q - m_0^2 \bar{q} q | N \rangle)$
 - s-quark matrix elements CP-even, relevant for all nuclear EDMs
 - Many other low energy observables can benefit from LQCD. NB: leptonic precision observables are generically sensitive to both UV and IR (complete) new physics scenarios.

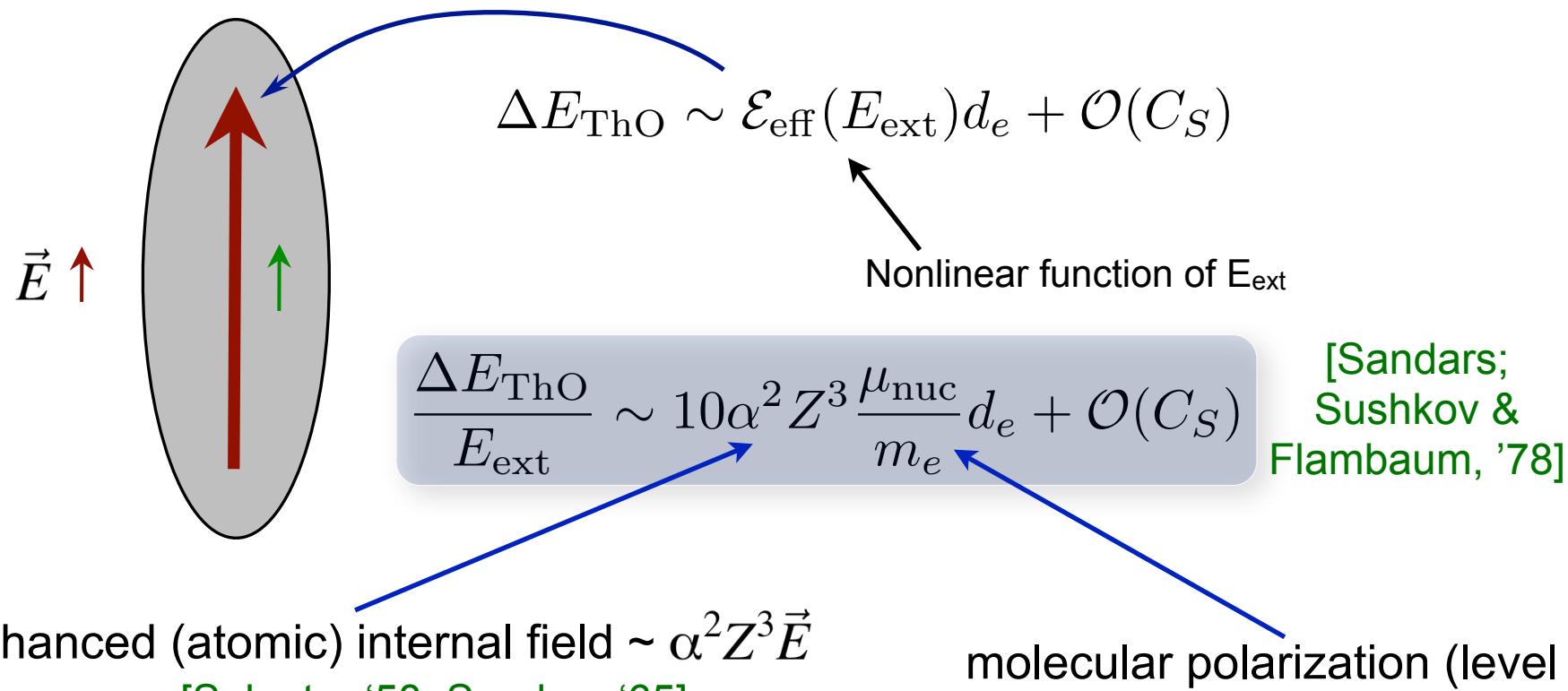
Extra Material

Paramagnetic EDMs - “Schiff enhancement”

Polar molecules (ThO [Harvard/Yale], also YbF [Imperial])

[Baron et al '13, Hudson et al '11]

[➡ talk by G. Gabrielse]



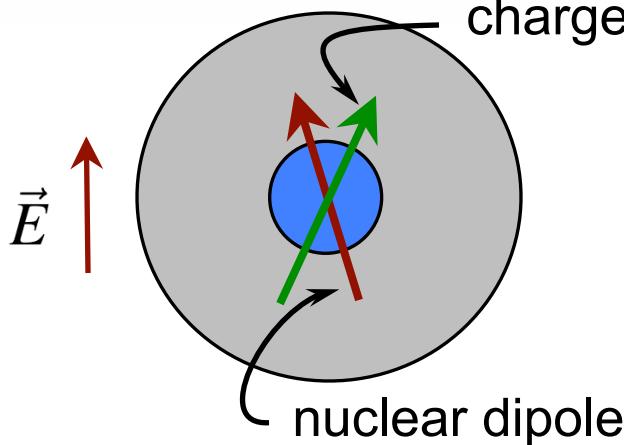
enhanced (atomic) internal field $\sim \alpha^2 Z^3 \vec{E}$
[Salpeter '58; Sandars '65]
(relativistic violation of Schiff screening which
naively implies $d_{\text{neutral atom}}(d_e)=0$ at the non-rel level)

molecular polarization (level
splitting in parity doublet)

Diamagnetic EDMs - “Schiff suppression”

Atoms (e.g. Hg [Washington], also Xe)

[Griffith et al '09]



charge distribution (finite size violation of Schiff screening,
which implies $d_{\text{neutral atom}}(d_{\text{nuc}})=0$)

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

$$d_{Hg} \sim -3 \times 10^{-17} S [e \text{ fm}^2] + \mathcal{O}(d_e, C_{qe}, C_{qq})$$

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

Schiff moment [Schiff '63]

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

NB: Schiff moment is dominant for large atoms (Hg, Xe, Ra). MQM is dominant for small nuclei and classes of molecules of recent interest (^{229}ThO , TaN)

• Octopole enhancements (e.g. Ra, Rn)

[Parker et al '15;
Chupp et al.]

Schiff moment $\mathcal{O}(10^2-10^3)$
larger than Hg
[Flambaum et al.]

Nuclear EDMs - avoiding Schiff screening

- Neutron EDM via UCN bottles [...., PSI, SNS, PNPI, TRIUMF, TUM, J-PARC...]
- Nuclear EDMs (e.g. p,D, ${}^3\text{He}$,...) in storage rings [BNL, FNAL?, COSY/Julich]

- proton - similar sensitivity to the neutron ($d \leftrightarrow u$)
- deuteron, and other light nuclei (e.g. ${}^3\text{H}$, ${}^3\text{He}$)

[Stetcu et al '08, de Vries et al '11]



$$d_D = (d_n + d_p)(\bar{\theta}, d_q, \tilde{d}_q) + d_D^{\pi NN}[\bar{g}_{\pi NN}^{(1)}(\bar{\theta}, \tilde{d}_q), \dots] \sim -5e(\tilde{d}_d - \tilde{d}_u) + \dots$$

[Khriplovich & Korkin '00; Lebedev, Olive, Pospelov, AR '04;
Liu & Timmermans '04; de Vries et al '11; Bsaisou et al '12]

Neutron EDM sum rules - further details

- Consider the two-point function of the nucleon interpolating current in the presence of CP-odd sources

$$\int d^4x e^{ip \cdot x} \langle \bar{j}_n(x), j_n(0) \rangle_{QP,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p) F_{\mu\nu} + \dots$$

- Features:
 - multiple interpolating currents with lowest dimension
 - New - chiral “ambiguity” of the nucleon current

$$j_n = 2\epsilon_{abc}(d_a^T C \gamma_5 u_b)d_c + \beta \times 2\epsilon_{abc}(d_a^T C u_b)\gamma_5 d_c$$

unphysical parameter

$$\langle 0 | j_n | n \rangle = (\lambda_1 + \beta \lambda_2) e^{i\alpha\gamma_5/2} v$$

CP-odd sources introduce an unphysical phase in the coupling of the nucleon current and the physical state, which can (unphysically) mix d and μ

Neutron EDM sum rules - further details

- Another (related) new feature - the nucleon current can now mix with CP-conjugate currents, $\tilde{j}_n = CPj_nCP$

- Need to account for mixing by re-diagonalizing at linear order in the source

$$j_n \rightarrow j_n + i\epsilon_{CP} \tilde{j}_n$$

- So the correlator is correspondingly rotated

$$\int d^4x e^{ip \cdot x} \langle \bar{j}_n(x), j_n(0) \rangle_{CP,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p) F_{\mu\nu} + \dots$$



$$\langle \bar{j}j \rangle_{F,CP} + i\epsilon_{CP} \langle j\bar{j} + \tilde{j}\bar{j} \rangle_F + \dots$$

$$\frac{i}{2} \frac{\langle \tilde{j}_n \bar{j}_n - j_n \bar{\tilde{j}}_n \rangle_{CP}}{\langle j_n \bar{j}_n - \tilde{j}_n \bar{\tilde{j}}_n \rangle}$$

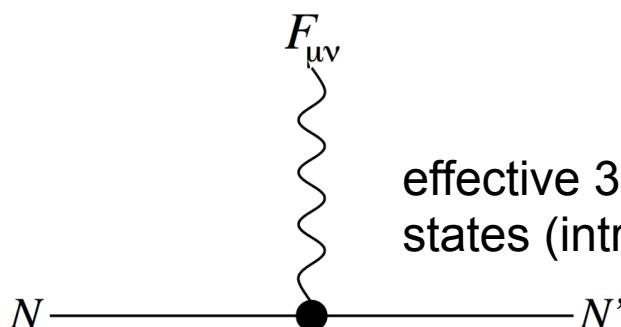
Neutron EDM sum rules - further details

- Work in a general basis of CP sources, as a cross-check
- Account for CP-odd current mixing to linear order (as above)
- Isolate EDM from a chirally-invariant structure in off-shell dipole form-factor (2-pt function, to first order in F)

$$\Pi_1(p) \cdot F \sim \{F\sigma\gamma_5, p\} \left(\frac{d_n \lambda^2 m_n}{(p^2 - m_n^2)^2} + \frac{A}{p^2 - m_n^2} + \dots \right) + \dots$$

Isolate tensor structure independent of unphysical phase α (avoids mixing of d and μ structures)

3-pt mixing with excited states cannot be exponentially suppressed with a Borel transform, due to lack of positivity in dispersive integral for 3-pt correlators. Must include mixing coefficient A explicitly in the fit.



effective 3-pt vertex allows mixing with excited states (introduces new fitting parameter A)

Neutron EDM sum rules - further details

- Work in a general basis of CP sources, as a cross-check
- Account for CP-odd current mixing to linear order (as above)
- Isolate EDM from a chirally-invariant structure in off-shell dipole form-factor (2-pt function, to first order in F)

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Isolate tensor structure independent of unphysical phase α (avoids mixing of d and μ structures)

3-pt mixing with excited states cannot be exponentially suppressed with a Borel transform, due to lack of positivity in dispersive integral for 3-pt correlators. Must include mixing coefficient A explicitly in the fit.

- Perform a self-consistent fit for the EDM, using other CP-even nucleon sum rules (mass, σ_N , etc) to determine $\{m_n, \lambda, A\}$

$$\lambda_1 + \beta \lambda_2$$

FAC criterion fixes $\beta=1$, i.e. to “optimize convergence” of the OPE

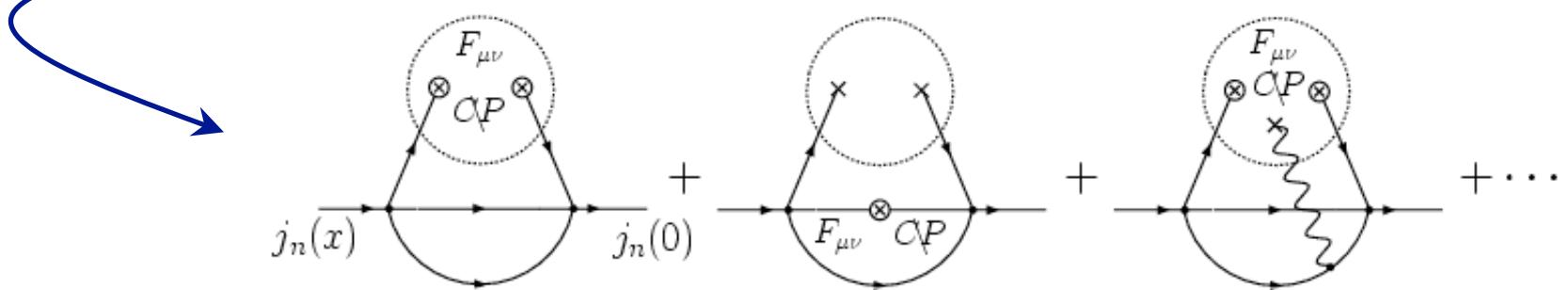
Neutron EDM sum rules - further details

- schematic structure of the OPE

[Pospelov & AR '99-'00]

$$\int d^4x e^{ip \cdot x} \langle \bar{j}_n(x), j_n(0) \rangle_{QP,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p) F_{\mu\nu} + \dots$$

$$\Pi_1(p) \cdot F \sim \{F \sigma \gamma_5, \not{p}\} \left(\frac{d_n \lambda^2 m_n}{(p^2 - m_n^2)^2} + \frac{A}{p^2 - m_n^2} + \dots \right) + \dots$$



- depends on vacuum condensates, e.g. $\langle \bar{q} \sigma_{\mu\nu} q \rangle_F = \chi e_q F_{\mu\nu} \langle \bar{q} q \rangle$
 $\langle \bar{q} G \sigma q \rangle = -m_0^2 \langle \bar{q} q \rangle$
- implicit dependence of condensates on the CP-odd sources determined via xPT, and saturation with π and η exchange.
(vacuum “realignment”)

Neutron/Proton EDM

- Results:

$$d_n(\bar{\theta}) \sim 3 \times 10^{-16} \bar{\theta} \text{ ecm}$$

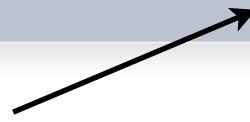
$$d_p(\bar{\theta}) \sim -4 \times 10^{-16} \bar{\theta} \text{ ecm}$$

- If the axion relaxes θ , the CEDM sources shift the minimum of the axion potential $V(\theta)$ away from zero

$$\theta_{ind} = \frac{1}{2} m_0^2 \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q}$$

$$d_p^{(PQ)} \sim (0.4 \pm 0.2) [4d_u - d_d - 5.3e(\tilde{d}_u + 0.13\tilde{d}_d) + \dots] + \mathcal{O}(d_s, w, C_{qq})$$

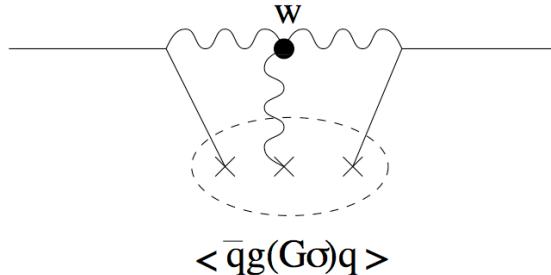
$$d_n^{(PQ)} \sim (0.4 \pm 0.2) [4d_d - d_u + 2.7e(\tilde{d}_d + 0.5\tilde{d}_u) + \dots] + \mathcal{O}(d_s, w, C_{qq})$$



Appearance of the same relative coefficients as the NQM appears accidental, as it depends (at $\sim 30\%$) on the choice of $\beta \in [0, 1]$

Further operators

- Weinberg operator:



$$d_n \sim \mu_n \frac{\langle N | \mathcal{O}_{CP} | N \rangle}{m_n \bar{N} i \gamma_5 N} \sim \mu_n \frac{3g_s m_0^2}{32\pi^2} w \ln(M^2/\mu_{IR}^2) \sim e 2 \times 10^{-2} \text{ GeV} w(1 \text{ GeV})$$

[Demir, Pospelov, AR '02]

$$\bar{g}_{\pi NN}^{(1)} = \bar{g}_{\pi NN}^{(1)}(w) \quad \text{suppressed by light quark masses}$$

- 4-quark (factorizable) operators:

$$d_n(C_{qq}) \sim (\text{few}) \times 10^{-2} \text{ GeV } C_{qq}$$

[Khatsimovsky et al '88;
Hamzaoui & Pospelov '99;
An, Ji & Xu '09]

$$\bar{g}_{\pi NN}^{(1)}(C_{ij}) = C_{ij} \frac{\langle q_i \bar{q}_i \rangle}{2f_\pi} \langle N | q_j \bar{q}_j | N \rangle$$

via PCAC, vacuum
saturation [Demir et al '03]

Results - summary

ThO (paramagnetic) (atomic/molecular)

$$\Delta E_{\text{ThO}} \sim -84 \text{ GeV} \left(\frac{d_e}{e \text{ cm}} \right) + \mathcal{O}(C_S(C_{qe}))$$

[Kozlov et al. 94-98; Quiney et al '98; Parpia '98; Chaudhuri & Nayak '08, Meyer & Bohn '08; Dzuba et al '11; Skripnikov et al '13]

Neutron EDM (chiralPT, NDA, QCD sum rules, ...)

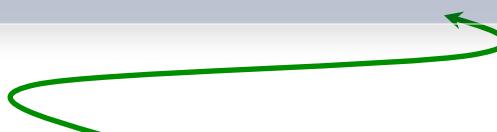
$$d_n(\bar{\theta}) \sim 3 \times 10^{-16} \bar{\theta} \text{ ecm} \Rightarrow |\theta| < 10^{-10}$$

$$d_n^{(PQ)} \sim (0.4 \pm 0.2)[4d_d - d_u + 2.7e(\tilde{d}_d + 0.5\tilde{d}_d) + \dots] + \mathcal{O}(d_s, w, C_{qq})$$

[Pospelov & AR '99,'00;
Hisano et al '12]

Hg EDM (diamagnetic) (atomic+nuclear+QCD)

$$d_{Hg} \sim 10^{-3} d_{\text{nuc}} \sim -3 \times 10^{-17} S(\bar{g}_{\pi NN}^{(0,1,2)}, d_n, d_p) [e \text{ fm}^3] + \mathcal{O}(d_e, C_{qq})$$

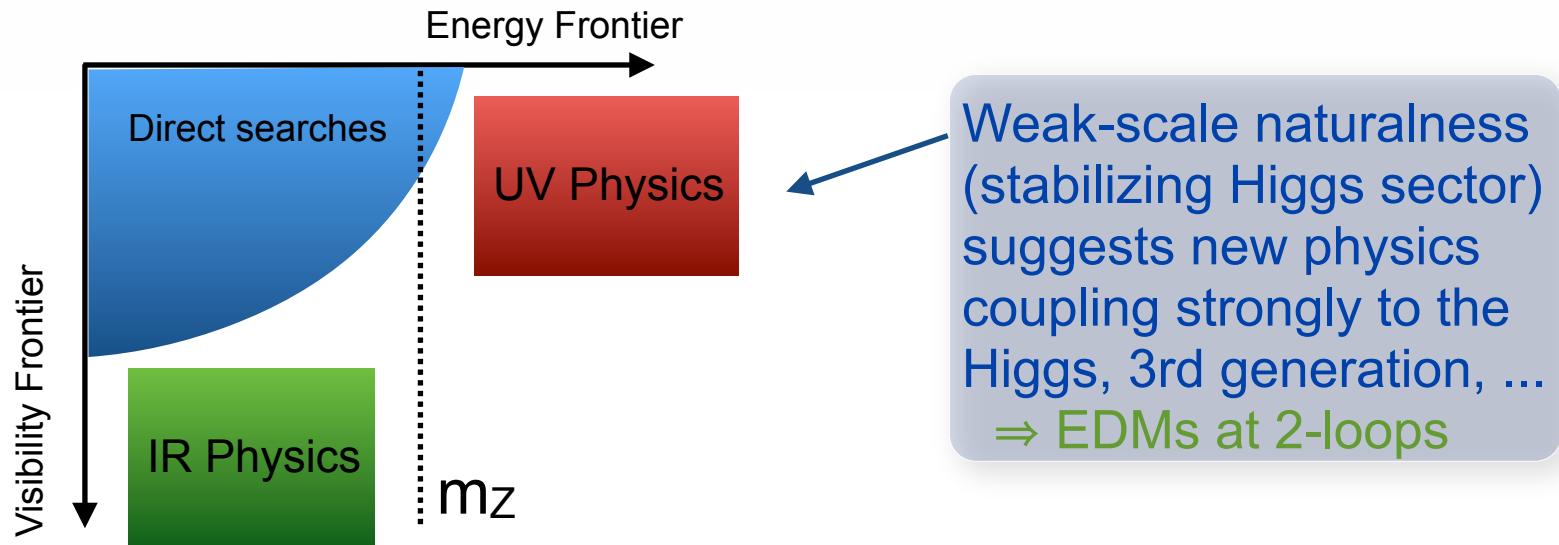


[Dzuba et al. '02; Flambaum et al. '86; Dmitriev & Senkov '03; de Jesus & Engel '05; Ban et al '10]

$$\bar{g}_{\pi NN}^{(1)} \sim (3 \pm 2)(\tilde{d}_u - \tilde{d}_d) + \mathcal{O}(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w) \quad [\text{Pospelov '01}]$$

NB: concern about precision of $S(\bar{g}_{\pi NN}^{(0)}, \bar{g}_{\pi NN}^{(1)}, \bar{g}_{\pi NN}^{(2)})$ [Ban et al '10]

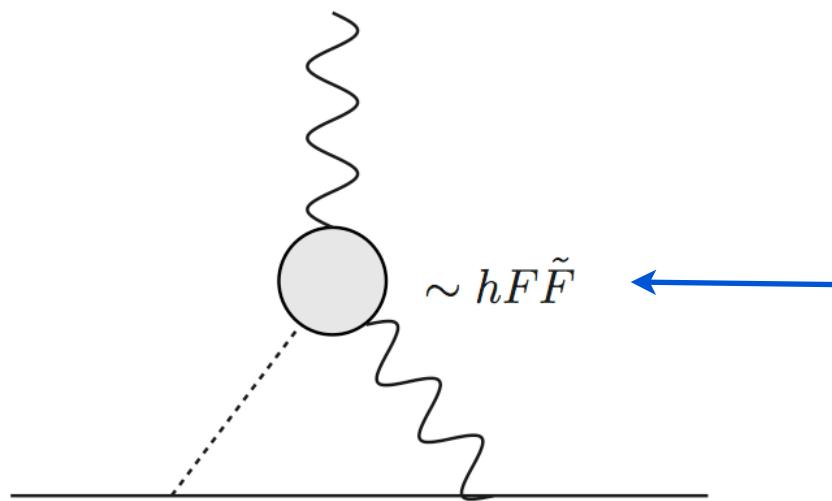
LHC-era tests of CP-violating new physics



Example 1 - CP-odd Higgs couplings

- Hints in 2012 that $\text{Br}(h \rightarrow \gamma\gamma) > \text{Br}_{\text{SM}}$ (have since dissipated)
- EDMs significantly constrain any CP-odd contribution to $h \rightarrow \gamma\gamma$

$$\Delta\mathcal{L} = \frac{1}{e^2 \tilde{\Lambda}^2} H^\dagger H \left(a_h g_1^2 B_{\mu\nu} \tilde{B}^{\mu\nu} + b_h g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu} \right) \rightarrow \frac{\tilde{c}_h v}{\tilde{\Lambda}^2} h F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots$$



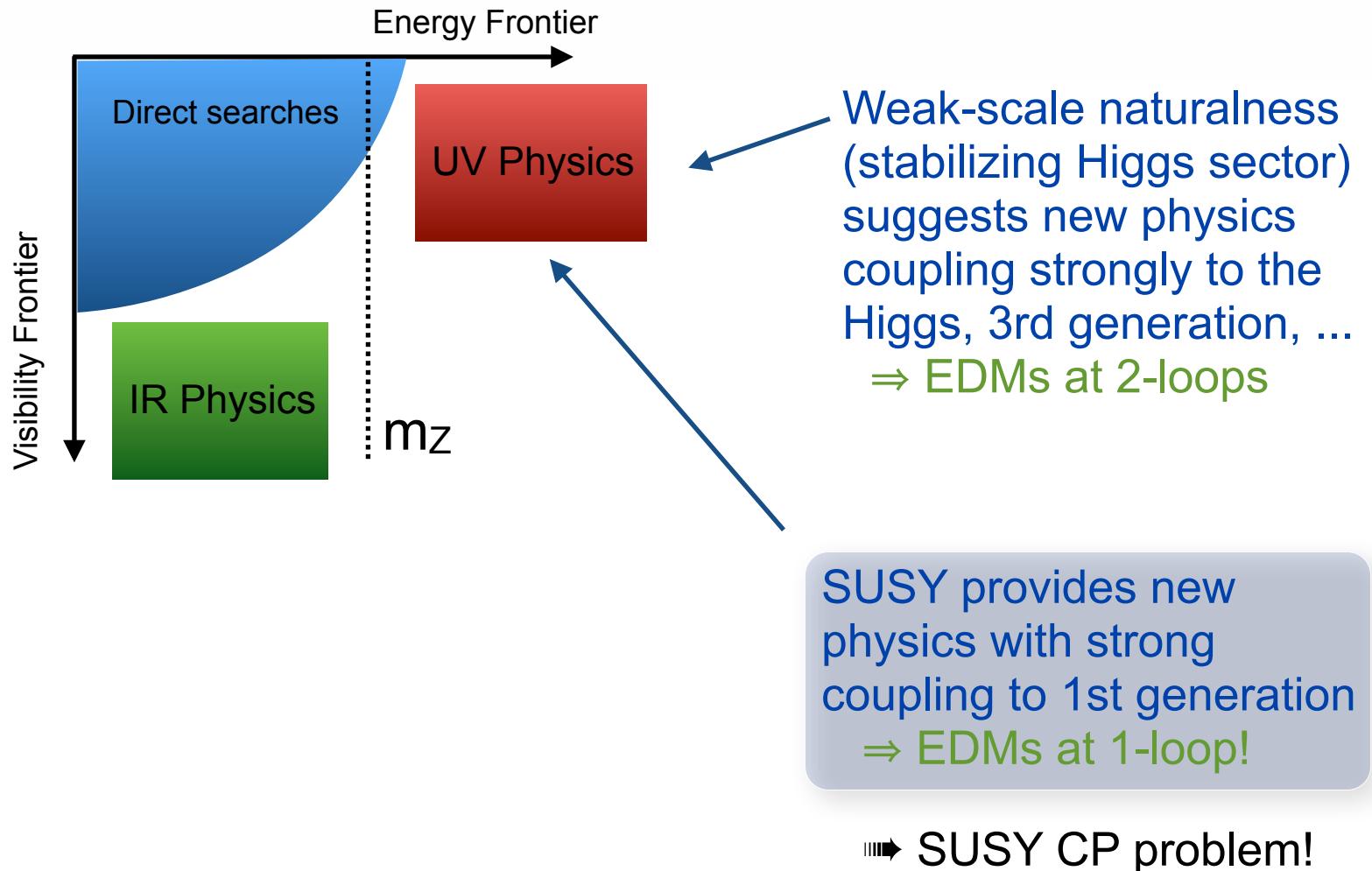
This interaction shifts $\text{Br}(h \rightarrow \gamma\gamma)$, but also generates EDMs!

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\text{SM}}} \simeq 1 + \left| \tilde{c}_h \frac{v^2}{\tilde{\Lambda}^2} \frac{8\pi}{\alpha A_{\text{SM}}} \right|^2$$

Current bound on d_e limits
 $\Delta \text{Br}(h \rightarrow \gamma\gamma) / \text{Br}_{\text{SM}} < \mathcal{O}(10^{-5})$
from this CP-odd operator!

[McKeen, Pospelov & AR '12]
[Harnik et al '12; Fan & Reece '13]⁵⁸

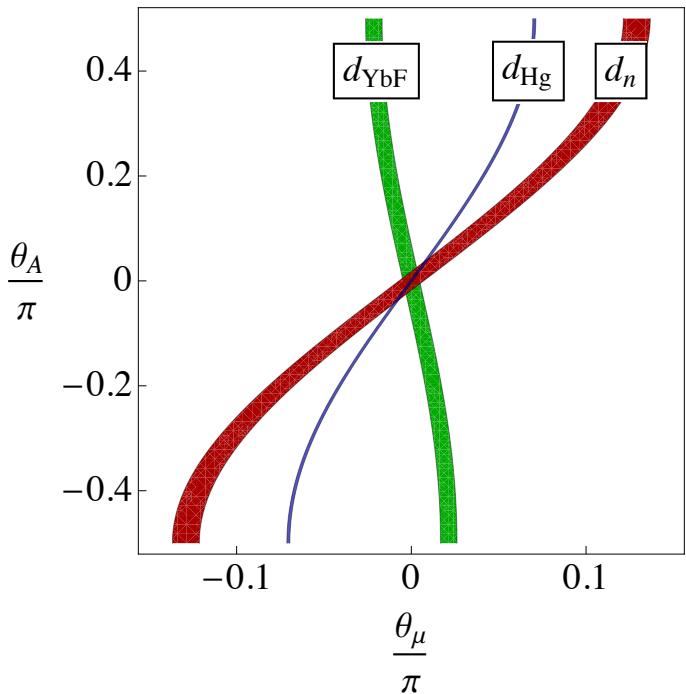
LHC-era tests of CP-violating new physics



Example 2a - (LHC era) SUSY CP Problem

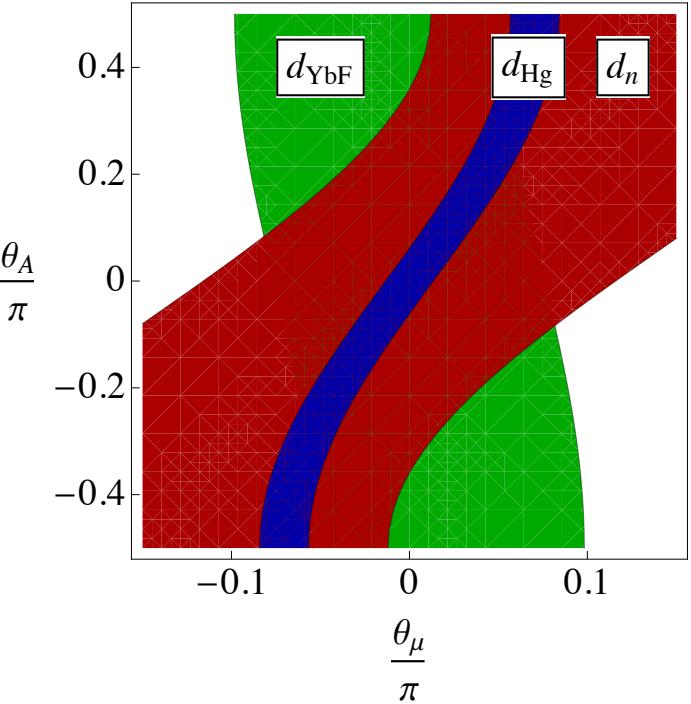
(pre-LHC)

$$M_{susy} = 500 \text{ GeV}$$



(2012/13)

$$M_{susy} = 2 \text{ TeV}$$



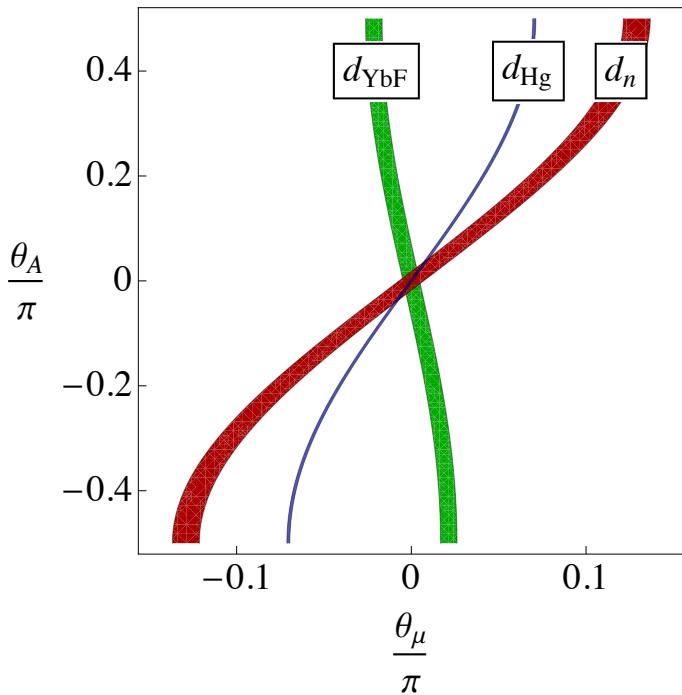
1st gen squarks
excluded by direct
searches at $\sim 1 \text{ TeV}$

EDMs have for many years required (tuned) $O(10^{-3})$ CP-odd phases for “generic” weak-scale SUSY. The LHC appears to have “resolved” this by pushing mass limits on 1st generation sfermions above a TeV.

Example 2a - (LHC era) SUSY CP Problem

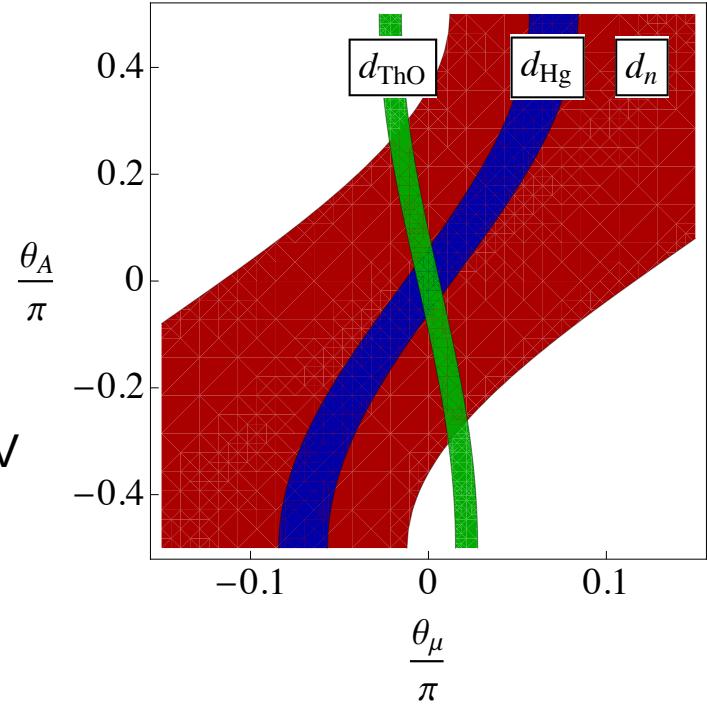
(pre-LHC)

$$M_{susy} = 500 \text{ GeV}$$



(now)

$$M_{susy} = 2 \text{ TeV}$$



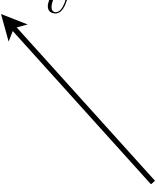
1st gen squarks
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EDMs have for many years required (tuned) $O(10^{-3})$ CP-odd phases for “generic” weak-scale SUSY. The LHC appears to have “resolved” this by pushing mass limits on 1st generation sfermions above a TeV. **Now tuning (at a TeV) being re-introduced via ThO limit on d_e .**

Example 2b - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h \gg m_Z$ points to PeV-scale s-partners (\rightarrow tuning, no soln to “little hierarchy” problem) [e.g. Arkani-Hamed et al '12]

$$m_h^2 \sim M_Z^2 + \frac{3}{\sqrt{2}\pi^2} G_F m_t^4 \ln \frac{m_{\tilde{t}}^2}{v^2}$$

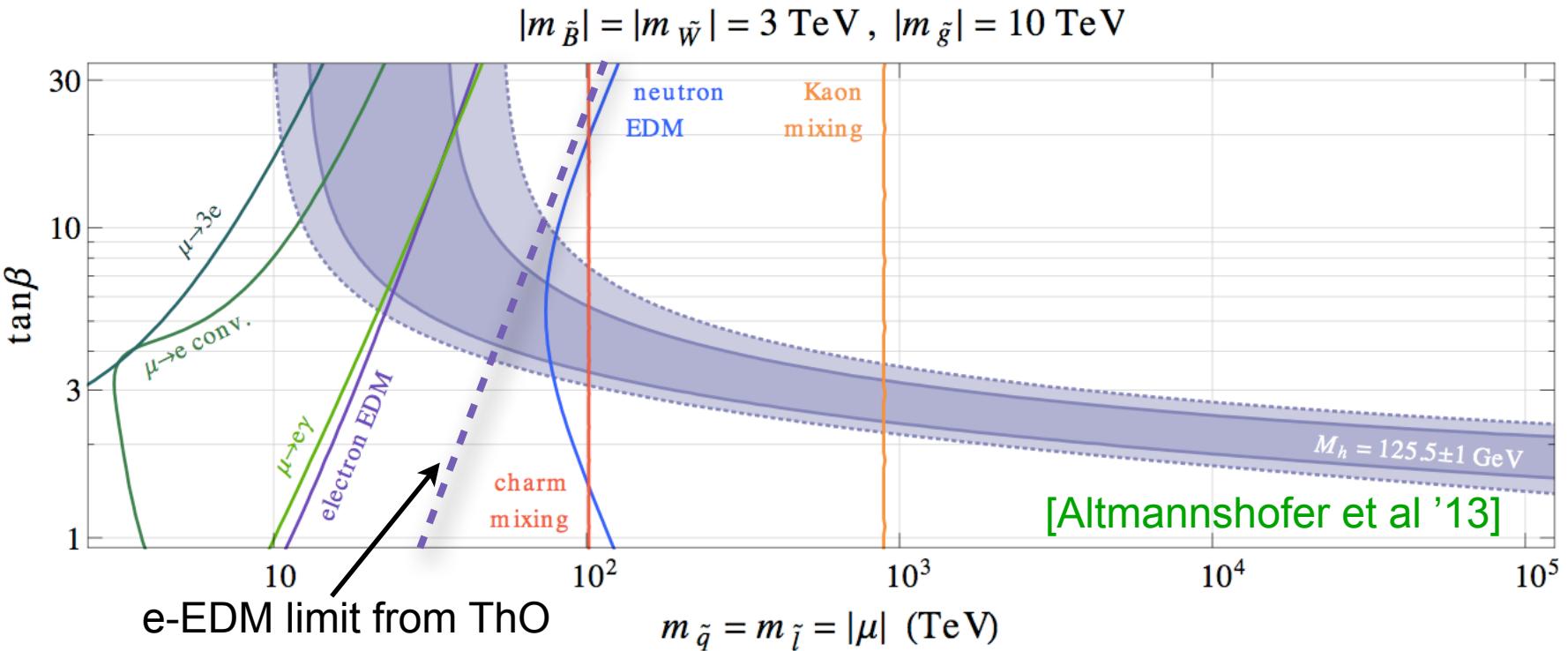
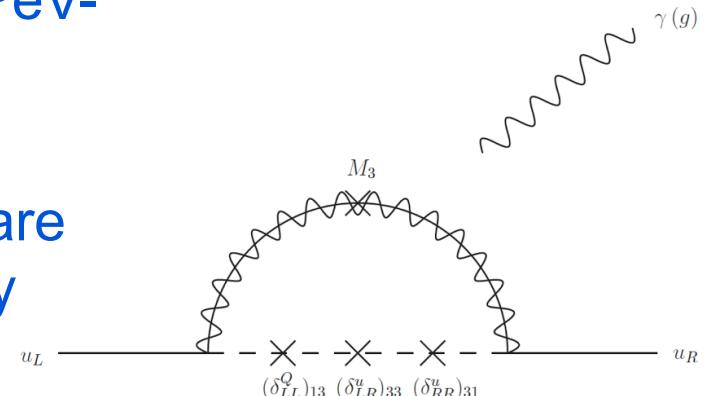


Need a large log correction
 $\rightarrow m_{\text{squark}} > 100-1000 \text{ TeV}$

Example 2b - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h \gg m_Z$ points to PeV-scale s-partners
- The PeV scale allows a generic flavour structure and, with TeV gauginos, EDMs are one of the few observables with sensitivity (via log-enhanced quark CEDMs)

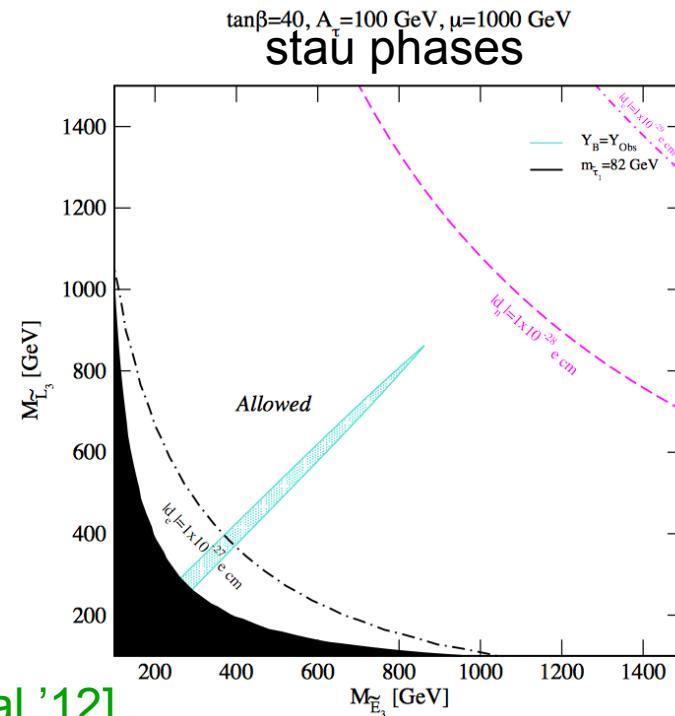
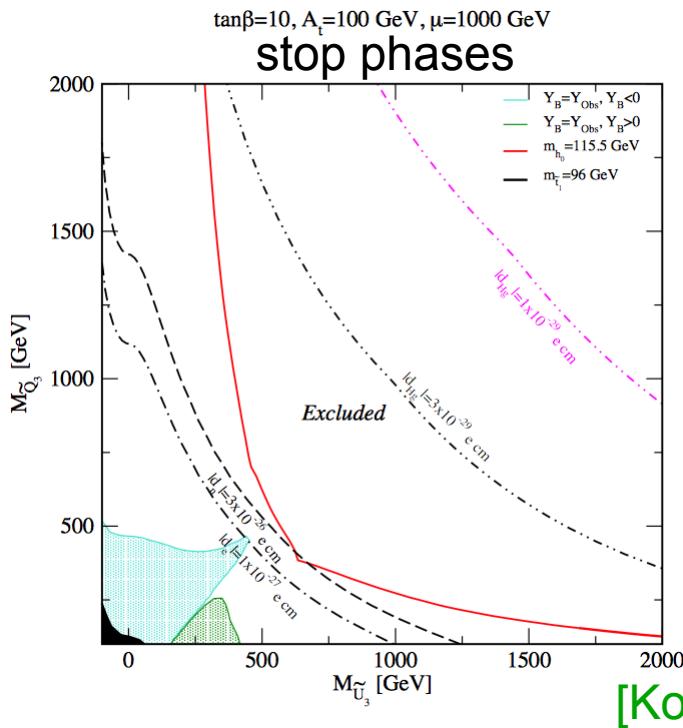
[McKeen, Pospelov & AR '13; Altmannshofer et al '13; Fuyuto et al '13]



NB: EDMs and EW baryogenesis

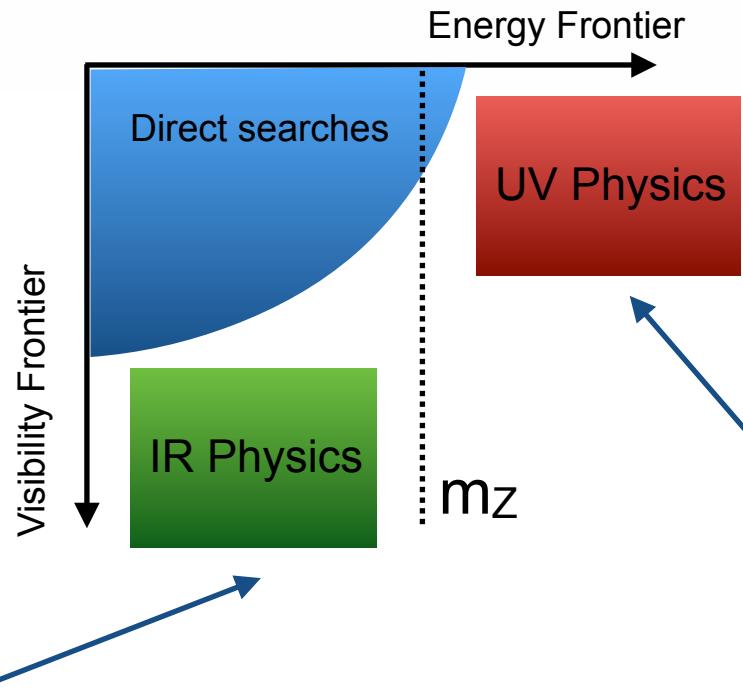
The primary empirical motivation for sizable EDMs is the need for new CP-phases to contribute to baryogenesis

- Models such as leptogenesis are (unfortunately) viable while only generating suppressed EDMs below the CKM level
- Electroweak baryogenesis is a target, as models generically require new states at the EW scale, and O(1) CP phases
 - for the minimal MSSM, there are strong limits from stop searches



[Kozaczuk et al '12]

LHC-era tests of CP-violating new physics



Light (UV-complete) hidden sectors, motivated e.g. by neutrino mass, dark matter phenomenology
⇒ (suppressed) EDMs at 2-loops

Weak-scale naturalness (stabilizing Higgs sector) suggests new physics coupling strongly to the Higgs, 3rd generation, ...
⇒ EDMs at 2-loops

SUSY provides new physics with strong coupling to 1st generation
⇒ EDMs at 1-loop!

⇒ SUSY CP problem!

Example 3 - EDM Sensitivity to hidden sectors

Standard Model



Hidden Sector

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portals}}(\mathcal{O}_3, \mathcal{O}_4, \mathcal{O}_5) + \mathcal{L}_{\text{hid}}$$



Not UV
complete

$$\text{axion portal} - \frac{a}{f_a} G \tilde{G} \rightarrow \text{AC "EDMs"}$$

$$d_n \propto \theta_{\text{eff}}(\rho_{\text{DM}}) \cos(m_a t)$$

[Graham, Rajendran, Budker et al]

light axion DM \rightarrow MHz oscillations,
opens up new experimental tests, e.g.
with NMR. However, the amplitude is
still well below current EDM sensitivity.