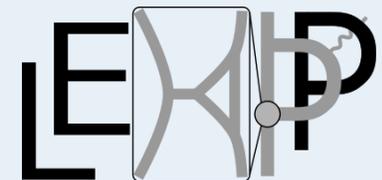


Permanent Electric Dipole Moments as probes of Fundamental Symmetries

CIPANP 2025, Madison
June 11, 2025

Skyler Degenkolb

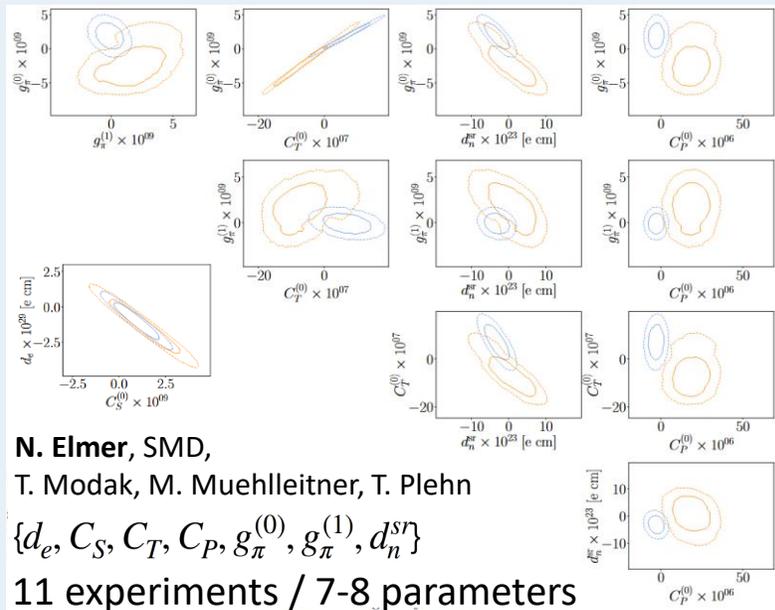
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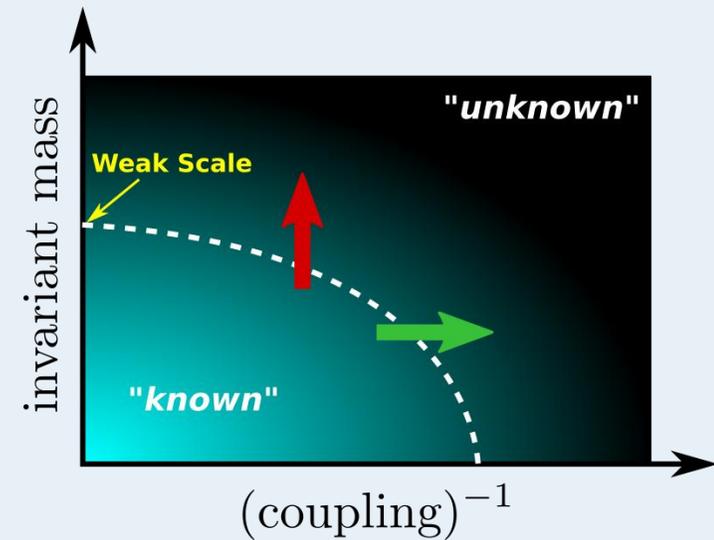
Permanent Electric Dipole Moments as probes of Fundamental Symmetries

Hadronic-level global analysis of EDMs
arxiv:2403.02052



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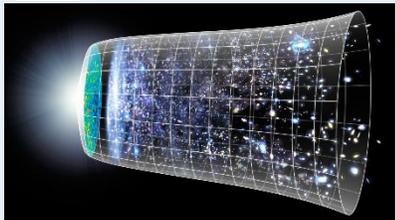
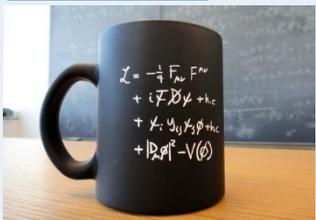
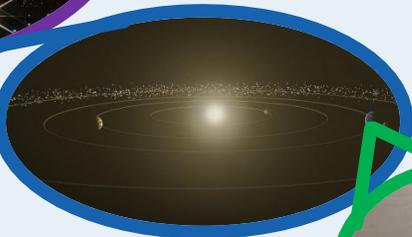
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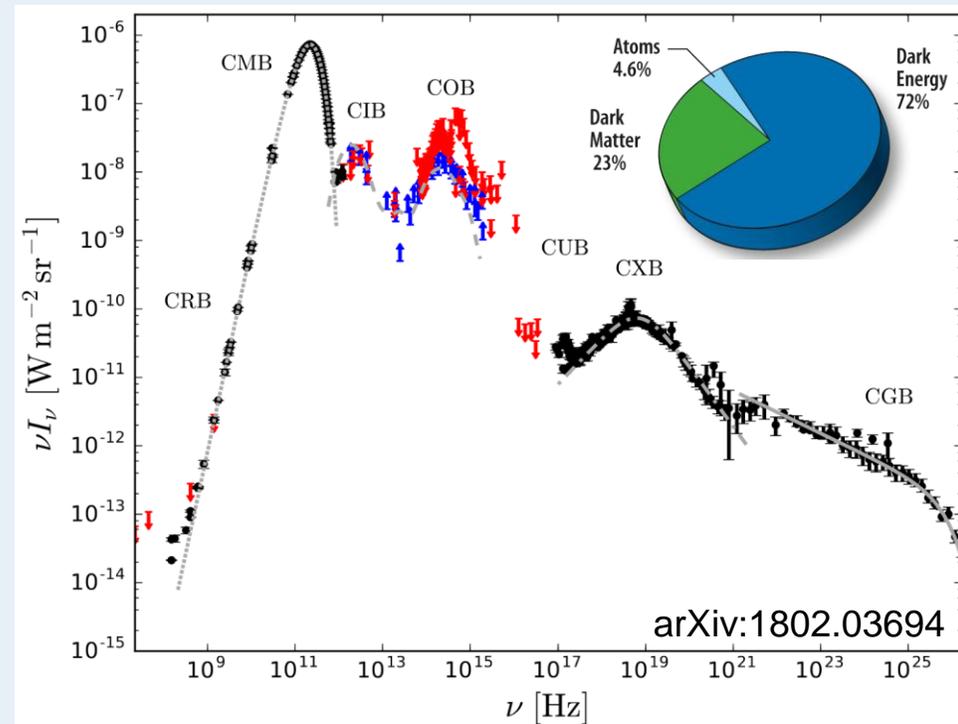
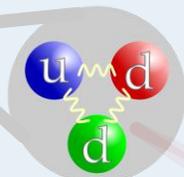


Observed photon density (CMB):

- $n_\gamma \approx 411 \text{ cm}^{-3}$

Baryon density and asymmetry:

- $n_B \approx 6 \times 10^{-10} n_\gamma$



Sakharov criteria for Baryogenesis:

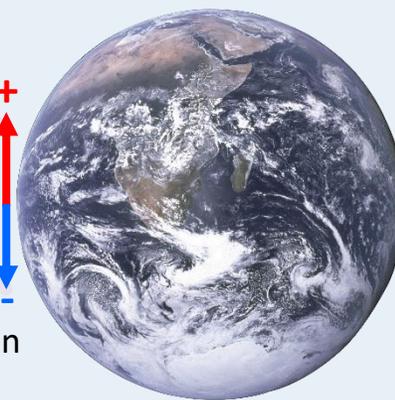
1. B non-conservation
2. **C and CP violation**
3. Far from thermal equilibrium

$$\mathcal{L}_{\text{fermion}} = -\frac{\mu}{2} \bar{\psi} \sigma^{\mu\nu} F_{\mu\nu} \psi - i \frac{d}{2} \bar{\psi} \sigma^{\mu\nu} \gamma^5 F_{\mu\nu} \psi$$

MDM

EDM

neutron (enlarged)

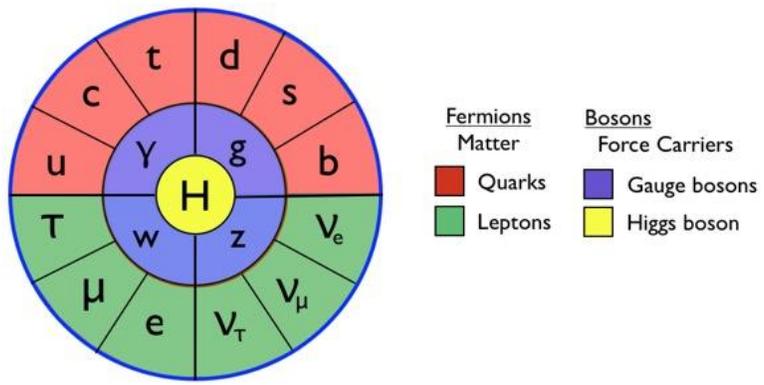


EDM separation
< 1 μm

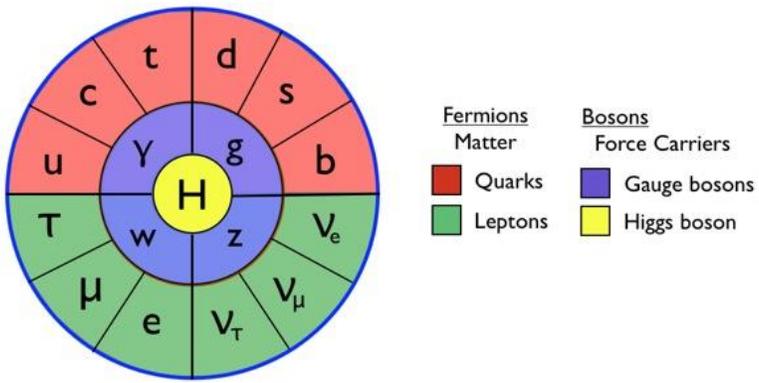
Strong CP problem:

- $|d_n| < 10^{-26} \text{ e}\cdot\text{cm}$ (measured)
- implies $|\theta_{\text{QCD}}| < 10^{-10}$ (too small)

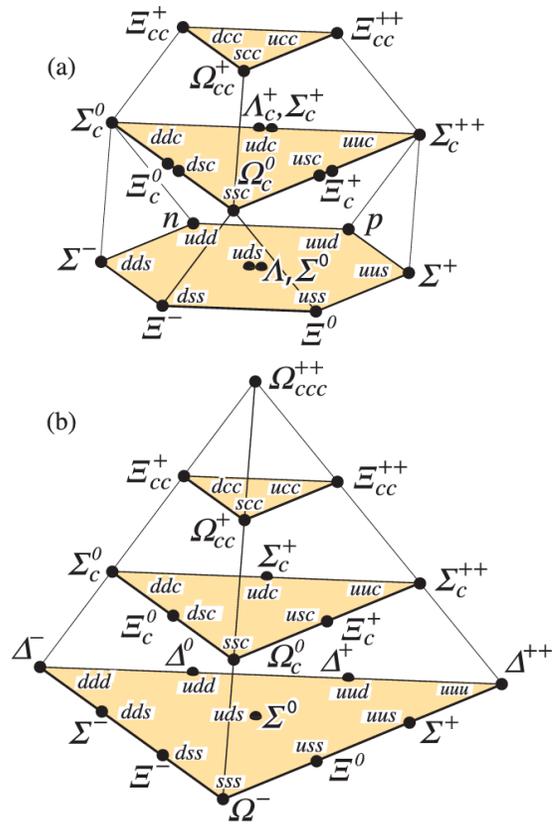
$$H_{\text{spin}} = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$$

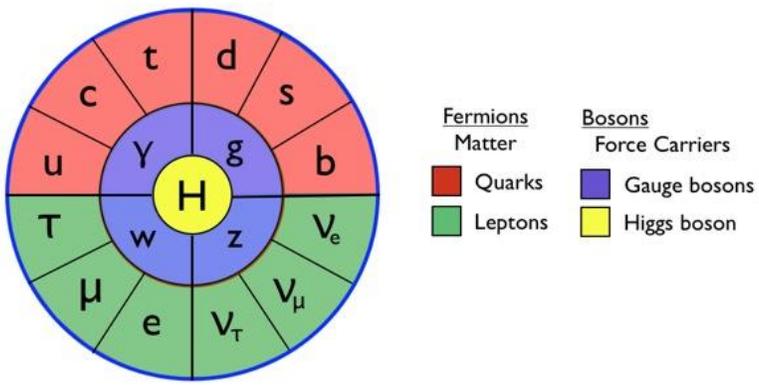


Particles of the Standard Model

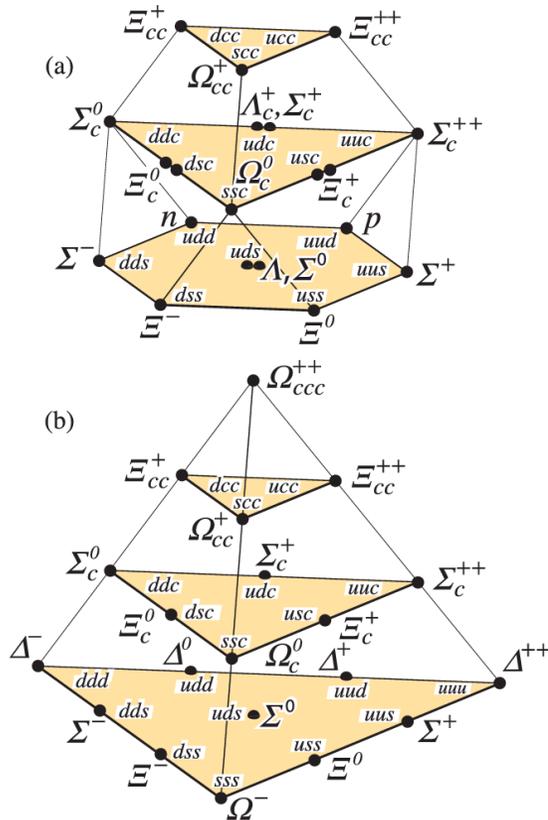


Particles of the Standard Model





Particles of the Standard Model

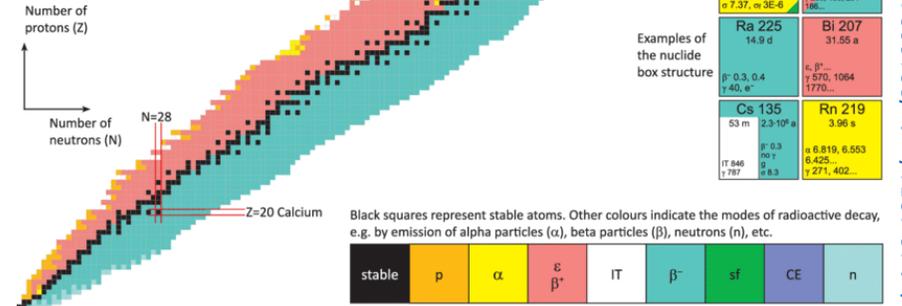


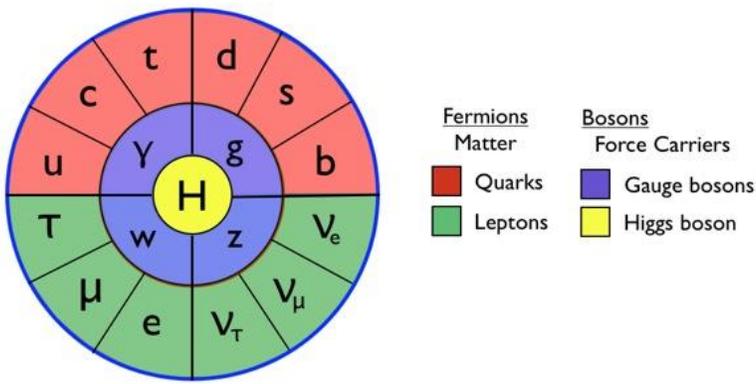
The Karlsruhe Nuclide Chart

A nuclide chart is a two dimensional representation of the nuclear and radioactive properties of all known atoms. A nuclide is the generic name for atoms characterized by the constituent protons and neutrons. The nuclide chart arranges nuclides according to the number of protons (vertical axis) and neutrons (horizontal axis) in the nucleus. Each nuclide in the chart is represented by a box containing the element symbol and mass number, half-life, decay types and decay energies, etc.

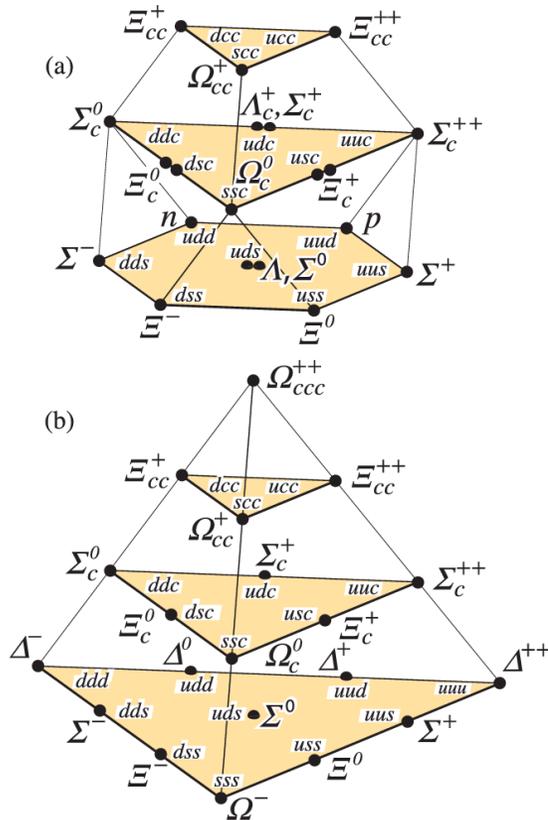
"Magic" numbers

In nuclear physics, a magic number is a number of protons or neutrons (e.g. 2, 8, 20, 28, 50, 82, 126) which give rise to a complete shell in the atomic nucleus. Lead 208 for example, which consists of 82 protons and 126 neutrons, is called "doubly magic" since both the proton and neutron numbers are "magic".





Particles of the Standard Model

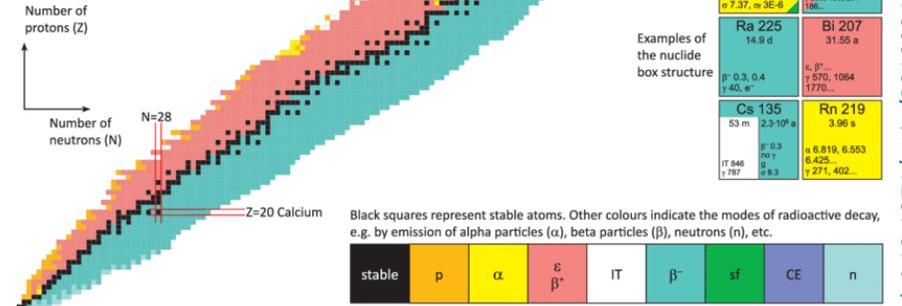


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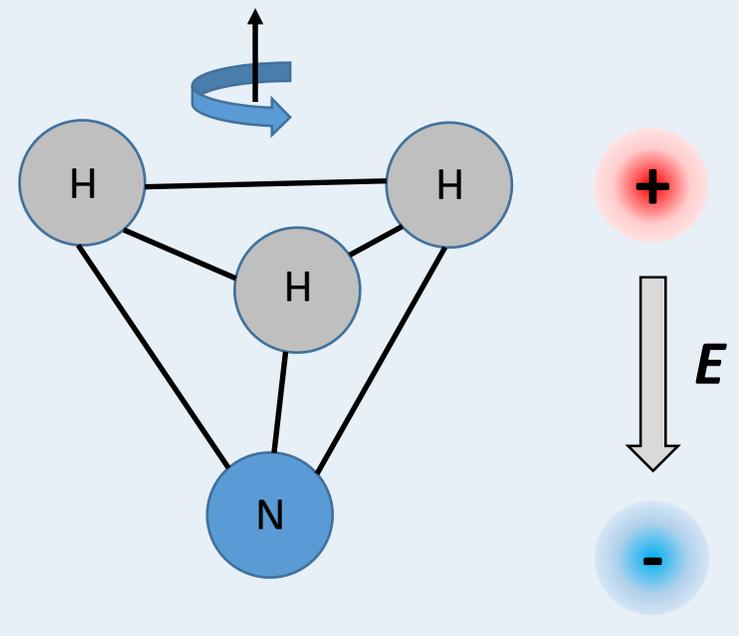
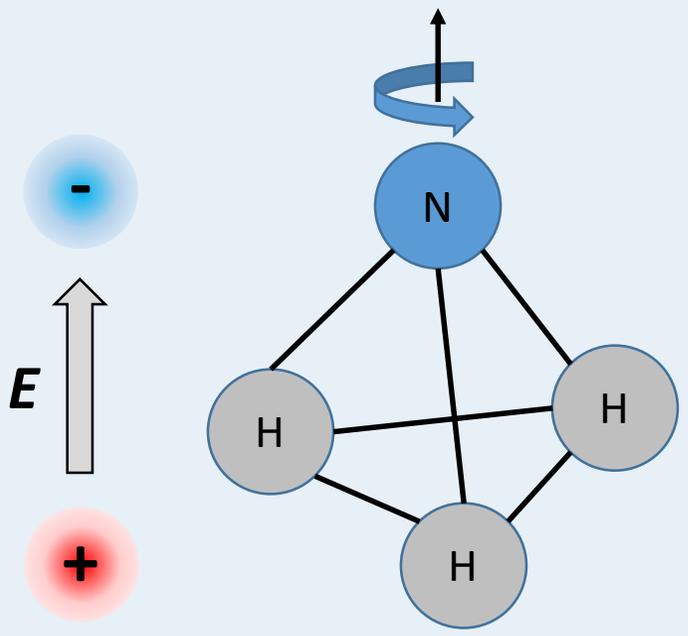
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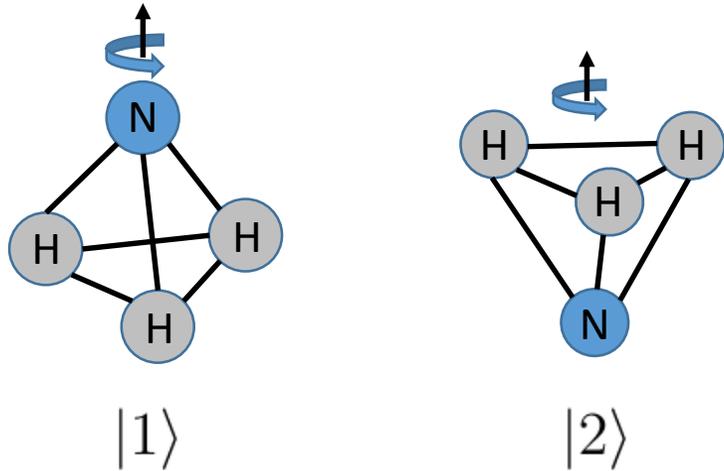
Periodic table of the elements

group	1*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
lanthanoid series	6	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			
actinoid series	7	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr			

Legend:
 Alkali metals (orange), Alkaline-earth metals (yellow), Transition metals (blue), Other metals (light blue), Other nonmetals (pink), Halogens (green), Noble gases (white), Flare-earth elements (21, 39, 57-71) and lanthanoid elements (57-71 only) (light green), Actinoid elements (light blue).



Molecular Dipole Moments are not Permanent



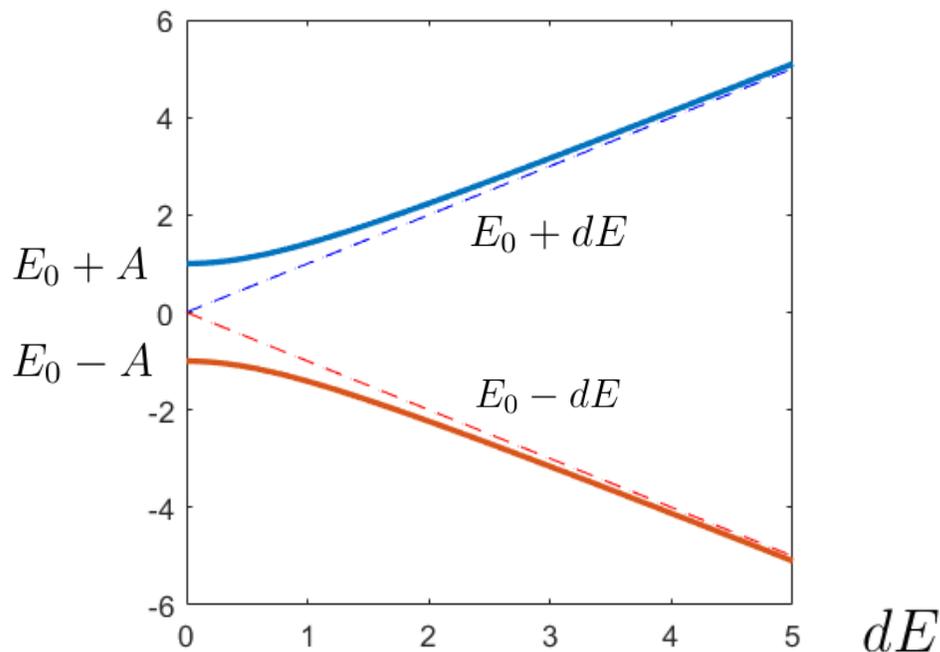
The *energy* eigenstates are:

$$\frac{1}{\sqrt{2}} (|1\rangle \pm |2\rangle)$$

Two limiting cases:

$$E_{\pm} = E_0 + \sqrt{A^2 + d^2 E^2}$$

$$E_0 \pm dE \quad (dE \gg A) \qquad E_0 \pm A \pm \frac{d^2 E^2}{2A} \quad (dE \ll A)$$



Wait a minute...

- **Schiff's theorem:** the field due to an EDM induces a displacement of the bound charges, which exactly cancels it*

$$H_0 = \sum \frac{p^2}{2m} + U(\mathbf{r})$$

Hamiltonian of the charge-system (no EDM)

*Schiff: *Phys. Rev.* **132**, 2194 (1963)
Engel et al., *Prog. Part. Nucl. Phys.* 71, 21 (2013)

EDMs should not be observable

- **Schiff's theorem:** the field due to an EDM induces a displacement of the bound charges, which exactly cancels it

$$H_0 = \sum \frac{p^2}{2m} + U(\mathbf{r})$$

*Add constituent EDMs
As a perturbation...*

$$\mathbf{d}_{\text{tot}} = \sum_i \mathbf{d}_i$$

(sum over constituents)

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*Add constituent EDMs
As a perturbation...*

$$\mathbf{d}_{\text{tot}} = \sum_i \mathbf{d}_i$$

(sum over constituents)

$$\begin{aligned} H &= H_0 - \sum \mathbf{d} \cdot \mathbf{E} \\ &= H_0 + \sum \mathbf{d} \cdot \frac{\nabla U(\mathbf{r})}{q} \\ &= H_0 + \sum \frac{i}{q} [\mathbf{d} \cdot \mathbf{p}, H_0] \end{aligned}$$

Now see what effect this has...

EDMs should not be observable

- **Schiff's theorem:** the field due to an EDM induces a displacement of the bound charges, which exactly cancels it

$$H_0 = \sum \frac{p^2}{2m} + U(\mathbf{r})$$

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Eigenstates receive an energy shift due to the perturbation:

$$\begin{aligned} |0\rangle \rightarrow |\tilde{0}\rangle &= |0\rangle + \sum_n \frac{|n\rangle \langle n| \sum \frac{i}{q} [\mathbf{d} \cdot \mathbf{p}, H_0] |0\rangle}{E_0 - E_n} \\ &= \left(1 + \sum \frac{i}{q} \mathbf{d} \cdot \mathbf{p} \right) |0\rangle \end{aligned}$$

EDMs should not be observable

- What is the total, observable, dipole moment after this shift?

$$\begin{aligned}\tilde{\mathbf{d}} &= \sum \mathbf{d} + \langle \tilde{0} | \sum q\mathbf{r} | \tilde{0} \rangle \\ &= \sum \mathbf{d} + \langle \tilde{0} | \left(1 - \sum \frac{i}{q} \mathbf{d} \cdot \mathbf{p} \right) \sum q\mathbf{r} \left(1 + \sum \frac{i}{q} \mathbf{d} \cdot \mathbf{p} \right) | \tilde{0} \rangle \\ &= \sum \mathbf{d} + i \langle 0 | \left[\sum q\mathbf{r}, \sum \frac{1}{q} \mathbf{d} \cdot \mathbf{p} \right] | 0 \rangle \\ &= \sum \mathbf{d} - \sum \mathbf{d} \\ &= 0\end{aligned}$$

But some details can save us!

- Schiff's theorem assumes:

- pointlike particles → *incorrect for nuclei*

$$\mathbf{S} = \frac{1}{10} \langle r^2 \mathbf{d} \rangle - \frac{1}{6Z} \langle r^2 \rangle \langle \mathbf{d} \rangle$$

Nuclear structure enhancements!

$$S \propto \frac{\eta \beta_1 \beta_3^2 A^{\frac{2}{3}} r_0^3}{E_+ - E_-}$$

...see Prog. Part. Nucl. Phys. **71**, 21 (2013)

- non-relativistic treatment → *incorrect for atomic electrons*

$$U_{\text{lab}} = -\mathbf{d}_{\text{lab}} \cdot \mathbf{E} = -\mathbf{d}_{\text{rest}} \cdot \mathbf{E} + \frac{\gamma}{1 + \gamma} (\boldsymbol{\beta} \cdot \mathbf{d})(\boldsymbol{\beta} \cdot \mathbf{E})$$

...see American Journal of Physics **75**, 532 (2007)

Form Factors (not only for composite particles...)

$$\begin{aligned} \langle p_f | j^\mu | p_i \rangle = & \bar{u}(p_f) \left[F_1(q^2) \gamma^\mu \right. \\ & + \frac{i\sigma^{\mu\nu}}{2m} q_\nu F_2(q^2) \\ & + i\epsilon^{\mu\nu\rho\sigma} \sigma_{\rho\sigma} q_\nu F_3(q^2) \\ & \left. + \frac{1}{2m} \left(q^\mu - \frac{q^2}{2m} \gamma^\mu \right) \gamma_5 F_4(q^2) \right] u(p_i) \end{aligned}$$

$$d = -\frac{F_3(0)}{2m}$$

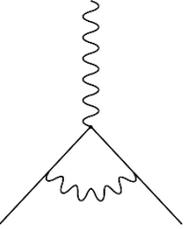
$$Q = F_1(0)$$

$$\mu = \frac{F_1(0) + F_2(0)}{2m}$$

$$a = F_4(0)$$

cf. electron g-2

$$\mu \rightarrow \mu + i\gamma^5 d$$



Form Factors (not only for composite particles...)

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 \langle p_f | j^\mu | p_i \rangle = & \bar{u}(p_f) \left[F_1(q^2) \gamma^\mu \right. \\
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 & \left. + \frac{1}{2m} \left(q^\mu - \frac{q^2}{2m} \gamma^\mu \right) \gamma_5 F_4(q^2) \right] u(p_i)
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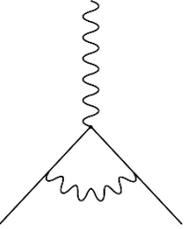
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$$d = -\frac{F_3(0)}{2m}$$

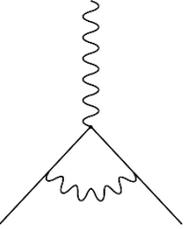
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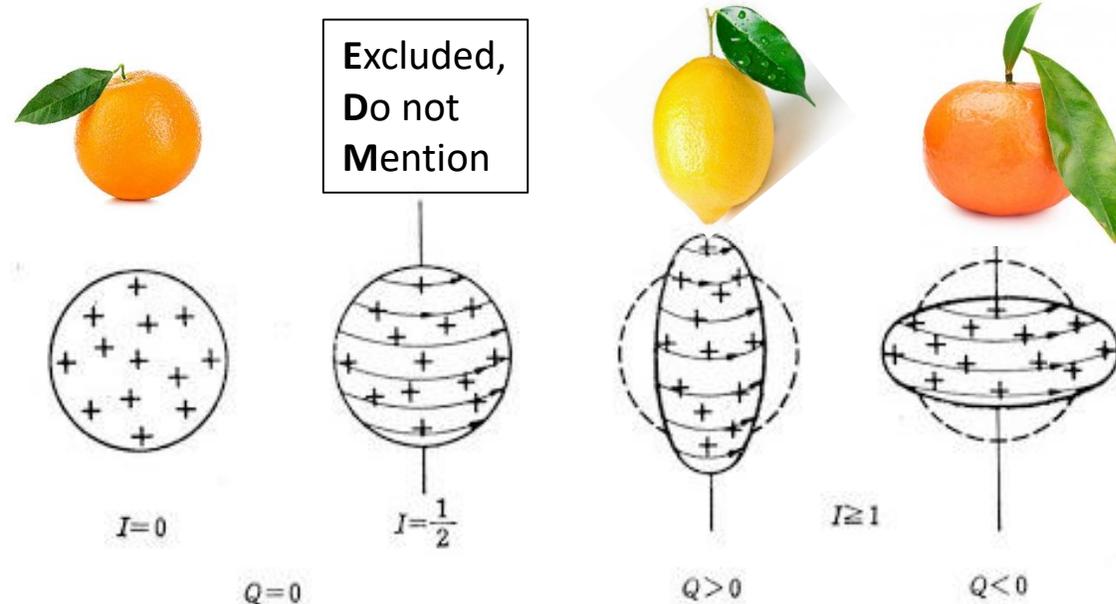
$$\mu \rightarrow \mu + i\gamma^5 d$$



Further structures, e.g. Schiff moment:

$$F_{n,p} \sim d_{n,p} + q^2 S_{n,p}$$

Moments that violate P and T: M0, E1, M2, E3, ...



Reflection asymmetry

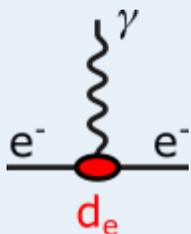
Broad categories, sources, and sensitivity

Open-shell atoms and molecules

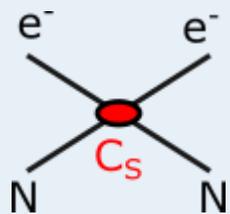
- “paramagnetic”
- Cs, Tl, YbF, ThO, HfF⁺

Main sensitivities:

- electron EDM



- semileptonic (nuclear spin independent)



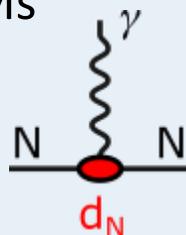
- others strongly suppressed

Closed-shell atoms and molecules

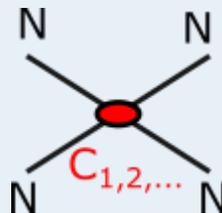
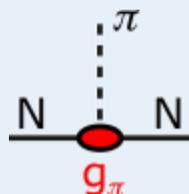
- “diamagnetic”
- Yb, Xe, Hg, Ra, TlF

Main sensitivities:

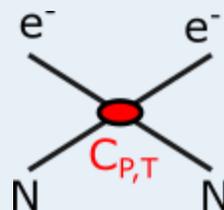
- nucleon EDMs



- nuclear forces



- semileptonic (nuclear spin-dependent)



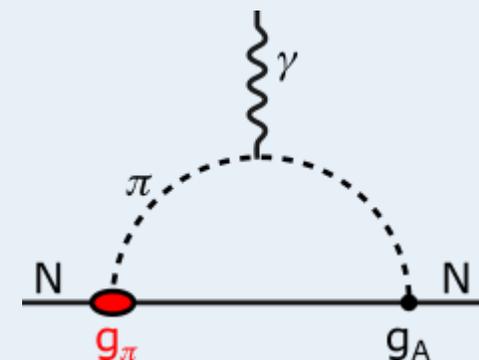
Particles and other...

- various properties
- $n, (\rho), \mu, \tau, \Lambda, \dots$

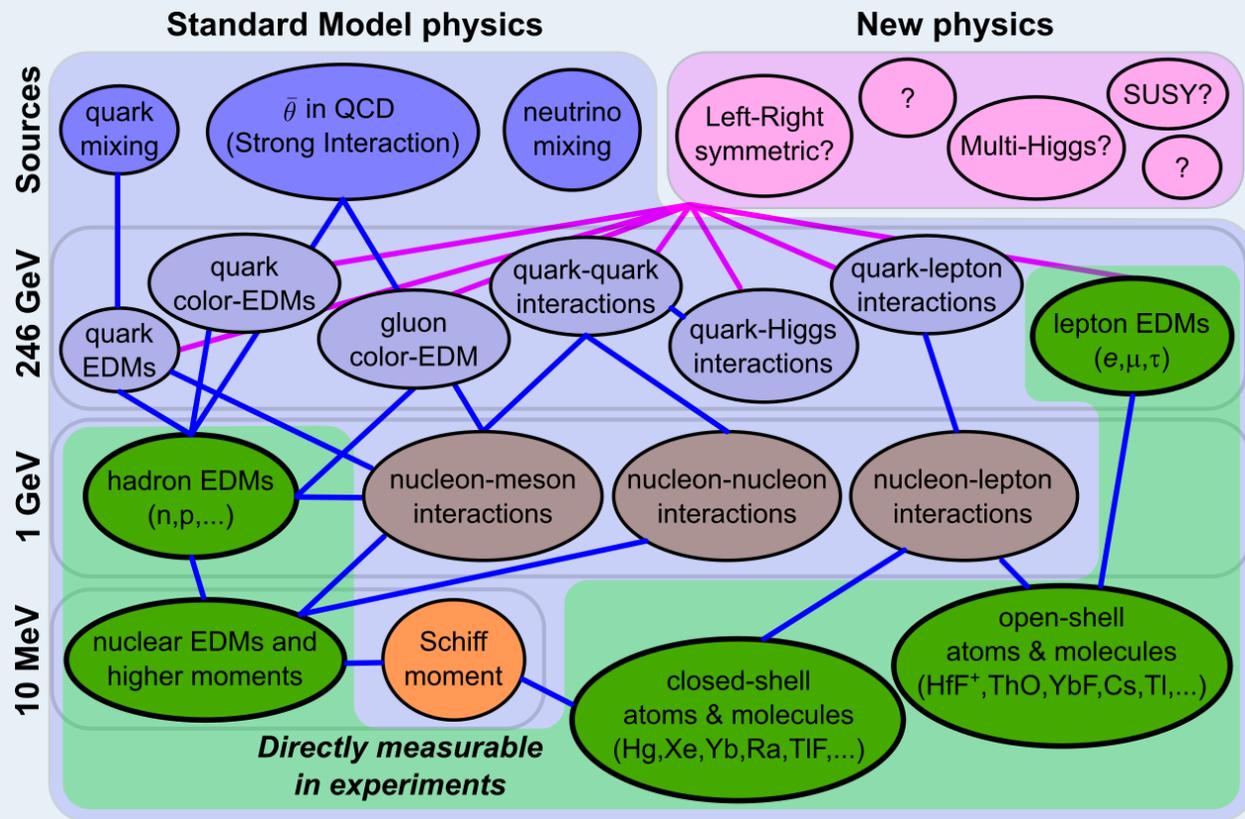
Main sensitivities:

- system dependent
- n constrains the QCD θ term

- May need to look at higher scales for a consistent interpretation...



Reality: many parameters, many experiments



EDMs as a “lightning rod” for new physics – without assumptions about the underlying model

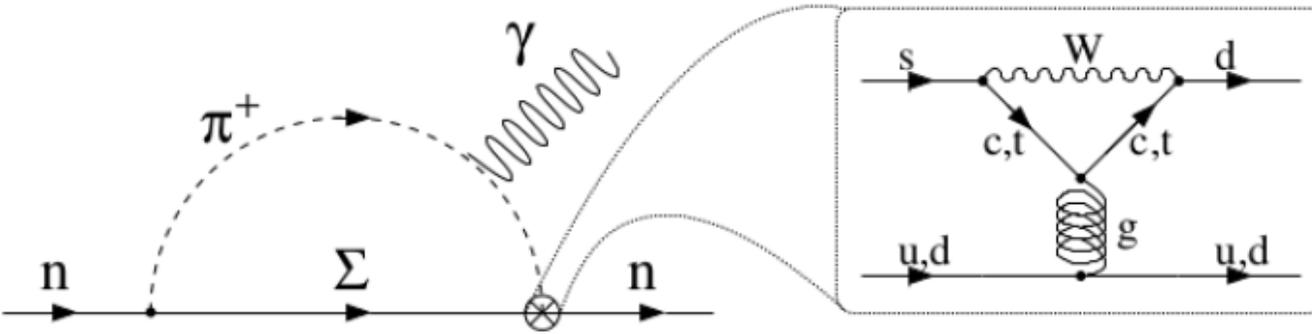
Also: clear prediction that *there is a signal to detect*

System i	Measured d_i [e cm]	Upper limit on $ d_i $ [e cm]	Reference
n	$(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-26}$	$2.2 \cdot 10^{-26}$	[69]
^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$	[70]
^{133}Cs	$(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	[71]
HfF^+	$(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$	$4.8 \cdot 10^{-30}$	[72]
ThO	$(4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \cdot 10^{-30}$	$1.1 \cdot 10^{-29}$	[73]
YbF	$(-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \cdot 10^{-28}$	$1.2 \cdot 10^{-27}$	[74]
^{199}Hg	$(2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \cdot 10^{-30}$	$7.4 \cdot 10^{-30}$	[75, 76]
^{129}Xe	$(-1.9 \pm 4.6_{\text{stat}} \pm 2.0_{\text{syst}}) \cdot 10^{-28}$	$1.0 \cdot 10^{-27}$	[77, 78]
^{171}Yb	$(-6.8 \pm 5.1_{\text{stat}} \pm 1.2_{\text{syst}}) \cdot 10^{-27}$	$1.5 \cdot 10^{-26}$	[79]
^{225}Ra	$(4 \pm 6_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	[80]
TlF	$(-1.7 \pm 2.9) \cdot 10^{-23}$	$6.5 \cdot 10^{-23}$	[81]
	Measured ω_i [mrad/s]	Rescaling factor x_i for d_i	Reference
HfF^+	$(-0.0459 \pm 0.0716_{\text{stat}} \pm 0.0217_{\text{syst}})^\dagger$	0.999	[72]
ThO	$(-0.510 \pm 0.373_{\text{stat}} \pm 0.310_{\text{syst}})$	0.982	[73]
YbF	$(5.30 \pm 12.60_{\text{stat}} \pm 3.30_{\text{syst}})$	1.12	[74]

Table 1: Measured EDM values and 95% CL for upper limits on their absolute values. For ^{129}Xe we combine two independent results with similar precision, using inverse-variance weighting. For the open-shell molecules, we also provide the measured angular frequencies and the rescaling factor which allows us to use $x_i d_i$ for each experimentally reported d_i . For the definition of x_i , see text. † The frequency for HfF^+ is scaled by a factor of 2 relative to Ref. [72], to consistently use Eq.(30) for all systems.

“Testing the Standard Model” vs. “New Physics”

Neutron EDM within the Standard Model (CKM):



Pospelov & Ritz, *Annals of Physics* 318 (2005): 119-169

- Current experimental limit: $10^{-26} e \text{ cm}$
- Standard Model CKM: $10^{-32} e \text{ cm}$
- Standard Model QCD: $10^{-16} e \text{ cm} \times \theta$ [???
- Standard Model PMNS

→ Insufficient for baryogenesis

Naïve estimate for generic new physics:

$$d_n \propto \frac{m_q}{\Lambda^2} \cdot e \cdot \phi_{\text{CPV}}$$

$\Lambda \approx 30 \text{ TeV}$

Statistical sensitivity, count-rate limited:

$$\sigma(d_n) \gtrsim \frac{\hbar}{2\alpha |\mathbf{E}| T \sqrt{N}}$$

↓

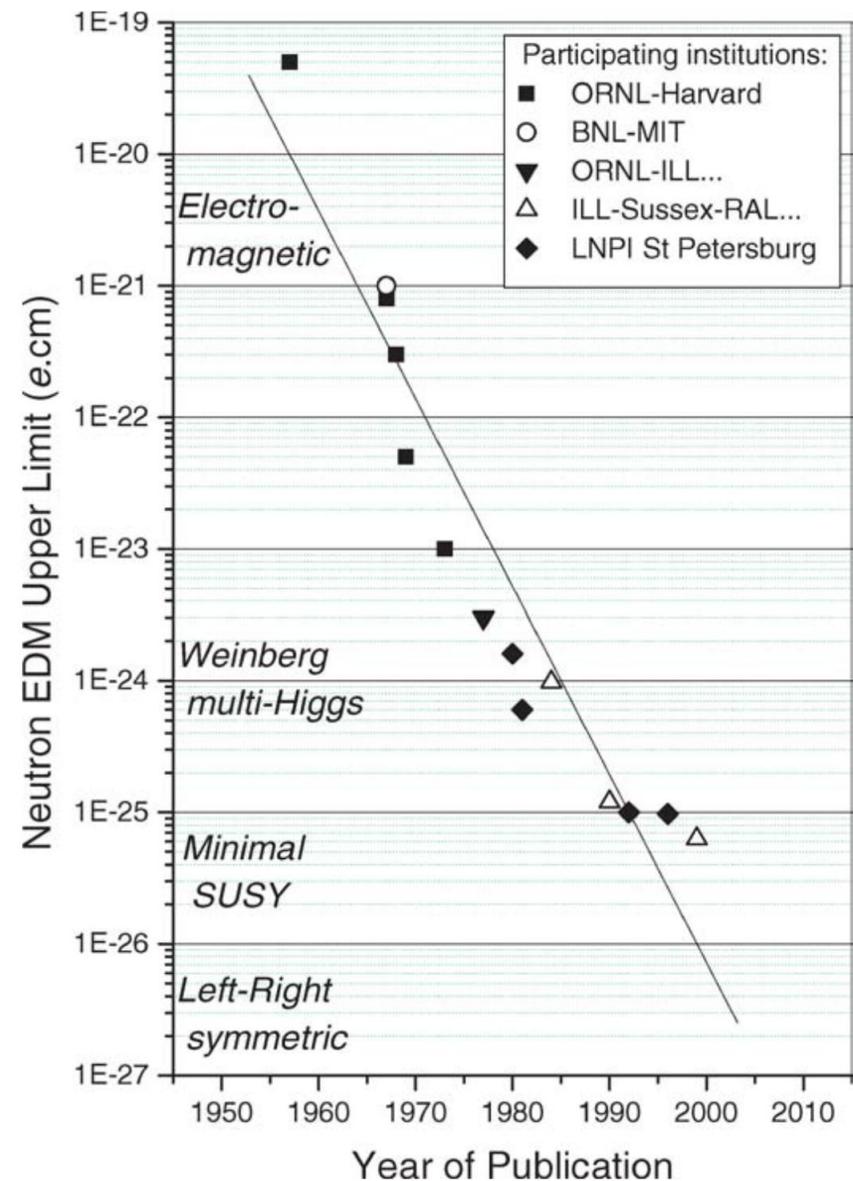
first saturate “classical” parameters
...then new approaches, quantum sensing

PRL 124, 081803 (2020)

Current limit (PSI):
 $2.2 \times 10^{-26} e \text{ cm}$, 95% C.L.

constraint diluted by 2-3 orders
of magnitude in global analysis!

“Testing the Standard Model” vs. “New Physics”



2005 review: [Nico & Snow, Annu. Rev. Nucl. Part. Sci.](#)

Statistical sensitivity of the 2020 PSI experiment:

$$\sigma(d_n) \gtrsim \frac{\hbar}{2\alpha |\mathbf{E}| T \sqrt{N}}$$

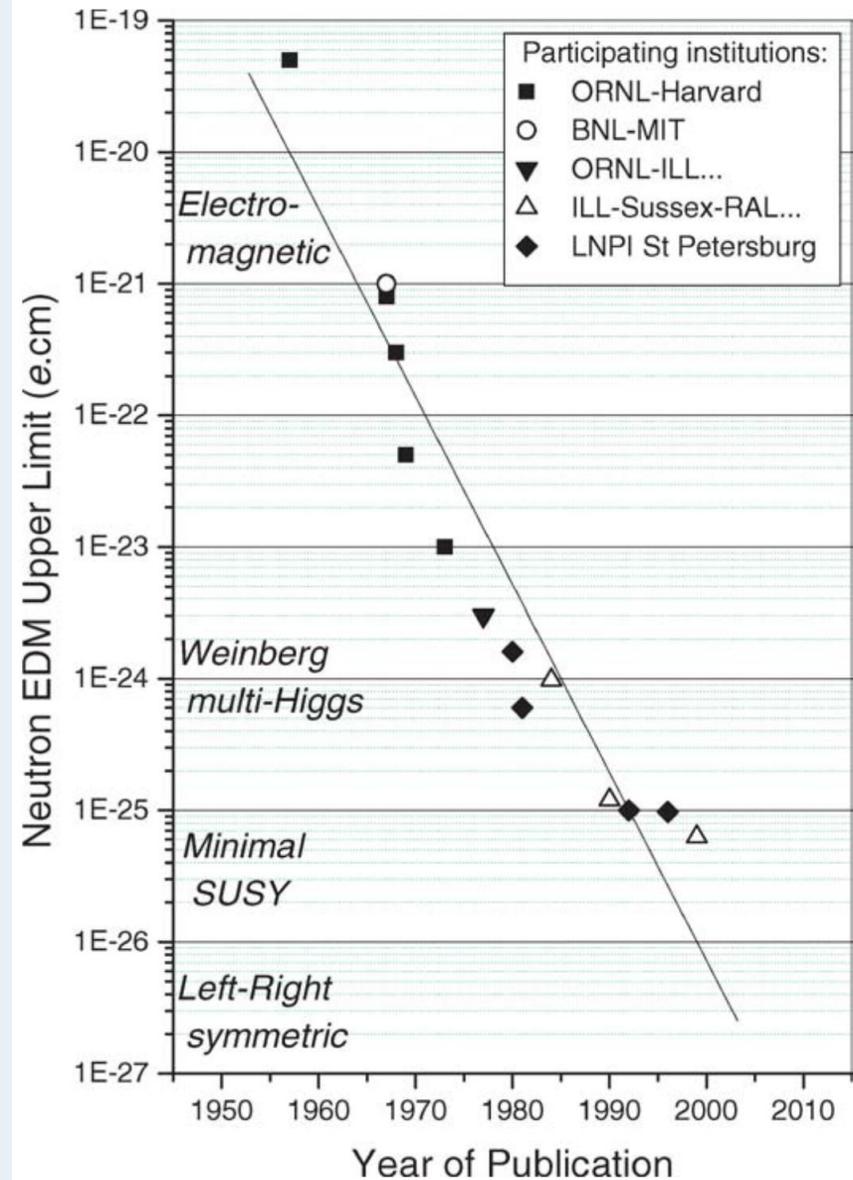
$\sigma(d_n)$ → Current limit (PSI): 2.2×10^{-26} e cm, 95% C.L.
 2α → Polarization contrast ≈ 0.8
 $|\mathbf{E}|$ → 11 kV/cm
 T → 180 s
 \sqrt{N} → $(54 \times 10^3) \times (10^4/\text{shot})$

Tour-de-force in systematics studies...

But statistics not much improved for 20 years!

...but now see arXiv:2504.13030

Example: (European) Neutrons in a global context



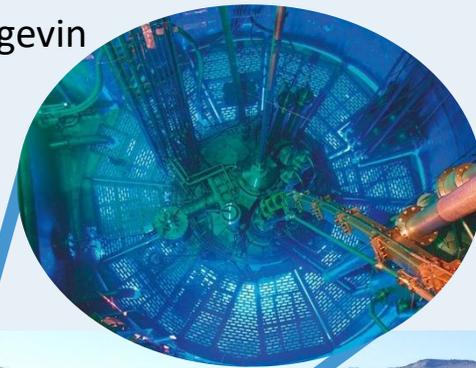
Paul Scherrer Institut
(PSI, Villigen)

- present limit
- *systematics*
- n2EDM

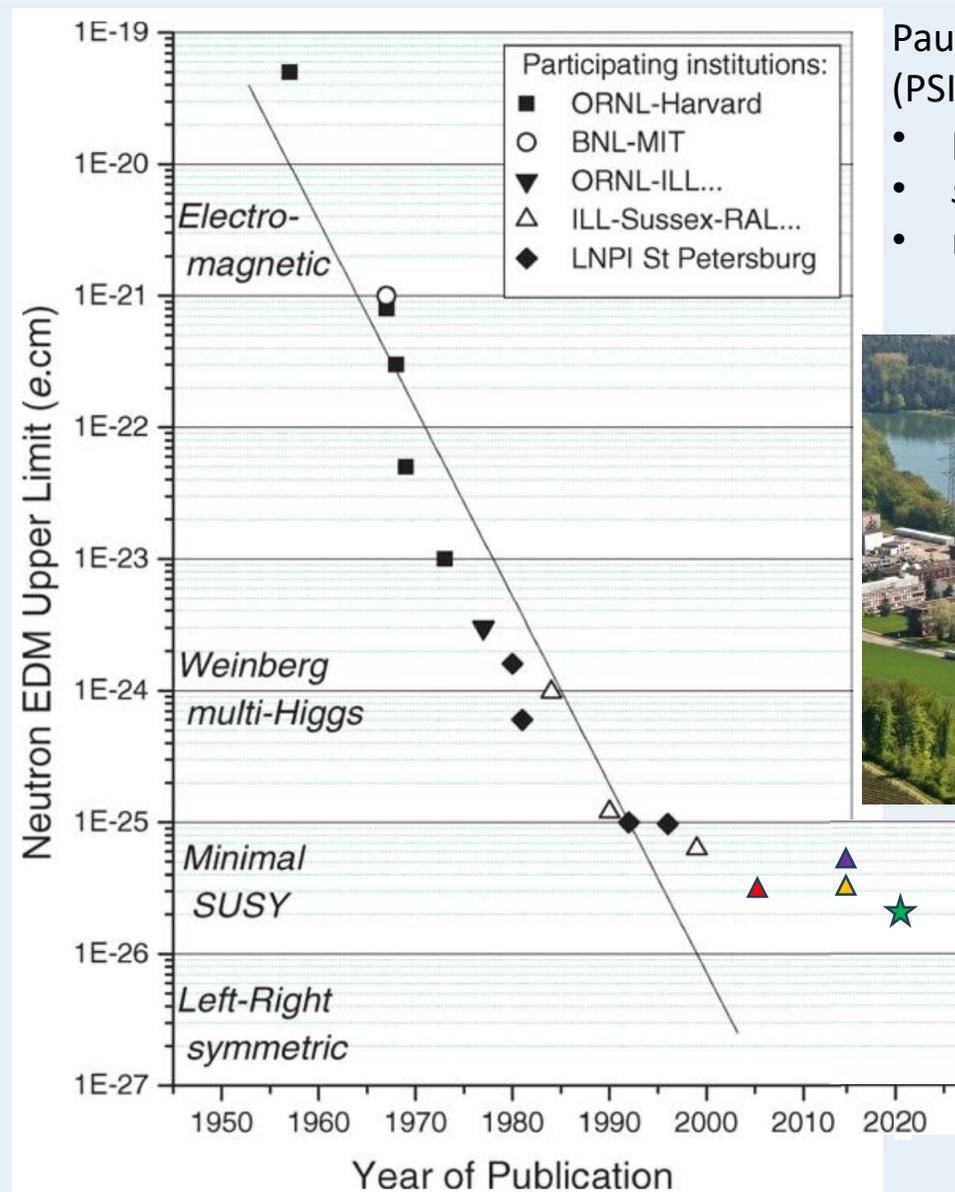


Institut Laue- Langevin
(ILL, Grenoble)

- previous limit
- *statistics*
- PanEDM



Example: (European) Neutrons in a global context



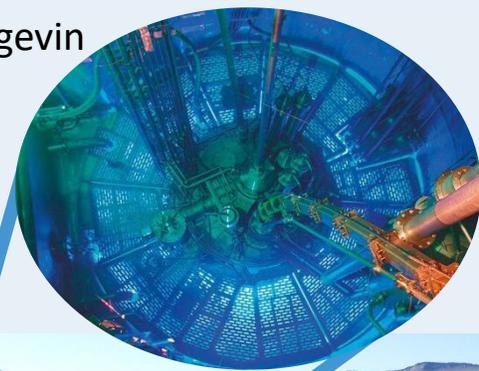
Paul Scherrer Institut (PSI, Villigen)

- present limit
- *systematics*
- n2EDM



Institut Laue- Langevin (ILL, Grenoble)

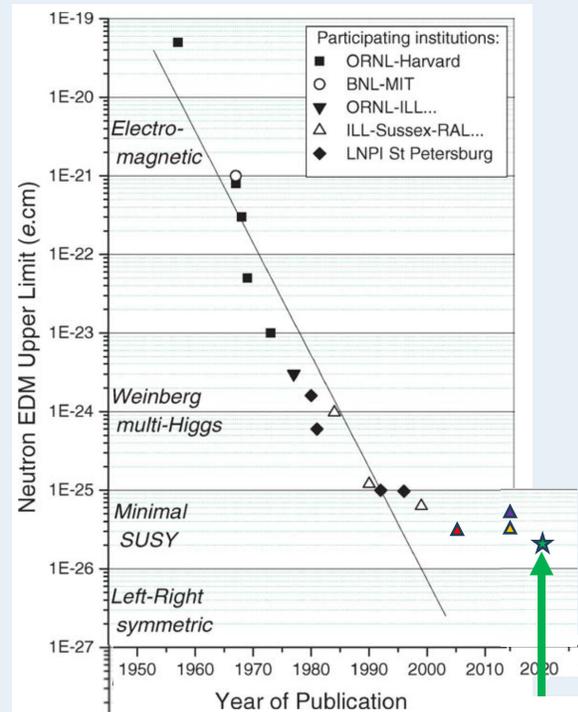
- previous limit
- *statistics*
- PanEDM



← Now strongly limited by available neutrons

← Sensitivity target for experiments now commissioning

Example: (European) Neutrons in a global context



No SM background (neglecting θ_{QCD})

Standard Model expectation

JNR (2022) 24(2), 123-143
potential reach with today's technology
(statistics only)

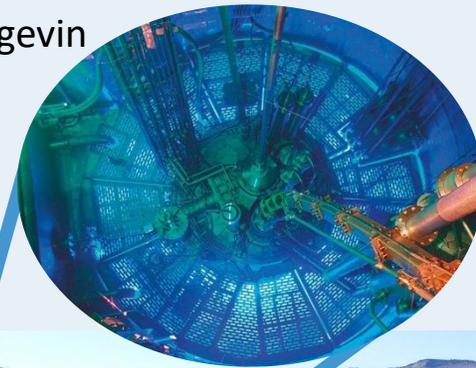
Paul Scherrer Institut (PSI, Villigen)

- present limit
- systematics
- n2EDM



Institut Laue- Langevin (ILL, Grenoble)

- previous limit
- statistics
- PanEDM



Very rough factors separating today's experiments and SM predictions:

How do 10^8 (*) electron and 10^7 atomic/molecular EDMs compare to 10^5-10^6 neutron?

$$\{d_e, C_S, C_T, C_P, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}\}$$

(*) or less... cf. PhysRevLett.129.231801

What would a finite EDM mean?

- CP violation from BSM and three SM sources (if we ignore neutrinos):

$$\mathcal{L}_{\text{CPV}} = \mathcal{L}_{\text{BSM}} + \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}}$$

- CKM CP-violation (Standard Model):

$$\mathcal{L}_{\text{CKM}} = -\frac{ig_2}{\sqrt{2}} \sum_{p,q} V_{pq} \bar{U}_L^p W^+ D_L^q + \text{H.c.}$$

- Strong CP-violation (Standard Model):

$$\mathcal{L}_{\bar{\theta}} = \frac{g_3^2}{32\pi^2} \bar{\theta} \text{Tr}(G^{\mu\nu} \tilde{G}_{\mu\nu})$$

*details: arXiv:2403.02052 and earlier:
Rev. Mod. Phys. **91**, 015001 (2019)
Phys. Rev. C **91**, 035502 (2015)
Prog. Part. Nucl. Phys. **71**, 21 (2013)*

Nearly-decoupled subspace: d_e and C_S

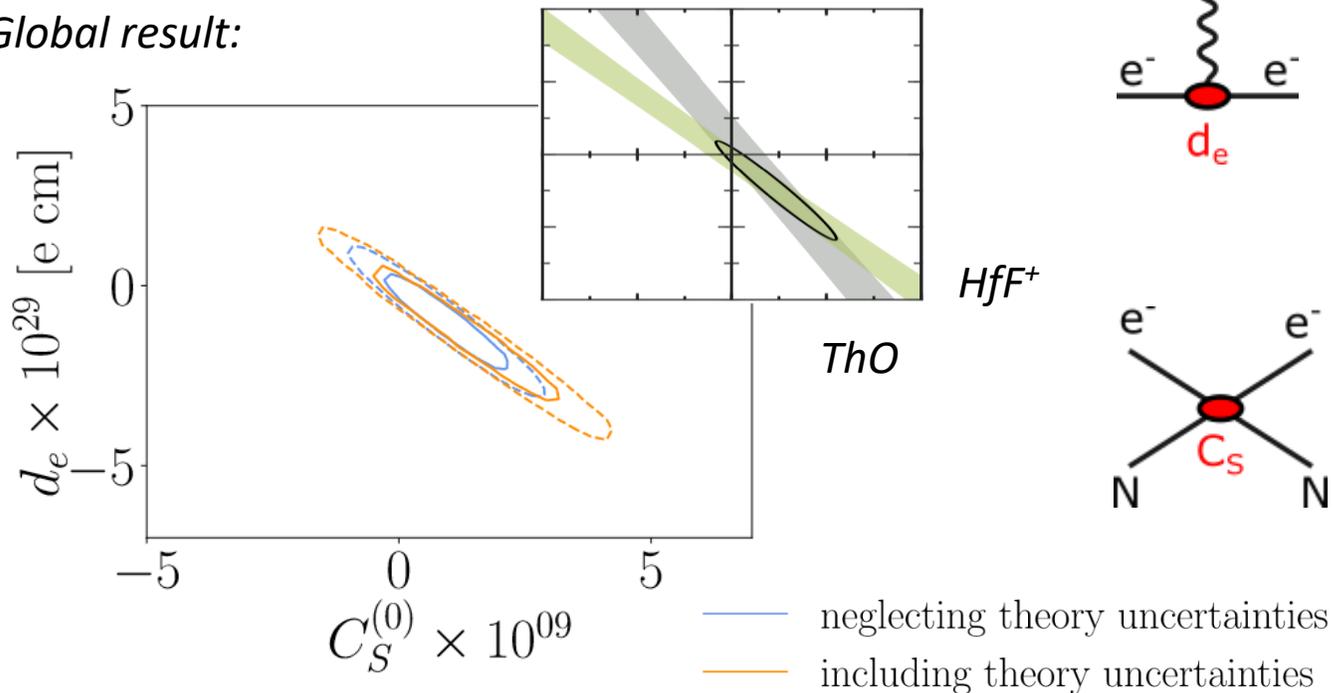
^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$	[48]
^{133}Cs	$(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$	[49]
HfF^+	$(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$	$4.8 \cdot 10^{-30}$	[50]
ThO	$(4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \cdot 10^{-30}$	$1.1 \cdot 10^{-29}$	[51]
YbF	$(-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \cdot 10^{-28}$	$1.2 \cdot 10^{-27}$	[52]

$$d_i = \sum_{c_j} \alpha_{i,c_j} c_j = \alpha_{i,d_e} d_e + \alpha_{i,C_S} C_S + \dots$$

$$c_j \in \{ d_e, C_S^{(0)}, C_T^{(0)}, C_P^{(0)}, g_\pi^{(0)}, g_\pi^{(1)}, d_n \}$$

arXiv:2403.02052

Global result:



at ~ 1 GeV

$$C_S^{(0)} = -g_S^{(0)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{ledq} - C_{lequ}^{(1)} \right)$$

$v \sim 246$ GeV

$$C_S^{(1)} = g_S^{(1)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{ledq} + C_{lequ}^{(1)} \right)$$

Open-shell systems still need hadronic structure...

^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$	[48]
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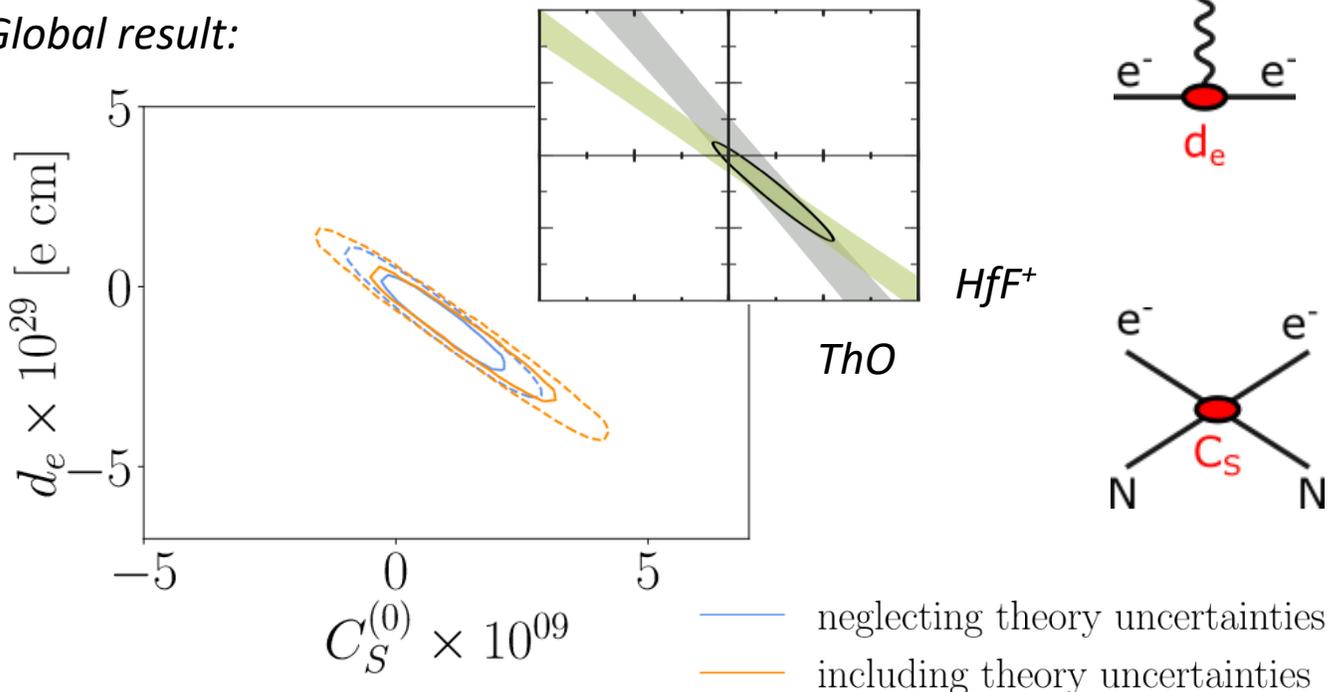
Hadronic structure:

$$g_S^{(0)} \bar{\psi}_N \psi_N = \frac{1}{2} \langle N | \bar{u}u + \bar{d}d | N \rangle$$

$$g_S^{(1)} \bar{\psi}_N \tau_3 \psi_N = \frac{1}{2} \langle N | \bar{u}u - \bar{d}d | N \rangle$$

arXiv:2403.02052

Global result:



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$v \sim 246$ GeV

$$C_S^{(1)} = g_S^{(1)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{ledq} + C_{lequ}^{(1)} \right)$$

Constructing, and deconstructing, an EDM

$$d_i = \sum_{c_j} \alpha_{i,c_j} c_j = \alpha_{i,d_e} d_e + \alpha_{i,C_S} C_S + \dots$$

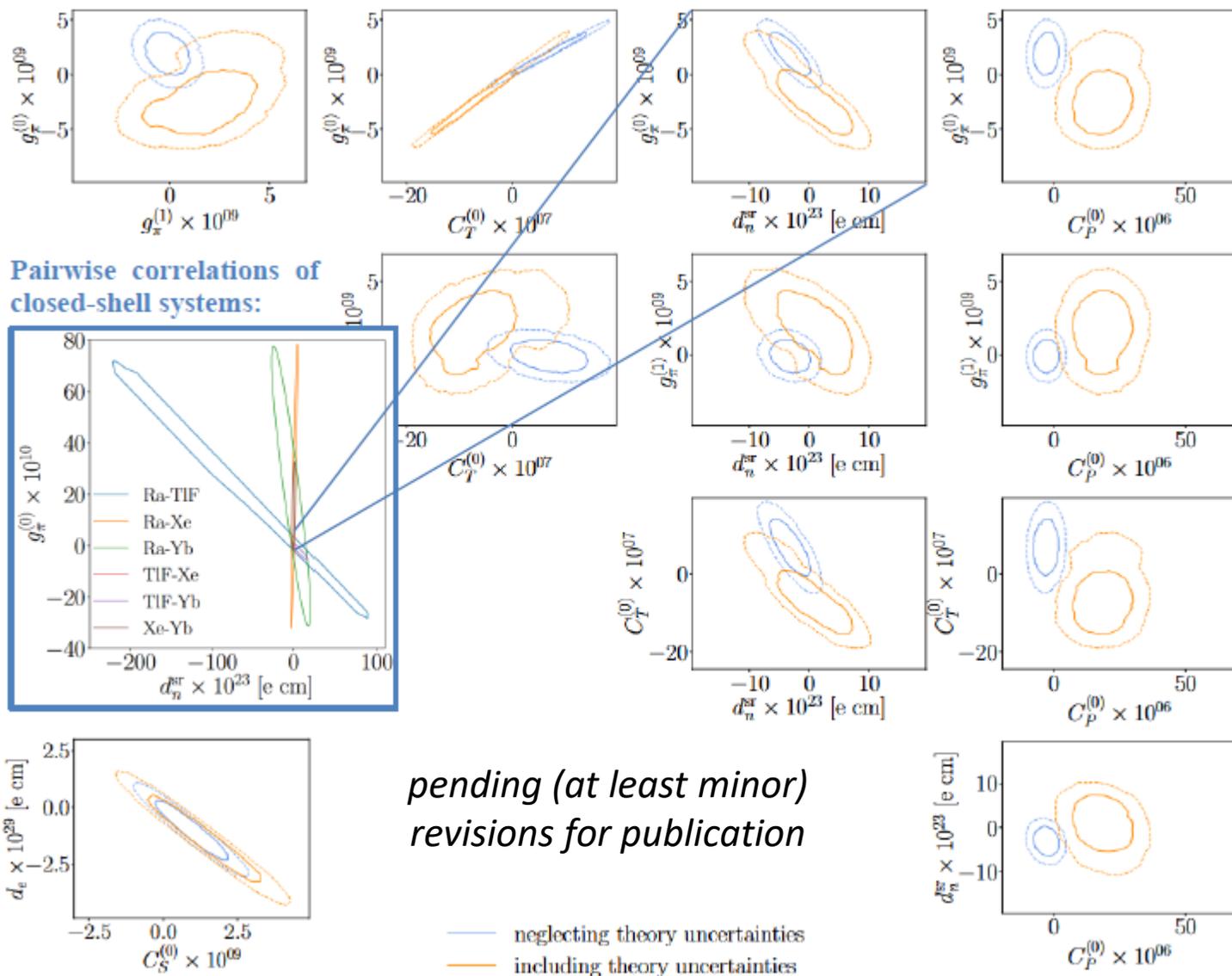
$$c_j \in \left\{ d_e, C_S^{(0)}, C_T^{(0)}, C_P^{(0)}, g_\pi^{(0)}, g_\pi^{(1)}, d_n \right\}$$

Schiff Moment parameterization:

$$\begin{aligned} k_{i,S} S_i &= \sum_{c_j \in \{d_n, p, g_\pi^{(0,1,2)}\}} \alpha_{i,c_j} c_j \\ &\approx k_{i,S} \left[s_{i,n} d_n + s_{i,p} d_p + \frac{m_N g_A}{F_\pi} (a_{i,0} g_\pi^{(0)} + a_{i,1} g_\pi^{(1)} + a_{i,2} g_\pi^{(2)}) \right] \\ &= k_{i,S} \left[s_{i,n} d_n^{sr} + s_{i,p} d_p^{sr} + \frac{m_N g_A}{F_\pi} (\tilde{a}_{i,0} g_\pi^{(0)} + \tilde{a}_{i,1} g_\pi^{(1)} + \tilde{a}_{i,2} g_\pi^{(2)}) \right] \end{aligned}$$

Contours, correlations, likelihoods:

$$\chi^2(C_j) = \sum_i \left(\frac{d_i^{\text{measured}} - d_i^{\text{calculated}}(C_j)}{\sigma_i^{\text{measured}}} \right)^2$$



Global analysis: 11 experiments / 7 parameters

Theory uncertainties mostly lack a statistical interpretation

- Assume flat likelihood
- Coefficients compatibly with zero do not constrain

Correlations are automatically built into the analysis

- Comagnetometer measurements so far neglect a sub-dominant EDM by construction
- Deliberately-correlated EDM experiments could offer complementary constraining power

Flat directions appear already with 4 or 5 parameters

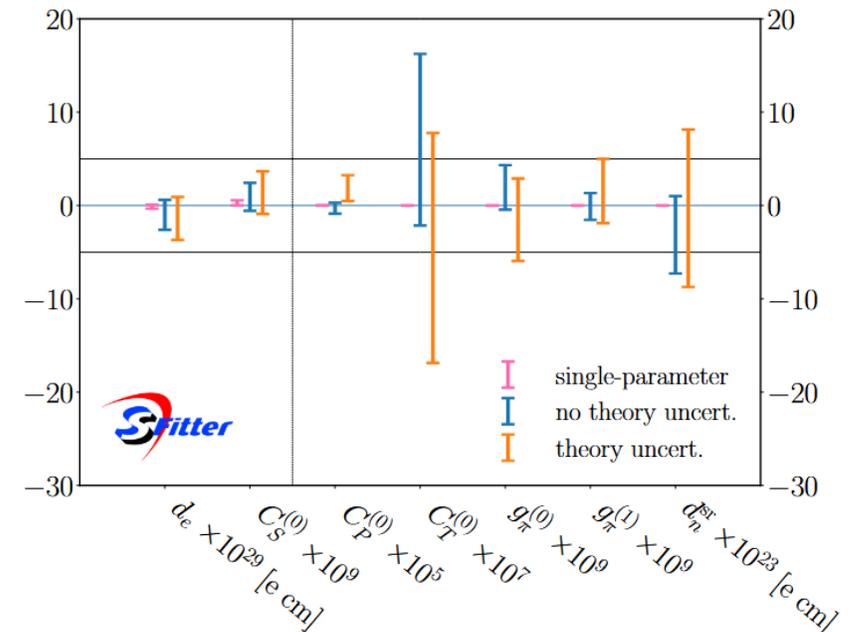
- Depends on treatment of neutron/proton, and pion loops

Formally: 7 parameters are overconstrained by 11 experiments

Reality: the experiments are insufficiently complementary!

- Well-constrained subspace (2 parameters: d_e , C_S)
- Poorly-constrained subspace (5 parameters / 5 measurements)
- Other parameters should really be included as well...

Hadronic scale global analysis: arXiv:2403.02052



“A Global View of the EDM Landscape”

SMD, Nina Elmer, Tanmoy Modak,
Margarete Mühleitner, Tilman Plehn

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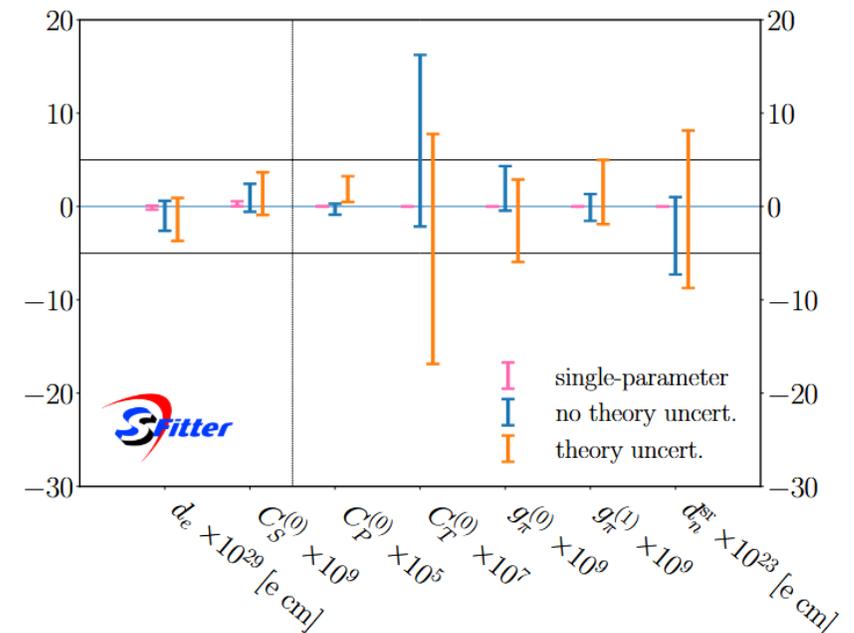
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“A Global View of the EDM Landscape”

SMD, Nina Elmer, Tanmoy Modak,
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New constraints: complementary atoms/nuclei

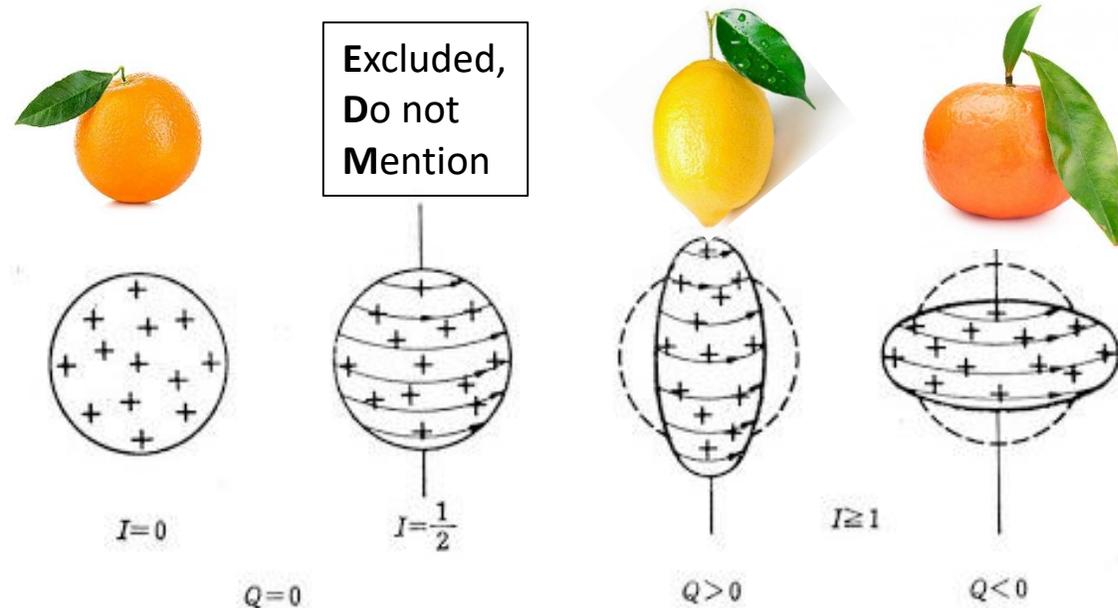
$$S = s_N d_N + \frac{m_N g_A}{F_\pi} [a_0 \bar{g}_\pi^{(0)} + a_1 \bar{g}_\pi^{(1)} + \cancel{a_2 \bar{g}_\pi^{(2)}}]$$

We do *not* expect large Schiff moments in $^{129}\text{Xe}/^{199}\text{Hg}$
(suppressed by the screening effect)

$$\longrightarrow d_A(\text{dia}) = \kappa_S S - \underline{[k_{C_T}^{(0)} C_T^{(0)} + k_{C_T}^{(1)} C_T^{(1)}]}$$

But deformed nuclei can actually have **enhanced** EDMs:

$$\longrightarrow d_A(\text{dia}) = \underline{\kappa_S S} - [k_{C_T}^{(0)} C_T^{(0)} + k_{C_T}^{(1)} C_T^{(1)}]$$



Reflection asymmetry

Caveats

System i	$\langle \sigma_n \rangle$	$\langle \sigma_p \rangle$	$\langle \sigma_z \rangle^{(0)}$
Tl	0.274	0.726	1
Cs	-0.206	-0.572	-0.778
^{199}Hg	-0.302	-0.032	-0.334
^{129}Xe	0.73	0.27	1
^{171}Yb	-0.3	-0.034	-0.334
^{225}Ra	0.72	0.28	1
TlF	0.274	0.726	1

Shell-model estimates
for deformed nuclei...
Residual inconsistencies...

System i	$k_{i,S} [\text{cm}/\text{fm}^3]$	$s_{i,n} [\text{fm}^2]$	$s_{i,p} [\text{fm}^2]$
Tl	$-4.2^{+2.1}_{-1.8} \cdot 10^{-18}$ [35]	$0.14^{\pm 0.03}$	$-0.38^{+1.38}_{-0.45}$
Cs	$-9.99^{+2.9}_{-4.1} \cdot 10^{-18}$ [35]		$0.1^{\pm 0.1}$
^{199}Hg	$-2.26^{\pm 0.23} \cdot 10^{-17}$ [115]	$0.6^{+1.33}_{-0.12}$	$0.06^{+0.20}_{-0.01}$
^{129}Xe	$3.62^{\pm 0.25} \cdot 10^{-18}$ [115]	$0.63^{+0.16}_{-0.12}$	$0.14^{\pm 0.03}$
^{171}Yb	$-2.10^{+0.22}_{-0.0} \cdot 10^{-17}$ [66, 116]	$0.54^{+0.13}_{-0.11}$	$0.054^{+0.016}_{-0.014}$
^{225}Ra	$-8.5^{+0.25}_{-0.3} \cdot 10^{-17}$ [18, 66, 116]	$0.63^{+0.16}_{-0.12}$	$0.14^{+0.04}_{-0.03}$
TlF	$-4.59^{\pm 0.41} \cdot 10^{-13}$ [115]	$0.14^{\pm 0.03}$	$-0.38^{+1.38}_{-0.45}$

Still missing/challenging:

- Some nuclear structure
 - Valence nucleon EDMs
 - Sign of some pion couplings
 - **Short-range forces**
- Hadronic matrix elements
- Sub-leading coefficients for open-shell molecules

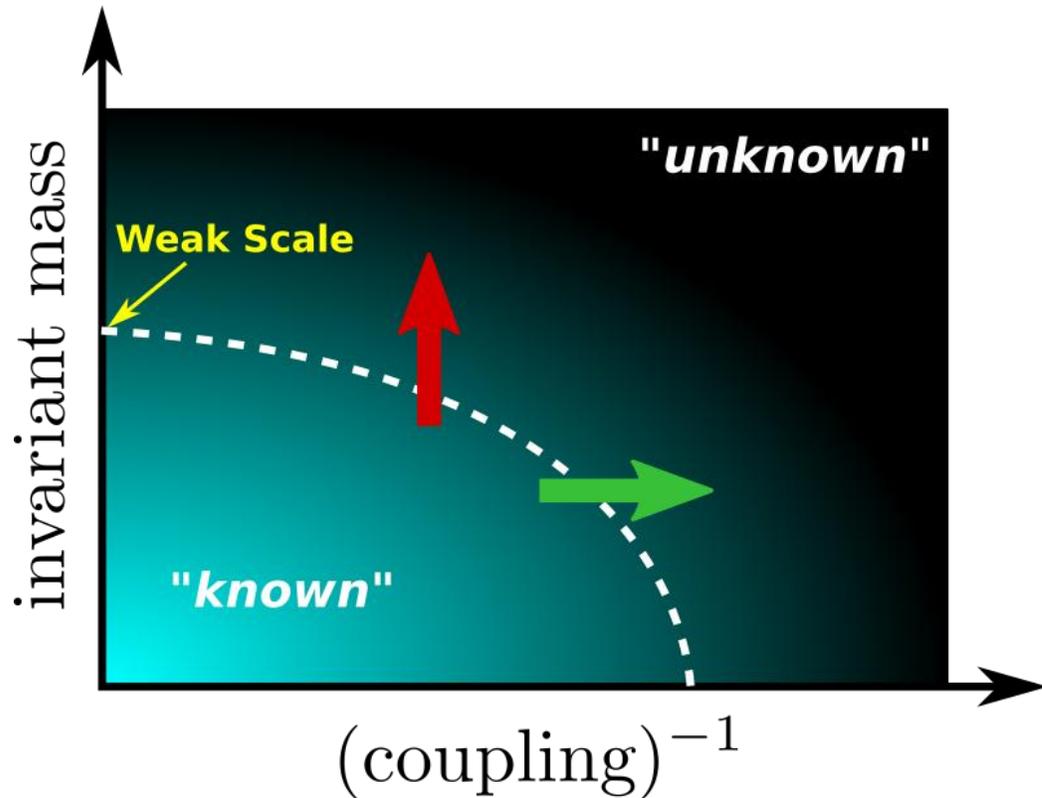
So what can we do/attempt now?

- Work upwards in energy (LEFT, ...)
- Add new experiments
- Include more parameters, and effects
 - MQM (beyond Cs...)
 - Muon and tau lepton (also indirect limits)
 - Short-range nuclear forces (hard...)
- Evaluate impact of improvements
 - Theory coefficients
 - Experimental bounds
 - Correlated experiments... new ideas?
- Constrain specific BSM scenarios

Still missing/challenging:

- Some nuclear structure
 - Valence nucleon EDMs
 - Sign of some pion couplings
 - **Short-range forces**
- Hadronic matrix elements
- Sub-leading coefficients for open-shell molecules

Thematic Recap



1

Write down the Lagrangian (Hamiltonian)!
Make the conventions clear...

2

More experiments is good;
complementary is better;
correlated might be best...

3

Theory values, and especially
uncertainties, can also improve a lot

Questions?

Seeking students and Post-Docs!

ANALYSIS

OUR NEW ~~TELESCOPE~~ WILL
ANSWER TWO KEY QUESTIONS:

- 1) WHY IS THERE ALL THIS MATTER?
- 2) CAN WE DO ANYTHING ABOUT IT?



what-if.xkcd.com

Special thanks to:

N. Elmer, T. Plehn, T. Modak (HD)

M. Mühlleitner (KIT)

Many, *many* colleagues who helped answer questions and pinpoint errors (see acknowledgements in 2403.02052)

EDMs 2026 at Les Houches!



March 1-6, 2026

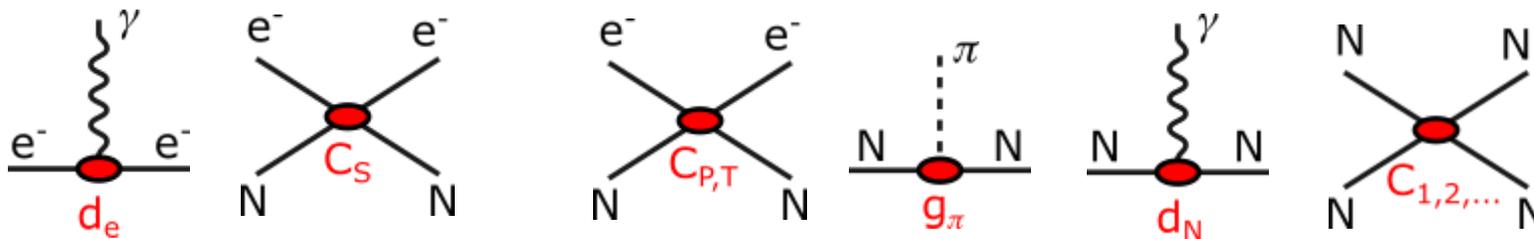
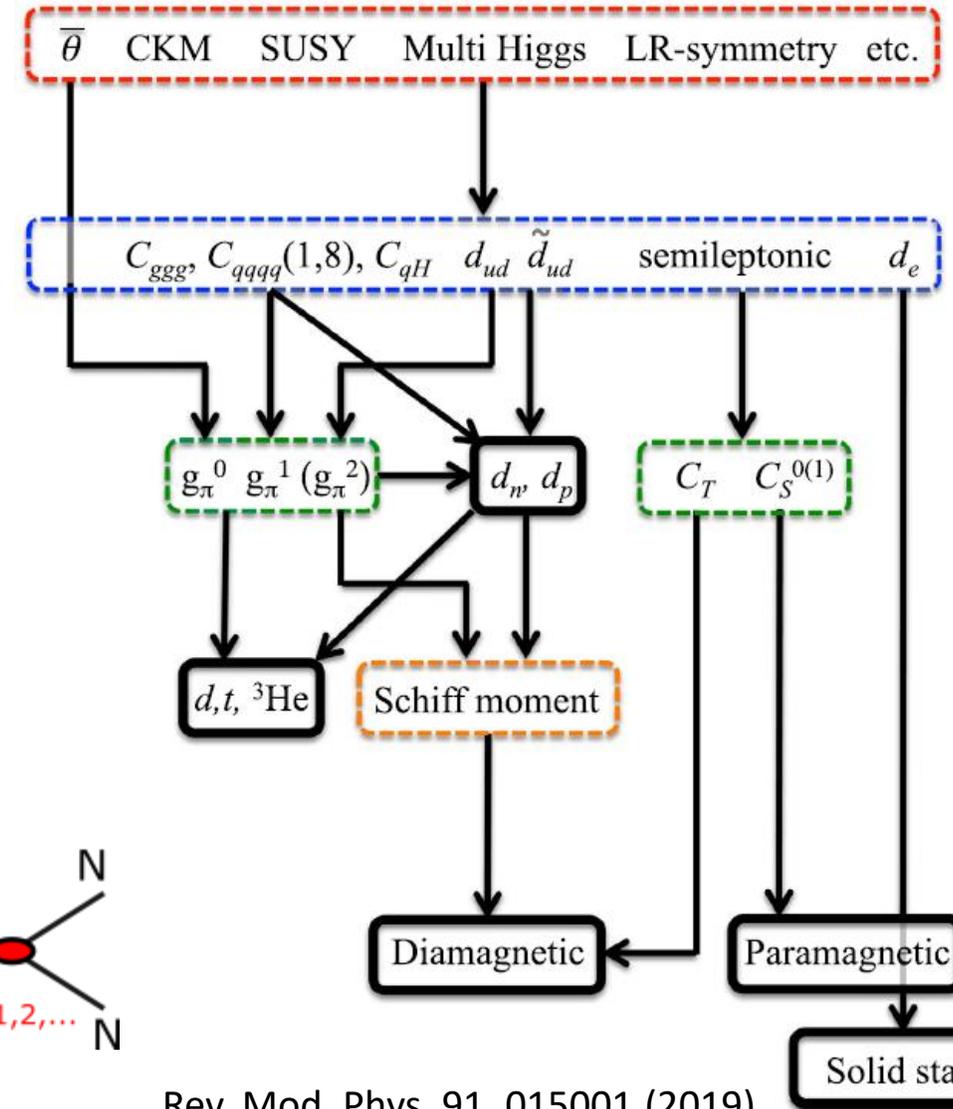
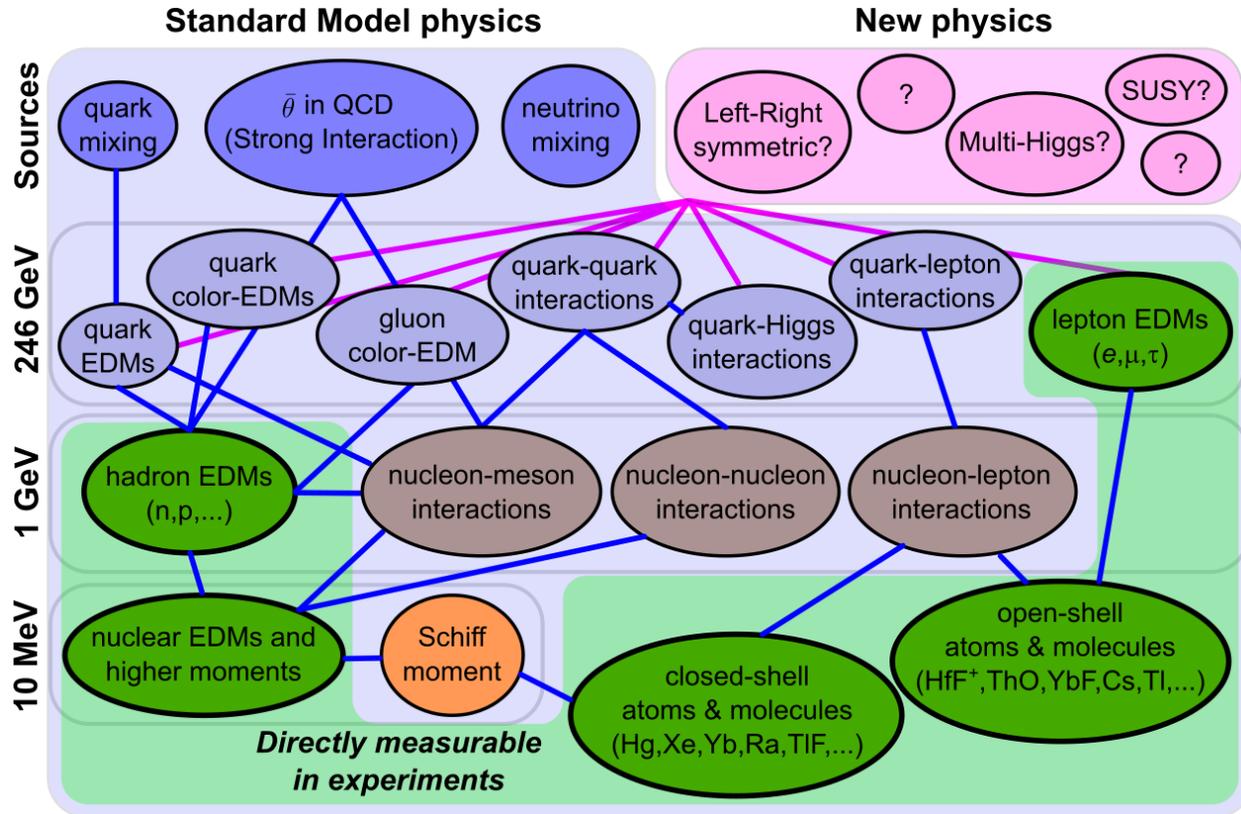
WE-Heraeus funding to cover participant room & board

Scientific program:

- Experiments targeting EDMs of the neutron, charged particles in storage rings, atoms, molecules...
- Theory for interpreting EDM, including hadronic, nuclear, atomic/molecular calculations...
- Phenomenological models and global analysis for CP-violating physics
- Connections between EDMs and other observables

Organizers: SMD, Stéphanie Roccia, Guillaume Pignol

Global analysis: 11 experiments / 7 parameters



Effective Hadronic-Scale Lagrangian

- Semileptonic interactions at the weak scale:

$$\begin{aligned} \mathcal{L}_{\text{EFT}} \supset & C_{leqd} (\bar{L}^j e_R) (\bar{d}_R Q_j) + C_{lequ}^{(1)} (\bar{L}^j e_R) \epsilon_{jk} (\bar{Q}^k u_R) + C_{lequ}^{(3)} (\bar{L}^j \sigma_{\mu\nu} e_R) \epsilon_{jk} (\bar{Q}^k \sigma_{\mu\nu} u_R) \\ & + C_{quqd}^{(1)} (\bar{Q}^j u_R) \epsilon_{jk} (\bar{Q}^k d_R) + C_{quqd}^{(8)} (\bar{Q}^j T^a u_R) \epsilon_{jk} (\bar{Q}^k T^a d_R) + \text{h.c.} \end{aligned}$$

- Low-energy constants at GeV energies, from weak-scale Wilson coefficients:

$$\begin{aligned} C_S^{(0)} &= -g_S^{(0)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{ledq} - C_{lequ}^{(1)} \right) & C_S^{(1)} &= g_S^{(1)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{ledq} + C_{lequ}^{(1)} \right) \\ C_T^{(0)} &= -g_T^{(0)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{lequ}^{(3)} \right) & C_T^{(1)} &= -g_T^{(1)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{lequ}^{(3)} \right) \\ C_P^{(0)} &= g_P^{(0)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{ledq} + C_{lequ}^{(1)} \right) & C_P^{(1)} &= -g_P^{(1)} \frac{v^2}{\Lambda^2} \text{Im} \left(C_{ledq} - C_{lequ}^{(1)} \right) \end{aligned}$$

Effective Hadronic-Scale Lagrangian

- Semileptonic interactions at the **hadronic** scale (w/ nonrelativistic nucleons):

$$\begin{aligned} \mathcal{L}_{eN} = & -\frac{G_F}{\sqrt{2}} (\bar{e}i\gamma_5 e) \bar{N} \left(C_S^{(0)} + C_S^{(1)} \tau_3 \right) N + \frac{8G_F}{\sqrt{2}} v_\nu (\bar{e}\sigma^{\mu\nu} e) \bar{N} \left(C_T^{(0)} + C_T^{(1)} \tau_3 \right) S_\mu N \\ & - \frac{G_F}{\sqrt{2}} (\bar{e}e) \frac{\partial^\mu}{m_N} \left[\bar{N} \left(C_P^{(0)} + C_P^{(1)} \tau_3 \right) S_\mu N \right] \end{aligned}$$

- Low-energy constants also depend on hadronic matrix elements:

$$\begin{aligned} g_S^{(0)} \bar{\psi}_N \psi_N &= \frac{1}{2} \langle N | \bar{u}u + \bar{d}d | N \rangle & g_T^{(0)} \bar{\psi}_N \sigma_{\mu\nu} \psi_N &= \frac{1}{2} \langle N | \bar{u}\sigma_{\mu\nu}u + \bar{d}\sigma_{\mu\nu}d | N \rangle \\ g_S^{(1)} \bar{\psi}_N \tau_3 \psi_N &= \frac{1}{2} \langle N | \bar{u}u - \bar{d}d | N \rangle & g_T^{(1)} \bar{\psi}_N \sigma_{\mu\nu} \tau_3 \psi_N &= \frac{1}{2} \langle N | \bar{u}\sigma_{\mu\nu}u - \bar{d}\sigma_{\mu\nu}d | N \rangle \\ g_P^{(0)} \bar{\psi}_N \gamma_5 \psi_N &= \frac{1}{2} \langle N | \bar{u}\gamma_5 u + \bar{d}\gamma_5 d | N \rangle \\ g_P^{(1)} \bar{\psi}_N \gamma_5 \tau_3 \psi_N &= \frac{1}{2} \langle N | \bar{u}\gamma_5 u - \bar{d}\gamma_5 d | N \rangle \end{aligned}$$

Effective Hadronic-Scale Lagrangian

- Semileptonic interactions at the **hadronic** scale:

$$\mathcal{L}_{eN} = -\frac{G_F}{\sqrt{2}} (\bar{e}i\gamma_5 e) \bar{N} (C_S^{(0)} + C_S^{(1)}\tau_3) N + \frac{8G_F}{\sqrt{2}} v_\nu (\bar{e}\sigma^{\mu\nu} e) \bar{N} (C_T^{(0)} + C_T^{(1)}\tau_3) S_\mu N$$

$$- \frac{G_F}{\sqrt{2}} (\bar{e}e) \frac{\partial^\mu}{m_N} \left[\bar{N} (C_P^{(0)} + C_P^{(1)}\tau_3) S_\mu N \right]$$

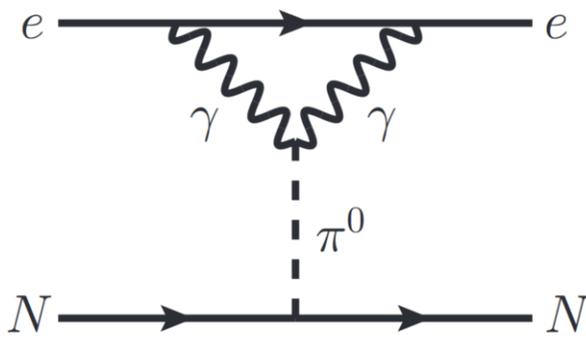
$$g_P^{(0)} \bar{\psi}_N \gamma_5 \psi_N = \frac{1}{2} \langle N | \bar{u} \gamma_5 u + \bar{d} \gamma_5 d | N \rangle$$

$$g_P^{(1)} \bar{\psi}_N \gamma_5 \tau_3 \psi_N = \frac{1}{2} \langle N | \bar{u} \gamma_5 u - \bar{d} \gamma_5 d | N \rangle$$

η replaces π ; factor $m_{ud}/m_s \approx 1/20$

$$C_P^{(0)} = g_P^{(0)} \frac{v^2}{\Lambda^2} \text{Im} (C_{ledq} + C_{lequ}^{(1)})$$

$$C_P^{(1)} = -g_P^{(1)} \frac{v^2}{\Lambda^2} \text{Im} (C_{ledq} - C_{lequ}^{(1)})$$



$$\langle N | \bar{q} i \gamma_5 q | N \rangle \propto g_{\pi NN} \frac{1}{m_\pi^2} \langle 0 | \bar{q} i \gamma_5 q | \pi \rangle$$

$$\sim g_{\pi NN} \frac{1}{f_\pi m_\pi^2} \langle 0 | \bar{q} q | 0 \rangle$$

$$\sim O(100)$$

Effective Hadronic-Scale Lagrangian

- “Long-range” nuclear forces, involving pion-nucleon couplings:

$$\begin{aligned}\mathcal{L}_{\pi N} = & \bar{N} \left[g_{\pi}^{(0)} \vec{\tau} \cdot \vec{\pi} + g_{\pi}^{(1)} \pi^0 + g_{\pi}^{(2)} (3\tau_3 \pi^0 - \vec{\tau} \cdot \vec{\pi}) \right] N \\ & + C_1 (\bar{N} N) \partial_{\mu} (\bar{N} S^{\mu} \bar{N}) + C_2 (\bar{N} \vec{\tau} N) \cdot \partial_{\mu} (\bar{N} S^{\mu} \bar{N} \vec{\tau}) + \dots\end{aligned}$$

- “Short-range” leftovers (can be absorbed differently):

$$\mathcal{L}_{N, \text{sr}} = -2\bar{N} \left[d_p^{\text{sr}} \frac{1 + \tau_3}{2} + d_n^{\text{sr}} \frac{1 - \tau_3}{2} \right] S_{\mu} N \nu_{\nu} F^{\mu\nu} - \frac{i}{2} F^{\mu\nu} \sum_{\ell} d_{\ell} (\bar{\ell} \sigma_{\mu\nu} \gamma_5 \ell)$$

- Nuclear Schiff moment (and MQM for $I > 1/2$):

$$k_{i,S} S_i = k_{i,S} \left[s_{i,n} d_n + s_{i,p} d_p + \frac{m_N g_A}{F_{\pi}} (a_{i,0} g_{\pi}^{(0)} + a_{i,1} g_{\pi}^{(1)} + a_{i,2} g_{\pi}^{(2)}) \right]$$

Effective Hadronic-Scale Lagrangian

- “Long-range” nuclear forces, involving pion-nucleon couplings:

$$\mathcal{L}_{\pi N} = \bar{N} \left[g_{\pi}^{(0)} \vec{\tau} \cdot \vec{\pi} + g_{\pi}^{(1)} \pi^0 + g_{\pi}^{(2)} (3\tau_3 \pi^0 - \vec{\tau} \cdot \vec{\pi}) \right] N \\ + C_1 (\bar{N} N) \partial_{\mu} (\bar{N} S^{\mu} \bar{N}) + C_2 (\bar{N} \vec{\tau} N) \cdot \partial_{\mu} (\bar{N} S^{\mu} \bar{N} \vec{\tau}) + \dots$$

- “Short-range” leftovers (can be absorbed differently):

$$\mathcal{L}_{N, \text{sr}} = -2\bar{N} \left[d_p^{\text{sr}} \frac{1 + \tau_3}{2} + d_n^{\text{sr}} \frac{1 - \tau_3}{2} \right] S_{\mu} N \nu_{\nu} F^{\mu\nu} - \frac{i}{2} F^{\mu\nu} \sum_{\ell} d_{\ell} (\bar{\ell} \sigma_{\mu\nu} \gamma_5 \ell)$$

- Nuclear Schiff moment (and MQM for $I > 1/2$):

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Assume:

$$d_p^{\text{sr}} \approx -d_n^{\text{sr}}$$

Effective Field Theory

General Effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

Dimension-Six terms for the neutron:

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{(6)} = & -\frac{i}{2} \sum_{l,q} d_q \bar{q} \sigma_{\mu\nu} \gamma^5 F^{\mu\nu} q \\ & -\frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma_{\mu\nu} \gamma^5 G^{\mu\nu} q \\ & + d_W \frac{g_s}{6} G \tilde{G} G + \sum_i C_i^{(4f)} O_i^{(4f)} \end{aligned}$$

Prog. Part. Nucl. Phys. **71**, 21 (2013)

Wilson coefficient	Operator (dimension)	Number
$\bar{\theta}$	Theta term (4)	1
δ_e	Electron EDM (6)	1
$\text{Im } C_{\ell e q u}^{(1,3)}, \text{Im } C_{\ell e q d}$	Semi-leptonic (6)	3
δ_q	Quark EDM (6)	2
$\tilde{\delta}_q$	Quark chromo EDM (6)	2
$C_{\tilde{G}}$	Three-gluon (6)	1
$\text{Im } C_{quqd}^{(1,8)}$	Four-quark (6)	2
$\text{Im } C_{\varphi ud}$	Induced four-quark (6)	1
Total		13

Complementary atoms/nuclei

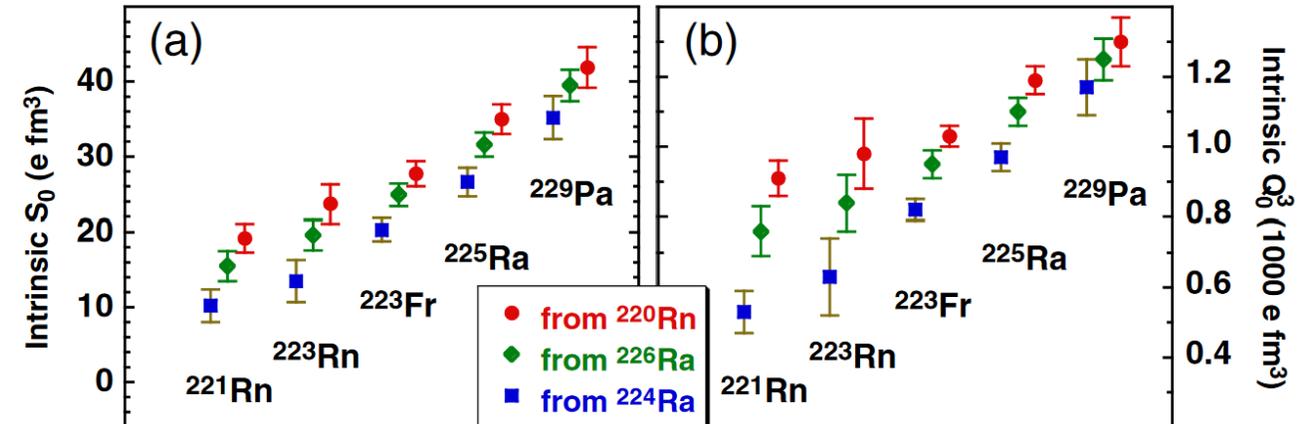
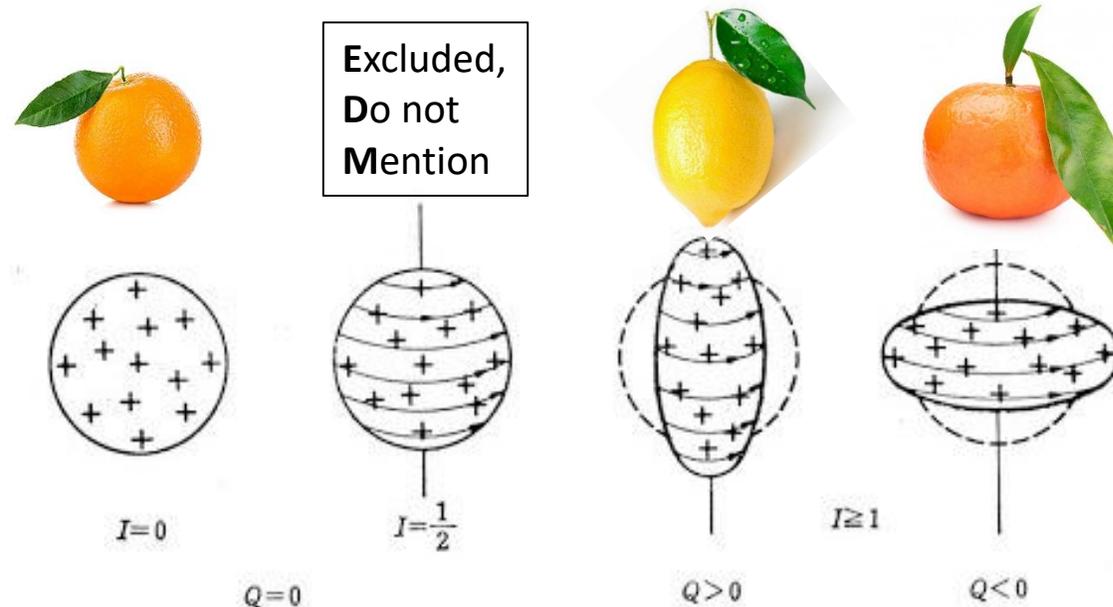
$$S = s_N d_N + \frac{m_N g_A}{F_\pi} [a_0 \bar{g}_\pi^{(0)} + a_1 \bar{g}_\pi^{(1)} + \cancel{a_2 \bar{g}_\pi^{(2)}}]$$

We do *not* expect large Schiff moments in $^{129}\text{Xe}/^{199}\text{Hg}$ (suppressed by the screening effect)

$$\longrightarrow d_A(\text{dia}) = \kappa_S S - \underline{[k_{C_T}^{(0)} C_T^{(0)} + k_{C_T}^{(1)} C_T^{(1)}]}$$

But deformed nuclei can actually have **enhanced** EDMs:

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Complementary atoms/nuclei

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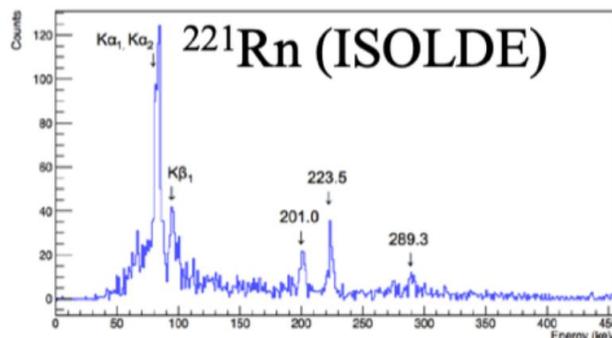
$$\longrightarrow d_A(\text{dia}) = \underline{\kappa_S S} - [k_{C_T}^{(0)} C_T^{(0)} + k_{C_T}^{(1)} C_T^{(1)}]$$

$$S \propto \frac{\eta \beta_2 \beta_3^2 A^{2/3} r_0^3}{E_+ - E_-}$$

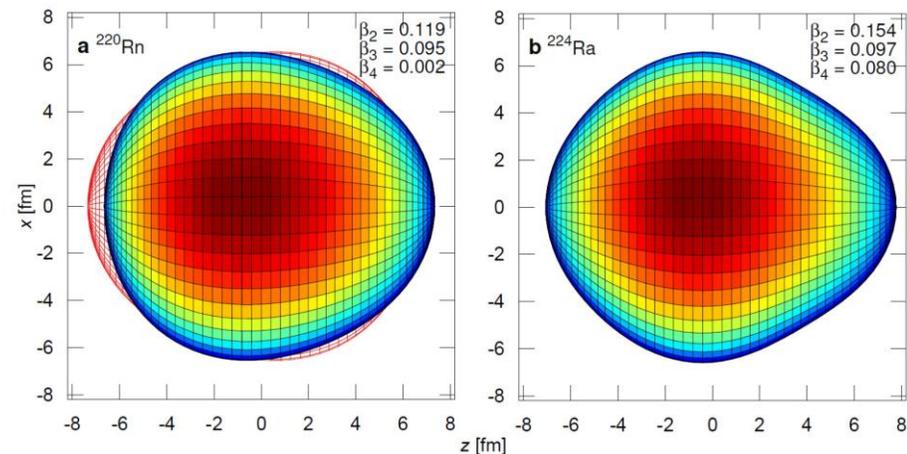
$$\frac{S_{Rn}}{S_{Hg}} = \frac{S_{Ra}}{S_{Hg}} \frac{S_{Rn}}{S_{Ra}} \approx 1000 \frac{\beta_2 \beta_3^2}{\beta_2 \beta_3^2} \frac{\Delta E_{Ra}}{\Delta E_{Rn}} \approx 50 - 100$$

50 keV
400 keV

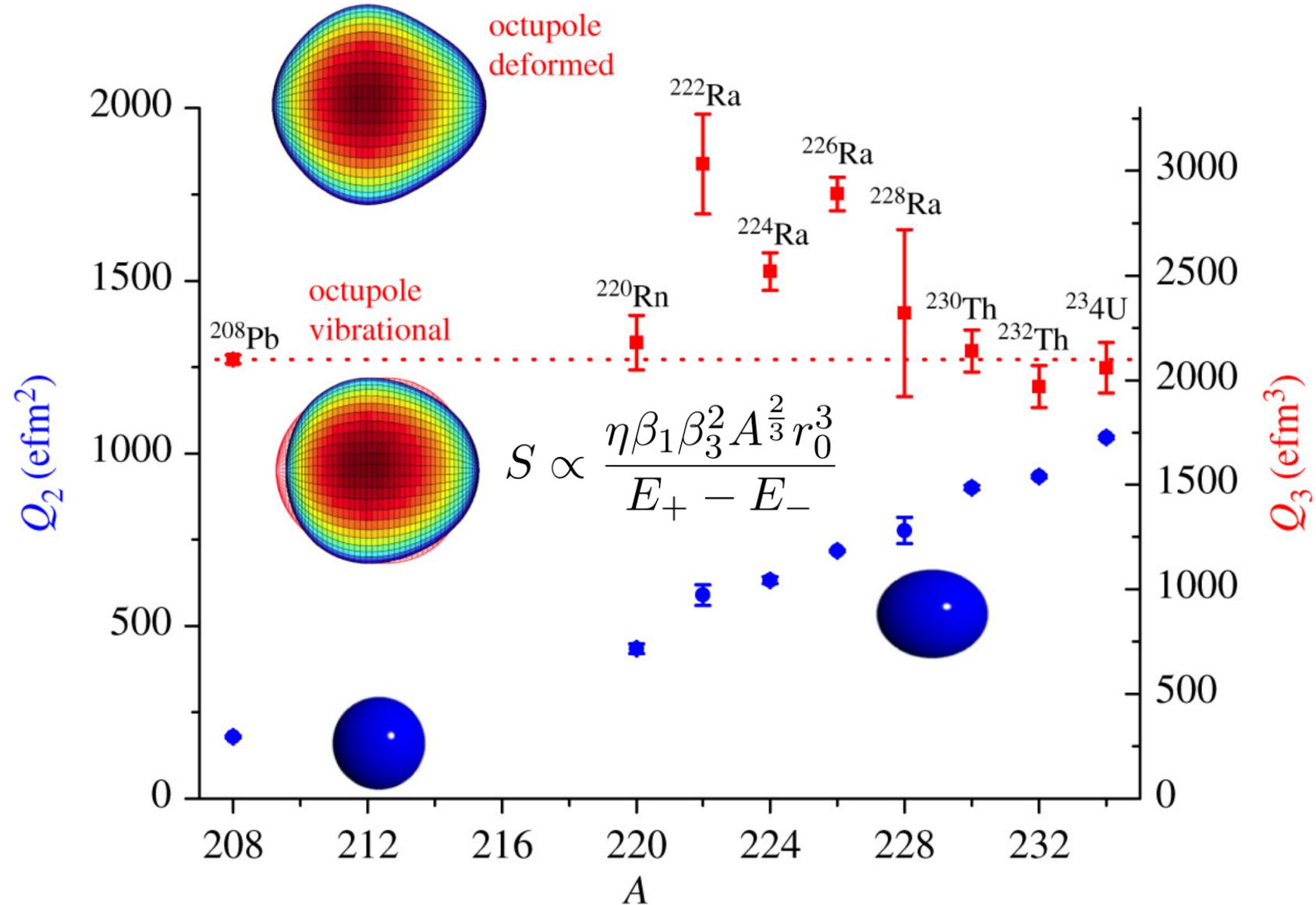
500-1000
(J. Engel et al.)



^{223}Rn : TBD



More nuclear structure





SuperSUN: High density UCN source



Phase I characterization

Measurement agrees with expectation (48 MW)

cf. [EPJ Conf. 219, 02006 \(2019\)](#) and [arXiv:2504.13030](#)

Total UCN output: 3.8×10^6 (integral of blue peak)

Source density: 270 UCN/cm³

Long storage times: 126000 UCN remaining after 20min

Expected density in PanEDM: 3.9 UCN/cm³ (58 MW)

Source characterization, PanEDM commissioning ongoing

Phase II expectation

Peak field: 2.1 T

Source density: 1670 UCN/cm³ (x5 gain)

Density in PanEDM: 40 UCN/cm³ (x10 gain)

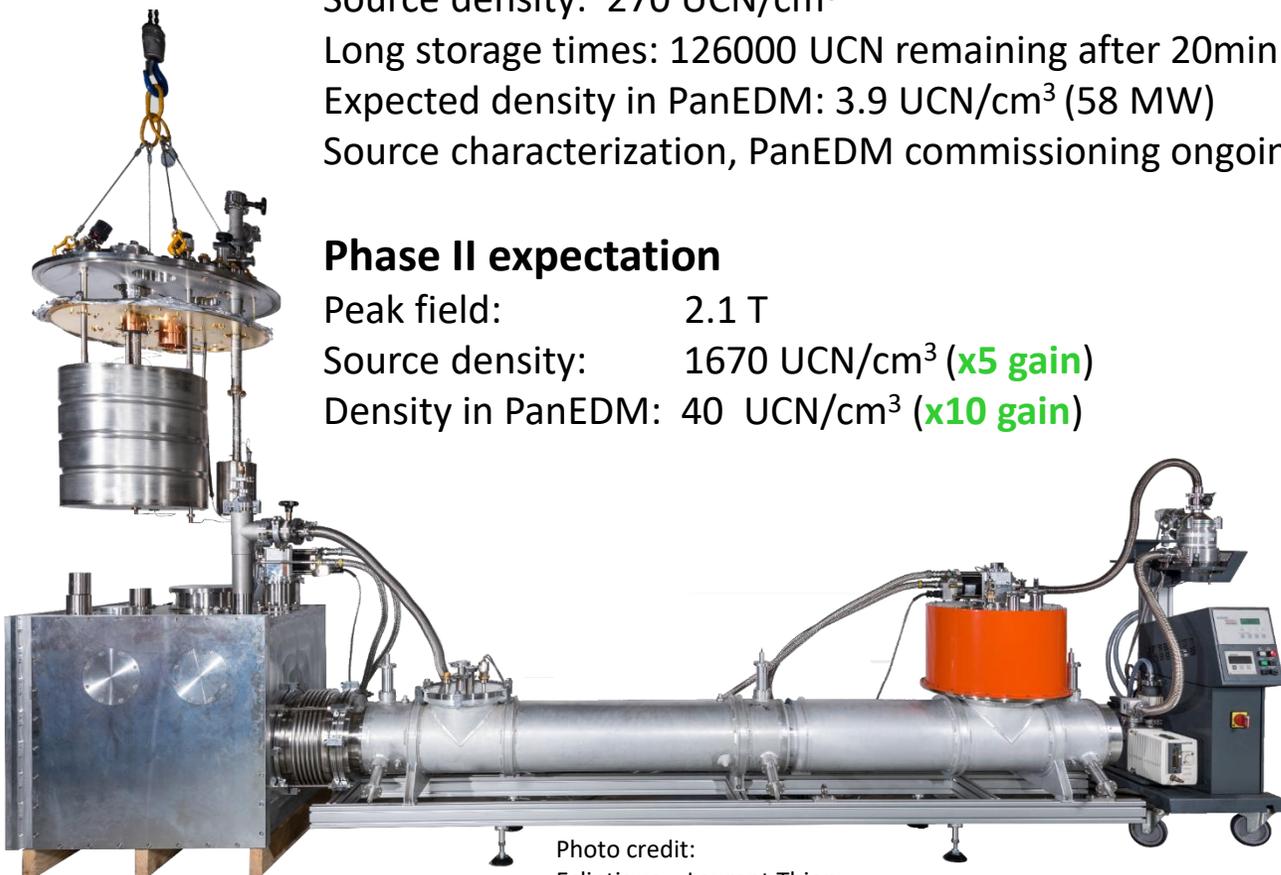
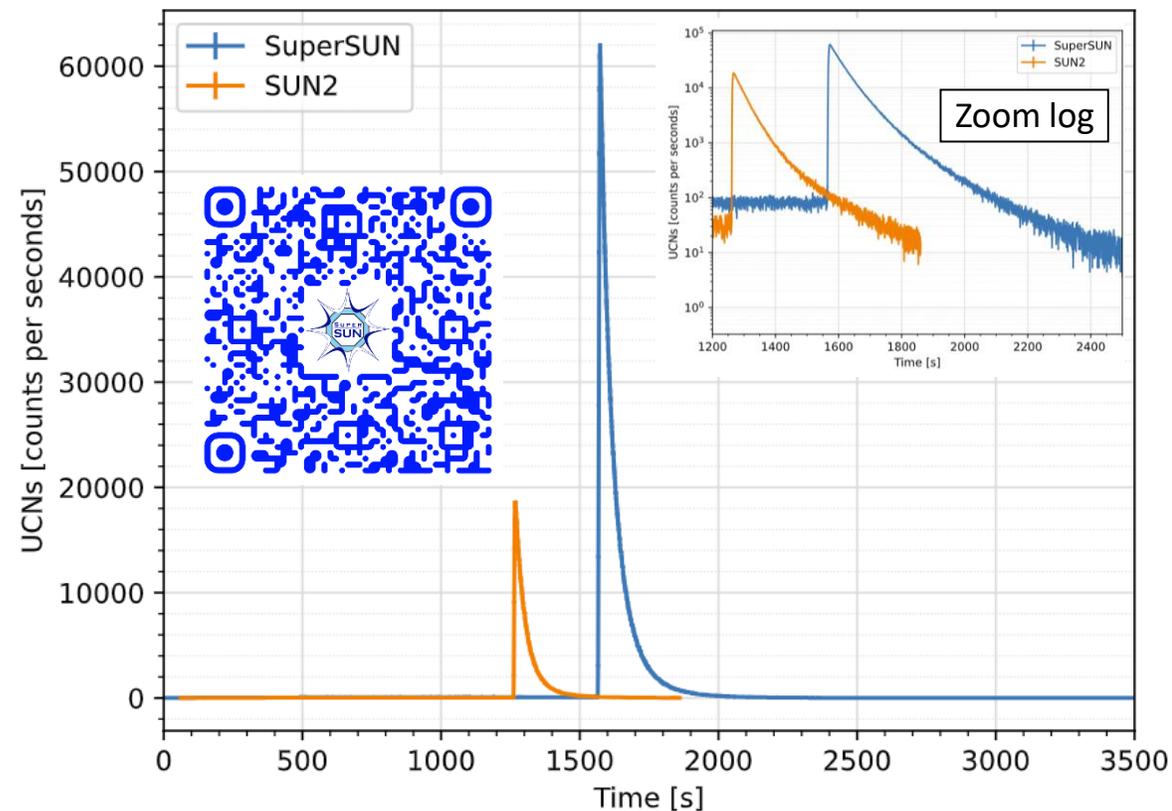


Photo credit:
Ecliptique – Laurent Thion.

Comparison to the prototype source SUN2



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SEIT 1386



SuperSUN: High density UCN source



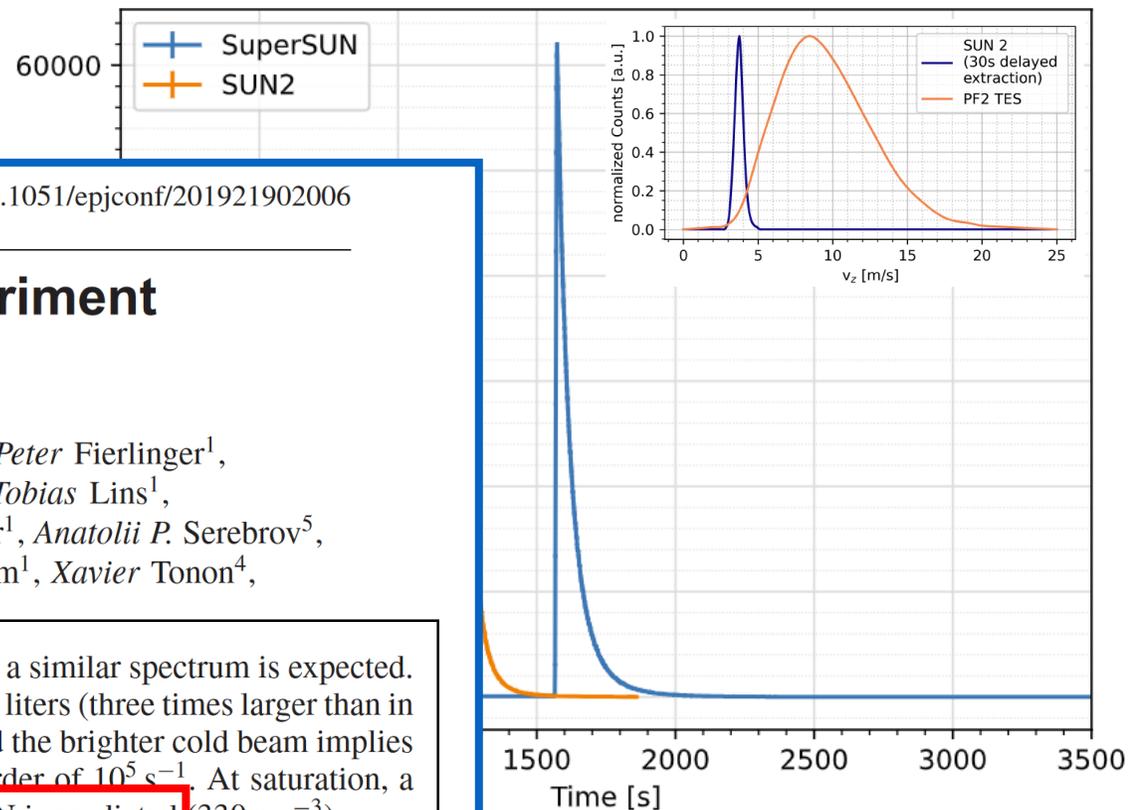
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Comparison to the prototype source SUN2



EPJ Web of Conferences **219**, 02006 (2019)

<https://doi.org/10.1051/epjconf/201921902006>

PPNS 2018

The PanEDM neutron electric dipole moment experiment at the ILL

David Wurm¹, Douglas H. Beck², Tim Chupp³, Skyler Degenkolb^{4,a}, Katharina Fierlinger¹, Peter Fierlinger¹, Hanno Filter¹, Sergey Ivanov⁵, Christopher Klau¹, Michael Kreuz⁴, Eddy Lelièvre-Berna⁴, Tobias Lins¹, Joachim Meichelböck¹, Thomas Neulinger², Robert Paddock⁶, Florian Röhrer¹, Martin Rosner¹, Anatolii P. Serebrov⁵, Jaideep Taggart Singh⁷, Rainer Stoepler¹, Stefan Stuibler¹, Michael Sturm¹, Bernd Taubenheim¹, Xavier Tonon⁴, Mark Tucker⁸, Maurits van der Grinten⁸, and Oliver Zimmer⁴

Ongoing work: spectrum, transfer efficiency and storage in external volumes, etc...

by material walls only, and a similar spectrum is expected. The converter volume is 12 liters (three times larger than in SUN2); scaling for this and the brighter cold beam implies a production rate on the order of 10^5 s^{-1} . At saturation, a total of 4×10^6 stored UCN is predicted (330 cm^{-3}).

3.8×10^6 UCN measured (fill-and-empty)



Photo credit: Ecliptique – Laurent Thion.



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