Theoretical overview on EDMs

*Highlight recent progress

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LANL → KEK

High Energy Accelerator Research Organization

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SSP 2025

Baryon asymmetry

One open question in our Universe:

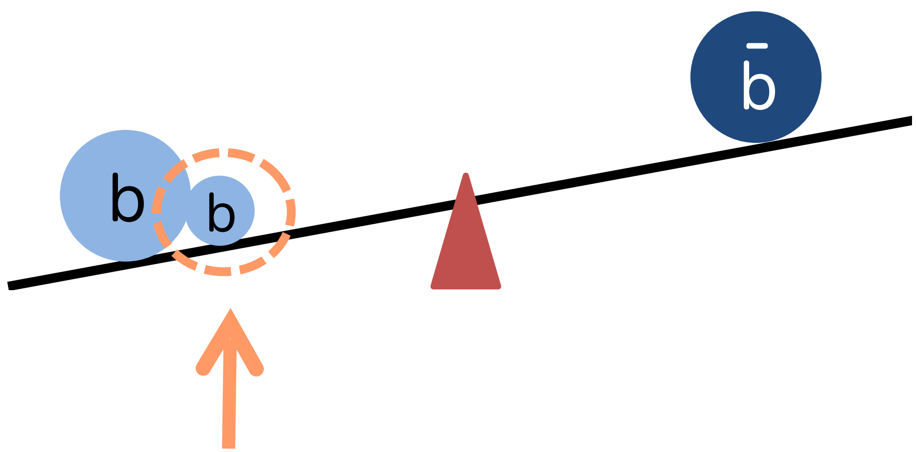
The Baryon Asymmetry of the Universe

Baryon

$10^{10} + 1$

Antibaryon

10^{10}



Left in the present Universe

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.105 \pm 0.055) \times 10^{-10}$$

PDG: PTEP(2020)083C01

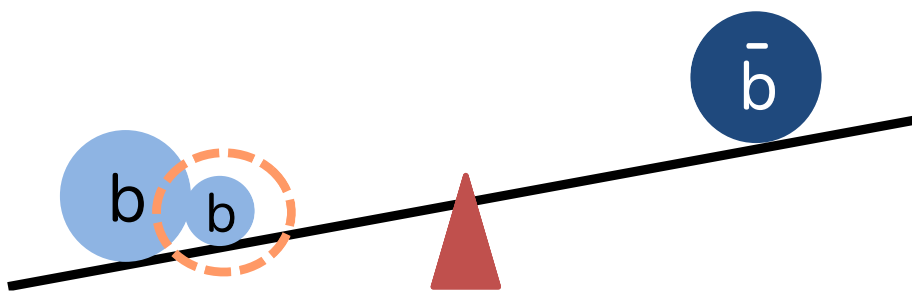
Baryon asymmetry

One open question in our Universe:

The Baryon Asymmetry of the Universe

Baryon $10^{10} + 1$

Antibaryon 10^{10}



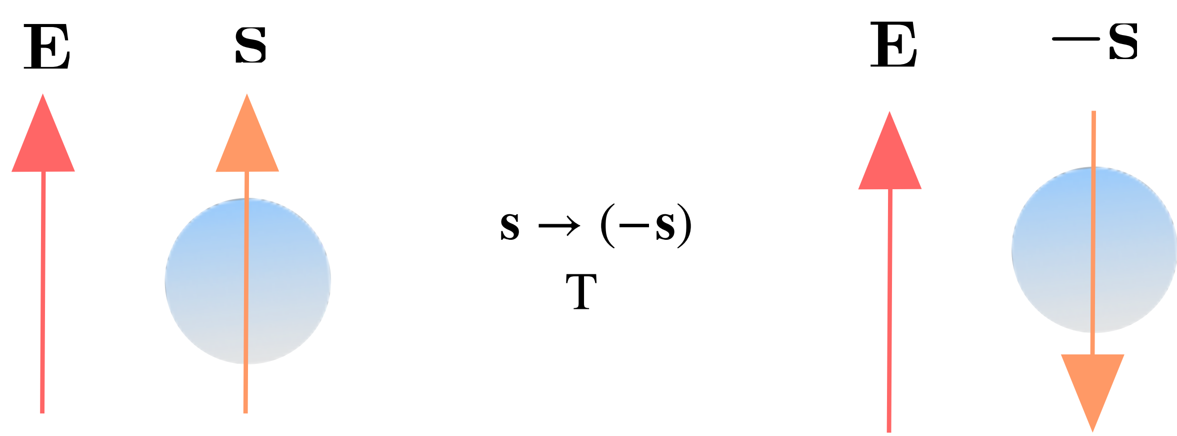
One necessary condition to create the BAU : CP violation

Electric Dipole Moment

$$H_{\mathrm{EDM}} = -\, d_f\ \mathbf{E} \cdot \mathbf{s}$$

$\mathbf{E}$: Electric field $\mathbf{s}$: spin

Violation of CP symmetry (= *T symmetry under CPT theorem*)



*Nonzero EDM (d_f) implies T-violating (= CP-violating) interactions

Electric Dipole Moment

The relativistic EDM interaction : $\mathscr{L}_{\mathrm{EDM}} = -\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$

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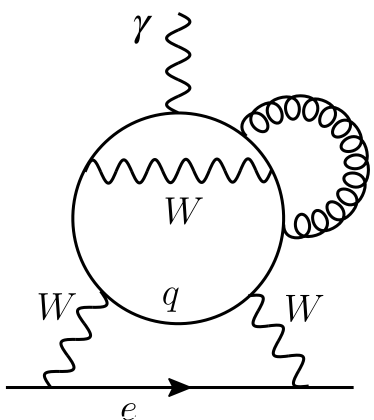
Ex) Electron EDM



4-loop diagram in the SM

T violation in the SM

$$\mathscr{L}_{\text{SM}} \supset -\frac{g_2}{\sqrt{2}} \bar{u}_i \gamma^\mu W_\mu^+ (V_{\text{CKM}})_{ij} d_j$$

$$d_e^{\text{CKM}} \sim \mathcal{O}(10^{-44})\ e\ \text{cm}$$

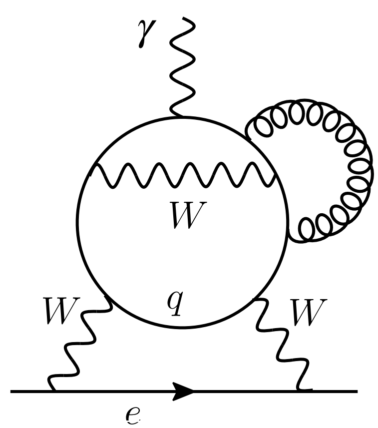
E. P. Shabalin, Sov. J. Nucl. Phys. 28, 75 (1978)
M. Pospelov, I.B. Khriplovich, SJNP53(1991)638, Yad. Fiz. 53(1991)1030
D. Ng, J. Ng, Mod. MPLA11(1996)211, W. Bernreuther, M. Suzuki, RMP63(1991)313
M. Pospelov and A. Ritz, PRD89(2014)056006

*See Y. Yamaguchi and N. Yamanaka PRL 125 (2020) 241802 for long-distance contributions

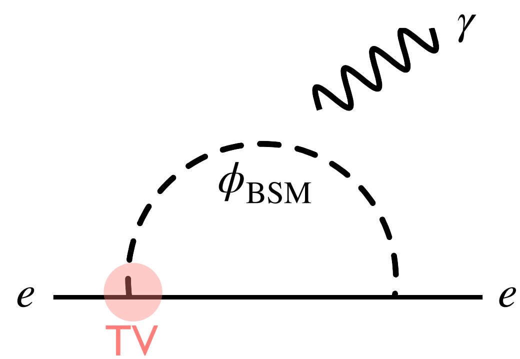
Electric Dipole Moment

The relativistic EDM interaction : $\mathscr{L}_{\text{EDM}} = -\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$

Ex) Electron EDM



4-loop diagram in the SM



1-loop diagram in BSM

$$d_e^{\text{CKM}} \sim \mathcal{O}(10^{-44})\ e\ \text{cm} \qquad \ll \qquad d_e^{\text{BSM}} \propto |C_{\text{TV}}| \sin\phi_{\text{BSM}}$$

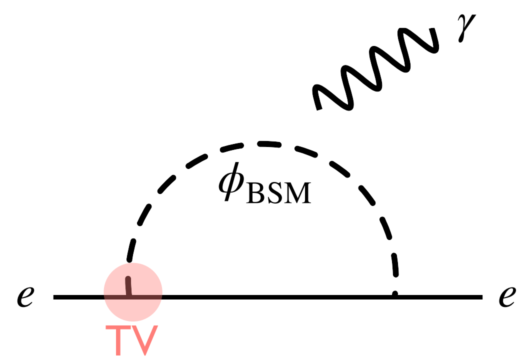
*EDMs in BSM can be much larger than the one from the SM

Electric Dipole Moment

The relativistic EDM interaction : $$\mathscr{L}_{\text{EDM}} = -\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$$

Ex) Electron EDM

4-loop diagram in the SM



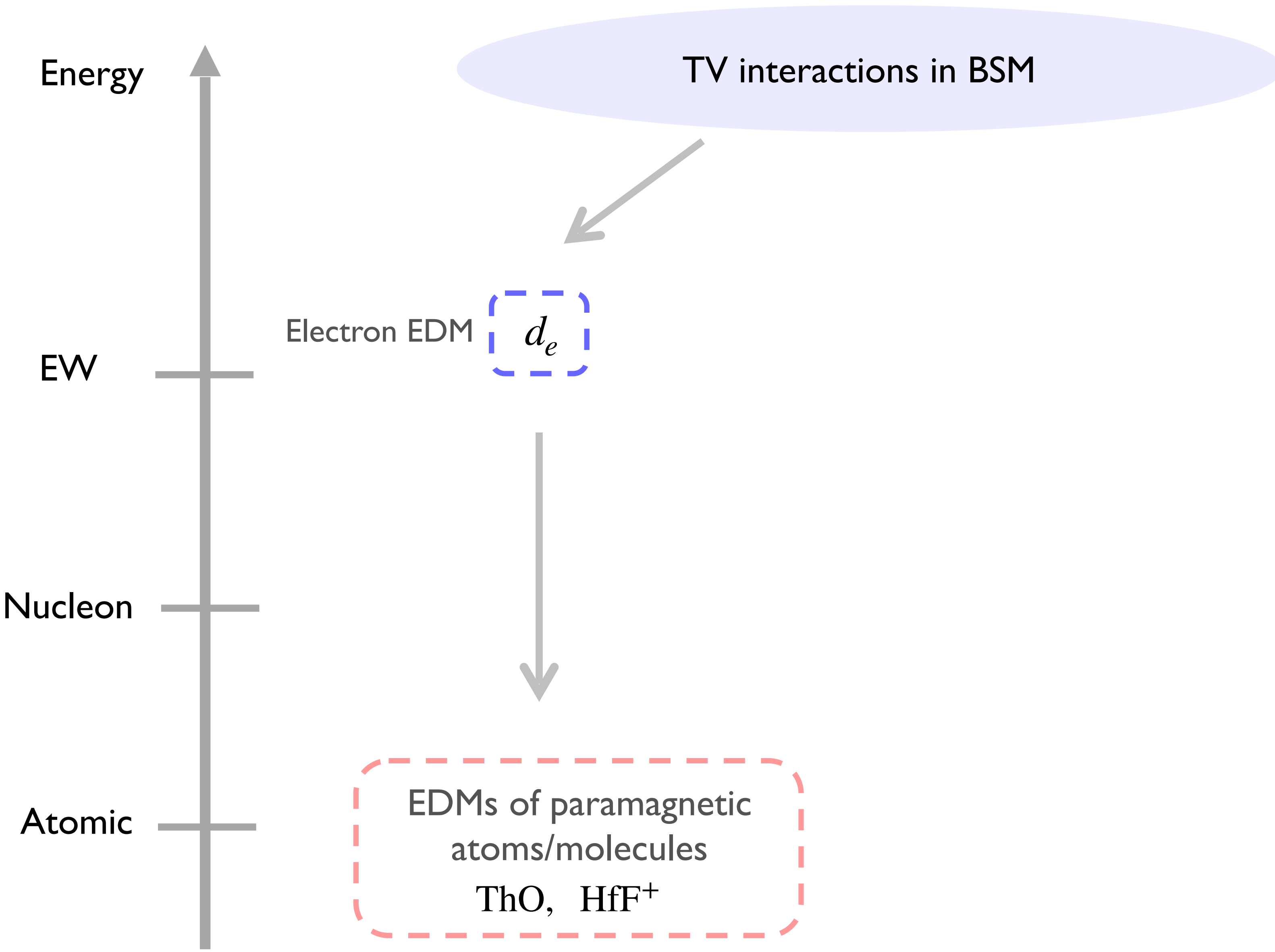
1-loop diagram in BSM

e.g., 1-loop $$d_f \sim (10^{-19}\ e\ \text{cm}) \cdot \left(\frac{v}{\Lambda_{\text{BSM}}}\right)^2 \cdot \boxed{|C_{\text{TV}}| \sin\phi_{\text{BSM}}} \cdot y_f \cdot F_{\text{loop}}$$

Large enough for BAU

Electric Dipole Moment

*Example, see more in Pospelov and Ritz: 0504231



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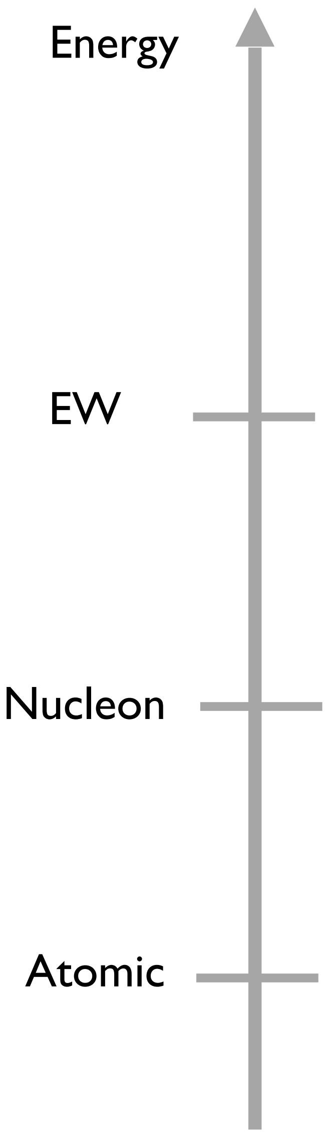
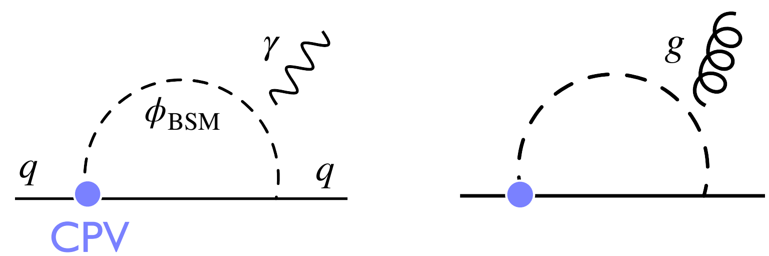
Electric Dipole Moment



TV interactions in BSM

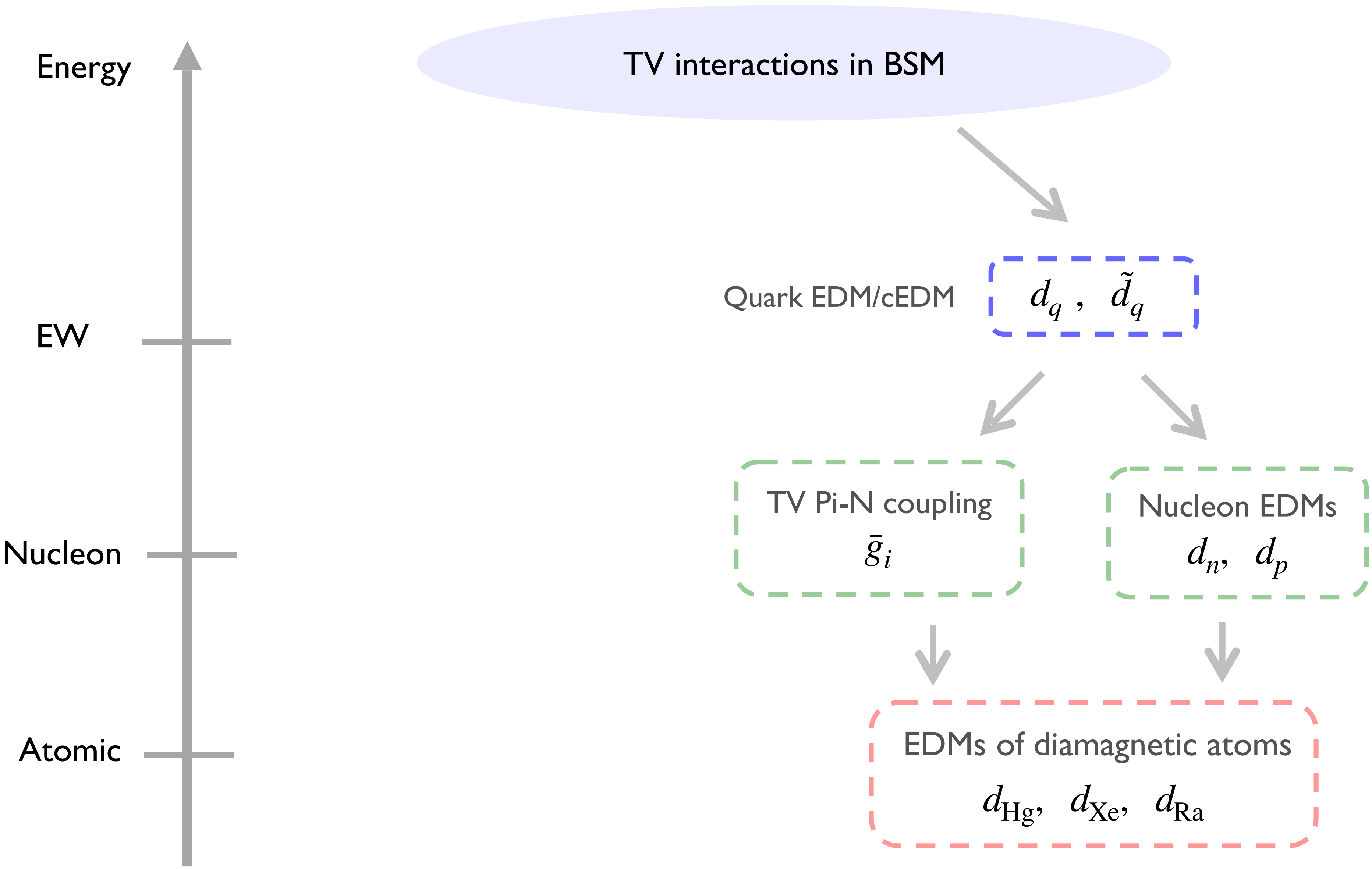
Quark EDM/cEDM $\boxed{d_q \, , \; \tilde{d}_q}$

Ex)



Electric Dipole Moment

*Example, see more in Pospelov and Ritz: 0504231



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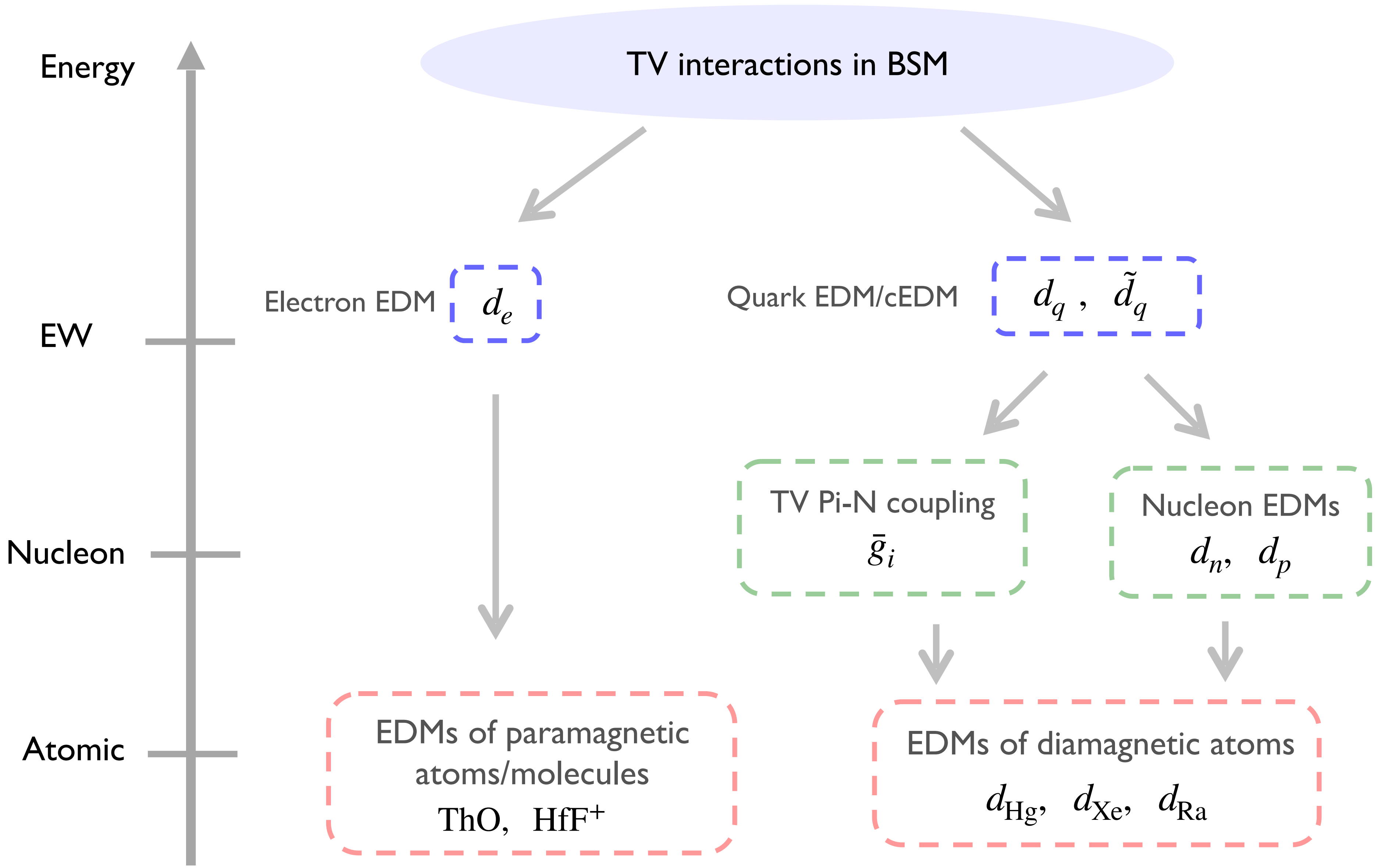
Electric Dipole Moment

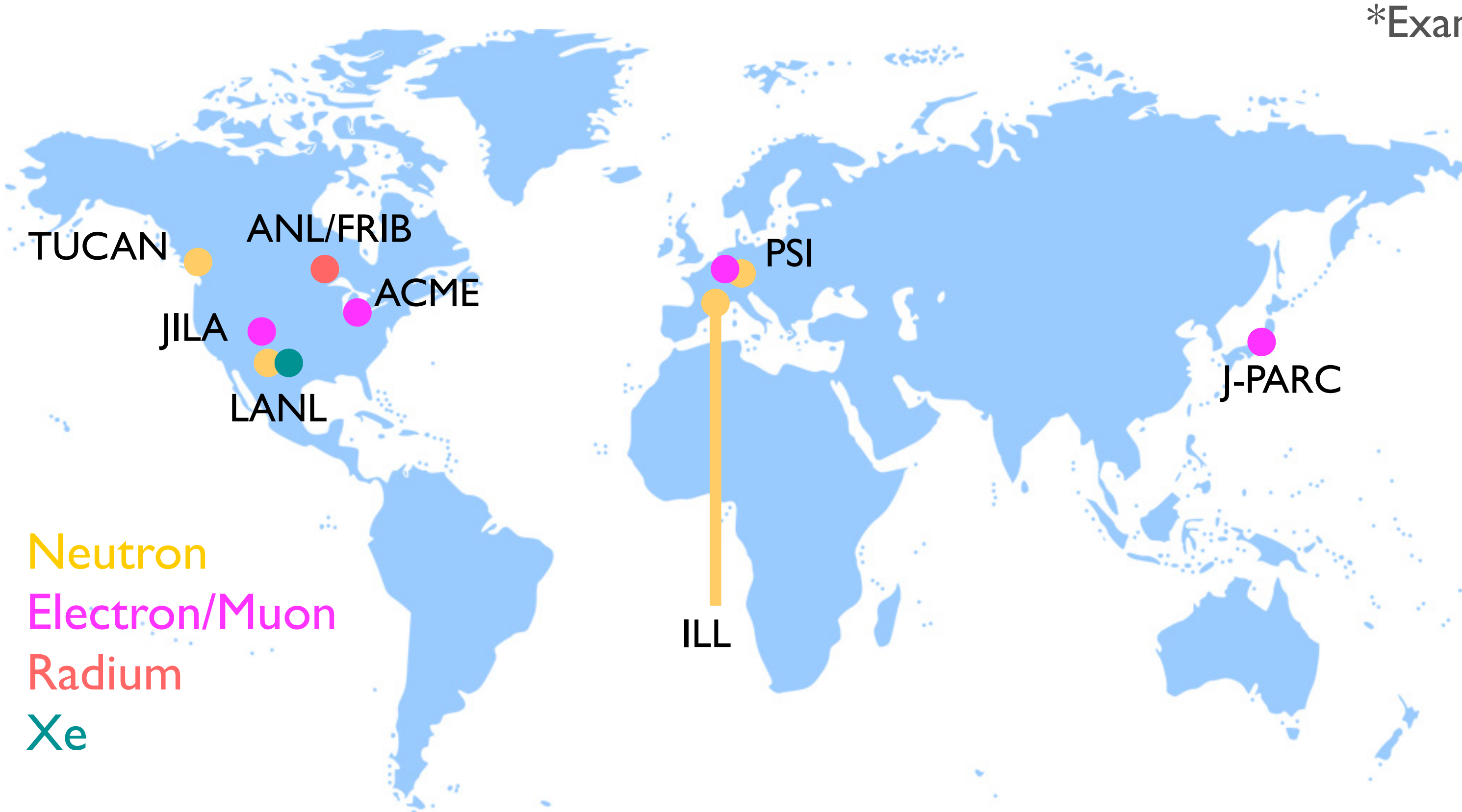


*Essential to probe different CPV sources

Searches for EDMs

Various EDM searches have been ongoing.

*Example



$$|d_e| < 4.1 \times 10^{-30}\ e\ \text{cm}$$

JILA Collaboration : Science 381 (2023) 6653

$$|d_n| < 1.8 \times 10^{-26}\ e\ \text{cm}$$

nEDM Collaboration, PRL124(2020)081803

See talk slides by
F. Piegsa, E. Miller, B. Lauss

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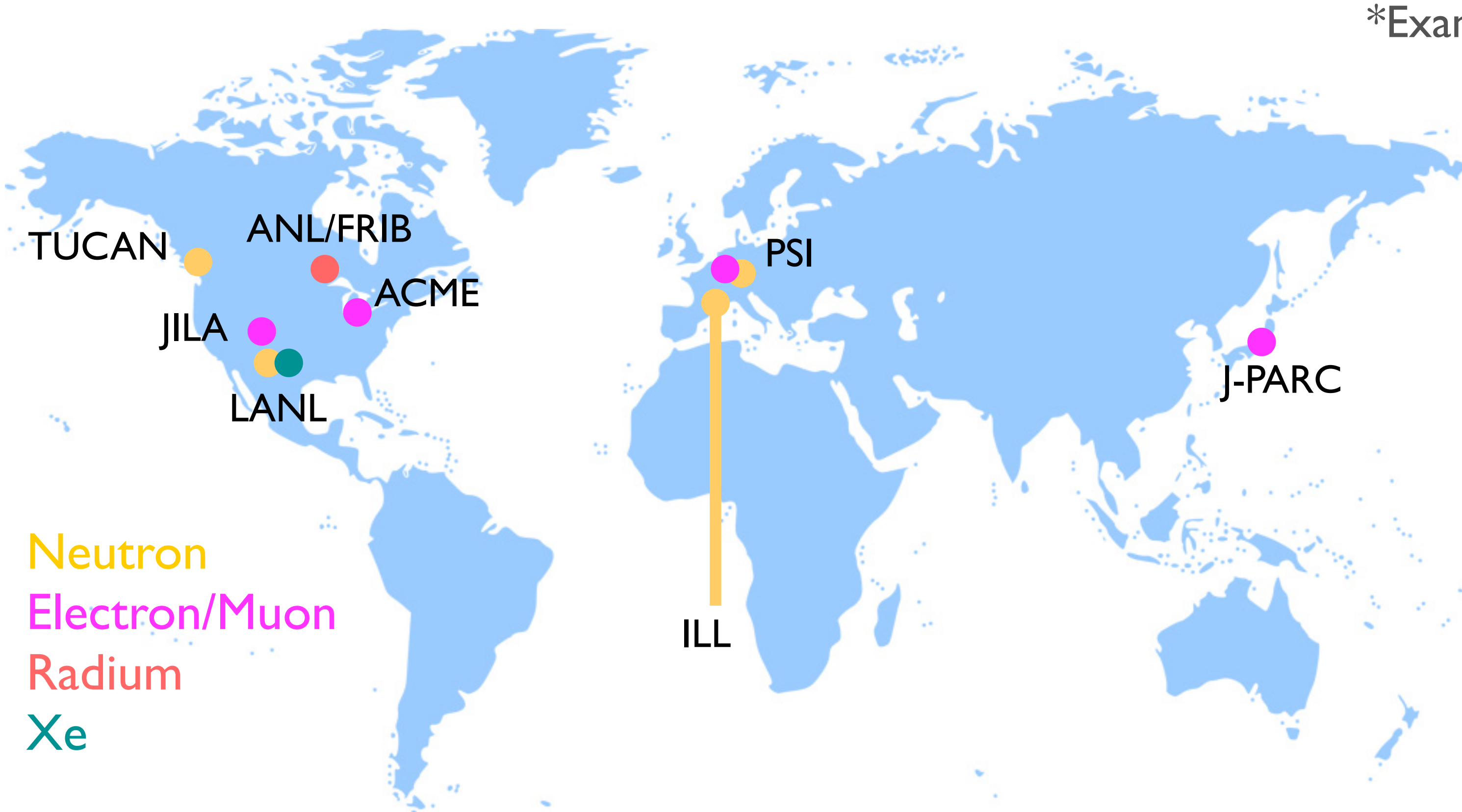

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nEDM Collaboration, PRL124(2020)081803

Future $\sim 10^{-31}$ $\sim 10^{-27}$

See talk slides by
F. Piegsa, E. Miller, B. Lauss

Electron EDM

Electron CPV interactions:

$$\mathscr{L} = -\frac{i}{2} d_e \, \bar{e} \sigma^{\mu\nu} \gamma_5 F_{\mu\nu} e - \frac{G_F}{\sqrt{2}} C_S \, \bar{e} i \gamma_5 e \, \bar{N} N$$

Electron EDM　　　　e-N interaction

Electron EDM

Electron CPV interactions:

$$\mathscr{L} = -\frac{i}{2} d_e \bar{e}\sigma^{\mu\nu}\gamma_5 F_{\mu\nu} e - \frac{G_F}{\sqrt{2}} C_S \bar{e} i\gamma_5 e \bar{N} N$$

Electron EDM   e-N interaction

Spin precession frequency :

$$\omega = -E_{\text{eff}} d_e + W_S C_S$$

E_{eff} : Effective electric field

W_S : Molecule constant

System	E_{eff} [GV cm^{-1}]	W_S [kHz]
ThO (ACME)	78	-282
HfF^+ (JILA)	23	-51

ACME Collaboration: Nature 562 (2018) 7727
JILA Collaboration: Science 381 (2023) 6653

M. Denis, T. Fleig, J. Chem. Phys. 145, 214307 (2016)
L.V. Skripnikov, J. Chem. Phys. 145, 214301 (2016).
V.A. Dzuba, et al, Phys. Rev. A 84, 052108 (2011).
T. Fleig and M. Jung, JHEP 2018 (7), 12

Electron EDM

Electron CPV interactions:

$$\mathscr{L} = -\frac{i}{2} d_e \bar{e}\sigma^{\mu\nu}\gamma_5 F_{\mu\nu} e - \frac{G_F}{\sqrt{2}} C_S \bar{e} i\gamma_5 e \bar{N}N$$

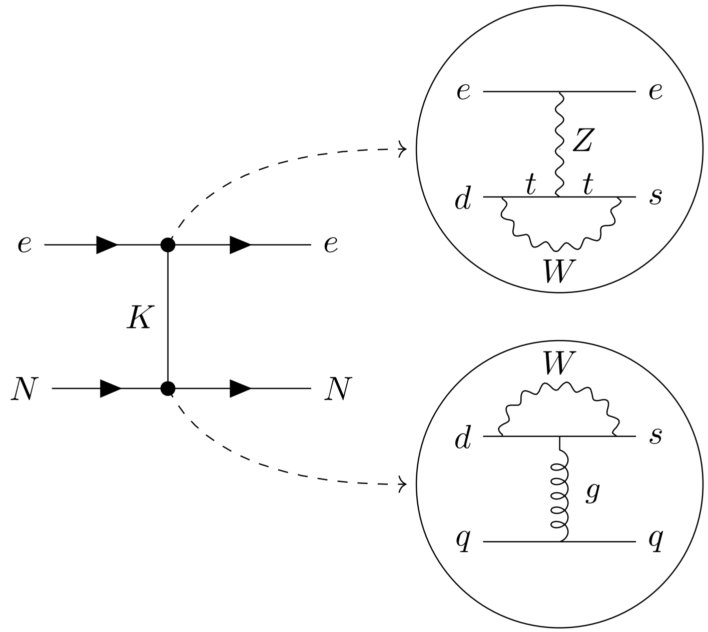
Electron EDM e-N interaction

✔ CKM contribution to C_S at EW^3 order

Y. Ema, T. Gao, M. Pospelov, PRL129(2022) 23, 231801

$$C_S \simeq 7 \times 10^{-16}$$

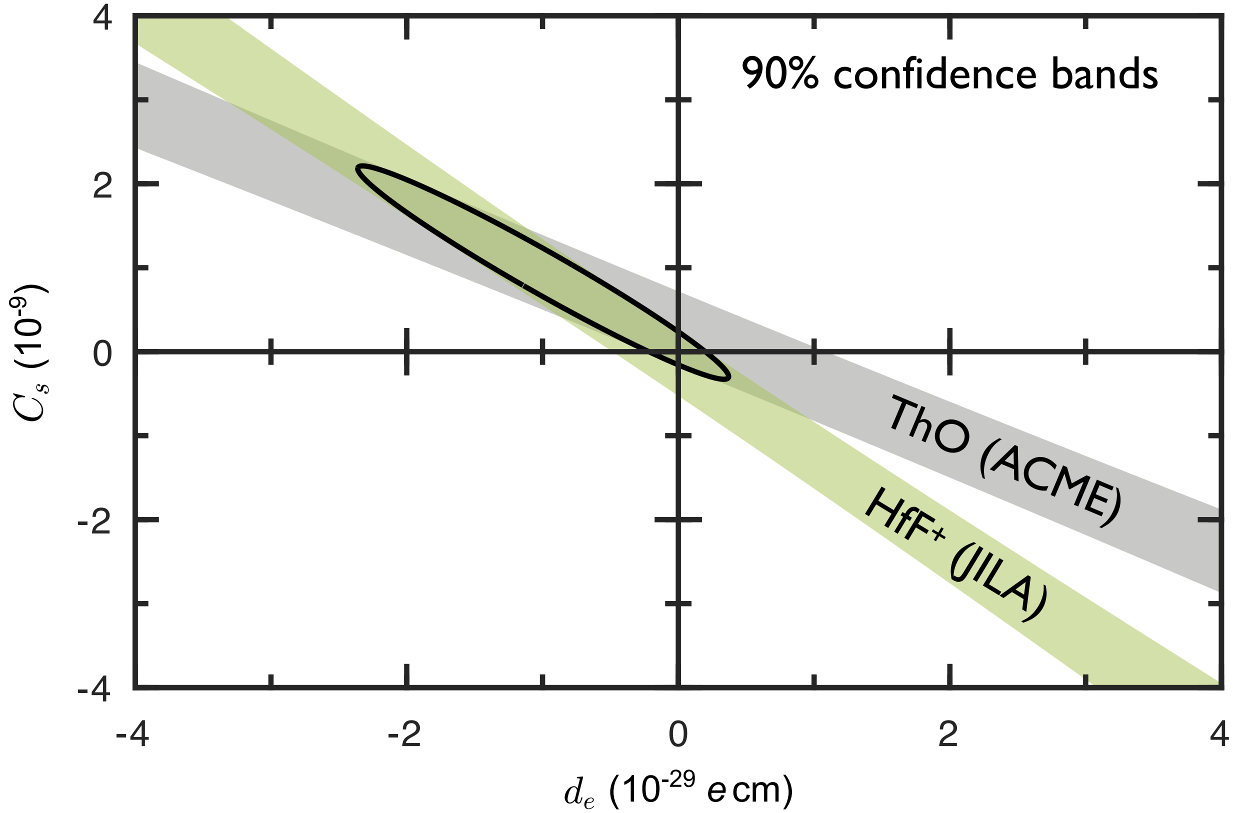
$$\omega = -E_{\text{eff}}\, d_e + W_S C_S$$



*Dominant SM contribution to paramagnetic systems

Electron EDM

JILA Collaboration: Science 381 (2023) 6653



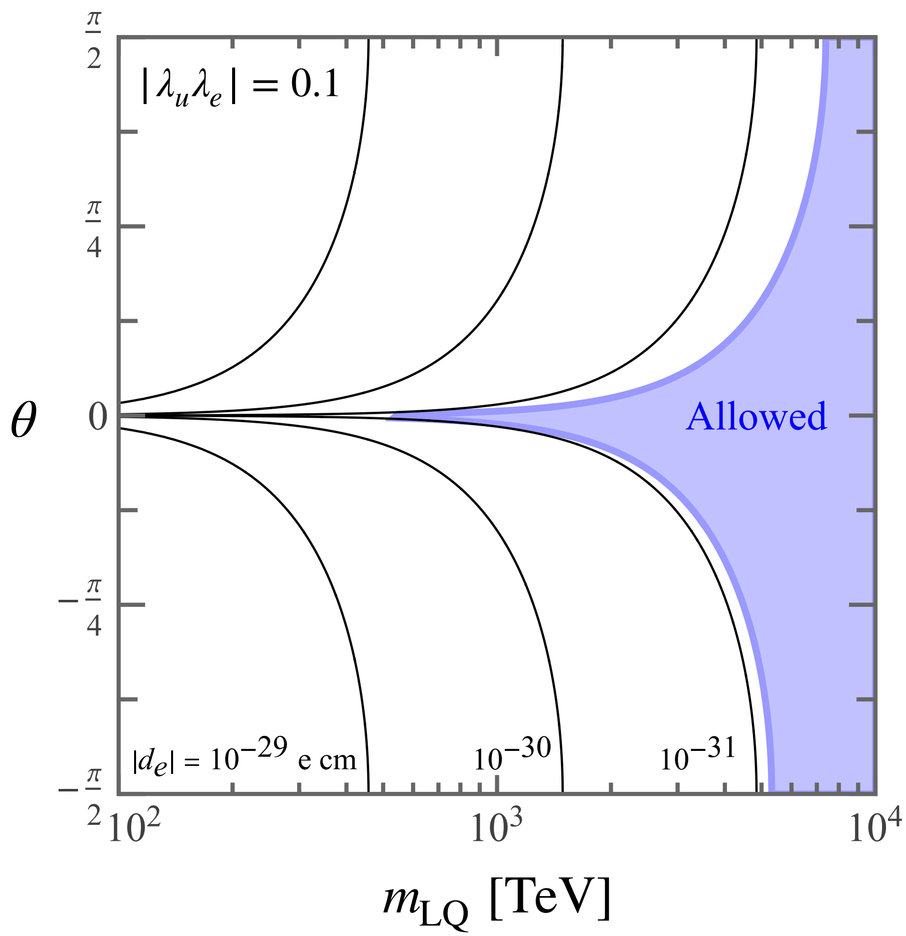
Combined Fit : $|d_e| < 2.1 \times 10^{-29}\ e\ \text{cm}$ $|C_S| < 1.9 \times 10^{-9}$

*Sole-source limit $\mathcal{O}(10^2)\ \text{TeV} \lesssim \Lambda_{\text{BSM}}$ $\mathcal{O}(10^3)\ \text{TeV} \lesssim \Lambda_{\text{BSM}}$

Stronger!

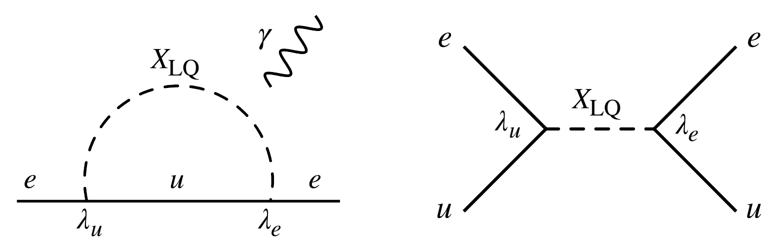
Implication for BSM

KF, M. Ramsey-Musolf, T. Shen, PLB788(2019)52



Ex) Scalar Leptoquark Model

$$\mathscr{L} = -\lambda_u \bar{u}_R X^a \epsilon^{ab} L^b - \lambda_e \bar{e}_R X^\dagger Q$$



$d_e,\ C_S \propto |\lambda_u \lambda_e| \sin\theta$

$$\frac{d_e}{C_S} \sim \frac{\text{One} - \text{loop}}{\text{Tree}} \sim 0.01$$

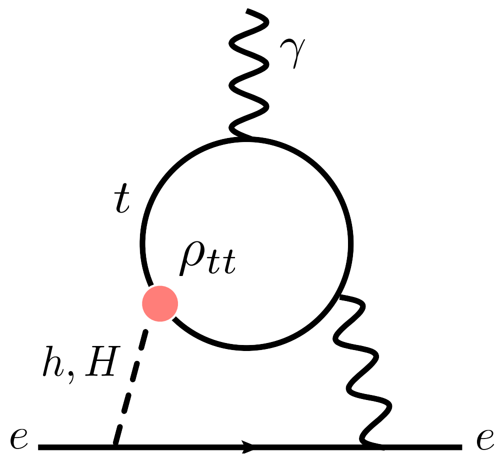
C_S dominates the system, leading to $|d_e| < \mathcal{O}(10^{-31})\ e\ \text{cm}$

Implication for Baryogenesis

KF, WS. Hou, and E. Senaha,
PLB 776 (2018) 402

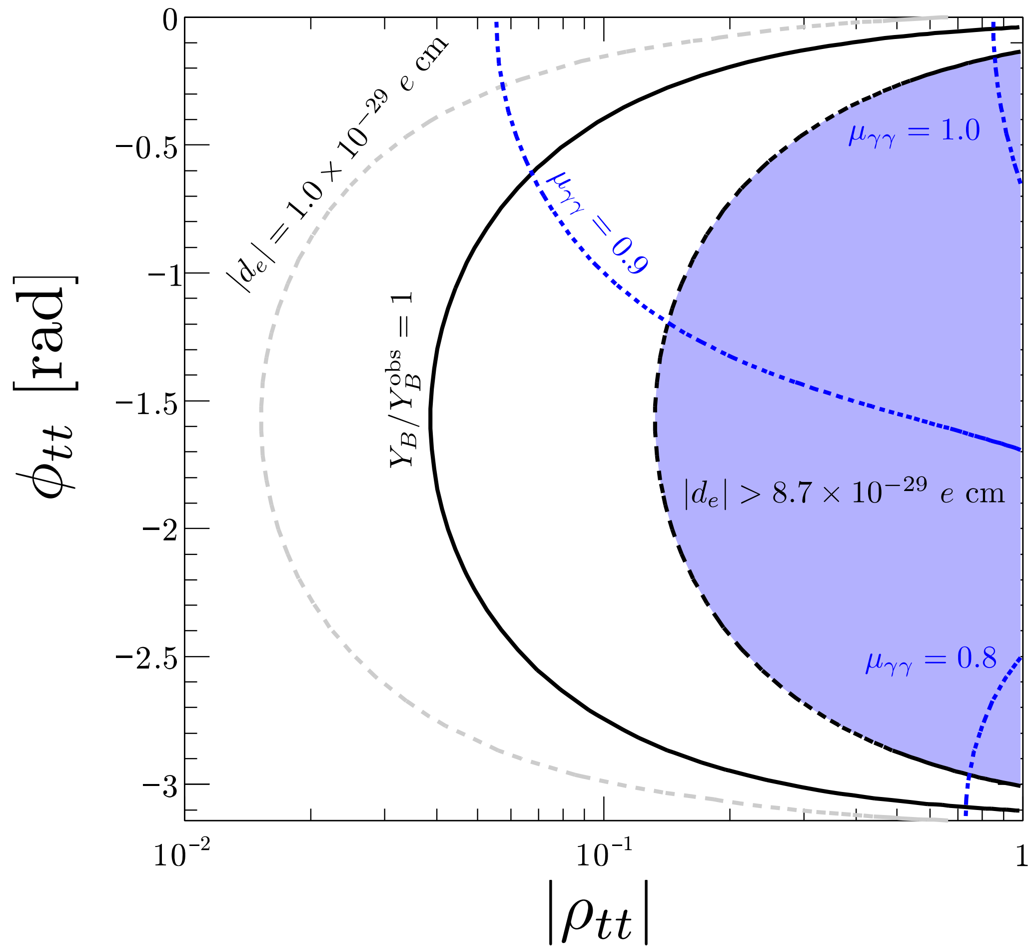
Electroweak Baryogenesis in General Two Higgs Doublet Model

CPV Top Yukawa



EDM : $d_e \propto |\rho_{tt}| \sin\phi_{tt}$

BAU : $n_B \propto |\rho_{tt}| \sin\phi_{tt}$



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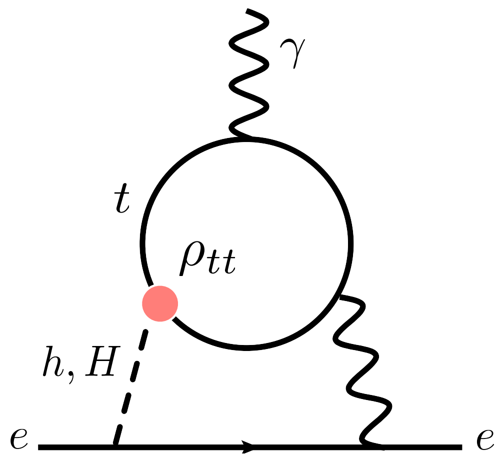

EDM : $d_e \propto |\rho_{tt}| \sin\phi_{tt}$

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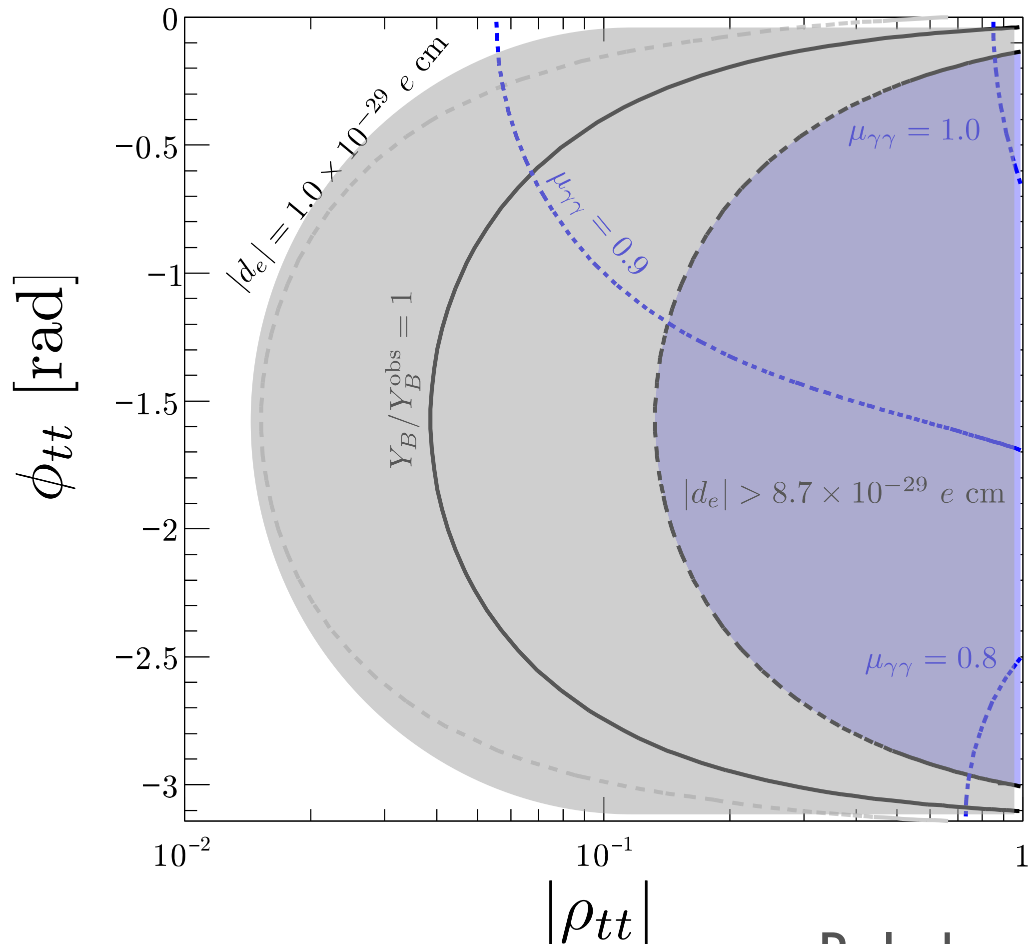
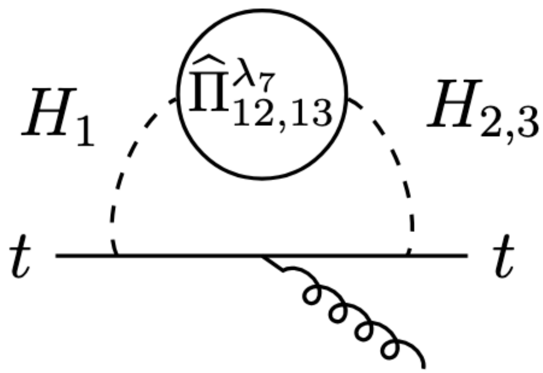


Ruled out.

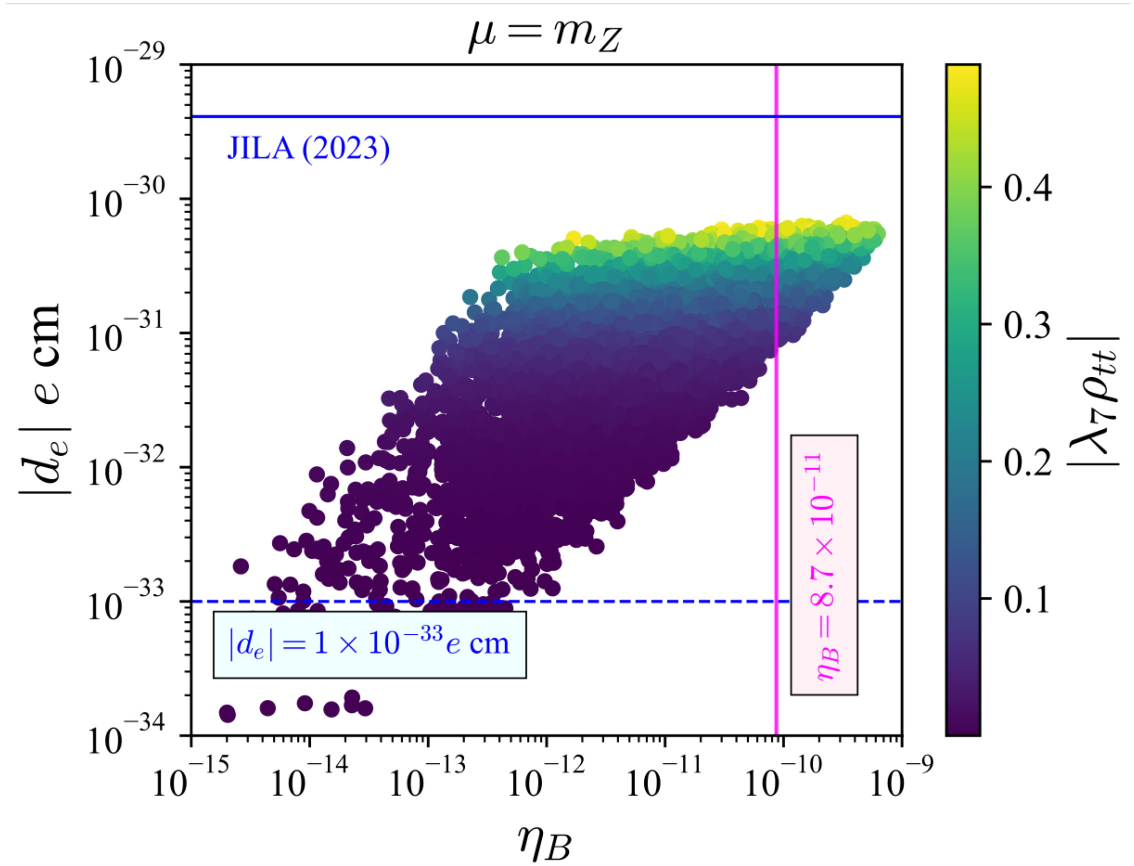
Implication for Baryogenesis

M. Aiko, M. Endo, S. Kanemura, Y. Mura
JHEP 07 (2025) 236

Electroweak Baryogenesis in General Two Higgs Doublet Model



Top-quark EDM and cEDM are induced.

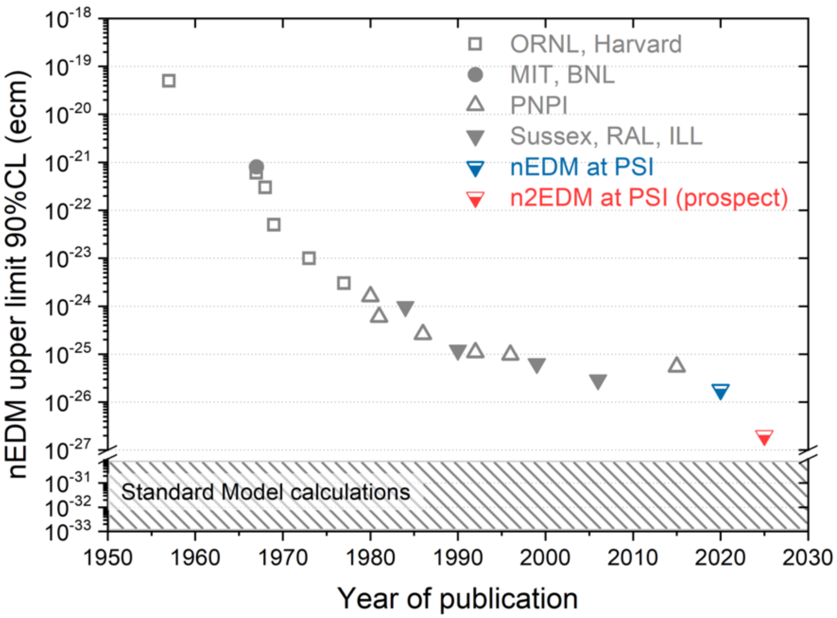


Another parameter choice (alignment limit) is still allowed.

Neutron/Atomic EDMs

A worldwide race is on-going!

PSI: https://www.psi.ch/en/ltp-ucn-physics/n2edm



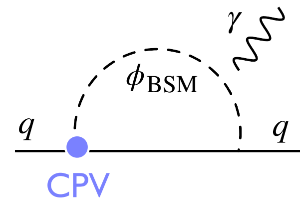
System	Current	Expected
n	$1.8 \times 10^{-13}\ e\ \text{fm}$	$\sim 10^{-14}\ e\ \text{fm}$
^{199}Hg	$6.2 \times 10^{-17}\ e\ \text{fm}$	$-$
^{225}Ra	$1.2 \times 10^{-10}\ e\ \text{fm}$	$\sim 10^{-15}\ e\ \text{fm}$
^{129}Xe	$1.4 \times 10^{-14}\ e\ \text{fm}$	$\sim 10^{-15}\ e\ \text{fm}$

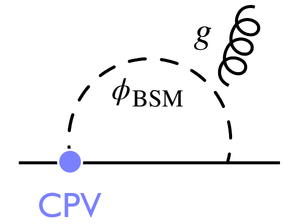
PRL124(2020)081803
PRL116(2016)161601
PRC94(2016) 025501
PRL123(2019)14, 143003

Contributions from various fundamental CPV interactions : $d_n\,(d_q, d_{\tilde{q}}, \cdots),\ d_{\text{atom}}\,(d_{\tilde{q}}, \cdots)$

Theoretical Challenge : Treatments of nonperturbative effects

Neutron/Atomic EDMs





Energy

Quark EDM Chromo EDM

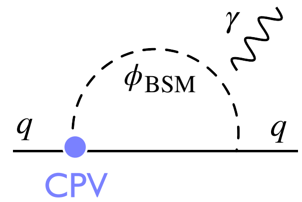
EW

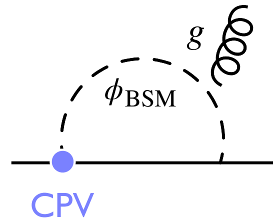
$$\mathscr{L} = -\frac{i}{2} d_q\, \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} - \frac{i}{2} g_s\, \tilde{d}_q\, \bar{q}\sigma^{\mu\nu}\gamma_5 T^A q G^A_{\mu\nu}$$

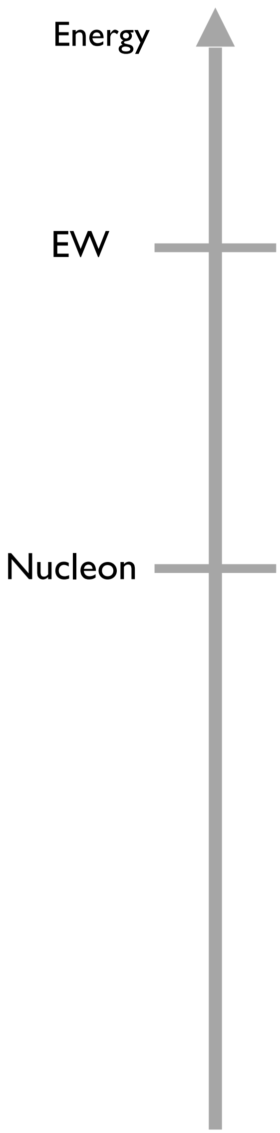
Nucleon

$d_n(d_q,\, \tilde{d}_q,\, \cdots)$ Neutron EDM

Neutron/Atomic EDMs







Quark EDM   Chromo EDM

$$\mathscr{L} = -\frac{i}{2} d_q\, \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} - \frac{i}{2} g_s\, \tilde{d}_q\, \bar{q}\sigma^{\mu\nu}\gamma_5 T^A q G^A_{\mu\nu}$$

$$d_n(d_q, \tilde{d}_q, \cdots) = g_T^u\, d_u + g_T^d\, d_d \; + (1 \pm 0.5) \times \left[1.1e \left(\tilde{d}_d + 0.5\, \tilde{d}_u \right) \right]$$

Lattice QCD
R. Gupta, B. Yoon, T. Bhattacharya, V. Cirigliano, Y.-C. Jang, and H.-W. Lin, PRD98(2018)091501.

QCD Sum Rule
PRD63(2001)073015
PRD85(2012)114044

$$g_T^u = 0.784(28)(10)$$
$$g_T^d = -0.204(11)(10)$$

*No lattice results available for chromo EDMs

Neutron/Atomic EDMs

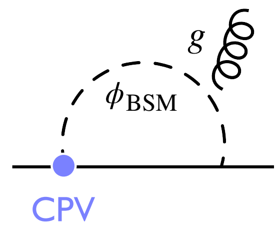
The same challenge exists…

Energy

EW

Chromo EDM

$$\mathscr{L} = -\frac{i}{2} g_s \tilde{d}_q \bar{q} \sigma^{\mu\nu} \gamma_5 T^A q G^A_{\mu\nu}$$



Nucleon

$$\mathscr{L} = \bar{g}_0 \bar{N} (\tau \cdot \pi) N + \bar{g}_1 \pi^3 \bar{N} N$$

CP-odd pion-nucleon interactions

J. de Vries, E. Mereghetti, C.-Y. Seng, and A. Walker-Loud, Phys. Lett. B 766, 254 (2017).

Atomic

$$d_{\rm atom} (\bar{g}_i, \cdots)$$

$$\bar{g}_0 = \frac{1}{2} \left(\tilde{d}_u + \tilde{d}_d \right) \left(\sigma^3_C + \frac{r \sigma^3}{\bar{m} \varepsilon} \right) \qquad \bar{g}_1 = -\left(\tilde{d}_u - \tilde{d}_d \right) \left(\sigma^0_C - \frac{r \sigma^0}{\bar{m}} \right)$$

*Unknown nucleon matrix elements

$$\sigma_C^{0,3} \sim \langle P \,|\, \bar{q} g_s (\sigma \cdot G) \tau^{0,3} q \,|\, P \rangle$$

Extraction from PDFs

C.-Y. Seng, PRL122, 072001 (2019).
S. Bhattacharya, KF, E. Mereghetti, T R. Richardson, PRC112(2025)025501

The unknown NMEs are related to nucleon parton distribution functions (PDFs):

Experimental data

$$\sigma_C^3 \approx -2m_N^2 \left[3\left(\mathscr{M}_3(e^u) - \mathscr{M}_3(e^d)\right) + B^u - B^d\right]$$

$$\sigma_C^0 \approx m_N^2 \left[3\left(\mathscr{M}_3(e^u) + \mathscr{M}_3(e^d)\right) + B^u + B^d\right]$$

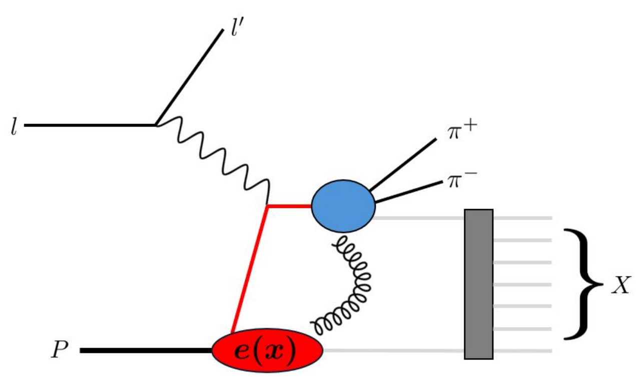
Spin-flavor symmetry

$\mathscr{M}_3$: 3rd moment of Twist 3 PDFs

B^q : nucleon form factor (*previously neglected)

$$\langle P | \bar{q} g_s G^{\alpha\mu} \sigma^\nu_\alpha q | P \rangle = m_N \left[A^q (m_N^2 g^{\mu\nu} - P^\mu P^\nu) + B^q P^\mu P^\nu\right]$$

Semi-inclusive deep inelasitc scattering



T. B. Hayward et al., Phys. Rev. Lett. 126, 152501 (2021).
A. Courtoy, A. S. Miramontes, H. Avakian, M. Mirazita, and S. Pisano, Phys. Rev. D 106, 014027 (2022).

$$\bar{g}_0 = (\tilde{d}_u + \tilde{d}_d) \times \begin{cases} +1.7 \\ -1.0 \end{cases} \mathrm{GeV}^2$$

$$\bar{g}_1 = -(\tilde{d}_u - \tilde{d}_d) \times \begin{cases} -1.5 \\ -9.6 \end{cases} \mathrm{GeV}^2$$

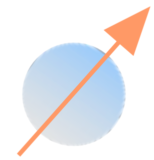
*Need more precise values by LQCD

Collaboration with D. Pefkou and A. Walker-Loud (CalLat)

Summary

One open question : The Baryon Asymmetry of the Universe

✔ New CP violation is necessary : EDM searches



$-d_{\mathrm{EDM}}\, \mathbf{E} \cdot \mathbf{s}$

- Multi-species EDM searches are essential to probe new CPV.
- New CPV source is severely constrained by electron EDM searches.
- Some parameter space for the successful BAU are now excluded by eEDM limits.

  *Multiple phases / Alignment limit in EWBG G2HDM / Other mechanisms

- Theoretical challenge first arises from the nonperturbative effect of the QCD.

  *Need a first-principle method, i.e., lattice QCD calculations

Thank you for your attention.