LA-UR-24-25200

Theory of Electric Dipole Moments

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Baryon asymmetry

One open question in our Universe:

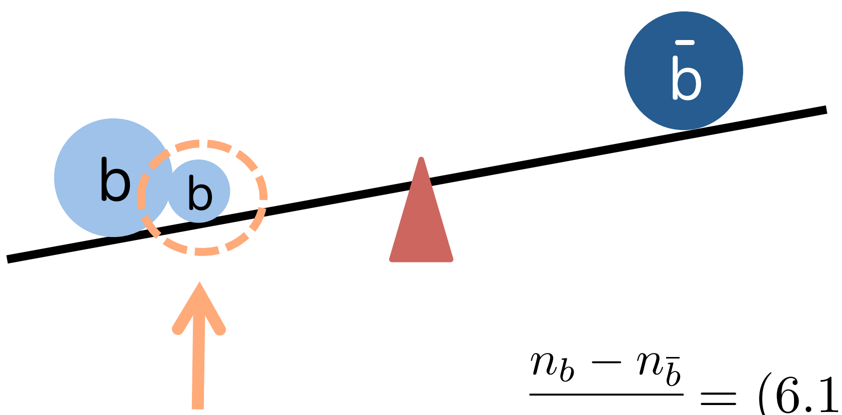
The Baryon Asymmetry of the Universe (BAU)

Baryon

$$10^{10} + 1$$

Antibaryon

$$10^{10}$$



Left in the present Universe

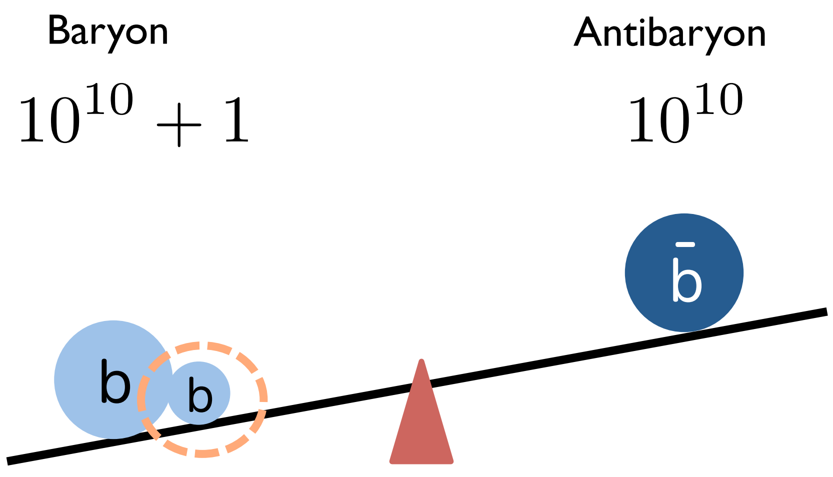
$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.105 \pm 0.055) \times 10^{-10}$$

PDG: PTEP(2020)083C01

Baryon asymmetry

One open question in our Universe:

The Baryon Asymmetry of the Universe (BAU)



One necessary condition to create the BAU : CP violation (CPV)

Electric Dipole Moments

Electric Dipole Moment is CPV quantity :

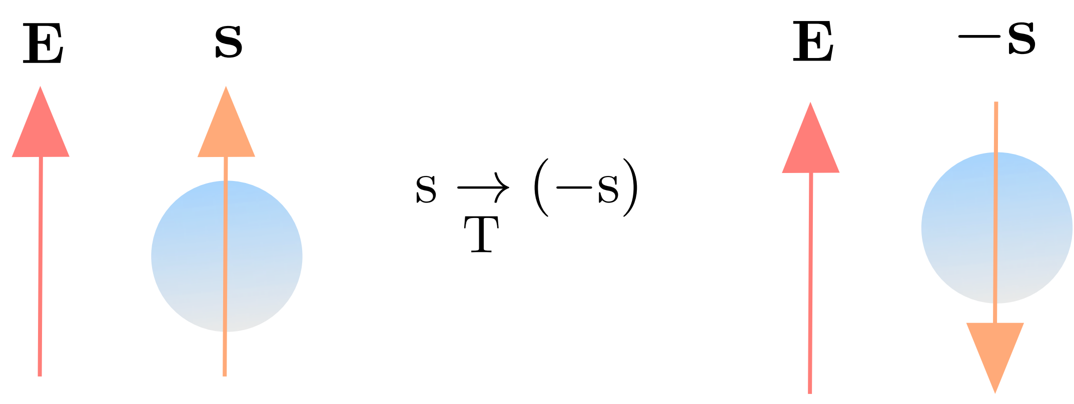
$$H_{\rm EDM} = -d_f \frac{\mathbf{s}}{|\mathbf{s}|} \cdot \mathbf{E}$$

$\mathbf{E}$: Electric field

$\mathbf{s}$: Spin

Violation of Time-reversal symmetry

CP violation under CPT theorem



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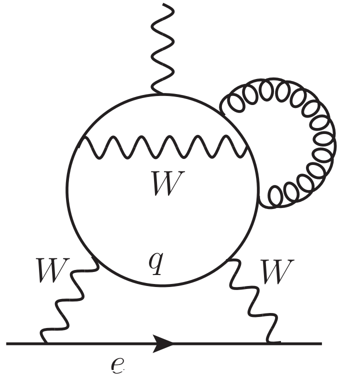

Ex) Electron EDM in the SM (4 loop)

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

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
Y. Yamaguchi and N. Yamanaka, PRL125(2020)241802

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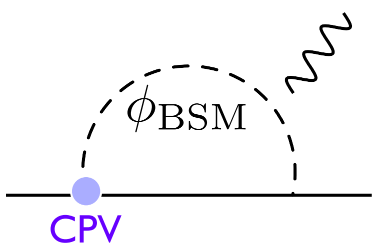
Violation of Time-reversal symmetry

CP violation under CPT theorem

e.g., 1-loop



$$d_e^{\rm BSM} \gg d_e^{\rm CKM}$$

*Lower loop level in BSM Physics

$$d_f \sim (10^{-16}\ e\ {\rm cm}) \times \left(\frac{v}{\Lambda_{\rm BSM}}\right)^2 \times \sin\phi_{\rm new} \times y_f\ F_{\rm loop}$$

Large enough for BAU

Electric Dipole Moments

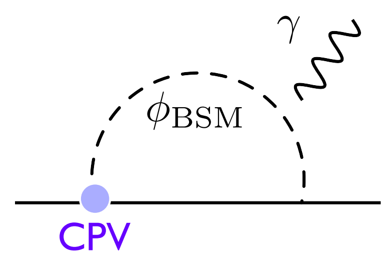
See more details in Pospelov and Ritz: 0504231

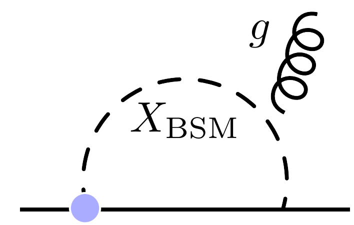
Energy

CP violation in underlying physics

e.g., QCD Theta — EDM — Chromo EDM

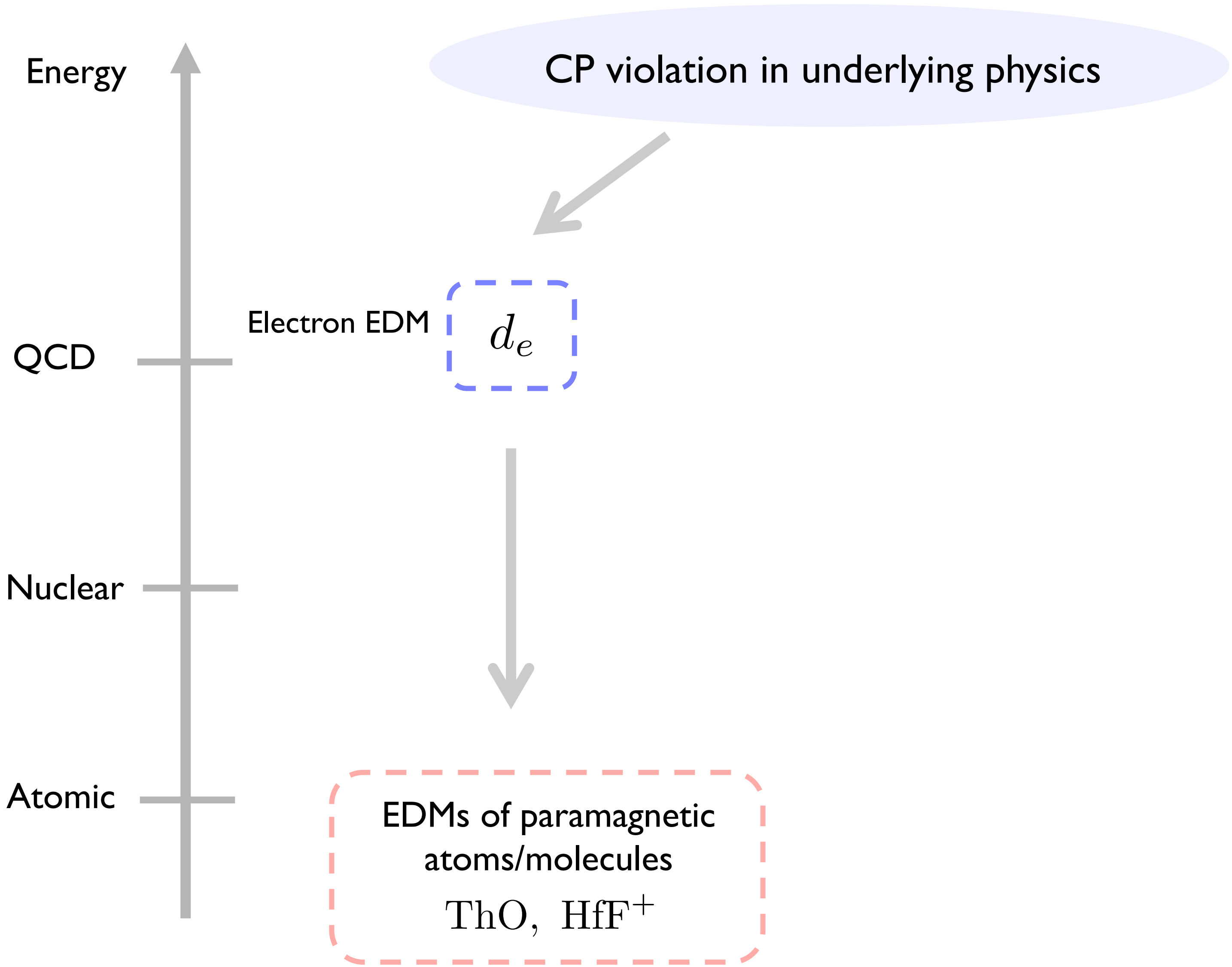
$$\mathcal{L} \supset \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{i}{2} d_f \bar{f} \sigma^{\mu\nu}\gamma_5 f F_{\mu\nu} - \frac{i}{2}\tilde{d}_f g_s \bar{f}\sigma^{\mu\nu}\gamma_5 T^A f G^A_{\mu\nu}$$





Electric Dipole Moments

See more details in Pospelov and Ritz: 0504231



Electric Dipole Moments

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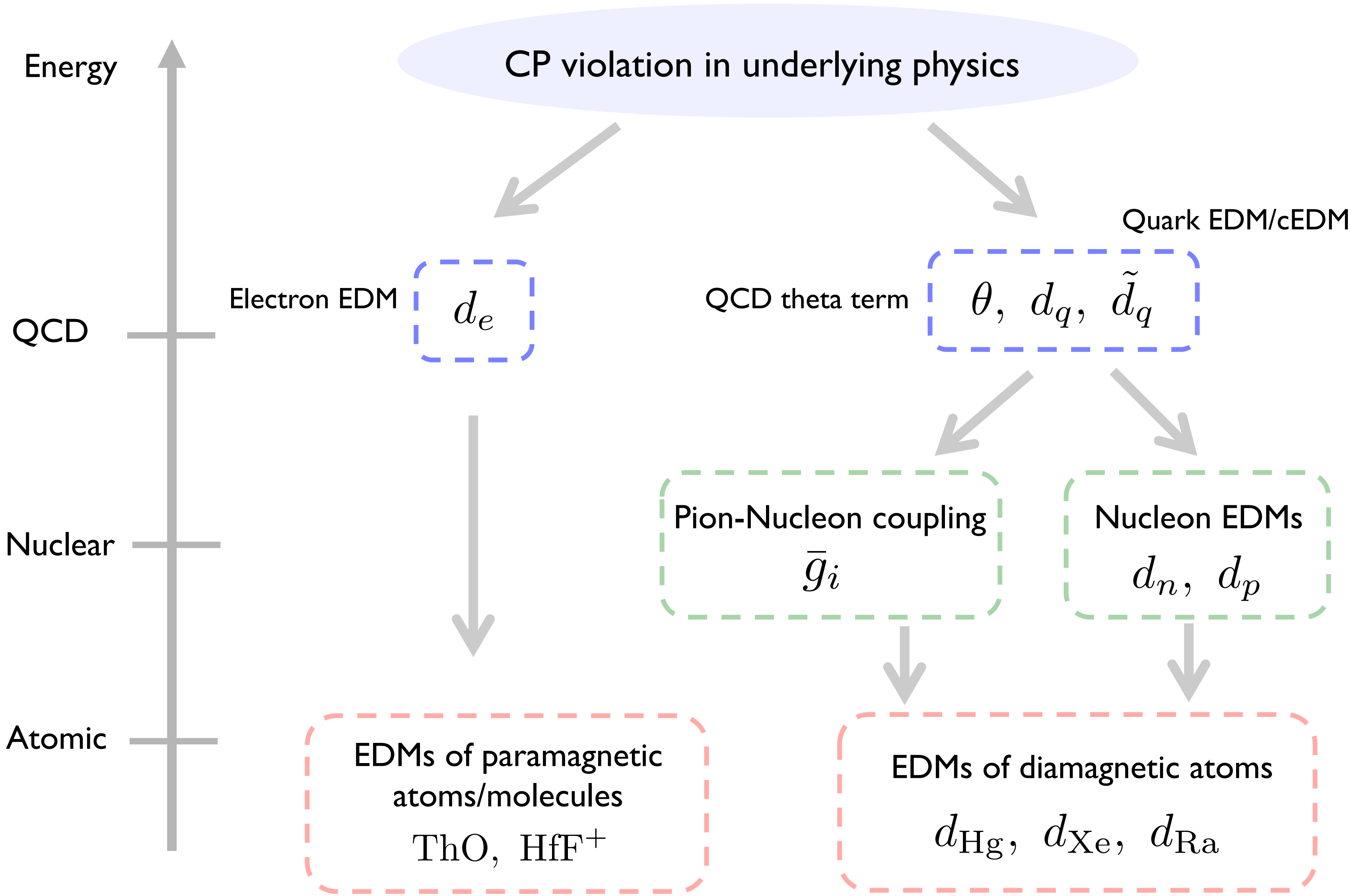
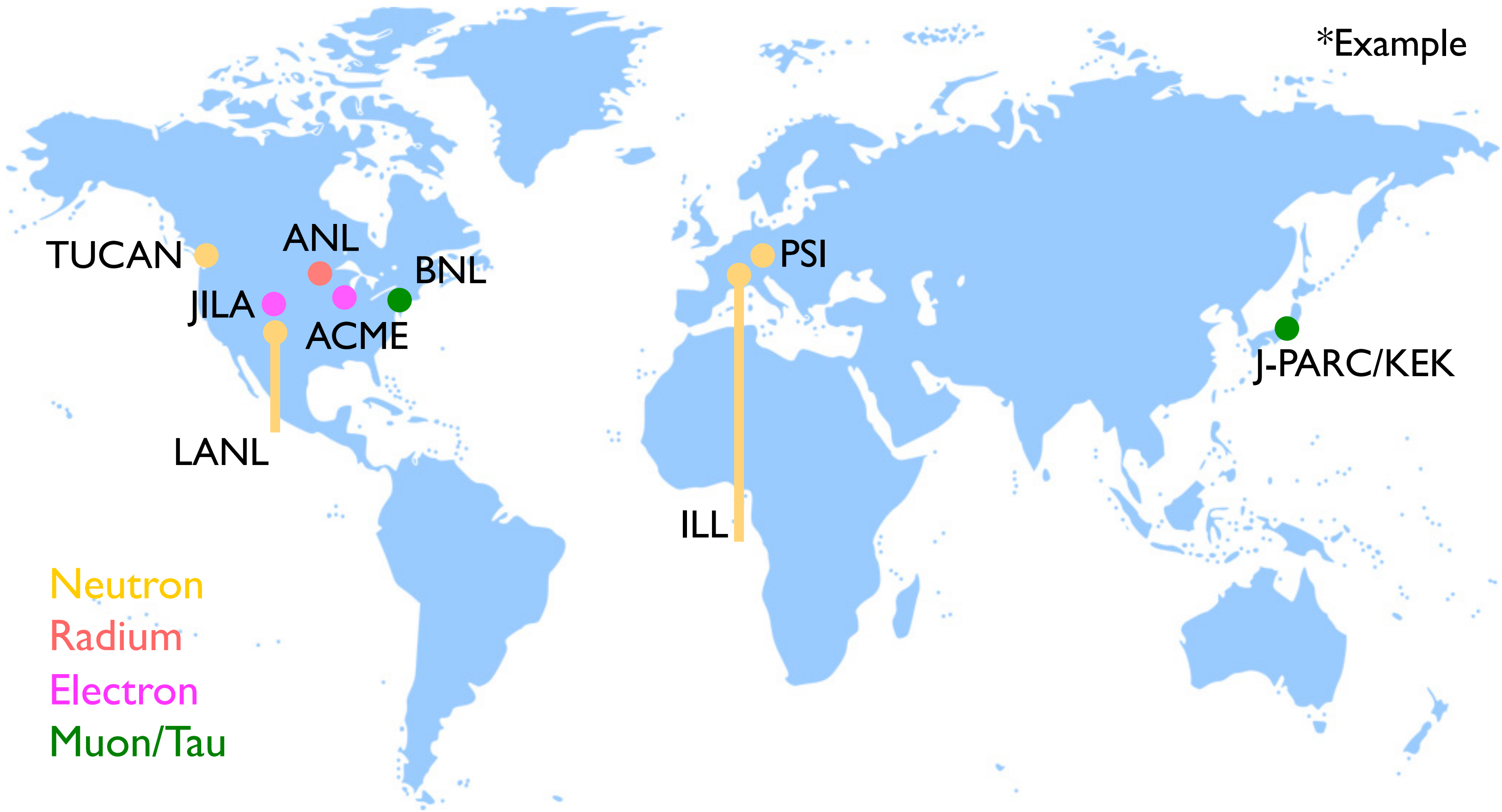


Searches for EDMs

See more info: EDMs world wide
https://www.psi.ch/en/nedm/edms-world-wide

Various searches for EDMs are ongoing and planned.



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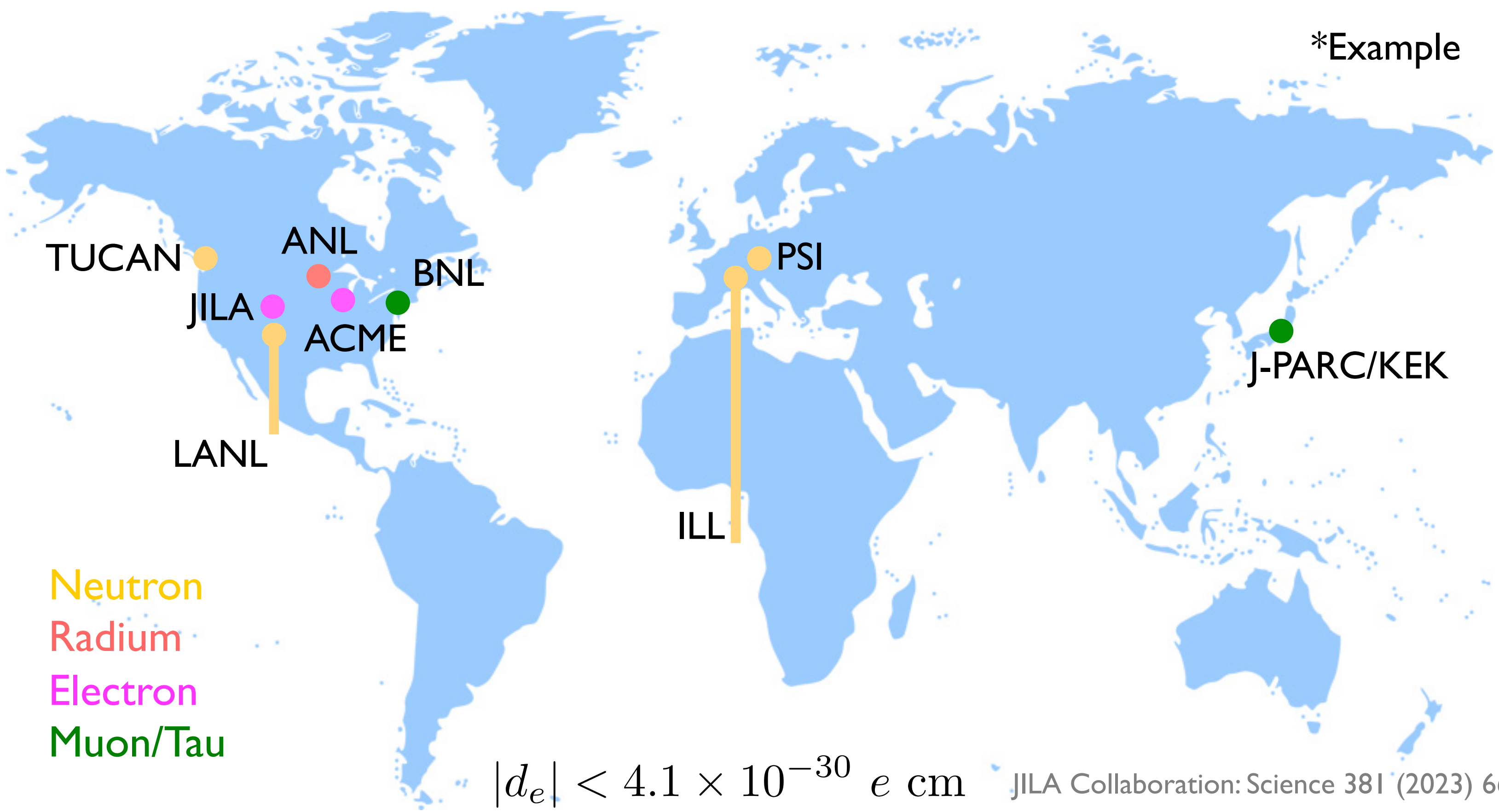

$|d_e| < 4.1 \times 10^{-30}\ e\ \mathrm{cm}$ JILA Collaboration: Science 381 (2023) 6653

$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$ nEDM Collaboration, PRL124(2020)081803

Electron EDM

Polar molecule systems are sensitive to leptonic CPV:

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

Electron EDM e-N interaction

Electron EDM

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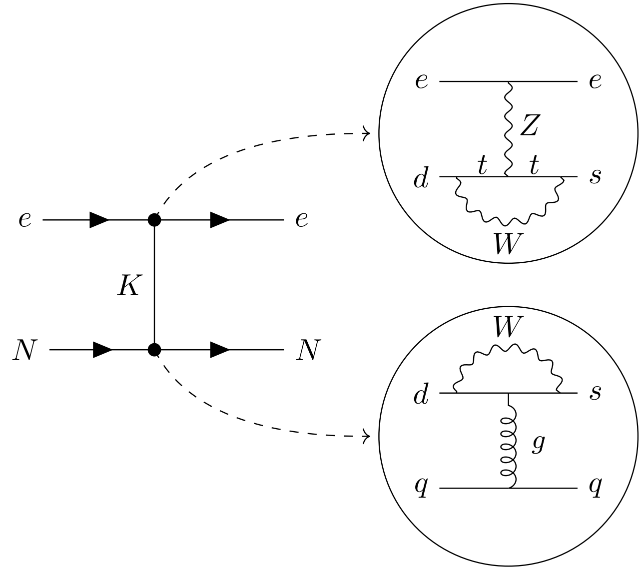
Electron EDM — e-N interaction

✔ CKM contribution to C_S at EW^3 order

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

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

$$d_e^{\rm equiv} = 1.0 \times 10^{-35} \; e \; {\rm cm}$$



*Dominant SM contribution to paramagnetic EDMs

Electron EDM

Polar molecule systems are sensitive to leptonic CPV:

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

Electron EDM　　　　e-N interaction

Spin precession frequency :

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

$E_{\rm eff}$: Effective electric field

W_S : Molecule constant

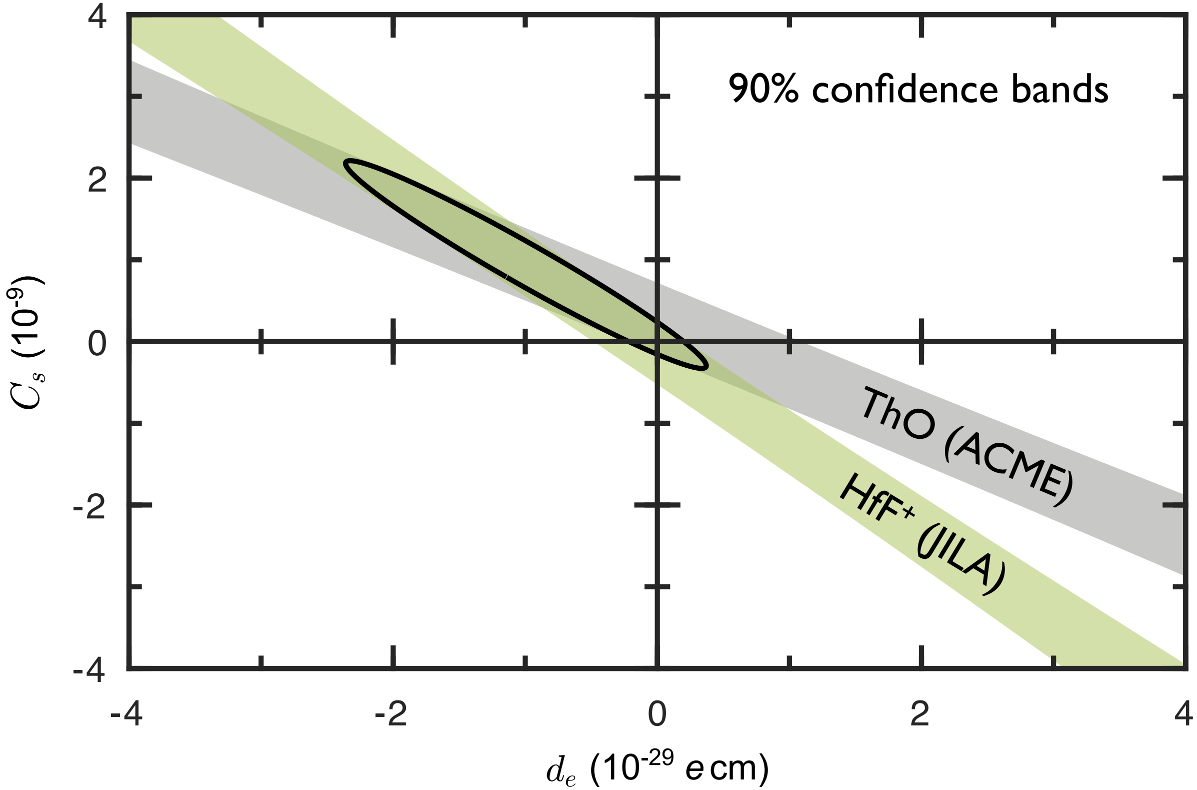
System	$E_{\rm eff}$ [GV cm^{-1}]	W_S [kHz]
ThO (ACME)	78	-282
HfF^+ (JILA)	23	-51

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

JILA Collaboration: Science 381 (2023) 6653



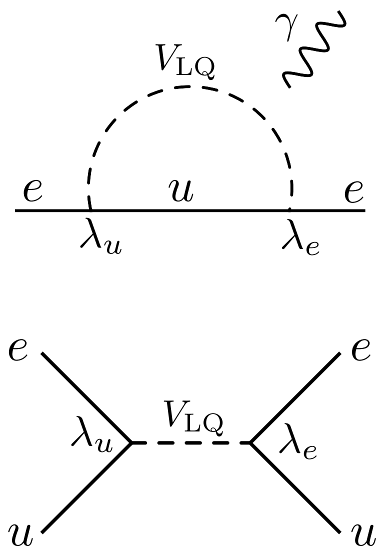
Combined Fit : $|d_e| < 2.1 \times 10^{-29}\ e\ \text{cm}$ $|C_S| < 1.9 \times 10^{-9}$

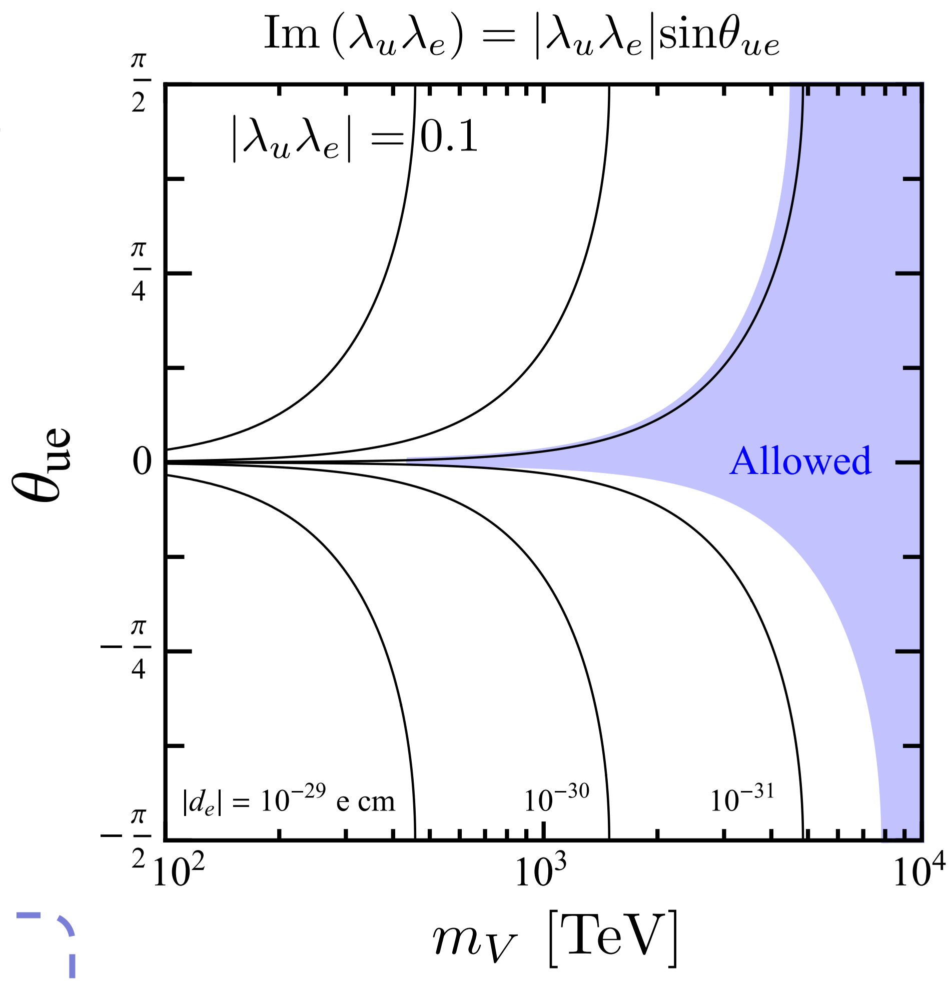
*Sole-source limit $10^3\ \text{TeV} \lesssim \Lambda_{\text{BSM}}$ $10^4\ \text{TeV} \lesssim \Lambda_{\text{BSM}}$

Implication for BSM

Ex) Scalar Leptoquark Model

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





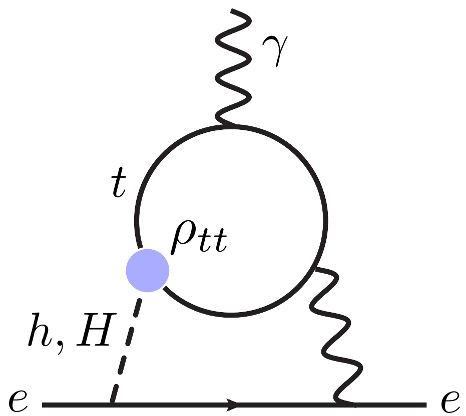
$$\frac{d_e}{C_S} \sim \mathcal{O}(10^{-2}) \quad |d_e| \lesssim 10^{-31}\ e\ \mathrm{cm}$$

Implication for Baryogenesis

Electroweak Baryogenesis in General Two Higgs Doublet Model

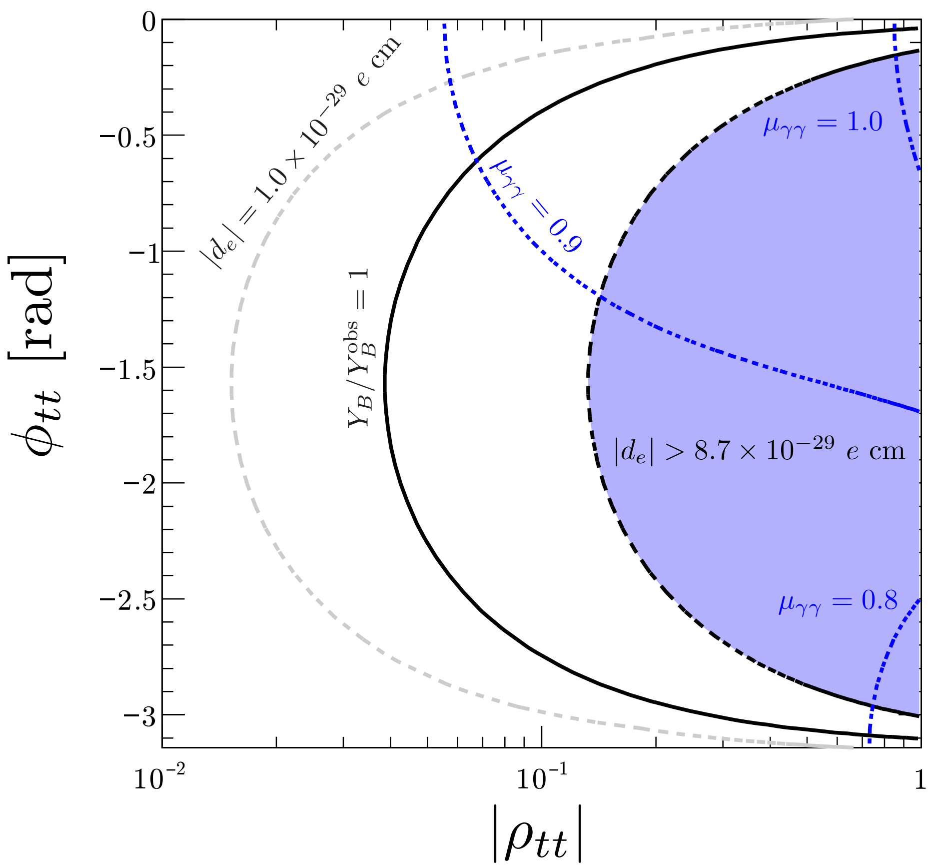
KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

CPV Top Yukawa



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

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



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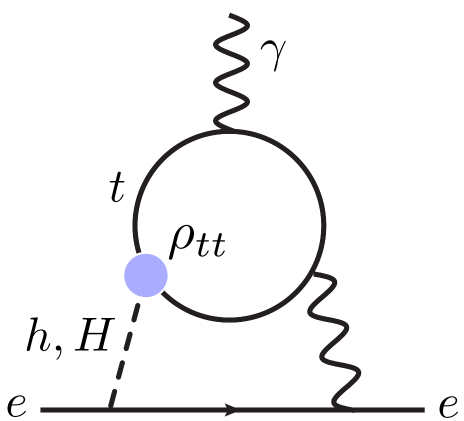
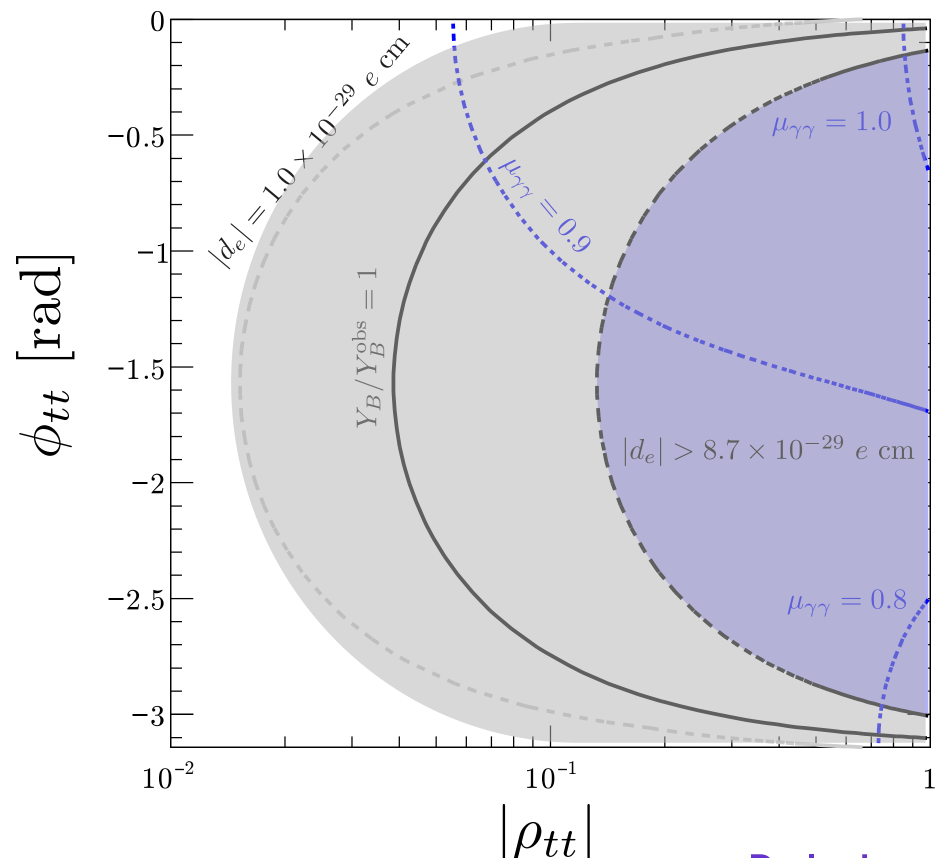


$d_e \propto |\rho_{tt}| \sin\phi_{tt}$

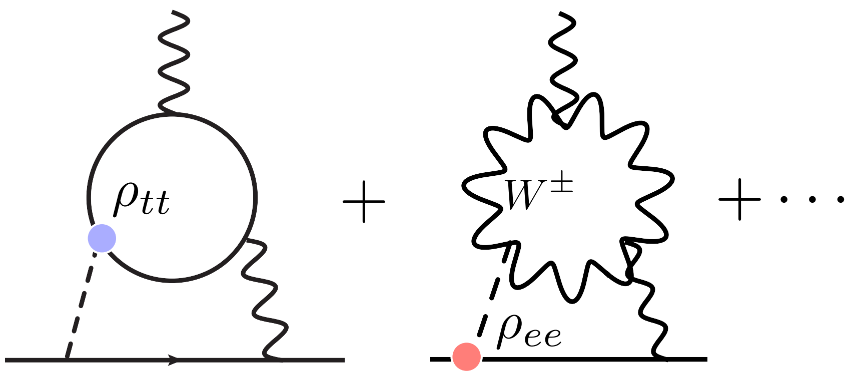


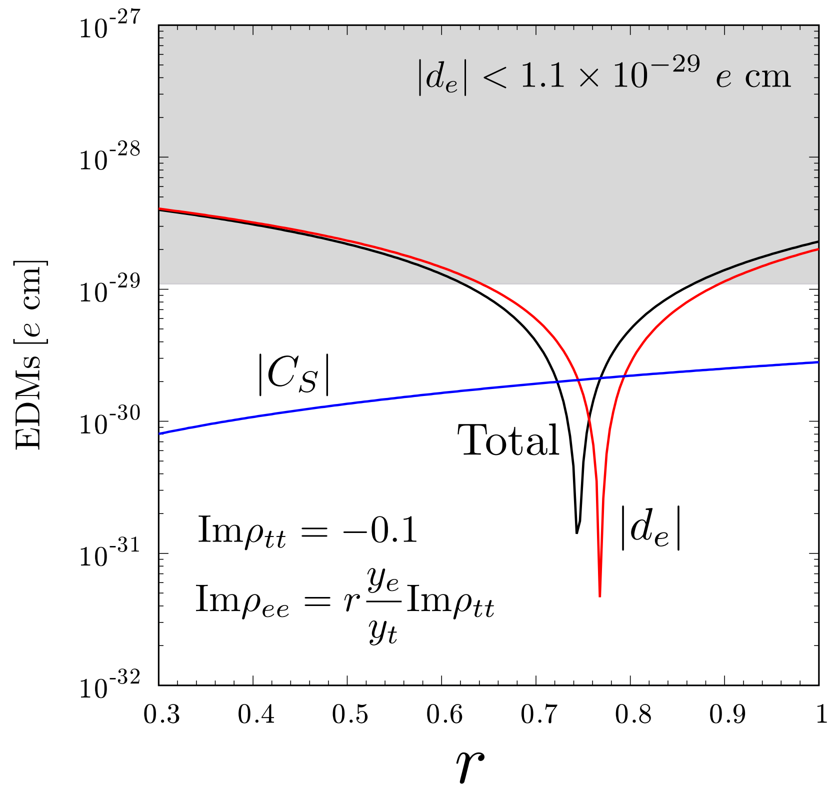
Ruled out.

Implication for Baryogenesis

Electroweak Baryogenesis in General Two Higgs Doublet Model

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





Cancellation occurs : $d_e = 0$

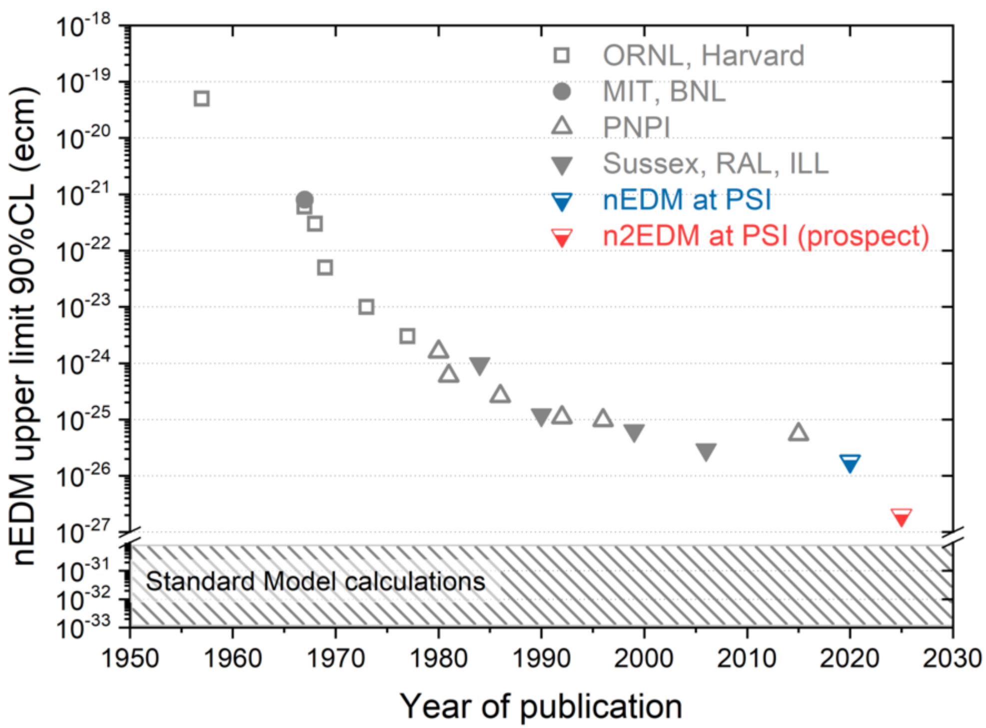
2HDM EWBG is still viable.

Other EDM searches are significant!

Neutron EDM

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

A worldwide race is on-going!



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

nEDM Collaboration, PRL124(2020)081803

*A factor of 10 improvement

$$d_n \sim \mathcal{O}(10^{-27})\ e\ \mathrm{cm}$$

n2EDM PRA103(2021)6, 062801
LANL : PRC97(2018)1, 012501

Contributions from various fundamental CPV interactions : $d_n(\theta, d_q, \tilde{d}_q, \cdots)$

*Need treatments of nonperturbative effects

Neutron EDM

QCD Theta : $\mathcal{L} \supset \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$

$$d_n(\theta, d_q, \tilde{d}_q, \cdots) = -(1.5 \pm 0.7) \times 10^{-3}\ \theta\ e\ \text{fm}$$

J. Dragos, T. Luu, A. Shindler, J. de Vries, and A. Yousif, PRC103(2021)015202

Various lattice-QCD groups have been making progress.

Recent Lattice QCD calculations	
Dragos 2019	$d_n = -0.00152(71)\ \theta\ e$ fm
Bhattacharya 2021	$d_n = -0.003(7)(20)\ \theta\ e$ fm
Bhattacharya 2021 with $N\pi$	$d_n = -0.028(18)(54)\ \theta\ e$ fm
Liang 2023	$d_n = -0.00148(14)(31)\ \theta\ e$ fm

Neutron EDM

Quark EDM and cEDM : $\mathcal{L} \supset -\frac{i}{2} d_q \bar{q} \sigma^{\mu\nu} \gamma_5 q F_{\mu\nu} - \frac{i}{2} \tilde{d}_q g_s \bar{q} \sigma^{\mu\nu} \gamma_5 T^A q G_{\mu\nu}$

$$d_n(\theta, d_q, \tilde{d}_q, \cdots) = g_T^u d_u + g_T^d d_d$$

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

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

Neutron EDM

Quark EDM and cEDM : $\mathcal{L} \supset -\frac{i}{2} d_q \bar{q} \sigma^{\mu\nu} \gamma_5 q F_{\mu\nu} - \frac{i}{2} \tilde{d}_q g_s \bar{q} \sigma^{\mu\nu} \gamma_5 T^A q G_{\mu\nu}$

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

$$+ (1 \pm 0.5) \times \left[1.1 e \left(\tilde{d}_d + 0.5 \tilde{d}_u \right) \right]$$

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

*No lattice results available for chromo EDMs

EDMs of Diamagnetic Atoms

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

System	Current	Expected
^{199}Hg	6.2×10^{-17} e fm	—
^{225}Ra	1.2×10^{-10} e fm	$\sim 10^{-15}$ fm
^{129}Xe	1.4×10^{-14} e fm	$\sim 10^{-15}$ fm @LANL

EDMs of Diamagnetic Atoms

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

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@LANL

$$\text{Ex)}\quad d_{\rm Ra} = (7.7\times10^{-4})\times[(2.5\pm7.5)\bar{g}_0 - (65\pm40)\bar{g}_1]\,e\ \text{fm}$$

Prog.Part. Nucl. Phys. 71, 21 (2013).
PRL121(2018)232501

Pion-Nucleon couplings : $\bar{g}_i(\theta, \tilde{d}_q, \cdots)$

$$\mathcal{L} \supset \bar{g}_0\bar{N}\tau\cdot\pi N + \bar{g}_1\bar{N}\pi^3 N$$

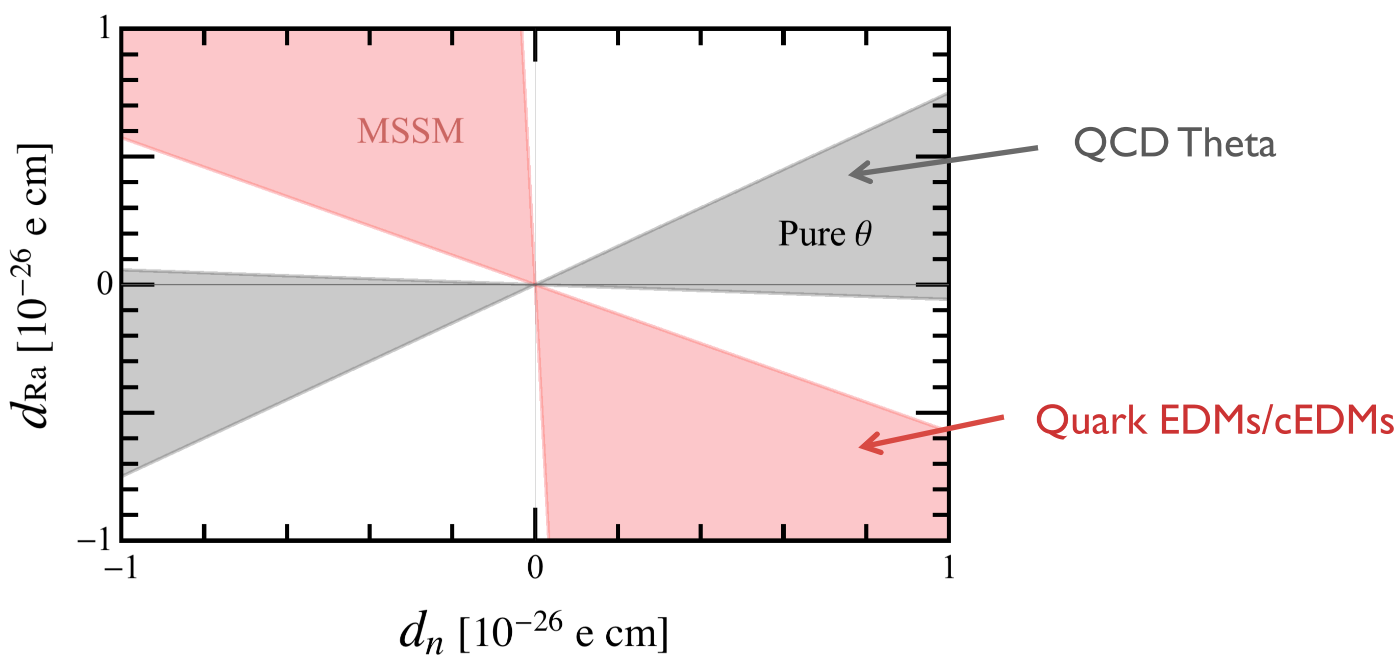
J. de Vries, et al, PRC 92, 045201 (2015)
M. Pospelov, PLB530(2002)123
J. de Vries, et al , PLB 766, 254 (2017)
C.-Y. Seng, PRL122, 072001 (2019)

*No direct LQCD calculations

Distinctive patters of EDMs

J. de Vries, P. Draper, **KF**, B. Lillard,
PRD104(2021)055039

Neutron vs Radium EDM



The prediction of $d_{\rm Ra}/d_n$ is different depending on underlying CPV interactions.

Importance of multi-species EDM searches!

Summary

One Big Mystery : The Baryon Asymmetry of the Universe

✔ New CP violation is necessary : EDM searches

- New CPV source is severely constrained by electron EDM searches.

- Successful parameter space for BAU can be now excluded.

  *Multiple phases and Models without EDMs

- Distinctive patterns of EDMs depending on CPV interactions.

✔ Multi-species EDM searches and Reduction of Theoretical Uncertainties