Electric dipole moment and CP violation in many-body systems

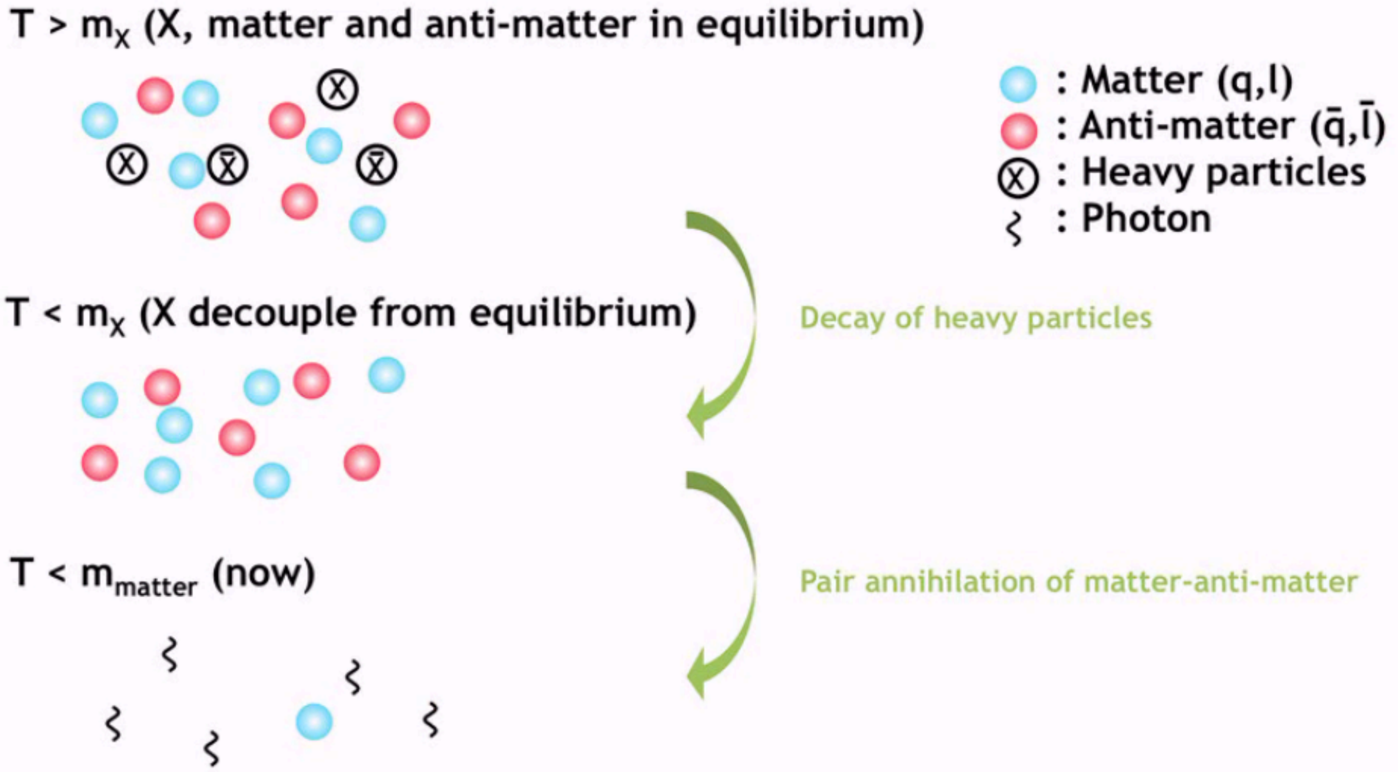
Nodoka Yamanaka
(Kennesaw State University/Riken)

Based on
NY, Int. J. Mod. Phys. E 26, 1730002 (2017);
NY, B. K. Sahoo, N. Yoshinaga, T. Sato, K. Asahi, B. P. Das, Eur. Phys. J. A 53, 54 (2017);
NY, PoS SPIN 2018, 094 (2019) [arXiv:1902.00527 [hep-ph]].

2021/04/21
KEK

Why did antimatter disappear (baryon number excess)?

Asymmetric decays generates excess of matters in the early Universe



$T > m_X$ (X, matter and anti-matter in equilibrium)

● : Matter (q, l)
● : Anti-matter $(\bar{q}, \bar{l})$
⊗ : Heavy particles
≀ : Photon

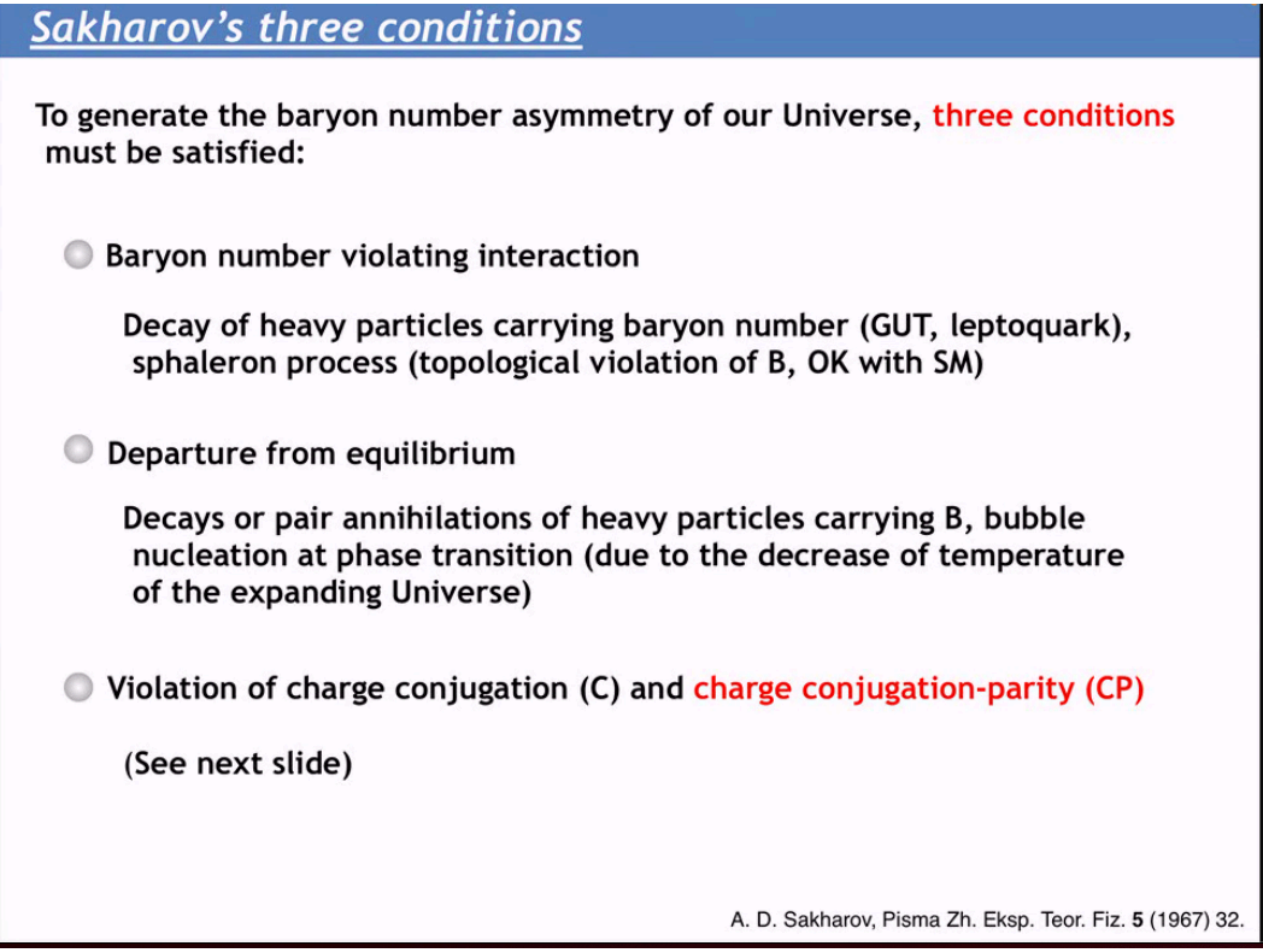
$T < m_X$ (X decouple from equilibrium)

Decay of heavy particles

$T < m_{matter}$ (now)

Pair annihilation of matter-anti-matter

➡ **Matter/photon ratio is a direct signature of baryon number asymmetry**



Sakharov's three conditions

To generate the baryon number asymmetry of our Universe, three conditions must be satisfied:

- Baryon number violating interaction

  Decay of heavy particles carrying baryon number (GUT, leptoquark), sphaleron process (topological violation of B, OK with SM)

- Departure from equilibrium

  Decays or pair annihilations of heavy particles carrying B, bubble nucleation at phase transition (due to the decrease of temperature of the expanding Universe)

- Violation of charge conjugation (C) and charge conjugation-parity (CP)

  (See next slide)

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32.

C, CP violations and baryon number asymmetry

P, C and CP transformation of initial & final states:

$$\begin{tikzcd}
f_L f'_L \arrow[r, leftrightarrow, "C"] \arrow[d, leftrightarrow, "P"'] \arrow[dr, leftrightarrow] & \bar{f}_L \bar{f}'_L \arrow[d, leftrightarrow, "P"] \arrow[dl, leftrightarrow, "CP"'] \\
f_R f'_R \arrow[r, leftrightarrow, "C"'] & \bar{f}_R \bar{f}'_R
\end{tikzcd}$$

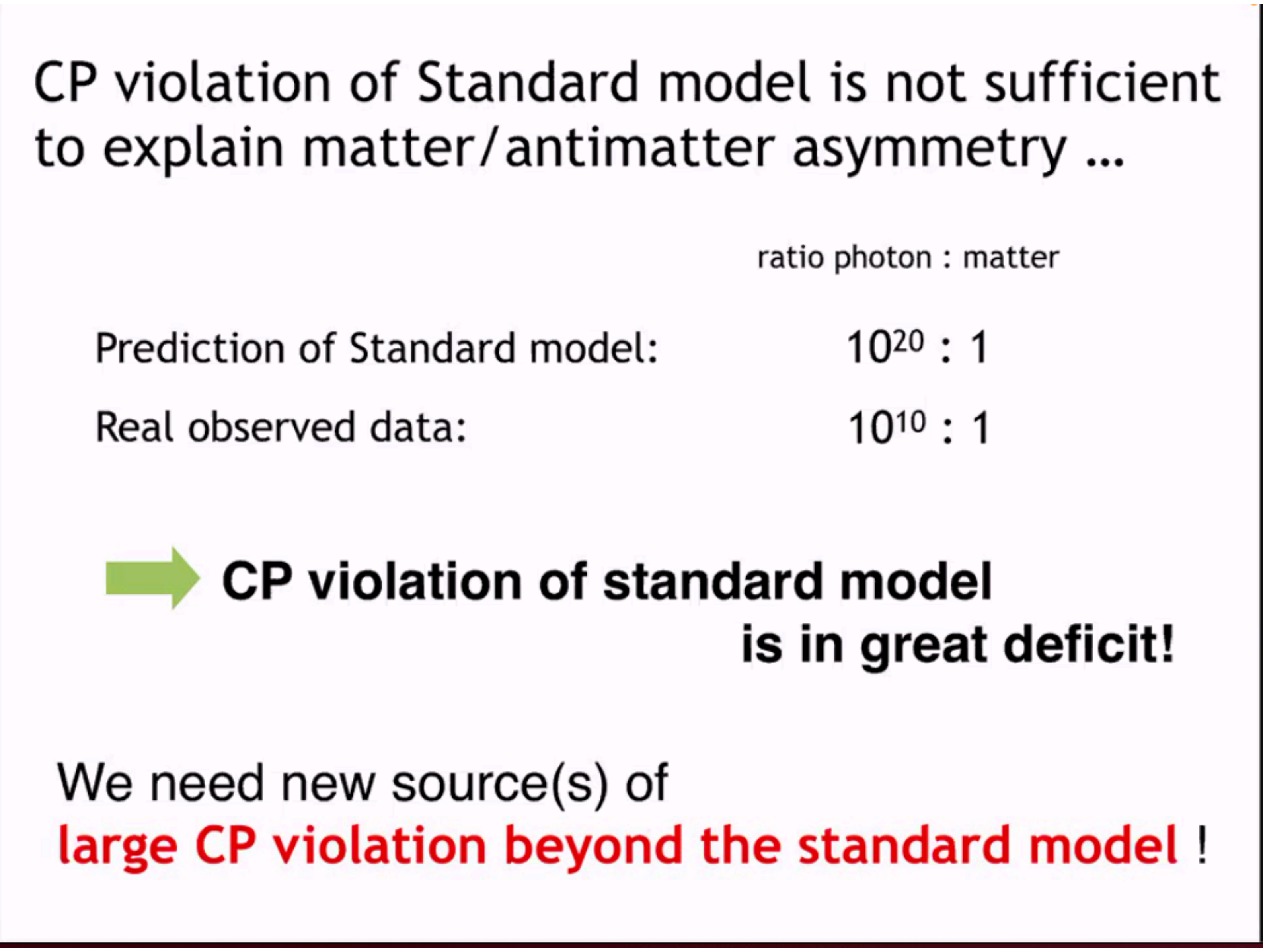
$$\begin{tikzcd}
X \arrow[r, leftrightarrow, "{C,\ CP}"] & \bar{X}
\end{tikzcd}$$

Baryon number asymmetry:

$$\epsilon \propto \Gamma(X \to f_L f'_L) + \Gamma(X \to f_R f'_R) - \Gamma(\bar{X} \to \bar{f}_L \bar{f}'_L) - \Gamma(\bar{X} \to \bar{f}_R \bar{f}'_R)$$

Similar relations hold for decays of other particles, other interactions

➡ **C & CP violations are both needed for baryon number asymmetric decays**



CP violation of Standard model is not sufficient to explain matter/antimatter asymmetry …

	ratio photon : matter
Prediction of Standard model:	$10^{20} : 1$
Real observed data:	$10^{10} : 1$

➡ **CP violation of standard model is in great deficit!**

We need new source(s) of
large CP violation beyond the standard model !

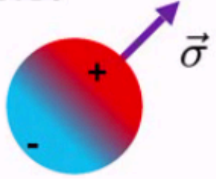
Electric dipole moment (EDM)

Electric dipole moment:

Permanent polarization of internal charge of a particle.

$$\vec{d}_\psi = \sum_i \langle \psi | Q_i e \vec{r}_i | \psi \rangle$$

⇒ This is what will be evaluated!



- **Direction:** $\vec{d} \propto \vec{\sigma}$
  (Spin is the only vector quantity in spin ½ particle)
- **Interaction:** $H_{\text{EDM}} = -d \, \langle \vec{\sigma} \rangle \cdot \vec{E}$
- **Transformation properties:**
  - Under parity tr.: $\begin{cases} \vec{E} \xrightarrow{\text{P}} -\vec{E} \\ \vec{\sigma} \xrightarrow{\text{P}} \vec{\sigma} \end{cases}$ → H_{EDM} is P-odd
  - Under time reversal: $\begin{cases} \vec{E} \xrightarrow{\text{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\text{T}} -\vec{\sigma} \end{cases}$ → H_{EDM} is CP-odd !

Experimental principle of EDM measurement (neutral sys.)

EDM and magnetic moment parallel to particle spin: $\vec{d}, \vec{\mu} \propto \vec{\sigma}$

➡ **Difference of spin precession frequency with parallel & opposite B and E in the presence of EDM!!**

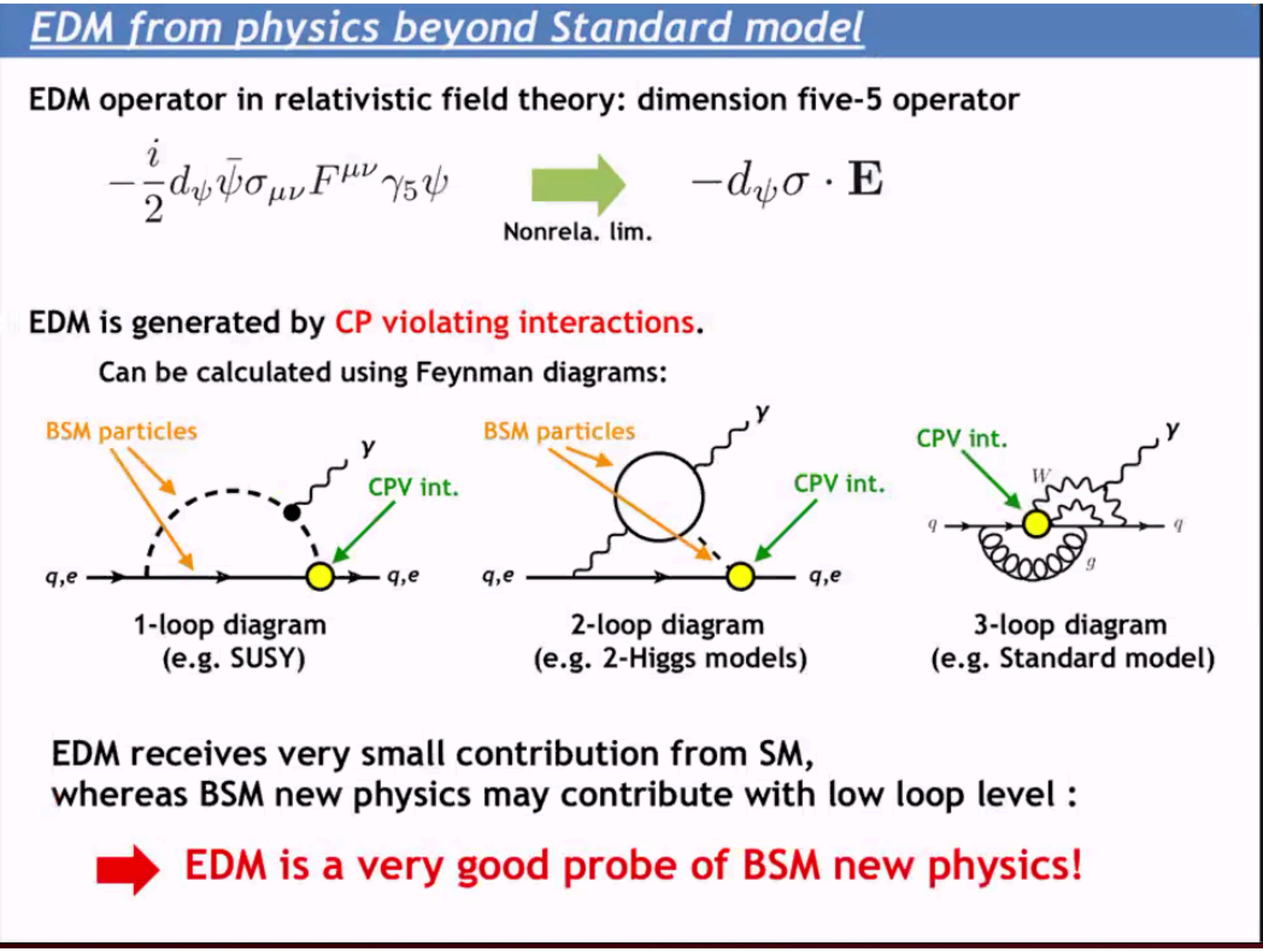
$\omega_{\uparrow\uparrow} = 2(\mu B + dE)/\hbar$

$\omega_{\uparrow\downarrow} = 2(\mu B - dE)/\hbar$

Measured EDM:

$$d = \frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})$$

Required Skills:
- Particle density
- Polarization of particles
- Long coherence time
- Strong electric field
- ...



EDM from physics beyond Standard model

EDM operator in relativistic field theory: dimension five-5 operator

$$-\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \xrightarrow[\text{Nonrela. lim.}]{} -d_\psi \sigma \cdot \mathbf{E}$$

EDM is generated by CP violating interactions.

Can be calculated using Feynman diagrams:

1-loop diagram
(e.g. SUSY)

2-loop diagram
(e.g. 2-Higgs models)

3-loop diagram
(e.g. Standard model)

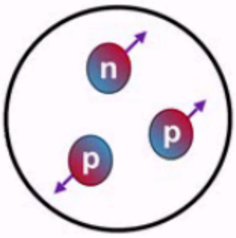
EDM receives very small contribution from SM,
whereas BSM new physics may contribute with low loop level :

➡ EDM is a very good probe of BSM new physics!

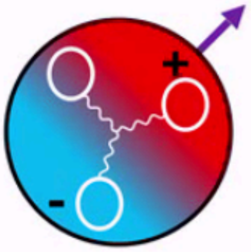
EDM of composite systems

The EDM is often measured in composite systems (neutron, atoms, molecules, nuclei)

The EDM of composite systems is not only generated by the EDM of the components, but also by CP violating many-body interactions.

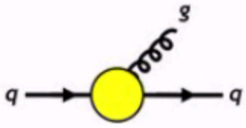


EDM of constituents

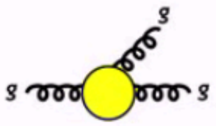


CP-odd many-body interaction

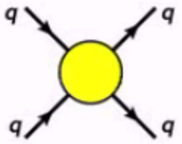
Example of QCD level many-body interactions inducing neutron EDM:



quark chromo-EDM



Weinberg operator



P, CP-odd 4-quark interaction

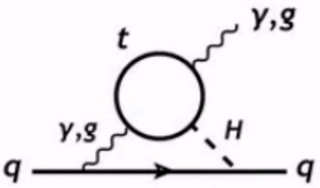
Effect of CPV many-body interaction may be enhanced/suppressed!

Elementary level CP violation and its origin

All these processes scale as $1/M_{NP}^2$

- **Quark EDM, chromo-EDM:**

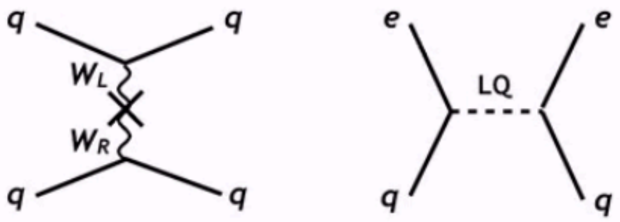
SUSY: 1-loop



2-Higgs doublet: 2-loop

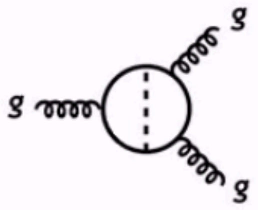
- **CP-odd 4-fermion interaction:**

  Tree level:
  * Left-right sym.
  * Scalar exchange (e.g. Higgs)
  * Leptoquarks



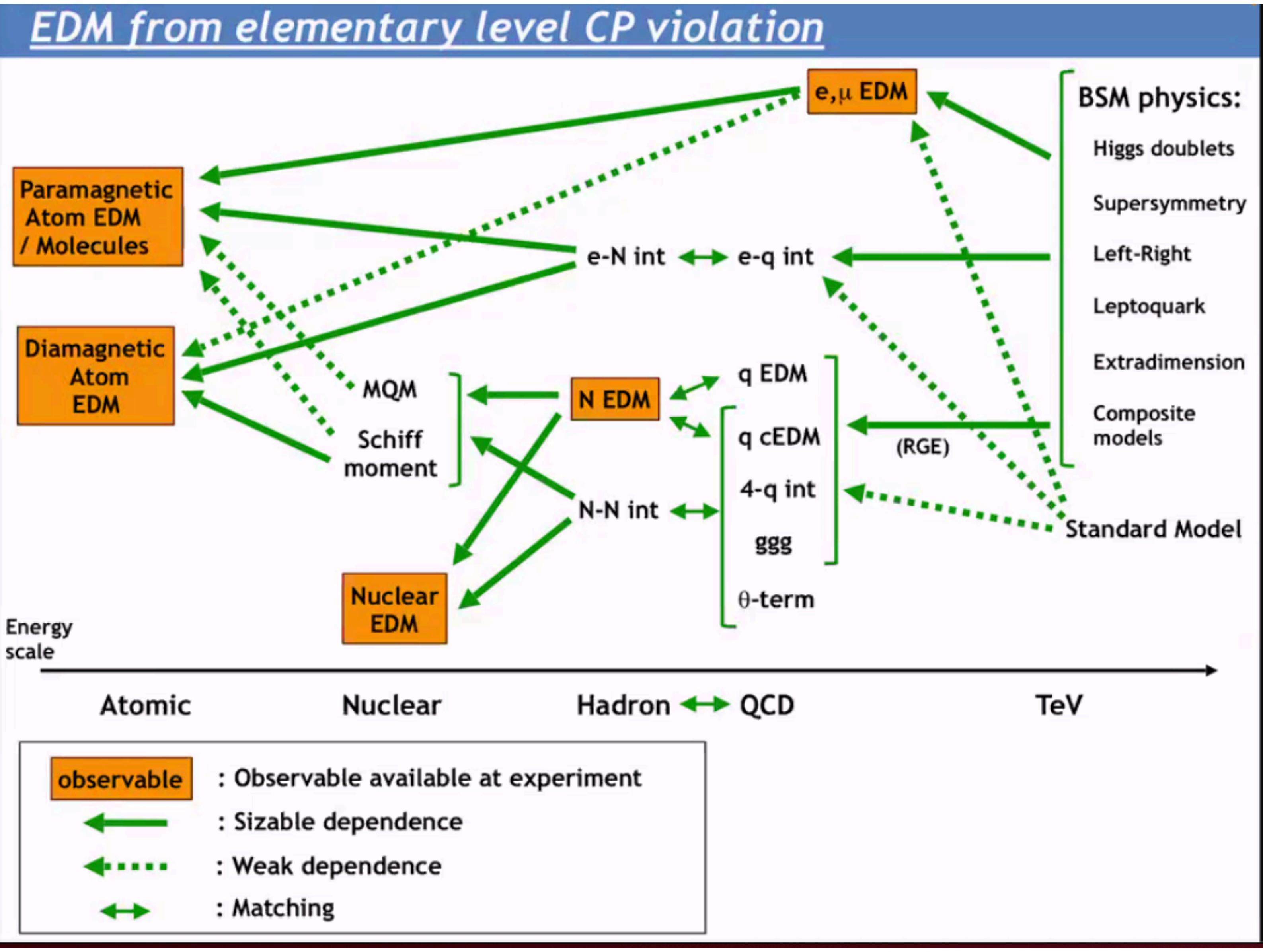
- **Weinberg operator:**

  2-loop diagram:
  * 2-Higgs doublet model
  * Vectorlike quark model



Probe BSM sectors
without LO interaction
with light quarks

EDM from elementary level CP violation



e,μ EDM

BSM physics:
- Higgs doublets
- Supersymmetry
- Left-Right
- Leptoquark
- Extradimension
- Composite models

Paramagnetic Atom EDM / Molecules

Diamagnetic Atom EDM

e-N int ↔ e-q int

MQM

Schiff moment

N EDM

N-N int

Nuclear EDM

q EDM

q cEDM

4-q int

ggg

θ-term

(RGE)

Standard Model

Energy scale

Atomic — Nuclear — Hadron ↔ QCD — TeV

observable : Observable available at experiment

← : Sizable dependence

←⋯ : Weak dependence

↔ : Matching

What is better in EDM experiments

⇒ Elementary level CPV is unknown and small : can be factorized

Unknown CP violating couplings beyond the standard model

$$d_A = (a_\pi^{(0)}\,\bar{G}_\pi^{(0)} + a_\pi^{(1)}\,\bar{G}_\pi^{(1)})\ e\,\mathrm{cm} + K_e\, d_e + \dots$$

Depends on the structure of the system!

⇒ Linear coefficients depends only on the structure of the system, not in NP

⇒ We want to evaluate coefficients and find interesting systems!

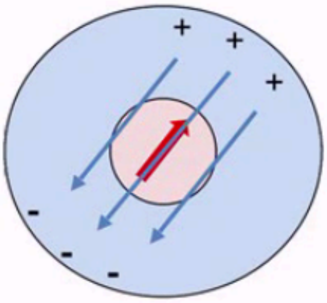
⇒ We want to find systems with large enhancement factors

(or understand and avoid suppression)

Atomic EDM and Schiff's screening

In atoms, EDM of nonrelativistic constituents suffers Schiff's screening

EDM of bare constituent



Atomic EDM :
screening via rearrangement

Typically, looses sensitivity by $\alpha_{QED}^2 \sim 10^{-4}$

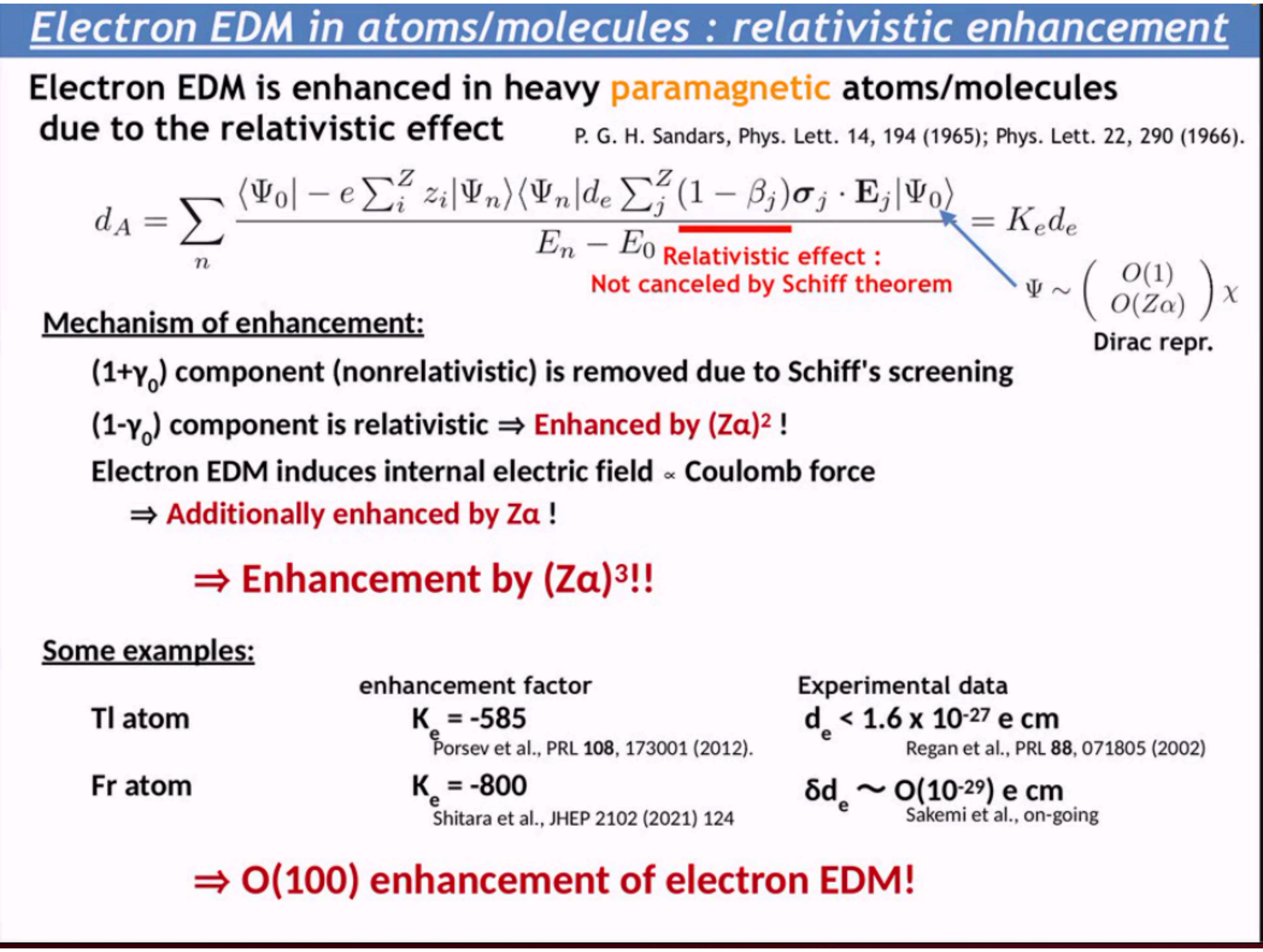
3(+1) leading P, CP-odd processes in atoms :

- **Relativistic effect of constituents (electrons in heavy atoms)**
- **CP-odd electron-nucleon interaction**
- **Schiff moment (residual nuclear moment due to nuclear finite size)**

L. I. Schiff, Phys. Rev. **132**, 2194 (1963).

- **Oscillating EDM of constituents (interaction with axion dark matter?)**

V. Flambaum et al., Phys. Rev. D **100**, 111301 (2019).



Electron EDM in atoms/molecules : relativistic enhancement

Electron EDM is enhanced in heavy paramagnetic atoms/molecules due to the relativistic effect

P. G. H. Sandars, Phys. Lett. 14, 194 (1965); Phys. Lett. 22, 290 (1966).

$$d_A = \sum_n \frac{\langle\Psi_0| -e\sum_i^Z z_i|\Psi_n\rangle\langle\Psi_n|d_e\sum_j^Z(1-\beta_j)\boldsymbol{\sigma}_j\cdot\mathbf{E}_j|\Psi_0\rangle}{E_n-E_0} = K_e d_e$$

Relativistic effect : Not canceled by Schiff theorem

$$\Psi \sim \begin{pmatrix} O(1) \\ O(Z\alpha) \end{pmatrix}\chi$$

Dirac repr.

Mechanism of enhancement:

$(1+\gamma_0)$ component (nonrelativistic) is removed due to Schiff's screening

$(1-\gamma_0)$ component is relativistic ⇒ Enhanced by $(Z\alpha)^2$!

Electron EDM induces internal electric field ∝ Coulomb force

⇒ Additionally enhanced by $Z\alpha$!

⇒ Enhancement by $(Z\alpha)^3$!!

Some examples:

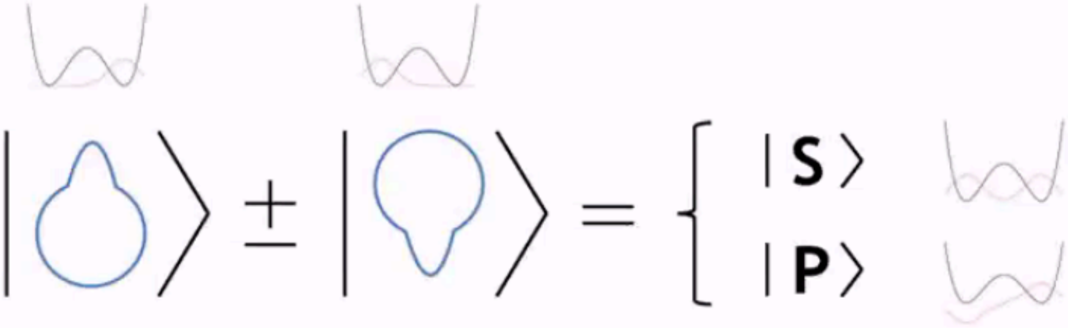
	enhancement factor	Experimental data
Tl atom	**$K_e = -585$** Porsev et al., PRL **108**, 173001 (2012).	**$d_e < 1.6 \times 10^{-27}$ e cm** Regan et al., PRL **88**, 071805 (2002)
Fr atom	**$K_e = -800$** Shitara et al., JHEP 2102 (2021) 124	**$\delta d_e \sim O(10^{-29})$ e cm** Sakemi et al., on-going

⇒ O(100) enhancement of electron EDM!

Enhancement in octupole systems: molecules, nuclei

Octupole deformed systems may enhance the CP violation by close opposite parity levels (parity doubling)

Each orientation corresponds to localized state in double well potential



Physical states are mixing between localized states

⇒ Nearly degenerate symmetric (S) and antisymmetric (P) states!

⇒ Close energy levels between opposite parity lead to enhancement!

Current electron EDM world record by ThO molecule : $d_e < 1.1 \times 10^{-29}$ e cm

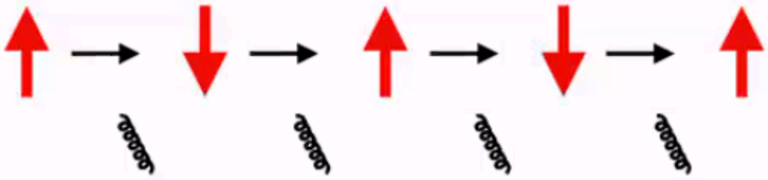
V. Andreev et al. [ACME Collaboration], Nature **562**, 355 (2018).

(parity doubling also occurs in heavy nuclear systems, see later)

Enhancement/suppression mechanism : scalar and spin

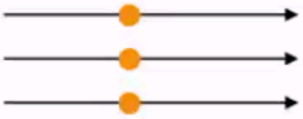
- **Spin (tensor, axial charges) : suppression**

In many-fermion system, spin tends to form singlet (pairing) : no enhancement

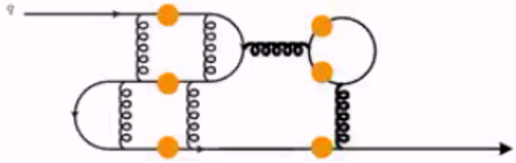


Quark EDM is a superposition of flipping after gluon emissions/absorptions
⇒ Quark EDM is suppressed

- **Scalar density : enhancement**



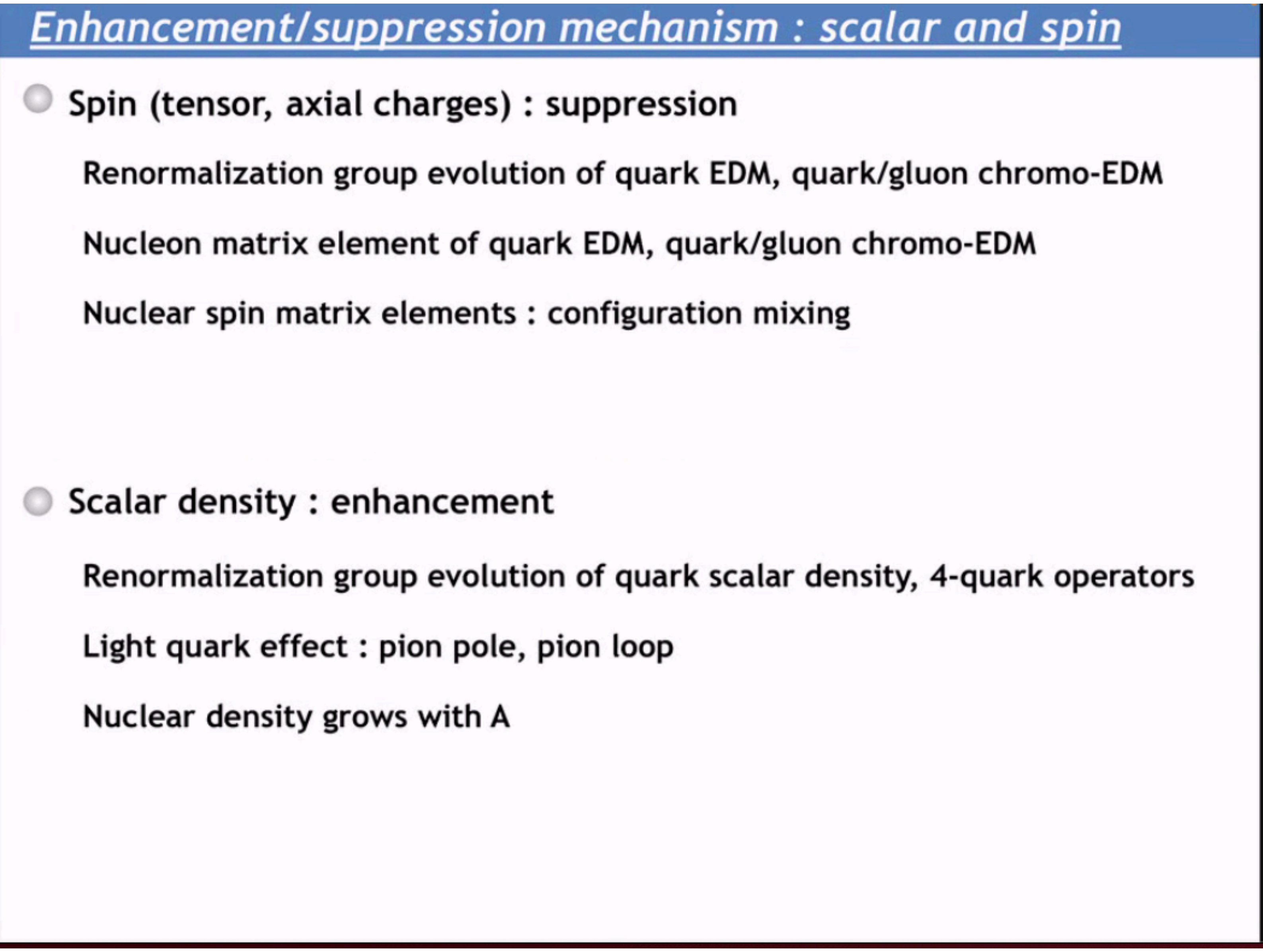
Scalar density grows with particle number



Relativistic effect : Z graph, loops

Scalar density of particles and antiparticles has the same sign
⇒ Becomes large with long worldline
⇒ Enhancement by relativistic effect

NY, T. M. Doi, S. Imai, H. Suganuma, Phys. Rev. D **88**, 074036 (2013);
NY, S. Imai, T. M. Doi, H. Suganuma, Phys. Rev. D **89**, 074017 (2014).



Enhancement/suppression mechanism : scalar and spin

- Spin (tensor, axial charges) : suppression
  - Renormalization group evolution of quark EDM, quark/gluon chromo-EDM
  - Nucleon matrix element of quark EDM, quark/gluon chromo-EDM
  - Nuclear spin matrix elements : configuration mixing

- Scalar density : enhancement
  - Renormalization group evolution of quark scalar density, 4-quark operators
  - Light quark effect : pion pole, pion loop
  - Nuclear density grows with A

Renormalization group evolution of CPV QCD operators

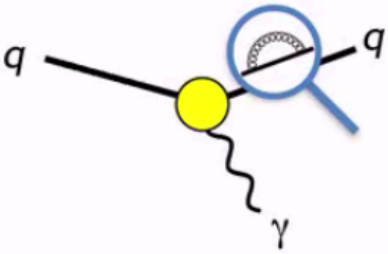
Change of energy scale modifies the coupling constants, mixes operators

Significant changes for quark/gluon operators due to QCD

Renormalization group equation:

$$\frac{d}{d\ln\mu}\mathbf{C}(\mu) = \hat{\gamma}^T(\alpha_s)\mathbf{C}(\mu)$$

C : Wilson coefficients of CPV operators



Anomalous dimension matrix:

$$\hat{\gamma}^{(0)} = \begin{pmatrix} 8C_F & 0 & 0 \\ 8C_F & 16C_F - 4n_c & 0 \\ 0 & 2n_c & n_c + 2n_f + \beta_0 \end{pmatrix}$$

Degrassi et al., JHEP **0511** (2005) 044
Yang et al., Phys. Lett. B **713** (2012) 473
Dekens et al. JHEP**1305**(2013)149

- **Renormalization = resummation of perturbative QCD corrections**
- **Large uncertainty due to nonperturbative effect below μ = 1 GeV**

⇒ We have to stop (perturbative) RG evolution and calculate the hadronic processes with nonperturbative methods

Renormalization group evolution of CPV QCD operators

- **Scalar density:**

$\bar{q}q \rightarrow 2\,\bar{q}q$

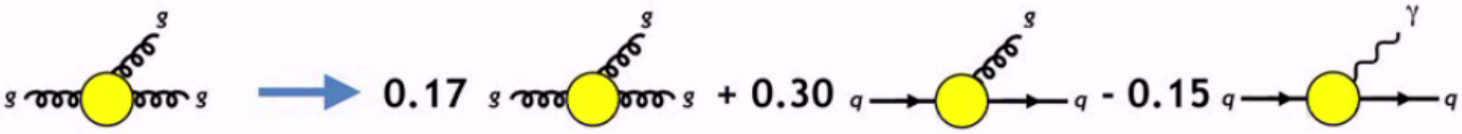
μ = 1 TeV → μ = 1 GeV

- **Quark EDM:**

$d_q \rightarrow 0.8\,d_q$

μ = 1 TeV → μ = 1 GeV

- **Weinberg operator:**

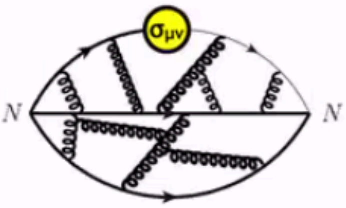


μ = 1 TeV → μ = 1 GeV

Roughly, scalar increases and spin decreases when scale goes down

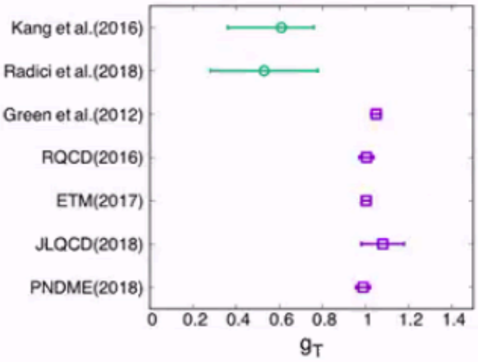
CP violating hadron matrix elements

At the hadronic scale, CP-odd quark-gluon operators must be matched to CP-odd hadron level interactions



Matrix elements like $\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$ are needed

Difficulties due to nonperturbative effect of QCD



Ideally, calculate with lattice QCD

(Sometimes, in conflict with other approaches)

But, difficult for gluonic quantities, like chromo-EDM

In these cases, phenomenological studies must be used

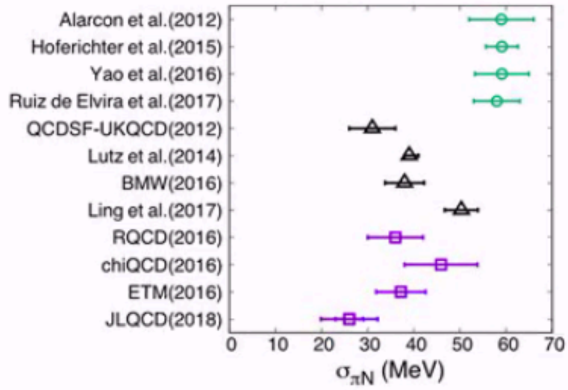
Some lattice results of nucleon matrix elements

- **Nucleon scalar density:** $\langle N|\bar{q}q|N\rangle$

Important input in EDM related ChPT

$\langle N|\bar{q}q|N\rangle$ ∼ 10 ⇒ enhanced

➡ Obey the rough rule

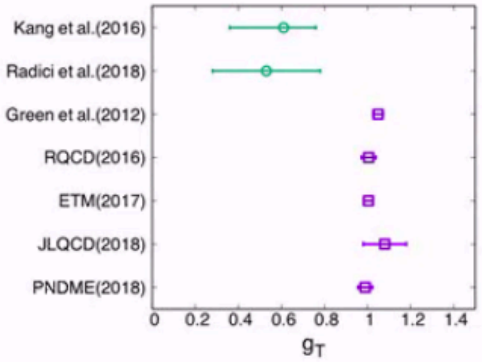


- **Nucleon tensor charge:** $\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$

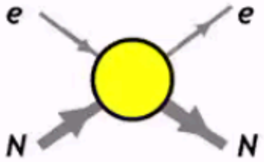
Contribution of the quark EDM to the nucleon EDM

$\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$ ∼ 1 < 5/3 (quark model) ⇒ suppressed

➡ Obey the rough rule



CP-odd electron-nucleon interaction : the most interesting?



P, CP-odd e-N interaction induces atomic EDM,
it is a pure atomic effect

In view of the above enhancement/suppression mechanisms, the CP-odd e-N interaction is the most interesting, because…

- Many new physics contribute at the tree level
- For scalar-pseudoscalar type $C_{SP}\bar{N}N\,\bar{e}i\gamma_5 e$

  Similar enhancement as the electron EDM in paramagnetic systems

  Hadronic part has scalar density enhancement $\langle N|\bar{q}q|N\rangle$

  ⇒ In many cases, more sensitive than electron EDM!
- For pseudoscalar-scalar $C_{PS}\bar{N}i\gamma_5 N\,\bar{e}e$ and tensor $C_T\bar{N}\sigma_{\mu\nu}N\,\bar{e}i\sigma^{\mu\nu}\gamma_5 e$ types

  Suppression due to spin, but EDM experiments of diamagnetic atom are very precise ! (c.f. $d_{Hg} < 7.4 \times 10^{-30}$ e cm, world record)

  Graner et al., Phys. Rev. Lett. **116**, 161601 (2016).

  Sensitivity to specific new physics through C_T, such as leptoquark

Pion-nucleon level enhancement/suppression

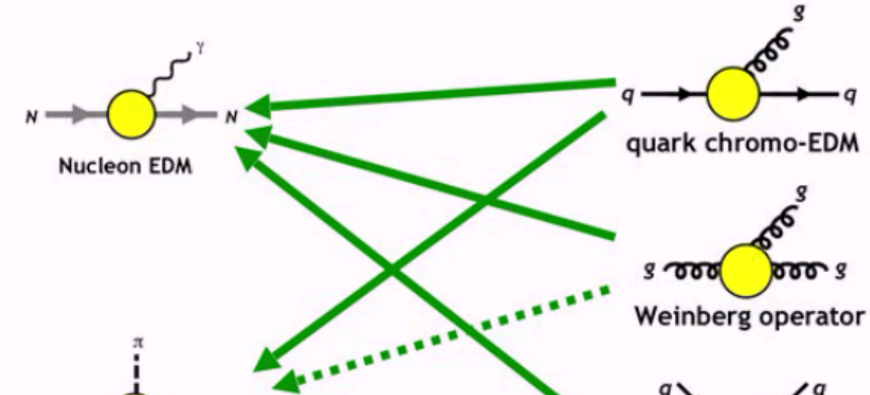
Unfortunately, not all hadron matrix elements are available from lattice QCD

Use chiral EFT to relate unknown ones with known ones

A rough rule of ChEFT :

Count the power of m_π^2 (or m_q) and match operators between QCD and pion-nucleon physics

Evidently, if the chiral representations of the CP-odd operators at the QCD and hadron levels do not match, we have a suppression by at least m_π^2.



J. de Vries et al., PRC **84**, 065501 (2011)

Nuclear EDM / Schiff moment from nucleon level CP violation

Two leading contributions to nuclear EDM/Schiff moment:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM (spin)

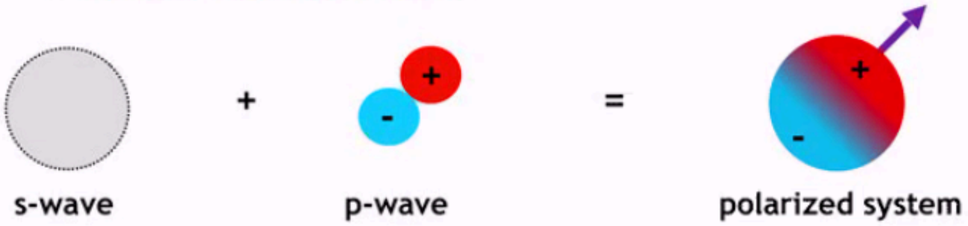
Strong pairing force : only unpaired nucleon(s) contribute

Nucleons are nonrelativisitic in nuclei

⇒ **Nucleon EDM is not enhanced in nuclei**

2) Polarization of the nucleus:

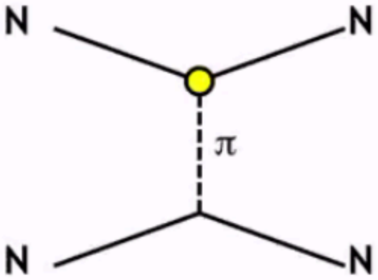
Polarize the whole system by the parity and CP mixing
due to CP-odd nuclear force



May be enhanced by the many-body effect?

P, CP-odd nuclear force

P, CP-odd nuclear force : pion exchange is dominant



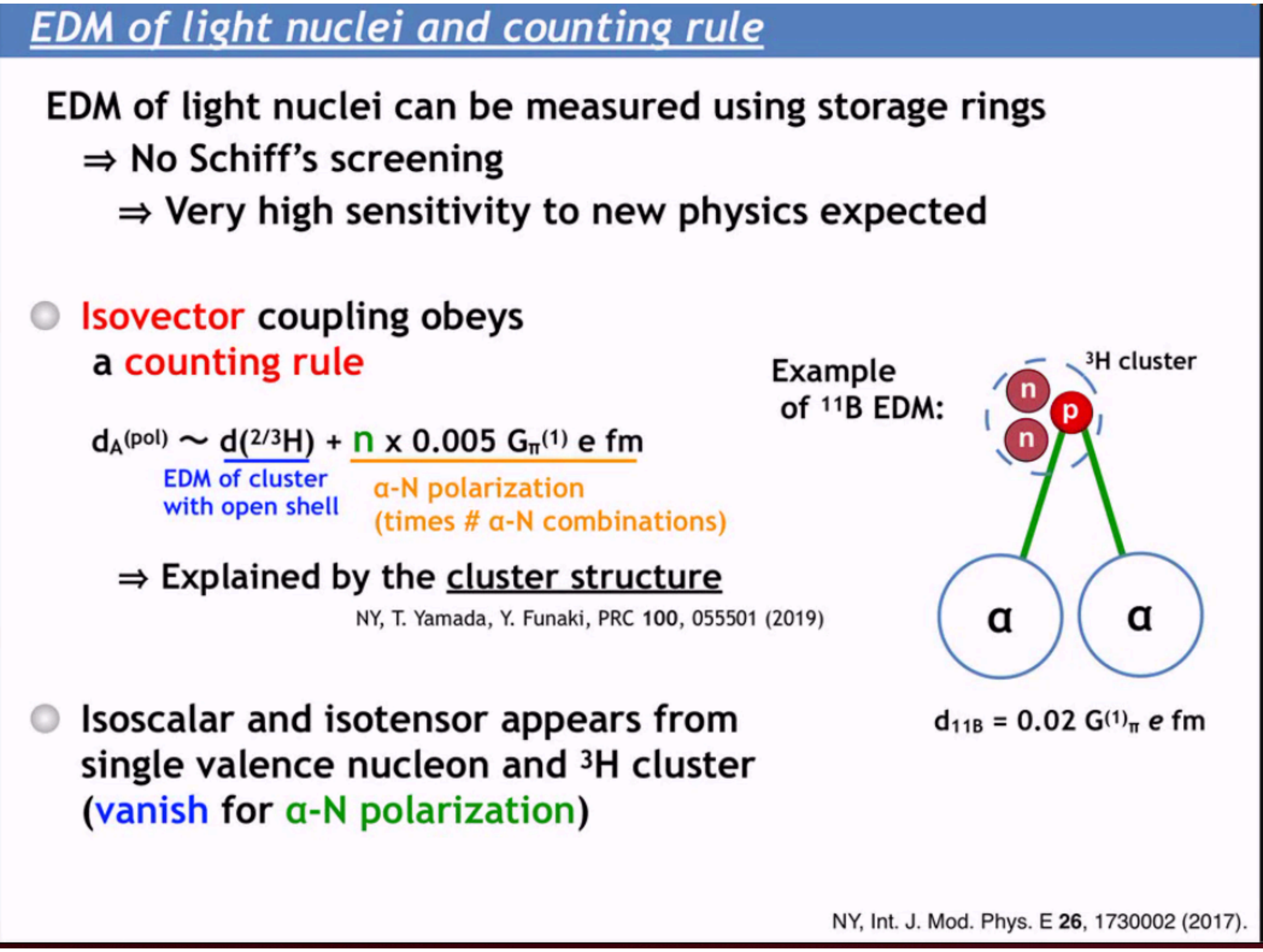
$$\sim \frac{1}{q^2 - m_\pi^2} \bar{N} N \; \bar{N} i \gamma_5 N$$

- P, CP-odd Hamiltonian (3-types):

$$\mathcal{H}_{PT} = -\frac{1}{8\pi m_N}\left[\left(\underbrace{\bar{G}_\pi^{(0)}}_{\text{Isoscalar}} \tau_a \cdot \tau_b + \underbrace{\bar{G}_\pi^{(2)}}_{\text{Isotensor}} (\tau_a \cdot \tau_b - 3\tau_a^z \tau_b^z)\right)(\sigma_a - \sigma_b) + \underbrace{\bar{G}_\pi^{(1)}}_{\text{Isovector}} (\tau_b^a \sigma_a - \tau_b^z \sigma_b)\right] \cdot \frac{\nabla_{ab} e^{m_\pi r_{ab}}}{r_{ab}}$$

$$\bar{G}_\pi^{(i)} \equiv g_{\pi NN} \bar{g}_{\pi NN}^{(i)}$$

- 4 important properties:
  - Coherence in nuclear scalar density : enhanced in nucleon number
  - One-pion exchange : suppress long distance contribution
  - Spin dependent interaction : closed shell has no EDM
  - Derivative interaction : contribution from the surface
- What is expected:
  - Polarization effect grows in *A* for small nuclei ?
  - May have additional enhancements with cluster structure, deformation, …



EDM of light nuclei and counting rule

EDM of light nuclei can be measured using storage rings

⇒ No Schiff's screening

⇒ Very high sensitivity to new physics expected

- **Isovector** coupling obeys a **counting rule**

$d_A^{(pol)} \sim \underbrace{d({}^{2/3}H)}_{\text{EDM of cluster with open shell}} + \underbrace{n \times 0.005\, G_\pi^{(1)}\, e\, \mathrm{fm}}_{\alpha\text{-N polarization (times \# } \alpha\text{-N combinations)}}$

⇒ Explained by the cluster structure

NY, T. Yamada, Y. Funaki, PRC **100**, 055501 (2019)

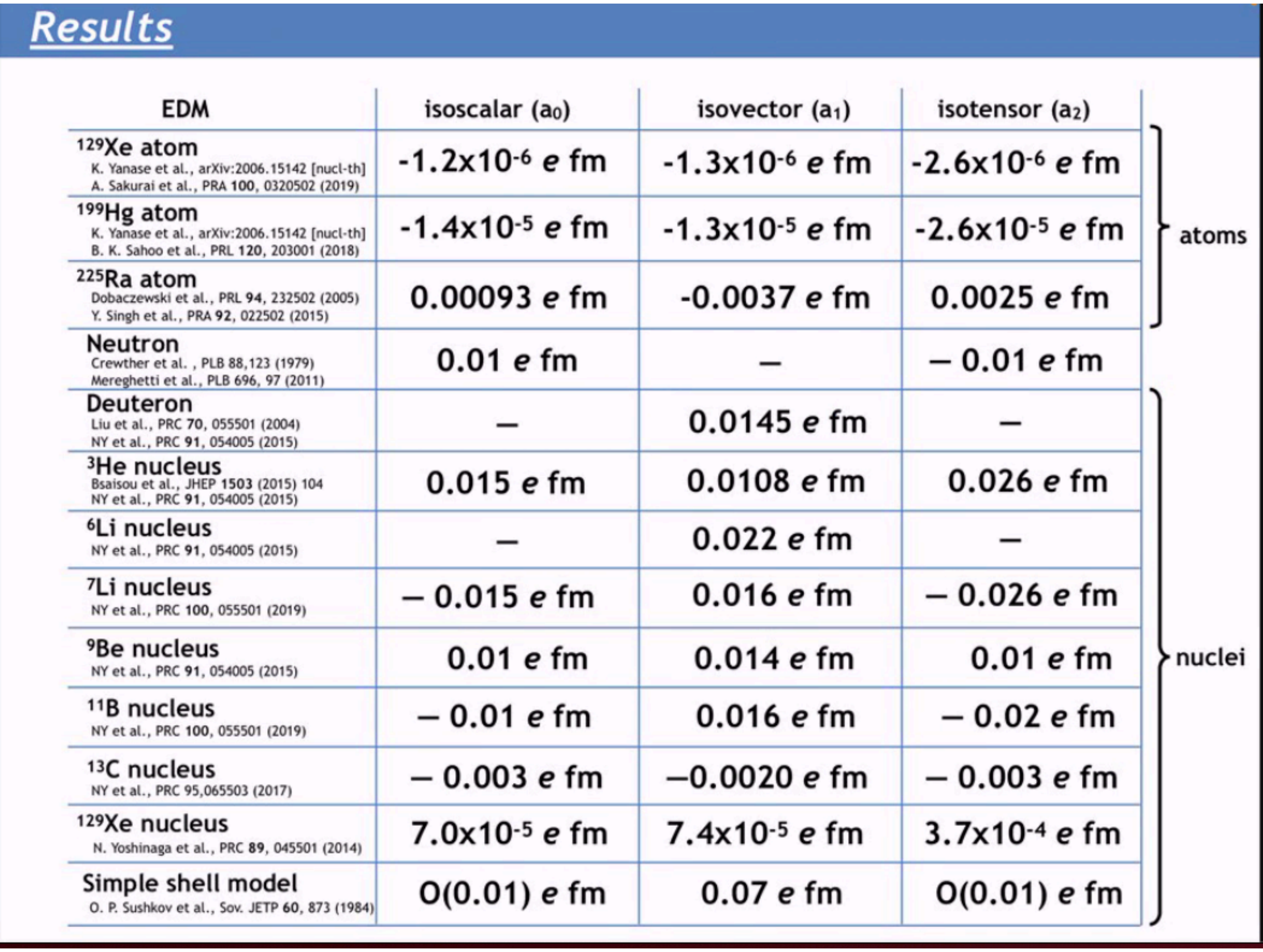
Example of ^{11}B EDM:

^3H cluster

$d_{11B} = 0.02\, G^{(1)}_\pi\, e\, \mathrm{fm}$

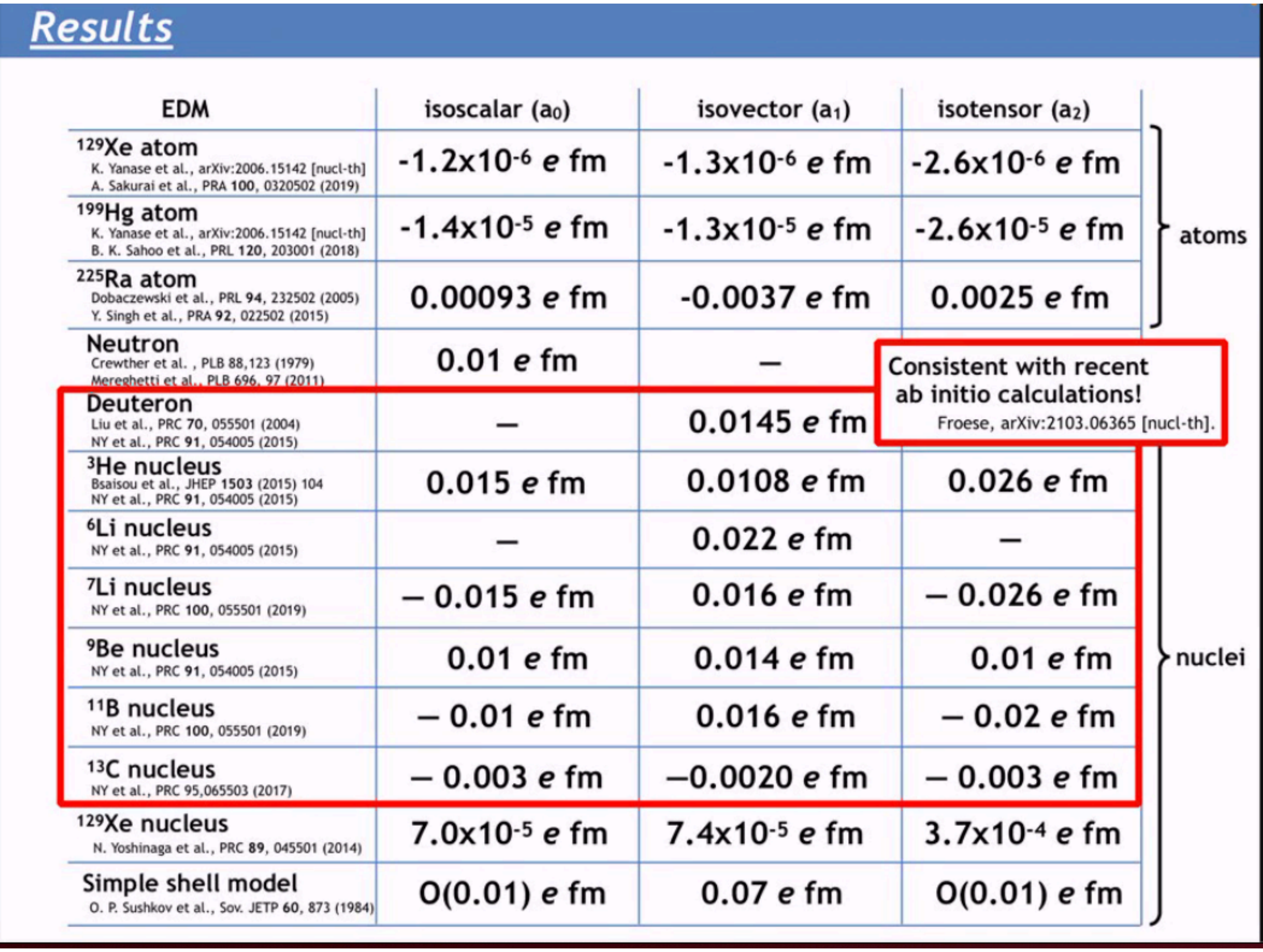
- Isoscalar and isotensor appears from single valence nucleon and ^3H cluster (vanish for α-N polarization)

NY, Int. J. Mod. Phys. E **26**, 1730002 (2017).



Results

EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)	
^{129}Xe atom K. Yanase et al., arXiv:2006.15142 [nucl-th] A. Sakurai et al., PRA **100**, 0320502 (2019)	-1.2x10^{-6} *e* fm	-1.3x10^{-6} *e* fm	-2.6x10^{-6} *e* fm	atoms
^{199}Hg atom K. Yanase et al., arXiv:2006.15142 [nucl-th] B. K. Sahoo et al., PRL **120**, 203001 (2018)	-1.4x10^{-5} *e* fm	-1.3x10^{-5} *e* fm	-2.6x10^{-5} *e* fm	
^{225}Ra atom Dobaczewski et al., PRL **94**, 232502 (2005) Y. Singh et al., PRA **92**, 022502 (2015)	0.00093 *e* fm	-0.0037 *e* fm	0.0025 *e* fm	
Neutron Crewther et al. , PLB 88,123 (1979) Mereghetti et al., PLB 696, 97 (2011)	0.01 *e* fm	–	– 0.01 *e* fm	
Deuteron Liu et al., PRC **70**, 055501 (2004) NY et al., PRC **91**, 054005 (2015)	–	0.0145 *e* fm	–	nuclei
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY et al., PRC **91**, 054005 (2015)	0.015 *e* fm	0.0108 *e* fm	0.026 *e* fm	
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015)	–	0.022 *e* fm	–	
^{7}Li nucleus NY et al., PRC **100**, 055501 (2019)	– 0.015 *e* fm	0.016 *e* fm	– 0.026 *e* fm	
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015)	0.01 *e* fm	0.014 *e* fm	0.01 *e* fm	
^{11}B nucleus NY et al., PRC **100**, 055501 (2019)	– 0.01 *e* fm	0.016 *e* fm	– 0.02 *e* fm	
^{13}C nucleus NY et al., PRC 95,065503 (2017)	– 0.003 *e* fm	–0.0020 *e* fm	– 0.003 *e* fm	
^{129}Xe nucleus N. Yoshinaga et al., PRC **89**, 045501 (2014)	7.0x10^{-5} *e* fm	7.4x10^{-5} *e* fm	3.7x10^{-4} *e* fm	
Simple shell model O. P. Sushkov et al., Sov. JETP **60**, 873 (1984)	O(0.01) *e* fm	0.07 *e* fm	O(0.01) *e* fm	



Results

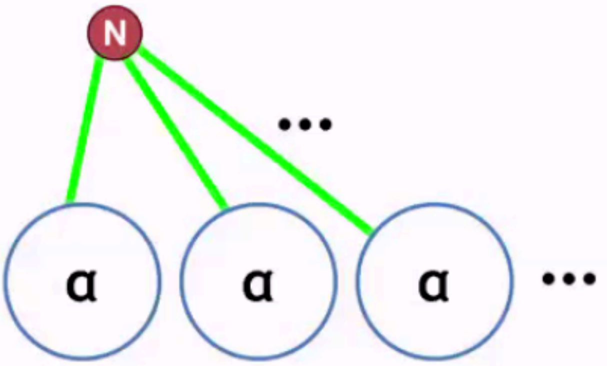
EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)	
^{129}Xe atom K. Yanase et al., arXiv:2006.15142 [nucl-th] A. Sakurai et al., PRA **100**, 0320502 (2019)	-1.2x10^{-6} *e* fm	-1.3x10^{-6} *e* fm	-2.6x10^{-6} *e* fm	atoms
^{199}Hg atom K. Yanase et al., arXiv:2006.15142 [nucl-th] B. K. Sahoo et al., PRL **120**, 203001 (2018)	-1.4x10^{-5} *e* fm	-1.3x10^{-5} *e* fm	-2.6x10^{-5} *e* fm	
^{225}Ra atom Dobaczewski et al., PRL **94**, 232502 (2005) Y. Singh et al., PRA **92**, 022502 (2015)	0.00093 *e* fm	-0.0037 *e* fm	0.0025 *e* fm	
Neutron Crewther et al. , PLB 88,123 (1979) Mereghetti et al., PLB 696, 97 (2011)	0.01 *e* fm	–		
Deuteron Liu et al., PRC **70**, 055501 (2004) NY et al., PRC **91**, 054005 (2015)	–	0.0145 *e* fm		nuclei
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY et al., PRC **91**, 054005 (2015)	0.015 *e* fm	0.0108 *e* fm	0.026 *e* fm	
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015)	–	0.022 *e* fm	–	
^{7}Li nucleus NY et al., PRC **100**, 055501 (2019)	– 0.015 *e* fm	0.016 *e* fm	– 0.026 *e* fm	
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015)	0.01 *e* fm	0.014 *e* fm	0.01 *e* fm	
^{11}B nucleus NY et al., PRC **100**, 055501 (2019)	– 0.01 *e* fm	0.016 *e* fm	– 0.02 *e* fm	
^{13}C nucleus NY et al., PRC 95,065503 (2017)	– 0.003 *e* fm	–0.0020 *e* fm	– 0.003 *e* fm	
^{129}Xe nucleus N. Yoshinaga et al., PRC **89**, 045501 (2014)	7.0x10^{-5} *e* fm	7.4x10^{-5} *e* fm	3.7x10^{-4} *e* fm	
Simple shell model O. P. Sushkov et al., Sov. JETP **60**, 873 (1984)	O(0.01) *e* fm	0.07 *e* fm	O(0.01) *e* fm	

Consistent with recent ab initio calculations!

Froese, arXiv:2103.06365 [nucl-th].

EDM of heavy nuclei : simple shell model

EDM of larger nuclei is larger?

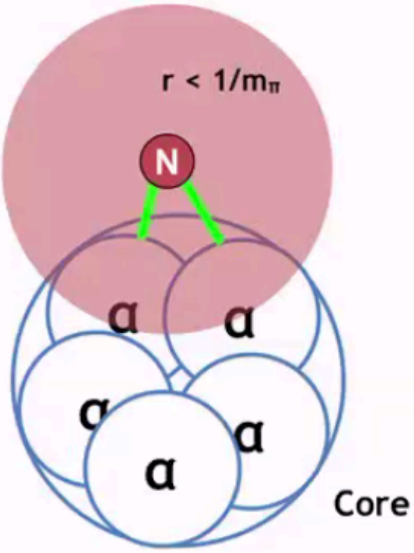


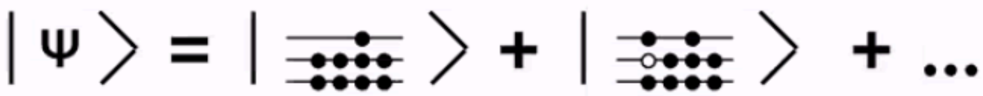
$d_A = (A/4) \times (\alpha\text{-N polarization})$??

➡ **No!**

Problems:

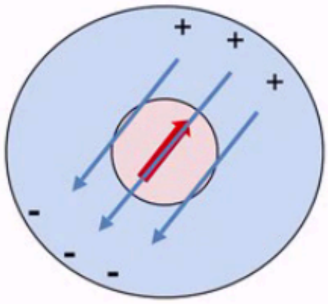
- pion is massive, nucleon cannot interact with the other side of the nucleus
- CP-odd nuclear force is a derivative interaction, interact with the surface
- Large nuclei have configuration mixings (destructive interference of angular momentum of valence nucleons)





We should have some upper limit in the sensitivity $d_A \sim 0.07\, G_\pi^{(1)}\, e\,\mathrm{fm}$

Nuclear EDM in atoms : Schiff moment



Nuclear EDM screened by rearrangement of atomic electrons.

⇒ Residual effect : nuclear Schiff moment

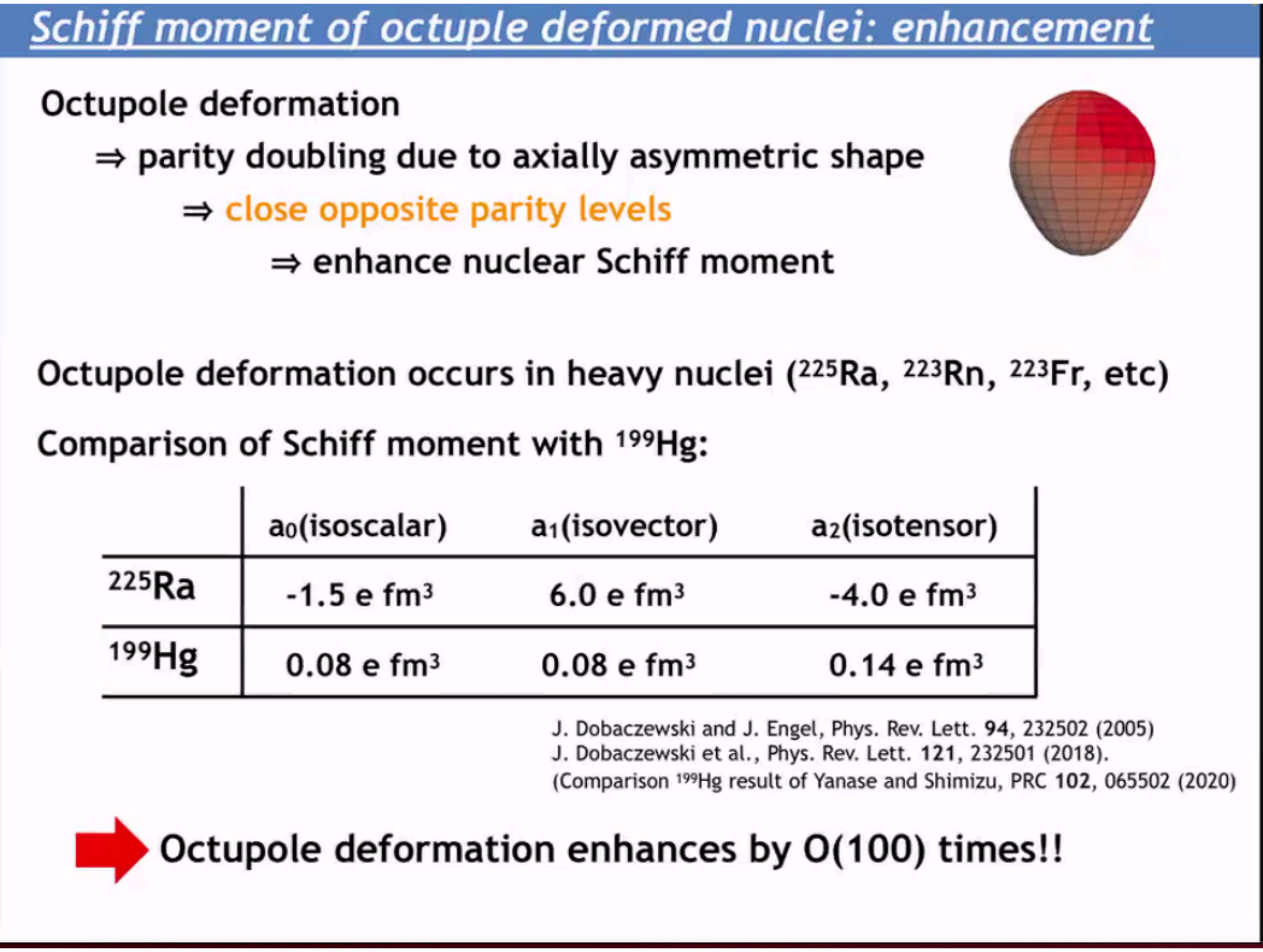
$$\hat{S} \equiv \frac{e}{2}\sum_{p=1}^{Z}\left(\frac{1}{5}r_p^2 - \frac{1}{3}\langle r^2\rangle_{\rm ch}\right) r_p$$

Atoms and molecules for which the EDM may be measured are limited by experimental conditions.

⇒ Limited number of cases to be studied

Two main nuclear level calculational methods

- Mean-field method : high computational cost for odd-nuclei
  (Hg Schiff moment calculation has large uncertainty)
  Ban et al., PRC **82**, 015501 (2010)
- Shell model : results for Xe and Hg
  $|G_\pi^{(1)}| < 5 \times 10^{-12}$ (from $d_{Hg} < 7.4 \times 10^{-30}$e cm)
  ⇒ Almost same limit as neutron EDM
  Yanase and Shimizu, PRC **102**, 065502 (2020)
  Yanase, PRC **103**, 035501 (2021)



Schiff moment of octuple deformed nuclei: enhancement

Octupole deformation

⇒ parity doubling due to axially asymmetric shape

⇒ close opposite parity levels

⇒ enhance nuclear Schiff moment

Octupole deformation occurs in heavy nuclei (^{225}Ra, ^{223}Rn, ^{223}Fr, etc)

Comparison of Schiff moment with ^{199}Hg:

	a_0(isoscalar)	a_1(isovector)	a_2(isotensor)
^{225}Ra	-1.5 e fm^3	6.0 e fm^3	-4.0 e fm^3
^{199}Hg	0.08 e fm^3	0.08 e fm^3	0.14 e fm^3

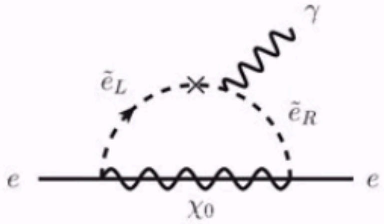
J. Dobaczewski and J. Engel, Phys. Rev. Lett. **94**, 232502 (2005)
J. Dobaczewski et al., Phys. Rev. Lett. **121**, 232501 (2018).
(Comparison ^{199}Hg result of Yanase and Shimizu, PRC **102**, 065502 (2020)

➡ Octupole deformation enhances by O(100) times!!

SUSY CP problem

In naive supersymmetric models with all possible soft SUSY breaking, the fermion EDM is generated at the one-loop level

Neutron and atomic EDMs are very sensitive to SUSY CP phases

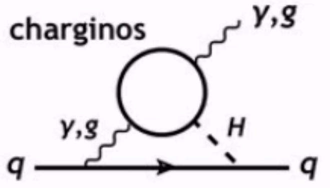


⇒ Very strong constraints on the CP phases of light sfermion ($\theta < 10^{-(2\text{-}3)}$ for $m_{SUSY} \sim$ TeV)

This lead phenomenologists to think of a more “natural” scenario where CP phases of sfermions are irrelevant, such as split-SUSY (very heavy sfermions)

Arkani-Hamed et al., Nucl. Phys. B **709** (2005) 3

In such scenarios, the EDM appears at two-loop level



Barr-Zee type diagram

⇒ Two-loop level CP violation is smaller

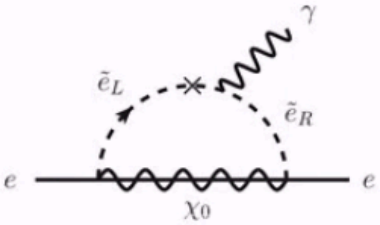
⇒ No need to tune SUSY CP phases

Ellis et al., JHEP 10 (2008) 049,
Nakai and Reece, JHEP 08 (2017) 031.

SUSY CP problem

In naive supersymmetric models with all possible soft SUSY breaking, the fermion EDM is generated at the one-loop level

Neutron and atomic EDMs are very sensitive to SUSY CP phases

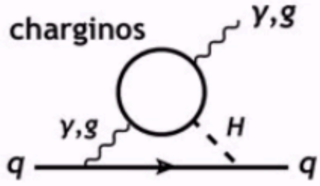


⇒ Very strong constraints on the CP phases of light sfermion ($\theta < 10^{-(2\text{-}3)}$ for $m_{SUSY} \sim$ TeV)

This lead phenomenologists to think of a more "natural" scenario where CP phases of sfermions are irrelevant, such as split-SUSY (very heavy sfermions)

Arkani-Hamed et al., Nucl. Phys. B **709** (2005) 3

In such scenarios, the EDM appears at two-loop level



Barr-Zee type diagram

⇒ Two-loop level CP violation is smaller

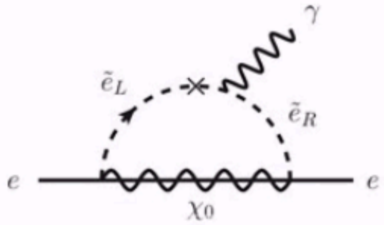
⇒ No need to tune SUSY CP phases

Ellis et al., JHEP 10 (2008) 049,
Nakai and Reece, JHEP 08 (2017) 031.

Compare with muon g-2

EDM and g-2 are generated by the same diagrams

(Difference of having γ_5 or not, imaginary or real couplings)



From recent muon g-2 exp. data of Fermilab (4.2σ from SM),

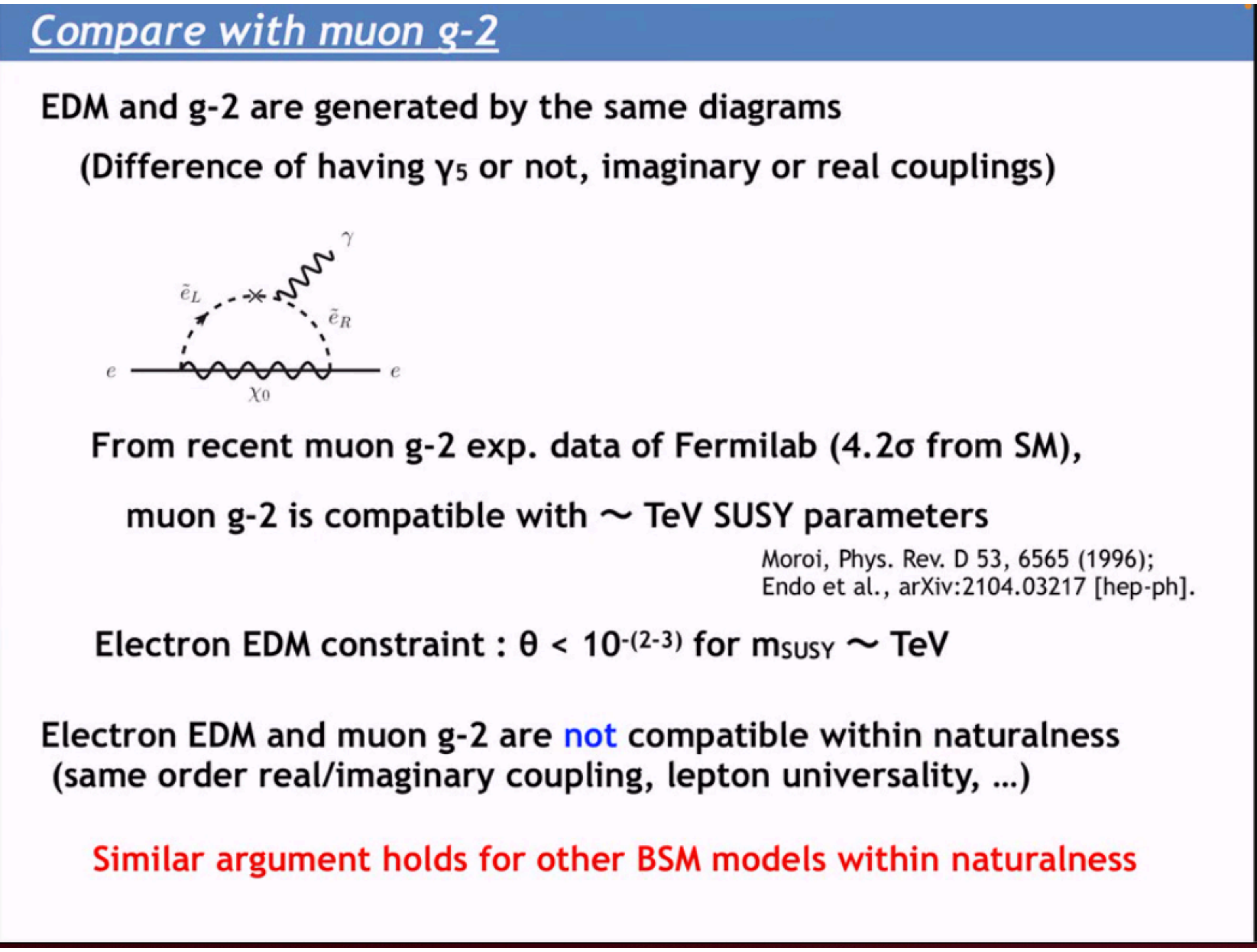
muon g-2 is compatible with ∼ TeV SUSY parameters

Moroi, Phys. Rev. D 53, 6565 (1996);
Endo et al., arXiv:2104.03217 [hep-ph].

Electron EDM constraint : $\theta < 10^{-(2\text{-}3)}$ for $m_{\mathrm{SUSY}} \sim$ TeV

Electron EDM and muon g-2 are not compatible within naturalness
(same order real/imaginary coupling, lepton universality, …)

Similar argument holds for other BSM models within naturalness



Compare with muon g-2

EDM and g-2 are generated by the same diagrams

(Difference of having γ_5 or not, imaginary or real couplings)

From recent muon g-2 exp. data of Fermilab (4.2σ from SM),

muon g-2 is compatible with ∼ TeV SUSY parameters

Moroi, Phys. Rev. D 53, 6565 (1996);
Endo et al., arXiv:2104.03217 [hep-ph].

Electron EDM constraint : $\theta < 10^{-(2\text{-}3)}$ for $m_{\mathrm{SUSY}} \sim$ TeV

Electron EDM and muon g-2 are not compatible within naturalness
(same order real/imaginary coupling, lepton universality, …)

Similar argument holds for other BSM models within naturalness

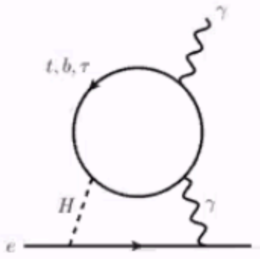
Higgs doublet models

Standard model Higgs boson does not have CP phase, but its extension may have it.

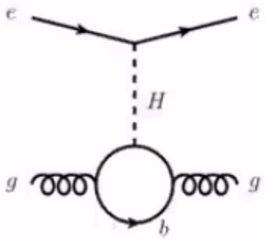
Higgs boson has very small interaction with light fermions (Yukawa)

The leading contribution involves heavy fermions.

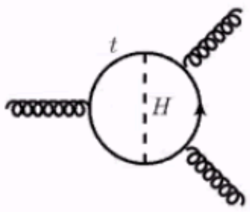
Leading contributions :



Fermion EDM
(Barr-Zee type diagram)



CP-odd electron-nucleon force
(gluon inside nucleon)



Weinberg operator
(gluon chromo-EDM)

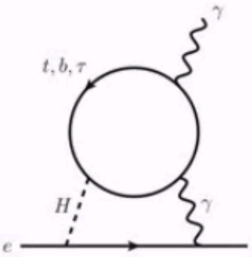
Higgs doublet models

Standard model Higgs boson does not have CP phase, but its extension may have it.

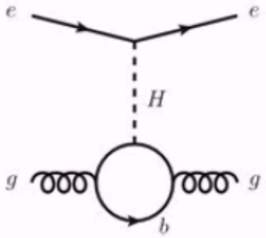
Higgs boson has very small interaction with light fermions (Yukawa)

The leading contribution involves heavy fermions.

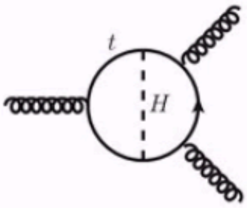
Leading contributions :



Fermion EDM
(Barr-Zee type diagram)



CP-odd electron-nucleon force
(gluon inside nucleon)



Weinberg operator
(gluon chromo-EDM)

Barr-Zee type diagram and CP-odd e-N force:
Suppressed by electron Yukawa, but interesting thanks to high sensitivity of paramagnetic molecular beam experiments ($d_e < 1.1 \times 10^{-29}$e cm)

V. Andreev et al. [ACME Collaboration], Nature **562**, 355 (2018).

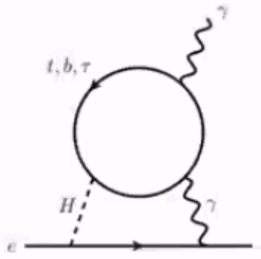
Higgs doublet models

Standard model Higgs boson does not have CP phase, but its extension may have it.

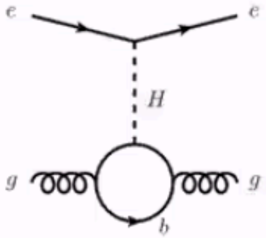
Higgs boson has very small interaction with light fermions (Yukawa)

The leading contribution involves heavy fermions.

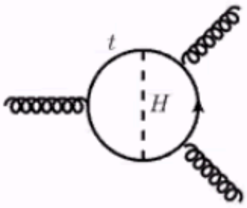
Leading contributions :



Fermion EDM
(Barr-Zee type diagram)



CP-odd electron-nucleon force
(gluon inside nucleon)



Weinberg operator
(gluon chromo-EDM)

Weinberg operator is not suppressed in the dimensional analysis, may be constrained by EDMs of neutron or diamagnetic atoms
⇒ Very interesting, but not well known due to hadron level uncertainty

Possible approaches:
- Lattice QCD calculations (very difficult)
- Effective field theory analysis
- Perturbative QCD analysis (higher twist pdf)

Leptoquark models

Leptoquarks : boson with lepton and baryon numbers.

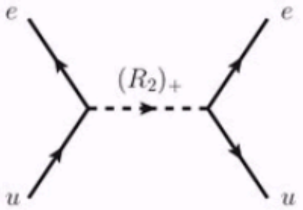
Natural effective models which may be arise in Grand unification.

(note that not all are constrained by proton decay)

Recently attracting attention in the context of B meson decay.

Atomic EDM is very sensitive to leptoquark models

⇒ CP-odd electron-nucleon interaction!



⇒ Very strong constraints on
the CP phases of leptoquarks
($\theta < 10^{-3}$ for $m_{LQ} \sim$ TeV)

Natural mechanisms to explain small CP phases are required.

Herczeg, Phys. Rev. D **68**, 116004 (2003),
Fuyuto et al., Phys. Lett. B **788** (2019) 52,
Yanase et al., Phys. Rev. D **99**, 075021 (2018).

What can we learn from EDM and model studies?

Essentially, nothing was discovered so far in LHC, so all models are even.

Nevertheless, EDM can constrain CP phases which cannot be by LHC, so EDM experiments have a strong diplomatic power in suggesting the directions of future particle physics studies (e.g. split-SUSY).

Now, what the EDM is suggesting us? (include my personal thought)

- SUSY : split-SUSY was nice to avoid SUSY CP problem, but “natural” CP phases will be killed in future EDM experiments.
- Leptoquark : very unlikely to be at TeV within natural CP phases. GUT scale is the most natural, but other tricky mechanisms to only remove CP phases at TeV?
- Extending Higgs sector : the Higgs exists, but many aspects not elucidated, such as Yukawa, CKM mixing/CP angles, etc.
  We also note that the CKM effect is also (indirectly) due to Higgs.
  This means, even not finding other CP phases than the CKM one is meaningful for the study of the Higgs sector.

Probably, the precise study of Higgs sector is the most promising.

What can we learn from EDM and model studies?

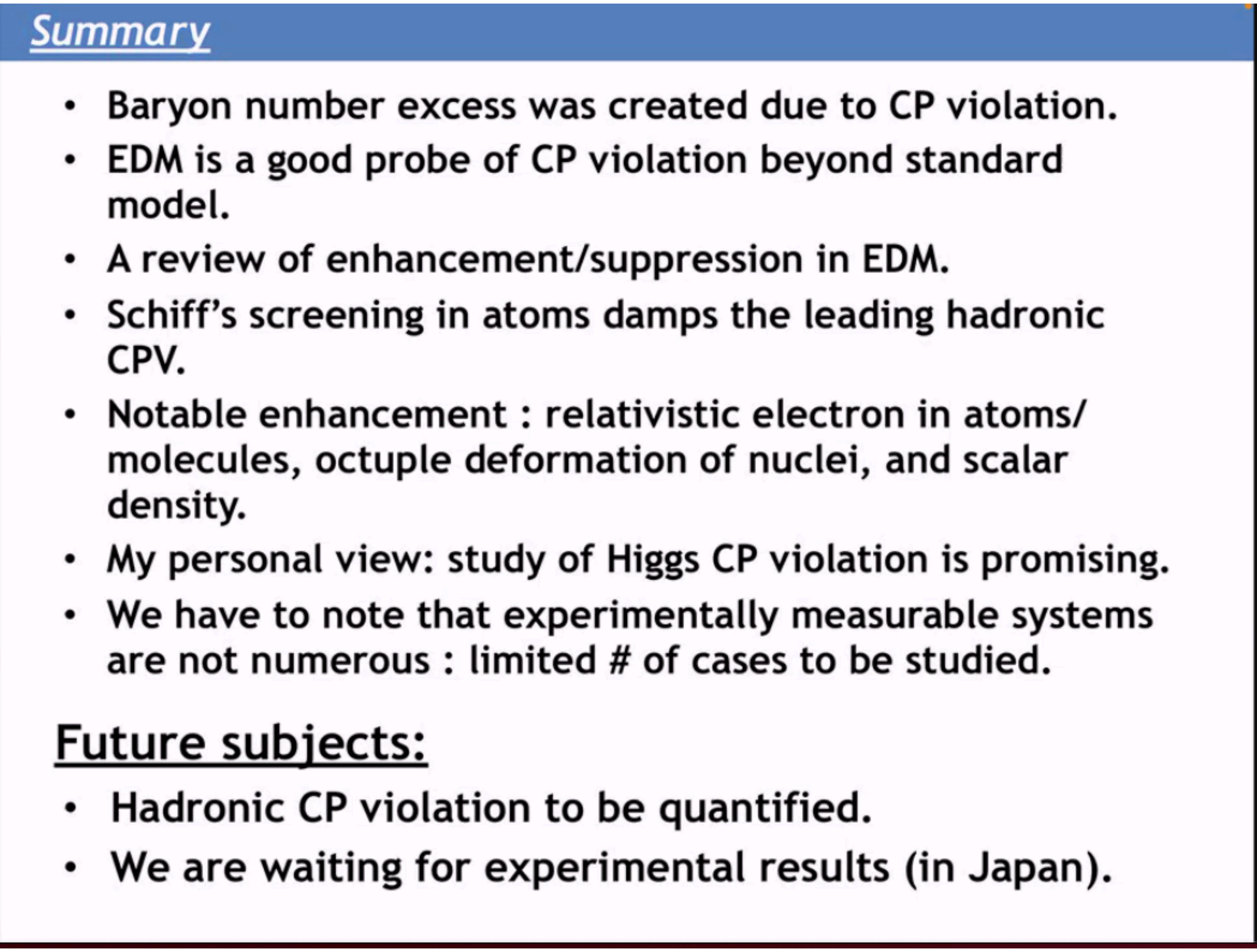
Essentially, nothing was discovered so far in LHC, so all models are even.

Nevertheless, EDM can constrain CP phases which cannot be by LHC, so EDM experiments have a strong diplomatic power in suggesting the directions of future particle physics studies (e.g. split-SUSY).

Now, what the EDM is suggesting us? (include my personal thought)

- SUSY : split-SUSY was nice to avoid SUSY CP problem, but "natural" CP phases will be killed in future EDM experiments.
- Leptoquark : very unlikely to be at TeV within natural CP phases. GUT scale is the most natural, but other tricky mechanisms to only remove CP phases at TeV?
- Extending Higgs sector : the Higgs exists, but many aspects not elucidated, such as Yukawa, CKM mixing/CP angles, etc.
  We also note that the CKM effect is also (indirectly) due to Higgs.
  This means, even not finding other CP phases than the CKM one is meaningful for the study of the Higgs sector.

Probably, the precise study of Higgs sector is the most promising.



Summary

- Baryon number excess was created due to CP violation.
- EDM is a good probe of CP violation beyond standard model.
- A review of enhancement/suppression in EDM.
- Schiff's screening in atoms damps the leading hadronic CPV.
- Notable enhancement : relativistic electron in atoms/ molecules, octuple deformation of nuclei, and scalar density.
- My personal view: study of Higgs CP violation is promising.
- We have to note that experimentally measurable systems are not numerous : limited # of cases to be studied.

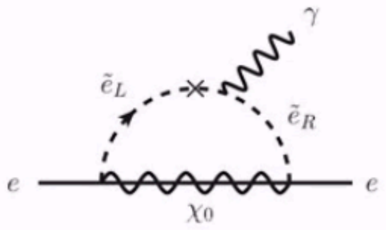
Future subjects:

- Hadronic CP violation to be quantified.
- We are waiting for experimental results (in Japan).

Compare with muon g-2

EDM and g-2 are generated by the same diagrams

(Difference of having γ_5 or not, imaginary or real couplings)



From recent muon g-2 exp. data of Fermilab (4.2σ from SM),

muon g-2 is compatible with ∼ TeV SUSY parameters

Moroi, Phys. Rev. D 53, 6565 (1996);
Endo et al., arXiv:2104.03217 [hep-ph].

Electron EDM constraint : $\theta < 10^{-(2\text{-}3)}$ for $m_{SUSY} \sim$ TeV

Electron EDM and muon g-2 are not compatible within naturalness
(same order real/imaginary coupling, lepton universality, ...)

Similar argument holds for other BSM models within naturalness