

Electric Dipole Moment (EDM) searches for leptons and hadrons

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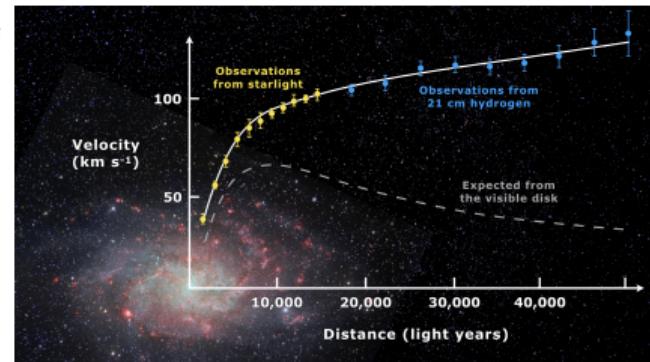
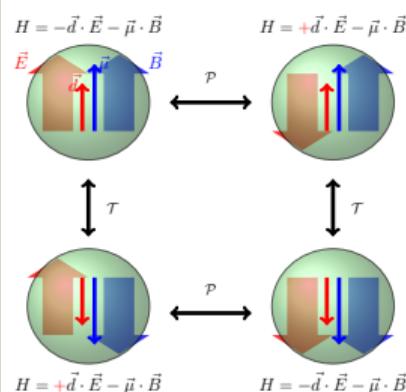
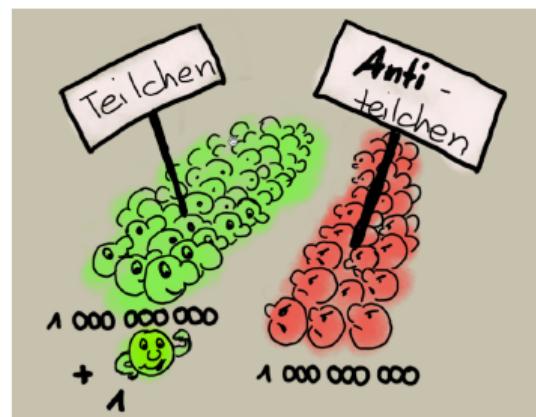


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Motivation

Standard Model of Particle Physics successful but ...

- Fails to explain matter-antimatter asymmetry in the universe
- Why is CP-violation in the strong sector not present (although allowed)?
- What does Dark Matter consists of?



source:M. De Leo, Wikipedia

Outline

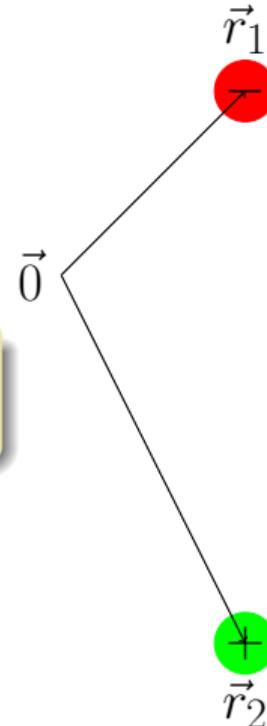
- **Introduction:**
Electric Dipole Moments
- **Experimental Methods:**
analyse spin precession
- **Experiments & Results:**
atoms, molecules, ions, solids, hadrons, leptons

Introduction

Electric Dipoles

Classical definition:

$$\vec{d} = \sum_i q_i \vec{r}_i$$



Order of magnitude

	atomic physics	hadron physics
charges	e	
$ \vec{r}_1 - \vec{r}_2 $	$1 \text{ \AA} = 10^{-8} \text{ cm}$	
EDM		
naive expectation	$10^{-8} e \cdot \text{cm}$	
observed	water molecule	
	$4 \cdot 10^{-9} e \cdot \text{cm}$	

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charges	e	e
$ \vec{r}_1 - \vec{r}_2 $	$1 \text{ \AA} = 10^{-8} \text{ cm}$	$1 \text{ fm} = 10^{-13} \text{ cm}$
EDM		
naive expectation	$10^{-8} e \cdot \text{cm}$	$10^{-13} e \cdot \text{cm}$
observed	water molecule	neutron
	$4 \cdot 10^{-9} e \cdot \text{cm}$	$< 1.8 \cdot 10^{-26} e \cdot \text{cm}$

$$\text{Operator } \vec{d} = q\vec{r}$$

\vec{d} is odd under parity transformation ($\vec{r} \rightarrow -\vec{r}$):

$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

Consequences:

In a state $|a\rangle$ of given parity the expectation value is 0:

$$\langle a|\vec{d}|a\rangle = -\langle a|\vec{d}|a\rangle$$

but if $|a\rangle = \alpha|P=+\rangle + \beta|P=-\rangle$

in general $\langle a|\vec{d}|a\rangle \neq 0 \Rightarrow$ i.e. molecules

Order of magnitude

Molecules can have large EDM because of degenerated ground states with different parity

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Order of magnitude

Molecules can have large EDM because of degenerated ground states with different parity

Elementary particles (including hadrons) have a definite parity and cannot posses an EDM

$$P|\text{had}\rangle = \pm 1 |\text{had}\rangle$$

unless

\mathcal{P} and time reversal \mathcal{T} invariance are violated!

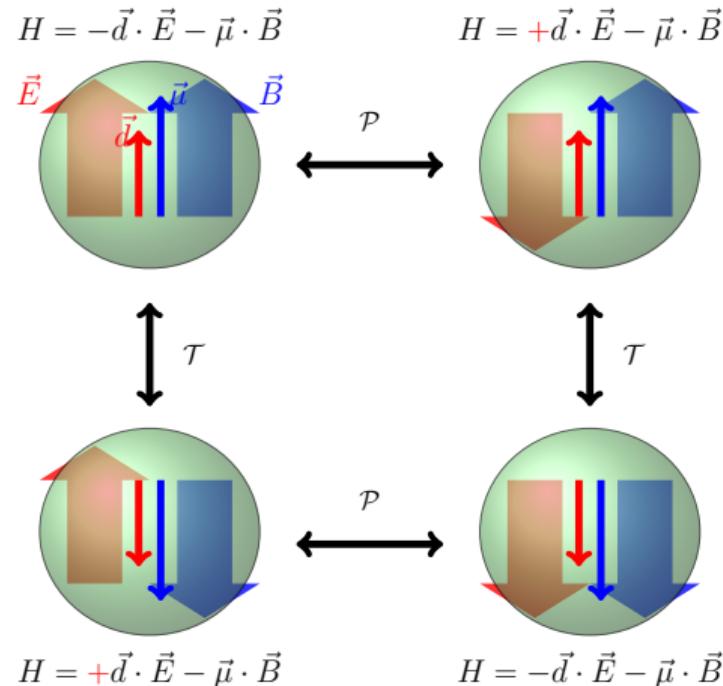
$$\text{In this case: } |\text{had}\rangle = |P=+\rangle + \epsilon |P=-\rangle$$

\mathcal{T} and \mathcal{P} violation of EDM

\vec{d} : EDM

$\vec{\mu}$: magnetic moment (MDM)
both \parallel to spin \vec{s}

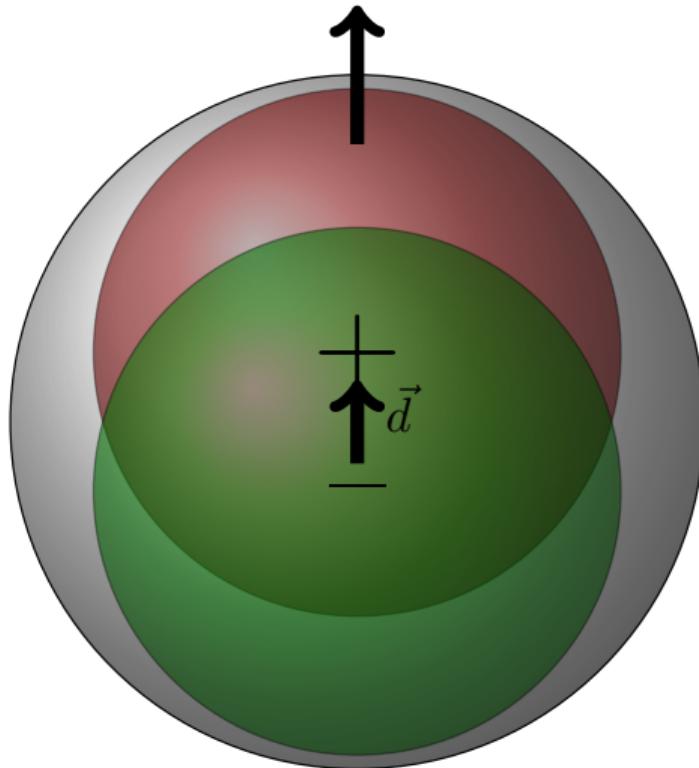
$H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} - d \frac{\vec{s}}{s} \cdot \vec{E}$
$\mathcal{T}: H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{E}$
$\mathcal{P}: H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{E}$



⇒ EDM measurement tests violation of fundamental symmetries \mathcal{P} and \mathcal{T} ($\stackrel{\mathcal{CP}\mathcal{T}}{=} \mathcal{CP}$)

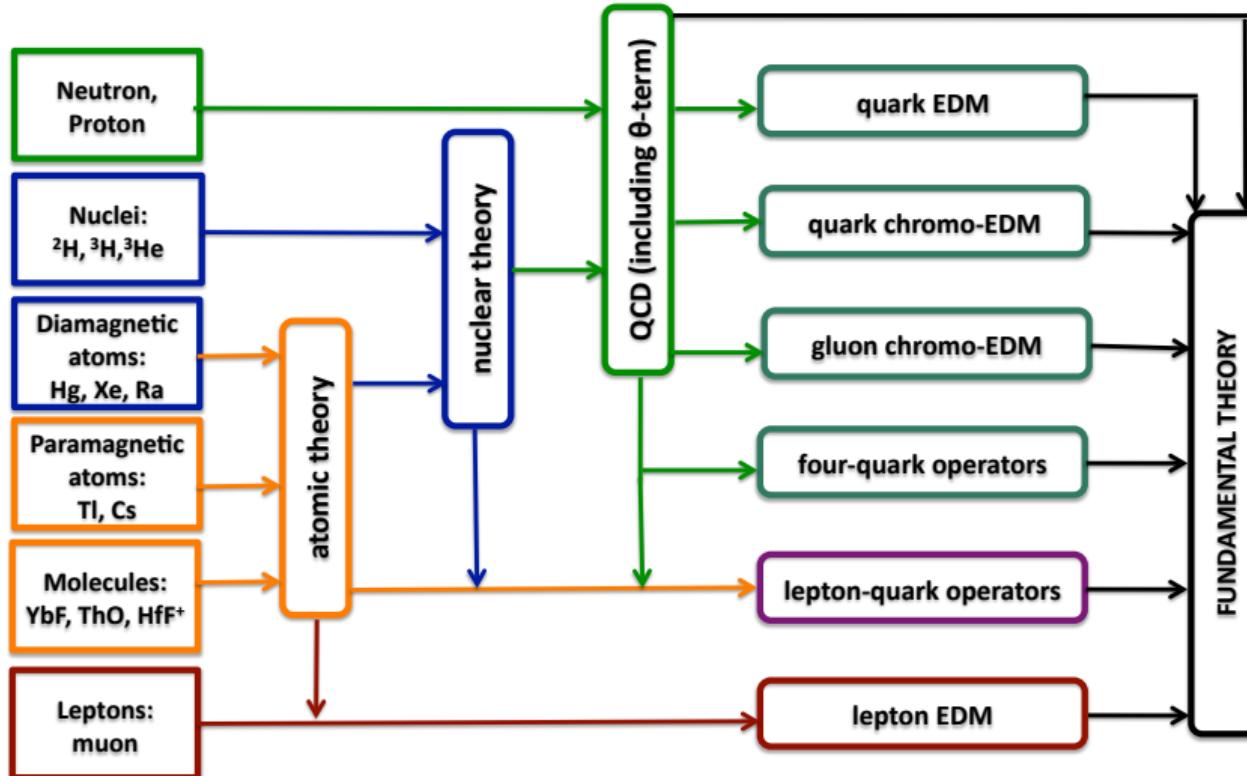
Electric Dipole Moments (EDM)

Spin \vec{s}



- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \stackrel{\mathcal{CPT}}{=} \mathcal{CP}$ and parity \mathcal{P} symmetry
- close connection to “matter-antimatter” asymmetry
- axion field leads to oscillating EDM

Why EDMs for many different particle species?



Experimental Methods

Experimental Method

Observe Spin Precession in electric and magnetic fields:

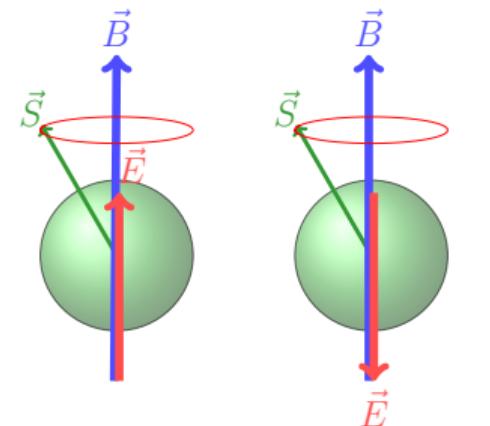
$$\vec{\Omega} = \frac{-d\vec{E} - \mu\vec{B}}{|\vec{S}|}, \quad \dot{\vec{S}} = \vec{\Omega} \times \vec{S}$$

Order of magnitude:

Neutron in earth B -field: $\Omega \approx 9000 \text{ s}^{-1}$

$$d_n = 1 \times 10^{-26} \text{ e} \cdot \text{cm}$$

in electric field $E = 10^7 \text{ V/m}$: $\Omega \approx 3 \times 10^{-6} \text{ s}^{-1}$



$$\Omega_{\uparrow\uparrow} = \Omega_{MDM} + \Omega_{EDM}$$

$$\Omega_{\uparrow\downarrow} = \Omega_{MDM} - \Omega_{EDM}$$

Requirements for EDM experiments

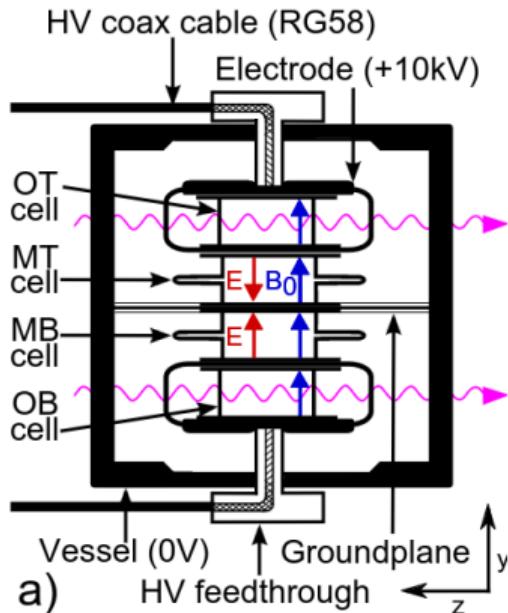
- Provide large electric field
 - two plates oppositely charged (the obvious way)
 - inside an atom/molecule
 - use motional electric field created by laboratory B -field
 - in bent crystals
- analyze decay of polarized particles (Λ, τ)
- Fight systematics:
Difference Measurement: $\vec{B} \uparrow\uparrow \vec{E}$ and $\vec{B} \uparrow\downarrow \vec{E}$

Statistical Error: $\sigma \approx \mathcal{O}\left(\frac{\hbar}{\sqrt{NET}}\right)$

N : nb. of particle, E : electric field, T : duration

Experiments

Hg atoms



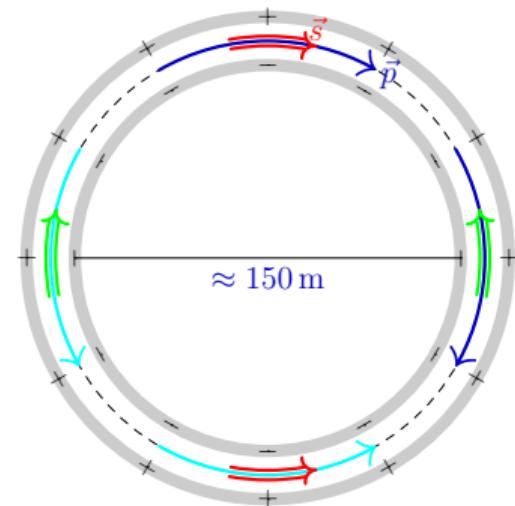
1 cm

neutrons



1 m

protons



100 m

Experiments & Results

Experiments/Activities around the world

Muons:

J-PARC
PSI
FNAL

charged hadrons:

BNL, protons
FZJ, deuteron

Solids:

Indiana, GGG

Λ, Ξ :

CERN

Tau:

Belle
BESIII

ions:
Boulder, HfF⁺

Neutrons:

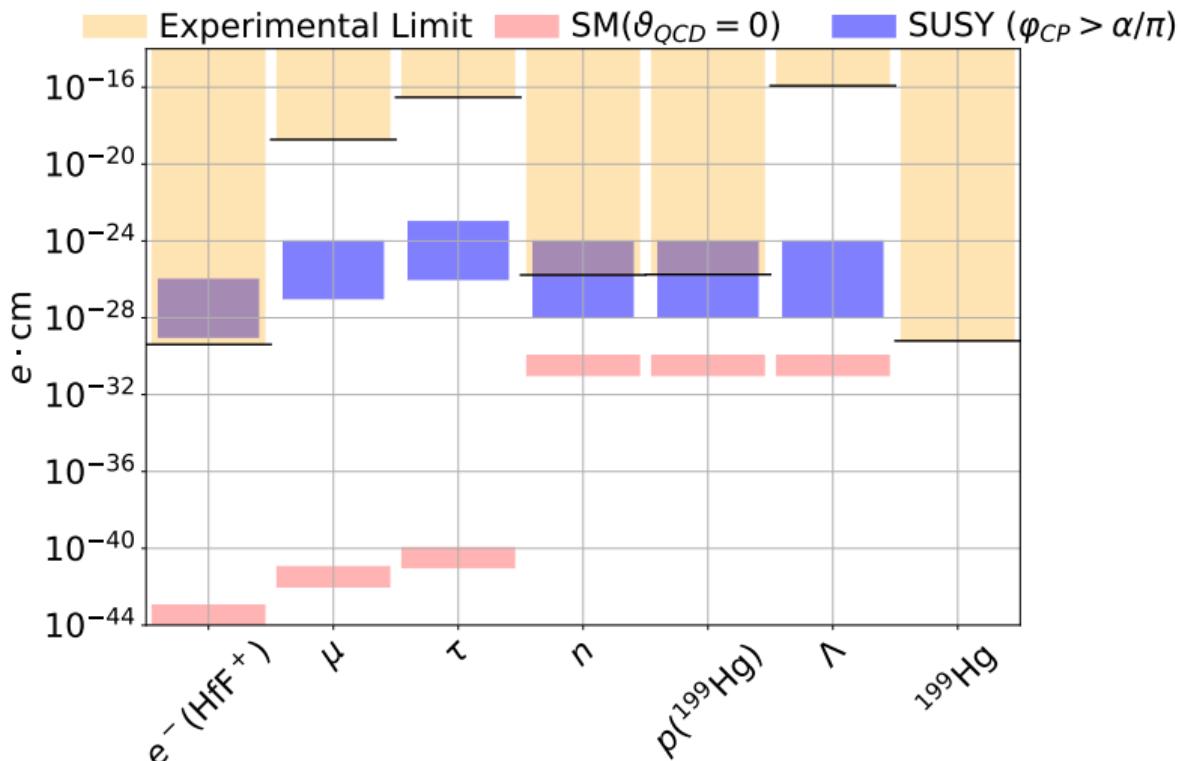
LANL
SNS
PSI
ILL
TRIUMF
J-PARC

atoms:

UW, Hg
Bonn, Hg
FZJ, Mainsz, ¹⁹⁹Xe
FRM-II, PTB ¹⁹⁹Xe
ANL ²²⁵Ra
Hefei, Yb

Molecules:
YbF, Imperial
ThO, Harvard
PbO, Yale
TlF, Yale

Results

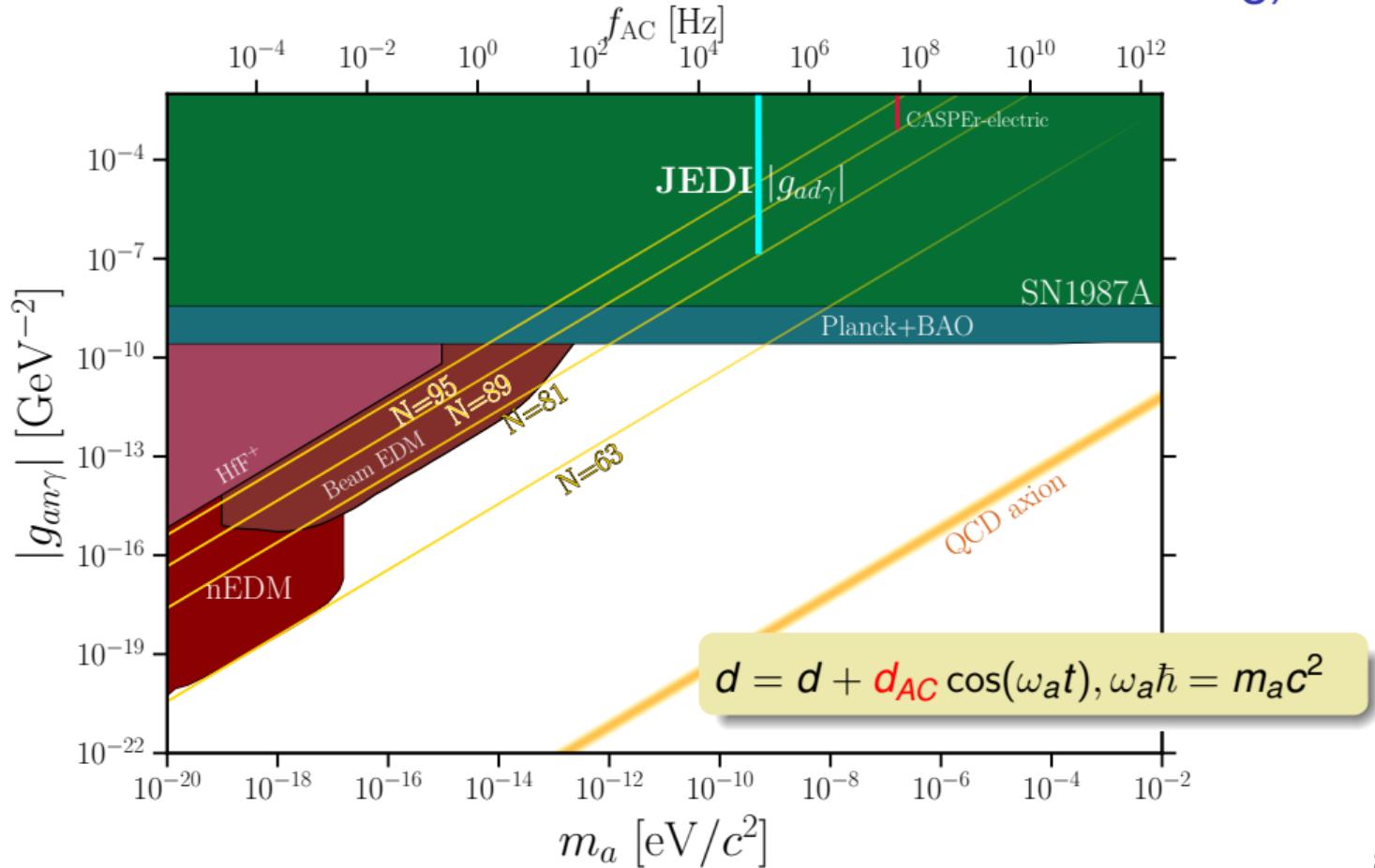


Impressive Limits, but no finite EDM found yet.

Perspectives

particle	current values	perspective
e^-	$-1.3 \pm 2.0(\text{stat}) \pm 0.6(\text{sys}) 10^{-29} e \cdot \text{cm}$	$1 \times 10^{-30} e \cdot \text{cm}$ (ACME)
μ	$-0.1 \pm 0.7(\text{stat}) \pm 1.2(\text{sys}) 10^{-19} e \cdot \text{cm}$ (μ^+)	$1 \times 10^{-21} e \cdot \text{cm}$ (FNAL,J-PARC)
	$-0.1 \pm 0.3(\text{stat}) \pm 0.7(\text{sys}) 10^{-19} e \cdot \text{cm}$ (μ^-)	$6 \times 10^{-23} e \cdot \text{cm}$ (PSI)
n	$0.0 \pm 1.1(\text{stat}) \pm 0.2(\text{sys}) 10^{-26} e \cdot \text{cm}$	$1 \times 10^{-28} e \cdot \text{cm}$ (n2EDM, PSI) $1 \times 10^{-27} e \cdot \text{cm}$ (TRIUMF)
p	$1.7 \times 10^{-25} e \cdot \text{cm}$ (90% CL, p)	$1 \times 10^{-29} e \cdot \text{cm}$ (storage ring)
	$-2.20 \pm 2.75(\text{stat}) \pm 1.48(\text{sys}) 10^{-30} e \cdot \text{cm}$ (Hg)	
Λ	$-3.0 \pm 7.4(\text{stat}) \pm ?(\text{sys}) 10^{-17} e \cdot \text{cm}$	$1.3 \times 10^{-18} e \cdot \text{cm}$ (LHC)
Λ_c^+, Ξ_c^+		$2.1 \times 10^{-17} e \cdot \text{cm}$ (LHC, bent crystals)
deuteron		$1 \times 10^{-17} e \cdot \text{cm}$ (COSY, magnetic ring)

Contribution to dark matter search (axion-gluon coupling)



Summary

Summary

- EDMs are unique probe to search for new CP-violating interactions and contribute to axion/ALP searches
- Measurements on as many particle species needed to understand fundamental interaction
- Already now impressive upper limits, but no non-zero effect yet
- Many plans for future experiments

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