High-sensitivity hadronic EDM Exp. with the hybrid/symmetric lattice

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XXVI Cracow Epiphany on Future of Particle Physics

Cracow (virtual), January 7-10, 2021

- Statistics for better than 10^{-29} *e*-cm for pEDM
- Matching systematics greatly reduced by symmetries

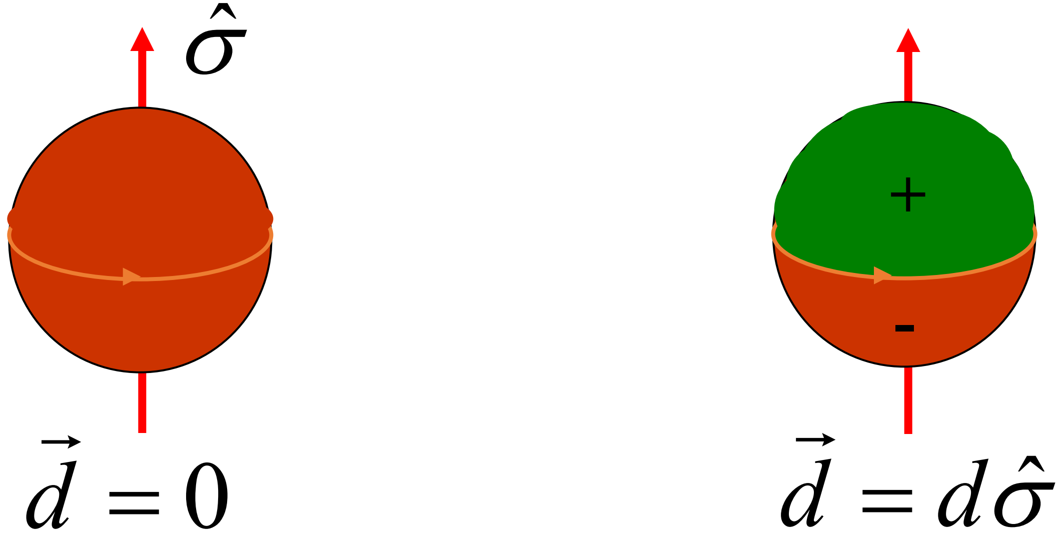
Outline

- Motivation
- Status of EDMs
- Storage ring EDM options
- Systematics with hybrid and hybrid symmetric lattices

Motivation of pEDM at 10^{-29} *e*-cm

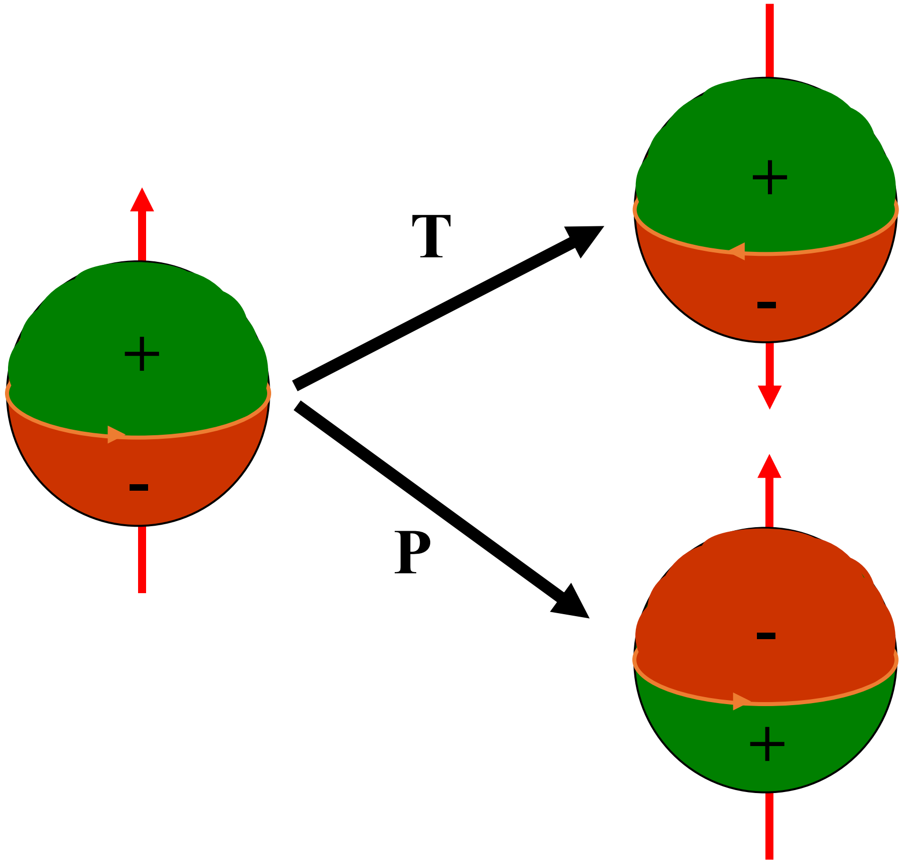
- Probe New Physics, at $>10^3$ TeV mass scale, Higgs CPV
- Improve sensitivity to θ_{QCD} by three orders of magnitude
- Together with ARIADNE probe high frequency axion dark matter
- Direct search for low frequency axion dark matter

EDM in systems with spin



The particle spin generates a magnetic dipole moment. If it also generates an EDM, then both P and T symmetries are violated

A Permanent EDM Violates both T & P Symmetries:



WRONG!

Electric Dipole Moments: P and T-violating when $\vec{d}$// to spin

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s},$$

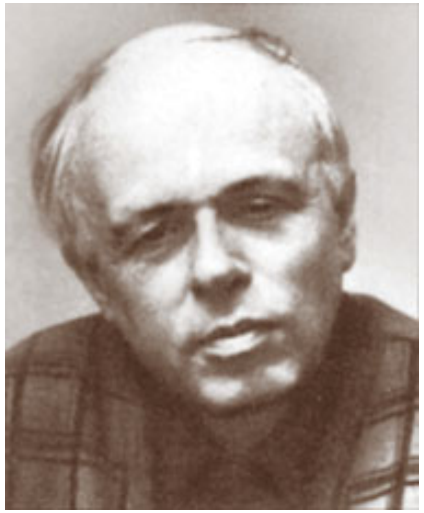
$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

T-violation: assuming CPT cons. → CP-violation

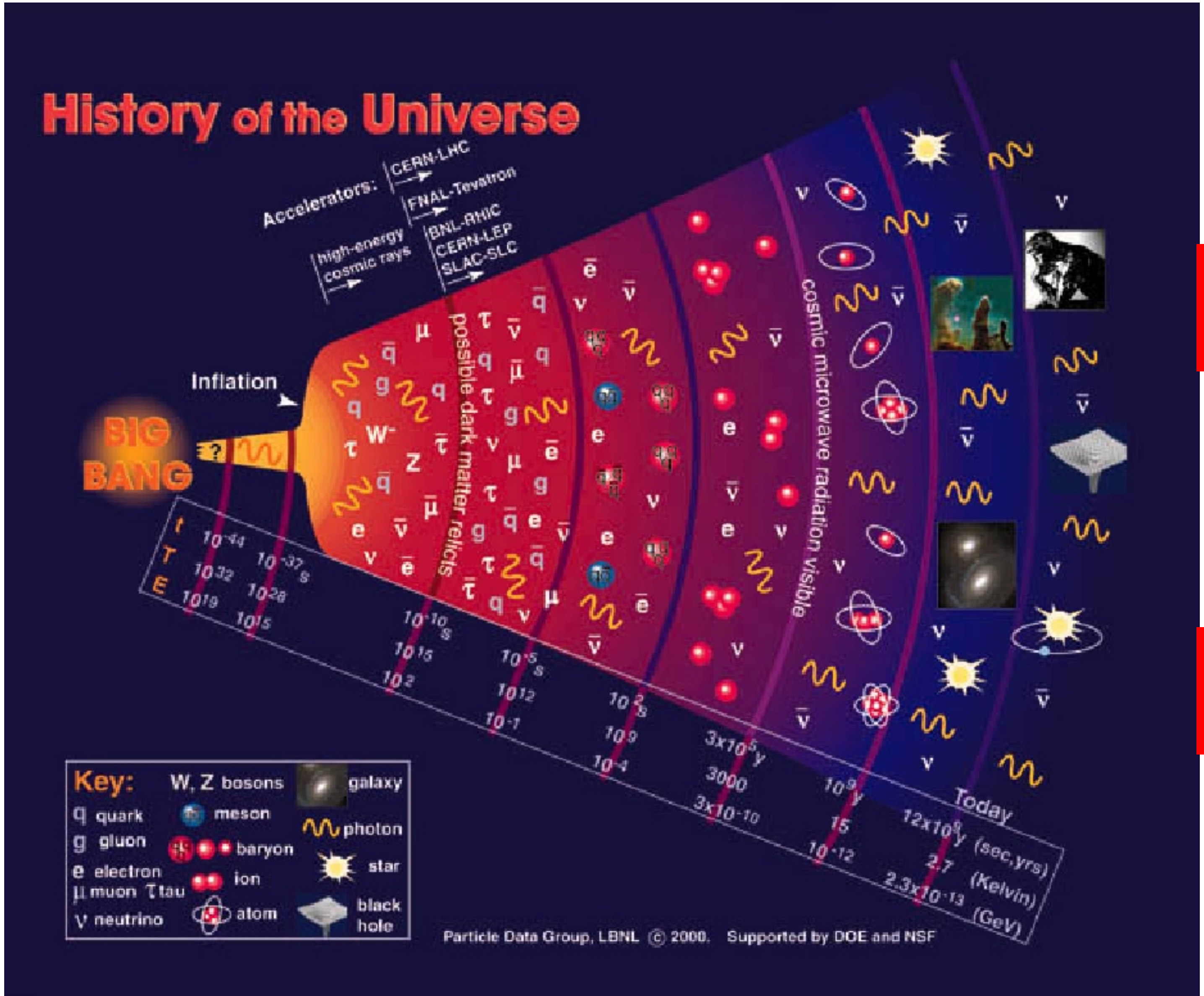
$$\text{T-Violation} \xrightarrow{\text{CPT}} \text{CP-Violation}$$



Andrei Sakharov 1967:

CP-Violation is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today....

Why is there so much matter after the Big Bang:



We see:

$$\frac{n_B}{n_\gamma} \approx (6.08 \pm 0.14) \times 10^{-10}$$

From the SM:

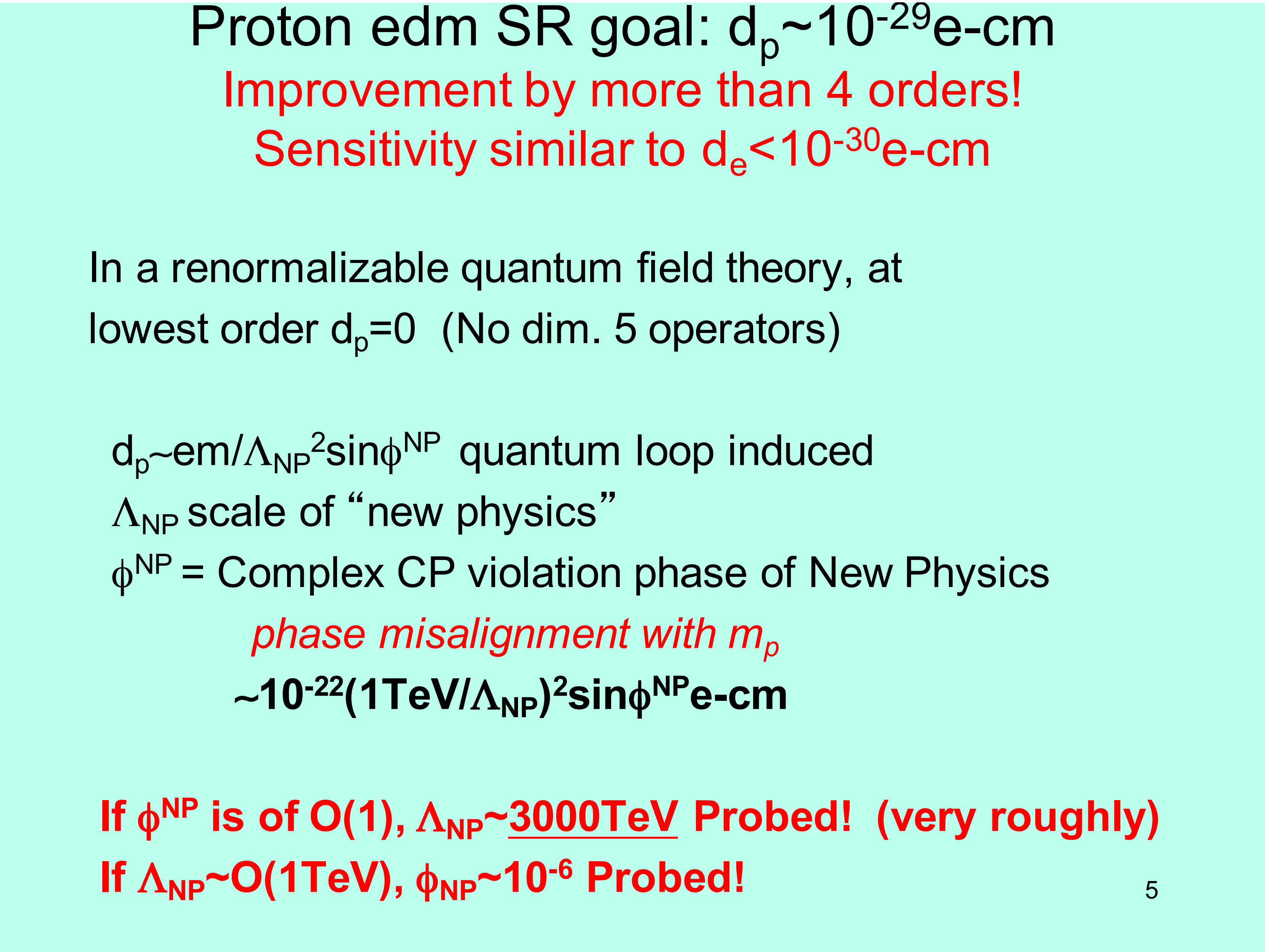
$$\frac{n_B}{n_\gamma} \approx 10^{-18}$$

Purcell and Ramsey:

"The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle…becomes a purely experimental matter"

Phys. Rev. 78 (1950)

Bill Marciano
Snowmass Workshop,
September 15, 2020



Proton edm SR goal: $d_p \sim 10^{-29}$e-cm

Improvement by more than 4 orders!
Sensitivity similar to $d_e < 10^{-30}$e-cm

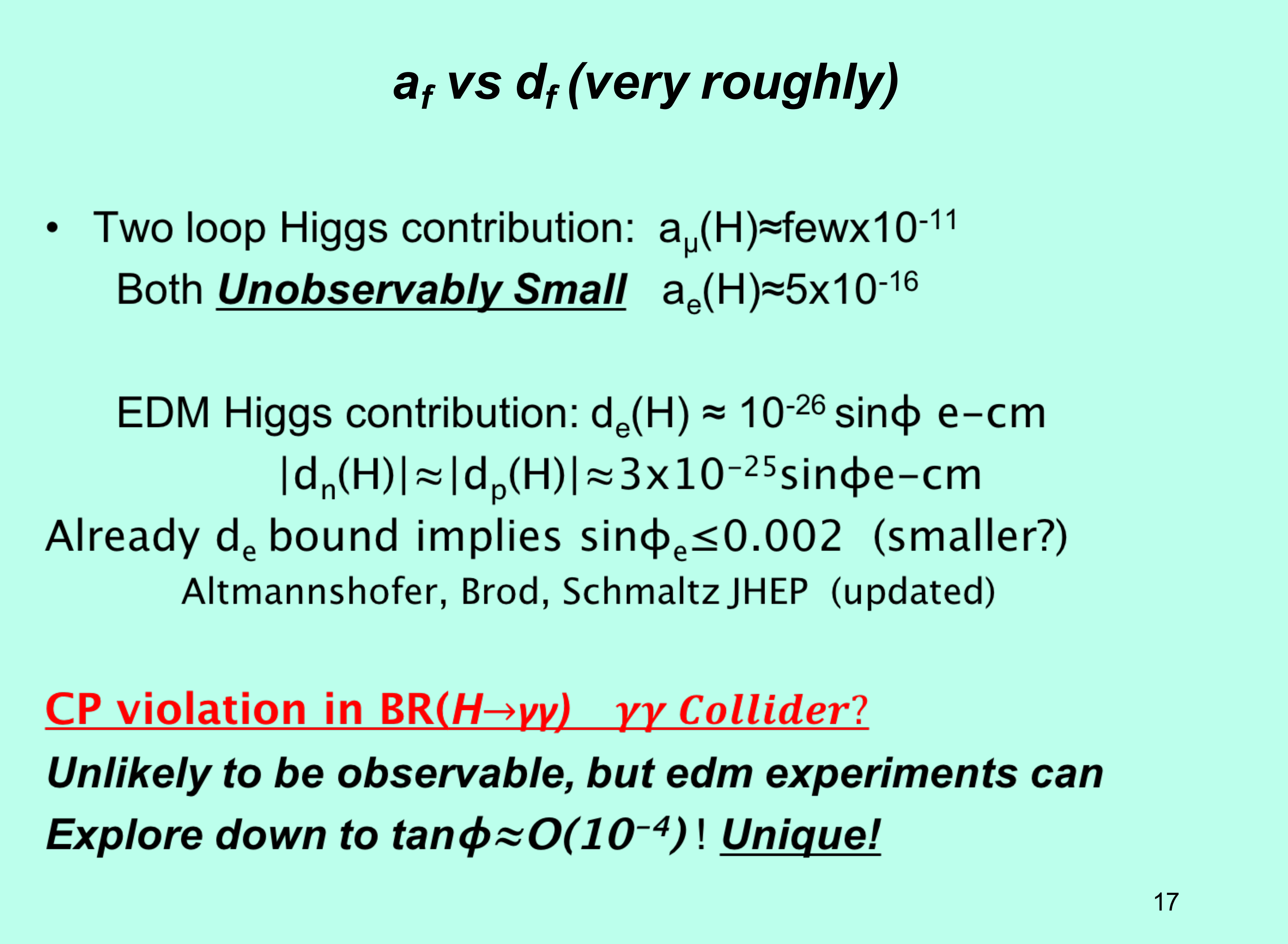
In a renormalizable quantum field theory, at lowest order $d_p = 0$ (No dim. 5 operators)

$d_p \sim em/\Lambda_{NP}^2 \sin\phi^{NP}$ quantum loop induced
Λ_{NP} scale of “new physics”
ϕ^{NP} = Complex CP violation phase of New Physics

phase misalignment with m_p

$\sim 10^{-22}(1\mathrm{TeV}/\Lambda_{NP})^2 \sin\phi^{NP}$e-cm

If ϕ^{NP} is of O(1), $\Lambda_{NP} \sim$ 3000TeV Probed! (very roughly)
If $\Lambda_{NP} \sim$ O(1TeV), $\phi_{NP} \sim 10^{-6}$ Probed!



a_f vs d_f (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx$ fewx10^{-11}

  Both ***Unobservably Small*** $a_e(H) \approx 5 \times 10^{-16}$

EDM Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e−cm

$|d_n(H)| \approx |d_p(H)| \approx 3 \times 10^{-25} \sin\phi$e−cm

Already d_e bound implies $\sin\phi_e \leq 0.002$ (smaller?)

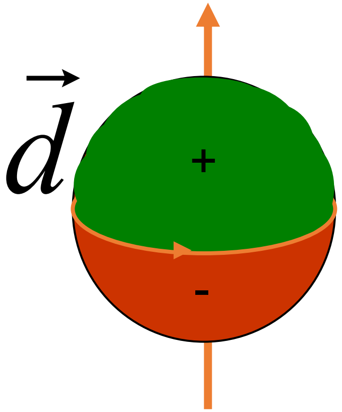
Altmannshofer, Brod, Schmaltz JHEP (updated)

CP violation in BR($H \rightarrow \gamma\gamma$) *γγ Collider*?

Unlikely to be observable, but edm experiments can

Explore down to tan$\phi \approx O(10^{-4})$! Unique!

The Electric Dipole Moment precesses in an Electric field



The EDM vector *d* is induced by the particle spin

$$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$$

Important attributes of an EDM Experiment

1. Polarization: state preparation, intensity of beams (statistics)

2. Interaction with an E-field: the higher the better (statistics)

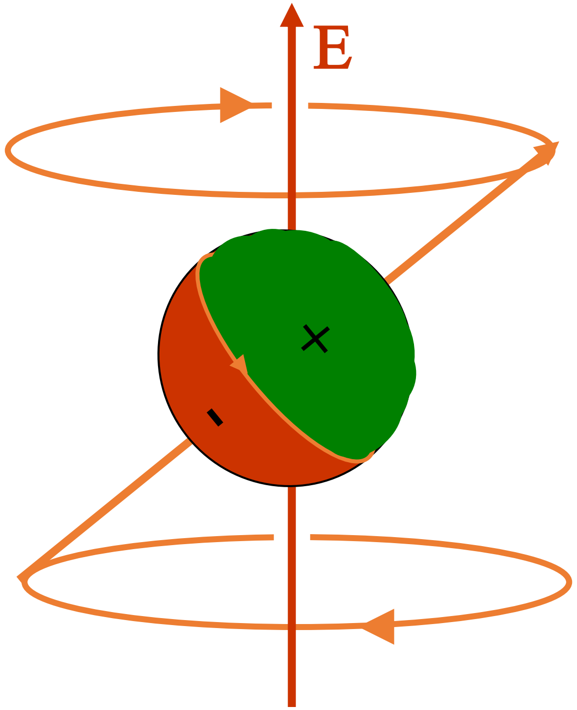
3. Analyzer: high efficiency analyzer (statistics)

4. Symmetry tools: combat systematic errors

5. Scientific Interpretation of Result! Easier for the simpler systems

Spin precession at rest

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$



Compare the Precession Frequencies with E-field Flipped:

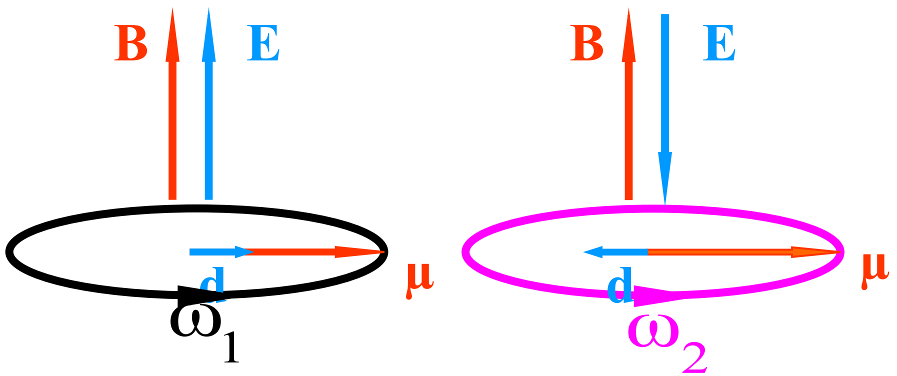
$$\hbar(\omega_1 - \omega_2) = 4dE$$

$$\boxed{\sigma_d \propto \frac{1}{EPA} \frac{1}{\sqrt{N\tau T}}}$$

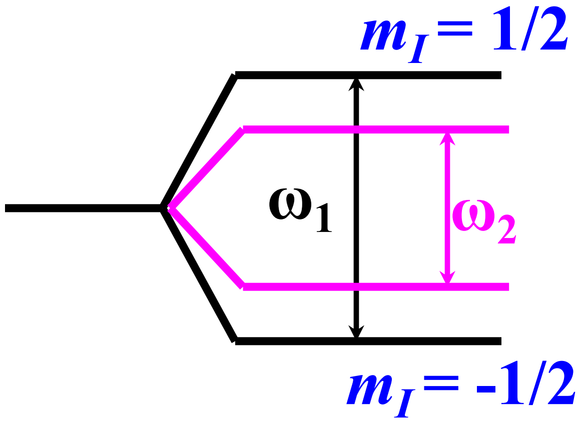
Yannis Semertzidis

Measuring an EDM of Neutral Particles

$$H = -(d\,E + \mu\,B) \bullet I/I$$



$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$



$$d = \frac{\hbar(\omega_1 - \omega_2)}{4E}$$

d = 10^{-28} e cm
E = 200 kV/cm

⇒ **δω = 10^{-7} rad/s →**
~1 turn/year

^{3}He Co-magnetometer

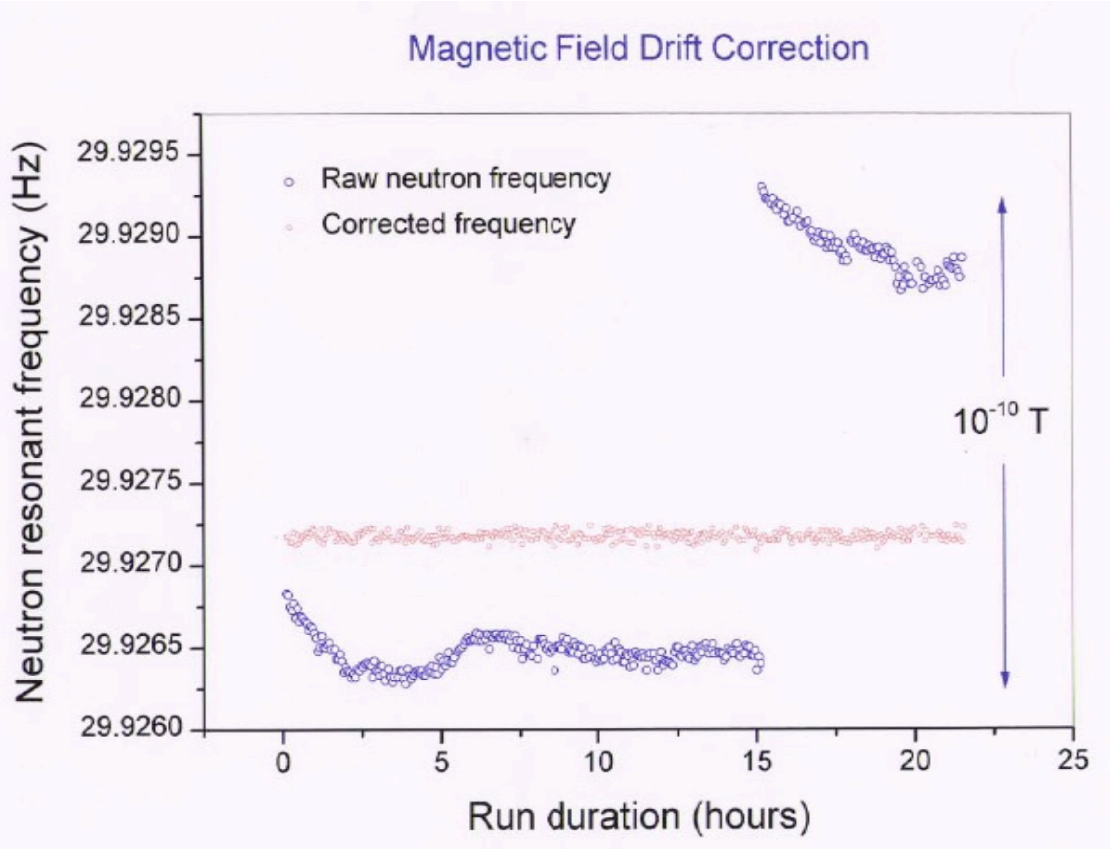
If nEDM = 10^{-26} e·cm,

10 kV/cm → 0.1 μHz shift

≅ B field of 2×10^{-15} T.

Co-magnetometer :

Uniformly samples the B Field faster than the relaxation time.



Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ Z^2 → ^{3}He EDM << 10^{-30} e-cm

Under gravity, the center of mass of He-3 is higher than UCN by Δh ≈ 0.13 cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B = 10^{-3}$.

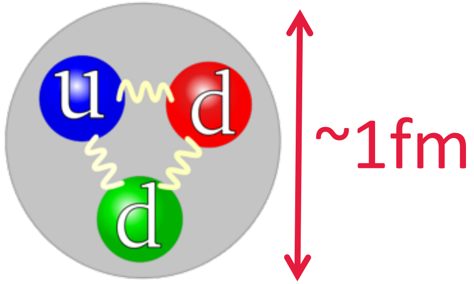
Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta}\ \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

The QCD Lagrangrian contains a theta-term violating both P-parity and T-time reversal symmetries.

Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta}\ \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times10^{-17}\right)\mathrm{e}\cdot\mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times10^{-16}\,\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

$$\text{Exp.: } d_n < 3\times10^{-26} e\cdot\mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

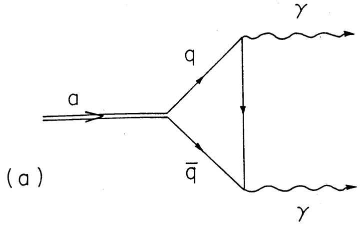
In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least ~9-10 orders of magnitude less! WHY?

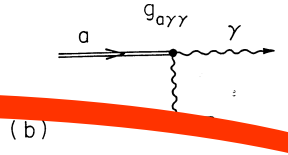
Strong CP-problem

$$L_{QCD,\bar{\theta}} = \left(\bar{\theta} - \frac{a\left(x\right)}{f_a}\right)\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), *$a(x)/f_a$*. It goes to zero naturally

Axion Couplings





- Gauge fields:
  - Electromagnetic fields
  -
  - Gluon Fields (Oscillating EDM,…)

$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Input to hadronic EDM

- Theta-QCD (part of the SM)
- CP-violation sources beyond the SM

A number of alternative simple systems could provide invaluable complementary information (e.g. neutron, proton, deuteron,…).

- At 10^{-29}e•cm pEDM is at least an order of magnitude more sensitive than the current nEDM plans

EDMs of different systems

Theta_QCD:

$$d_n \simeq -d_p \simeq 3\times10^{-16}\,\bar{\theta}\ \mathrm{e\cdot cm}$$

$$d_D\left(\bar{\theta}\right)/d_N\left(\bar{\theta}\right) \approx 1/3$$

Super-Symmetry (SUSY) model predictions:

$$d_n \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) - 0.27e\left(d_u^c - d_d^c\right)$$

$$d_p \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right)$$

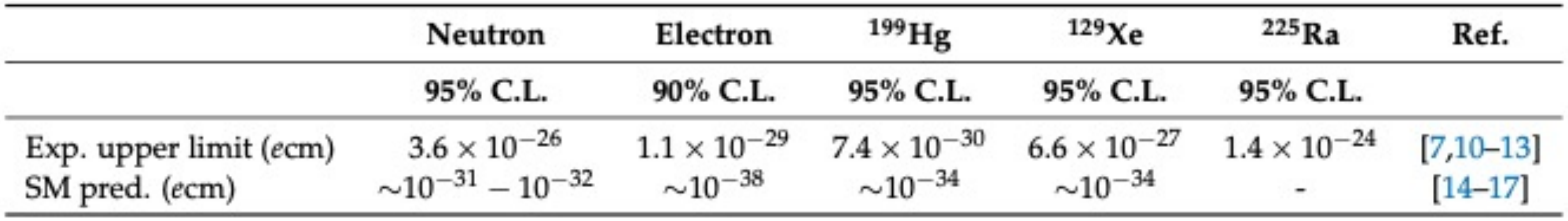
$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right)$$

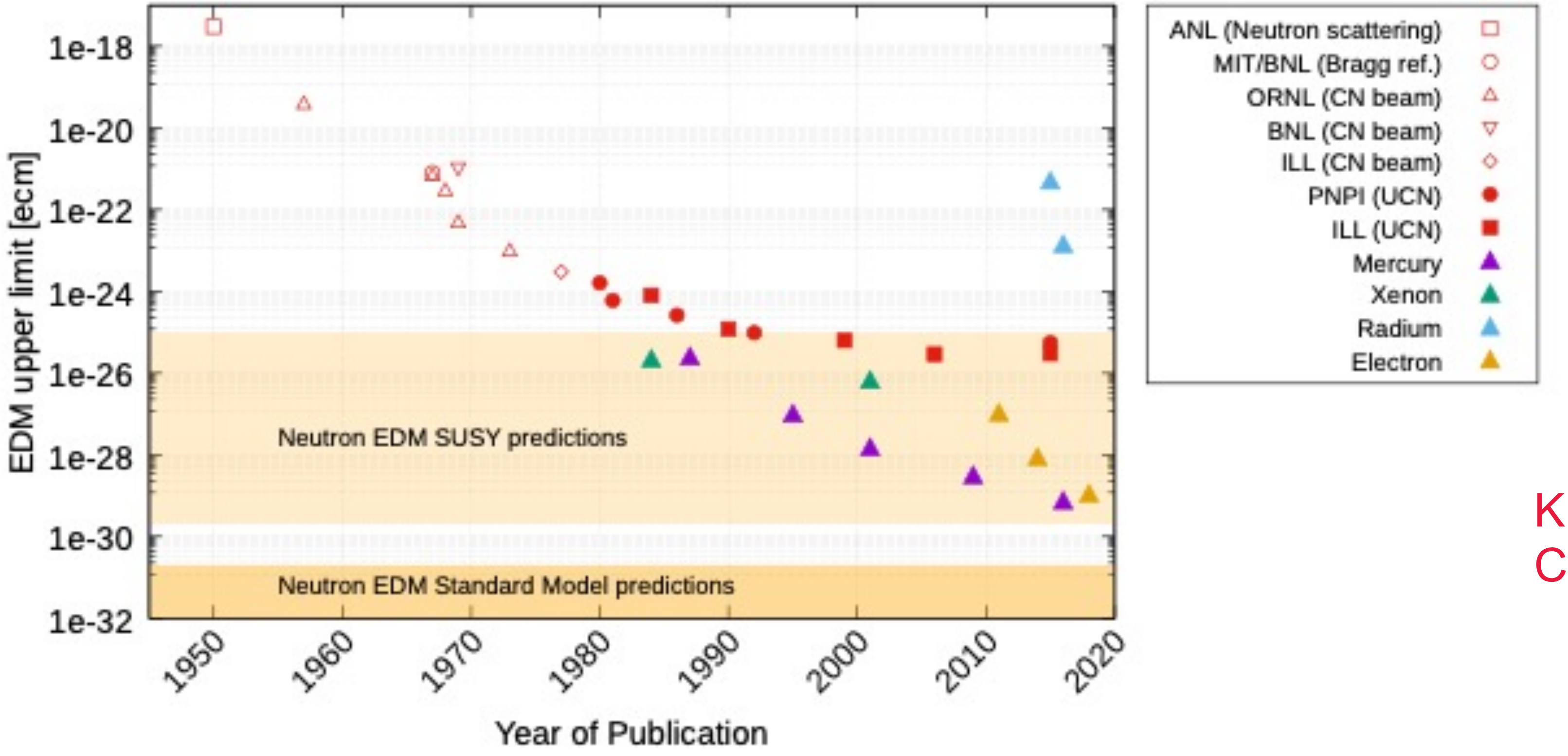
$$d_N^{I=1} = \left(d_p - d_n\right)/2$$

$$d_N^{I=0} = \left(d_p + d_n\right)/2$$

Recent EDM experimental limits

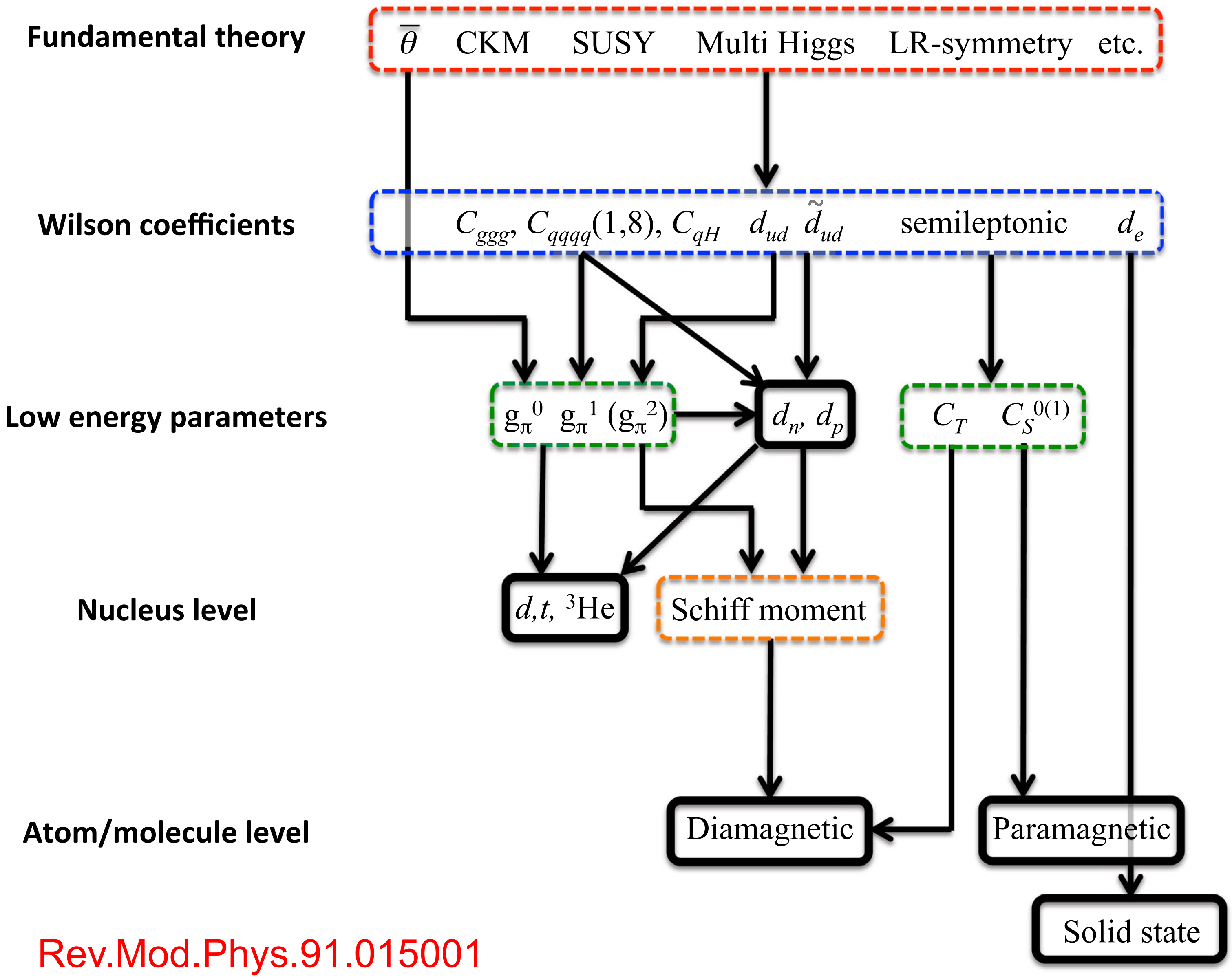


	Neutron	Electron	^{199}Hg	^{129}Xe	^{225}Ra	Ref.
	95% C.L.	90% C.L.	95% C.L.	95% C.L.	95% C.L.	
Exp. upper limit (*e*cm)	3.6×10^{-26}	1.1×10^{-29}	7.4×10^{-30}	6.6×10^{-27}	1.4×10^{-24}	[7,10–13]
SM pred. (*e*cm)	$\sim 10^{-31} - 10^{-32}$	$\sim 10^{-38}$	$\sim 10^{-34}$	$\sim 10^{-34}$	-	[14–17]



Kuchler (TUCAN and HeXeEDM Collaborations, 2019)

Physics of EDMs



Fundamental theory

$\bar{\theta}$ CKM SUSY Multi Higgs LR-symmetry etc.

Wilson coefficients

C_{ggg}, $C_{qqqq}(1,8)$, C_{qH} d_{ud} $\tilde{d}_{ud}$ semileptonic d_e

Low energy parameters

g_π^0 g_π^1 (g_π^2) d_n, d_p C_T $C_S^{0(1)}$

Nucleus level

d, t, ^{3}He Schiff moment

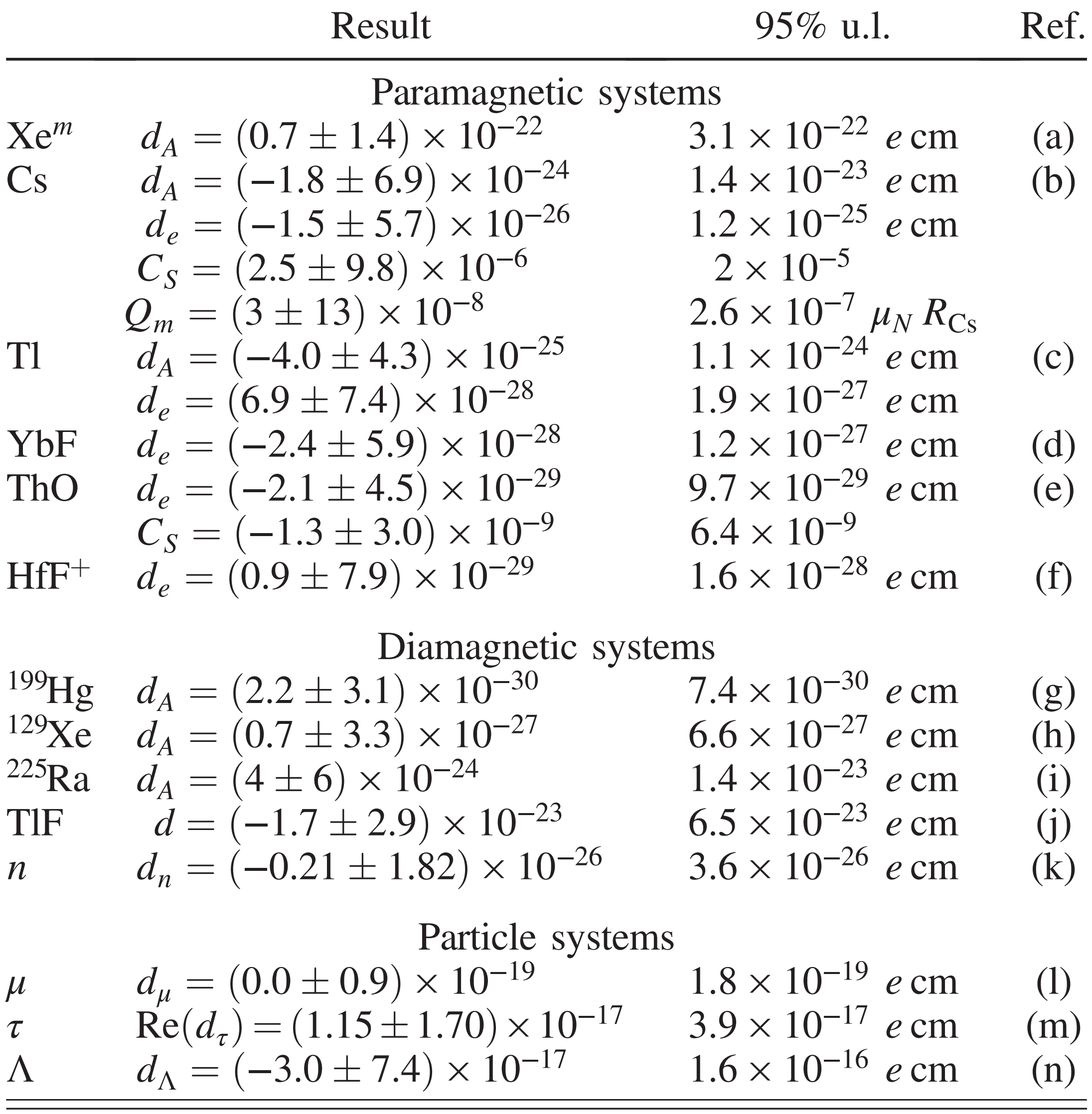
Atom/molecule level

Diamagnetic Paramagnetic

Solid state

Rev.Mod.Phys.91.015001

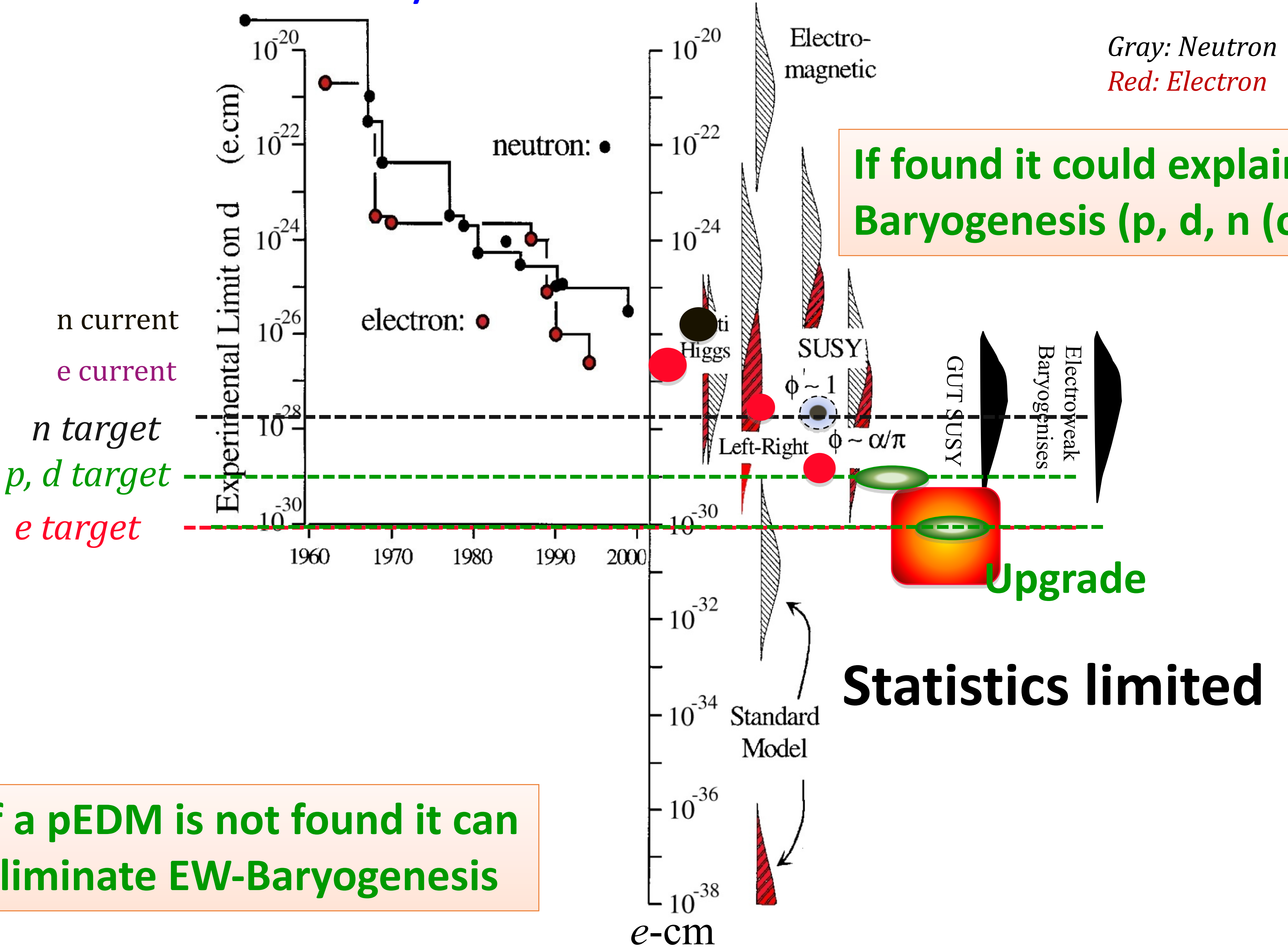
Current EDM limits



	Result	95% u.l.	Ref.
	Paramagnetic systems		
Xe^m	$d_A = (0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e cm	(a)
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23} e cm	(b)
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25} e cm	
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7} $\mu_N R_{\mathrm{Cs}}$	
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24} e cm	(c)
	$d_e = (6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27} e cm	
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e cm	(d)
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29} e cm	(e)
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28} e cm	(f)
	Diamagnetic systems		
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e cm	(g)
$^{129}\mathrm{Xe}$	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27} e cm	(h)
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e cm	(i)
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e cm	(j)
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26} e cm	(k)
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e cm	(l)
τ	$\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17} e cm	(m)
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16} e cm	(n)

Rev.Mod.Phys.91.015001

Sensitivity to Rule on Several New Models



Gray: Neutron
Red: Electron

If found it could explain Baryogenesis (p, d, n (or ^{3}He))

Statistics limited

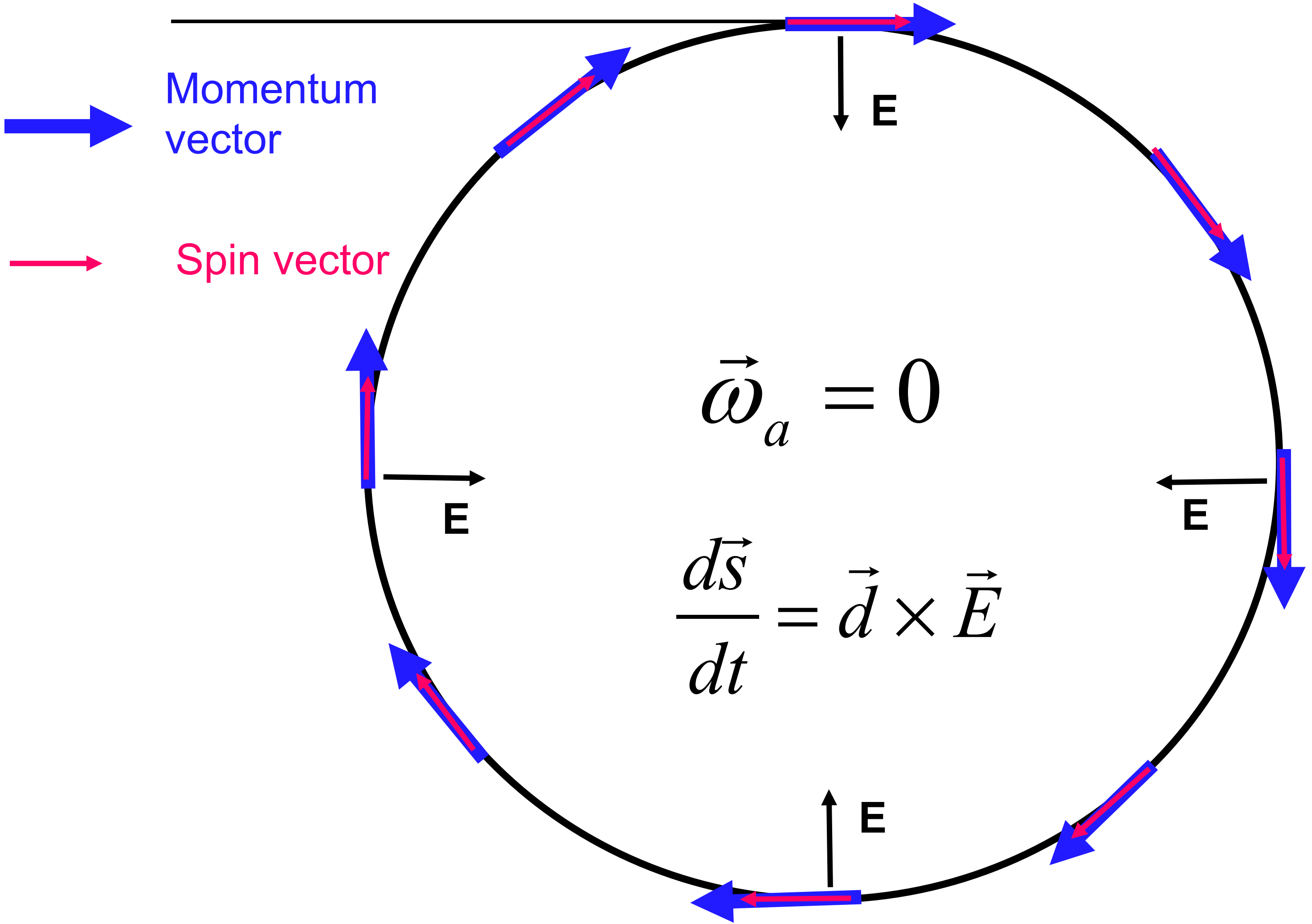
If a pEDM is not found it can eliminate EW-Baryogenesis

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<7\times10^{-30}$	$<10^{-30}$	10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-29}$-10^{-31}	10^{-25}-10^{-27}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<2\times10^{-25}$	$\sim10^{-29}$	10^{-29}

The sensitivity to EDM is optimum when the spin vector is kept aligned to the momentum vector



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

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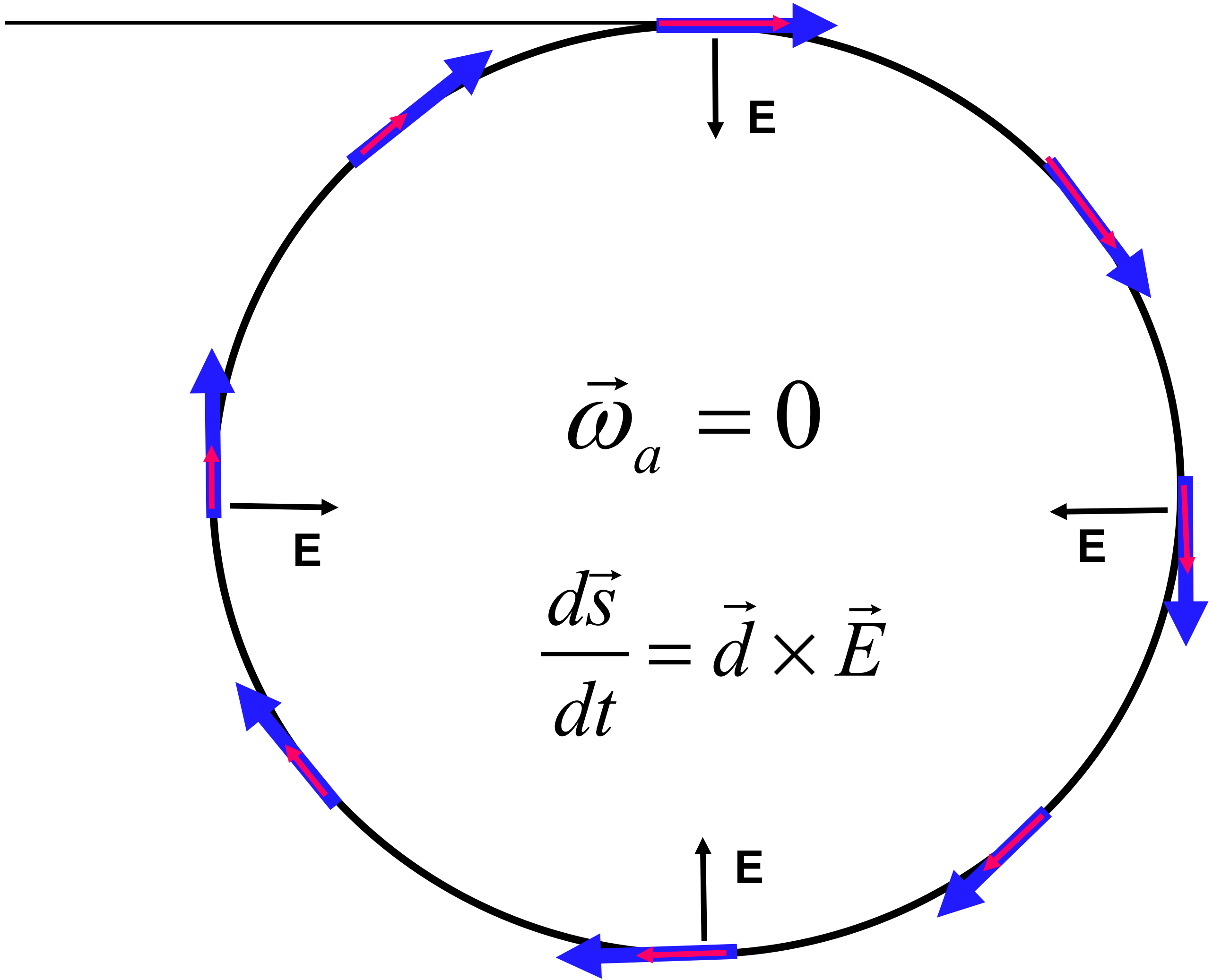
The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM (*d*) signal.



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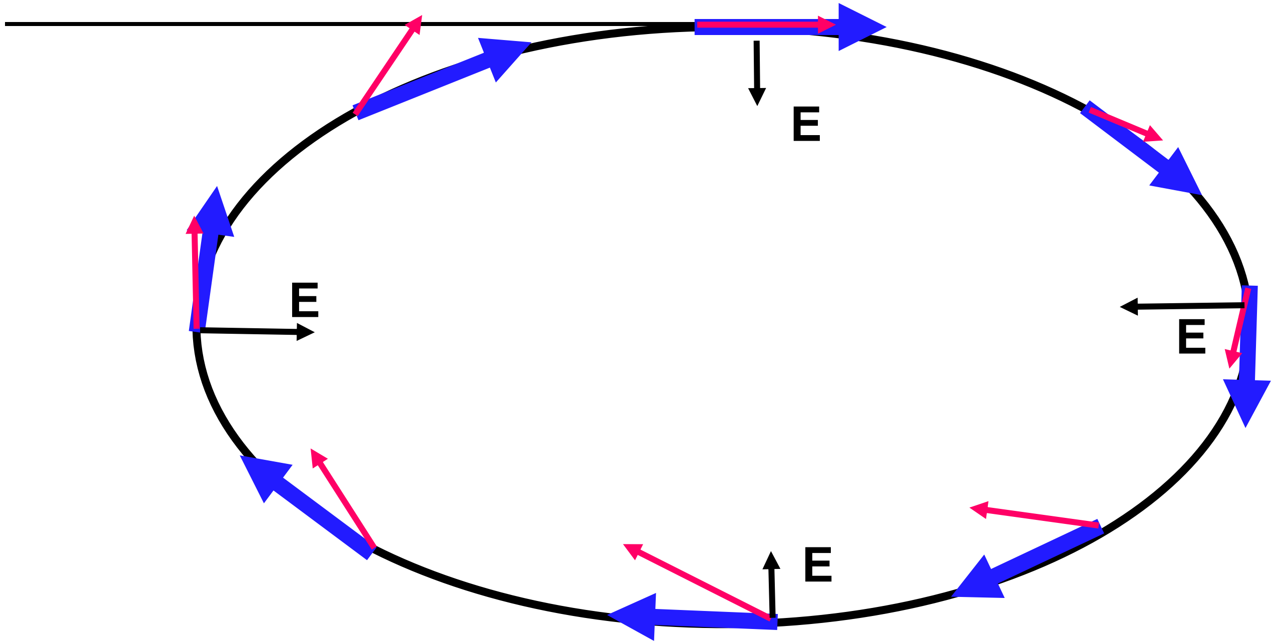


$$\vec{\omega}_a = 0 \qquad \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Freezing the horizontal spin precession

$$\vec{\omega}_a = \frac{e}{m}\left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta}\times\vec{E}$$

- The spin precession is zero at "magic" momentum (0.7 GeV/c for protons, 3.1GeV/c for muons,…)

$$p = \frac{m}{\sqrt{a}}, \text{ with } a = \frac{g-2}{2}$$

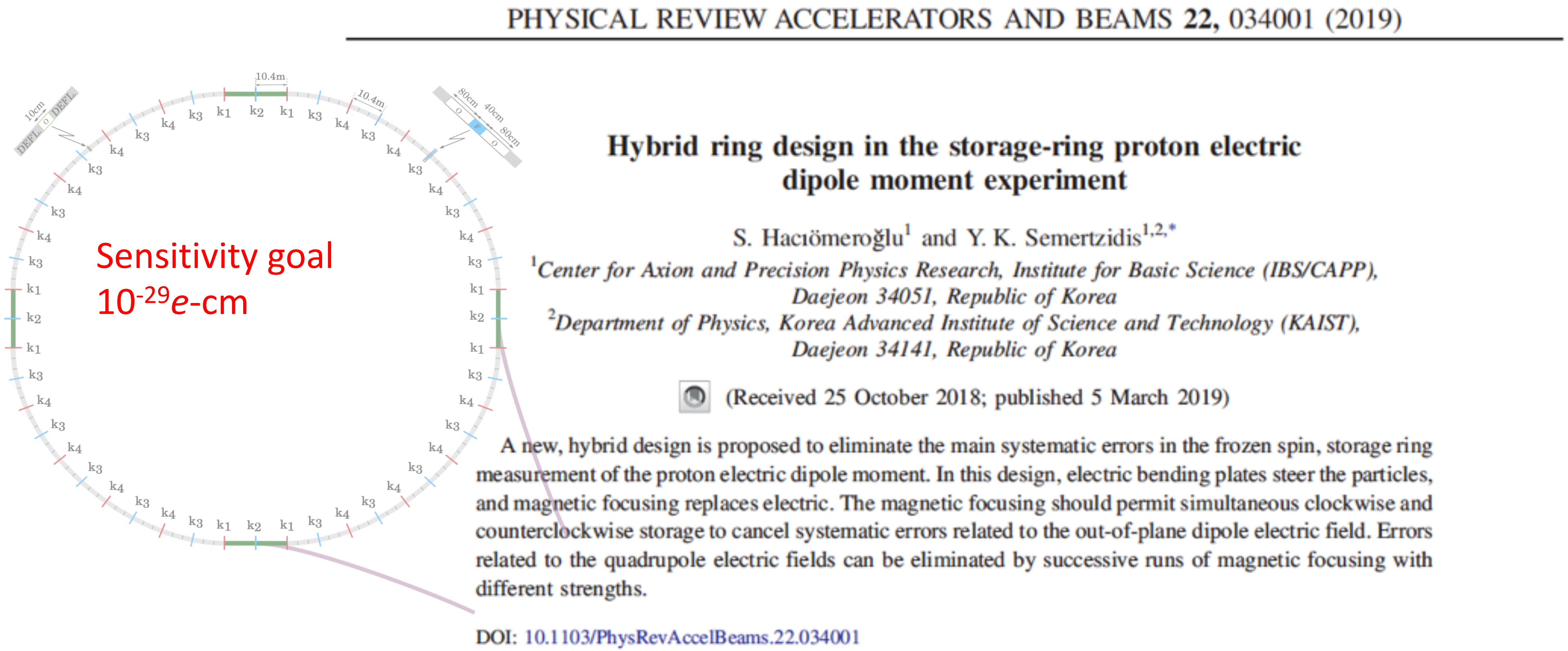
- The "magic" momentum concept was first used in the last muon g-2 experiment at CERN, at BNL & FNAL.

Storage Ring Electric Dipole Moments exp. options

Fields	**Example**	**EDM signal term**	**Comments**
Dipole magnetic field **(B)** **(Parasitic)**	Muon g-2	Tilt of the spin precession plane. **(Limited statistical sensitivity due to spin precession)**	Eventually limited by geometrical alignment. **Requires consecutive CW and CCW injection to eliminate systematic errors**
Combination of electric & and magnetic fields **(E, B)** **(Combined lattice)**	Deuteron, ^{3}He, proton, etc.	Mainly: $\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$	High statistical sensitivity. **Requires consecutive CW and CCW injection to eliminate systematic errors**
Radial Electric field **(E)** & Electric focusing **(E)** **(All electric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Requires demonstration of adequate sensitivity to radial B-field syst. error**
Radial Electric field **(E)** & Magnetic focusing **(B)** **(Hybrid, symmetric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Only lattice to achieve direct cancellation of main systematic error source**

Hybrid lattice storage ring

- It eliminates the main syst. error sources: ext. B-fields



Sensitivity goal
$10^{-29}e$-cm

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 034001 (2019)

Hybrid ring design in the storage-ring proton electric dipole moment experiment

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[1] *Center for Axion and Precision Physics Research, Institute for Basic Science (IBS/CAPP), Daejeon 34051, Republic of Korea*
[2] *Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea*

(Received 25 October 2018; published 5 March 2019)

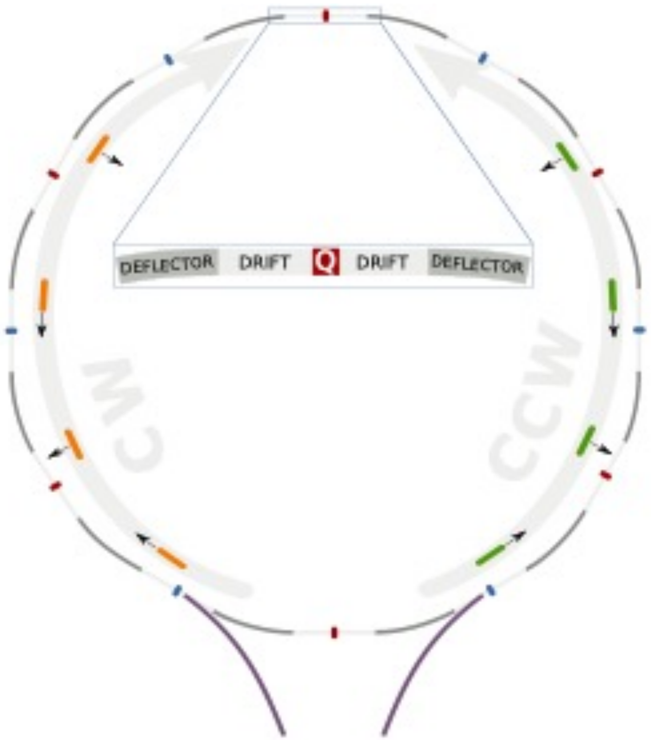
A new, hybrid design is proposed to eliminate the main systematic errors in the frozen spin, storage ring measurement of the proton electric dipole moment. In this design, electric bending plates steer the particles, and magnetic focusing replaces electric. The magnetic focusing should permit simultaneous clockwise and counterclockwise storage to cancel systematic errors related to the out-of-plane dipole electric field. Errors related to the quadrupole electric fields can be eliminated by successive runs of magnetic focusing with different strengths.

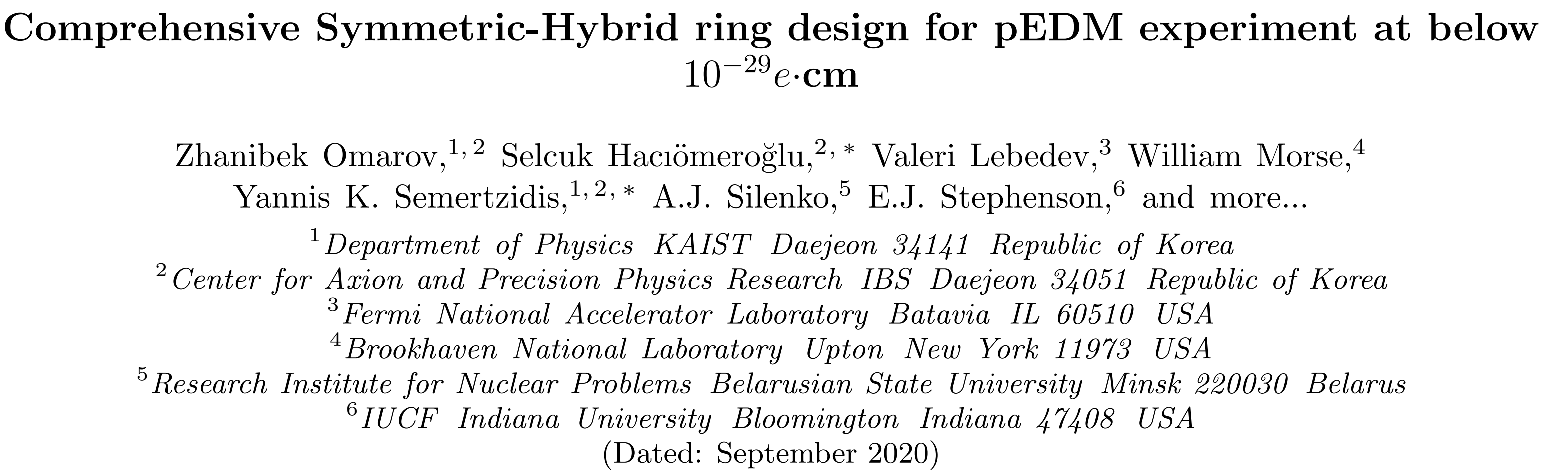
DOI: 10.1103/PhysRevAccelBeams.22.034001

Hybrid, symmetric lattice storage ring

- It eliminates the main syst. error sources: ext. B-fields
- Reduces major systematic error sources by several orders of magnitude

arXiv:2007.10332v2 [physics.acc-ph] 29 Dec 2020



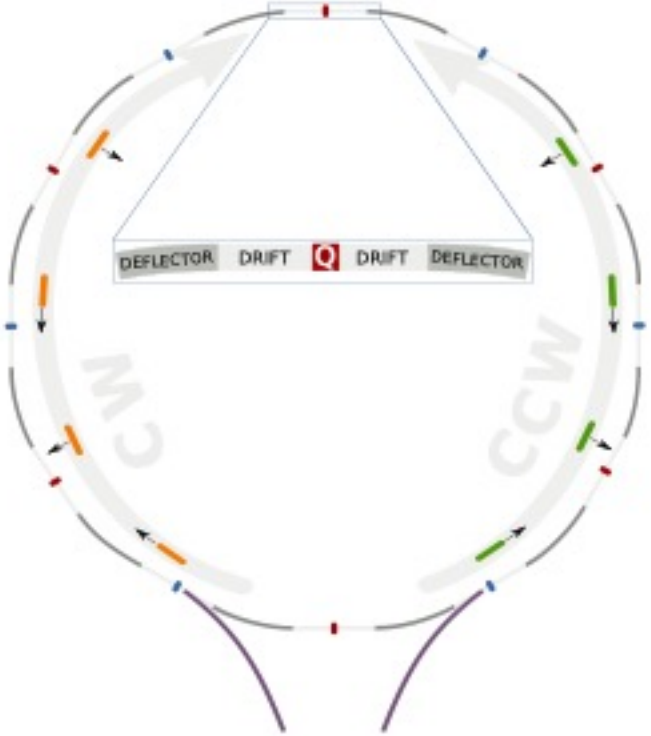


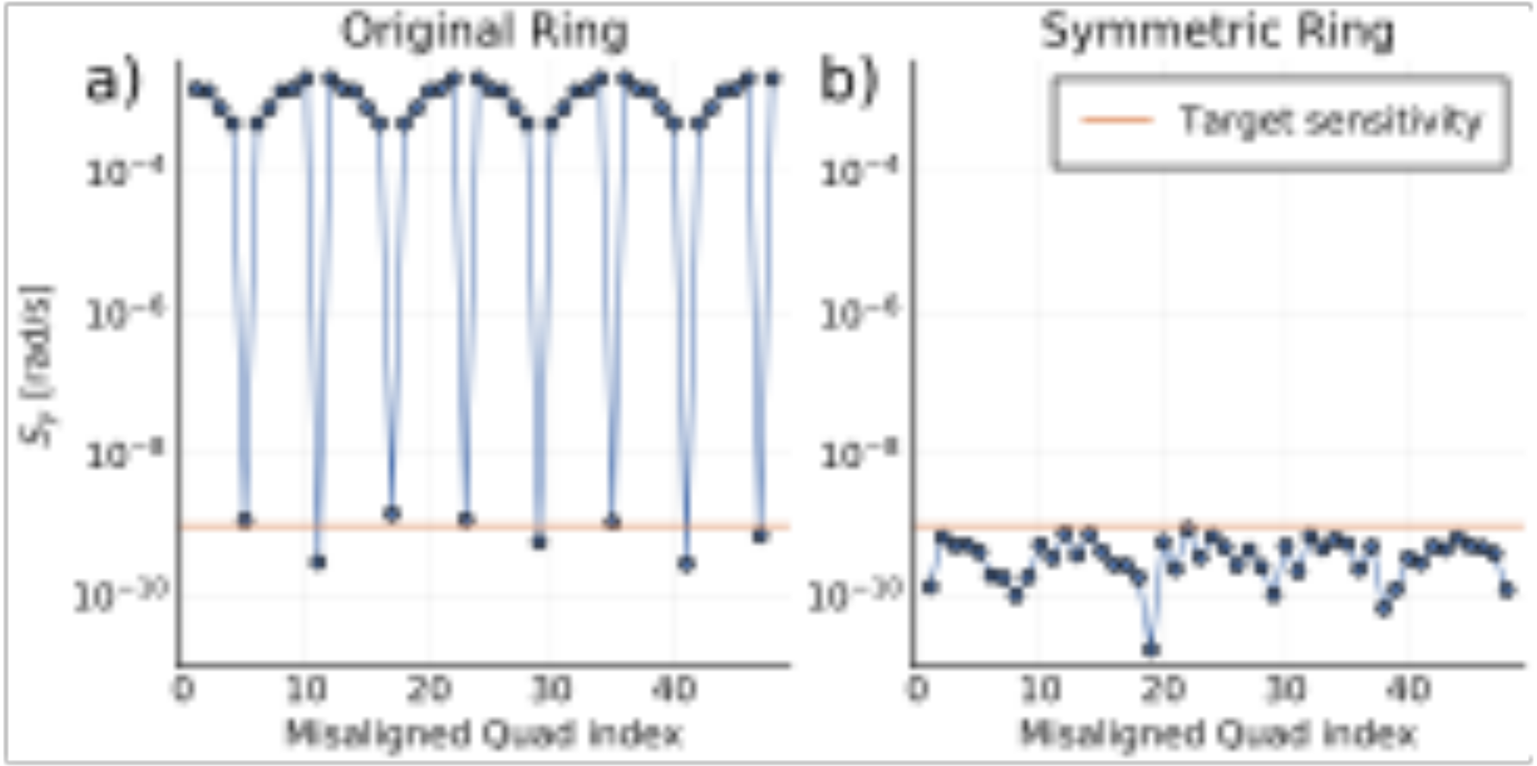
Comprehensive Symmetric-Hybrid ring design for pEDM experiment at below $10^{-29} e{\cdot}\mathrm{cm}$

Zhanibek Omarov,[1,2] Selcuk Hacıömeroğlu,[2,*] Valeri Lebedev,[3] William Morse,[4]
Yannis K. Semertzidis,[1,2,*] A.J. Silenko,[5] E.J. Stephenson,[6] and more...
[1] *Department of Physics KAIST Daejeon 34141 Republic of Korea*
[2] *Center for Axion and Precision Physics Research IBS Daejeon 34051 Republic of Korea*
[3] *Fermi National Accelerator Laboratory Batavia IL 60510 USA*
[4] *Brookhaven National Laboratory Upton New York 11973 USA*
[5] *Research Institute for Nuclear Problems Belarusian State University Minsk 220030 Belarus*
[6] *IUCF Indiana University Bloomington Indiana 47408 USA*
(Dated: September 2020)

Hybrid, symmetric lattice storage ring. Great for systematic error reduction.

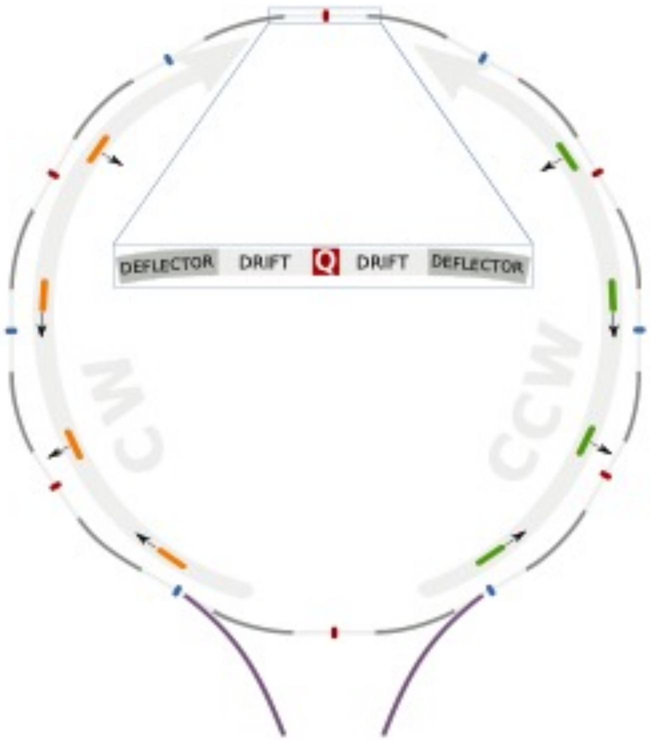
arXiv:2007.10332v2 [physics.acc-ph] 29 Dec 2020





Hybrid, symmetric lattice storage ring

arXiv:2007.10332v2 [physics.acc-ph] 29 Dec 2020



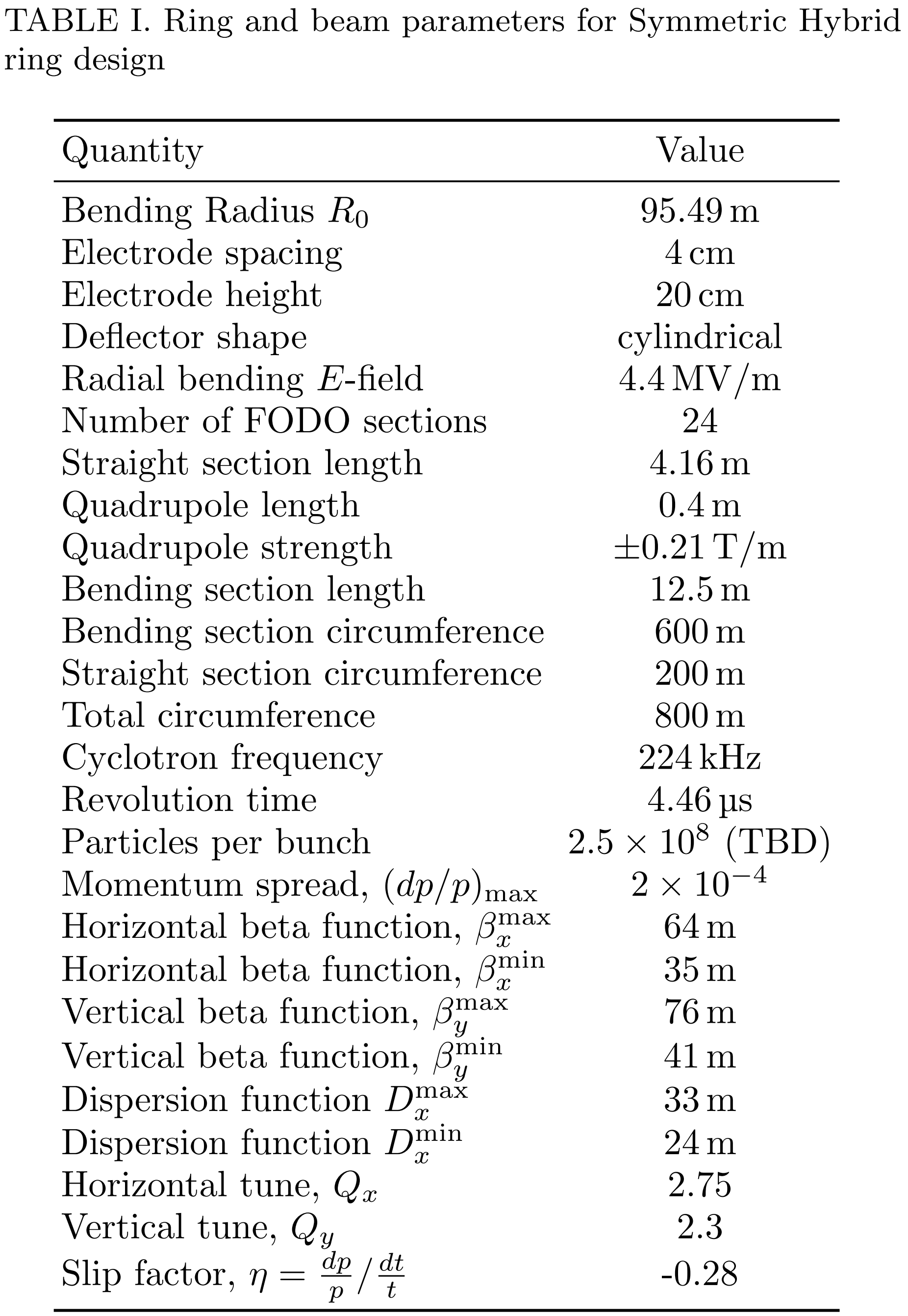
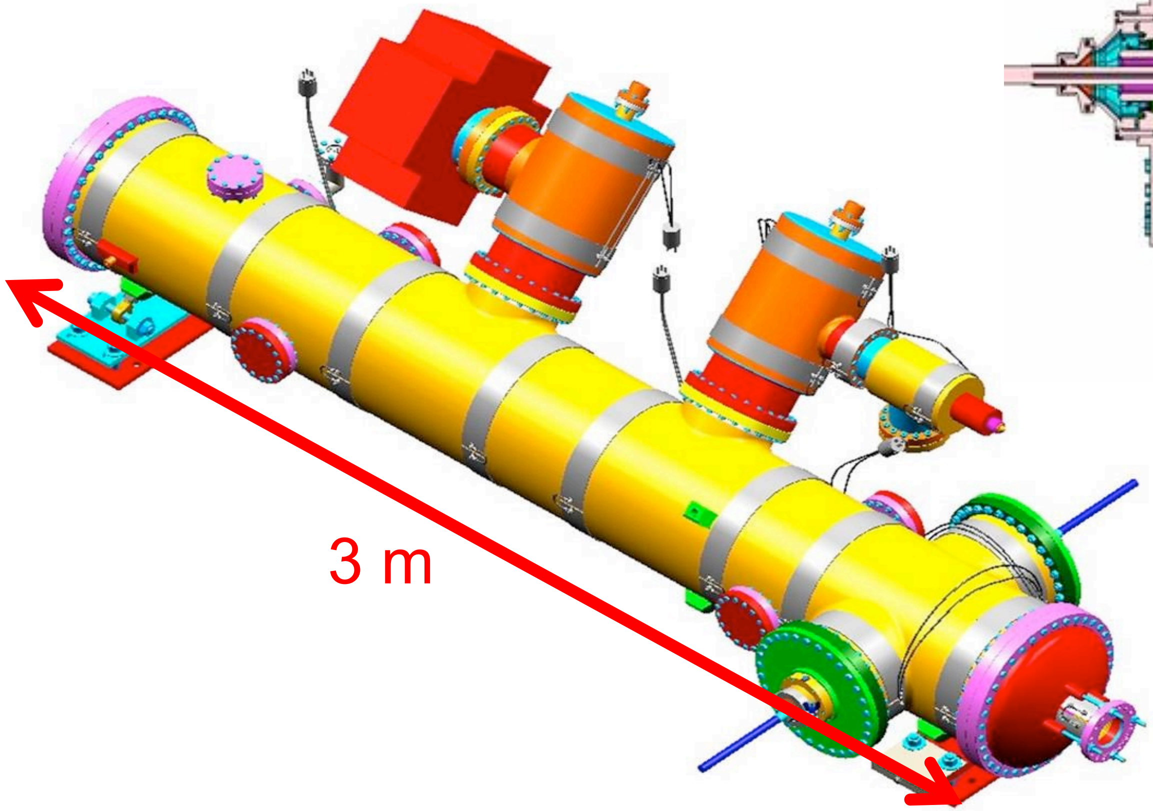
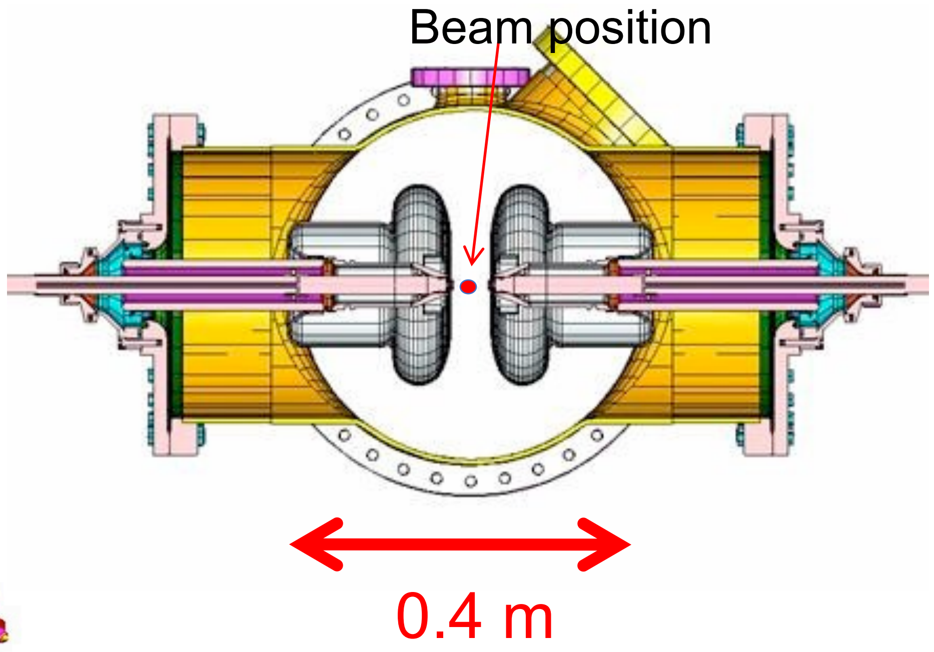


TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

Quantity	Value
Bending Radius R_0	95.49 m
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial bending E-field	4.4 MV/m
Number of FODO sections	24
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	±0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Straight section circumference	200 m
Total circumference	800 m
Cyclotron frequency	224 kHz
Revolution time	4.46 µs
Particles per bunch	2.5×10^8 (TBD)
Momentum spread, $(dp/p)_{\max}$	2×10^{-4}
Horizontal beta function, $\beta_x^{\max}$	64 m
Horizontal beta function, $\beta_x^{\min}$	35 m
Vertical beta function, $\beta_y^{\max}$	76 m
Vertical beta function, $\beta_y^{\min}$	41 m
Dispersion function $D_x^{\max}$	33 m
Dispersion function $D_x^{\min}$	24 m
Horizontal tune, Q_x	2.75
Vertical tune, Q_y	2.3
Slip factor, $\eta = \frac{dp}{p} / \frac{dt}{t}$	-0.28

E-field plate modules: The (26) FNAL Tevatron ES-separators ran for years with harder specs





Proton Statistical Error (230MeV): 10^{-29} *e*-cm

$$\boxed{\sigma_d = \frac{2\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}}$$

τ_p : 10^3s Polarization Lifetime (Spin Coherence Time)

A : 0.6 Left/right asymmetry observed by the polarimeter

P : 0.8 Beam polarization

N_c : 4×10^{10}p/cycle Total number of stored particles per cycle (10^3s)

T_{Tot}: 10^7s Total running time per year

f : 1% Useful event rate fraction (efficiency for EDM)

E_R : 4.5 MV/m Radial electric field strength

How the srEDM exp. at 10^{-29} *e*-cm works

- ✓Required radial E-field <5 MV/m, for 40mm plate separation

- ✓Beam and spin dynamics stable for required beam intensity

- ✓Spin coherence time estimated $>10^3$s

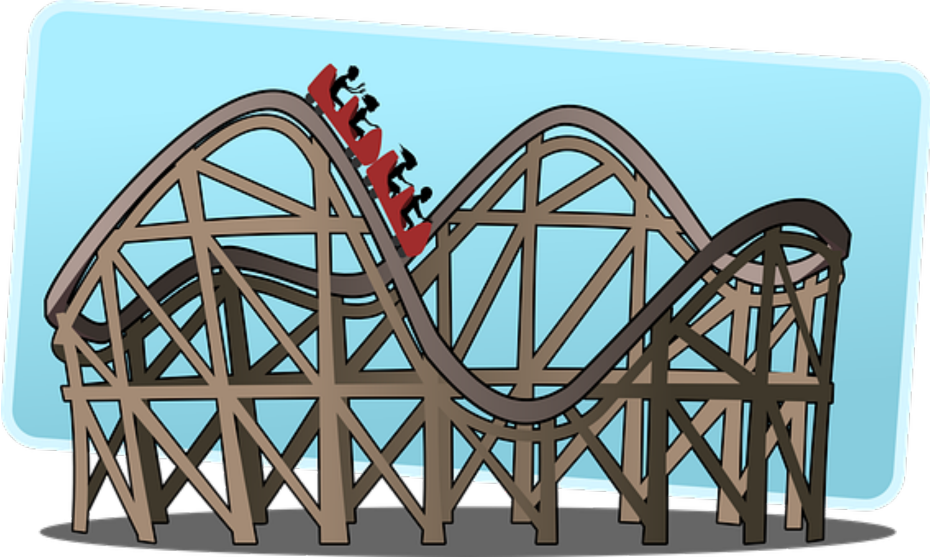
- ✓Alternate magnetic focusing all but eliminating external B-field sensitivity

- ✓Symmetric lattice significantly reducing systematic error sources

- ✓Required ring planarity <0.1mm; CW & CCW beam separation <0.01mm

Ring planarity critical to control geometrical phase errors

- The beam planarity requirement: <0.1mm, within existing technology
- Clock-wise (CW) and counter-clock-wise (CCW) beam storage split to <0.01mm. SQUID-based BPMs (S-BPM) resolution: 10nm/sqrt(Hz)!

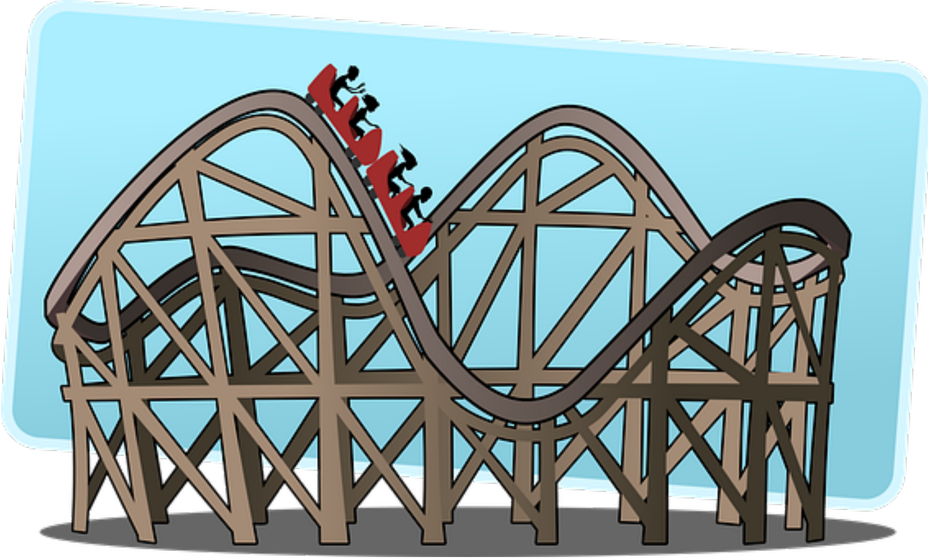


Ring planarity critical to control geometrical phase errors

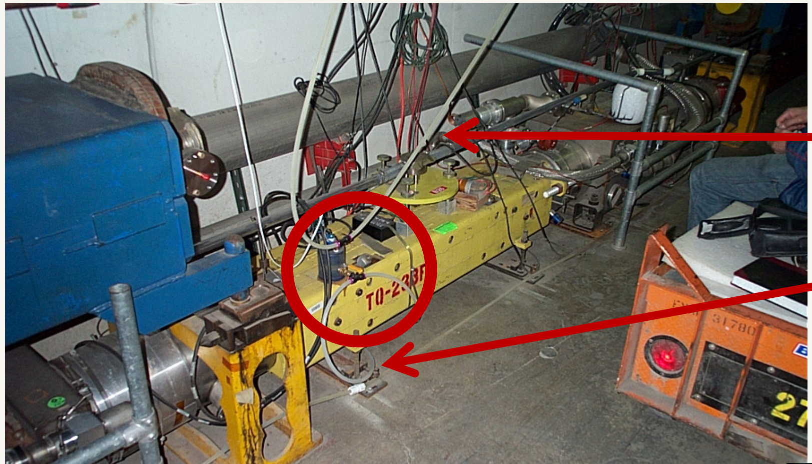
- Numerous studies on slow ground motion in accelerators, Hydrostatic Level System for slow ground motion studies at Fermilab.

- Thorough review by Vladimir Shiltsev (FNAL):

https://arxiv.org/pdf/0905.4194.pdf



Tevatron Sensors on Quad



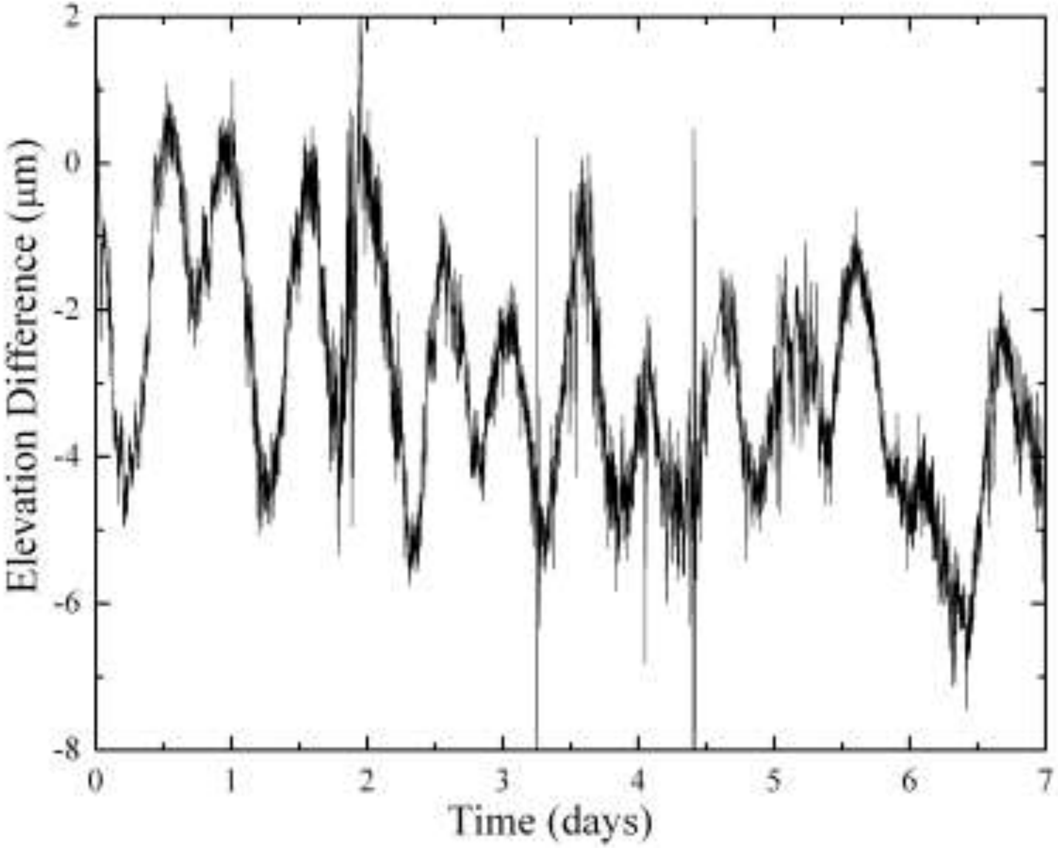
Air Line

Water line

In the circle is a water level pot on a Tevatron quadrupole

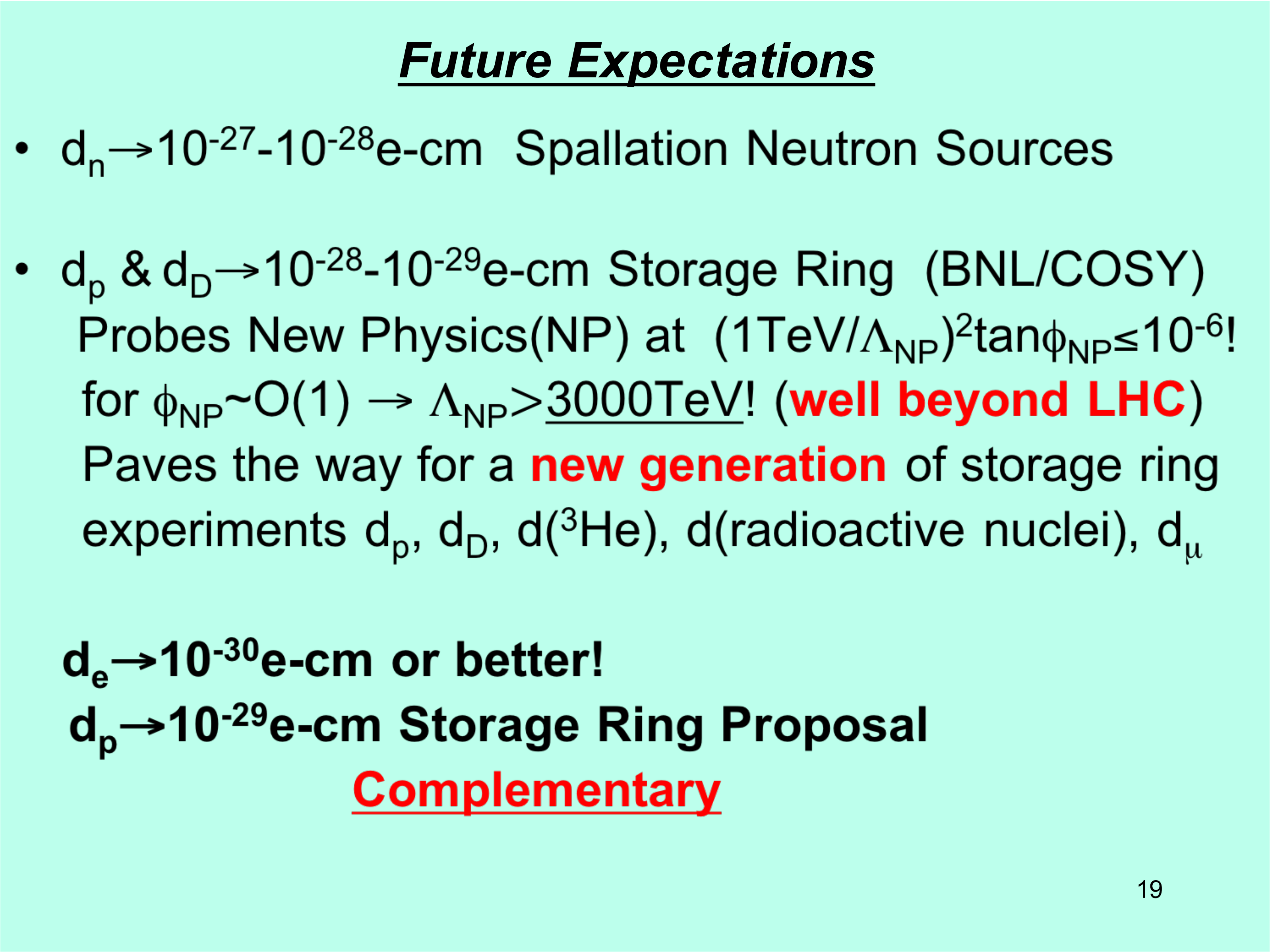
HLS measurements at Fermilab

Fig.35. HLS probe on Tevatron accelerator focusing magnet.



Bill Marciano

Snowmass Workshop,
September 15, 2020



Future Expectations

- $d_n \rightarrow 10^{-27}$-10^{-28}e-cm Spallation Neutron Sources
- d_p & $d_D \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring (BNL/COSY)
  Probes New Physics(NP) at $(1\text{TeV}/\Lambda_{NP})^2 \tan\phi_{NP} \leq 10^{-6}$!
  for $\phi_{NP} \sim O(1) \rightarrow \Lambda_{NP} > \underline{3000\text{TeV}}$! (**well beyond LHC**)
  Paves the way for a **new generation** of storage ring experiments d_p, d_D, $d(^3\text{He})$, d(radioactive nuclei), d_μ

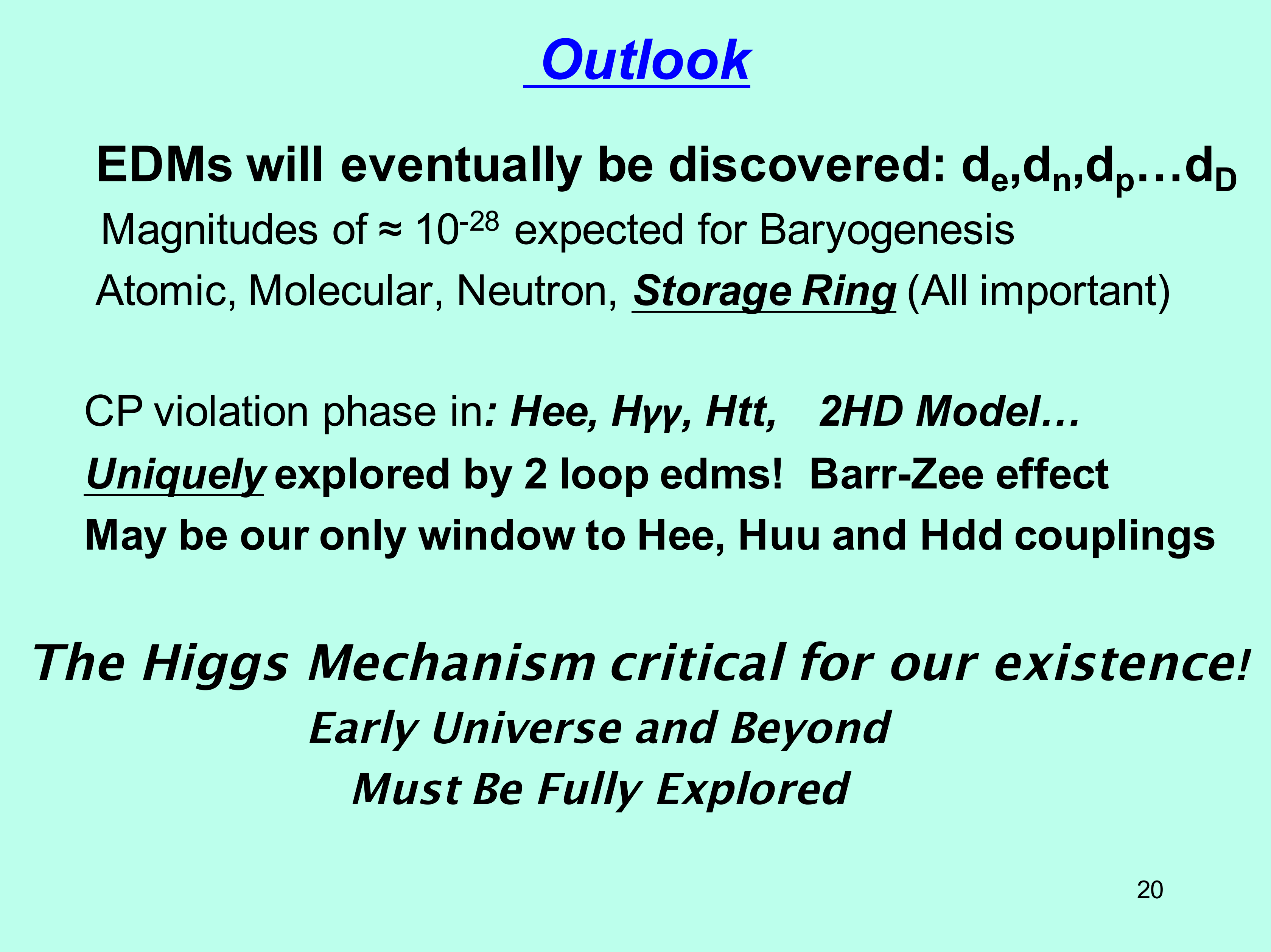
$d_e \rightarrow 10^{-30}$e-cm or better!

$d_p \rightarrow 10^{-29}$e-cm Storage Ring Proposal

Complementary

Bill Marciano

Snowmass Workshop,
September 15, 2020



Outlook

EDMs will eventually be discovered: d_e,d_n,d_p…d_D

Magnitudes of ≈ 10^{-28} expected for Baryogenesis

Atomic, Molecular, Neutron, ***Storage Ring*** (All important)

CP violation phase in***: Hee, Hγγ, Htt, 2HD Model…***

Uniquely **explored by 2 loop edms! Barr-Zee effect**

May be our only window to Hee, Huu and Hdd couplings

The Higgs Mechanism critical for our existence!

Early Universe and Beyond

Must Be Fully Explored

Storage ring EDM Collaboration

Snowmass LOI, 2020

Storage Ring EDM Collaboration members (*) and LOI endorsers:

Jim Alexander,[7] Vassilis Anastassopoulos,[34*] Rick Baartman,[26*] Stefan Baessler,[37*] Franco Bedeschi,[19] Martin Berz,[17*] Michael Blaskiewicz,[4*] Themis Bowcock,[31*] Kevin Brown,[4*] Dmitry Budker,[9,29*] Sergey Burdin,[31] Gianluigi Casse,[31*] Giovanni Cantatore,[36*] Timothy Chupp,[32*] Hooman Davoudiasl,[4*] Milind V. Diwan,[4*] George Fanourakis,[20*] Antonios Gardikiotis,[28,34*] Claudio Gatti,[18*] James Gooding,[31*] Renee Fatemi,[30] Wolfram Fischer,[4*] Peter Graham,[25*] Frederick Gray,[22*] Selcuk Haciomeroglu,[6*] Georg H. Hoffstaetter,[7*] Haixin Huang,[4*] Marco Incagli,[19*] Hoyong Jeong,[16*] David Kaplan,[13*] On Kim,[6,15*] Ivan Koop,[5*] Marin Karuza,[35*] David Kawall,[27*] Valeri Lebedev,[8*] MyeongJae Lee,[6*] Soohyung Lee,[6*] Alberto Lusiani,[24,19*] William J. Marciano,[4*] Marios Maroudas,[34*] Andrei Matlashov,[6*] Francois Meot,[4*] James P. Miller,[3*] William M. Morse,[4*] James Mott,[3,8] Zhanibek Omarov,[6,15*] Yuri F. Orlov,[7*] Cenap Ozben,[11*] SeongTae Park,[6*] Giovanni Maria Piacentino,[33*] Boris Podobedov,[4*] Matthew Poelker,[12] Dinko Pocanic,[37*] Joe Price,[31*] Deepak Raparia,[4*] Surjeet Rajendran,[13*] Sergio Rescia,[4*] B. Lee Roberts,[3*] Yannis K. Semertzidis,[6,15*] Alexander Silenko,[14*] Edward Stephenson,[10*] Riad Suleiman,[12*] Michael Syphers,[21*] Pia Thoerngren,[23*] Volodya Tishchenko,[4*] Nikolaos Tsoupas,[4*] Spyros Tzamarias,[1*] Alessandro Variola,[18*] Graziano Venanzoni,[19*] Eva Vilella,[31*] Joost Vossebeld,[31*] Peter Winter,[2] Eunil Won,[16*] Konstantin Zioutas.[34*]

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10)Indiana University, Bloomington, Illinois, USA
11)Istanbul Technical University, Istanbul, Turkey
12)JLAB, Newport News, Virginia, USA
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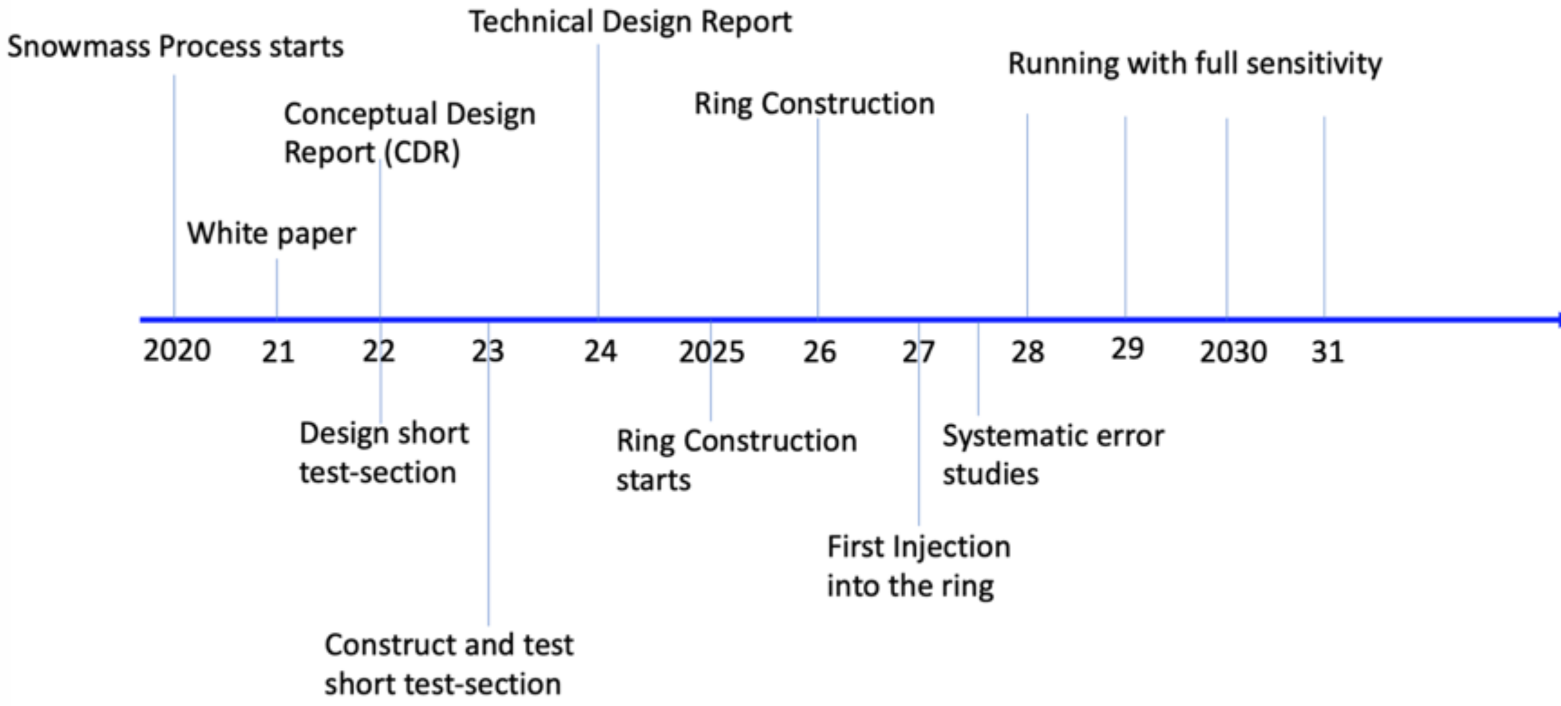
Technically driven timeline

- We have submitted our LOI to the Snowmass Process in the US and writing a White Paper for it.
- Preparing a CDR document, critical studies are finished

- Most of the collaborators are either Muon g-2 collaborators and/or original Storage ring EDM proponents



Snowmass Process starts

White paper

Conceptual Design Report (CDR)

Technical Design Report

Ring Construction

Running with full sensitivity

2020 21 22 23 24 2025 26 27 28 29 2030 31

Design short test-section

Construct and test short test-section

Ring Construction starts

First Injection into the ring

Systematic error studies

Summary

✓EDM physics is must do, exciting and timely

✓Hybrid, symmetric ring lattice works well. Minimized systematic error sources. Statistics and systematics to $10^{-29}e$-cm

✓E-field strength similar to TEVATRON (FNAL) ES-separators, ran for years…

✓Working EDM lattice with long SCT and large enough acceptance provides the statistics

✓Ring planarity <0.1mm, CW & CCW beam separation <0.01mm

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15. …

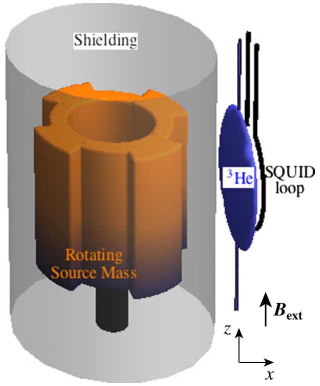
Extra slides

ARIADNE (monopole-dipole interactions, sensitive to axions) and proton EDM can help find the dark matter or exclude axions!

ARIADNE:
Axion Resonant InterAction
DetectioN Experiment

ARIADNE needs a CP violating phase to see an effect.

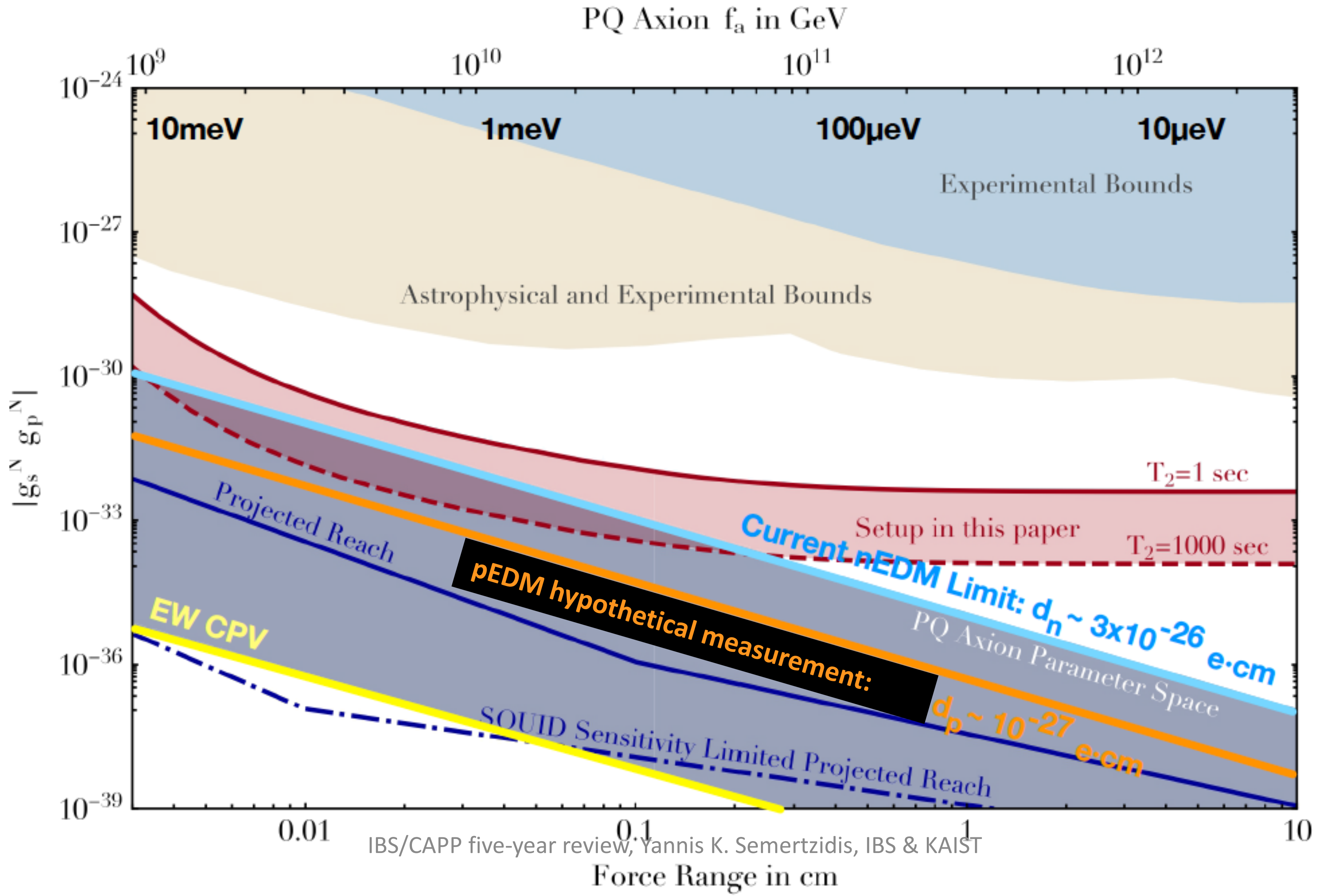
$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$



ARIADNE

- If ARIADNE finds a signal, then we are done. We will know the axion mass → axion dark matter experiment.
- If ARIADNE doesn’t observe a signal, then it could be due to the absence of extra CP-violating source.
- Proton EDM experiment can clarify the situation. The large axion mass can be probed effectively.

Probing high-mass axions with ARIADNE and pEDM

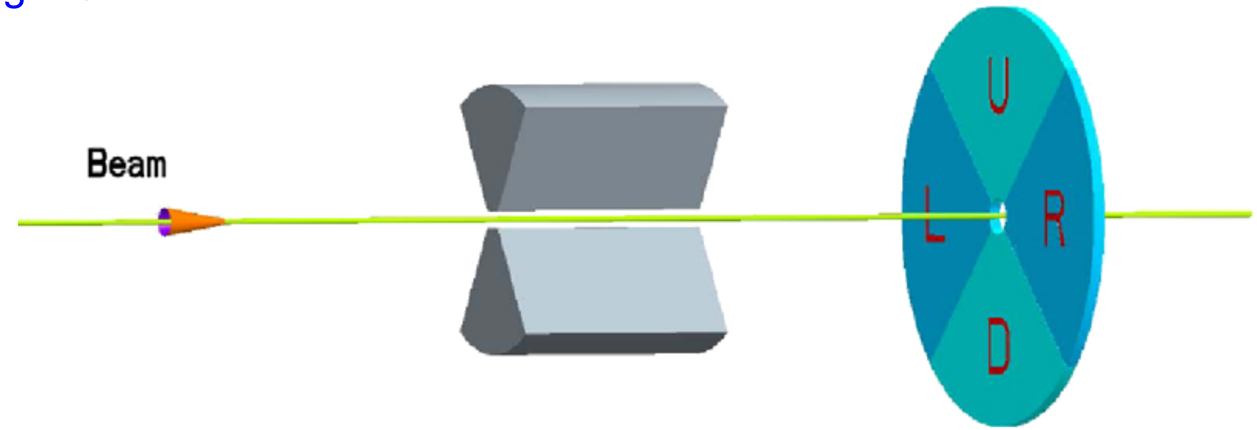


pEDM polarimeter principle: probing the proton spin components as a function of storage time

“defining aperture” polarimeter target

Micro-Megas TPC detector and/or MRPC

Extraction: lowering the vertical focusing



$$\varepsilon_H = \frac{L-R}{L+R}$$

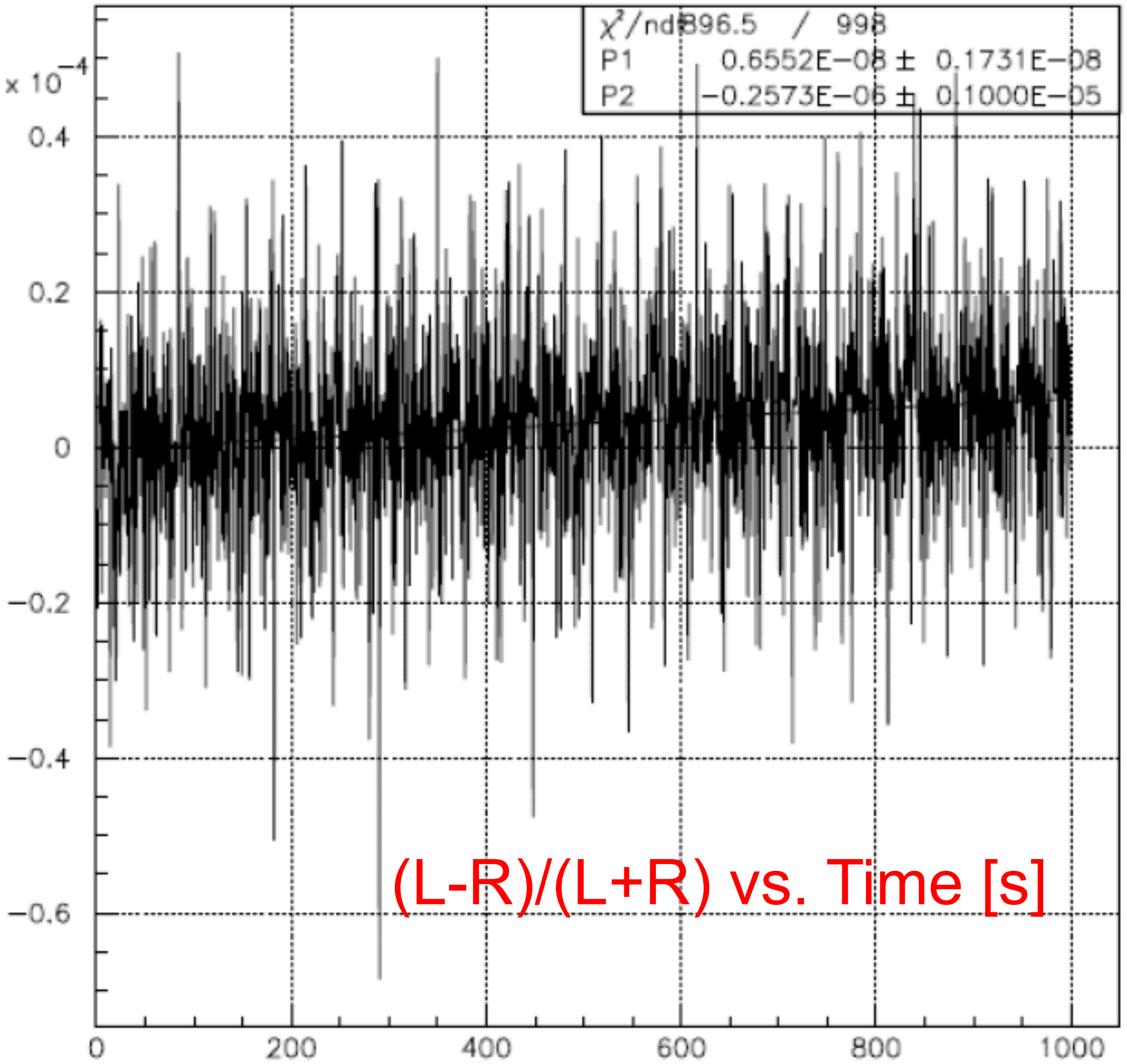
carries EDM signal
increases slowly with time

$$\varepsilon_V = \frac{D-U}{D+U}$$

carries in-plane (g-2)
precession signal

The EDM signal: early to late change

- Comparing the (left-right)/(left+right) counts vs. time we monitor the vertical component of spin



(L-R)/(L+R) vs. Time [s]

M.C. data

Spin Coherence Time

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (second order effects)

- They Cause a spread in the g-2 frequencies:

$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Correct by tuning plate shape/straight section length plus fine tuning with sextupoles (current plan) or cooling (mixing) during storage (under evaluation).

Is the polarimeter analyzing power good at P_{magic}? YES!

Analyzing power can be further optimized

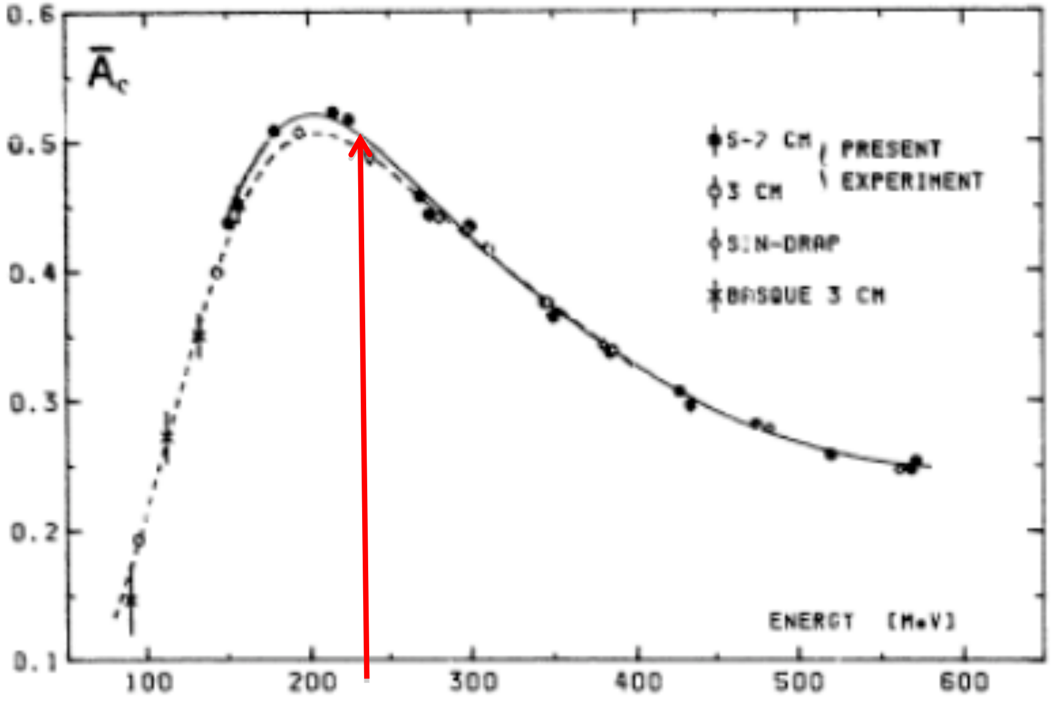
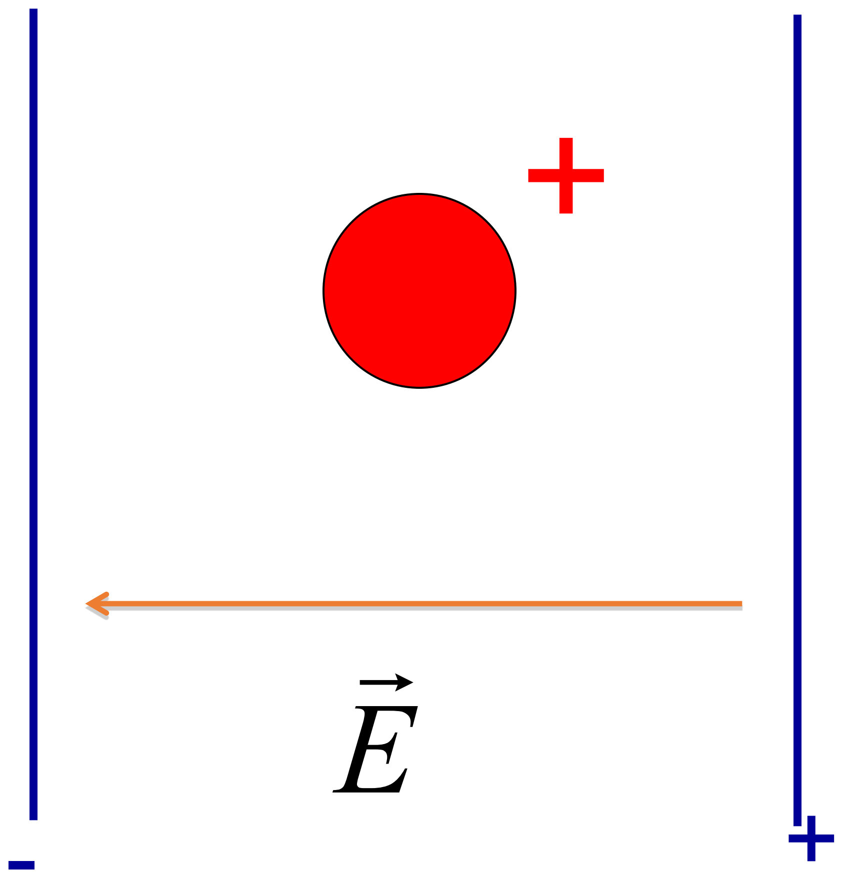
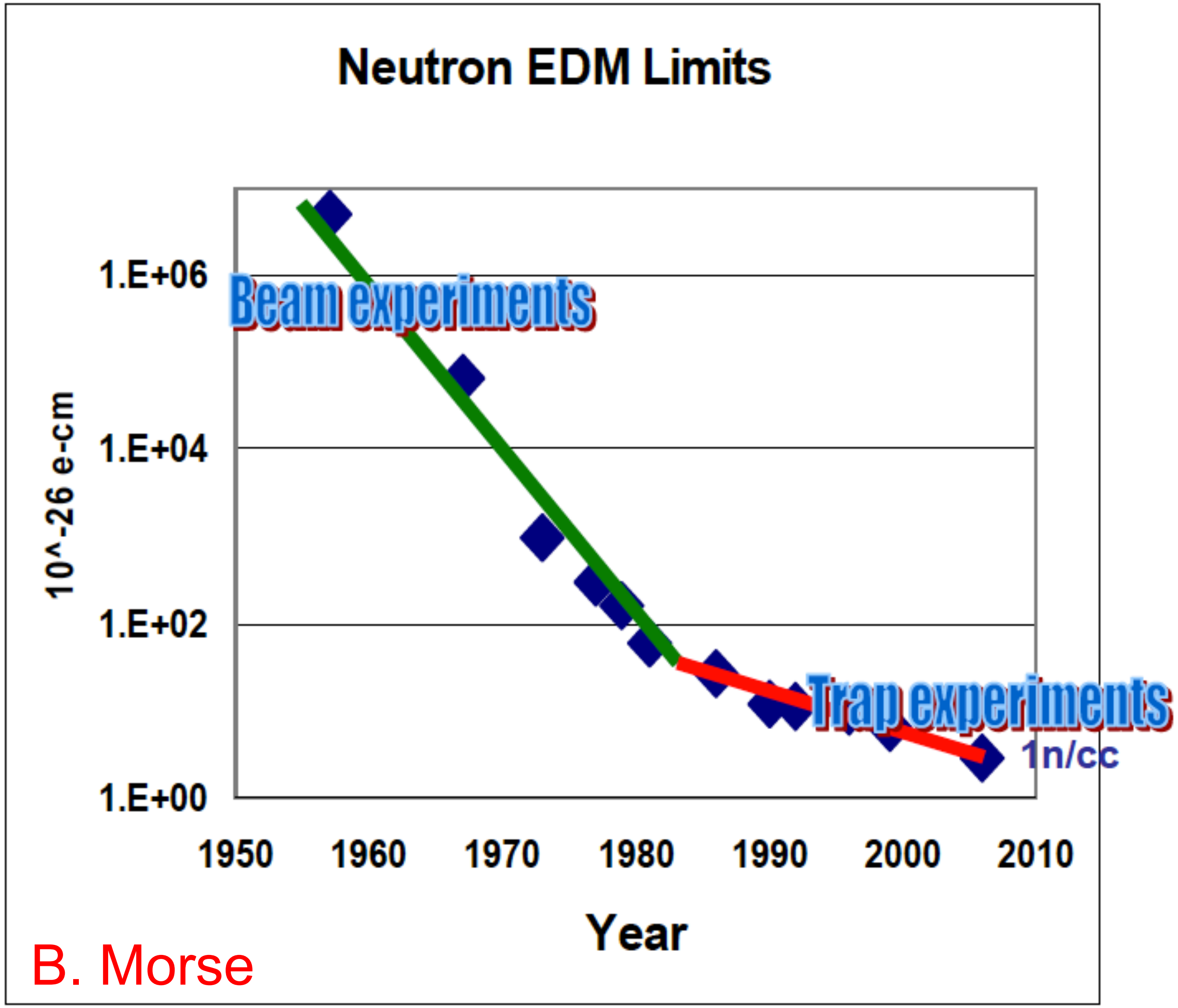


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.

A charged particle between Electric Field plates would be lost right away.




Neutron EDM Limits
1.E+06
1.E+04
1.E+02
1.E+00
10^-26 e-cm
1950
1960
1970
1980
1990
2000
2010
Year
Beam experiments
Trap experiments
1n/cc

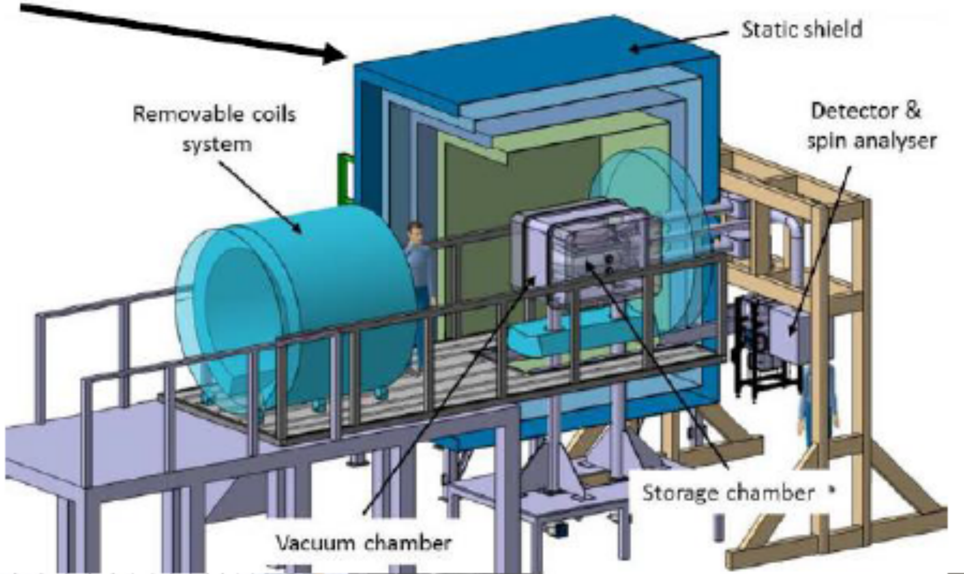
B. Morse

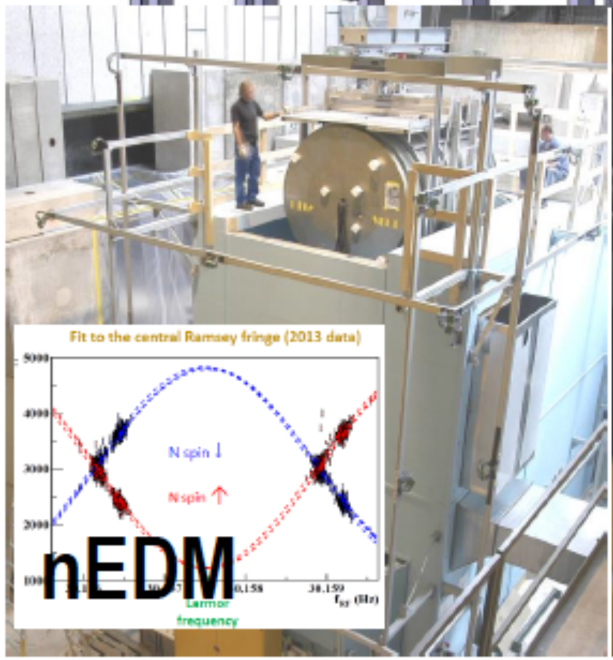
K. Kirch

The nEDM@PSI collaboration

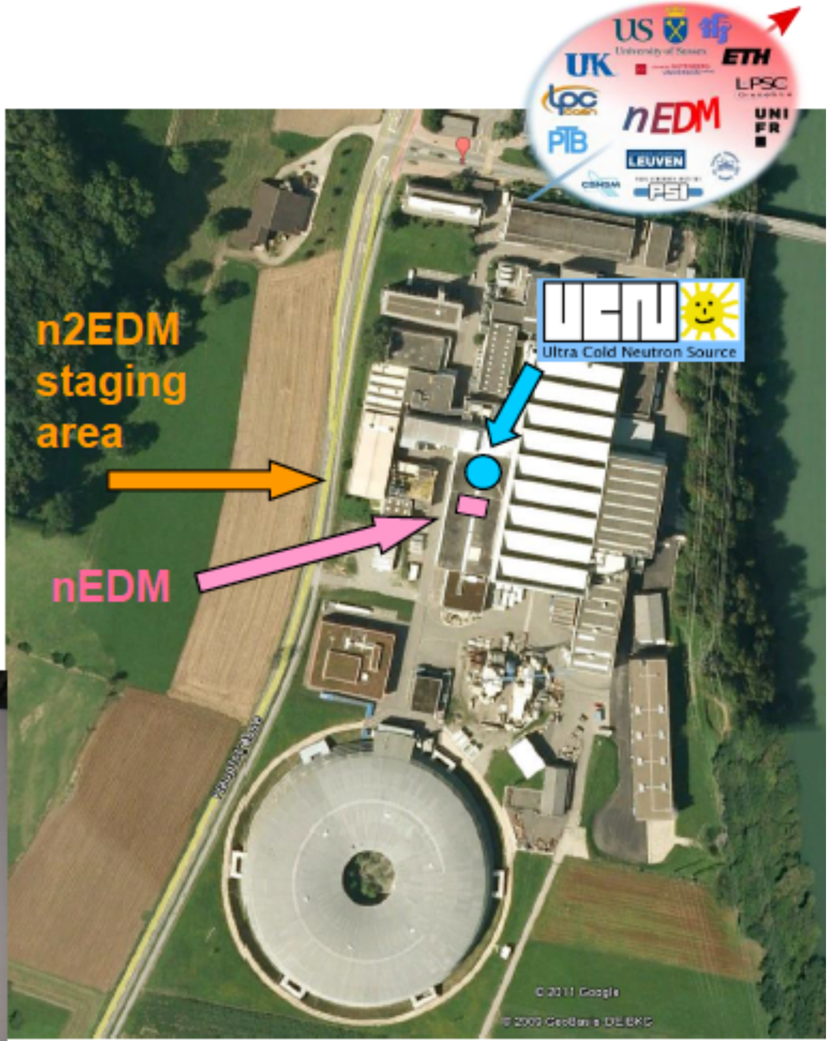
13 Institutions, 7 Countries, 50 individuals

n2EDM





temperature stabilized, shielded room for n2EDM staging



The target sensitivity for nEDM is 10^{-26}ecm or better, for n2EDM 10^{-27}ecm or better

Key Features of nEDM@SNS

Brad Filippone

- Sensitivity: ~2×10^{-28} e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- **Polarized ^{3}He co-magnetometer**
  - Also functions as neutron spin precession monitor via spin-dependent n-^{3}He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via "dressed spins"
    - Extra RF field allows synching of n & ^{3}He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary ^{3}He diffusion (mfp)- big change in geometric phase effect on ^{3}He

Arguably the most ambitious of all neutron EDM experiments

History/Status of nEDM@SNS

- **2011:** NSAC Neutron Subcommittee
- **2013:** Critical R&D successfully demonstrated
- **2014-2017:** Critical Component Demonstration (CCD) phase begun
  - Build working, full-scale, prototypes of technically-challenging subsystems (use these in the full experiment)
  - 4yr NSF proposal for 6.5M$ CCD funded
  - DOE commitment of ≈ 1.8M$/yr for CCD
- **2018-2020:** Large scale Integration and Conventional Component Procurement
- **2021:** Begin Commissioning and Data-taking

P. Fierlinger

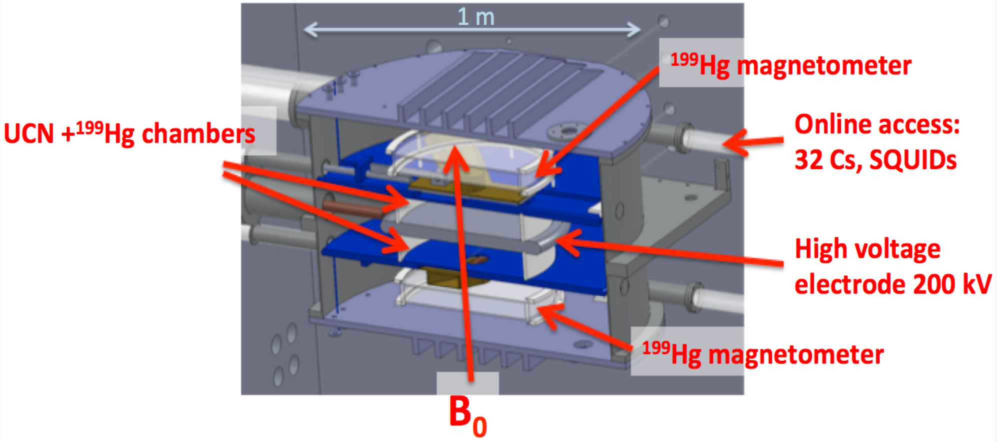
The TUM EDM experiment

SLOW NEUTRONS
DFG SPP 1491

EDM
nedm.ph.tum.de

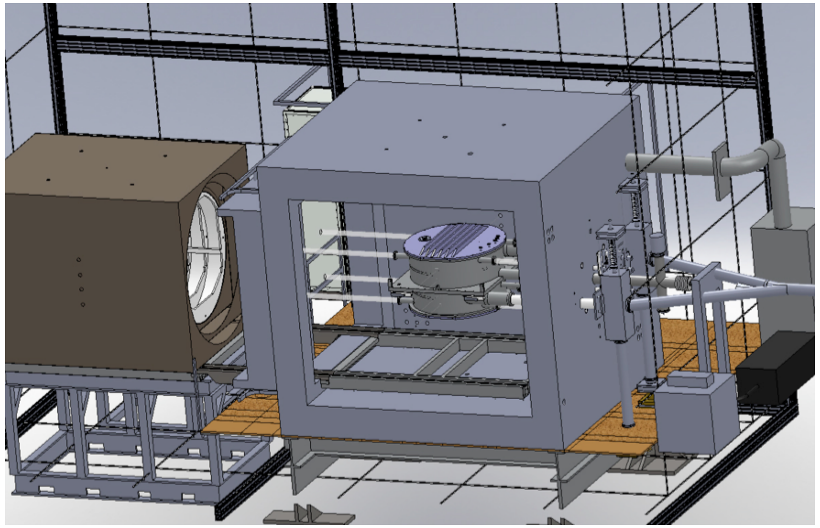
- Initially a ‘conventional’ Ramsey experiment
- UCN trapped at room temperature, ultimately cryogenic trap
- Double chamber with co-magnetometer option
- ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUID magnetometers
- Portable and modular setup, including magnetically shielded room
- Ultimate goal: 10^{-28} ecm sensitivity, staged approach (syst. and stat.)

Double chamber in SF6 container



I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

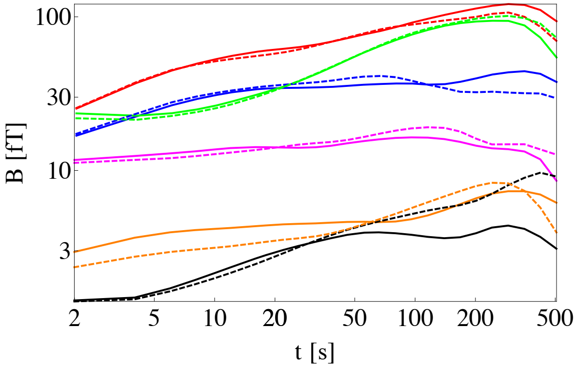
Modular shield setup

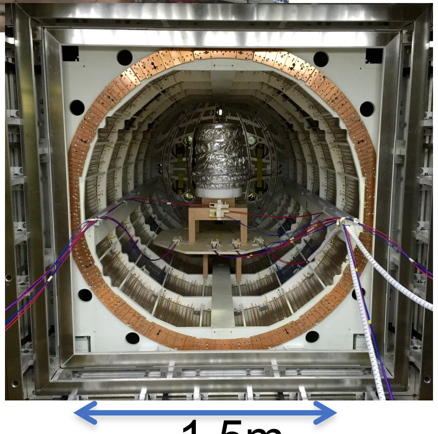


Most hardware built & tested

E.g.: passive magnetic shielding factor > 6 million @ 1 mHz
(without ext. compensation coils!)

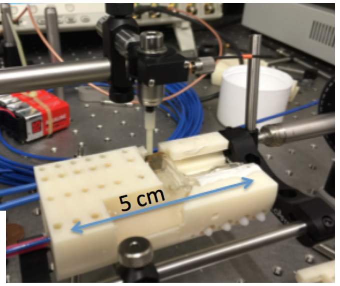
I.Altarev et al., arXiv:1501.07408
I. Altarev et al., , arXiv:1501.07861

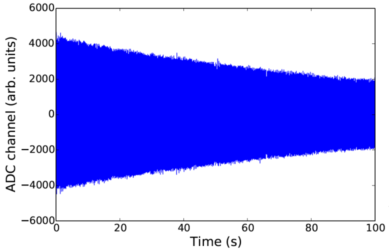




- The smallest gradients over an extended volume ever realized: < 50 pT / m stable gradient over EDM cell volume
- Residual field drift < 5 fT in typical Ramsey cycle time
- Hg and Cs magnetometry on $<$ 20 fT level:

Cs sensor head assembly

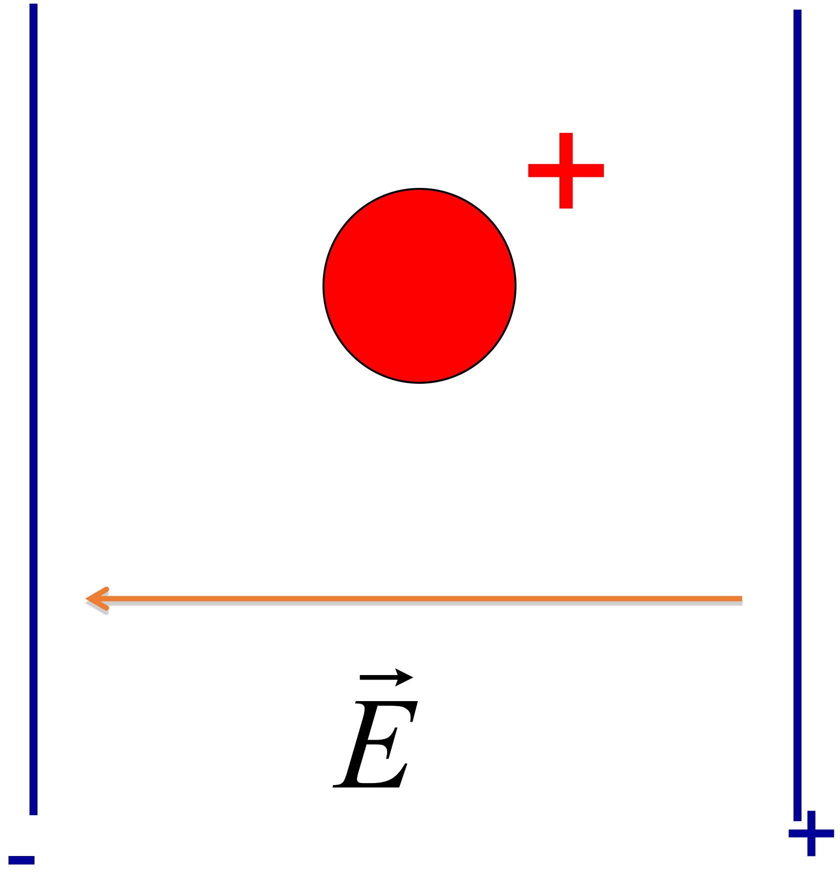




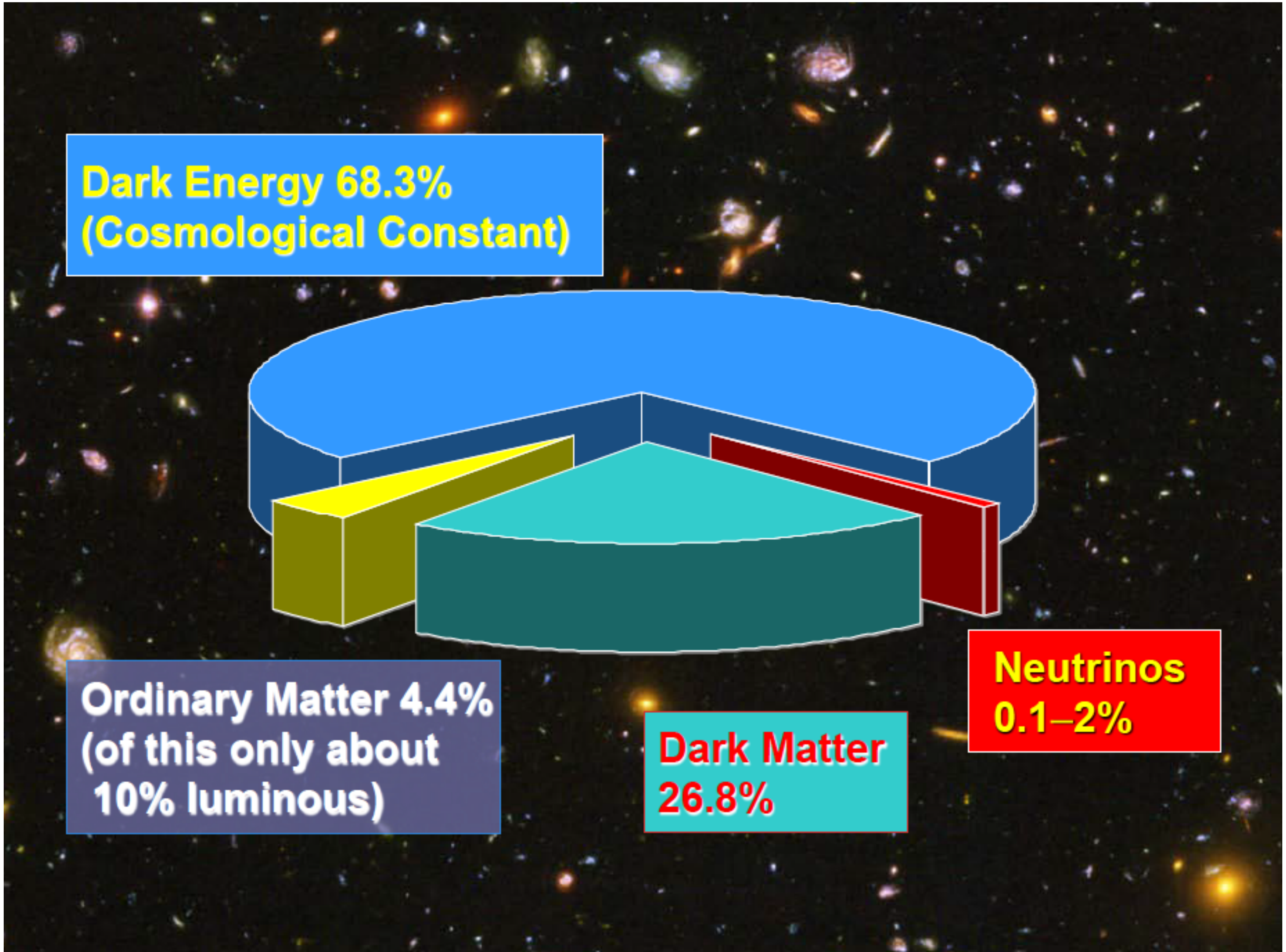
Raw 199-Hg FPD signal

- Basically all magnetic field related systematics under control

A charged particle between Electric Field plates would be lost right away…



Cosmological inventory



Dark Energy 68.3%
(Cosmological Constant)

Ordinary Matter 4.4%
(of this only about
10% luminous)

Dark Matter
26.8%

Neutrinos
0.1–2%

Axion Dark matter

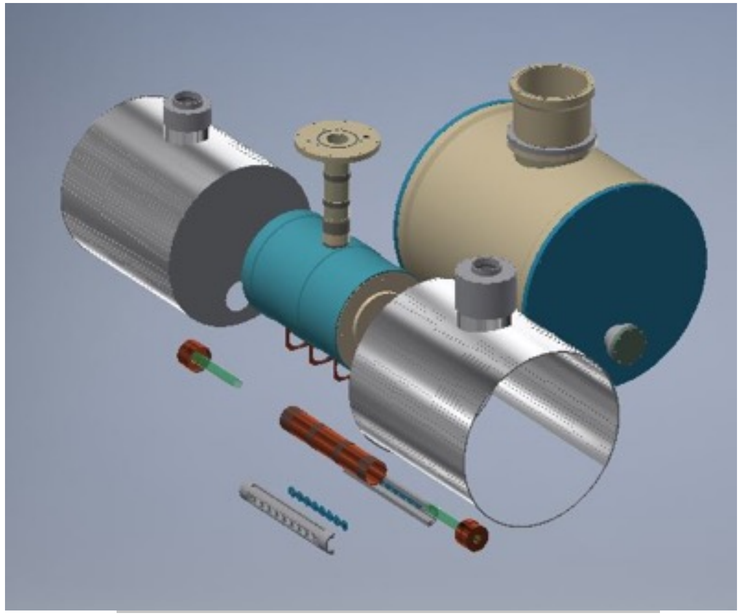
- Dark matter: 0.3-0.5 GeV/cm^3
- Axions in the 1-300μeV range: 10^{12}-10^{14}/cm^3, classical system.
- Lifetime ~7×10^{44}s (100μeV / m_a)^5
- Cold Dark Matter ($v/c \sim 10^{-3}$), Kinetic energy ~$10^{-6} m_a$, very narrow line in spectrum.

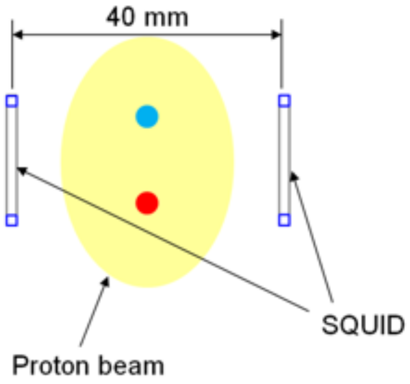
Axion Dark matter

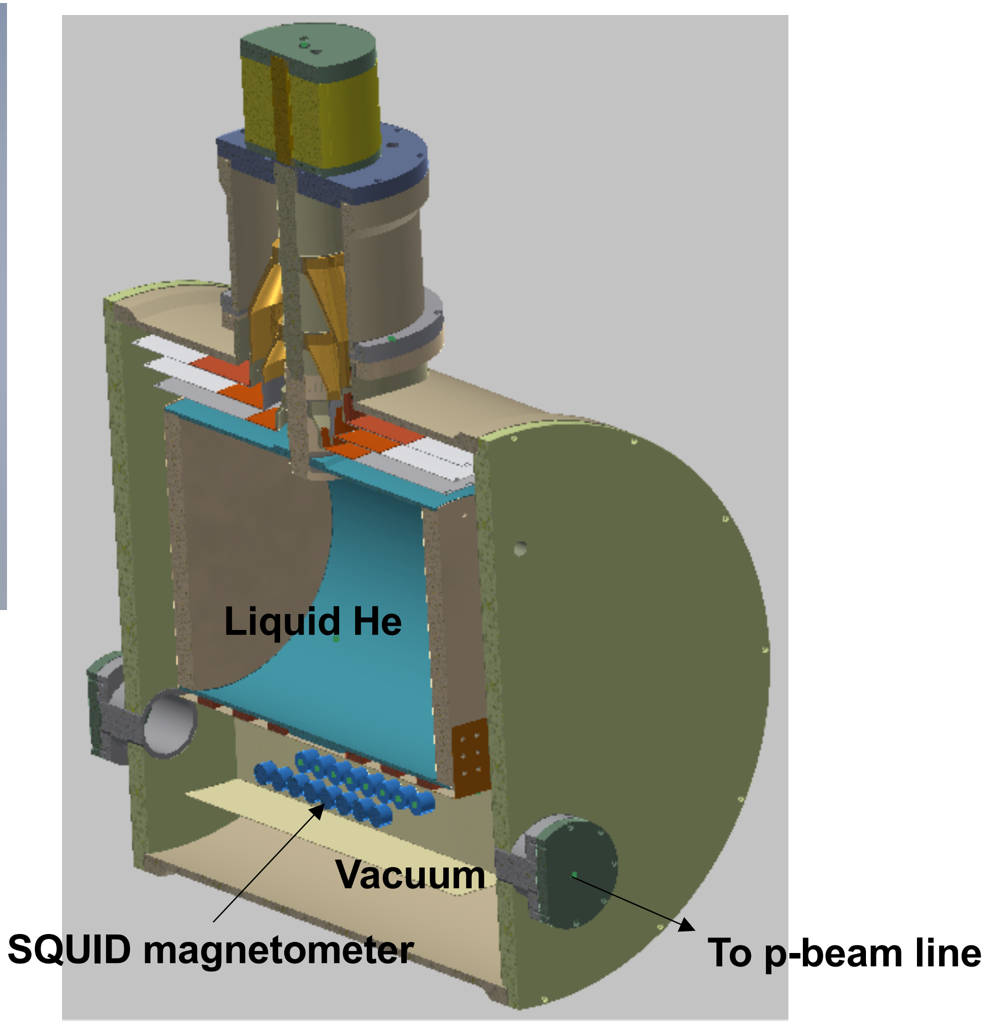
- Velocity range: <$10^{-3}c$ (bound in galaxies)
- Mass range: >10^{-22}eV (size of galaxies)
- Coherence length (De Broglie wavelength):

$$l_{DB} \approx 1\text{m} \times \left(\frac{1\text{meV}}{m_a} \right)$$

Beam position monitor: SQUID array

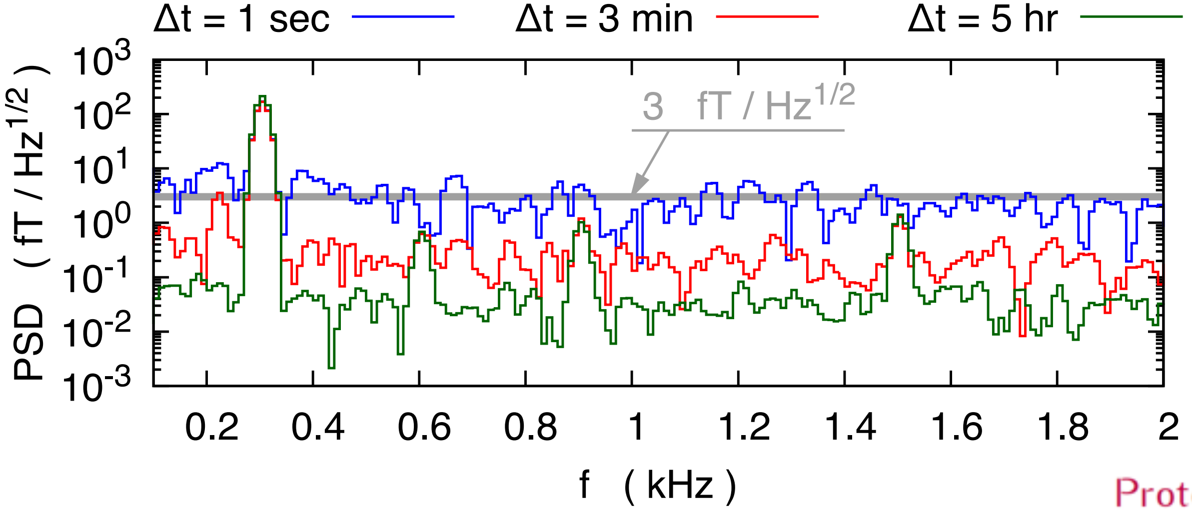






Cylindrical Dewar: original design (KRISS)

SQUID-based BPMs, Korea



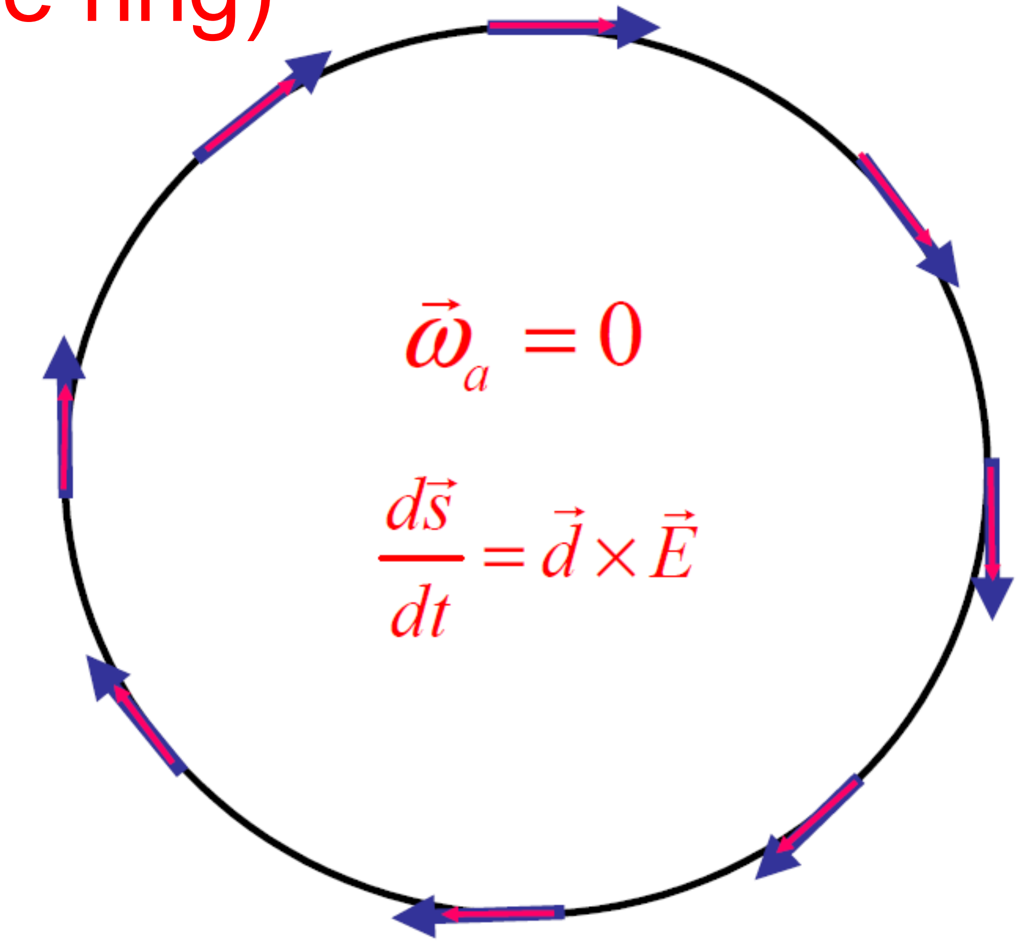
Next: Testing the concept at an accelerator in Korea.

- The new design is to be delivered by summer
- Will be $2\text{fT}\sqrt{\text{Hz}}$
- We will make wire tests in Korea
- Would be good to test here at COSY

Selcuk Haciomeroglu, IBS-CAPP

Storage Ring EDM experiments

(or how to create a Dirac-like particle in a storage ring)



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$