21 November 2017
PBC-EDM Physics, Systematics

Physics reach, Systematic errors

Yannis Semertzidis, IBS/CAPP and KAIST

Proton, and deuteron

- Storage ring p,d EDMs @ $<10^{-29}$e-cm level
- Physics reach is great, oscillating theta_QCD sensitivity! Paper on the archive: 1710.05271
- Systematic errors, progress is satisfactory, workshop early next year.

Marciano, CM9/KAIST/Korea, Nov 2014

Generic Physics Reach of $d_p \sim 10^{-29}$e-cm

$d_p \sim 0.01(m_p/\Lambda_{NP})^2 \tan\phi^{NP} e/2m_p$

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

If ϕ^{NP} is of O(1), Λ_{NP}~<u>3000TeV</u> Probed!

If Λ_{NP}~O(1TeV), ϕ_{NP}~10^{-7} Probed!

<u>Unique Capabilities!</u>

Physics relevance, comparison with other activities

- The physics reach of a proton and a deuteron experiment at the 10^{-29} *e*-cm is unique:

- Theta_QCD vs. New Physics: help from n, p, and d, ^{199}Hg, electron EDM values.

- Certain systematic errors, e.g., geometrical phases, cancel in clockwise vs. counterclockwise. Unique to storage ring method.

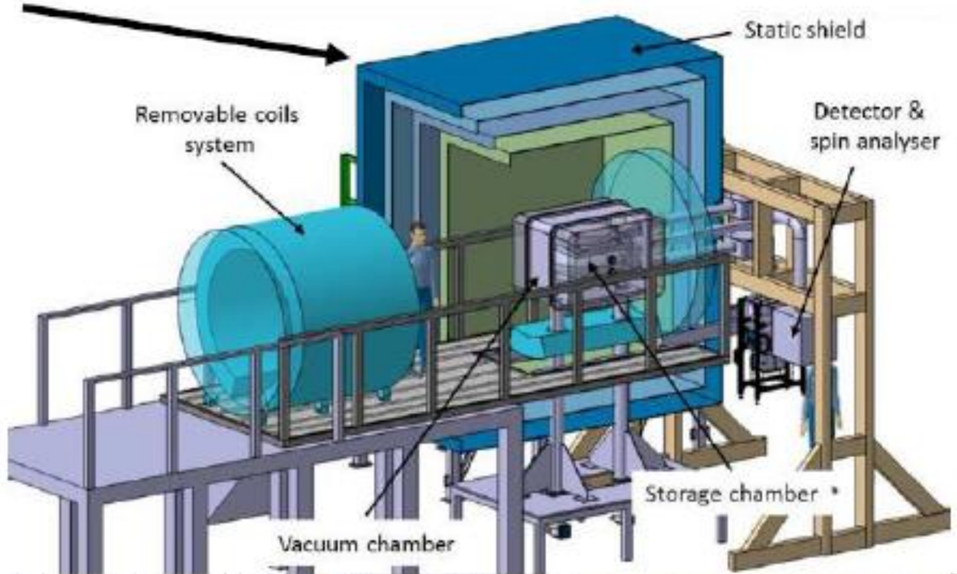
K. Kirch

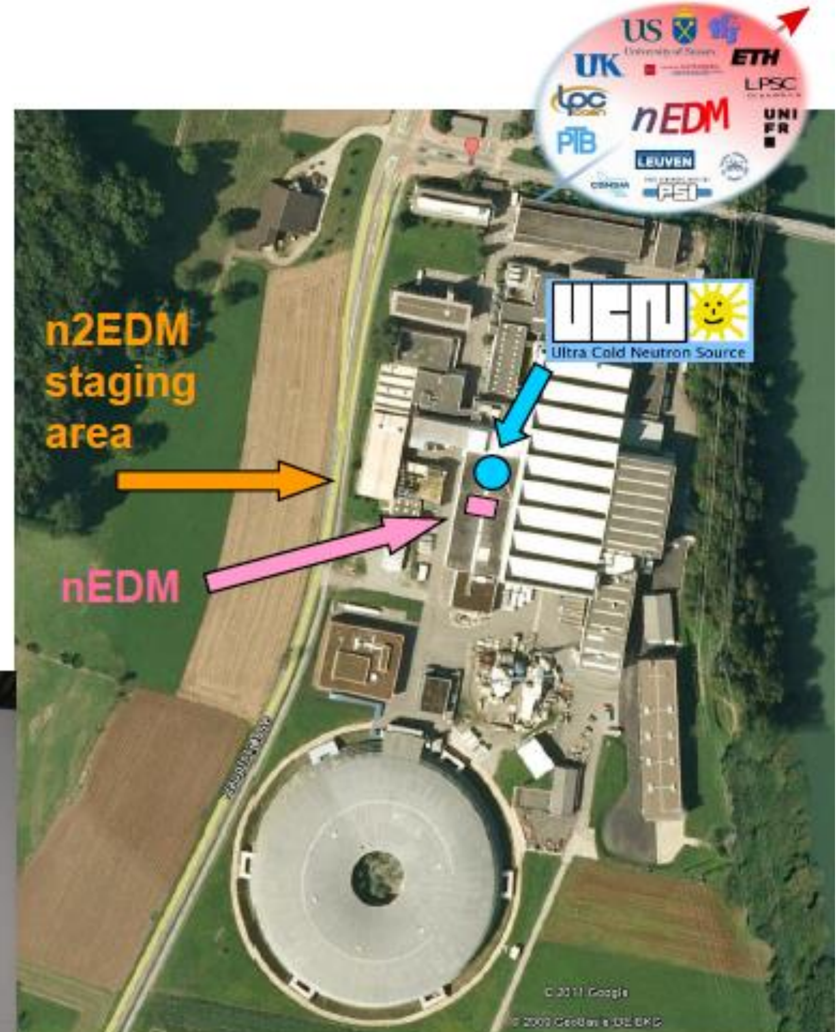
The nEDM@PSI collaboration

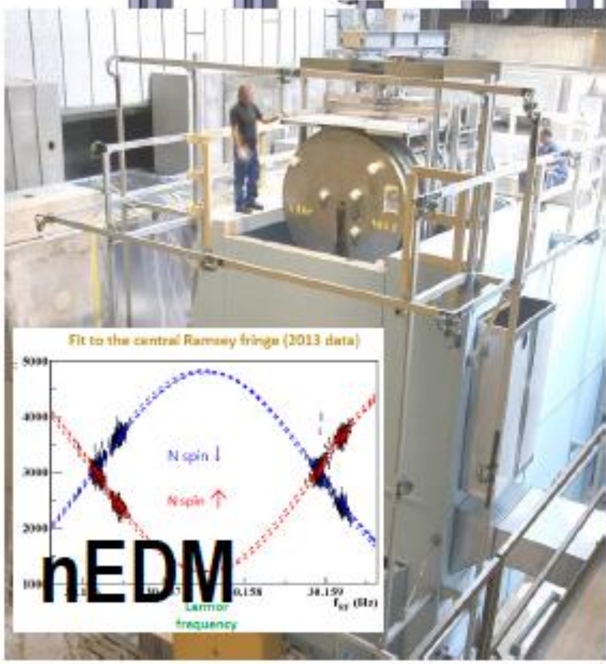
13 Institutions, 7 Countries, 50 individuals

PAUL SCHERRER INSTITUT

n2EDM







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

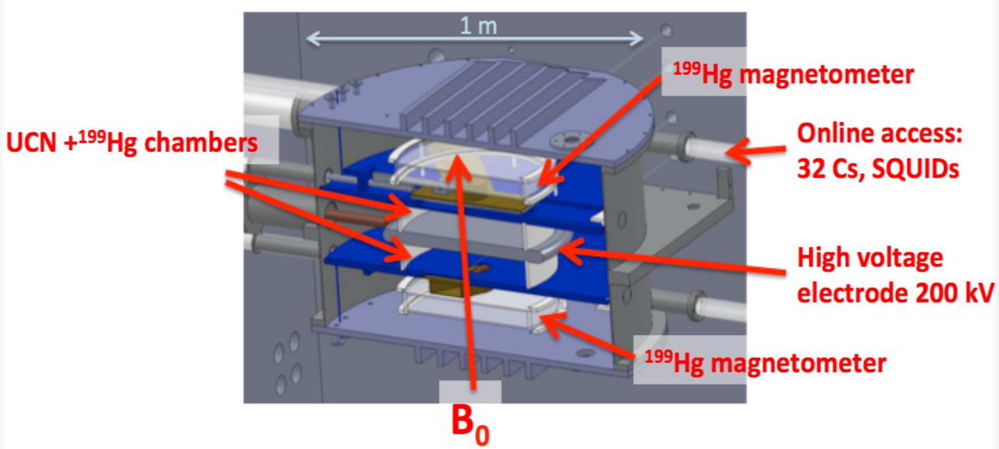
P. Fierlinger

The TUM EDM experiment

nedm.ph.tum.de

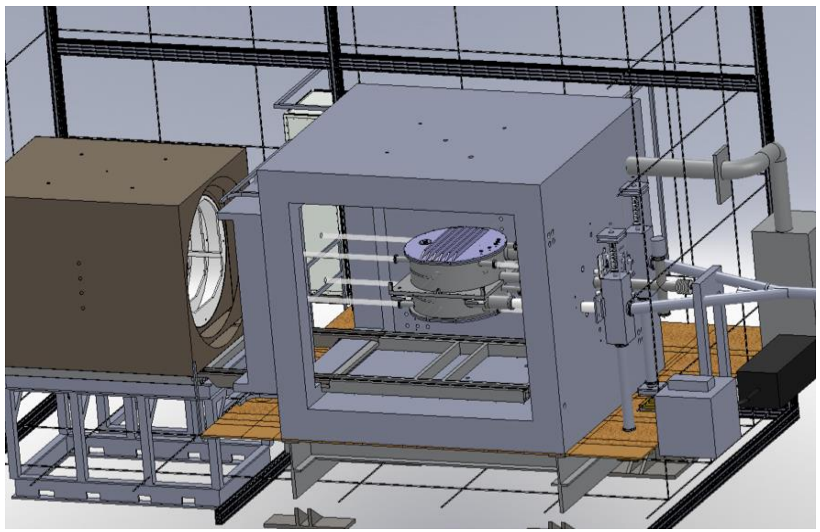
- Initially a 'conventional' Ramsey experiment
- UCN trapped at room temperature, ultimately cryogenic trap
- Double chamber with co-magnetometer option
- ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUID magnetometers
- Portable and modular setup, including magnetically shielded room
- Ultimate goal: 10^{-28} ecm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



^{199}Hg EDM limit results

$d_{Hg} = (2.20 \pm 2.75_{stat} \pm 1.48_{syst}) \times 10^{-30} e \cdot \text{cm}$. We u
the ^{199}Hg EDM $|d_{Hg}| < 7.4 \times 10^{-30} e \cdot \text{cm}$ (95% C.L.),

TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{Hg}/(1.9\ \text{fm}^2)$	$1.6 \times 10^{-26}\ e \cdot \text{cm}$	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{Hg}/(0.2\ \text{fm}^2)$	$2.0 \times 10^{-25}\ e \cdot \text{cm}$	[21]
$\bar{g}_0$	$\mathbf{S}_{Hg}/(0.135\ e \cdot \text{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \text{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \text{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22, 23]
$(\widetilde{d}_u - \widetilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14} \text{cm}^{-1})$	5.7×10^{-27} cm	[25]
C_S	$\mathbf{d}_{Hg}/(5.9 \times 10^{-22}\ e \cdot \text{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{Hg}/(6.0 \times 10^{-23}\ e \cdot \text{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{Hg}/(4.89 \times 10^{-20}\ e \cdot \text{cm})$	1.5×10^{-10}	see text

Physics strength comparison (Marciano)

System	Current limit [e cm]	Future goal	Neutron equivalent
Neutron	$<1.6 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg atom	$<0.7 \times 10^{-29}$		10^{-25}-10^{-26}
^{129}Xe atom	$<6 \times 10^{-27}$	$\sim 10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		$\sim 10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<5 \times 10^{-25}$	$\sim 10^{-29}$-10^{-30}	10^{-29}-10^{-30}

CP-violation phase from Higgs

EDMs will eventually be discovered: $d_e, d_n, d_p \ldots d_D$

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

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

Marciano

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

Uniquely explored by 2 loop edms! Barr-Zee effect

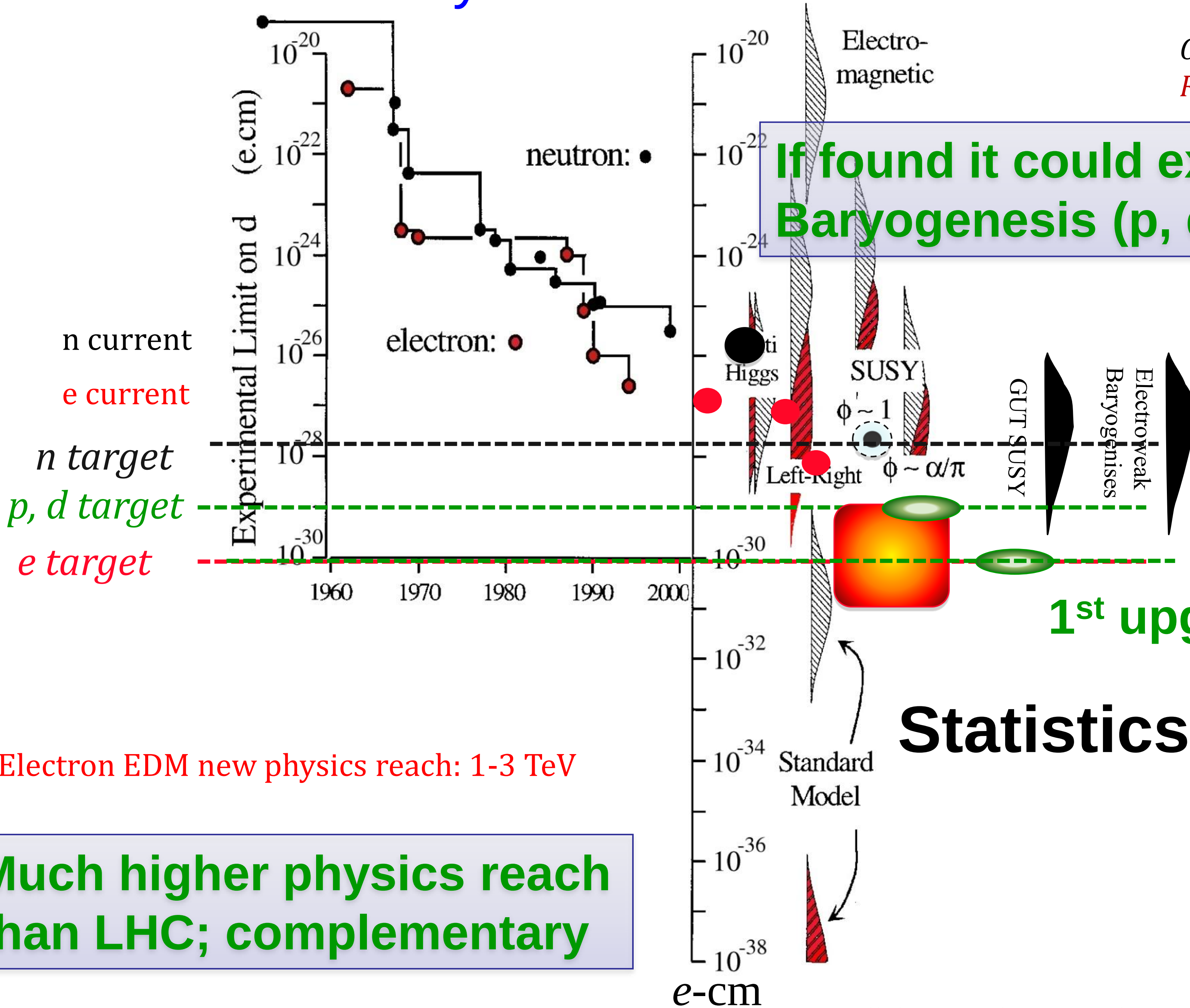
May be our only window to Hee, Huu and Hdd couplings

Guided by experiment: *H→γγ   (H→$\tau^+\tau^-$, $\mu^+\mu^-$) etc.*

Updates Anxiously Anticipated!

The Higgs may be central to our existence!

Sensitivity to Rule on Several New Models



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

1st upgrade

Statistics limited

Electron EDM new physics reach: 1-3 TeV

Much higher physics reach than LHC; complementary

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

EDM goals (done)

- The EDM experiments are gearing up, getting ready:

- ^{199}Hg EDM <0.7x10^{-29} e-cm sensitivity

- nEDM at PSI 10^{-26} e-cm sensitivity, 1st stage
- nEDM at PSI 10^{-27} e-cm sensitivity, 2nd stage

- nEDM at SNS ~2×10^{-28} e-cm starting data taking 2021

EDM status (cont'd)

- ThO, current limit on eEDM: 10^{-28} *e*-cm, next goal $\times$10 improvement.

- TUM nEDM effort, making progress in B-field shielding, met B-field specs, goal: 10^{-28} *e*-cm, staged approach

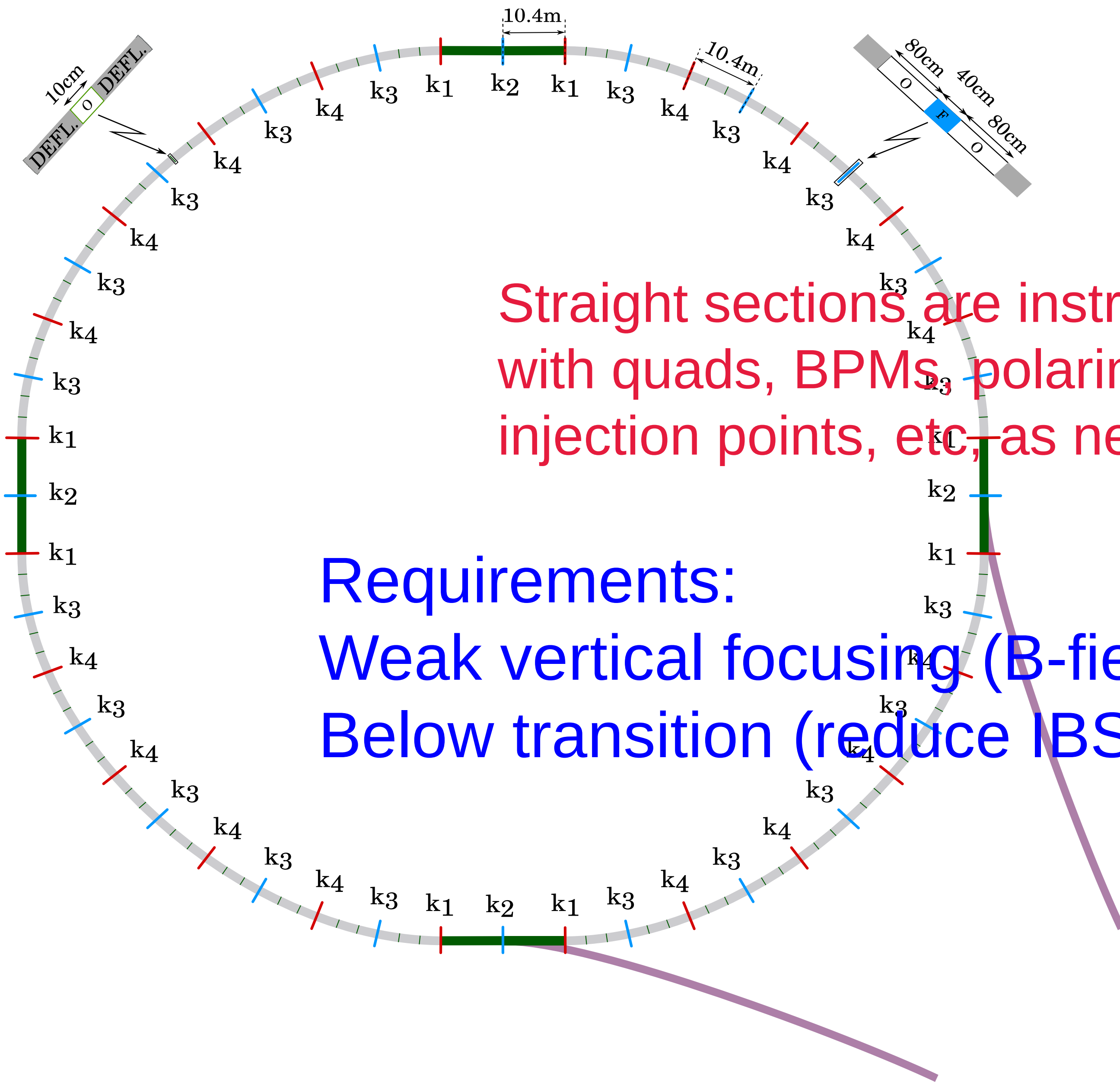
- ^{225}Ra EDM, ~5 $\times$ 10^{-22} e-cm now, ~3 $\times$ 10^{-28} *e*-cm w/ FRIB

- Storage ring EDM: p,dEDM goals ~10^{-29} - 10^{-30} *e*-cm Strength: statistics, CW-CCW storage.

EDM experiments

- The neutron EDM experiments are making progress. Best goal: ~10^{-28} *e*-cm
- ^{199}Hg limits keep getting better. Currently setting best nEDM limit 1.6×10^{-28}*e*-cm & pEDM 5×10^{-25}*e*-cm
- eEDM limit ~10^{-28}*e*-cm (equivalent to 10^{-27}*e*-cm for nEDM and pEDM: by a factor of m_q/m_e).

The proton EDM ring (alternate gradient)



Straight sections are instrumented with quads, BPMs, polarimeters, injection points, etc., as needed.

Requirements:

Weak vertical focusing (B-field sensitivity)

Below transition (reduce IBS)

Currently, on systematic errors

- The magnetic field shielding work is under control. Simulations, consistent w/ analytical estimations, show Clockwise (CW) and Counter-clockwise (CCW) B-field geometrical phase cancel. Reset the shielding requirements to 10-100nT.

- Hardware dev. achieved specs: <10nT

- The SQUID-based gradiometer to specs is done. Proceeding for 5x better sensitivity system

Currently, on systematic errors

- Electrostatic quadrupole position tolerances by high precision beam/spin dynamics simulations are underway.

- An independent application is being used to study the same. Teleconferences are used to communicate the results.

- We will have a workshop early (March?) next year to summarize all progress

Currently, on systematic errors

- A consensus is building up to go with the proton EDM first as simpler.
- We are considering various lattices for an all-electric field
- Working on the prototype scale and purpose

Search for axion dark matter in storage rings

Axion dark matter search with the storage ring EDM method

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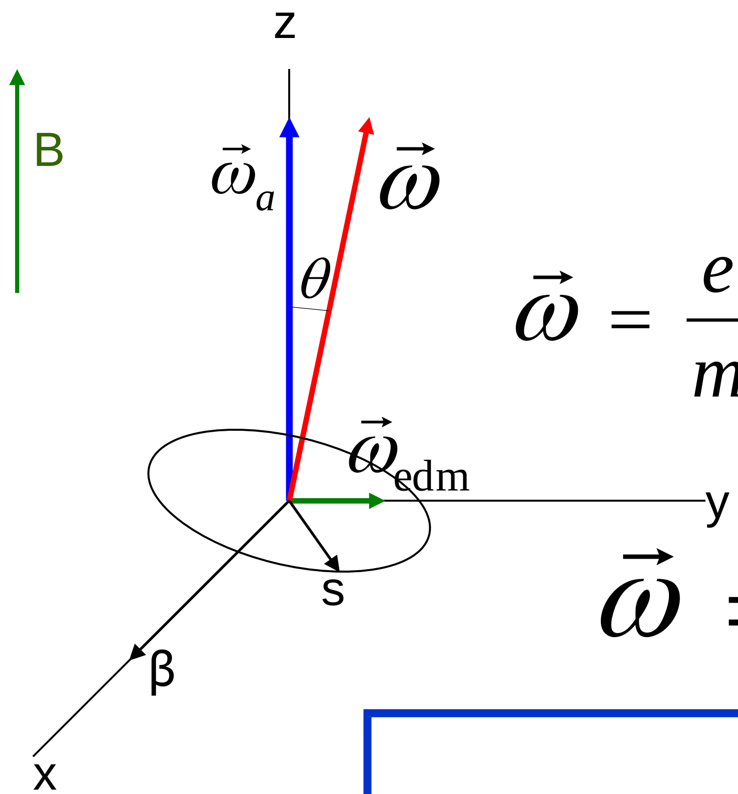
arXiv:1710.05271v1 [hep-ex] 15 Oct 2017

Abstract

We propose using a modified storage ring EDM method to search for the axion dark matter induced EDM oscillation in nucleons. The method uses a combination of B and E-fields to produce a resonance between the $g-2$ precession frequency and the background axion field oscillation to greatly enhance the sensitivity to it. An axion frequency range of 100Hz to 100MHz can be scanned with large sensitivity, corresponding to f_a range of 10^{13} GeV $\leq f_a \leq 10^{19}$ GeV the breakdown scale of the global symmetry generating the axion or axion like particles (ALPs).

Indirect Muon EDM limit from the g-2 Experiment



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{v}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

Ron McNabb's Thesis 2003: $< 2.7\times 10^{-19}\,\mathrm{e}\cdot\mathrm{cm}\ 95\%\ \mathrm{C.L.}$

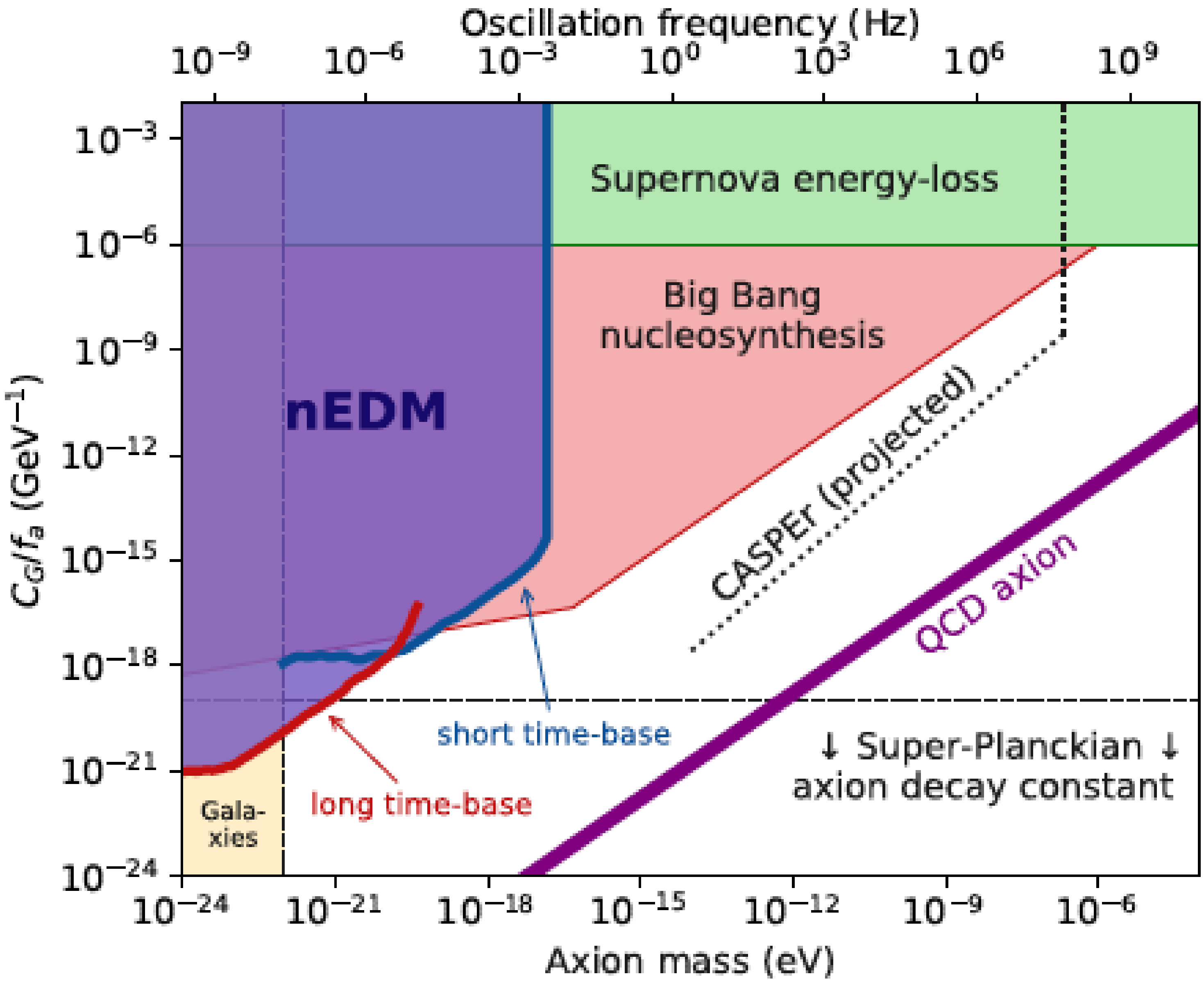
Axion dark matter search in storage rings

- A modified storage ring EDM method can search for the oscillating theta term.
- Oscillating axion field in resonance with the g-2 frequency.
- Frequency range: 100MHz all the way down to sub-micro-Hz.
- Great physics output, simpler systematic errors

Search for axion dark matter in storage rings

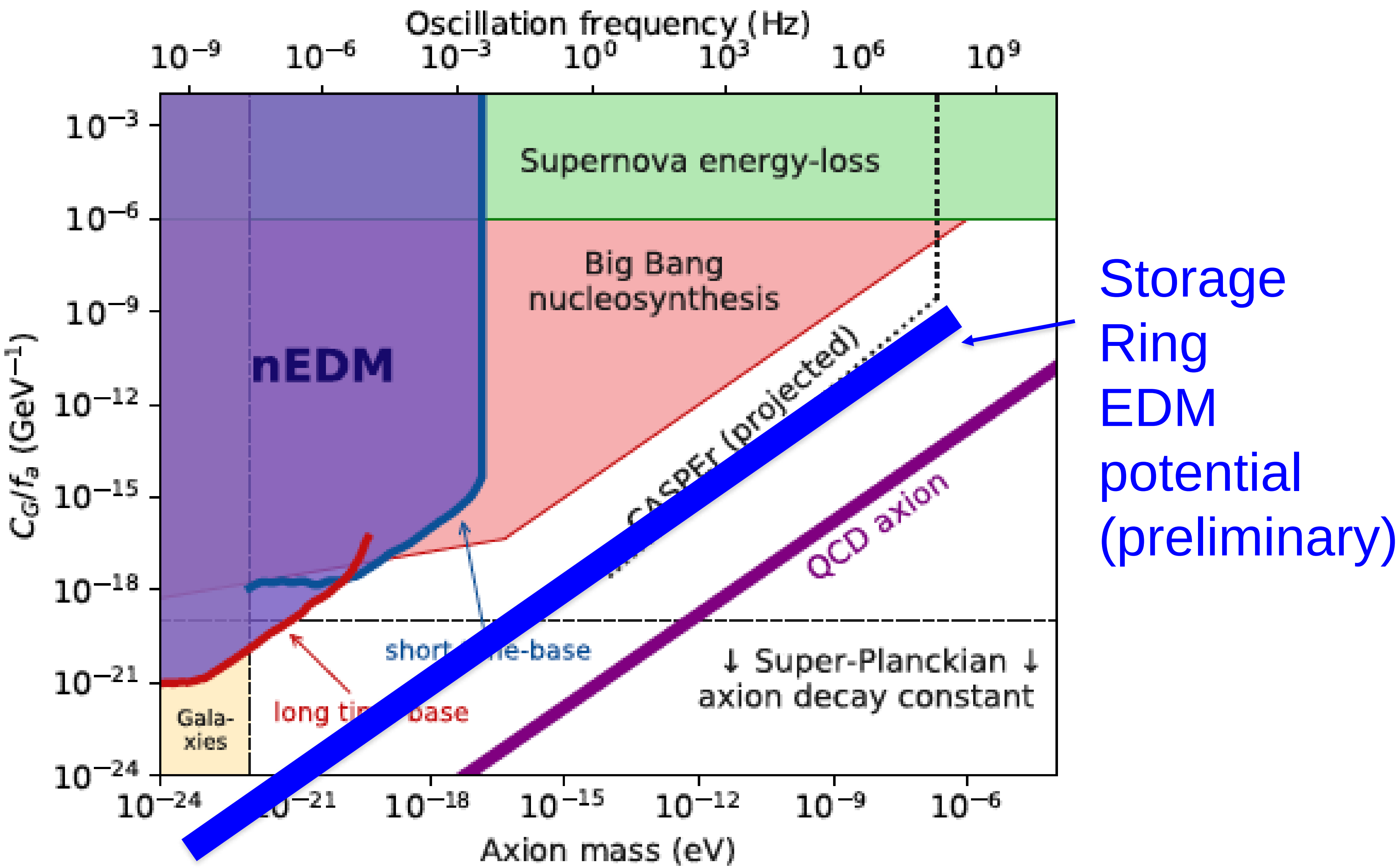
- The axion field (dark matter) induces an oscillating EDM in nucleons P. Graham and S. Rajendran PRD 84, 055013, 2011 and PRD 88, 035023, 2013.

- A combination of the storage ring EDM method plus the g-2 principle we can search for axion dark matter!
- Large effective E-field
- High statistical power
- Large axion frequency coverage
- Can take advantage of large axion coherence time since the stability of the g-2 tune is shown to be at the 10^{-10} level! (Work at COSY)



arXiv:1708.06367v1

PhysRevX.7.041034



arXiv:1708.06367v1

Summary

- Physics reach strong for p,dEDM < 10^{-29} e-cm
- Physics reach enriched with oscillating theta_QCD sensitivity! Probing axion dark matter for axion mass below 0.5 micro-eV.

- Systematics: Hardware development is going well.
- High precision software work in parallel. Workshop early next year.

Extra slides

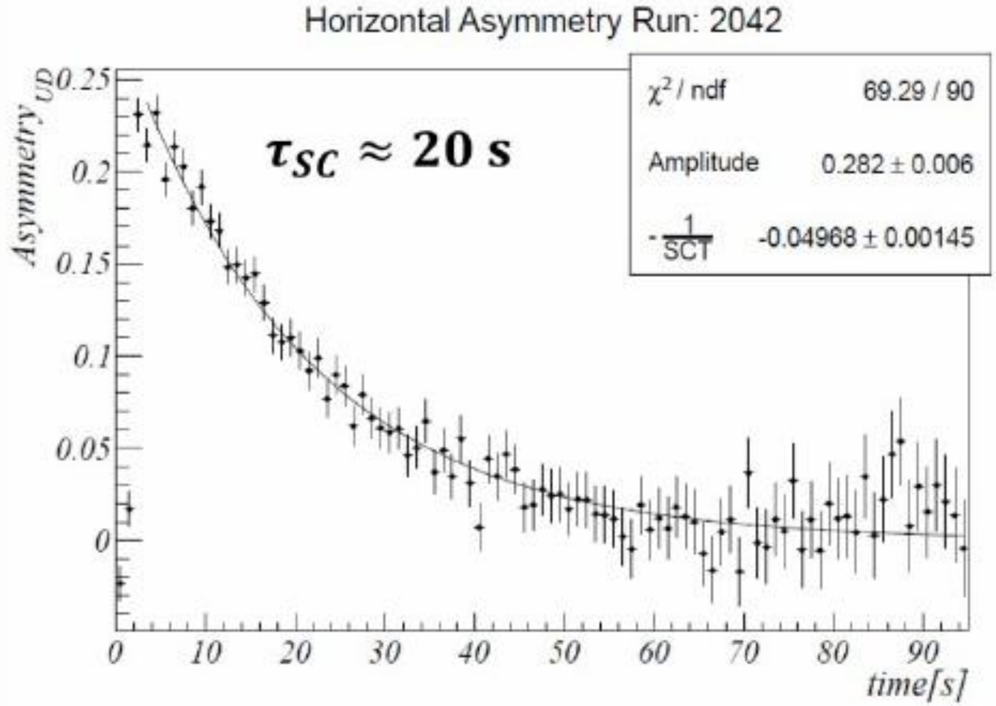
Measurement Principle

Martin Gaisser/CAPP

Beam Preparation:

- Inject vertically polarized deuteron beam
- Accelerate
- Cool (with e-cooler) and bunch
- Put spin into horizontal plane (with rf-solenoid on spin tune resonance)

Watch decay of up-down asymmetry (horizontal polarization)

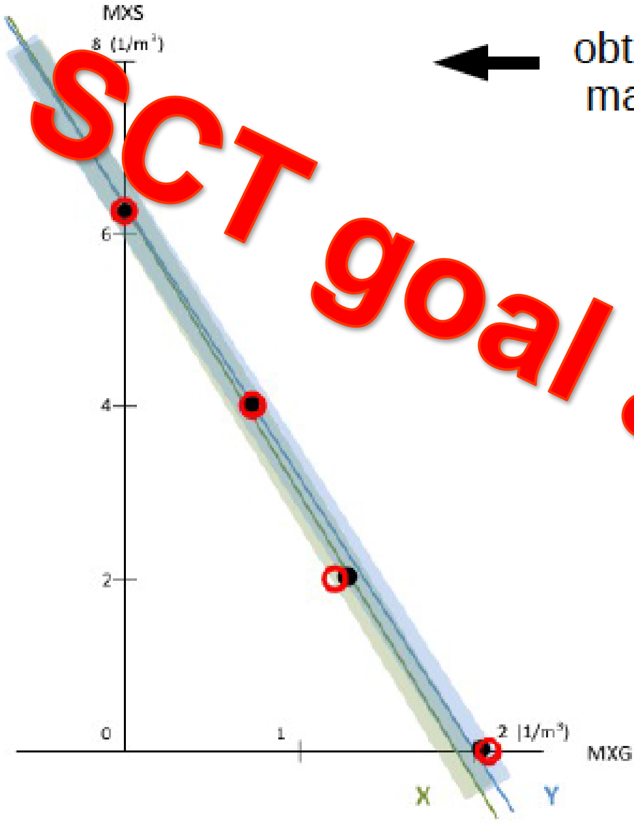


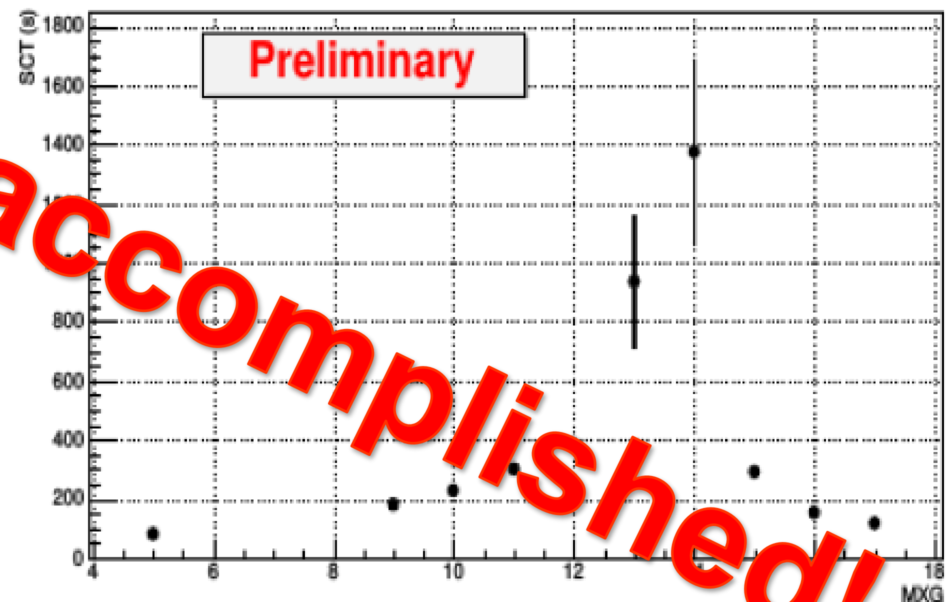
Sextupole Scans

CAPP
Center for Axion and Precision Physics Research

Martin Gaisser/CAPP

obtain this picture by rastering the MXS-MXG plane,
maximum SCT lies on zero chromaticity lines

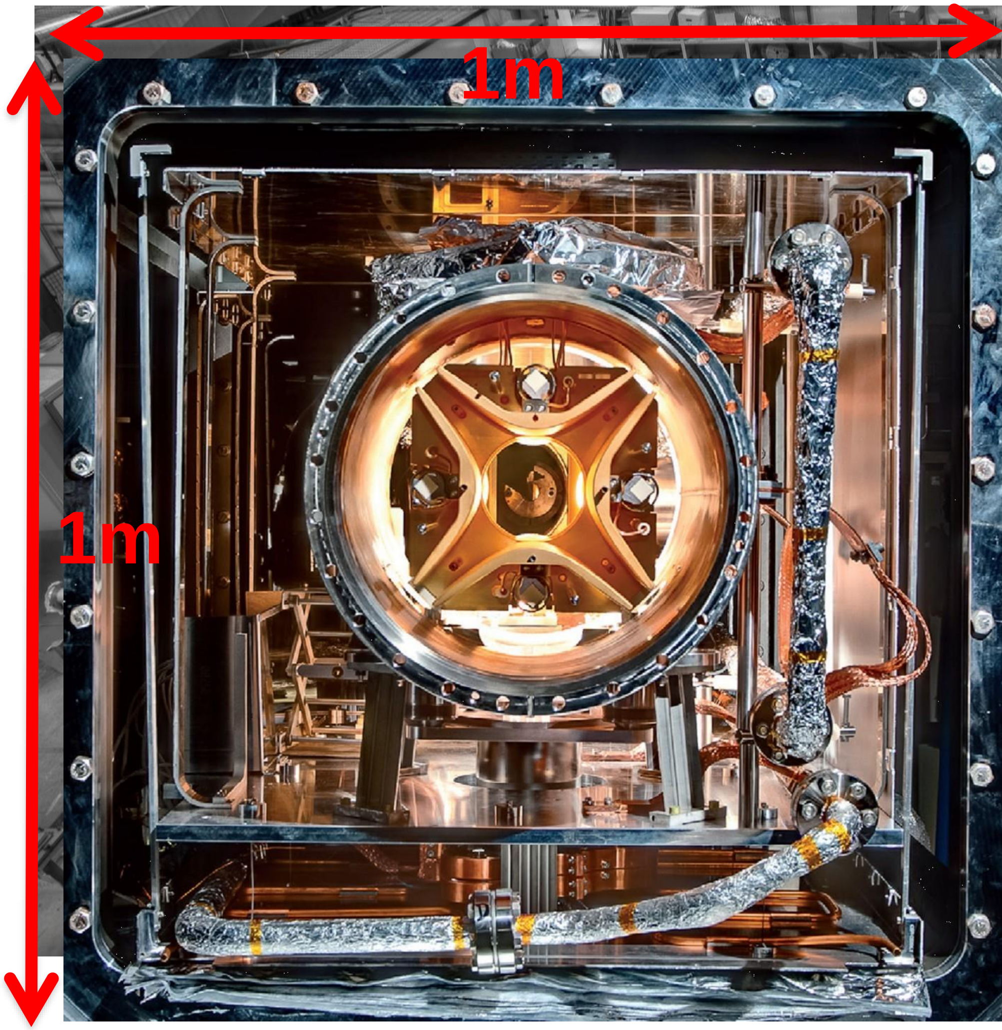


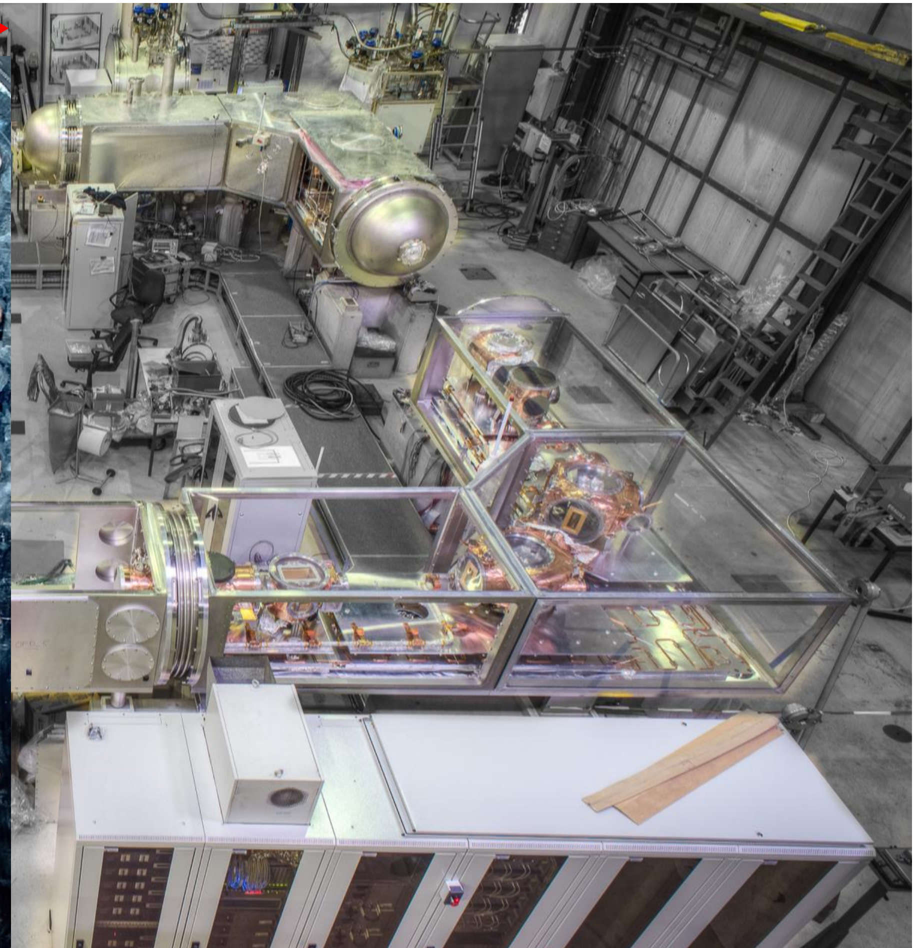


Sextupole strength

SCT goal accomplished!

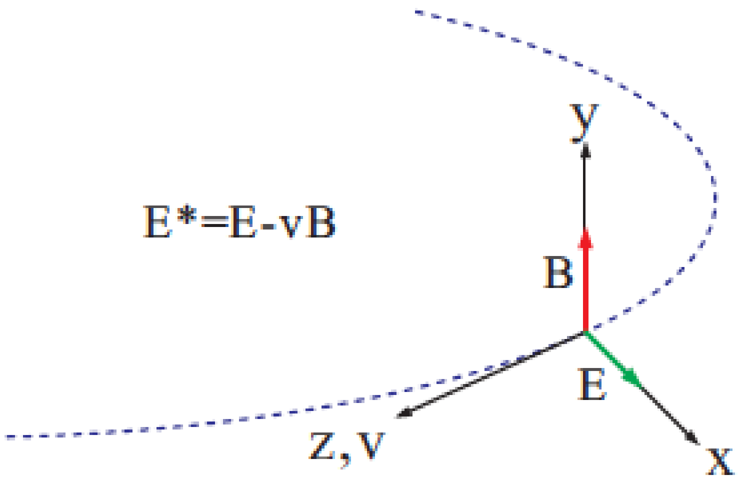
Currently: CSR, Heidelberg, 35 m circ., 10^{-13} Torr



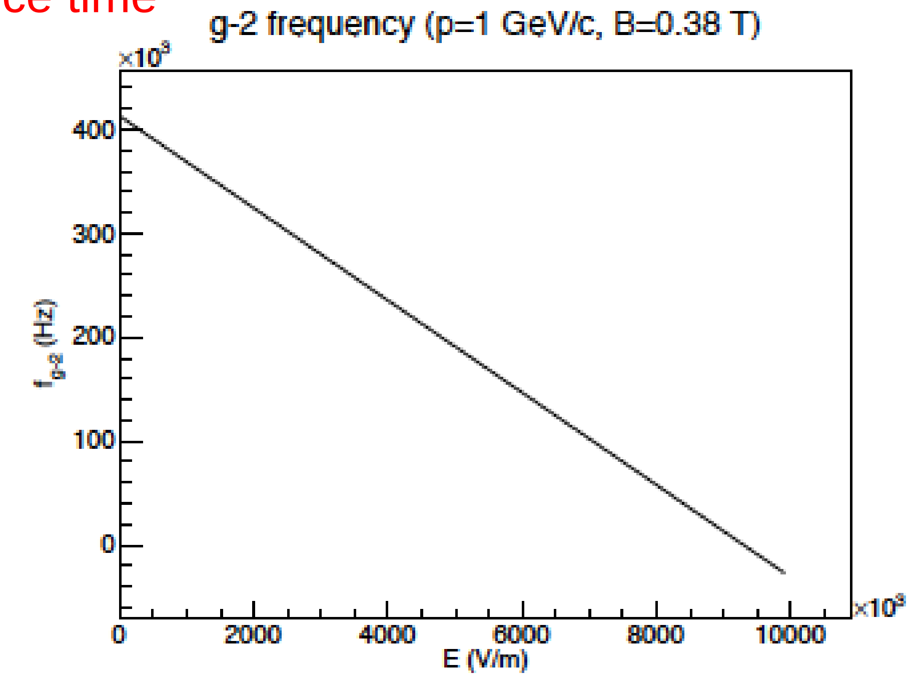


Search for axion dark matter in storage rings (1710.05271)

- Large effective E-field
- Statistics
- Superb tune stability, long spin coherence time



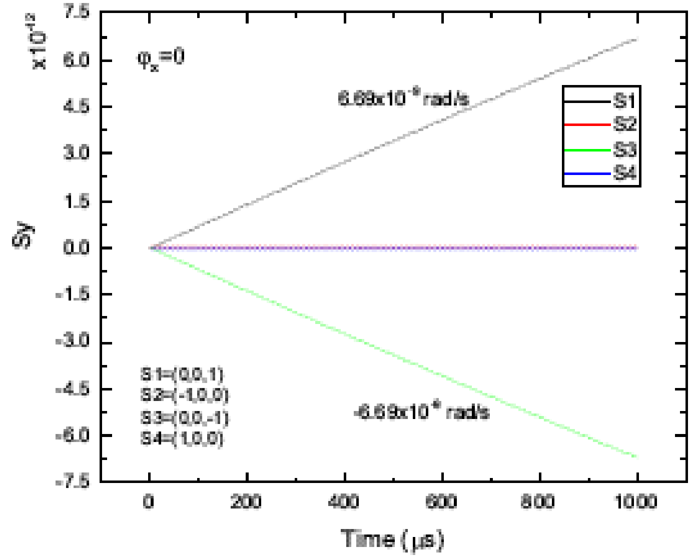
(a) The coordinate of B, E and v



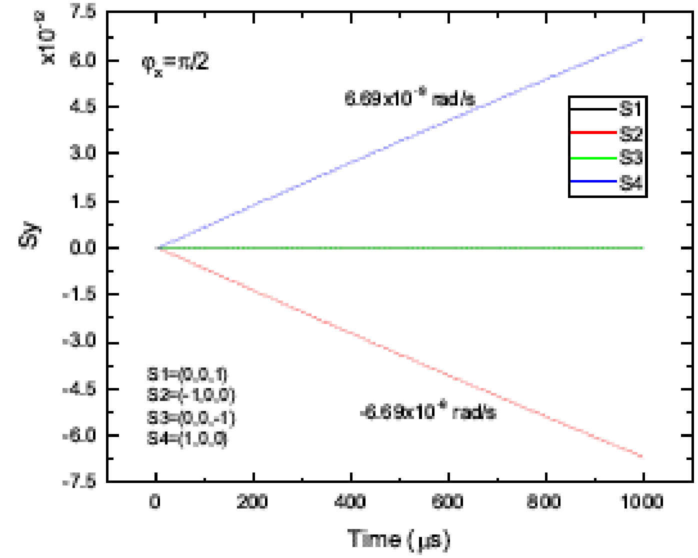
(b) $g-2$ frequency vs E field

Figure 2: E/B combined ring for $g-2$ frequency tunning

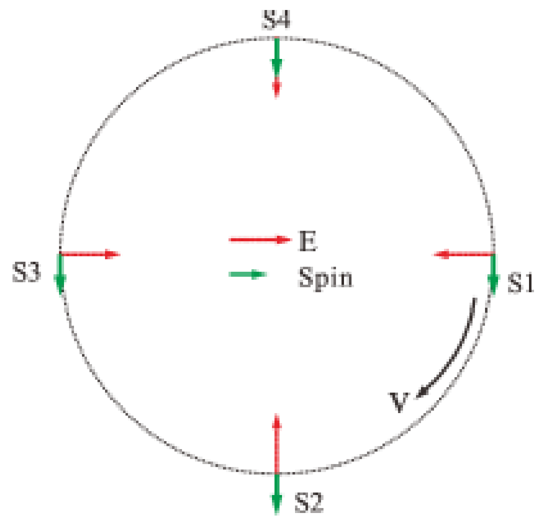
Spin direction



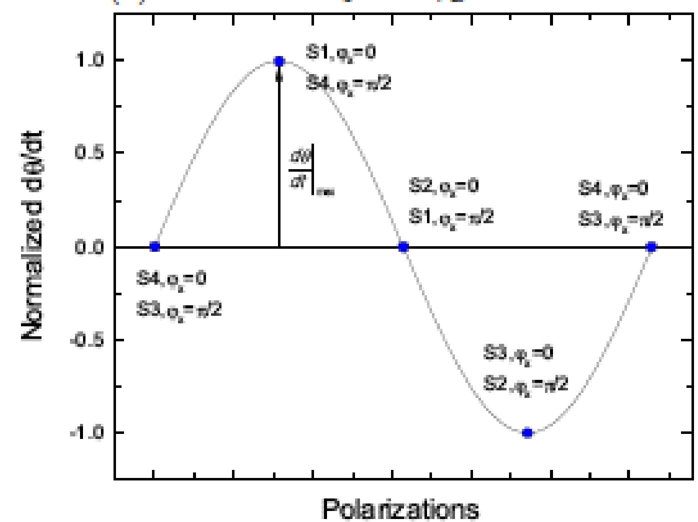
(a) Initial axion phase $\phi_x = 0$



(b) Initial axion phase $\phi_x = 0$



(c) Initial axion phase $\phi_x = \pi/2$



(d) Vertical precession rate vs. initial spin with different axion phase

Figure 4: Vertical spin precession with different initial polarization

Deuteron

Table 1: Examples of experiment parameters for frequency tunning and results of sensitivity calculation (Deuteron). The analyzing power was assumed to be $A = 0.36$ for both B-ring and E/B combined ring.

B (T)	P (GeV/c)	f_{g-2} (Hz)	E_r (V/m)	E* (V/m)	Sensitivity (e·cm) a	Sensitivity (e·cm) b	Ring
0.38	0.9429	10^2	8.82×10^6	4.23×10^7	1.9×10^{-31}	1.9×10^{-31}	E/B ring ($r = 10$ m)
0.38	0.9433	10^3	8.80×10^6	4.24×10^7	6.0×10^{-31}	1.9×10^{-31}	
0.38	0.9473	10^4	8.65×10^6	4.27×10^7	1.9×10^{-30}	1.9×10^{-31}	
0.38	**0.988**	$\mathbf{10^5}$	$\mathbf{7.05 \times 10^6}$	4.60×10^7	5.5×10^{-30}	$\mathbf{1.8 \times 10^{-31}}$	
0.38	1.035	2×10^5	5.06×10^6	5.00×10^7	7.2×10^{-30}	1.6×10^{-31}	
0.38	1.133	4×10^5	3.47×10^5	5.86×10^7	8.7×10^{-30}	1.4×10^{-31}	
0.38	1.239	6×10^5	-5.47×10^6	6.83×10^7	9.1×10^{-30}	1.2×10^{-31}	
0.38	1.355	8×10^5	-1.26×10^7	7.93×10^7	9.1×10^{-30}	1.0×10^{-31}	
0.38	1.484	10^6	-2.14×10^7	9.21×10^7	8.8×10^{-30}	8.8×10^{-31}	
0.80	2.513	10^6	-9.13×10^6	2.01×10^8	4.0×10^{-30}	4.0×10^{-31}	
0.9198	2.7574	10^6	0	2.28×10^8	3.5×10^{-30}	3.5×10^{-31}	B ring ($r = 10$ m)
9.1977	27.574	10^7	0	2.75×10^9	9.3×10^{-31}	9.3×10^{-31}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.
b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.

Proton

Table 2: Examples of experiment parameters for frequency tunning and results of sensitivity calculation (Proton). The analyzing power used for E/B combined ring was $A = 0.6$ and $A = 0.25$ was used for B field only ring.

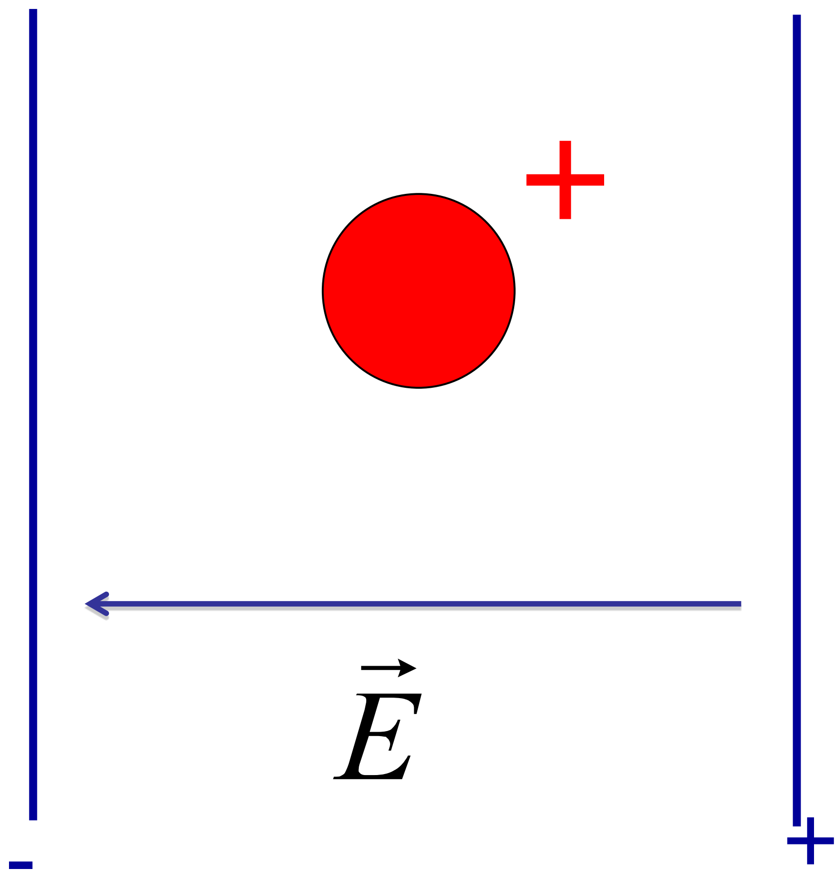
B (T)	P (GeV/c)	f_{g-2} (Hz)	E_r (V/m)	E^* (V/m)	Sensitivity (e·cm)		Ring
					a	b	
0.00010	0.6984	10^2	-8.00×10^6	8.02×10^6	1.0×10^{-30}	1.0×10^{-30}	E/B ring ($r = 52$ m)
0.00008	0.6982	10^3	-8.00×10^6	8.01×10^6	3.2×10^{-30}	1.0×10^{-30}	
-0.00017	0.6964	10^4	-8.00×10^6	7.97×10^6	1.0×10^{-29}	1.0×10^{-30}	
-0.00243	0.6747	10^5	-8.00×10^6	7.57×10^6	3.4×10^{-29}	1.1×10^{-30}	
-0.00495	0.6519	2×10^5	-8.00×10^6	7.15×10^6	5.0×10^{-29}	1.1×10^{-30}	
-0.01523	0.7103	4×10^5	-1.10×10^7	8.24×10^6	6.2×10^{-29}	9.8×10^{-31}	
-0.02002	0.6711	6×10^5	-1.10×10^7	7.51×10^6	8.3×10^{-29}	1.1×10^{-30}	
-0.02666	0.6643	8×10^5	-1.20×10^7	7.38×10^6	9.8×10^{-29}	1.1×10^{-30}	
-0.03327	0.6583	10^6	-1.30×10^7	7.27×10^6	1.1×10^{-28}	1.1×10^{-30}	
0.36587	1.0968	10^7	0	8.33×10^7	3.1×10^{-29}	3.1×10^{-31}	B ring ($r = 10$ m)
3.65868	10.9684	10^8	0	1.09×10^9	7.4×10^{-30}	7.4×10^{-32}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.
b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.
Analyzing power A : $A = 0.6$ for E/B ring, $A = 0.25$ for B ring

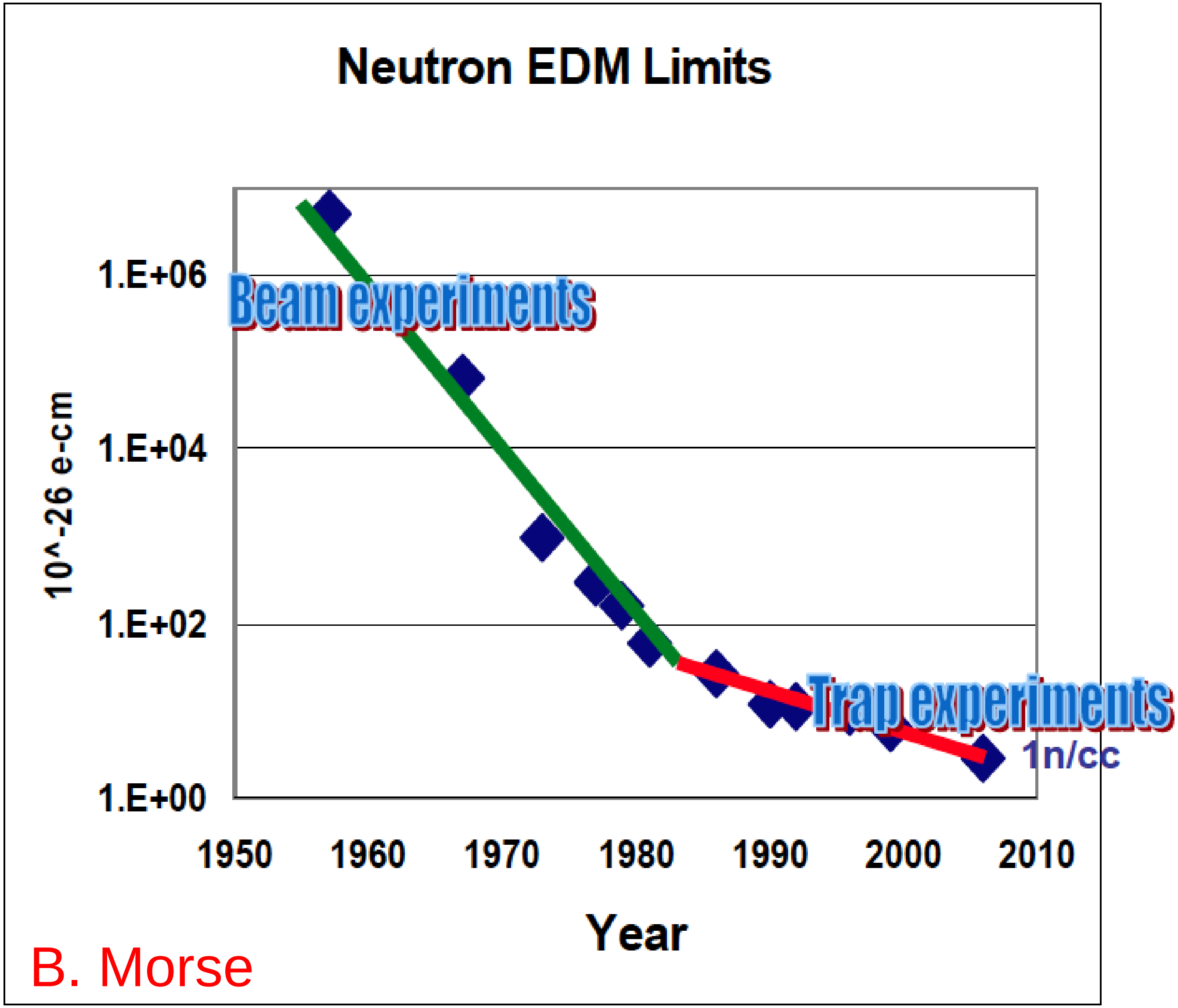
History/Status of nEDM@SNS

- **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

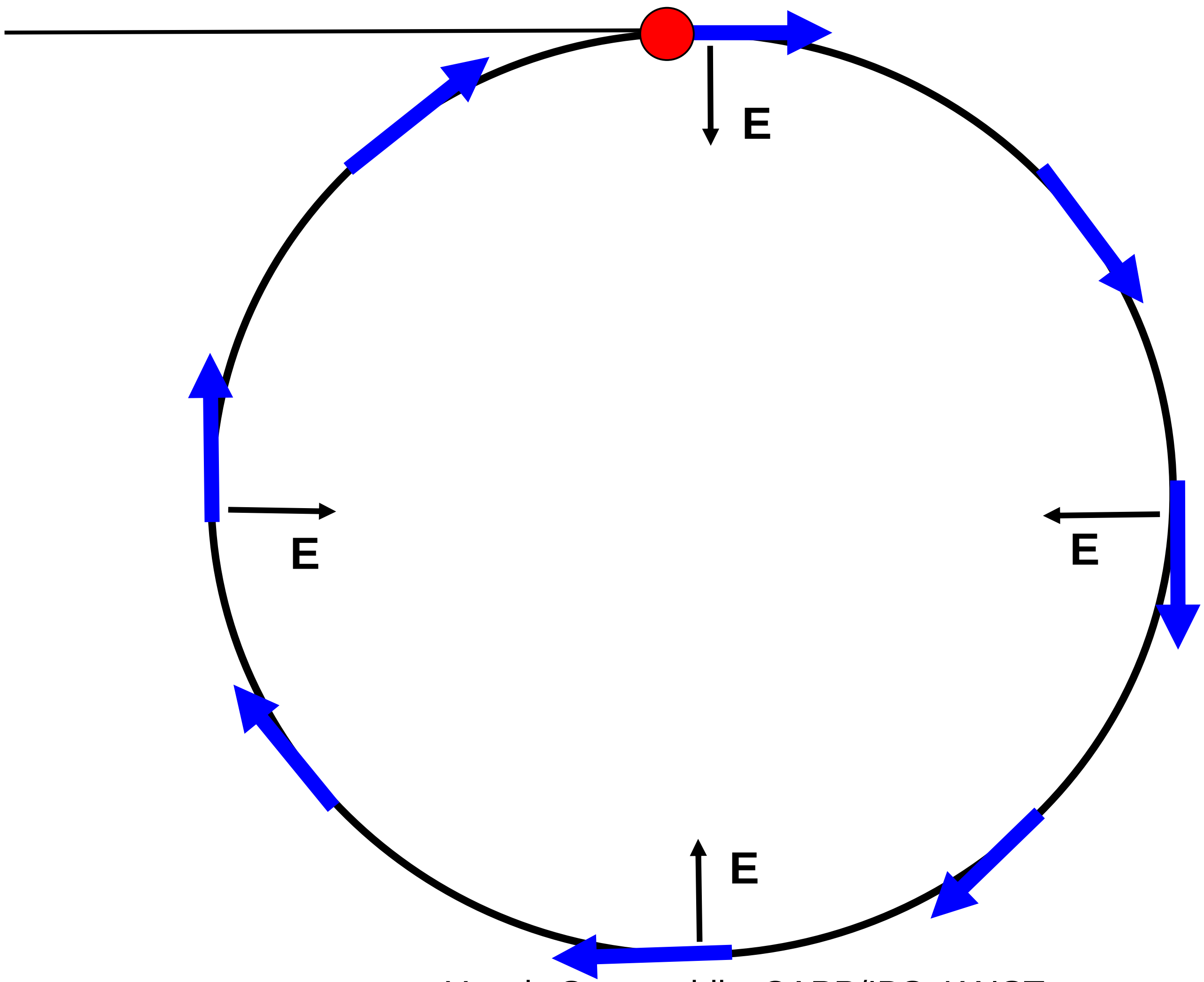
A charged particle between Electric Field plates would be lost right away…



Proton storage ring EDM experiment is combination of beam + a trap



Stored beam: The radial E-field force is balanced by the centrifugal force.

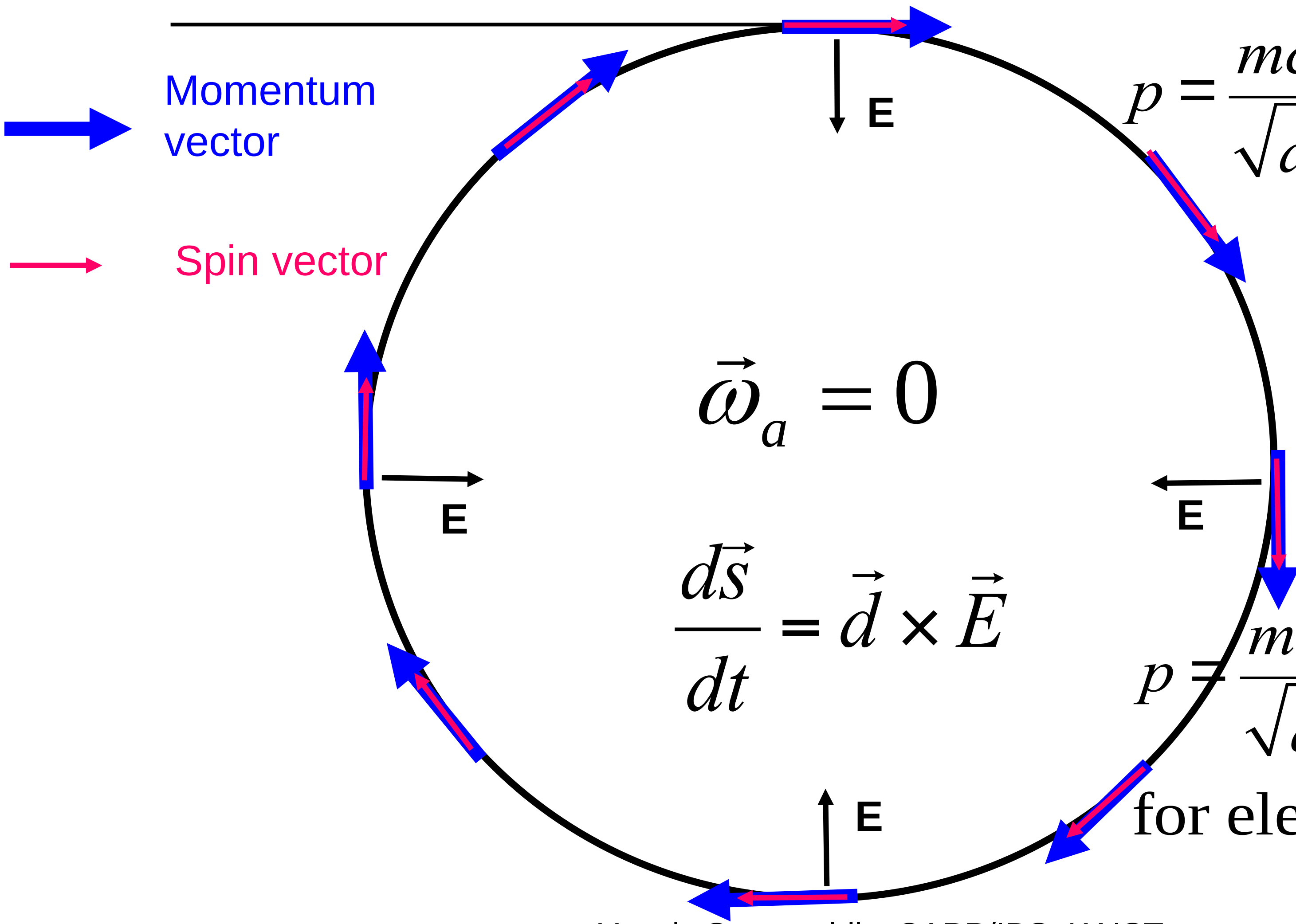


The Electric Dipole Moment precesses in an Electric field

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

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector

at the magic momentum



$$p = \frac{mc}{\sqrt{a}} = 0.7\ \text{GeV/c}$$

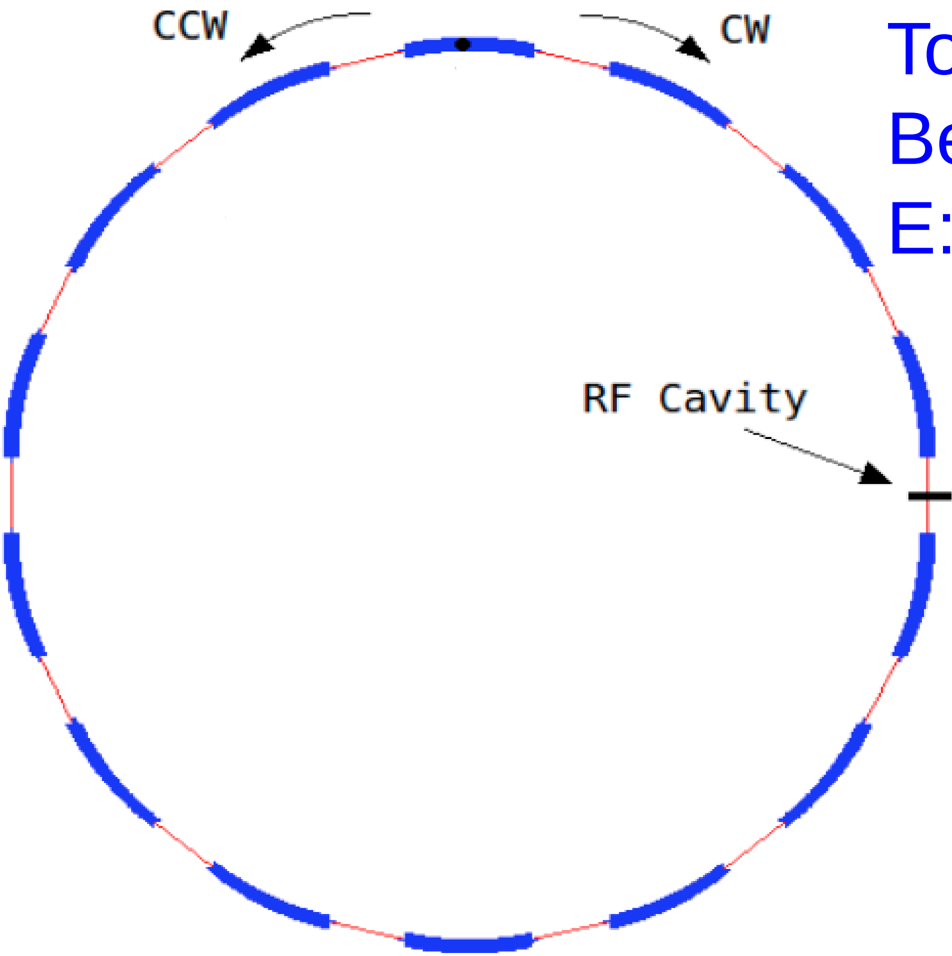
$$\vec{\omega}_a = 0$$

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

$$p = \frac{mc}{\sqrt{a}} = 15\text{MeV/c}$$

for electrons!

Example: The proton EDM ring



Total circumference: 300 m
Bending radius: 40 m
E: 10 MV/m

Weak vertical focusing
Stronger horizontal focusing