Storage ring EDM experiment and its application to axion search

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Workshop on The strong CP puzzle and axions
LPSC, Grenoble France
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Outline

1. Introduction to storage ring EDM experiment
2. Polarimeter and sensitivity of the srEDM experiment
3. Storage ring technique for axion search
   - ✓ Axion coupled oscillating EDM
   - ✓ Resonance of g-2 precession with oscillating EDM
4. Sensitivity of the AxionEDM experiment
5. Summary and plans

IBS/CAPP

- **Center for Axion and Precision Physics (CAPP) at Institute for Basic Science (IBS) (Director: Yannis Semertzidis)**
- **Web site: http://capp.ibs.re.kr/html/capp_en/**
- **Located at KAIST campus in Daejeon, South Korea**

We are working on:

- **Axion-dark matter search**
  - ✓ **Microwave resonance cavity axion search (Cryogenics, Electronics, Super conducting magnet, SQUID, etc.)**
  - ✓ **ARIADNE, GNOME**
- **Storage ring Proton/Deuteron EDM**
  - ✓ **Polarimeter, Beam position monitoring (with magnetic shielding), Beam dynamics, etc.**
  - ✓ **Storage ring axion search**
- **Muon g-2 experiment**
  - ✓ **Fermi lab. muon g-2, J-PARC**
- **Others (COMET, etc)**

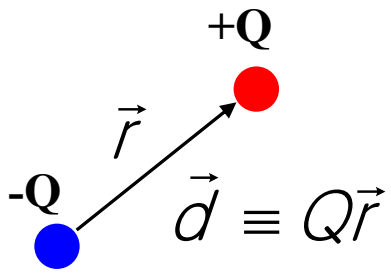
Patras workshop, 2016
(next week, 20~24, June)
https://axion-wimp2016.desy.de/

EDM and CP violation

❖Motivation

- ✓Strong CP problem, Θ_{QCD}
- ✓Matter-antimatter asymmetry (Baryogenesis)

Electric Dipole Moment



➢ P, T violation due to an EDM

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

$$T(\vec{B},\vec{\sigma}\ change): H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$P(\vec{E}\ change): H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$\mu = g\frac{q}{2m}, d = \eta\frac{q}{2mc}$$

A nonzero particle EDM violates P, T, and assuming CPT conservation, also CP violation.

Searching EDM

- Current EDM bounds
  - ✓ SM predicts non-vanishing EDM
    - $|d_e| < 10^{-38}$ e.cm
    - $|d_{n,p}| < 10^{-31}$ e.cm
    - Beyond current experiment limit
  - ✓ SUSY prediction: 10^{-25}~10^{-28} e·cm (nEDM limit)
  - ✓ Neutron EDM bound: $\mathbf{|d_n|<2.9x10^{-26}}$ e.cm ('06)
  - ✓ Proton EDM bound: $|d_{p|}$ <7.9x10^{-25} e.cm ('09, ^{199}Hg)
  - ✓ Electron EDM bound: $|d_e|$ <8.7x10^{-29} e. cm ('14,ThO)
- Target sensitivity level in the storage pEDM experiment
  - ✓ High statistics (10^{11} protons/store) is achievable using storage ring
  - ✓ Goal **10^{-29} e·cm** (statistical limit in about one year)
  - ✓ → 10^{-30} e·cm (with an upgrade)
- Physics reach >10^3 TeV

✓ The first EDM experiment started by Smith, Purcell and Ramsey in 1951 (and published in 1957) obtaining a limit of $|d_n| < 5 \times 10^{-20}$ e·cm.

EDM and spin precession/principle

❖ **Spin dynamics (with EDM and MDM) in magnetic+electric field (T-BMT equation)**

$$\frac{d\vec{s}}{dt} = \vec{\mu} x \vec{B} + \vec{d} x \vec{E} = \vec{s} \times (\vec{\omega}_a + \vec{\omega}_{edm})$$ (for particle at rest)

$$\mu = g(e\hbar / 2m), \quad d = \eta(e\hbar / 2mc)$$

$$with\ \vec{\beta} \cdot \vec{E} = \vec{\beta} \cdot \vec{B} = 0$$

(T-BMT equation: for moving particle)

$$\vec{\omega} = -\frac{e}{m}\left[a\vec{B} - \left(\frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} + \eta \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right], a = \frac{g-2}{2}$$

MDM in B-field

MDM in induced B-field

EDM term

$$\underbrace{\qquad\qquad\qquad\qquad}_{\vec{\omega}_a} \qquad \vec{\omega}_{edm}$$

Storage ring technique for EDM search

g-2 precession in **pure electric ring**

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

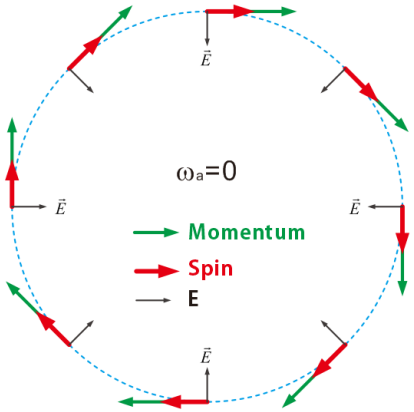
for the proton (a=1.792847357(23)) >0

$$\vec{\omega}_a = 0 \quad at \quad p = \frac{m}{\sqrt{a}} = 0.700740\ \mathrm{GeV/c}$$: magic momentum

❖ **Use frozen spin method (static EDM measurement)**

- ✓ Spin freezes to the momentum direction
- ✓ a>0 particles (p,e, etc.): use magic momentum
  - **Pure electric ring**
  - **CW/CCW beams (minimize systematic error!)**
- ✓ a<0 (deuteron) : use E+B field
- ✓ spin precesses only on the vertical plane!

$$\vec{\omega}_{EDM} = -\frac{e\eta}{2m}\frac{\vec{E}}{c}$$



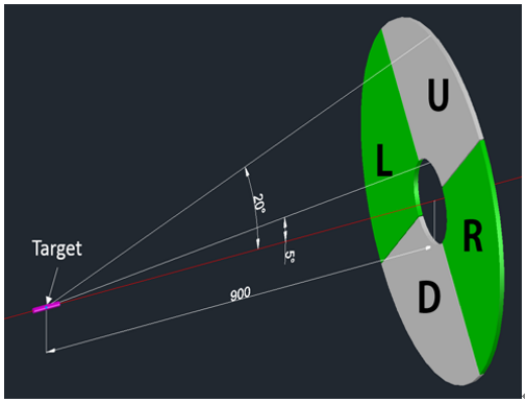
❖ Storage ring EDM collaboration is trying to establish the experiment at CERN

- ✓EDM Kick-off meeting at CERN in Mar. 2017
- ✓Second meeting at Juelich, Germany (Mar. 2018)

Polarimeter and asymmetry

❖ **Use asymmetrical proton scattering on Carbon target**

- Hadronic elastic scattering (spin-orbit interaction)
- Asymmetrical proton hit distribution on the detector plane
- L/R (U/D) asymmetry for vertical (horizontal) component of proton polarization

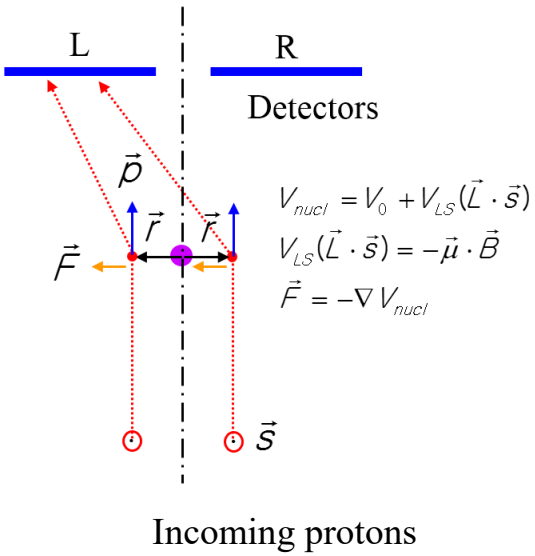


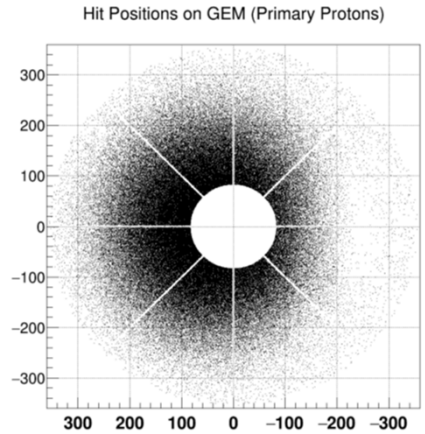
➢ For spin 1/2 particle

$$\sigma(\theta) = \sigma_{unpol}(\theta)[1 + P_y A_y]$$

$$L/R \text{ asymmetry } \varepsilon_{LR} = \frac{L-R}{L+R} = P_y A_y$$

$$P_y = \frac{1}{A_y}\frac{L-R}{L+R}$$

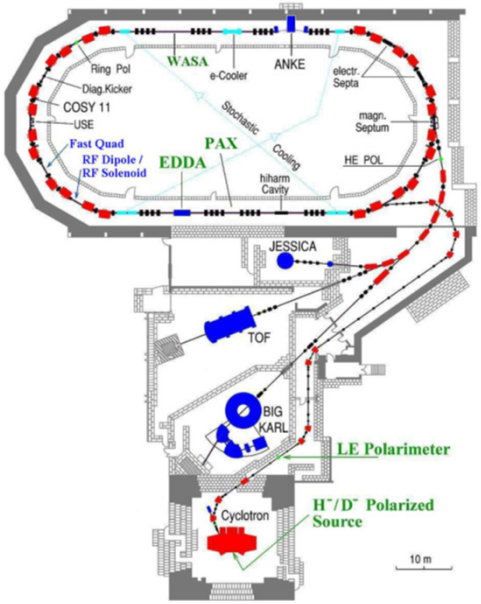




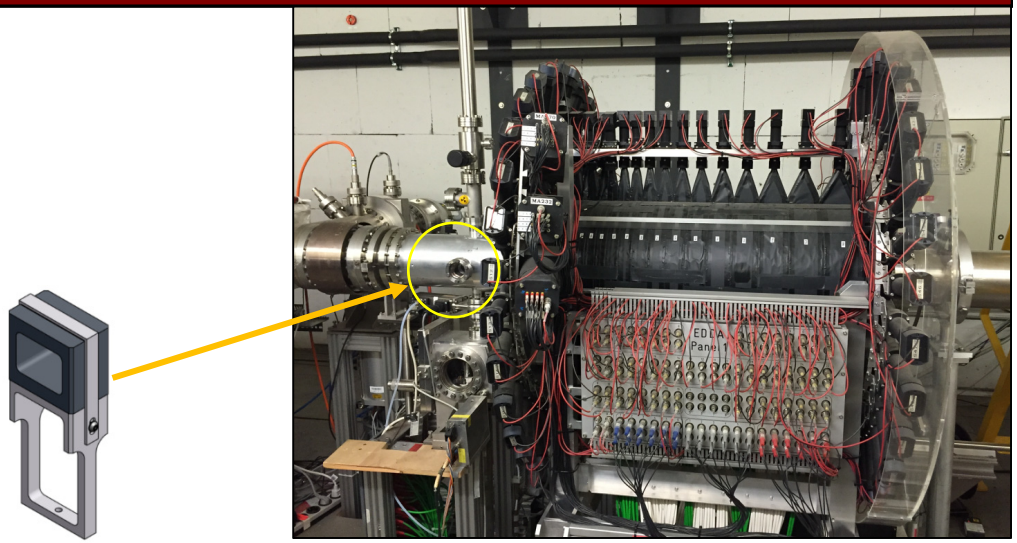
Simulation by Hoyong Jeong

- P_y is calculated from the asymmetry with known A_y
- P_y changes in time due to the precession in E field.

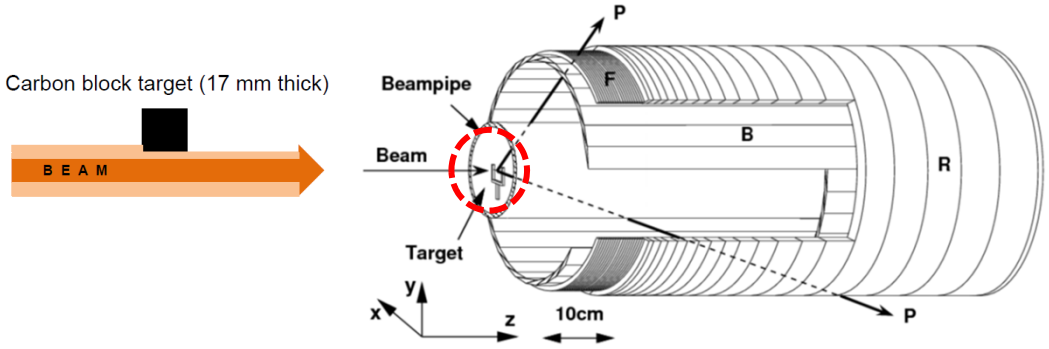
Slow beam extraction to target



COSY ring (Juelich, Germany)



COSY carbon tube target



COSY EDDA detector
FZJ, Juelich, Germany

Statistical error of measured EDM *d* (statistical sensitivity)

L/R asymmetry for vertical polarization

$$\varepsilon_{LR}(t) = \frac{L-R}{L+R}(t) = pA\theta_t \qquad \theta_t = \frac{dE}{\hbar/2}t$$

P: degree of beam polarization
d : EDM, *E*: Electric field, *t* : measurement time

Statistical error for *d*

$$\sigma_d = \frac{2\hbar}{PAE\sqrt{N_{tot} f T_{tot} \tau_p}}$$

where P is the degree of polarization, A analyzing power and E is the electric field causing the spin precession. If we use the parameters P = 0.8, A = 0.6, E = 10.5 MV/m, N_{tot} =4 × 10^{10} particles/storage, an effective detection efficiency of f = 0.011, total running time T_{tot} = 10^7 s/year, and spin coherence time of τ_p= 10^3 s, the resulting statistical error is **~1.8 × 10^{-29} e.cm per year**.

Spin precession rate

11.1 Expected signal of the pEDM experiment

The expected EDM signal, assuming the spin is along the momentum, is estimated by

***From pEDM proposal**

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} \Rightarrow \frac{1}{2}\hbar\omega = dE \Rightarrow \frac{d\theta}{dt} = \frac{2dE}{\hbar} \Rightarrow$$
$$\theta(t) = \theta_0 + \frac{2dE}{\hbar}t, \qquad (11.1)$$

where d, E are assumed to be orthogonal to each other. For E=10.5 MV/m, 95% E-field coverage of the ring, and an EDM of d=10^{-29} e·cm, the rate of change in the vertical spin component is

$$\theta(t) = \theta_0 + \frac{2dEc}{\hbar c}t = \theta_0 + \frac{2\times10^{-31}\,\mathrm{e\cdot m}\times10.5\mathrm{MV/m}\times0.95\times3\times10^{8}\mathrm{m/s}}{197\ \mathrm{MeV\ fm}}t \Rightarrow$$

$$\theta(t) = \theta_0 + 3\frac{\mathrm{nrad}}{\mathrm{s}}t.$$

We can make the following observations from equations (11.1) and (1

- In pEDM experiment, spin processes on the vertical plane.
- The storage time will be 1000 s.
- EDM signal of ~**3 μrad/1000s**
  - ✓ Projected systematic error << 1 ppm
  - ✓ Need long spin coherence time
  - ✓ **Already achieved >1000 s SCT (COSY)**

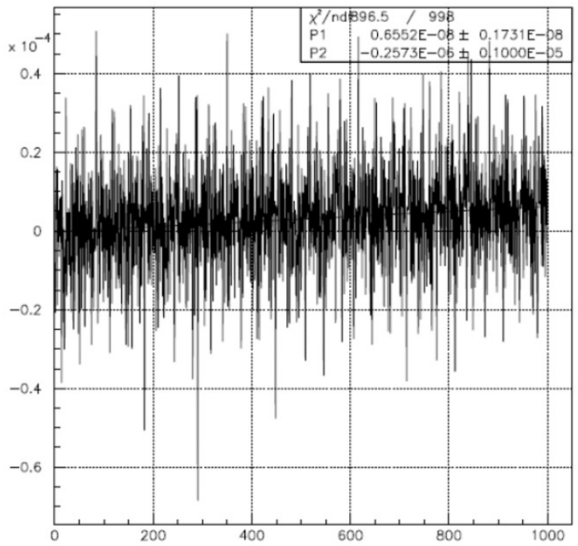


Figure 11.1: (L-R)/(L+R) vs. time [s], is as well as the fit results to two parameters (slope and dc offset). The total counts used are 4×10^{12}, with P_0=0.8, and A=0.6. The slope is estimated with 3.8 sigma statistical accuracy. The fit results confirm the result of eq. (11.3).

Statistical errors and figure of merit

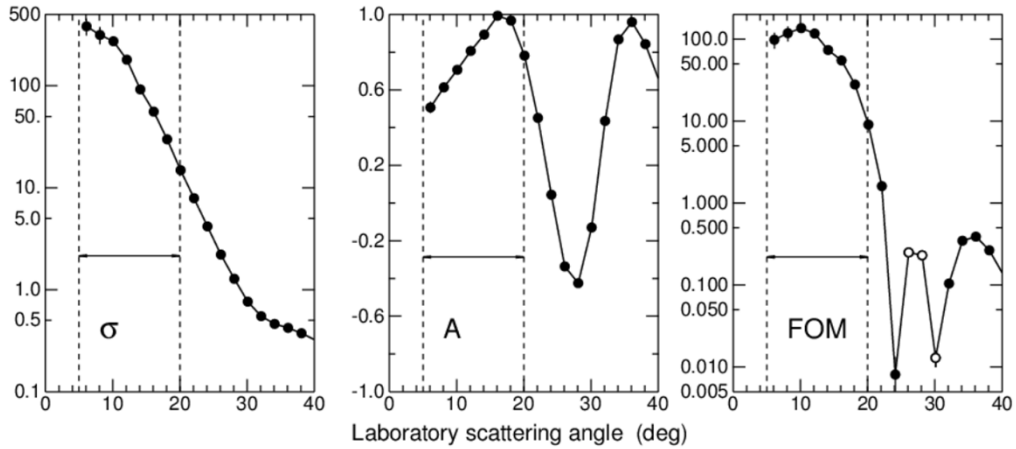
L/R asymmetry $\varepsilon_{LR} = \dfrac{L-R}{L+R} = p_y A_y(\theta)$

The uncertainty in the asymmetry is given by

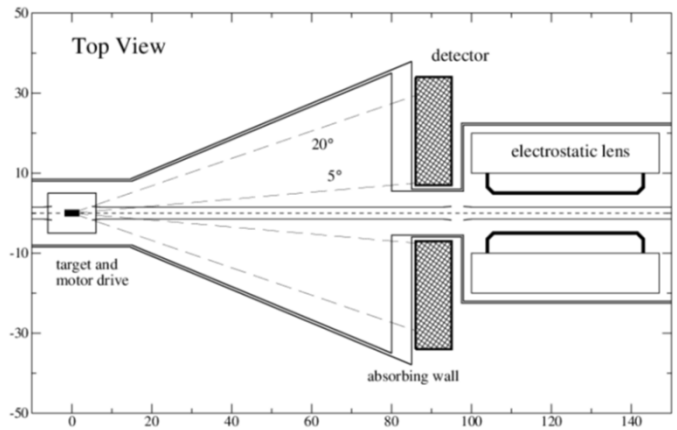
$$\sigma_{p_y}^2 = \frac{\sigma_{LR}^2}{A_y^2} = \frac{1}{2N_0 A_y^2}$$

The denominator is called the '**Figure Of Merit**'.

$FOM \equiv \sigma A^2 \quad \leftarrow 2N_0 \propto \sigma : differential\ cross\ section$



Optimum angle (FOM) range: 5~20 deg.



pEDM polarimeter
(from pEDM proposal)

AxionEDM search

Storage ring EDM method for axion search

About axion induced oscillating EDM

- Dark matter axion background field is oscillating
  - ✓ $a=a_0\cos(\omega_a t)$
  - ✓ $\omega_a \approx m_a c^2/\hbar$, m_a: axion mass
- The oscillating axion field is coupled with
  - ✓ Photon $P_{sig} = \eta^2_{g_{a\gamma\gamma}} \left(\frac{\rho_a}{m_a}\right) B_0^2 V C Q_L$ $\quad a \rightarrow \gamma\gamma$
  - ✓ gluons, fermions, nucleon, etc. → Oscillating EDM

$$a(t) = a_0 \cos(m_a t) \Rightarrow \quad d(t) = d_0 \cos(m_a t + \phi_x)$$

➢ Generic feature

$$d_n = 2.4\times10^{-16}\frac{a}{f_a} e\cdot cm \approx 9\times10^{-35}\cos(m_a t)[e\cdot cm]$$

Peter W. Graham and Surjeet Rajendran.
Phys. Rev. D, 84, 055013, (2011)
Phys. Rev. D, 88, 035023, (2013)

Axion coupled EDM measurement using storage ring method

srEDM

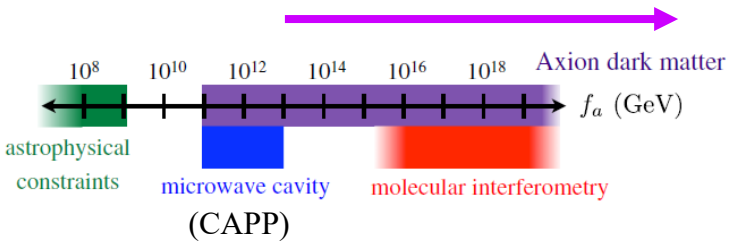
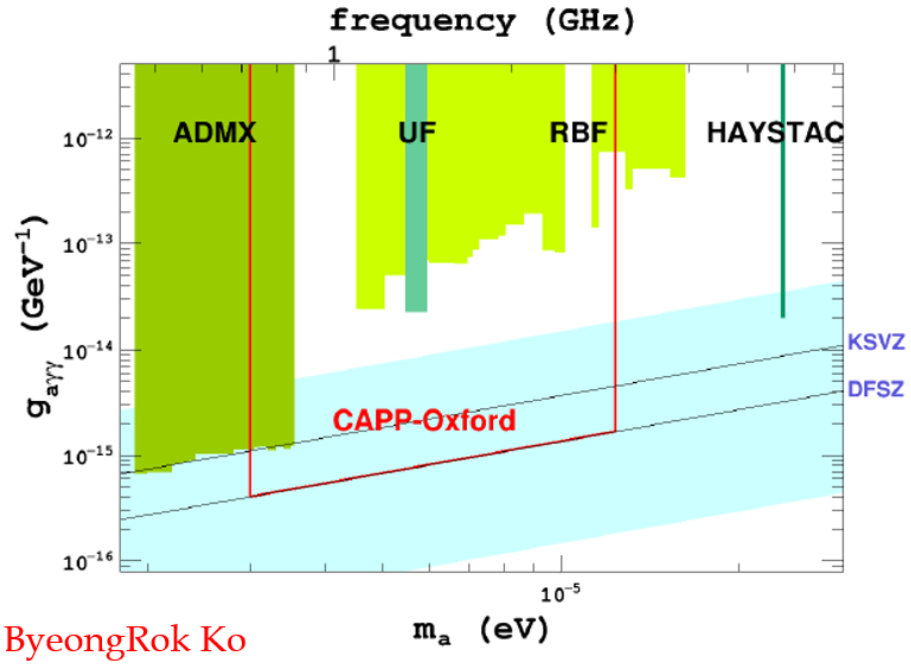


FIG. 1 (color online). (Color Online) The parameter space of the axion in f_a (GeV). Values of $f_a < 10^9$ GeV are ruled out by astrophysical constraints (green). Values of $f_a \gtrsim 10^{11}$ GeV allow the axion to be the dark matter (purple). The (blue) region labeled "microwave cavity" shows the region of parameter space that is potentially observable with microwave cavity experiments, e.g. ADMX. The (red) region labeled "molecular interferometry" shows the range of f_a which is potentially observable with the experiments proposed here. The lower limit on this region may in fact be lower than shown, depending on technological advances.

Peter W. Graham, Surjeet Rajendran,
Phys. Rev. D 84, 055013 (2011).



ByeongRok Ko

Experiments on axion search(a→γ)

- **Our proposal:**
  - Scan **frequency range 10^{-9} Hz~10^8 Hz** using storage ring technique.
  - axion parameter space: 10^{13} GeV $\leq f_a \leq 10^{30}$ GeV

Spin tracking for AxionEDM search

In particle at rest

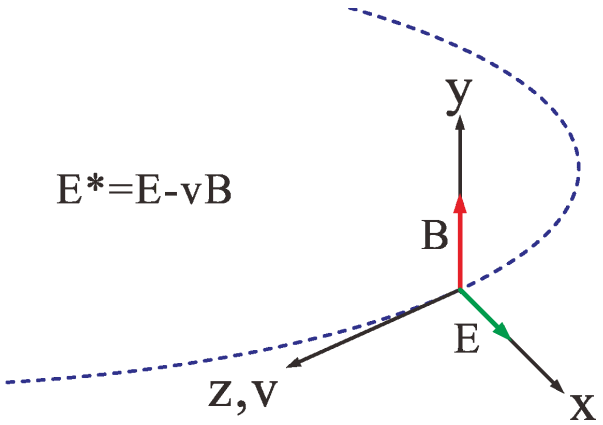
$$\frac{d\vec{s}}{dt} = \vec{\mu} x \vec{B} + \vec{d} x \vec{E} = \vec{s} \times (\vec{\omega}_a + \vec{\omega}_{edm})$$

$$\mu = (ge/2m)s = ge\hbar/4m, \;\; d = (\eta e/2mc)s = \eta e\hbar/4mc$$

In a storage ring

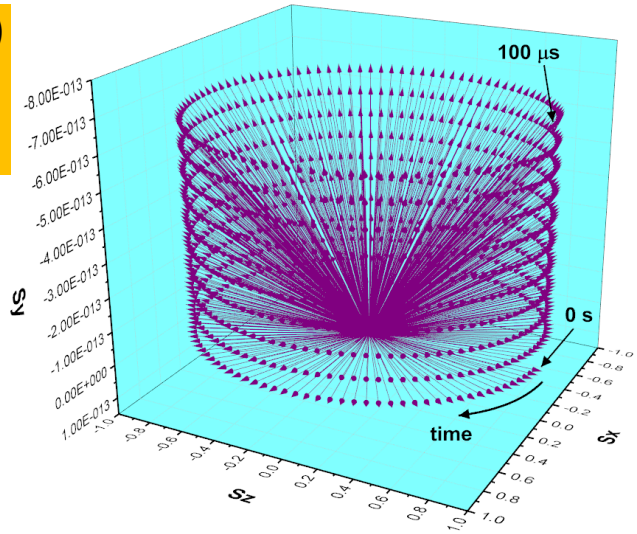
$$\frac{d\vec{\beta}}{dt} = \frac{e}{\gamma m}\left[\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} - \vec{\beta}\frac{\vec{\beta}\cdot\vec{E}}{c}\right]$$

$$\frac{d\vec{s}}{dt} = \frac{e}{m}\vec{s} \times \left[\left(\frac{g}{2} - \frac{\gamma-1}{\gamma}\right)\vec{B} - \left(\frac{g-2}{2}\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} - \frac{\gamma}{\gamma+1}\left(\frac{\vec{\beta}\cdot\vec{E}}{c}\right)\vec{\beta} + \vec{\beta}\times\vec{B}\right)\right]$$

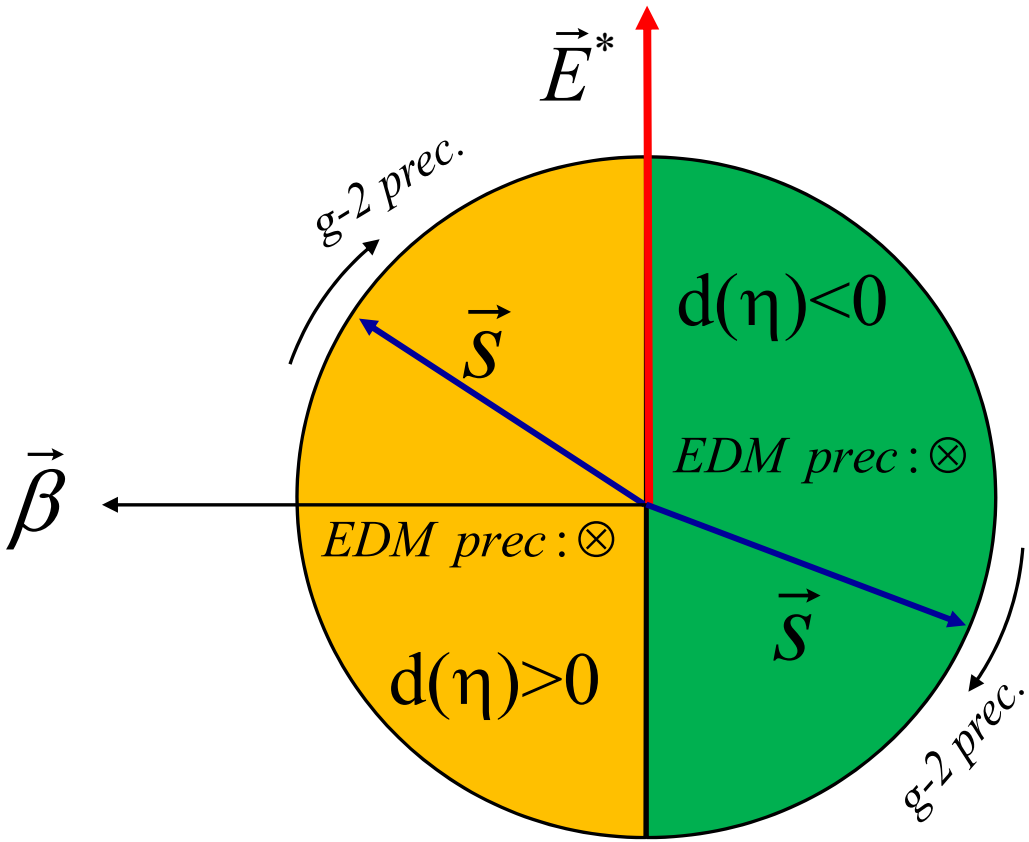


$$d(t) = d_0 \cos(\omega_a t + \varphi)$$

$$\eta(t) = \frac{d(t)4mc}{e\hbar}$$



EDM precession at resonance condition



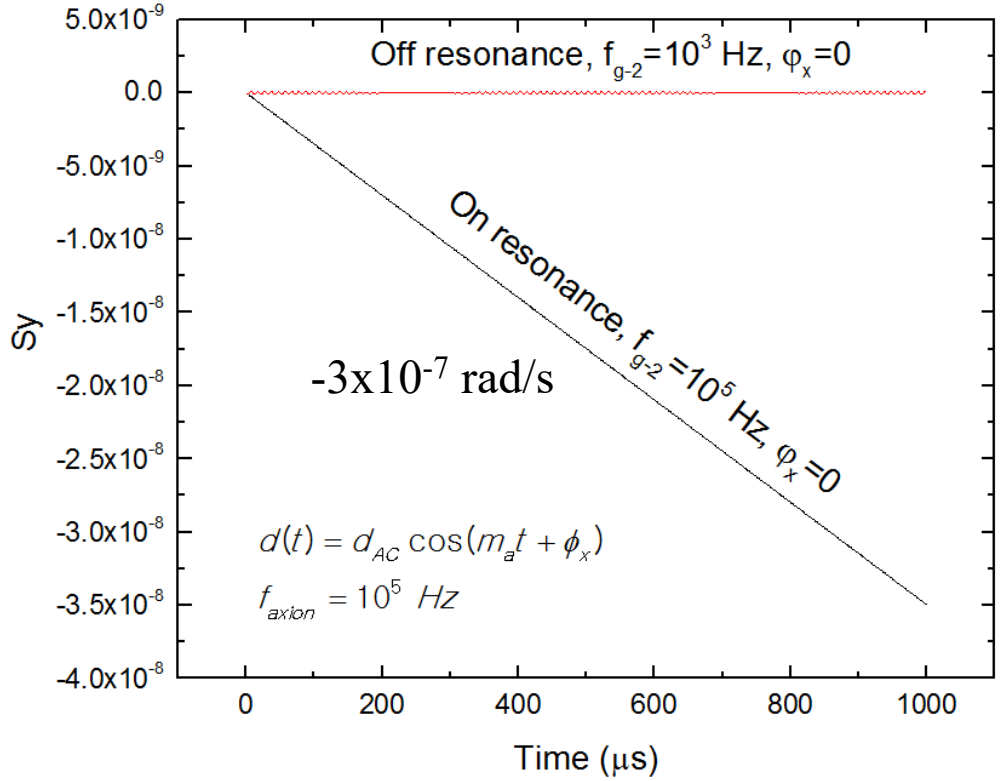
$$\left.\frac{d\vec{s}}{dt}\right|_{EDM} = \frac{e\eta}{2mc}\vec{s}\times\vec{E}^*$$

$$d(t) = d_0\cos(\omega_a t + \varphi)$$

$$\eta(t) = \frac{d(t)4mc}{e\hbar}$$

Resonance of Axion induced oscillating EDM with g-2 precession in storage ring

Deuteron, $d_0=10^{-27}$ e.cm



$$\vec{\omega}_a = -\frac{e}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$\vec{\omega}_d = -\frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

$$\omega_d = \frac{d\theta}{dt} = -\frac{d}{\hbar}E^*, \quad E^* = E + c\beta B$$

Benefit from strong effective E field!

Static EDM and oscillating EDM experiments

❖ **Static EDM measurement**

- ✓ Use frozen spin (FS) method
- ✓ Spin precesses only on the vertical plane
- ✓ No precession on the ring plane

$$\omega_{edm} = -\frac{e\eta}{2m}\frac{E}{c}$$

❖ **Axion-EDM measurement uses non-zero g-2 precession**

- ✓ Resonance method
- ✓ Spin precession on the ring plane
- ✓ Benefit from larger effective E-field ($\vec{E}^* = \vec{E}_0 + \vec{v} \times \vec{B}$)
- ✓ More sensitive
- ✓ Also uses FS method for low frequency search (<mHz)

$$\omega_{edm} = \frac{d\theta}{dt} = -\frac{d}{s\hbar}E^*, \boxed{E^* = E + c\beta B}$$

s=1/2 for protons, 1 for deuterons

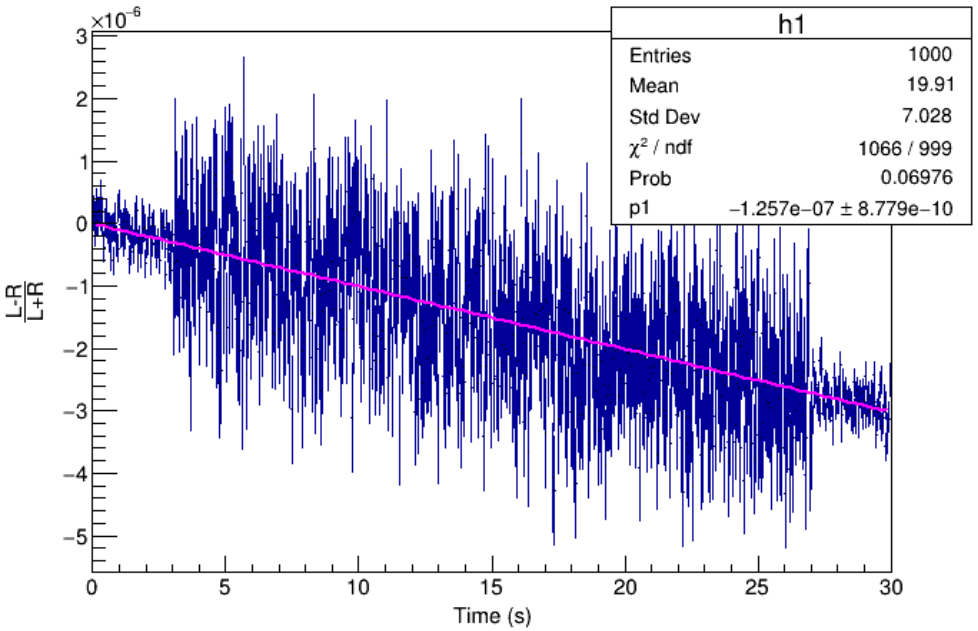
Estimation of the sensitivity

Error for the EDM d

$$\sigma_d = \frac{s\hbar}{E^*}\sigma_{\omega_{edm}}$$

From asymmetry simulation

$f_{axion}=10^5$ Hz

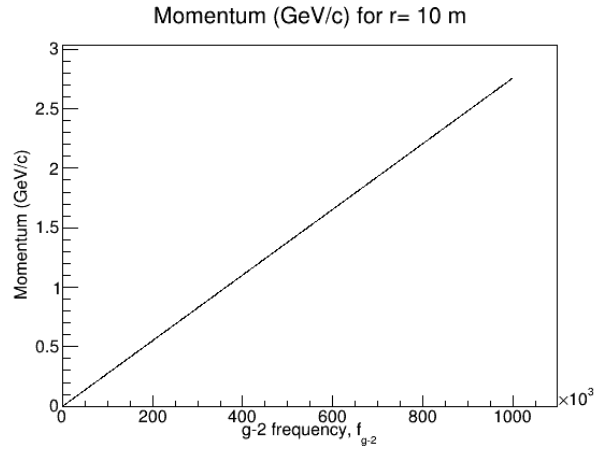


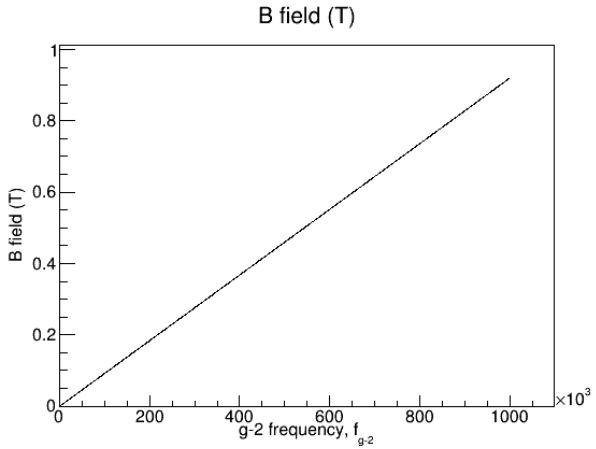
Simulated L/R asymmetry with linear fit

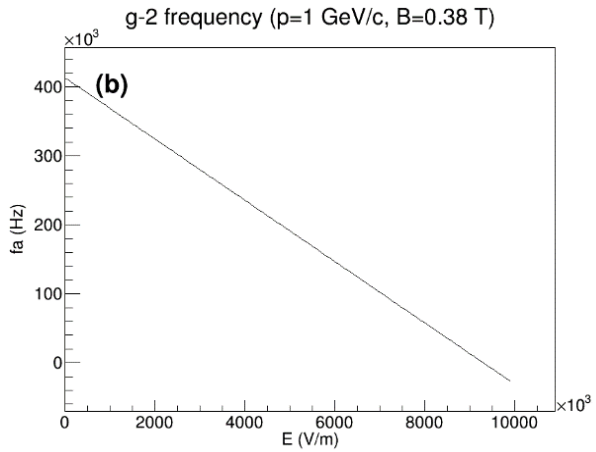
$$L/R \text{ asymmetry } \varepsilon_{LR} = P_y A_y = \frac{L-R}{L+R}$$

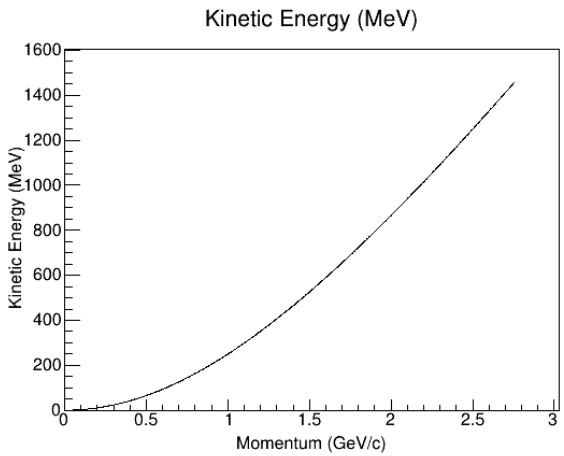
Determination of storage ring parameters

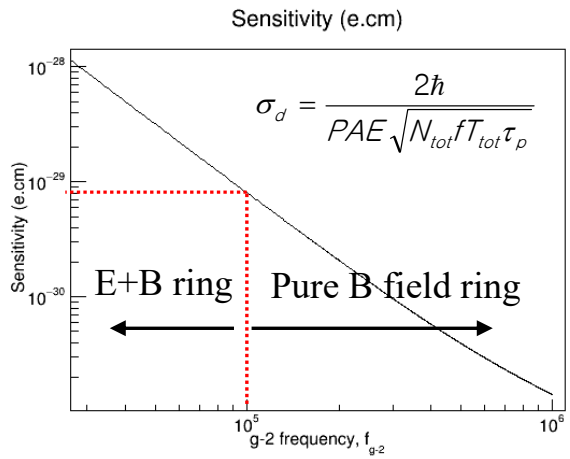
Pure magnetic ring for deuteron, a=-0.14
Ring bending radius r=10m

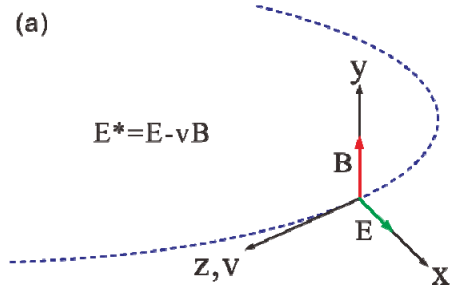












Use E+B combined ring to improve the sensitivity

Sensitivity calculation results for Deuteron

B (T)	P (GeV/c)	f_{g-2} (Hz)	Er (V/m)	E* (V/m)	Sensitivity(e.cm), 8x10^7 s measurement						Ring
					SCT=10^3 s		SCT=10^4 s		SCT=10^5 s		
					Q=3E6	Q=1E10	Q=3E6	Q=1E10	Q=3E6	Q=1E10	
0.3800	0.9428	1.E+01	8.82E+06	4.23E+07	9.9E-31	9.9E-31	3.1E-31	3.1E-31	9.9E-32	9.9E-32	
0.3800	0.9429	1.E+02	8.82E+06	4.23E+07	9.9E-31	9.9E-31	3.1E-31	3.1E-31	1.4E-31	9.9E-32	
0.3800	0.9433	1.E+03	8.80E+06	4.24E+07	9.9E-31	9.9E-31	4.3E-31	3.1E-31	3.8E-31	9.9E-32	
0.3800	0.9473	1.E+04	8.65E+06	4.27E+07	1.4E-30	9.9E-31	8.3E-31	3.1E-31	1.2E-30	9.9E-32	E/B ring
0.3800	0.9880	1.E+05	7.05E+06	4.60E+07	3.5E-30	9.1E-31	3.5E-30	2.9E-31	3.5E-30	9.1E-32	A=0.36
0.3800	1.0345	2.E+05	5.06E+06	5.00E+07	4.6E-30	8.4E-31	4.5E-30	2.7E-31	4.5E-30	9.8E-32	r=10 m
0.3800	1.1326	4.E+05	3.47E+05	5.85E+07	5.5E-30	7.2E-31	5.5E-30	2.3E-31	5.5E-30	5.2E-32	
0.3800	1.2386	6.E+05	-5.47E+06	6.82E+07	5.8E-30	6.2E-31	5.3E-30	2.0E-31	5.8E-30	1.1E-31	
0.3800	1.3546	8.E+05	-1.26E+07	7.93E+07	5.7E-30	5.3E-31	3.9E-30	1.7E-31	5.7E-30	1.0E-31	
0.3800	1.4836	1.E+06	-2.14E+07	9.20E+07	5.5E-30	4.6E-31	3.5E-30	1.4E-31	5.5E-30	1.0E-31	
0.8000	2.5124	1.E+06	-9.13E+06	2.01E+08	1.6E-30	1.5E-31	2.5E-30	6.6E-32	2.5E-30	4.6E-32	
0.9198	2.7574	1.E+06	0.0	2.28E+08	5.3E-30	4.4E-31	3.4E-30	1.4E-31	5.3E-30	9.7E-32	A=0.15
9.1977	27.5740	1.E+07	0.0	2.75E+09	3.3E-30	3.7E-32	4.4E-30	2.5E-32	4.4E-30	2.4E-32	r=10 m

E^*: effective electric field, SCT: spin coherence time, Q:axion quality factor, A: analyzing power of the polarimeter, r: ring radius

Sensitivity calculation results for Proton

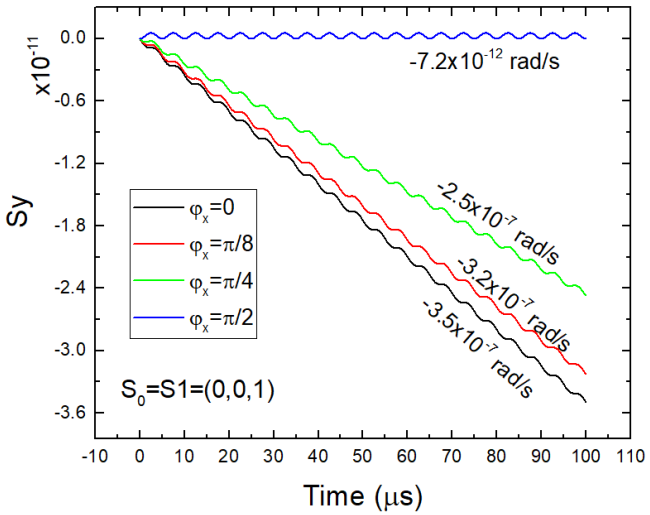
B (T)	P (GeV/c)	f_{g-2} (Hz)	Er (V/m)	E* (V/m)	Sensitivity(e.cm), $8x10^7$ s measurement						
					SCT=10^3 s		SCT=10^4 s		SCT=10^5 s		
					Q=3E6	Q=1E10	Q=3E6	Q=1E10	Q=3E6	Q=1E10	
0.00011	0.6984	1.E+01	-8.0E+06	8.02E+06	1.6E-30	1.6E-30	5.0E-31	5.0E-31	1.6E-31	1.6E-31	
0.00010	0.6984	1.E+02	-8.0E+06	8.02E+06	1.6E-30	1.6E-30	3.6E-31	3.6E-31	2.2E-31	1.6E-31	
0.00008	0.6982	1.E+03	-8.0E+06	8.01E+06	1.6E-30	1.6E-30	6.9E-31	5.0E-31	6.1E-31	1.6E-31	
-0.00015	0.6960	1.E+04	-8.0E+06	7.97E+06	2.2E-30	1.6E-30	1.9E-30	4.1E-31	1.9E-30	1.6E-31	E/B ring
-0.00243	0.6747	1.E+05	-8.0E+06	7.57E+06	6.4E-30	1.7E-30	4.9E-30	5.3E-31	6.4E-30	1.7E-31	A=0.6
-0.00495	0.6519	2.E+05	-8.0E+06	7.15E+06	9.6E-30	1.8E-30	9.5E-30	5.6E-31	6.7E-30	2.0E-31	r=52 m
-0.01523	0.7103	4.E+05	-1.1E+07	8.24E+06	1.2E-29	1.1E-30	1.2E-29	4.8E-31	1.2E-29	2.3E-31	
-0.02002	0.6711	6.E+05	-1.1E+07	7.51E+06	1.6E-29	1.7E-30	1.4E-29	5.3E-31	1.6E-29	2.9E-31	
-0.02666	0.6643	8.E+05	-1.2E+07	7.38E+06	1.8E-29	1.7E-30	1.8E-29	5.4E-31	1.8E-29	3.4E-31	
-0.03327	0.6583	1.E+06	-1.3E+07	7.27E+06	2.1E-29	1.7E-30	2.1E-29	5.5E-31	2.1E-29	3.8E-31	
0.36587	1.0968	1.E+07	0.0	8.33E+07	4.4E-29	3.6E-31	4.4E-29	1.9E-31	4.4E-29	2.4E-31	A=0.25
3.65868	10.9684	1.E+08	0.0	1.09E+09	2.3E-29	3.9E-32	3.4E-29	5.8E-32	3.4E-29	5.8E-32	r=10 m

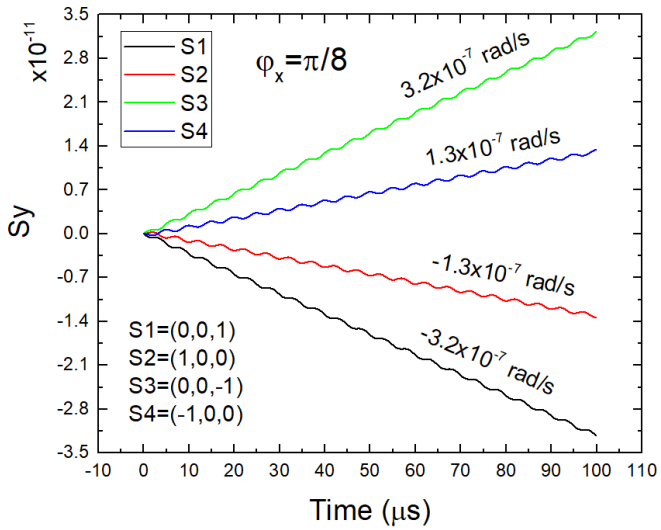
E^*: effective electric field, SCT: spin coherence time, Q:axion quality factor, A: analyzing power of the polarimeter, r: ring radius

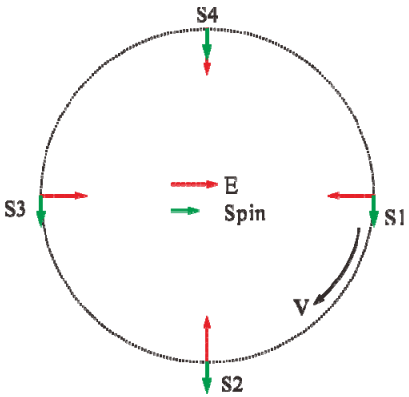
Axion phase effect

$$d(t) = d_0 \cos(\omega_a t + \varphi_x)$$

→ φ_x=0 means d is parallel to s, positive and max.







ω_{EDM} depends on the initial axion phase (φ_x). However actual ω_{EDM} can be obtained from the measurement of two orthogonal initial spin settings.

$$\omega_{EDM} = \sqrt{\omega_{EDM,S1}^2 + \omega_{EDM,S2}^2}$$

❖ Axion phase is not an experimentally controllable parameter

Low frequency (<mHz) measurement with FS conditions

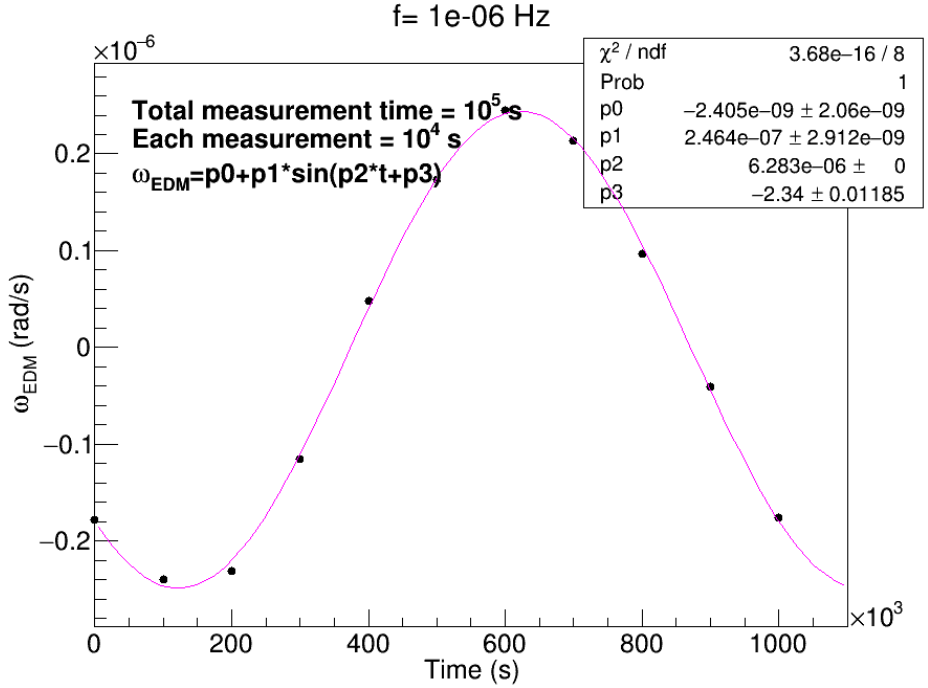
❖ Example: with $d_0=10^{-27}$ e.cm

FS condition	
Particl	Deuteron
Momentum	0.988 GeV/c
B-field	0.3995 T
E-field	9.77873E+06 V/m
E*	4.60393E+07 V/m

AP=0.36, SCT=10^4 s

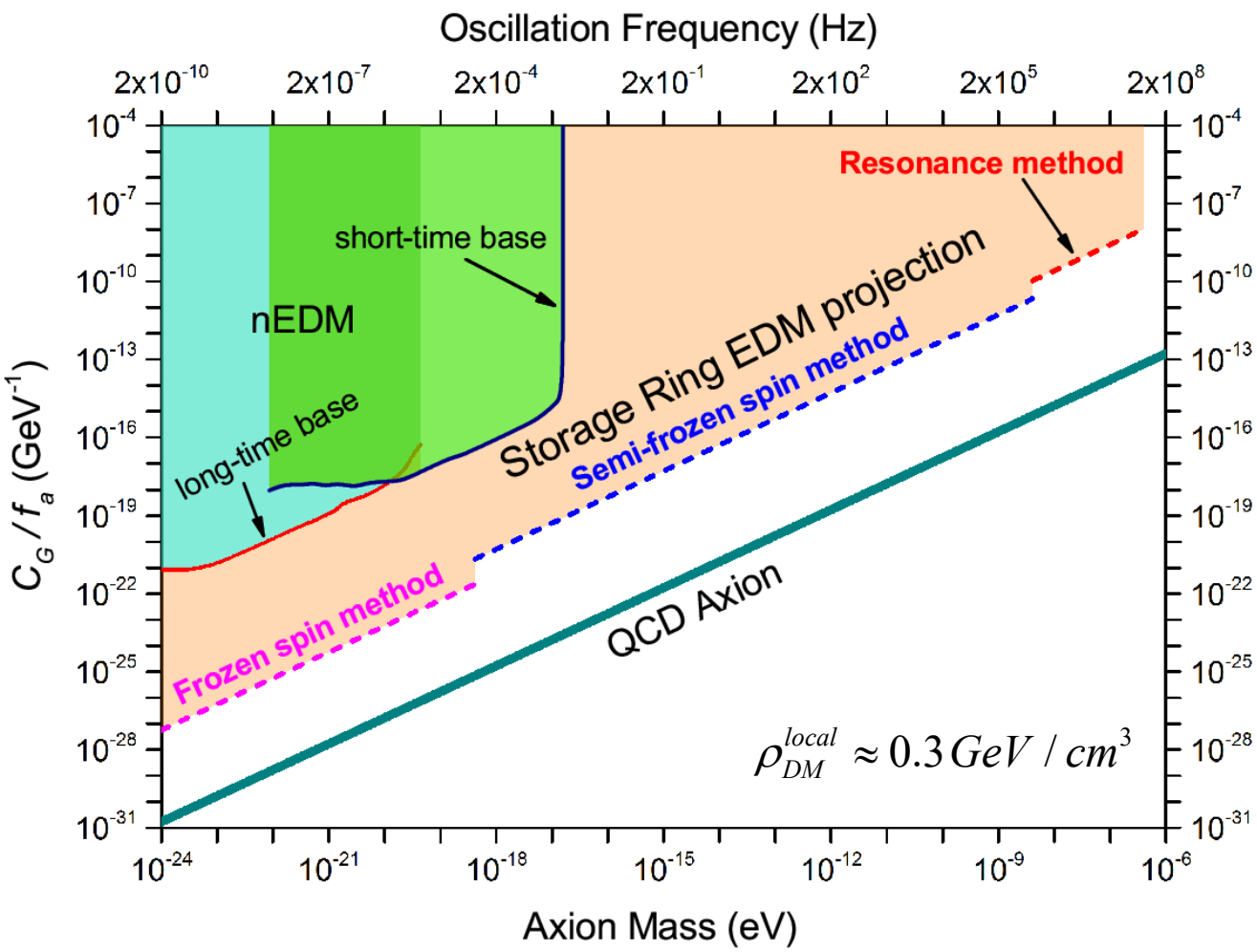
No extra measurement is required for the axion search in this frequency region (<mHz). One can do the static EDM experiment with frozen spin conditions and do the analysis for axion signal search afterwards.

$f_{axion}=10^{-6}$ Hz



❖ **Sensitivity =4.2x10^{-31} e.cm for 4 years of measurement (8x10^7 s)**

Experiment limit



nEDM: Ultra-cold neutron trap experiment

Summary and plan

- Static EDM search using the storage ring with frozen spin method (cpEDM collaboration), **~10^{-29} e.cm**
- We propose using **the storage ring EDM method to measure the axion** induced oscillating EDM at the resonance conditions between the axion frequency and g-2 precession frequency (> mHz). Bellow mHz region can be searched using frozen spin condition.
- The resulting **sensitivity reaches up to ~10^{-32} e.cm for an oscillating EDM** which have never been implemented so far.
- **A wide range of frequency (10^{-9} Hz~10^{8} Hz) of axion dark matter** can be tested using both deuterons and protons in the same storage ring.
- **One experiment → two physics measurements (EDM+Axion)**

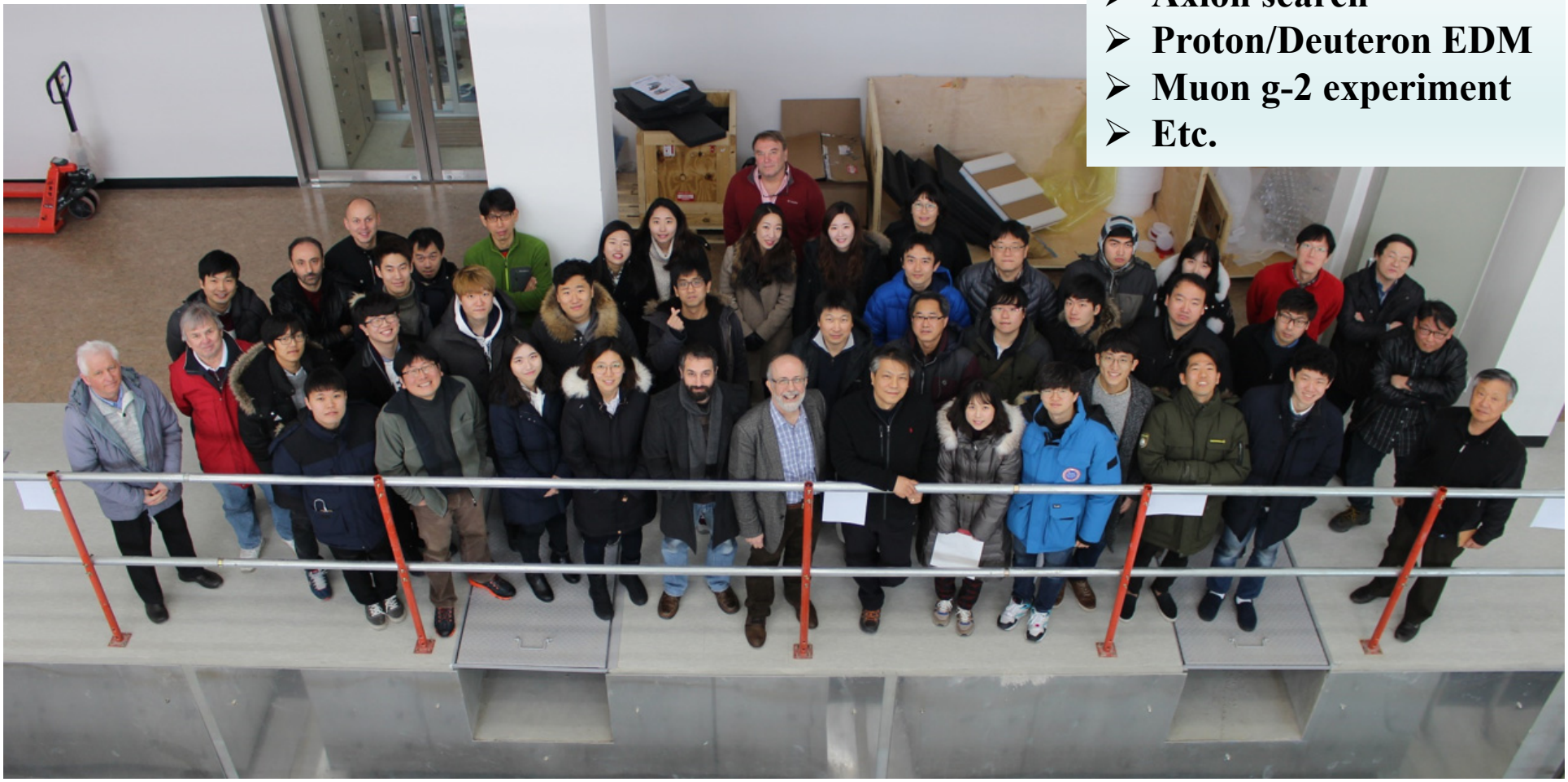
- **Plans: Preparing proposal for the measurement at COSY (Juelich, Germany)**

➢ **This work can be found in the arXiv: http://arxiv.org/abs/1710.05271**

Center for Axion and Precision Physics (IBS/CAPP, KAIST)

We are working on:

- **Axion search**
- **Proton/Deuteron EDM**
- **Muon g-2 experiment**
- **Etc.**



http://capp.ibs.re.kr/html/capp_en/

Located at KAIST campus in Daejeon, South Korea

Thank you!