A new method with minimized systematic error sources to detect axion dark matter in storage rings using an rf Wien filter

On Kim[1] and Yannis K. Semertzidis[1,2]

[1]Institute for Basic Science, Center for Axion and Precision Physics Research

[2]Korea Advanced Institute of Science and Technology, Physics Department

2022 July 7th

41th International Conference on High Energy Physics

CAPP

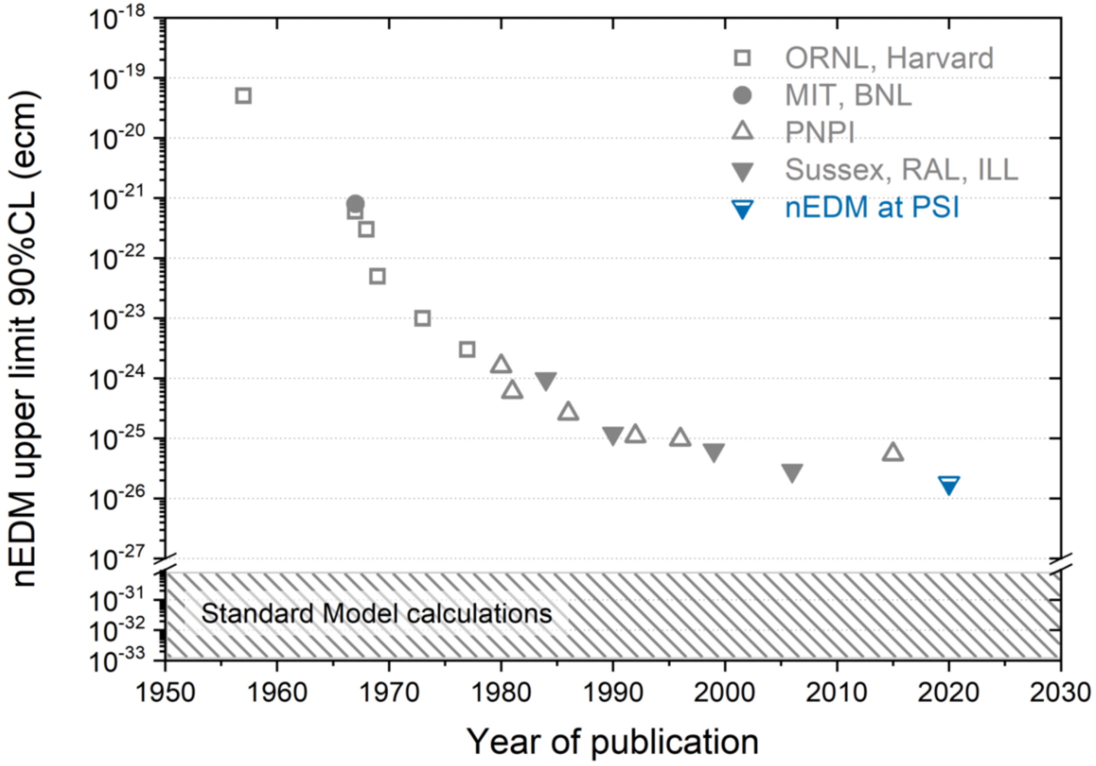
Center for Axion and Precision Physics Research

Axion Dark Matter

- Strong CP problem: why $\theta_{CP} \ll \mathcal{O}(1)$?

$$d_n \sim \bar{\theta} \times 10^{-16}\ e \cdot \text{cm}$$

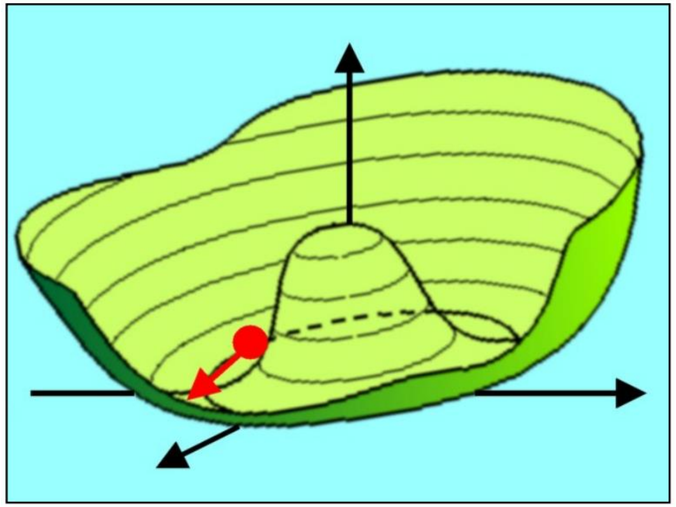
$$\bar{\theta} < 5 \times 10^{-11}$$



C. Abel et al. Phys. Rev. Lett. 124, 081803 (2020)

- Peccei-Quinn theory *Phys. Rev. Lett. 38, 1440 (1977)*

$U_{PQ}(1)$ spontaneous symmetry breaking induces a dynamical pseudoscalar field: Axion



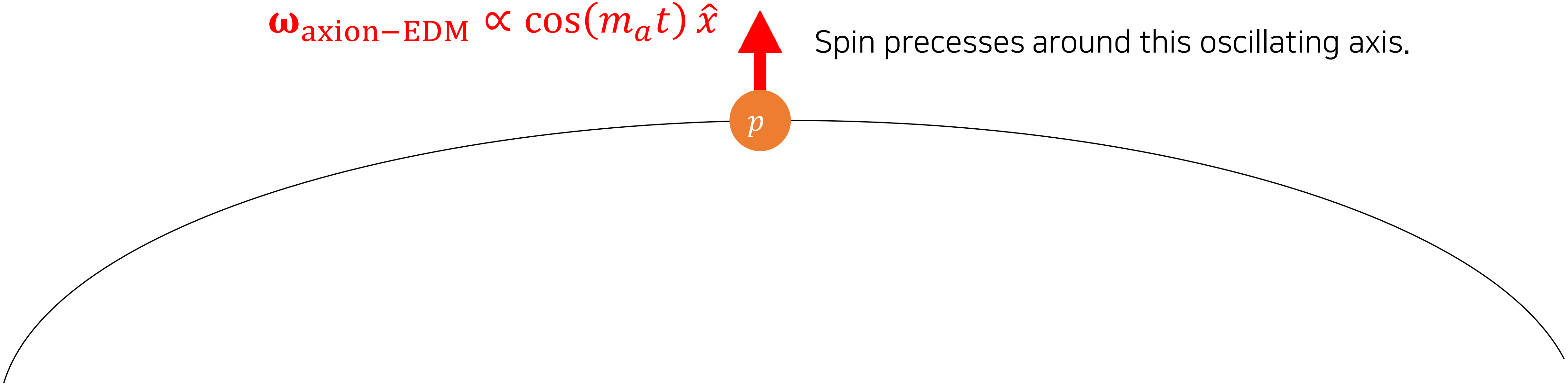
Georg Raffelt

- Dark Matter (DM) candidate

Axions or Axion-Like Particles (ALPs) can constitute some or all DM ⇒ Axion-like dark matter

Storage ring probes of axion DM

- Couplings with axion-like DM through nucleon EDM P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
  - ALP DM-EDM $(g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}) \Rightarrow$ oscillating EDM at m_a. For the QCD axion: $d_N^{\mathrm{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.



Oscillating EDM

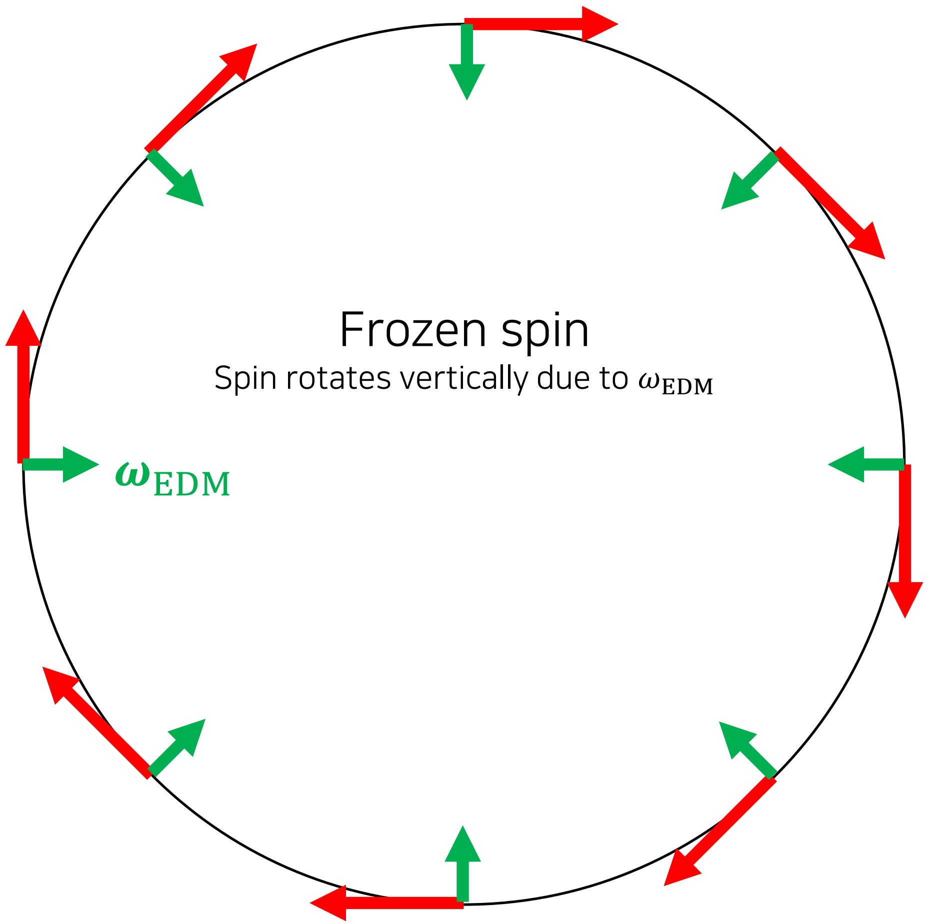
- How should we detect it?
- First, review the frozen spin method for the static d.

$$\boldsymbol{\omega}_a \approx -\frac{q}{m}\left[G\mathbf{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\boldsymbol{\beta}\times\mathbf{E}}{c} + \frac{\eta}{2}\left(\frac{\mathbf{E}}{c} + \boldsymbol{\beta}\times\mathbf{B}\right)\right]$$

MDM ($g-2$ precession)
In-plane

EDM
Out-of-plane

$$\mu = g\frac{q}{2m}S, \qquad d = \eta\frac{q}{2mc}S \qquad G \equiv \frac{g-2}{2}$$



Oscillating EDM

- How should we detect it?
- What if $d = d_0 \cos(m_a t)$ oscillates?
  (used an extreme case for illustration)

$$\boldsymbol{\omega}_a \approx -\frac{q}{m}\left[G\mathbf{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\boldsymbol{\beta} \times \mathbf{E}}{c} + \frac{\eta}{2}\left(\frac{\mathbf{E}}{c} + \boldsymbol{\beta} \times \mathbf{B}\right)\right]$$

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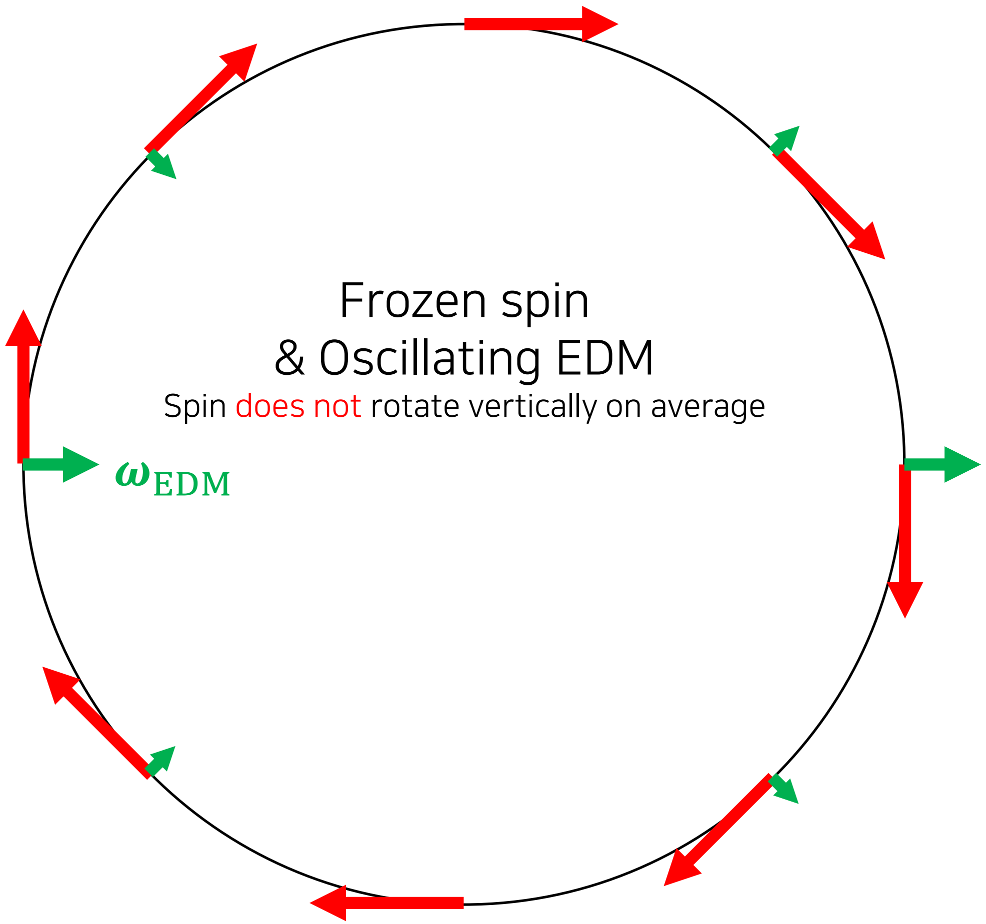

Oscillating EDM

- How should we detect it?

- Why don't we make spin precess in the ring plane at the same frequency?
(used an extreme case for illustration)

$$\boldsymbol{\omega}_a \approx -\frac{q}{m}\left[G\mathbf{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\boldsymbol{\beta}\times\mathbf{E}}{c} + \frac{\eta}{2}\left(\frac{\mathbf{E}}{c} + \boldsymbol{\beta}\times\mathbf{B}\right)\right]$$

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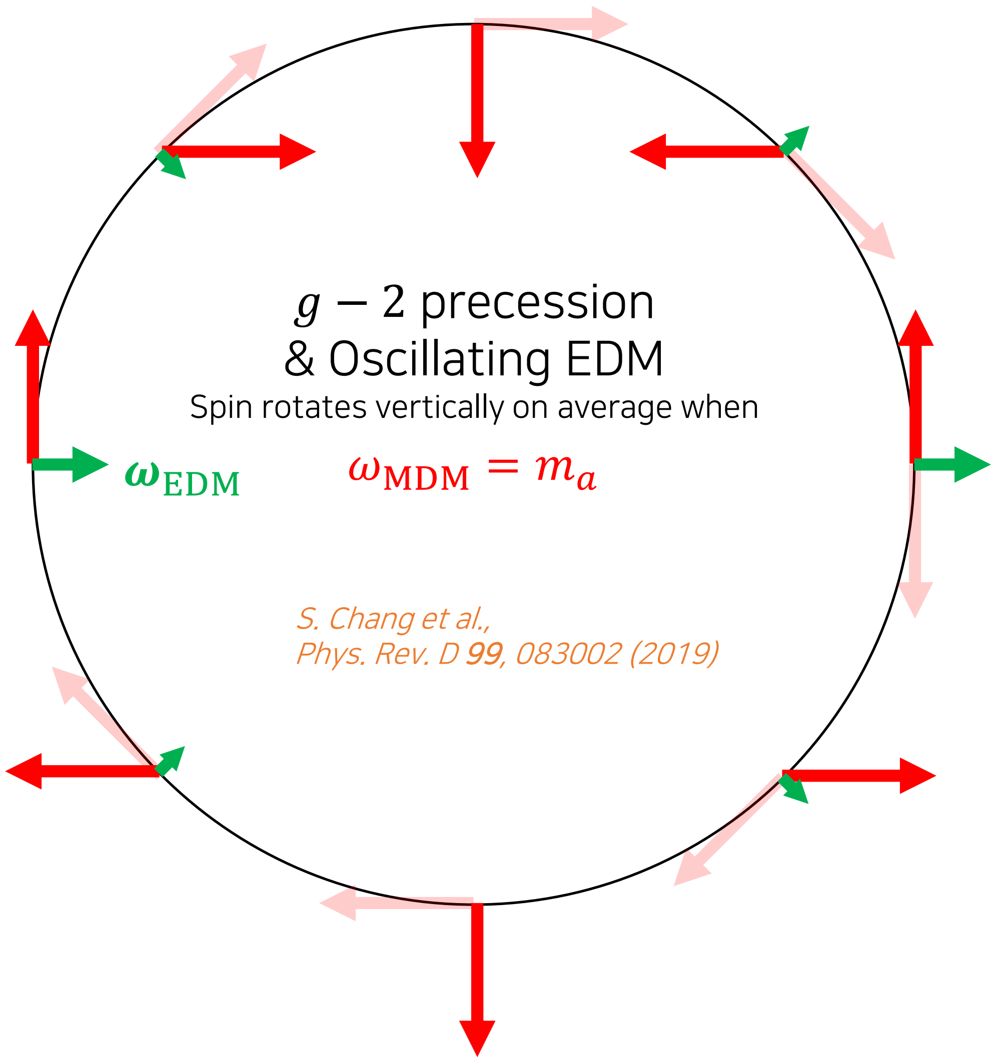
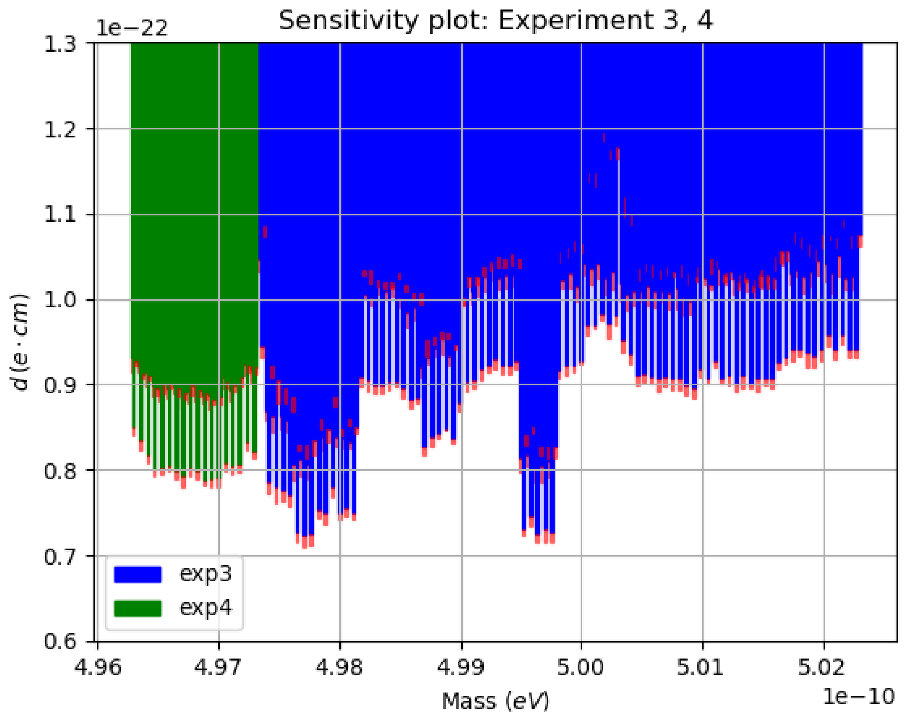
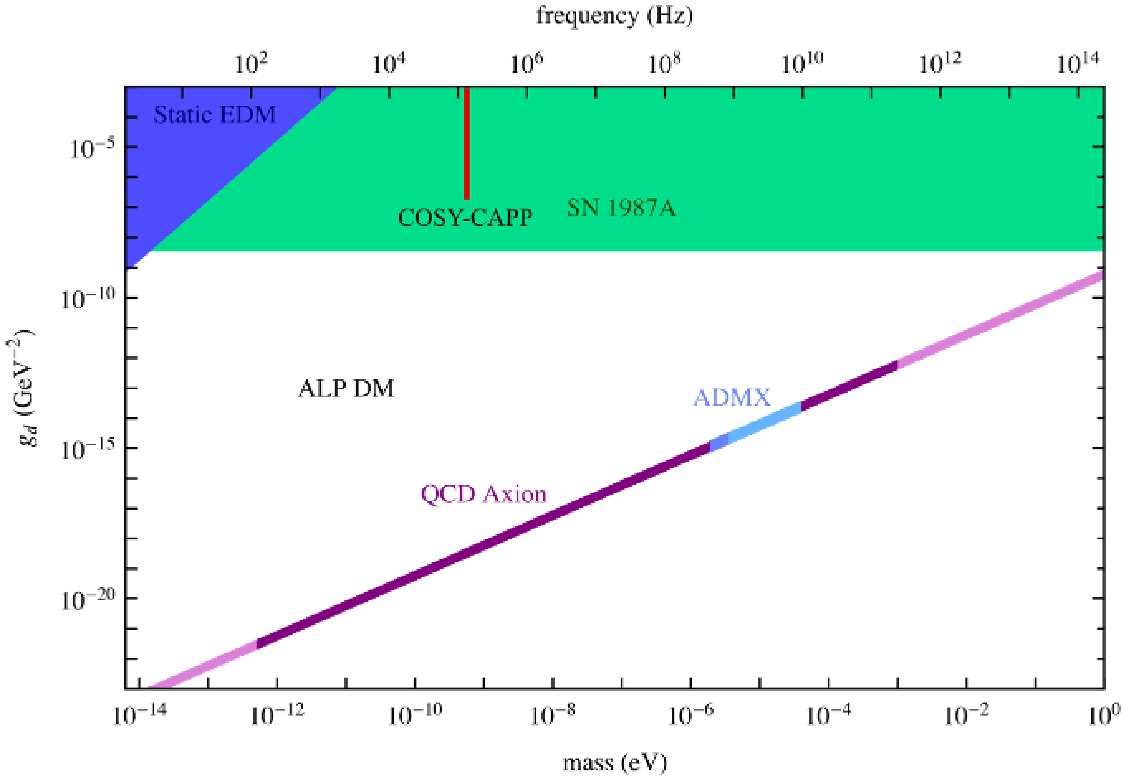


S. Chang et al.,
Phys. Rev. D ***99****, 083002 (2019)*

First axion DM search in a storage ring

- IBS-CAPP and COSY collaborated to conduct a precursor experiment at COSY in 2019.
  - Total measurement time: ~4 days.
  - Total statistics: 2M hits.
- Preliminary analysis (Seung Pyo Chang (IBS-CAPP)): $d \lesssim 10^{-22}\ e \cdot \mathrm{cm}$ at $m_a \approx 0.5\ \mathrm{neV}$.





A new method using an rf Wien filter

- The resonance condition of the previous method is: $\omega_{\mathrm{MDM}}(\equiv \omega_{g-2}) = m_a$.
- Not very practical to "manipulate" ω_{g-2} for scanning m_a, because one needs to change the momentum accordingly ($p = Br_0$ for a magnetic ring).

- New idea is to add another knob to tune the resonance with an rf field inside the storage ring.

$$\left|\omega_{g-2} \pm \omega_{rf}\right| = m_a$$

- Natural candidate is an rf Wien filter (WF) which exerts no Lorentz force on the beam by design.

$$\mathbf{E}_{\mathrm{WF}} = E_0^{\mathrm{WF}} \cos(\omega_{\mathrm{WF}} t + \phi_{\mathrm{WF}})\hat{e}_x,$$
$$\mathbf{B}_{\mathrm{WF}} = \frac{E_0^{\mathrm{WF}}}{\beta c} \cos(\omega_{\mathrm{WF}} t + \phi_{\mathrm{WF}})\hat{e}_y$$

$\Rightarrow$

$$\mathbf{F}_{\mathrm{WF}} = q(\mathbf{E}_{\mathrm{WF}} + \mathbf{v} \times \mathbf{B}_{\mathrm{WF}}) = 0$$

$$\left|\omega_{g-2} \pm \omega_{\mathrm{WF}}\right| = m_a$$

A new method using an rf Wien filter

- Putting all possibilities together

Axion-induced EDM search in storage rings

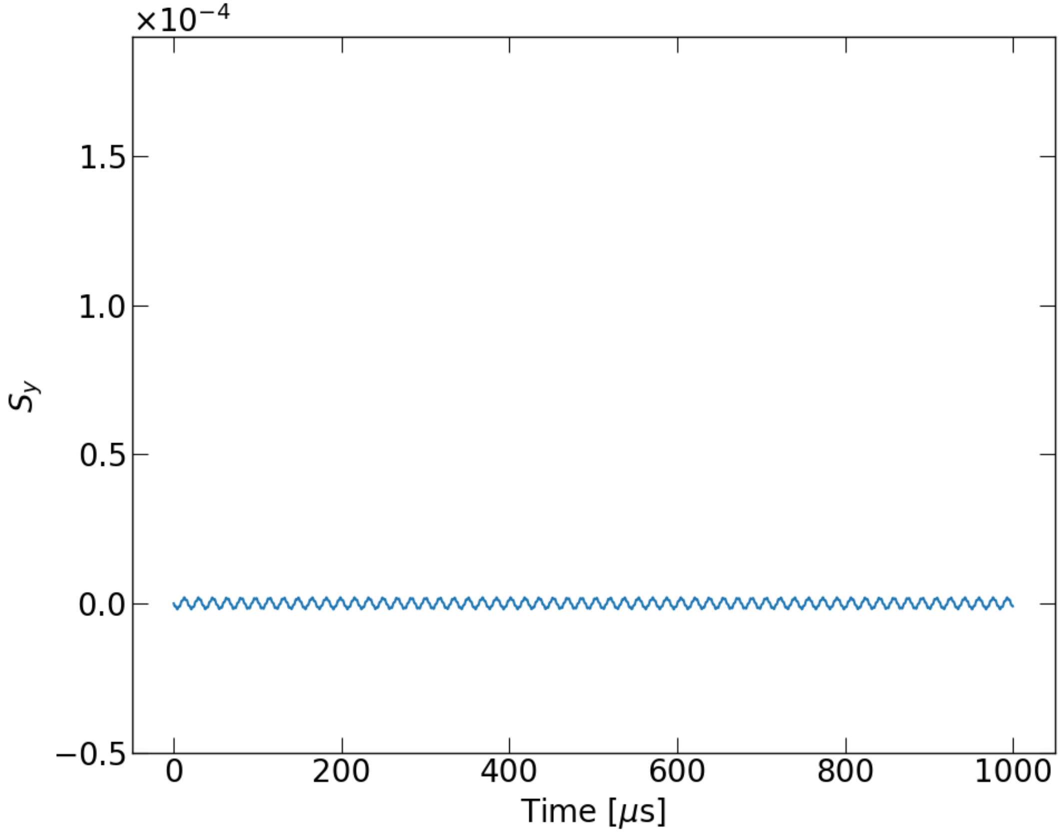
Method	srEDM	srEDM + WF	srAxionEDM	srAxionEDM + WF
Measurement target	d_{DC}	d_{DC}	d_{AC}	d_{AC}
Resonance condition	$\omega_{g-2} = 0$	$\omega_{g-2} = \omega_{\mathrm{WF}}$	$\omega_{g-2} = \omega_{\mathrm{axion}}$	$\omega_{g-2} = \lvert\omega_{\mathrm{axion}} \pm \omega_{\mathrm{WF}}\rvert$
Spin vertical slope (ω_d)	$\frac{d_{\mathrm{DC}}}{s\hbar}E^*$	$\frac{d_{\mathrm{DC}}}{s\hbar}E^* C_{\mathrm{WF}}$	$\frac{d_{\mathrm{AC}}}{2s\hbar}E^*$	$\frac{d_{\mathrm{AC}}}{2s\hbar}E^* C_{\mathrm{WF}}$
References	*PRL* ***93***, *052001 (2004)* *RSI* ***87***, *115116 (2016)*	*PRAB* ***16***, *114001 (2013)* *PRAB* ***23***, *024601 (2020)*	*PRD* ***99***, *083002 (2019)* *EPJC* ***80***, *107 (2020)*	*PRD* ***104***, *096006 (2021)*

Frozen-spin	Highly constrained by systematic effect	Challenging to change ω_{g-2}	1. Practical way to scan m_a by tuning ω_{WF}. 2. Avoid systematic effects by carefully tuning ω_{WF}. 3. No need to build a new storage ring.

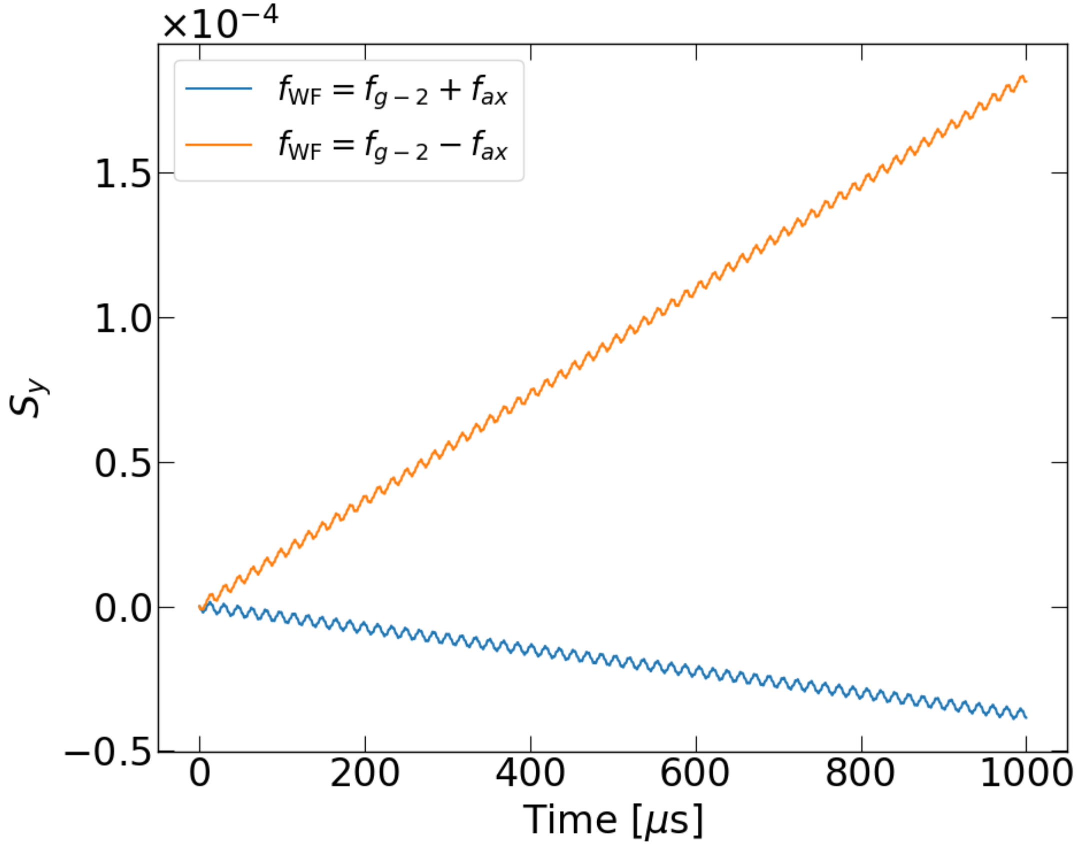
Numerical verification

- High precision spin tracking simulation
- No approximation in Lorentz force & T-BMT equations. Used $f_{g-2} \approx 120$ kHz and $f_{\text{axion}} = 180$ kHz as an example.

Without WF

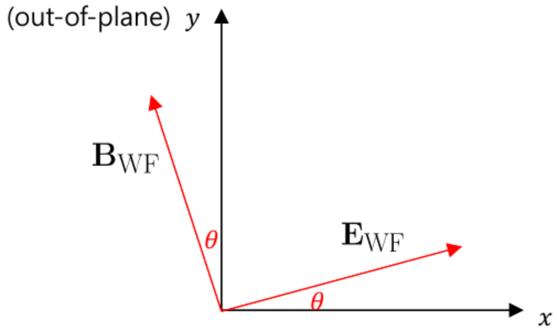


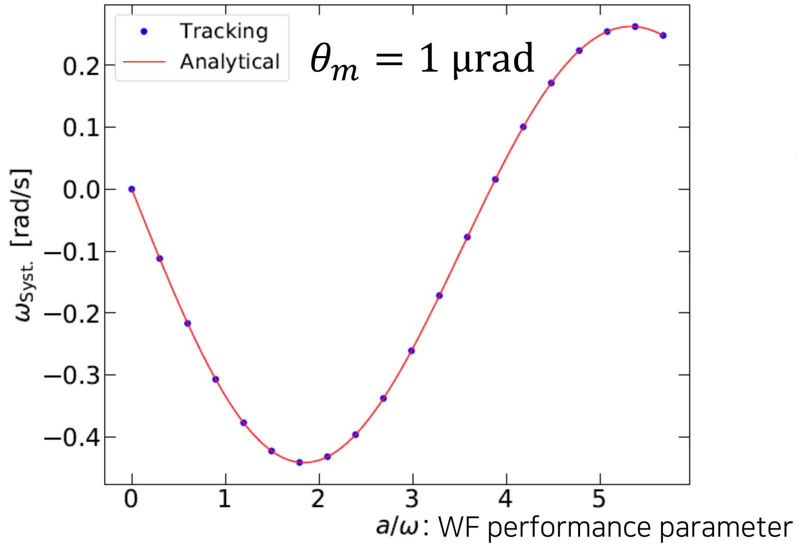
With WF



Systematic effects

- "Frozen spin" suffers from field errors (B_r, E_v) ⇒ And beautifully resolved by CW/CCW beam, hybrid & symmetric ring design Z. Omarov *et al.*, PRD **105**, 032001 (2022)
- When we drop the frozen-spin and those dc field errors are not the problem. But an rf field errors can be critical, for instance from small misalignments of the WF.
- The systematic "false EDM" signal is huge.





Analytical estimation

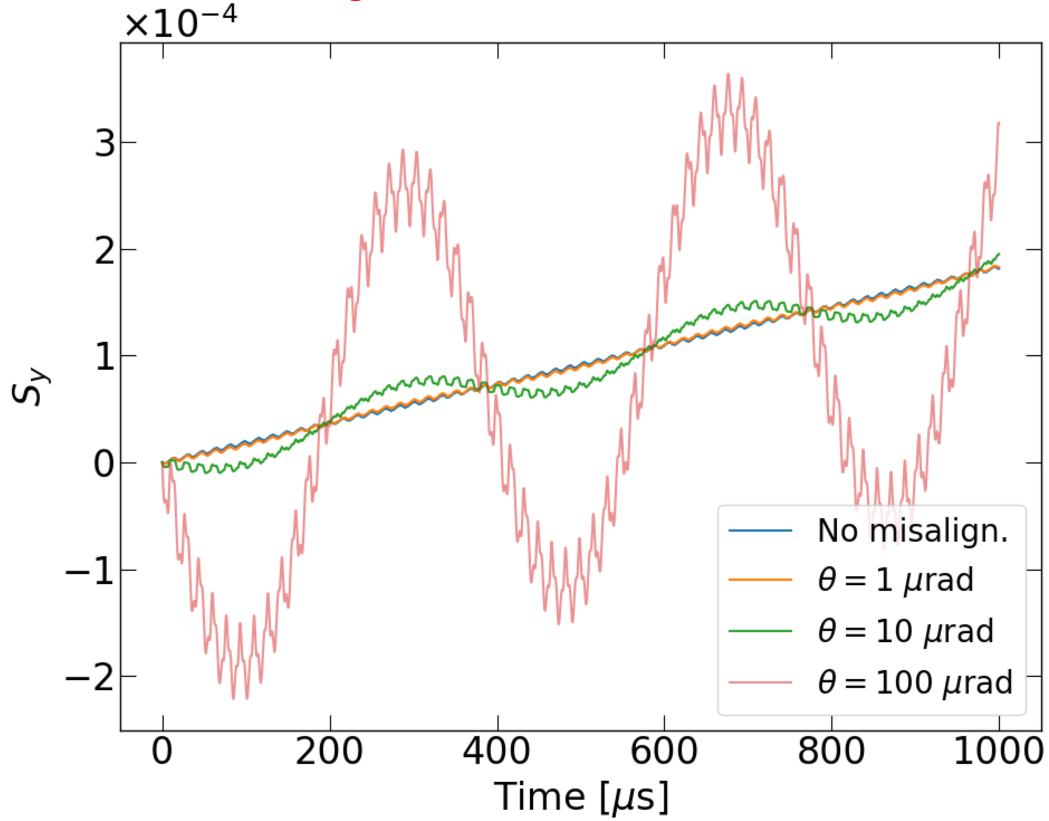
$$\left\langle \left(\dot{S}_y\right)_{\text{Syst.}} \right\rangle = -\frac{1}{2}\theta_m a \left[J_0\left(\frac{a}{\omega}\right) + J_2\left(\frac{a}{\omega}\right)\right]$$

Typical EDM signal ~ $\mathcal{O}(1\ \text{nrad/s})$

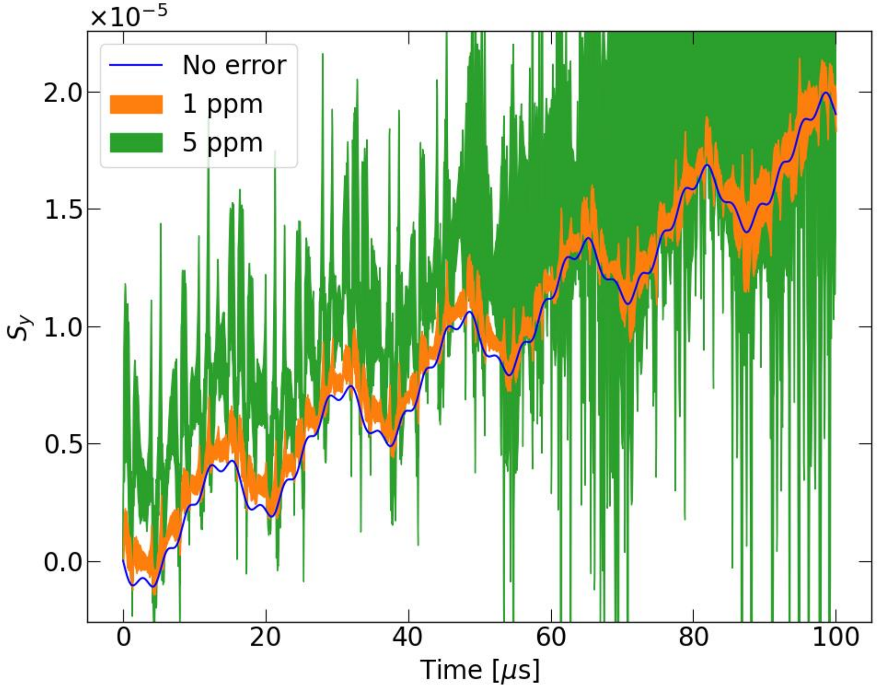
Systematic effects

- New method using the WF vetoes the described systematic effect by using distinct resonant frequency.

$$\omega_{g-2} = |\omega_{\rm WF} \pm m_a|$$



- Typical field errors of $\mathcal{O}(1\ \text{ppm})$ also turned out not significant.



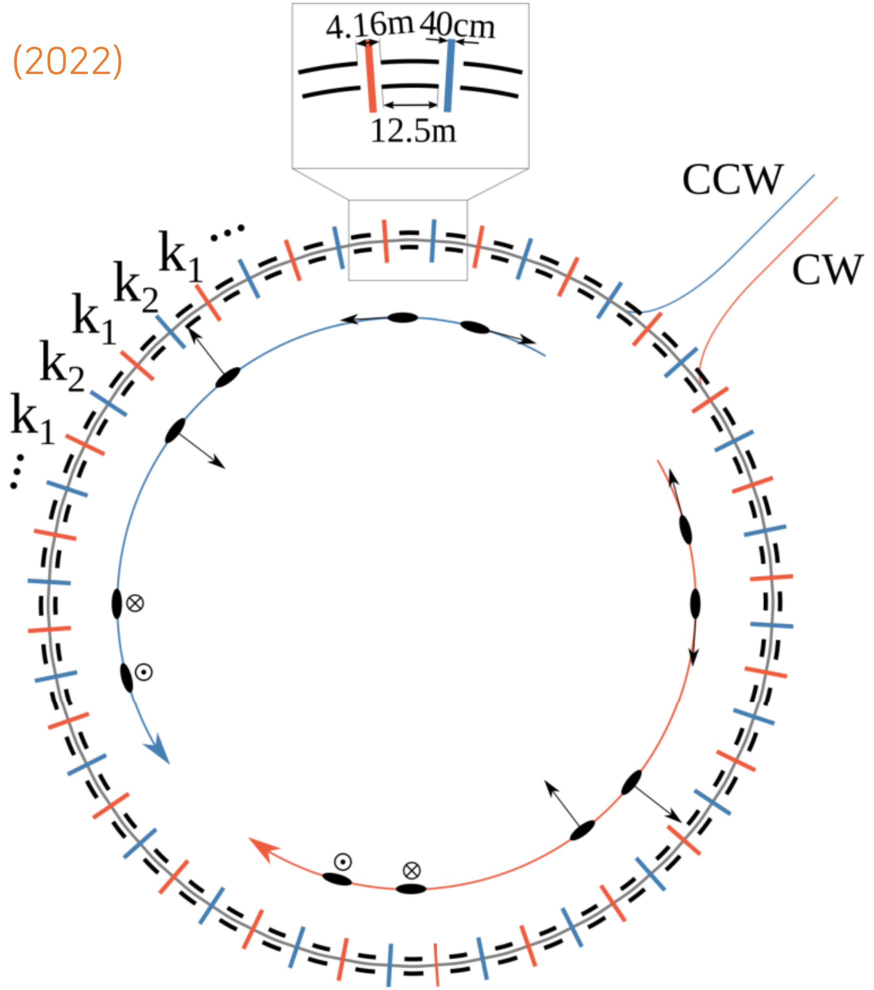
- In general, if there appears a signal, one can tell if it's a true or false signal by readjusting $\omega_{\rm WF}$ & ω_{g-2} targeting the same m_a.

Snowmass proposal: pEDM experiment

- Comprehensive studies are underway to realize the pEDM experiment.
  - Snowmass proposal arXiv:2205.00830
  - Symmetric-hybrid lattice design Z. Omarov *et al.*, PRD **105**, 032001 (2022)

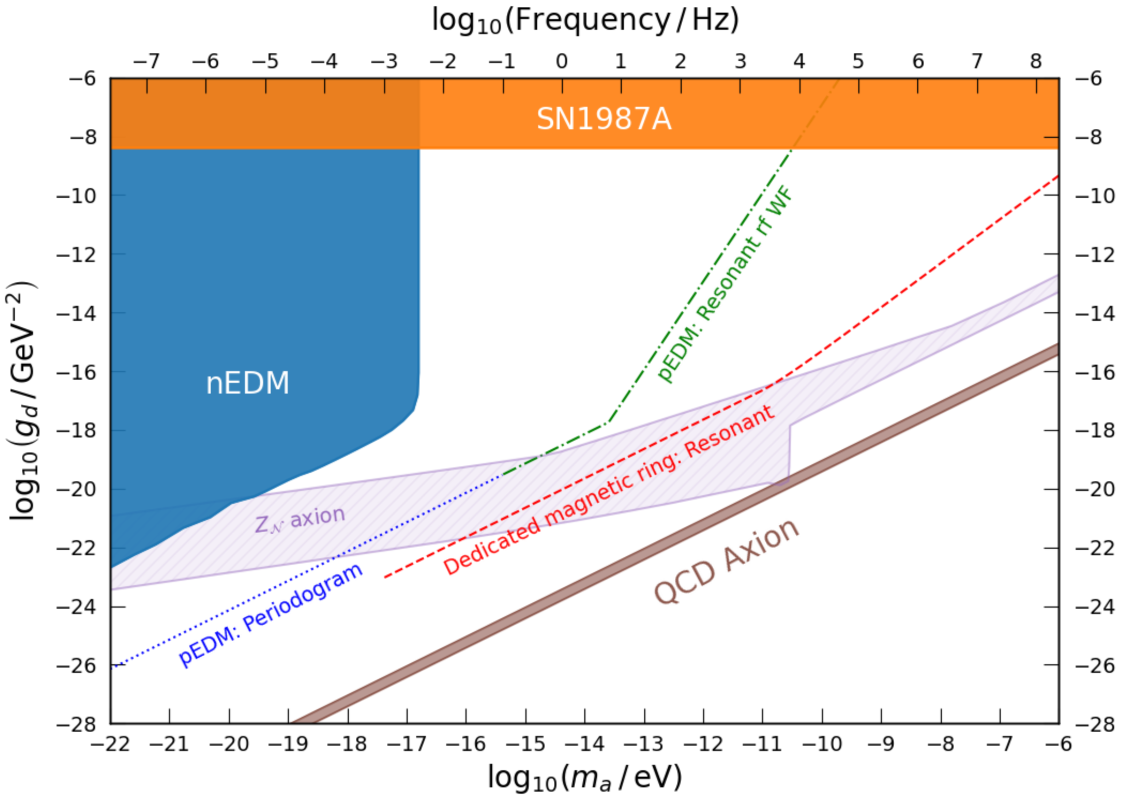
The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis [*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]



Sensitivity

- Axion-EDM coupling g_d



- Theoretically-motivated
  - QCD axion P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
  - $Z_{\mathcal{N}}$ axion L. Luzio *et al.*, JCAP **2021**, 001, JHEP **2021**, 184
- Excluded
  - (Direct) nEDM C. Abel *et al.*, PRX **7**, 041034 (2017)
  - (Indirect) SN1987A P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
- Projected sensitivity (preliminary)
  - Parasitic to proposed pEDM experiment.
    - Periodogram: Oscillating EDM is effectively dc EDM.
    - Resonant rf WF: apply WF to make a resonance.
  - Dedicated magnetic ring (assuming $B \approx 1$ T).
    - Tune ω_{g-2} or ω_{WF}.
- Other experiments
  - CASPEr D. Budker *et al.*, PRX **4**, 021030 (2014)
  - nEDM beams I. Schulthess *et al.*, arXiv:2204.01454

Summary

- Storage ring EDM method is applicable to search for axion-like dark matter.
  - Spin precession as observables. Projected EDM sensitivity $\sim \mathcal{O}(10^{-29}\ e \cdot \mathrm{cm})$.
  - Sensitive to relatively low mass regions ($m_a \lesssim \mu\mathrm{eV}$).

- New method utilizing an rf Wien filter has been studied.
  - Wider scannable range by tuning the WF frequency.
  - Minimal systematic effects.
  - Applicable to existing storage rings.
  - Parasitically applicable to pEDM experiment.

Thank you for your attention!

Backups

Axion coupling with SM particles

- In general, there are three sorts of axion-SM couplings

$g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$

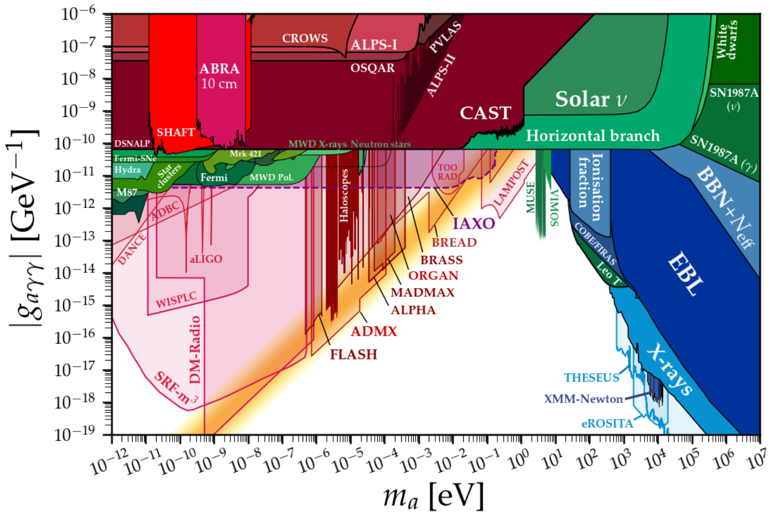
Haloscope
Helioscope
Light Shinning through Wall
…

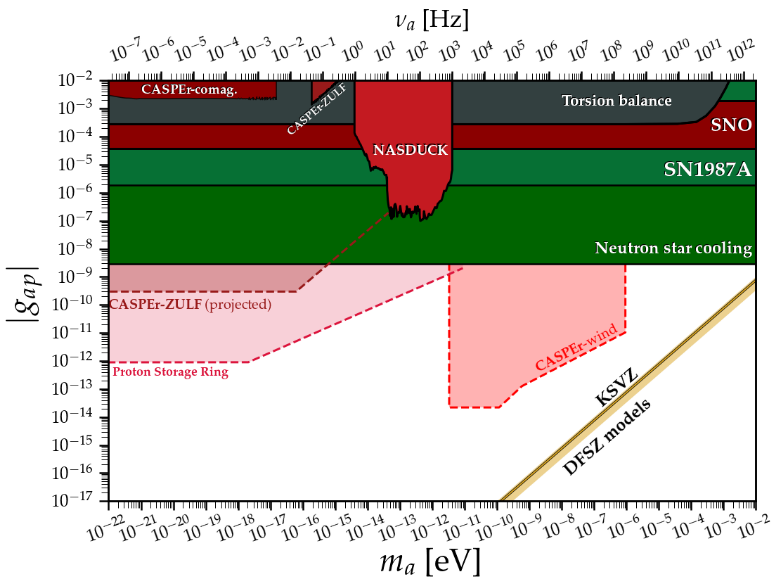
$g_{aff} \nabla a \cdot \hat{\mathbf{S}}$

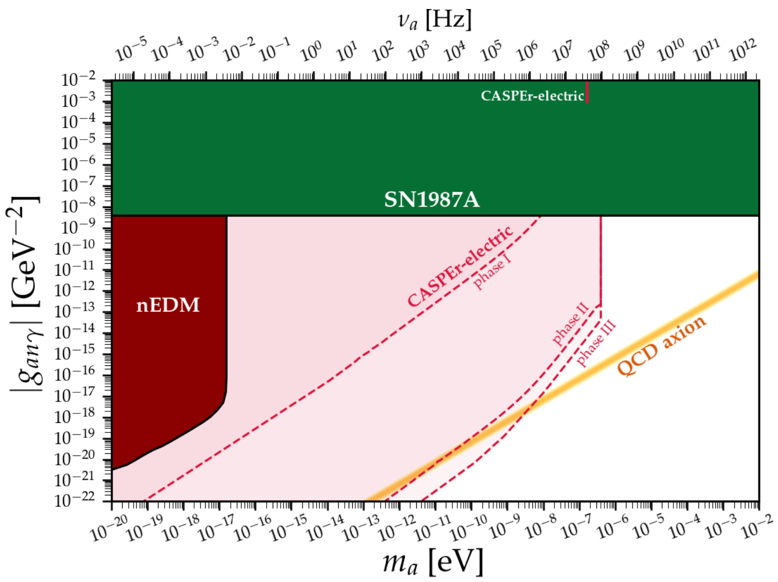
ARIADNE
CASPEr
Storage ring
…

$g_{\mathrm{EDM}} a \hat{\mathbf{S}} \cdot \mathbf{E}$

nEDM
CASPEr
Storage ring
…







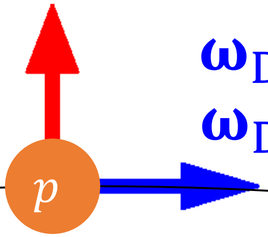
Source: Ciaran O'Hare, https://cajohare.github.io/AxionLimits

Storage ring probes of DM/DE

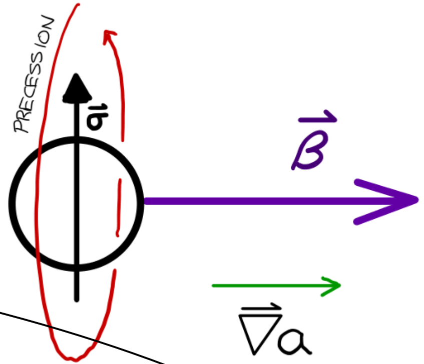
P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

- Couplings with dark matter (DM) and dark energy (DE)
  - ALP or vector DM wind ($g_{aNN} \nabla a \cdot \hat{\sigma}_N$) ⇒ anomalous longitudinal oscillating B field.
  - DE wind ⇒ anomalous longitudinal B field.

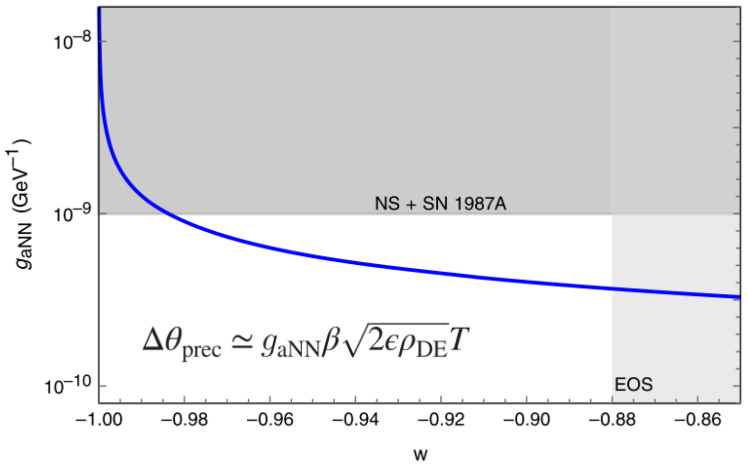
Storage ring is an optimal probe for wind coupling since β is large!



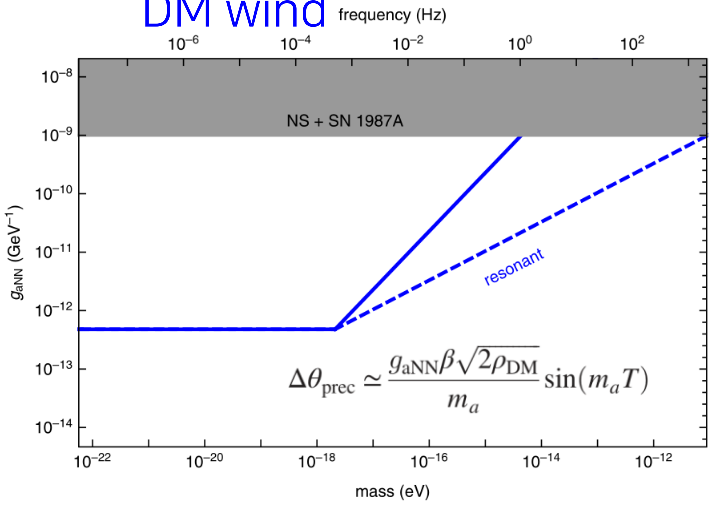
$$\boldsymbol{\omega}_{\mathrm{DM}} \propto \cos(m_a t)\,\hat{\beta}$$
$$\boldsymbol{\omega}_{\mathrm{DE}} \propto \hat{\beta}$$



DE wind



DM wind



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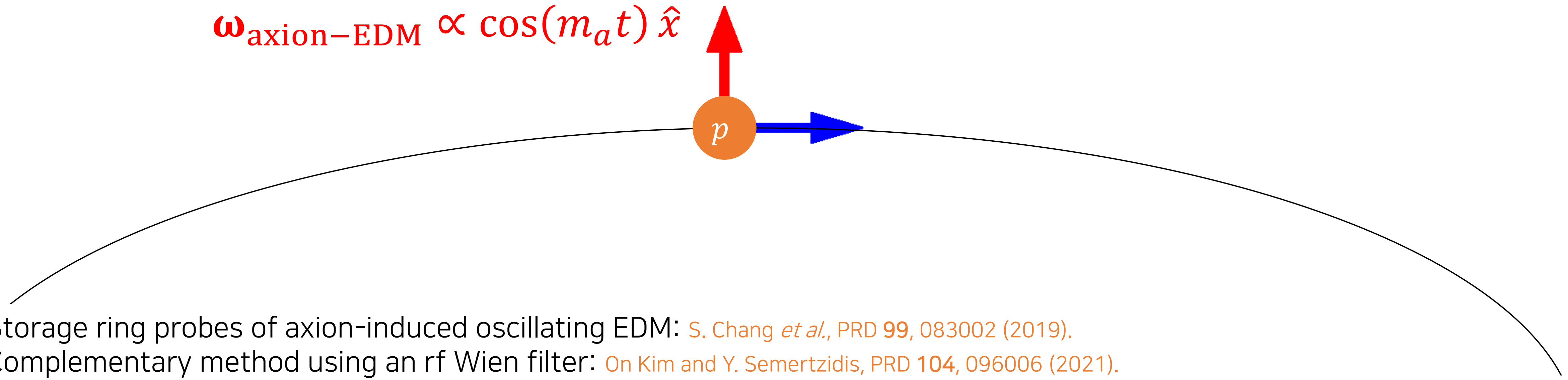


- Storage ring probes of axion-induced oscillating EDM: S. Chang *et al.*, PRD **99**, 083002 (2019).
- Complementary method using an rf Wien filter: On Kim and Y. Semertzidis, PRD **104**, 096006 (2021).
- Allows parasitic measurement with pEDM experiment: (LF) periodogram + (HF) rf resonance.

Statistical sensitivity

- Weighting the data taking
- Essentially we seek for non-zero asymmetry (ϵ) as a EDM signal: $\epsilon = \frac{L-R}{L+R} = PA\theta$
- Because $\theta(t)$ grows with time, it's better to have large statistics at later time than earlier.
- As an extreme limit, consider taking ALL statistics at time T.

$$\frac{\epsilon(T)}{T} = P_0 A \omega_d e^{-T/\tau_p}$$

- This enhances the sensitivity by ~50%.

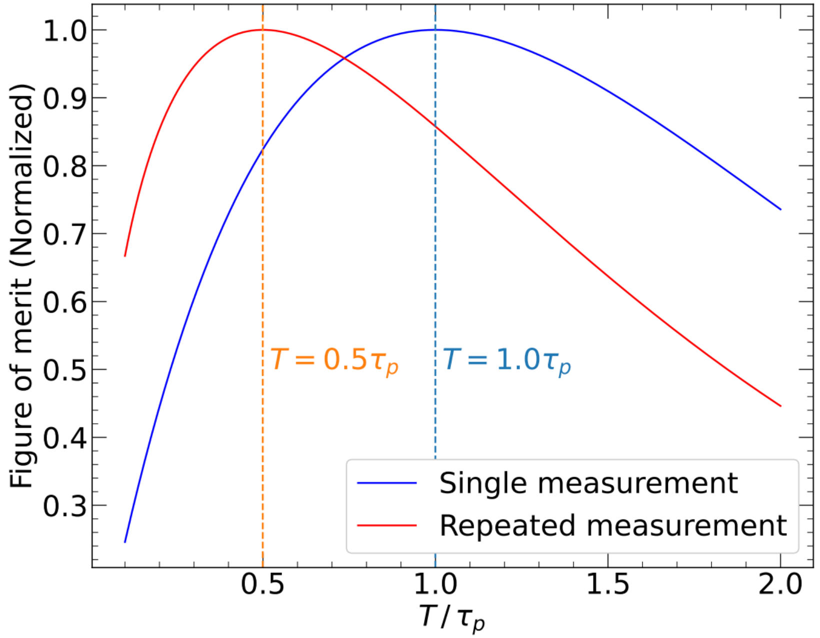
  Considering the repeated measurements, we have:

$$\sigma_{\omega_d} = \frac{1}{P_0 A e^{-T/\tau_p}\sqrt{N_{\mathrm{cyc}} T_{\exp} T}}$$

optimized when $T = 0.5\,\tau_p$.

$$\omega_d = \frac{d_{\mathrm{AC}}}{2s\hbar} E^* C_{\mathrm{WF}}$$

$$\sigma_d = \frac{4.67 s\hbar}{P_0 A E^* C_{\mathrm{WF}} \sqrt{\kappa N_{\mathrm{cyc}} T_{\exp} \tau_p}}$$



Statistical sensitivity

- Statistical sensitivity has been modified accordingly in presence of the WF.

$$\sigma_d = \frac{4.67 s\hbar}{P_0 A E^* C_{\mathrm{WF}} \sqrt{\kappa N_{\mathrm{cyc}} T_{\mathrm{exp}} \tau_p}}$$

- Putting ideal experimental conditions:

$$\sigma_d = 9.3 \times 10^{-31}\ [e \cdot \mathrm{cm}] \left(\frac{s}{1/2}\right) \left(\frac{0.8}{P_0}\right) \left(\frac{0.6}{A}\right) \left(\frac{100\ \mathrm{MV/m}}{E^*}\right) \left(\frac{0.59}{C_{\mathrm{WF}}}\right) \sqrt{\left(\frac{1.1\%}{\kappa}\right) \left(\frac{10^{11}}{N_{\mathrm{cyc}}}\right) \left(\frac{1\ \mathrm{yr}}{T_{\mathrm{exp}}}\right) \left(\frac{10^3\ \mathrm{s}}{\tau_p}\right)}$$

- Spin
- Initial polarization
- Analyzing power
- Effective E field: $E^* \equiv E_0 - vB_0$
- WF coefficient: $C_{\mathrm{WF}} = -J_1\left(\frac{a_{\mathrm{WF}}}{\omega_{\mathrm{WF}}}\right)$, $a_{\mathrm{WF}} \equiv \frac{q}{m}\frac{G+1}{\gamma^2}\frac{E_0^{\mathrm{WF}}}{\beta c}$
- Polarimeter efficiency
- Number of particles per cycle
- Total experiment time
- Spin coherence time: $P = P_0 e^{-t/\tau_p}$