Precision experiments at storage rings: The search for axion-like particles

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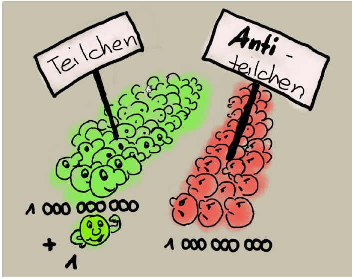
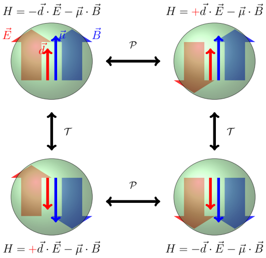
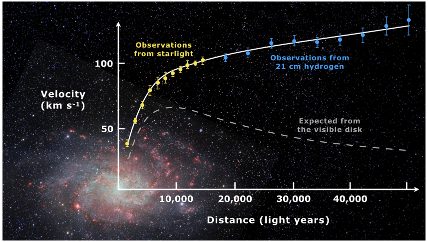
Motivation

Standard Model of Particle Physics successful but . . .

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







source:M. De Leo, Wikipedia

Outline

- Introduction:
  Axions and Axion-like particles
- Experimental Method:
  How to search for axions/ALPs in storage rings
- Experiment:
  Analysis & Results of first experiments
- Next steps

Axion/Axion Like Particle (ALPs)

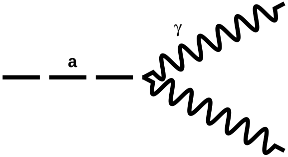
Axions/Axion Like Particles (ALPs)

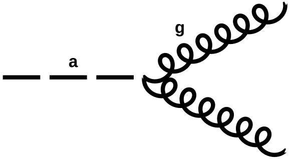
- hypothetical pseudoscalar elementary particle postulated by Peccei,Quinn,Wilczek,Weinberg to resolve the strong CP problem
- axion are also Dark Matter candidates
- axion like particles (ALP): similar properties as axions, (but ALPs don't solve the strong QCD problem)
- huge experimental effort to search for axion/ALPs (haloscopes, helioscopes, light shining through the wall, mainly coupling to photons)
- in storage rings with polarized beams axion-gluon/nucleon coupling can be studied

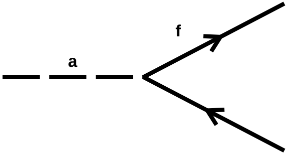
[1]

Axion Coupling

$$\mathcal{L}: -\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad -\frac{\alpha_s}{8\pi}\frac{C_G}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} \qquad -\frac{1}{2}\frac{C_N}{f_a}\,\partial_\mu a\, \bar{\Psi}_f\gamma^\mu\gamma^5\Psi_f$$







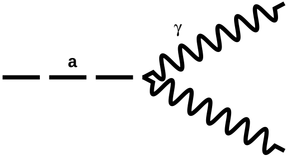
Electric Dipole Moment (EDM)

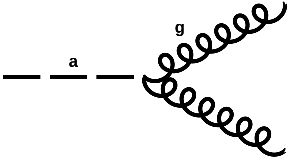
axion wind term

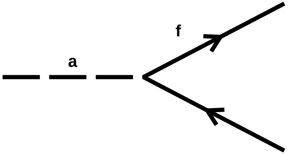
For low axion masses, if axions saturate dark matter they can be described by classical field: $a(t) = a_0 \cos(\omega_a t + \varphi_a)\,, \quad m_a c^2 = \hbar\omega_a\,, \quad \text{Coupling} \propto \frac{1}{f_a} \propto m_a$

Axion Coupling

$$\mathcal{L}: -\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \quad -\frac{\alpha_s}{8\pi}\frac{C_G}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} \quad -\frac{1}{2}\frac{C_N}{f_a}\,\partial_\mu a\,\bar{\Psi}_f\gamma^\mu\gamma^5\Psi_f$$







Electric Dipole Moment (EDM)

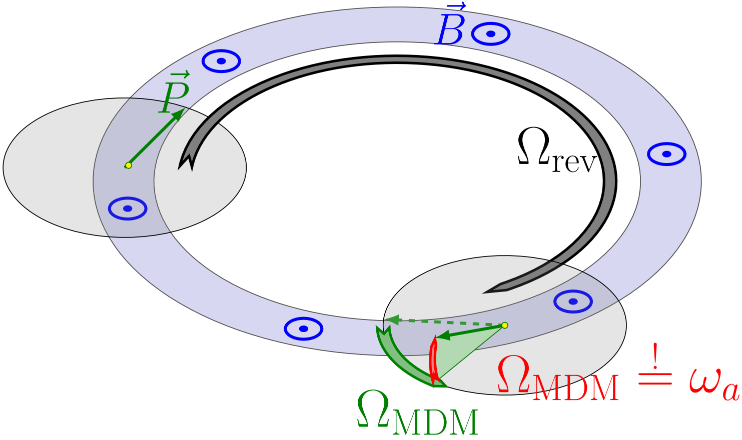
axion wind term

studied by many experiments

accessible in storage ring experiments with spin polarized beams

Experimental Method

Principle of Experiment



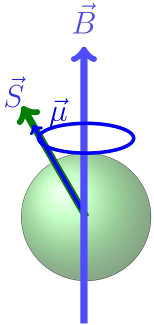
Observe polarization vector $\vec{P}$ in storage ring

Spin Motion in Storage Ring

with respect to momentum vector in magnetic field

$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{\mathrm{MDM}} \qquad\qquad\qquad\qquad) \times \vec{S}$$

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m} G\vec{B} \quad , \qquad \vec{\mu} = g\frac{q\hbar}{2m}\vec{S} = (1+G)\frac{q\hbar}{m}\vec{S}$$



S	spin
B	magnetic field
G	magnetic anomaly
g	g-factor
μ	magnetic moment
q, m	mass, charge

[2, 3, 4]

Spin Motion in Storage Ring

with respect to momentum vector in magnetic field

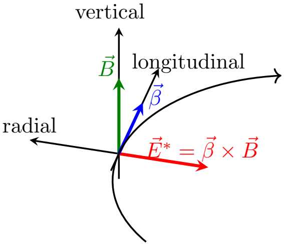
$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}} + \vec{\Omega}_{\mathrm{wind}}) \times \vec{S}$$

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\, G\vec{B}$$

$$\vec{\Omega}_{\mathrm{EDM}} = -\frac{1}{S\hbar} d\, c\, \vec{\beta} \times \vec{B}$$

$$\vec{\Omega}_{\mathrm{wind}} = -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar\partial_0 a(t)\right)\vec{\beta}$$

$$|\vec{\Omega}_{\mathrm{MDM}}| \gg |\vec{\Omega}_{\mathrm{EDM}}|, |\vec{\Omega}_{\mathrm{wind}}|$$



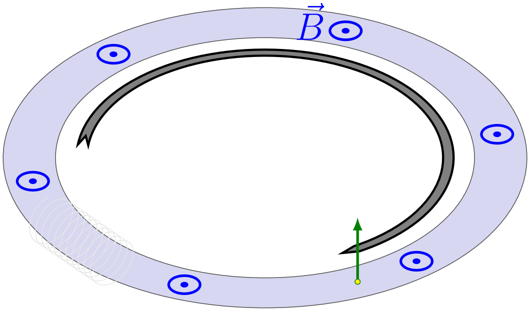
axion field: $a(t) = a_0 \cos(\omega_a t + \varphi_0)$ $d = d_{\mathrm{DC}} + d_{\mathrm{AC}} \cos(\omega_a t + \varphi_0)$ (EDM)

$\hbar\omega_a = m_a c^2$ $d_{AC} = a_0 g_{ad\gamma} \propto C_g$

[2, 3, 4] oscillating EDM ↗ ↖ ALP-EDM coupling

Principle of Experiment

- store polarized hadrons



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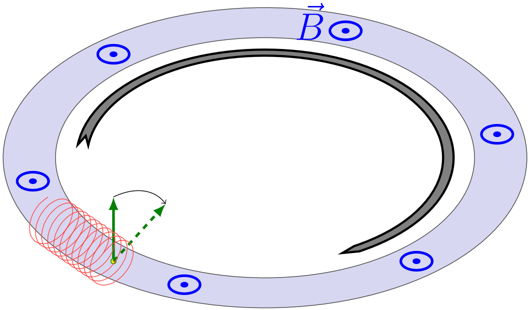
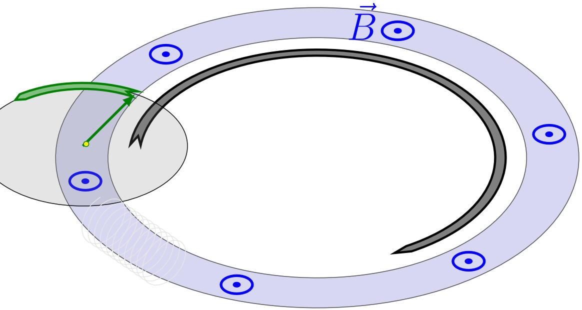


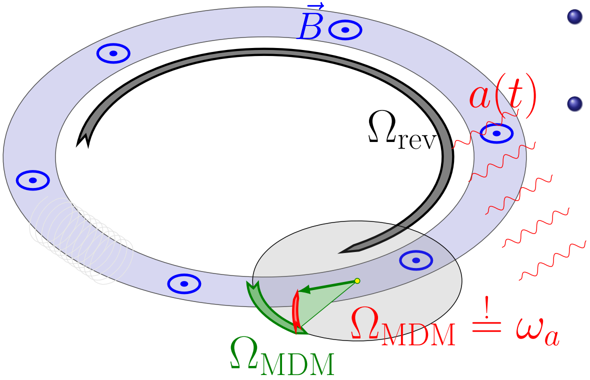
- store polarized hadrons
- flip polarization into horizontal plane,

Principle of Experiment



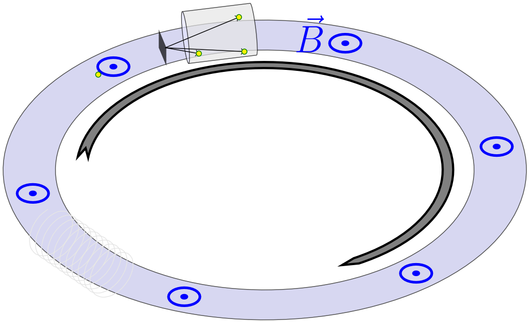
- store polarized hadrons
- flip polarization into horizontal plane,
- maintain precession in horizontal plane for $\approx$ 100s

Principle of Experiment



- store polarized hadrons
- flip polarization into horizontal plane,
- maintain precession in horizontal plane for ≈ 100s
- if $m_a c^2 \equiv \hbar\omega_a \stackrel{!}{=} \Omega_{\rm MDM}\hbar$, polarization will turn out of the horizontal plane, resulting in a vertical polarization component, if the relative phase of axion field and a spin precession match.

Principle of Experiment



- store polarized hadrons
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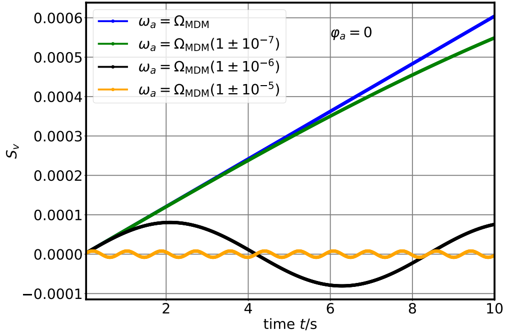
- Vertical polarization can be measured using a carbon target and a polarimeter.
  Left-right asymmetry A_{LR} is proportional to vertical polarization

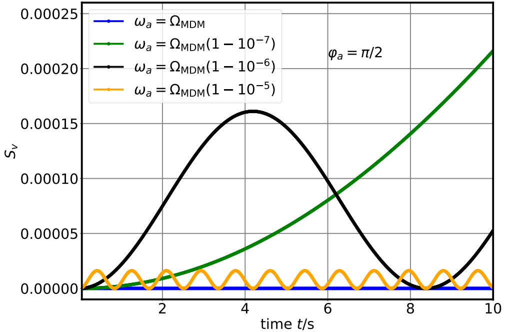
Properties of Method

- AC measurement (i.e. systematics are under control)
- axion wind effect enhanced in storage rings ($v_{\rm particle} \approx c$)
  $\vec{\Omega}_{\rm wind} = -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar\partial_0 a(t)\right)\vec{\beta}$
- One can look for ALPs at a given mass given by $\Omega_{\rm MDM}$ or scan a certain mass range by varying $\Omega_{\rm MDM}$

Expected Build-up

$a(t) = a_0 \cos(\omega_a t + \varphi_a)$ axion phase φ_a not known!
If your are unlucky, build-up is zero.





[5]

Remedy: Inject 4 pulses with 90 degree polarization phase difference.
$\rightarrow$ You cannot miss the signal.

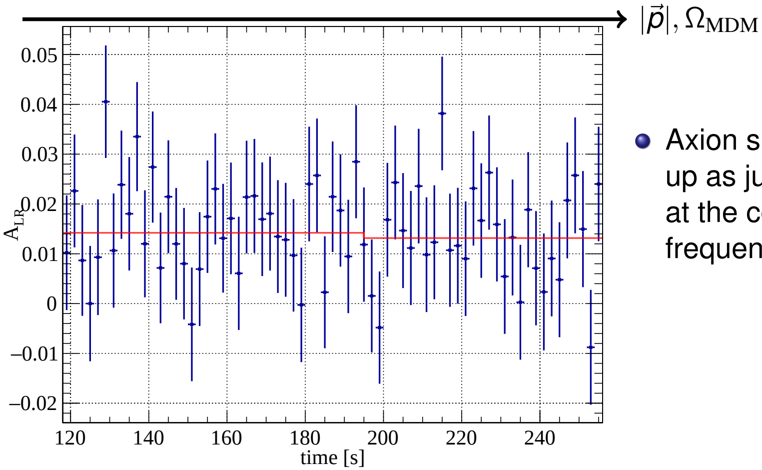
Analysis & Results

COoler SYnchrotron COSY

- pol. deuteron beam
  $p \approx 970\text{MeV}/c$
- polarization $P \approx 0.40$
- $\approx 10^9$ stored particles per 300 s cycle
- $\Omega_{\mathrm{MDM}} \approx 2\pi \cdot 120\,\text{kHz}$
- JEDI (Jülich Electric Dipole moment Investigations) collaboration

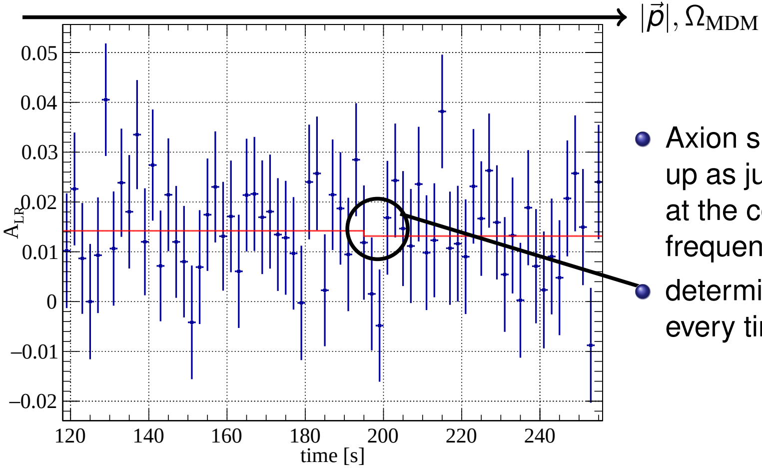
JEDI

Left-Right Asymmetry A_{LR} Scan



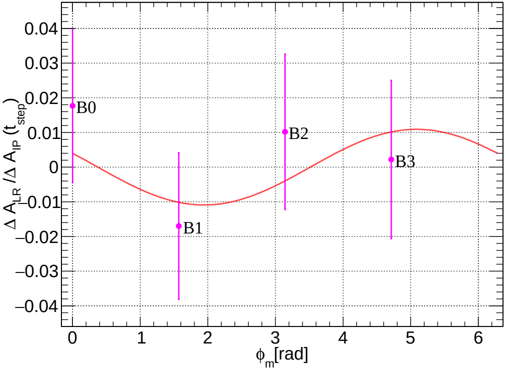
- Axion signal would show up as jump in asymmetry at the corresponding frequency $\omega_a \propto m_a$

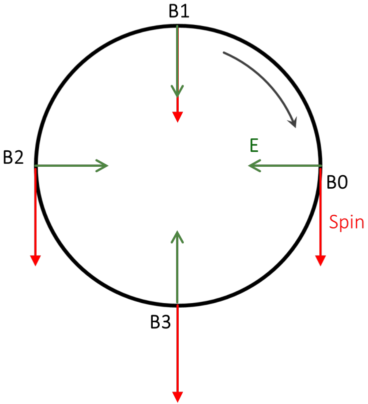
Left-Right Asymmetry A_{LR} Scan



- Axion signal would show up as jump in asymmetry at the corresponding frequency $\omega_a \propto m_a$
- determine jump ΔA_{LR} for every time bin

Typical Asymmetry Measurement





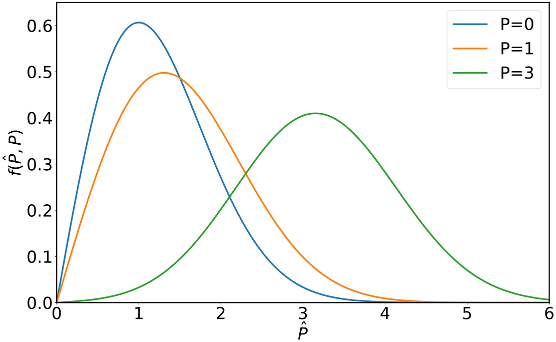
Fit: $f(\Phi_m) = C_1 \cos(\Phi_m) + C_2 \sin(\Phi_m)$

$\hat{A} = \sqrt{C_1^2 + C_2^2}$

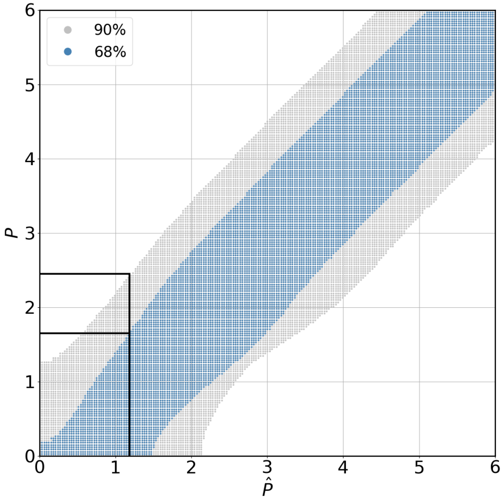
Problem

Fit will always find an amplitude ($\hat{A} \geq 0$), now use $\hat{P} = \dfrac{\hat{A}}{\sigma}$, $\quad \sigma$: uncertainty

$$f(\hat{P}|P)\,\mathrm{d}\hat{P} = e^{-\frac{\hat{P}^2+P^2}{2}}\,\hat{P} I_0(\hat{P}P)\,\mathrm{d}\hat{P},\ \text{Rice distribution}$$

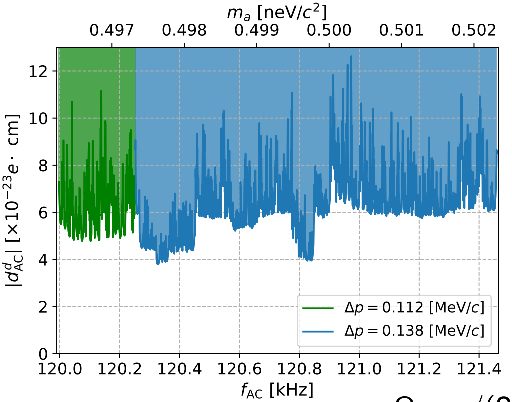


$\hat{P} = \hat{A}/\sigma \rightarrow$ Confidence Interval



- procedure based on Feldman-Cousins methods [6]
- on vertical axis read off the measured $\hat{P}$
- vertical axis gives lower and upper limit for true P
- limit on P directly related to limit on d_{AC}

Results on Oscillating EDM d_{AC}, 90% CI

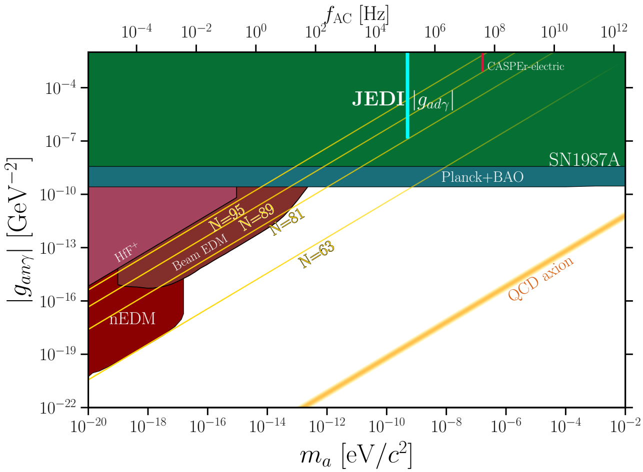


$\equiv \Omega_{\mathrm{MDM}}/(2\pi)$

- a few days of beam time
- $\dfrac{\Omega_{\mathrm{MDM}}}{2\pi} = f_{AC} = \dfrac{1}{2\pi}\dfrac{m_a c^2}{\hbar} = \gamma G f_{\mathrm{rev}}$

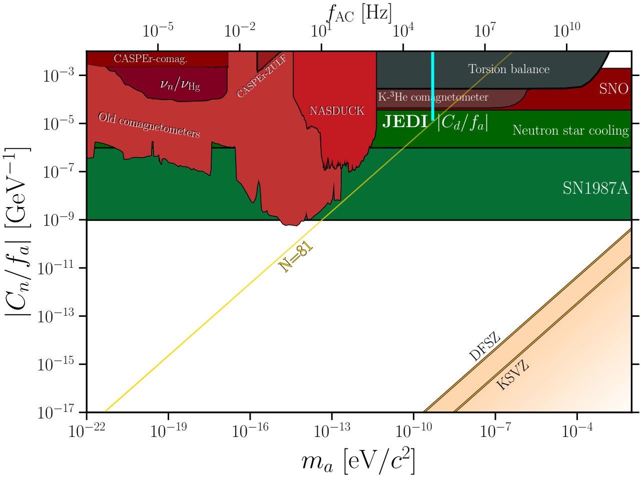
[7] submitted to PRX

Axion Coupling to EDM operator $g_{ad\gamma}$ (Axion/Gluon Coupling))



- $g_{ad\gamma} = \dfrac{d_{AC}}{a_0}$
  $a_0 = 0.55$ GeV/cm^3
  (Dark Matter is saturated by ALPs)
- assume no axion wind effect
- yellow lines (parallel to QCD axion lines): models with light QCD axion
- JEDI limit comparable or even better compared to other experiments
- Limits from SN1987A, Planck+BAO have strong model dependence

Axion Wind Effect: Coupling to Nucleons C_N/f_a



- storage ring experiments particularly sensitive to axion wind effect ($\beta = \mathcal{O}(1)$)

Next steps?

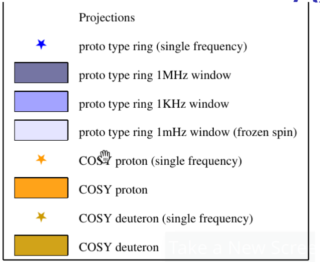
How to Explore a Wider Mass Range m_a

Up to now experiment was performed in a very narrow frequency range. How to access wider mass range?

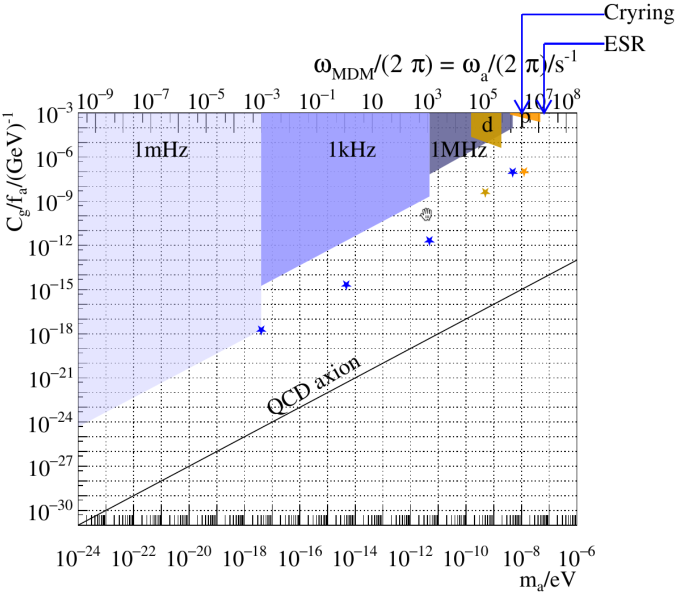
$$\Omega_{\mathrm{MDM}} = \gamma G \Omega_{rev}$$

1. modify beam energy (changes γ, Ω_{rev})
2. use different nuclei (changes G)
3. Use additional electric field
   $$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$
   allows to reduce $\vec{\Omega}_{\mathrm{MDM}}$ down to 0

Axion Searches at Storage Rings



Estimate for one year (10^7 seconds) running time [5] for COSY and a prototype storage ring for EDM measurements



Summary & Outlook

Summary & Outlook

- Axion/ALPs well motivated candidates for cold dark matter
- First storage ring experiment at COSY performed by JEDI collaboration to search for ALPs
- In an engineering run (few days of data taking) limits reached which are comparable to other experiments
- In general: Experiments with polarized beams (and targets) at storage ring have great potential ...

Literature I

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- S. P. Chang, S. m. c. Hacıömeroğlu, O. Kim, S. Lee, S. Park, and Y. K. Semertzidis, “Axionlike dark matter search using the storage ring edm method,” *Phys. Rev. D*, vol. 99, p. 083002, Apr 2019. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevD.99.083002
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Literature II

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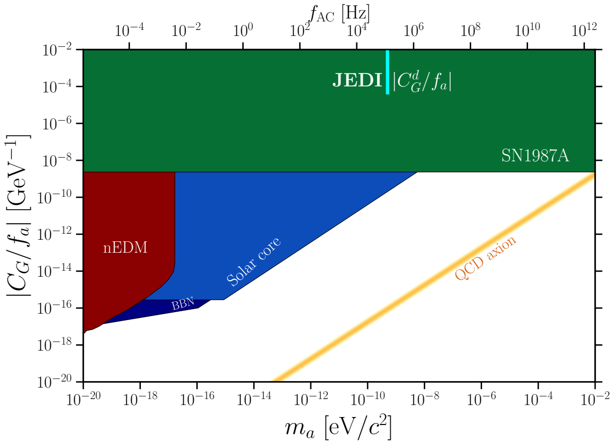
Spare Slides

90% CI on Axion Gluon Coupling C_g/f_a



$$\frac{C_g}{f_a} = \frac{d_{AC}}{a_0}\,\frac{2mc^2}{e\hbar c}\,\frac{1}{S\kappa_a}\,,$$

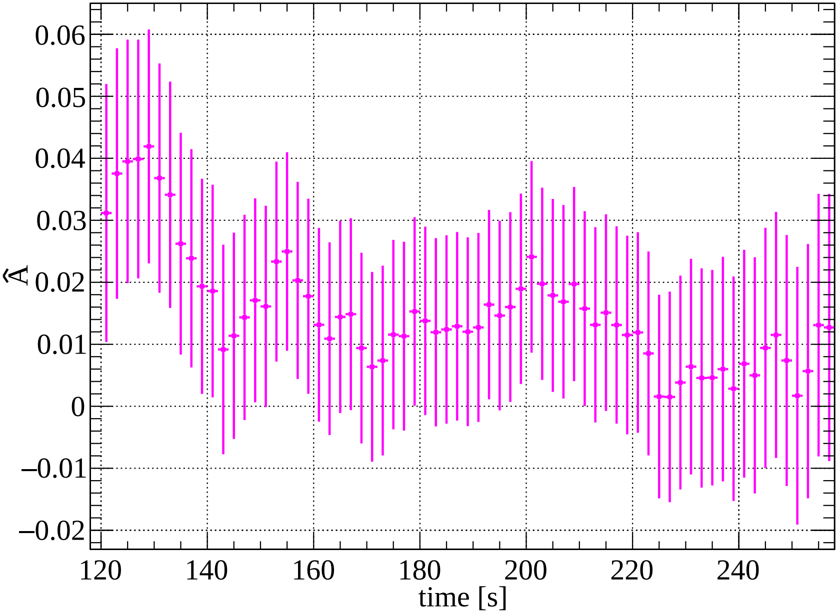
$$\kappa_a = 0.0046$$

$$g_{ad\gamma} = \frac{d_{AC}}{a_0}\,\frac{\sqrt{4\pi\alpha}}{e\hbar c}$$

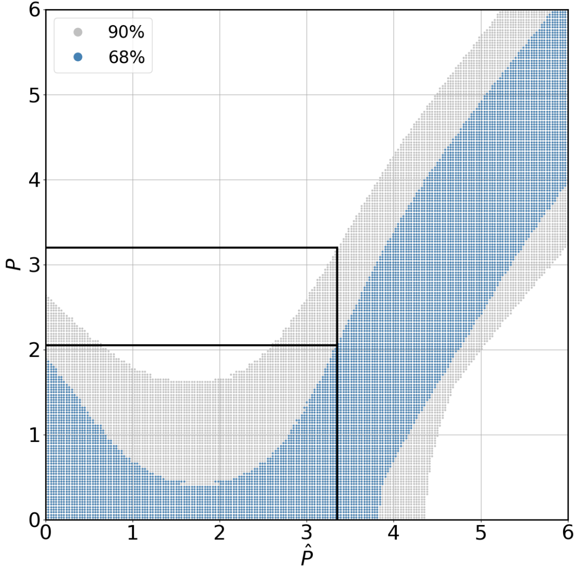
$$\frac{g_{ad\gamma}}{C_g/f_a} = \frac{\sqrt{4\pi\alpha}S\kappa_a}{2mc^2}$$

$$= 3.7\cdot 10^{-3}/\mathrm{GeV}$$

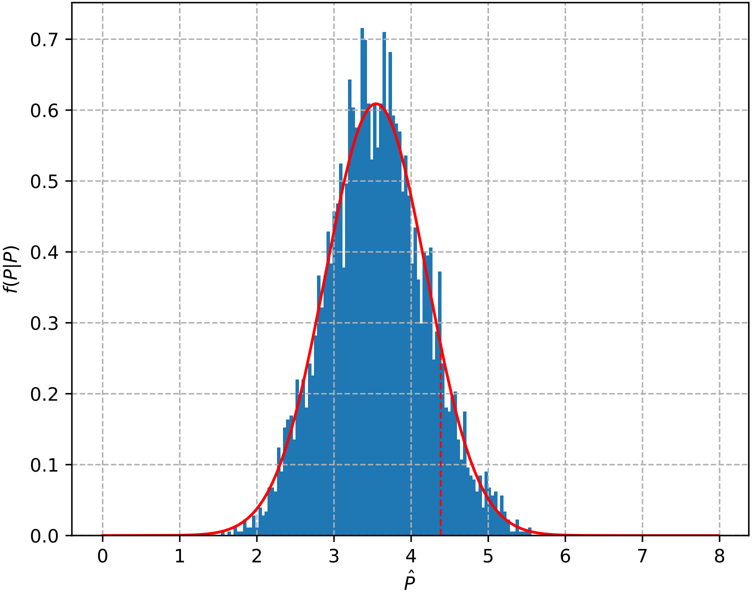
Amplitudes $\hat{A}$ for a Single Cycle



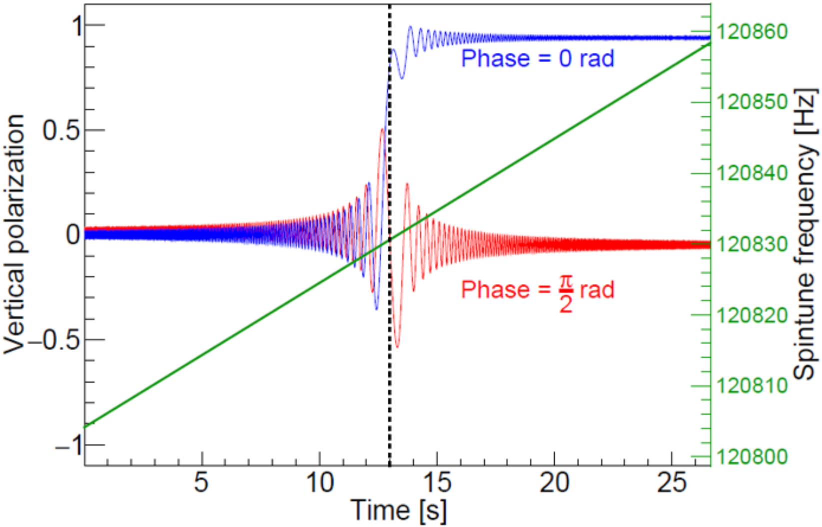
CI for eight Cycles



$\hat{P}$ distribution for 8 cycles



Expected Jump in Polarisataion



Artificial Signal Using RF Wien Filter