Storage ring as an ALP antenna – experimental proof of principle

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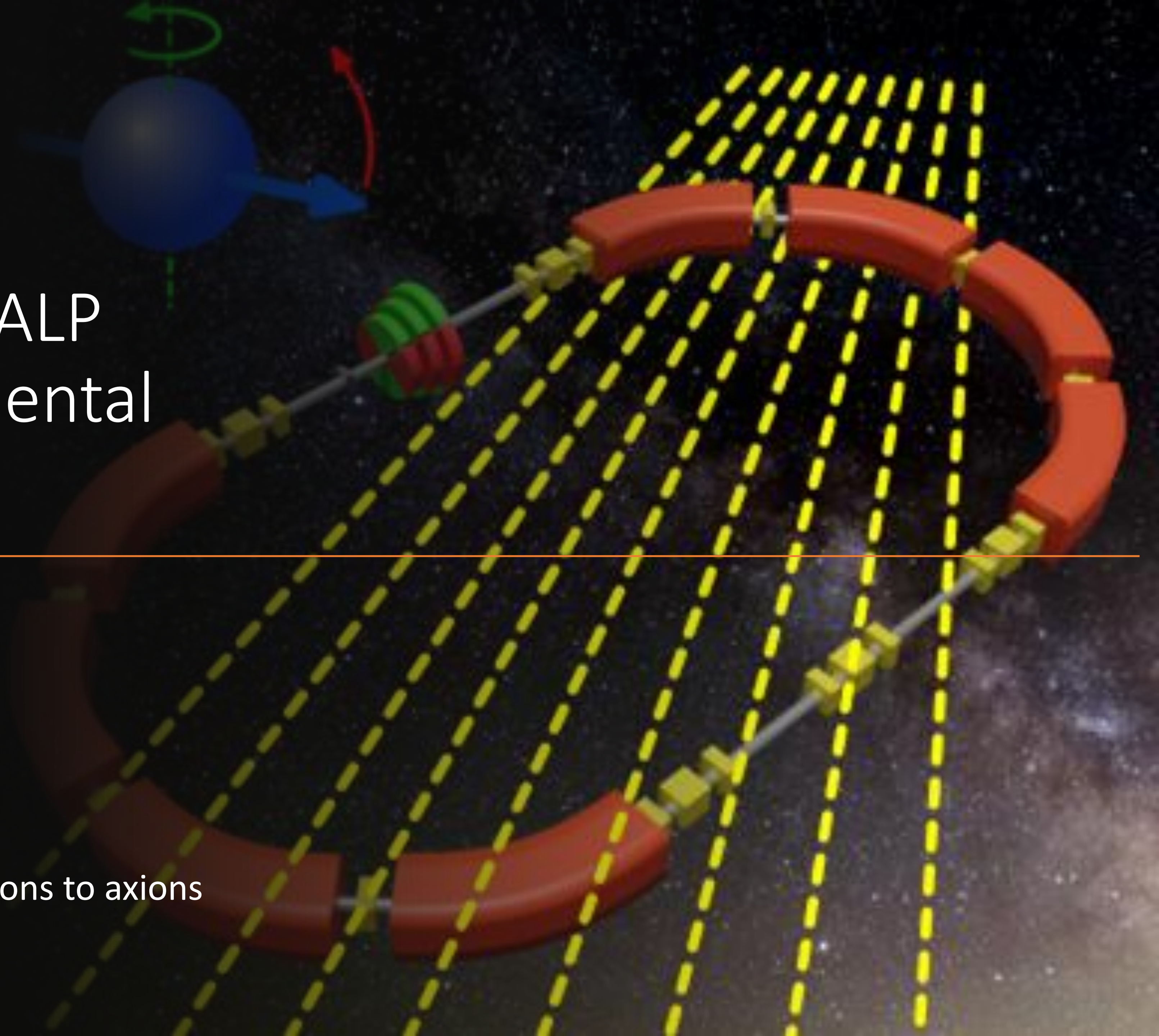
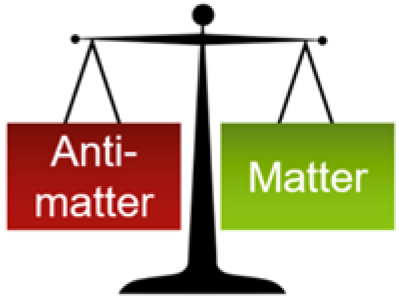
JEDI Collaboration

Workshop at 1-GeV scale: from mesons to axions
Kraków 19.09.2024



Problem I:
puzzling matter/antimatter asymmetry



- After Big Bang: matter and antimatter balanced
- Currently:

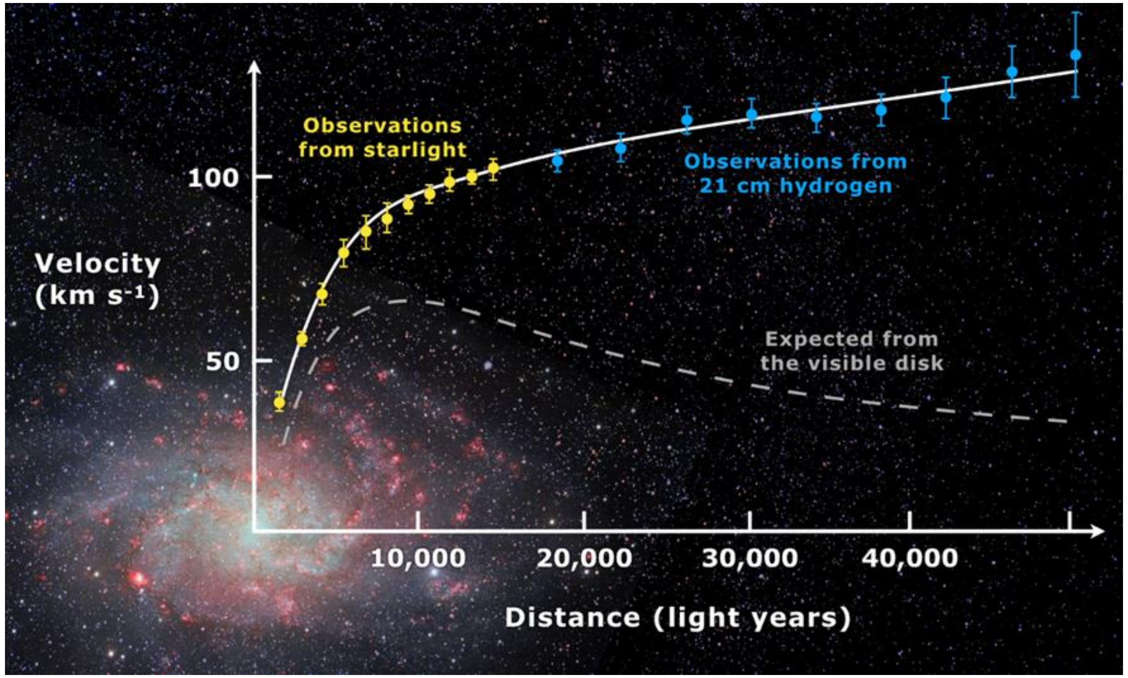
$$\eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx \begin{cases} 10^{-10} & \text{measured} \\ 10^{-18} & \text{from SCM} \end{cases}$$

Bennet et al., Astrophys. J. Suppl. 148 (2003)
Barger et al., PLB 566 (2003)

Bernreuther et al., Lect. Notes Phys. 591 (2002)

- Why?
- CP violation is needed to explain the surplus of matter Sakharov, Soviet Physics Uspekhi 5 (1991)

Problem II: nature of dark matter



Rotation curve of galaxy Messier33

M. D. Leo, https : / / en . wikipedia . org / wiki / Galaxy _ rotation _ curve

Only about 1/5 of the universe is made of visible matter.

Large experimental evidence:

- Rotation curves of galaxies
- Gravitational lensing

What is the rest, i.e. Dark Matter made of?
Axions? ALPs?
Physics BSM!

Hunt for ALPs as coherently oscillating waves, inducing oscillating EDMs in SM particles.

Axions and Axionlike Particles (ALPs)

Strong CP problem

- Puzzling smallness of CP violation in strong interaction
- Peccei-Quinn symmetry proposed to explain it — Peccei, Quinn, PRL 38 (1977)
- Spontaneous PQ symmetry breaking $\longrightarrow$ existence of axions — Wilczek, PRL 40 (1978)
- Generalization of this concept - ALPs — Kim, PRL 43 (1979); Dine et al, PLB 104 (1981)

Nature of Dark Matter

- Axions/ALPs good candidates for cold dark matter — Di Luzio et al, J. Cosmol. Astropart. Phys. 10 (2021)
- Light, stable at large time scales, almost non-interacting

ALPs characteristics

Graham, PRD 84 (2011), 88 (2013)

If ALPs saturate the dark matter → described as classical field

$$a(t) = a_0 \cos(\boldsymbol{\omega_a}(t - t_0) + \boldsymbol{\phi_a})$$

$\boldsymbol{\omega_a}$ ALP oscillation frequency – connected to its mass $\hbar\omega_a = m_a c^2$

$\boldsymbol{\phi_a}$ local phase of ALP field – unknown

- Mass: $m_a \in (10^{-22}, 10^{-7})\ \frac{\mathrm{eV}}{c^2}$
- Lifetime $\tau_a = \frac{h}{m_a v^2}$
- Coherence length $l_a = \frac{h}{m_a v} > 12\ \mathrm{km}$ for $v = 10^{-3} c$

ALP couplings

light shining through wall (ALPS, CROWS, OSQUAR)

polarisation (PVLAS, BMV)

Helioscope (CAST)

haloscopes (ADMX, CAST-CAPP, CAST-RADES)

conversion in crystallines (SOLAX, COSME)

with photons

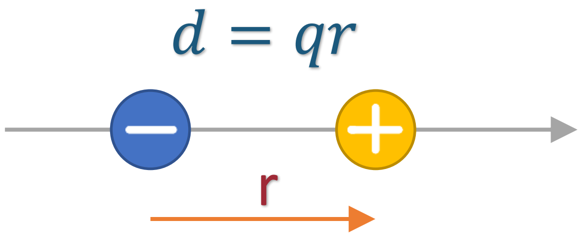
with gluons

nuclear magnetic resonance CASPEr

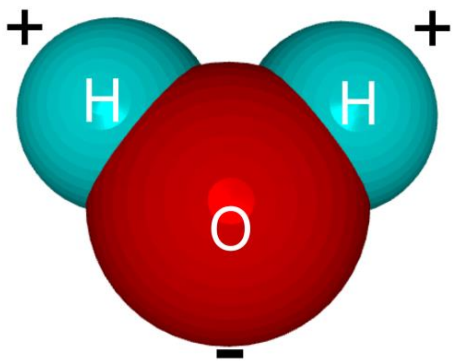
with EDM

with nucleons

ALPs and Electric Dipole Moment



ALP – gluon coupling introduces an oscillating Electric Dipole Moment (EDM) ‖ spin



$$d(t) = d_{\mathrm{dc}} + d_{\mathrm{ac}} \cos[\omega_a (t - t_0) + \phi_a(t_0)]$$

ALP-induced oscillations

ALPs introduce oscillating coupling to spin of nucleons:

- Oscillating electric dipole moment — Graham et al., PRD 84 (2011)
- Axion wind effect — Graham et al., PRD 88 (2013)

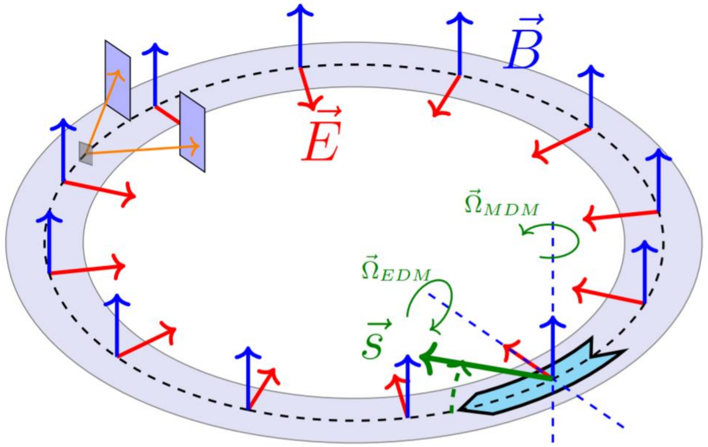
Idea: use spin precession of a polarized beam in storage ring, look for resonance with ω_a

Spin dynamics in a storage ring

Spin precession of a particle possessing EDM and MDM in the presence of ***E*** and ***B*** field is described by Thomas-BMT equation

Fukuyama et al, Int. J. Mod. Phys A28 (2003)

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



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

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

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

G: magnetic anomaly

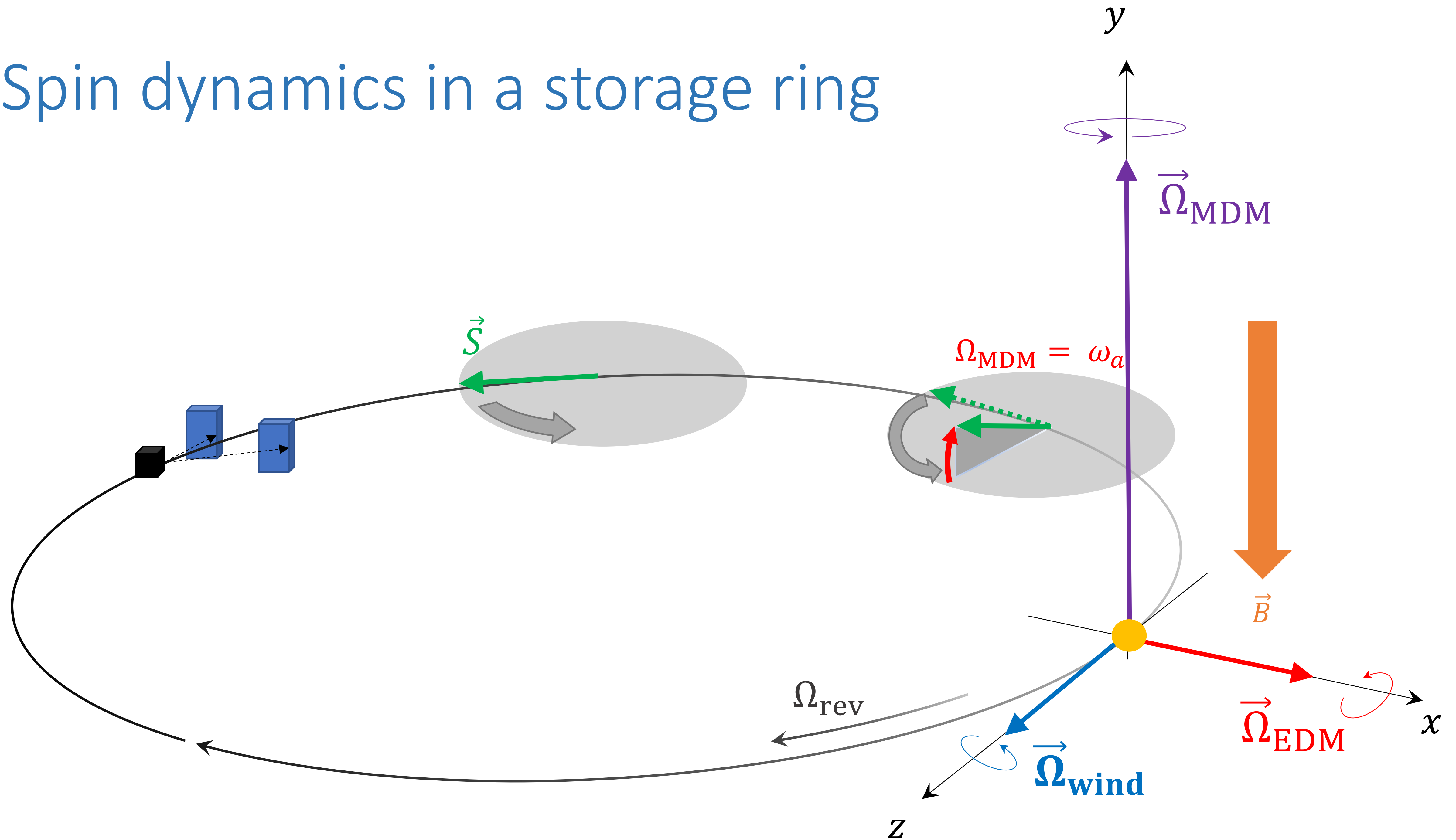
$d(t)$: Electric Dipole Moment

$$d(t) = d_{\mathrm{dc}} + \boldsymbol{d}_{\mathbf{ac}}\cos(\omega_a t + \phi_a)$$

C_N: Coupling constant

$$\partial_0 a(t) = \omega_a a_0 \sin(\omega_a t + \phi_a)$$

Spin dynamics in a storage ring



The JEDI project

2011 - JEDI collaboration forms at COSY Jülich, Germany

Goals:

1. **Work on prerequisites for (static) EDM search using storage rings**
   - Alignment of ring elements, field stability, homogeneity, shielding
   - Hardware developments
   - Spin tracking
   - Beam intensity at least $\mathbf{N = 4 \times 10^{10}}$ particles per fill
   - High polarization $\boldsymbol{P = 0.8}$
   - Large electric fields $\boldsymbol{E = 10}$ **MV/m**
   - Long spin conference times $\boldsymbol{\tau \sim}$ **1000 s**
   - Efficient polarimetry with $\boldsymbol{A_y \sim 0.6}$ and detection efficiency $\boldsymbol{f \sim 0.005}$

2. **perform precursor experiment**
   learn how to keep systematics under control

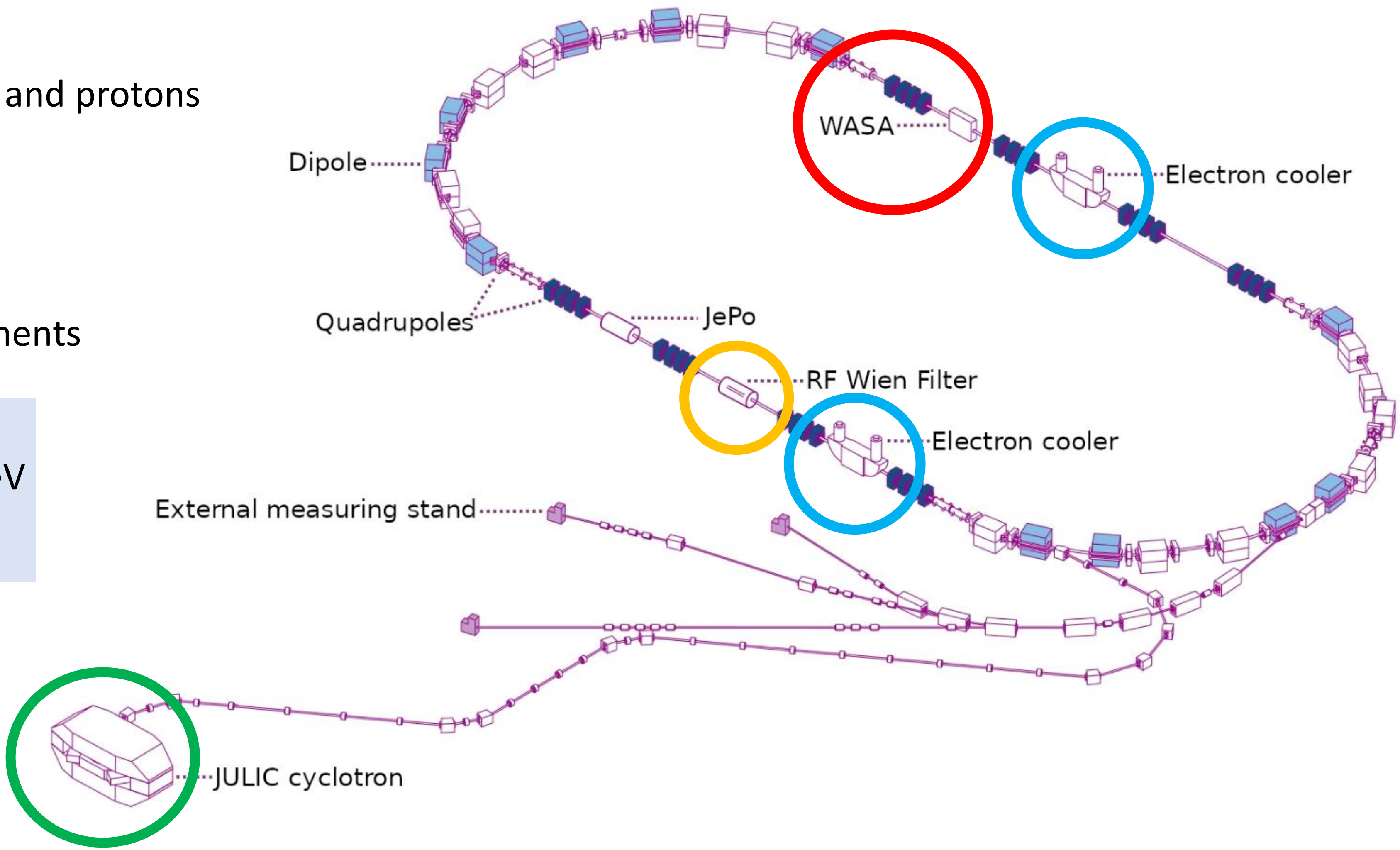
3. **… search for axions/ALPs**

With these parameters, statistical sensitivity of a 1-year run is

$$\sigma_{stat} = \frac{2\hbar}{\sqrt{Nf\tau PA_yE}} = 2.4 \times 10^{-29}\ e \cdot \text{cm}$$

Cooler Synchrotron COSY

- Circumference 184 m
- **Polarized** / unpolarized **deuterons** and protons
- $p = 0.3 - 3.7$ GeV/c
- **Internal** and **external** experiments
- 2 **electron** coolers
- 2 **stochastic** coolers
- Hadron physics / **Precision** experiments
- Selected working conditions:
  - Deuteron beam
  - $p = 0.97$ GeV/c, $T = 238$ MeV

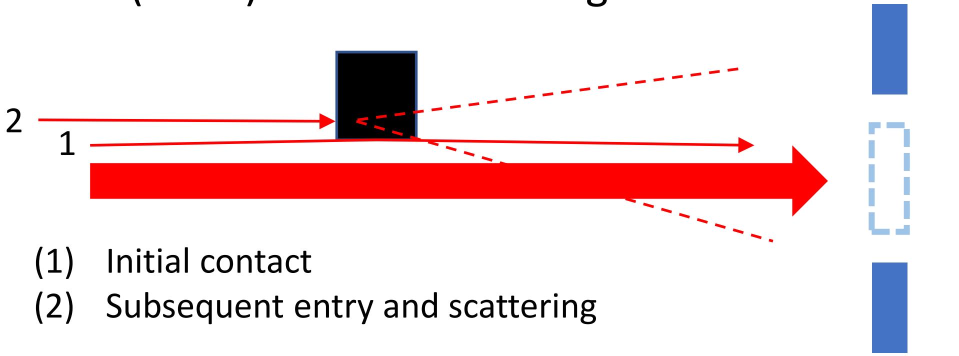


Prerequisites: Polarimetry

d+C at forward angles

white noise beam extraction – a non-destructive method

Thick (2mm) block carbon target



(1) Initial contact
(2) Subsequent entry and scattering

Spin - orbit interaction gives the asymmetry in azimuthal distribution of reaction products:

Left-right asymmetry

$$\mathrm{A_{LR}} = \frac{N_L - N_R}{N_L + N_R} = P_y A_y$$

Vertical polarization,

ALP signal

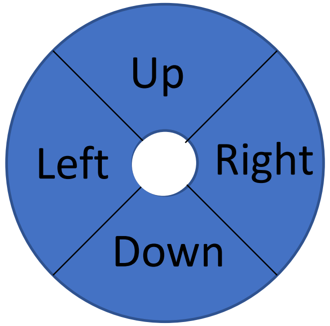
Up - down asymmetry

$$\mathrm{A_{UD}} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y$$

Horizontal polarization

systematics, normalization

Prerequisites: Polarimetry WASA-at-COSY

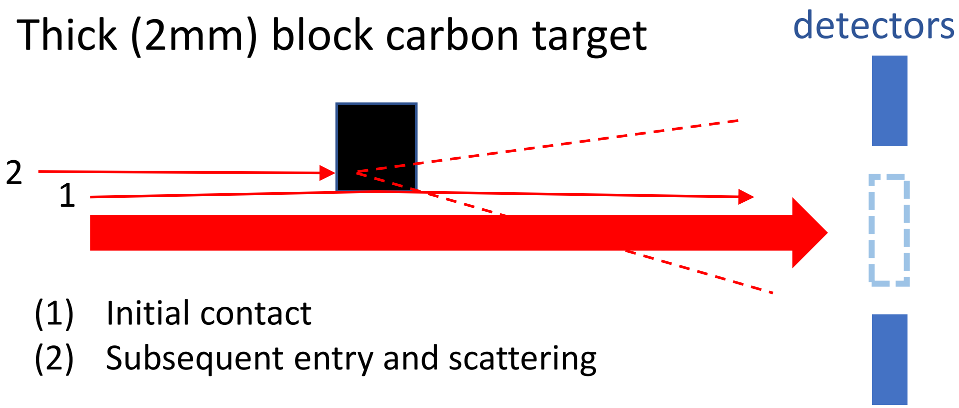


Detector-beam view

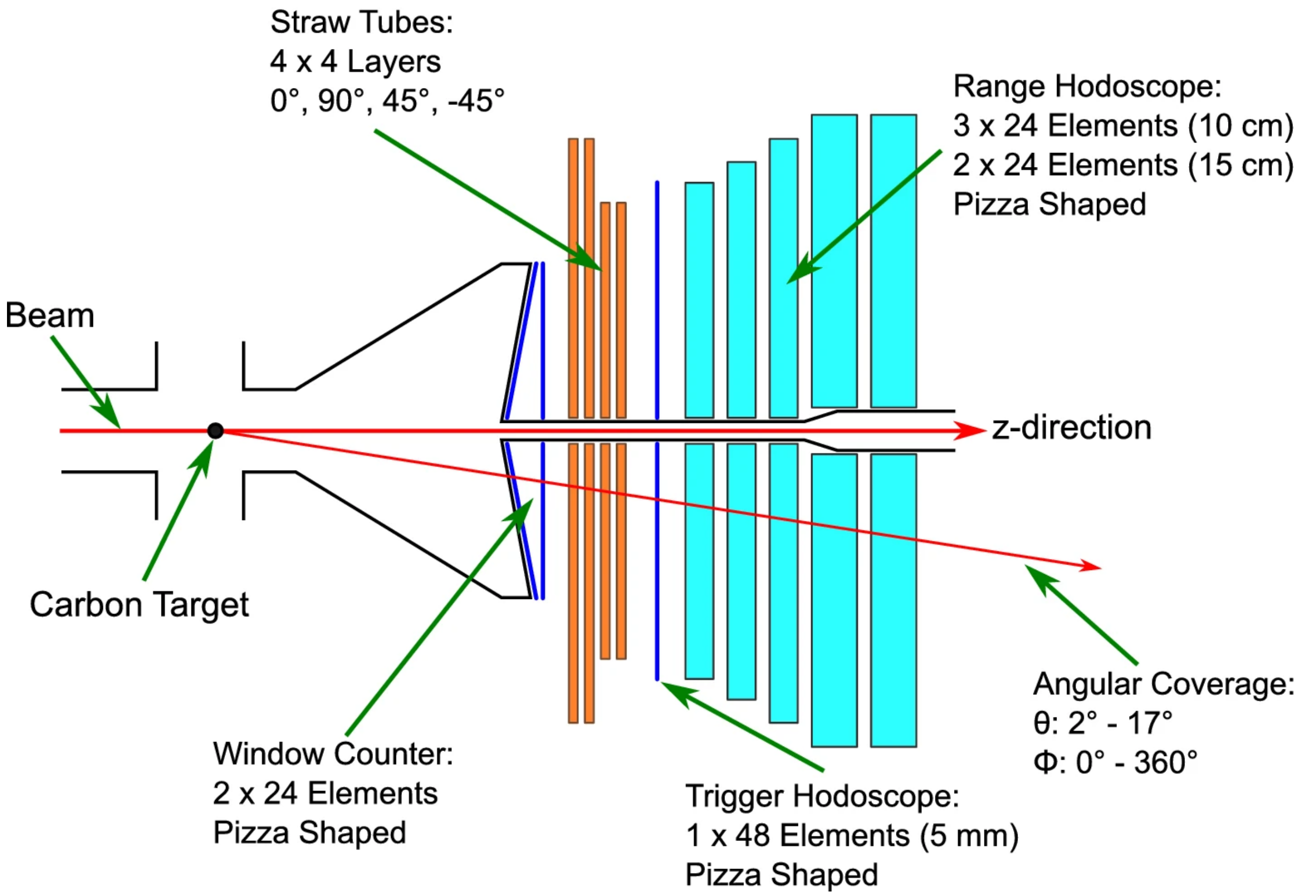
d+C at forward angles

sampling the beam with white noise beam extraction

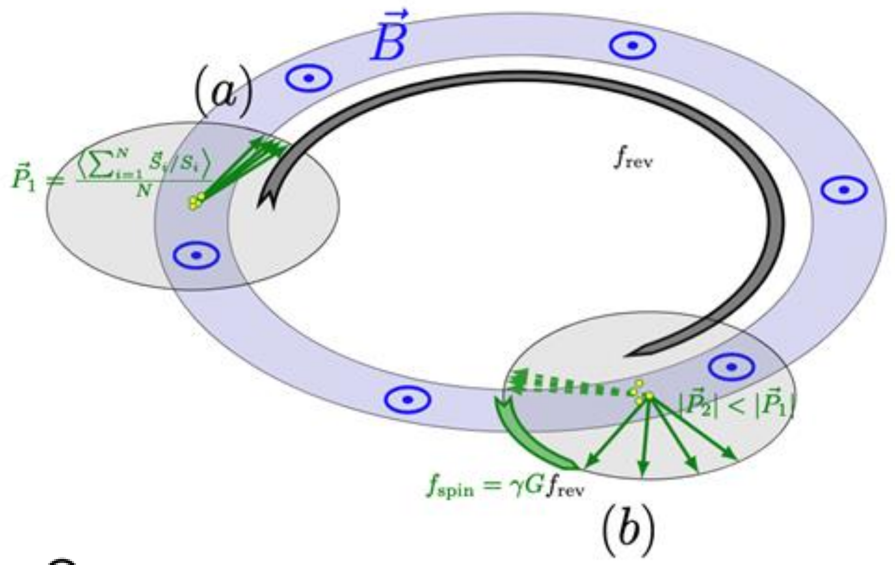
Thick (2mm) block carbon target



(1) Initial contact
(2) Subsequent entry and scattering



Prerequisites: long spin coherence times



$$\nu_s = \frac{\Omega_{\mathrm{MDM}}}{\Omega_{\mathrm{rev}}} = \gamma G \approx -0.161 \qquad f_s = 121\ \mathrm{kHz}$$

SCT = complex interplay of:

- Beam emittance
- Momentum spread
- Beam chromaticity
- Orbit deviations

Optimization:

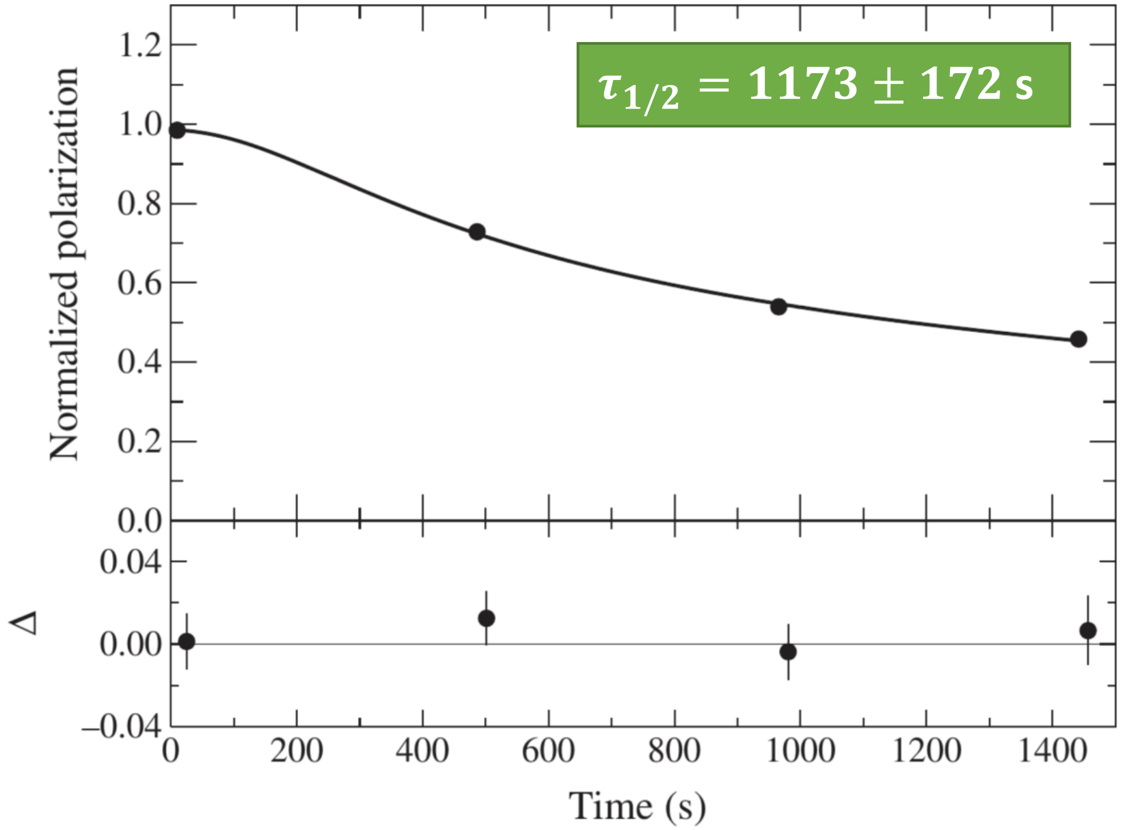
- Beam bunching
- Cooling
- Careful sextupole correction

Measurement of in-plane polarization:

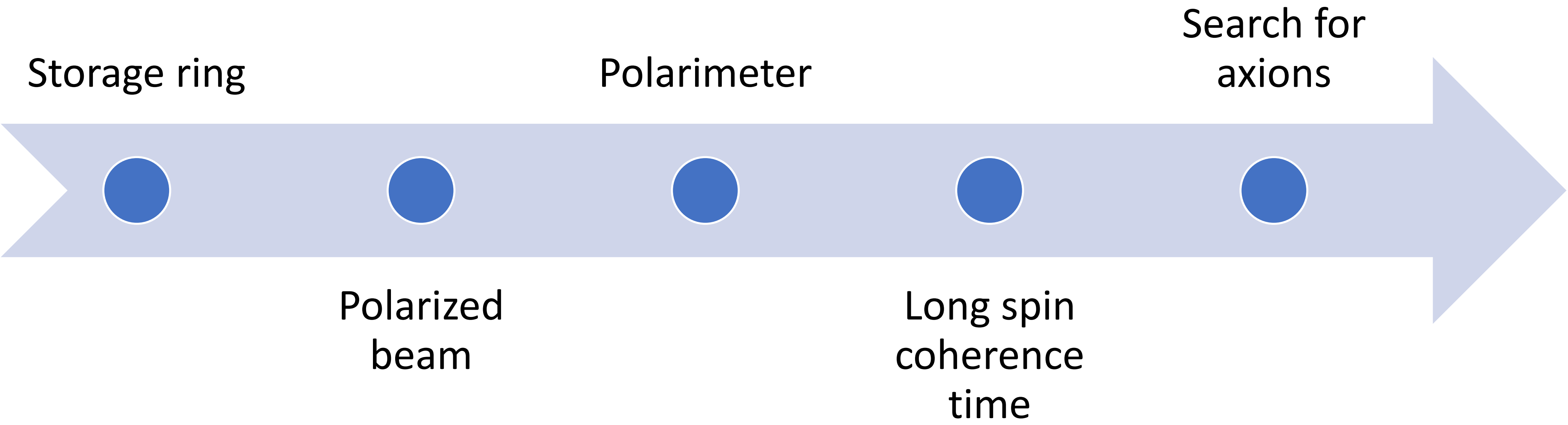
- Events are time-stamped to collect statistics
- Within a time bin (~2 s) , events are distributed into nine angular bins, assuming ν_s
- In-plane polarization ~ to max UD asymmetry amplitude, ν_s is determined thereby too

Bagdasarian et al, Phys Rev AB 17 (2014)
Eversmann et al., PRL 115 (2015)

Guidoboni et al, PRL 117 (2016)



What next?

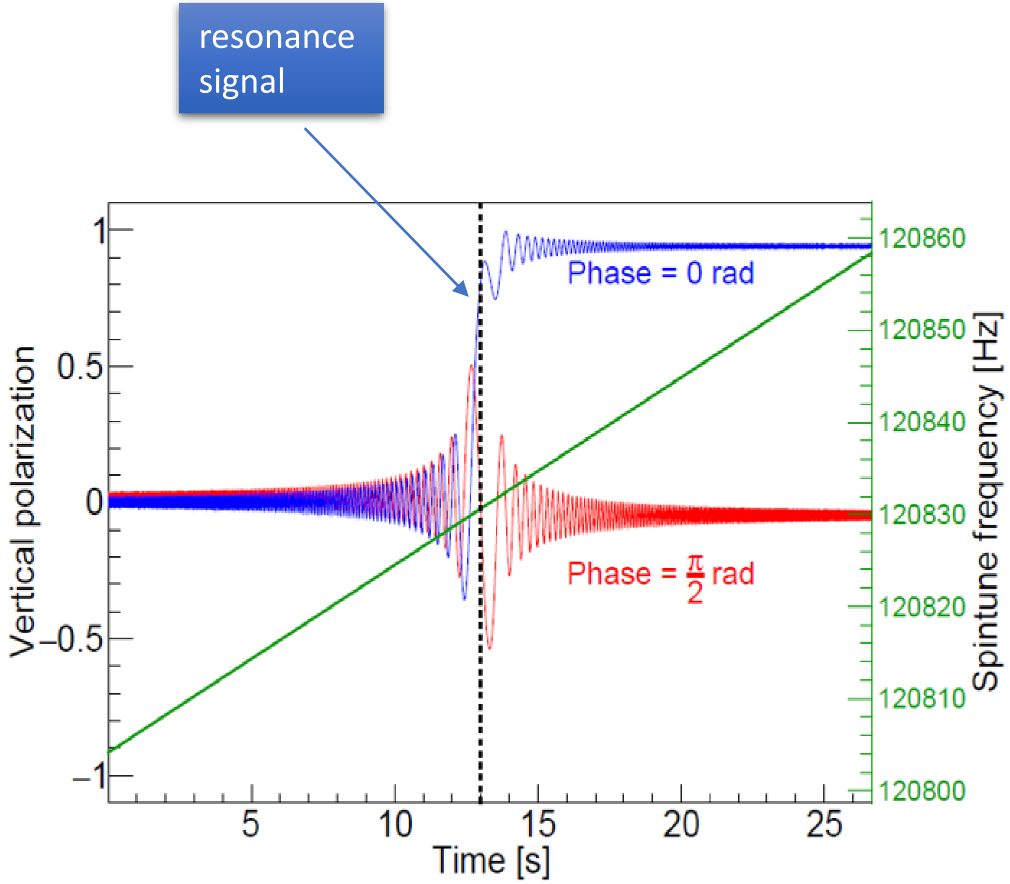


$m_a = ?$

$\phi_a = ?$

Experimental method

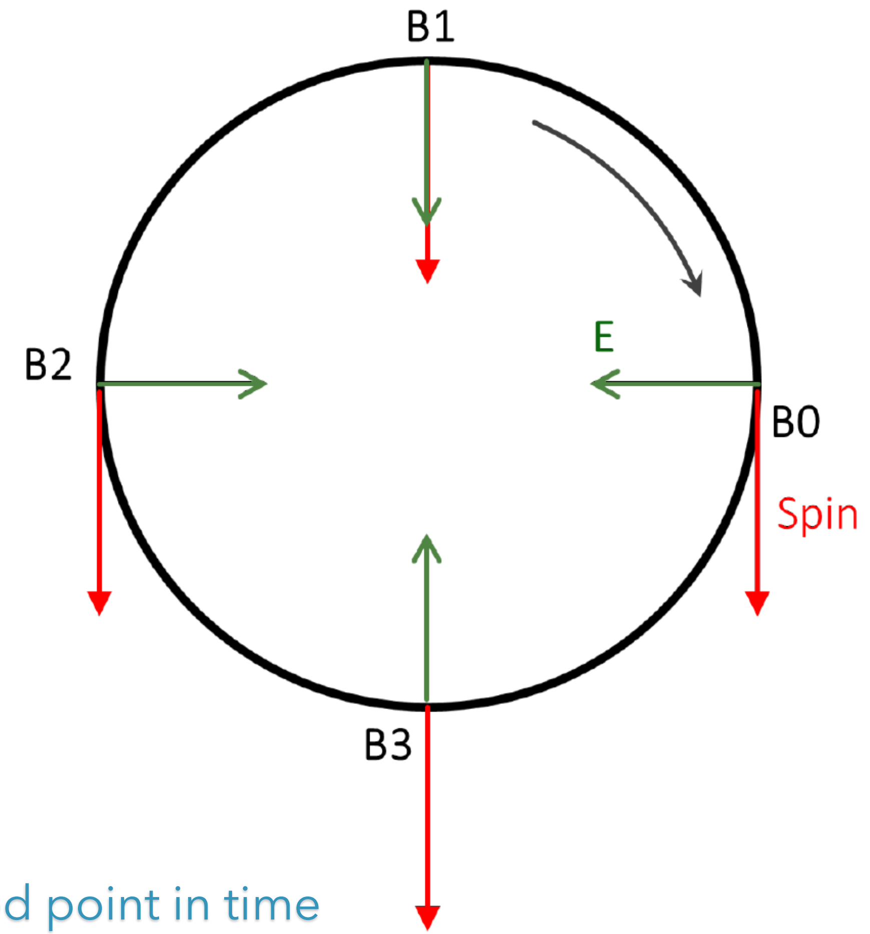
- Ramp frequency in search of resonance
- Describe the polarization jump at resonance crossing
- Phase plays an important role in determining the jump



Unknown frequency ω_a	• Scan the frequency for resonance • Signal: Jump in vertical polarization
Unknown phase ϕ_a	• Use beams with perpendicular polarization: 4 bunches • Sensitive to all phases

Phase problem solution: four beam bunches

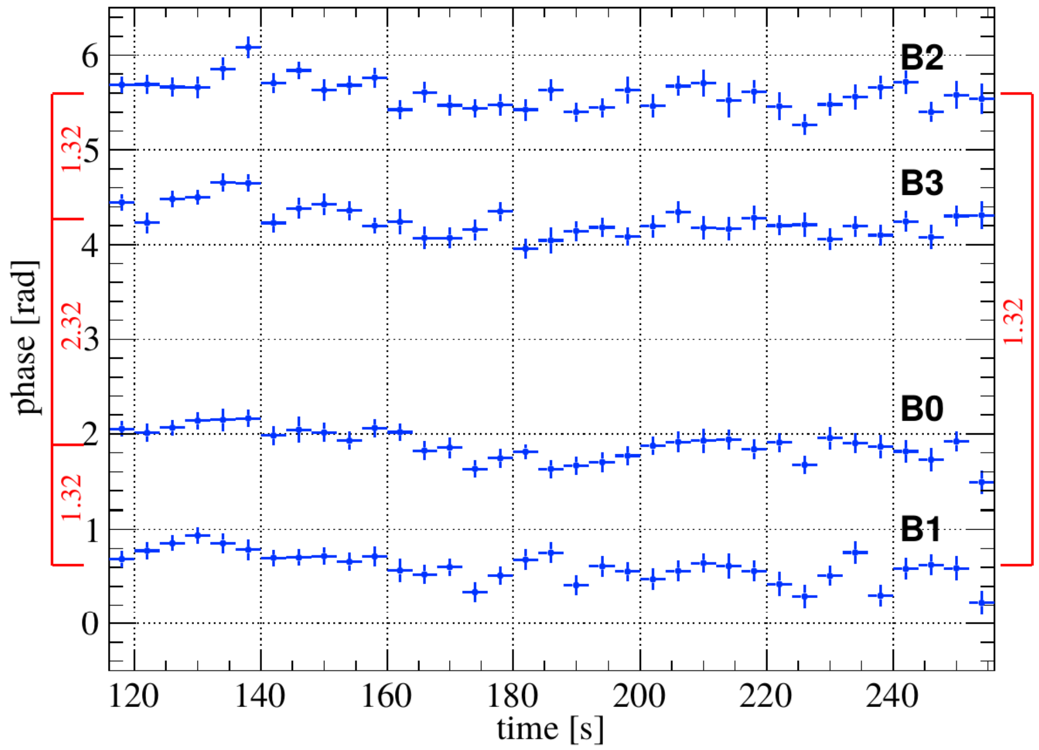
- Simultaneous searches with perpendicular beam polarisation using 4 bunches
- Subsequent bunches have perpendicular polarisation
- Alternate bunches have opposite polarisation direction



A top-down view of the ring – fixed point in time

Phase problem solution: four beam bunches

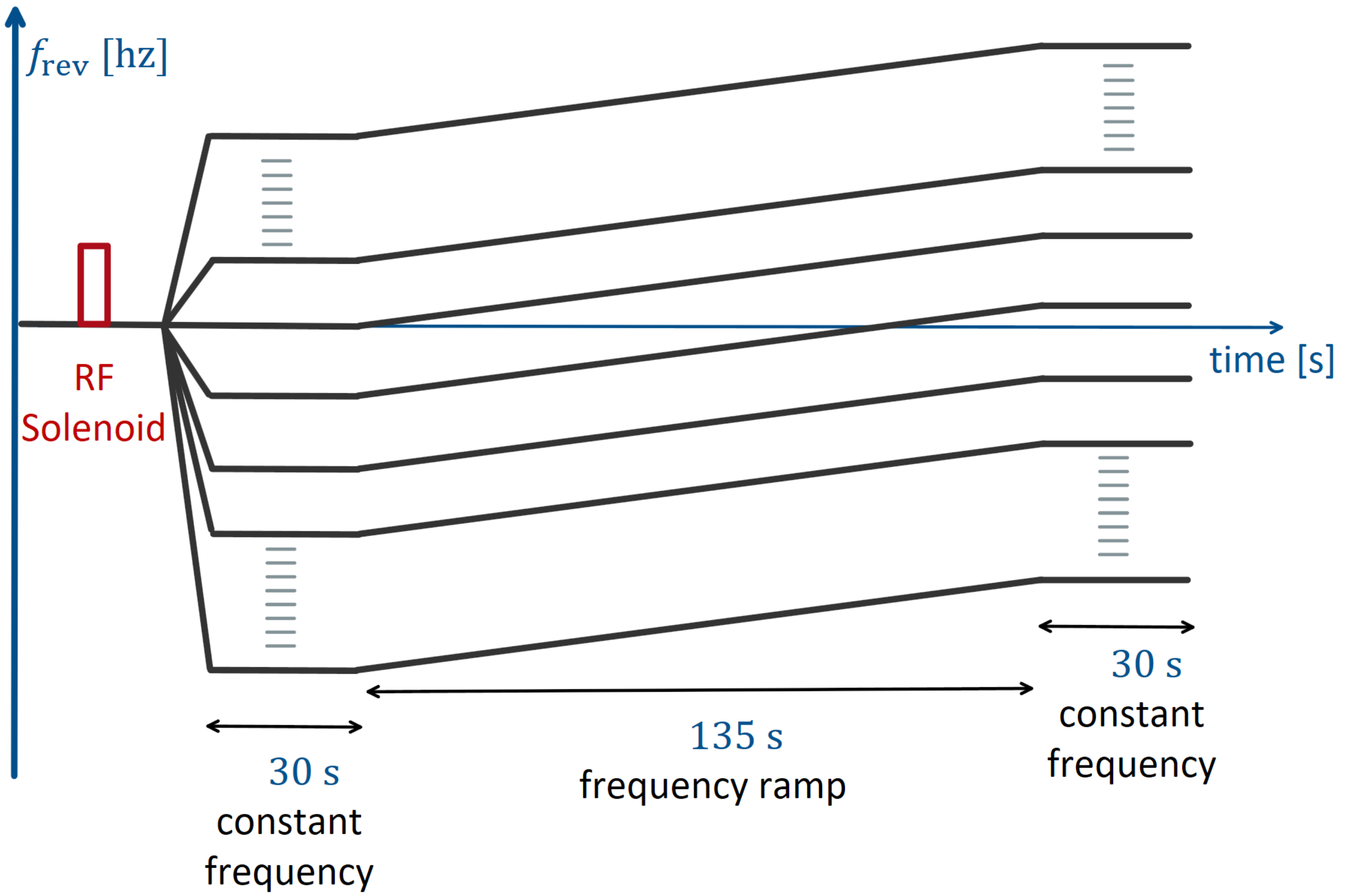
- Simultaneous searches with perpendicular beam polarization using 4 bunches
- Subsequent bunches have perpendicular polarization
- Alternate bunches have opposite polarization direction



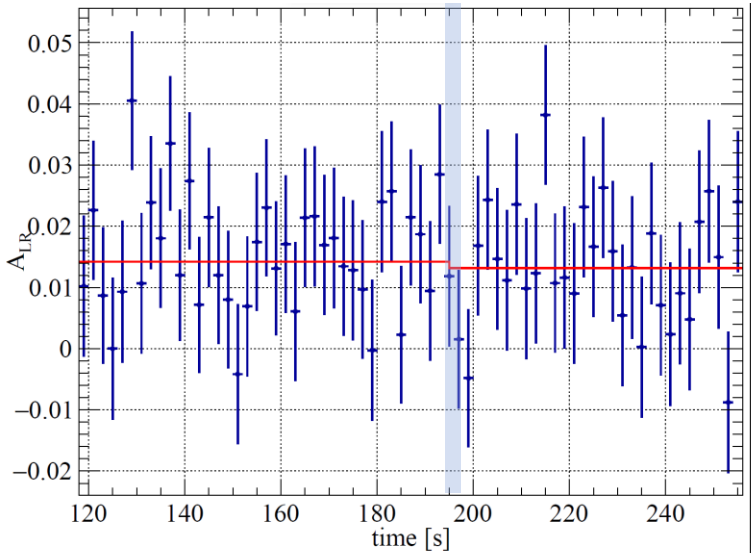
Frequency scan management

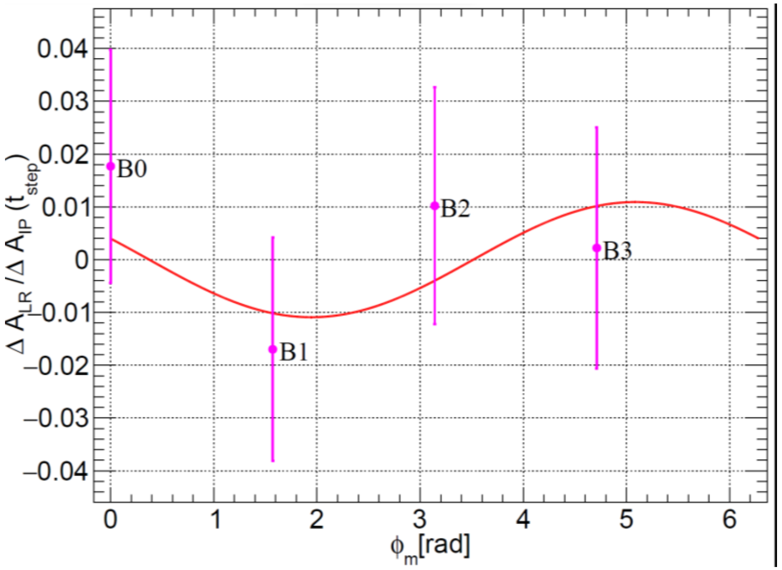
- Vary the beam revolution frequency in search of resonance
- Measure polarization as a function of time in cycle
- About 100 scans
  - Frequency range
    119997 Hz – 121457 Hz
    Total width ≈ 1500 Hz
  - ALP mass range

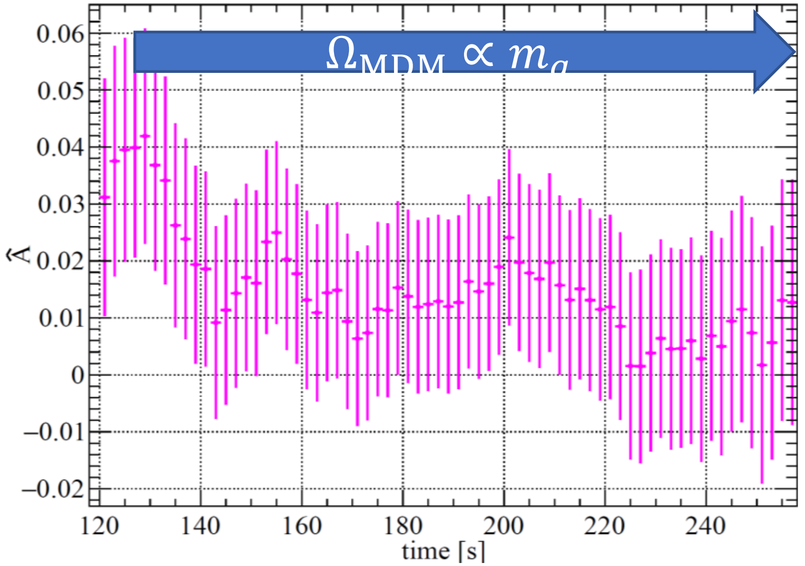
    0.495 neV – 0.502 neV



Axion scan – course of analysis







Single beam bunch: search for a step
Repeat for all bunches

For a single time-bin, combine data from all bunches, extract amplitude from sinusoidal fit:

$$f(\phi_m) = C_1 \sin\phi_m + C_2 \cos\phi_m$$

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

ϕ_m - angle between E and spin

Repeat for all time bins / ALP masses

Axion scan – course of analysis

Feldman and Cousins PRD, 57, 3873 (1998)

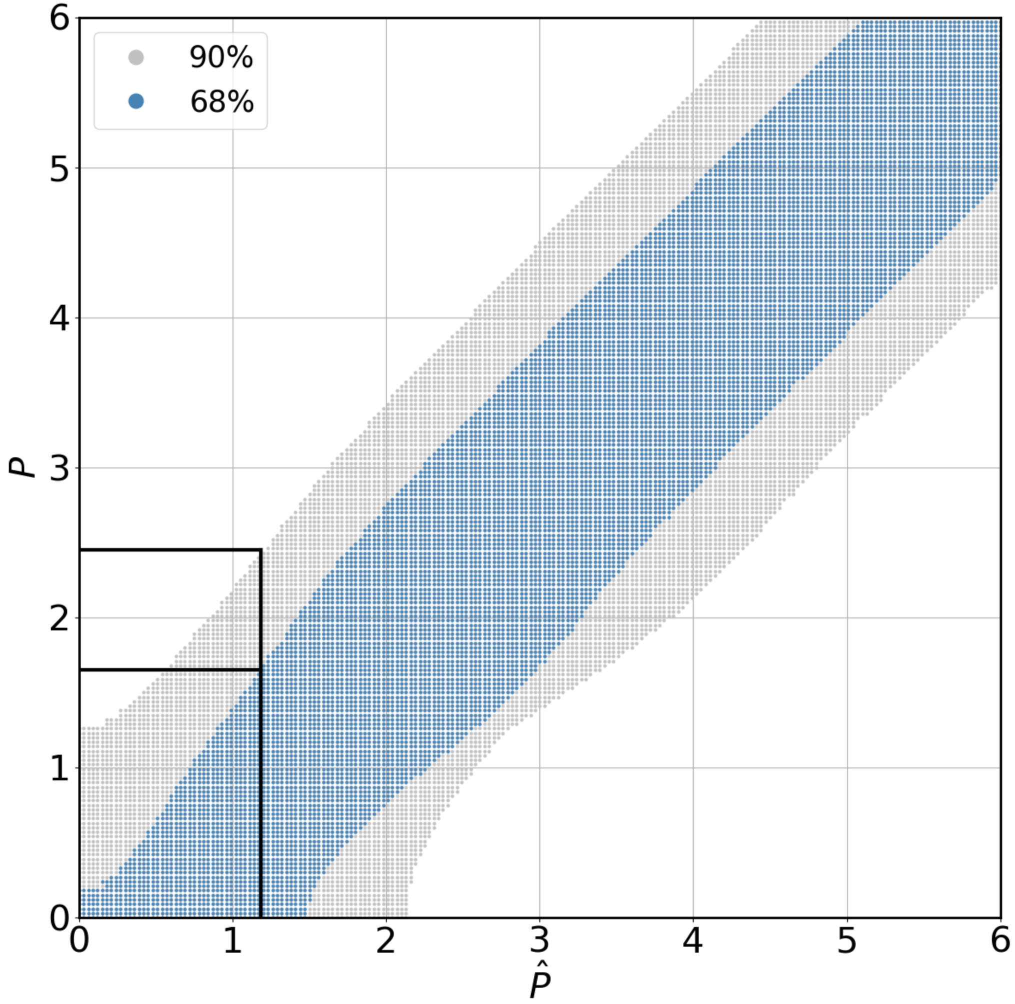
Feldman Cousins method – use of probability density function

Deal with the systematics

Construct confidence intervals

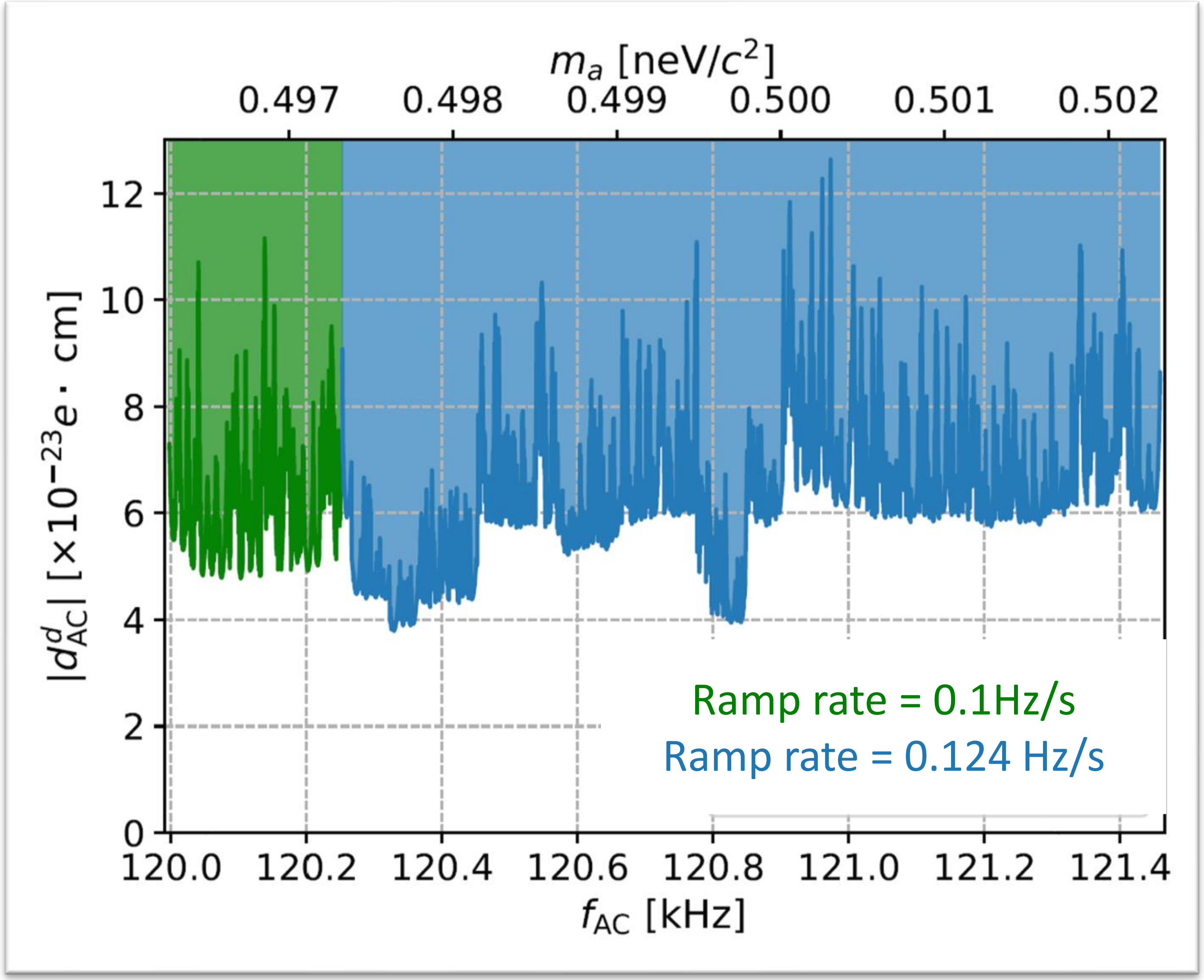
Calculate true value A for an estimated $\hat{A}$ at 90% confidence level

*(P and $\hat{P}$ are amplitudes normalized by uncertainties)



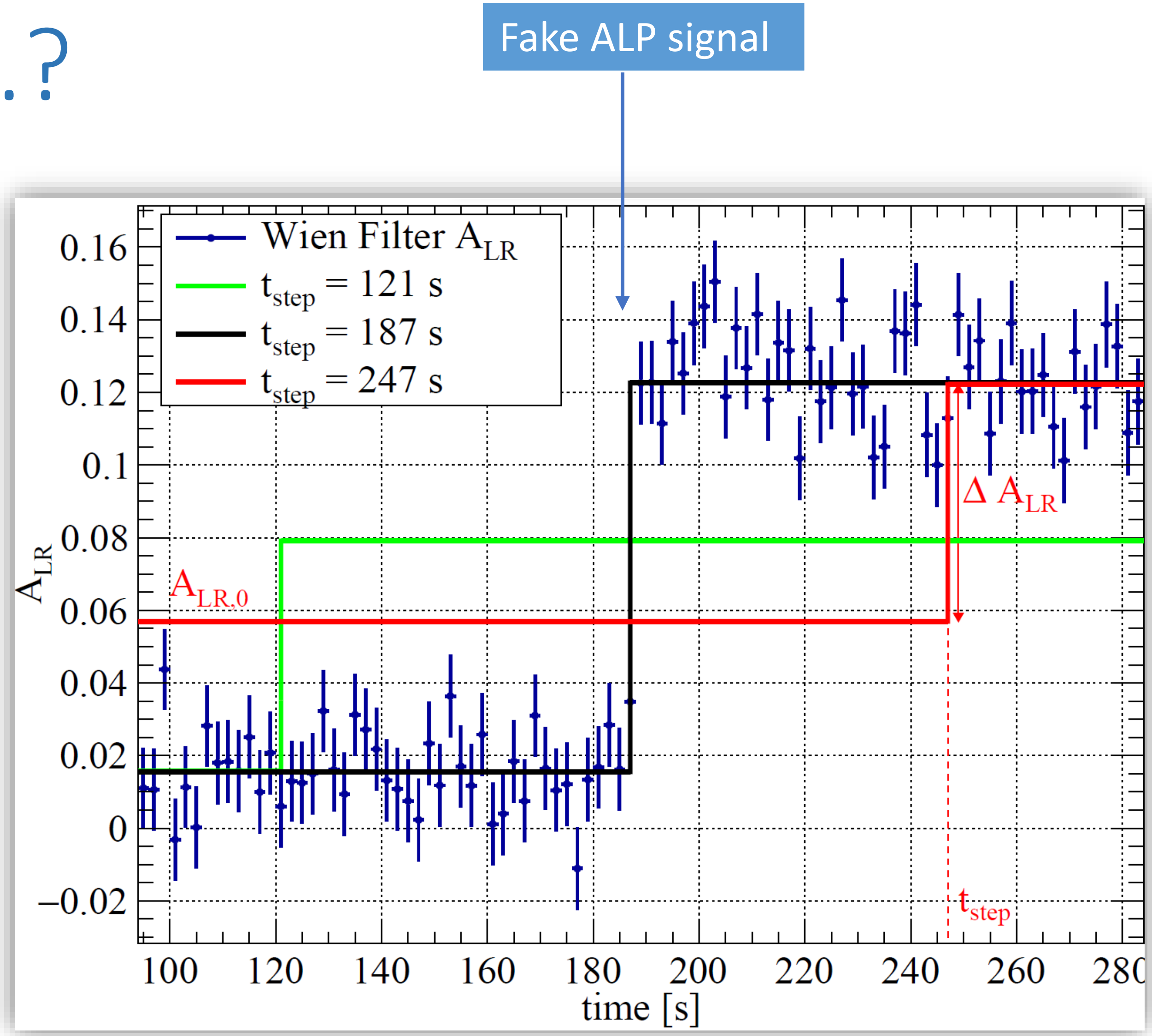
Axion/ALP hunting - results

- No axion/ALP signal observed
- 90% CL upper limits on d_{AC} in the scanned mass range determined
- Sensitivity $\sim 10^{-23} e \cdot$ cm after only 4 weeks of beam time, and **only a few days of production runs**

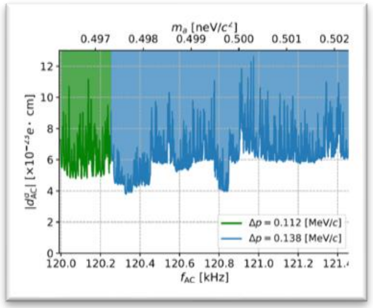


Would we have seen it...?

- A test of methodology needed
- rf Wien filter present in the COSY ring, radial B
- WF set at fixed frequency, crossing scans performed...
- Vertical polarization jump observed!
- Size and position matched the expectations

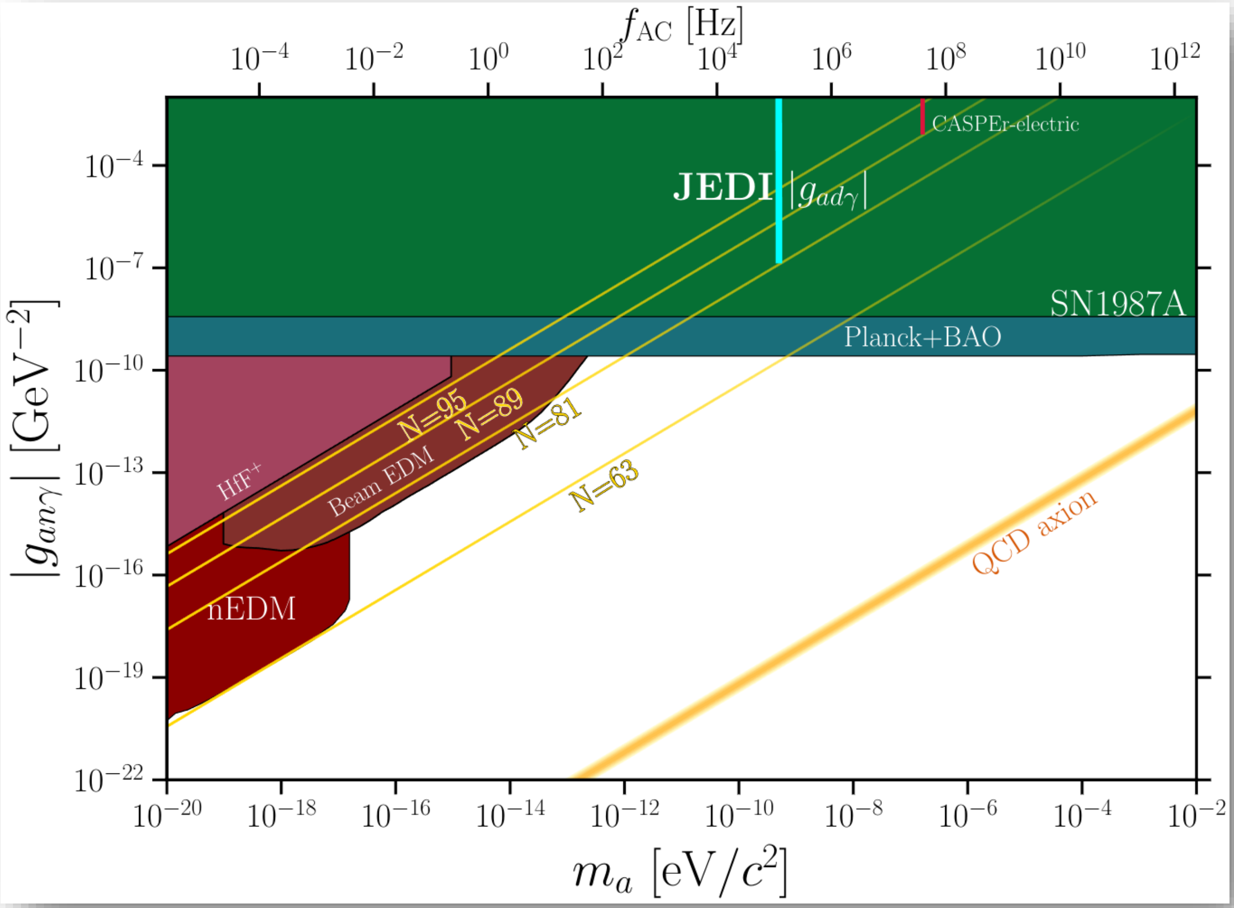


Constraints on ALP-EDM coupling

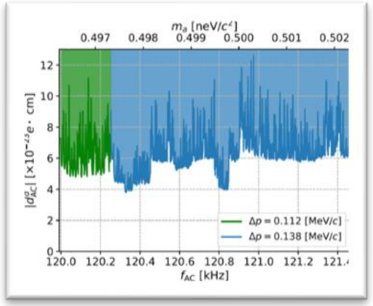


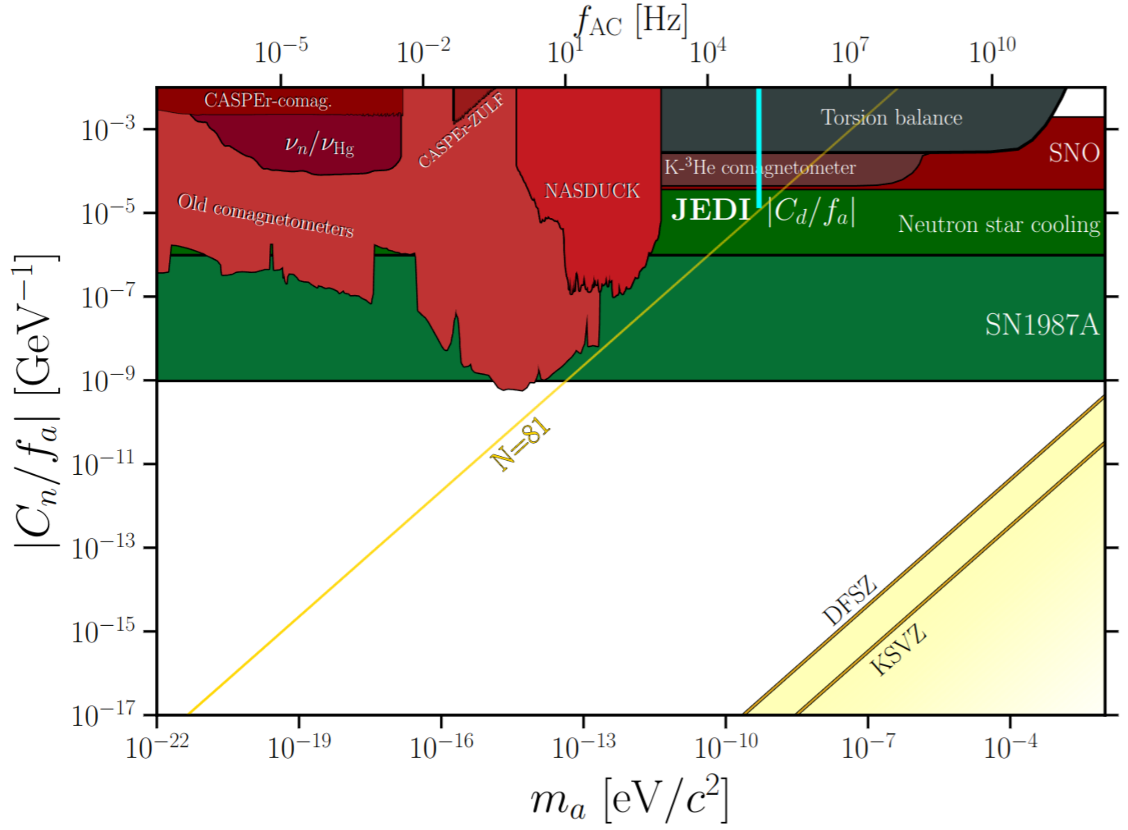
- Coupling of ALP to deuteron EDM $|g_{ad\gamma}| < 1.7 \times 10^{-7}\,\mathrm{GeV}^{-2}$ (assumming it is the only effect)

- SN1987A and Plack+BAO results are model dependent and need to be experimentally verified

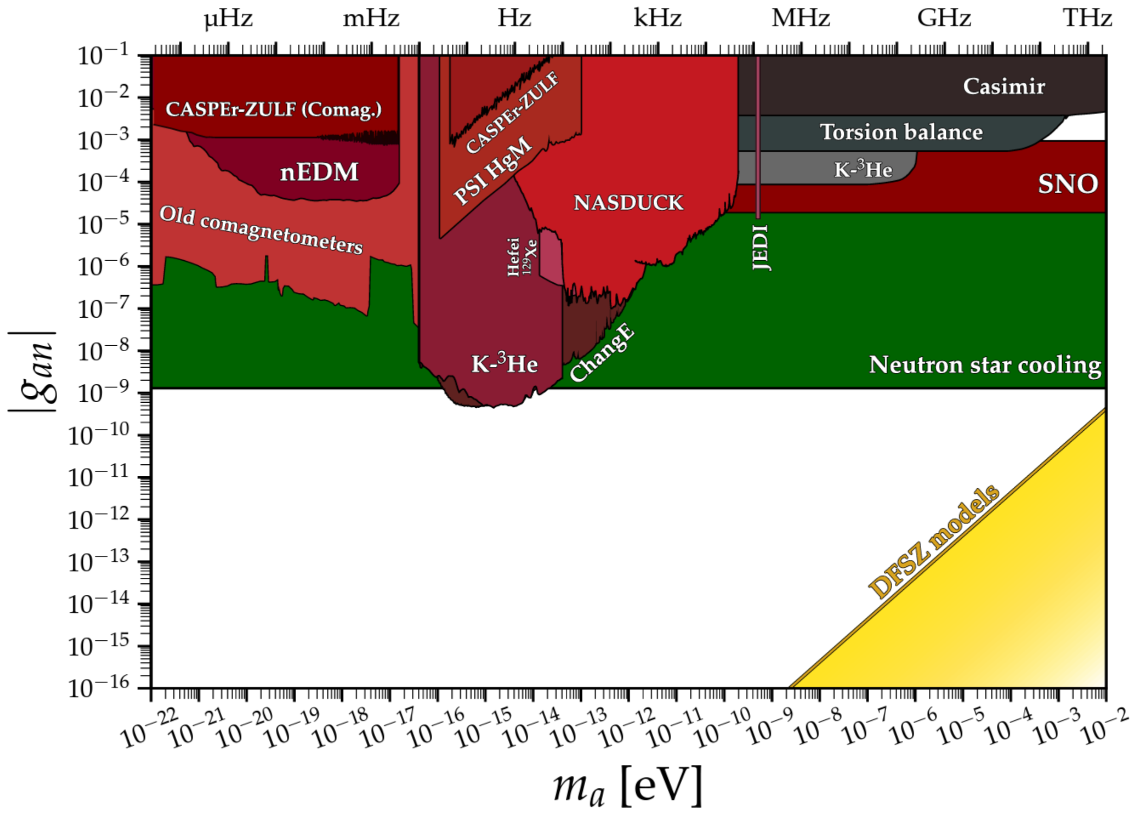


ALP - nucleon coupling



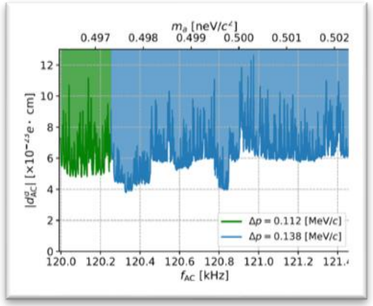


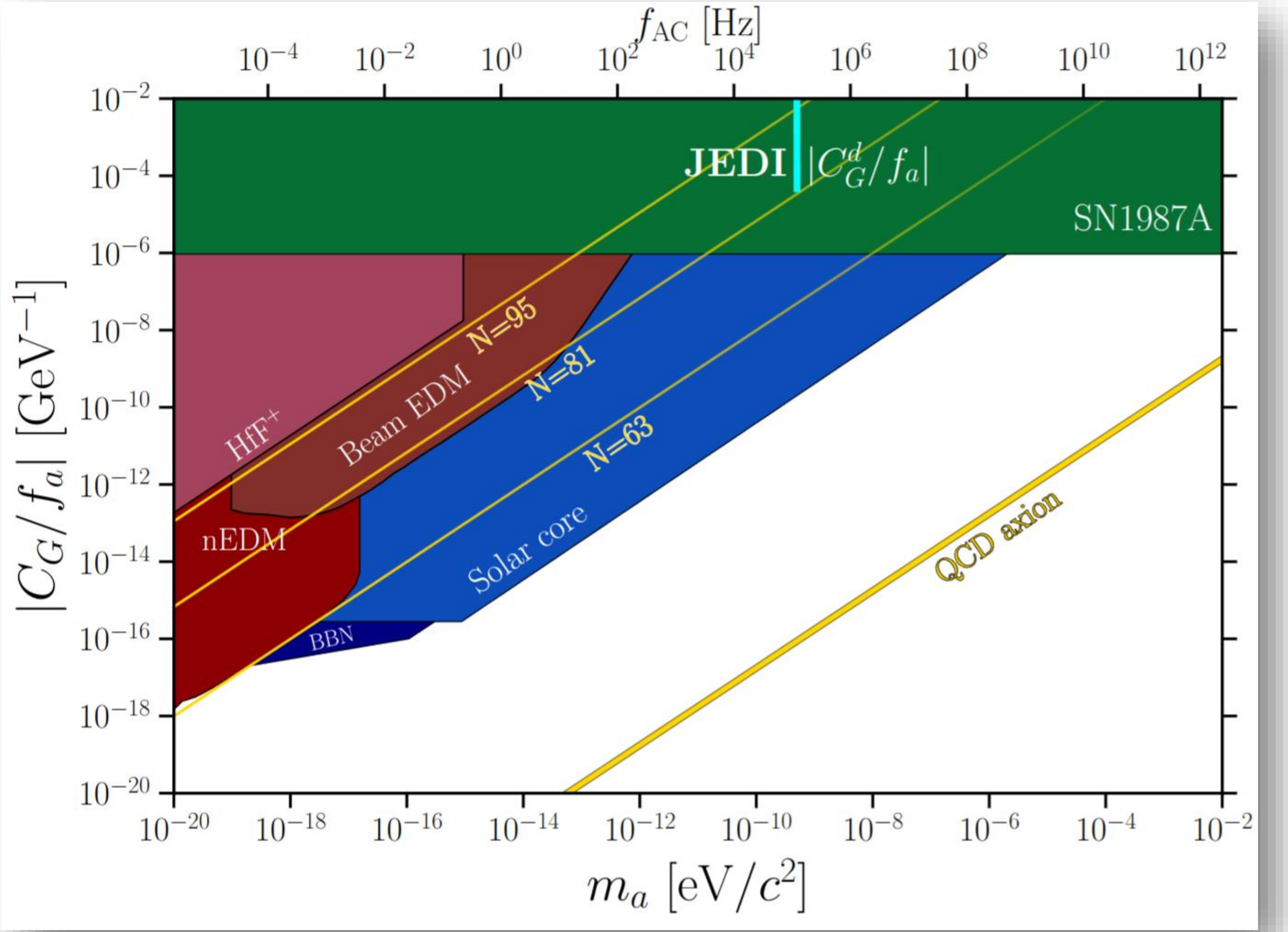
S. Karanth et al., PRX 13, 031004 (2023)



R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

ALP-gluon coupling





Figures adapted from C. O'Hare, "cajohare/axionlimits: Axionlimits," (2020), https://doi.org/10.5281/zenodo.3932430

More details...

PHYSICAL REVIEW X **13**, 031004 (2023)

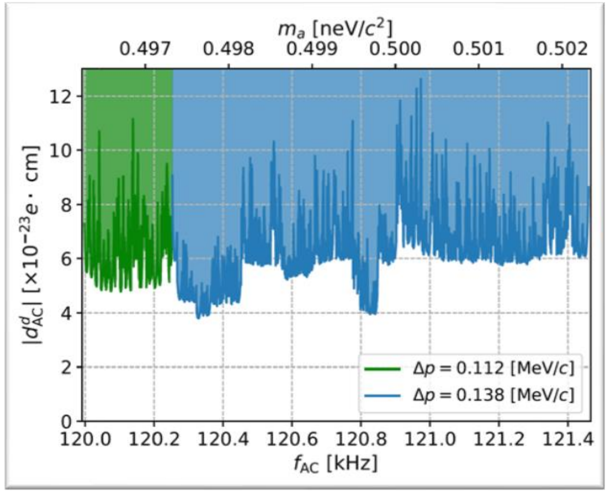
First Search for Axionlike Particles in a Storage Ring Using a Polarized Deuteron Beam

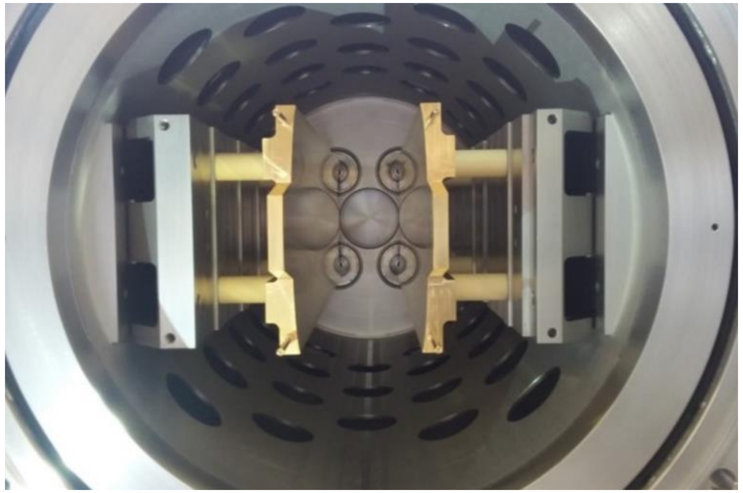
S. Karanth,[1,*] E. J. Stephenson,[2,†] S. P. Chang,[3,4] V. Hejny,[5] S. Park,[4] J. Pretz,[5,6,7] Y. K. Semertzidis,[3,4] A. Wirzba,[5,8] A. Wrońska,[1] F. Abusaif,[6,5,¶] A. Aggarwal,[1] A. Aksentev,[9] B. Alberdi,[6,5,**,††] A. Andres,[6,5] L. Barion,[10] I. Bekman,[5,‡] M. Beyß,[6,5] C. Böhme,[5] B. Breitkreutz,[5,§] C. von Byern,[6,5] N. Canale,[10] G. Ciullo,[10] S. Dymov,[10] N.-O. Fröhlich,[5,‖] R. Gebel,[5,11] K. Grigoryev,[5,§] D. Grzonka,[5] J. Hetzel,[5] O. Javakhishvili,[12] H. Jeong,[13] A. Kacharava,[5] V. Kamerdzhiev,[5,§] I. Keshelashvili,[5,§] A. Kononov,[10] K. Laihem,[6,§] A. Lehrach,[5,7] P. Lenisa,[10] N. Lomidze,[14] B. Lorentz,[11] A. Magiera,[1] D. Mchedlishvili,[14,19] F. Müller,[6,5] A. Nass,[5] N. N. Nikolaev,[15,16] A. Pesce,[5] V. Poncza,[6,5] D. Prasuhn,[5,§] F. Rathmann,[5] A. Saleev,[10] D. Shergelashvili,[14] V. Shmakova,[10,§] N. Shurkhno,[5,§] S. Siddique,[6,5,§] J. Slim,[6,11,‖] H. Soltner,[17] R. Stassen,[5] H. Ströher,[5,7] M. Tabidze,[14] G. Tagliente,[18] Y. Valdau,[5,§] M. Vitz,[5,6] T. Wagner,[5,6,§] and P. Wüstner[17]

(JEDI Collaboration)

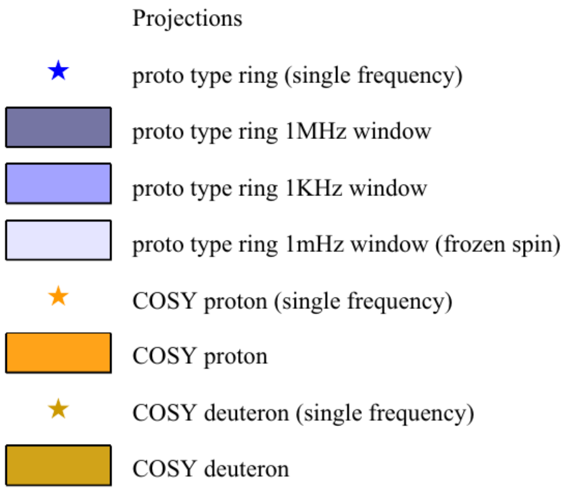
Summary

- ALPs induce an oscillating EDM and/or axion wind effect, allowing to use storage rings with polarized beams as ALP antennas
- Proof-of-principle experiment performed for ALP mass range 0.495-0.502 neV
- Wien filter used to test the methodology
- Results:
  - Upper limit on deuteron EDM
    $$|d_{ac}| < 6.4 \times 10^{-23}\ e \cdot \mathrm{cm}$$
  - Constraint on ALP-deuteron EDM coupling
    $$|g_{ad\gamma}| < 1.7 \times 10^{-7}\ \mathrm{GeV}^{-2}$$
- Successful demonstration of a novel method to search for axions

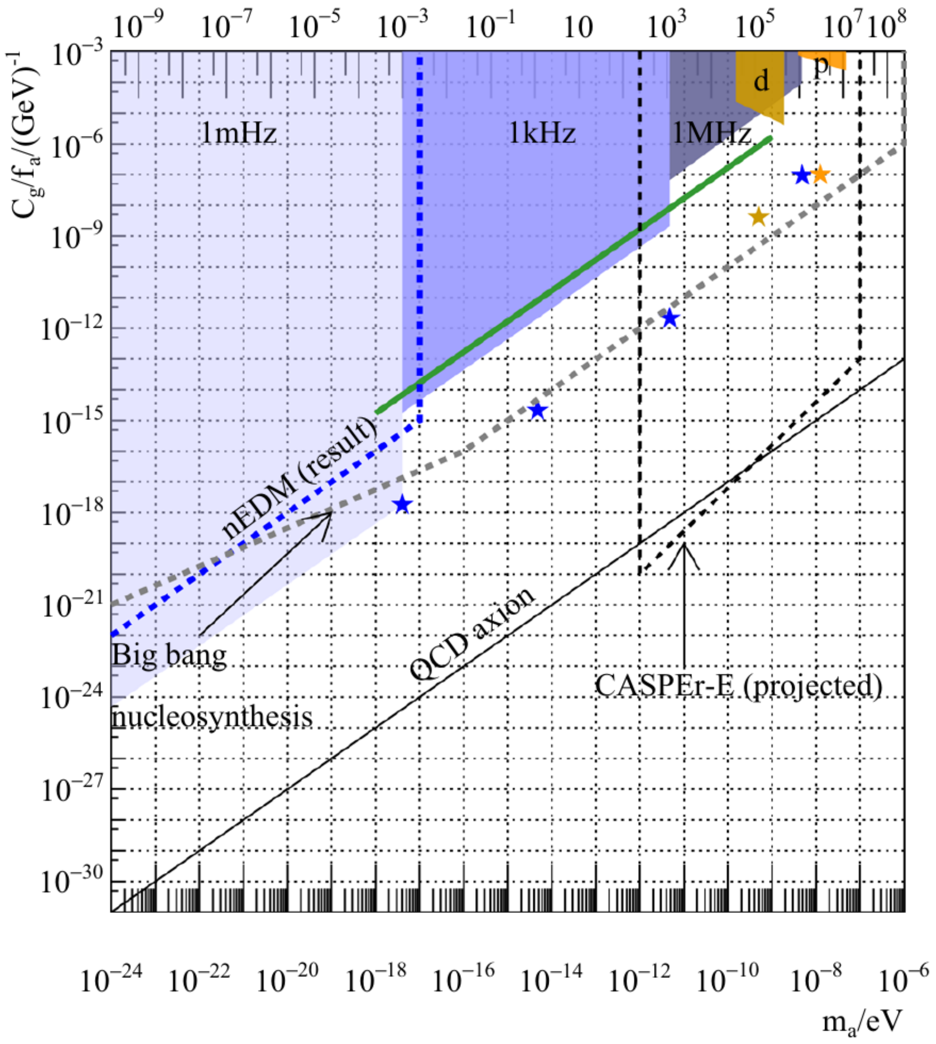




Outlook



Sensitivity for axion-gluon coupling in a 1-year run.



Pretz, J. et al., Eur. Phys. J. C 80, 107 (2020).

Outlook

- The elaborated method has potential for a broad ALP mass range
- Better sensitivity easily possible (factor 10)
- New storage rings for static EDM searches proposed (U.S.A., Europe), combining radial **E** and vertical **B** field → could be used for ALP hunt to scan the whole mass range of interest!
- Unfortunately, COSY was shut down in autumn 2023
- Experiments can be performed at RHIC, NICA, GSI/FAIR, wherever polarised hadrons available