Results from the first search for axion-like particles in storage rings

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On behalf of the JEDI collaboration

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Axion / axion-like particle (ALPs)

Why is strong interaction CP invariant?

- Dynamic CP violating term
- Pseudoscalar axion

What is the nature of dark matter?

- Light, small interaction and stable at a large time scale
- Axions good candidates.

Axions

Solves strong CP problem

Strict correlation between m_a and f_a

DM candidate

Axion like particles

Does not solve strong CP problem

No strict correlation

DM candidate

m_a mass

f_a decay constant

Axion / axion-like particle (ALPs)

Act as classical axion field $a(t) = a_0 \cos(\boldsymbol{\omega}_a t + \boldsymbol{\phi}_a)$

- ω_a ALP oscillation frequency – connected to axion mass $\hbar\omega_a = m_a c^2$
- ϕ_a Local phase of ALP field – unknown and changes with every new measurement

Oscillating coupling to spin of nucleons or nuclei:

- - Oscillating electric dipole moment
- - Axion wind effect

P. W. Graham et al., PRD 84, 055013 (2011)

P. W. Graham et al., PRD 88, 035023 (2013)

Time development of the spin direction of a beam of polarized charged particles in a storage ring. Precisely measured

Spin dynamics in a storage ring

Spin precession in a storage ring with $\vec{E}$ and $\vec{B}$ is given by Thomas-BMT equation.

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

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

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\left(G + \frac{1}{\gamma}\right)\vec{B}$$

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

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

G: magnetic anomaly

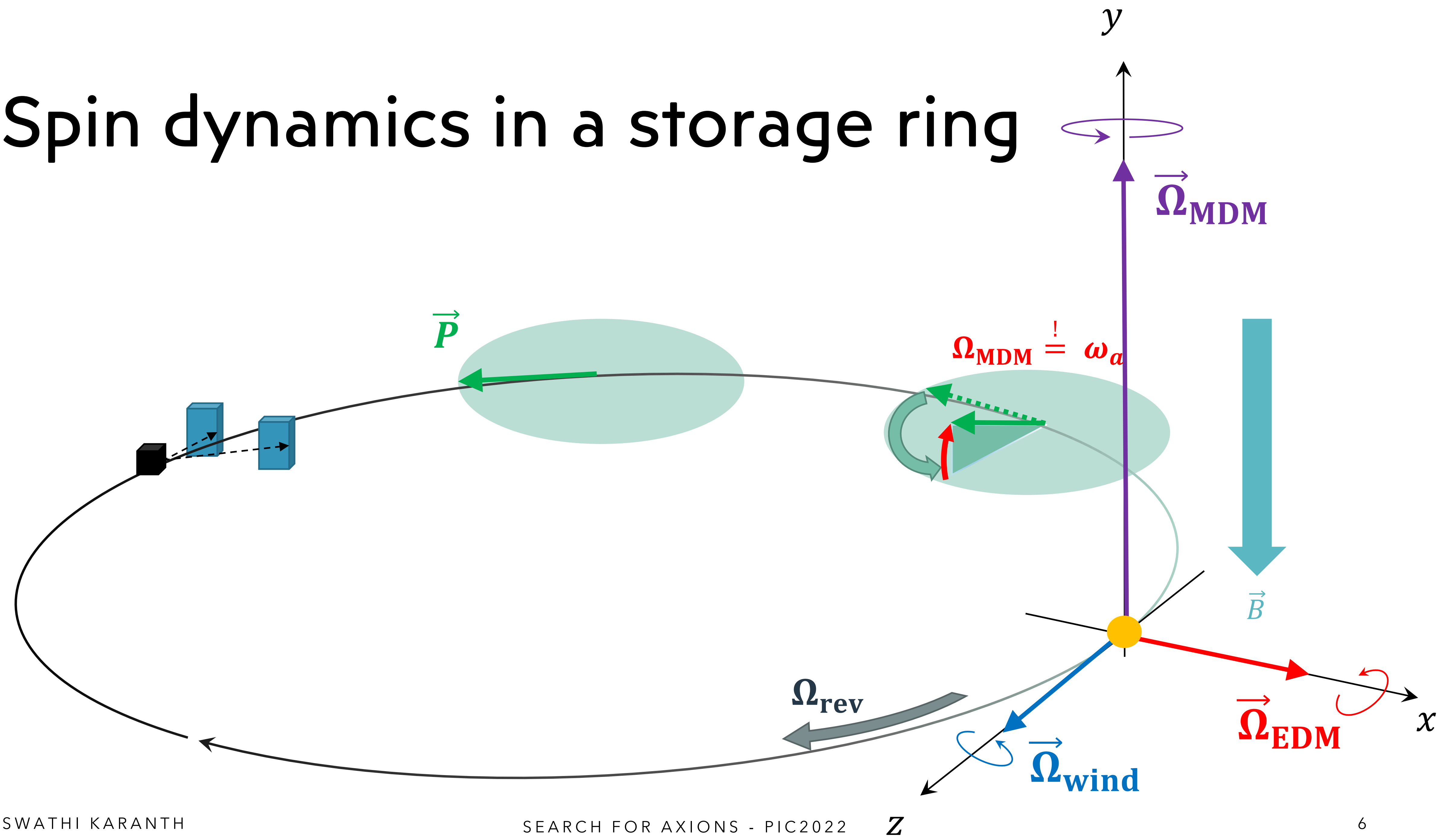
$d(t)$: Electric Dipole Moment

$$d(t) = d_{\mathrm{DC}} + d_{\mathrm{AC}} a_0 \cos(\omega_a t + \phi_a)$$

C_N: Coupling constant

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

Spin dynamics in a storage ring



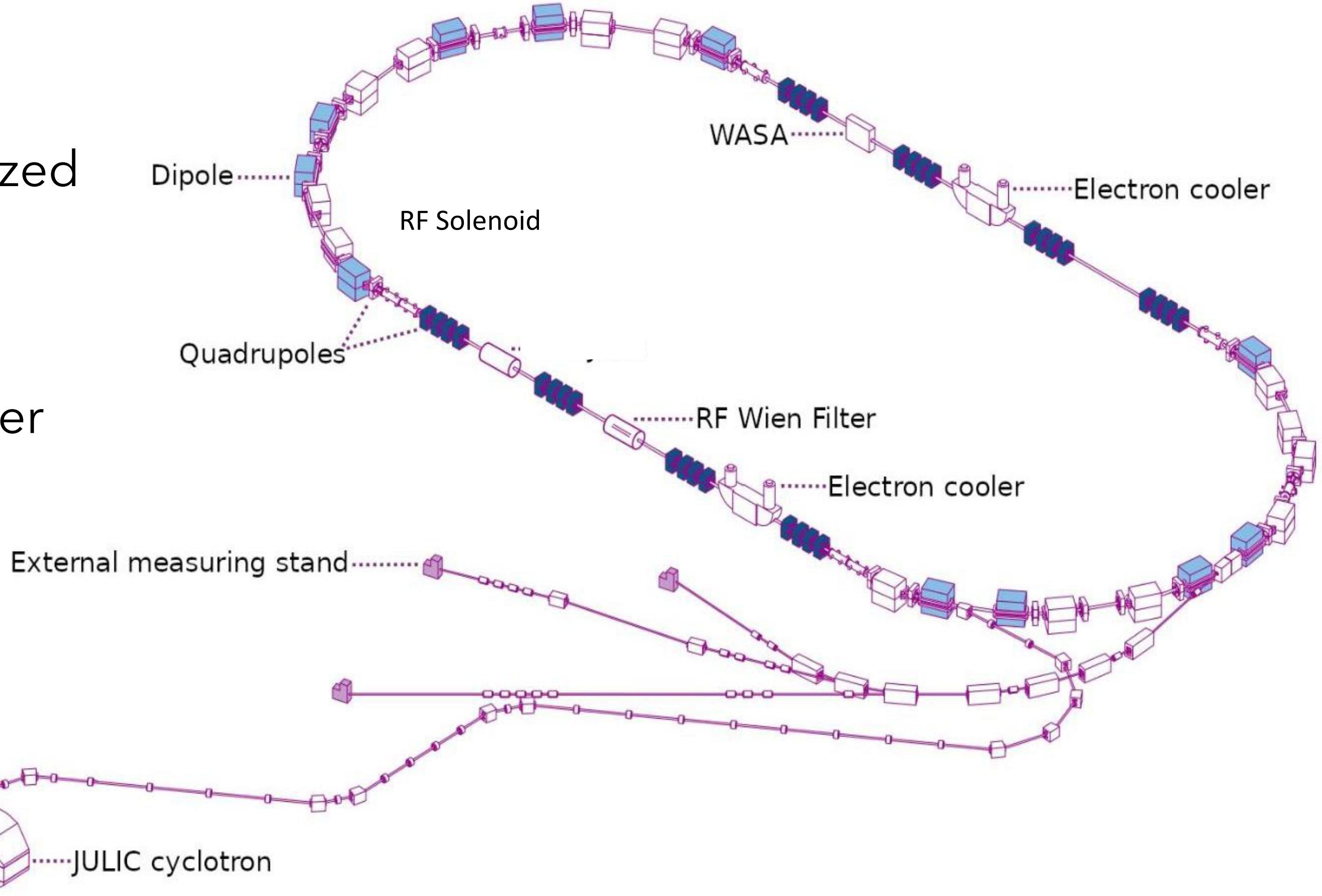
JEDI Collaboration

http://collaborations.fz-juelich.de/ikp/jedi/

- Search for Electric Dipole Moments of charged particles at COSY Juelich, Germany.
- Work on prerequisites for EDM search using storage rings.
  - Beam intensity at least $\mathbf{N=4 \times 10^{10}}$ particles per fill
  - High polarization $\boldsymbol{P=0.8}$
  - Long spin conference times $\boldsymbol{\tau\sim 1000\ \mathrm{s}}$
  - Efficient polarimetry with $\boldsymbol{Ay\sim 0.6}$ and detection efficiency $\boldsymbol{f\sim 0.005}$
- A proof-of-principle experiment to search for ALPs.

Cooler Synchrotron COSY

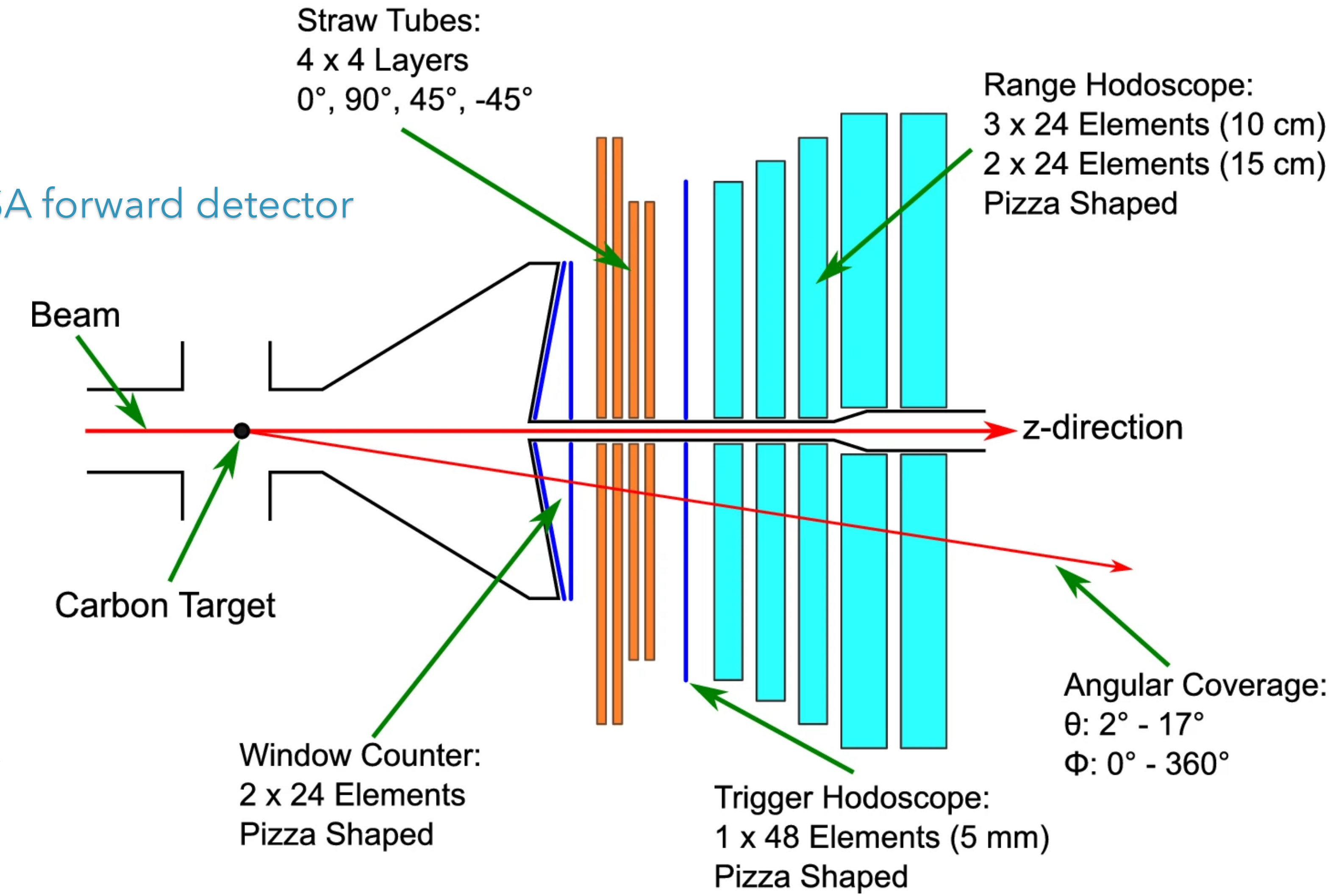
- Circumference184 m
- Accelerate and store **polarized**/unpolarized **deuterons** and protons.
- $p = 0.3 - 3.7 \mathrm{GeV/c}$
- WASA forward detector as the polarimeter
- Selected working conditions
  - Polarised deuteron beam
  - $p = 0.97\ \mathrm{GeV/c},\ T = 238\ \mathrm{MeV}$



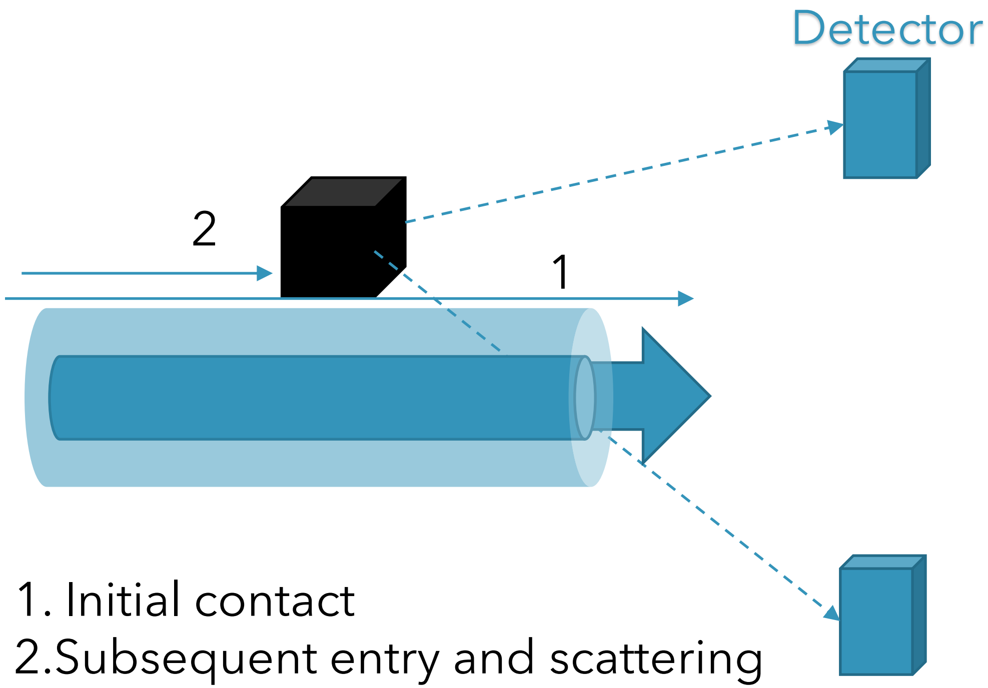
Polarimeter

- Use forward angle elastic scattering on carbon target.
- White noise beam extraction.

WASA forward detector

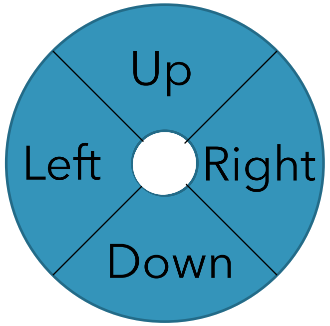


Polarimeter



1. Initial contact
2. Subsequent entry and scattering

Detector-beam view



Spin - orbit interaction gives the asymmetry in events.

Left-right asymmetry

$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} = P_y A_y$$ → ALP signal

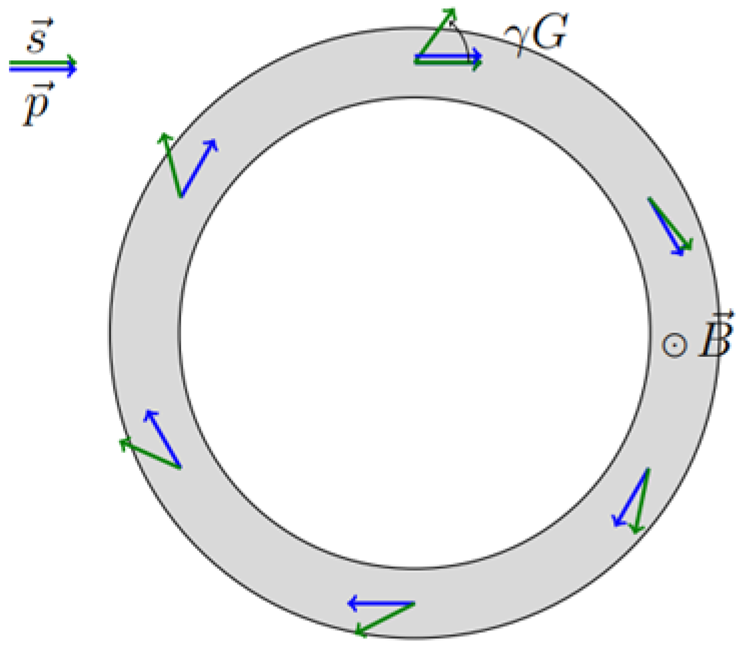
Up - down asymmetry

$$A_{UD} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y$$ → Check horizontal pol.

Requires unfolding to find the in-plane polarisation.

Long Spin Coherence Time

$\nu_s = \gamma G \approx -0.16 \quad f_{\text{spin}} = 121\text{kHz}$



Complexity

- Beam emittance
- Momentum spread
- Beam chromaticity
- Orbit deviation

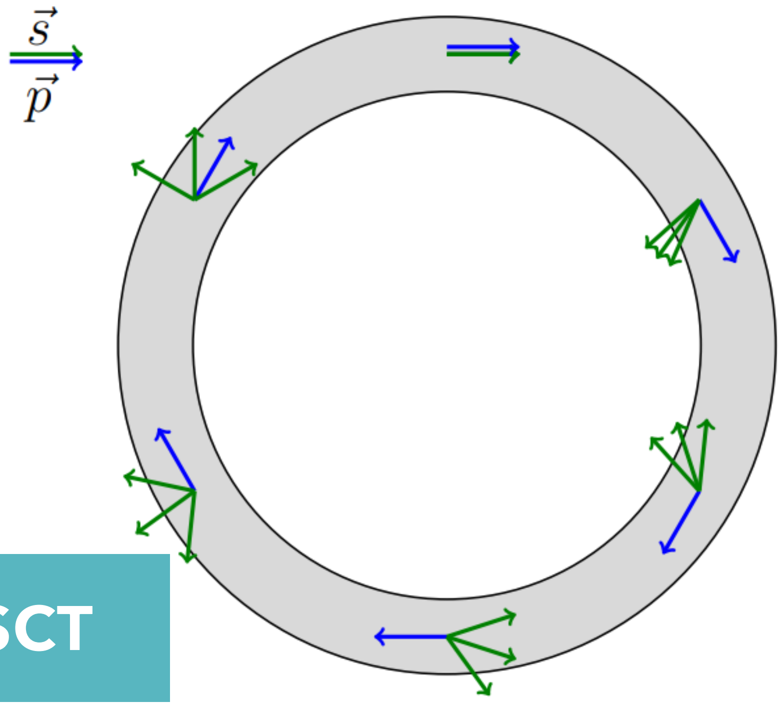
→ Depolarisation

$$\frac{\Delta\nu}{\nu} = \frac{\Delta\gamma}{\gamma} \propto \frac{\Delta p}{p}$$

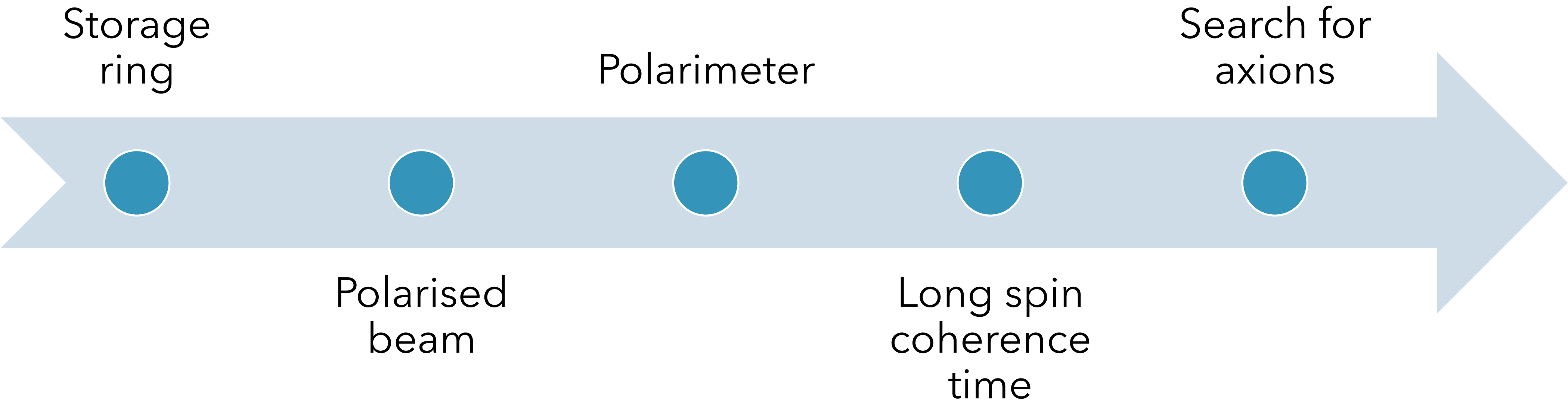
Optimisation

- Beam bunching
- Cooling
- Careful sextupole correction

→ **Long SCT**



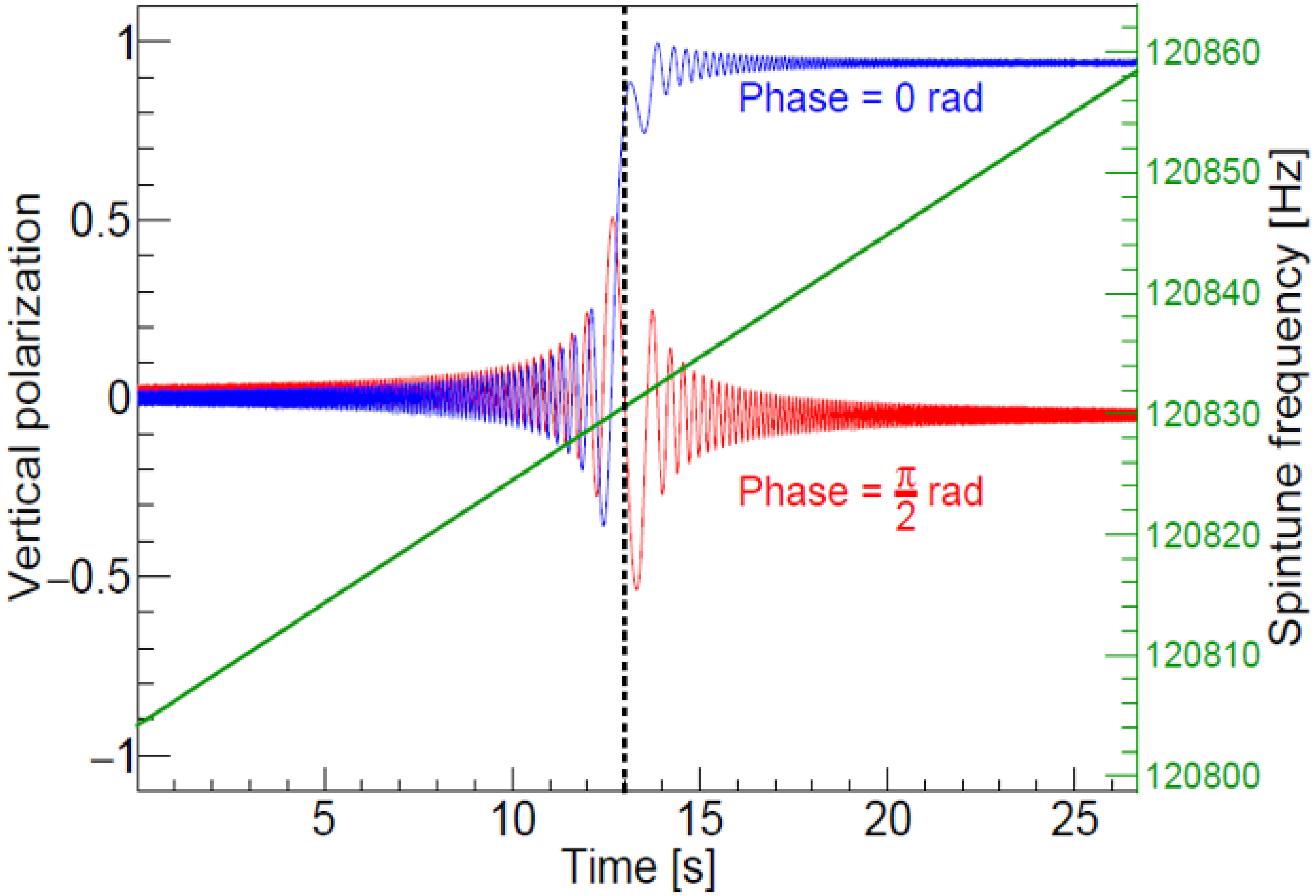
What next?



But we do not know mass of axion.

Model calculations

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

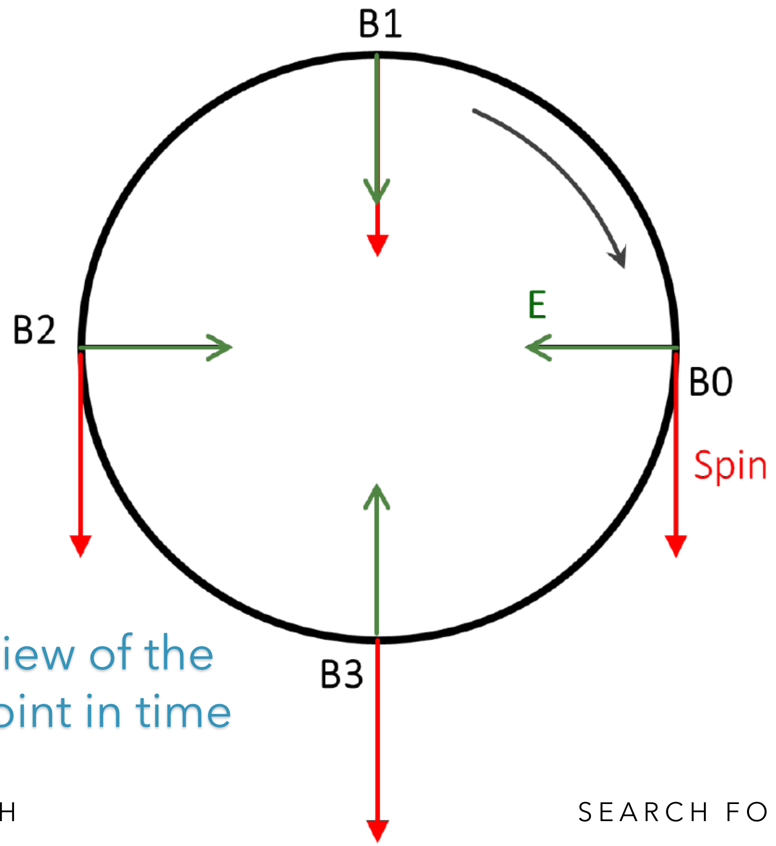


Unknown frequency ω_a	• Scan the frequency for resonance • Signal: Jump in vertical polarisation
Unknown phase ϕ_a	• Use beams with perpendicular polarisation. • Different bunches have different jump value.

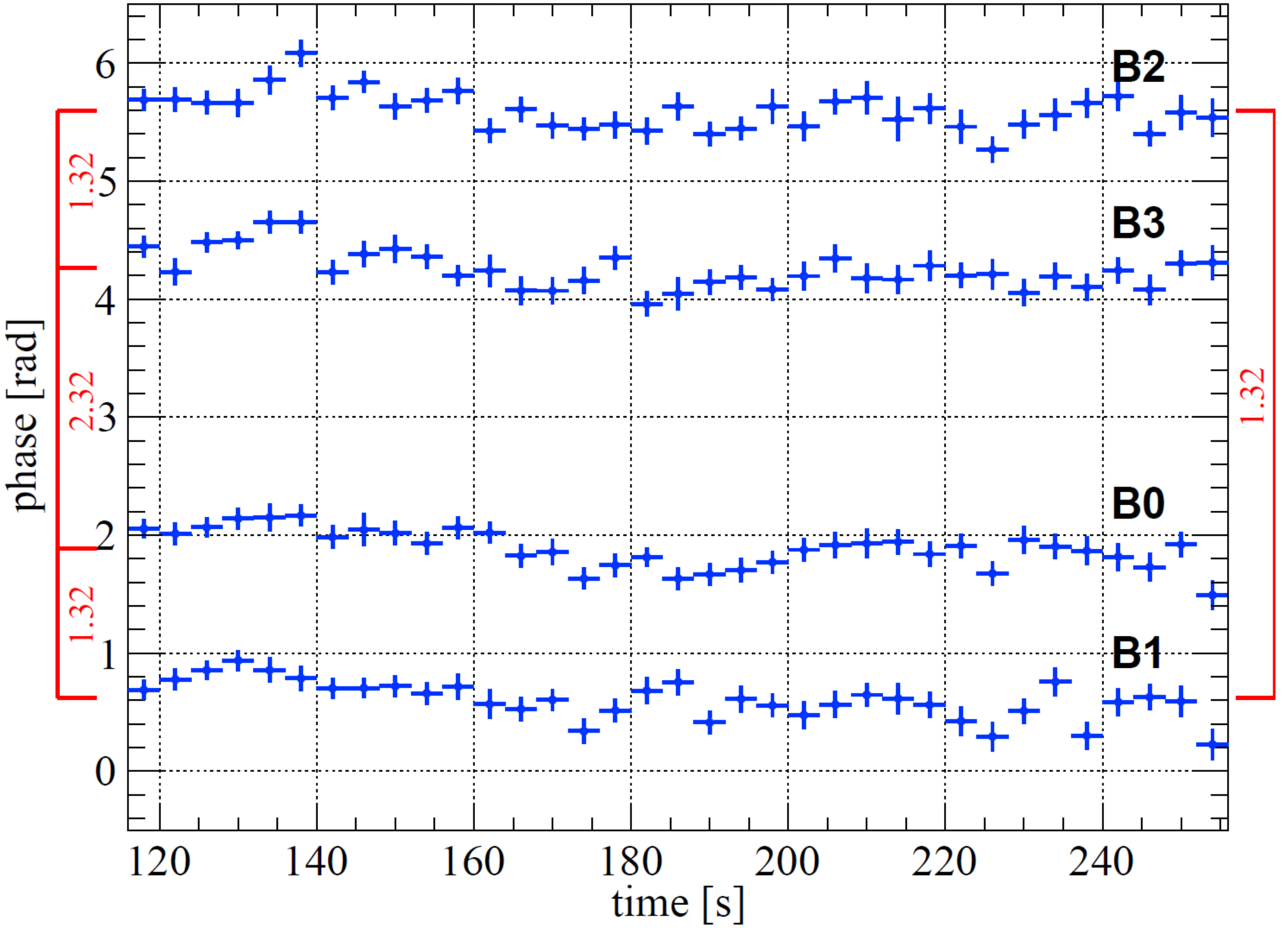
Unknown phase and 4 bunches

Simultaneous searches with perpendicular beam polarization using 4 bunches.

E in the particle frame



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

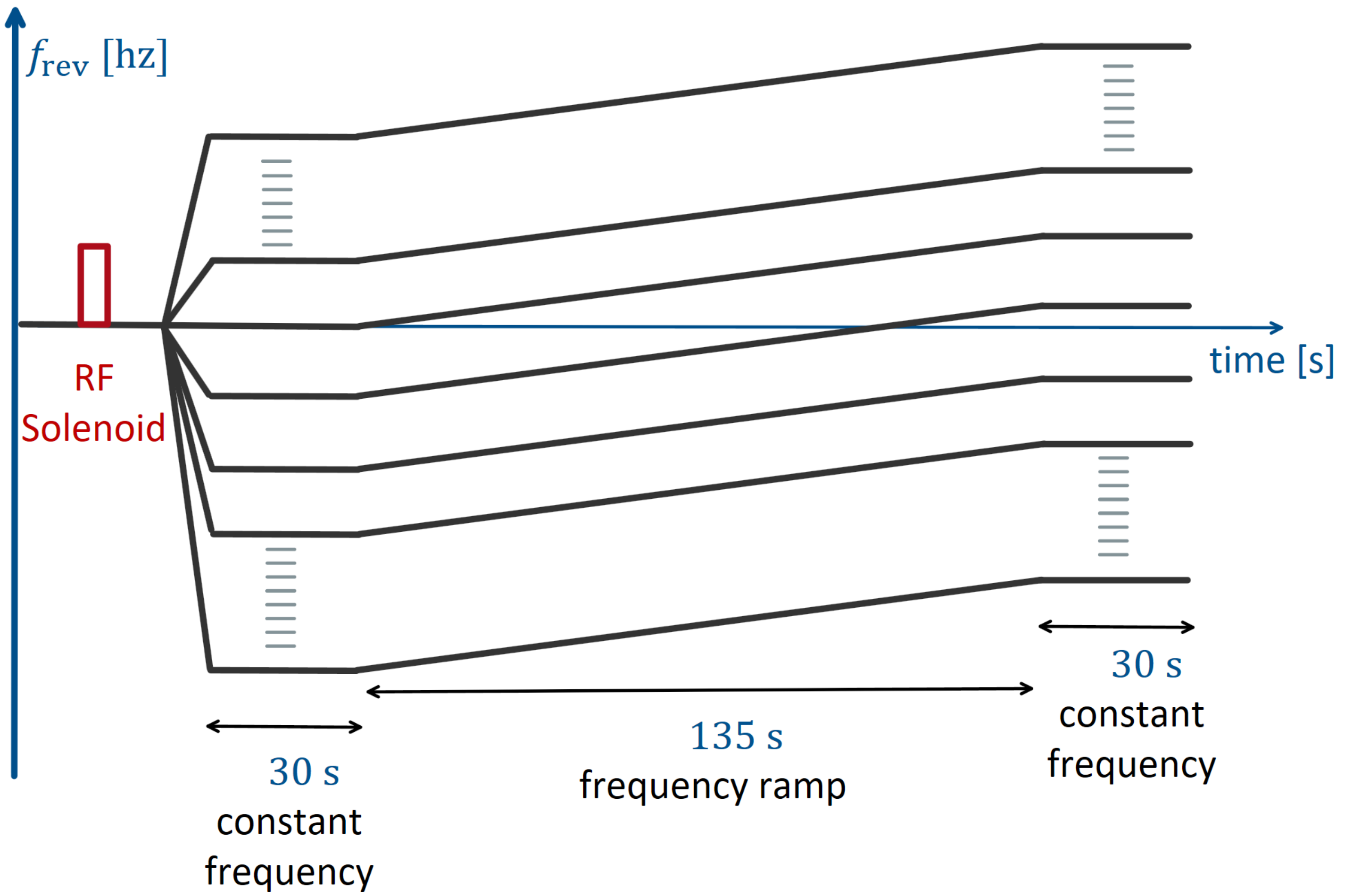


At the detector – fixed point in the ring

Scan management

- Vary the spintune frequency in search of resonance.
- Measure polarization as a function of time.
- About 100 scans
  - Frequency Range
    119997 Hz – 121457 Hz
    Total width ≈ 1500 Hz
  - ALP mass range
    0.496 neV – 0.502 neV

$$\text{ramp rate} = \begin{cases} 0.1 \\ 0.124 \end{cases} \text{Hz/s}$$

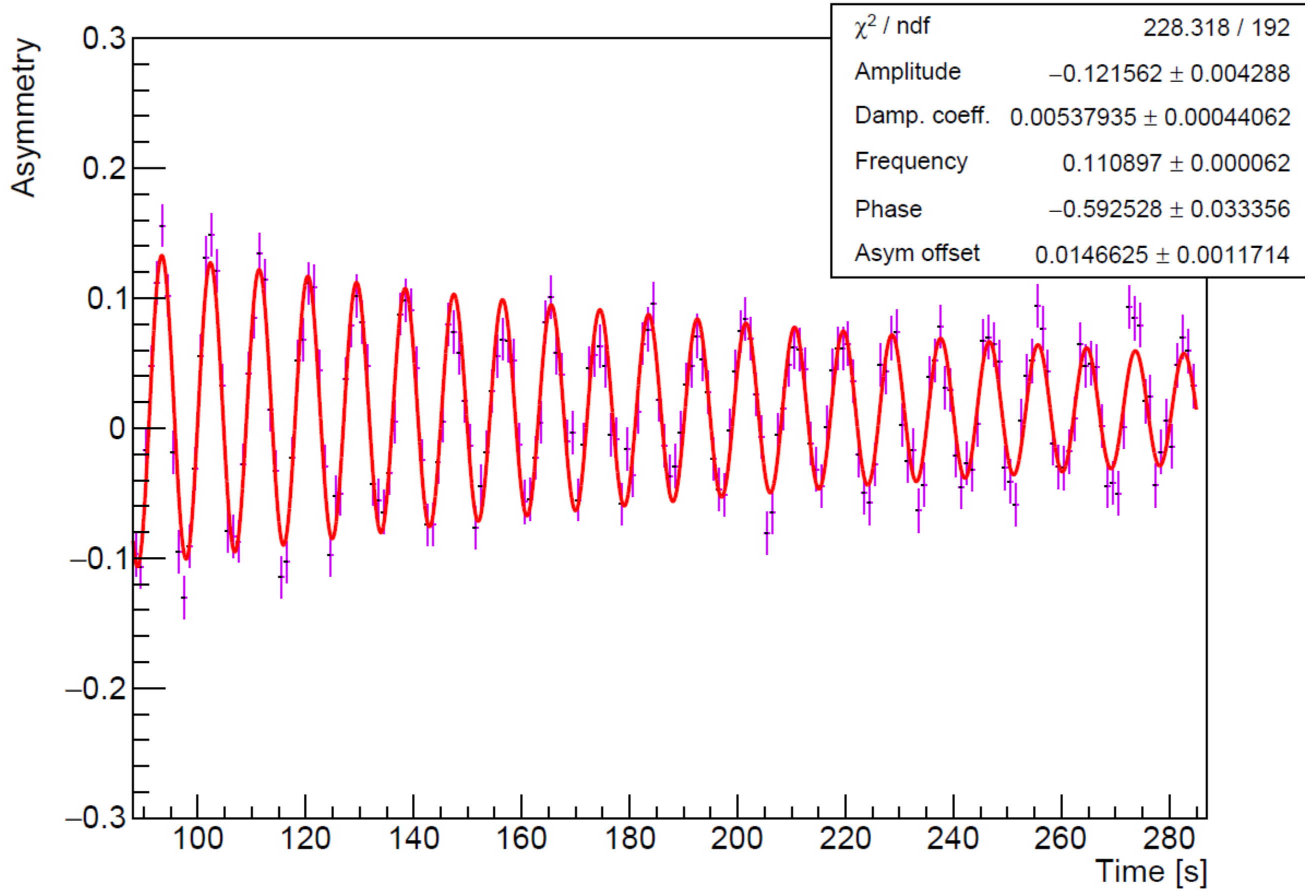


RF Wien filter test

Set WF with radial magnetic field.

Produces driven oscillations.

Revolution/turn $\epsilon = \frac{f_{osc}}{f_{rev}}$.



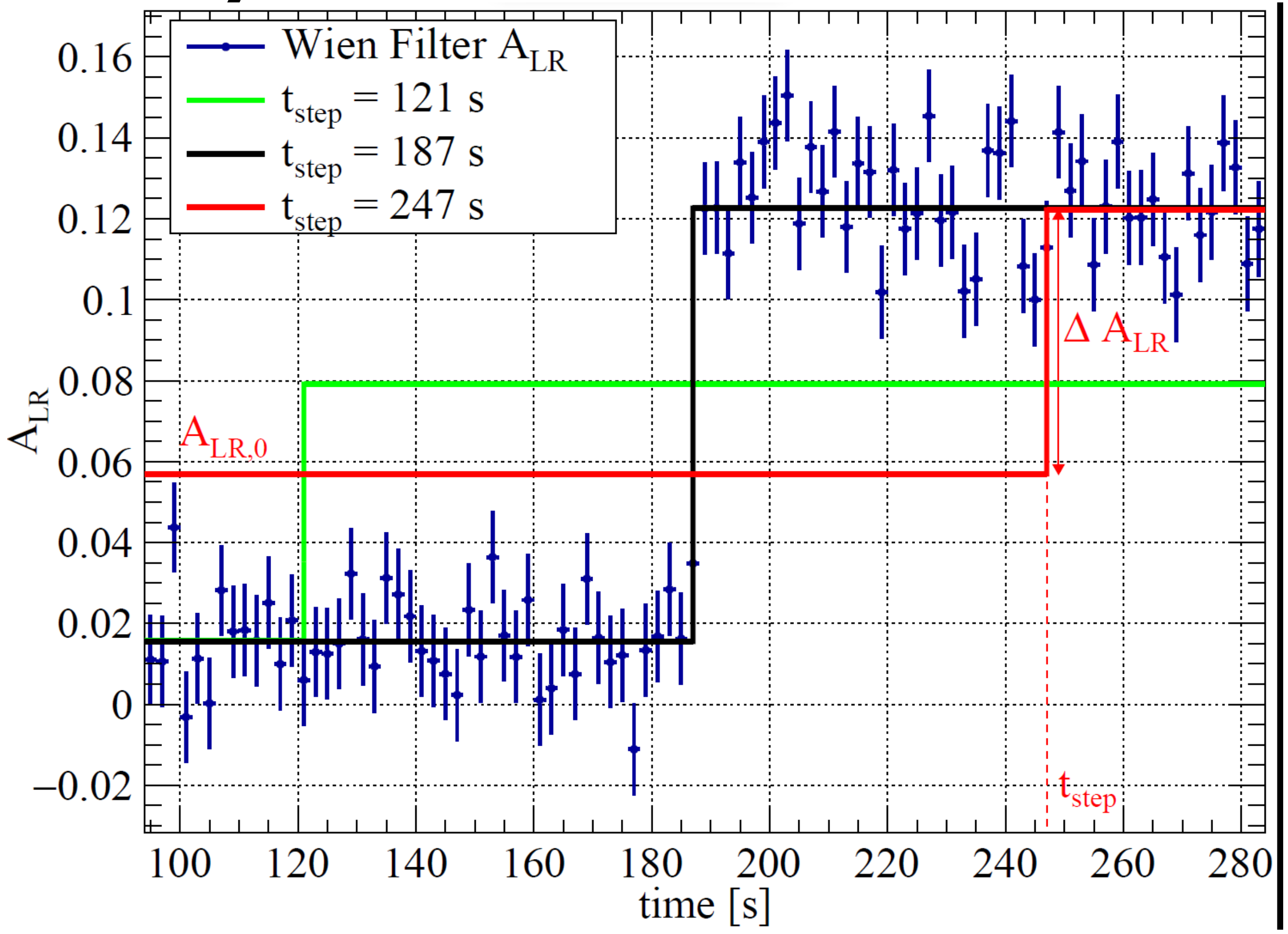
Wien filter test and analysis of data

A test of methodology.

Scans to cross a fixed f_{WF}.

The size of the jump is as expected based on the calibration/driven oscillation ϵ.

A check for the calibration used to calculate the d_{AC} from data.



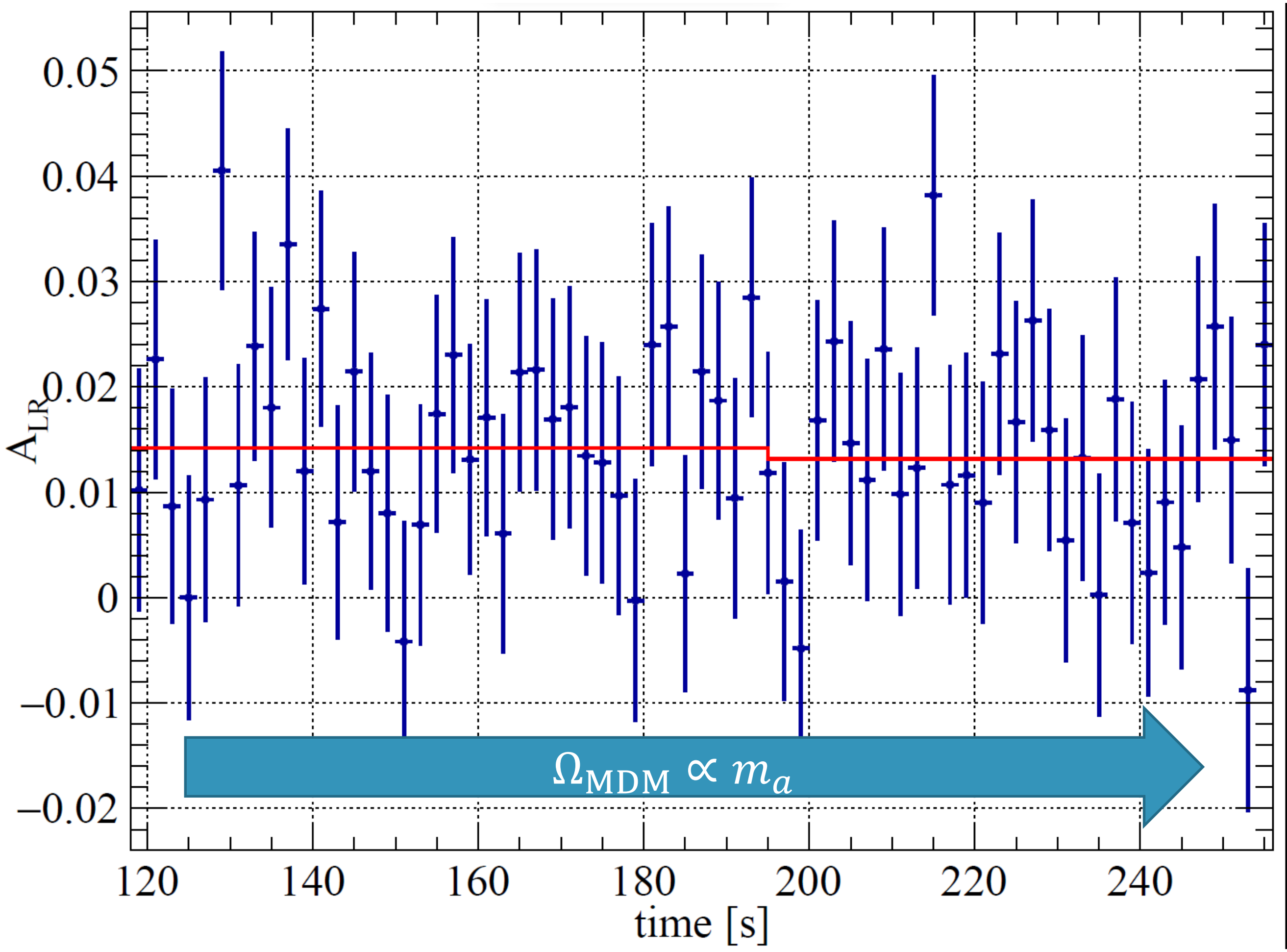
Experimental data from WF

Axion scan - example

Data from a single bunch with a step function fit.

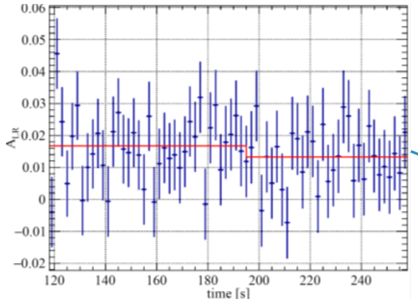
$$\Delta A_{LR} = -0.00105(233)$$

Jump must be present in all four bunches to be considered as a signal

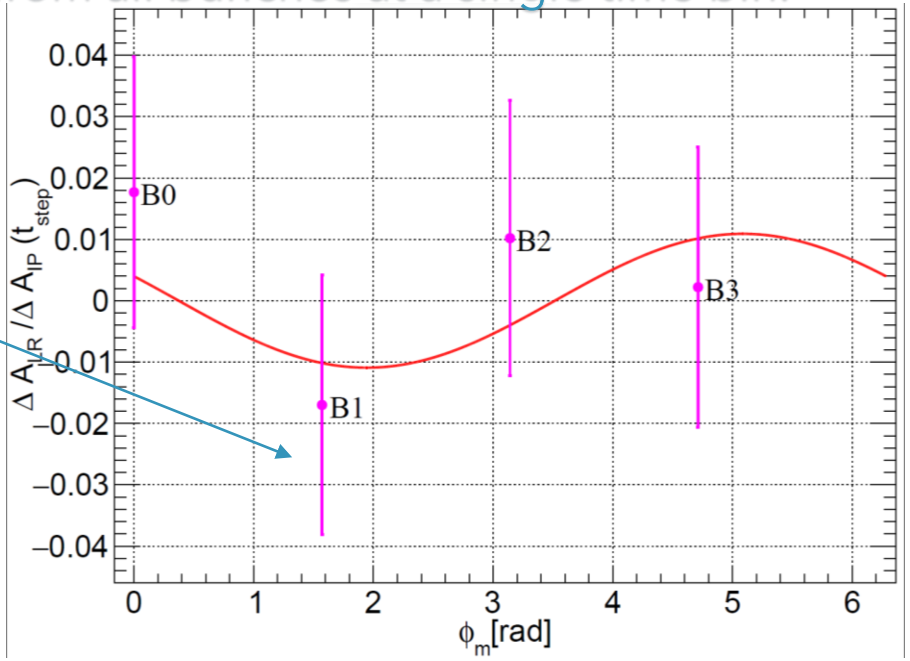


Experimental data from WF

Axion scan



Jumps from all bunches at a single time bin.



The amplitude $\hat{A}$ is calculated from the sinusoidal fit.

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

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

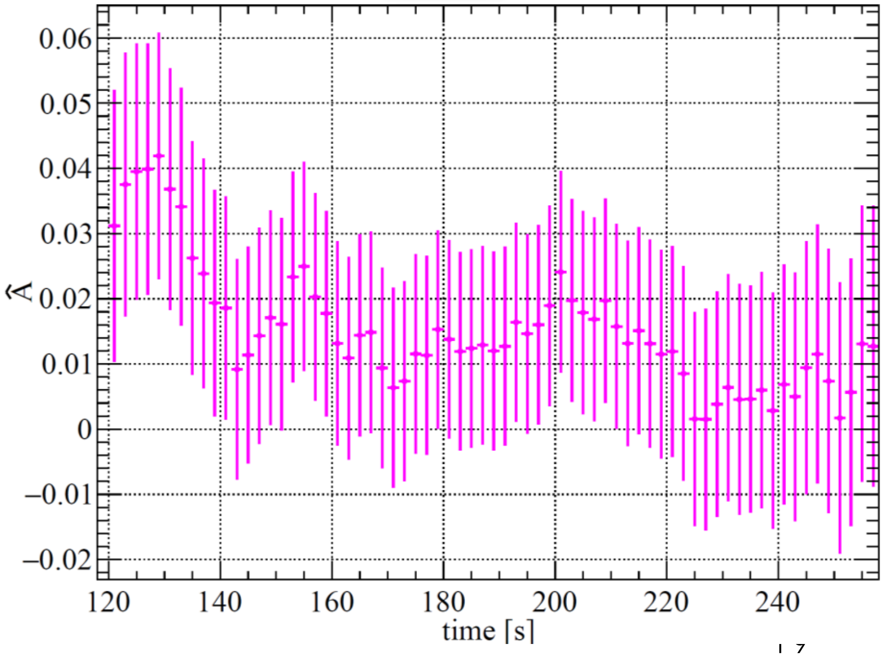
ϕ_m - angle between **E** and **S**

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.



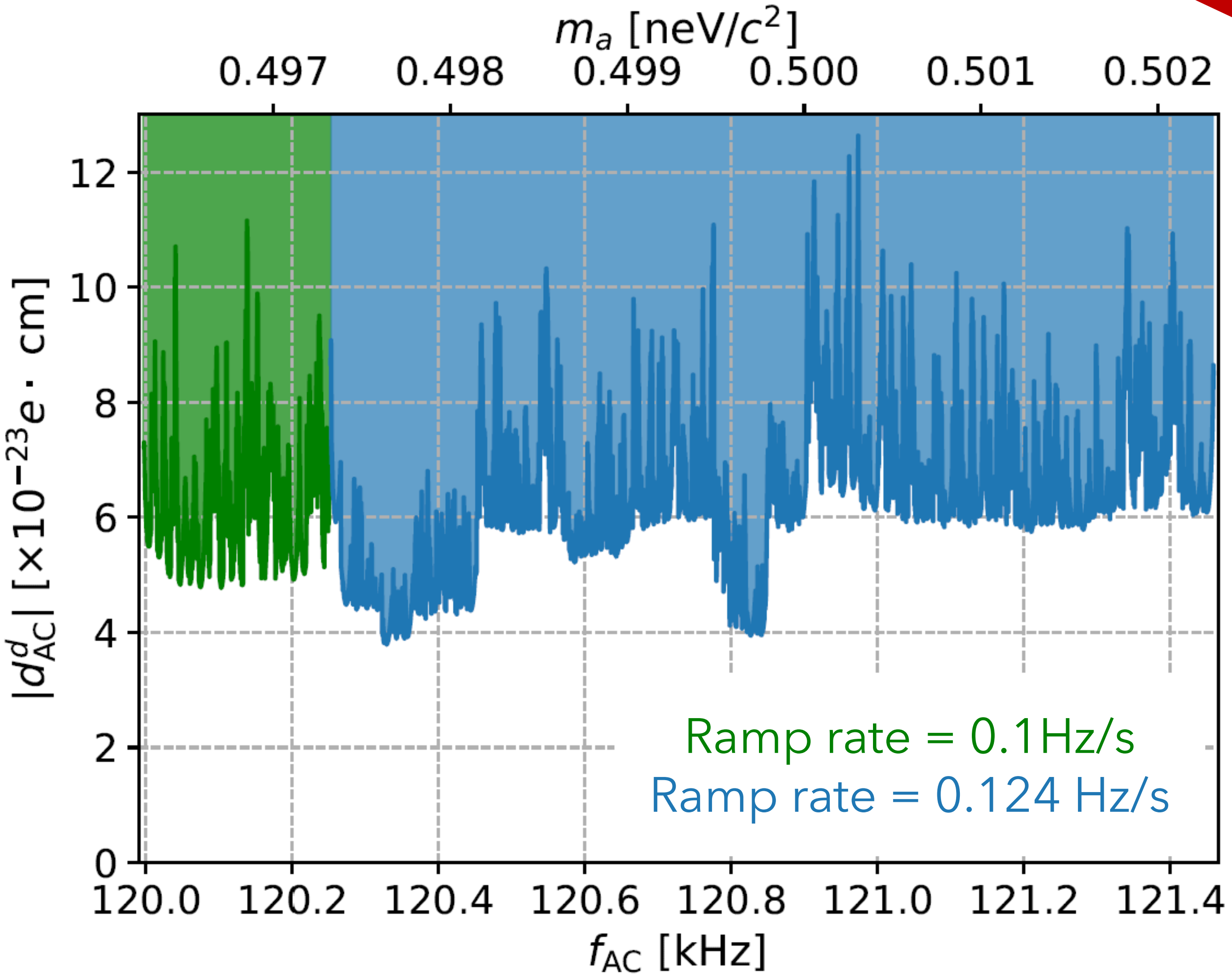
Gary J. Feldman and Robert D. Cousins PRD, 57, 3873 (1998)

Bound on oscillating EDM of deuteron

First result

90 % CL upper limit on the ALPs induced oscillating EDM

Average of individual points $|d_{\mathrm{AC}}| < 6.4 \times 10^{-23} e \cdot \mathrm{cm}$



Karanth et al, arXiv:2208.07293[hep ex]

Bound on ALP-EDM coupling

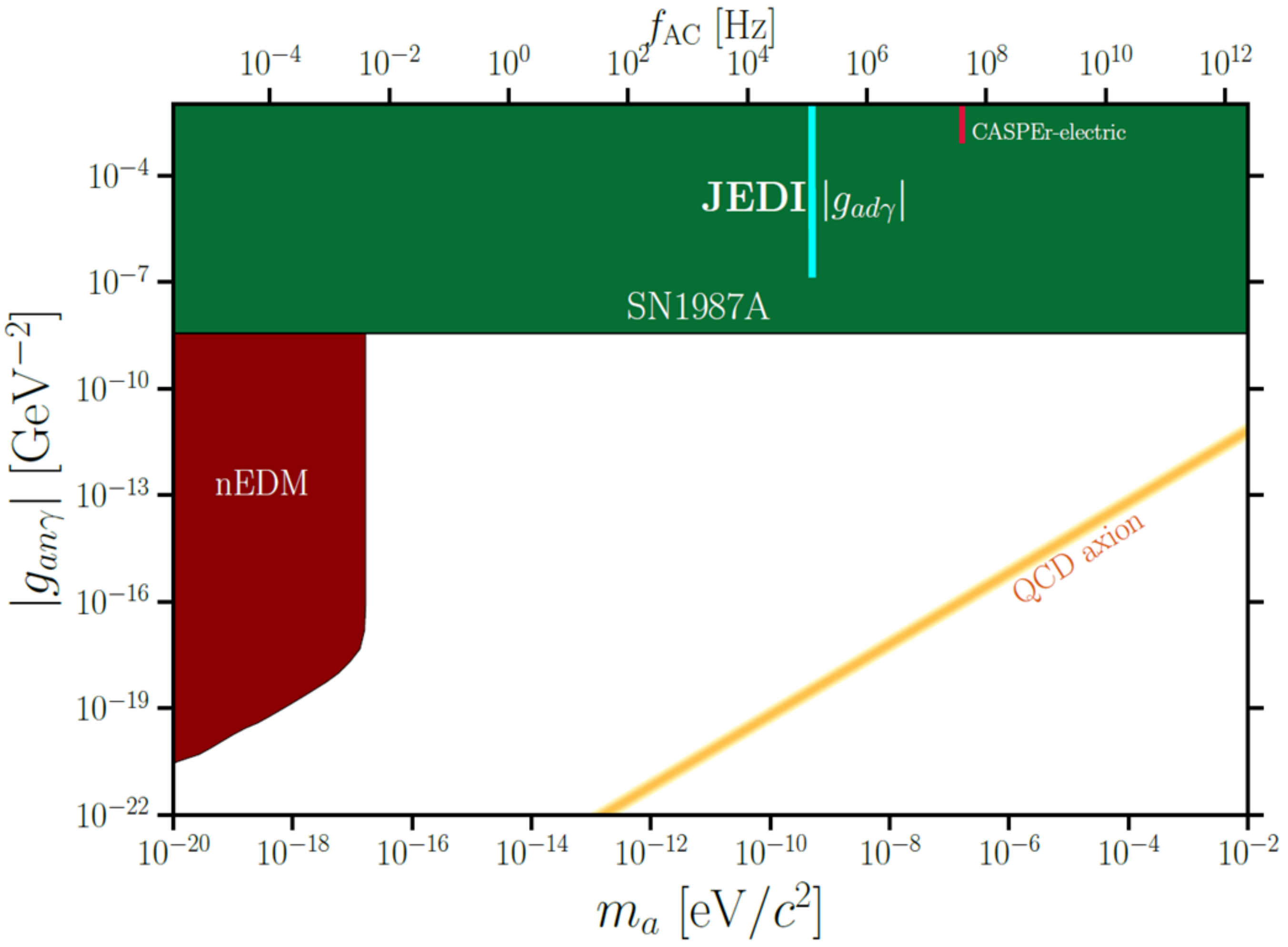
Coupling of ALP to deuteron EDM

$|g_{ad\gamma}| < 1.7 \times 10^{-7} \mathrm{GeV}^{-2}$

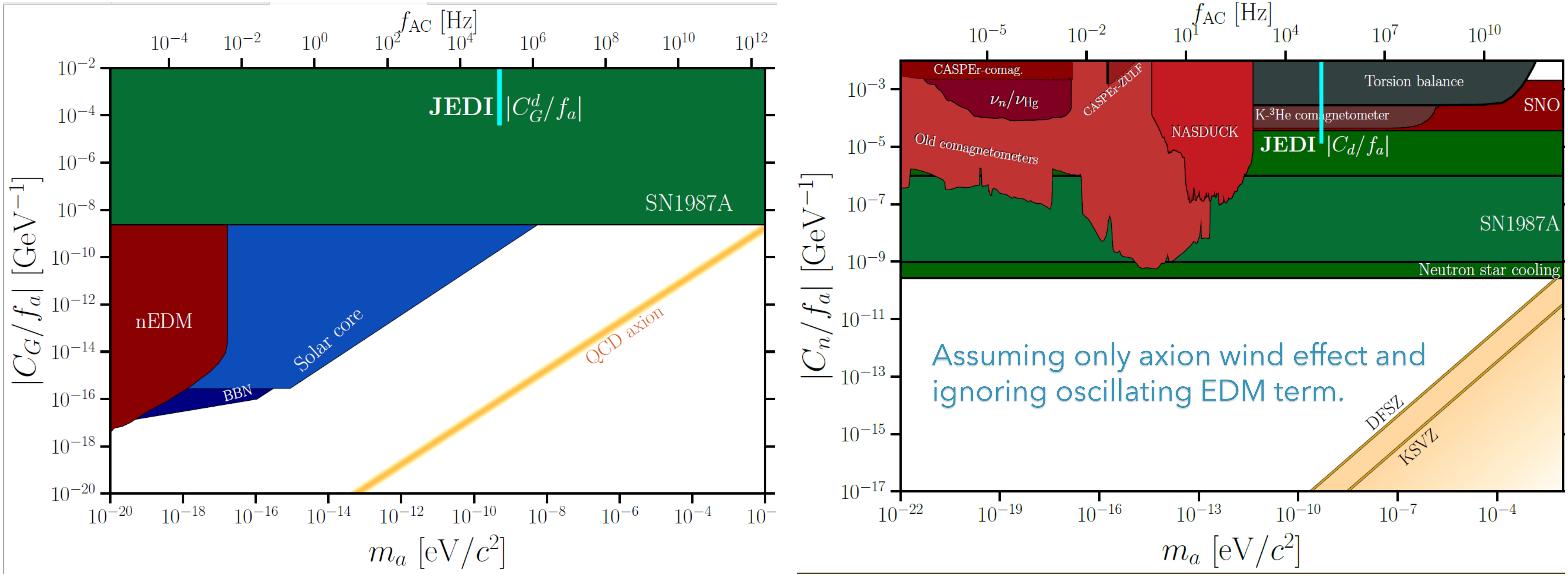
Only few days of data taking.

Karanth et al, arXiv:2208.07293[hep ex]

Figure courtesy of C. O'Hare, "cajohare/axionlimits: Axionlimits," (2020), URL https://doi.org/10.5281/zenodo.3932430



ALP-gluon and ALP-nucleon coupling



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

Summary

ALP induces an oscillating EDM (d_{AC}) and/or an axion wind effect, allows searching for ALPs in a storage ring.

Polarized deuteron beam to search for resonance.

Frequency range $119997\ \mathrm{Hz} - 121457\ \mathrm{Hz}$. Total width $\approx 1500\ \mathrm{Hz}$.

ALP mass range $0.496\ \mathrm{neV} - 0.502\mathrm{neV}$

Wien filter used as a test to observe a signal at resonance crossing.

Result from the search:

First upper limit on deuteron EDM $|d_{\mathrm{AC}}| < 6.4 \times 10^{-23} e \cdot \mathrm{cm}$

First Bound on ALPs and deuteron EDM coupling $|g_{ad\gamma}| < 1.7 \times 10^{-7} \mathrm{GeV}^{-2}$

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JEDI

JÜLICH FORSCHUNGSZENTRUM

Thank You

Erasmus+

erc European Research Council

Extra Slides

Axion – gluon coupling

nEDM - through nuclear spin precession in electric and magnetic field (Result published)

Cosmic **A**xion **S**pin **P**recession **E**xperiment (CASPEr), an NMR-based dark-matter search

Mass range

$$10^{-22}\ \mathrm{eV} \le \mathrm{m_a} \le 10^{-6}\ \mathrm{eV}$$

Frequency

$$10^{-9}\ \mathrm{Hz} \le \mathrm{f} \le 10^{6}\mathrm{Hz}$$

Axion – photon coupling

Axion **D**ark **M**atter e**X**periment

Haloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM

Cern **A**xion **S**olar **T**elescope

Etc.

Mass range $\mathrm{m_a} \approx \mu\mathrm{eV}\ \mathrm{f} \approx \mathrm{GHz}$

Confidence interval

Feldman Cousins [ref] using the probability density function PDF

- Deal with the systematics
- Construct confidence intervals

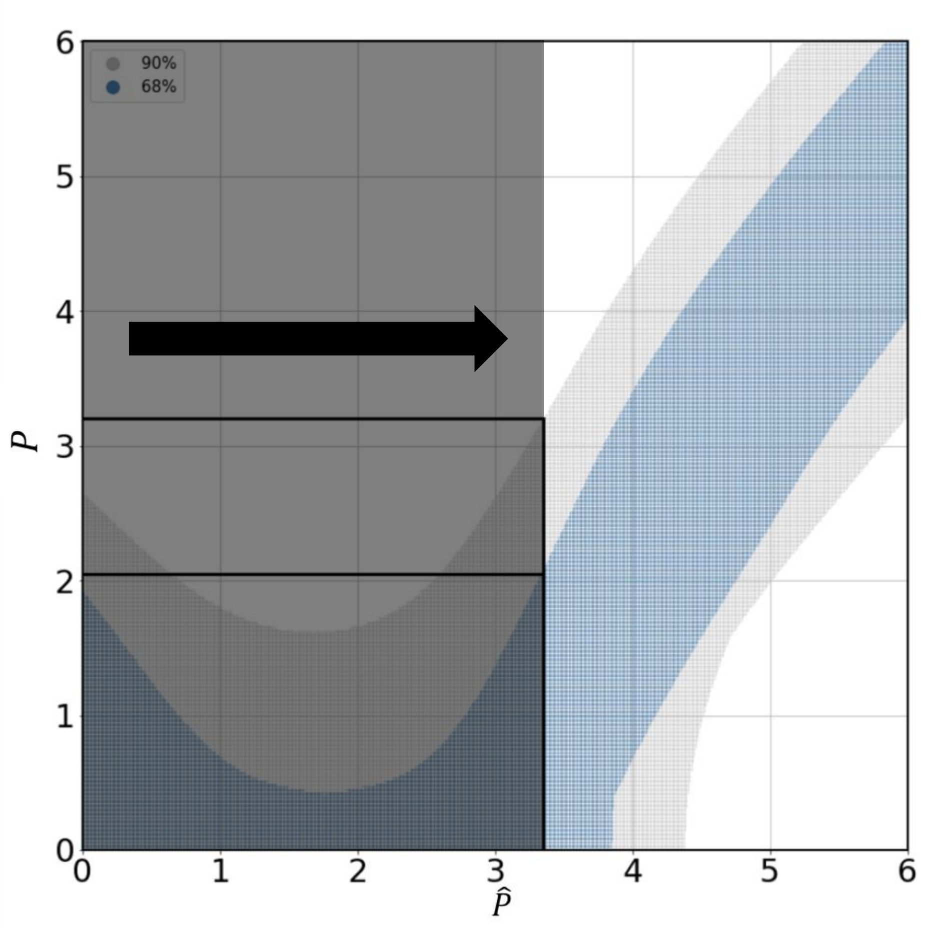
Modified to include the average of multiple cycles.

$$\hat{P} = \hat{A}/\sigma$$

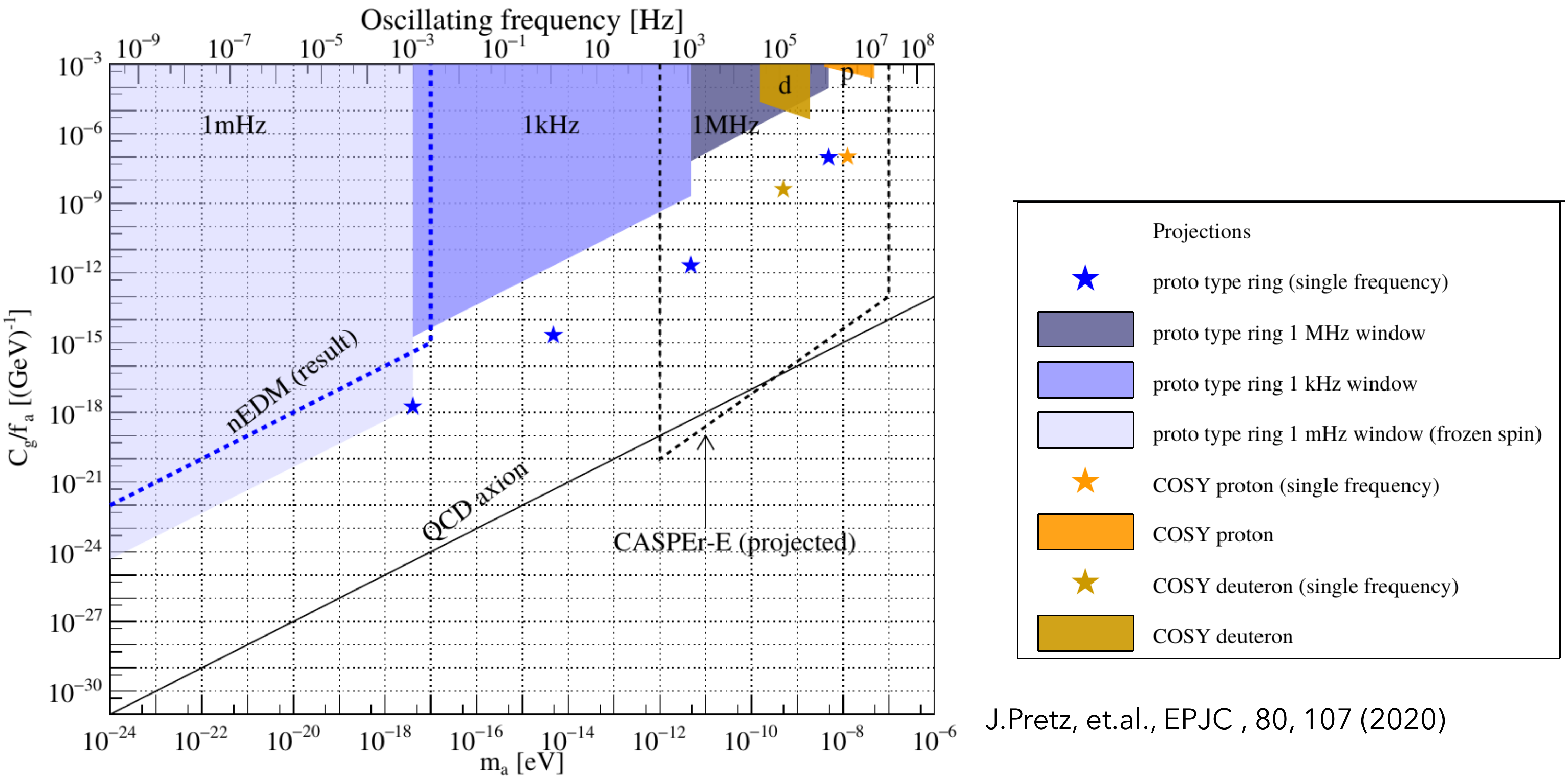
$\hat{P}$ denote the estimated value

P denote the true value

For $\hat{P} < 3.42$ i.e., $< \hat{P} >$ interval is calculated at the expectation value $P = 3.3$



68% (blue)and 90% (grey) confidence interval for analysis of 8 cycles.



J.Pretz, et.al., EPJC , 80, 107 (2020)

Future experiments – at COSY and other rings

High beam intensity.

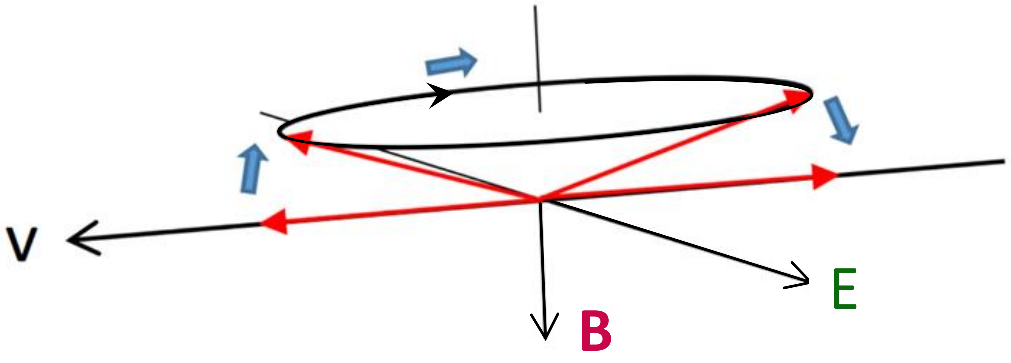
Large polarization and long spin coherence times.

Slower ramp speed. Depends on:

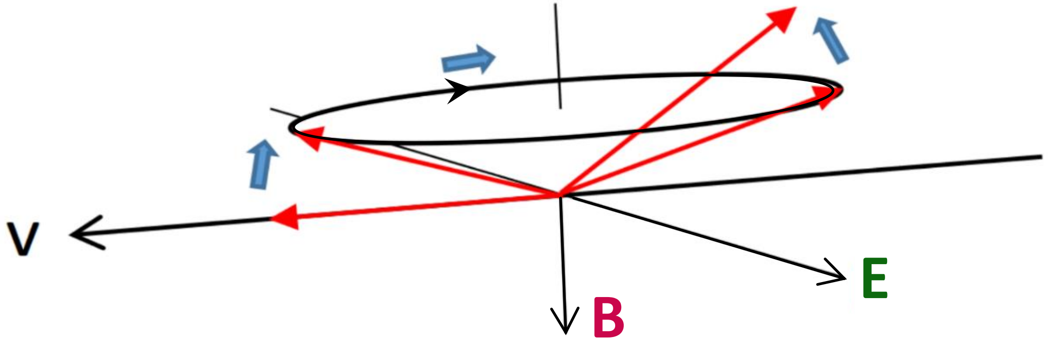
- Coherence time of axion;
- Resonance width;

Larger frequency overlap with adjacent scans.

How to search ALPs in a storage ring?



Static EDM



Oscillating EDM

Axion oscillation frequency (f_{AC}) = Spin tune frequency (f_{spin}) ⇒ Accumulation of vertical polarization