Search for axions and ALPs at NICA

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HEP INSPIRE: > 6000 publications on axions

Hopeless task to exhaust even A in this telephone directory

Why axions:

Resolution of the CP puzzle in QCD (R. Peccei & H. Quinn (1977))

Weakly interacting relic axions: unique QCD motivated candidate for dark matter

Principal manifestations in spin physics:

1. axion-photon conversion in magnetic fileds and light shining through wall (Marcel Aymé, Le Passe-muraille (1941))
2. oscillating electric dipole moments of particles in the galactic axion halo
3. pseudomagnetic field acting on spins in motion w.r.t. to the axion field (P. Vorobiev, I.Kolokolov, I. Fogel (1989), R. Barbieri (1989))

Worldwide dedicated large scale axion detectors (Y. Semertzidis, this conf)

Spins in storage rings: 3 orders in magnitude stronger pseudomagnetic field compared to that acting on spins at rest in the terrestrial laboratories

JEDI collaboration: the pioneering search for axions with deuterons at COSY (S. Karanth et al. (2023))

Fundamental symmetries with spin at NICA supplemented with bypasses: stored spin as a broadband axion antenna & realization of the frozen-spin search for the EDM of deuterons (Y. Senichev et al. (2022))

CP Puzzle in QCD: P & T violating

$$L_{\bar{\theta}} = -\frac{1}{32\pi^2}\bar{\theta} g_S^2 G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{a\rho\sigma}$$

preserves renormalizibilty

$$G^{a\mu\nu}\tilde{G}^a_{\mu\nu} = \partial_\mu K^\mu\,, \qquad K^\mu = \epsilon^{\mu\nu\rho\sigma}\left(A^a_\nu G_{\rho\sigma} - \frac{1}{3}g_s f^{abc}A^a_\nu A^b_\rho A^c_\sigma\right)$$

Does not contribute to the perturbation theory action and can be thrown away

Adler-Bell[-Jackiw anomaly and instanton vacuum

$$\partial_\mu J^\mu_A = -\frac{N}{32\pi^2}\bar{\theta} g_S^2 G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + 2i\bar{\Psi}_R \mathbf{M}\Psi_L$$

Chiral transformation relegates CP-violation to the fermion sector

V. Baluni (1979)
R. Crewther et al. (1979)

$$L_{CPV} = 3m^*\bar{\theta}(\bar{\Psi}i\gamma_5\Psi)\,. \qquad m^* = \frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s} \approx \frac{m_u m_d}{m_u + m_d}$$

Exact Peccei-Quinn chiral symmetry $U(1)_{PQ}$ if there is a massless quark

CP-violation → P- and T-odd static EDM of nucleons and light nuclei

$$d_N \sim \bar{\theta}\frac{m^*}{\Lambda_{QCD}}\mu_N \approx \bar{\theta}\times 10^{-16}\ \mathrm{e\cdot cm}$$

Chiral suppression factor $\kappa_{(a)} \sim \frac{m^*}{\Lambda_{QCD}} \approx 10^{-2}$ w.r.t. the nuclear magneton

QCD well admits $\bar{\theta} \sim 1$

$d_n < 1.8\times 10^{-26}$ e·cм. (PSI, C. Abel et al. (2020)) → $\bar{\theta} \sim 10^{-10}$.

Swap the QCD angle for the dynamic pseudoscalaar field: $\bar{\theta} \to \frac{1}{f_{(a)}}a(x)$

Spontaneous breaking of U(1)$_{PQ}$ → light pseudoscalar axion as a likely source of dark matter

Weinberg (1978): fundamental similarity between the πNN and aNN PS(PV) interactions

$$\frac{\hbar}{2f_{(a)}}g_f\partial_\mu a(x)\overline{\Psi}\gamma^\mu\gamma_5\Psi \quad \to \quad m_{(a)} \approx m_\pi \frac{f_\pi}{f_{(a)}}\frac{\sqrt{m_u m_d}}{m_u+m_d},$$

"Invisible" light axion: M. Shifman, V. Zakharov, A. Vainshtein (1980), J.E. Kim (1979) (KSVZ)
A.Zhitnitskii (1980), M. Dine, W. Fischler, M. Srednicki (1981) (DFSZ)

Le Passe-muraille

Still another footprint of the ABJ anomaly

$$L_{a\gamma\gamma} = -g_{a\gamma\gamma}\,\frac{1}{f_{(a)}c}\,\frac{\alpha}{\pi}\,a(x)\,\mathbf{E}(x)\mathbf{B}(x) \qquad g_{a\gamma\gamma} \sim 1$$

KSVZ (1980)

Light shining through wall: Primakoff conversion of laser light to axions in a magnetic field, then axions penetrate the wall and regenerate the light via inverse Primakoff effect Anselm (1985)

Sikivie (1883) haloscopes: resonant excitation of the microwave cavity tuned to the axion mass by a galactic axion field penetrating the cavity in a magnetic field e.g, CAPP-CAST Collab. (2022)

Semertzidis, this conf.

Extension of Anselm's approach: axion mediated cross-talk of two rf cavities separated by the rf screening wall (Salnikov et al. (2023))

Cosmological version of Anselm's mechanism: a direct 250 TeV gamma form GRB 221009A (z=0.15) must have been absorbed by generation of e+e- on relic photons (Nikishov effect), but could cross the universe in the disguise of an axion which converts back to gamma in the Milky Way magnetic fields (Troitsky (2022))

Common problem to resonant methods is an unknown axion mass: do we search under the right streetlamp?

Relic axion dark matter ($m_{(a)} < 10^{-7}$ eV)

Coherent axion galactic halo $a(x) = a_0 \cos\left(\omega_{(a)} t - \boldsymbol{k}_{(a)} \cdot \boldsymbol{x}\right)$

$$\omega_{(a)} = \frac{m_{(a)} c^2}{\hbar} \qquad a_0 = \frac{1}{m_{(a)}} \sqrt{\frac{2\rho_{\rm DM}\hbar}{c^3}}$$

Oscillating EDM $d_{\rm N}^{(a)}(x) = \frac{a(x)}{f_{(a)}} \kappa_{(a)} \frac{\mu_{\rm N}}{c}$

Preskill, Wise, Wilczek (1983)
Abbott, Sikivie (1983)
Dine, Fischler (1983)
Review: Sikivie (2021)

Spins in storage rings move ~1000 times faster than Earth w.r.t. galatic halo axions → enhanced pseudomagnetic field, Foldy-Wouthuysen treatment is mandatrory Silenko (2021,2022, this conf)

Instantaneous spin rotation

$$\boldsymbol{\Omega}^{(a)} = \frac{a_0}{f_{(a)}} \left[g_{\rm f}\omega_{(a)} \sin\left(\omega_{(a)} t\right) \frac{\boldsymbol{v}}{c} - \kappa_{(a)}\gamma \cos\left(\omega_{(a)} t\right) \frac{\boldsymbol{v}}{c} \times \boldsymbol{\Omega}_{\rm c} \right]$$

pseudomagnetic field (= rf solenoid) oscillating EDM (= Wien filter)

π/2 phase shift of two spin rotators with orthogonal spin rotation axes --- spin rotatuions are in sync

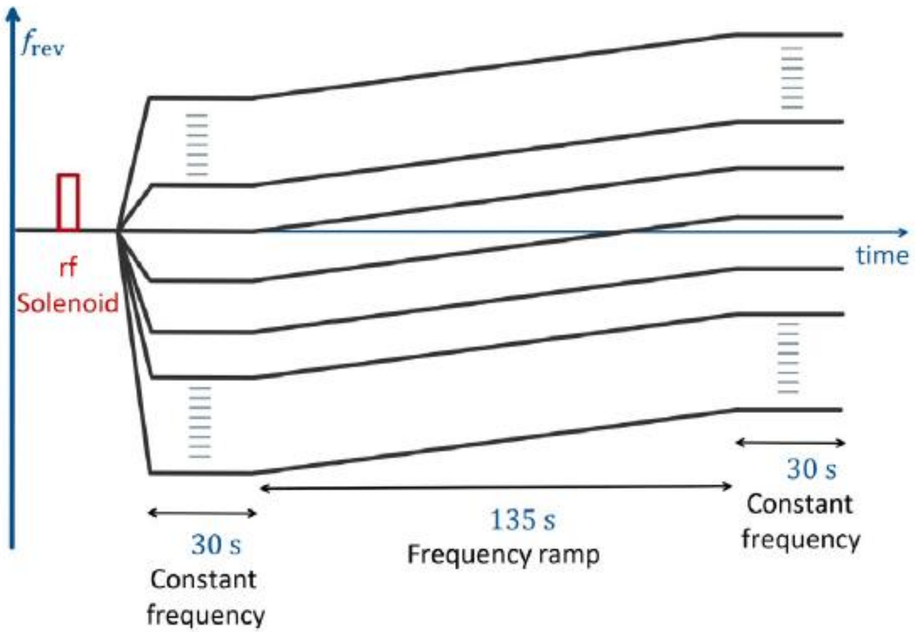
Axion induced resonance spin-flip angular velocity Silenko (2022), NNN (2022)

$$\Omega_{\rm res} = \frac{a_0}{2f_{(a)}} \frac{v}{c} \gamma \left| g_{\rm f} G - \kappa_{(a)} \right| \Omega_{\rm c}$$ is independent of the spin-axion phase difference

JEDI collaboration at COSY: First Ever Search for Axionlike Particles in a Storage Ring Using a Polarized Deuteron Beam,

S. Karanth et al. (JEDI), Phys. Rev. X 13, 031004 (2023)

- Search for the NMR-like axion induced (partial) spin-flip at $\Omega^{(a)} = G\gamma\,\Omega_c$
- Store vertically polarized beam
- Rotate the spin into the ring plane by the rf solenoid
- The axion mass (frequency) is unknown: search for the resonant spin flip by Froissart-Stora scan ramping the beam energy (revolution frequency f_{rev})
- The axion (or ALP) signal: (partial) spin flip, aka build up of vertical polarization once the resonance condition is met
- Change of beam parameters during a ramp



Δp (MeV/c)	Δf_{rev} (Hz)	$\Delta \dot{f}_{rev}$ (Hz/s)	Δf_{spin} (Hz)	$\Delta \dot{f}_{spin}$ (Hz/s)
0.138	81.0	0.600	16.8	0.124
0.112	66.15	0.490	13.5	0.100

Dynamics of the Froissart-Stora scan: axion phase ambiguity

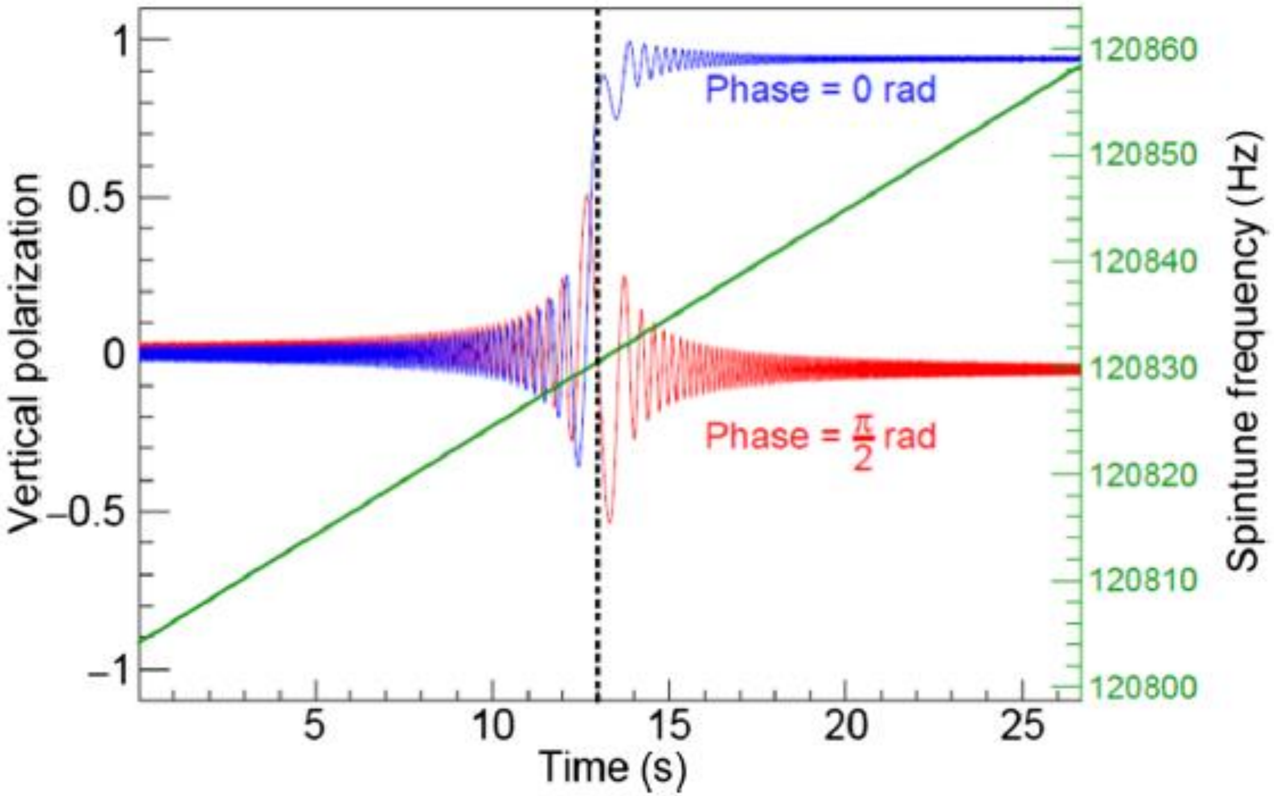
Duration of the spin-jump must be shorter than the axion coherence time $\tau_a = \frac{h}{m_a v^2}$,

JEDI sensitive to m_a = 0.5 neV, virial velocity of axions v ~10^{-3} → $\tau \sim 10$ s, tune ramp rate poperly

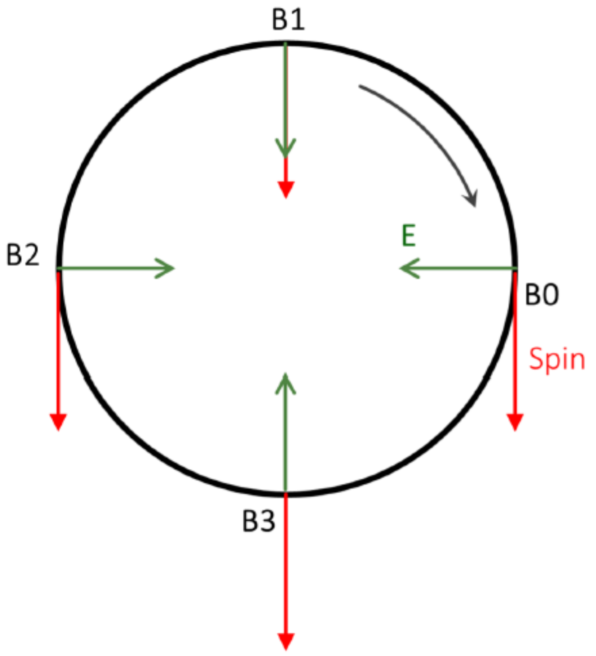
Spin-flip frequency is independent of the entirely unknown relative spin-axion phase Δ

But the resonant spin jump is ~ cos Δ

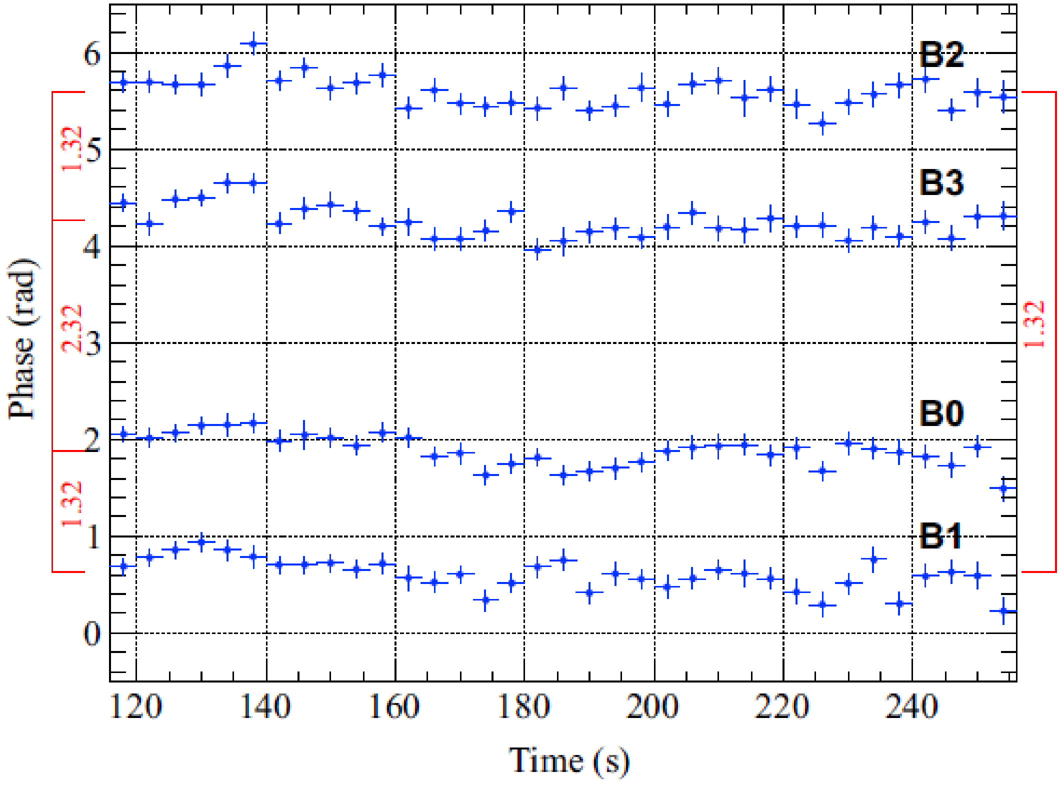
N.B. Rotation of spin from the initial vertical to the horizontal one is entirely free of the phase ambiguity



JEDI multibunch resolution of the phase ambiguity



Spin phase stability of 4 bunches

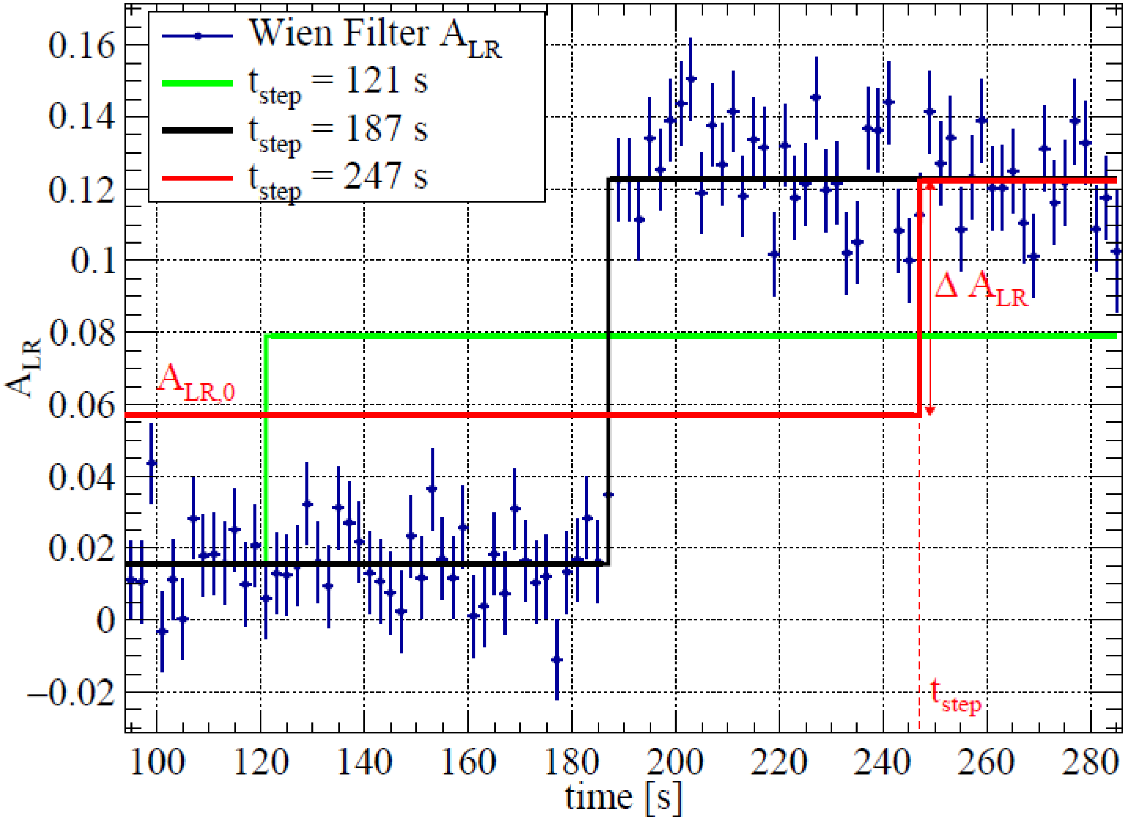


JEDI: calibration of the polarimeter by Wien filter as a resonant spin rotator

Asymmetry data collection for
2s per single data point

The step is located at the resonance with the axion mass, which is unknown.

The true t_{step} is a fit parameter, corresponds to the maximum of the spin asymmetry jump.



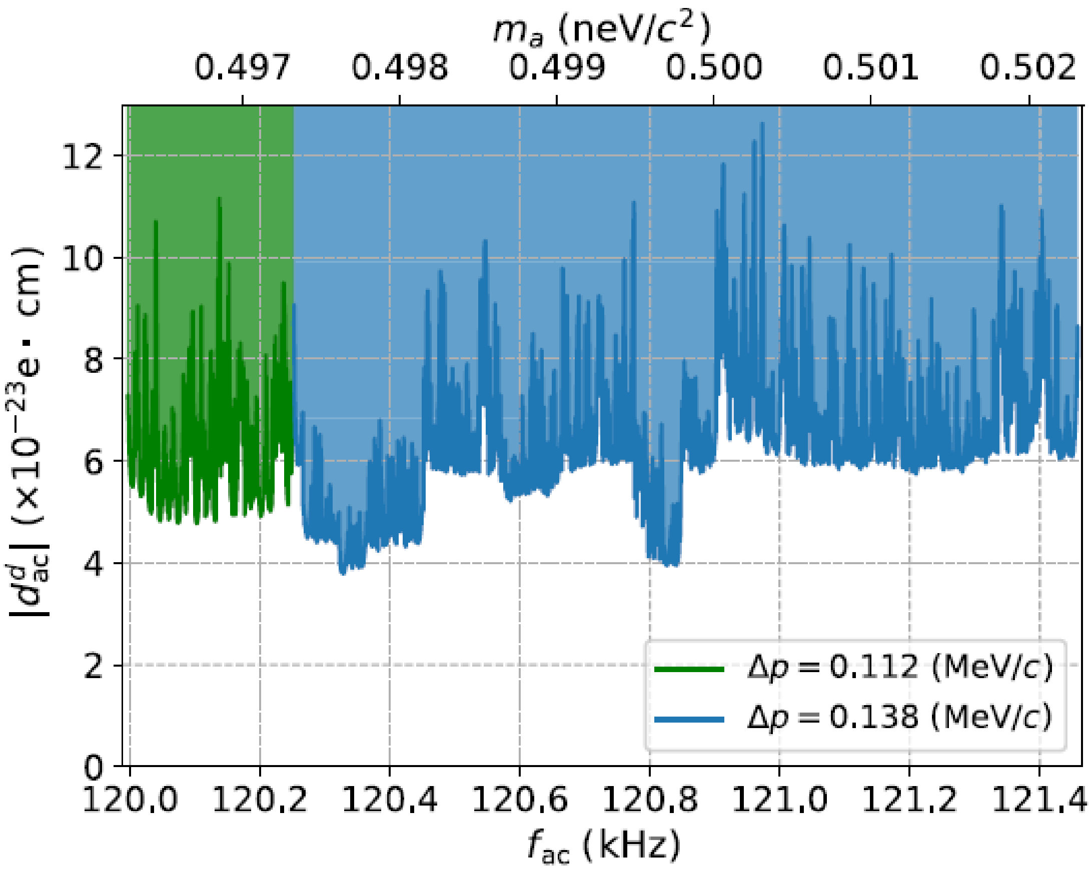
For calibration of a response to the axion fi
pseudomagnetic field acting along the 180 m circumference of the COSY ring.

JEDI results-1

Altogether 103 ramps

Frequency range 120-121.4 kHz

Axion mass range 4.95-5.02 neV/c^2



90% confidence level sensitivity for excluding the axion (ALP) induced oscillating EDM of the deuteron (assuming the EDM dominance)

Basically no direct experimental upper bounds in the PDG tables on the static EDM of bare protons and deuterons to compare with

Further interpretation of the JEDI axion bounds vs. theory

Resolution of the QCD CP puzzle → Weinberg's relation for the axion mass

Can be relaxed if we live in the Z_N symmteric dark world (Hook (2018))

N mirror and degenerate worlds linked by the axion field (odd possitive N)

Our world is one of these

$$m_a \simeq \left(\frac{1-z}{\pi(1+z)}\right)^{1/4} m_\pi f_\pi \mathcal{N}^{3/4} z^{\mathcal{N}/2} \frac{1}{f_a} \qquad z = m_u/m_d \approx 0.474$$

At fixed coupling f_a the axion mass scales approximately as $2^{-\mathcal{N}/2}$

Unorthodox pseudoscalar axion-like particles (ALPs) unrelated to the QCD CP puzzle are not subject to the Weinberg's mass-coupling constraint

Scalar dark mater? Unobservable in spin experiments

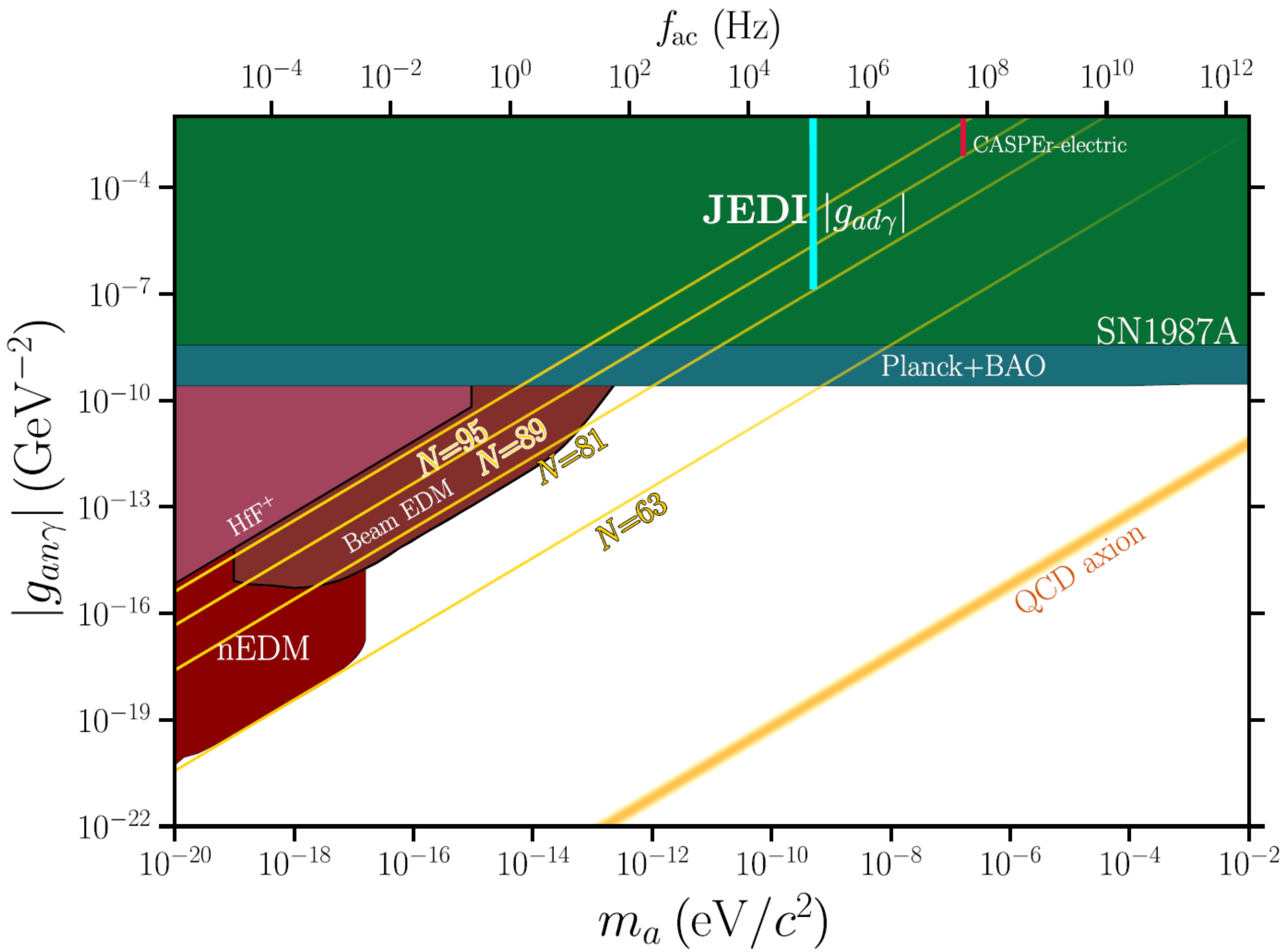
JEDI results-2: dEDM bound on the γda coupling vs. γna coupling bounds

References in the JEDI paper

JEDI bound ecxludes Z_N models with N > 81

SN1987A bound derives from an analysis of N → a N cooling --- was challenged as model dependent (N. Bar et al. (2020))

Axion mass is a major known unknown: there is no conflict whatsoever between different bounds in non-overlapping mass intervals



JEDI results-3: Limits on JEDI axion-deuteron vs. axion-neutron coupling

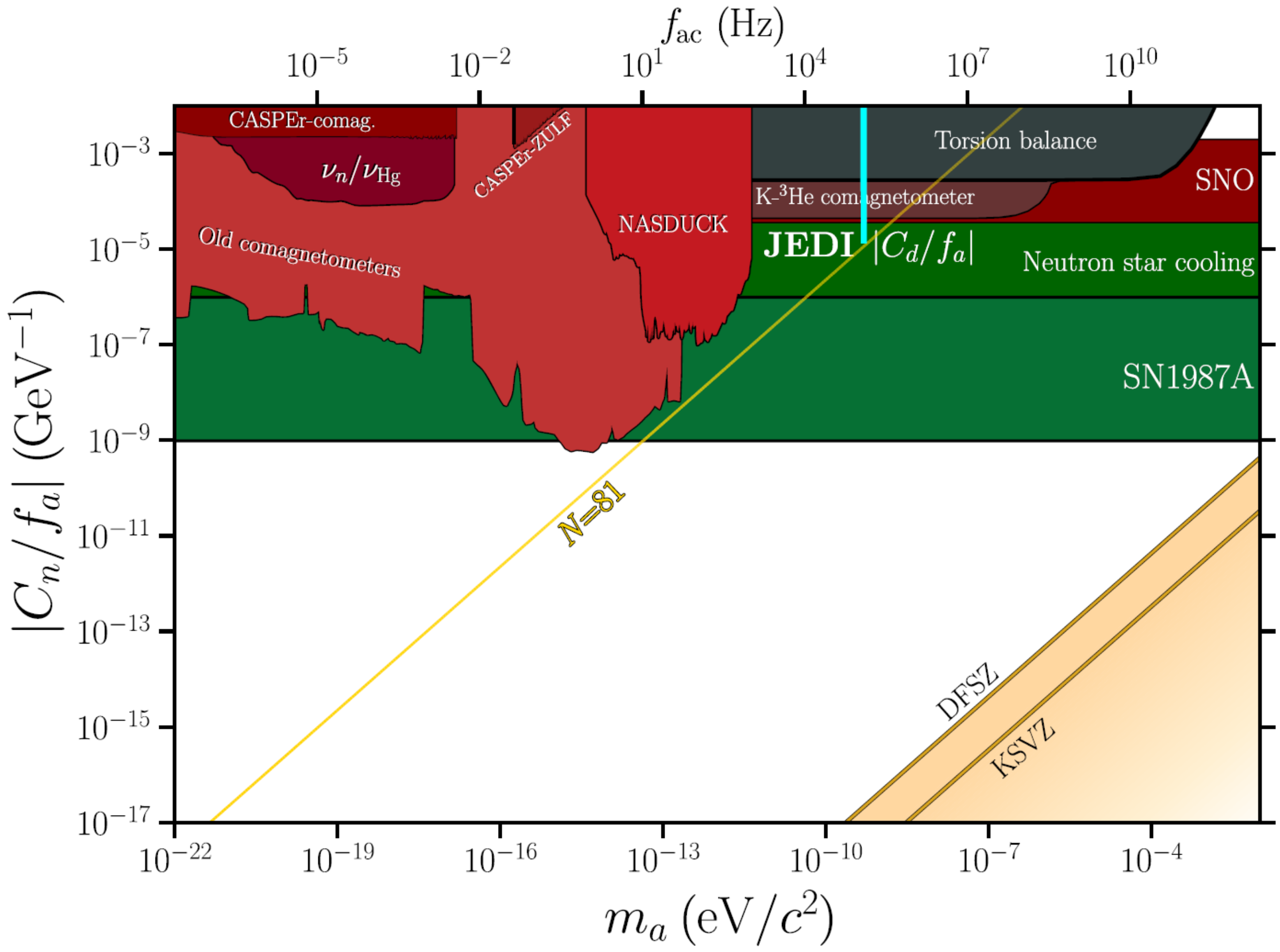
References in the JEDI paper

Pure Weinberg interaction without the EDM term

The NMR like experiments probe the axion pseudomagnetic field

Star cooling via axion emission

SN1987 bounds are model dependent



Axions at PTR (Prototype Test Ring, CPEDM Collaboration)

Pretz et al. (2020), NNN (2022)

In all magnetic rings axion masses acsessible with spin as an axion antenna are bounded from below

PTR : hybrid E+B confinement of 45 MeV frozen spin protons on orbit

Prime motivation: test of the frozen spin approach to a search for the EDM of protons

Cyclotron frequency $$\boldsymbol{\Omega}_c = \frac{q}{m\gamma}\left(-\boldsymbol{B} + \frac{\boldsymbol{v}\times\boldsymbol{E}}{v^2}\right)$$

Frozen spin $$\boldsymbol{\Omega}_s^{\mathrm{mdm}} = \frac{q}{m}\left\{-G\,\boldsymbol{B} + \left(G - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{v}\times\boldsymbol{E}}{c^2}\right\}$$ =0 → zero mass axion antenna

$$\boldsymbol{\Omega}_s^{\mathrm{edm}} = -d\{\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}\}\,.$$

Lift the frozen spin condition, but retain the beam momentum and cyclotron frequency $$\Delta\boldsymbol{B} = \frac{1}{v^2}[\boldsymbol{v}\times\Delta\boldsymbol{E}]$$

The axion resonance at $$\omega_a = -G_p\gamma\Omega_c\frac{\Delta E}{E_0}$$, broadband axion antenna: ~ 0-0.5 MHz

Arguably short horizontal spin coherence time of protons → change of paradigm: look for axion induced rotation of the vertical spin into ring plane, buildup of precessing in-plane polarizatioin

Advantages: large lifetime of the vertical polarization → long ramps with frequency coverage much longer than in JEDI expt,

no spin phase ambiguity

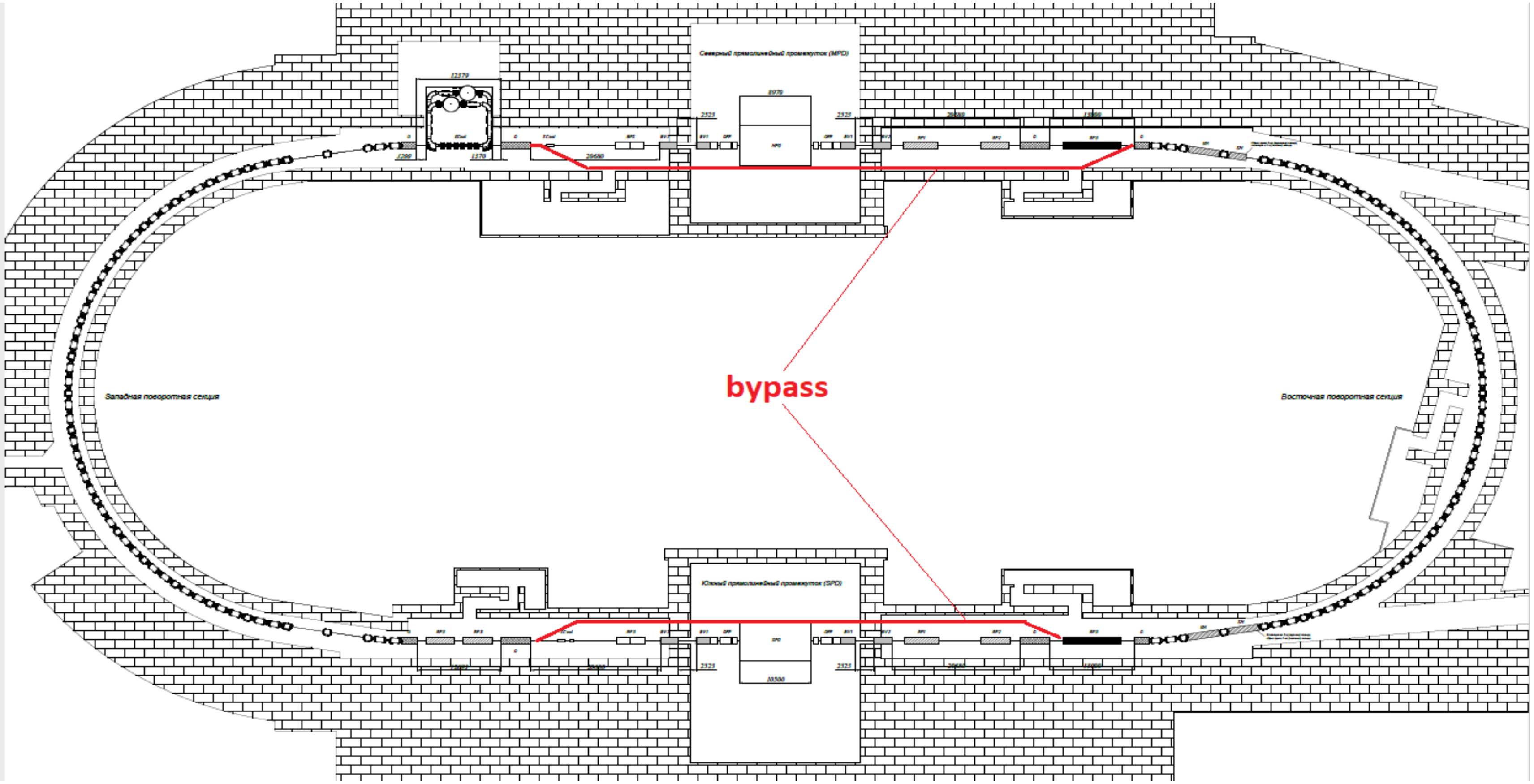
Learn to ramp hydrid ring

NICA as a hybrid axion antenna with E+B. bypasses

Y. Senichev et al. (2022)
A. Melnikov, this conf.
Y. Senichev, this conf.
A. Aksentev, this conf.

Prime motivation: quaisi-frozen deuteron spin at NICA to searcy for the deuteron EDM

Two approx. 100 m bypasses will endow NICA with partial features of PTR



Bypass:

- Alternating (air coil?) dipoles and electrostatic deflectors
- 1:1 telescope for the particle momentum
- Poor man's easy solution for the Wien filter
- Rotates spin around vertical axis and changes the axion antenna tune
- Realistic deflectors with E = 5 MeV/m
- Scan maintaining the intergral Wien filter features
- Effective length of the Wien filter per bypass ~ 25 m
- Band width at a fixed energy and orbit

$$\Delta f_s = \frac{(1+G)\, q\, E\, L}{2\pi\, mc^2\gamma^2\beta^2}\, f_{rev} \rightarrow 2 \times 35/\gamma^2\beta \text{ kHz}$$

- Double the bandwidth by field reversal in the bypass
- Operation at lowest possible energy is preferred
- Protons: axion resonance buildup of the horizontal polarization

Spin coherence time: crucial issue for protons

C. Weidemann et al., Phys. Rev. ST Accelerators and Beams, 18, 020101 (2015)

- 49.3 MeV protons in COSY
- Without spin-flips the vertical polarization lifetime (2.7 +/- 0.5) 10^3 s
- 99 spin flips during 300 s
- Flipping polarization lifetime 240 s.
- Strong evidence for the polarization loss by spin decoherence in the horizontal plane
- Arguablly the spin coherence time ~ $1/\gamma^2$ A.Lechrach et al. e-Print: 1201.5773 [hep-ex]
- More experimental scrutiny on stretchcing spin coherence time is in order (sextupoles ?)

Summary and outlook

- By the beauty considerations, when ordering fundamental symmetries Nature was unlikely to overlook axions as a solution to the strong CP problem
- Axions are promising source of dark matter
- JEDI paved a way to spins in storage rings as axion antennas
- Bypasses will enhance a potential of NICA as the fundamental physics facility
- Inextricably intertwined searches for axions and EDM's in storage ring

Thanks for your attention ！

Comment on alternating polarization bunches at NICA and eIC: imperative for killing the systematics

- Lessons from the JEDI Pilot bunch experiment at COSY (to be released in 1-2 weeks)
- Orbit preserving RF Wien filter as a spin flipper
- Rapid cycling switches with operarion time < 20-50 ns
- NICA: 22 bunches with bunch separation > 75 ns
- Store up polarized bunches
- Switch RF Wien filter off for odd-numbered bunches while flipping spins of even-numbered bunches
- At injection energy the spin flip in < 20-50 s
- Then accelerate the alternating polarization bunched beam to nominal energy
- Any rotation into the longitudinal polarization presences the alterating polarization of bunches
- eIC with 320 bunches is similar to NICA, but after upgradt to ~ 1000 bunches relax the demand for rapid cycling by lengthening the WF gating out/in to families of bunches with empty bunches in between

QFS at NICA (Yu. Senichev et al): bypass with the radial E-field to rotate EDM