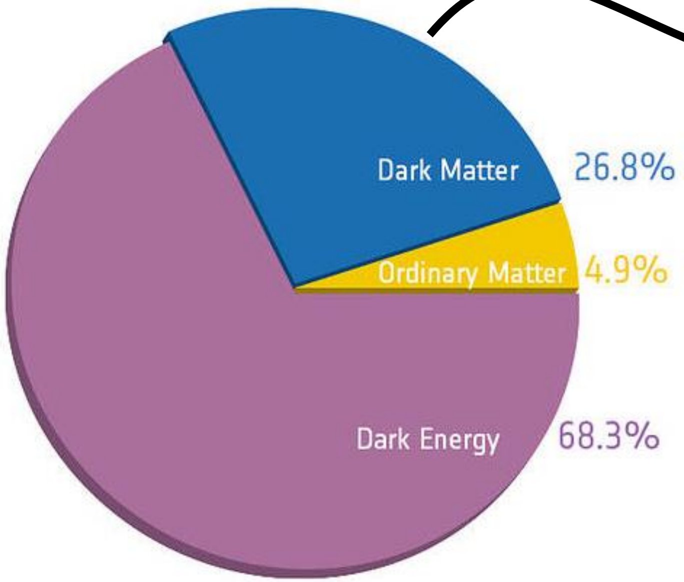
Constraining the coupling between axion-like dark matter and photons using an antiproton superconducting detection circuit in a cryogenic Penning trap

Jack Devlin (CERN, RIKEN)

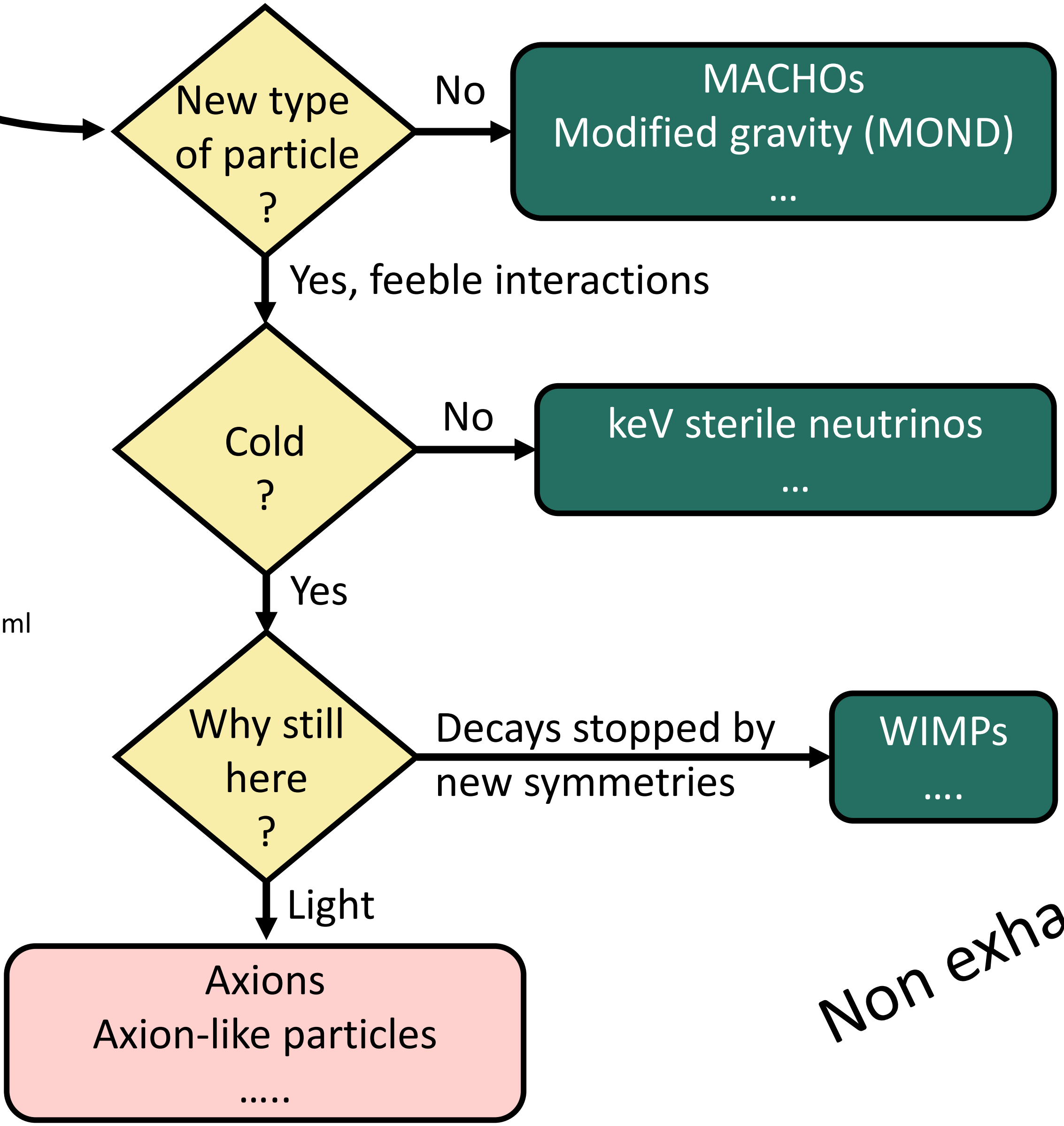
Outline

1. Axion-like dark matter
2. The BASE experiment
3. Detecting ALPs at BASE
4. Future perspectives

Why axion-like dark matter?



https://www.nasa.gov/mission_pages/planck/multimedia/pia16878.html



Motivated by symmetry →

Non exhaustive !

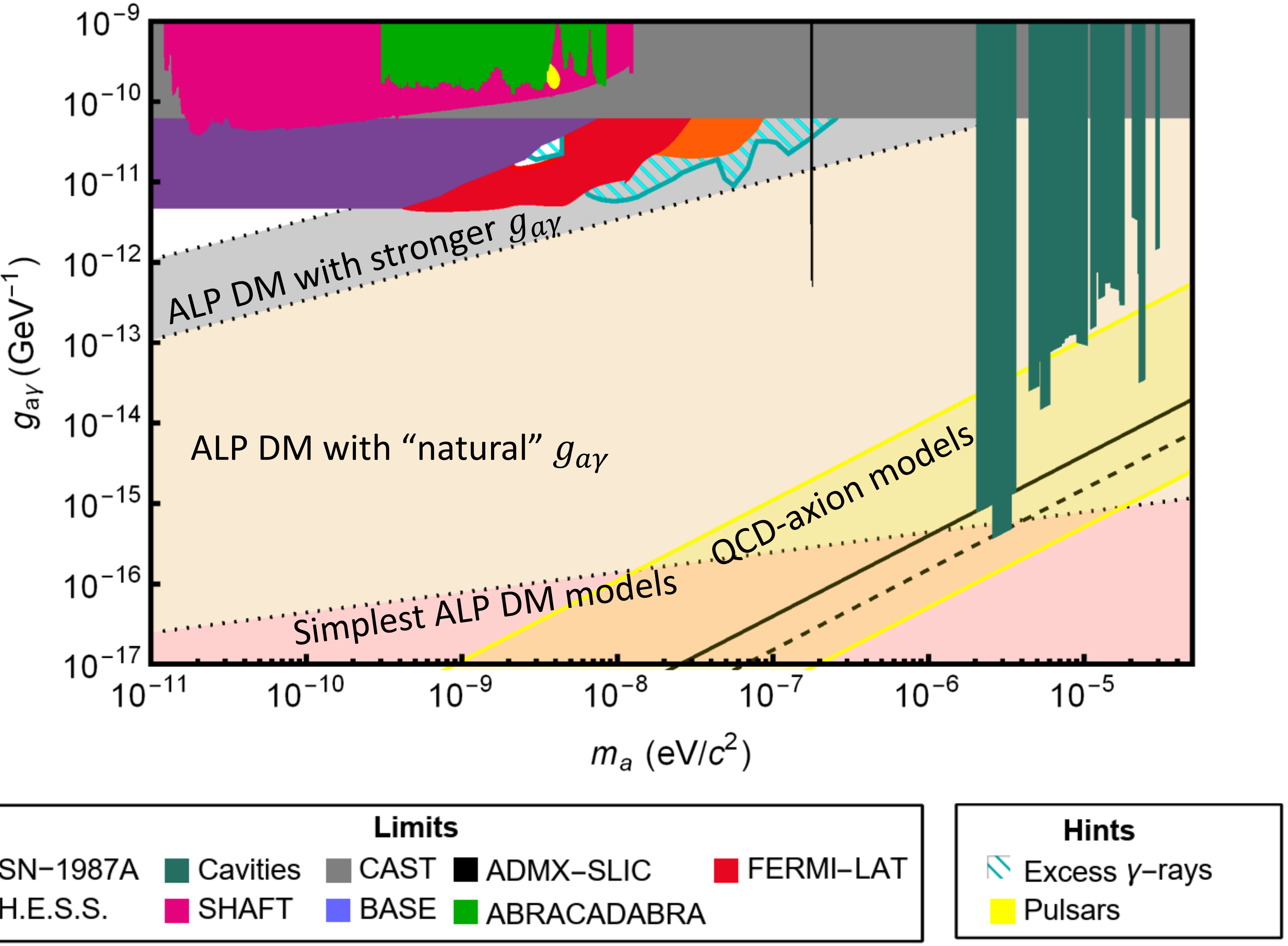
ALP-photon coupling

Axion-like particles are (light) pseudoscalar bosons which, if generated via the misalignment mechanism, form a BEC and behave like a classical scalar field

ALP-photon coupling

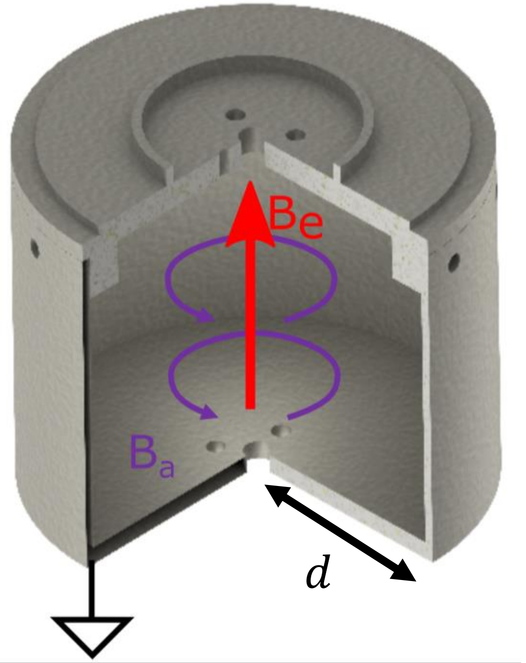
$$\mathcal{L}_{\text{int}} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

"Easy" to make an ALP candidate consistent with observed dark matter density and early universe evolution



P. Arias et al., JCAP **06** 013 (2012)

How to detect very low mass ALPs



Axions can couple to photons via the interaction term $\mathcal{L}_{\text{int}} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

This modifies Maxwell's equations

$$\nabla \cdot \vec{E} = \rho - g_{a\gamma}\, \vec{B} \cdot \nabla a$$
$$\nabla \times \vec{B} - \partial_t \vec{E} = \vec{J} + g_{a\gamma}(\vec{B}\partial_t a - \vec{E} \times \nabla a)$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} + \partial_t \vec{B} = 0$$

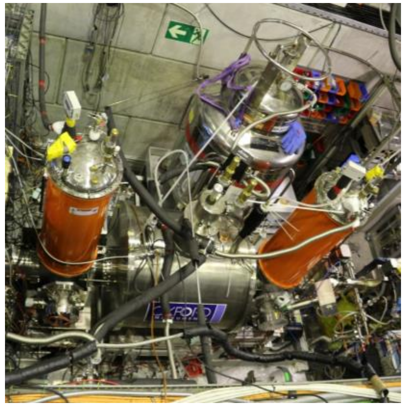
Inside a conducting housing with $d \ll \lambda_a$, and where there is a strong field B_e, the axions source a magnetic field

$$|\vec{B}_a| = \frac{1}{2} r g_{a\gamma} |\vec{B}_0| \sqrt{\rho_a \hbar c}$$

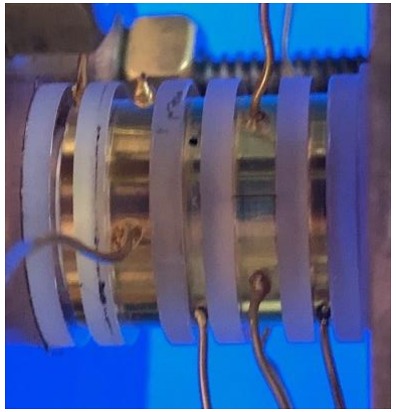
Sikivie et al. PRL **112**, 131301 (2014); Y. Kim et al. Phys. Dark Universe **26**, 100362 (2019).

The BASE experiment

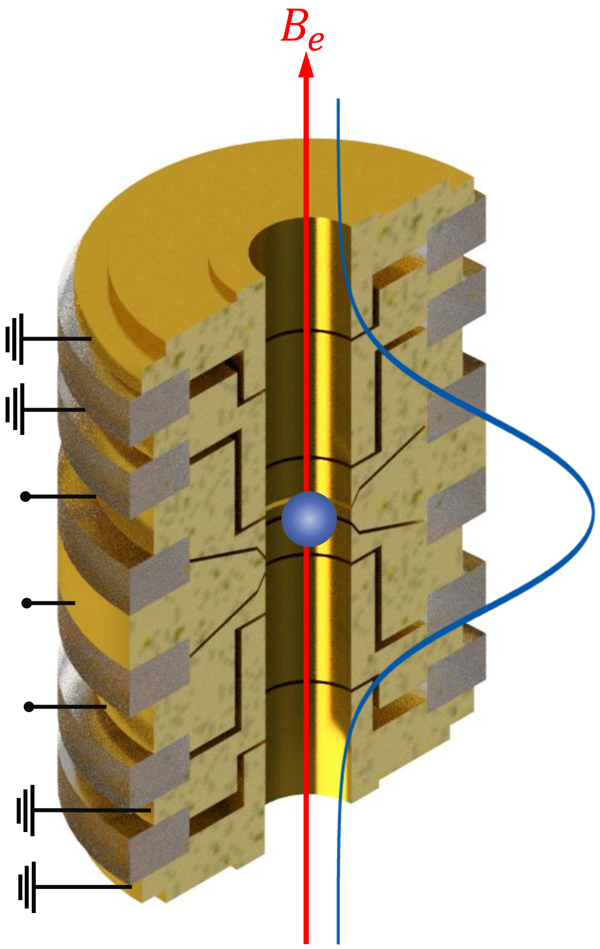
1.95 T B field from solenoid



Voltages applied to ring-shaped electrodes



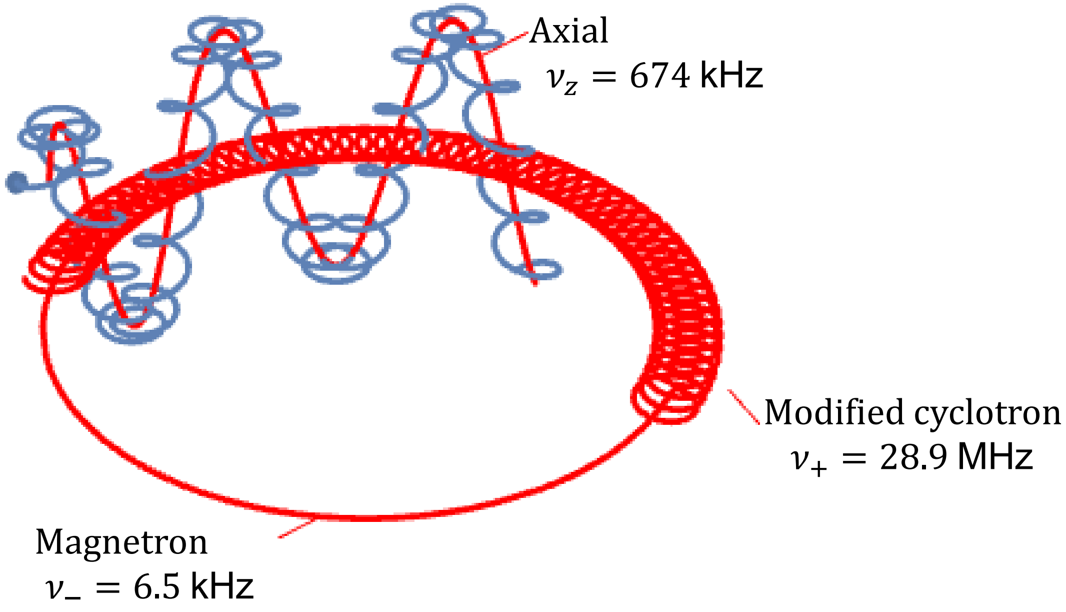
A Penning trap



$\Phi(0,z)$

$$\Phi(\rho,z) = V_0 C_2 (z^2 - \frac{\rho^2}{2})$$

Orbit is sum of three normal modes



$$\sqrt{\nu_z^2 + \nu_+^2 + \nu_-^2} = \nu_c = \frac{q}{2\pi m} B_e$$

Measure frequencies and get access to charge-to-mass ratio and magnetic field

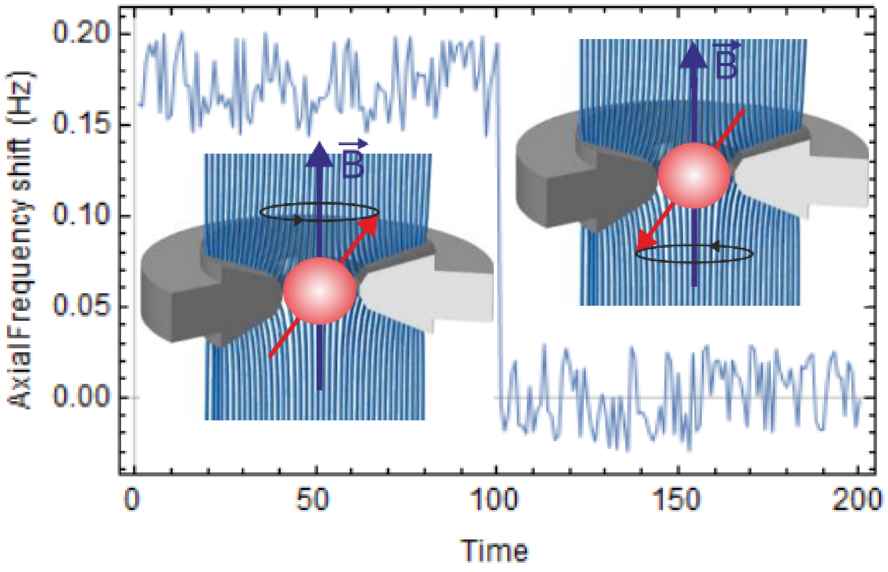
Measuring magnetic moments

$$\frac{g}{2} = \frac{2\pi\, \nu_L}{B_e \mu_N} = \frac{\nu_L}{\nu_c}$$

ν_L is the Larmor frequency, the frequency at which rf can most easily flip the spin

To measure ν_L, just need a way to identify the antiproton spin state

Detecting changes in the direction or size of μ



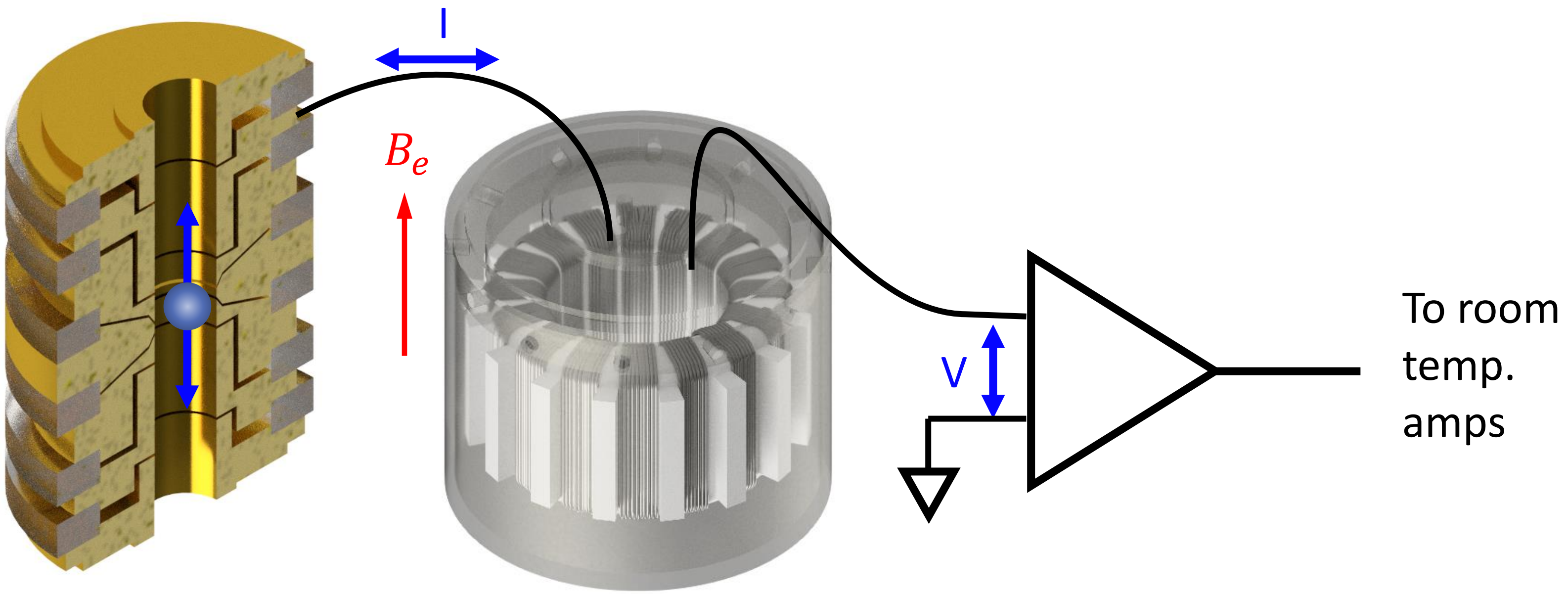
The particle has a total magnetic moment μ (spin + orbital)

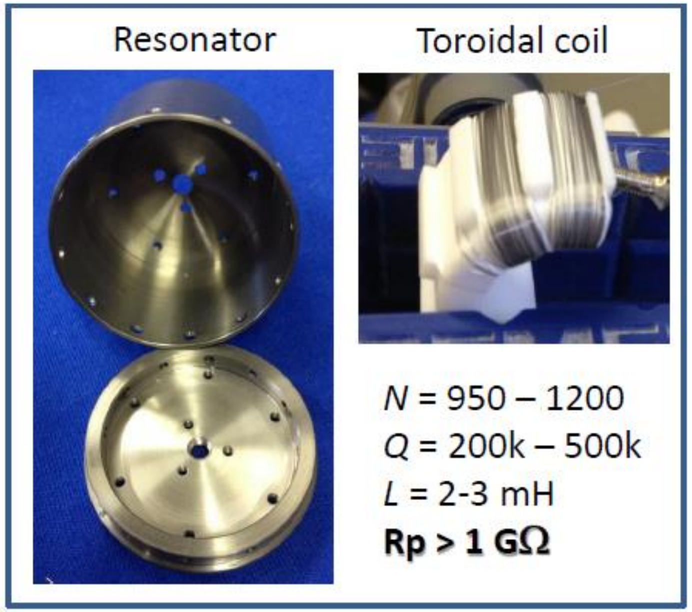
If we add an inhomogeneous field $B = B_0 + B_2(z^2 - \rho^2/2)$ then there is an additional force $\nabla(\mu \cdot B)$ which contributes to the axial trapping force

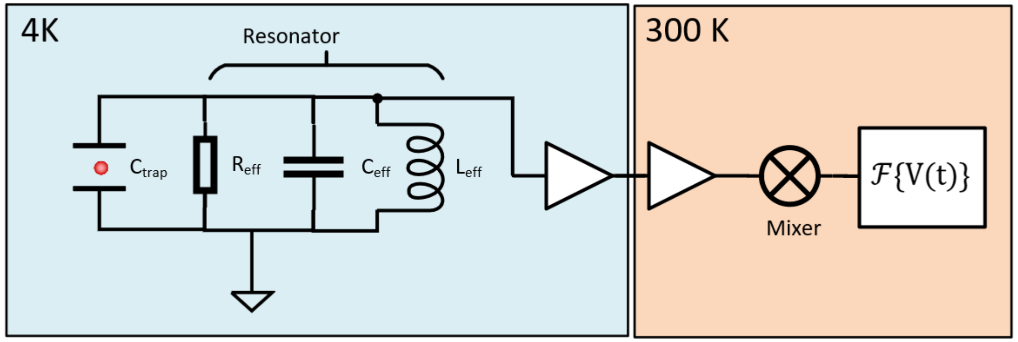
This shifts the axial frequency depending on μ, so the spin state can be identified

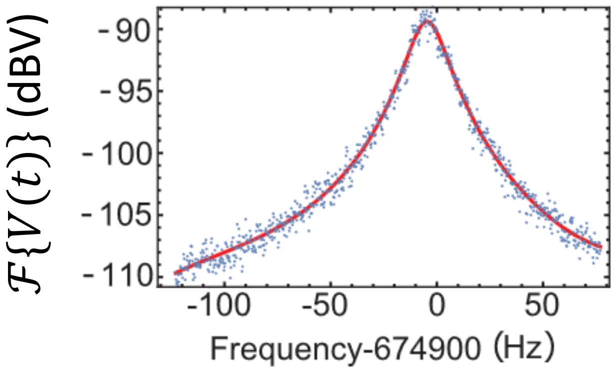
The BASE frequency detection system

Measurement of ~1 fA image currents induced in trap electrodes





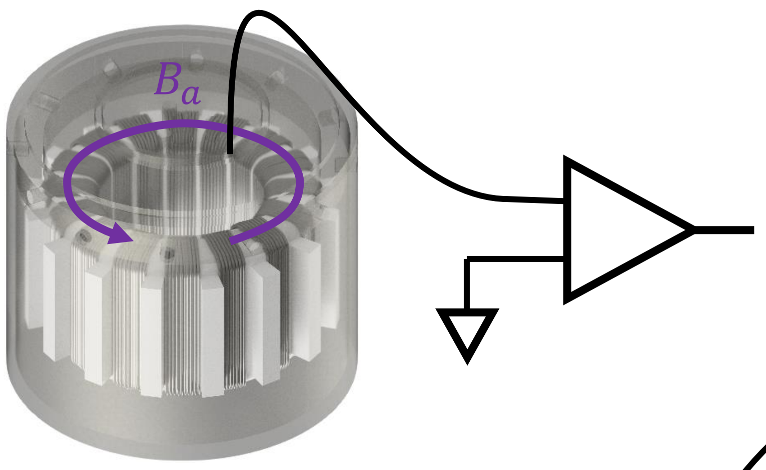




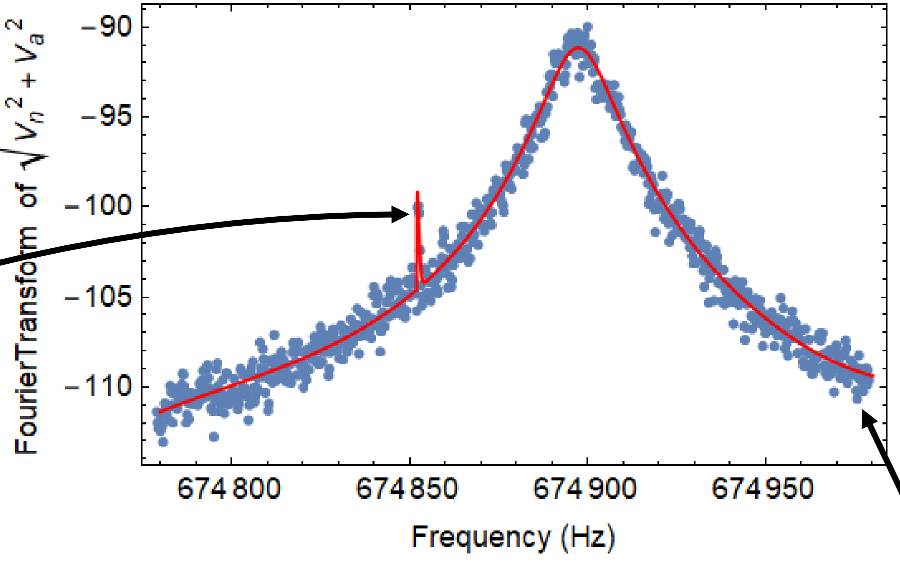
Resolving single antiproton spin flips requires the highest Q and lowest temperature LC resonant detectors ever built- **BASE-CERN is the state of the art**

H. Nagahama *et al.*, Rev. Sci. Instrum. **87**, 113305 (2016).

Expected ALP signal



$$V_{\text{rms}} = \sqrt{V_n^2 + V_a^2}$$



The axion signal

$$V_a = \frac{\pi}{2} Q \sqrt{f(\nu, Q, \mathbf{q})}\, \kappa \nu_a l N_{\mathrm{T}} (r_2^2 - r_1^2) g_{a\gamma} ||\mathbf{B}_e|| \sqrt{\rho_a \hbar c}\,.$$

The resonator background

$$V_n = \sqrt{e_n^2 \Delta\nu + \kappa^2 4 k_B T_z \Delta\nu R_p f(\nu, Q, \mathbf{q})}$$

$f(\nu,Q,\mathbf{q})$ is a lorentzian line-shape function proportional to Re{Z}

e_n is the equivalent input noise of the amplifier

κ is the coupling constant

Q is the resonator Q-factor

N_T is the number of turns

l is the length of the toriod along the magnet B field

r_1 is the inner radius of the toroid

r_2 is the outer radius

$g_{a\gamma}$ is the coupling constant

B is the static magnetic field

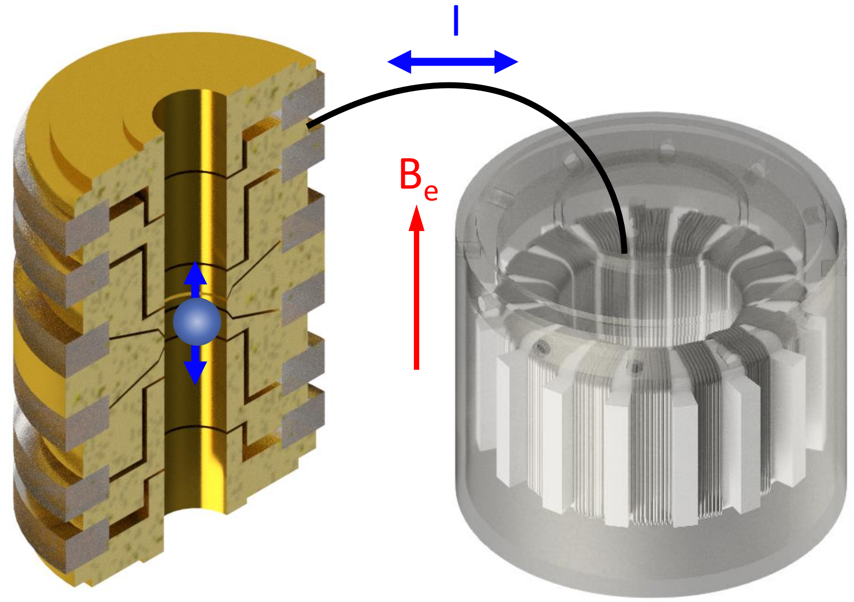
ρ_a is the dark matter density

How to measure T_z?

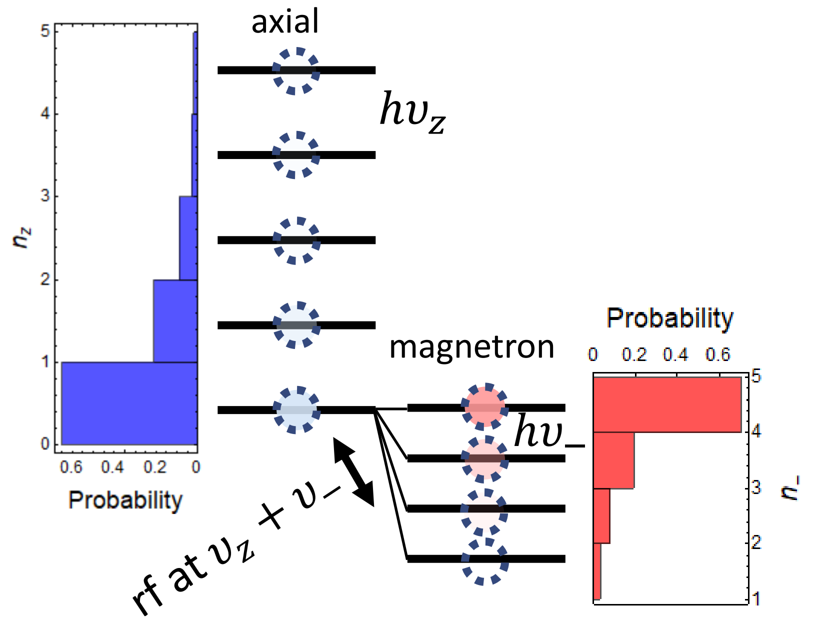
J. A. Devlin et al., Phys. Rev. Lett. **126**, 041301 (2021).

A “Boltzmann” thermometer

1.



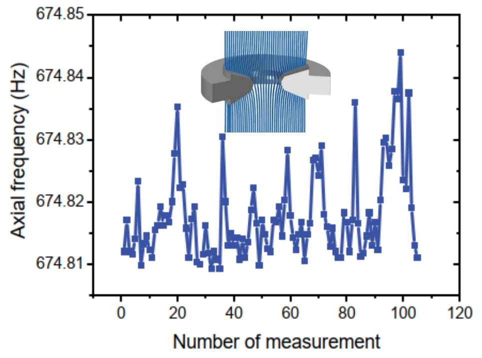
2.



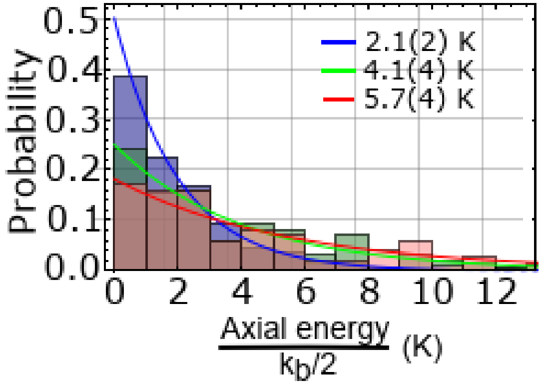
Trapped antiproton’s axial motion reaches thermal equilibrium with the detector- can use it as a “quantum” sensor

3.

Magnetic inhomogneity gives axial frequency shift proportional to $\mu \propto n_-$

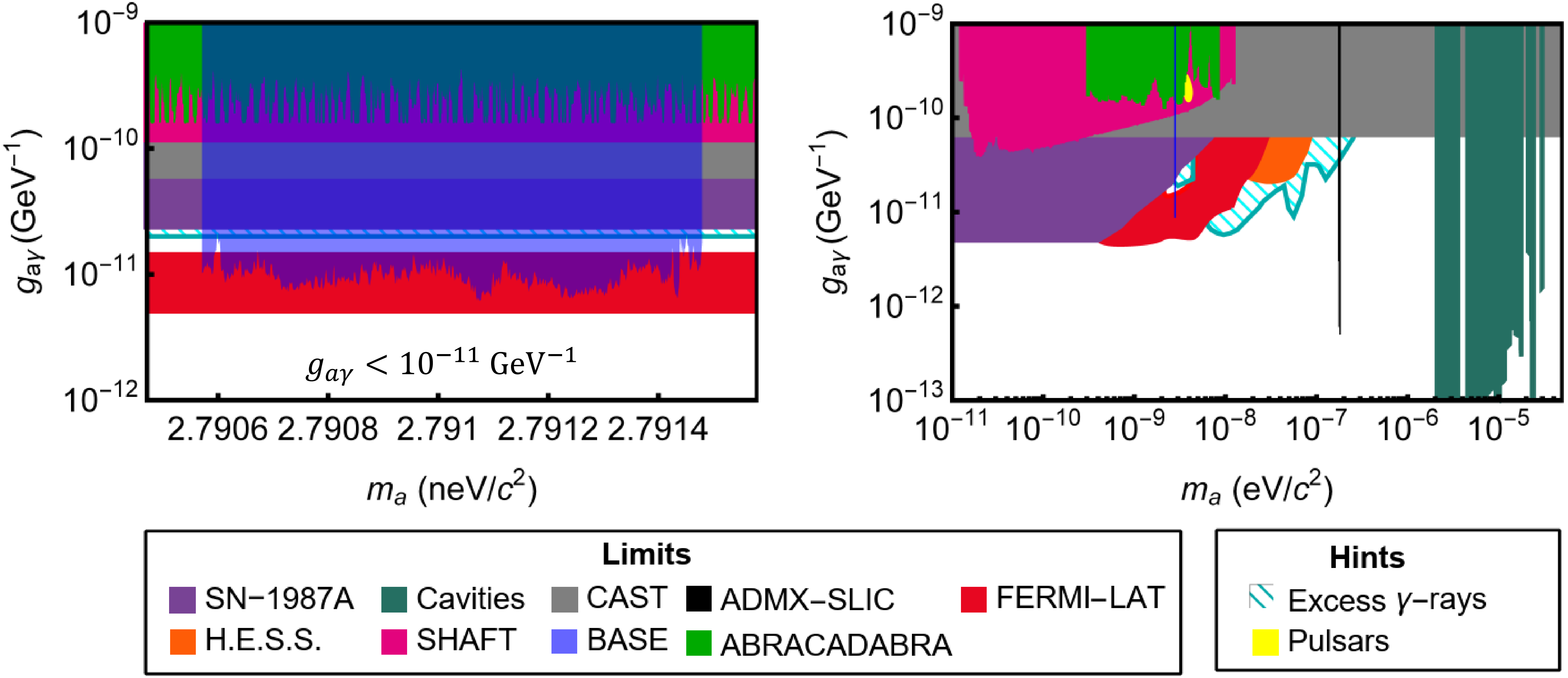


Knowing strength of inhomogeneity, can determine T_z



Limits

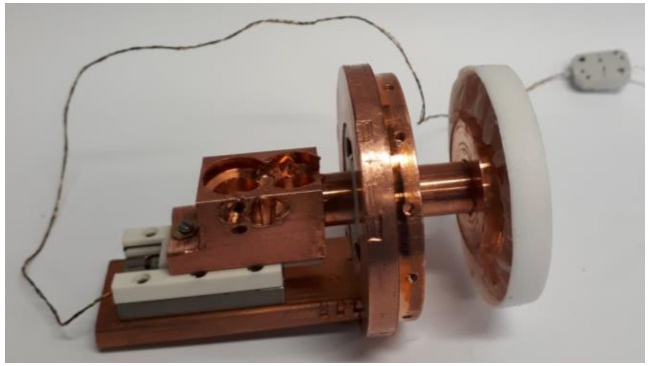
We use maximum likelihood estimation to estimate $g_{a\gamma}$, and then decide if we have a discovery, or set limits

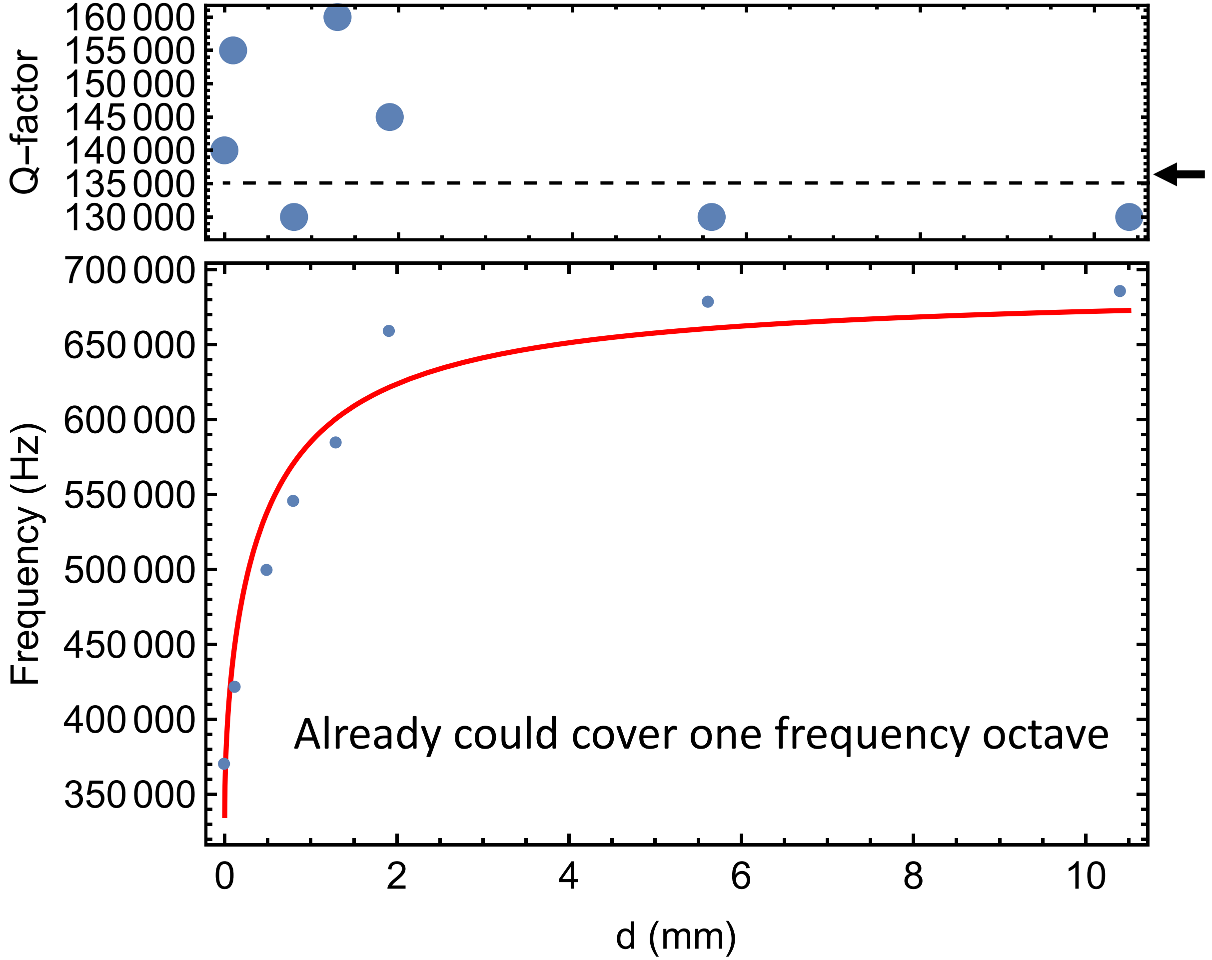


J. A. Devlin et al., Phys. Rev. Lett. **126**, 041301 (2021); J. W. Foster et al. Phys. Rev. D **97** (2018).

Next step: frequency tuning

Cryogenic adjustable capacitance with no loss of Q already developed





Frederik Volksen

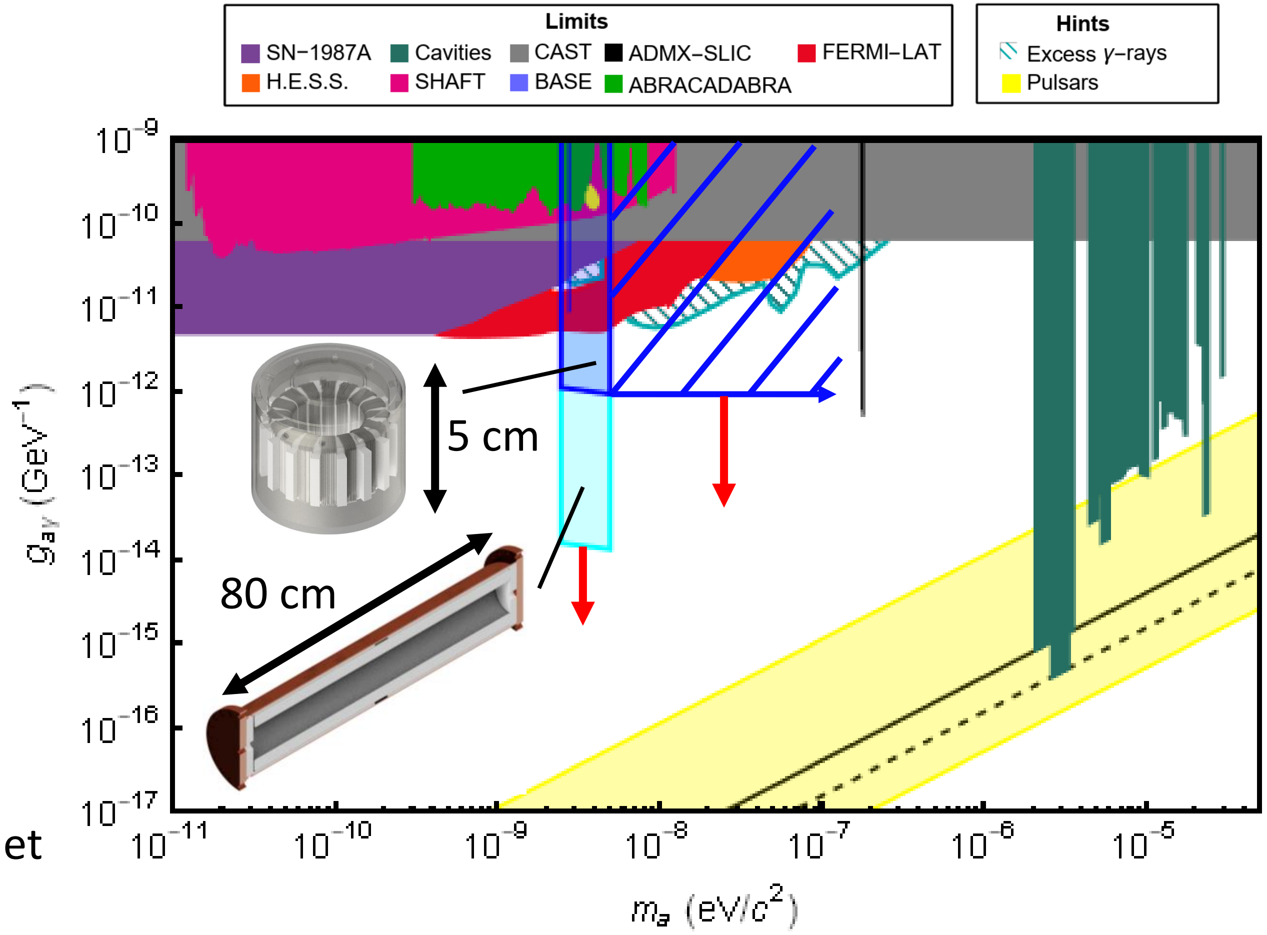
Future potential

Small detector(s): 5 cm long, 5 cm diameter

- **Immediately realizable with BASE technology today**, 6-9 months assembly time
  ($\frac{e_n}{\kappa} = 2.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, 7 T, 1 year acquisition)
- Possible in the short term with detector RnD work using BASE know-how
  ($\frac{e_n}{\kappa} = 2.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, 7 T, 1 year acquisition, use multiple higher frequency coils without excessive Q-loss)

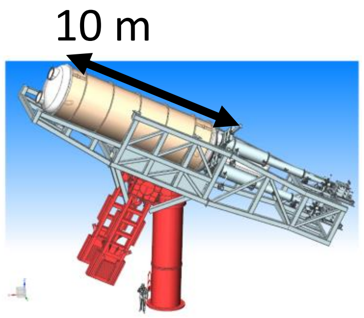
Large detector: 80 cm long, 14 cm diameter

- Optimistic projection, "normal" Penning trap magnet
  ($\frac{e_n}{\kappa} = 2.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, 7 T, 1 year acquisition, 10 mK, Q=200,000)



Pushing the sensitivity further

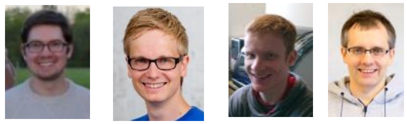
Much large detector volumes- **in discussion with RADES/babyIAXO**
Colder detectors- **laser cooled resonators?**
Lower noise amplifiers – particle assisted readout?



arXiv:2010.12076 [physics.ins-det]

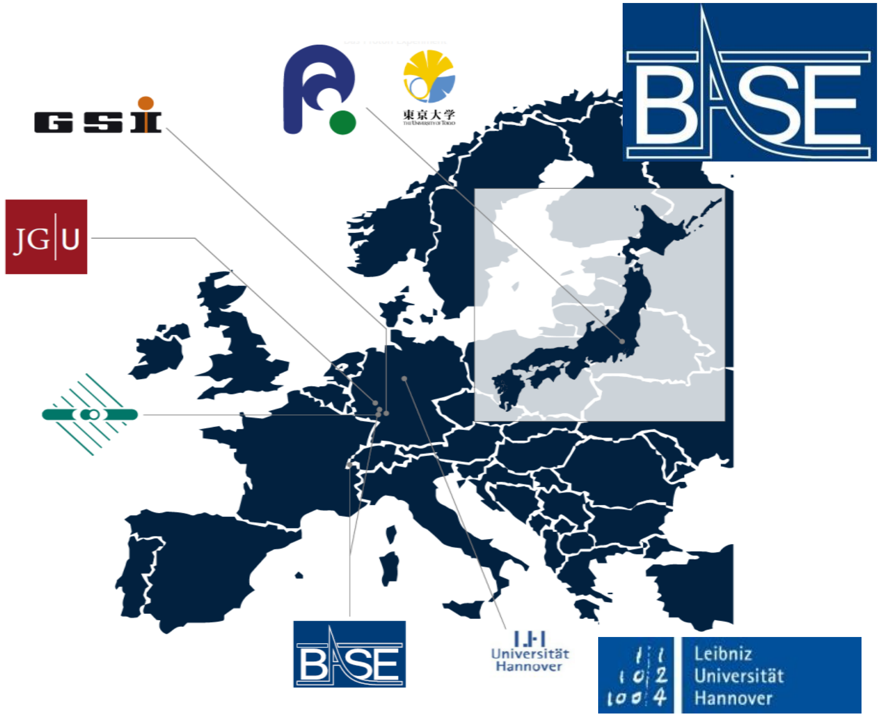
Thank you!

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies

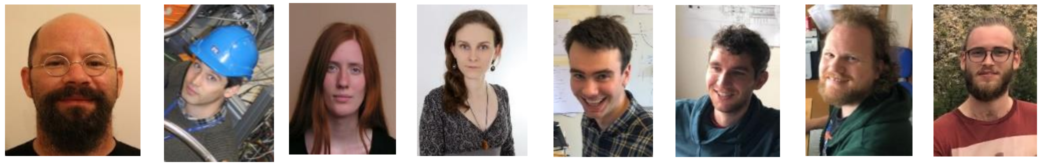


- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio
- **Hannover/PTB:** QLEDS-laser cooling project, new technologies

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015).



Institutes: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig



Team at CERN