Detecting dark matter at BASE-CERN

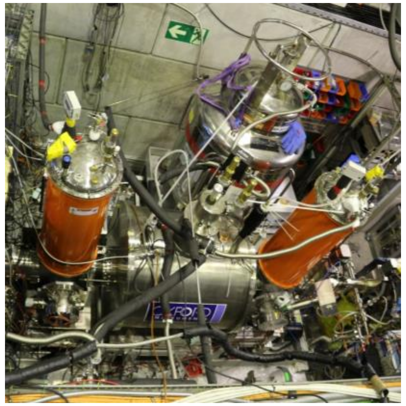
Jack Devlin (CERN, RIKEN)

Outline

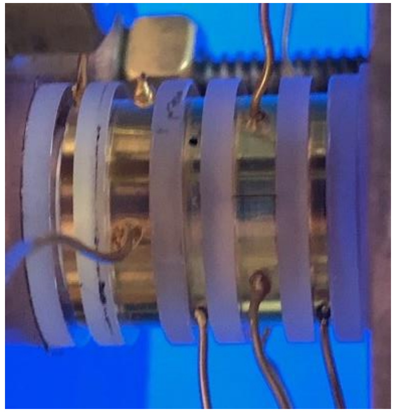
1. Couplings between antiprotons and dark matter
2. Dark matter decays in the BASE detectors
3. Future perspectives

The BASE experiment

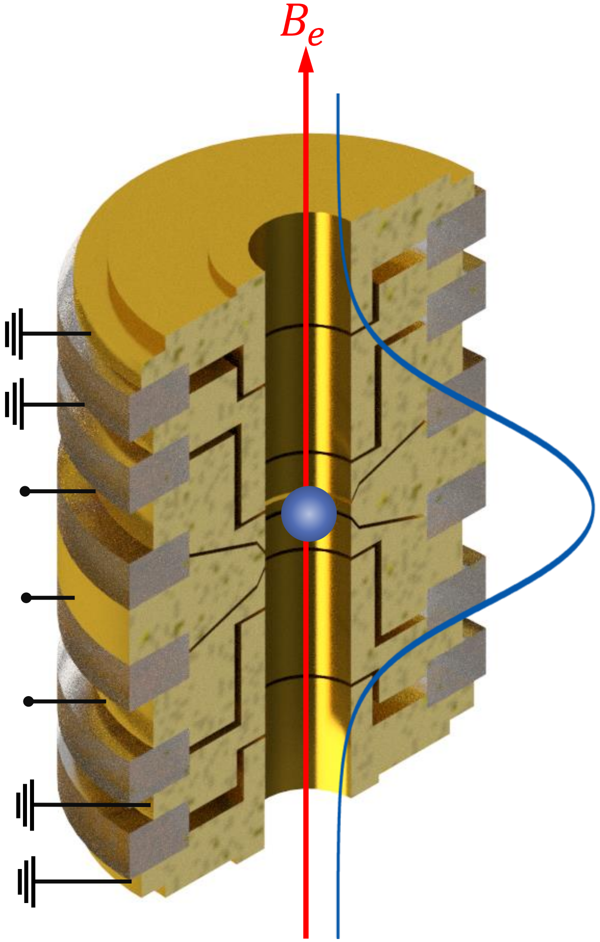
1.95 T B field from solenoid



Voltages applied to ring-shaped electrodes



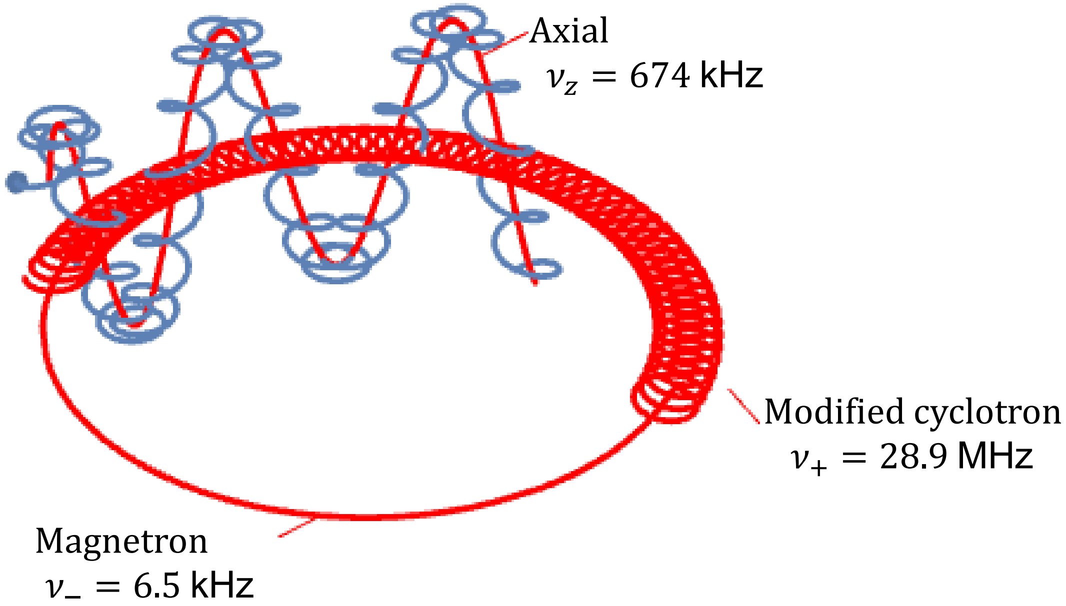
A Penning trap



$\Phi(0,z)$

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

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

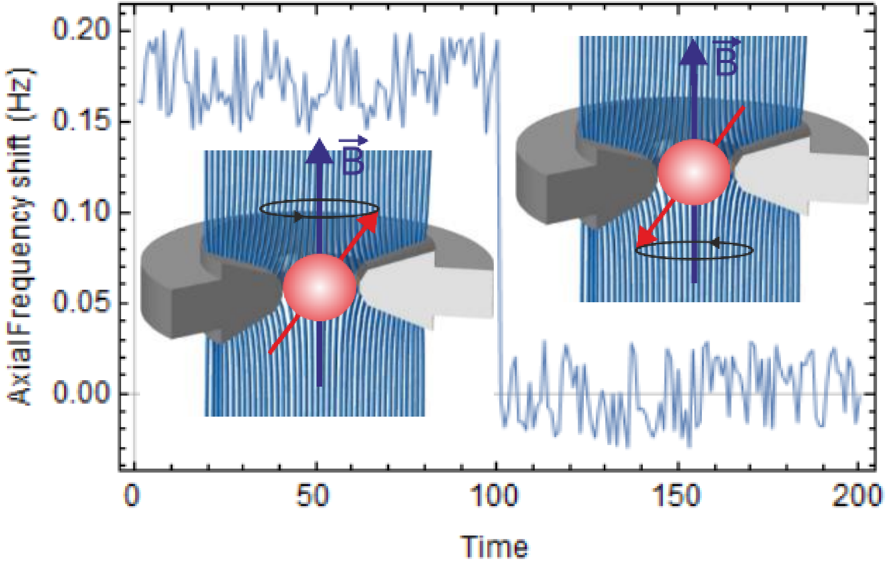
Measuring magnetic moments

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

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

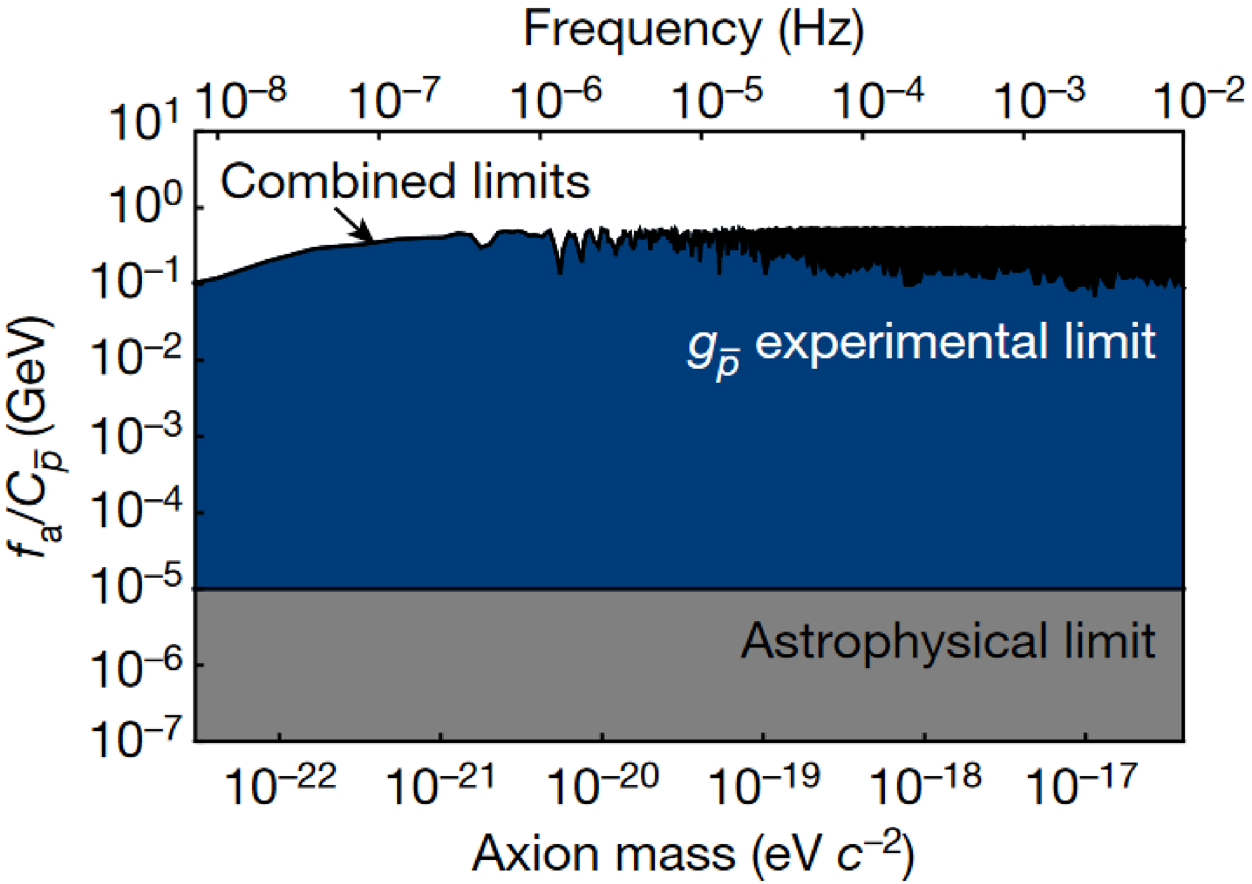
Couplings between dark matter and antiprotons

Measure the coupling $\mathcal{L}_{\text{int}} = -\frac{\partial a}{f_a}\bar{\psi}\gamma^{\mu}\gamma^{5}\,\psi$ between ultralight, pseudoscalar ALP relic dark matter and $\bar{p}$

Interaction

$$H_{\text{int}} = -\frac{C_{\bar{p}}a_0}{2f_a}\sin(\omega_a t)\,\vec{\sigma}_{\bar{p}}\cdot\vec{p}_a$$

between the momentum of the axion field $\vec{p}_a$ and the antiproton spin vector $\vec{\sigma}_{\bar{p}}$ oscillating at the axion Compton frequency $\omega_a = m_a c^2/\hbar$



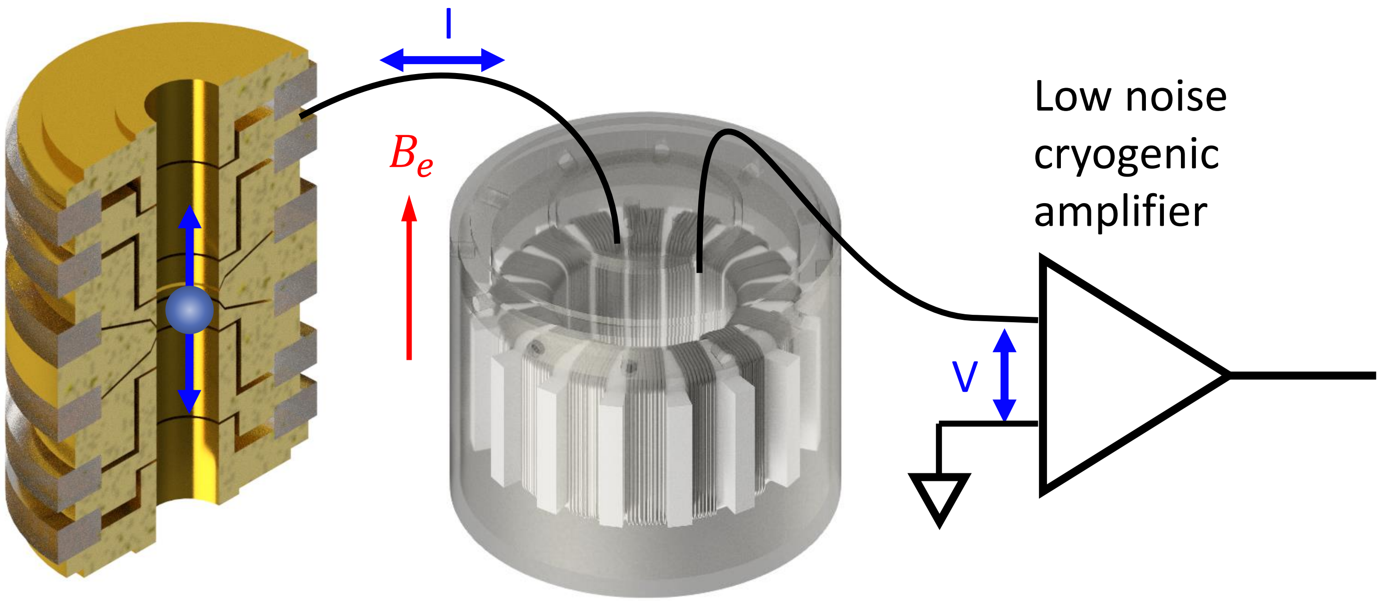
Should cause characteristic time dependent variation in ν_L, by constraining the size of this a-$\bar{p}$ coupling limits extracted

a- $\bar{p}$ coupling limits a natural bi-product of precision CPT tests

C. Smorra *et al.*, Nature **575**, 310 (2019).

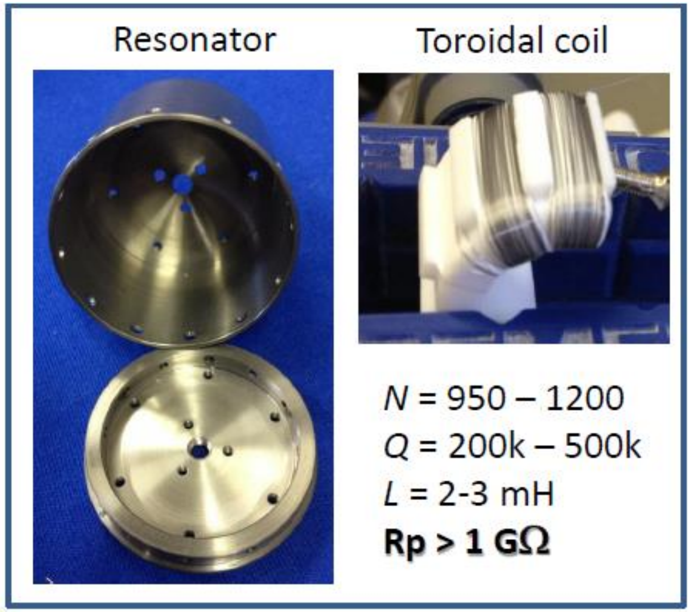
The BASE frequency detection system

Measurement of ~1 fA image currents induced in trap electrodes

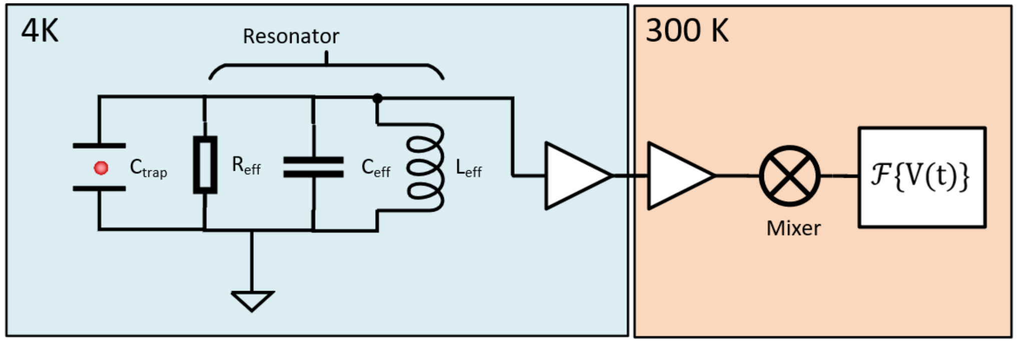


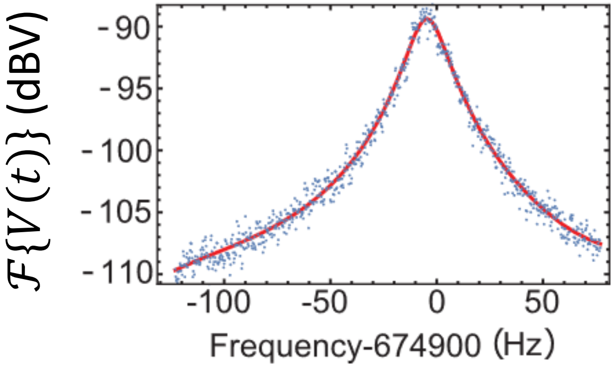
Low noise cryogenic amplifier

To room temp. amps



N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ

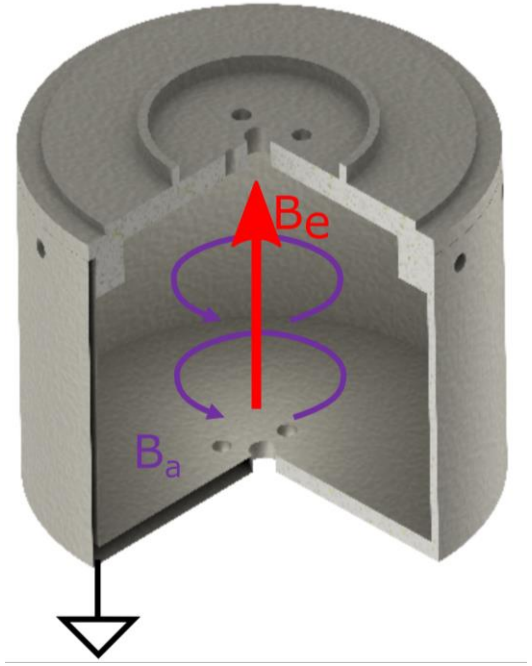




Resolving single antiproton spin flips requires the highest Q and lowest temperature LC resonant detectors ever built- **BASE-CERN is the state of the art**

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

Conversion of Axion-like particles into photons in the detector



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

This modifies Maxwell’s equations

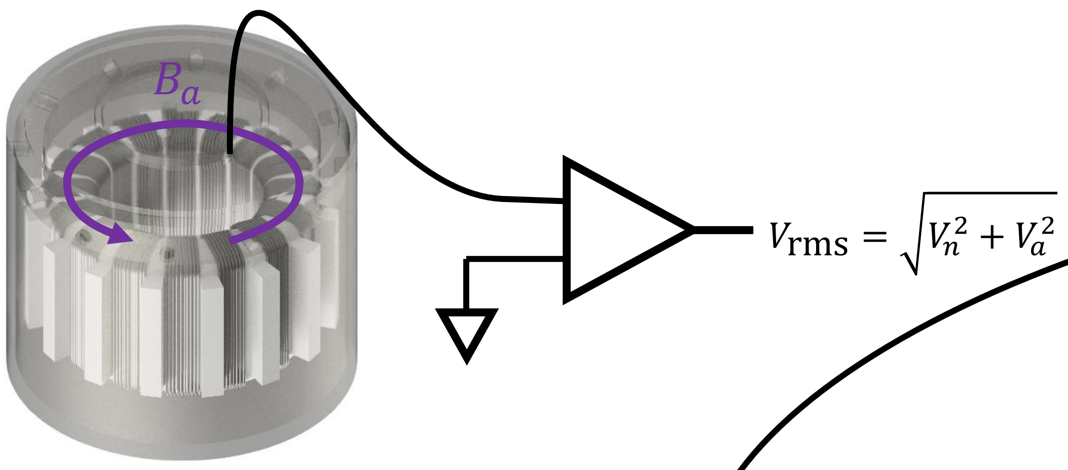
$$\nabla \cdot \vec{E} = \rho - g_{a\gamma}\,\vec{B} \cdot \nabla a$$
$$\nabla \times \vec{B} - \partial_t \vec{E} = \vec{J} + g_{a\gamma}(\vec{B}\partial_t a - \vec{E} \times \nabla a)$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} + \partial_t \vec{B} = 0$$

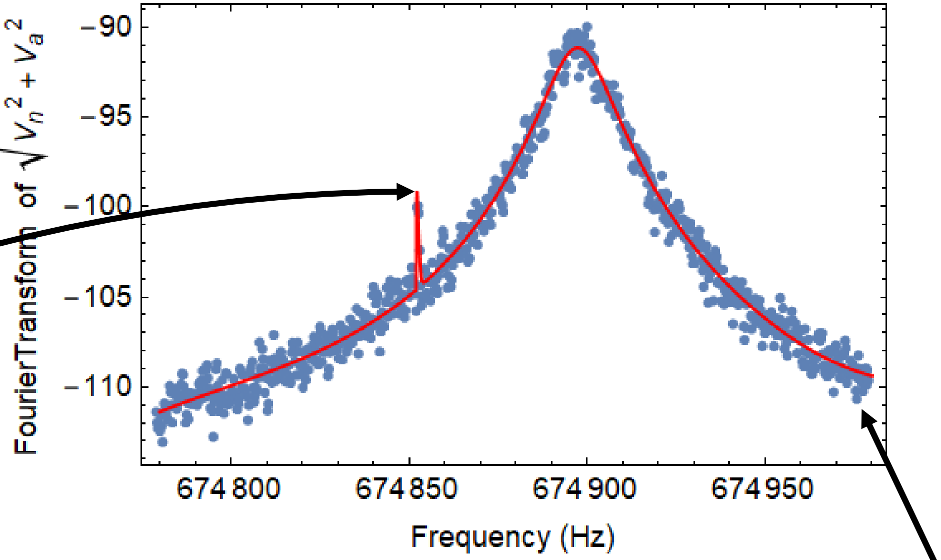
Inside the resonator housing, $d \ll \lambda_a$, and where there is a strong field B_e, the axions source a magnetic field

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

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

Expected signal





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(ν,Q,**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

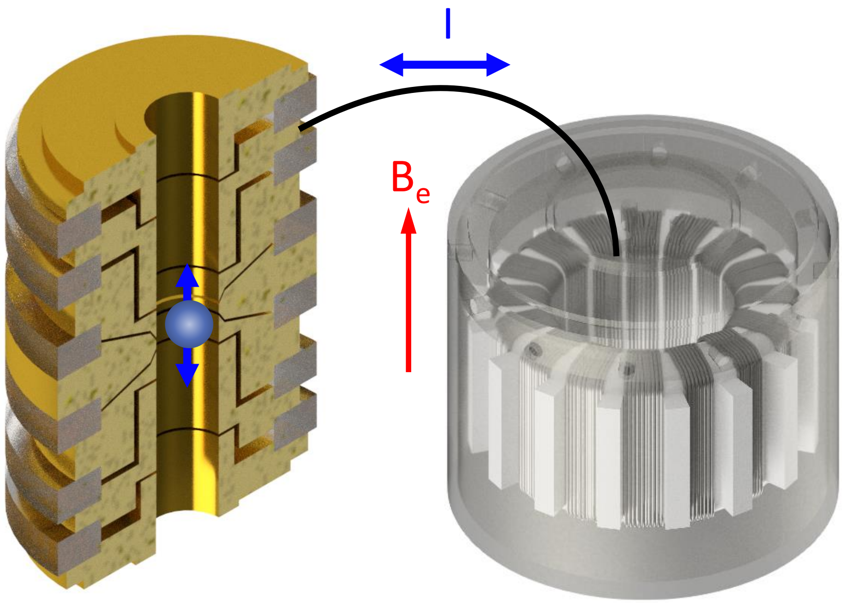
ρ_a is the dark matter density

How to measure T_z?

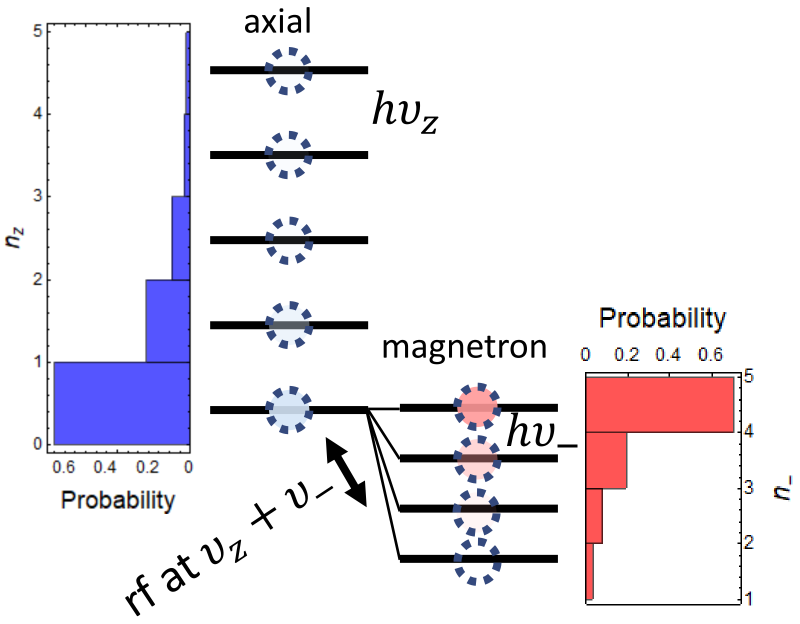
J. A. Devlin et al., Phys. Rev. Lett. **126**, 041301 (2021).

A quantum “Boltzmann” thermometer

1.



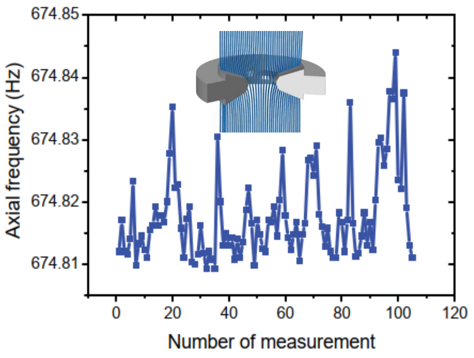
2.



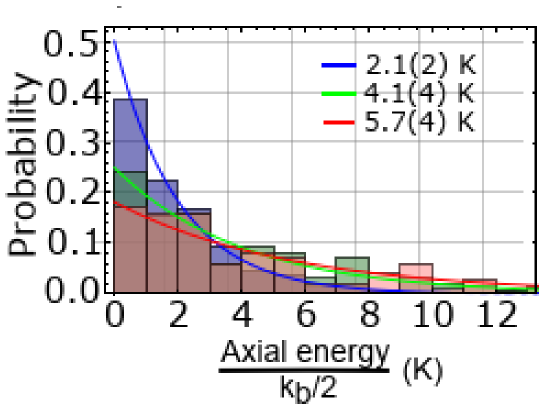
Trapped antiproton’s axial motion reaches thermal equilibrium with the detector- can use it as a “quantum” sensor

3.

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

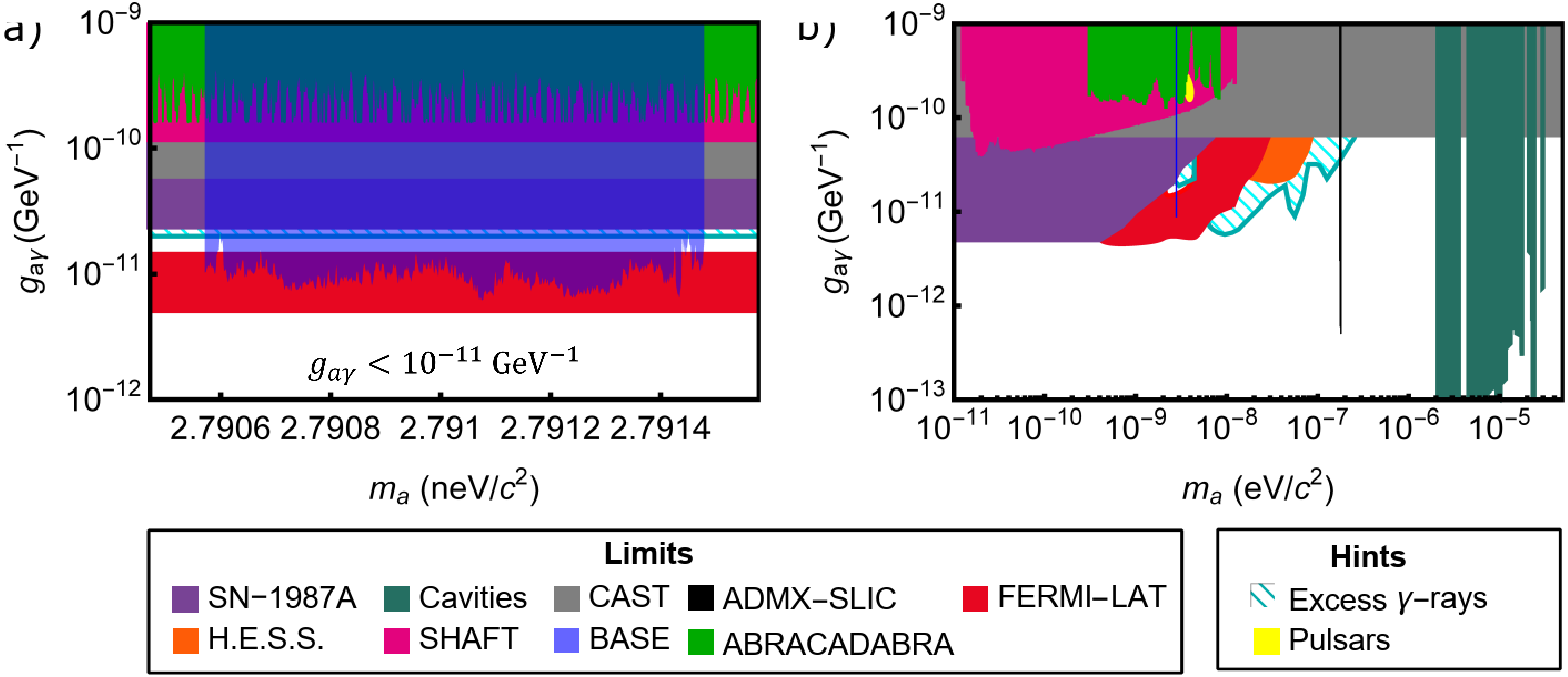


Knowing strength of inhomogeneity, can determine T_z



Limits

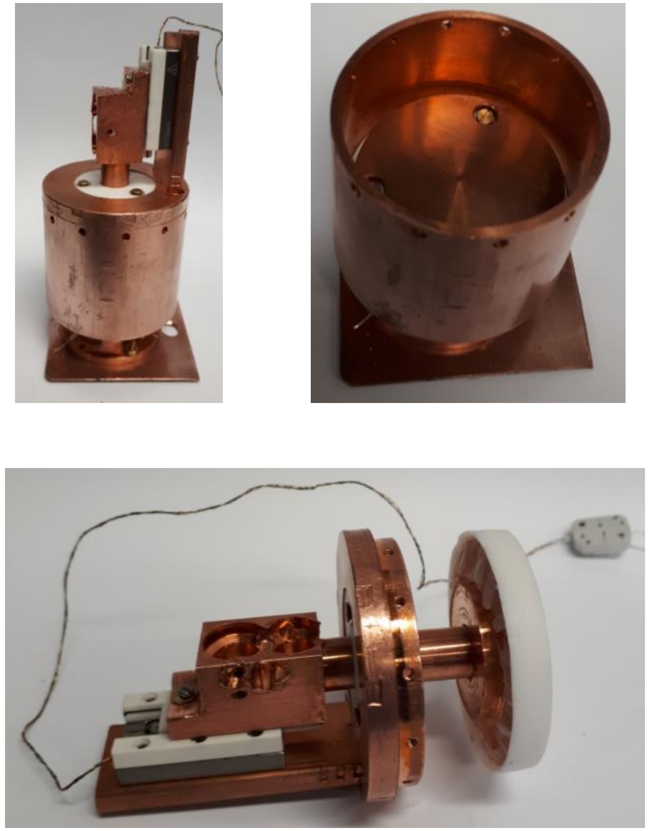
We use maximum likelihood estimation to estimate $g_{a\gamma}$, and then decide if we have a discovery, or set limits

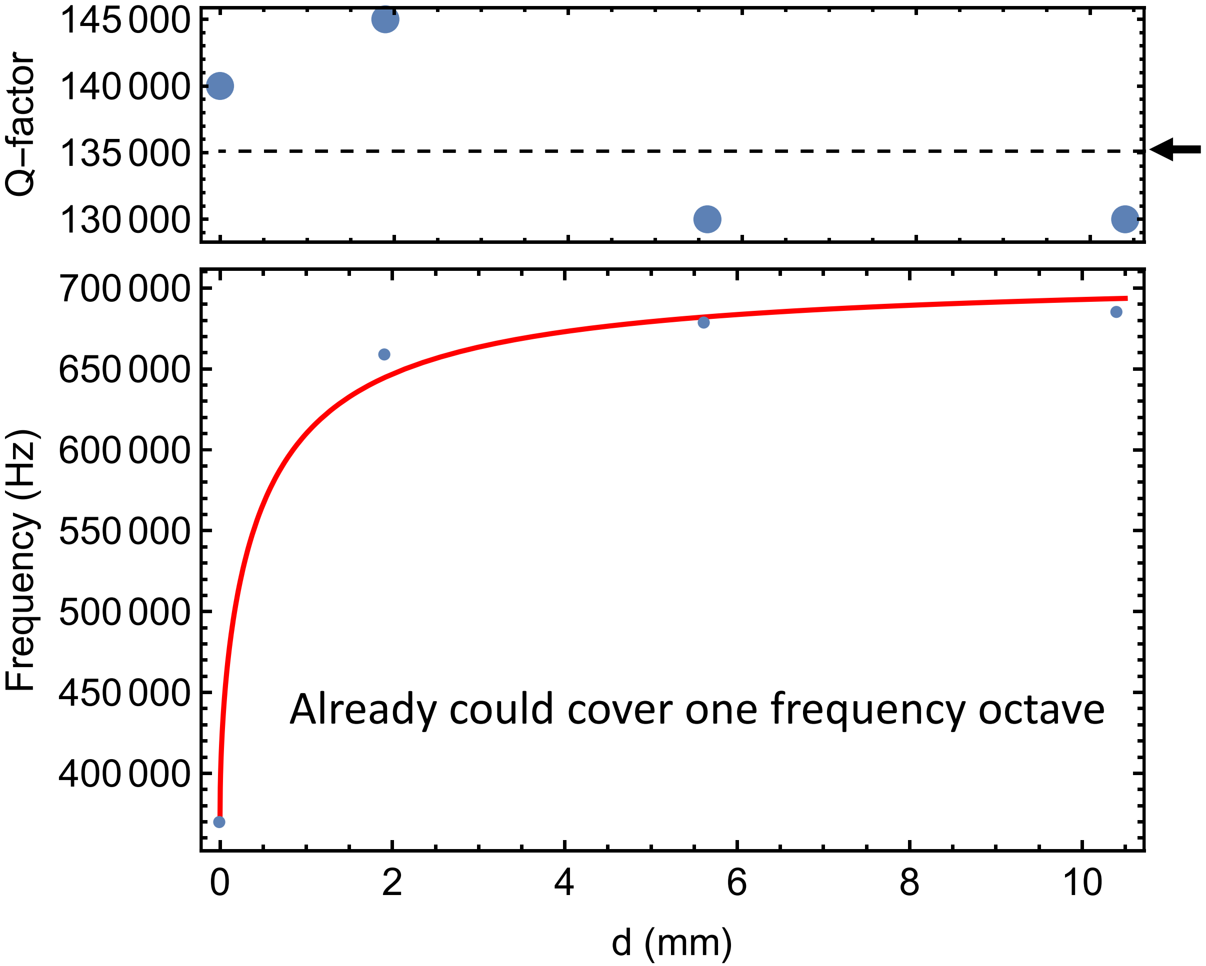


J. A. Devlin et al., Phys. Rev. Lett. **126**, 041301 (2021); J. W. Foster et al. Phys. Rev. D **97** (2018).

Next step: frequency tuning

Cryogenic adjustable capacitance with no loss of Q already developed





Already could cover one frequency octave

Frederik Volksen

Future potential

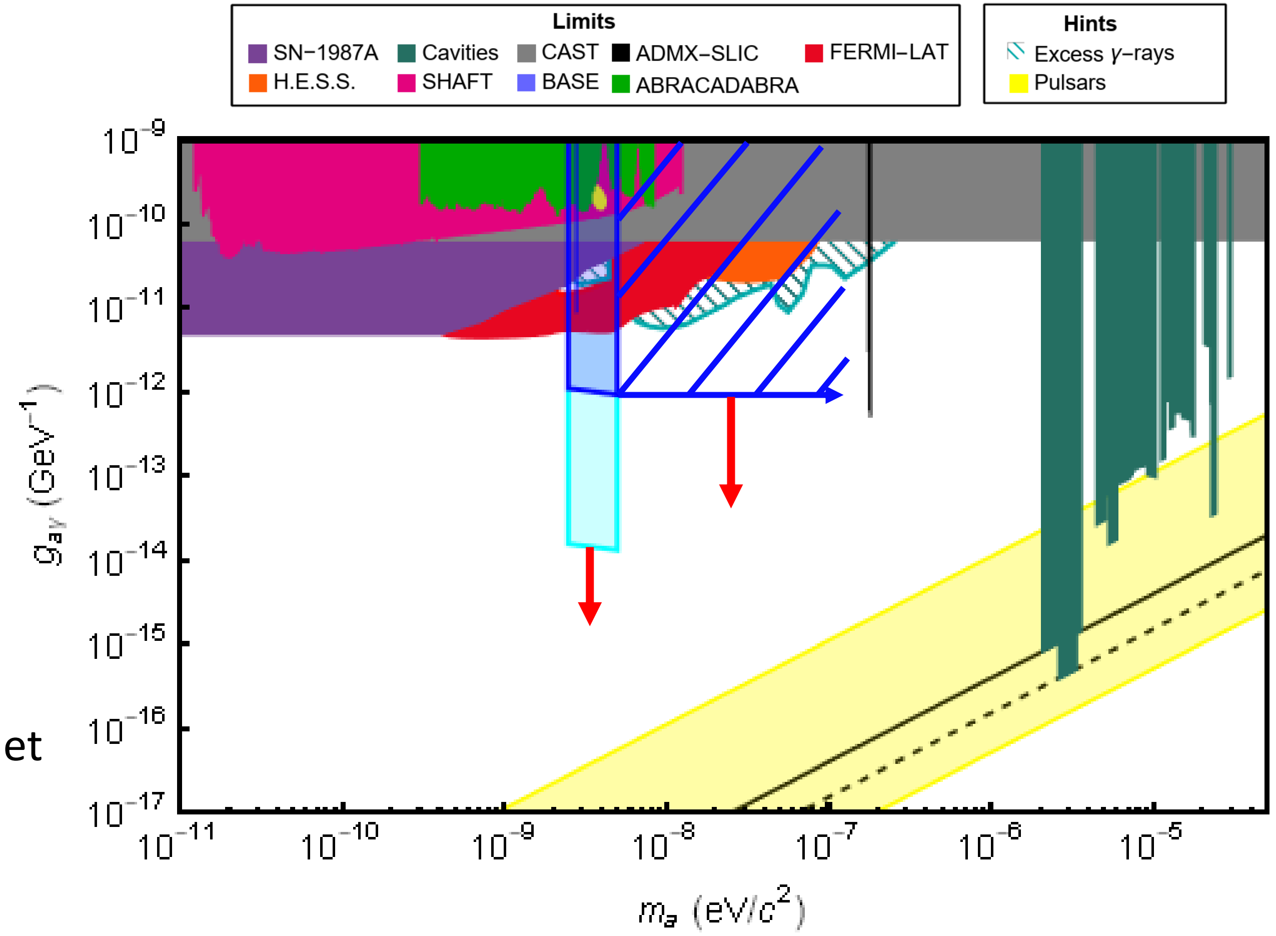
Small detector(s): 5 cm long, 5 cm diameter

🟦 **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?

Input from other CERN experts appreciated!
e.g. NbTi coating or HTS tape for large cavities.

Takeaway message-unique possibilities at BASE

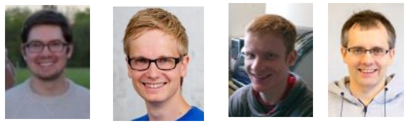
1. Long-term investigations of **antiproton**-relic **dark matter** coupling

2. Transfer **state-of-the-art technologies** developed for high precision antimatter measurements to detect relic dark matter particles

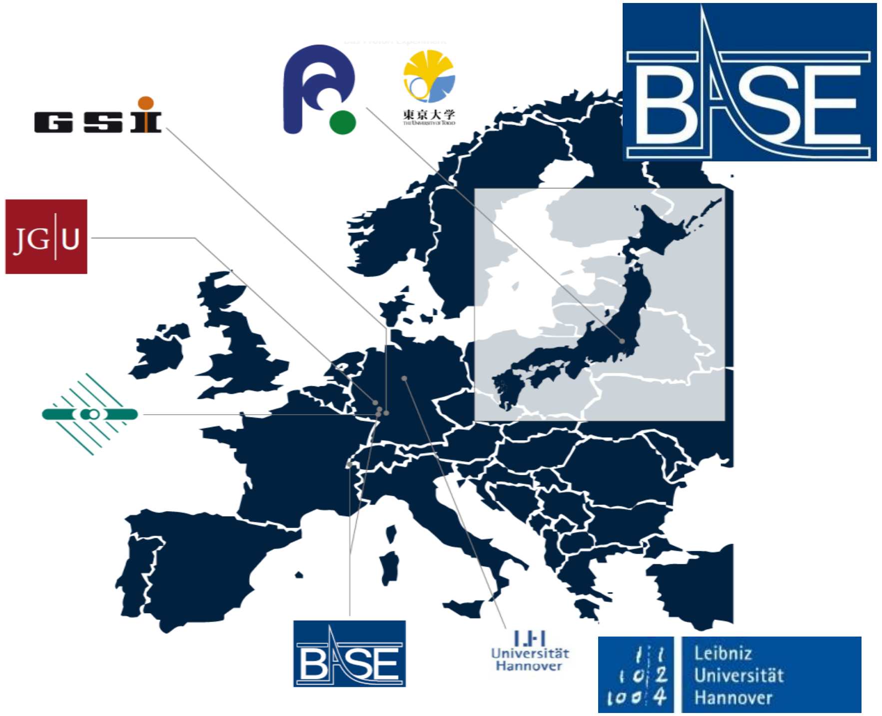
3. BASE Penning traps at CERN as an interface between **quantum measurement** techniques and large detectors for weak EM radiation

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




The European Physical Journal volume 224 · number 1 · February 2015

EPJ ST

Special Topics

THE BASE EXPERIMENT

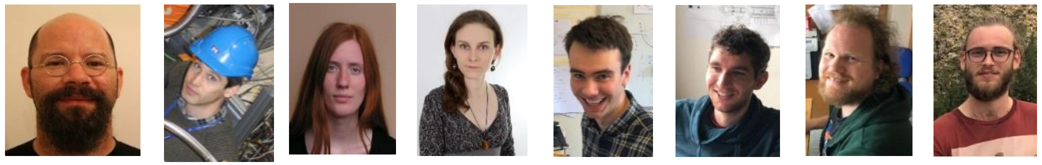
Experiment of the moment

Physik Journal

In die Falle gegangen
An der Schwelle zum Laser
Auf Dauer befristet
DPG-Preise 2017

RIKEN 東京大学 JOHANNES GUTENBERG UNIVERSITÄT MAINZ Leibniz Universität Hannover GSI

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



Team at CERN

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