A ppb measurement of the antiproton magnetic moment

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on behalf of the BASE collaboration

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LETTER

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A parts-per-billion measurement of the antiproton magnetic moment

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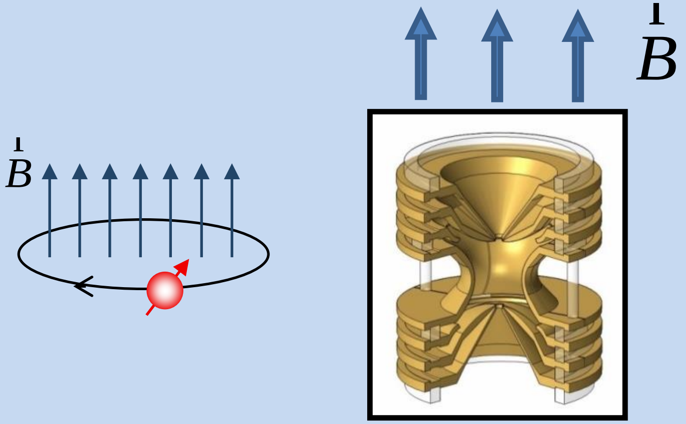
Motivation:

- **Test of CPT invariance as fundamental symmetry in the Standard Model of particle physics**
- **Probe for new interactions, e.g. Standard Model Extension or CPT-odd dimension-five interactions**
- **The mechanism which generates the matter excess in the universe is not understood**
- **Determination of a fundamental antiparticle property**

C. Smorra et al., Nature 550, 371 (2017).

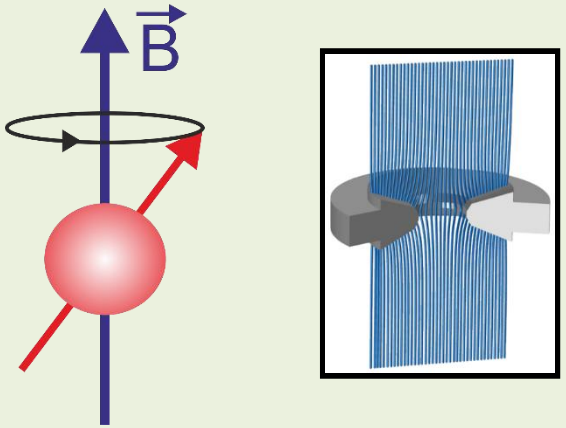
High-precision measurements in Penning traps

Cyclotron Frequency



$$\omega_c = \frac{q}{m} B$$

Larmor Frequency

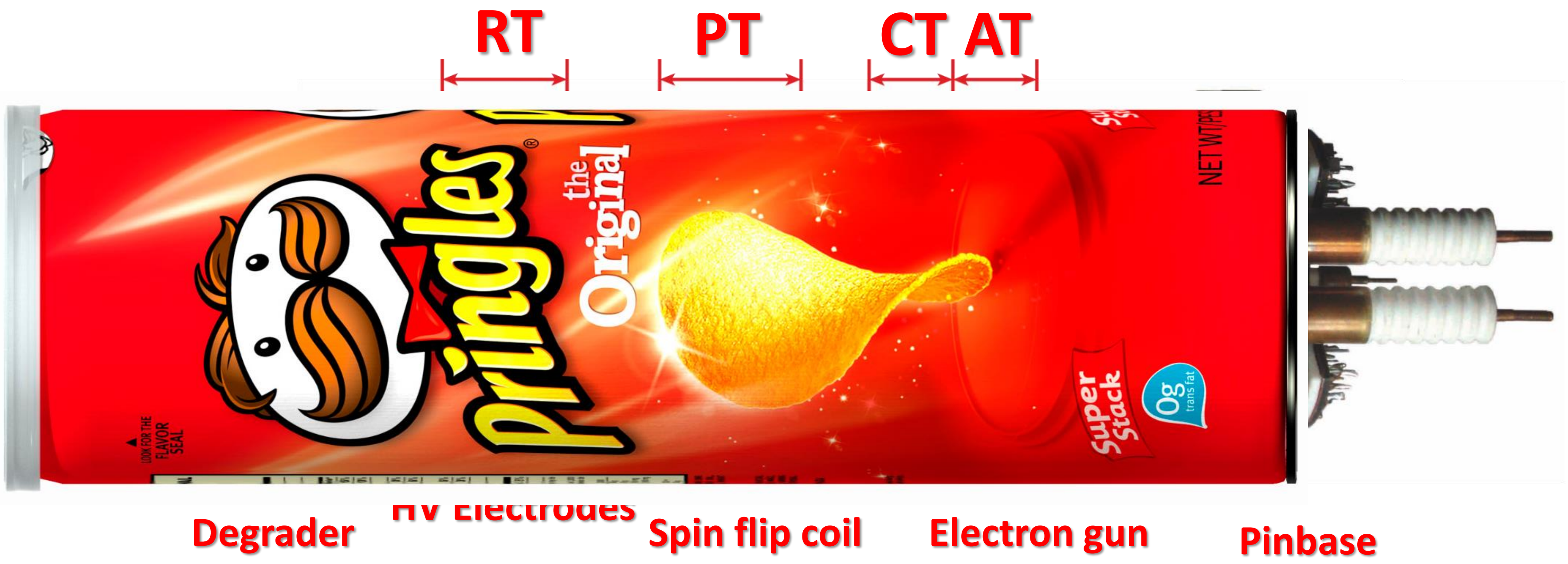


$$\omega_L = g \frac{e}{2m_p} B$$

$$\frac{\omega_L}{\omega_c} = \frac{g}{2} = \frac{\mu}{\mu_N}$$

H. G. Dehmelt and P. Ekström, Bull. Am. Phys. Soc. 18, 72 (1973).
D. J. Wineland and H. G. Dehmelt, J. Appl. Phys. 46, 919 (1975).

The BASE four Penning-trap system



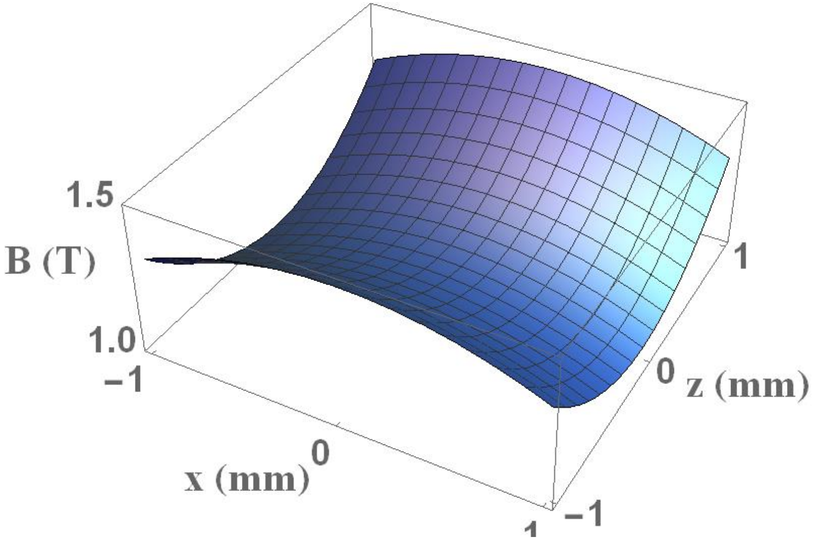
RT: Reservoir Trap: Offline source for single antiprotons

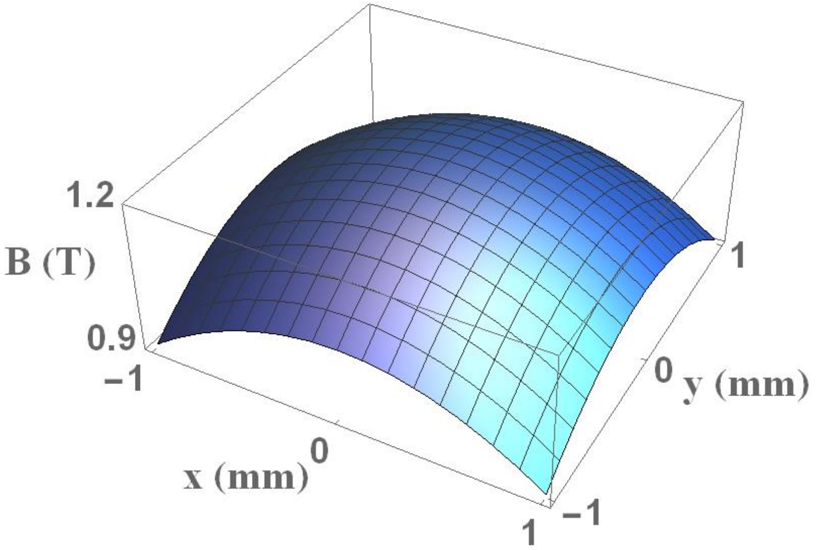
PT: Precision Trap: Homogeneous field for frequency measurements

CT: Cooling Trap: Fast cooling of the cyclotron motion

AT: Analysis Trap: Spin-state detection in a magnetic bottle: **B_2 = 300000 T / m^2**

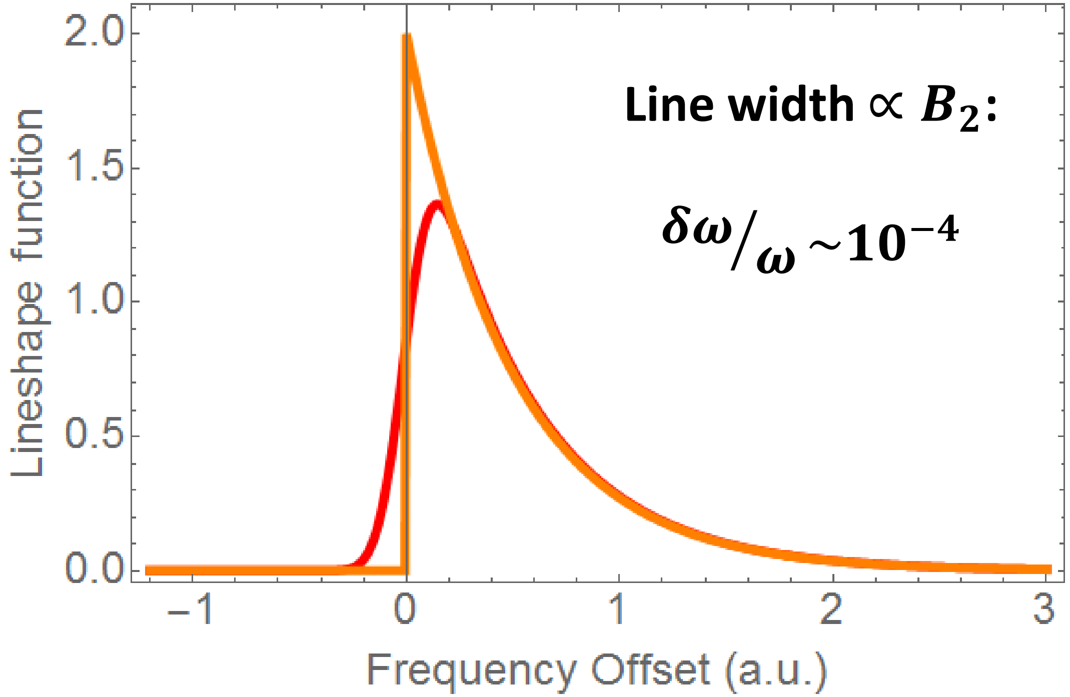
Measurements in the Analysis Trap





$$\omega_c = \frac{q}{m} B$$

$$\omega_L = g \frac{e}{2m_p} B$$



Line width $\propto B_2$:

$$\delta\omega/_{\omega} \sim 10^{-4}$$

$$\frac{\omega_L}{\omega_c} = \frac{g}{2} = \frac{\mu}{\mu_N}$$

In the magnetic bottle:
Measurement limits at the 10^{-6} level

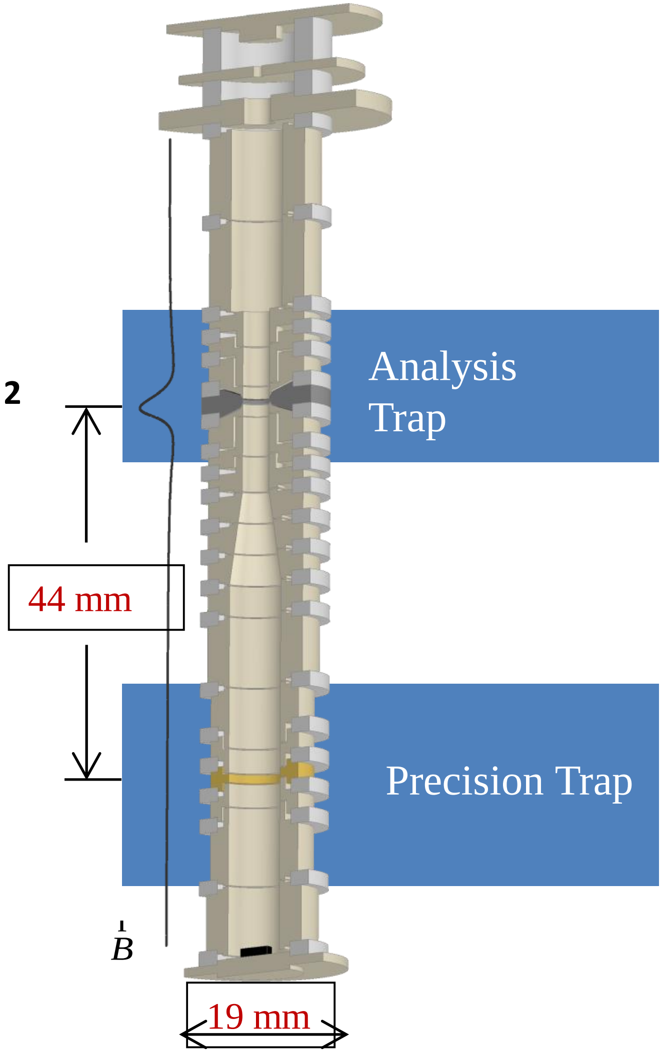
Double Trap Measurement Principle

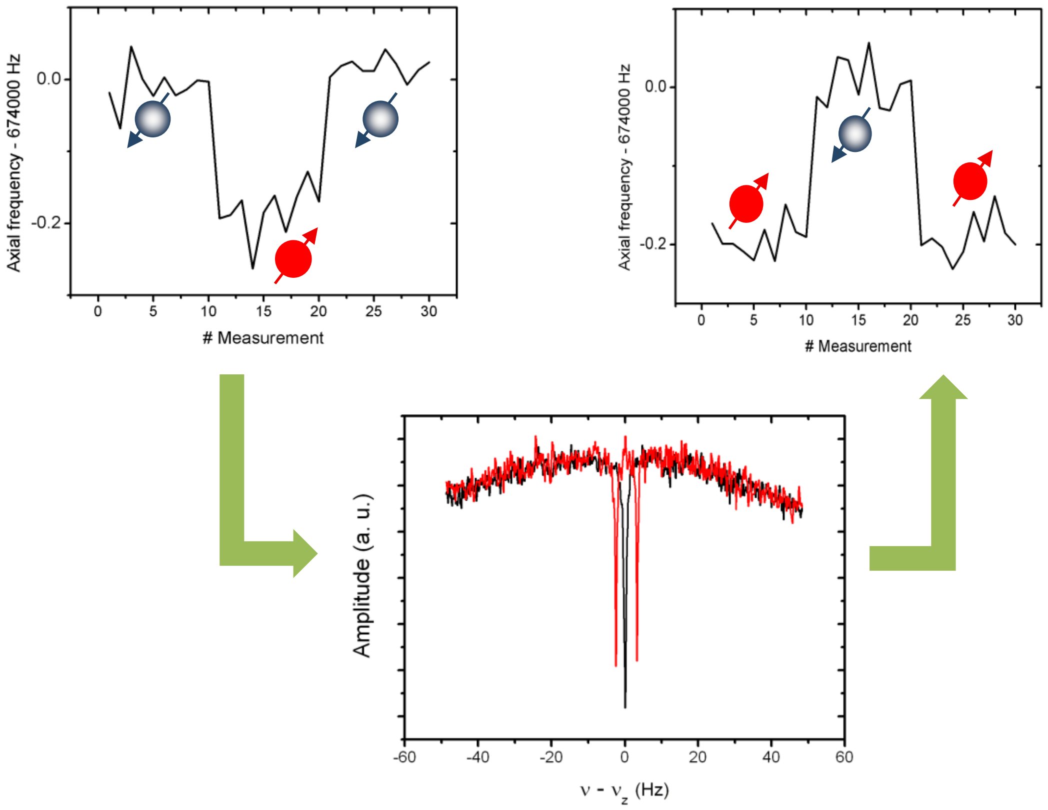
High precision due to spatially separated spin state analysis and precision frequency measurements.

Proton trap system (Mainz University)

$B_2 = 300000$ T/m²

$B_2 < 5$ T/m²





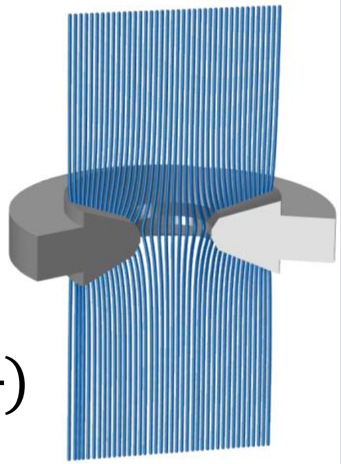
H. Dehmelt and P. Ekström, Bull. Am. Phys. Soc. 18, 72 (1973).
E. A. Cornell et al., Phys. Rev. A 41, 312 (1990).
H. Häffner, Phys. Rev. Lett.85, 5308 (2000).
A. Mooser, K. Franke *et al.* Phys. Lett. B 723, 78 (2013).

REQUIREMENT
SINGLE SPIN-FLIP DETECTION

Spin-state readout in a magnetic bottle

$$\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$$

$$B_z = B_0 + B_2 \left(z^2 - \frac{\rho^2}{2}\right)$$



The magnetic bottle couples also the magnetic moment to the radial motion to the axial frequency!

$$\frac{\Delta\nu_z}{\nu_z} = \frac{1}{4\pi\, m_p\, \nu_z^2} \frac{B_2}{B_0} \left[h\nu_+ \left(n_+ + \frac{1}{2}\right) + h\nu_- \left(n_- + \frac{1}{2}\right) + \frac{g}{2} h\nu_c n_S \right]$$

orbital angular momentum

spin angular momentum

Measurement needs to be done at constant n_+, n_-!

$$\frac{dn_{+,-}}{dt} \sim \frac{q^2}{2\, m_p\, h\, \nu_{+,-}} n_{+,-} \Lambda^2 \langle e_n(t), e_n(t-\tau) \rangle$$

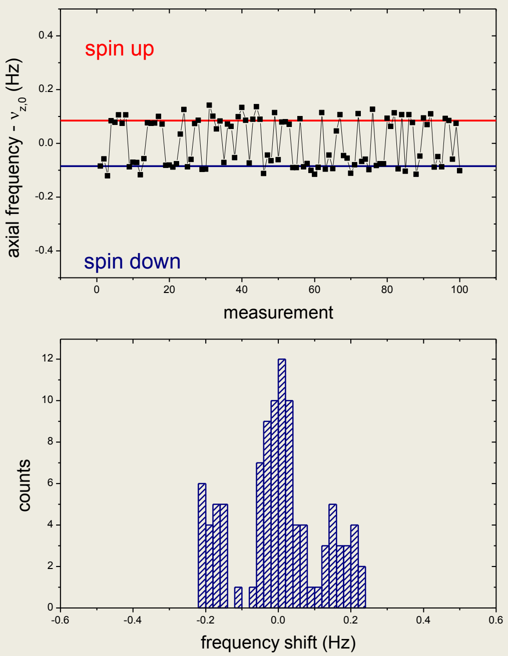
Energy in the mode

Electric field noise density

Challenges – High-Fidelity Single Spin-Flip Resolution

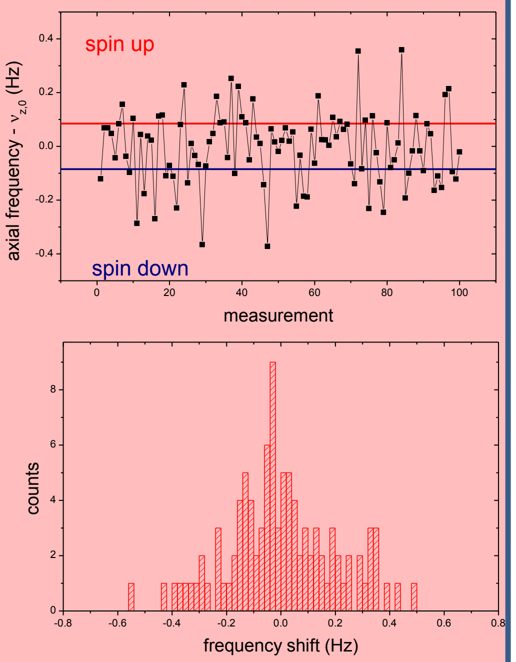
observation of antiproton spin transitions with high-fidelity requires ultra-cold particles

cold particle (50mK)



high-fidelity spin state resolution

hot particle (1K)



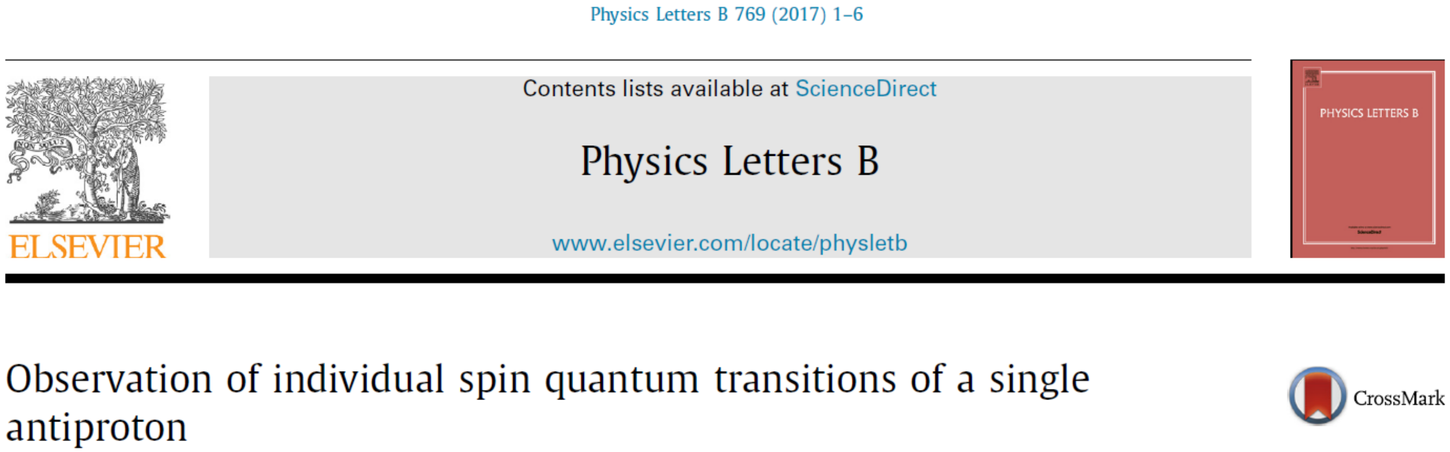
fidelity at 65%, not useful for measurements

- Physics
  - heating by rf at a noise density of about $100\ \mathrm{pV}/\sqrt{\mathrm{Hz}}$ drive radial cyclotron quantum transitions.
  - transition rates scale with the cyclotron quantum number.

$$\frac{dn_{+,-}}{dt} \approx \frac{q^2}{2m_{\bar{p}}h\nu_{+,-}} n_{+,-} \Lambda^2 \langle e_n(t), e_n(t-\tau) \rangle$$

C. Smorra *et al.*, Phys. Lett. B **769**, 1-6 (2017).

Single antiproton spin-transitions


Physics Letters B 769 (2017) 1–6

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Physics Letters B

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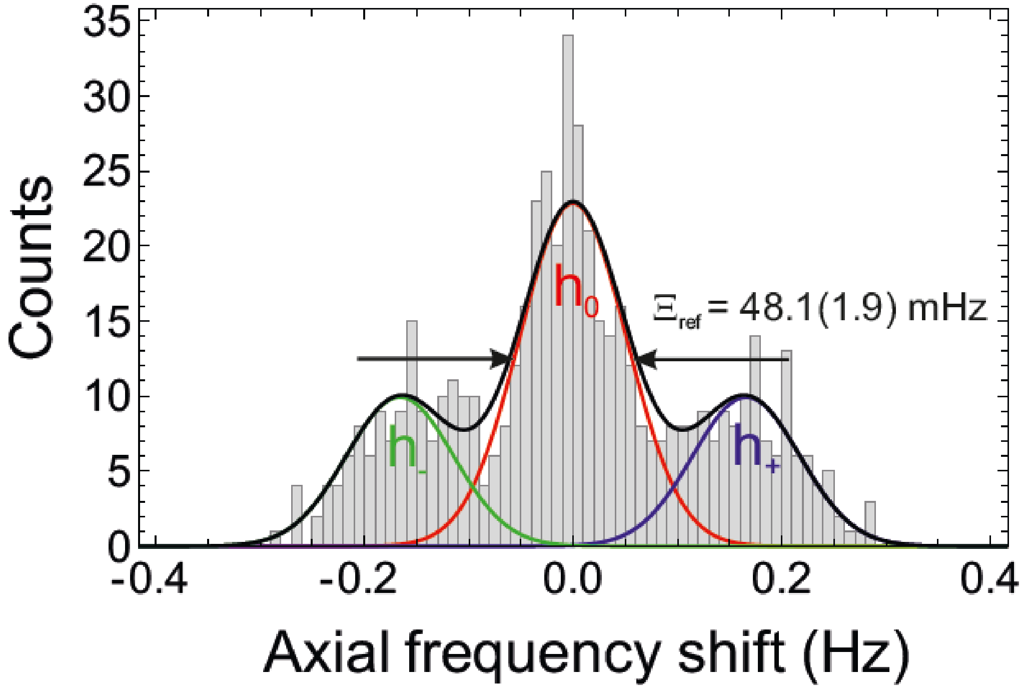
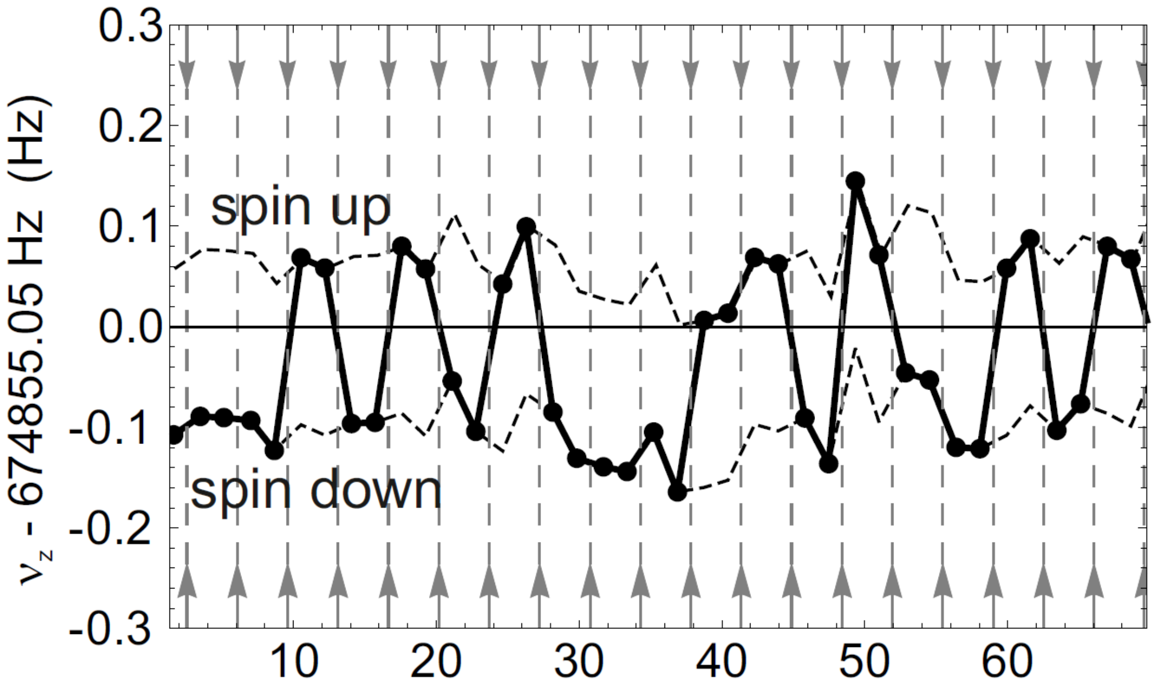
Observation of individual spin quantum transitions of a single antiproton

- **Single spin transitions can be identified with a high fidelity (Average spin-state fidelity > 92 %)**
- **Enables an antiproton g-factor measurement with the double-trap method**

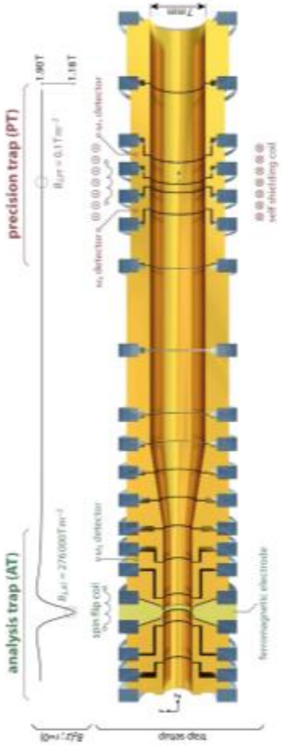




C. Smorra et al., Phys. Lett. B 769, 1-6 (2017).

How to get a cold antiproton?

- Cold particle is prepared by resistive cooling in the PT



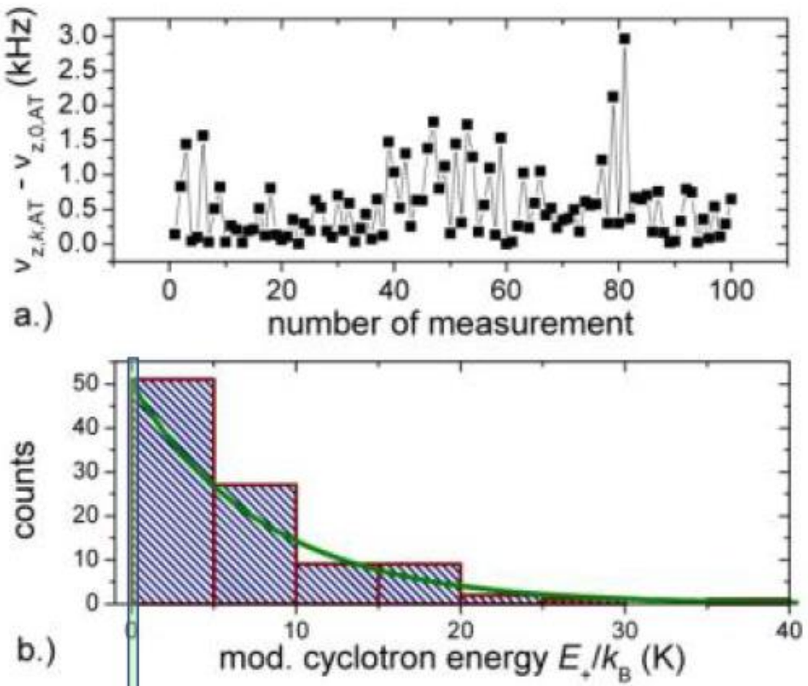
thermalize particle (6 min.)

12 min.

Analyze temperature using the magnetic bottle

particle below threshold -> **MEASURE**

particle above threshold

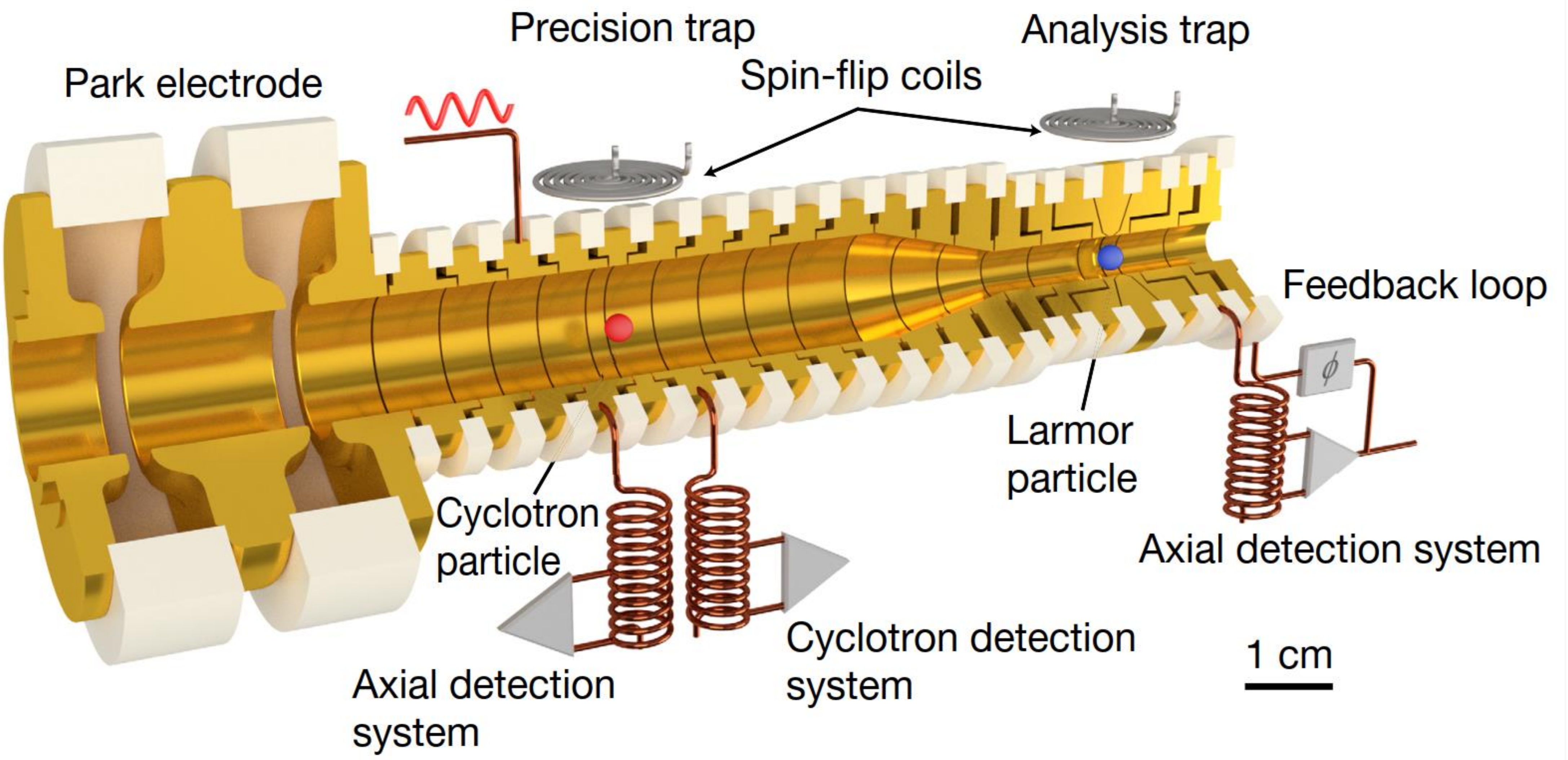


particles with single spin-flip resolution are in this temperature range

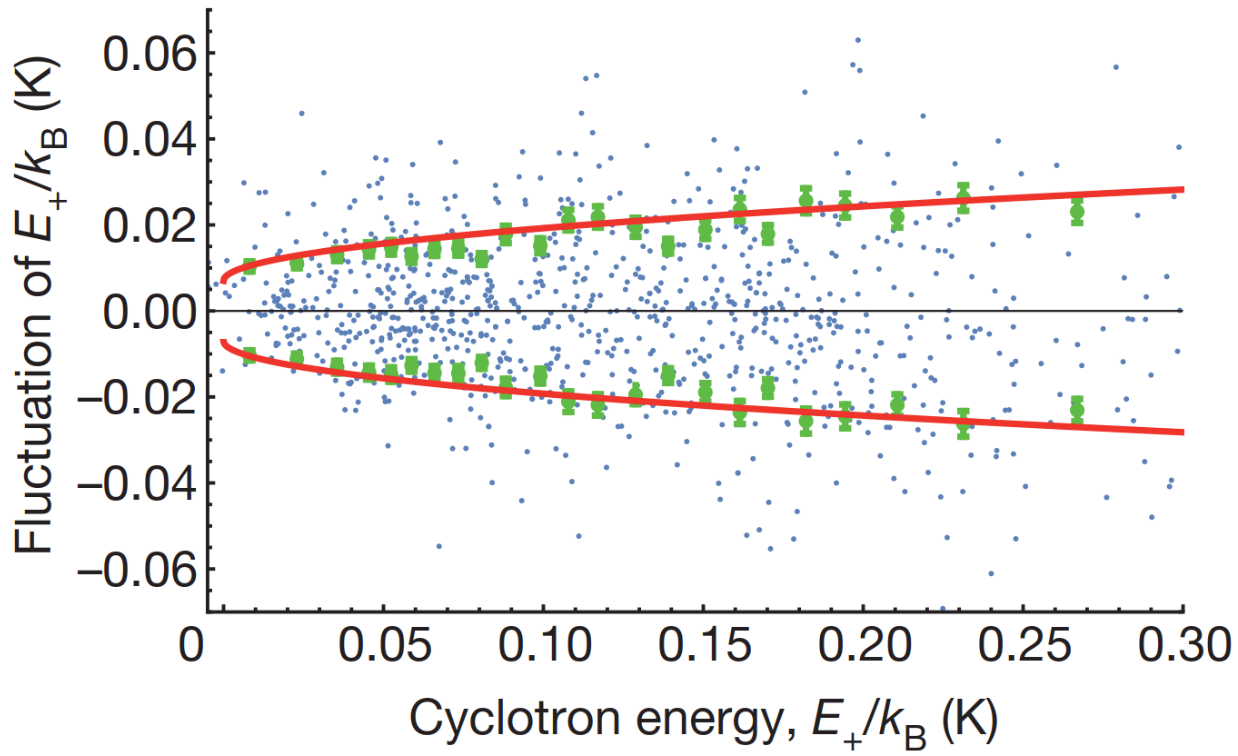
NOTE: each cyclotron frequency measurement heats the particle to about 300K

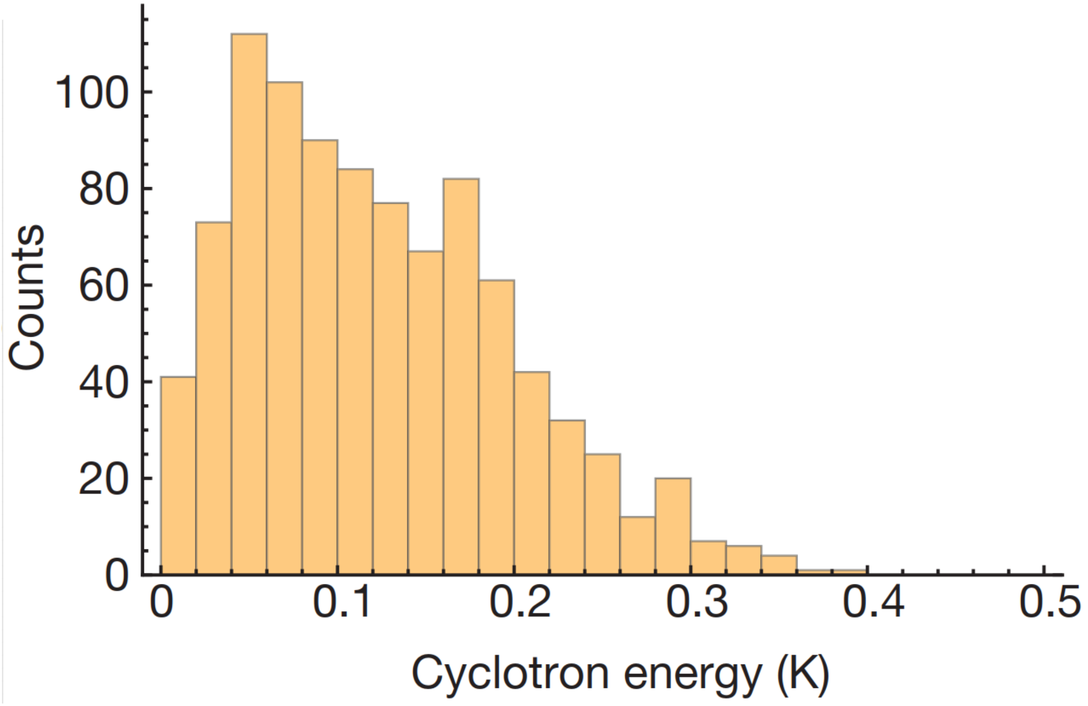
A cooling cycle requires ~ 12 h to get a particle below 100 mK!

A new multi-trap measurement scheme



What is the heating rate of the Larmor antiproton?



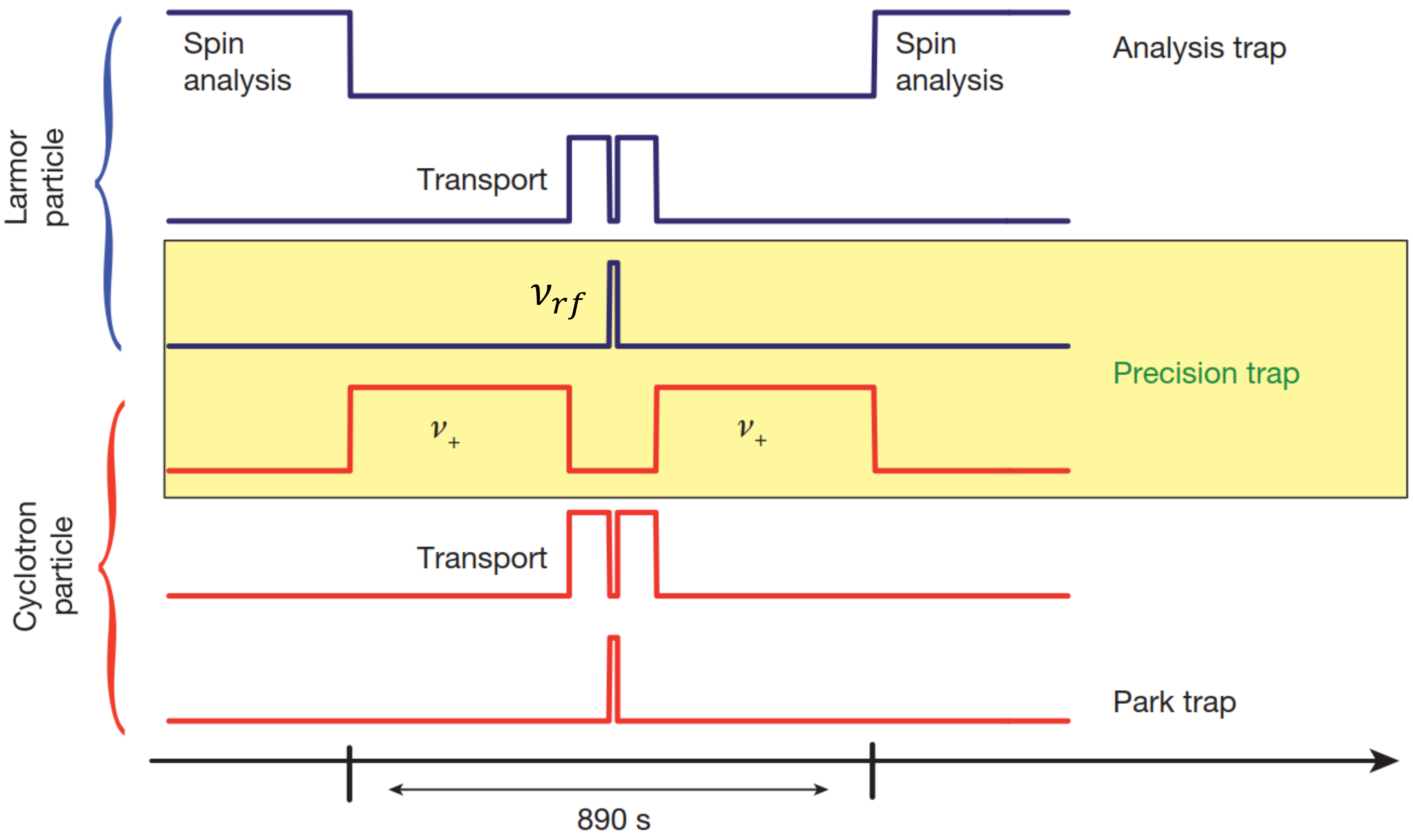


Mean heating rate < 22 mK / SQRT(cycle)

75 measurement cycles before recooling is needed

Mean Spin-state fidelity > 80%

The measurement cycle



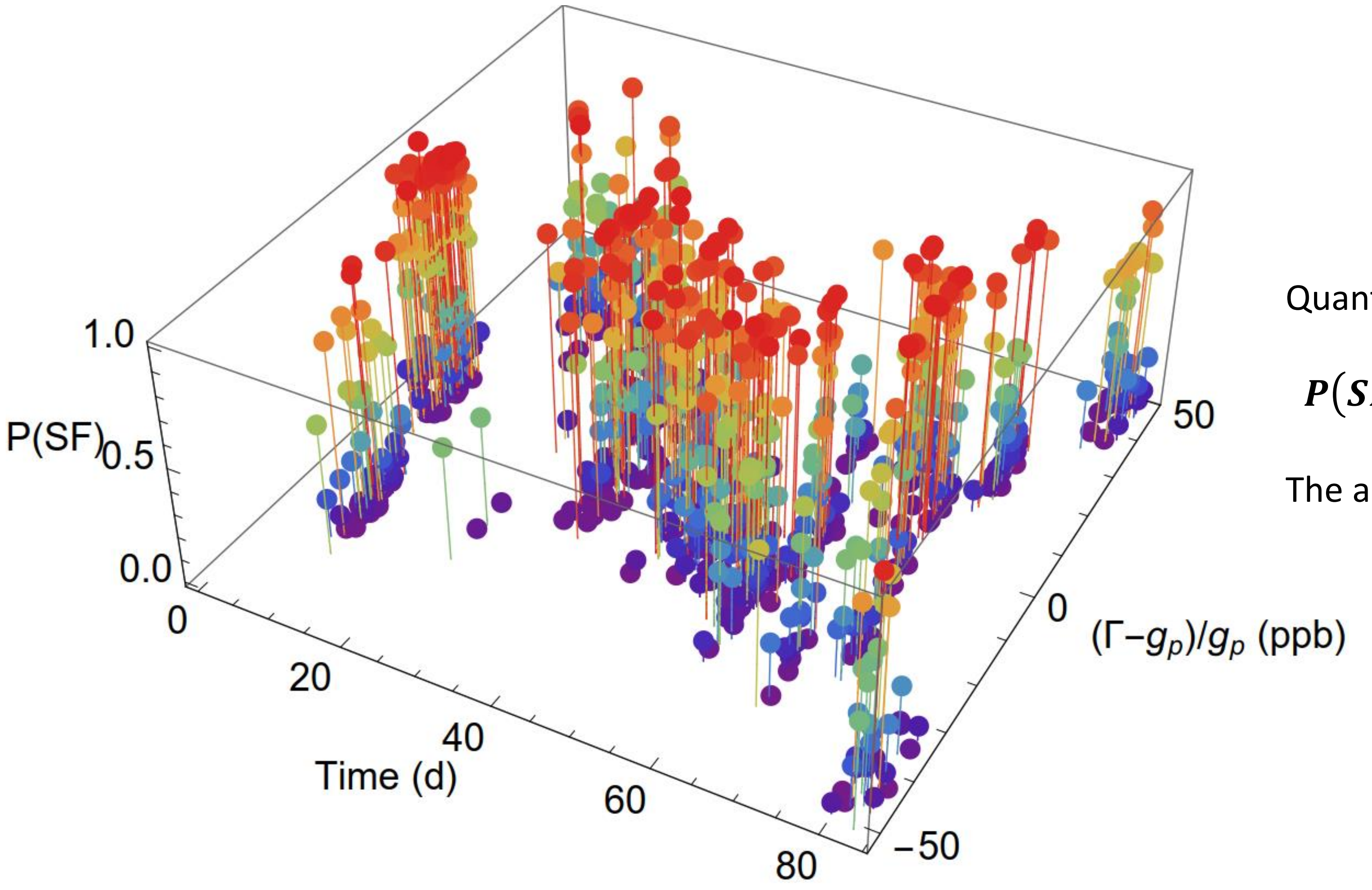
Quantities of interest:

$$P\left(SF\ in\ PT\ |\ \nu_{z,AT,before}, \nu_{z,AT,after}\right)$$

The associated g-factor ratio:

$$\Gamma = \frac{\nu_{rf}}{\langle \nu_{c,PT} \rangle}$$

Data overview



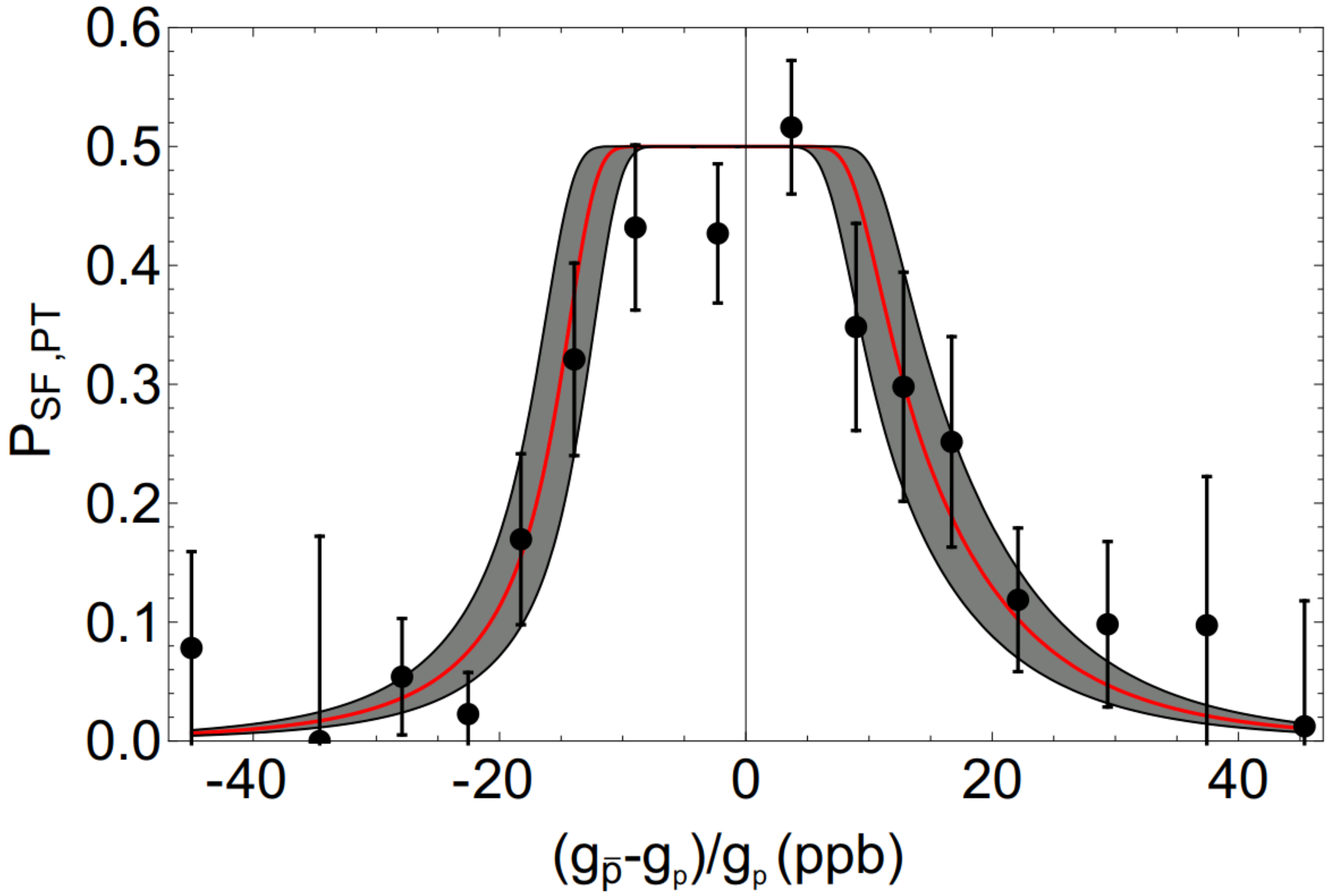
Quantities of interest:

$$P\left(SF\ in\ PT \mid \nu_{z,AT,before}, \nu_{z,AT,after}\right)$$

The associated g-factor ratio:

$$\Gamma = \frac{\nu_{rf}}{\langle \nu_{c,PT} \rangle}$$

Result



Lineshape:

Incoherent Rabi resonance

- Boltzmann distribution of axial energy
- Drive saturation
- Magnetic field fluctuations
- Cyclotron frequency shift due to the sideband temperature limit

Likelihood analysis results in:

$$\frac{g_{\bar{p},\mathrm{exp}}}{2} = 2.7928473453(30)$$

Systematics

Table 1 | Error budget of the antiproton magnetic moment measurement

Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)
Image-charge shift	0.05	0.001
Relativistic shift	0.03	0.003
Magnetic gradient	0.22	0.020
Magnetic bottle	0.12	0.009
Trap potential	−0.01	0.001
Voltage drift	0.04	0.020
Contaminants	0.00	0.280
Drive temperature	0.00	0.970
Spin-state analysis	0.00	0.130
Total systematic shift	0.44	1.020

Difference in radial energy

Difference in axial temperature

Placing the two antiprotons on similar trajectories during the frequency measurements is the limiting systematic effect

Solutions: More homogeneous magnetic field / improved axial temperature measurements

Conclusion I

Proton magnetic moment (2014): $g_p/2 = 2.792\,847\,350\,(9)$

A. Mooser et al., Nature 509, 596-599 (2014).

Antiproton magnetic moment: $g_{\bar{p}}/2 = 2.792\,847\,344\,1\,(42)$

CPT invariance holds up to the reached level of precision

$$\left(\frac{g_p}{2} - \frac{g_{\bar{p}}}{2}\right) = -6\,(19) \cdot 10^{-9}$$

C. Smorra et al., Nature 550, 371-374 (2017).

Proton magnetic moment (2017): $g_p/2 = 2.792\,847\,344\,62\,(82)$

$$\left(\frac{g_p}{2} - \frac{g_{\bar{p}}}{2}\right) = 0.5\,(7.4) \cdot 10^{-9}$$

G. Schneider et al., Science 358, 1081-1084 (2017).

Examples for CPT-odd interactions

- Minimal Standard Model Extension
  - Dirac's Equation with lowest order CPT-odd contributions:

$$(i\gamma^{\mu}\partial_{\mu}-a_{\mu}\gamma^{\mu}-b_{\mu}\gamma_5\gamma^{\mu}-m)\psi=0.$$

- Non-minimal Standard Model Extension
  - Contains higher dimensional operators and explicit antiparticle coefficients

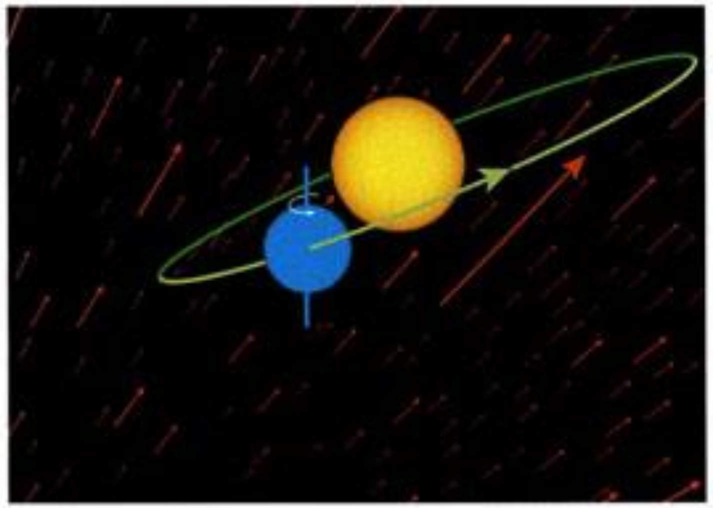


Figure from V.A. Kostelecky

- Interactions by CPT-odd dimension-five operators:

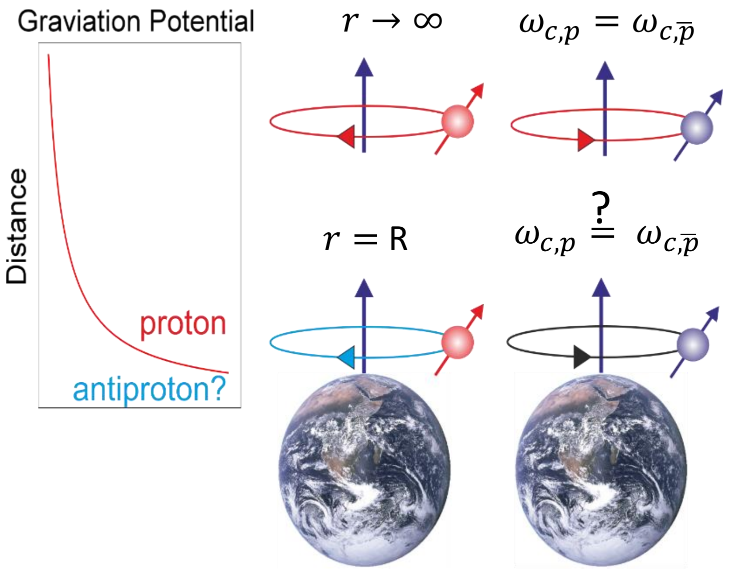
$$\hat{H}^{A}_{\text{int}} = f^{0}\boldsymbol{B}\cdot\Sigma,$$

Y. V. Stadnik et al., Phys. Rev. D 90, 045035 (2014).

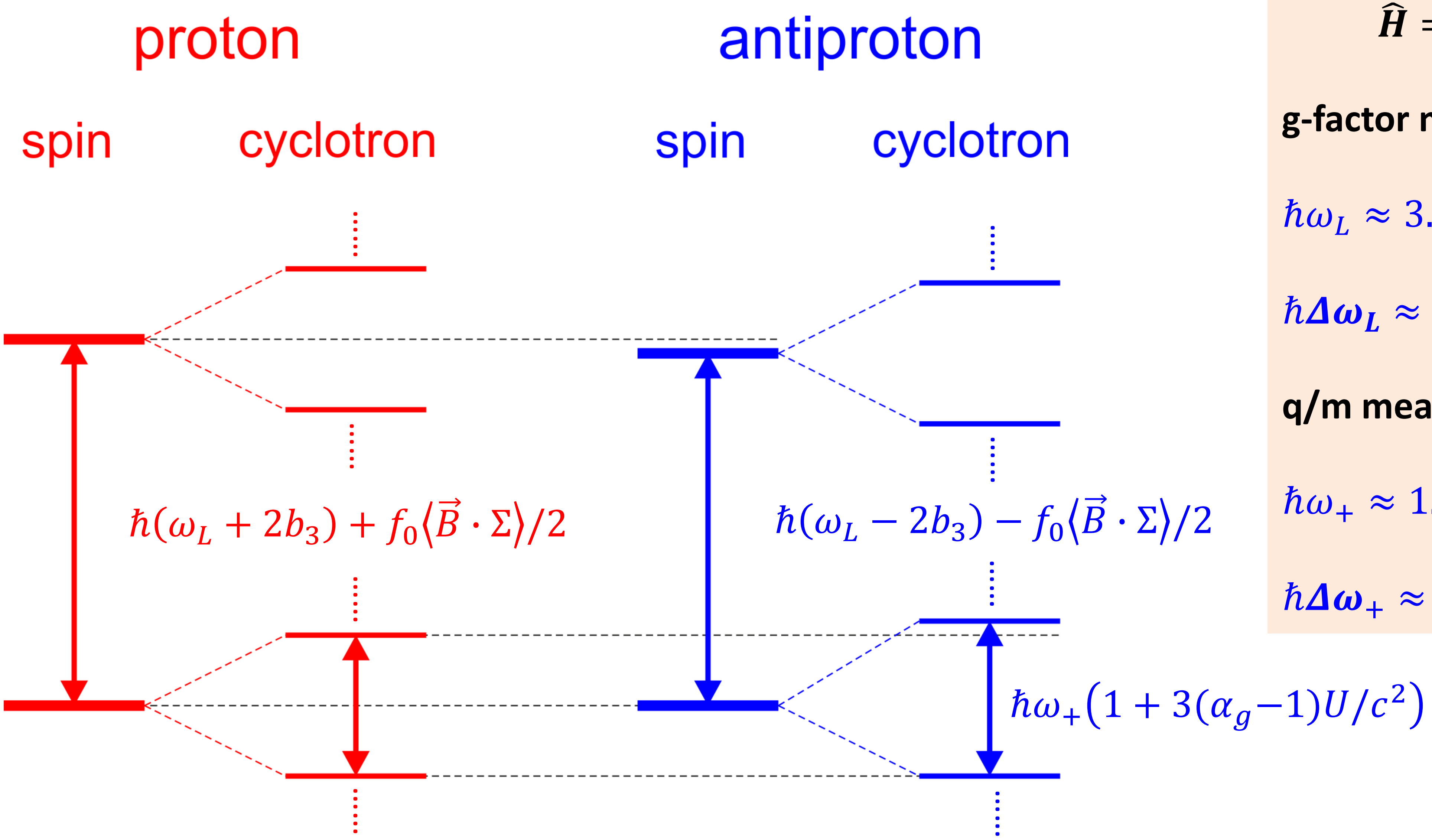
- Antiparticle gravitational anomalies:

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{m_p}{m_{\bar{p}}}\left(1+3\left(\alpha_g-1\right)Uc^{-2}\right)$$

R. J. Hughes, & M. H. Holzscheiter, Phys. Rev. Lett. 66, 854-857 (1991).
R. J. Hughes, Contemporary Physics, 34:4, 177-191 (1993).



Modification of the quantum level structure



$$\hat{H} = \widehat{H_0} + \hat{V}$$

g-factor measurements:

$\hbar\omega_L \approx 3.4 \cdot 10^{-16}$ GeV

$\boldsymbol{\hbar\Delta\omega_L \approx 5 \cdot 10^{-25}}$ **GeV**

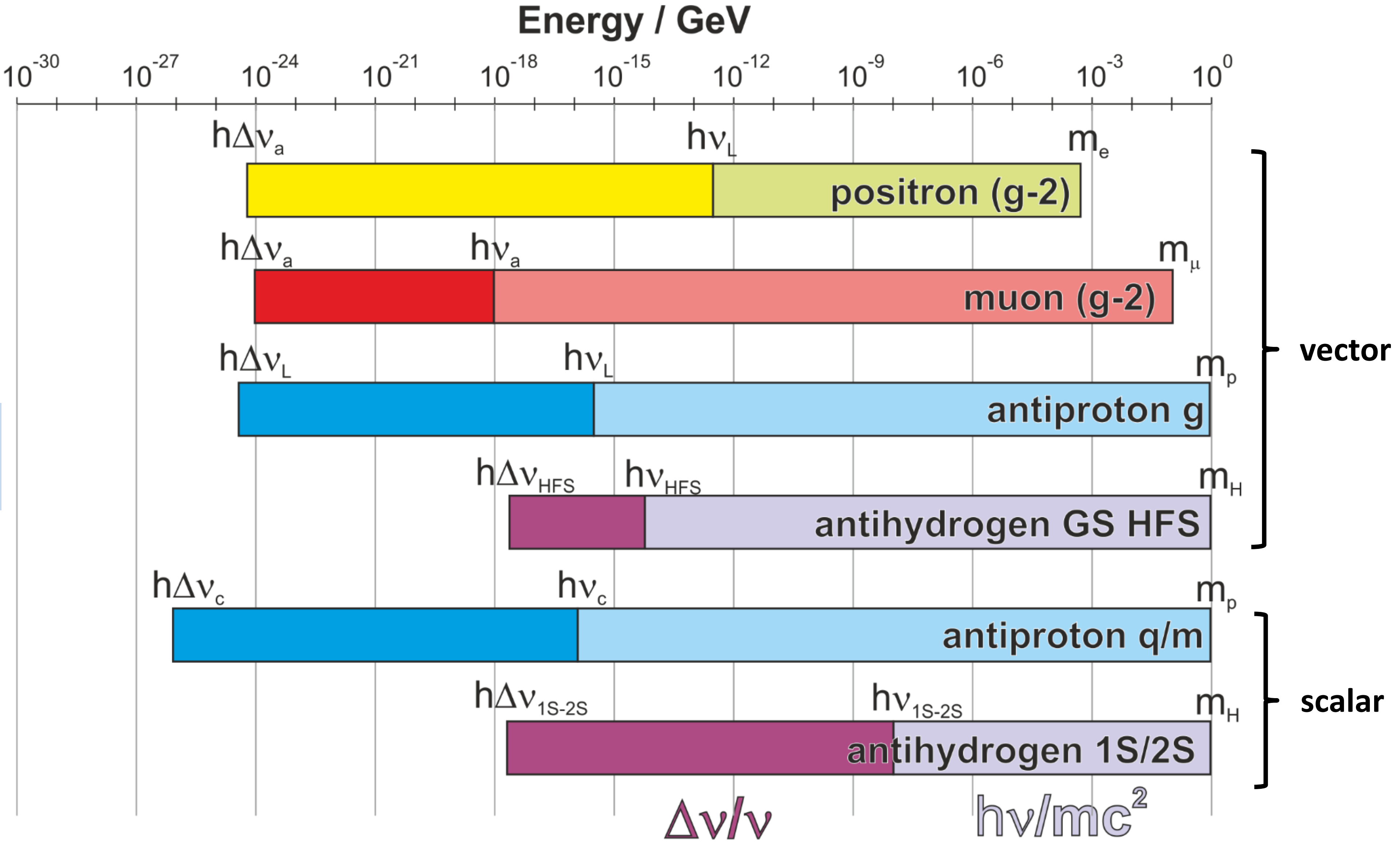
q/m measurements:

$\hbar\omega_+ \approx 1.2 \cdot 10^{-16}$ GeV

$\boldsymbol{\hbar\Delta\omega_+ \approx 8 \cdot 10^{-27}}$ **GeV**

Limits of selected experiments

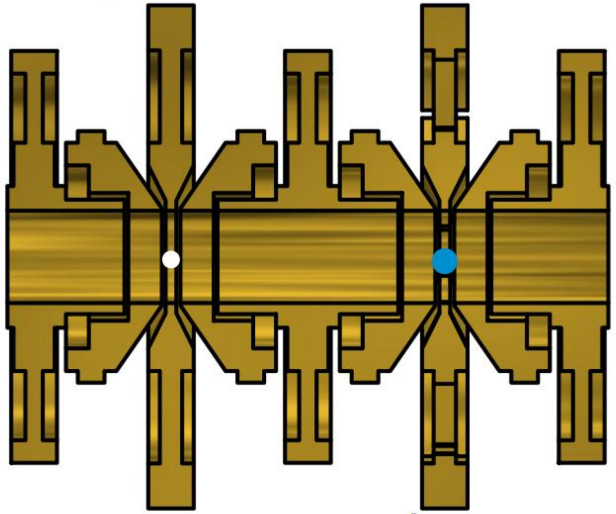
$$\frac{\delta E}{E} = \frac{h\,\Delta v}{m\,c^2}$$



Conclusions and Outlook

- The antiproton magnetic moment has been measured with 350-fold improved precision
- Improvement is based on single quantum sensitivity and the novel two particle scheme

- We target to improve the limits on BSM physics by another factor 10 to 100
- New methods are being developed @ BASE-Mainz (g-factor proton)



Thank you for your attention!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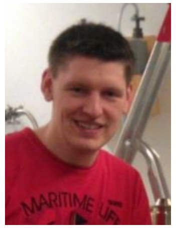
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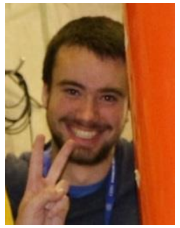
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