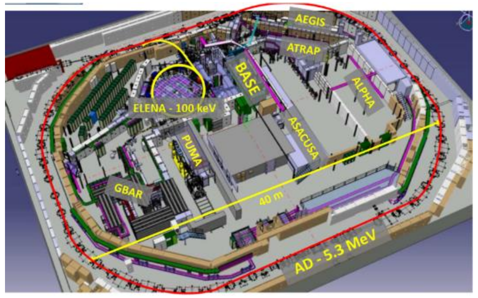
Superconducting Joints for the BASE Coil System



Thomas Hepworth

University of Winnipeg/CERN

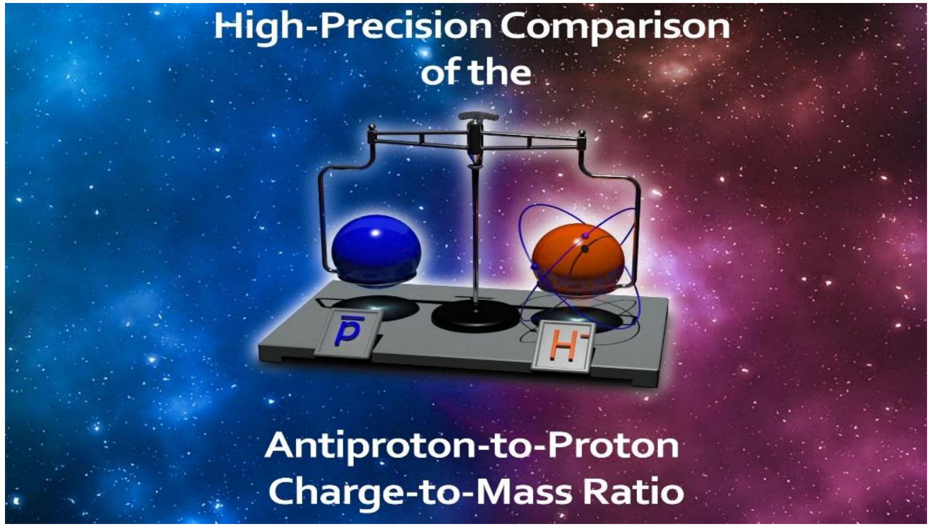
07/08/2024

What is BASE?

- Baryon Antibaryon Symmetry Experiment
  - Founded at CERN in 2013

- Measurements of the fundamental properties of protons/anti-protons
  - Magnetic moment
  - proton/antiproton q/m ratio

Borchert, M.J., Devlin, J.A., Erlewein, S.R. *et al.*
A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio.
Nature **601**, 53–57 (2022). https://doi.org/10.1038/s41586-021-04203-w



- Use Penning trap systems to make extremely precise measurements

Physics Motivation

- Charge-Parity-Time invariance is one of the most fundamental discrete symmetries in the standard model
  - All matter/anti-matter particles should have same fundamental properties

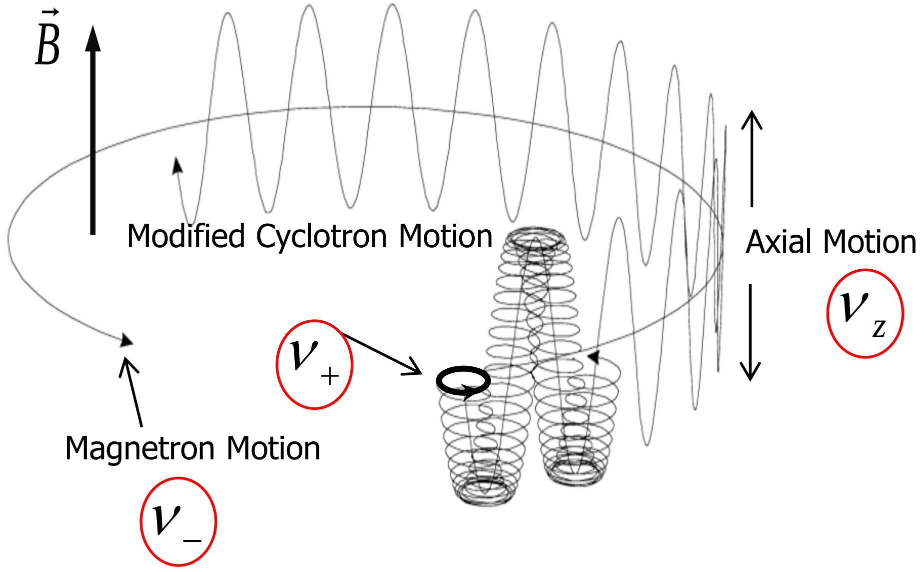
- CPT violation is a potential source for the observed baryon asymmetry of the universe in some models

Quantity	Expectation	Observation
Baryon/Photon Ratio	10^{-18}	$0.6*10^{-9}$
Baryon/Antibaryon Ratio	1	10,000

- BASE compares properties of protons/anti-protons as a very precise direct test of CPT

Penning Traps

- Primary tool of BASE

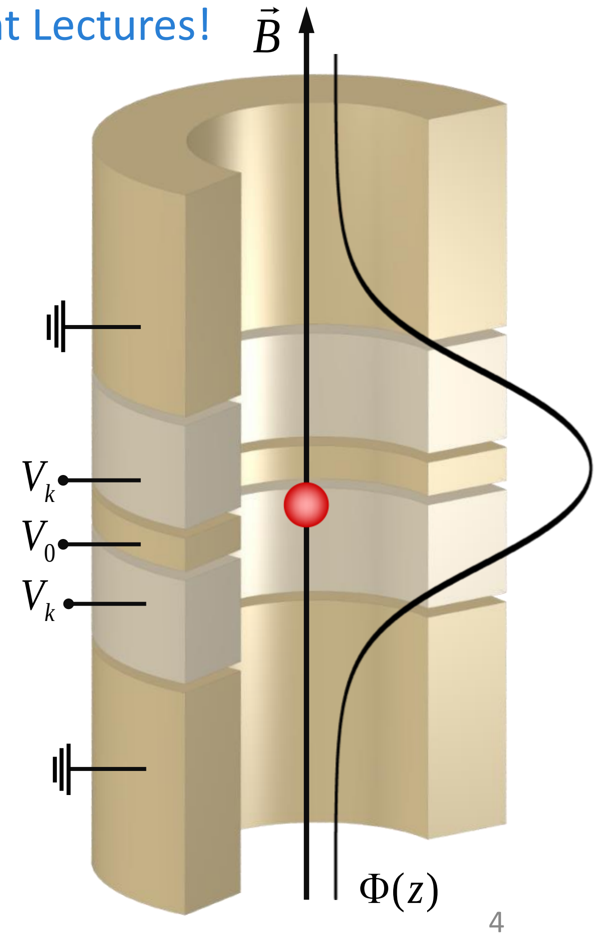


radial confinement: $\vec{B} = B_0 \hat{z}$

axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$

I hope you attended the Summer Student Lectures!

Axial	680 kHz
Magnetron	8 kHz
Modified Cyclotron	28.9 MHz



Schematic of BASE Penning trap

- How do these frequencies tell us q/m or g_p?

Invariance Theorem

- For properly aligned traps:

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2} \longrightarrow \nu_c = \frac{1}{2\pi}\frac{q_p}{m_p}B \text{ !!}$$

G. Gabrielse, The true cyclotron frequency for particles and ions in a Penning trap, International Journal of Mass Spectrometry, Volume 279, Issues 2–3, 2009, Pages 107-112, ISSN 1387-3806, https://doi.org/10.1016/j.ijms.2008.10.015.

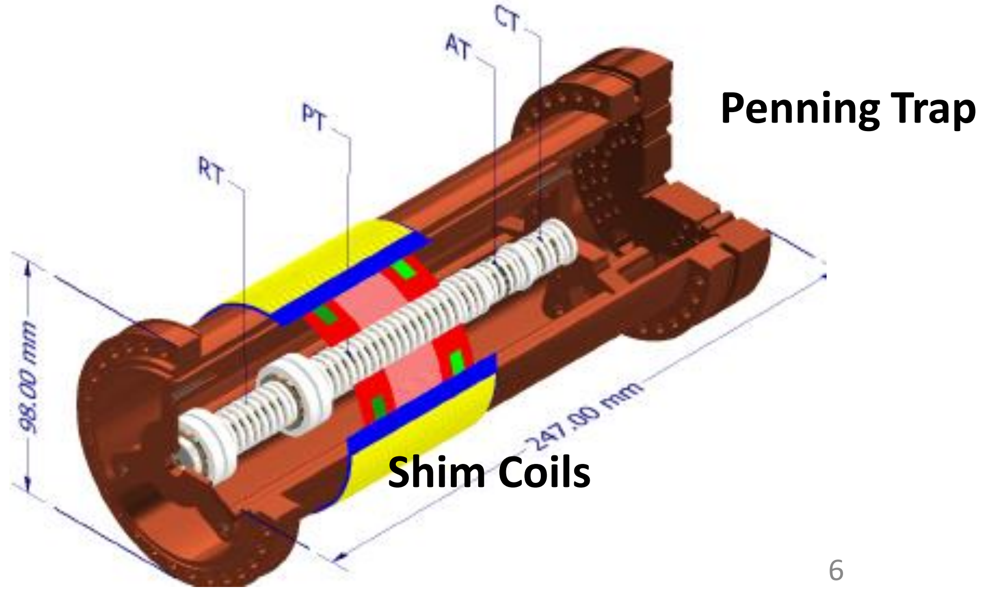
- For precise measurements of q/m we must precisely measure:
  - 3 different trap frequencies
  - B, the magnetic field

- B must be homogenous across the trap, and not change over time

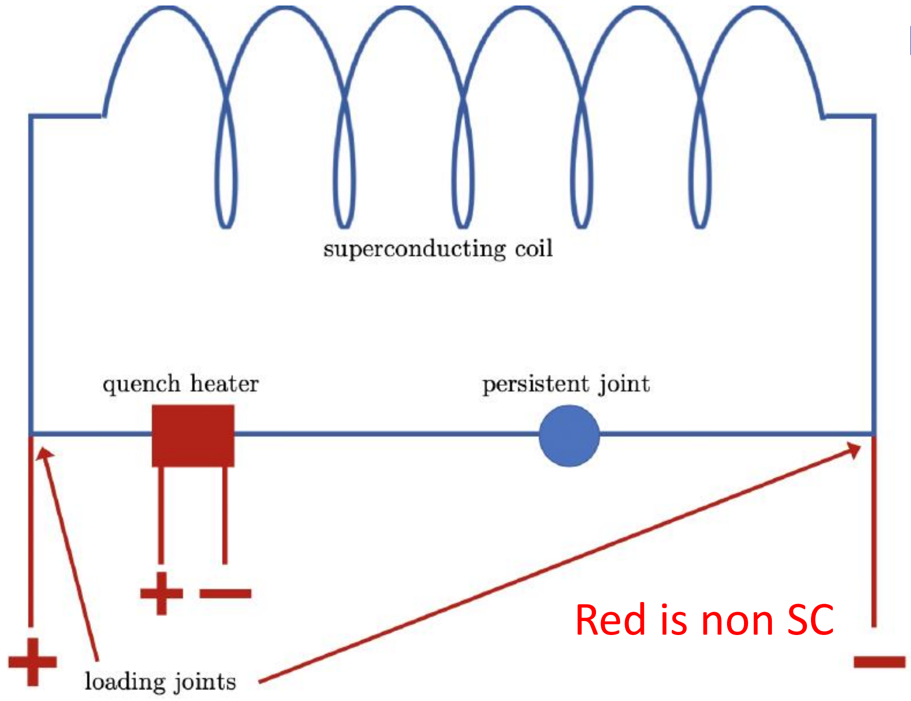
Superconducting Shim Coil System

- Magnetic field expansion in our trap:
  $$B(z) = B_0 + B_1 z + B_2 z^2 + \cdots$$
  - Around center of trap at z = 0

- By using a set of shim coils, we can tune B_0, B_1 and B_2 around the center of our trap (the PT)

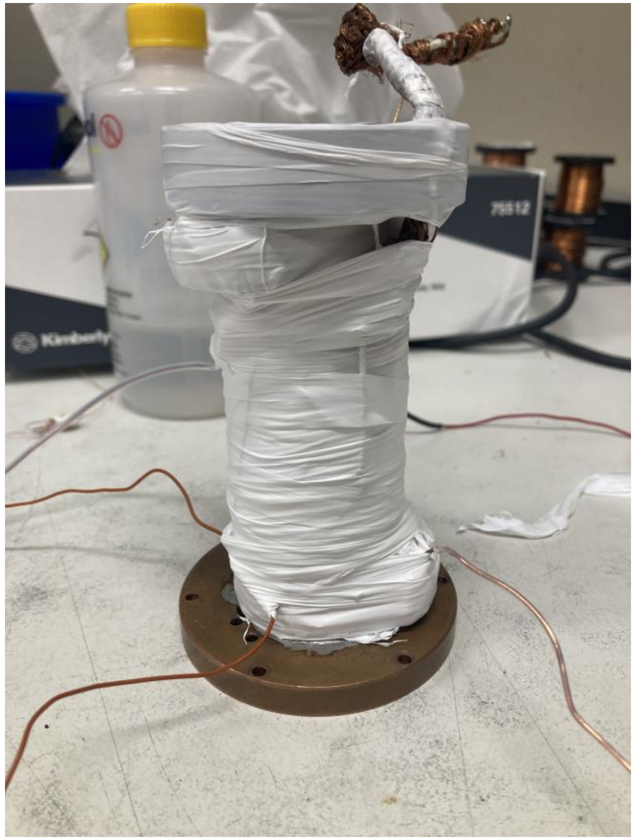


Superconducting Coil Schematic



Blue is SC

Red is non SC



- A loaded Persistent Coil produces stable field without needing current supply – a perfect candidate for long term field control!

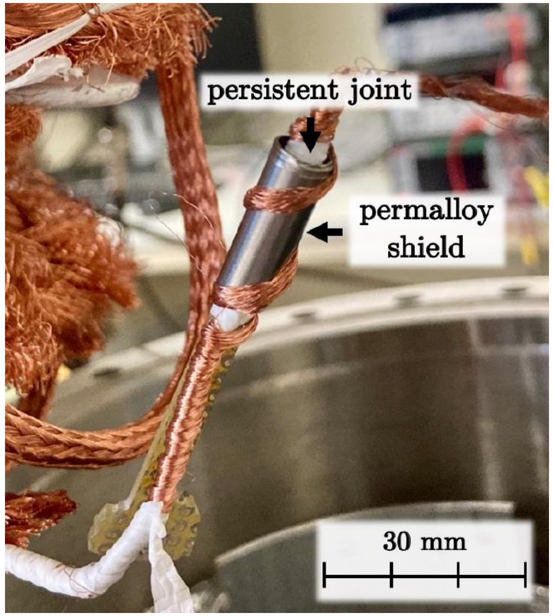
Superconducting Electrical Joints

- Good joints are necessary for a good system
  - My role is to test joints and develop alternative ways to make them for comparison
- 2 Types:
  - Loading: Put current into the system
  - Persistent: Keep current flowing in the coil
- Any experiments coil system is only as good as its joints!
  - BASE joints can go at least **2 months**

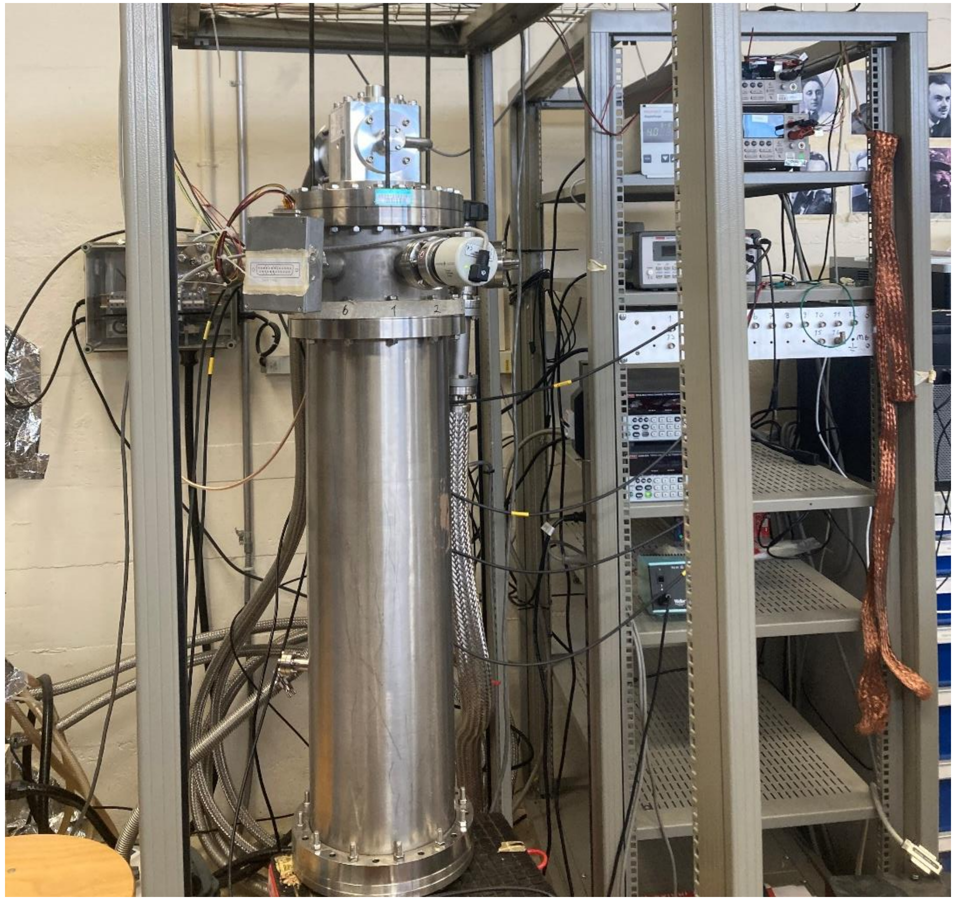
Current BASE Joints

- Superconducting NbTi coil (φ = 125 µm)
- Copper loading joint connects Cu to NbTi
  - Passes current into system

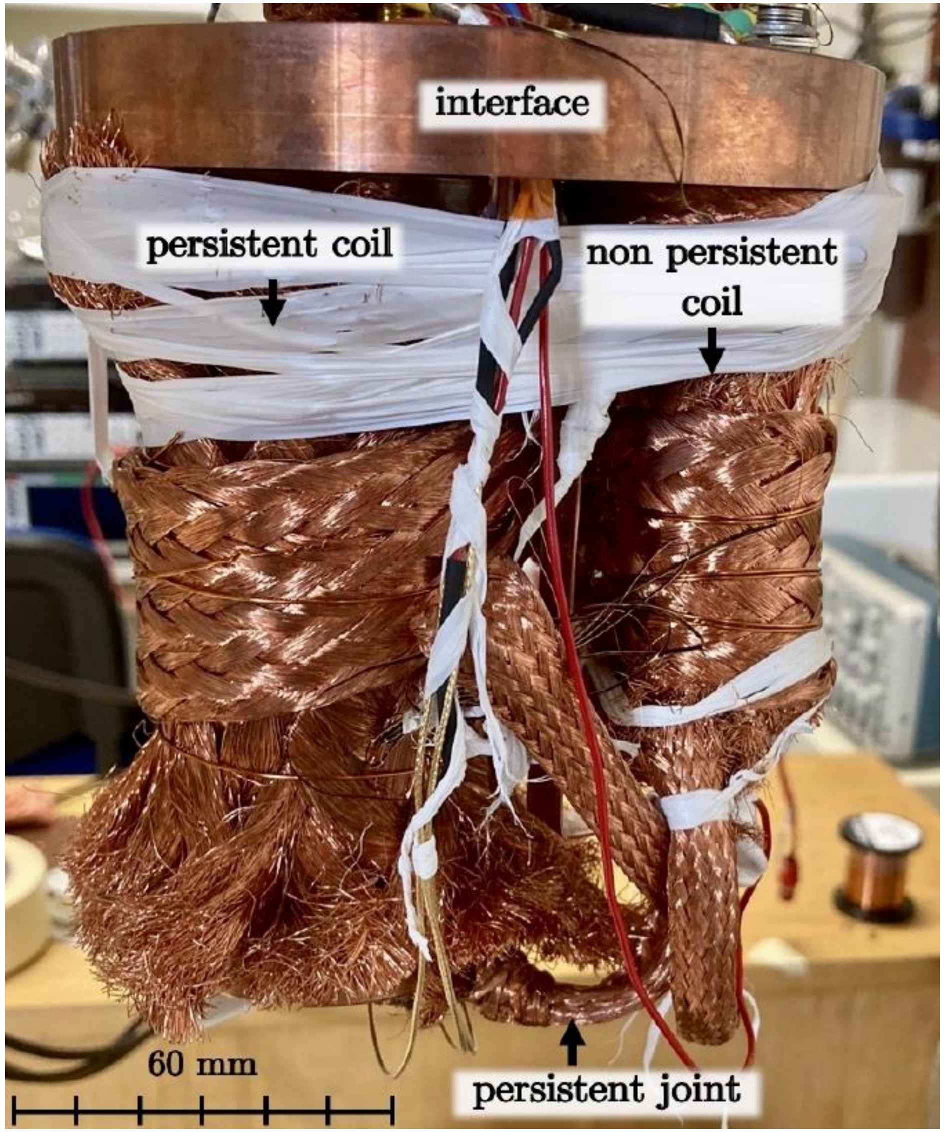
- Spot Welded Persistent Joint
  - Inside permalloy shield



Test Setup



Lowest Operating Temperature:	3.2 K
Lowest Operation Pressure	4 e-8 mbar

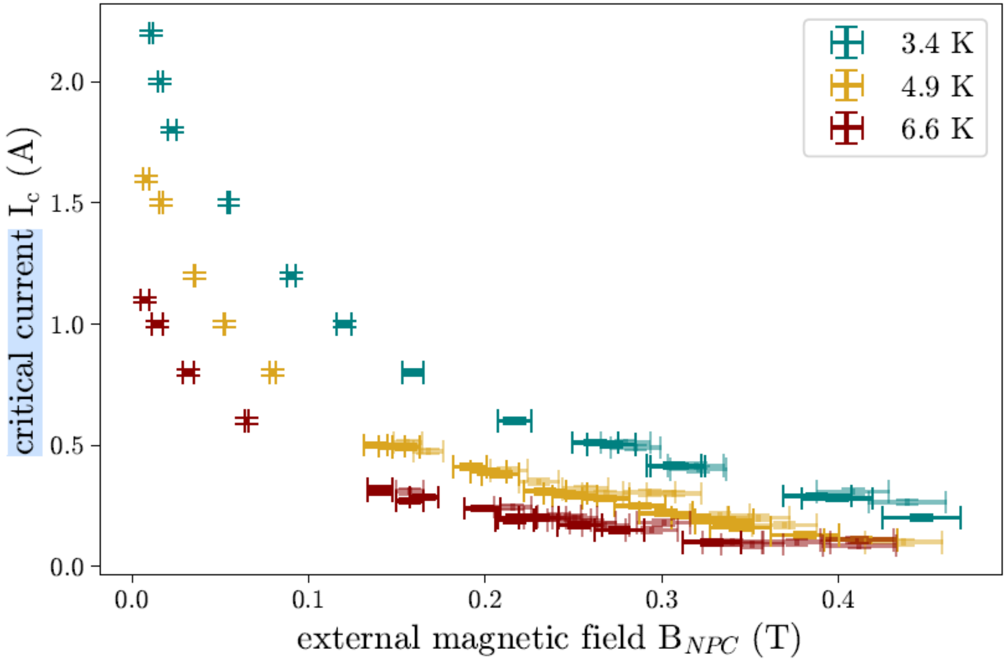


Testing a Joint

- Loading current as a function of B field
  1. Change values of external field with NPC
  2. Measure the critical current we see in the PC

- Of course, B_1 and $B_2 = 0$ is ideal
  - $B(z) = B_0 + B_1 z + B_2 z^2 + \cdots$

Development of a Test Setup to Characterize Persistent Joints for Future High Precision Penning Trap Experiments, Bachelor Thesis by Maylin Schiffelholz Gottfried Wilhelm Leibniz Universität Hannover



- New: I am implementing a new cryogenic hall probe for these tests
  - This should reduce problems with overheating the system

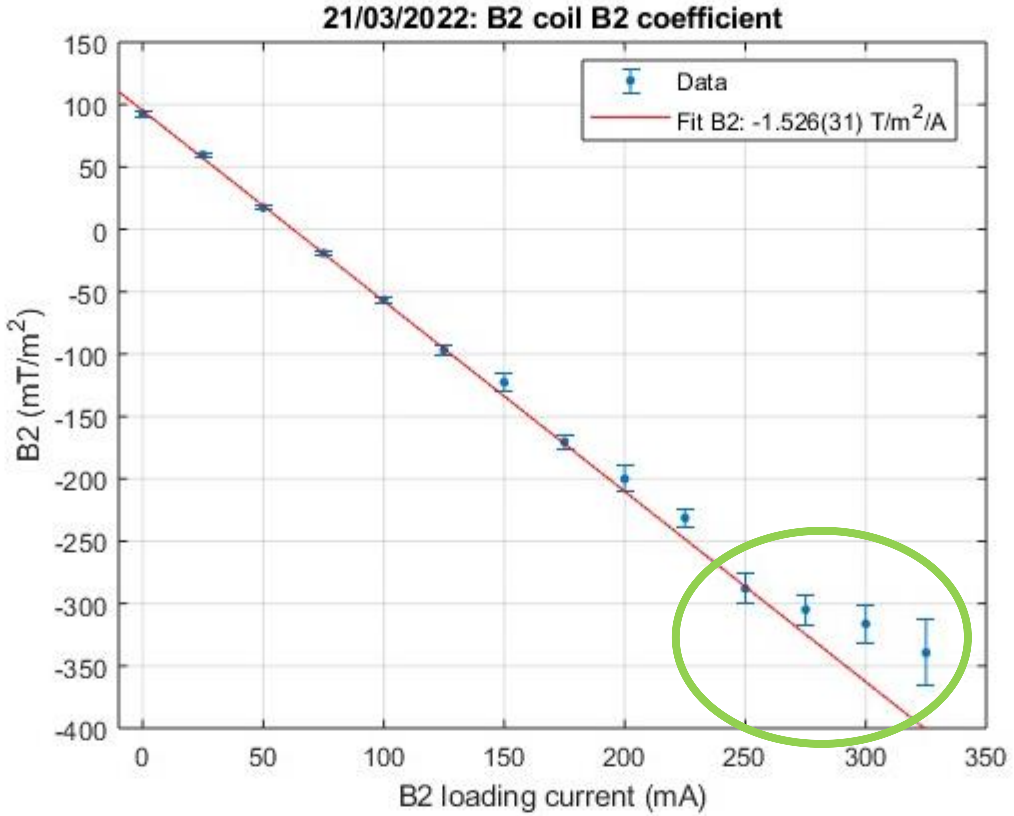
Tuning B_1 and B_2

- Joints stop operating persistently at loading currents near 250 mA

- If we can do Better than this, a better joint has been made!

	2021 residual	2024 *tunning
B1 (linear)	0.0270(7) T/m	0.011 T/m
B2 (quadratic)	0.1298(8) T/m^2	0 (0.0003) $\mathrm{T/m^2}$

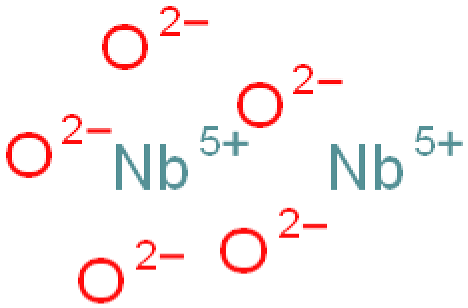
- Problem: To make B1 = 0. We need to load several amps (which we can’t sustain with our persistent joint)



New BASE Joint Concept

- When not in vacuum, NbTi oxidizes

- Formation of Nb_2O_5 layer affects superconductivity



- Solution: Remove this layer with acid and store NbTi wire in vacuum chamber before we implement – no loses in superconductivity
  - This is done for RF cavities in CERN accelerators

- This has not been done with single NbTi wires
  - Critical currents of >200A in joints using copper matrix setup

Patel, D., Kim, SH., Qiu, W. *et al.* Niobium-titanium (Nb-Ti) superconducting joints for persistent-mode operation. *Sci Rep* **9**, 14287 (2019) https://doi.org/10.1038/s41598-019-50549-7

Conclusion/Outlook

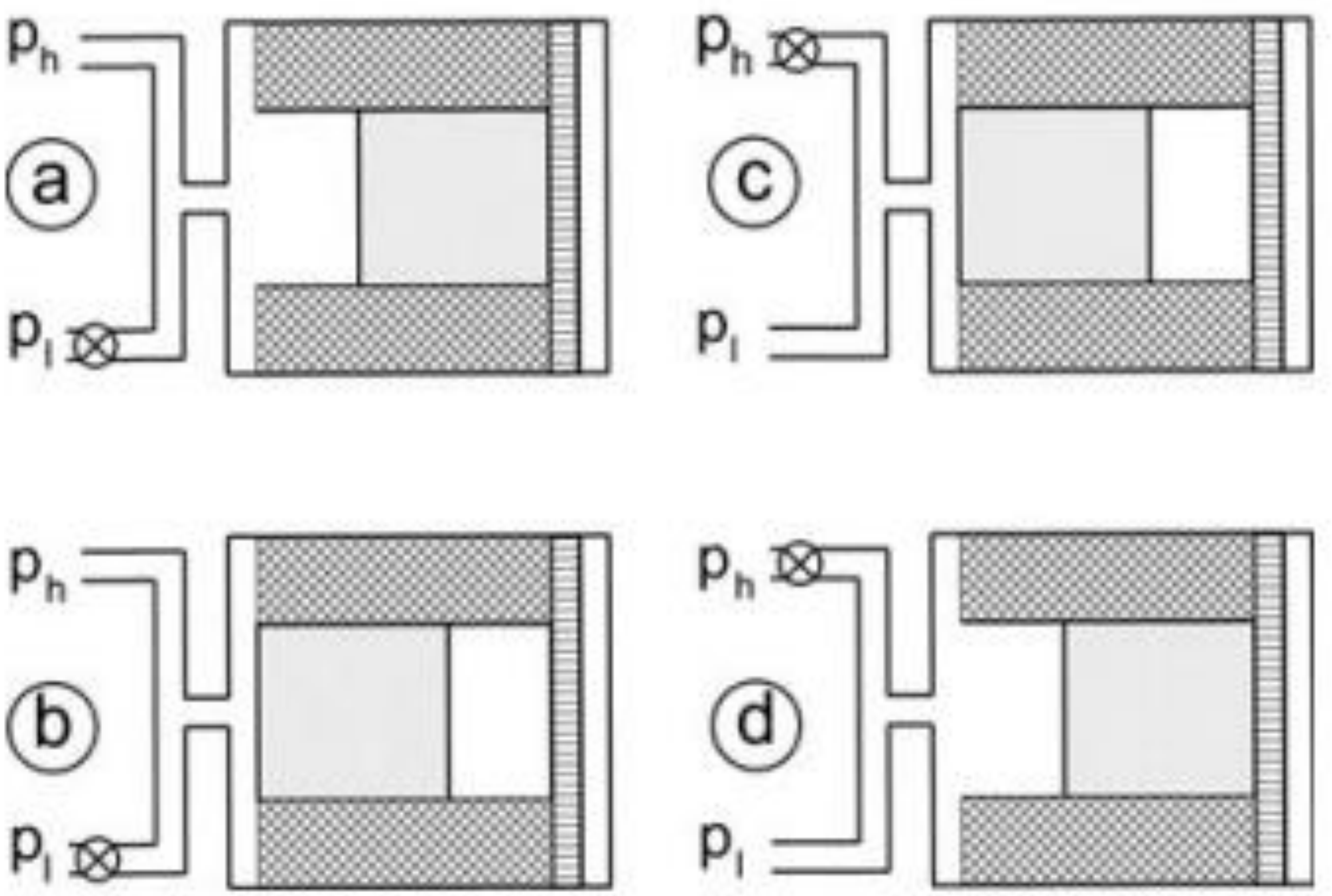
- BASE makes world leading measurements of protons/anti-protons
- The primary systematics they must account for are magnetic field inhomogeneities
- This is done with a Shim coil system, where good SC joints are a must!
- Joint development and testing will continue for the rest of the summer
  - Currently commissioning old joints and preparing NbTi samples for acid treatment

Thanks to my supervisor Barbara Maria-Latacz for picking me to be apart of BASE for the summer

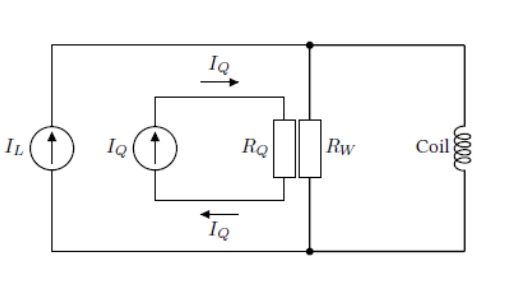
BASE and BASE-STEP Students :D

Backups

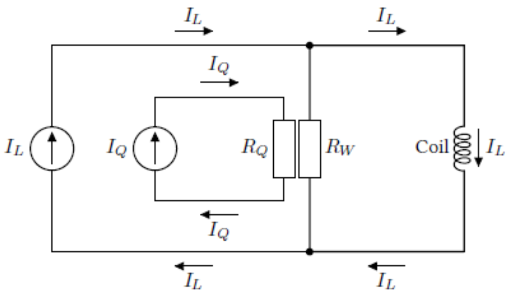
- https://link.springer.com/content/pdf/10.1007/s10909-011-0373-x.pdf



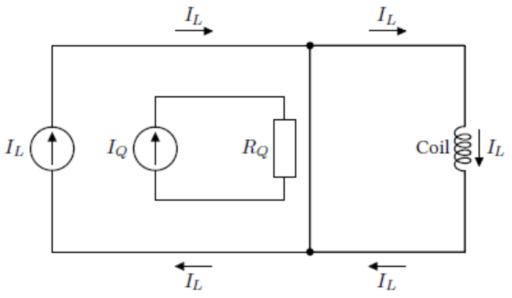
Coil Loading Sequence



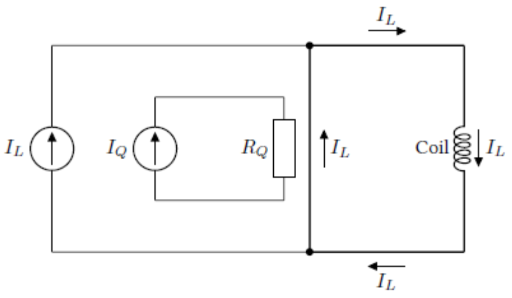
(a) The quench current I_Q dissipates power in the quench heater R_Q and warms up part of the superconducting wire above its critical temperature. This creates a small resistance R_W in the superconducting coil.



(b) Applying a loading current to the coil initially creates an induced current of same magnitude in the opposite direction, however, this current decays over R_W with a time constant $\tau = \frac{L}{R}$ and after a short time the full loading current flows through the coil.



(c) After removing the quench current and making the coil persistent, flux conservation keeps the current flowing through the field-creating part of the coil.

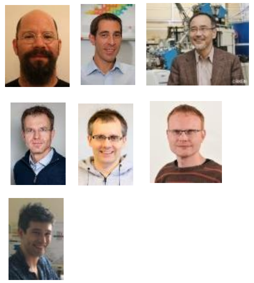


(d) After the external loading current is removed, the current flowing in the coil is conserved and the system can be decoupled from the outside to reduce noise.

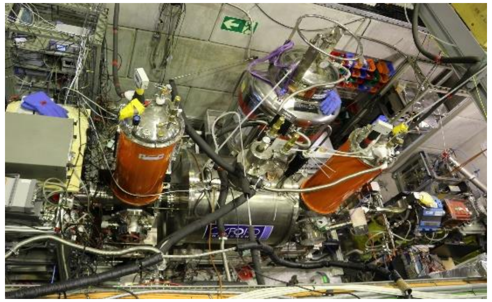
Figure 1.9: Coil loading scheme: (a) Apply quench current. (b) Apply loading current. (c) Remove quench current. (d) Remove loading current.

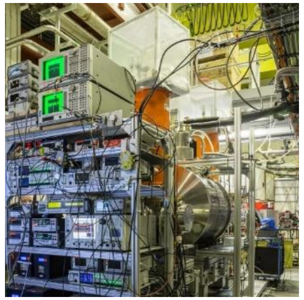
Scientific Activities and Highlights - Overview

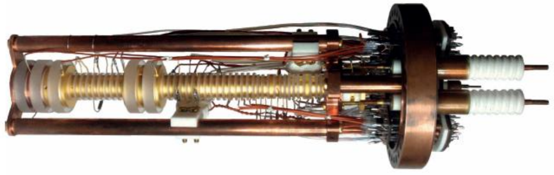
BASE-CERN | Exotics
BASE-Mainz | BASE-Lepton
BASE-Logic
BASE-STEP
BASE-CDM



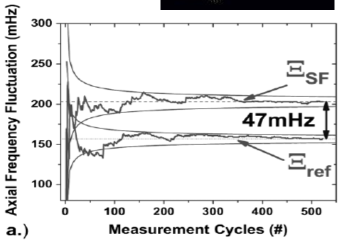
- **General:** Use ultra-high precision methods to measure fundamental constants and study fundamental symmetries with highest fractional accuracy
- **Main tools:** advanced Penning trap systems





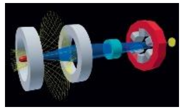


2011



S. Ulmer, et al., **PRL 106, 253001 (2011)**

2012



2013

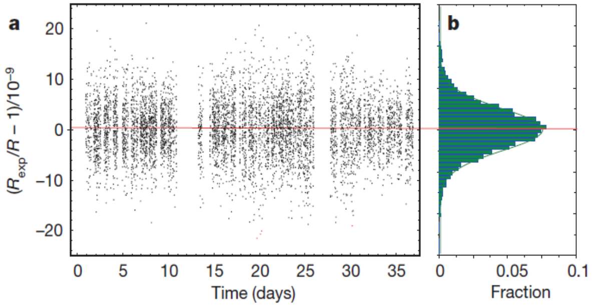
3ppb proton moment

2014

A. Mooser, S. Ulmer, et al., **Nature 509, 596 (2014)**

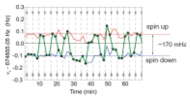
2015

$$1+\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} = 1(69)\times 10^{-12}$$

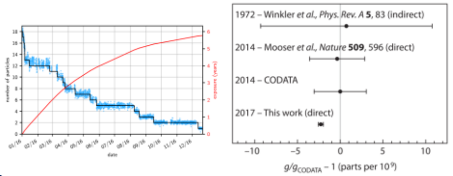


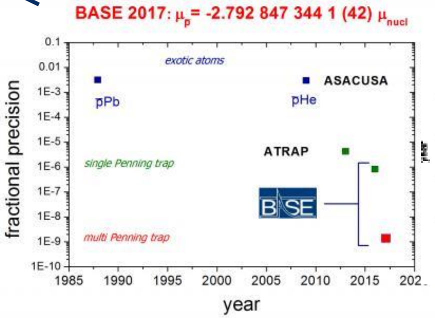
S. Ulmer, et al., **Nature 524, 196 (2015)**

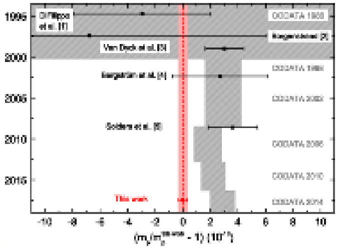
2016



2017 pbar moment, proton moment, pbar lifetime, proton mass

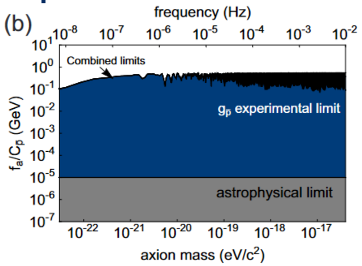






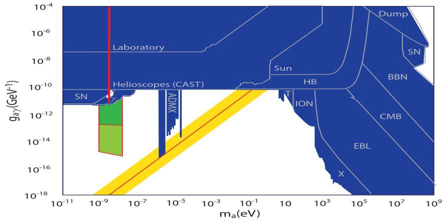
G. Schneider et al., Science **358**, 1081 (2017).
C. Smorra *et al.*, Nature **550**, 371 (2017)

2019

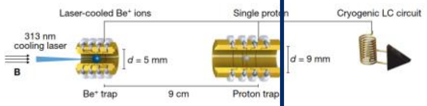


BASE, Nature **575**, 310 (2019)

2021

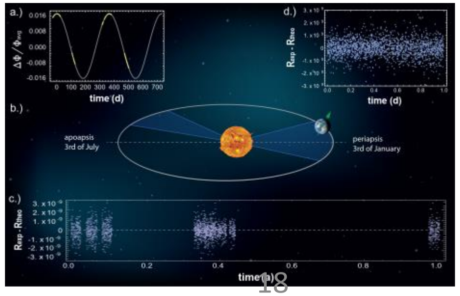


J. A. Devlin, et al., **PRL, accepted (2021)**



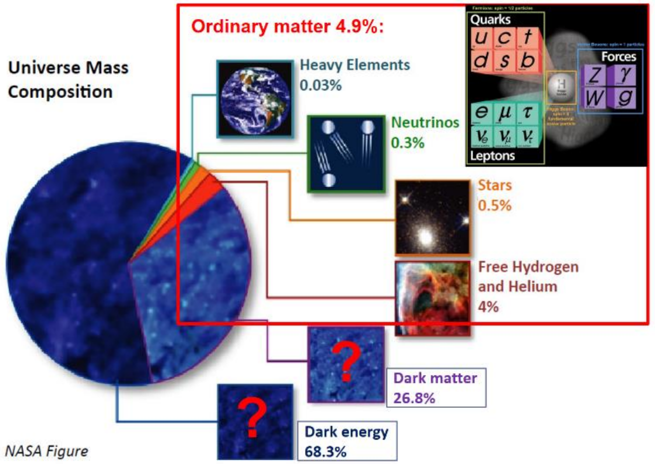
M. A. Bohman, et al., **Nature 596, 514 (2021)**

2022



S. Ulmer, et al., **Nature, accepted (2021)**

Matter / Antimatter Asymmetry



NASA Figure

Combining the Λ-CDM model and the SM, our predictions of the baryon to photon ratio are **inconsistent by about 9 orders of magnitude**

Naive Expectation	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observation	
Baryon/Photon Ratio	$0.6 * 10^{-9}$
Baryon/Antibaryon Ratio	10 000

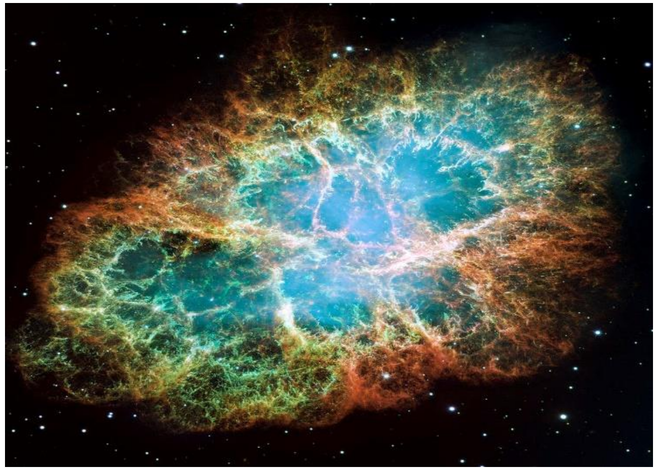
Sakharov conditions

1.) B-violation (plausible)

2.) CP-violation (observed / too small)

3.) Arrow of time (less motivated)

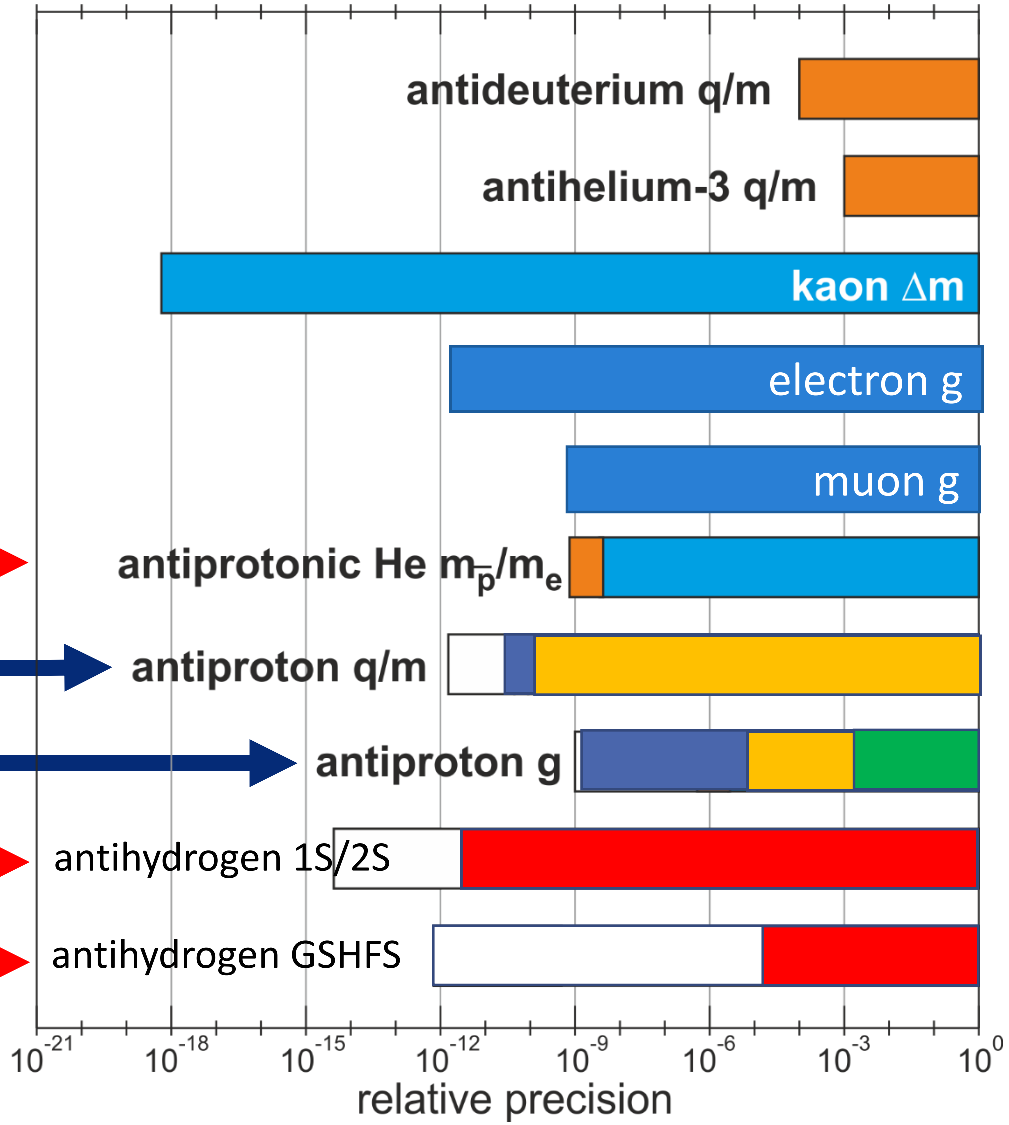
Alternative Source: CPT violation – adjusts matter/antimatter asymmetry by natural inversion given the effective chemical potential.



Experimental signatures sensitive to CPT violation can be derived from precise comparisons of the fundamental properties of simple matter / antimatter conjugate systems

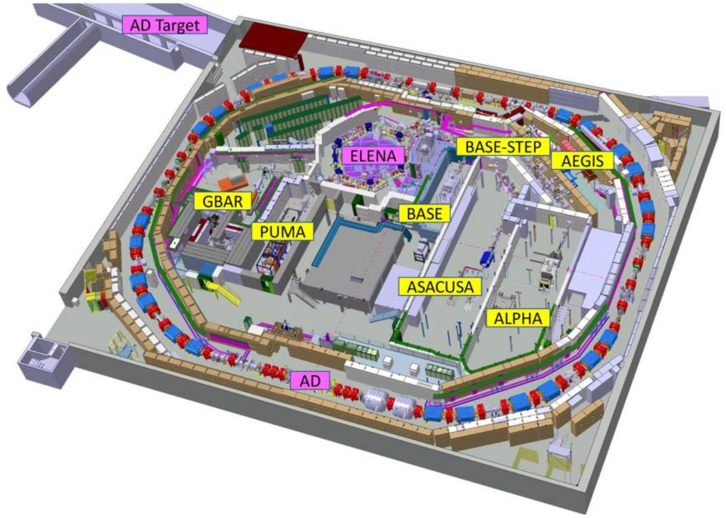
CPT tests based on particle/antiparticle comparisons

Recent
Past
Planned



CERN ALICE

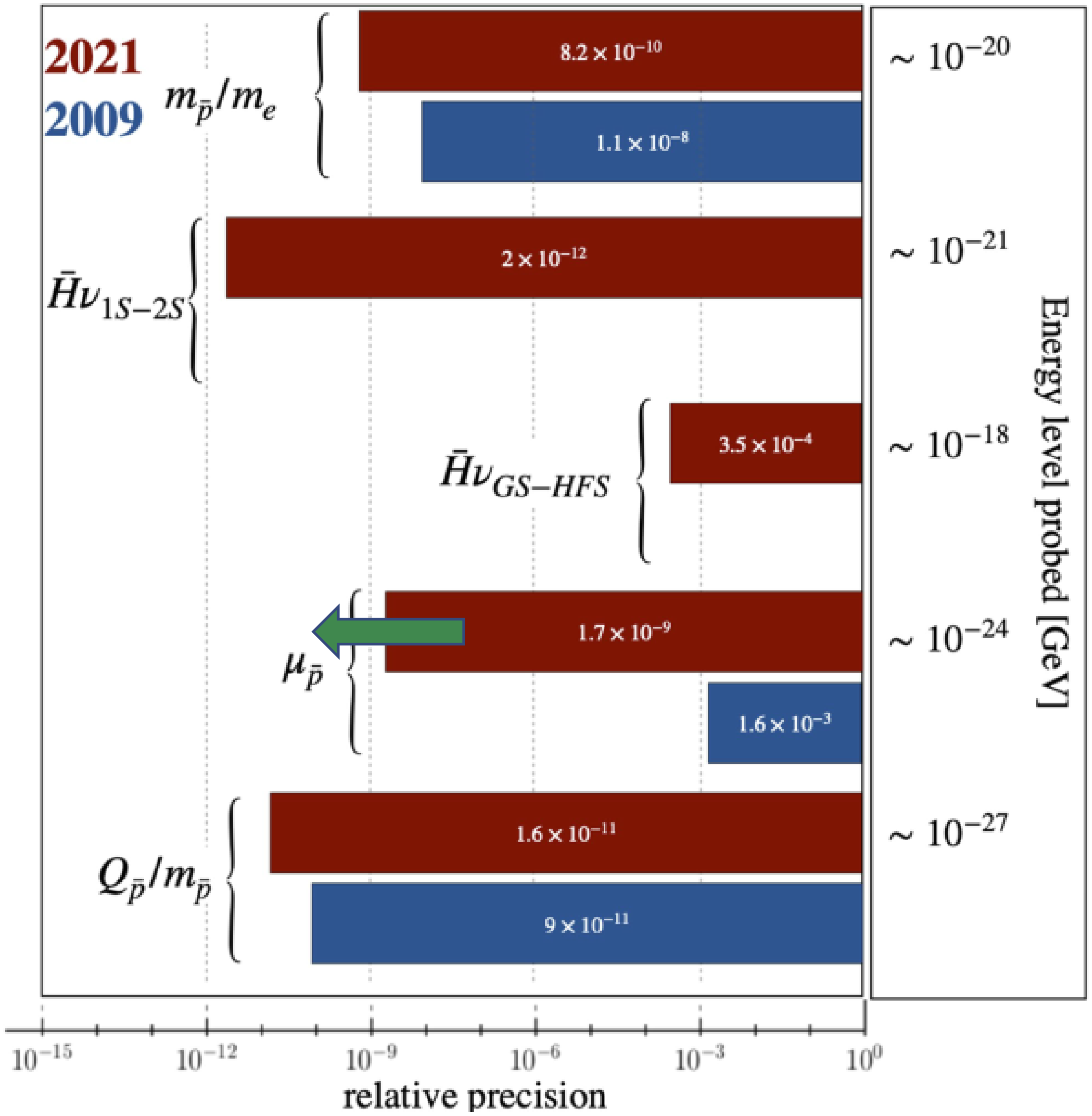
CERN AD



R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabriesle et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer et al., Nature **524**, 196-200 (2015).
ALICE Collaboration, Nature Physics **11**, 811–814 (2015).
M. Hori et al., Science **354**, 610 (2016).
H. Nagahama et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **541**, 506 (2017).
M. Ahmadi et al., Nature **586**, doi:10.1038/s41586-018-0017 (2018).

comparisons of the fundamental properties of simple matter / antimatter conjugate systems

10 years of Community Progress



current goal

recent study

M. Borchert, et al., **Nature 601, 53 (2022)**

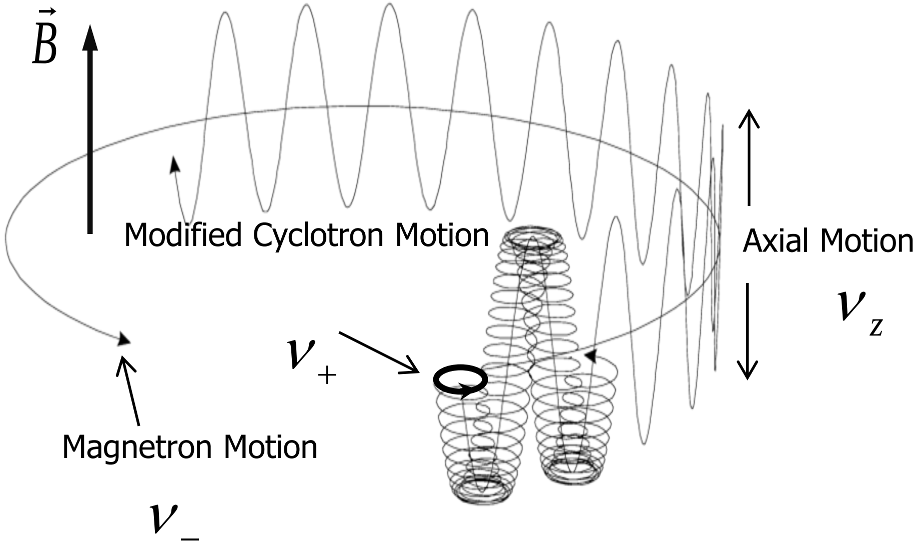
Coming soon: studies of the ballistsic properties of antihydrogen by ALPHA-g, GBAR, AEgIS.

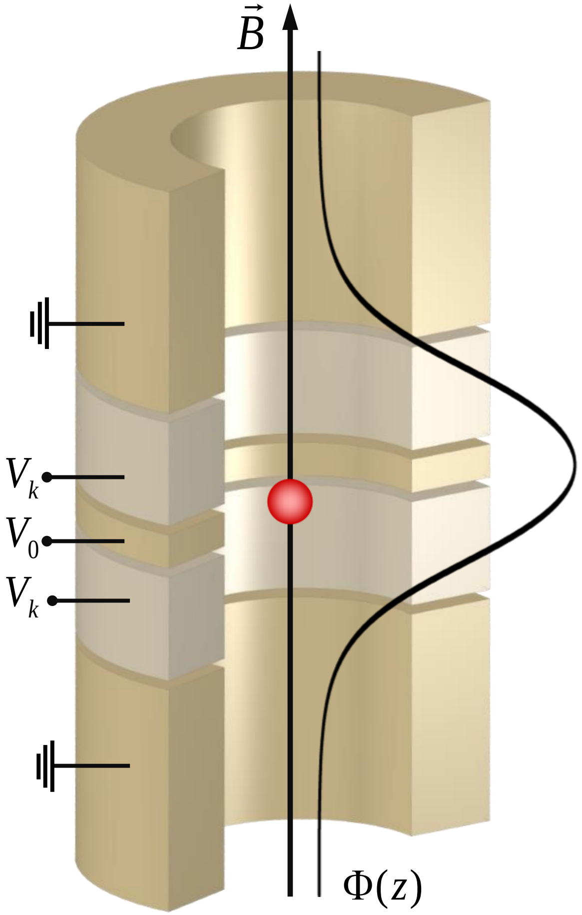
Main Tool: Penning Trap

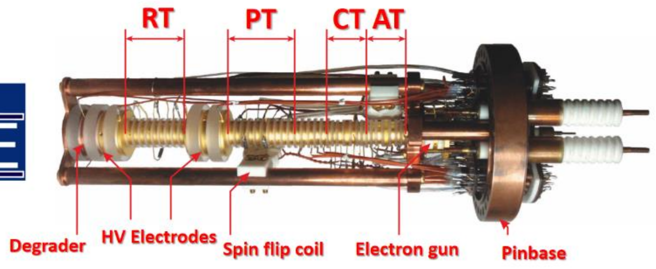
BASE – Multi-Trap-System

radial confinement: $\vec{B} = B_0 \hat{z}$

axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$







Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements. Trap is "power failure save".

Precision Trap: Homogeneous field for frequency measurements, B_2 < 0.5 µT / mm² **(10 x improved)**

Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma$ < 4 s **(10 x improved)**

Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, B_2 = 300 mT / mm²

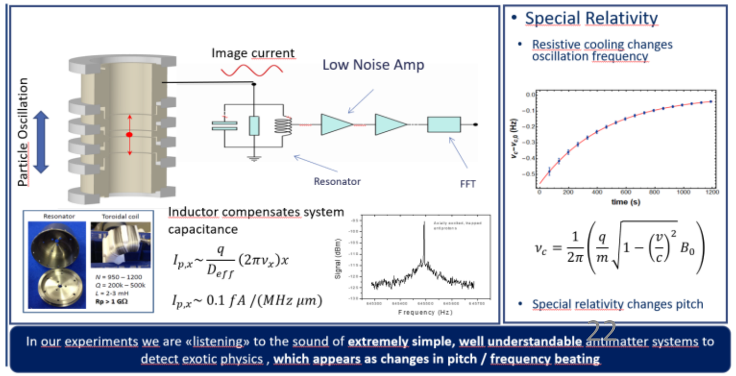
Invariance Theorem

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Gives undisturbed access to cyclotron frequencies

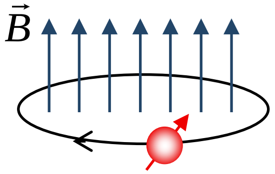
$$\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

Axial	$\nu_z = 680\,\text{kHz}$
Magnetron	$\nu_- = 8\,\text{kHz}$
Modified Cyclotron	$\nu_+ = 28{,}9\,\text{MHz}$

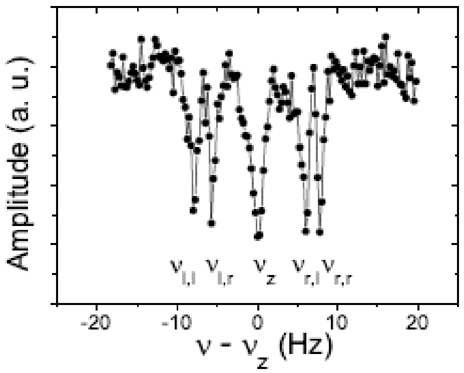


Measurements in Precision Penning Traps

Cyclotron Motion



simple



S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

g: mag. Moment in units of nuclear magneton

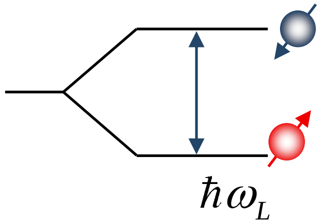
$$\omega_c = \frac{e}{m_p} B$$

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

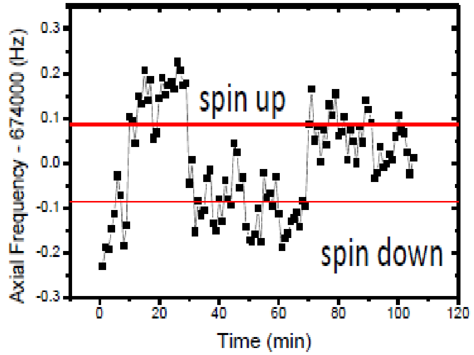
$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

Larmor Precession



difficult



A. Mooser, S. Ulmer, *et al.* PRL 106, 253001 (2011)

Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

High Precision Mass Spectrometry

High Precision Magnetic Moment Measurements

The Result

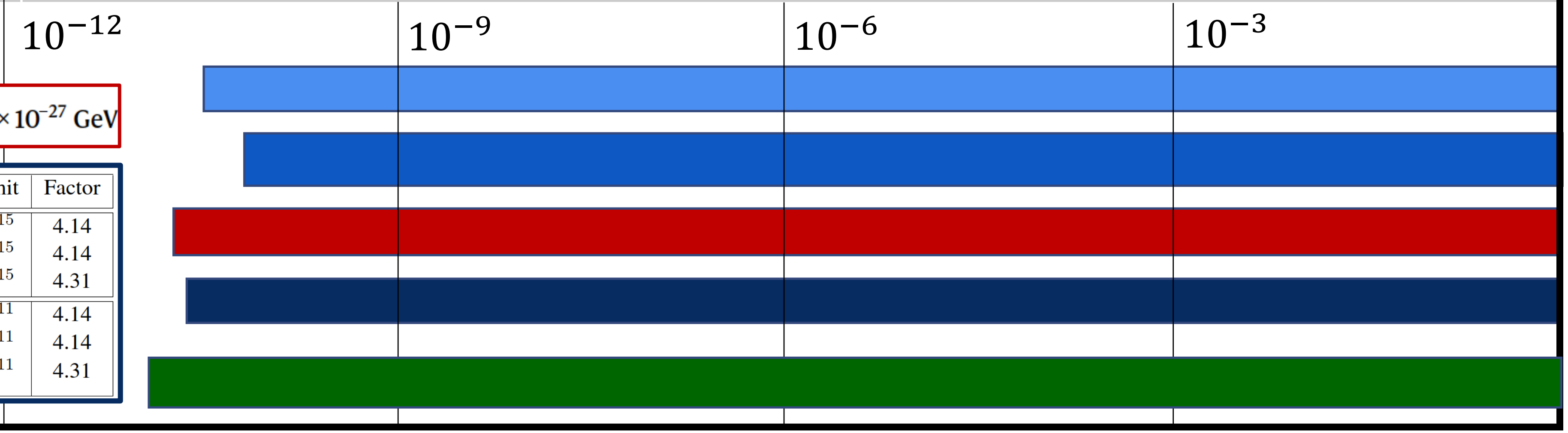
- Most precise test of CPT invariance in the baryon sector

Campaign	R_{exp}	$\sigma(R)_{stat}$	$\sigma(R)_{sys}$
2018-1-SB	1.001089218748	$27 * 10^{-12}$	$27 * 10^{-12}$
2018-2-SB	1.001089218727	$47 * 10^{-12}$	$49 * 10^{-12}$
2018-3-PK	1.001089218748	$19 * 10^{-12}$	$14 * 10^{-12}$
2018-1-SB	1.001089218781	$19 * 10^{-12}$	$23 * 10^{-12}$
Result	**1.001 089 218 757 (16)**		

SME Limits

$$|\delta\omega_c^{\overline{p}} - R_{\overline{p},p,\mathrm{exp}}\delta\omega_c^{p} - 2R_{\overline{p},p,\mathrm{exp}}\delta\omega_c^{e^-}| < 1.96 \times 10^{-27}\ \mathrm{GeV}$$

Coefficient	Previous Limit	Improved Limit	Factor
$\lvert\tilde{c}_e^{XX}\rvert$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\lvert\tilde{c}_e^{YY}\rvert$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\lvert\tilde{c}_e^{ZZ}\rvert$	$< 2.14 \cdot 10^{-14}$	$< 4.96 \cdot 10^{-15}$	4.31
$\lvert\tilde{c}_p^{XX}\rvert, \lvert\tilde{c}_p^{*XX}\rvert$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\lvert\tilde{c}_p^{YY}\rvert, \lvert\tilde{c}_p^{*YY}\rvert$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\lvert\tilde{c}_p^{ZZ}\rvert, \lvert\tilde{c}_p^{*ZZ}\rvert$	$< 7.85 \cdot 10^{-11}$	$< 1.82 \cdot 10^{-11}$	4.31

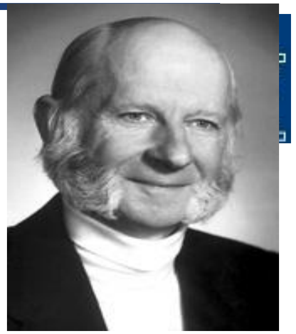


Result consistent with CPT invariance

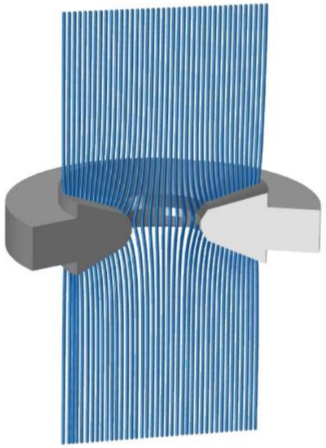
$$R_{\overline{p},p} = -1.000\,000\,000\,003\ (16)$$

Ding et al., Phys. Rev. D 102, 056009 (2020)

Larmor Frequency – extremely hard



Measurement based on continuous Stern Gerlach effect.



Energy of magnetic dipole in magnetic field $\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$

Leading order magnetic field correction $B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$

This term adds a spin dependent quadratic axial potential
-> Axial frequency becomes a function of the spin state

$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

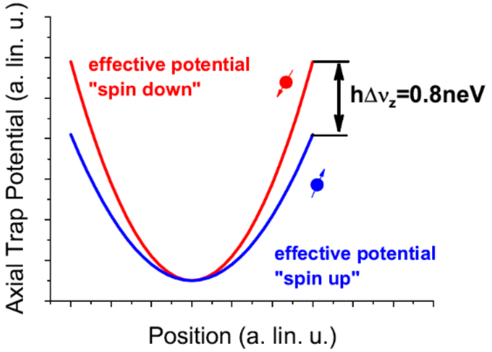
the curse (and blessing): 1000 times harder than electron experiments

- Very difficult for the proton/antiproton system.

$$B_2 \sim 300000\ T/m^2$$

- Most extreme magnetic conditions ever applied to single particle.

$$\Delta\nu_z \sim 170\ mHz$$

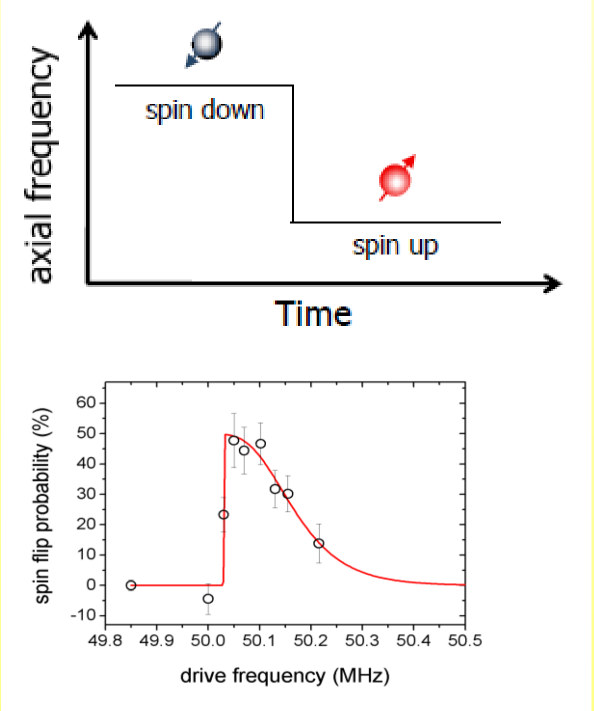


Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

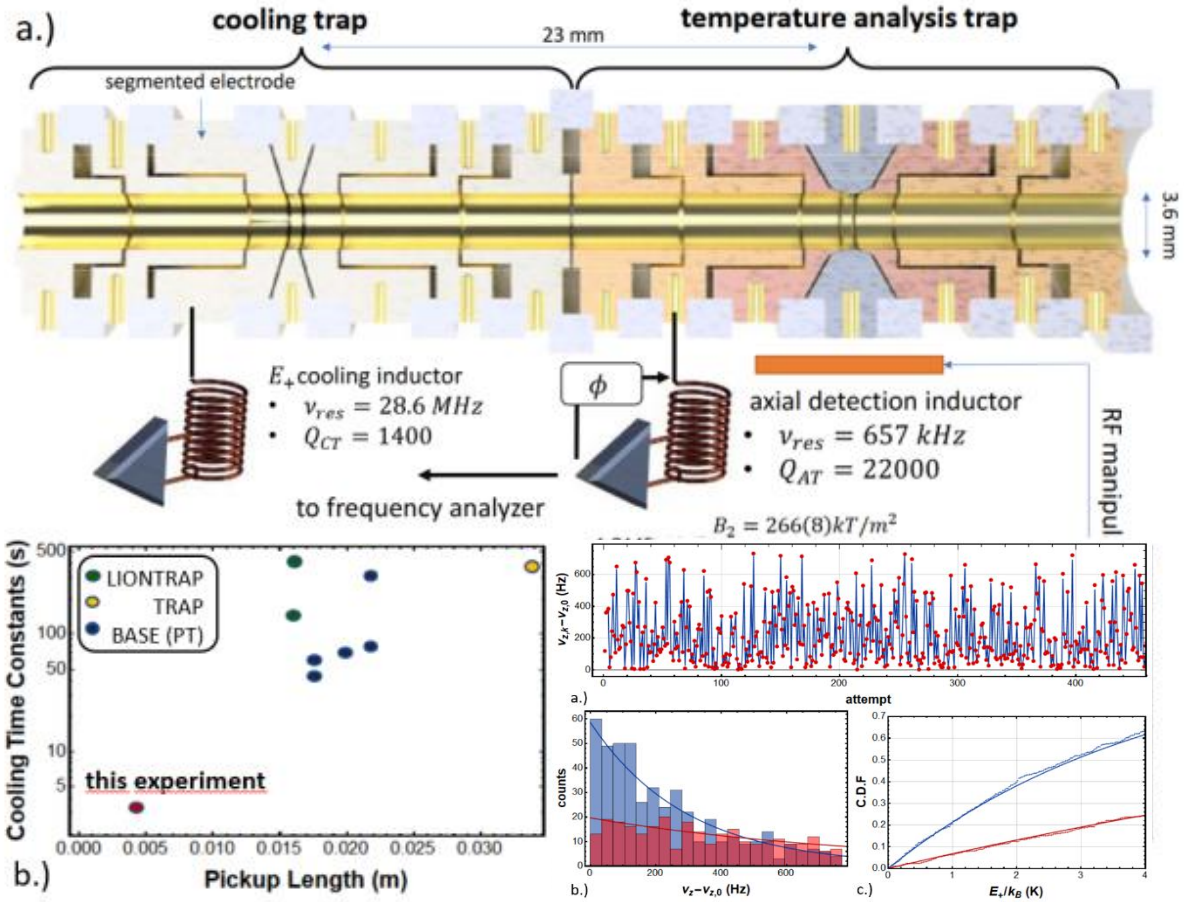
Limited to p.p.m level

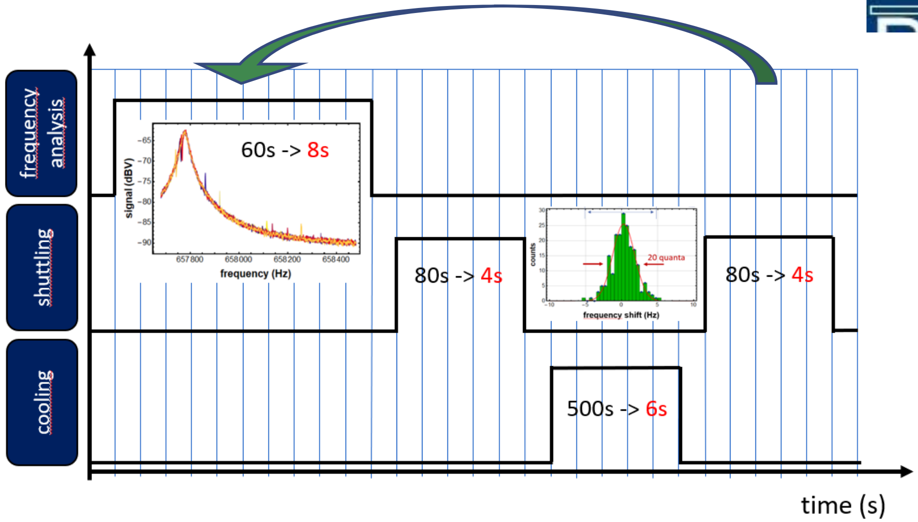


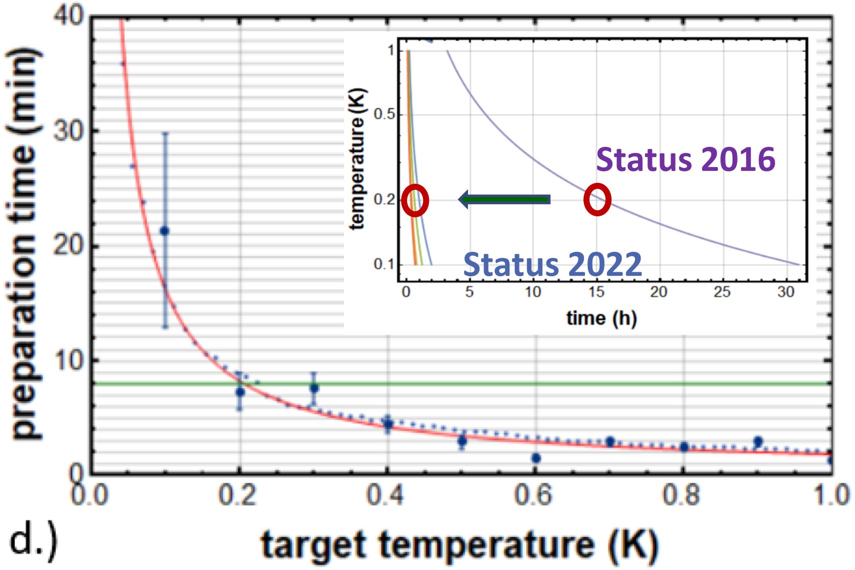
S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Sub-Thermal Cooling

- Prepare particle with low radial temperature based on a 4K resisitive cooling circuit.





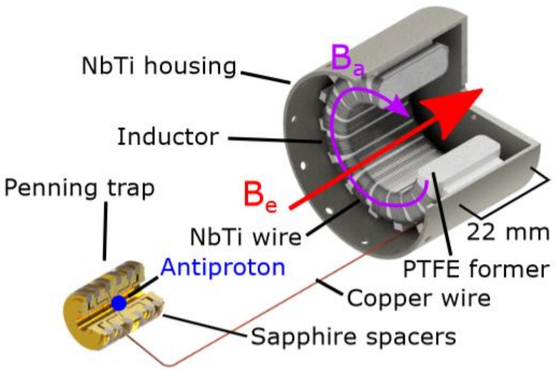


- Demonstrated single spin flip resolution in 8 min. of preparation time, took 15h in 2016.

Constraining Axion/Photon Coupling

J. Devlin et al., (BASE collaboration), Physical Review Letters. **126,** 041301 (2021).

- Axions at the right Compton frequency would source a radio-frequency signal that could be picked up by our single particle detection systems

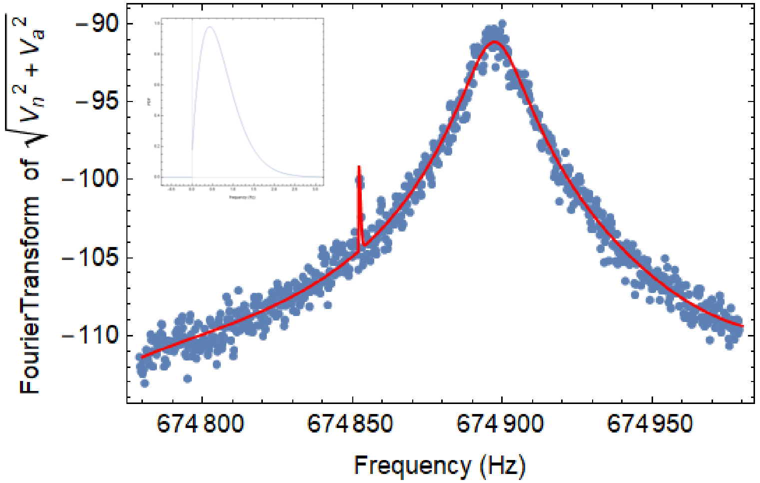


- Important feature: cold axions and axion like particles oscillate at their Compton frequencies

$$\nu_a = m_a c_0^2 / h$$

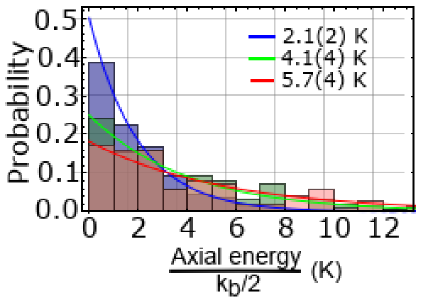
- In a strong external magnetic field **axions can convert into photons** via the inverse Primakoff effect.

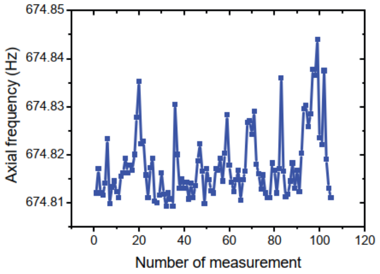
$$\boldsymbol{B_a} = -\frac{1}{2} g_{a\gamma} r \sqrt{\rho_a c_0 \hbar} B_e \boldsymbol{e_\phi}$$

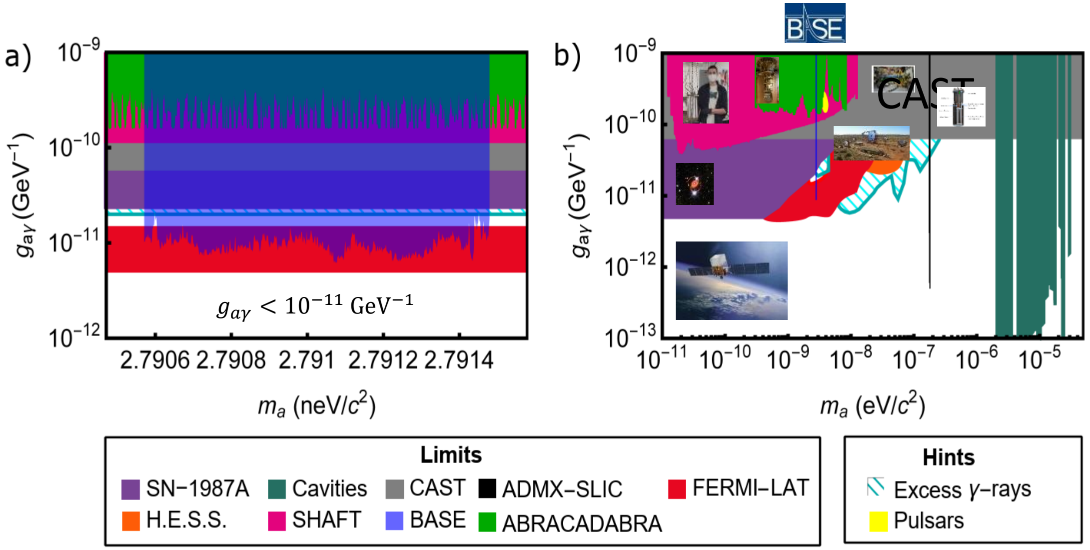


- Axion signal: $V_a = \frac{\pi}{2} g_{a\gamma} \nu_a \sqrt{\rho_a \hbar c_0} * Q\sqrt{\tau(\nu, Q, p)} \kappa N_T (r_2^2 - r_1^2) B_e$
- Noise-Floor: $V_n = \sqrt{e_n^2 \Delta\nu + 4 k_B T_z R_p \tau(\nu, Q, p) \kappa^2 \Delta\nu}$

The most important parameter to derive **appropriate limits** is the resonator temperature T_z







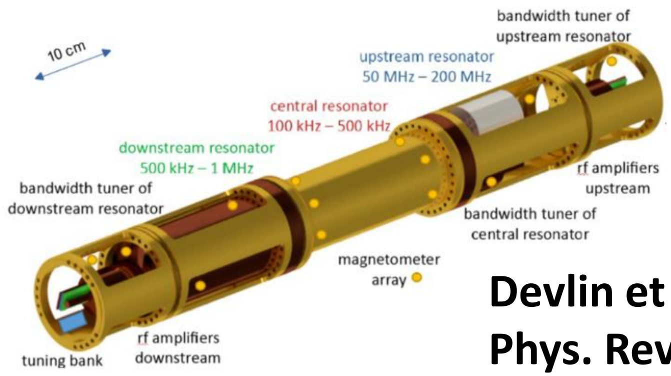
Penning trap: calibrated by single particle quantum thermometry

Future Projection

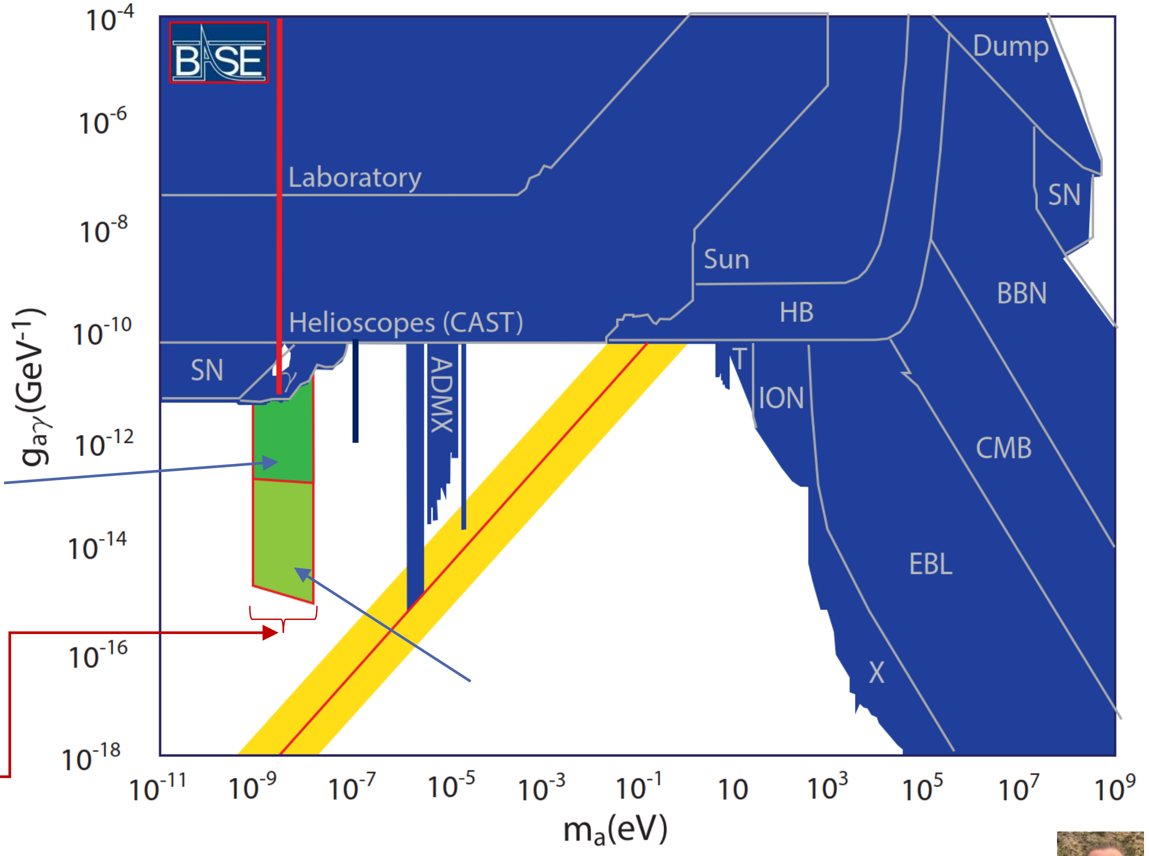
- With a purpose-built experiment we should be able to improve sensitivity considerably

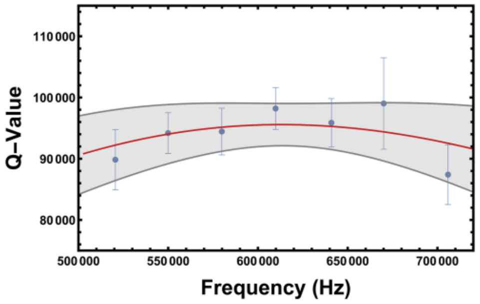
$$\frac{V_a}{V_n} \propto \frac{\pi}{2} g_{a\gamma}\sqrt{\nu_a \rho_a \hbar c_0} * \sqrt{\frac{f(Q)}{4k_B g(T_z)}}\sqrt{(r_2 - r_1)}(r_2 + r_1)^{3/2} B_e$$

Parameter	Current	New	Factor
Temperature	$5.5\,K$	$0.05K - 0.1K$	> 3
Q	$40\,k$	$160\,k$	> 1.4
e_n	$1\,nV/\sqrt{Hz}$	$0.1\,nV/\sqrt{Hz}$	> 3
B_0	$1.8\,T$	$7.0\,T$	3.9
Geometry	1	16	16
Peak Sens.	1		> 260



Devlin et al., BASE, Phys. Rev. Lett. 126, 041301





Bandwidth-gain: x 3000

Technologies available to build such an experiment / discussion with IAXO started

Summary of SME Limits by BASE

- Magnetic Moment Measurements

Coefficient	Limit
$\|\tilde{b}_p^{z}\|$	$< 1.8 \cdot 10^{-24}$ GeV
$\|\tilde{b}_p^{XX} + \tilde{b}_p^{YY}\|$	$< 1.1 \cdot 10^{-8}$ GeV^{-1}
$\|\tilde{b}_p^{ZZ}\|$	$< 7.8 \cdot 10^{-9}$ GeV^{-1}
$\|\tilde{b}_p^{*z}\|$	$< 3.5 \cdot 10^{-24}$ GeV
$\|\tilde{b}_p^{*XX} + \tilde{b}_p^{*YY}\|$	$< 7.4 \cdot 10^{-9}$ GeV^{-1}
$\|\tilde{b}_p^{*ZZ}\|$	$< 2.7 \cdot 10^{-8}$ GeV^{-1}

Coefficient	Limit
$\tilde{b}_p^{*X}$	$< 9.7 \cdot 10^{-25}$ GeV
$\tilde{b}_p^{*Y}$	$< 9.7 \cdot 10^{-25}$ GeV
$\|\tilde{b}_p^{*XX} - \tilde{b}_p^{*YY}\|$	$< 5.4 \cdot 10^{-9}$ GeV^{-1}
$\tilde{b}_p^{*XZ}$	$< 3.7 \cdot 10^{-9}$ GeV^{-1}
$\tilde{b}_p^{*YZ}$	$< 3.7 \cdot 10^{-9}$ GeV^{-1}
$\tilde{b}_p^{*XY}$	$< 2.7 \cdot 10^{-9}$ GeV^{-1}

- 2022 Charge-to-Mass Ratio Measurement

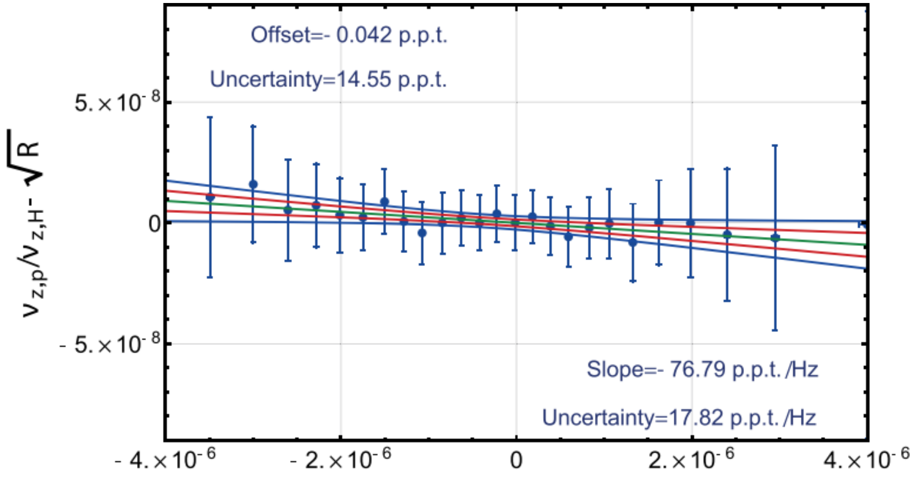
Coefficient	Previous Limit	Improved Limit	Factor
$\|\tilde{c}_e^{XX}\|$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\|\tilde{c}_e^{YY}\|$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\|\tilde{c}_e^{ZZ}\|$	$< 2.14 \cdot 10^{-14}$	$< 4.96 \cdot 10^{-15}$	4.31
$\|\tilde{c}_p^{XX}\|, \|\tilde{c}_p^{*XX}\|$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\|\tilde{c}_p^{YY}\|, \|\tilde{c}_p^{*YY}\|$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\|\tilde{c}_p^{ZZ}\|, \|\tilde{c}_p^{*ZZ}\|$	$< 7.85 \cdot 10^{-11}$	$< 1.82 \cdot 10^{-11}$	4.31

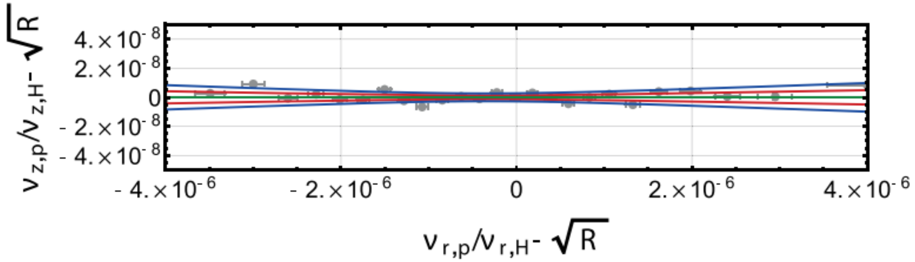
- Time-base Charge-to-Mass analysis ongoing

Work in progress, to be finished within the next 3 months.

Dominant Systematic Limitations

- Lineshape Shift





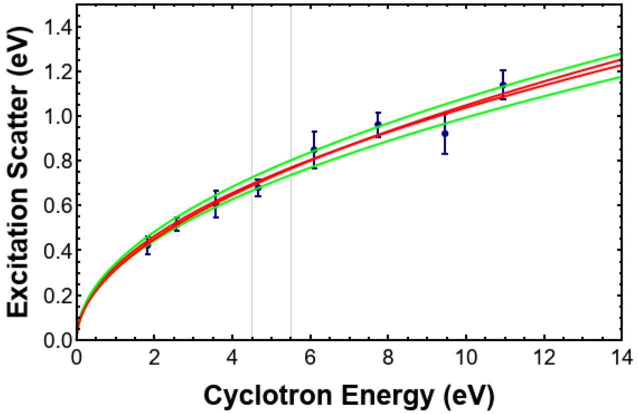
- Scaling of particle frequency with respect to frequency center of the detection resonator leads to frequency dependent shift of the measured frequency ratio.

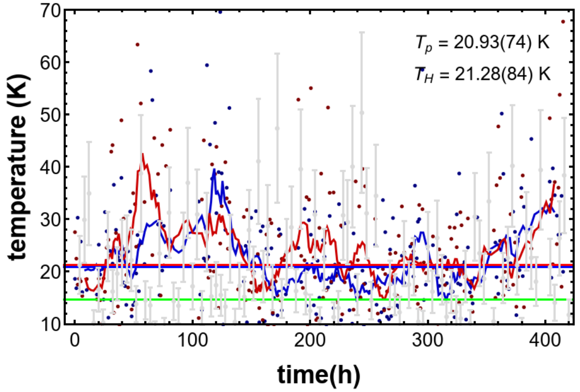
Strong suppression in PEAK measurements

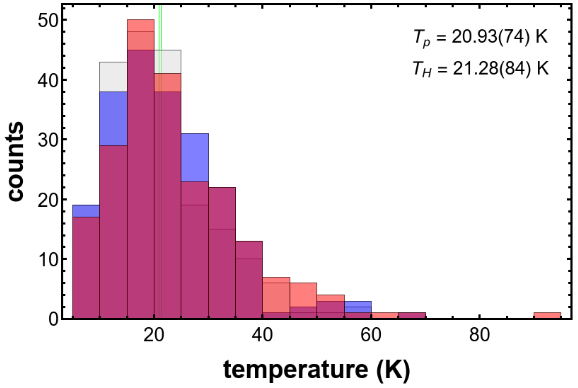
- Temperature Shifts

$$\frac{\Delta\nu_c}{\nu_c} = \frac{\nu_+}{\nu_c^2}\Delta\nu +_+ \frac{\nu_z}{\nu_c^2}\Delta\nu_z \approx \frac{1}{4\pi^2 m_0 \nu_z^2}\frac{B_2}{B_0}k_B T_z = -23.5(1.5)\,\frac{\text{p.p.t.}}{\text{K}},$$

$$E(t) = \left(\frac{1}{2}\frac{qE_0}{m} * t + \rho_{0,th}\right)^2 = E_{exc} + 2\sqrt{E_{th}}\sqrt{E_{exc}} + E_{th}$$







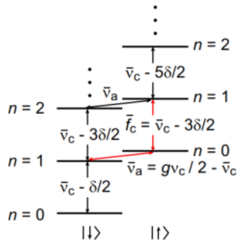
Continuously measured in PEAK measurements

Electron/Positron Magnetic Moment

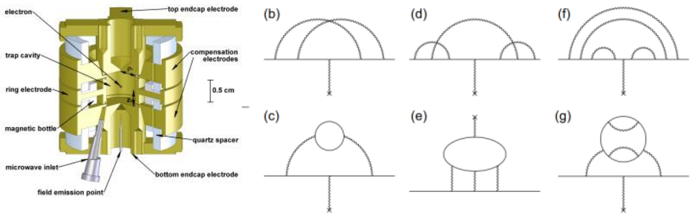
Prototype Fundamental Physics Experiment: A stable lepton in an empty, conducting box

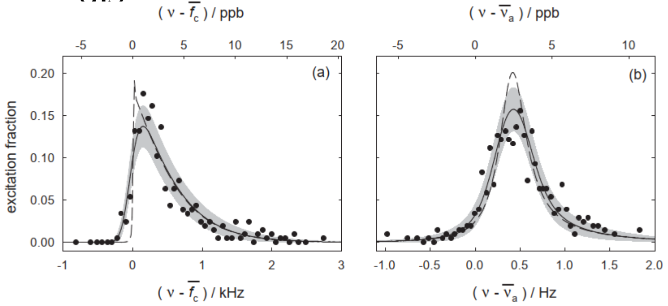
- **Status** G. Gabrielse, D. Hanneke, B. Odom, B. D'Urso, et al.

$$\frac{g_e}{2} = 1.001\,159\,652\,180\,73\,(28)\,(0.28\,p.p.t)$$



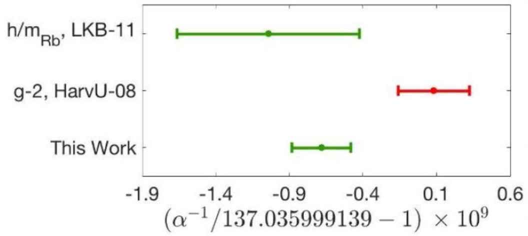
$$\frac{g_e}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \cdots + \alpha_{\mu,\tau} + \alpha_{had} + \alpha_{weak}$$





Experiment is dominantly limited by magnetic bottle strength B_2

- Smoothing of cyclotron edge
- Width of transition line



Most precise test of QED

- **Electron and Proton**

Parameter	e^-/e^+	$p/\bar{p}$
B_2	$1539\,T/m^2$	$278\,000\,T/m^2$
$\Delta\nu_z$	$3\,Hz$	$0.17\,Hz$
ν_z	$200\,MHz$	$0.6\,MHz$
μ	μ_B	μ_N
m	$1/1836$ u	$1\,u$

Have the methods at hand to reduce the magnetic bottle strength by a factor of 30

- **Muon**

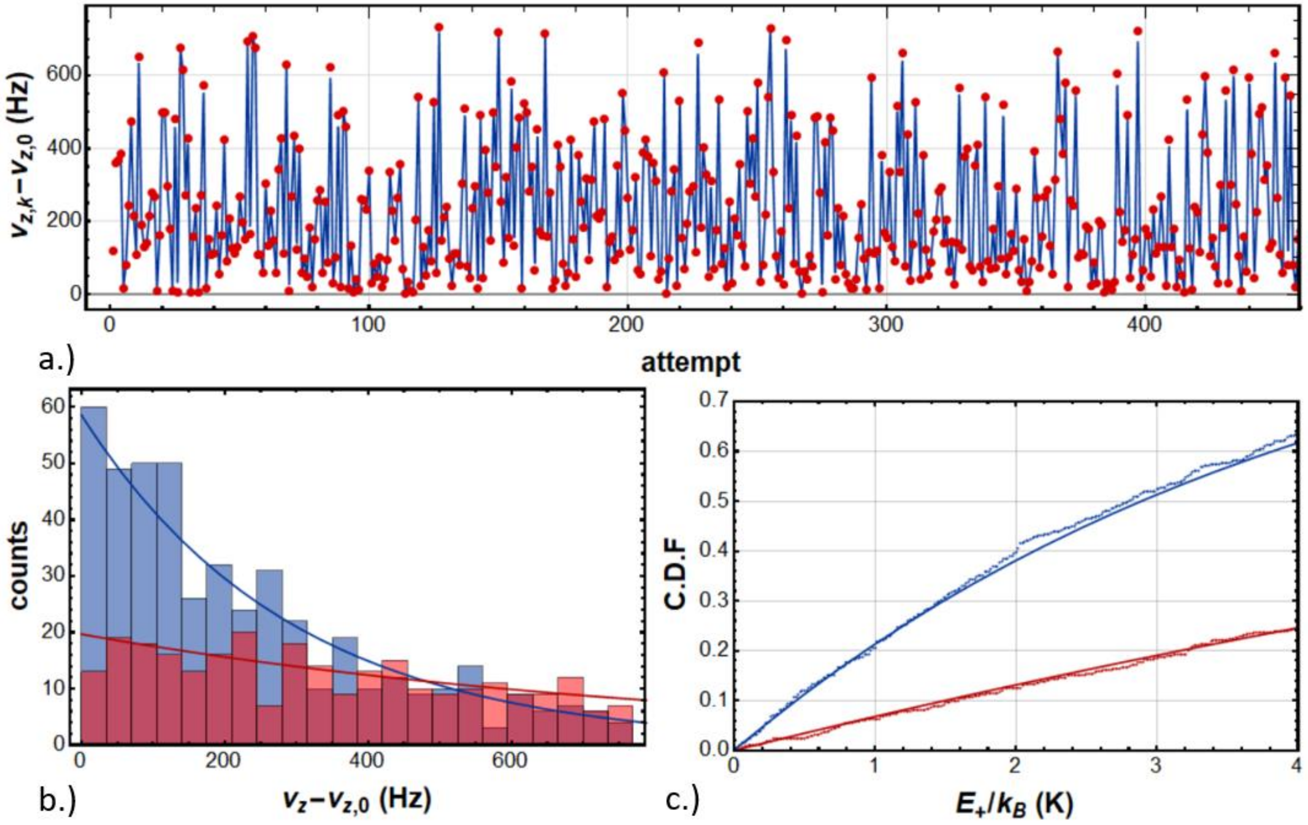
$$\frac{g_\mu}{2} = 1.001\,165\,920\,80\,(63)\,(0.63\,p.p.b.)$$

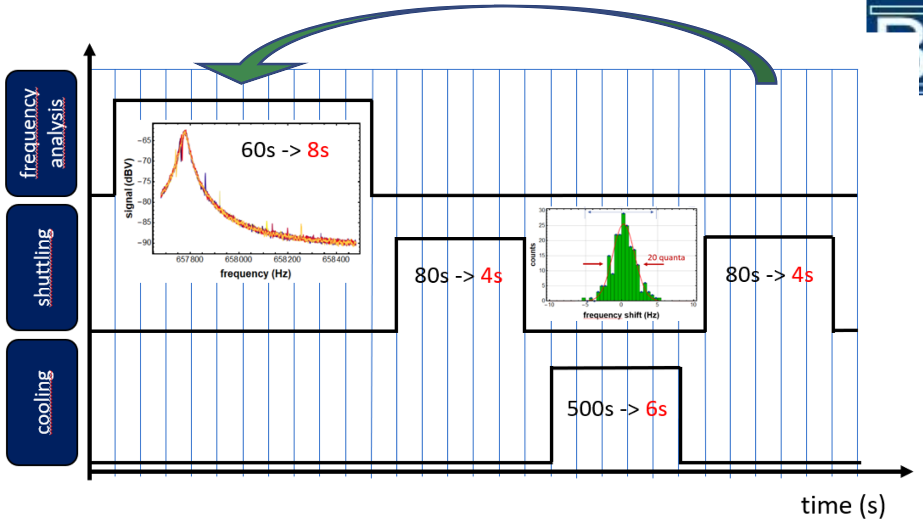
Potential to probe same physics as $(g-2)_\mu$

headroom for a factor of 100 of improvement

Sub-Thermal Cooling

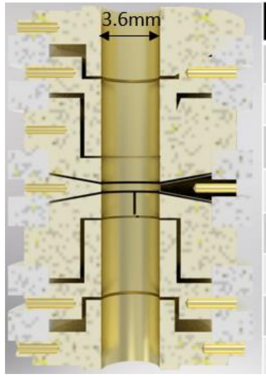
- Prepare particle with low radial temperature based on a 4K resisitive cooling circuit.





- Thermalization is stopped once particle at low radial temperature is found.

- New cooling trap implemented



Parameter	2016 measurement (PT)	2022 measurement (CT)
detector temperature	12.8 K	4.2 K
detection Q	450	1250
R_p	75.000 Ω	360.000 Ω
pickup length (D_{eff})	21.5 mm	4.8 mm
thermalization time τ	370 s	4.2 s
Transport time	2 x 78 s	2 x 4.6 s
Readout time	64 s	16 s

- Improves sub-thermal cooling cycles from hours to minutes (factor of 60 improvement)