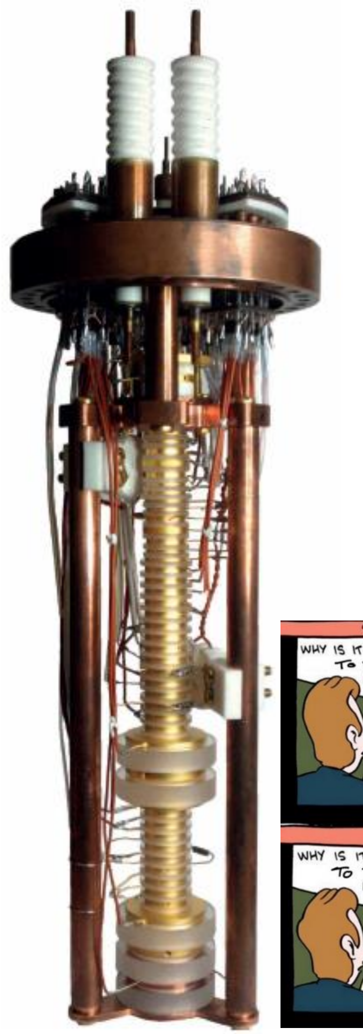
Progress 2024
BASE Collaboration

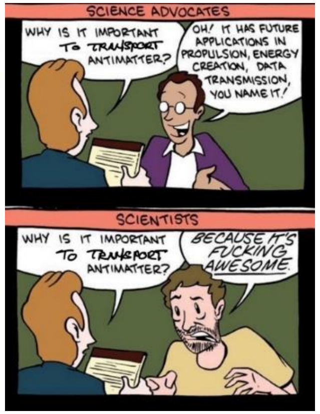
Stefan Ulmer, Barbara Latacz, Christian Smorra

for the BASE collaboration

HHU Düsseldorf, RIKEN, MPI-K, PTB, and CERN

2025 / 02 / 11



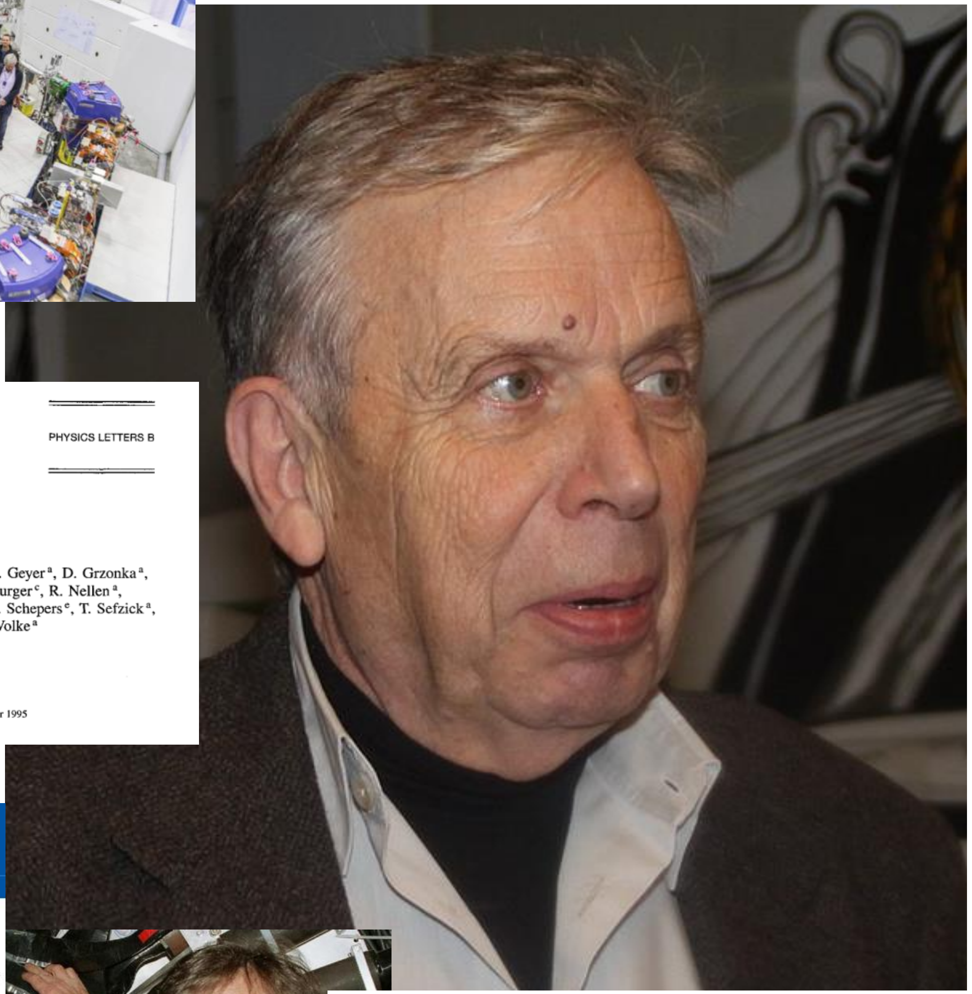


BASE uses single particles in advanced Penning trap systems, to study the fundamental properties of protons and antiprotons with high precision.

Dedication

- To Walter Oelert – + 25.11.2024 (affiliated to Jülich, Bochum, **Mainz**)
  - First detection of 11 antihydrogen atoms with an energy of 1GeV
  - Chair of CERN's antimatter program until 2017
  - Instrumental role in establishing the Extra Low Energy Antiproton Synchrotron ELENA
- Mail from 17.10.2024 on p-transport:
- "Wow!!! That's fantastic! Congratulations! Those were already old plans back in the LEAR days, but they were never realized. Now you've made it happen for protons, and I think that's just amazing!
- My heartfelt congratulations to you and your team.
- …

Once again, congratulations! Walter"



ELSEVIER

1 February 1996

PHYSICS LETTERS B

Physics Letters B 368 (1996) 251–258

Production of antihydrogen

G. Baur [a], G. Boero [b], S. Brauksiepe [a], A. Buzzo [b], W. Eyrich [c], R. Geyer [a], D. Grzonka [a], J. Hauffe [c], K. Kilian [a], M. LoVetere [b], M. Macri [b], M. Moosburger [c], R. Nellen [a], W. Oelert [a], S. Passaggio [b], A. Pozzo [b], K. Röhrich [a], K. Sachs [a], G. Schepers [e], T. Sefzick [a], R.S. Simon [d], R. Stratmann [d], F. Stinzing [c], M. Wolke [a]

[a] IKP, Forschungszentrum Jülich GmbH, Germany
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Received 8 December 1995; revised manuscript received 21 December 1995
Editor: L. Montanet

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ANTIMATTER | FEATURE

Setting the record straight

25 November 2005

Walter Oelert, leader of the team that 10 years ago obtained the first antimatter atoms, talks to Tomasz Rozek about the fact and fiction surrounding the discovery.

Dan Brown's novel *Angels and Demons* has been enormously popular. A secret brotherhood murders a physicist who managed to produce the first antimatter on Earth. You have surely heard about the book?

I have even read it. Indeed the author has me killed at the very beginning.

Correct. You die and the antimatter stolen from CERN is used to blackmail the Vatican. CERN does produce antimatter, and the contact of antimatter with ordinary matter results in annihilation where large quantities of energy appear. Aren't you scared that one day Brown's scenario may become real?

No, since there is no way to produce and store a large quantity of antimatter.

First atoms of antimatter produced at CERN

4 JANUARY, 1996

Geneva, 4 January 1996. In September 1995, Prof. Walter Oelert and an international team from Jülich IKP-KFA, Erlangen-Nuernberg University, GSI Darmstadt and Genoa University succeeded for the first time in synthesising atoms of antimatter from their constituent antiparticles. Nine of these atoms were produced in collisions between antiprotons and xenon atoms over a period of three weeks. Each one remained in existence for about forty billionths of a second, travelled at nearly the speed of light over a path of ten metres and then annihilated with ordinary matter. The annihilation produced the signal which showed that the anti-atoms had been created.

BASE – Collaboration

- **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
- **BASE-STEP:** Development of transportable antiproton traps
- **Hannover/PTB:** BASE-LOGIC / QLEDS-laser cooling project, new technologies
- **BASE-HHU:** Offline antiproton studies
- **BASE-CDM:** Axion Haloscope at HHU
- More to come – BASE-Lepton / BASE Deuteron / BASE MCP…

Institutes: RIKEN, MPIK, CERN, HHU, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig, ETH Zuerich, ICL

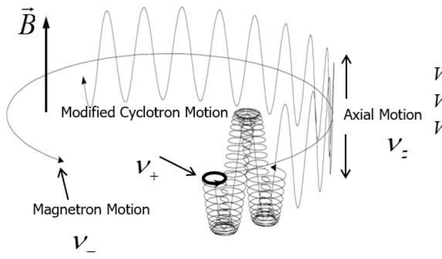
BASE/BASE-STEP Team at CERN, HHU, Mainz

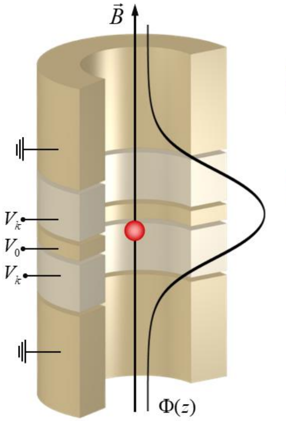
Six experiments, 11 institutes, about 30 collaborators

BASE in a Nutshell

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

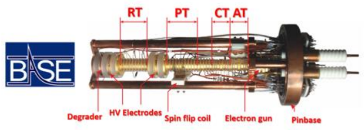
axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$





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

BASE – Multi-Trap-System



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

Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$ **(10 x improved)**

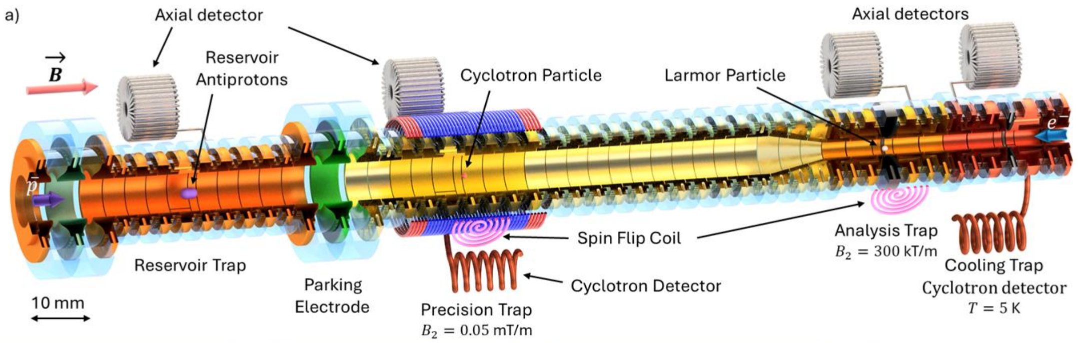
Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s **(10 x improved)**

Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ mT / mm^2$

Invariance Theorem

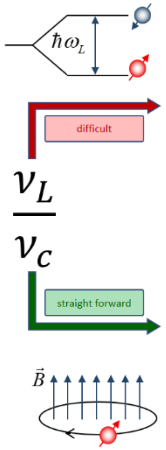
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Gives undisturbed access to cyclotron frequencies $\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$



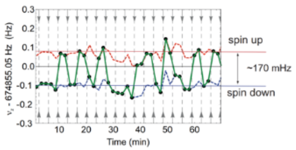
- New antiproton catching system and low energy antiproton vacuum technology.
- Magnetic shimming system for magnetic field gradient compensation.
- Upgraded AT electronics for error-free nondestructive Spin Quantum Transition Spectroscopy
- Cooling trap with 80 times improved cooling time.

First Non-Destructive Coherent Quantum Transition Spectroscopy with a Single Antiproton Spin



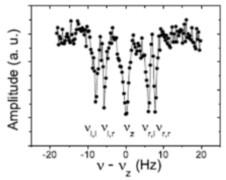
Continuous Stern Gerlach Effect

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

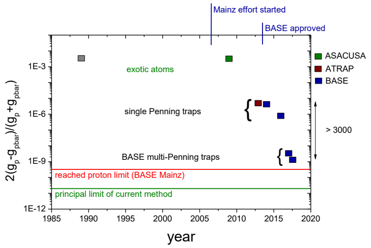


$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

Image Current Measurements



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



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

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

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

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

BASE Annual Summary 2024

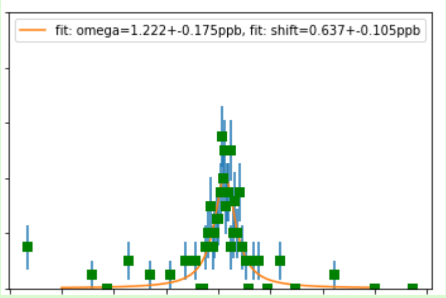
Experiment ONLINE throughout entire year 2024

Antiproton Run – Continuous Reservoir Monitoring – 472 days

Coherent Antiproton Magnetic Moment Measurement Campaign

AD-ELENA Online Operation

Antiproton Magnetic Moment Measurement Campaign

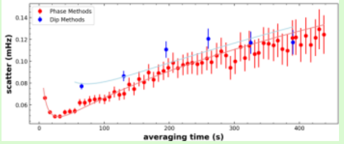


2024/04/30
Start of AD/ELENA physics operation

Implementation of new measurement concepts

Fully phase coherent measurements

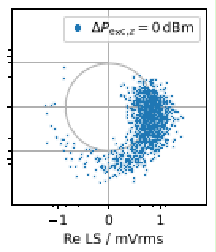
AT – axial phase methods

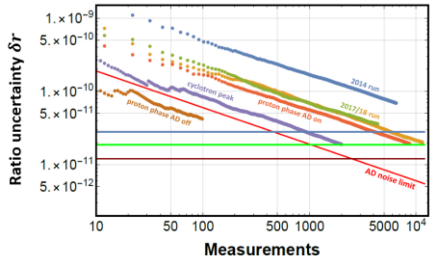


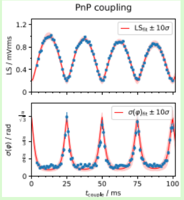
Jan. Feb. Mar. Apr. May June July Aug. Sep. Oct. Nov. Dec. Jan.

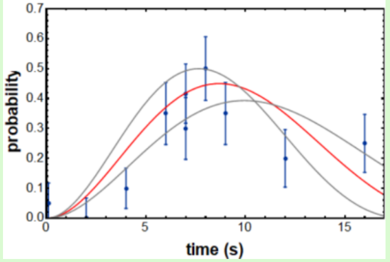
Start of ELENA commissioning

Two Phys. Rev. Lett. Published in June 2024

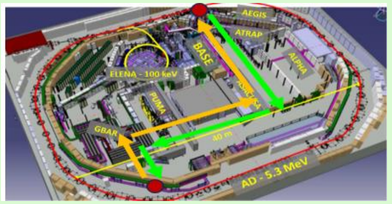


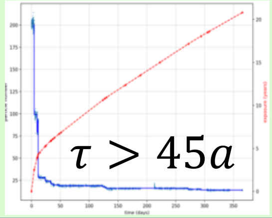






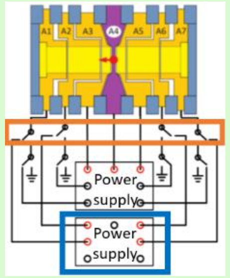
First proton transport out of CERN's AMF





Achieved a statistical resolution of order 80ppt to 120ppt, systematic data analysis not yet completed

Systematic Studies Ongoing

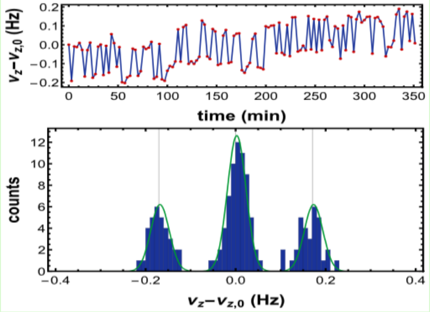


AT multipole operation

AT Heating Rates

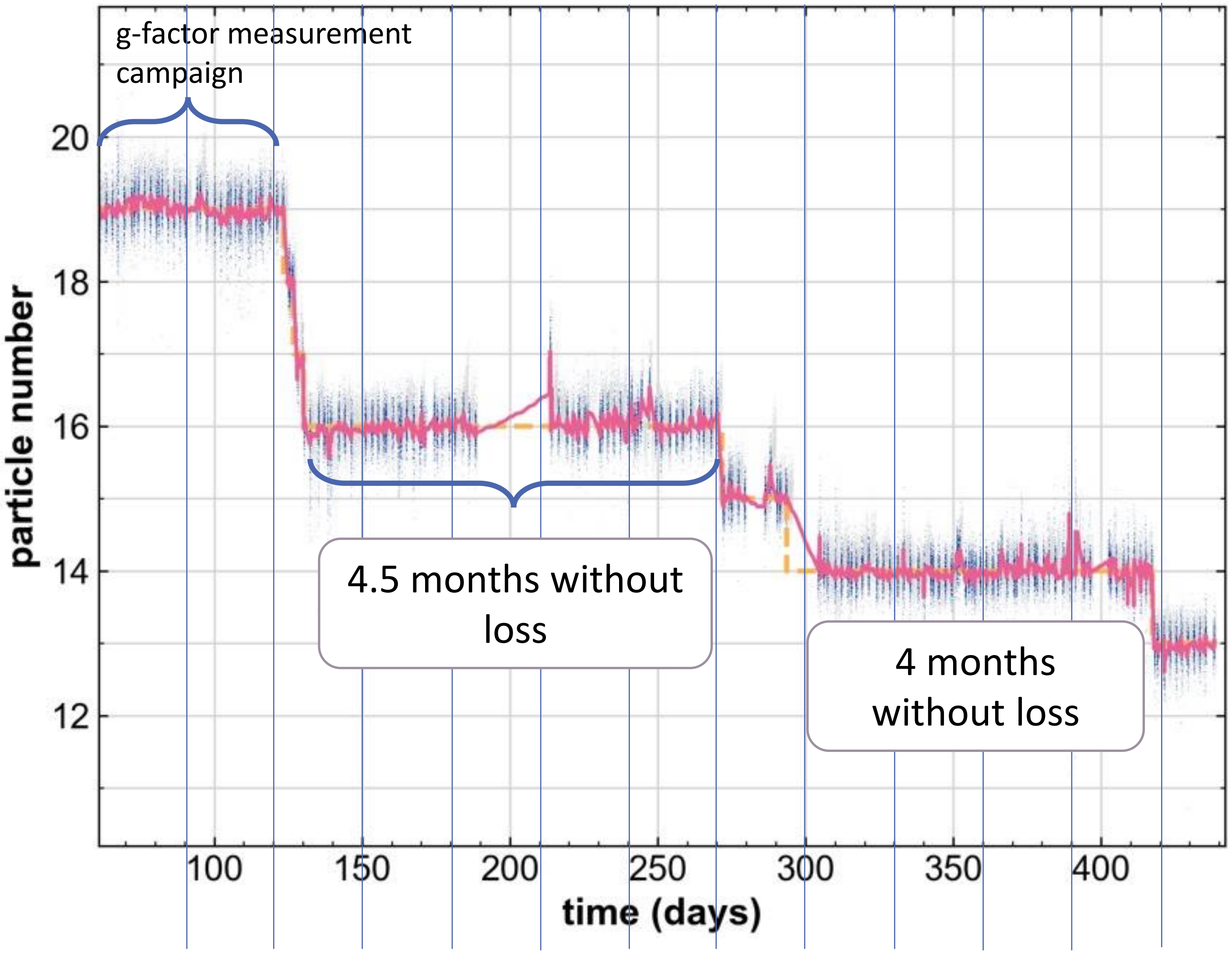
AT Spin Detection

Phase Sensitive Cyclotron Frequency Measurements



Antiproton reservoir operation with particles trapped in October 2023

2024 Particle Consumption



Losses due to electron contamination of the transport section (BML/BML/EJW)

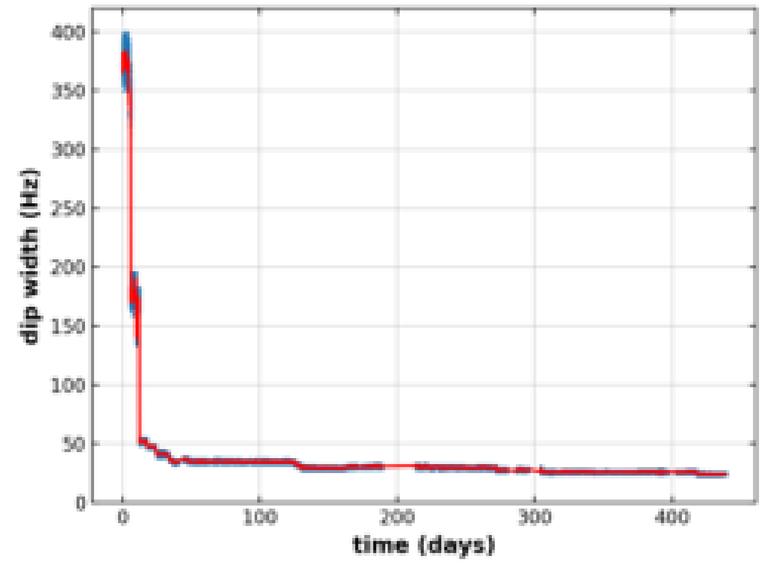
Losses due to electronics modification when switching from 5-pole to 9-pole mode (BML/IA/SU)

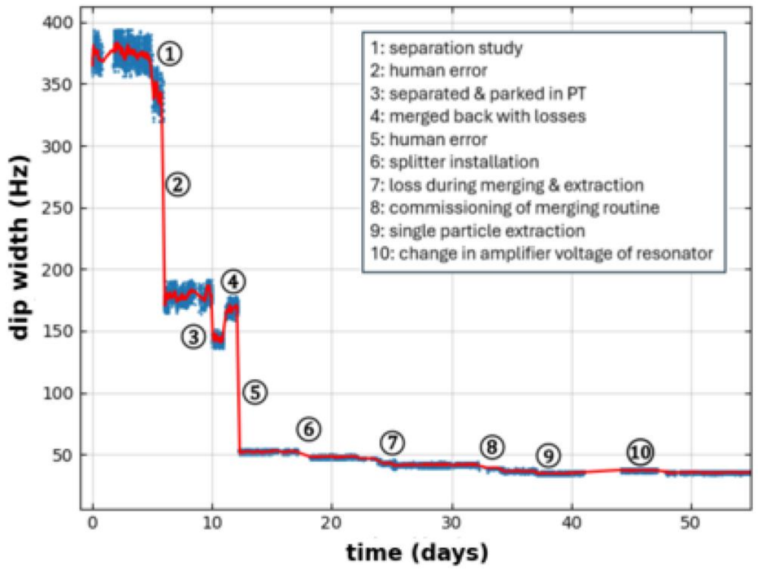
Losses due to uncontrolled high-Q excitation of the cyclotron mode (BA/PG)

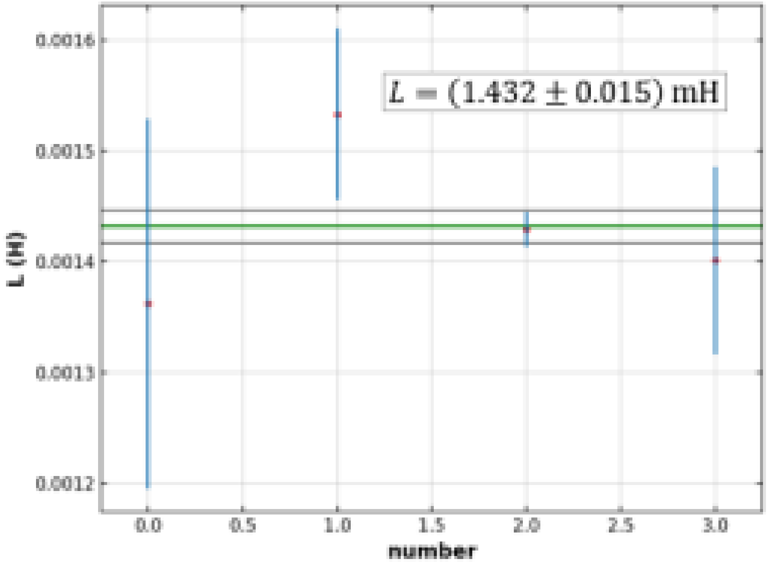
Power supplies of transport system not correctly initialized after control system restart (SU)

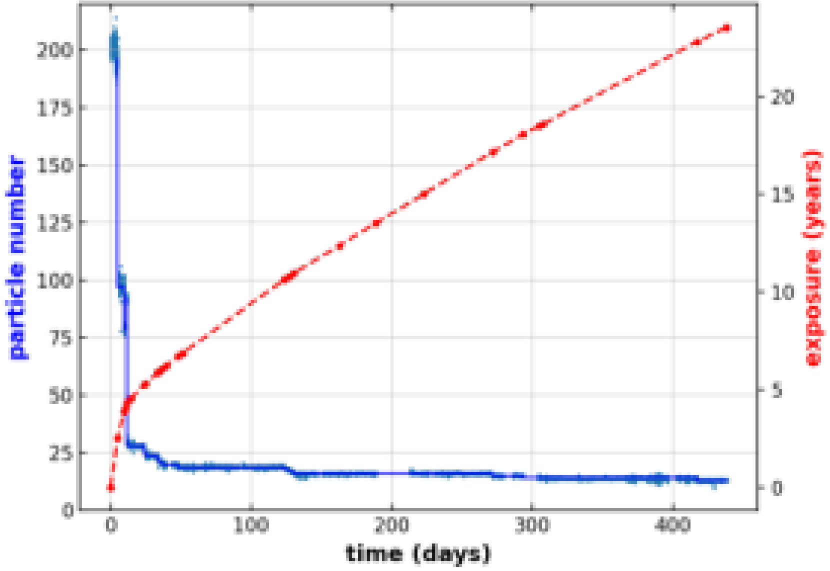
6 antiprotons used during the entire 2024 RUN

Updated Antiproton Lifetime









Based on an antiproton reservoir trapped on 27th of October 2023

Experiments with these particles still ongoing after **472 days** of trapping.

Initially trapped: 25 particles

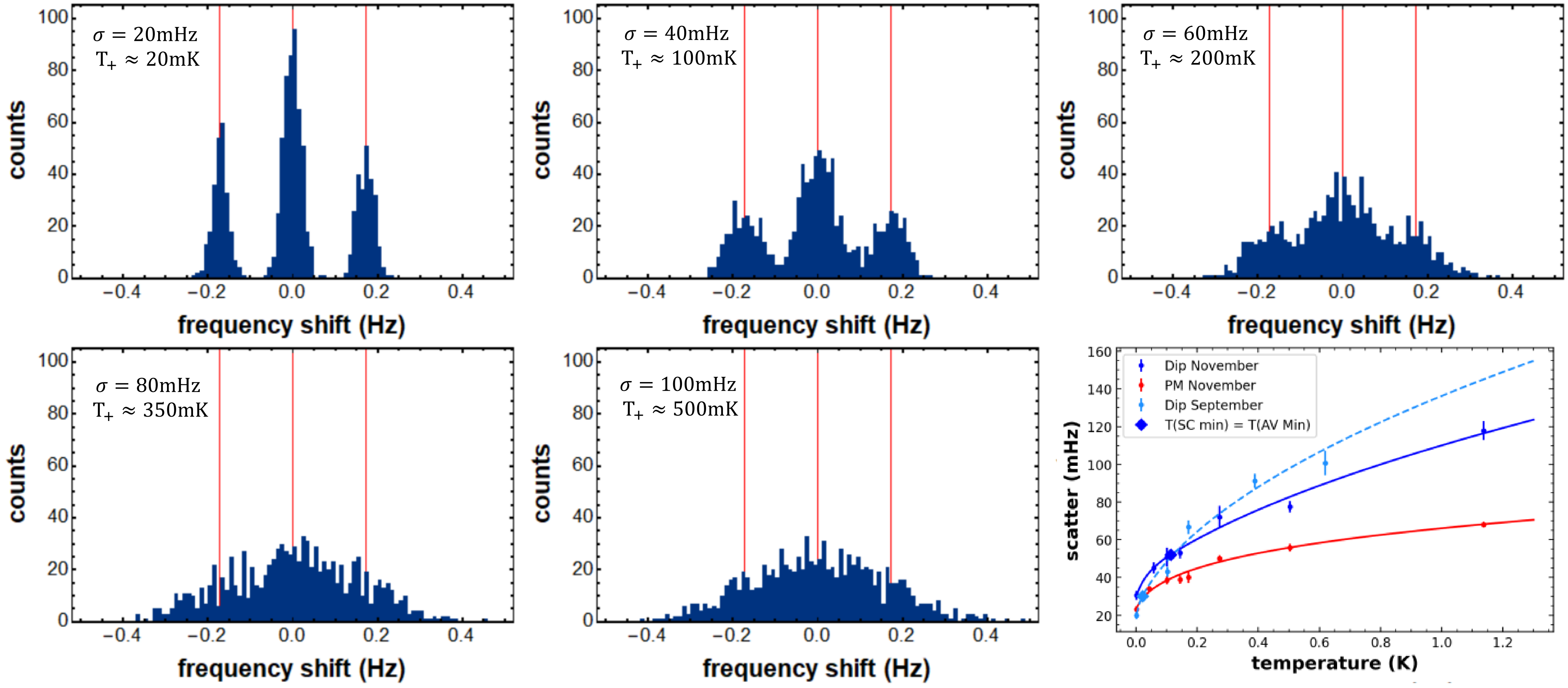
Still in the reservoir: 18 particles

Lost in 2024 a total 7 particles

Lifetime update: > 46.8y

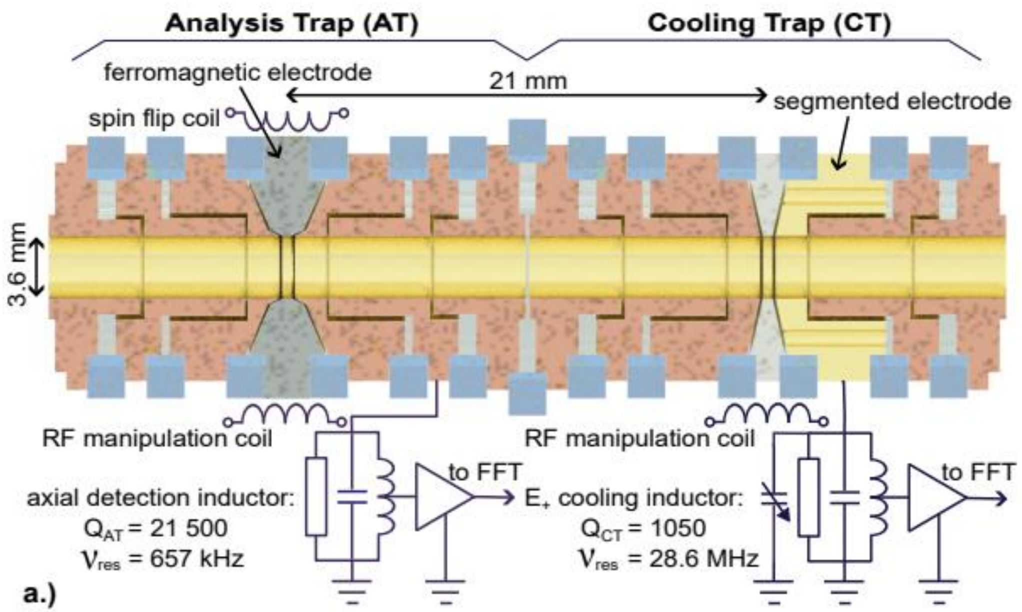
Cyclotron Heating Rates:

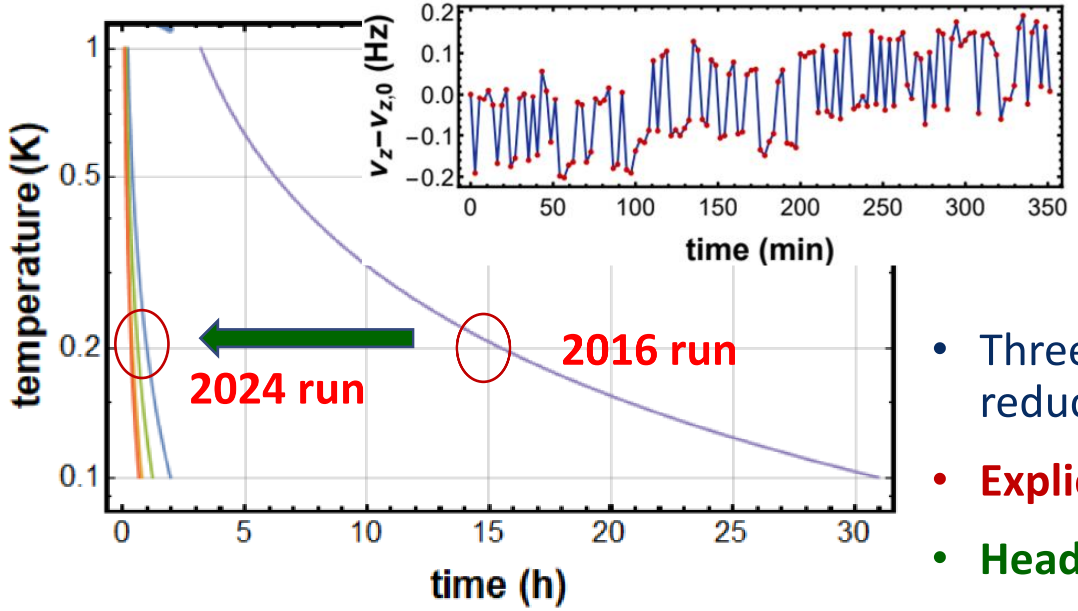
$$\zeta_+ = \frac{q^2 n_+}{2 m_{\bar{p}} \hbar \omega_+} S_E(\omega_+)$$

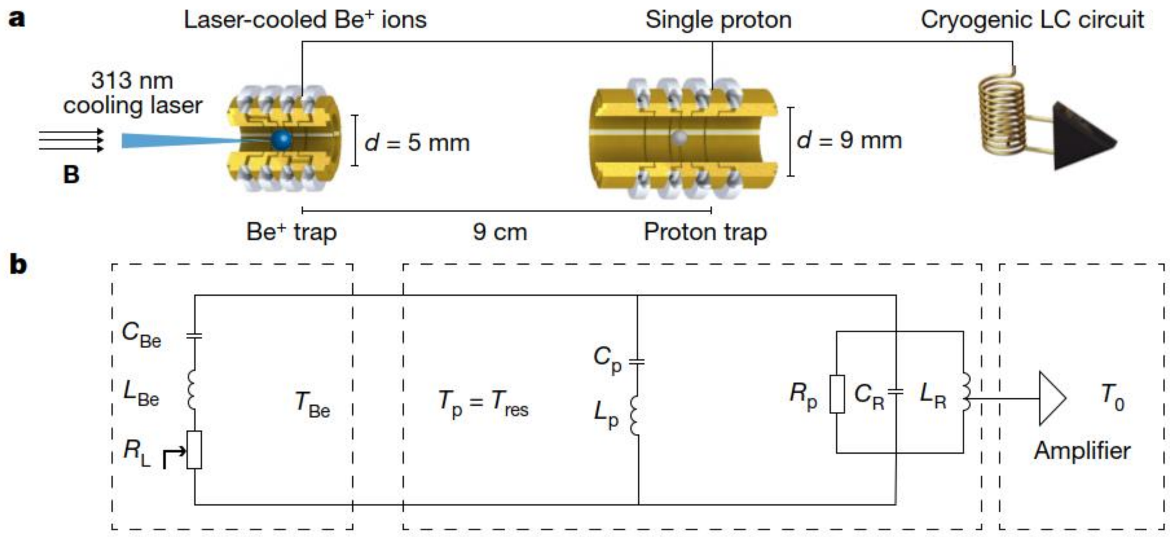


- **Put a lot of effort into our particle cooling techniques with CT at CERN and SC at Mainz**

Improved Cooling Techniques / Maxwell Deamon / Sympathetic







C. Will et al. Phys. Rev. Lett. 023002 (2024)
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.133.023002

B. M. Latacz et al. Phys. Rev. Lett. 053201 (2024)

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.133.053201

Demonstrated cooling of the axial mode of a proton to 170mK

Further progress, now: 80mK.

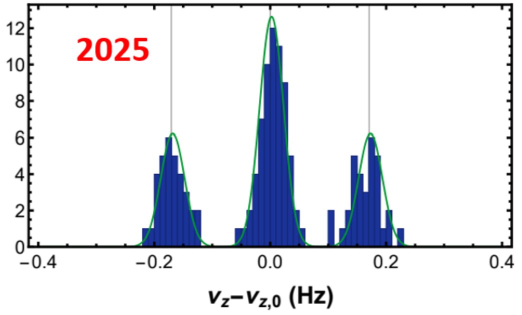
Applicable to the antiproton

- Three-fold temperature reduction gives additional factor of three in time reduction for particle preparation at given threshold.
- **Explicitly demonstrated:** robust 200mK particle preparation in 8 minutes.
- **Headroom: Colder Electronics – SQUID detectors – 100mK traps**

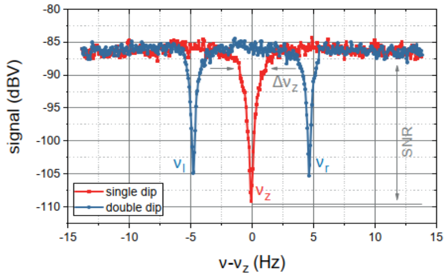
Measurement Sequence

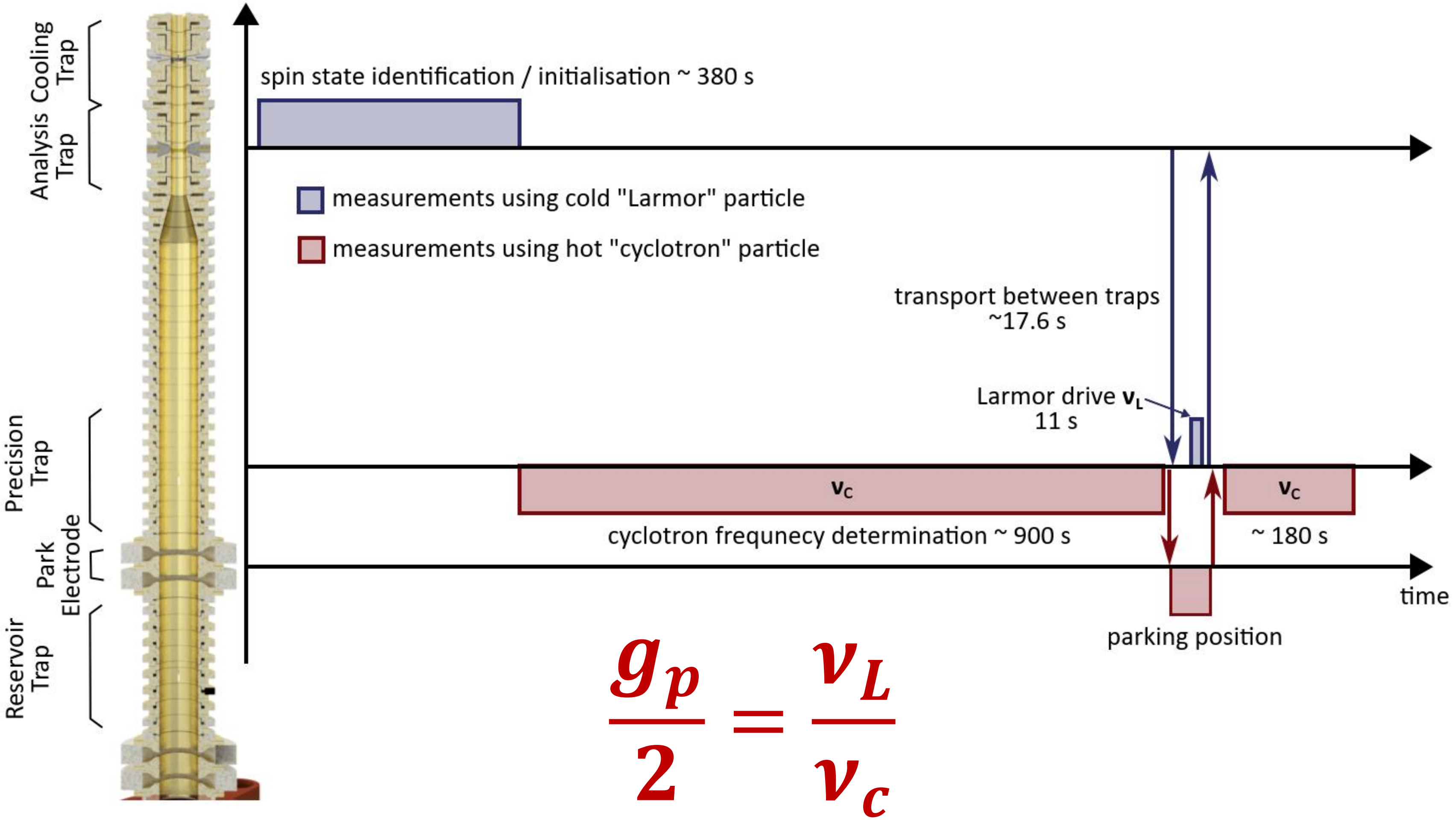
- At CERN, we are using a two-particle/three-trap technique to sample the magnetic moment resonance

Cold particle which always has single spin resolution



Hot particle that measures the magnetic field by cyclotron measurements

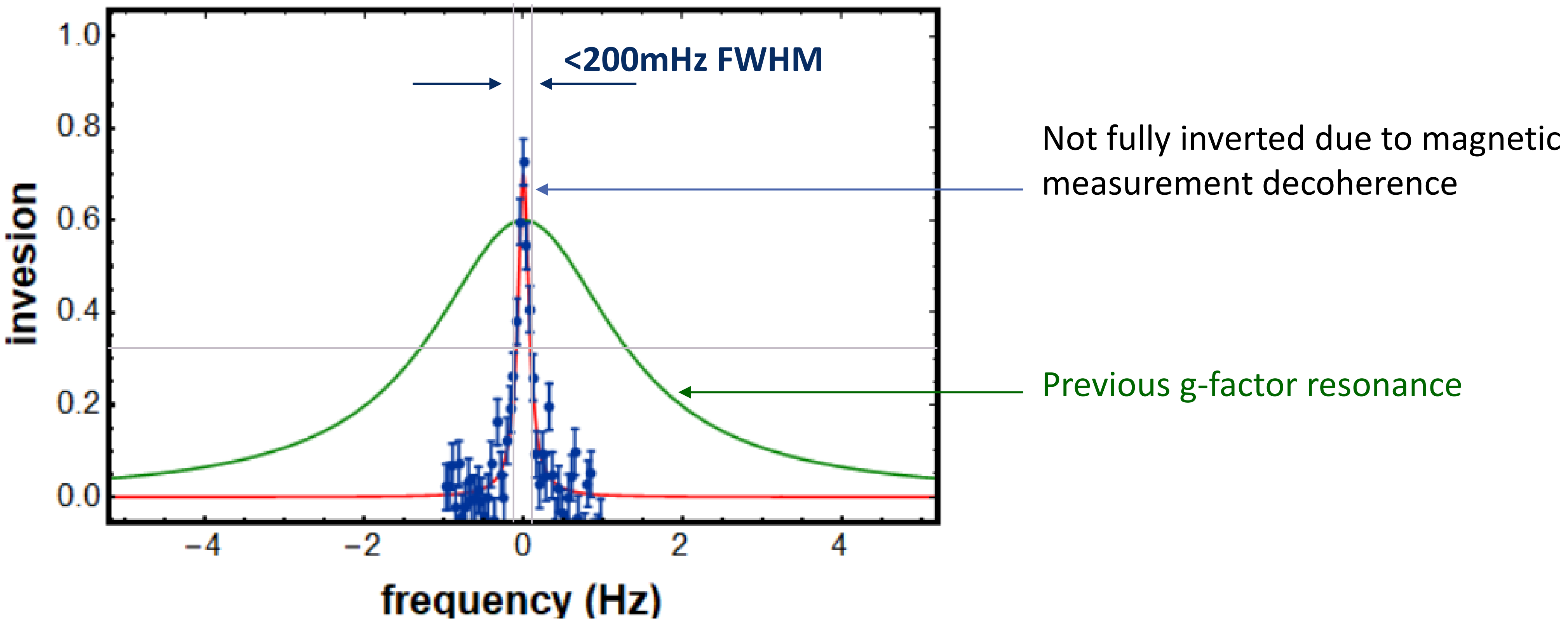




$$\frac{g_p}{2} = \frac{\nu_L}{\nu_c}$$

Antiproton Magnetic Moment Measurements

- Antiproton: data collected between 28.12.2023 and 26.01.2024
- Proton: measurement carried out May to July 2023



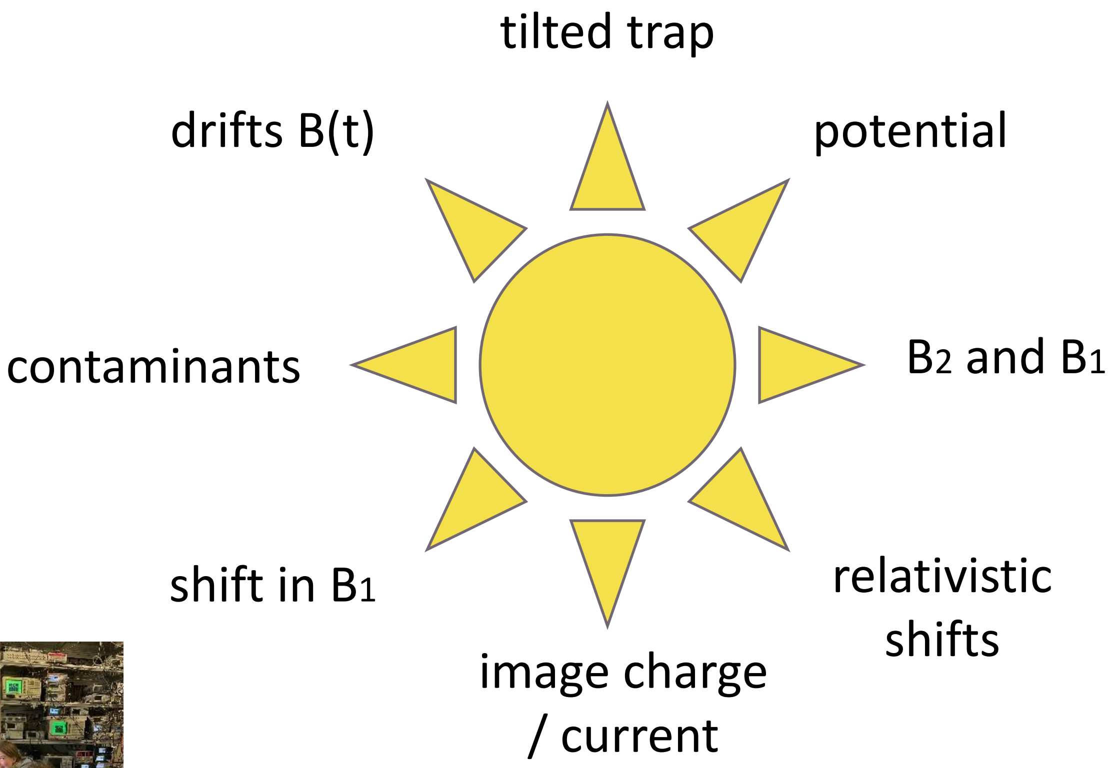
- **Statistical resolution for both antiproton and proton at about 80 ppt (6.4mHz) to 100 ppt (8.1mHz line center).**
- **Systematic studies ongoing** (tough at this accuracy in the AD)**.**

Systematic Frequency Shifts

Question: How well does the invariance theorem meet our assumptions, and how large are the deviations?

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

- **misalignment of B-axis and E-axis cancels out**
- **Elliptic disturbances in trapping potential cancel out.**

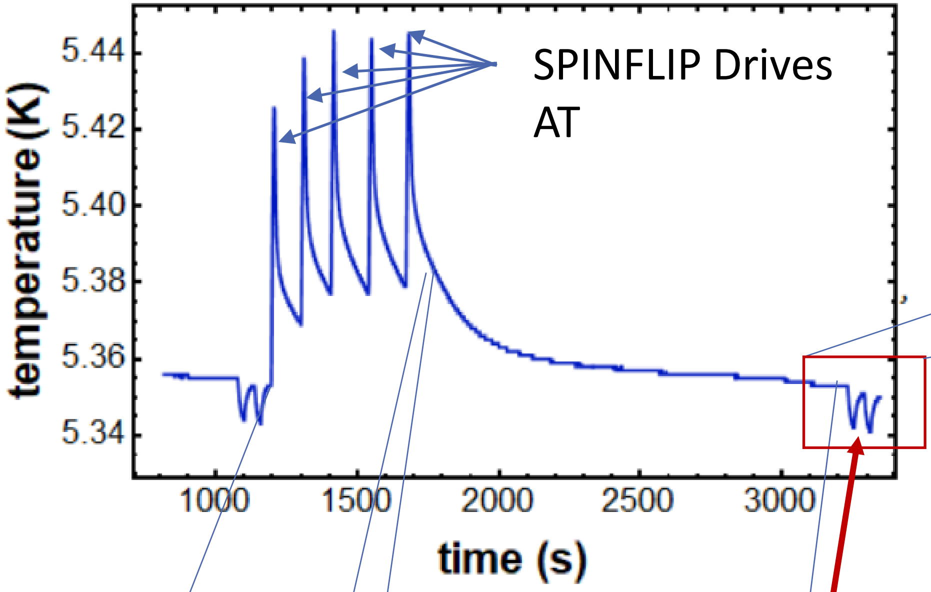


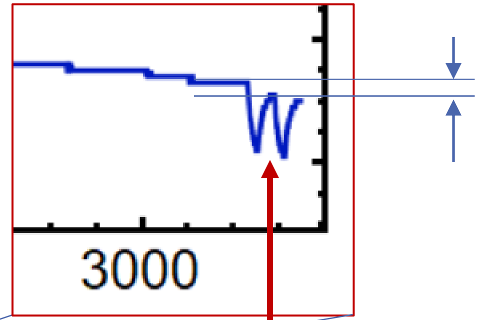
shift	shift with uncertainty (p.p.t.) for g-factor
Image Charge Shift	43.6 (< 0.1)
Trap misalignment	3.12 (0.1)
Relativistic Shift	36.1(4.0)
C_4 shift	10.1 (1.1)
C_6 shift	< 5
B_1 shift	6.5(0.6)
Magnetic bottle shift	< 1
Axial magnetic bottle shift	< 1
B_4 Shift	< 1
C_3/B_1 Shift	0.13(0.01)
Dip and Axial resonator shift	24.3(23.3).
Particle Identicality	0(16)
PT Spinflip Drive Shift (axial resonator)	
AT Spin flip fidelity shift	0(3)
PT Spinflip Drive Shift (thermal)	17.4(1.4)
Drift of the particle due to transport procedure	under evaluation
Spin flip identification uncertainties	under evaluation
Lineshape	under evaluation

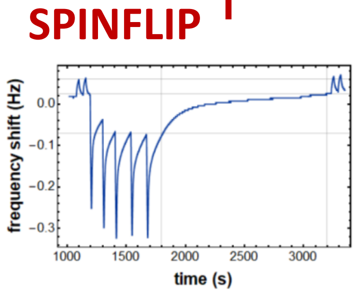
In addition to this: trap related technical shifts.

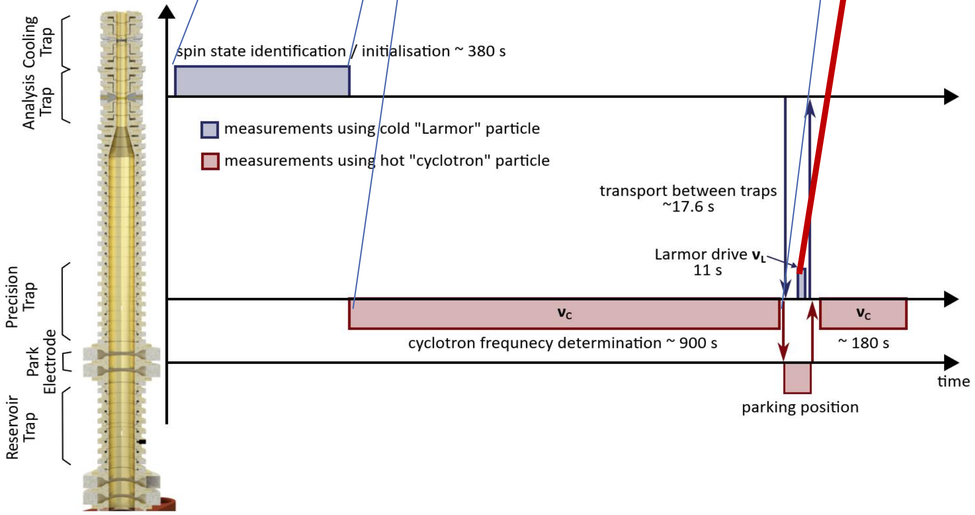
Currently, these systematic studies are still ongoing.

Dominant Systematic Uncertainty







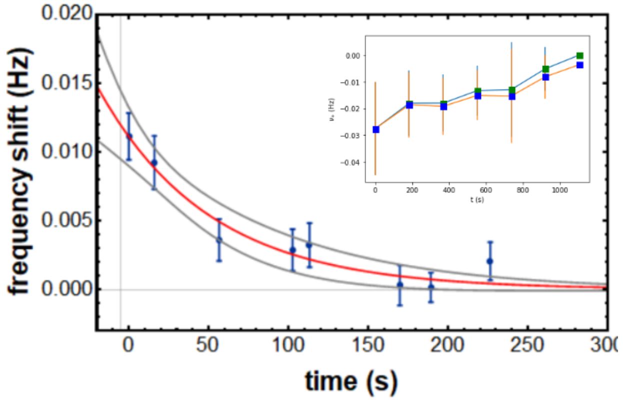


This discrepancy bothers us, since different trap temperatures during cyclotron frequency measurements and spinflip drive, so the basic assumption of the g-factor measurement

$$\frac{g_p}{2} = \frac{\nu_L}{\nu_c} = \frac{g_p}{2} \cdot \frac{\frac{q}{m}}{\frac{q}{m}} \cdot \frac{B_{SF}}{B_{cyc}}$$

where $B_{SF} = B_{cyc}$ is not necessarily given.

- Temperature dependent paramagnetic susceptibility of copper:

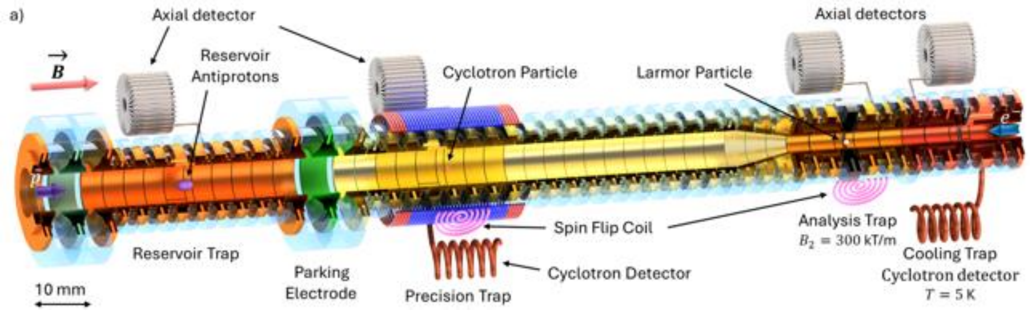


- Explicit shift measurements with uncertainty of 70ppt to 100ppt. (dominant systematics)
- Trap of silver and titanium
- Develop techniques towards single particle measurements.

Towards a Single Particle Measurement

- Did one of these measurements already 10 years ago at Mainz – resonance sampling took 1.5 years – here at CERN, in the AD during yets, it would take 6 years.

- Optimization towards higher performance:
  - Cooling trap (PRL Latacz)
  - Implement real time cooling (part of the YETS program)
  - Higher temperature acceptance (great progress in the last run)
  - Better analysis trap with high multipole suppression

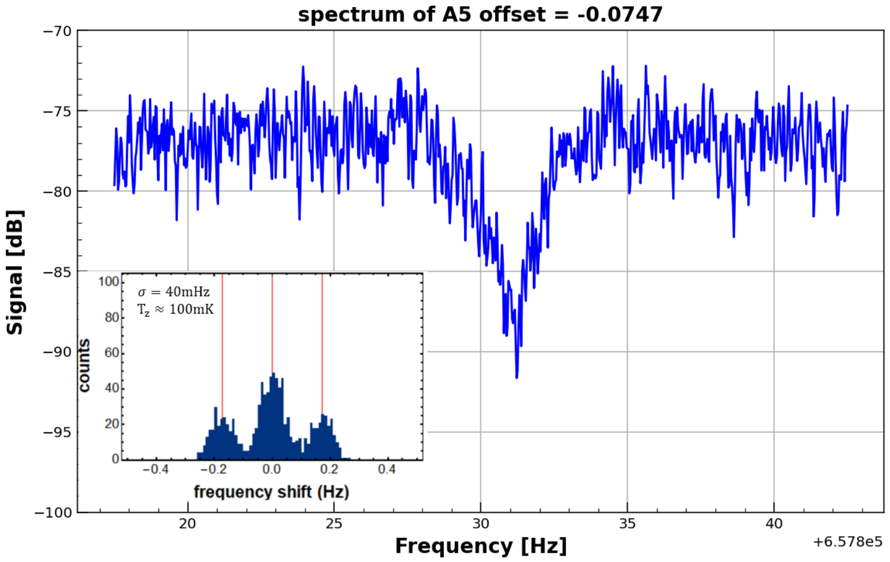


Analysis Trap Optimization


- Smallest trap used in precision Penning trap physics, with an inner diameter of only 3.6mm.
- Sensitive to disturbance of trapping potential due to interaction with the thermal axial detection reservoir.

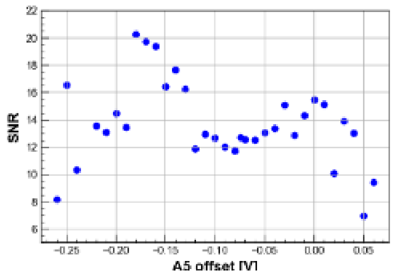
$$\nu_z = \nu_{z,0}\left(1 + \frac{3}{4}\left(\frac{C_4}{C_2^2} - \frac{5}{4}\frac{C_3^2}{C_2^3}\right)\left(\frac{E_z}{qV_0}\right)\right)$$

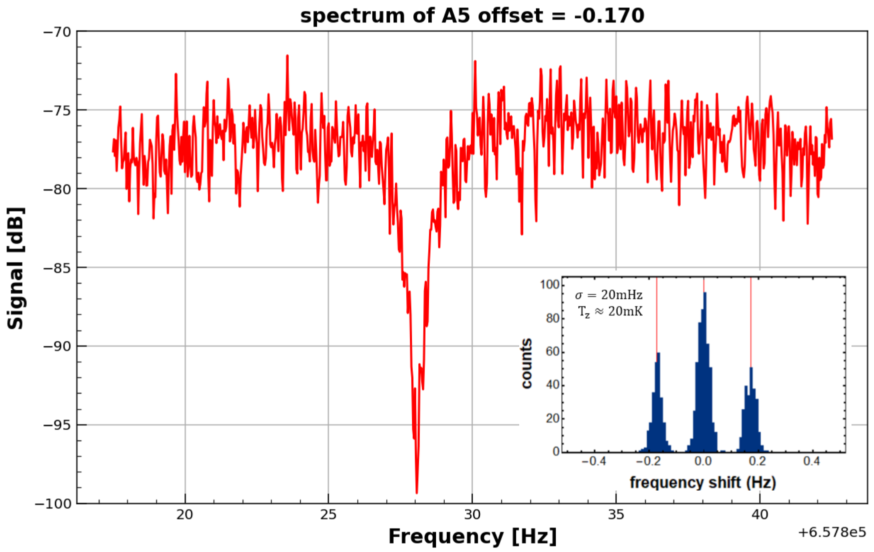
$$\chi(T_z, C_4, C_6, \nu_z) = \frac{1}{T_z}\int dT \cdot \exp\left(-\frac{T}{T_z}\right)\chi_0\left(T_z, C_4, C_6, \nu_z\right)$$



SNR of 13 dB

Asymmetric Harmonicity Tuning





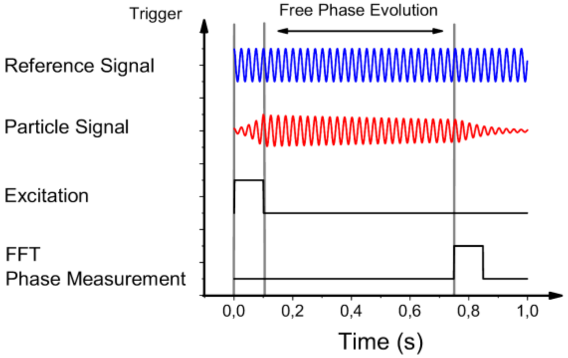
SNR of 22 dB

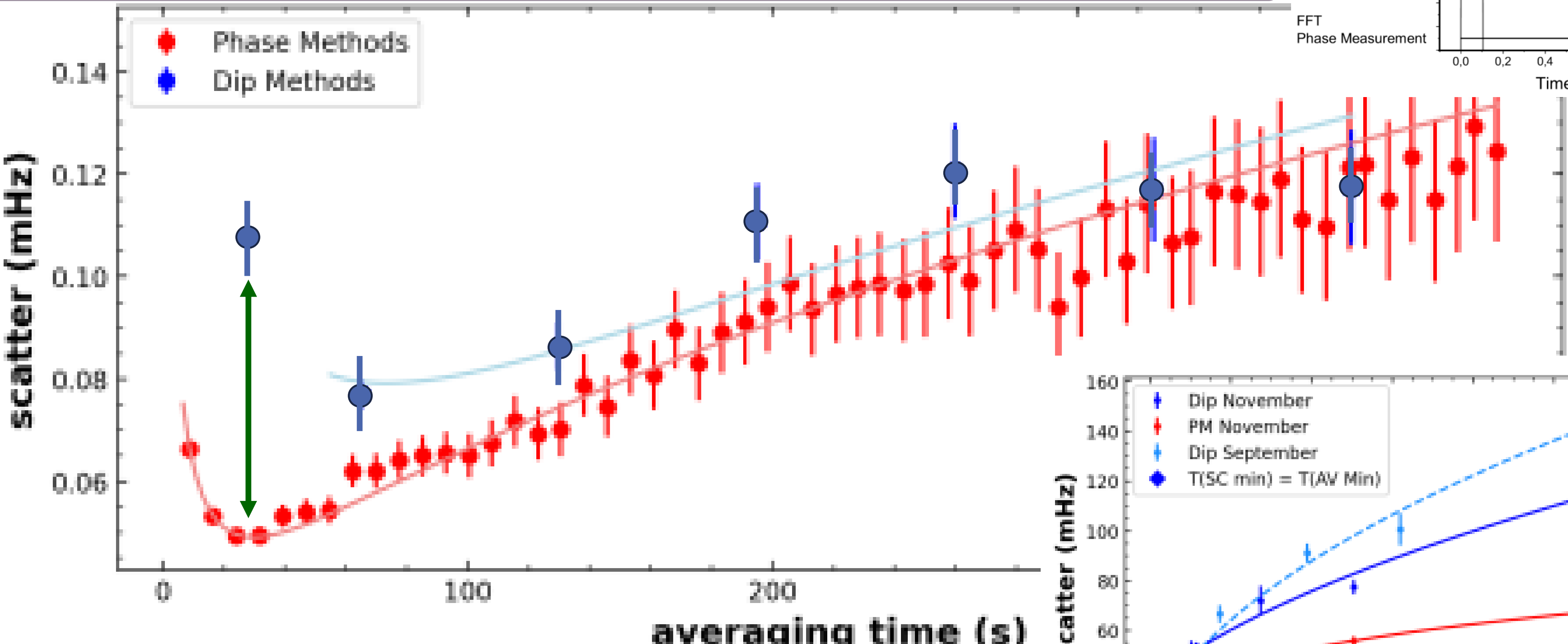
Much more harmonic trap -> Improved spin state detection / phase detection possible / higher temperature acceptance -> important step todwards single particle measurement

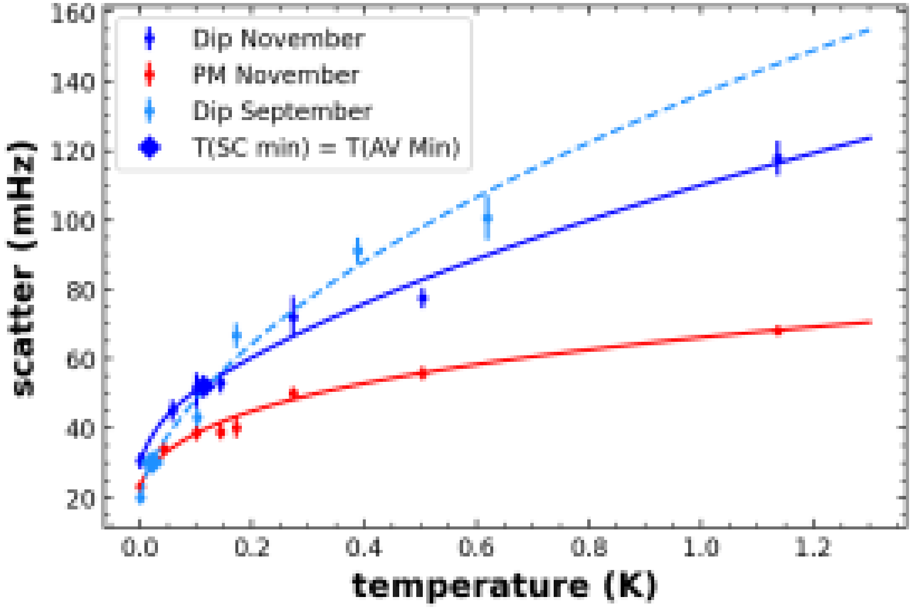
Analysis Trap Phase Methods

Idea: Detect phase evolution in comparison to a know reference signal – Detection much faster





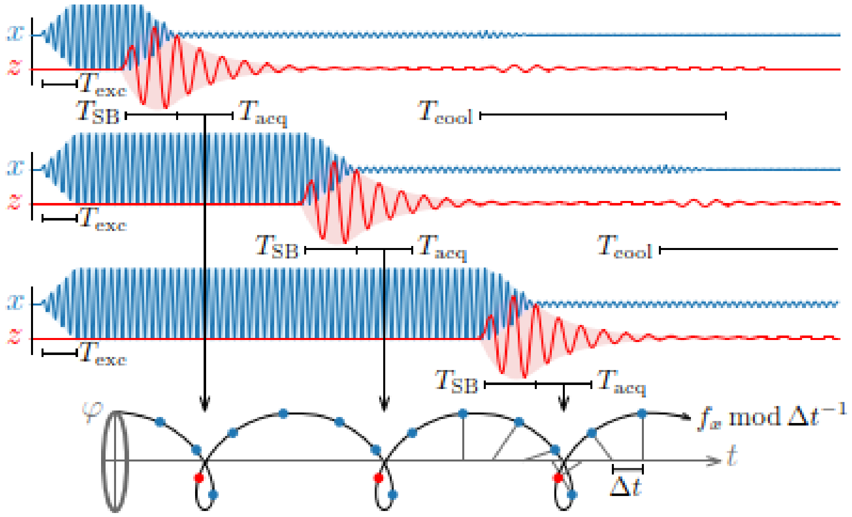


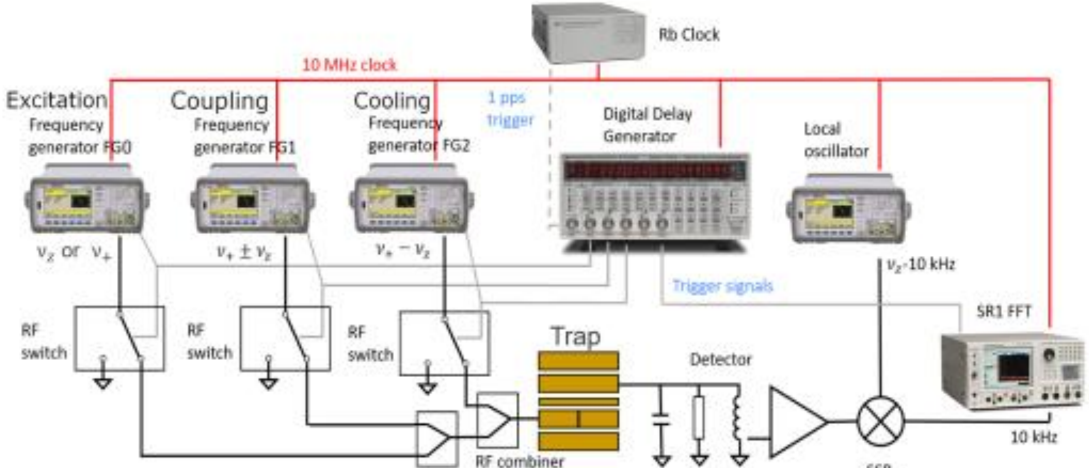


About 4-fold improved temperature acceptance…
Can detect now spin states at 800mK radial temperatures, to effcitively less cyclotron mode cooling required

Development of Phase Sensitive Detection

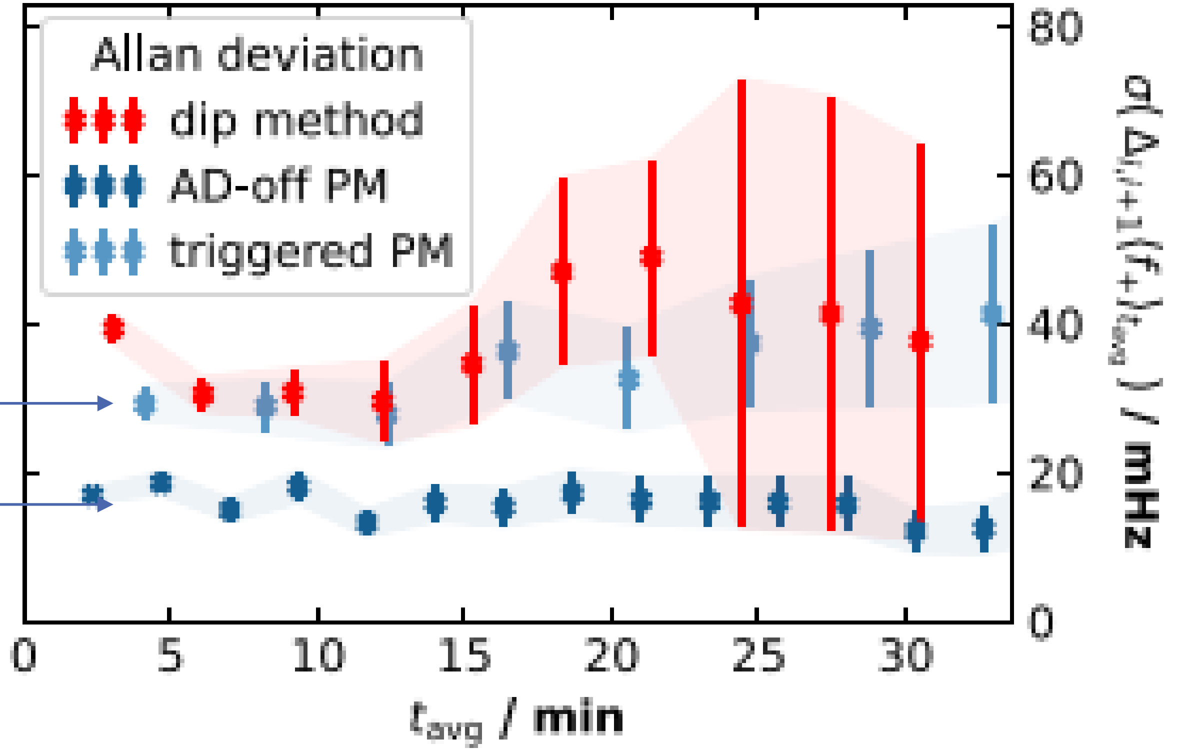
- How the technique works:





AD-ON – triggered (1.1 ppb)

AD-OFF (500 ppt)



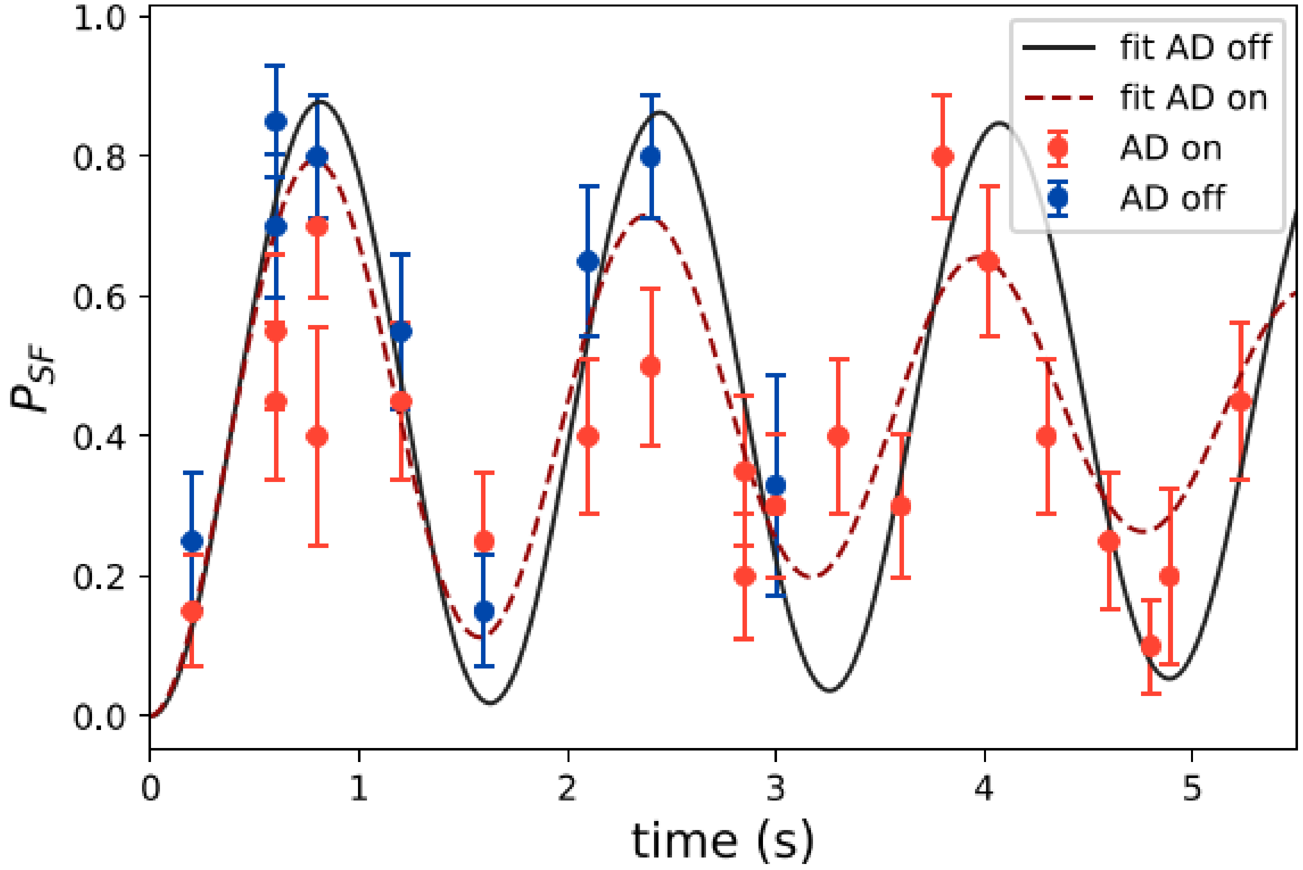
Experiment resultution during the run is currently completely limited by the AD imposed magnetic field fluctuations

Coherent Spin Spectroscopy

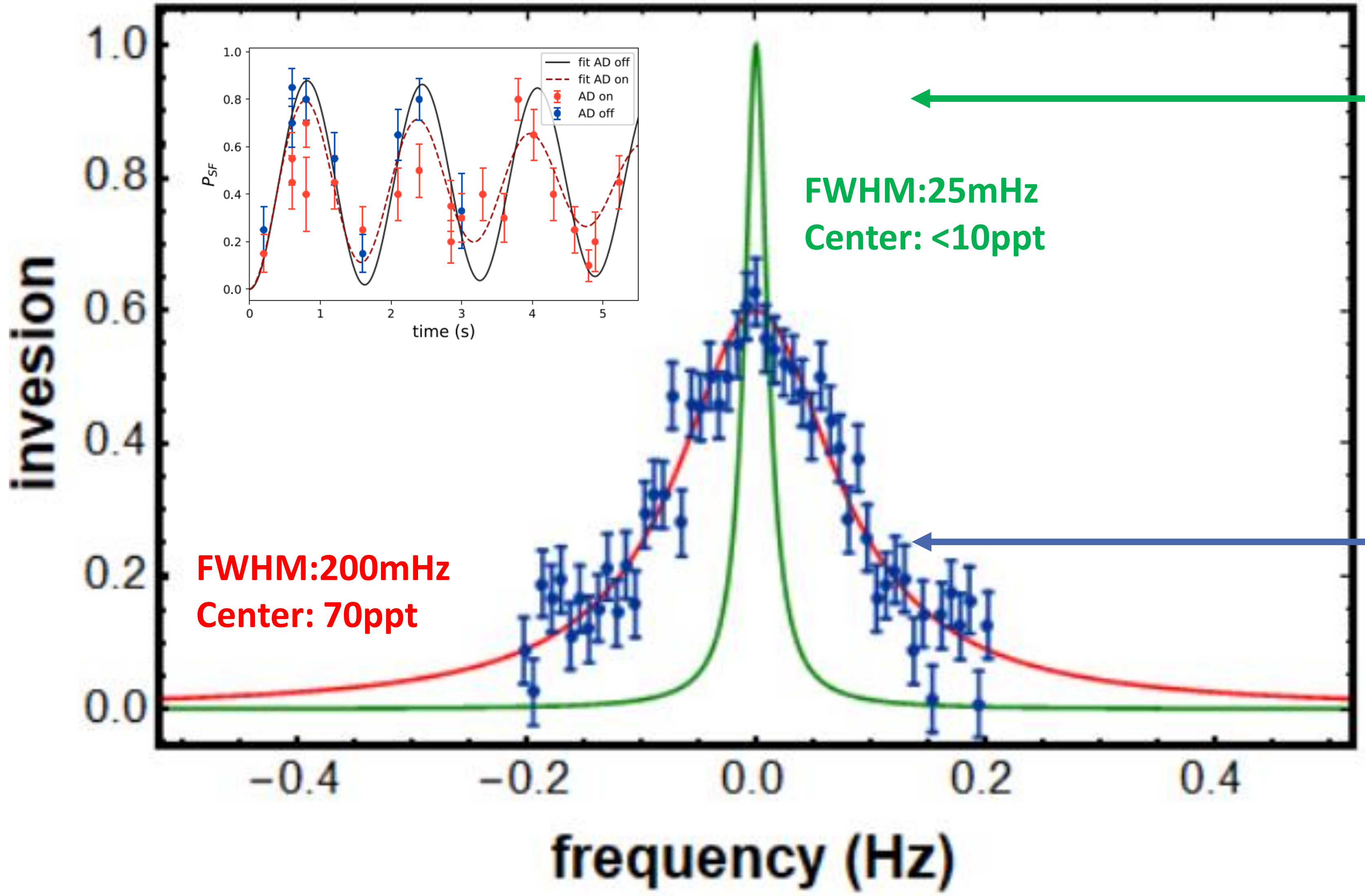
- Demonstrated for the first time with antiprotons.
- Derived spin-coherence times of order 40s!

$$P_{SF} = \frac{\Omega^2}{\Omega^2 + \Delta^2} \sin^2\left(\pi\sqrt{\Omega^2 + \Delta^2} t\right)$$

Estimated Full-Width-at-Half-Maximum of the Rabi-resonance width is at 25mHz or at 300 p.p.t.



Forecast: Fully Coherent Single Particle Measurement

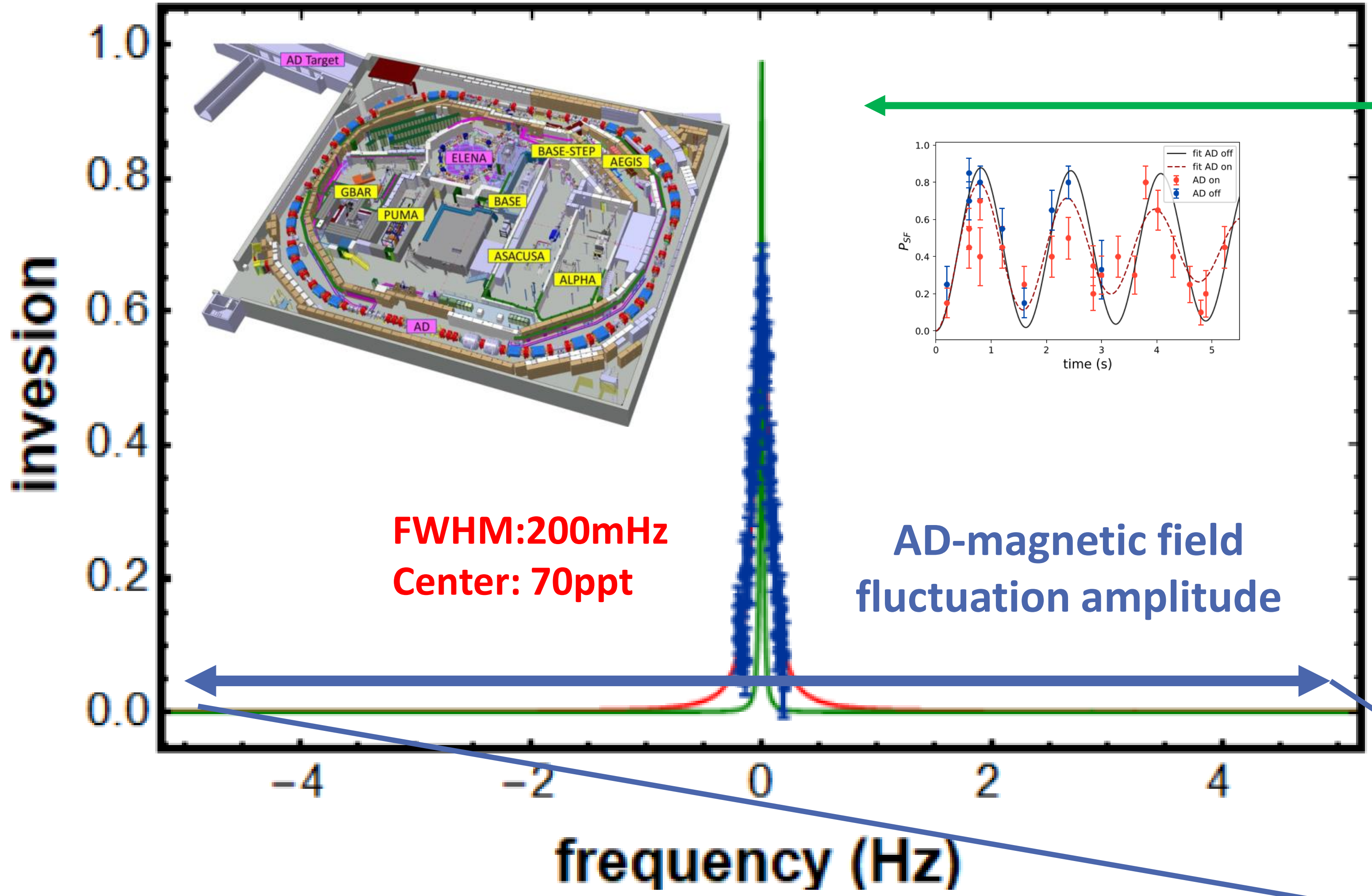


Possible based on 40s spin cohérence time measurement

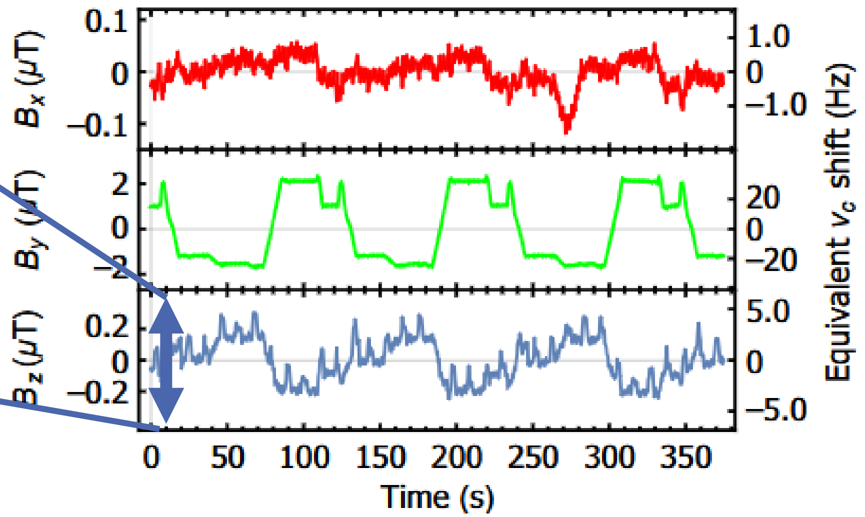
Measured 2024/2025 with AD-OFF and currently running

Possible to improve the antiproton magnetic moment value by another factor of 10 in statistics (10 ppt) at reduced systematic uncertainty (but didn’t have time to implement it)

Problem: AD Fluctuation



Possible based on 40s spin cohérence time measurement



Not anymore possible to measure in the AD-Hall

Charge-to-Mass Ratio Measurements

- Status: Measurement at 16ppt resolution (420uHz line-center) exists.
- **Perspective: Next precision goal would be the p.p.t. level**

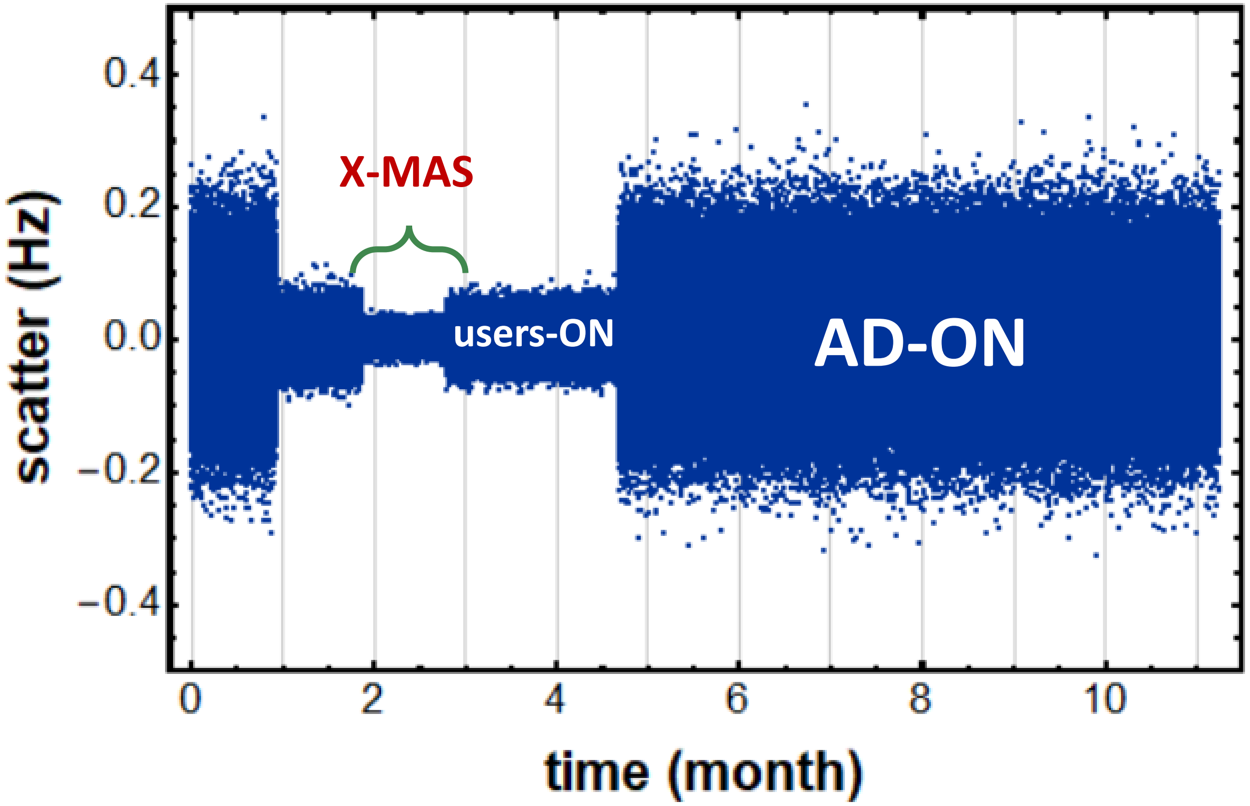
	AD/ELENA-ON	BASE best (AD/ELENA OFF)	BASE best (OFFLINE)	Best Penning Traps (MPIK)
Fluctuation	2000ppt / 60mHz / 4nT (shielded)	200ppt / 6mHz / 0.4nT	200ppt / 6mHz / 0.4nT	70ppt / 2.2mHz / 0.13nT
Precision goal	2ppt	2ppt	2ppt	2ppt
Measurements	1.000.000	10.000	10.000	820
Continuous Sampling	7.5 years	28 days	28 days	2.5 days
Realistic Sampling	23 years	3 months	3 months	2.5 days
Total measurement time	**> 1 lifetime of an Exp.Phys.**	**3 years (AD)**	**9 months**	**2 weeks?**

If CPT-V: Noone would ever be able to confirm!
(and we would likely not trust ourselves…)

Not possible to optimize, due to bckgrnd noise

How can we make these experiments better?

- Situation in AD/ELENA
- BASE frequency fluctuation



- If you want to be 50 years old, and still as happy about christmas as a 5 year old child – JOIN BASE!

	BASE-CERN	State of art (other exp.)
Frequency ratio scatter	1700 ppt	50 ppt
(AD shutdown)	250 ppt – 800 ppt	
Quality measurement time	Nights & weekends in shutdown periods (5 months/year) 15% duty cycle	24/7 100% duty cycle

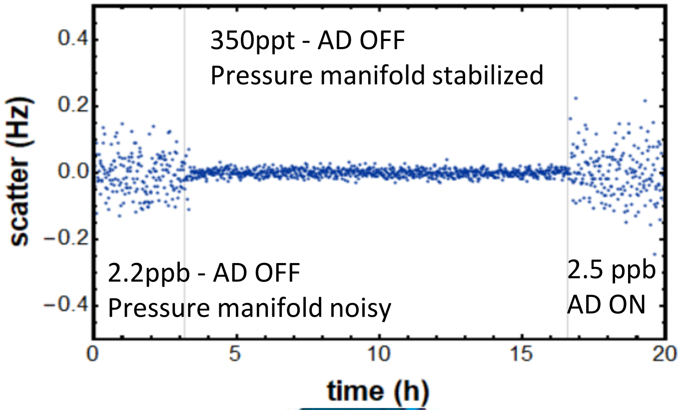
Are not anymore naturally progressing along physics ideas, and spend a good amount of time «waiting» for the accelerator to shut-off.

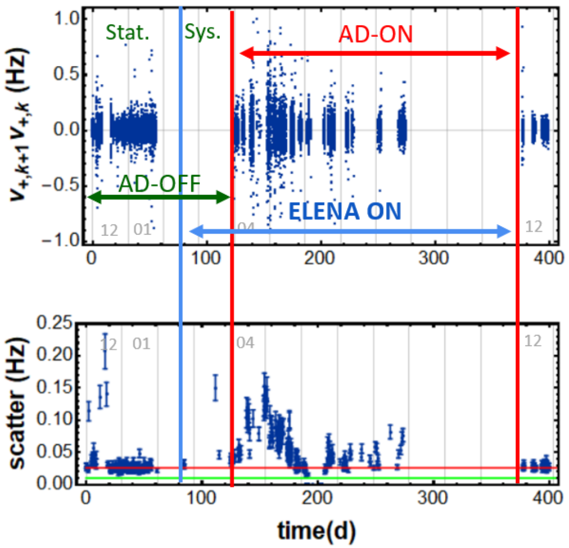
Passive Shielding → expensive, boring, already quite optimized

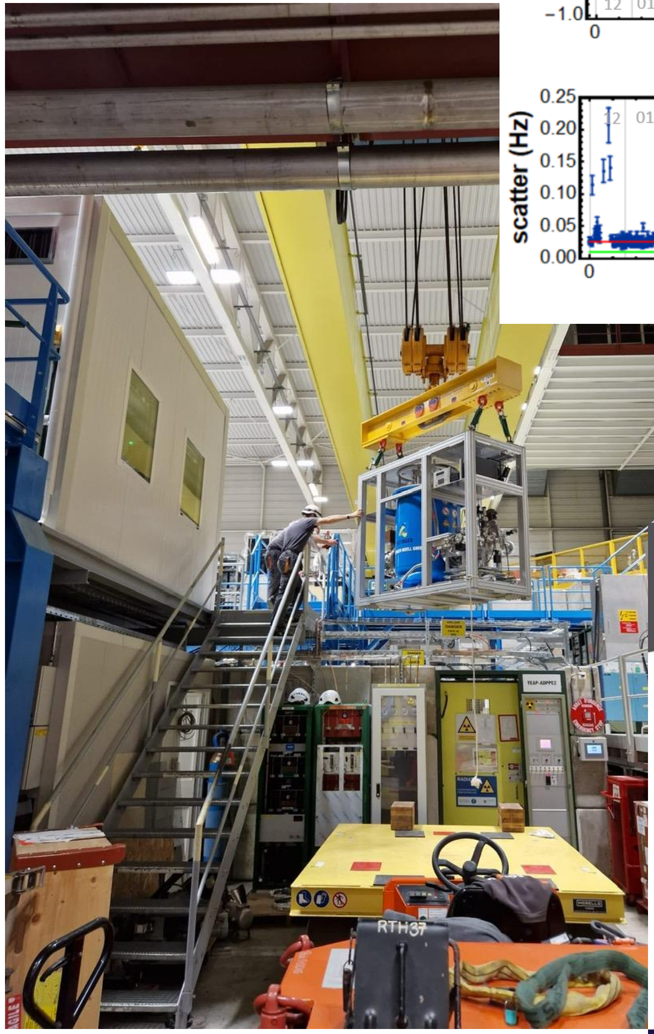
Antiproton and $H_2^+/\overline{H}_2^-$ transport → New technology, exciting, multiplicative

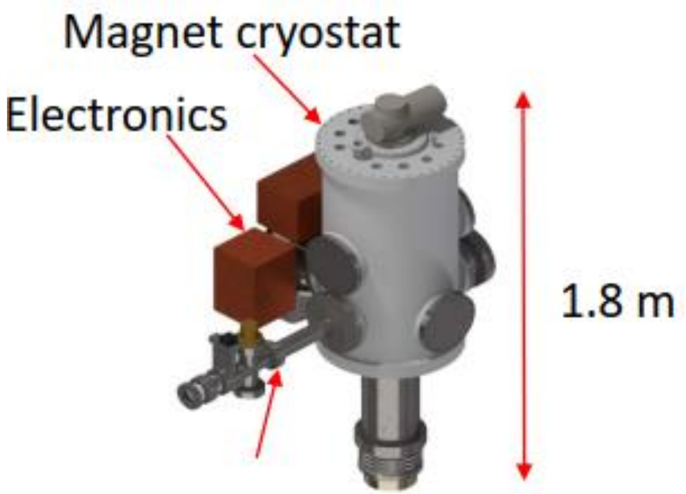
To make these experiments better….

- BASE experiments limited by fluctuations imposed by the CERN accelerator chain









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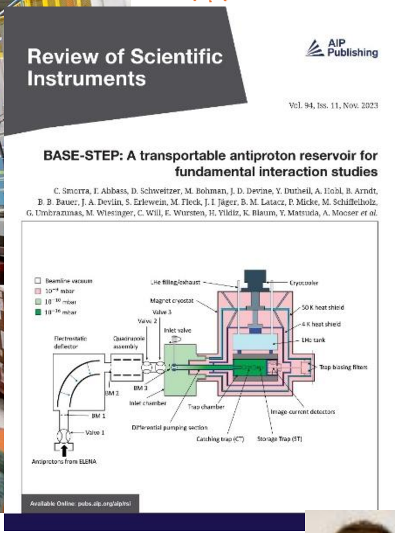

Review of Scientific Instruments

AIP Publishing

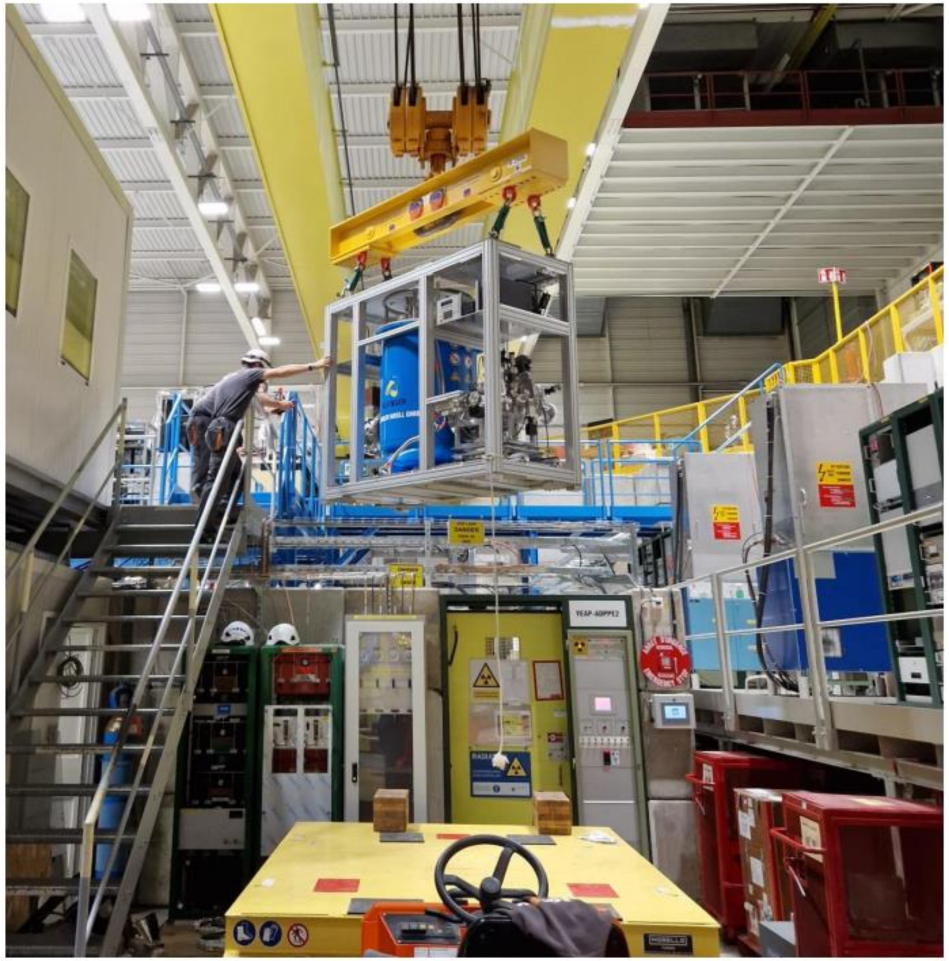
Vol. 94, Iss. 11, Nov. 2023

BASE-STEP: A transportable antiproton reservoir for fundamental interaction studies

- Antiproton transport to dedicated precision laboratory space at HHU Düsseldorf.

- New chair to support BASE Physics created at HHU in 2022 – clear long-term perspective of BASE Physics program
- SFB-TR (DFG), with several BASE-related projects involved, in preparation (HHU/Mainz).

Transport of Protons



Task List

1.) Load protons into an open trap system

2.) Observe the particles and check the vacuum (no loss detected)

3.) Disconnect the device from the installation in the zone

4.) Crane out of the hall

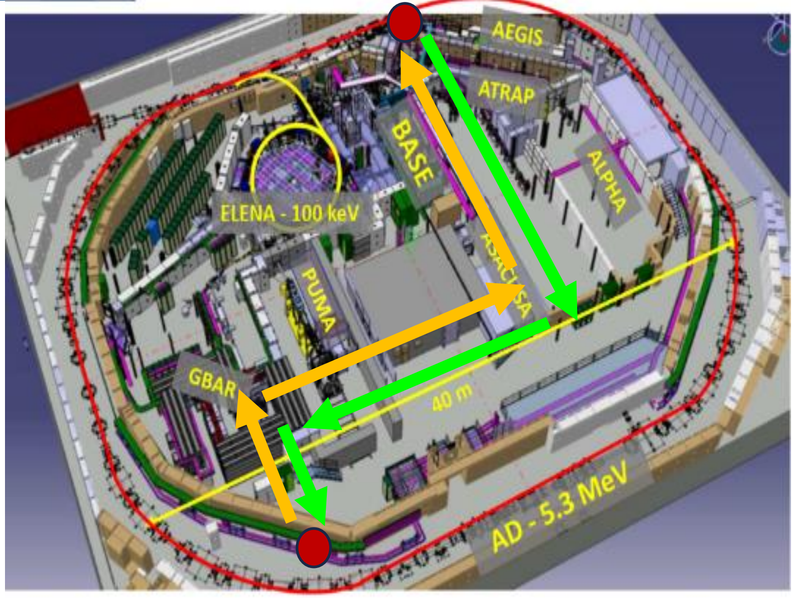
5.) Drive it around on a truck at CERN

6.) Move back to experiment zone

7.) Continue experiments

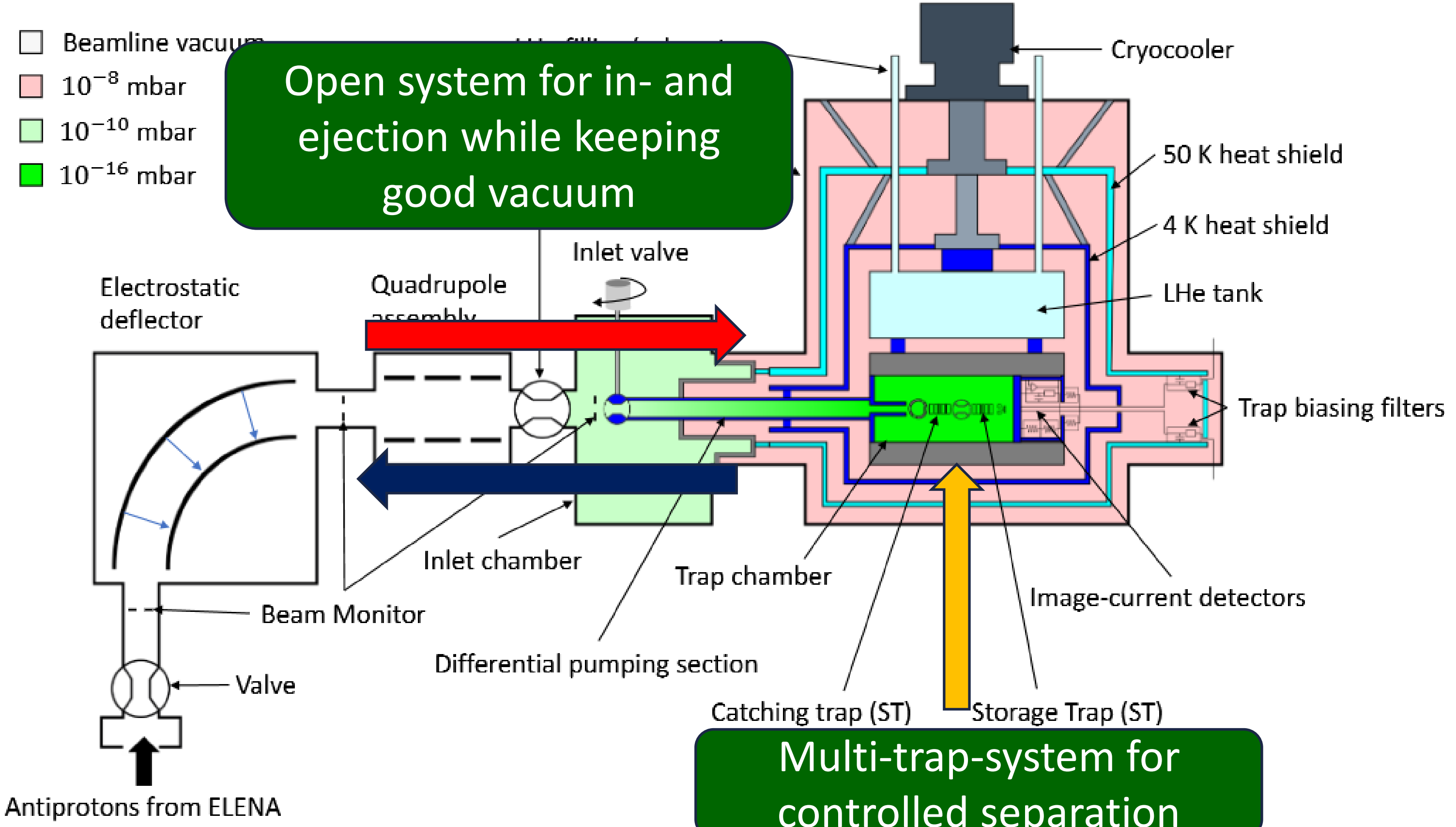
8.) Extract particles

BASE-STEP-Transport – Loaded with Protons



Particle Extraction

- Gabrielse transported electrons in a **closed and pinched single-trap** in 1993.

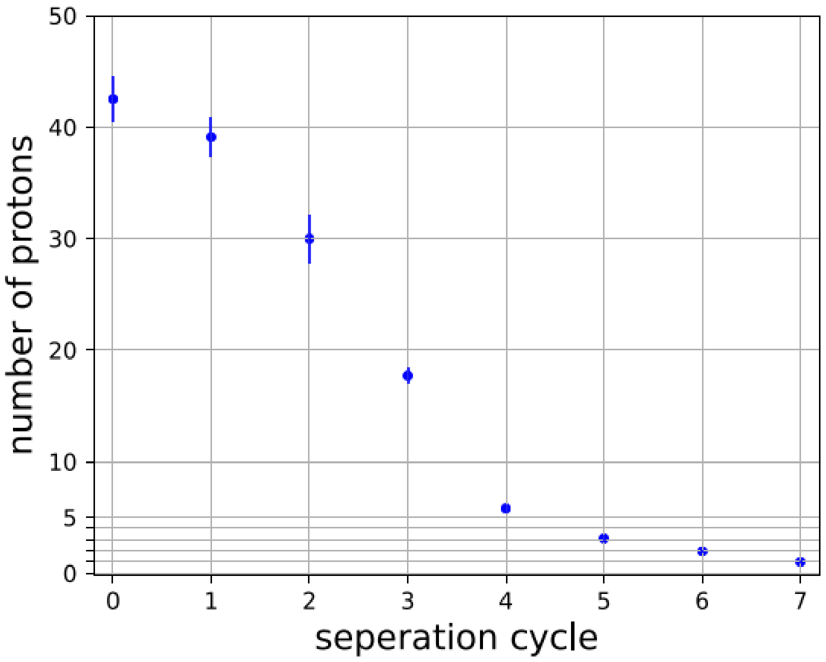


Open system for in- and ejection while keeping good vacuum

Multi-trap-system for controlled separation

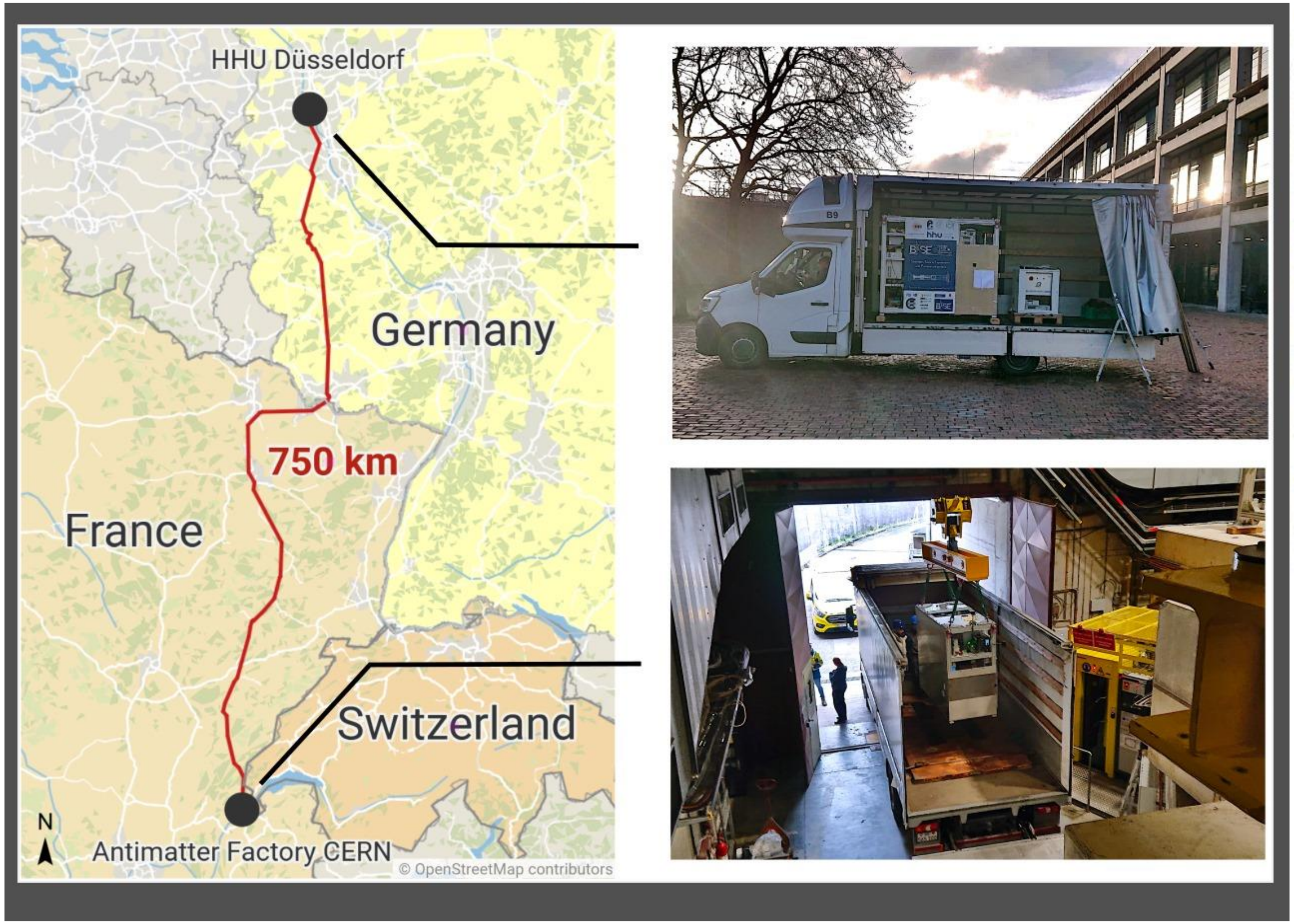
Loss-less transport of about 100 particles has been demonstrated. Excellent Vacuum.

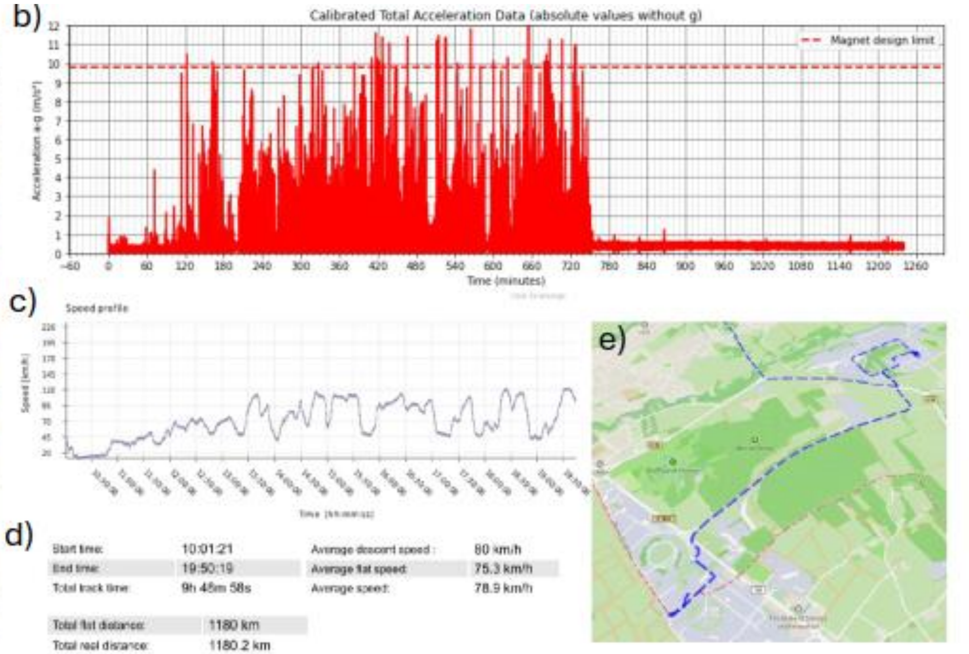
Demonstrated After Transport



1. Separation of particles from the transport reservoir
2. Extraction of particles from the trap

Transport of STEP to HHU Düsseldorf



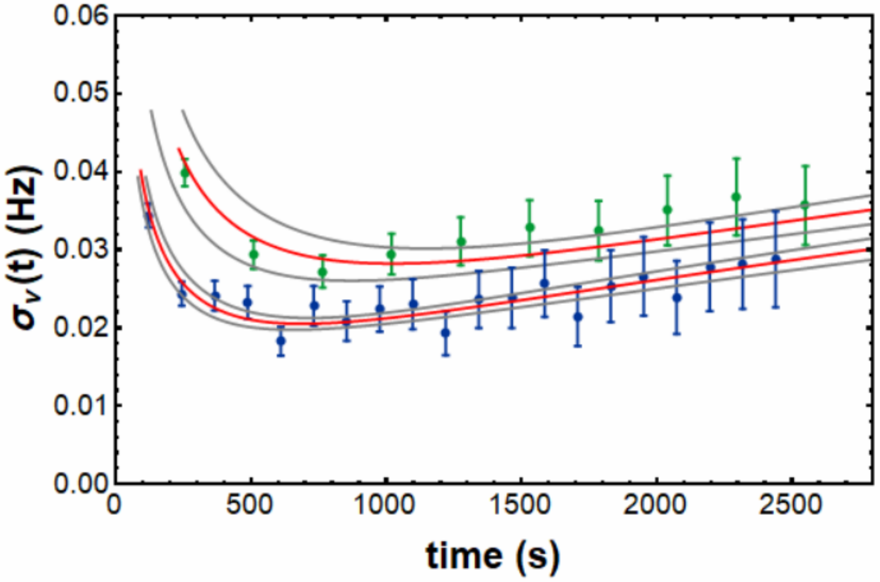


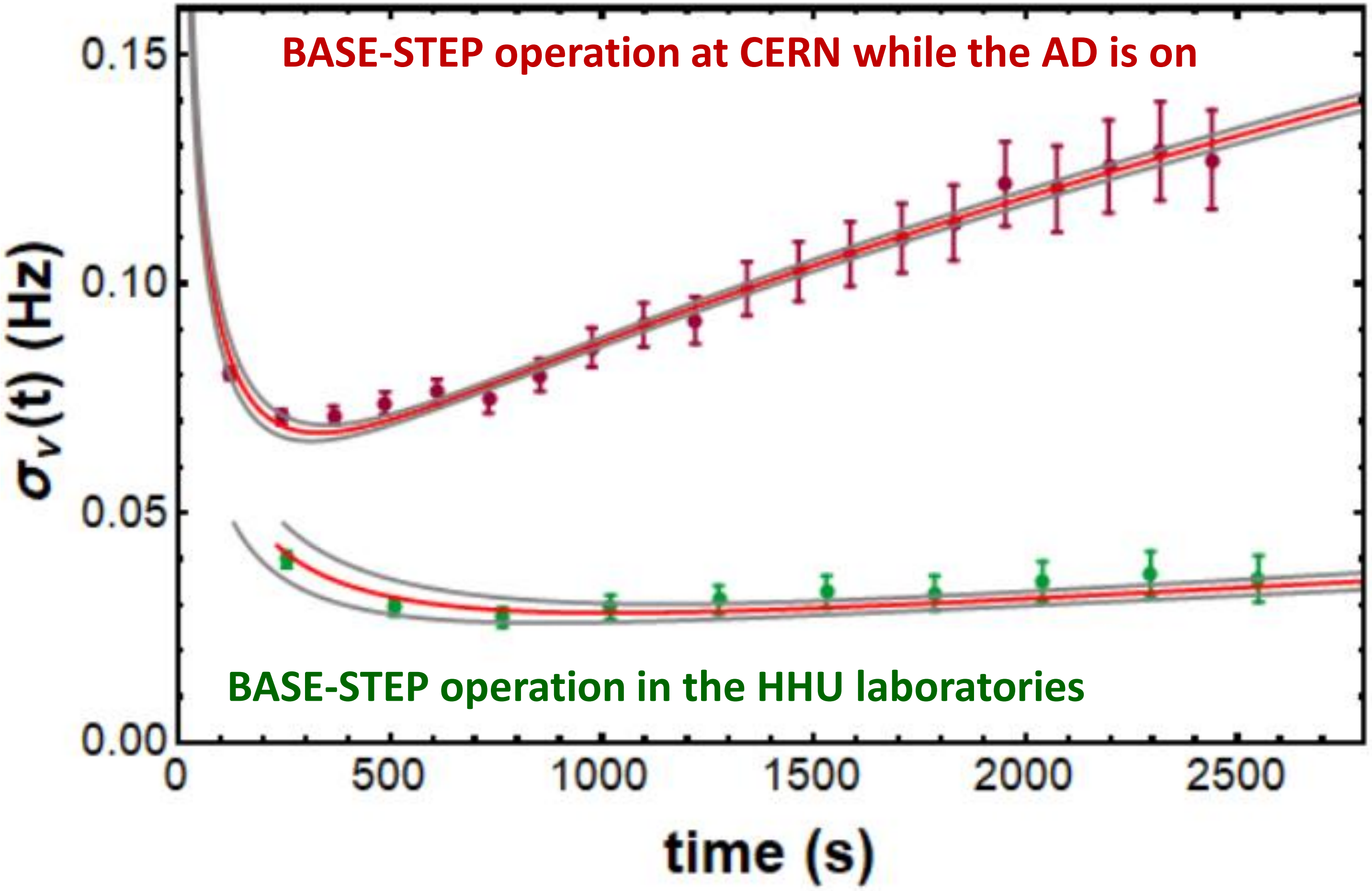
Transport of BASE-STEP to HHU has been demonstrated

Currently: Uprade of the system in the HHU laboratories.

Plans: First antiproton transport in 2025

Performance of STEP at HHU





Clear potential for considerably improved experiments in the offline laboratories at HHU.

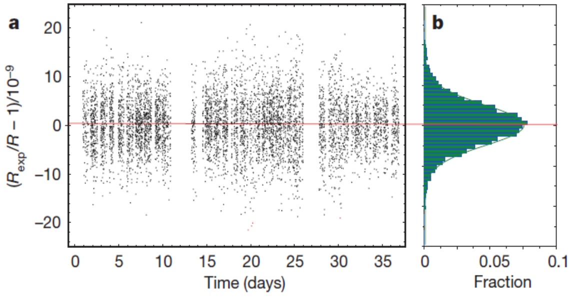
BASE Tracking Record – Fundamental Constants

2013 2014 2015 2017 2019 2022 2025 2031

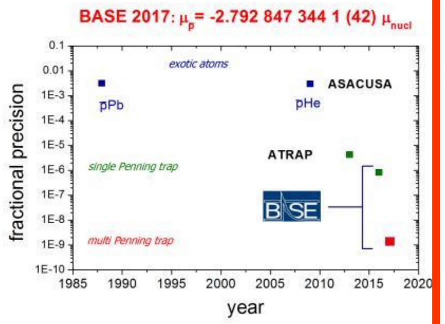
3ppb proton moment

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

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

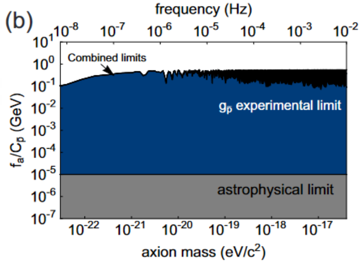


S. Ulmer, et al., **Nature 524, 196 (2015)**

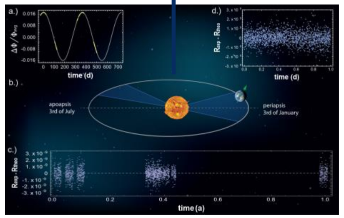


G. Schneider et al., Science **358**, 1081 (2017)

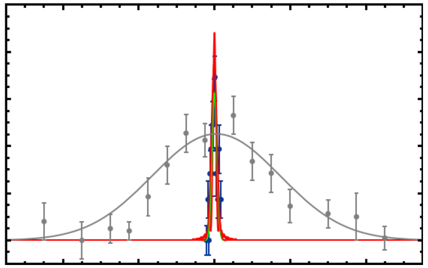
C. Smorra *et al.*, Nature **550**, 371 (2017)



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



S. Ulmer et al, **Nature 601.**7891 (2022)



B. Latacz et al, **in progress since 2022**

Have shown that this could already be 10 times better

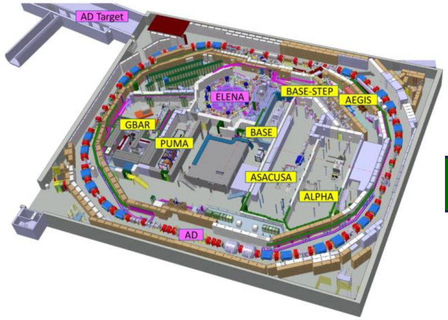
Maybe the next fundamental constant iteration

Two years of averaging and systematic studies for each of these measurement campaigns, limited by AD-hall operation

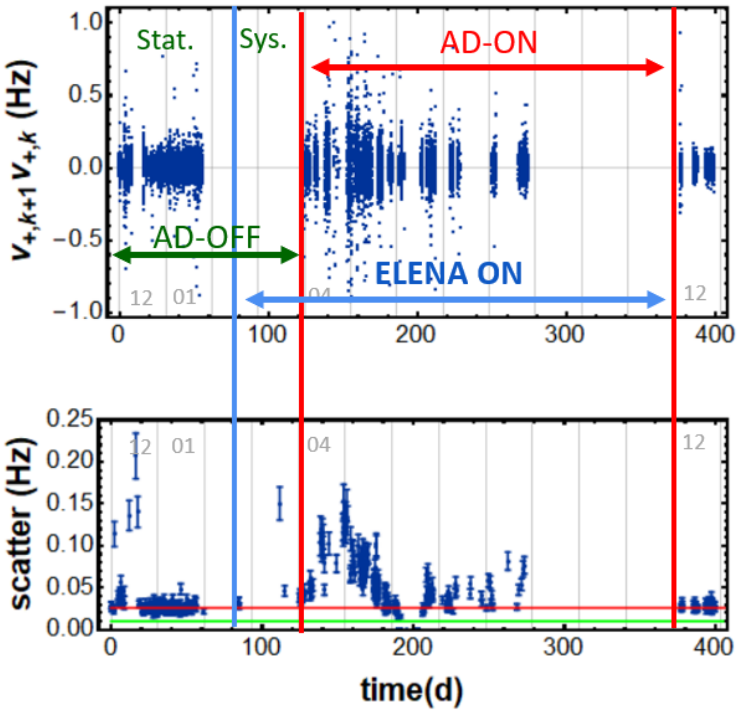
Since here, improved measurements only possible due to reservoir operation. Allimproved measurements offline.

BASE getting slower – in particular due to AD operation in the background.

Reason: BASE/AD Interaction



	BASE best (OFFLINE)
Fluctuation	200ppt / 6mHz / 0.4nT
Precision goal	2ppt
Measurements	10.000
Continuous Sampling	28 days
Realistic Sampling	1 months
Total measurement time	**3 months**



AD/ELENA-ON
2000ppt / 60mHz / 4nT (shielded)
2ppt
1.000.000
7.5 years
23 years
> 1 lifetime of an Exp.Phys.

Operating BASE in the AD/ELENA Facility feels a bit like owning a 300PS sports-car with engine throttled to 50PS

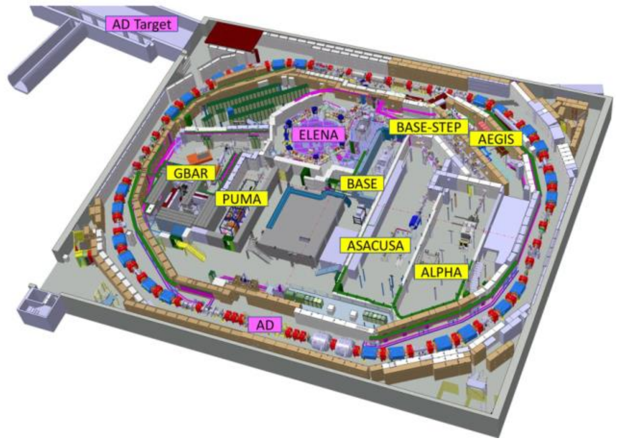
BASE-CERN – Offline Laboratory

- We request an offline laboratory for BASE-CERN, on the CERN campus, to be supplied with antiprotons from the AD-hall.
- Plan: Move BASE from the AD into this offline laboratory.

- **Wish List:**
  - At least $70\ \mathrm{m}^2$, better $100\ \mathrm{m}^2$ of space.
  - Air conditioning and temperature stabilization to fluctuations below 200 mK during the day.
  - Magnetic background fluctuations at amplitudes below 10 nT or better.
  - Connection to the LHe recovery-manifold of CERN.
  - Optimal would be a space, that has access to an industry crane for dewar handling and to place the large equipment.
  - A total hight of >4.5 m to be able to take care of the cryo-liquid maintenance with the existing flexible transfer-lines.

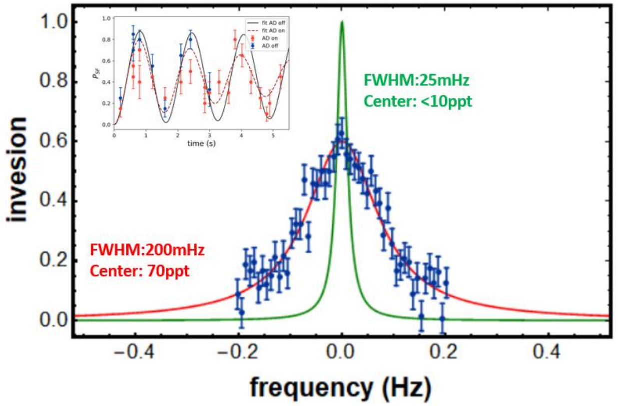
Guaranteed: 100-fold improved measurements of the antiproton fundamental properties at much improved iteration rate.

A lot of headroom for additional ideas: operation of two experiments to synchonuously measure moments and mass ratios, antihydrogen molecular ion



LOAD

TRANSPORT



MEASURE

Precision Offline Laboratory at CERN

- If space for not only one trap experiment – **operate magnetic moment and charge to mass ratio measurements in parallel**
- Place an antiproton container in the corner loaded with 100000 pbars and **sample lifetime to millions of years…**
- Parallelled measurements in different orientations
- Open an exotic physics program beyond antiproton, e.g. do spectroscopy on Pb^{81+} and U^{91+}
- Place in parallel a lepton moment experiment there to perform most precise tests of the SM at CERN (QED sector)

- **Guaranteed:** 100-fold improved measurement of the antiproton fundamental properties.
- Multiplicative impact to many additional antimatter experiments, opening new branches of physics:

Antimatter Molecule Spectroscopy

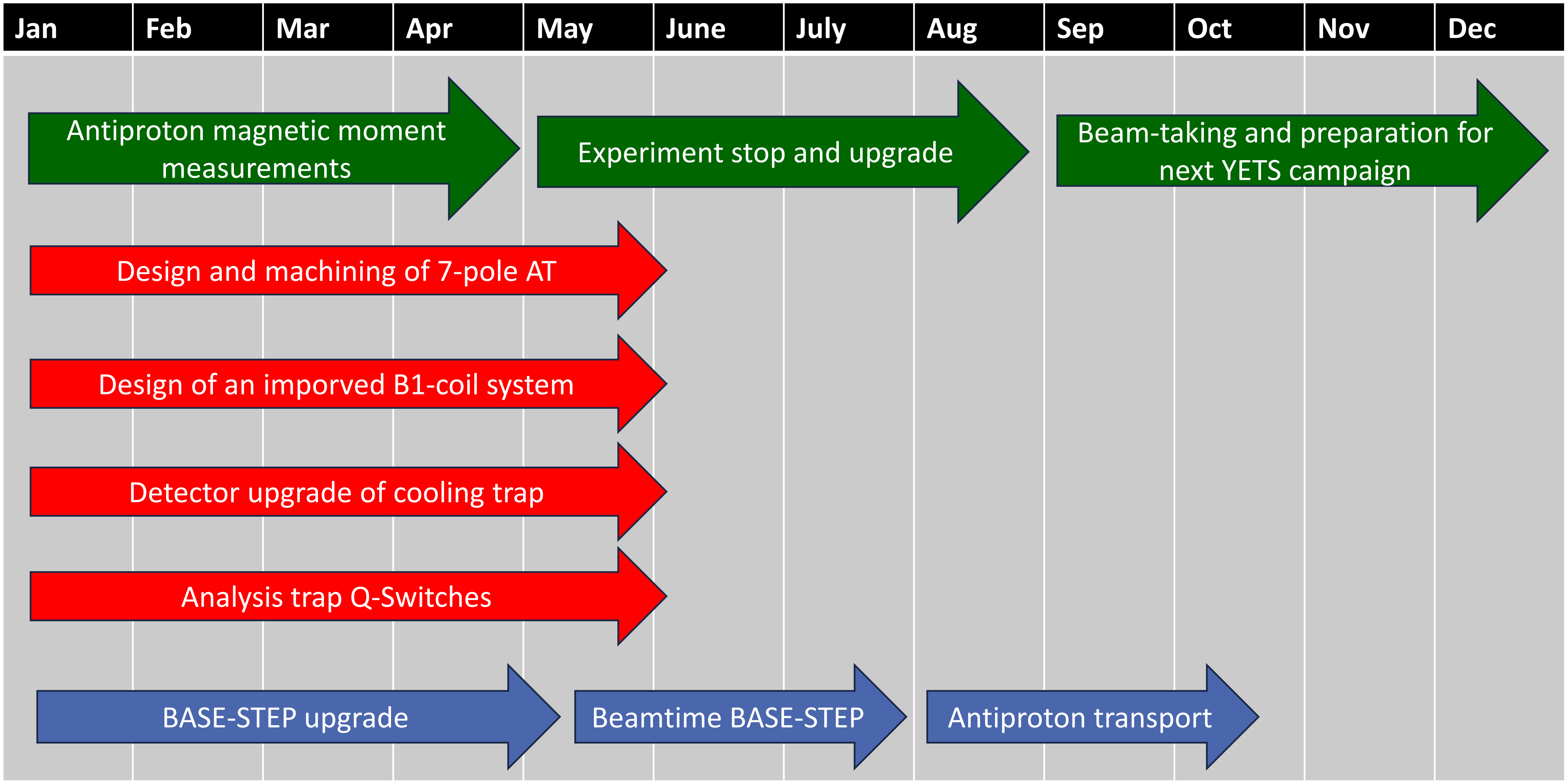
Muonic Antihydrogen

Antihydrogen transport

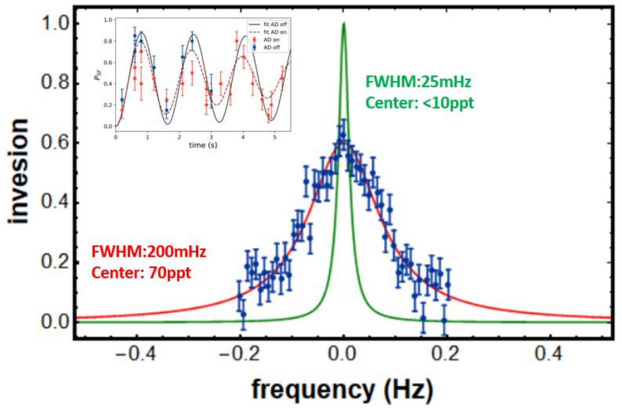
Quantum Logic

Of course – if we talk about an offline laboratory for BASE, why not talking about an offline building for the entire AD community and other ultra-high-precision efforts that could be attracted to CERN???

BASE Planning 2025



Summary



- Measurement of the antiproton magnetic moment with a statistical resolution of about 100ppt. Systematic studies ongoing.

- Great progress with phase sensitive detection of the axial oscillator in the AT, which is an important step towards a double trap measurement.
- Great progress in phase sensitive detection of the cyclotron oscillator for a fully coherent single particle measurement of the antiproton moment.
- Spin cohérence equivalent to 24mHz line-width has been demonstrated.

All methods to measure the green resonance demonstrated: Not implemented into the experiment scheme, due to a lack of calm offline time – we would anyway not be able to do all the systematic studies at the required resolution in the only 3 calm months per year which we have available

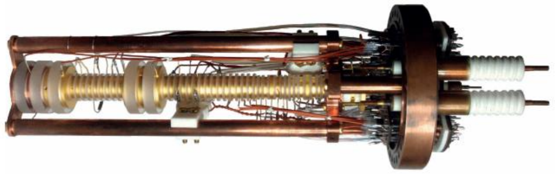
- **First proton transport in BASE STEP demonstrated.**
  Goal: Transport pbars in 2025.

We request an offline laboratory at CERN, please support this request…

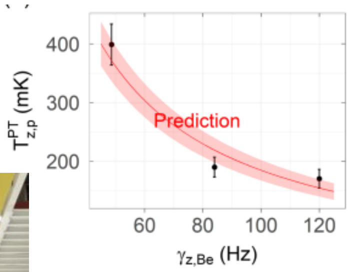
BASE Tracking Record

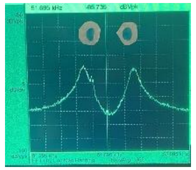
- BASE-CERN
- BASE-Mainz
- BASE-Logic
- BASE-STEP
- BASE-CDM
- BASE-Lepton
- Exotics

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



2023

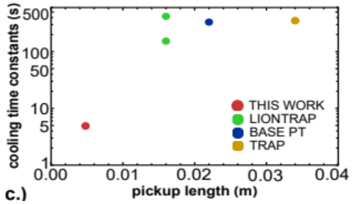


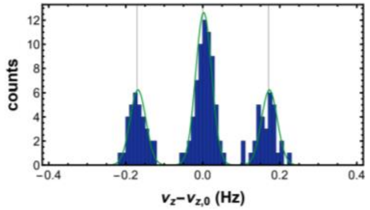


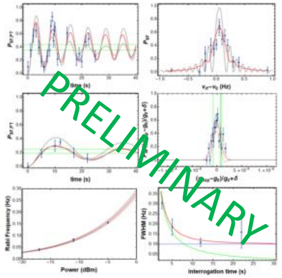
C. Will, et al. PRL 133 (2024)

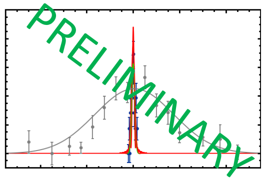
2024

B.M. Latacz, M. Fleck, S. Ulmer, et al. **PRL 133.5 (2024)**

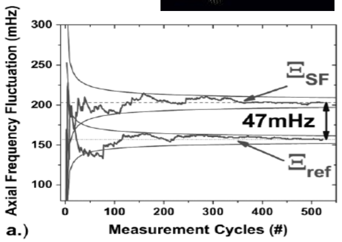






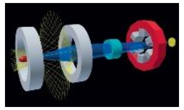


2011



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

2012



2013

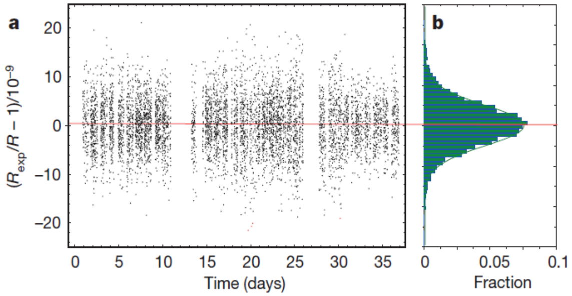
3ppb proton moment

2014

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

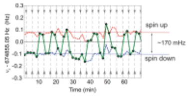
2015

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



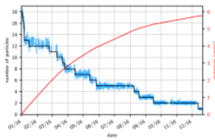
S. Ulmer, et al., **Nature 524, 196 (2015)**

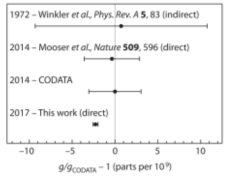
2016



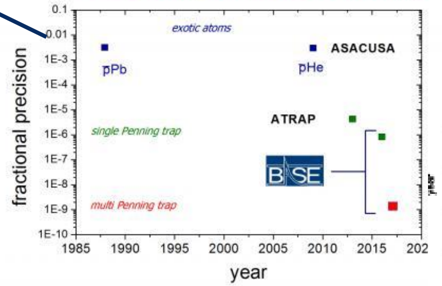
2017

pbar moment, proton moment, pbar lifetime, proton mass



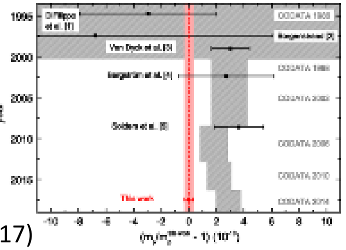


BASE 2017: μ_p = -2.792 847 344 1 (42) μ_{nucl}

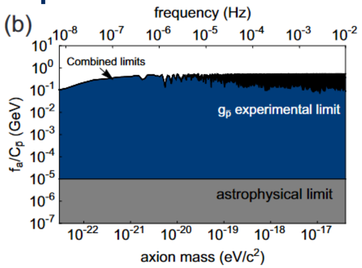


G. Schneider et al., Science **358**, 1081 (2017)

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



2019



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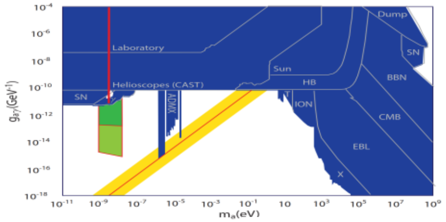

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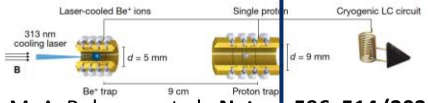

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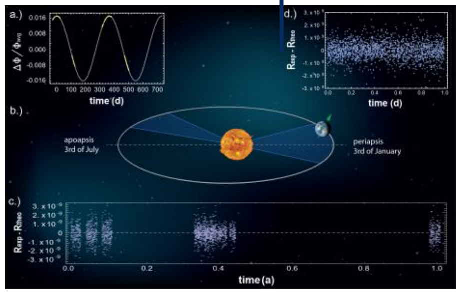

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Thank you for your attention!

BASE

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