Zuoz -Low energy Particle Physics II.

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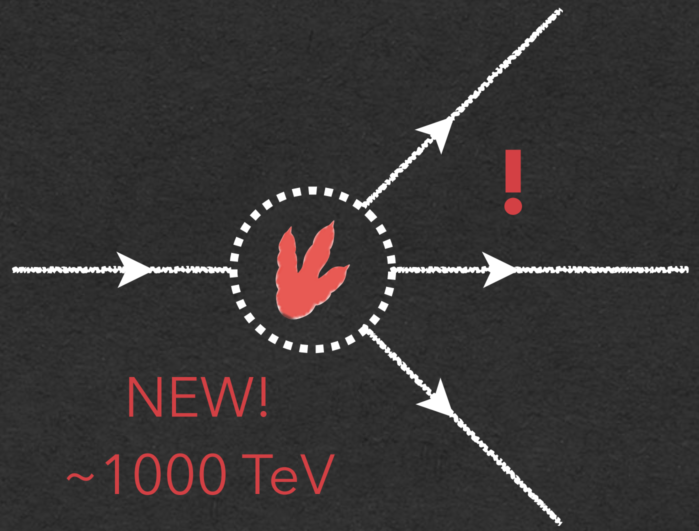
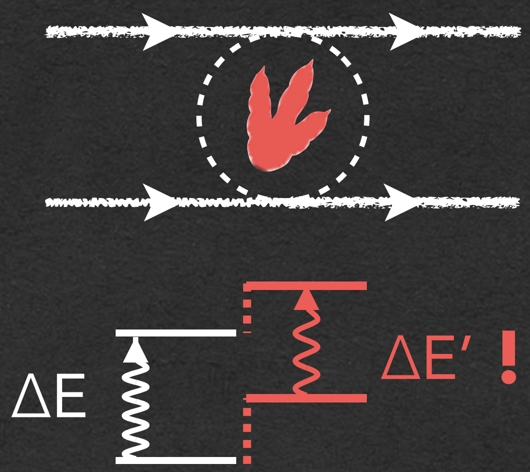
ETH zürich

The intensity- and precision frontier

- Complementary way to search for new physics
- We are looking for rare events, and small energy shifts
- Indirect search, to see the "footprint" of new physics by precise observation of particles, in forms of:

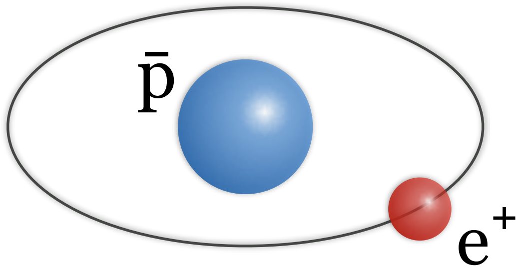


Forbidden decays / precision decays



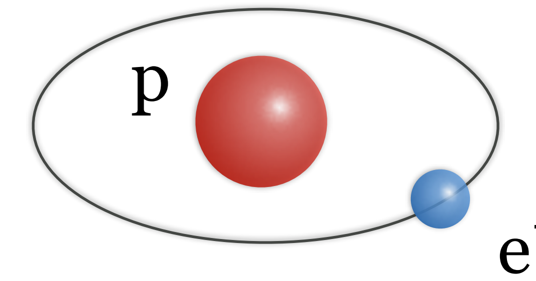
Energy shifts in interactions

Hydrogen - comparison to other exotic atoms



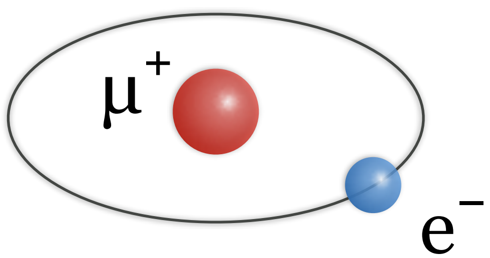
- antihydrogen

- Orbits: **r ~ 1/m** , $E_0 \sim m/n^2$
- Fine structure: LS coupling - spin- and angular momentum of the orbiter, Dirac equation
- Lamb: shifts from various QED corrections
- Hyperfine structure: nuclear spin
- Finite size effect, $\mathbf{E_{fs}} \sim m^3R^2$



- hydrogen

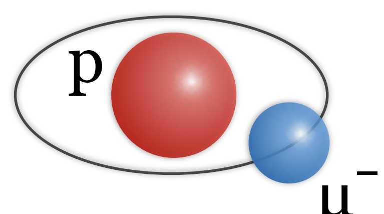
Muonium



$$m_\mu \approx 200 m_e$$

- No finite size effects!
- Lighter nucleus, larger recoil
- Large QED effects

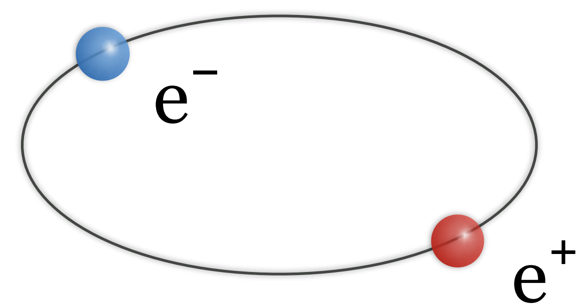
Muonic hydrogen



$$m_\mu \approx 200 m_e$$

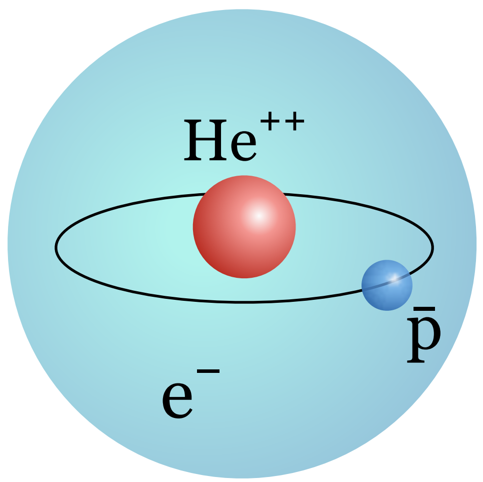
- orbits 200-times closer to the proton
- sensitive to finite size and nuclear effects

Positronium



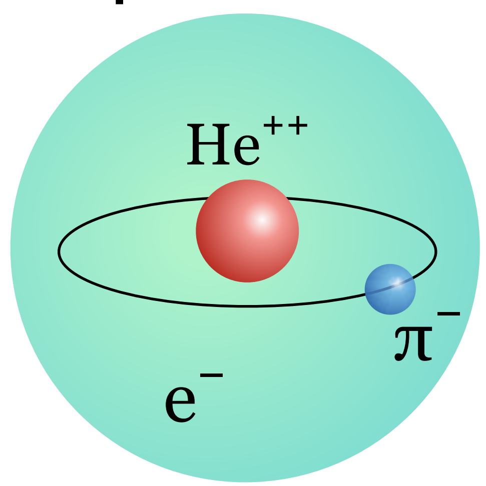
- reduced mass: m/2
- roughly half the hydrogen energies (twice the radius)
- no finite size effects
- large QED effects and recoil correction

antiprotonic He



- rel. 3-body QED

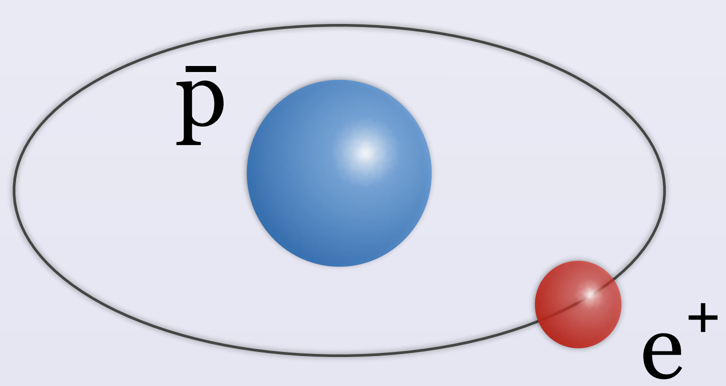
pionic He

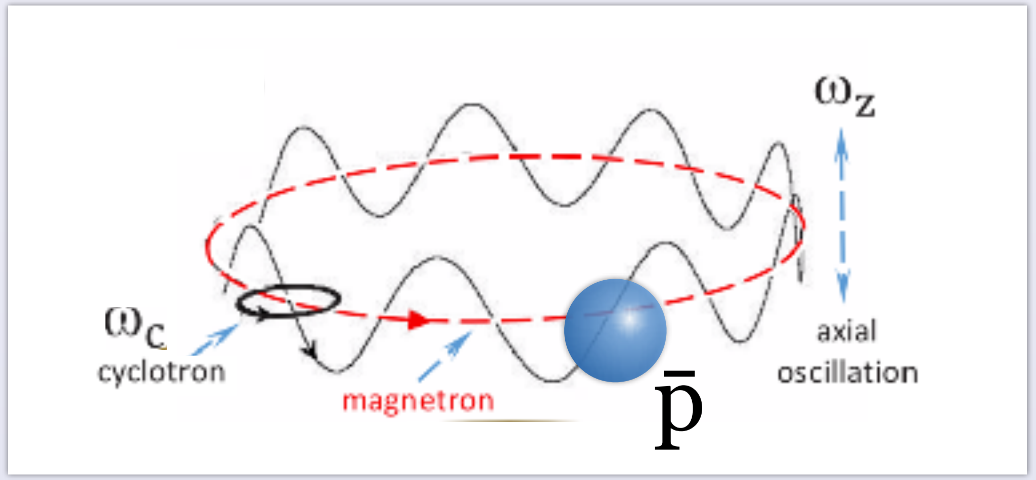


- Pion: spin 0 boson! Klein-G. equation

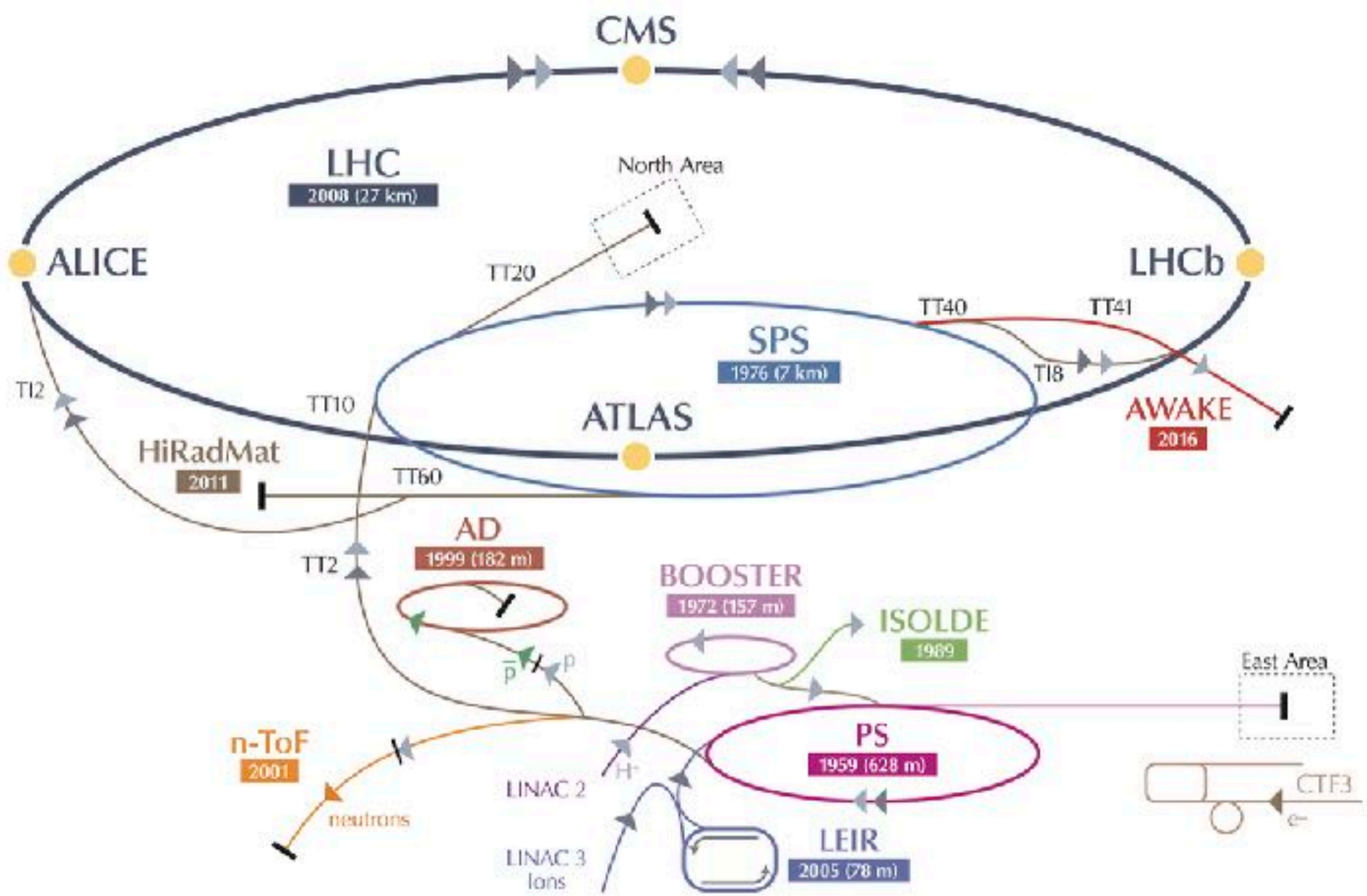
- 3-body problem, excited Rydberg state
- First splitting: antiproton/pion angular momentum + electron spin
- 4He: no nuclear spin!

Precision experiments in ion traps

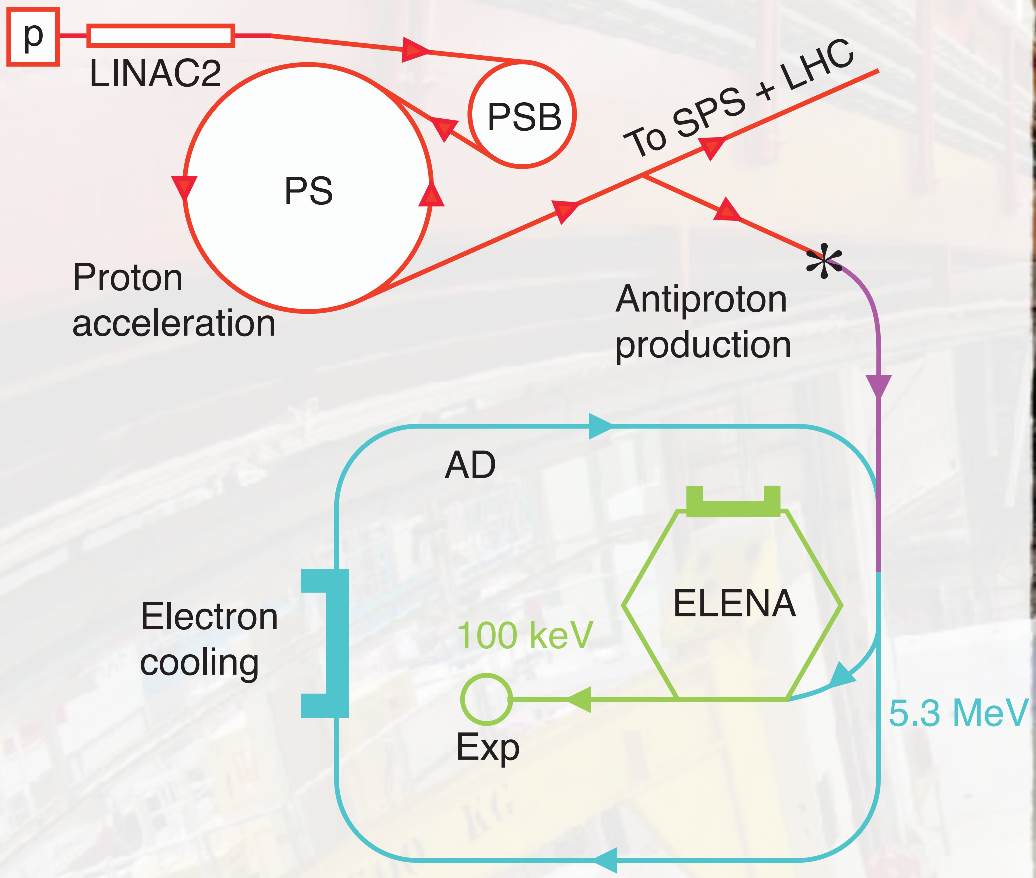




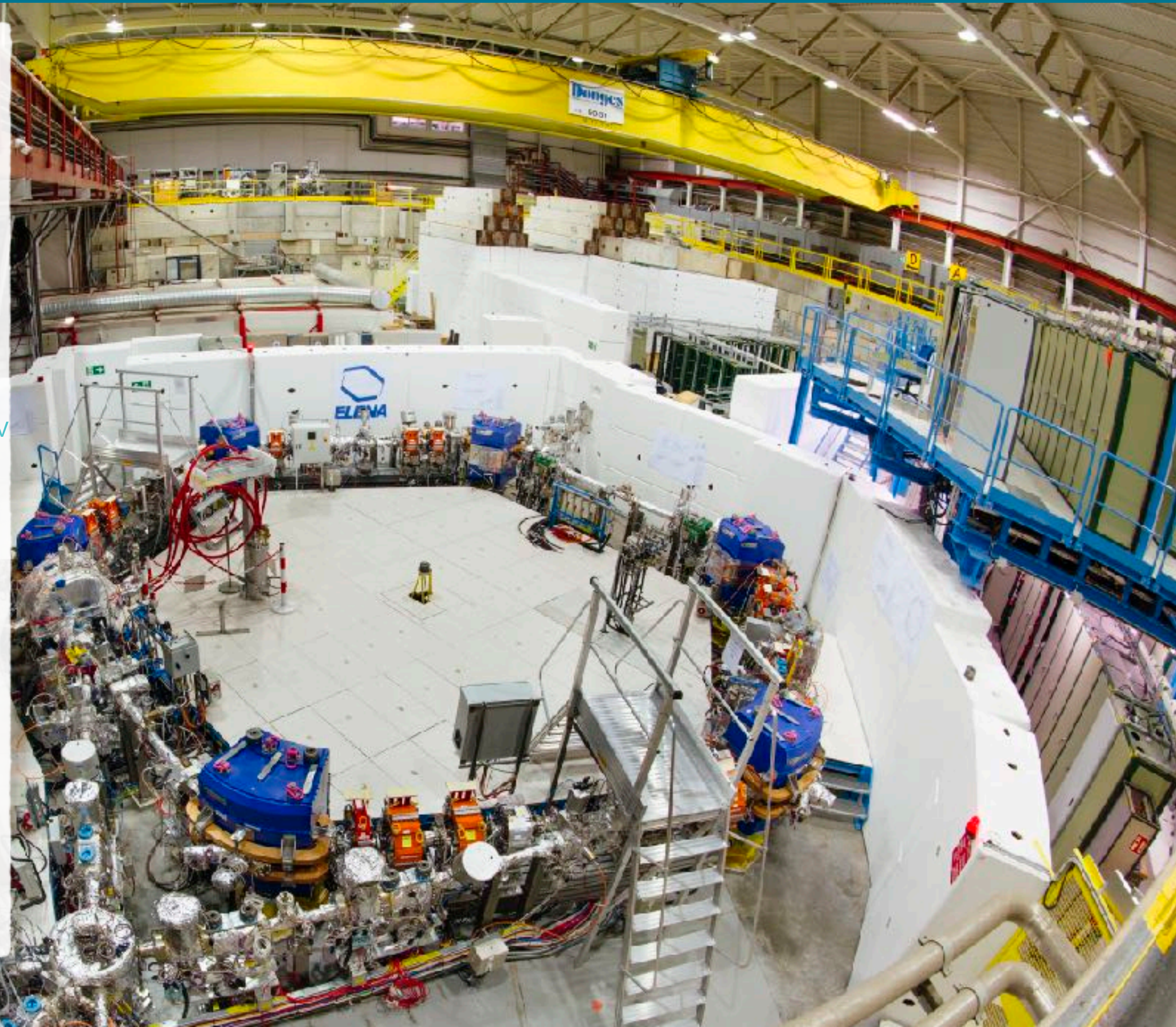
CERN facilities - creating antiprotons



The Antimatter Factory @ CERN



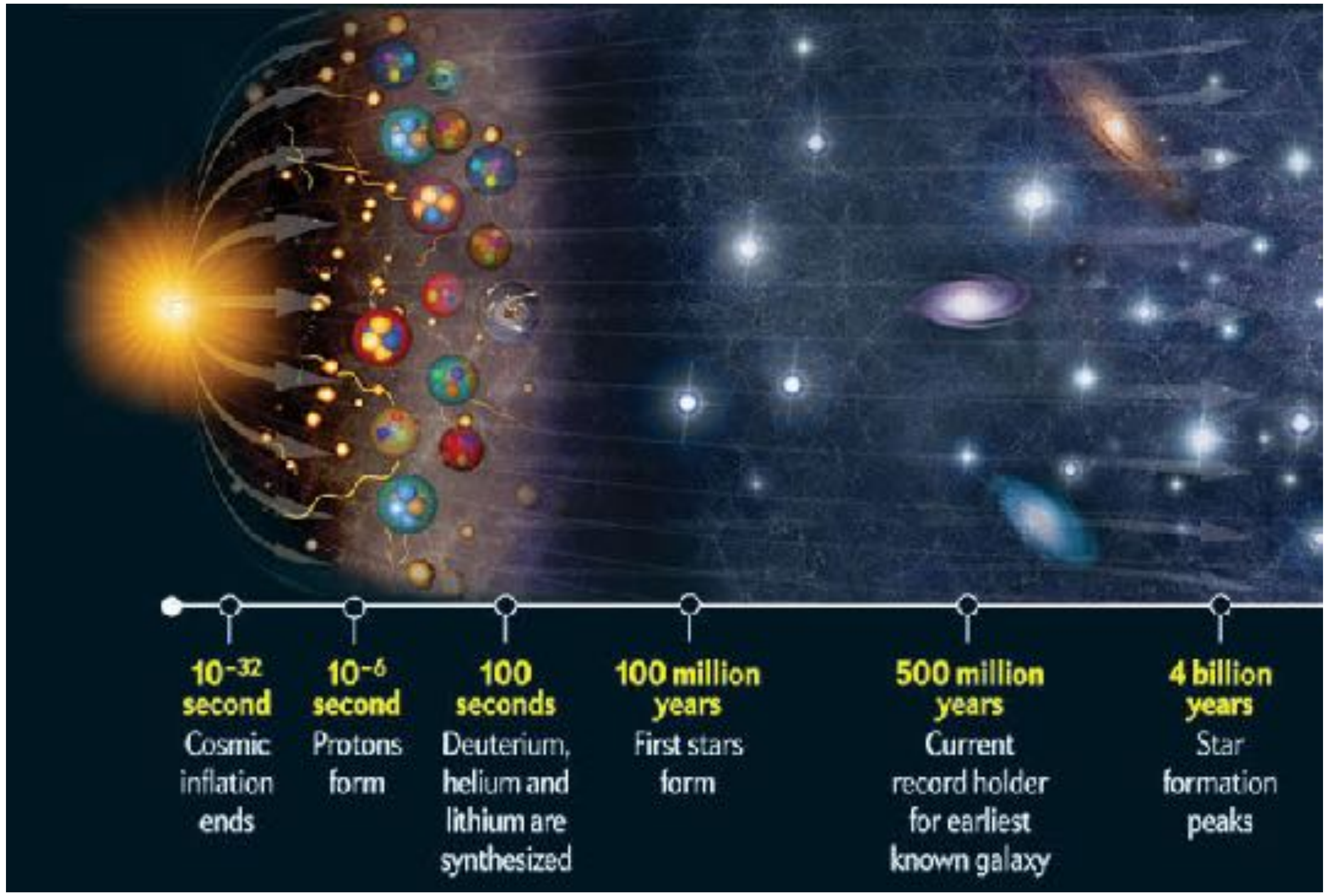
- Ca. 3×10^7 antiprotons from PS on iridium target
- From E~3 GeV to E=5.3 MeV deceleration in AD
- Further deceleration to 70 keV in ELENA, few 10^6 antiprotons in ~2 min cycles



Necessary ingredients for baryon assymetry (Sakharov's conditions)

Violation of B, L, CP…

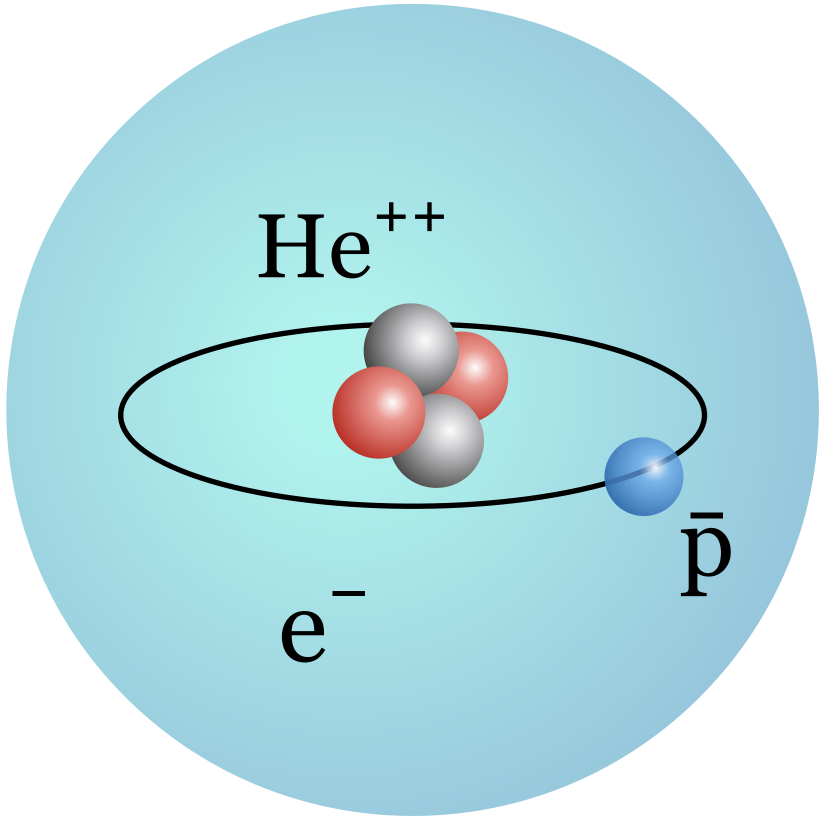
- CP violation:
- Too small to explain baryon asymmetry (SM only explains 10^{-10} of what we need!)
- Need new phenomena.
  - Many theories, such as:
    - **CP violation in the leptonic sector**
    - **Lorentz/CPT violation**



- Violating CPT has huge consequences, means also Lorentz violation

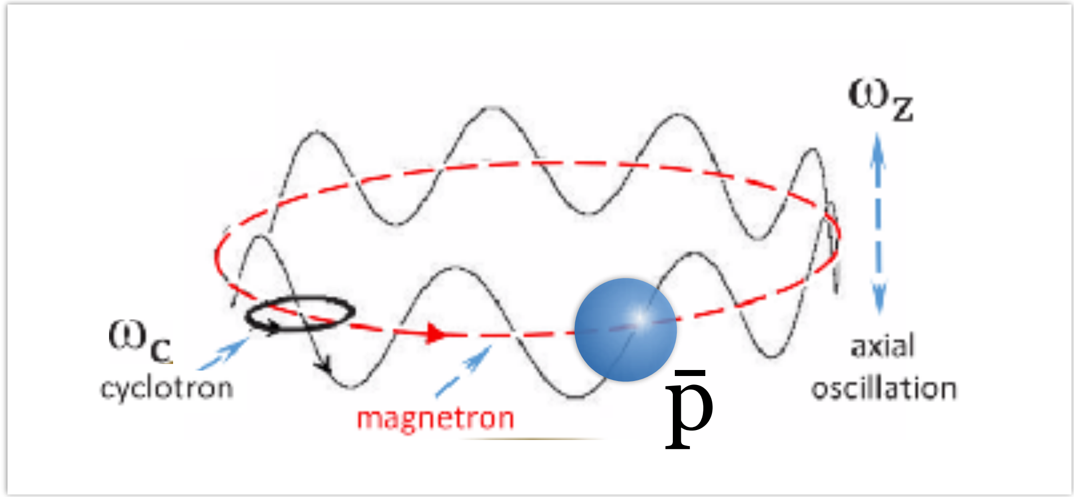
The challenge of making measurements with antiprotons

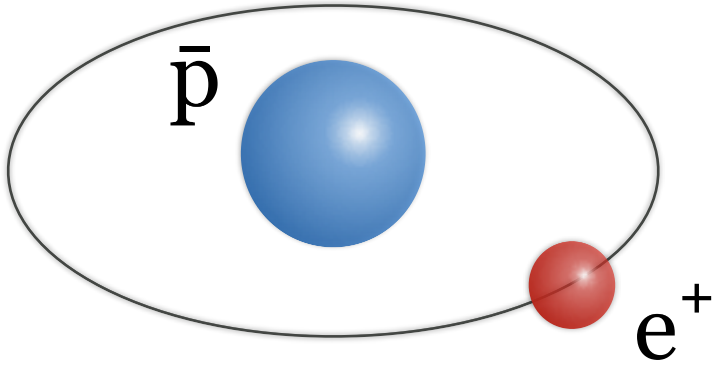
Other exotic atoms:

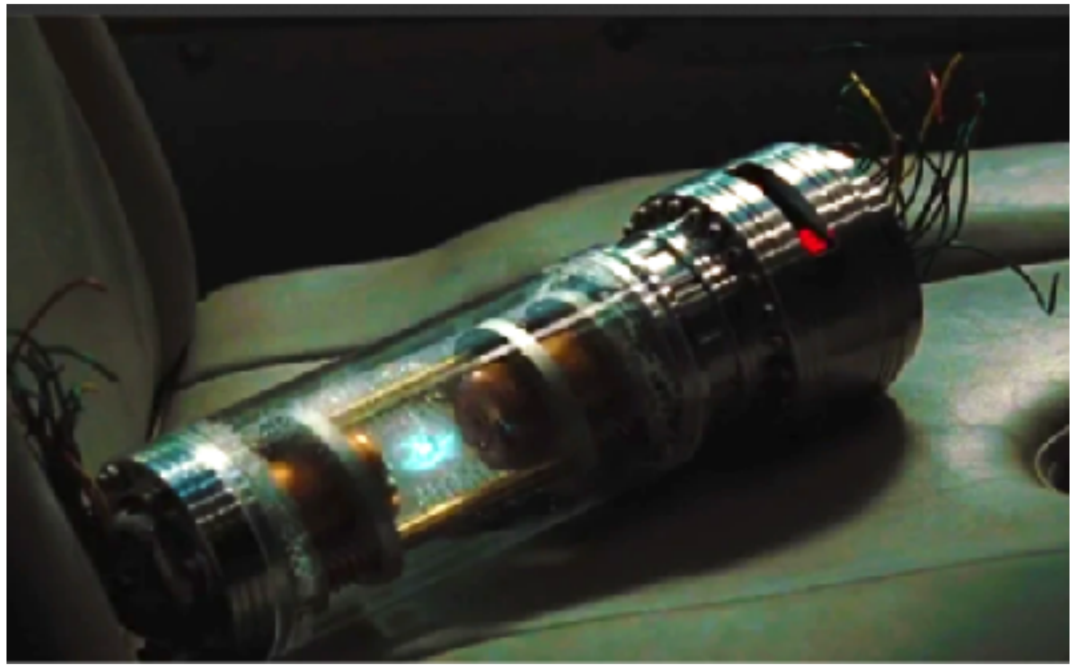


Only way to keep p̄ in the vicinity of matter

Both antiprotons and positrons must be captured in electrostatic fields

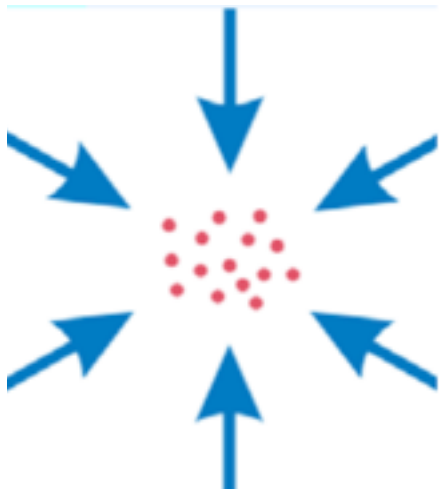


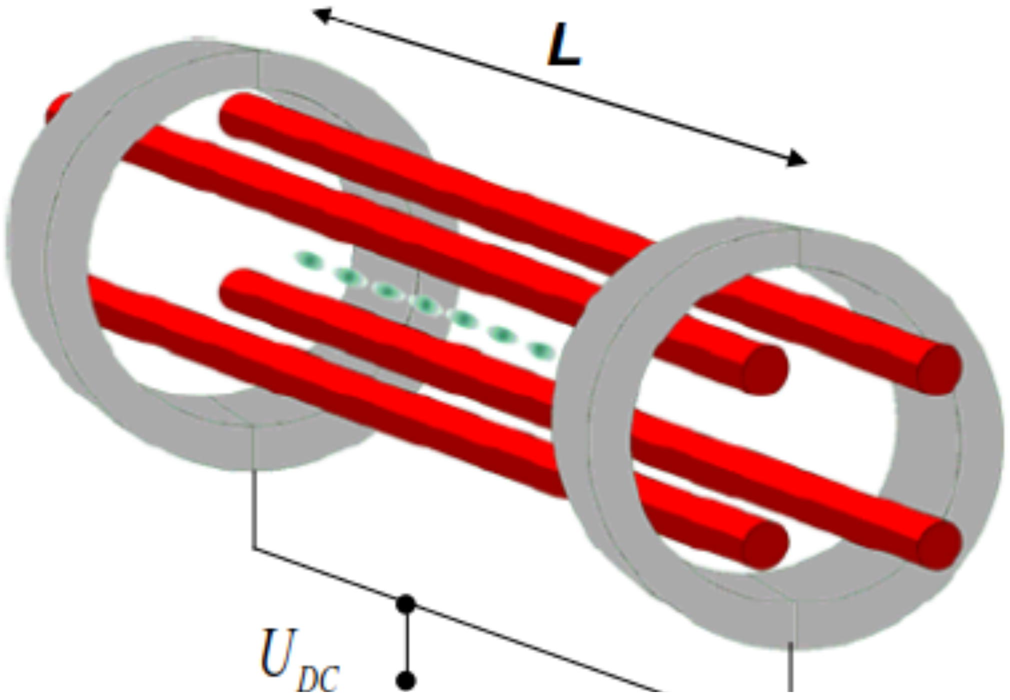


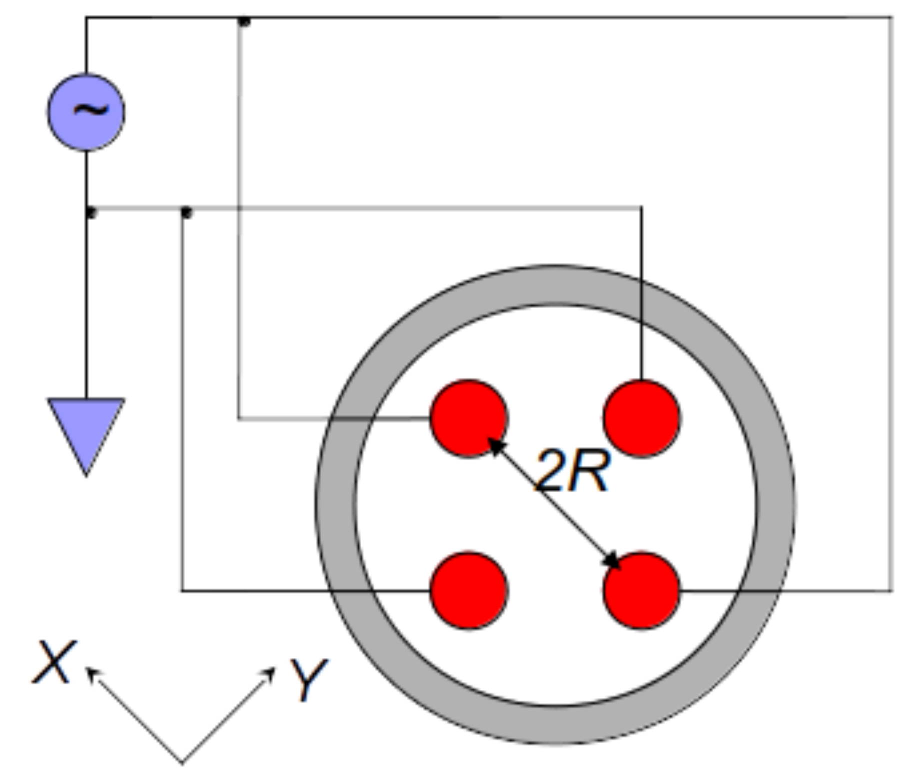


… how Hollywood imagines it

Ion traps - the Paul trap

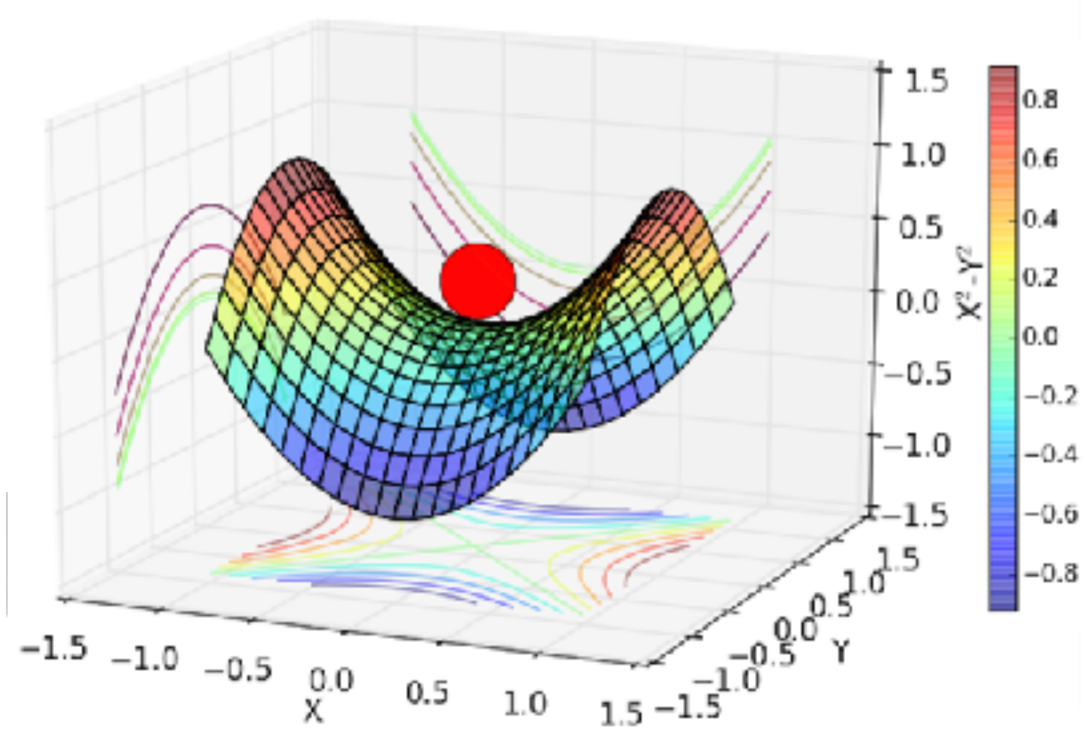






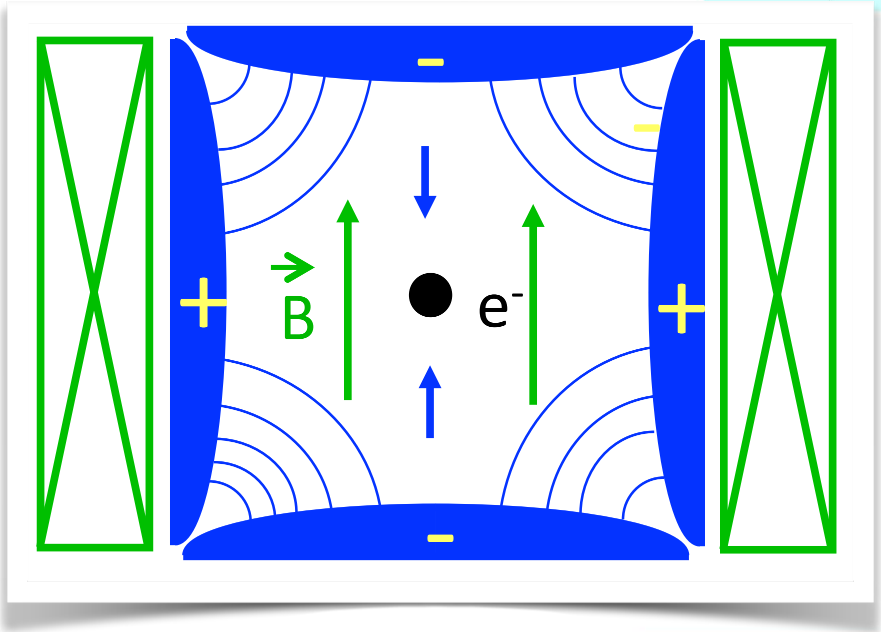
In 3 dimensions, we can't construct a static electric potential that traps in every direction.

Best we can do is a saddle.



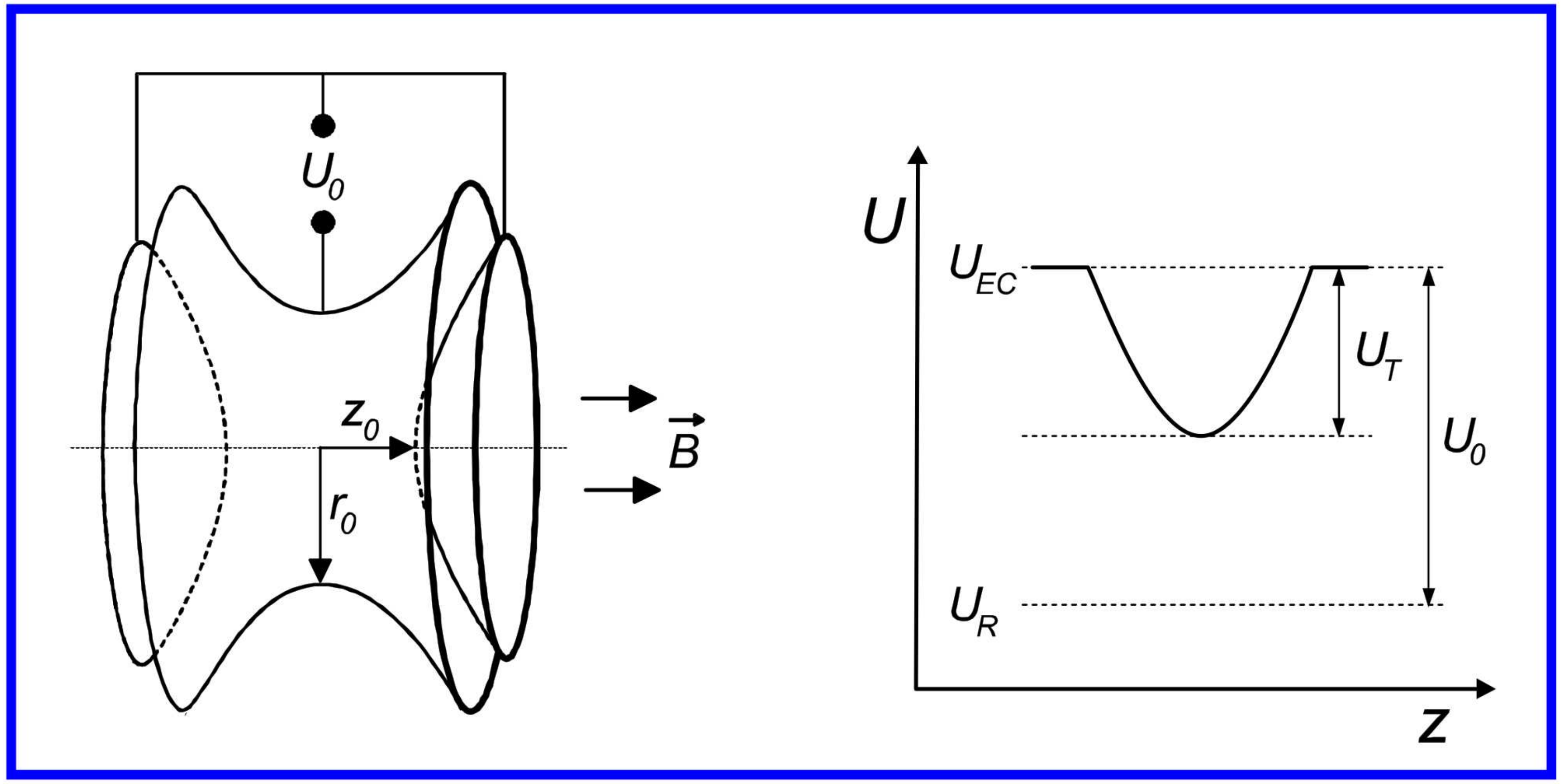
Changing polarity at a given frequency (rotating the saddle) can trap a particle of a given q/m ratio

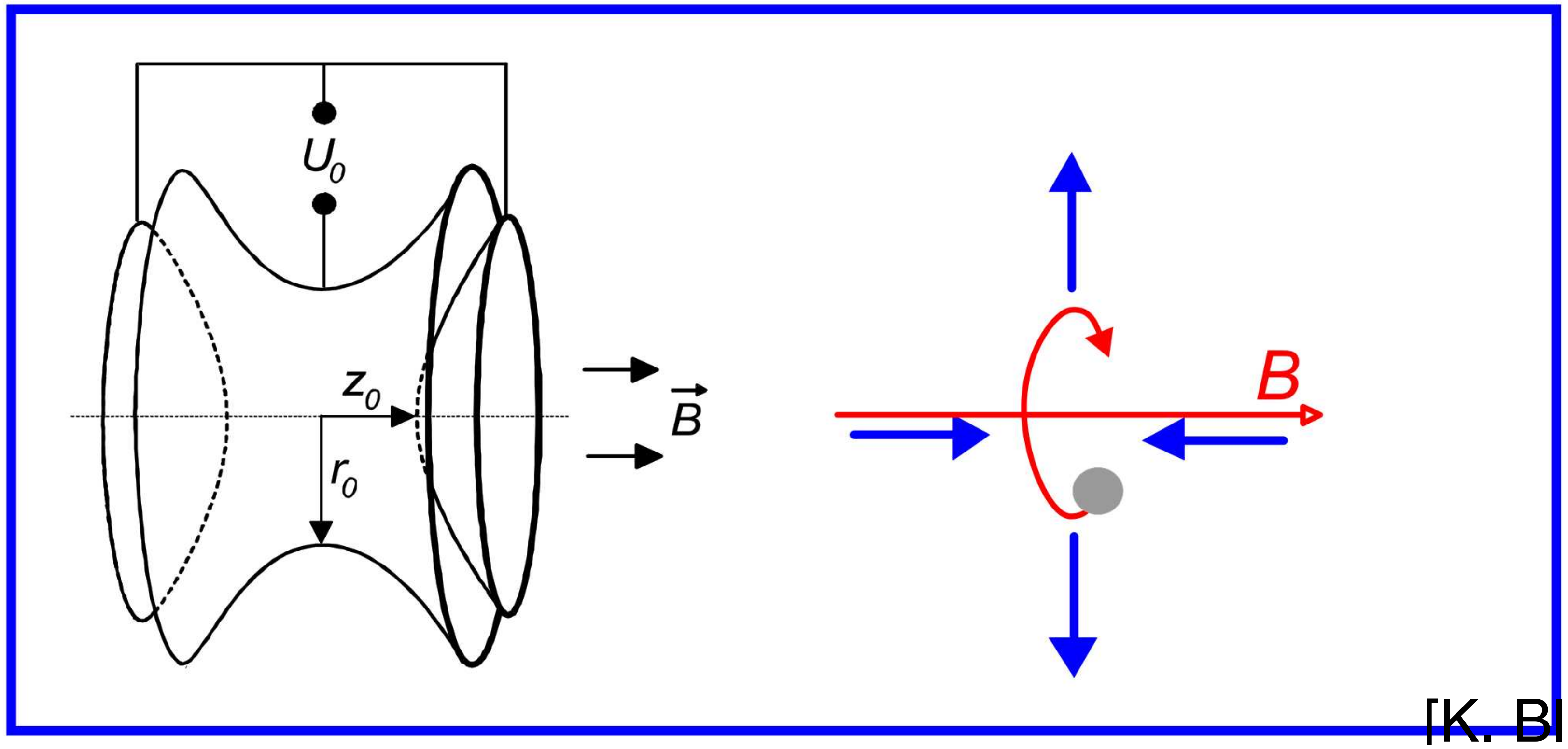
Working principle of a Penning trap



axial harmonic potential

radial confinement with magnetic field

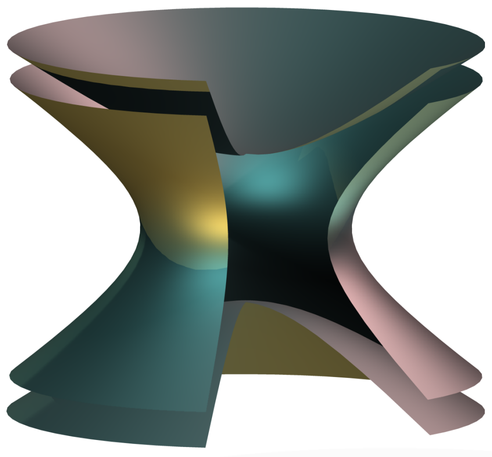


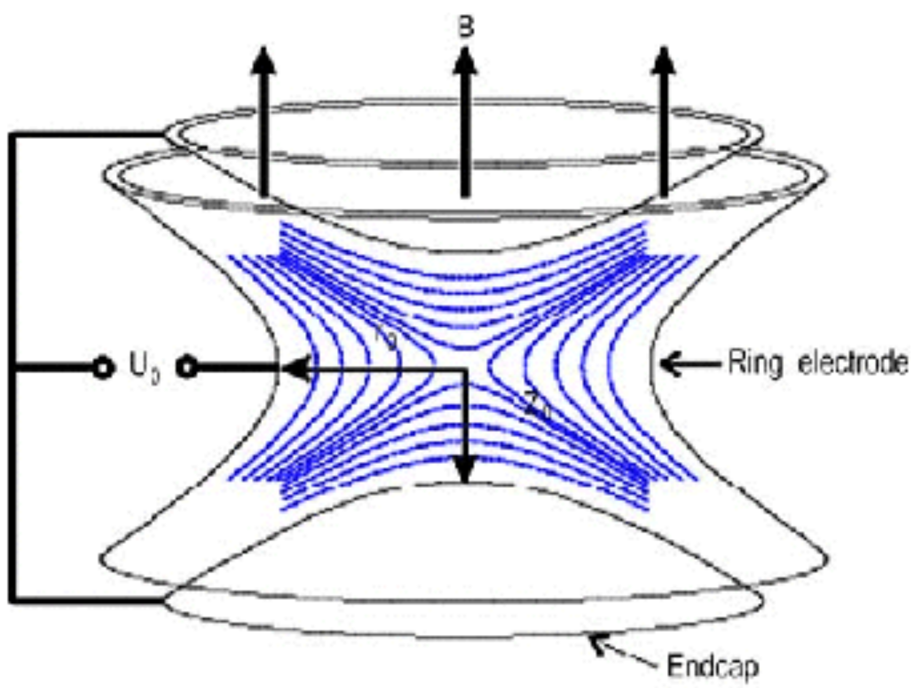


[K. Blaum]

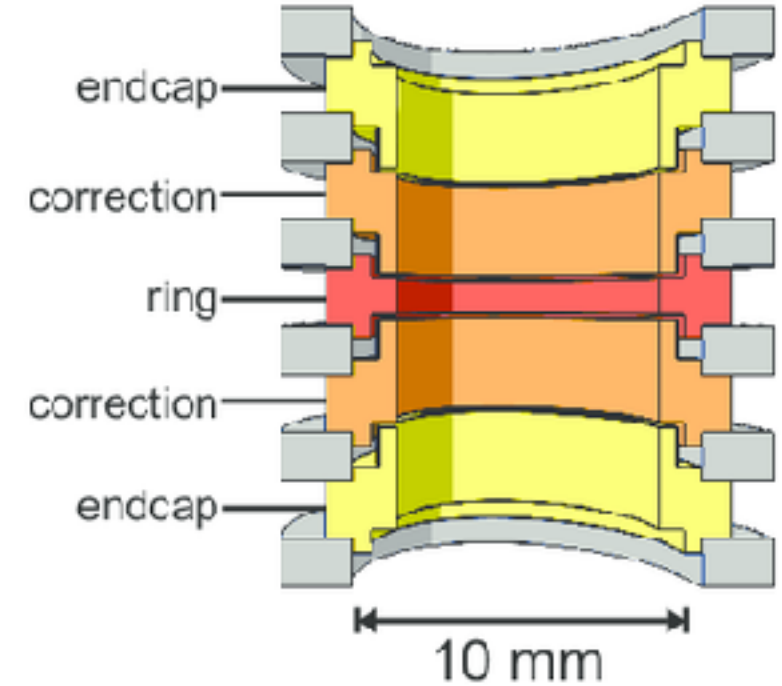
Penning trap - electrode configuration

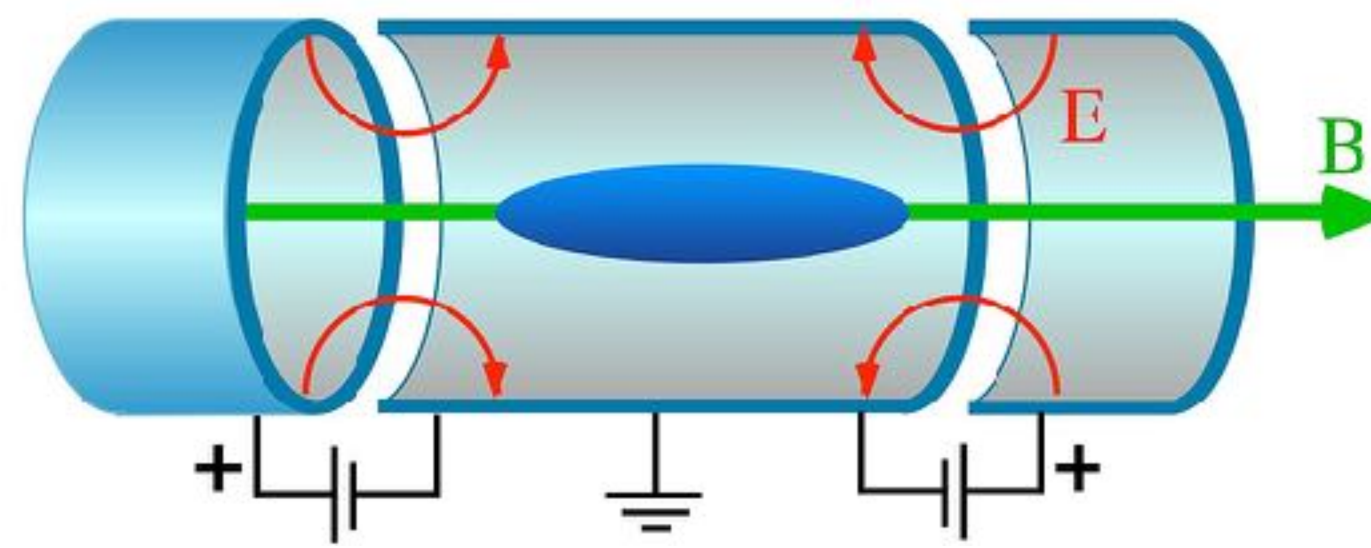
- The ideal trap electrode shape is difficult to manufacture



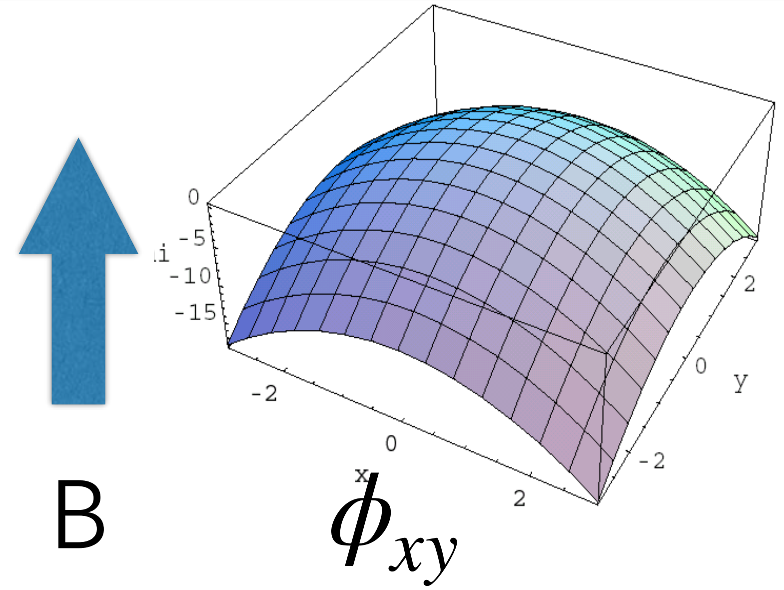


- Simple modifications make it easier to make:





- The magnetic field $\vec{B} = \begin{pmatrix} 0 \\ 0 \\ B \end{pmatrix}$ confine the particle in the x-y plane.
- The electric field $\vec{E} = \vec{\nabla}\phi = \frac{V_0}{2d^2}\begin{pmatrix} x \\ y \\ -2z \end{pmatrix}$ confine the particle in the z-direction
- Classical motion:



$$m\vec{a} = q(\vec{E} + \frac{\dot{\vec{r}}}{c} \times \vec{B}) = q\frac{V_0}{2d^2}\begin{pmatrix} x \\ y \\ -2z \end{pmatrix} + q\frac{\dot{\vec{r}}}{c} \times \begin{pmatrix} 0 \\ 0 \\ B \end{pmatrix}$$

$\rightarrow$ z-axis: $mz'' = -\frac{qV_0}{d^2}z$

$\Rightarrow$ harmonic oscillation in axial direction $z = z_0 \cos(\omega_z t + \phi_z)$ with $\omega_z = \frac{qV_0}{md^2}$

$\rightarrow$ x-y plane: - Only B-field in z-direction $\rightarrow$ pure cyclotron motion $\omega_c = \frac{eB}{mc}$

- Adding the small electrostatic pot. $\phi_{xy} = \frac{V_0}{4d^2}(x^2 + y^2)$

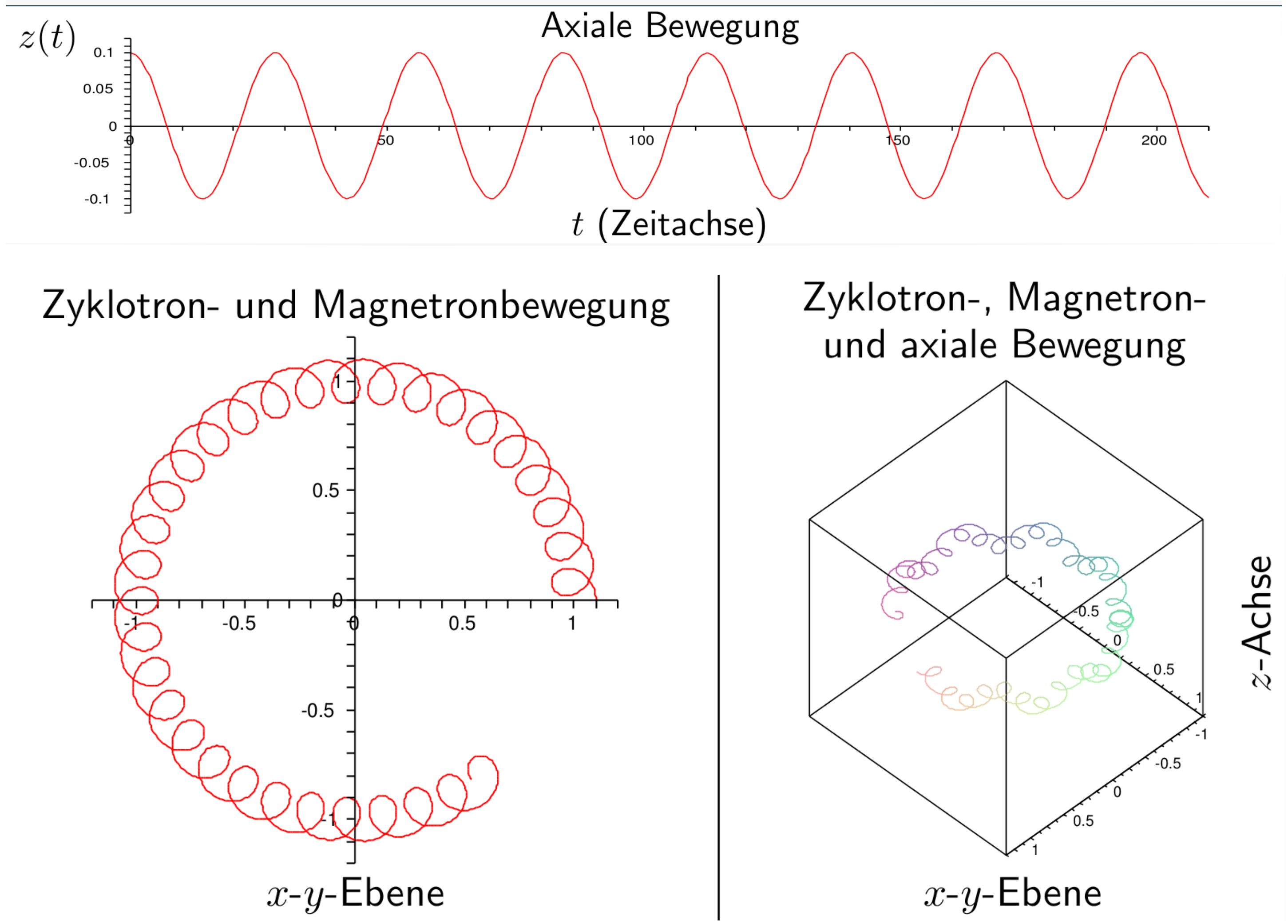
$\rightarrow$ magnetron motion and small modification of cyclotron frequency

$$\begin{pmatrix} x \\ y \end{pmatrix} = r_+ \begin{pmatrix} \cos(\omega_+ t + \phi_+) \\ \sin(\omega_+ t + \phi_+) \end{pmatrix} + r_- \begin{pmatrix} \cos(\omega_- t + \phi_-) \\ \sin(\omega_- t + \phi_-) \end{pmatrix}$$

ω_- ω_+

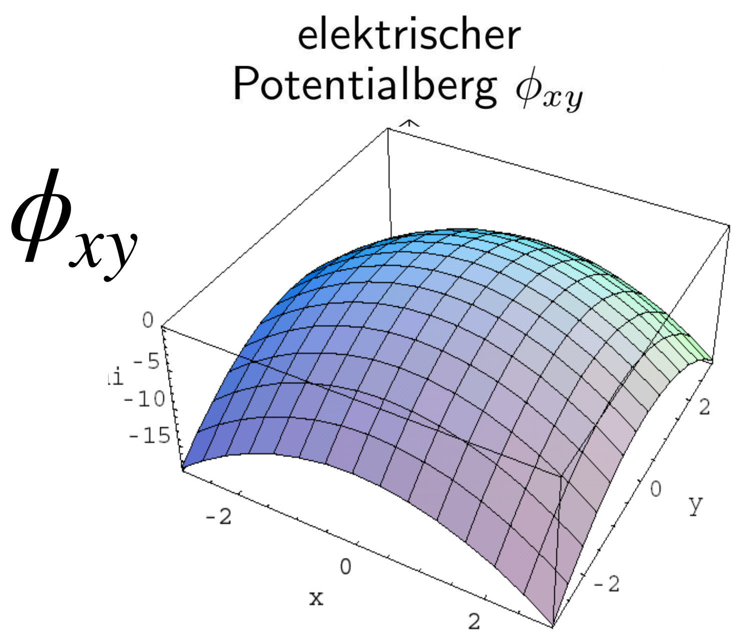
$$\omega_\pm = \frac{eB}{2mc} \pm \sqrt{\left(\frac{eB}{2mc}\right)^2 + \frac{eV_0}{2md^2}}$$

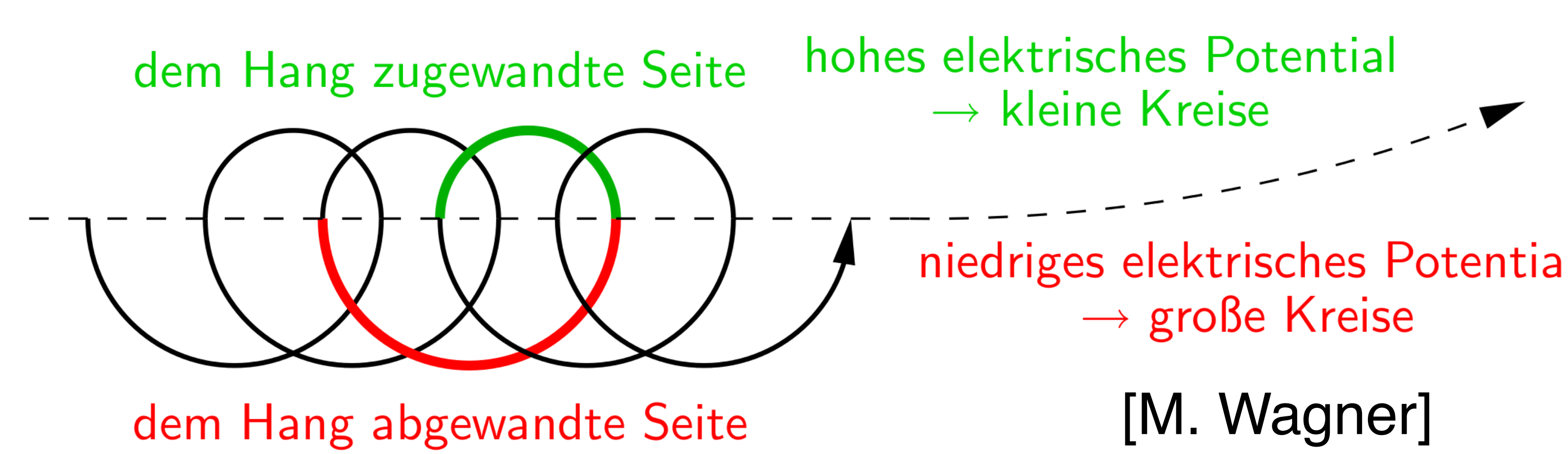
Classical motion in a Penning trap



- In experiment:
  $\omega_+ : \omega_z : \omega_- \approx 10^7 : 10^3 : 1$

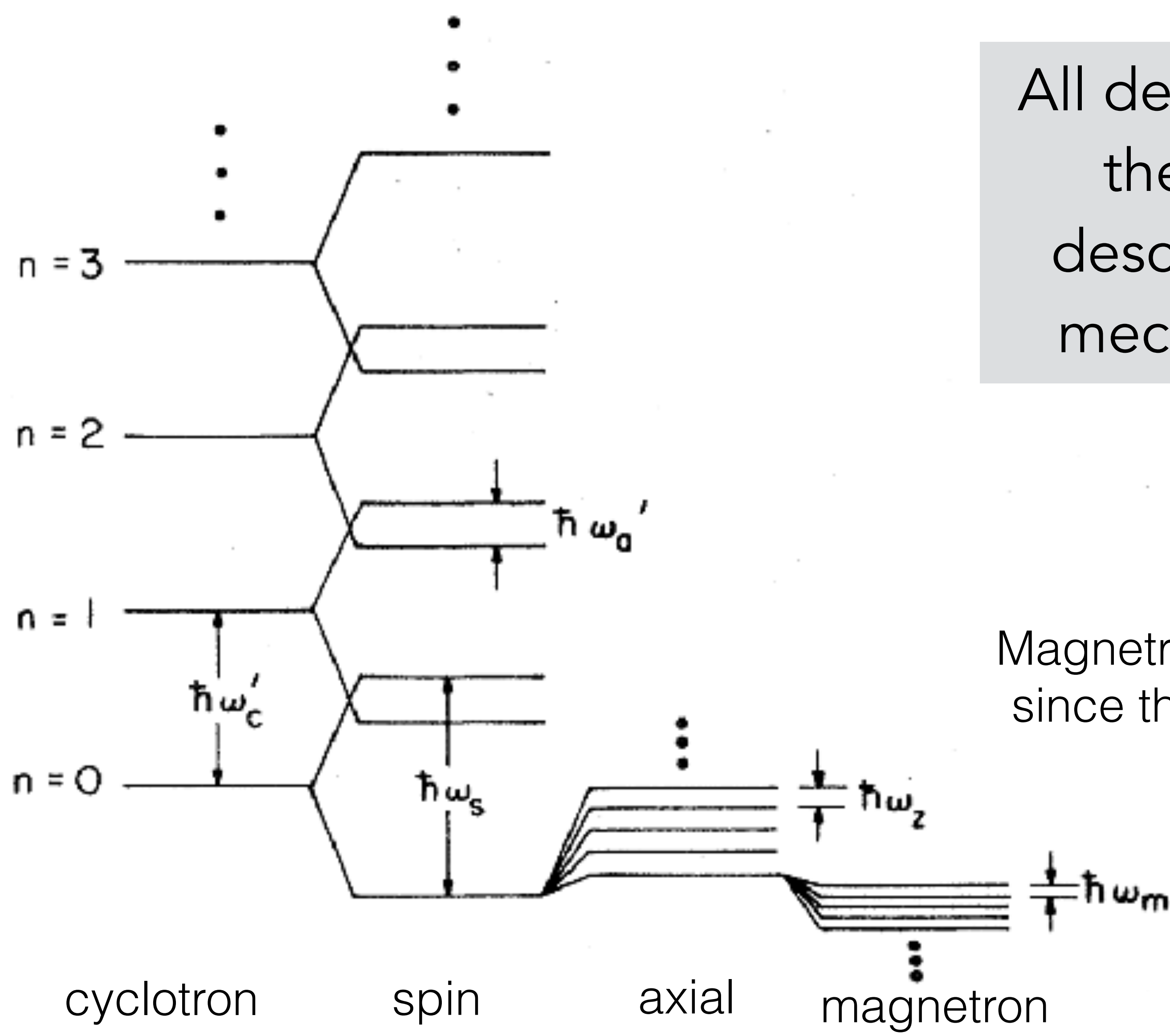
- ω_+: Cyclotron frequency
- ω_-: Magnetron frequency
- ω_z: Axial frequency





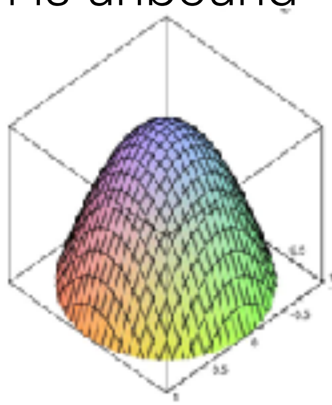
[M. Wagner]

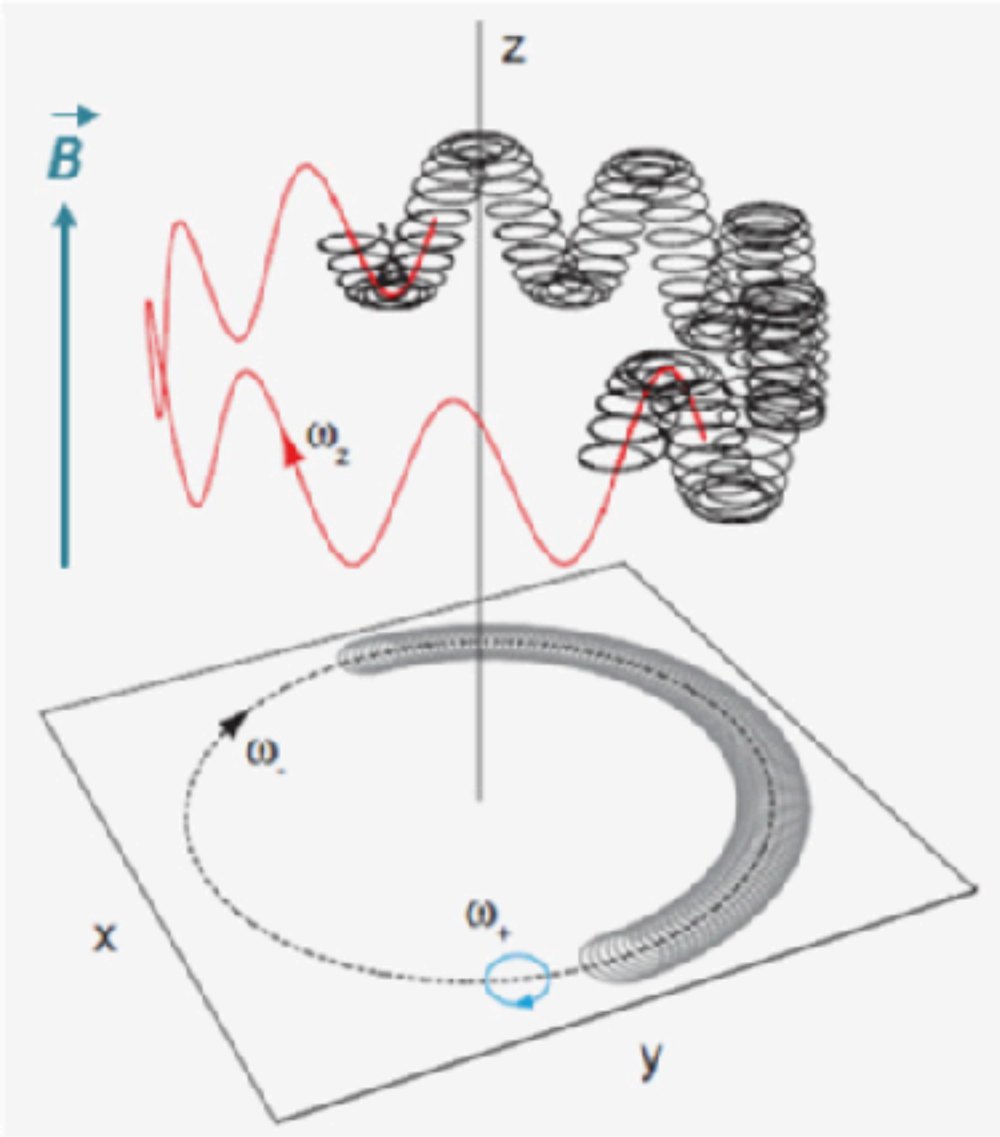
Quantized energy levels in a Penning trap



All degree of freedom of the motion can be described as quantum mechanical oscillators

Magnetron levels are inverted since the motion is unbound



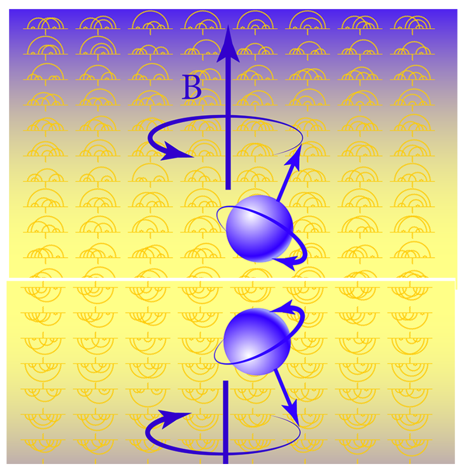


	frequency	damping time	quantum number
spin	$\omega_s/2\pi \approx 149.7$ GHz	$\gamma_s^{-1} \approx 5$ year	$m_s = \frac{1}{2}$ or $m_s = -\frac{1}{2}$
cyclotron	$\omega_c'/2\pi \approx 149.5$ GHz	$\gamma_c^{-1} \approx 10$ s	$\bar{n}_c = 5.6 \times 10^{-32}$
axial	$\omega_z/2\pi \approx 115$ MHz	$\gamma_z^{-1} \approx 0.03$ s	$\bar{n}_z = 100$
magnetron	$\omega_m/2\pi \approx 48$ kHz	$\gamma_m^{-1} \approx 10^{12}$ s	$\bar{n}_m = 100$

Measurement of g factors in Penning traps

We want to measure is g, which is proportional to the energy needed for a spin flip

$$\hbar\omega_s = |2\mu_s B| = \frac{g}{2}\frac{\hbar e B}{m}.$$



We measure the B-field in the same system measuring the cyclotron frequency from a cyclotron jump

$$\hbar\omega_c = \frac{\hbar e B}{m}.$$

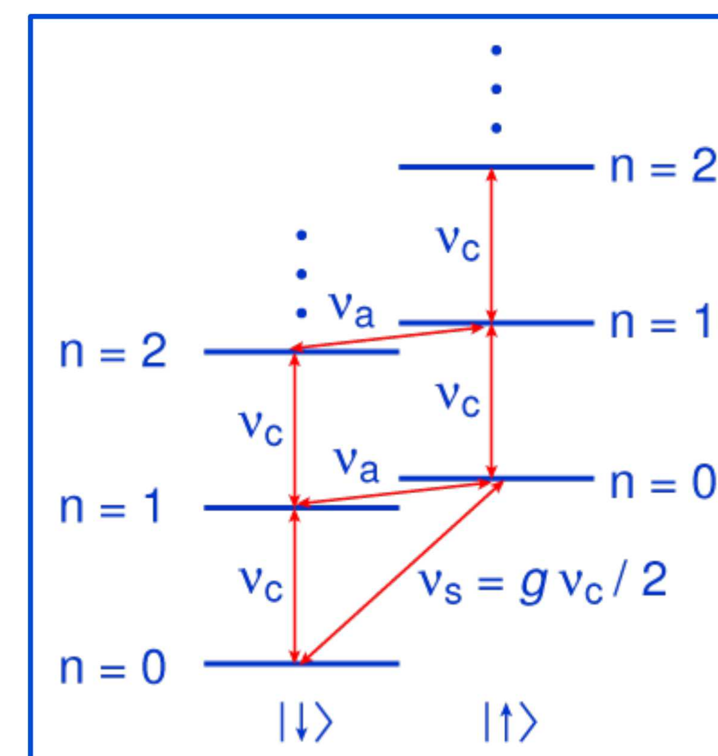
$$\frac{g}{2} = \frac{\omega_s}{\omega_c} = \frac{\nu_s}{\nu_c}.$$

Eliminates the B-field and the mass dependence

Complication

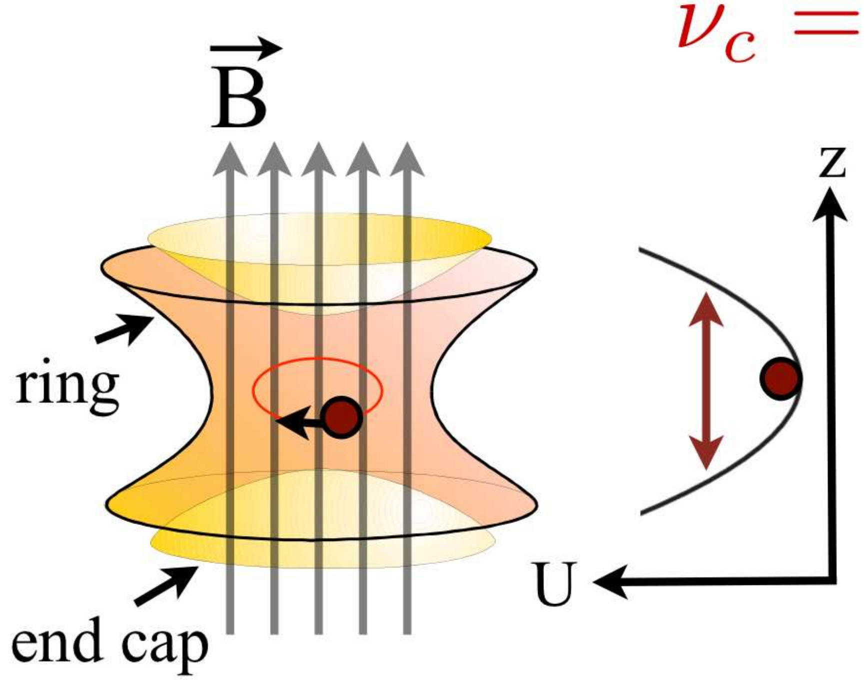
Experimentally, a Penning trap is used to keep the electron in a small region of a homogeneous magnetic field. An electron in a Penning trap has three orthogonal motional modes, a cyclotron motion in the Penning trap ω_c' slightly modified by the electrostatic trap potential, axial motion ω_z, and magnetron motion ω_m . Connection:

$$\omega_c = \sqrt{\omega_+^{\ 2} + \omega_-^{\ 2} + \omega_z^{\ 2}}$$



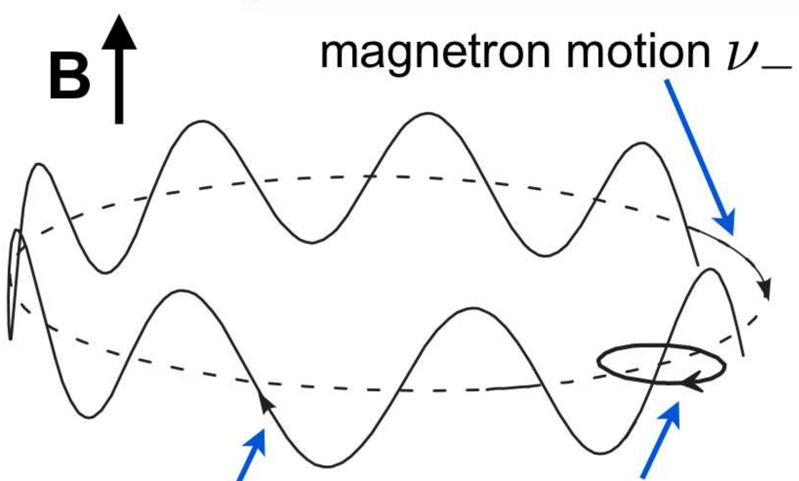
Measurement principle of magnetic moments

cyclotron frequency $\nu_c = \frac{e \cdot B}{2\pi m}$

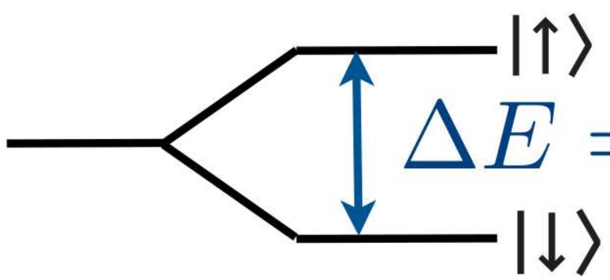


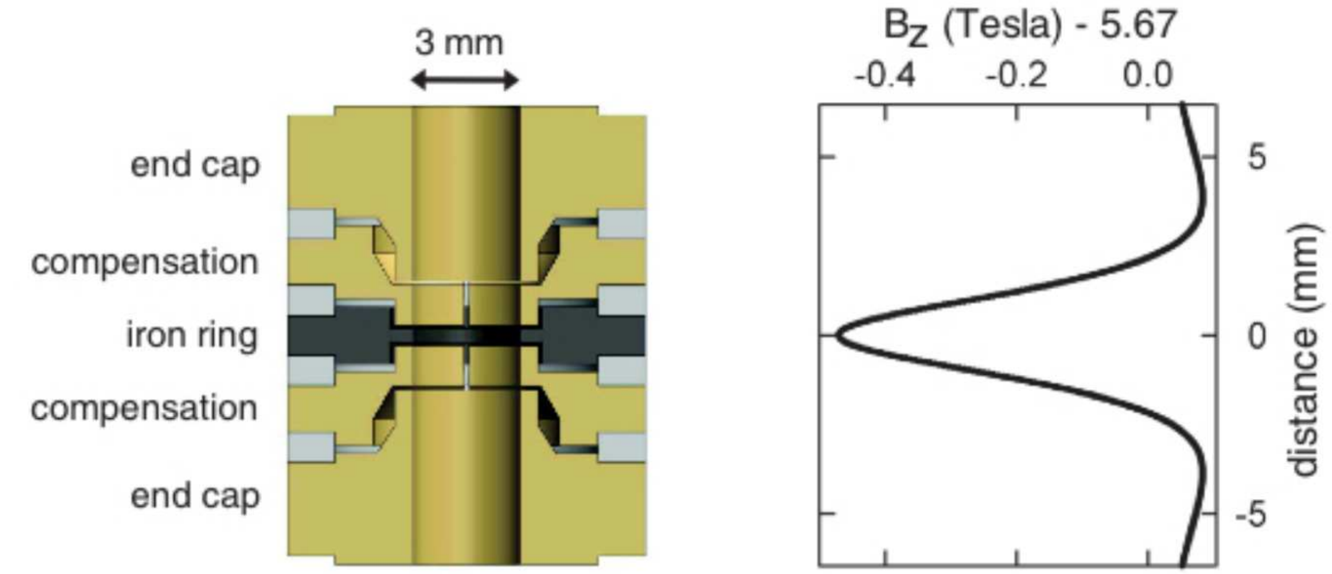
Brown-Gabrielse Invariance Theorem

$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$



Larmor frequency $\nu_L = g\frac{e \cdot B}{4\pi m}$





$$\Delta\nu_z \propto \left[\frac{g m_s}{2} + \left(n + \frac{1}{2}\right) + \frac{\nu_-}{\nu_+}\left(\ell + \frac{1}{2}\right)\right]$$

axial motion sensitive to spin state

Measurement in separate trap locations

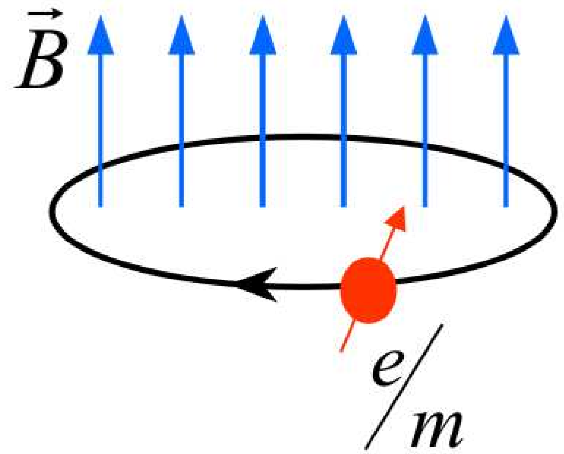
$$\omega_c = \frac{e}{m_p} B$$

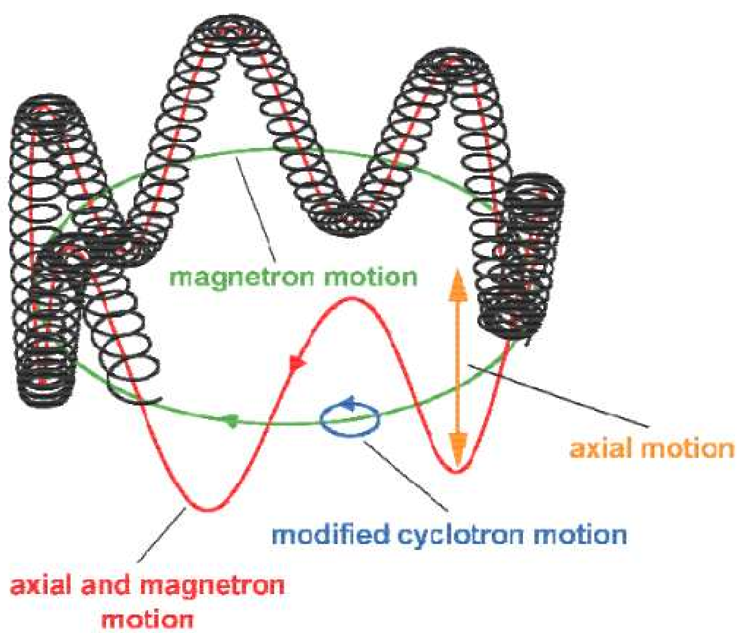
Cyclotron frequency

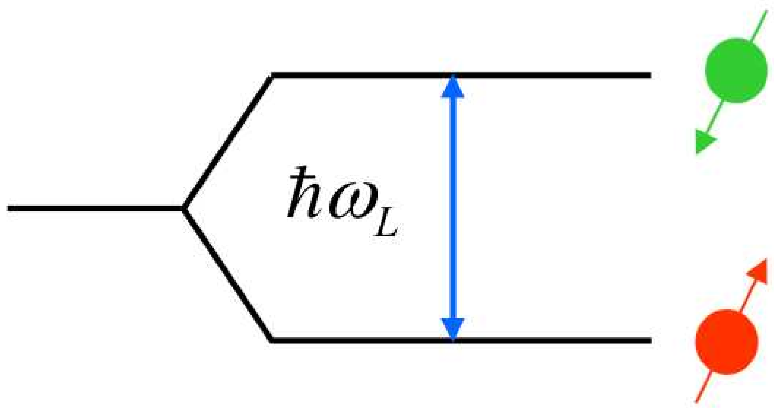
$$g = 2\frac{\omega_L}{\omega_c}$$

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

Larmor frequency







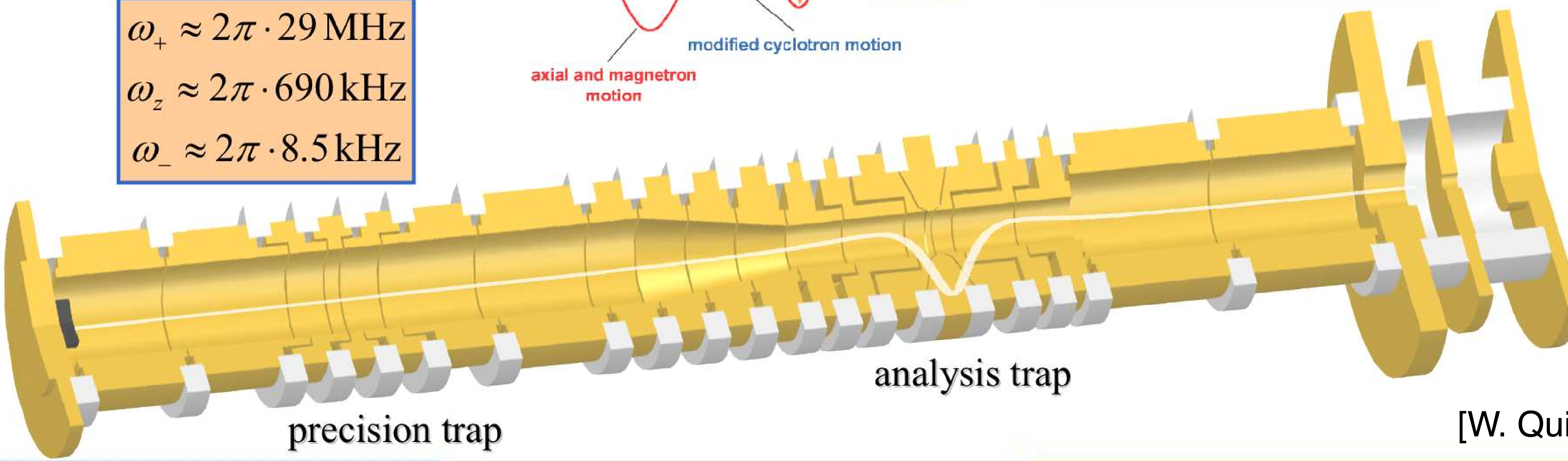
$$\omega_c = \sqrt{\omega_+^{\ 2} + \omega_-^{\ 2} + \omega_z^{\ 2}}$$

$$\omega'_z(\uparrow) - \omega'_z(\downarrow) = \Delta\omega_z$$

$\omega_+ \approx 2\pi \cdot 29\,\mathrm{MHz}$

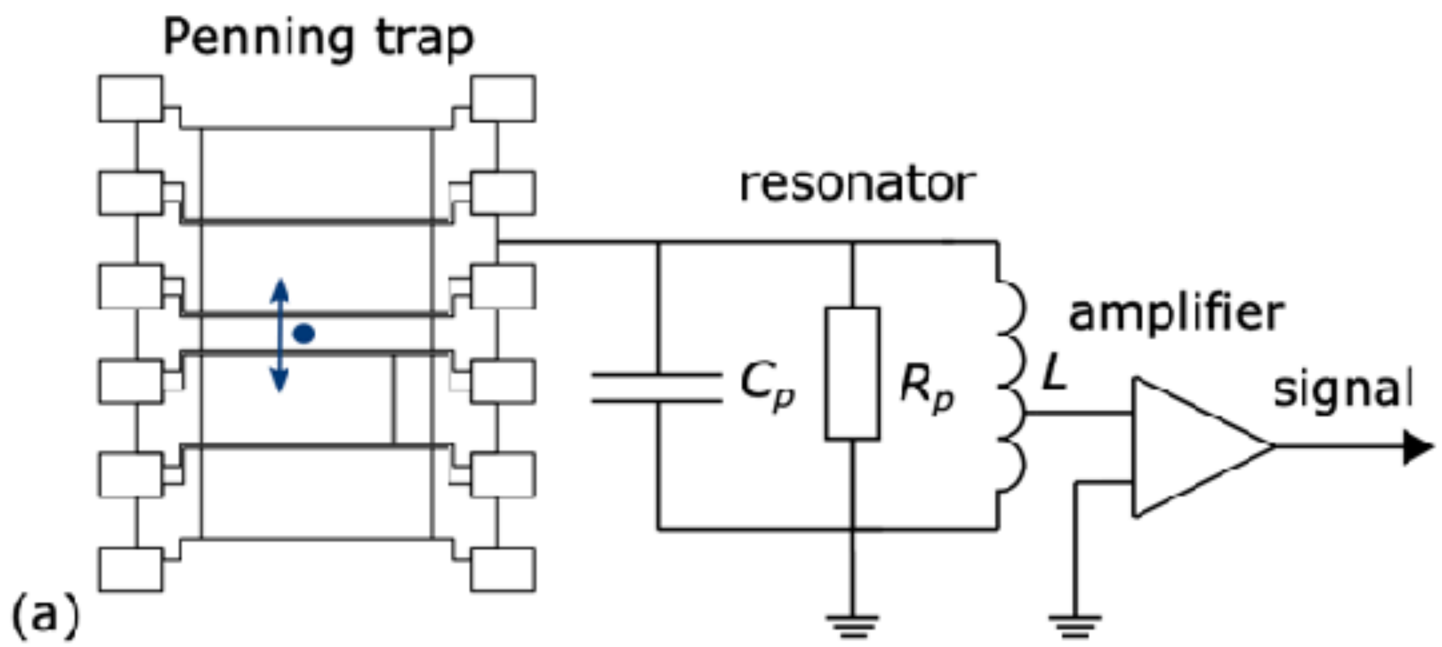
$\omega_z \approx 2\pi \cdot 690\,\mathrm{kHz}$

$\omega_- \approx 2\pi \cdot 8.5\,\mathrm{kHz}$



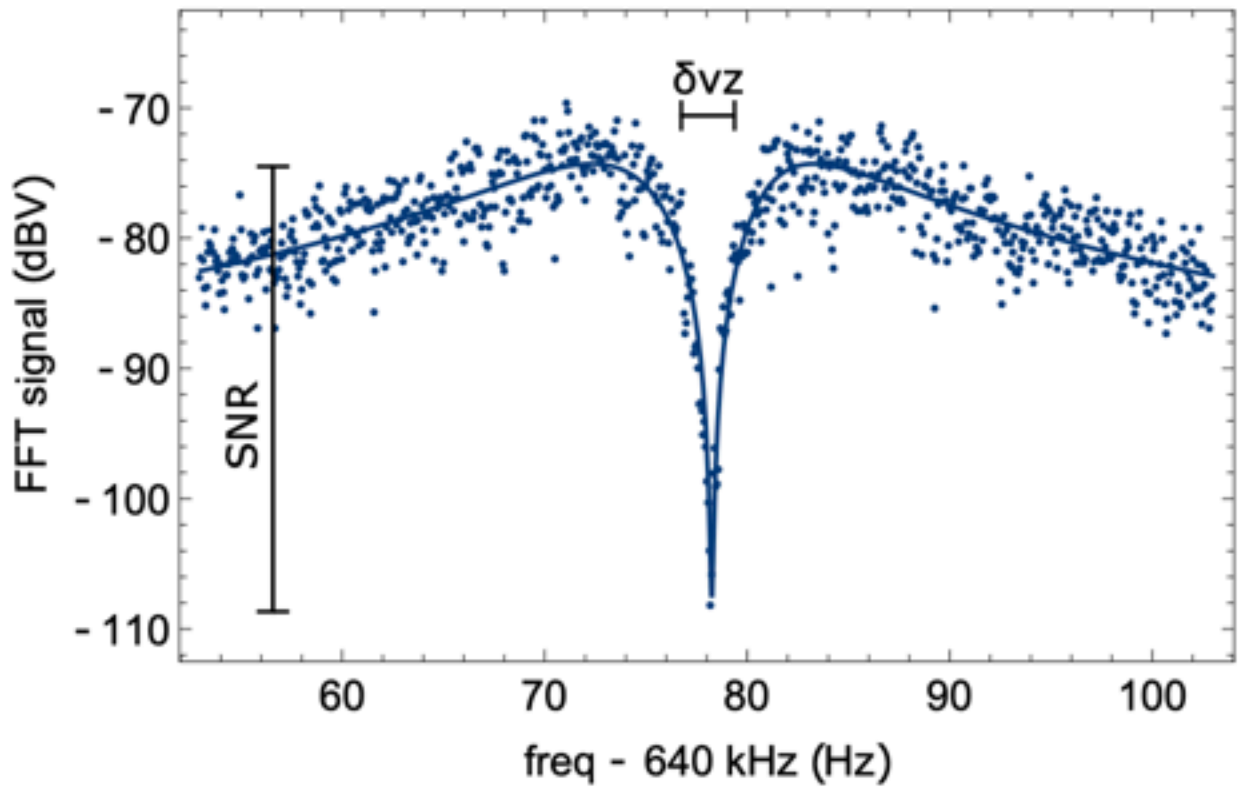
[W. Quint]

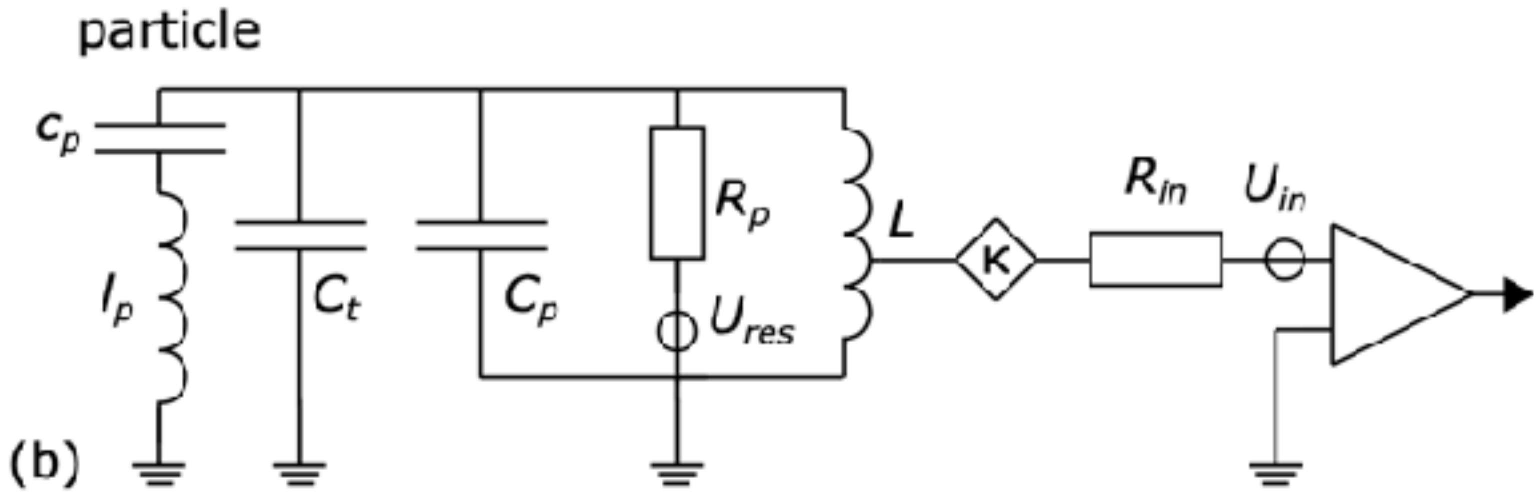
Axial frequency detection



The particle oscillates in axial direction inside the Penning trap, and induces image currents in the trap electrodes. Depending on the strength of coupling, it thermalizes

- Axial dip with single particle





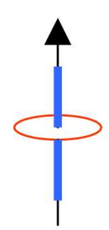
In thermal equilibrium, the particle shorts the thermal resonator noise at the axial frequency, that appears as a dip in the FFT spectrum

Measurement of the cyclotron frequency

Gabrielse

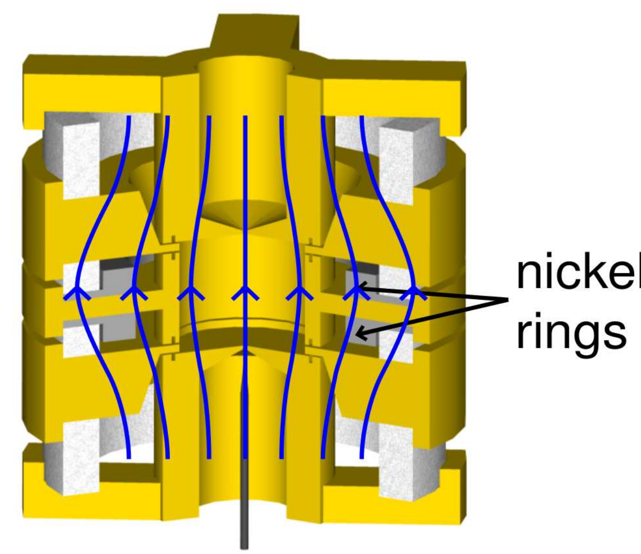
cyclotron frequency	$\nu_C = 150$ **GHz**	**too high to detect directly**
axial frequency	$\nu_Z = 200$ **MHz**	**relatively easy to detect**

Couple the axial frequency ν_Z to the cyclotron energy.



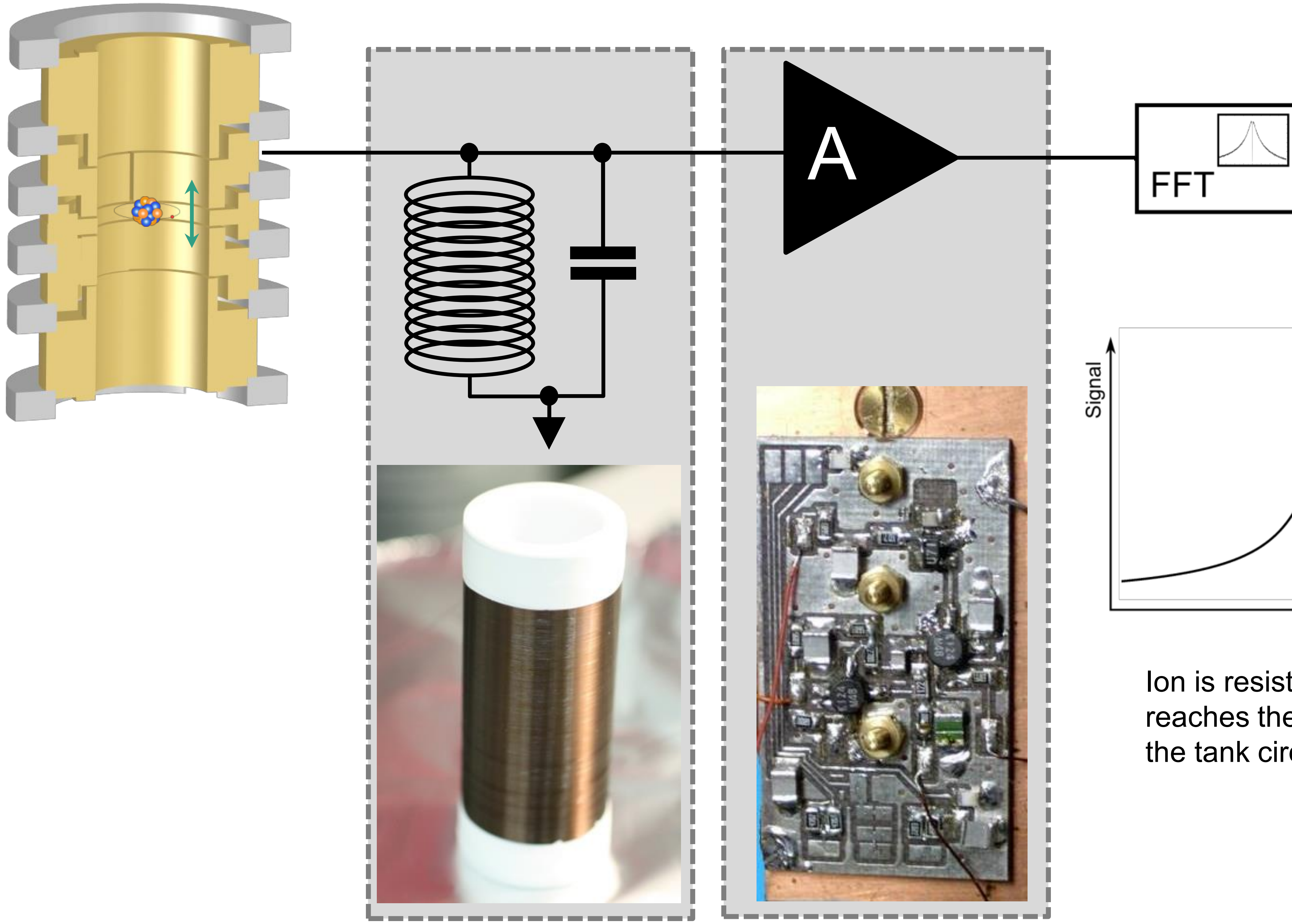
B

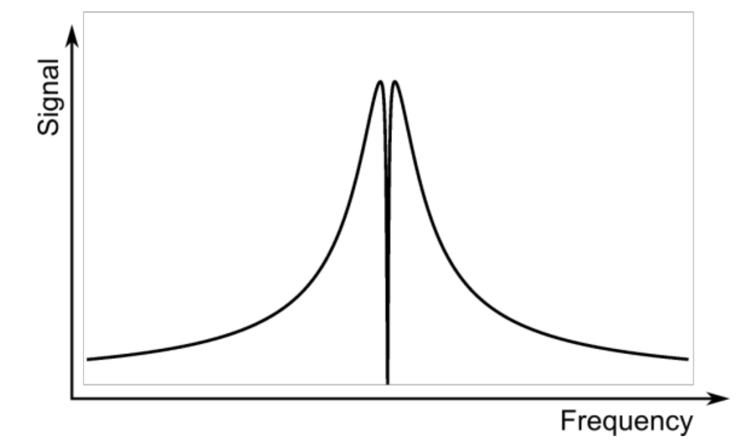
Small measurable shift in ν_Z indicates a change in cyclotron energy.



$$B_z = B_0 + B_2 z^2$$

Is “not” possible to directly detect the cyclotron frequency
$\rightarrow$ Couple the cyclotron and spin frequencies to the axial frequency
When a spin or cyclotron jump occurs $\rightarrow$ small but measurable change of the axial frequency.





Ion is resistively cooled until it reaches thermal equilibrium with the tank circuit

Oscillating ion induces image charges in trap electrodes

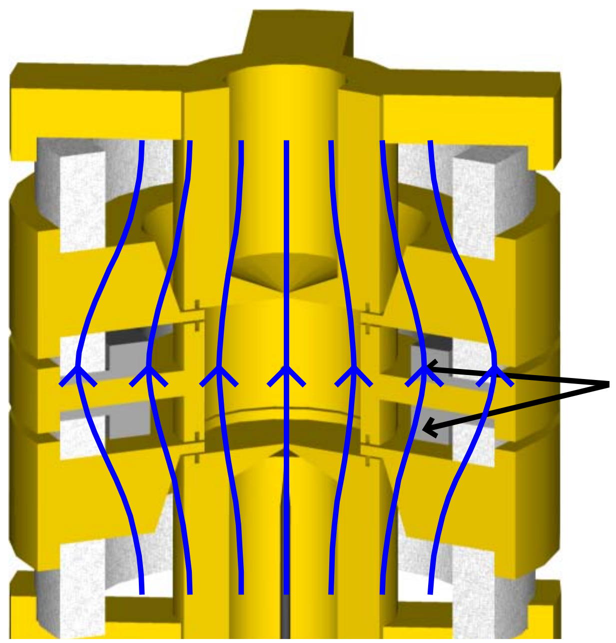
Tank circuit with high impedance
R_p = 50 MΩ
Q = 3200

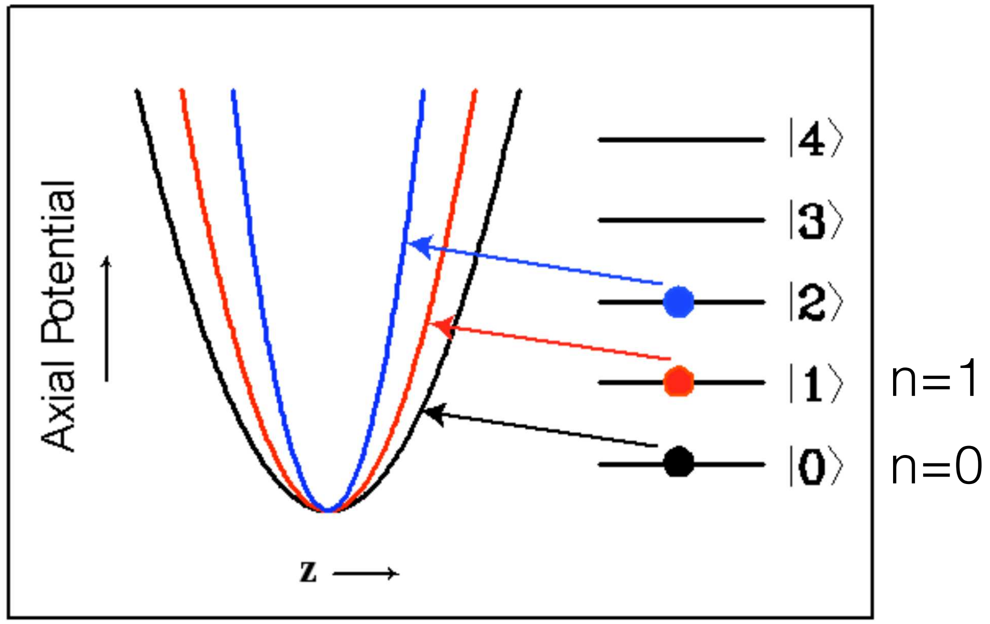
Cryogenic ultra low-noise amplifier
e_n = 400pV/ √Hz
$i_n \leq$ 10fA/ √Hz

Fast Fourier Transformation to obtain the frequency information

Sturm

Detection of a cyclotron jump

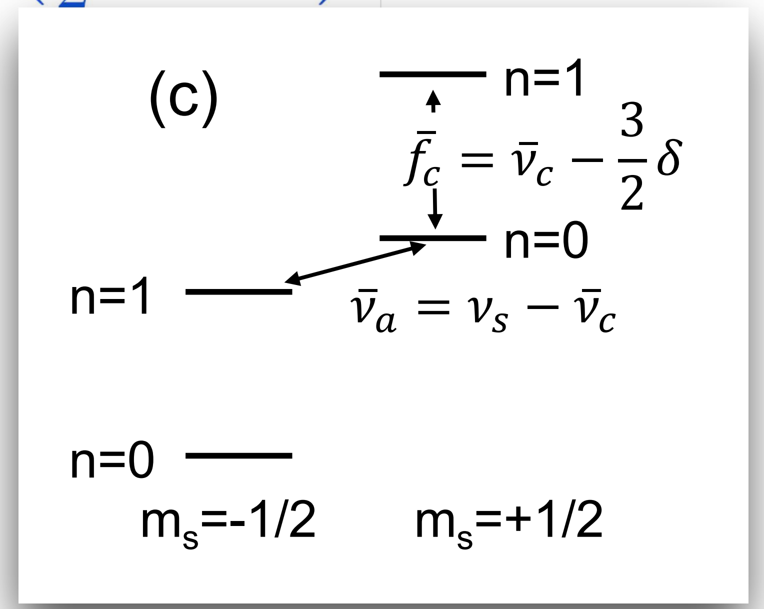




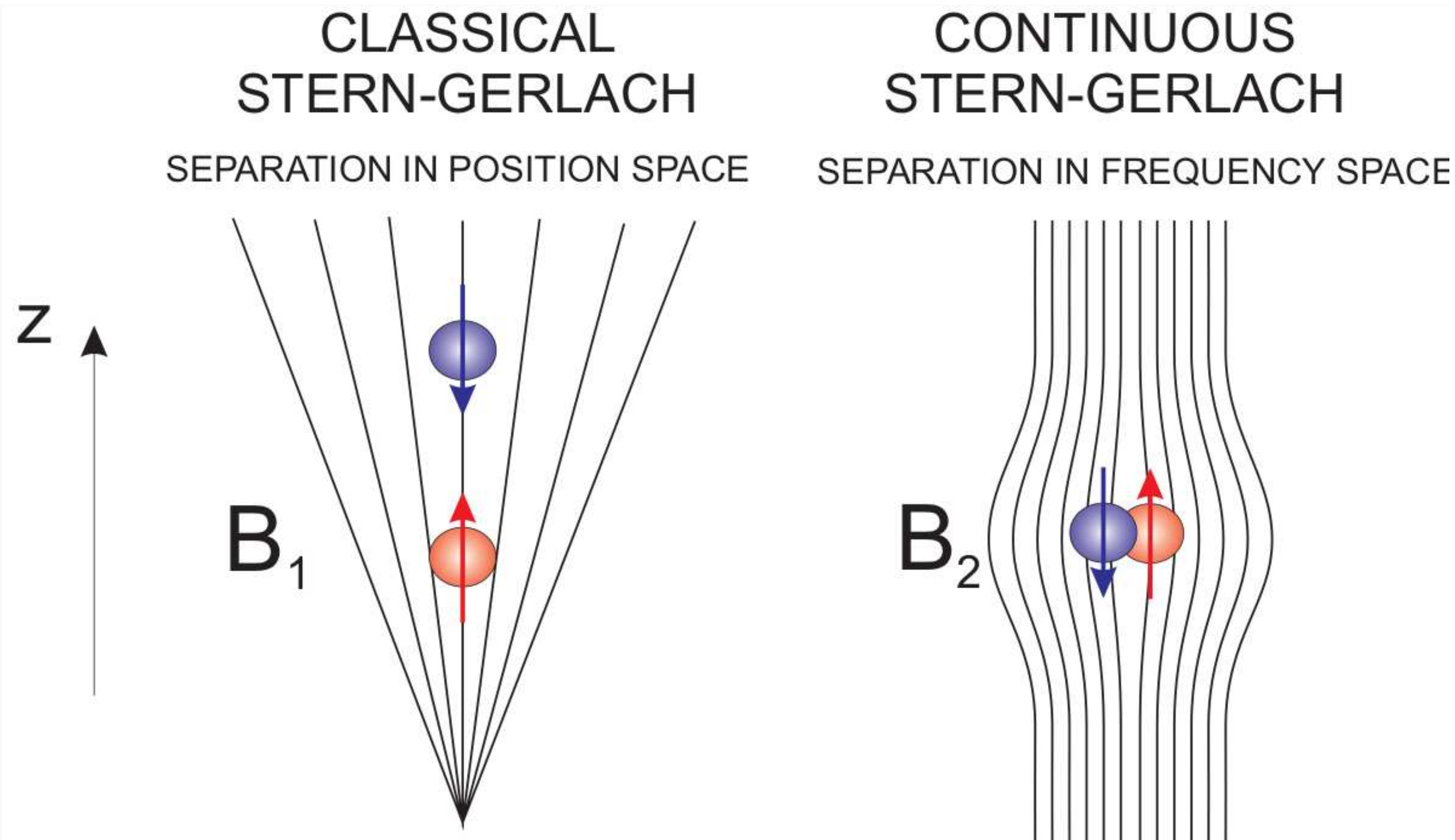
$$H_{z0} + H'_z = \frac{1}{2} m \omega_{z0}^2 z^2 - \mu_{s,c} B_2 z^2$$

$$\frac{\Delta \nu_z}{\nu_z} \approx 2 \times 10^{-8} \left(\frac{g}{2} m_s + n \right)$$

- To produce a cyclotron quantum jump a microwave drive is injected in the trap so that for 20% of the time is inducing a transition from n=0 to n=1
- A successful quantum jump is observed by measuring a tiny shift of the axial frequency

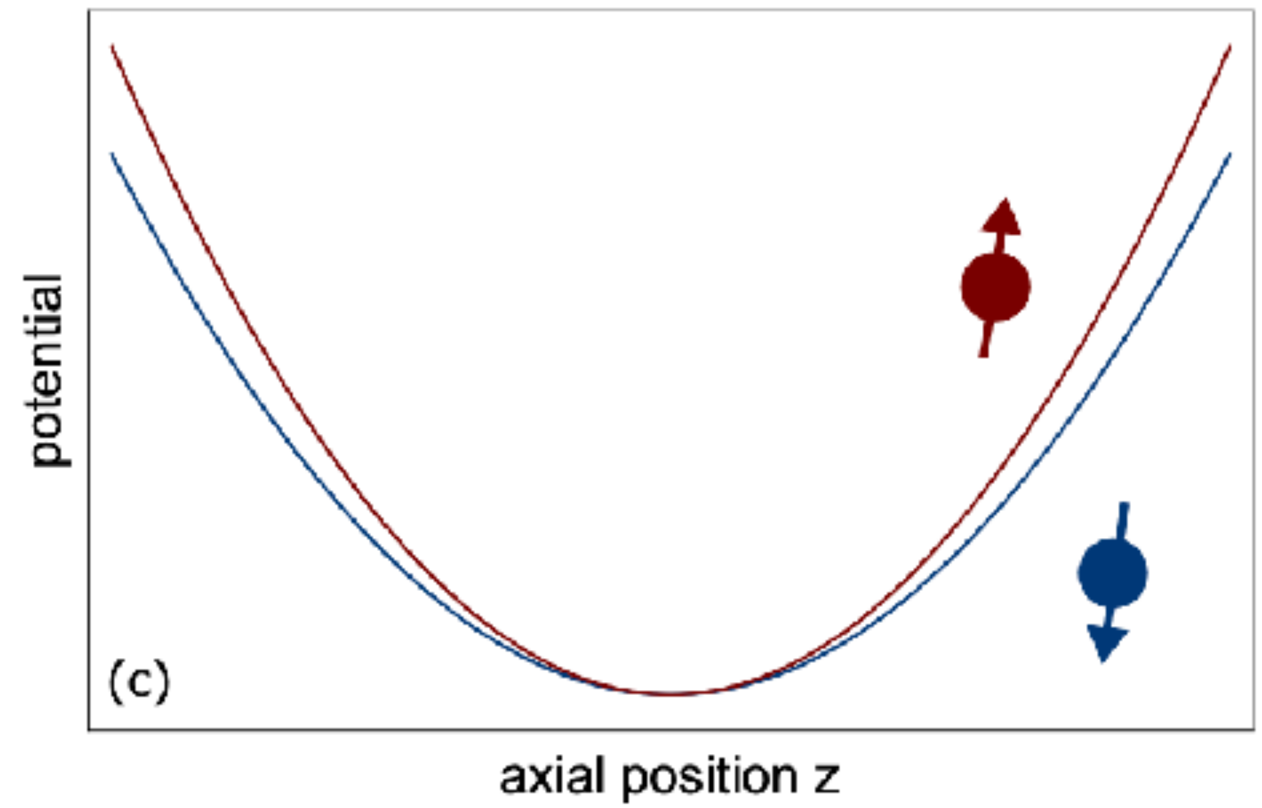


Classical- and continuous Stern-Gerlach-effect



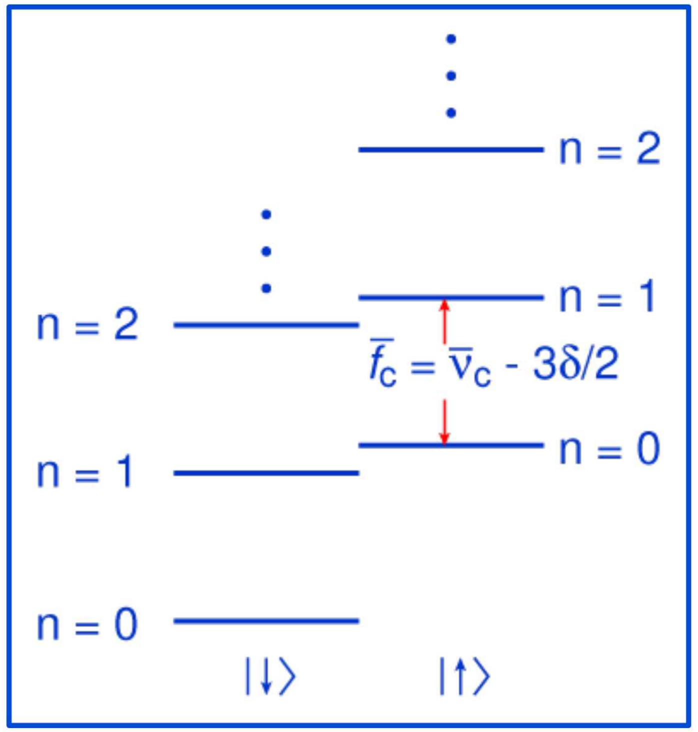
$$\Delta z = \frac{\mu L^2}{2KE} B_1 \qquad \Delta\omega_z = \frac{\mu}{m\omega_z} B_2$$

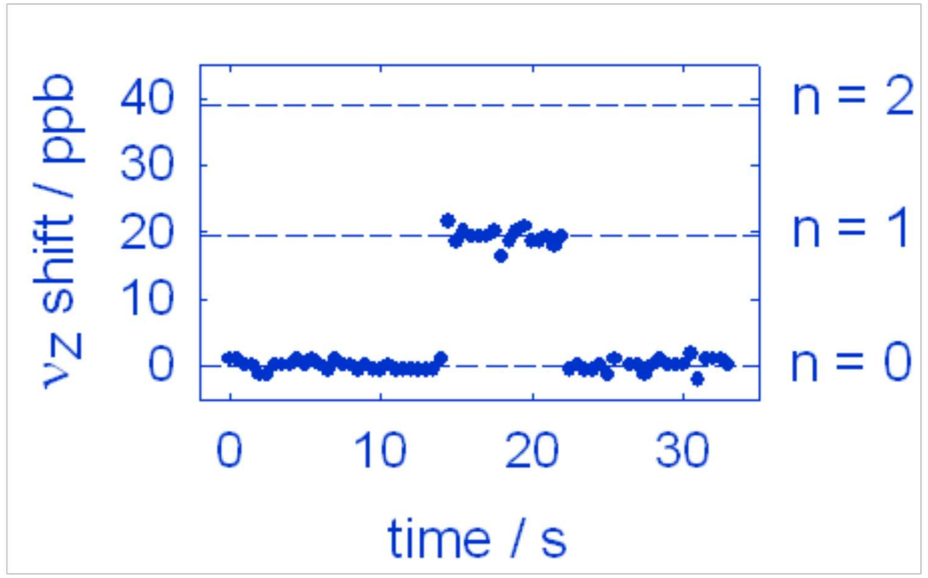
- Axial frequencies are modified depending on the spin state



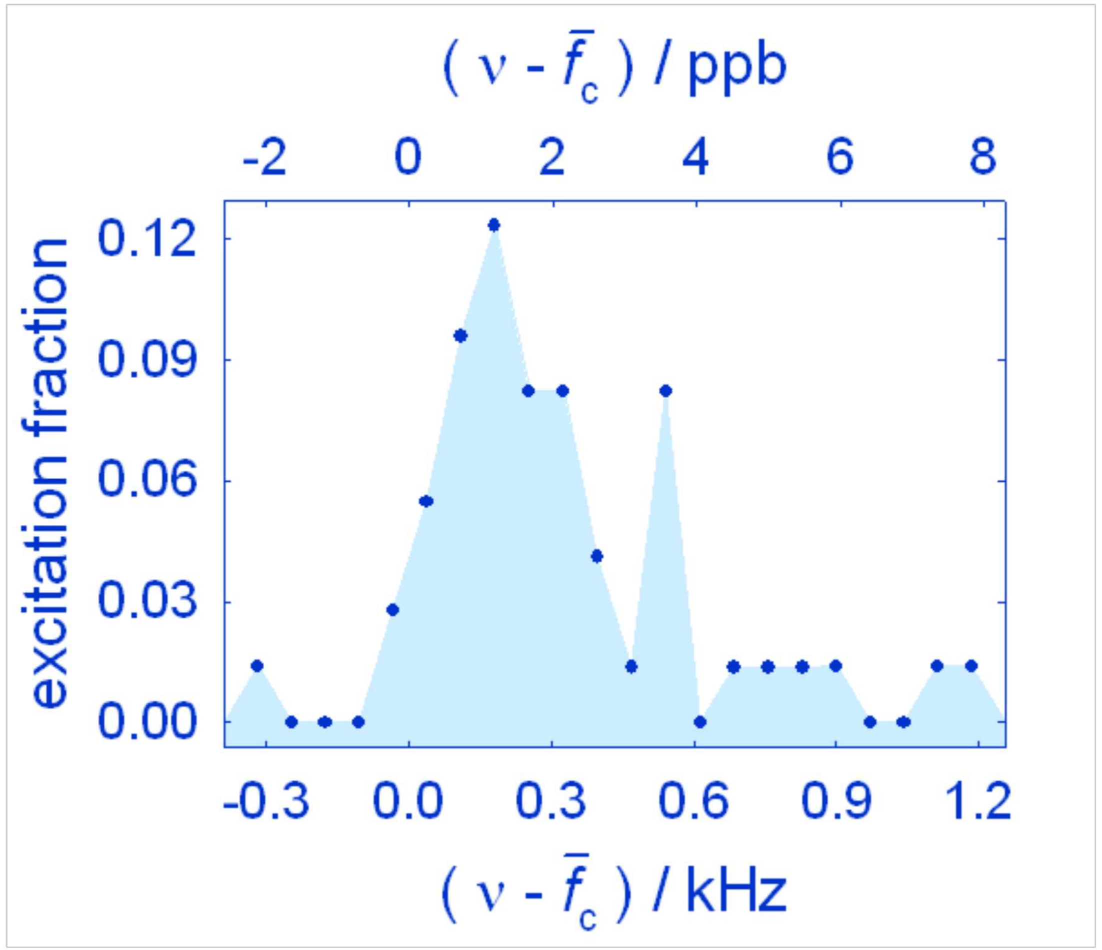
- With axial measurement in the analysis trap, the spin states can be analyzed

Quantum jumps spectroscopy: Cyclotron jumps





- With the e^- in the $|0,\uparrow\rangle$ state, pulse the cyclotron drive (150 GHz)
- Look for excitations to n = 1
- Make a histogram of excitations versus frequency



Must mention: electron g-2

Measurement of the Electron Magnetic Moment

X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]

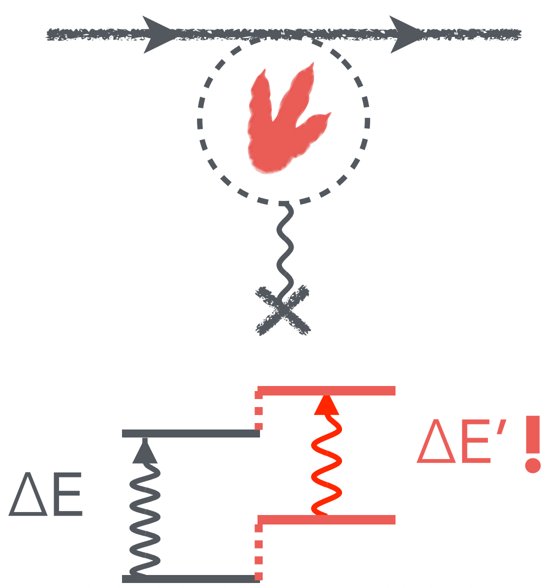
[1] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Center for Fundamental Physics, Northwestern University, Evanston, Illinois 60208, USA*

(Dated: September 28, 2022)

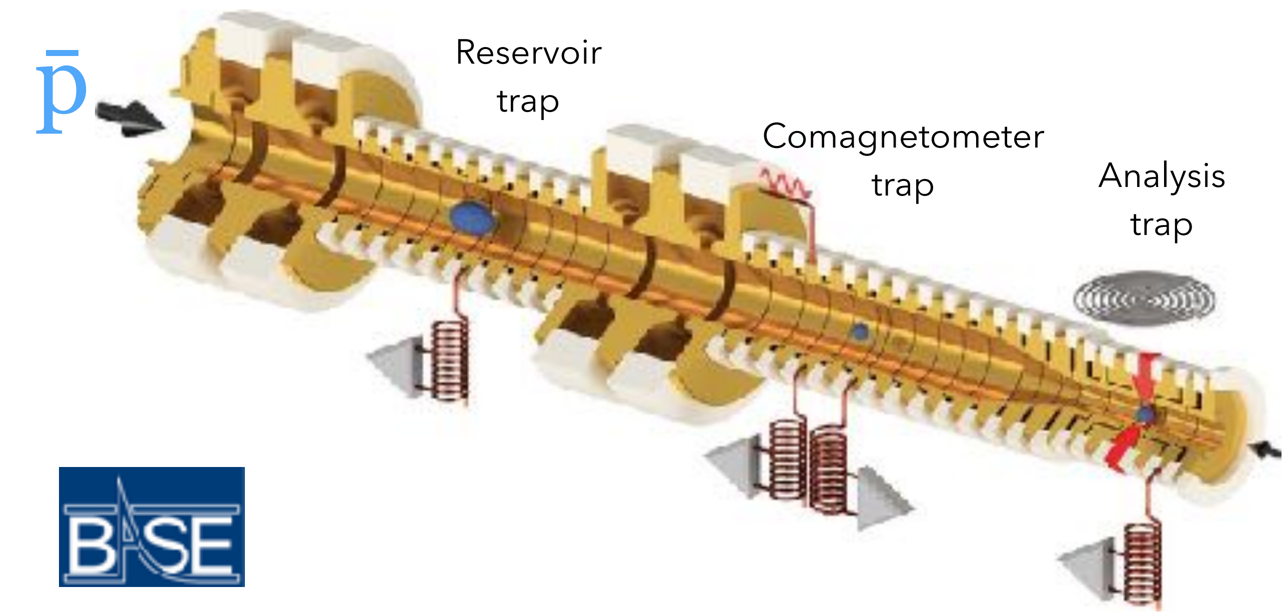
The electron magnetic moment in Bohr magnetons, $-\mu/\mu_B = 1.001\,159\,652\,180\,59\,(13)\;[0.13\text{ ppt}]$, is consistent with a 2008 measurement and is 2.2 times more precise. The most precisely measured property of an elementary particle agrees with the most precise prediction of the Standard Model (SM) to 1 part in 10^{12}, the most precise confrontation of all theory and experiment. The SM test will improve further when discrepant measurements of the fine structure constant α are resolved, since the prediction is a function of α. The magnetic moment measurement and SM theory together predict $\alpha^{-1} = 137.035\,999\,166\,(15)\;[0.11\text{ ppb}]$

arXiv:2209.13084v1

BASE experiment



Single antiproton in trap, compared to proton: Baryon Antibaryon Symmetry Experiment: **BASE @ CERN**

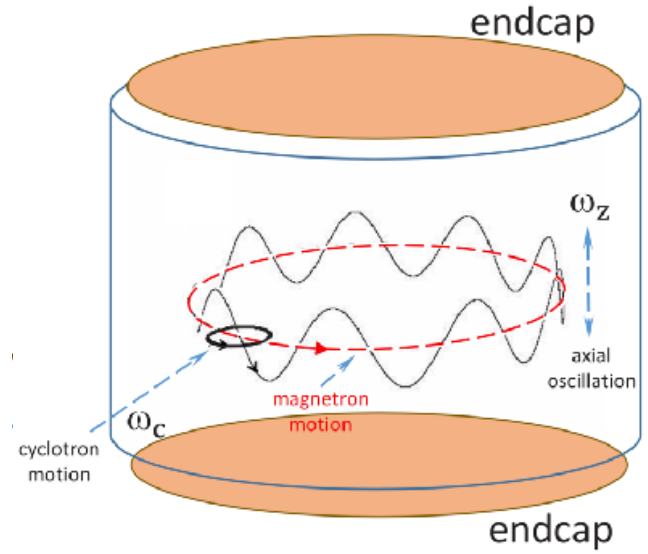


Measurement of the cyclotron frequency:

$$\omega_c \sim \frac{Q_{\bar{p}}}{m_{\bar{p}}} \cdot B$$

Spin-precession (Larmor) frequency:

$$\omega_L \sim \frac{g_{\bar{p}}}{2} \frac{Q_{\bar{p}}}{m_{\bar{p}}} B \rightarrow g_{\bar{p}} = \frac{2\omega_L}{\omega_c}$$



Result: comparison of the p and p̄ Q/m ratio and g-factor (magnetic moments:)

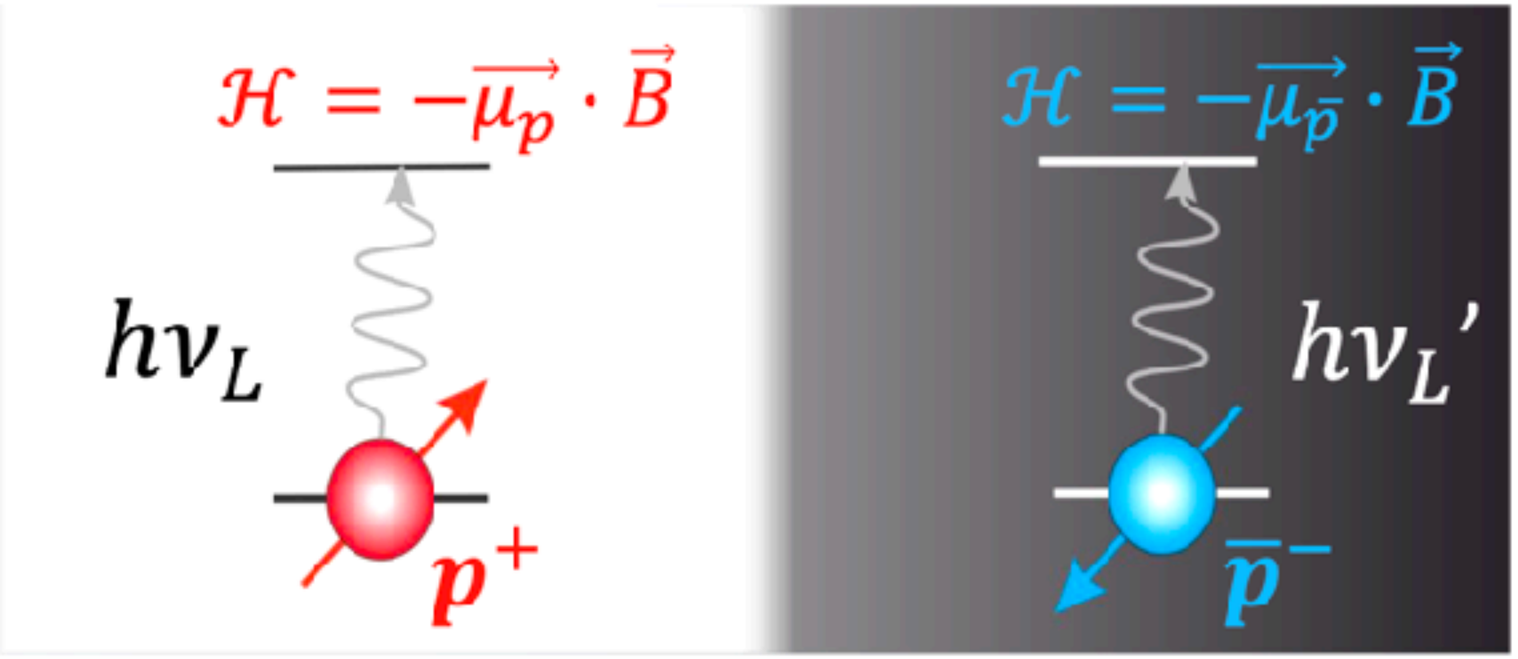
$$\frac{g_{\bar{p}}}{2} = 2.7928473453(30)$$

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} + 1 = 3(16) \times 10^{-12}$$

Nature, 524 196–199, (2015)
Nature 550, 371 (2017)
Nature 601 53-57 (2022)

Single antiproton / proton in a Penning trap

Fundamental properties of conjugate particles/antiparticles are supposed to be identical.

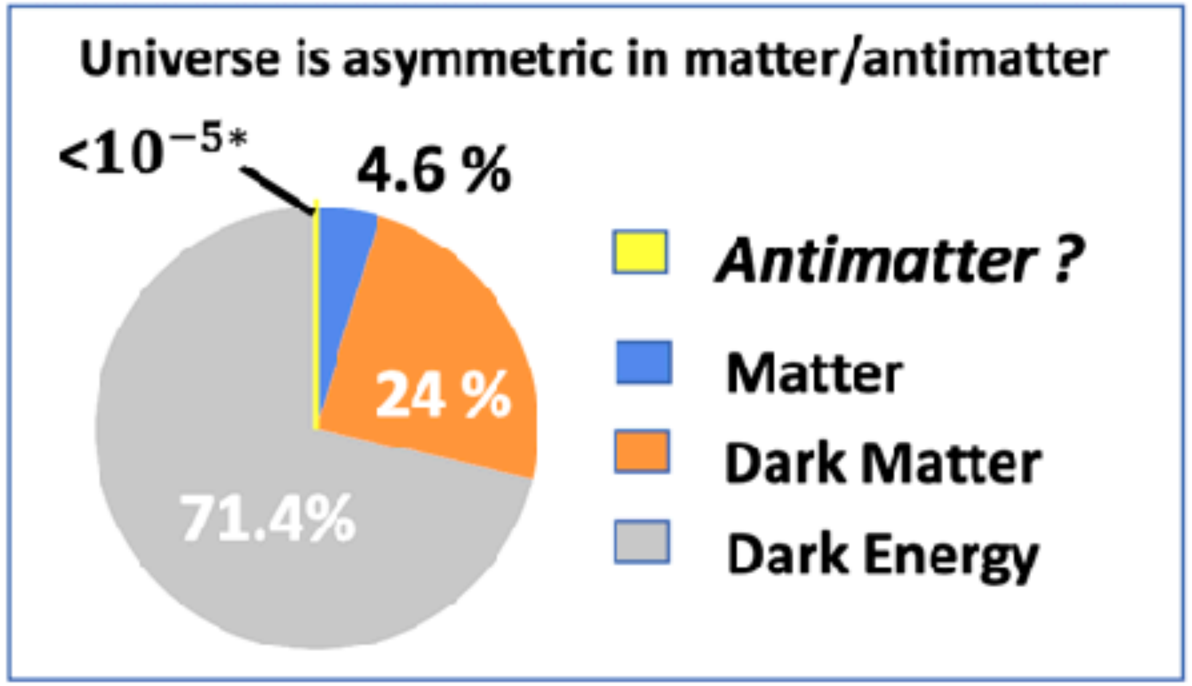


Test of fundamental symmetries:
CPT invariance is linked to Lorentz-invariance and the construction of Quantum Field Theory.

M. Charlton, S. Erikson, G. M. Shore, "Antihydrogen and Fundamental Physics", Springer Verlag, ISBN 978-3-030-51713-7 (2020).

The matter excess in the universe is not understood.
Antimatter abundance is irrelevant on cosmic scales,
e.g. composition of high-energy cosmic rays,
absence of annihilation radiation

R. Kappl et al., J. Cosmology Astropart. Phys. 09, 051 (2014).
S. Dupourqué, L. Tibaldo, P. von Ballmoos, Phys. Rev. D 103, 083016 (2021).

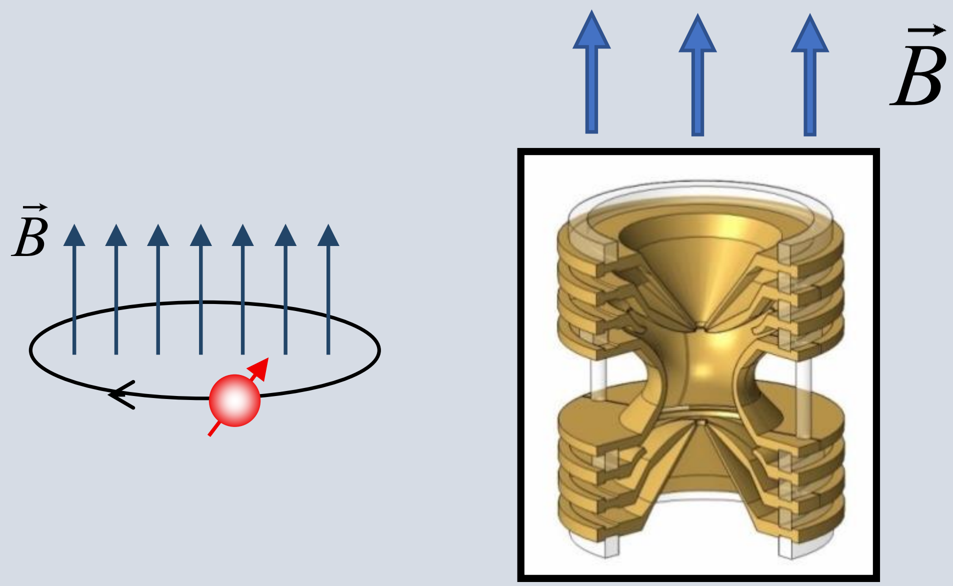


No process that is asymmetric in the production/annihilation of particles and antiparticles has been observed.

Usual measurements: charge to mass & magnetic moment

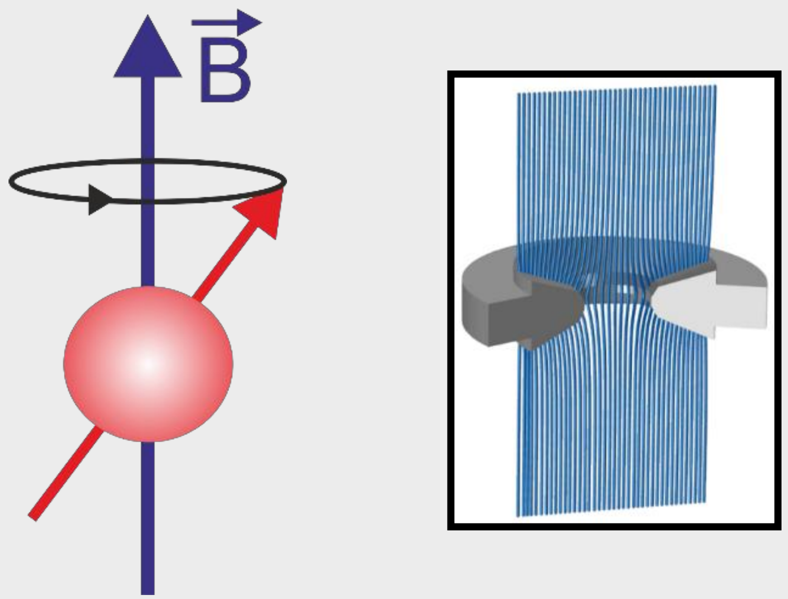
Smorra

Cyclotron Frequency



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

Larmor Frequency



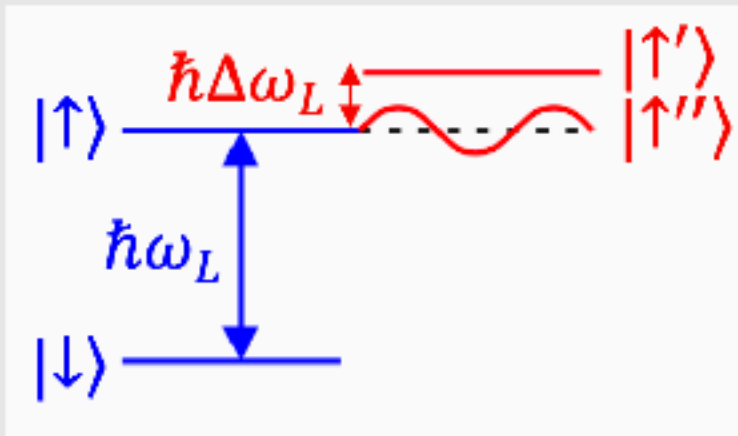
$$\omega_L = g \frac{e}{2m_p} B$$

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

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

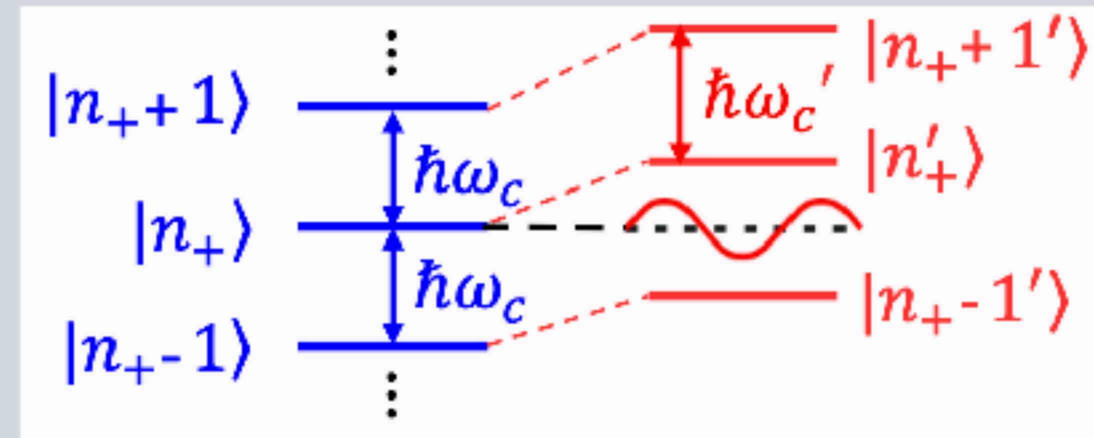
Or any other ratio of masses

Larmor Frequency modifications



Lorentz- and CPT-violation
Axion wind / Axion-like particles
(Permanent electric dipole moment)

Cyclotron Frequency modifications



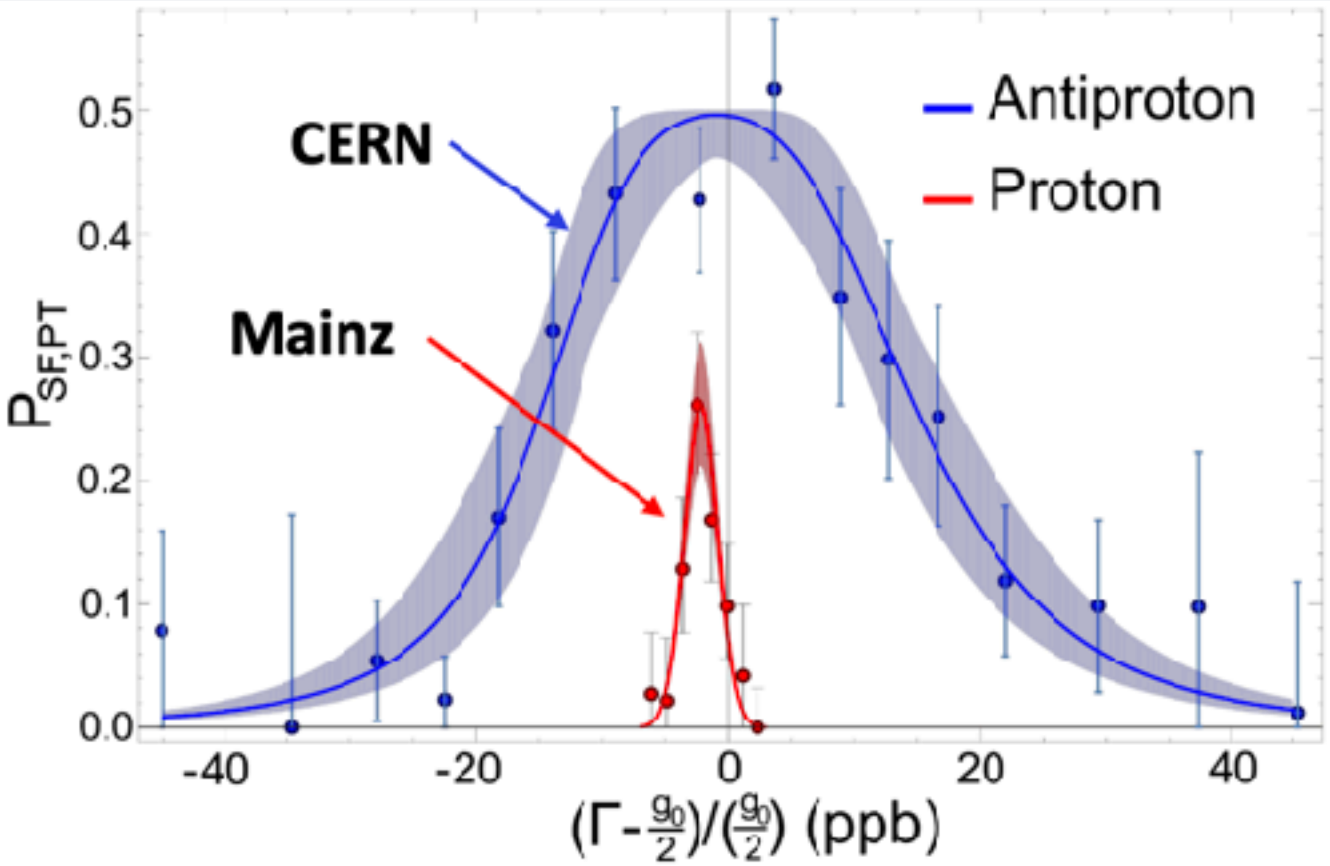
Lorentz and CPT-violation
Antiproton gravitation anomalies

$$\Delta\omega_L = \frac{\Delta g}{2}\frac{q}{m}B + \Delta\omega_{Axion}\sin(\omega_a t) + d_{EDM}\cdot\left|\vec{E}\right|/\hbar$$

$$\Delta\omega_C = \Delta\left(\frac{q}{m}\right)B + (3\alpha - 2)\frac{U_{grav}}{c^2}$$

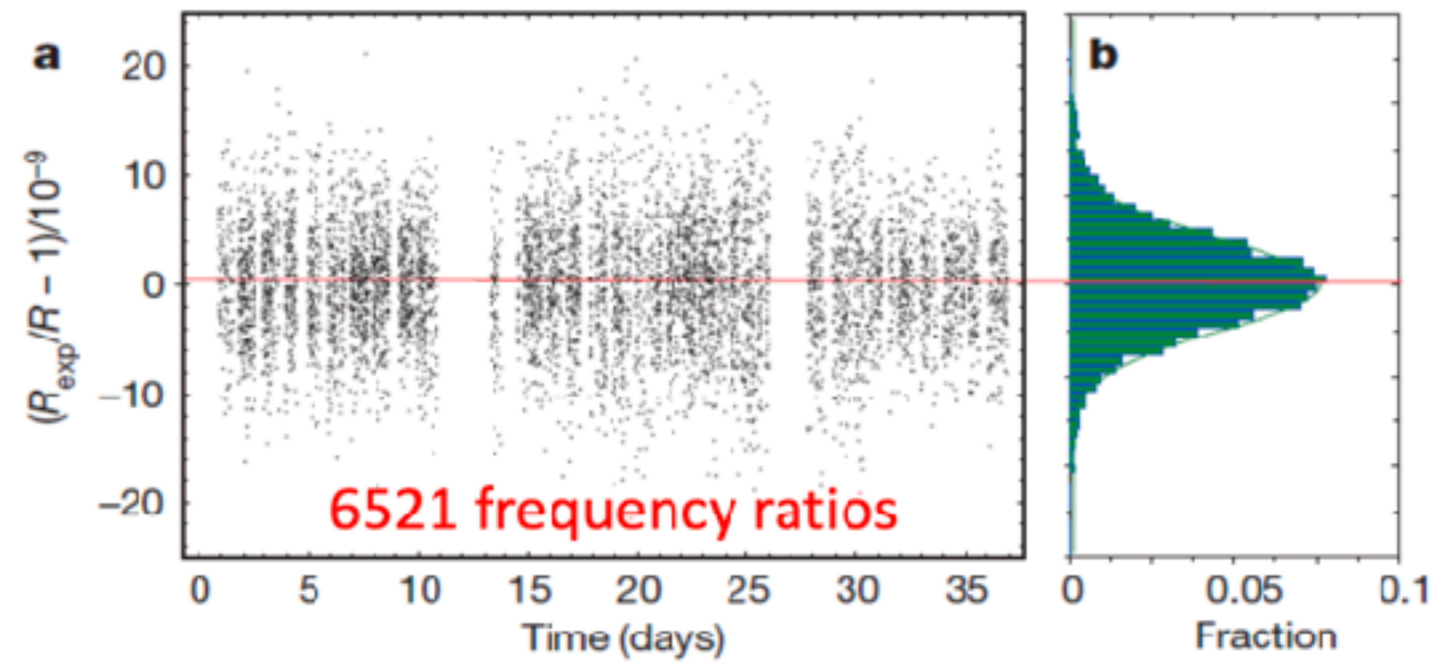
Standard Model Extension: Y. Ding et al., Phys. Rev. D **94**, 056008 (2016).
Axions: P. Graham et al., Ann. Rev. Nucl. Part. Sci. **65**, 485 (2015).
C. Smorra, Y. Stadnik et al., Nature **575**, 310-314 (2019).
EDM: D. Budker, Y. Semertzidis et al., (in preparation).
Antimatter gravitation: R. J. Hughes et al., Phys. Rev. Lett. **66**, 854 (1991).

First generation precision measurements with BASE



$$\left|\frac{g_p}{2}-\frac{g_{\bar{p}}}{2}\right| < 0.3\ (8.3)\ 10^{-9}$$

C. Smorra et al., Nature **550**, 371 (2017).
G. Schneider et al., Science **358**, 1081-1084 (2017).



$$\frac{(q/m)_{\bar{p}}}{(q/m)_p}+1=1(64)(26)\times 10^{-12}$$

S. Ulmer et al., Nature **524**, 196 (2015).
G. Gabrielse, Int. J. Mass Spectr. 251, 273-280 (2006).

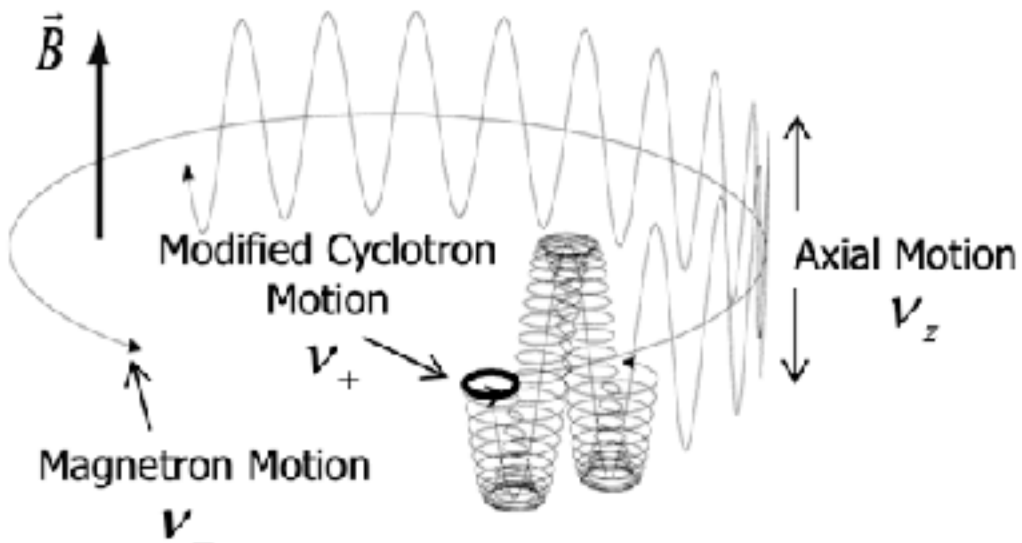
$$\frac{\omega_{L,p/\bar{p}}}{\omega_{c,p/\bar{p}}}=\frac{g_{p/\bar{p}}}{2}=\pm\frac{\mu_{p/\bar{p}}}{\mu_N}$$

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}}=\frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

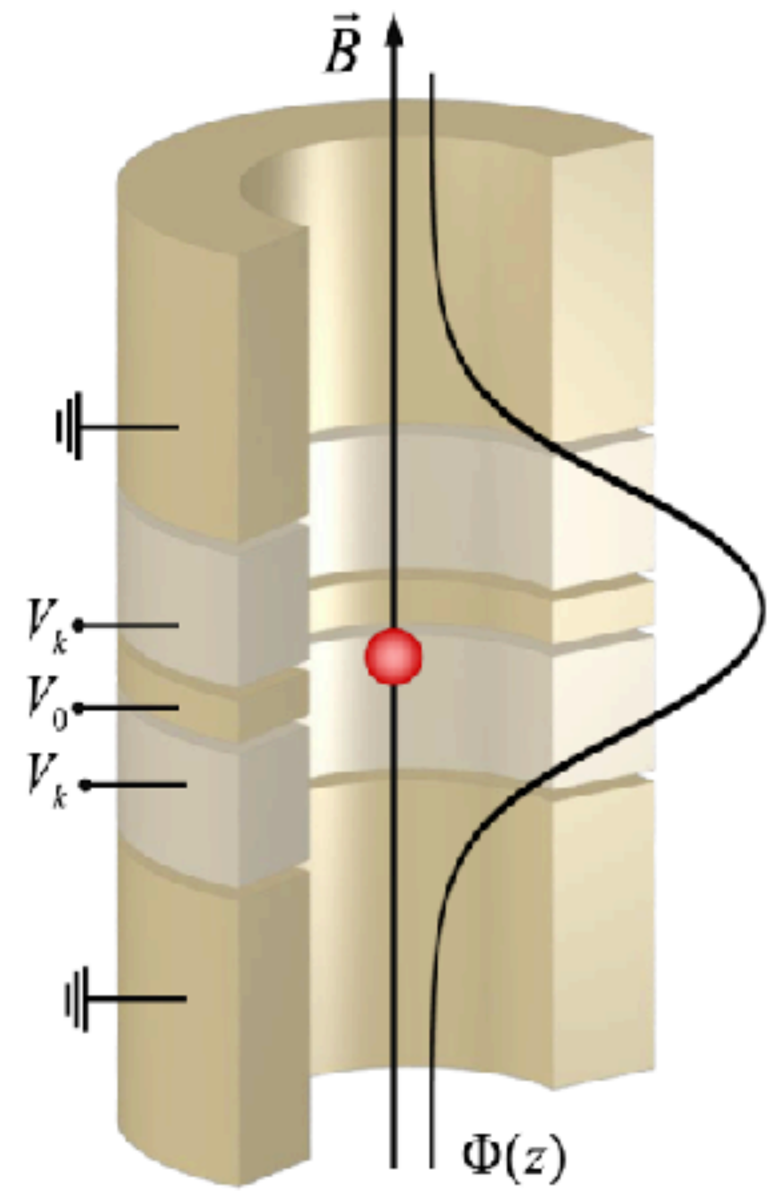
Single antiproton / proton in a Penning trap

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

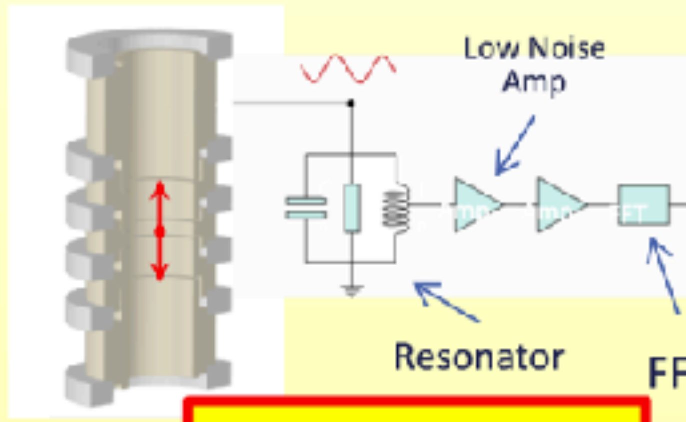
axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$



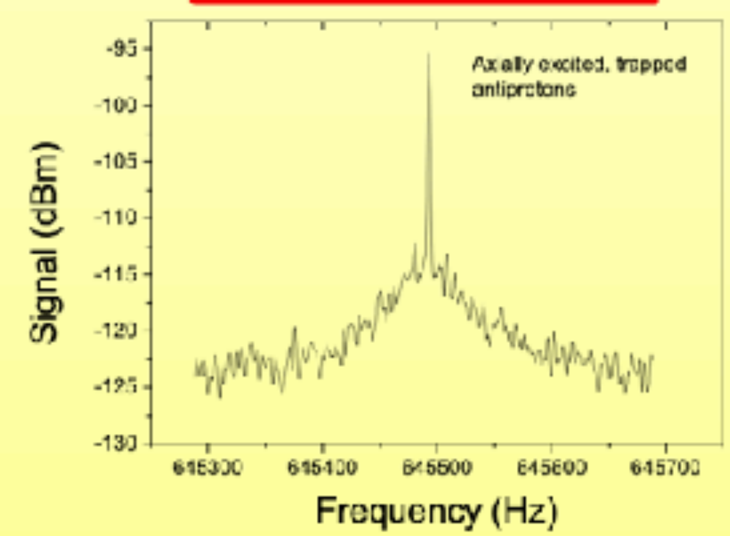
Axial	$\nu_z = 680\,\mathrm{kHz}$
Magnetron	$\nu_- = 8\,\mathrm{kHz}$
Modified Cyclotron	$\nu_+ = 28{,}9\,\mathrm{MHz}$

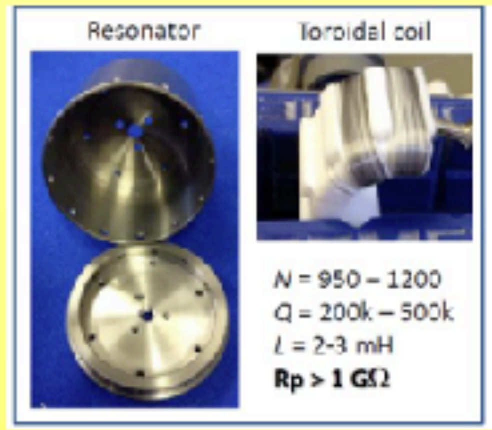


Detection



currents: 1 fA





Invariance-Relation

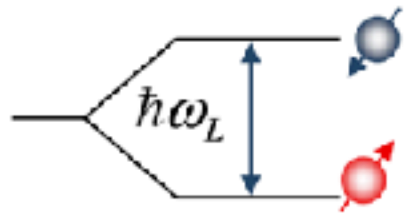
$$\nu_c = \sqrt{\nu_+^{\,2} + \nu_-^{\,2} + \nu_z^{\,2}}$$

Cyclotron Frequency

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

Cyclotron frequency relates measurable quantity to fundamental properties of trapped charged particle

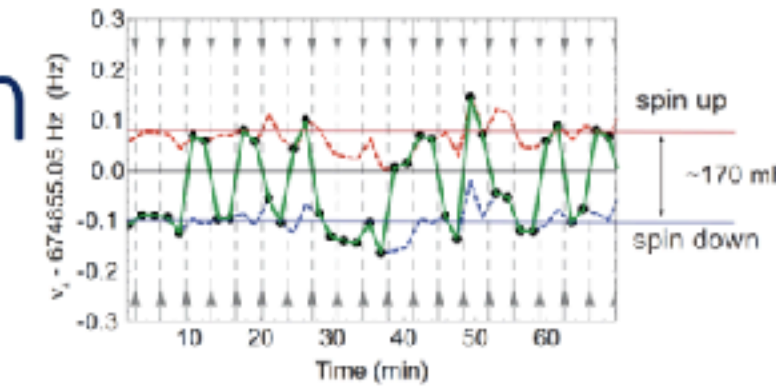
Slides: S. Ulmer



difficult

Continuous Stern Gerlach Effect

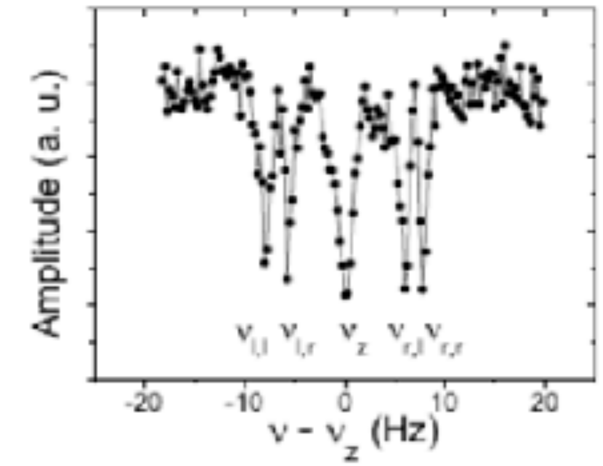
C. Smorra *et al.*, Phys. Lett. B 769, 1 (2017)



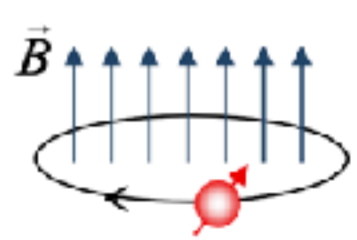
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

straight forward

Image Current Measurements



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



Slides: S. Ulmer

Continuous Stern-Gerlach effect with antiprotons

Slides: S. Ulmer

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 function of spin state

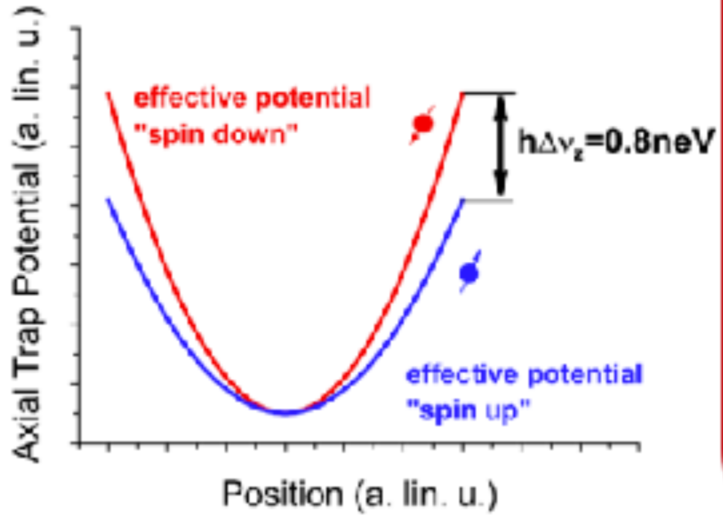
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

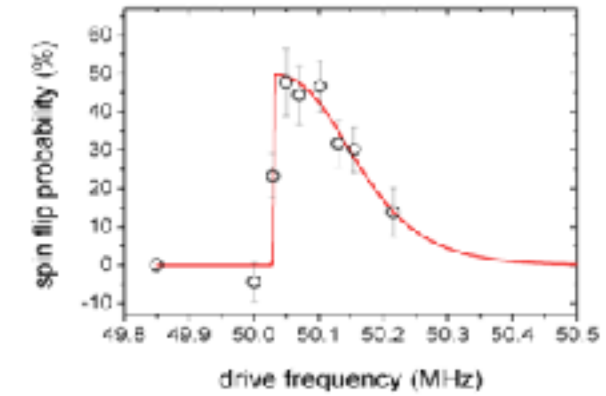
$$\Delta\nu_z \sim 170\ mHz$$



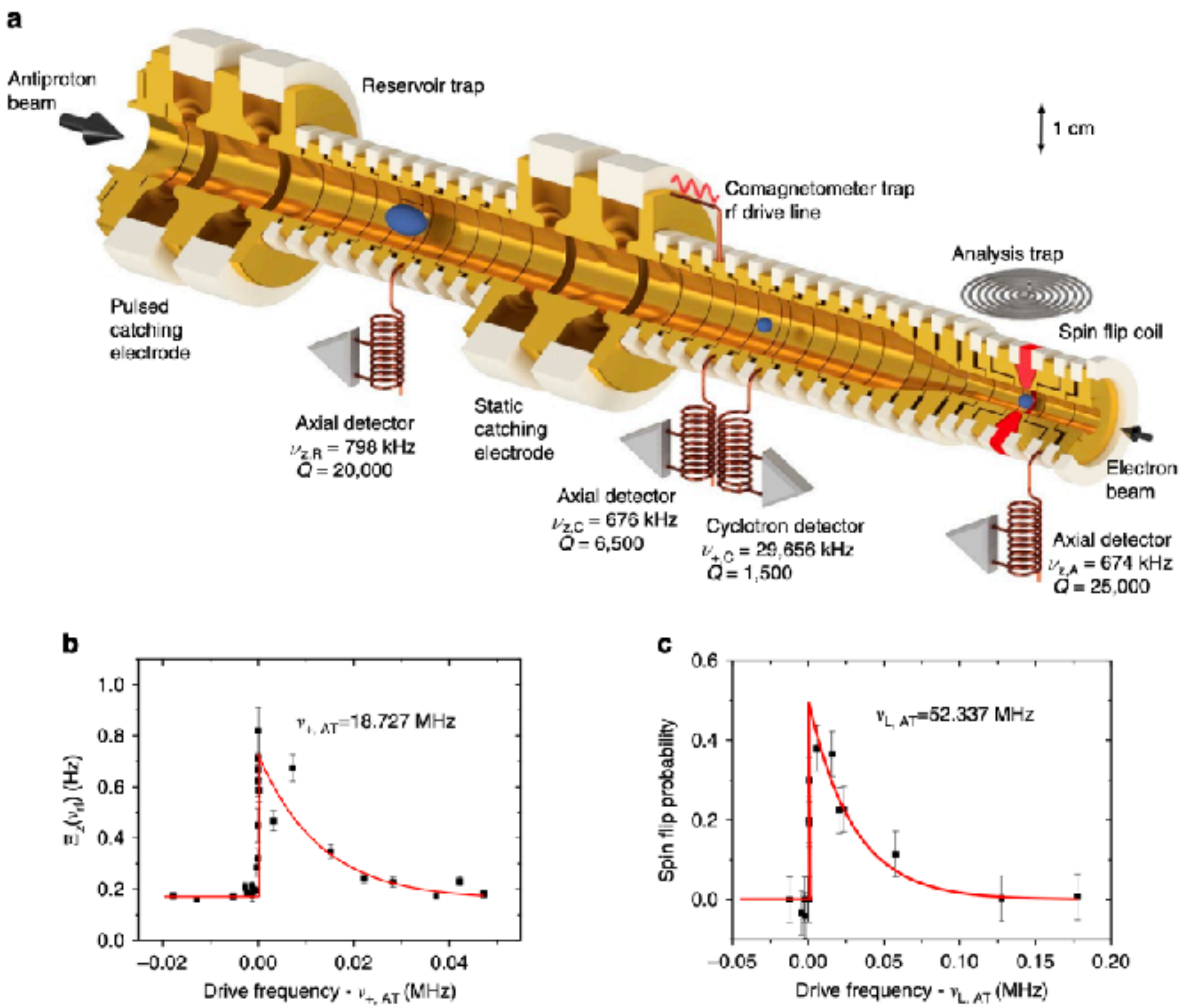
Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement



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

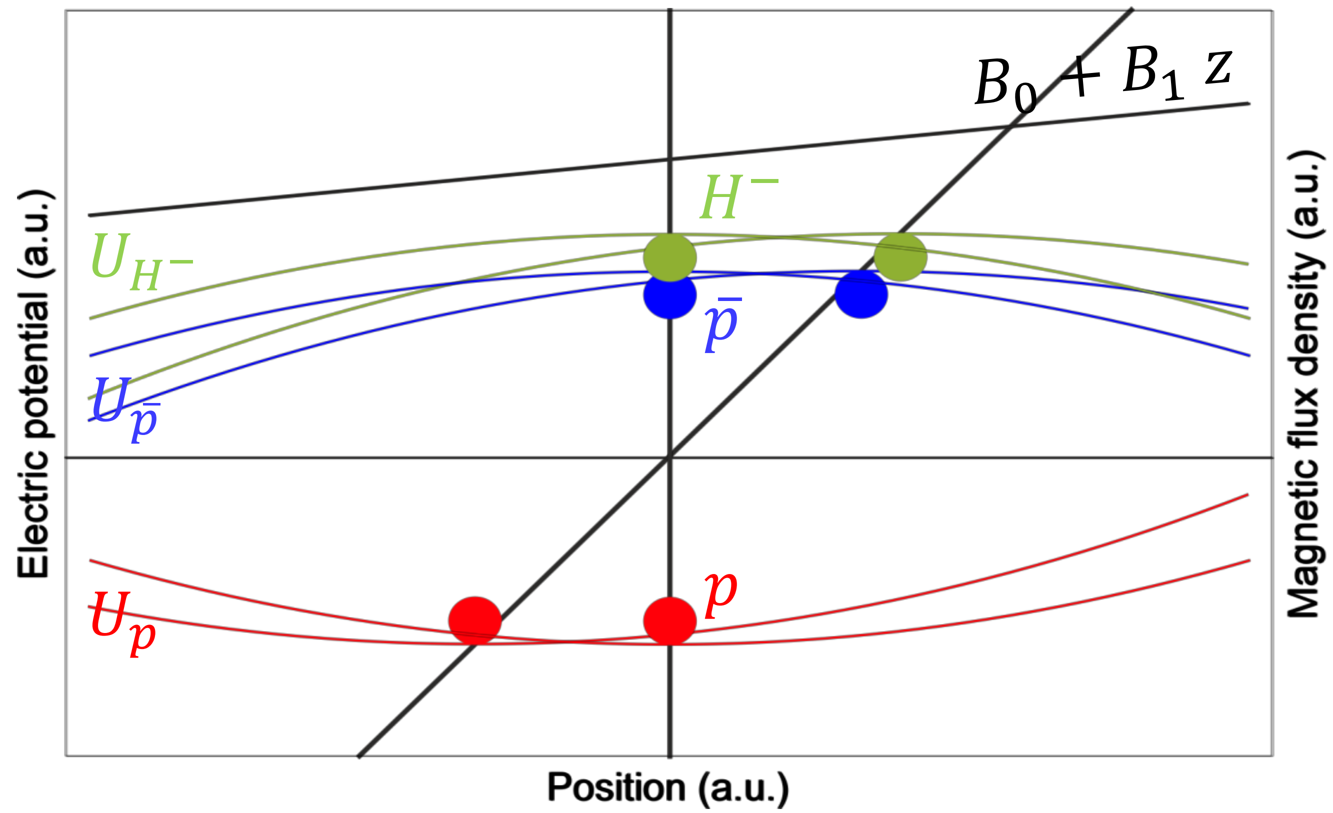


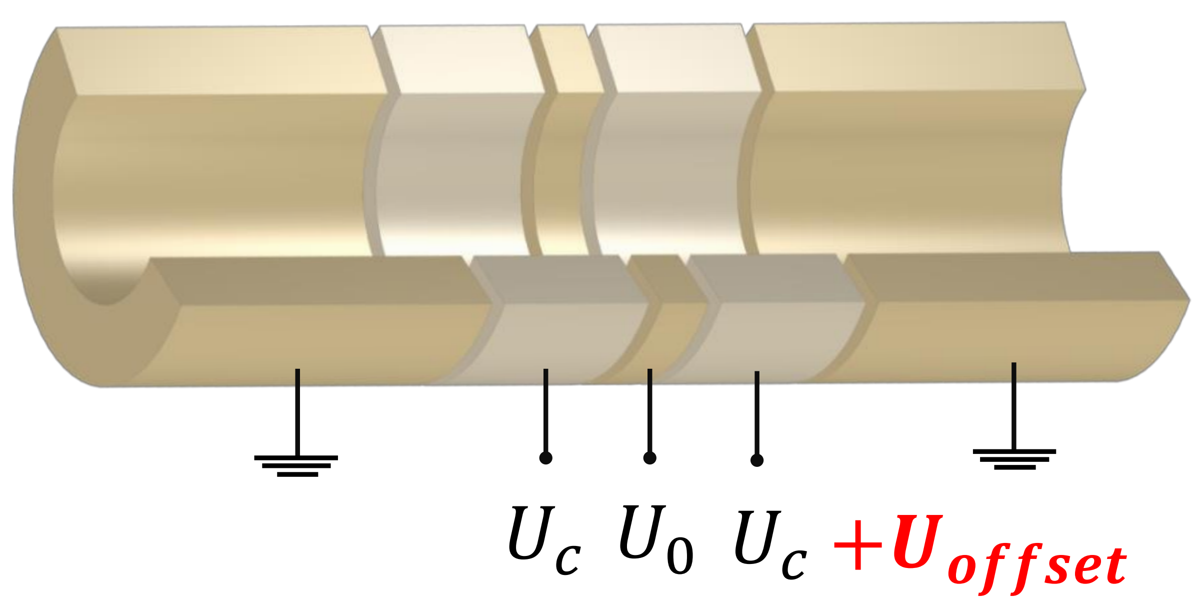
DOI: 10.1038/ncomms14084

Two particle: Larmor partilce (L) in analysis trap, cyclotron particle (C) in precision trap. Measurement cycle (ca 900 s):

1. Initialization of the spin state of (L) in the analysis trap with alternating spin-flip drives and axial frequency measurements
2. Measurement of the cyclotron frequency of (C) in 3 consecutive times
3. Particle (C) is transversed to the parking electronde
4. Partilce (L) moved into the precision trap, RF spin-flip pulse is initiaded
5. Particle (L) (C) brought back to initial positions
6. Spin state of (L) identified
7. Cyclotron frequency of (C) are measured 3 times

Why reference it to He ions?





- Systematic uncertainties due to the particle position are large (~10^{-9})
- No significant uncertainties in converting the mass ratio

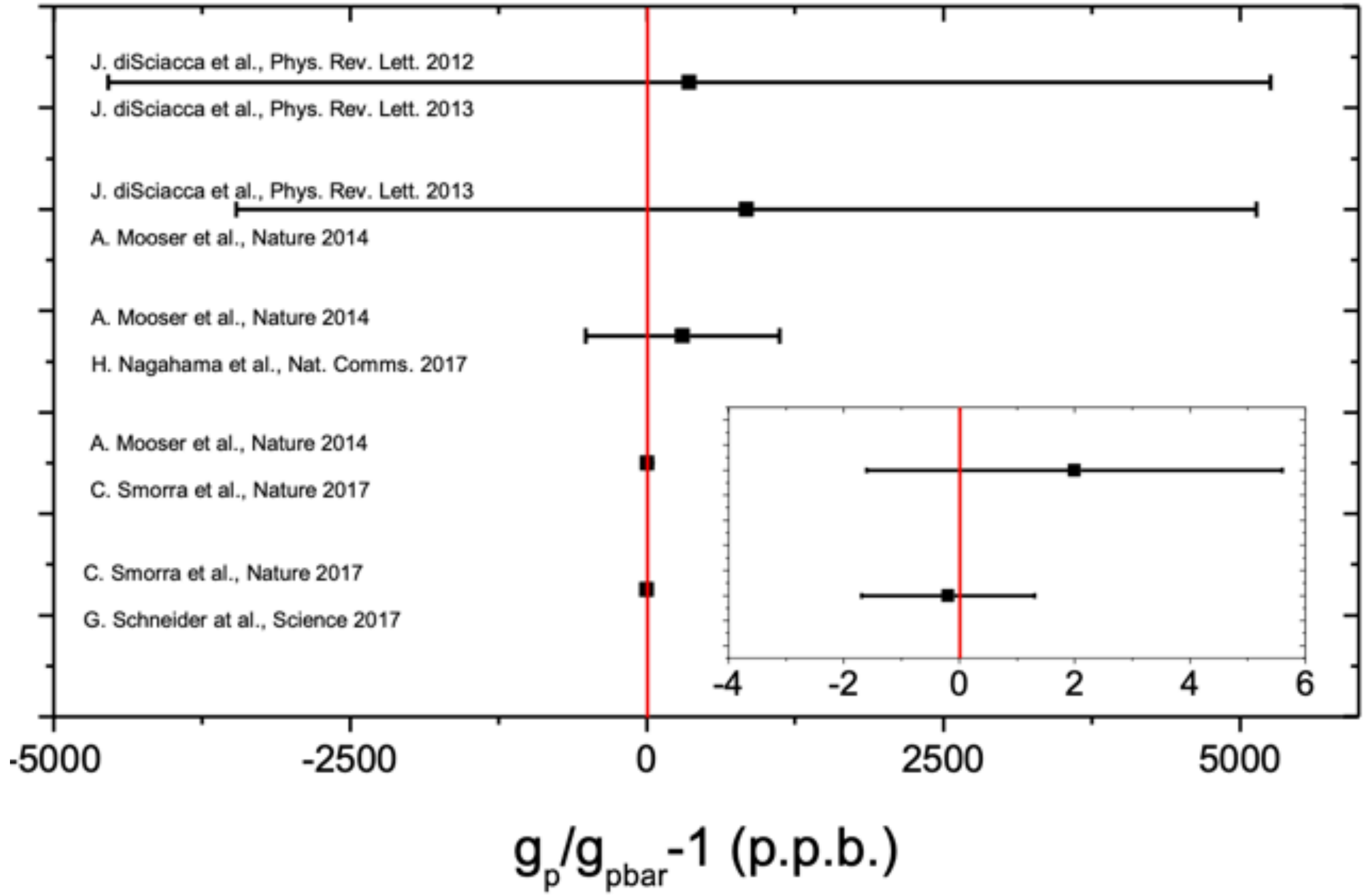
$$\frac{m_{H^-}}{m_p} = (1 + 2\frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p})$$

R_{theo} = 1.0010892187542(2) (0.2 ppt)

- Measure free cyclotron frequencies of antiproton and H^- ion.

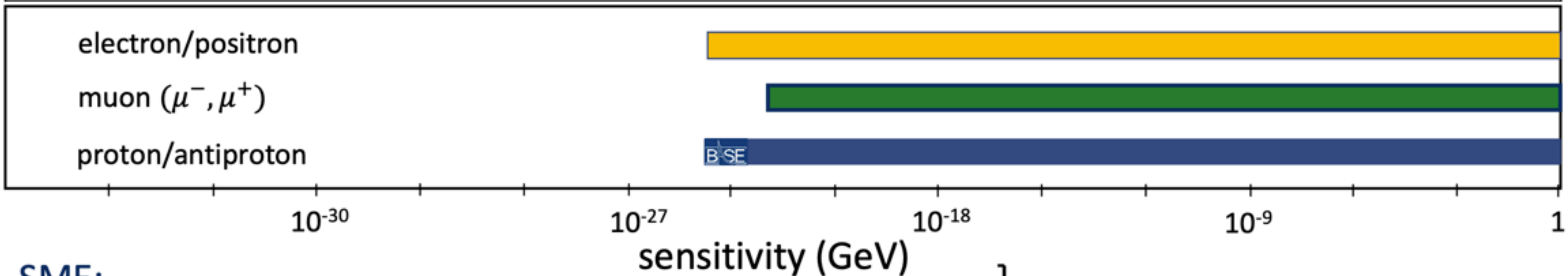
Magnetic moment measurements

Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	CPT $\lvert g_p/g_{\bar{p}} \rvert - 1$	Collaboration
2011	2.792 847 353 (28)	2.786 2 (83)	0.002 4 (29)	Pask (ASACUSA)
2013	2.792 846 (7)	2.792 845 (12)	0.000 000 4 (49)	diSciacca (ATRAP)
2014	**2.792 847 349 8 (93)**	2.792 845 (12)	0.000 000 8 (43)	Mooser(BASE)/diSciacca (ATRAP)
2016	**2.792 847 349 8 (93)**	**2.792 846 5 (23)**	**0.000 000 30 (82)**	**Mooser/Nagahama (BASE)**
2017/1	**2.792 847 349 8 (93)**	**2.792 847 344 1 (42)**	**0.000 000 002 0 (36)**	**Mooser/Smorra (BASE)**
2017/2	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**-0.000 000 000 2 (15)**	**Schneider/Smorra (BASE)**



CPT tests

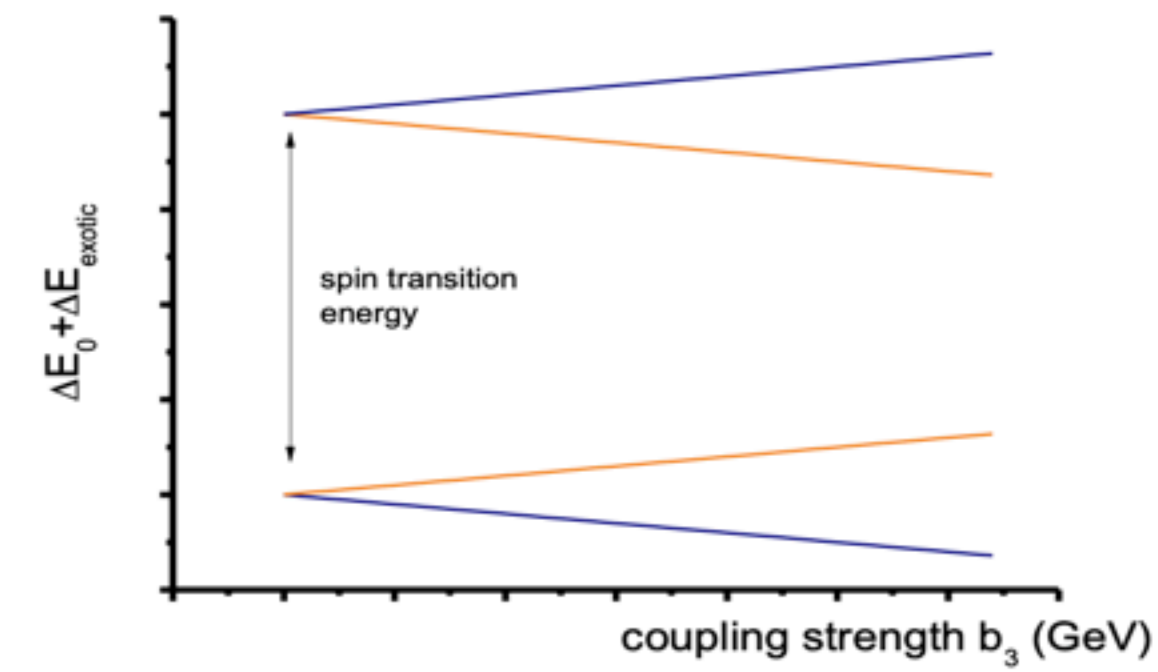
Year	Matter $g/2$	Antimatter $\bar{g}/2$	CPT $\lvert g/\bar{g}\rvert - 1$	System	SME $\lvert b_L\rvert$ (GeV)	$\lvert f_X^0\rvert$ (μ_B)
1987	1.001 159 652 188 9 (43)	1.001 159 652 187 9 (43)	0.000 000 000 000 5 (21)	electron/positron	$6 * 10^{-25}$	$2 * 10^{-12}$
2006	1.001 165 921 5 (11)	1.001 165 920 4 (12)	0.000 000 001 1 (12)	muon (μ^-, μ^+)	$1 * 10^{-23}$	$3 * 10^{-11}$
2017	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**0.000 000 000 2 (15)**	**proton/antiproton**	$5 * 10^{-25}$	$2 * 10^{-12}$



SME:

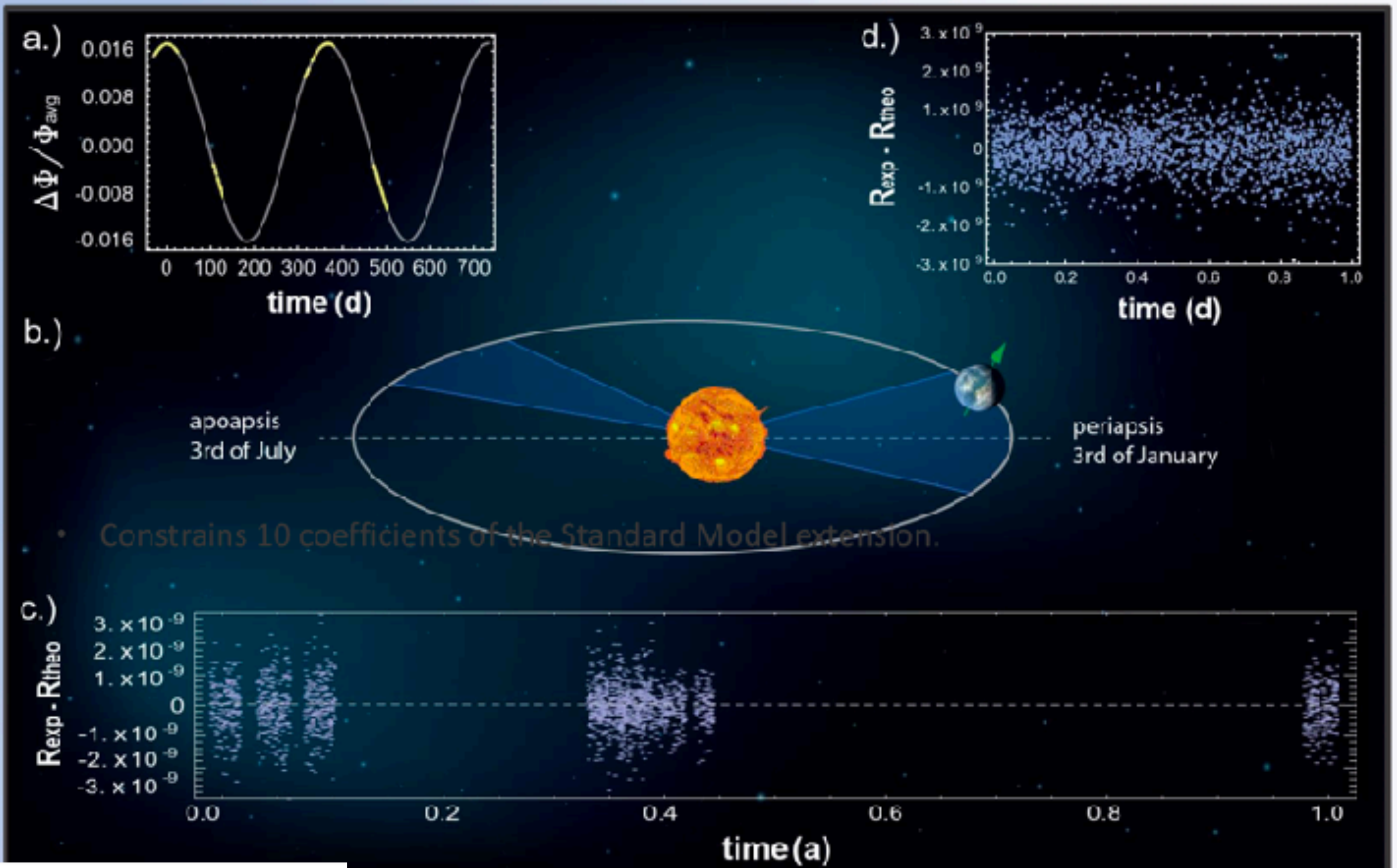
$$\left(i\gamma^\mu D_\mu - m - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu\right)\psi = 0$$

$$b_\mu\gamma_5\gamma^\mu \rightarrow b_x\begin{pmatrix}-\sigma_x & 0\\ 0 & \sigma_x\end{pmatrix}+b_y\begin{pmatrix}-\sigma_y & 0\\ 0 & \sigma_y\end{pmatrix}+b_z\begin{pmatrix}-\sigma_z & 0\\ 0 & \sigma_z\end{pmatrix}$$



Recent improvements

Improved comparison of the proton/antiproton q/m ratios: $\left(\frac{q_{\bar{p}}}{m_{\bar{p}}}\right) / \left(\frac{q_p}{m_p}\right) = -1.000\,000\,000\,003\,(16)$



Constrain of 10 coefficients of the Standard Model Extension:

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

Differential test for gravitational anomalies of antiprotons:

$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{sun}}}{c^2}(\alpha_{g,D} - 1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right)$$

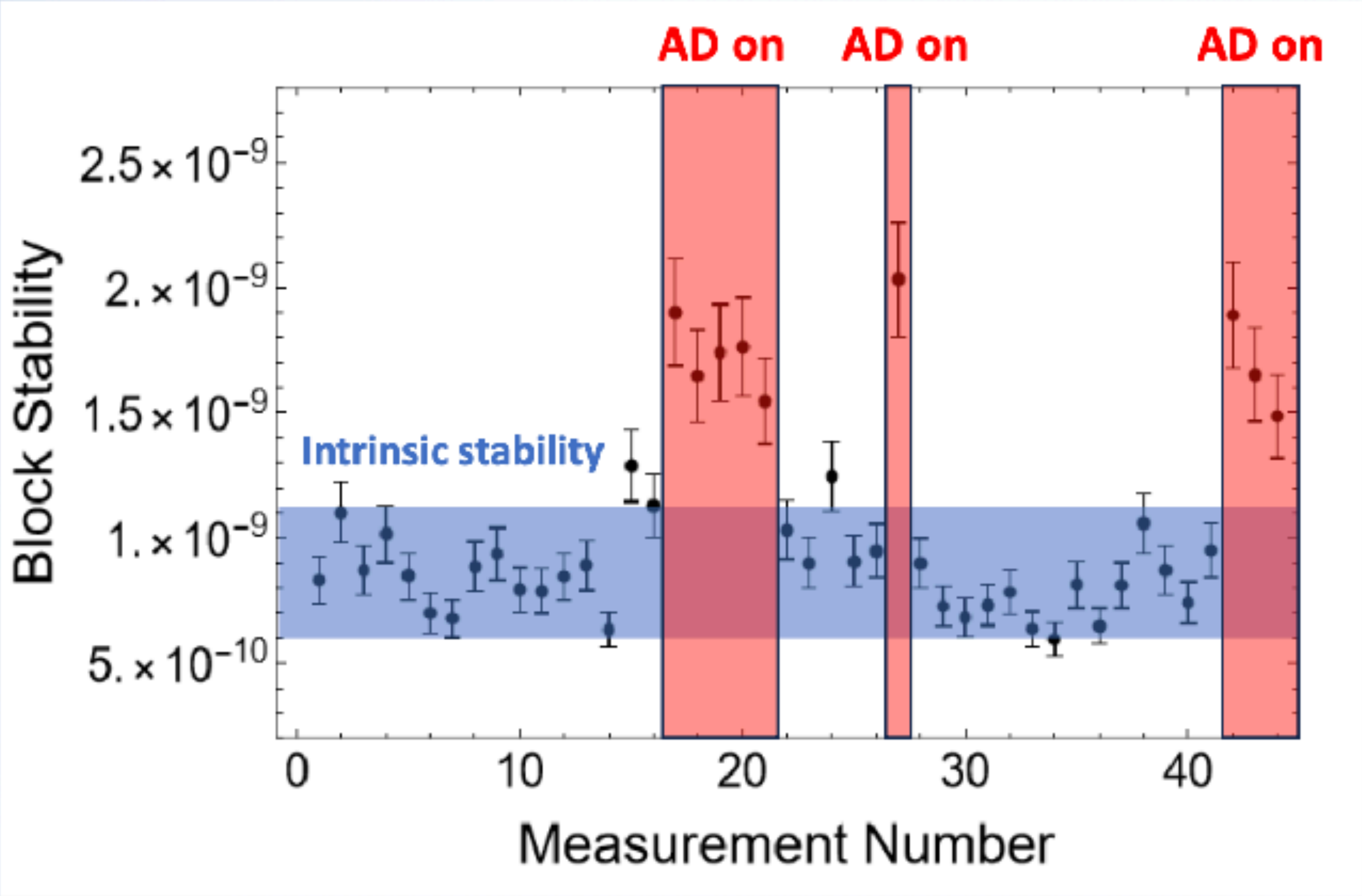
Property	Limit
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

M. Borchert et al., Nature **601**, 53–57 (2022).

Slides: Smorra

Limitations by magnetic field fluctuations

Impact on frequency ratio measurements in the BASE-CERN apparatus



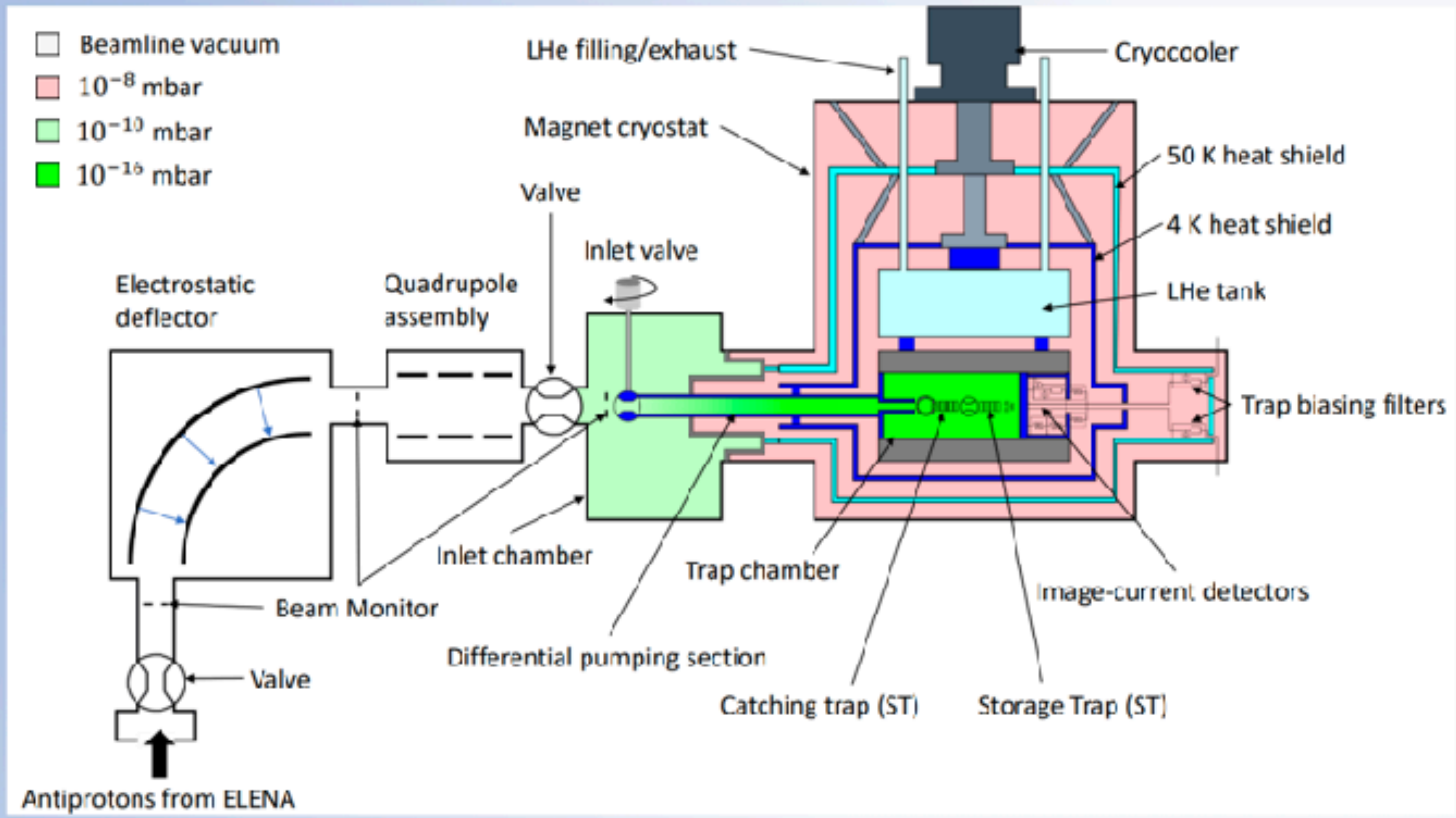
About 45 mins per block,
40 frequency measurements

Block stability of cyclotron frequency shifts:

$$\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\nu_{c,2i} - \nu_{c,2i-1}}{\nu_{c,2i}}\right)^2}$$

BASE-Step: antiprotons outside BASE

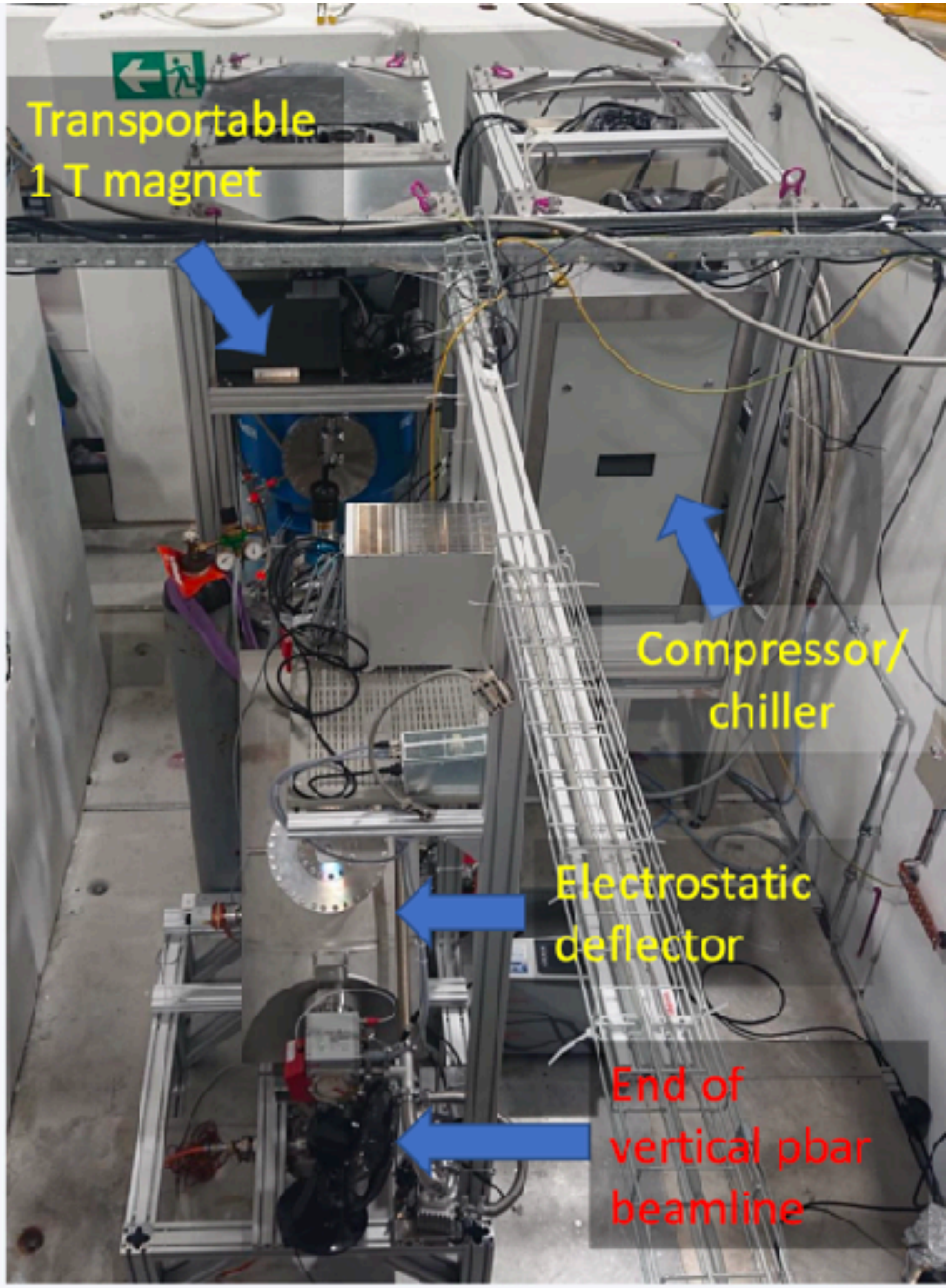
Equipment to receive and transport antiprotons



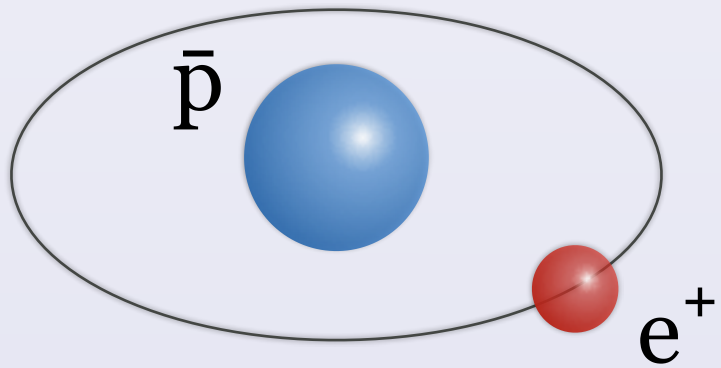
Basis is the reservoir trap system developed in BASE, but:

- The trap system is inside a transportable superconducting magnet
- The trap can has an open injection/ejection channel for antiprotons

C. Smorra et al., Int. J. Mass Spectr. 389, 10-13 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).



Precision experiments with antihydrogen



Formation of antihydrogen

1) Direct spontaneous radiative recombination

$$\mathrm{\bar{p}} + \mathrm{e}^{+} \rightarrow \mathrm{\bar{H}} + h\nu, \quad \Gamma_{\mathrm{srr}} \sim n_e T_e^{-0.63}$$

Dipole allowed free-bound transition that favours capture into strongly bound state.

2) Three body recombination

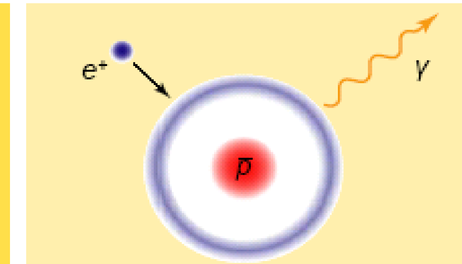
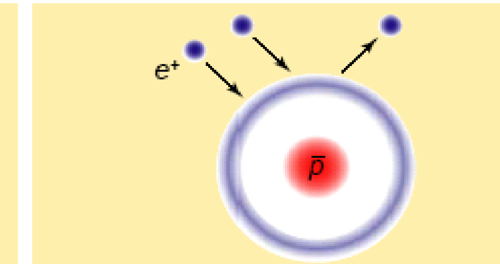
$$\mathrm{\bar{p}} + \mathrm{e}^{+} + \mathrm{e}^{+} \rightarrow \mathrm{\bar{H}} + \mathrm{e}^{+}, \quad \Gamma_{\mathrm{tbr}} \sim n_e^2 T_e^{-4.5}$$

Elastic encounter of 2 e^+ in the $\bar{p}$ continuum thus energy transfer around kT_e -> capture into weakly bound state

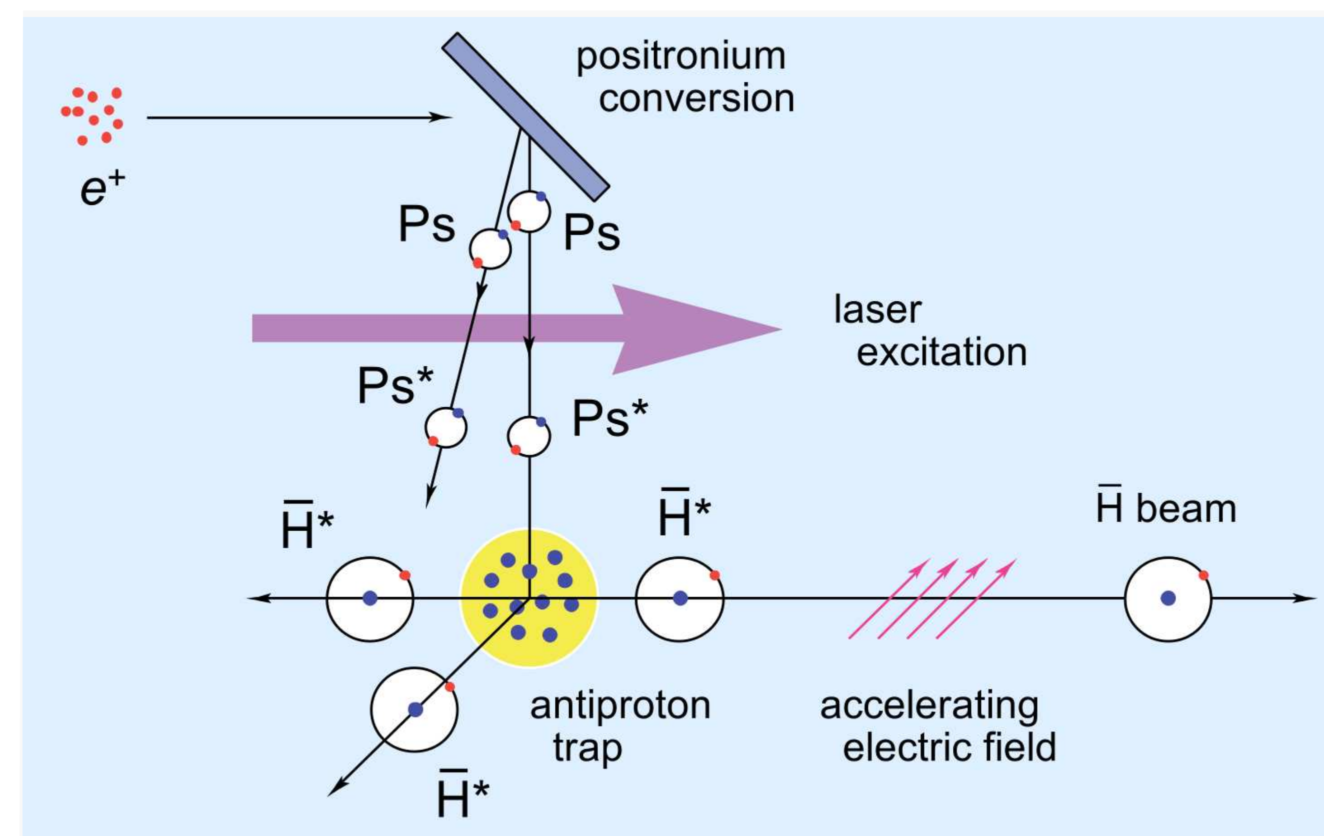
3) Charge- exchange with Ps

$$\bar{p} + Ps^{*} \rightarrow \bar{H}^{*} + e^{-} \qquad \sigma \sim \pi a_o^2 n_{Ps}^4$$

Necessary ingredients: high density, low energy antiprotons and positrons

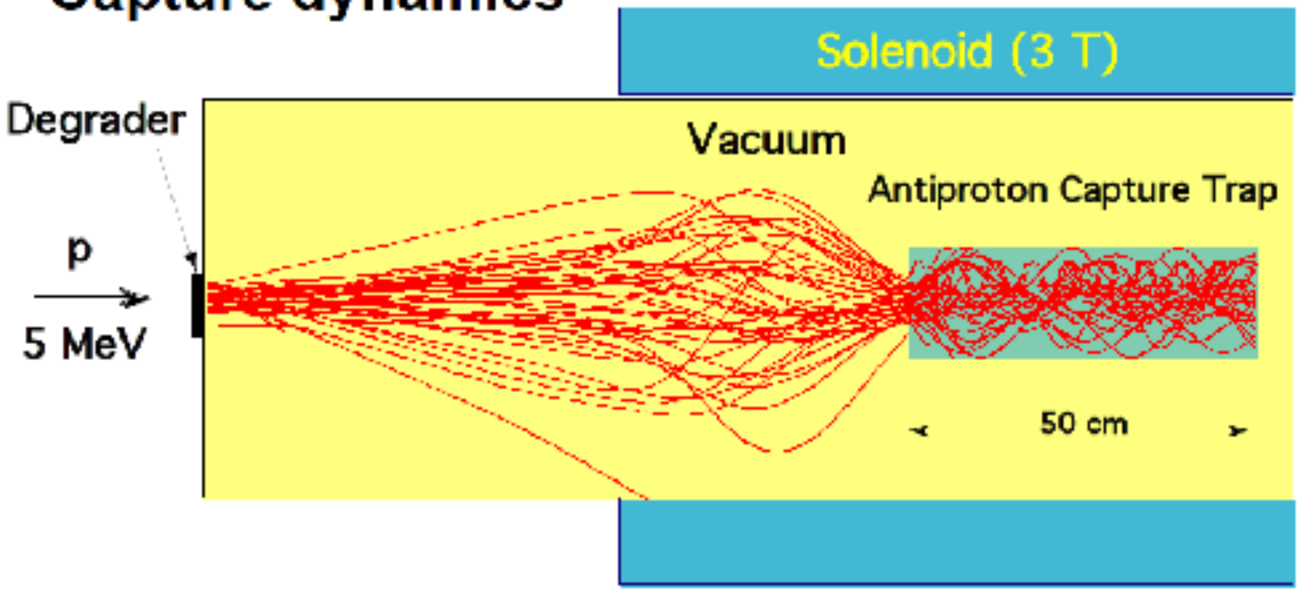
	Radiative Recombination	Three-Body Recombination
Principle		
Temperature depend.	$\propto T^{-2/3}$	$\propto T^{-9/2}$
e^+ density dependence	$\propto n_e$	$\propto n_e^2$
Final internal states	$n < 10$	$n >> 10$
Expected rates	few 10 Hz	unknown

[J. Stevefelt *et al.*, PRA **12** (1975) 1246] [M. E. Glinsky *et al.*, Phys. Fluids B **3** (1991) 1279]

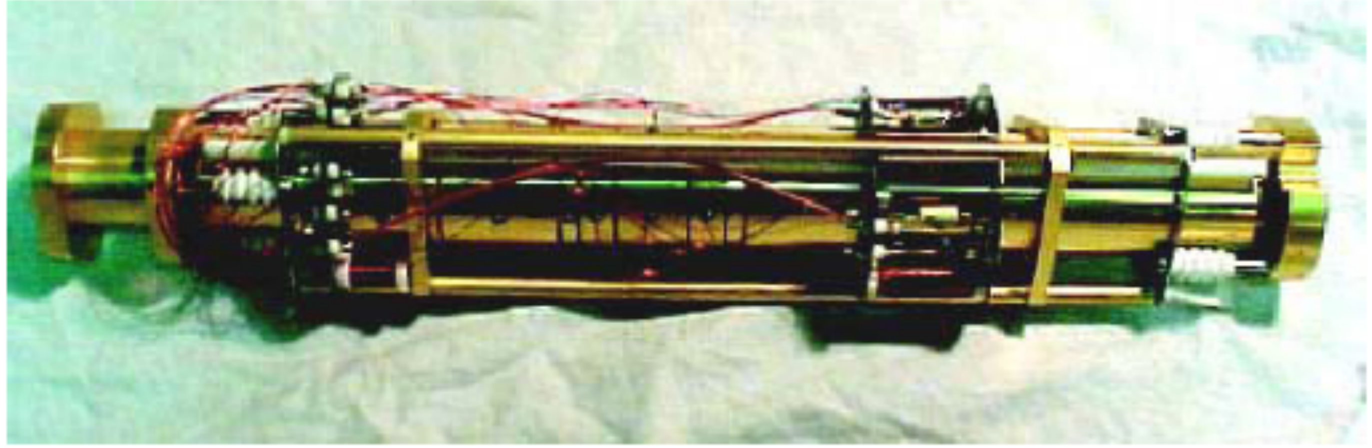


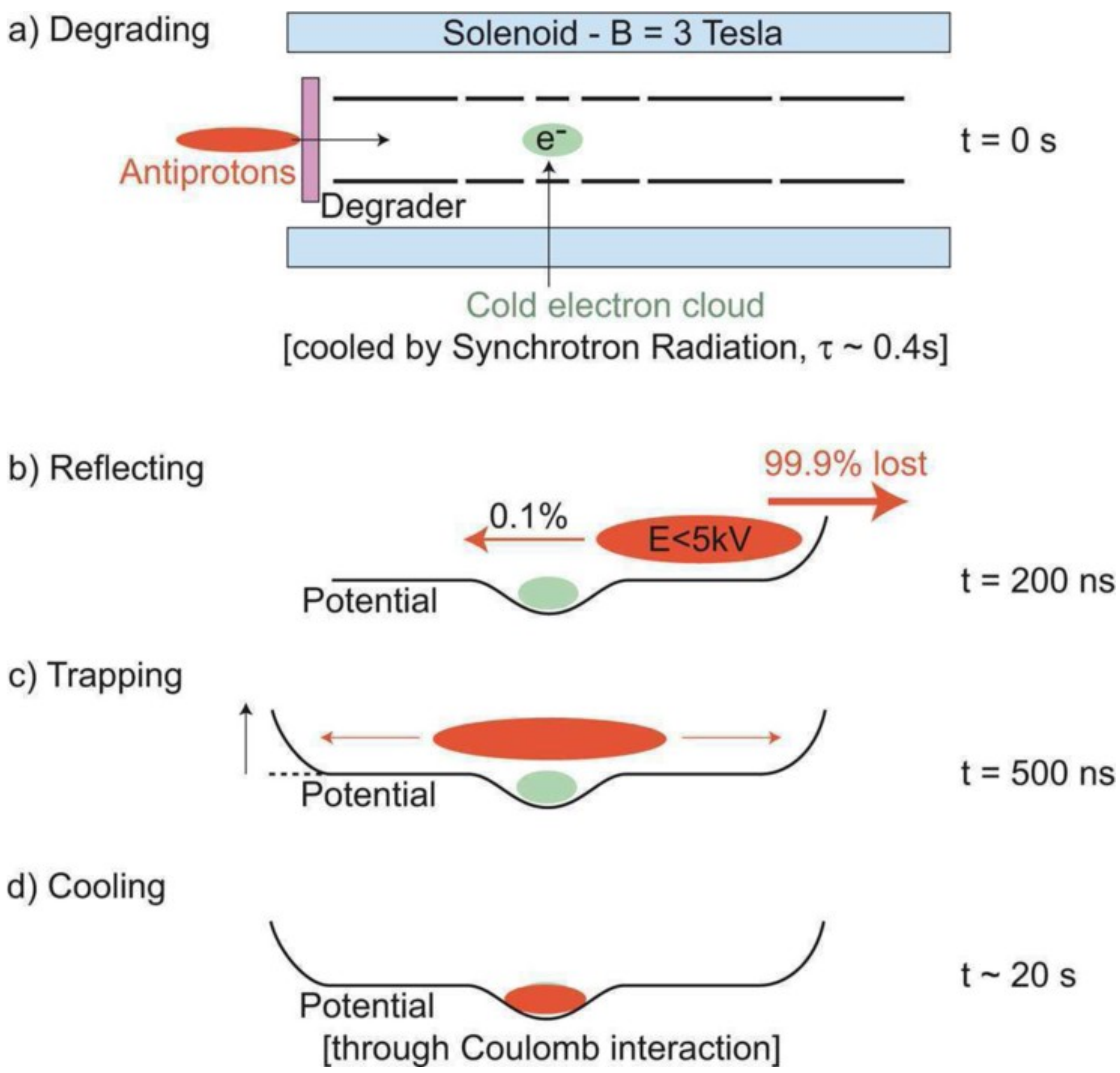
Trapping of antiprotons

- **Capture dynamics**



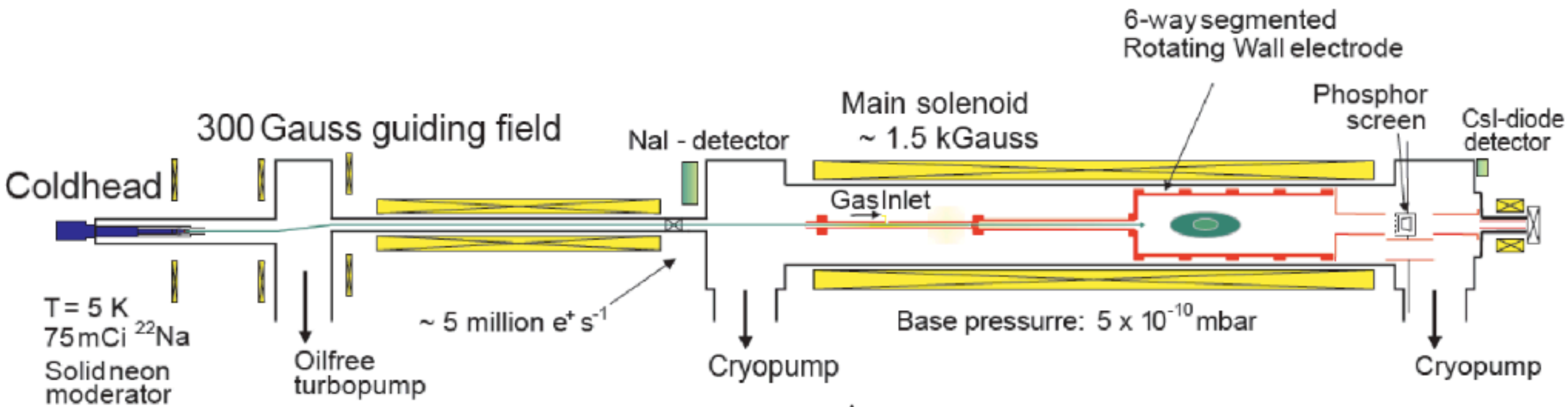
- **Capture trap (50 cm)**

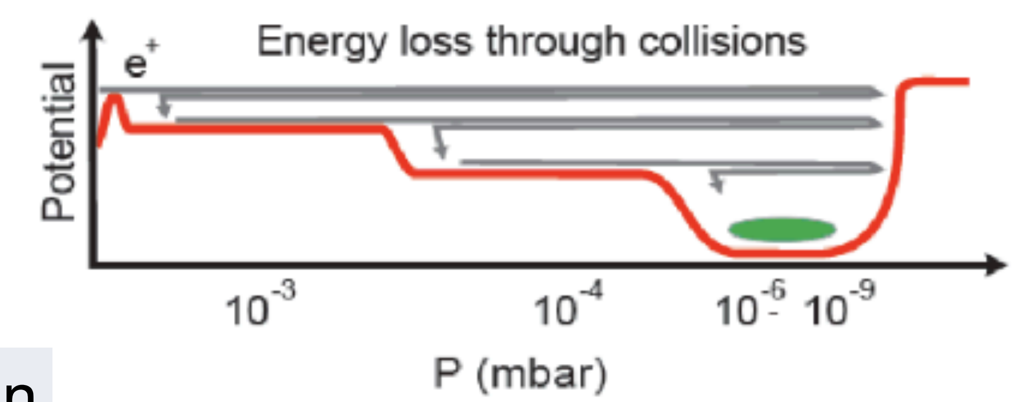




Stacking up to 10^5 antiprotons

Cooling and trapping of positrons





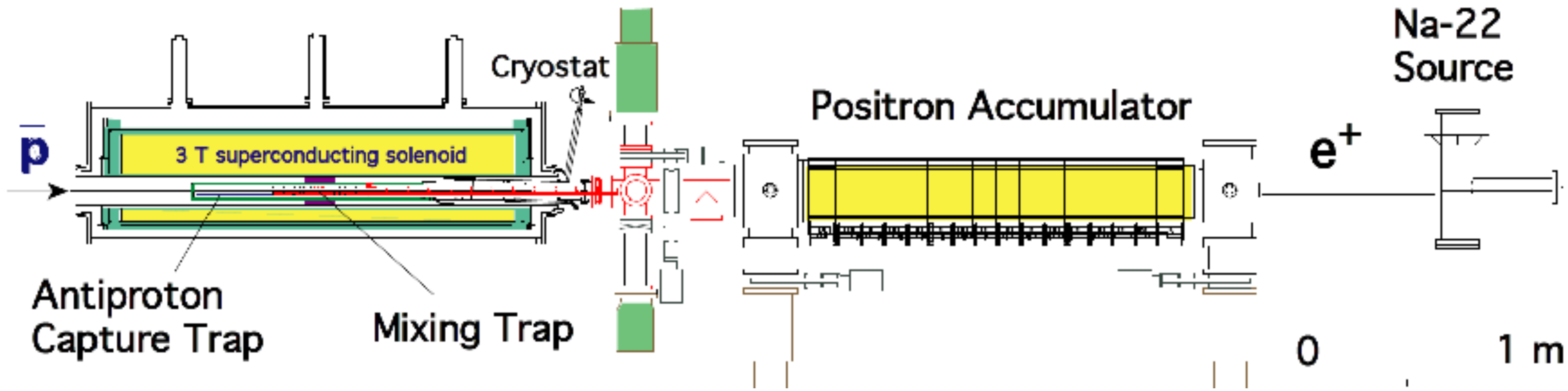
Few million e+ / sec

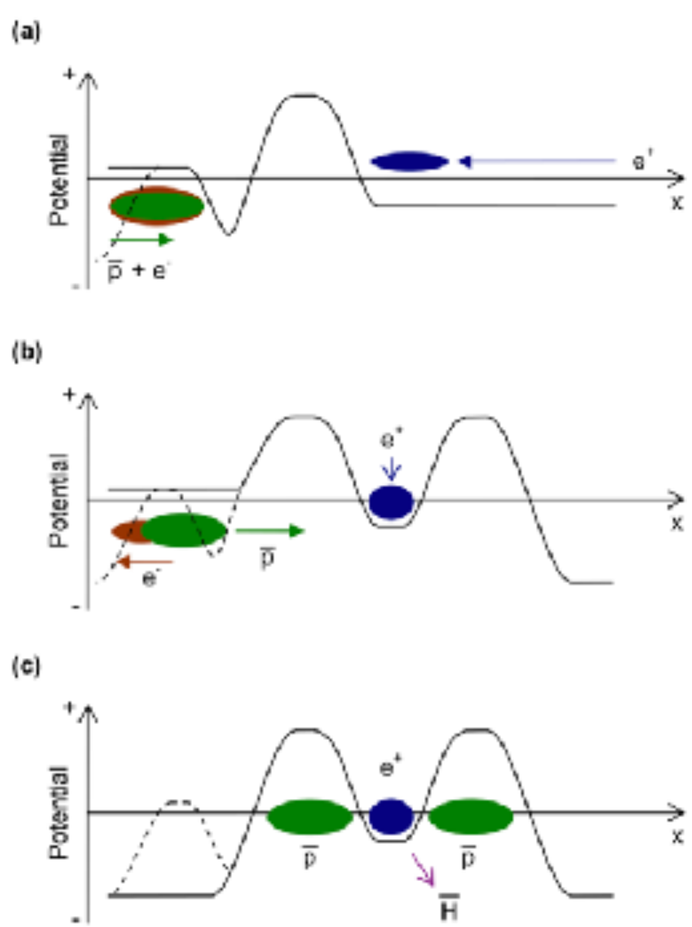
(1) Source: Na-22, 545 keV, but moderation on solid neon

(2) Transport to main solenoid

(3) In main solenoid: 3 regions of decreasing density N2 buffer gas and potential:
- The gas provides the dissipation mechanism. To prevent annihilation: differential pumping.
- Rotating wall: makes the plasma spin faster, and squeeze axially (angular momentum conservation)
- Lowering the electrode voltage evaporative cooling: plasma reaches several 10's of degree Kelvin

Transfer to mixing trap



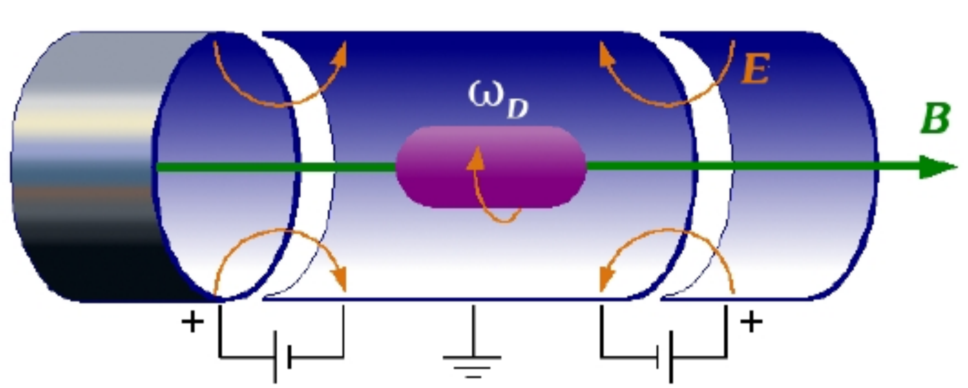


Transfer efficiency ~ 35%:
50 x 10^6 in mixing trap

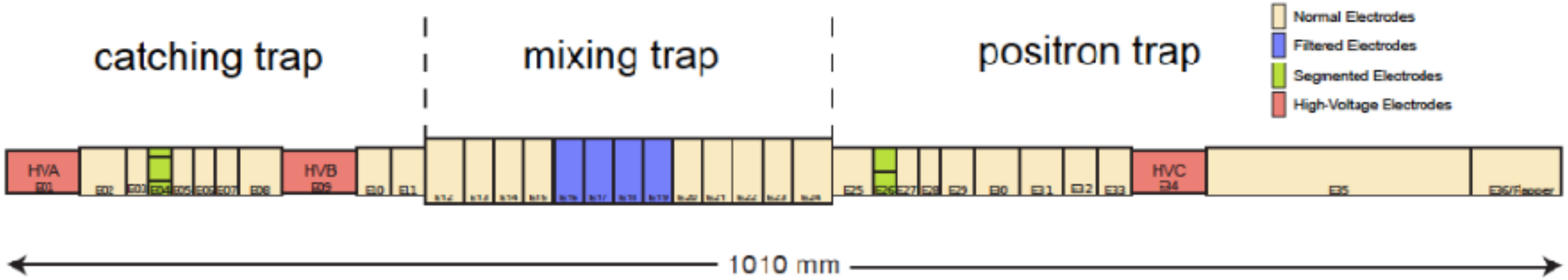
Positron plasma :
r~2mm, l~32mm,
n~2.5 x 10^8 / cm^3

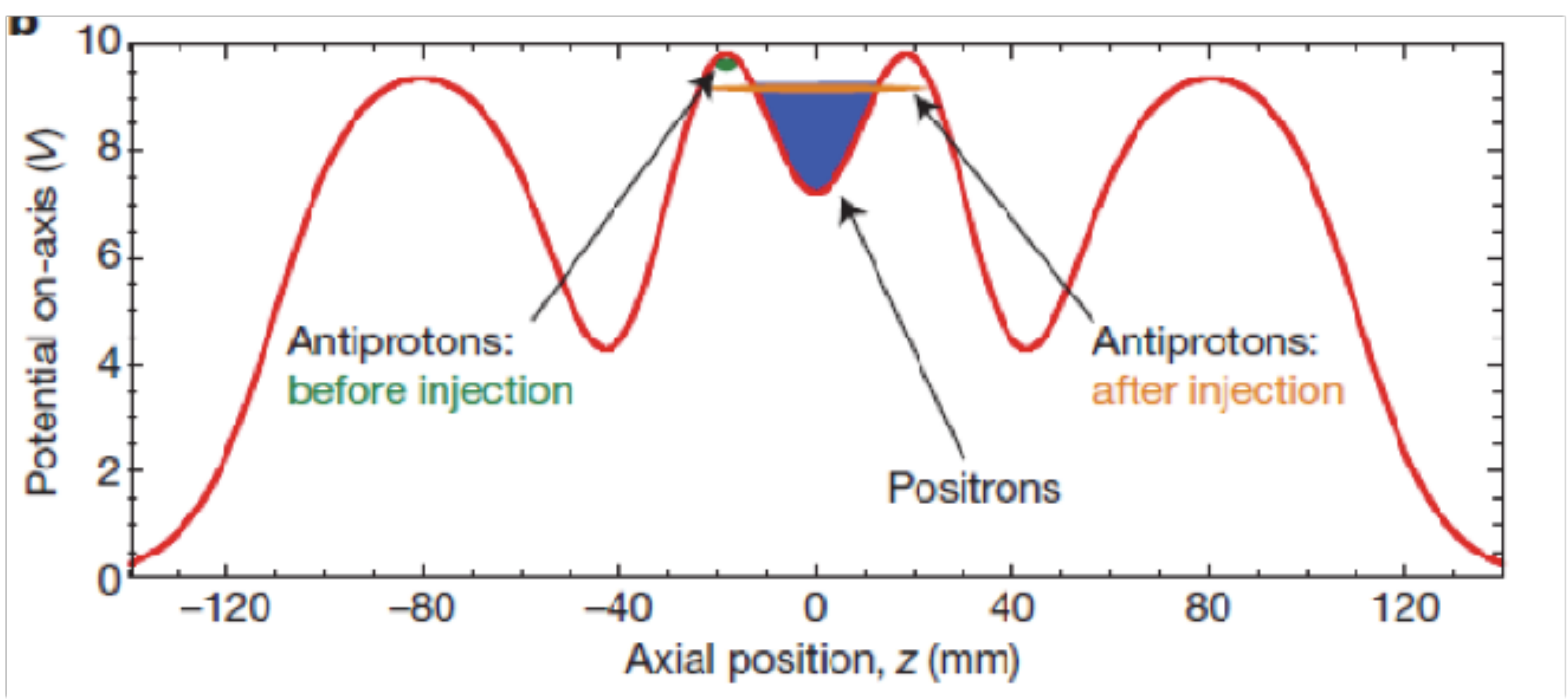
Lifetime: ~hours

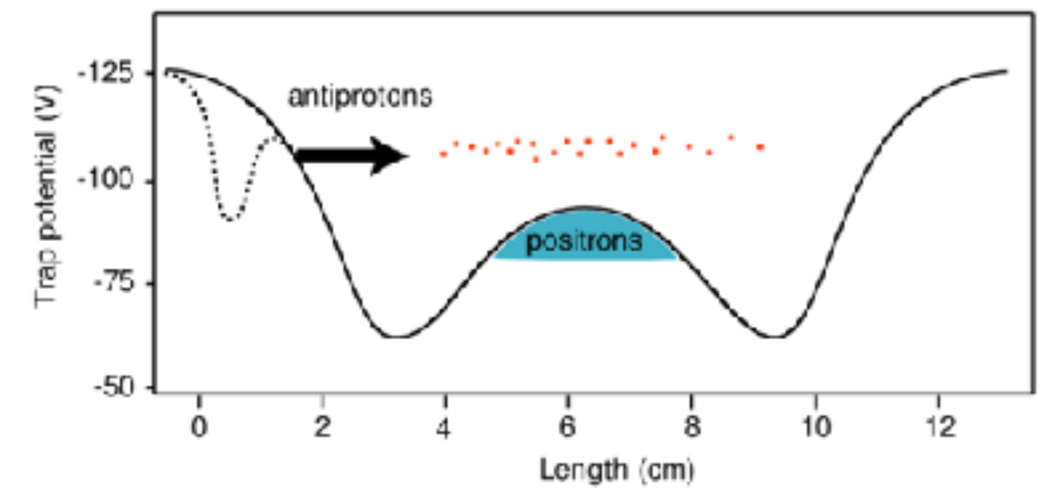
Penning-Malberg trap



Positron-antiproton mixing

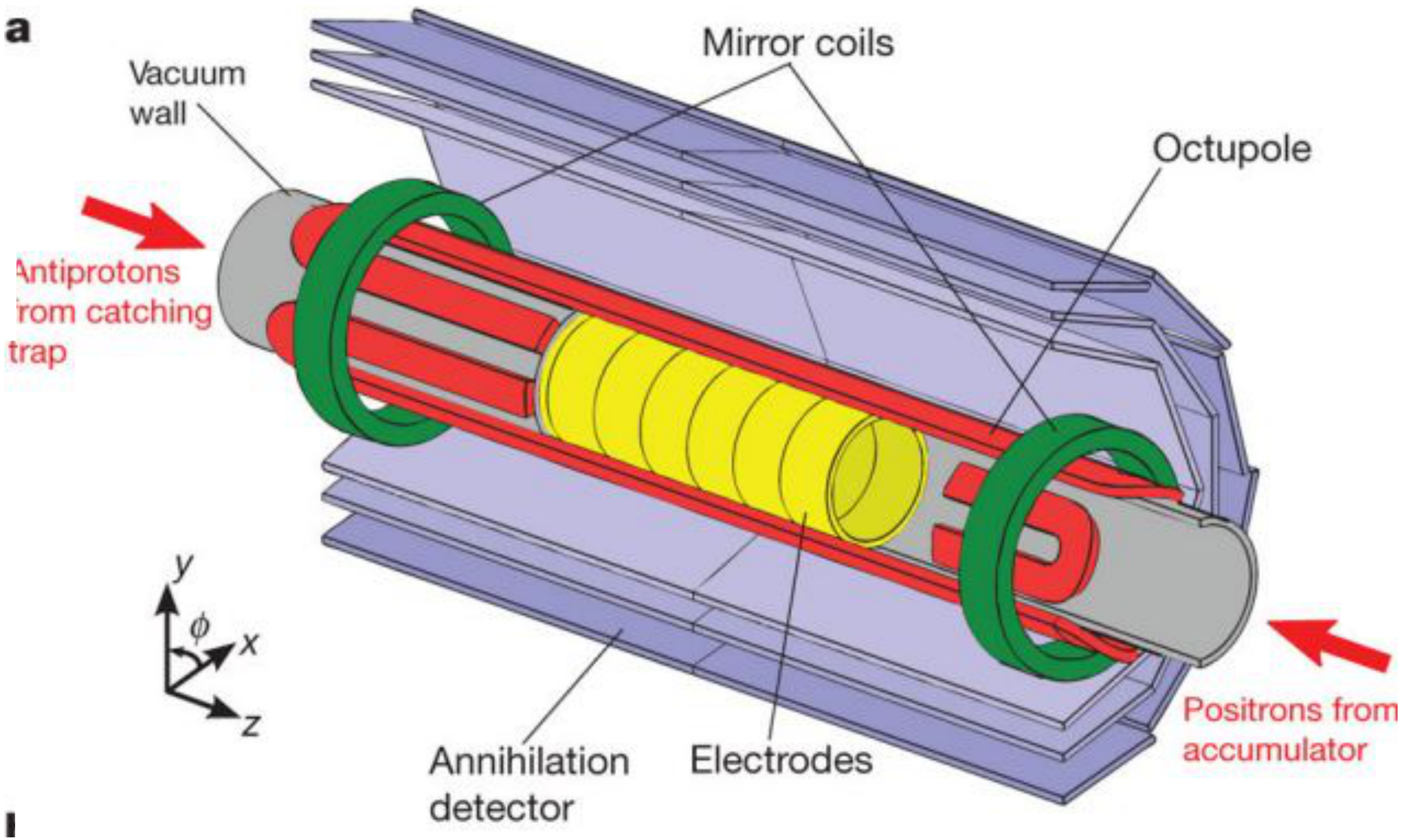






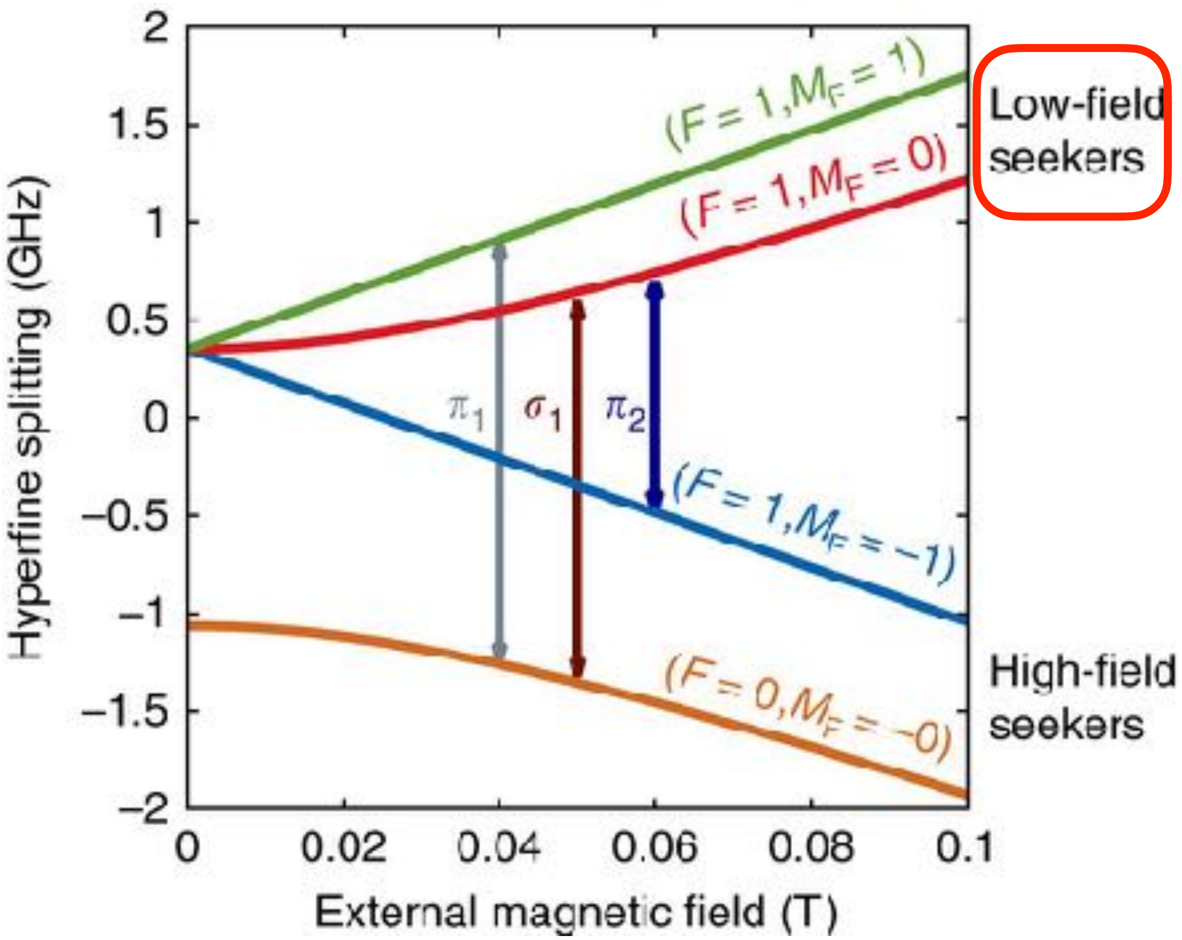
Oscillating RF field excite the $\bar{p}$ so that it overlaps with the e^+

ALPHA experiment - first trapping of $\bar{H}$



Atoms with magnetic moment acquire a potential in a magnetic field according to the formula:

$$U = -\vec{\mu} \cdot \vec{B} \quad \Rightarrow \quad \textbf{Force} \quad \vec{F} = \vec{\mu} \nabla \vec{B}$$



Zeeman-splitting, Breit-Rabi diagram

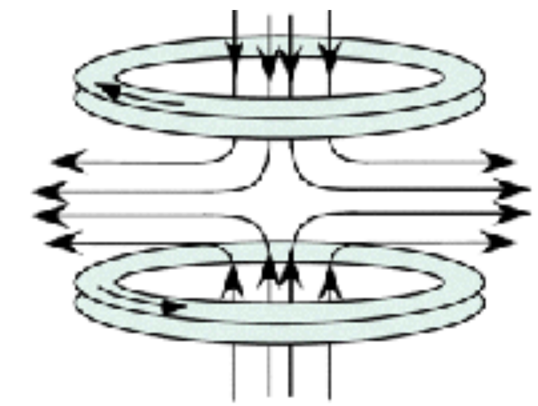
Trappable states

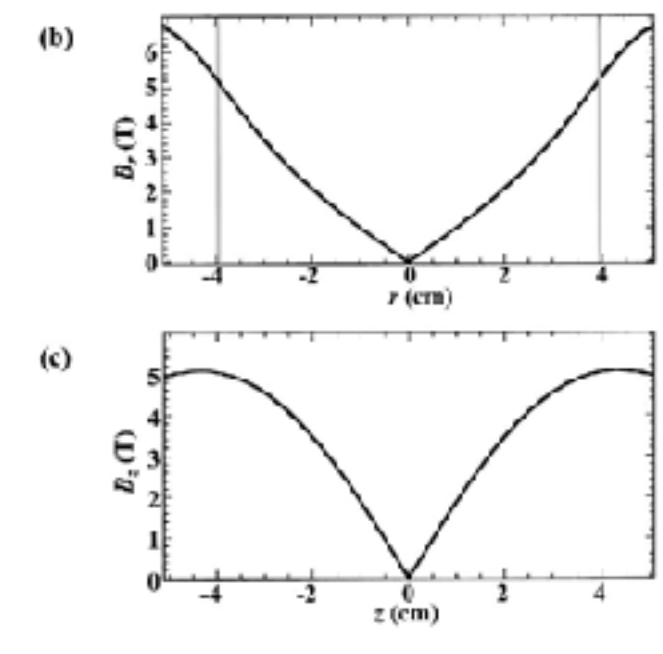
Trapping condition

$$\mu B \geq k_B T$$

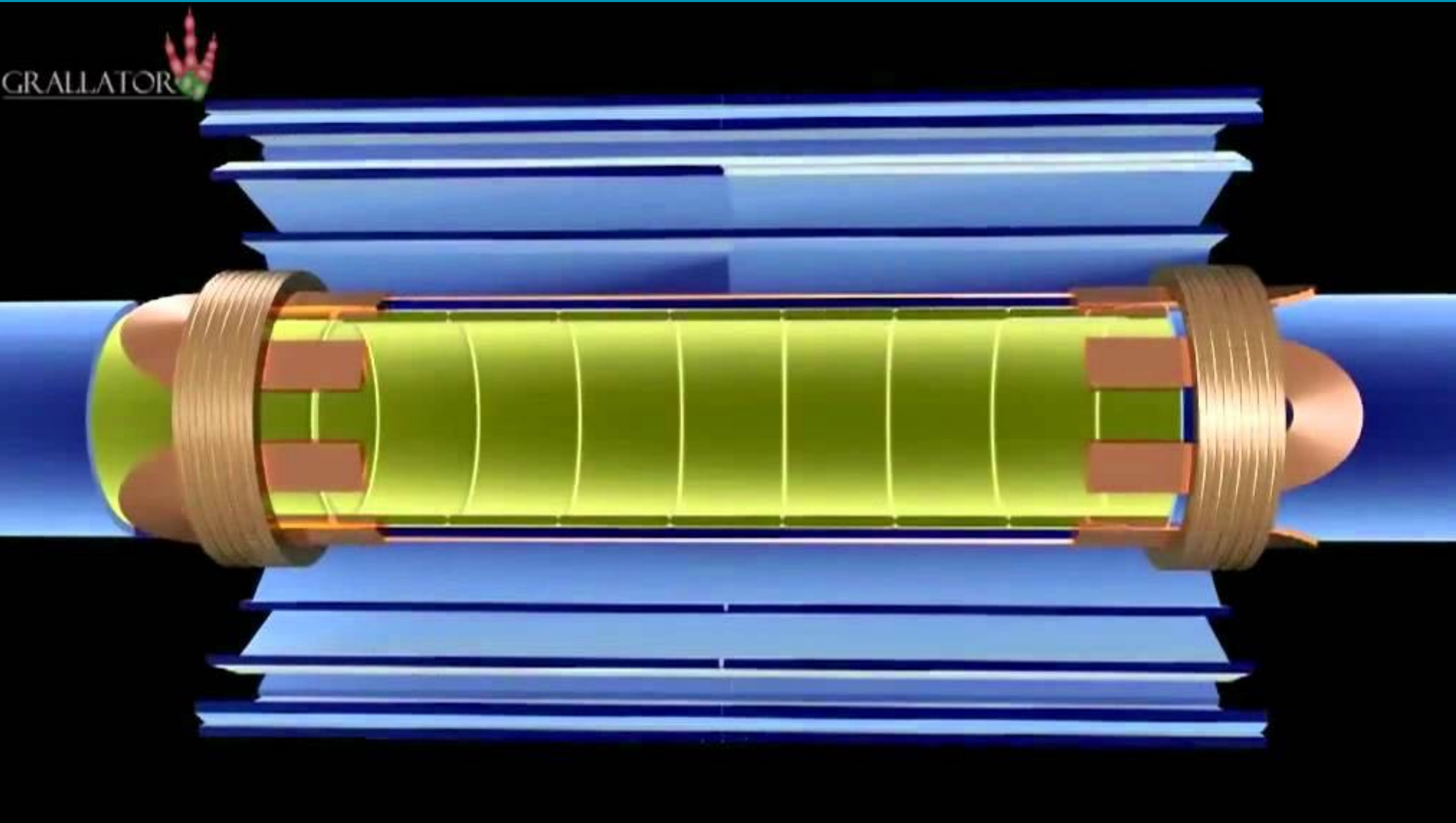
Requires cold atoms: 0.6 K for 1T field

Anti-Helmholtz coil configuration - magnetic quadrupole field

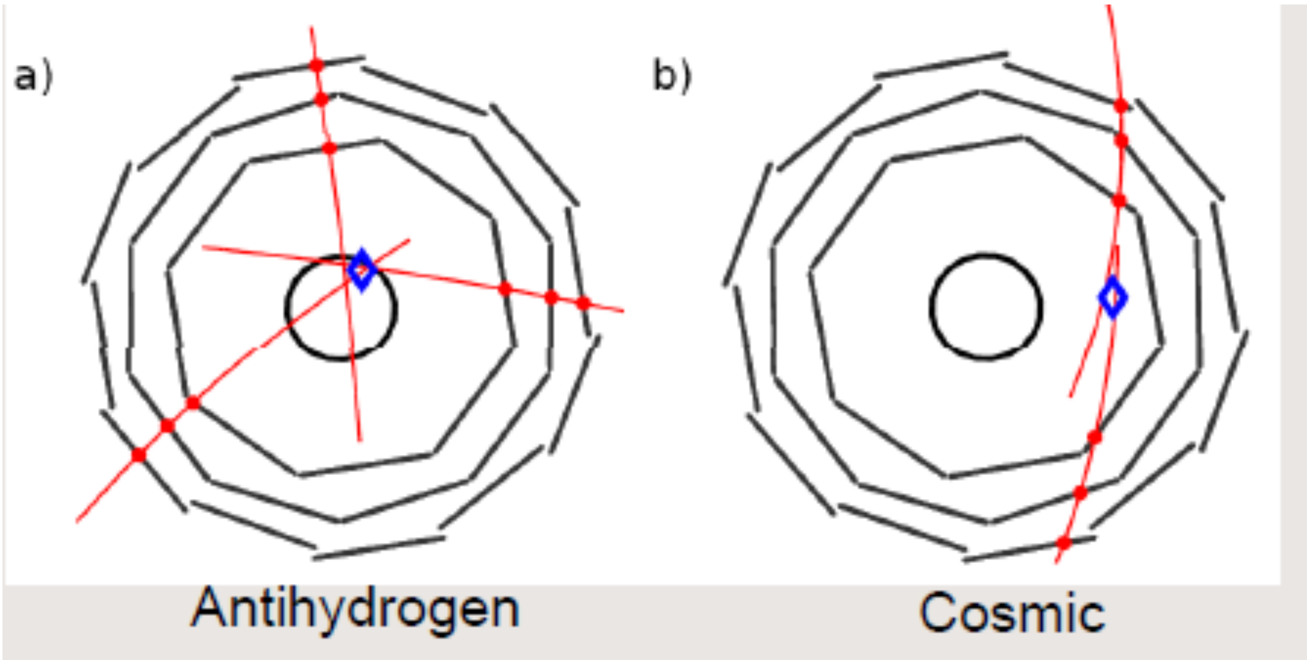




The ALPHA experiment in 2009



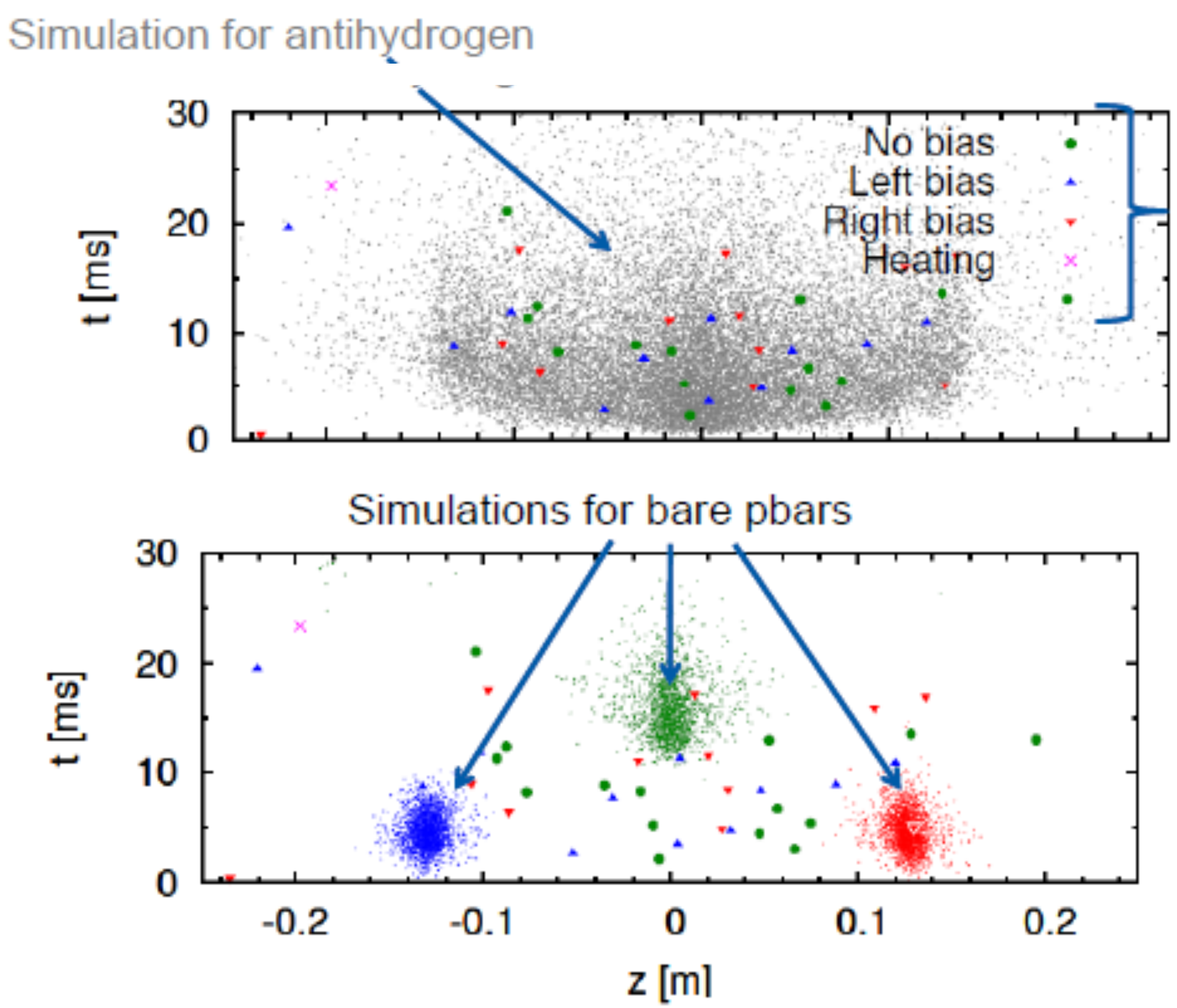
To demonstrate trapping ramp down magnetic field and look for annihilations on the beam pipe



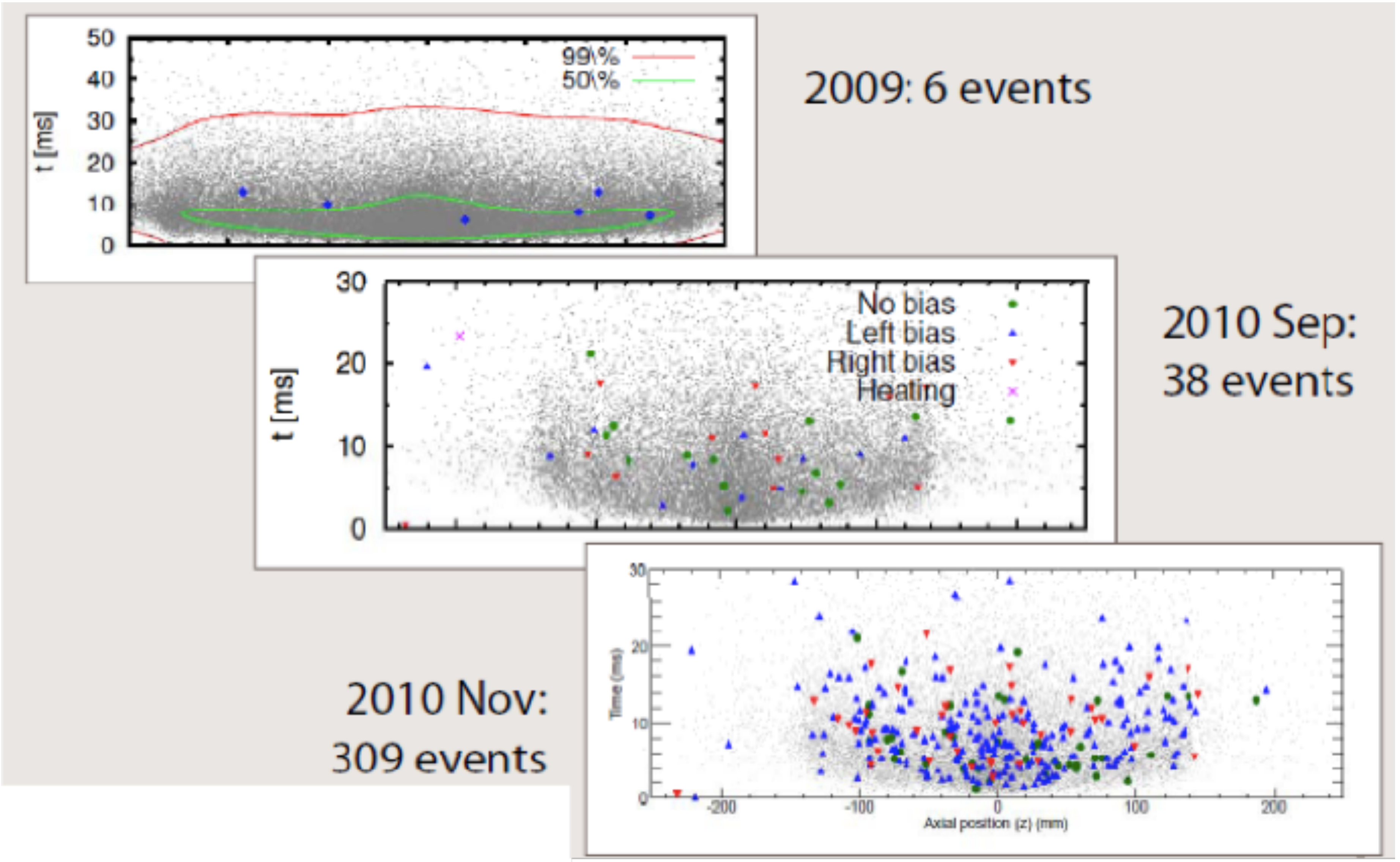
- Potential problem: „mirror trapping“ of bare $\bar{p}$ in homogenous B field —> Solution:

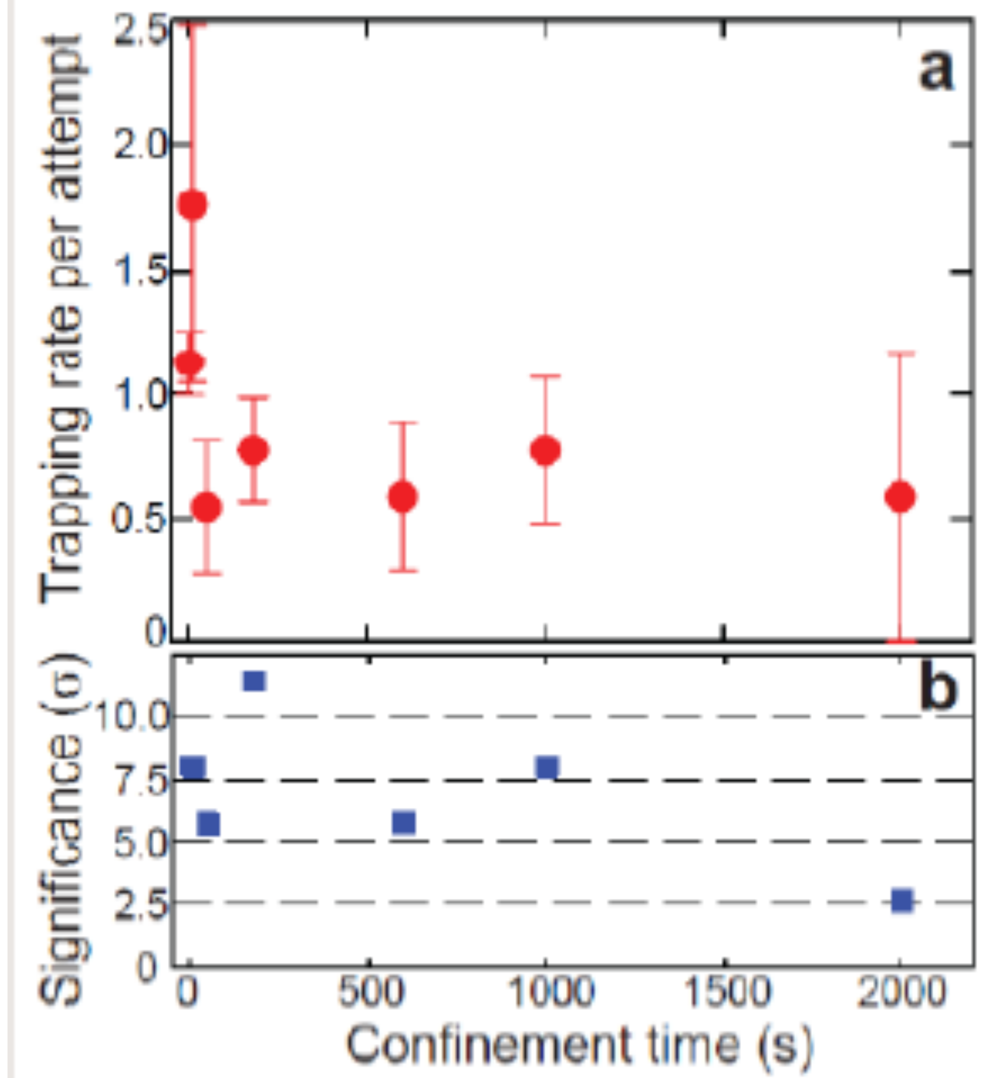
- Mixing with heated e+ (suppresses anti-H production)
- Release anti-H while applying E field: pbars would be deflected

- Background from cosmics: rejected by topology



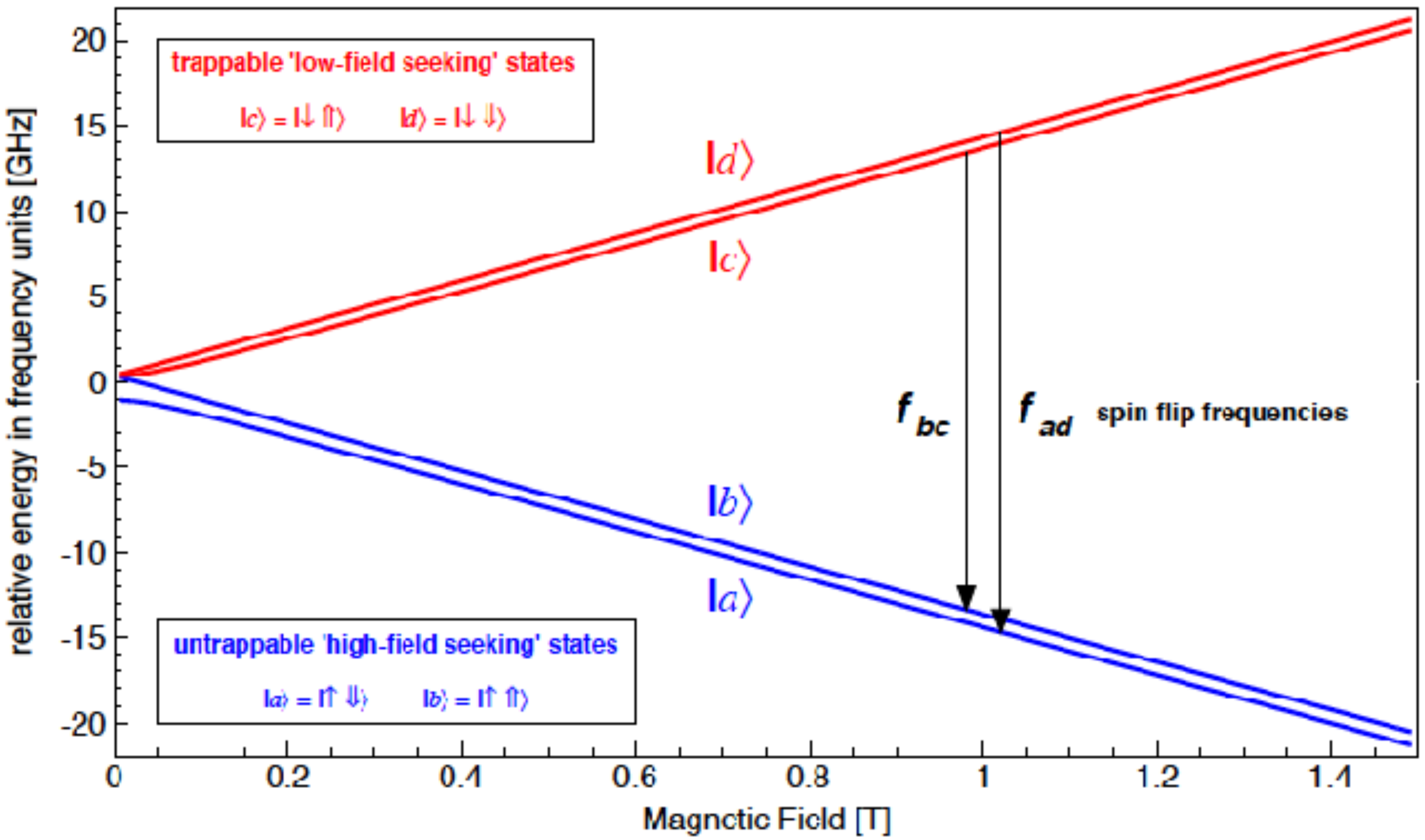
Antihydrogen trapping rates and confinement time

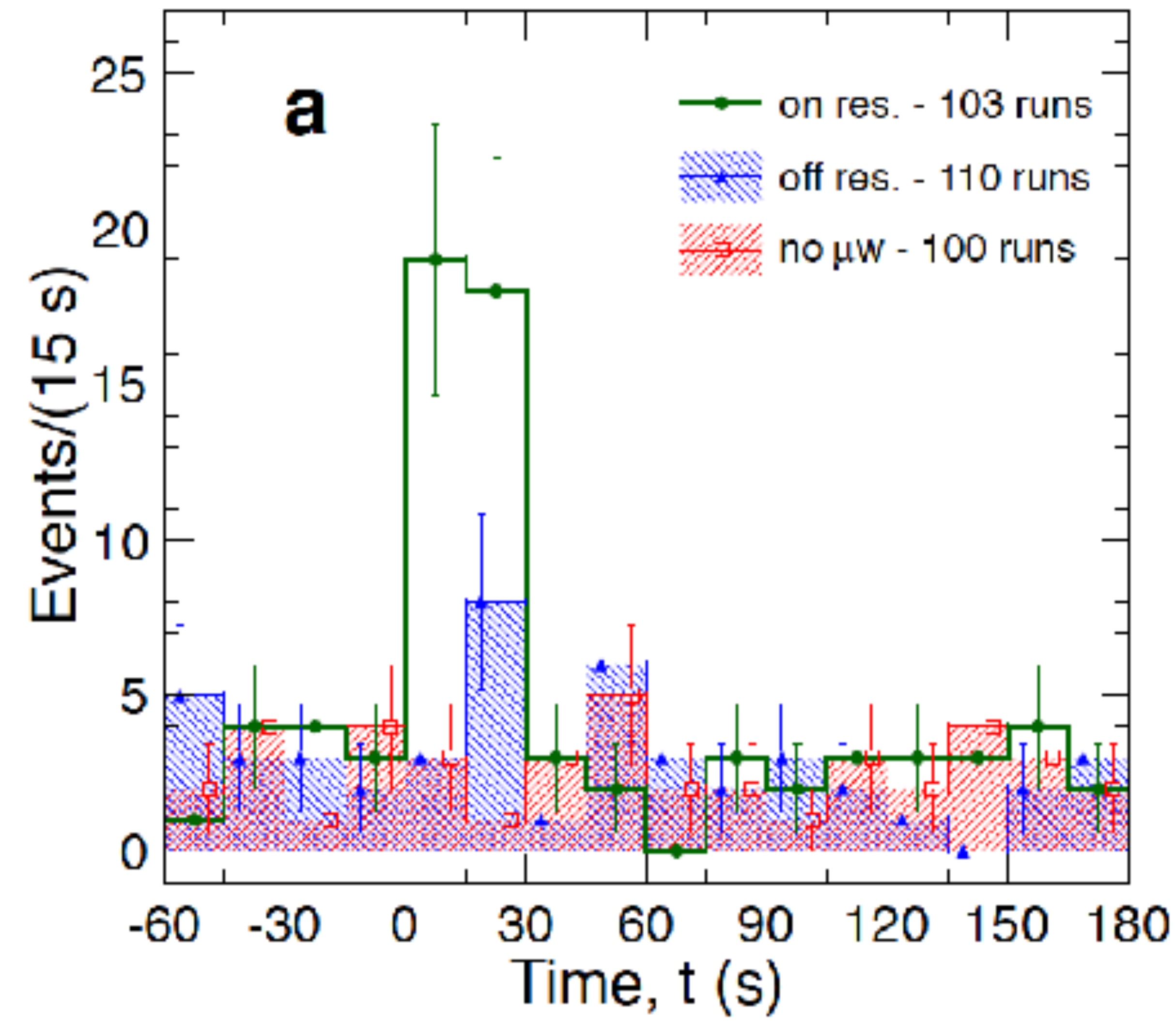




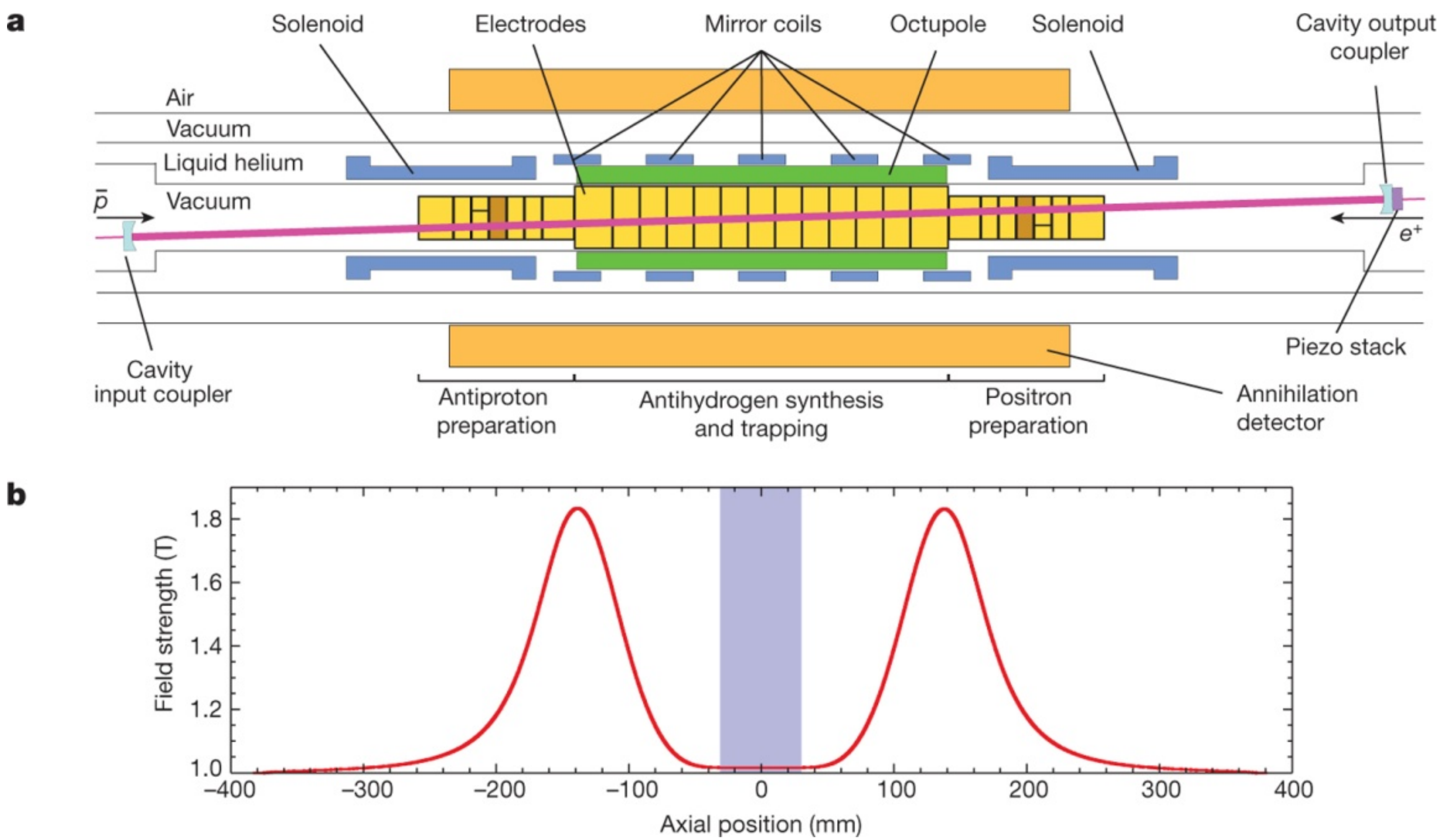
Confinement time up to 1000 s -> allows for precision spectroscopy of anti-hydrogen:
- $\bar{H}$ in the ground state (remember $\bar{H}$ formed in highly excited Rydberg state takes about 1 second to de-excite to ground state)
- Present numbers: >20 antihydrogen atoms every 4 minutes, accumulating several 1000 $\bar{H}$ in 8 hours

First interaction of Antihydrogen with radiation





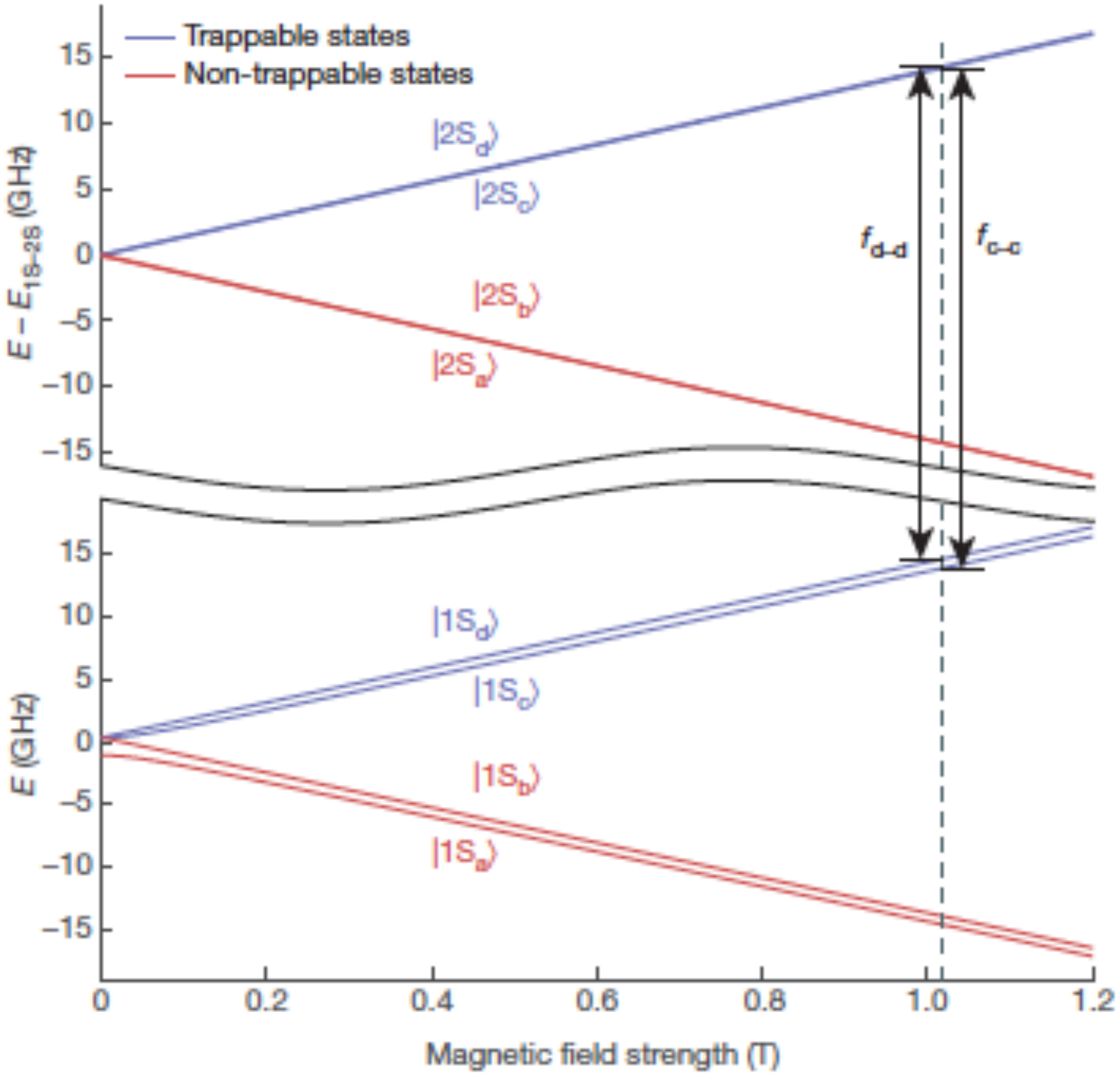
First detection of the 1S-2S transition



Two-photon transition at 243-nm driven by a resonant cavity locked to the frequency, passing through the centre of the trap

M Ahmadi *et al. Nature* **541,** 506–510 (2017) doi:10.1038/nature21040

ALPHA-2: First detection of the 1S-2S transition



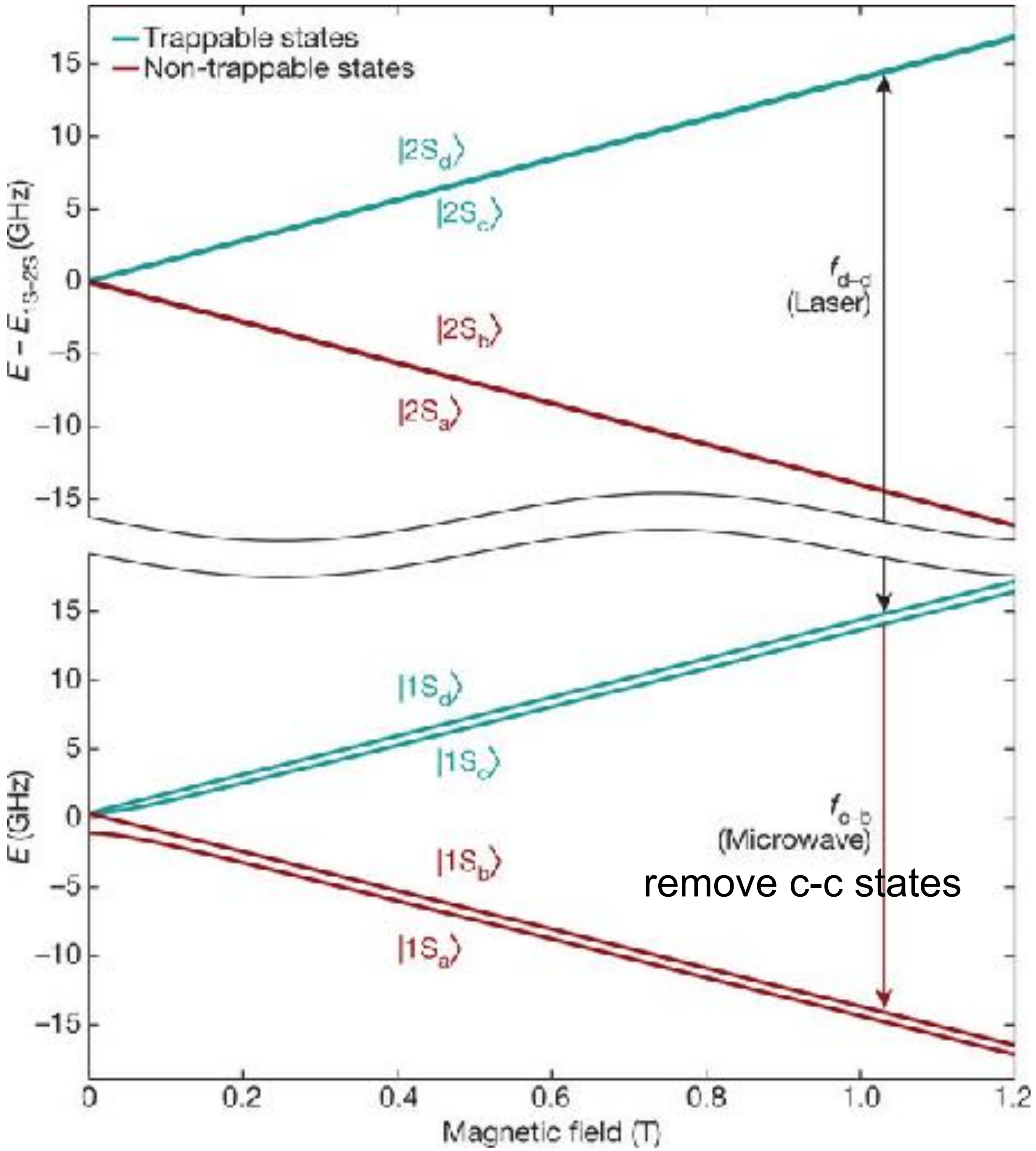
When laser on resonance —> number of trapped $\bar{H}$ depleted because of photoionisation of atoms in the same excitation laser.

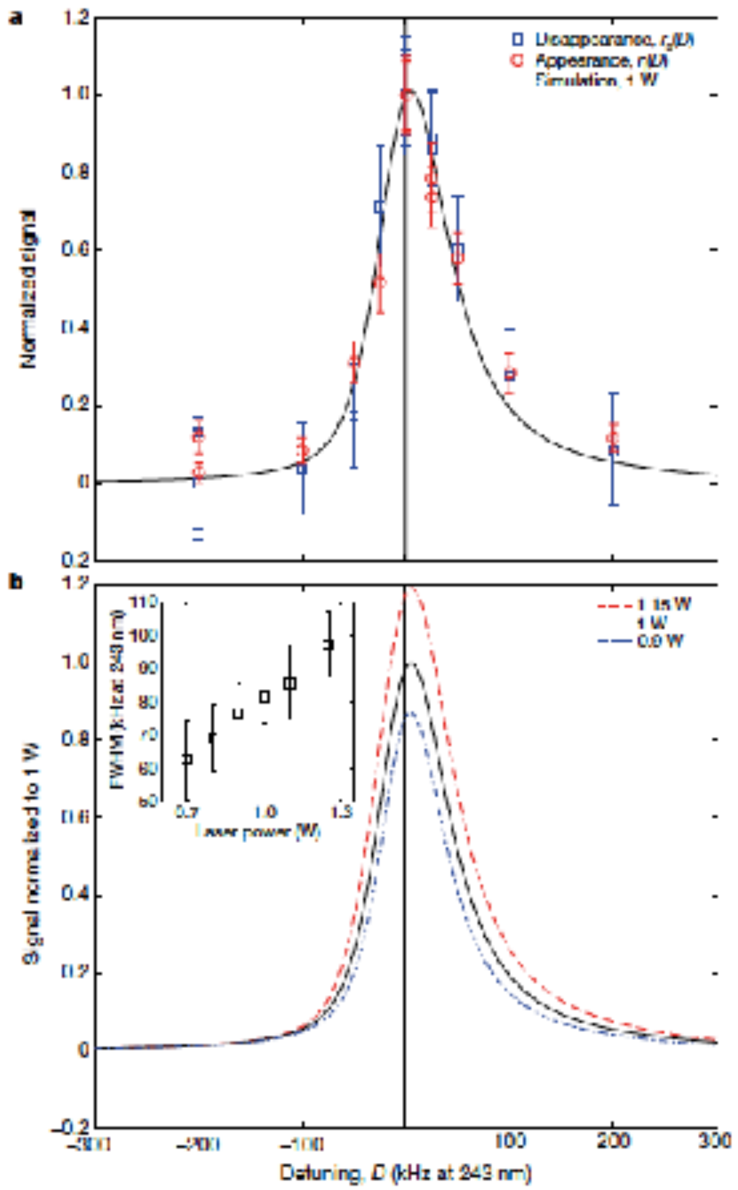
Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

$$f_{d-d} = 2{,}466{,}061{,}103{,}064(2)\ \text{kHz}$$
$$f_{c-c} = 2{,}466{,}061{,}707{,}104(2)\ \text{kHz}$$

No difference between hydrogen and antihydrogen transition frequency at the level of 10^{-10}

Measurement of the 1S-2S line shape





Laser drives 1S-2S transition (2-photon)
A third photon drives it to continuum: lost in the trap
Microwave removes 1Sc states, then ramping down the magnet probes 1Sd atoms

Measured transition:

$$f_{d-d} = 2{,}466{,}061{,}103{,}079.4(5.4)\,\mathrm{kHz}$$

Calculation for hydrogen in 1T field

$$f_{d-d} = 2{,}466{,}061{,}103{,}080.3(0.6)\,\mathrm{kHz}$$

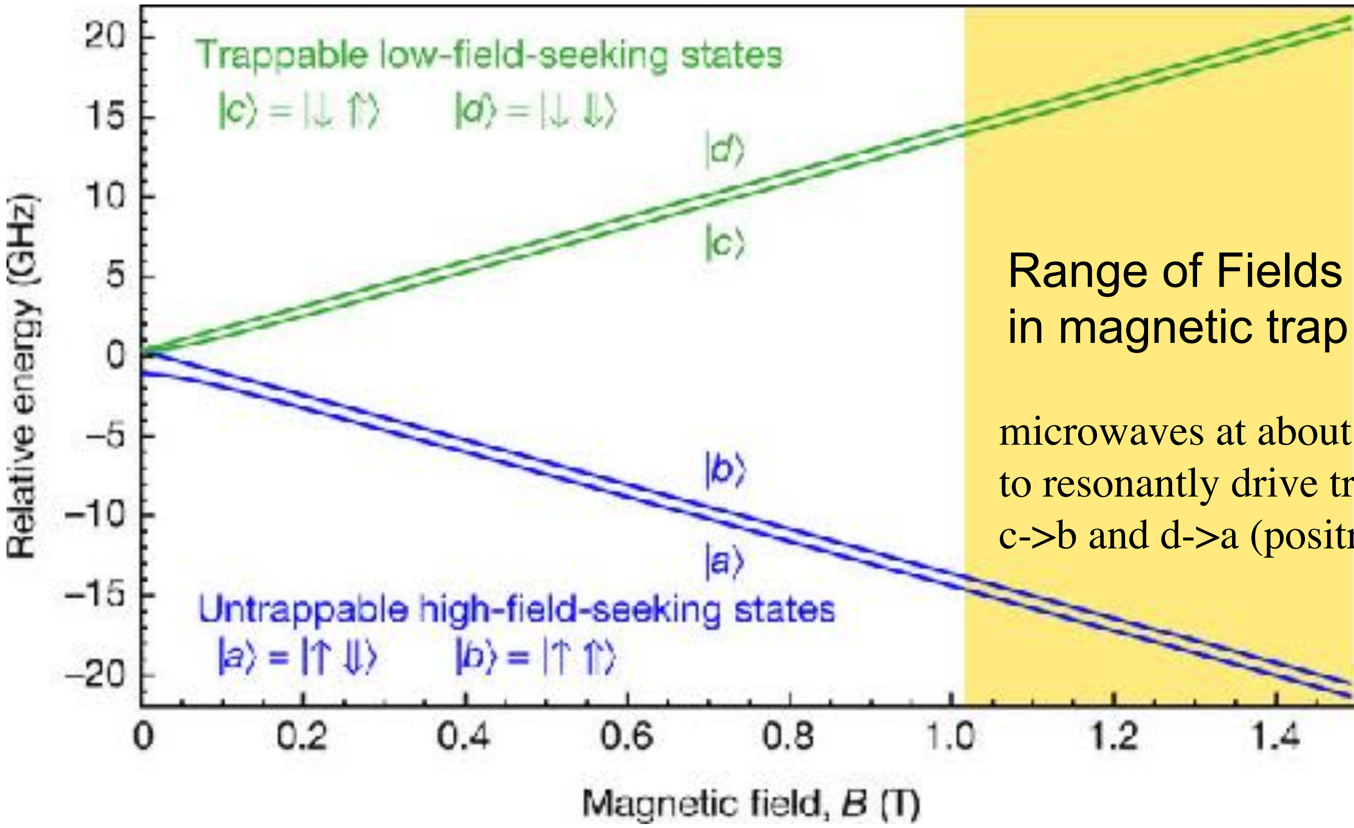
Results in agreement within

$$2 \times 10^{-12}$$

Prospects: laser cooling to decrease the temperature —> narrower line

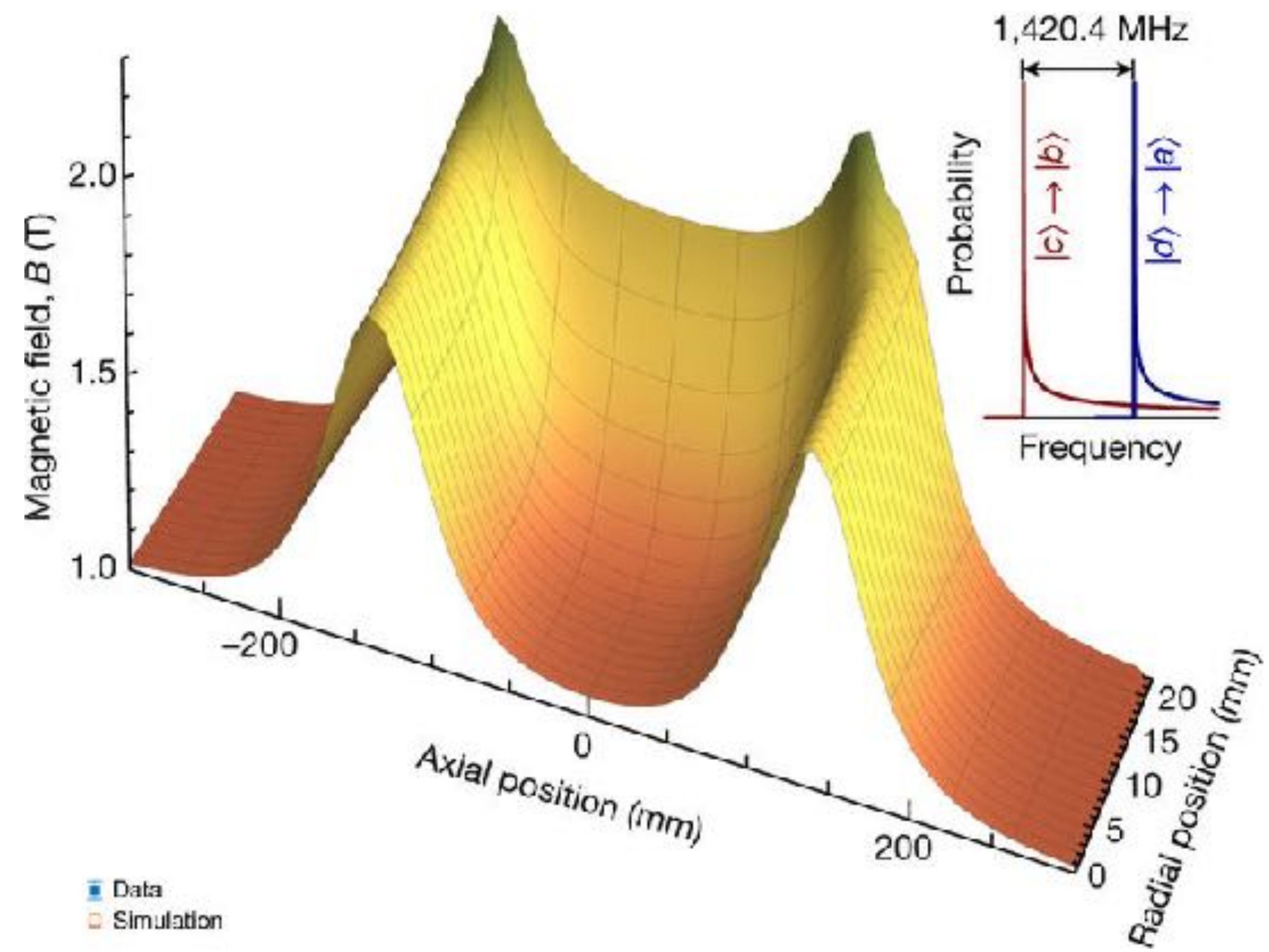
Measurement of the HFS in ALPHA

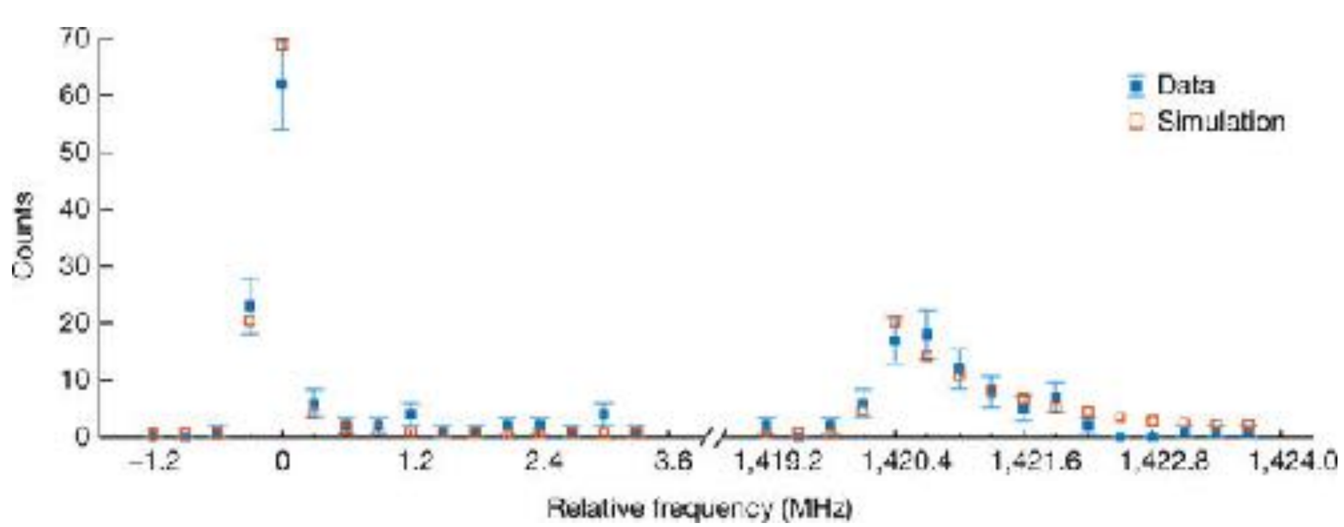
Onset at the magnetic field minimum



Range of Fields in magnetic trap

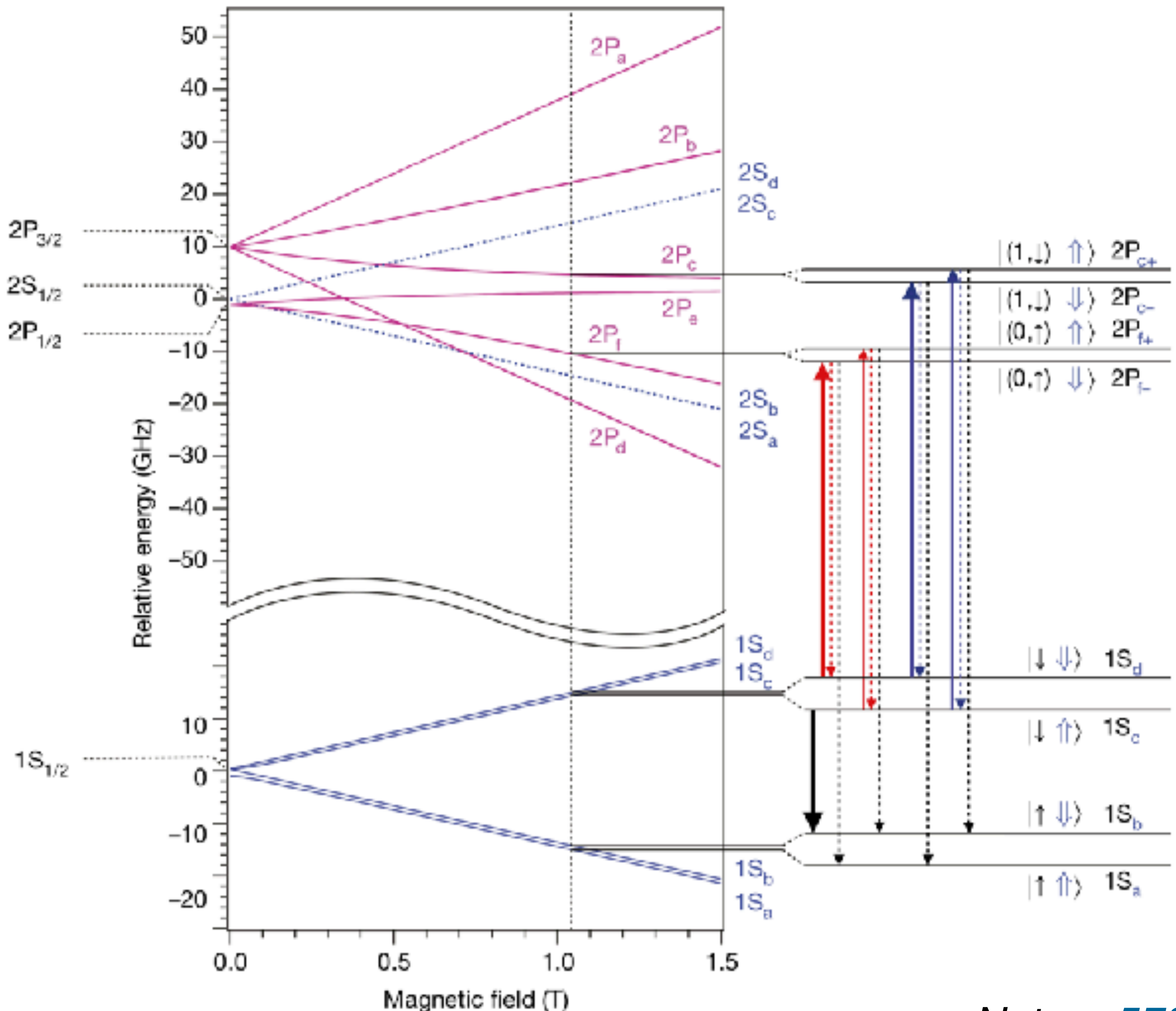
microwaves at about 29 GHz
to resonantly drive transitions
c->b and d->a (positron spin flip)



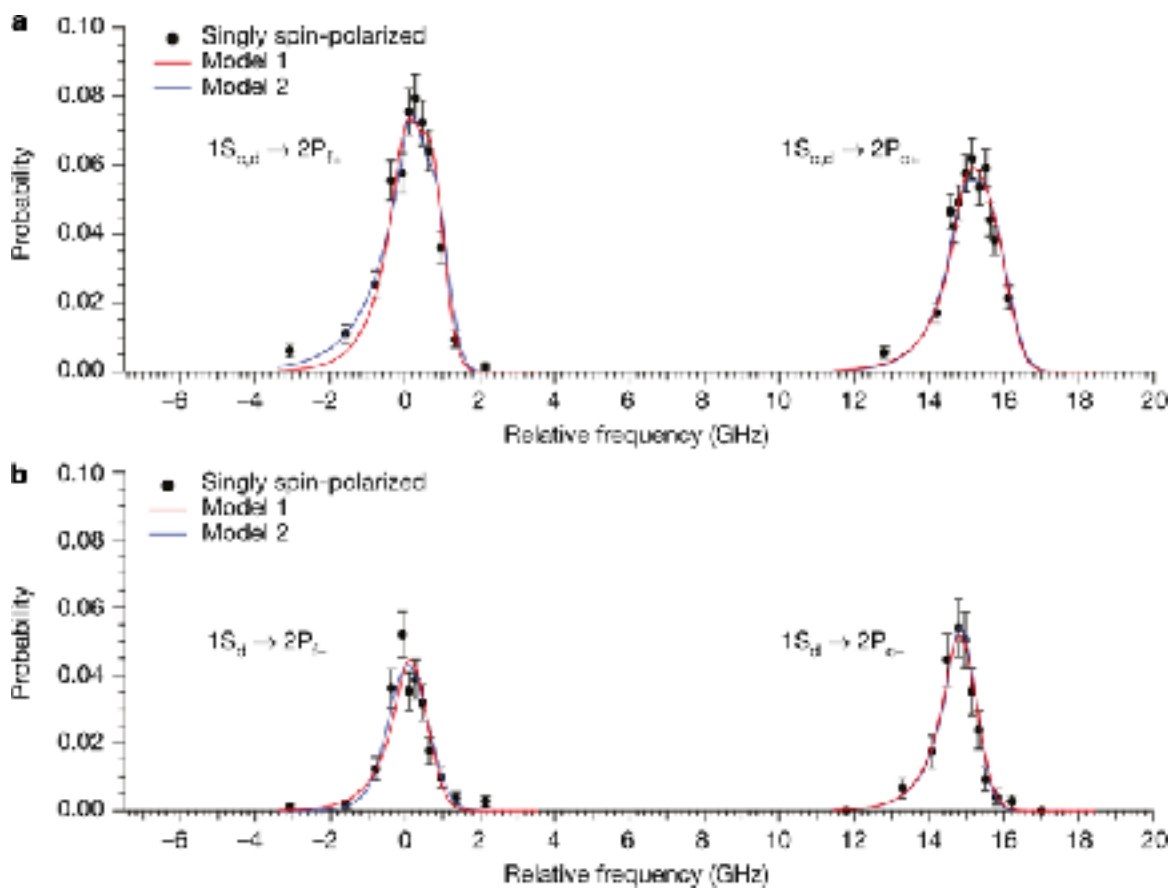


$1{,}420.4 \pm 0.5$ MHz,
in agreement with hydrogen

Measurement of the $\bar{H}$ Lamb shift in ALPHA



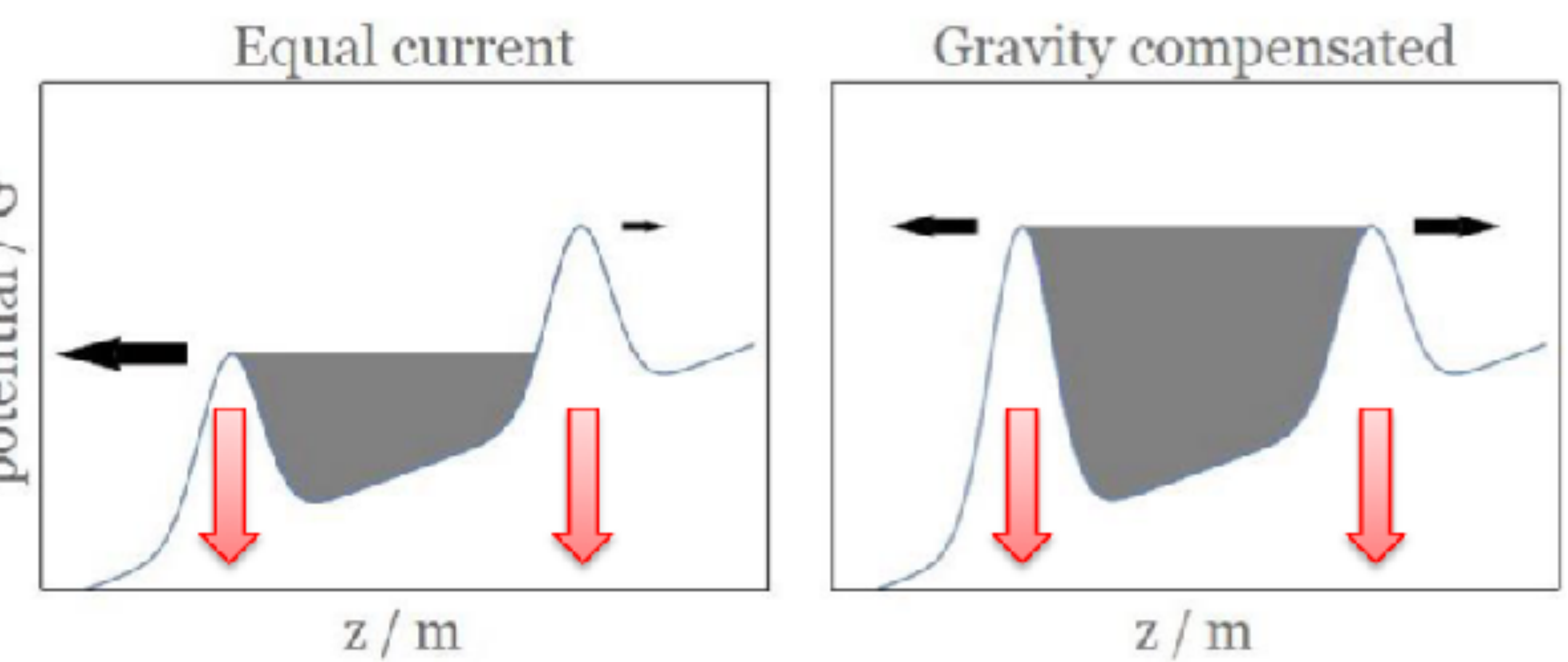
Fine-structure splitting (2P1/2–2P3/2) in antihydrogen, combined with previously measured value of the 1S–2S transition frequency

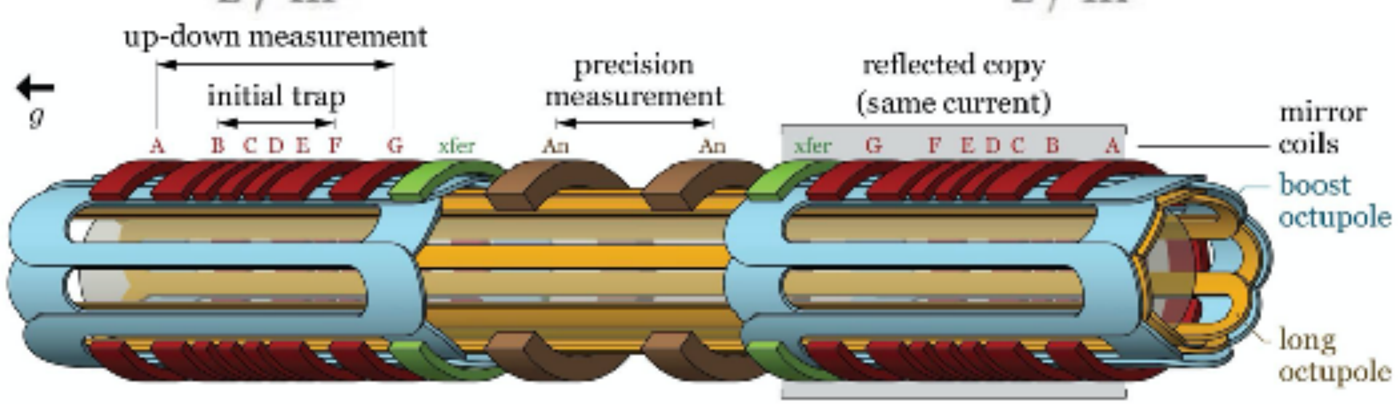


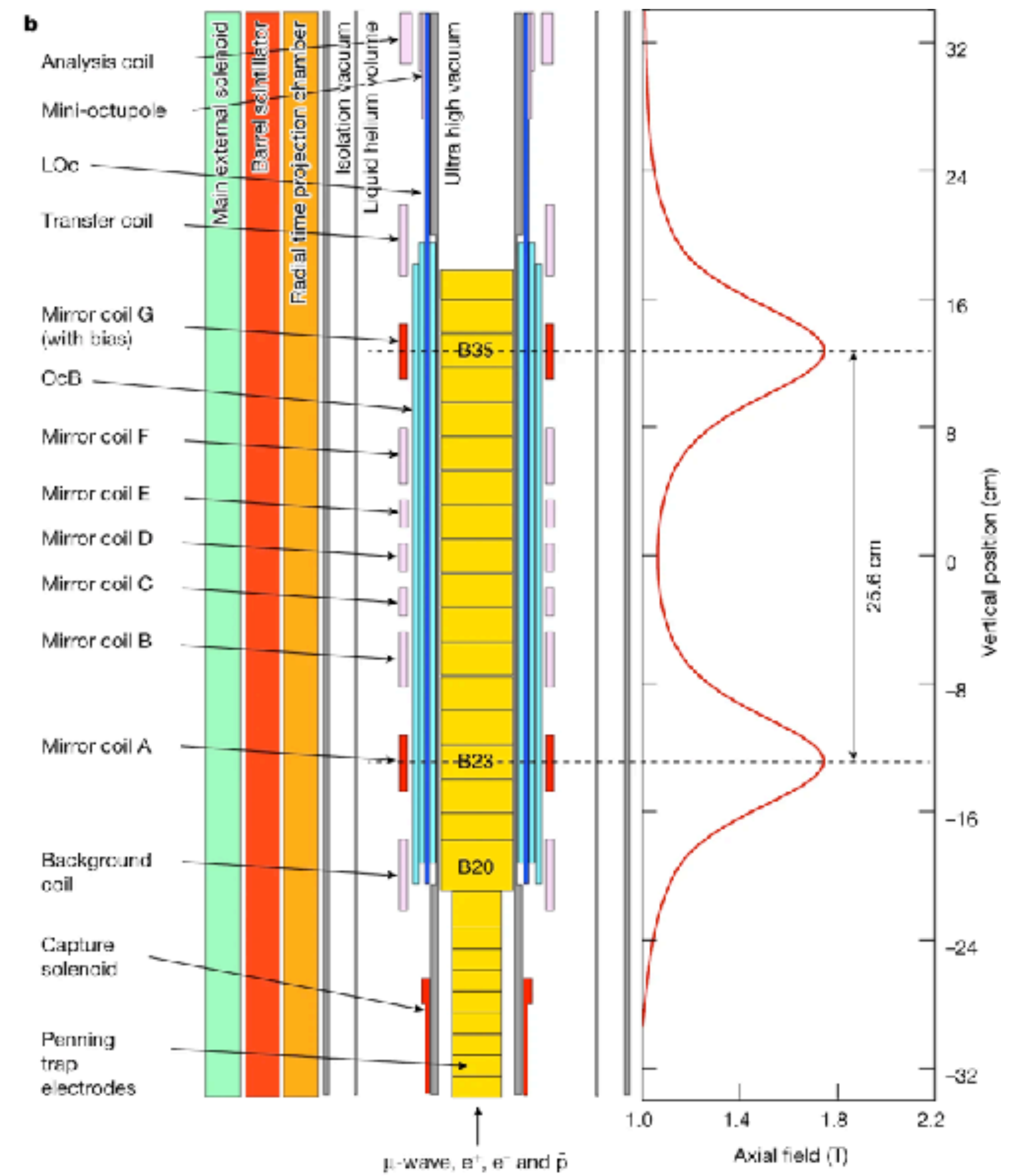
Data points obtained from the detected spin-flip events, normalized to the total number of trapped antihydrogen atoms

Nature 578, 375–380(2020)

Vertical trap → 1% measurement
- Laser cooling not necessary, though it helps.
- Slow down the magnet turnoff by a factor of ten.
- Turnoff the mirror coils only, radial confinement
- Current imbalance in mirror coils can tune the result
- Further future interferometry: atomic fountain measurements →0.0001%







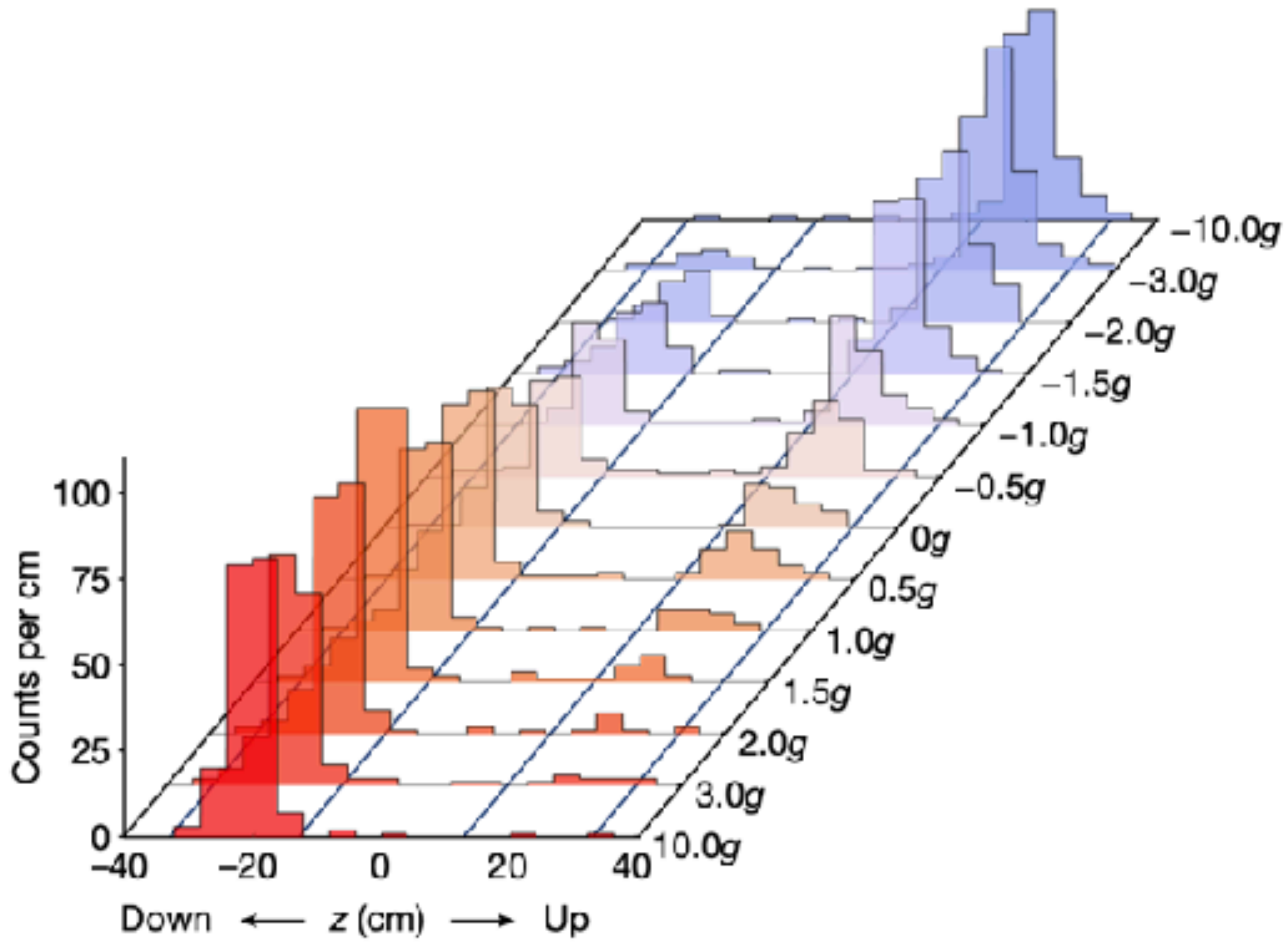
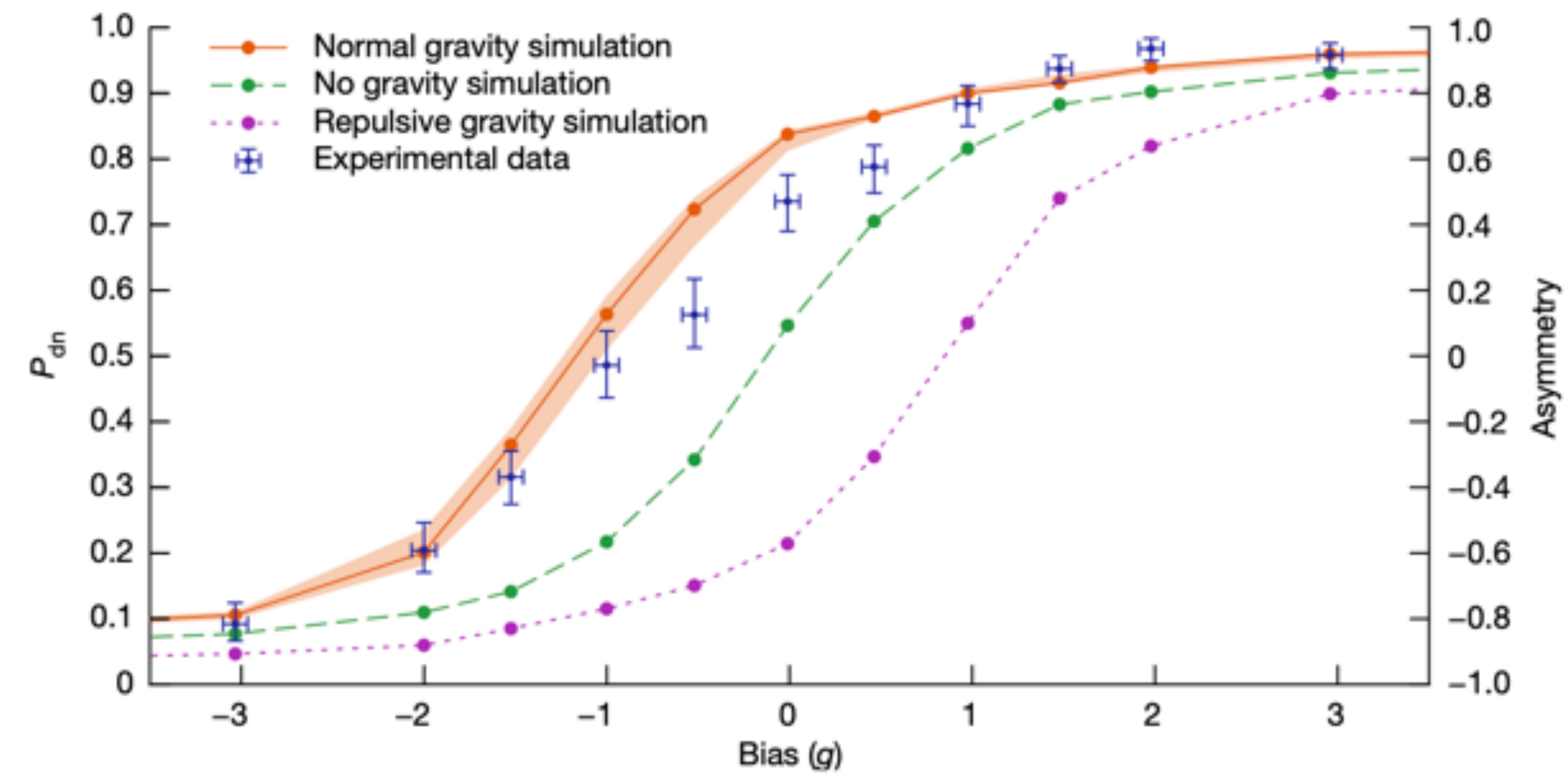


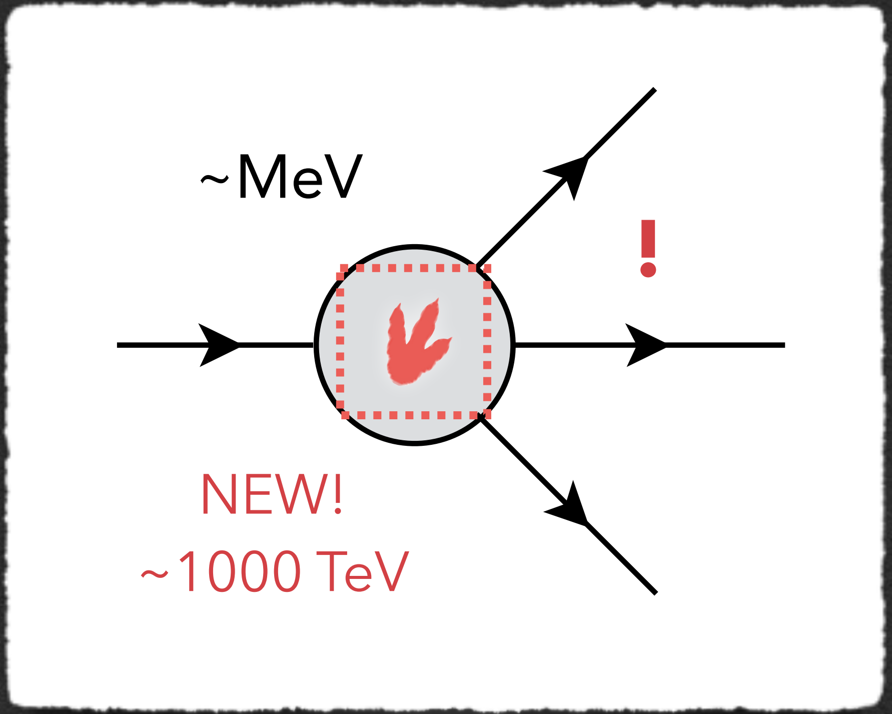
Fig. 3 | Escape histograms. The raw event z-distributions are displayed as histograms for each of the bias values, including the ±10g calibration runs. These are uncorrected for background or detector relative efficiency. The time window represented here is 10 s to 20 s of the magnet ramp-down. The z-cut regions are indicated by the solid, diagonal lines. Explicitly, the acceptance regions in z are [−32.8, −12.8] and [12.8, 32.8] cm for the 'down' and 'up' regions, respectively.



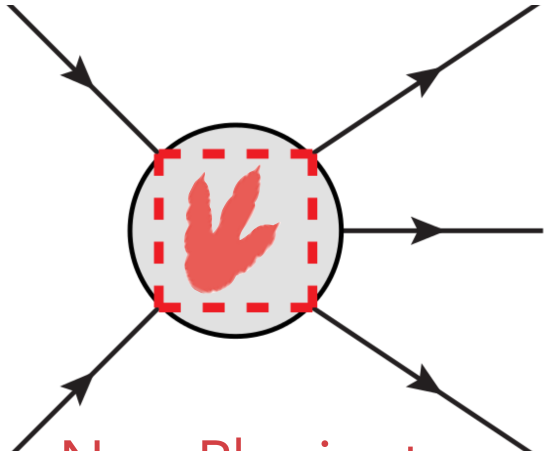
$$a_{\bar{g}} = (0.75 \pm 0.13 \text{ (statistical + systematic)} \pm 0.16 \text{ (simulation)})g, \text{ where } g = 9.81 \text{ m s}^{-2}$$

Nature **volume 621**, pages 716–722 (2023)

Precision decays

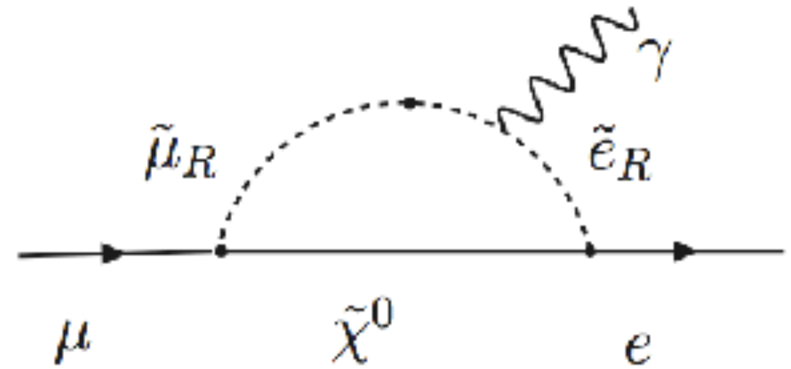


Decays forbidden by Standard Model



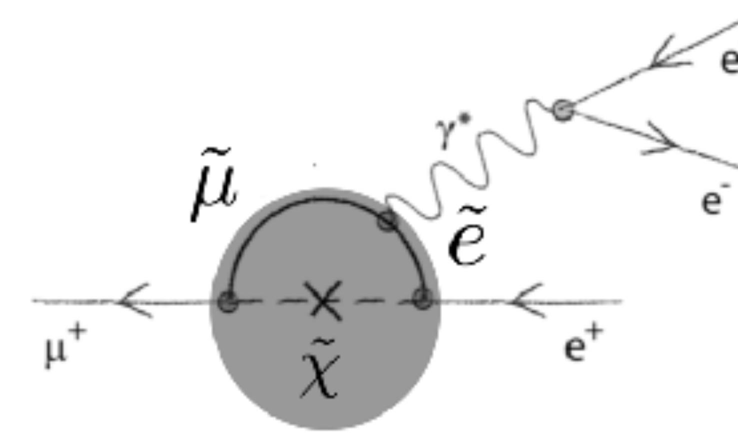
New Physics to
~ 1000 TeV scale

MEG



$$\mu^+ \rightarrow e^+ + \gamma$$

Mu3e

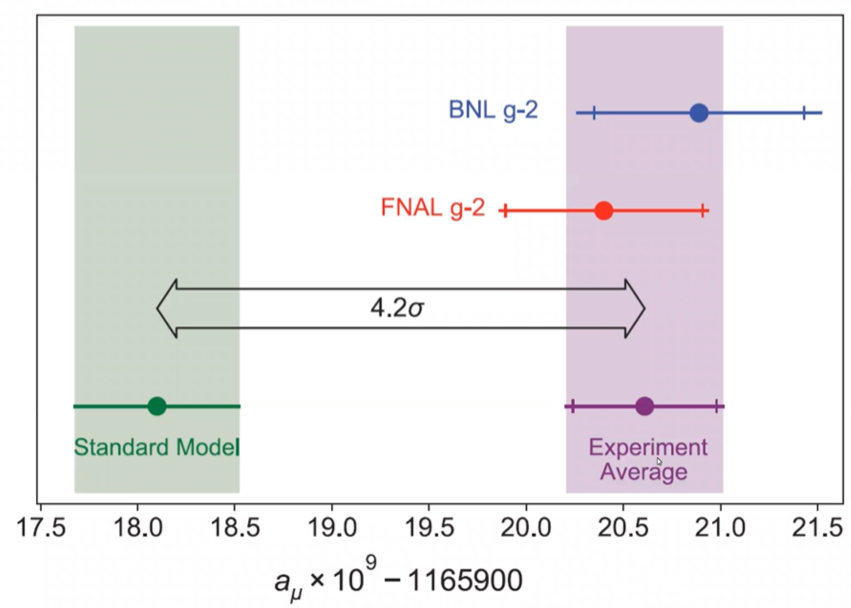


$$\mu^+ \rightarrow e^+ + e^- + e^+$$

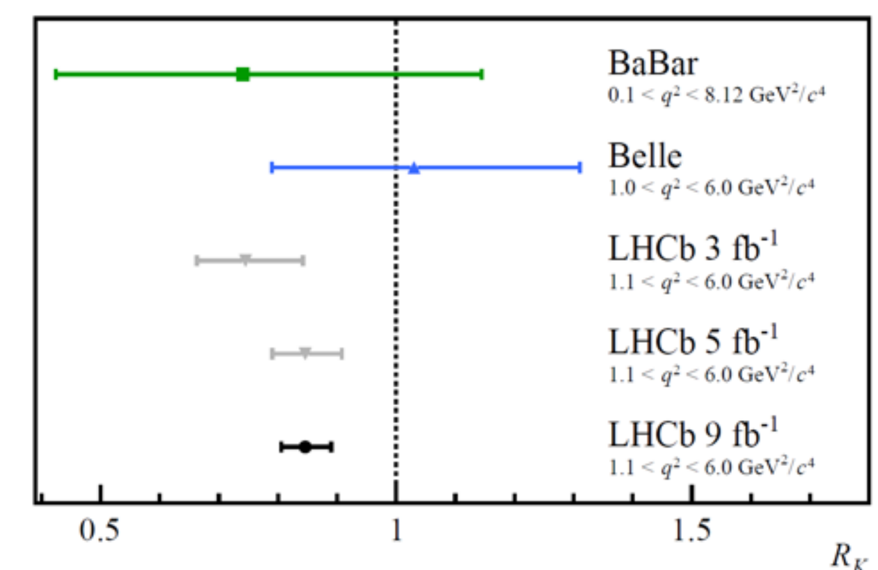
- Charged lepton flavour violation

- Flavour tensions piling up in multiple different experiments!

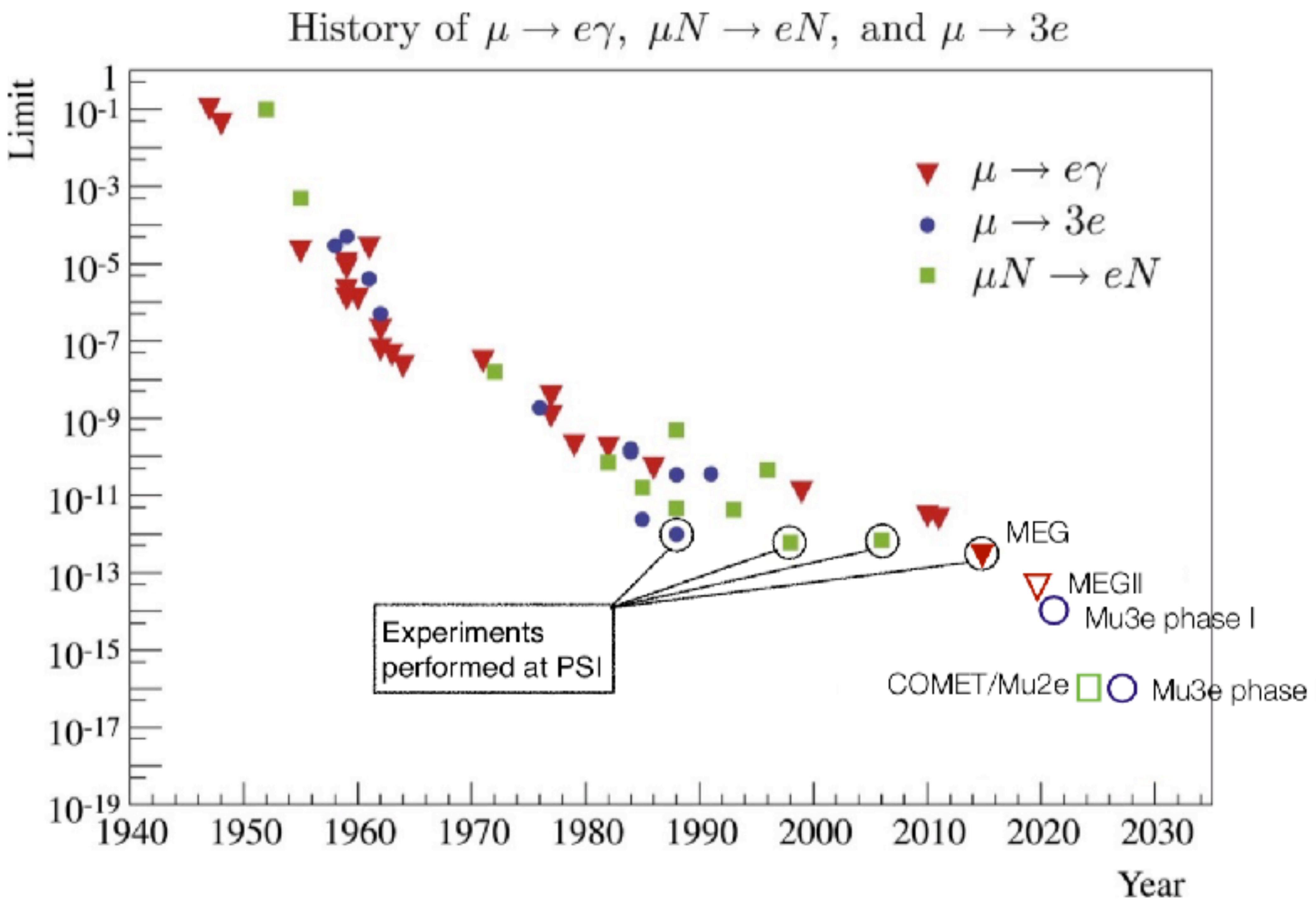
Muon g-2 (4.2 σ)



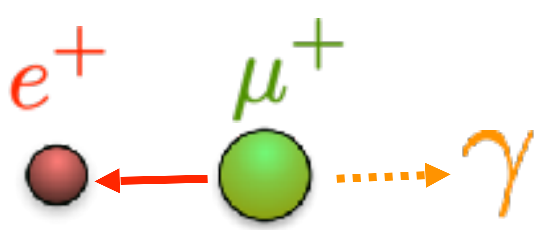
B Decays (2-4σ)



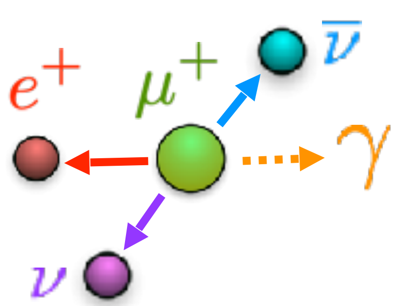
Searches for charged lepton flavor violation



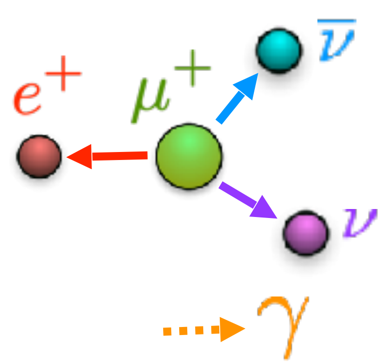
Signature



Backgrounds

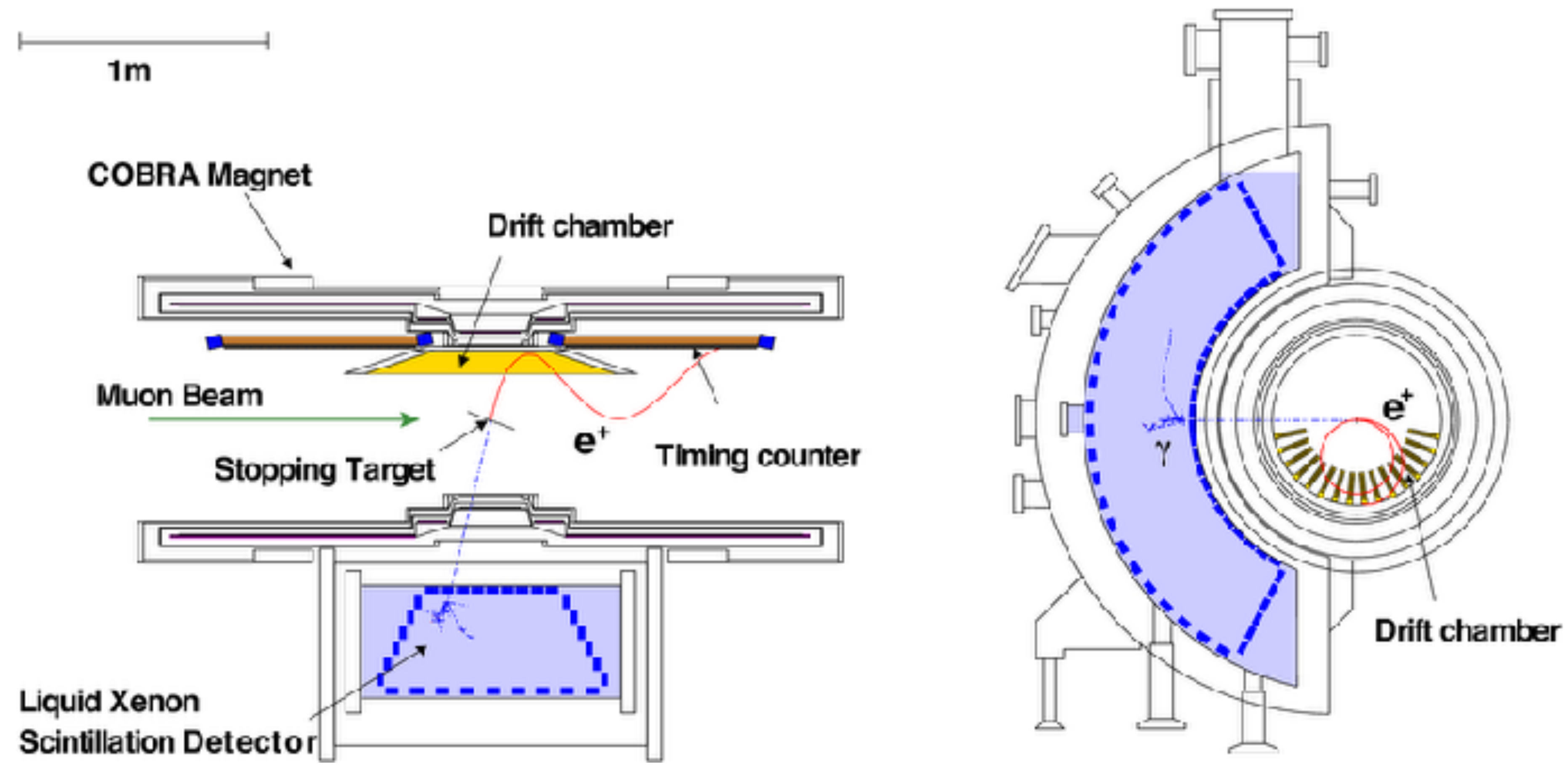


SM radiative



Accidental

MEG setup



Branching ratio at 90% C.L.:

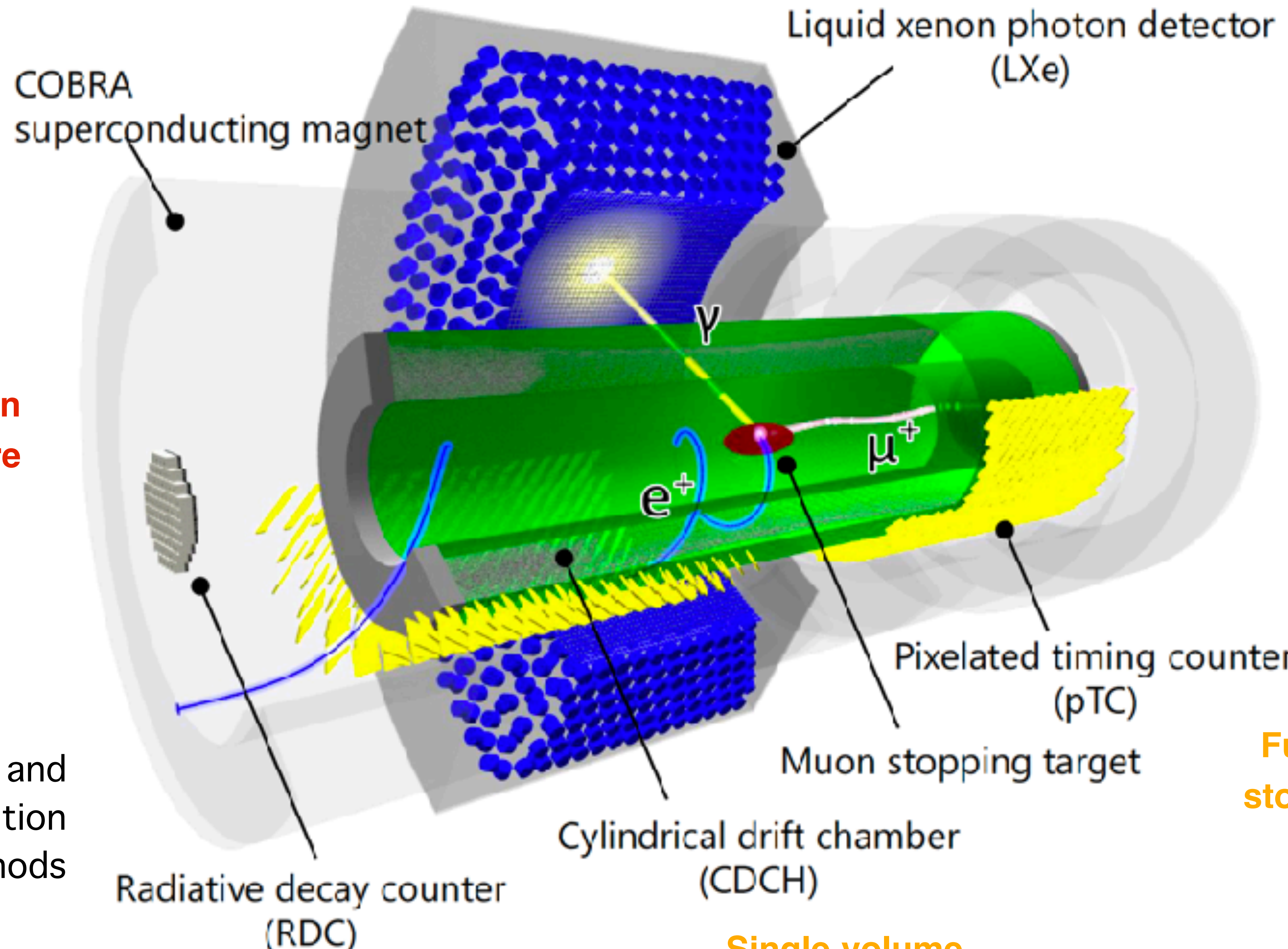
$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$$

MEG II setup

Better uniformity w/ 12x12 VUV SiPM

x2 Resolution everywhere

x2 Beam Intensity



35 ps resolution w/ multiple hits

Full available stopped beam intensity 7×10^7

Updated and new Calibration methods

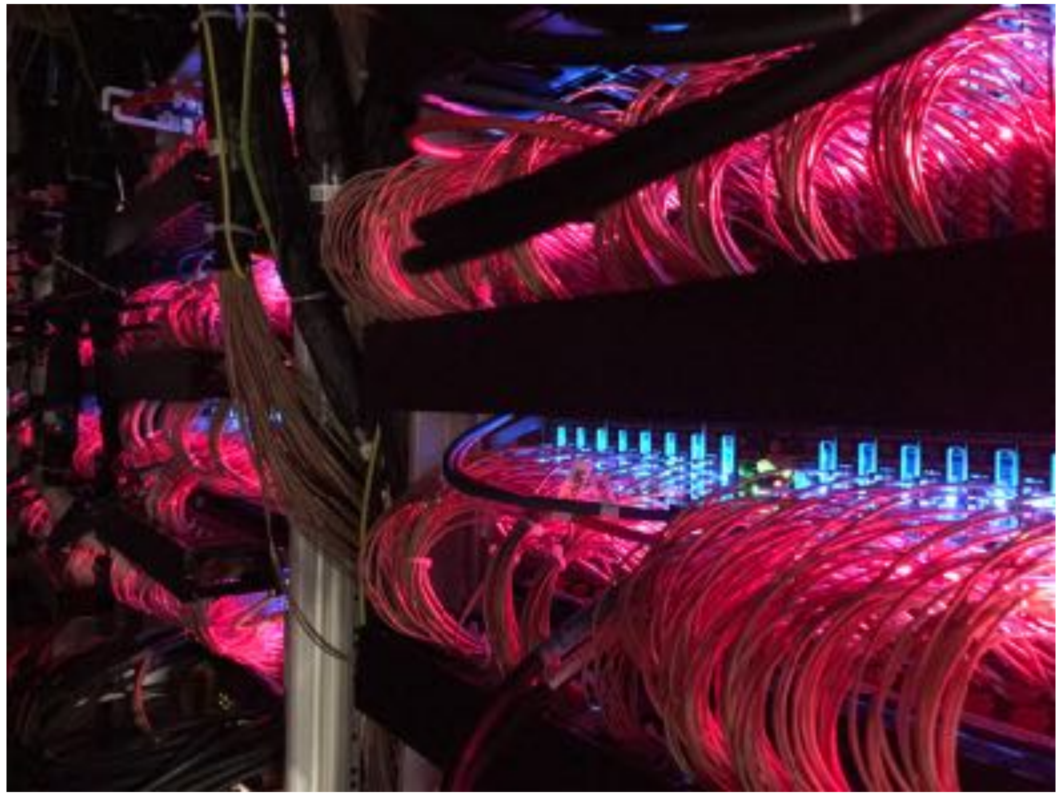
Quasi mono-chromatic positron beam

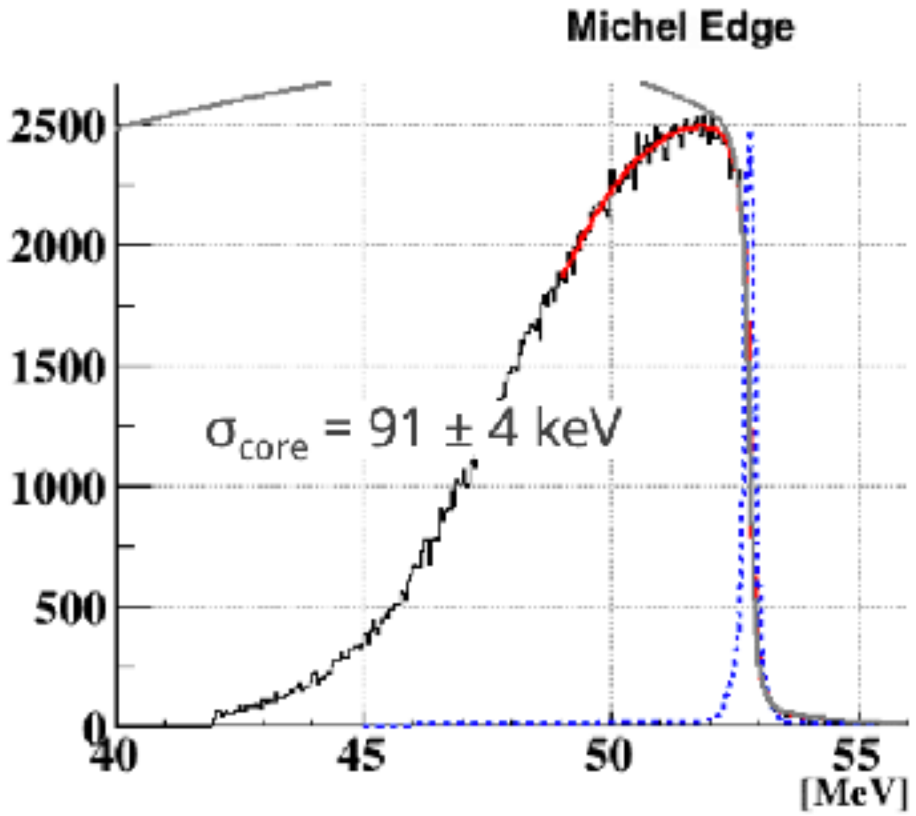
Background rejection

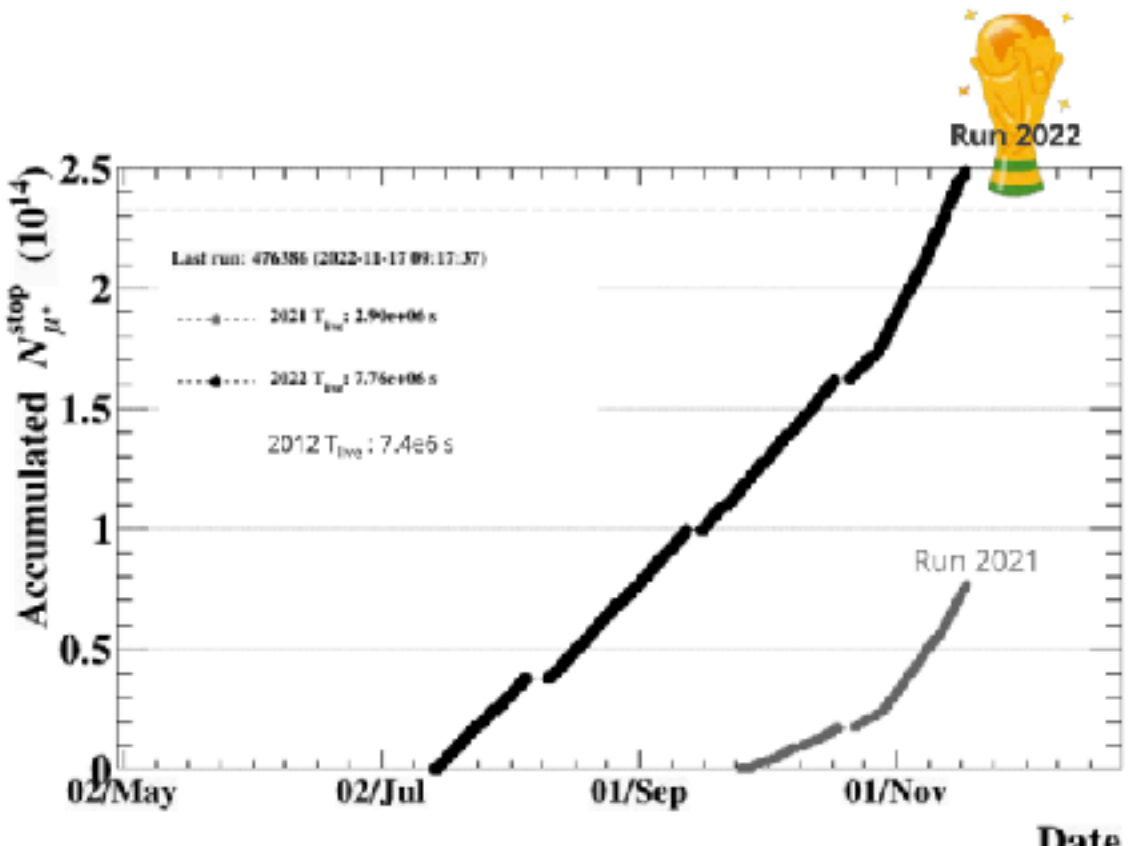
Single volume $He:iC_4H_{10}$

Latest news from MEG-2 and currents status

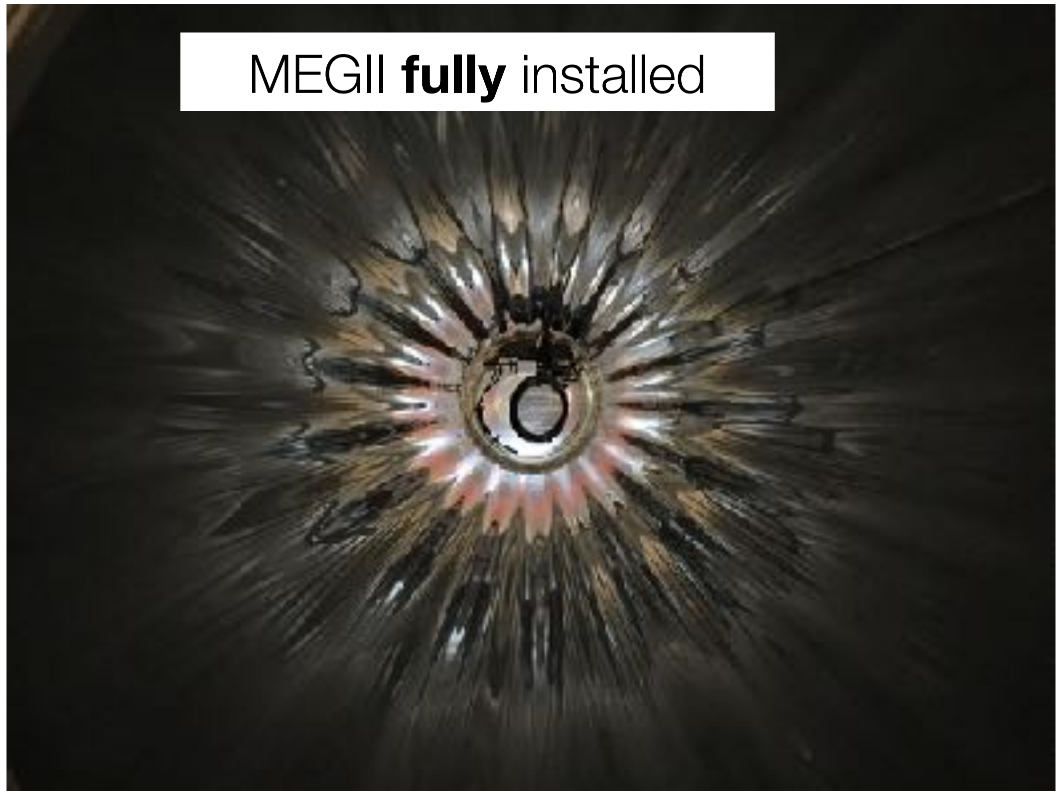
- Physics run started at the end of September 2021, collecting statistics at the moment
- Goal sensitivity of ~ 6×10^{14}
- Next to the main program: exotic searches, like X17



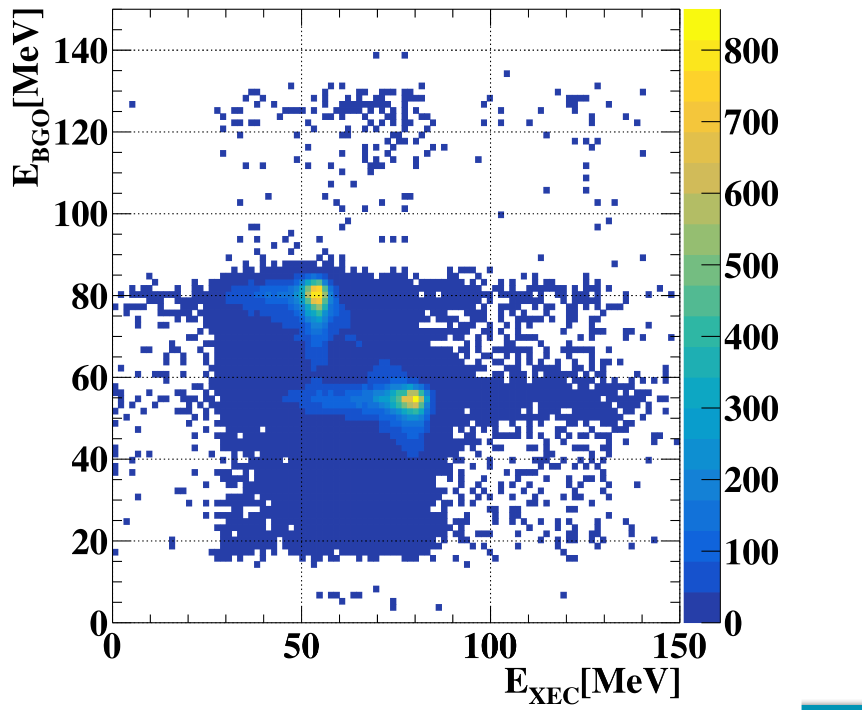




Longest run we ever achieved, ×3 statistics of 2021

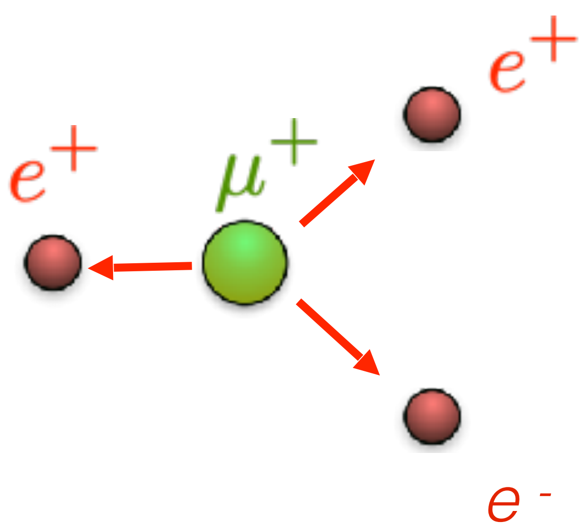


Data from the **first** Physics Run2021



Mu3e, the $\mu^+ \rightarrow e^+ e^+ e^-$ search

Signature event

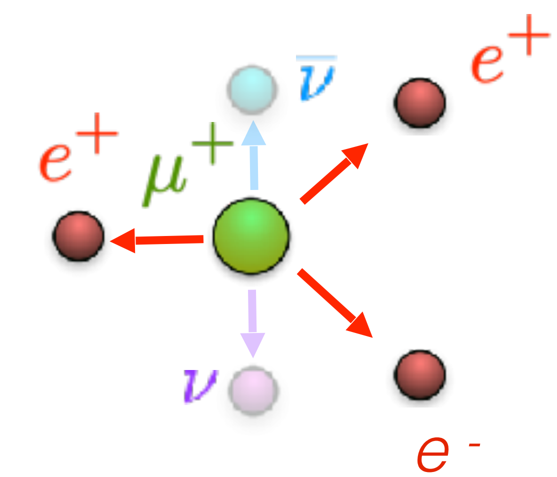


$\Delta t_{eee} = 0$

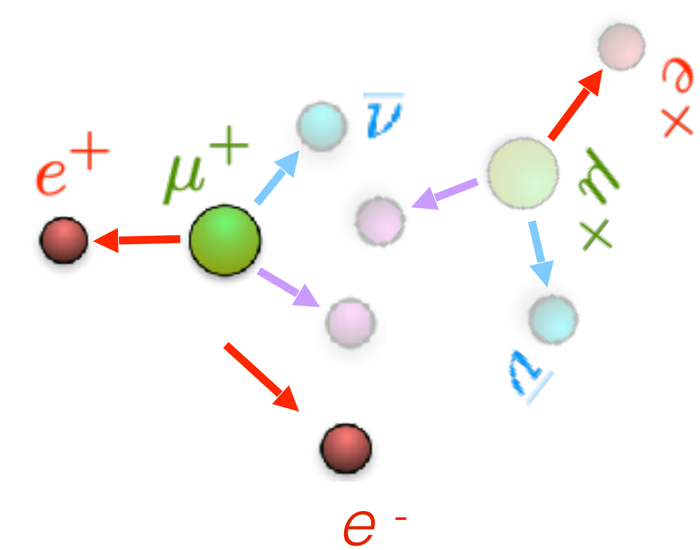
$\Sigma \overline{p}_e = 0$

$\Sigma E_e = m_\mu$

Background



- SM allowed

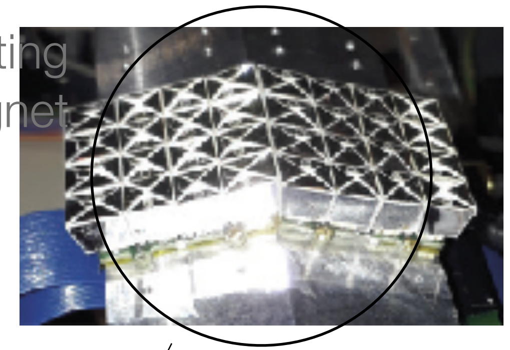


- Accidental
- Bhaba-scatterin

Mu3e experiment - hardware construction

Superconducting solenoid Magnet

Homogeneous field 1T

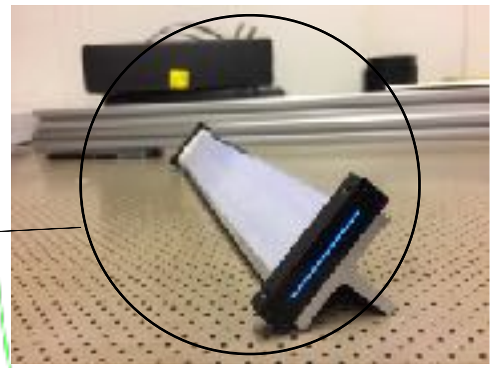


Tile detector

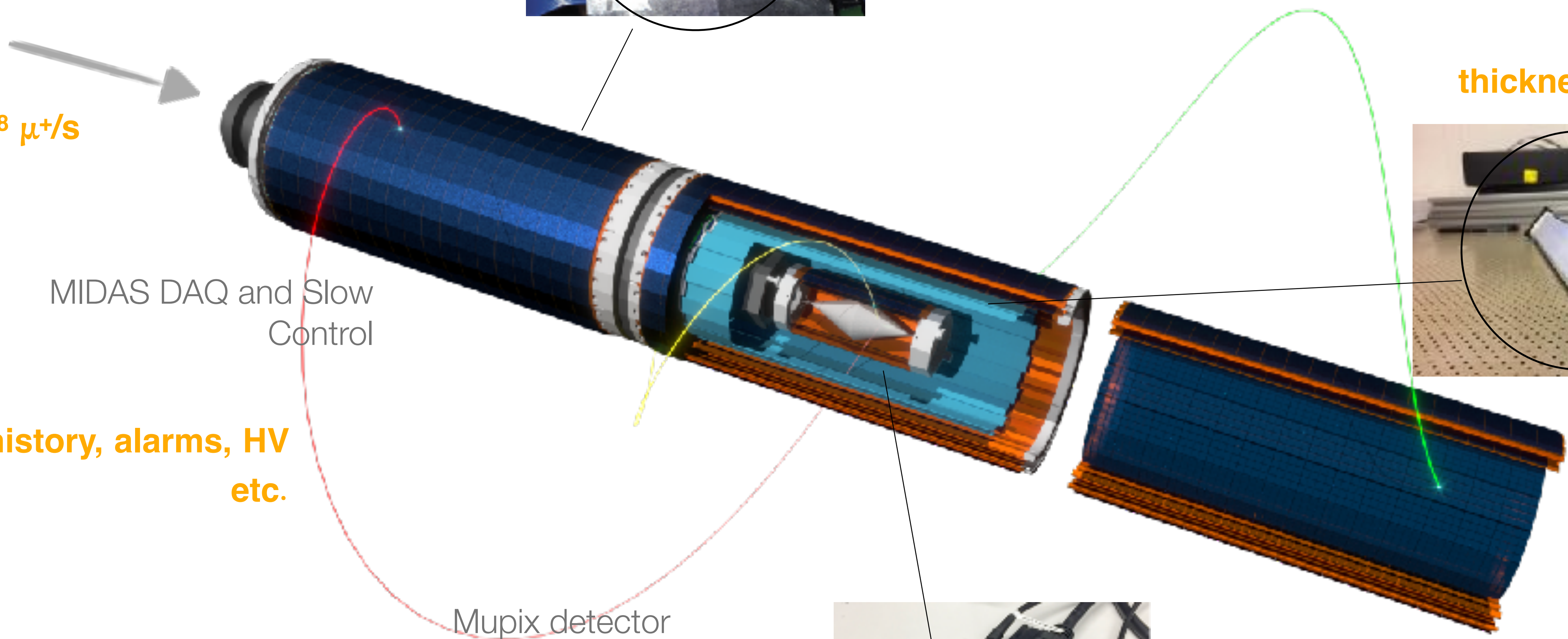
70 ps resolution w/ single hit

Fibre hodoscope

< 500 ps resolution w/ multi hits thickness: < 0.3% X_0



10^8 μ^+/s

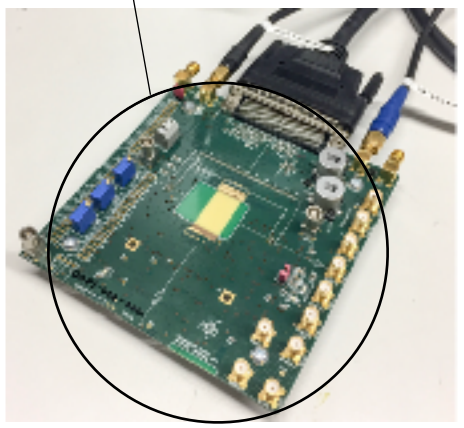


MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Mupix detector

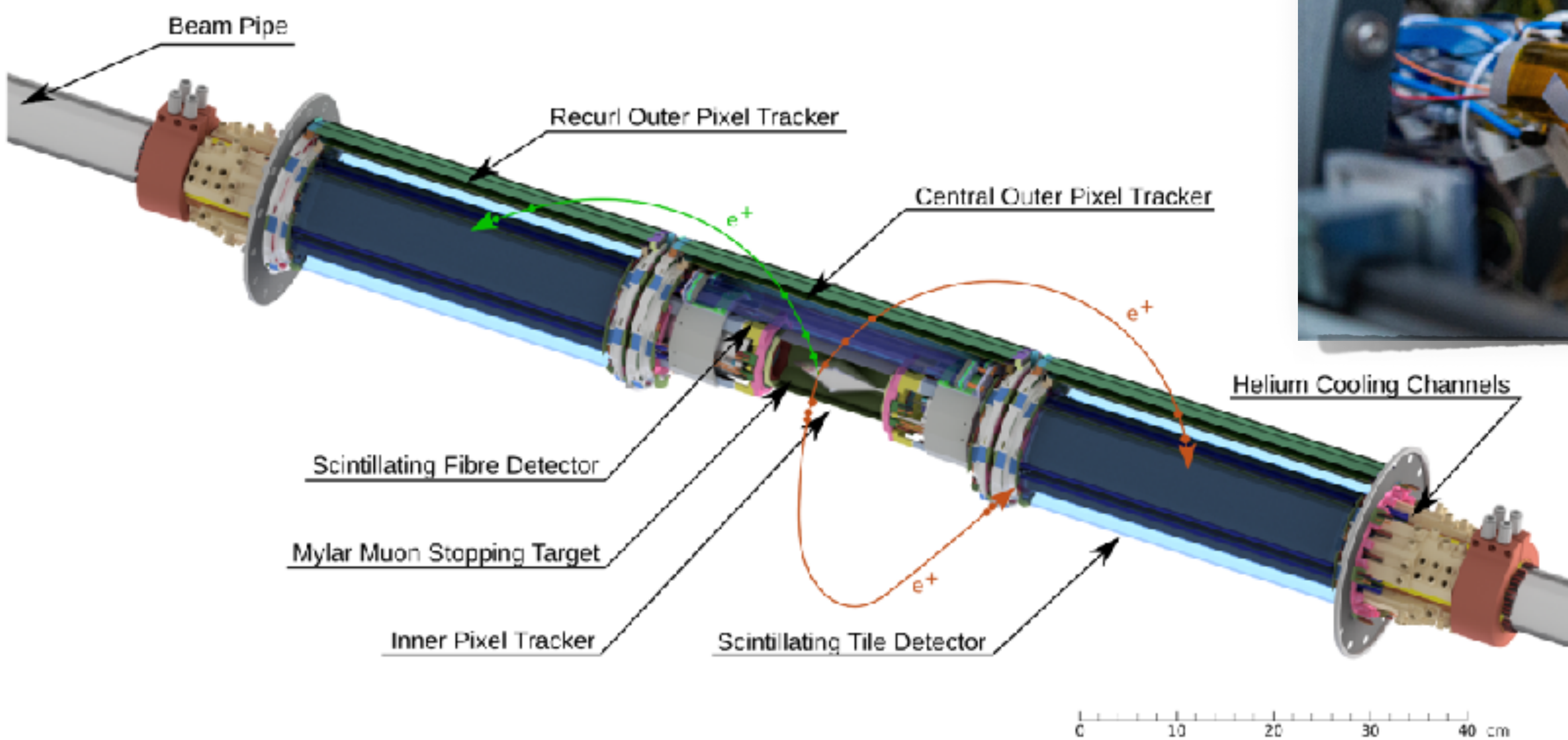
Tracking, integrate sensor and readout in the same device: 50 um thick 1 layer: ~ 0.1% X_0

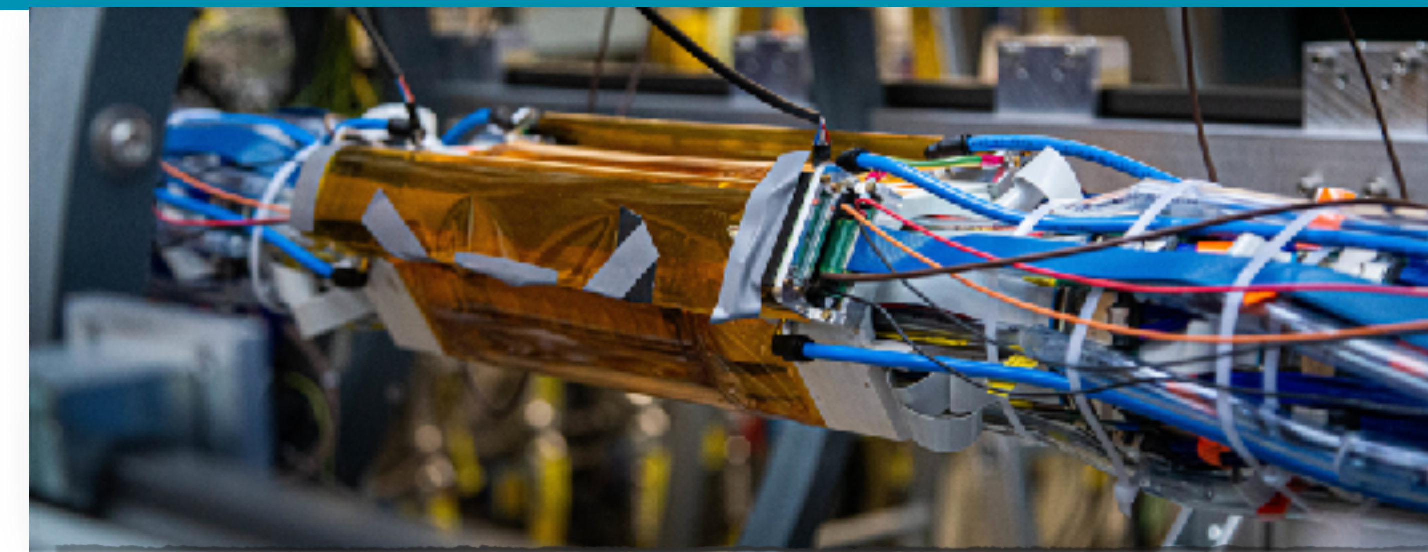


Muon Beam and target

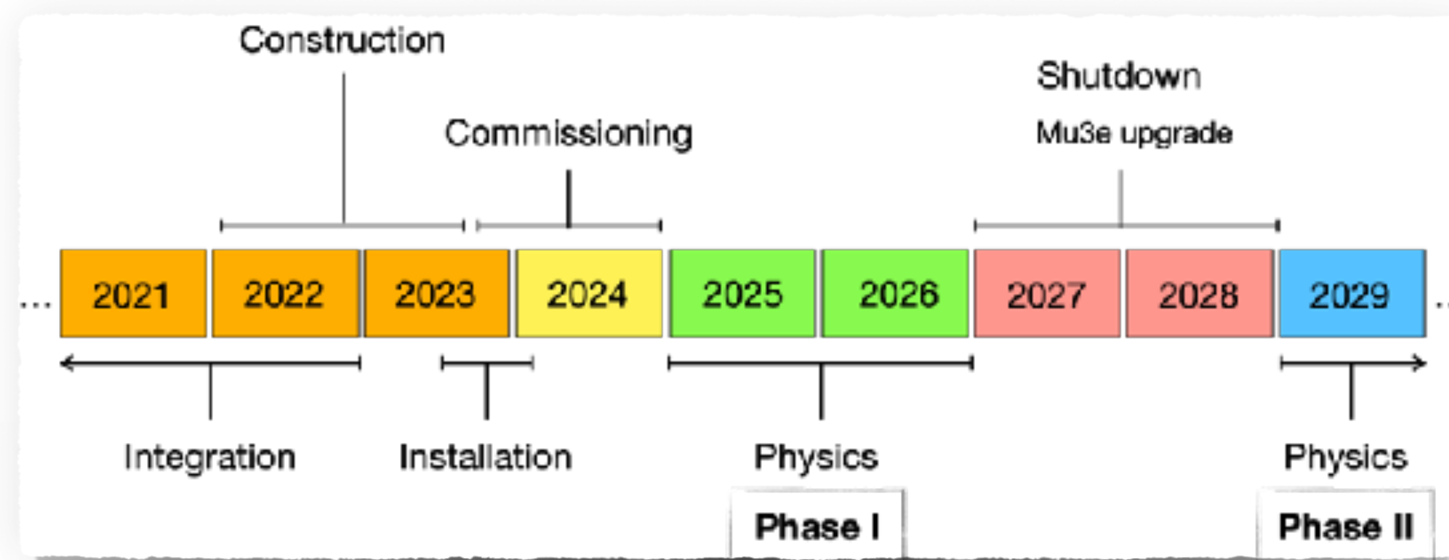
Full available beam intensity O(10^8)

Mu3e status





- **Experimental design** is complete and has been extensively validated
- Two few-month-long **commissioning** runs
- Phase I **construction** has started (production and quality-control pipelines are being consolidated) and the **installation** at PSI is foreseen for the end of 2023

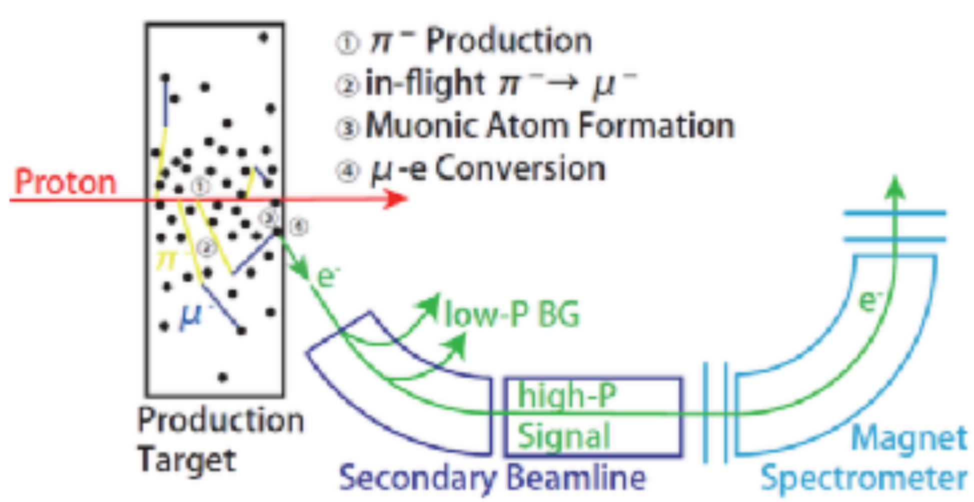


Searches for Muon to Electron conversions

- Current best limit: $B(\mu^- N \rightarrow e^- N) < 6.5 \times 10^{-13}$ (90% C.L., Ti) Eggli, Thesis Uni. Zürich (1995)
  $B(\mu^- N \rightarrow e^- N) < 7.0 \times 10^{-13}$ (90% C.L., Au) Bertl et al., Eur. Phys. J. C **47**, 337 (2006)

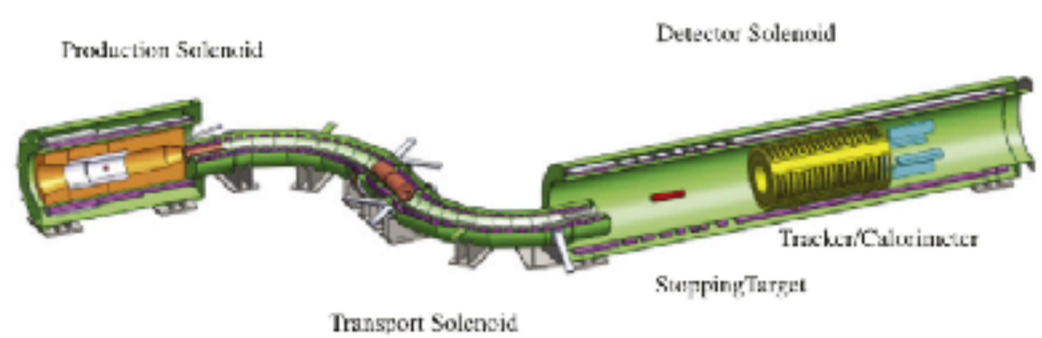
- To reduce backgrounds requires pulsed beams
- Efforts under way at J-PARC and Fermilab

DeeMe at J-PARC



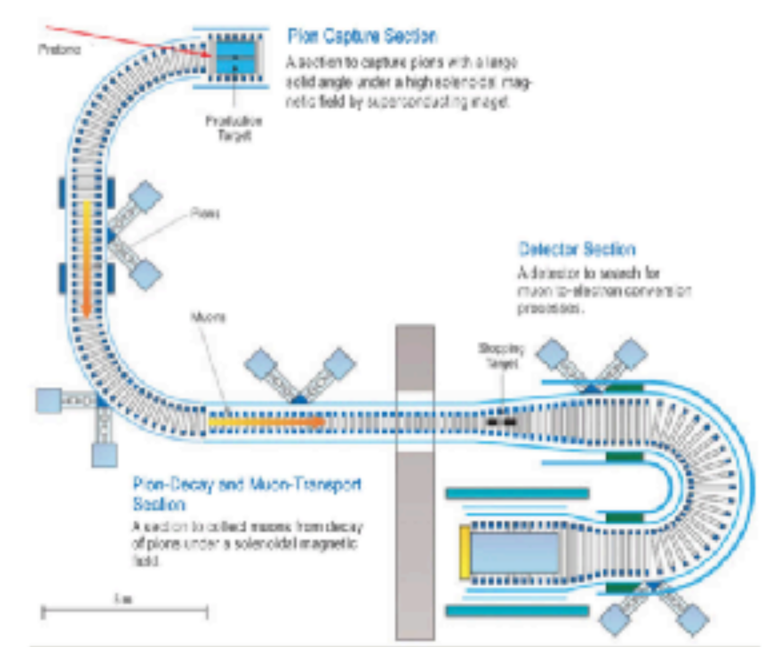
Improve limit by 1 - 2 orders of magnitude depending on target

Mu2e at J-Fermilab



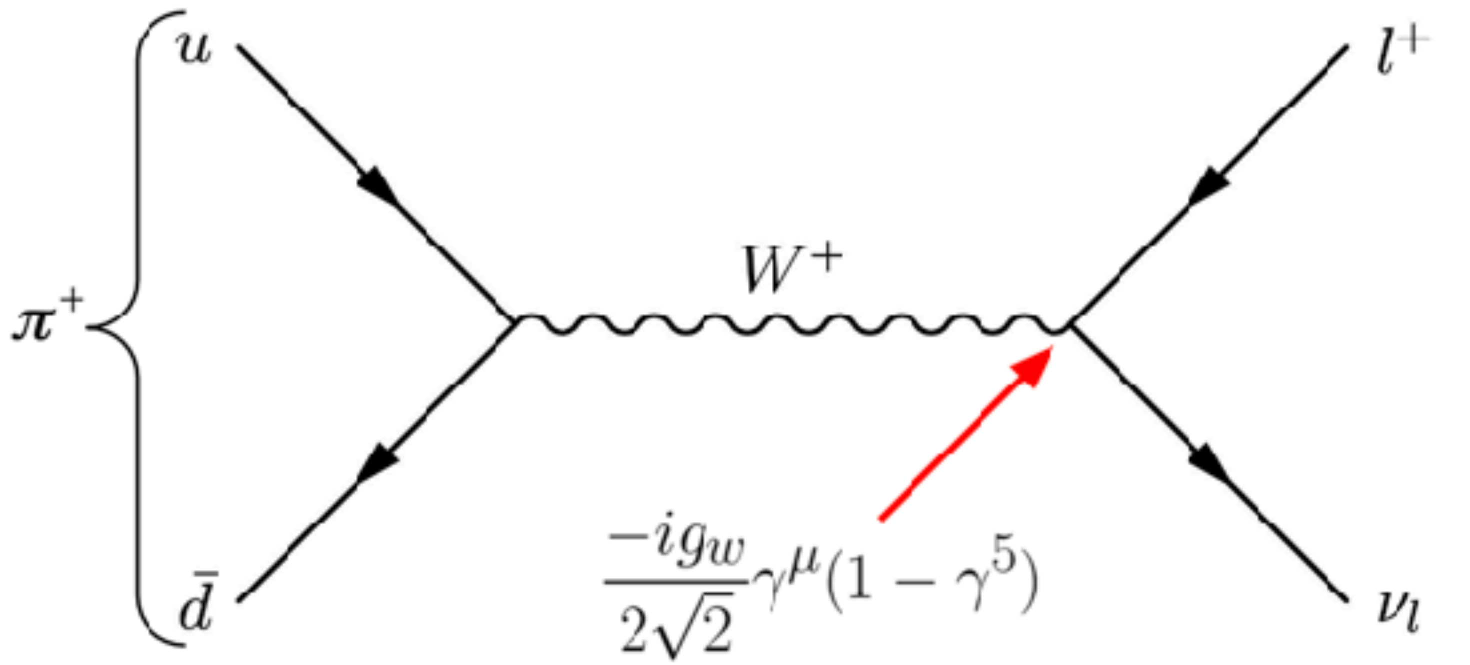
Improve limit by 4 orders by 2025

COMET at J-PARC



Improve limit by 2 orders by 2020 and 4 orders by 2023

Phase I. Branching ratios to leptons



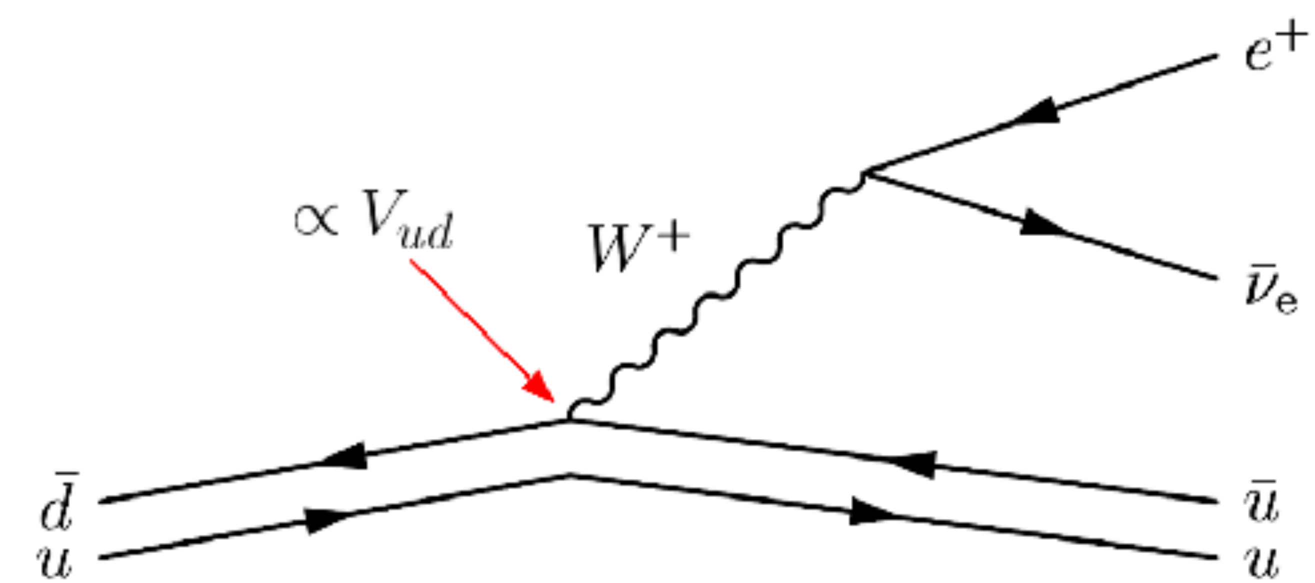
Current situation:

- SM[1]: $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.23524(15) \times 10^{-4}$
- Exp.[2]: $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.2327(23) \times 10^{-4}$

Phase II. Pion beta decay

PIONEER goals:

- Measure pion beta-decay for a direct measurement of V_{ud}:

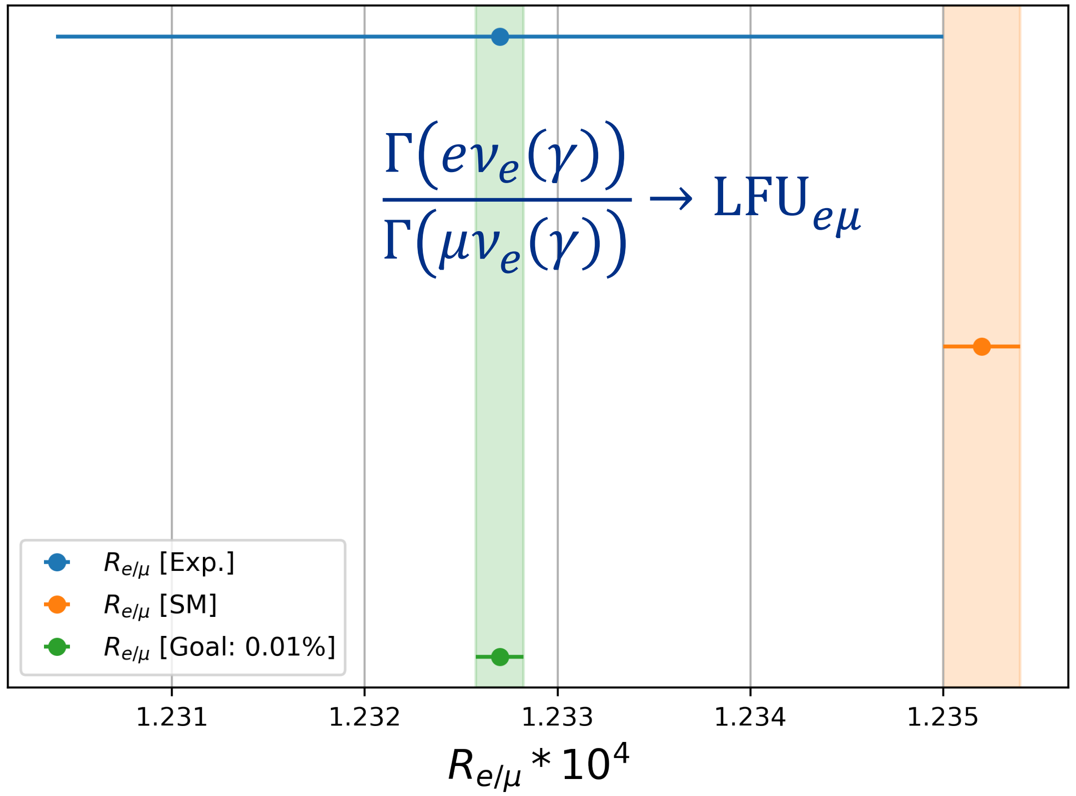


1 & 2: Altmannshofer, W., et al. arXiv preprint (2022) arXiv:2203.01981 [hep-ex].
1: V. Cirigliano and I. Rosell, Phys. Rev. Lett. 99, 231801 (2007), arXiv:0707.3439 [hep-ph].
2: A. Aguilar-Arevalo et al. (PIENU), Phys. Rev. Lett. 115, 071801 (2015), arXiv:1506.05845 [hep-ex]

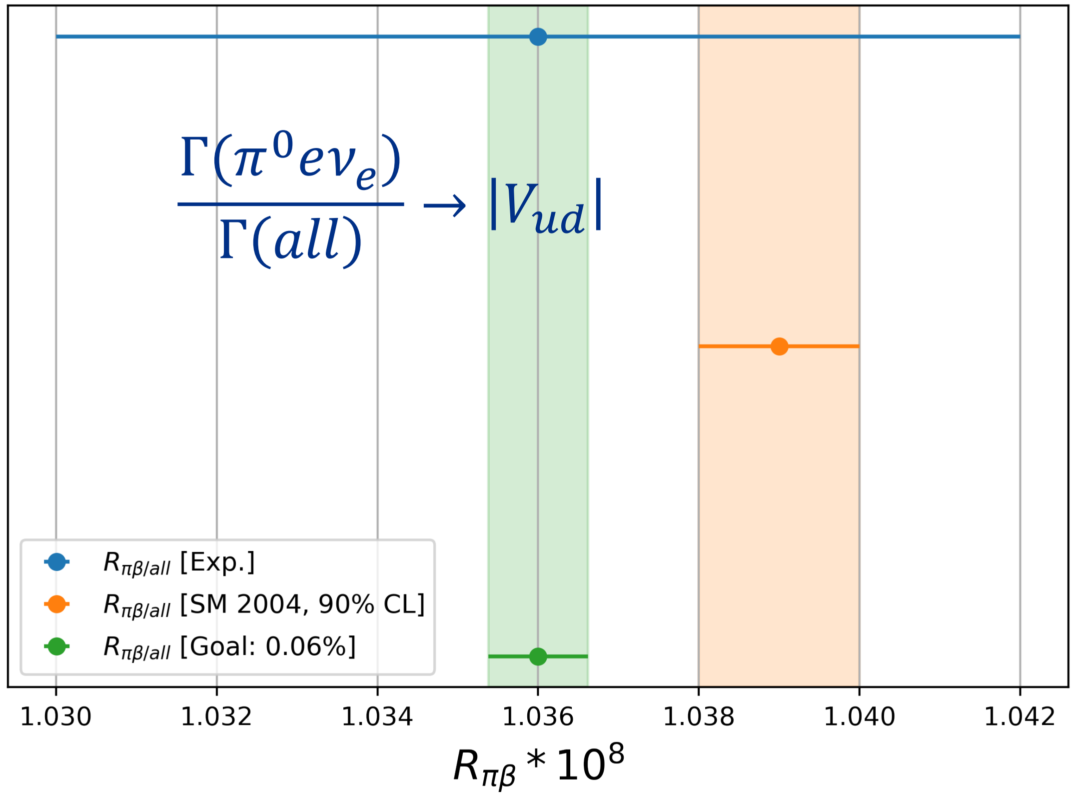
3: R. Aaij et al. (LHCb), Phys. Rev. D 97, 072013 (2018), arXiv:1711.02505 [hep-ex].
4: D. P. Aguillard et al. (The Muon g−2 Collaboration) Phys. Rev. Lett. 131, 161802 (2023) arXiv:2308.06230 [hep-ex].
5: A. Carvunis, A. Crivellin, D. Guadagnoli, and S. Gangal, (2021), arXiv:2106.09610 [hep-ph].

Goals of the PIONEER measurements

- Phase I: approach theoretical predictions (x15)



- Phase II: 3-10 fold increase



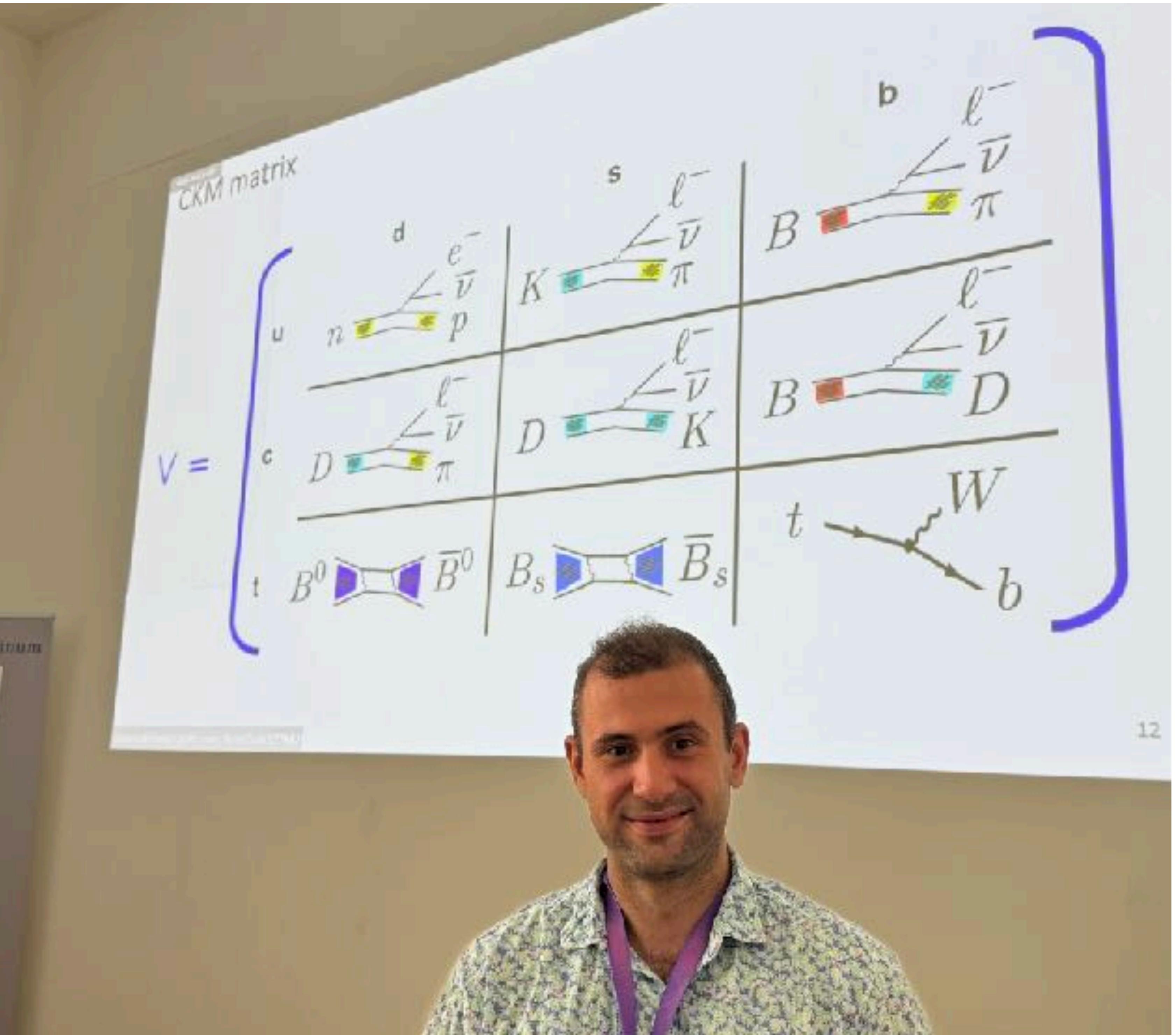
Motivation:

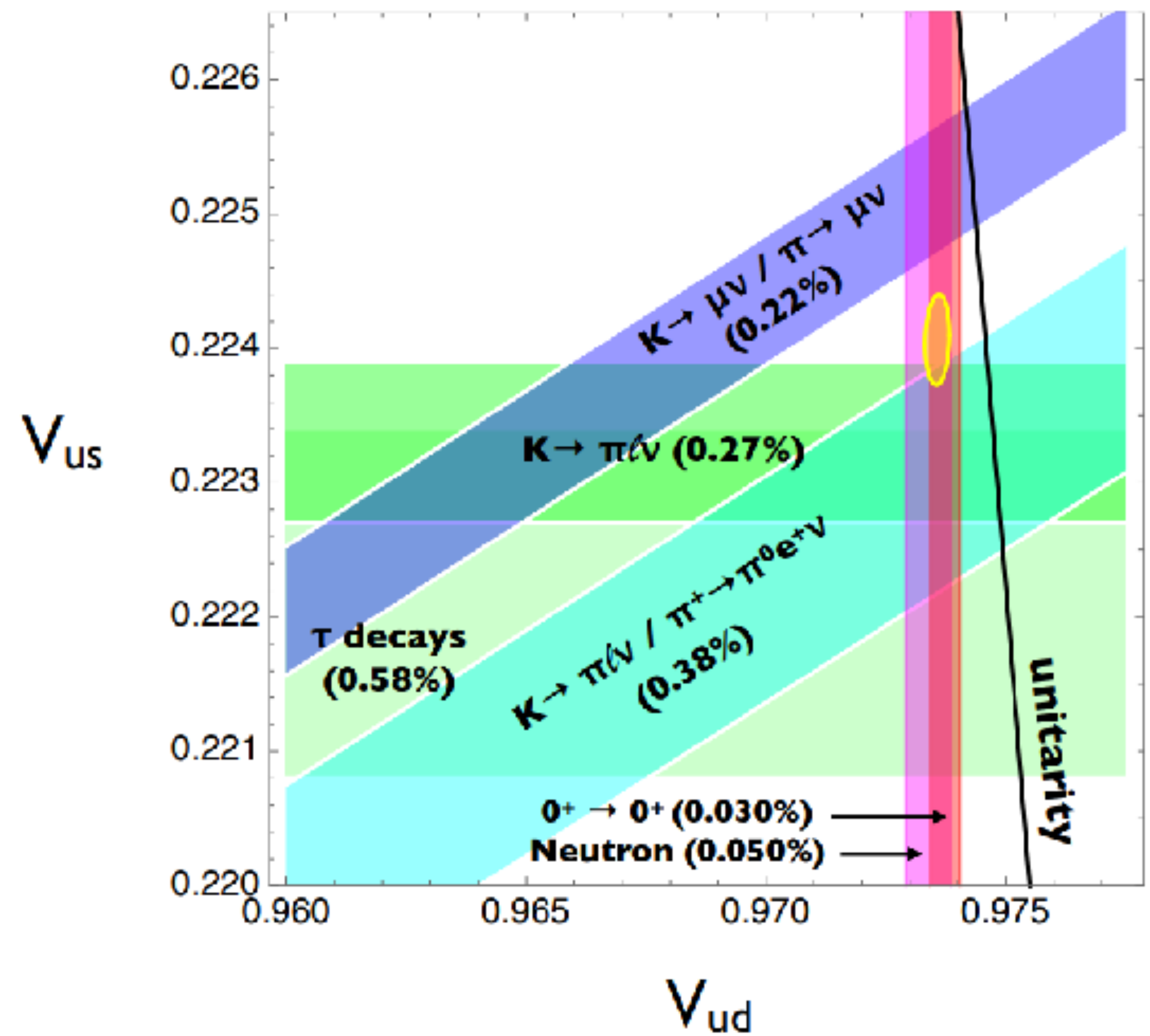
- Hints for lepton flavour universality violation in $B \rightarrow D^{(*)}$ decays[3]
- Anomalous μ magnetic moment measurement[4]
- Observed forward-backward asymmetry in $B \rightarrow D^{(*)}$ decays to e/μ[5]

Motivation:

- Hints for Cabibbo angle anomaly combining results of various experiments[3]

https://arxiv.org/abs/2203.01981

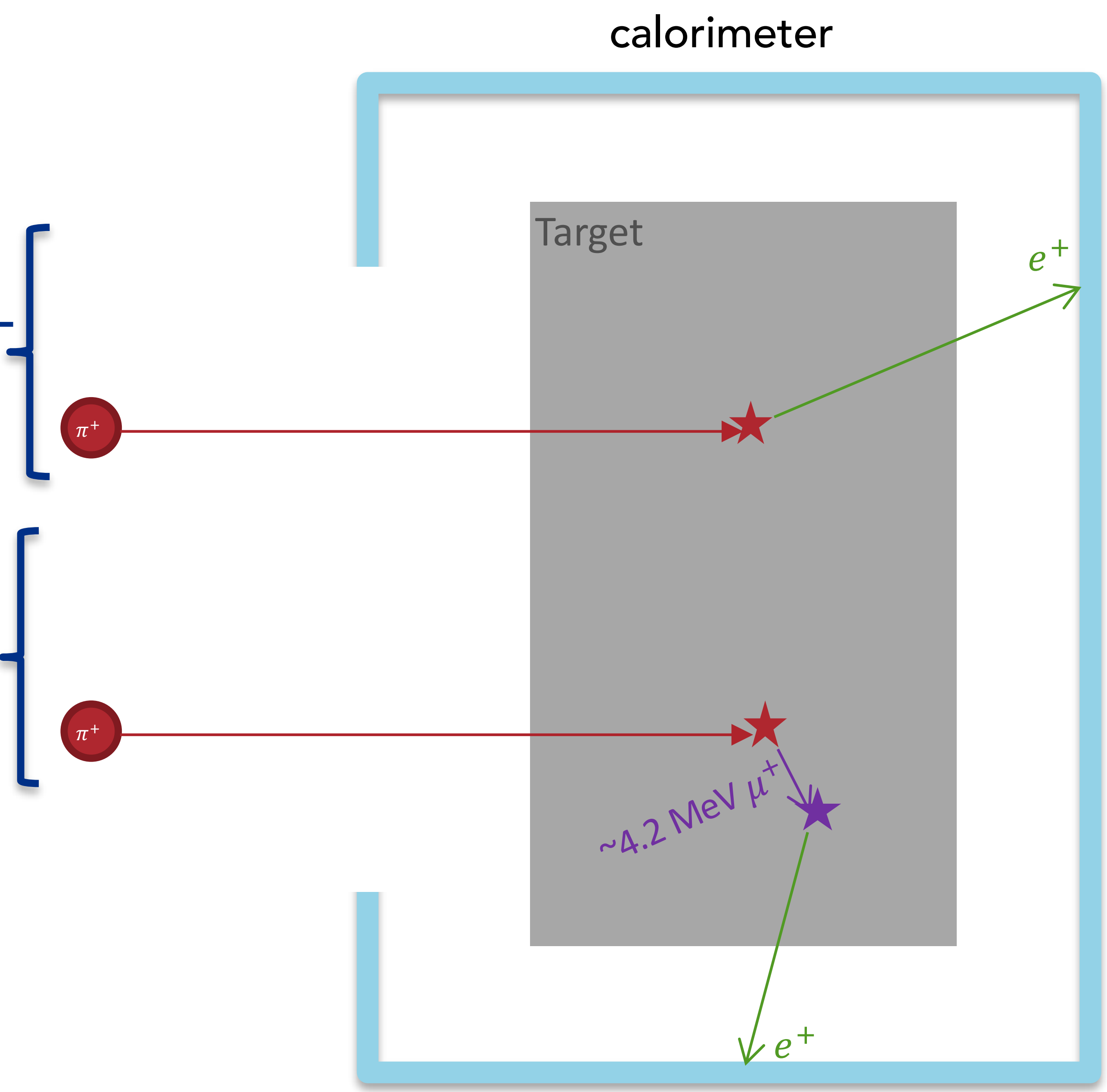

CKM matrix
V =
d
s
b
u
c
t
12

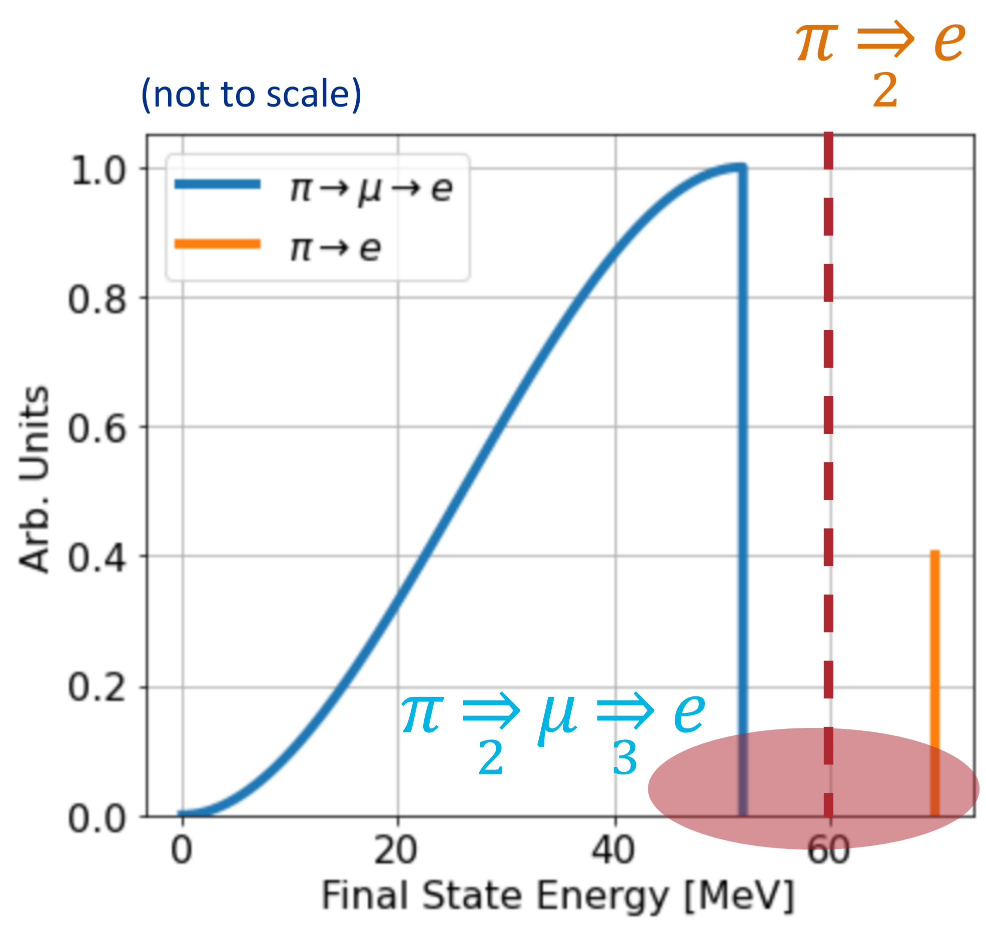

V_{us}
V_{ud}
0.226
0.225
0.224
0.223
0.222
0.221
0.220
0.960
0.965
0.970
0.975
K→ μν / π→ μν (0.22%)
K→ πℓν (0.27%)
τ decays (0.58%)
K→ πℓν / π⁺→π⁰e⁺ν (0.38%)
0⁺ → 0⁺ (0.030%)
Neutron (0.050%)
unitarity

How to measure a branching ratio?

$$\pi^+ \rightarrow e^+$$

$$\pi^+ \rightarrow \mu^+ \rightarrow e^+$$

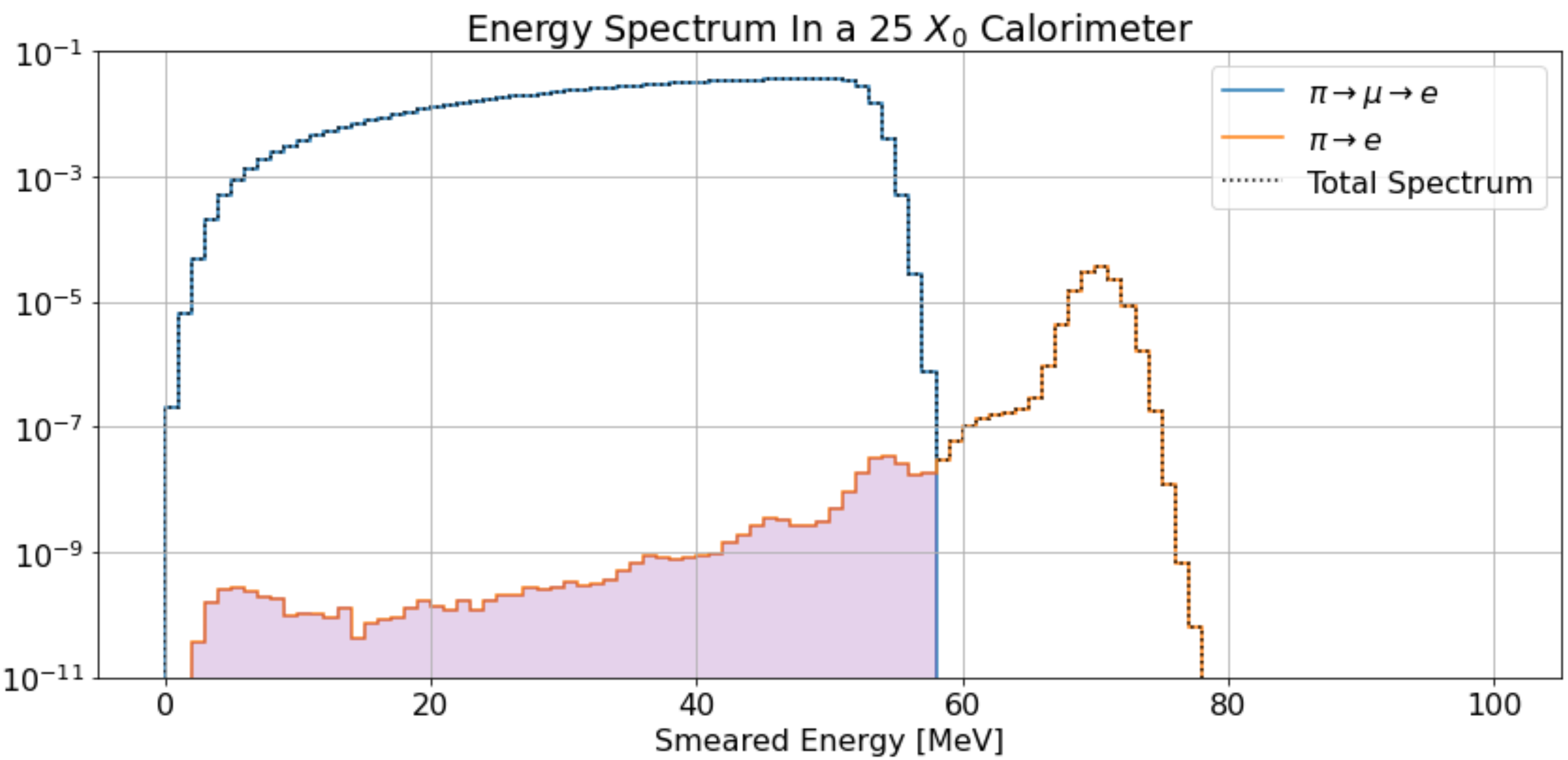


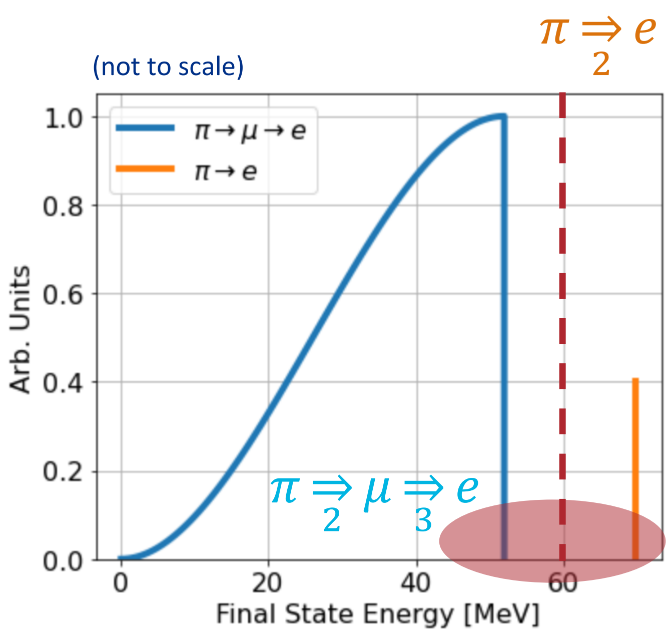


$$R_{e/\mu} = \frac{N_{right}}{N_{left}}$$

Pion
Muon
Electron

The devil in the details: measuring tails in an energy spectra





$$R_{e/\mu} = \frac{N_{right}}{N_{left}}[1 + C_{tail}]$$

The key to success: measure the tail!

What we need: a trigger to suppress π→μ

PIONEER schematics

PIONEER will need:

① High intensity, low momentum **pion beam**

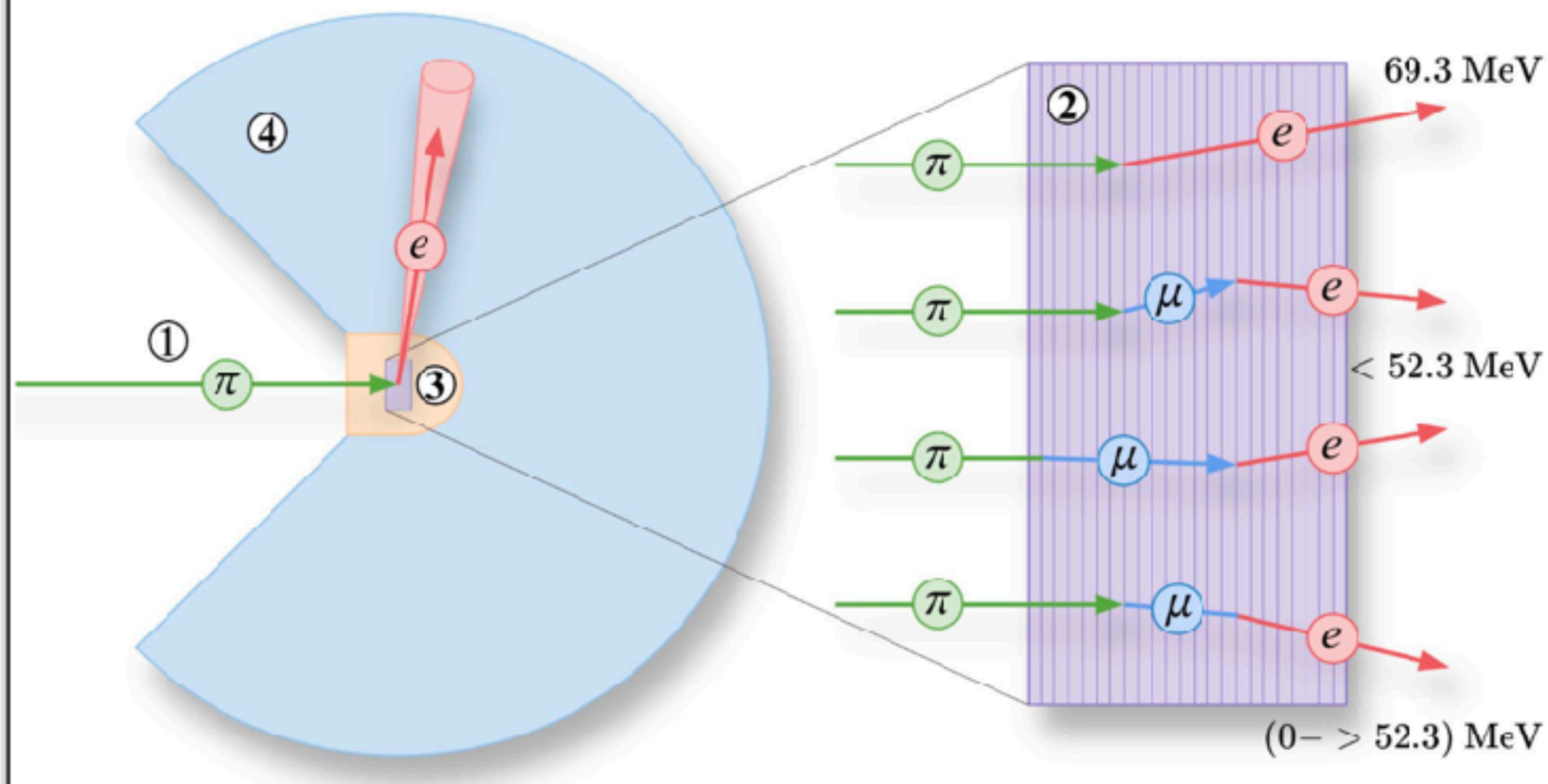
② Highly segmented **active target (ATAR)** with good energy and time resolution

③ **Tracker** to link ATAR and calorimeter signal

④ Fast **calorimeter** with excellent energy resolution, 25 radiation lengths deep and covering 3π sr solid angle

⑤ Entrance detectors, fast readout and electronics, DAQ,..

Schematic plan:



From S.Hochrein

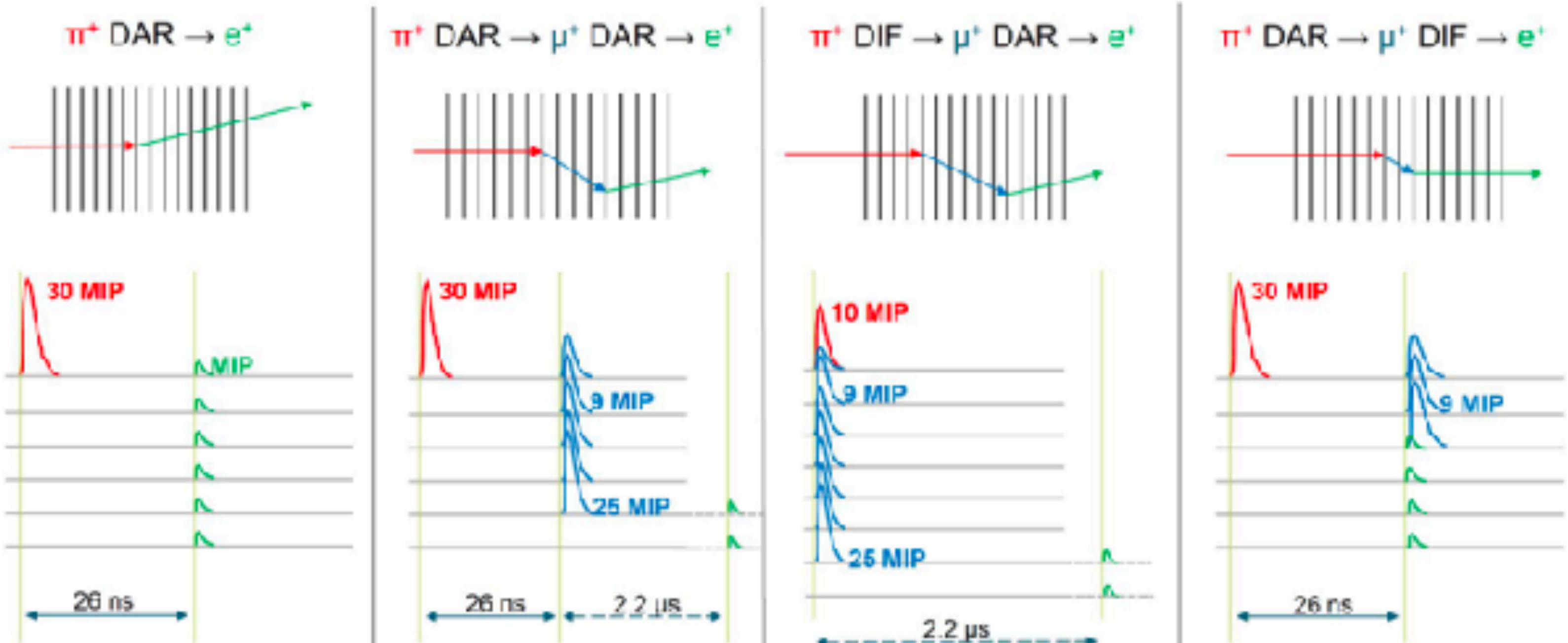
The sensitive target - ATAR

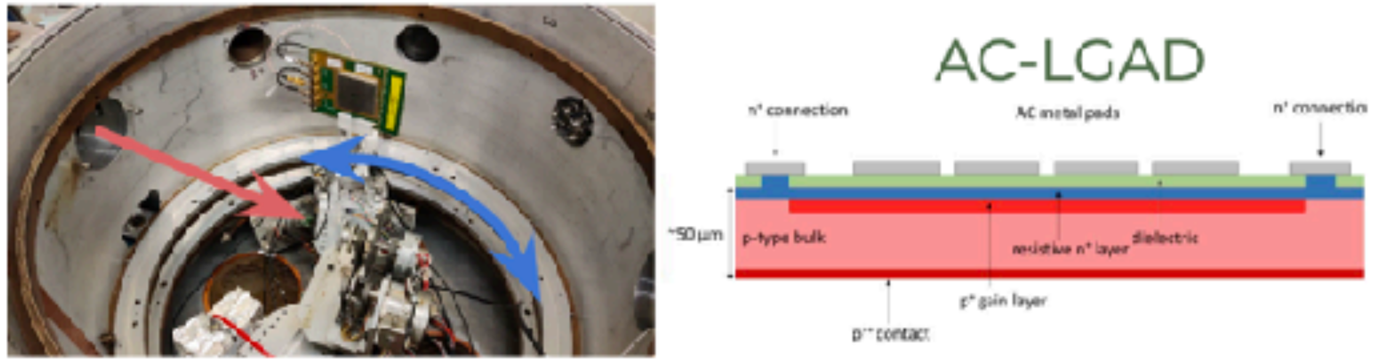
Test beam 2023 at CENPA:

- Characterization of AC-LGAD prototypes
- Measurement of angular dependent gain

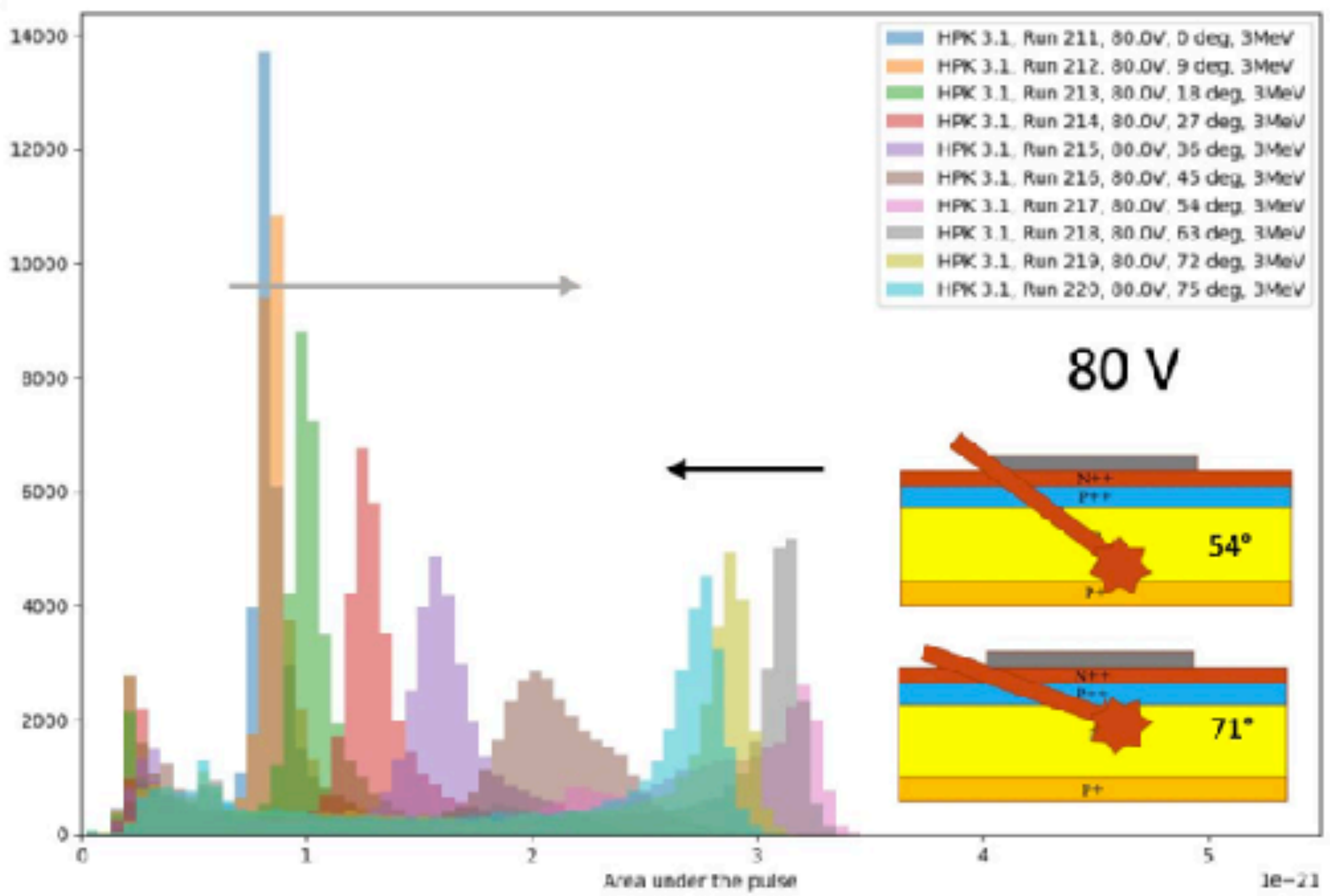
Key parameters[1,2]:

- High granularity, minimal blind/ dead regions
- Fast timing
- Good energy resolution over large dynamic range





Gain saturation[3]:



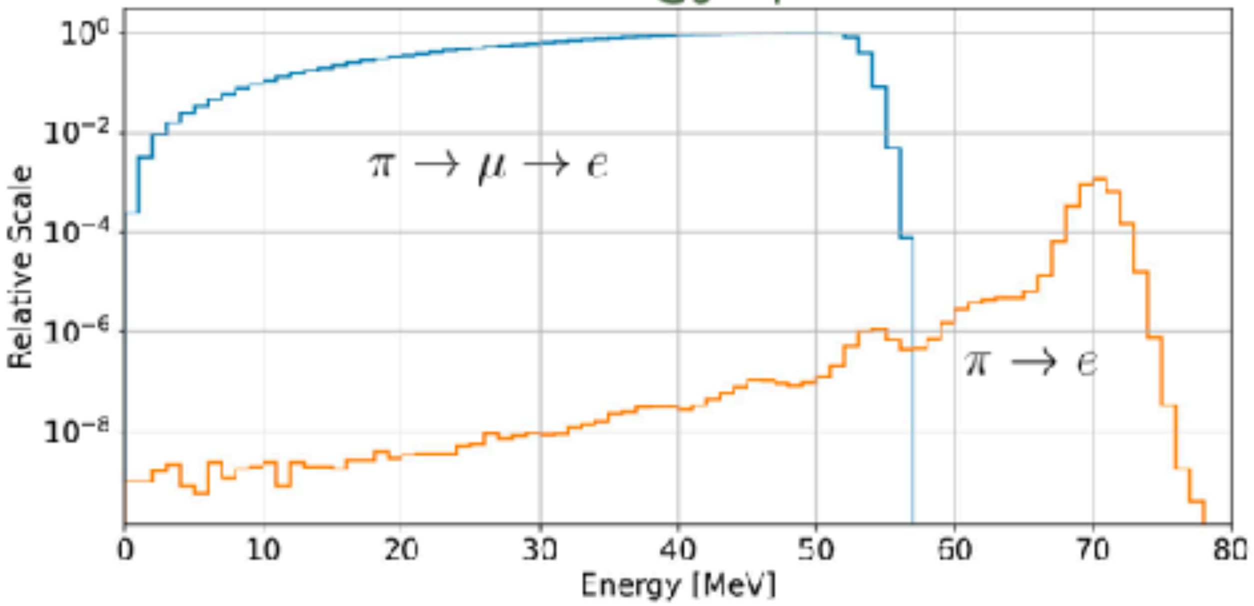
Test beam 2023 at PSI:

- Explore possibility of a LYSO calorimeter

Key parameters:

- Energy resolution
- Uniformity
- Fast detector response

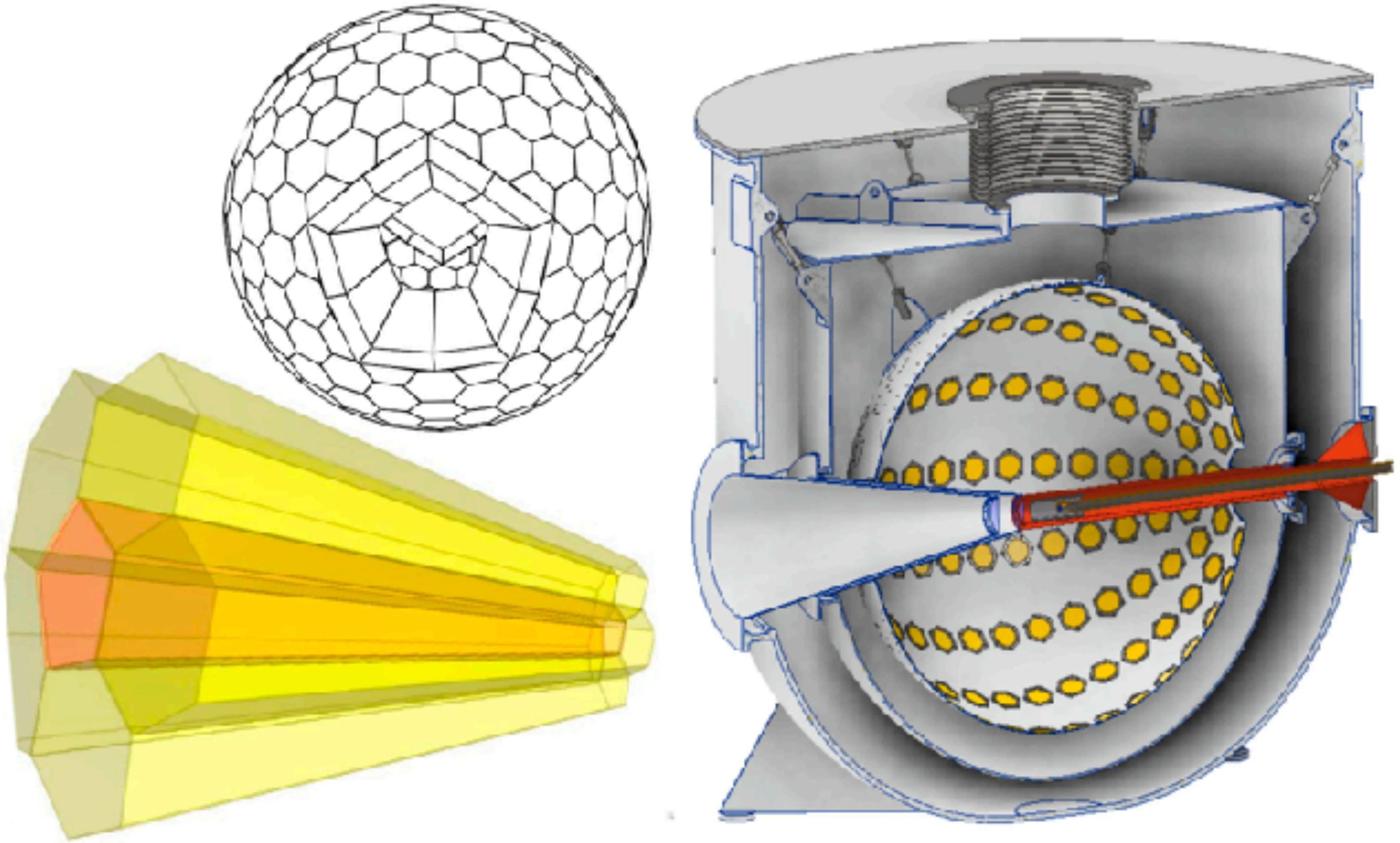
Simulated energy spectrum[1]



Possible calorimeter choices[1]:

LYSO crystals

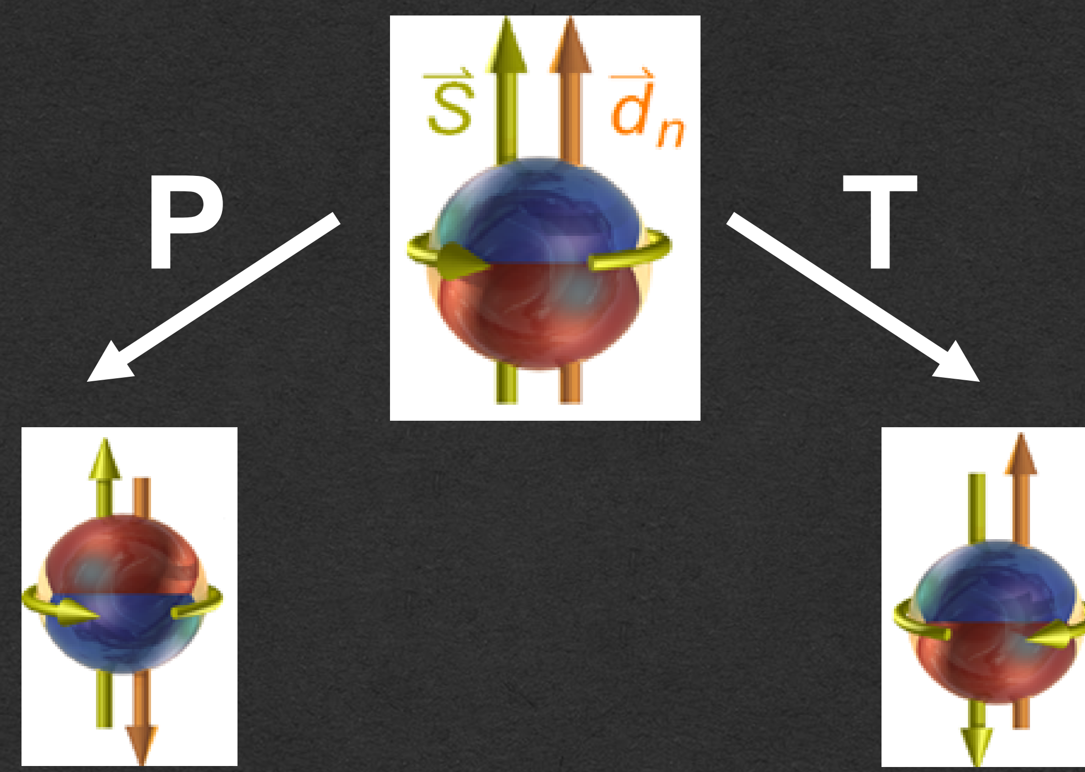
Liquid Xenon (LXe)



From S.Hochrein

Things we did not discuss:

Neutron EDM, muon EDM, muon g-2…..



Motivation: Barion Asymmetry

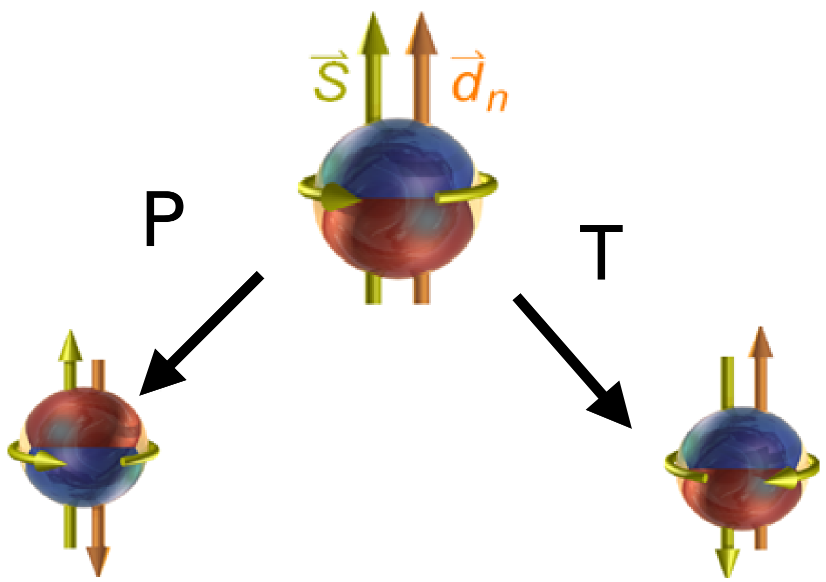
SM expectation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$$

vs.

Observed*:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$



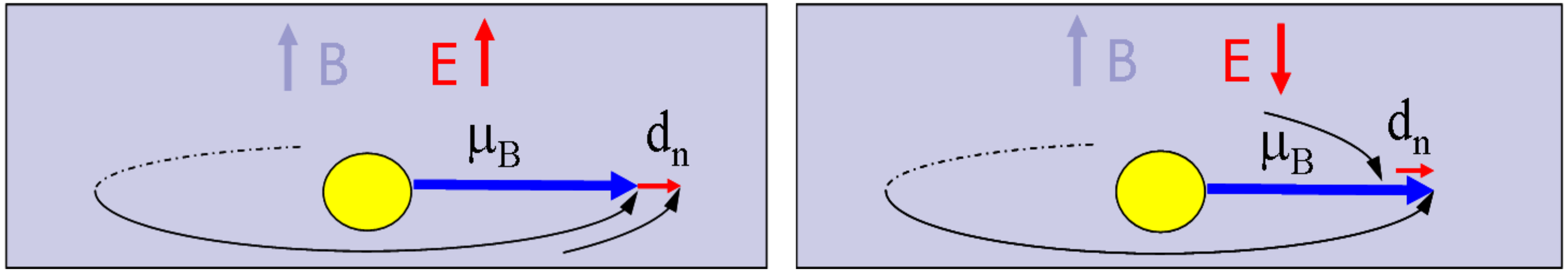
- New physics is needed to explain the BA
- more CP violation is a necessary ingredient
- EDMs are sensitive probes for CP-violation
- Several EDM discoveries are needed to uncover underlying physics

- Neutrons in a bottle, superimposed E, B fields

$$H = \underbrace{\vec{\mu} \cdot \vec{B}}_{\text{C-even, P-even, T-even}} + \underbrace{\vec{d} \cdot \vec{E}}_{\text{C-even, P-odd, T-odd}}$$

	C	P	T
$\vec{\mu}$	-	+	-
$\vec{d}$	-	+	-
$\vec{E}$	-	-	+
$\vec{B}$	-	+	-

Measure the difference of precession frequencies in parallel/anti-parallel fields:

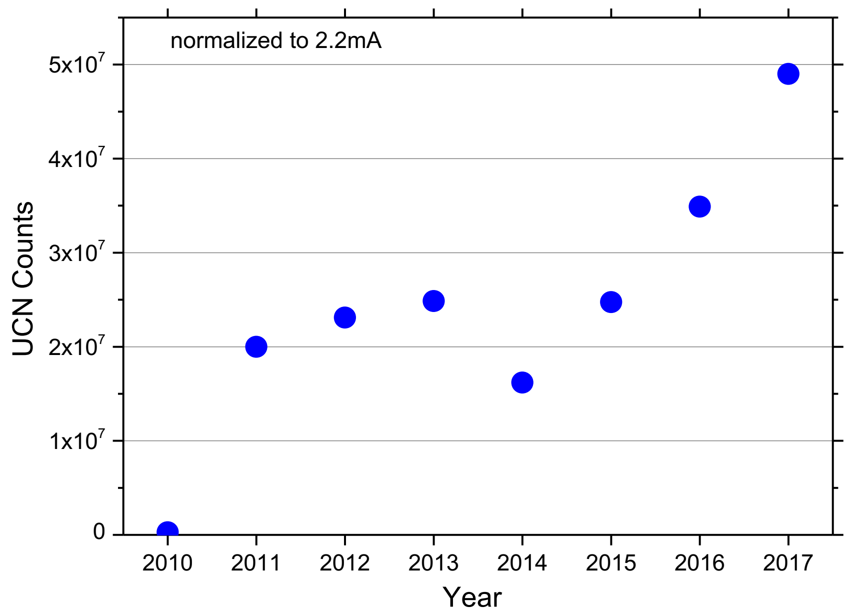


$$\hbar \Delta\omega = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)$$

for $d_n < 10^{-26}$ → $\Delta\omega < 60$ nHz

$\omega_L \approx 30$Hz

- delivery of ~4 M UCN every 300 s during HIPA operation

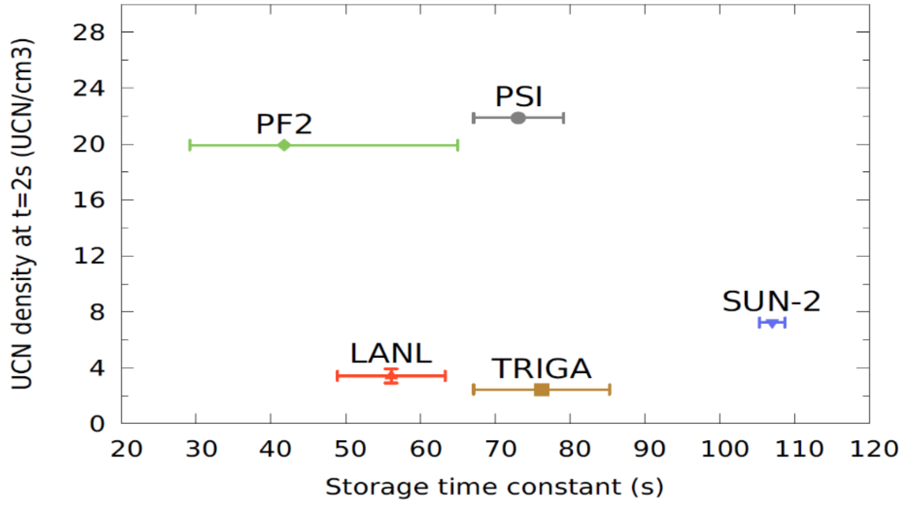


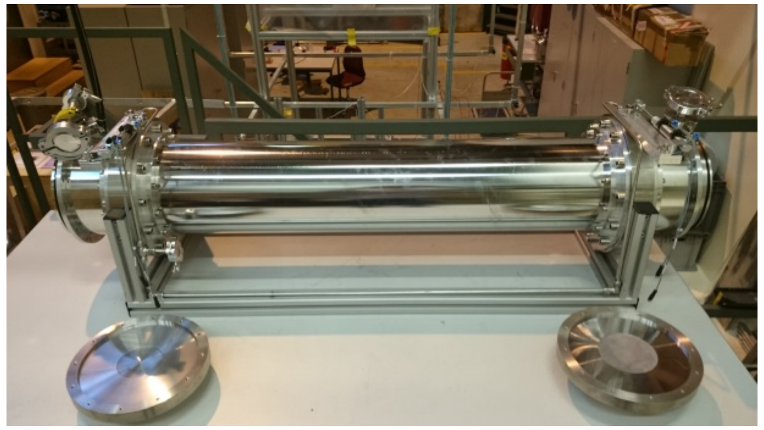
Neutrons can be contained (in material vessels) for long times, if they are below certain energies

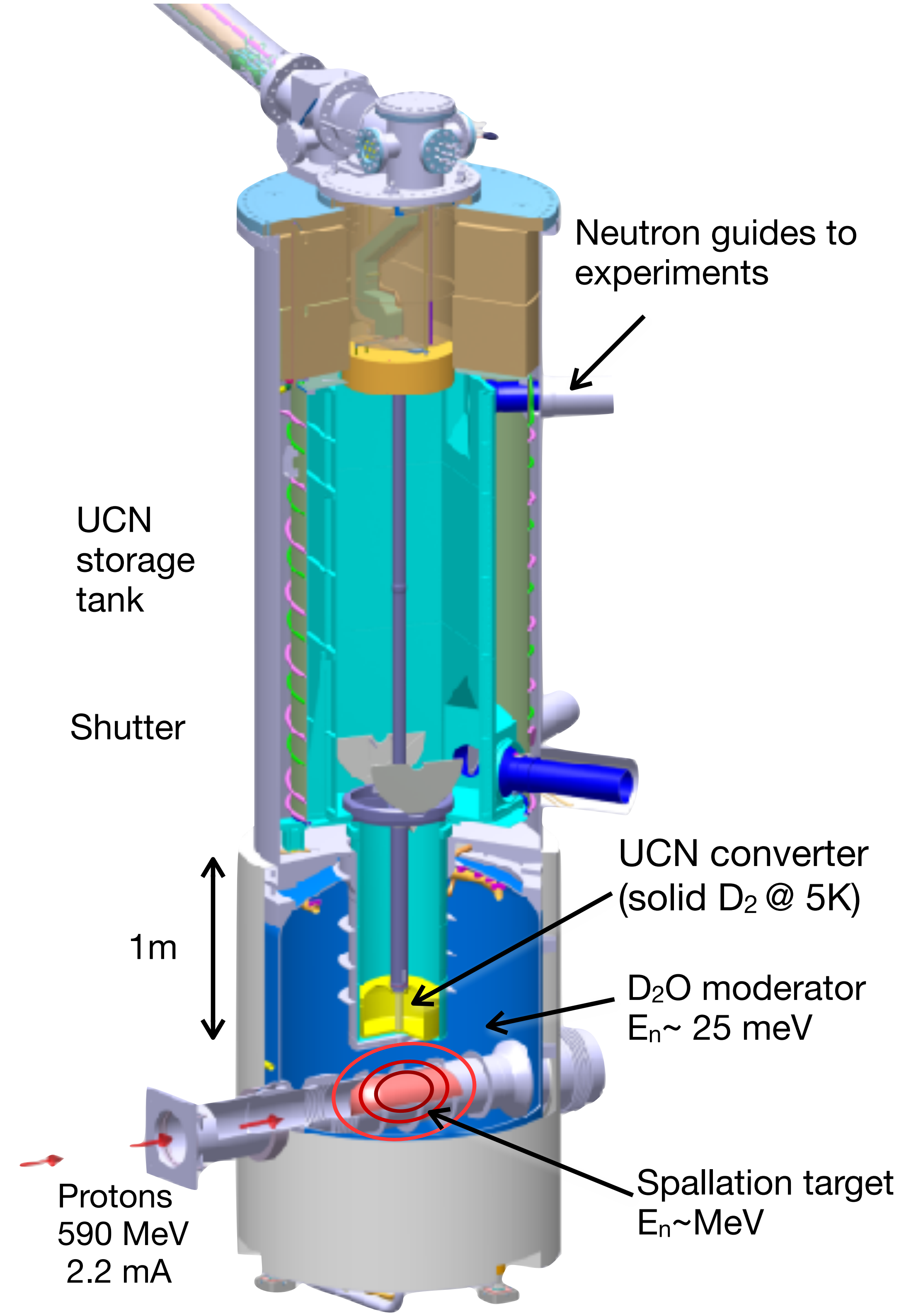
$$350 \text{ neV} \leftrightarrow 8 \text{ m/s} \leftrightarrow 500 \text{ Å} \leftrightarrow 3 \text{ mK}$$

- Largest worldwide UCN density in PSI measured using standardized vessel

PSI (2017) 34 UCN /cm3



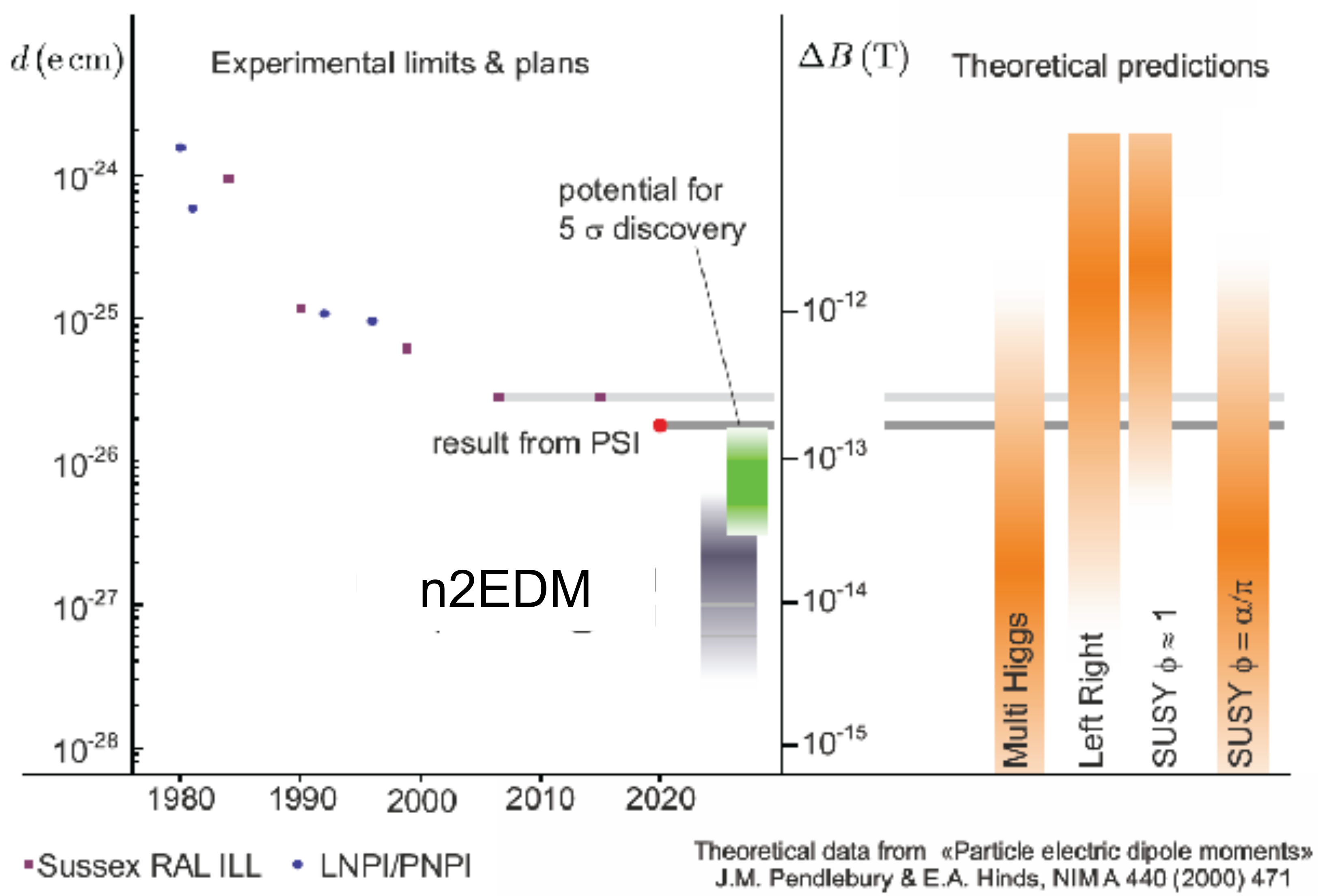


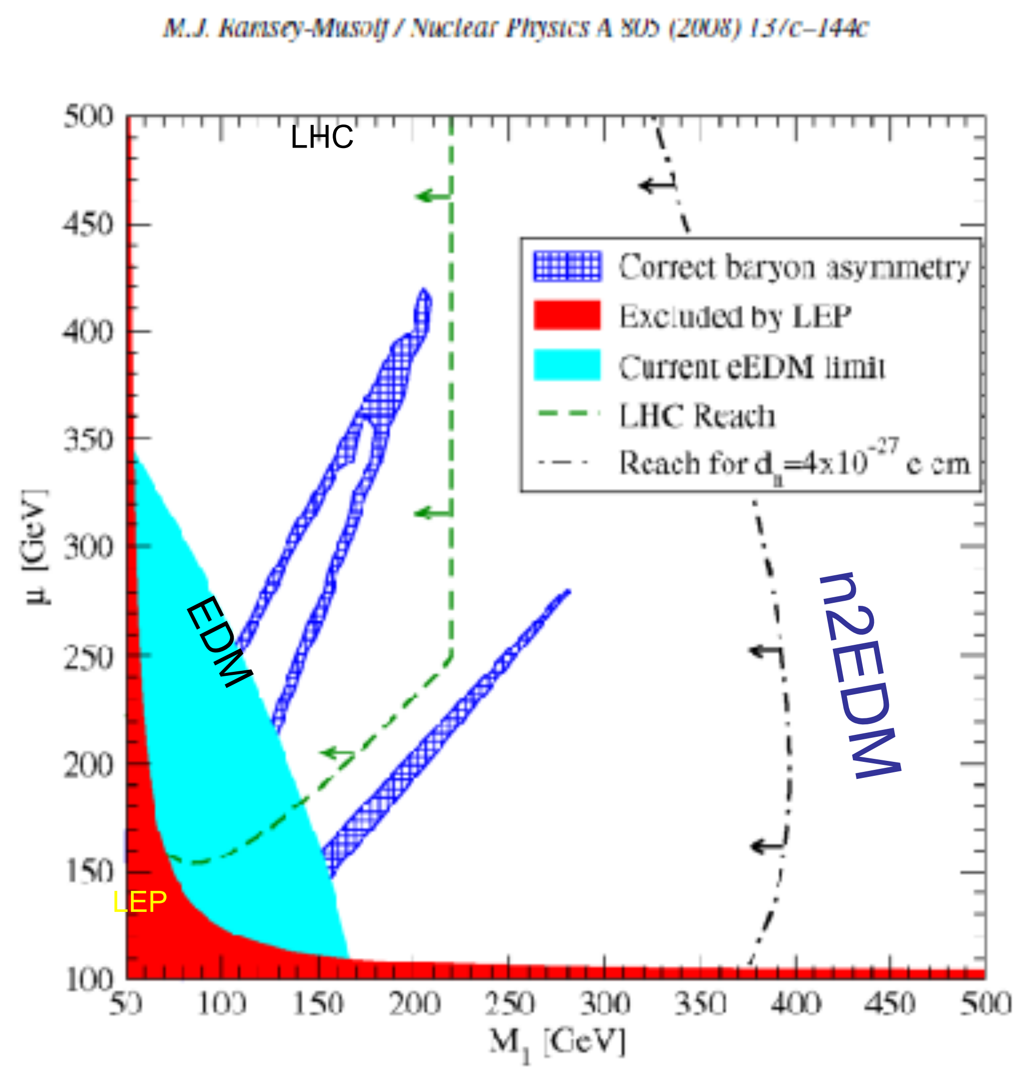


nEDM and nEDM-2

Best current nEDM limit from first PSI measurement

$d_n < 1.8 \cdot 10^{-26}$ ecm   C.Abel et al.   Phys.Rev.Lett. 124 (2020) 081803



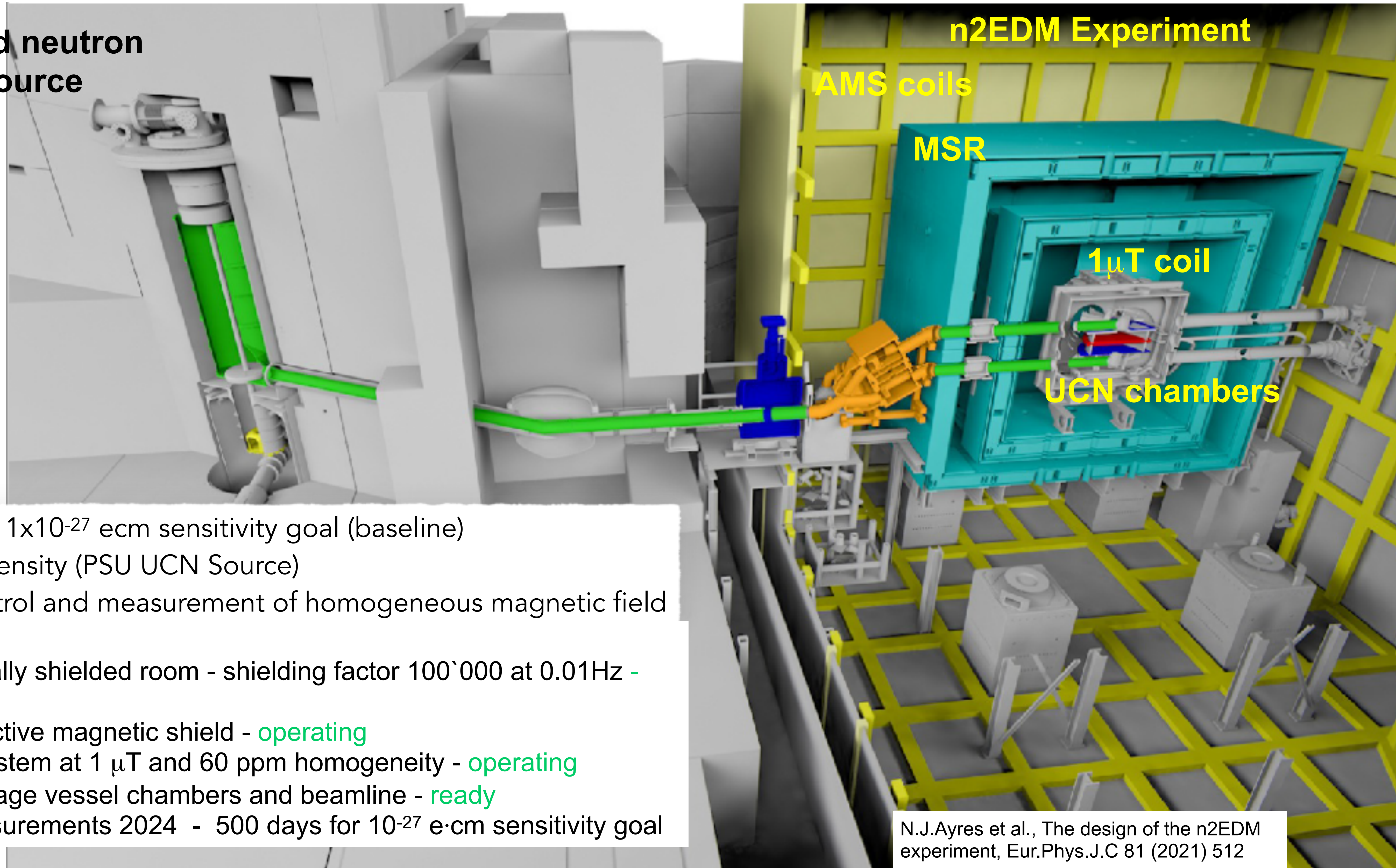


New apparatus n2EDM@PSI - will improve sensitivity by at least a factor 10 in the baseline setup - **1×10^{-27} ecm**
- potential to rule out a large parameter space of theories

E.g: nEDM and LHC sensitivity to supersymmetric baryogenesis in the **minimal supersymmetric standard model (MSSM).** Supersymmetric mass μ and gaugino mass M1 parameter space leading to observed value of the baryon asymmetry.

nEDM-2 setup

Ultracold neutron (UCN) Source

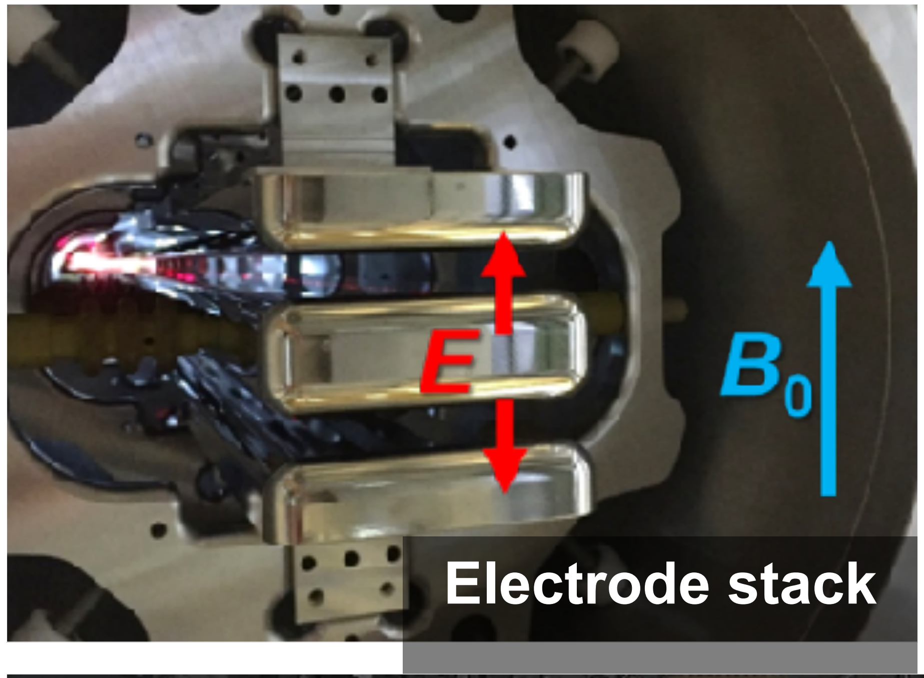


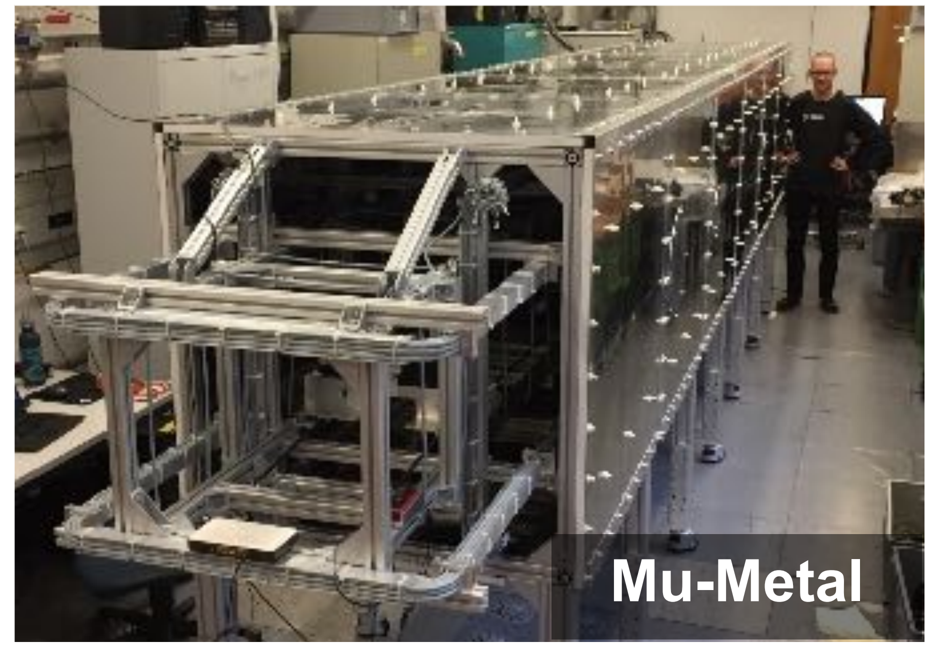
Essential to reach 1x10^{-27} ecm sensitivity goal (baseline)
- highest UCN intensity (PSU UCN Source)
- ultraprecise control and measurement of homogeneous magnetic field

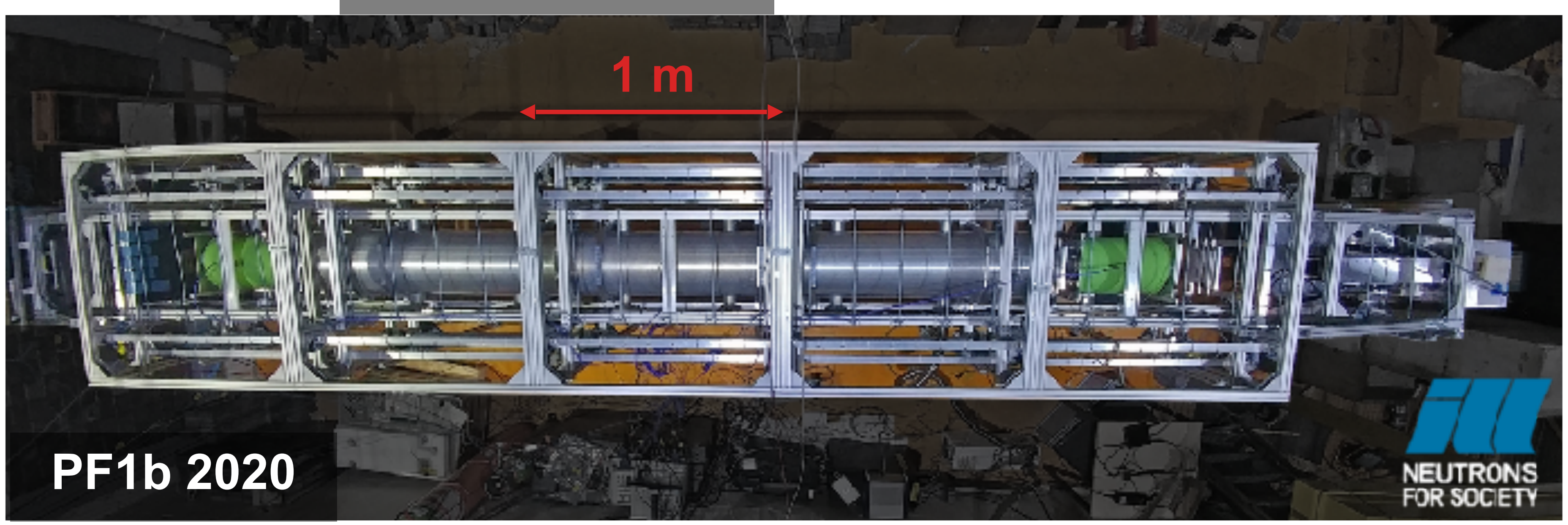
- record magnetically shielded room - shielding factor 100`000 at 0.01Hz - operating
- 57 km coils for active magnetic shield - operating
- magnetic field system at 1 μT and 60 ppm homogeneity - operating
- UCN double storage vessel chambers and beamline - ready
- start nEDM measurements 2024 - 500 days for 10^{-27} e·cm sensitivity goal

N.J.Ayres et al., The design of the n2EDM experiment, Eur.Phys.J.C 81 (2021) 512

Neutron Beam EDM - towards alternative methods precision



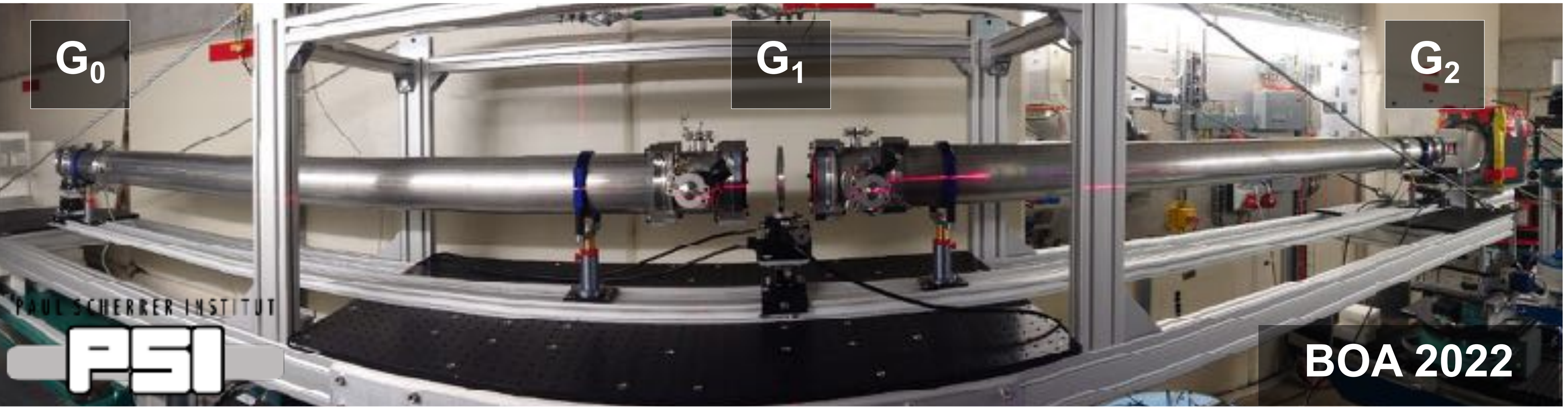




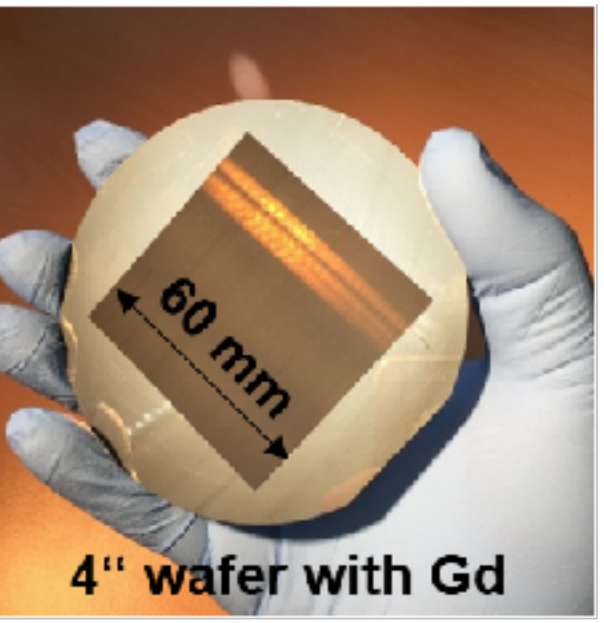
- New complementary neutron EDM search using a pulsed beam
- Project based in Bern with proof-of-principle experiments at PSI and ILL
- Full-scale experiment intended for ESS (European Spallation Source), competitive to UCN experiments

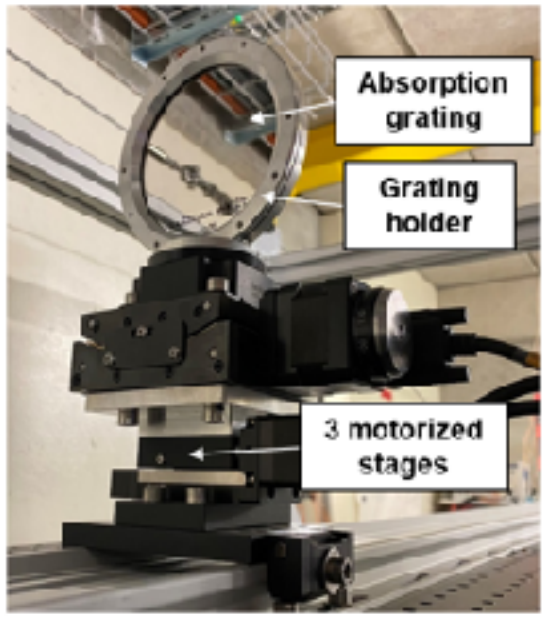
Piegsa, *PRC* 88, 045502 (2013)
Chanel et al., *EPJ Conf.* 219, 02004 (2019)
Schulthess et al., *PRL* 129, 191801 (2022)

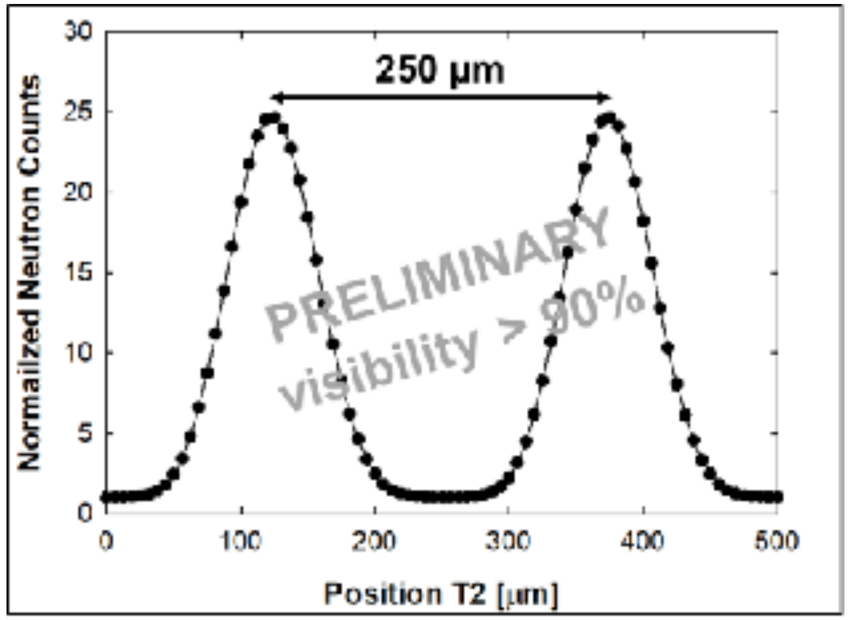
QNeutron - towards measuring the neutron charge



- Neutron Talbot-Lau interferometer using absorption gratings
- Proof-of-principle phase with experiments at PSI and ILL
- Goal: measure the neutron charge with improved sensitivity at ESS

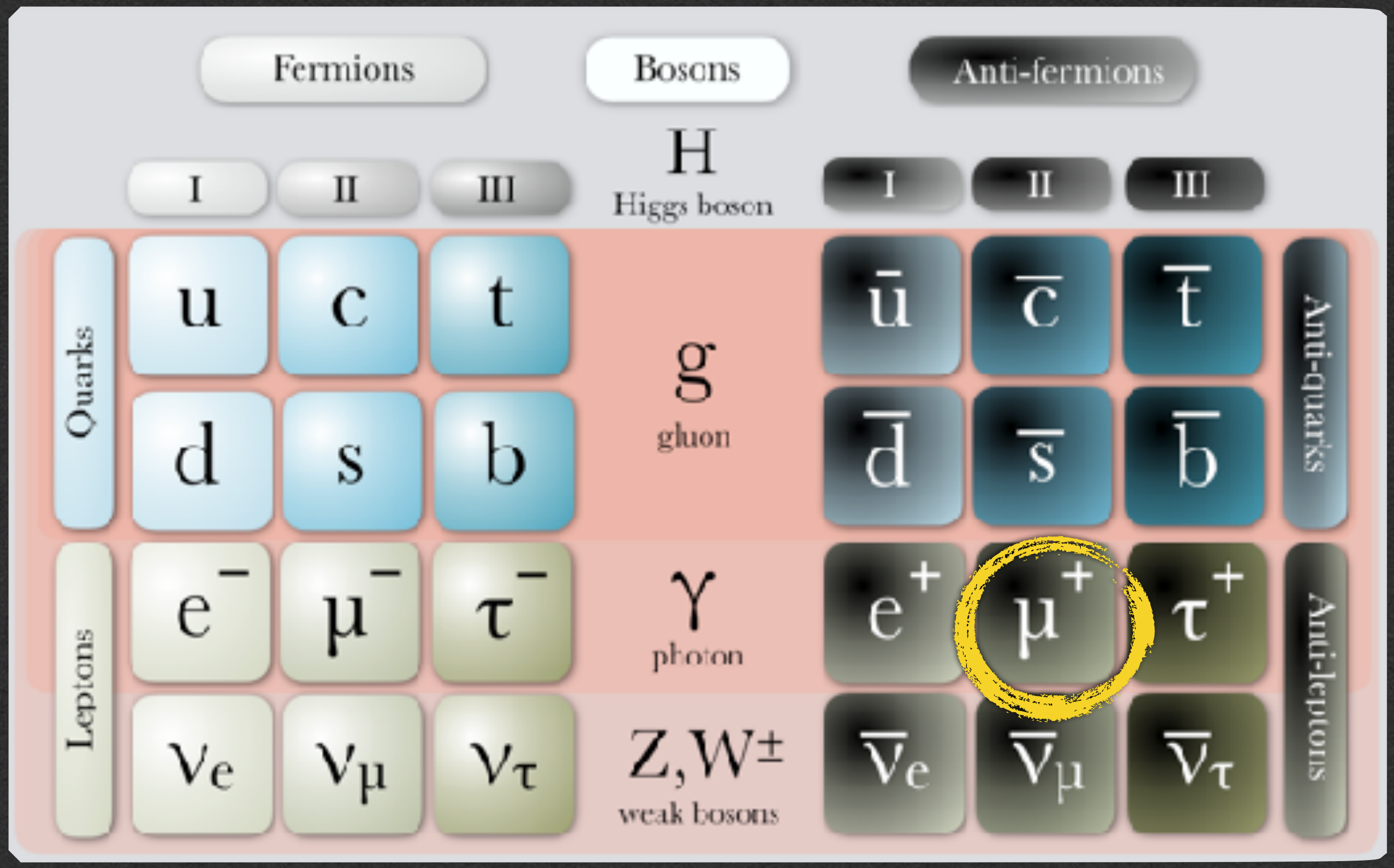






Piegsa, *PRC* 98, 045503 (2018)

Experiments with muon beams



PAUL SCHERRER INSTITUT PSI

muEDM at PSI

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

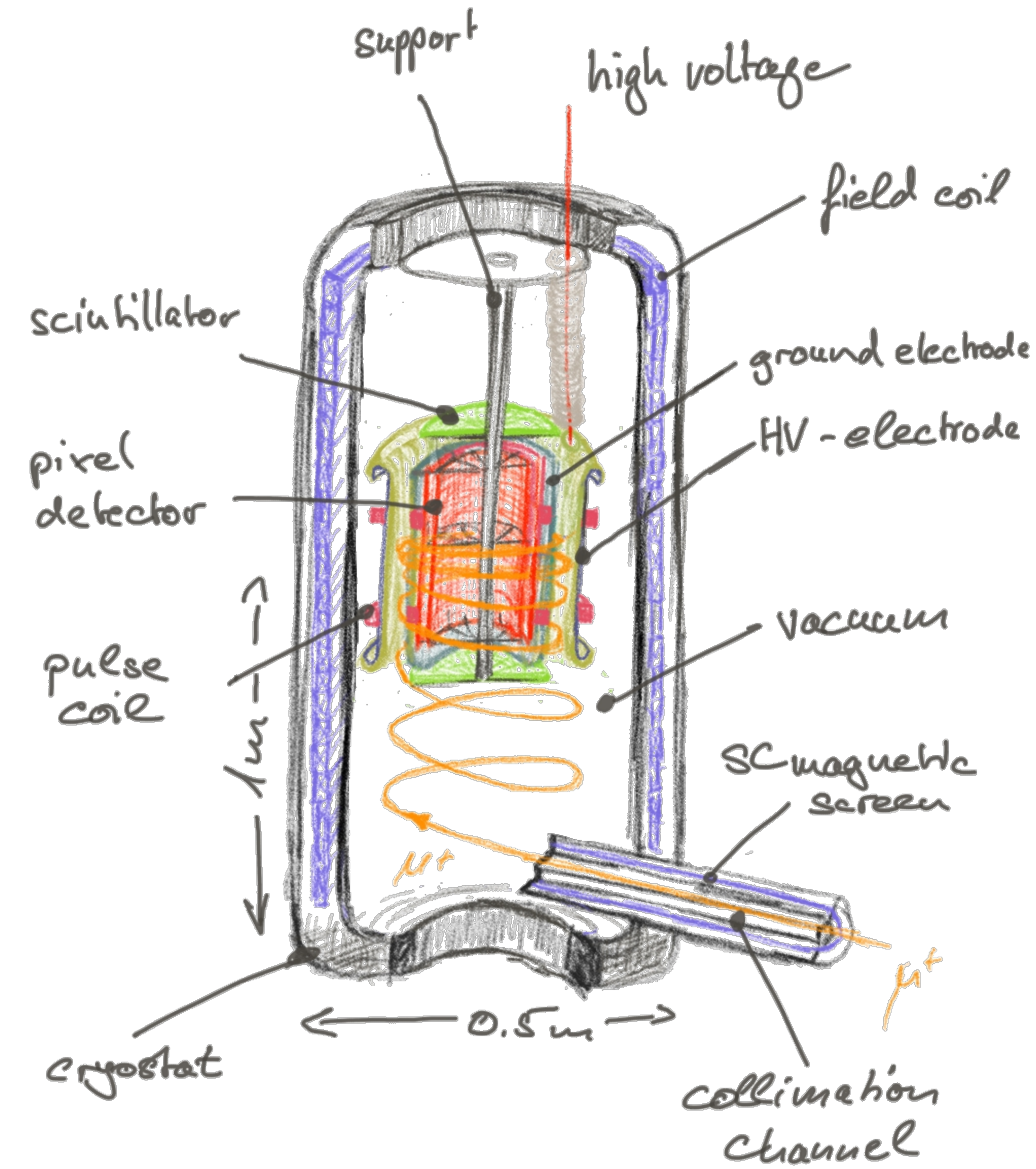
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

FNSNF
Swiss National Science Foundation

Phase approach using the frozen-spin technique in a compact solenoid

- Demonstration phase 2022 – 2027: $\sigma(d) \leq 3 \times 10^{-21}$
- Dedicated instrument 2029 – 203?: $\sigma(d) \leq 6 \times 10^{-23}$
- Possible signal (EFT analysis) : $d \sim \text{few} \times 10^{-22}$

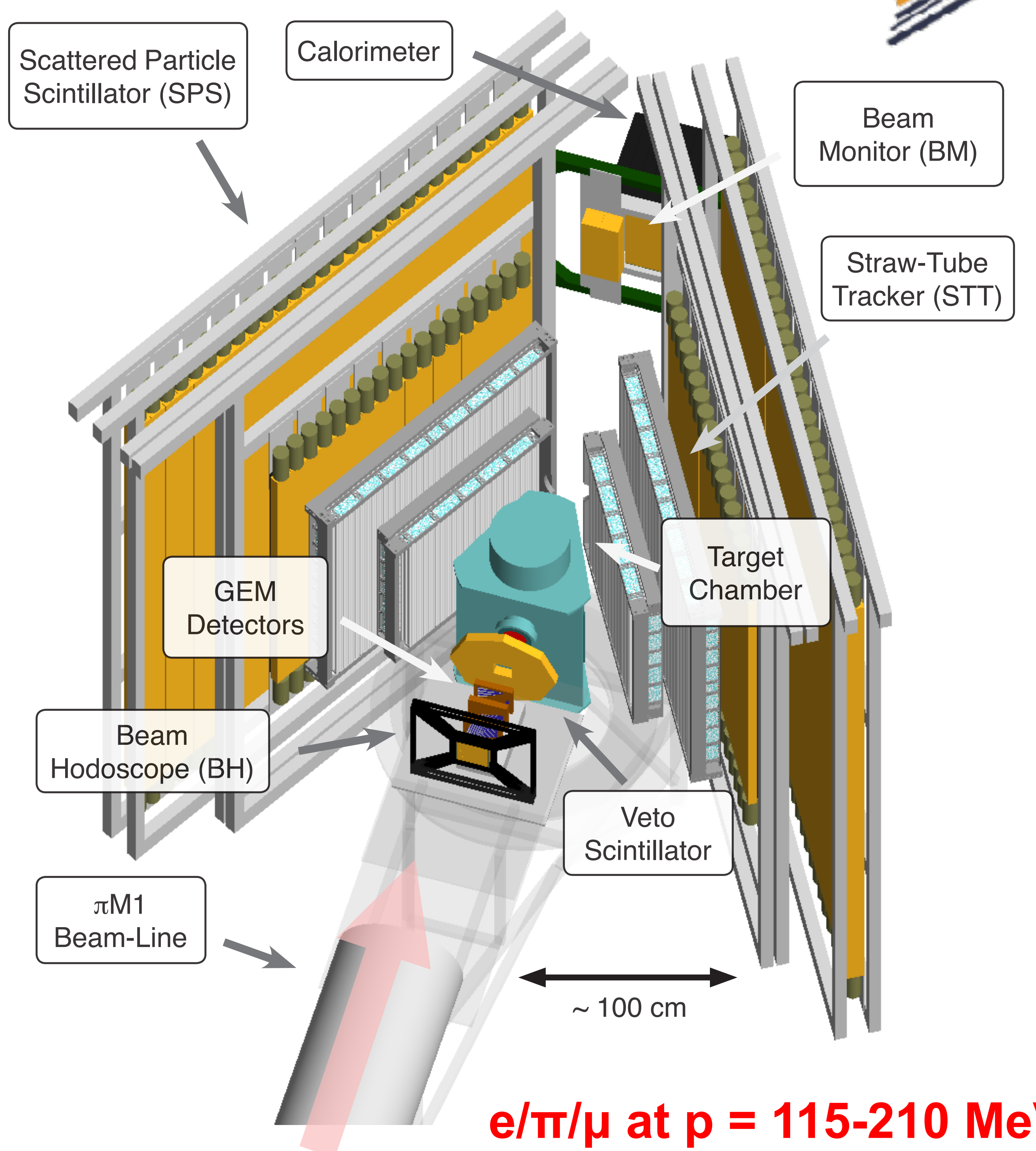
- New collaboration (welcome to join!) with institutions from: Germany, Italy, Switzerland and UK



contact: P. Schmidt-Wellenburg

MUSE experiment

- Proton form factor + radius + 2γ + lepton universality measurement at PSI with elastic scattering of $e^{\pm}$, $\mu^{\pm}$ from hydrogen
- Fall 2022: Scattering data
  - Took data in all experiment kinematics on H, C, empty cell
  - Second veto detector, inside the target chamber, used to reduce background
- Upgrades since Fall 2022
  - Progress in analysis, improving coding, debugging, geometry, noise suppression, corrections, tracking, reconstructed time and position resolutions
- 2023: Long run 1.
  - 5 months beam time awarded and scheduled
  - Reviewed 2022 operations at spring 2023 collaboration meeting, for 2023 operation planning
- 2024 and 2025: Similar beam times expected



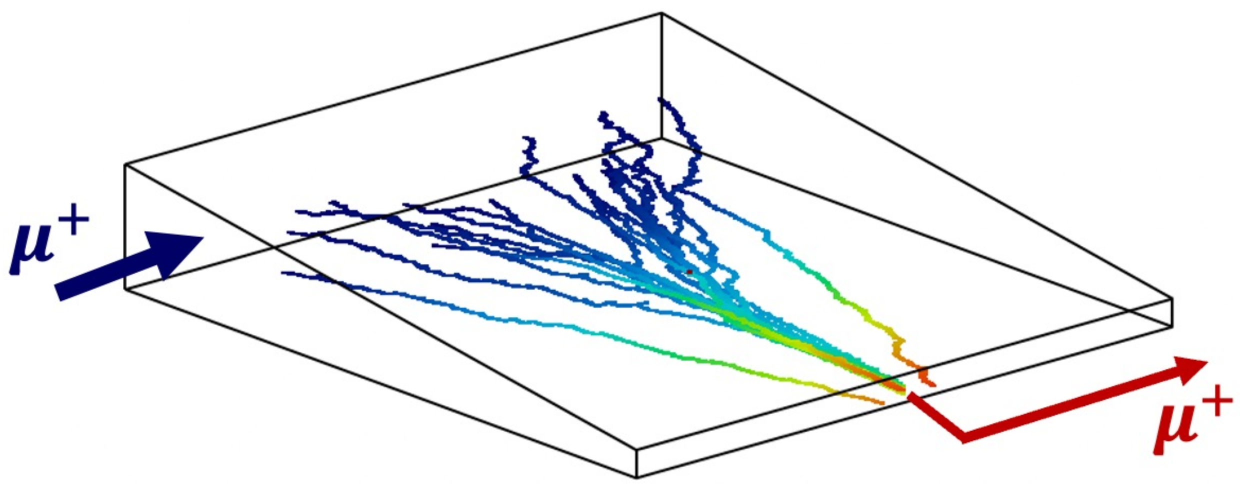
e/π/μ at p = 115-210 MeV/c

muCool project: bright positive muon beam at keV energy

User-driven development

HIMB
Beam

E: 4 MeV
ΔE (FWHM): 800 keV
$\sigma_x \sigma_{x'} = 2000$ mm mrad



muCool
Beam

E: 10 keV
ΔE: <100 eV
$\sigma_x \sigma_{x'} = 20$ mm mrad

Windowless cryogenic He gas target with density gradients and complex E-field placed in a solenoid

Status

- Muon compression in the He gas target has been demonstrated in various regimes.

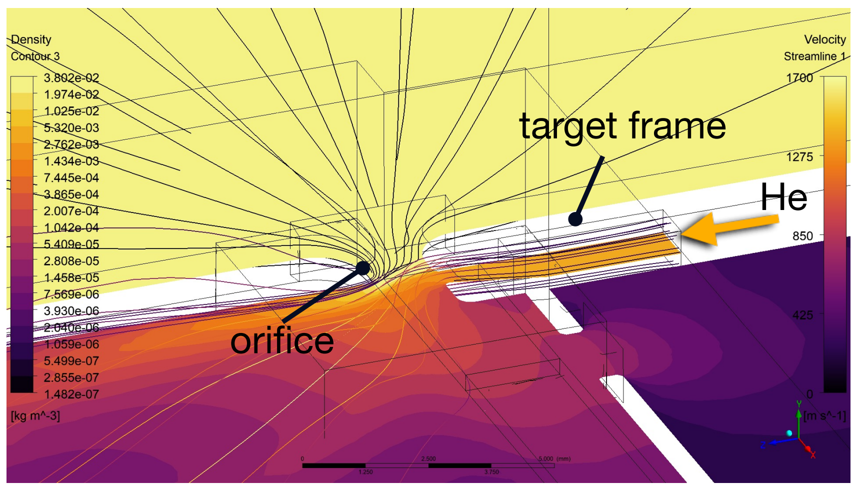
  Phys. Rev. Lett. 125.164802 (2020)

  Eur. Phys. J. C 79:430 (2019)

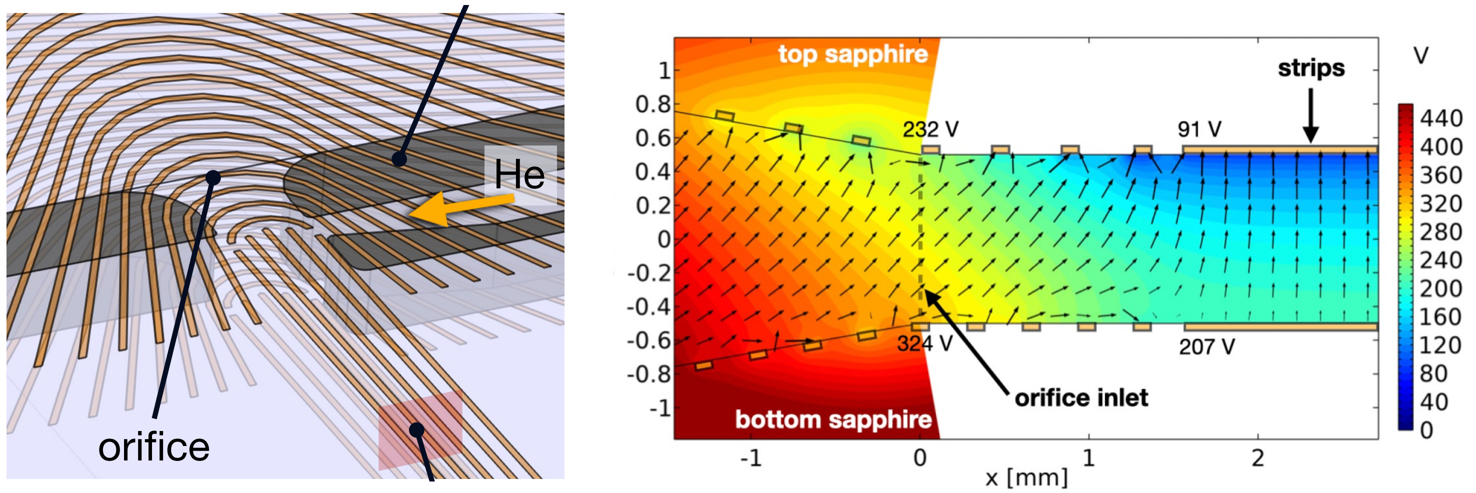
  Phys. Rev. Lett. 112.224801 (2014)

- Target with extraction orifice, gas injection, differential pumping and coupling into reaccelerating region being prepared

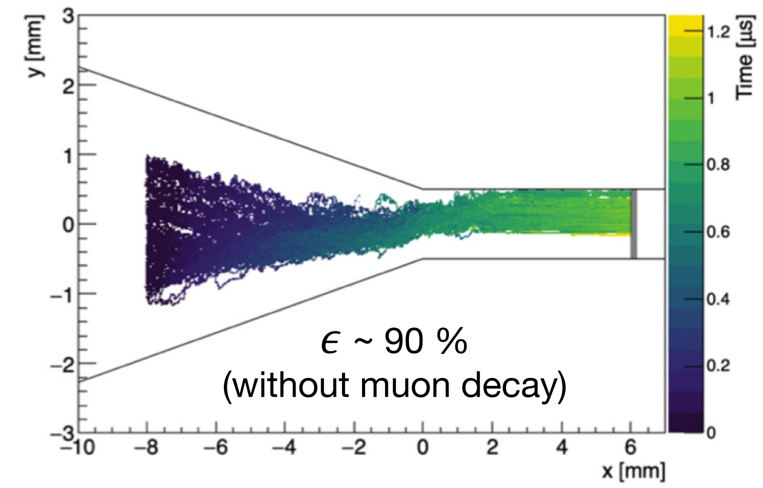
Gas simulations



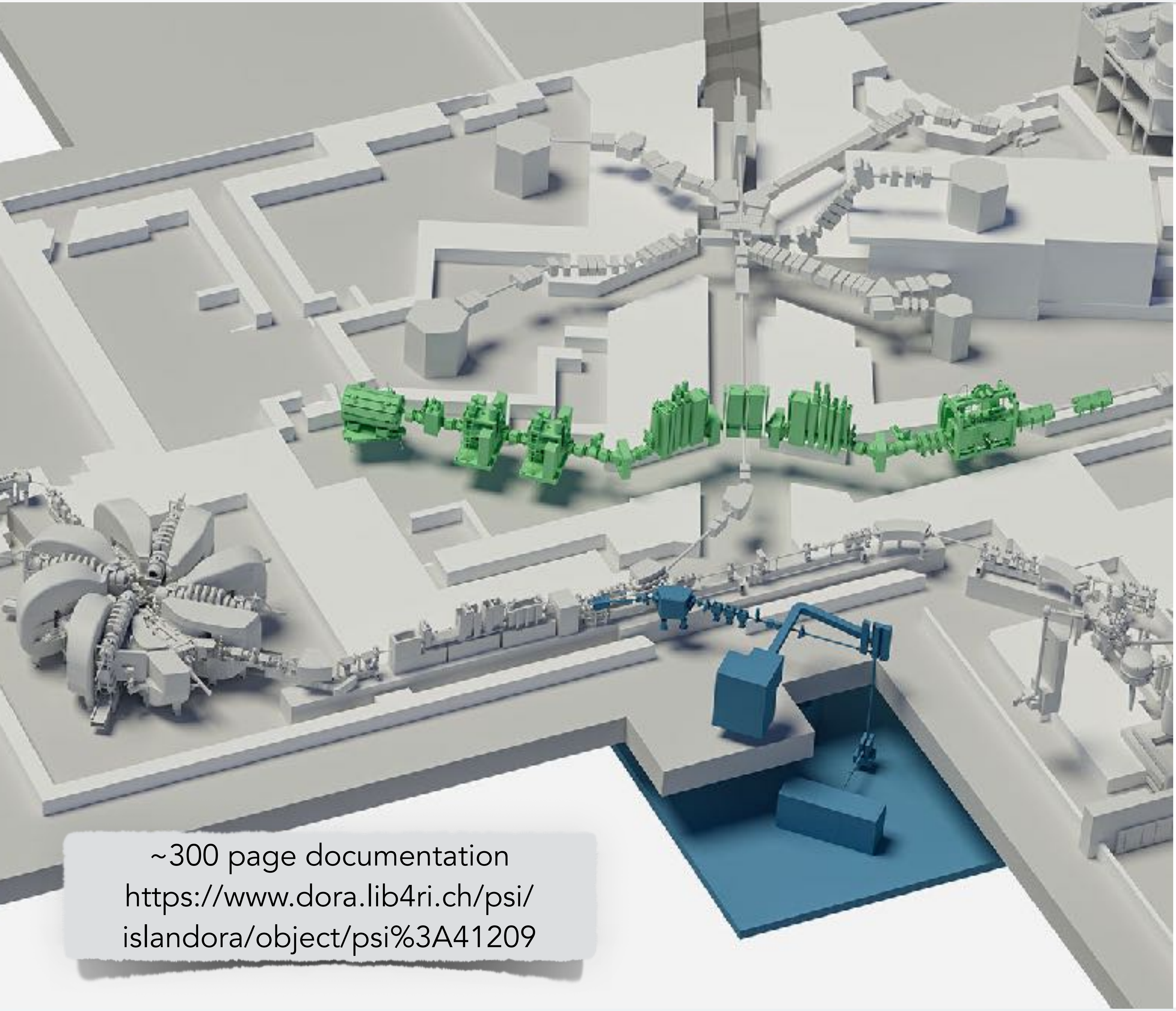
Electric field design



Muon trajectories



Major PSI upgrade: the IMPACT project



~300 page documentation
https://www.dora.lib4ri.ch/psi/islandora/object/psi%3A41209

HIMB

- Construction of new **target station TgH** at the place of the existing TgM
- Construction of two new solenoid-based beamlinesfor μSR and particle physics delivering 10^{10} surface muons per second

Keeps PSI on the forefront of muon physics for the next 20 years

TATTOOS

- Construction of new **spallation target** with online isotope mass separation
- Production of radioisotopes for medical applications in quantities suitable for clinical studies

Enables novel cancer therapies with isotopes suitable for simultaneous imaging and treatment

Thank you!