Towards a test of the Weak Equivalence Principle of gravity with anti-hydrogen

https://gbar.web.cern.ch

The GBAR collaboration

P. Adrich[1], P. Blumer[2], G. Caratsch[2], M. Chung[3], P. Cladé[4], P. Comini[5], P. Crivelli[2], O. Dalkarov[6], P. Debu[5], A. Douillet[4,7], D. Drapier[4], P. Froelich[8,20], N. Garroum[4,21], S. Guellati-Khelifa[4,9], J. Guyomard[4], P-A. Hervieux[10], L. Hilico[4,7], P. Indelicato[4], S. Jonsell[8], J-P. Karr[4,7], B. Kim[11], S. Kim[12], E-S. Kim[13], Y.J. Ko[11], T. Kosinski[1], N. Kuroda[14], B.M. Latacz[5,22], B. Lee[12], H. Lee[12], J. Lee[11], E. Lim[13], L. Liszkay[5], D. Lunney[15], G. Manfredi[10], B. Mansoulié[5], M. Matusiak[1], V. Nesvizhevsky[16], F. Nez[4], S. Niang[15,22], B. Ohayon[2], K. Park[11,12], N. Paul[4], P. Pérez[5], C. Regenfus[2], S. Reynaud[4], C. Roumegou[15], J-Y. Roussé[5], Y. Sacquin[5], G. Sadowski[5], J. Sarkisyan[2], M. Sato[14], F. Schmidt-Kaler[17], M. Staszczak[1], K. Szymczyk[1], T.A. Tanaka[14], B. Tuchming[5], B. Vallage[5], A. Voronin[6], D.P. van der Werf[18], A. Welker[22], D. Won[12], S. Wronka[1], Y. Yamazaki[19], K-H. Yoo[3], P. Yzombard[4]

Why study the gravitational behavior of antimatter ?

- Test of the weak equivalence principle

$$m_i\,\vec{a} = m_G\,\vec{g}$$

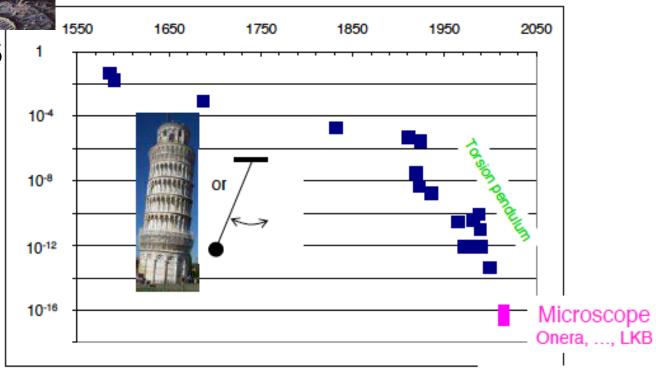
Inertial mass ? = ? Gravitational mass

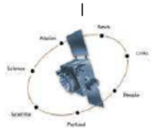
- Tests on 'usual' matter

  Torsion balances → 10^{-13}

  Space mission MICROSCOPE (see previous talk)

  (CNES,OCA,ONERA,...,LKB) → 10^{-15}





- Test on antimatter

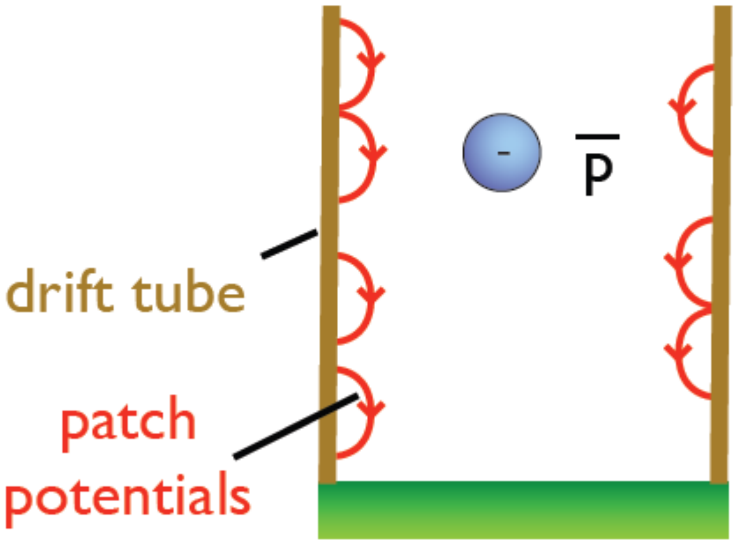
  Indirect indications cyclotron frequencies proton/antiproton (~clock)

(Gabrielse, PRL 82, 3198, 1999) $\left|\frac{q}{m}\right|_p = \left|\frac{q}{m}\right|_{\bar{p}}$ ~ 10^{-10}

(Borchet, Nature, 601,53-57, 2022) $\left|\frac{q}{m}\right|_p = \left|\frac{q}{m}\right|_{\bar{p}}$ ~10^{-11}

Why antihydrogen ?

- Free fall of charged antiparticles (e^+, $\bar{p}$)

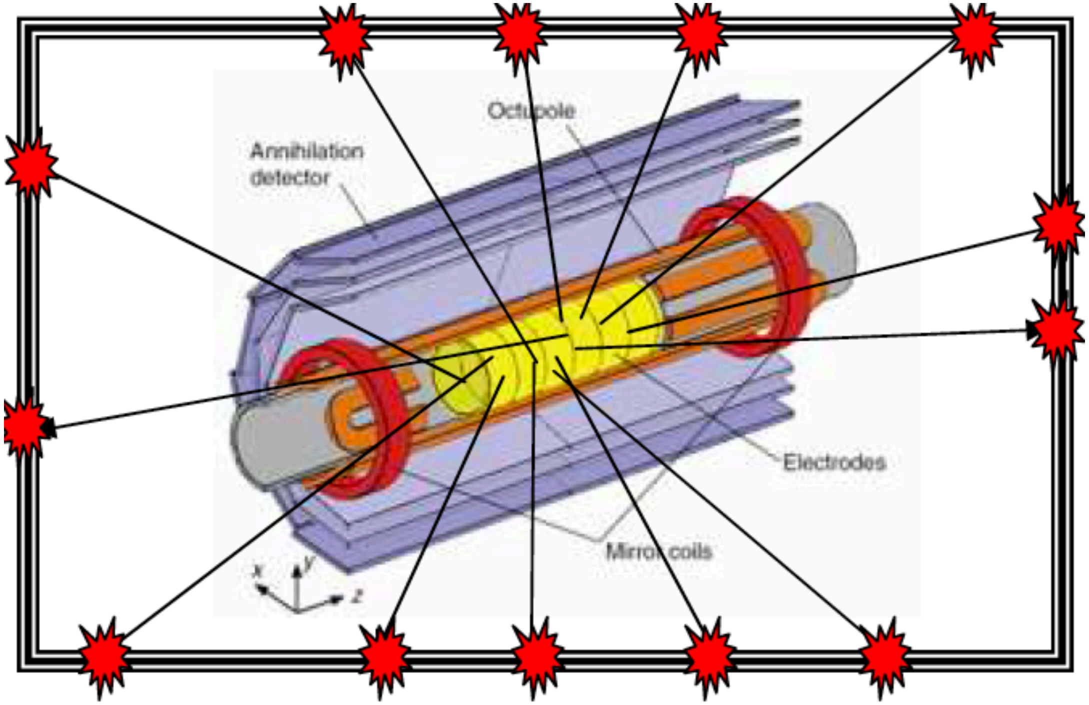


Requires
$\bar{e}^+$: $E < 10^{-12}$ V/m !
$\bar{p}$: $E < 10^{-7}$ V/m !

- Simplest neutral anti-atom: $\bar{H}$ ($\bar{p}$ e^+) and (e^+e^-)

A demonstration experiment

ALPHA collaboration, 2013



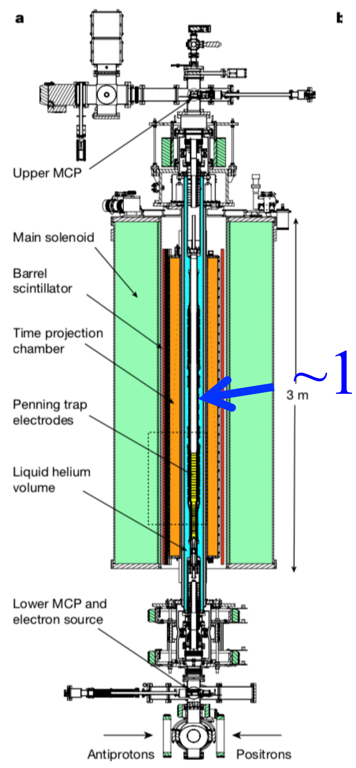
- ~ 1 trapped $\bar{\mathrm{H}}$ atom at each run
- Release atoms
- 434 annihilations

$$-65 \leq \frac{m_i}{m_G} \leq 110$$

95% confidence level

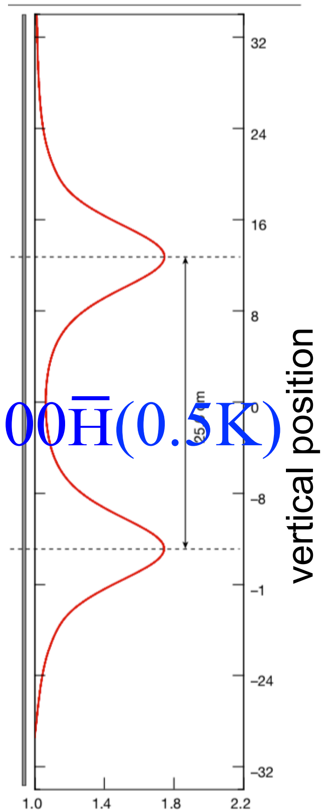
ALPHA collaboration, Nature Comm. **4**, 1785 (2013)

Observation of gravity on the motion of $\overline{H}$

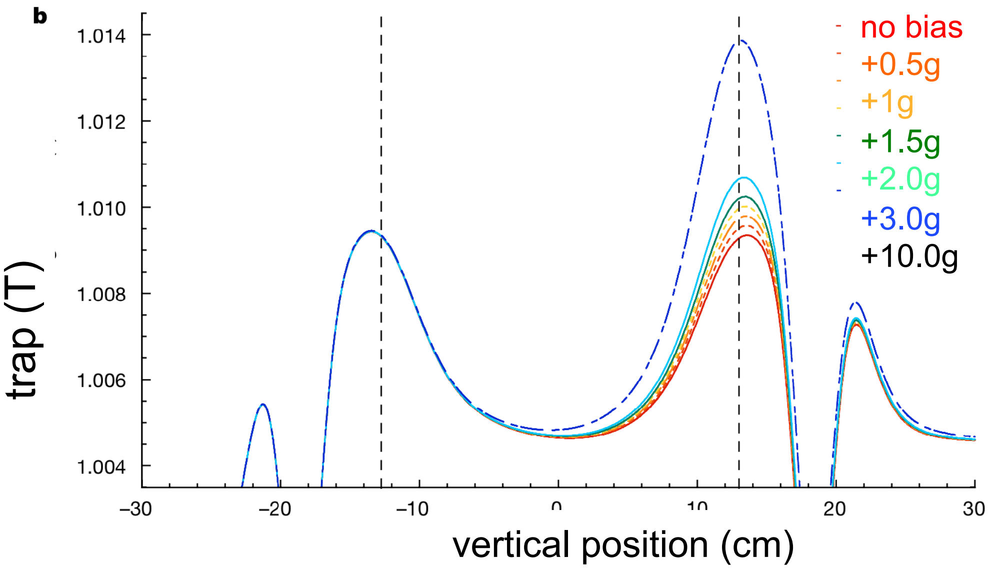


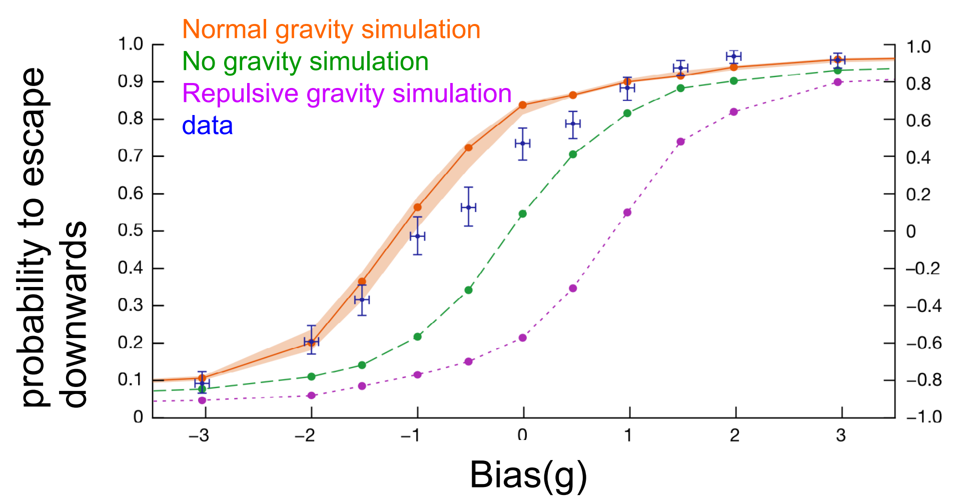
~100$\overline{H}$(0.5K)

vertical magnetic trap



magnetic field trap (T)





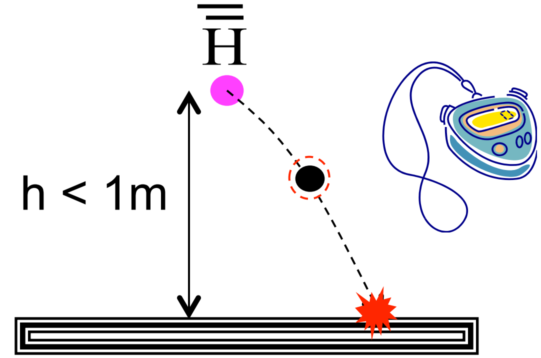
Alpha-g coll. Nature 621, 717 2023, $\bar{g}/g = 0{,}75(13)(16)$

The GBAR project: principle

- Free fall: $v_f \sim$ few m/s

  Good precision on $\bar{g}$ if $\Delta v_{iz} < 1$ m/s   T < 100 µK

  Ex: **T = 10 µK → 1% on $\bar{g}$** with 1500 atoms



- Laser cooling of $\bar{H}$: challenging ! (λ = 121 nm)

Principle: 1. produce an $\overline{\bar{H}}^{+}$ ion ($\bar{p}^{-}\, e^{+}\, e^{+}$):

$$\bar{p} + Ps \rightarrow \bar{H} + e^{-}$$

$$\bar{H} + Ps^{*}(3D) \rightarrow \bar{H}^{+} + e^{-}$$

2. sympathetic cooling by laser-cooled ions

$$\bar{H}^{+} + Be^{+} + h\upsilon \rightarrow \bar{H}^{+}(4neV)$$

3. photodetachment at threshold (λ = 1.64 µm) → $\bar{H}$ at rest

$$\bar{H}^{+}(4neV) + h\upsilon @ 1.6\,\mu m \rightarrow \bar{H} @ rest$$

Initial proposal J. Walz and T. Hänsch, General Relativity and Gravitation **36**, 561 (2004)

Birth certificate P. Perez et al., proposal SPSC-P-342, accepted by CERN in 2012.

The ion trappers' mission

- ~ 1 $\bar{H}^+$ ion every 100s

$E_{moy}(\bar{H}^+) \cong E_{moy}(\bar{p})$ ~ 1-6 keV (depending on chosen Ps state)
$\Delta E(\bar{H}^+) \cong \Delta E(\bar{p})$ ~ 200-300 eV ~ **10^6 K**
$\Delta t_{creation}$ ~ 10-20 ns, $\Delta x \sim \Delta y$ ~ 1mm, Δz ~ 10mm

- Objective: trap and cool to T ~ **10 μK** ~ neV

11 orders of magnitude with efficiency close to 100% …

- Strategy: sympathetic cooling by laser-cooled ions in RF (Paul) traps

- Trapping well depth ~ 20 eV
  → pre-cooling necessary

A. Douillet, L. Hilico and J.P. Karr

Photo-detachment and detection

Photo-detachment (λ = 1.64 µm) (P. Cladé, S. Guellati, C. Blondel, and C. Drag)

- Horizontal beam
- Just above threshold to minimize recoil from positron ejection
- But $\sigma \to 0$ like $(E\text{-}E_{thr})^{3/2}$
- Best compromise: ΔE ~ 1 µeV.
  Photon recoil ~ 0.2 $m.s^{-1}$ Positron recoil ~ 0.3 $m.s^{-1}$
  Photo-detachment time ~ 150 µs with 1W over $(10µm)^2$
- laser source: cw OPO pumped by fiber laser (2W).

Detection (people from GBAR collaboration)

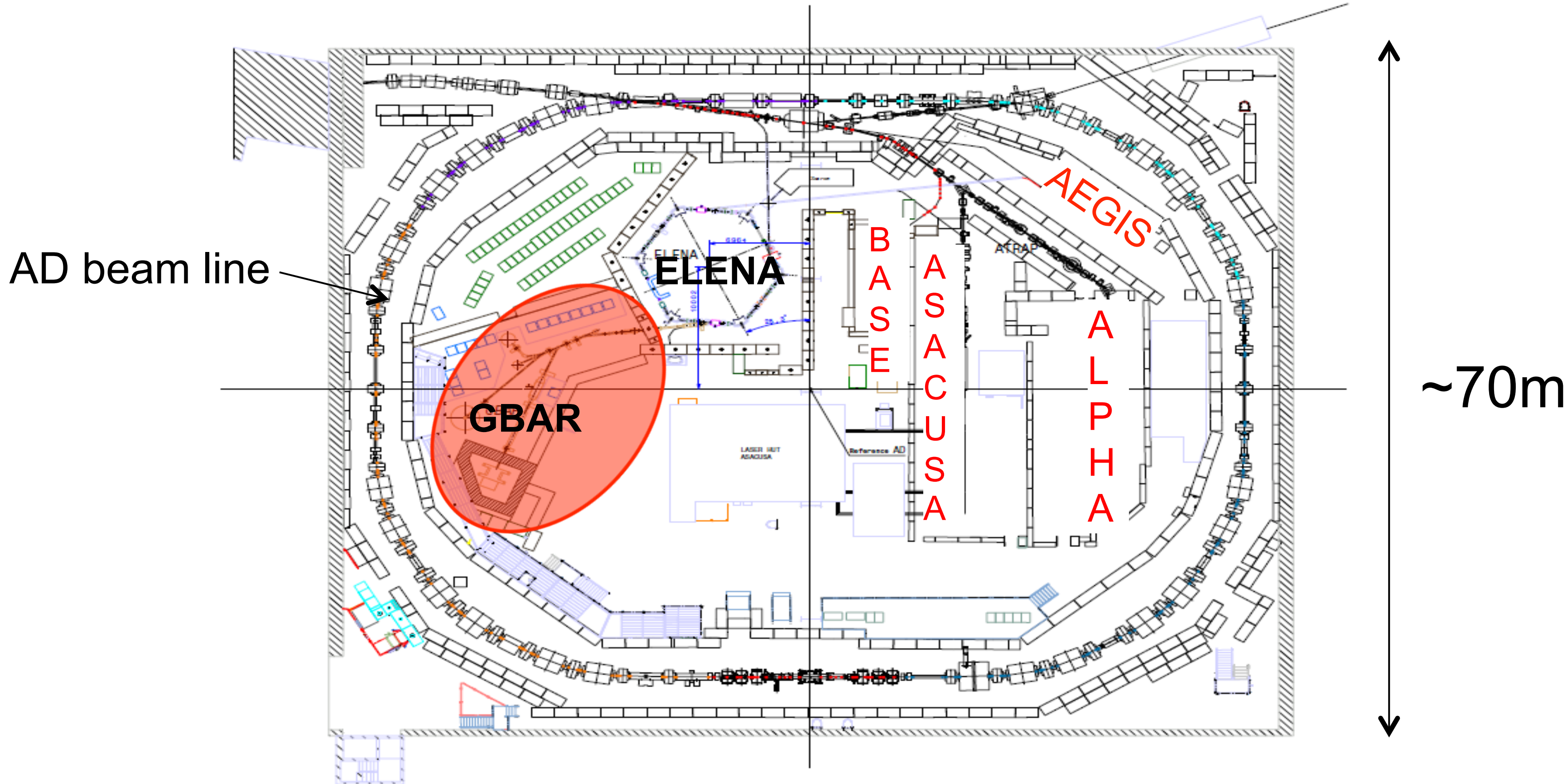
- p-p annihilation emits charged pions (π^+, π^-)
- Time Projection Chambers: trajectories of charged particles
  precision on the annihilation vertex ~ 1 mm
- Scintillating detectors to get precise annihilation time

Antiproton Decelerator (AD) CERN

p (26GeV) -> metallic target
10^6 collisions -> pairs $p\ \bar{p}$

Deceleration in AD : 0.96 c ->0.1 c

AD Hall

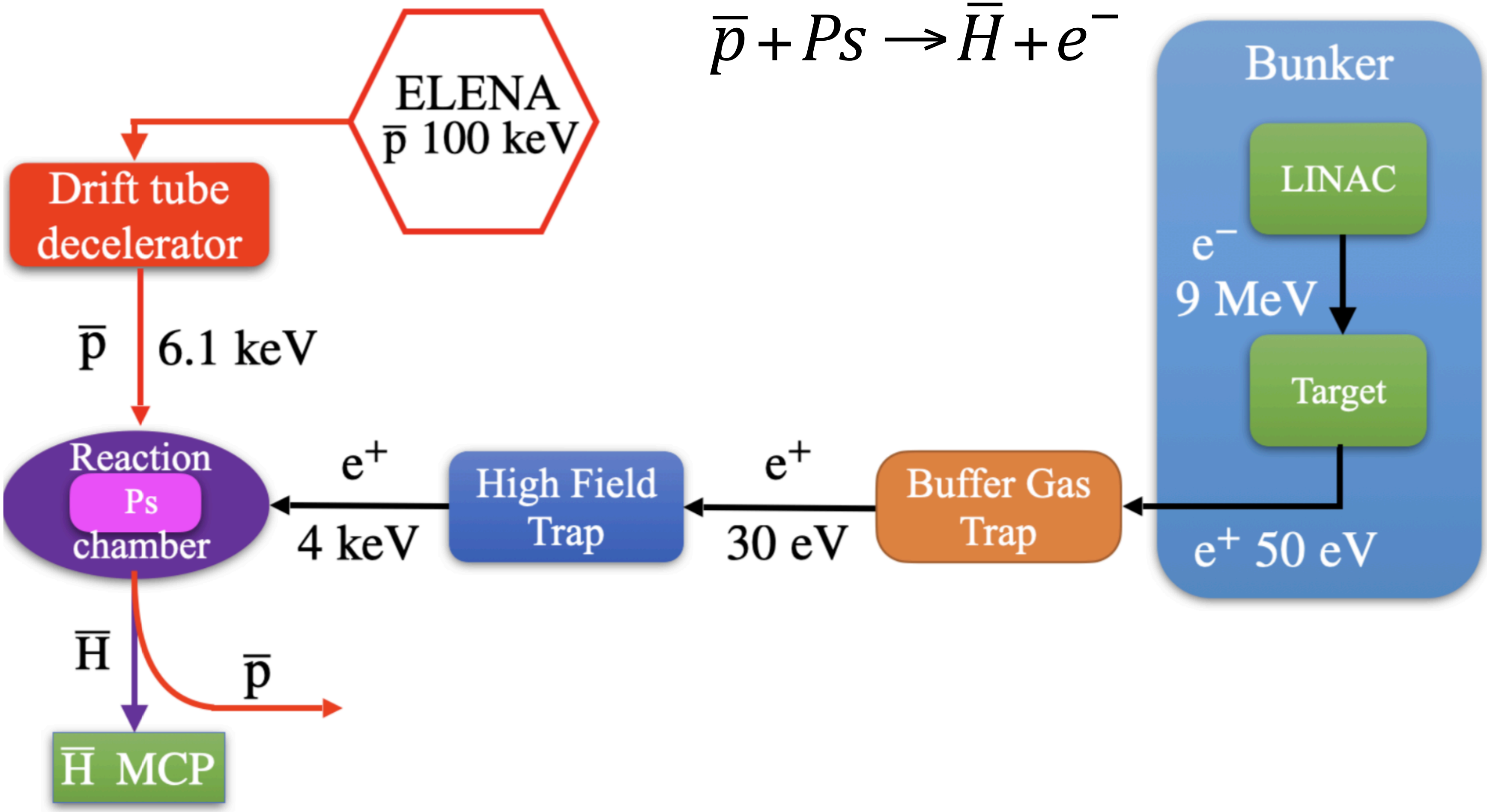


ELENA : Extra Low Energy Antiproton : 5.3 MeV ->0.1 MeV (0.1c -> 0.014c)

bunches of ~ 7 10^6 $\bar{p}$ every 120 s @100keV <-> ~ 4 x 10^6m/s

Set up for first production of $\overline{\mathrm{H}}$ from GBAR

$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$



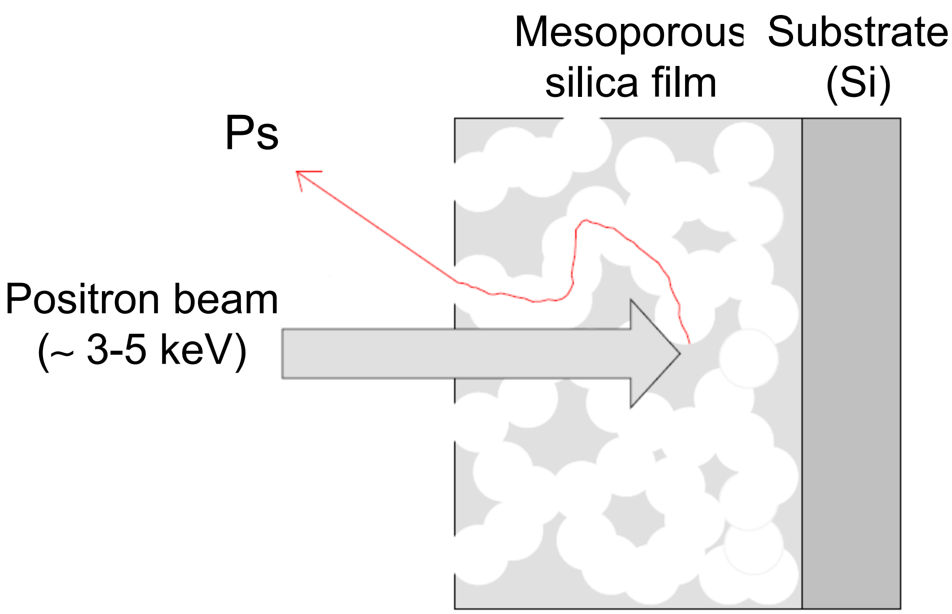
Production of Ps

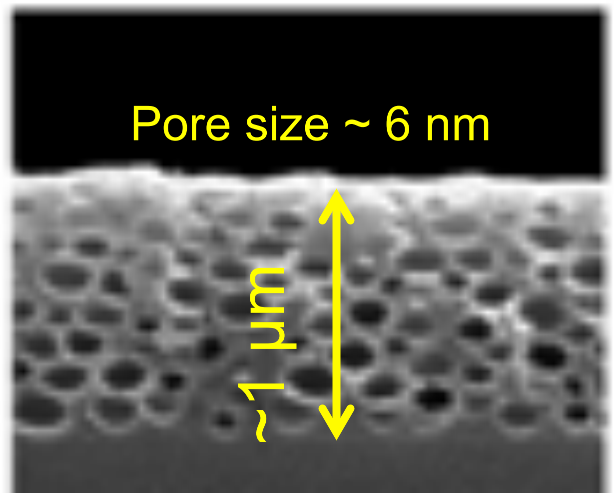
- Produce Ps (e^+e^-) in sufficient quantity

→ Intense source of positrons

'usual' source: $^{22}Na \rightarrow {}^{22}Ne + e^+ + \nu_e + \gamma$ too small intensity

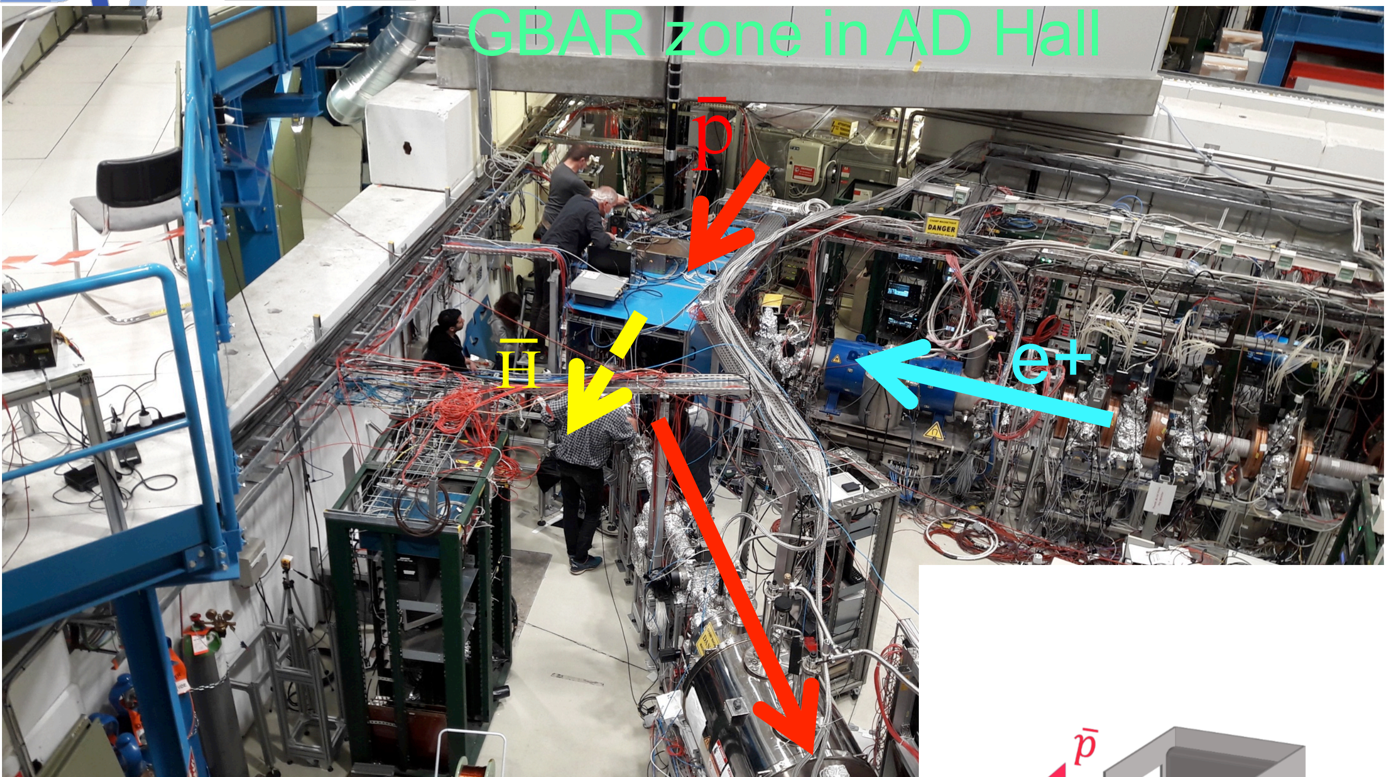
LINAC high-energy e^- on high-Z metallic target: e^+e^- pair creation

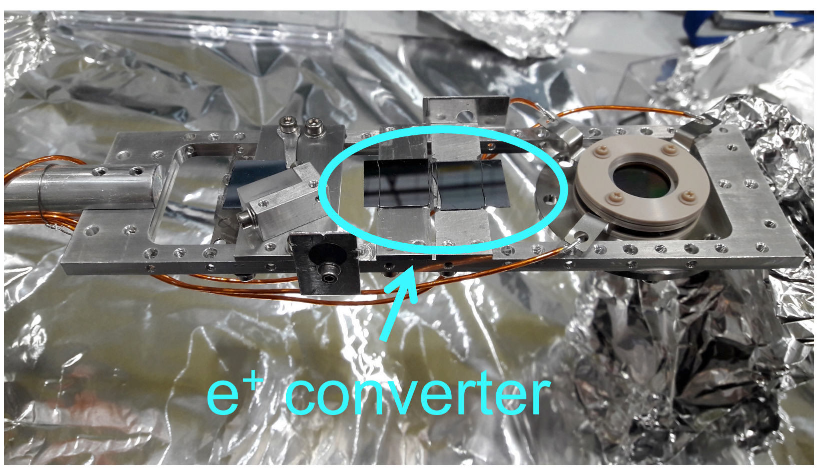


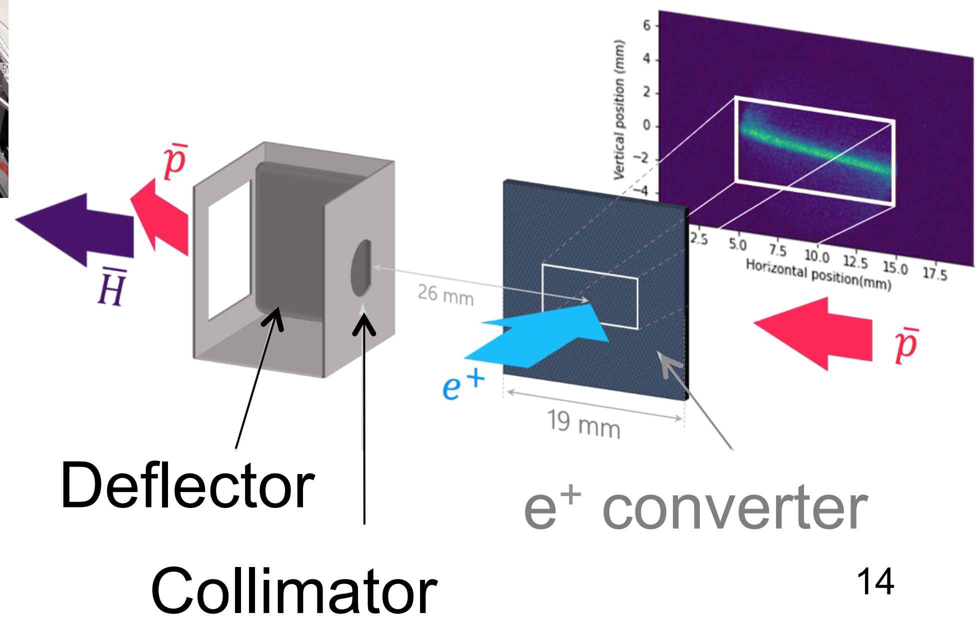


- Excellent conversion efficiency (> 30% !)
- Ps energy: < 0.1 eV

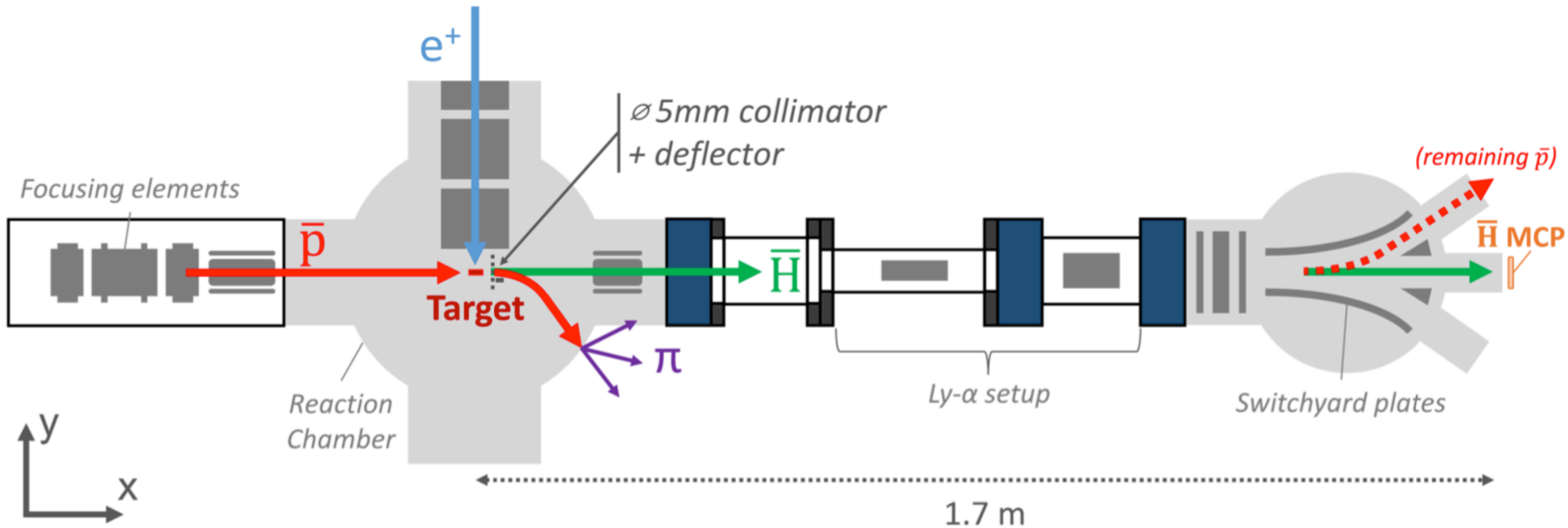
GBAR experiment at CERN

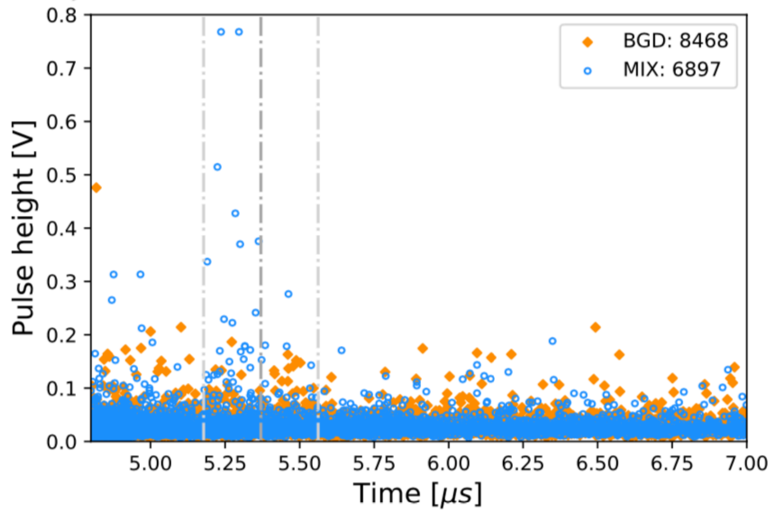


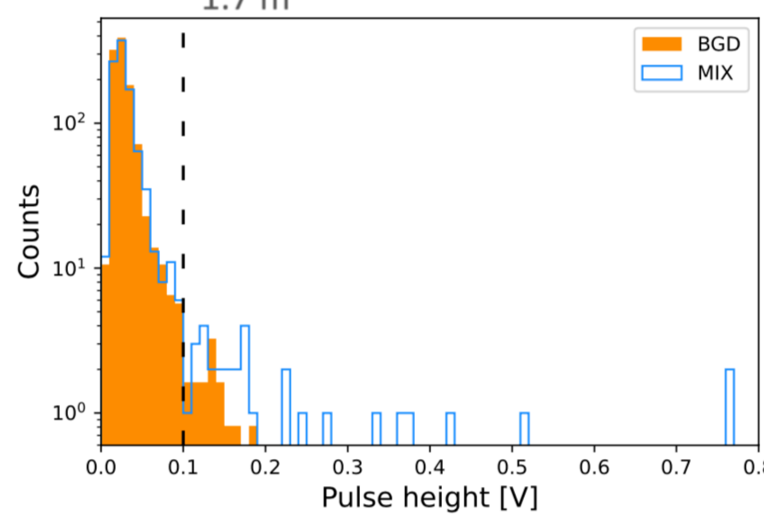




First production of $\overline{\mathrm{H}}$ from GBAR



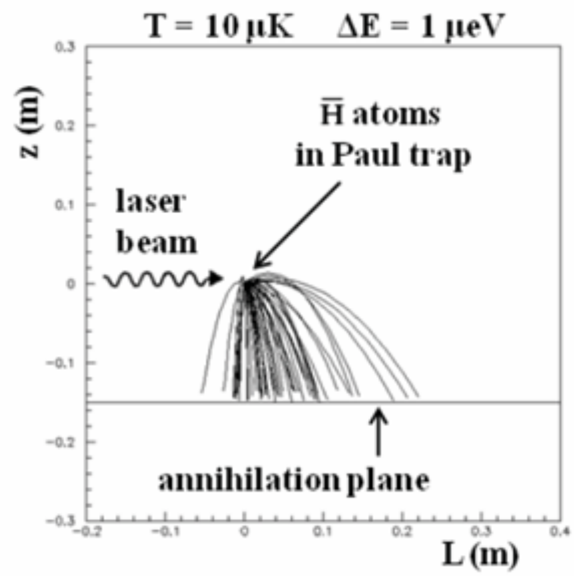




P. Aldrich et al, “Production of antihydrogen atoms by 6 keV antiprotons through a positronium cloud”, accepted for publication in EPJC

Quantum reflection of antihydrogen

Theoretical contribution to the project initiated by the team “Quantum Fluctuations and Relativity” and now P. Cladé, S Guellati, J. Guyomard and S. Reynaud (see next talk)



Quantum reflection of antihydrogen atoms from the Casimir potential of the detection plate

- suppresses close contact with the plate and therefore prevents annihilation
- would bias the free fall measurement, if not properly accounted for

Bias correction implemented thanks to theoretical evaluations :

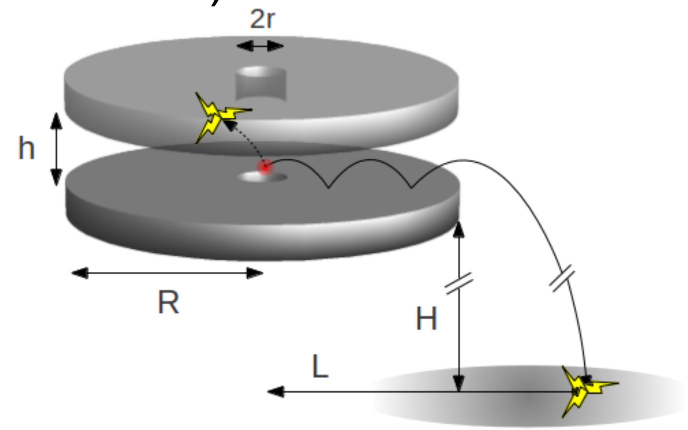
- Casimir-Polder potential for real plates
- Quantum reflection of cold antihydrogen atoms as a function of their energy, to be taken into account in the data analysis.

Possible improvements

Quantum reflection could be used for :

- reducing the initial distribution of vertical velocities of cold antihydrogen atoms in GBAR (initial idea)
- improving the accuracy in the measurement of *g* with respect to unrestricted free fall ($\sim 10^{-4}$)

(see J. Guyomard talk)

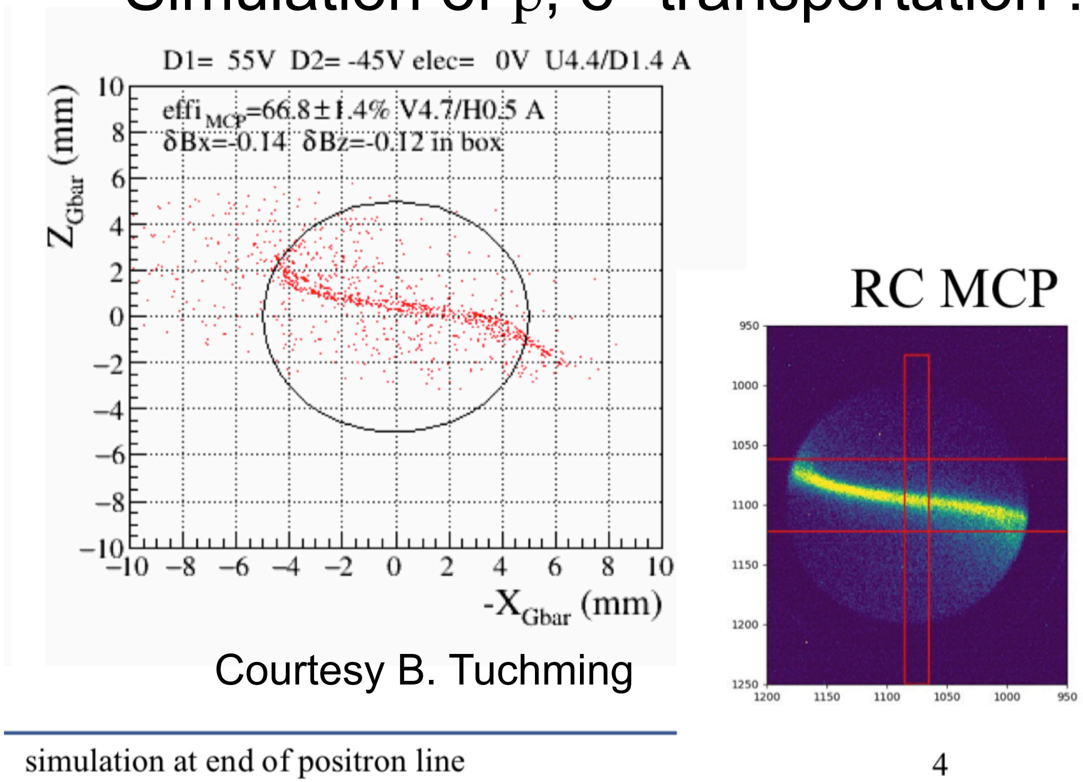


Experimental studies of quantum reflection with cold hydrogen : GRASIAN international collaboration (https:\\grasian.eu)

On a longer term, quantum reflection could be used for trapping ultracold hydrogen/antihydrogen atoms in the quantum states above a matter slab (Eur Phys J. C. 123,1-10 (2020) and improving the accuracy by quantum spectroscopy measurements (strong analogy with measurements on ultracold neutrons)

Current : optimization of $\bar{\mathrm{H}}$ production

- Simulation of $\bar{p}$, e^+ transportation : qualitative agreement



Courtesy B. Tuchming

➔ indications of E, B stray fields contributions

- Trapping $\bar{p}$ in magnetic high field trap => cooling of $\bar{p}$ with e^-

summary and outlook

- We have demonstrated our first production H atoms on GBAR setup.
- We have a qualitative agreement for charged particles transportation between experiment and simulation. We are working to optimize those transportations (better control of stray fields, etc).
- Before the long shut down (LS3) 2026- mid2027 :
  - trapping $\bar{p}$ and improving $\bar{H}$ production
  - measuring the cross section of $\bar{H}$ +Ps -> $\bar{H}^+$ +e$^-$

  with H$^-$ beam (100keV) from ELENA (CERN) assuming invariance by charge conjugation : H$^-$ photoionization then : H + Ps -> H$^-$ + e$^+$.
  - measurement of the $\bar{H}$ Lamb shift (2S-2P)

Conclusion

Very long term experiment…

Thank you for your attention

LKB

BASE / gbar

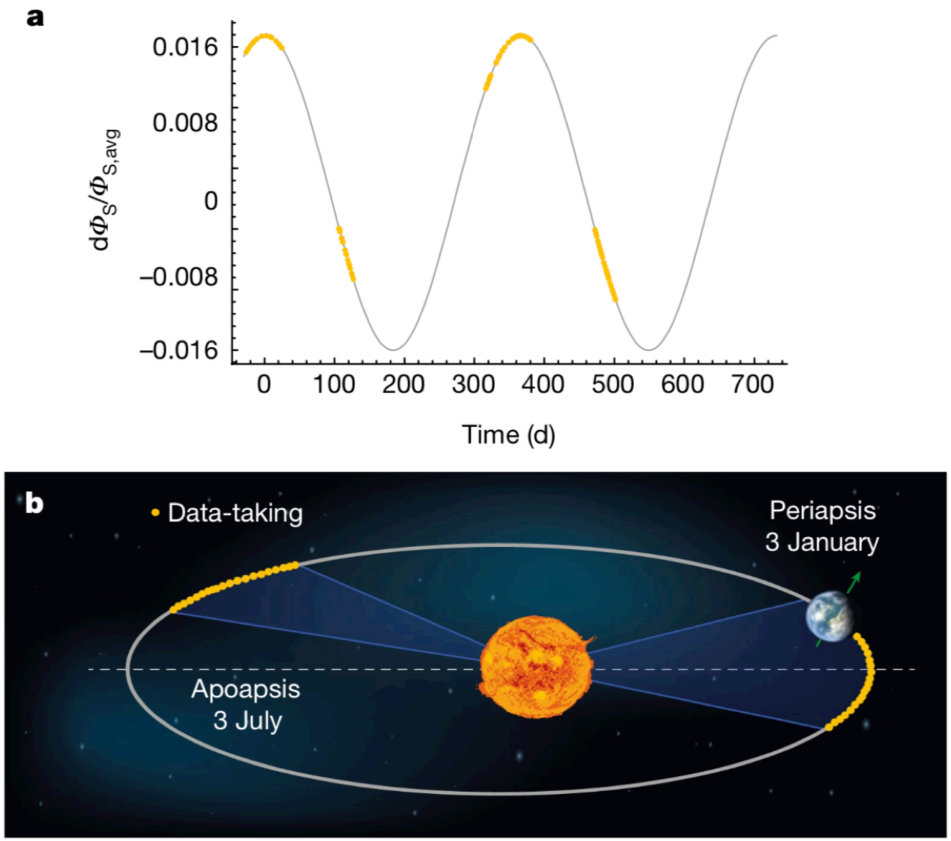
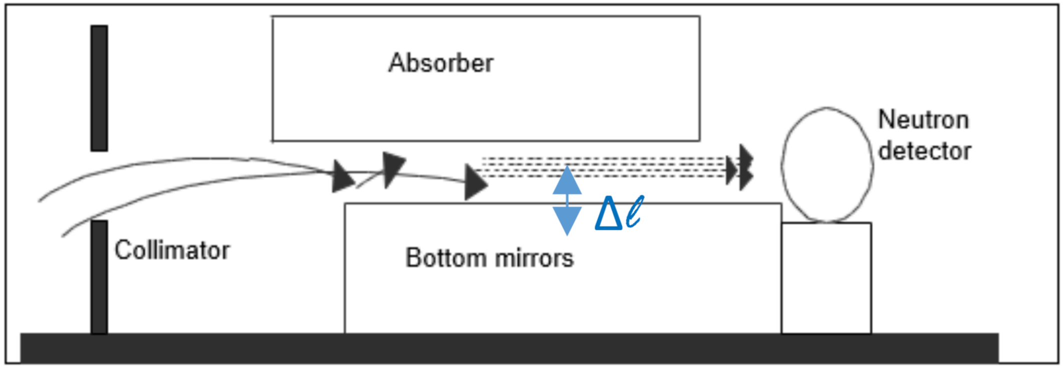
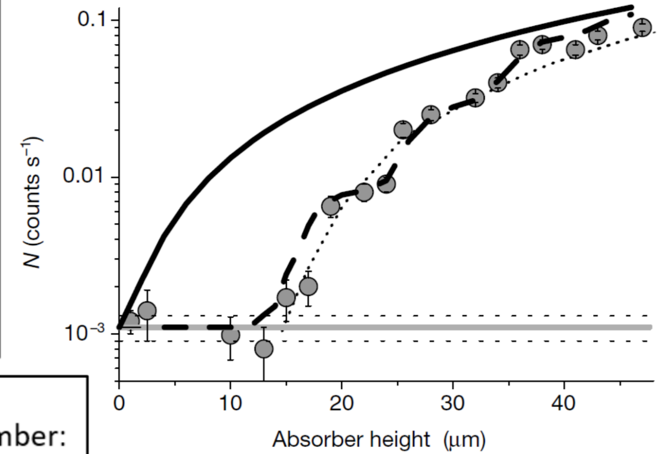


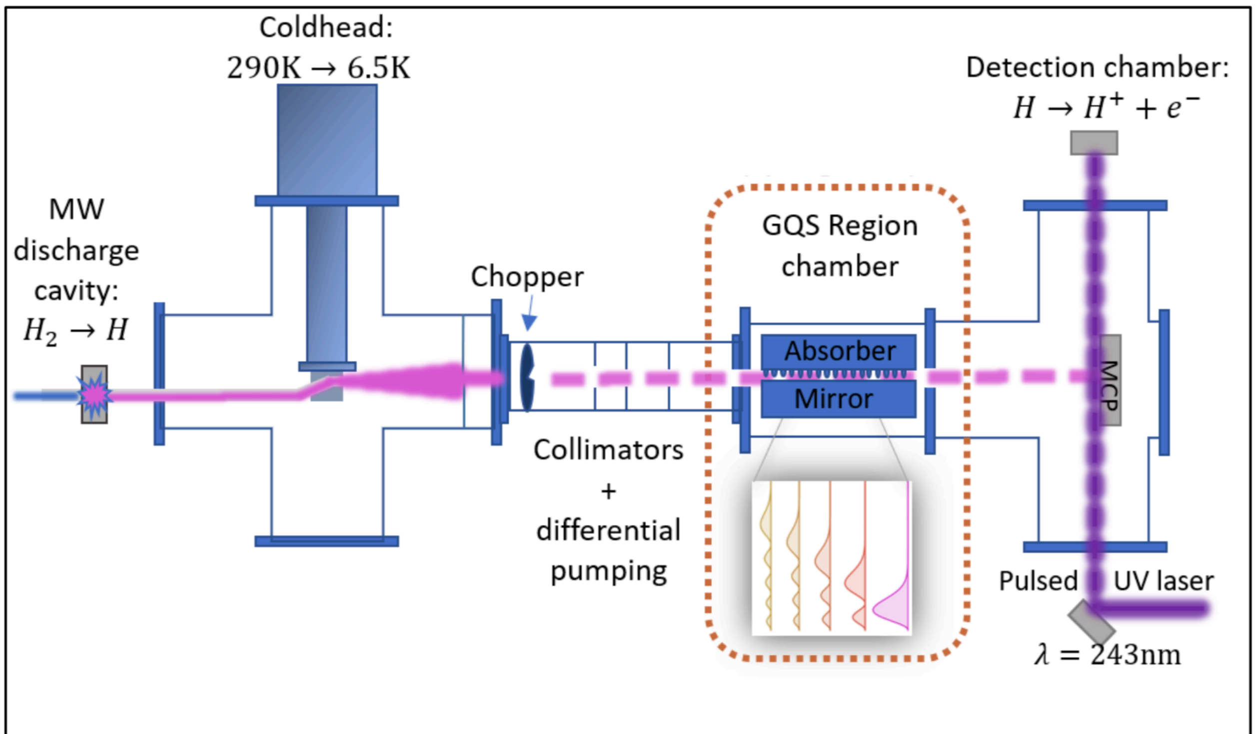
Fig. 3 | Trajectory of the Earth on its orbit around the Sun. a, Variation of the gravitational potential in the BASE laboratory, sourced by the elliptical orbit of the Earth around the Sun. The yellow scatter points represent the data-taking windows. **b**, Scaled orbit; the blue shaded areas indicate the trajectorial fraction covered by the measurement reported here.

Nature, vol 601, p53, Jan 2022

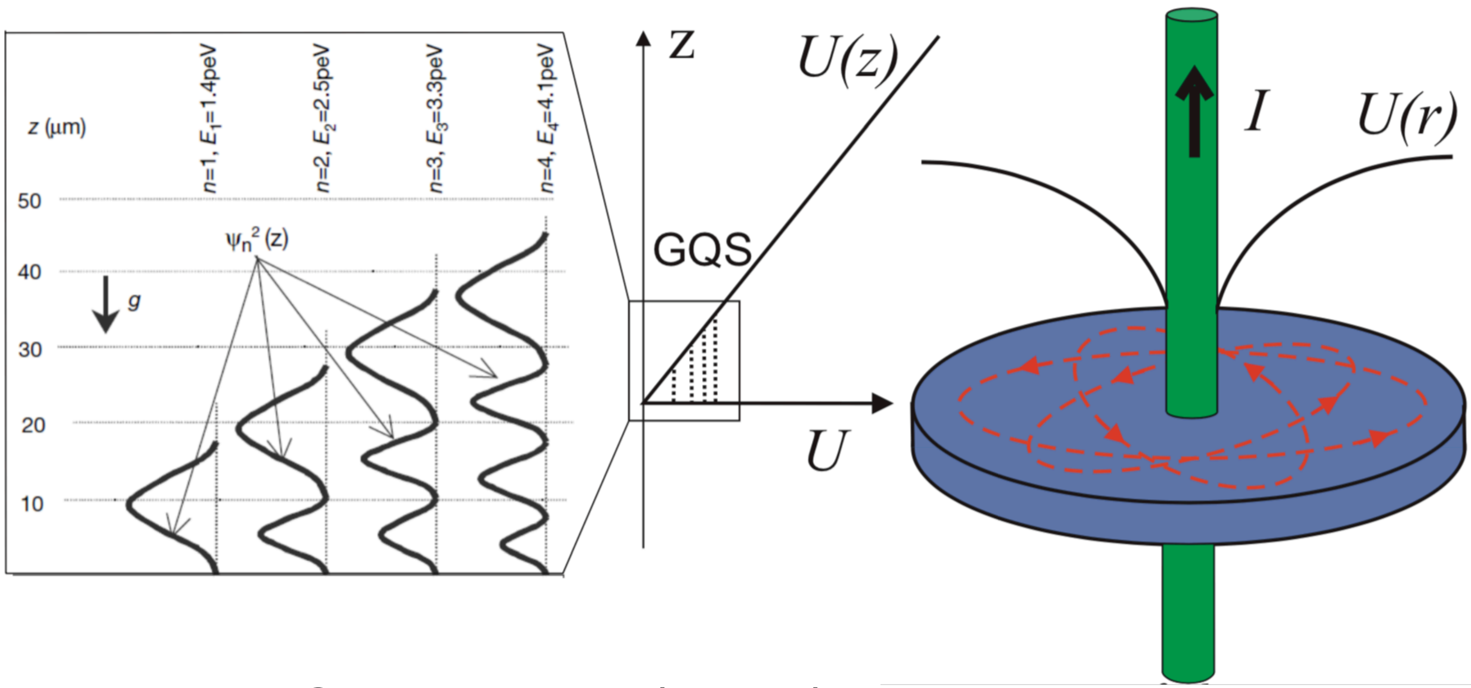
GRASIAN: demonstration experiment







trap MGT



Eur Phys J. C. 123,1-10 (2020)