Measuring the gravitational interaction between matter and antimatter

(and some tests of CPT)

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CERN

Caveats: Any operator affecting antimatter–matter interactions affects also matter–matter interactions which are (very!) well constrained.

Equivalence Principle and Bound Kinetic Energy

M. Hohensee, H. Müller, R. B. Wiringa
PRL 111,151102 (2013)

"in the SME, EEP violation in antimatter can be constrained by tests using bound systems of normal matter"

...an anomaly that violates the weak equivalence principle for free particles generates anomalous gravitational redshifts in the energy of systems in which they are bound, in proportion to the systems' internal kinetic energy...

We consider the role of the internal kinetic energy of bound systems of matter in tests of the Einstein equivalence principle... We survey the sensitivities of existing and planned experimental tests of the equivalence principle, and report new *constraints at the level of between a few parts in 10^6 and parts in 10^8 on violations of the equivalence principle for matter and antimatter*.

Theoretical aspects of antimatter and gravity

Diego Blas ,19 February 2018
https://doi.org/10.1098/rsta.2017.0277

Another important caveat comes from the composite nature of nucleons. In fact, the virtual content (or self-energy or binding energy) is very important in nucleons at rest. This has been used to claim that, since most of the mass of antihydrogen comes from gluons, only a 1% deviation for Δ_a is possible when one considers the gravitation of antihydrogen, given the current constraints on the gravitation of hydrogen [1]. This argument says nothing about new charges which do not affect the gluons, and thus I do not think is very strong in this framework. Also, an important contribution to the nucleon itself comes from virtual antiquarks. Since the exact amount depends on the nuclear binding energy, this effect will be different for different nuclei, and thus the bounds from the equivalence principle can be recycled to constrain it [2]. *The final bound that this implies for Δ_a is model-dependent, but in the simplest scenarios it seems to be of order* $\Delta_a \lesssim 10^{-7}$

[1] Fischler M, Lykken J, Roberts T. 2008
Direct observation limits on antimatter gravitation.
(http://arxiv.org/abs/0808.3929)

[2] Alves DSM, Jankowiak M, Saraswat P. 2009
Experimental constraints on the free fall acceleration of antimatter.
(http://arxiv.org/abs/0907.4110)

For quite sometime, (direct) experimental tests with antimatter will lag behind ...

Gravity...

- attempt to build a quantum theory of gravity...
- New quantum scalar and vector fields are allowed in some models (KK)

Einstein field: tensor graviton (spin 2, "Newtonian")
+ Gravi-vector (spin 1)
+ Gravi-scalar (spin 0)

- Such fields may mediate interactions violating the equivalence principle

M. Nieto and T. Goldman, Phys. Rep. 205,5 221-281 (1992)

Scalar: "charge" of particle equal to "charge of antiparticle" : attractive force
Vector: "charge" of particle opposite to "charge of antiparticle": repulsive/attractive force

$$V = - \frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s} \right)$$

Jagannathan & Singh, Phys. Rev. D 33 (2475) (1986)

Cancellation effects in matter experiment if a~b and v~s

(how could such a cancellation arise naturally?)

CPT...

although CPT is part of the "standard model",
the SM can be extended to allow CPT violation

CPT violation and the standard model

Don Colladay and V. Alan Kostelecký
Department of Physics, Indiana University, Bloomington, Indiana 47405
(Received 22 January 1997)

Phys. Rev. D 55, 6760–6774 (1997)

Modified Dirac eq. in SME

CPT & Lorentz violation

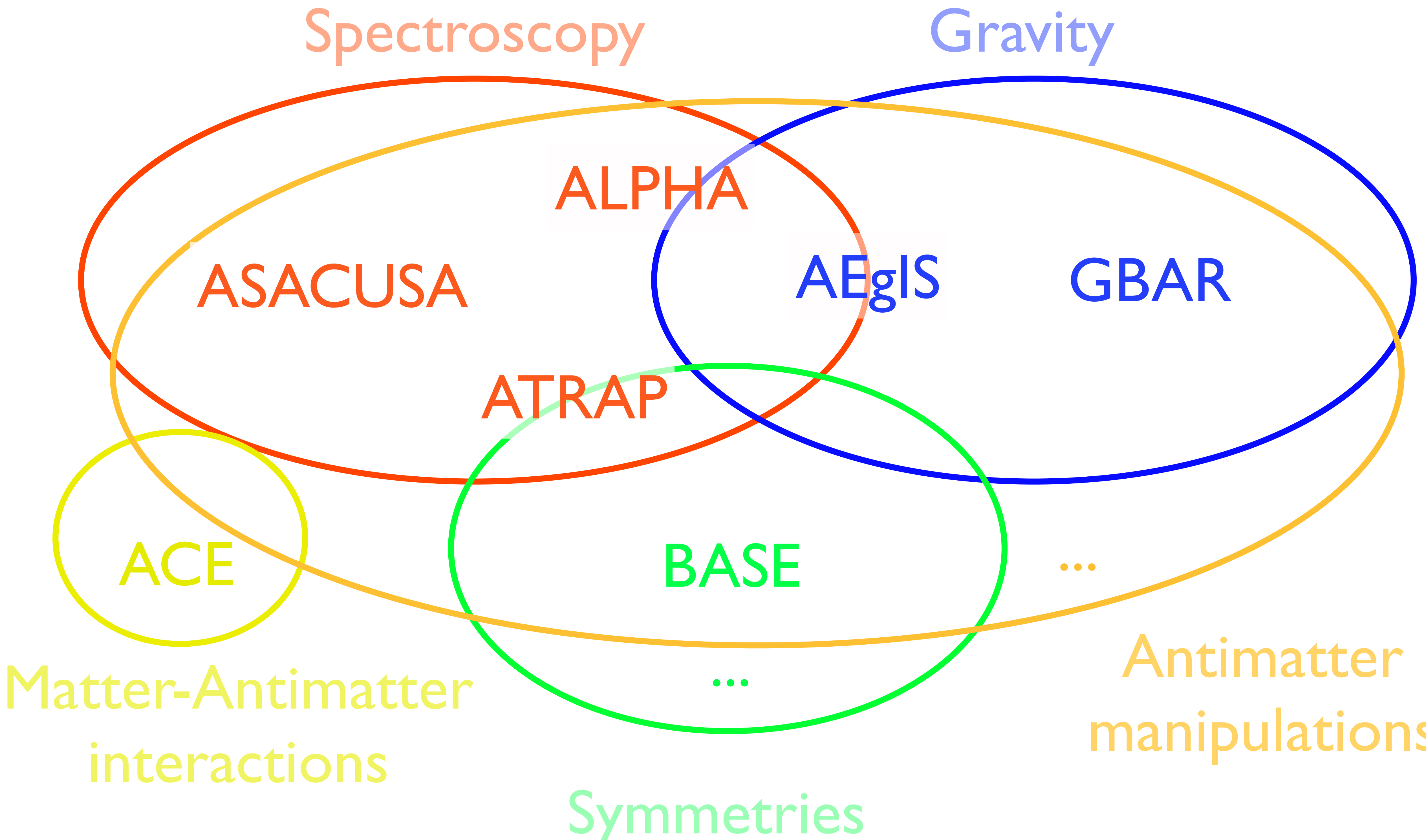
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu - \tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0\,.$$

Lorentz violation

- Spontaneous Lorentz symmetry breaking by (exotic) string vacua
- Note: if there is a preferred frame, sidereal variation due to Earth's rotation might be detectable

if Lorentz invariance is broken, new possibilities for scalar and vector couplings become possible...

Experiments at CERN's Antiproton Decelerator (antiprotons and antihydrogen)



first stop: indirect tests of gravity

Preferred candidate system: antiprotons

Indirect tests: ATRAP & BASE

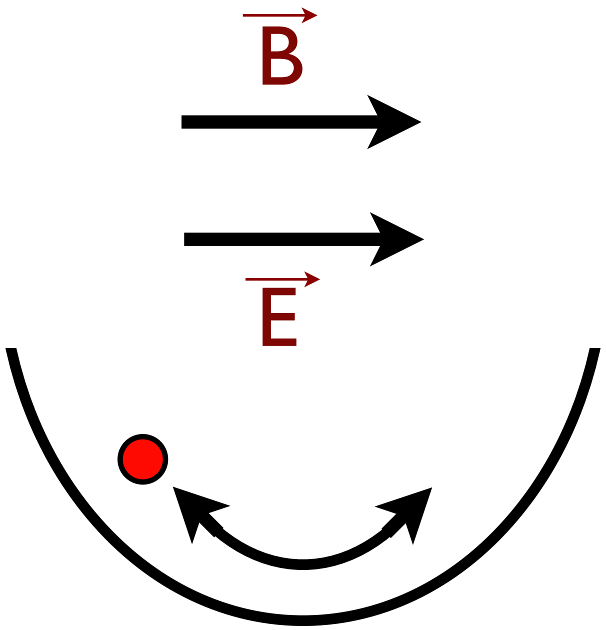
(absence of gravitational redshift)

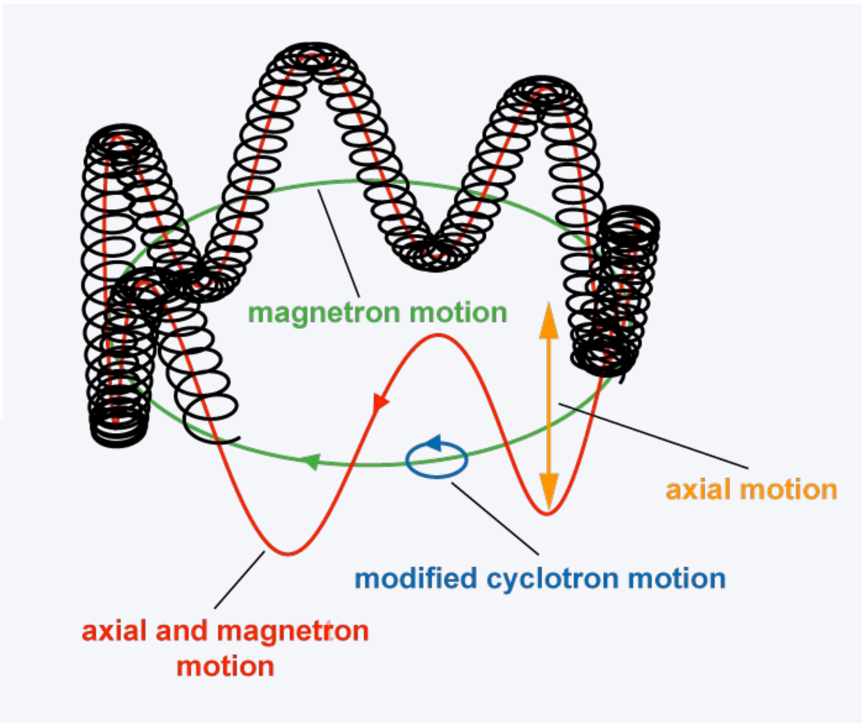
In a magnetic field, charged particles follow cyclotron orbits:

$$\omega_c = Bq/m$$

Add an electrical potential well V_0 (d = trap dimension):

$$\omega_z^2 = -qV_0/md^2$$





More generally: motion in Penning trap:

http://gabrielse.physics.harvard.edu/gabrielse/papers/1990/1990_tjoelker/chapter_2.pdf

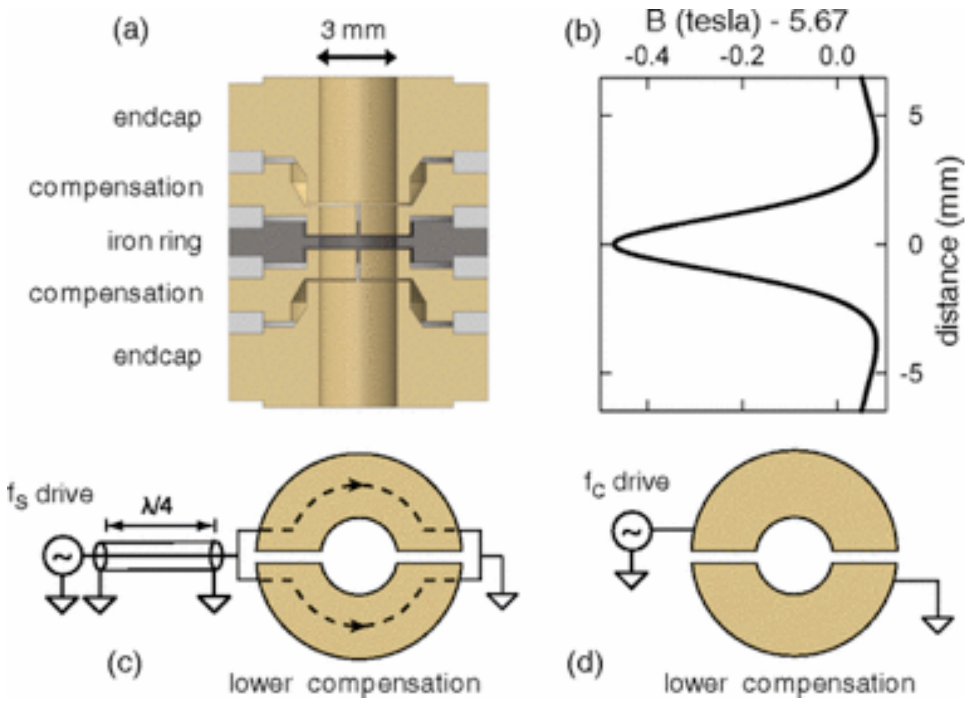
← strong homogeneous axial magnetic field to confine particles radially and a quadrupole electric field to confine the particles axially

modified cyclotron motion	magnetron motion	axial motion
$\omega_+ = \frac{\omega_c}{2} + \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}}$	$\omega_- = \frac{\omega_c}{2} - \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}}$	$\omega_z = \sqrt{\frac{q}{m_p} 2c_2 U_0}$
O(100 MHz)	O(1 MHz)	O(10 kHz)

Indirect tests: ATRAP & BASE

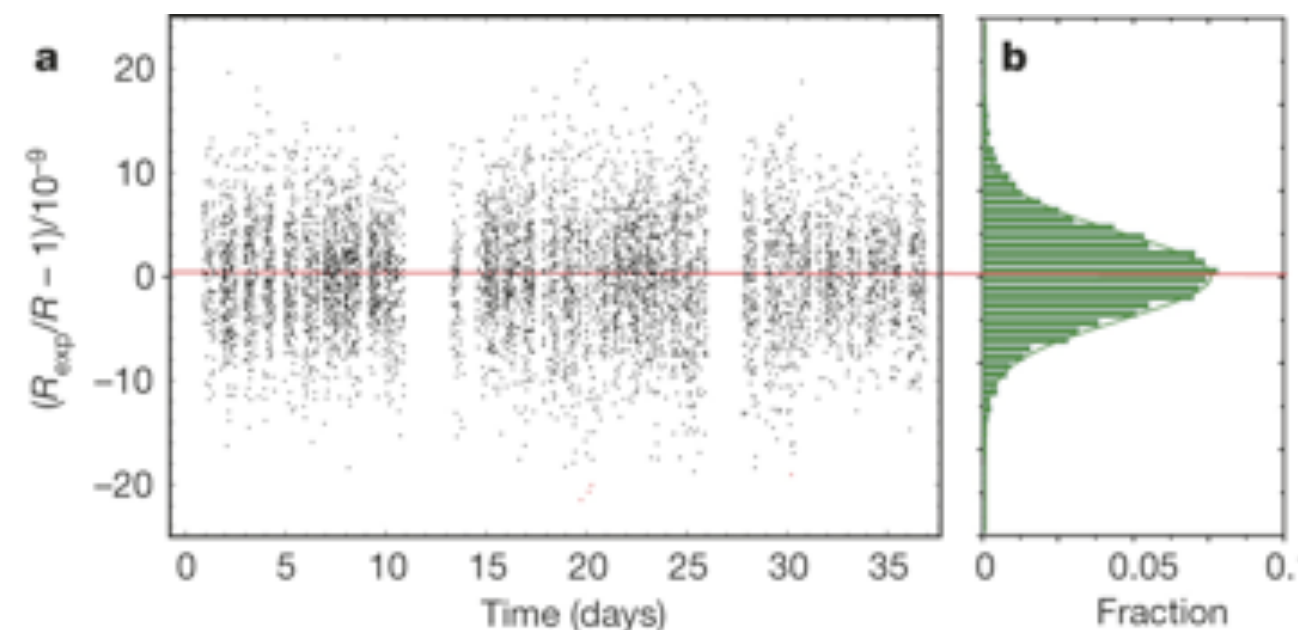
(absence of gravitational redshift)

DiSciacca, J. *et al.* One-particle measurement of the antiproton magnetic moment. Phys. Rev. Lett. 110, 130801 (2013)

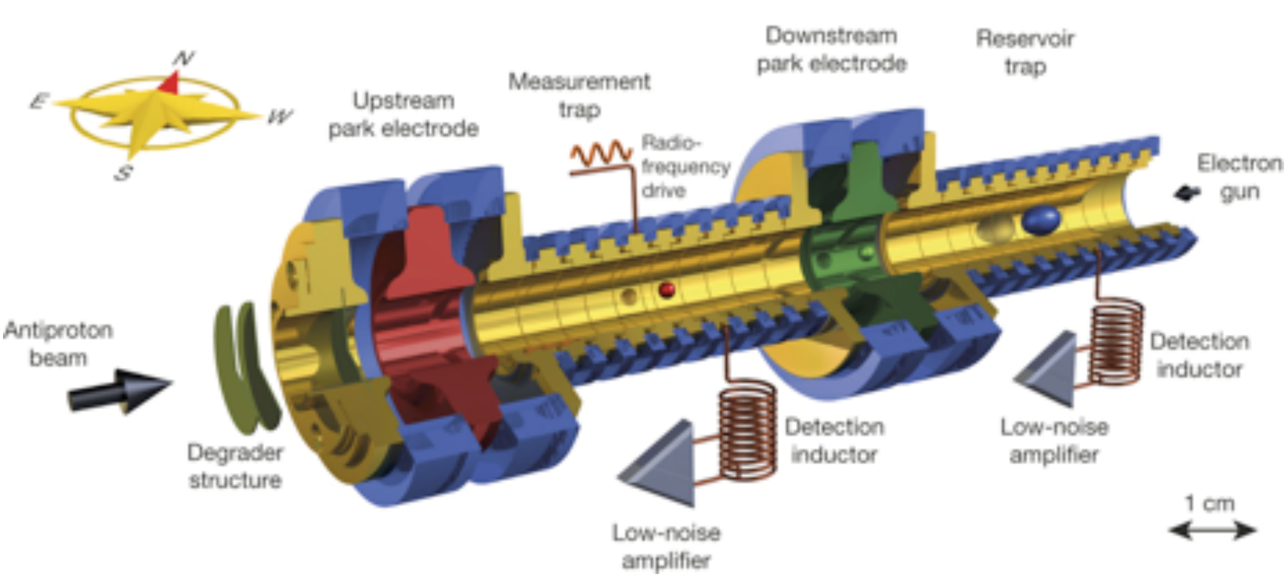


BASE: $(q/m)_{\bar{p}}/(q/m)_p - 1 = 1(69) \times 10^{-12}$ (2015)

All measured antiproton-to-H⁻ cyclotron frequency ratios as a function of time



S. Ulmer. et al. Nature 524,196–199 (13 August 2015)



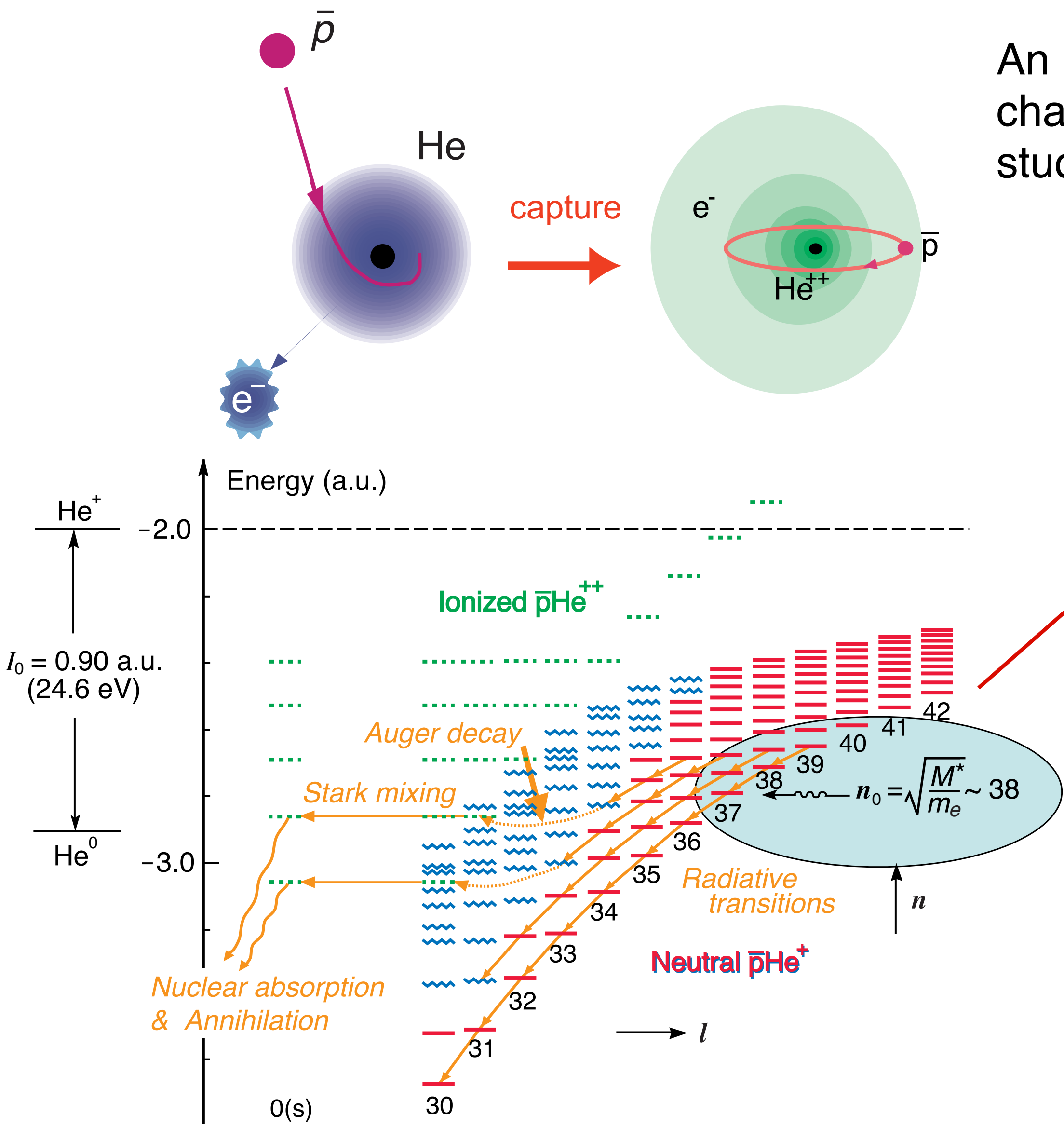
$$(\nu_{c,p} - \nu_{c,\bar{p}})/(\nu_{c,p}) = -3(\alpha_g - 1)U/c^2$$

$$|\alpha_g - 1| < 8.7 \times 10^{-7}$$

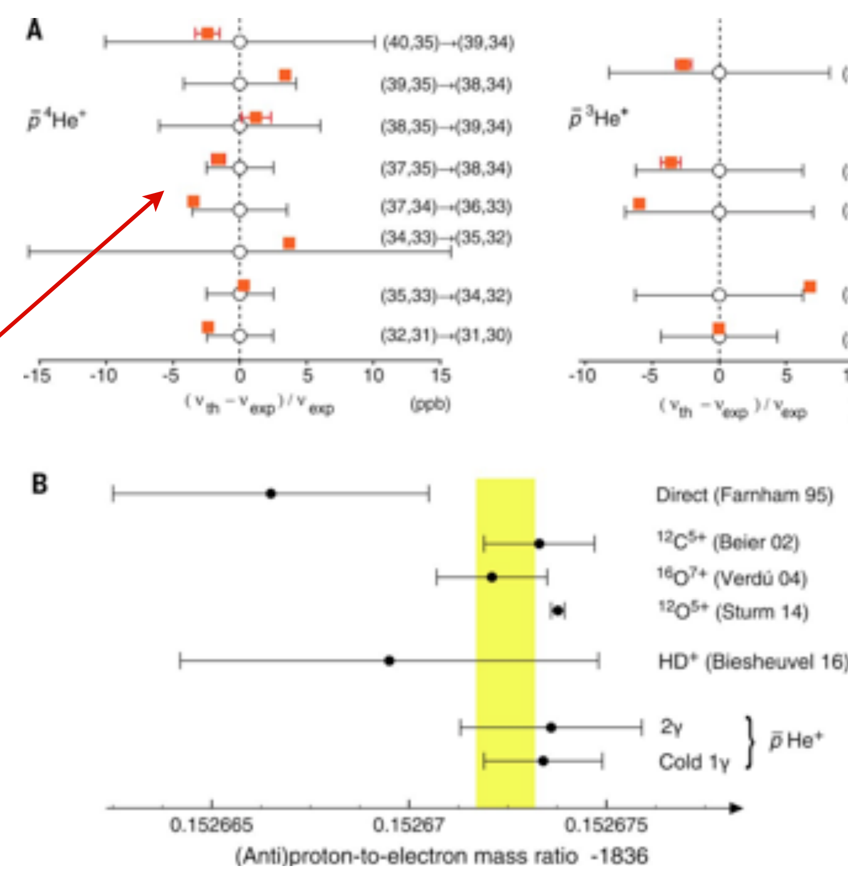
Constraints on the gravitational properties of antiprotons and positrons from cyclotron-frequency measurements

Richard J. Hughes and Michael H. Holzscheiter, Phys. Rev. Lett. 66, 854 – Published 18 February 1991

Indirect tests: ASACUSA ($\bar{p}He^+$ spectroscopy)

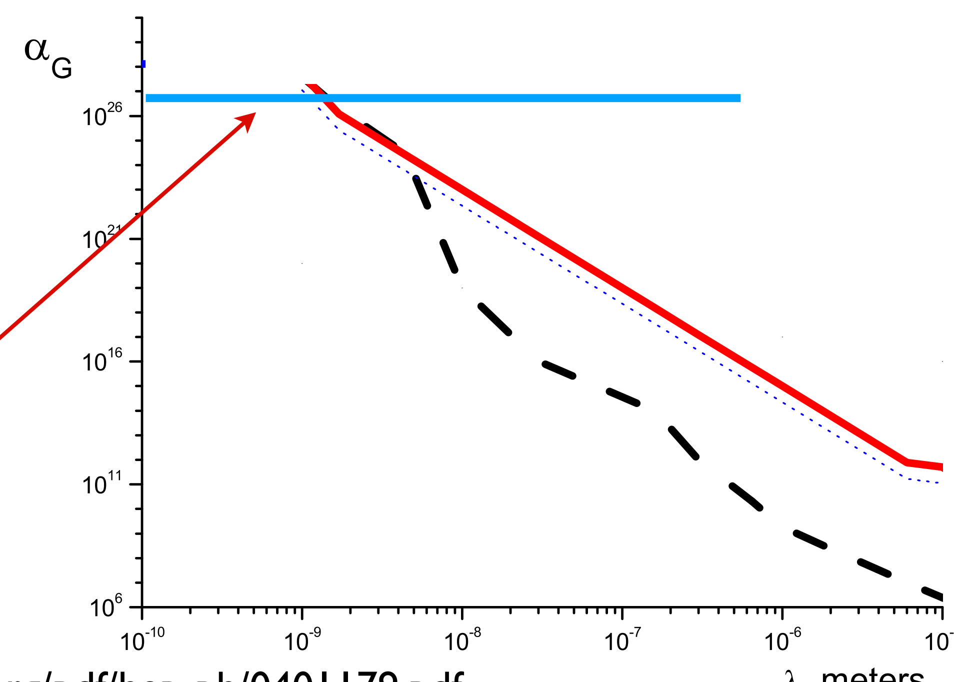


An additional force between a nucleus of mass M and an antiproton would change the spectrum of such an atom. The effective orbit radius r_0 for usually studied antiproton-nucleus atoms is about a few hundreds fm.



M. Hori *et al.*, Science 04 Nov 2016: Vol. 354, Issue 6312, pp. 610-614 DOI: 10.1126/science.aaf6702

$$V_{\rm eff}(r) = G\frac{m_1 m_2}{r}\left(1 + \alpha_G e^{-r/\lambda}\right)$$



Constraints on α_G from ASACUSA measurements with $\bar{p}He$.

The diagonal lines come from measurements of Casimir and van der Waals forces on neutron quantum states in the Earth's gravitational field.

V. Nesvizhevsky, K. Protasov, https://arxiv.org/pdf/hep-ph/0401179.pdf

next stop: direct tests of gravity

Preferred candidate system: Antihydrogen

Antihydrogen production processes

Radiative recombination: BH + BH ➞ BH’ + GW

TBR:
3-body recombination

ALPHA
ATRAP
ASACUSA

AEgIS
GBAR

RCE:
Resonant charge exchange

Temperature
$(T_{e+} \Rightarrow T_{\bar{H}} \sim 50K)$

Rate ~ Rate (trappable)

n *(if trapped)*

Temperature
$T_{\bar{p}}$

Rate ~ Rate (n_{Ps}, v_{Ps})

n *(if trapped or slow)*

Antihydrogen production processes

Radiative recombination: $\bar{p} + e^{-} \rightarrow \bar{H} + \text{gamma}$

TBR:
3-body recombination

ALPHA
ATRAP
ASACUSA

Temperature

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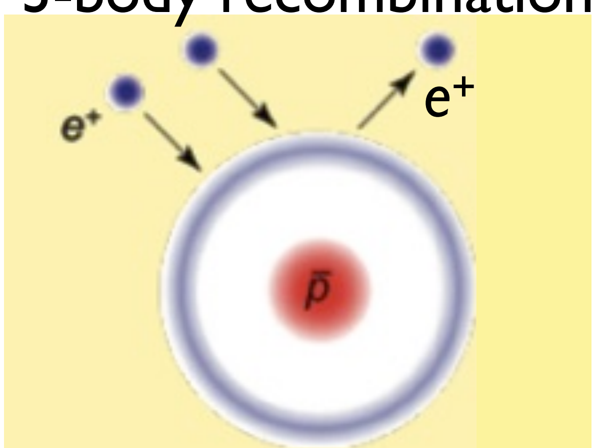
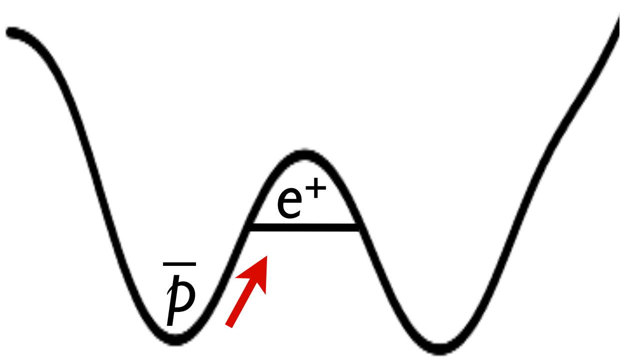


ALPHA
ATRAP
ASACUSA



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AEgIS
GBAR

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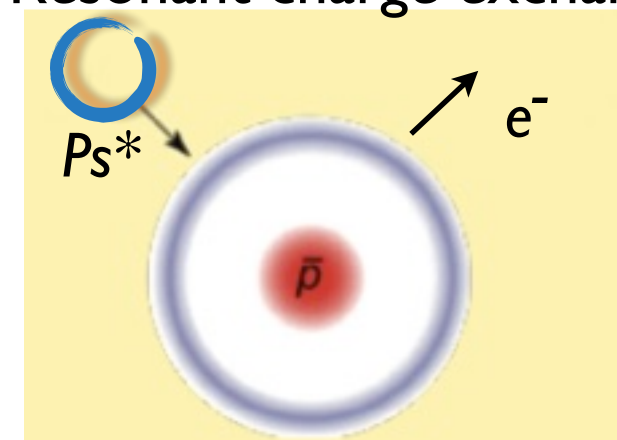


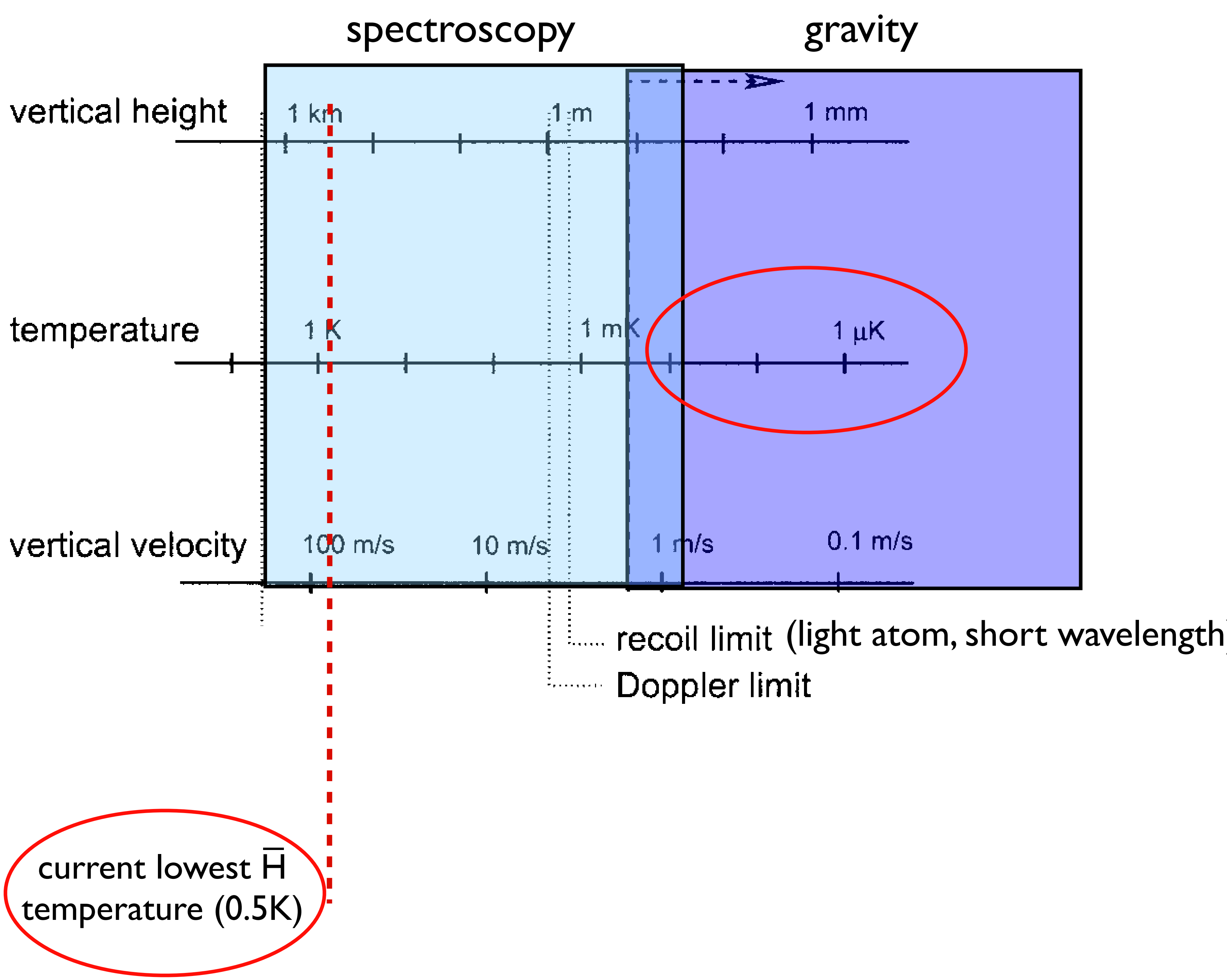
Temperature

$T_{\bar{p}}$

Rate ~ Rate (n_{Ps},v_{Ps})

n *(if trapped or slow)*

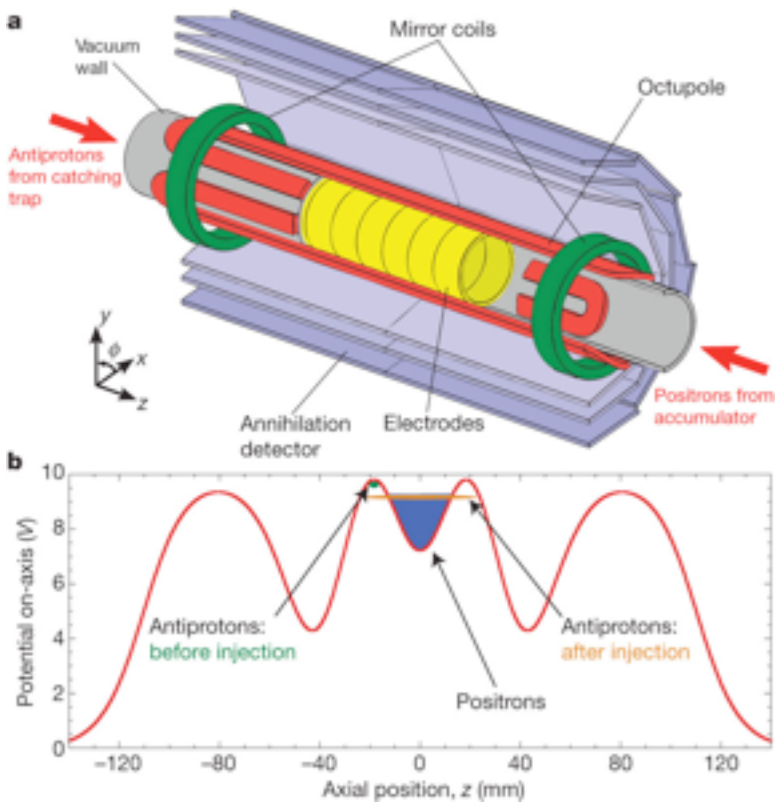
the importance of working at low temperature

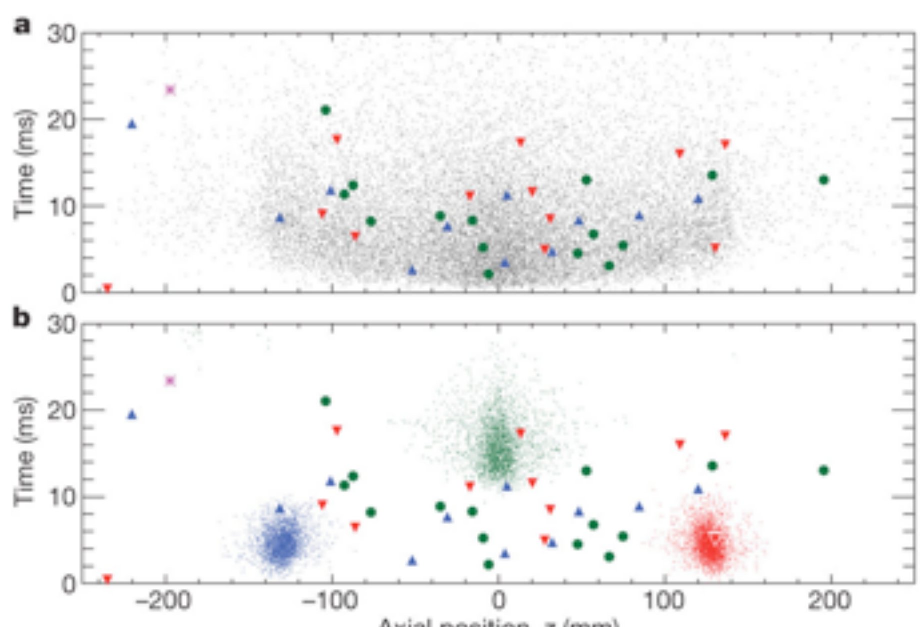


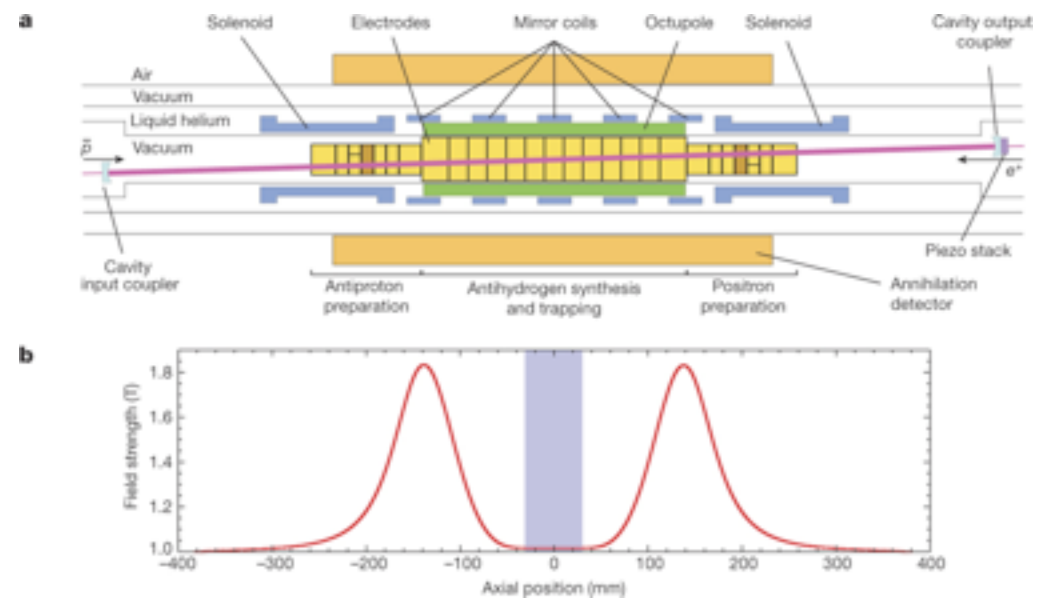
ALPHA results (trapping, 1s-2s spectroscopy)

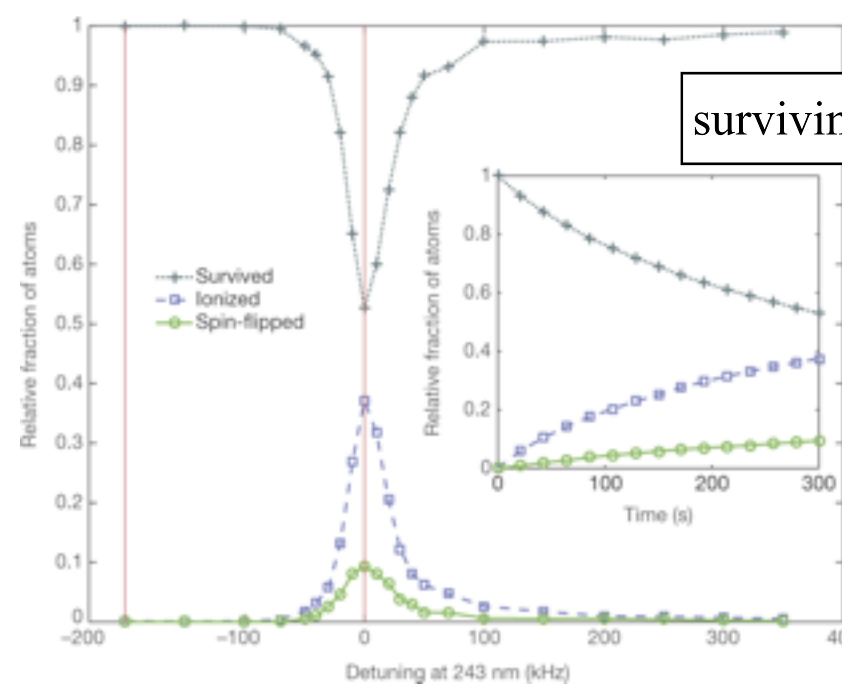
G. B. Andresen et al., Nature 468, 673–676 (02 December 2010)

M. Ahmadi et al., Nature 541, 506–510 (26 January 2017)









surviving fraction: 58% ± 6%

1s-2s to 10^{-10}

further results:

microwave transitions in GS $\bar{H}$

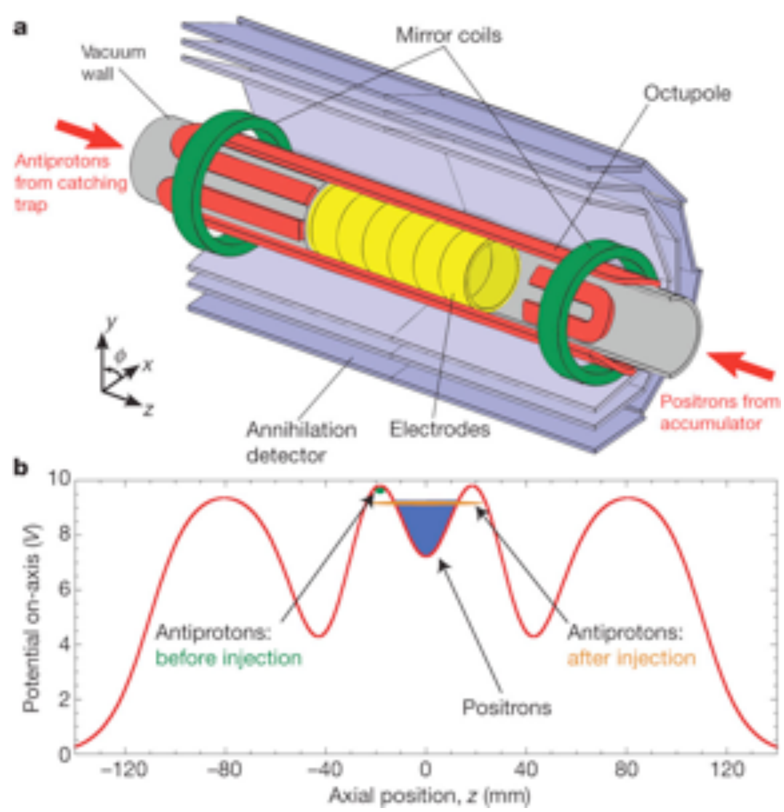
$HFS_{\bar{H}}$ = 1,420.4±0.5 MHz
M.Ahmadi et al., ALPHA collaboration, Nature **548**, 66–69 (03 August 2017)

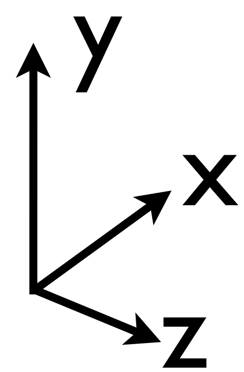
$q(\bar{H}) < 0.71 \times 10^{-9}$ e

M. Ahmadi et al., ALPHA collaboration, Nature **529**, 373–376 (2016)

trapping of ~ 10 $\bar{H}$ simultaneously (similar for ATRAP)

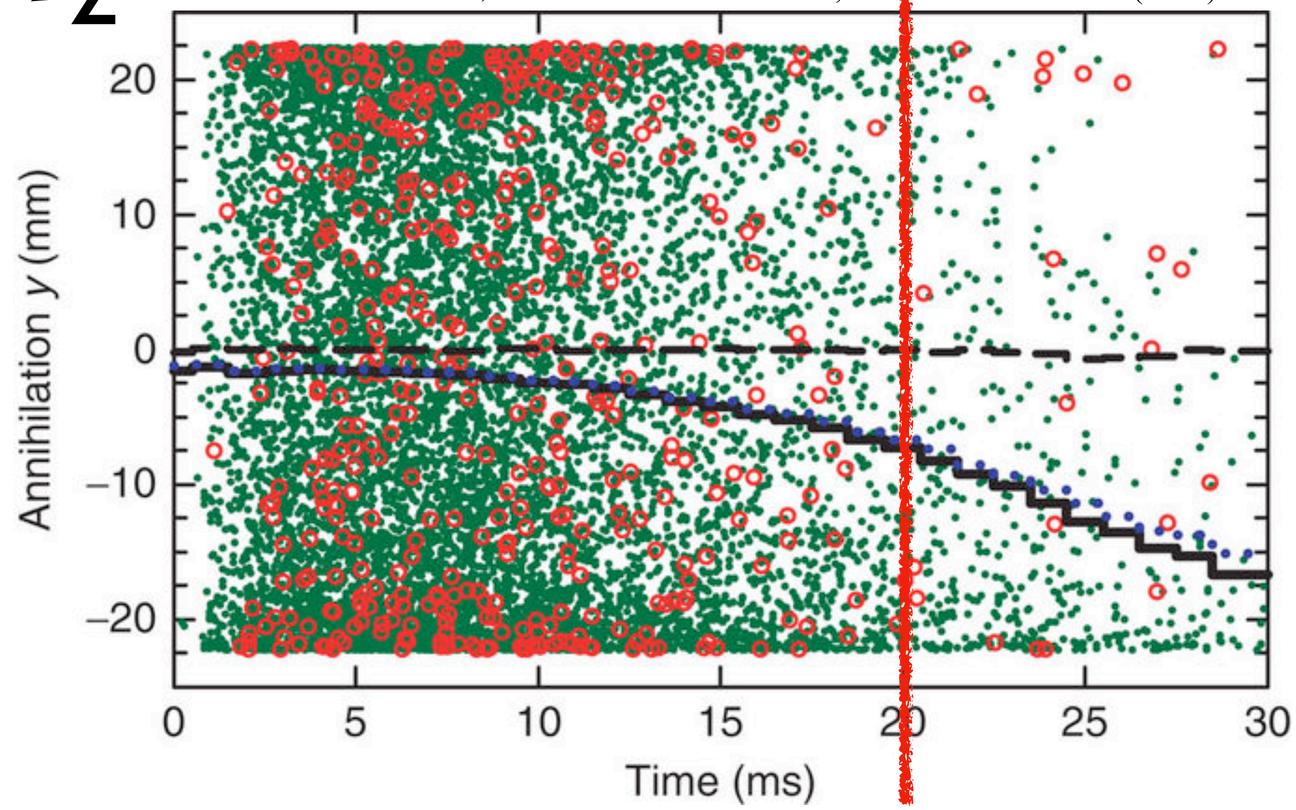
ALPHA results (gravity at 0.5K)

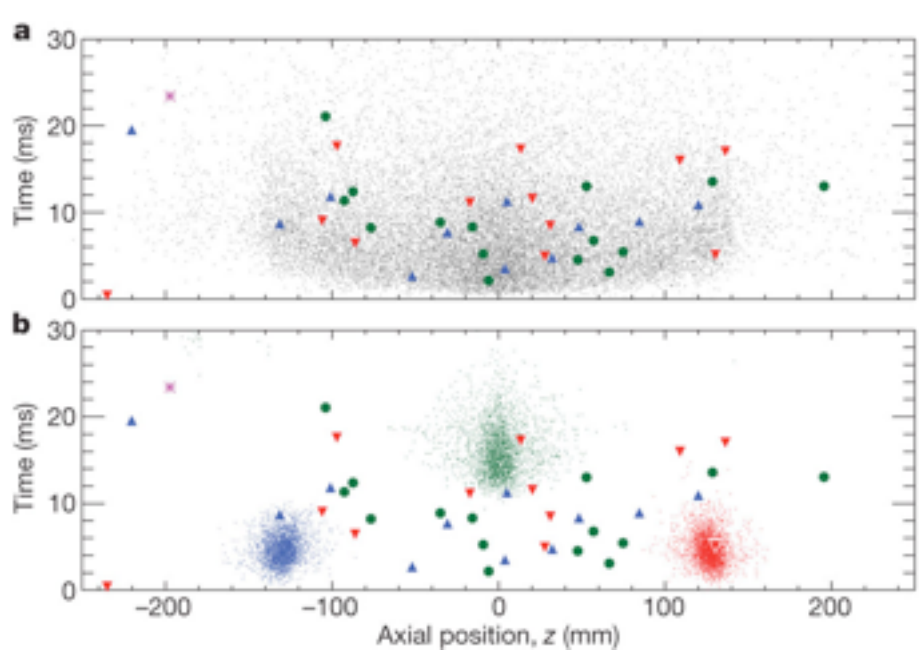




$F \equiv M_g / M$

ALPHA collaboration, Nature Communications **4**, Article number: 1785 (2013)



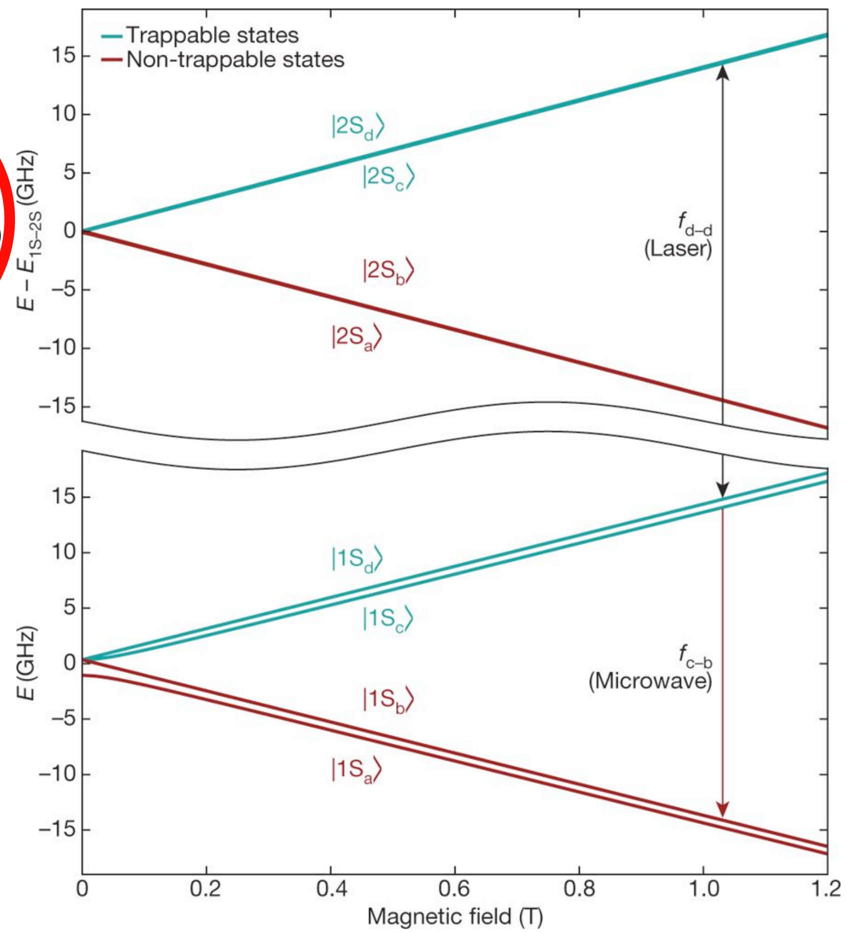


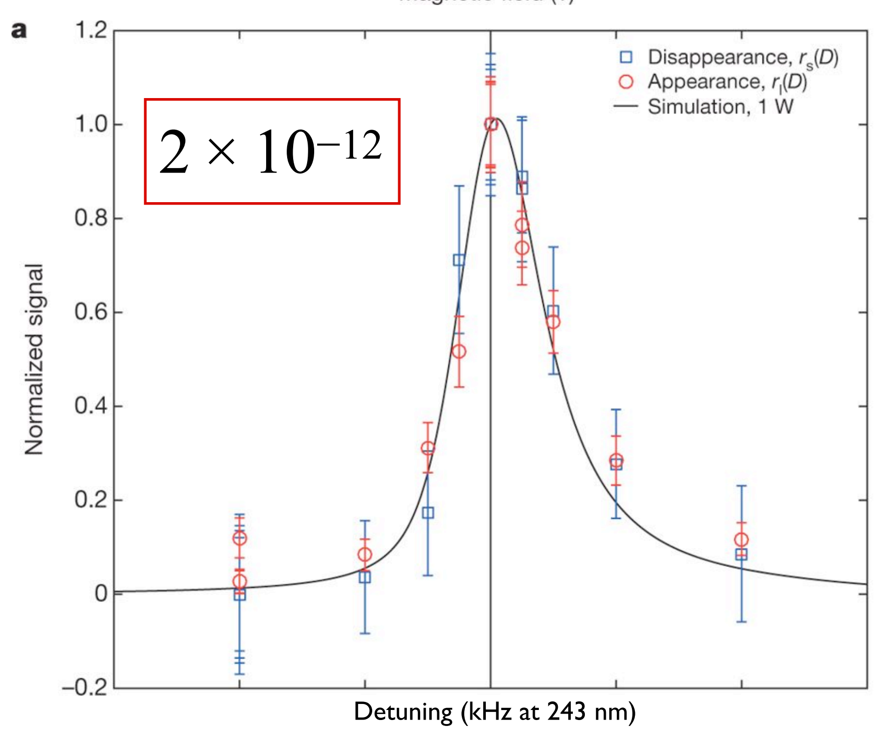
$F_{\bar{H}} < 110$

"... cooling the anti-atoms, perhaps with lasers, to 30 mK or lower, and by lengthening the magnetic shutdown time constant to 300 ms, we would have the statistical power to measure gravity to the $F = \pm 1$ level ..."

ALPHA results (1s-2s spectroscopy, ALPHA-g)

2018





[M. Ahmadi et al., Nature **vol. 557**, pages71–75 (2018)]

2018 installation and commissioning of a second experiment with vertical trap (ALPHA-g)

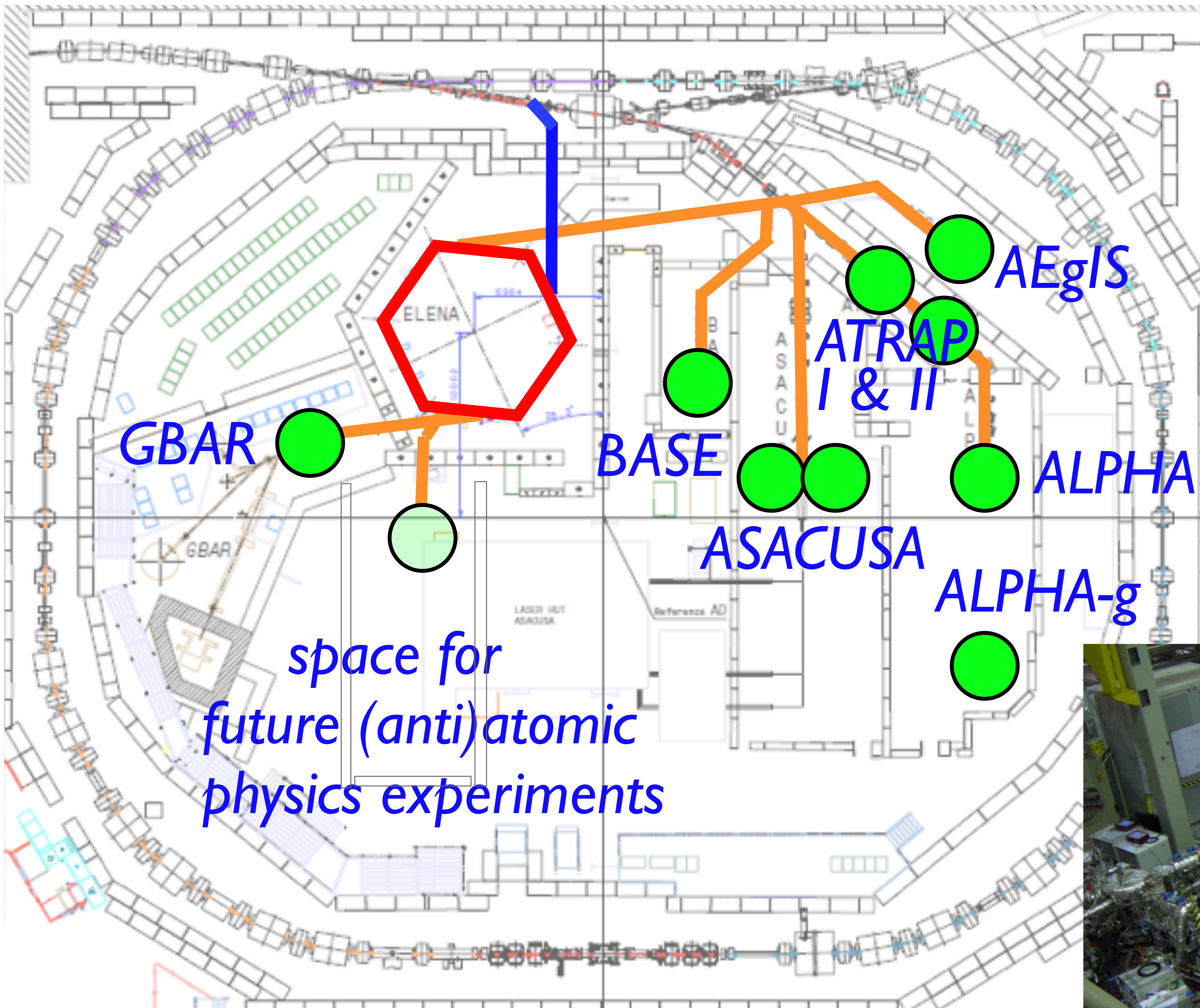
2018 first laser-cooling of $\overline{\mathrm{H}}$ on 1s-2p

Outlook: 100's ~ 1000's of trapped $\overline{\mathrm{H}}$ (through stacking) in B~1T field at temperature O(50) mK

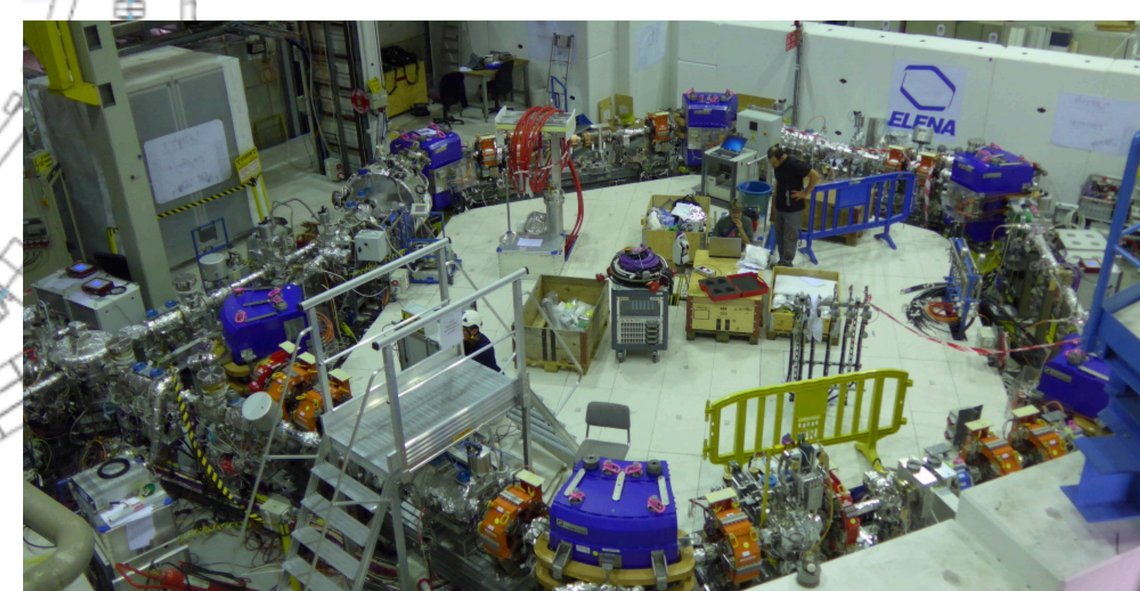
Two main challenges: more / colder antiprotons

current methods for trapping them are quite inefficient

ELENA: a new decelerator down to 100 keV



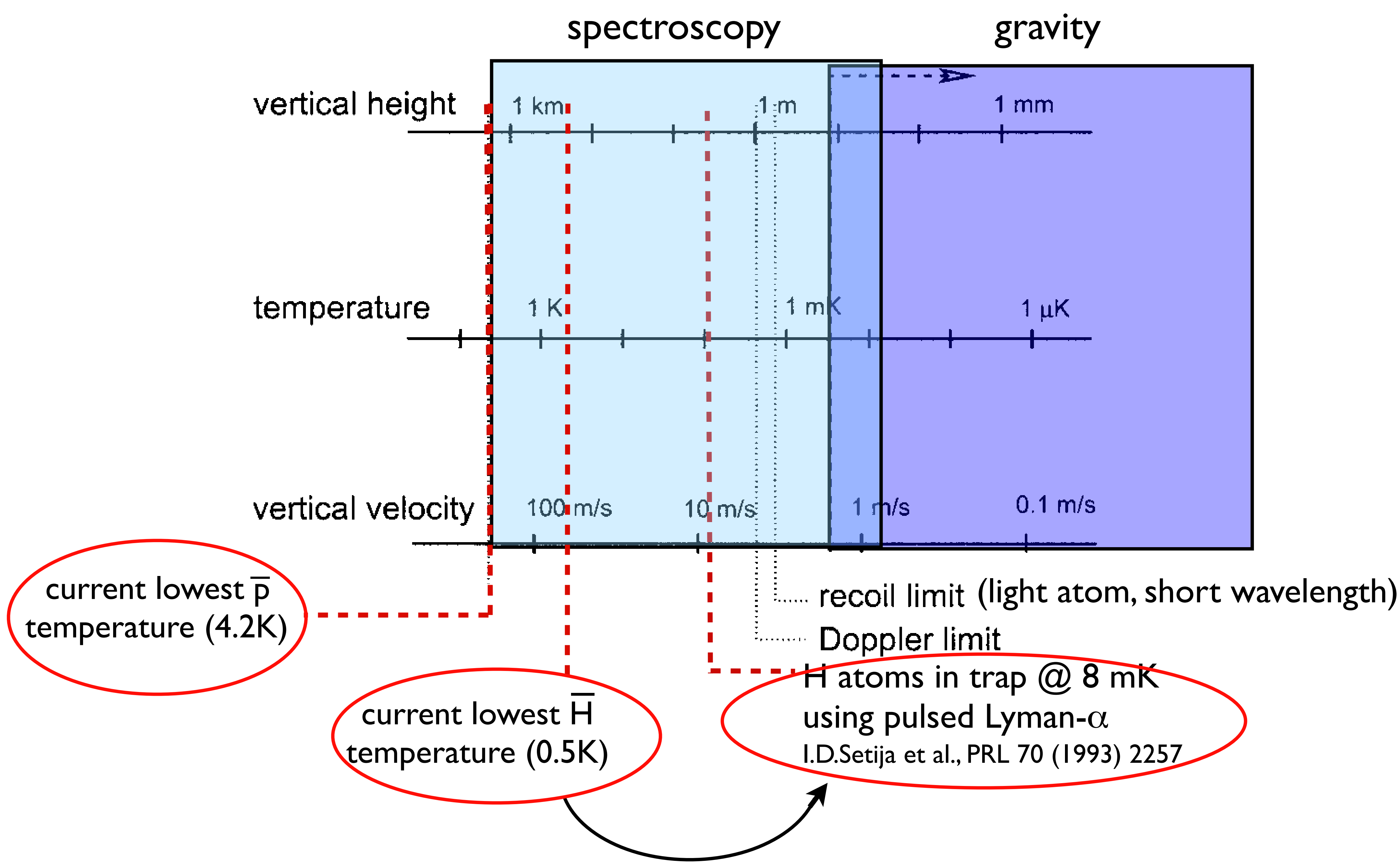
- dramatically slows down the antiprotons from the AD
- increases the *antiproton* trapping efficiency x 100
- allows 4 experiments to run in parallel
- space for new experiments



Facility shut down until mid-2021

Two main challenges: more / colder antiprotons

"Ultra-cold" (~1 μK) Antihydrogen



1S→2P laser cooling: cw Lyman-α source

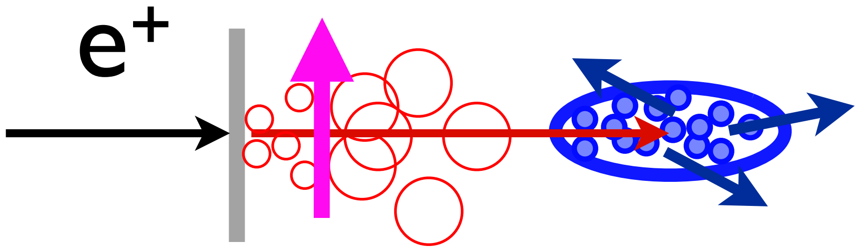
Eikema, Walz, Hänsch, PRL 86 (2001) 5679

alternative antihydrogen production method: RCE

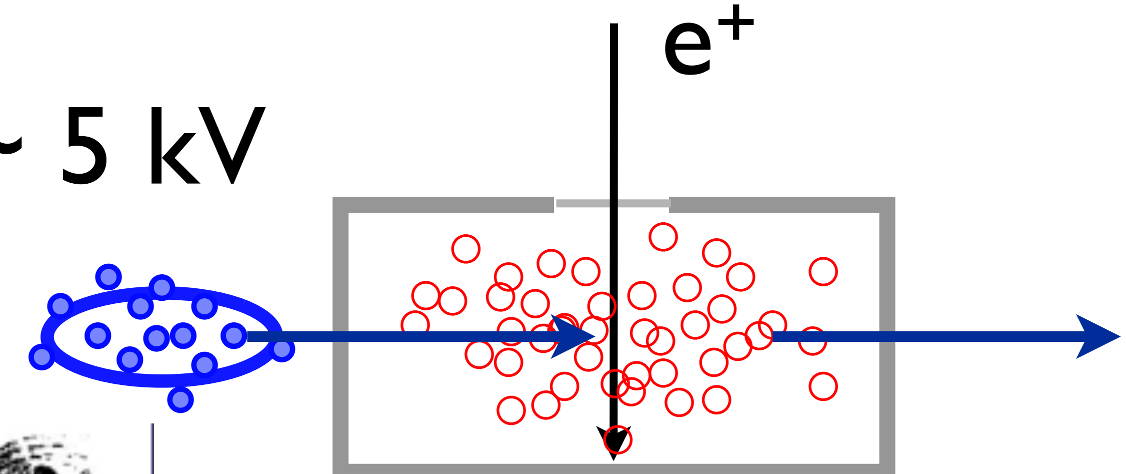
$T_{\bar{H}} \sim T_{\bar{p}}$

AEḡIS | **GBAR**

$T_{Ps} \sim 100$ K



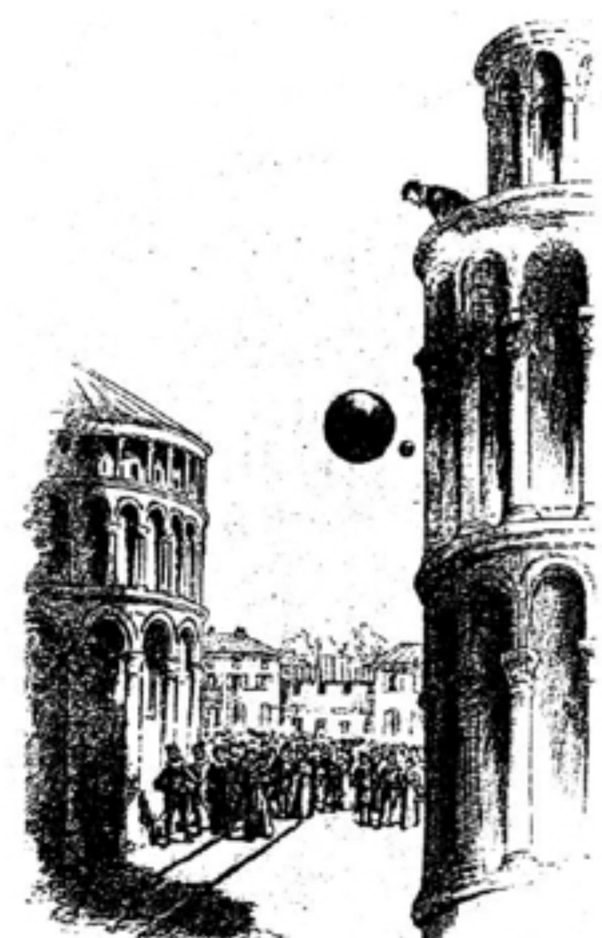
$E_p \sim 5$ kV



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

cold $\bar{H}^*$

but: low rate!



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

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

hot $\bar{H}^+$

but: low rate!

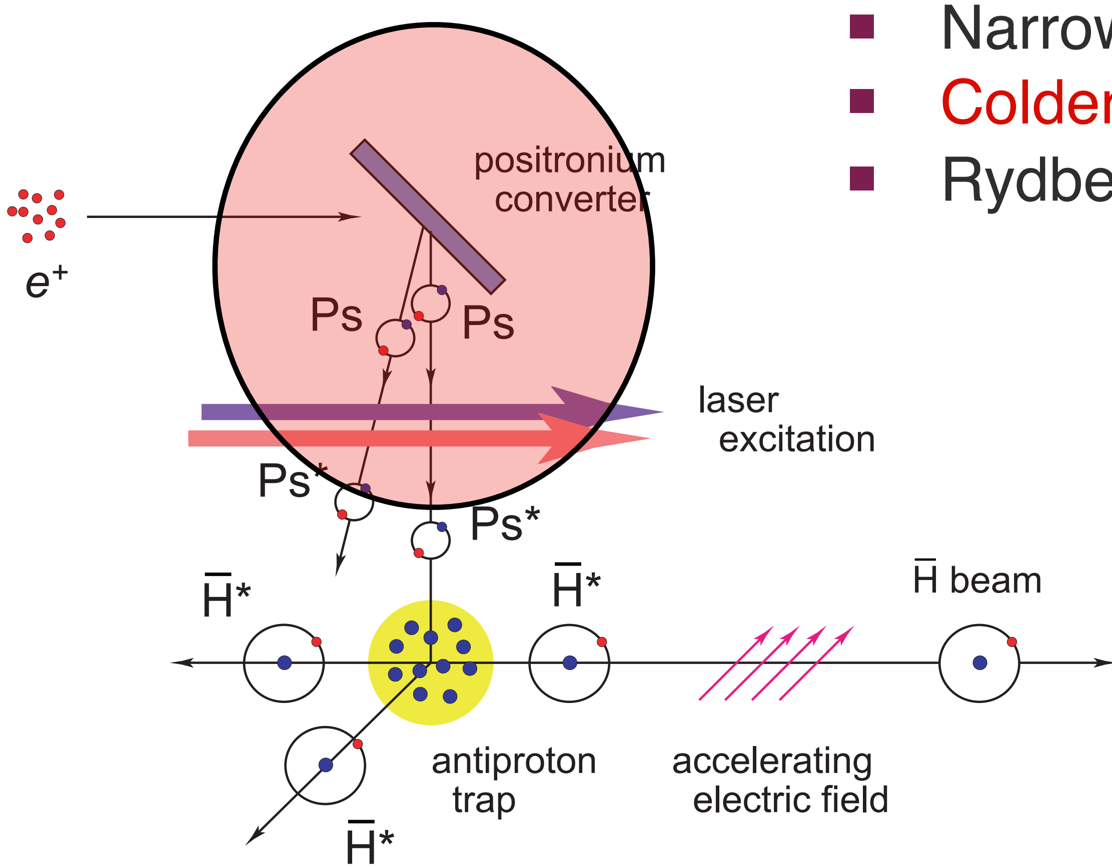
Schematic overview: AEgIS

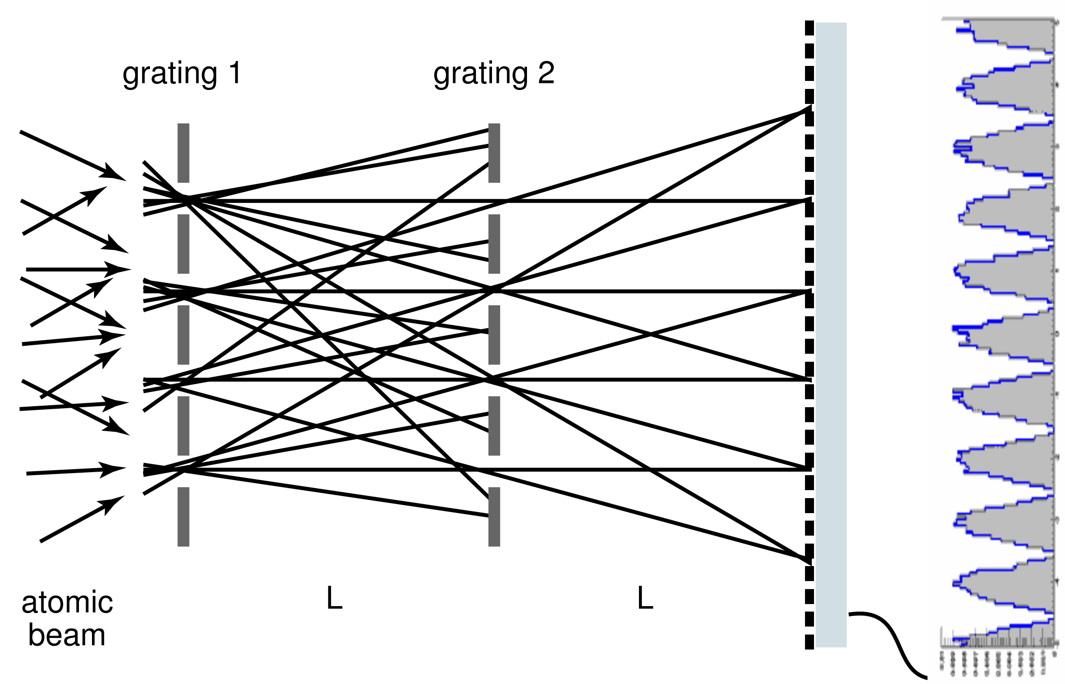
Physics goals: measurement of the gravitational interaction between matter and antimatter, $\bar{H}$ spectroscopy, ...

- Anti-hydrogen formation via Charge Exchange process with Ps*
  - o-Ps produced in SiO_2 target close to $\bar{p}$; laser-excited to Ps*
  - $\bar{H}$ temperature defined by $\bar{p}$ temperature

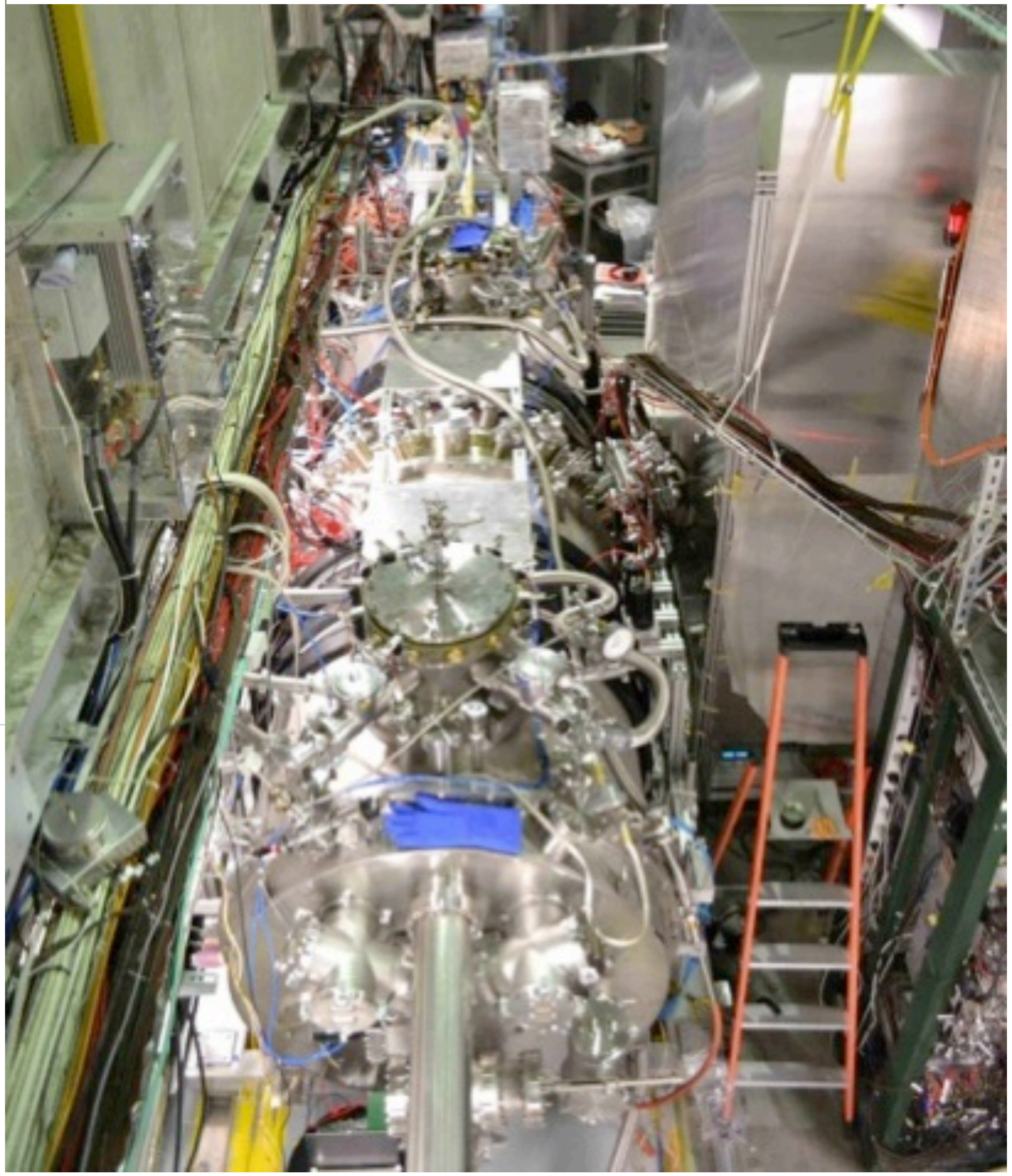
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

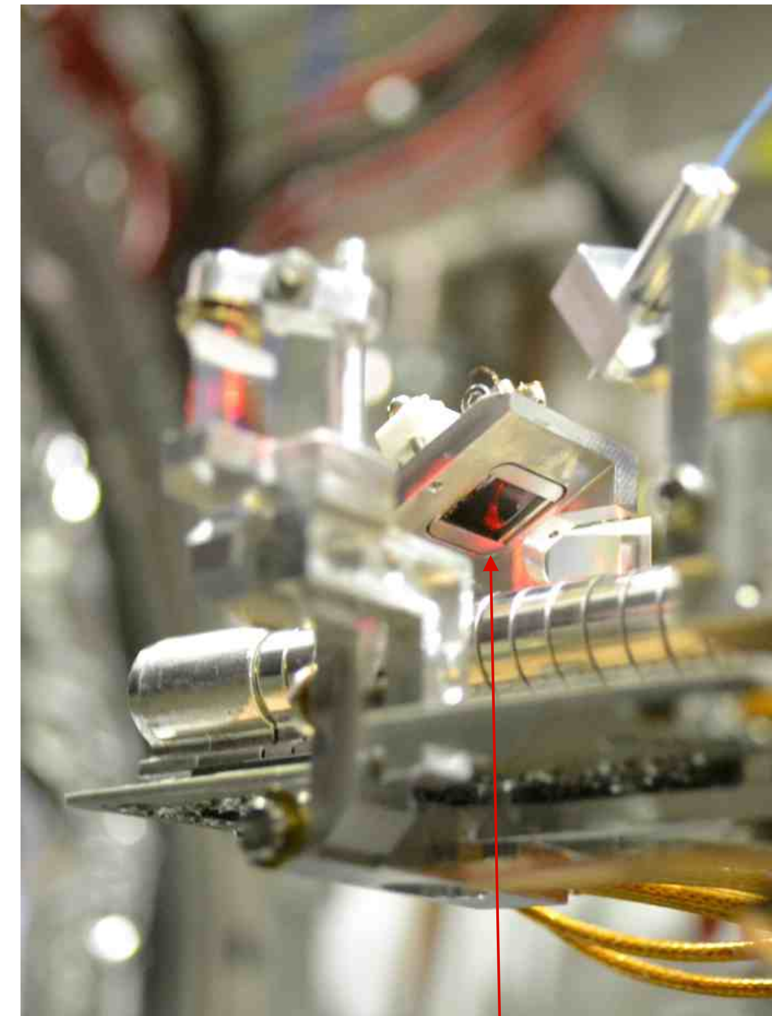
- Advantages:
- Pulsed $\bar{H}$ production (time of flight – Stark acceleration)
- Narrow and well-defined $\bar{H}$ *n*-state distribution
- Colder production than via mixing process expected
- Rydberg Ps & $\sigma \approx a_0 n^4 \rightarrow \bar{H}$ formation enhanced

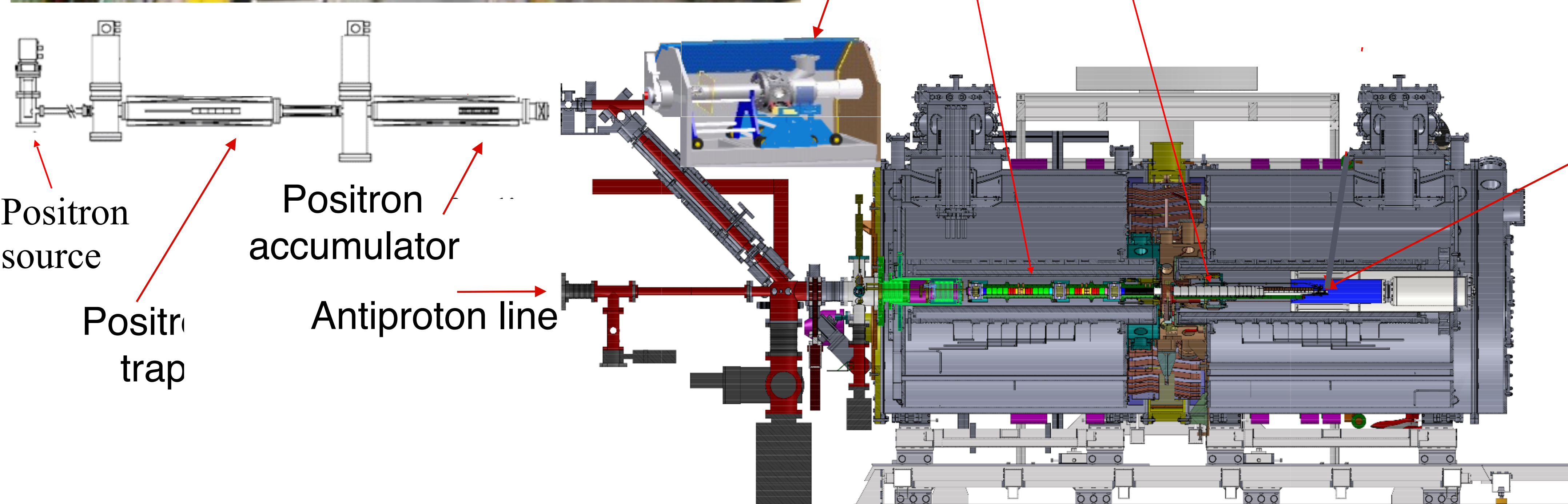




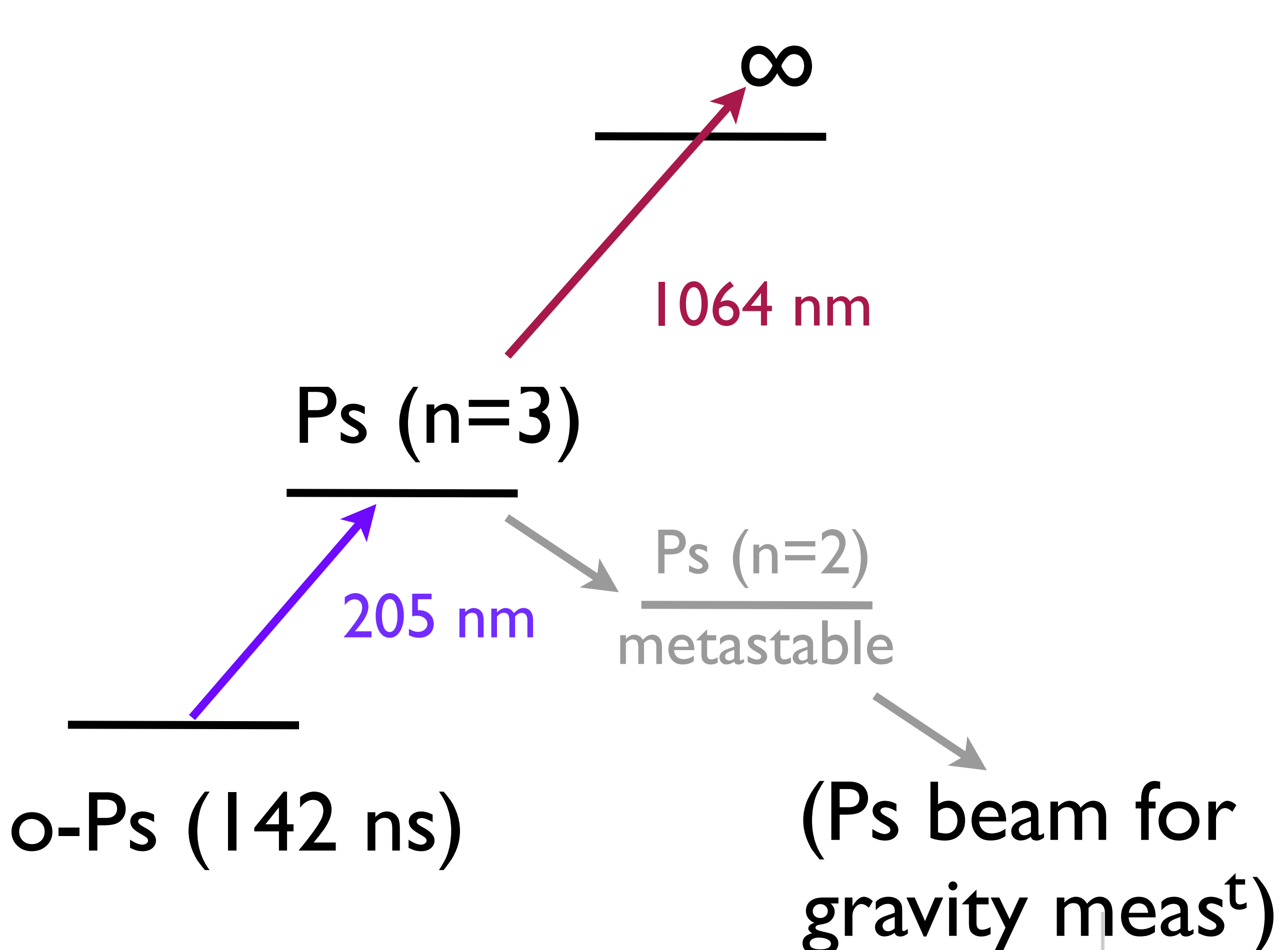
AEgIS experiment

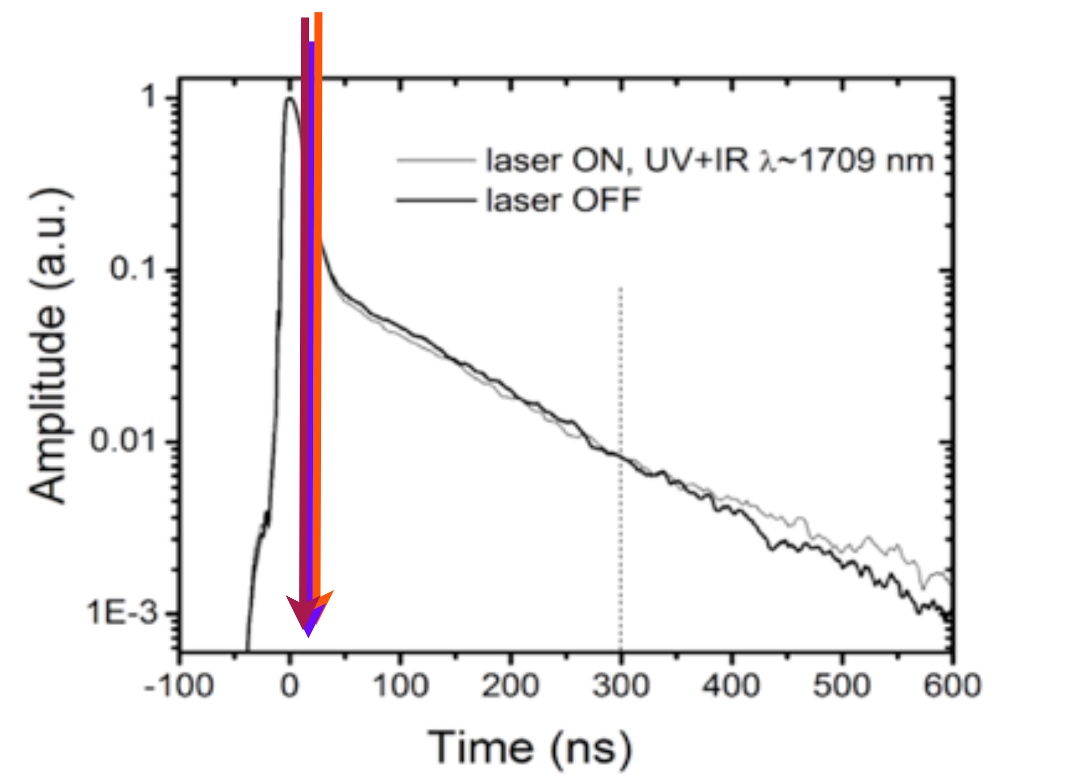


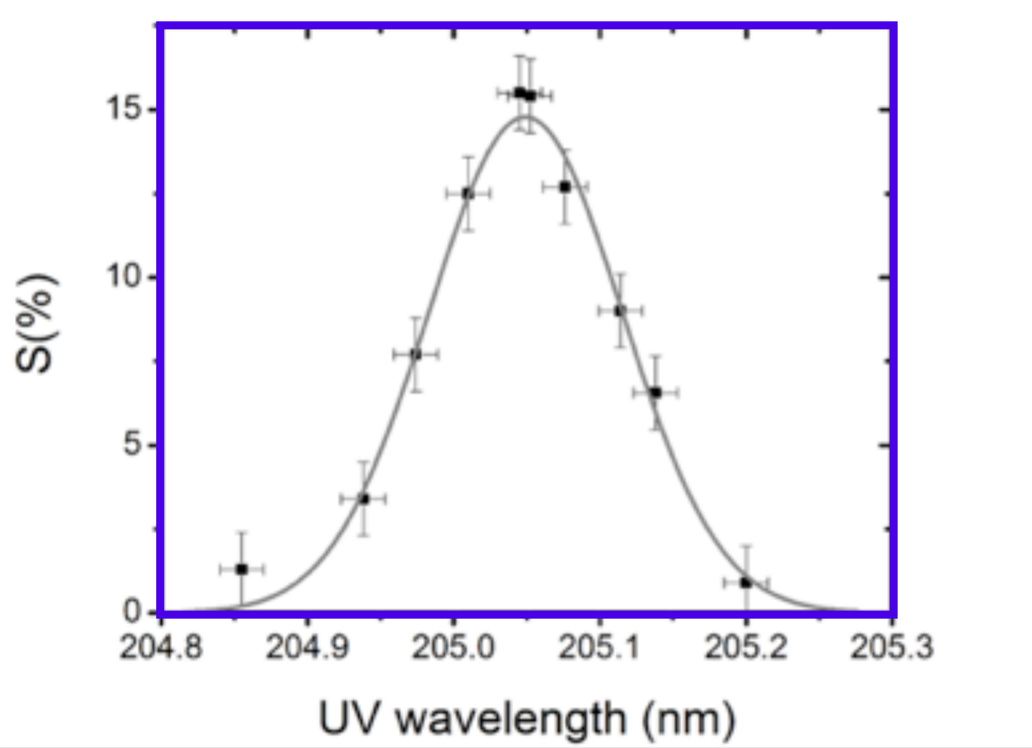




Ps: excitation into Rydberg states







very long-term goals: gravity, spectroscopy in sub-mK traps
sympathetic cooling to the rescue

GBAR experiment

cooling of $\bar{H}^+$

J.Walz and T. Hänsch, Gen. Rel. and Grav. 36 (2004) 561

formation of $\bar{H}^+$ (binding energy = 0.754 eV)

how? perhaps through $Ps(2p)+\bar{H}(1s) \rightarrow \bar{H}^+ + e^-$

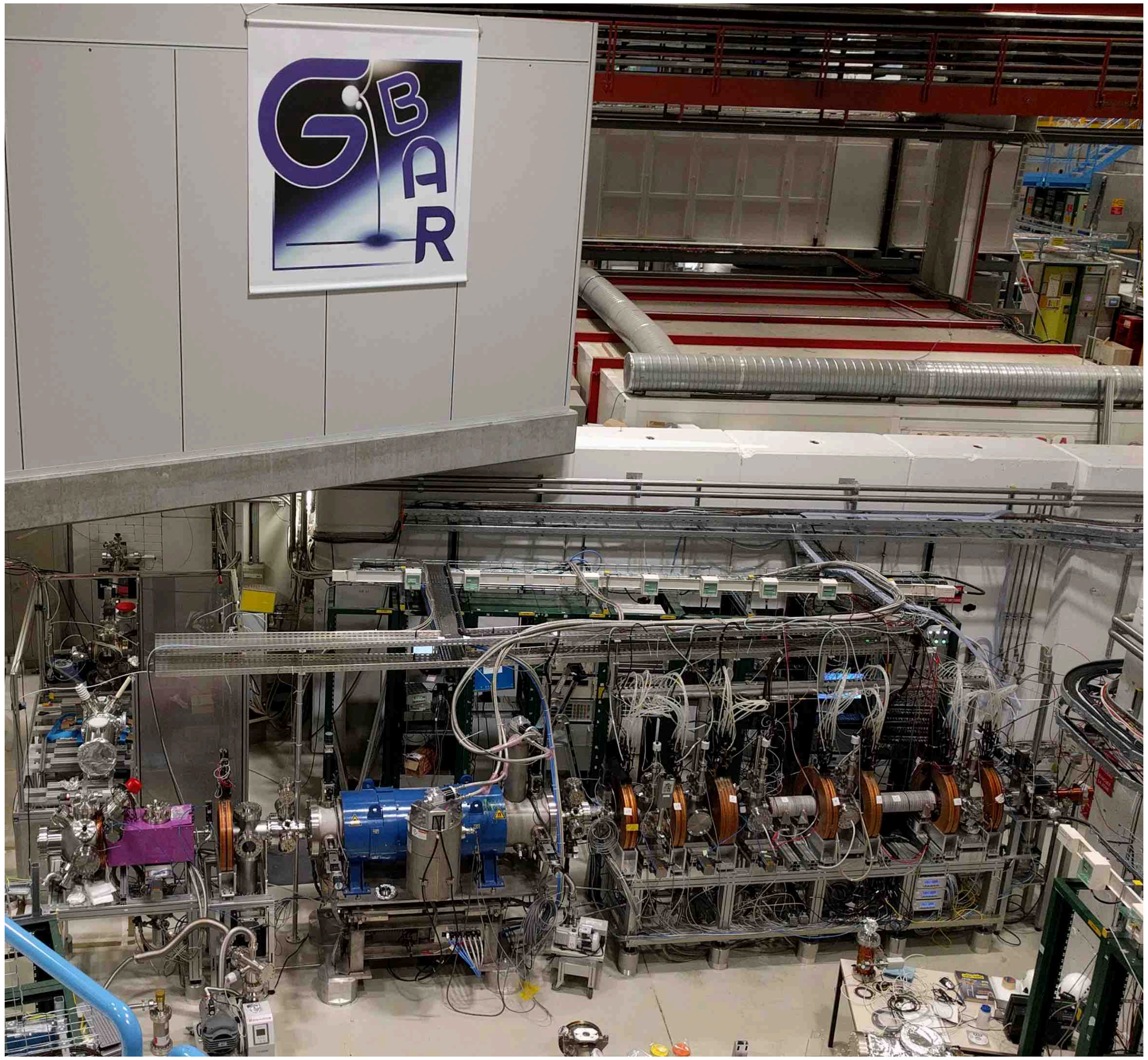
Roy & Sinha, EPJD 47 (2008) 327

sympathetic cooling of $\bar{H}^+$

e.g. $In^+ \rightarrow 20\ \mu K$

photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"



→ sympathetic cooling of $\bar{H}^+$ to ~ μK

→ O(1%) on g

very long-term goals: gravity, spectroscopy in sub-mK traps
sympathetic cooling to the rescue

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Roy & Sinha, EPJD 47 (2008) 327

sympathetic cooling of $\bar{H}^+$

e.g. In^+ → 20 μK

photodetachment at ~6083 cm^{-1}

gravity measurement via “TOD”

→ sympathetic cooling of $\bar{H}^+$ to ~ μK

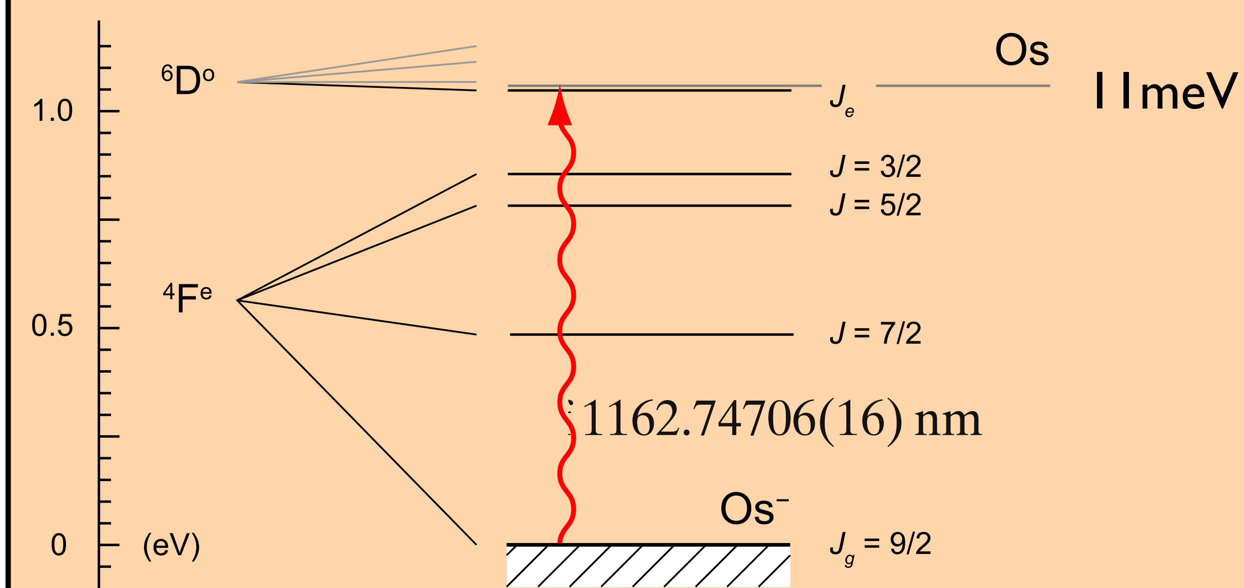
→ O(1%) on *g*

Anion cooling for AEḡIS: Os^-, La^-, C_2^-

cooling of $\bar{p}$

Warring et al, PRL 102 (2009) 043001

Fischer et al, PRL 104 (2010) 073004



very weak cooling

→ best to start at ~ 4K and cool to Doppler limit ($T_D \approx 0.24\ \mu K$)

→ sympathetic cooling of $\bar{p}$ to < mK

→ < mK antihydrogen (pulsed production)

other measurements with antihydrogen-like atoms & ions...

$\bar{H}$: charge neutrality ... gravity

good perspectives for mK (sub-mK?) $\bar{H}$ in the coming 5 years, and certainly for test of gravity at the 100% ~ 1% level

other measurements with antihydrogen-like atoms & ions...

$\bar{H}$: charge neutrality ... gravity

Ps charge neutrality ... gravity (lepton sensitivity)

o-Ps: 142 ns

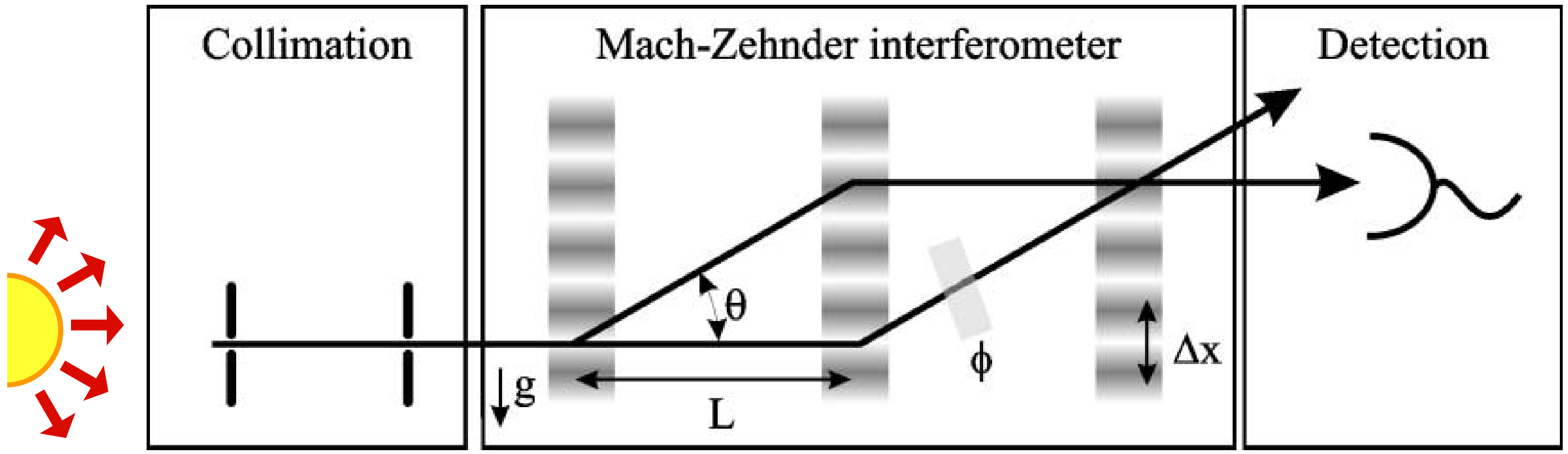
→ Ps(2s): 1.1 μs

positronium...

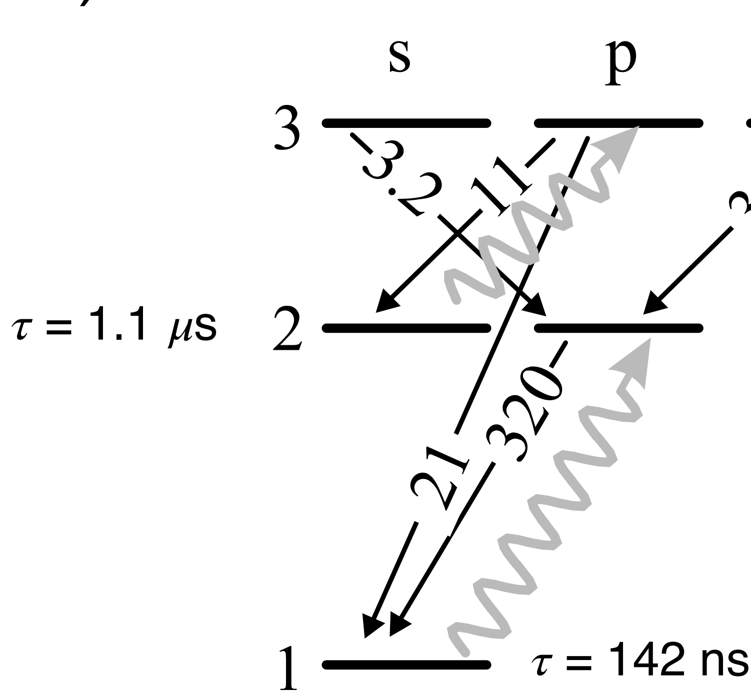
<u>physics interest</u>: QED atomic spectrum, gravity (via matter wave interferometry)

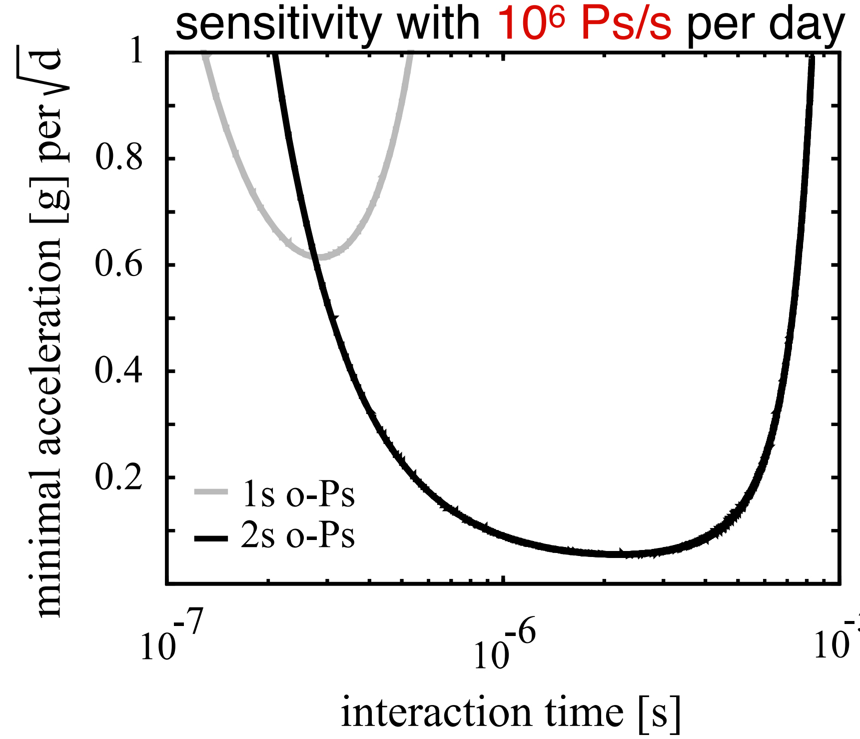
M. Oberthaler, Volume 192, Issues 1–2, (2002) 129

Ps source
(2π or better)



λ(1s) = 243.1nm
λ(2s) = 1312.5nm





v_{Ps} ~ 100 km/s → interaction time of 1 μs ~ 10 cm

other measurements with antihydrogen-like atoms & ions...

$\bar{H}$: charge neutrality ... gravity

Ps, muonium: gravity (lepton sensitivity)

Muonium antimatter gravity experiment (MAGE)

Thomas Philipps (MAGE and muCool collaborations)

EPJ web of conferences 181 (2018) 01017

challenges: flux, temperature, lifetime

other measurements with antihydrogen-like atoms & ions...

$\bar{H}$: charge neutrality ... gravity

Ps, muonium: gravity (lepton sensitivity)

$\mu\bar{p}$: gravity (2nd generation), antiproton charge radius

$$(\mu^{+}e^{-})^{*} + \bar{p} \rightarrow (\bar{p}\mu^{+})^{*} + e^{-}$$

additional challenge:
transport $\bar{p}$ to PSI

other measurements with antihydrogen-like atoms & ions...

$\bar{H}$: charge neutrality ... gravity

Ps, muonium: gravity (lepton sensitivity)

$\mu\bar{p}$: gravity (2nd generation), antiproton charge radius

$\bar{p}p$, $\bar{p}d$: gravity (baryon sensitivity), spectroscopy, ...
charge neutrality ...

protonium...

physics interest: QCD-induced shift, broadening of QED atomic spectrum

"traditionally" formed by injecting $\bar{p}$ into liquid hydrogen

spontaneous formation in n~40, Stark mixing, rapid annihilation

spectroscopy resolution determined by fluorescence detector resolution

alternative: pulsed formation via co-trapped $\bar{p}$ and H^-

- photo-ionize $H^- \rightarrow H + e^-$
- charge exchange $H + \bar{p} \rightarrow p\bar{p}(40) + e^-$

improvements:

formation rate increased if n(H) >> 1

life time increased if n(H) >> 1

- charge exchange $H^* + \bar{p} \rightarrow p\bar{p}(900) + e^-$

→ long-lived cold Rydberg protonium

→ trap/beam

→ precision laser spectroscopy on $p\bar{p}$

→ gravity measurement

other measurements with antihydrogen-like atoms & ions...

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ions: $\bar{H}^+$ gravity, CPT (ultra-cold $\bar{H}$)

ions: H_2^+, resp. $\bar{H}_2^-$ proton-electron mass ratio μ

$\bar{p}N$: trapped $\bar{p}$ (AD) + radioisotopes (ISOLDE) = PUMA

longer-term outlook

- advances on spectroscopy with $\bar{H}$ and $\bar{p}He^+$, as well as in precision measurements with $\bar{p}$ have been impressive in the last few years...
- in these systems, CPT tests now reach ~ 10^{-12} and have the potential to improve sensitivity by several orders of magnitude in the coming years
- *direct* tests of the WEP are becoming feasible, with precisions that can be expected to initially reach % or ‰ level in a number of antimatter systems

work towards ultra-cold $\bar{H}$ will open up additional experimental techniques and should lead not only to improved precision tests of CPT, but also of the gravitational interaction: atomic fountains, & laser-interferometric techniques, benefitting from the past and ongoing progress in the fields of atomic physics, quantum optics, molecular physics, ...

Further antihydrogen-like systems like $\bar{p}\mu^+$, Ps, $\bar{p}p$, $\bar{H}^+$, $\bar{H}_2^-$ and others (and much patience and ingenuity) offer additional opportunities for intriguing tests (gravity, high sensitivity measurements of antiproton/positron mass ratio, gravity tests in purely baryonic or leptonic systems, ...)

Thank you for your attention