Fundamental physics with antihydrogen

Michael Doser
CERN

What measurements are we talking about?

1) Precise spectroscopic comparison between $\bar{H}$ and H

test of the fundamental CPT symmetry

2) Measurement of the gravitational behavior of $\bar{H}$

test of the Weak Equivalence Principle

3) other measurements in antihydrogen(-like) systems

tests of other fundamental symmetries or assumptions

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)

CPT & Lorentz violation

Modified Dirac eq. in SME

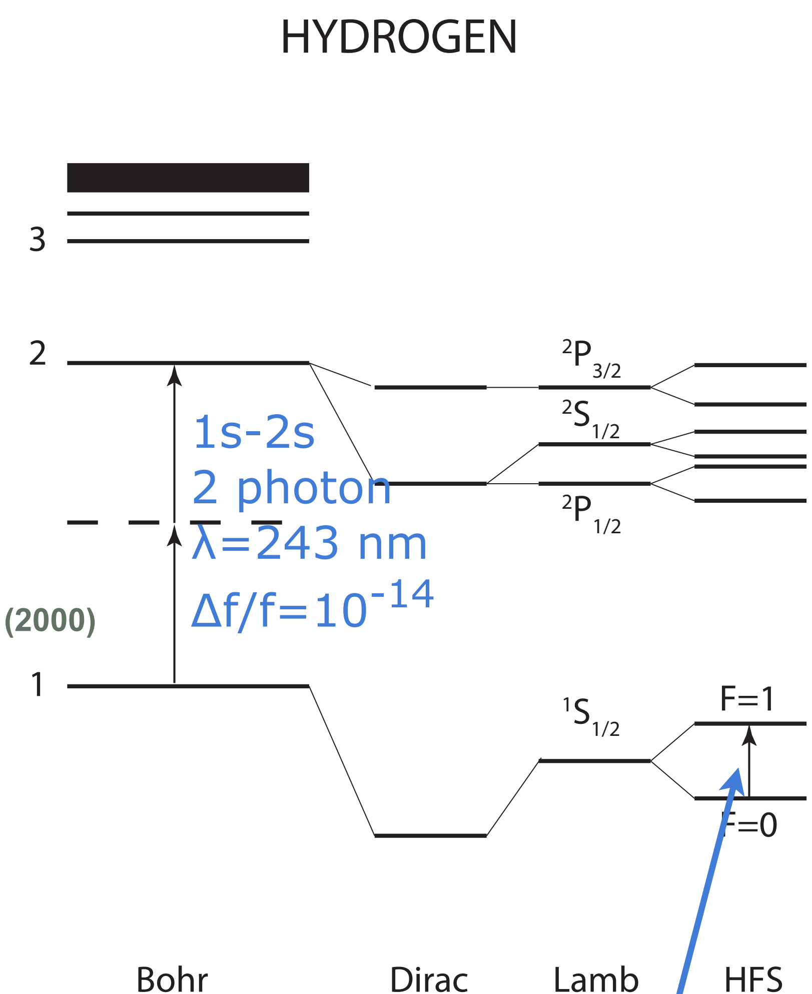
$$\left(i\gamma^\mu D_\mu - m_e - \boxed{a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu}\right.$$
$$\left. - \boxed{\tfrac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu}\right)\psi = 0\,.$$

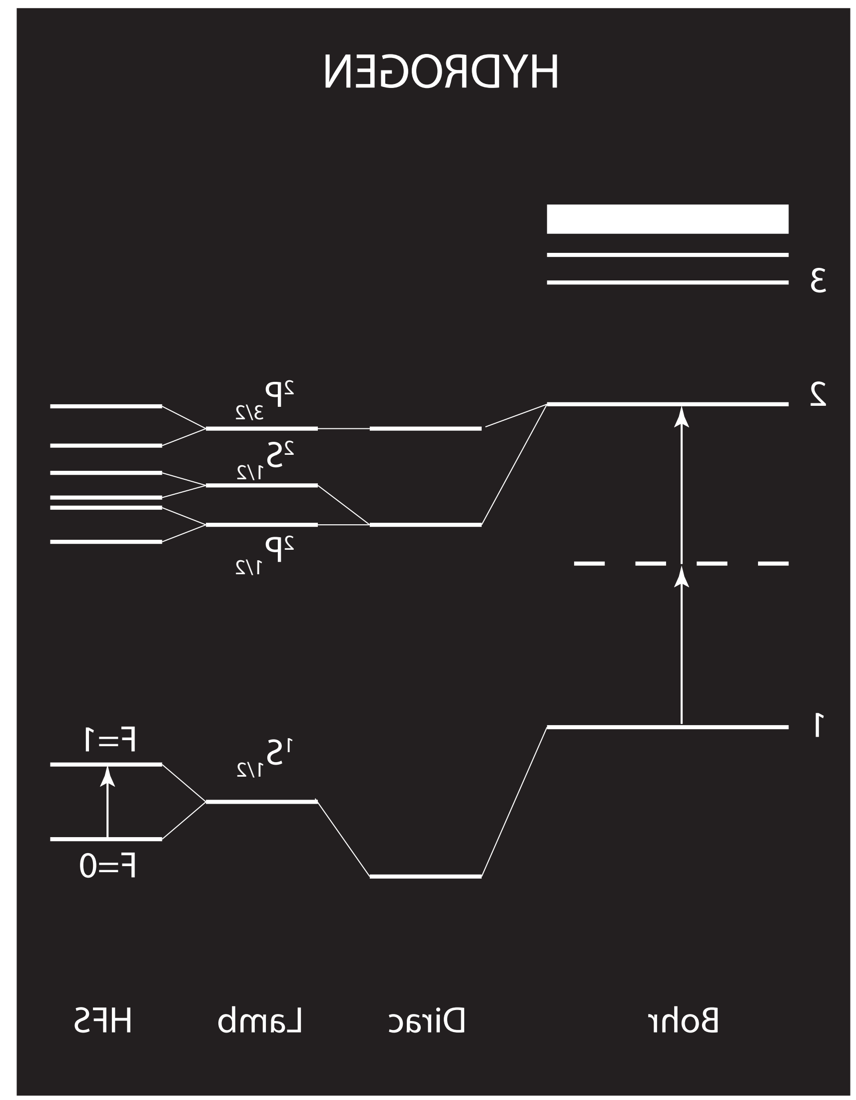
Lorentz violation

- 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

Goal of comparative spectroscopy: test CPT symmetry

Hydrogen and Antihydrogen



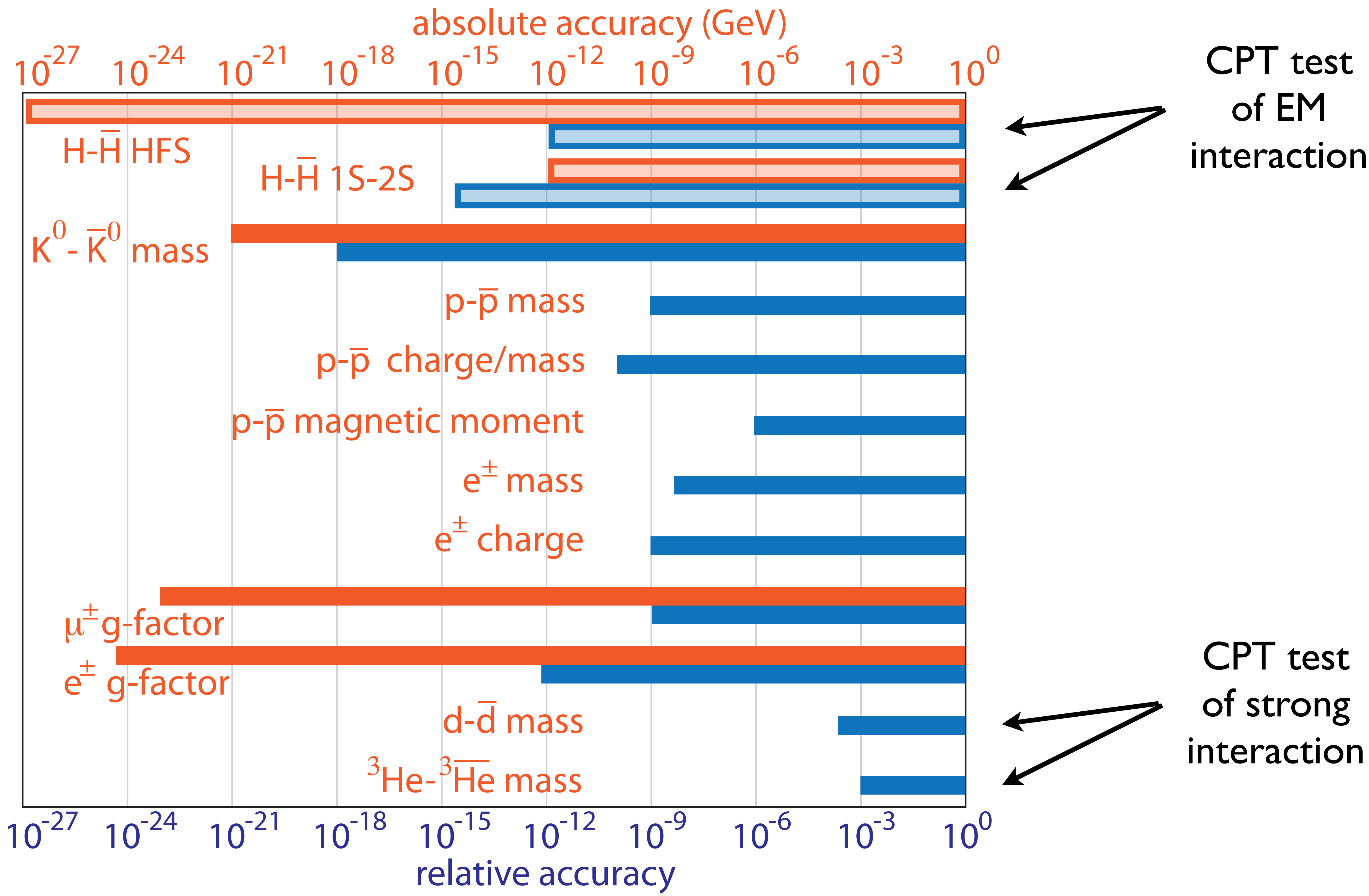


1s-2s
2 photon
λ=243 nm
$\Delta f/f=10^{-14}$

T. Hänsch et al.,
Phys. Rev. Lett. 84, 5496–5499 (2000)

Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

N. F. Ramsey,
Physica Scripta T59, 323 (1995)



Inconsistent definition of figure of merit: comparison difficult

Pattern of CPT violation unknown (P: weak interaction; CP: mesons)

Absolute energy scale: standard model extension (Kostelecky)

Motivation

- General relativity is a classical (non quantum) theory;
- EEP violations may appear in some quantum theory
- New quantum scalar and vector fields are allowed in some models (Kaluza Klein ….)

Einstein field: tensor graviton (Spin 2, "Newtonian")

+ Gravi-vector (spin 1)

+ Gravi-scalar (spin 0)

- These 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

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

Phys. Rev. D 33 (2475) (1986)

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

The reality:

(focus on gravity measurements, since spectroscopic measurements are covered by following talks, although the following holds there as well)

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(focus on gravity measurements, since spectroscopic measurements are covered by following talks, although the following holds there as well)

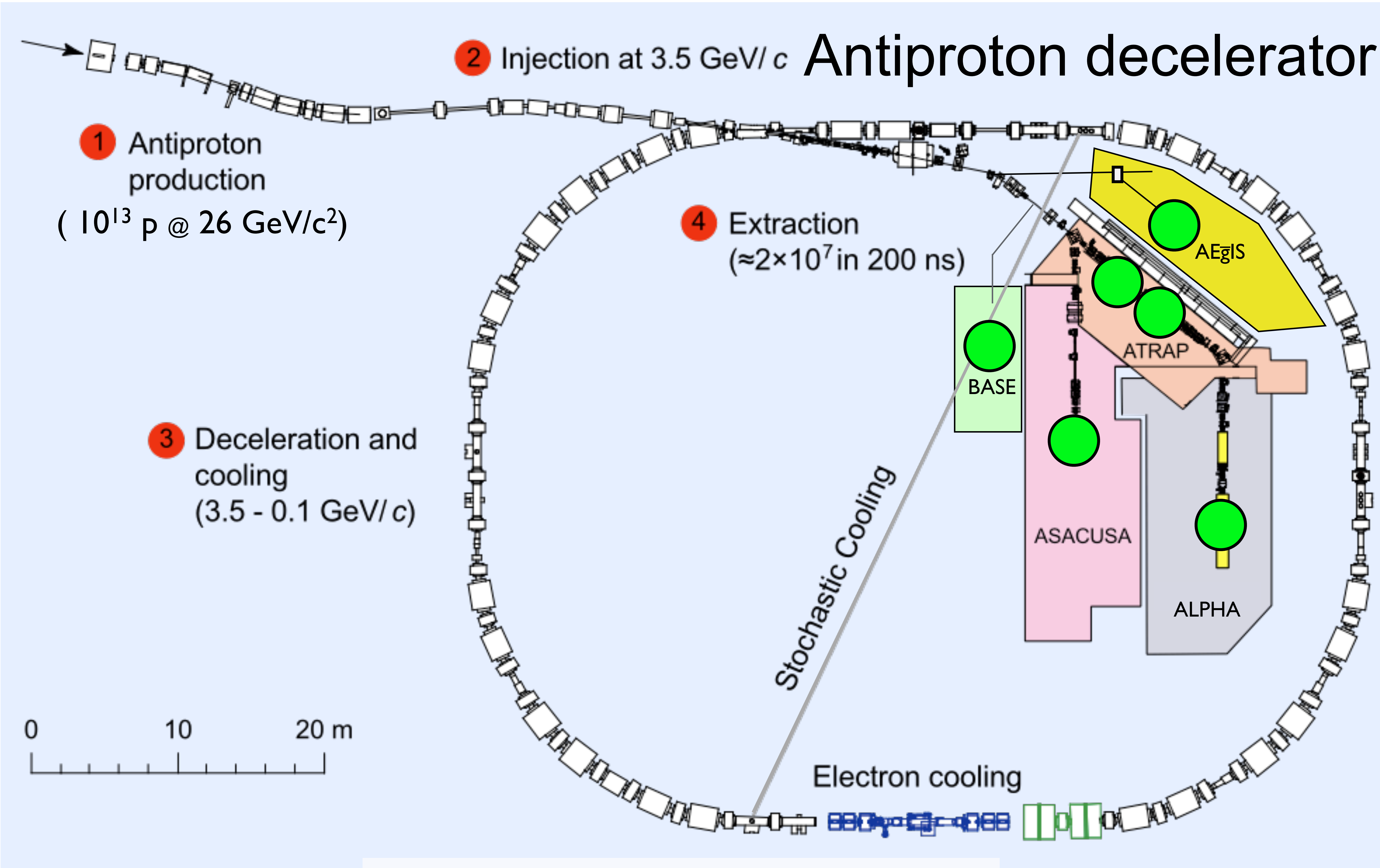
in real estate:

location, location, location

in $\bar{H}$ experiments:

rate, temperature, flux

Two main challenges: colder / more antiprotons
current methods for trapping them are quite inefficient

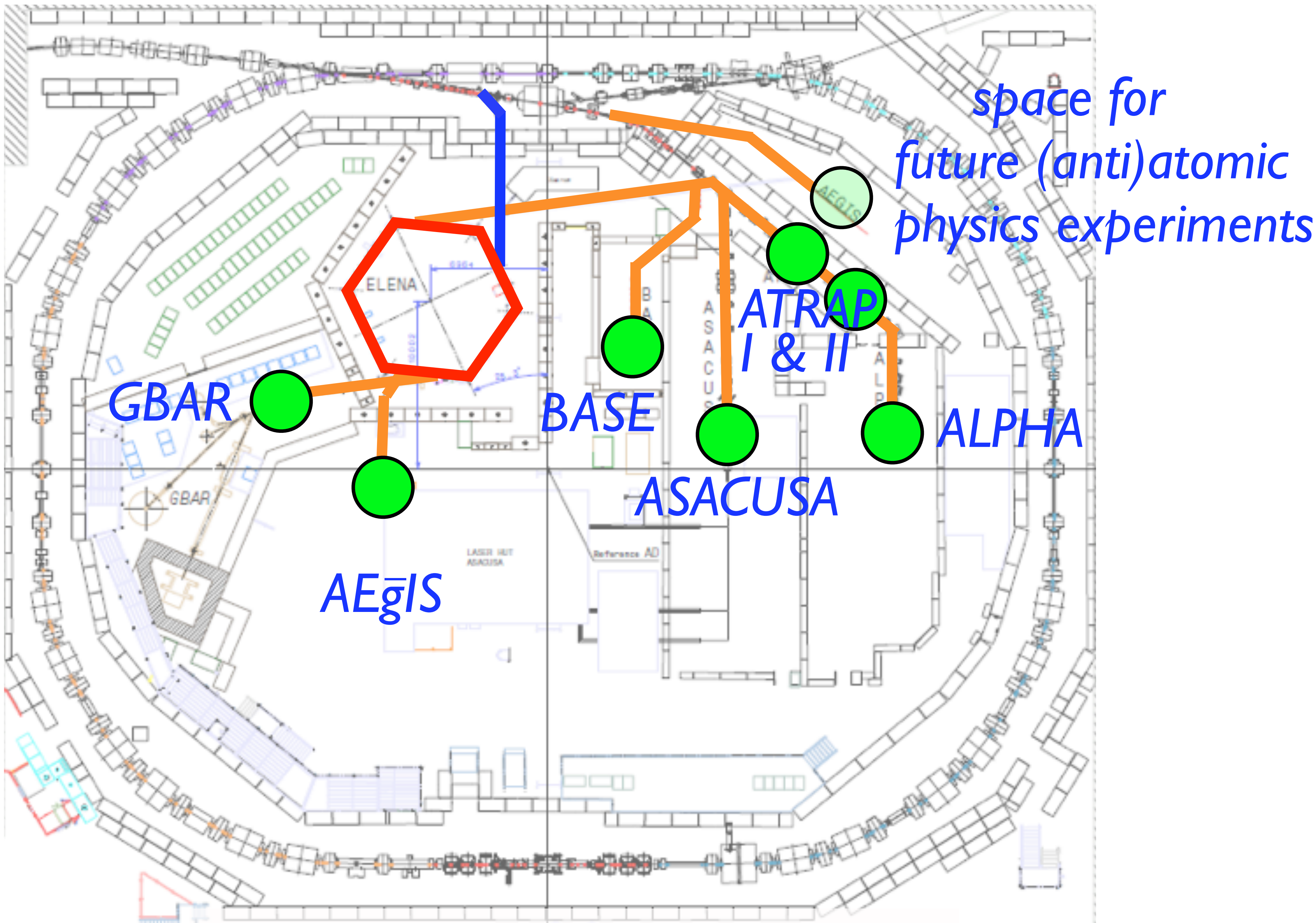


extraction at 5.3 MeV

Two main challenges: colder / <u>more</u> **antiprotons**

current methods for trapping them are very inefficient

ELENA to the rescue

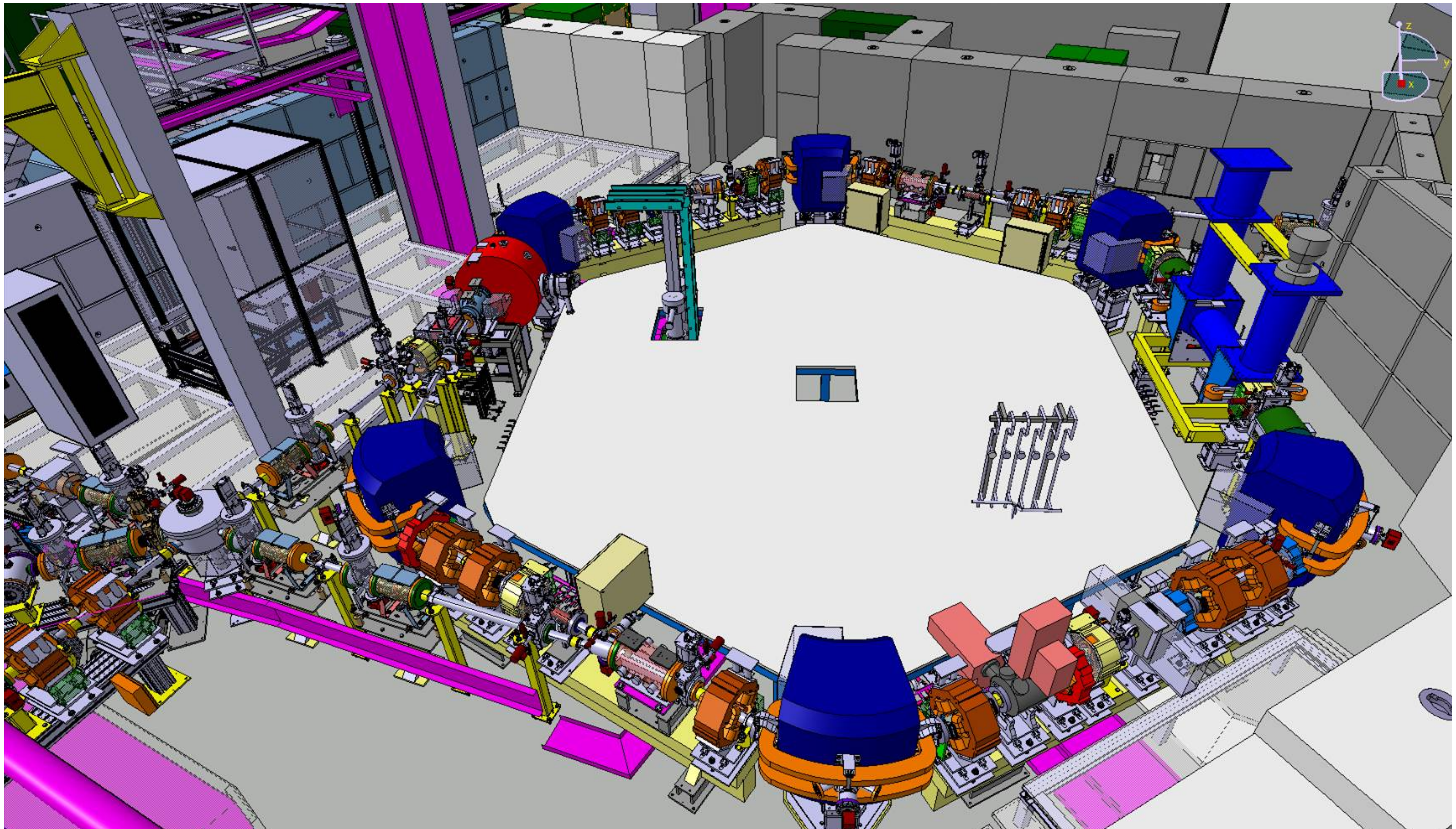


extraction at 100 keV

ELENA is a tiny new decelerator that:

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

start in 2017



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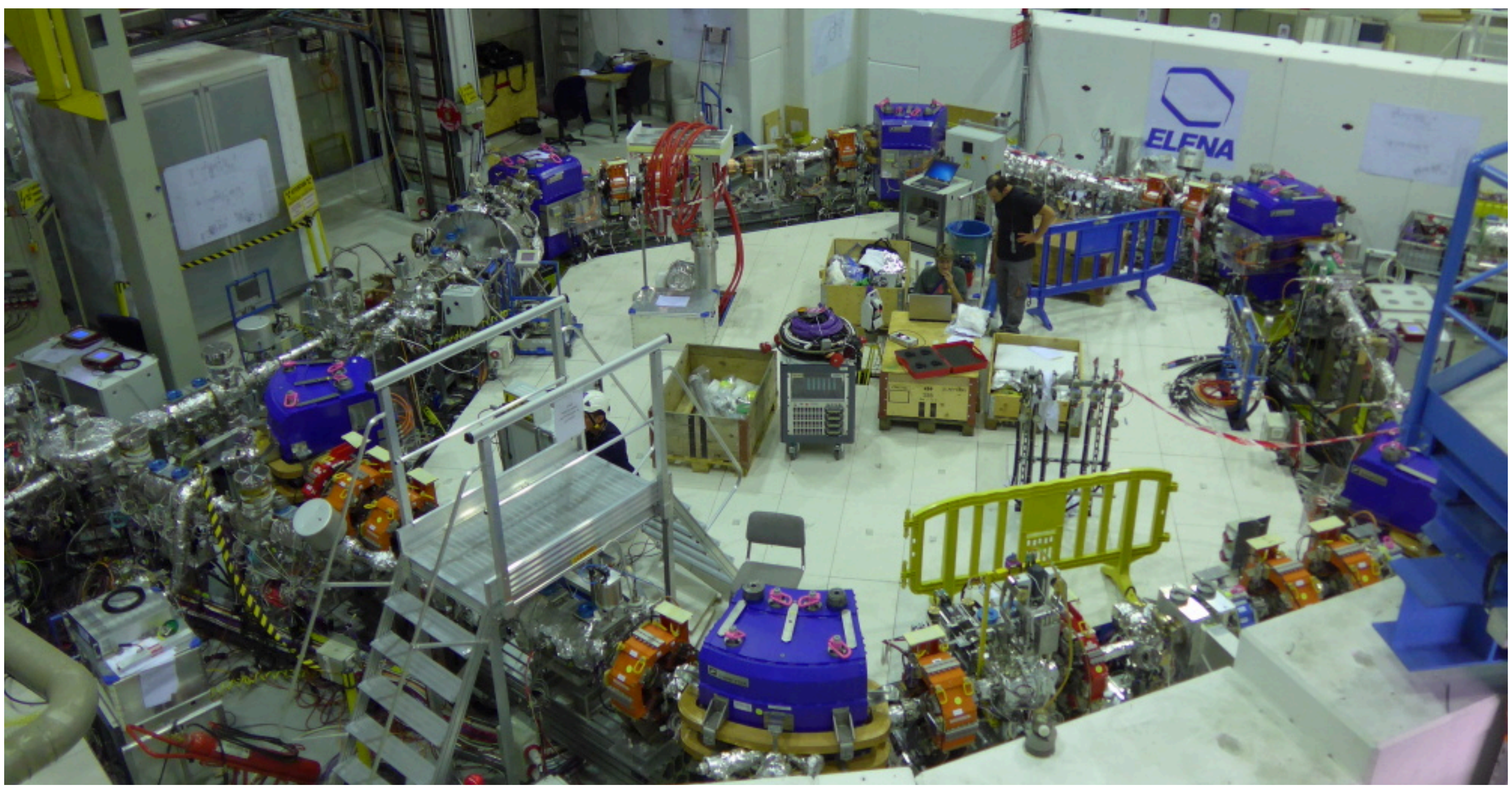
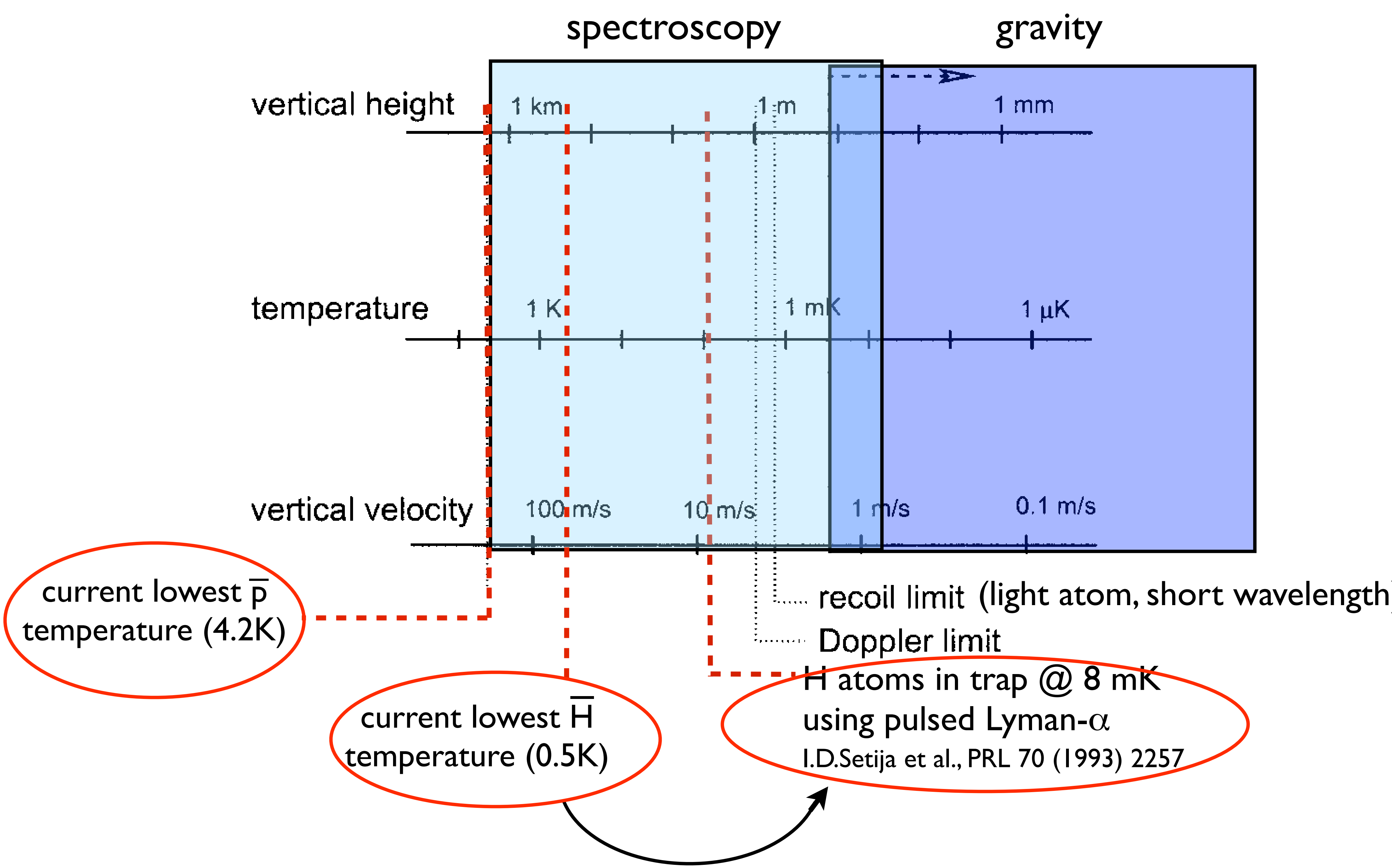


Two main challenges: colder / more antiprotons

"Ultra-cold" (~1 μK) Antihydrogen



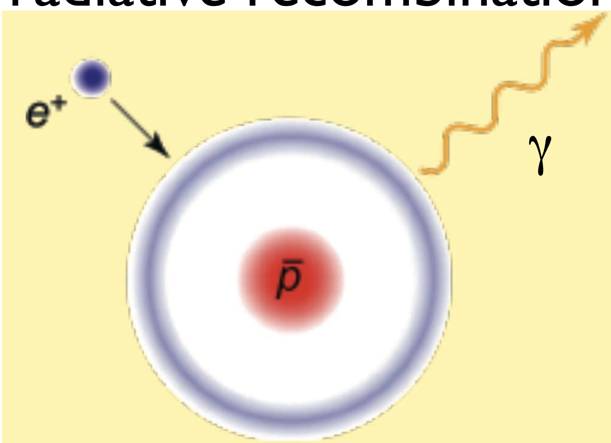
1S→2P laser cooling: cw Lyman-α source

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

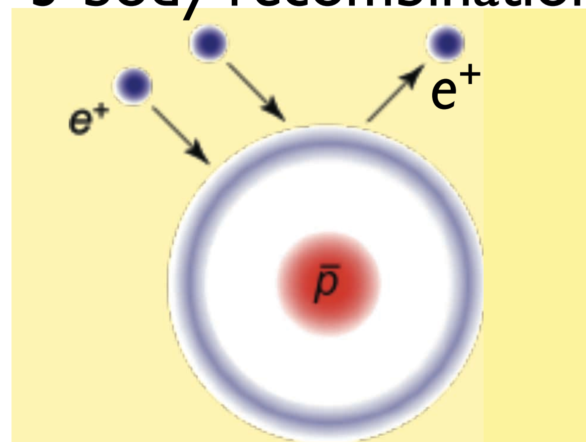
Antihydrogen production processes

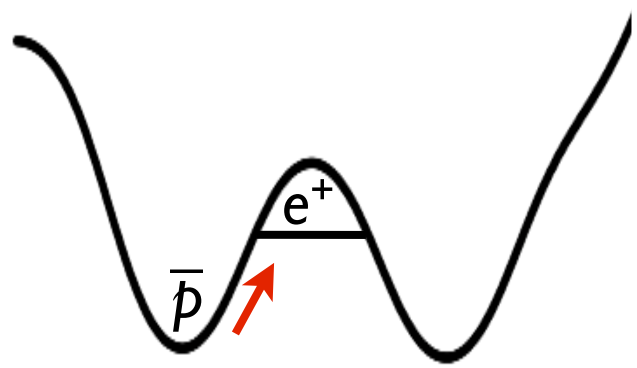
$10^5 \sim 10^7\ \bar{p}$ $10^8 \sim 10^{10}\ e+$

radiative recombination

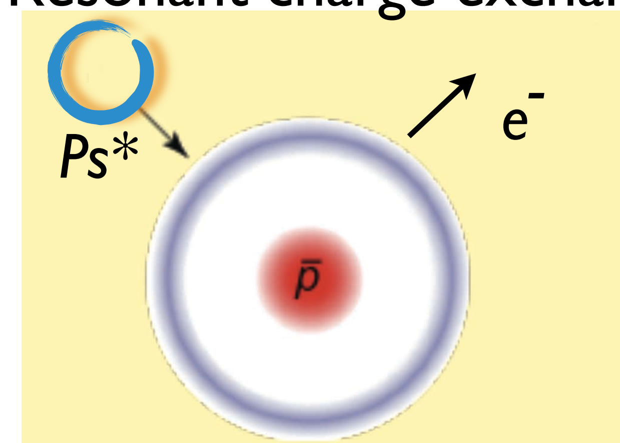


TBR:
3-body recombination





RCE:
Resonant charge exchange



Temperature (T_{e+})
Rate
n

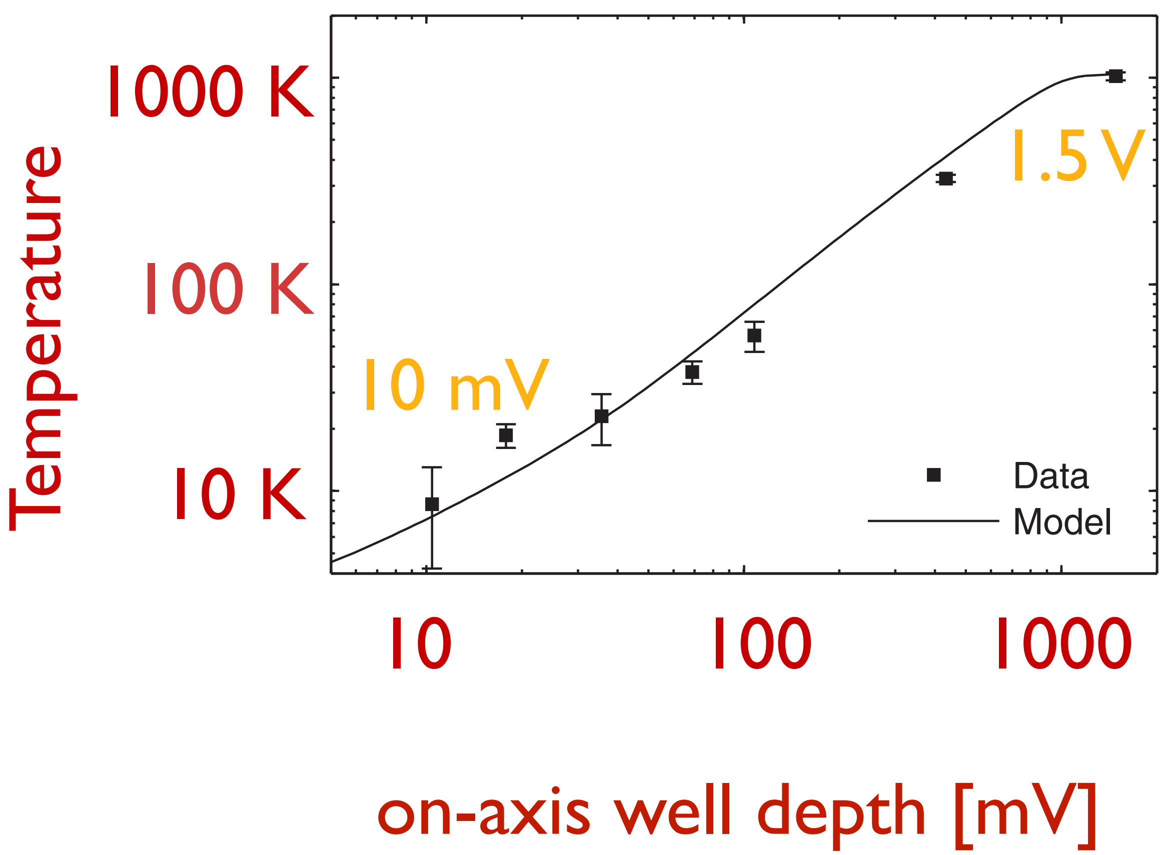
Temperature (T_{e+})
Rate ~ Rate
n *(if trapped)*

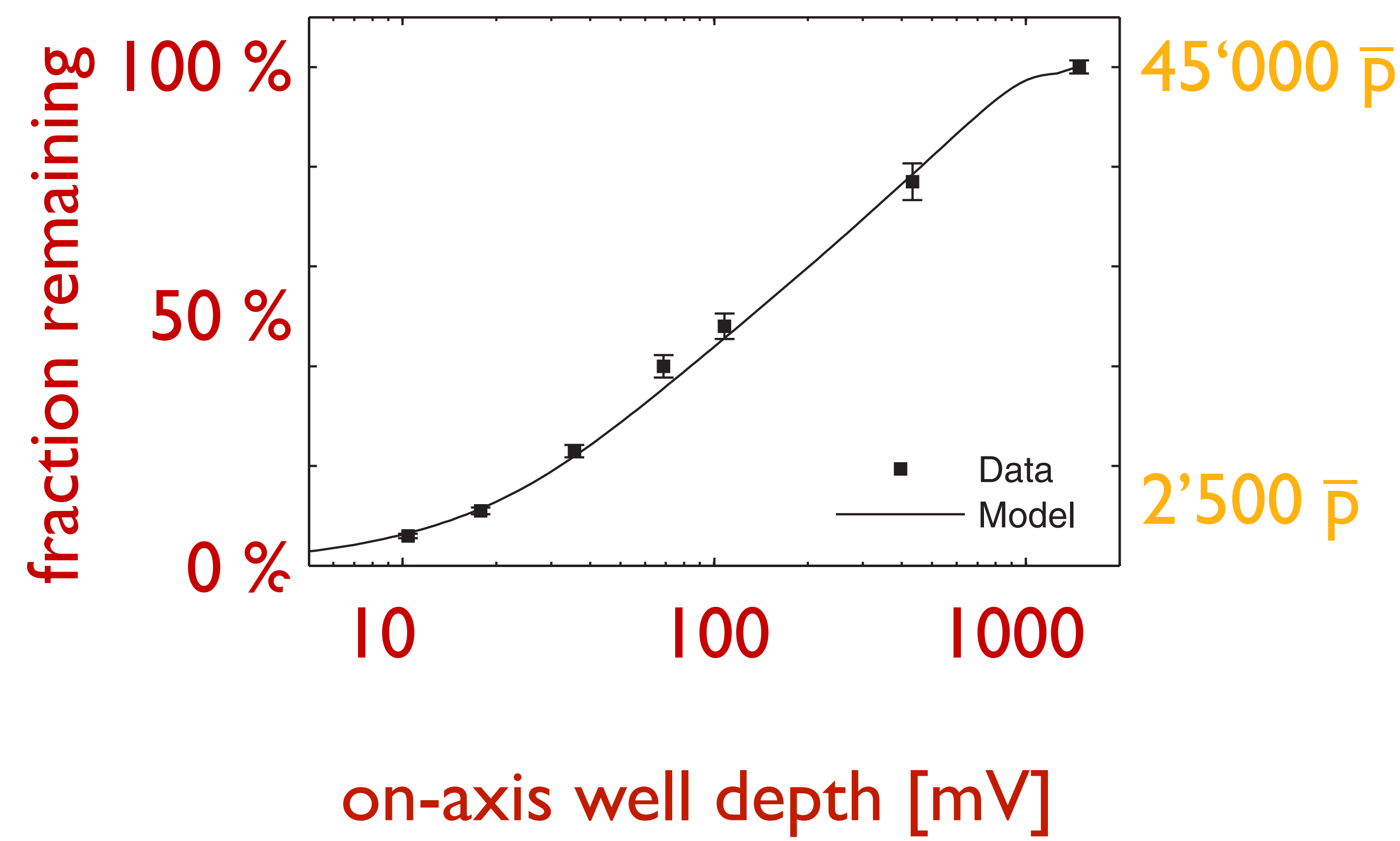
Temperature $T_{\bar{p}}$
Rate ~ Rate
n *(if trapped or slow)*

Reaching the few K regime

evaporative cooling of antiprotons (ALPHA)

PRL **105,** 013003 (2010)





essential to avoid reheating:

- great care needed on noise reduction;
- can not use electron cooling to pre-cool
- bring e^+ to cold $\bar{p}$, not vice-versa, or use autoresonant excitation of $\bar{p}$

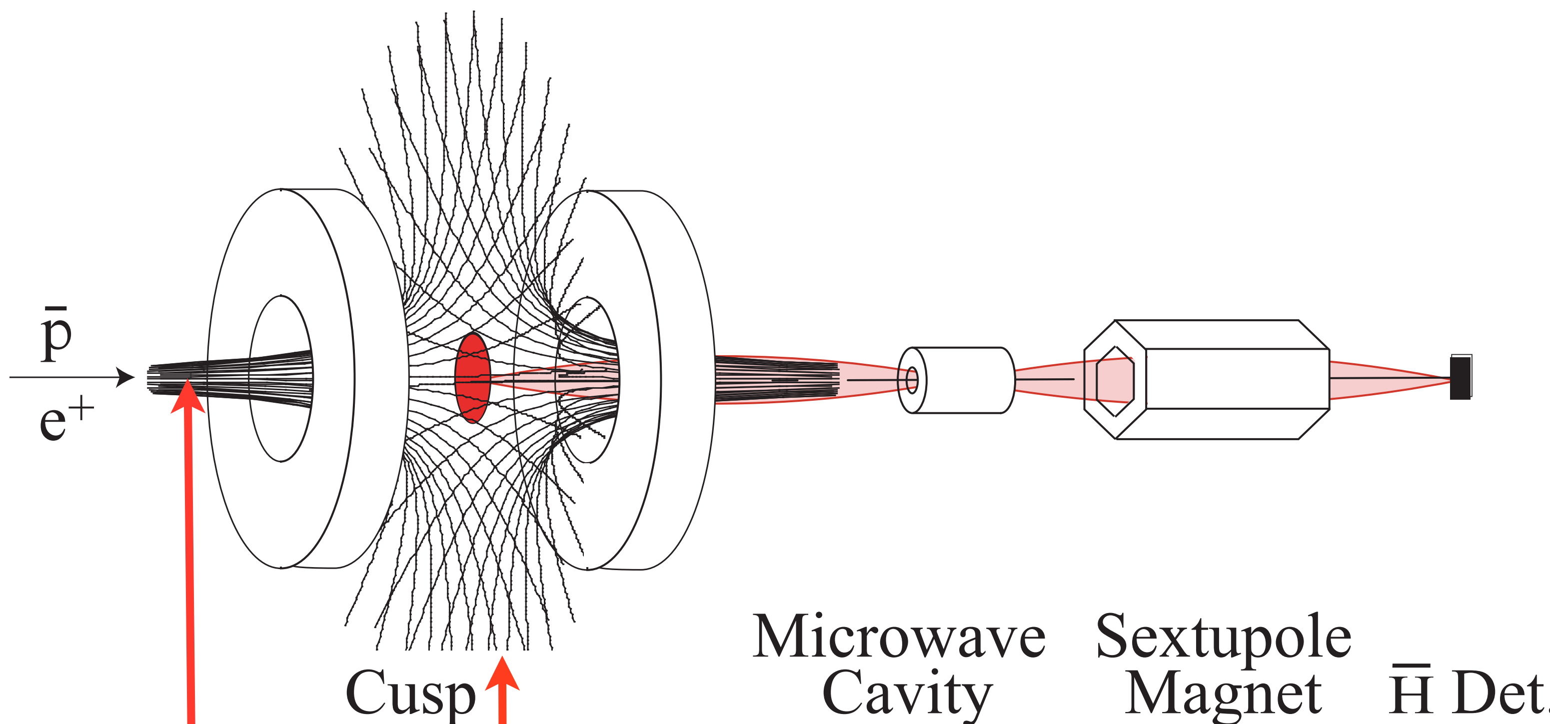
Temperature of produced $\bar{H}$

TBR: fraction trapped out of fraction made ~ 10^{-4}

challenge inherent in TBR: e^+ plasma physics → trade-off between # and temperature

possible increase in cold $\bar{H}$ rate by laser-cooling Be^+ to sympathetically cool e^+ but is cooling efficient enough to counteract heating through $\bar{p}$ injection?

ASACUSA beam (2014)



Rate: few atoms/hour

Rydberg states ? Many still in n>29

Velocity? T~ 100K-1000K?

Focusing of low-field seekers

TBR: same trade-off between # and temperature

Formation: TBR

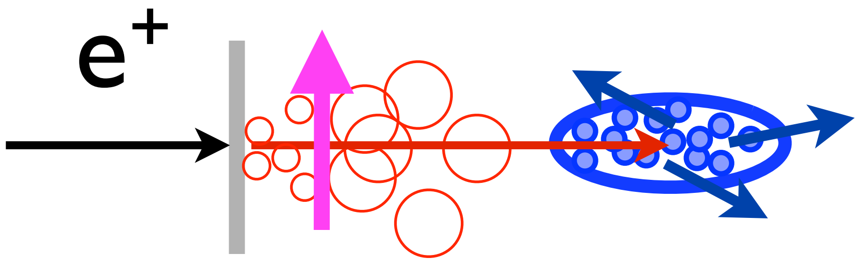
Under reasonable assumptions & measuring both transitions to extrapolate to zero field ➠ measurement to 1×10^{-7} appears possible (with a rate of ~ 1Hz of ground-state atoms)

alternative production method: RCE

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

AEḡIS

$T_{Ps} \sim 100$ K

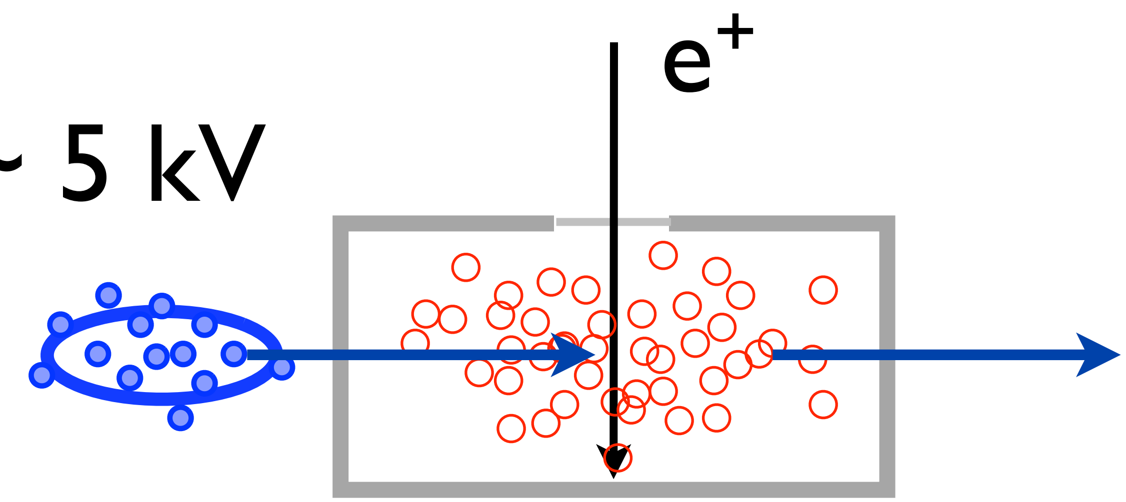


$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

cold $\bar{H}^*$

GBAR

$E_p \sim 5$ kV



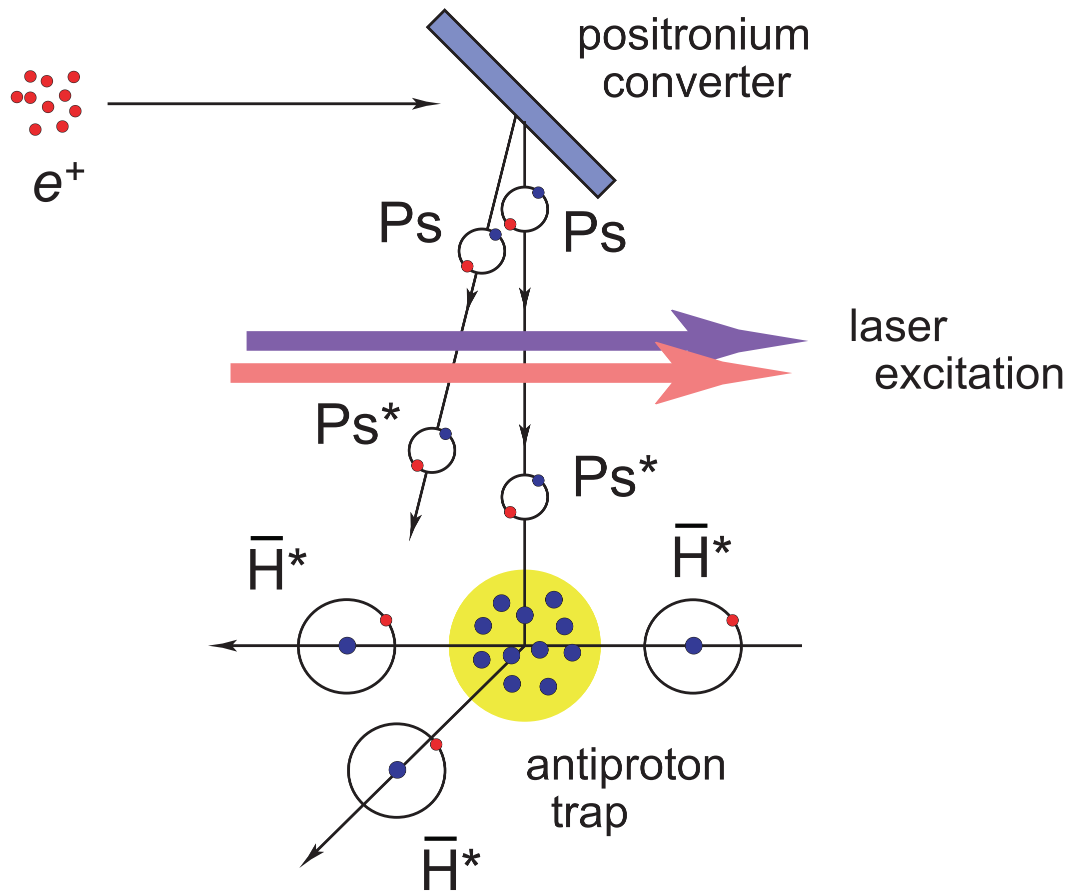
$$Ps + \bar{p} \rightarrow \bar{H} + e^-$$

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

hot $\bar{H}^+$

Schematic overview: pulsed horizontal beam of $\bar{H}$

production: charge exchange



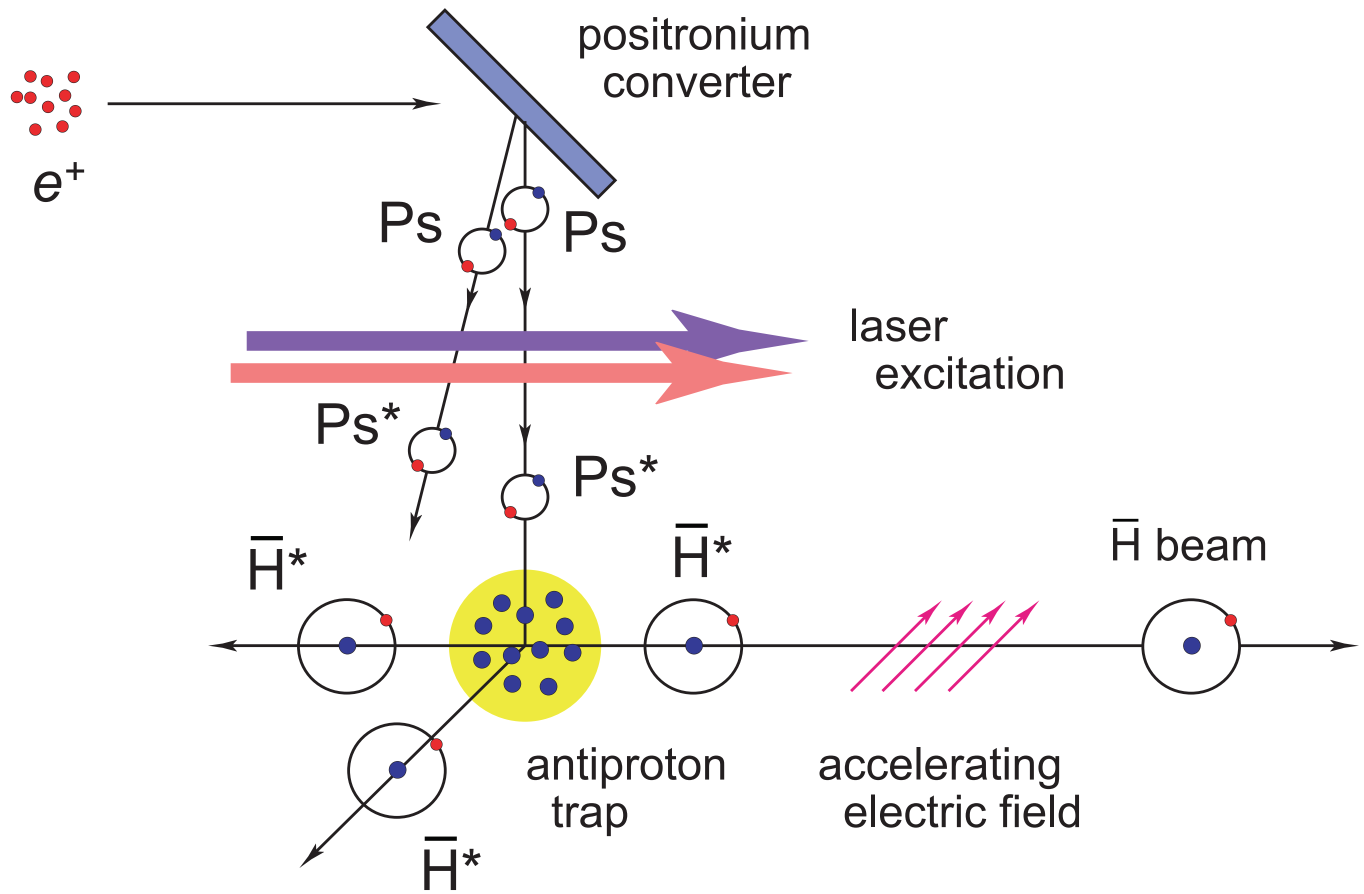
$\sigma \approx a_0 n^4$

time-of-flight: pulsed production

beam divergence: ultra-cold $\bar{p}$

Schematic overview: pulsed horizontal beam of $\overline{\mathrm{H}}$

beam formation: Stark acceleration



$\sigma \approx a_0 n^4$

$F = -\frac{3}{2} n k \vec{\nabla} E$

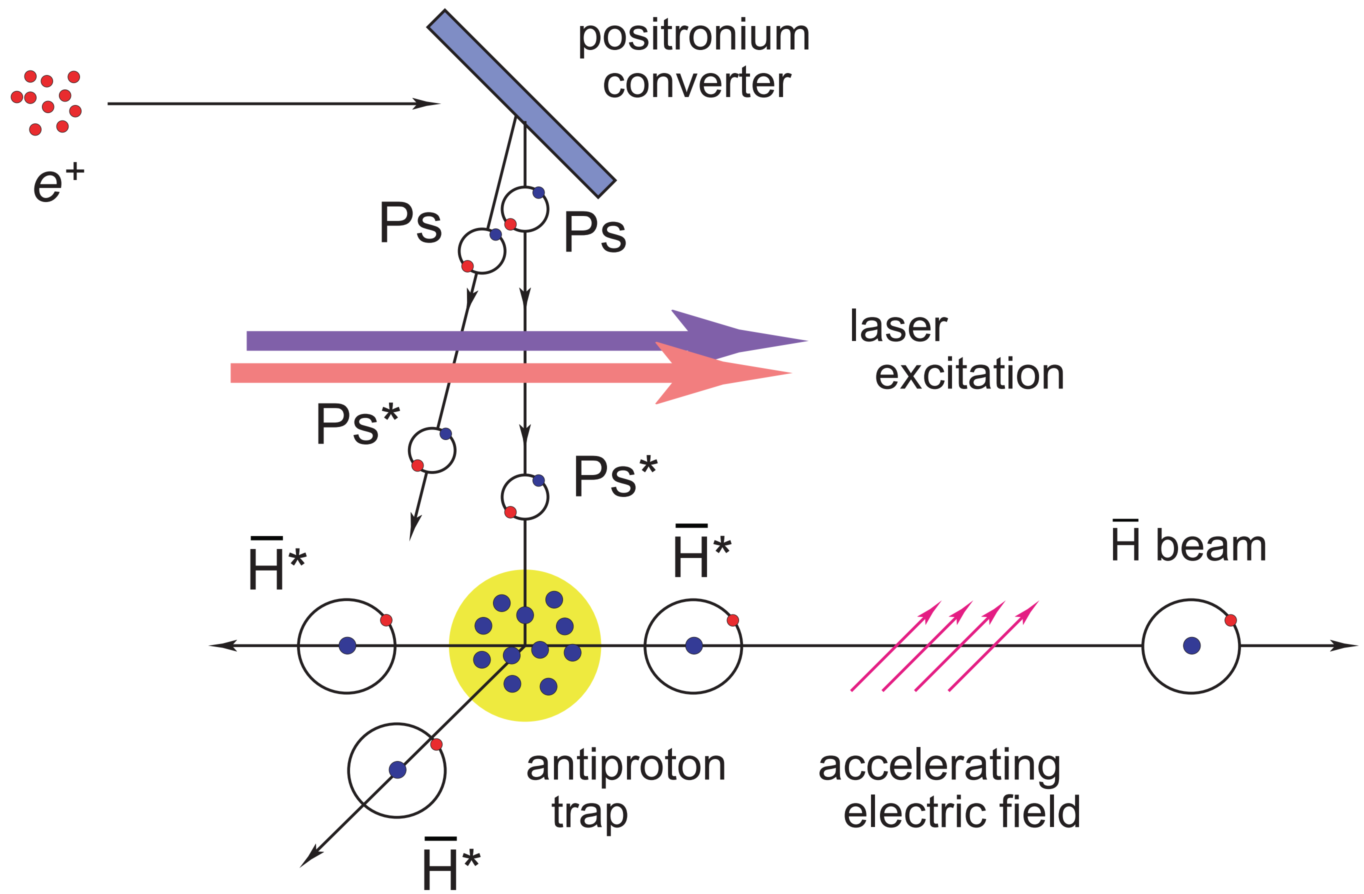
time-of-flight: pulsed production

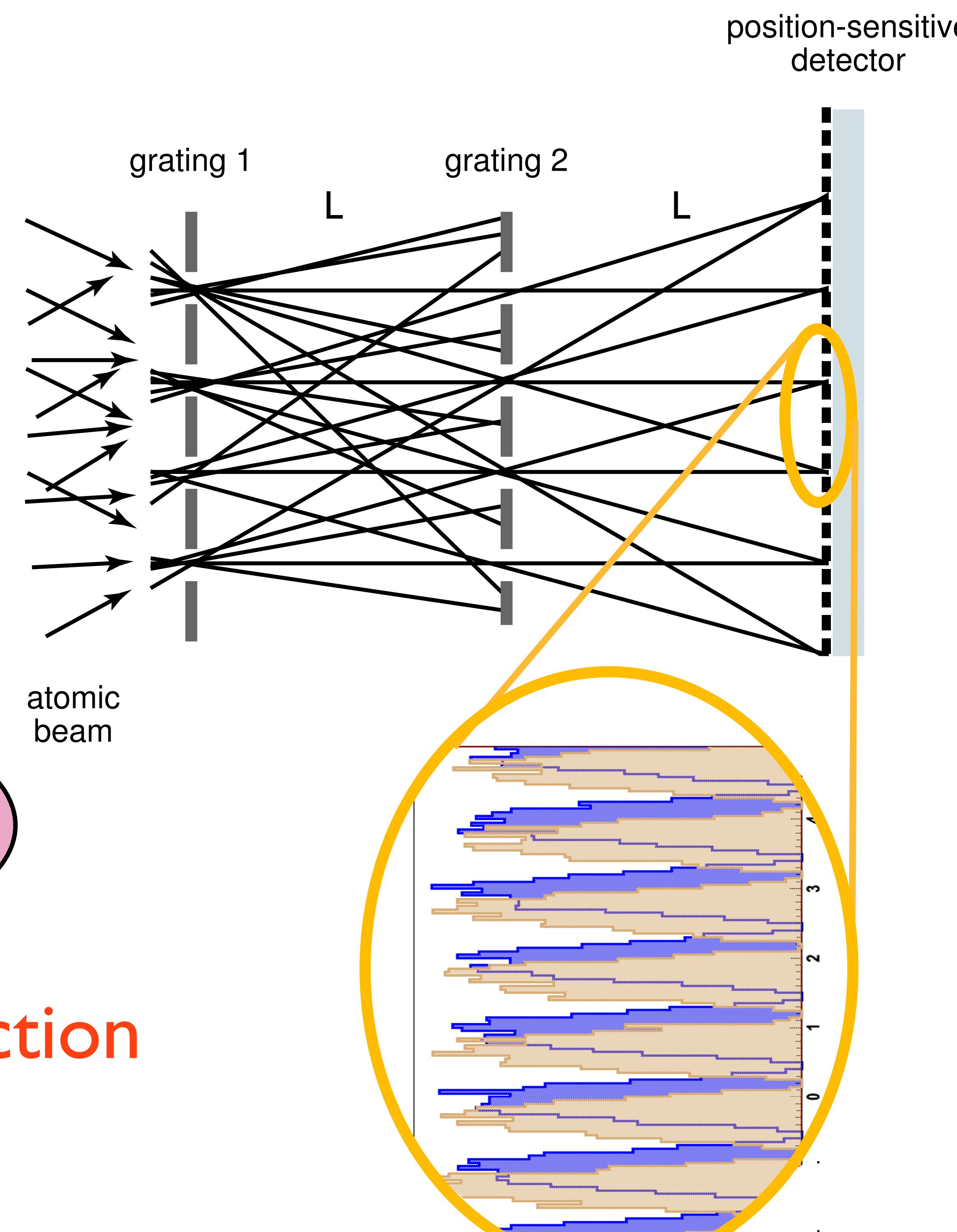
beam divergence: ultra-cold $\overline{\mathrm{p}}$

Schematic overview: pulsed horizontal beam of $\bar{H}$

measurement: deflectometer

[M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]
[A. Kellerbauer *et al.*, Phys. Rev. A **54** (1996) 3165]





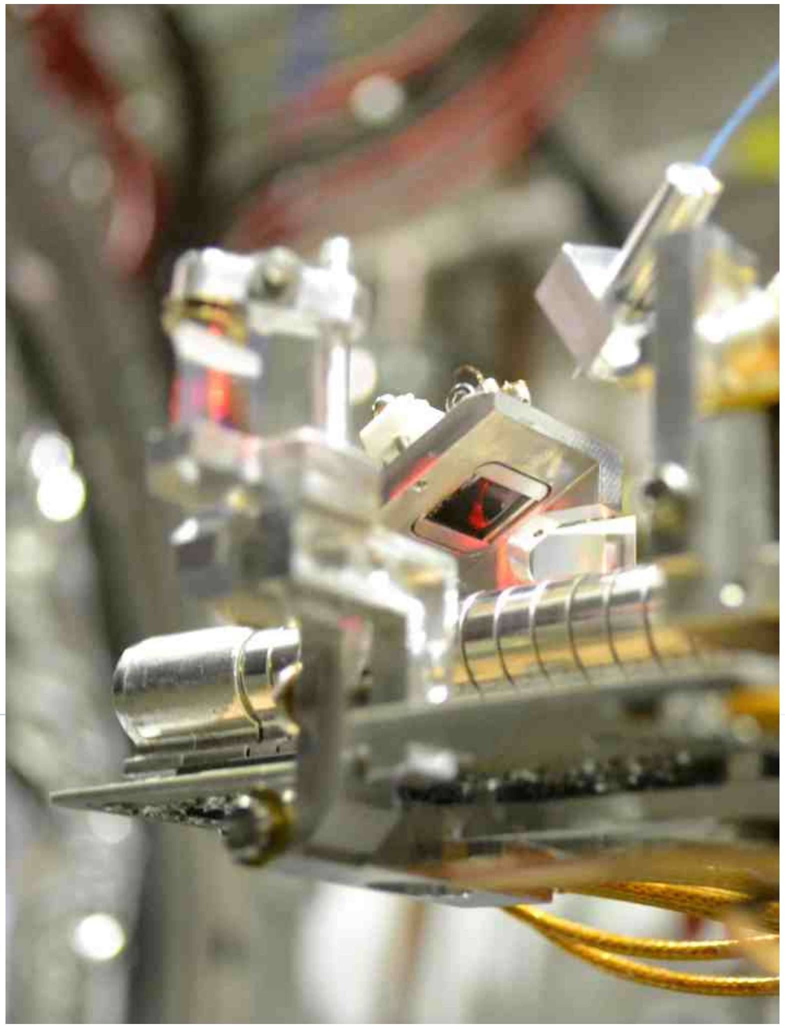
$$\sigma \approx a_0 n^4$$

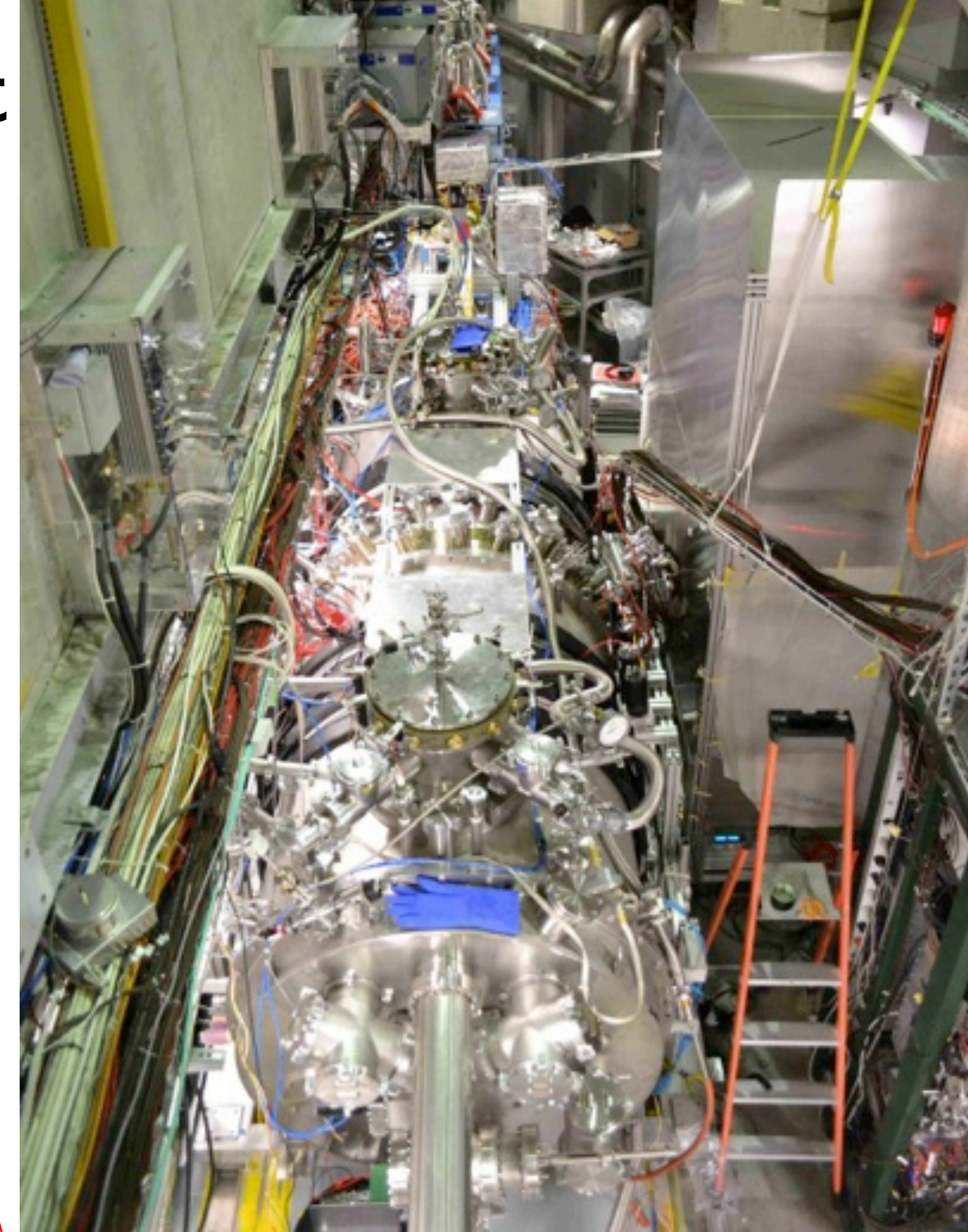
$$F = -\frac{3}{2}\, n\, k\, \vec{\nabla} E$$

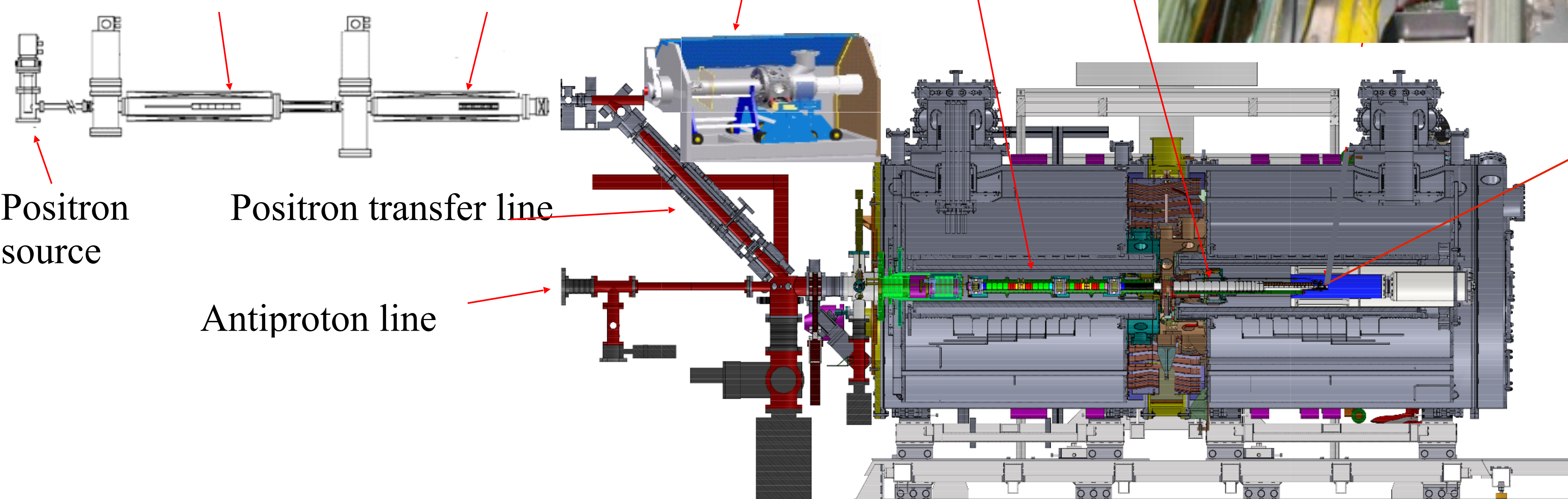
time-of-flight:
beam divergence:

pulsed production
ultra-cold $\bar{p}$

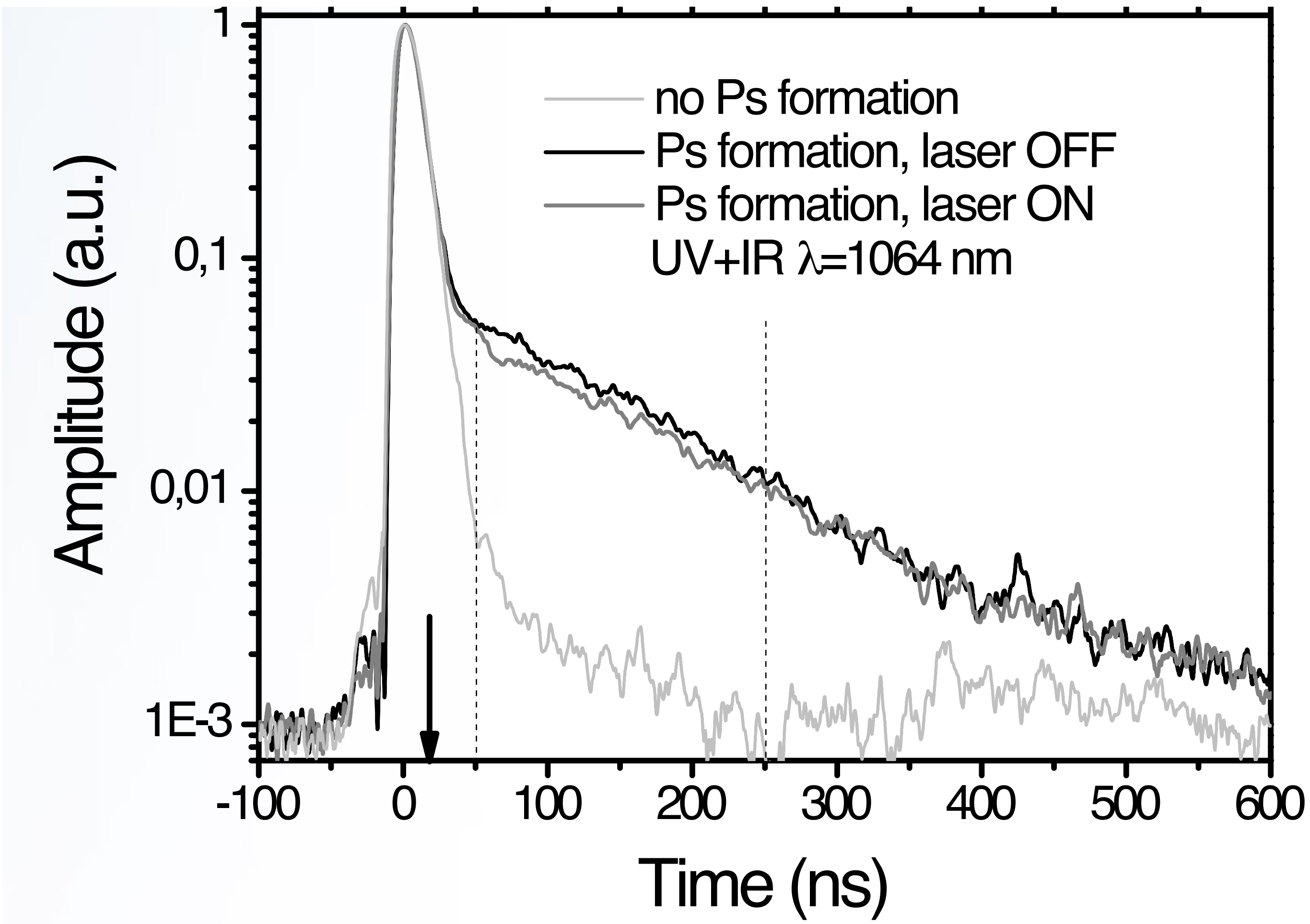
AE$\bar{g}$IS experiment

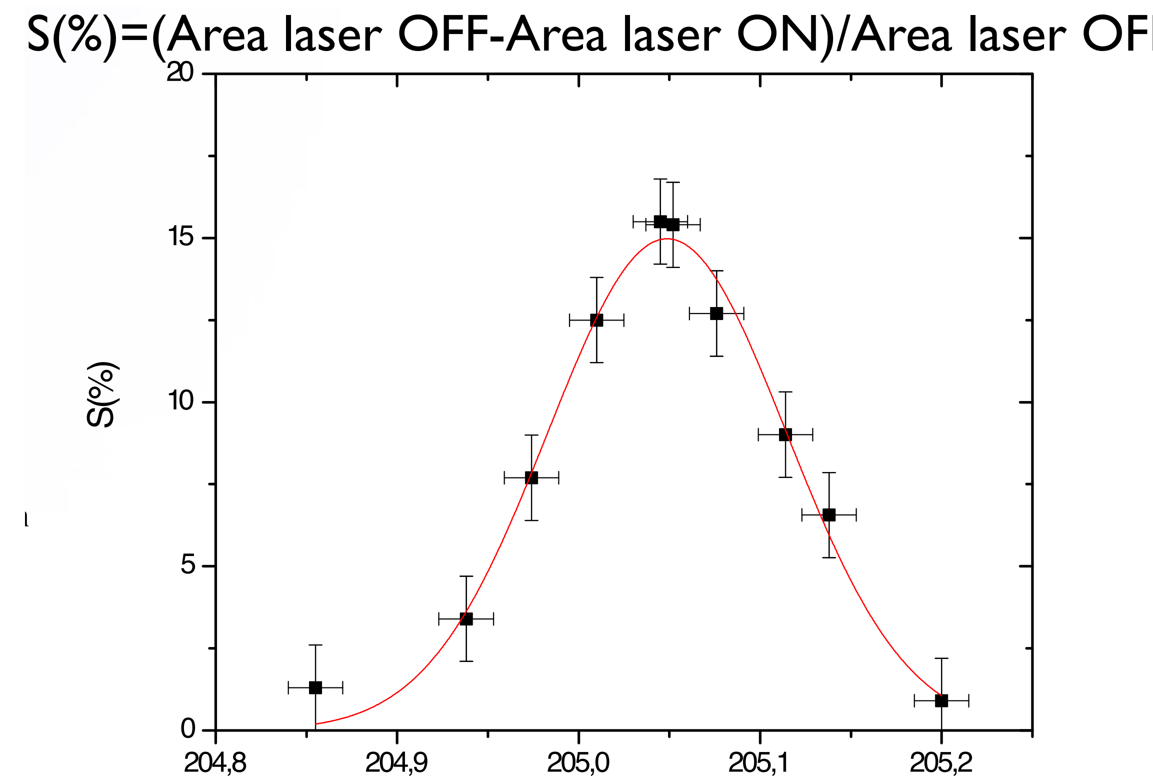


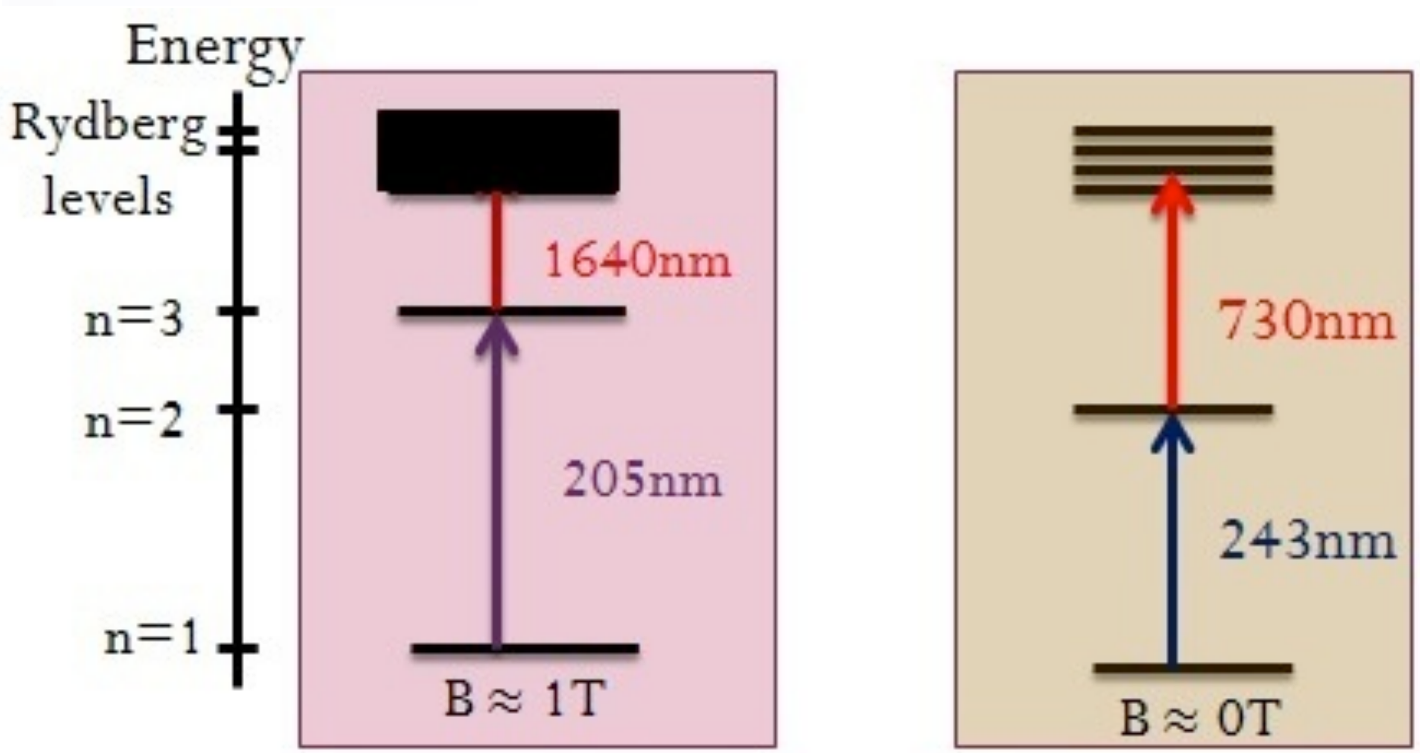


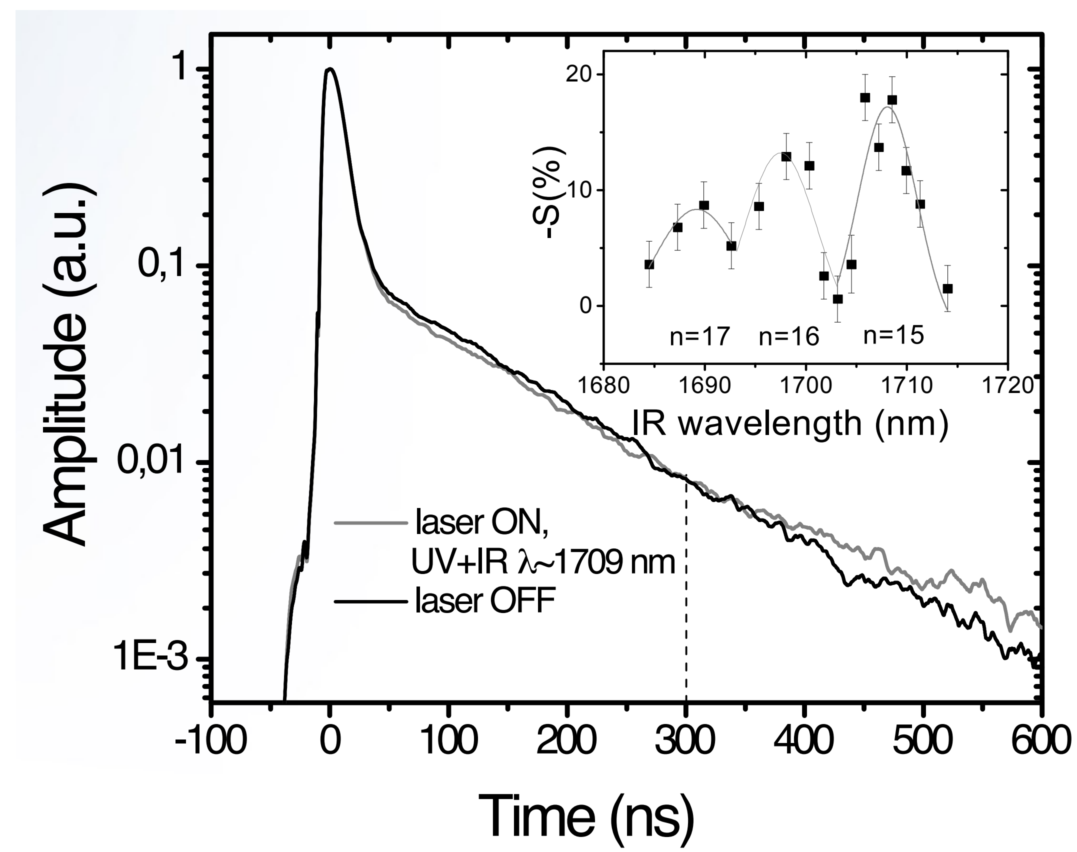


Ps excitation laser system(s) → Ps* formation



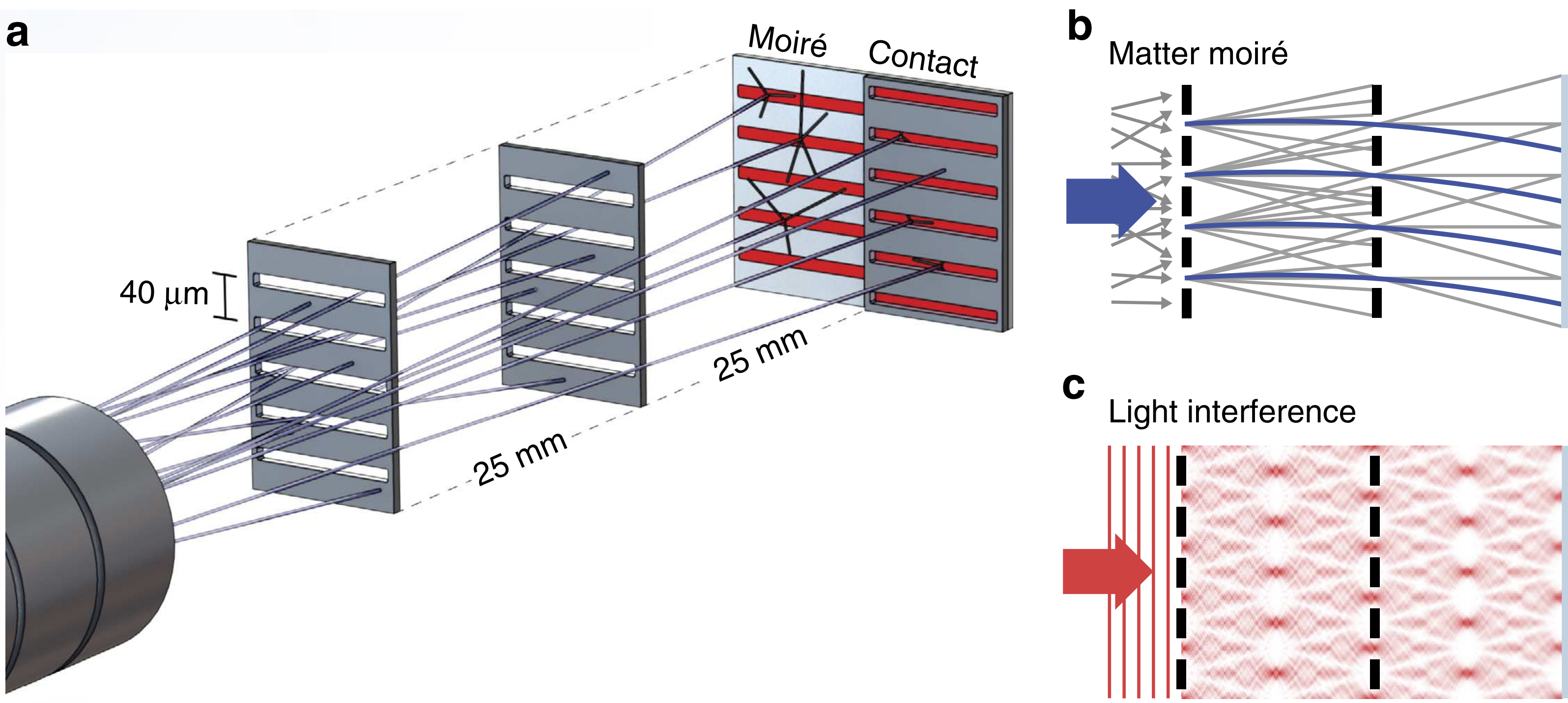


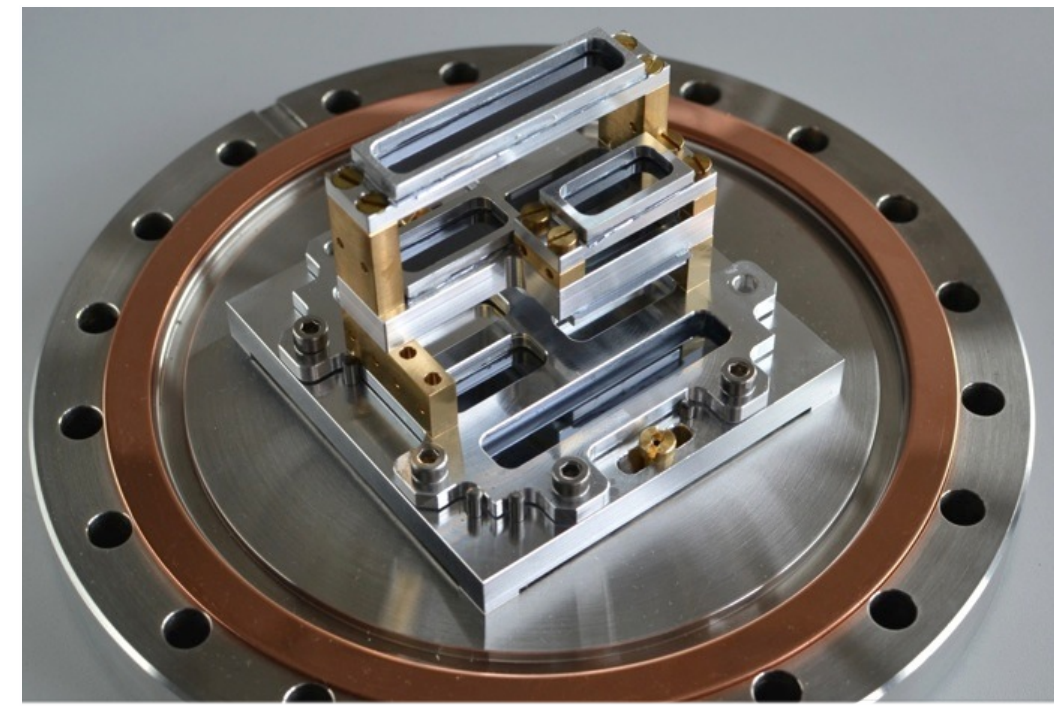


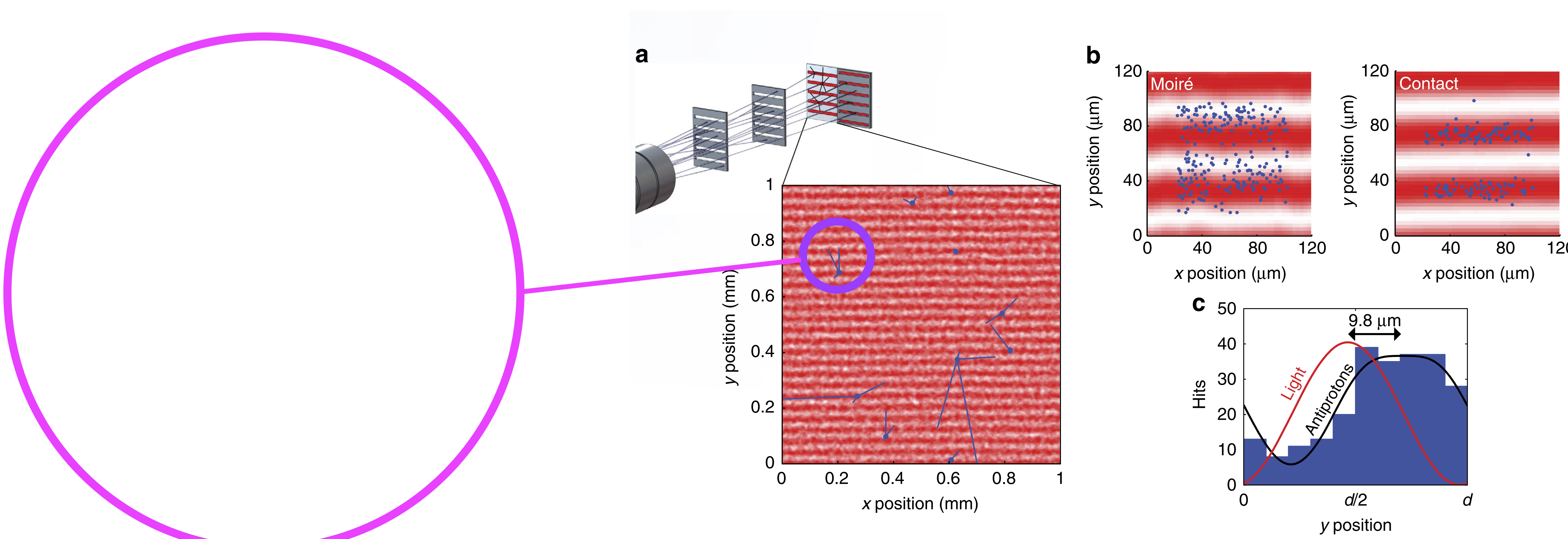


S. Aghion et al., Phys. Rev. A 94, 012507

Deflectometer test with antiprotons

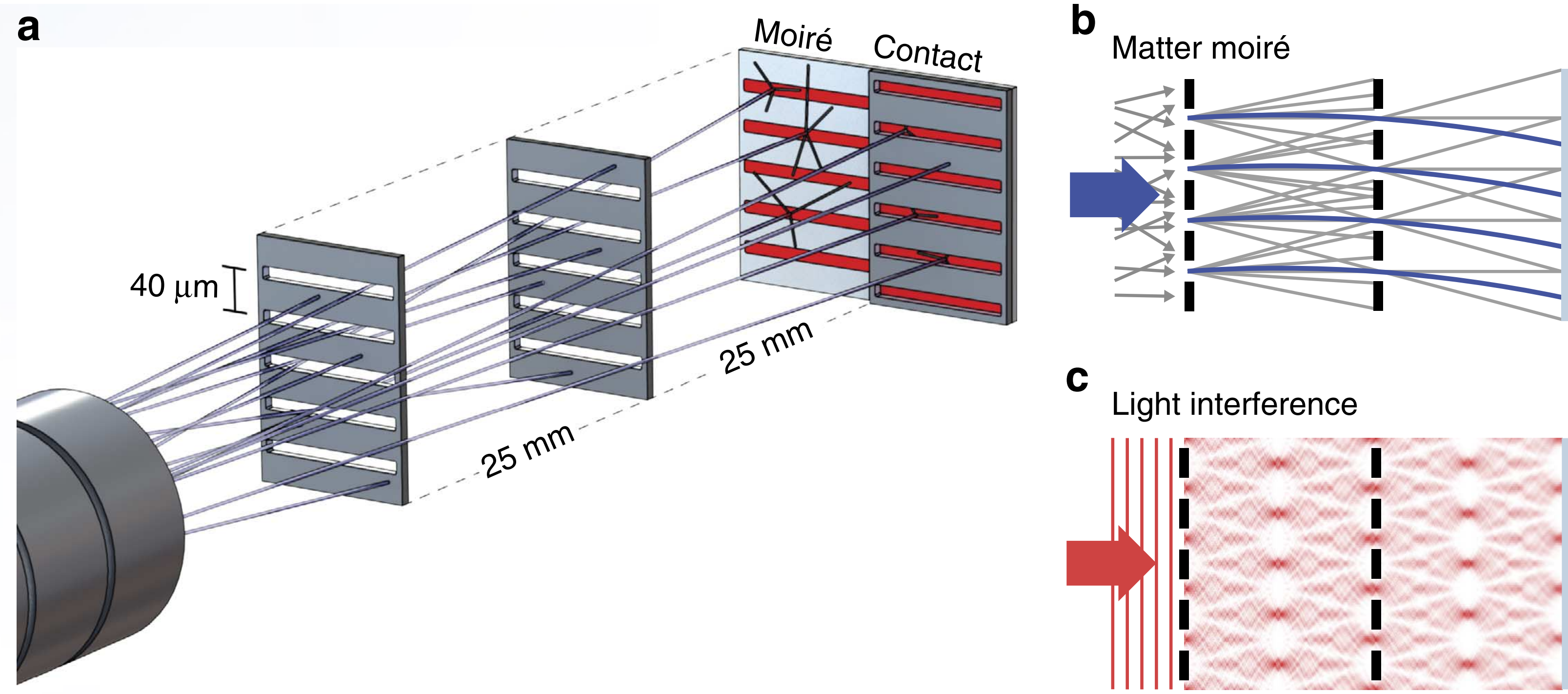


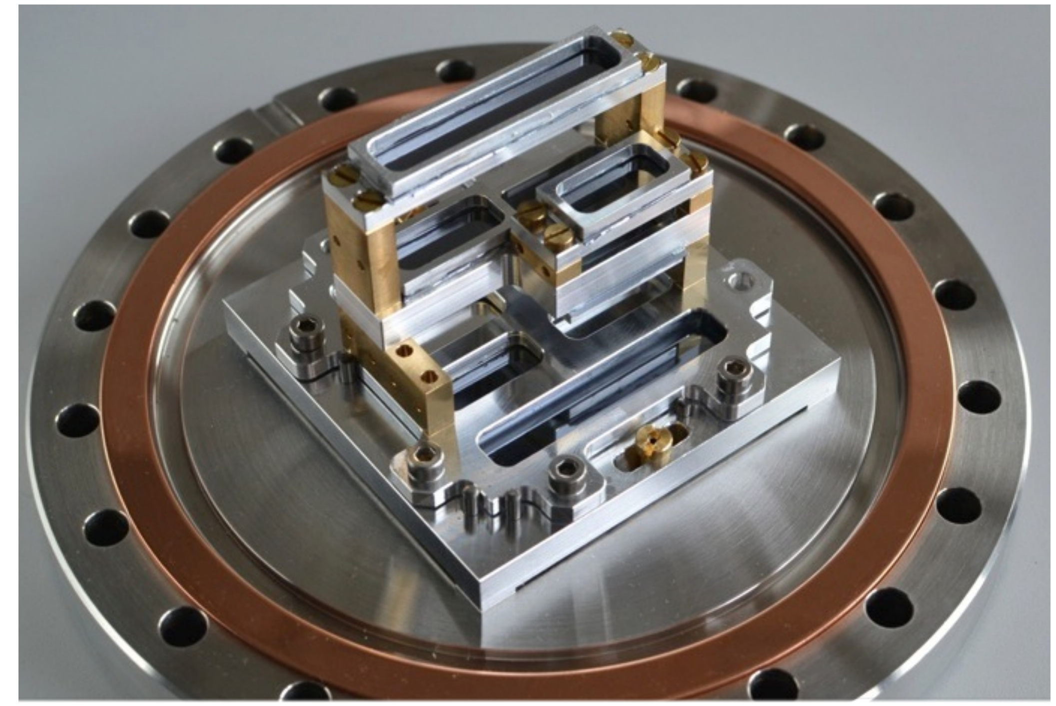


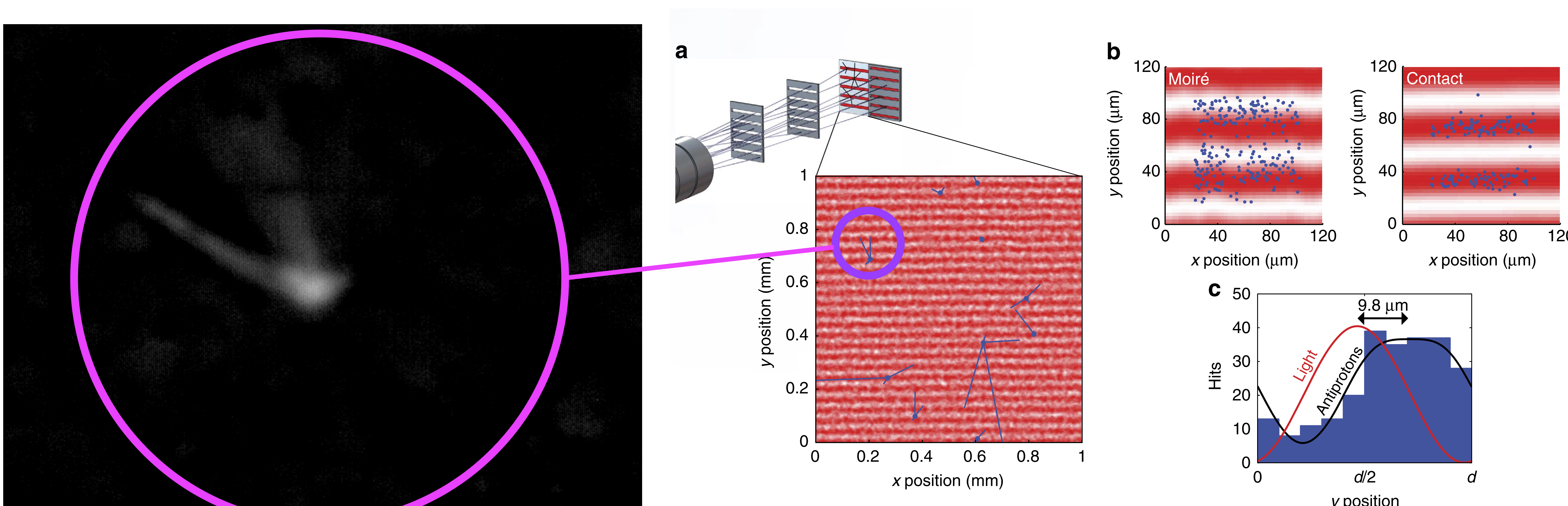


S. Aghion et al.,"A moiré deflectometer for antimatter", Nature Communications 5 (2014) 4538

Deflectometer test with antiprotons







S. Aghion et al.,"A moiré deflectometer for antimatter", Nature Communications 5 (2014) 4538

challenge remains: sub-mK $\bar{H}$ for gravity, spectroscopy
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) → $\bar{H}^+$ + e$^-$

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. In$^+$ → 20 μK

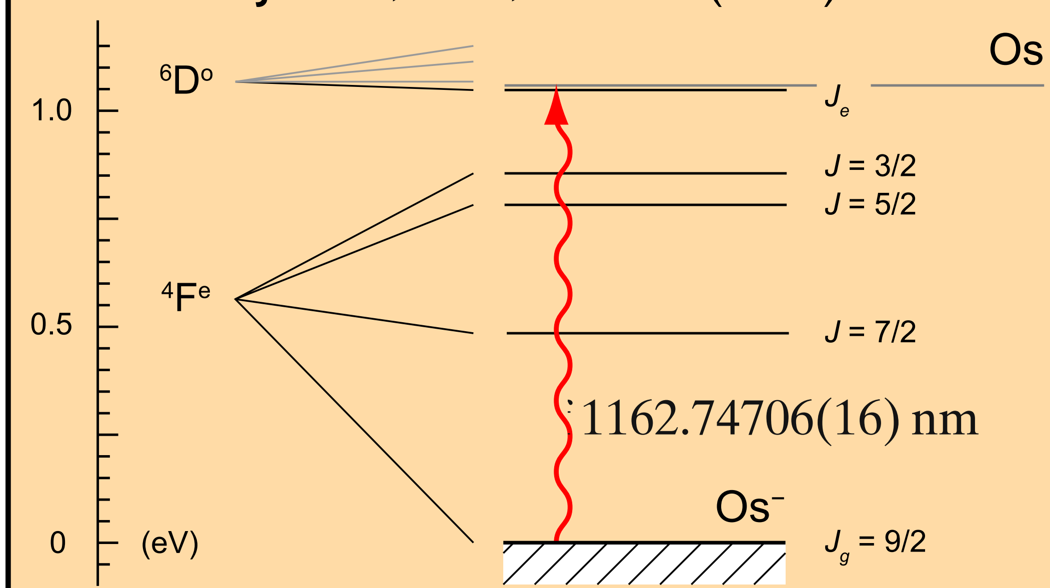
photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"

Anion cooling for AE$\bar{g}$IS: Os$^-$, La$^-$, C_2^-

cooling of $\bar{p}$

Warring et al, PRL 102 (2009) 043001
Fischer et al, PRL 104 (2010) 073004
Jordan, et al.,PRL 115 (2015) 113001

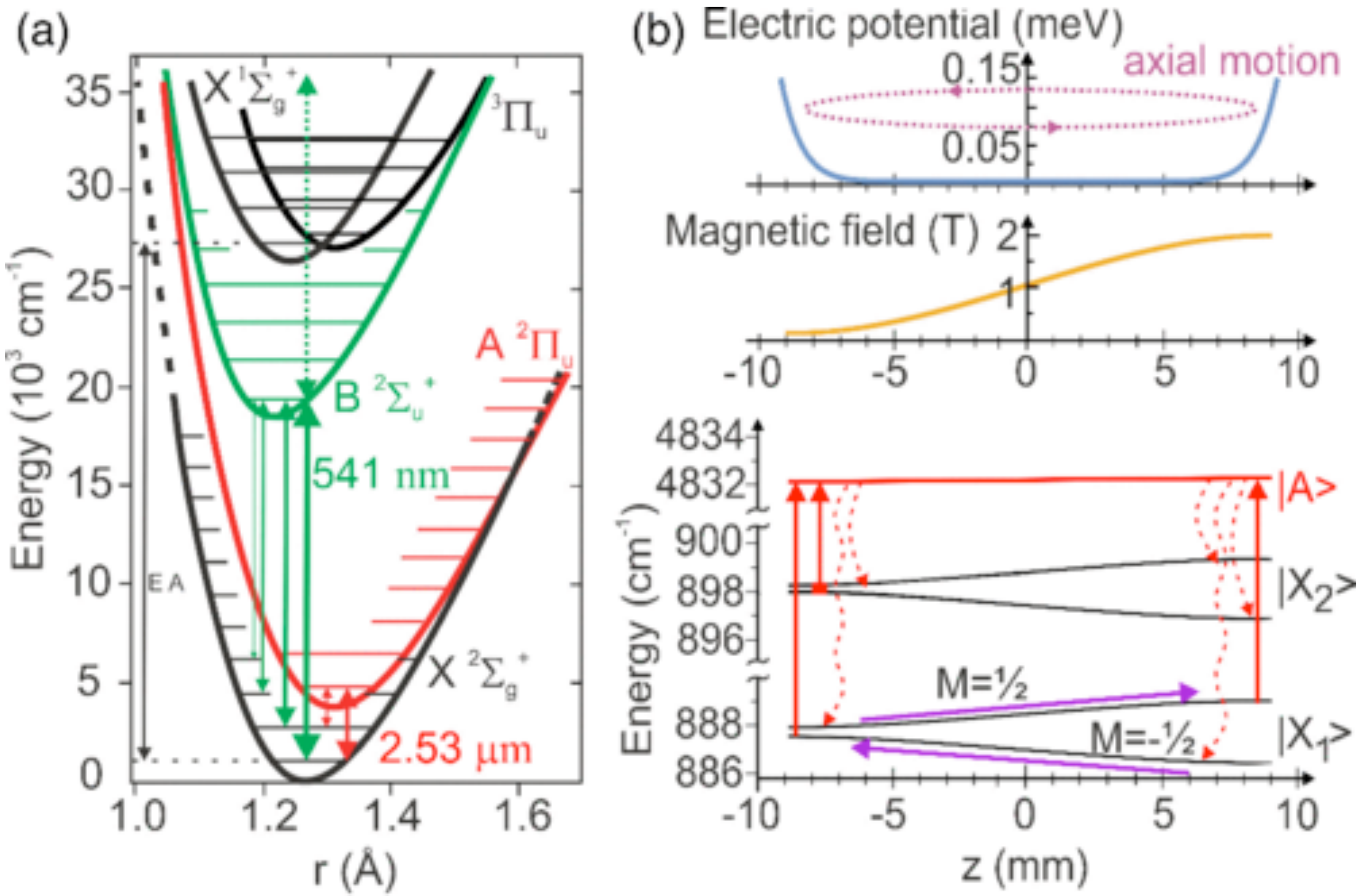


very weak cooling

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

should allow reaching same precision on **g** as with atoms (10^{-6} or better)

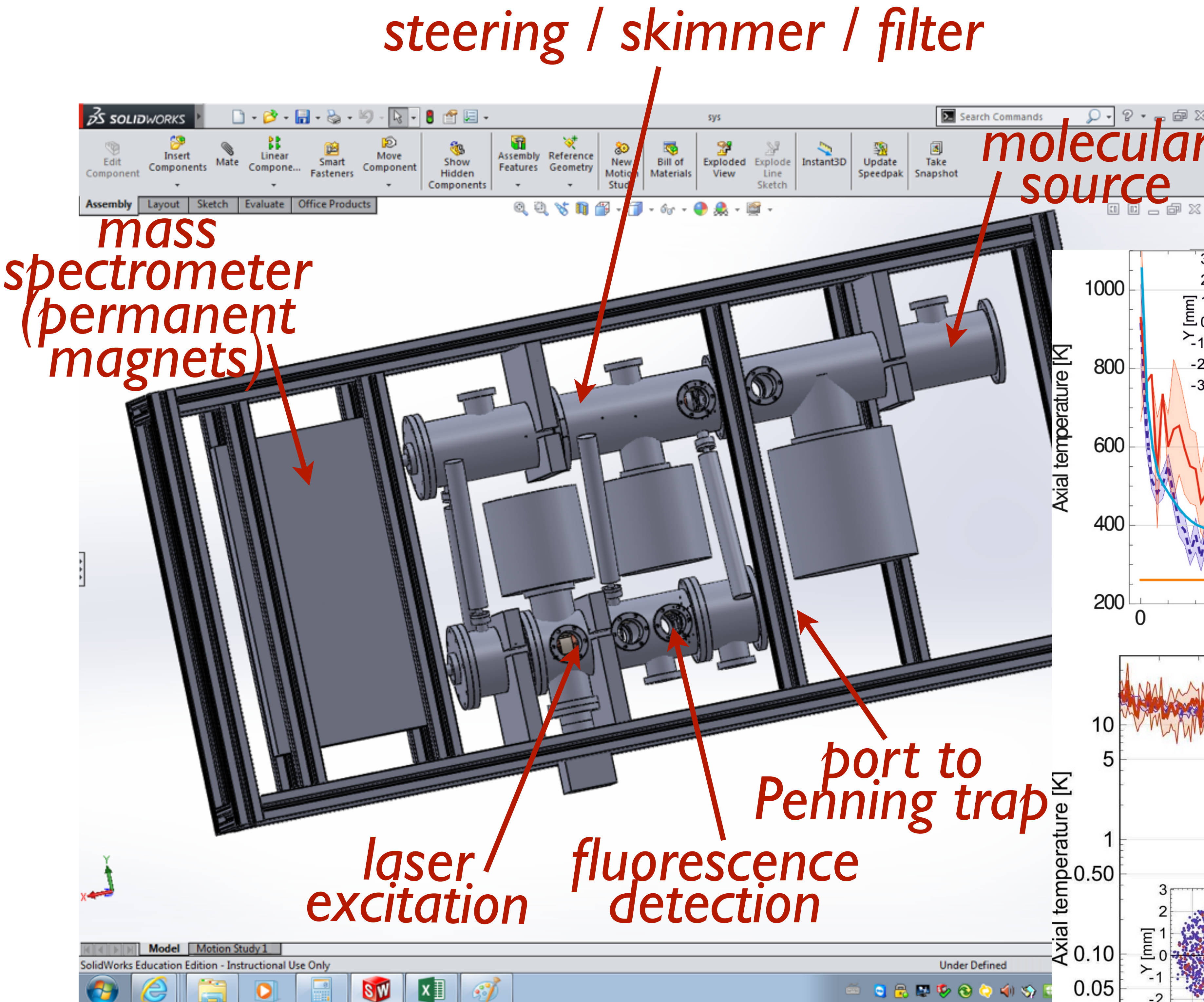
Anion cooling for AE$\bar{g}$IS: C_2^- Sisyphus cooling in a Penning trap

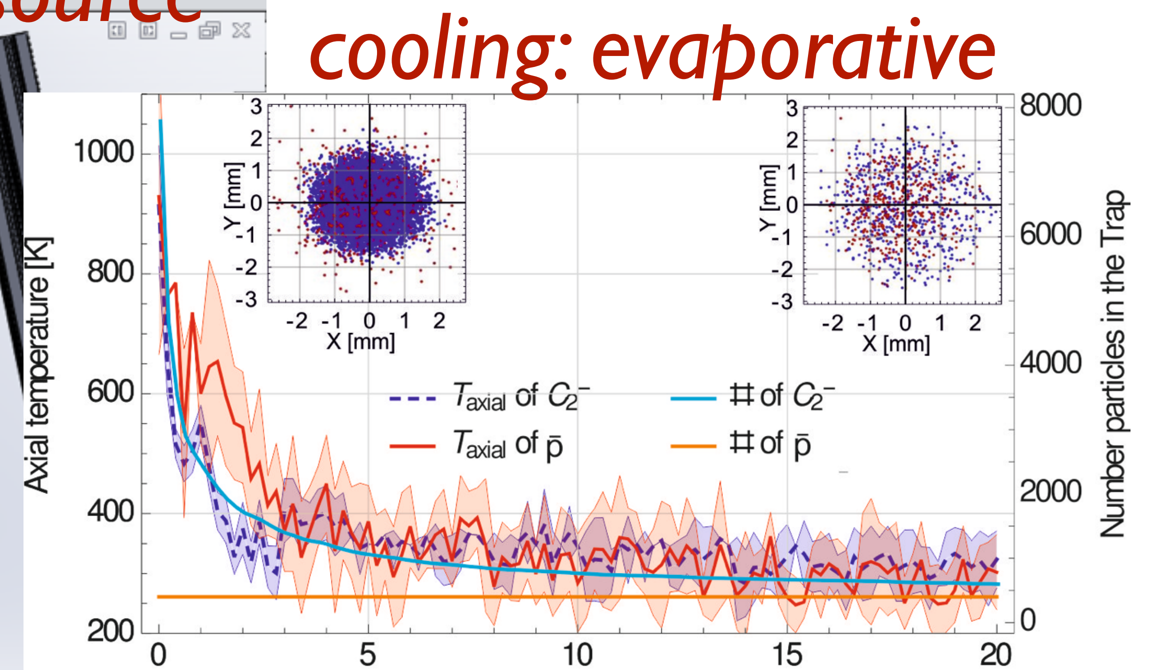


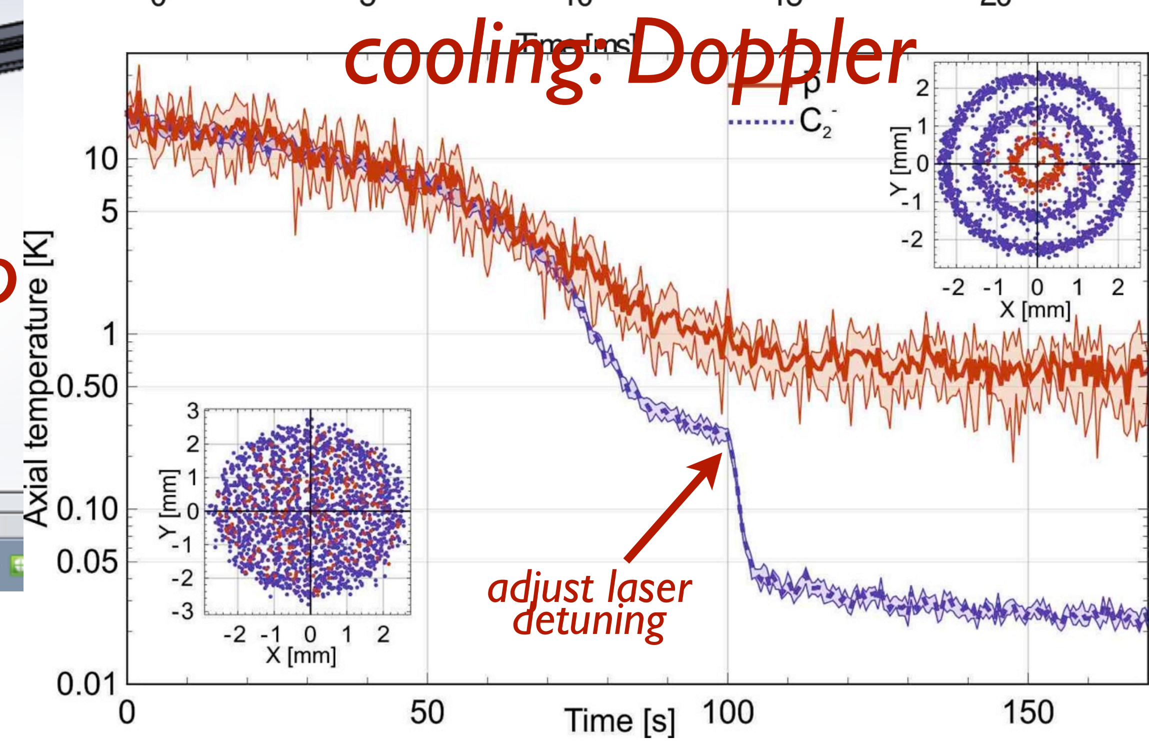
Electronic and vibrational levels of C_2^-
Arrow width ~ Franck-Condon transition strength

P. Yzombard et al., Phys. Rev. Lett. 114, 213001

test set-up (“Borealis”) at CERN = framework for technology developments towards sub-mK antihydrogen







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

$\bar{H}$: charge neutrality ... (can GBAR do this as well?)

Ps, muonium: gravity (lepton sensitivity)

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

$\bar{p}p$, $\bar{p}d$: gravity (baryon sensitivity) - Rydberg protonium

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

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

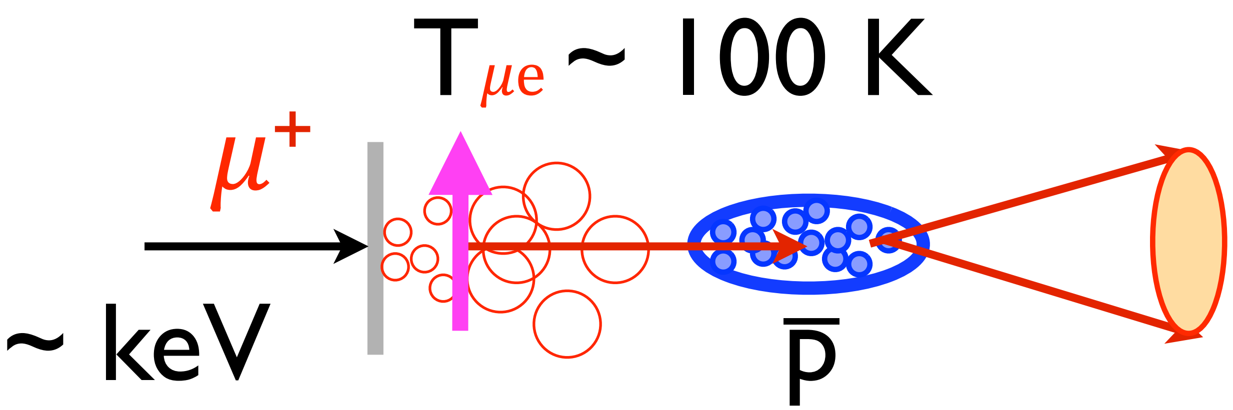
muonic antihydrogen

Muonium Emission into Vacuum from Mesoporous Thin Films at Cryogenic Temperatures

A. Antognini, P. Crivelli, T. Prokscha, K. S. Khaw, B. Barbiellini, L. Liszkay, K. Kirch, K. Kwuida, E. Morenzoni, F. M. Piegsa, Z. Salman, and A. Suter

Phys. Rev. Lett. 108, 143401

several groups: AE$\bar{g}$IS, Base, GBAR



Transportable Traps

Scheme to extract single antiprotons from a reservoir has been developed recently
Trapping of antiprotons for > 5 years has been demonstrated

First step towards transportable antiproton traps.

C. Smorra et al., Int. Journ. M.S. ***114*** *213001 (2014)*

Stefan Ulmer, Workshop on Physics beyond Colliders, CERN 2016

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

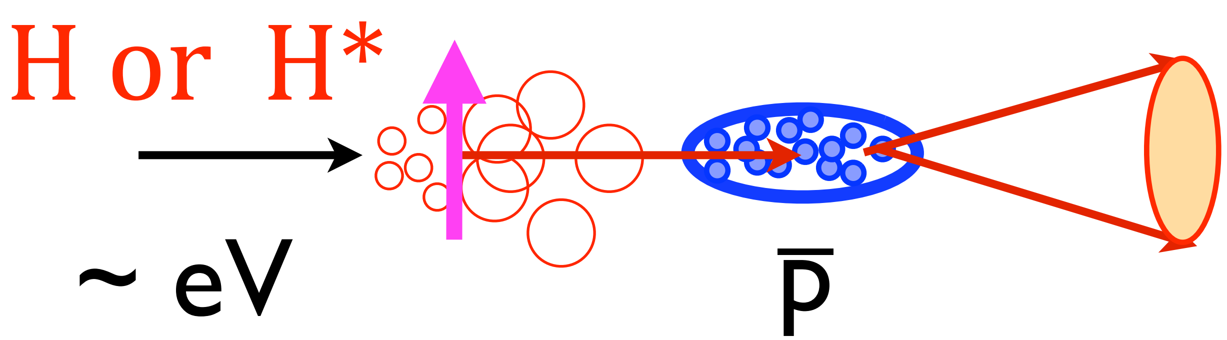
pulsed formation: t_0 ~ few ns

→ possibility of a pulsed beam

→ charge radius of antiproton

→ gravity with Rydberg muonic antihydrogen protonium

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



e.g. molecular NH_3 beam,
laser dissociation,
laser excitation,
Stark deceleration of H*

pulsed formation: t_0 ~ few ns

→ possibility of a protonium beam

→ precision spectroscopy with (long-lived) Rydberg protonium

→ gravity with (long-lived) Rydberg protonium

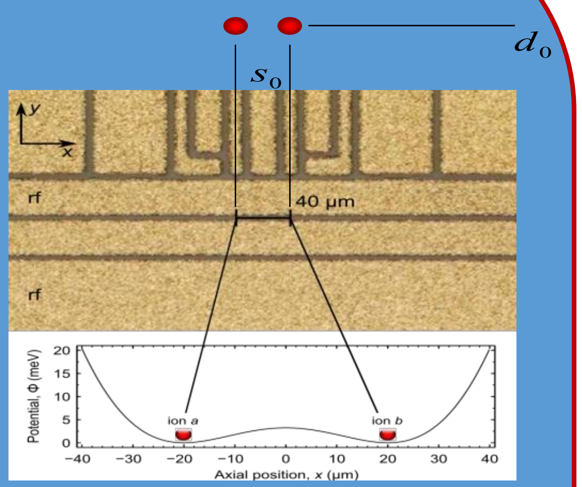
Potential of the antihydrogen ion

Charged particle

Sympathetic cooling has been demonstrated in Paul traps

Doppler temperatures can be reached easily

Stripping by «resonant» lasers is a routine.



Scheme has been demonstrated for two co-trapped laser-cooled Be-ions.

Is planned to be established and applied to antihydrogen ions by the gbar collaboration and to antiprotons by the BASE collaboration.

Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

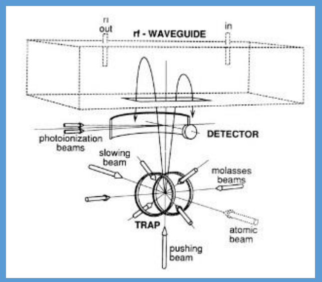
See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

Production of a high-quality beam

Cool particles sympathetically.

Accelerate particles with electric field.

Strip one positron.

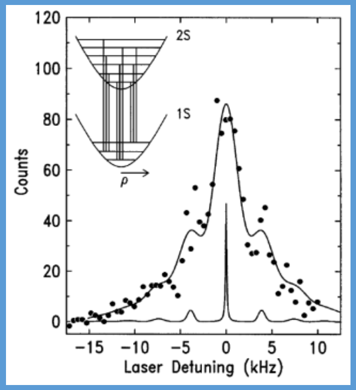


Apply to ASACUSA ideas (Rabi / Ramsey beam-scheme)

1S/2S spectroscopy at improved temperature distribution

Apply the «classical» ideas by ALPHA and ATRAP however with drastically improved initial temperature distribution

Smaller gradient traps, higher precision



ALPHA BASE ATRAP GBAR AEgIS

Stefan Ulmer,
Workshop on Physics beyond Colliders, CERN 2016

ions: H_2^+, resp. $\bar{H}_2^-$

J.P. Karr et al., Journal of Physics: Conference Series **723** (2016) 012048

“the realization of an H_2^+ optical clock, is much more challenging. Our accuracy estimates show that it may allow for tests of μ time variation at the 10^{-17}/yr level, improving current limits by one order of magnitude. The main drawback of H_2^+ is its light mass causing a larger second-order Doppler shift. On the plus side, this also leads to higher vibrational transition frequencies, allowing for better clock stability. Finally, a clock based on H_2^+ would represent, like atomic hydrogen masers, a clock with a ’calculable’ frequency, in this case providing a direct, 11-digit link from the SI second to the values of fundamental physical constants. Unlike H masers, however, an H_2^+ clock would operate at optical wavelengths and benefit from many of the techniques developed for ion-based optical atomic clocks.

proton-electron mass ratio μ

antiproton-positron mass ratio $\bar{\mu}$

@ 10^{-17}/yr level

$\bar{H}_2$ formation: TBR with trapped $\bar{H}$, or $\bar{H}^+ + \bar{H} \rightarrow \bar{H}_2 + e^+$

$\bar{H}_2^-$ formation: $\bar{H}_2$ photo-ionization? or ionization via ~50 eV e^+?

$\rightarrow \bar{H}_2^- + e^+$

ions: H_2^+, resp. $\bar{H}_2^-$

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p.s. : $\bar{H}\bar{D}^-$ would also be a very promising system, but ...

Outlook

work towards ultra-cold $\overline{\mathrm{H}}$ might open up other intriguing tests (gravity, spin-dependent forces, high sensitivity measurements of antiproton/positron mass ratio, gravity tests in purely baryonic or leptonic systems,...)

but

such tests will require formation of antihydrogen-like systems like $\bar{p}\mu^+$, Ps, $\bar{p}p$, $\overline{\mathrm{H}}^+$, $\overline{\mathrm{H}}_2^-$ (and *very!* much patience and ingenuity will be needed to get there...)

Indirect limits on EEP validity for antimatter systems

"Red shift type" argument — R. J. Hughes et al., PRL 66,7 (1991)

Cyclotron frequency of p and pbar in the same magnetic field

$$\left|\frac{\omega_c - \overline{\omega}_c}{\omega_c}\right| < 9 \cdot 10^{-11}$$

G. Gabrielse et al PRL 82 (3198) (1999)

⟹ If matter and antimatter are coupled to the same tensor field: $\alpha_{p\bar{p}} < 3 \cdot 10^{-6}$

For anomalous interaction coupling to antimatter with R_{Earth} < range < Distance Earth-Sun: $\alpha_{p\bar{p}} < 10^{-1}$

- The limit is model dependent
- Exact CPT is assumed

SN1987A

$\alpha_{\nu\bar{\nu}} < 10^{-5} - 10^{-6}$ Neutrino-antineutrino arrival time difference

- Only one ■$_e$ detected, several caveats
- Model dependent

S. Pakvasa et al., Phys. Rev. D 39 (1989) 176

The "Schiff argument" — S.I. Schiff PRL 1 254 (1958)

Virtual e+ e- pairs in the atoms

WEP violation for e+ ⟹ m_I-m_G should depend on Z

$\alpha_{e+e-} < 10^{-6}$

- Several criticisms
- Uncorrected renormalization procedure…

M. Nieto et al Phys. Rep. 205 (5) 221 (1991)

M. Charlton et al Phys. Rep 241 65 (1994)

R. Hughes Hyp. Int.76 3 (1996)

K_0 $\overline{K}_0$

CPLEAR coll. Phys. Lett. B 452 (1999) 425 — Very stringent limits

$\alpha_{K_0\overline{K}_0} < 10^{-9} - 10^{-14}$ Depending on the range of the anomalous interaction