Fundamental physics with antihydrogen and antiprotons at the AD

Michael Doser
CERN

What measurements are we talking about?

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

tests of fundamental symmetry (CPT)

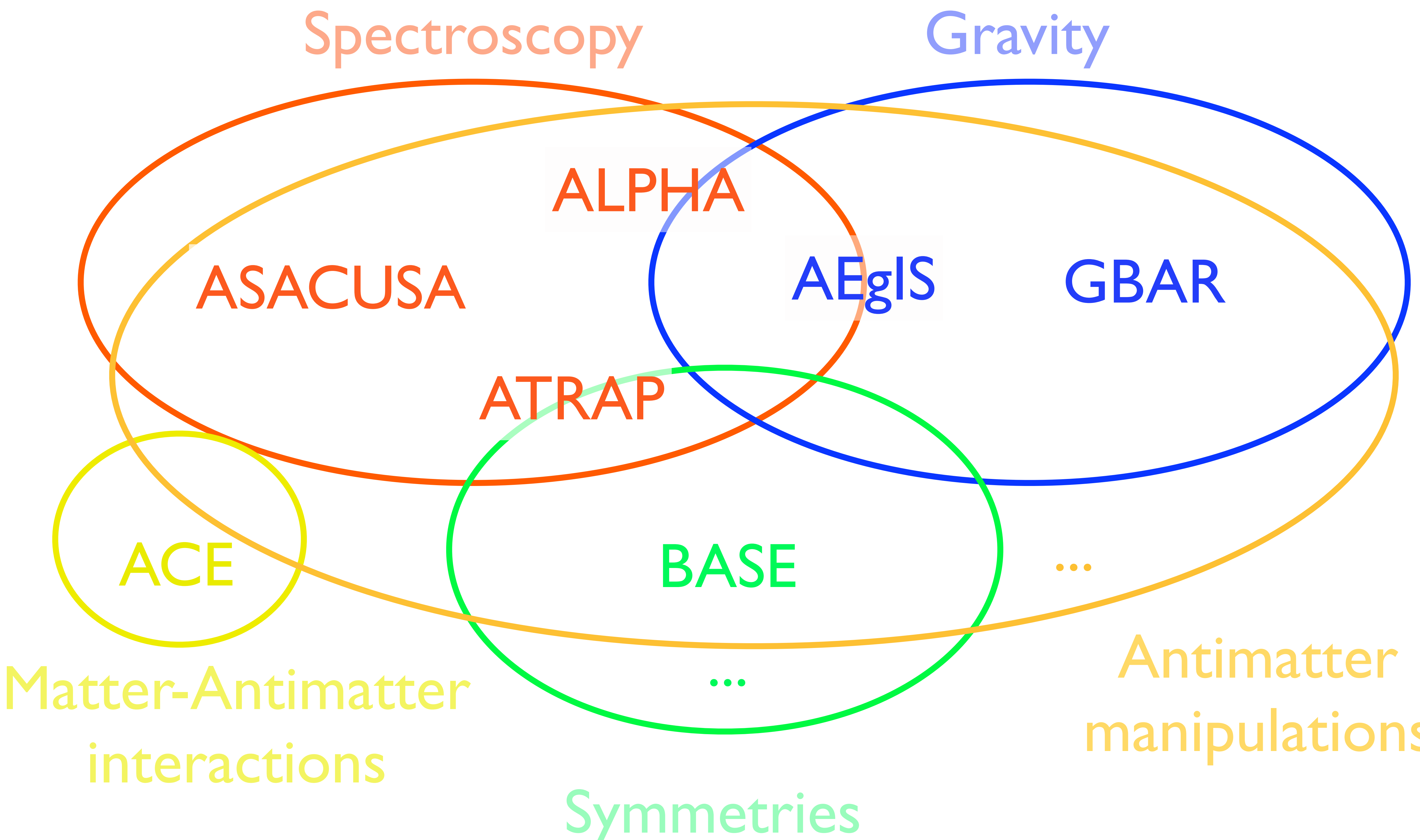
2) Measurement of the gravitational behavior of antimatter

tests of the Weak Equivalence Principle

3) other measurements in antihydrogen(-like) systems

positronium, protonium, antiprotonic helium, ...

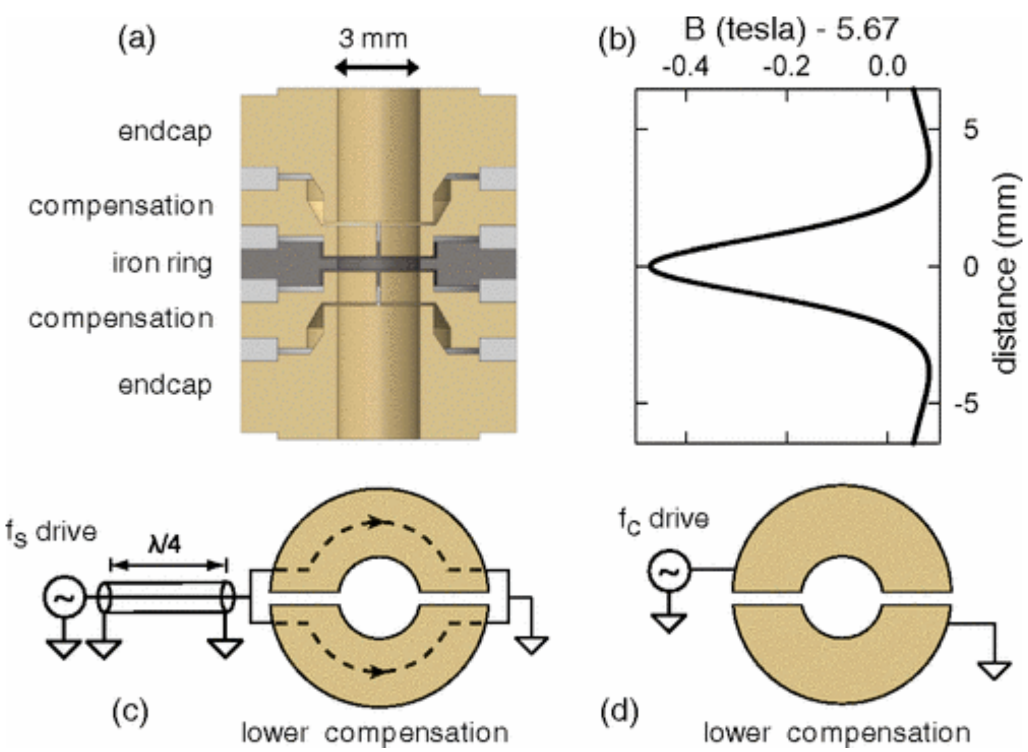
Experiments at the AD
(antiprotons and antihydrogen)

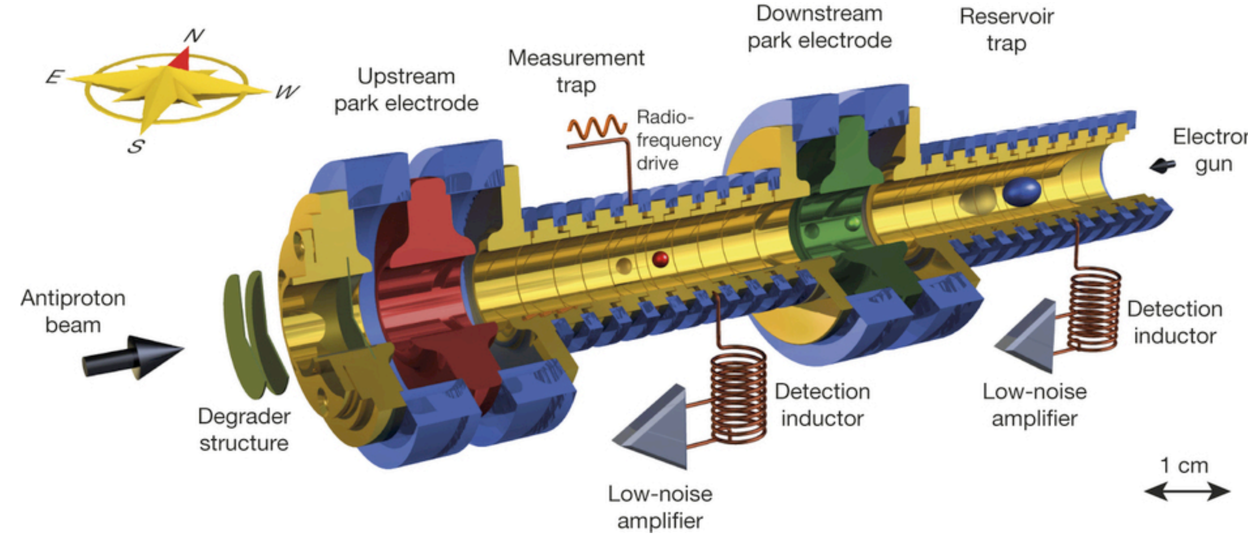


ATRAP & BASE

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

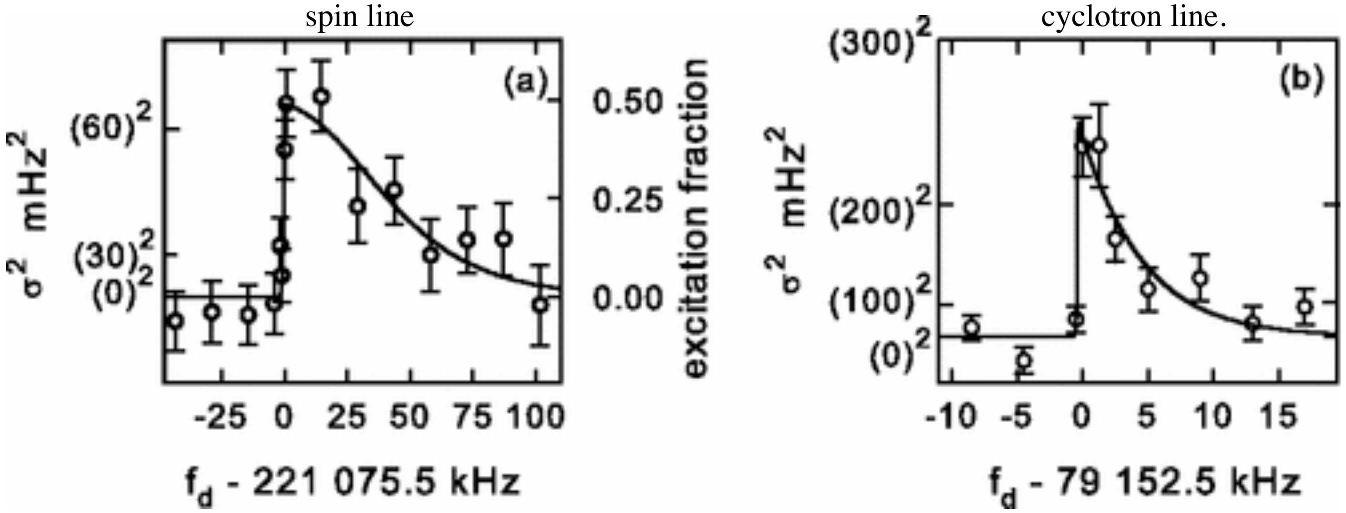
S. Ulmer. *et al.* Nature 524,196–199 (13 August 2015)



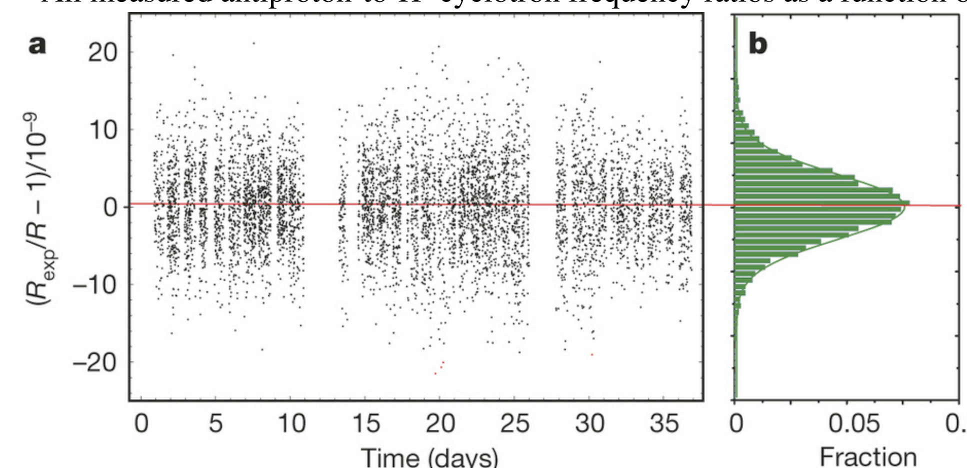


spin line

cyclotron line.



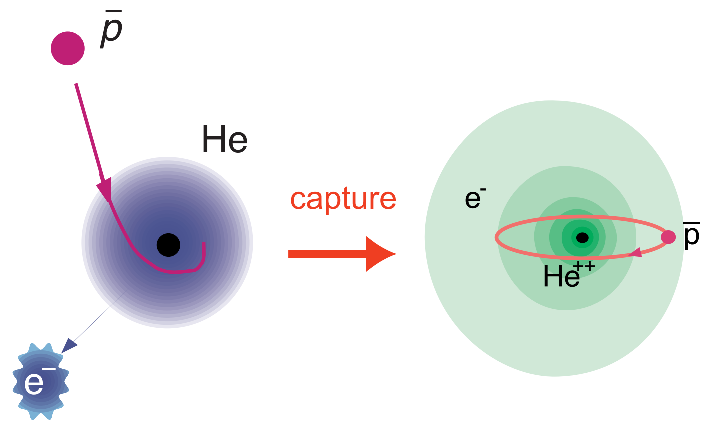
All measured antiproton-to-H⁻ cyclotron frequency ratios as a function of time

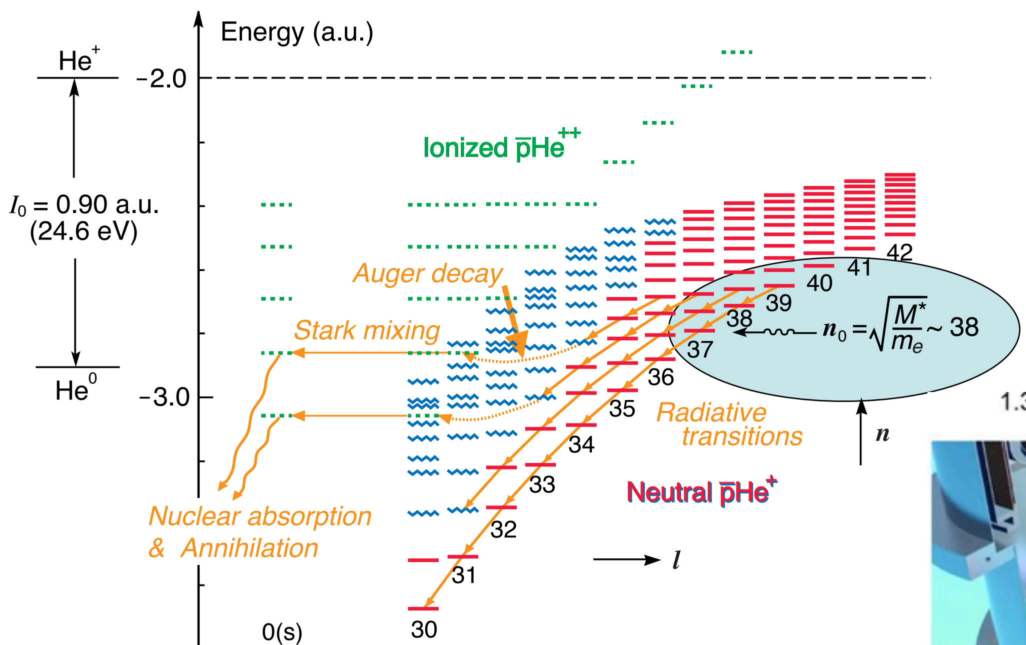


$(q/m)_{\bar{p}}/(q/m)_p - 1 = 1(69) \times 10^{-12}$

$\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005$ (factor 6 improvement by BASE in 2017)

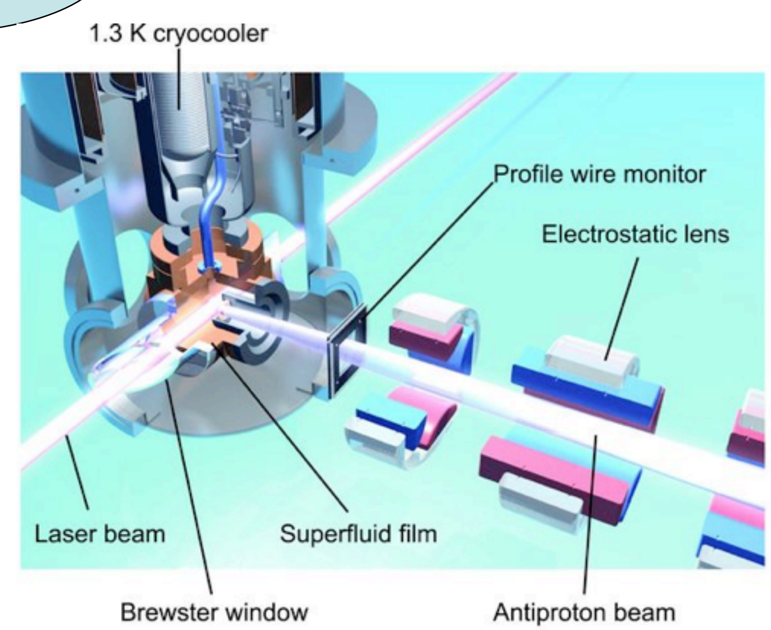
ASACUSA results ($\bar{p}He^+$ spectroscopy)

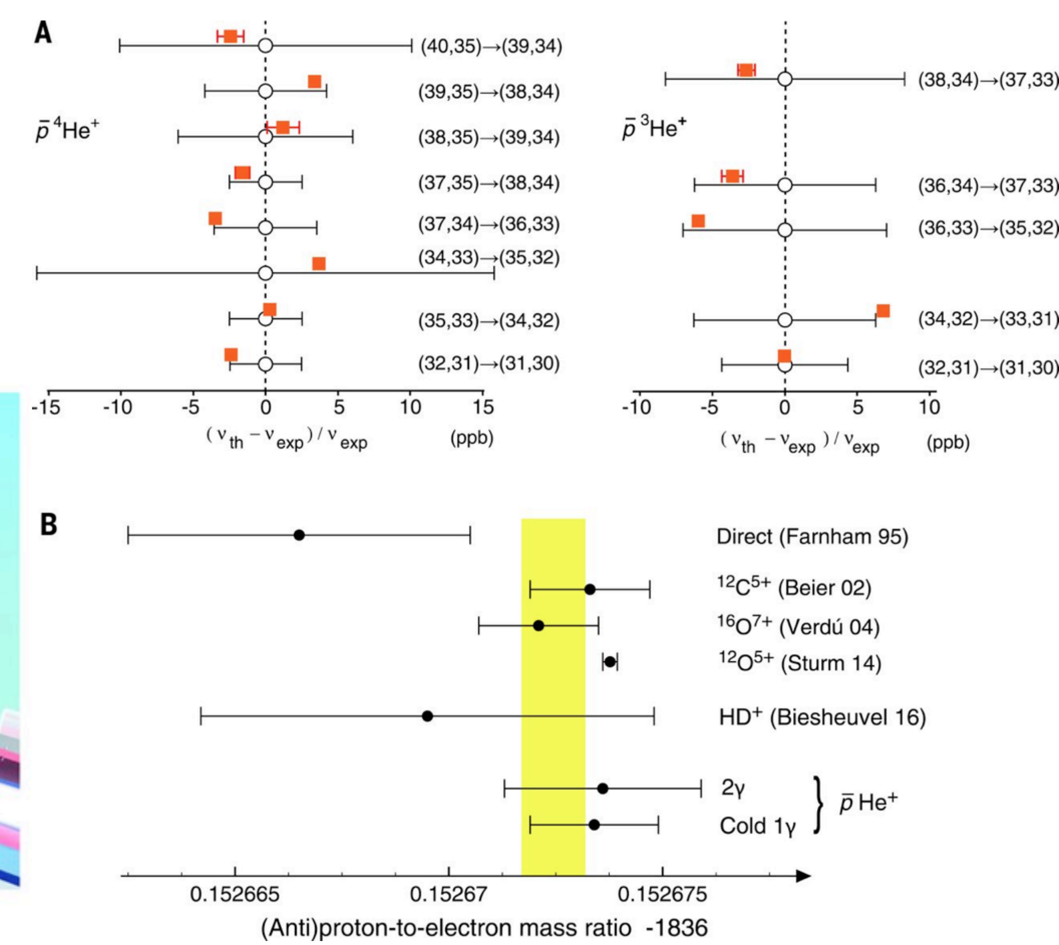




By comparing the calculated and experimental $\bar{p}He^+$ frequencies, the ratio $M_{\bar{p}}/m_e$ can in principle be determined to a fractional precision of $<1 \times 10^{-10}$

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



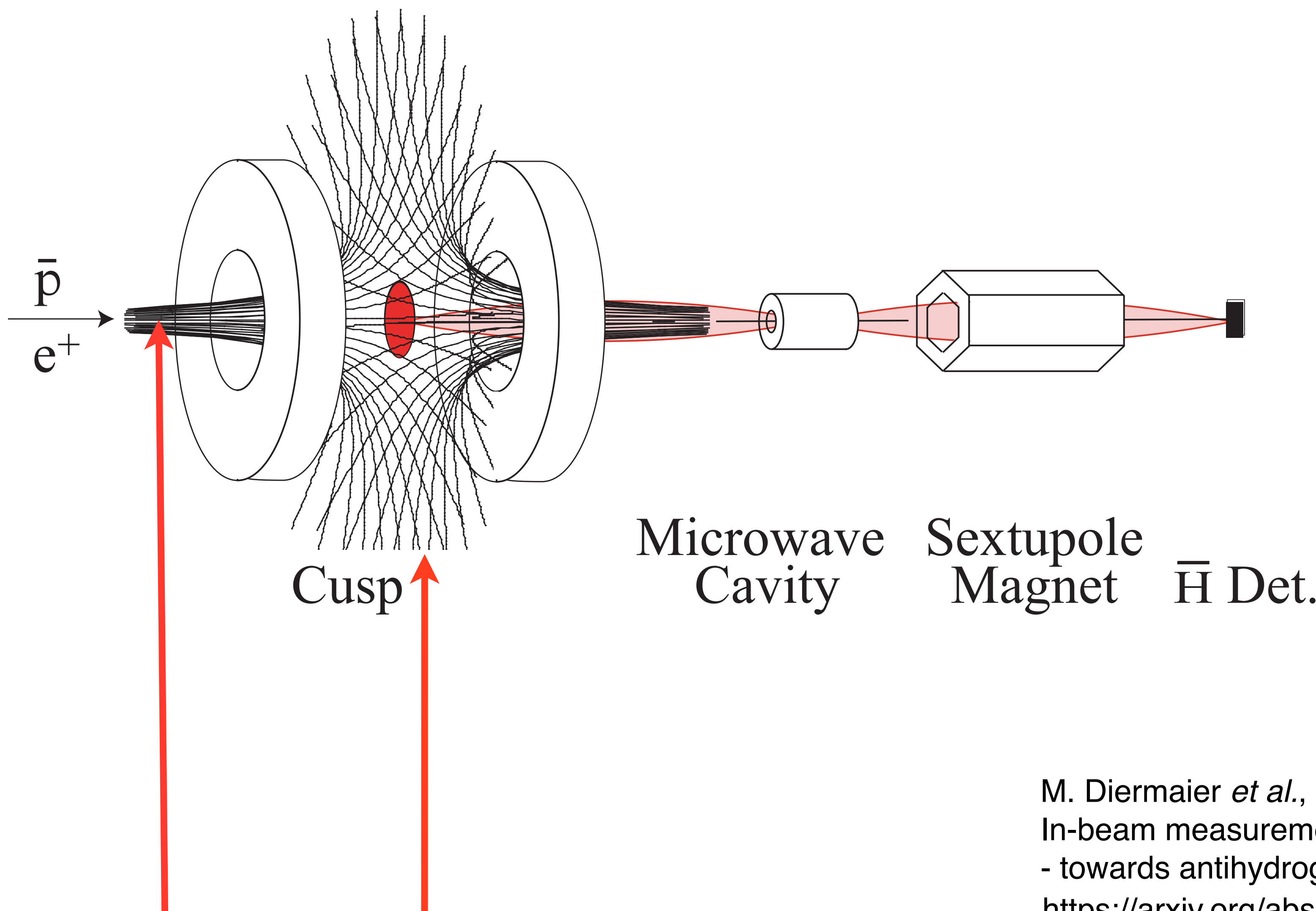


Combining with ATRAP/BASE:

$\Delta(m_{\bar{p}},m_p), \Delta(q_{\bar{p}},q_p) < 5 \times 10^{-10}$ (90% CL)

ASACUSA beam (2014)

$\bar{H}$ ground state hyperfine splitting:



TBR: Formation

Focusing of low-field seekers

N. Kuroda et al.,
Nature Communications **5**, Article number: 3089 (2014)
doi:10.1038/ncomms4089

Rate: few atoms/hour
Rydberg states ? Many still in n>29
Velocity? T~ 100K-1000K?

M. Diermaier *et al.*,
In-beam measurement of the ***hydrogen*** hyperfine splitting
- towards antihydrogen spectroscopy
https://arxiv.org/abs/1610.06392

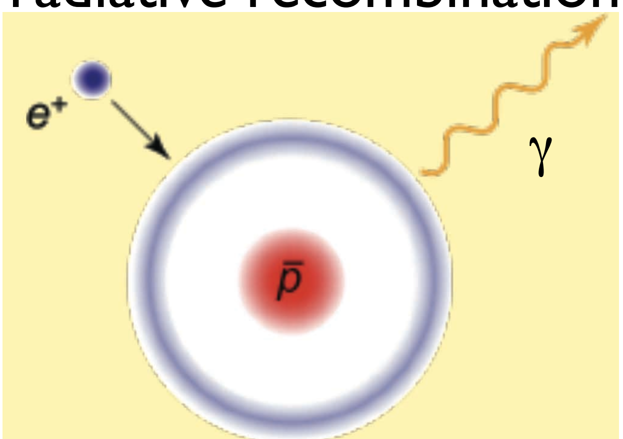
Under reasonable assumptions & measuring both transitions to extrapolate to zero field ➟ measurement to $O(10^{-9})$ appears possible (with a rate of ~ 1Hz of ground-state atoms)

Antihydrogen production processes

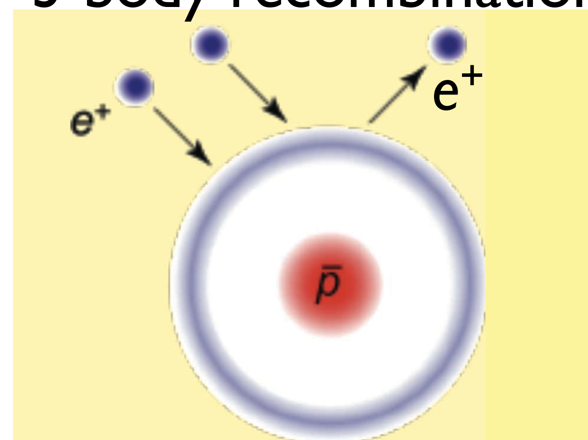
$10^5 \sim 10^7\ \bar{p}$

$10^8 \sim 10^{10}$ e+

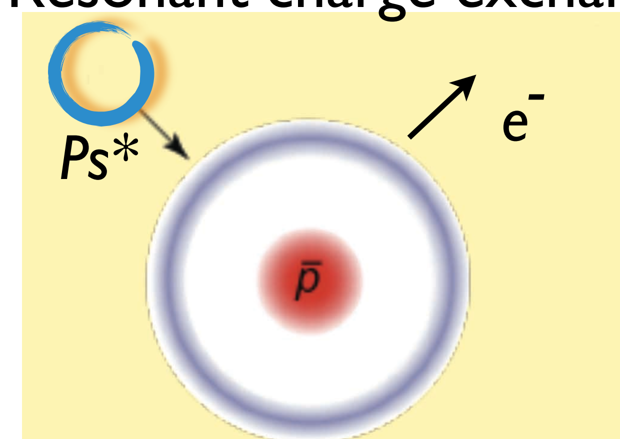
radiative recombination



TBR:
3-body recombination



RCE:
Resonant charge exchange

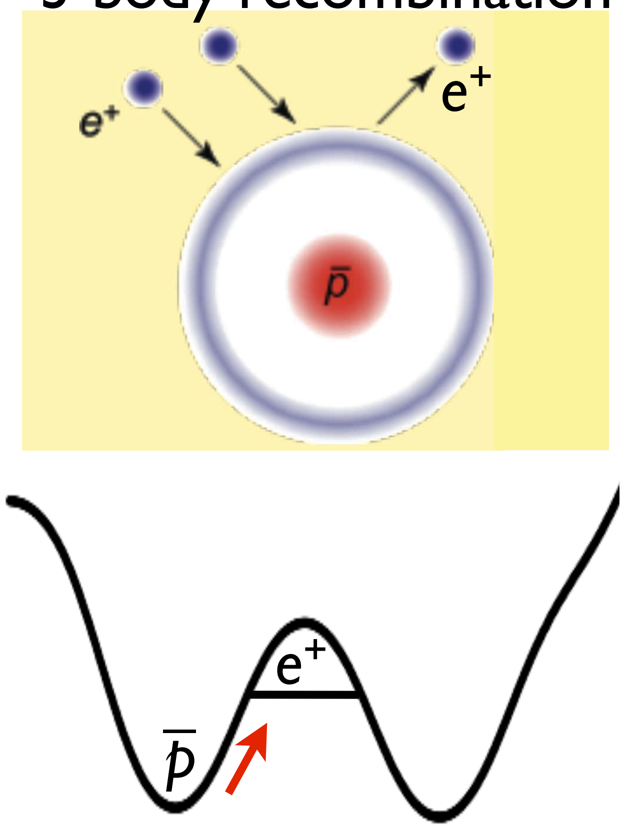


very low rate

Antihydrogen production processes

TBR:

3-body recombination



ALPHA
ATRAP
ASACUSA

Temperature
(T_{e+})

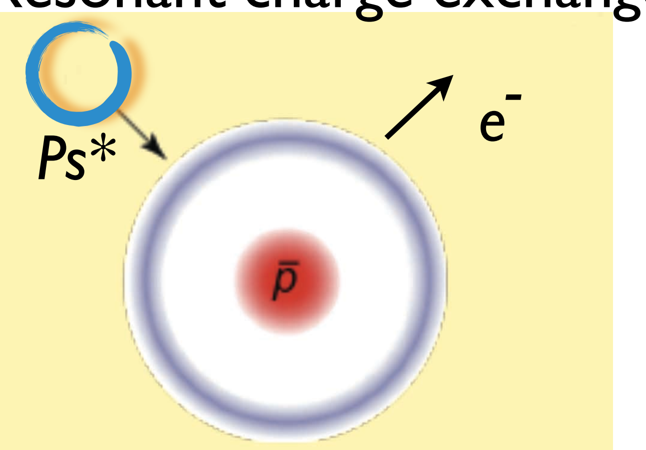
Rate ~ Rate (trappable)

n *(if trapped)*

RCE:

Resonant charge exchange

AEgIS
GBAR



Temperature
$T_{\bar{p}}$

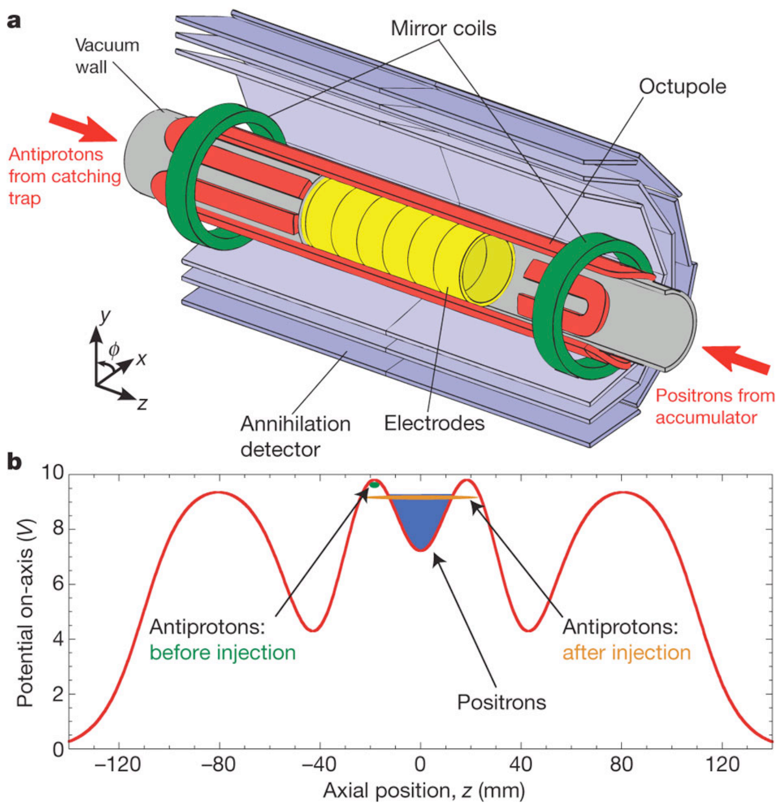
Rate ~ Rate (n_{Ps},v_{Ps})

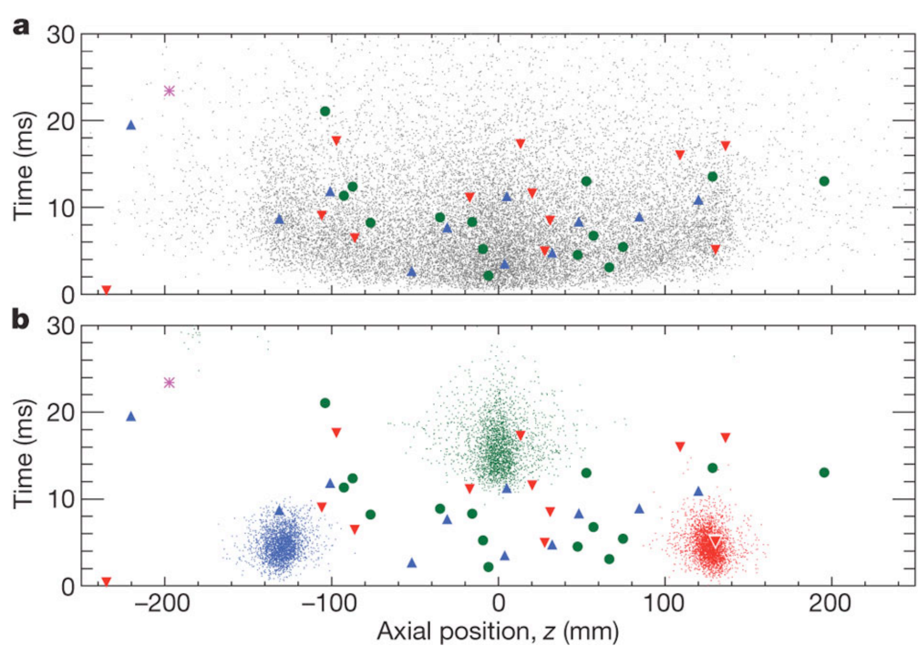
n *(if trapped or slow)*

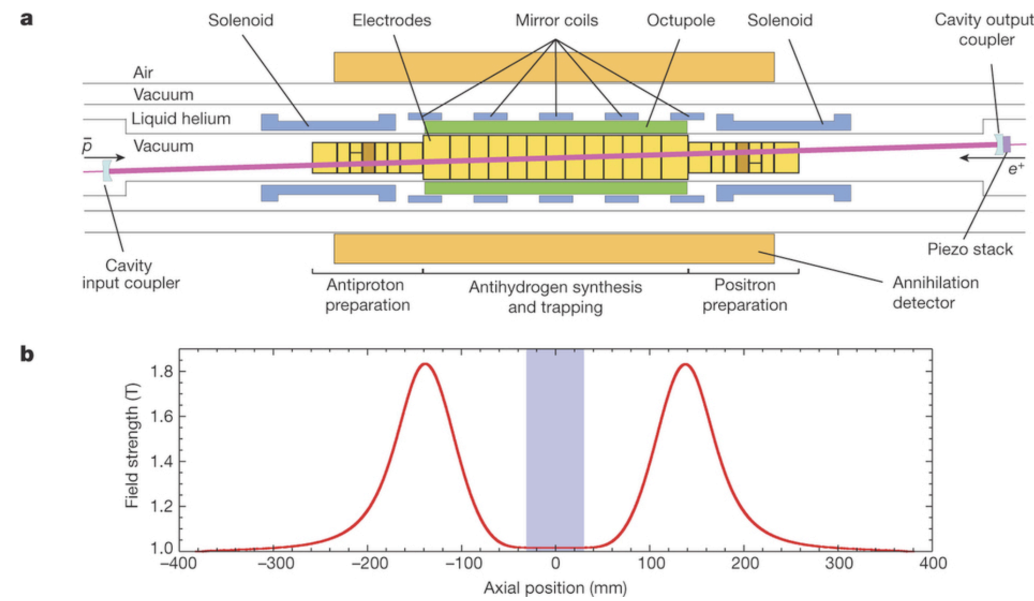
ALPHA results (trapping, 1s-2s spectroscopy)

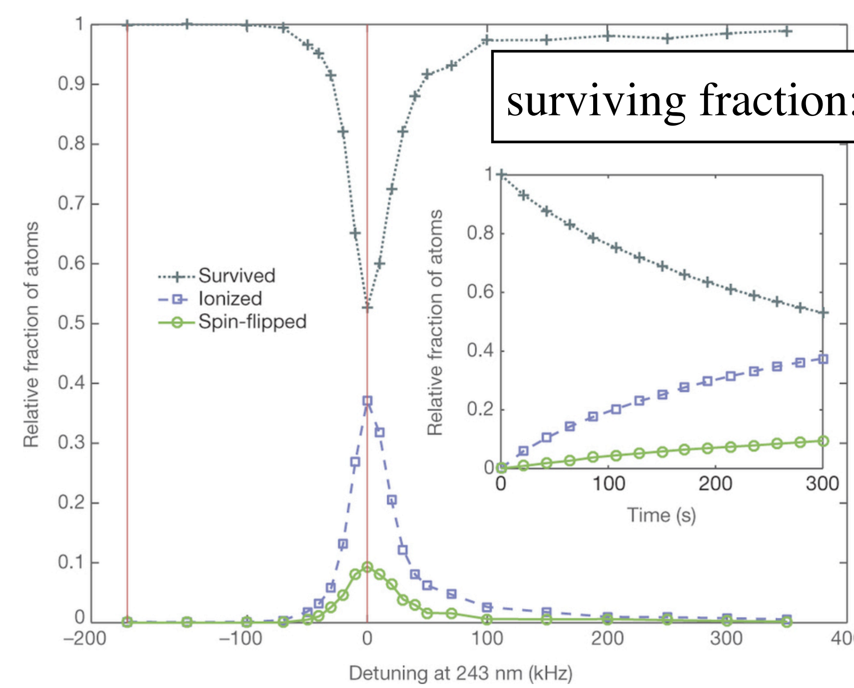
G. B. Andresen et al., Nature 468, 673–676 (02 December 2010)

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









surviving fraction: 58% ± 6%

further results:

microwave transitions in GS $\bar{H}$

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

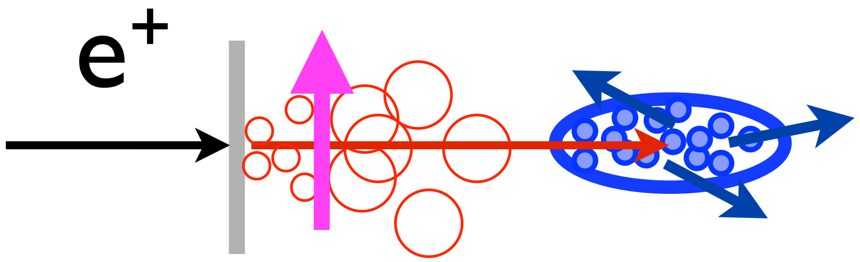
trapping of ~ 10 $\bar{H}$ simultaneously (similar for ATRAP)

alternative antihydrogen production method: RCE

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

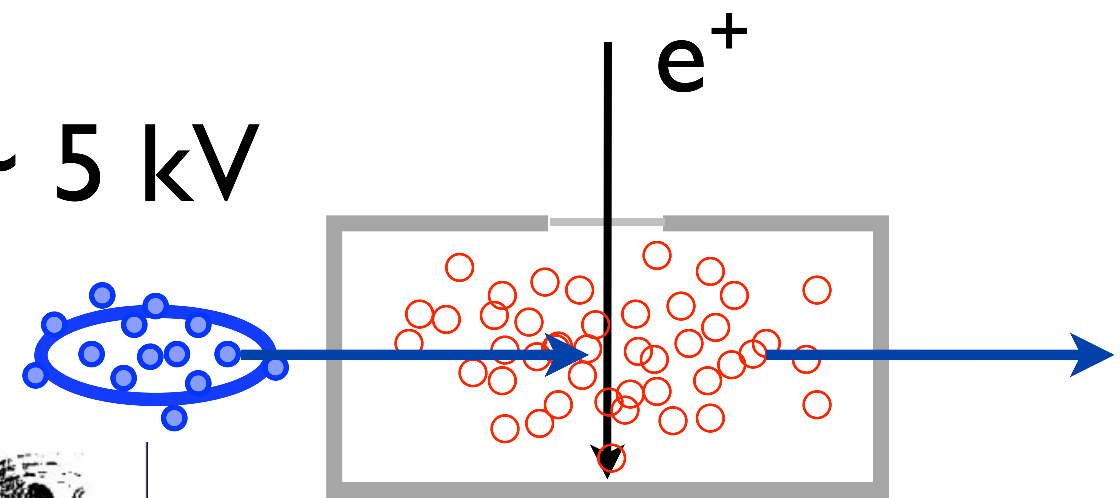
AEḡIS

$T_{Ps} \sim 100$ K

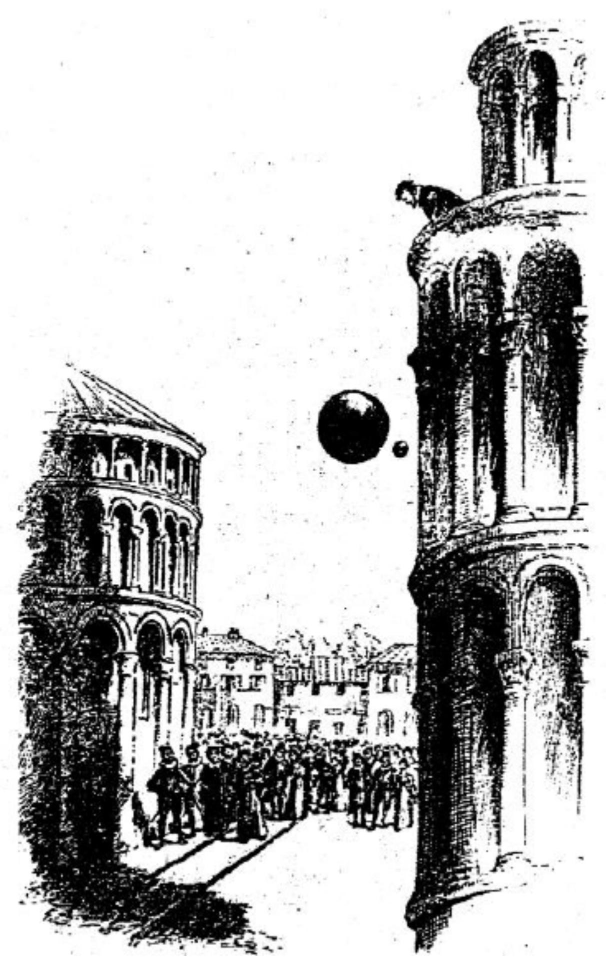


GBAR

$E_p \sim 5$ kV



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



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

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

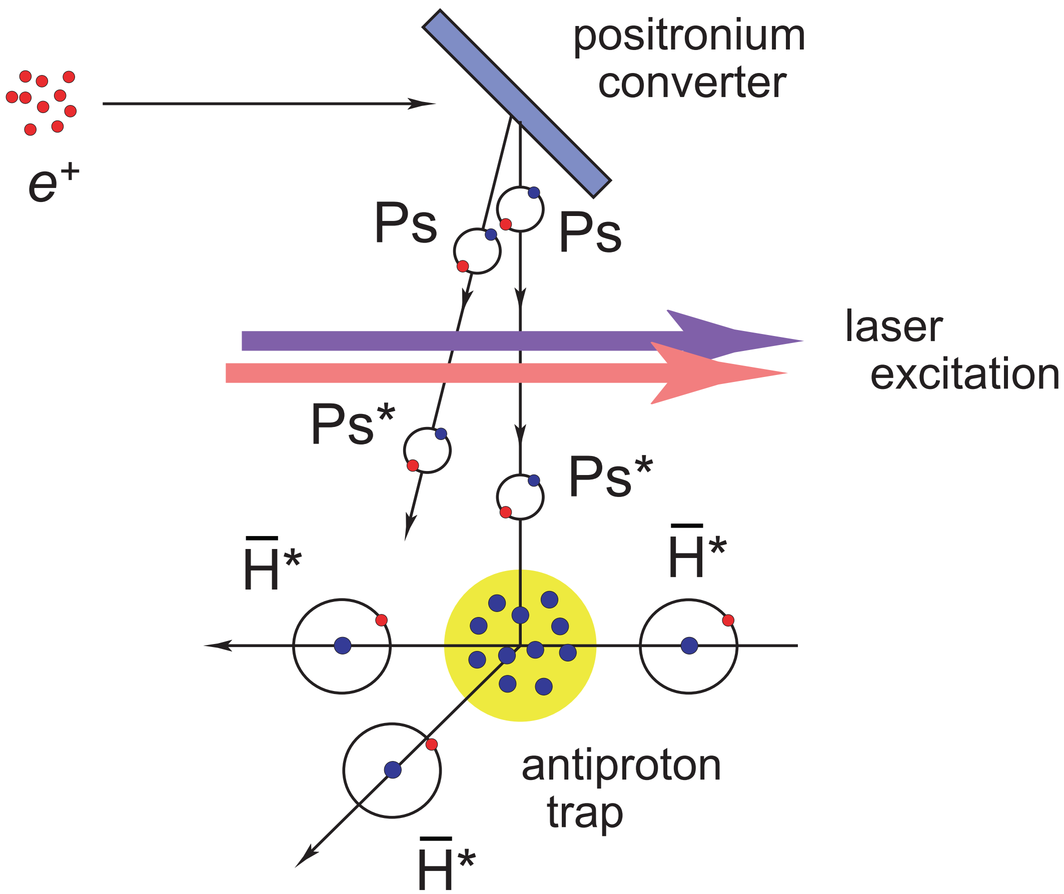
cold $\bar{H}^*$

hot $\bar{H}^+$

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

production: charge exchange
beam formation: Stark acceleration
measurement: deflectometer

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



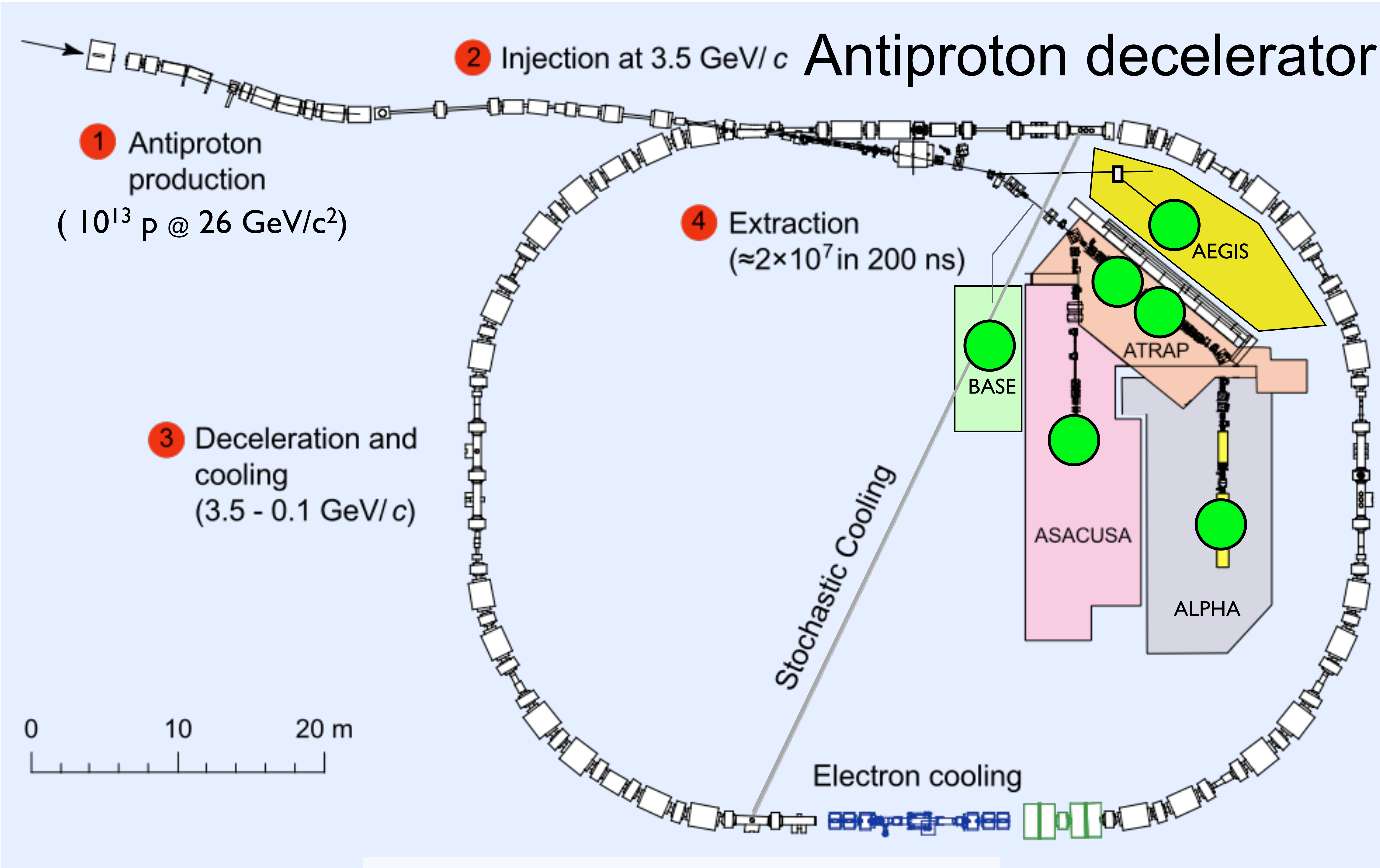
$$\sigma \approx a_0 n^4$$

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

time-of-flight: pulsed production

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

Two main challenges: more / colder antiprotons

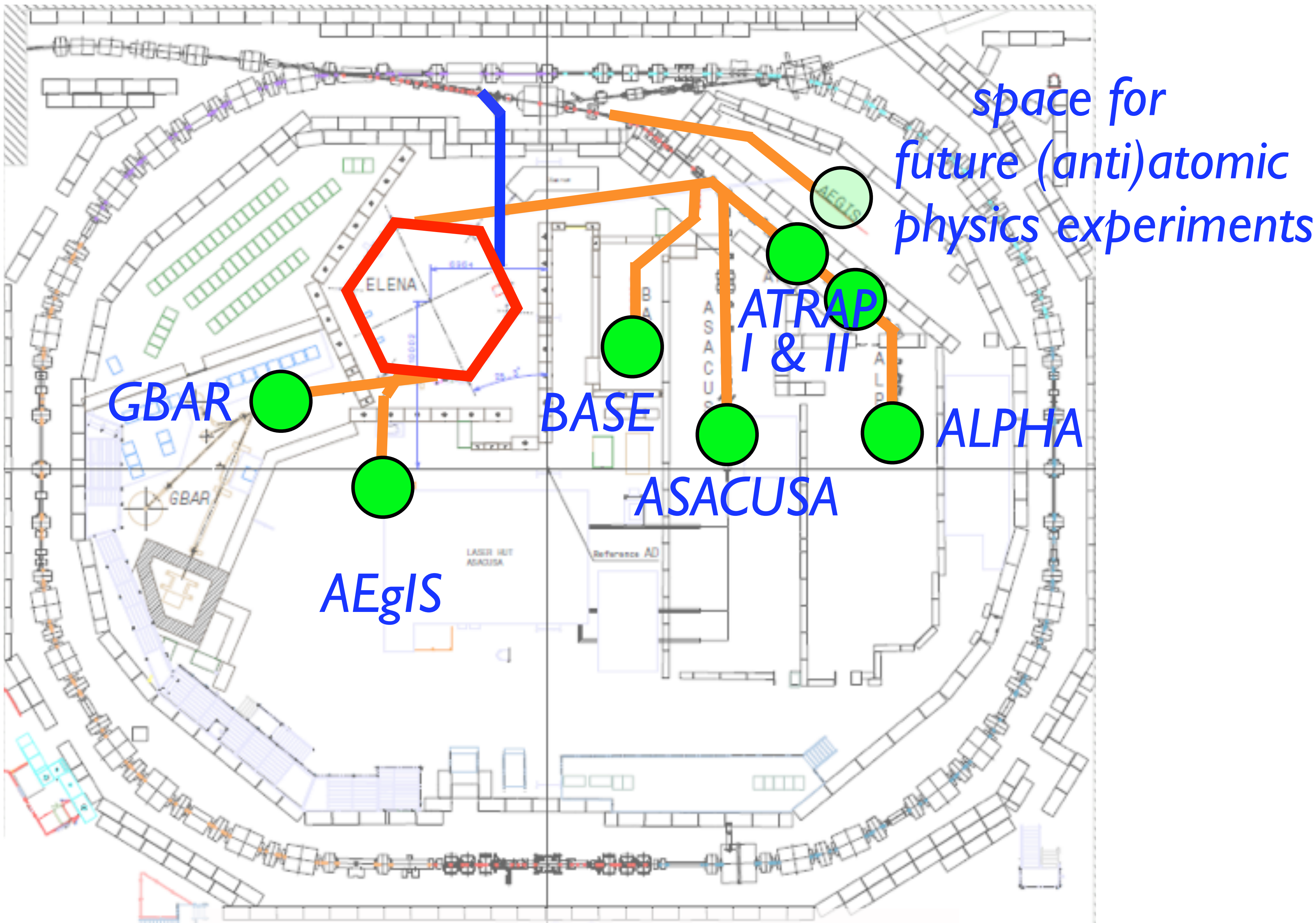


extraction at 5.3 MeV

Two main challenges: more / colder antiprotons

current methods for trapping them are quite inefficient

ELENA to the rescue

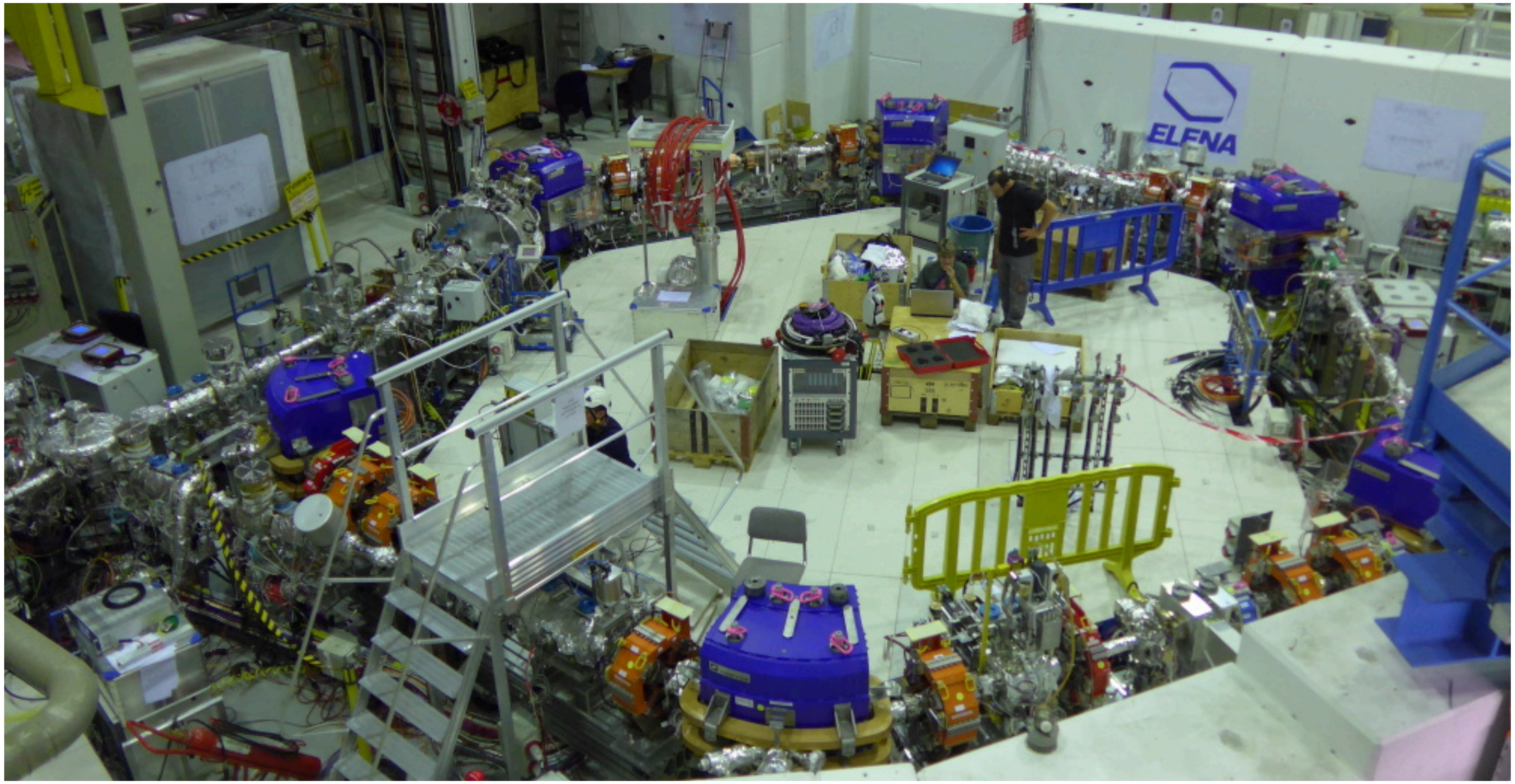


extraction at 100 keV

ELENA is a tiny new decelerator that:

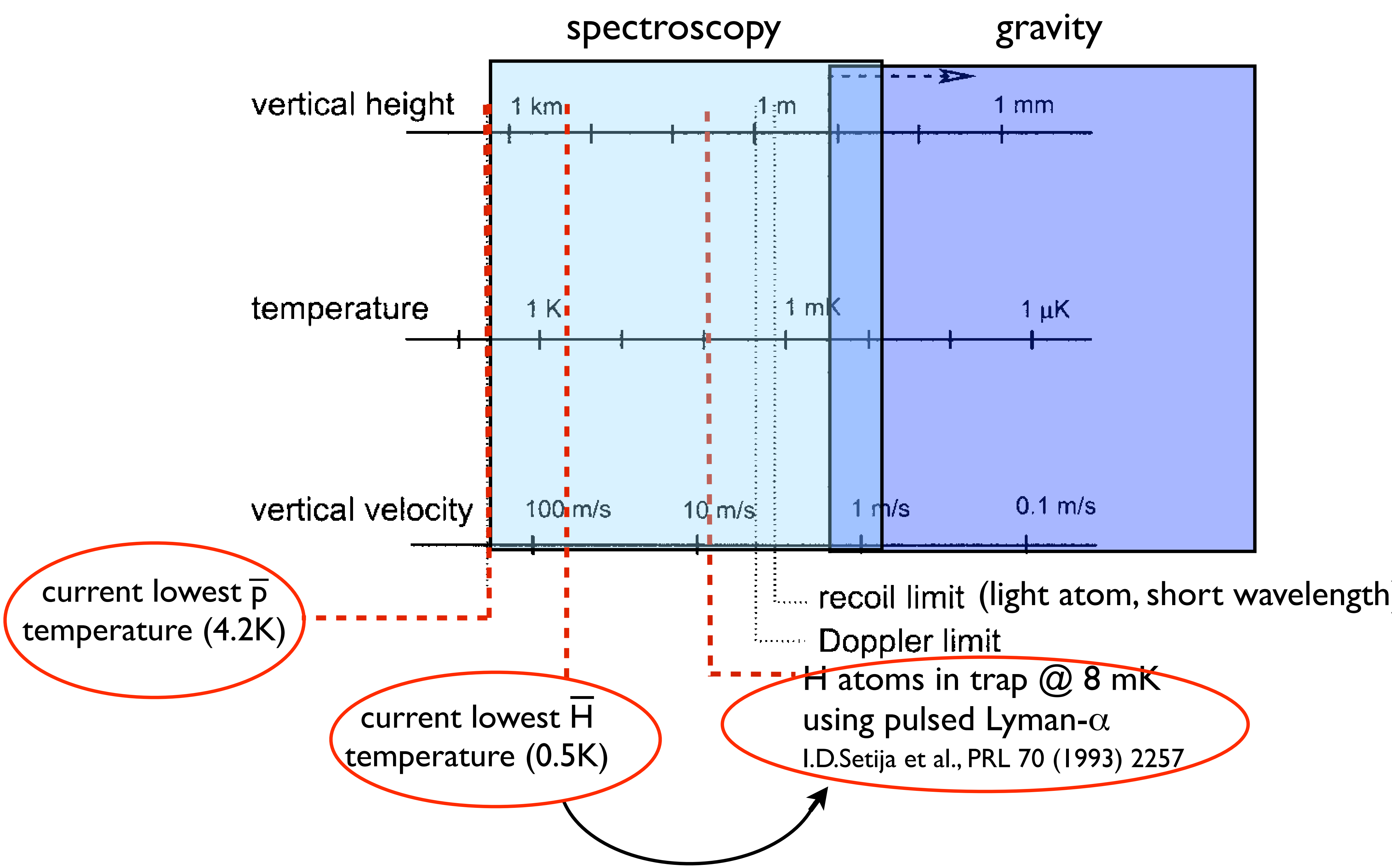
- dramatically slows down the antiprotons from the AD
- increases the *antiproton* trapping efficiency x 100
- allows 4 experiments to run in parallel
- allows new experiments to come in

commissioning started in Nov. 2017



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

2016

Temperature of produced $\bar{H}$

(critical for trapping, gravity measurements)

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?

Outlook: 10‘s ~ 100’s of trapped $\bar{H}$ (through stacking)

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

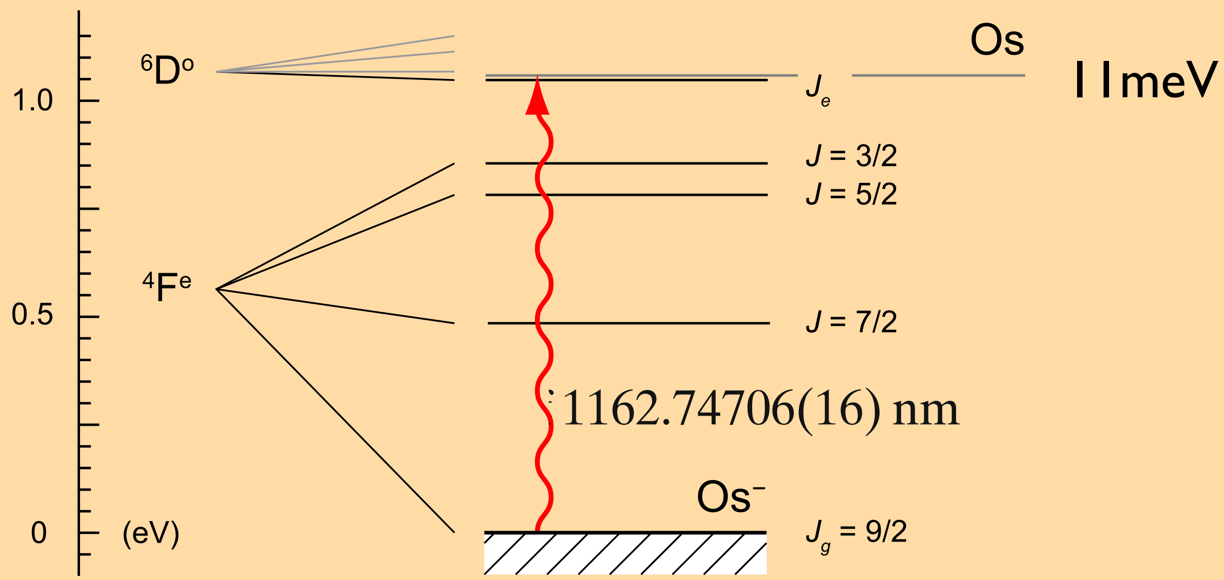
photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"

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

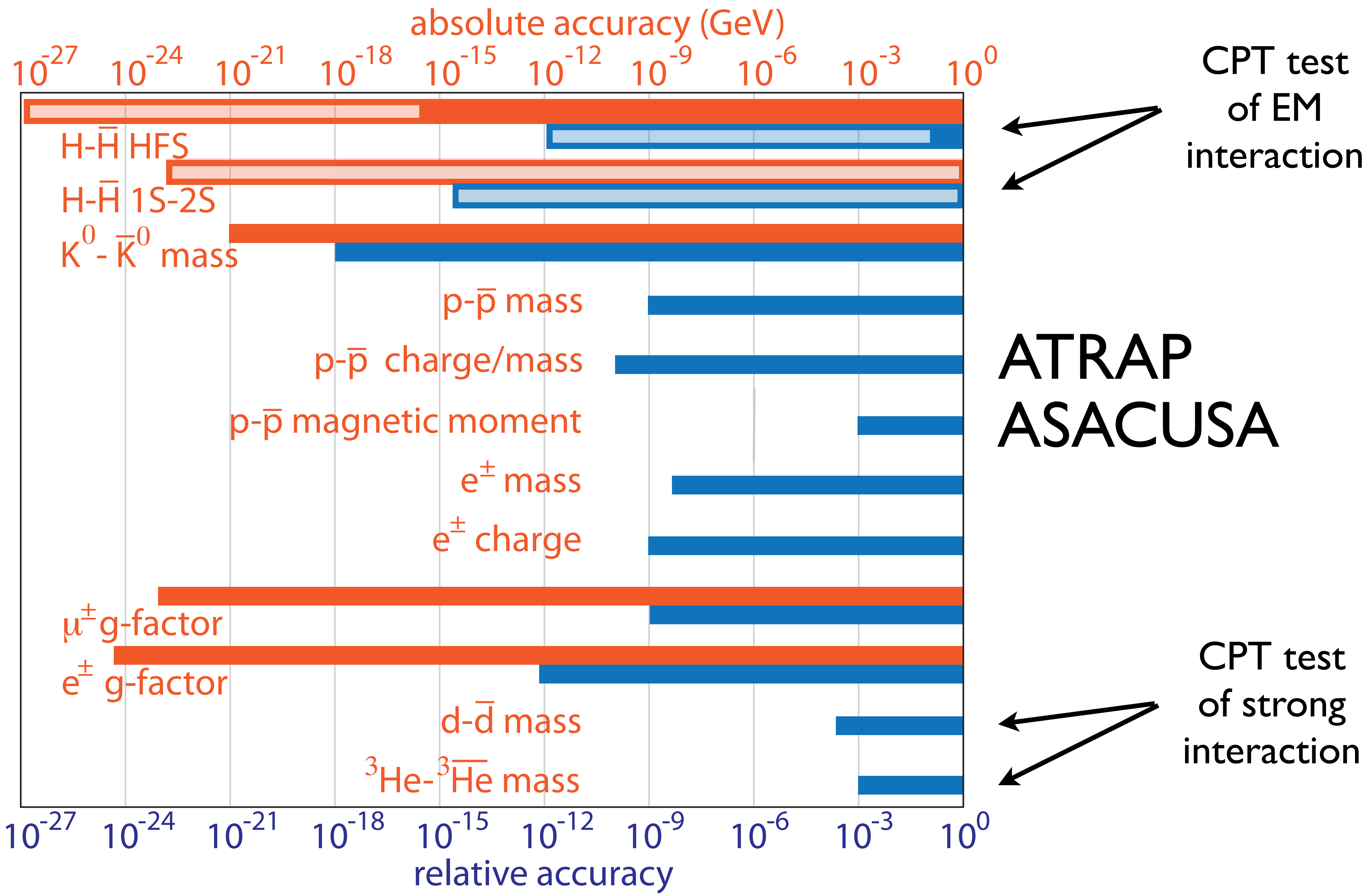


very weak cooling

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

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

2013

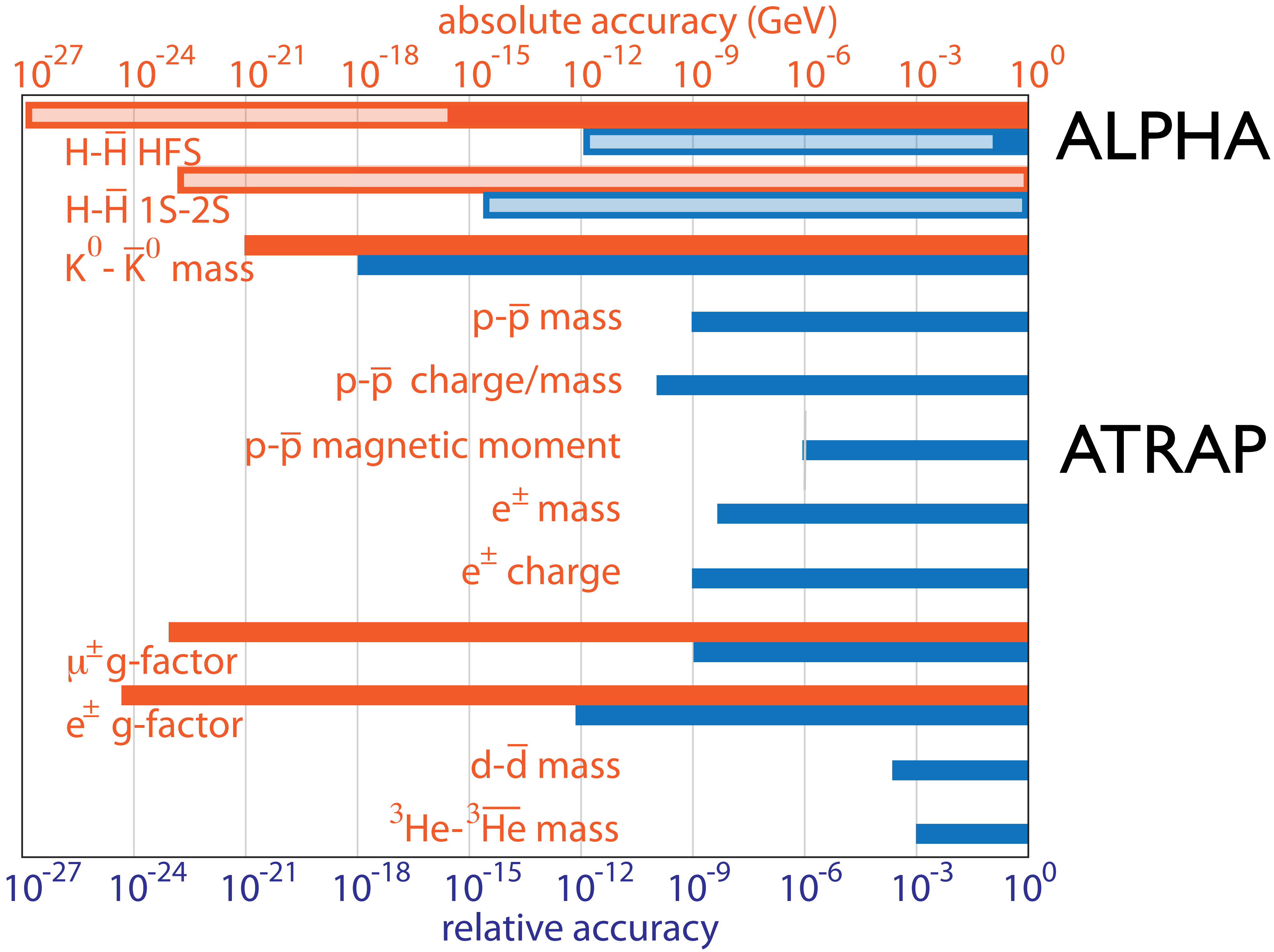


Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky)

2015



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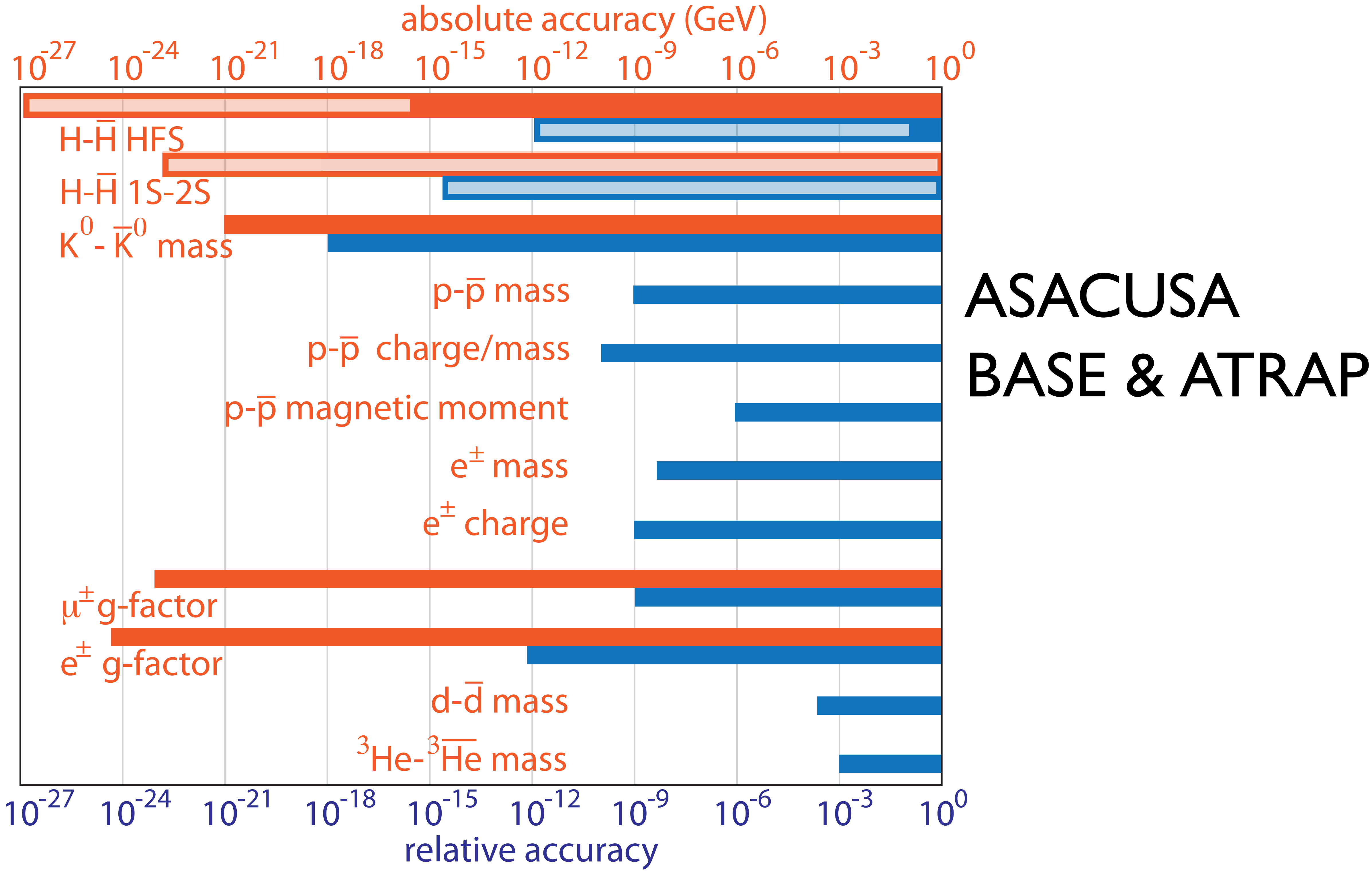

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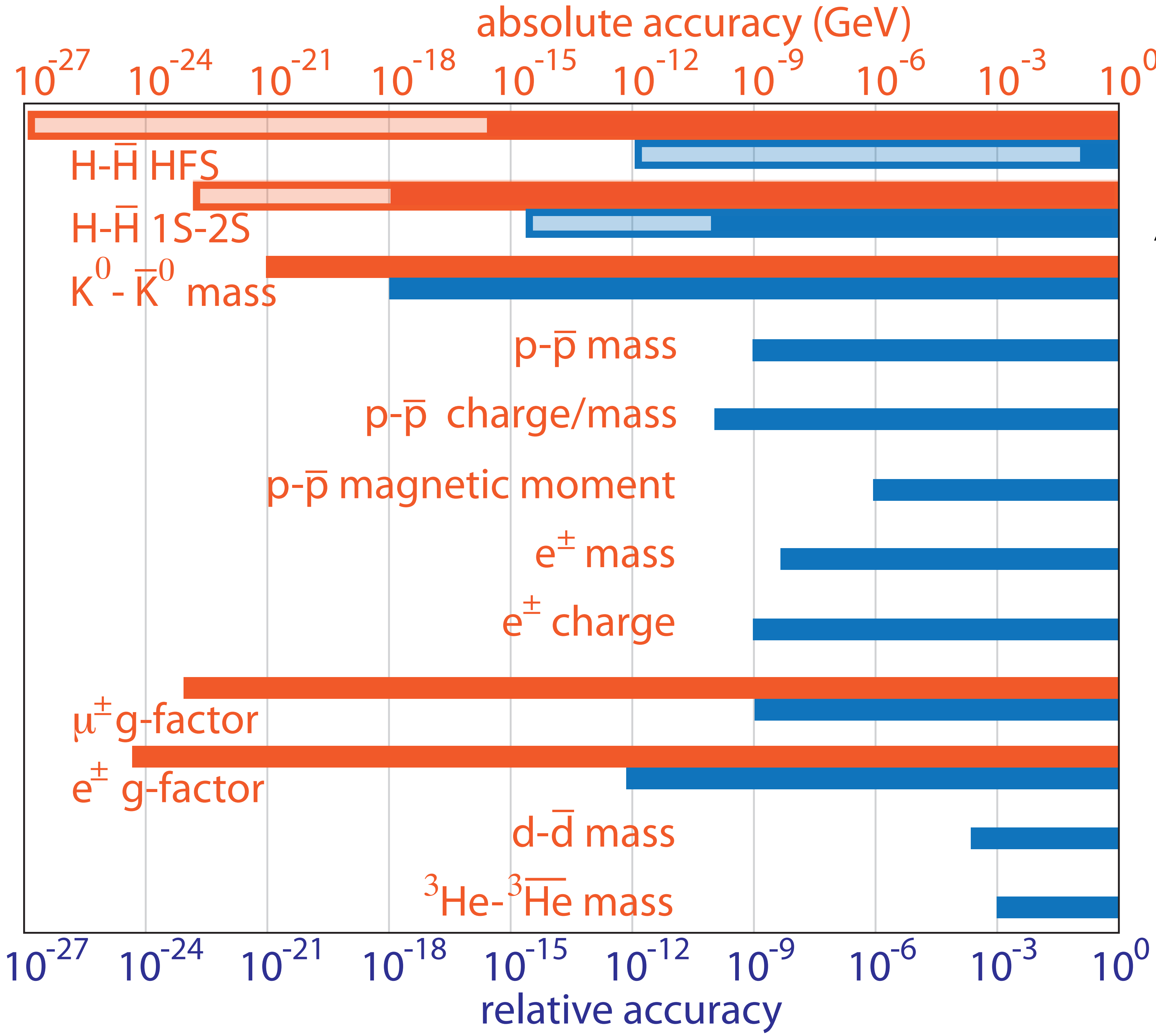
2017



ALPHA

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)

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

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

Ps, muonium: gravity (lepton sensitivity)

$\mu\bar{p}$: gravity (2nd 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

$\bar{p}N$: trapped $\bar{p}$ + radioisotopes = PUMA to summarize the situation...

Trapping of antihydrogen:

ATRAP and ALPHA: large progress in last years
main challenge now: enough cold enough constituents
small numbers of antihydrogen atoms in the ground state trapped in 2010
first measurement of 1s-2s to 10^{-10} in 2016
assuming 1 mK: 1s-2s spectroscopy to ~ 10^{-12} (perhaps in a "few" years)

Beams of antihydrogen:

ASACUSA: continuous beam (ground state atoms!) and $\bar{p}He^+$
AEGIS: working towards pulsed sub-K beam
main challenge now: formation mechanisms and rates, cold enough $\bar{p}$
low precision gravity measurement and in-flight spectroscopy of
HFS to 200 Hz (10^{-6})

Trapped antiprotons:

BASE: conceivable reach: $(q/m)_{\bar{p}}/(q/m)_p$ to 10^{-12} , $\mu_{\bar{p}}/\mu_p$ to 10^{-9}

From 2017, new low energy $\bar{p}$ accelerator ELENA: new experiments, experimental opportunities for many years