Antimatter spectroscopy
&
the gravitational interaction between matter and antimatter (and quite some tests of CPT)

Michael Doser
CERN

What measurements are we talking about?

1) Measurement of the gravitational behavior of antimatter

tests of the Weak Equivalence Principle

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

tests of fundamental symmetry (CPT)

3) related measurements in antihydrogen(-like) systems

antiprotonic helium, positronium, protonium, ...

Gravity...

- 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 (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

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

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

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

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)

CPT & Lorentz violation

Modified Dirac eq. in SME

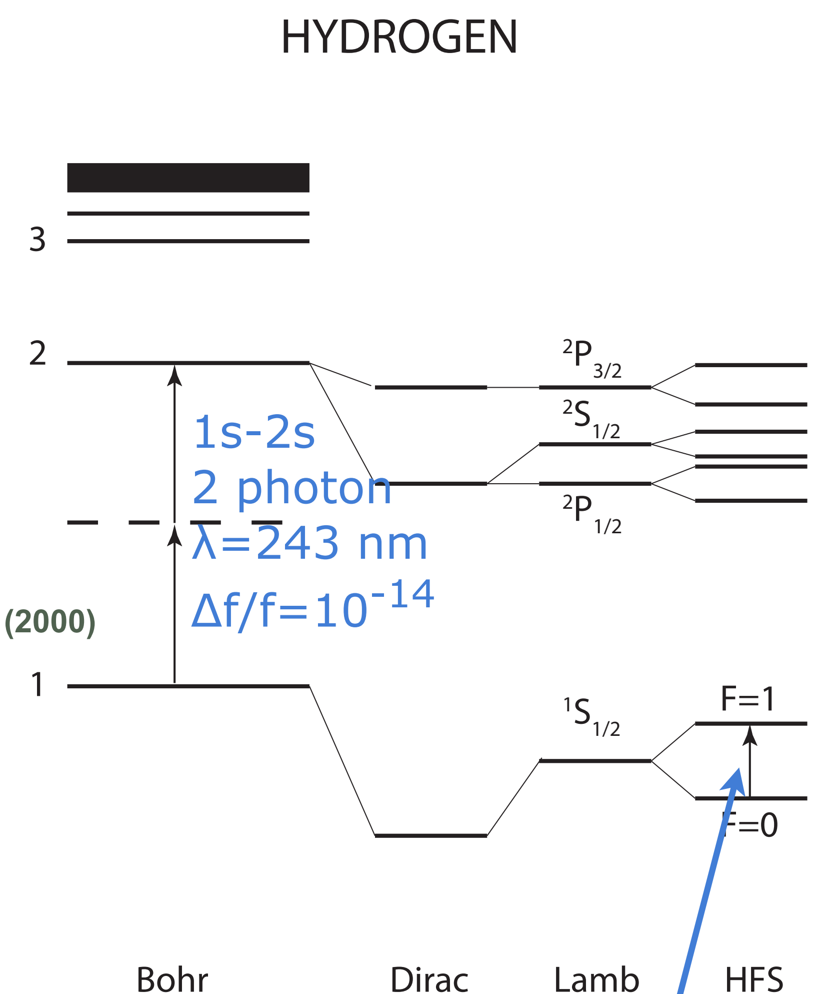
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu - \tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0\,.$$

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

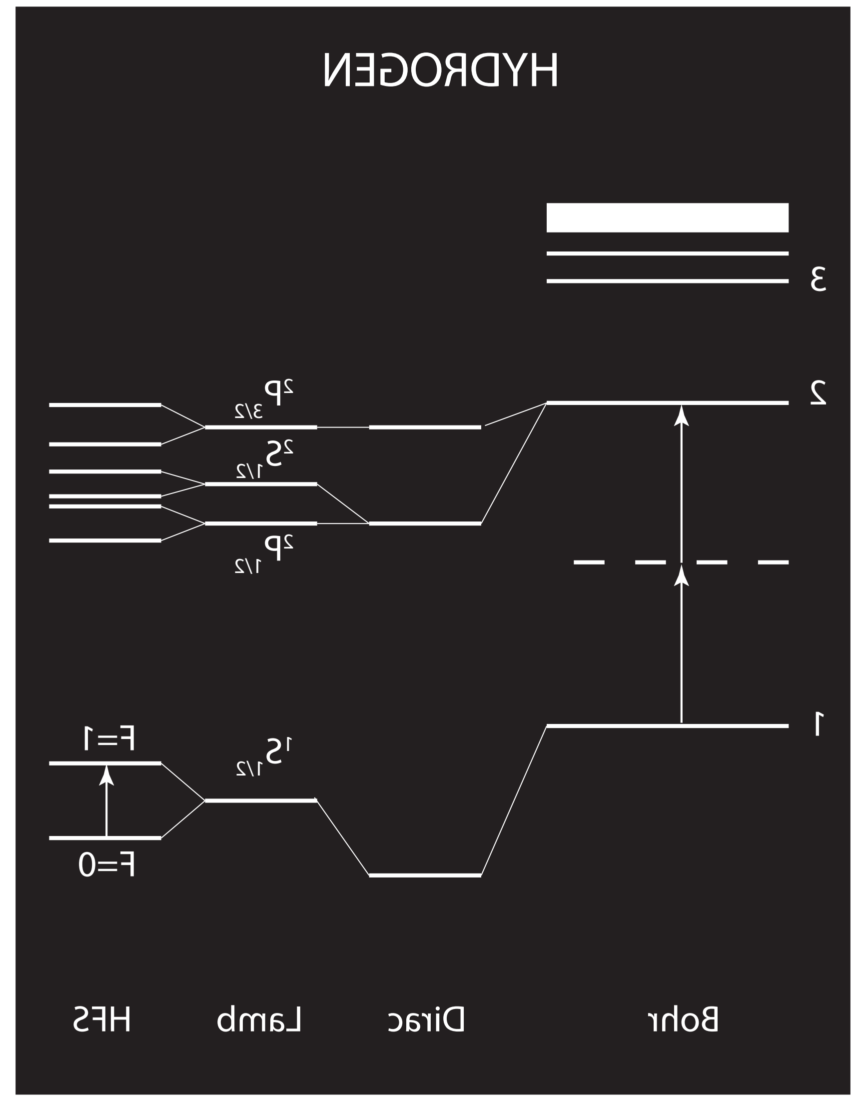
Goal of comparative spectroscopy: test CPT symmetry

Hydrogen and Antihydrogen



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

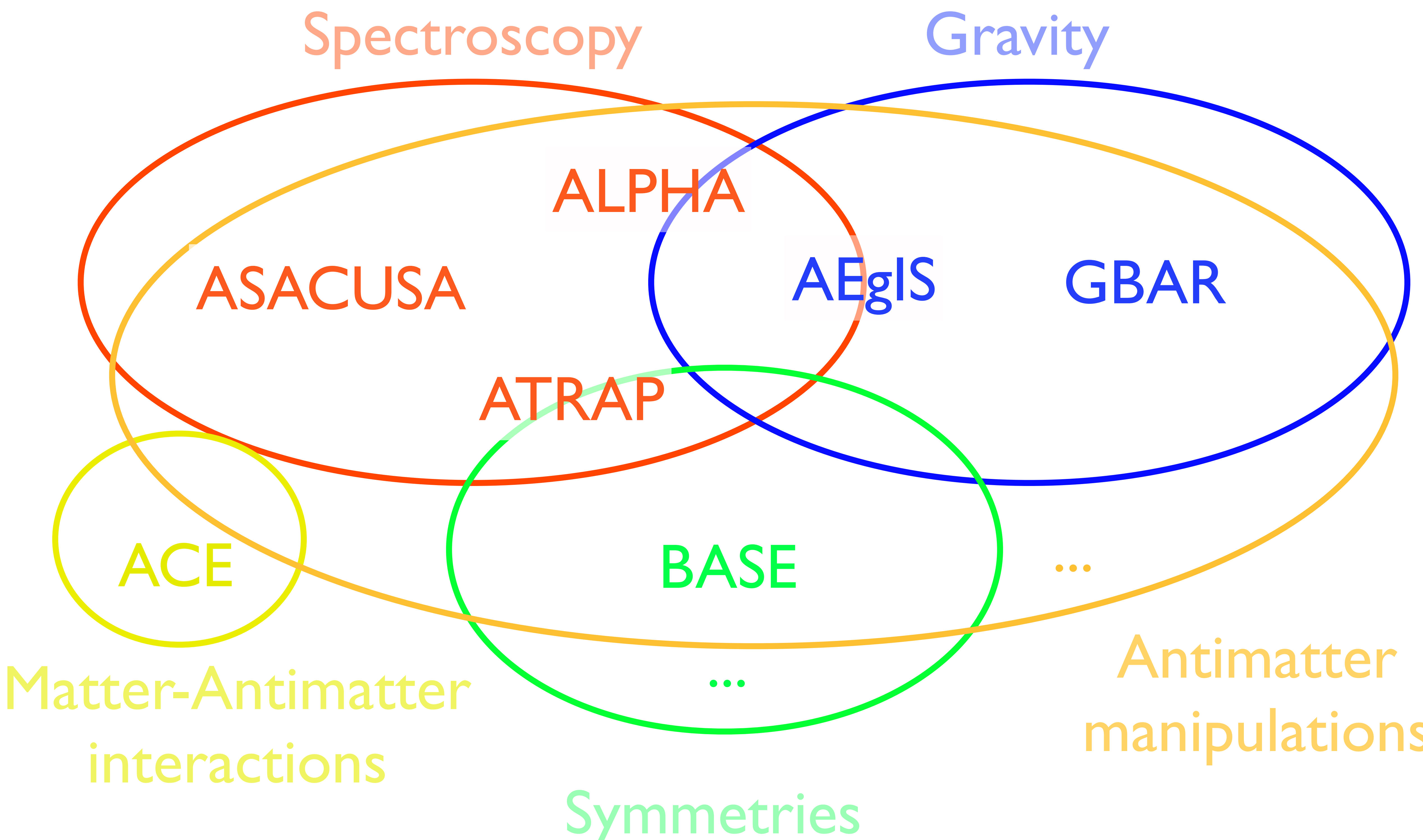
T. Hänsch et al.,
Phys. Rev. Lett. 84, 5496–5499 (2000)



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

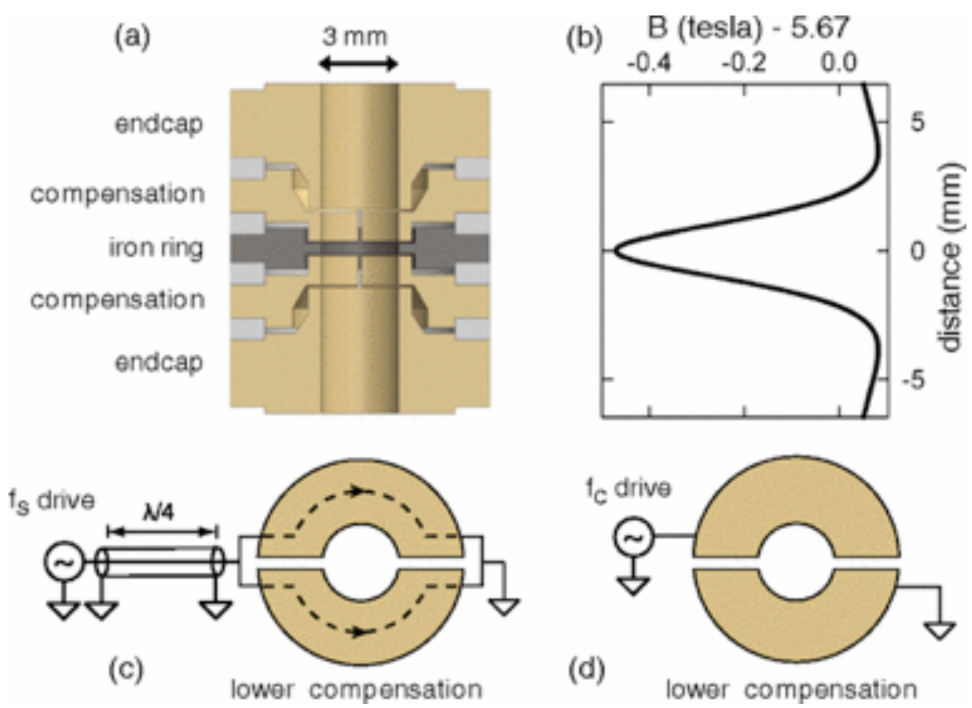
N. F. Ramsey,
Physica Scripta T59, 323 (1995)

Experiments at the AD
(antiprotons and antihydrogen)

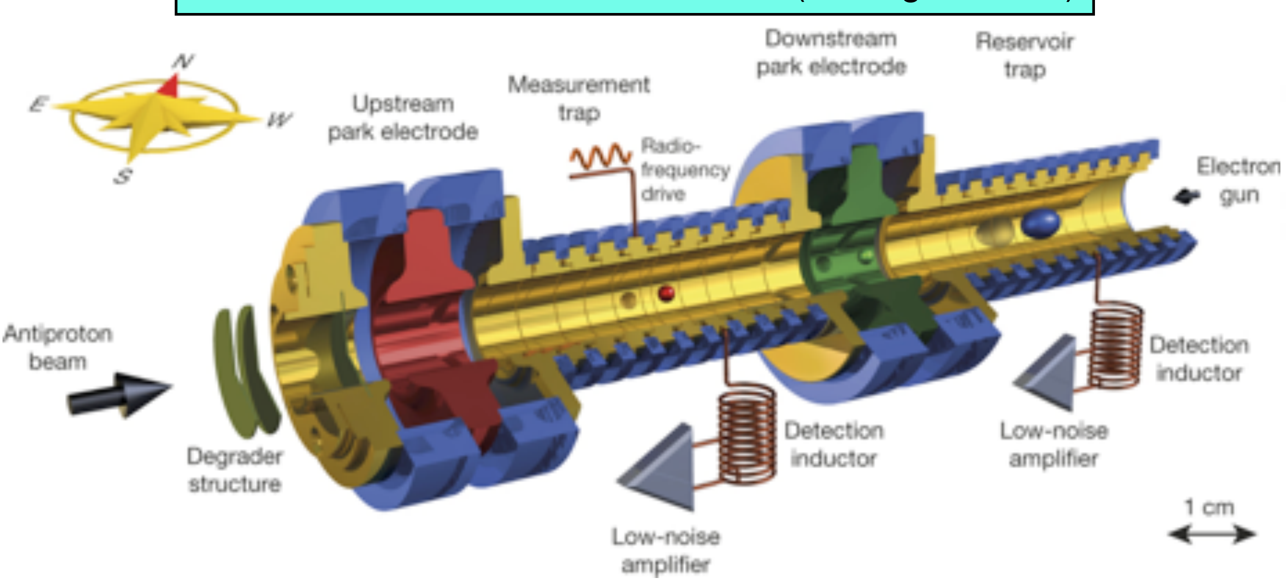


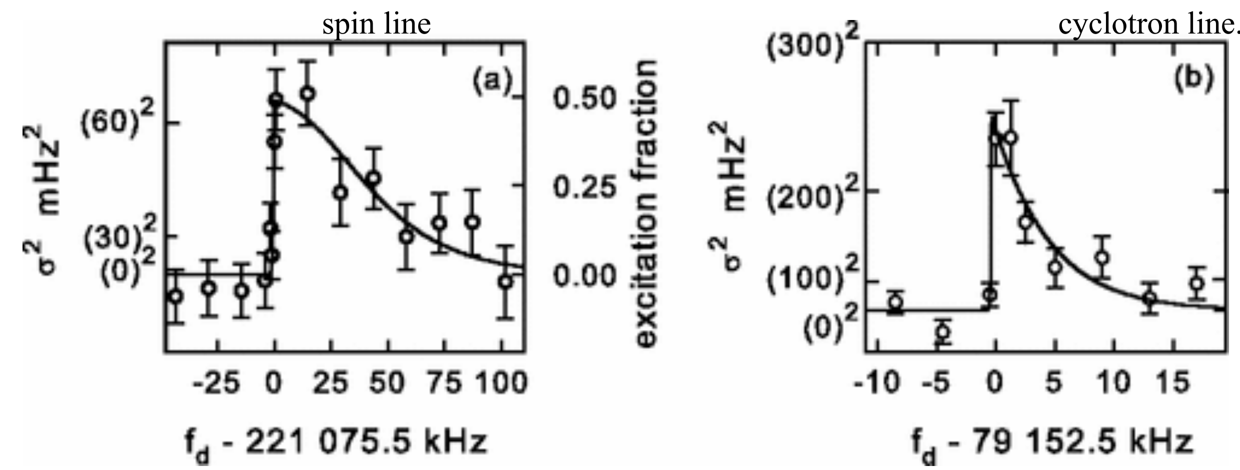
ATRAP & BASE

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)

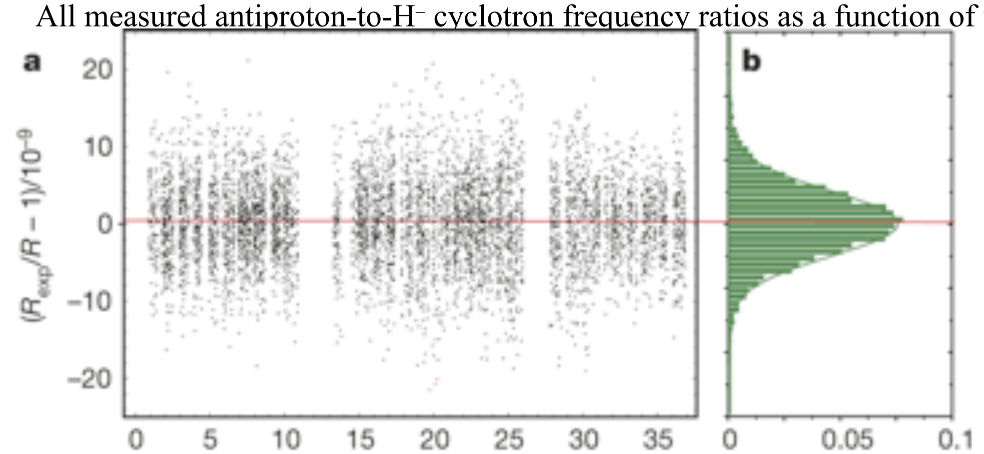




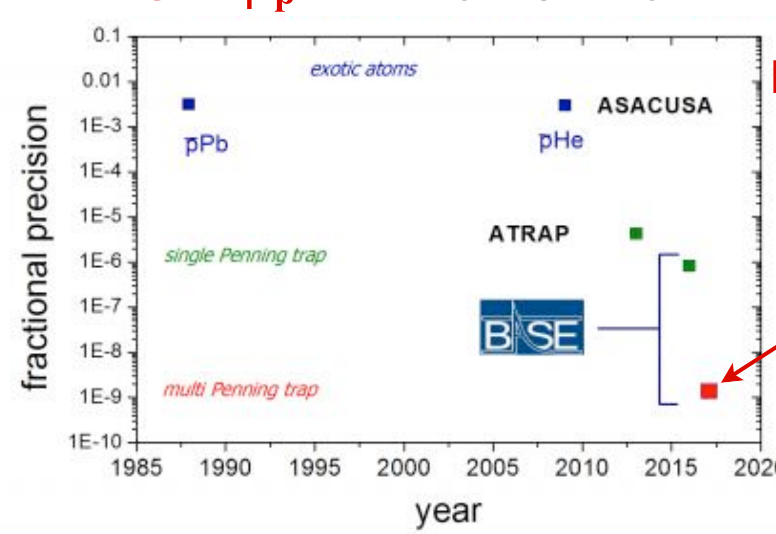
ATRAP: $\mu_p/\mu_{\bar{p}}$ = −1.000000±0.000005 (2013)

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



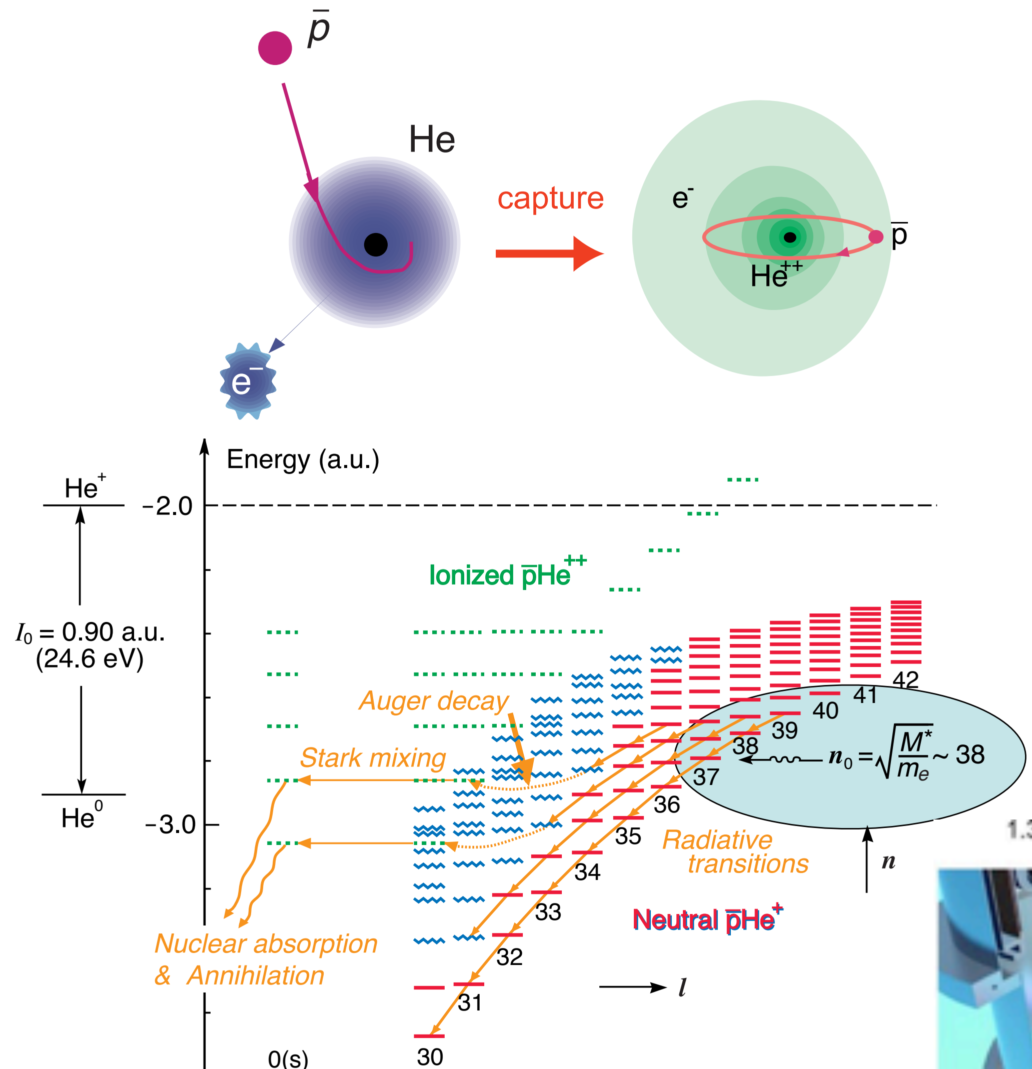
BASE: $\mu_{\bar{p}}$ = -2.792 847 344 1 (42) (2017)



μ_p = 2.792 847 350 0 (90)

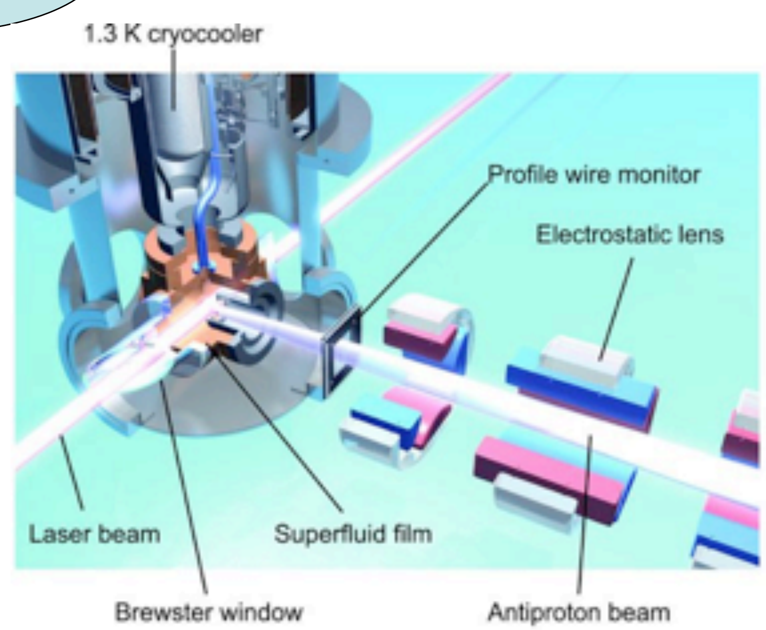
C. Smorra et al., BASE collaboration, Nature **550**, 371–374 (19 October 2017)

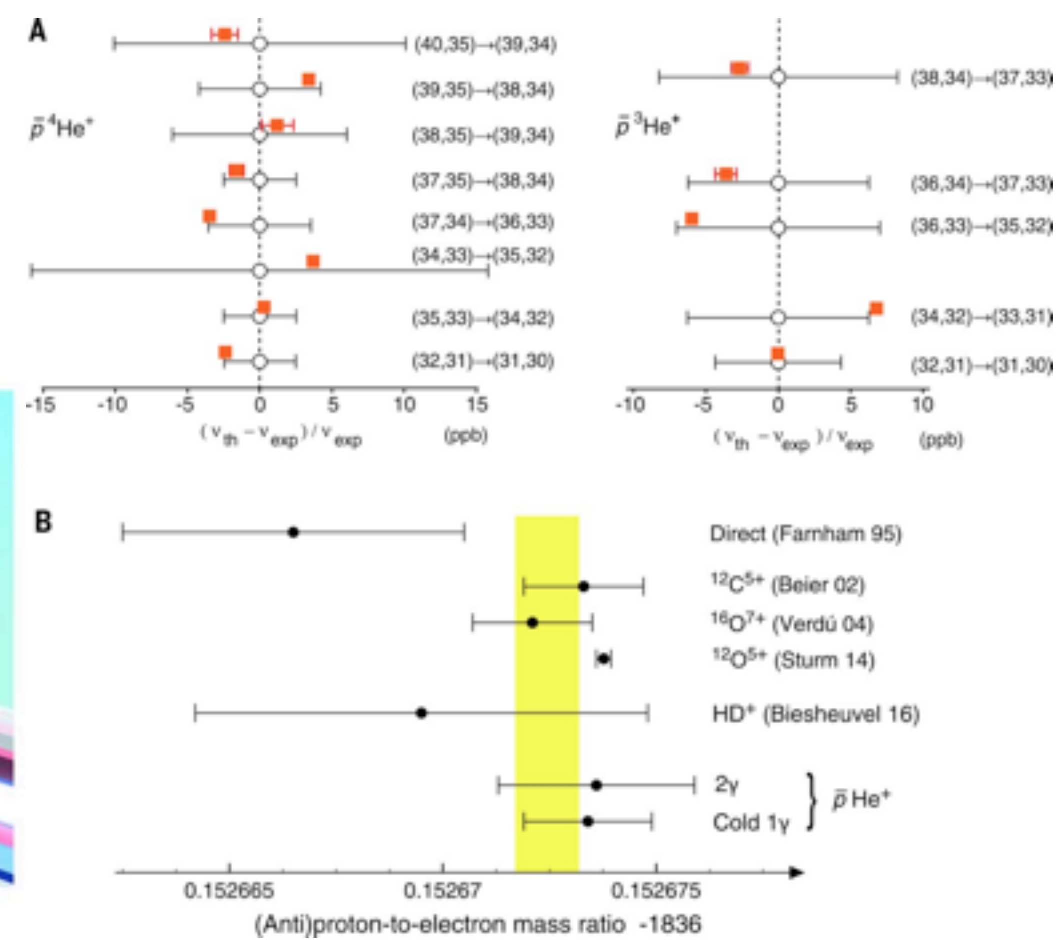
ASACUSA results ($\bar{p}He^+$ spectroscopy)



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:

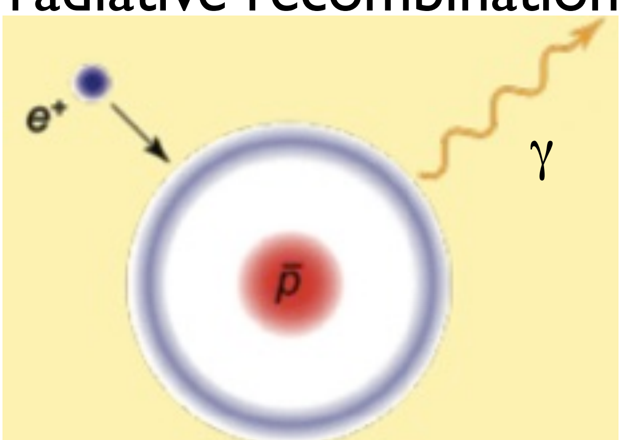
$\Delta(m_{\bar{p}},m_p), \Delta(q_{\bar{p}},q_p)$ $< 5 \times 10^{-10}$ (90% CL)

Antihydrogen production processes

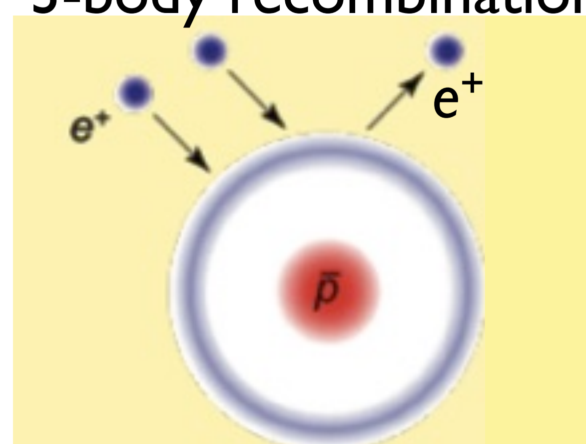
$10^5 \sim 10^7\ \bar{p}$

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

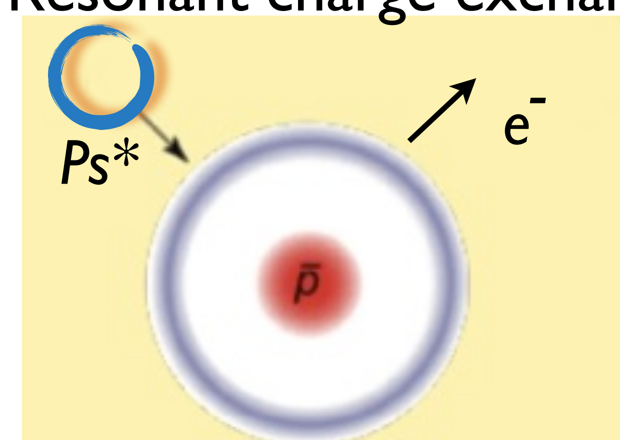
radiative recombination



TBR:
3-body recombination



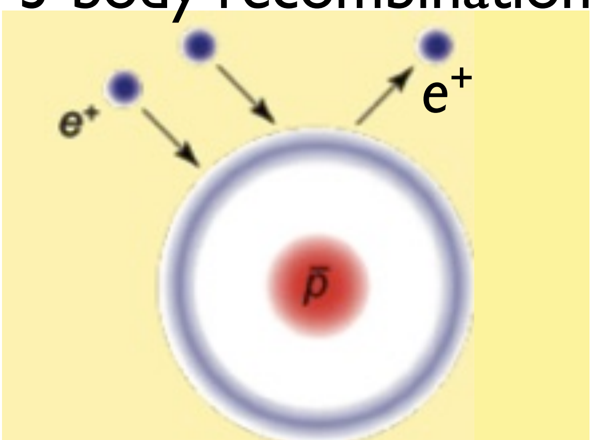
RCE:
Resonant charge exchange

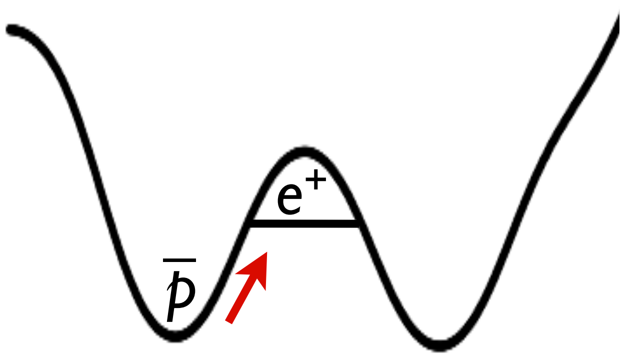


very low rate

Antihydrogen production processes

TBR:
3-body recombination





ALPHA
ATRAP
ASACUSA

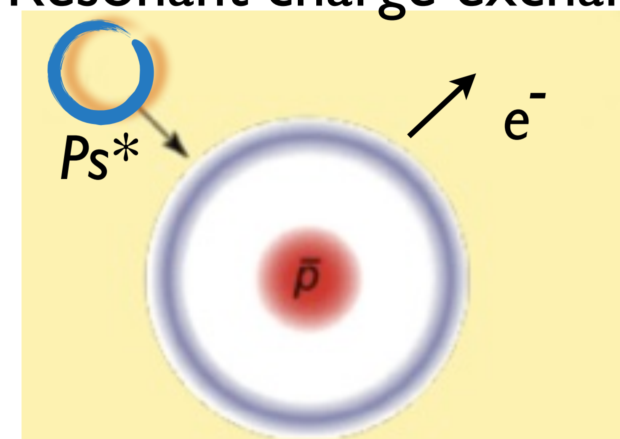
Temperature
(T_{e+})

Rate ~ Rate (trappable)

n *(if trapped)*

RCE:
Resonant charge exchange

AEgIS
GBAR



Temperature
$T_{\bar{p}}$

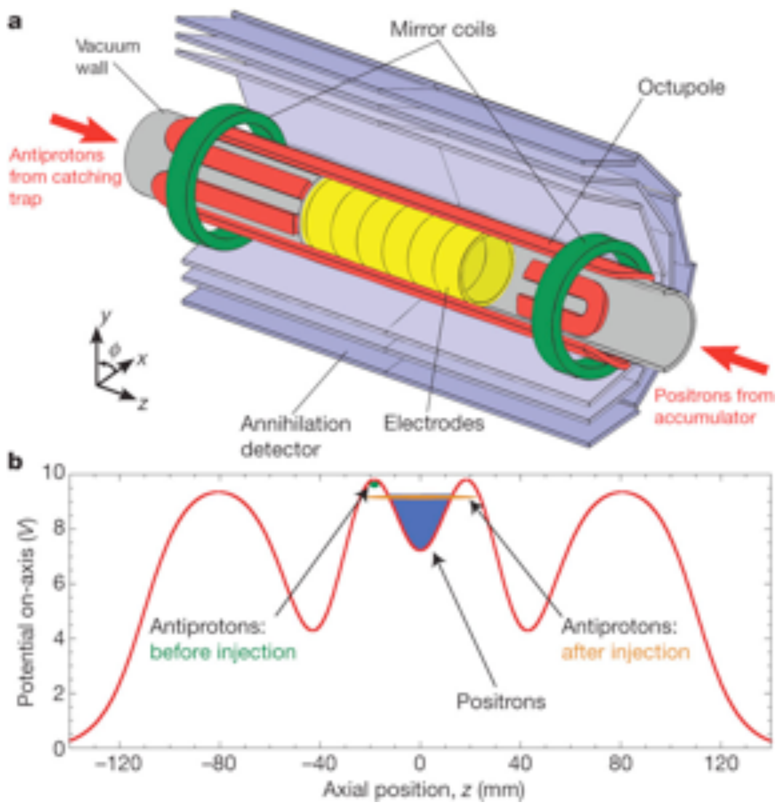
Rate ~ Rate (n_{Ps},v_{Ps})

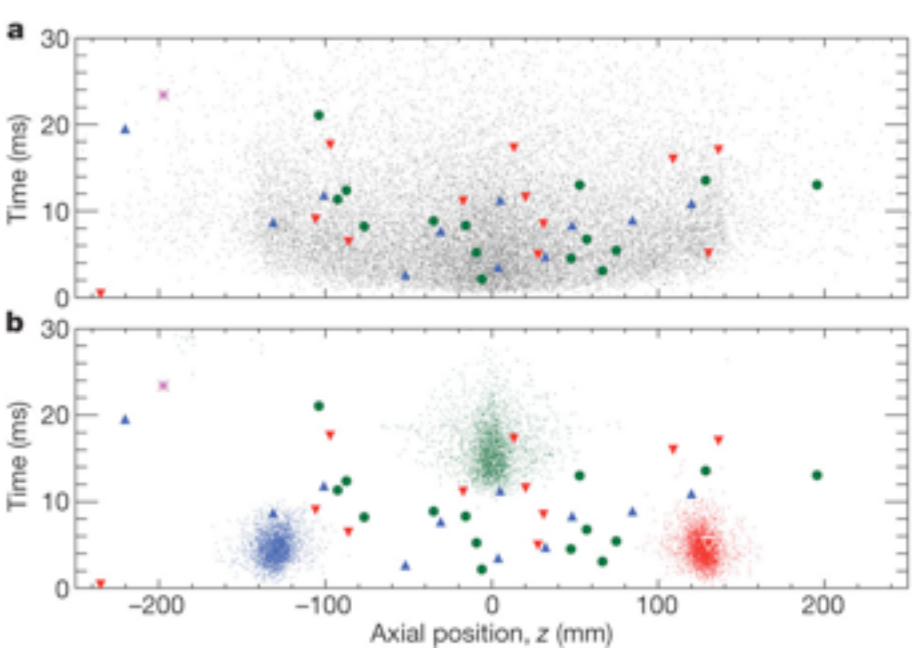
n *(if trapped or slow)*

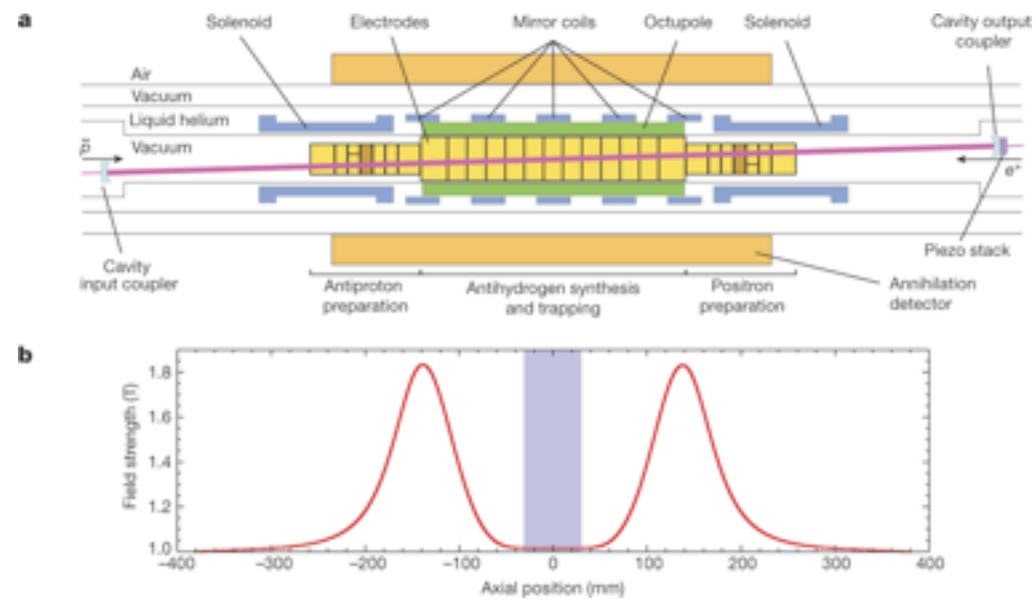
ALPHA results (trapping, 1s-2s spectroscopy)

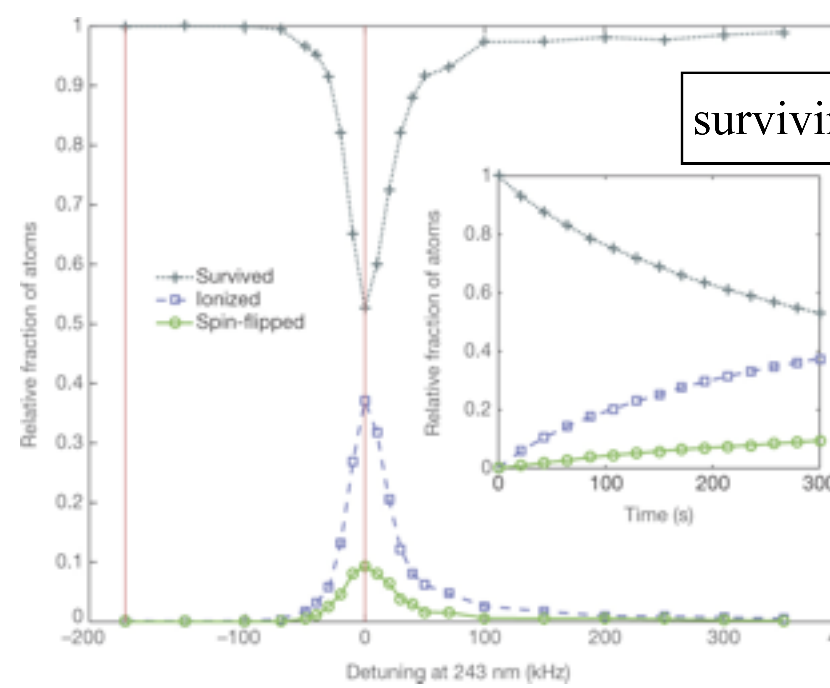
G. B. Andresen et al., Nature 468, 673–676 (02 December 2010)

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









surviving fraction: 58% ± 6%

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

further results:

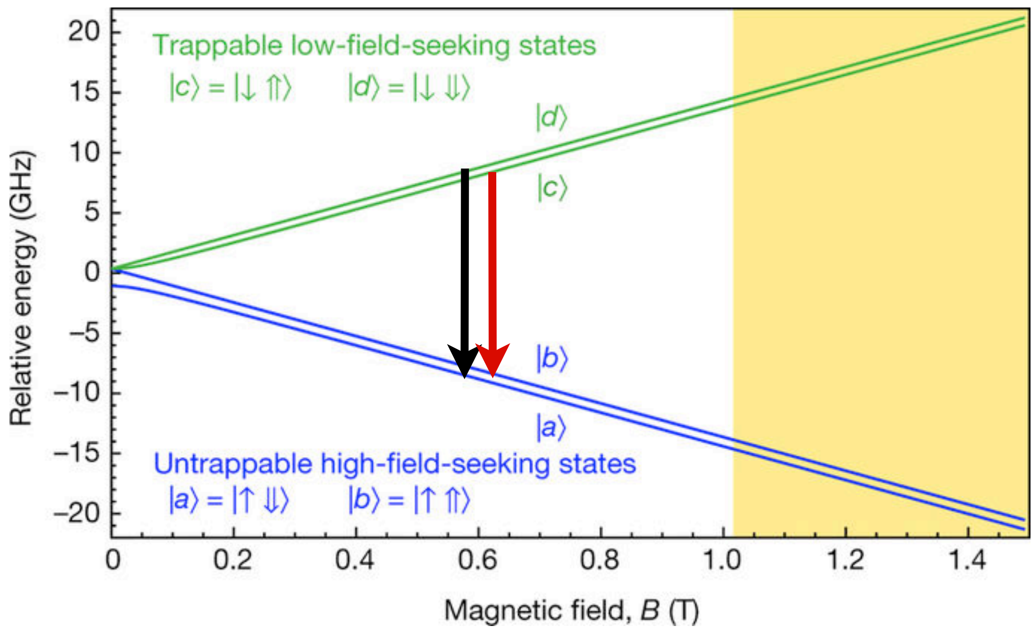
$q(\bar{H}) < 0.71 \times 10^{-9}$ e

Nature volume 529, pages 373–376 (21 January 2016) doi:10.1038/nature16491

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

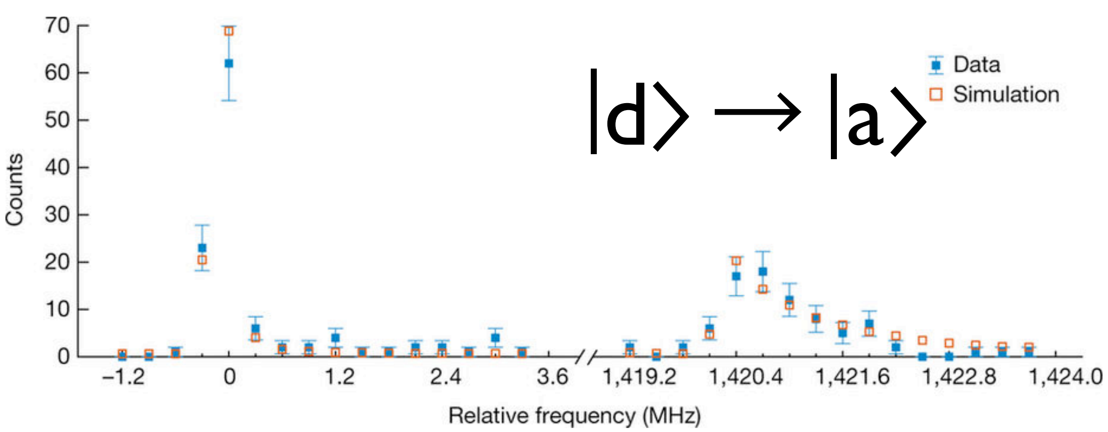
ALPHA results (trapping, 1s-2s spectroscopy)

microwave transitions in GS $\bar{\mathrm{H}}$



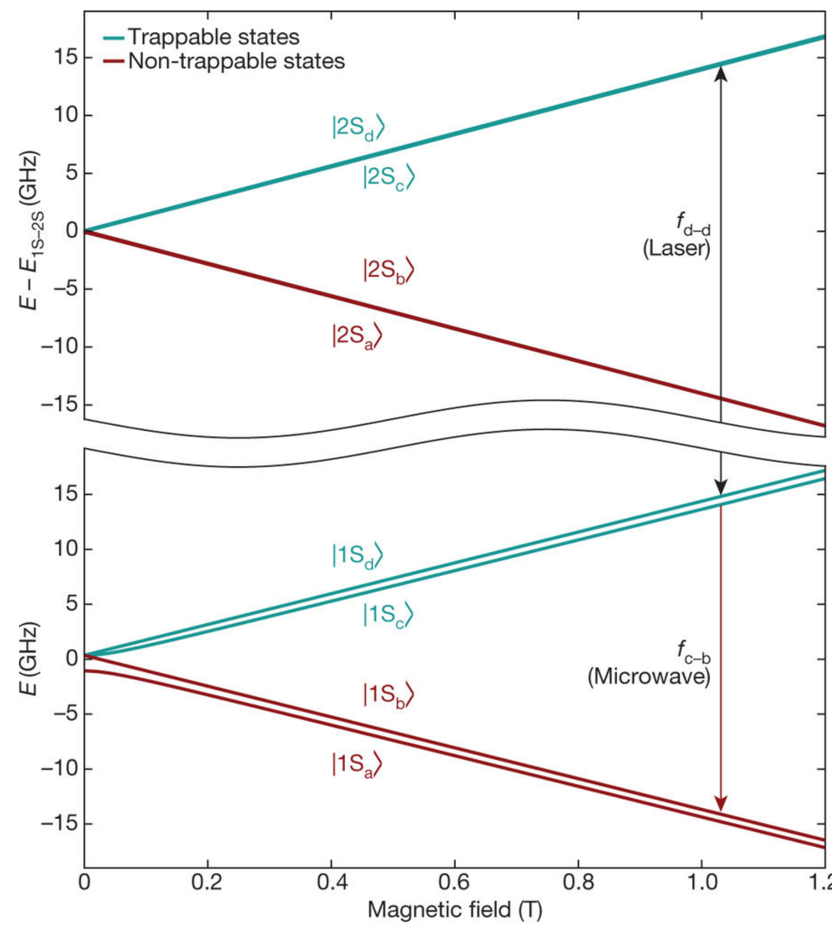
|c⟩ ⟶ |b⟩

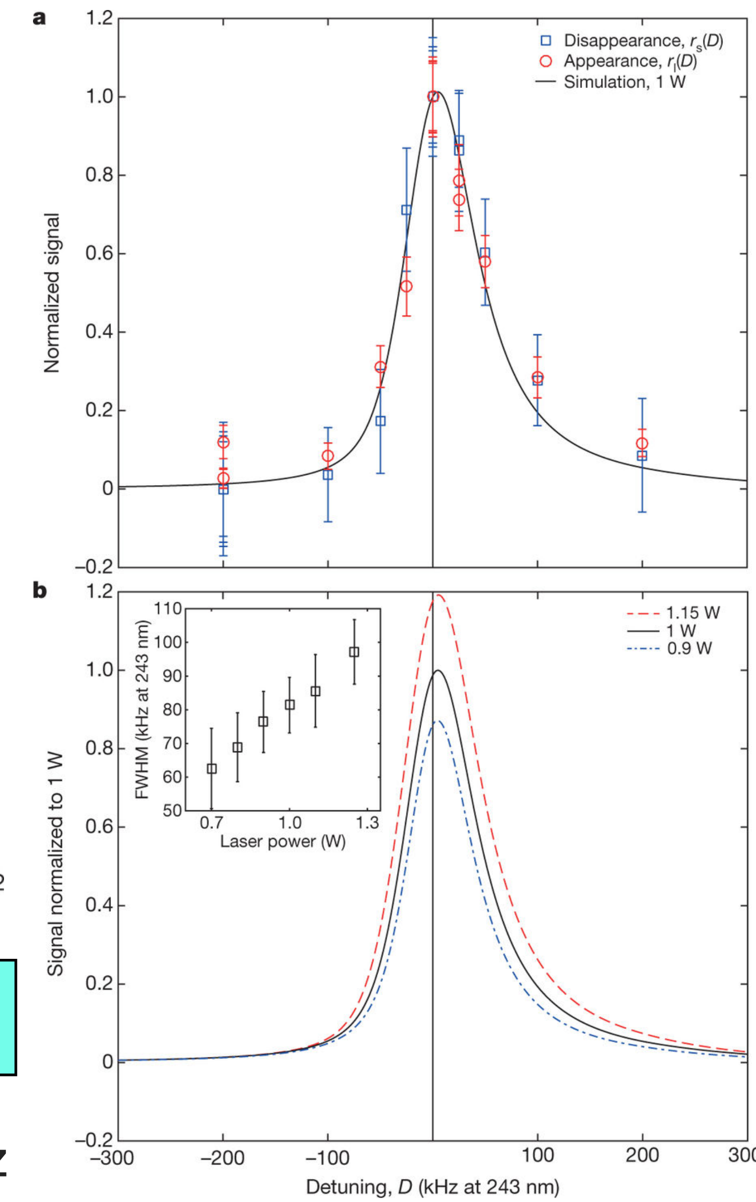
|d⟩ ⟶ |a⟩



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

1s-2s spectroscopy





Nature (2018)
doi:10.1038/s41586-018-0017-2

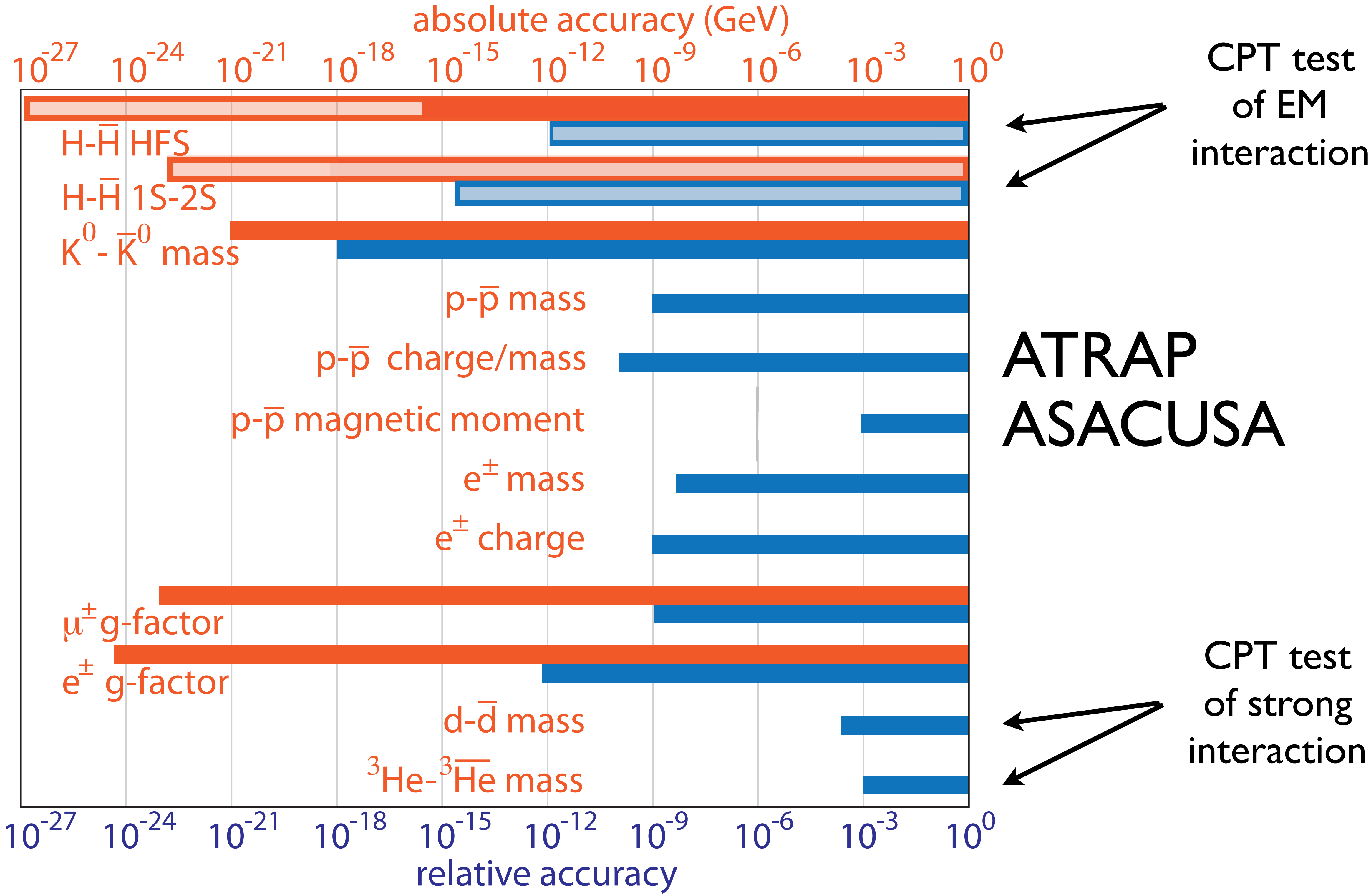
$f^{\bar{\mathrm{H}}}_{d-d}$ =2,466,061,103,079.4(5.4)kHz

(f^{H}_{d-d} =2,466,061,103,080.3(0.6)kHz for Hydrogen @ 1.03285(63) T)

2 x10^{-12} Relative precision

intermediate summary...

2013

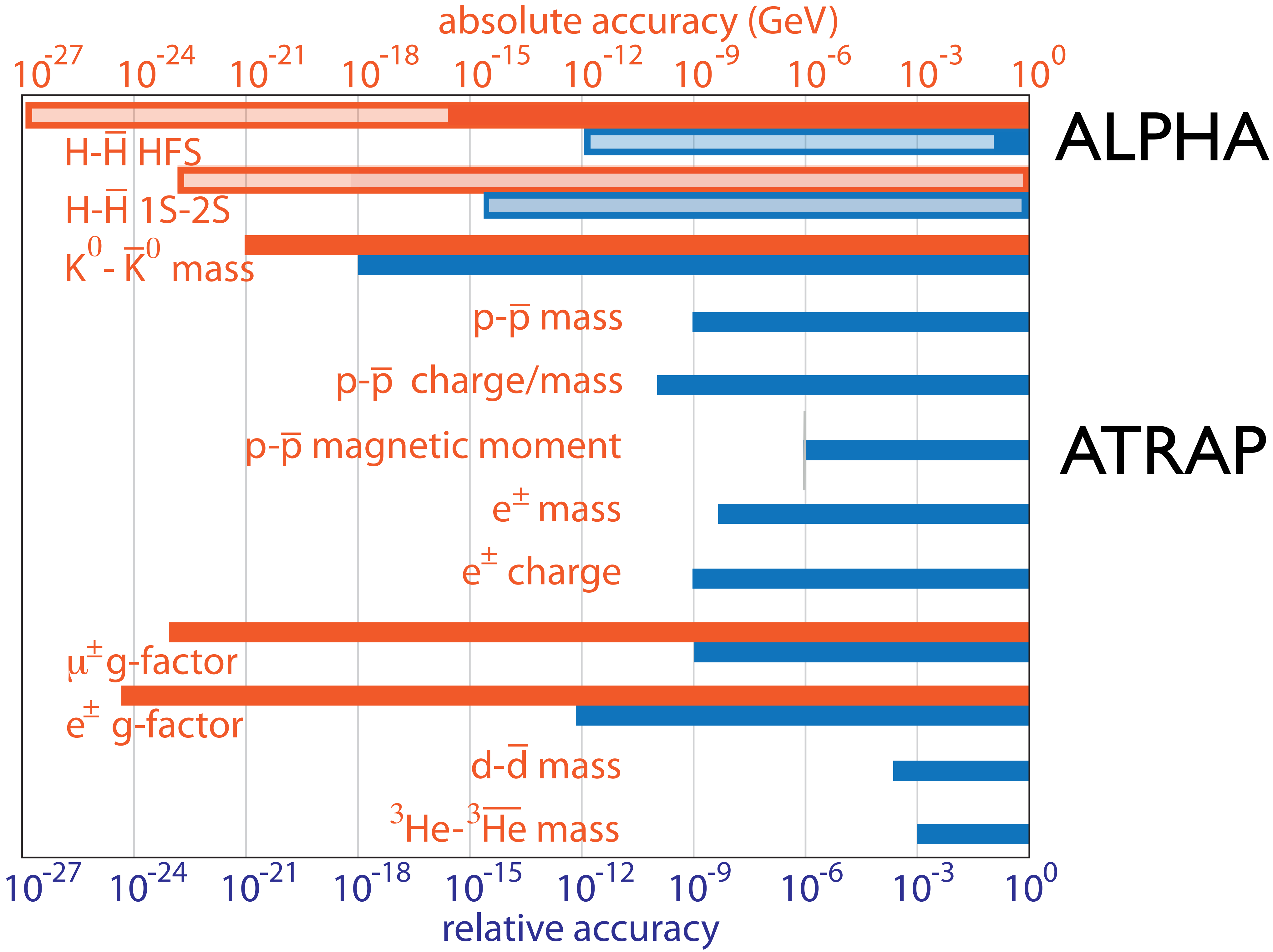


Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky)

2015



Inconsistent definition of figure of merit: comparison difficult

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

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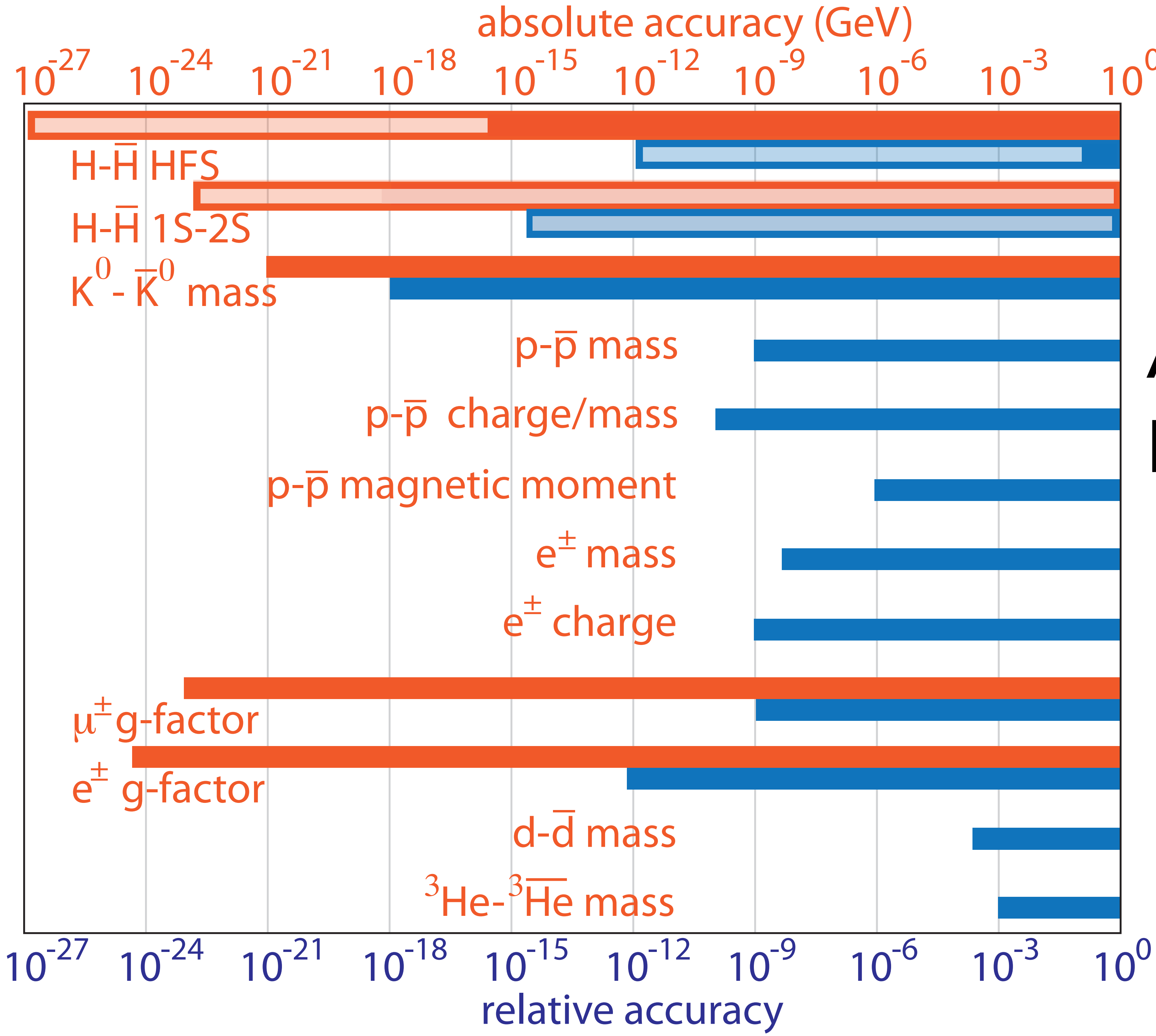
2016



ASACUSA

BASE & ATRAP

Inconsistent definition of figure of merit: comparison difficult

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

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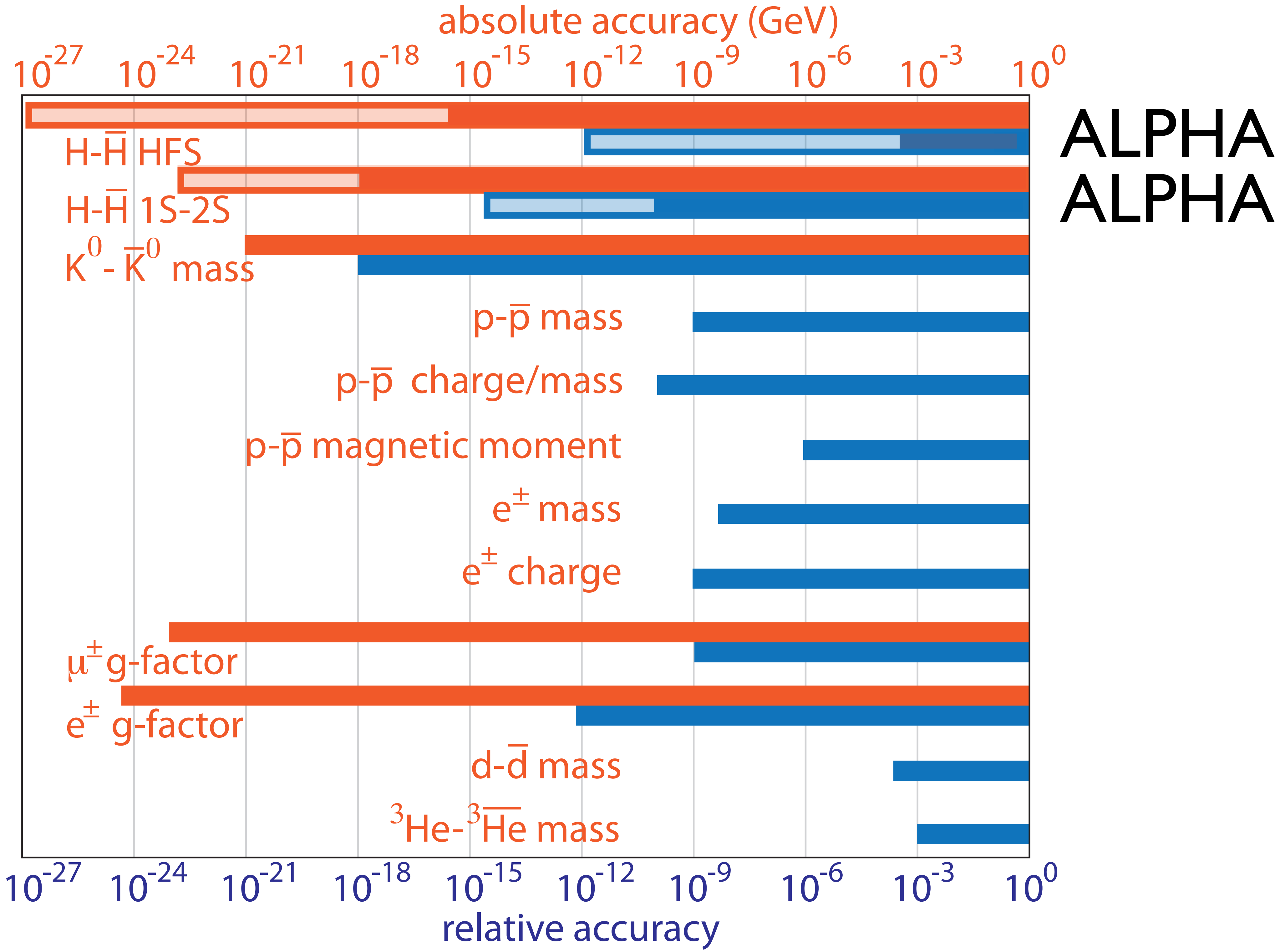
2017



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

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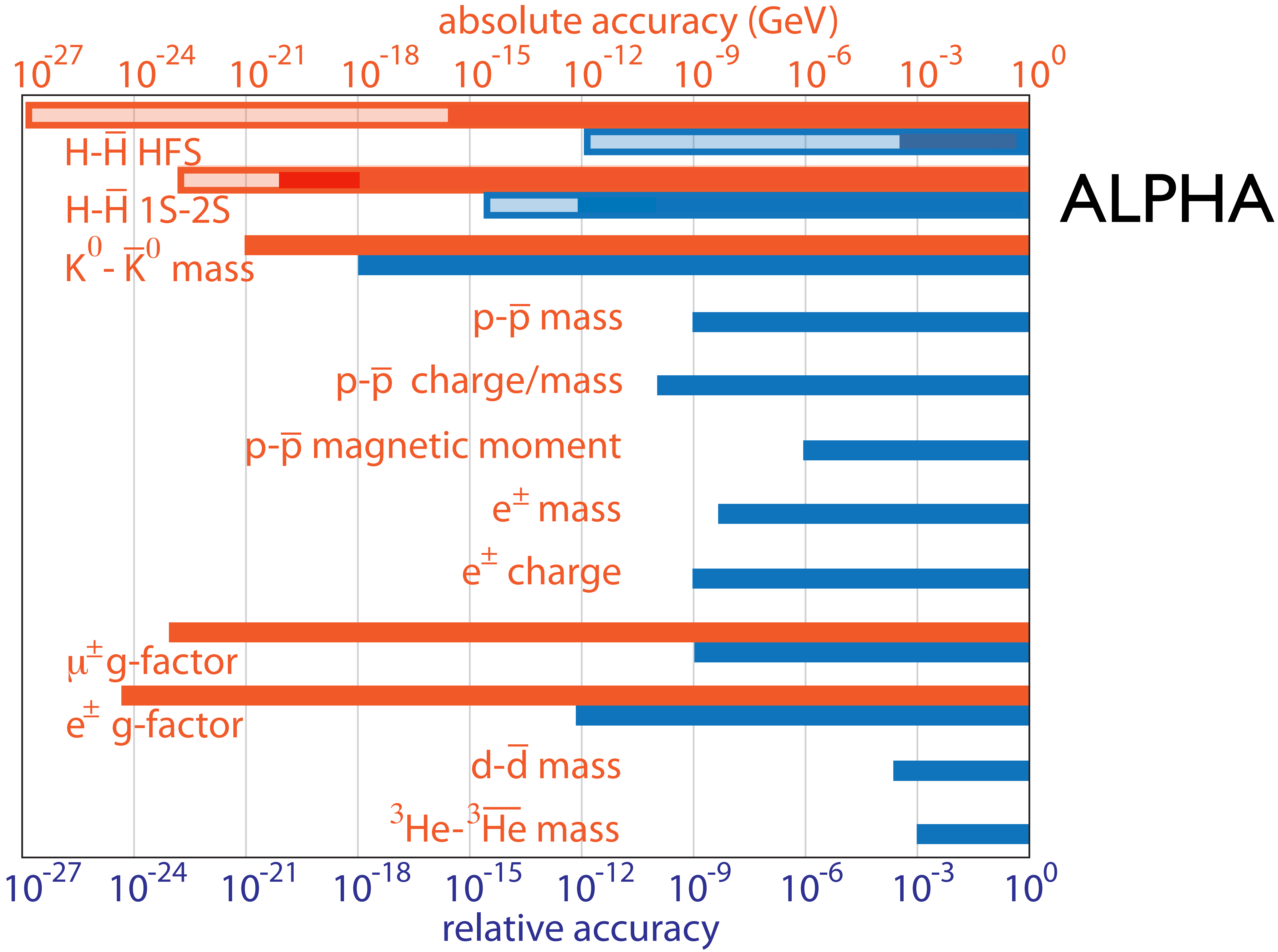
2018



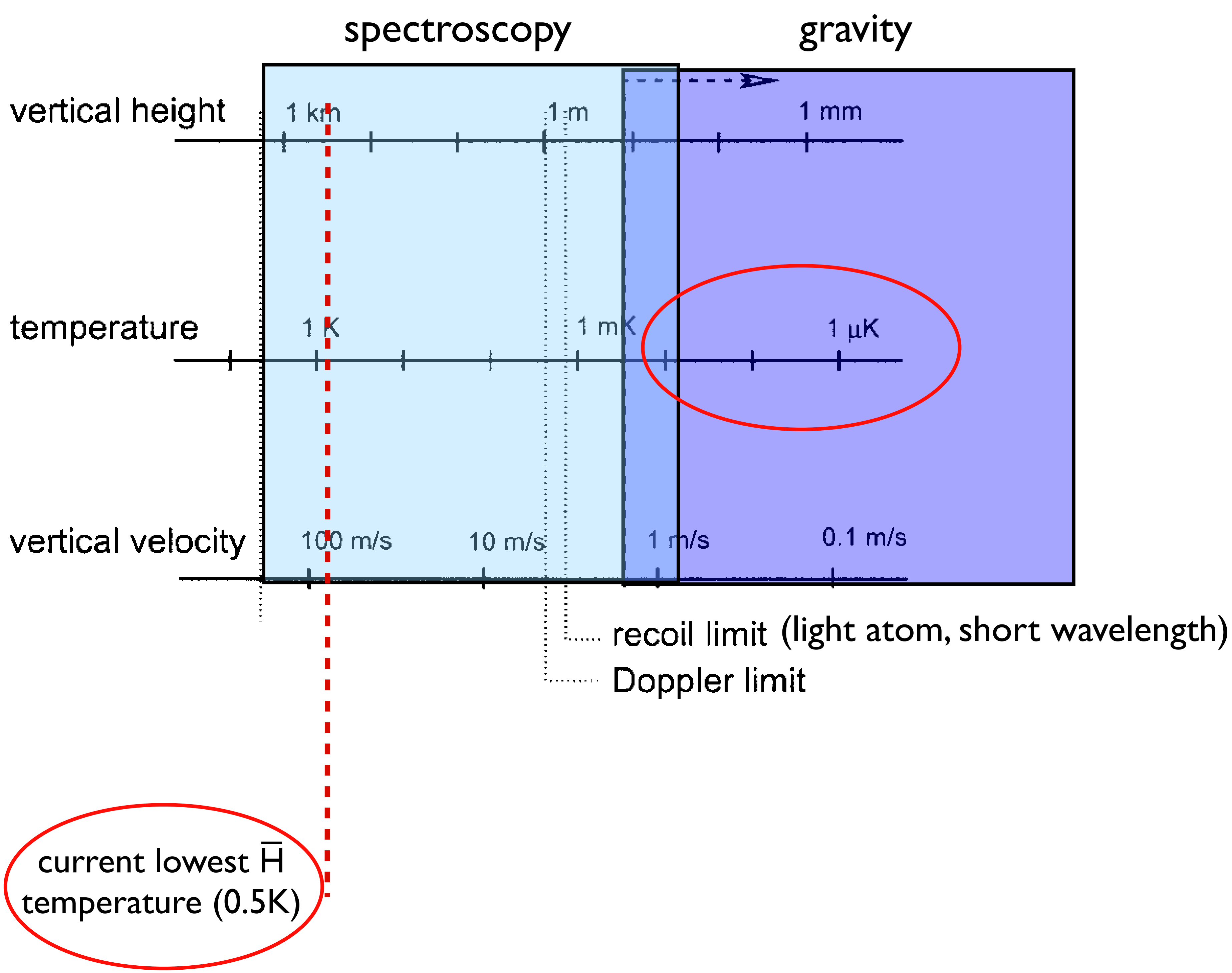
Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky)

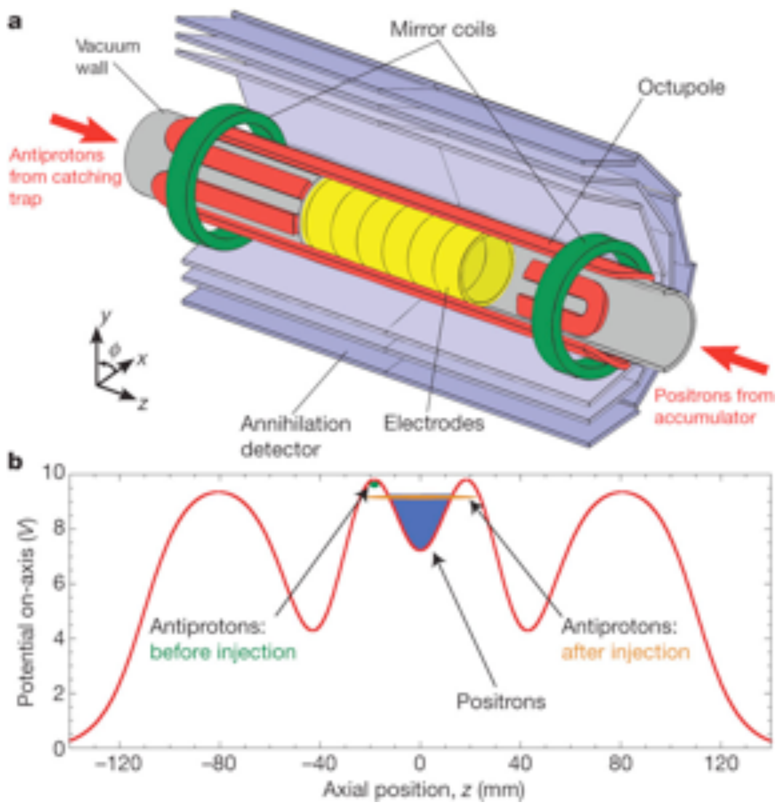
next stop: gravity

the importance of working at low temperature



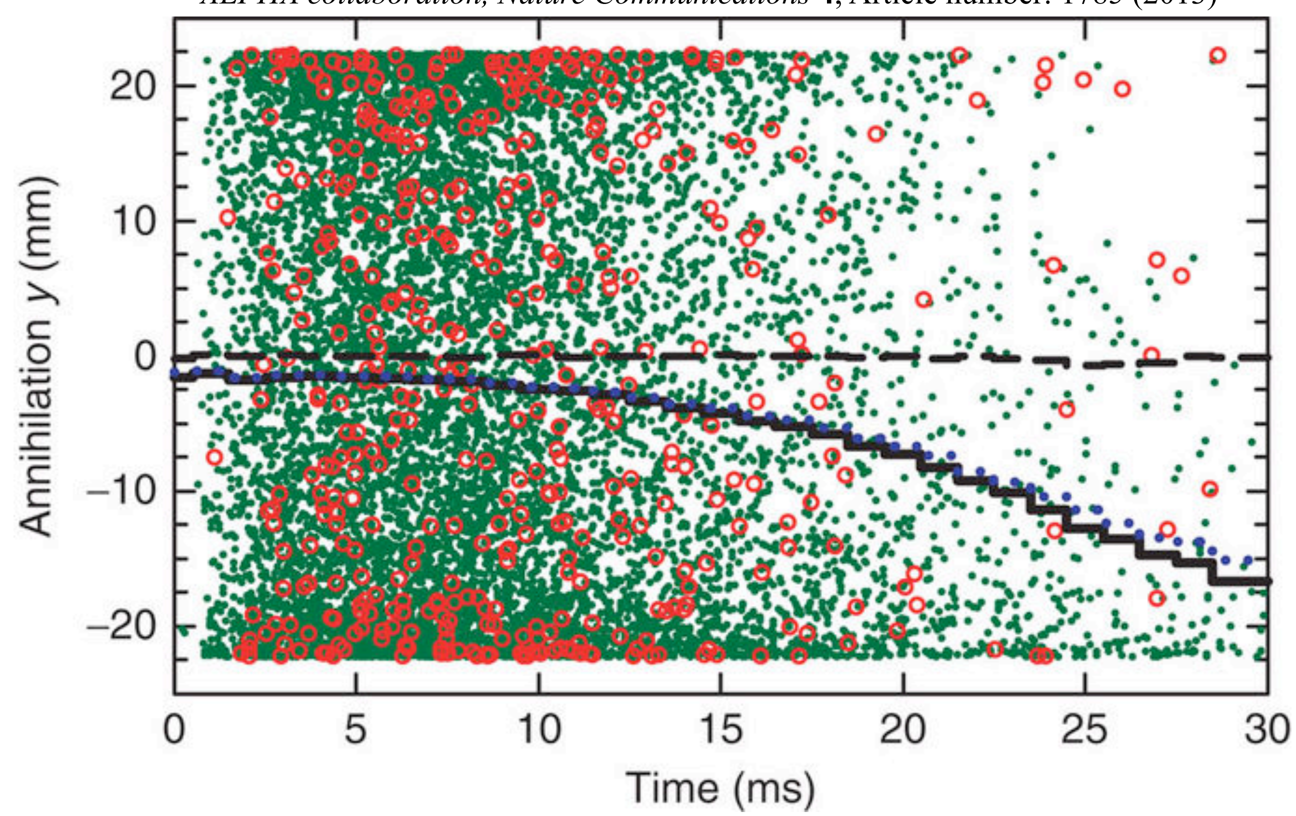
ALPHA results (gravity at 0.5K)

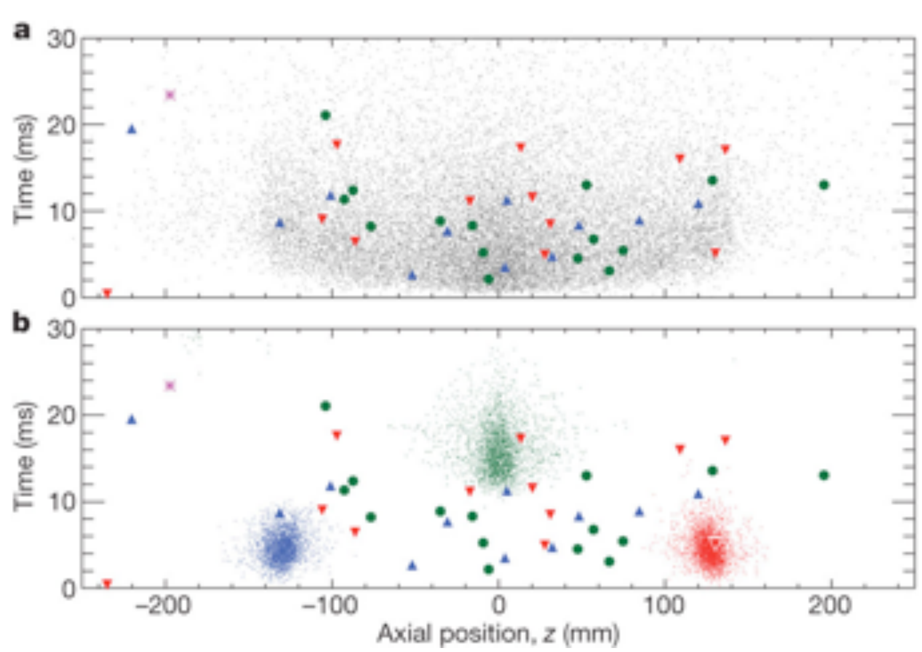
Nature Communications volume 4, Article number: 1785 (2013)
doi:10.1038/ncomms2787



$$F \equiv M_g/M$$

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=±1 level ..."

Temperature of produced $\bar{H}$

2017 (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?

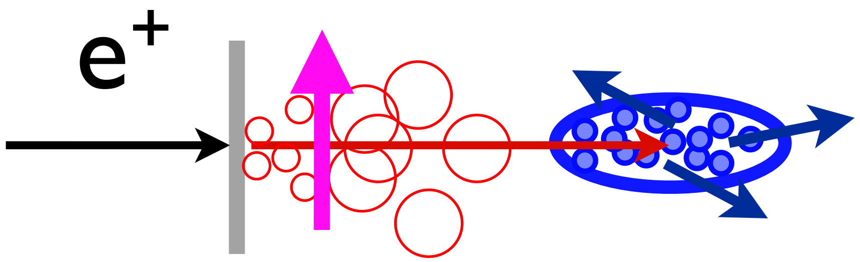
Outlook: 10's ~ 100's of trapped $\bar{H}$ (through stacking)

alternative antihydrogen production method: RCE

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

AEgIS

$T_{Ps} \sim 100$ K



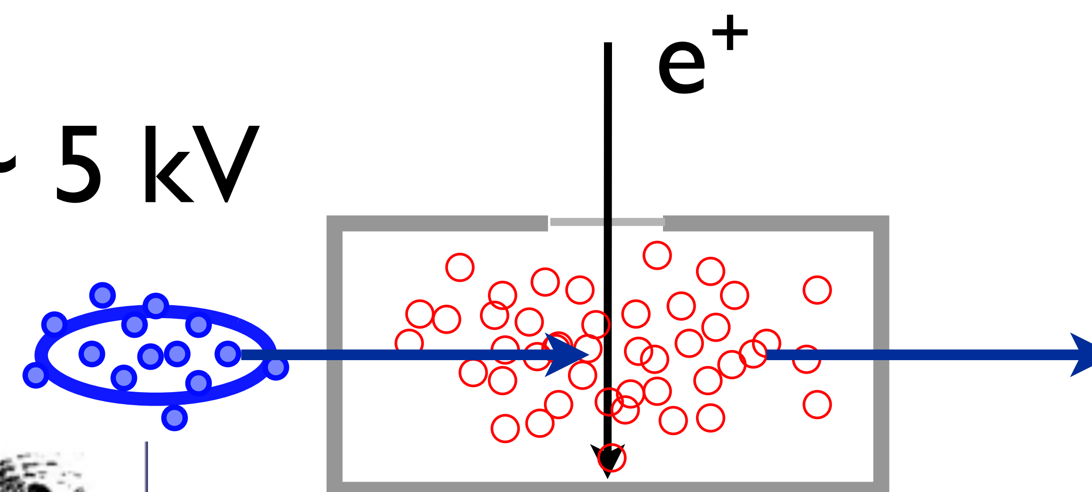
$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$

cold $\bar{H}^*$

but: low rate!

GBAR

$E_p \sim 5$ kV



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

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

hot $\bar{H}^+$

but: low rate!

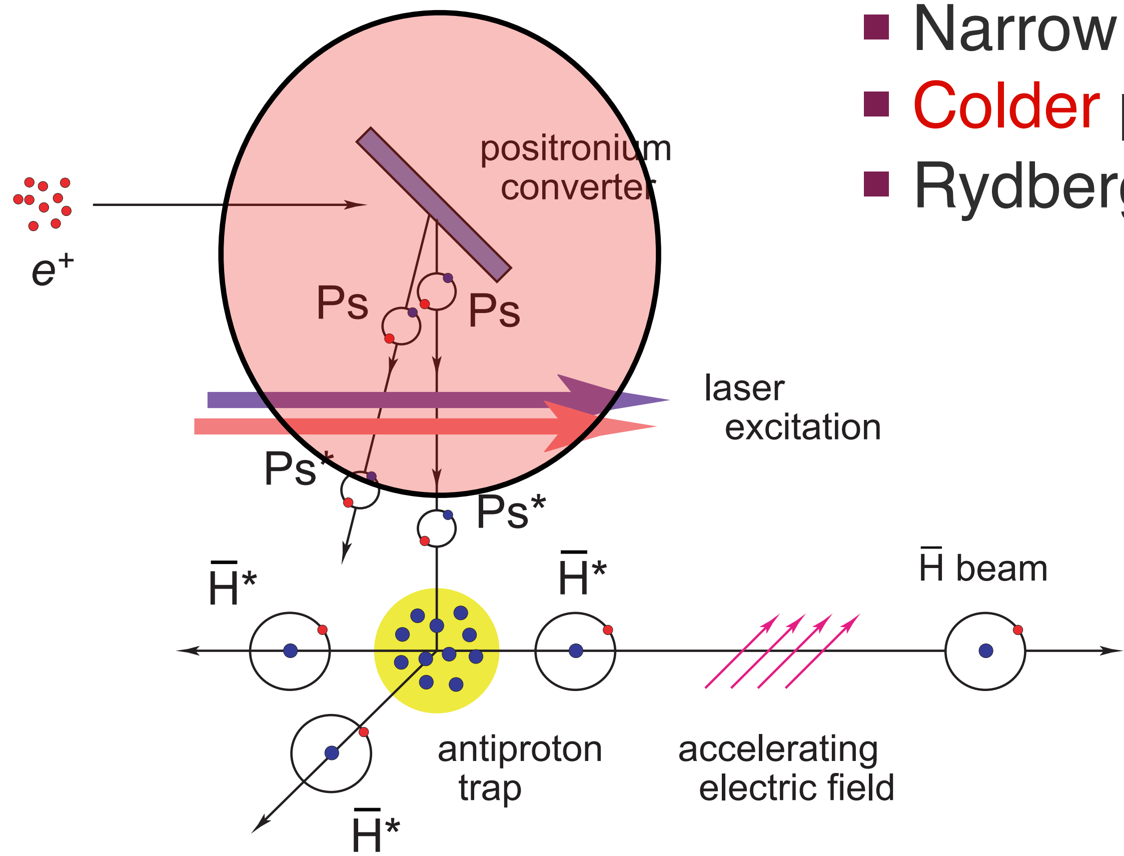
Schematic overview

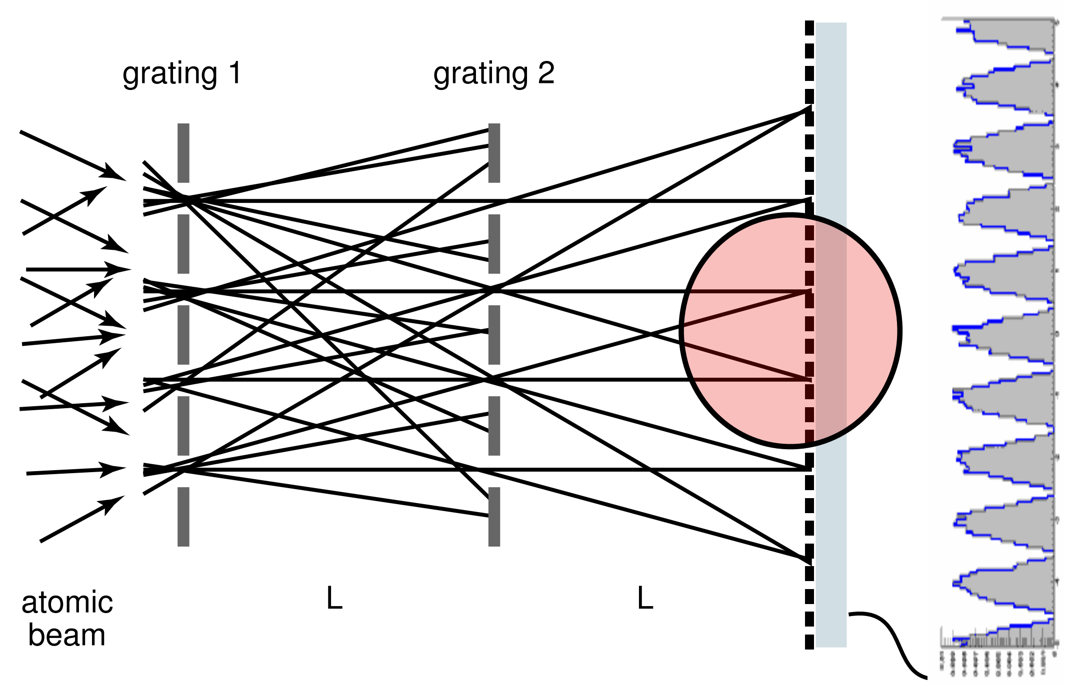
Physics goals: measurement of the gravitational interaction between matter and antimatter, $\overline{\mathrm{H}}$ spectroscopy, ...

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

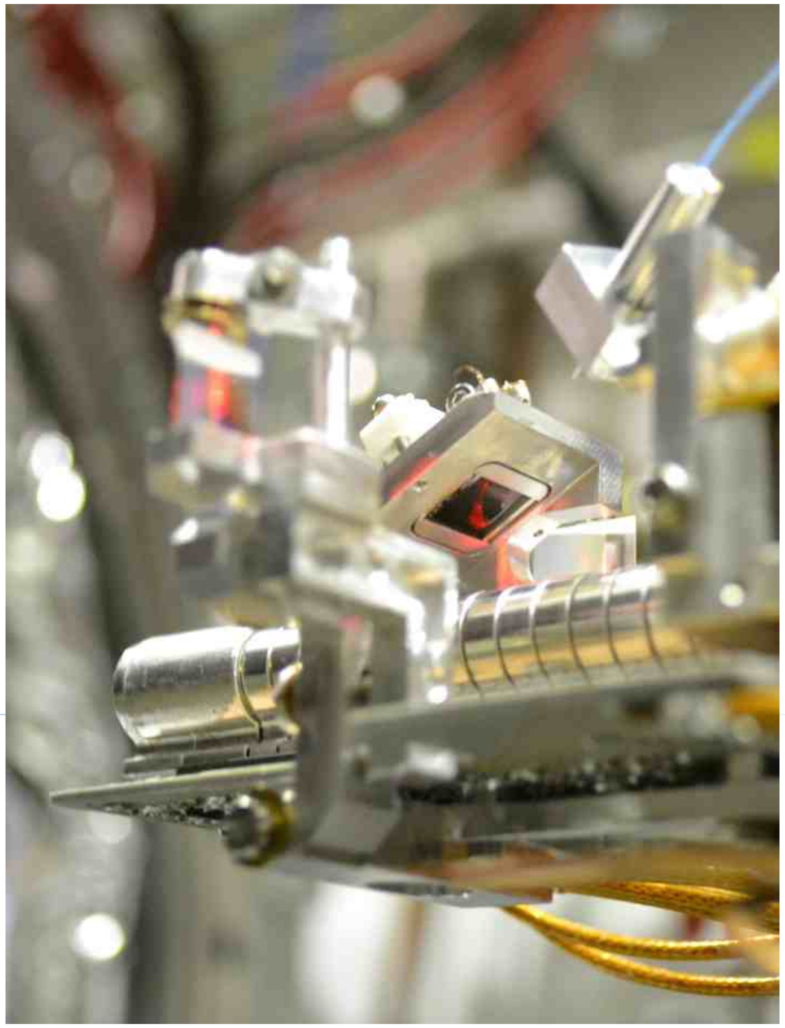
$$\mathrm{Ps}^* + \overline{p} \rightarrow \overline{\mathrm{H}}^* + e^-$$

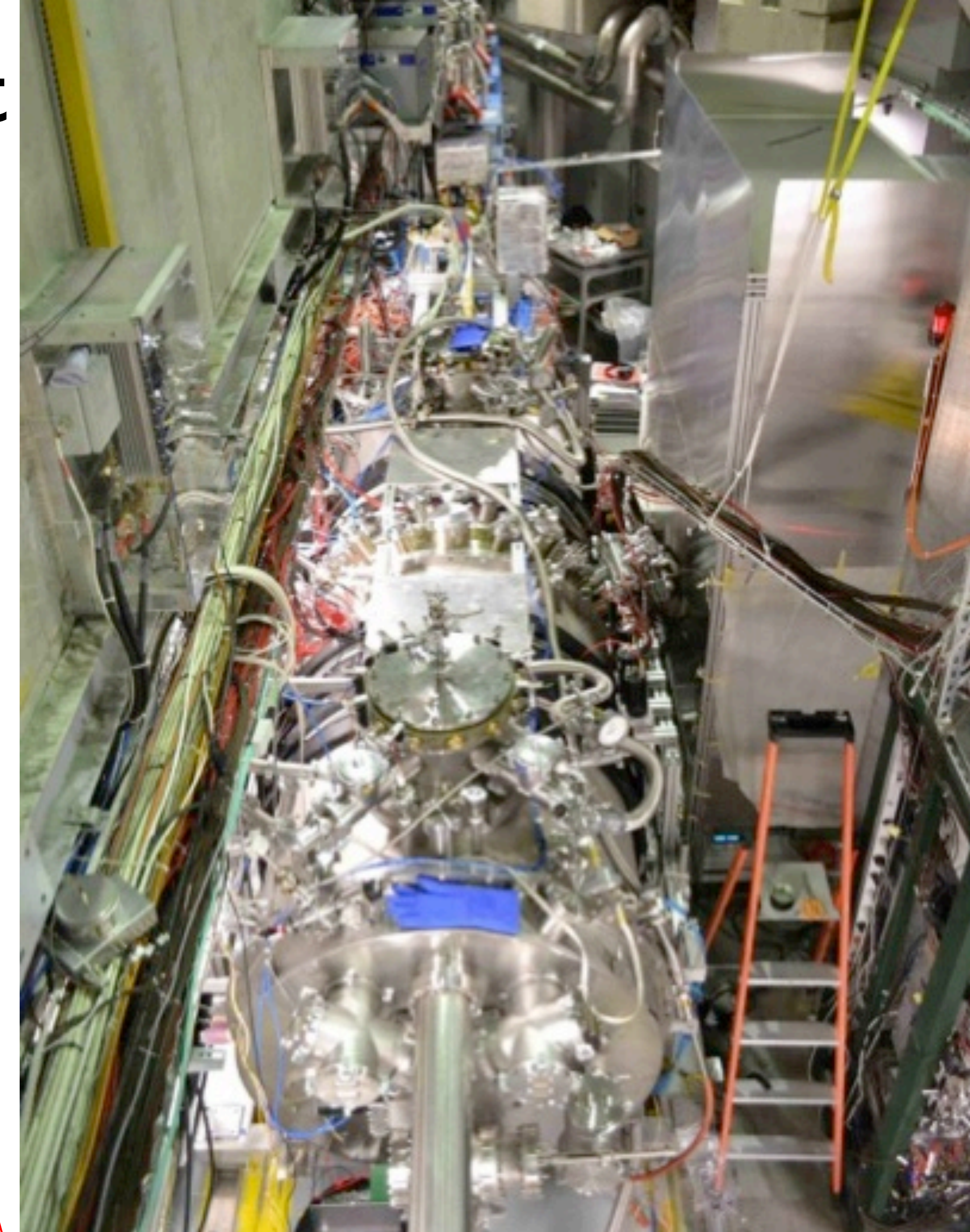
- Advantages:
  - Pulsed $\overline{\mathrm{H}}$ production (time of flight – Stark acceleration)
  - Narrow and well-defined $\overline{\mathrm{H}}$ *n*-state distribution
  - Colder production than via mixing process expected
  - Rydberg Ps & $\sigma \approx a_0 n^4 \rightarrow \overline{\mathrm{H}}$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

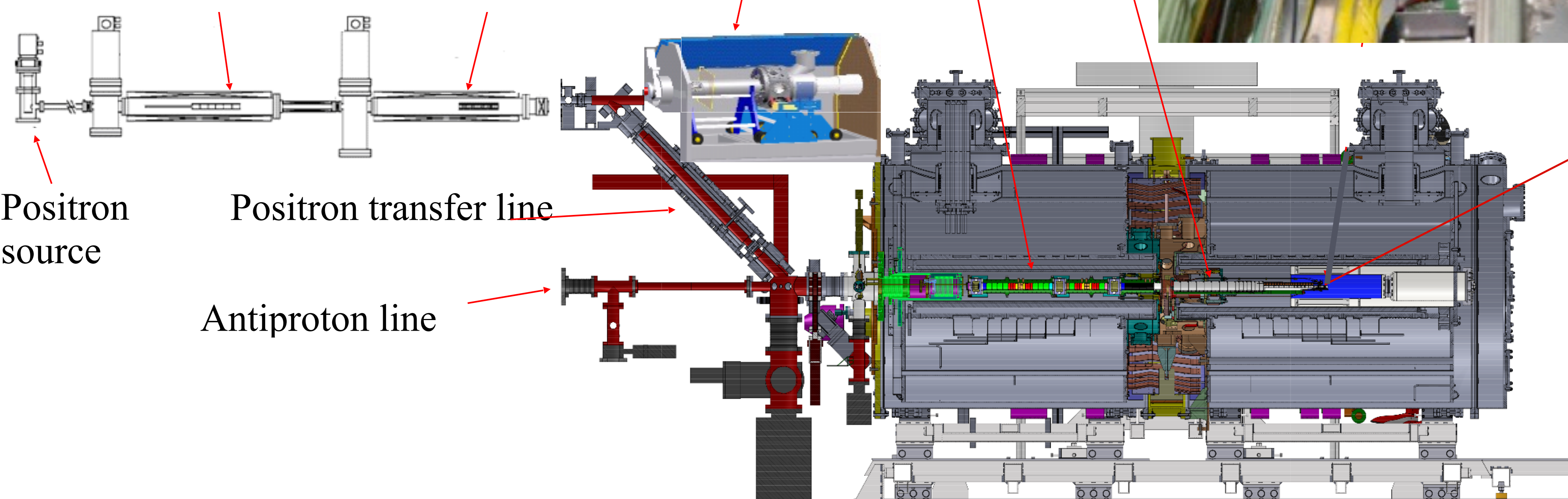




AE$\bar{g}$IS experiment

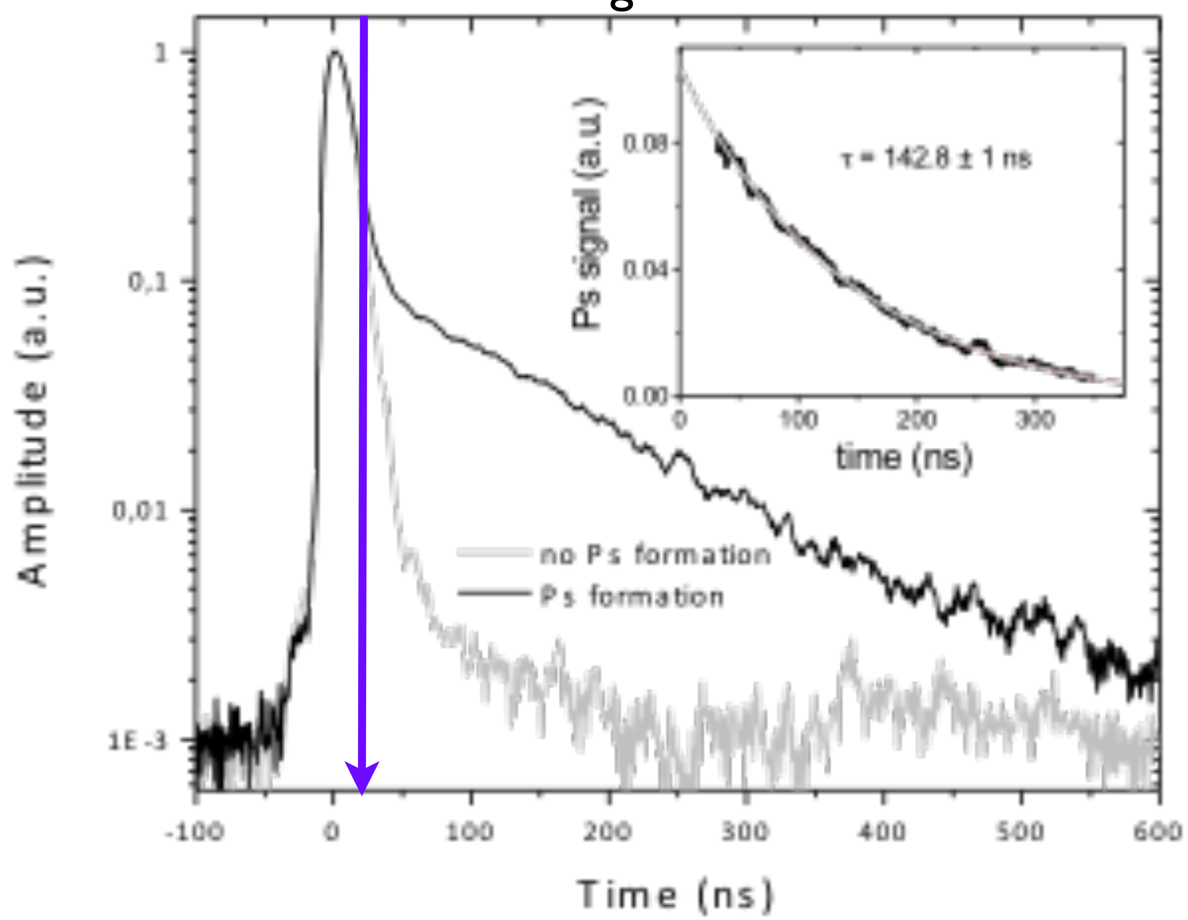


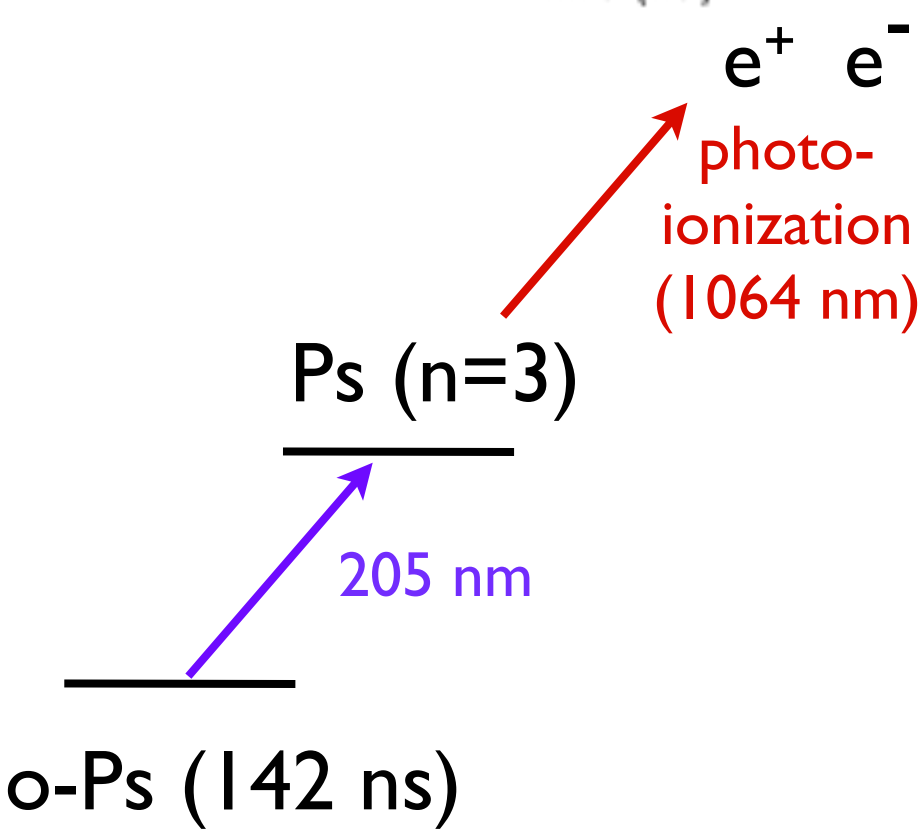




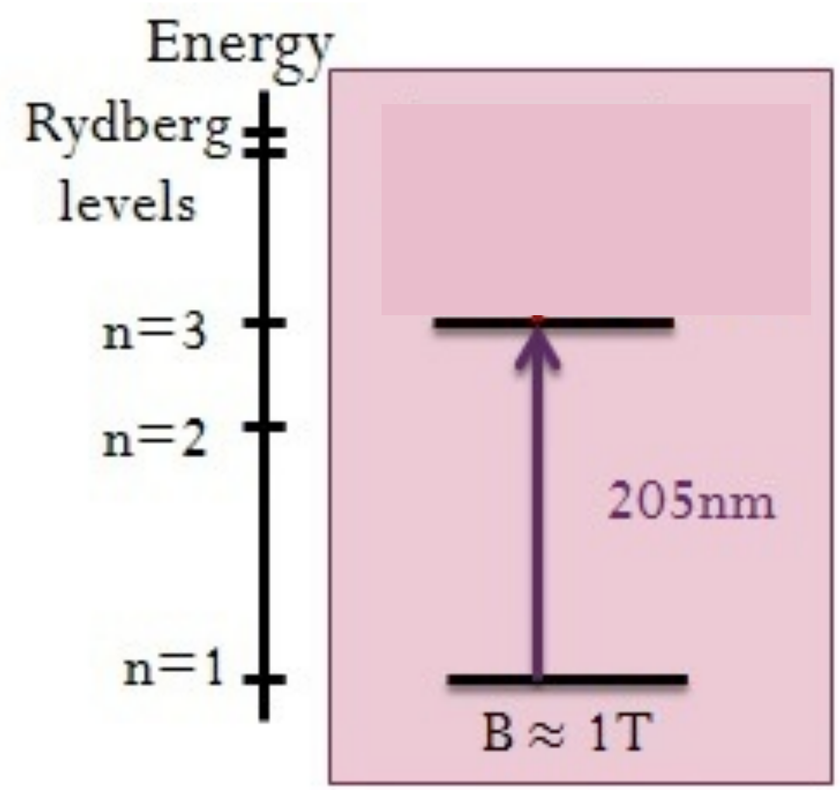
Single Shot Positronium Lifetime Spectroscopy

average of 15 shots





Ps excitation into n=3



Energy 60μJ, pulse 2ns, waist 6mm x 8mm, σ ~ 110GHz

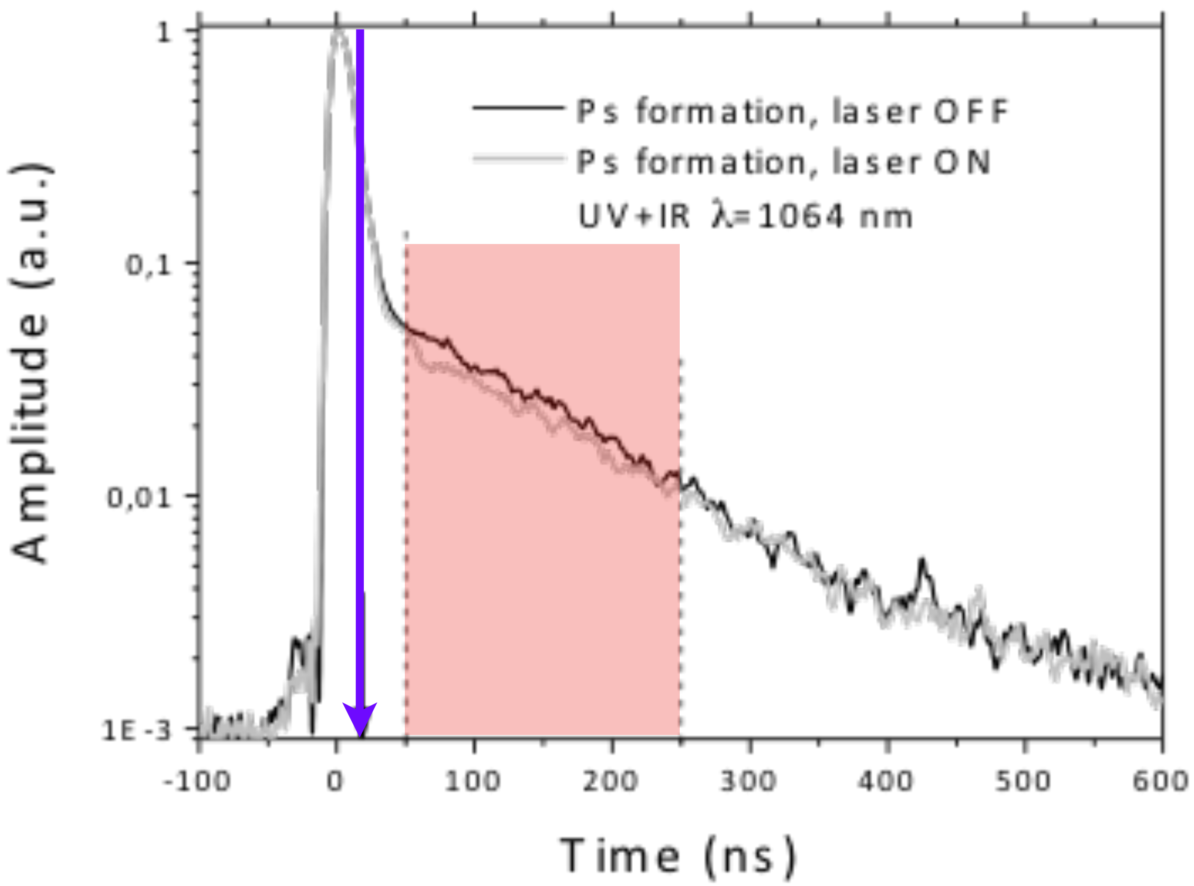
expect *decease* of o-Ps population on resonance

➔ *decrease* in (delayed) annihilation rate

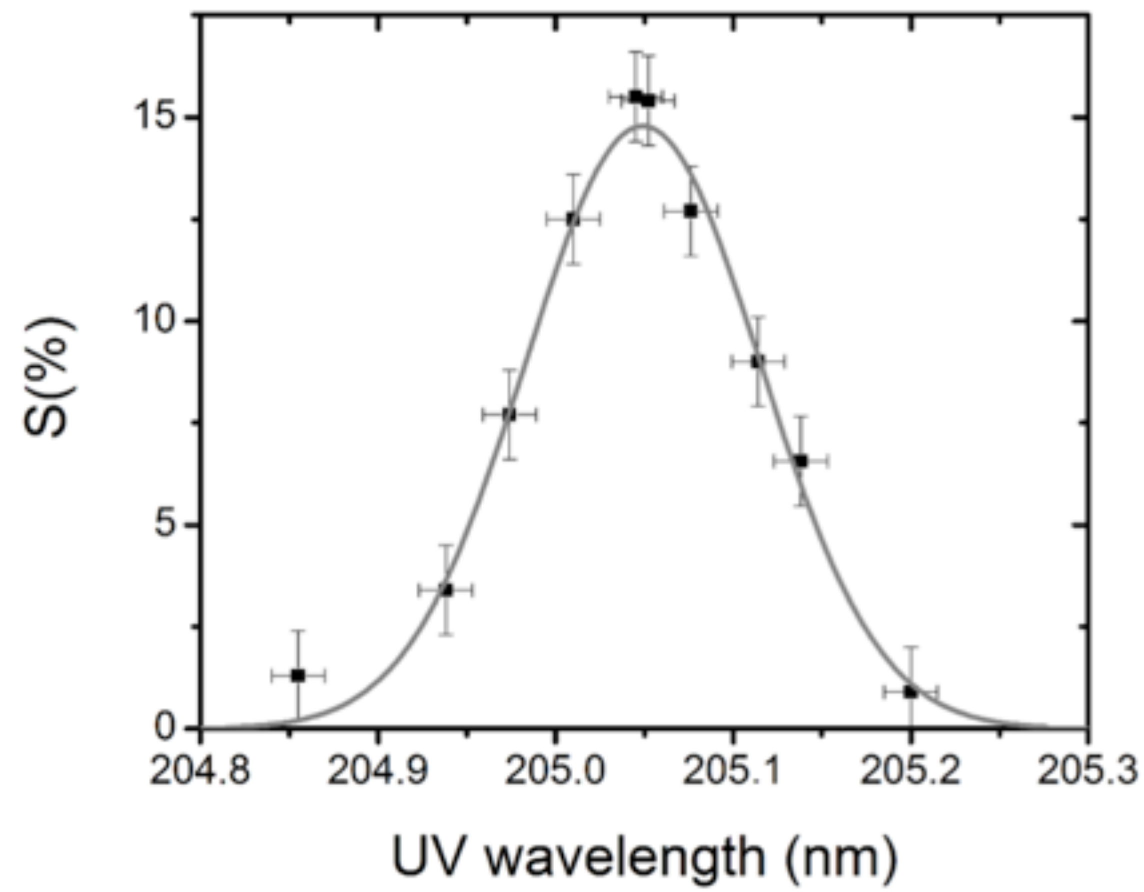
S. Aghion et al. Nucl. Instr. Meth. in Phy. Res Sect. B 362:86 92, 2015

Measurement of Ps decay signal, alternating UV on/off, and scanning over UV wavelength

average of 15 shots



3P excitation line centered at 205.05±0.02 nm



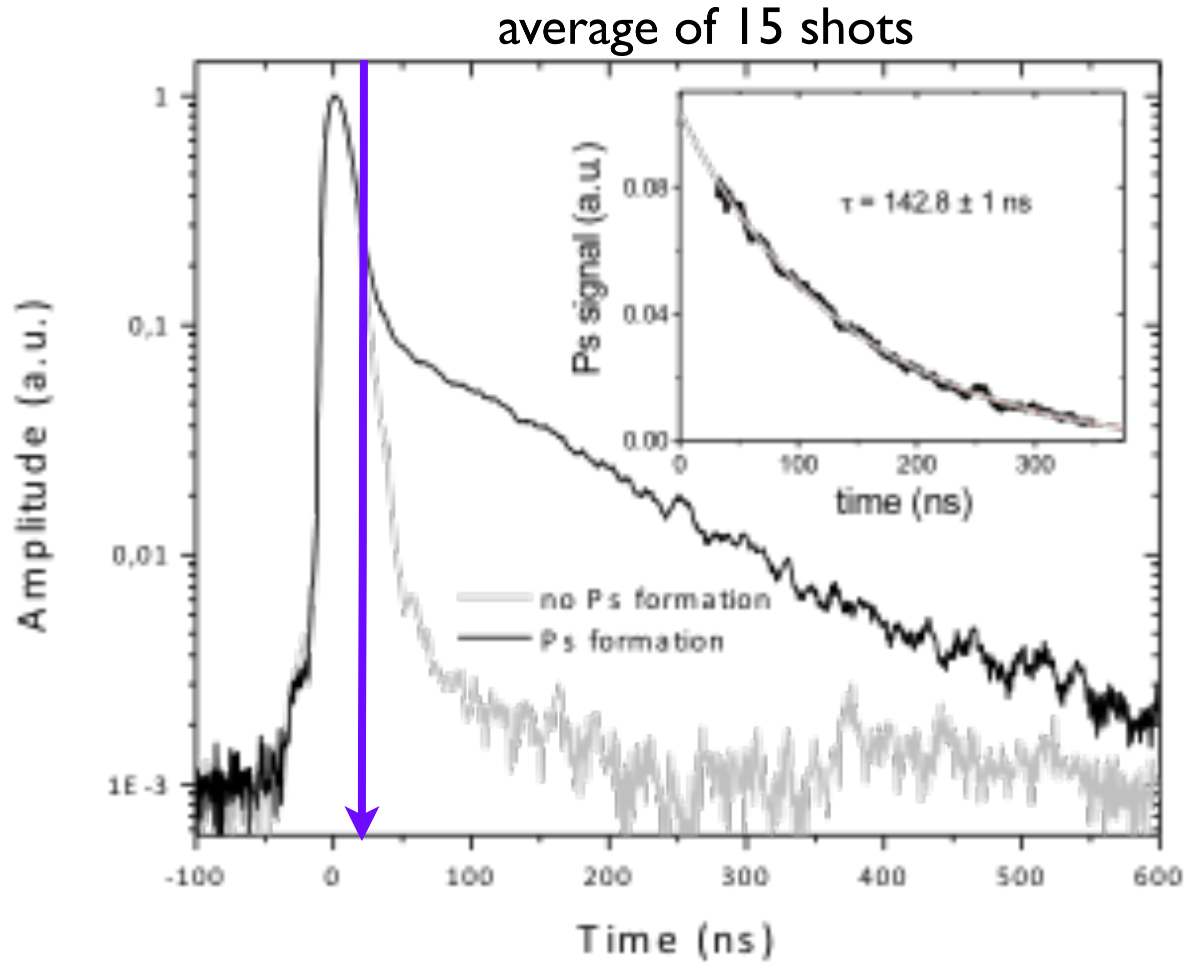
$$S(\%) = \frac{(\text{Area laser OFF} - \text{Area laser ON})}{\text{Area laser OFF}}$$

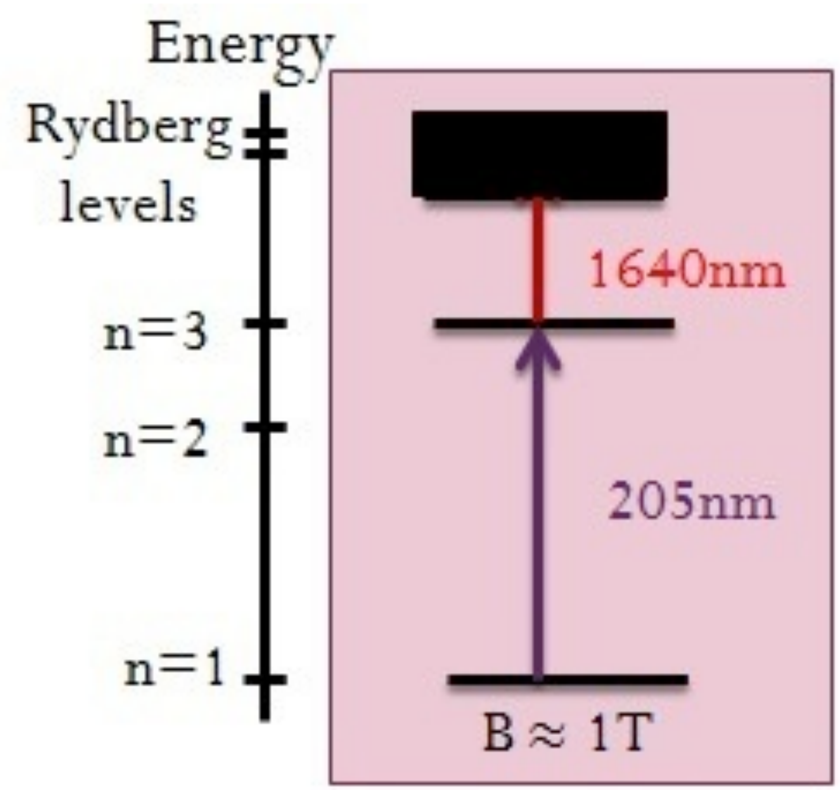
Excitation + photoionization efficiency ~ 15% (limited by laser linewidth)

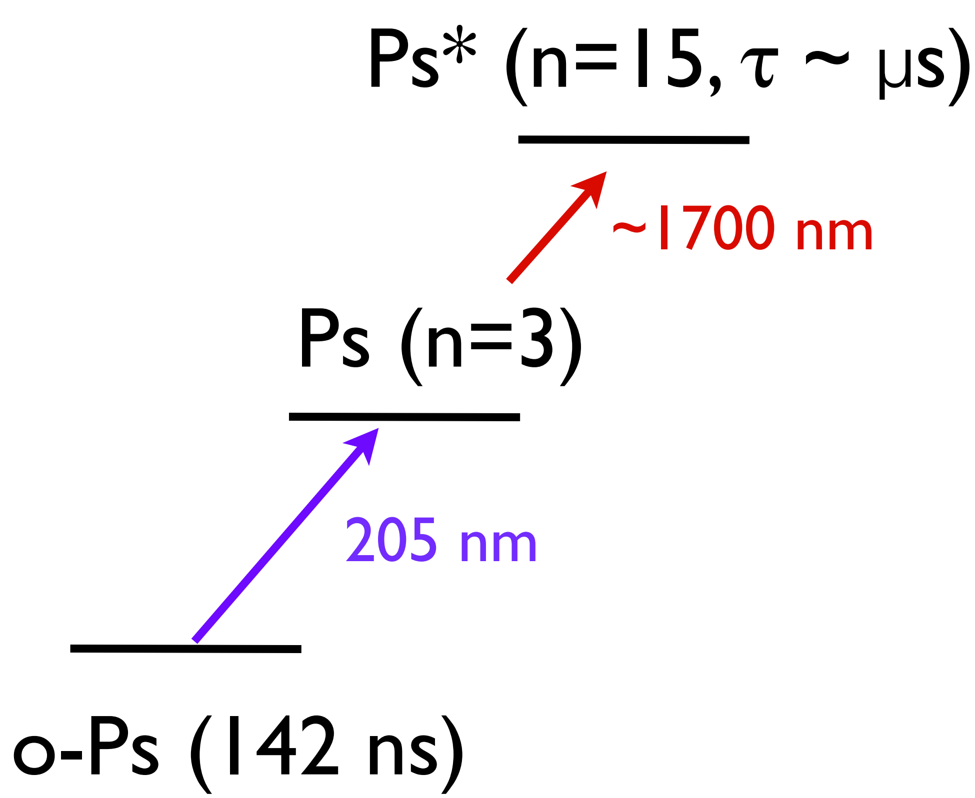
From this measurement, extract an average temperature of the excited o-Ps : T ~1300K (Doppler broadening)

S. Aghion et al., PRA 94, 012507 (2016)

Ps excitation from n=3 into n~15



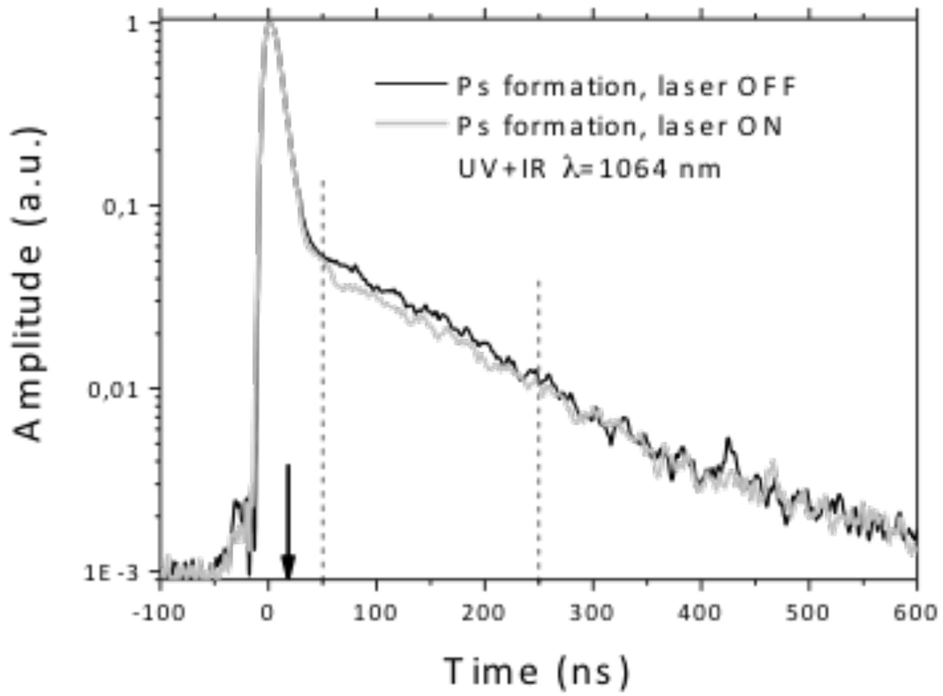


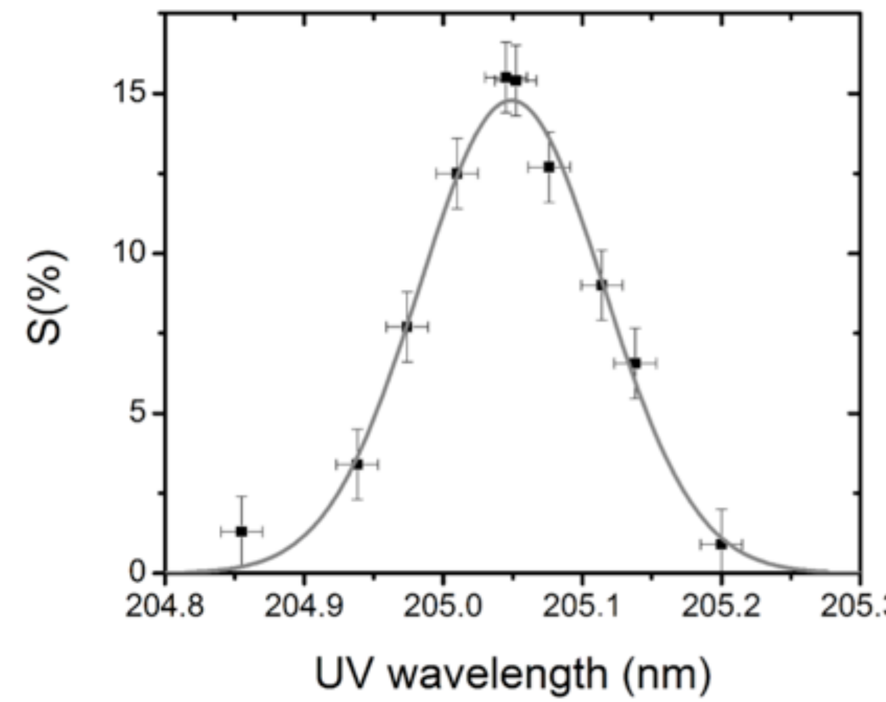


expect *decrease* of o-Ps population on resonance and *appearance* of long-lived Ps*

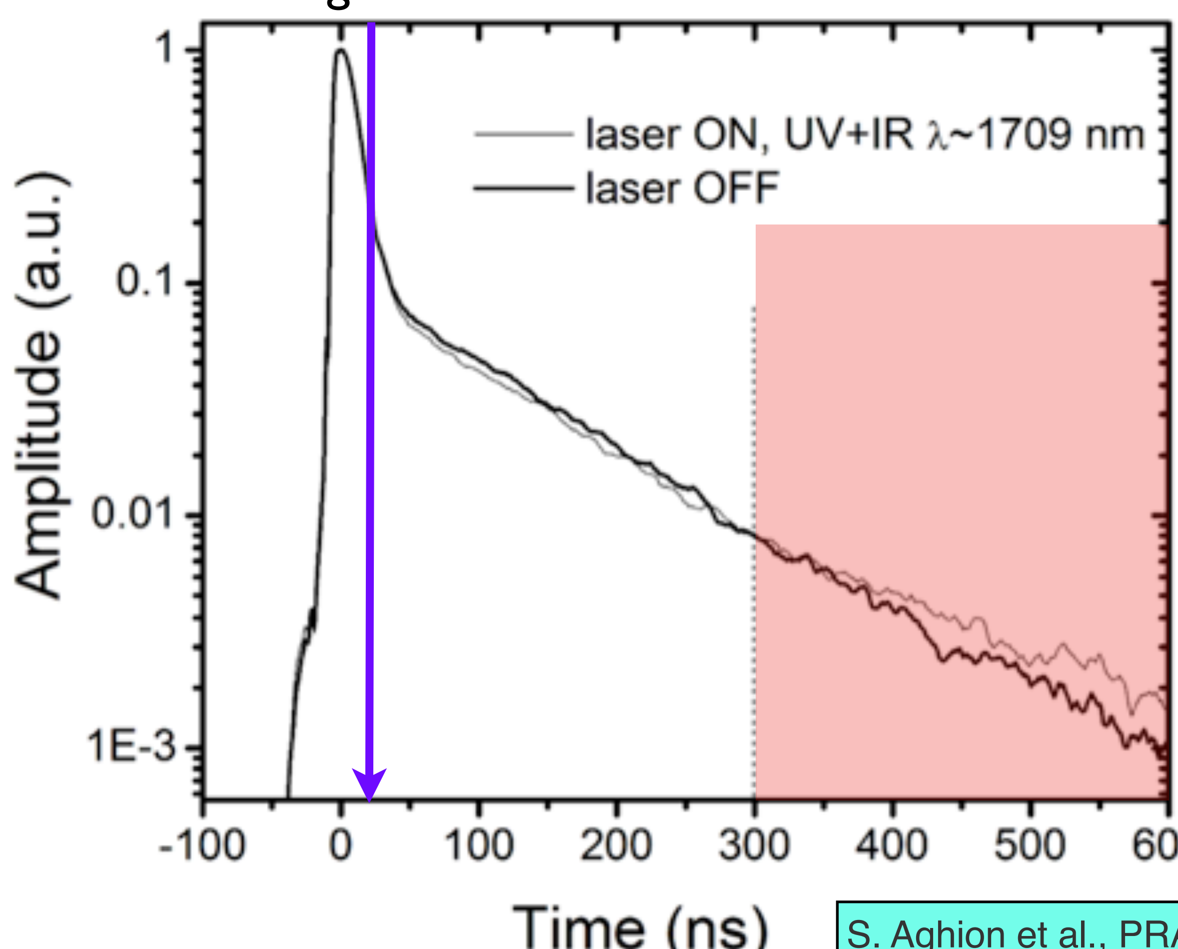
➔ *increase* in (very delayed) annihilation rate

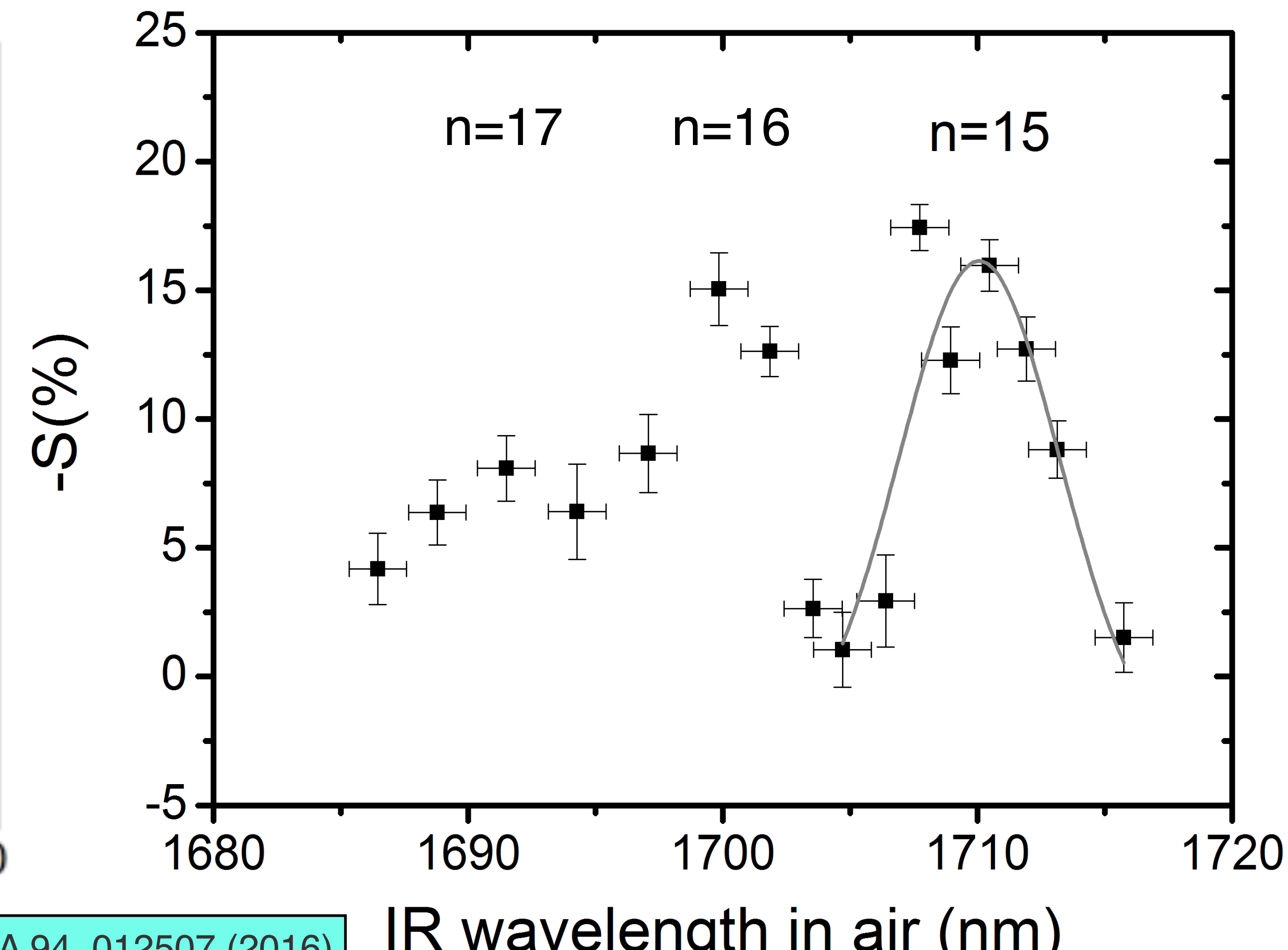
Measurement of Ps decay signal, alternating UV+IR on/off, and scanning over IR wavelength





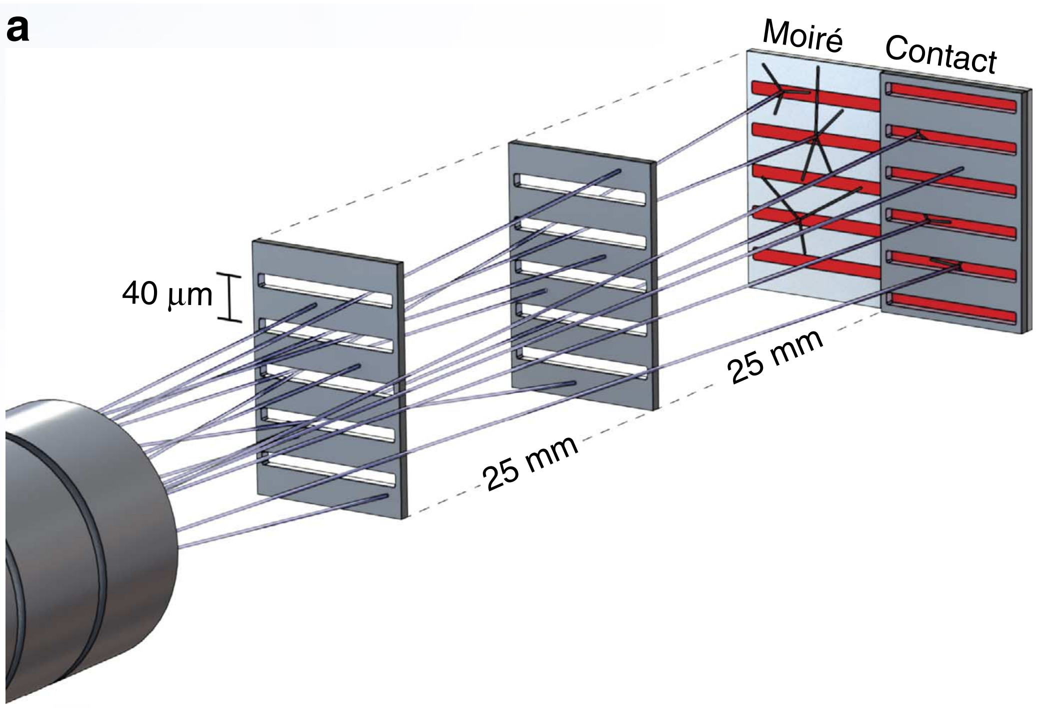
average of 40 shots

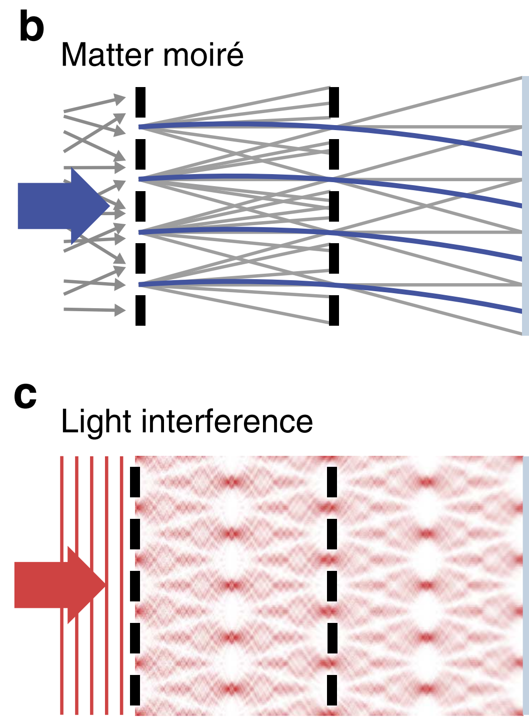


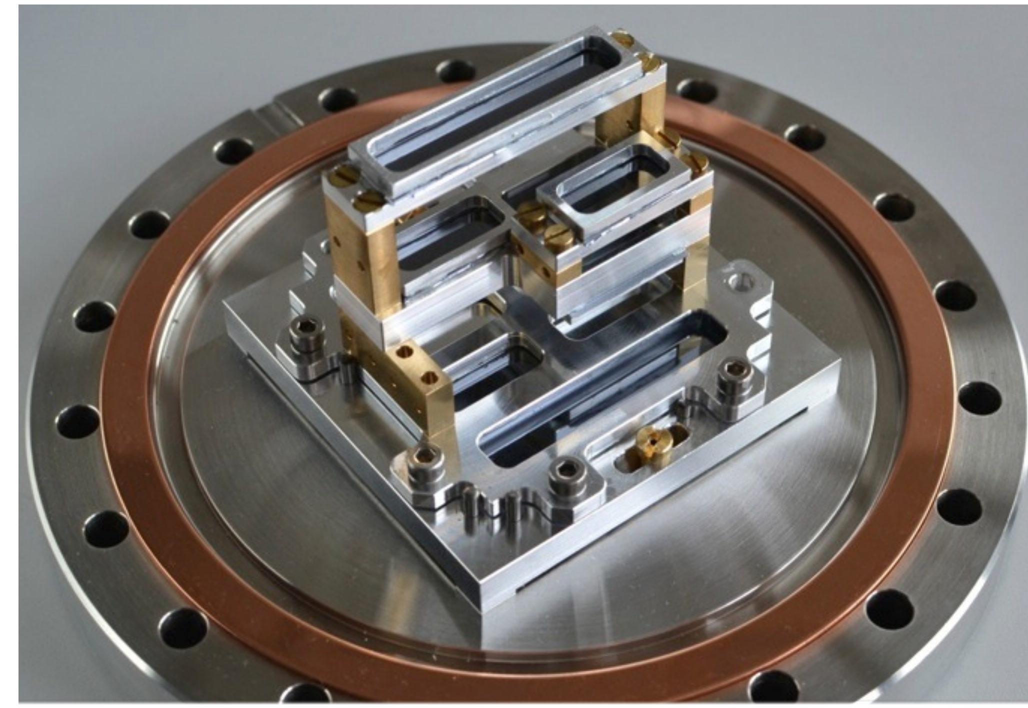


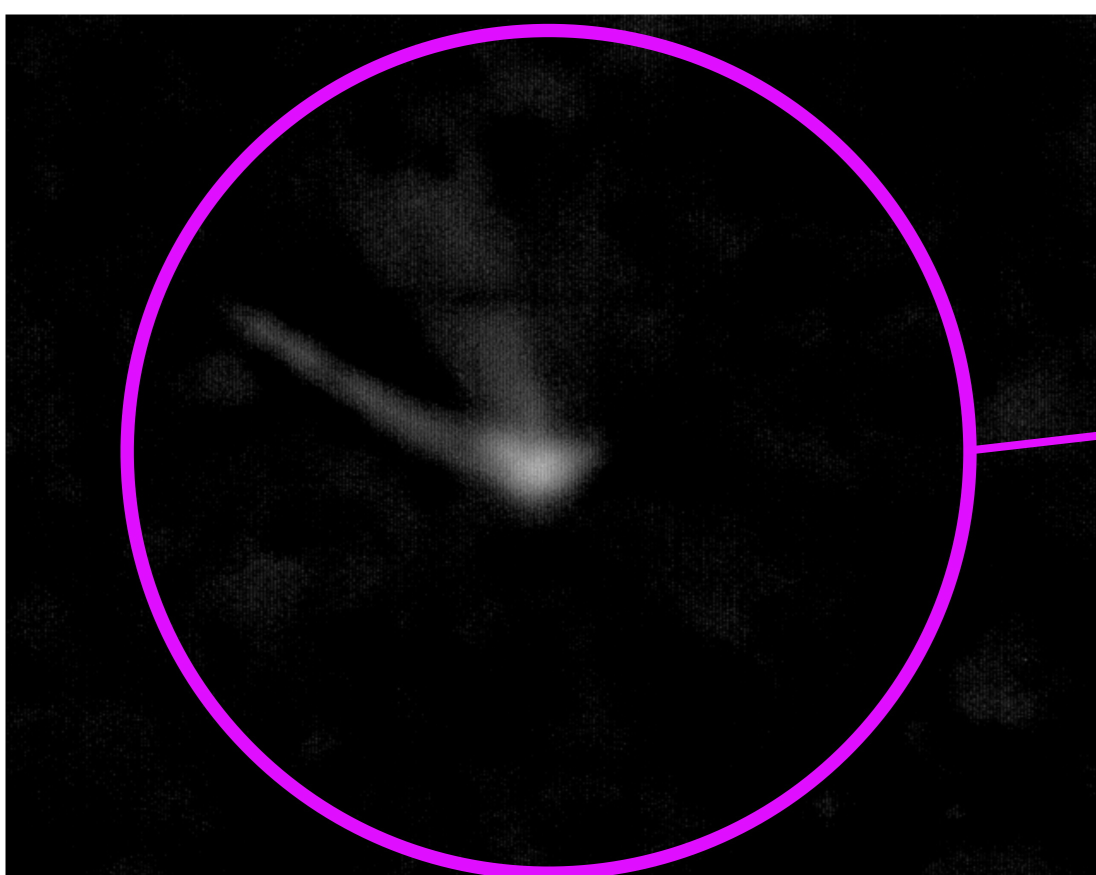
S. Aghion et al., PRA 94, 012507 (2016)

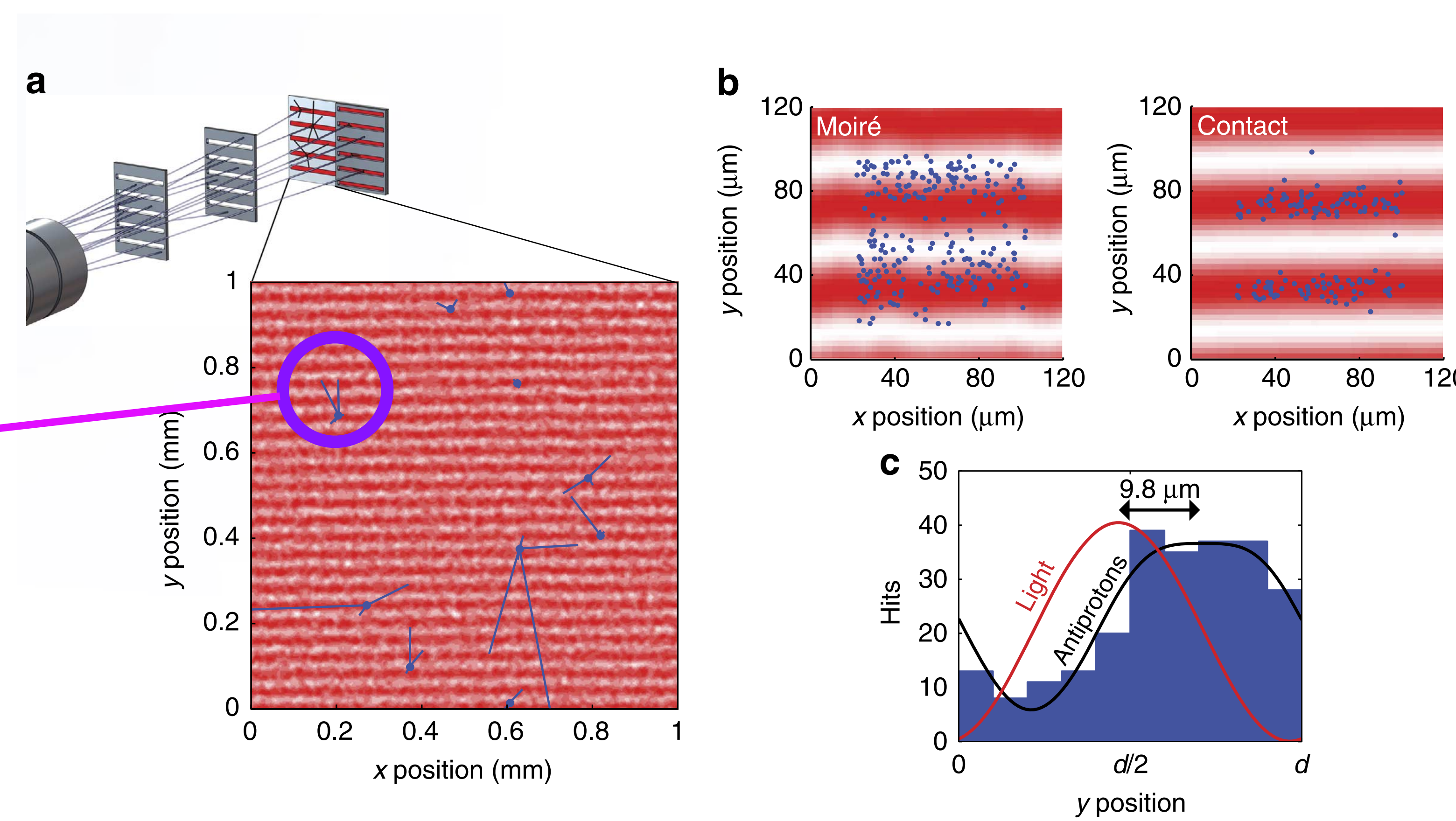
Deflectometer test with antiprotons





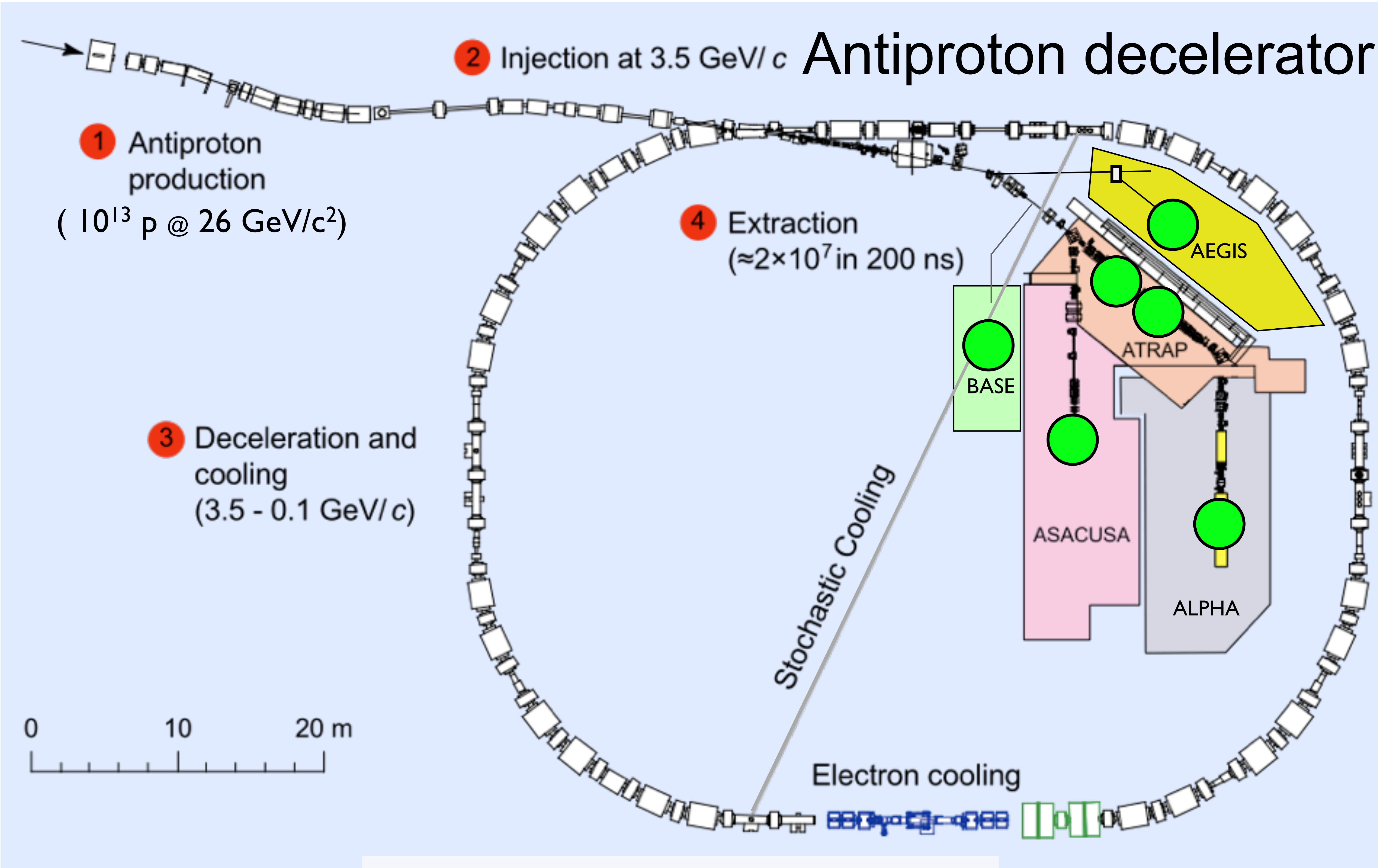






S. Aghion et al.,"A moiré deflectometer for antimatter", Nature Communications 5 (2014) 4538

Two main challenges: more / colder antiprotons

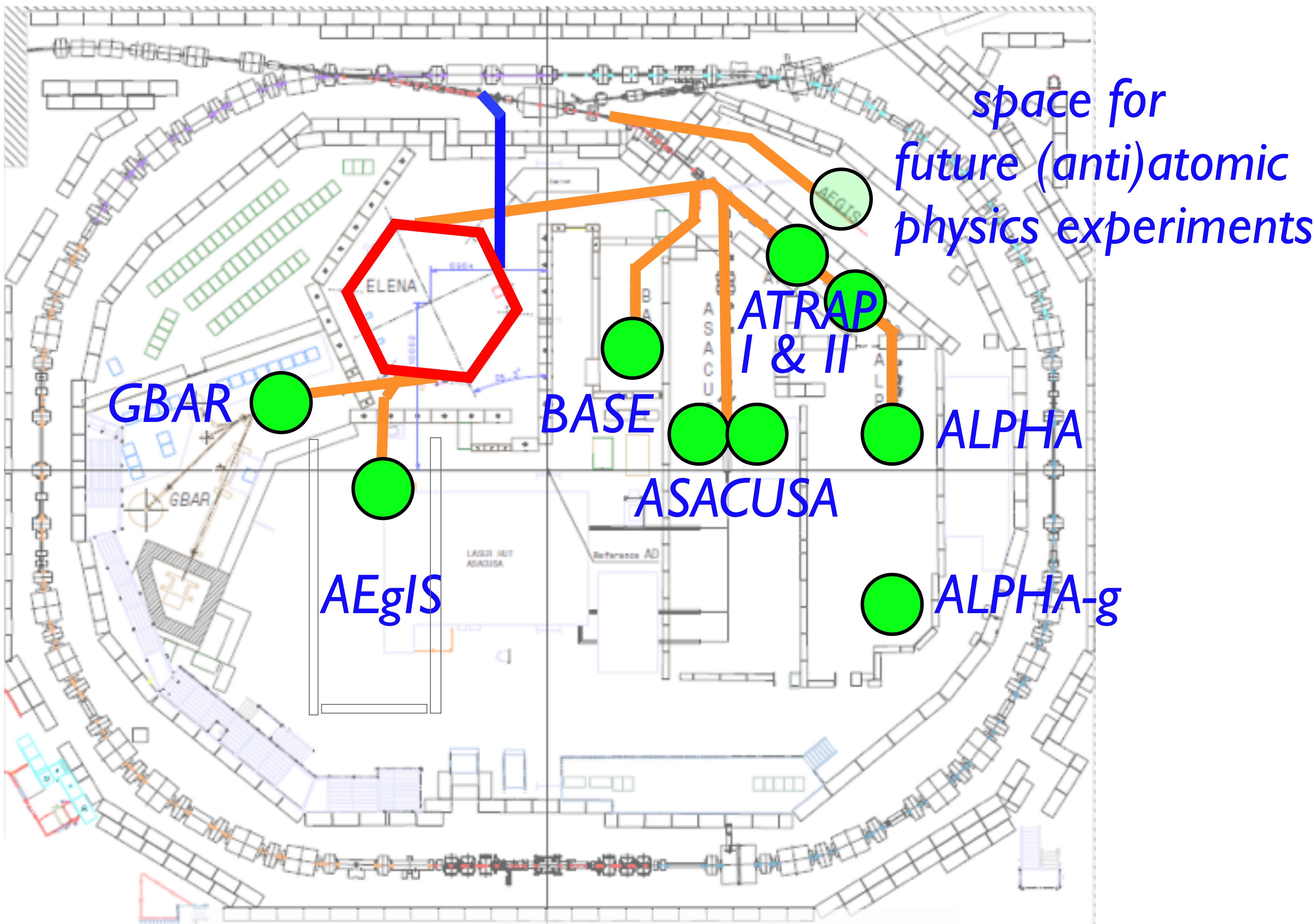


extraction at 5.3 MeV

Two main challenges: more / colder antiprotons

current methods for trapping them are quite inefficient

ELENA to the rescue

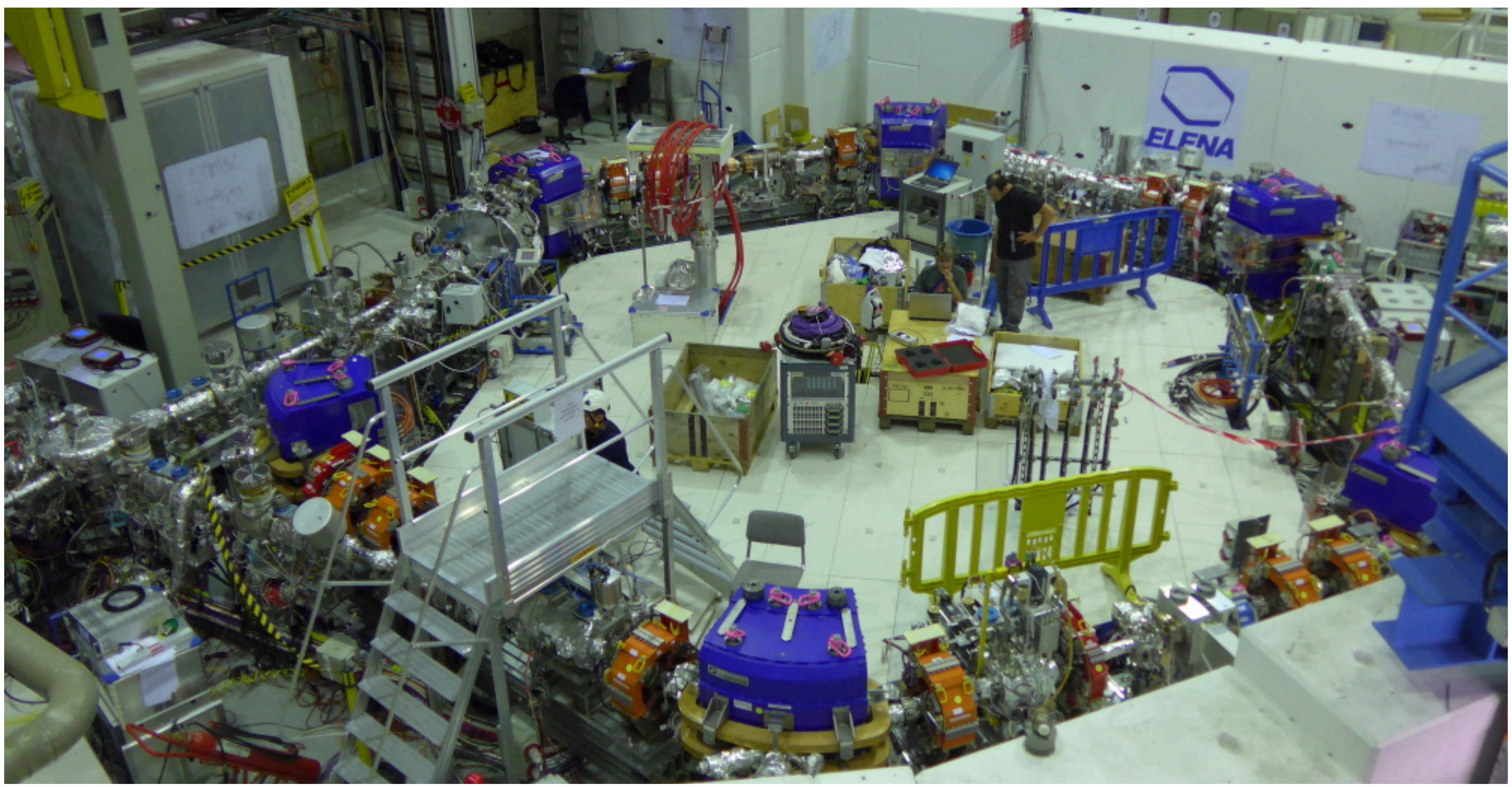


extraction at 100 keV

ELENA is a tiny new decelerator that:

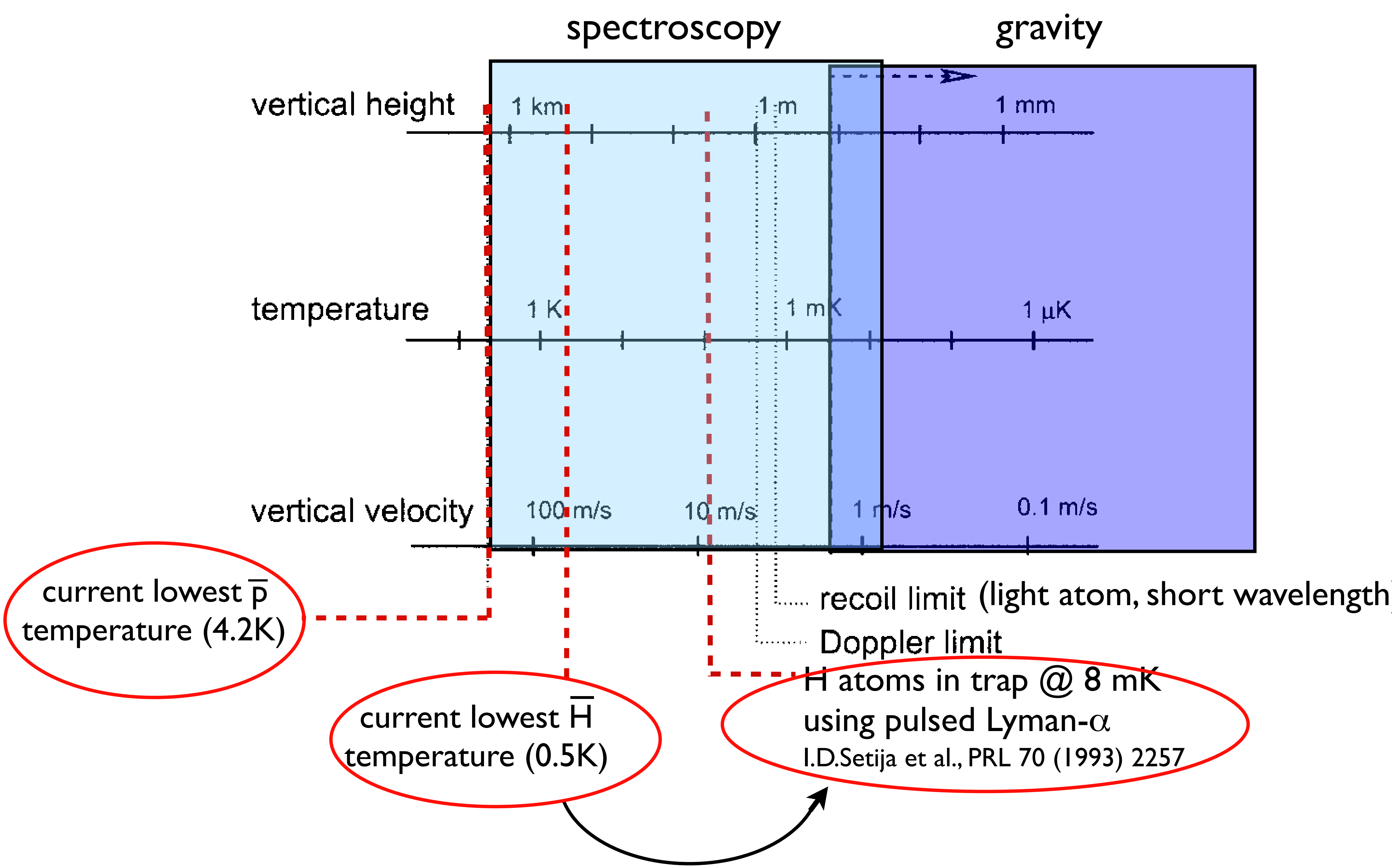
- dramatically slows down the antiprotons from the AD
- increases the *antiproton* trapping efficiency x 100
- allows 4 experiments to run in parallel
- allows new experiments to be considered

commissioning
started in 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 *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 μK

photodetachment at ~6083 cm^{-1}

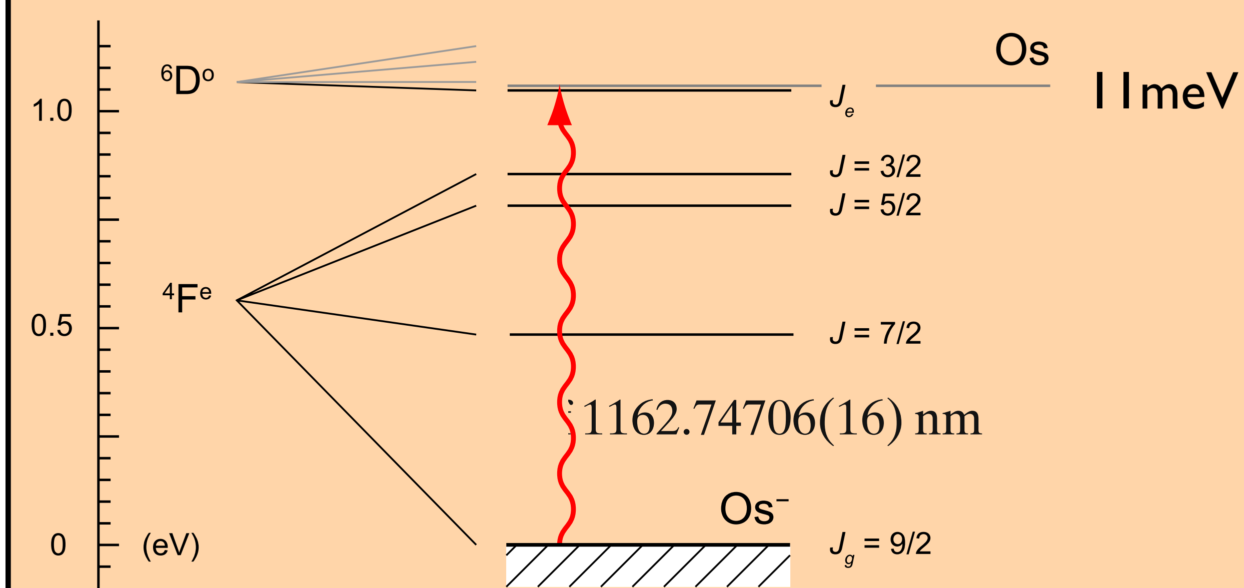
gravity measurement via “TOD”

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



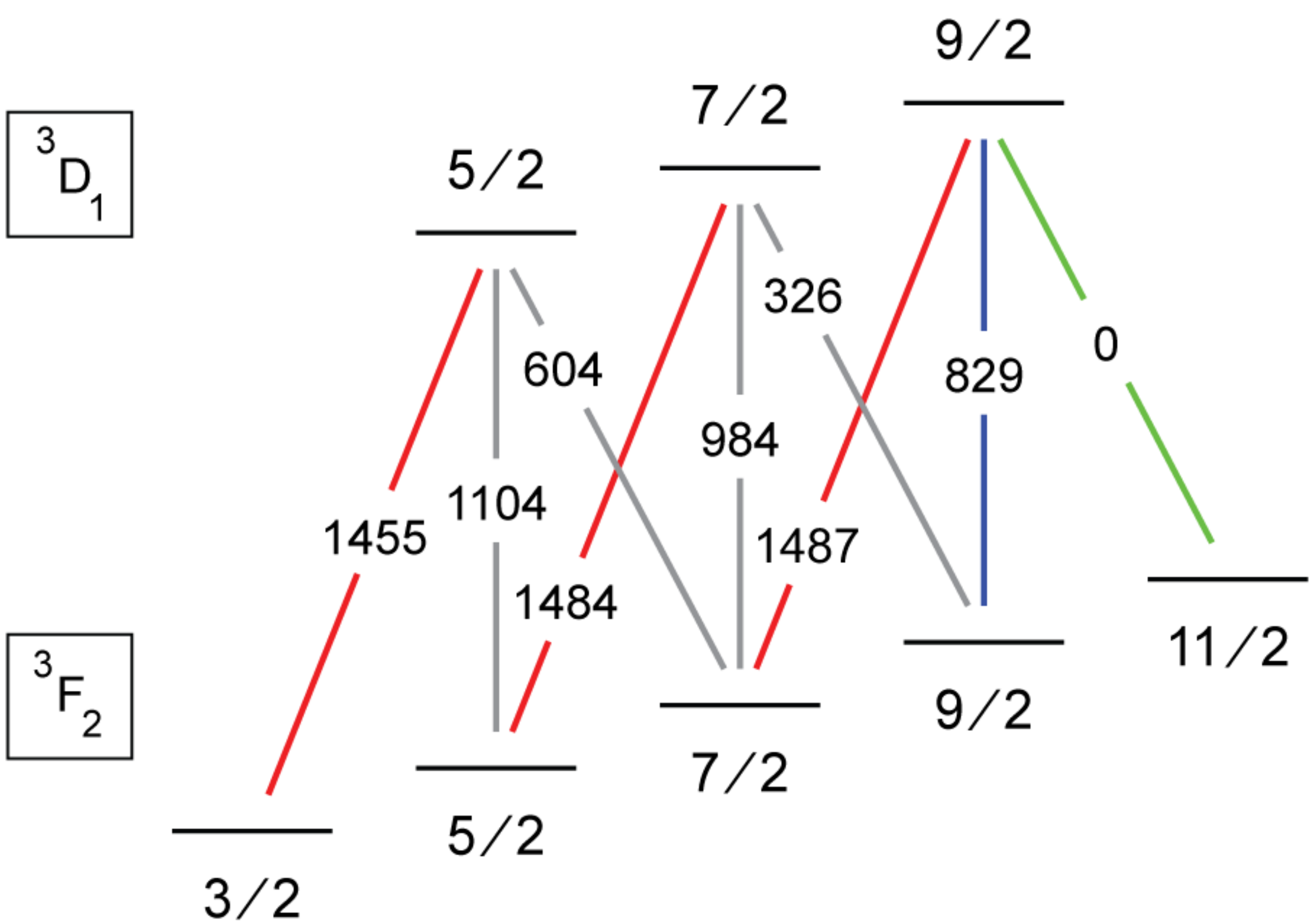
very weak cooling

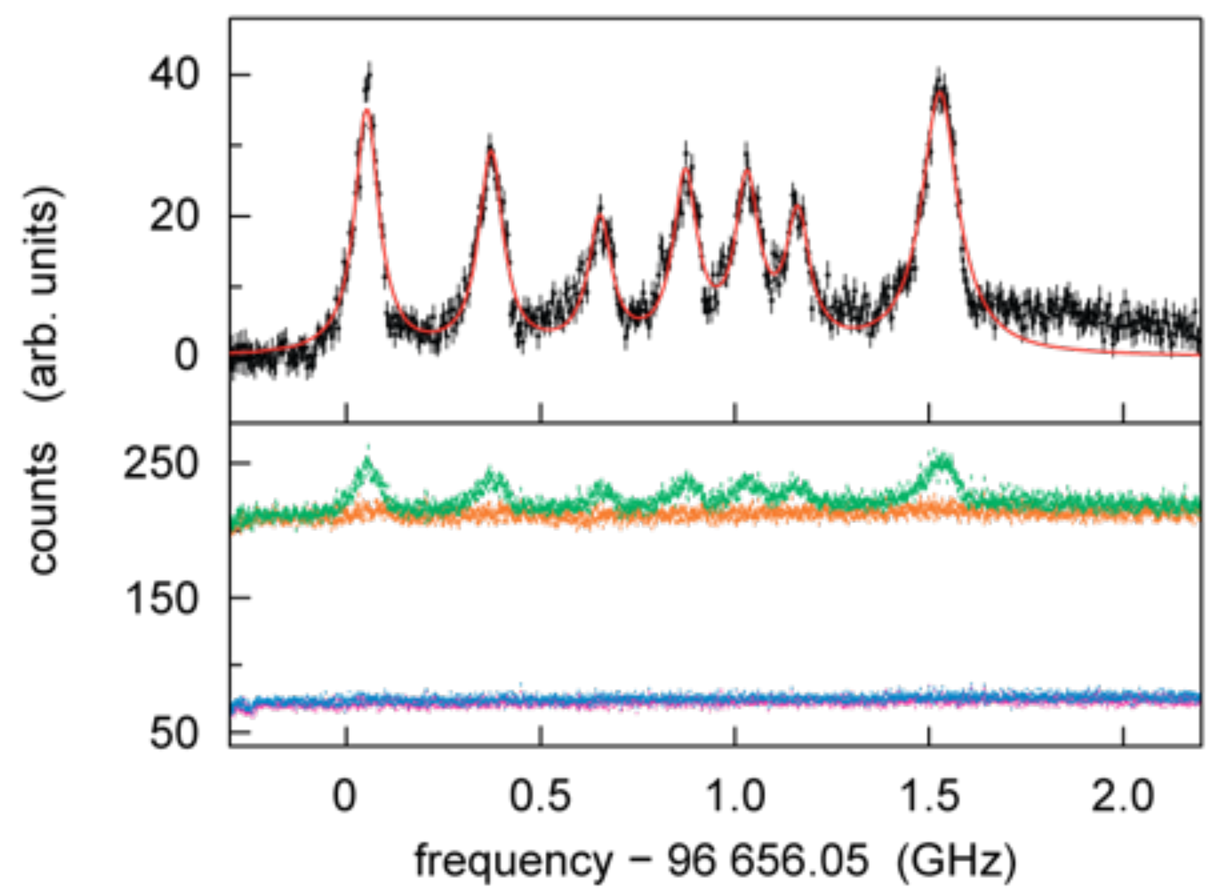
→ best to start at ~ 4K and cool to Doppler limit ($T_D \approx 0.24\ \mu K$)

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

laser-cooling of anions (➞ sympathetic cooling of antiprotons)

ongoing work in Heidelberg with La$^-$: HF transitions fully characterized
transition (cooling) rate of several kHz
(only) 3 laser wavelengths required for cooling

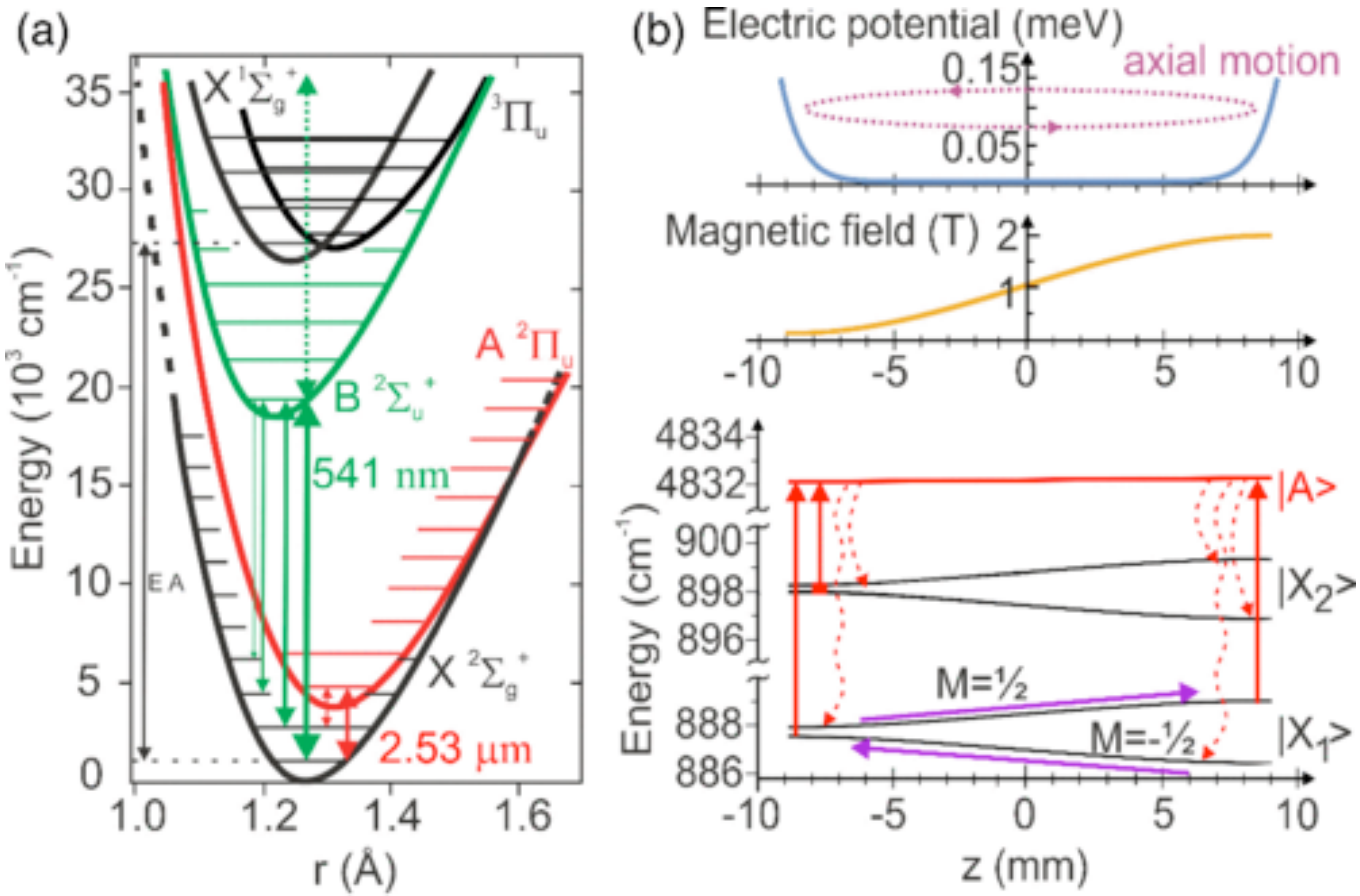




- next step: trapping, cooling of La$^-$

E. Jordan, G. Cerchiari, S. Fritzsche, and A. Kellerbauer
Phys. Rev. Lett. 115, 113001

Anion cooling for AEgIS: C_2^- Sisyphus cooling



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

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

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), spectroscopy, ...

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

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

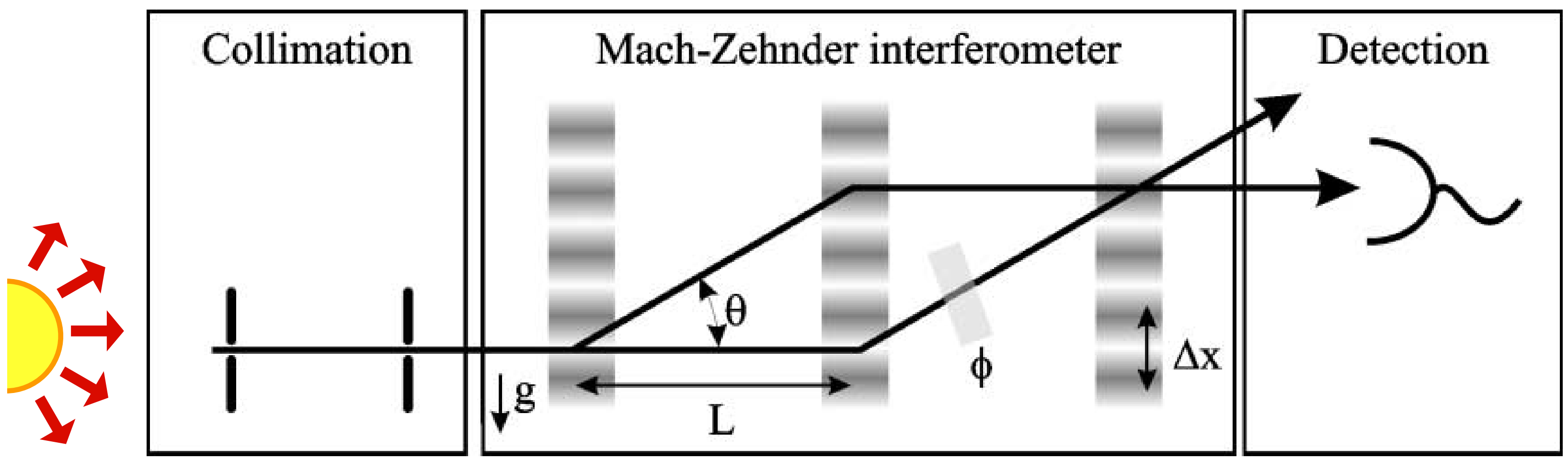
$\bar{p}N$: trapped $\bar{p}$ (AD) + radioisotopes (ISOLDE) = PUMA

positronium...

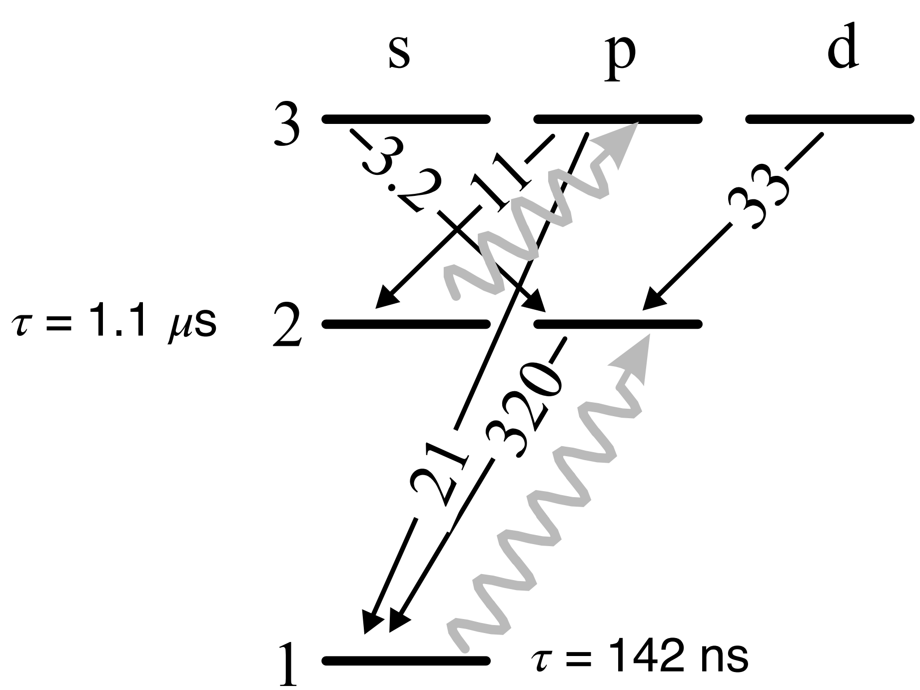
physics interest: QED atomic spectrum, gravity (via matter wave interferometry)

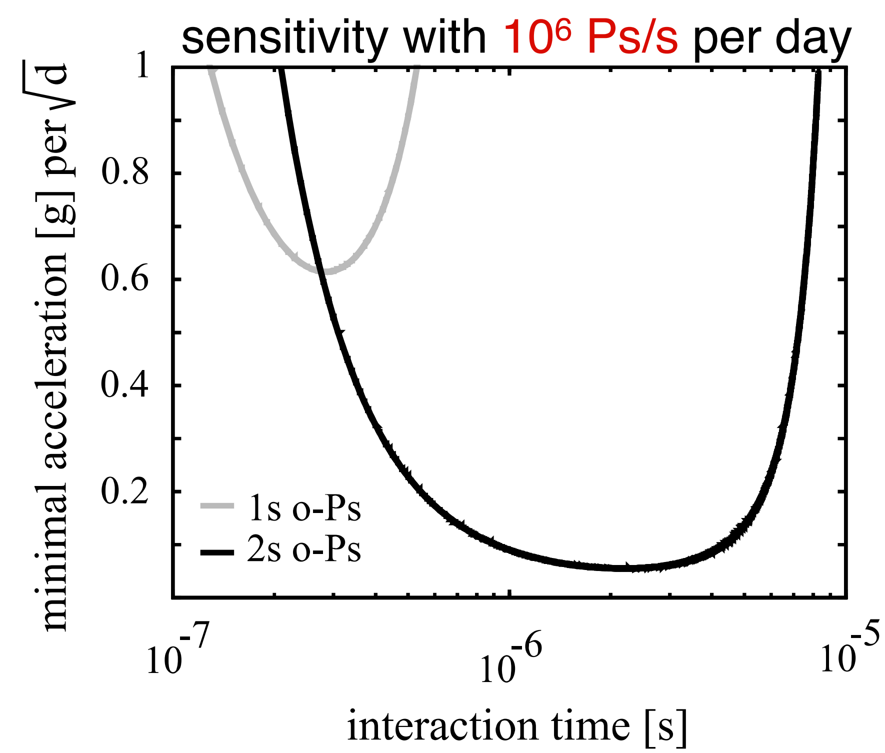
M. Oberthaler, NIMB, Volume 192, Issues 1–2, (2002) 129

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

protonium...

<u>physics interest</u>: QCD-induced shift, broadening of QED atomic spectrum

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

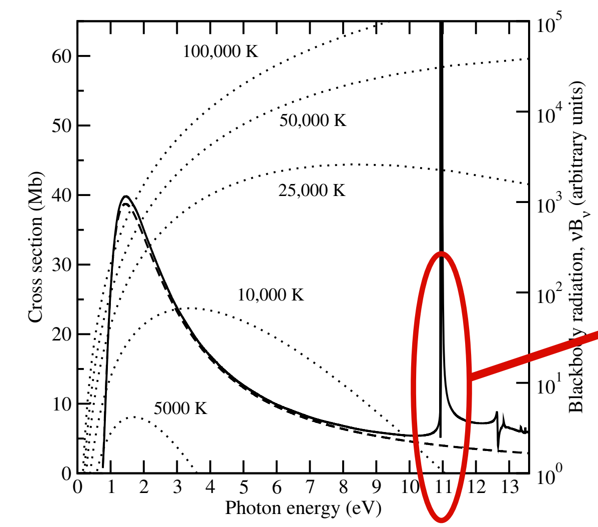
spontaneous formation in n~40, Stark mixing, rapid annihilation

spectroscopy resolution determined by fluorescence detector resolution

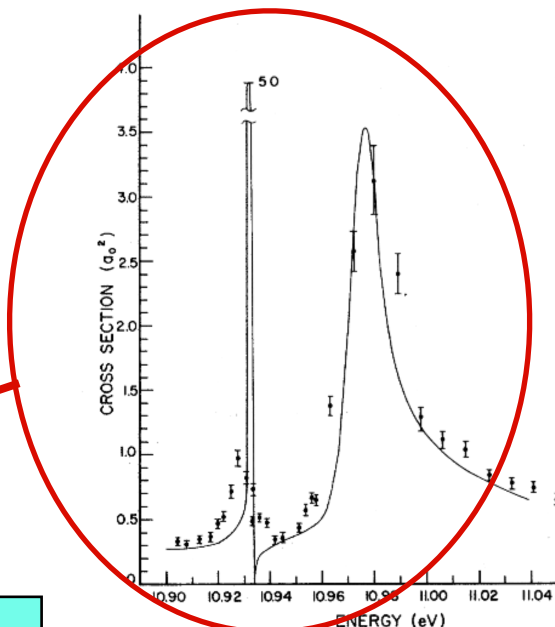
alternative: pulsed formation via co-trapped $\bar{p}$ and H^-

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

pulsed formation ➞ laser spectroscopy on $p\bar{p}$;
resolution determined by laser resolution



H. Sadeghpour, A. Dalgarno, R. Forrey, The Astrophysical Journal Letters, 709:L168–L171, 2010



H. C. Bryant et al., PRL 38 (1977) 228

improvements: formation rate increased if n(H) >> 1

improvements: life time increased if n(H) >> 1

➞ long-lived cold Rydberg protonium ➞ trap/beam ➞ gravity measurement
precision spectroscopy

Summary and 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 further orders of magnitude in the coming years
- tests of the WEP are becoming feasible, with precisions that can be expected to initially reach % or ‰ level

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 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, ...)