Experiments on antimatter at CERN

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

Phys. Rev. D 55, 6760–6774 (1997)

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

Modified Dirac eq. in SME

CPT & Lorentz violation

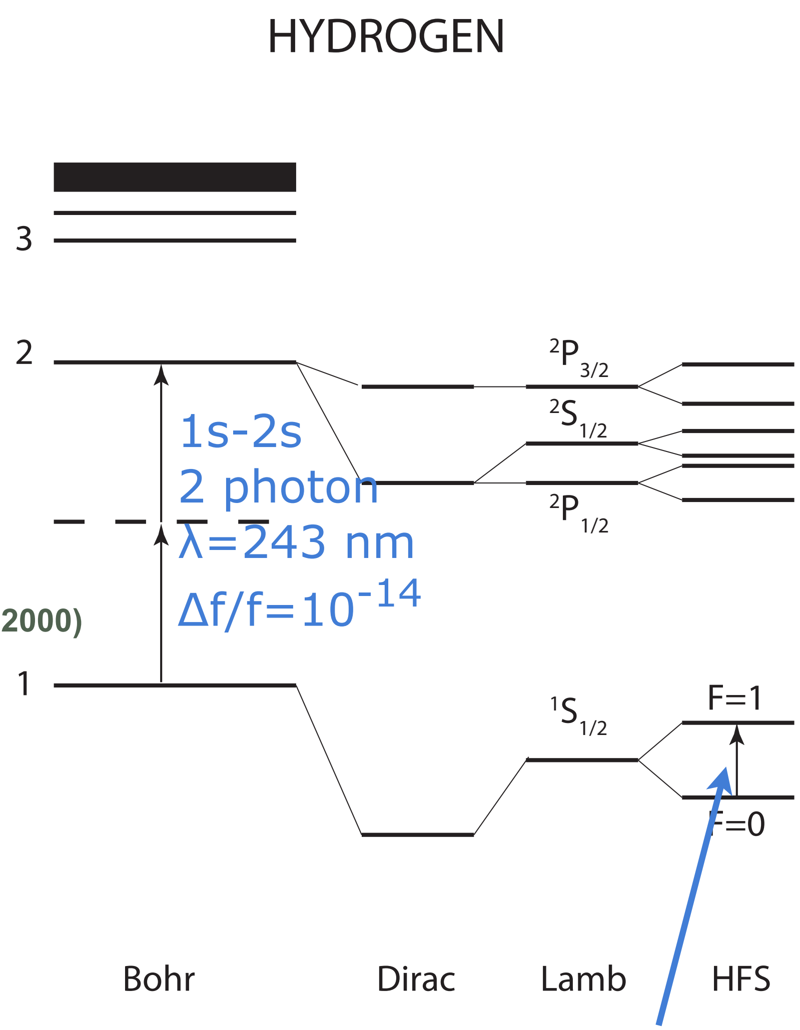
$$(i\gamma^{\mu}D_{\mu} - m_e - \boxed{a^e_{\mu}\gamma^{\mu} - b^e_{\mu}\gamma_5\gamma^{\mu}}$$
$$- \boxed{\tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^{\mu}D^{\nu} + id^e_{\mu\nu}\gamma_5\gamma^{\mu}D^{\nu}})\psi = 0\,.$$

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

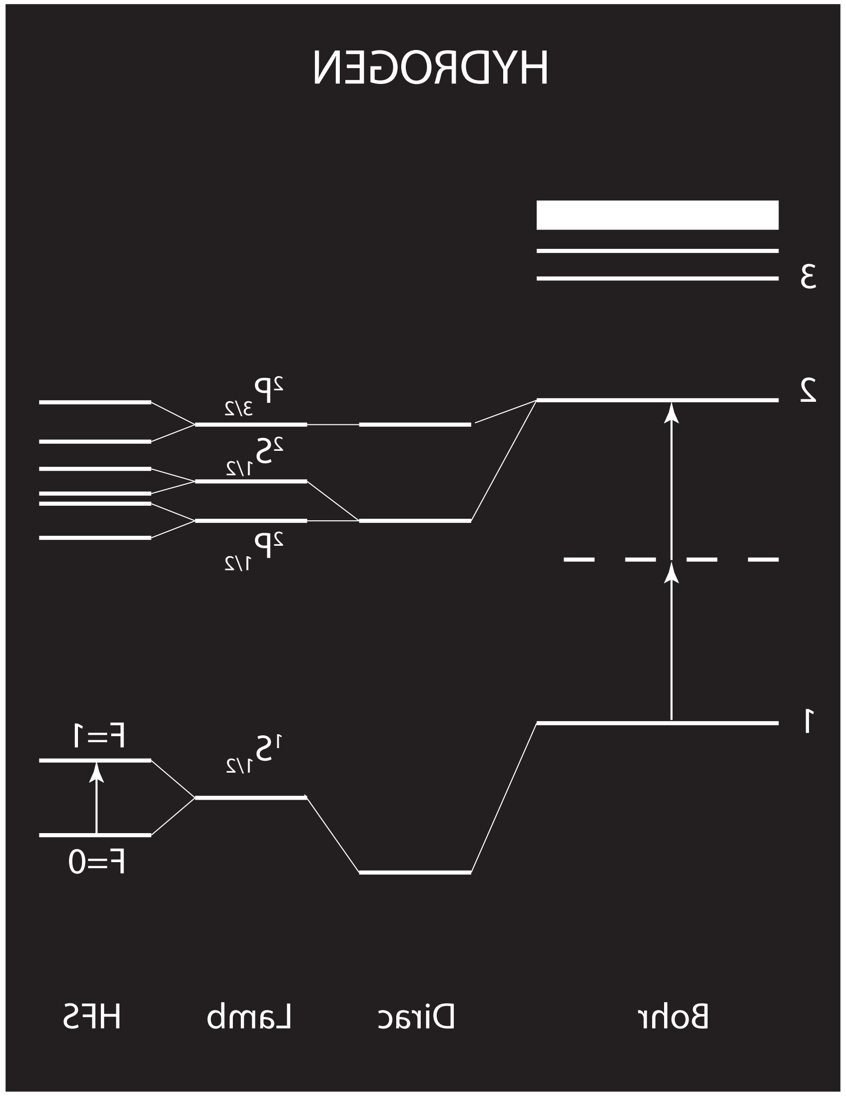


1s-2s
2 photon
λ=243 nm
$\Delta f/f=10^{-14}$

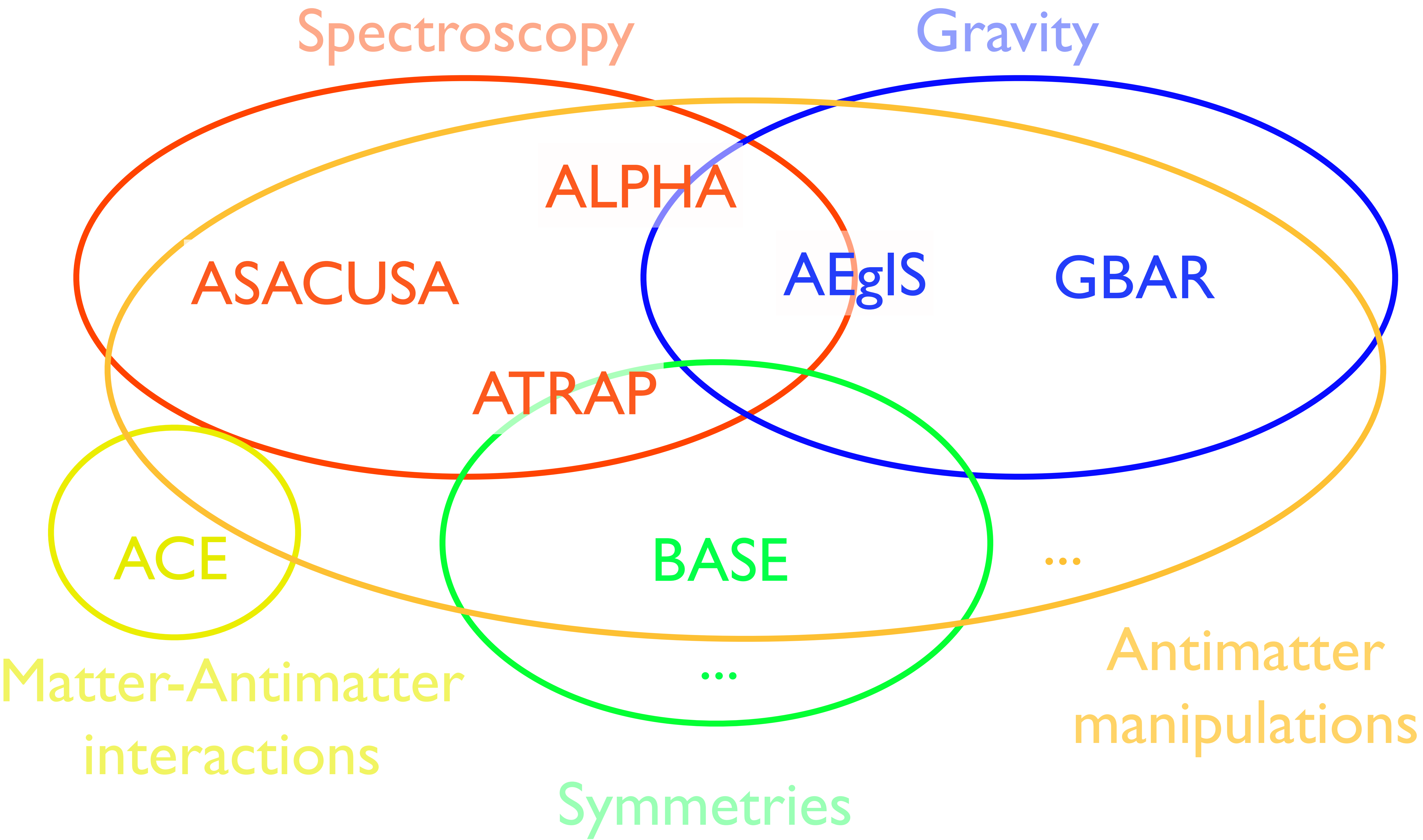
T. Hänsch et al.,
Phys. Rev. Lett. 84, 5496–5499 (2000)

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)



Spectroscopy

Gravity

ALPHA

ASACUSA

AEgIS

GBAR

ATRAP

ACE

BASE

...

...

Matter-Antimatter interactions

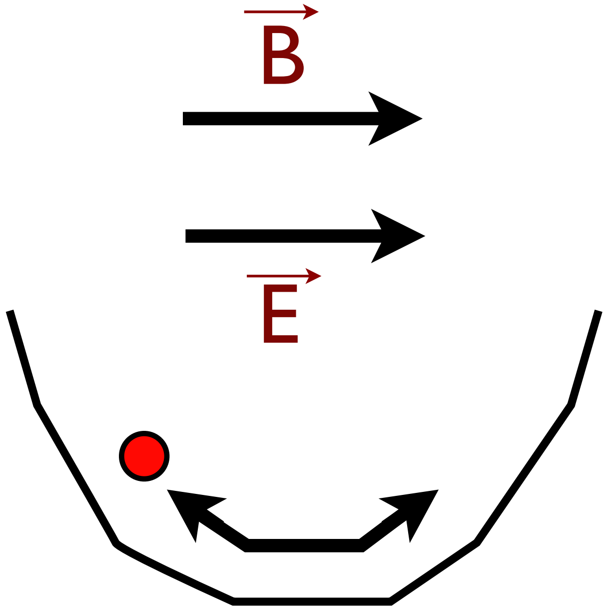
Symmetries

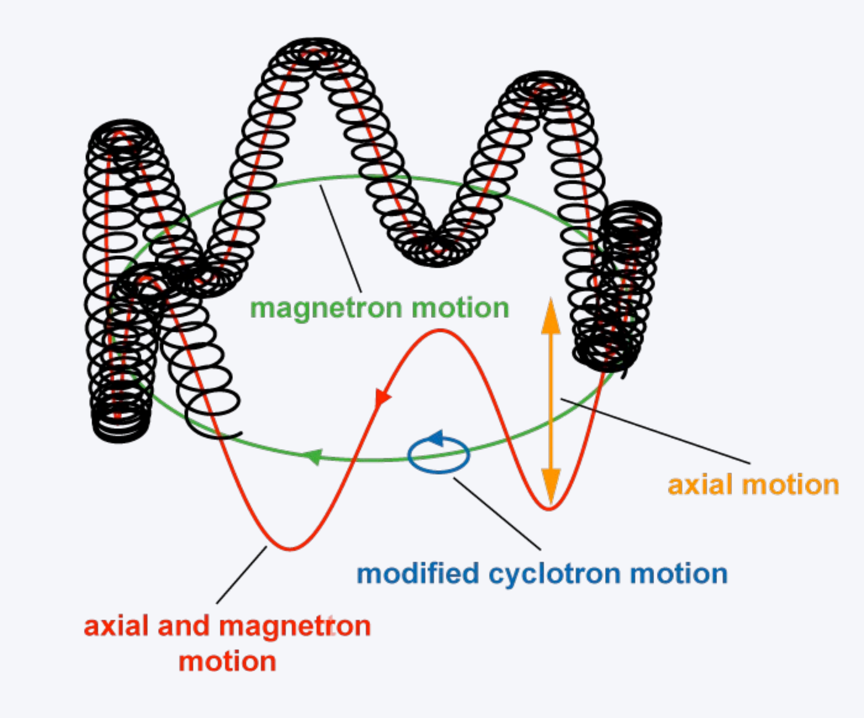
Antimatter manipulations

ATRAP & BASE

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

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}}$$

O(100 MHz)

magnetron motion

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}}$$

O(1 MHz)

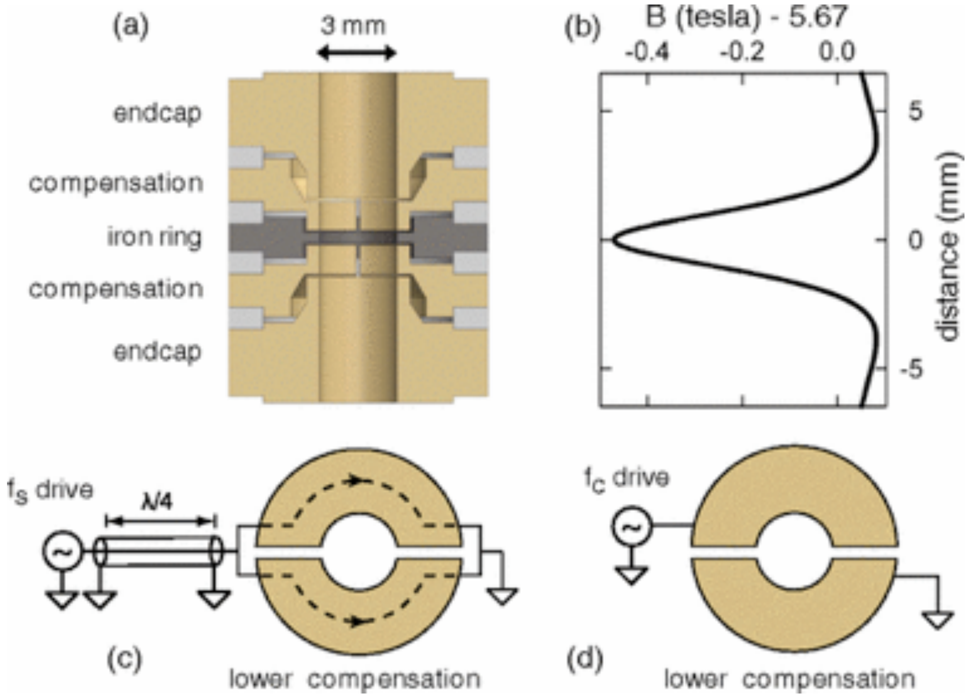
axial motion

$$\omega_z = \sqrt{\frac{q}{m_p} 2c_2 U_0}$$

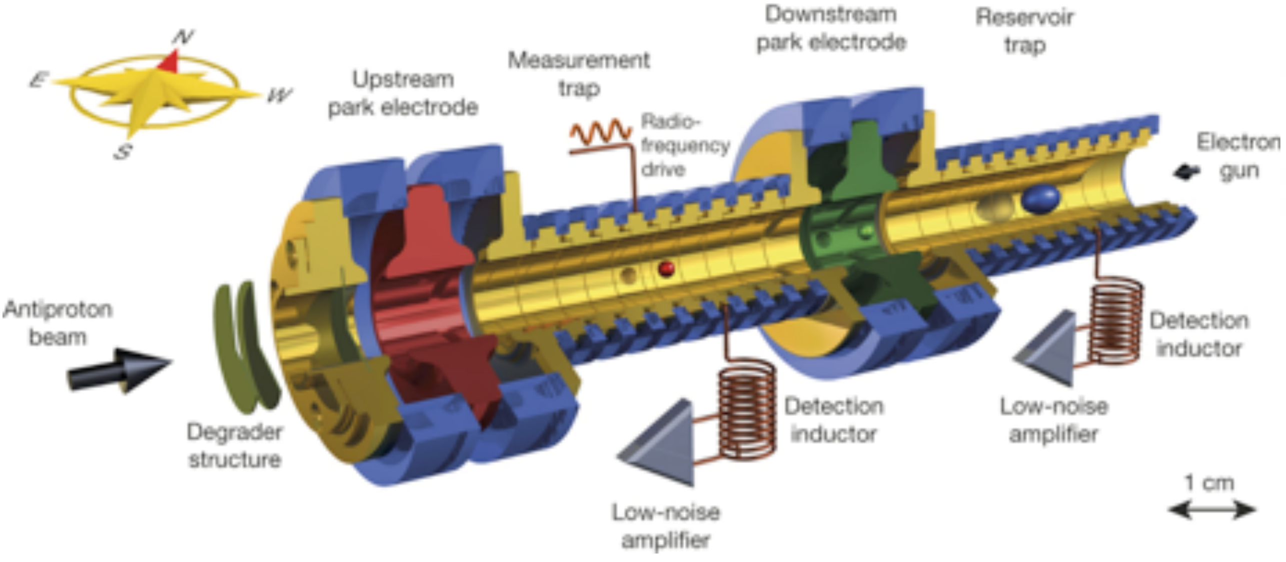
O(10 kHz)

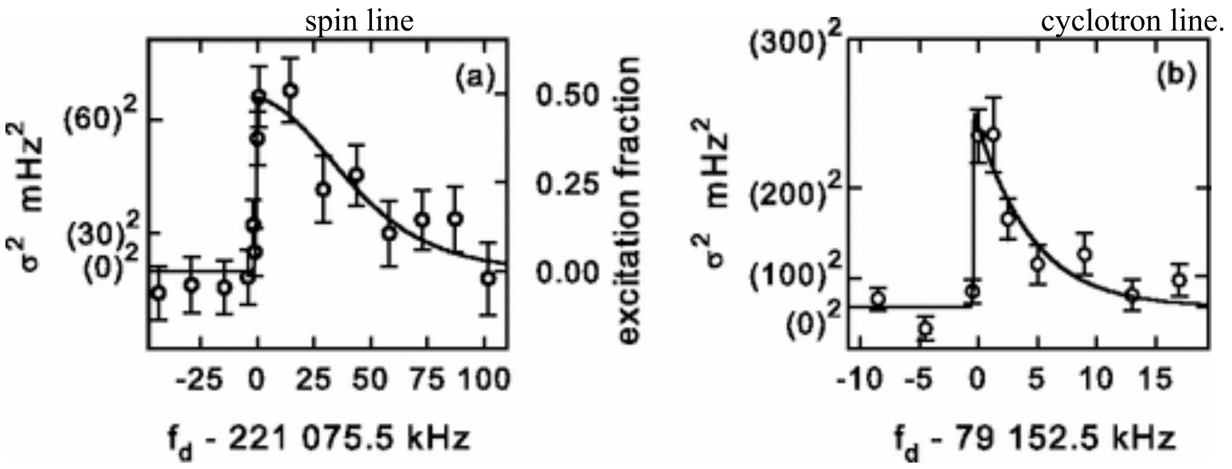
ATRAP & BASE

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)

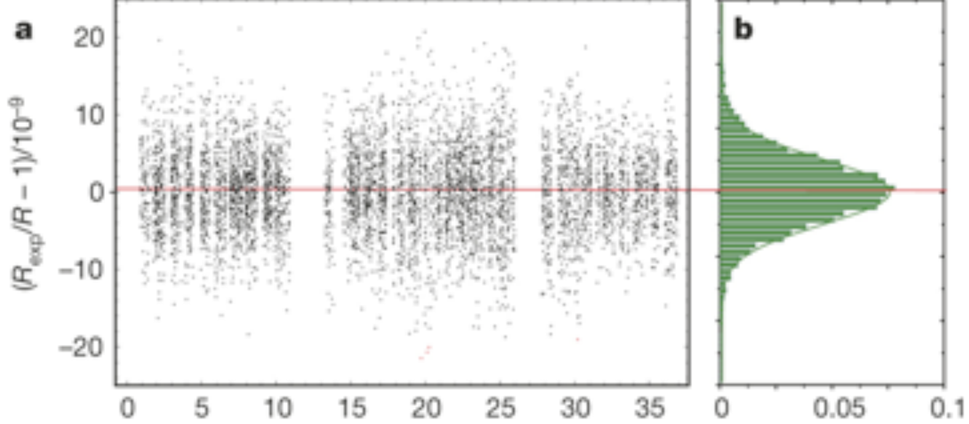




ATRAP: $\mu p/\mu \bar{p} = -1.000000 \pm 0.000005$ (2013)

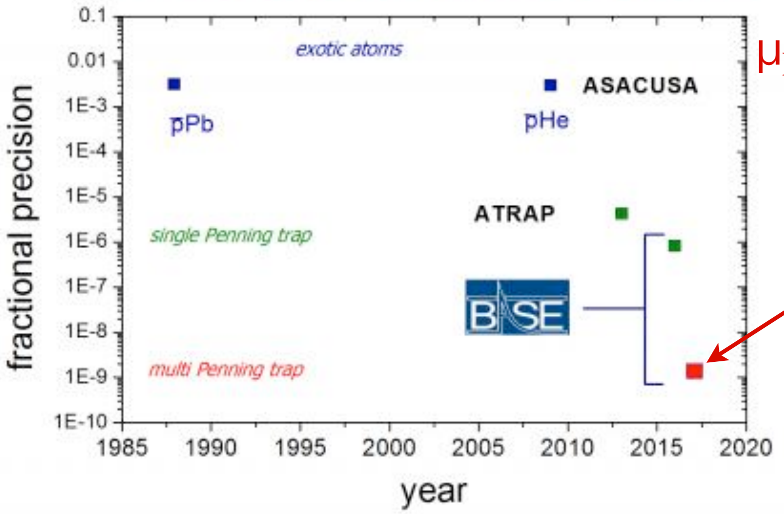
BASE: $(q/m)_{\bar{p}}/(q/m)_p - 1 = 1(69) \times 10^{-12}$ (2015)

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



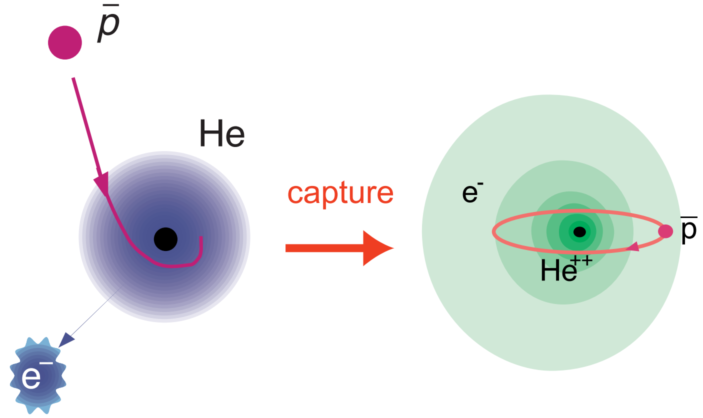
BASE: $\mu_{\bar{p}}$ = -2.792 847 344 1 (42) (2017)

μ_p = 2.792 847 350 0 (90)



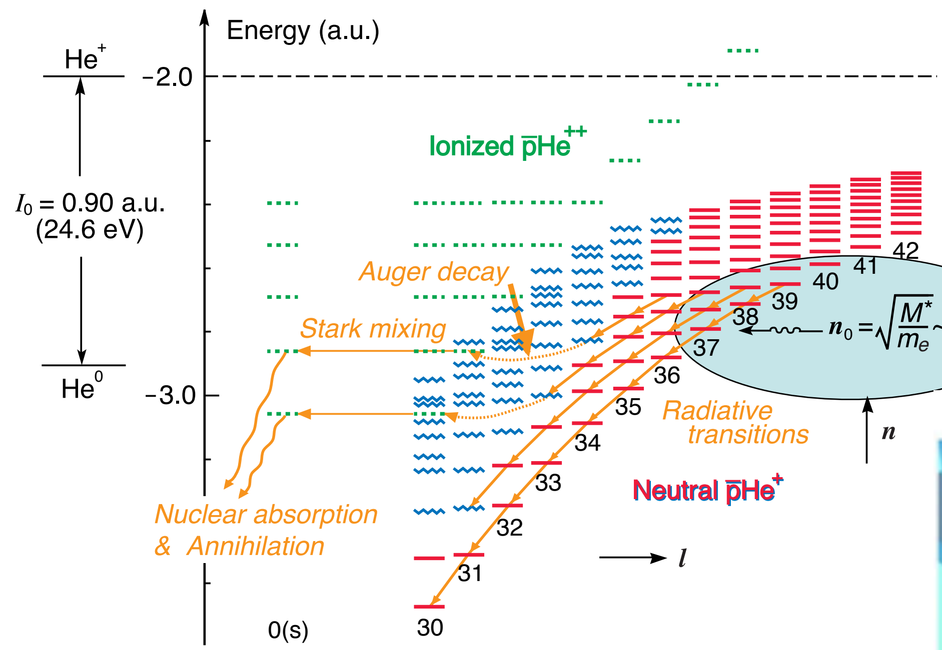
C. Smorra et al., BASE collaboration, Nature **550**, 371–374 (19 October 2017)

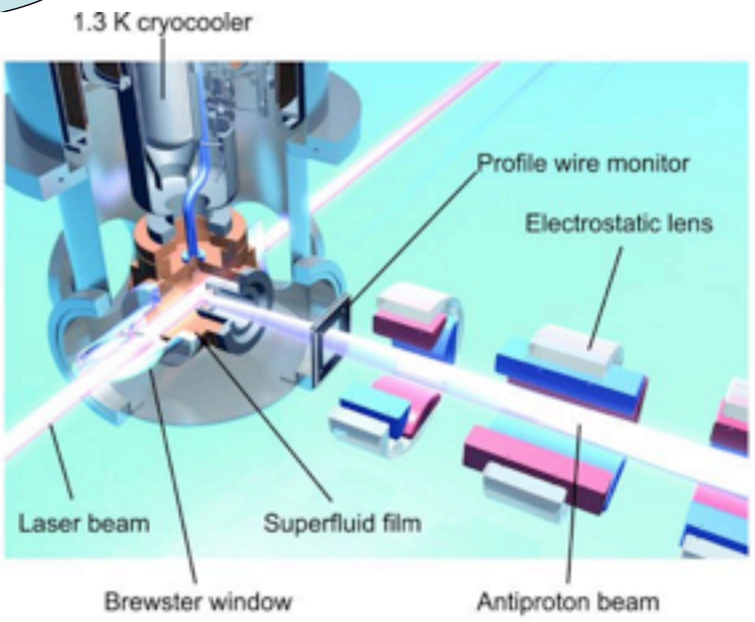
ASACUSA results ($\bar{p}He^+$ spectroscopy)

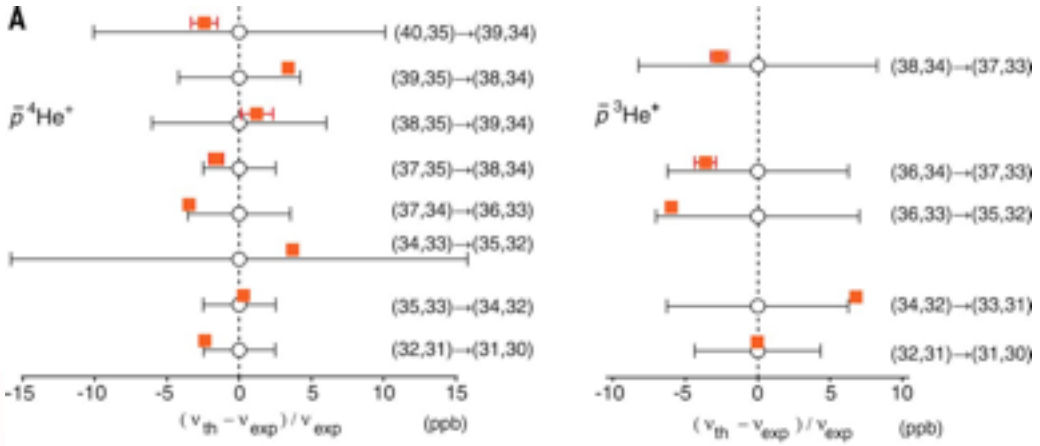


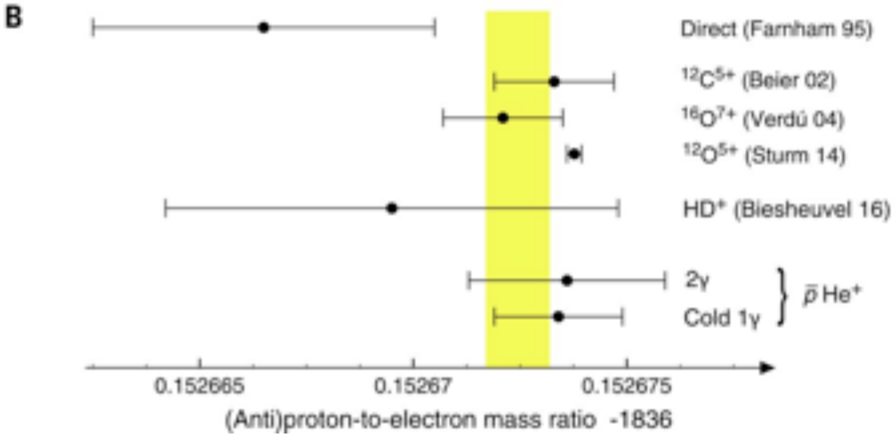
By comparing the calculated and experimental $\bar{p}He^+$ frequencies, the ratio $M_{\bar{p}}/m_e$ can in principle be determined to a fractional precision of <1 × 10^{-10}

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









Combining with ATRAP/BASE:

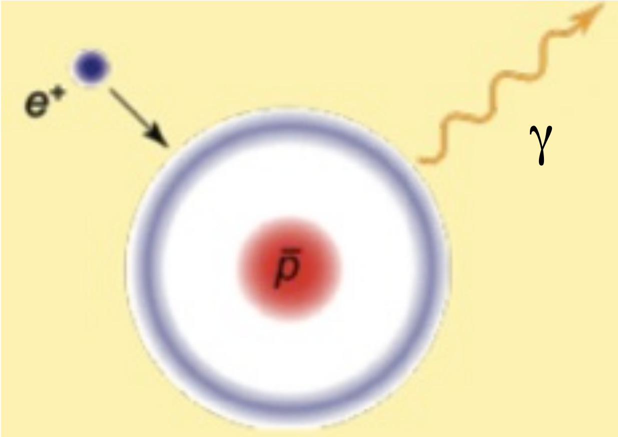
$\Delta(m_{\bar{p}},m_p)$, $\Delta(q_{\bar{p}},q_p)$ < 5 × 10^{-10} (90% CL)

Antihydrogen production processes

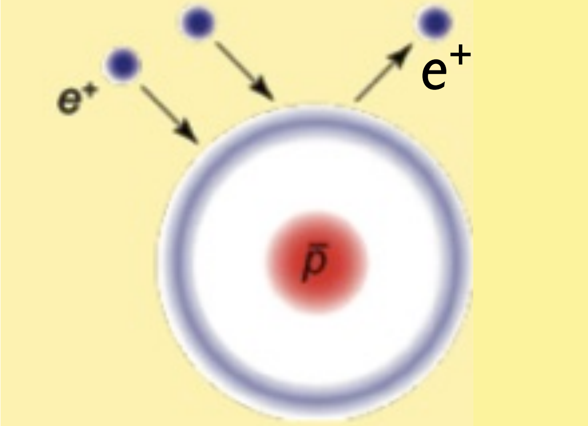
$10^5 \sim 10^7\ \bar{p}$

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

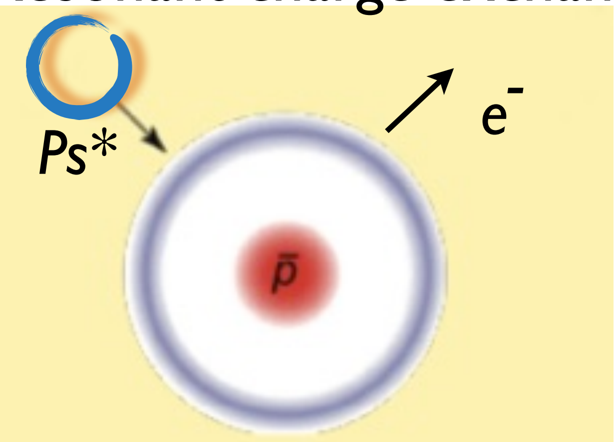
radiative recombination



TBR:
3-body recombination



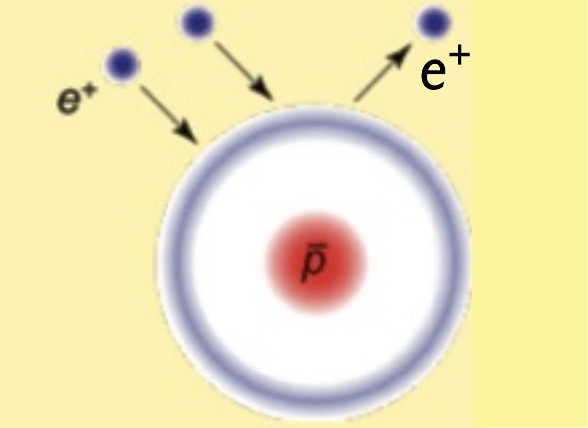
RCE:
Resonant charge exchange



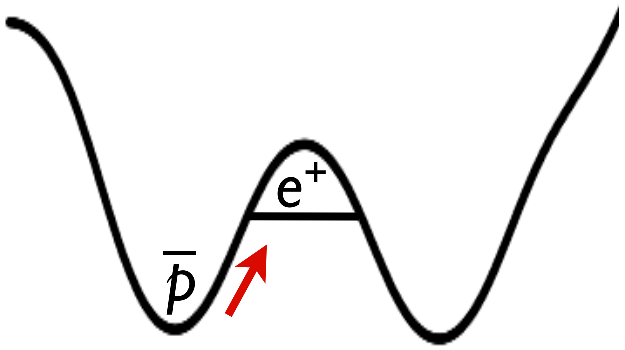
very low rate

Antihydrogen production processes

TBR:
3-body recombination



ALPHA
ATRAP
ASACUSA



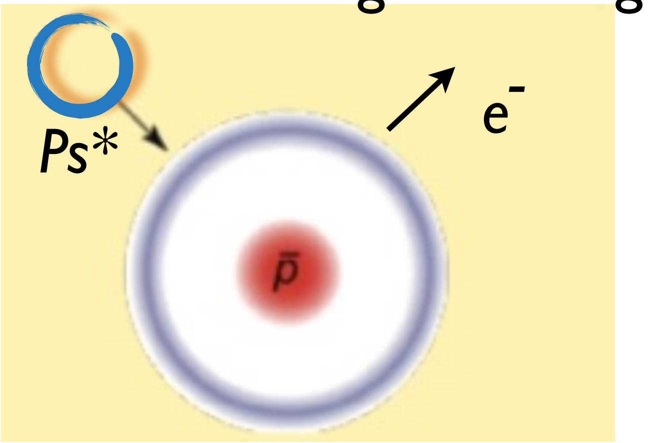
Temperature
(T_{e+})

Rate ~ Rate (trappable)

n *(if trapped)*

RCE:
Resonant charge exchange

AEgIS
GBAR



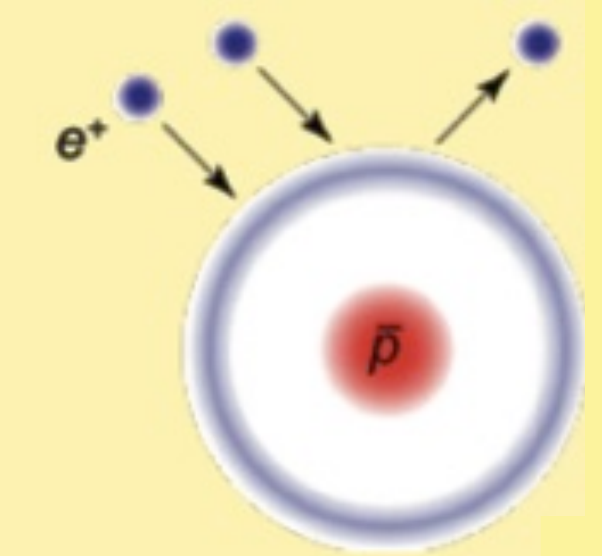
Temperature
$T_{\bar{p}}$

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

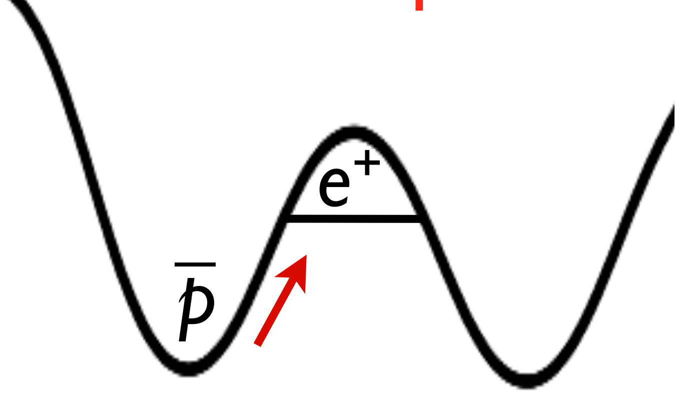
n *(if trapped or slow)*

ALPHA: antihydrogen formation & trapping

3-body recombination

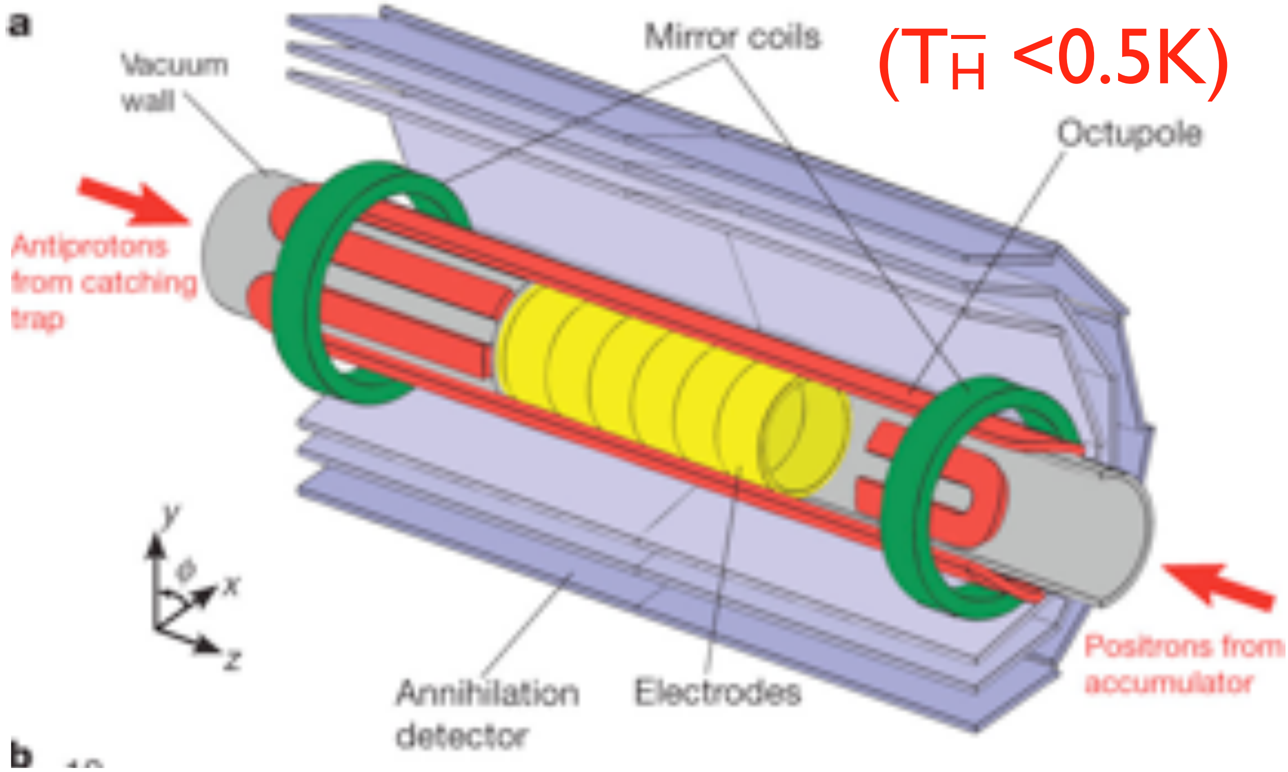


continuous process

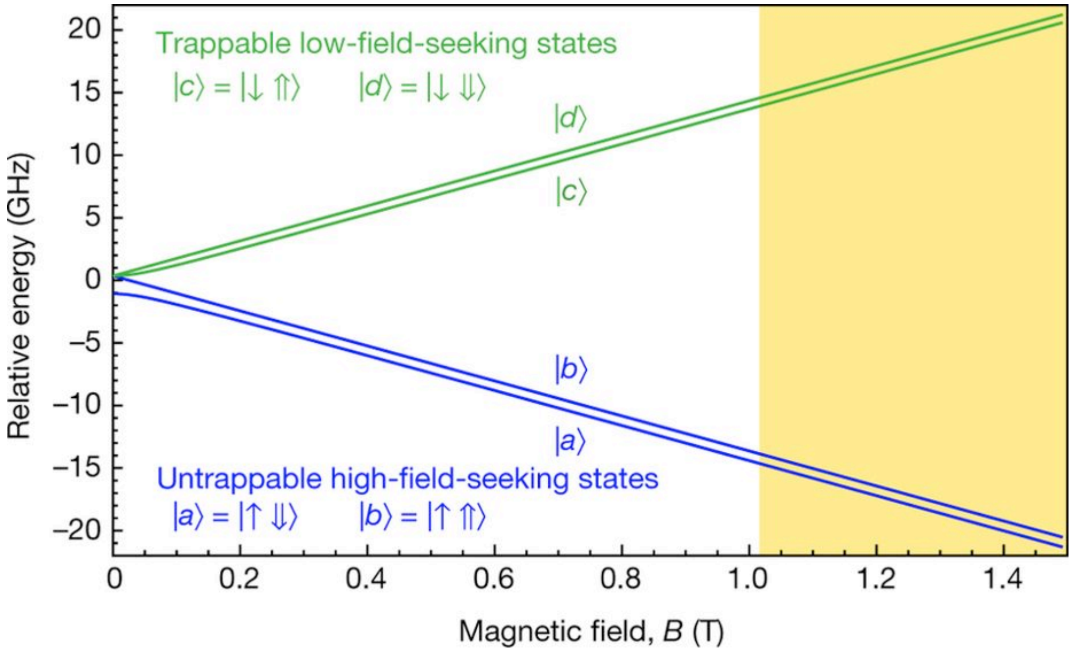


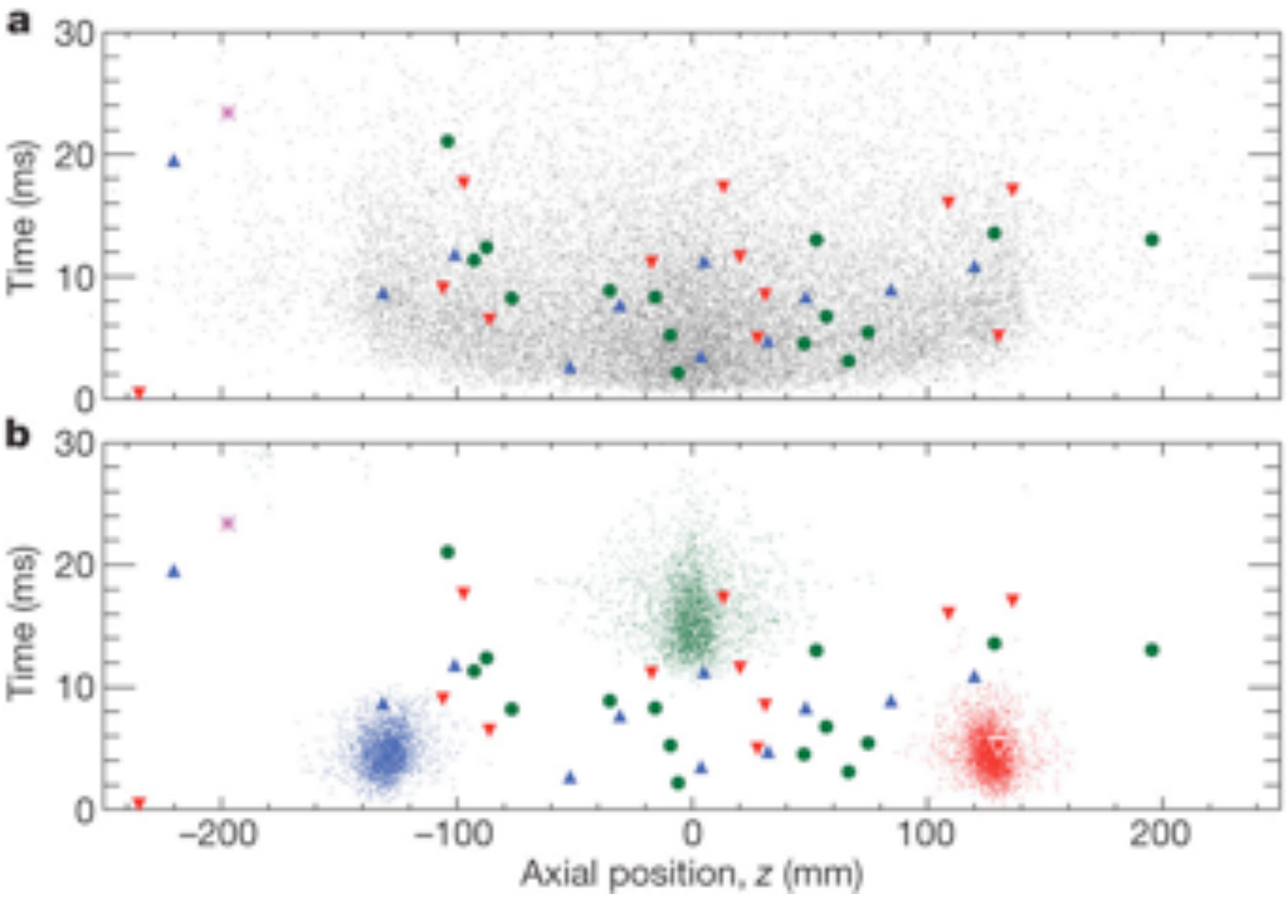
$v_{\bar{H}} \sim v_{e^+}$ ($T_{\bar{H}} >> T_{e^+}$)

($T_{\bar{H}}$ <0.5K)



trapping in B-field gradient

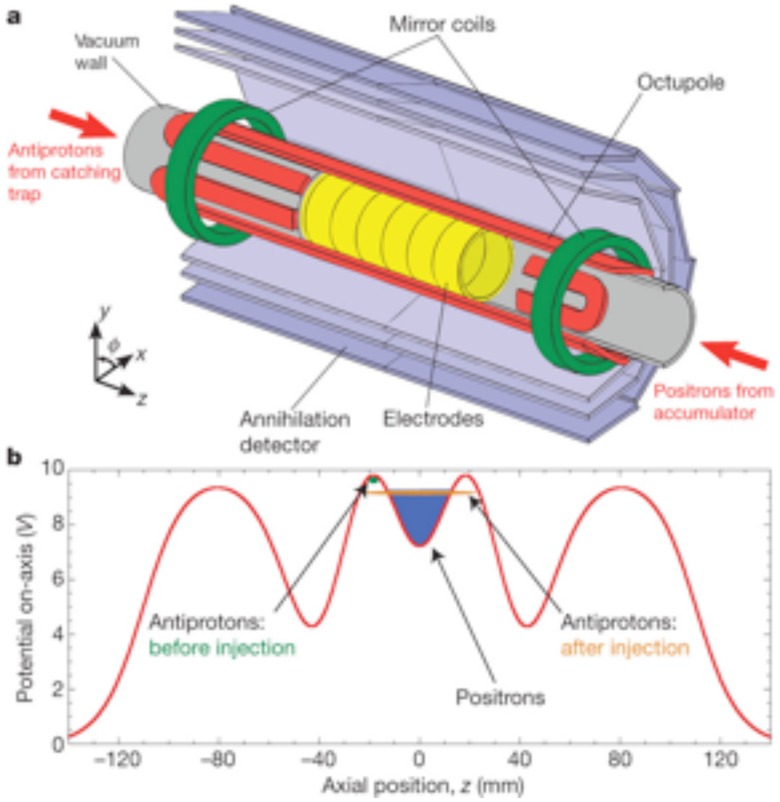


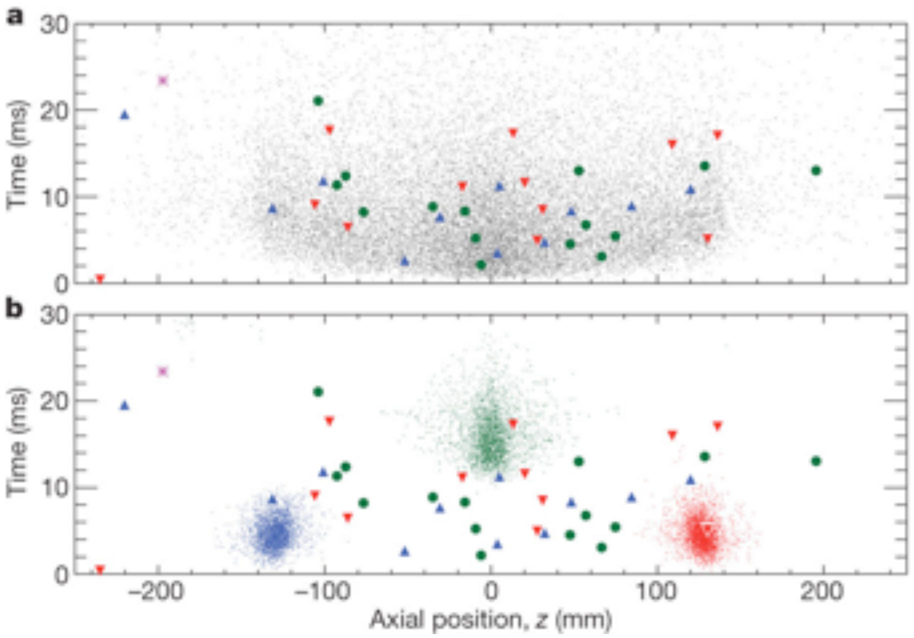


G. B. Andresen et al., Nature 468, 673–676 (02 December 2010)

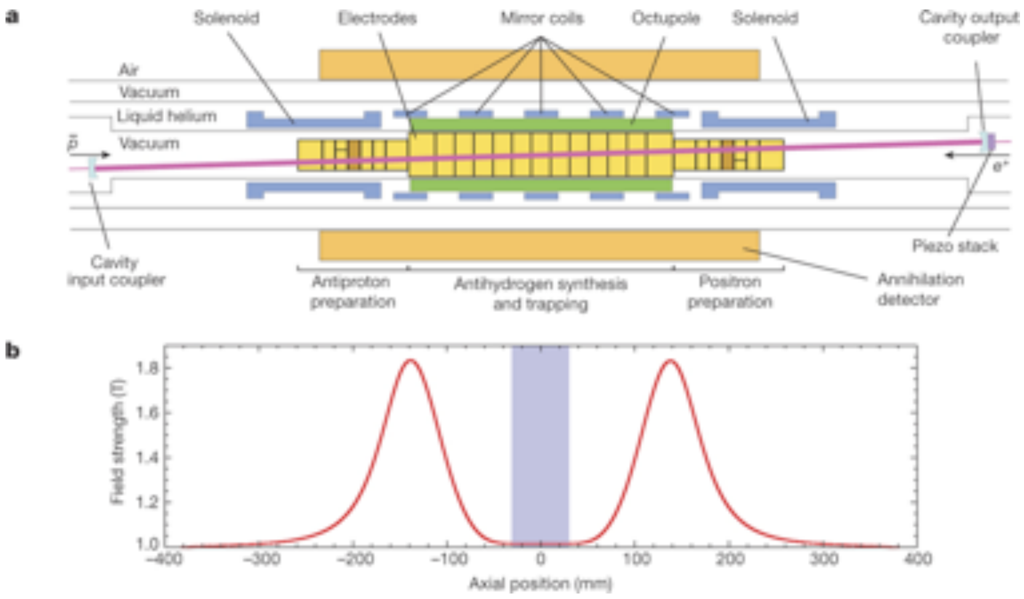
ALPHA results (trapping, 1s-2s spectroscopy)

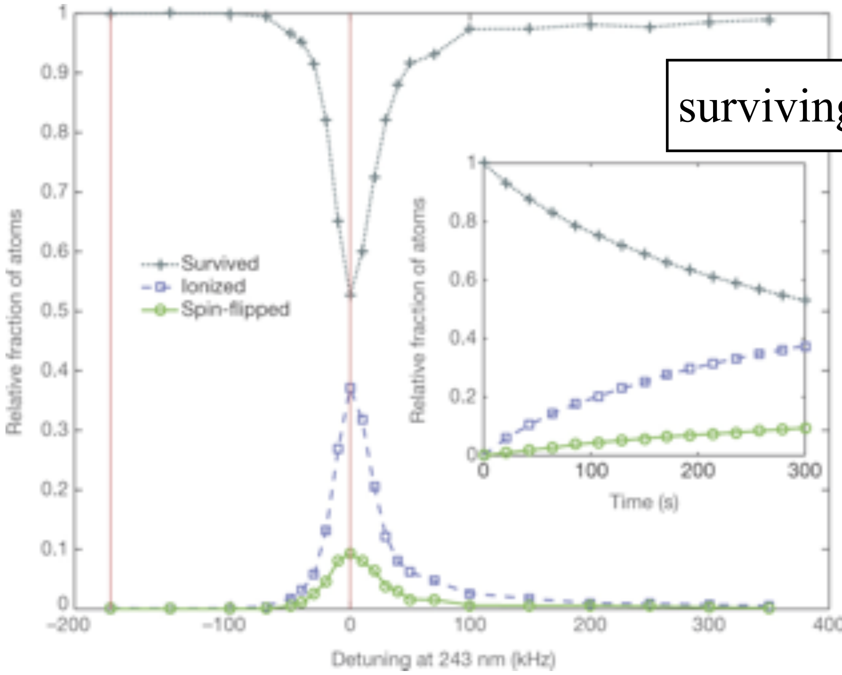
G. B. Andresen et al., Nature 468, 673–676 (02 December 2010)





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





surviving fraction: 58% ± 6%

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

further results:

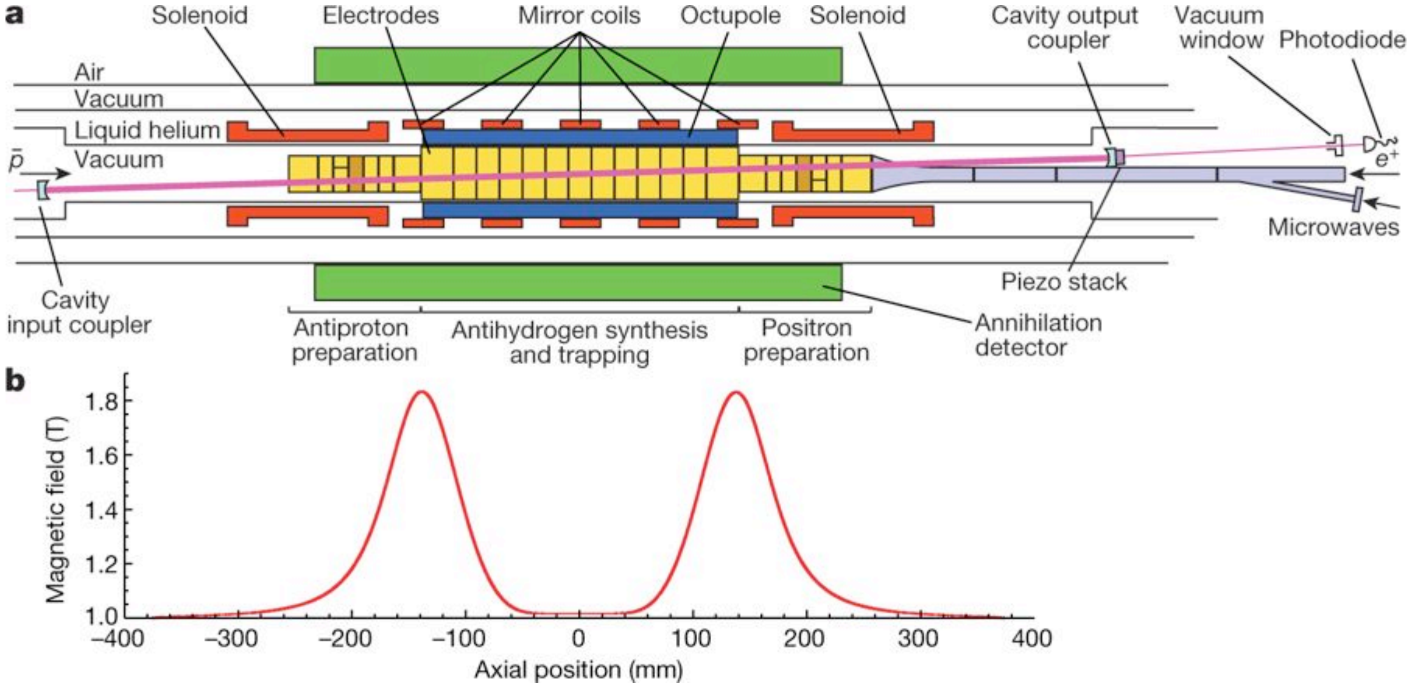
$q(\bar{H}) < 0.71 \times 10^{-9}$ e

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

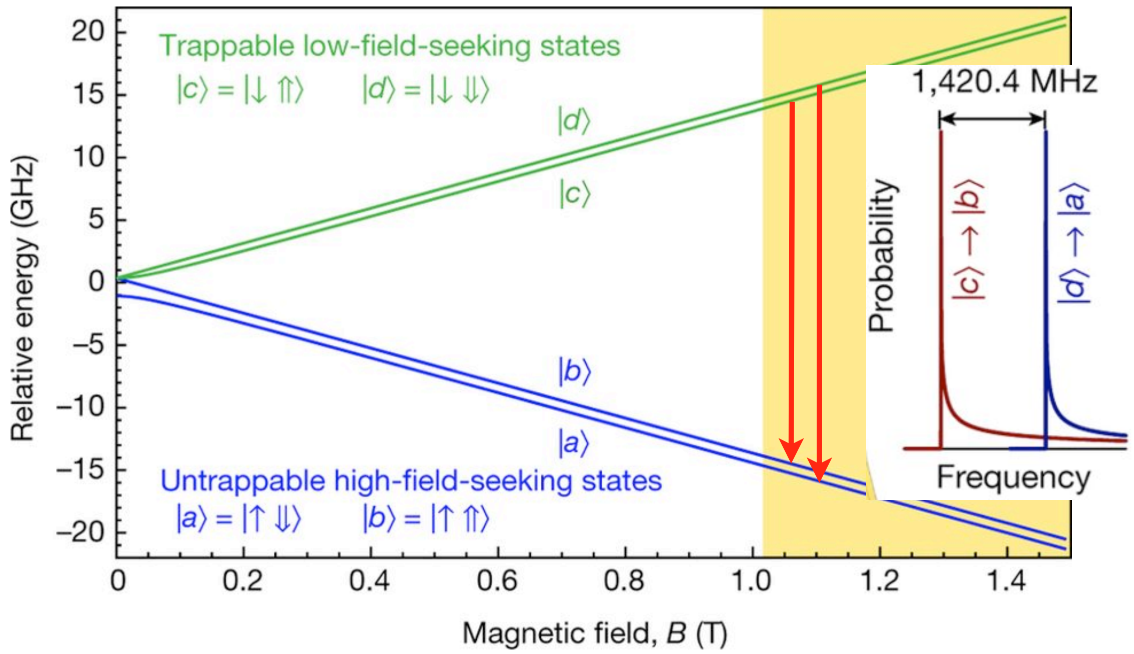
trapping of ~ 10 $\bar{H}$ simultaneously (similar for ATRAP)

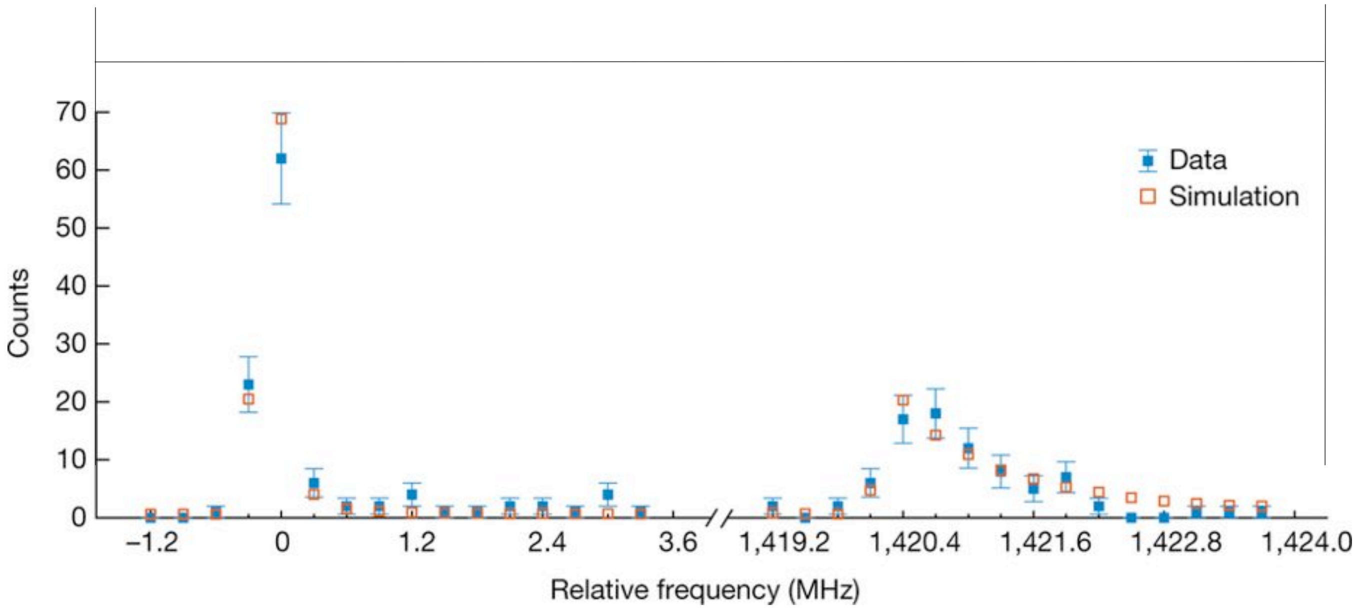
ALPHA: antihydrogen hyperfine splitting

M. Ahmadi et al., Nature 548, 66–69 (03 August 2017)



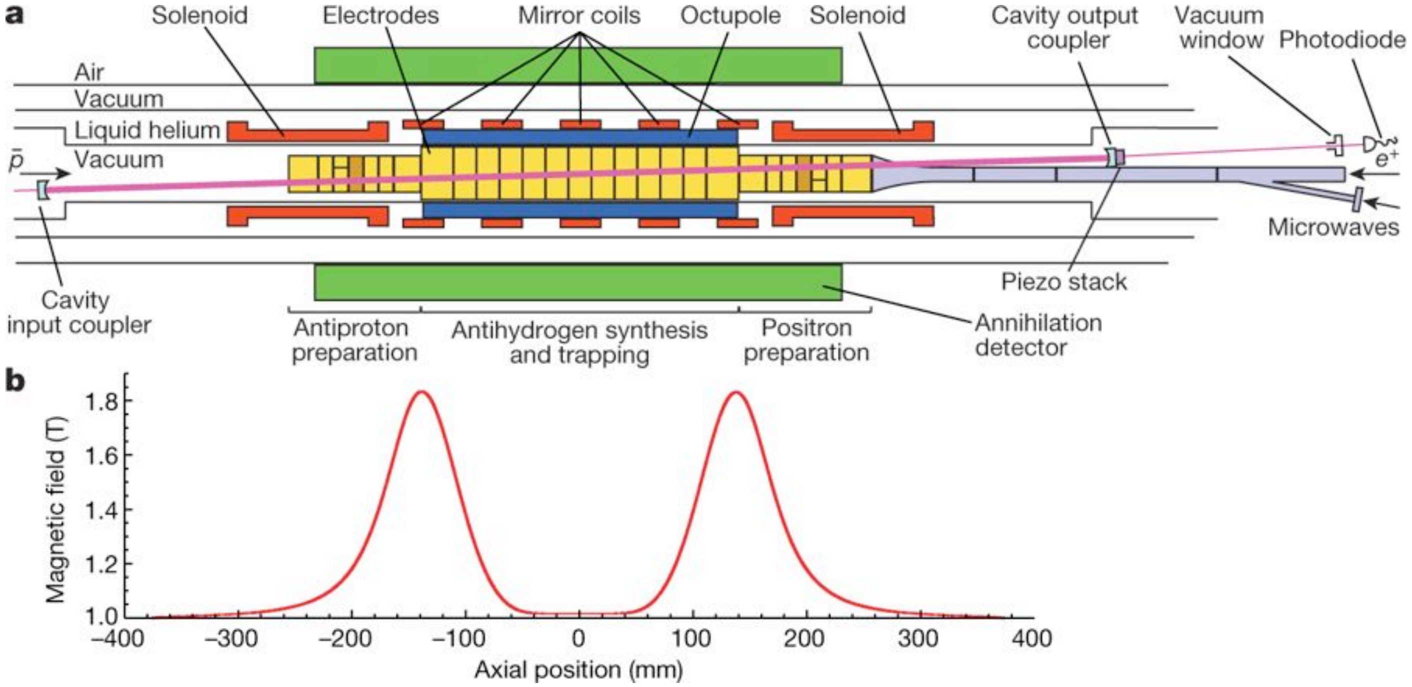
$\mathrm{HFS}_{\bar{\mathrm{H}}}$ = 1,420.4±0.5 MHz





ALPHA: antihydrogen precision spectroscopy

M. Ahmadi et al., Nature 557, 71–75 (2018)



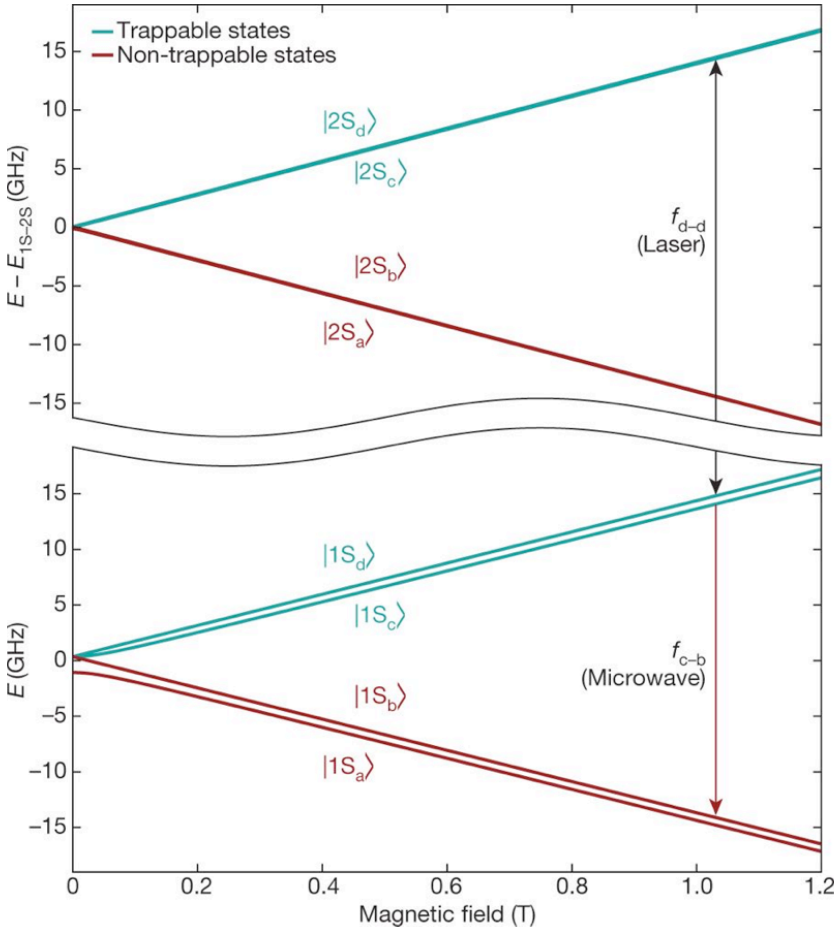
initial population 50:50 $1S_c$ and $1S_d$

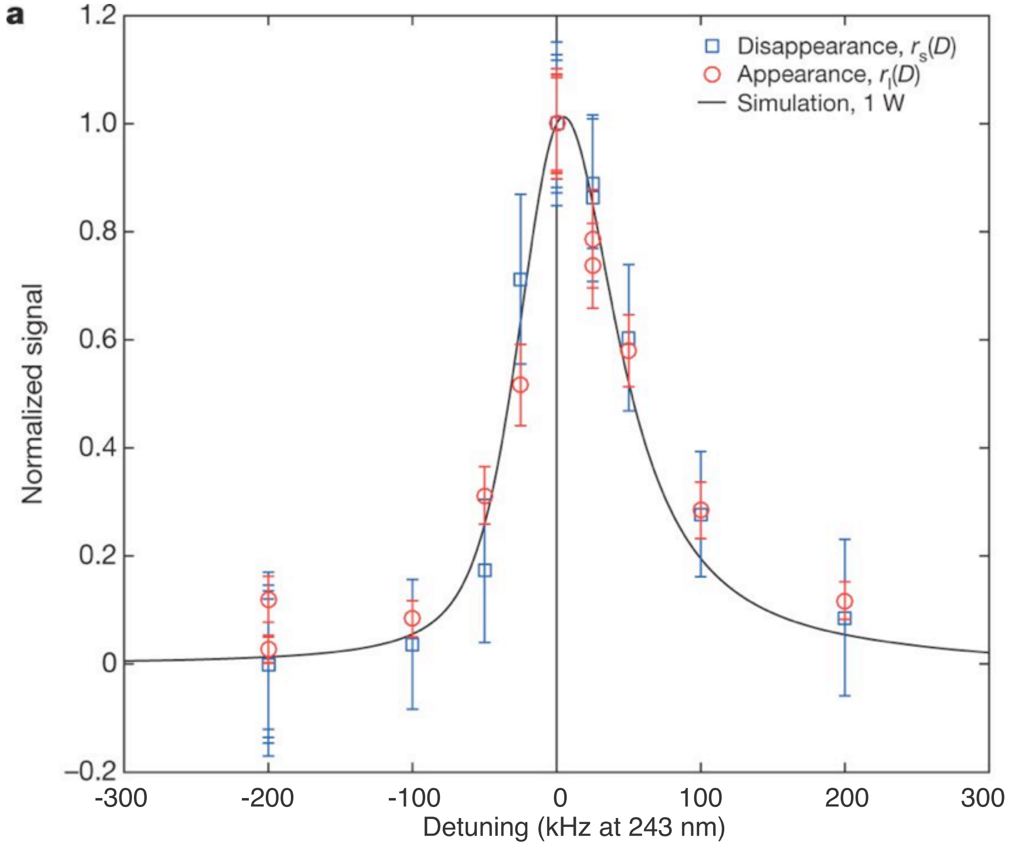
count $1S_d$ population: 2γ excite into $2S_d$

- photo-ionize $2S_d$ with 3rd γ
- decay into (untrapped) $1S_a$, $1S_b$

count $1S_c$ population: μwave into $1S_b$

count remaining $1S_d$ population: dump

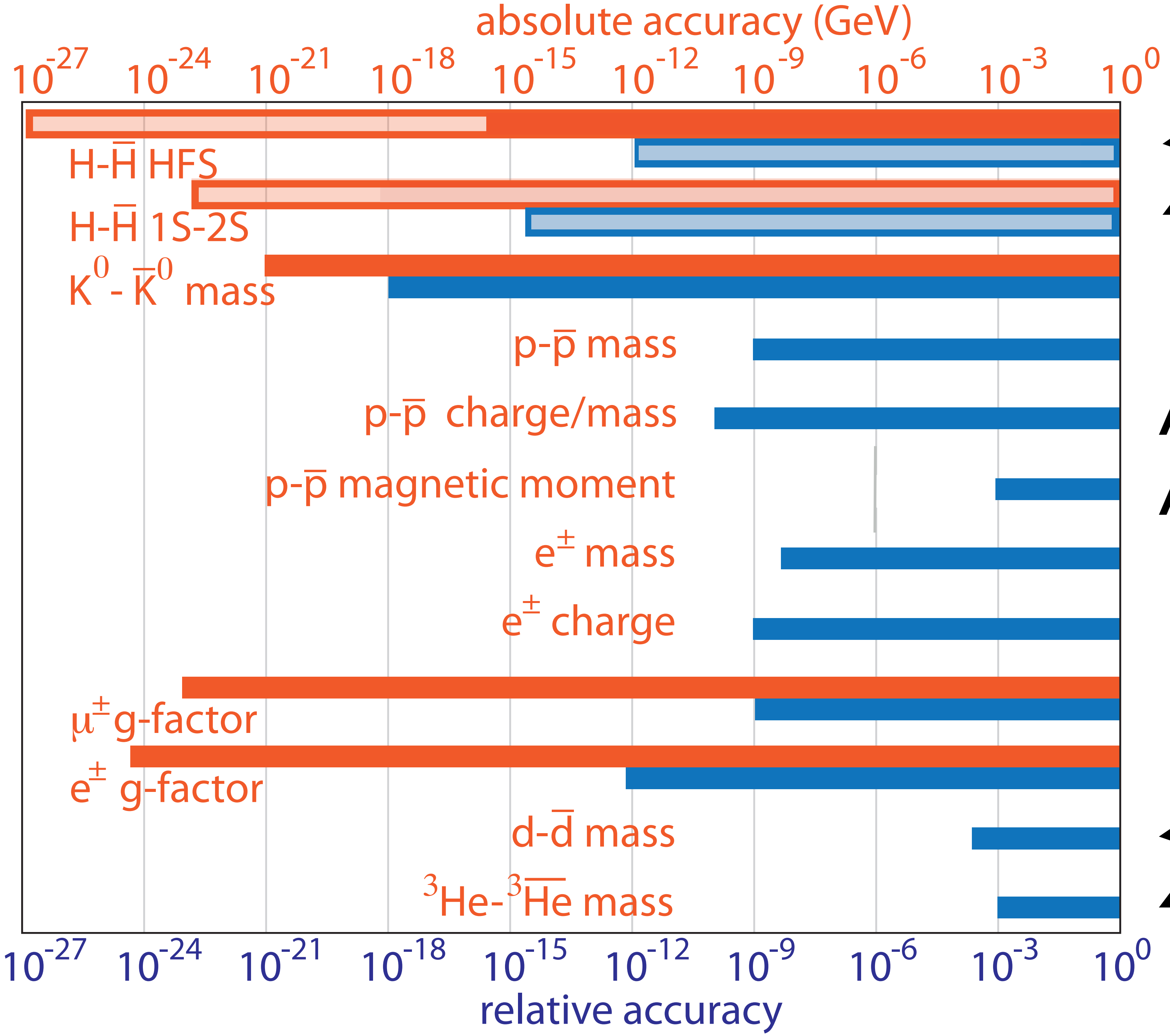




1S-2S to 10^{-12}

intermediate summary…

2013



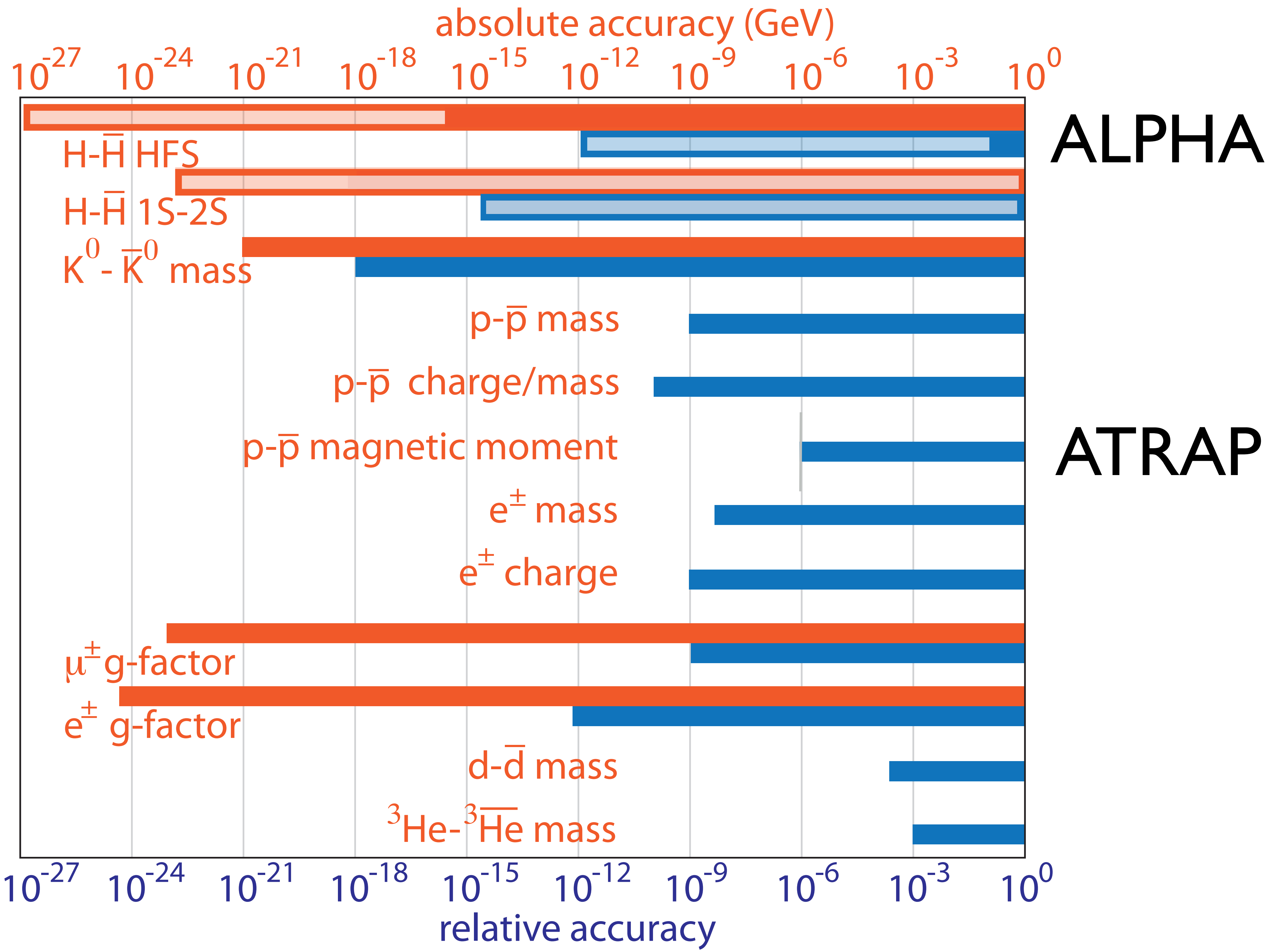
CPT test
of EM
interaction

ATRAP
ASACUSA

CPT test
of strong
interaction

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

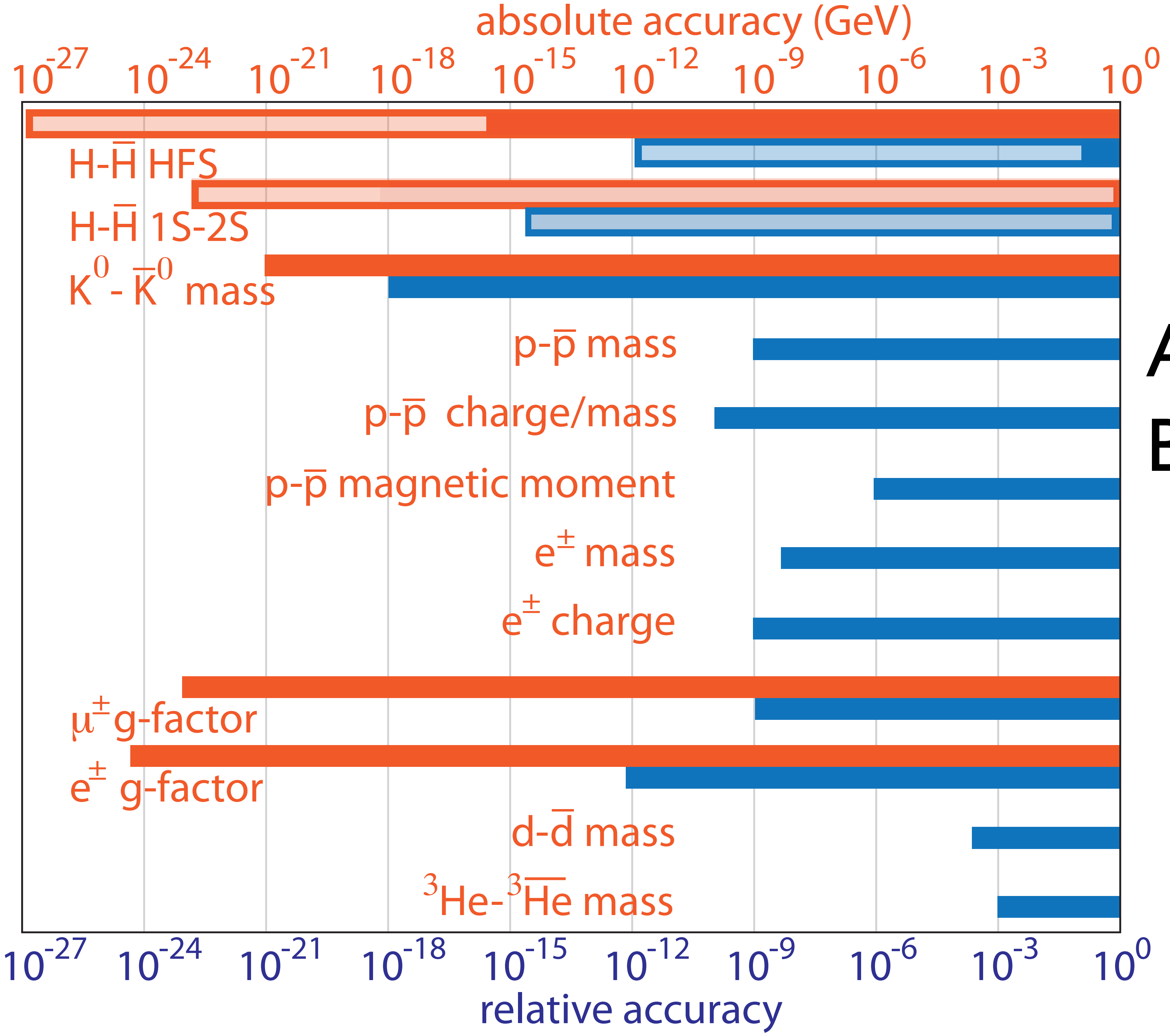


Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky)

2016



ASACUSA

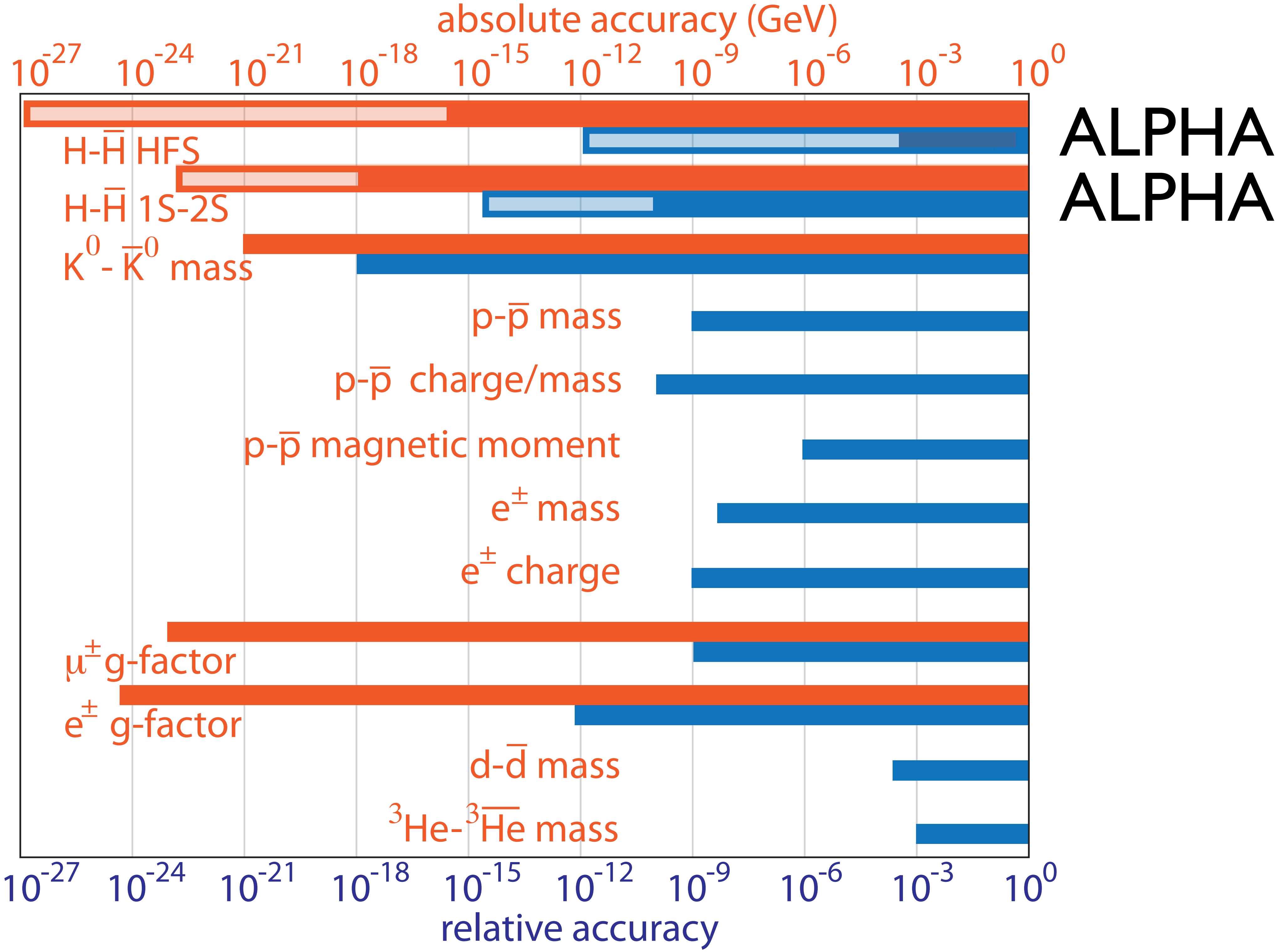
BASE & ATRAP

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)

2017

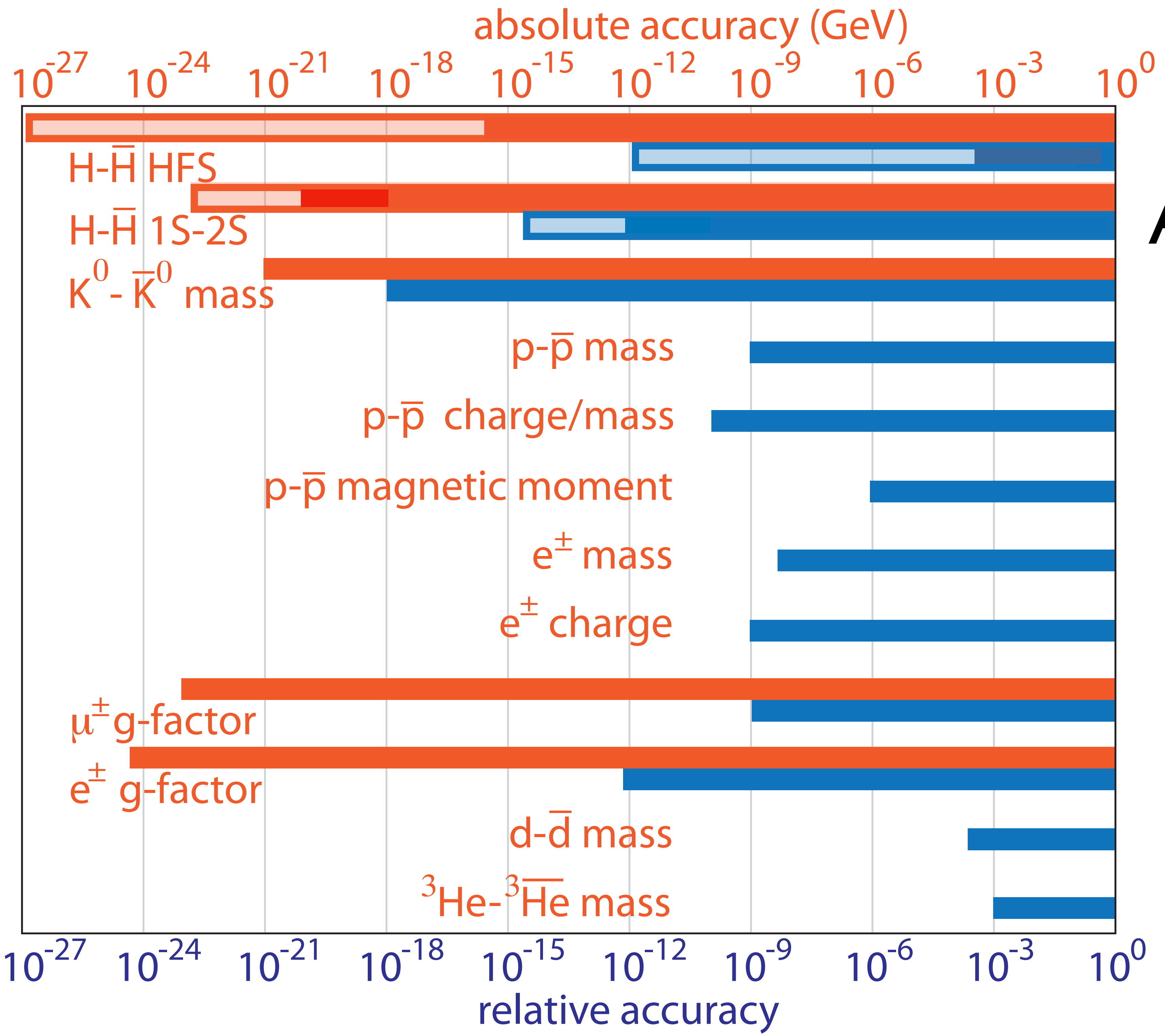


Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky)

2018



ALPHA

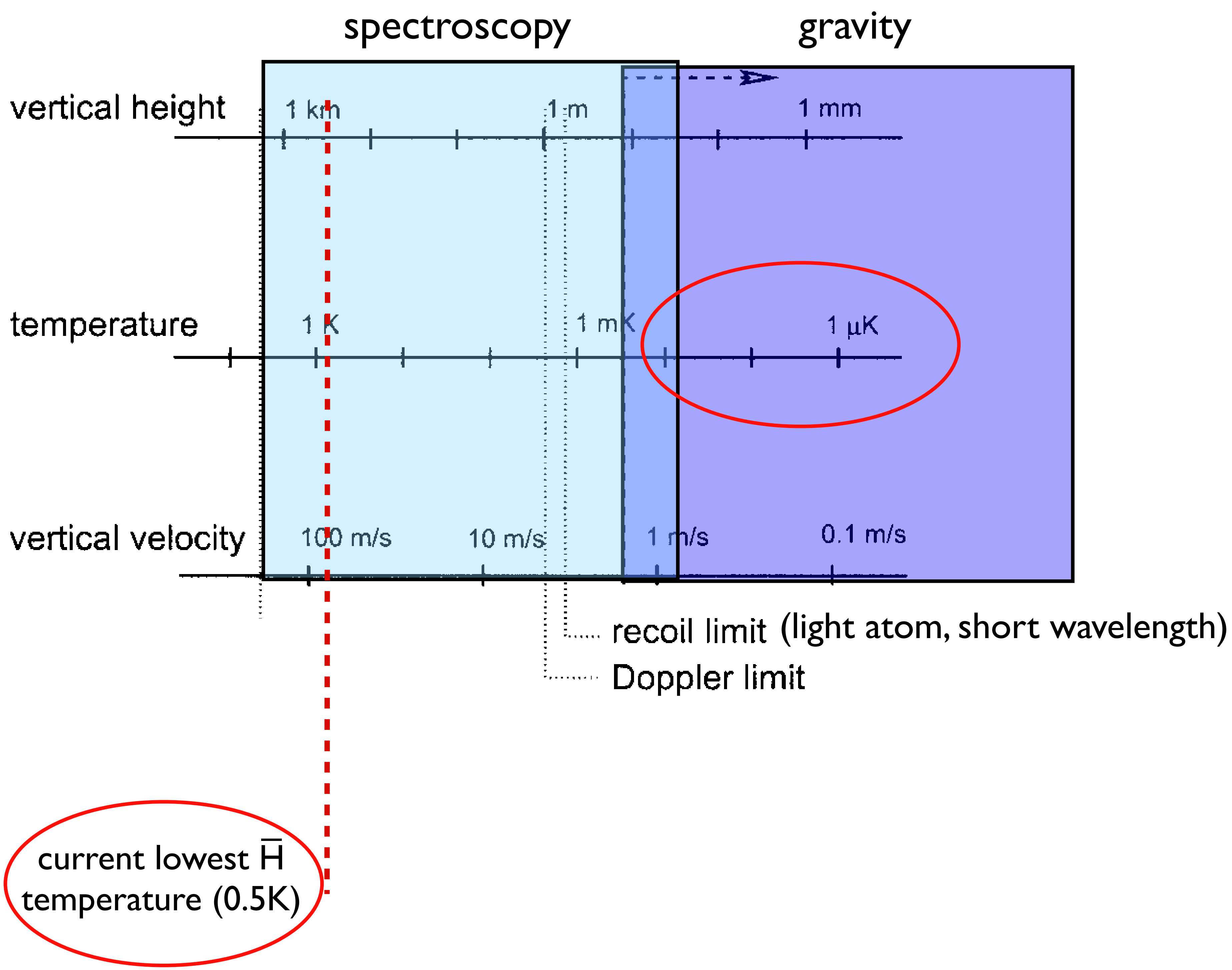
Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky)

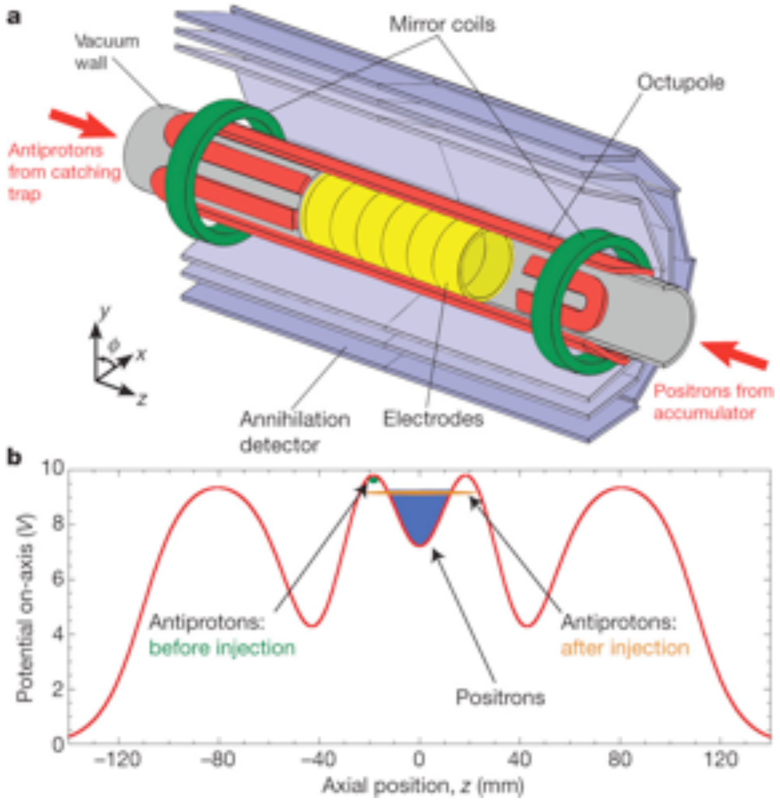
next stop: gravity

the importance of working at low temperature



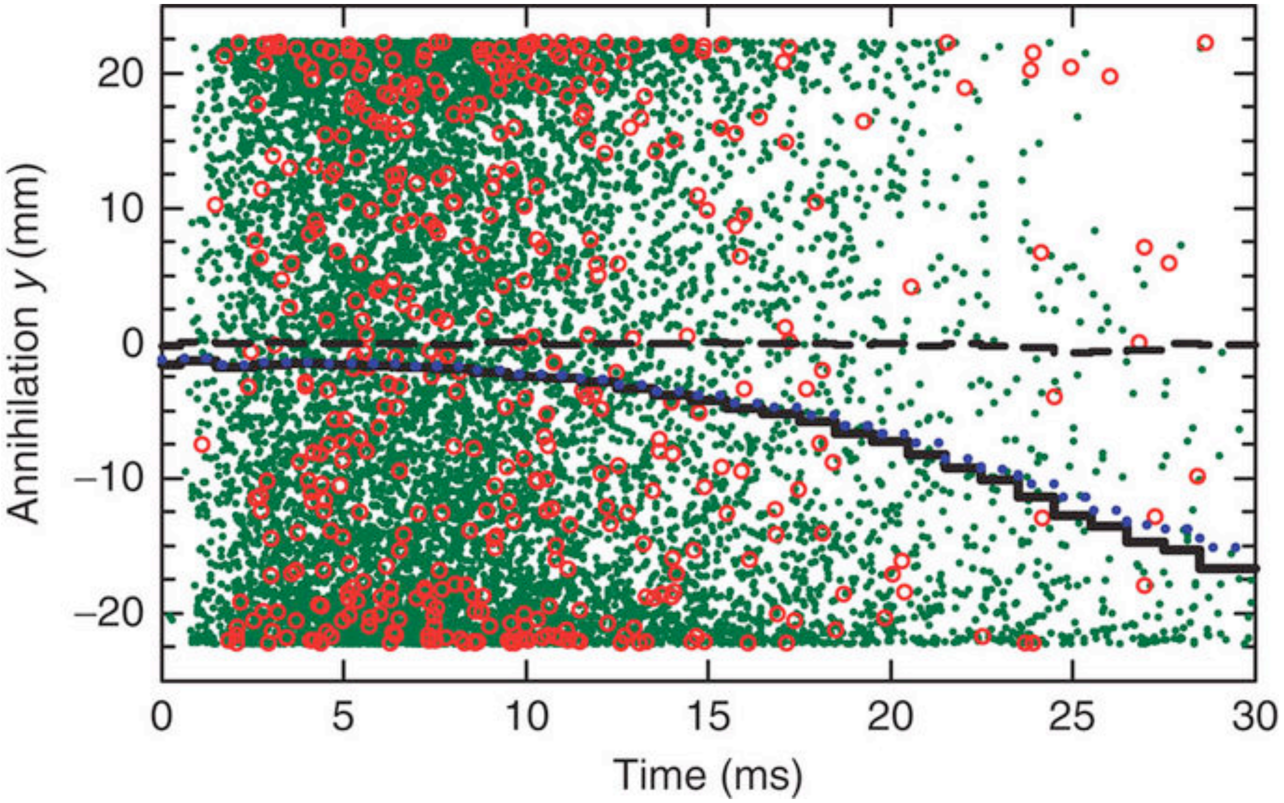
ALPHA results (gravity at 0.5K)

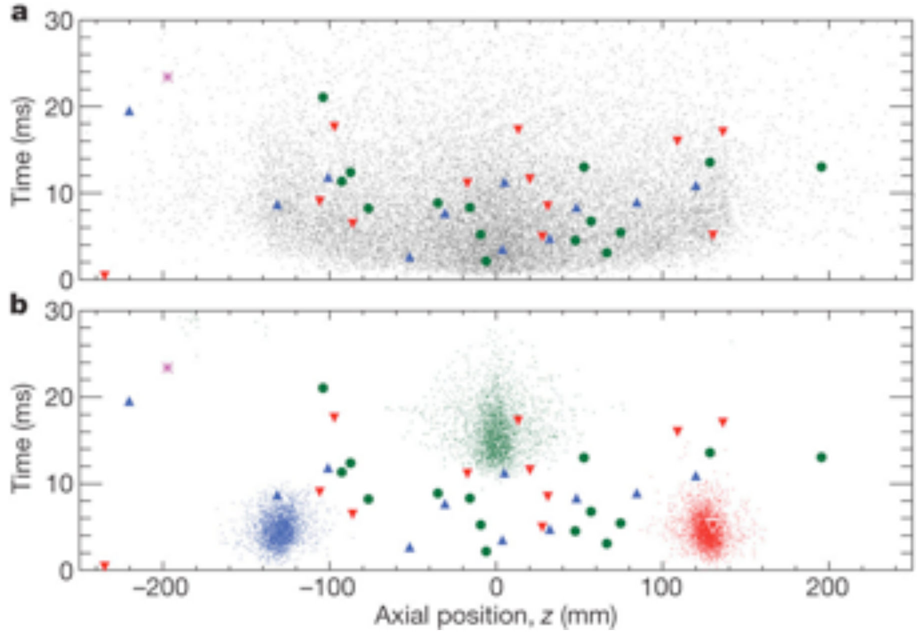
Nature Communications volume 4,
Article number: 1785 (2013)
doi:10.1038/ncomms2787



$$F \equiv M_g/M$$

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





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

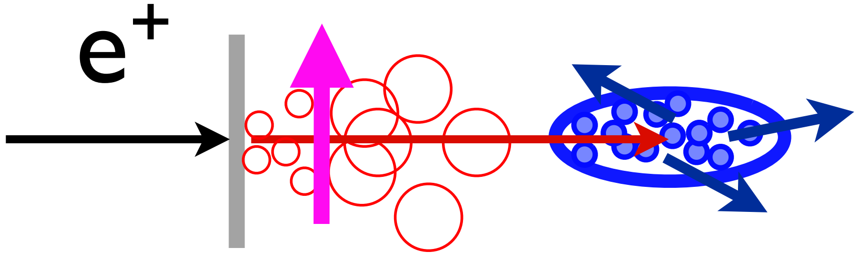
“... cooling the anti-atoms, perhaps with lasers, to 30 mK or lower, and by lengthening the magnetic shutdown time constant to 300 ms, we would have the statistical power to measure gravity to the F=±1 level ...“

alternative antihydrogen production method: RCE

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

AE$\bar{\text{g}}$IS

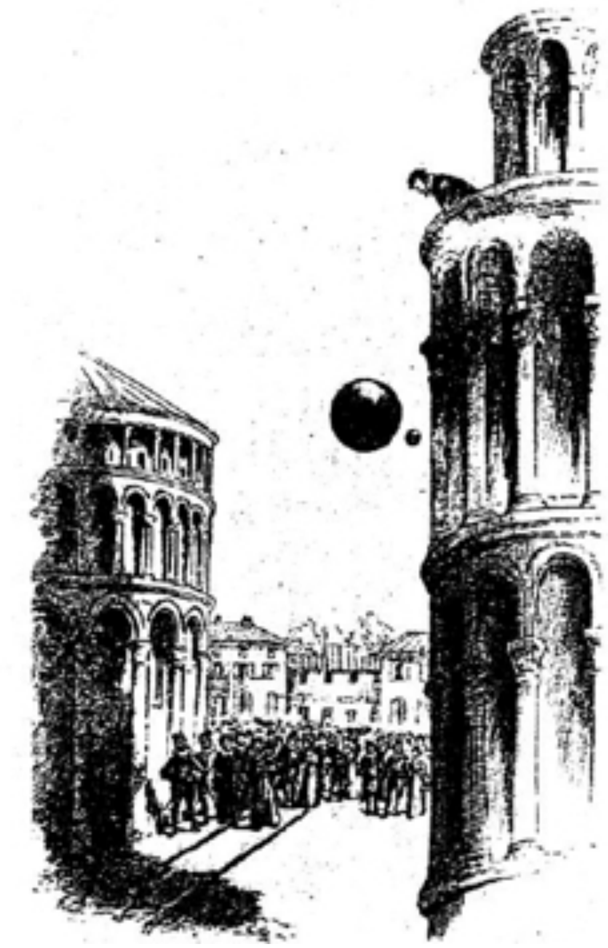
$T_{Ps} \sim 100$ K



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

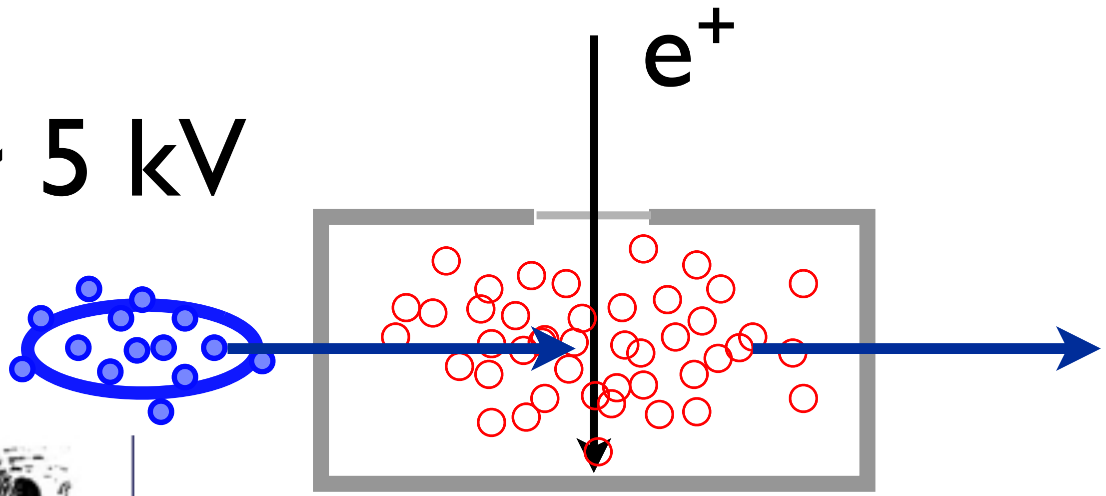
cold $\bar{H}^*$

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!

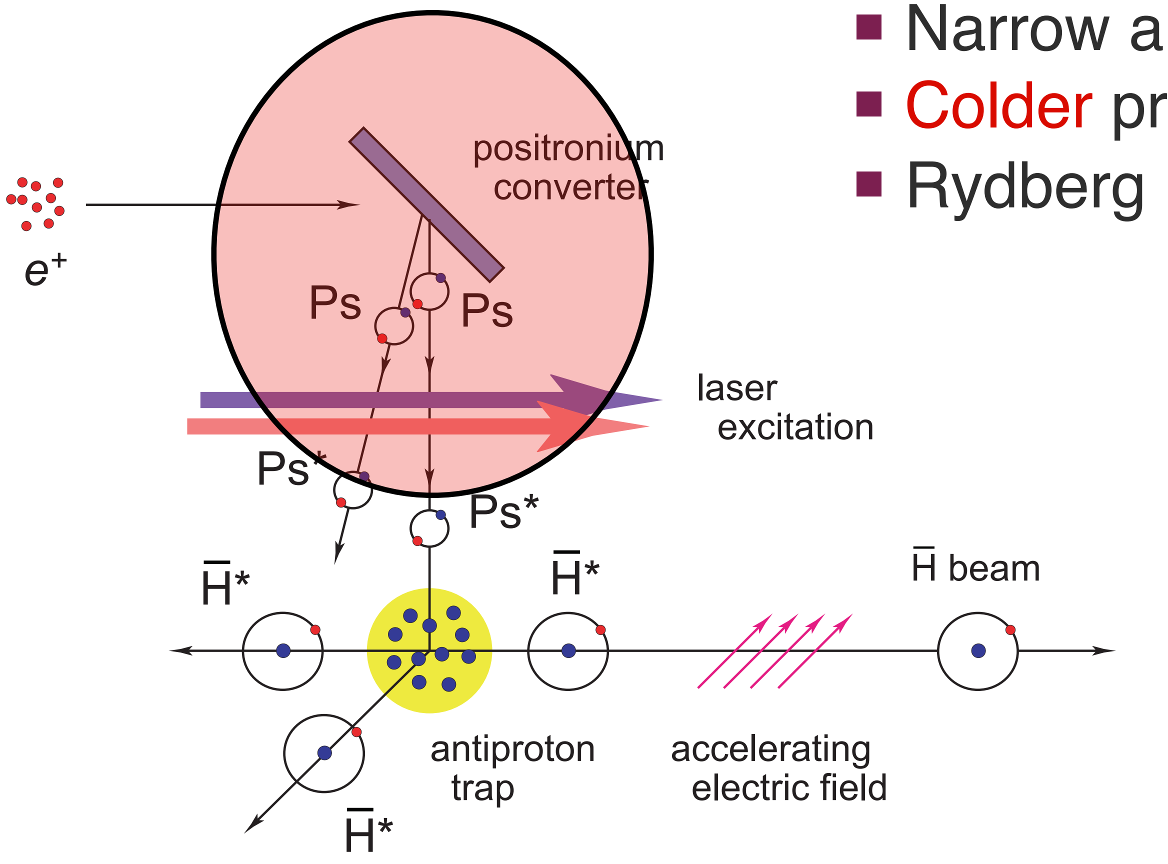
Schematic overview

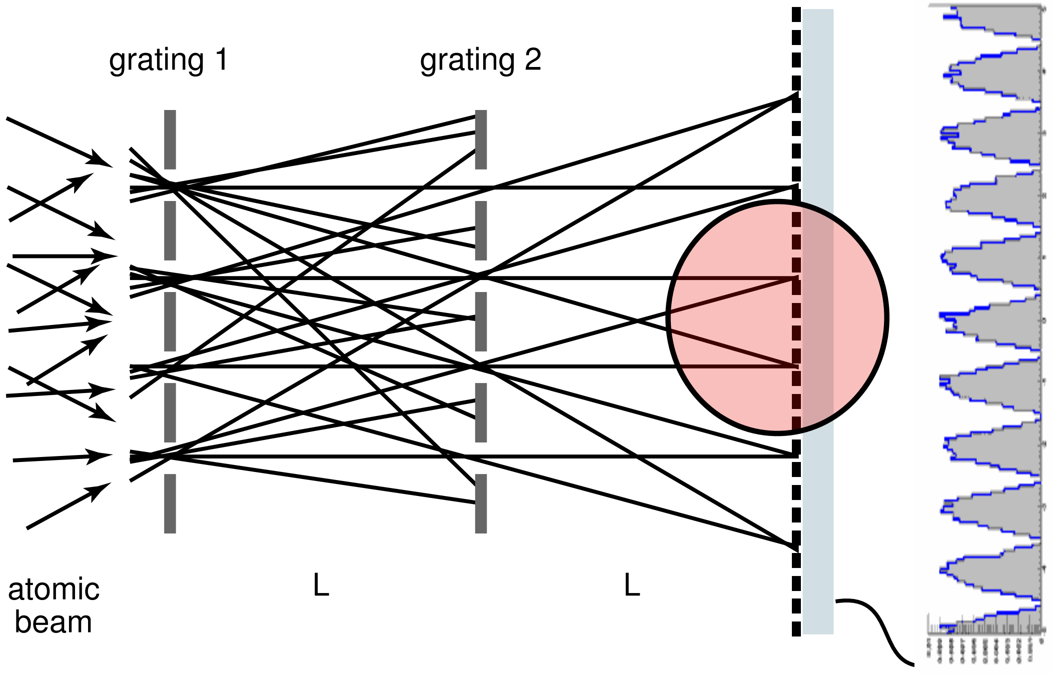
Physics goals: measurement of the gravitational interaction between matter and antimatter, $\bar{\mathrm{H}}$ spectroscopy, ...

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

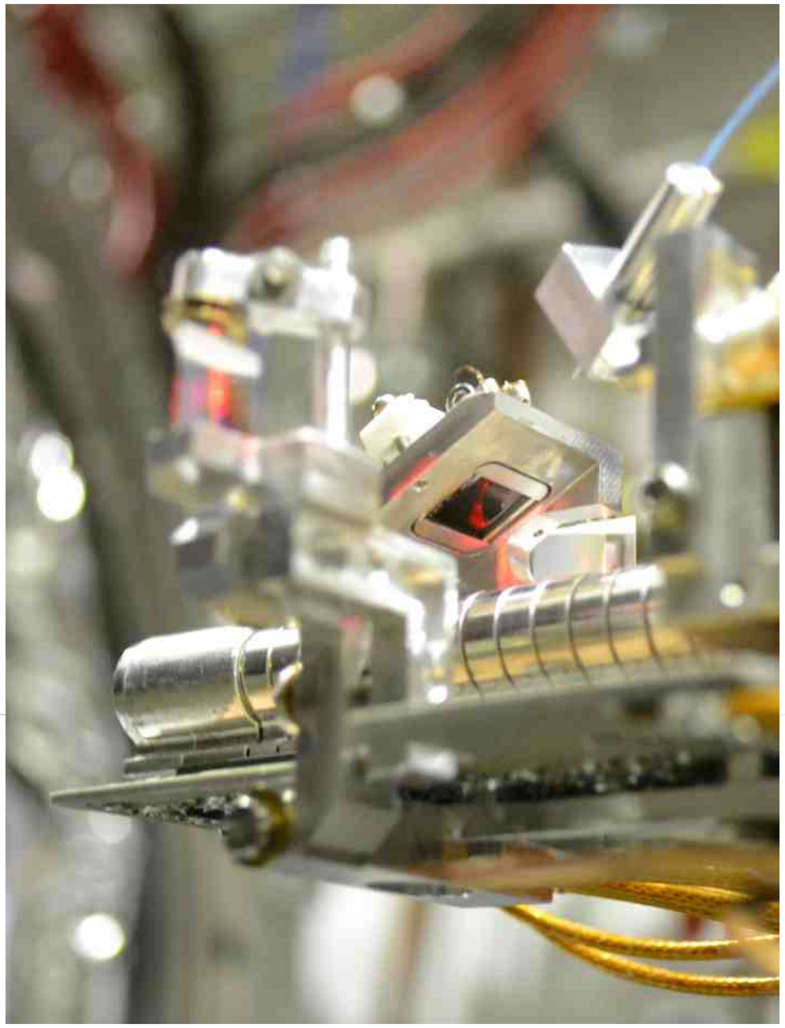
$$\mathrm{Ps}^* + \bar{p} \rightarrow \bar{\mathrm{H}}^* + e^-$$

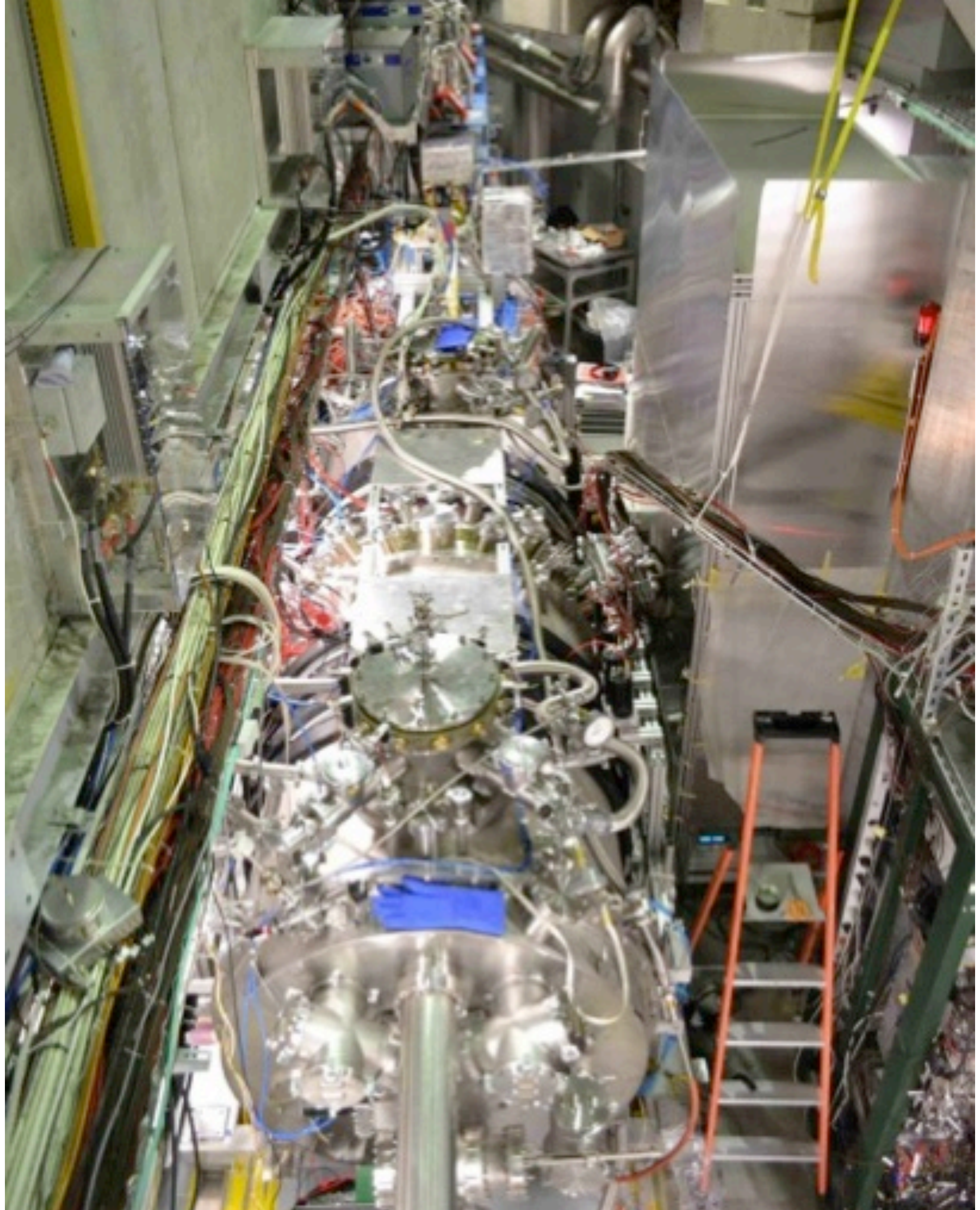
- Advantages:
  - Pulsed $\bar{\mathrm{H}}$ production (time of flight – Stark acceleration)
  - Narrow and well-defined $\bar{\mathrm{H}}$ *n*-state distribution
  - Colder production than via mixing process expected
  - Rydberg Ps & $\sigma \approx a_0 n^4 \rightarrow \bar{\mathrm{H}}$ formation enhanced

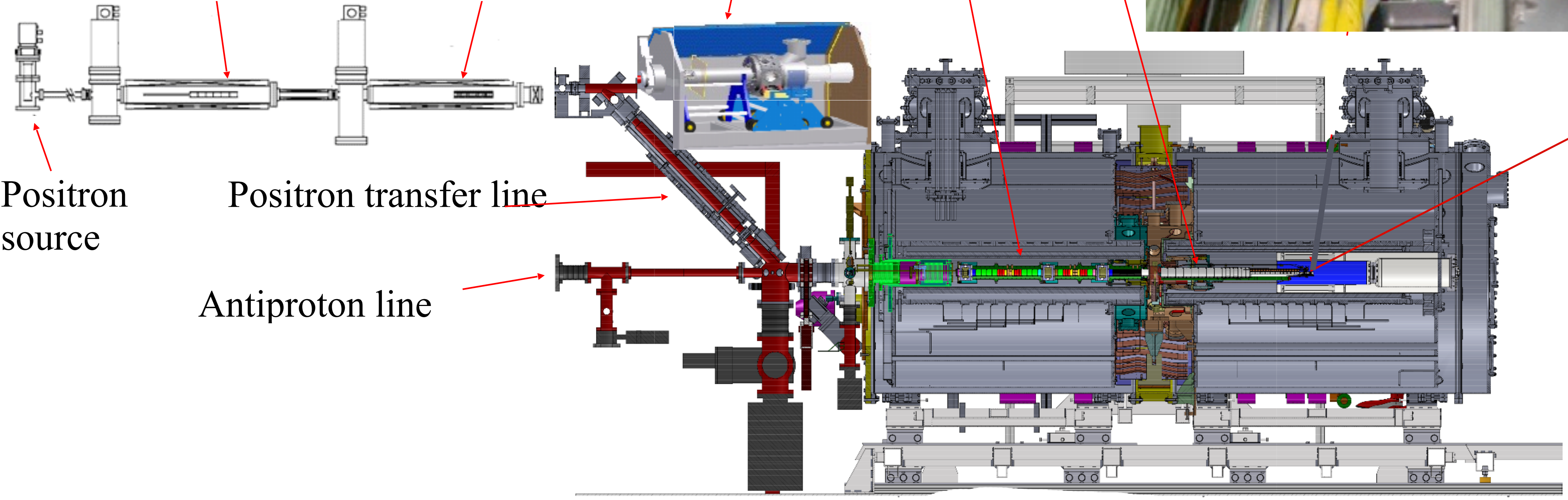




AE$\bar{g}$IS experiment







Chamber for Ps experiments

1T trap

Positron trap

Positron accumulator

5T trap

Target for Ps production and $\overline{\text{H}}$ formation

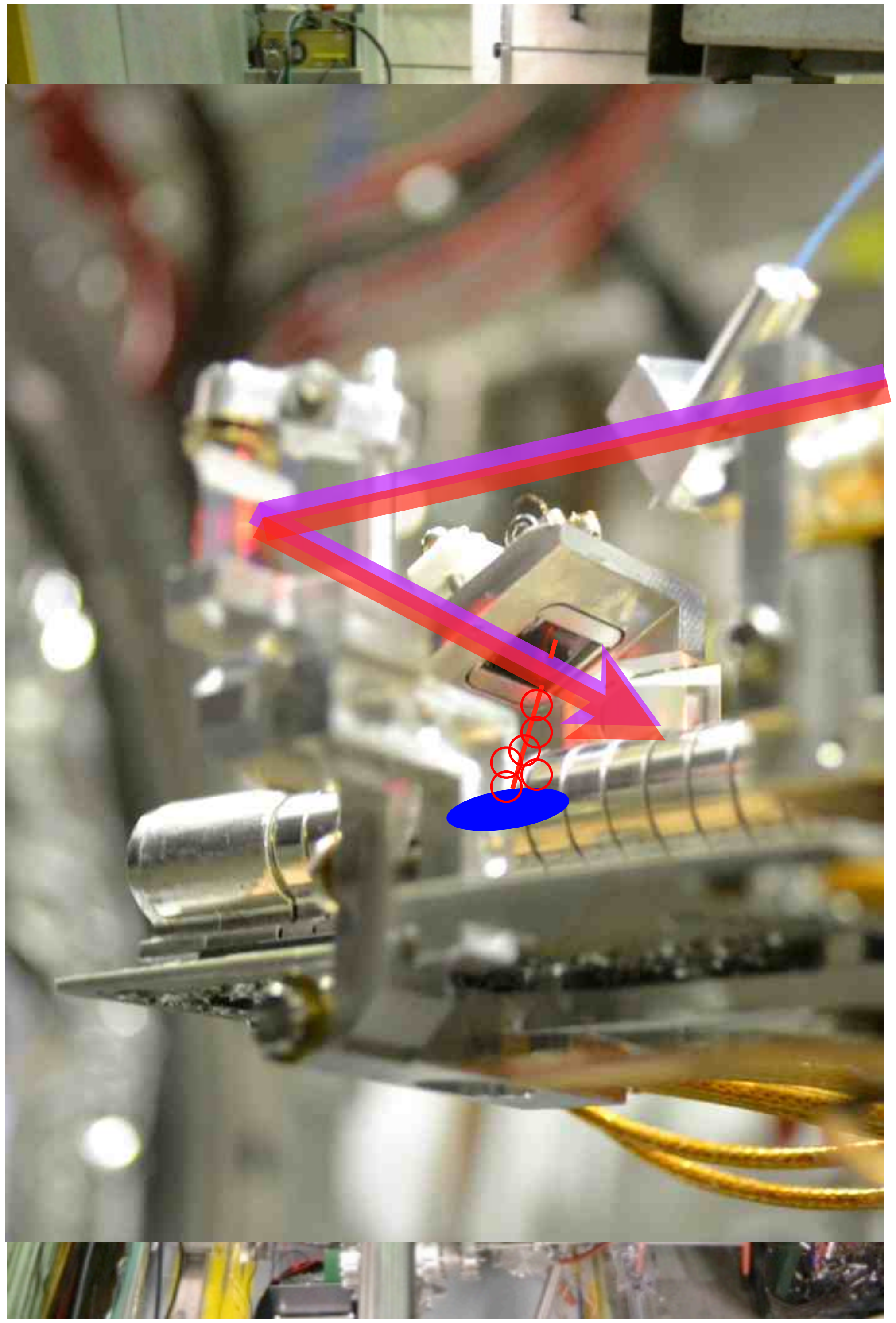
Positron source

Positron transfer line

Antiproton line

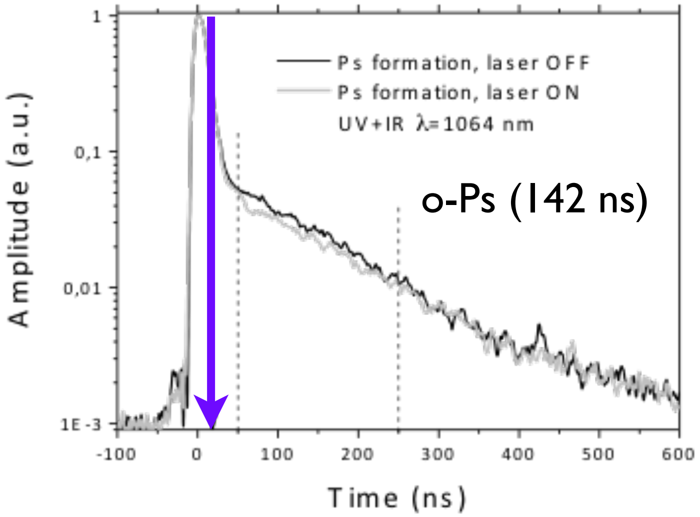
AEḡIS

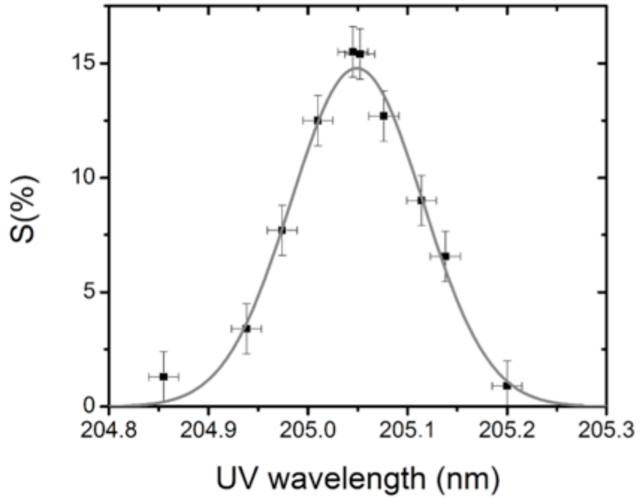
positronium excitation



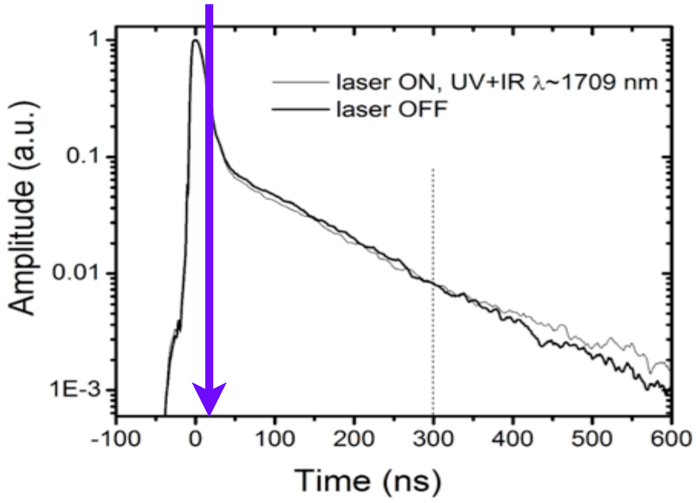
$1 \xrightarrow{205\text{ nm}} 3 \xrightarrow{1064\text{ nm}}$ continuum

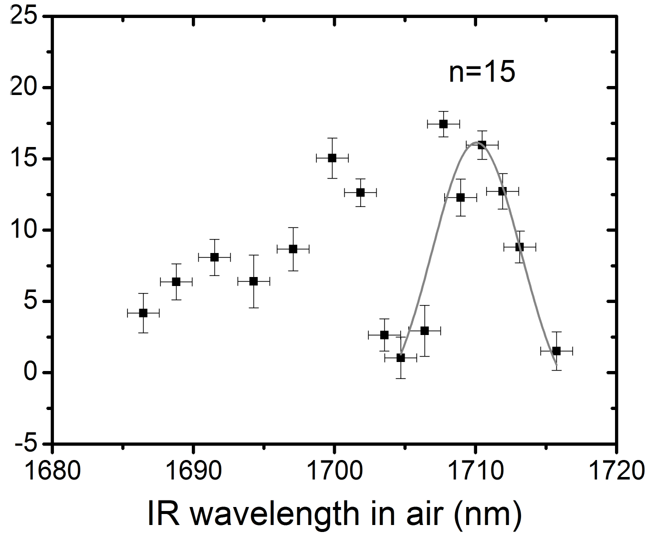
3P excitation line centered at 205.05±0.02 nm





$1 \xrightarrow{205\text{ nm}} 3 \xrightarrow{1700\text{ nm}}$ nS (τ ~ μs)

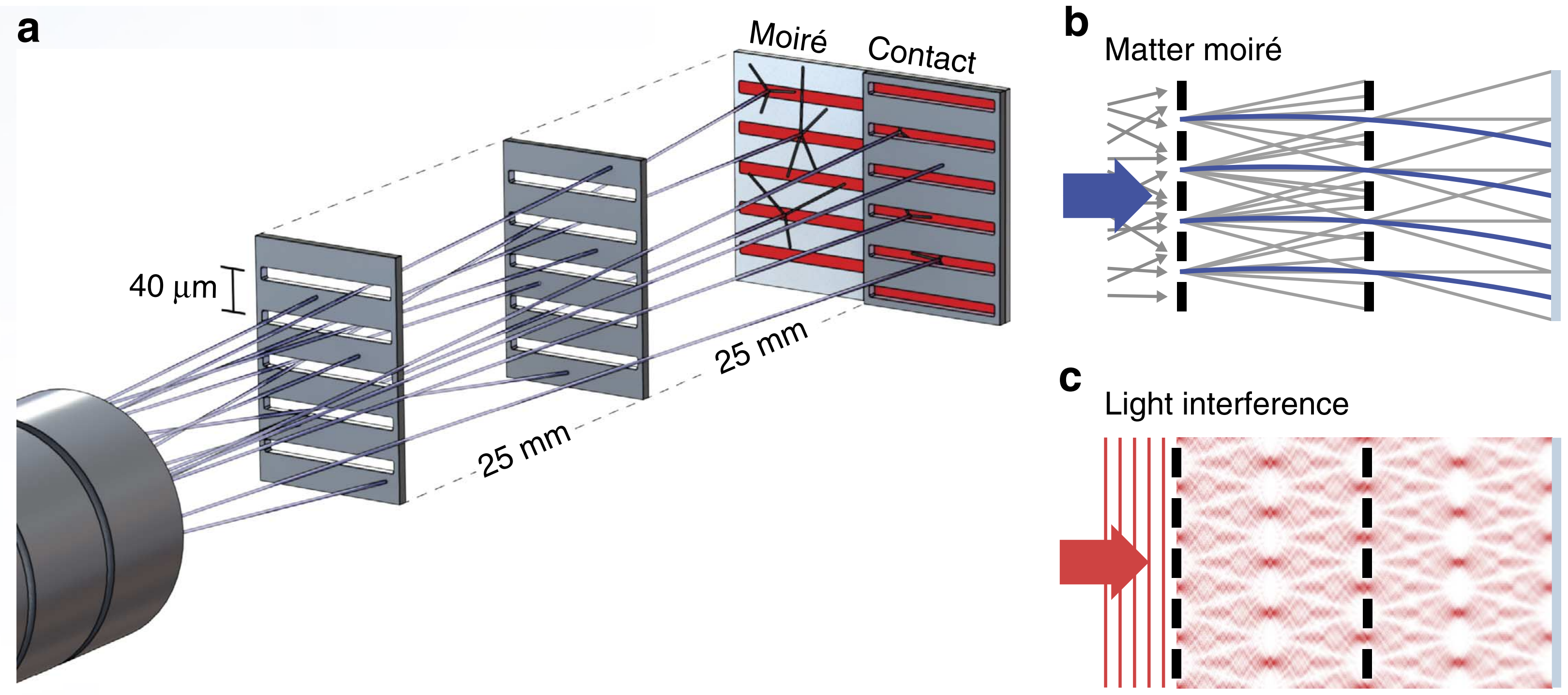


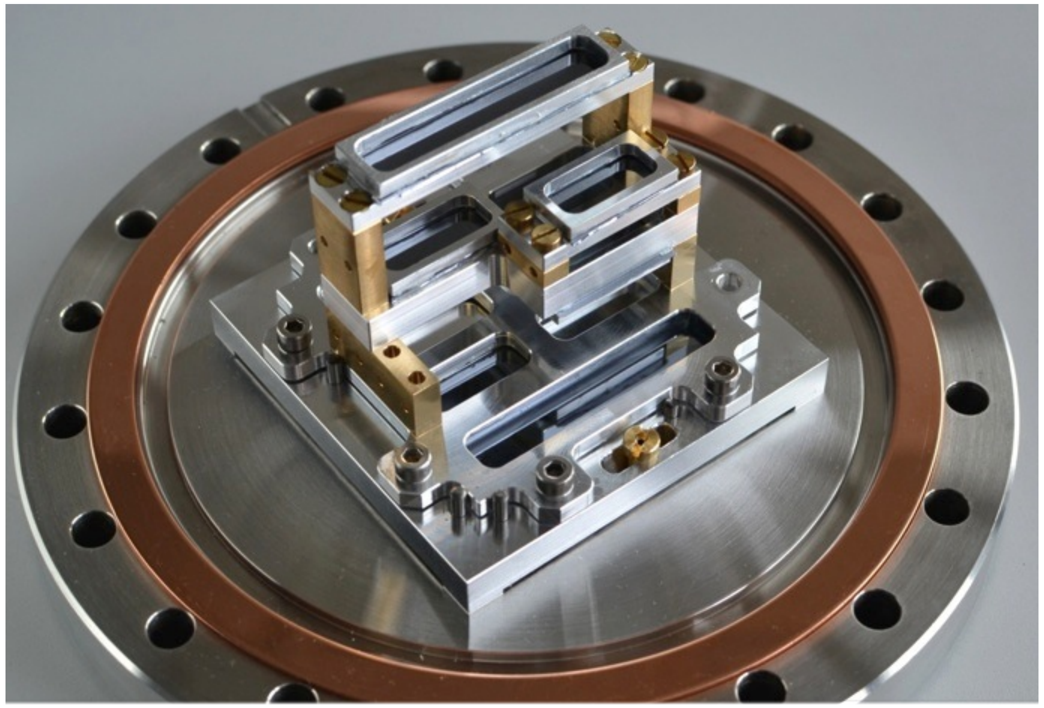


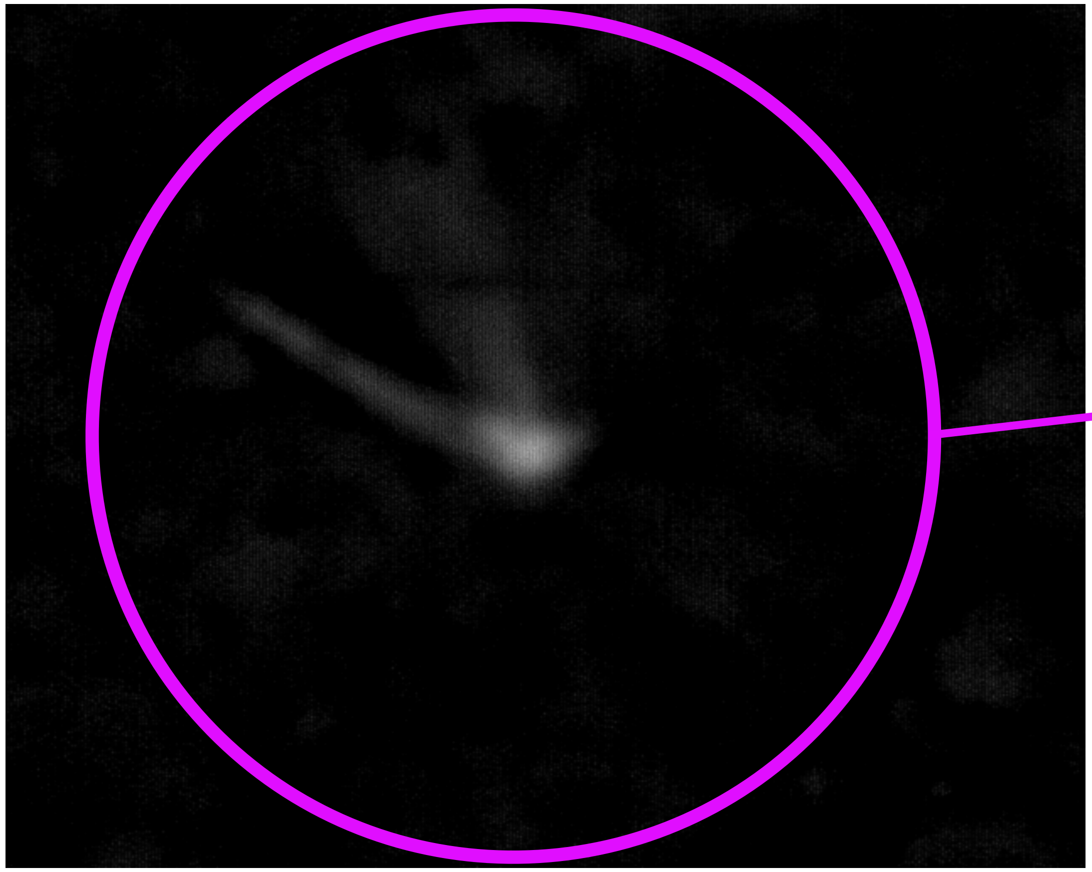
S. Aghion et al. (AEgIS Collaboration) Phys. Rev. A94 (2016) 012507

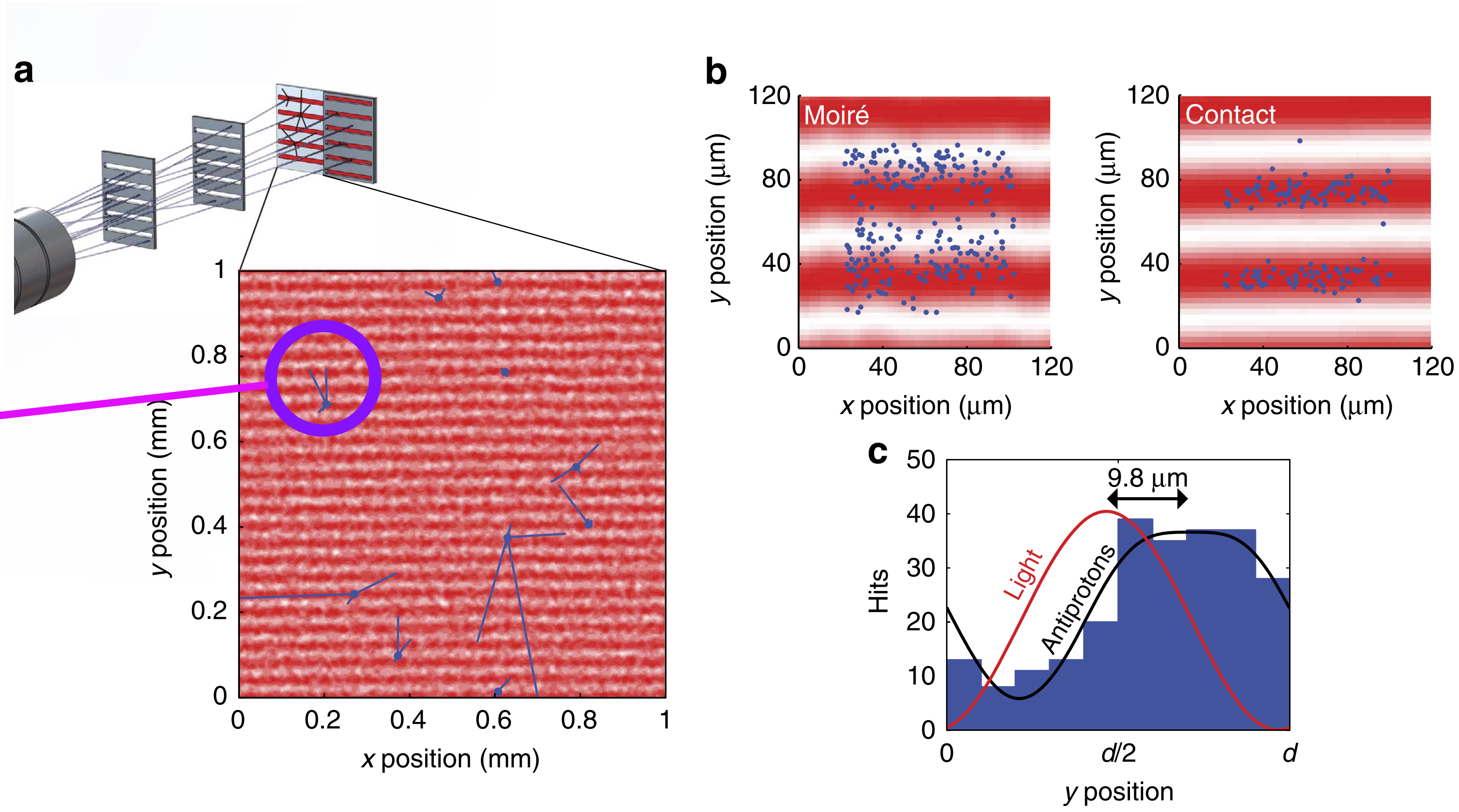
precision (QED) tests with Ps in future?

Deflectometer test with antiprotons



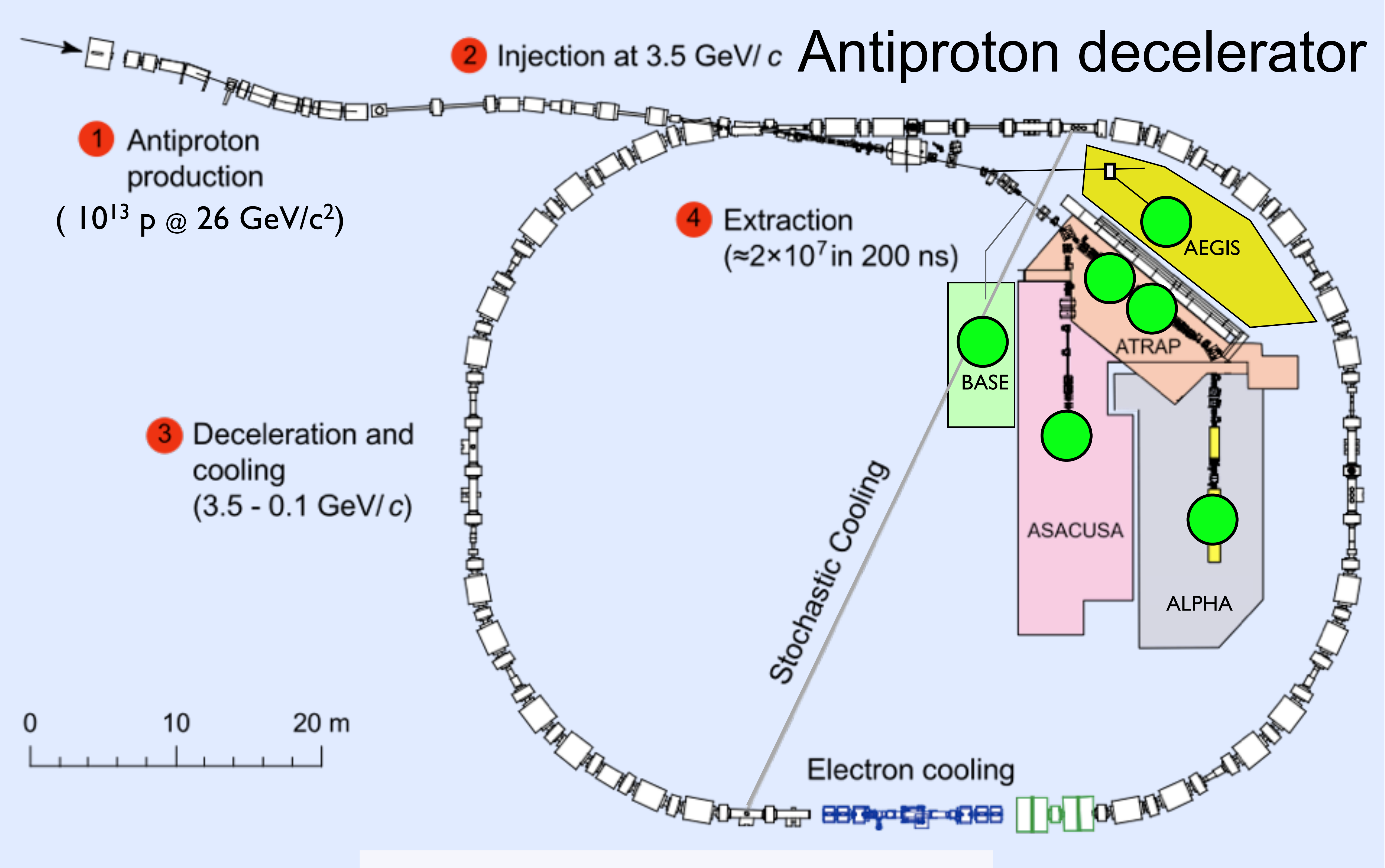






S. Aghion et al.,"A moiré deflectometer for antimatter", Nature Communications 5 (2014) 4538

Two main challenges: more / colder antiprotons

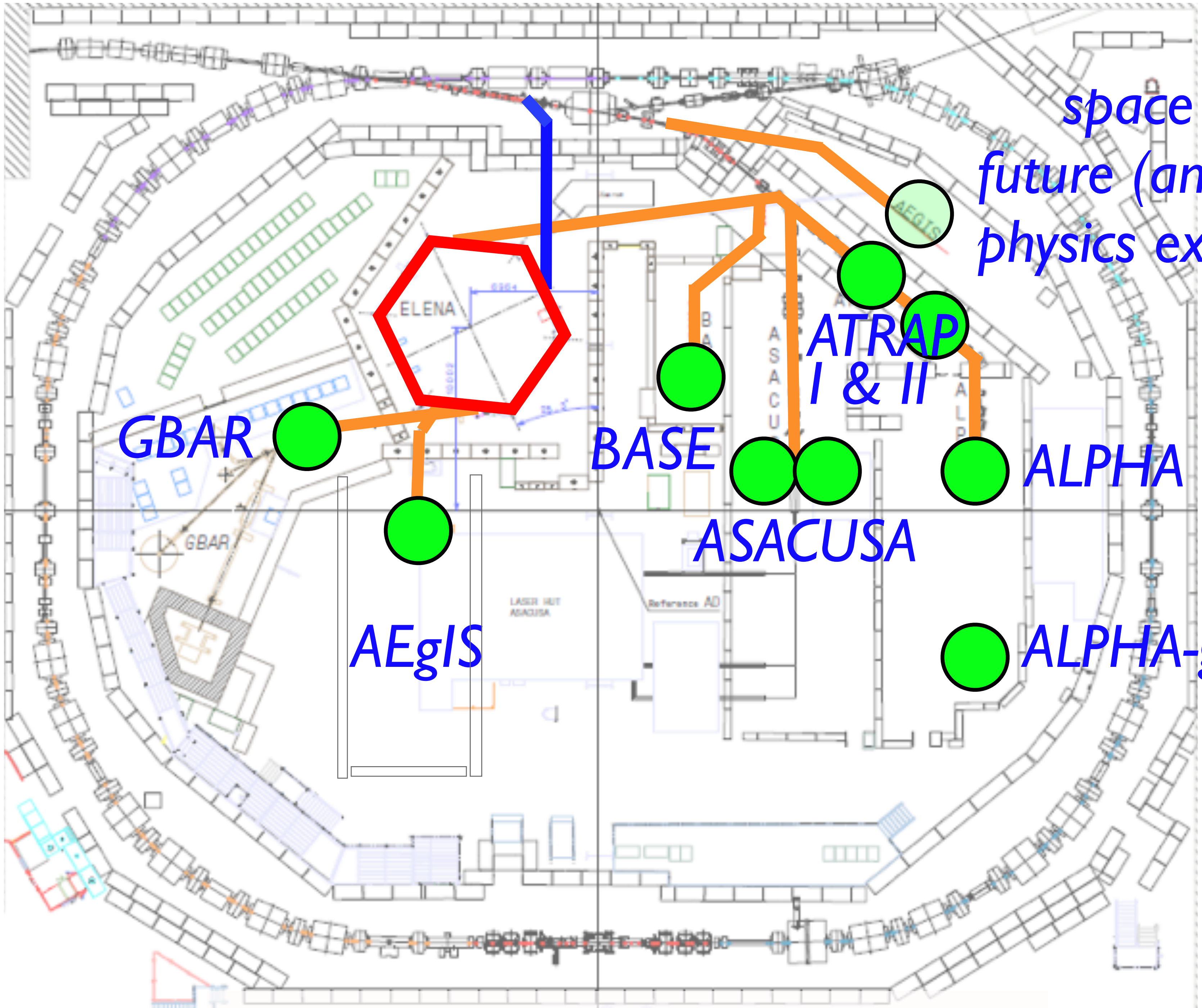


extraction at 5.3 MeV

Two main challenges: more / colder antiprotons

current methods for trapping them are quite inefficient

ELENA to the rescue

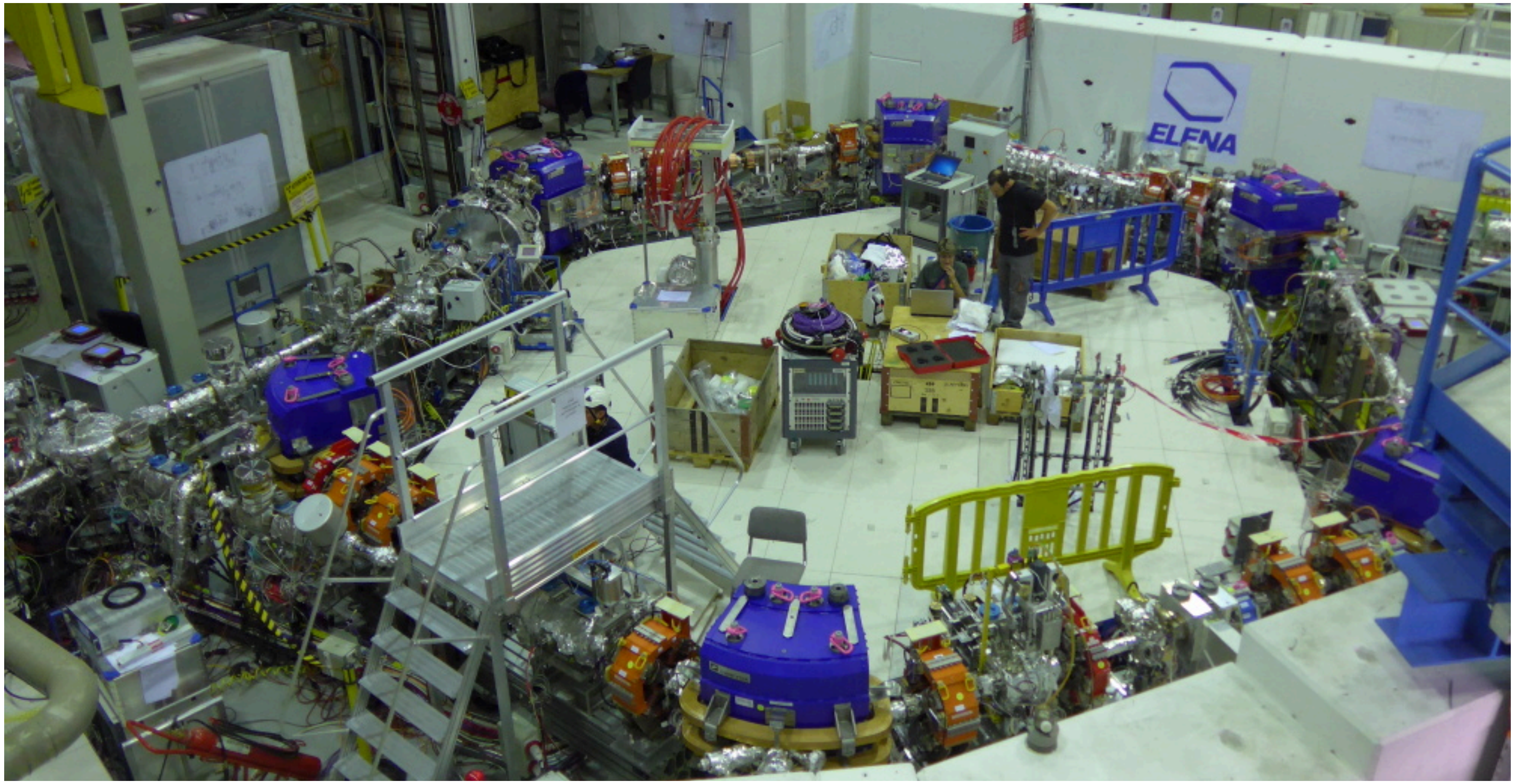


extraction at 100 keV

ELENA is a tiny new decelerator that:

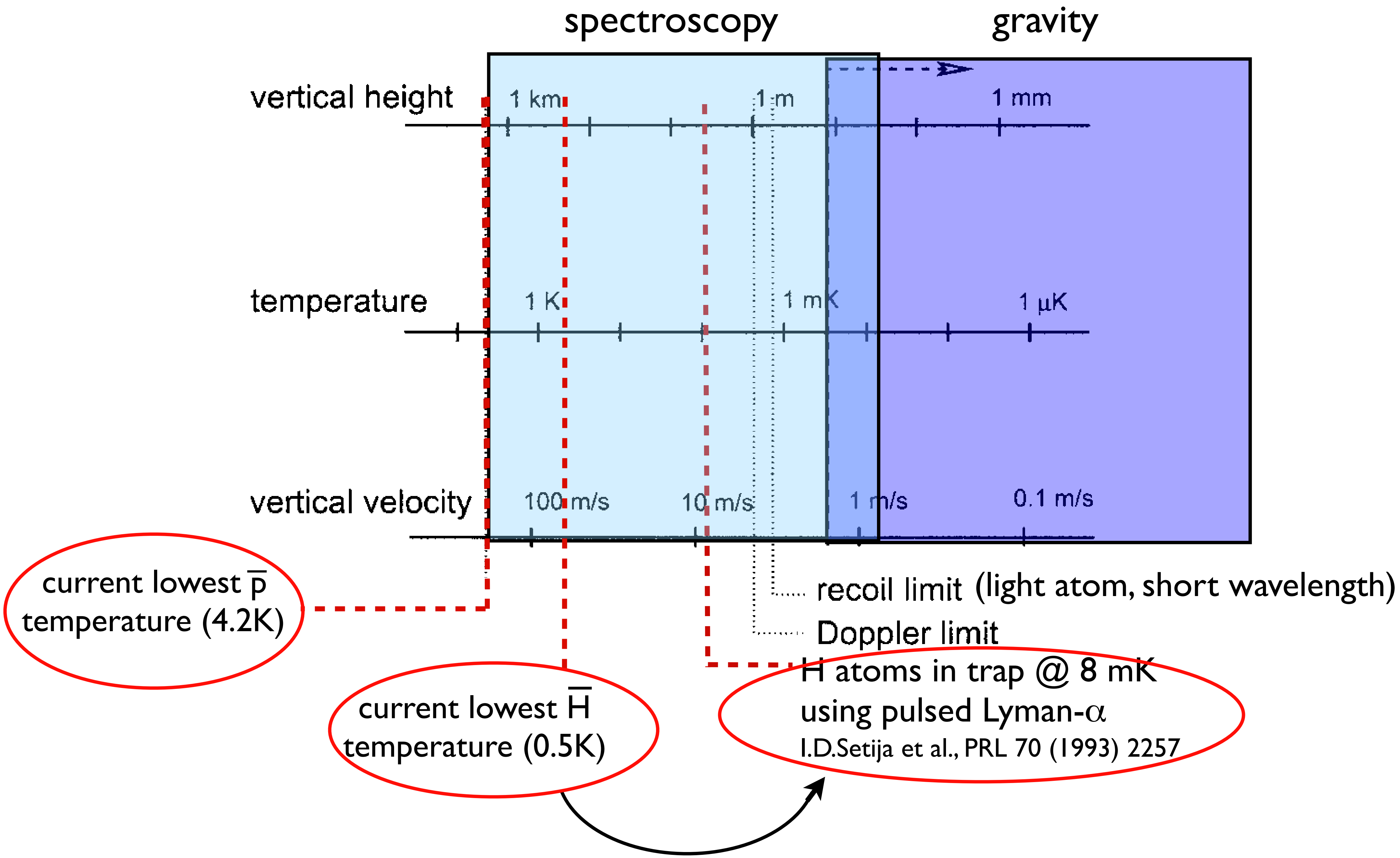
- dramatically slows down the antiprotons from the AD
- increases the *antiproton* trapping efficiency x 100
- allows 4 experiments to run in parallel
- allows new experiments to be considered

commissioning started in 2017



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

“Ultra-cold” (~1 μK) Antihydrogen



current lowest $\overline{p}$ temperature (4.2K)

current lowest $\overline{H}$ temperature (0.5K)

recoil limit (light atom, short wavelength)

Doppler limit

H atoms in trap @ 8 mK
using pulsed Lyman-α
I.D.Setija et al., PRL 70 (1993) 2257

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) → $\bar{H}^+$ + e^-

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. In^+ → 20 µK

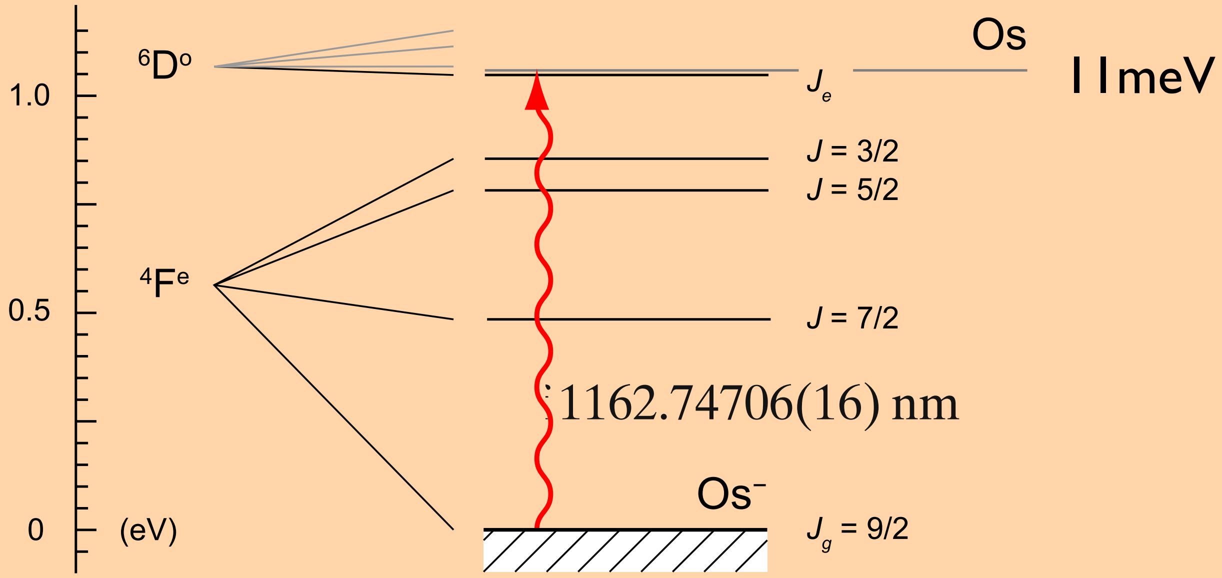
photodetachment at ~6083 cm^{-1}

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

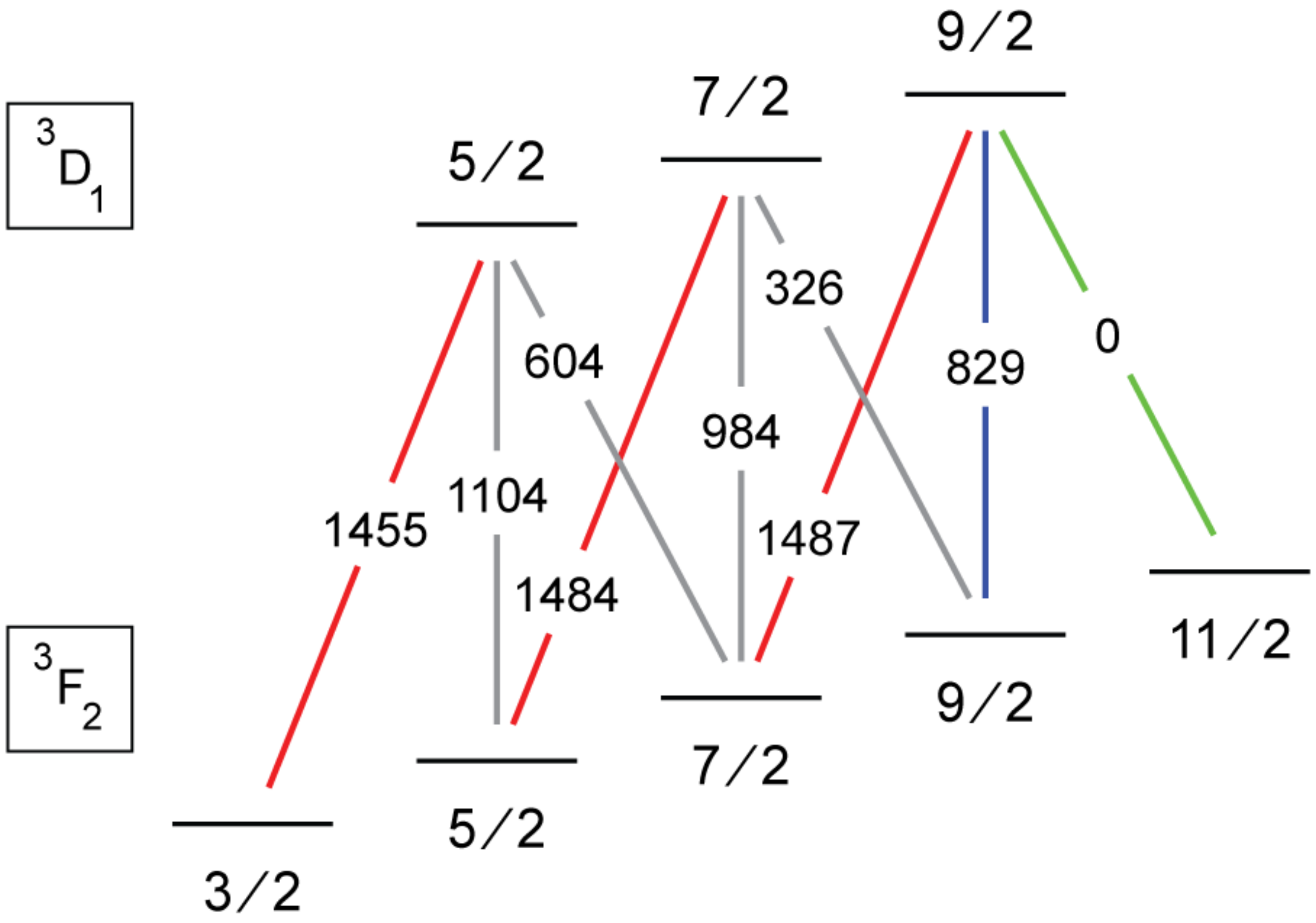


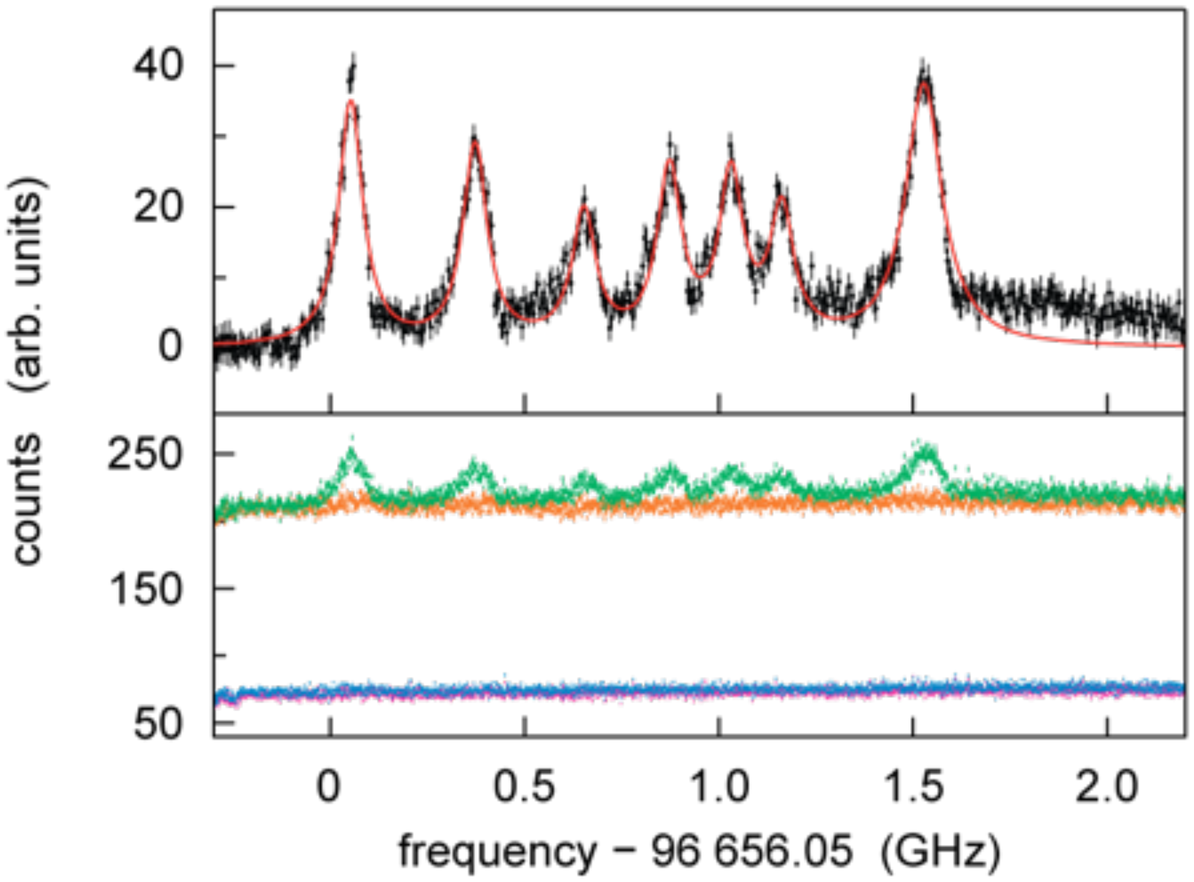
very weak cooling
→ best to start at ~ 4K and cool
to Doppler limit ($T_D \approx 0.24\ \mu K$)

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

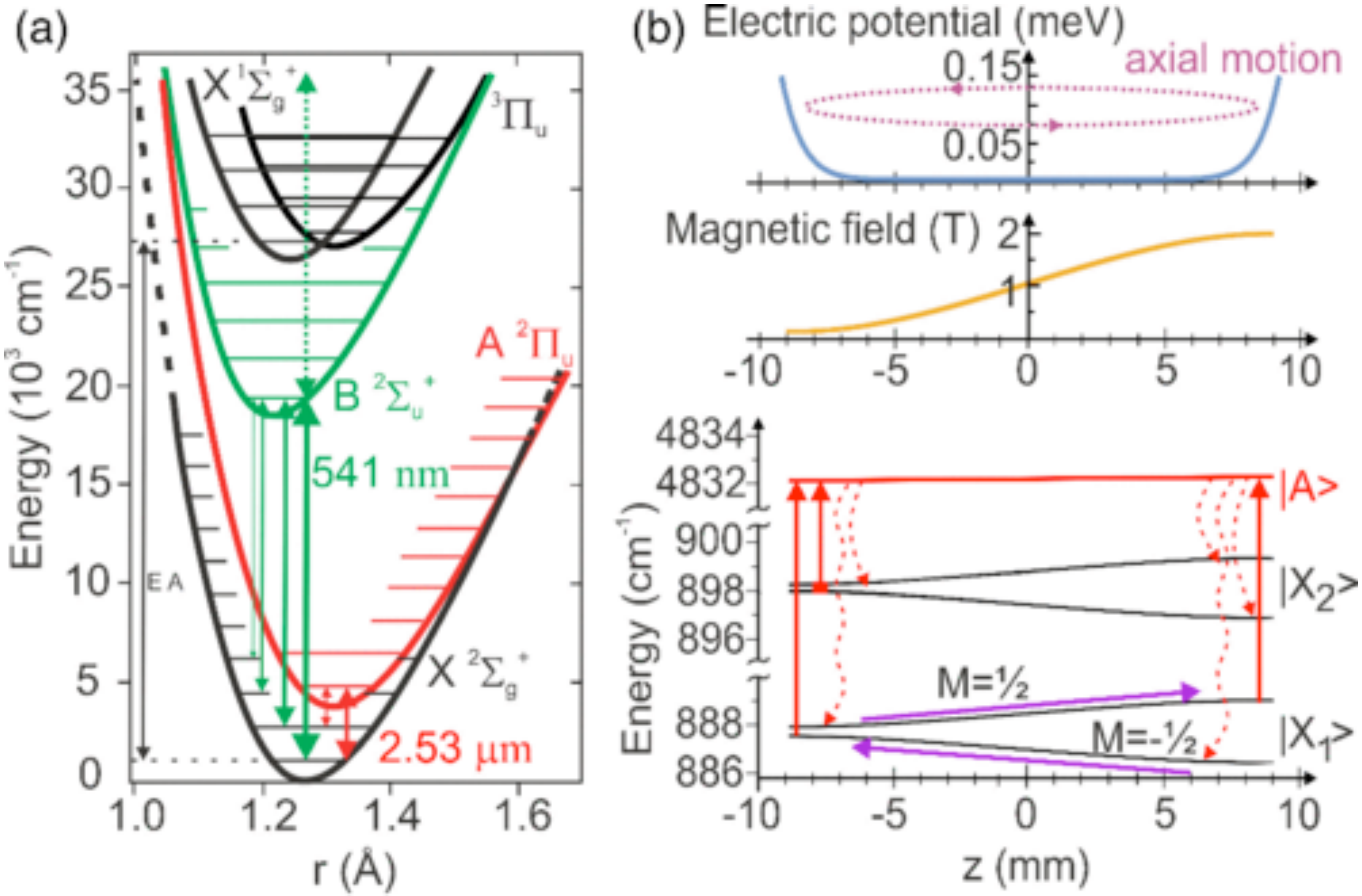




E. Jordan, G. Cerchiari, S. Fritzsche, and A. Kellerbauer
Phys. Rev. Lett. 115, 113001

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

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

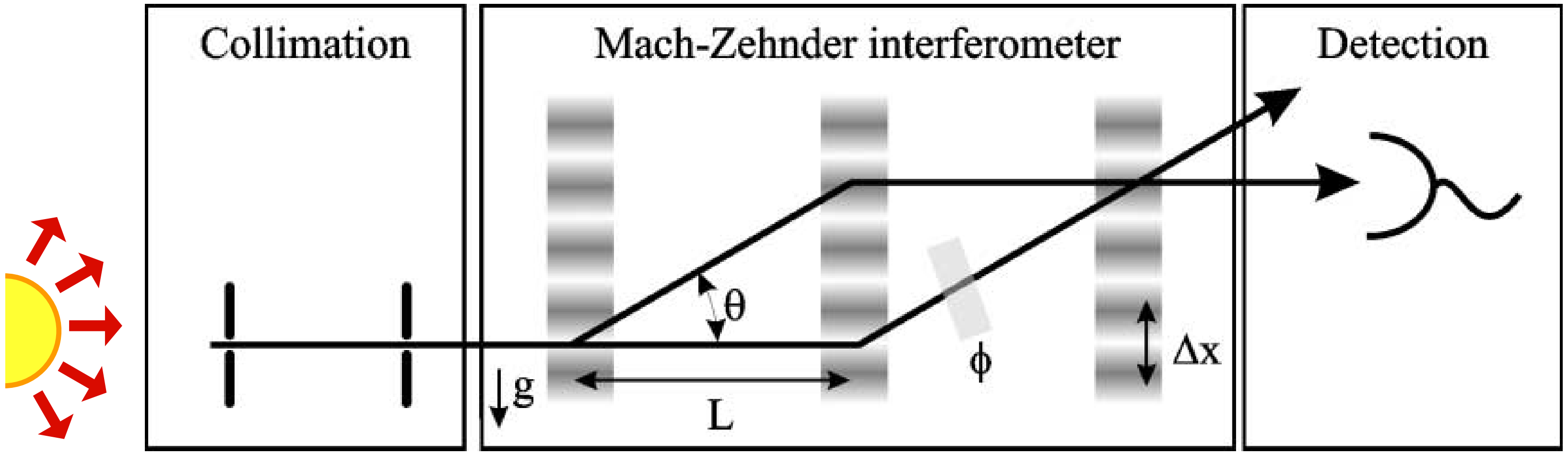
$\bar{p}N$: trapped $\bar{p}$ (AD) + radioisotopes (ISOLDE) = PUMA

positronium...

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

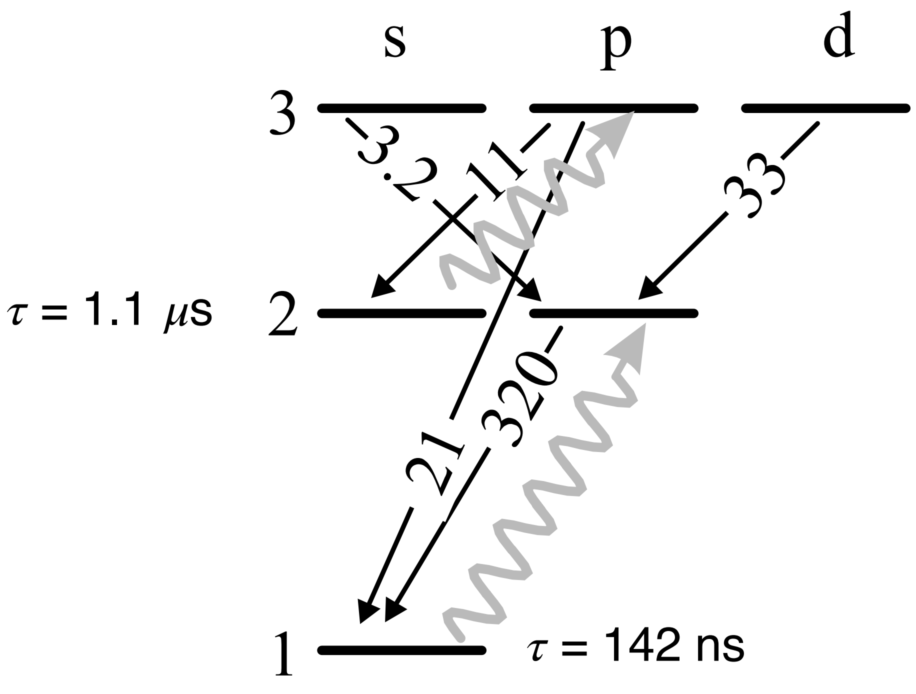
M. Oberthaler, NIMB, Volume 192, Issues 1–2, (2002) 129

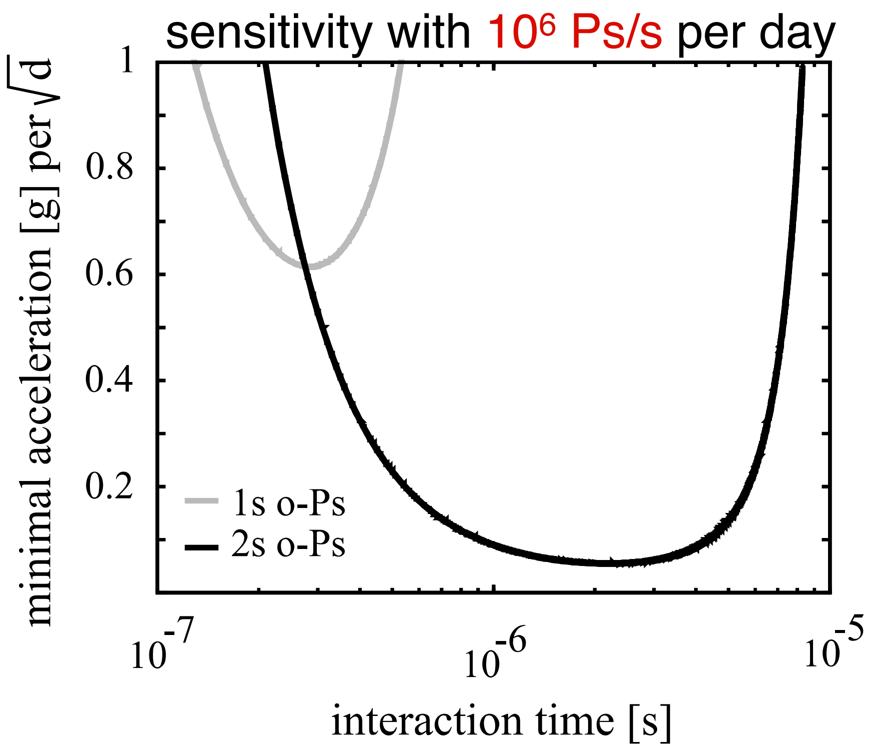
Ps source
(2π or better)



$\lambda(1s)$ = 243.1nm

$\lambda(2s)$ = 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

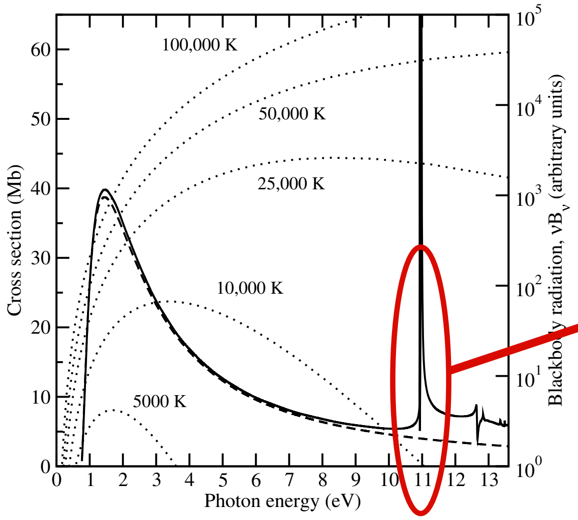
spontaneous formation in n~40, Stark mixing, rapid annihilation

spectroscopy resolution determined by fluorescence detector resolution

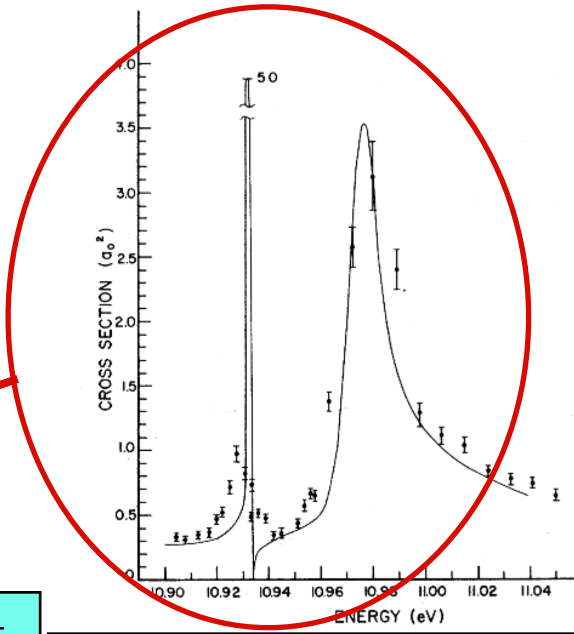
alternative: pulsed formation via co-trapped $\bar{p}$ and H^-

- 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 $\bar{\mathrm{H}}$ and $\bar{\mathrm{p}}\mathrm{He}^+$, as well as in precision measurements with $\bar{\mathrm{p}}$ 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 $\bar{\mathrm{H}}$ 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 $\bar{\mathrm{p}}\mu^+$, Ps, $\bar{\mathrm{p}}\mathrm{p}$, $\bar{\mathrm{H}}^+$, $\bar{\mathrm{H}}_2^-$ (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, ...)