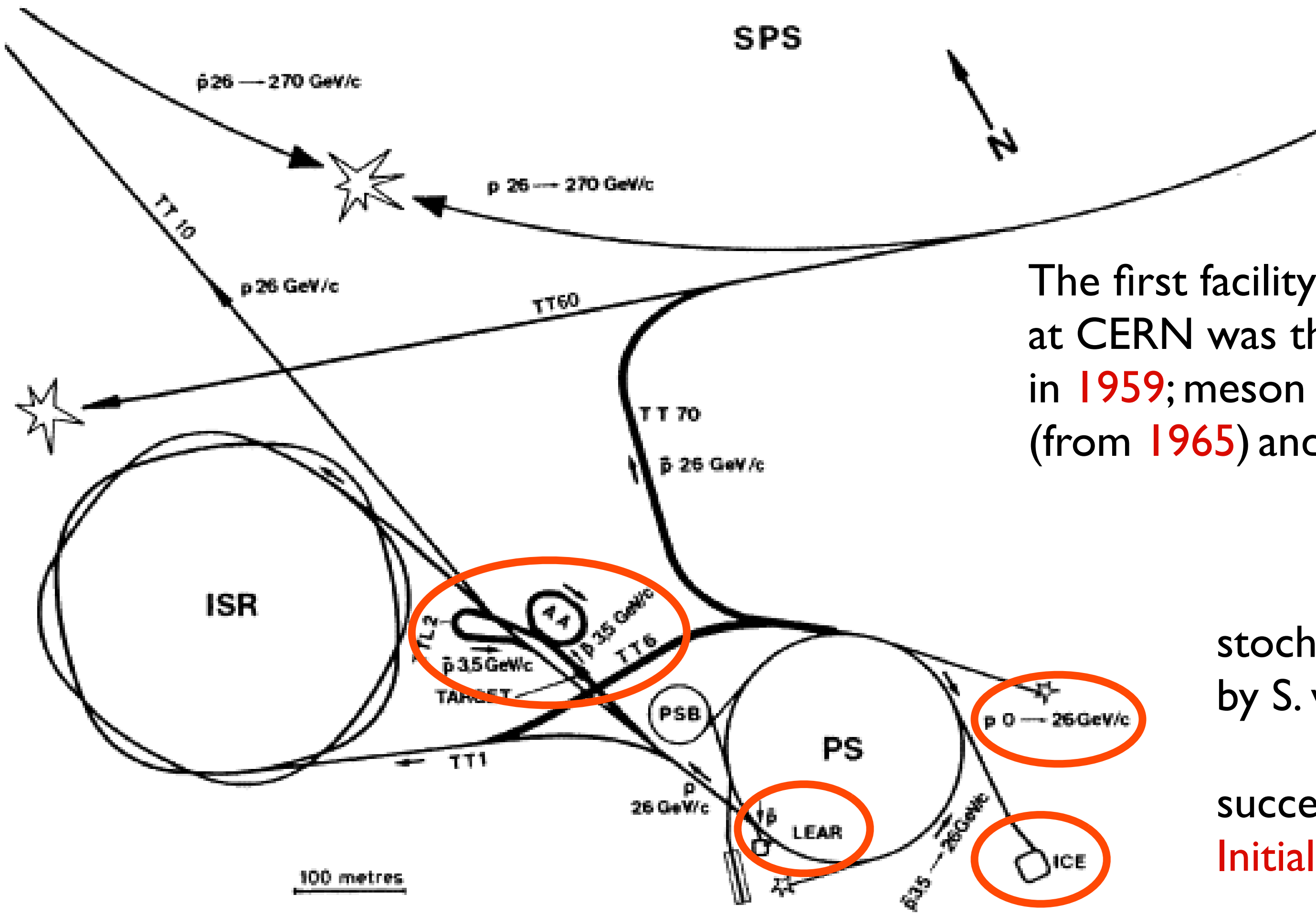
A short history of antiprotonic atoms, and an outlook for future nuclear physics studies with antiprotons

- Determination of antiproton parameters
- Nuclear physics
- Tests of fundamental symmetries [WEP]

ECT*, June 16, 2019

Michael Doser / CERN

Antiprotons at CERN: a short pre-history



The first facility capable of producing antiprotons at CERN was the Proton Synchrotron; completed in 1959; meson spectroscopy with antiprotons (from 1965) and exotic atoms incorporating them

stochastic cooling (proposed in 1968 by S. van der Meer, published in 1972);

successfully tested in the Initial Cooling Experiment (ICE) in 1978

Antiproton Accumulator (AA), Antiproton Collector (AC) and low energy antiproton ring (LEAR):

proposed and rapidly built: AA start-up in 1980, LEAR began operation in 1982, AC from 1987 onwards

beam parameters of the CERN facilities

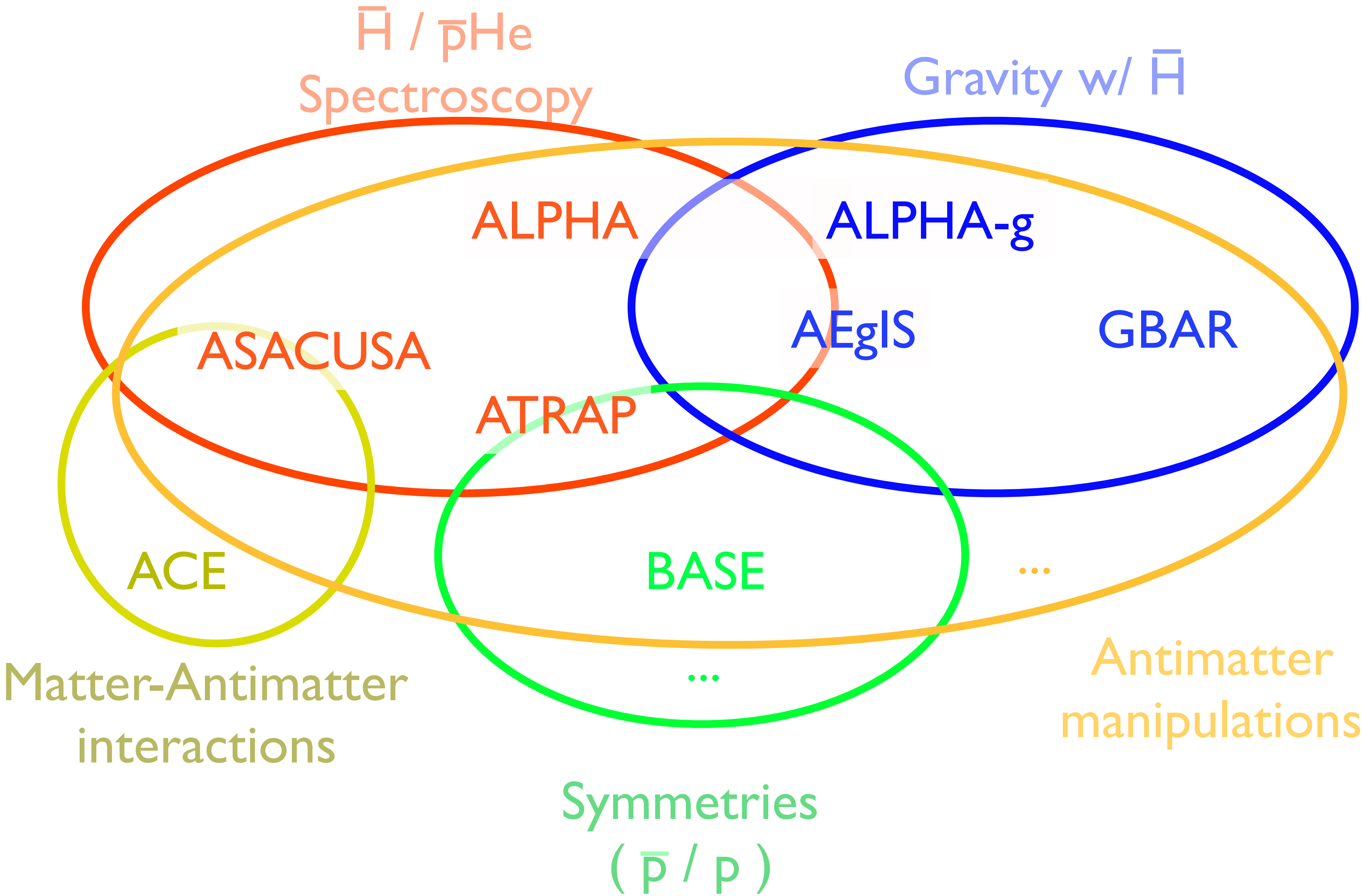
PS — low fraction of $\bar{p}$ among dominant π^- background $O(10^{-6})$, pulsed source (μs spills every 10 s)

LEAR — continuous source (hour-long spills of 10^6 $\bar{p}$/s) of $\bar{p}$ @ momenta down to 100 MeV/c

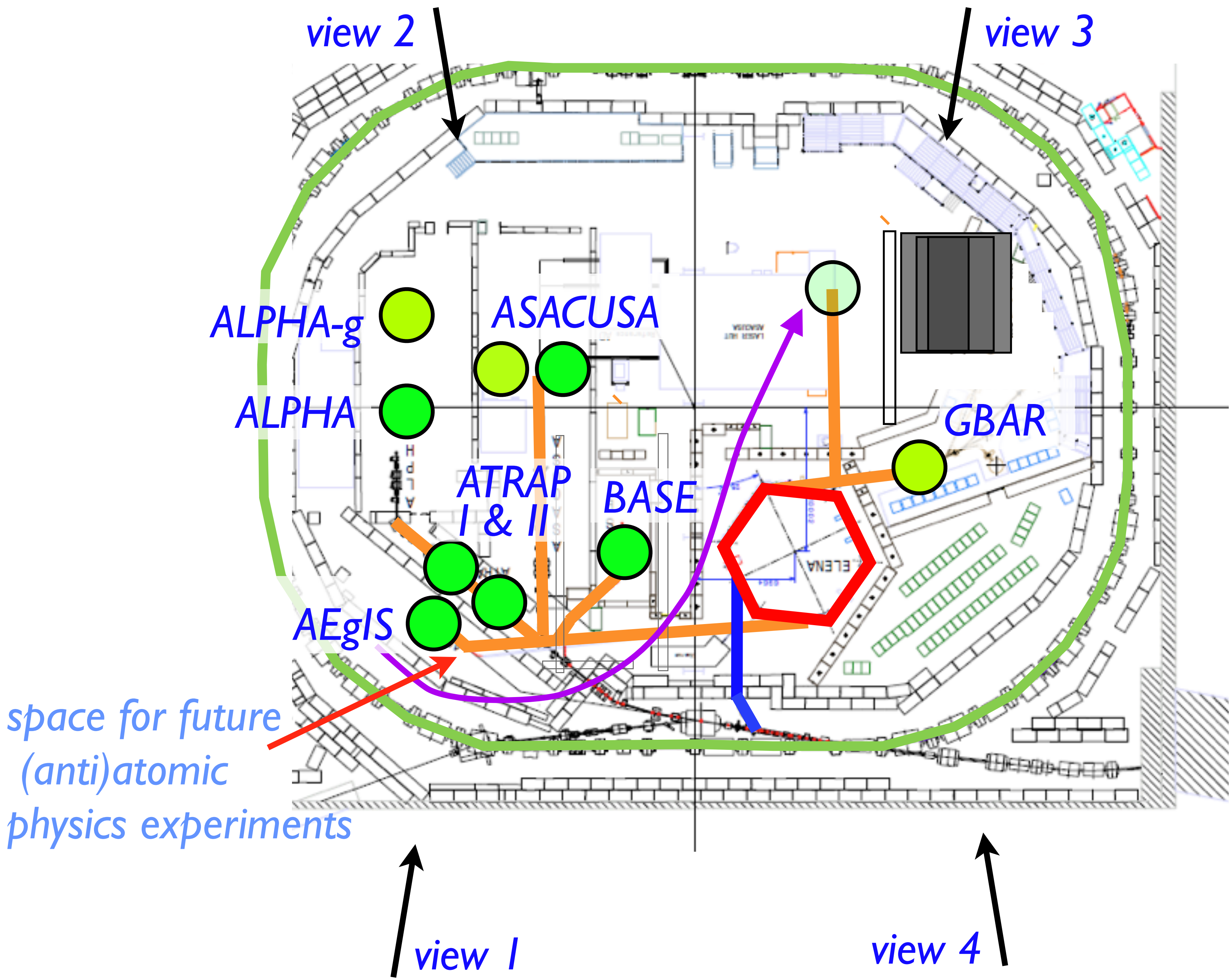
AD — pulsed source (*200 ns* spills every 100 s) of 3×10^7 $\bar{p}$ @ 100 MeV/c

ELENA — pulsed source (~*200 ns* spills every 100 s) of 10^7 $\bar{p}$ @ 100 keV

physics at the AD

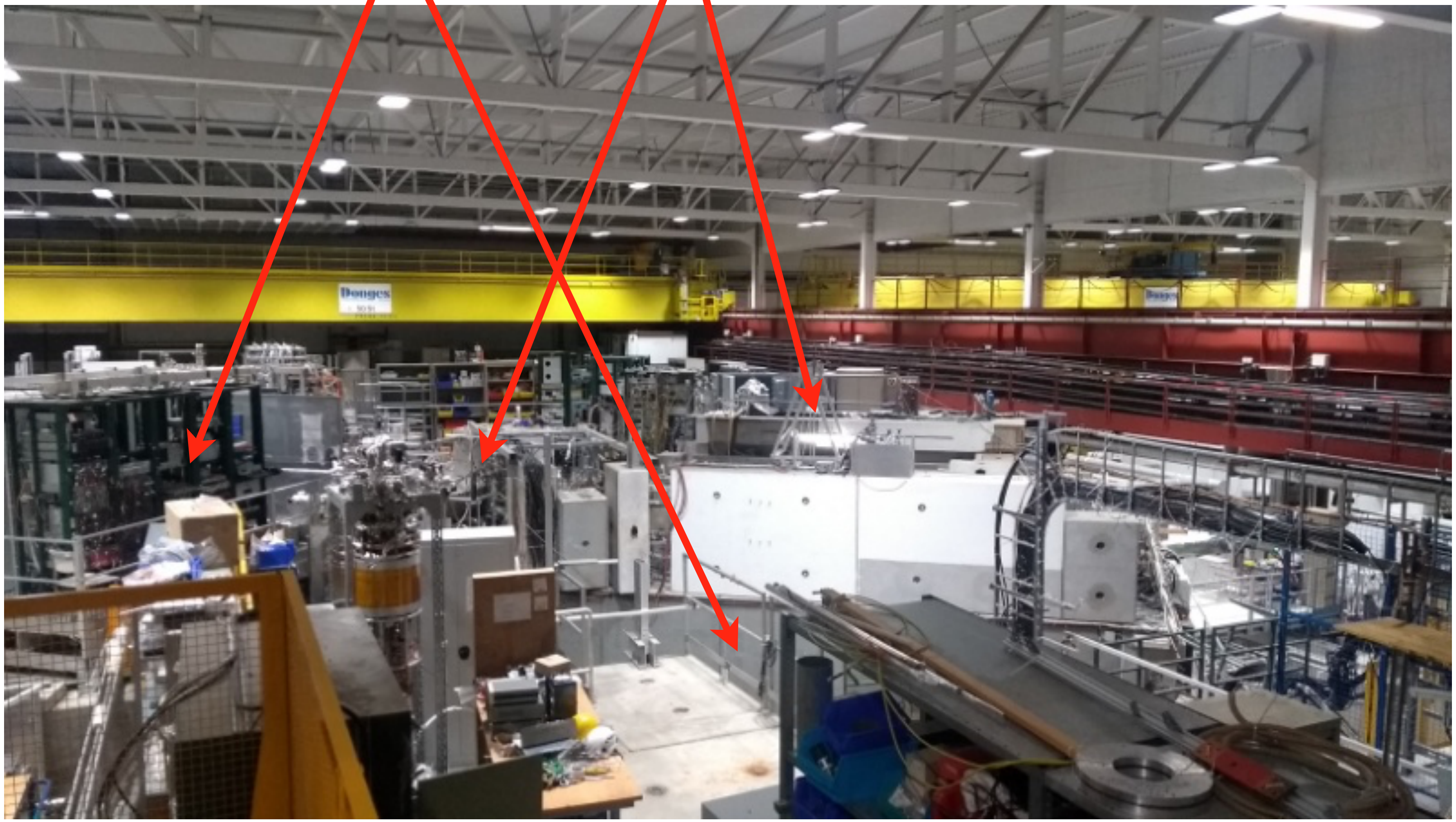


overview of AD facility



overview of AD facility

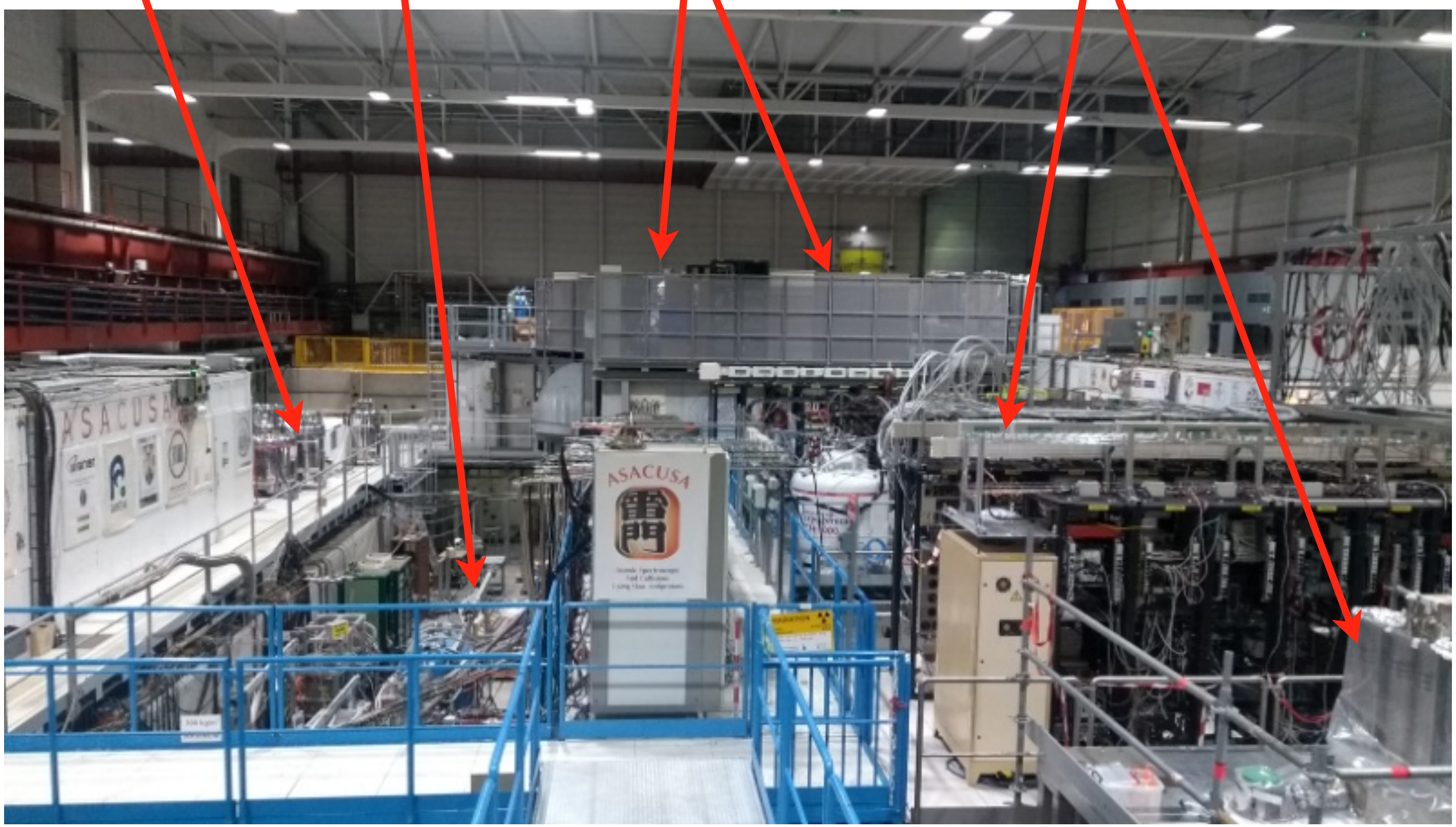
AEgIS ATRAP



view I

overview of AD facility

BASE ASACUSA ATRAP ALPHA



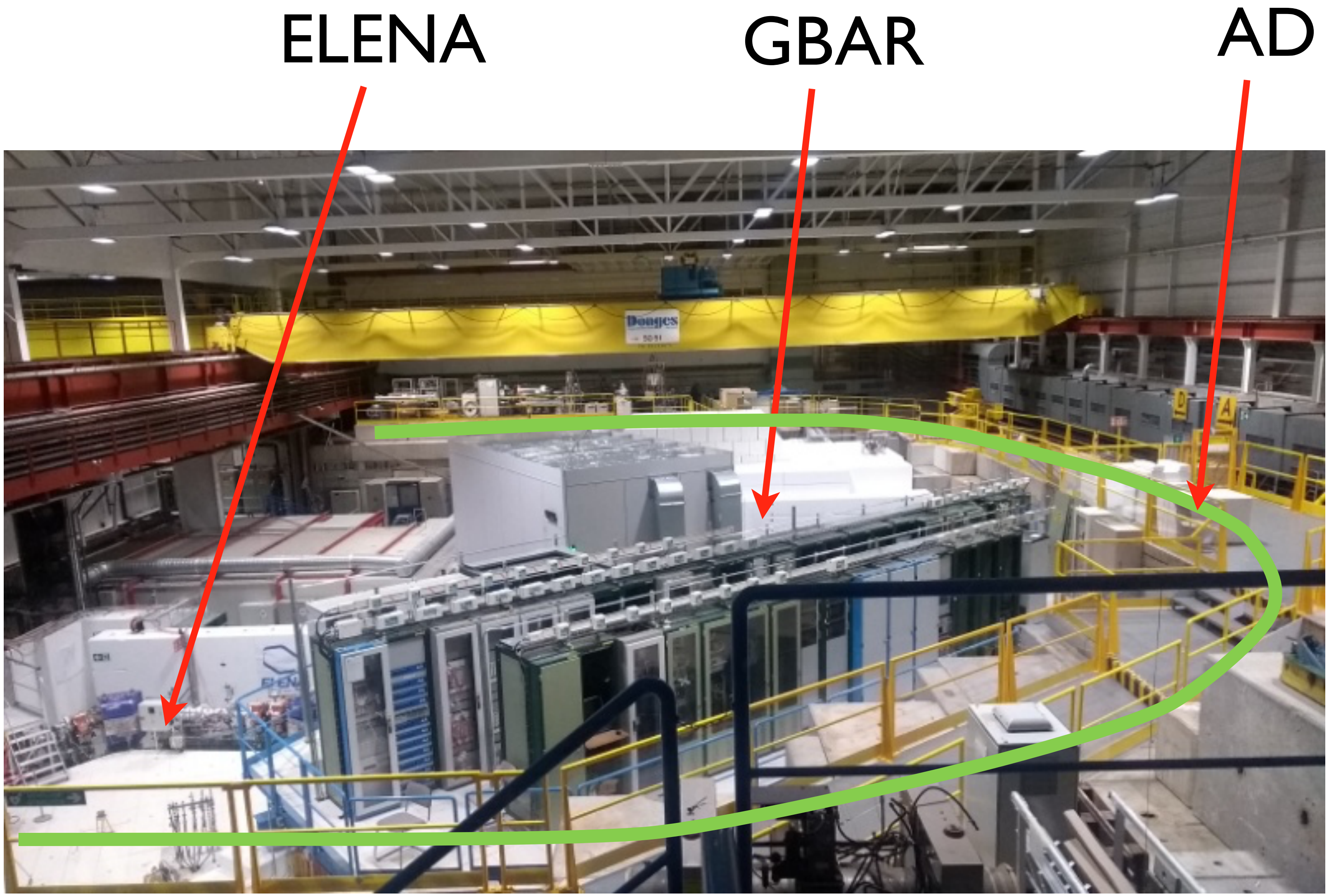
view 2

overview of AD facility

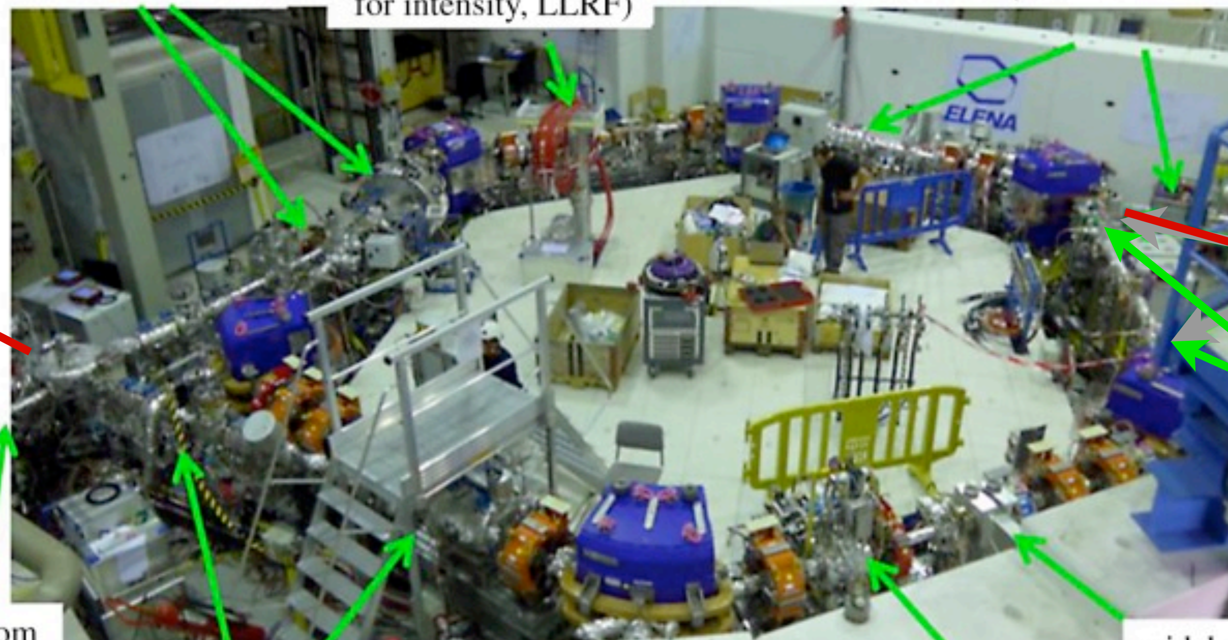
GBAR

view 3

overview of AD facility



view 4



[AD values]

momentum range, MeV c^{-1}	100–13.7	ejected beam population (total of all bunches)	1.8×10^7 **[3.5×10^7]**
kinetic energy range, MeV	5.3–0.1	number of extracted bunches	4 (experiments run in parallel) **[1]**
machine tunes h/v[a]	2.46/1.46	$\Delta p/p$ of extracted bunches, (95%)[d]	2.5×10^{-3}
circumference, m	30.4	bunch length at extraction, (95%), [m] / [ns][d]	1.3 / 300 **[200]**
repetition rate, s[b]	≈100	emittance (h/v) at extraction, π µm, (95%)[d]	6/4 **[1 / 2]**
injected beam intensity	3×10^7	nominal (dynamic) vacuum pressure, Torr	3×10^{-12}

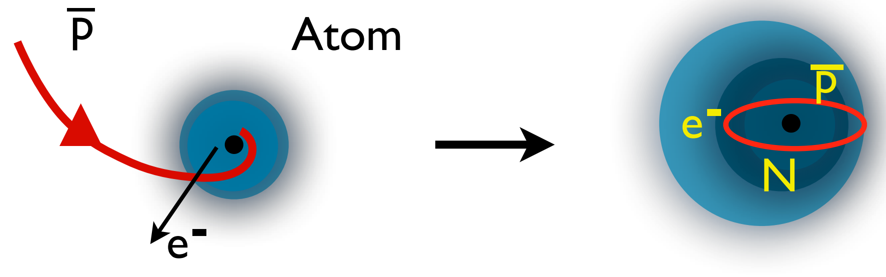
[a]With sufficient tuning range, e.g. to avoid resonances. [b]Limited by the AD repetition rate; the expected ELENA cycle length is ≈25 s.
[c] Less extracted bunches is an option leading to slightly larger emittances and momentum spreads. [d]Present best guesses based on simulations.

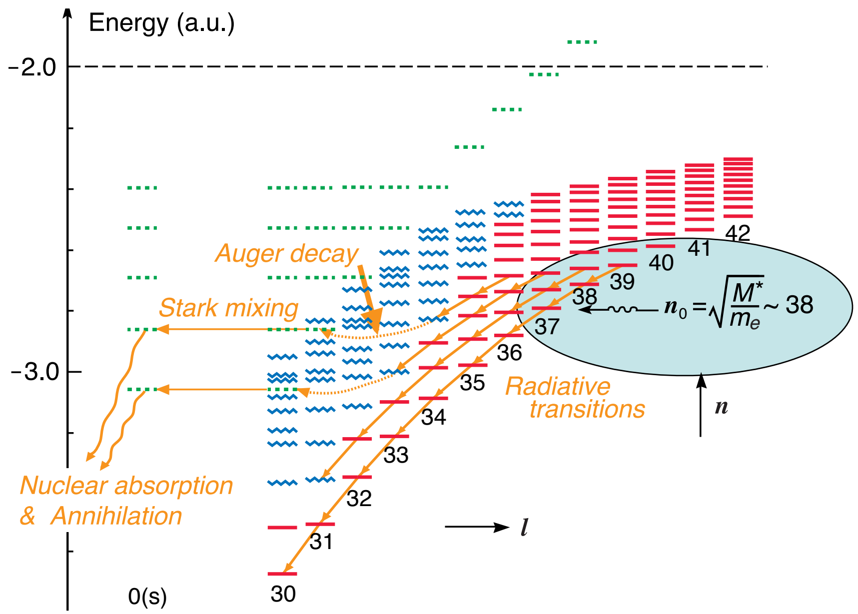
W. Bartmann *et al.*, Philos Trans A Math Phys Eng Sci. 2018 Mar 28; 376(2116): 20170266 https://royalsocietypublishing.org/doi/10.1098/rsta.2017.0266

antiprotonic (and other exotic) atoms:

atomic physics processes (Rydberg states, cascades, binding energies, lifetimes)

nuclear physics processes: the deeply bound states' energy levels and lifetimes are affected by strong-interaction effects, which in turn provide the opportunity to study nuclear forces at large distances ("nuclear stratosphere") as well as isotope-related nuclear deformations





example: antiprotonic helium

As the capture and subsequent de-excitation process occurs on time-scales of ps ~ ns, muons, pions, kaons, antiprotons, but also shorter-lived baryons, such as Σ^-, or even potentially Ξ^- and Ω^-, can form exotic relatively long-lived atoms

antiprotonic atoms:

formation : inject antiprotons into gas/liquid/solid

$n_0 = \sqrt{M^*/m_e}$ ~ 38 for $\bar{p}$He

but: not stable against Auger emission, Stark mixing

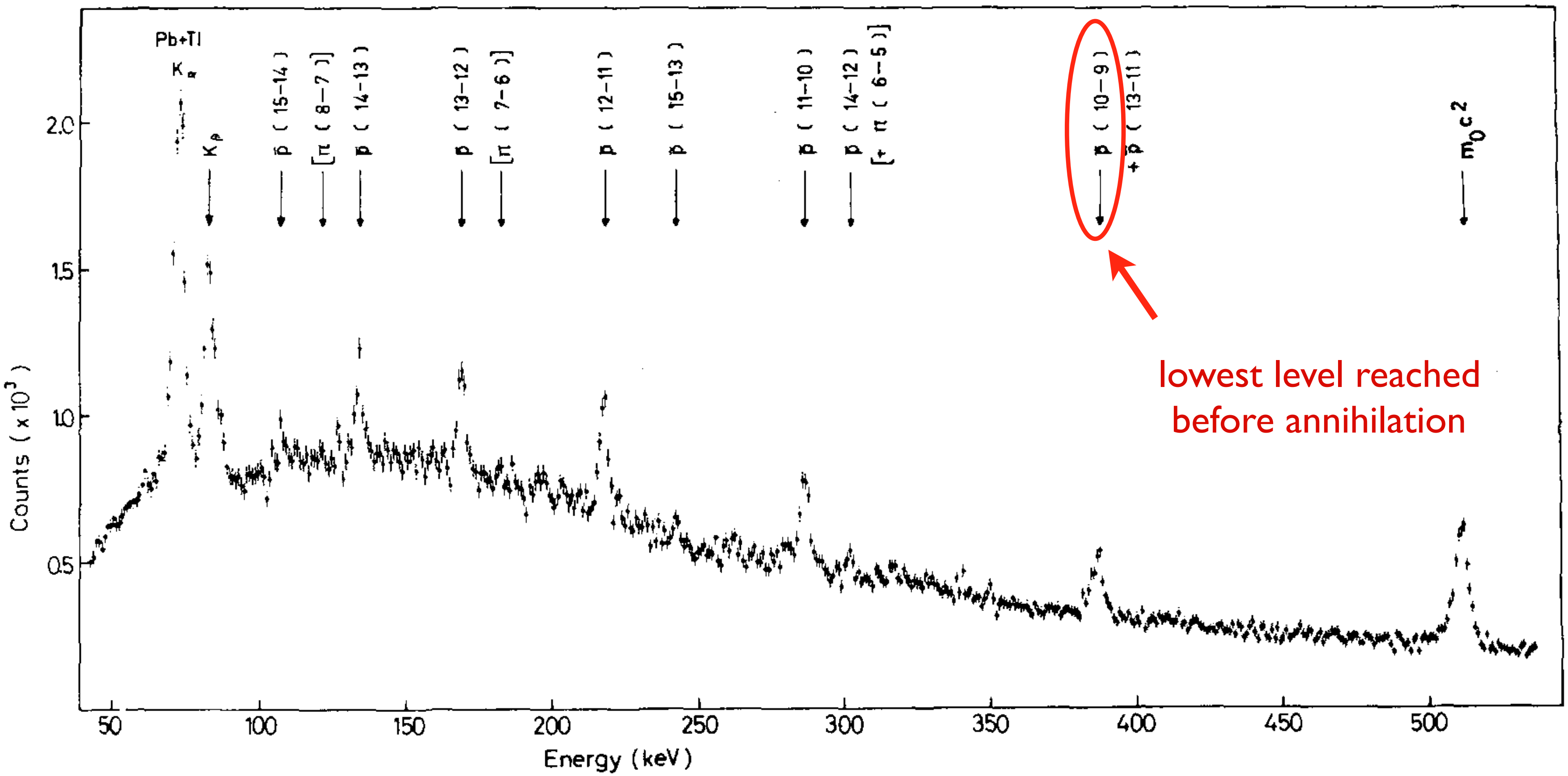
→ only $\bar{p}$He has metastable states ($\tau \sim \mu s$)

(possibly also $\bar{p}$Li : K. Sakimoto, Phys. Rev. A 84, 032501)

spectroscopy : mainly fluorescence spectroscopy (resolution relatively poor)

strong interaction effects may affect the lowest-lying bound states, shifting their energy level, modifying the lifetime of the state, and changing the transition probabilities (and thus the transition intensities) with respect to a pure QED reference value

In (1970), the first x-ray transitions of antiprotonic atoms ($\bar{p}$-^{81}Tl) were detected and investigated by Bamberger



X-ray spectrum of the first antiprotonic atom to be observed: $\bar{p}$ -^{81}Tl obtained from 14 x 10^6 stopped antiprotons measured with a 10 cm^3 Ge (Li)-detector

A. Bamberger et al., Phys. Lett. B 33 (1970) 233

Comparison between the measured and calculated transitions allowed the authors to give:

• 68% CL upper limit on any mass difference between protons and antiprotons of ($|m_{\bar{p}} - m_p| < 0.5$ MeV) (relative precision of 5×10^{-4})

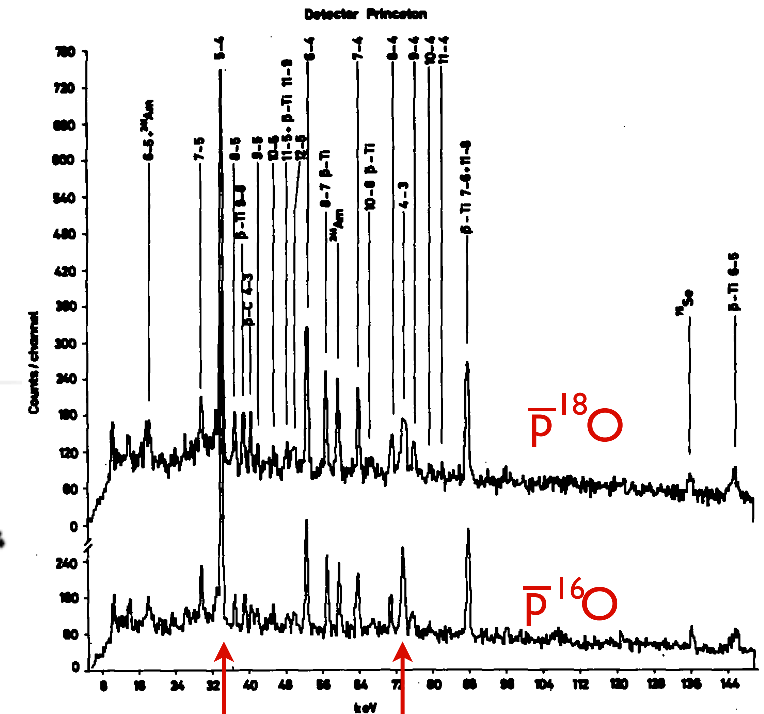
• Only a consistency check on the equality of the magnetic moment of the proton and of the antiproton could be provided, the (limited) accuracy of the measurements precluding any quantitative statement at the time.

It subsequently took several more years for more precise measurements of the transitions in antiprotonic atoms $\bar{p}$-Pb and $\bar{p}$-U to result in improved measurements of antiproton parameters: the anomalous magnetic moment in 1972 [Fox].

J. Fox et al., PRL 29 (1972) 193

Further measurements, still at Brookhaven [Robertson], of the fine structure splitting continued to improve the knowledge of the antiproton mass $m_{\bar{p}} = 938.229 \pm 0.049$ MeV

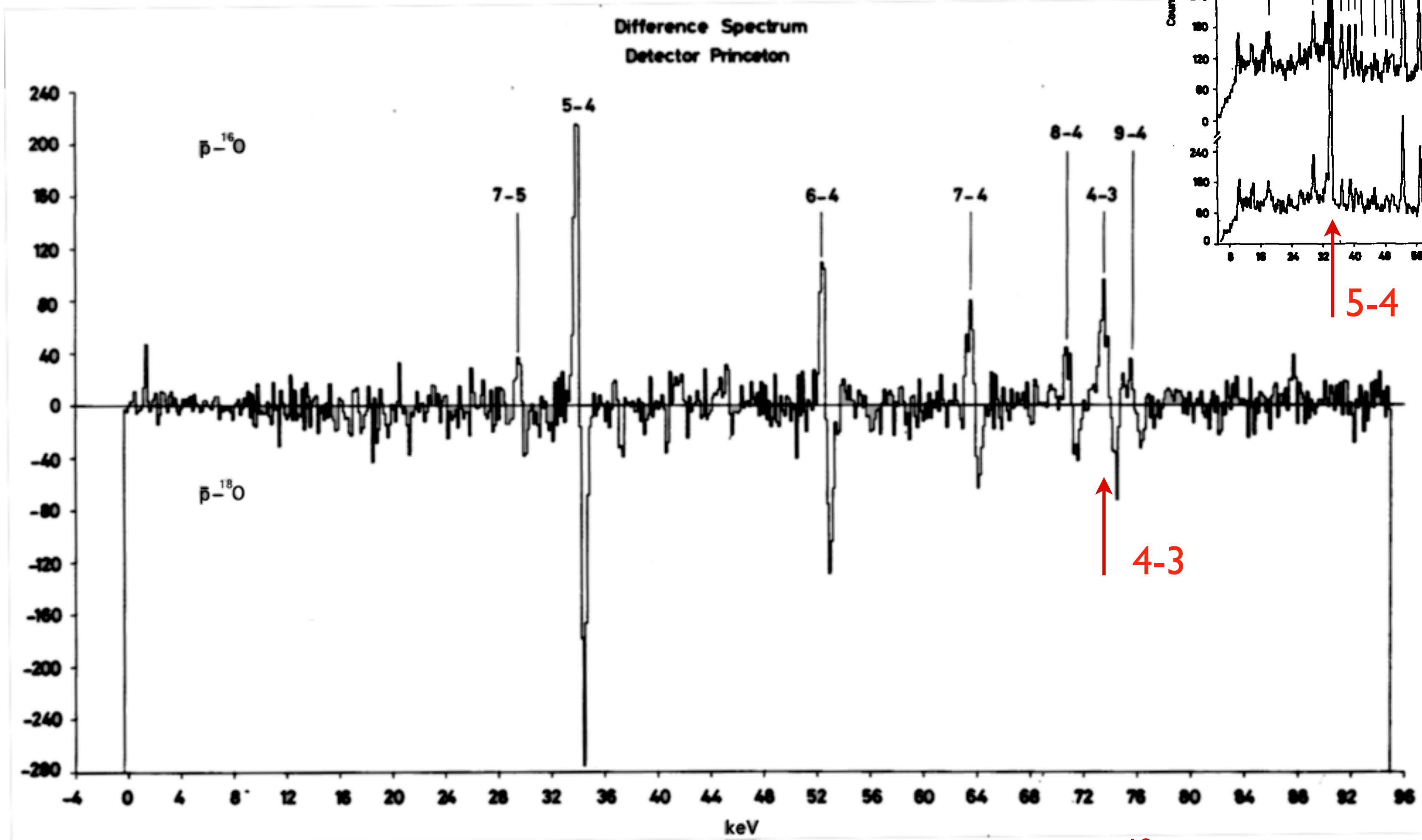
P. Robertson et al., Phys. Rev. C 16 (1977) 1945 nuclear physics



5-4

4-3

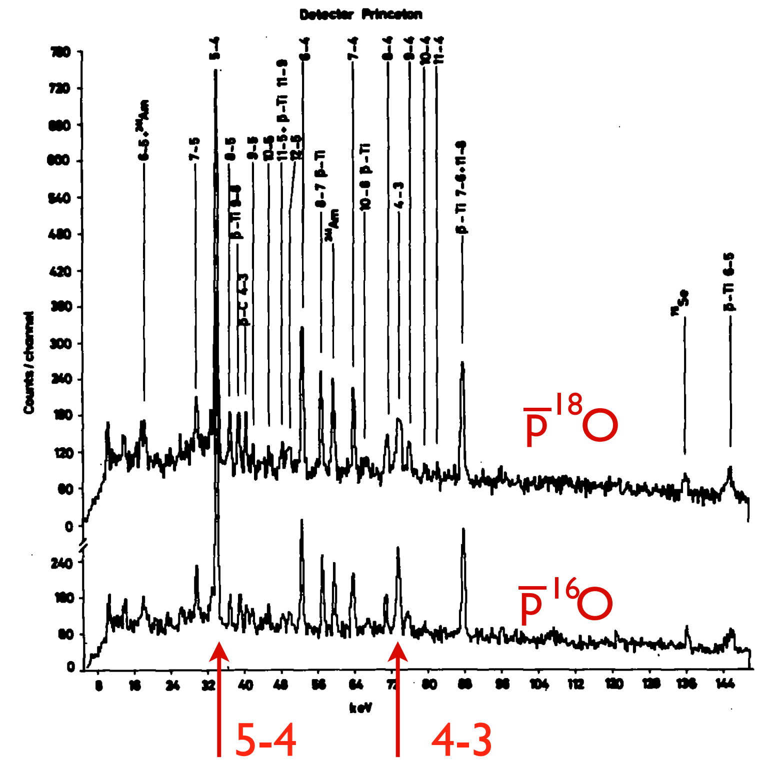
lowest level reached before annihilation / last observable transition



Antiprotonic oxygen: difference spectrum of $\bar{p}$ - ^{16}O and $\bar{p}$ - ^{18}O

H. Poth et al., Nucl. Phys. A 294 (1978) 435

nuclear physics



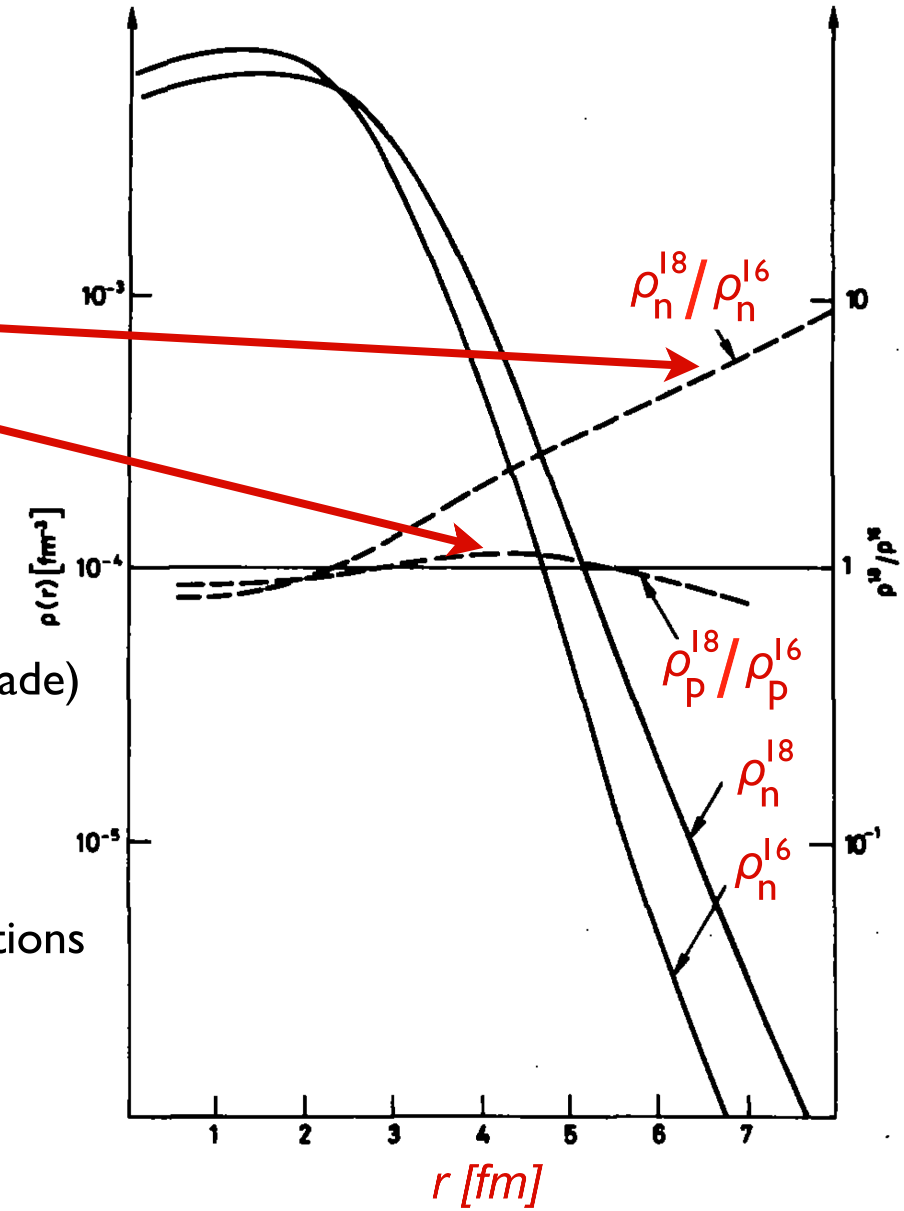
Nucleus	Last observable transition	Γ_{up} (eV)	Γ_{low} (eV)	ε_{low} (eV)
1	2	3	4	5
N	$4 \to 3$	0.13 ± 0.03 (0.10)	205 ± 70 (144)	3 ± 50 (-31)
^{16}O	$4 \to 3$	0.64 ± 0.11 (0.62) [a]	320 ± 150 (480) [a]	-124 ± 36 (-111) [a]
^{18}O	$4 \to 3$	0.80 ± 0.12 (1.05) [a]	550 ± 240 (659) [a]	-189 ± 42 (-167) [a]
P	$5 \to 4$	1.14 ± 0.25 (1.42)		
S	$5 \to 4$	3.04 ± 0.70 (2.20)	650 ± 100 (673)	-60 ± 40 (-79)

H. Poth et al., Nucl. Phys. A 294 (1978) 435

<u>nuclear physics</u>

analyze $\bar{p}$-N interaction in terms of optical potential

$$V_{\mathrm{SI}} = -\frac{2\pi}{\mu}\left(1+\frac{m_{\bar{p}}}{M}\right)\left[A^{\mathrm{eff}}_{\bar{p}\mathrm{p}}\rho_{\mathrm{p}}(r)+A^{\mathrm{eff}}_{\bar{p}\mathrm{n}}\rho_{\mathrm{n}}(r)\right],$$



derive shifts / widths of the atomic levels
(only visible in last observable transition of the cascade)

compare with measurement → $\rho_n(r)$, $\rho_p(r)$ distributions

$\bar{p}$-atoms test essentially the large-*r* region of nuclear density

H. Poth et al., Nucl. Phys. A 294 (1978) 435

nuclear physics: the PS209 experiment

Probing the diffuse neutron halo at the nuclear surface with $\bar{p}$

Neutron density distributions can be sampled in (heavy) nuclei by correlating measurements of their:

- antiprotonic x-ray cascade (annihilation radius, energy shifts)
- with a radiochemical determination of the same nuclei (annihilation on n / p)

after they have been exposed to antiproton capture and annihilation (and are consequently one mass unit lighter).

The PS209 experiment at LEAR investigated a range of 34 different nuclei, from ^{40}Ca to ^{238}U via both techniques

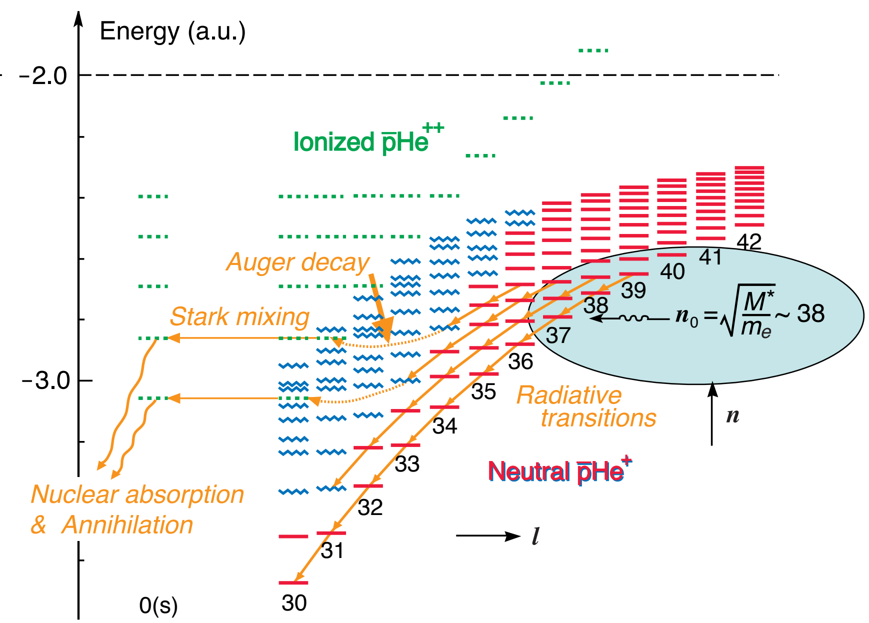
If proton distributions are constrained to the values from electron scattering or muonic x-ray measurements, then the neutron density distribution is best reproduced in terms of a half-density radius compatible with that of the proton, but a significantly larger diffuseness in the case of neutron-rich nuclei.

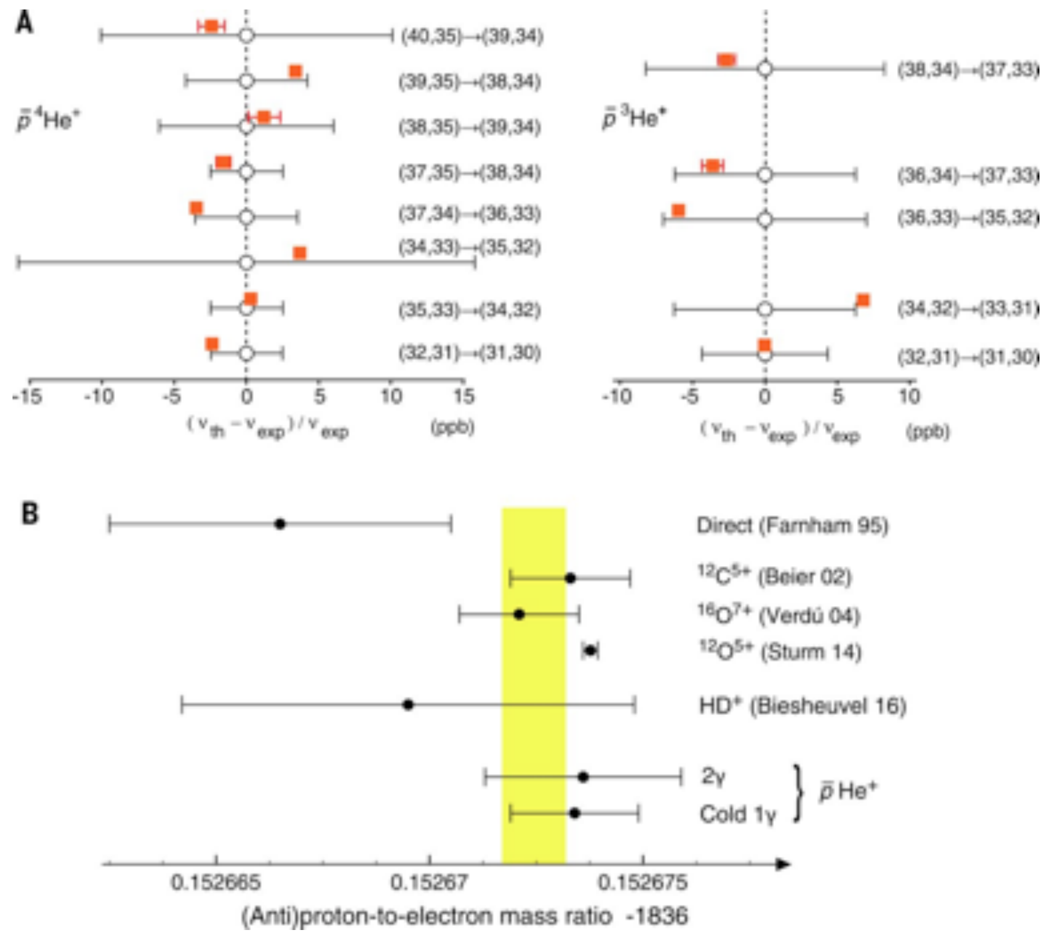
A. Trzcinska et al., Phys. Rev. Lett. 87 (2001) 082501
A. Trzcinska et al., Hyperfine Interact (2009) 194:271–276

antiprotonic helium:

metastable states formed (PS205, ASACUSA)

→ laser-spectroscopy of transitions becomes possible (huge gain in precision w.r.t. X-ray spectroscopy for precision determinations of the $\bar{p}$ mass, charge and μ)





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

CPT tests: going from atoms to traps

mass

quantity	year	value	rel. precision	method	ref.
$\lvert m_p - m_{\bar{p}} \rvert$	1970	< 0.5 MeV	5×10^{-4}	$\boxed{\bar{p}\text{-Tl}}$	[8]
$\lvert m_p - m_{\bar{p}} \rvert$	1977	$< 0.05 MeV$	5×10^{-5}	$\boxed{\bar{p}\text{-Zr and } \bar{p}\text{-Y}}$	[25]
$m_{\bar{p}}/m_p$	1990	0.999999977(42)	4×10^{-8}	trapped $\bar{p}$	[74]
$m_{\bar{p}}/m_p$	1995	0.9999999995(11)	1×10^{-9}	trapped $\bar{p}$	[66]
$(q/m)_{\bar{p}}/(q/m)_p$	1999	-0.99999999991(9)	5×10^{-11}	trapped $\bar{p}$	[63]

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

magnetic moment

$(\mu_p - \lvert \mu_{\bar{p}} \rvert)/\mu_p$	1972	(-0.04 ± 0.1)	3×10^{-2}	$\boxed{\bar{p}\text{-Pb}}$	[79]
$(\mu_p - \lvert \mu_{\bar{p}} \rvert)/\mu_p$	2009	$(2.4 \pm 2.9) \times 10^{-3}$	10^{-3}	$\boxed{\bar{p}\text{-He}}$	[70]
$\mu_{\bar{p}}/\mu_p$	2013	-1.000000(5)	5×10^{-6}	trapped $\bar{p}$	[78]

Antiproton parameters determined by different techniques

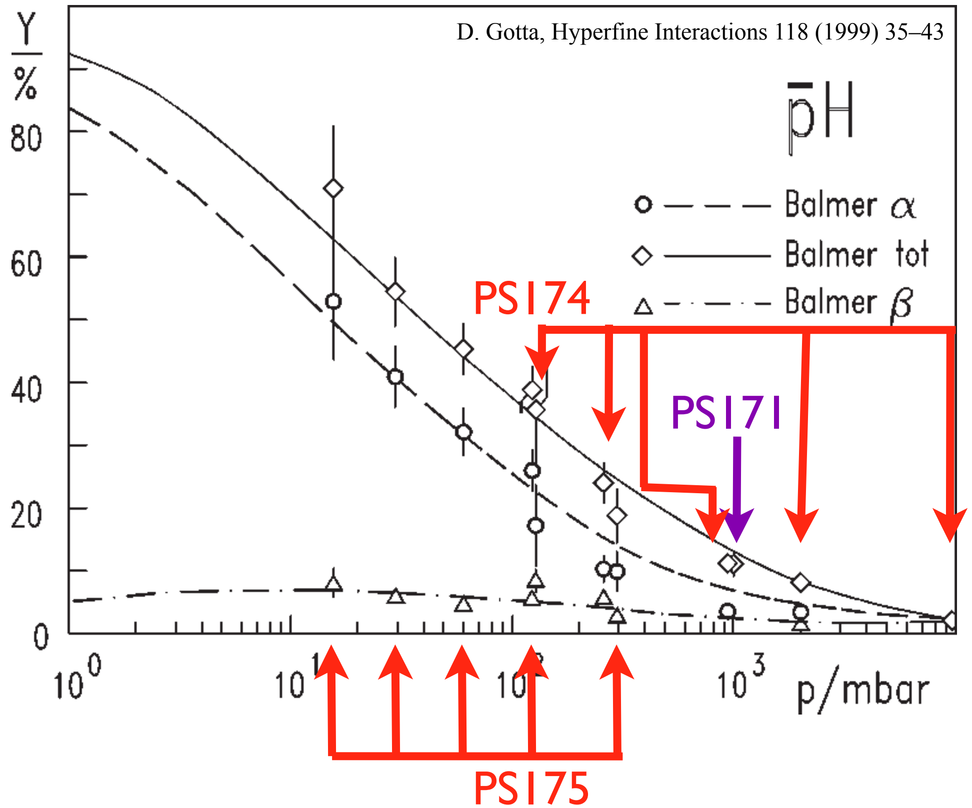
[8]: A. Bamberger et al., Phys. Lett. B 33 (1970) 233
[25]: P. Robertson et al., Phys. Rev. C 16 (1977) 1945
[79]: J. Fox et al., PRL 29 (1972) 193
[70]: T. Pask et al. (ASACUSA collaboration), Phys. Lett. B 678 (2009) 55
[74]: G. Gabrielse et al., PRL 65 (1990) 1317
[66]: G. Gabrielse et al., PRL 74 (1995) 3544
[63]: G. Gabrielse et al., PRL 82 (1999) 3198
[78]: G. Gabrielse et al., PRL 110 (2013) 130801

the simplest antiprotonic atoms: protonium (and deuteronium)

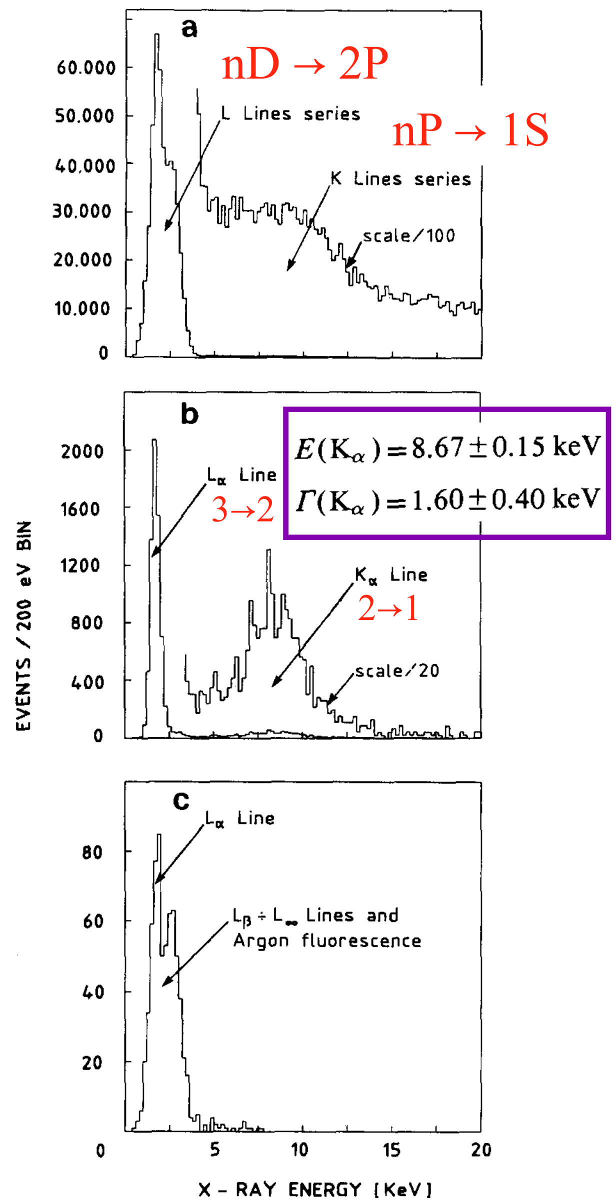
- inject $\overline{p}$ into hydrogen (gas, liquid); it will replace the electron of the hydrogen atom at a radius of ~ 5×10^{-9} cm
- the resulting protonium will have a large angular momentum and a principal quantum number n of $\sqrt{m_p/2m_e} \sim 30$
- during de-excitation, (n,l) QN are reshuffled $\longrightarrow$ annihilation dominantly from $l = 0$ (possibly high n)
- density-dependent Stark mixing $\longrightarrow$ cascade to low ($n = 1..3$) states only in low-density hydrogen gas (low stopping power)

G. Reifenröther and E. Klempt, Nuclear Physics A, 503 (1989) 885

<u>the simplest antiprotonic atoms:</u> protonium



ASTERIX PS171



M. Ziegler et al., Phys. Lett. B 206 (1988) 151

QED predictions for the energies of K_α = 9.37 keV

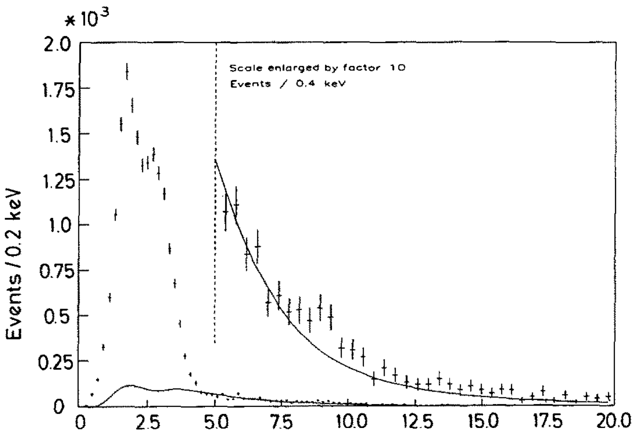
strong interaction: broadening and shift of the s and p states of the $\bar{p}p$ atom

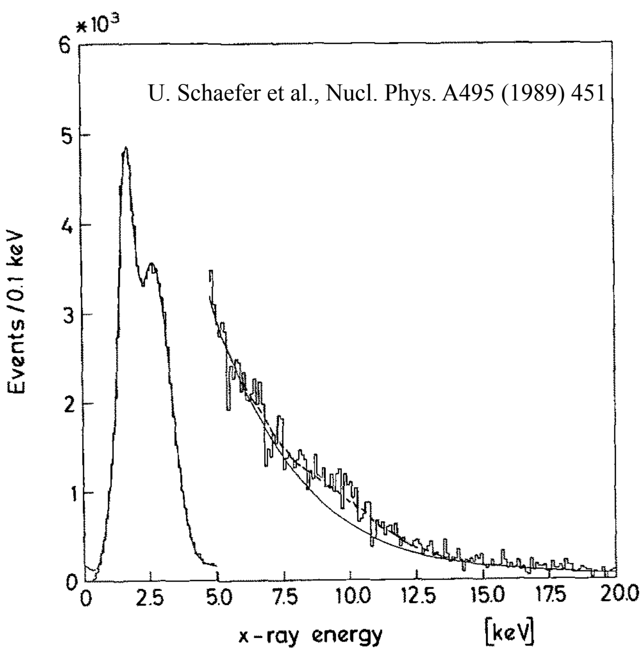
<u>the simplest antiprotonic atoms:</u>

protonium

ε_{1s}=–706.4±18.2 eV, Γ_{1s}=1054±65 eV

caveat: internal bremsstrahlung!

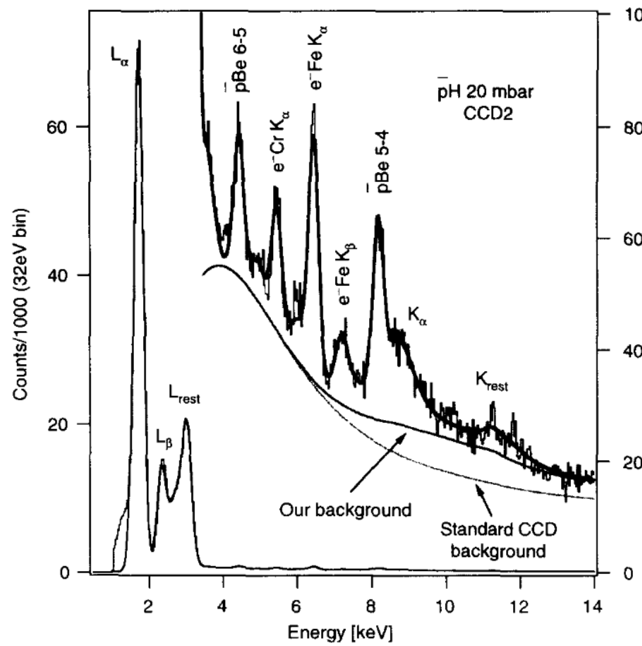




Charged particles accelerated in the annihilation emit inner bremsstrahlung radiation with a sizeable yield in the X-ray energy region below 10 keV

3D → 2P

M. Augsburger et al. / Nuclear Physics A 658 (1999) 149–162



$$\epsilon_{1s} = -721.1 \pm 14.1 \text{ eV},$$

$$\Gamma_{1s} = 1096.7 \pm 42.3 \text{ eV},$$

$$^3S_1: \quad \epsilon_{1s} = -785 \pm 35 \text{ eV}$$

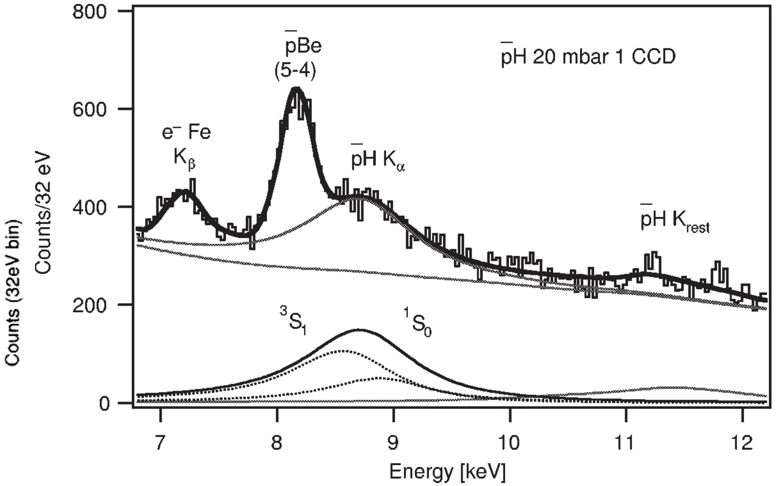
$$\Gamma_{1s} = 940 \pm 80 \text{ eV}$$

$$^1S_0: \quad \epsilon_{1s} = -440 \pm 75 \text{ eV}$$

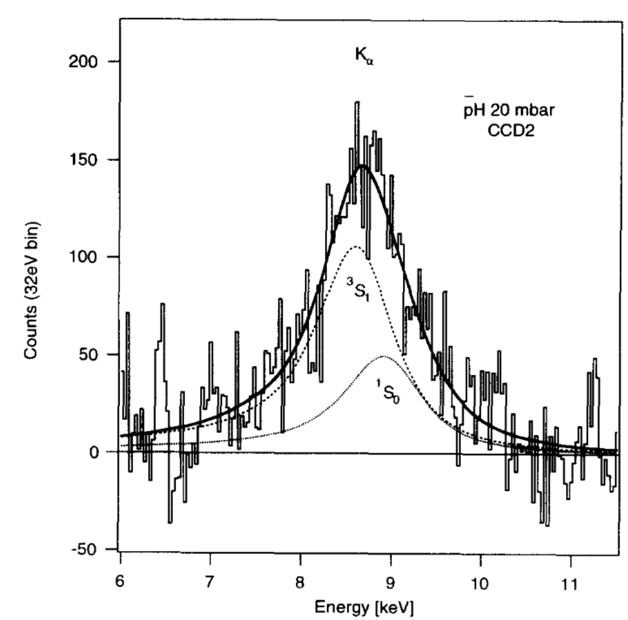
$$\Gamma_{1s} = 1200 \pm 250 \text{ eV}$$

2P → 1S

M. Augsburger et al., Hyperfine Interactions 118 (1999) 59–62

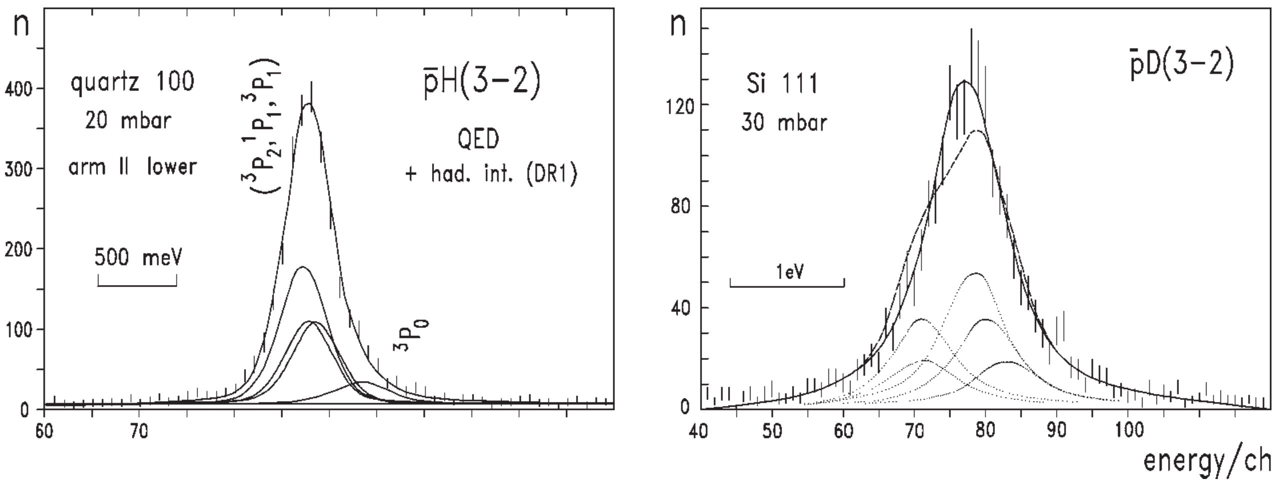


M. Augsburger et al. / Nuclear Physics A 658 (1999) 149–162

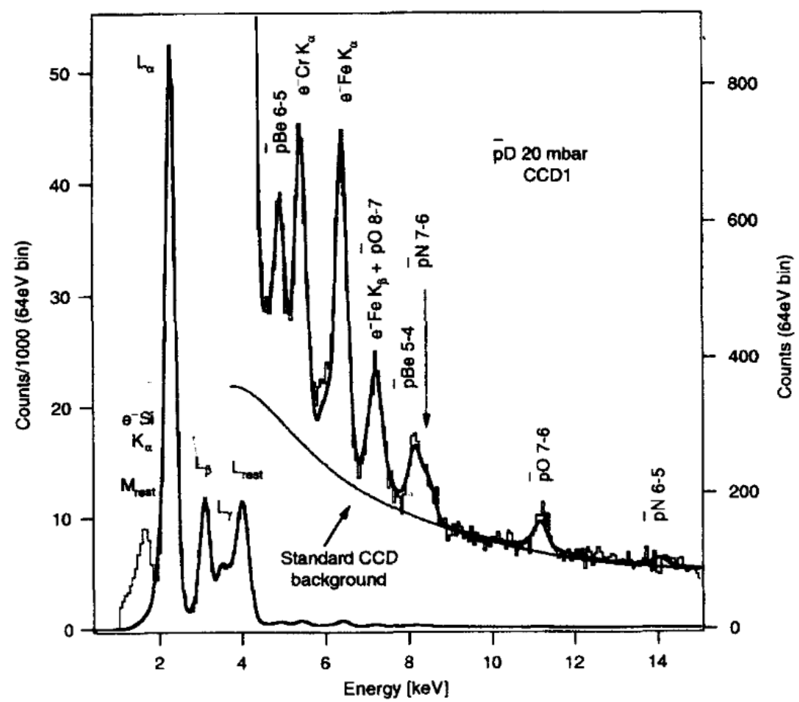


<u>the simplest antiprotonic atoms:</u> ... and deuteronium

D. Gotta, Hyperfine Interactions 118 (1999) 35–43



M. Augsburger et al. / Nuclear Physics A 658 (1999) 149–162



In $\bar{p}D$ because of the more frequent annihilation from p levels as compared to $\bar{p}H$, no clear evidence was found for the ground state transition (1% of 2p population in $\bar{p}H$)

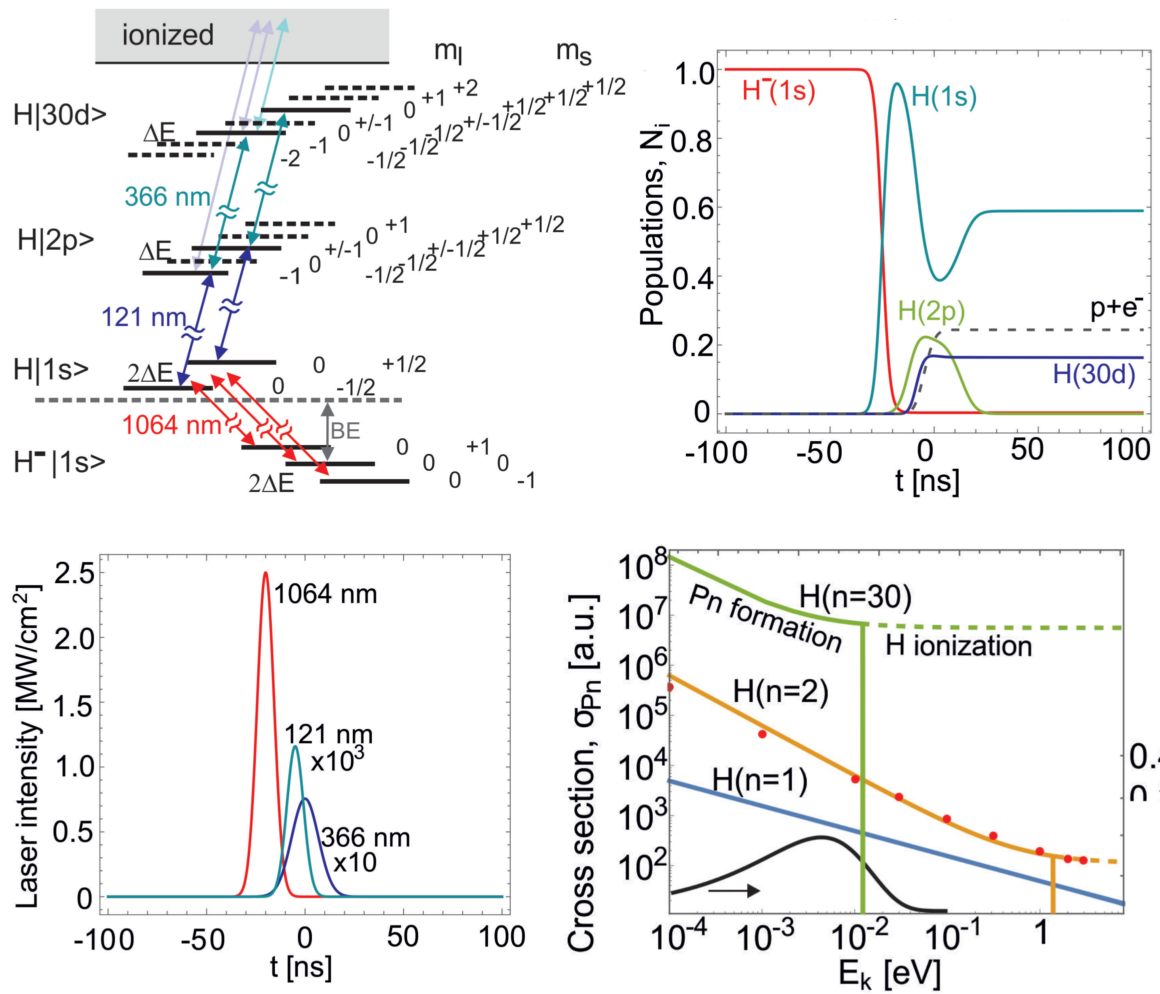
So: the direct measurement of the 2p-level width was the only possibility at all to determine hadronic effects in $\bar{p}D$.

“A re-measurement of the Lyman transitions with the forthcoming generation of CCD detectors is desirable and should be able to improve the accuracy by a factor of 5. Such an experiment requires a continuous antiproton beam of the order of 10^5/s, which, however, will not be available in the near future.”

simplest systems: an improved $\bar{p}p$ (and $\bar{p}d$) production method

S.Gerber, D.Comparat, M.D., in prep.

- co-trap H^- (or D^-) and $\bar{p}$ in a Penning trap
- photo-ionize H^-
- laser-excite $H \rightarrow H^*(30)$
- charge-exchange reaction: $H^*(30) + \bar{p} \rightarrow \bar{p}p(n) + e^-$



- (detect fluorescence & annihilation ($\pi^{\pm}$, π^0))

complex systems: heavier antiprotonic atoms

- established method: capture in gas/solid;
  Stark mixing upon collisions, practically immediate annihilation, from high-n s-states

- proposed method: trapped anion together with antiprotons, photo-detachment of electron, excitation into a Rydberg state, lifetime O(ms), possibly even trappable (large dipole) ...

  → spectroscopy of Rydberg antiprotonic atoms

  → clean cascade (vacuum → no Stark mixing)

  → controlled annihilation (à la ASACUSA $\bar{p}$He) measurements with pulsed-formed antiprotonic atoms:

example: Cs^- as a source of antiprotonic Cs: $(Cs^+\bar{p})^*$

proposal by F. Robicheaux to form a beam of $(Cs\,\bar{p})^*$ by passing a neutral beam of Cs^* through trapped $\bar{p}$

J. Robicheaux, J. Phys. B **43,** 015202 (2010)

variant: co-trap Cs^- and $\bar{p}$

→ pulsed formation of a thermal $(Cs^+\bar{p})^*$ "beam"

passage through e^+ → thermal $(\bar{H})^*$ "beam"

generally: pulsed formation of beams of $\bar{p}p^*$, $\bar{p}d^*$, Ps^*, ...

(in addition of course to pulsed formation of beams of $\bar{H}^*$)

<u>measurements with pulsed-formed antiprotonic atoms:</u>

AEgIS

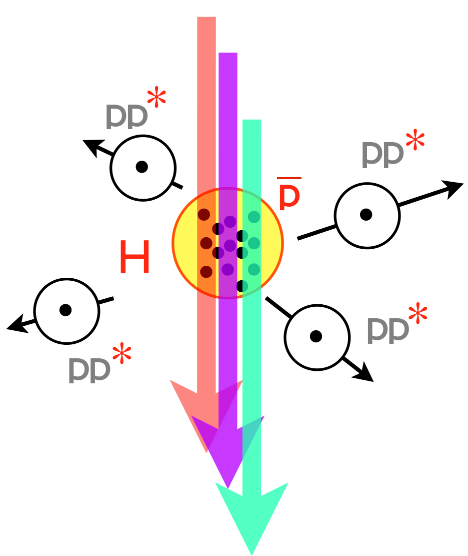
passing these neutral beams of antiprotonic atoms through gratings (*optical* gratings required for Rydberg atoms ?) allows testing the WEP for a range of matter - antimatter systems (purely antimatter, purely leptonic, purely baryonic, ...)

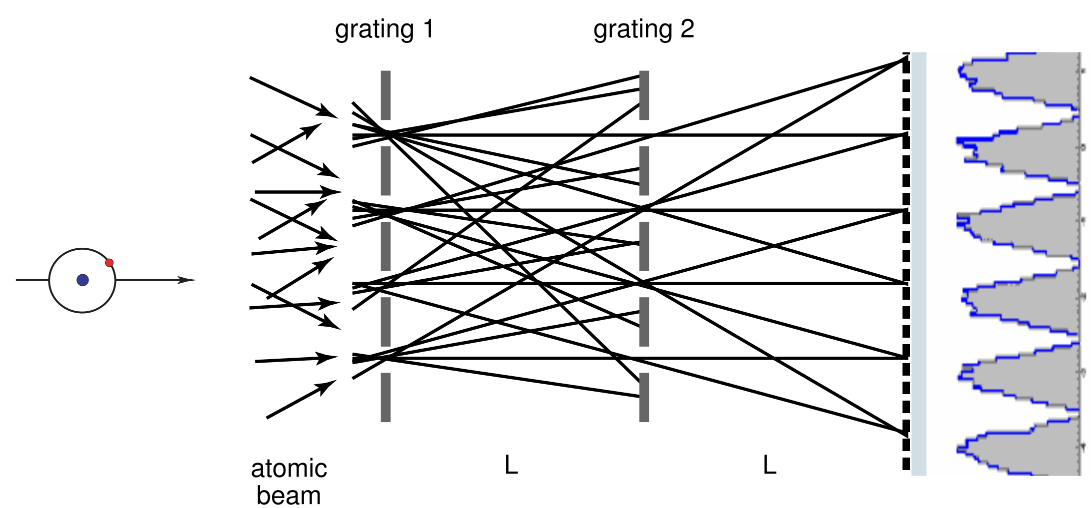
$$\mathrm{Cs}^* + e^+ \rightarrow \mathrm{Ps}^*$$

$$\mathrm{Ps}^* + \bar{p} \rightarrow \bar{\mathrm{H}}^*(30) + e^+$$

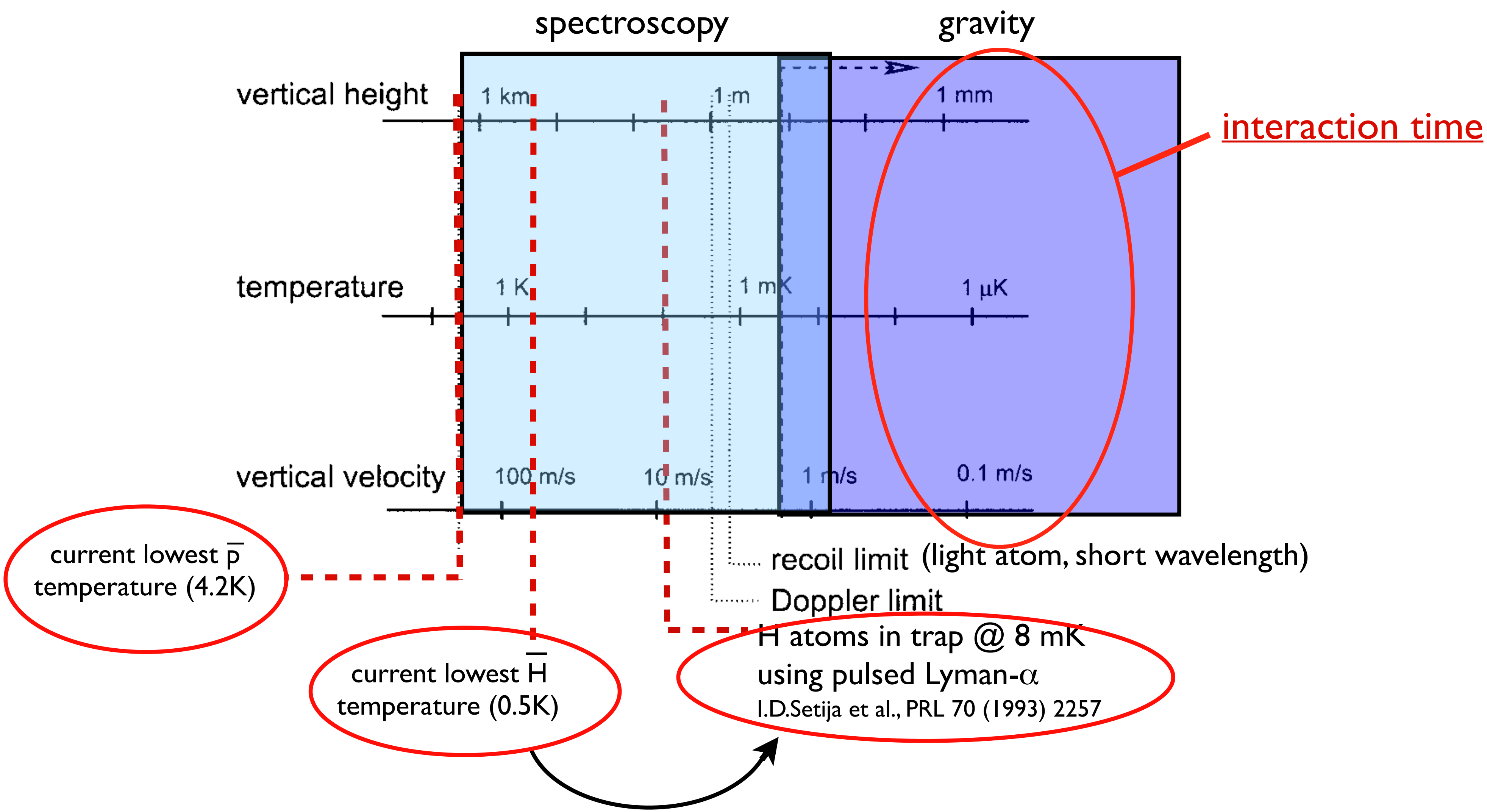
$$\mathrm{Cs}^* + \bar{p} \rightarrow \bar{p}\mathrm{Cs}^*(30) + e^+$$

$$\mathrm{H}^* + \bar{p} \rightarrow \bar{p}p^*(2000) + e^+$$





gravity tests with antiprotonic atoms require ultra-low temperatures



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

Eikema, Walz, Hänsch, PRL 86 (2001) 5679 measurements with pulsed-formed antiprotonic atoms (and ions):

AEgIS experiment

cooling of $\bar{p}$

La^- Warring et al, PRL 102 (2009) 043001

Fischer et al, PRL 104 (2010) 073004

C_2^- P.Yzombard et al., Phys. Rev. Lett. 114, 213001

sympathetic cooling of $\bar{p}$ to sub-mK

Note: beam experiments have a weak dependence of gravity measurement on (transverse) temperature (→ flux into gravity-sensitive detector) as long as flight times are ~ ms or longer

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)

$$\boxed{\begin{array}{l} Ps(2p) + \bar{p} \rightarrow \bar{H} + e^- \\ Ps(2p)+\bar{H}(1s) \rightarrow \bar{H}^+ + e^- \end{array}}$$

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. $Be^+ \rightarrow 10\ \mu K$

photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"

measurements with trapped antihydrogen atoms:

ALPHA-g experiment

cooling of (trapped) $\bar{H}$

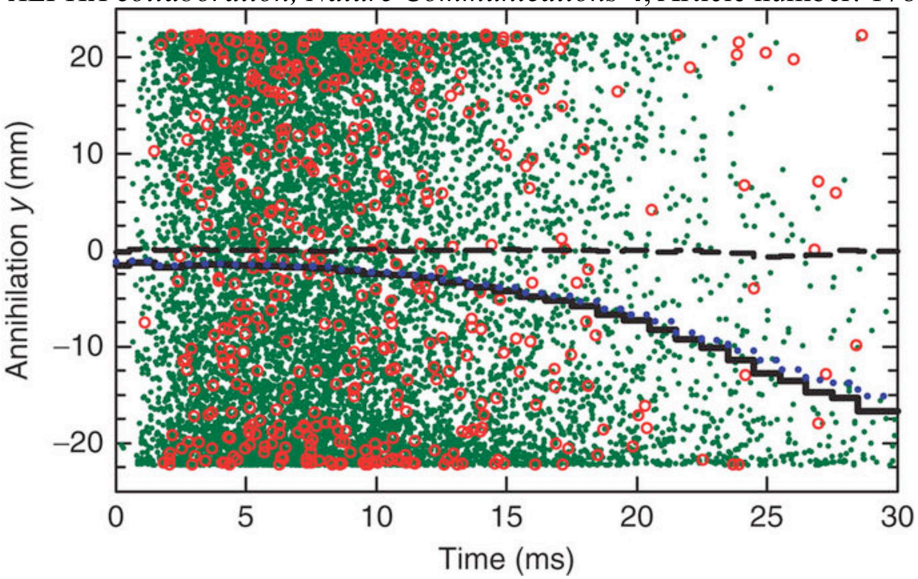
on 1s-2p transition (121 nm)

CW → low power → time

open trap → $\bar{H}$ atoms released, look at asymmetry between atoms flying towards the upper, and the lower half of the apparatus

intermediate step towards atomic fountain and high precision test of gravity with trapped $\bar{H}$

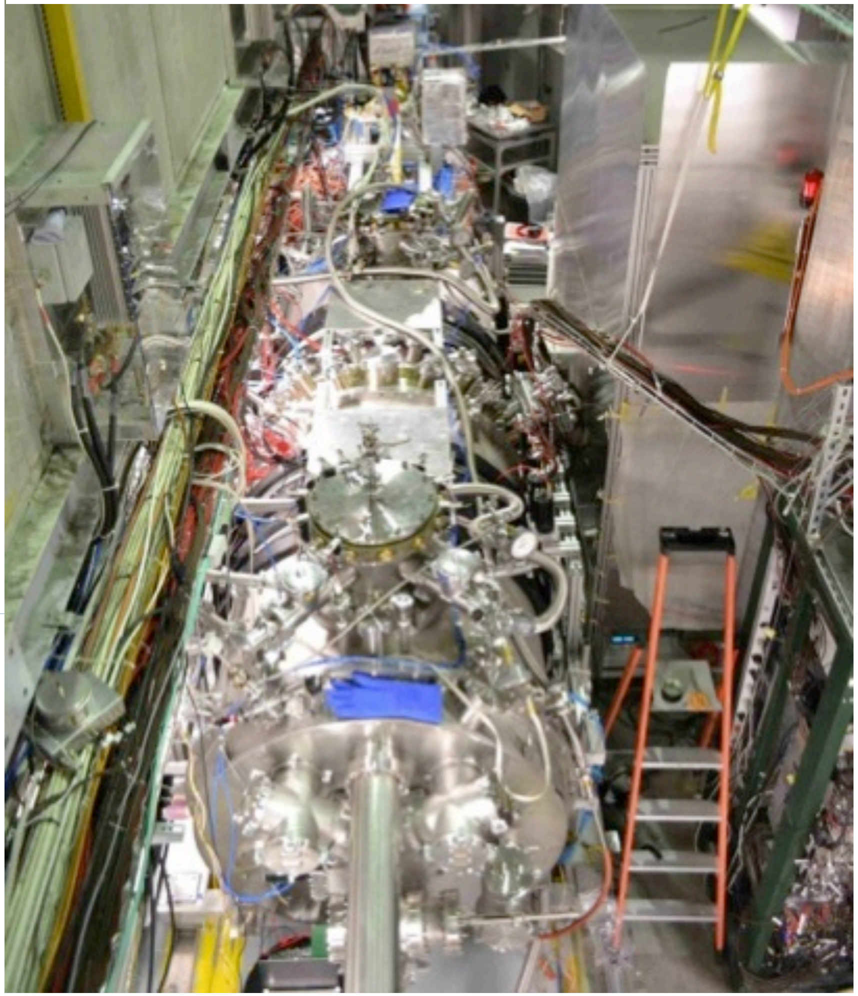
ALPHA collaboration, Nature Communications **4**, Article number: 1785 (2013)

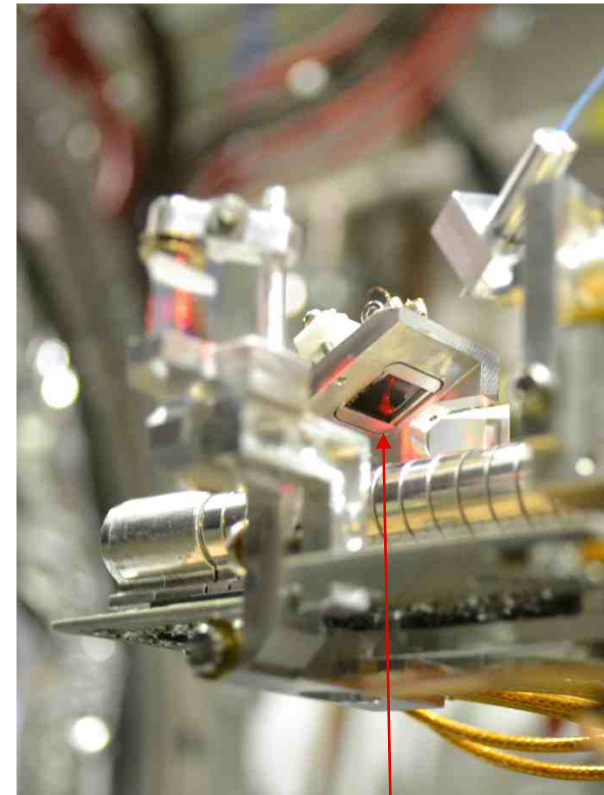


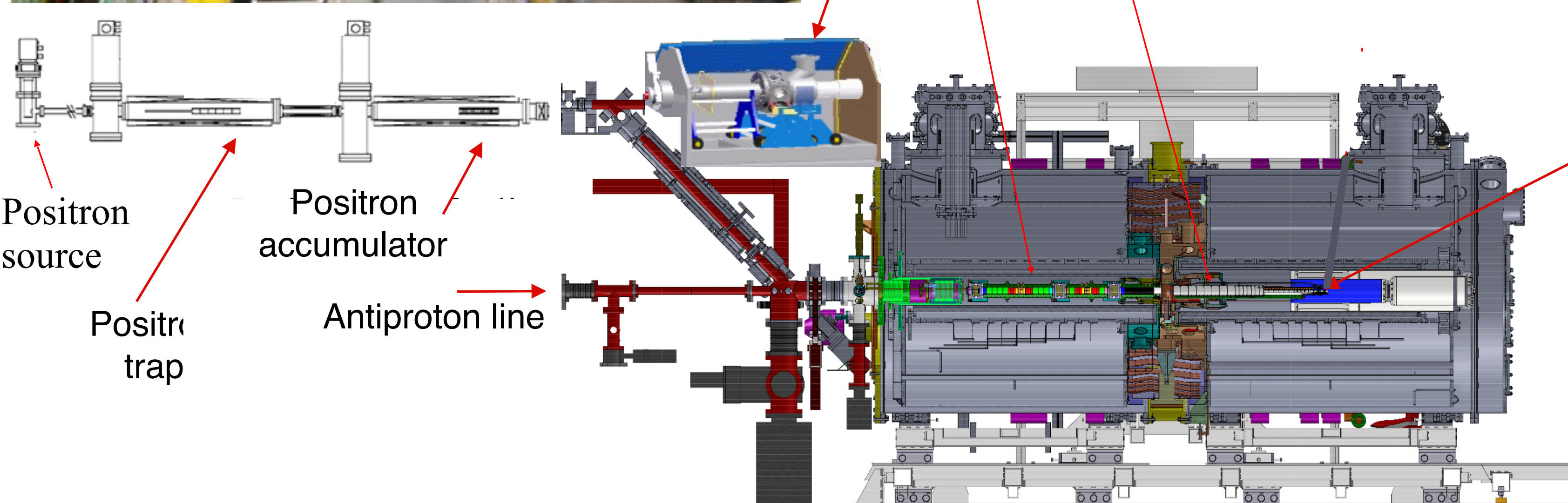
$F_{\bar{H}} < 110$

"... 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 $F=\pm1$ level ..."

AEgIS experiment







antiprotonic atoms (and molecules?): ground state for $\bar{H}$, in Rydberg states for others:

wide range of systems feasible, wide range of approaches

ELENA extends the armory (antihydrogen ions, high rates, novel antiprotonic systems amenable to study)

- ELENA pulsed beams, 10^7/pulse@100 keV
- AD extraction @ 100~500 MeV/c remains possible in DEM
- continuous extraction from traps feasible, not yet developed

tests of the WEP: wide range of systems feasible (including purely baryonic and leptonic systems, mixed and pure antimatter systems)

spectroscopy: "straightforward" to produce any antiprotonic atom from the corresponding anion, in a long-lived Rydberg state. Rydberg transitions can be precisely probed; QCD-affected levels however are very difficult to access (other than through fluorescence)