Results and strategies for measuring the gravitational interaction of antimatter

Michael Doser / CERN

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

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

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

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

but also 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)

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

What measurements are we talking about?

1) Measurement with charged antimatter

probe the gravitational potential using $\bar{p}$ as “clocks”: BASE

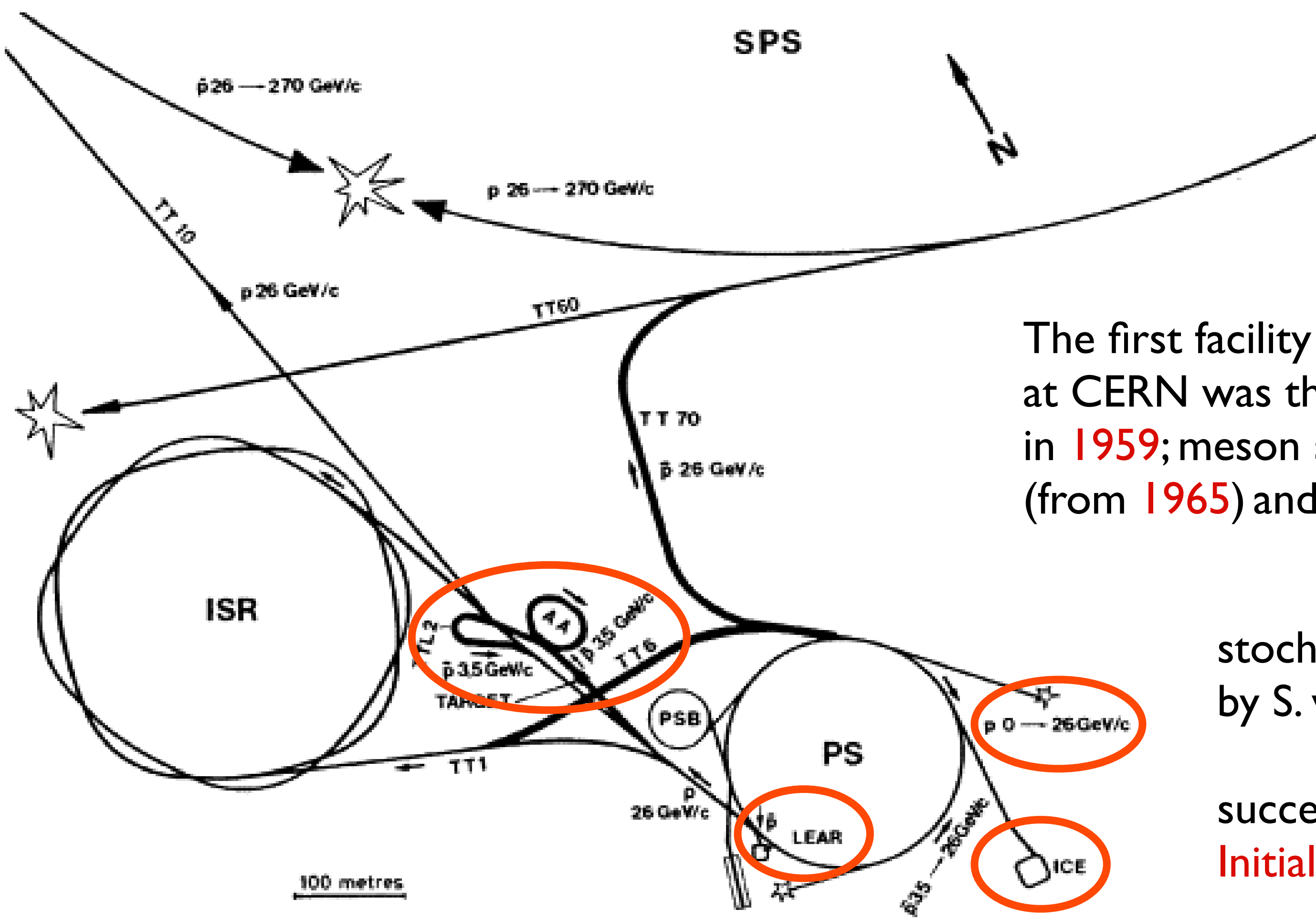
2) Measurements with neutral antimatter: $\bar{H}$

Direct measurements with AEgIS, ALPHA-g, GBAR

3) related measurements in antiatomic systems

Potential future: positronium, protonium, antiprotonic atoms, ...

Antiprotons at CERN: a brief 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);

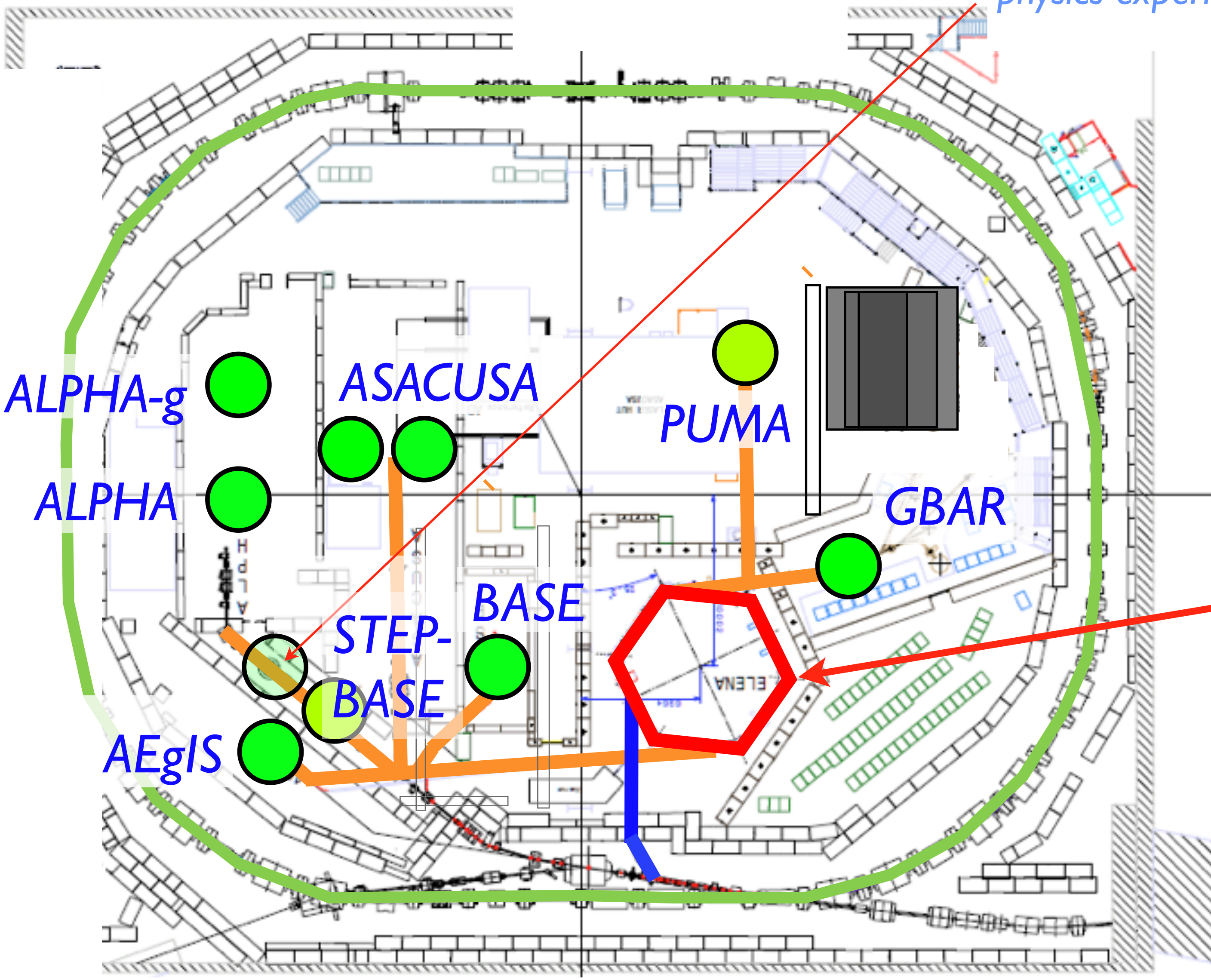
successfully tested in the Initial Cooling Experiment (ICE) in 1978

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

AA start-up in 1980, LEAR began operation in 1982, AC from 1987 onwards

AD start in 2000, ELENA commissioning in 2018: looking at further very active decades with antiprotons

overview of AD facility

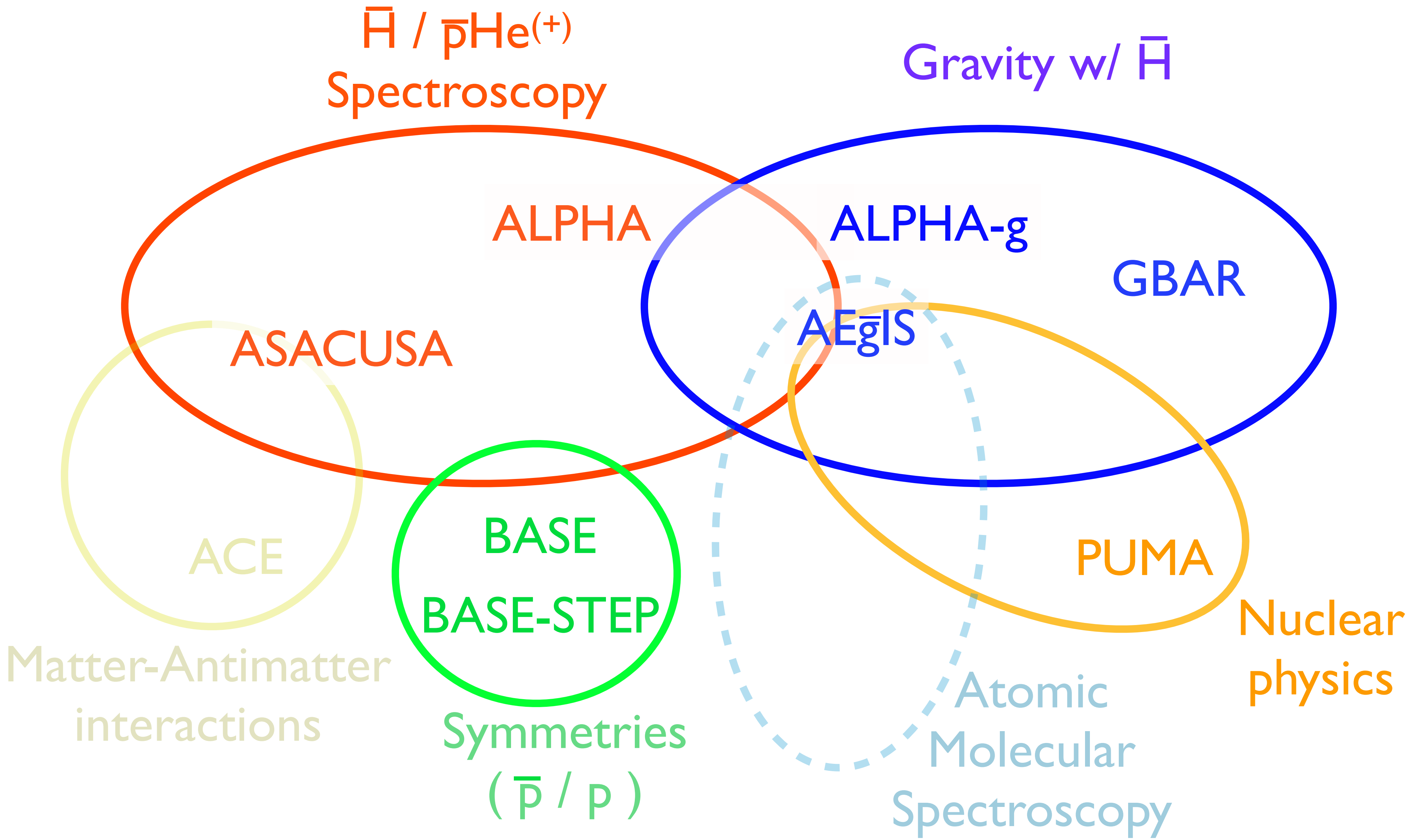


ELENA: extraction of antiprotons at 100 keV; trapping efficiency goes from ~1% at AD to O(100%);

10^7 $\bar{p}$ /100s

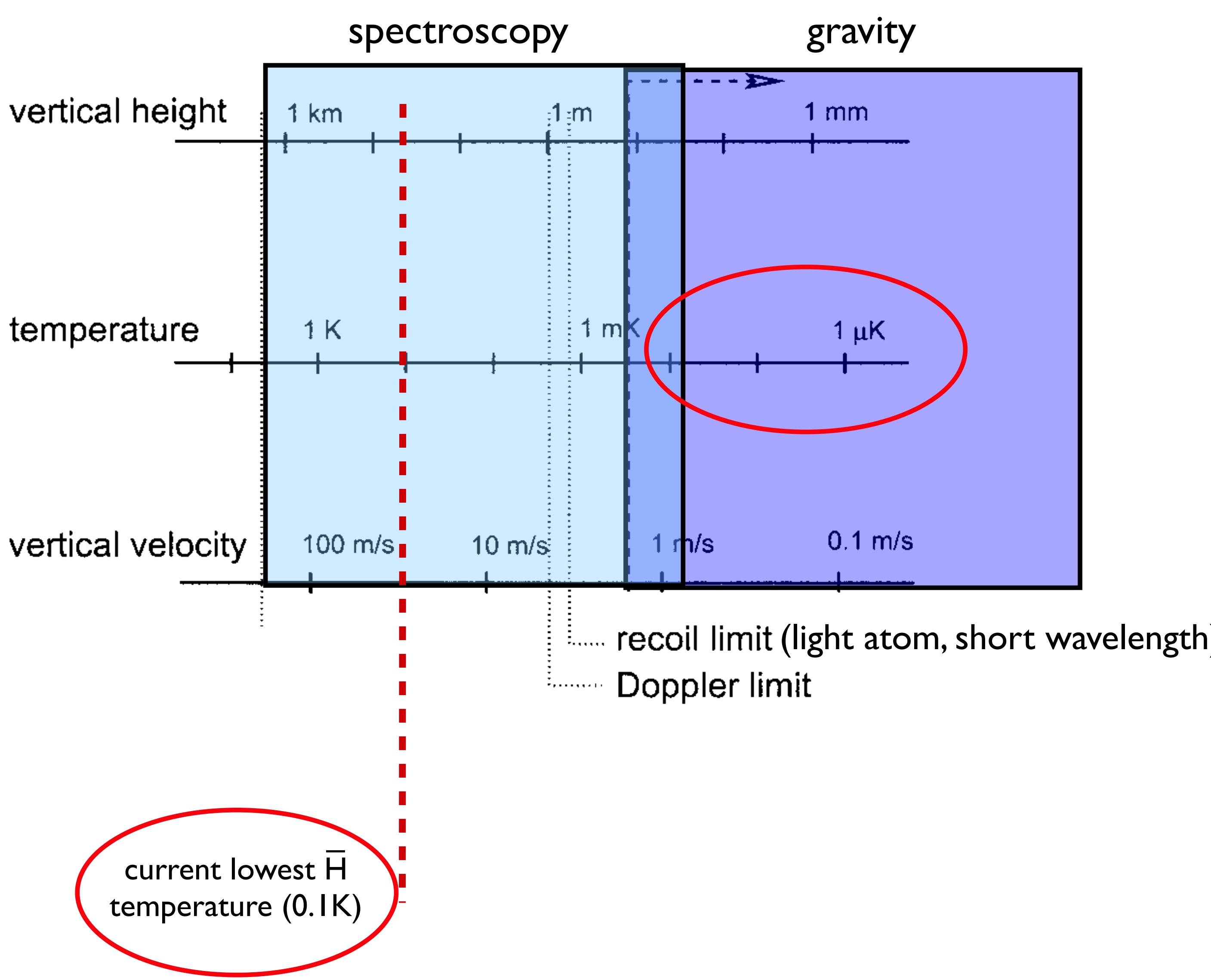
in operation since 2021

physics at the AD



expanding physics reach by including nuclear, molecular physics

the importance of working at low temperature



antiprotons for WEP tests

charged particles

BASE: precision comparative cyclotron frequency measurements of trapped p ($\bar{p}$)

neutral systems

AEgIS: pulsed formation and beam of $\bar{H}$* ($\bar{H}$)

ALPHA-g: release of trapped $\bar{H}$

GBAR: formation, trapping and cooling of $\bar{H}^+$

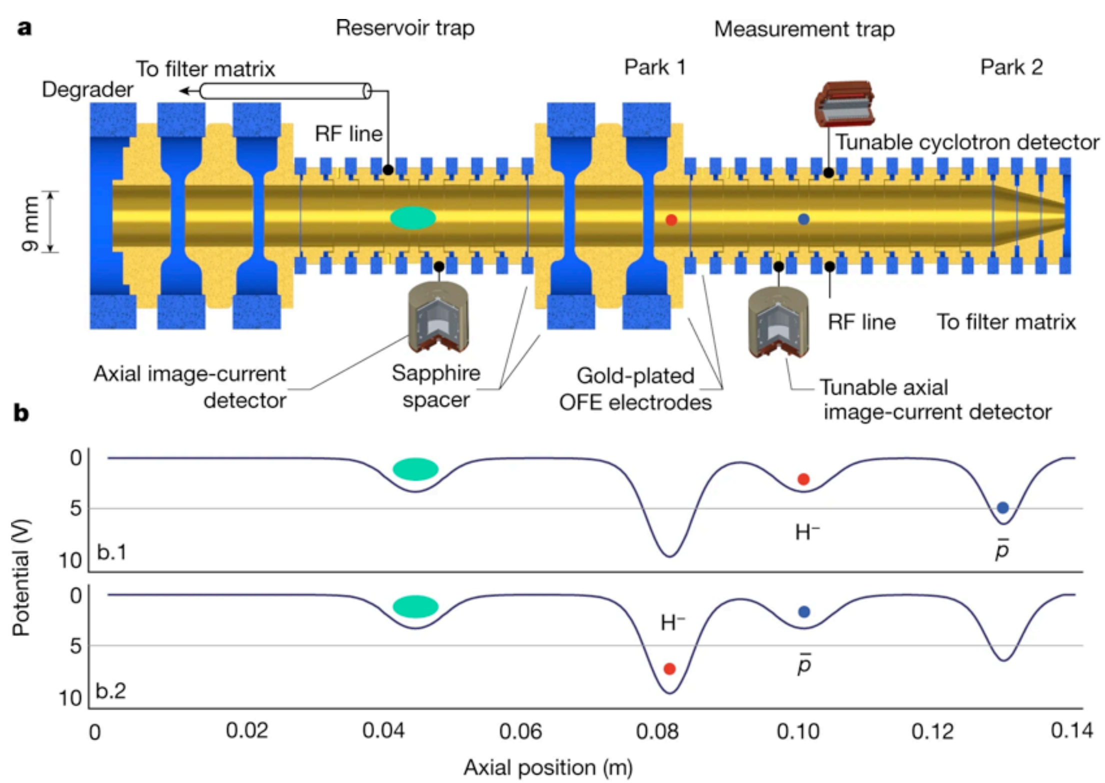
anomalous gravitational scalar or tensor couplings to antimatter would cause clocks formed from matter/ antimatter conjugates to oscillate at different frequencies

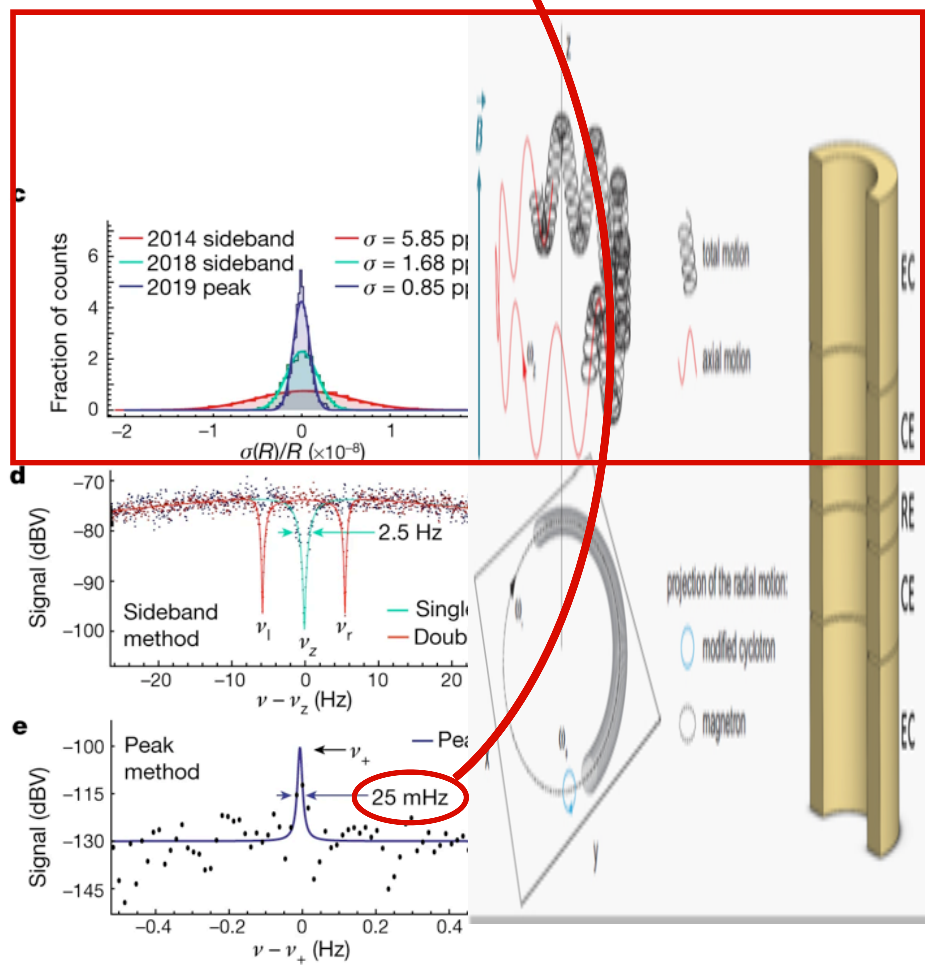
BASE

antimatter "clock": free cyclotron frequency ν_c of p ($\bar{p}$) in B-field

motion = three independent harmonic oscillators at the modified cyclotron frequency $\nu_+ \approx 29.6$MHz and the magnetron frequency $\nu_- \approx 6.9$kHz, perpendicular to the magnetic field $B_0\mathbf{e}_z$, and at the axial frequency $\nu_z \approx 640$kHz, oscillating along B

$$\nu_c = (qB_0)/(2\pi m) = (\nu_+^2 + \nu_Z^2 + \nu_-^2)^{1/2}$$

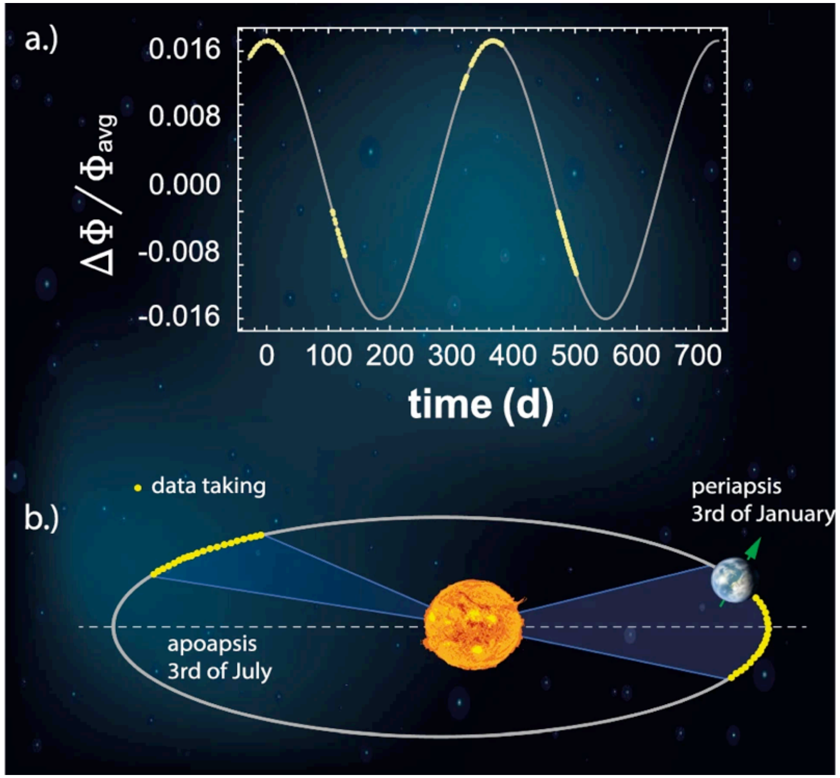




Borchert, M.J., Devlin, J.A., Erlewein, S.R. *et al*. A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio. *Nature* **601**, 53–57 (2022)

measured the antiproton-to-proton charge-to-mass ratio with a fractional precision of 16 p.p.t. in different gravitational potentials

the first differential, and thus model independent, test of the weak equivalence principle of clocks for antimatter, showing no violation at the level of 3 %.



Latacz, B.M., Arndt, B.P., Bauer, B.B. et al. BASE—high-precision comparisons of the fundamental properties of protons and antiprotons. Eur. Phys. J. D 77, 94 (2023).

antihydrogen for WEP tests

AEgIS: pulsed formation and beam of $\bar{H}^*$ ($\bar{H}$)

ALPHA-g: release of trapped $\bar{H}$

GBAR: formation, trapping and cooling of $\bar{H}^+$

1 ALPHA-g : continuous formation via $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$

2 AEgIS : pulsed formation via $\bar{p} + Ps^* \longrightarrow \bar{H} + e^-$

3 GBAR: pulsed formation via

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

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

1

ALPHA

Traps for charged particles and continuously formed ground-state antihydrogen

Penning-Malmberg trap for charged particles

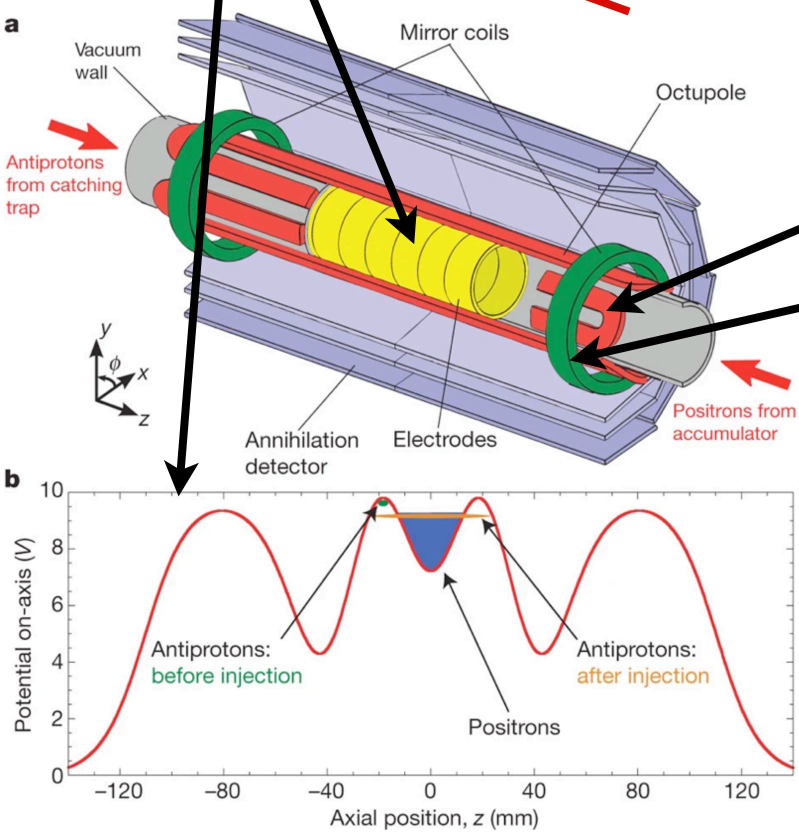
Magnetic multipole trap for neutral atoms (HFS)

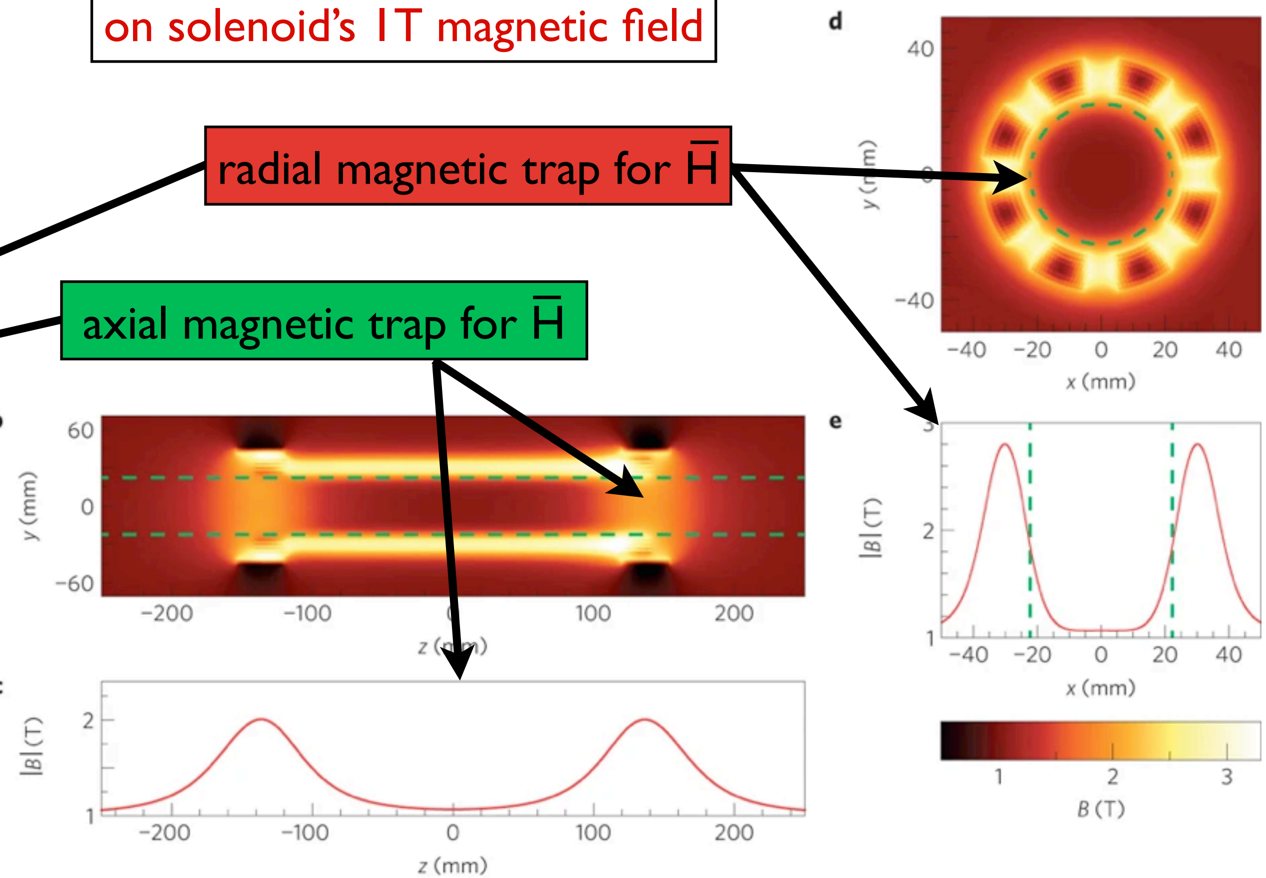
$\vec{B}_{solenoid}$

multipole fields superimposed on solenoid's 1T magnetic field

radial magnetic trap for $\bar{H}$

axial magnetic trap for $\bar{H}$





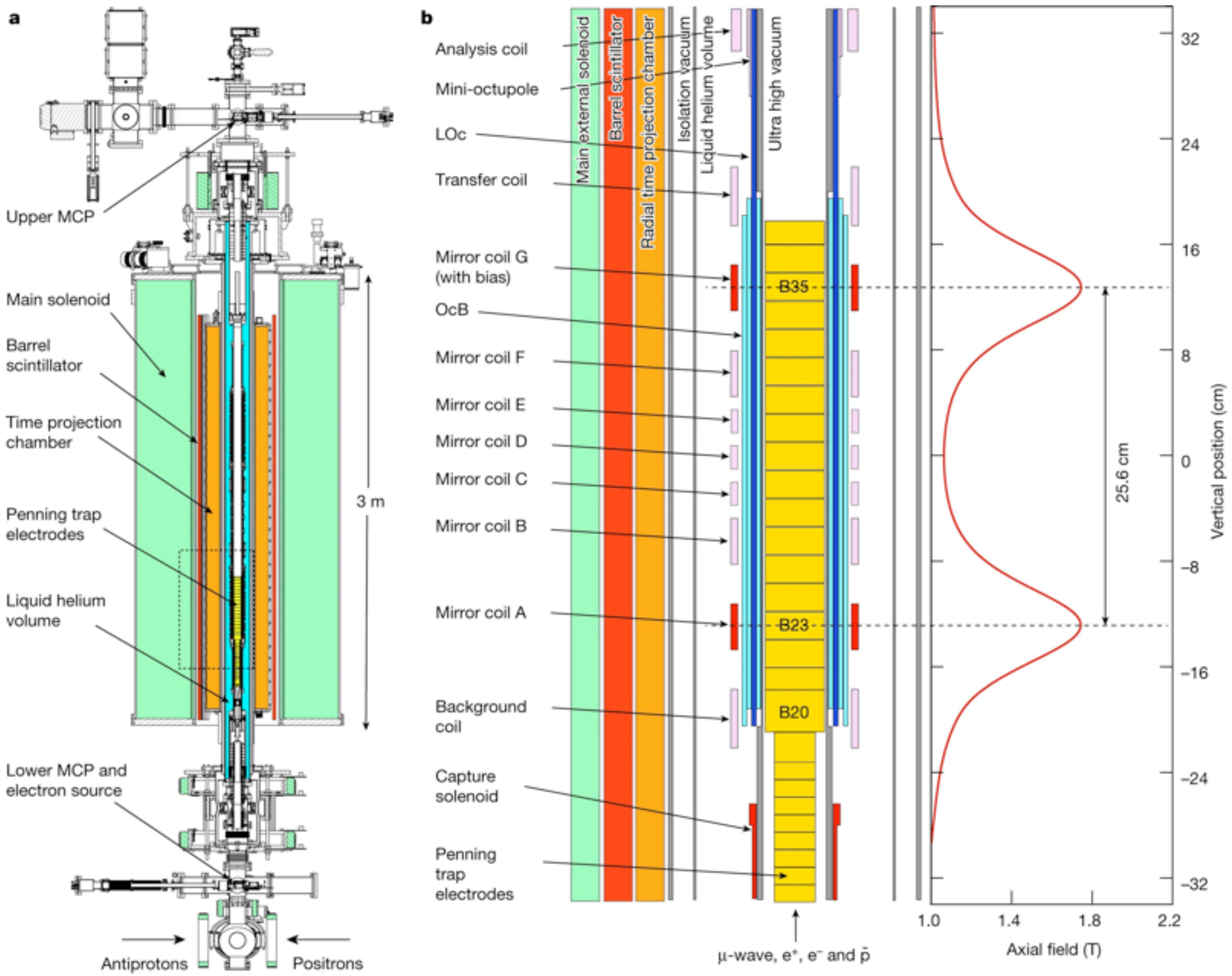
G.B. Andresen at al, *Nature* **vol. 468**, pages 673–676 (2010)

The ALPHA collaboration, *Nature Physics* **vol. 7**, pages 558–564 (2011)

1

ALPHA-g

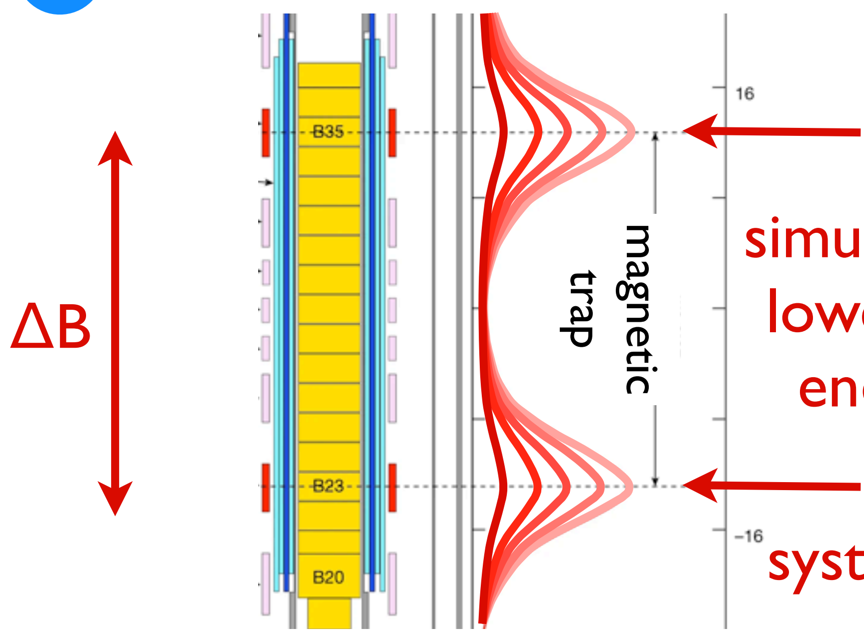
From (~static) horizontal magnetic trap to (continuously modifiable) vertical magnetic trap:



E.K. Anderson et al., *Nature* **vol. 621**, pages 716–722 (2023)

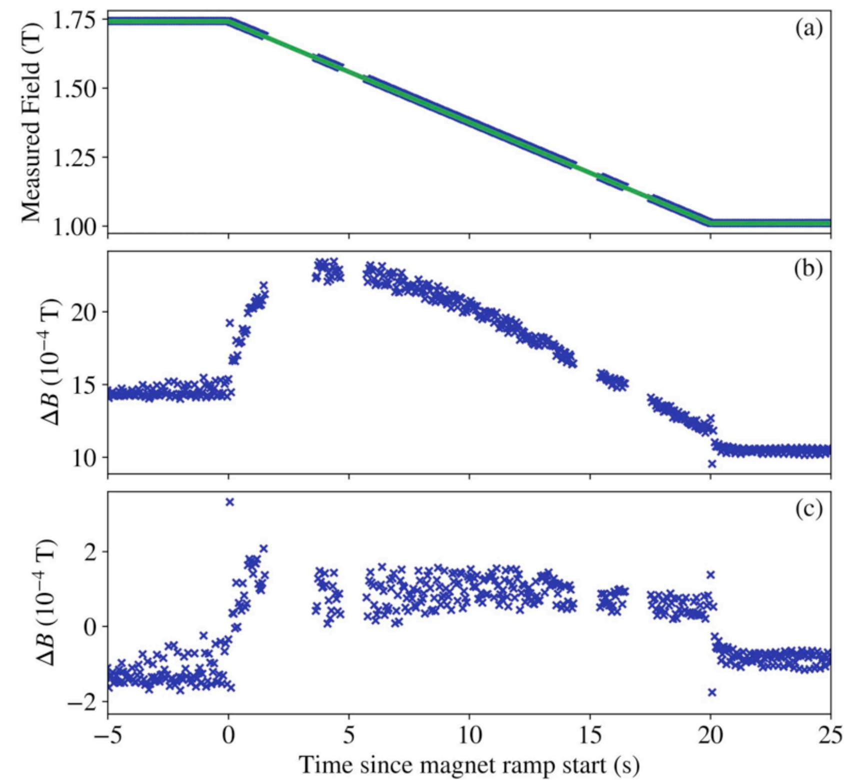
ALPHA-g

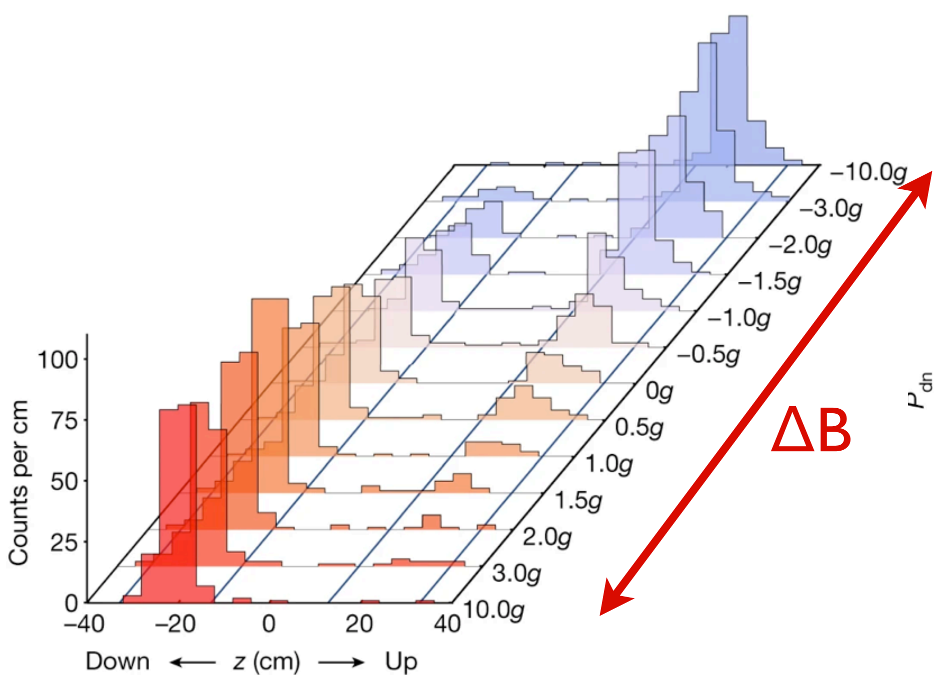
1

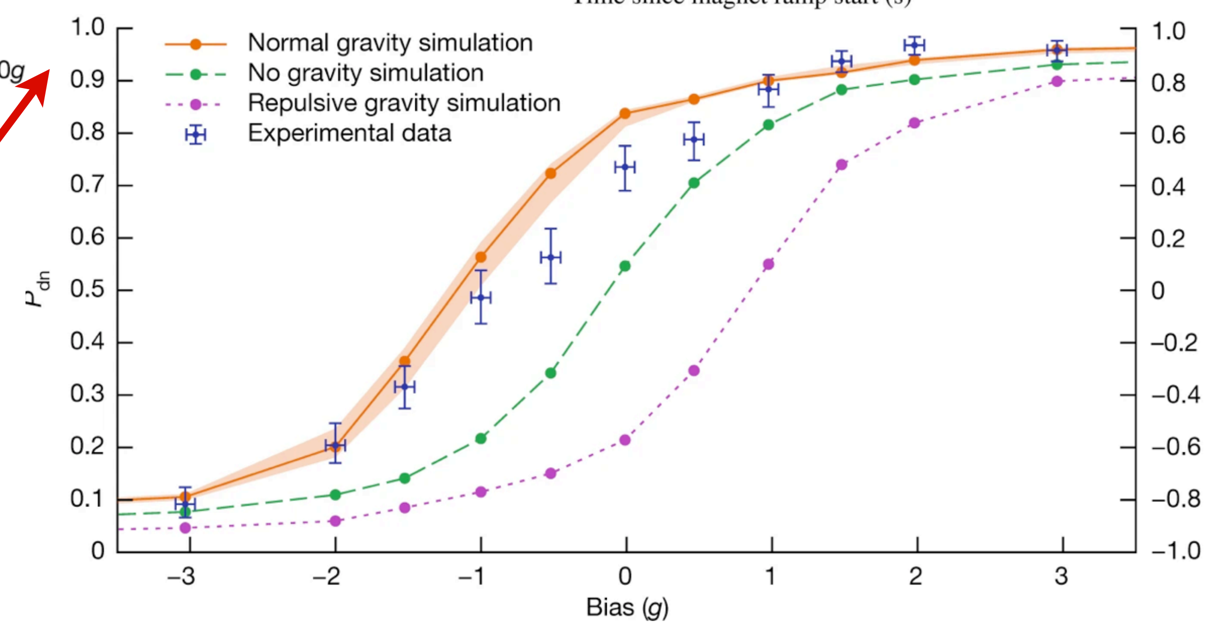


simultaneous lowering of end coils

systematics!







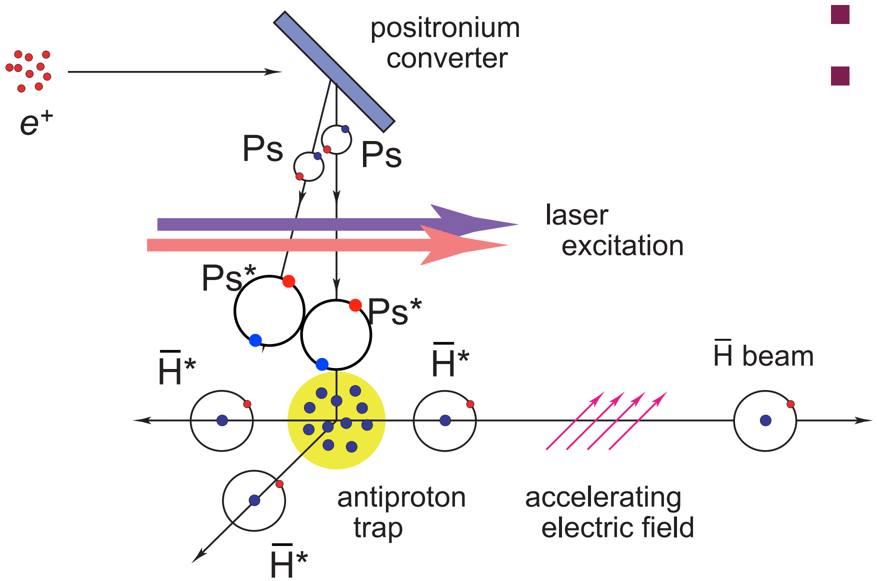
$\bar{g}$ = (0.75±0.13 (statistical+systematic) ± 0.16 (simulation)) g

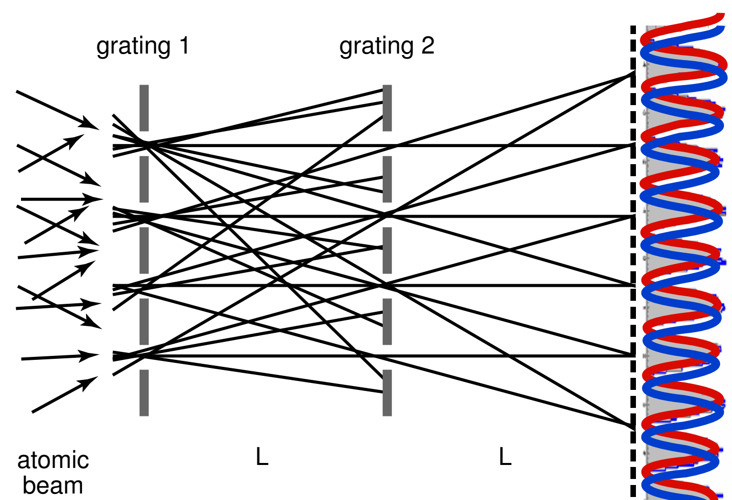
E.K. Anderson et al., *Nature* **vol. 621**, pages 716–722 (2023)

Schematic overview

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

- Anti-hydrogen formation via Charge exchange process with P
  - o-Ps produced in SiO_2 target close to $\bar{p}$; laser-excited to Ps
  - $\bar{H}$ temperature defined by $\bar{p}$ temperature
- Advantages:
  - Pulsed $\bar{H}$ production (time of flight – Stark acceleration)
  - Narrow and well-defined $\bar{H}$ n-state distribution
  - Colder production than via standard process possible
  - Rydberg Ps & $\sigma \approx a_0 n^4$ → $\bar{H}$ formation enhanced





goal:
$\Delta g/g \sim 1\%$
with 1000 $\bar{H}$

pulsed production of H*

horizontal beam formation

gratings produce periodic pattern on detector; measure gravity-induced vertical shift of fringes

AEgIS

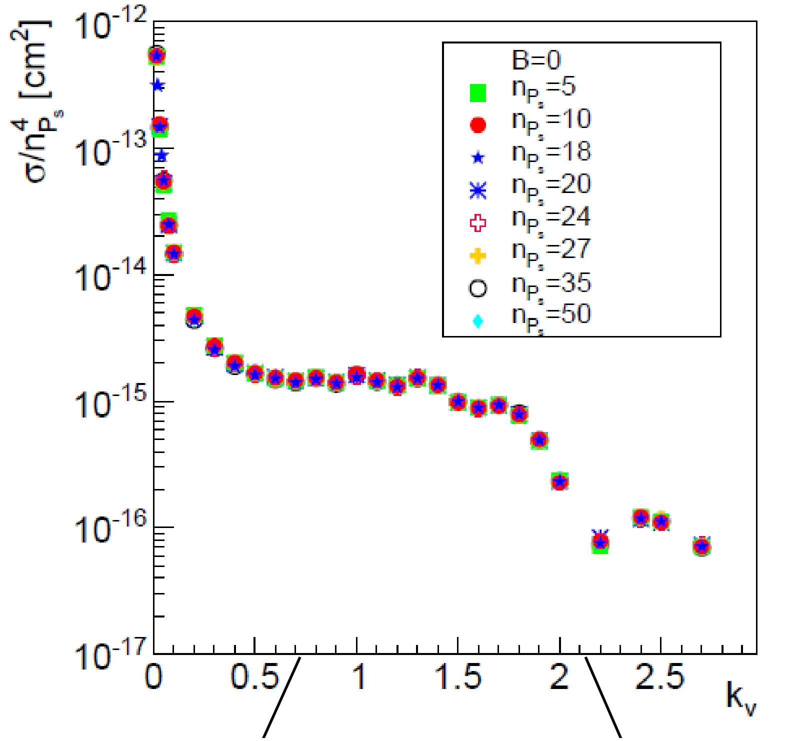
why Rydberg Ps ?

charge exchange: $Ps^{*}_{n} + \bar{p} \rightarrow H^{*} + e^{-}$

$$\sigma_{CE} \propto n^{4}$$

D. Krasnicky, C. Canali, R. Caravita, G. Testera, Phys. Rev. A 94, 022714 (2016)

DATA COMPARISON BETWEEN n=10 and n=50



$v_{Ps} = 3\ 10^{4} m/s$ $\quad$ $v_{Ps} = 1.2\ 10^{5} m/s$

FIG.2: Normalized cross section

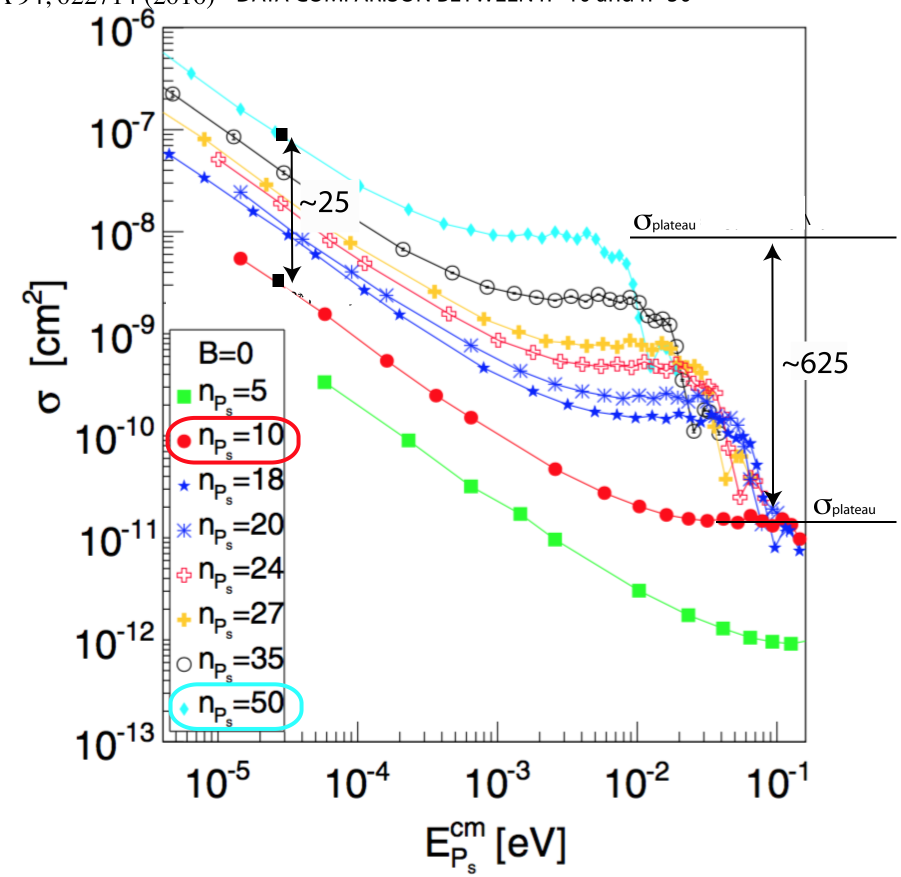


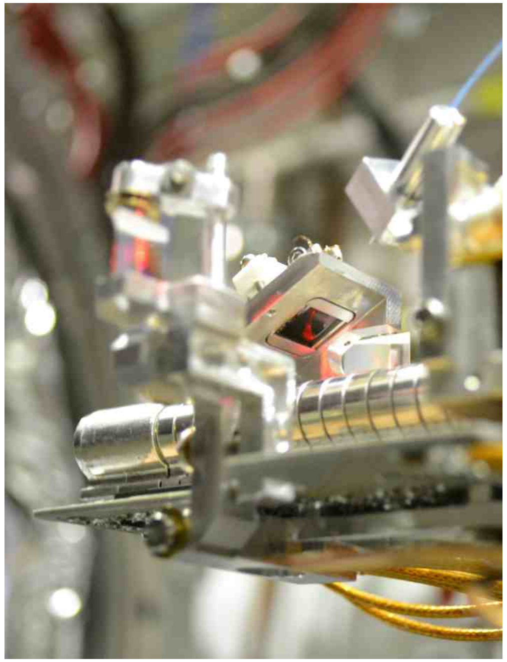
FIG. 3. Charge-exchange cross section σ as a function of the P_s center-of-mass energy. The plot shows the same points of Fig. 2. The lines simply connect the points to help the graphical interpretation.

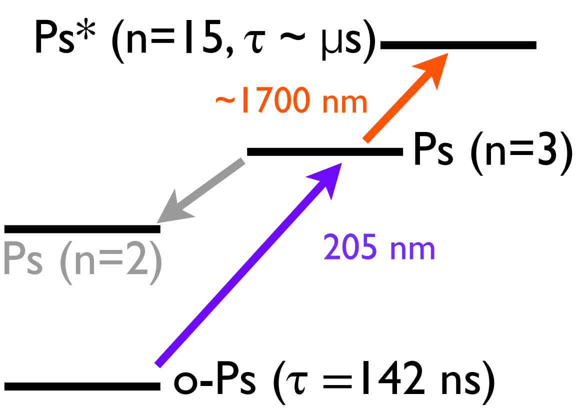
② # Challenges:

AEgIS

Pulsed formation:

$\bar{H}$ formation region: $\bar{p}$ Penning traps, Ps production target





S. Aghion et al., Phys. Rev. A 98, 013402 (2018)

Temperature:

cooling of $\bar{p}$

sympathetic cooling of $\bar{p}$ to ~ mK through anions

A. Kellerbauer & J. Walz, New J. Phys. 8 (2006) 45

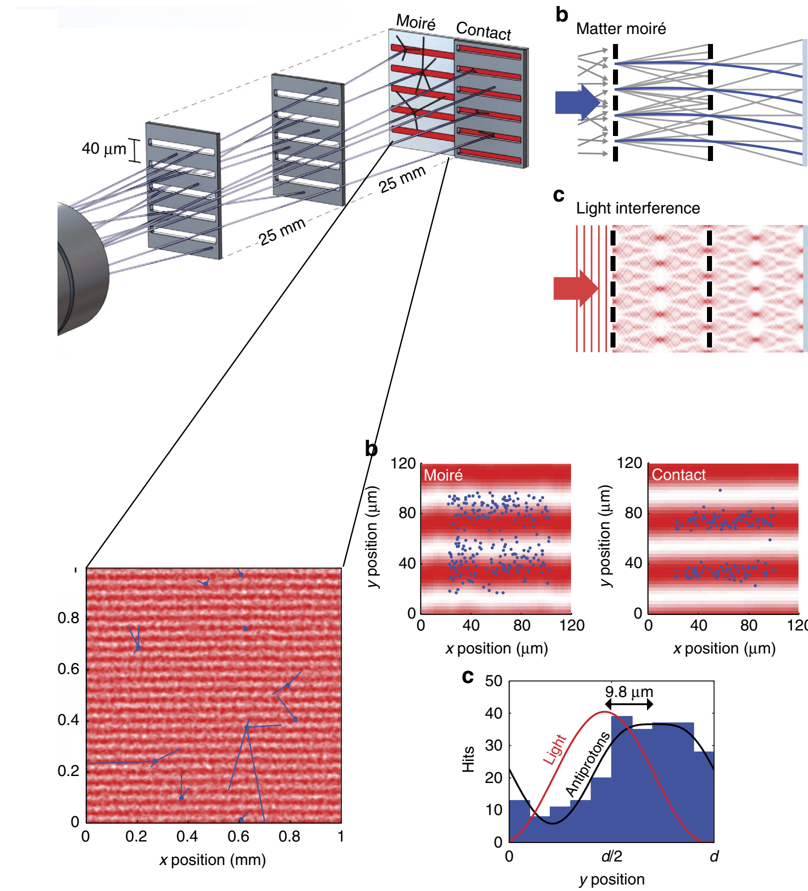
La^- Warring et al, PRL 102 (2009) 043001; E. Jordan et al., PRL 115 (2015) 113001

C_2^- P. Yzombard et al., PRL 114, 213001

*<u>Note</u>: **beam** experiments have a weak dependence of gravity measurement on (transverse) temperature (→ figure of merit is the flux into gravity-sensitive detector) as long as flight times are ~ ms or longer*

dedicated experiments to establish laser-cooling of anionic systems under way

Measurement:



principle established with $\bar{p}$; displacement of $\bar{p}$ annihilation vertices (blue dots) measured relative to light (red)

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

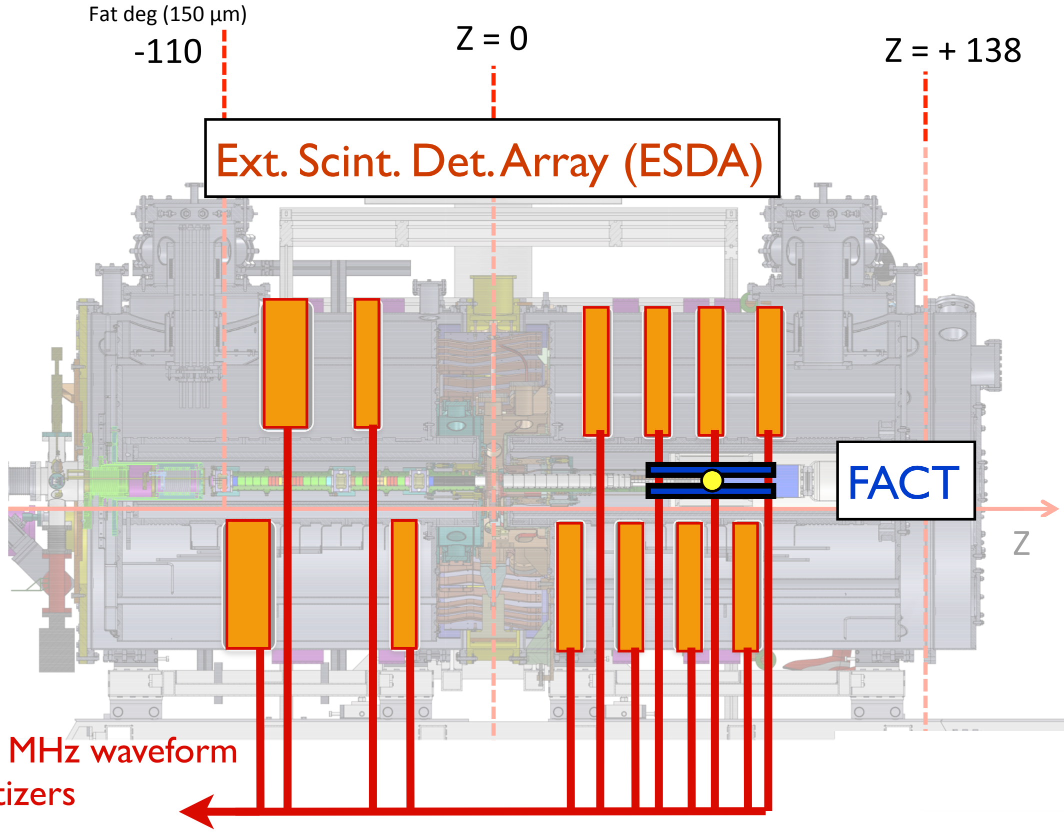
and many more...

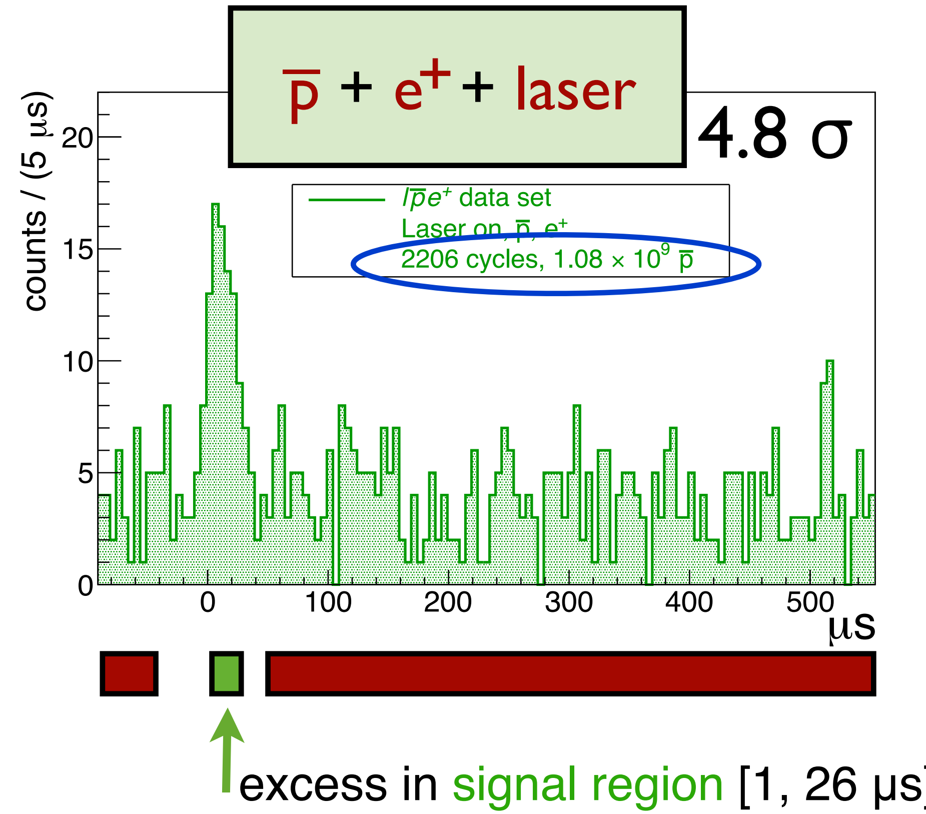
2 Pulsed production of $\overline{H}$ in 2018

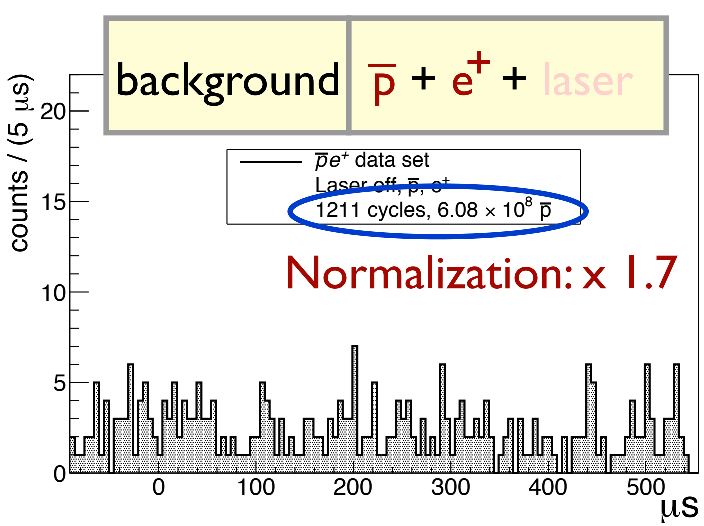
$Ps^* + \bar{p} \rightarrow \overline{H}^* + e$

$\overline{H}$ detectors: scintillating slab array (mips), FACT (vertex tracker)

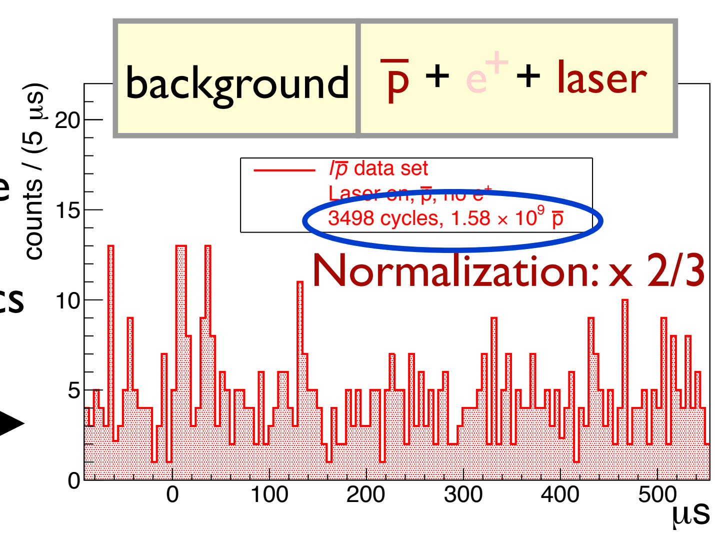
C. Amsler et al. (AEgIS collaboration), Nature Comms. Phys. 4:19 (2021)







long time average rate compatible with cosmics rate



= 0.05 $\overline{H}$ / cycle

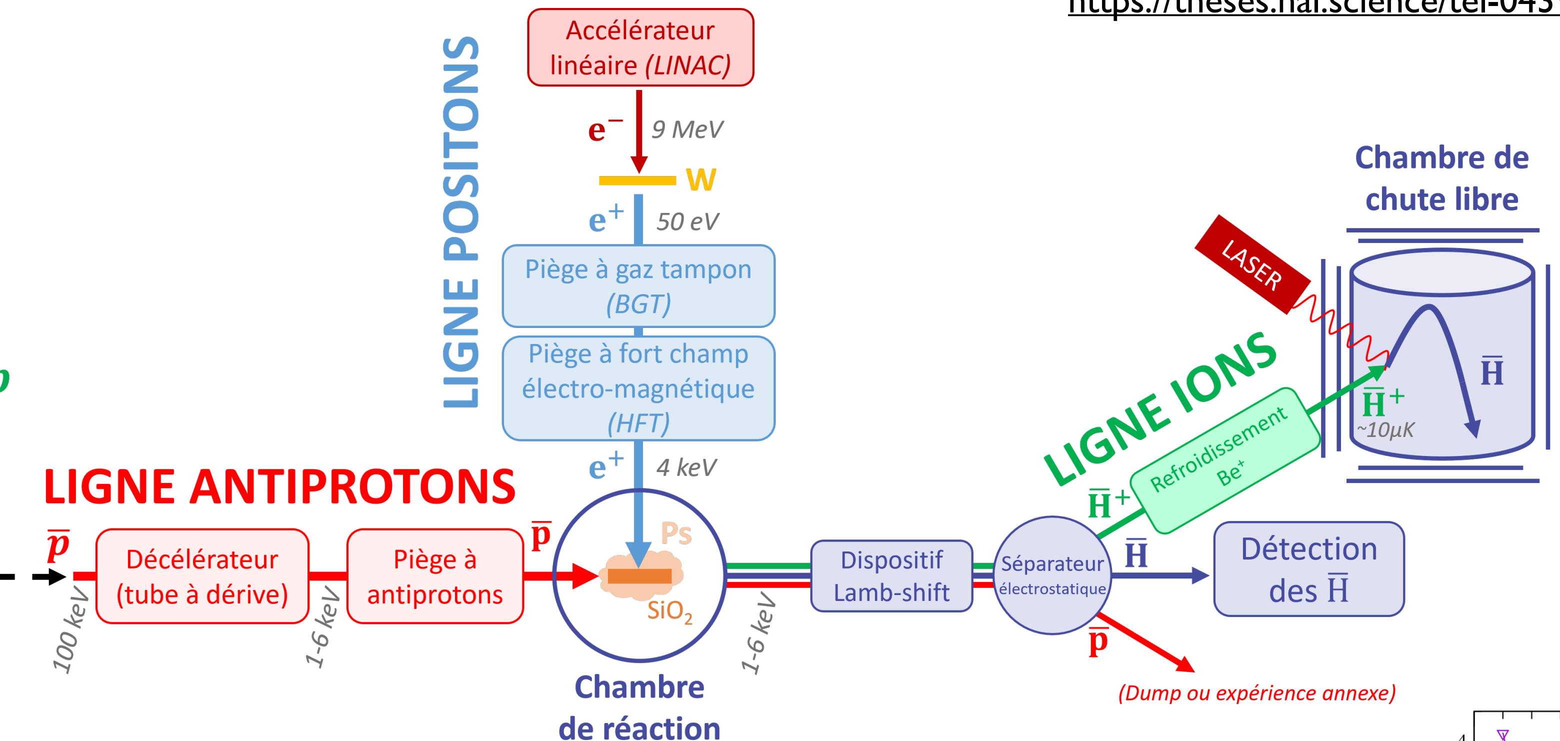
in 2024:

- rate x 1000
- pulsed beam

3

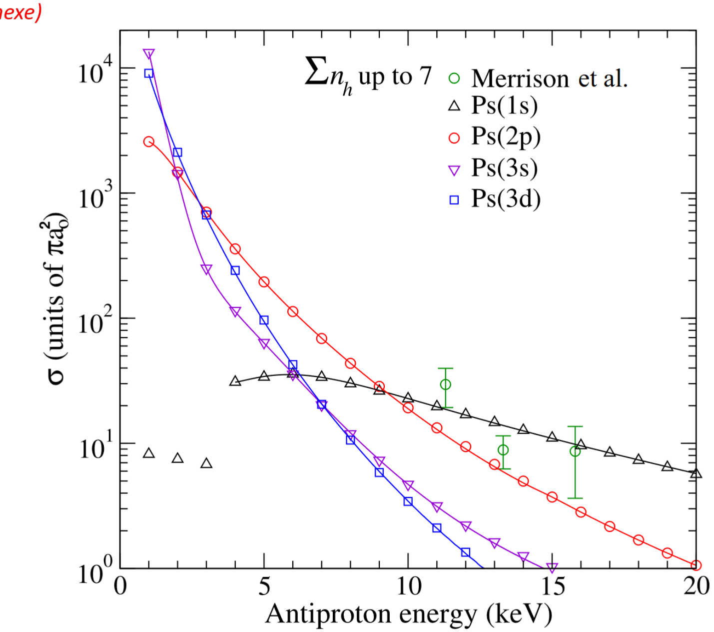
GBAR

Synthesis of antihydrogen from in-flight charge exchange of decelerated antiprotons in positronium for the GBAR experiment
PhD thesis Corentin Roumegou
https://theses.hal.science/tel-04391275/



sympathetic cooling to O(10 µK) before neutralization by photodetachment

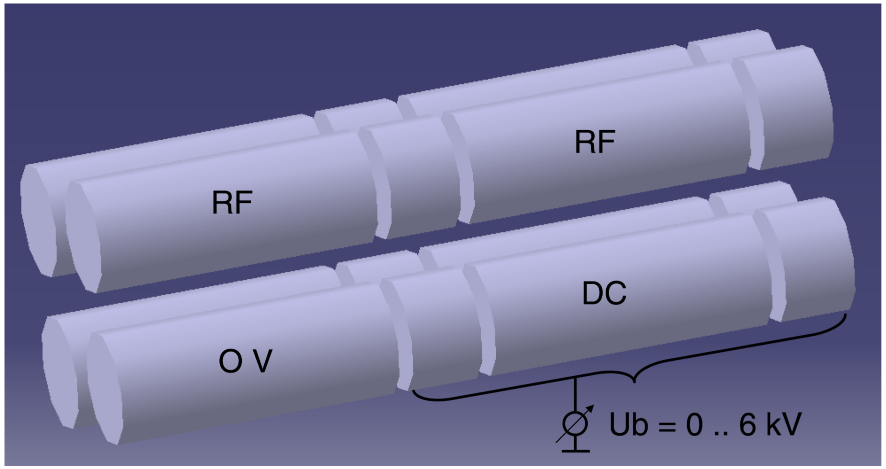
$$\bar{p} + Ps \longrightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \longrightarrow \bar{H}^+ + e^-$$



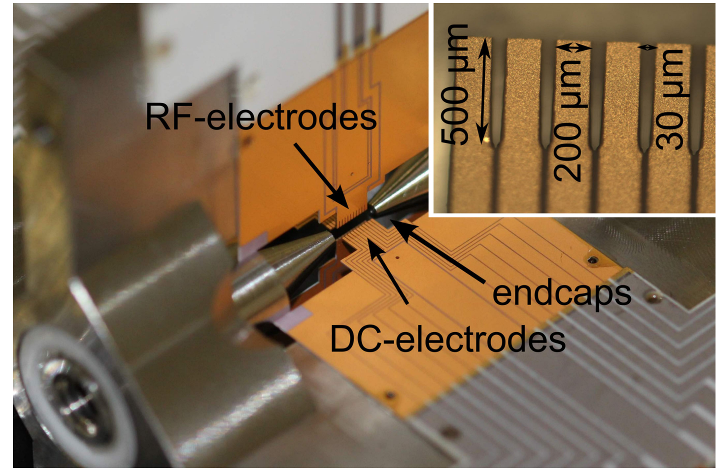
3

GBAR

Antihydrogen ion and Be+ ion trap

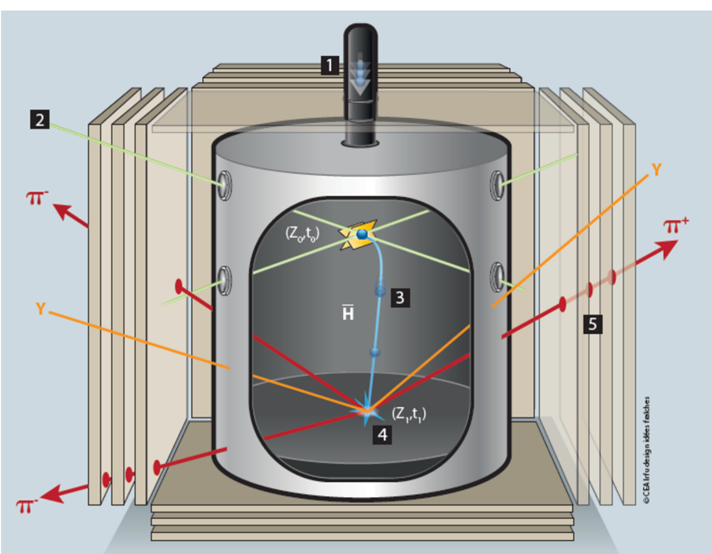


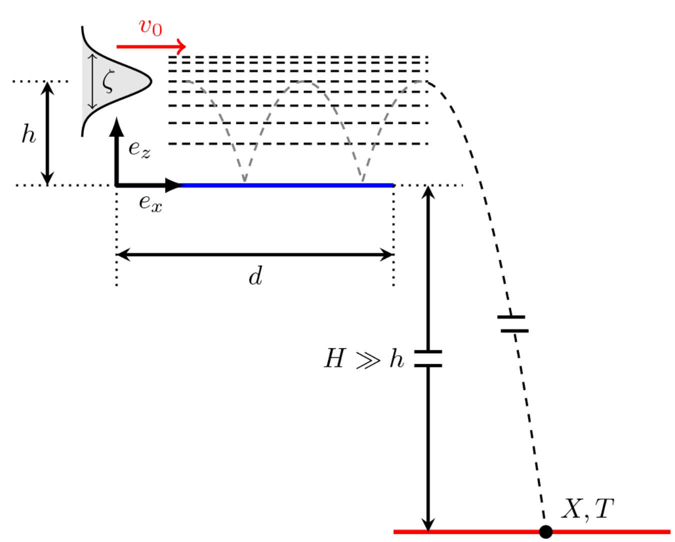
(a) First RF paul trap



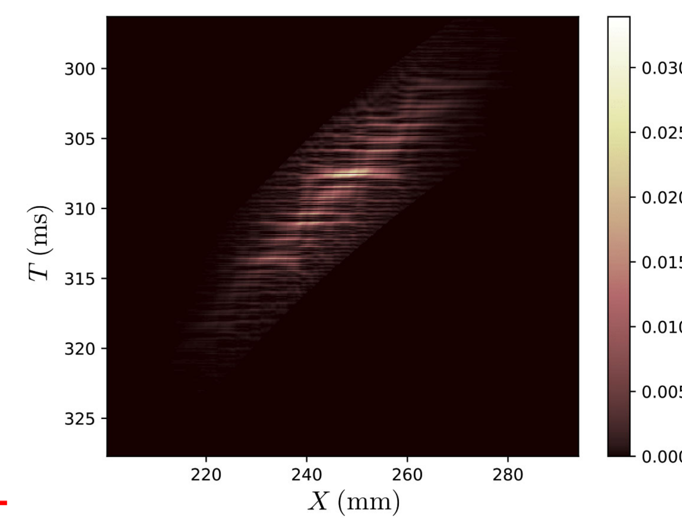
(b) Final precision trap

Principle of gravity measurement with $\bar{H}$ (after photodetachment of e+)





(a) Scheme of "quantum free fall"



(b) Probability current density $|J(X,T)|$

GBAR

First formation of $\overline{H}$ by GBAR

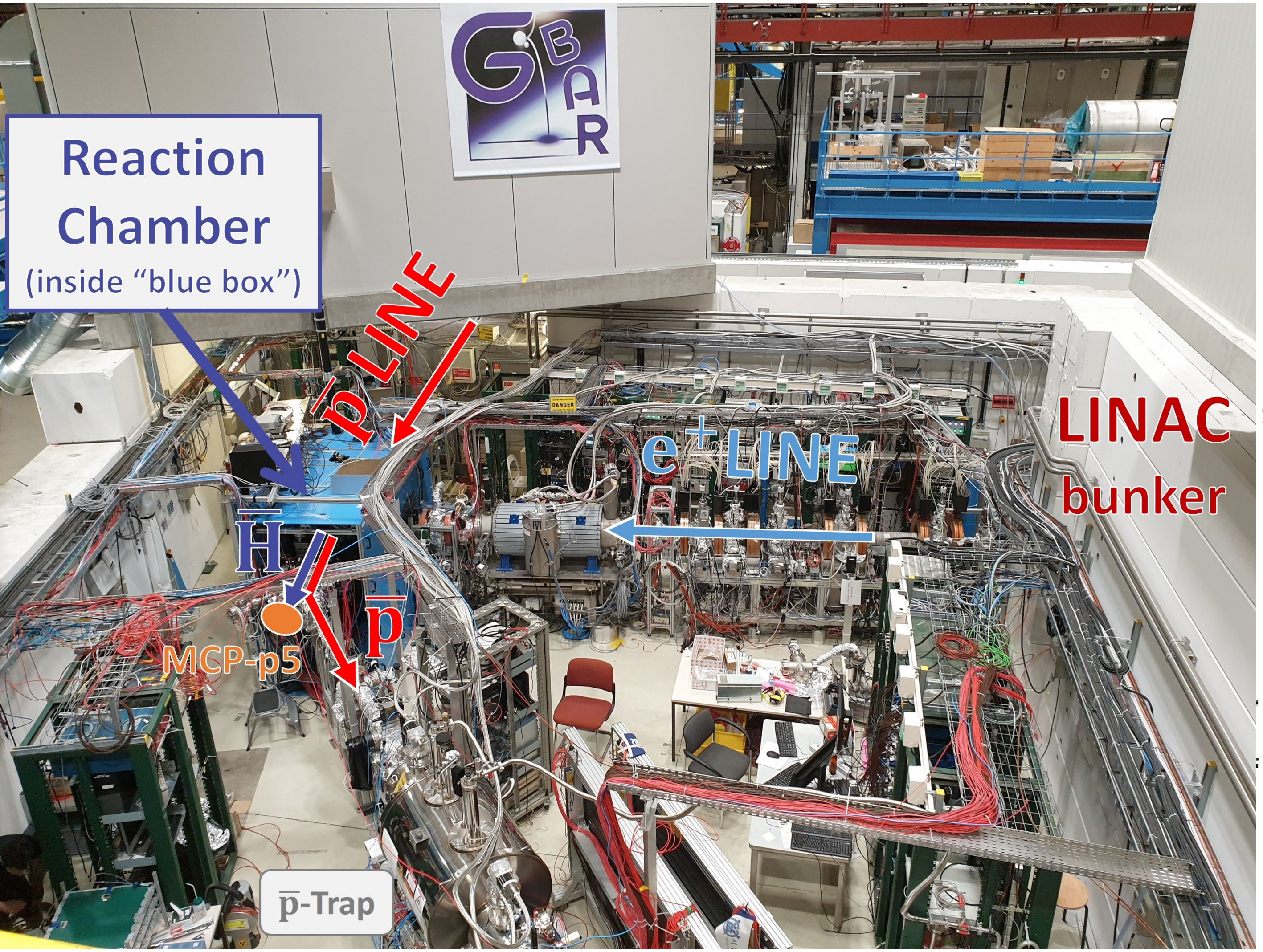
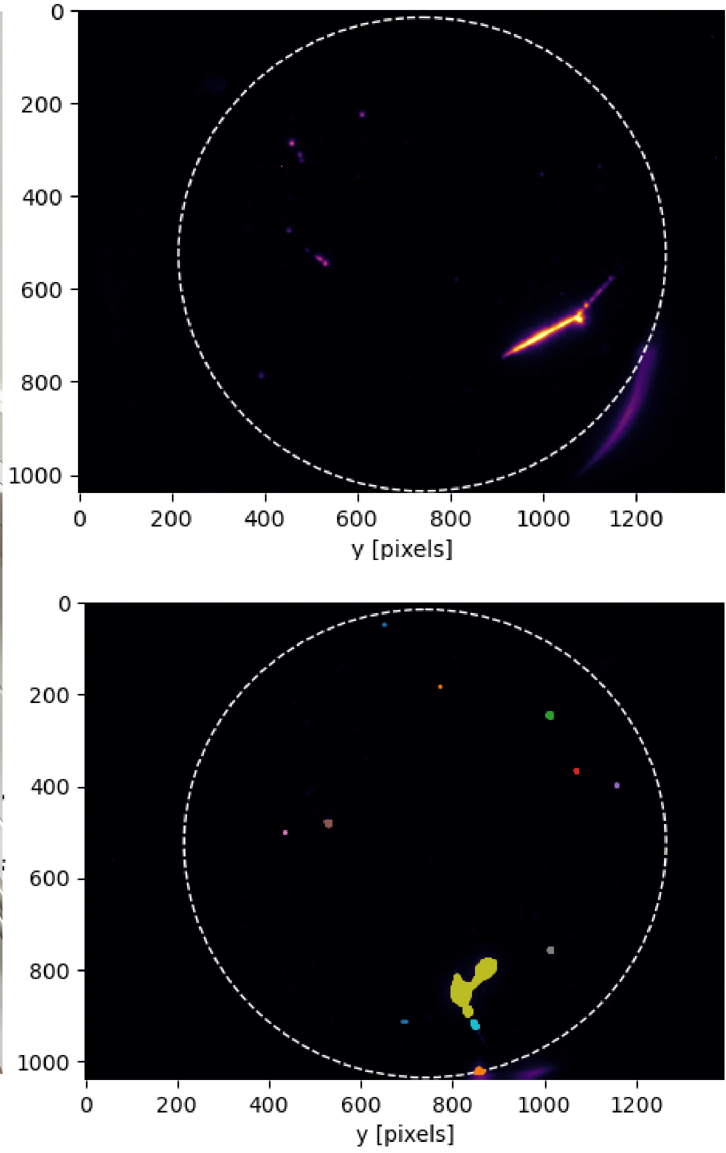


Figure 5.1 : GBAR experimental area during 2022 beamtime



This gives an excess of 18.8 ± 5.0 events in the mixing runs with a significance of 4.1 σ. $(2.9 \pm 0.9) \times 10^{-3}$ $\overline{H}$/pulse

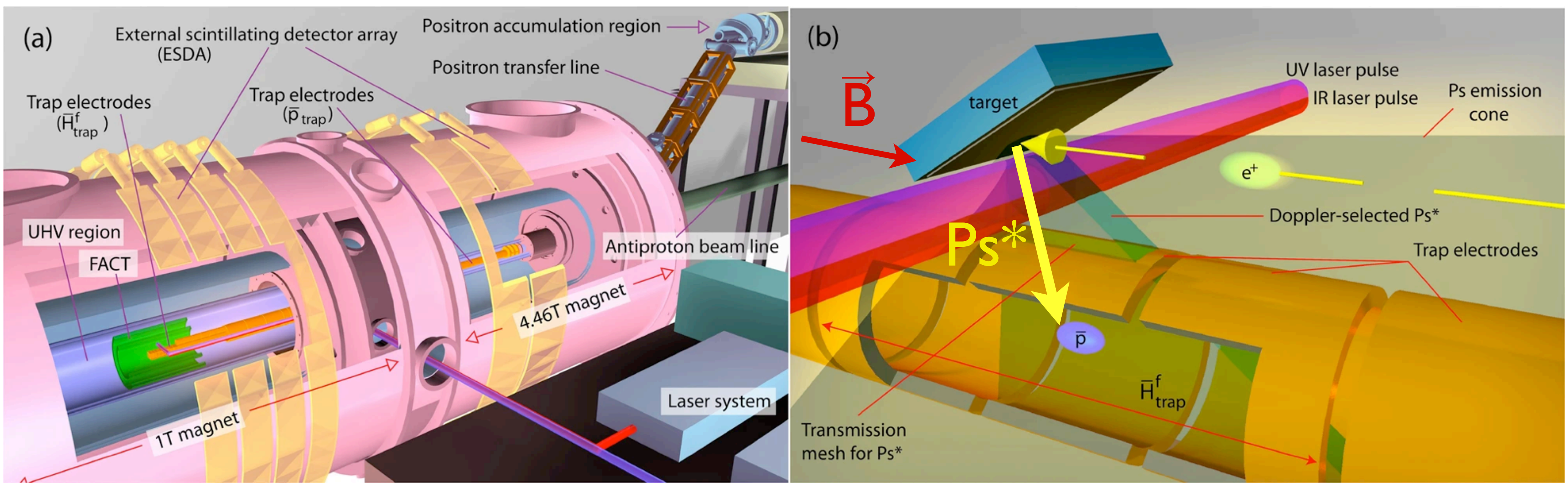
Significant improvements are under way on multiple parts of the apparatus to enhance efficiencies and $\overline{H}$ (and $\overline{H}^{+}$) production rates

2

back to AEgIS:

- Ps gymnastics (for better $\bar{H}$ beam but also as inertial sensor)
- redesigned apparatus for required flux (~1-10 $\bar{H}$/pulse, 10^4 needed for %)
- other inertial test systems (purely leptonic, baryonic)

old design needs radical improvements



2

Upgrade of AEgIS to AEgIS-2

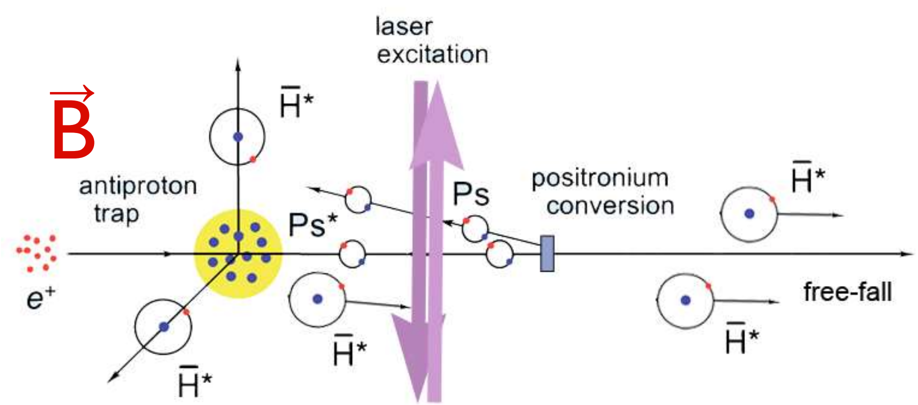
Main goal of AEgIS Phase 2: a first proof-of-concept inertial measurement with pulsed antihydrogen

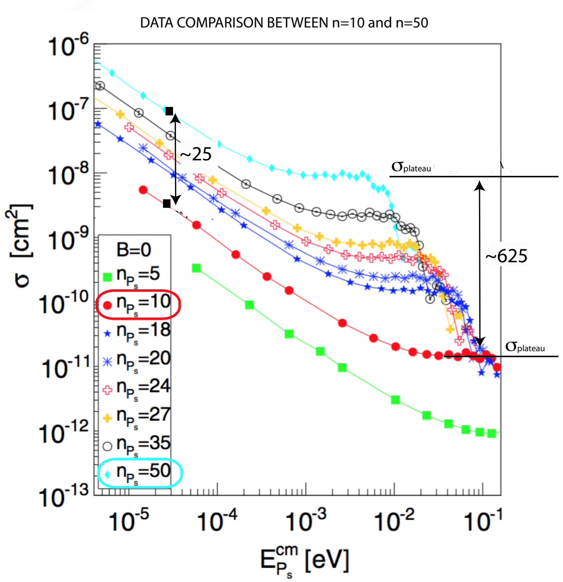
Take-home messages from the AEgIS Phase 1

- The antihydrogen source intensity must be increased by 2 orders of magnitude
- The temperature of the produced atoms must be reduced by 1 order of magnitude
- The first gravitational measurement has to be designed to use Rydberg antihydrogens
- The free-fall should take place in the most homogeneous volume of the AEgIS magnet

New AEgIS Phase 2 configuration

- Positronium conversion target on-axis
- Laser excitation in a Doppler-free scheme
- Positrons passing through resting antiprotons





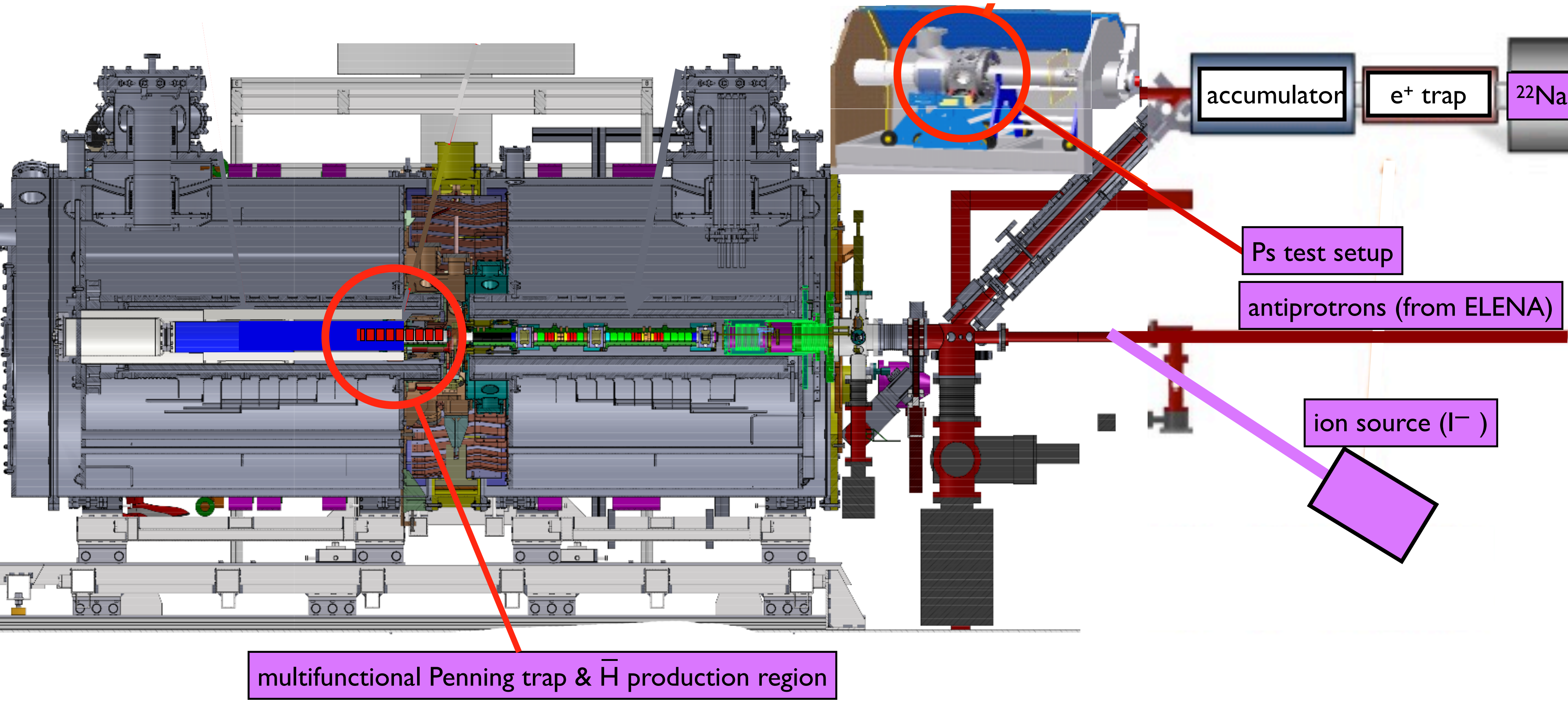
Ps $\perp$ to $\vec{B}$: field ionization $\rightarrow n_{max} \sim 15$

Ps // to $\vec{B}$: field ionization $\rightarrow n_{max} \gtrapprox 35$

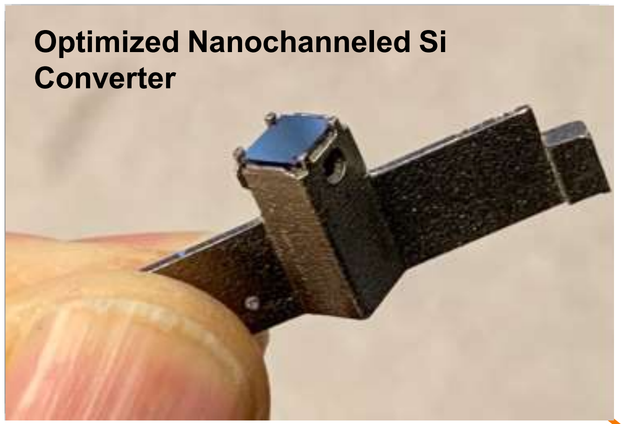
cryogenic optimized Ps target: cold Ps

AD$\rightarrow$ ELENA: #$\bar{p}$ x 100

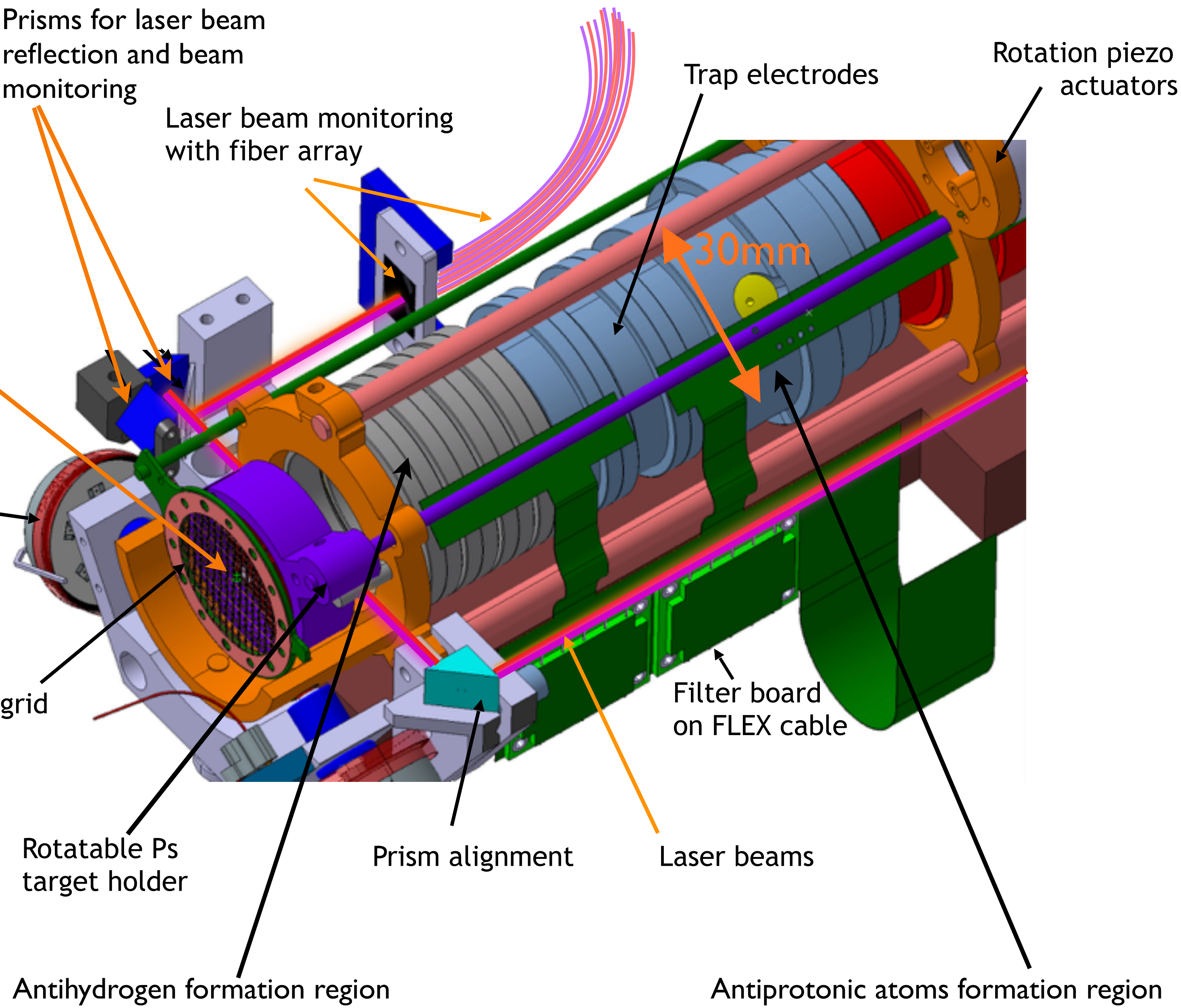
2 Upgrade of AEgIS to AEgIS-2

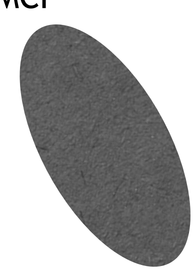


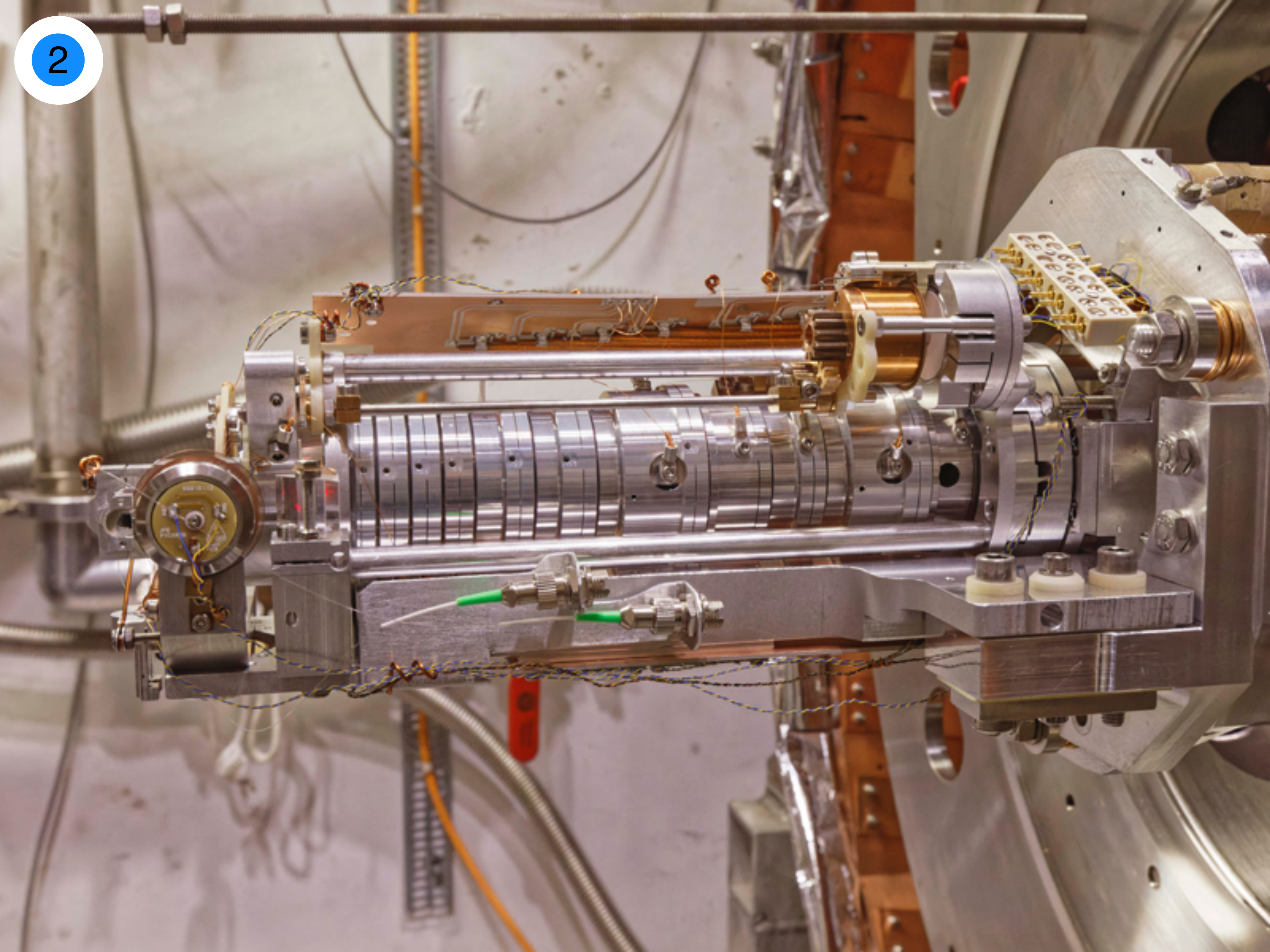
2 pulsed production of $\bar{H}$ (new geometry)



on-axis miniature Ps formation target



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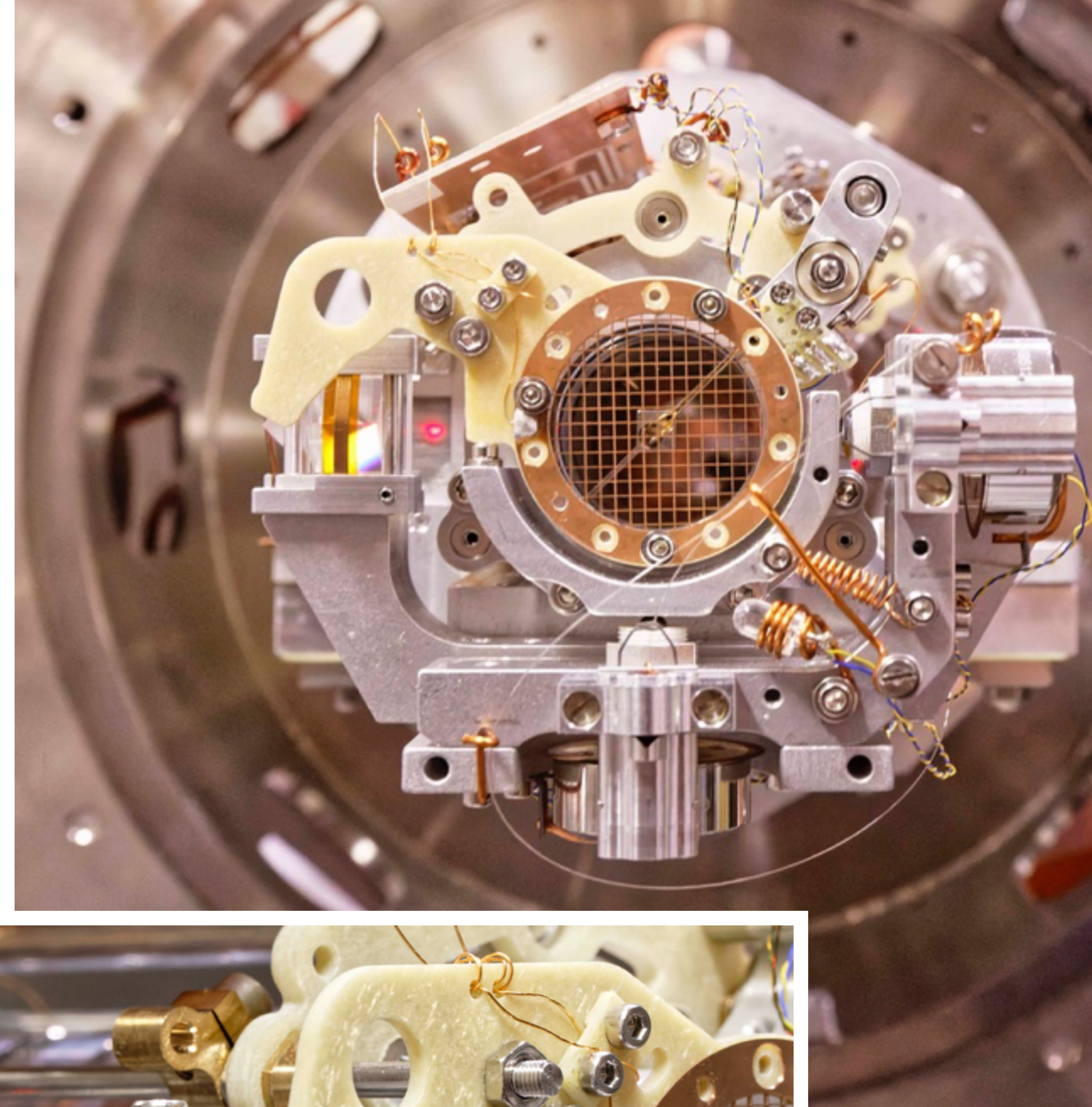
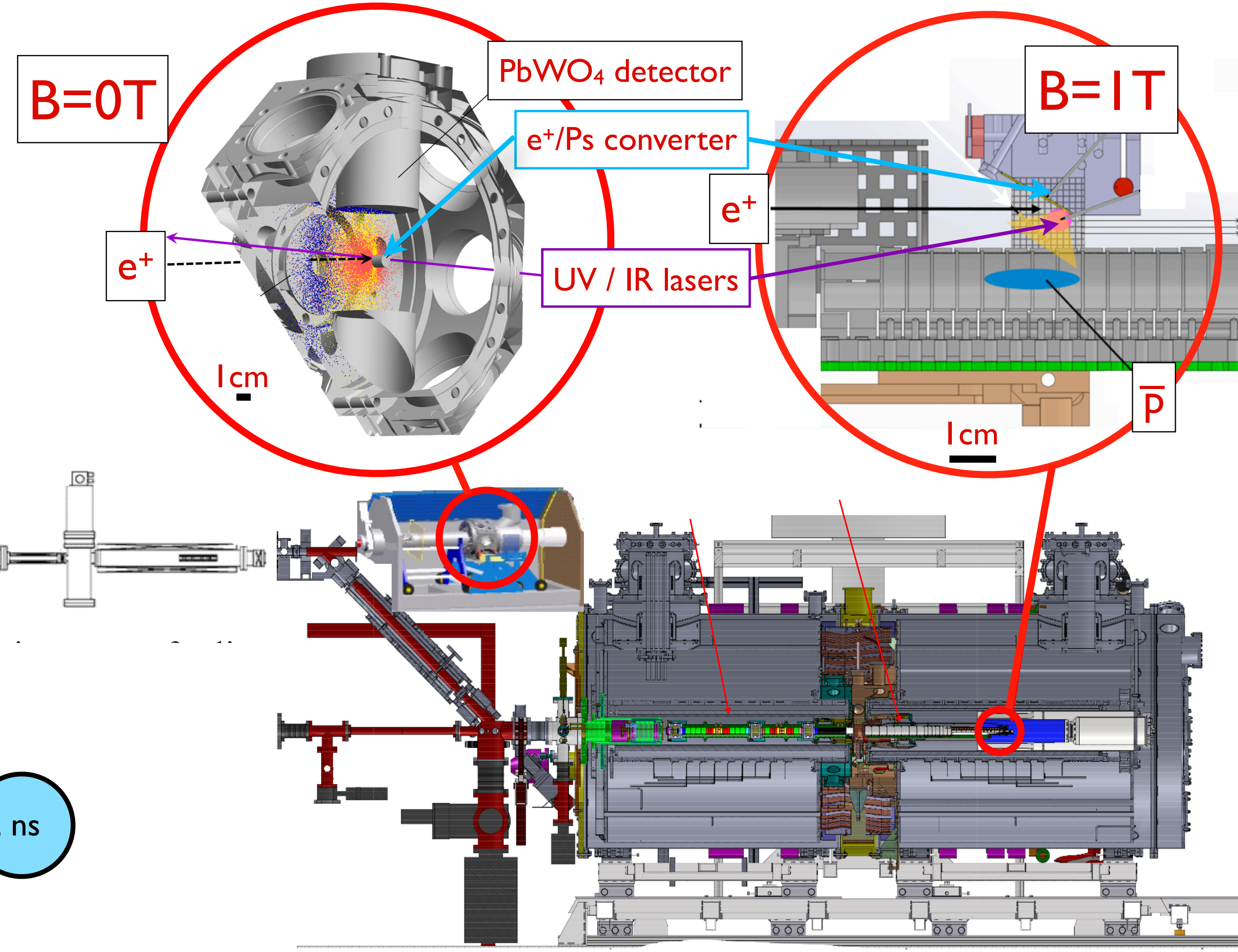
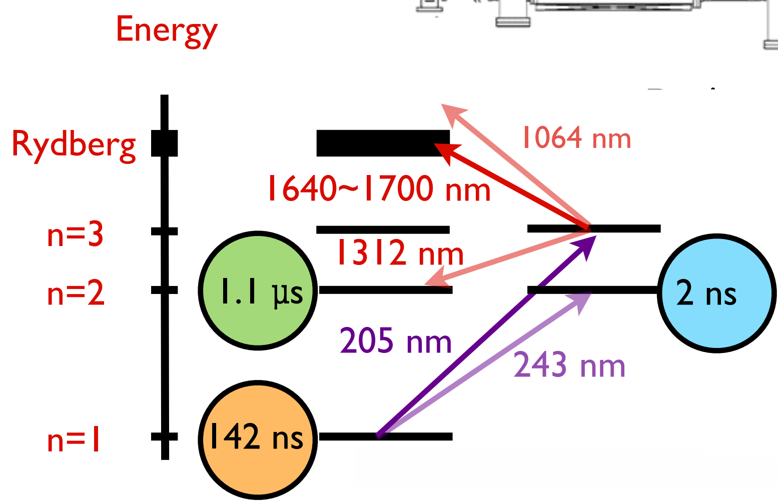


2 Positronium





towards formation of "intense" metastable Ps or Rydberg Ps beam for inertial sensing with Ps

Efficient Rydberg positronium production → intense Ps source

Efficient 2^3S positronium production by stimulated decay from the 3^3P level → long-lived Ps

Laser cooling of Ps via 1^3S - 2^3P transition → beam of meta-stable Ps

2

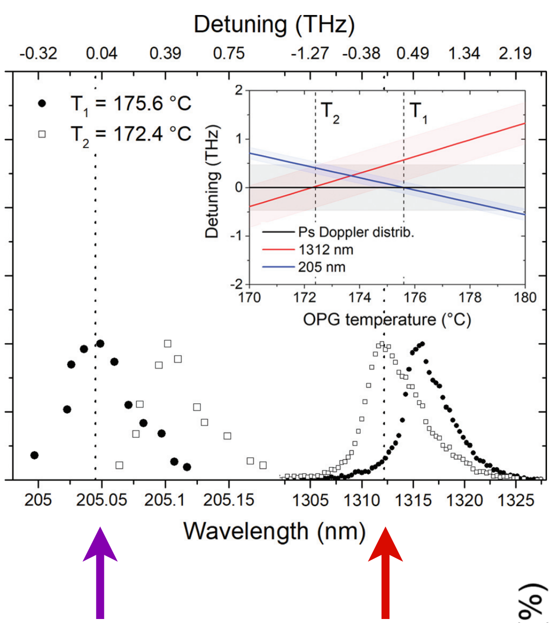
stimulated formation of metastable 2^3S Ps*

B=0T

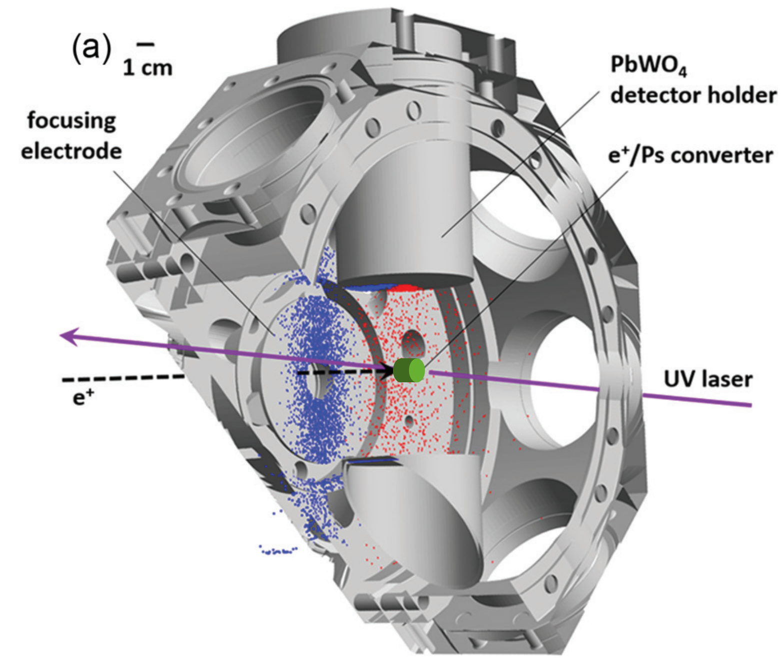
UV excitation: $1\,^3S \rightarrow 3\,^3P$

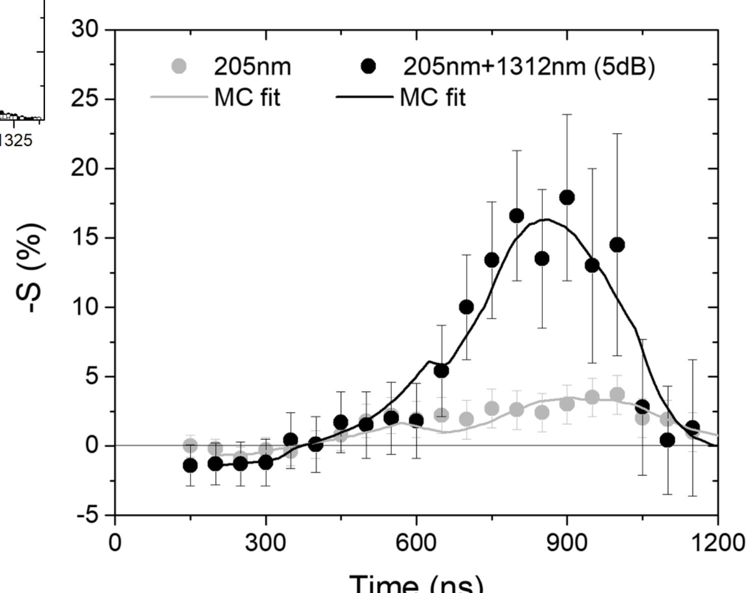
stimulated decay: $3\,^3P \rightarrow 2\,^3S$ (29.7±1.9)%

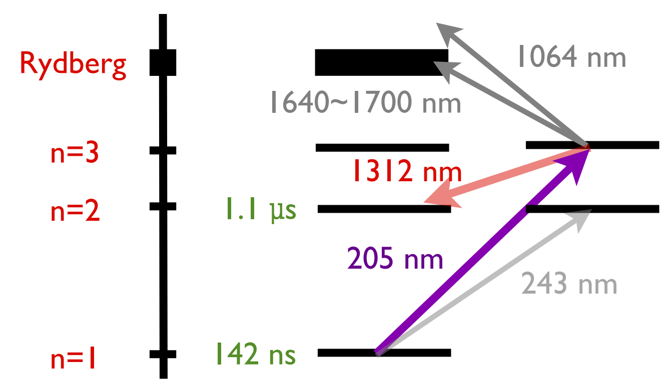
spontaneous decay: $3\,^3P \rightarrow 2\,^3S$ (9.7±2.7)%



simultaneous production of 205.05 nm and 1312.2 nm with a single system is (*barely*) feasible...







improvements on laser system (second separate system now complete)

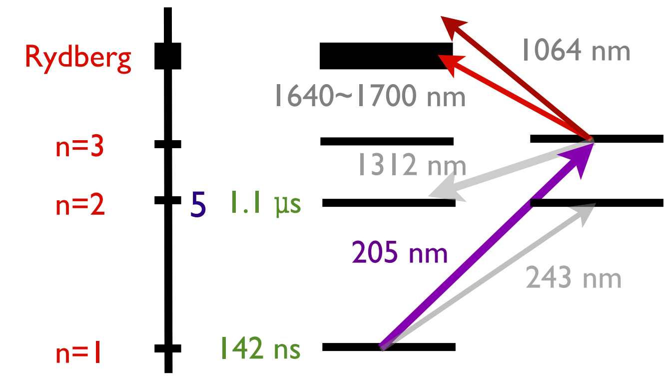
➔ improved beam intensity ➔ inertial sensing, grating tests, spectroscopy

Phys. Rev. A 100, 063414 – Published 1 Dec 2019

2

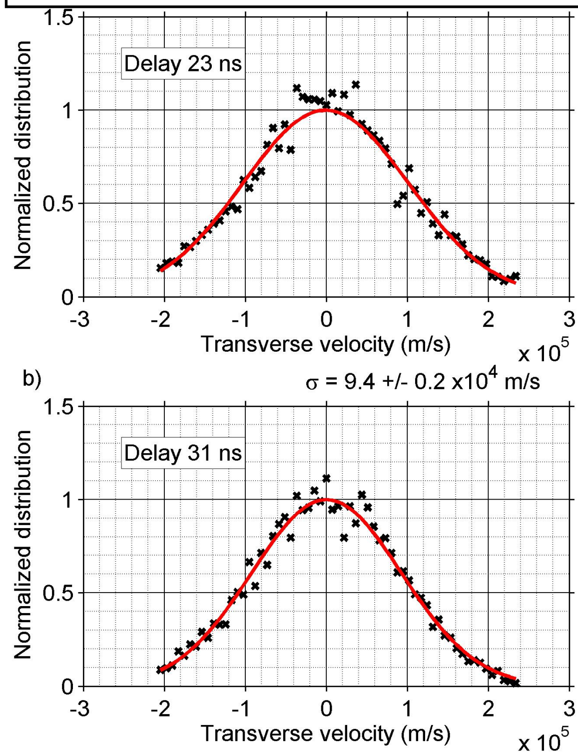
Ps* velocimetry

B=1T



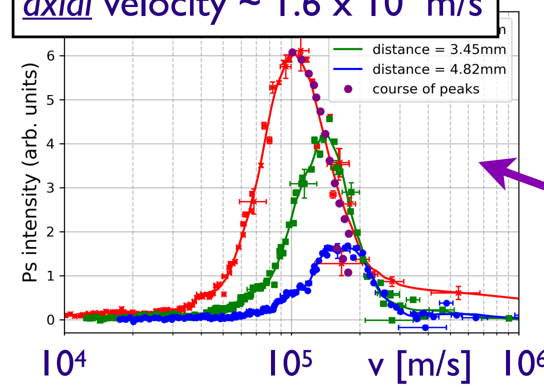
transverse velocity (σ ~ 1 x 10^5 m/s)

probed by UV Doppler velocimetry

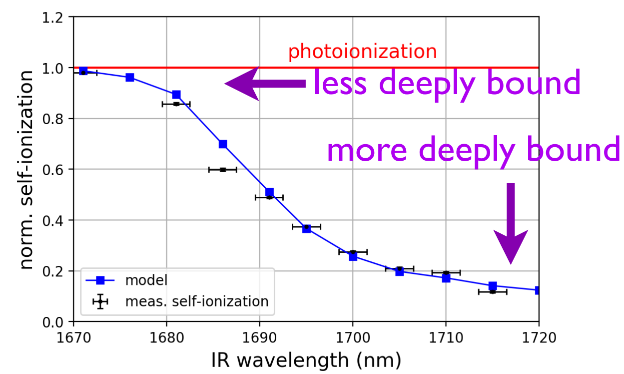


Doppler broadening ⊗ laser bandwidth

axial velocity ~ 1.6 x 10^5 m/s



probed by laser timing



self-ionization

M. Antonello et al. (AEgIS Collaboration), Phys. Rev. A 102 (2020) 013101

Key findings

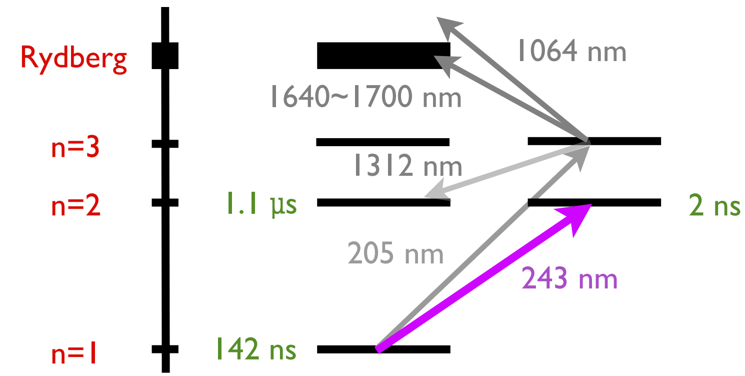
- Positronium excited to n = 15 – 17 in a 1T magnetic field
- Rydberg Ps **self-ionizes** due to the **motional Stark electric field**
- Limiting factor: Ps cannot be excited at higher levels than n = 17

2

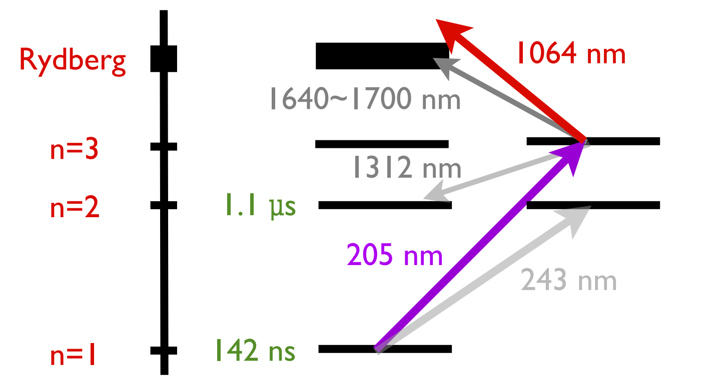
laser-cooling of Ps

two independent laser systems are available ➔ combine them!

① interact laser pulse @ 243 nm
(pulse length 100 ns)



② after cooling, Ps Doppler-profile
to extract velocity distributions
(transverse, longitudinal)

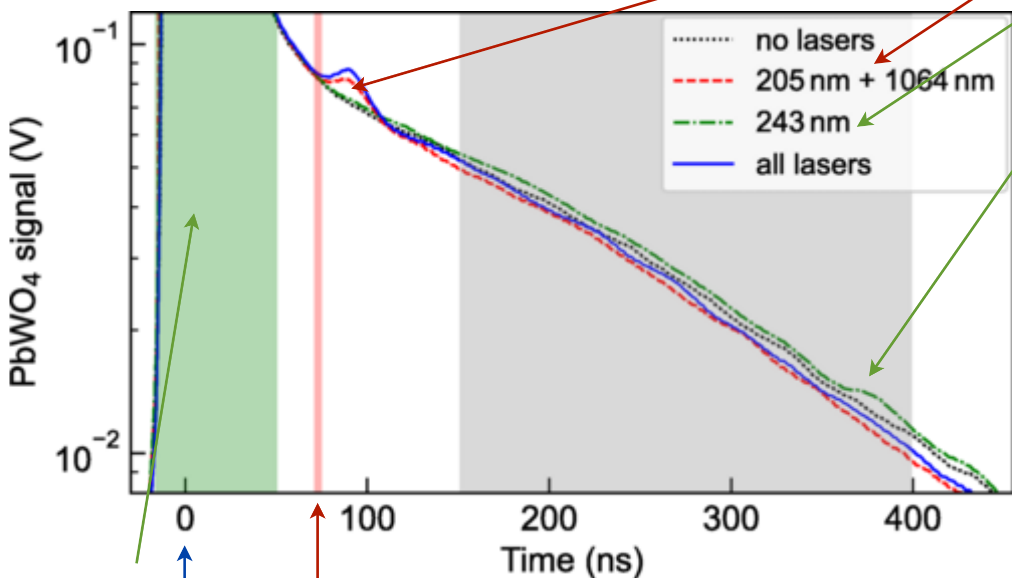


laser-cooling of Ps ➔ possible enhancement in $\overline{\mathrm{H}}$ production rate, Ps beam

laser-cooling of Ps

probing lasers (velocity-selective) ionization

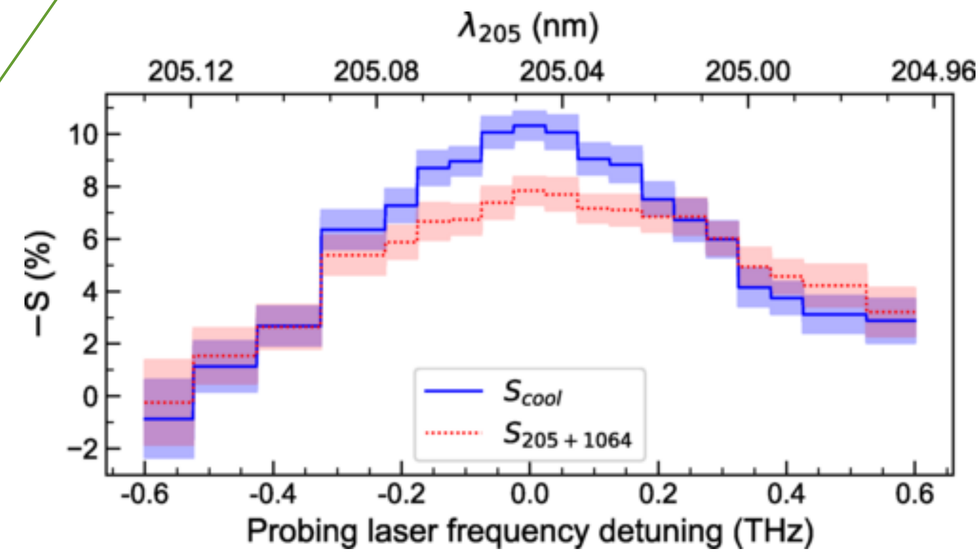
cooling laser



cooling laser

probing lasers

e+ injection, Ps formation



We observe two different laser-induced effects. The first effect is an increase in the number of atoms in the ground state after the time Ps has spent in the long-lived 2 ^{3}P states. The second effect is one-dimensional Doppler cooling of Ps, reducing the cloud's temperature from 380(20) to 170(20) K.

L.T. Glöggler et al. (AEḡIS Collaboration)
Phys. Rev. Lett. 132, 083402 – Published 22 February 2024

accepted in PRL

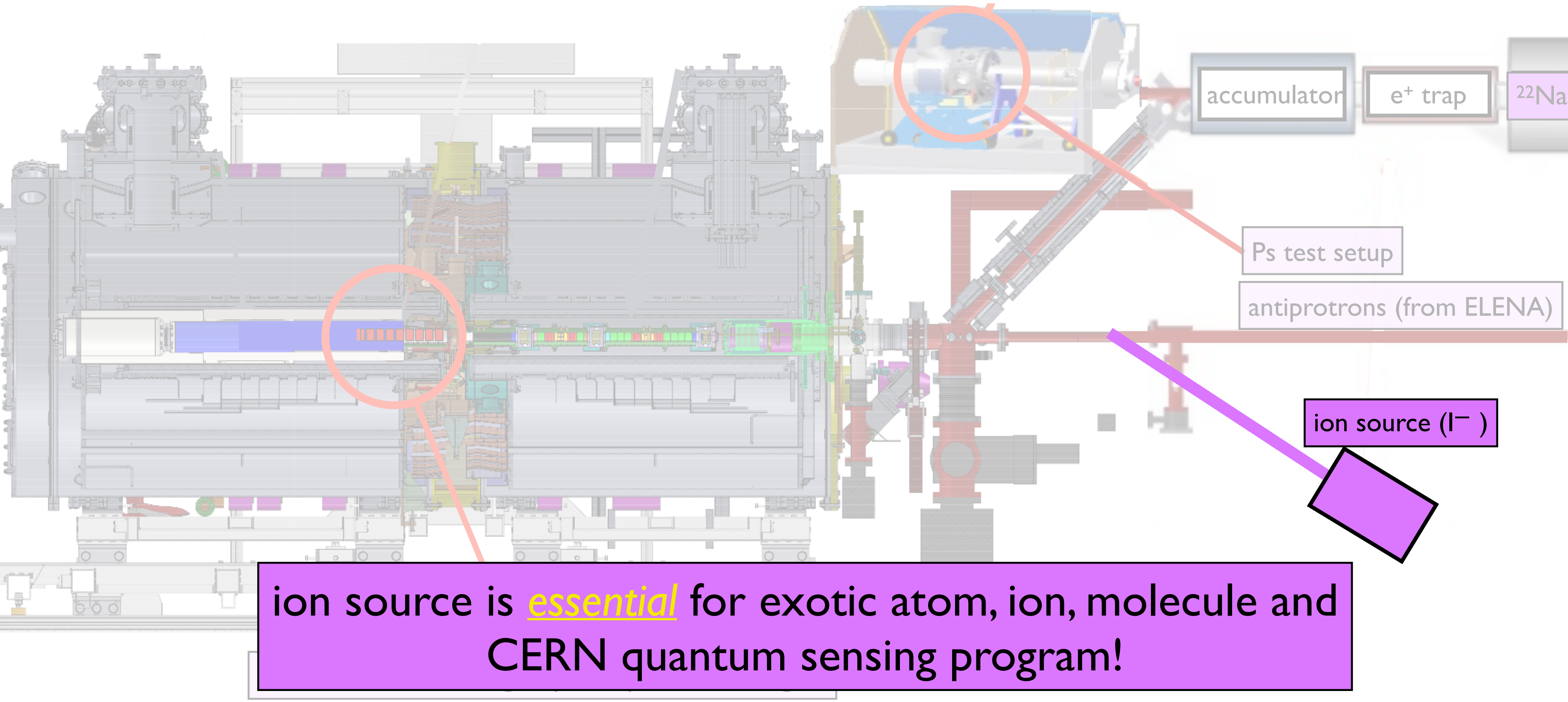
paper ~~submitted~~... and new measurements planned with improved system

laser-cooling of Ps ➔ possible enhancement in $\overline{\text{H}}$ production rate, Ps beam

➔ inertial sensing with low divergence, long-lived Ps beam

2

Upgrade of AEgIS to AEgIS-2

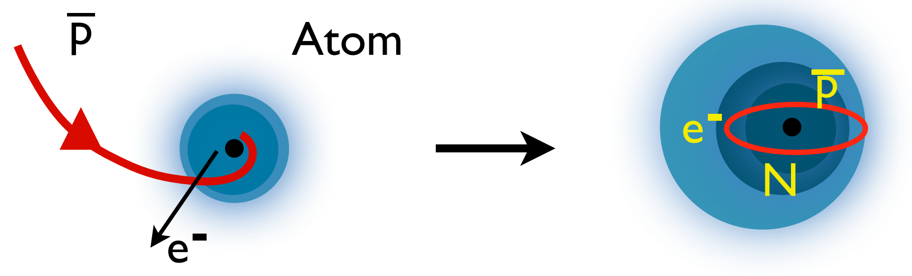


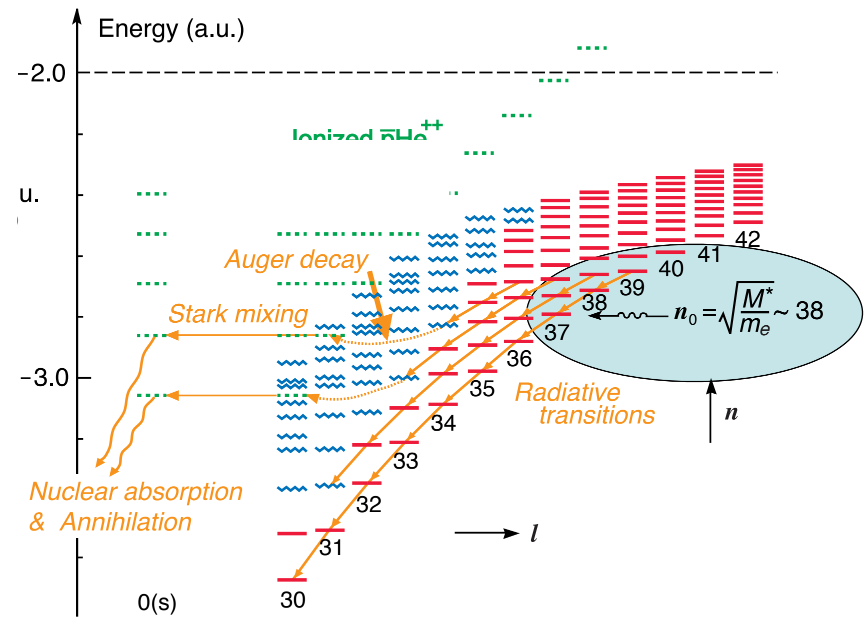
ion source is *essential* for exotic atom, ion, molecule and CERN quantum sensing program!

antiprotonic Rydberg 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

formation process: inject antiprotons into solid/ liquid/gaseous target material

established method: Rydberg atom formation; Stark mixing upon collisions, practically immediate annihilation, from high-n s-states

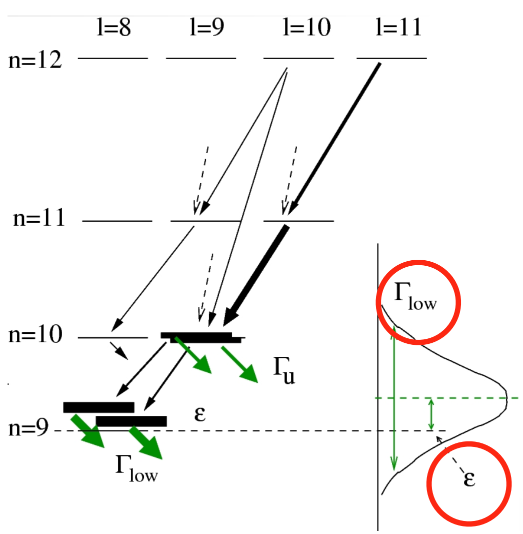
consequence: only $\bar{p}$He metastable states; all other antiprotonic atoms cascade rapidly, Stark mixing via collisions with other atoms ⟶ not possible to study them

X-rays in cascade of antiprotonic atoms

1 Correlate measurements of:

- antiprotonic x-ray cascade
(annihilation radius, energy shifts)

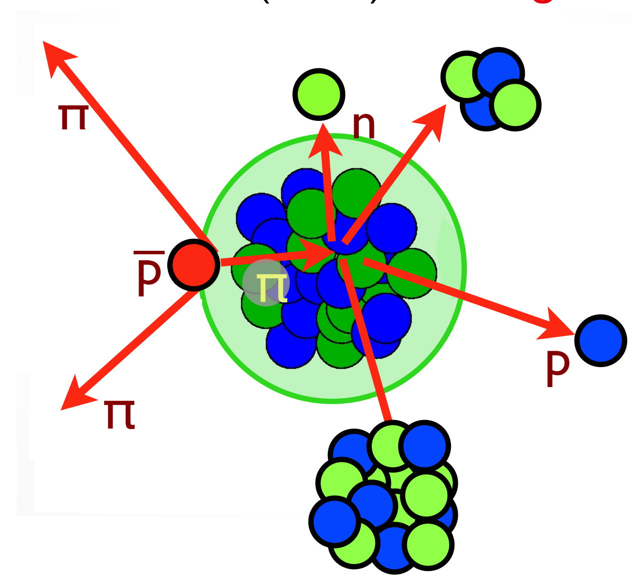
$\bar{p}Pb^{+}$



Annihilation with nucleus

2

- $\bar{p}$-p or $\bar{p}$-n → change in (Z, N) of mother nucleus
- resulting pions can interact with the (Z',N') and fragment it



but it can also survive and may remain trapped

→producing (initially hot, but coolable) trapped highly charged isotopes

fragmentation is not the dominant process

a wide swathe of radioisotopes can be produced
(identified via spectroscopy with irradiated foils)

⟶ ***starting point for subsequent manipulations***

AE$\bar{g}$IS : an improved production method for $\bar{p}$-atoms

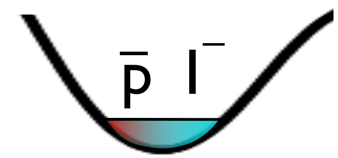
Antiprotonic atoms ⟶ novel Highly Charged Ionic systems

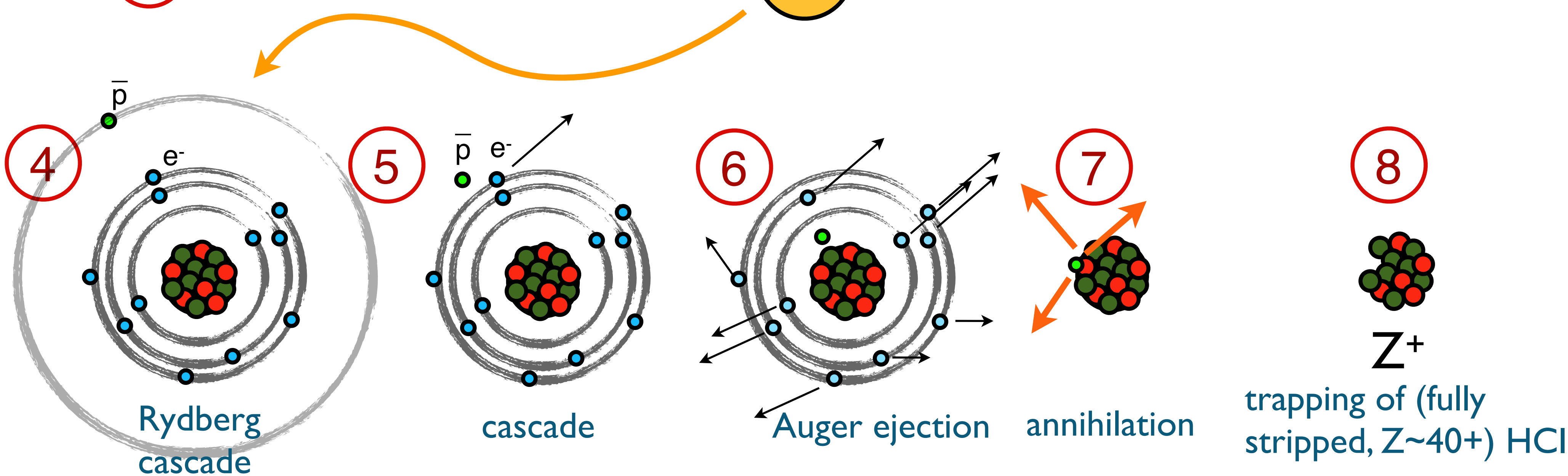
M. Doser, Prog. Part. Nucl. Phys, (2022), https://doi.org/10.1016/j.ppnp.2022.103964

<u>multi-step process that builds on existing techniques</u> (Iodine source from Torun)

1 formation and capture of HCI

1. photo-detachment: $I^- \rightarrow I^0 + e^-$ (γ_1)
2. 2_{opt} Rydberg excitation: $I^0 \rightarrow I^*$ ($\gamma_2 + \gamma_3$)
3. Charge exchange: $\bar{p} + I^* \rightarrow \bar{p}I^{+*} + e^-$ ($\bar{p}$ + $Ps^* \rightarrow \bar{p}e^{+*} + e^-$)





AEḡIS : an improved p̄p* (and p̄d*) production method

S. Gerber, D. Comparat, M.Doser, Phys. Rev. A 100, 063418 (2019)

- co-trap H^- (or D^-) and $\bar{p}$ in a Penning trap

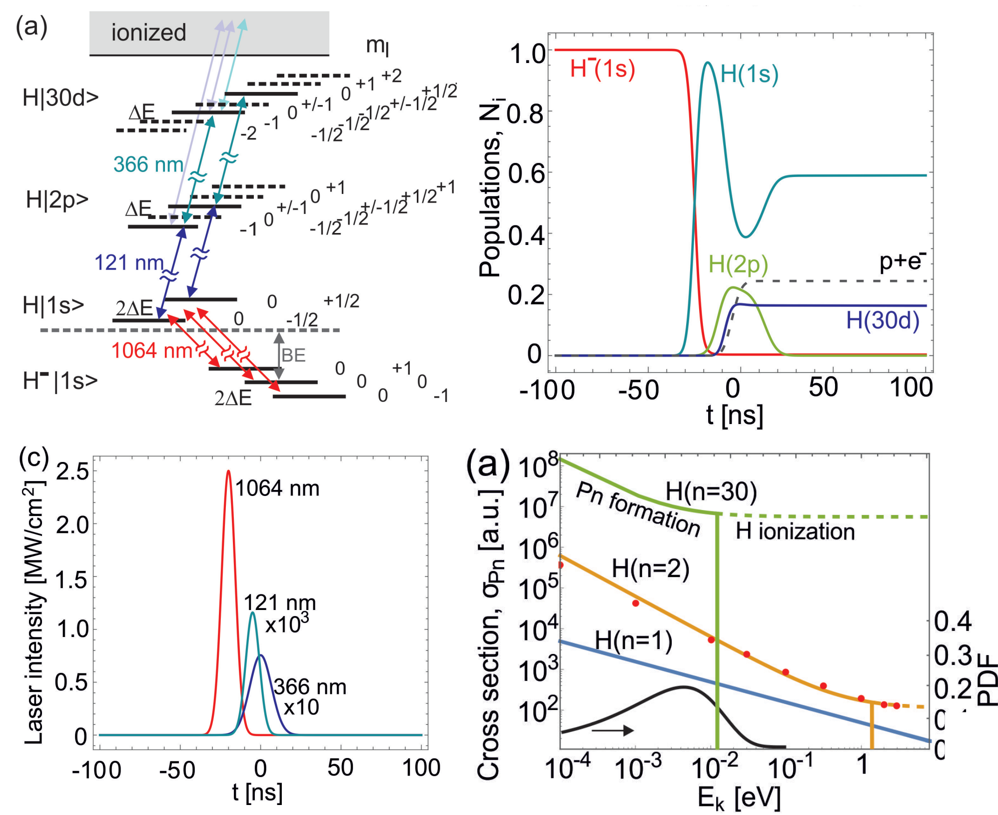
- photo-ionize H^-

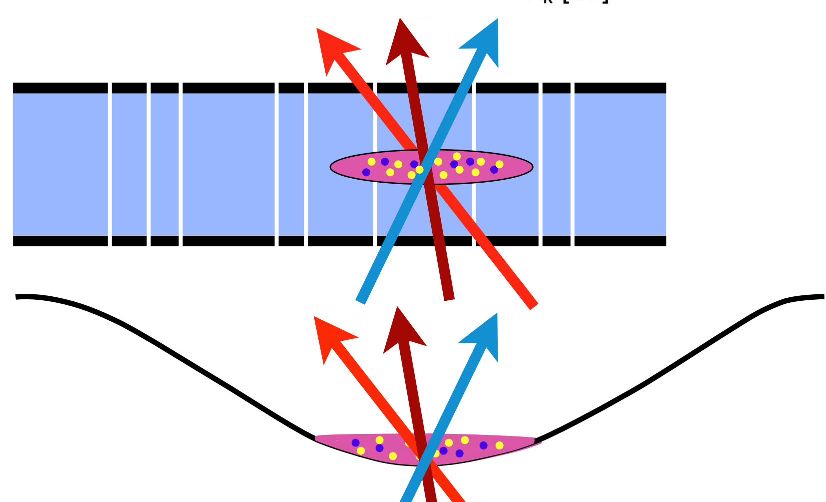
- laser-excite H $\underset{2\gamma}{\rightarrow}$ H*(30)

- charge-exchange reaction:
  $H^*(30) + \bar{p} \rightarrow \bar{p}p(n) + e^-$ *(n~2000)*

long lived!

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





pulsed process: impart slight v_z to $\bar{p}$, anion before formation → slow horizontally traveling neutral matter/antimatter beam

→ inertial sensing w/ protonium

AE$\bar{g}$IS : an improved $\bar{p}X^*$ production method

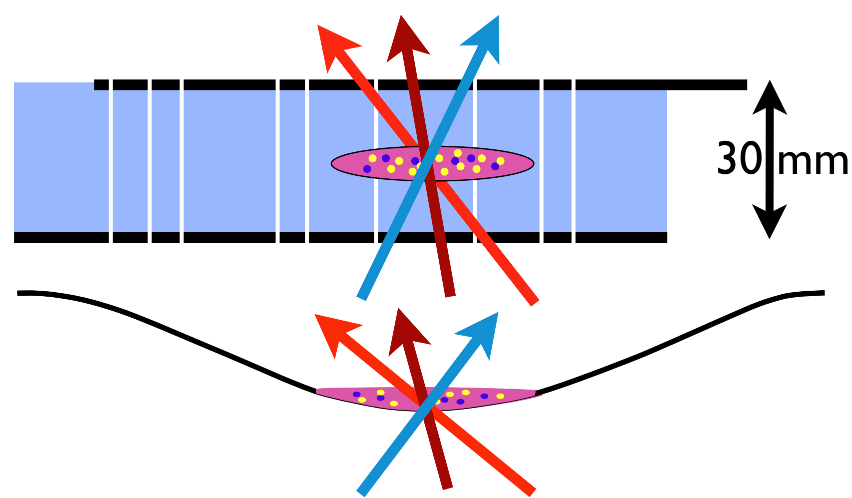
(using Rb as an example starting point)

G. Kornakov, G. Cerchiari et al., subm. Phys. Rev. C

- co-trap Rb^- and $\bar{p}$ in a Penning trap (use stable $^{37}_{85}Rb$)
- photo-ionize Rb^-
- laser-excite $Rb \underset{2\gamma}{\rightarrow} Rb^*(30)$
- charge-exchange reaction:
  $Rb^*(30) + \bar{p} \rightarrow \bar{p}Rb(n) + e^-$ *(n~2000)*
- sympathetically-cooled $Rb^- \rightarrow v_{\bar{p}Rb(n)}$ is low:
  $T_{\bar{p}Rb} \sim 100\ \mu K \leftrightarrow v_{Rb} \sim 0.3$ mm/ms
  (~100 mm/ms @ 10K)

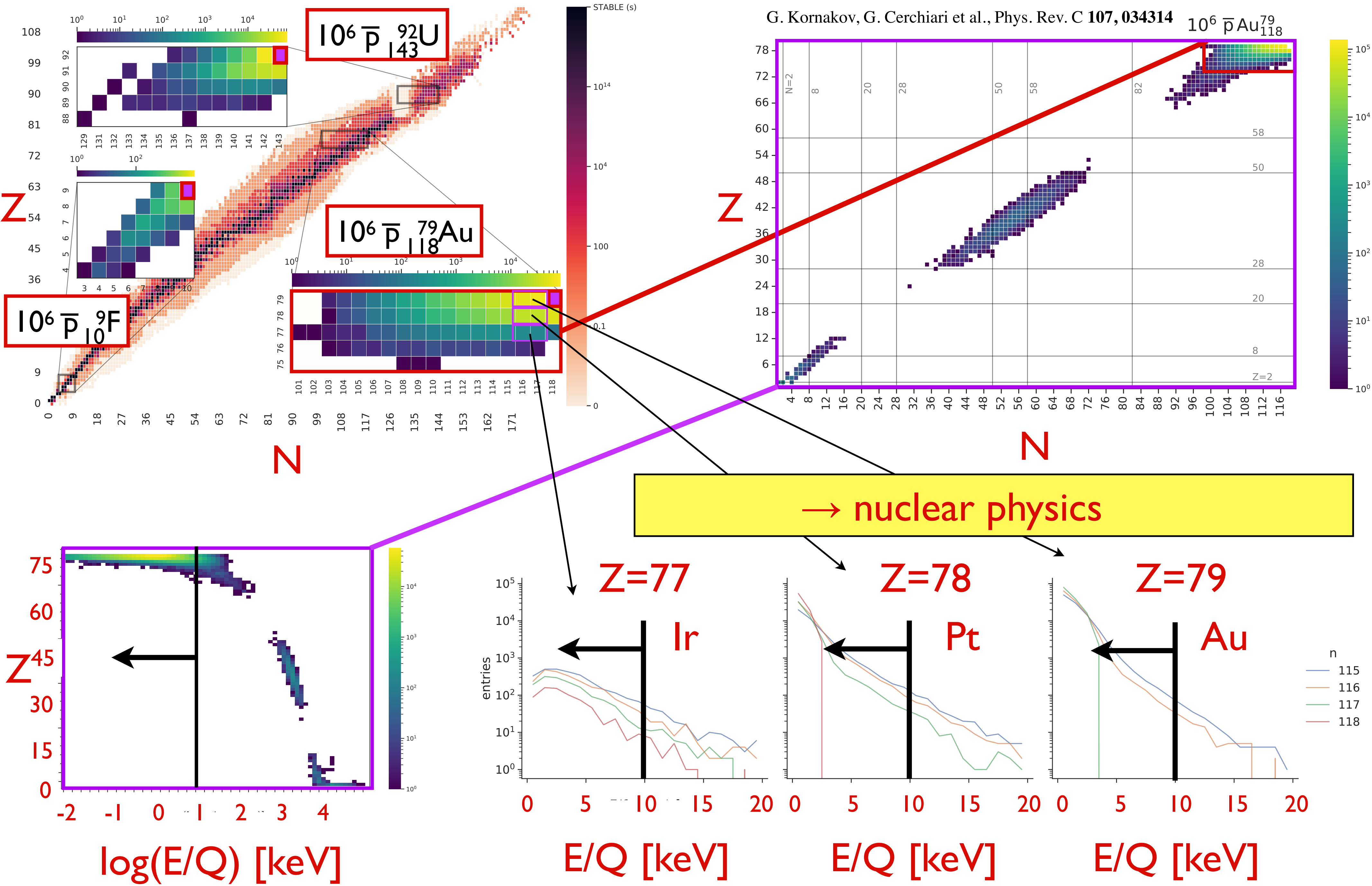
much slower!

(but antimatter:matter tiny)

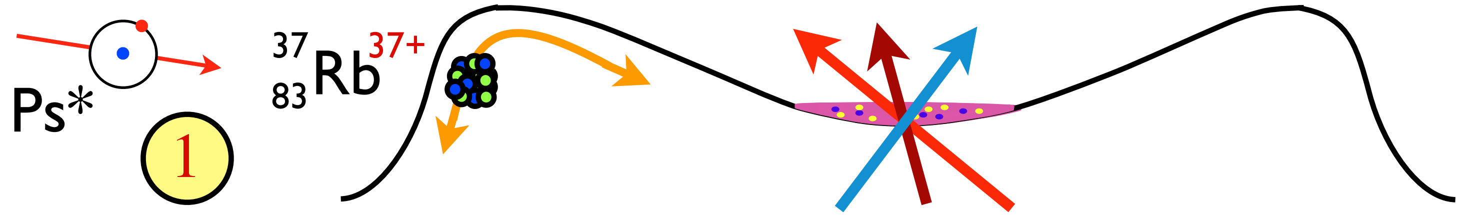


→ inertial sensing w/ neutral $\bar{p}X^*$ atoms

AEḡIS : a novel (trapped) radioisotope production method



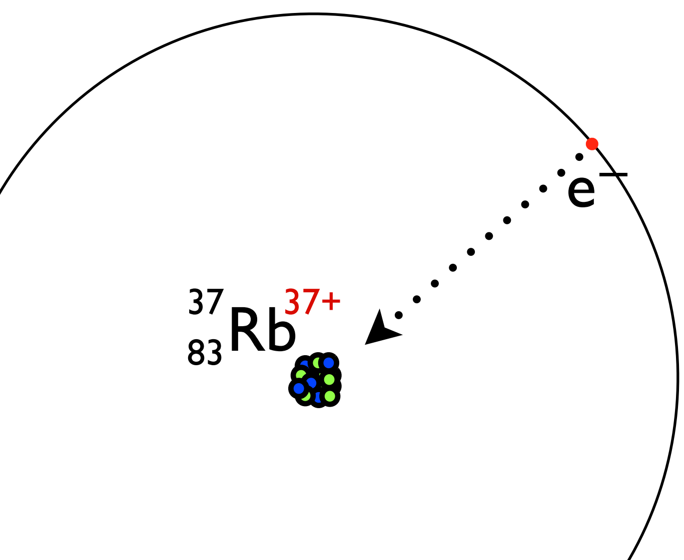
AEḡIS : a novel hollow atom(ic ion)



• in nearby Penning trap, produce Ps*

charge-exchange reaction 1:
$Ps^* + {}^{37}_{83}Rb^{37+} \longrightarrow {}^{37}_{83}Rb^{36+} * + e^+$

→ spectrocopic QED tests, BSM

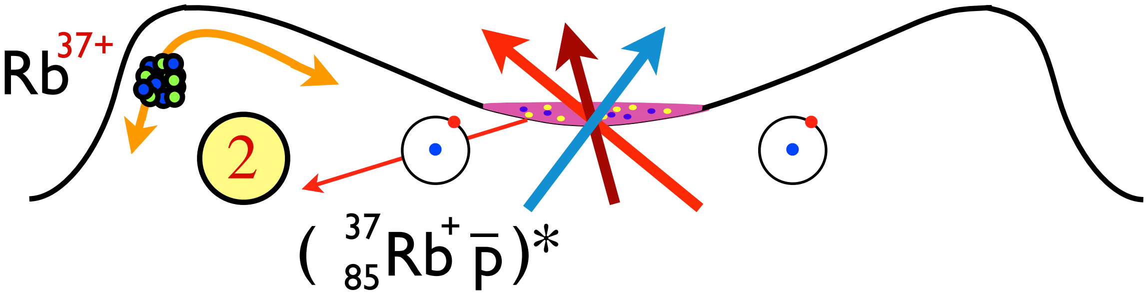


→ ***<u>Rydberg ionic atom</u> (electronic or antiprotonic) of a radio-isotopic HCI = hydrogen-like Z~40 ion***

→ ***Atomic spectroscopy of trapped ionic systems is very sensitive to exotic interactions, benefits from long lifetime of Rydberg atom***

→ ***<u>ground-state</u> hydrogen-like Z~40 ion : qubit?***

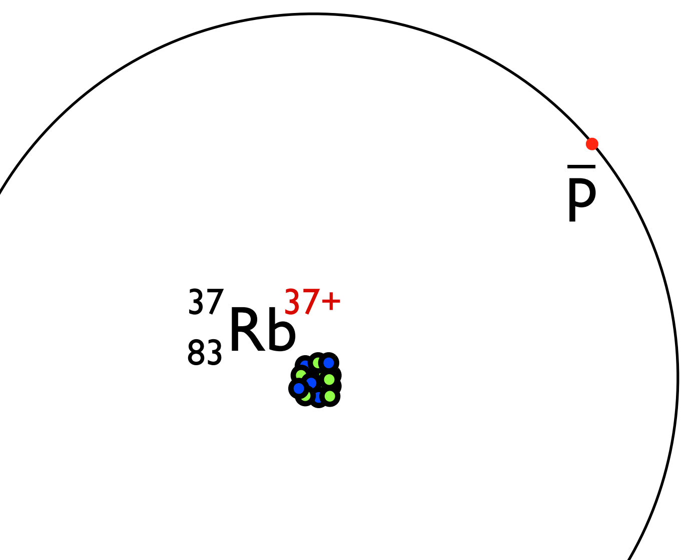
AEḡIS : a novel hollow atom(ic ion)



- in nearby Penning trap, produce Ps* (or $\bar{p}$Rb* again)

charge-exchange reaction 2:
$(\bar{p}Rb)^* + {}^{37}_{83}Rb^{37+} \longrightarrow (\bar{p}\ {}^{37}_{83}Rb)^{36+\,*} + Rb^+$

→ spectrocopic QED tests, BSM



→ ***<u>Rydberg ionic atom</u> (electronic or antiprotonic) of a radio-isotopic HCI = hydrogen-like Z~40 ion***

→ ***Atomic spectroscopy of trapped ionic systems is very sensitive to exotic interactions, benefits from long lifetime of Rydberg atom***

→ ***very clean fluorescence spectroscopy: QCD effects?***

AEḡIS : a novel dark matter search

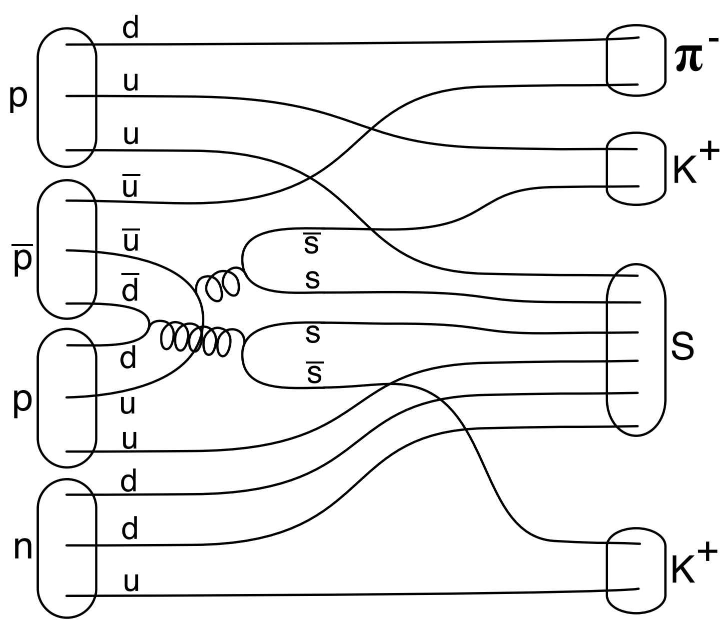
***sexaquark: uuddss bound state** ($m \sim 2m_p$) [Glennys Farrar https://arxiv.org/abs/1708.08951]*

not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region
astrophysical bounds can be evaded
standard model compatible (uuddss bound state)

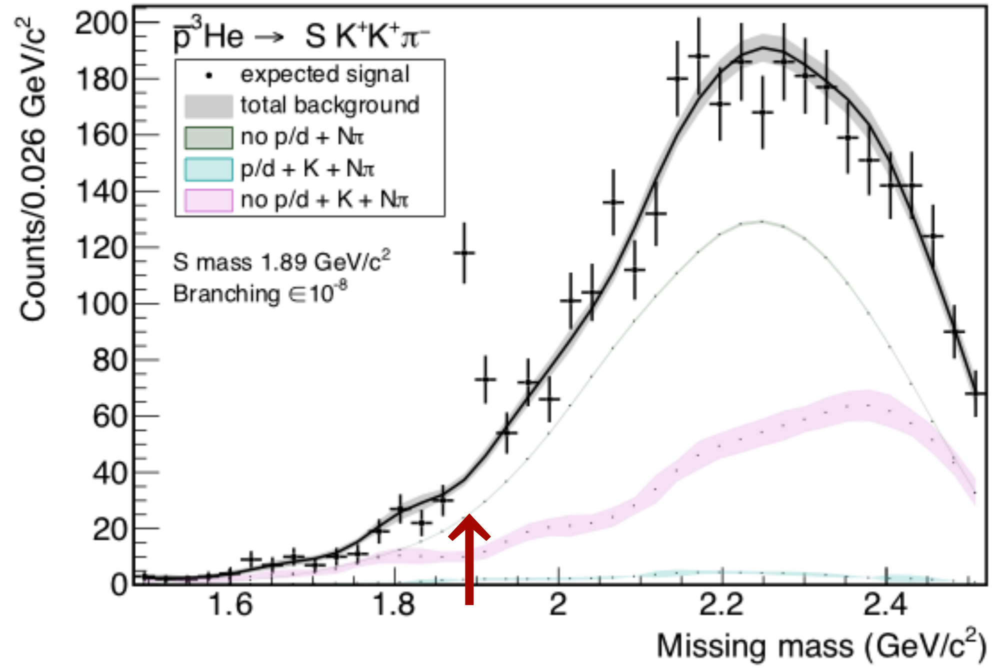
→ novel DM search

formation reaction:
$(\bar{p}\ ^3He)^* \rightarrow S(uuddss) + K^+K^+\pi^-$

S= +2, Q= -1



Geant-4 simulation



→ ***in-trap formation of antiprotonic atoms***
charged particle tracking, PID
detection of spectator p, d

→ ***sensitivity down to 10^{-9}***

Summary:

Tests of the WEP with antimatter systems have just started and have many years of improvements ahead of them.

Charge exchange processes between Rydberg systems and single charged particles provide controlled access to unique exotic systems, with which not only gravity but also possible novel gravity-like interactions can be explored.

We've just started *working* with antimatter Rydberg systems and have just started *thinking* about antiprotonic Rydberg systems, but it is clear that there are many opportunities and open questions, from tests of fundamental symmetries to studies of exotic atoms to nuclear physics to searches for dark matter, and many more...

thank you for your attention!

the end

antihydrogen molecular ion: $\bar{H}_2^-$ ~ H_2^+

Observation of a molecular bond between ions and Rydberg atoms, N. Zuber et al., Nature vol. 605, pages 453–456 (2022)

Semiclassical Treatment of High-Lying Electronic States of H_2^+, T. J. Price and Chris H. Greene, J. Phys. Chem. A 2018, 122, 43, 8565–8575, https://doi.org/10.1021/acs.jpca.8b07878

H_2^+ has very narrow transitions, clock @ 10^{-15} level; how to form antimatter analog?

H_2^+ and HD^+: Candidates for a molecular clock, J.-Ph.Karr, J. of Mol. Spectr. 300, 2014, 37-43

current thinking: $\bar{H} + \bar{H} + \gamma \rightarrow \bar{H}_2^- + e^+$

H_{nl}-$H_{n'l'}$ Associative ionization

M. Zammit et al., Phys. Rev. A **100**, 042709 (2019)

(~continuous, extremely low numbers, very low rate)

alternatively: $Ps^* + \bar{p} + \bar{p} \overset{?}{\rightarrow} \bar{H}_2^{-(*?)} + e^-$

Three-body recombination

(pulsed, requires ridiculous n(Ps), very low rate? state?)

alternatively: $\bar{H}^* + (\bar{p}p)^* \overset{?}{\rightarrow} \bar{H}_2^{-(*?)} + e^+$

Rydberg atom - Rydberg atom associative ionization (but is Penning ionization >> ?)#

(pulsed, high instantaneous density... rate? state?)

"associative ionisation between two excited states is less than a tenth of the Penning ionisation" - M Cheret *et al* 1982 *J. Phys. B: At. Mol. Phys.* **15** 3463

alternatively: $\bar{H}^* + \bar{p} + \gamma + \gamma \overset{?}{\rightarrow} \bar{H}_2^{-(*?)}$

photo-associative Raman process (STIRAP) to combine atom & ion into a molecular ion ($Li + Cs^+ \rightarrow (LiCs)^+$)

Formation of a molecular ion by photoassociative Raman processes, D. Sardar[1], S. Naskar[1,2], A. Pal[1], H. Berriche[3,4] and B. Deb[1,5] , J. of Phys. B: Atomic, Molecular and Optical Physics, Volume 49, Number 24 (2016) https://iopscience.iop.org/article/10.1088/0953-4075/49/24/245202

further antiprotonic Rydberg molecules

- *pulsed formation*: trapped *anionic molecule* together with antiprotons, photo-detachment of electron; one molecule already being targeted: C_2^- (T($\bar{p}C^{(+)}{}_2$)~mK)

cold $\bar{H}$ ←
- laser-cool $\bar{H}$ (Doppler limit ~ 10mK) ALPHA
- sympathetically cool $\bar{p}$ with laser-coolable anion C_2^- AEgIS

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

- *pulsed formation*: co-trapped *multiple anion species A^-,H^-* with antiprotons; photo-detach & excite H^- to form $\bar{p}p^*$ photo-detach & excite A^- to form A^* (and $\bar{p}A^{(+)*}$)

Rydberg atom interactions between: A^* , $\bar{p}A^{(+)*}$, $\bar{p}p^*$

(for example: $\bar{p}Cs^{(+)*} + \bar{p}p^* \rightarrow \bar{p}\bar{p}p^* + Cs^+$???) (Ps^-/Ps^+ analog)

further (trapped) antiprotonic Rydberg (ionic) molecules

- ***starting from trapped HCI's***: trapped *HCI^{Z+}* (from $\bar{p}\ ^{Z+1}A$):
  - near-by production of protonium or antiprotonic atom
  - charge exchange
  - sympathetic cooling with e.g. Cs+

$$HCI^{Z+} + \bar{p}p^{*} \rightarrow \bar{p}\ HCI^{Z+*} + p)$$

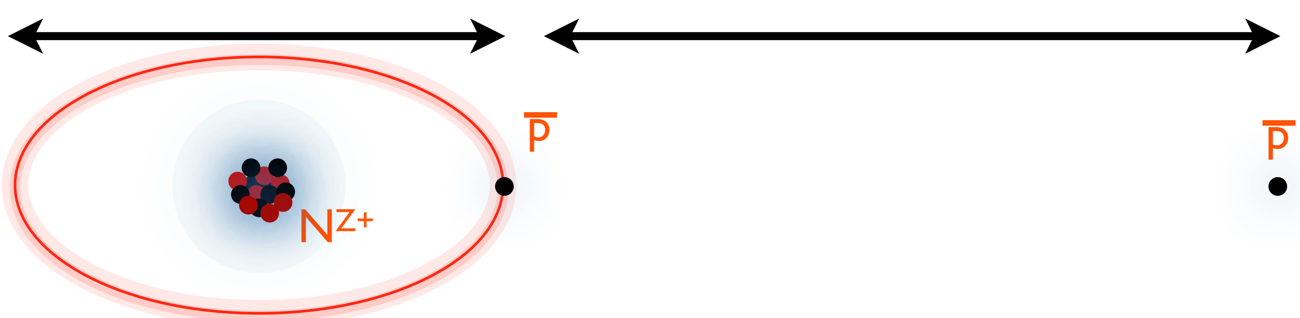
e.g. $(\bar{p}\ ^{37}_{83}Rb)^{36+}*$

results in: highly charged antiprotonic cold Rydberg cation

- ***3-body formation***: combine with nearby cold anions ($\bar{p}$, X^{-})

$$\bar{p} + \bar{p}\ HCI^{Z+*} \rightarrow (\bar{p}\ HCI^{Z+*}\ \ \bar{p})_{\text{molecular ion}} + \gamma$$

$(\bar{p}\ ^{37}_{83}Rb)^{36+}*$

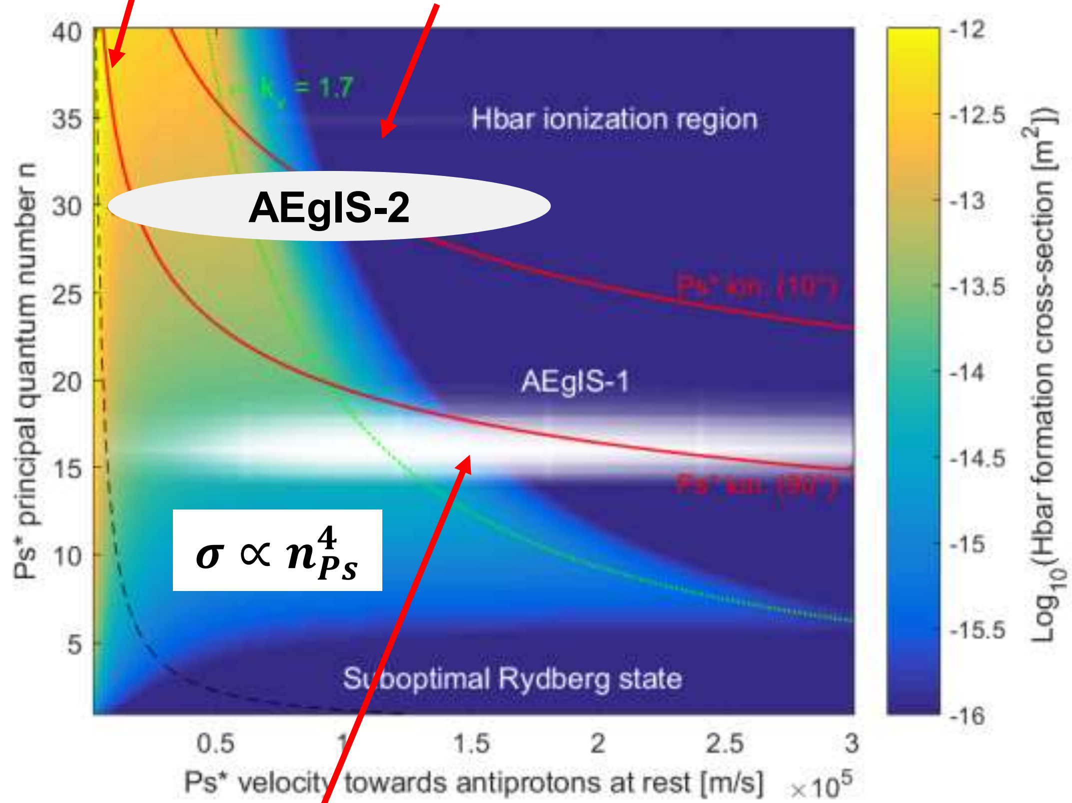


towards (pulsed formation of) matter-antimatter Rydberg systems ...

- positronium (spectroscopy, inertial sensing in metastable beams)
- antiprotonic Rydberg atoms (with $\bar{p}$ instead of e^-)
- antiprotonic molecules ($\overline{H}_2^-$, others ?)
- search for a novel dark matter candidate

Limit from motional Stark ionization

AEgIS-2 target Ps* distribution [1]

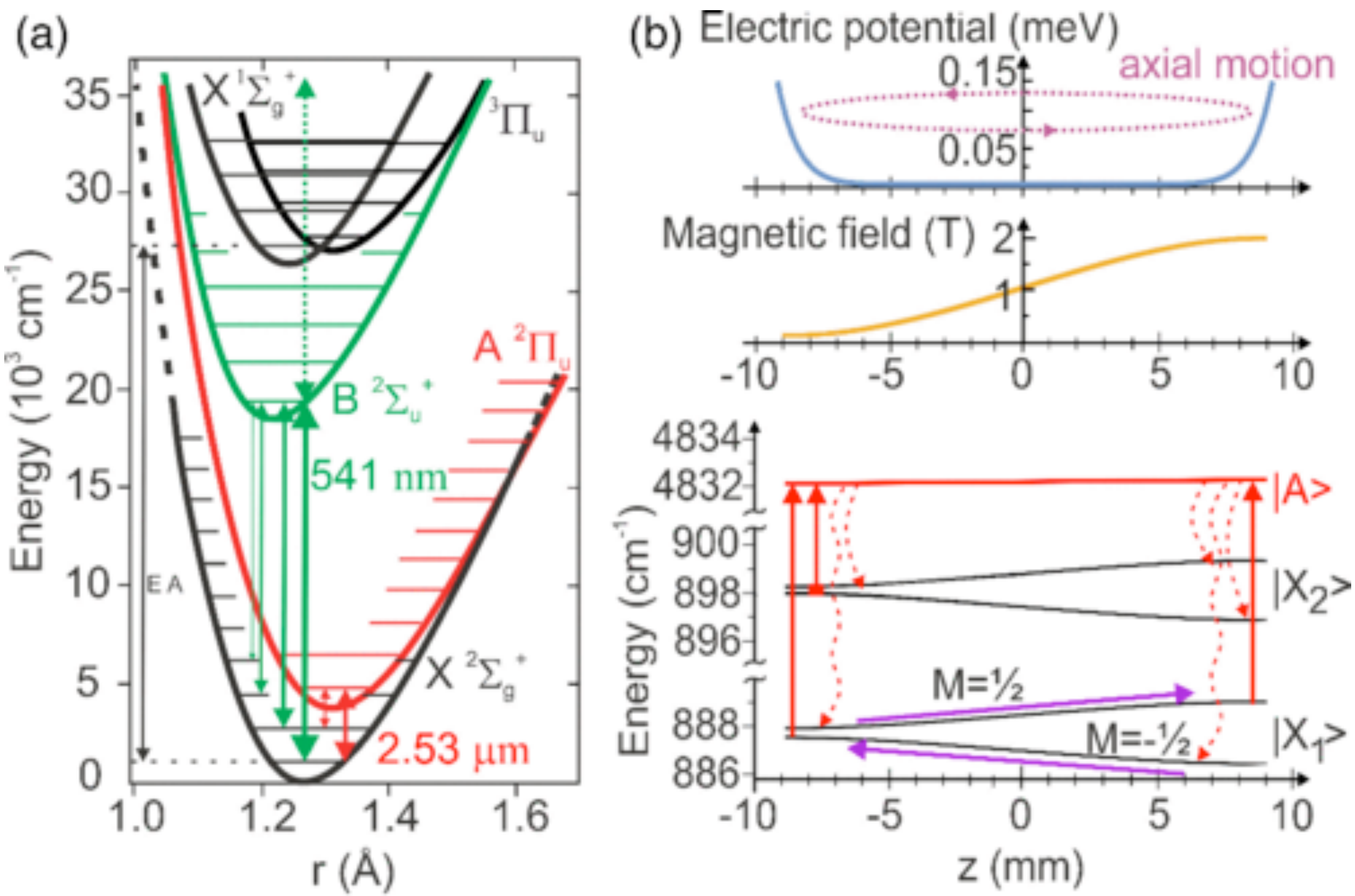


AEgIS-1 Ps* distribution

[1] S. Mariazzi et al., J. Phys. B (2021) 085004

Anion cooling for AEgIS: C_2^-

Sisyphus cooling



Electronic and vibrational levels of C_2^-

Arrow width ~ Franck-Condon transition strength

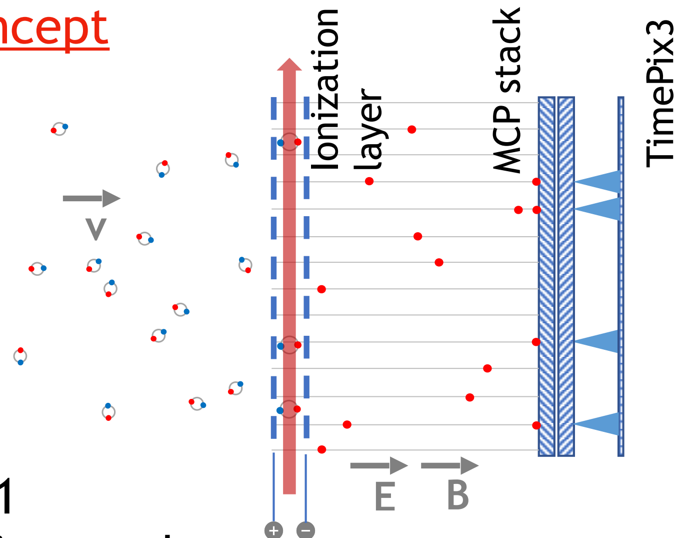
P. Yzombard et al., Phys. Rev. Lett. 114, 213001 *antiprotonic atoms → a range of possible investigations, covering:*

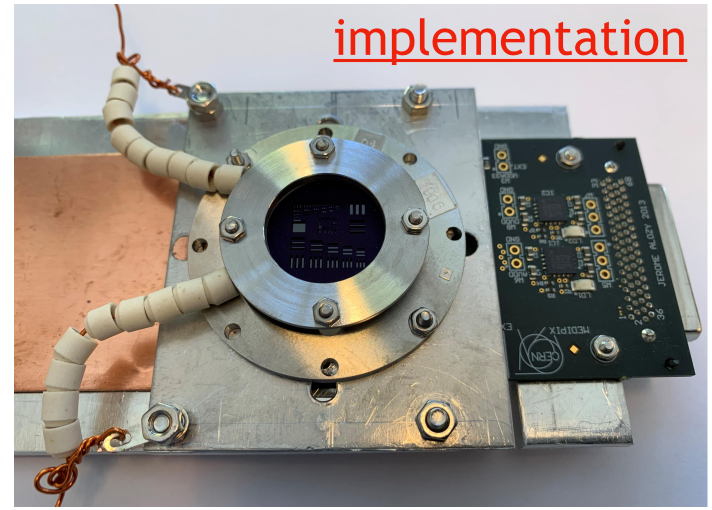
- $\bar{p}$EDM
- formation of very interesting antiprotonic molecules ($\bar{p}\bar{p}p$, $\bar{H}_2^-$, ...)
- controlled study of antiprotonic atoms (radioisotopes)
- study of tidal effects in nuclear matter
- production of fully stripped ions → *Rydberg constant*
- studies of antiproton-induced nuclear fragmentation
- production of (currently unavailable at CERN) radio-isotopes
- polarized antiprotons
- antineutrons: low E $\bar{n}$ emission and nuclear interactions

These are pipe dreams for now, but that doesn't mean we shouldn't think about whether they make sense, and if so, keeping them in our sights for when we can start thinking about making them a reality.

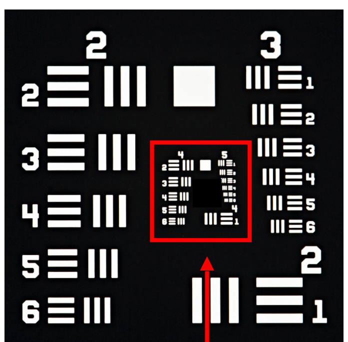
high-resolution position-sensitive detector for $\bar{H}$ / Ps

concept

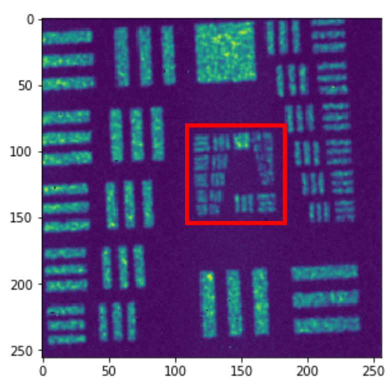




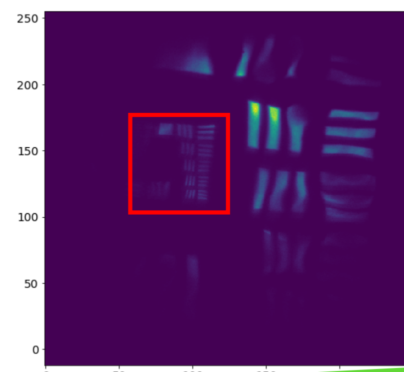
USAF-51
resolution mask



smallest feature size ~35 μm

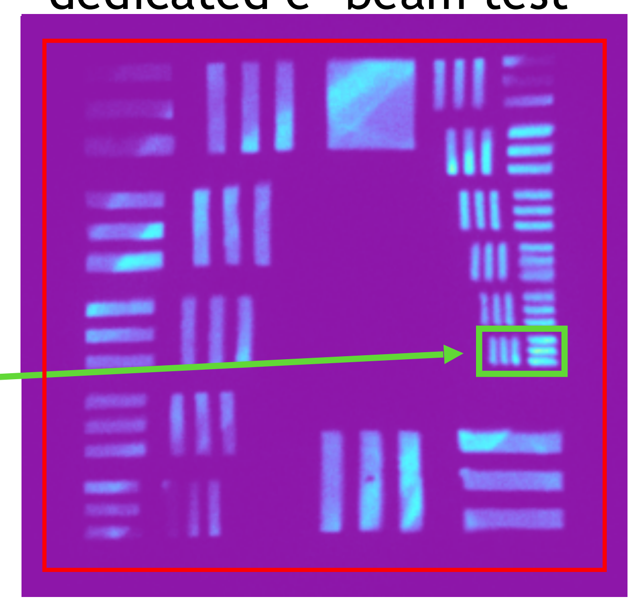


Am-241 source on TPX3 (ASIC + Si sensor + Al layer)



Am-241 source on TPX3 (ASIC) + MCP stack

dedicated e^+ beam test



Positron beam on TPX3 (ASIC) + MCP stack

→ Spatial resolution: 12 um (down to 5 um with UV light)
Temporal resolution: 15 ns