Pulsed production of antihydrogen (and other antiprotonic systems) for precision tests of fundamental symmetries

Michael Doser / CERN

AEḡIS collaboration

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RRI

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

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

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

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

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

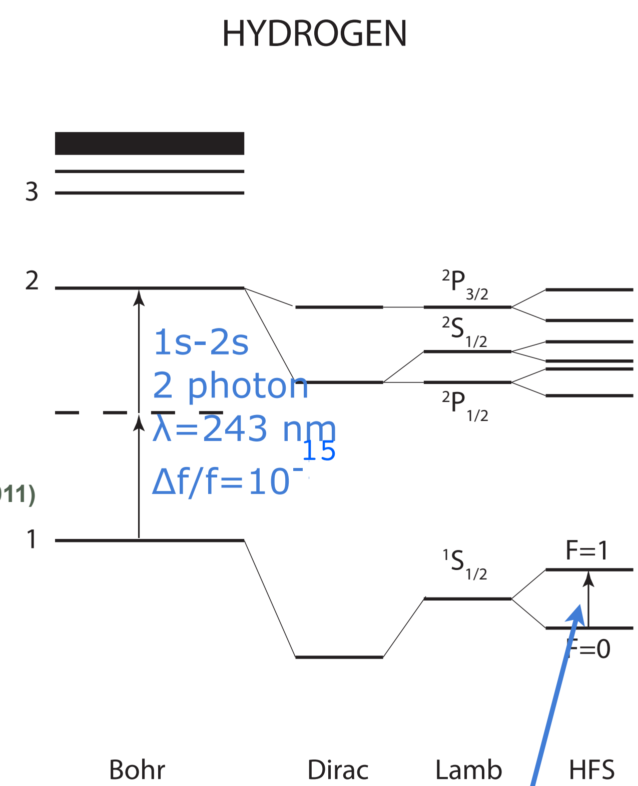
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu - \tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0 .$$

Lorentz violation

- Spontaneous Lorentz symmetry breaking by (exotic) string vacua
- Note: if there is a preferred frame, sidereal variation due to Earth's rotation might be detectable

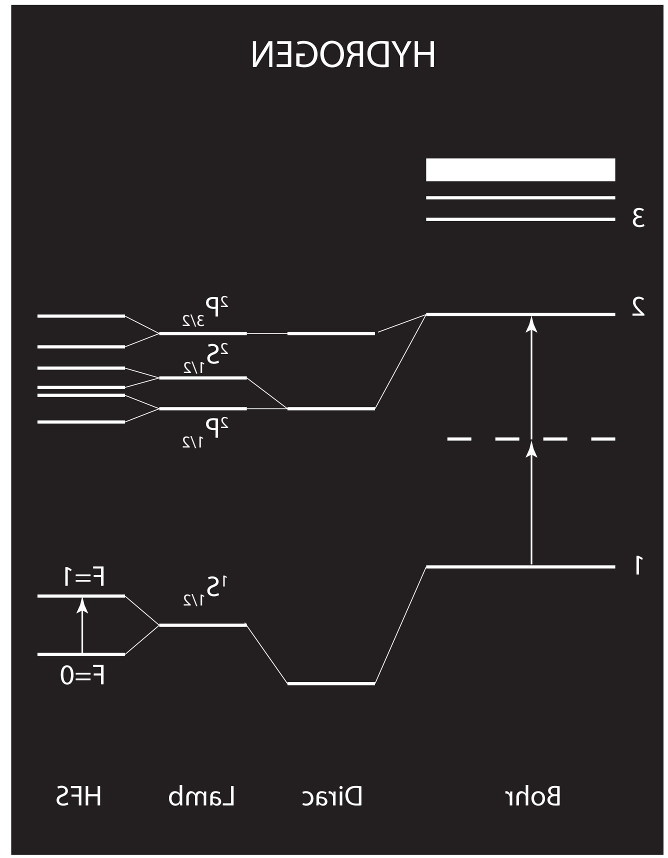
Goal of comparative spectroscopy: test CPT symmetry

e.g. in Hydrogen and Antihydrogen



1s-2s
2 photon
λ=243 nm
$\Delta f/f=10^{-15}$

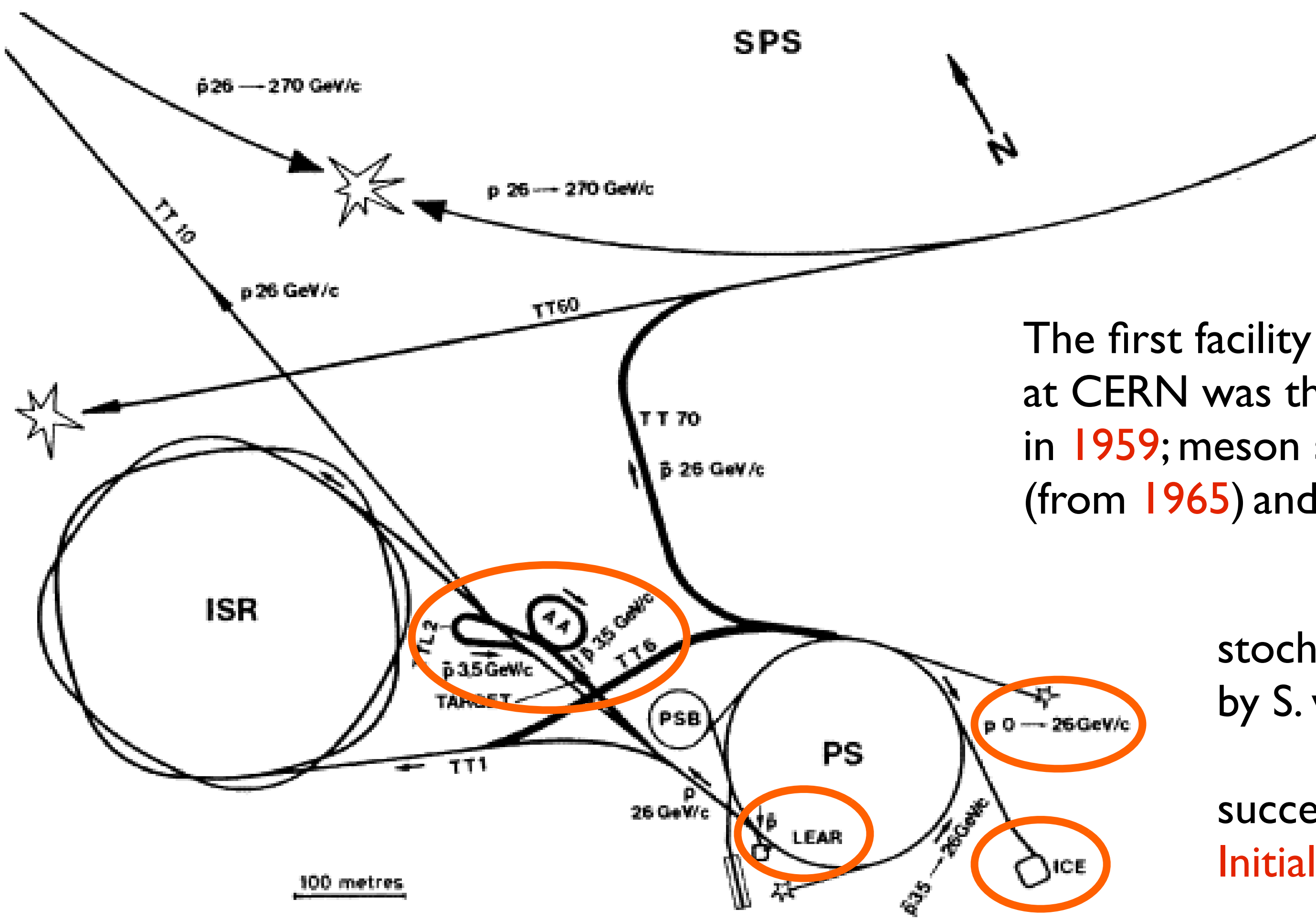
T. Hänsch et al.,
Phys. Rev. Lett. 107, 203001 (2011)



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

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

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

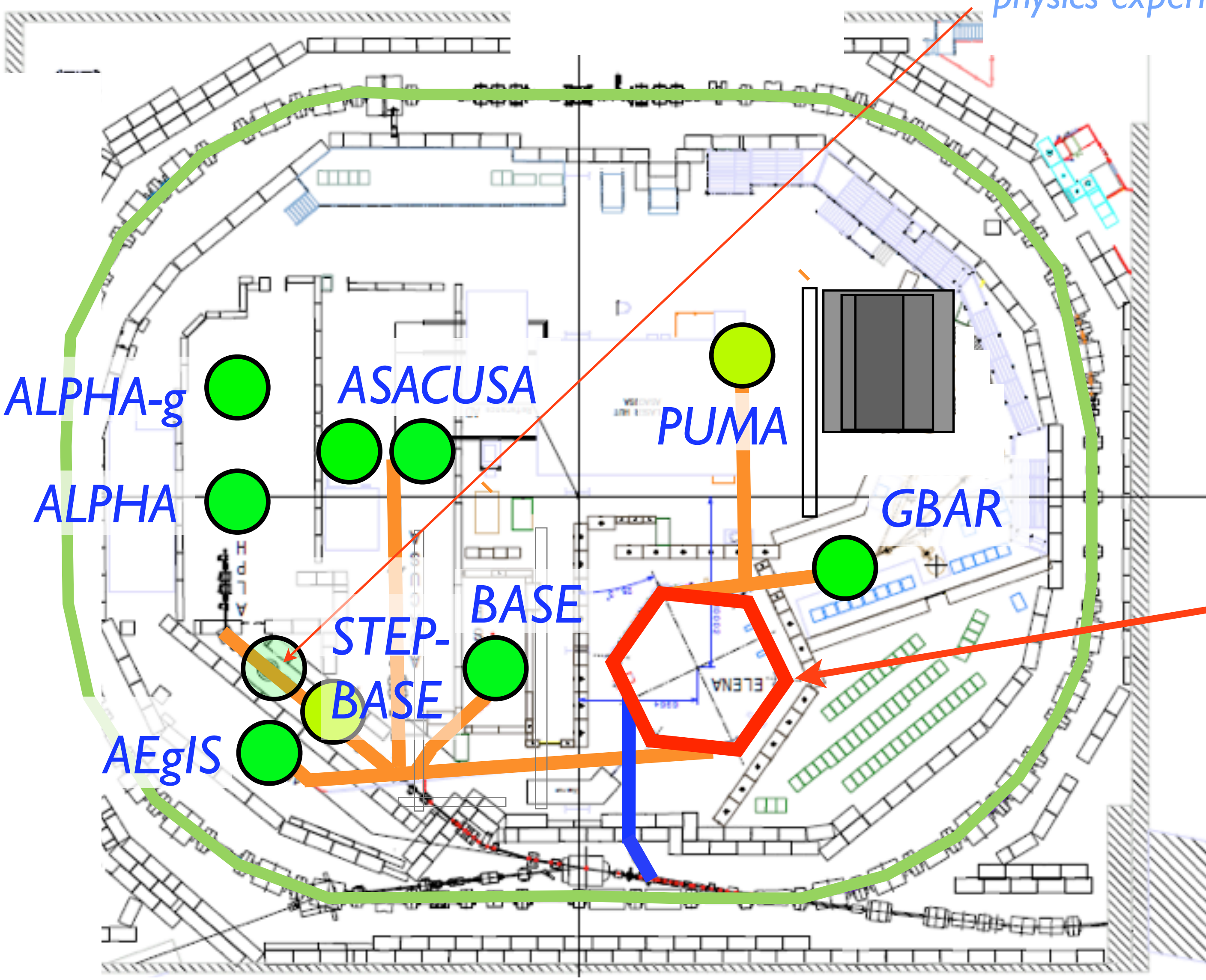
Antiproton Accumulator (AA), Antiproton Collector (AC) and low energy antiproton ring (LEAR):

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

AD start in 2000, ELENA commissioning in 2018: looking at another very active decade with antiprotons

overview of AD facility

space for future
(anti)atomic
physics experiments

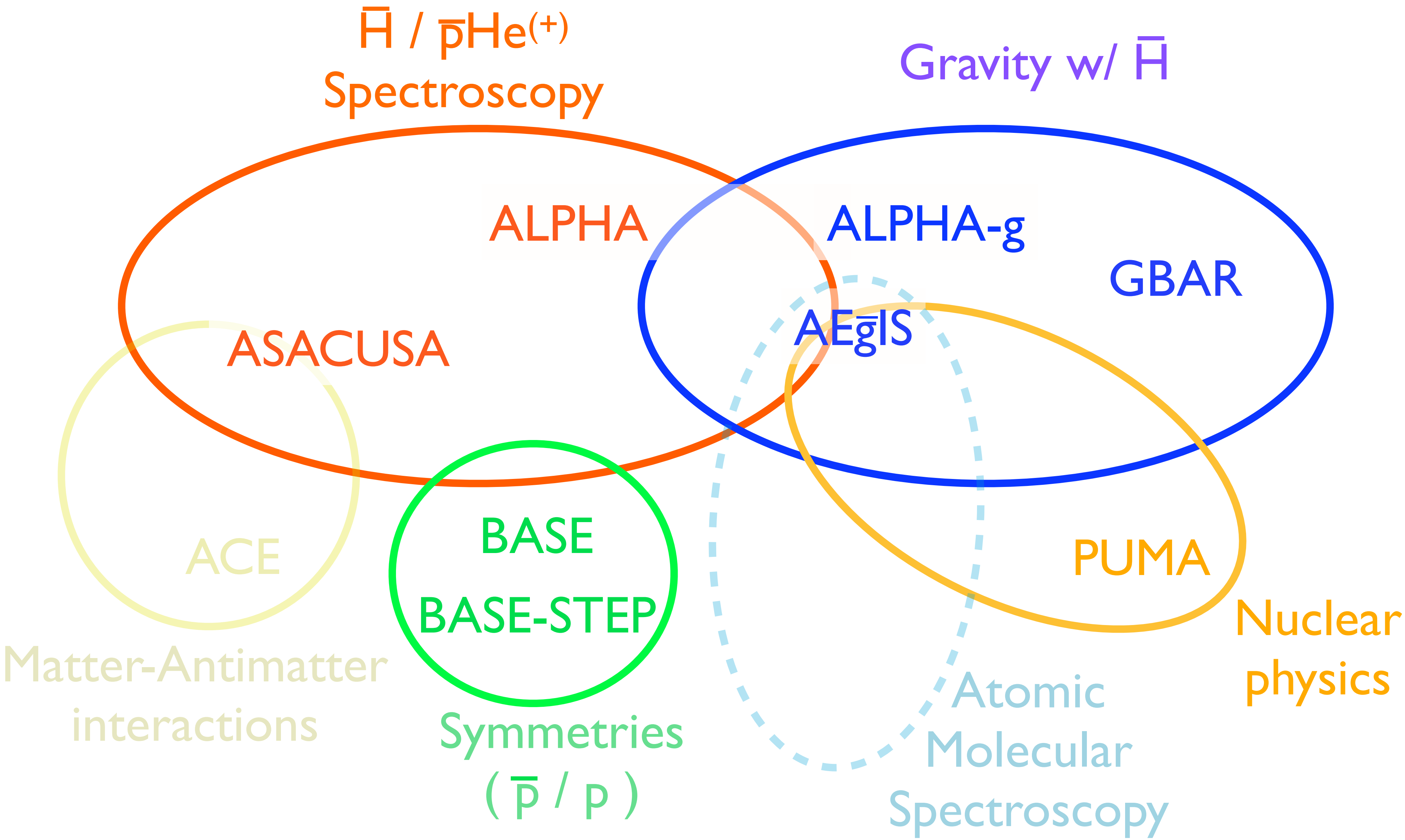


ELENA: extraction of antiprotons at 100 keV; trapping efficiency goes from ~1% at AD to O(100%);

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

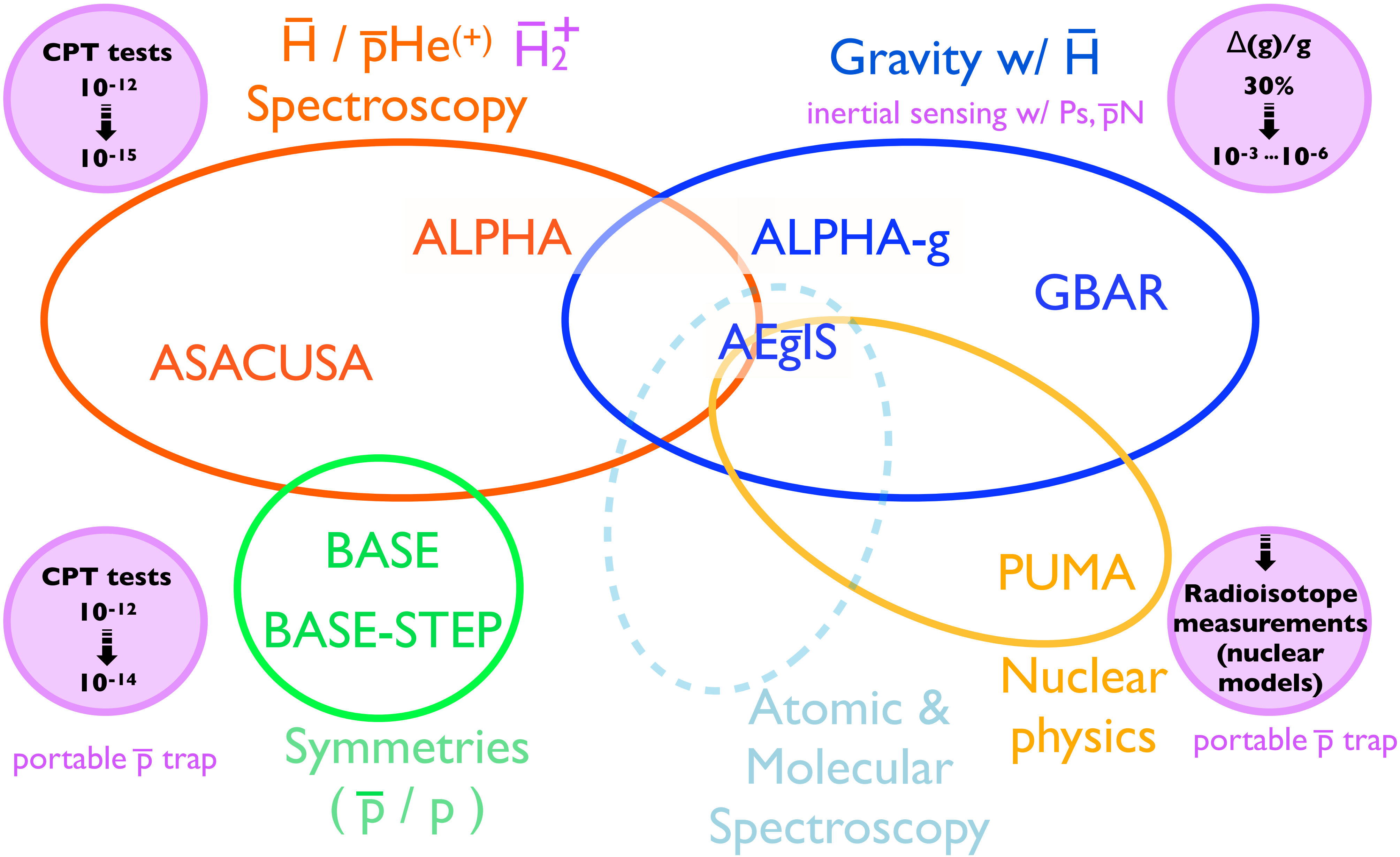
in operation since 2021

physics at the AD



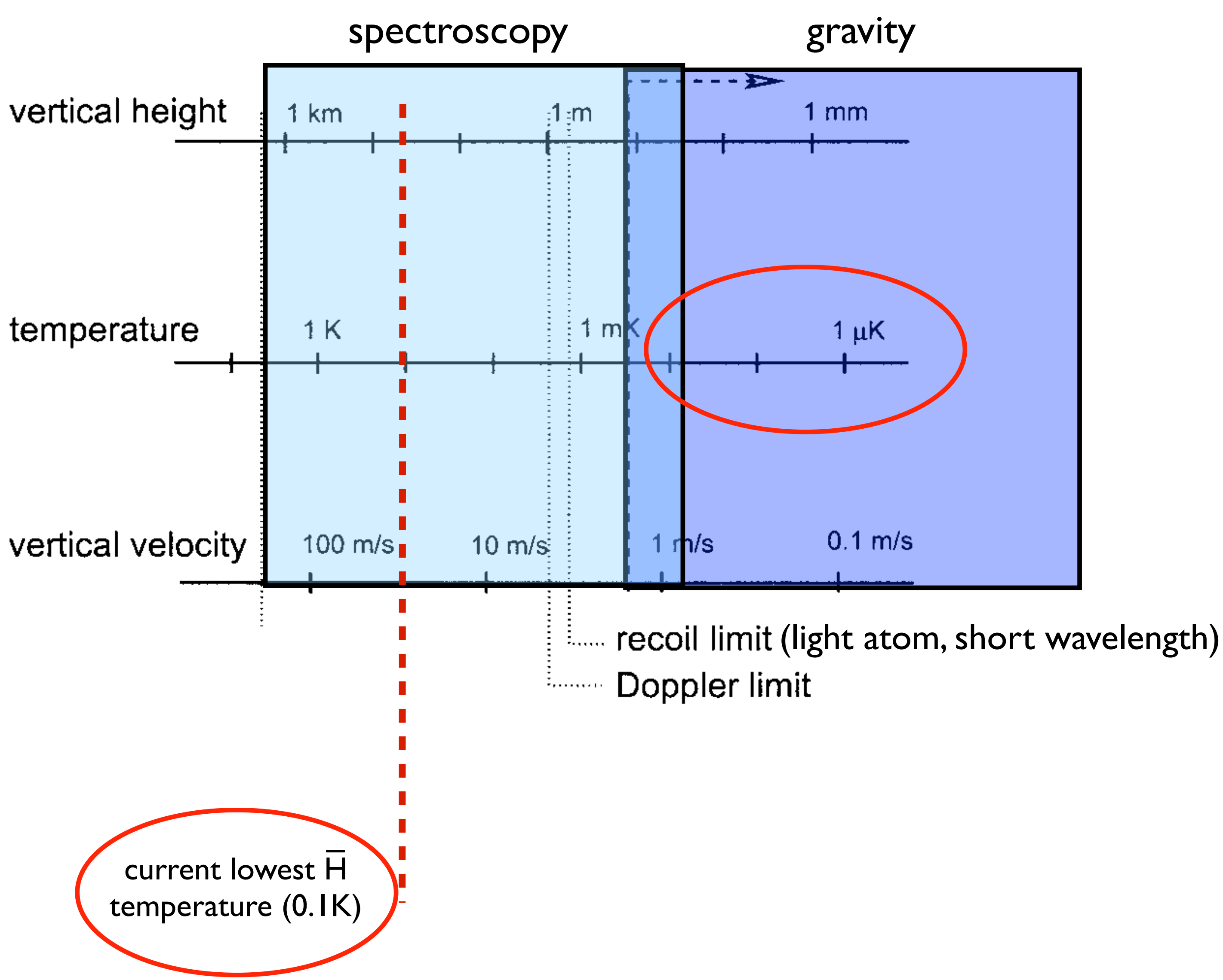
expanding physics reach by including nuclear, molecular physics

status and outlook for physics at the AD (next 10 years)



rapidly expanding physics reach (incl. nuclear, molecular physics, ...)

the importance of working at low temperature

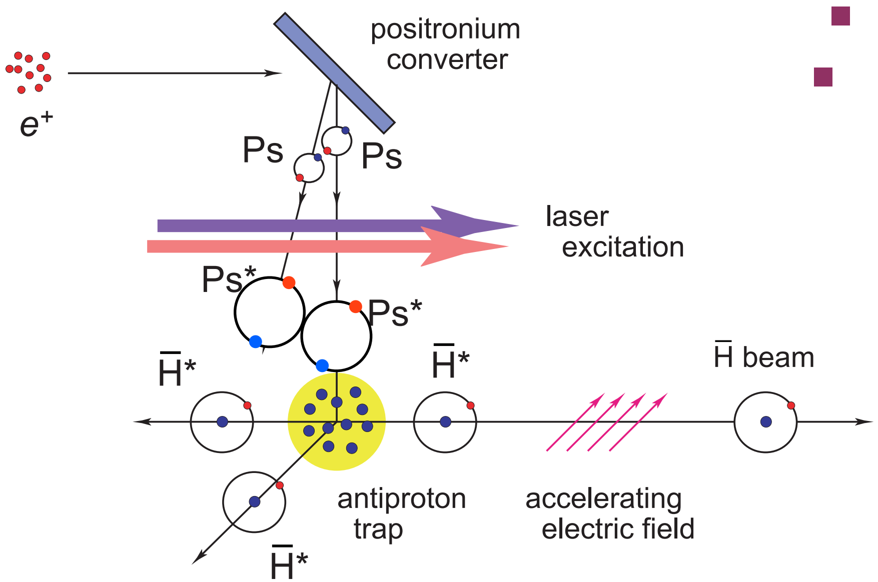


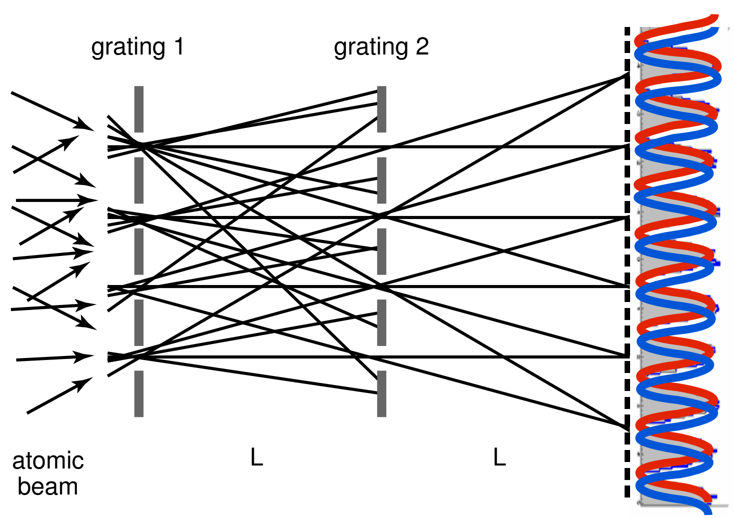
Schematic overview: AE$\bar{g}$IS (Antimatter Experiment: gravity, Interferometry, Spectroscopy)

Physics goals: measurement of the gravitational interaction between matter and antimatter, $\bar{H}$ spectroscopy, antiprotonic atoms (pp, pCs), Ps, ...

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

- 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 & $\sigma \approx a_0 n^4$ $\rightarrow$ $\bar{H}$ formation enhanced





pulsed production of $\bar{H}$*

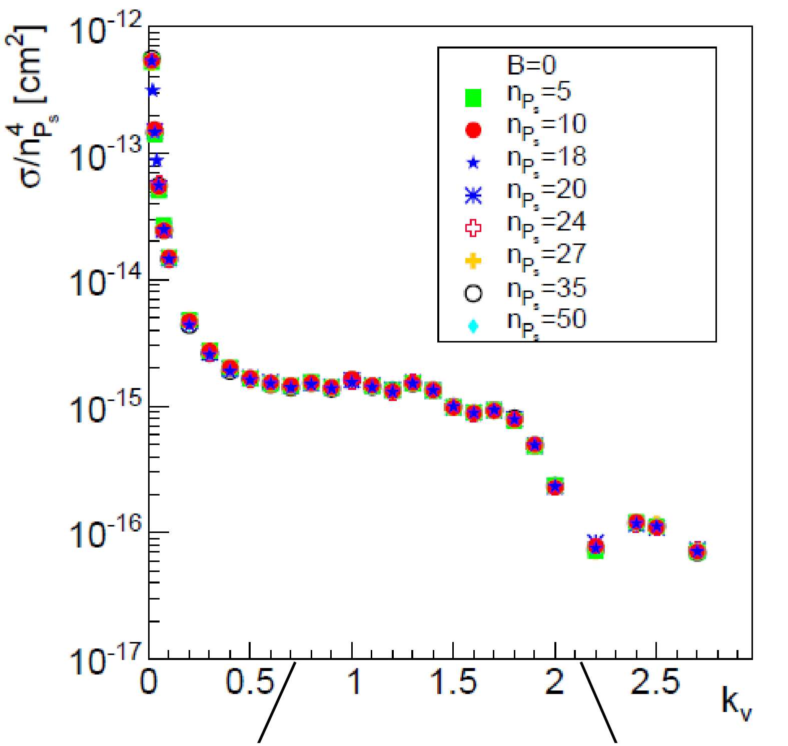
horizontal beam formation

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

why Rydberg systems ?

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)



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

FIG.2: Normalized cross section

DATA COMPARISON BETWEEN n=10 and n=50

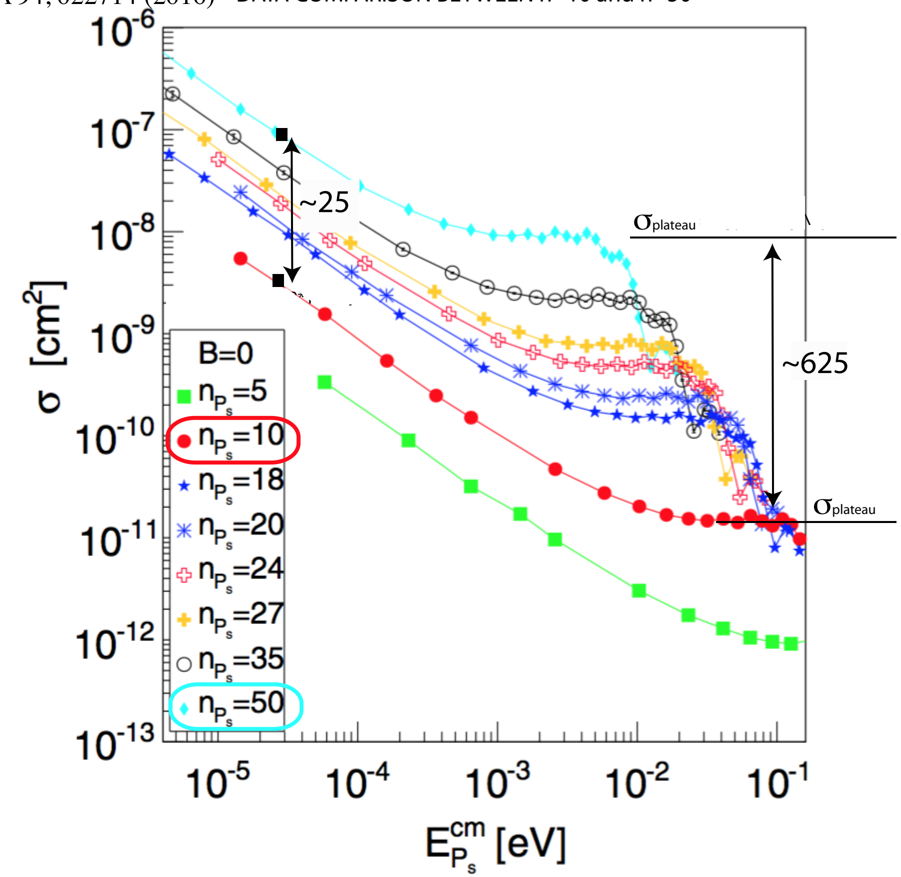
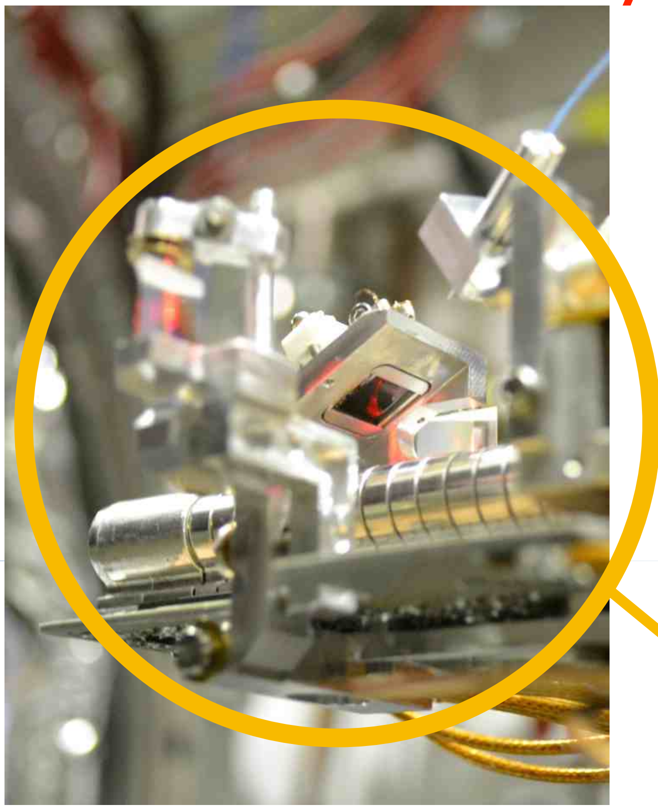
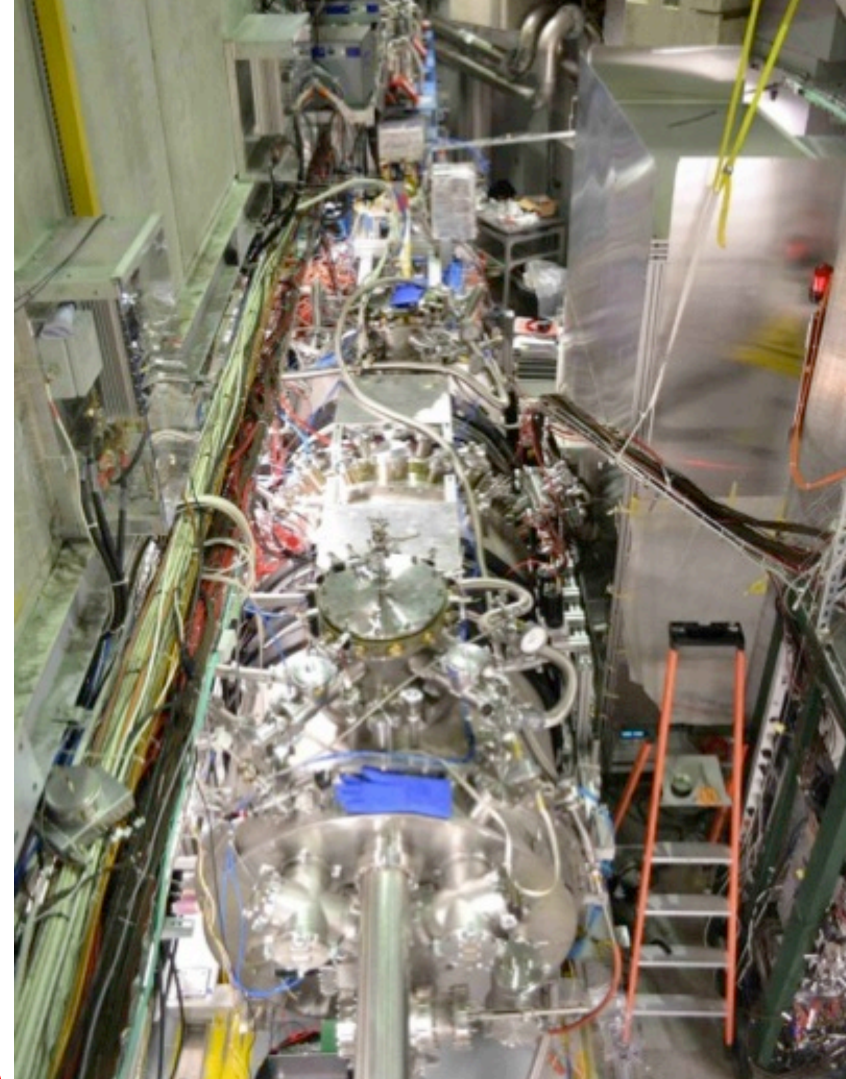
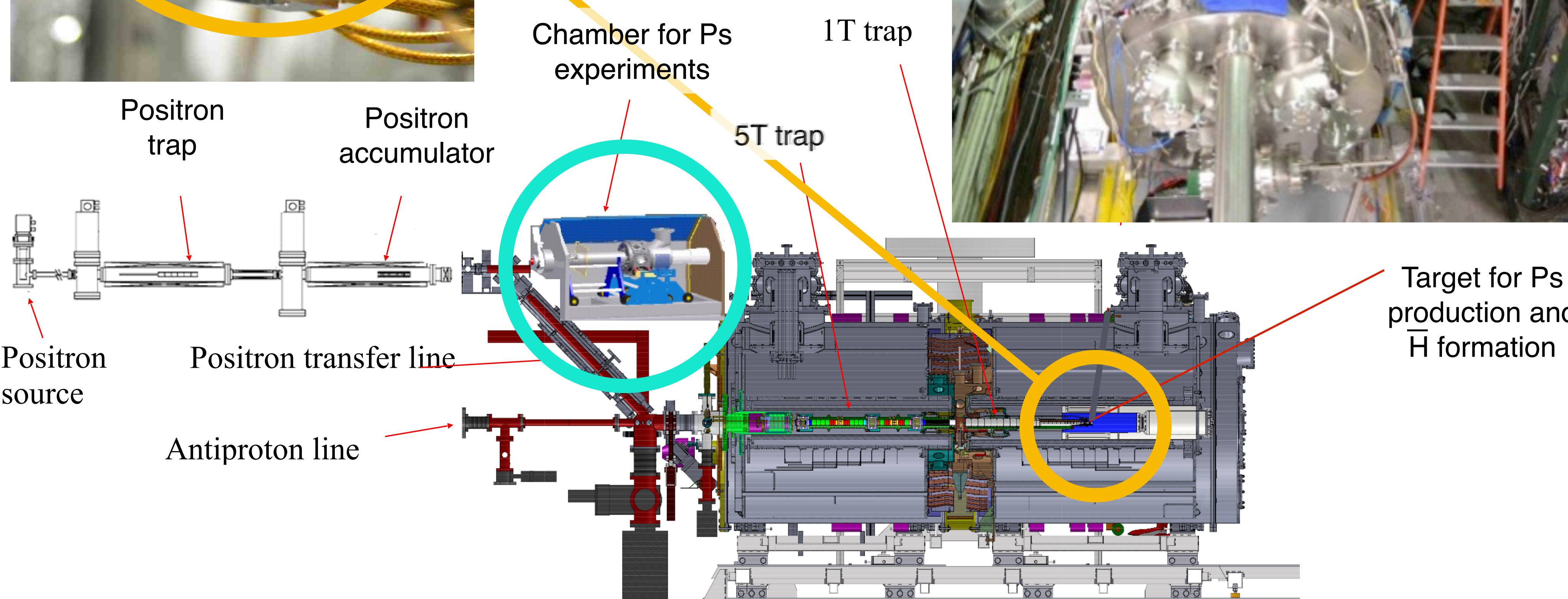


FIG. 3. Charge-exchange cross section σ as a function of the P_s center-of-mass energy. The plot shows the same points of Fig. 2. The lines simply connect the points to help the graphical interpretation.

AE$\bar{g}$IS experiment



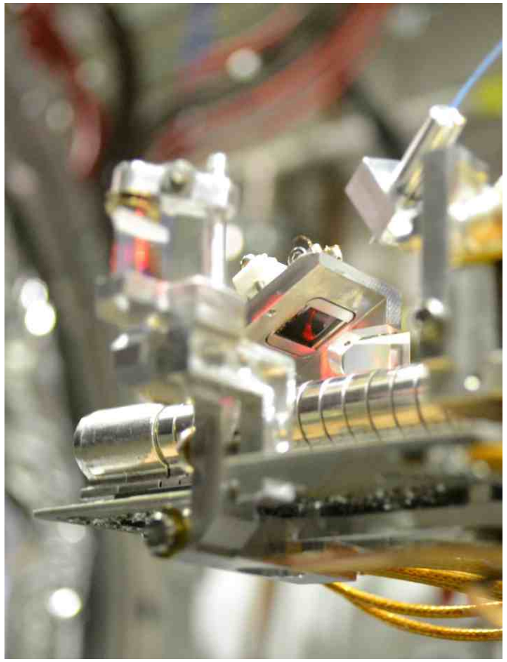


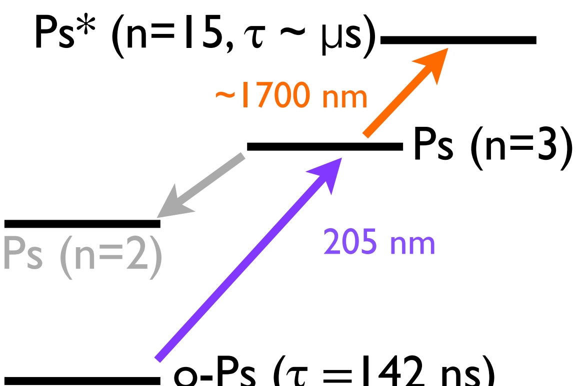


Challenges:

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

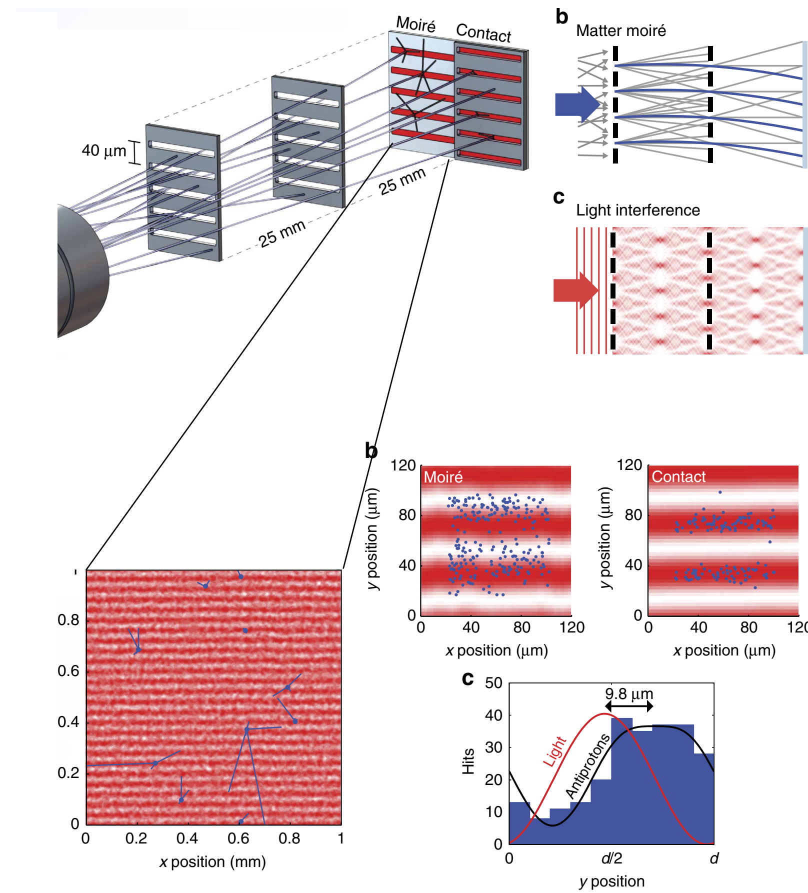
La^- Warring et al, PRL 102 (2009) 043001 E. Jordan et al., PRL 115 (2015) 113001

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

Note: ***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:

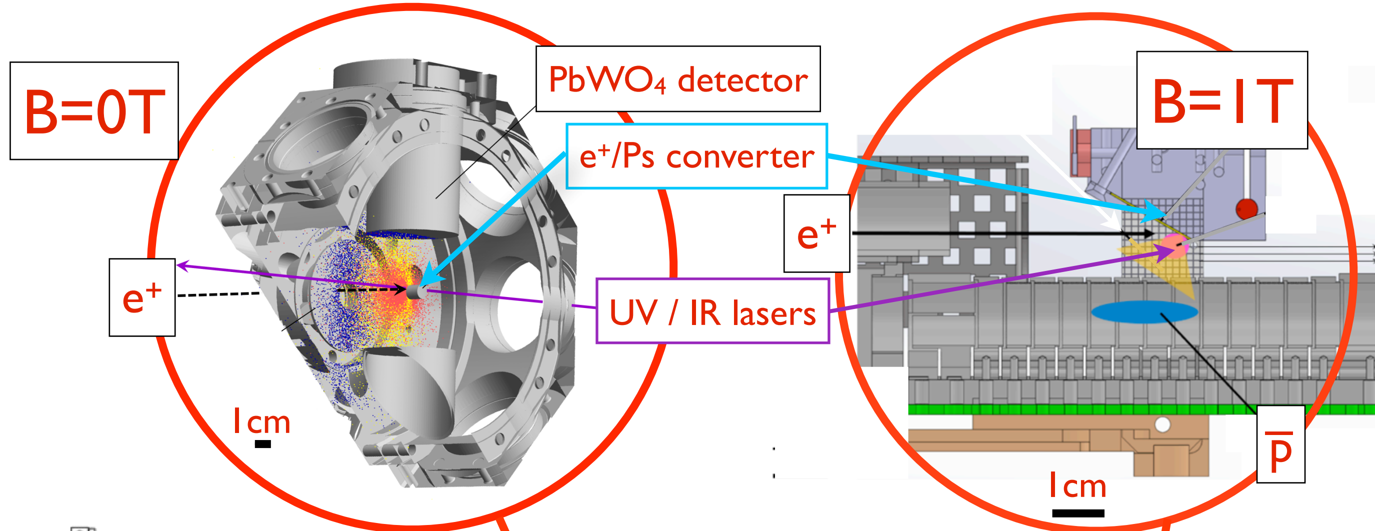


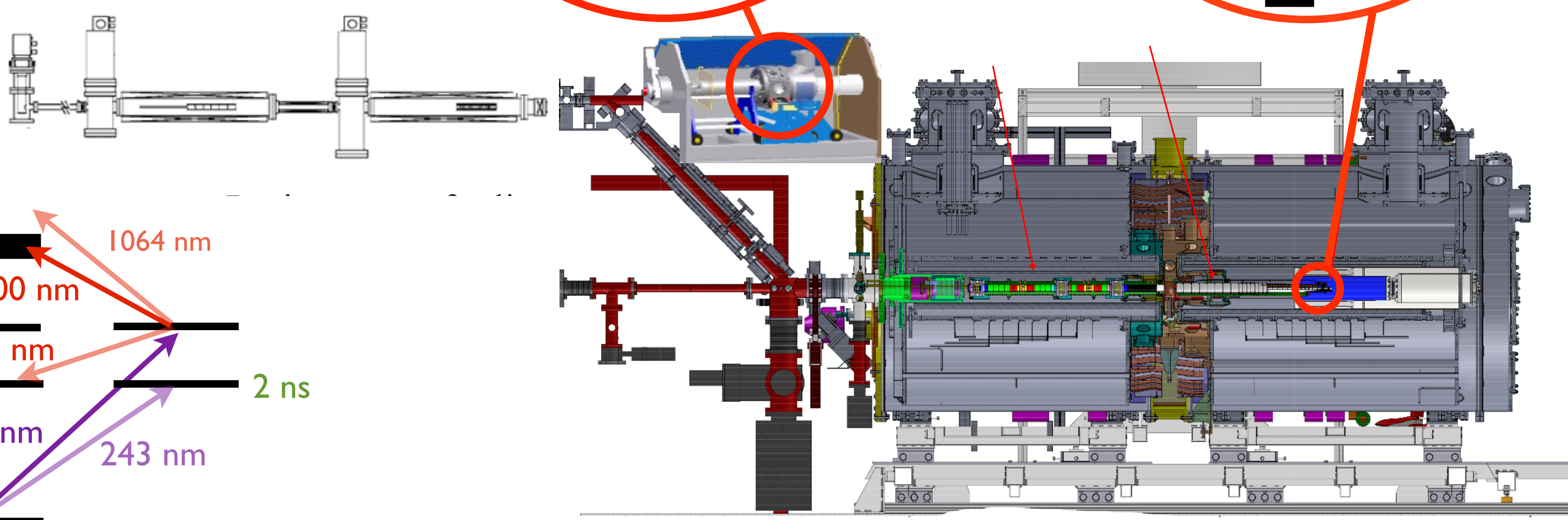
principle established with $\bar{p}$; displacement of $\bar{p}$ annihilation vertices (blue dots) measured relative to light (red)

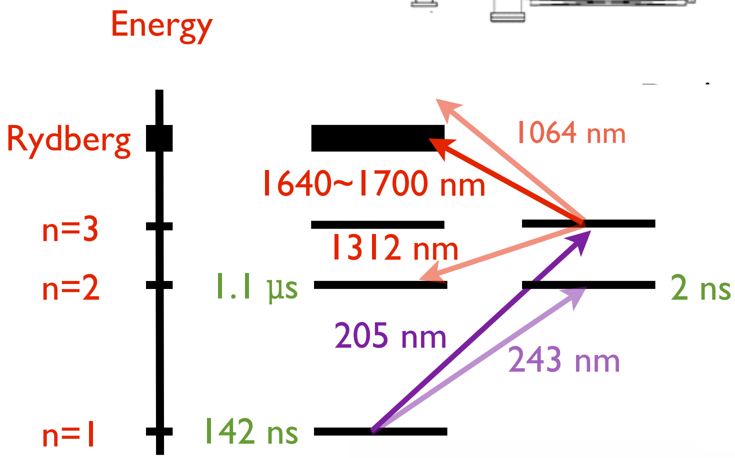
S. Aghion et al., "A moiré deflectometer for antimatter", Nature Communications 5 (2014) 4538

and many more...

Positronium







Efficient Rydberg positronium production → pulsed $\bar{H}$ production

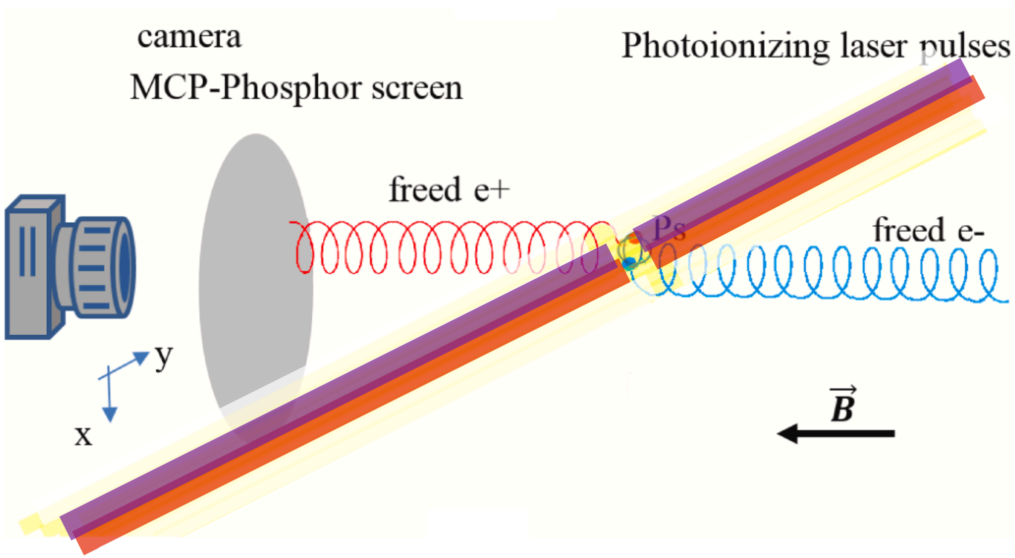
Efficient 2^3S positronium production by stimulated decay from the 3^3P level → x3 over spontaneous decay

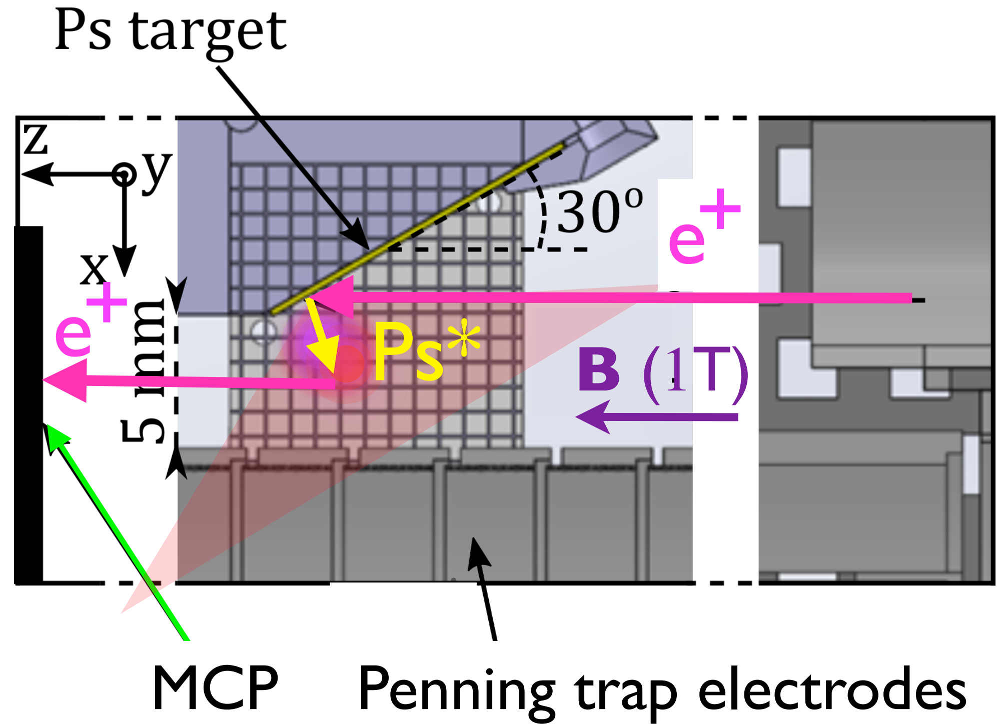
Velocity selected production of 2^3S metastable positronium → beam of meta-stable Ps

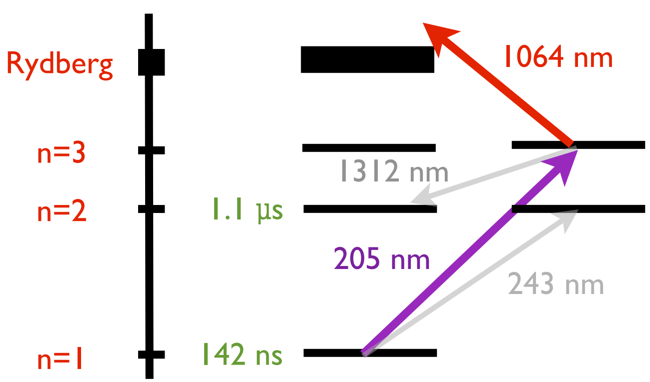
ongoing work on: further manipulations, enhanced 2^3S production, formation of "intense" metastable Ps or Rydberg Ps beam for inertial sensing, high resolution state-selective imaging, test bed for interferometry, spectroscopy, ...

Ps* imaging

B=1T

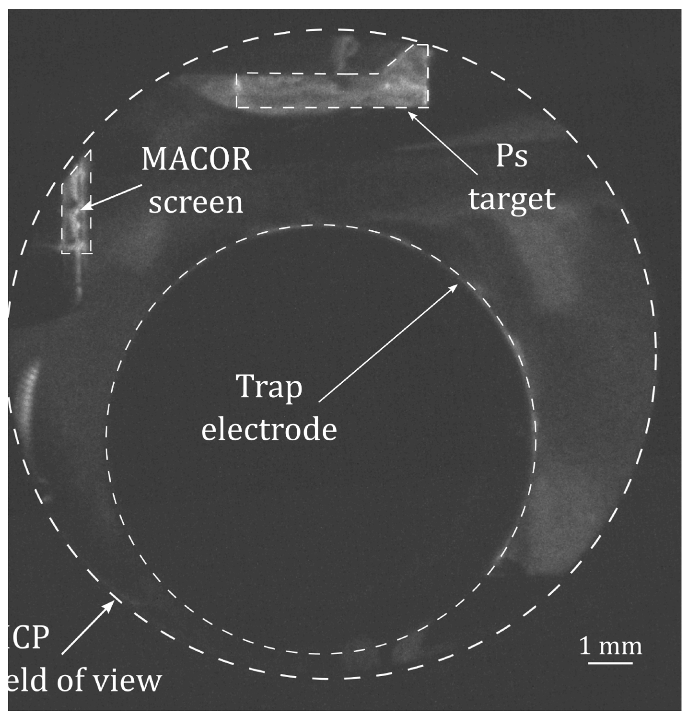


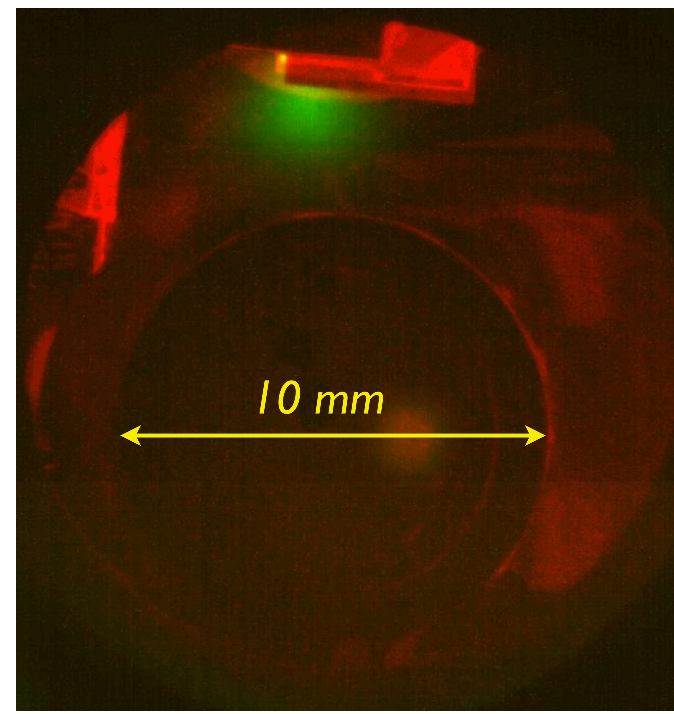




1064 nm : photoionization

1640~1700 nm : velocity-dependent self-ionization (motional Stark effect)



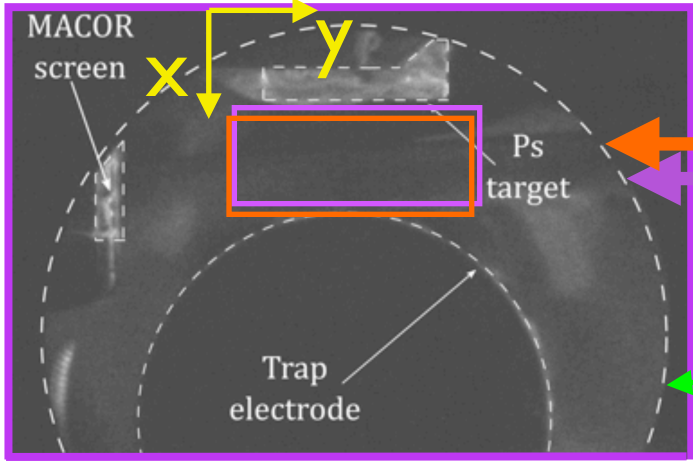


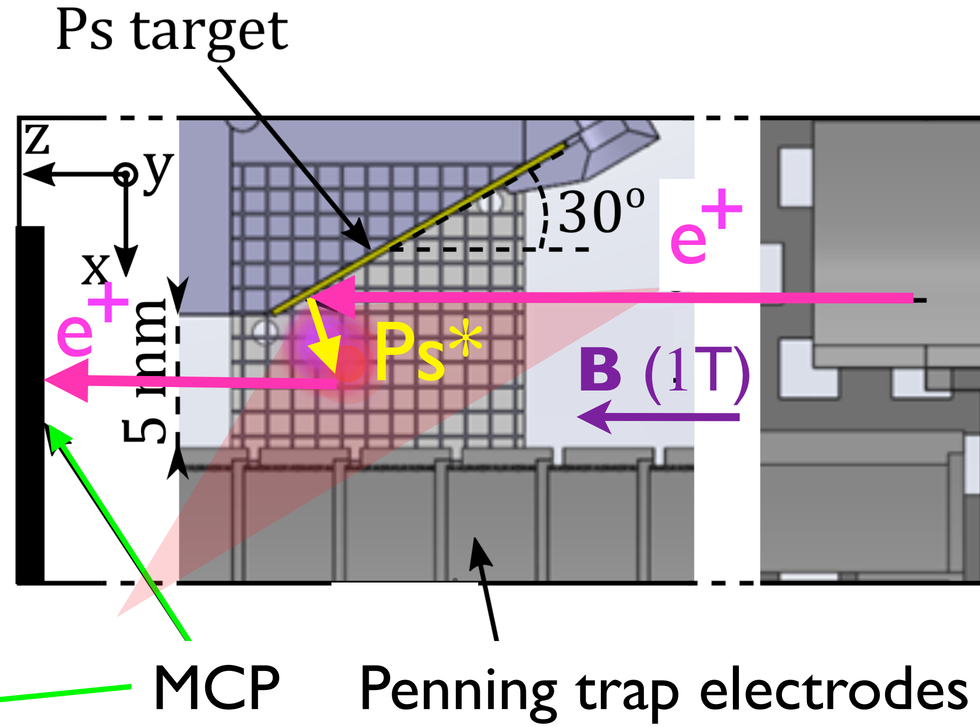
detection of:
electrons positrons

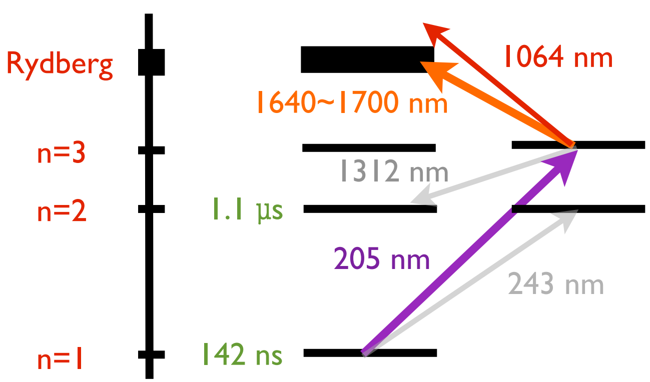
Ps* velocimetry

B=1T

Scan 1→3 laser timing, frequency







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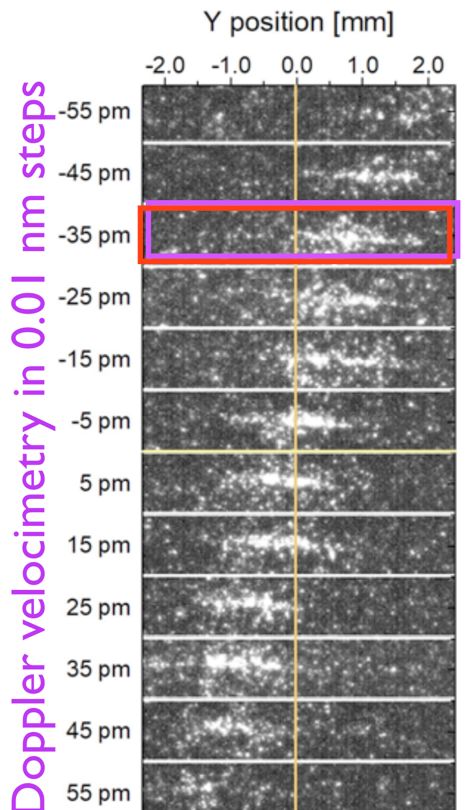
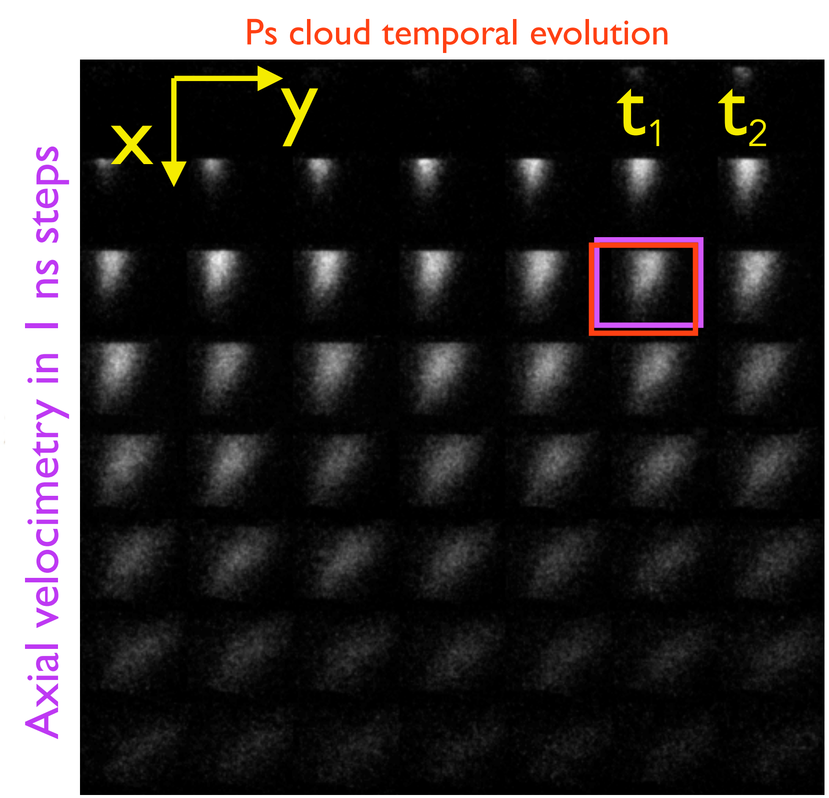
1640~1700 nm : velocity-dependent self-ionization (motional Stark effect)



NIM B, Volume 457, 15 October 2019, 44-48



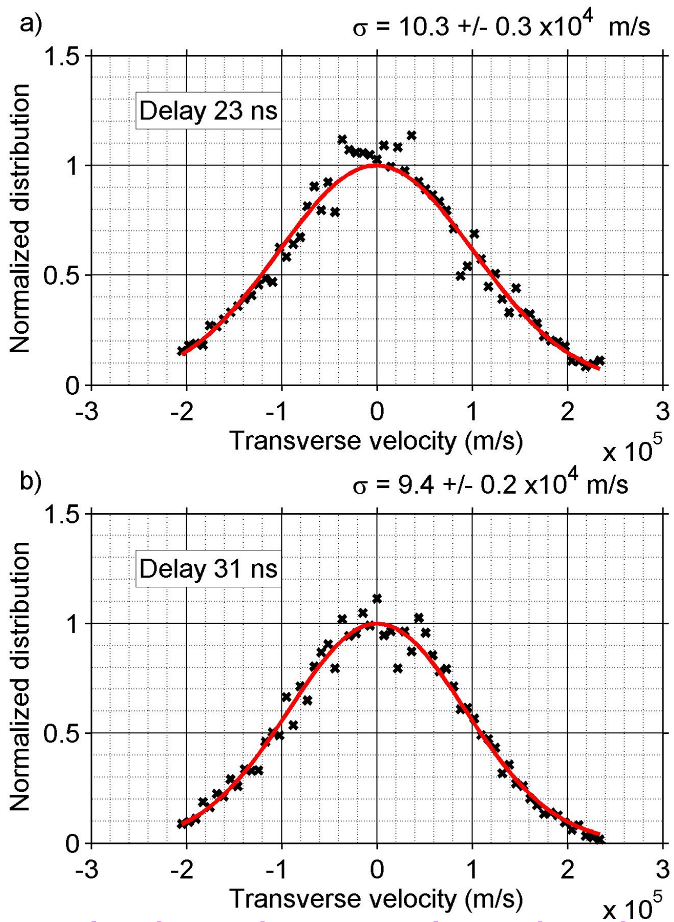
Ps* velocimetry

B=1T

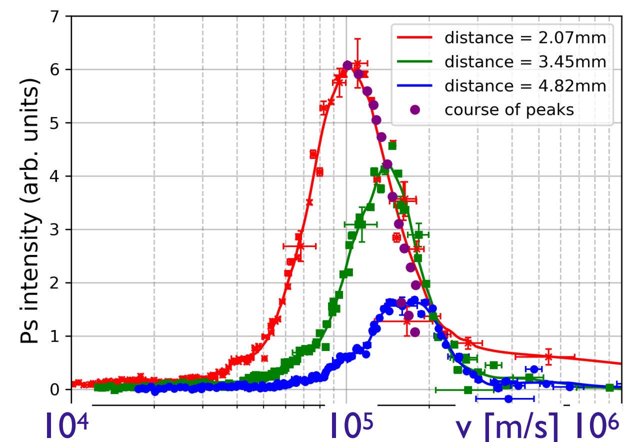
transverse velocity (σ ~ 1 x 10 ^{5} m/s)

axial velocity ~ 1.6 x 10 ^{5} m/s

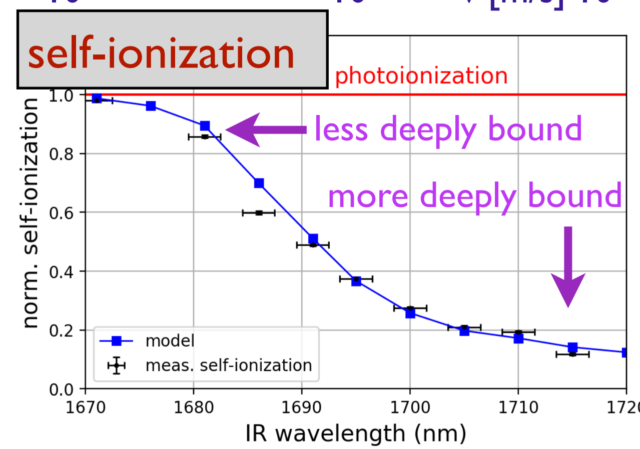
probed by UV Doppler velocimetry



Doppler broadening ⊗ laser bandwidth



probed by laser timing



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

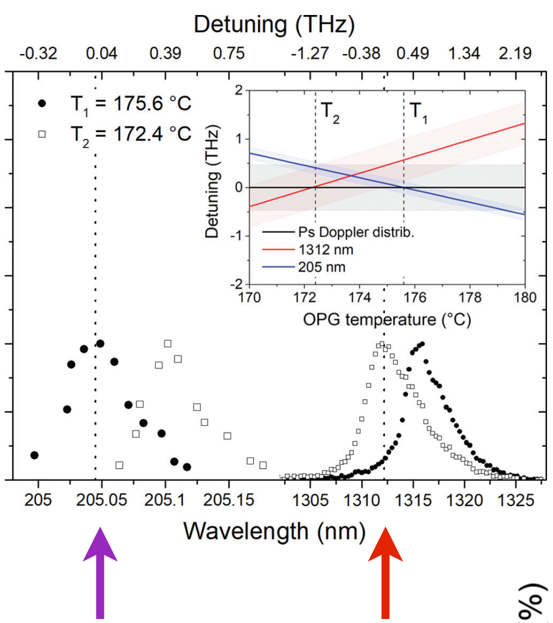
stimulated formation of metastable 2^3S Ps*

B=0T

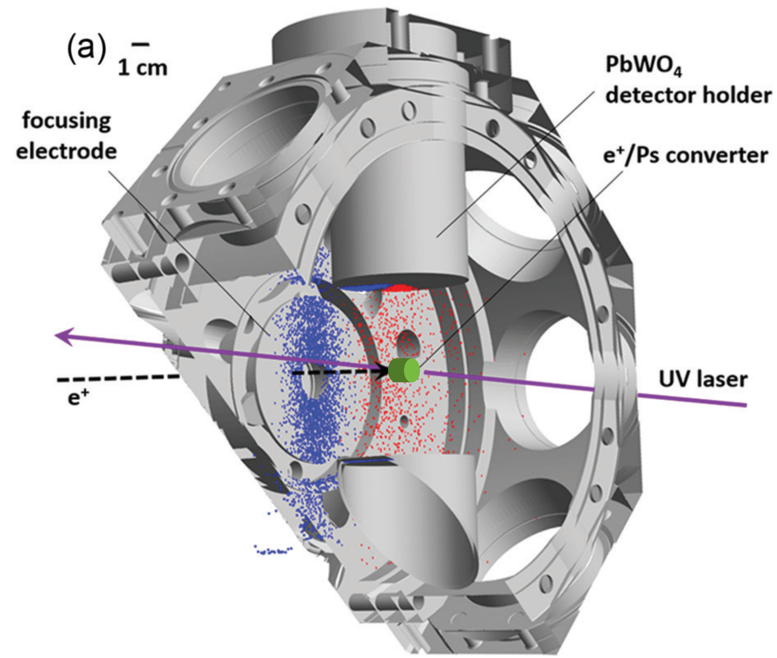
UV excitation: $1\,^3S \rightarrow 3\,^3P$

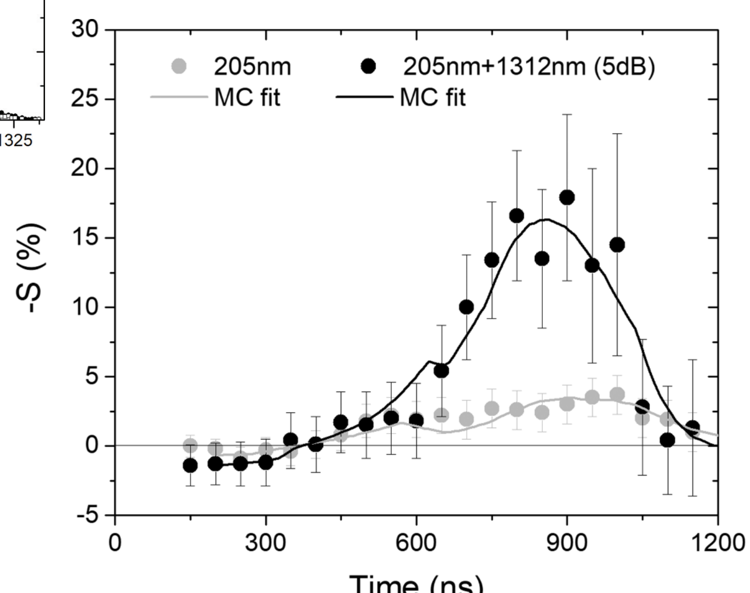
stimulated decay: $3\,^3P \rightarrow 2\,^3S$ (29.7±1.9)%

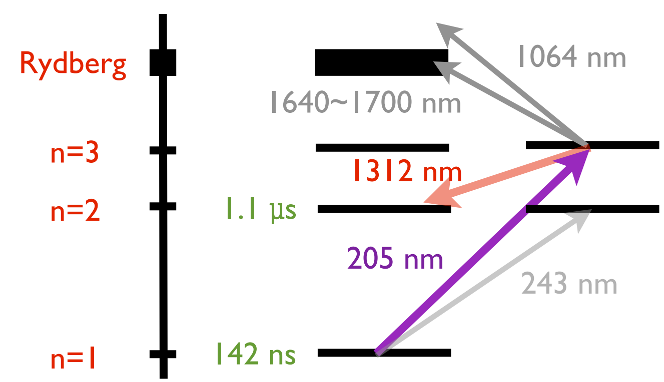
spontaneous decay: $3\,^3P \rightarrow 2\,^3S$ (9.7±2.7)%



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

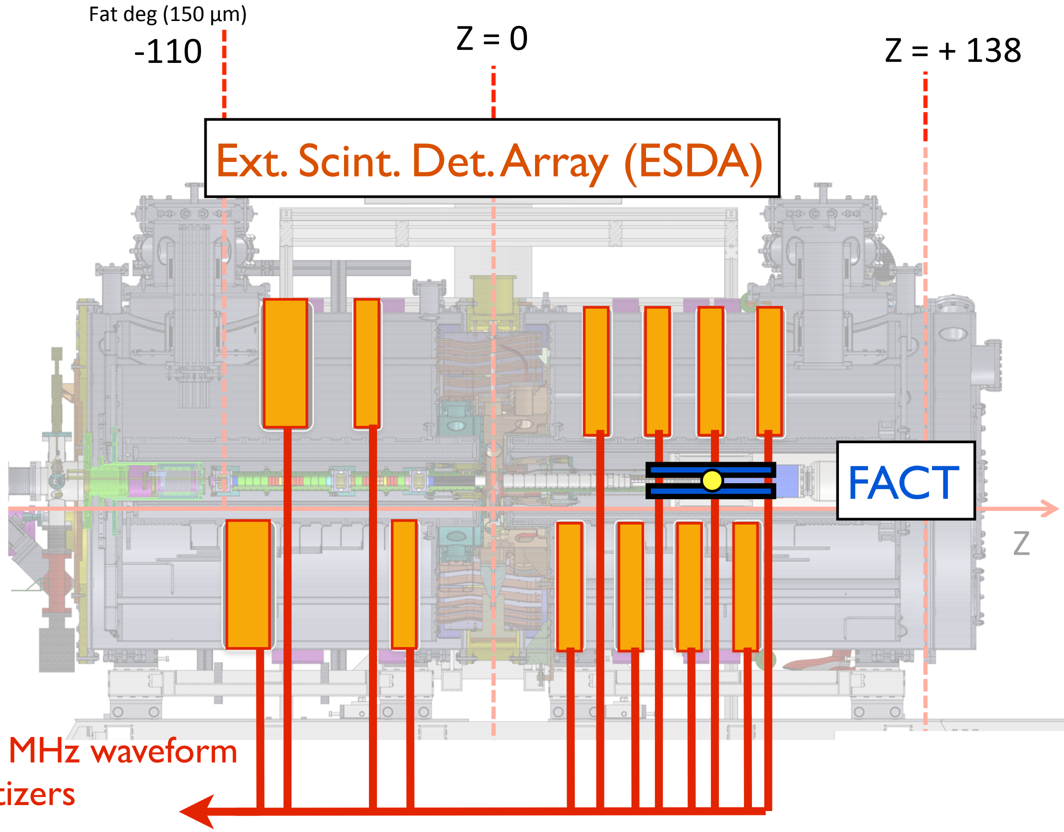
Phys. Rev. A 100, 063414 – Published 1 Dec 2019

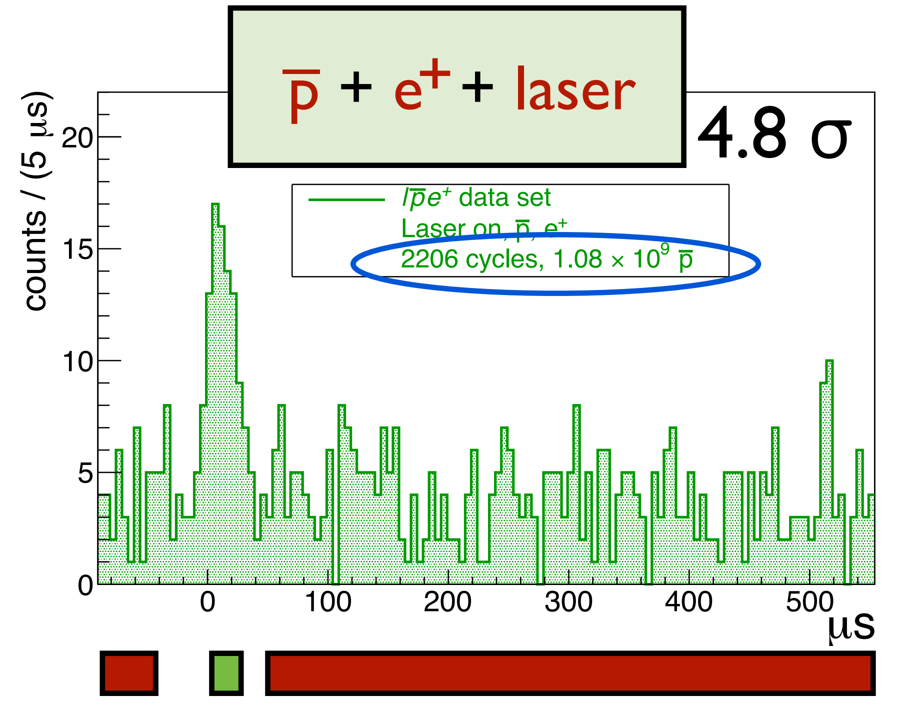
Pulsed production of $\bar{H}$ in 2018

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

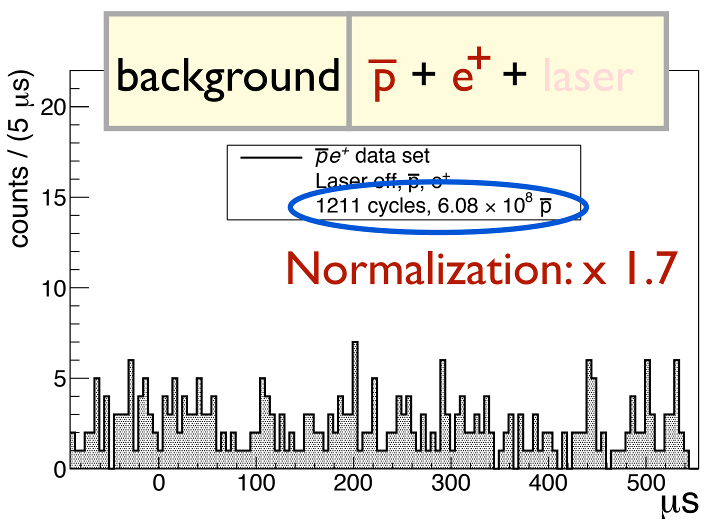
$\bar{H}$ detectors: scintillating slab array (mips), FACT (vertex tracker)

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

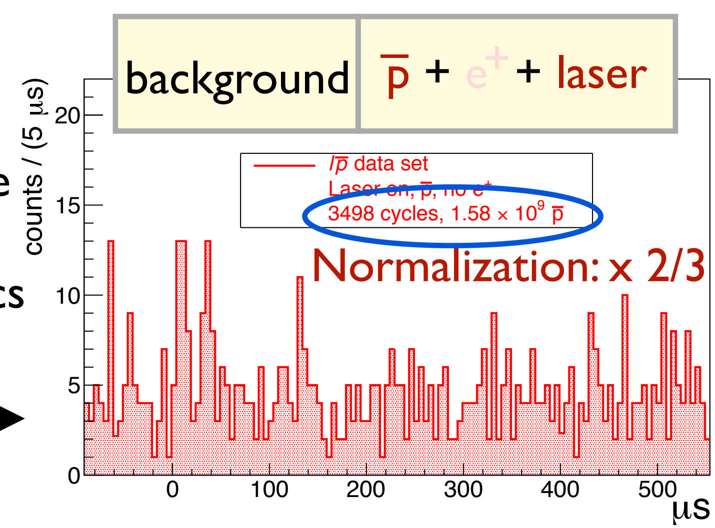




excess in signal region [1, 26 µs]



long time average rate compatible with cosmics rate



= 0.05 $\bar{H}$ / cycle

in 2022:

- rate x 1000
- pulsed beam

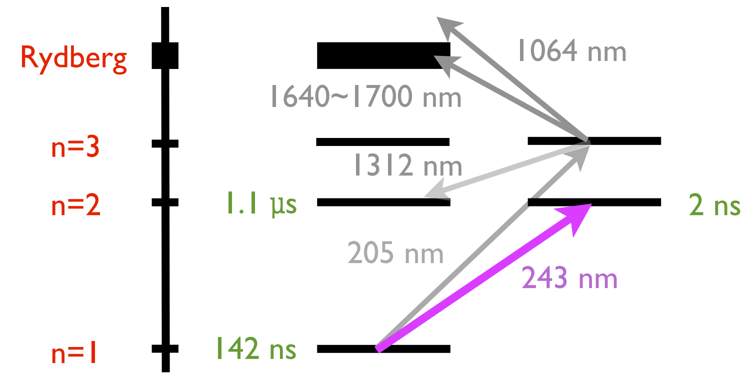
towards (pulsed formation of) matter-antimatter Rydberg systems ...

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

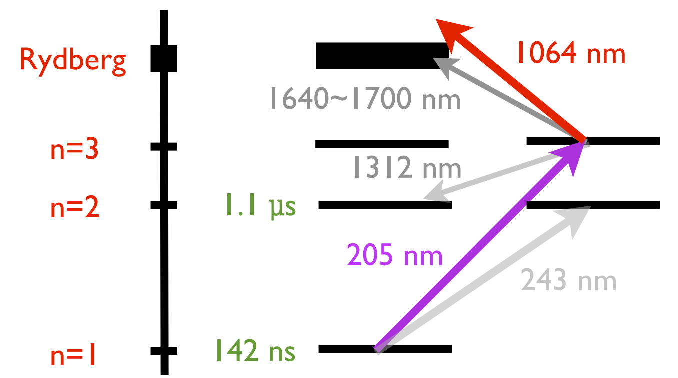
laser-cooling of Ps

two independent laser systems are available ➔ combine them!

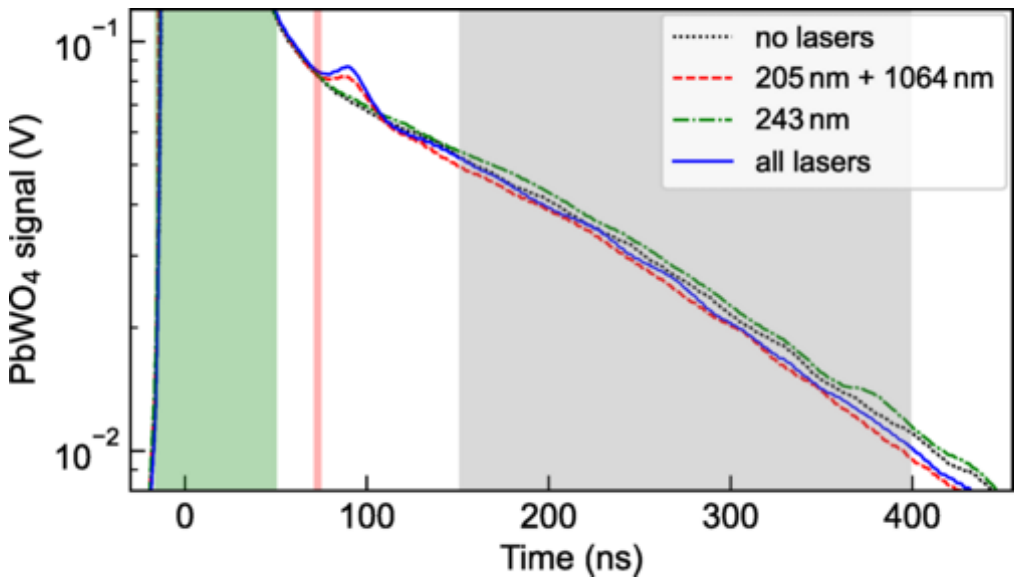
① interact laser pulse @ 243 nm (pulse length 100 ns)

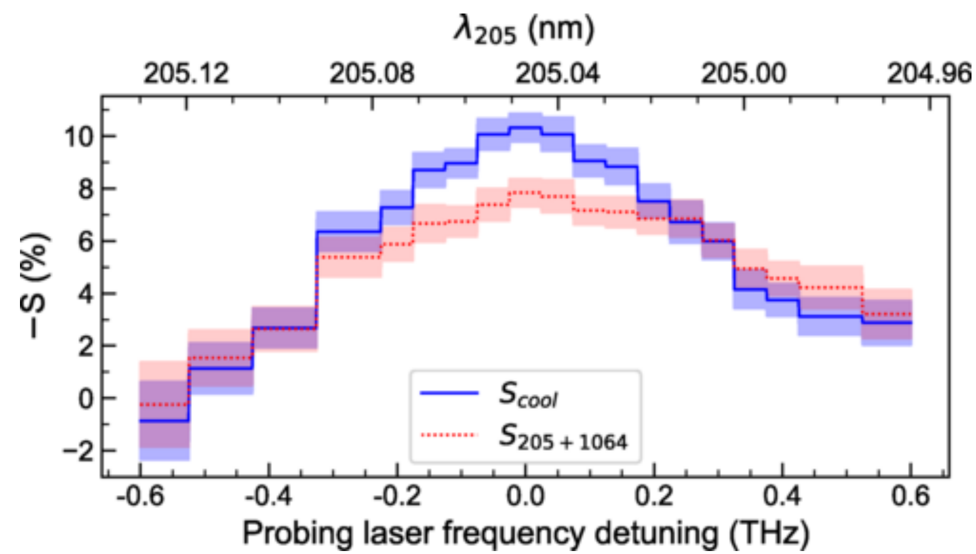


② after cooling, Ps Doppler-profile to extract velocity distributions (transverse, longitudinal)



laser-cooling of Ps





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

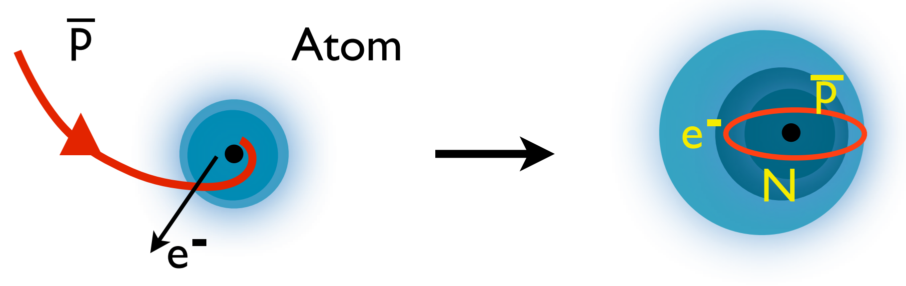
paper ~~submitted~~... and new measurements planned with improved system

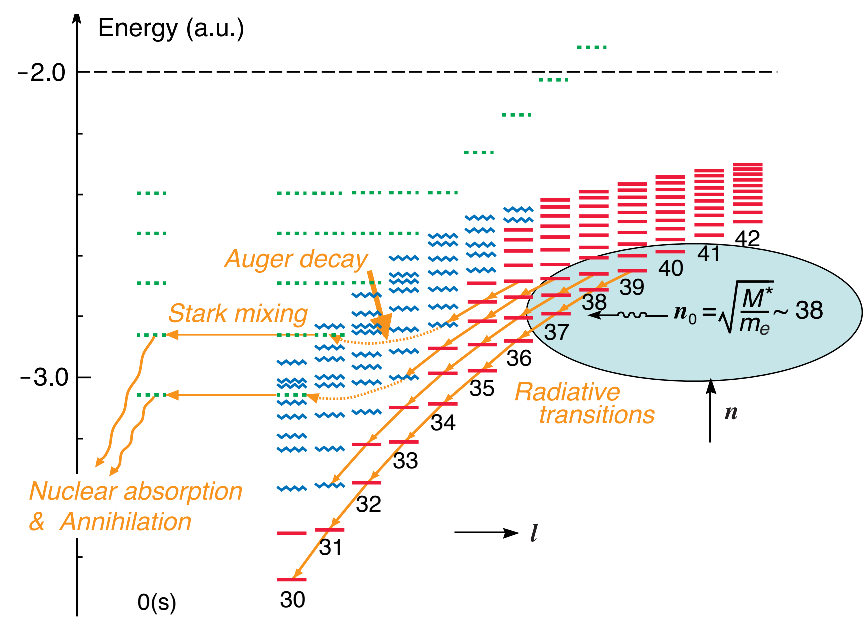
laser-cooling of Ps ➔ possible enhancement in $\overline{\mathrm{H}}$ production rate, Ps beam

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

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

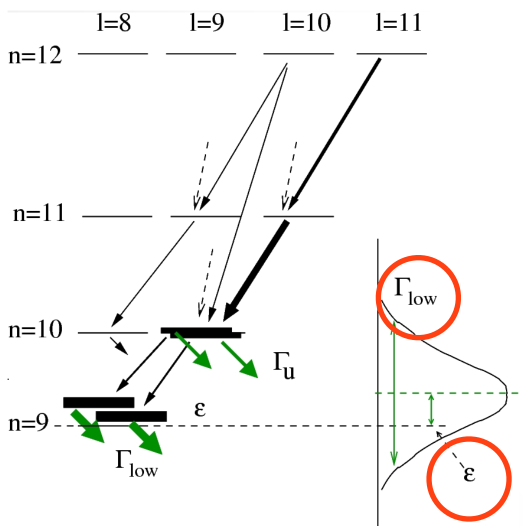
X-rays in cascade of antiprotonic atoms

1

Correlate measurements of:

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

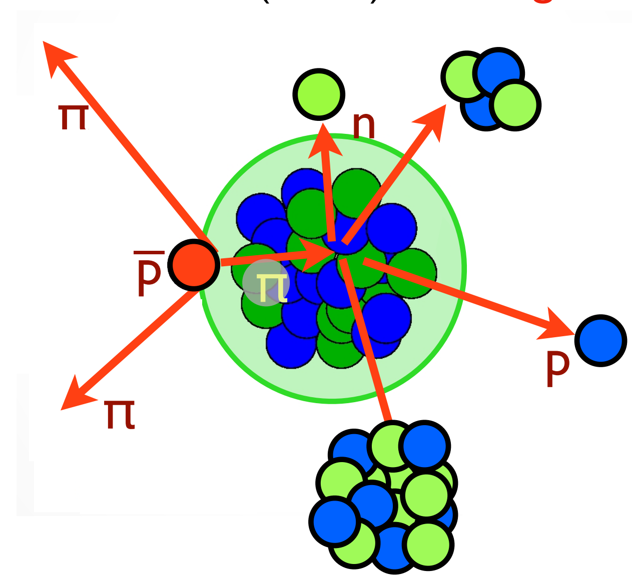
$\bar{p}Pb^{+}$



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 : heavier antiprotonic Rydberg atoms

- established method: capture in gas/solid; Rydberg atom formation; 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. Temperature $\bar{p}X^{(+)*}$ ~ 10 K

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

→ *spectroscopy* of Rydberg antiprotonic atoms

→ clean cascade (vacuum → no Stark mixing)

→ controlled annihilation (à la ASACUSA $\bar{p}$He)

→ nuclear fragments highly charged, trappable

AEḡIS : an improved production method for p̄-atoms

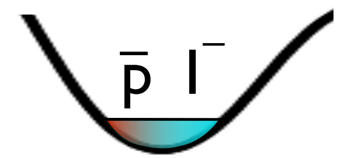
Antiprotonic atoms ⟶ novel Highly Charged Ionic systems

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

***multi-step process that builds on existing techniques* (Iodine source from Torun)**

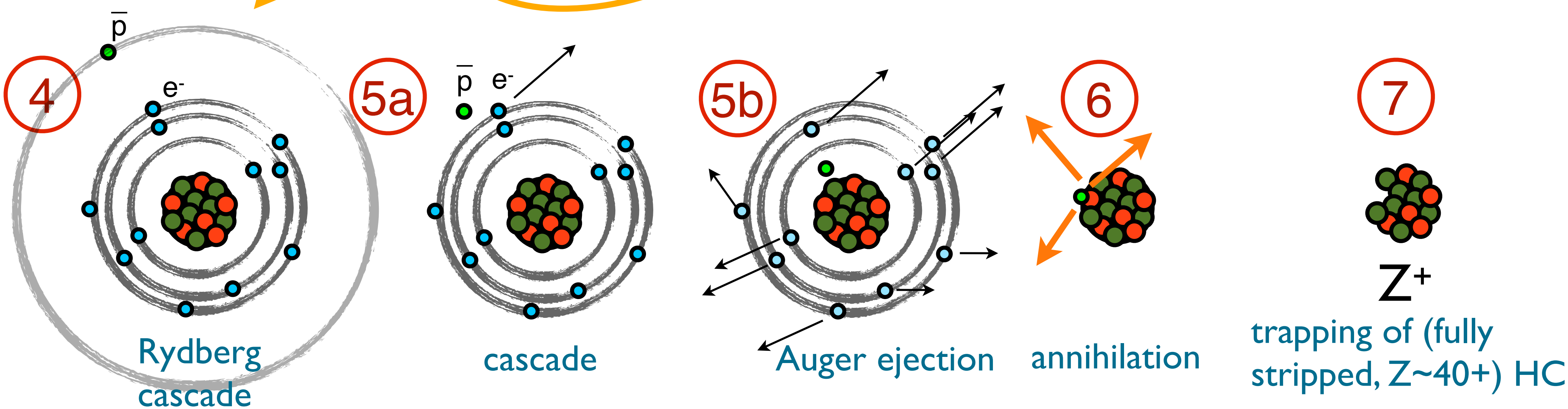
1 formation and capture of HCI

1 photo-detachment: $I^- \rightarrow I^0 + e^-$ (γ_1)



2_{opt} Rydberg excitation: $I^0 \rightarrow I^*$ ($\gamma_2 + \gamma_3$)

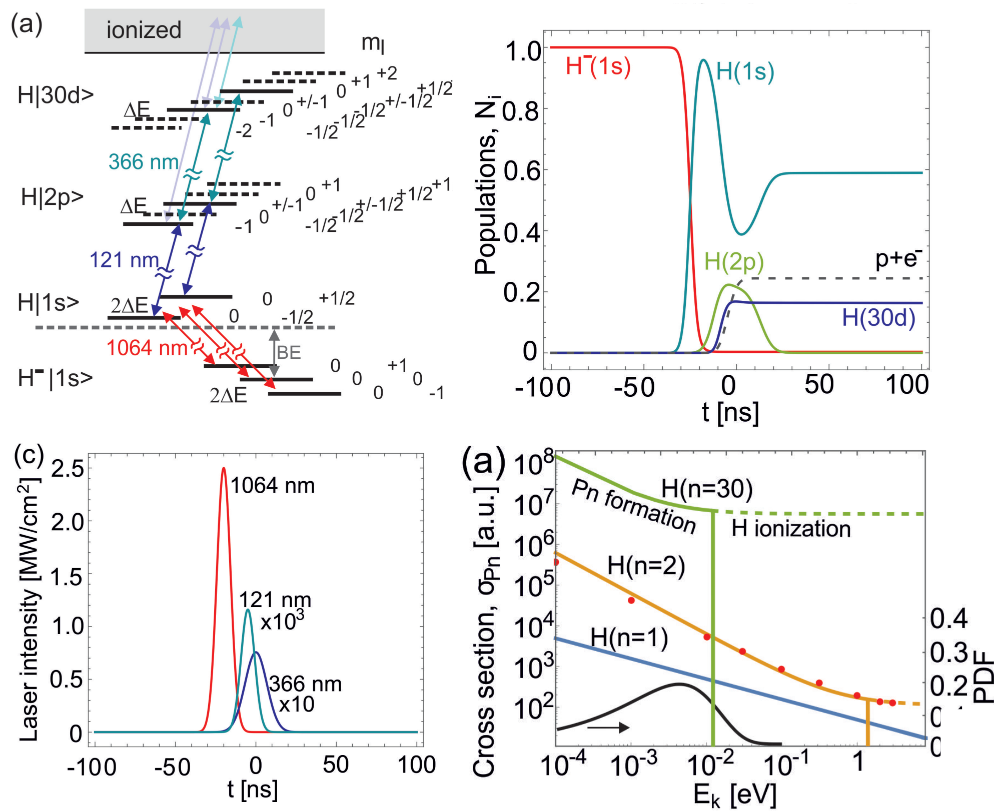
3 Charge exchange: $\bar{p} + I^* \rightarrow \bar{p}I^{+*} + e^-$ $(\bar{p} + Ps^* \rightarrow \bar{p}e^{+*} + e^-)$

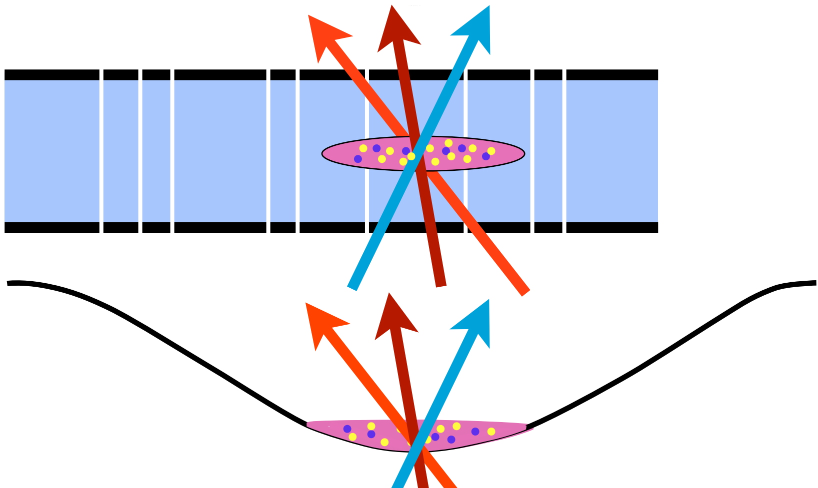


AE$\bar{g}$IS : an improved $\bar{p}p^*$ (and $\bar{p}d^*$) production method

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





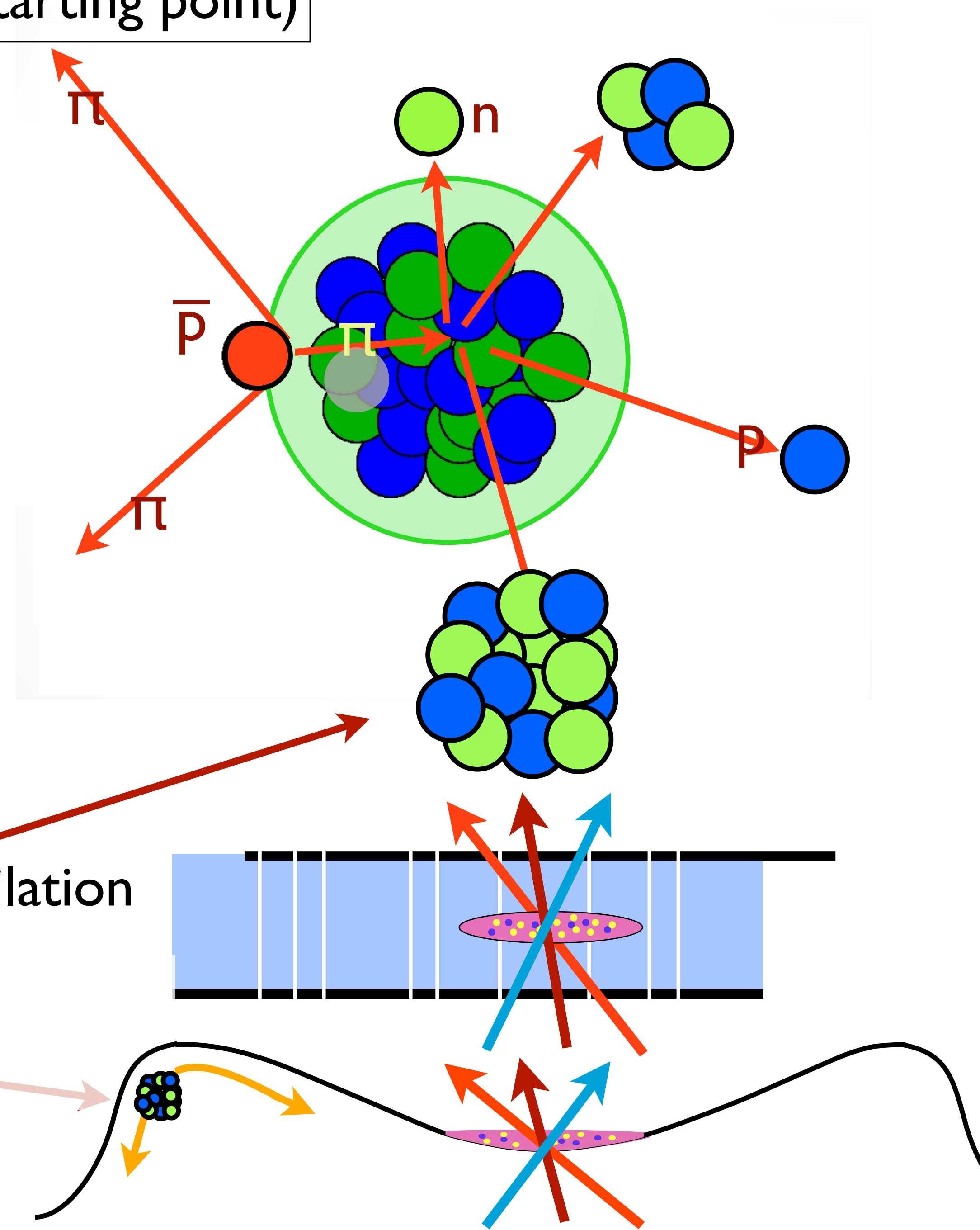
AE$\bar{g}$IS : a novel radioisotope production method

(using Rb instead of I as an example starting point)

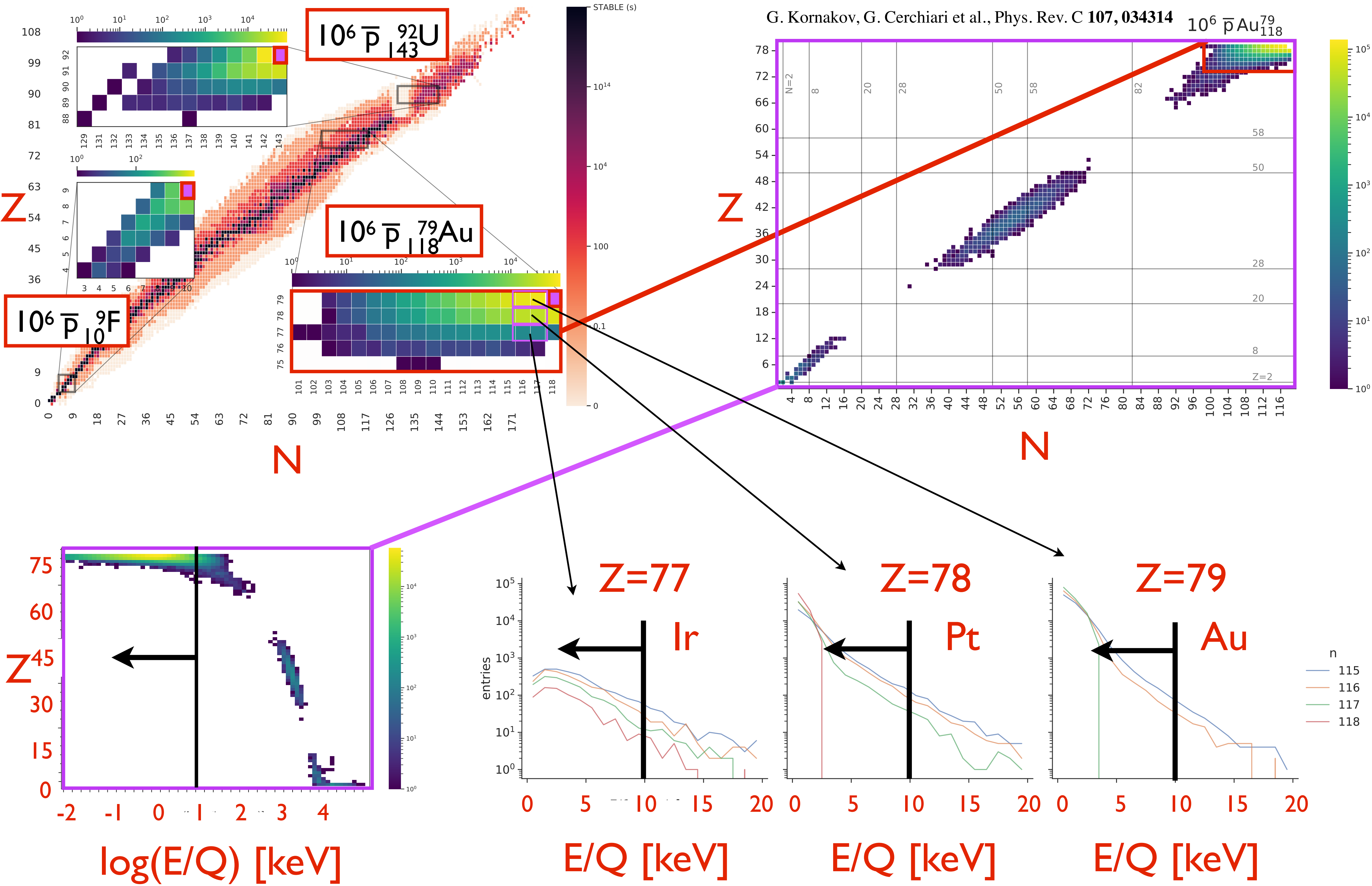
G. Kornakov, G. Cerchiari et al., Phys. Rev. C 107, 034314 (2023)

- co-trap Rb^- and $\bar{p}$ in a Penning trap (use stable $^{37}_{85}$Rb)
- photo-ionize Rb^-
- laser-excite Rb $\xrightarrow[2\gamma]{}$ Rb*(30)
- charge-exchange reaction:
  $Rb^*(30) + \bar{p} \rightarrow \bar{p}Rb(n) + e^-$ *(n~2000)*
- Auger-stripping, then peripheral annihilation
- trap nuclear remnant (e.g. $^{37}_{83}Rb^{37+}$), sympathetically cool to μK (e.g. Ca^+)

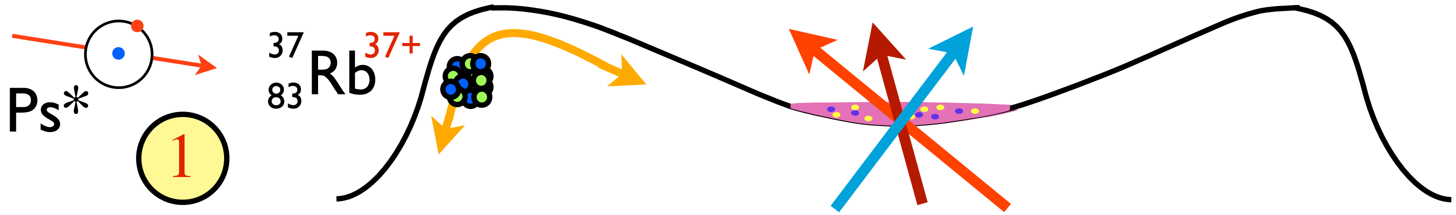
$\rightarrow$ Penning trap mass spectrometry



AEḡIS : a novel radioisotope production method

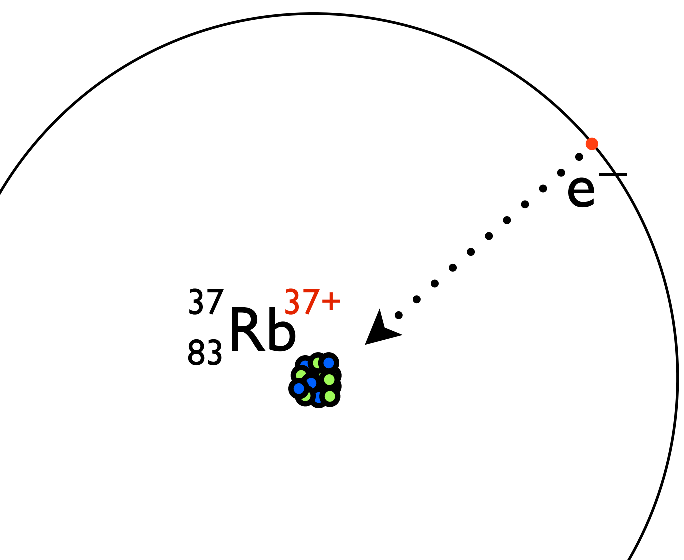


AE$\bar{g}$IS : a novel hollow atom(ic ion)



- in nearby Penning trap, produce Ps*

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

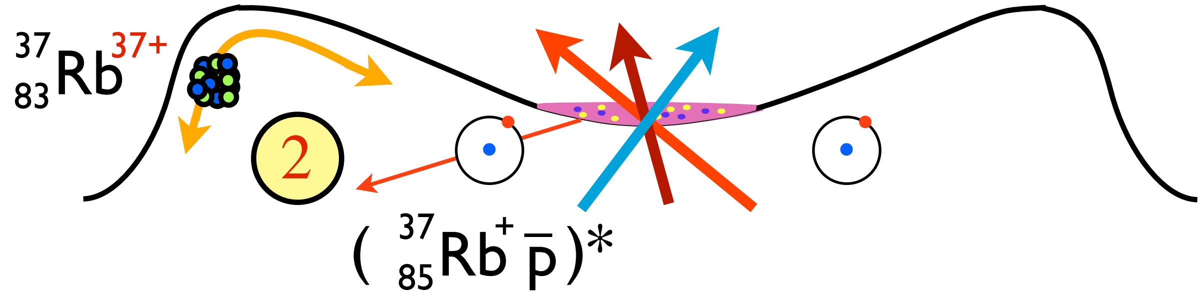


→ ***<u>Rydberg ionic atom</u> (electronic or antiprotonic) of a radio-isotopic HCI = hydrogen-like Z~40 ion***

→ ***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?***

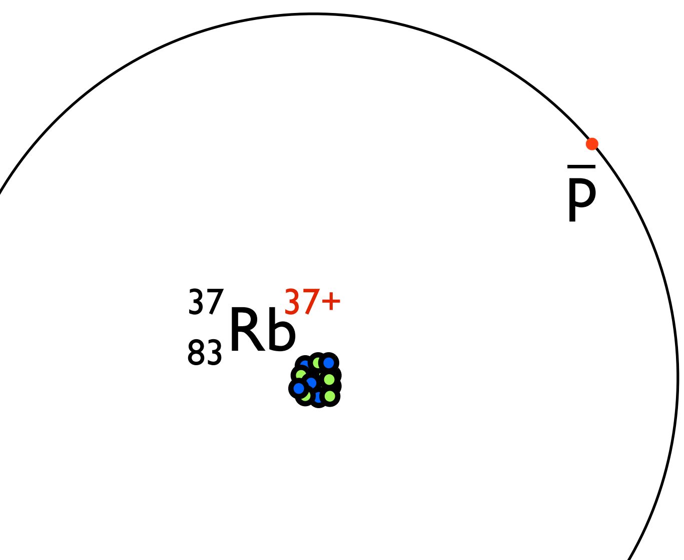
AE$\bar{g}$IS : a novel hollow atom(ic ion)



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

charge-exchange reaction 2:

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



→ ***Rydberg ionic atom** (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?*

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 (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+

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

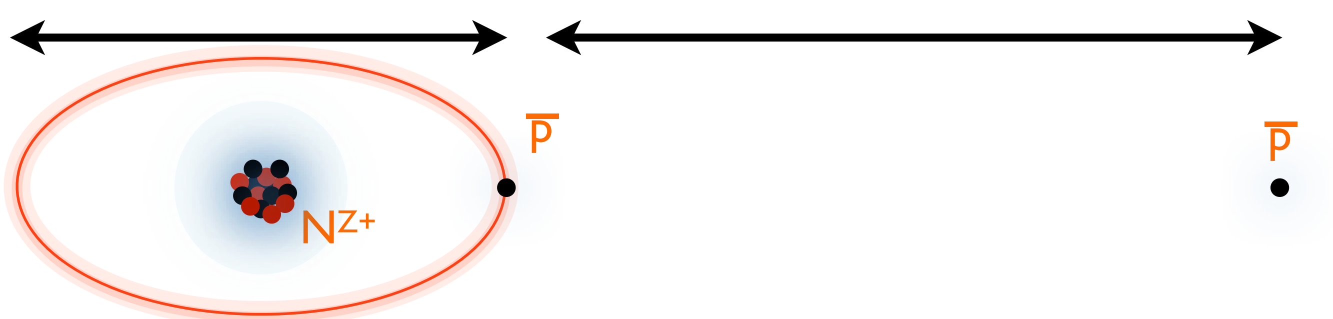
e.g. $(\bar{p}\ ^{37}_{83}Rb)^{36+}*$

results in: highly charged antiprotonic cold Rydberg cation

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

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

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



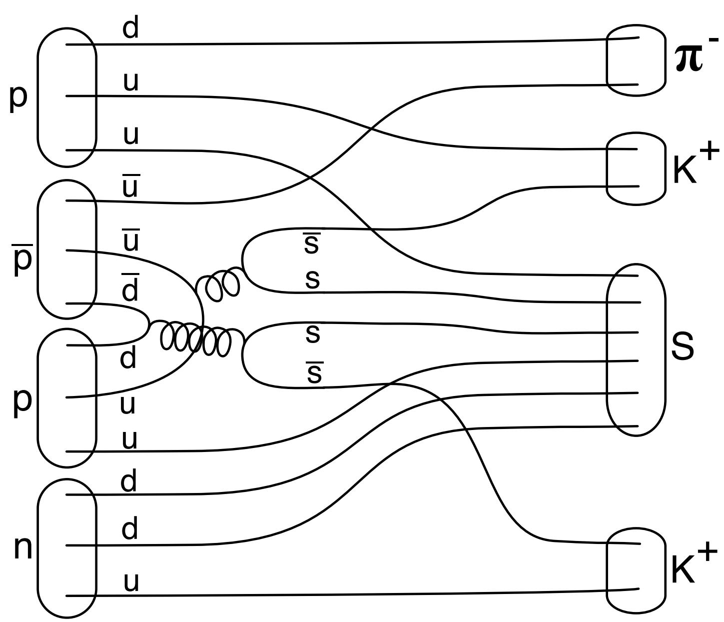
AEḡIS : a novel dark matter search

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

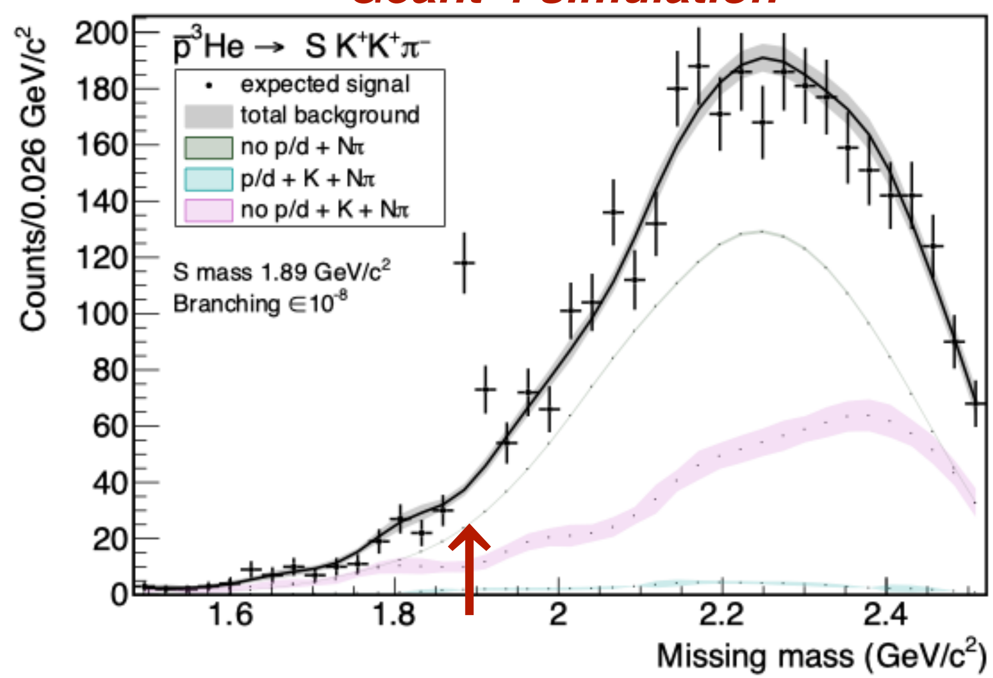
not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region
astrophysical bounds can be evaded
standard model compatible (uuddss bound state)

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

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}***

Upgrade of AEgIS to AEgIS-2 (2020-2023)

(ELENA: antiproton energy decreased from 5.3 MeV to 100 keV)

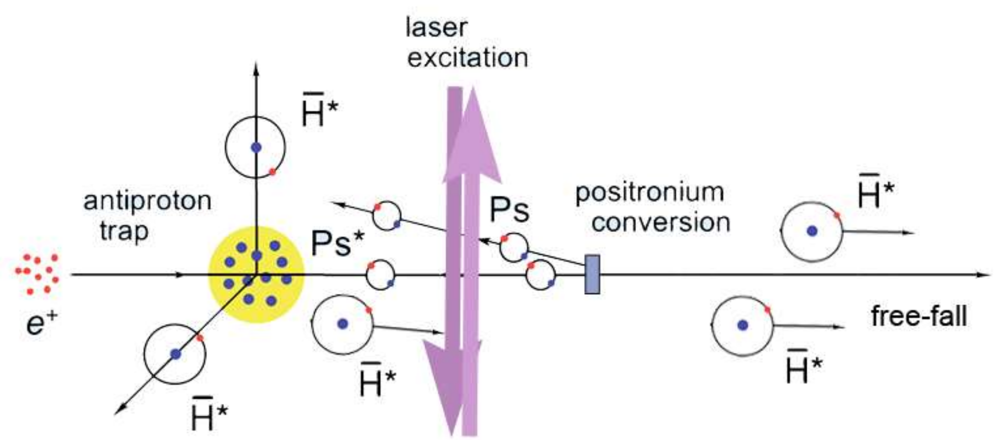
Main goal of AEgIS Phase 2: a first proof-of-concept inertial measurement with pulsed antihydrogen

Take-home messages from the AEgIS Phase 1

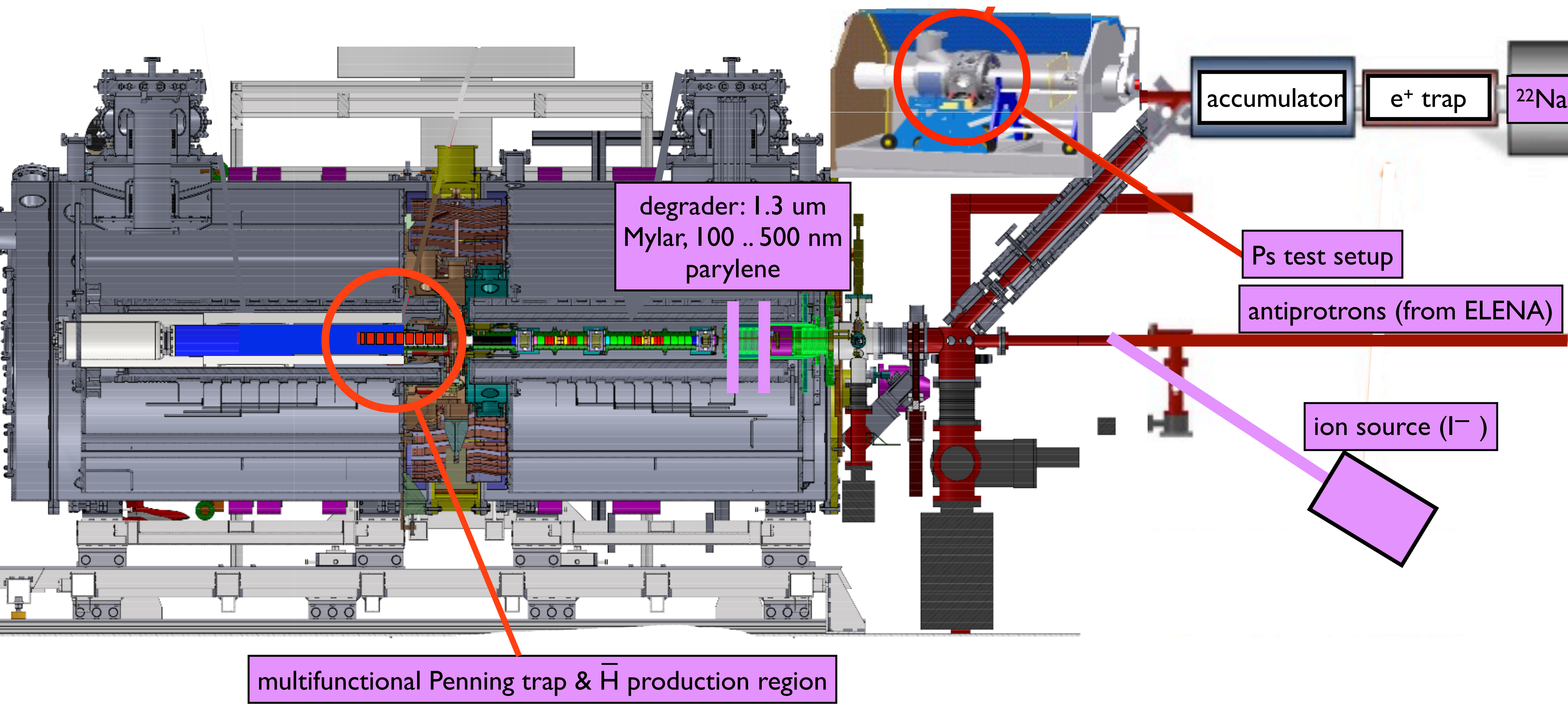
- The antihydrogen source intensity must be increased by 2 orders of magnitude
- The temperature of the produced atoms must be reduced by 1 order of magnitude
- The first gravitational measurement has to be designed to use Rydberg antihydrogens
- The free-fall should take place in the most homogeneous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

New AEgIS Phase 2 configuration

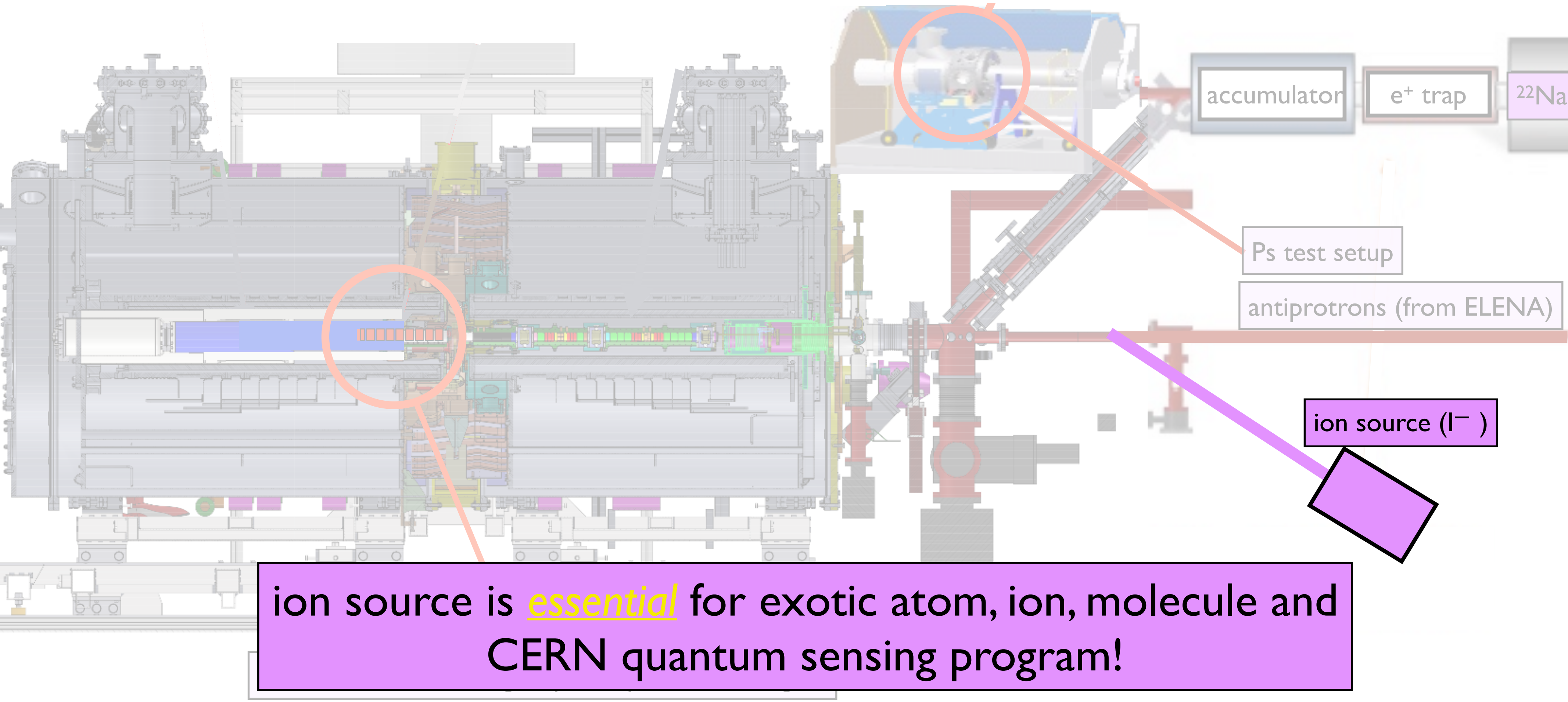
- Positronium conversion target on-axis
- Laser excitation in a Doppler-free scheme
- Positrons passing through resting antiprotons



Upgrade of AEgIS to AEgIS-2 (2020-2022)

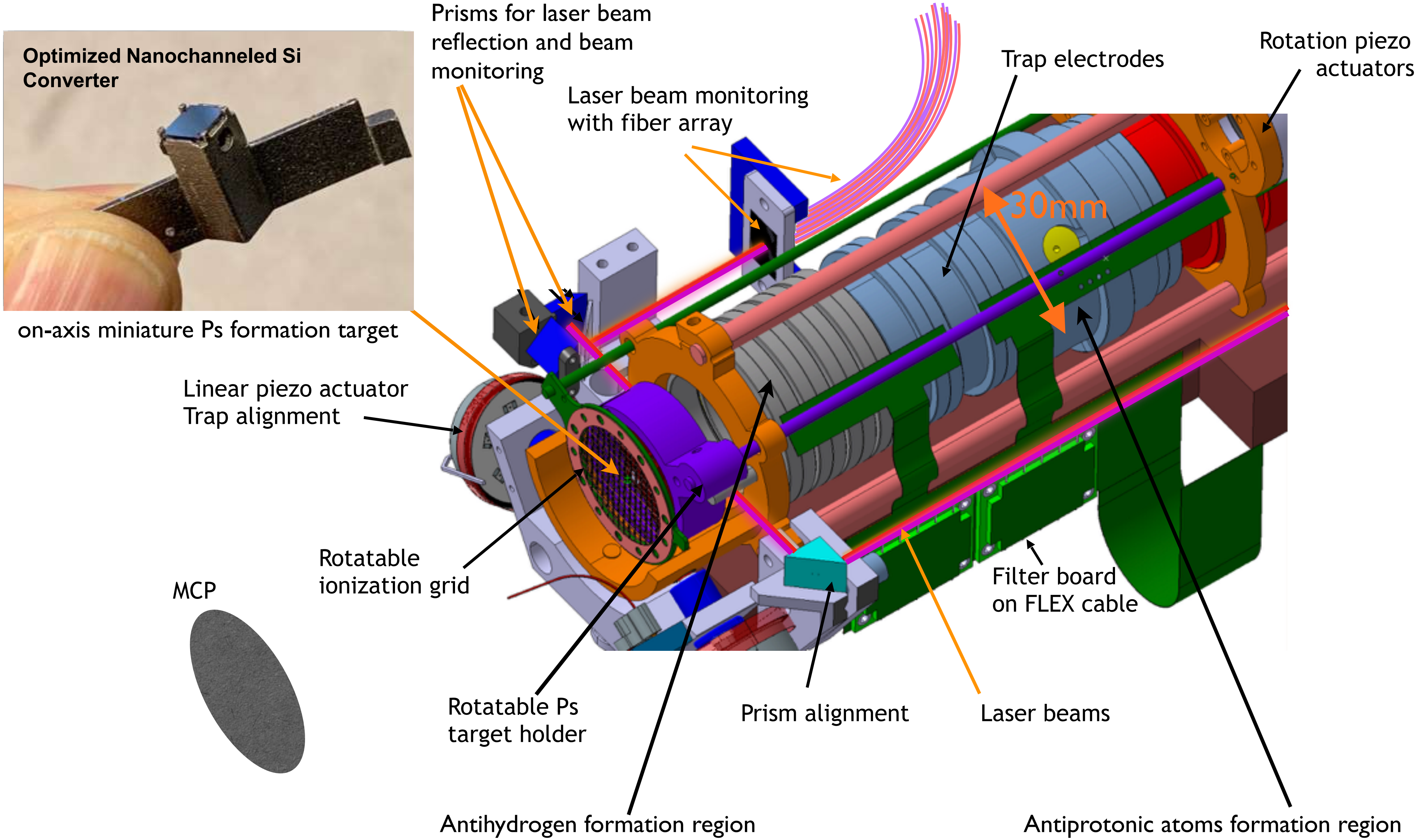


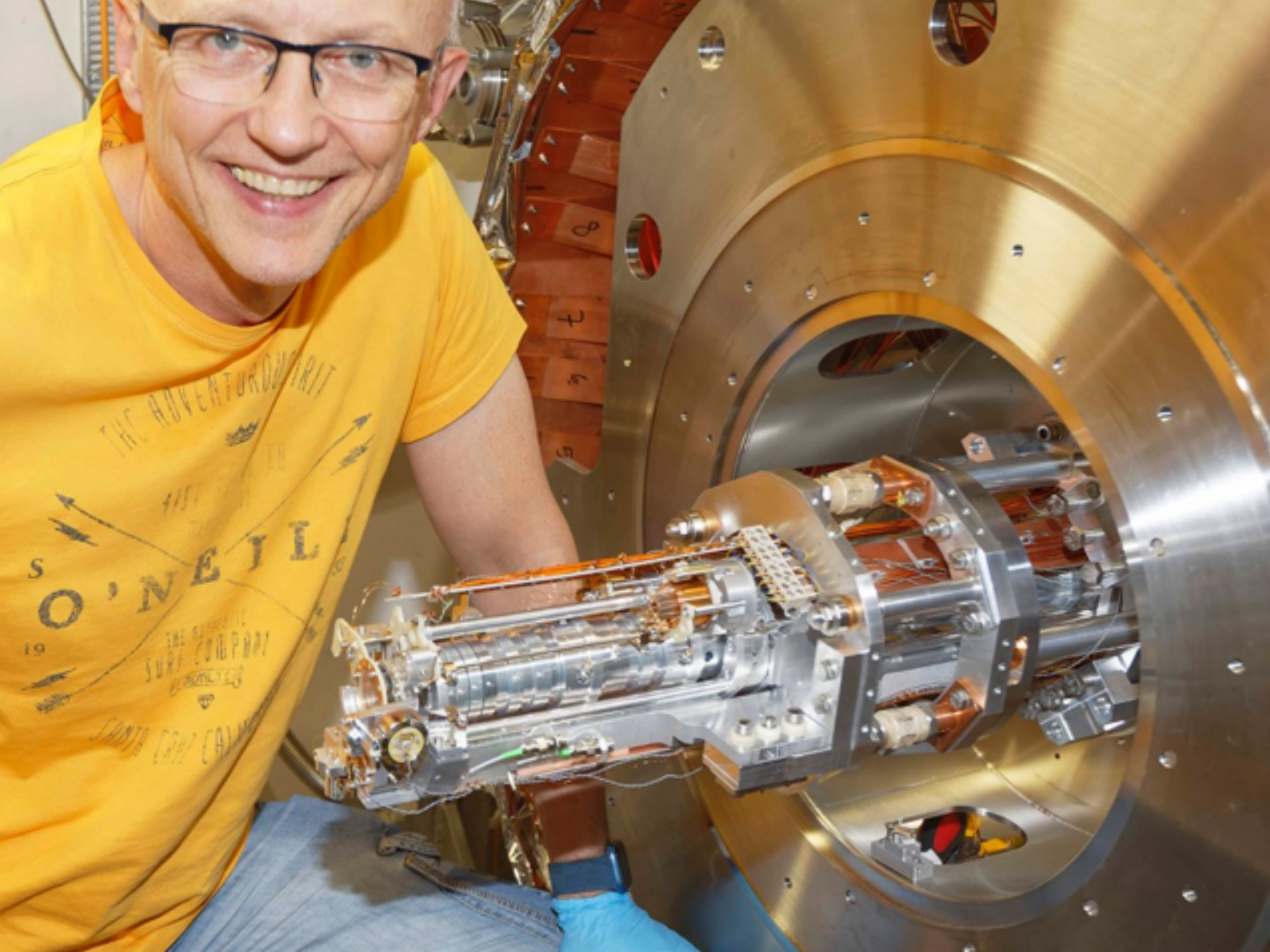
Upgrade of AEgIS to AEgIS-2

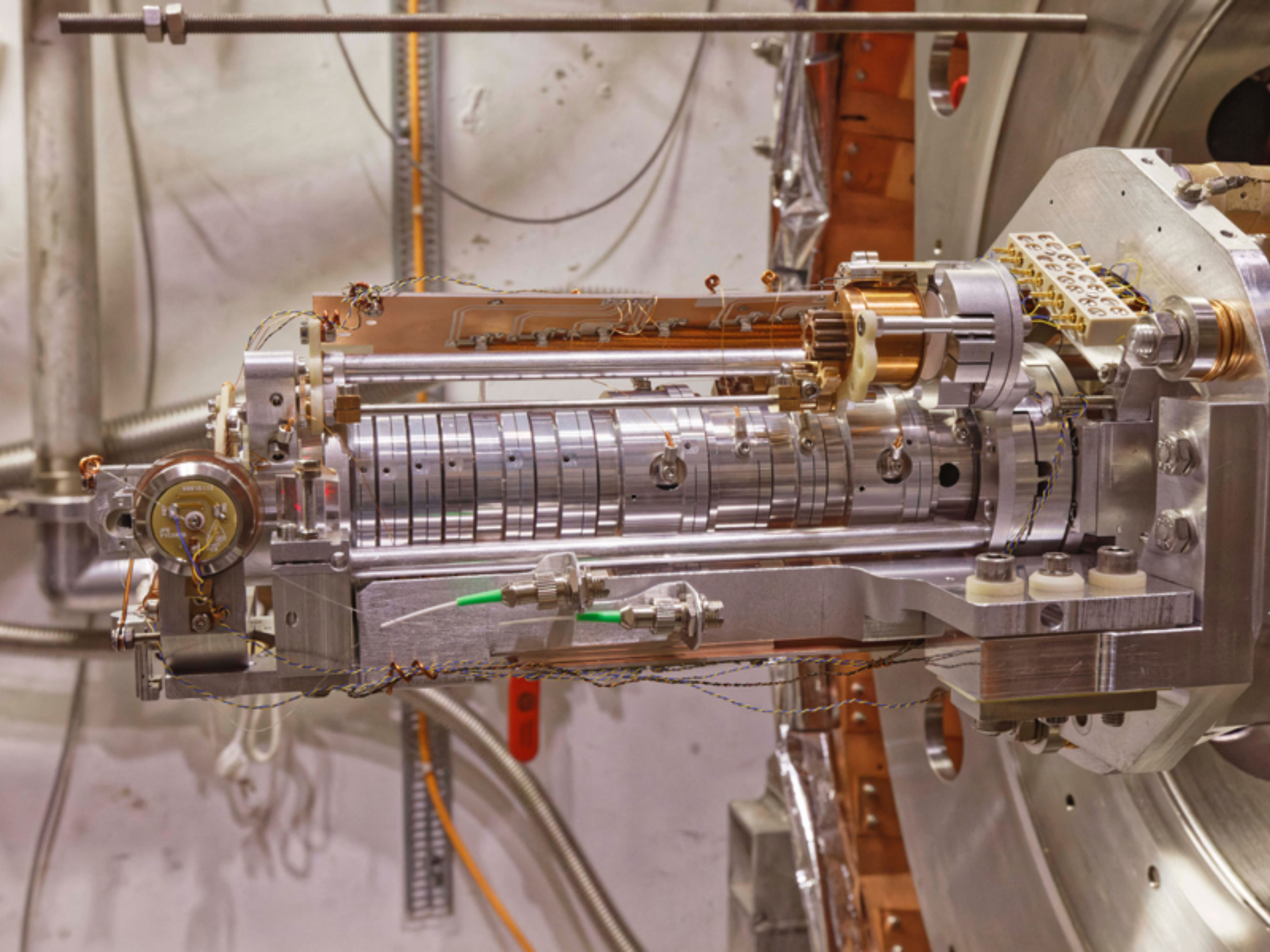


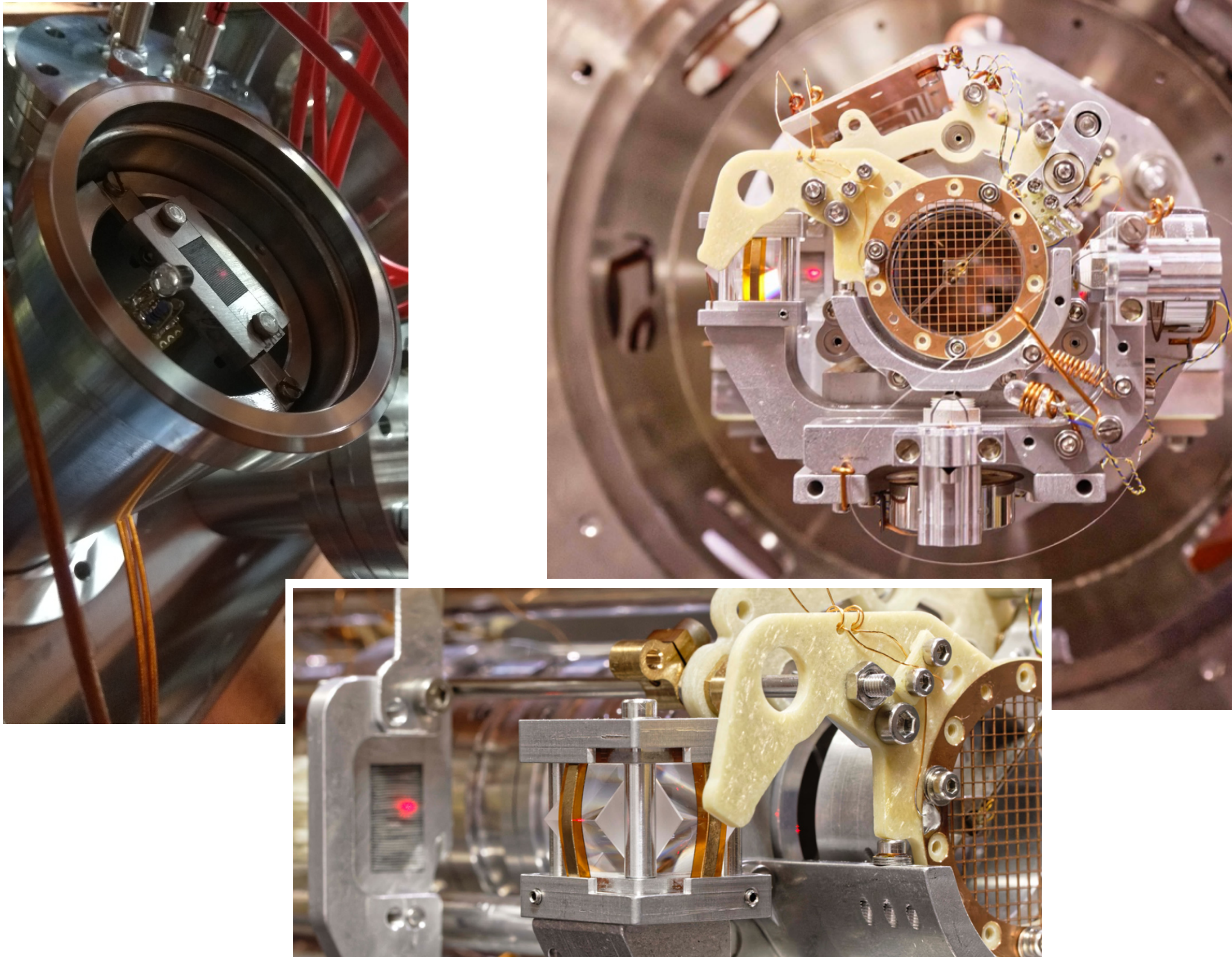
ion source is *essential* for exotic atom, ion, molecule and CERN quantum sensing program!

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









Summary:

Pulsed formation of $\bar{H}^*$ and Ps^* now well under control, and work on beam formation has started.

Charge exchange processes between Rydberg systems and single charged particles provide controlled access to unique exotic systems, with which fundamental symmetries, nuclear physics and possible novel interactions can be explored. Ions are the key to this new field.

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