Pulsed production of antihydrogen in the AEḡIS experiment (for precision tests of fundamental symmetries)

AEḡIS collaboration

CIPANP / Orlando 2022

Michael Doser / CERN

Tests of fundamental symmetries with antimatter

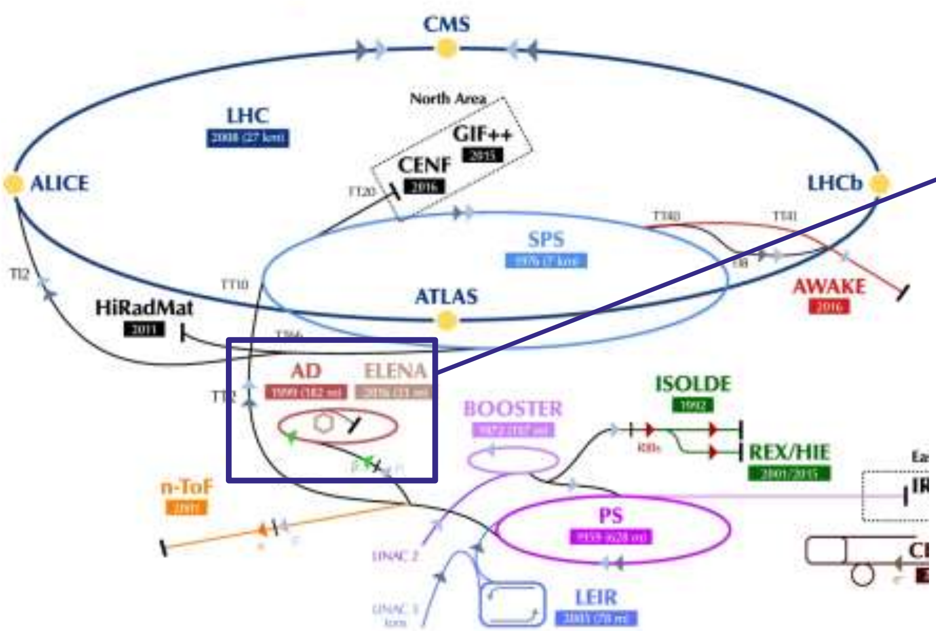
CPT: precision spectroscopy of antihydrogen, antiprotonic He, antiprotons

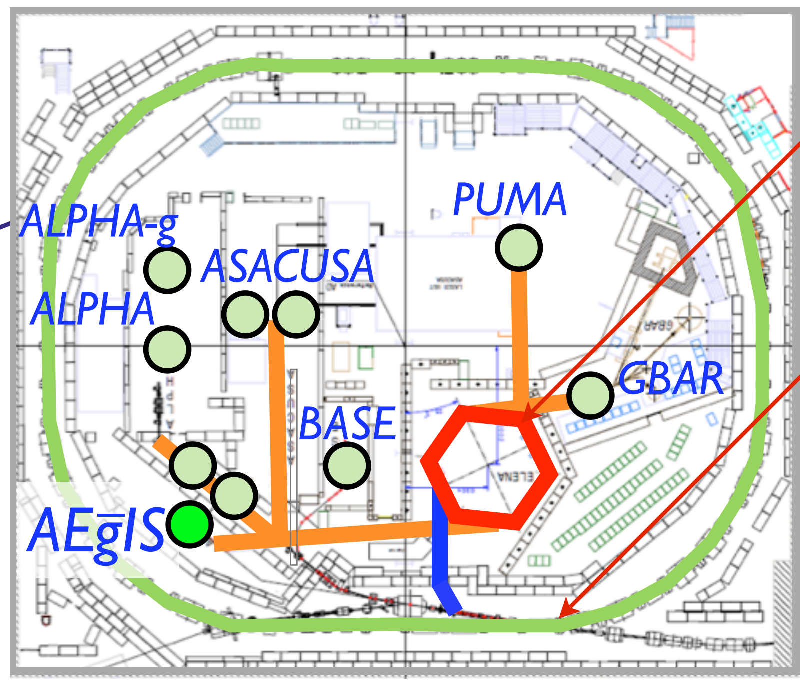
WEP: gravitational behavior of neutral antimatter systems

BSM: precision spectroscopy of exotic antiprotonic systems

nuclear physics: antiprotonic atoms as gateway systems

The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEḡIS) collaboration aims at performing direct experimental tests of the Weak Equivalence Principle (WEP) using anti-atoms. The chosen method is the direct detection of the free-fall trajectory of a pulsed beam of horizontally traveling antihydrogen atoms.





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

10^7 p̄ /100s

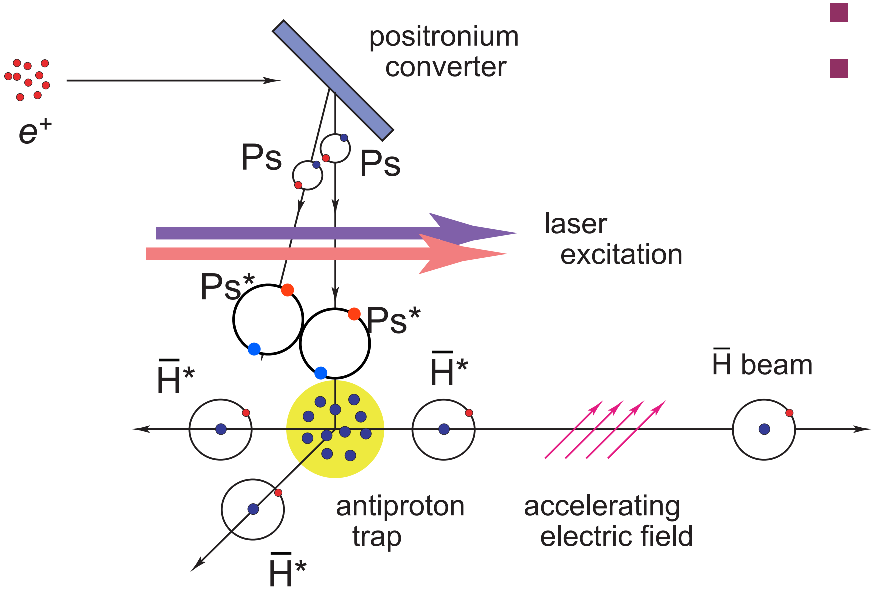
in operation since 2021

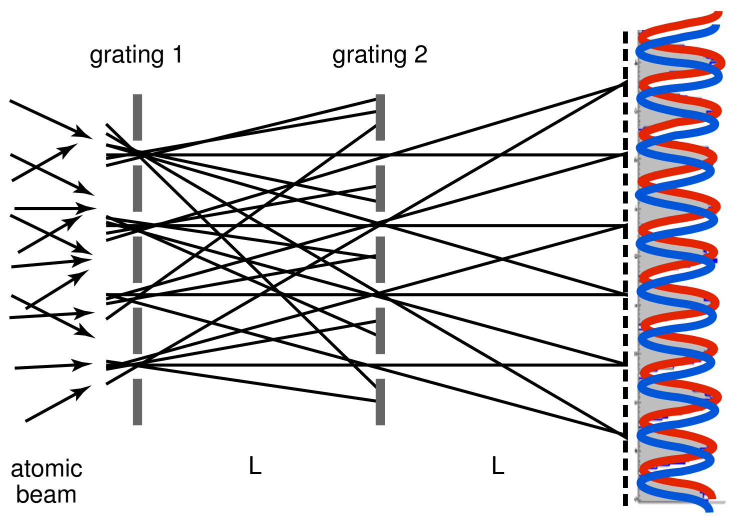
Schematic overview: AE$\bar{g}$IS (Antimatter Experiment: gravity, Interferometry, Spectroscopy)

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

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

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



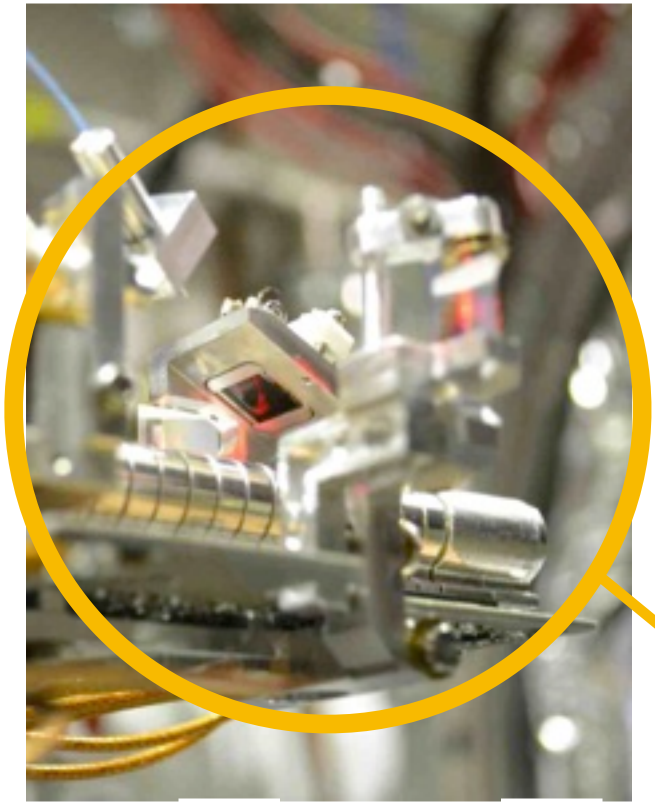


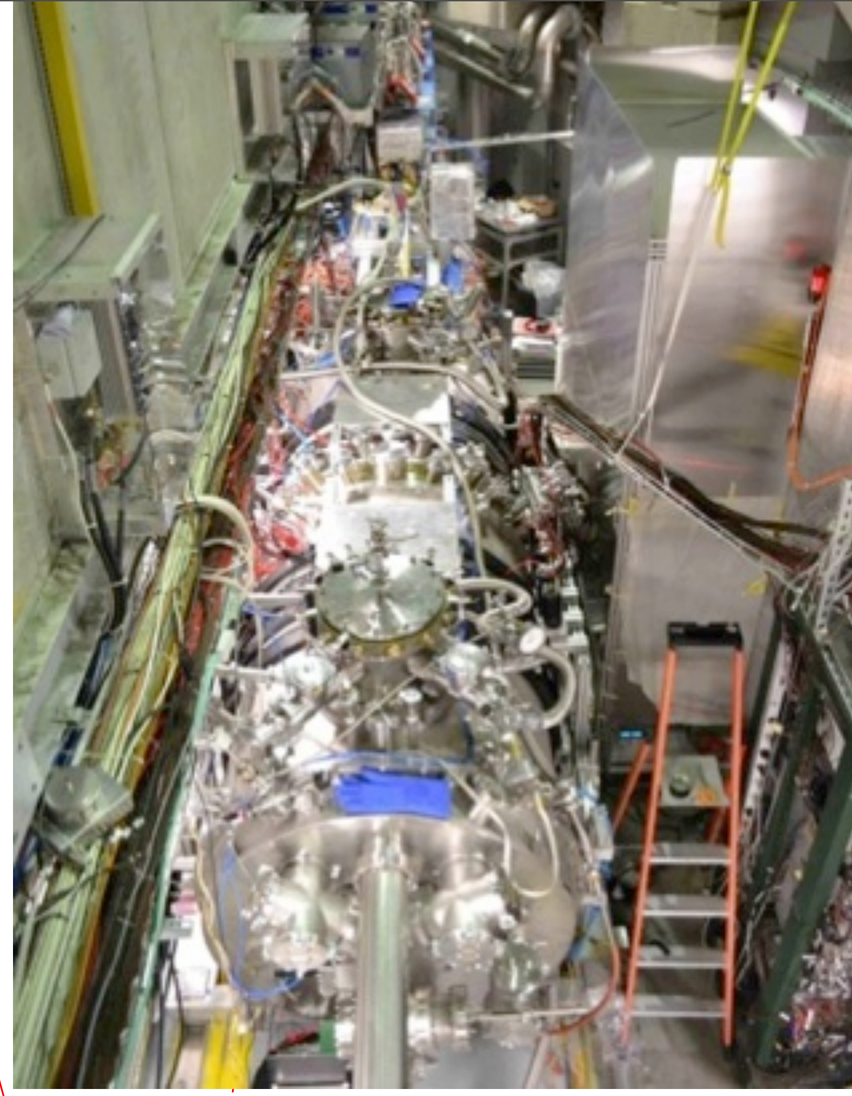
pulsed production of $\bar{H}$*

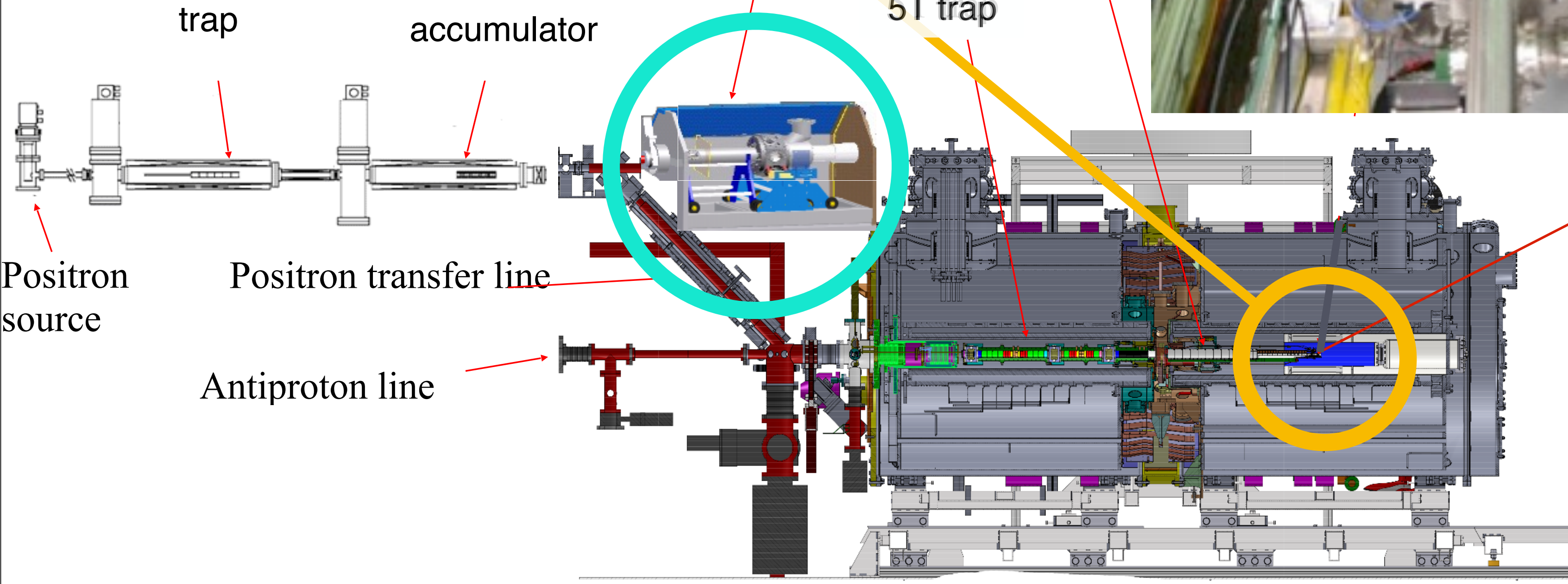
horizontal beam formation

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

AE$\bar{g}$IS experiment



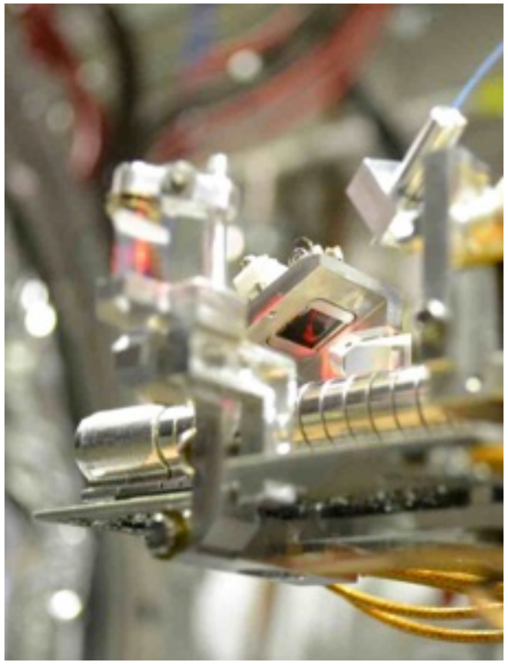


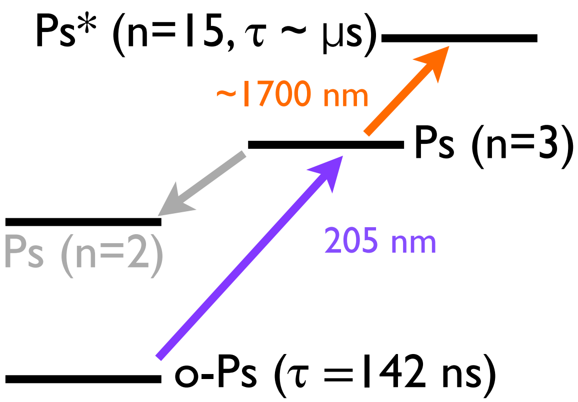


Challenges: (and many more...)

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

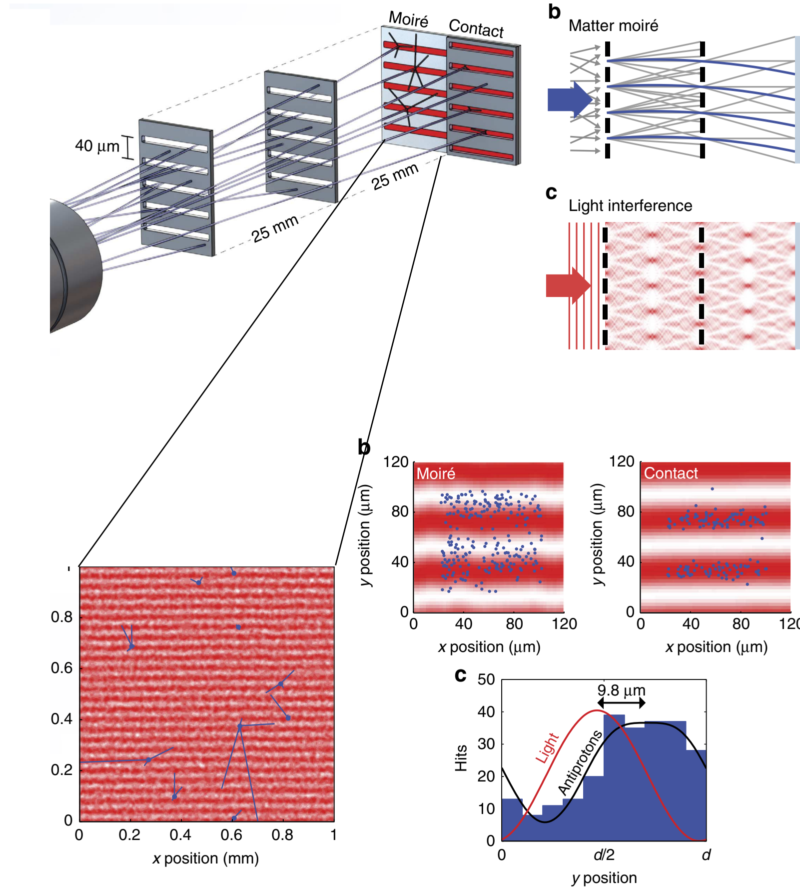
La^- Warring et al, PRL 102 (2009) 043001
E. Jordan et al., PRL 115 (2015) 113001

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

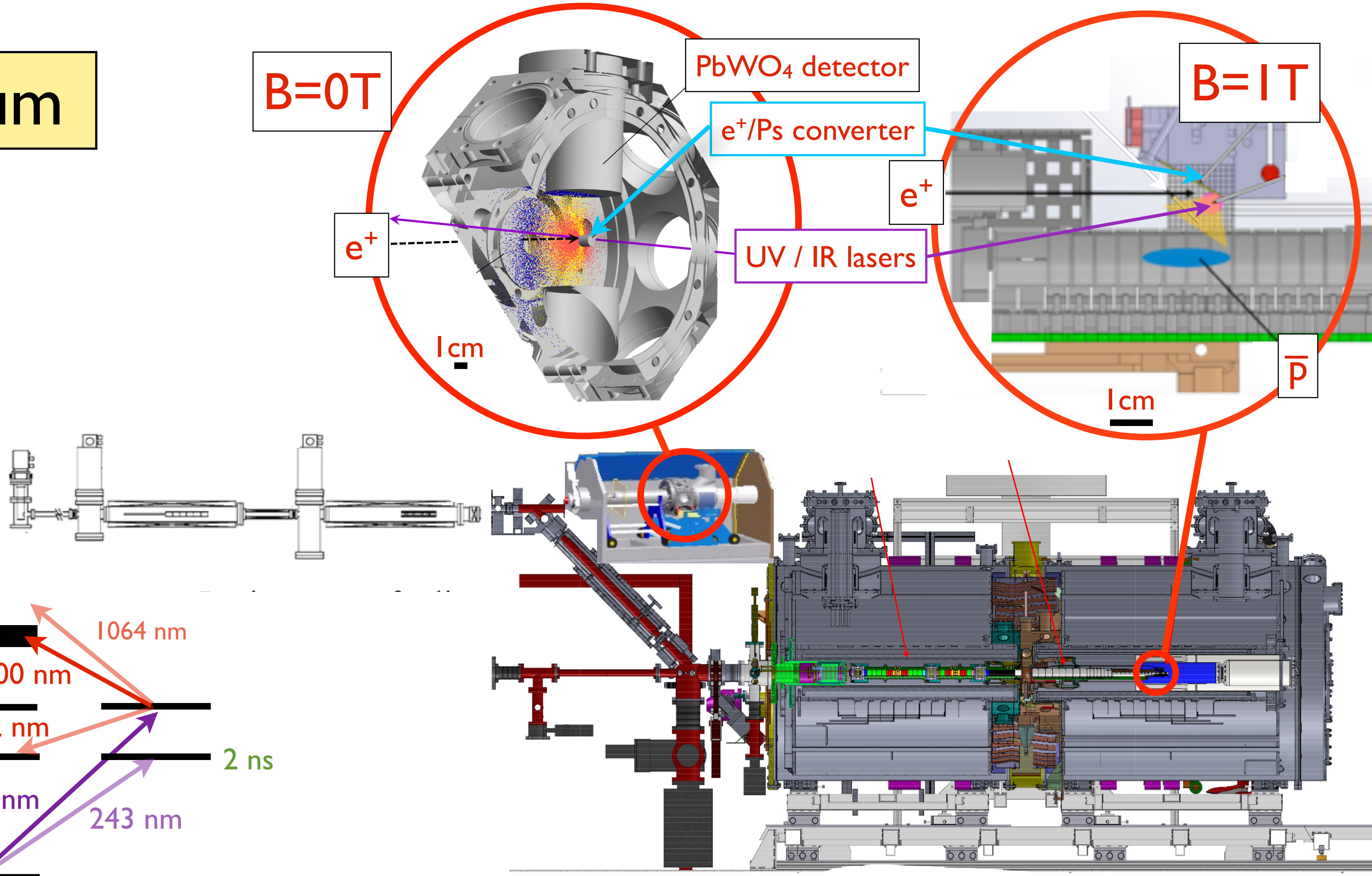
Measurement:

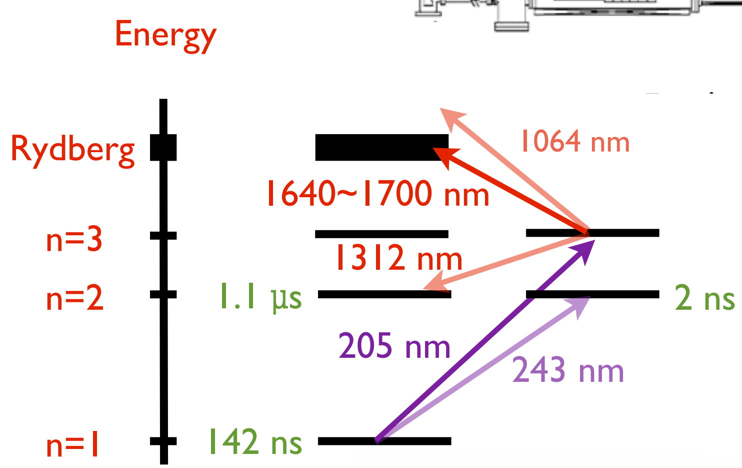


principle established with $\bar{p}$; displacement of $\bar{p}$ annihilation vertices (blue dots) measured relative to light (red) (aN sensitivity!)

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

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

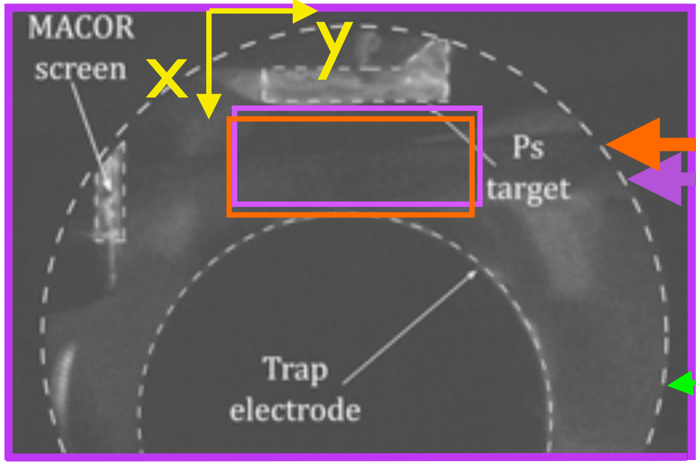
Velocity selected production of 2^3S metastable positronium → beam of meta-stable Ps

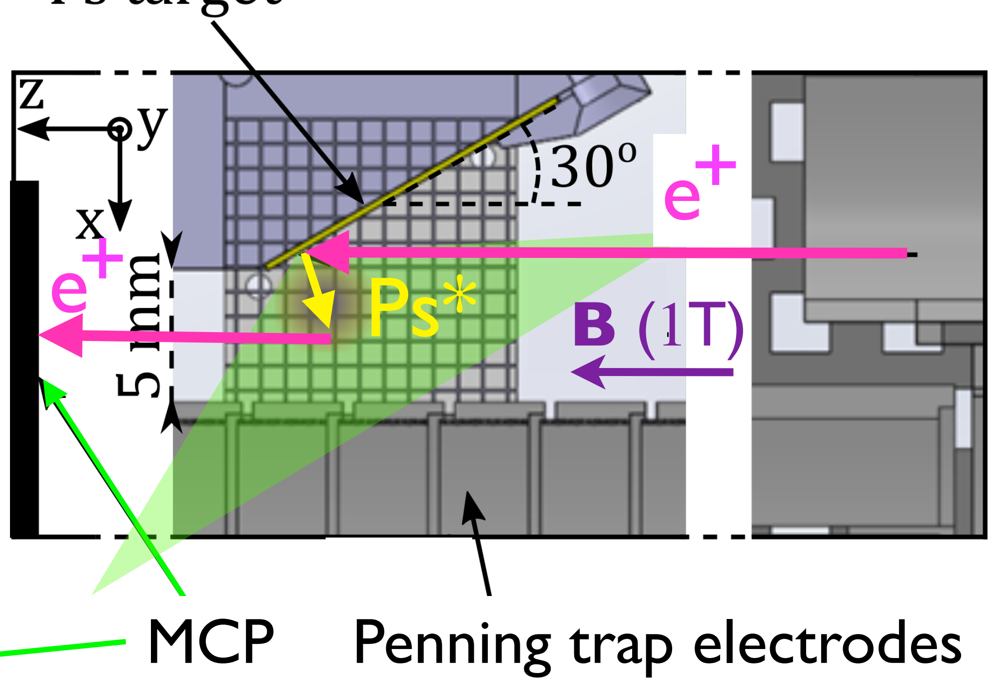
ongoing work on: further manipulations, enhanced 2^3S production, formation of "intense" metastable Ps or Rydberg Ps beam for inertial sensing, high resolution state-selective imaging, test bed for interferometry, spectroscopy, ...

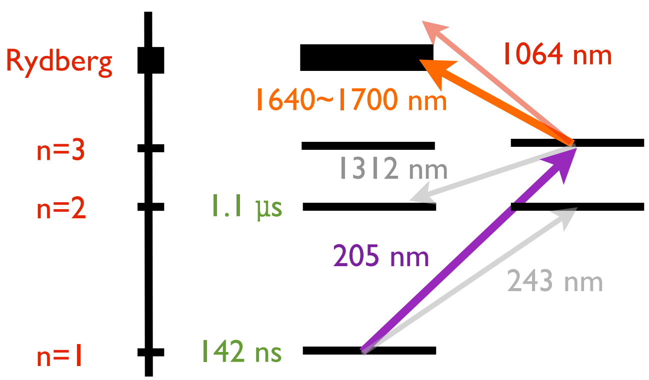
Ps* velocimetry

B=1T

Scan 1→3 laser timing, frequency

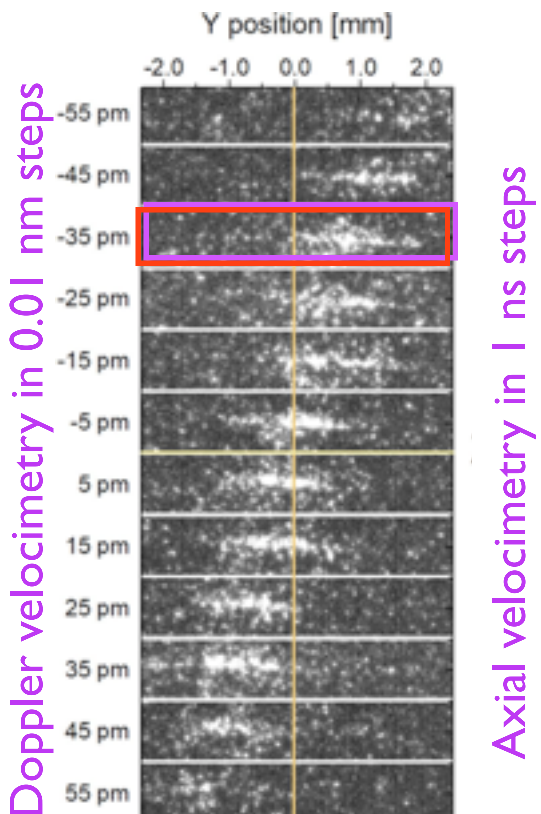




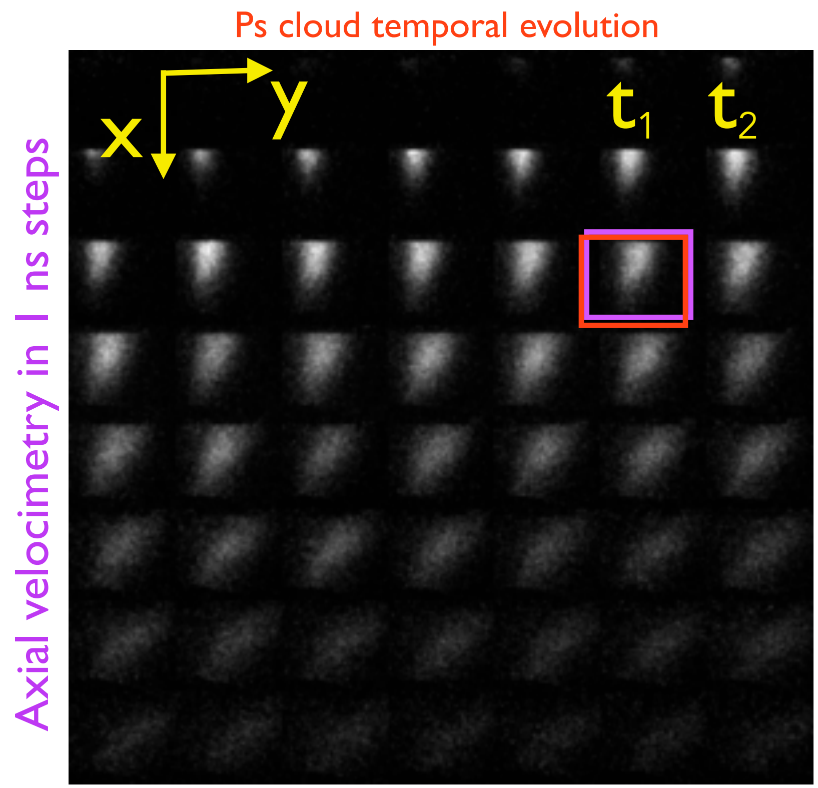


1064 nm : photoionization

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



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

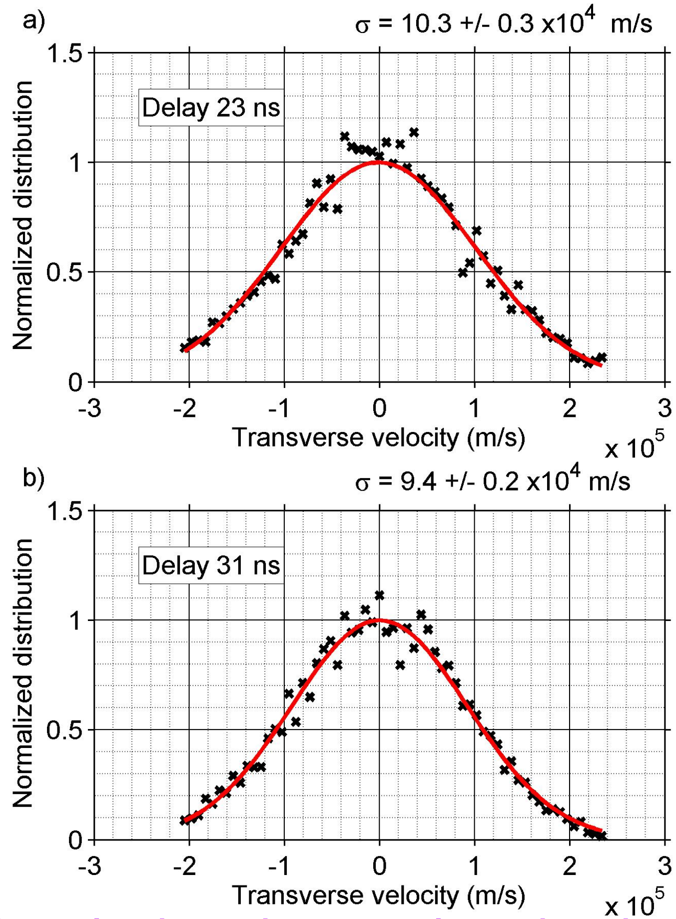


Ps* velocimetry

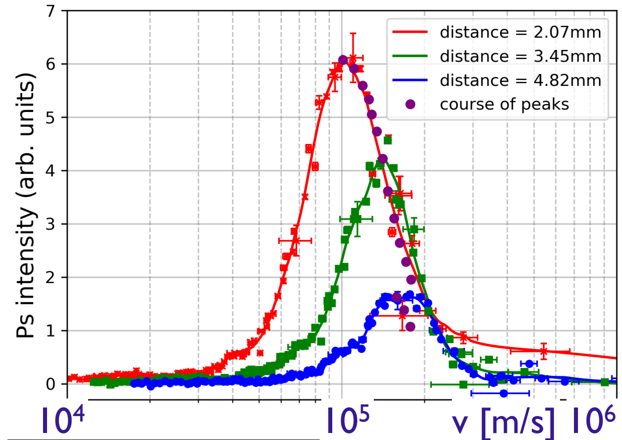
B=1T

transverse velocity (σ ~ 1 x 10^5 m/s) *axial* velocity ~ 1.6 x 10^5 m/s

probed by UV Doppler velocimetry

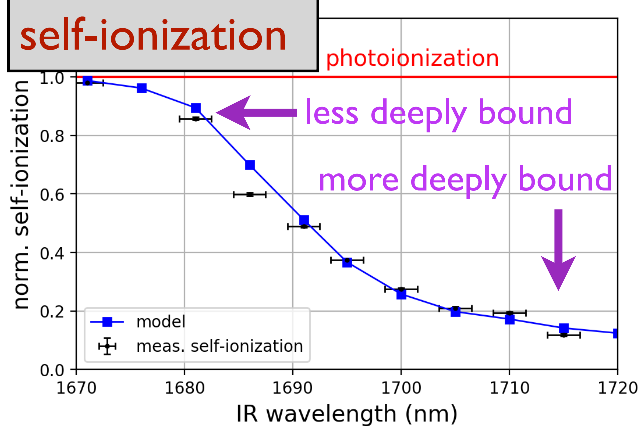


Doppler broadening ⊗ laser bandwidth



probed by laser timing

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

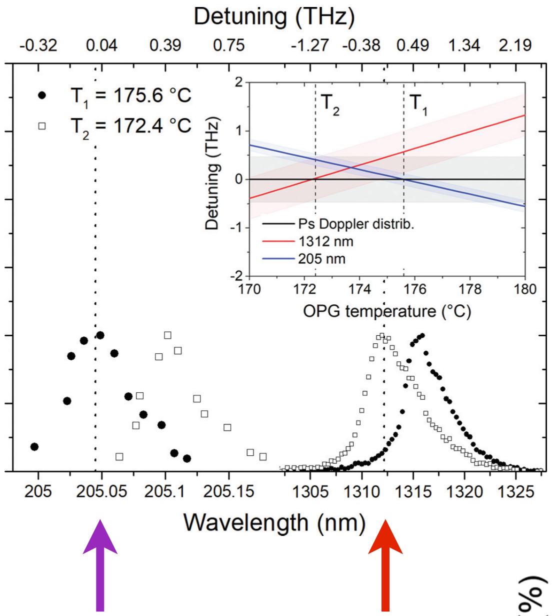
stimulated formation of metastable 2^3S Ps*

B=0T

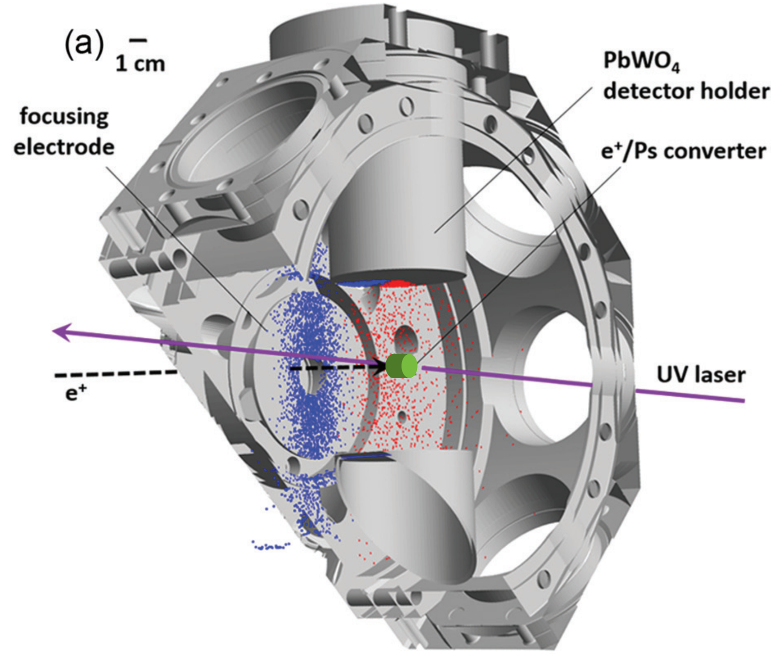
UV excitation: $1\ ^3S \rightarrow 3\ ^3P$

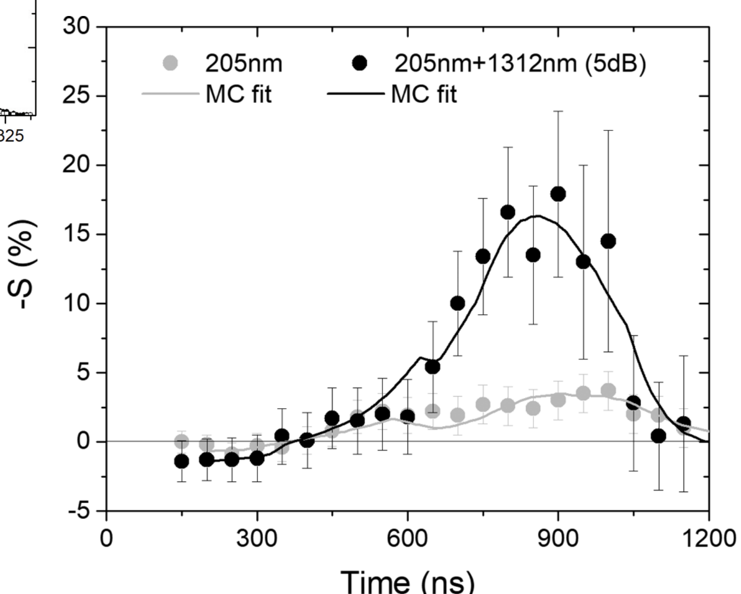
stimulated decay: $3\ ^3P \rightarrow 2\ ^3S$ (29.7±1.9)%

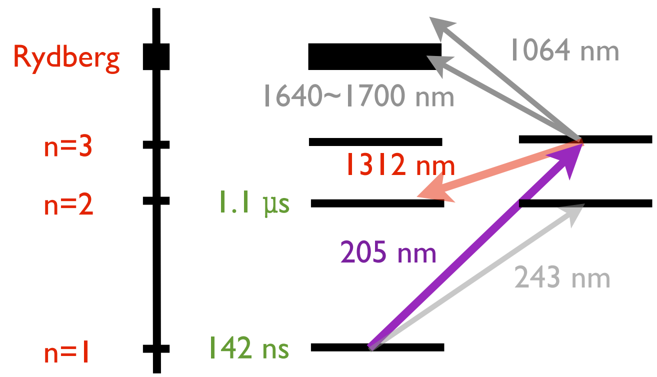
spontaneous decay: $3\ ^3P \rightarrow 2\ ^3S$ (9.7±2.7)%



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







improvements on laser system (second separate system almost complete)

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

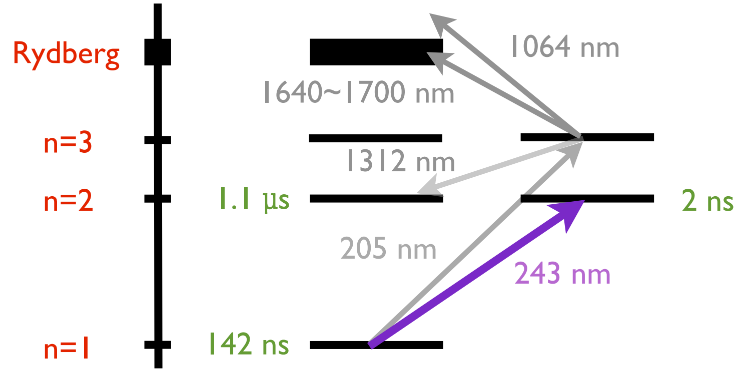
Phys. Rev. A 100, 063414 – Published 1 Dec 2019

laser-cooling of Ps

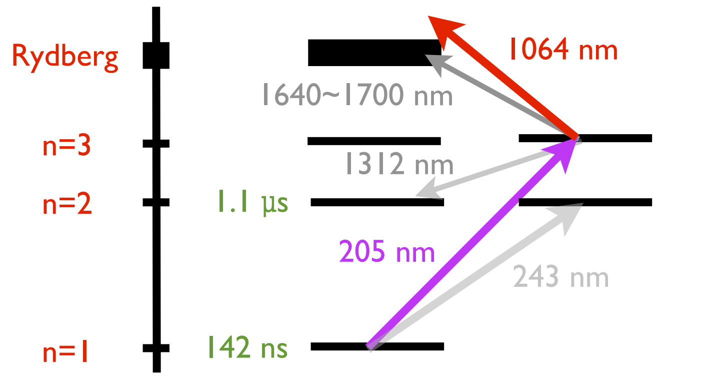
B=0T

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)



measurements ongoing

more work is needed before laser-cooling of Ps can be established

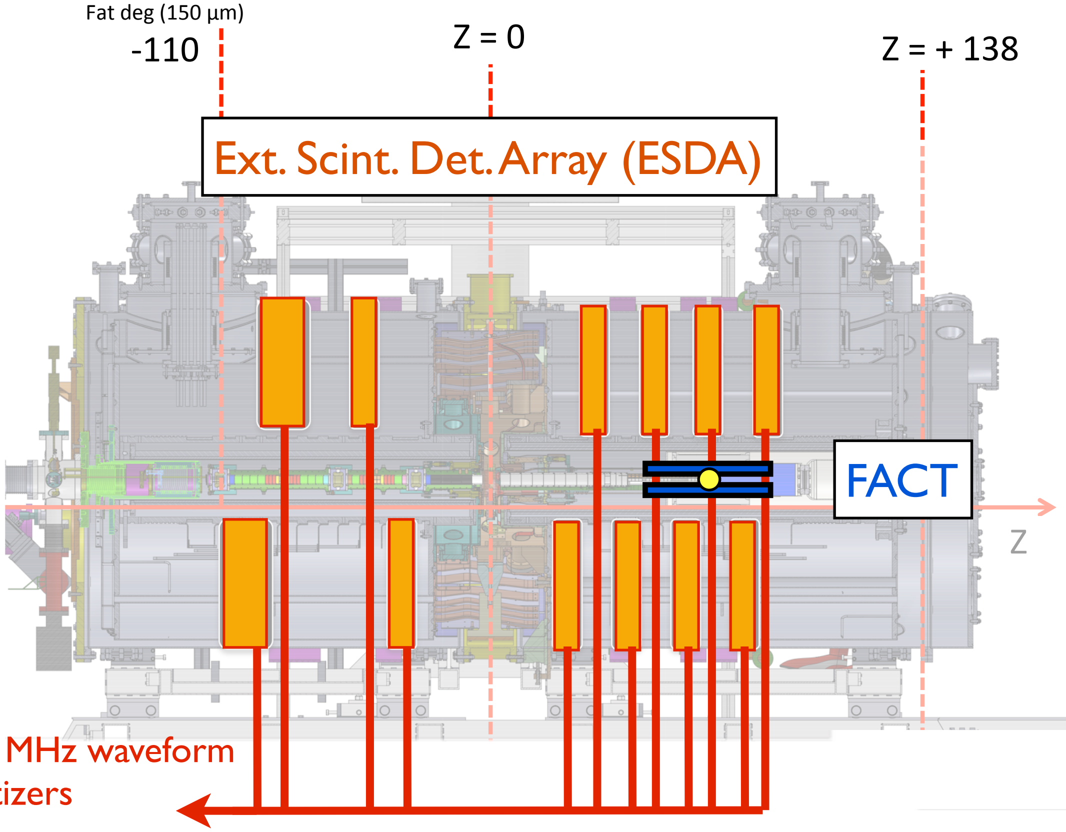
but: if feasible ➔ possible enhancement in $\bar{H}$ production rate, Ps beam

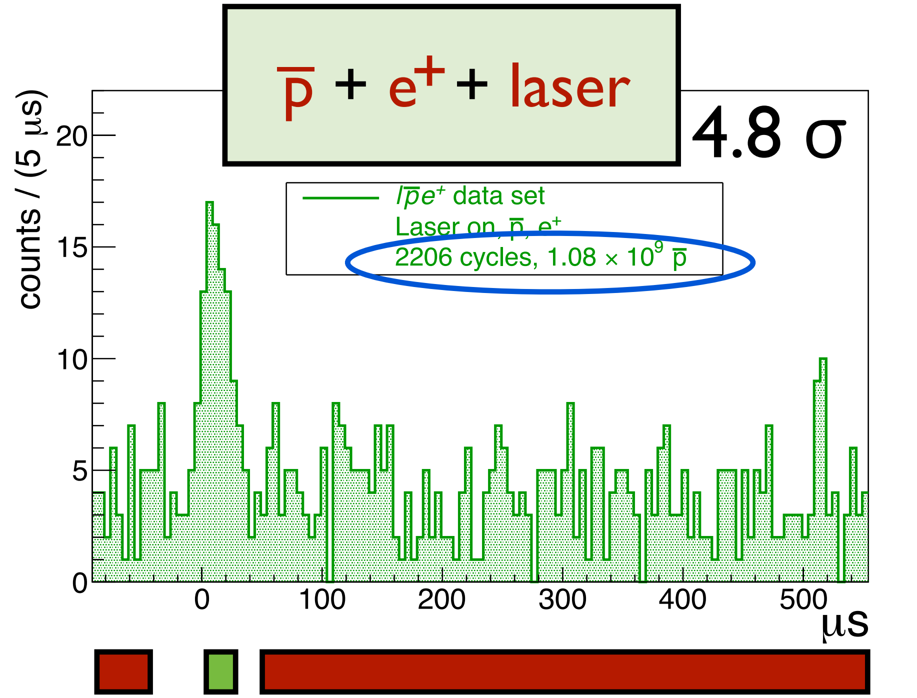
Pulsed production of $\bar{H}$ in 2018

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

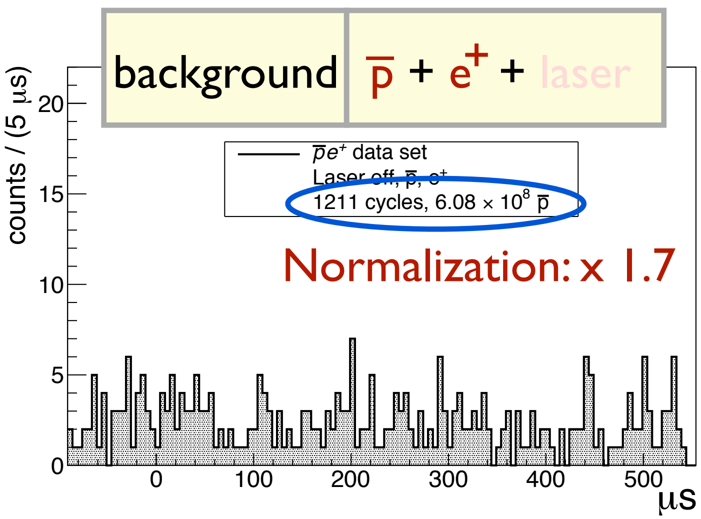
$\bar{H}$ detectors: scintillating slab array (mips), FACT (vertex tracker)

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

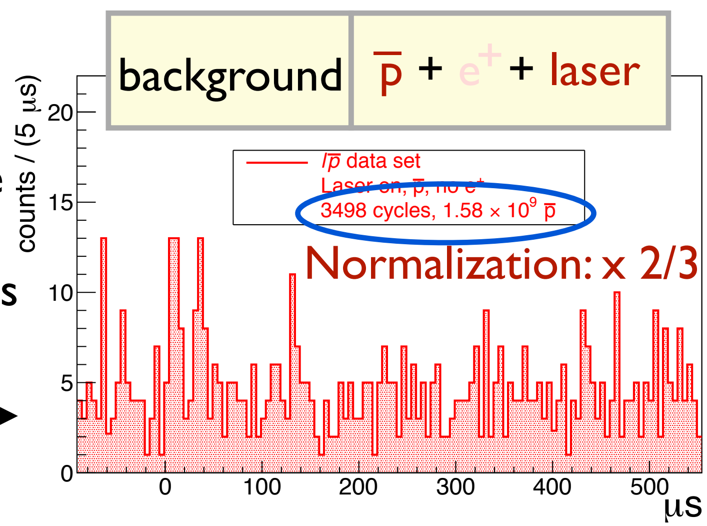




excess in signal region [1, 26 μs]



long time average rate compatible with cosmics rate



= 0.05 $\bar{H}$ / cycle

in 2022:

- rate x 1000
- pulsed beam

ingredients for gravity w/ $\bar{H}$

- main experimental results obtained during AEgIS phase 1
  - → validation of the inertial sensing methodology with $\bar{p}$
  - → Ps excitation to Rydberg levels in strong magnetic fields
  - → First pulsed antihydrogen production
- AEgIS phase 2: #($\bar{H}$)x10^3; pulsed beam; interferometry

antiprotonic Rydberg atoms:

- antiprotonic Rydberg atoms (with $\bar{p}$ instead of e^-)
  - → precision spectroscopy of Rydberg states (CPT)
  - → nuclear physics (trapped cold radio-isotopic HCI's)

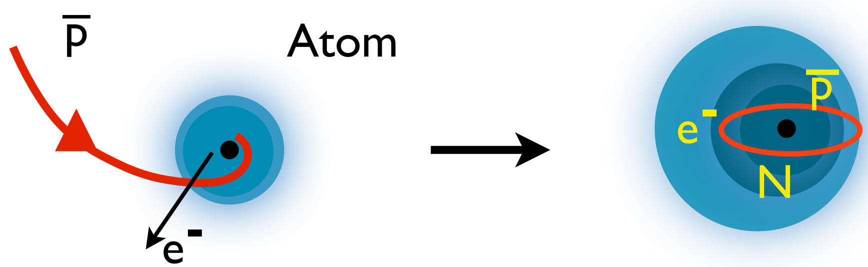
antiprotonic Rydberg atoms:

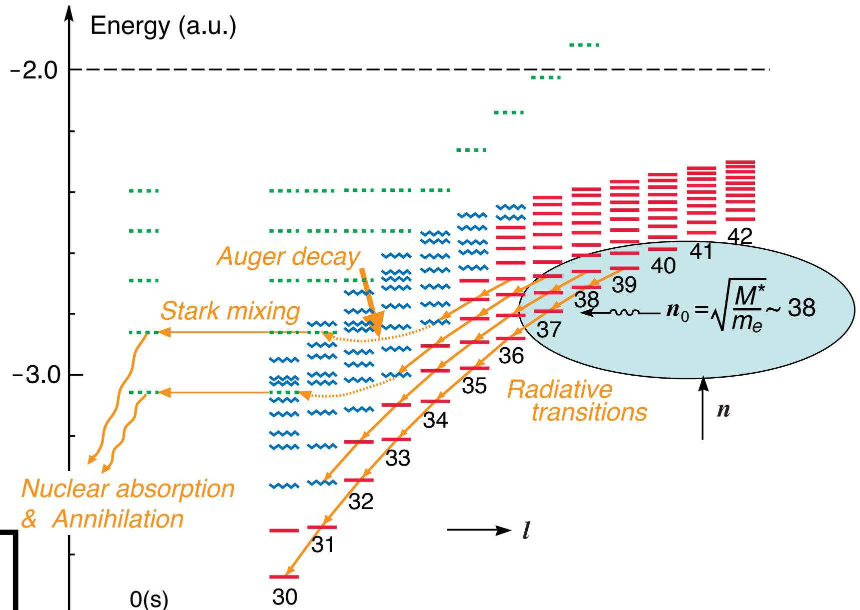
atomic physics processes (Rydberg states, cascades, binding energies, lifetimes)

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")

• nuclear fragments from annihilation: highly charged, trappable





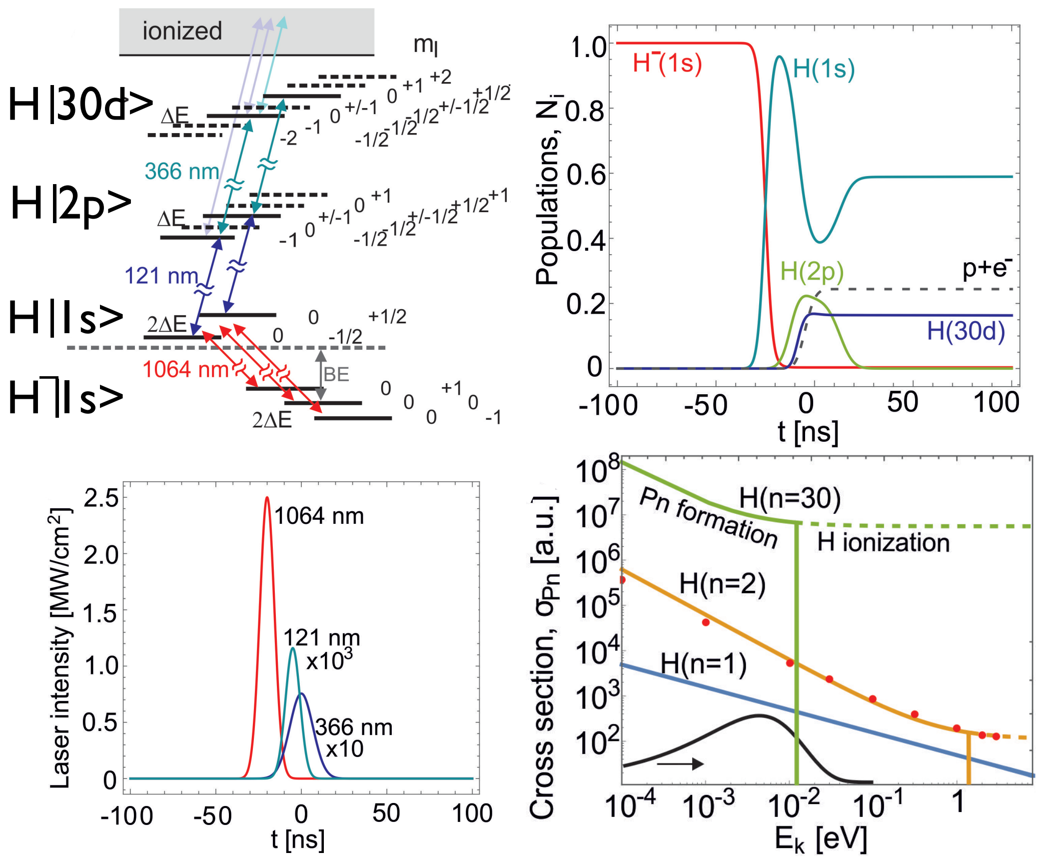
example: antiprotonic helium

established formation process: inject anti-protons into solid/gaseous target material

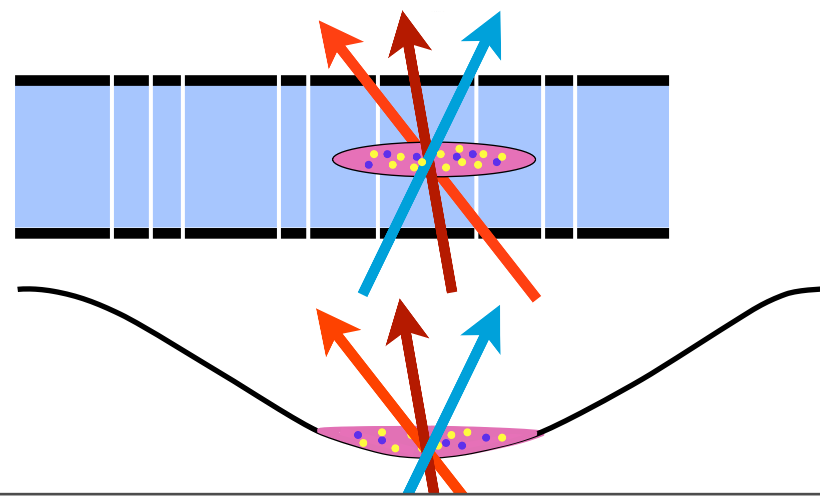
proposed formation method: trapped anion together with antiprotons, photo-detachment of electron, excitation into a Rydberg state, lifetime O(ms), possibly even trappable. Temperature $pX^{(+)*}$ ~ 10 K

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 & e⁻ cool them
- photo-ionize H⁻
- laser-excite H $\xrightarrow[2\gamma]{}$ H*(30)
- charge-exchange reaction: $H^*(30) + \bar{p} \rightarrow \bar{p}p(n) + e^-$ *(n~2000)*
- detect fluorescence & annihilation ($\pi^\pm$, π^0)



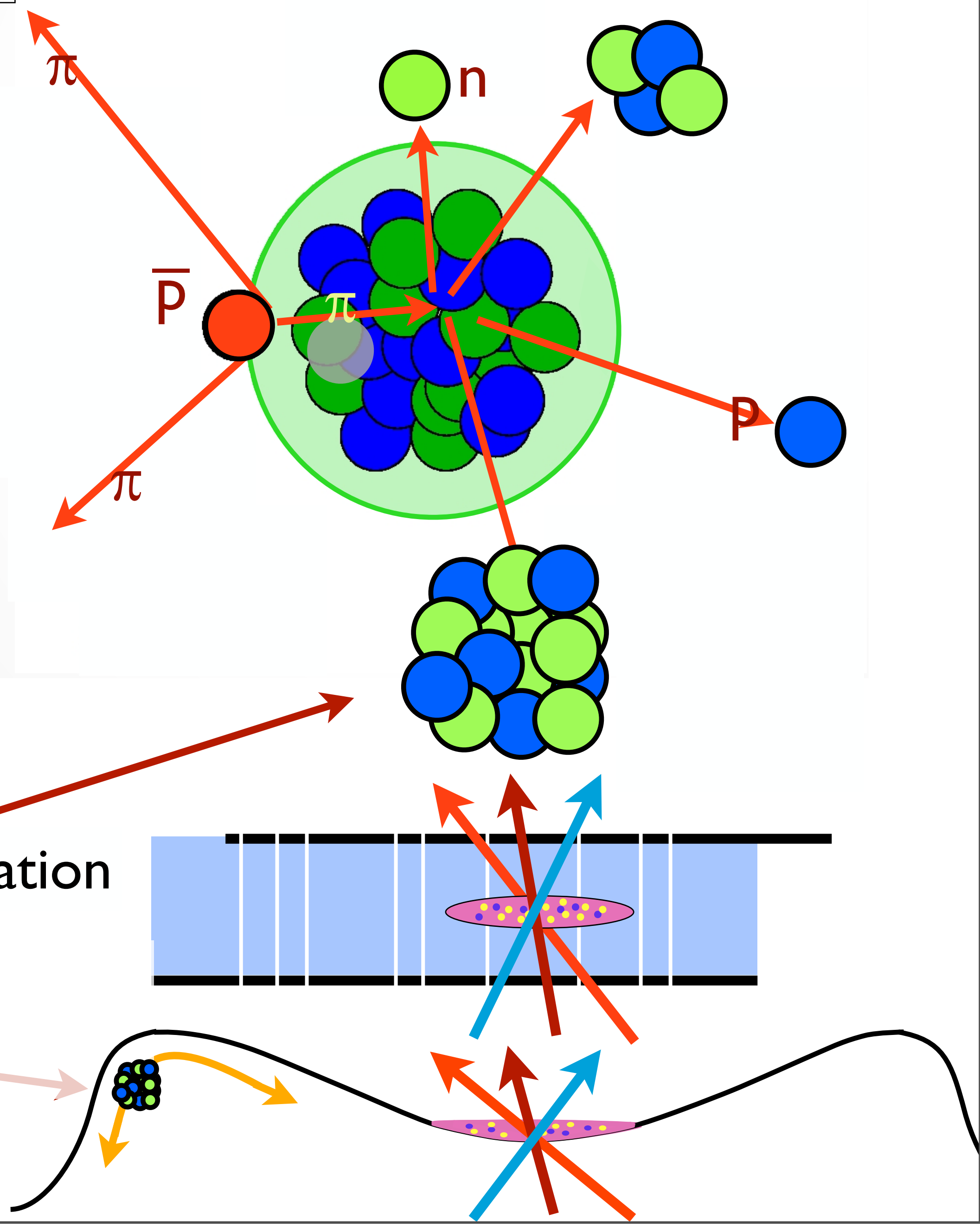
AEḡIS : a novel radioisotope production method

(using Rb as an example starting point)

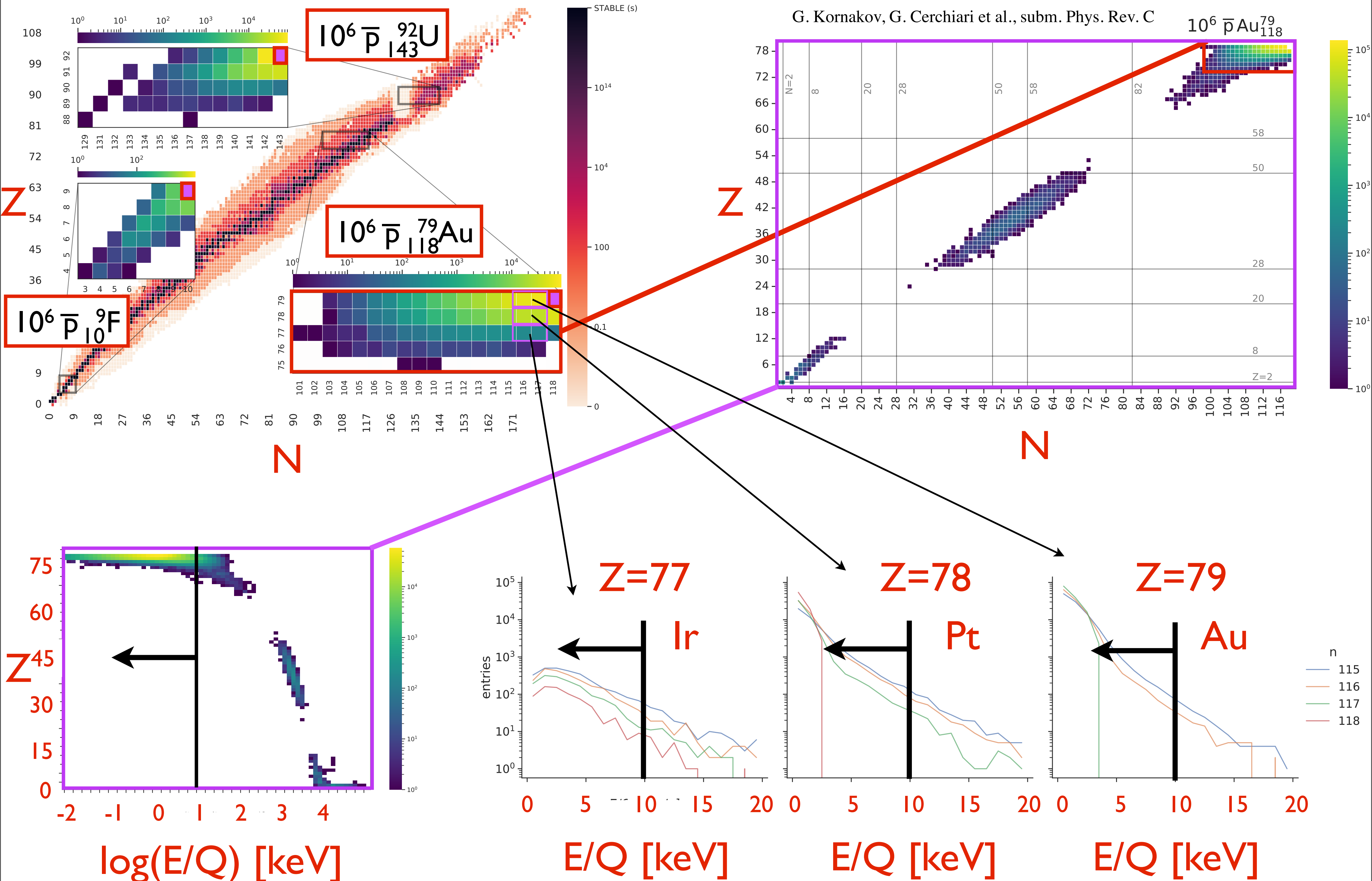
G. Kornakov, G. Cerchiari et al., subm. Phys. Rev. C

- 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)*
- Auger-stripping, then peripheral annihilation
- trap nuclear remnant (e.g. $^{37}_{83}Rb^{37+}$), sympathetically cool to μK (e.g. Ca^+)

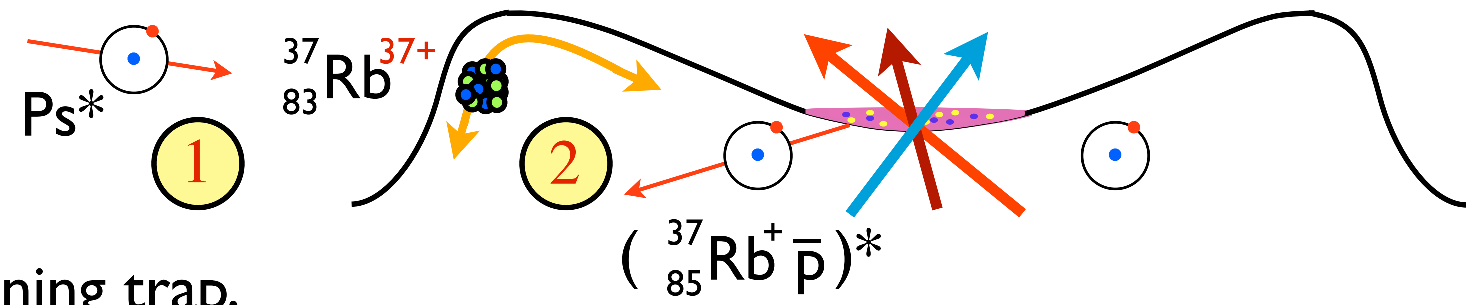
→ Penning trap mass spectrometry



AEḡIS : a novel radioisotope production method



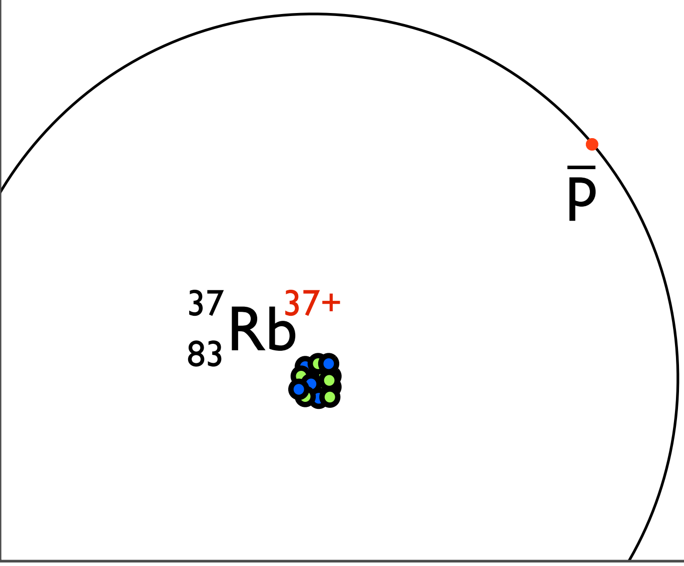
AE$\bar{g}$IS : a novel hollow atom(ic ion)



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

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

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



→ ***<u>Rydberg ionic atom</u> (electronic or antiprotonic) of a radio-isotopic HCI***

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

Summary:

Pulsed formation of $\overline{H}^*$ and Ps* now well under control; work on increased production rates, beam formation and interferometry has started.

Charge exchange processes between Rydberg systems and single charged particles provide <u>controlled</u> access to unique exotic systems, with which fundamental symmetries, nuclear physics and possible novel interactions can be explored.

thank you for your attention!

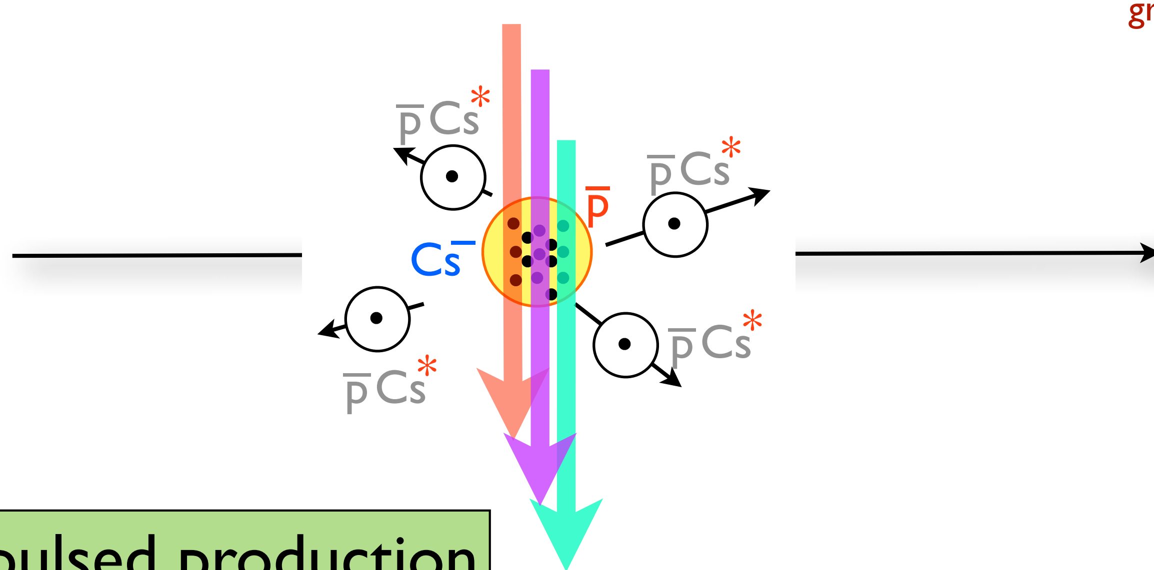
THE END

AE$\bar{g}$IS : meas^{ts} with pulsed-formed $\bar{p}$-Rydberg atoms

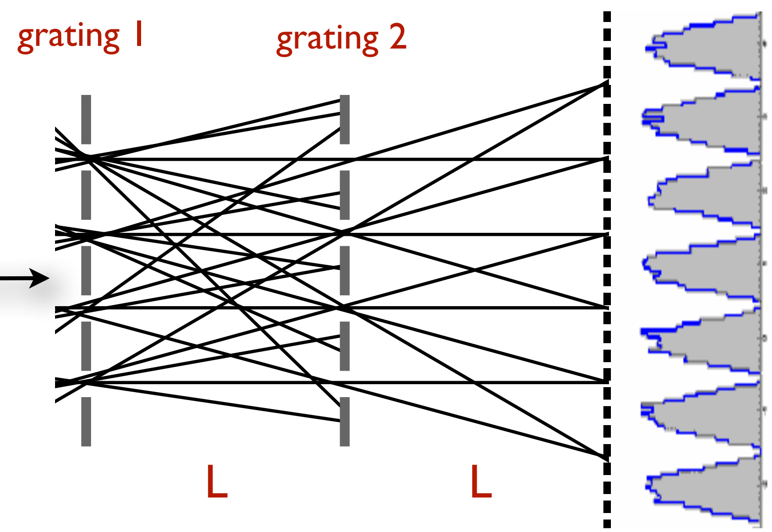
passing these neutral beams of antiprotonic atoms through gratings (*optical* gratings required for Rydberg atoms) may allow testing the WEP for a range of matter - antimatter systems (purely antimatter, purely leptonic, purely baryonic, ...)

$$Cs^- + \gamma + \gamma + \gamma \longrightarrow Cs^* + e^-$$
$$Cs^* + \bar{p} \longrightarrow \bar{p}Cs^*(n) + e^-$$

formation w/ $\bar{p}$ at rest
$Cs^- \longrightarrow \bar{p}Cs^*$ into 4π
$H^- \longrightarrow \bar{p}p^*$ into 4π



pulsed production



gravity measurement

Upgrade of AEgIS to AEgIS-2

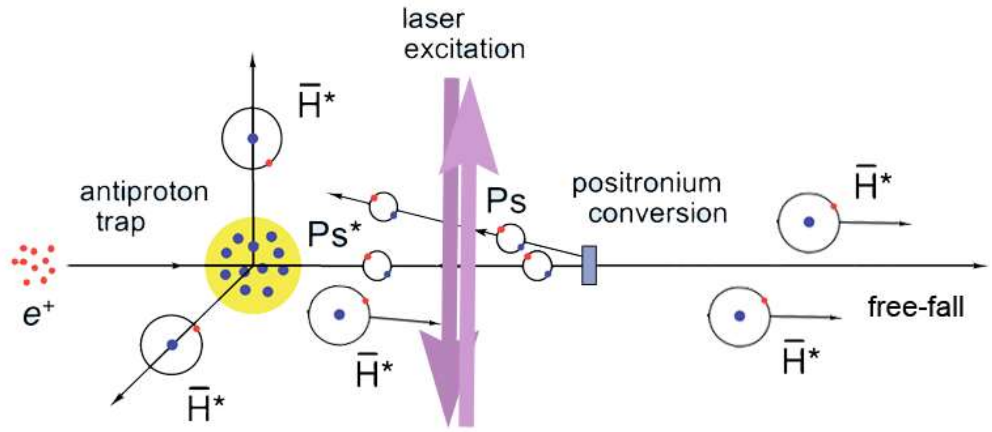
Main goal of AEgIS Phase 2: a first proof-of-concept inertial measurement with pulsed antihydrogen

Take-home messages from the AEgIS Phase 1

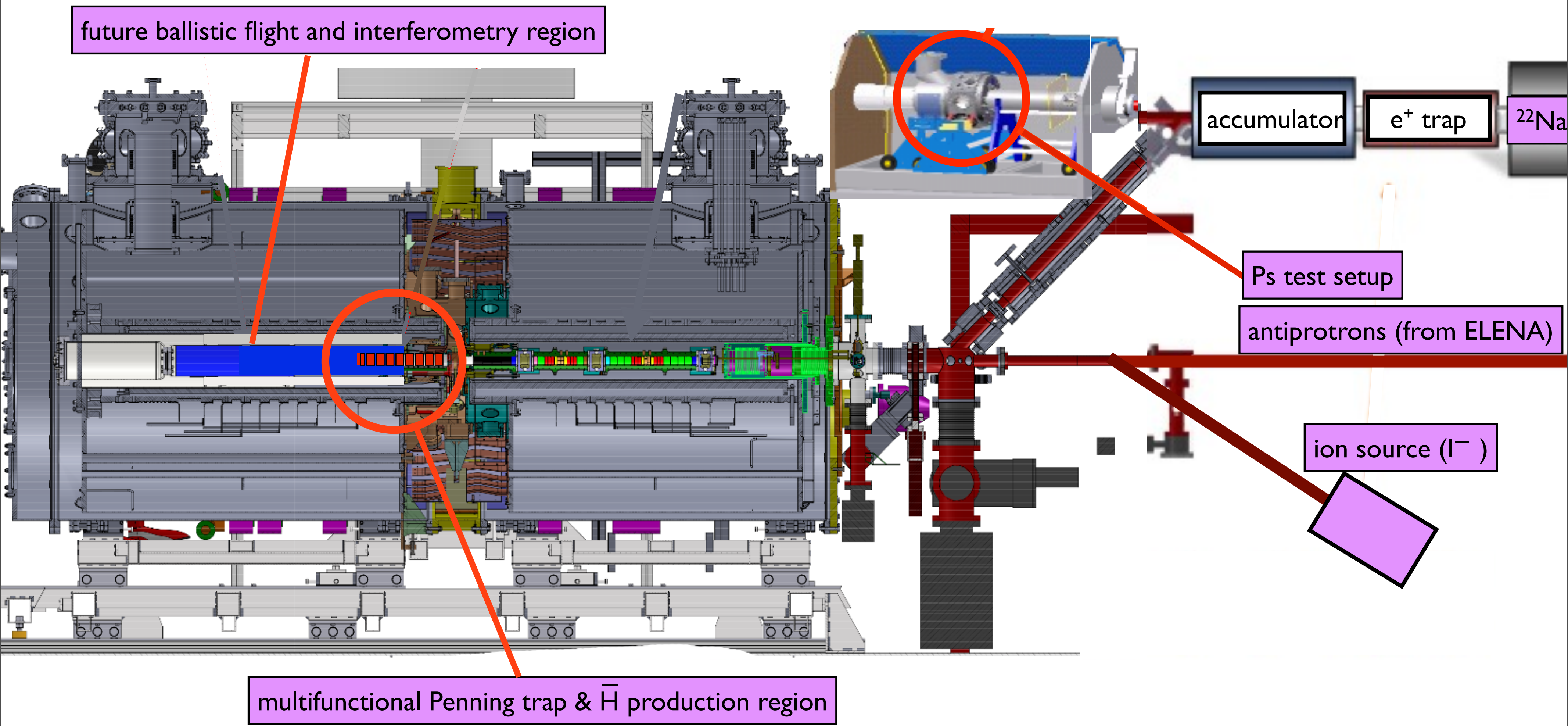
- The antihydrogen source intensity must be increased by 2 orders of magnitude
- The temperature of the produced atoms must be reduced by 1 order of magnitude
- The first gravitational measurement has to be designed to use Rydberg antihydrogens
- The free-fall should take place in the most homogeneous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

New AEgIS Phase 2 configuration

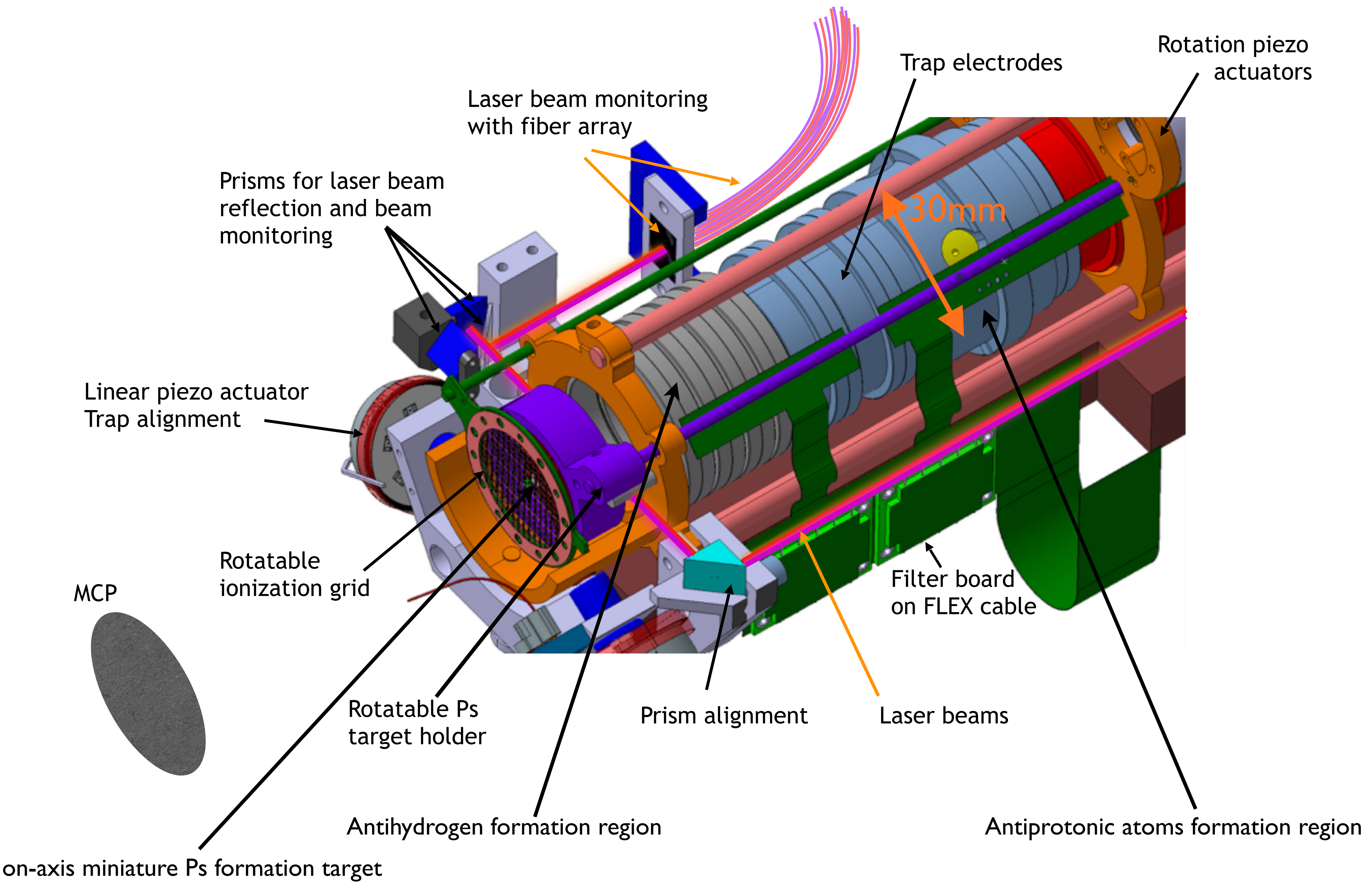
- Positronium conversion target on-axis
- Laser excitation in a Doppler-free scheme
- Positrons passing through resting antiprotons

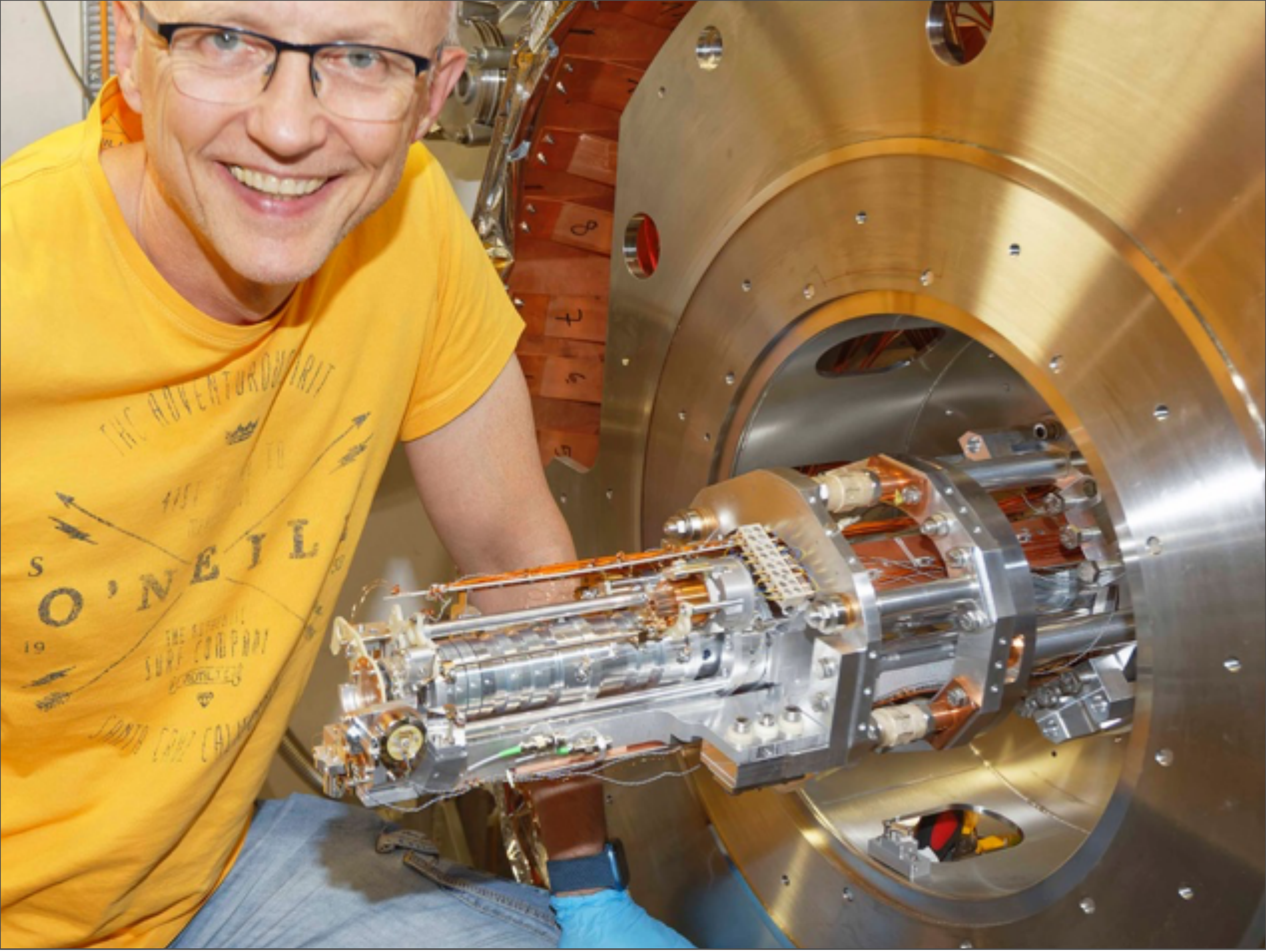


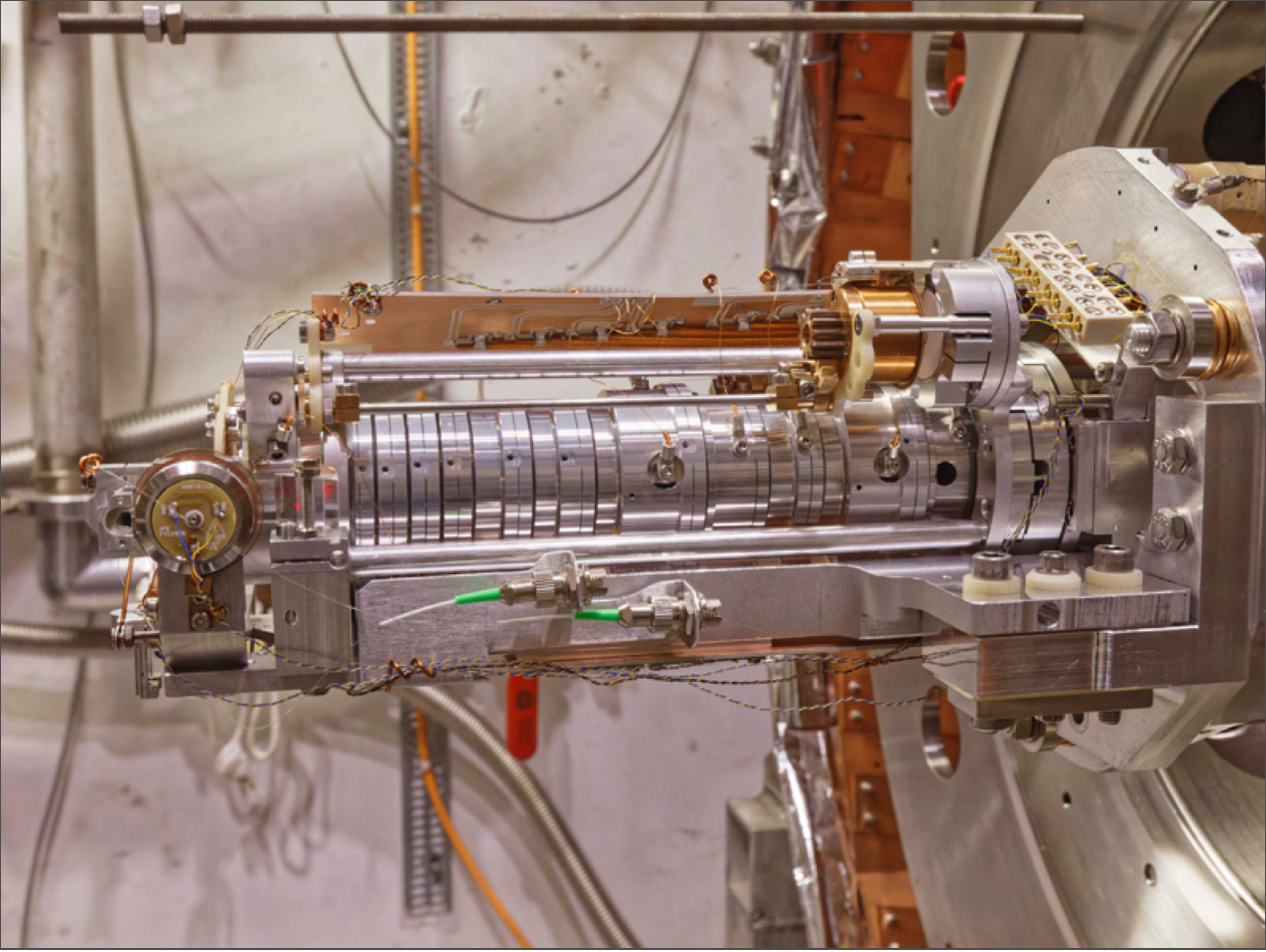
Upgrade of AEgIS to AEgIS-2

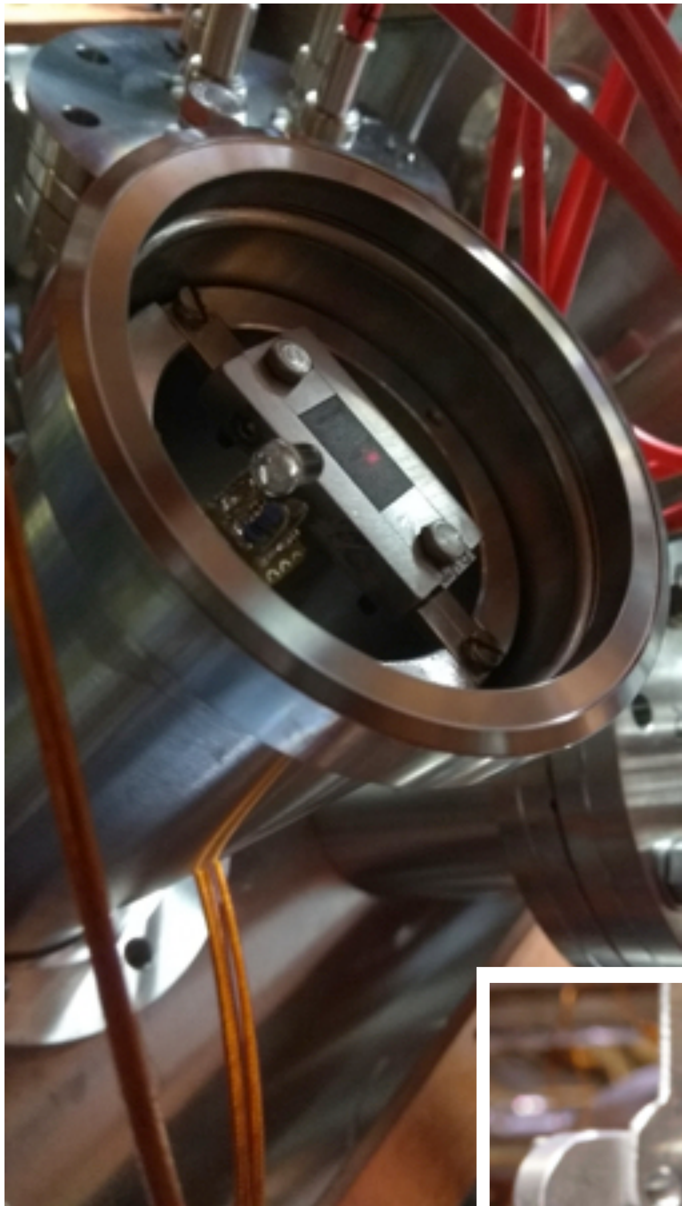


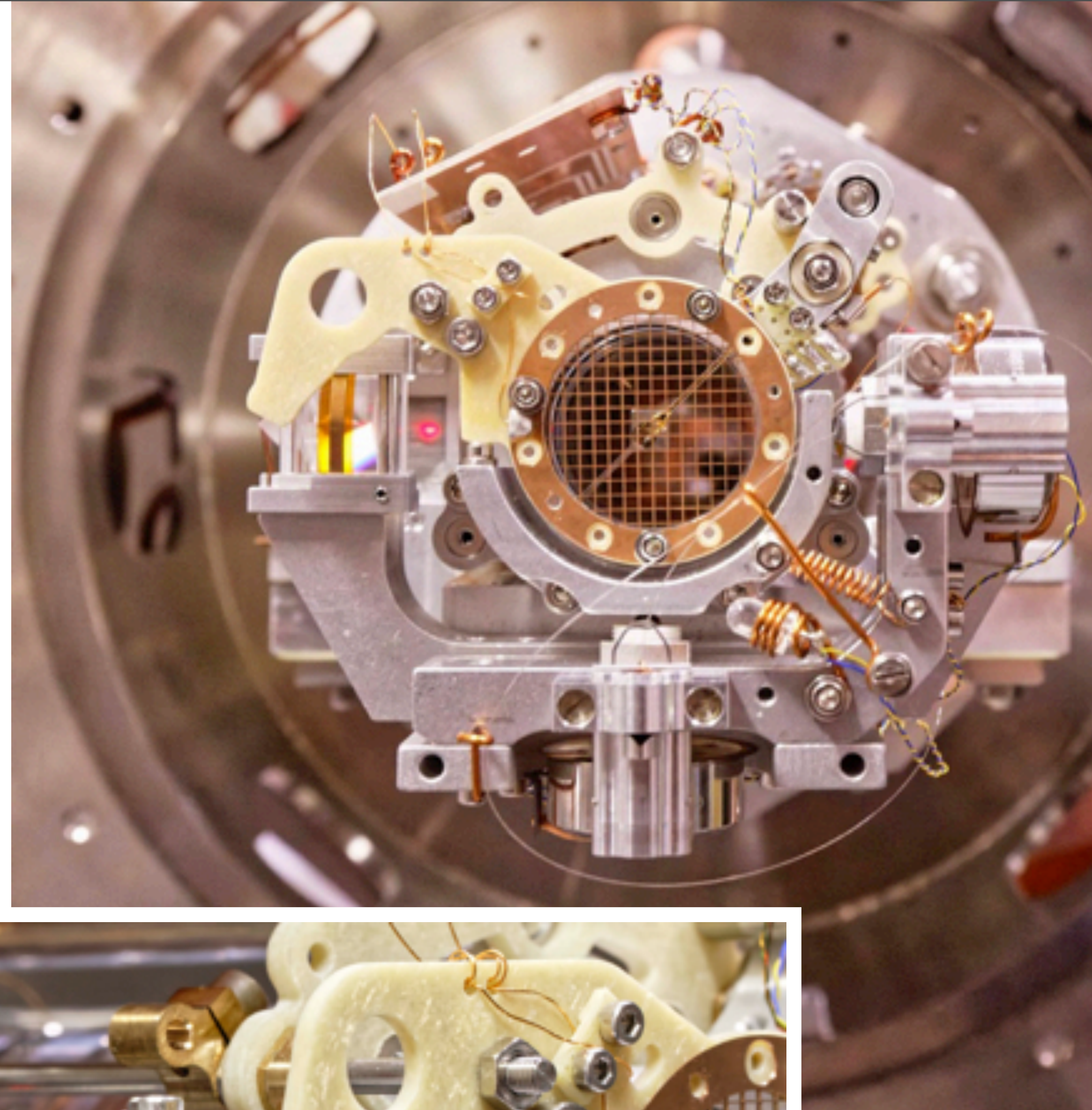
pulsed production of $\bar{H}$ (new geometry)











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.

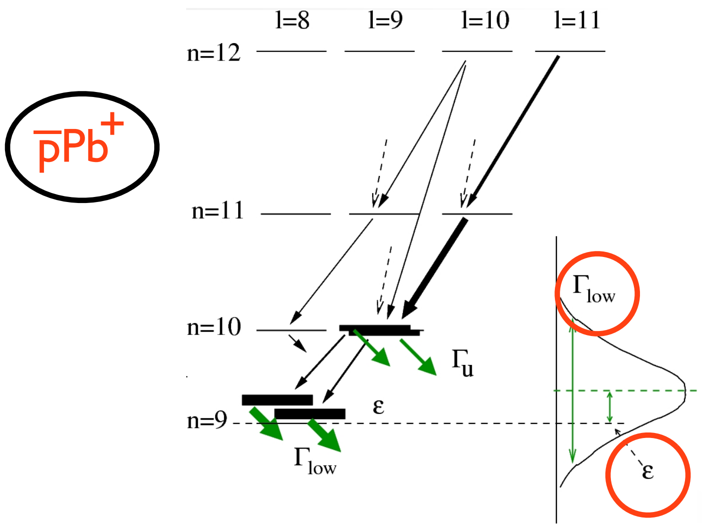
Probing the diffuse neutron halo at the nuclear surface with $\bar{p}$

nuclear physics: the PS209 experiment

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

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

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



strong interaction effects for lowest-lying bound states

→ shifting of energy levels,
→ change in lifetime of the state,
→ change in transition probabilities (intensities)

w.r.t. a pure QED reference value

→ annihilation radius, energy shifts

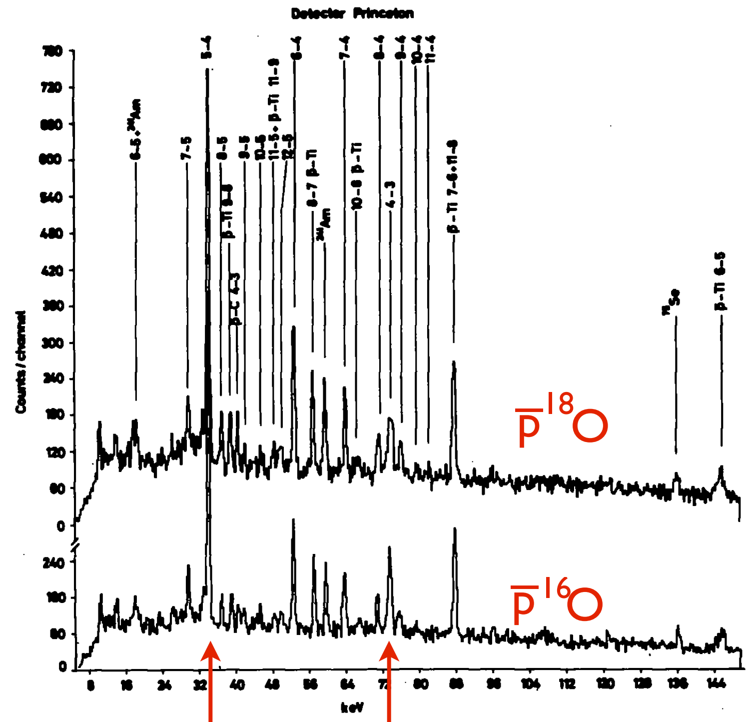
- with a radiochemical determination of the same nuclei (annihilation on n / p)

(in AEgIS : perhaps through TOF mass spectroscopy ?)

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

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

nuclear physics: isotopic effects



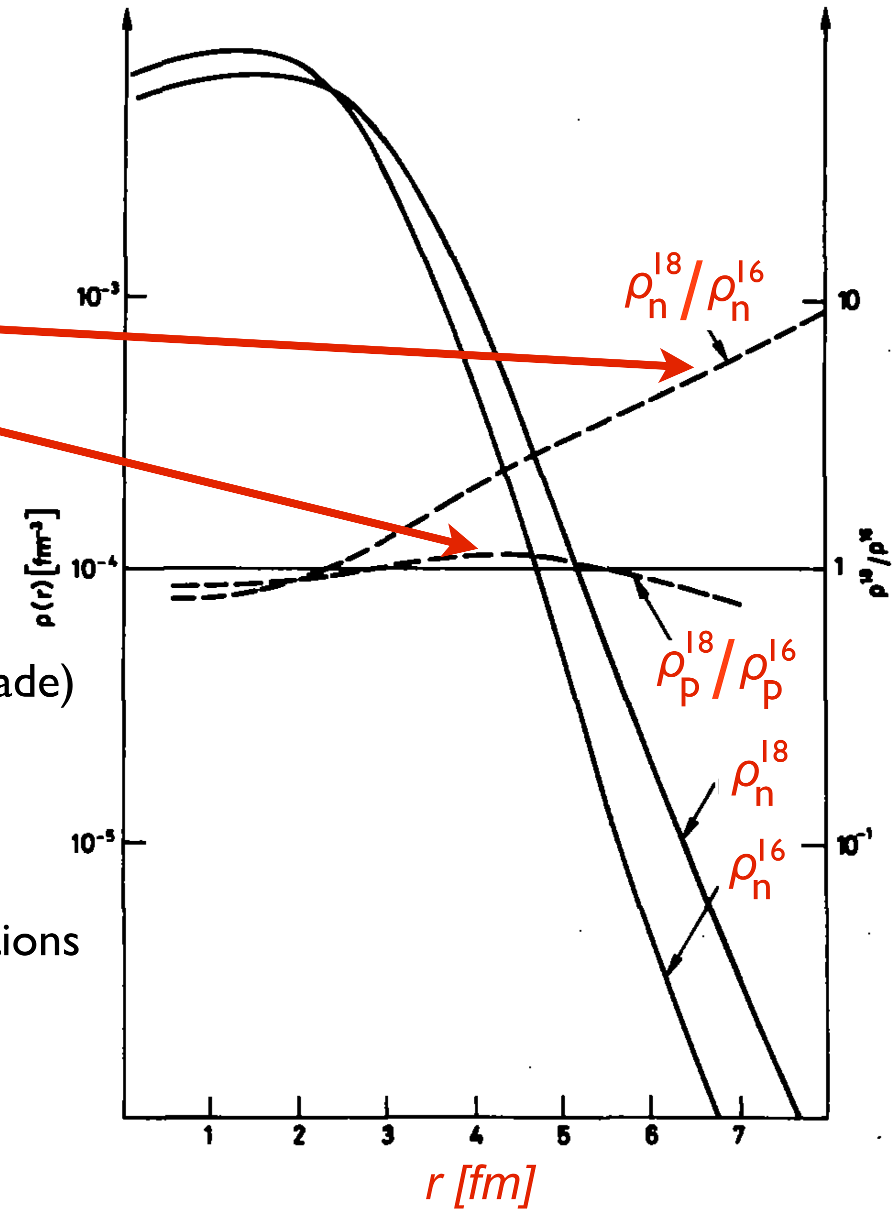
Nucleus	Last observable transition	Γ_{up} (eV)	Γ_{low} (eV)	ε_{low} (eV)
1	2	3	4	5
N	4 → 3	0.13±0.03 (0.10)	205±70 (144)	3±50 (− 31)
^{16}O	4 → 3	0.64±0.11 (0.62) [a]	320±150 (480) [a]	−124±36 (−111) [a]
^{18}O	4 → 3	0.80±0.12 (1.05) [a]	550±240 (659) [a]	−189±42 (−167) [a]
P	5 → 4	1.14±0.25 (1.42)	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

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

nuclear physics

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

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



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

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

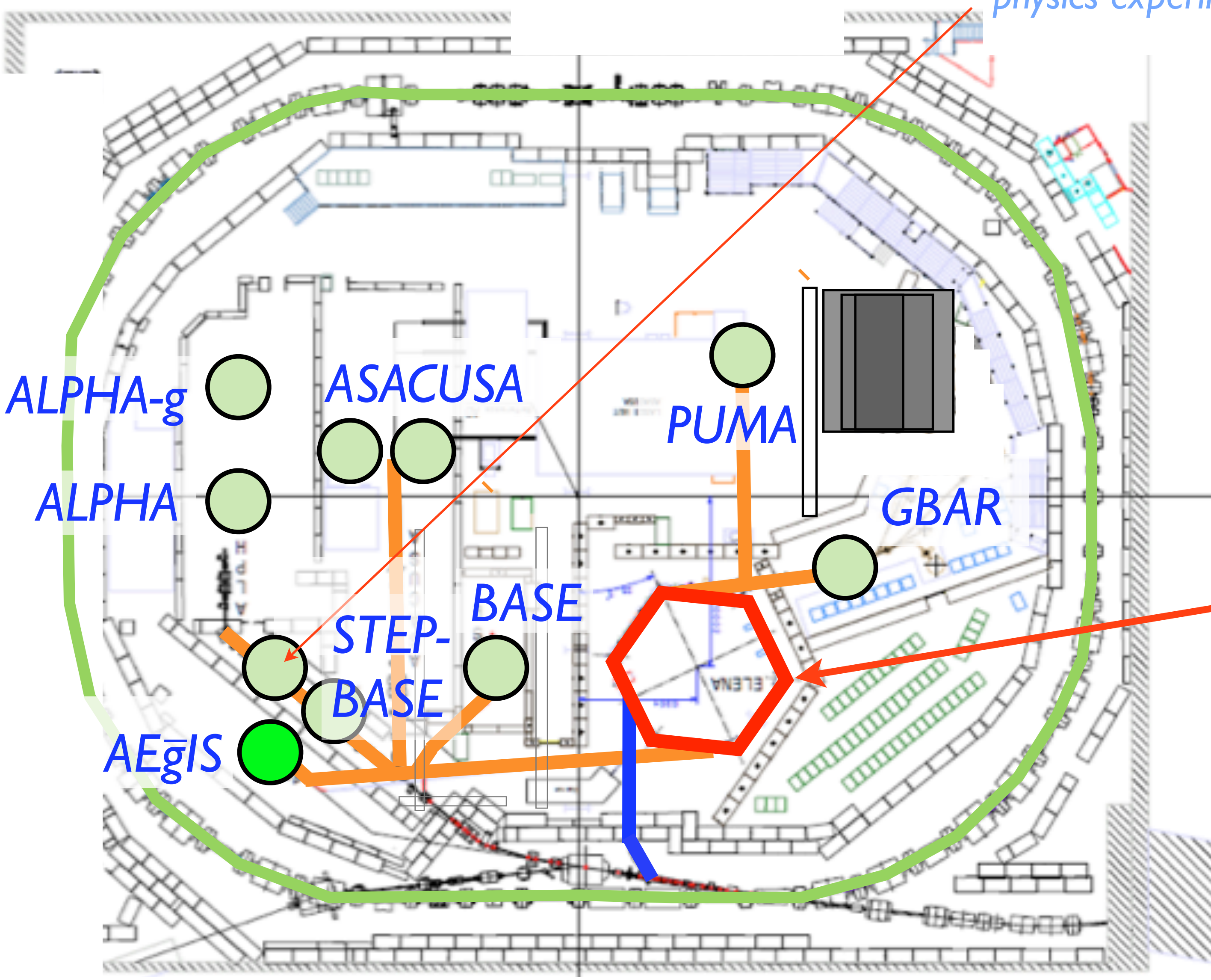
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0\,.$$

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

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