Antiprotonic atoms as a gateway system for BSM investigations

Michael Doser / CERN Ascona 5/7/23

Disclaimer!

(Almost) no experimental results;
Certainly no theoretical results;

Instead: suggestions for building potentially interesting systems in which BSM might be probed differently than in existing systems - IOW: *speculative*

a few words on charge exchange processes

starting with ground state atoms:

charge exchange: $(A^+e^-) + x^- \rightarrow (A^+x^-)^*_n + e^-$

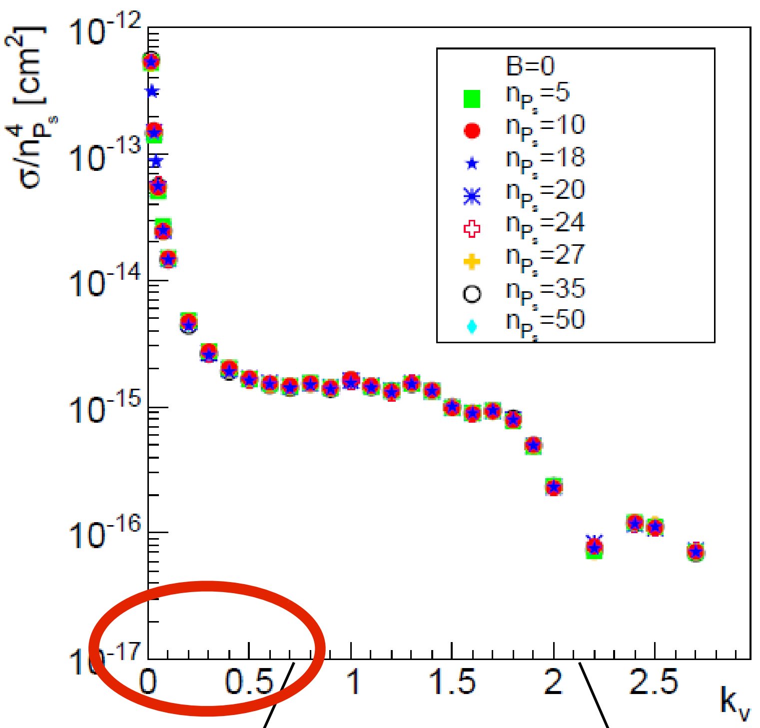
starting with Rydberg atoms:

for antiprotons: $X^*_n + \bar{p} \rightarrow \bar{p}X^*_{n'} + e^-$

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

why Rydberg systems ?

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



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

FIG.2: Normalized cross section

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

high n

low relative velocity

t_0

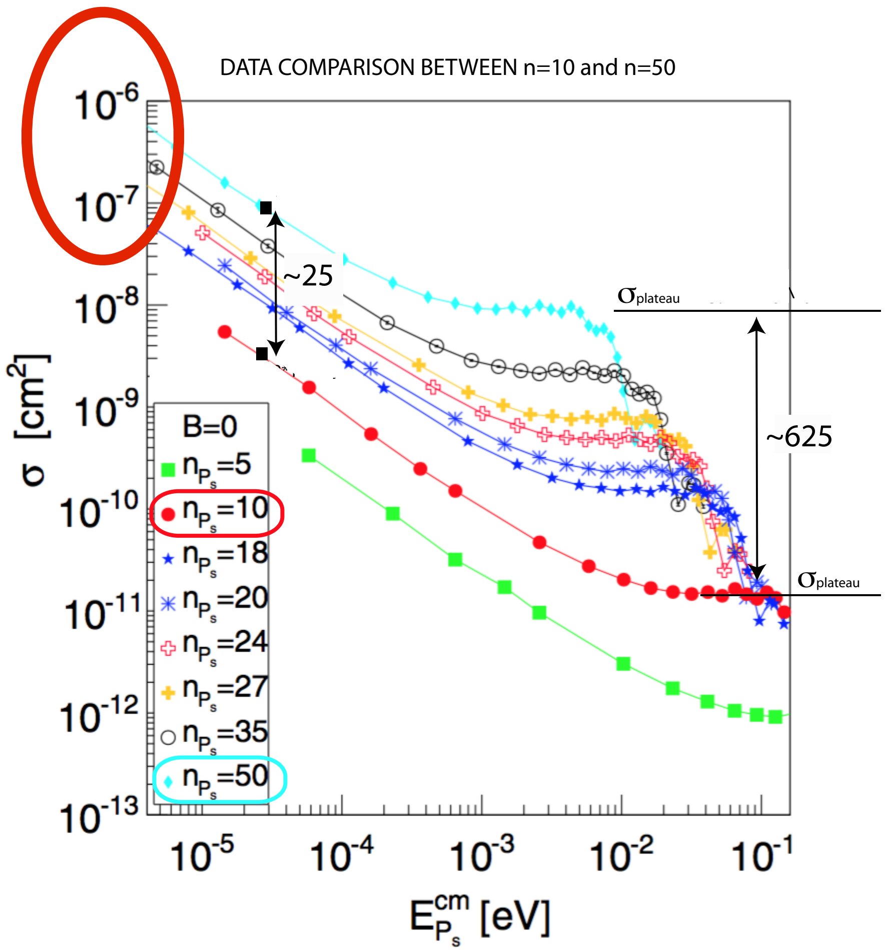


FIG. 3. Charge-exchange cross section σ as a function of the P_s center-of-mass energy. The plot shows the same points of Fig. 2. The lines simply connect the points to help the graphical interpretation.

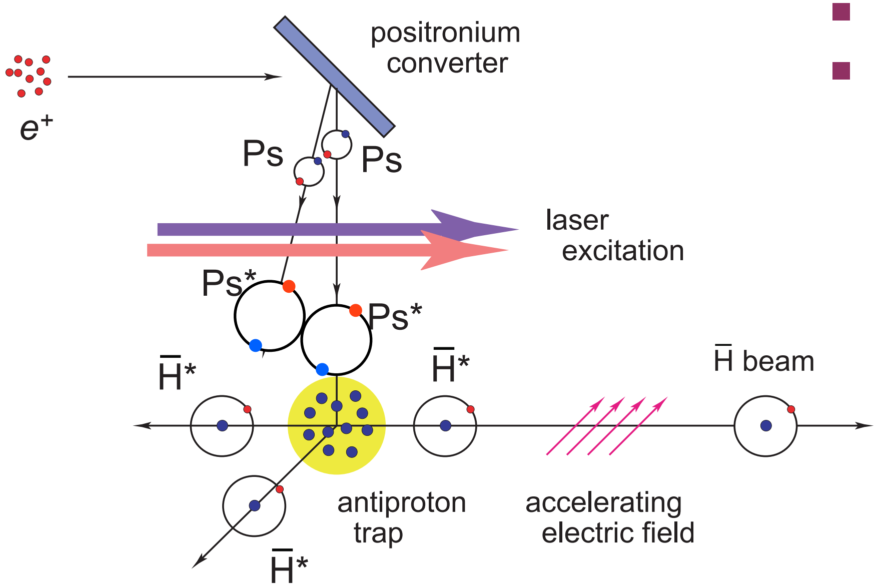
D. Krasnicky, C. Canali, R. Caravita, G. Testera, Phys. Rev. A 94, 022714 (2016)

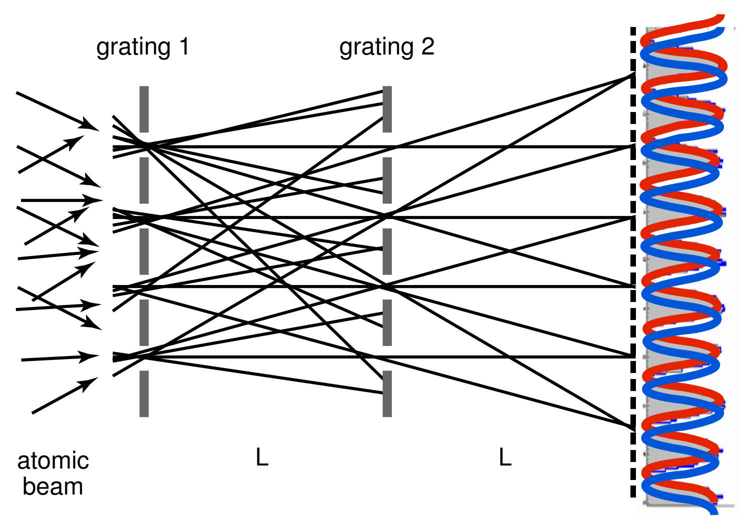
An example: AE$\bar{g}$IS (Antimatter Experiment: gravity, Interferometry, Spectroscopy)

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



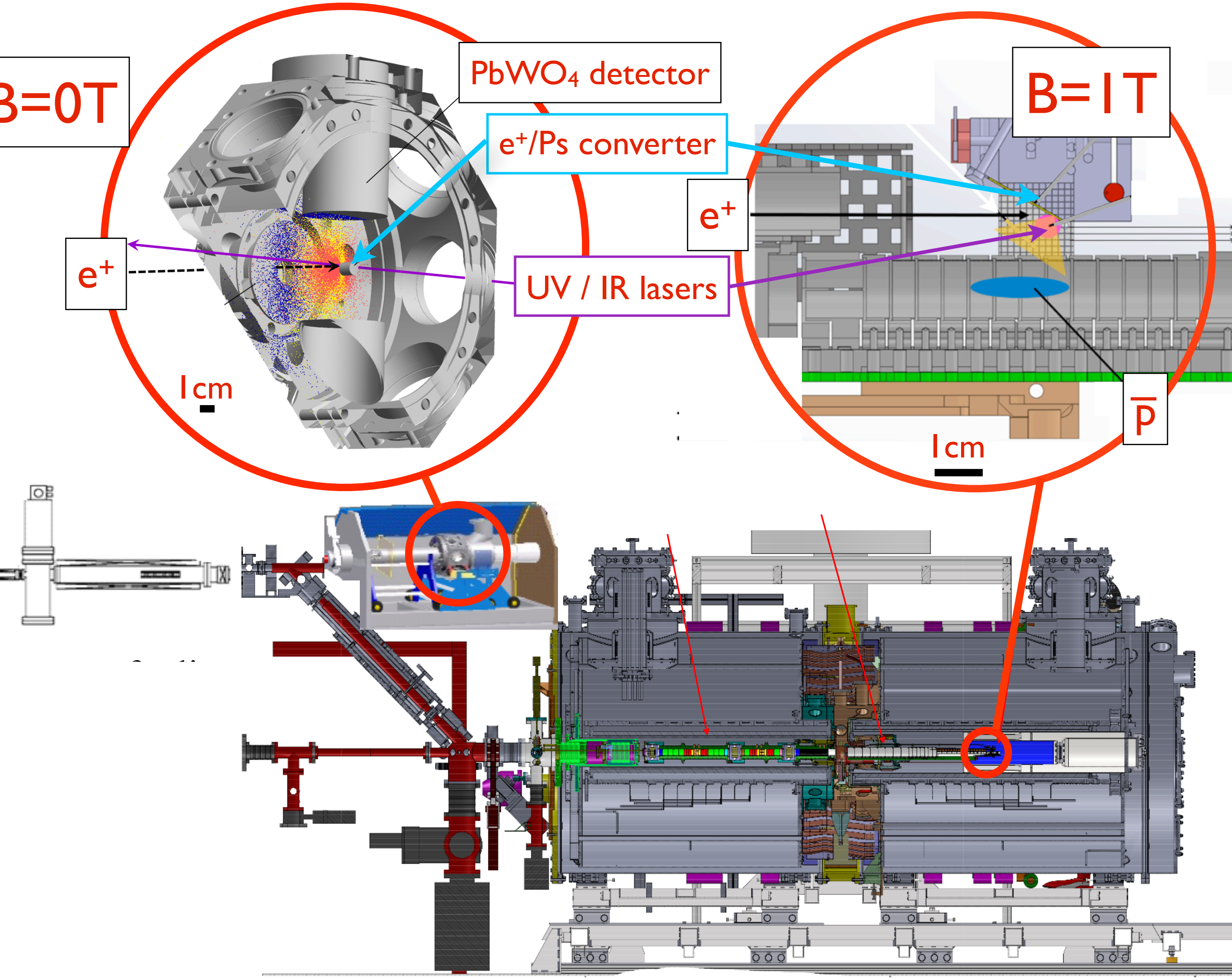


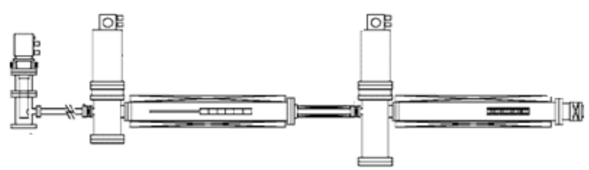
pulsed production of $\bar{H}^*$

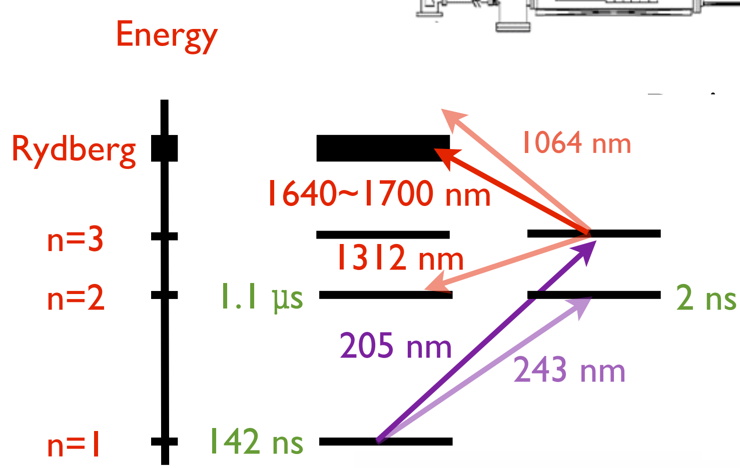
horizontal beam formation

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

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

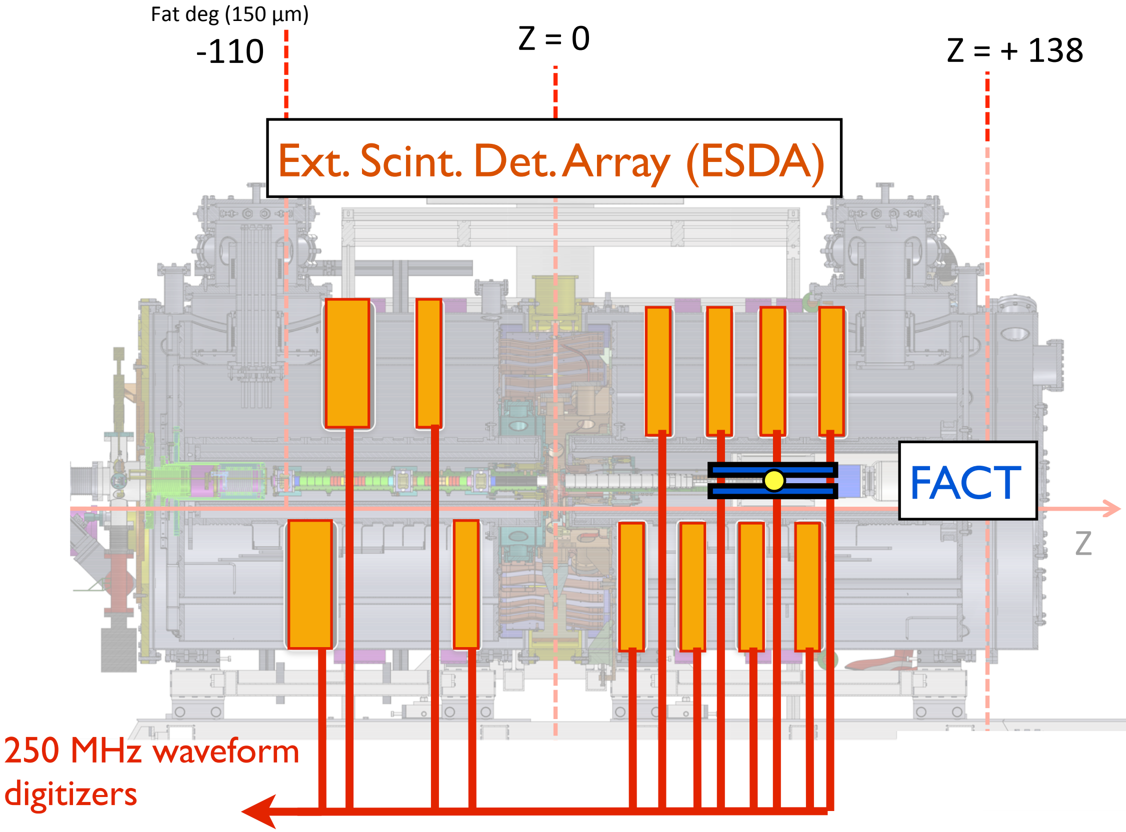
Velocity selected production of 2^3S metastable positronium → beam of meta-stable Ps

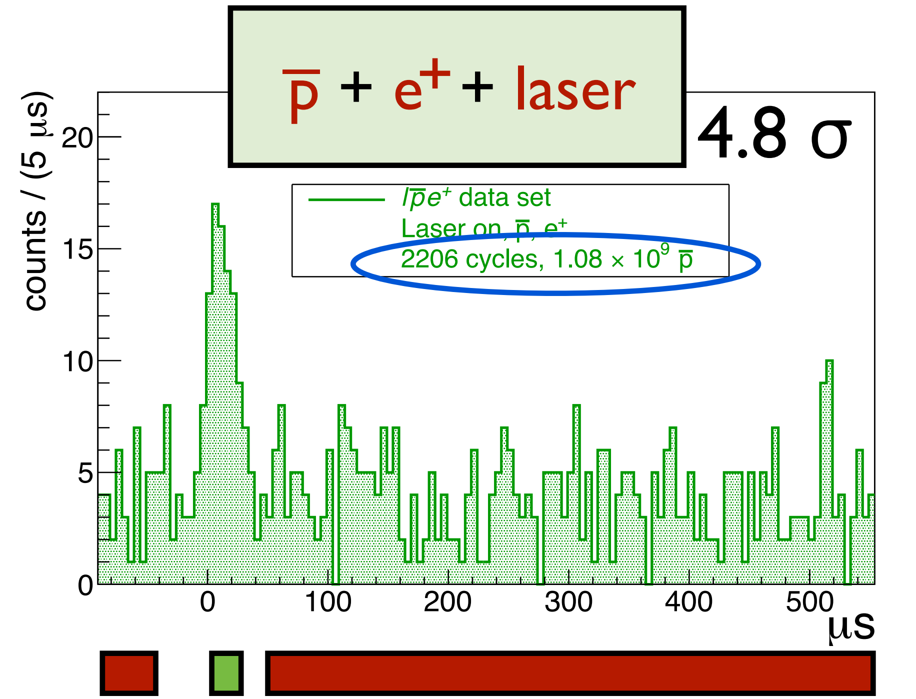
Pulsed production of $\bar{H}$ in 2018

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

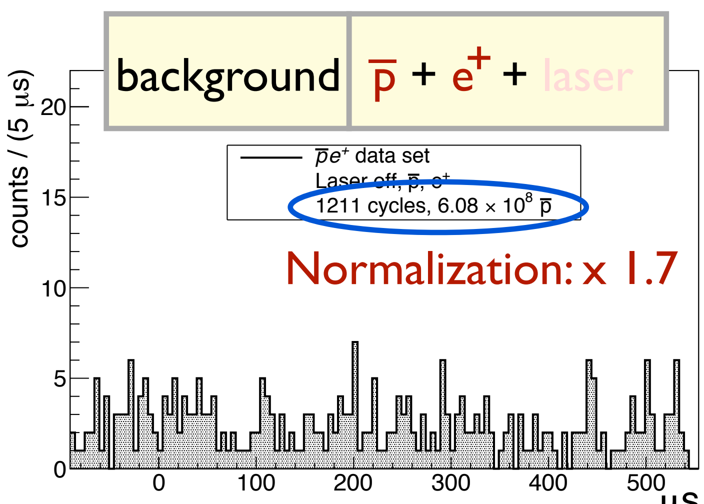
$\bar{H}$ detectors: scintillating slab array (mips), FACT (vertex tracker)

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

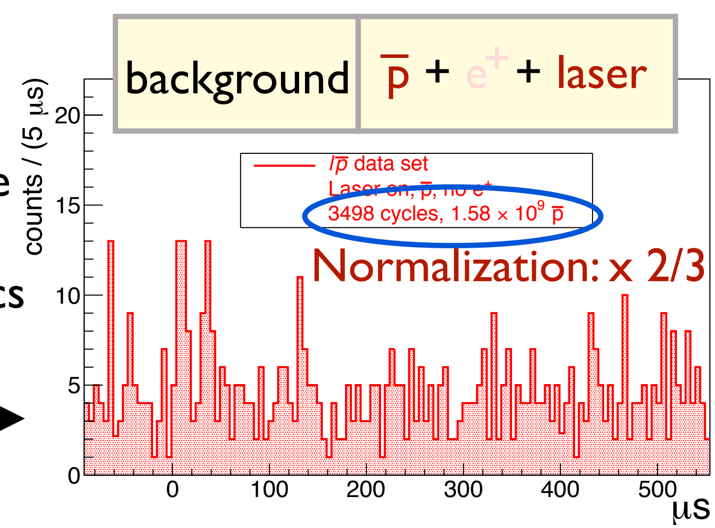




excess in signal region [1, 26 μs]



long time average rate compatible with cosmics rate



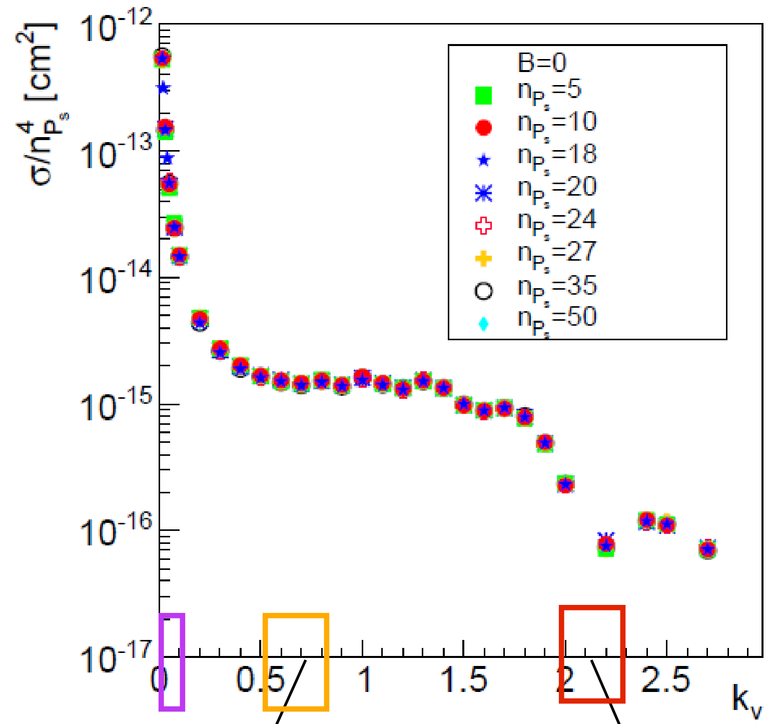
= 0.05 $\bar{H}$ / cycle

in 2023:

- rate x 1000
- pulsed beam

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

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



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

Why so low?

- $T_{\bar{p}}$ ~ 1000 K, v_{Ps} ~ 10^5 m/s
- n_{Ps} ~ 18
- $\#_{\bar{p}}$ ~ 10^5 , $\#_{Ps^*}$ ~10^5

How to improve?

(for antiprotonic systems: $X^*_n + \bar{p} \rightarrow \bar{p}X^*_{n'} + e^-$)

- $T_{\bar{p}}$ ~ 1~10 K, T_X ~ 1~10K
- $n_X \gg 18$
- $\#_{\bar{p}} \gg 10^5$,$\#_{X^*} \gg 10^5$

= 0.05$\bar{H}$ / cycle

in 2023:

- rate x 1000
- pulsed beam

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

- antiprotonic Rydberg atoms and ions (with $\bar{p}$ instead of e^-)
  - trapped fully stripped HCI's of radio-isotopes

spectroscopic tests of QED, search for BSM interactions, investigation of novel trapped radioisotopes (nuclear physics, masses, transitions)

- antiprotonic molecules ($\bar{H}_2^-$, others ?)

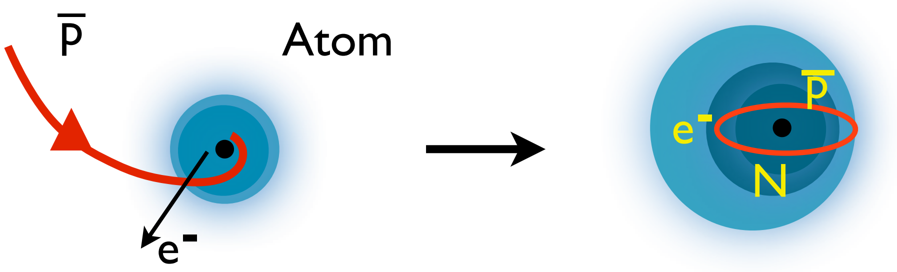
spectroscopic tests of CPT, QED, search for $\bar{p}$EDM

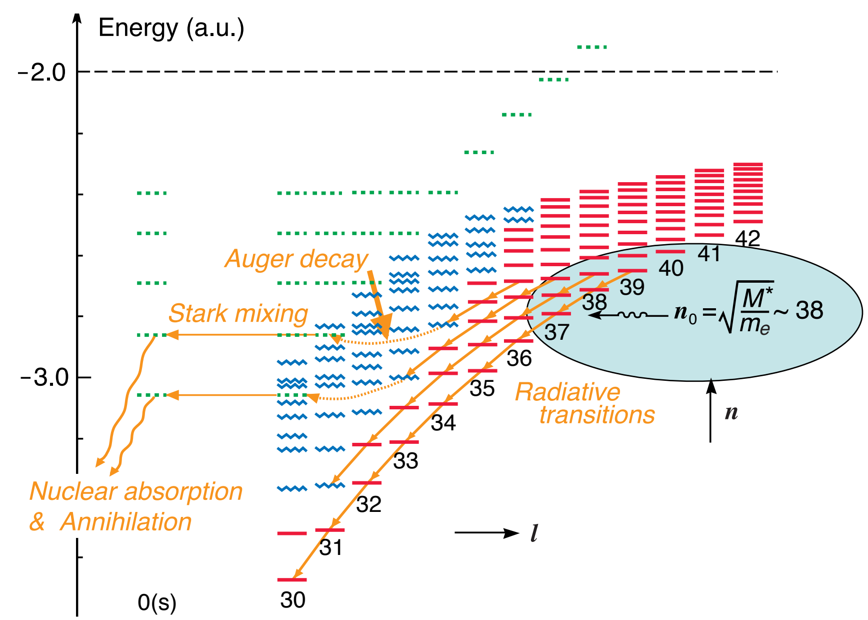
- search for a novel dark matter candidate

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/gaseous target material

consequence: only p̄He metastable states; all other antiprotonic atoms cascade rapidly (O(ns))
Stark mixing via collisions with other atoms ⟶ only fluorescence spectroscopy is possible
Annihilation from high nS states very likely

AEgIS : heavier "long-lived" 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 1 antiprotons, photo-detachment of electron 2

Temperature $\bar{p}$ ~ 10 K, X^- ~ 10 K, $\bar{p}X^{(+)*}$ ~ 10 K

→ *fluorescence spectroscopy* of Rydberg antiprotonic atoms

→ clean cascade (vacuum → no Stark mixing)

→ longer decay cascade (à la ASACUSA $\bar{p}$He)

X-rays in cascade of antiprotonic atoms

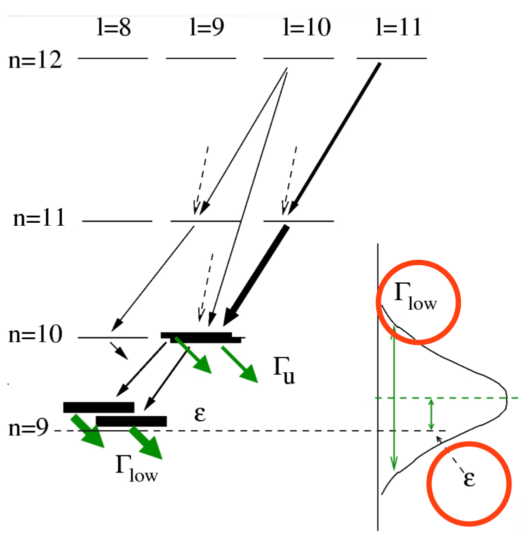
Annihilation with nucleus

3

Correlate measurements of:

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

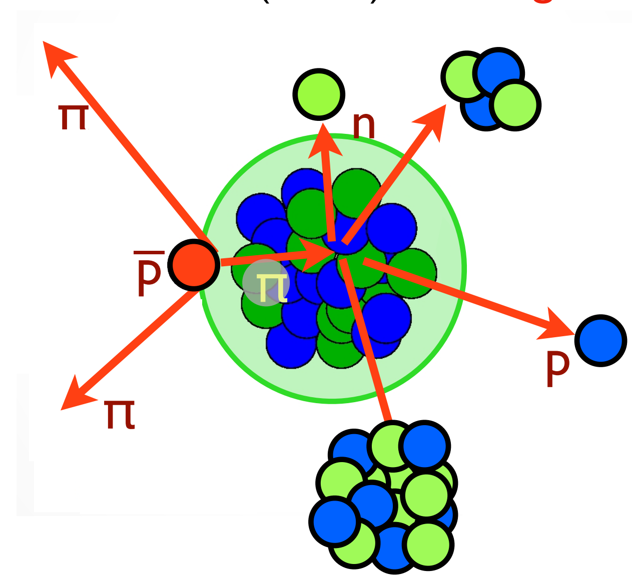
$\bar{p}Pb^{+}$



PUMA experimental program

4

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



fragmentation is not the dominant process
a wide swathe of radioisotopes with N,Z close to the mother nucleus can be produced

→ nuclear fragments highly charged, trappable

(production of trapped nuclear fragments also works if starting with cations)

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)

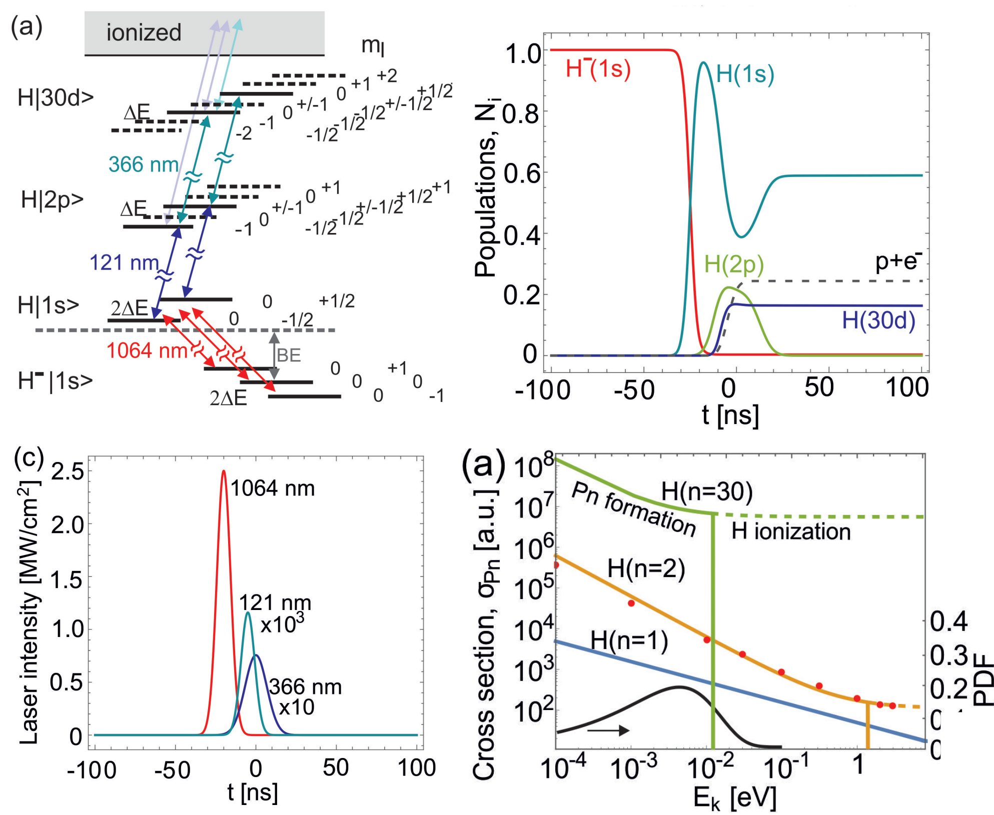
- co-trap H$^-$ (or D$^-$) and $\bar{p}$ in a Penning trap

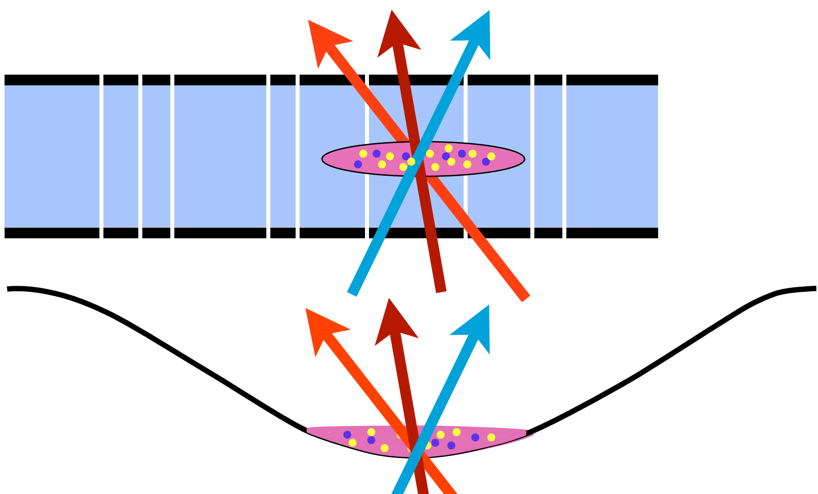
- photo-ionize H$^-$

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

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

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



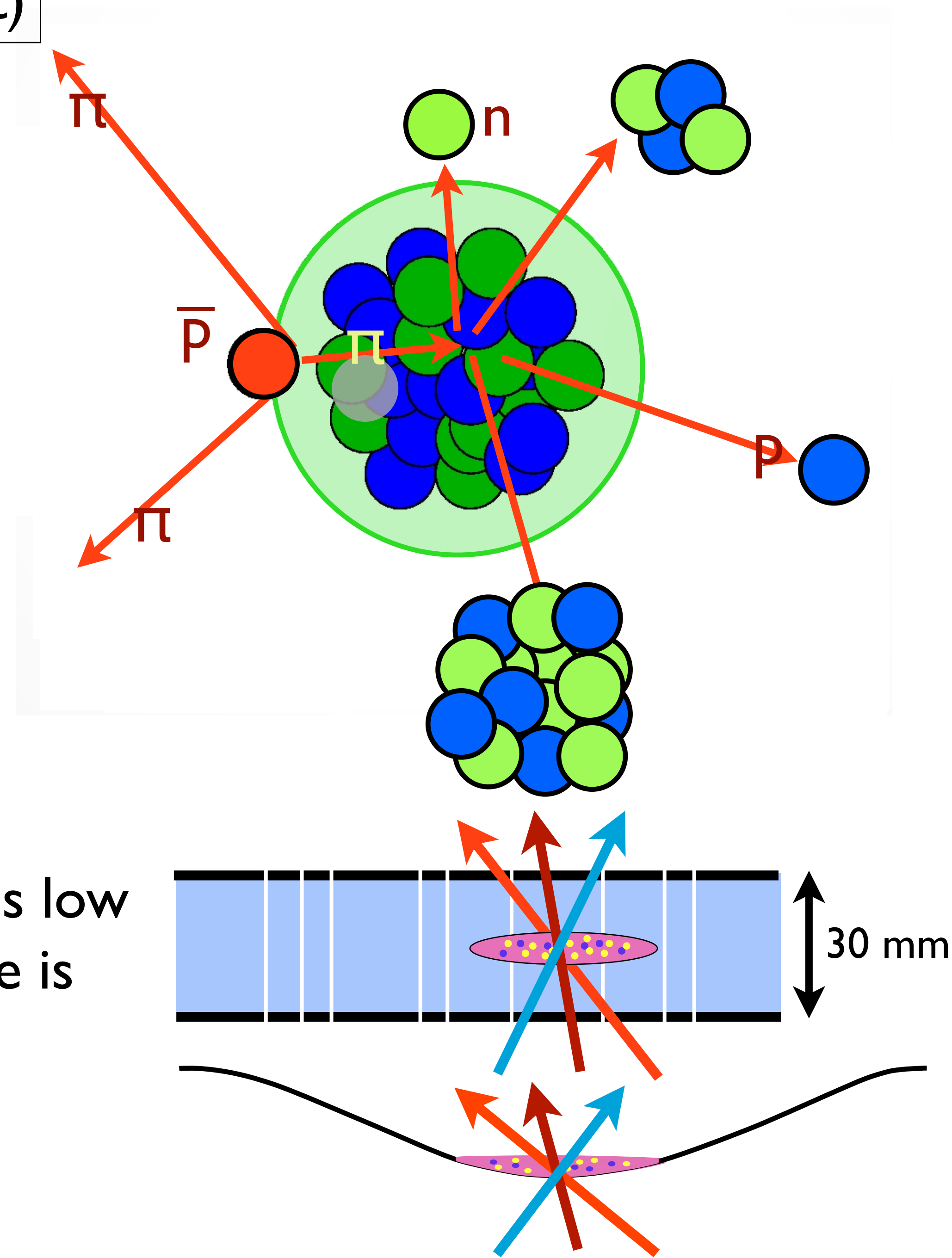


- or carry out experiments w/ long-lived protonium, e.g. test of the WEP, inertial sensing, ...

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

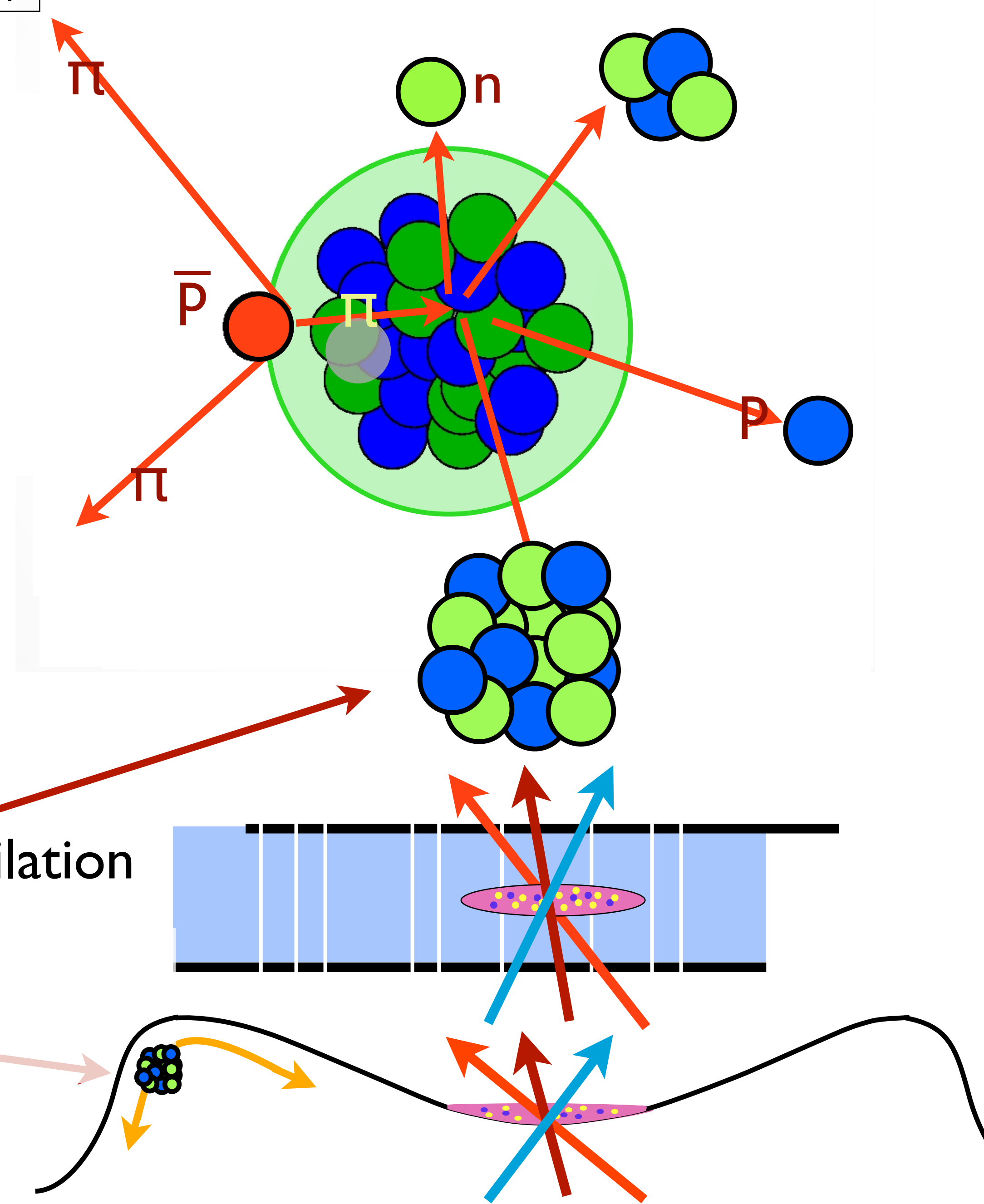


- co-trap Rb^- and $\bar{p}$ in a Penning trap (use stable $^{37}_{85}Rb$)
- photo-ionize Rb^-
- laser-excite Rb $\xrightarrow[2\gamma]{}$ Rb*(30)
- charge-exchange reaction:
  $Rb^*(30) + \bar{p} \rightarrow \bar{p}Rb(n) + e^-$ *(n~2000)*
- sympathetically-cooled Rb^- $\rightarrow$ $V_{\bar{p}Rb(n)}$ is low
  (Annihilation with Rb before electrode is reached)

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

(using Rb as an example starting point)

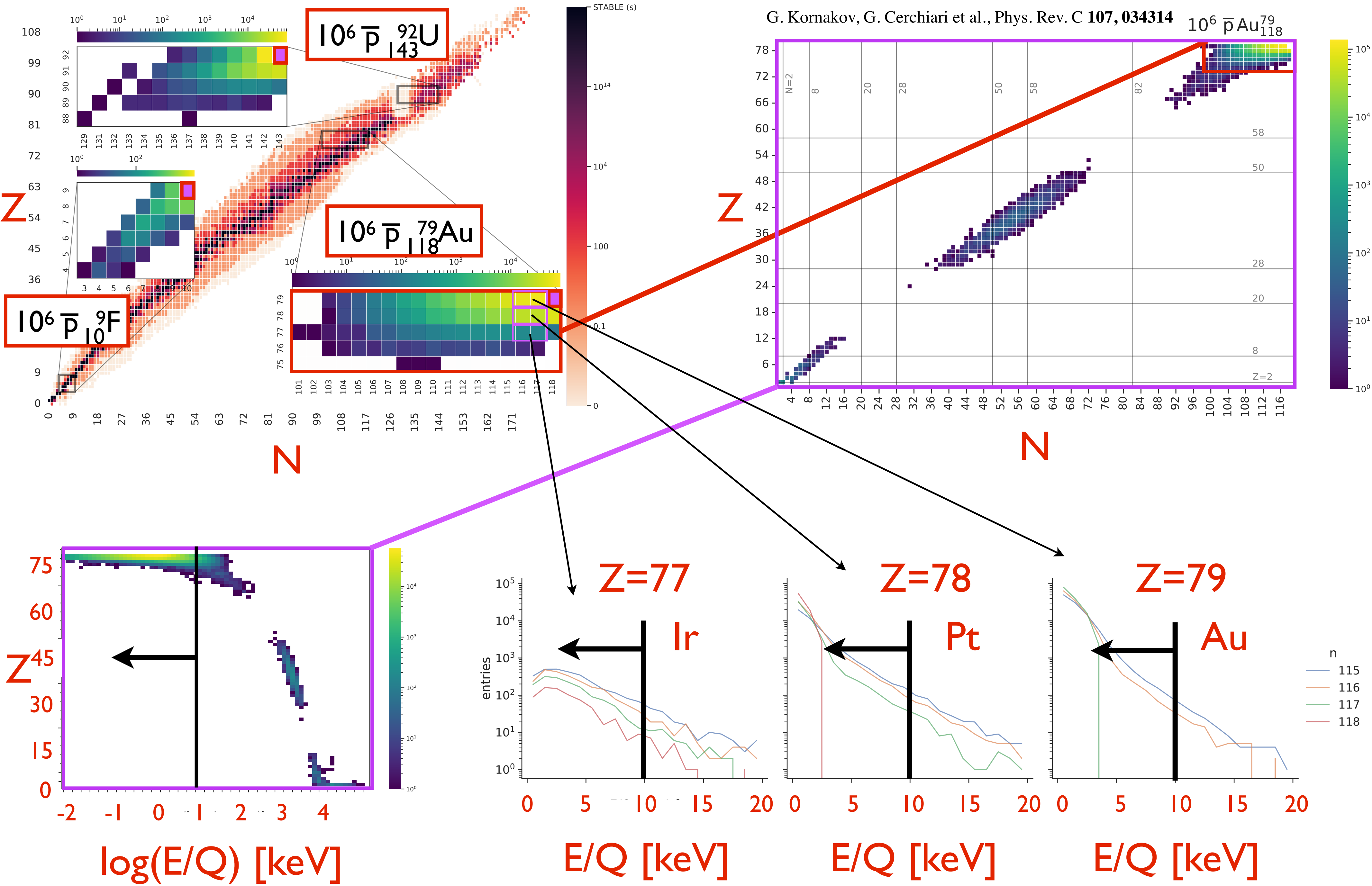
G. Kornakov, G. Cerchiari et al., subm. Phys. Rev. C



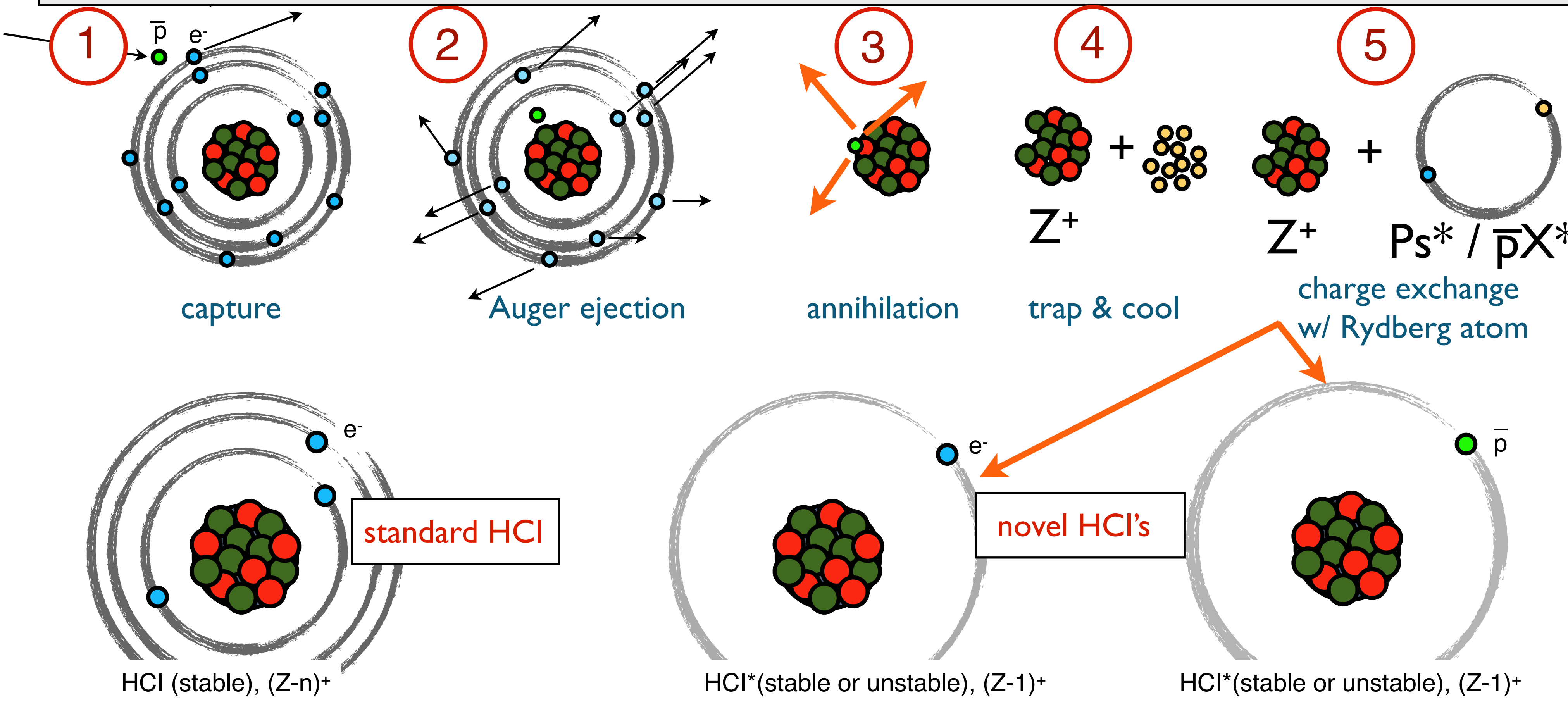
- co-trap Rb^- and $\bar{p}$ in a Penning trap (use stable ${}^{37}_{85}Rb$)
- photo-ionize Rb^-
- laser-excite Rb $\xrightarrow[2\gamma]{}$ Rb*(30)
- charge-exchange reaction:
  $Rb^*(30) + \bar{p} \rightarrow \bar{p}Rb(n) + e^-$ *(n~2000)*
- Auger-stripping, then peripheral annihilation
- trap nuclear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

→ Penning trap mass spectrometry

AEḡIS : a novel radioisotope production method



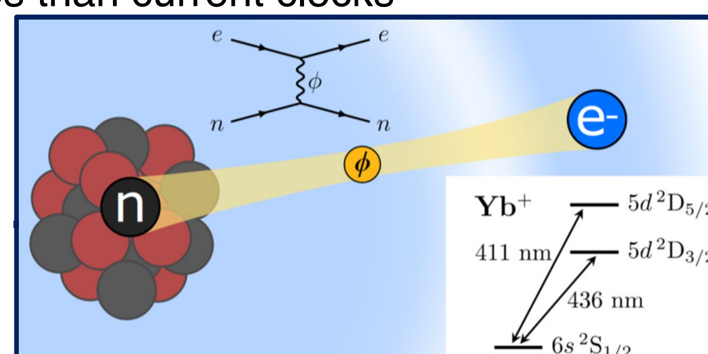
a novel Hydrogen-like hollow atom(ic ion): step-by-step



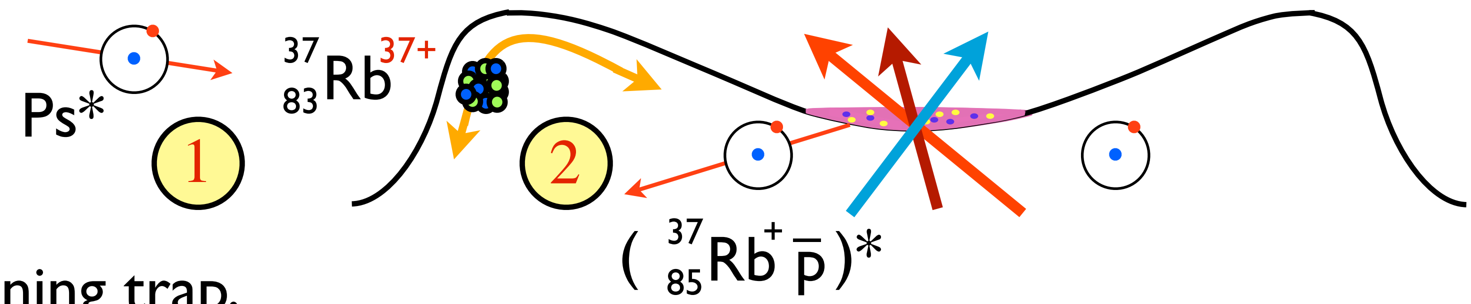
M. Doser, Prog. Part. Nucl. Phys, (2022), https://doi.org/10.1016/j.ppnp.2022.103964

HCIs: **much larger** sensitivity to variation of α and dark matter searches than current clocks

- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot



a novel Hydrogen-like hollow atom(ic ion): step-by-step



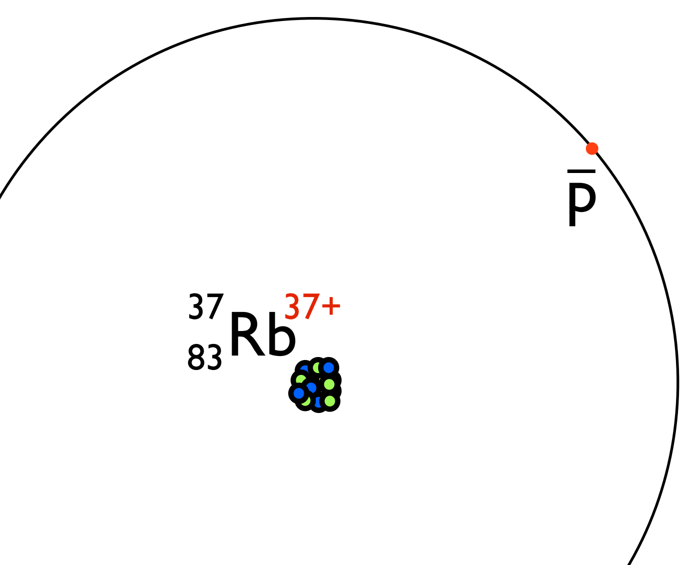
- in nearby Penning trap, produce Ps* (or $\bar{p}$Rb* again)

charge-exchange reaction 1:

$Ps^{*} + {}^{37}_{83}Rb^{37+} \longrightarrow {}^{37}_{83}Rb^{36+*} + e^{+}$

charge-exchange reaction 2:

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



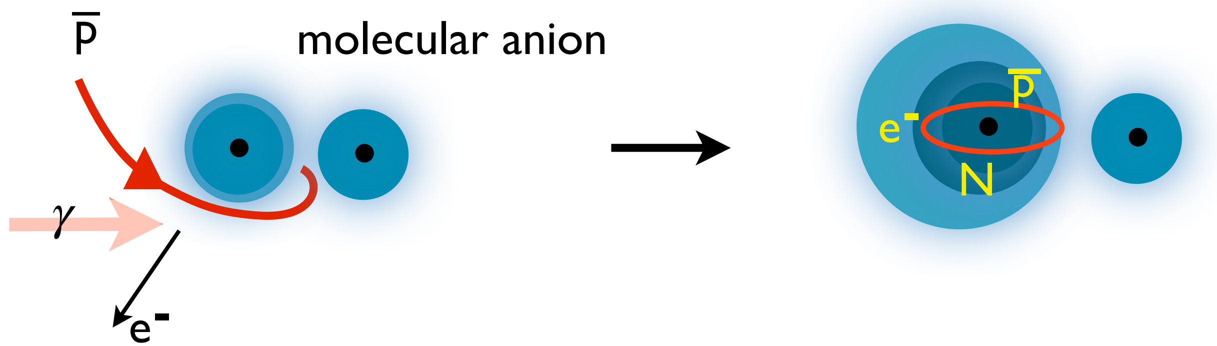
→ ***Rydberg ionic atom** (electronic or antiprotonic) of a radio-isotopic HCI*

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

Sympathetic cooling prior to charge exchange: ultracold hydrogen-like Rydberg HCI's

antiprotonic molecules:

formation process: as for antiprotonic atoms, i.e. possible co-trapping of $\bar{p}$ and anionic molecules, formation initiated by photo-detachment



but: antiproton rapidly selects one atom, resulting antiprotonic atom cascades rapidly (O(ns))

→ long lifetimes require Rydberg states

→ association of Rydberg atoms / ions (formed via charge exchange)

→ charge exchange with Rydberg molecule

molecules: very numerous very narrow transitions (molecular clock) ; $\bar{p}$EDM (à la RaF)

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

Three-body recombination

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

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

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

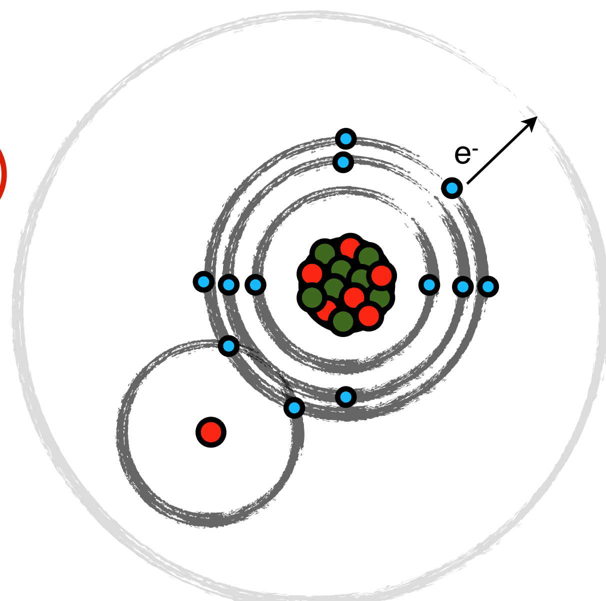
photo-associative Raman process (STIRAP) to combine atom & ion into a molecular ion ($Li + Cs^+ \rightarrow (LiCs)^+$)

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

formation of (other) antiprotonic Rydberg molecules

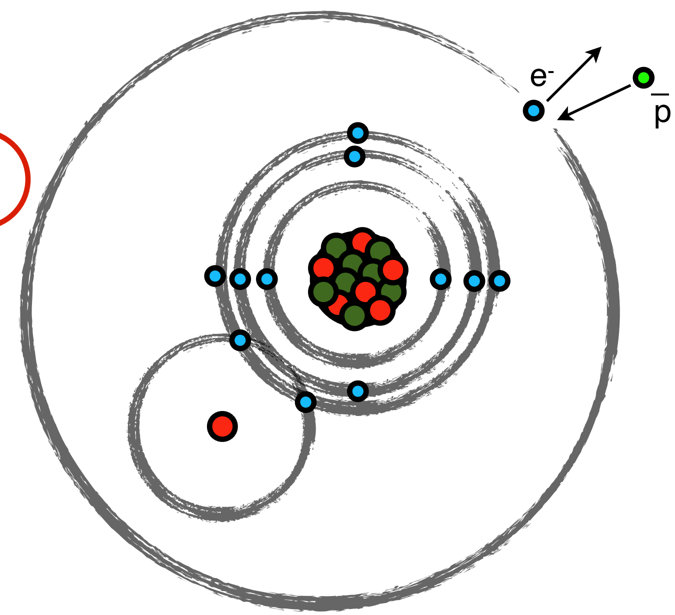
0 photo-detachment (if starting from an anionic molecule)

1



Rydberg excitation

2



charge exchange

further (trapped) antiprotonic Rydberg (ionic) molecules

- *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: $\bar{p}Cs^{(+)*} + \bar{p}p^* \longrightarrow \bar{p}\bar{p}p^* + Cs^+$ (???) — (Ps^-/Ps^+ analog)
  M. Emami-Razavi & J. Darewych, EPJD **75**, 188 (2021)

  $\bar{p}Cs^{(+)*} + \bar{p}p^* \longrightarrow \bar{p}\bar{p}Cs^{(2+)*} + p$ (?) — doubly antiprotonic Cs

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

$$X^- + X^- + \bar{p}\ HCI^{Z+*} \longrightarrow (\bar{p}\ HCI^{Z+*}X^-)_{\text{molecular ion}} + X^-$$

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

Antiatomic atoms : a novel dark matter search

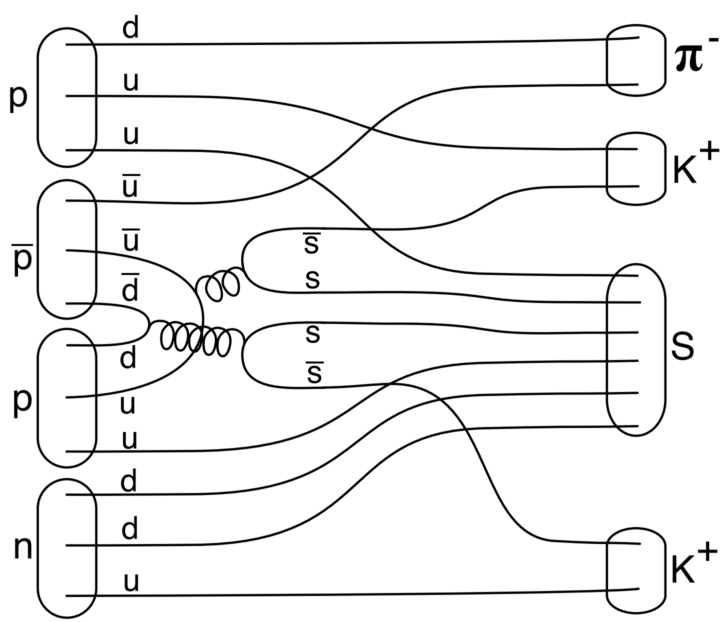
***sexaquark: uuddss bound state** ($m \sim 2m_p < 2m_\Lambda$)*

https://arxiv.org/abs/1708.08951

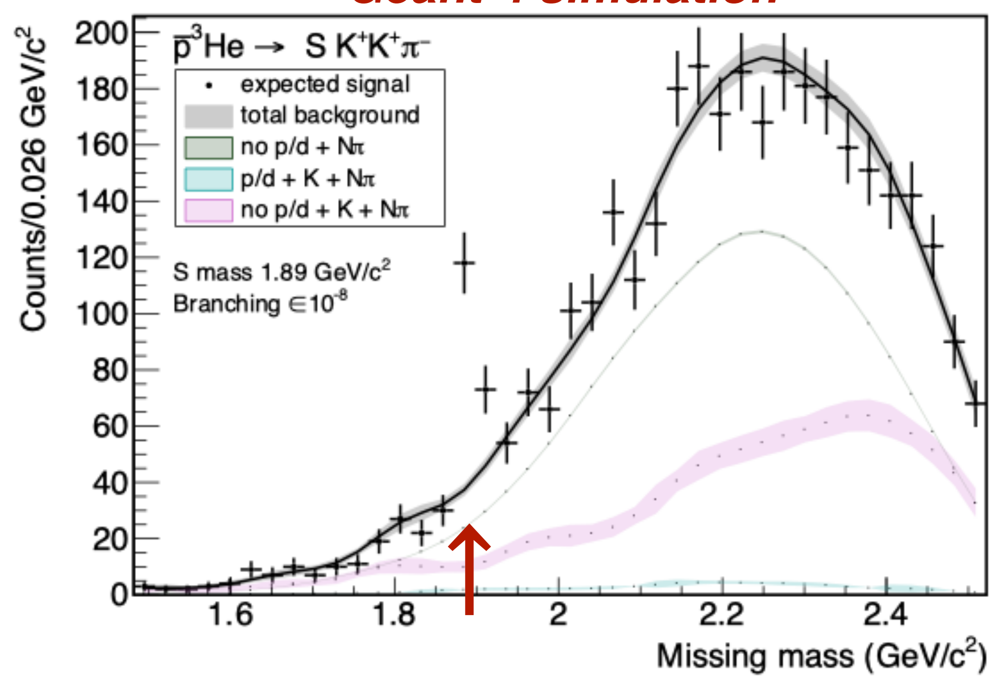
not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region
astrophysical bounds can be evaded
standard model compatible (uuddss bound state)

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

S= +2, Q= -1



Geant-4 simulation



https://arxiv.org/abs/2302.00759

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

→ ***sensitivity down to 10^{-9}***

Summary & outlook:

Charge exchange pulsed formation of $\overline{H}^*$ between Ps* and $\overline{p}$ is well under control; beam formation under work. Extendable to other Rydberg atoms.

Charge exchange processes between Rydberg systems and single charged particles provide controlled access to unique exotic systems, with which fundamental symmetries, nuclear physics, possible novel interactions or a specific dark matter candidate could be explored (admittedly sometimes at the price of quite some gymnastics...)

What's next? First attempts to valide the pulsed formation of few K antiprotonic atoms (using I^-), trapping of nuclear remnants, characterization of the trapped remnants (2024). Possibly additional anionic systems in 2024/2025 (including anionic molecular precursor states).

THE END

Antiatomic atoms : antineutron production

$$p + \bar{p} \not\rightarrow n + \bar{n}$$

Table 3
Selected annihilation reactions energetically compatible with $\bar{n}$ formation within or at the surface of the nucleus.

Reaction	Final state energy [u]	Lifetime of initial state isotope	Lifetime of final state isotope
$^{7}Be + \bar{p} \rightarrow$ "^{8}Li"	0.0022u	53 d	839 ms
$^{8}B + \bar{p} \rightarrow$ "^{9}Be"	0.0202u	730 ms	*stable*
$^{11}C + \bar{p} \rightarrow$ "^{12}B"	0.0049u	20 m	20 ms
$^{13}N + \bar{p} \rightarrow$ "^{14}C"	0.0103u	10 m	5730 y
$^{24}Na + \bar{p} \rightarrow$ "^{25}Ne"	0.0004u	15h	0.6 s
$^{33}P + \bar{p} \rightarrow$ "^{34}Si"	0.0004u	25 d	$<$ 210 ns
$^{40}Ca + \bar{p} \rightarrow$ "^{41}K"	0.008u	*stable*	*stable*
$^{212}Rn + \bar{p} \rightarrow$ "^{213}At"	0.0051u	24 m	125 ns
$^{216}Th + \bar{p} \rightarrow$ "^{217}Ac"	0.009u	27 ms	69 ns

Table 4
Selected annihilation reactions energetically compatible with free antineutron formation.

Reaction	Final state energy [u]	Lifetime of initial state isotope	Lifetime of final state isotope
$^{8}B + \bar{p} \rightarrow {}^{8}Be + \bar{n}$	0.0018u	770 ms	8 x 10^{-17}s
$^{11}C + \bar{p} \rightarrow {}^{11}B + \bar{n}$	0.0007u	20 m	*stable*
$^{15}O + \bar{p} \rightarrow {}^{15}N + \bar{n}$	0.0016u	122 s	*stable*
$^{18}F + \bar{p} \rightarrow {}^{18}O + \bar{n}$	0.0004u	109 m	*stable*
$^{22}Na + \bar{p} \rightarrow {}^{22}Ne + \bar{n}$	0.0015u	2.6 y	*stable*
$^{211}Rn + \bar{p} \rightarrow {}^{211}At + \bar{n}$	0.0013u	15 h	7 h
$^{216}Th + \bar{p} \rightarrow {}^{216}Ac + \bar{n}$	0.0009u	27 ms	0.4 ms

$$^{A}_{Z}N + \overline{p} \longrightarrow {}^{A}_{Z-1}N + \overline{n}$$

Deep annihilation? QGP?

Table 3
Selected annihilation reactions energetically compatible with $\bar{n}$ formation within or at the surface of the nucleus.

Reaction	Final state energy [u]	Lifetime of initial state isotope	Lifetime of final state isotope
$^{7}Be + \bar{p} \rightarrow$ "^{8}Li"	0.0022u	53 d	839 ms
$^{8}B + \bar{p} \rightarrow$ "^{9}Be"	0.0202u	730 ms	*stable*
$^{11}C + \bar{p} \rightarrow$ "^{12}B"	0.0049u	20 m	20 ms
$^{13}N + \bar{p} \rightarrow$ "^{14}C"	0.0103u	10 m	5730 y
$^{24}Na + \bar{p} \rightarrow$ "^{25}Ne"	0.0004u	15h	0.6 s
$^{33}P + \bar{p} \rightarrow$ "^{34}Si"	0.0004u	25 d	$<$ 210 ns
$^{40}Ca + \bar{p} \rightarrow$ "^{41}K"	0.008u	*stable*	*stable*
$^{212}Rn + \bar{p} \rightarrow$ "^{213}At"	0.0051u	24 m	125 ns
$^{216}Th + \bar{p} \rightarrow$ "^{217}Ac"	0.009u	27 ms	69 ns

Unbound low energy antineutrons?

Table 4
Selected annihilation reactions energetically compatible with free antineutron formation.

Reaction	Final state energy [u]	Lifetime of initial state isotope	Lifetime of final state isotope
$^{8}B + \bar{p} \rightarrow {}^{8}Be + \bar{n}$	0.0018u	770 ms	8 x 10^{-17}s
$^{11}C + \bar{p} \rightarrow {}^{11}B + \bar{n}$	0.0007u	20 m	*stable*
$^{15}O + \bar{p} \rightarrow {}^{15}N + \bar{n}$	0.0016u	122 s	*stable*
$^{18}F + \bar{p} \rightarrow {}^{18}O + \bar{n}$	0.0004u	109 m	*stable*
$^{22}Na + \bar{p} \rightarrow {}^{22}Ne + \bar{n}$	0.0015u	2.6 y	*stable*
$^{211}Rn + \bar{p} \rightarrow {}^{211}At + \bar{n}$	0.0013u	15 h	7 h
$^{216}Th + \bar{p} \rightarrow {}^{216}Ac + \bar{n}$	0.0009u	27 ms	0.4 ms