# The GBAR experiment and a measurement of the $\overline{\mathrm{H}}$ Lamb shift

Paolo Crivelli on behalf of the GBAR collaboration

Institute for Particle Physics and Astrophysics, ETH Zurich

EXA 2017, 11th of September 2017 – Vienna (Austria)

# Gravitational Behaviour At Rest (GBAR)

Approved @CERN in 2012
Collaboration: 18 Institutes and about 60 scientists

Irfu
Laboratoire Kastler Brossel
Physique quantique et applications
ETH Zürich
P.N.Lebedev Physical Institute of the Russian Academy of Science
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

IPCMS
Swansea University
Prifysgol Abertawe
ILL
NEUTRONS FOR SCIENCE®
Institut Laue-Langevin
Stockholm University
RIKEN

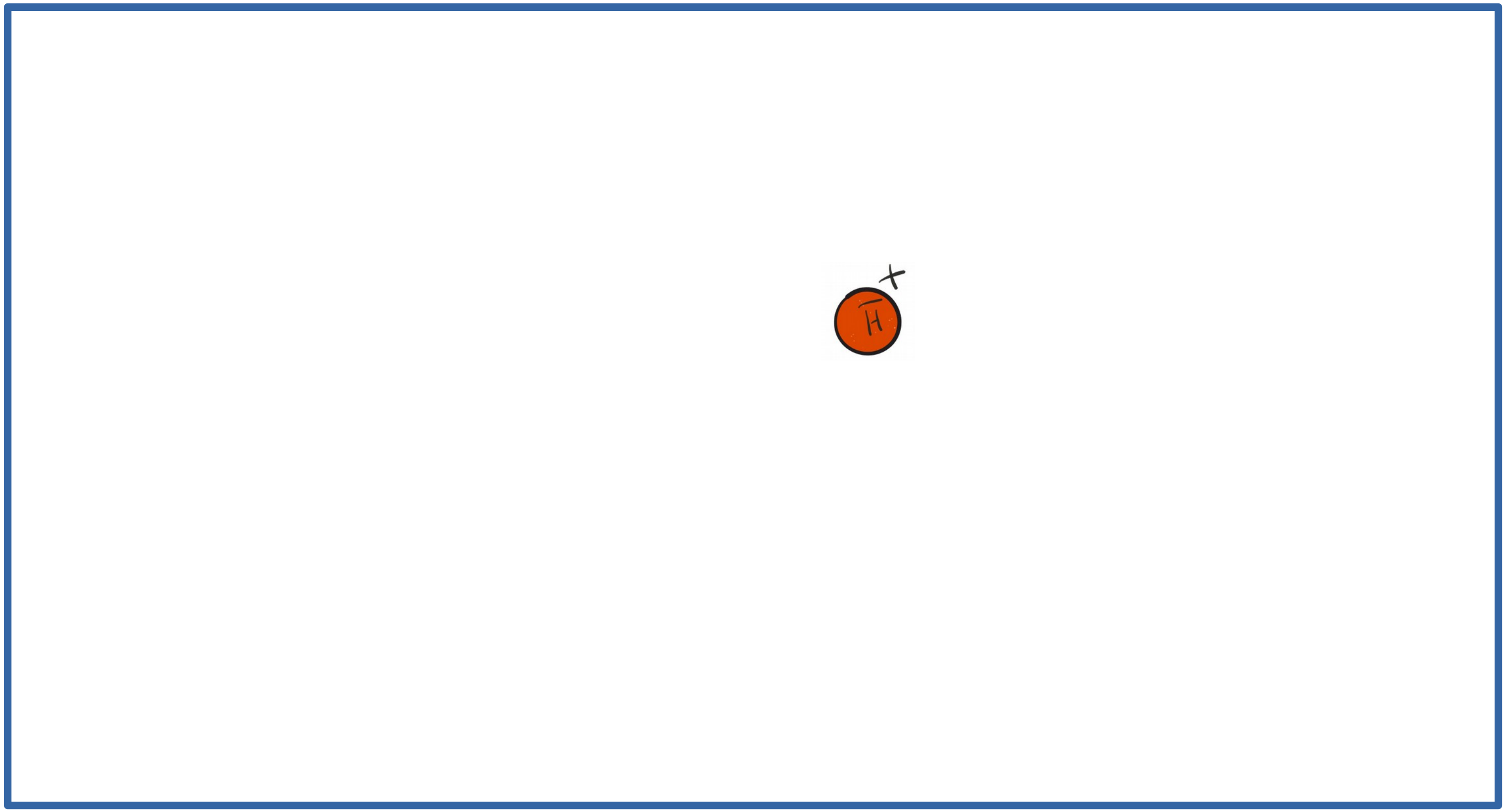
CSNSM
NARODOWE CENTRUM BADAŃ JĄDROWYCH
Świerk
서 울 대 학 교
SEOUL NATIONAL UNIVERSITY
東京大学
THE UNIVERSITY OF TOKYO

UPPSALA UNIVERSITET
ibS Institute for Basic Science
UNIST
ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY
KOREA UNIVERSITY

Status: installation started this year coinciding with commissioning of the upgrade of the AD, ELENA ring (see talk of C. Carli today at 14:30)
Goal: test the gravitational behaviour of anti-hydrogen at the 1% level (1 phase) and at $10^{-4}$-$10^{-5}$ or better in a second step using QM gravitational states
(see talk of A. Voronin tomorrow at 14:00)

# Gravitational Behaviour At Rest (GBAR) – Principle

J. Walz and T.W. Hänsch, General Relativity and Gravitation 36, 561 (2004).



1) Produce anti-hydrogen ions $\bar{H}^+ = \bar{p}\, e^+ e^+$

Vacuum vessel

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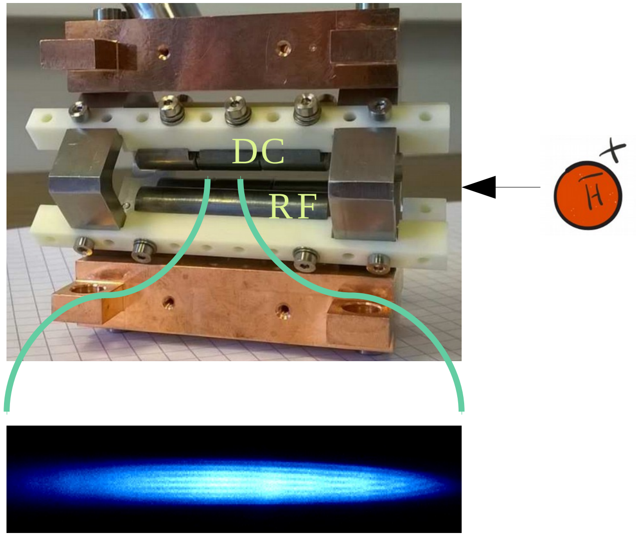

Paul trap with about 1000 $Be^+$

Vacuum vessel

1) Produce anti-hydrogen ions $\overline{H}^{+} = \bar{p}\, e^{+}\, e^{+}$

2) Sympathetic cooling with $Be^+$ : Paul trap → 1 mK

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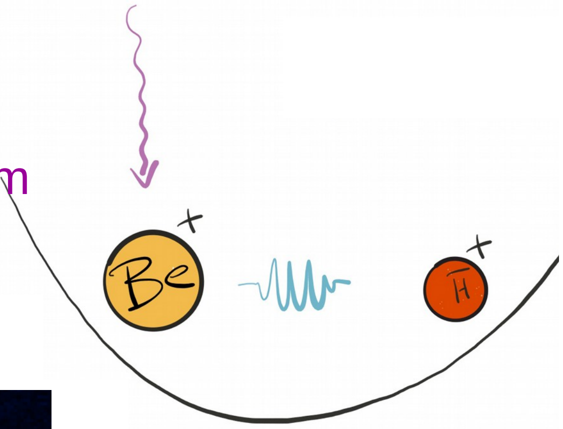
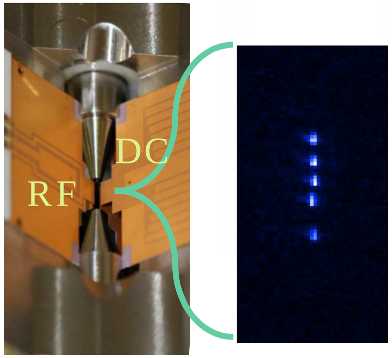
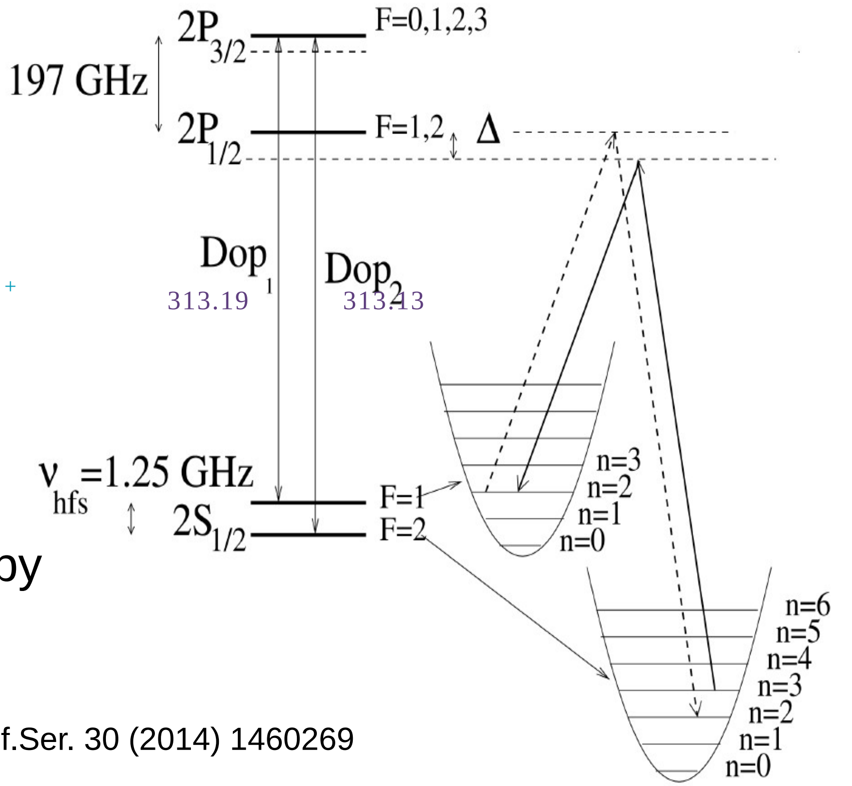
Raman
Sidenband
Cooling
laser 313 nm





Traps being prepared by
LKB and JSU Mainz
Tested with Be$^+$/Mg$^+$

L. Hilico et al.,Int.J.Mod.Phys.Conf.Ser. 30 (2014) 1460269



Vacuum vessel

1) Produce anti-hydrogen ions $\overline{H}^+ = \overline{p}\, e^+ e^+$

2) Sympathetic cooling with Be$^+$ : Paul trap → 1 mK, precision trap → 10 $\mu$K

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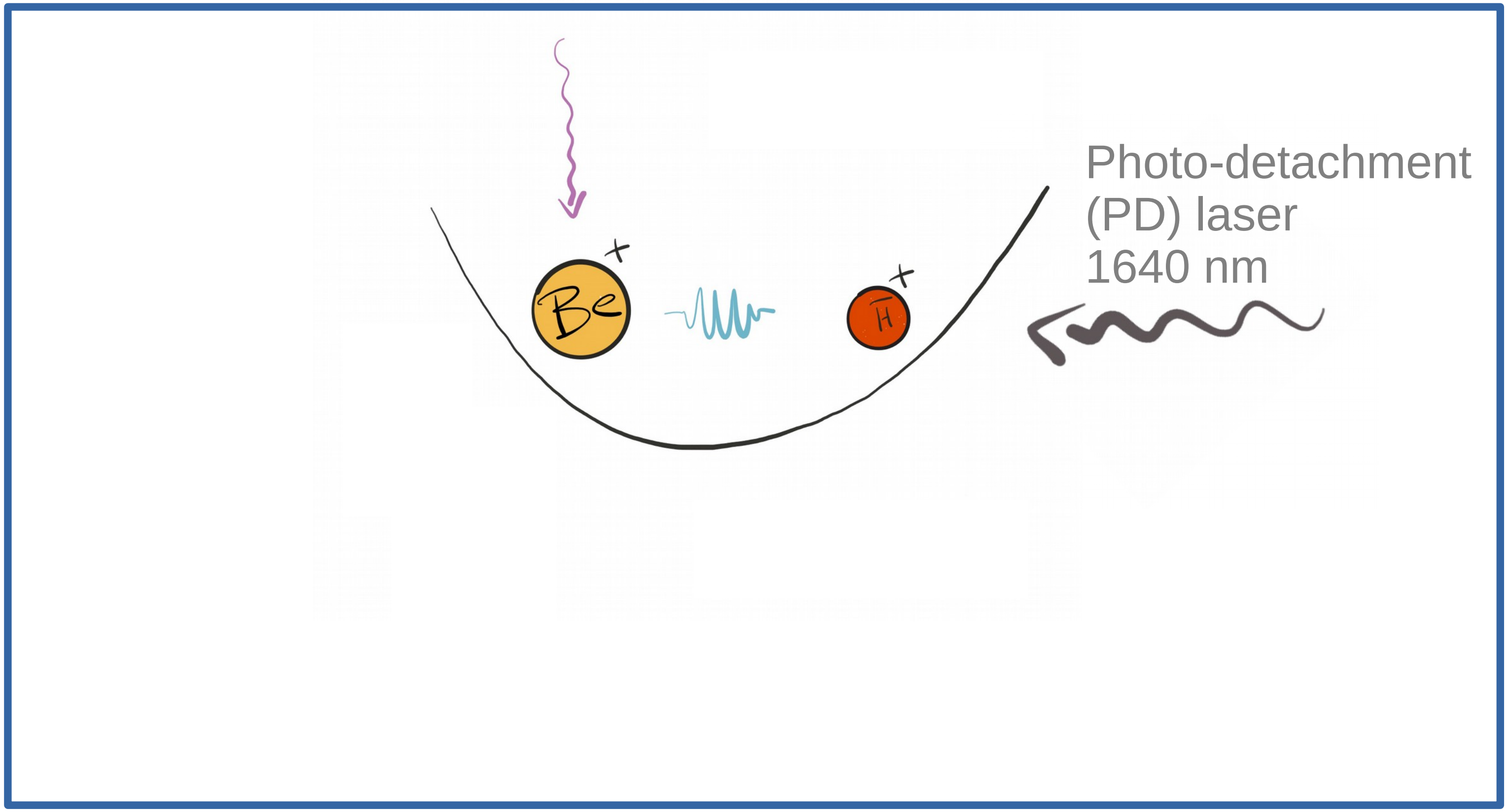

1) Produce anti-hydrogen ions $\bar{H}^+ = \bar{p}\, e^+\, e^+$

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3) Photodetachment of $e^+$ → ultra cold neutral anti-hydrogen (approx. 1 m/s)

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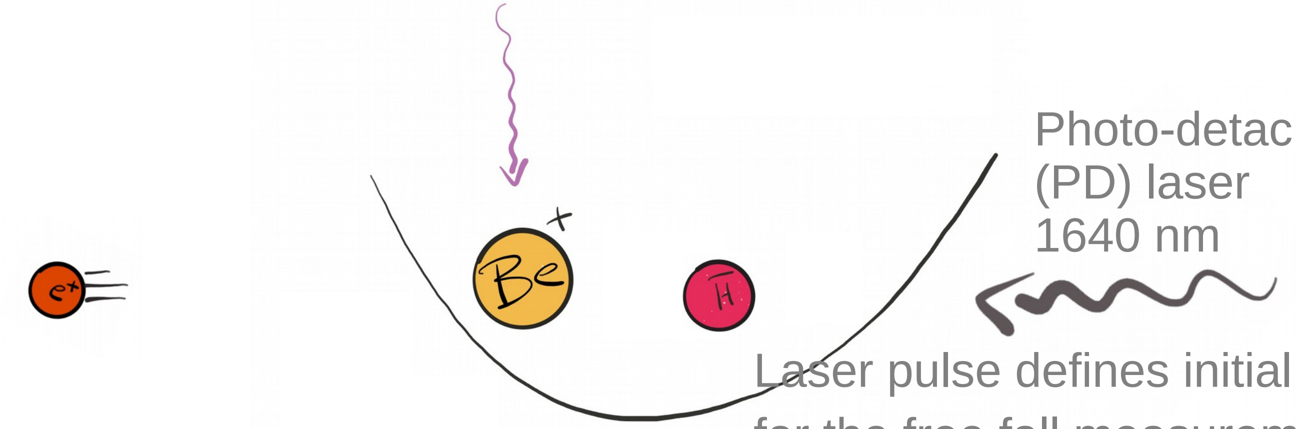

Photo-detachment
(PD) laser
1640 nm

Laser pulse defines initial time $t_0$ for the free fall measurement.

PD $\Delta E$=15 μeV above threshold
→ recoil of 1 m/s

$$\sigma = 3.8 \times 10^{-16} \Delta E^{3/2}\,\mathrm{cm}^2$$

K. R .Lykke, K. K. Murray, W. C. Lineberg, Phys. Rev. A43, 6104 (1991)

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Vacuum vessel

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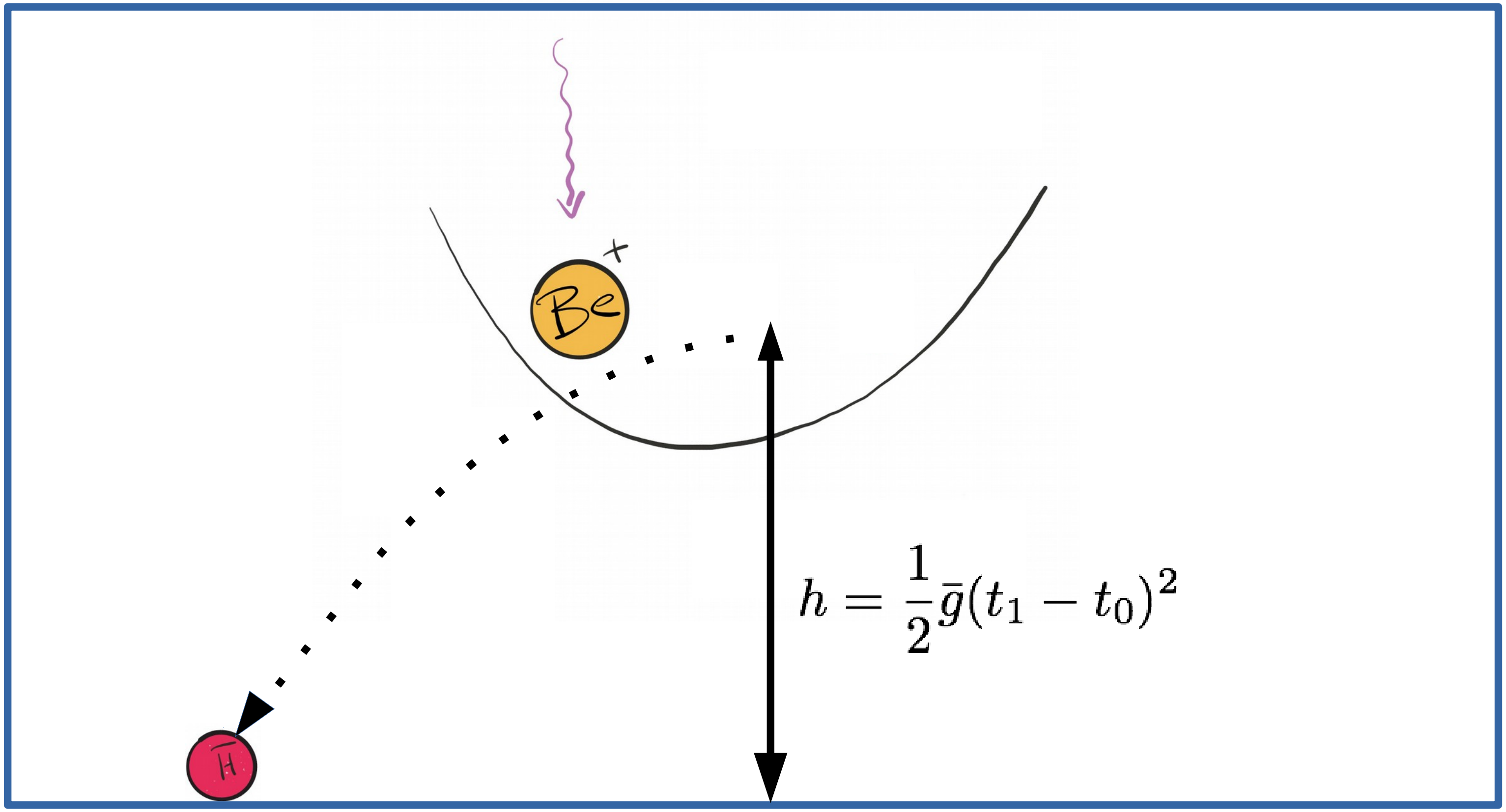

$$h = \frac{1}{2}\bar{g}(t_1 - t_0)^2$$

1) Produce anti-hydrogen ions $\overline{\mathrm{H}}^+ = \bar{p}\, e^+ e^+$

Vacuum vessel

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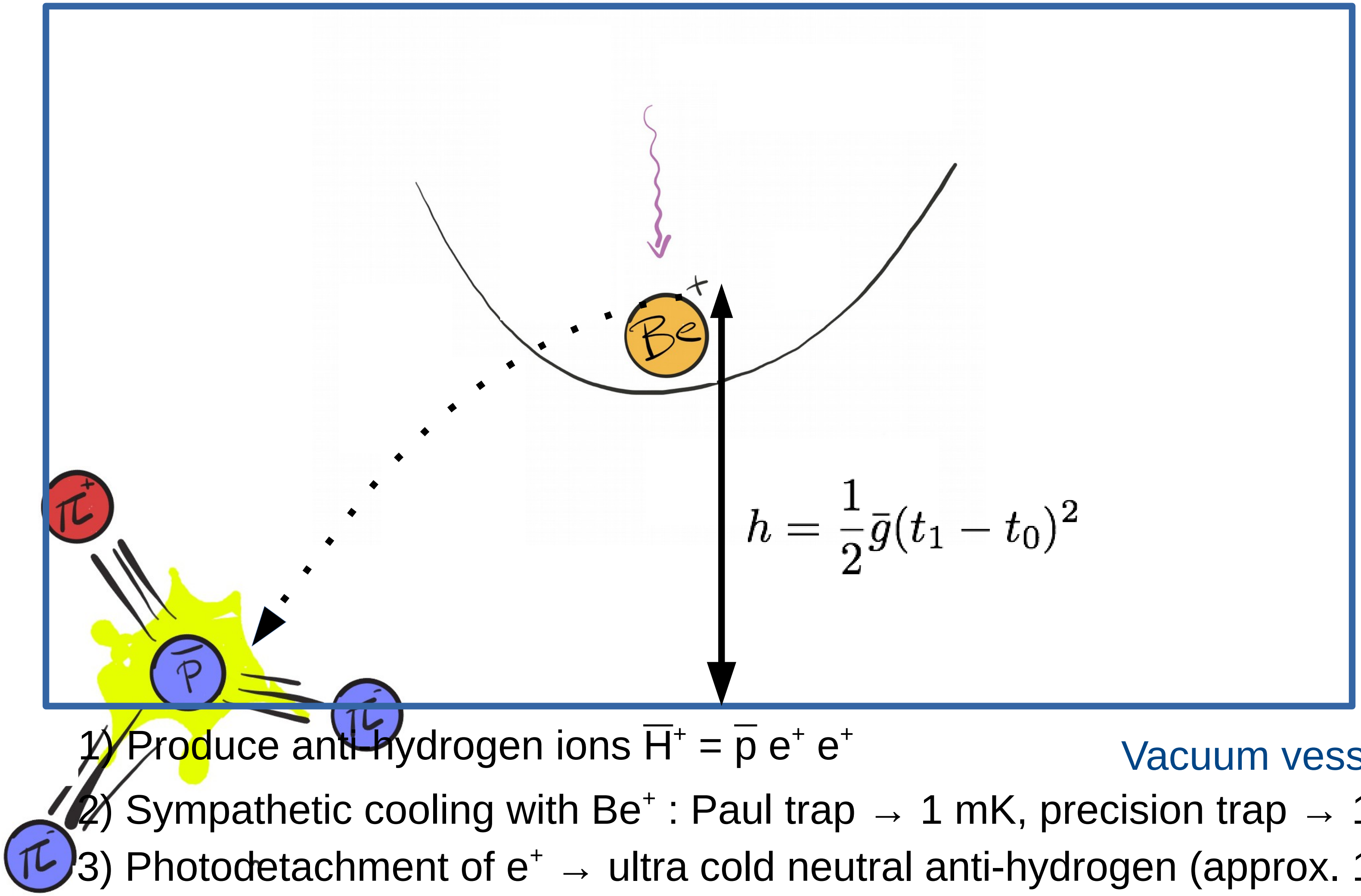

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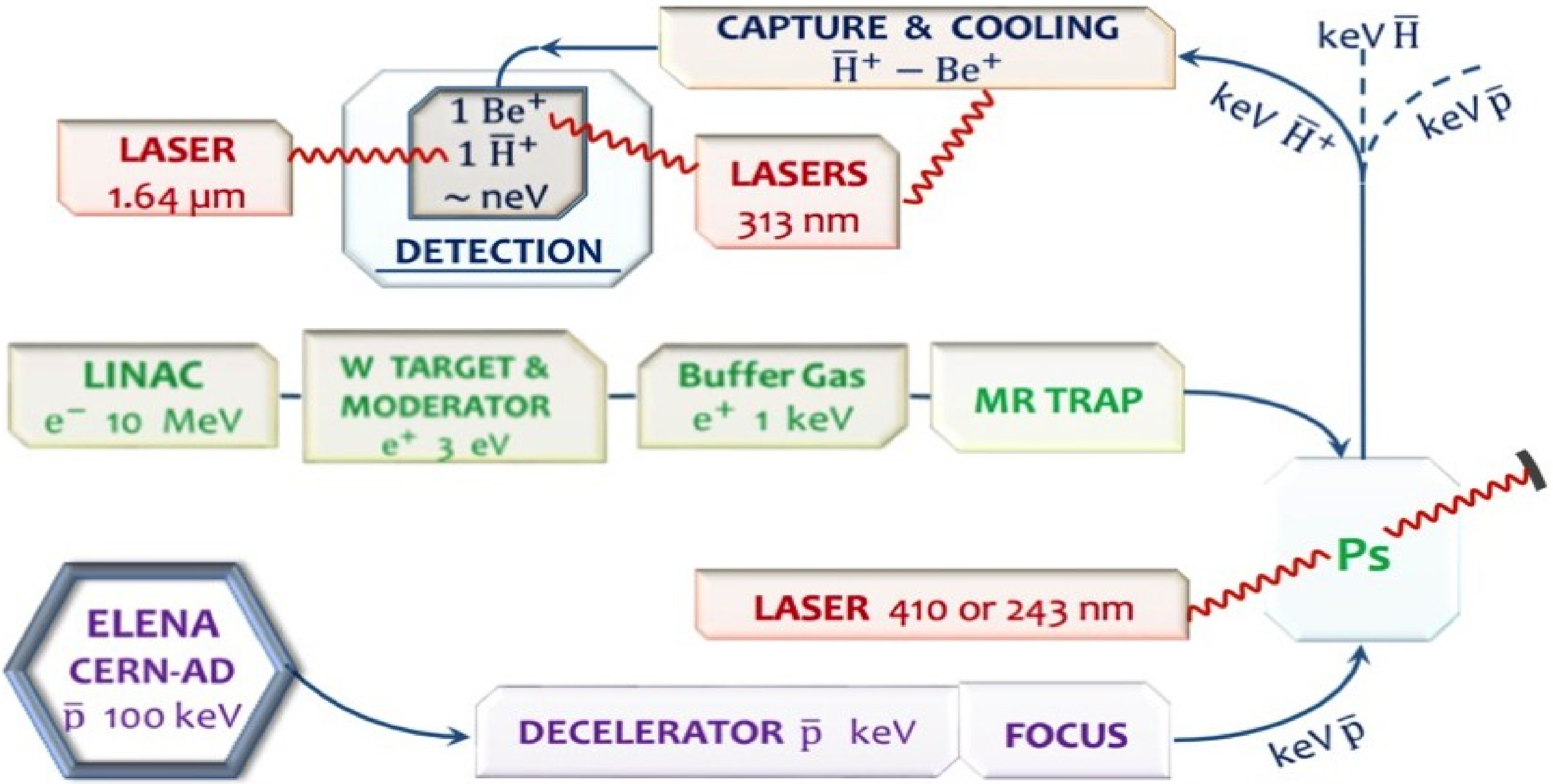
3) Photodetachment of $e^+$ → ultra cold neutral anti-hydrogen (approx. 1 m/s)

4) Measurement of the free fall time: detection of charged pions
from $\bar{p}$ annihilations with a 4π micromegas tracker.

# Gravitational Behaviour At Rest (GBAR) – Scheme



$\bar{H}^+$ production via two step charge exchange reactions:

$$1)\ \mathrm{Ps} + \bar{p} \rightarrow \bar{H} + e^-$$

$$2)\ \mathrm{Ps} + \bar{H} \rightarrow \bar{H}^+ + e^-$$

EXP. $\bar{H}$: J. P. Merrison et al. Phys. Rev. Lett. 78, 2728 (1997).
EXP. $\bar{H}$: A . Speck et al., Phys. Lett. B597, 257 (2004).

TH. $\bar{H}^+$: P. Comini and P.-A. Hervieux, New J. Phys. 15, 095022 (2013)

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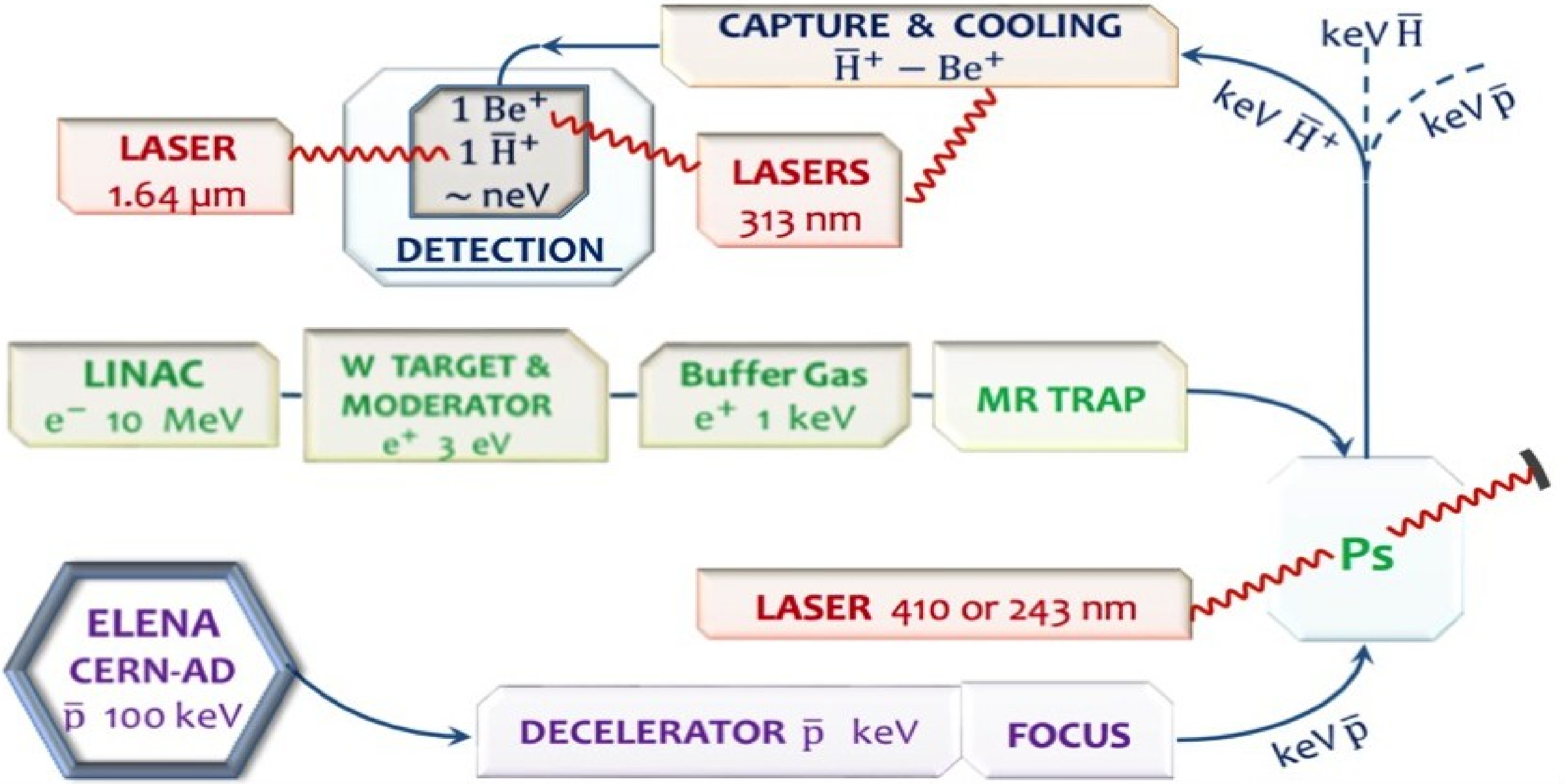

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$$2)\ \mathrm{Ps} + \bar{\mathrm{H}} \rightarrow \bar{\mathrm{H}}^+ + \mathrm{e}^-$$

$$\Rightarrow \quad R_{\bar{\mathrm{H}}^+} \propto N_{\bar{\mathrm{p}}} n_{Ps}^2 \frac{1}{E_{\bar{\mathrm{p}}}^2}$$

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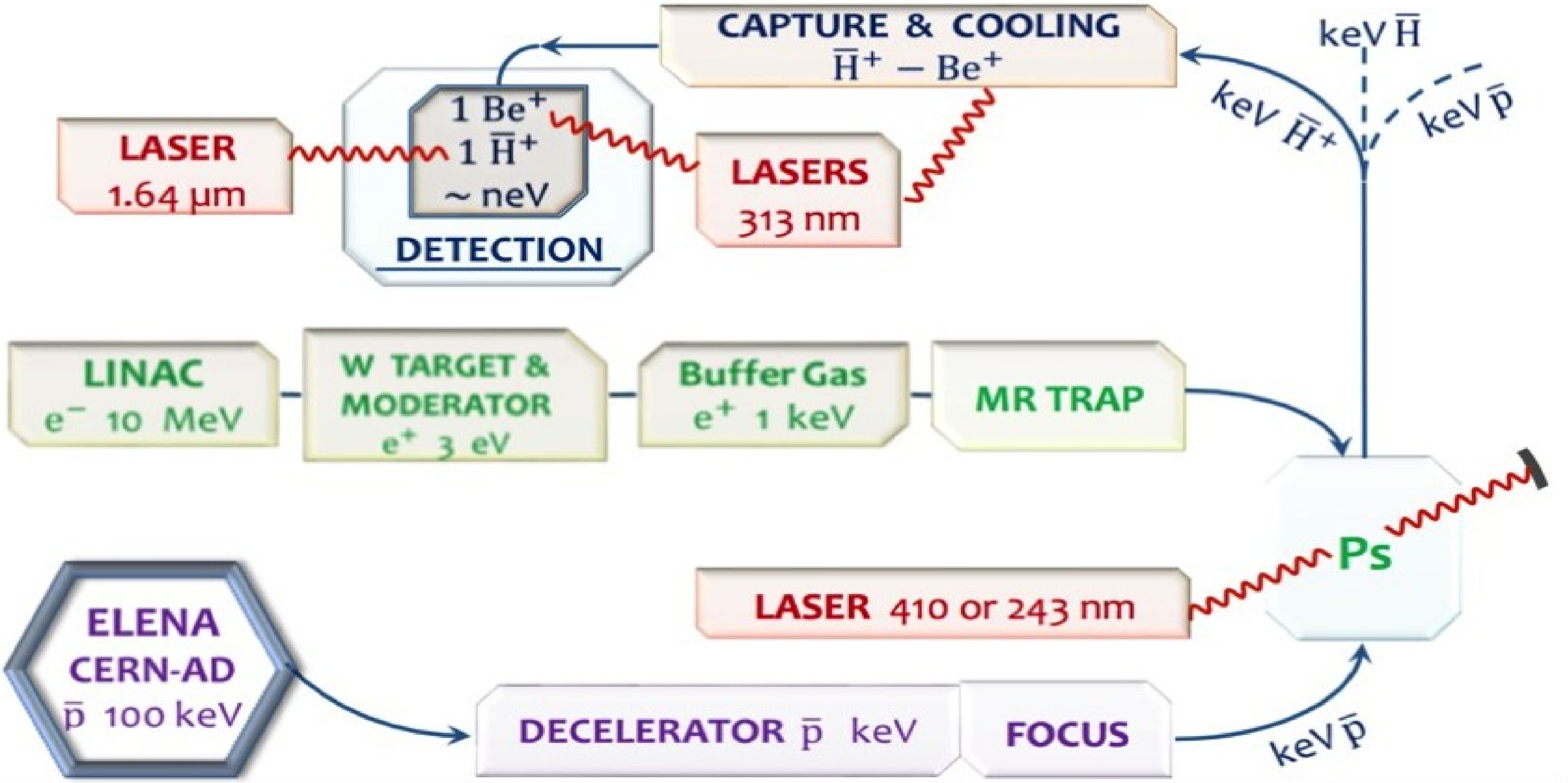

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ELENA

LINAC

DECELERATOR
+ $\bar{p}$ TRAP (after LS2)

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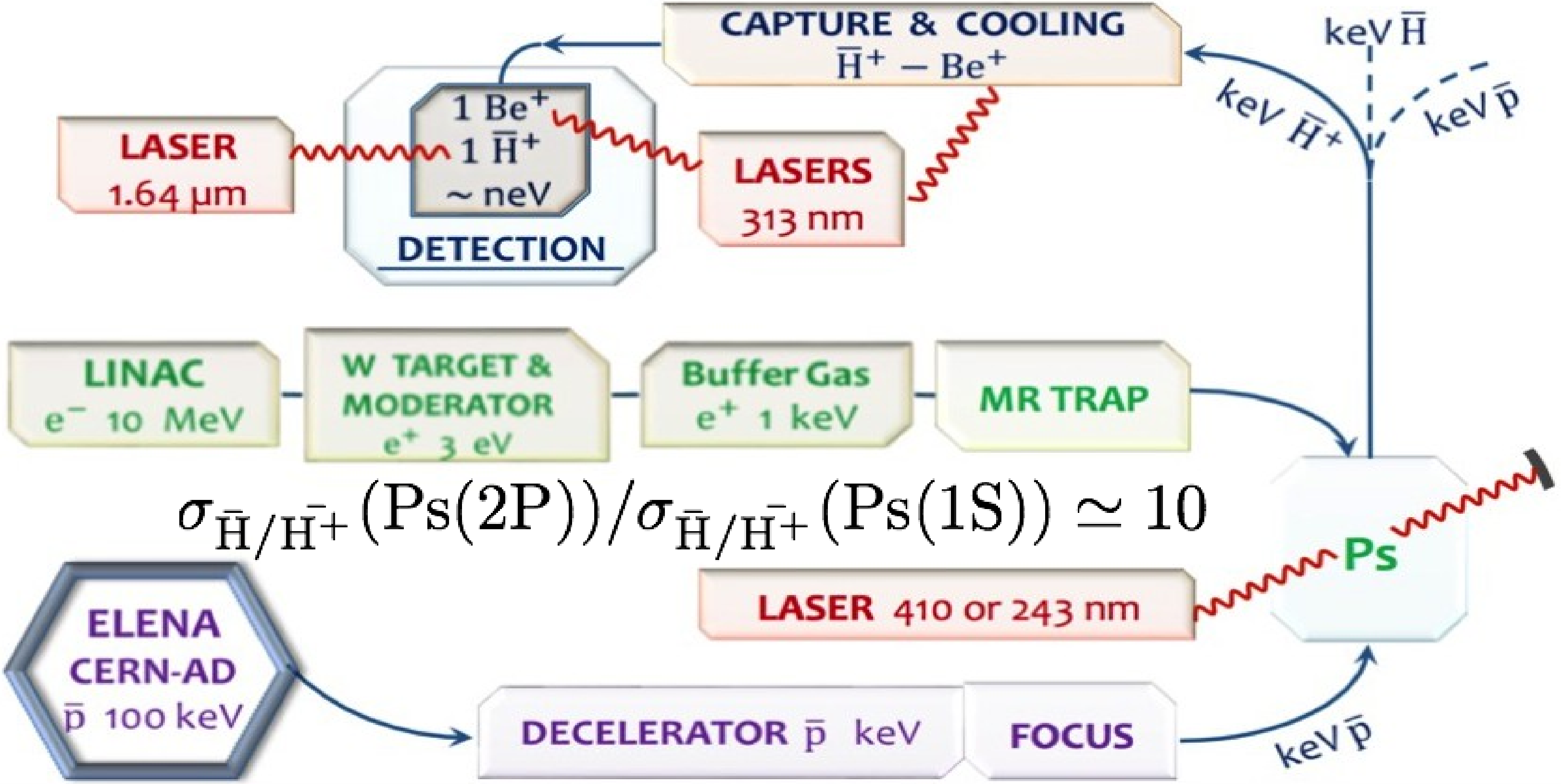

$$\sigma_{\bar{H}/\bar{H}^+}(Ps(2P))/\sigma_{\bar{H}/\bar{H}^+}(Ps(1S)) \simeq 10$$

$\bar{H}^+$ production via two step charge exchange reactions:

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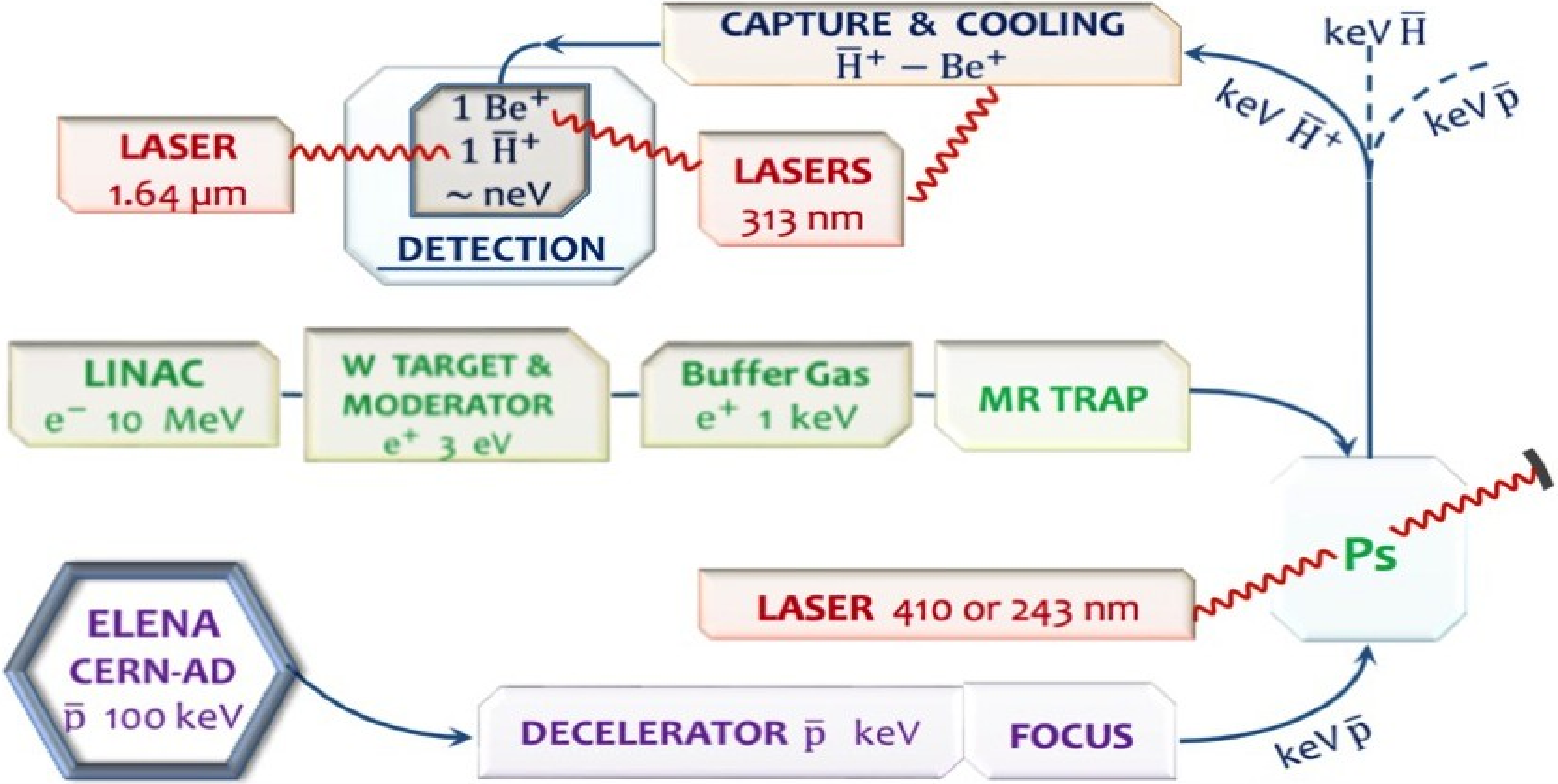

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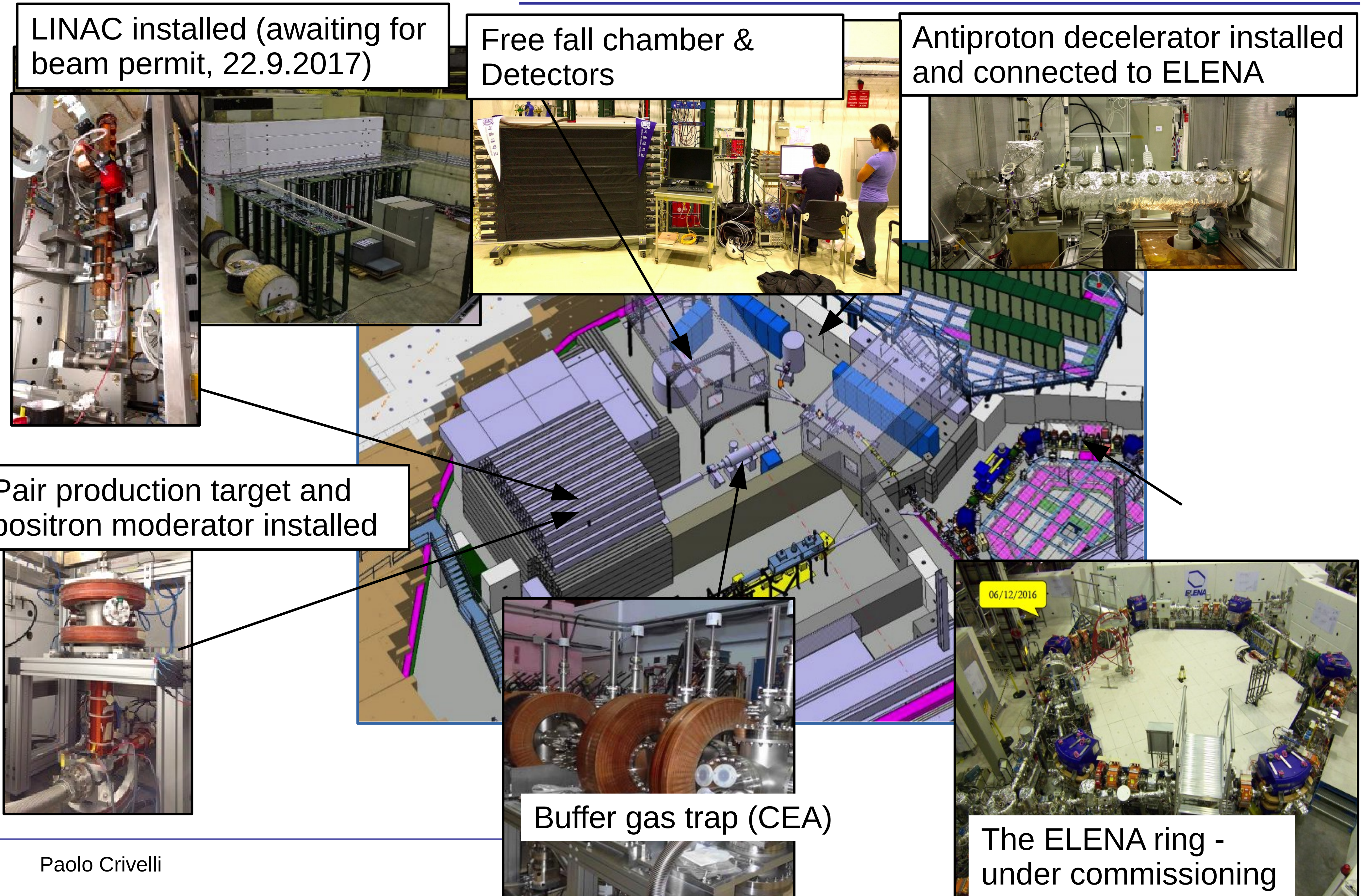
$$2)\ \mathrm{Ps} + \bar{\mathrm{H}} \rightarrow \bar{\mathrm{H}}^+ + \mathrm{e}^-$$

$$\Rightarrow \quad R_{\bar{\mathrm{H}}^+} \simeq 1 \quad \text{per ELENA cycle}$$

# GBAR- Status and layout



LINAC installed (awaiting for beam permit, 22.9.2017)

Free fall chamber & Detectors

Antiproton decelerator installed and connected to ELENA

Pair production target and positron moderator installed

Buffer gas trap (CEA)

The ELENA ring - under commissioning

# Outlook for GBAR

- Experiment under installation: LINAC, pair production target and positrons beam line (tested with electrons have been installed).

- First micromegas triplet (full tracker 6 triplets) and 1 module of the TOF (tot. 4) detectors were tested in the AD with cosmics.

- LINAC commissioning at CERN should start next week. Positron pair production target and slow positron beam line will follow. Installation of buffer gas trap and production of Ps by the end of 2017/beginning 2018.

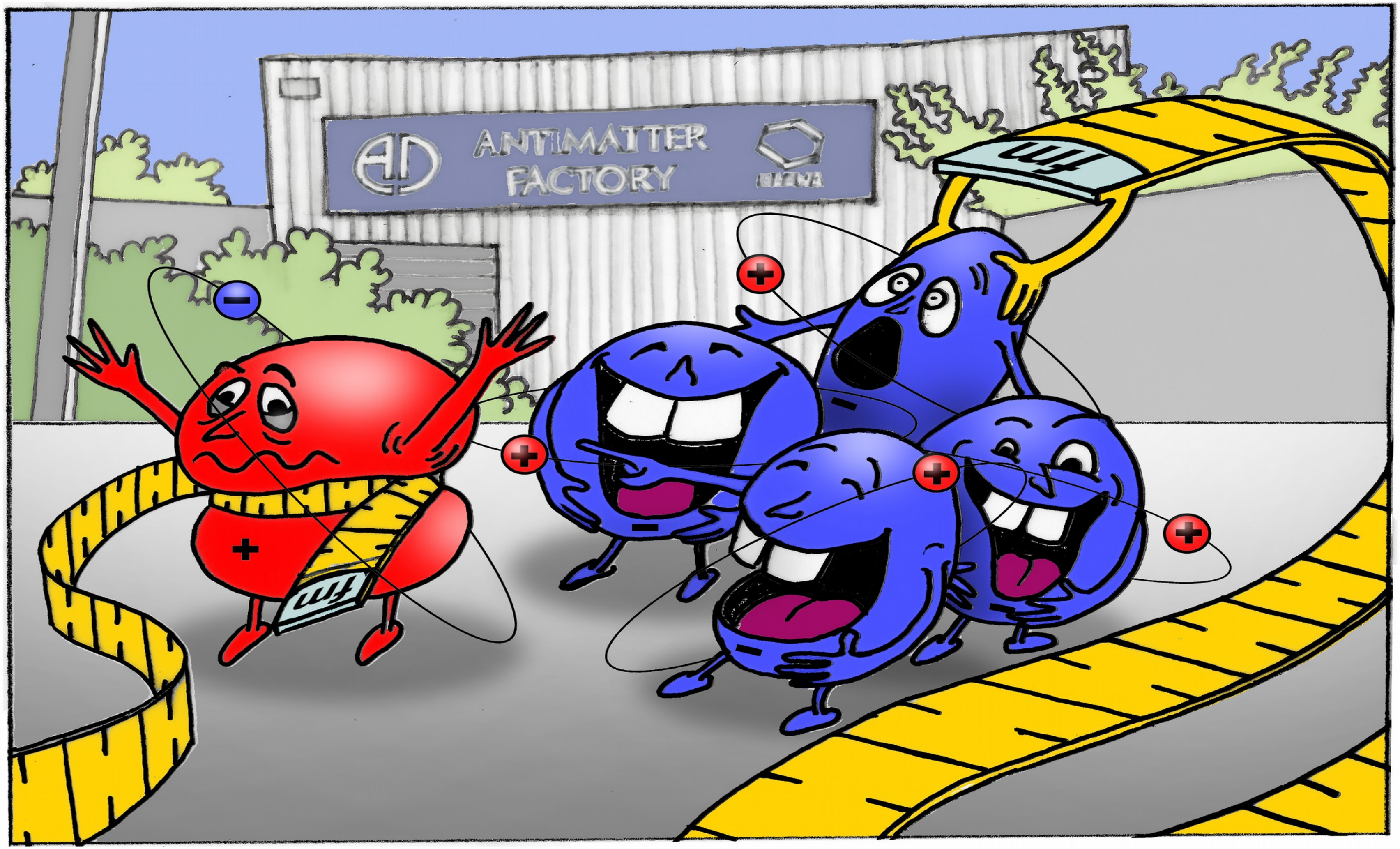
- First anti-protons from ELENA in 2018 → attempt production of $\overline{\mathrm{H}}$.

-During CERN long shutdown (end of 2018 and May 2021) a lot of work ahead: test of H and H- production including Ps excitation → optimization of the two step reaction.

- Installation of the anti-proton trap, ion traps and free fall chamber.

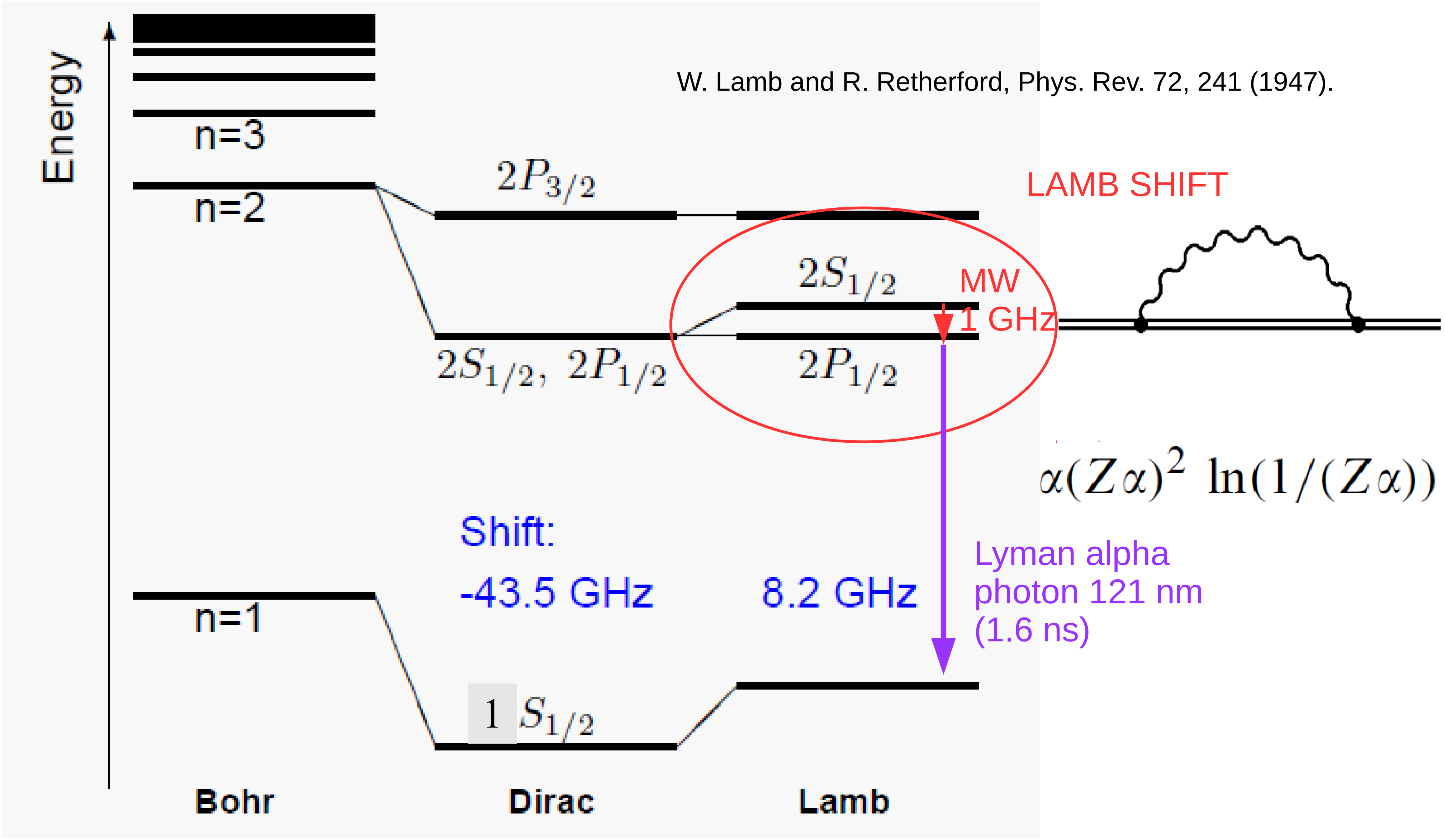
- In 2021: first attempts to produce and trap $\overline{\mathrm{H}}^+$ and measurements of the $\overline{\mathrm{H}}$ free fall.

# $\overline{\mathrm{H}}$ Lamb shift (parasitic) measurement in GBAR



P. Crivelli, D. Cooke, M. Heiss, Phys. Rev. D 94, 052008 (2016)

# Lamb shift - QED corrections



W. Lamb and R. Retherford, Phys. Rev. 72, 241 (1947).

LAMB SHIFT

MW
1 GHz

$$\alpha(Z\alpha)^2 \ \ln(1/(Z\alpha))$$

Shift:

-43.5 GHz

8.2 GHz

Lyman alpha
photon 121 nm
(1.6 ns)

# Determination of the proton charge radius via H Lamb Shift

The finite size of the proton contributes with a correction that is given by:

$$\Delta E = \frac{1}{12}\alpha^4 m_r^3 r_p^2$$

W. Aron and J. Zucchelli, Phys. Rev. 105, 1681 (1957).

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From the best current determination of the Lamb shift with direct microwave transition one can extract the proton charge radius $r_p$ at a level of 3% (independent on the Rydberg constant)

S.R. Lundeen, F.M. Pipkin, Phys. Rev. Lett. 46, 232 (1981).

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Motivated by proton radius puzzle prompted by the muonic hydrogen experiment at PSI (see R. Pohl talk this afternoon) R. Pohl et al, Nature 466, 213 (2010); A. Antognini et al. Science 25, 417 (2013).

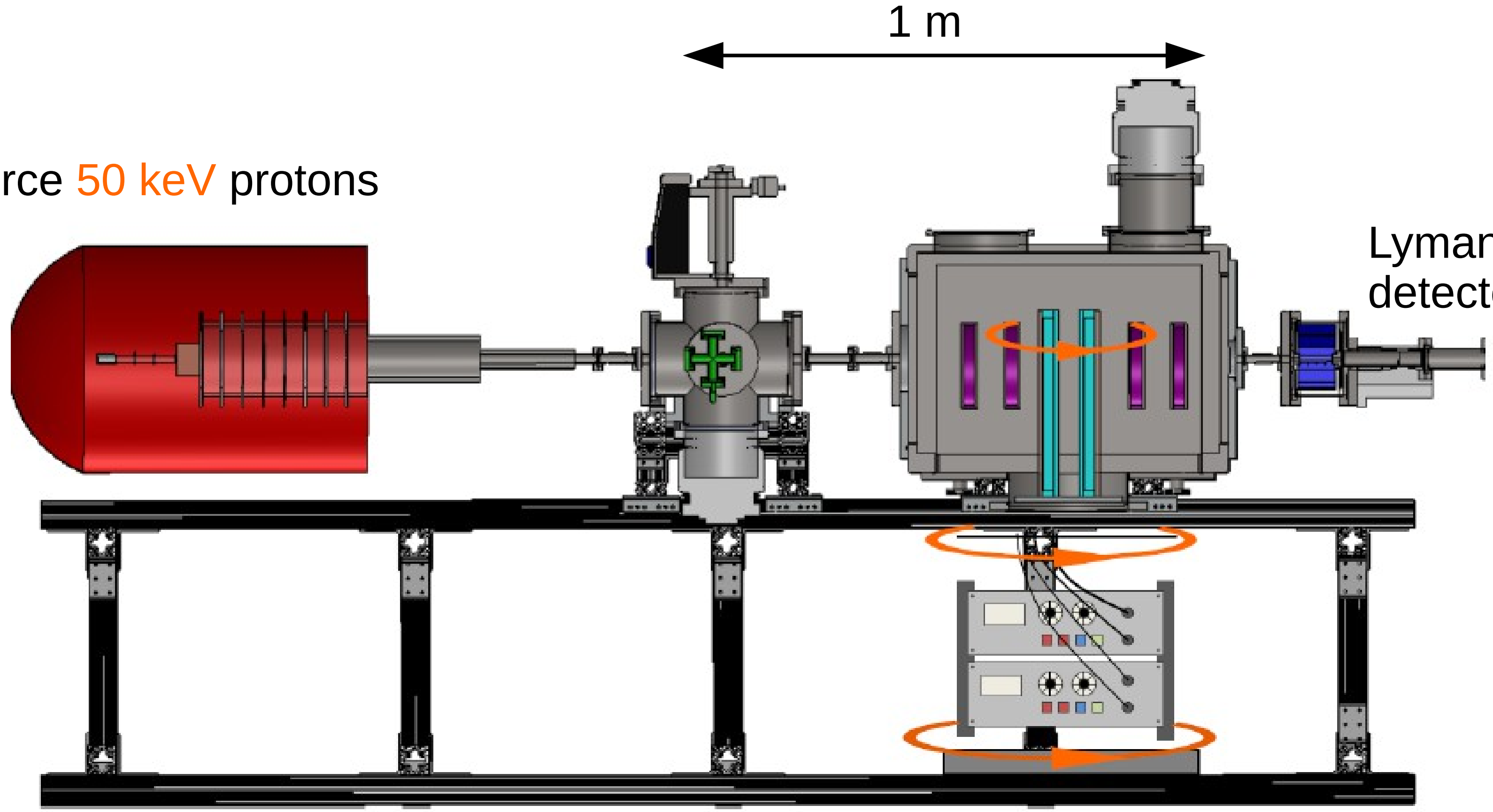
→ New measurement at the York University in Toronto to improve the precision of the Lamb shift. With clever refinement of the SOF technique, E. A. Hessels et al. should be able to reduce the systematic uncertainties in order to determine $r_p$ at a level of 1% uncertainty.

E. A. Hessels, Frontiers in Optics 2015, OSA Technical Digest (online) (Optical Society of America, 2015), paper LTu2G.2.

# New determination of the Lamb shift at York University (ongoing)

PROTON SOURCE → CHARGE EXCHANGE → HYPERFINE STATE QUENCH → DOPPLER LASER → QUADRUPOLE → SEPARATED OSCILLATORY FIELDS → QUADRUPOLE → HYPERFINE STATE QUENCH → DETECTOR

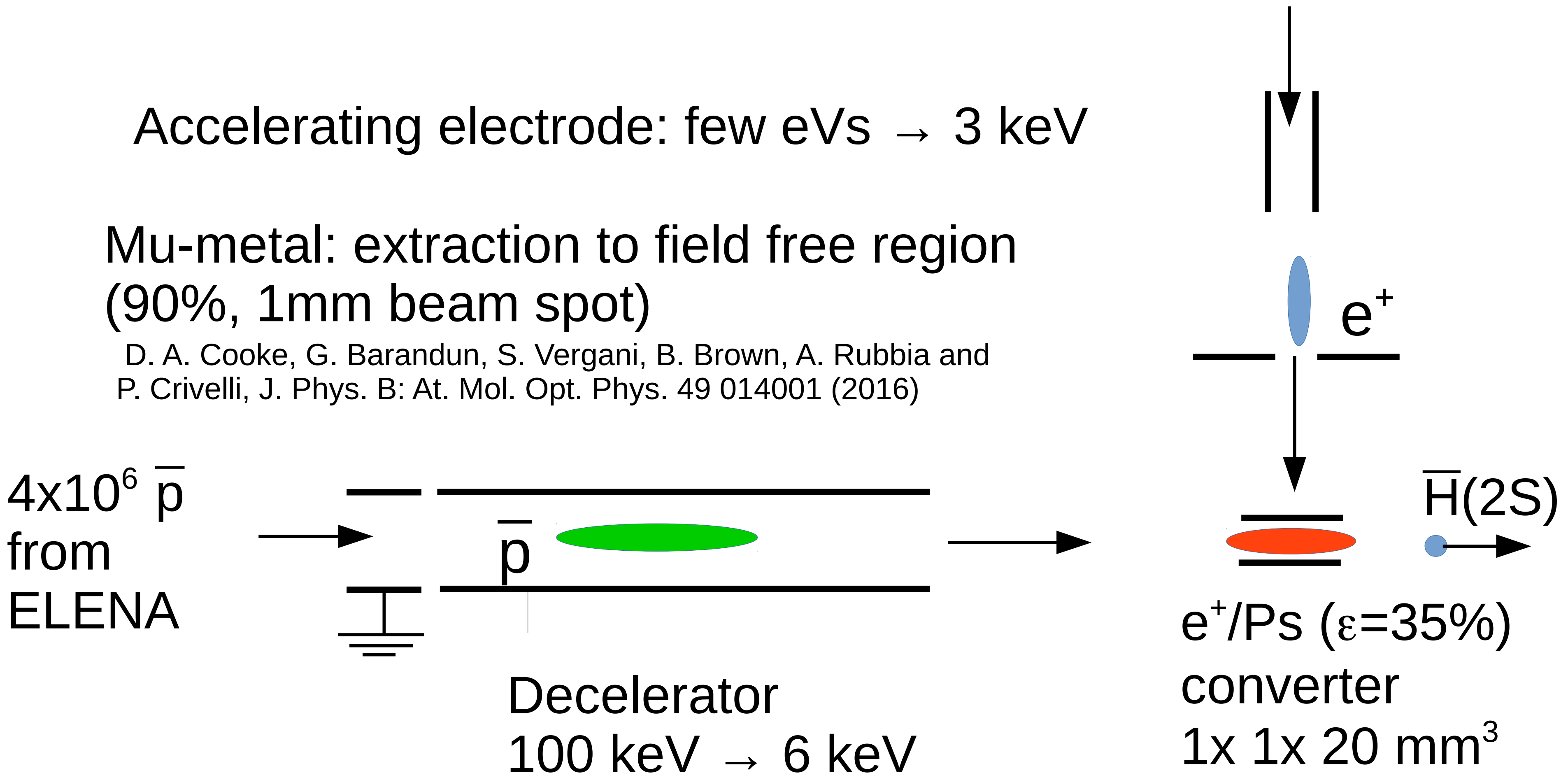
Ion source 50 keV protons



Lyman alpha detector

From Eric Hessels talk-
Proton Puzzle Mainz June 3, 2014

# Scheme of $\overline{\mathrm{H}}$ (2S) beam production



3 x10$^9$ Positrons from accumulator in 30 ns bunches

Accelerating electrode: few eVs → 3 keV

Mu-metal: extraction to field free region (90%, 1mm beam spot)

D. A. Cooke, G. Barandun, S. Vergani, B. Brown, A. Rubbia and P. Crivelli, J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016)

4x10$^6$ $\bar{p}$ from ELENA

$\bar{p}$

Decelerator
100 keV → 6 keV

$e^+$

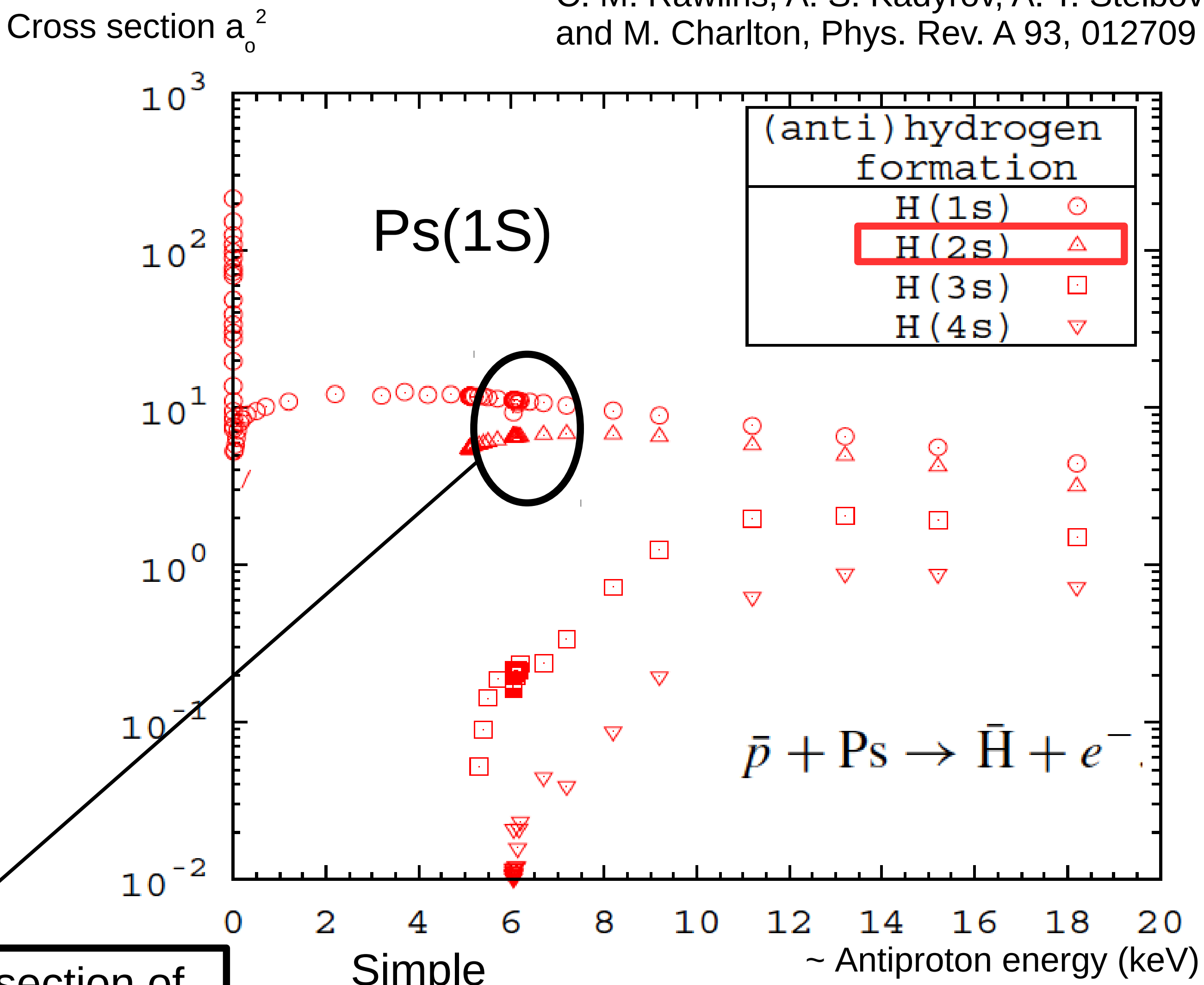
$\overline{\mathrm{H}}$(2S)

$e^+$/Ps ($\varepsilon$=35%) converter
1x 1x 20 mm$^3$

D. Cooke, P. Crivelli et al. Hyp.  Int. 233, 67 (2015)

# $\overline{\mathrm{H}}$ production cross sections via charge exchange

C. M. Rawlins, A. S. Kadyrov, A. T. Stelbovics, I. Bray, and M. Charlton, Phys. Rev. A 93, 012709 (2016).



For 6 keV cross section of H(2S) around 2.2x$10^{-16}$ cm$^2$

Simple estimate

$$N_{\overline{\mathrm{H}}(2S)} = \sigma_{\overline{\mathrm{H}}} \cdot N_{\overline{\mathrm{p}}} \cdot n_{Ps} \cdot L \simeq 50$$

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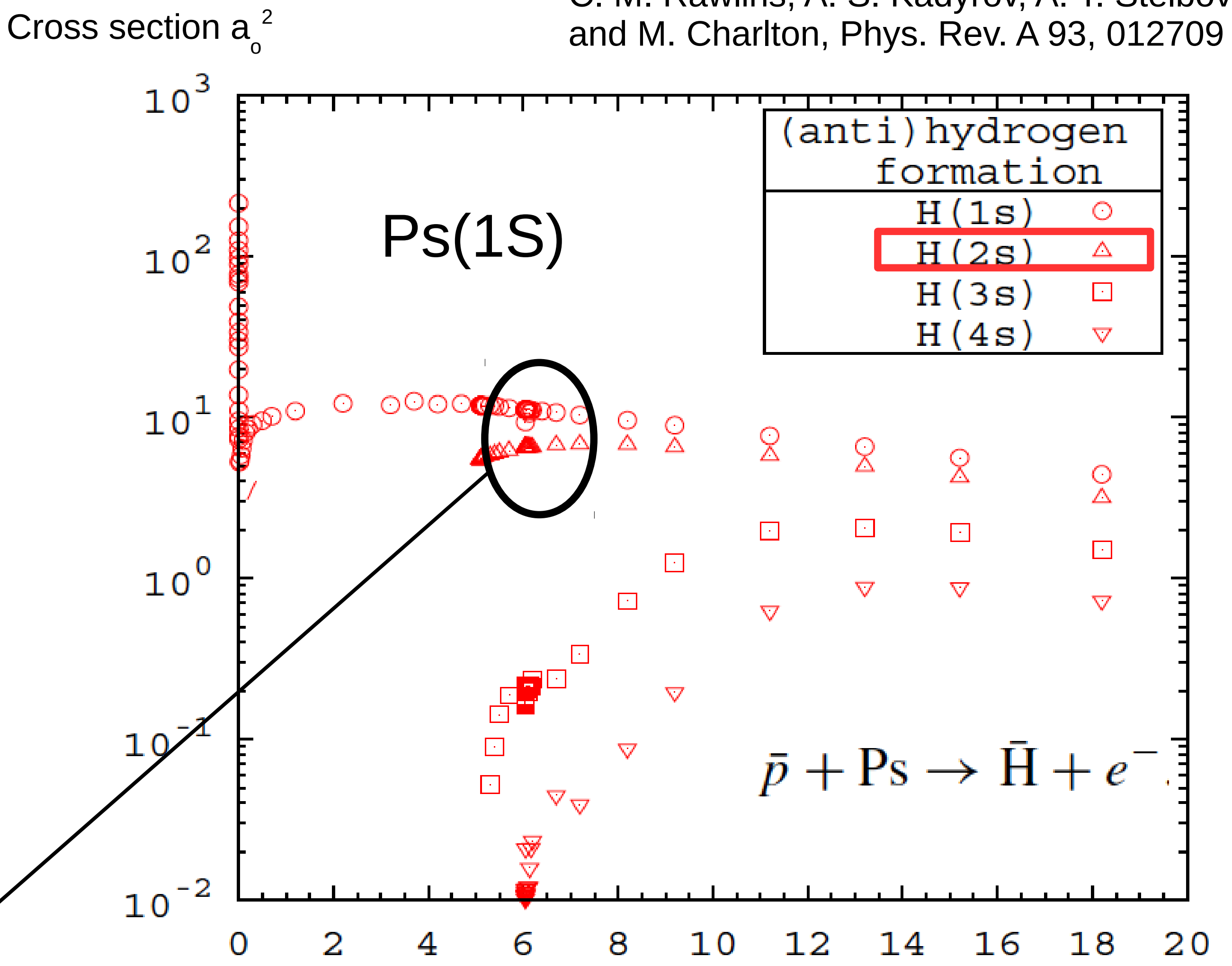
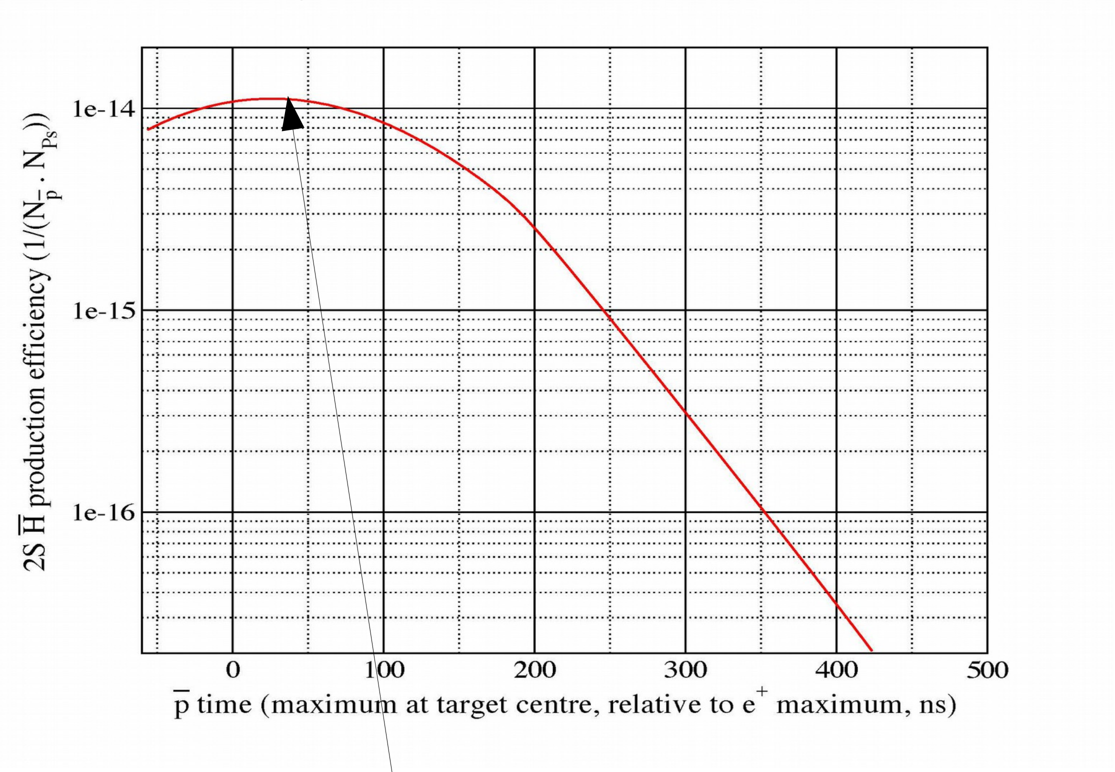


For 6 keV cross section of H(2S) around $2.2\times10^{-16}$ cm$^2$

# $\overline{\mathrm{H}}(2S)$ production rate via charge exchange

$1\mathrm{x}10^{-14}$



**G4 simulation:**
to properly take into account time evolution of Ps density, Ps decay and antiprotons time and spatial distribution.

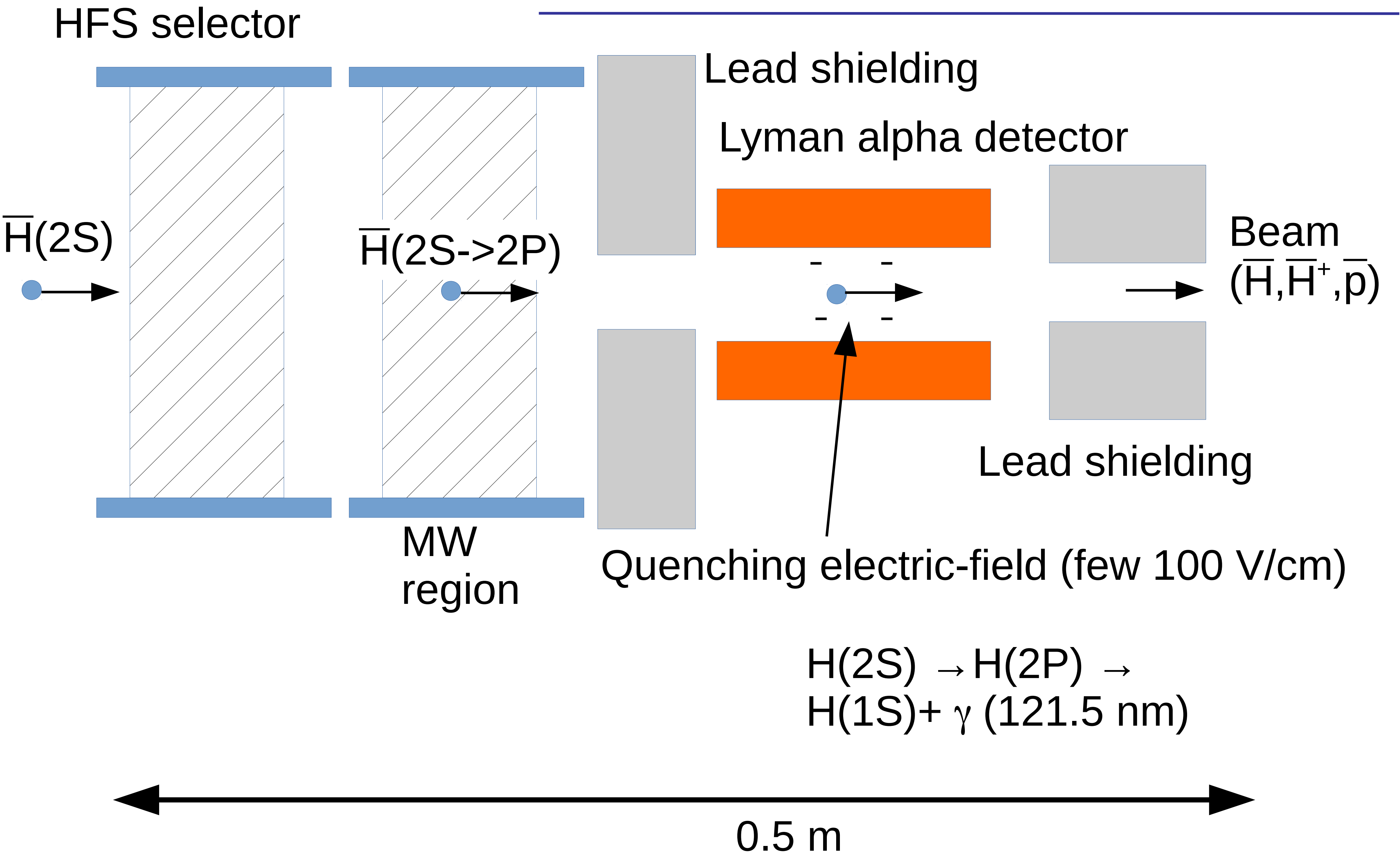
$$N_{\overline{\mathrm{H}}(2S)} = \epsilon_{ce} \cdot N_{\bar{\mathrm{p}}} \cdot N_{\mathrm{Ps}} \simeq 20$$

per ELENA pulse

$2.25 \mathrm{~x~} 10^{6}$

$9.45 \mathrm{~x~} 10^{8}$

# Measurement principle



HFS selector

$\overline{H}$(2S)

$\overline{H}$(2S->2P)

MW region

Lead shielding

Lyman alpha detector

Beam ($\overline{H}$,$\overline{H}^+$,$\overline{p}$)

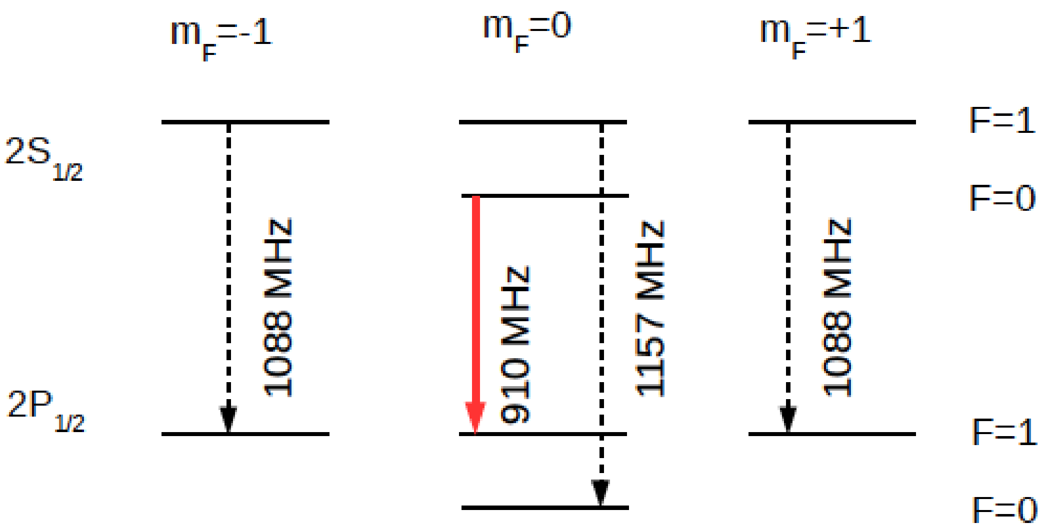
Lead shielding

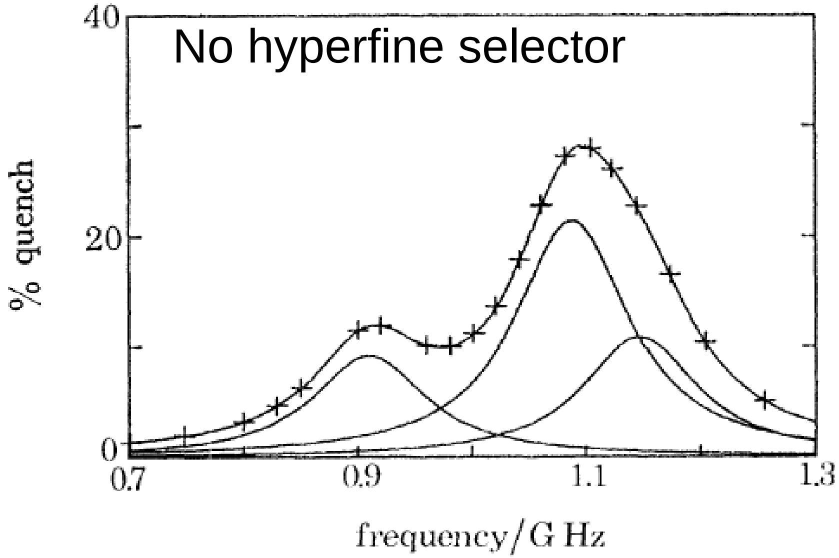
Quenching electric-field (few 100 V/cm)

H(2S) → H(2P) → H(1S)+ γ (121.5 nm)

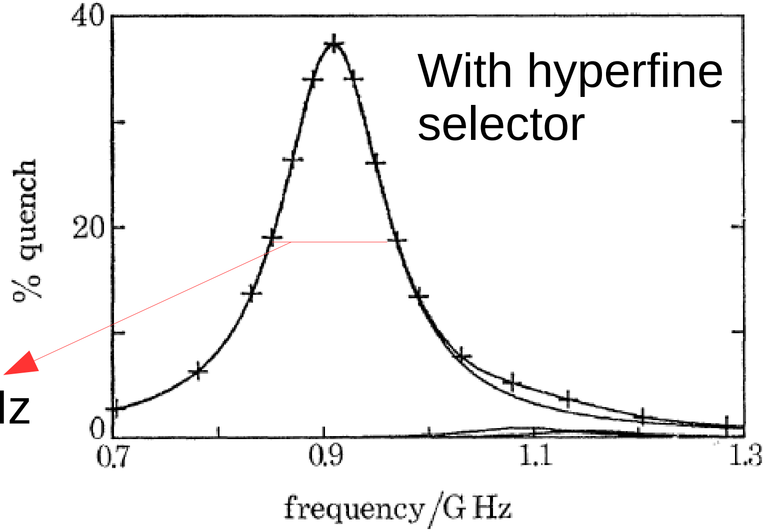
0.5 m

# Expected lineshape




No hyperfine selector

Linewidth 160 MHz


With hyperfine selector

G. Newton; D. A. Andrews; P. J. Unsworth, Phil. Trans. of the Royal Soc. of London. Series A, Math. and Phys. Sciences 290, 373. (1979).

# Lyman alpha detector

Lyman alpha detectors were developed for rocket astronomy program in the vacuum ultraviolet, efficiencies up to 50-60% were reported for $CS_2$ gas detectors limited by transmission of LiF or Mg2 windows.

A. K. Stober, R. Scolnik, and J. P. Hennes, APPLIED OPTICS 2, 735 (1963)
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Bollinger and Pipkin Rev. Sci. Instr.52 , 938 (1981)

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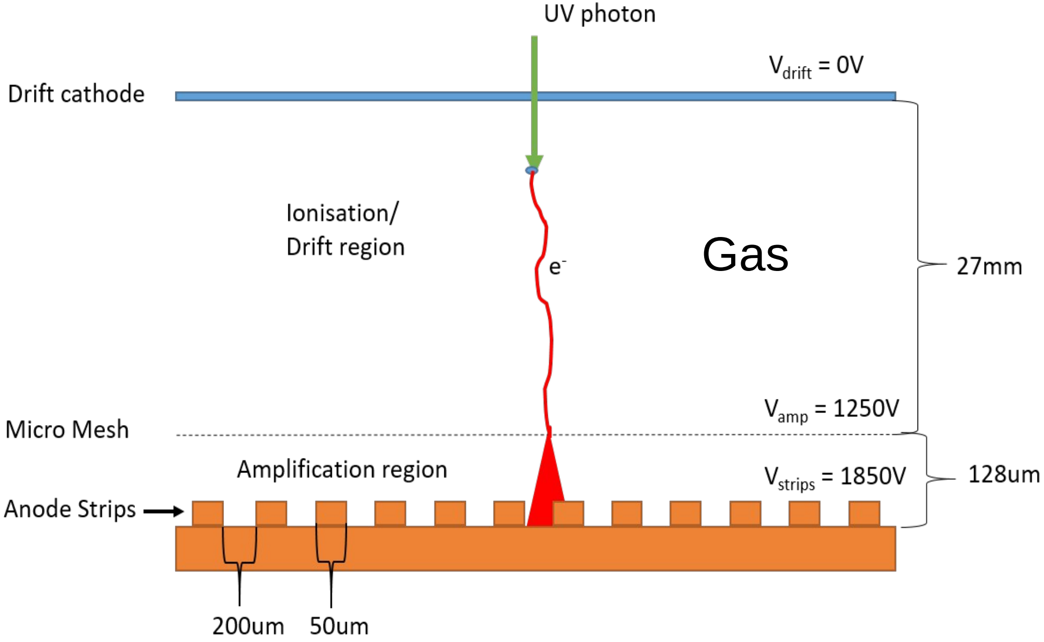
High efficiency relies on the large photo-ionization cross section (9 Mbarn) of $CS_2$, however $CS_2$ is toxic and is not gaseous at room temperature.
Alternative we identified: DME (Dimethyl ether). Large cross section (5-10 Mbarn), gaseous and non toxic (+ available at ETHZ).
Ionization threshold for DME: 10.025 eV (123.6 nm) comparable with $CS_2$ .

K. Kameta et al., J. Chem. Phys. 96, 4911 (1992)

# Lyman alpha detector prototype based on micromegas

Y. Giomataris, P. Rebourgeard, J. P. Robert, and G. Charpak, Nucl. Instrum. Methods Phys. Res., Sect. A 376, 29 (1996).



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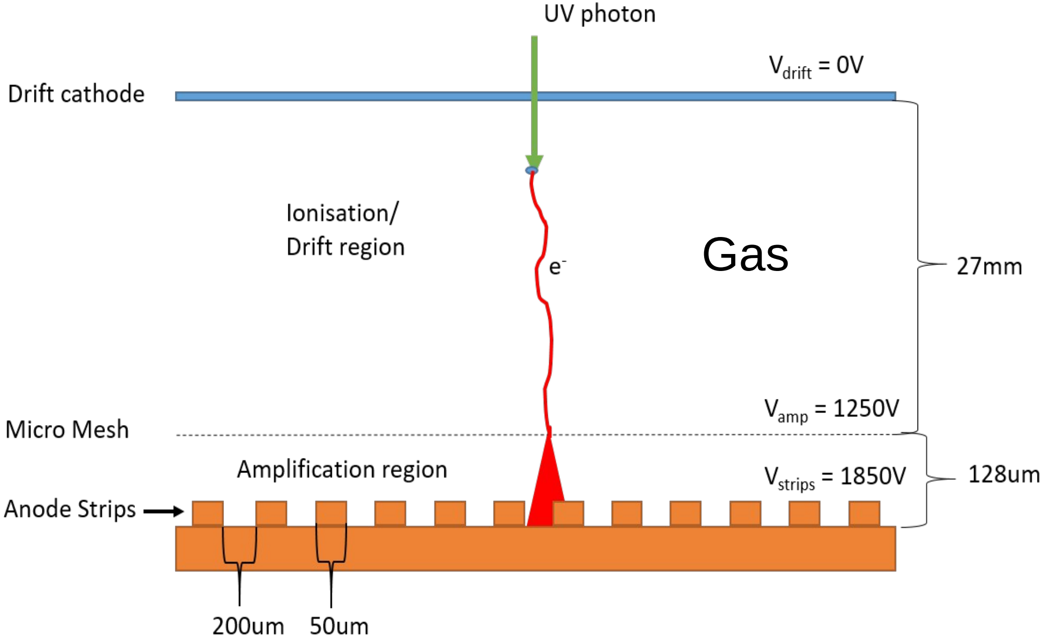
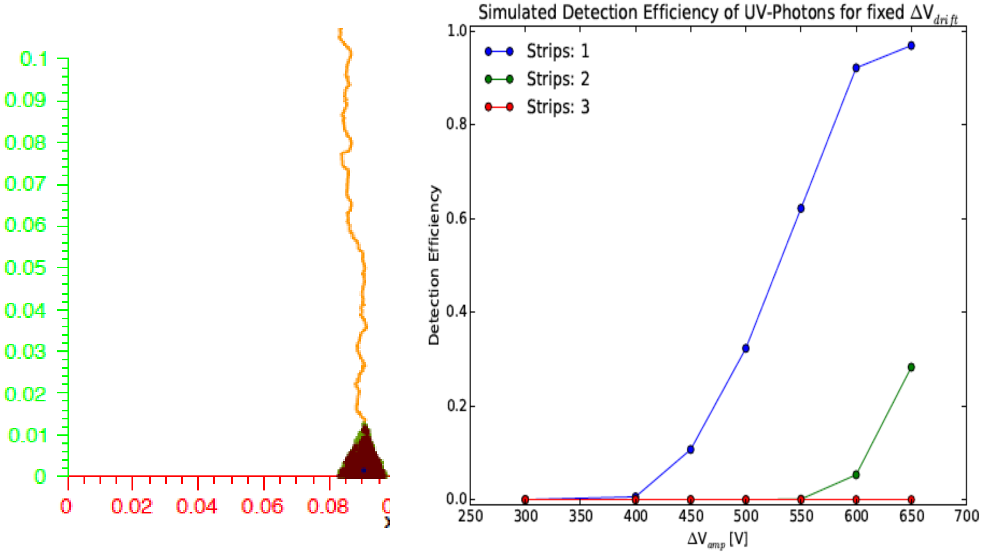


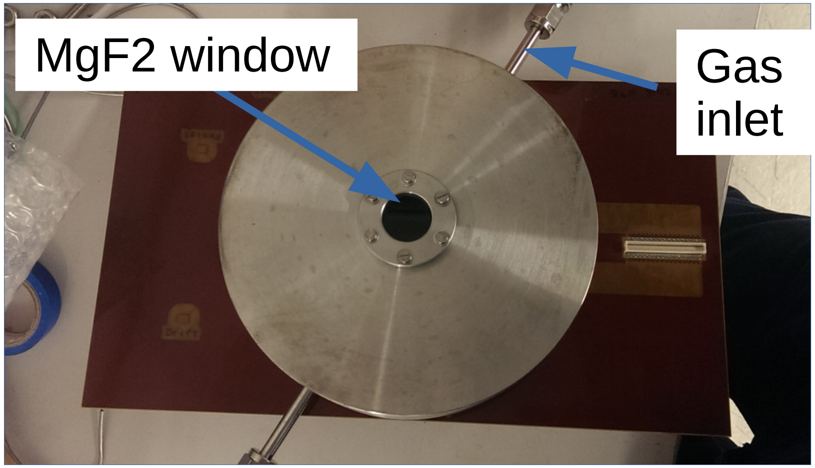
Garfield simulation



-Prototype detector based on micromegas and a Lyman alpha (Ly) source (discharge tube with Ly filter) have been built.

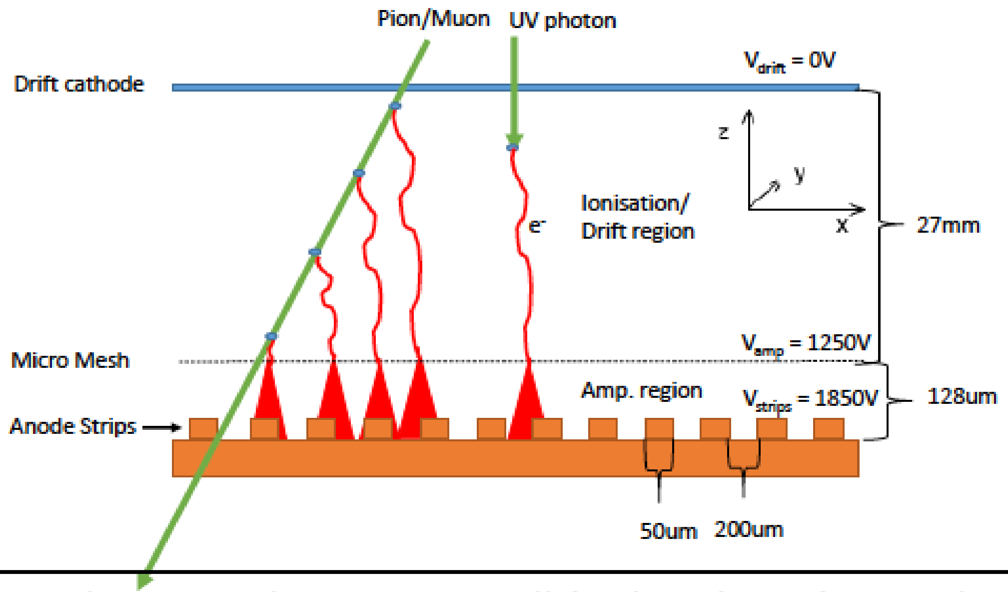
- Single Lyman alpha photons detected

- Efficiency should be improved. Better geometry of drift region and scan parameters



Detector prototype

# Advantages of micromegas detector (MMD)

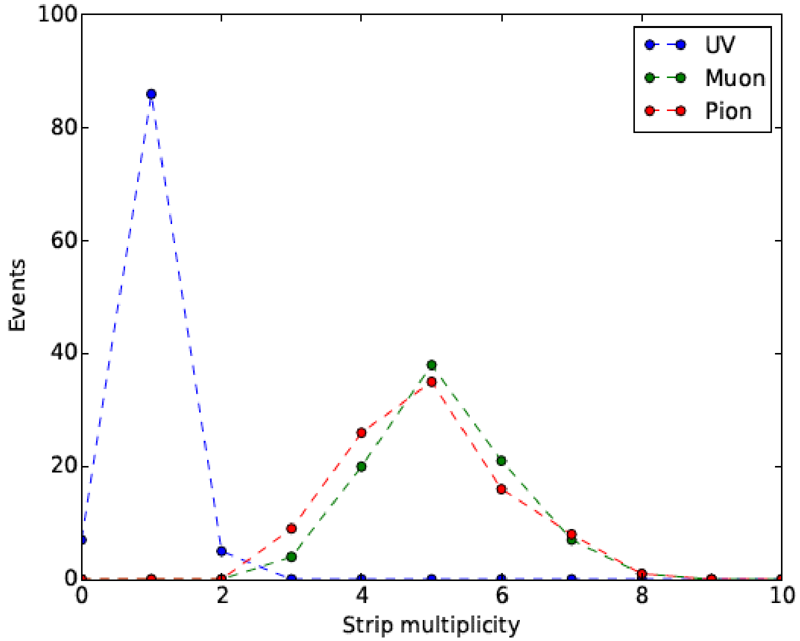


-Even though experiment is pulsed background from possible antiprotons annihilation in time coincidence with the expected signal.
→ Idea to use MMD for discrimination of those events.

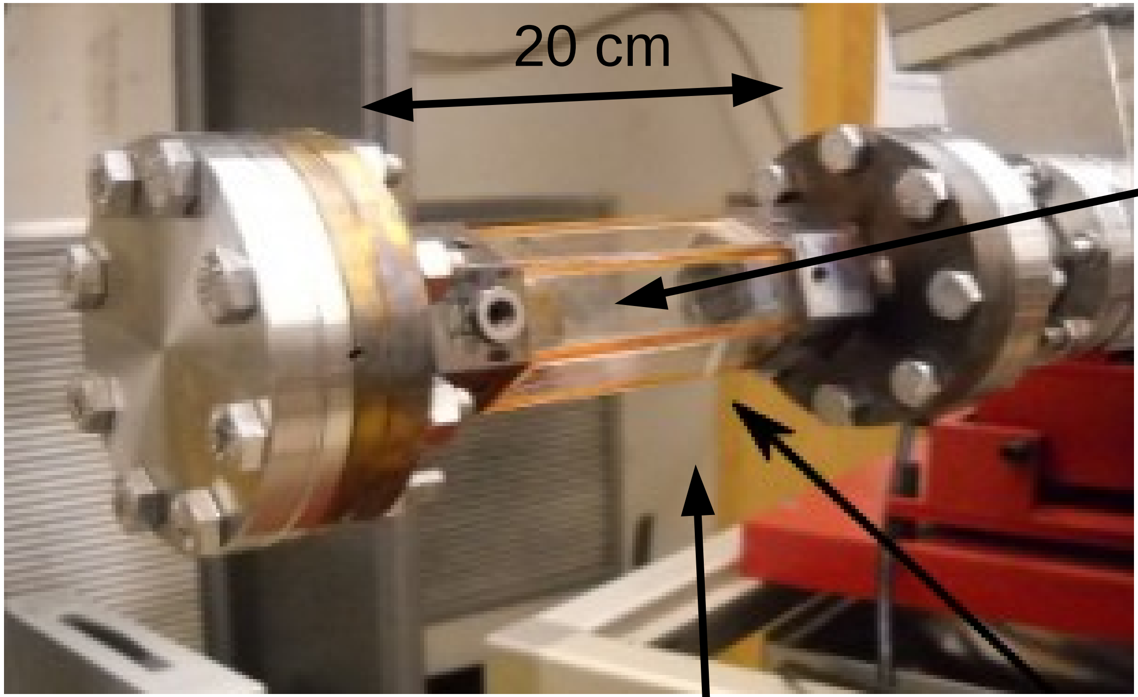
Pions (from antiprotons annihilations) and cosmics generate about 20 electrons in the drift region.

→ many more strips are hit + total deposited charge is much larger than UV photon (only a single electron in drift region).

→ suppression by cutting on the number of strips that are hit and requiring an upper cut on the charge, estimated suppression factor of $10^4$.



# MgF$_2$ vacuum pipe



The internal diameter of the vacuum pipe made of MgF2 windows should be around 6  cm.

From Eric Hessels talk-
Proton Puzzle Mainz June 3, 2014

MgF2 windows

Six micromegas detectors will be placed around the MgF$_2$ pipe.

# Estimated signal rate and accuracy

$$N_d = \underbrace{\epsilon_q}_{0.6} \cdot \underbrace{\epsilon_t}_{0.8} \cdot \underbrace{\epsilon_d}_{0.4} \cdot \underbrace{\epsilon_{\mathrm{F}=0}}_{0.25} \cdot \underbrace{N_{\overline{\mathrm{H}}(2S)}}_{20} \simeq 1$$

per ELENA pulse

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per ELENA pulse

Pulsed beam + time of flight → excellent S/N ratio.
Signal window approx. 1 μs → accidental rate $10^{-3}$
Using MMD it seems possible to suppress correlated background from possible time coincident antiprotons annihilations at the same level.

Number of events detected per day on resonance
(assuming a duty cycle of ELENA of 80%) approx 700 events.
Simulation of line shape with the expected S/N ratio → line centre determined with an uncertainty of 100 ppm for 1 months of data taking.

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per ELENA pulse

With Ps in the 2P state and the $\bar{p}$ trap → 2 orders of magnitude larger rate.

Pulsed beam + time of flight → excellent S/N ratio.
Signal window approx. 1 $\mu$s → accidental rate $10^{-3}$
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Number of events detected per day on resonance (assuming a duty cycle of ELENA of 80%) approx 700 events.
Simulation of line shape with the expected S/N ratio → line centre determined with an uncertainty of 100 ppm for 1 months of data taking.

# Systematics

Main source of systematic: AC Stark shift which will be below 100 kHz. By measuring the line shape at different MW powers this could be corrected for extrapolating to zero intensity.

Other sources of systematic

1) First and second order Doppler shift which for the given momentum and spread after the decelerator of the H(2S) are at a level of 10 kHz

2) Other shifts such as motional Stark Shift and Zeeman at a level of few kHz, assuming the magnetic field in the excitation region will not exceed the field of the earth.

# Outlook for $\overline{\mathrm{H}}$ Lamb shift measurement

- A Lamb shift measurement of $\overline{\mathrm{H}}$ at a level of 100 ppm seems possible thanks to ELENA and the GBAR LINAC → complementary Lorentz and CPT test (see talk of A. Vargas) and determination of $\overline{\mathrm{p}}$ charge radius at 10% level.

- A prototype of the Lyman alpha detector based on micromegas technology has been built.

- First step: detection of the production of H(2S) via charge exchange (p+Ps) by quenching the 2S->2P with an electric field.

- N. Kuroda from Tokyo University wants to contribute with the MW system.

- A first measurement of the transition (1000 ppm) would just require a single MW cavity, further improvements with hyperfine state selector.

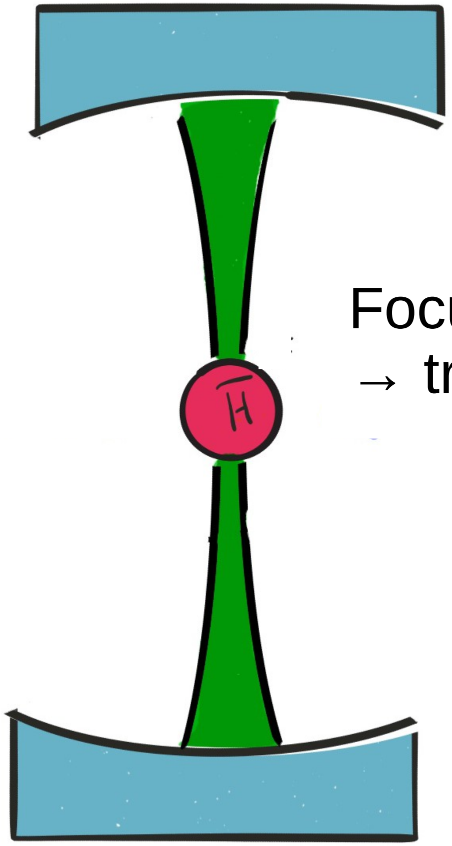
- If ELENA and Ps production in GBAR ok -> first attempts could be done in 2018. During the CERN long shutdown (LS2) measurement can be done with normal hydrogen using protons to be ready after LS2 (2021).

# $\overline{H}$ optical trapping at the magic wavelength

P. Crivelli and N. Kolachevsky, arXiv:1707.02214

Ultra cold anti-hydrogen atoms produced in GBAR could be optically trapped at the magic wavelength (lowest order Stark shifts for the 1S and 2S levels are equal) calculated recently for H to be 514.6 nm.

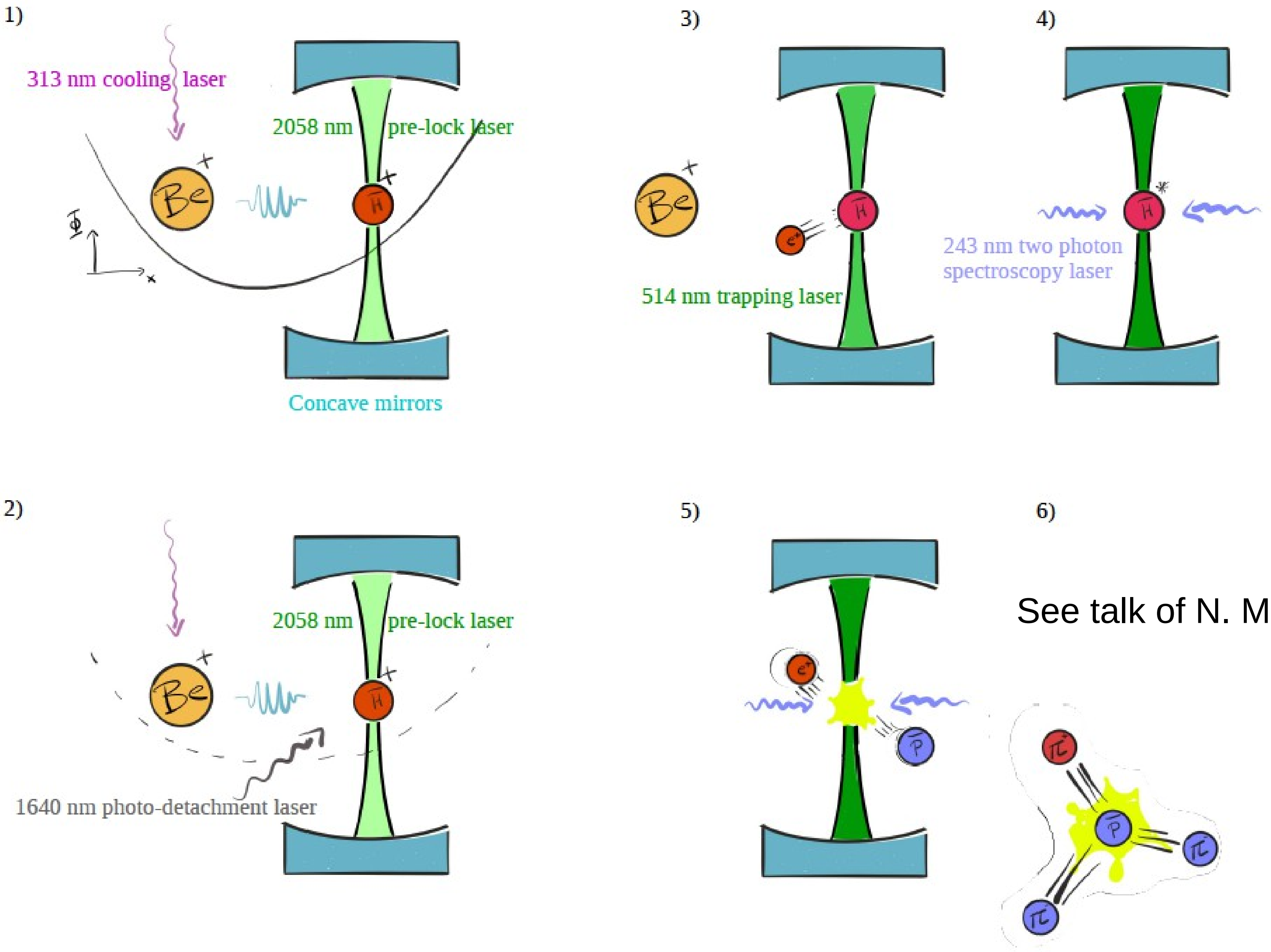
C. M. Adhikari, A. Kawasaki and U. D. Jentschura, Phys. Rev. A 94, 032510 (2016)



Focused standing wave trap: 3 kW circulating power
→ trap depth 26 mK (300 times the recoil energy of 72 μK)

# Optical trap loading & 1S-2S measurement

P. Crivelli and N. Kolachevsky, arXiv:1707.02214



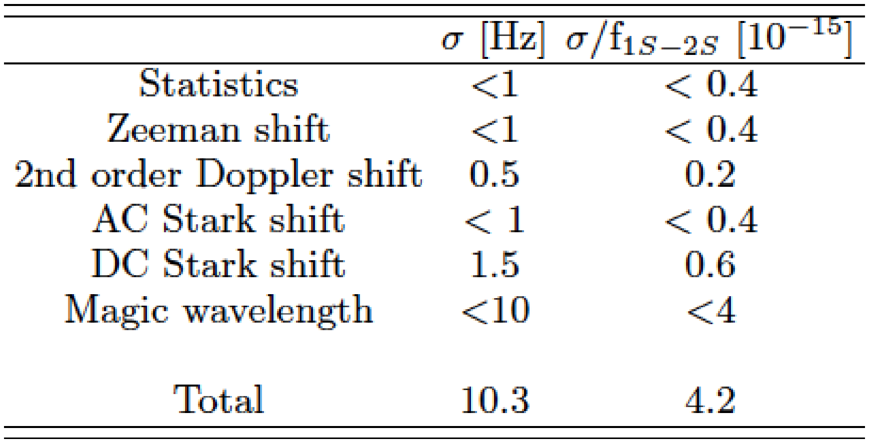
See talk of N. Madsen

# 1S-2S: expected signal rate and systematics

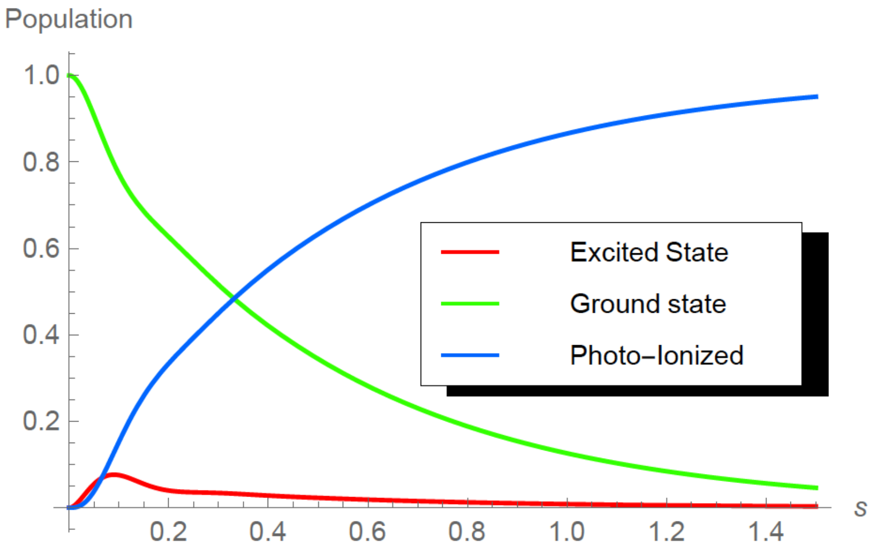
P. Crivelli and N. Kolachevsky, arXiv:1707.02214

Expected signal rate per day (assuming 8 hours duty cycle and 1 $\bar{H}^+$ per ELENA cycle)

$$R = \epsilon_d \cdot N_{\bar{\mathrm{H}}^+} \simeq 144$$



|  | $\sigma$ [Hz] | $\sigma/f_{1S-2S}$ [$10^{-15}$] |
|---|---|---|
| Statistics | <1 | < 0.4 |
| Zeeman shift | <1 | < 0.4 |
| 2nd order Doppler shift | 0.5 | 0.2 |
| AC Stark shift | < 1 | < 0.4 |
| DC Stark shift | 1.5 | 0.6 |
| Magic wavelength | <10 | <4 |
|  |  |  |
| Total | 10.3 | 4.2 |



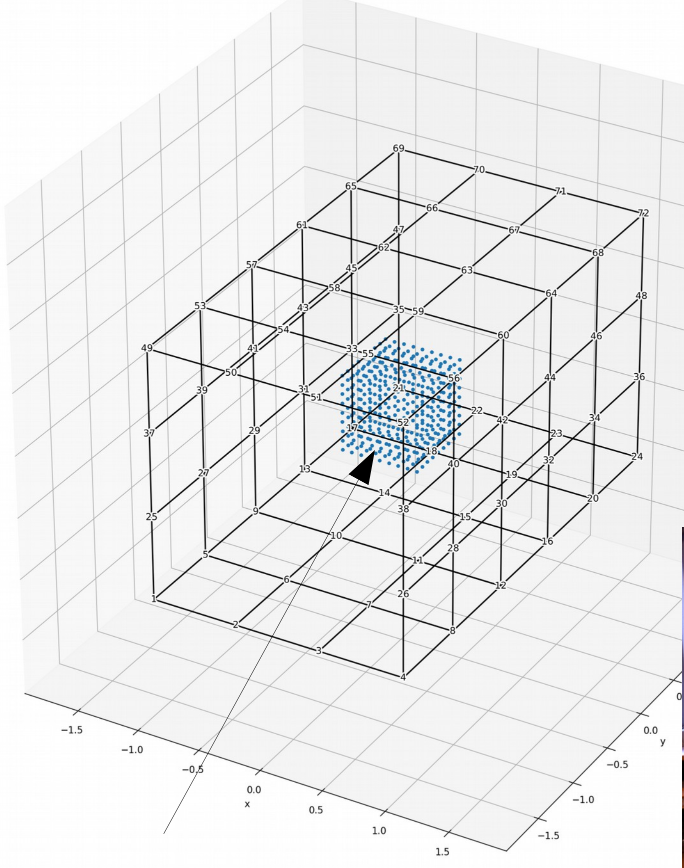
Experiment very challenging but expected signal rate seems promising
→ measurement of the anti-hydrogen 1S-2S transition at a level that would be comparable and even super-seed its matter counter (measured at MPQ with a relative fractional accuracy of 4.2 x $10^{-15}$).
→ very sensitive test of Lorentz and CPT symmetry.

Thank you for your attention and
to the organizers for the very kind invitation

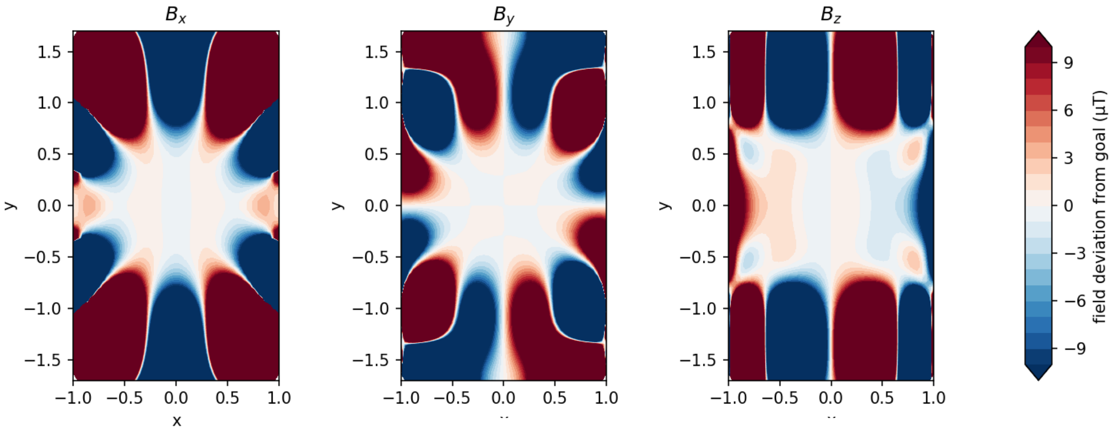
# Back up slides

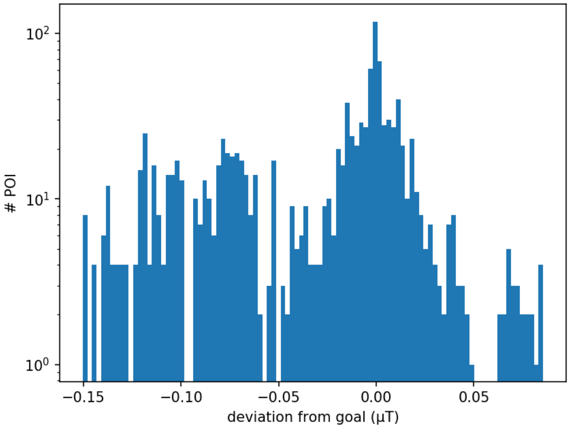
# Active B-field stabilization

Magnetic field gradients in free fall region should be kept < 2 μT/m to reach an accuracy below $10^{-3}$ → achievable with external active stabilization.



60cm³ free fall chamber volume



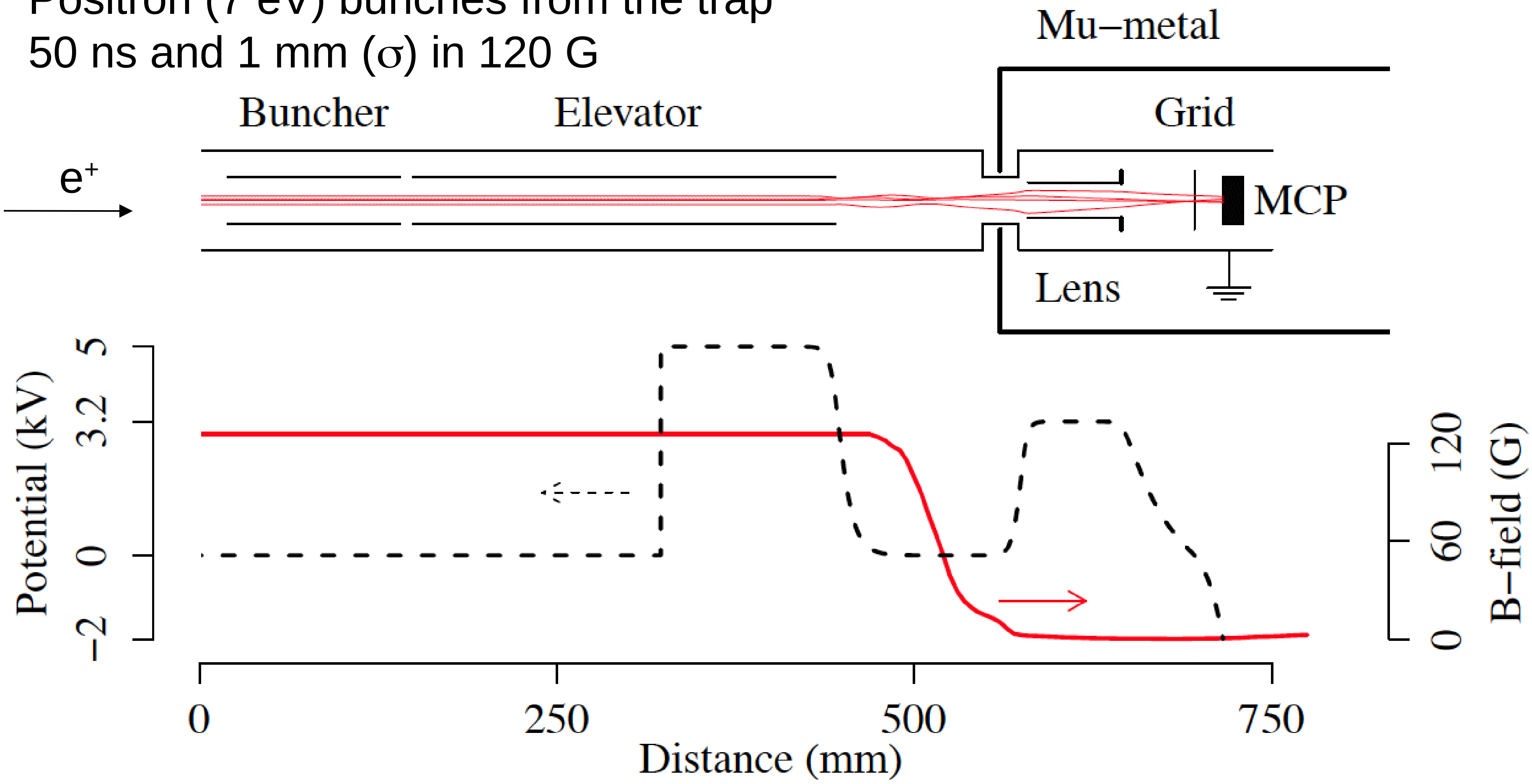


Preliminary calculations performed by M. Rawlik (ETHZ Kirch's group, nEDM@PSI ), open source software available: https://github.com/rawlik/Coils.jl/blob/master/example.ipynb

# Bunching and extraction to a field free e-m region

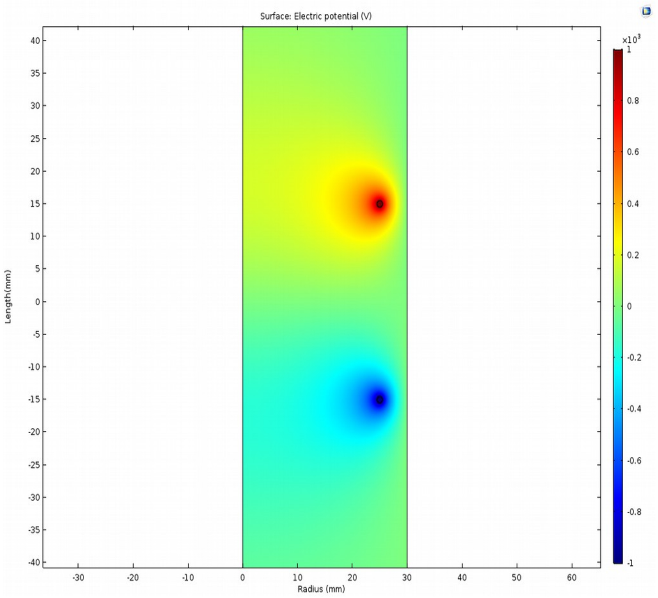
D. A. Cooke G., Barandun, S Vergani,, B Brown, A Rubbia and P Crivelli, J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016), arXiv:1508.06213 [physics.ins-det].

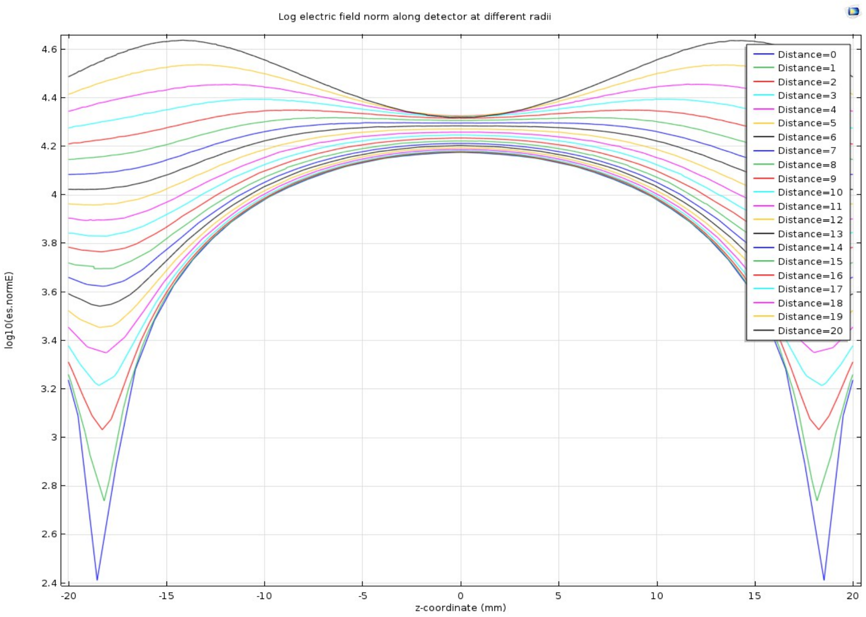
Positron (7 eV) bunches from the trap
50 ns and 1 mm (σ) in 120 G



- On target (kept at ground): positron bunches of 1 ns with a beam spot of 1 mm
- extracted to the field free  e-m region with 90 % efficiency.

# Quenching field



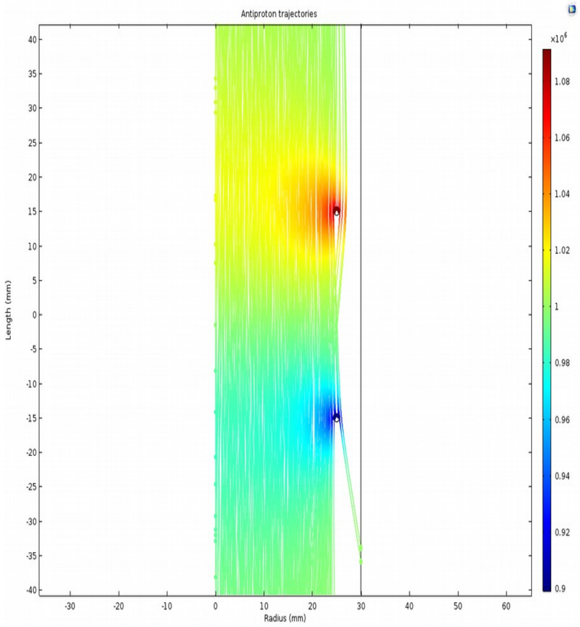


Calculated quenching field for 2 rings of 50 mm diameter separated by 30 mm.
→ 100 V/cm for 2 cm → 5 ns quench lifetime

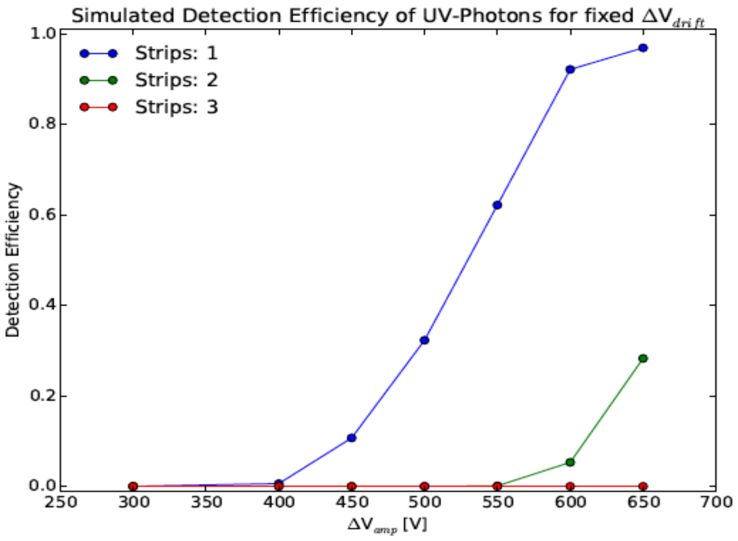
Rev. Sci. Instrum. 86, 063504 (2015)

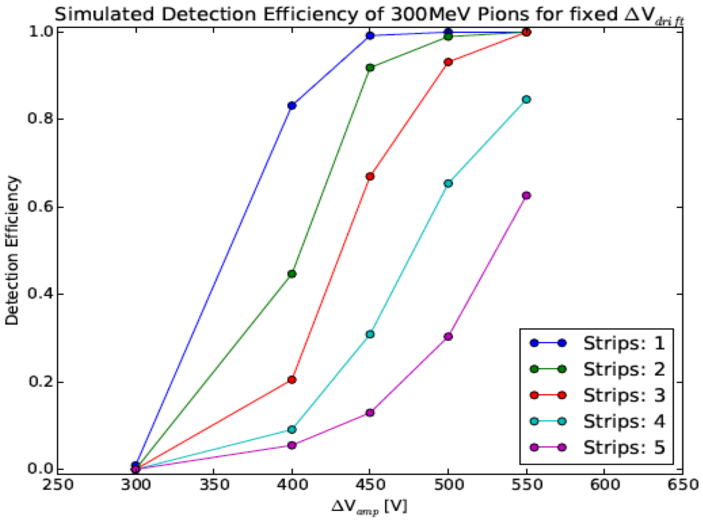
→ almost 100 % of quench probability.

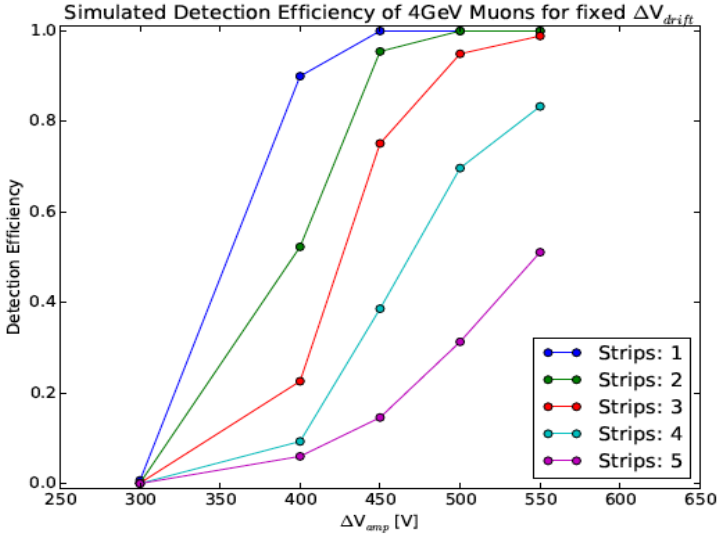
The trajectories of the pbars are also simulated. Only very off-axis charged particles are affected y the quenching field



# Lyman alpha vs Pion and Muons







Discrimination between UV photons and pion or muons via multiplicity of hits on the strips.