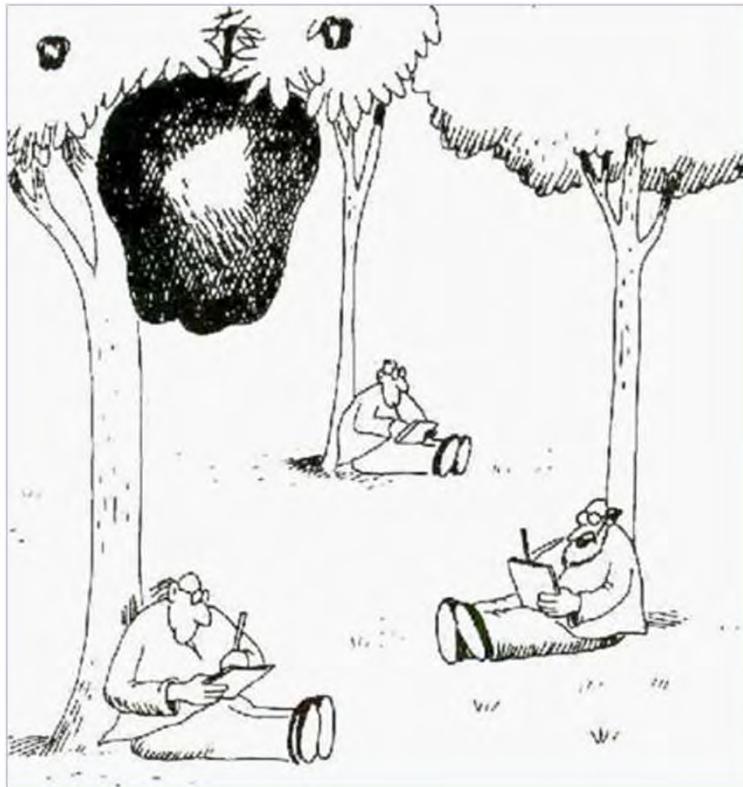


Gravitational Behaviour of Antihydrogen at Rest

David Lunney (for the AD-7/GBAR Collaboration)

IJCLab (ex-CSNSM) IN2P3/CNRS, Université Paris-Saclay, Orsay

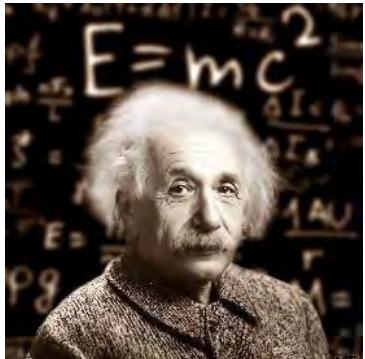
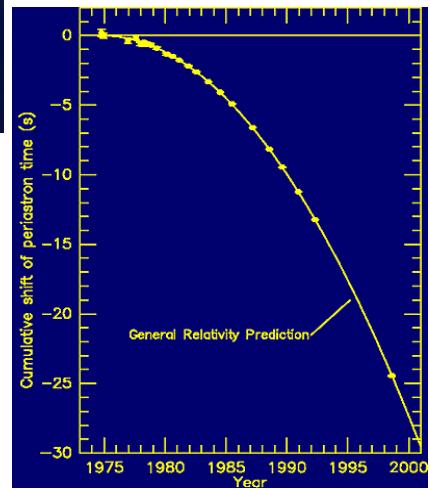
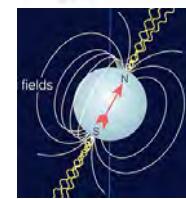
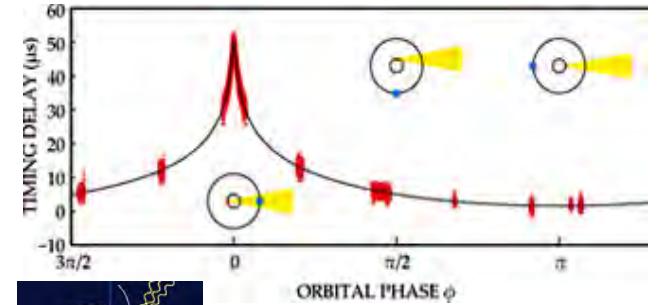
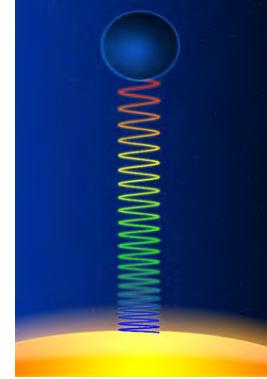
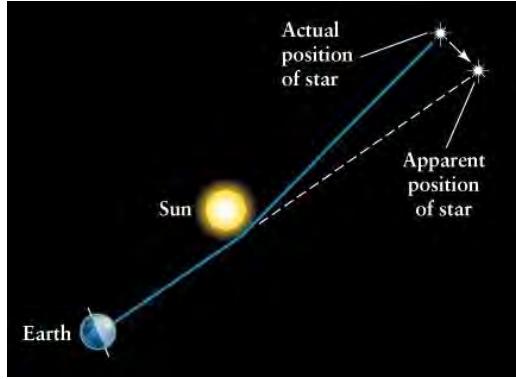
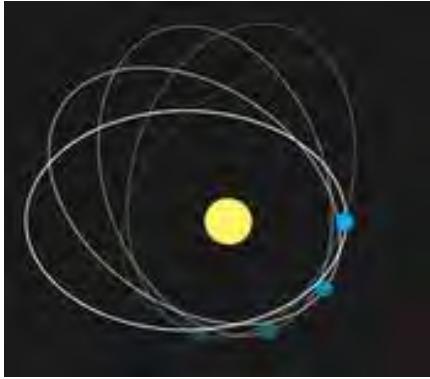


"Nothing yet – how about you, Newton?"
-Gary Larson, *The Far Side*

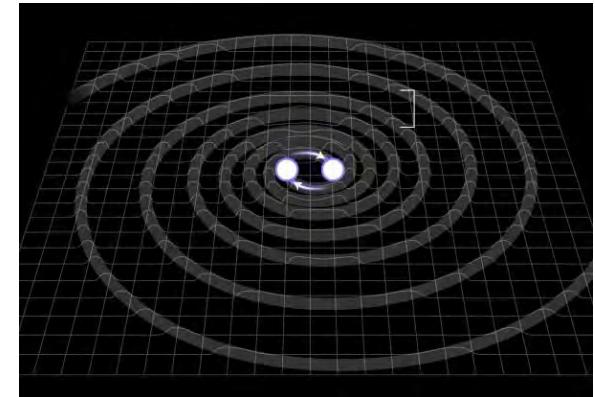
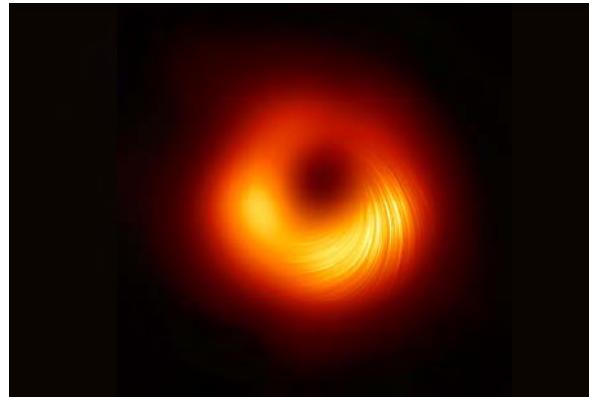
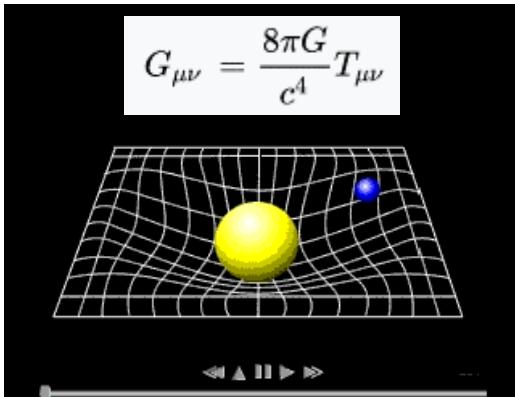


"To you it was fast."
-Eric Lewis, *The New Yorker*

Einstein: General Relativity



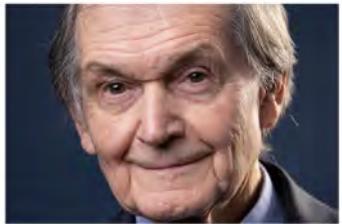
- 1905: Special Relativity (plus other papers!)
- 1907: equivalence principle of falling bodies
- 1915: theory of GR presented (Mercury's perihelion)
- 1919: Dyson, Eddington & Davidson (solar eclipse)
- 1959: Gravitational Redshift (Pound-Rebka experiment)
- 1964: Shapiro Delay (radio waves)
- 1974: Taylor-Hulse pulsar (Nobel prize in 1993)
- 2015: Gravitational waves (Nobel prize in 2017)
- 2019: First Black Hole image (Event Horizon Telescope)



The Nobel Prize in Physics 2020

Roger Penrose

"for the discovery that black hole formation is a robust prediction of the general theory of relativity"



Reinhard Genzel

"for the discovery of a supermassive compact object at the centre of our galaxy"



Andrea Ghez

"for the discovery of a supermassive compact object at the centre of our galaxy"



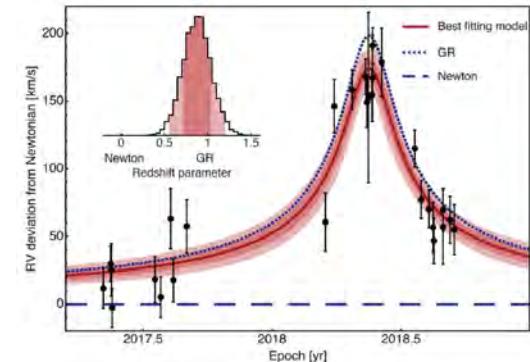
REPORT

Science (2019)

GRAVITATION

Relativistic redshift of the star S0-2 orbiting the Galactic Center supermassive black hole

Tuan Do^{1*}, Aurelien Hees^{2,1}, Andrea Ghez¹, Gregory D. Martinez¹, Devin S. Chu³,



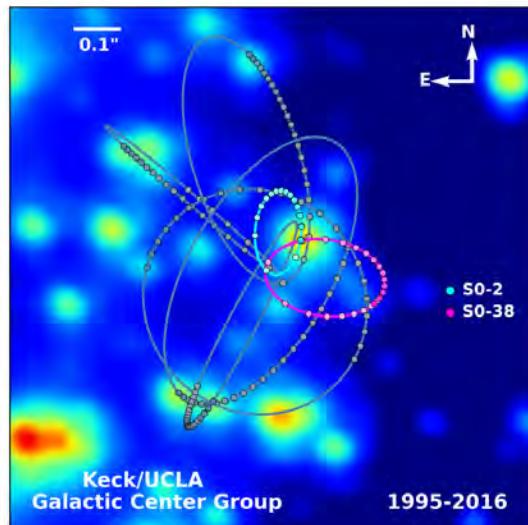
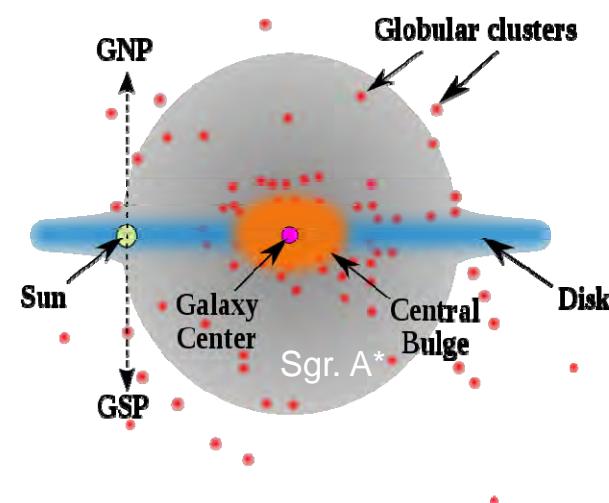
A&A 615, L15 (2018)
<https://doi.org/10.1051/0004-6361/201833718>
 © ESO 2018

Astronomy & Astrophysics

LETTER TO THE EDITOR

Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole*

GRAVITY Collaboration*, R. Abuter⁸, A. Amorim^{6,13}, M. Bauböck¹, J. P. Berger^{5,8}, H. Bonnet⁸, W. Brandner³, V. Cardoso^{13,15}, Y. Clénet², P. T. de Zeeuw^{11,1}, J. Dexter^{14,1}, A. Eckart^{4,10,1*}, F. Eisenhauer¹, N. M. Förster Schreiber¹, P. Garcia^{7,13}, F. Gao¹, E. Gendron², R. Genzel^{1,12,1*}, S. Gillessen^{1,1*}, M. Habibi¹, X. Haubois⁹, T. Henning², S. Hippel³, M. Horrobin⁴, A. Jiménez-Rosales¹, L. Jochum⁹, L. Jocou⁵, A. Kaufer⁹, P. Kervella², S. Lacour², V. Lapeyrère², J.-B. Le Bouquin⁵, P. Léna², M. Nowak^{17,2}, T. Ott¹, T. Paumard²,



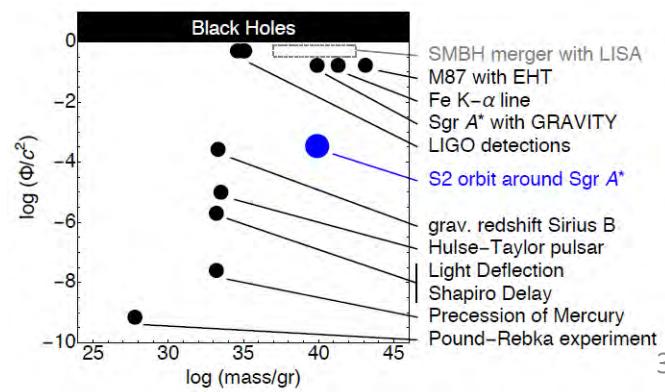
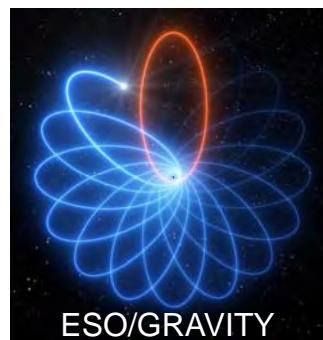
A&A 636, L5 (2020)
<https://doi.org/10.1051/0004-6361/202037813>
 © GRAVITY Collaboration 2020

LETTER TO THE EDITOR

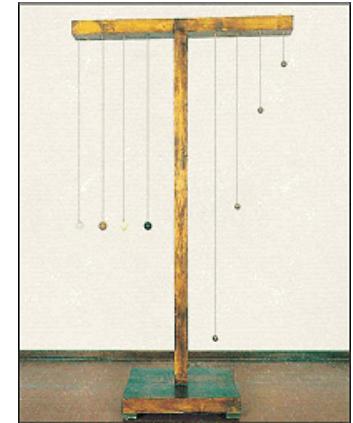
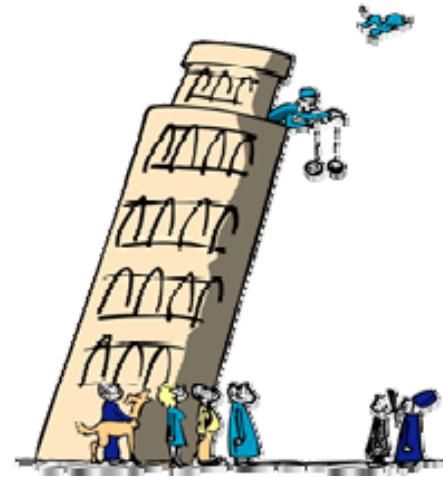
Detection of the Schwarzschild precession in the orbit of the star S2 near the Galactic centre massive black hole

GRAVITY Collaboration*: R. Abuter⁸, A. Amorim^{6,13}, M. Bauböck¹, J. P. Berger^{5,8}, H. Bonnet⁸, W. Brandner³, V. Cardoso^{13,15}, Y. Clénet², P. T. de Zeeuw^{11,1}, J. Dexter^{14,1}, A. Eckart^{4,10,1*}, F. Eisenhauer¹, N. M. Förster Schreiber¹, P. Garcia^{7,13}, F. Gao¹, E. Gendron², R. Genzel^{1,12,1*}, S. Gillessen^{1,1*}, M. Habibi¹, X. Haubois⁹, T. Henning², S. Hippel³, M. Horrobin⁴, A. Jiménez-Rosales¹, L. Jochum⁹, L. Jocou⁵, A. Kaufer⁹, P. Kervella², S. Lacour², V. Lapeyrère², J.-B. Le Bouquin⁵, P. Léna², M. Nowak^{17,2}, T. Ott¹, T. Paumard²,

Astronomy & Astrophysics

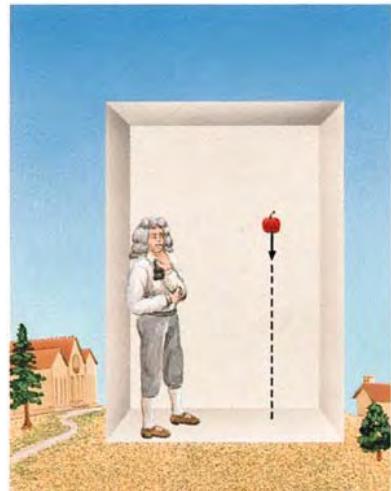


Relativity: the equivalence principle



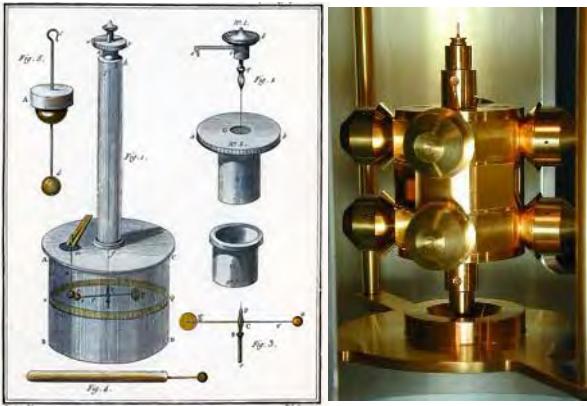
$$m_{\text{gravity}} = m_{\text{inertia}}$$

Early EP experiments



Testing the equivalence principle

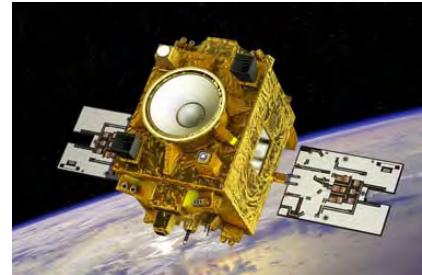
The torsion balance



Coulomb → Eötvös → Eöt-Wash (Seattle)
T.A. Wagner, S. Schlamminger, J.H. Gundlach &
E.G. Adelberger, *Class. Quantum Grav.* (2012)



J.G. Williams, S.G. Turyshev and D.H. Boggs,
Class. Quantum Grav. 29, 184004 (2012)



Physics ABOUT BROWSE PRESS COLLECTIONS

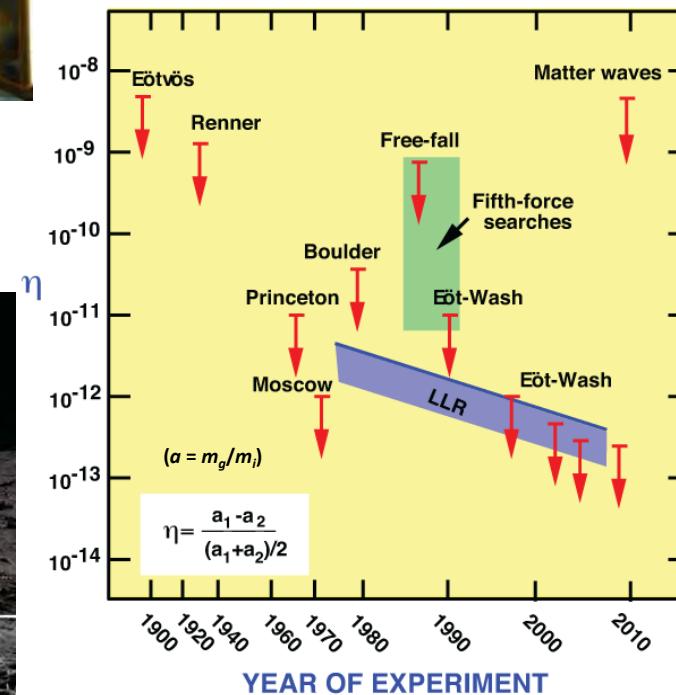
Synopsis: Space Tests of the Equivalence Principle

December 4, 2017

The MICROSCOPE satellite mission has tested the equivalence principle with unprecedented precision, showing no deviations from the predictions of general relativity.

[Print](#) [f](#) [t](#) [e](#)

MICROSCOPE Mission:
First Results of a Space
Test of the Equivalence
Principle
Pierre Touboul et al.
Phys. Rev. Lett. 119, 231101
(2017)

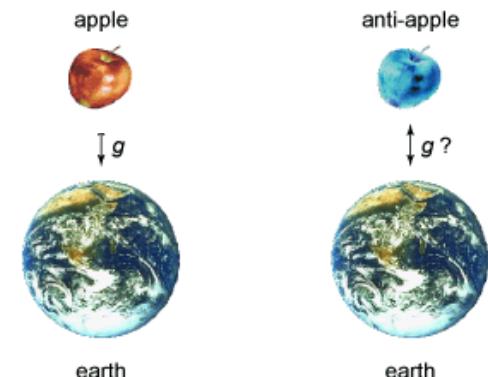


C.M. Will, *Living Rev. Relativity* (2014)

EP holds!

Different locations,
different masses...

...but never tested
with antimatter!



“anti” gravity?

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = 0$$

$$\begin{array}{ccc} \mathbf{a}_t & \uparrow & \mathbf{a}_v \\ \downarrow & & \downarrow \\ \bar{\mathbf{a}}_t & \downarrow & \bar{\mathbf{a}}_v \end{array}$$

GR: tensor interaction
spin-2 graviton
“charge” is mass

EM: vector interaction
spin-1 photon
charge: + or -

tensor + vector gravity?
different acceleration
(antimatter faster)

Standard Model Extension (SME):

effective field theory adding General Relativity (GR)
& CPT/Lorentz violation (LV)

$$L_{\text{SME}} = L_{\text{SM}} + L_{\text{LV}} + L_{\text{GR}}$$

A. Kostelecky and J.D. Tasson
Phys. Rev. D (2011)

$$L = \frac{1}{2} \underbrace{(m + \frac{5}{3} N^w m^w \bar{c}_{TT}^w)}_{m_{i,\text{eff}}} v^2 - gz \underbrace{(m + N^w m^w \bar{c}_{TT}^w + 2\alpha N^w (\bar{a}_{\text{eff}})_T^w)}_{m_{g,\text{eff}}}$$

Isotropic ‘Parachute’ Model (IPM)

$$\frac{1}{3} m^w \bar{c}_{TT}^w = \alpha (\bar{a}_{\text{eff}})_T^w$$

Matter

$$m_{i,\text{eff}} = m_{g,\text{eff}} \\ \mathbf{a} = \mathbf{g}$$

Antimatter

$$m_{i,\text{eff}} \neq m_{g,\text{eff}} \\ \bar{\mathbf{a}} = \mathbf{g} \left(1 - \frac{4m^w N^w}{3m} \bar{c}_{TT}^w\right)$$

antimatter slower!
different acceleration
(not “antigravity”)

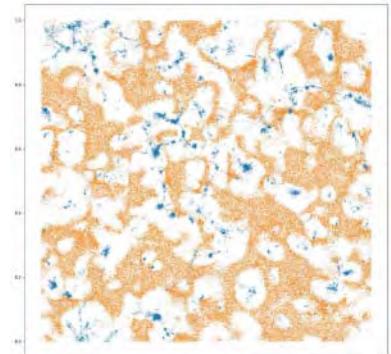


Negative mass – antigravity in GR (G. Chardin, 1997)
Dirac-Milne Universe (A. Benoit-Levy & G. Chardin, 2012)

Matter – antimatter repulsive

New simulations:
G. Manfredi et al., PRD, 2018
G. Manfredi et al., PRD, 2020

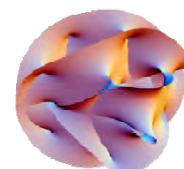
No dark matter!



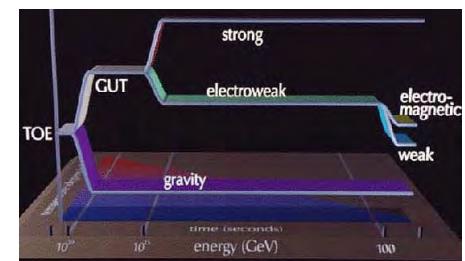
Antigravity – a crazy idea?

(J. Scherk, Phys. Lett. B, 1979)

Gravitational acceleration of Antimatter
(Nieto and Goldman, Phys. Rep., 1991)



Quantum gravity



Pulsar timing array signal:
cosmic strings? primordial BH?
APS Physics 14, 15 (2021)



The goal of GBAR: (first ever) test EP with antimatter



GBAR - CERN AD-7
Patrice Pérez (IRFU)
Spokesperson:

Free fall of
antihydrogen (at rest!)

Witteborn & Fairbank, Nature (1968):
gravitational fall of the positron ($E_g = 6E-11 \text{ V/m} !$)

M. Holtzscheiter et al. (CERN PS-200):
gravitational fall of the antiproton

Gabrielse et al. (CERN AD-2) Phys. Rev. Lett. (1999):
trapped antiproton/proton comparisons (indirect)

CLEAR Collaboration, Phys. Lett. B (1999):
kaon-antikaon limits (indirect)

Supernova 1987A, e.g. Phys. Rev. D (1989):
(anti)neutrino time of flight (hypothesis)

Cassidy et al. Phys. Rev. Lett. (2015):
Rydberg Ps for free fall experiment

The AEgis Collaboration (CERN AD-6):
Interferometry of neutral antihydrogen beam

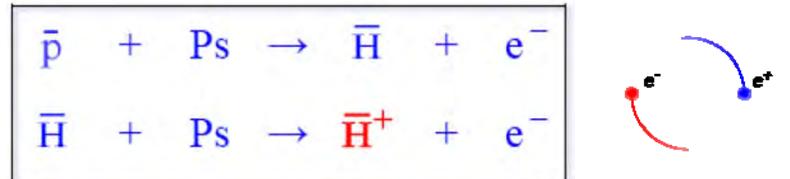
The ALPHA-g Collaboration (CERN AD-5):
Neutral antihydrogen

past
(indirect)
attempts

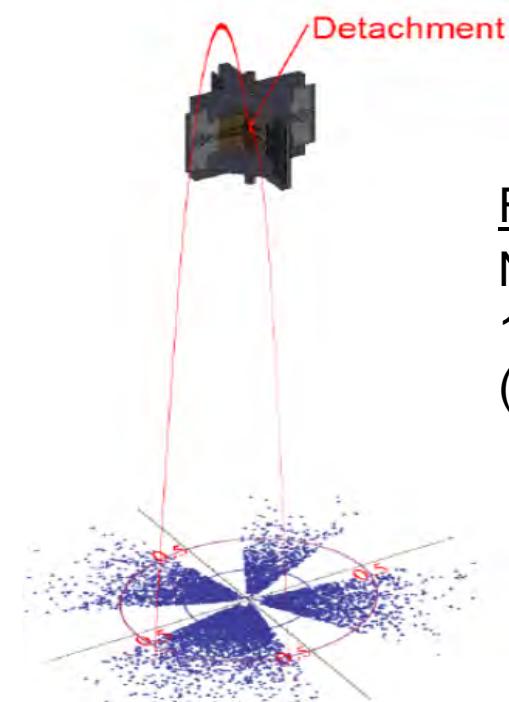
current
attempts

use of anti-hydrogen ions
(for sympathetic cooling)

J. Walz and T.W. Haensch, Gen. Rel. Grav. 36, 561 (2004)



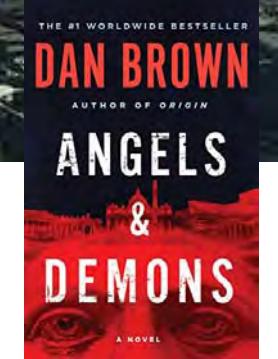
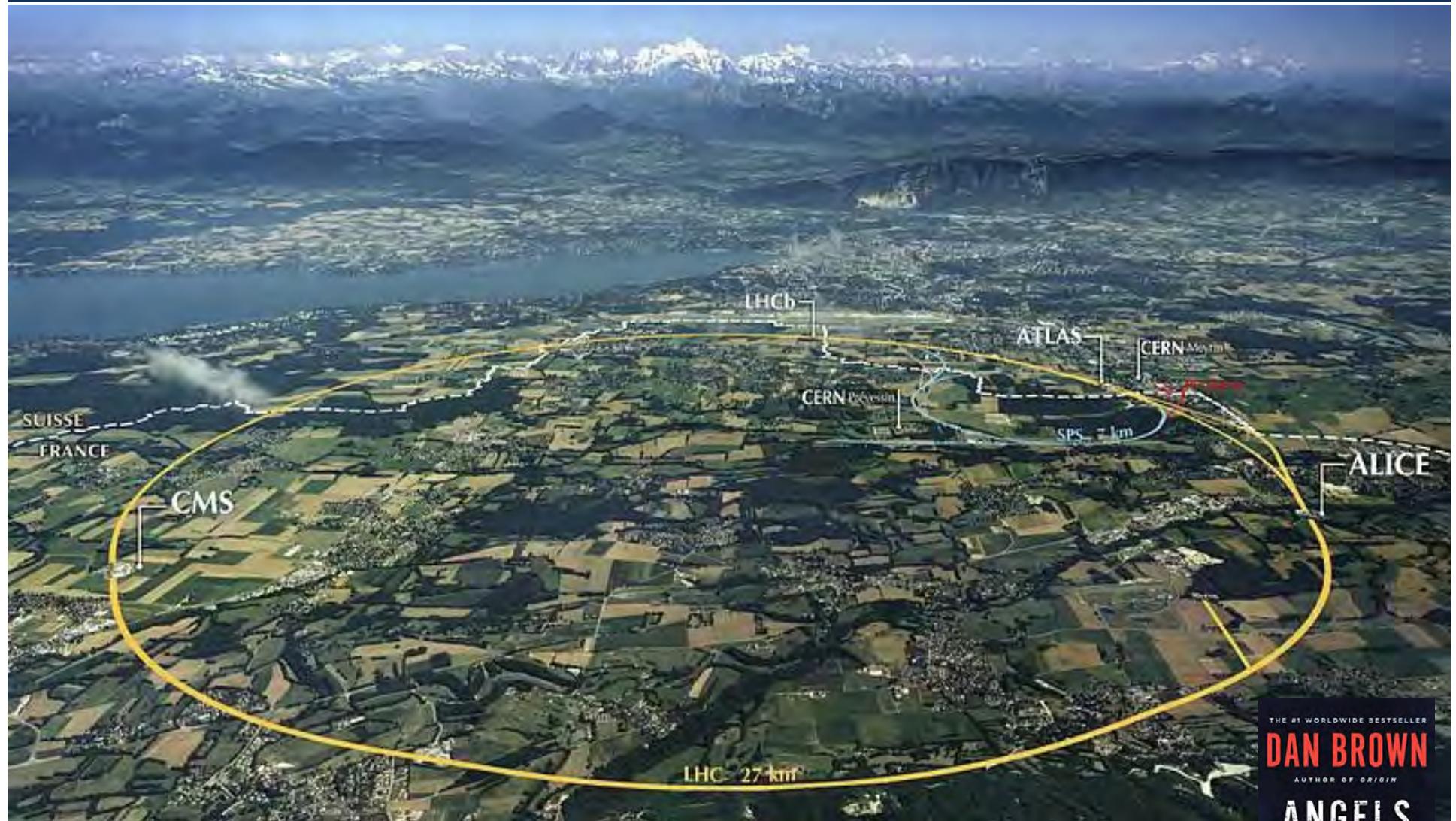
P. Pérez & A. Rosowsky, NIM A 545, 20 (2005)



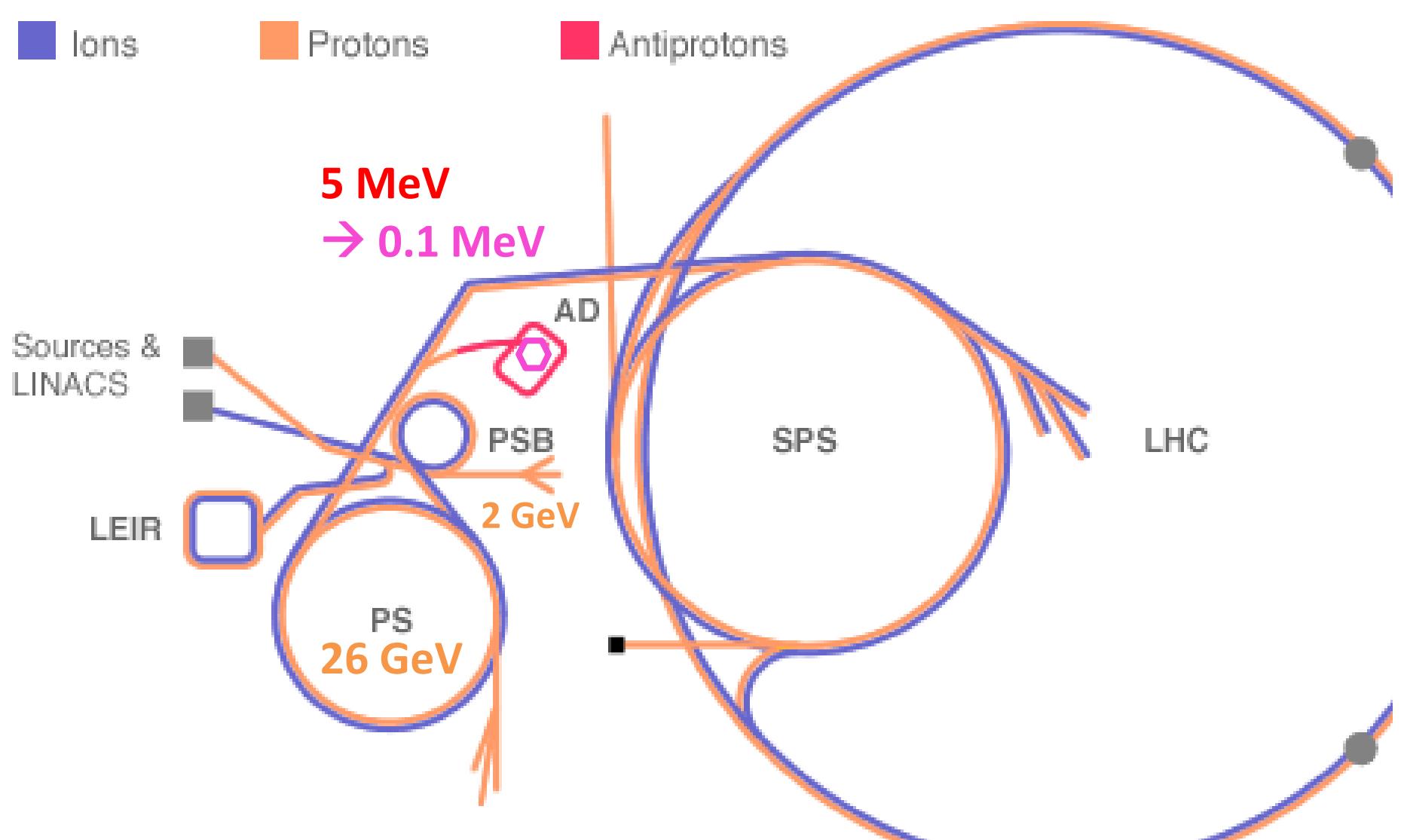
For 1 \bar{H}^+ :
Need $10^7 \bar{p}$
 10^{12} Ps/cm^2
 $(10^{10} e^+)$

Image: S. Wolf (Mainz)

CERN – home of antimatter



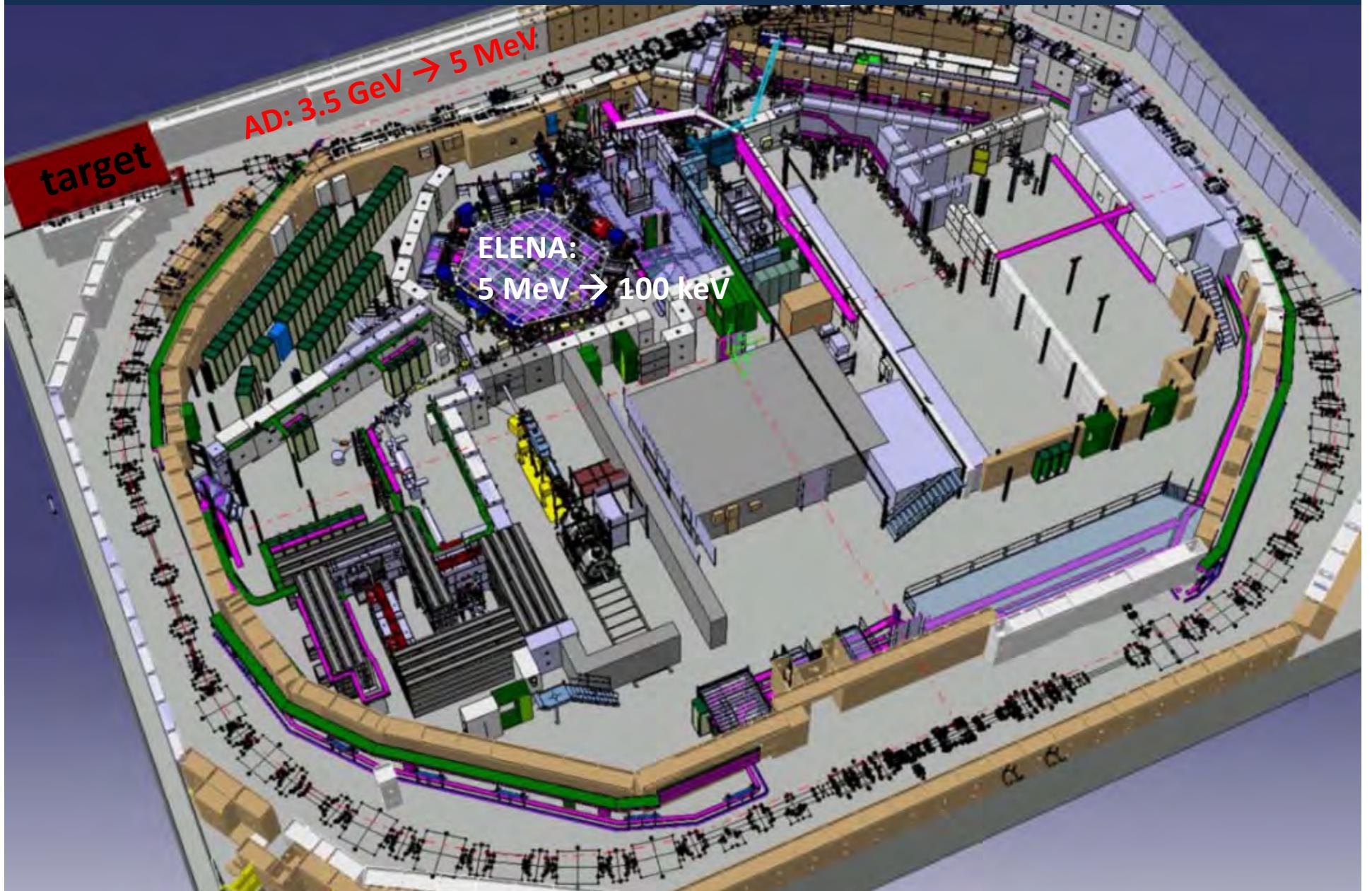
The CERN accelerator chain



The AD – CERN’s “antimatter factory”



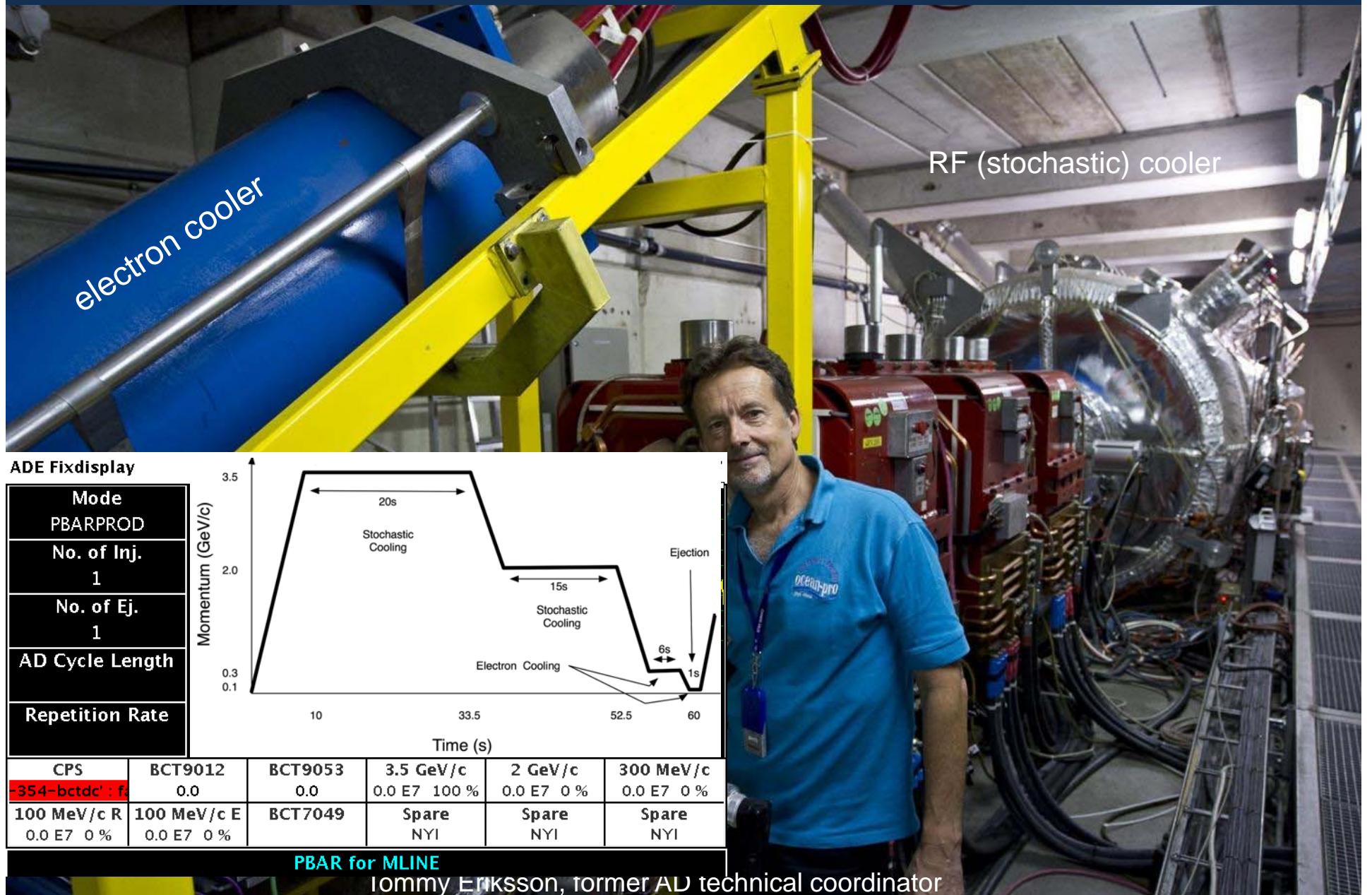
The CERN-AD (Antiproton Decelerator) facility



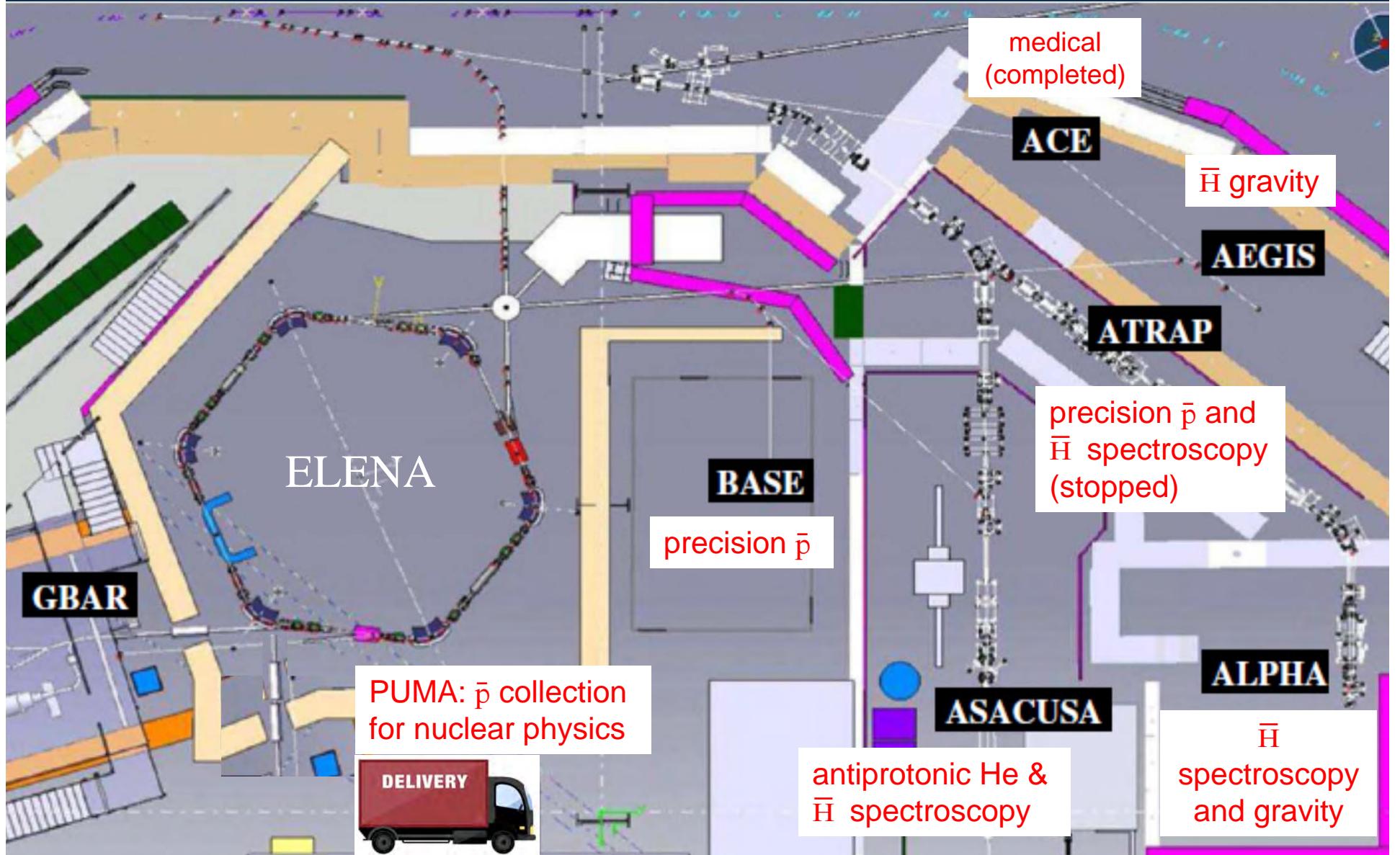
The AD storage ring



The AD coolers (needed for deceleration)

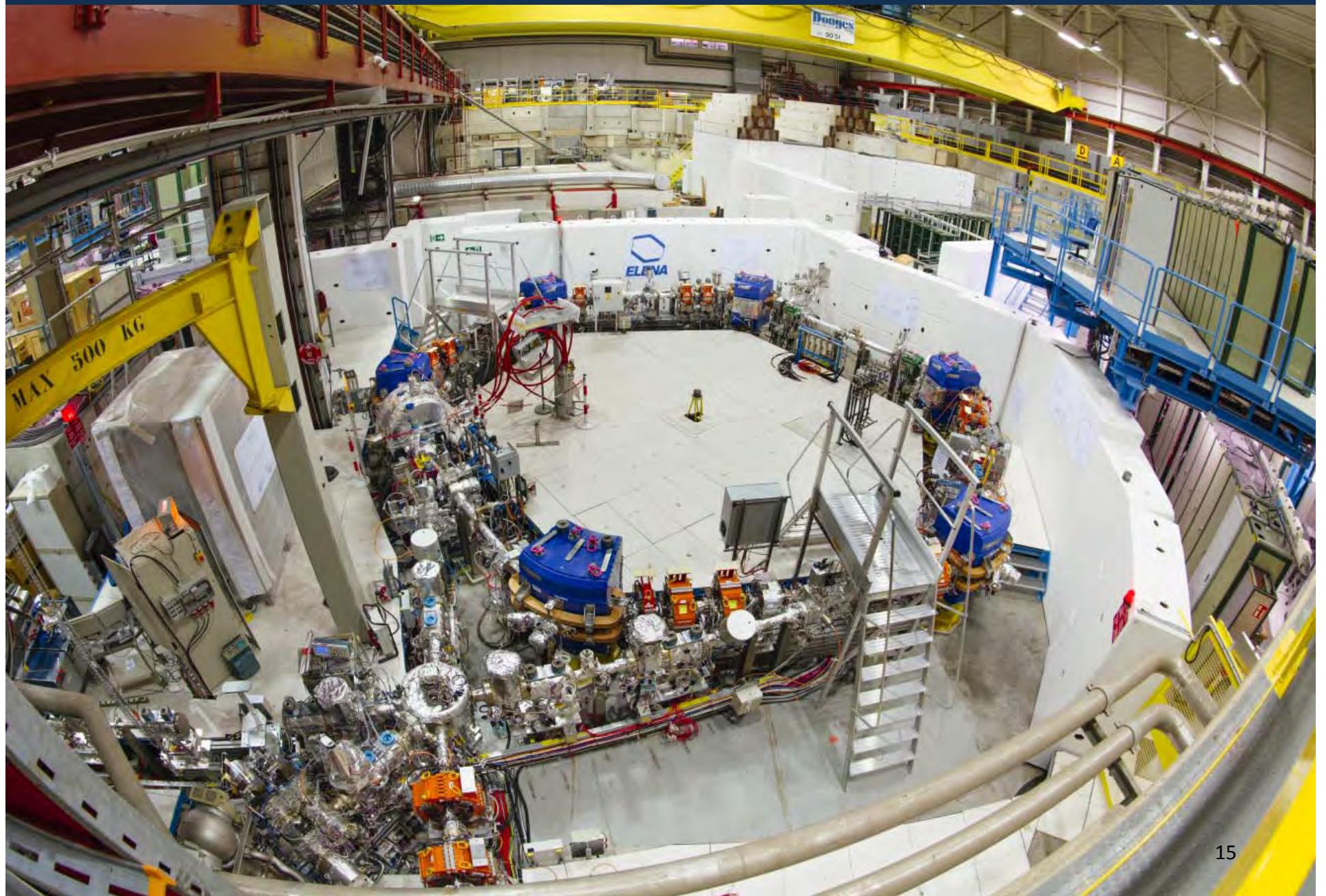


AD Experimental Hall

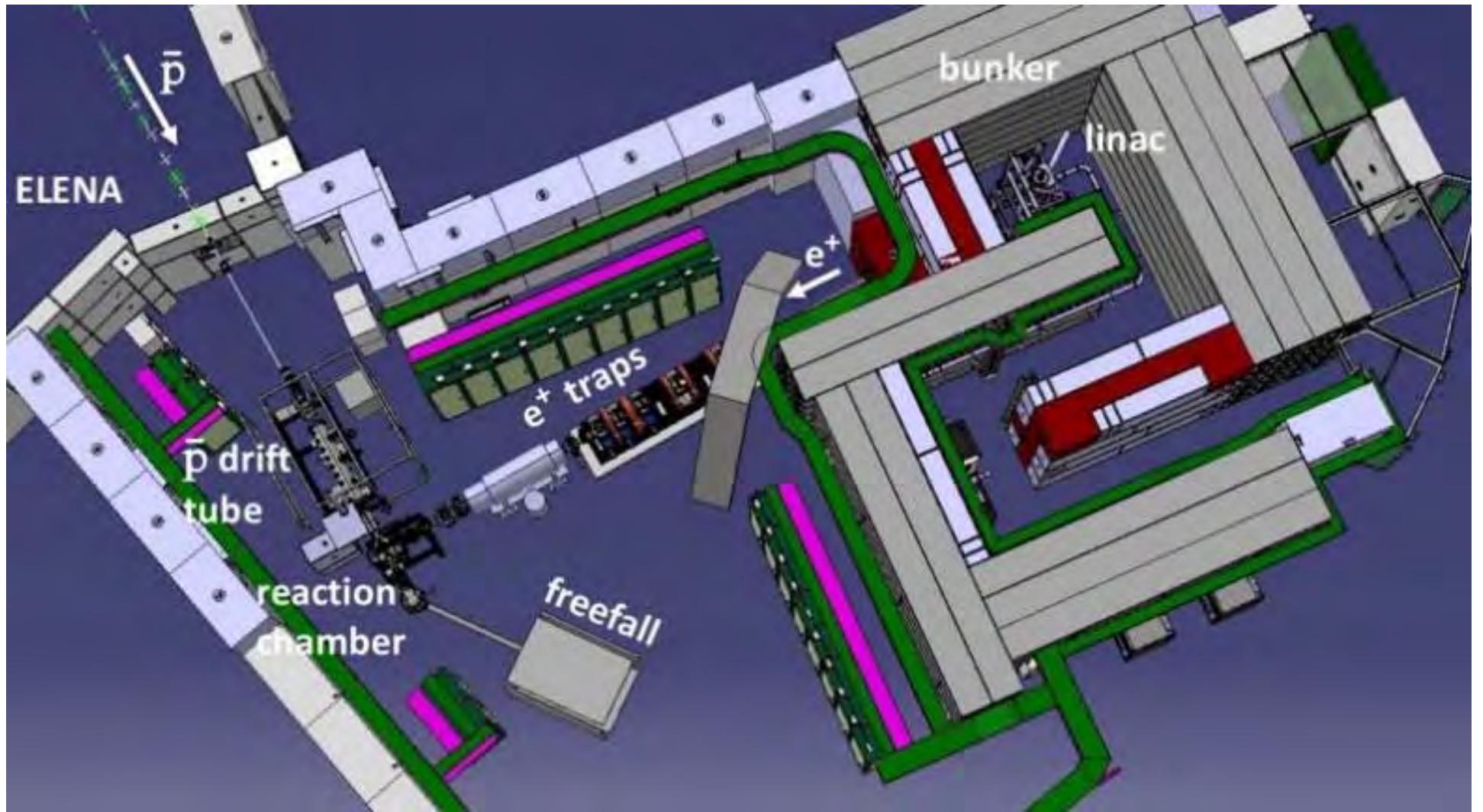


an antimatter physics program unique worldwide!

Extra Low ENergy Antiproton ring



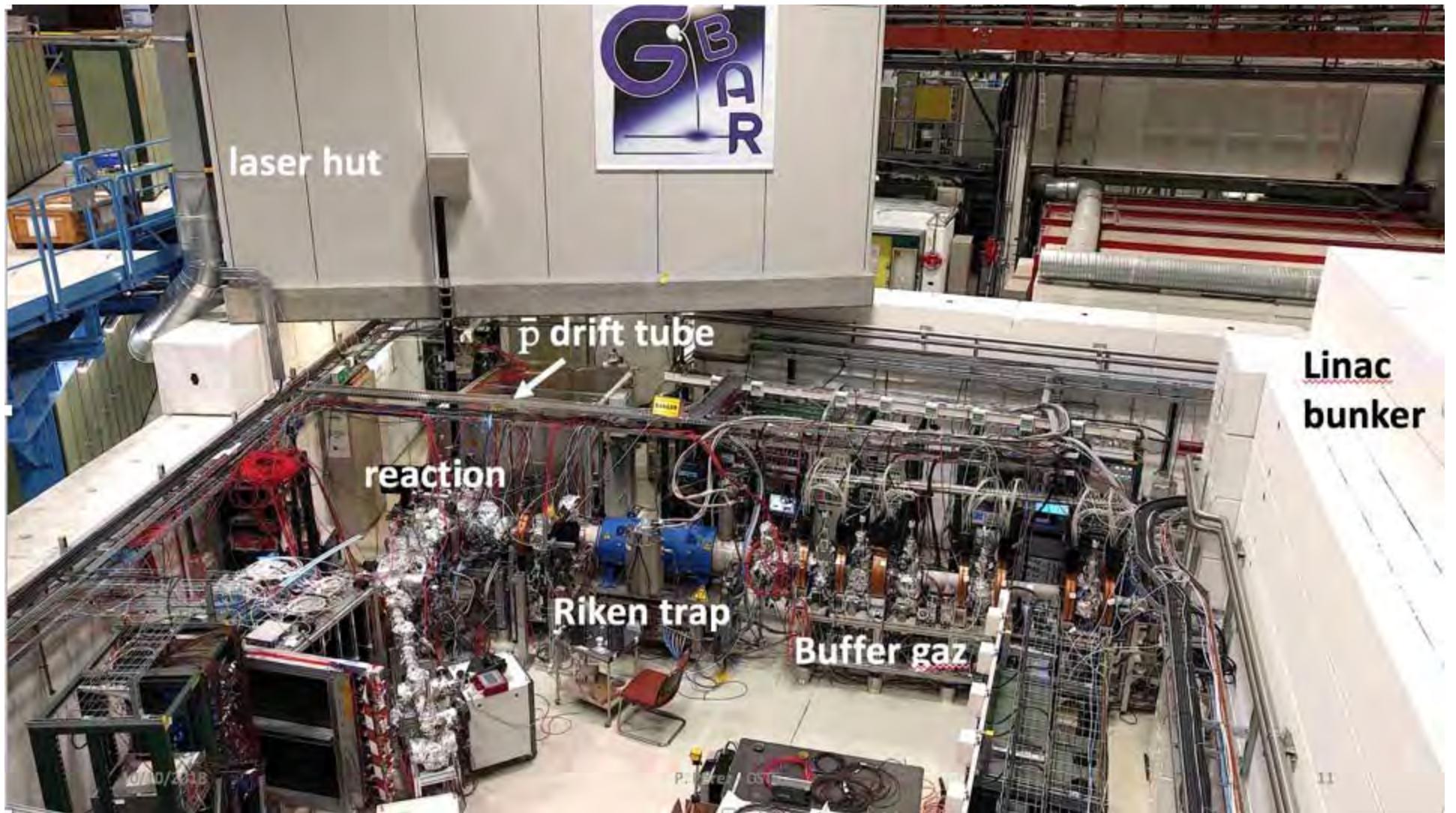
GBAR layout at CERN-AD



GBAR zone in 2017



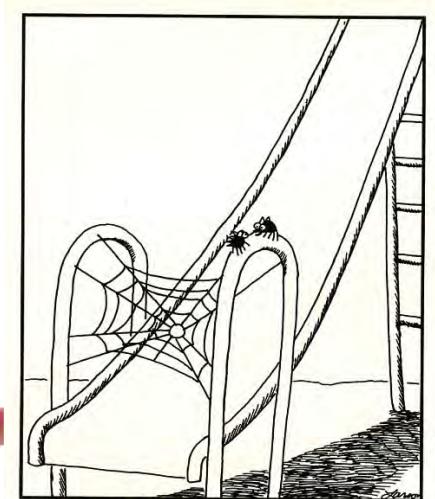
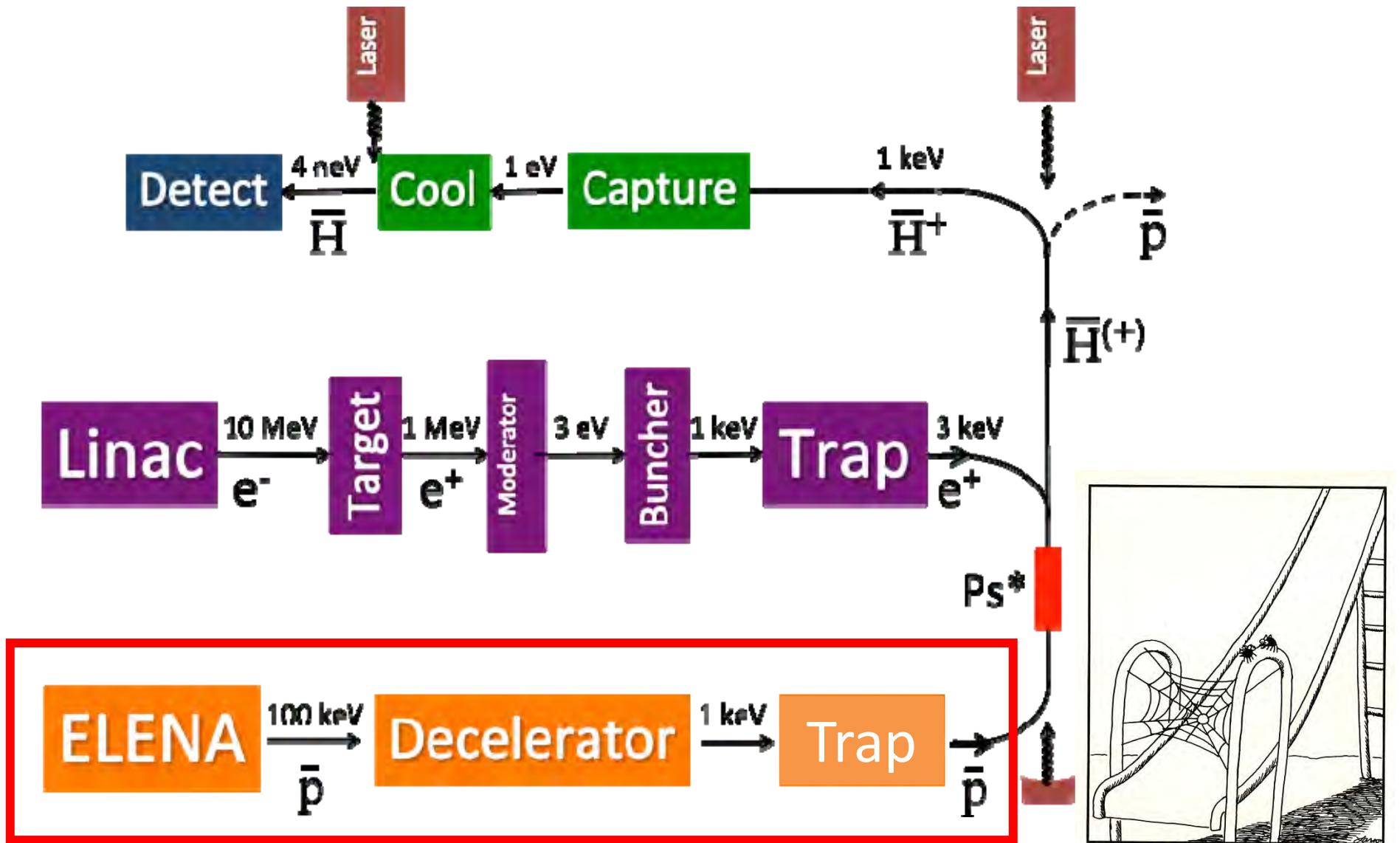
GBAR zone in 2018



more pictures at: cern.ch/gbar

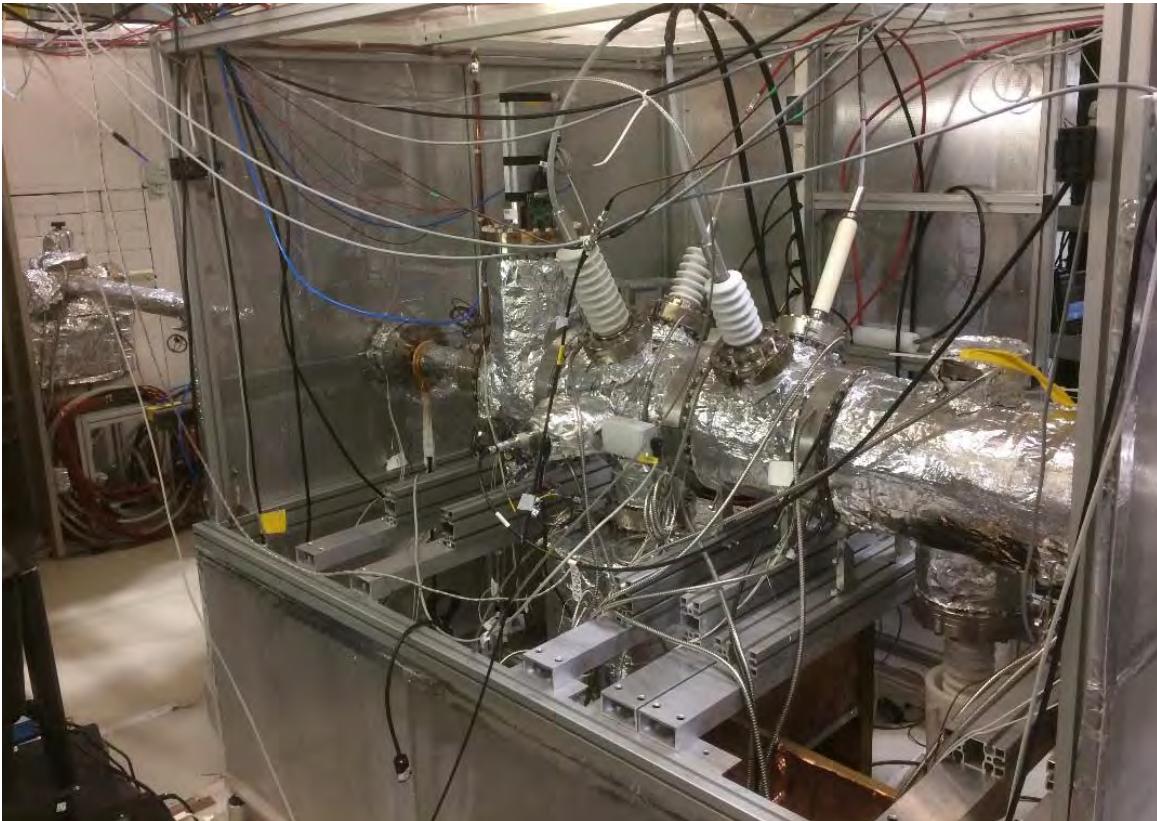
11

GBAR Schematic

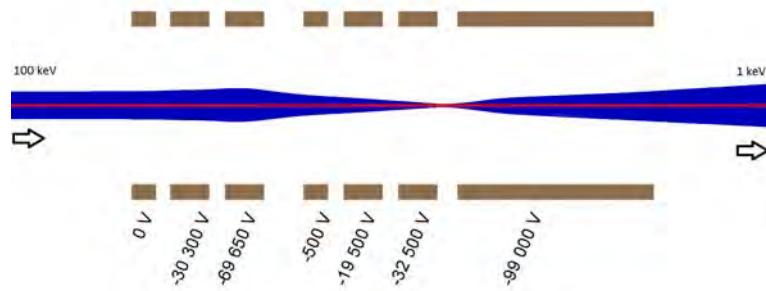
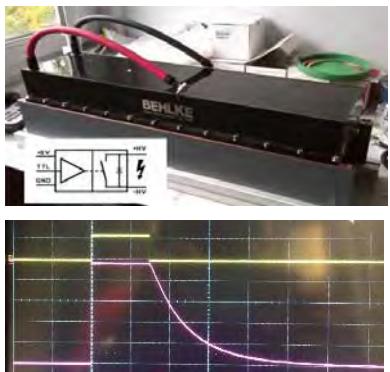


Gary Larson - *The Far Side*

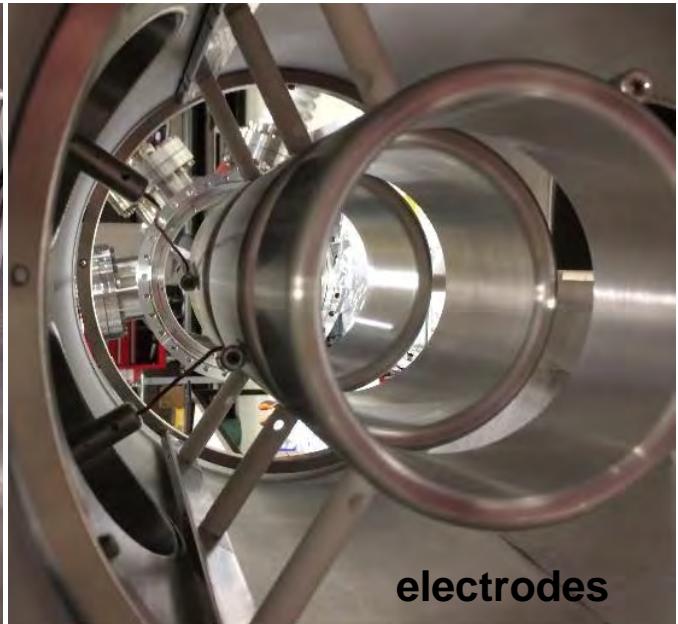
GBAR antiproton decelerator setup



decelerator connected to ELENA



A. Husson (CSNSM/U.Paris-Saclay) PhD thesis (2018)
B. Kim (SNU) and A. Welker (CERN) → NIM A (2021)



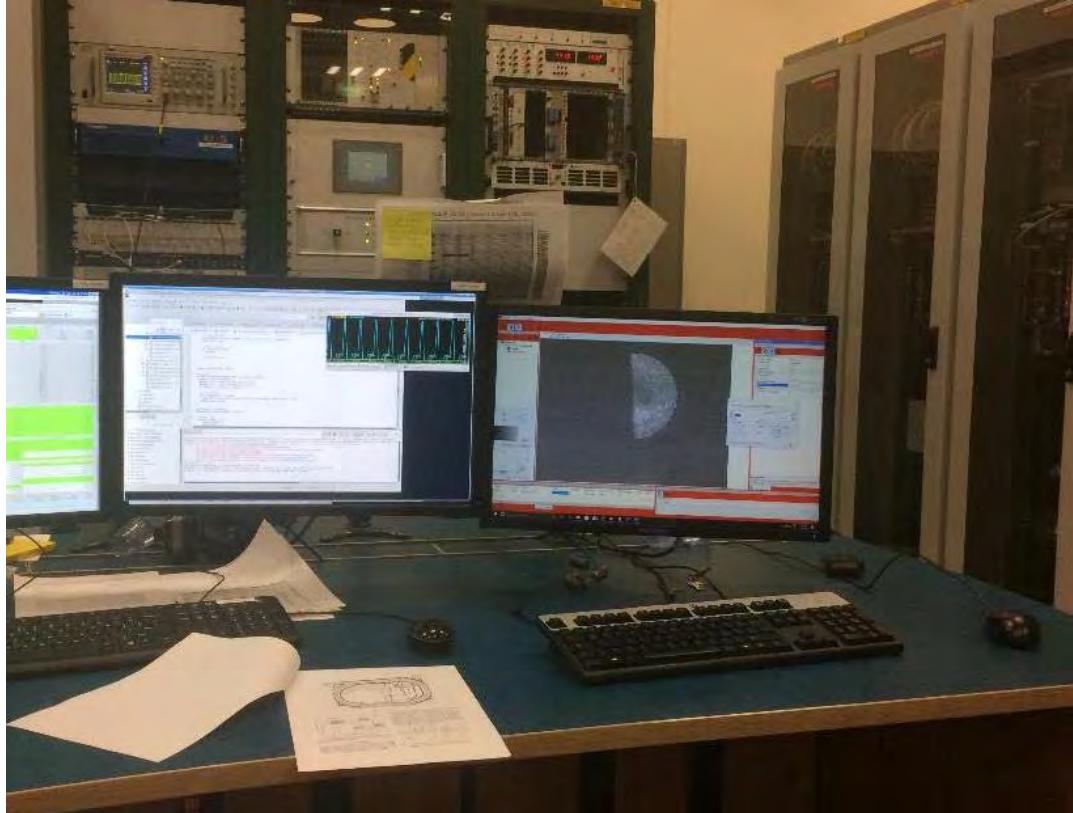
electrodes



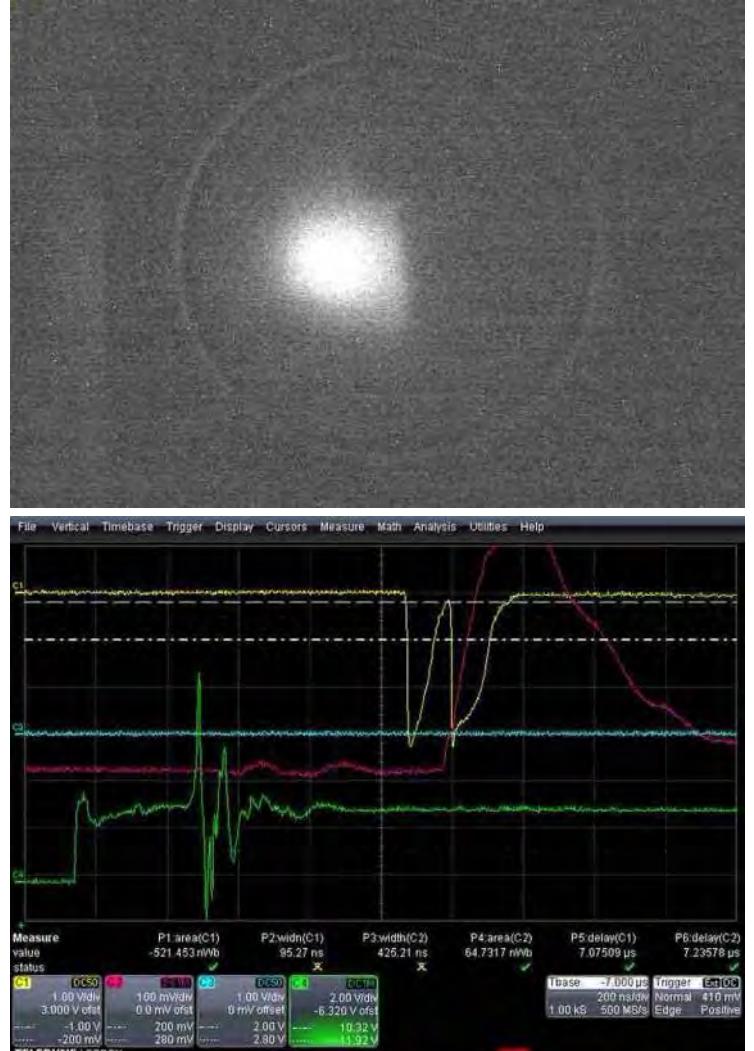
drift tube

First beams from ELENA

H^- : July 10, 2018

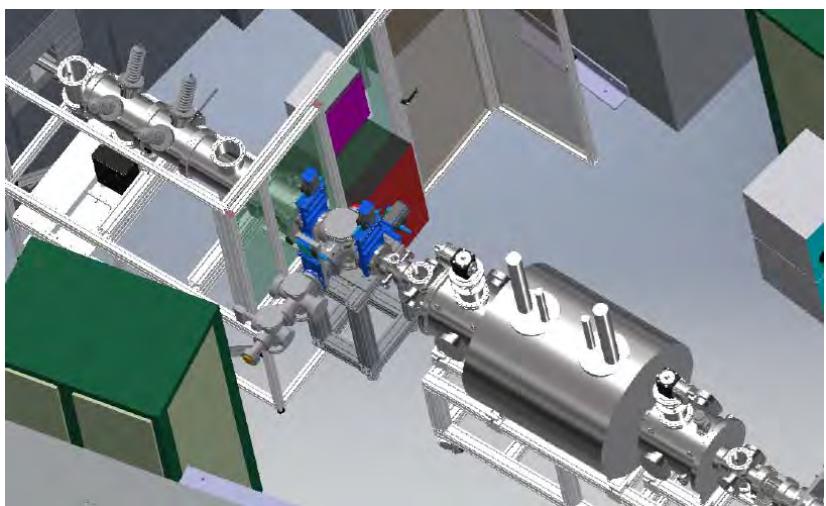
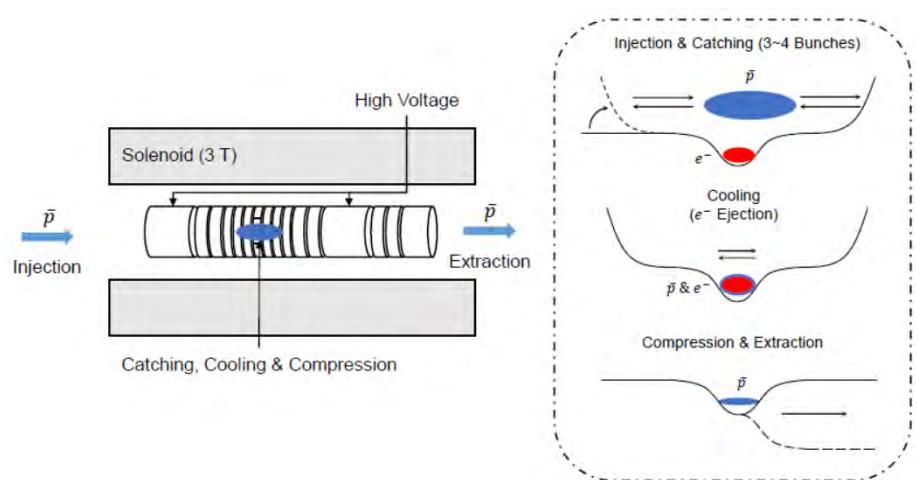


\bar{p} : July 20, 2018



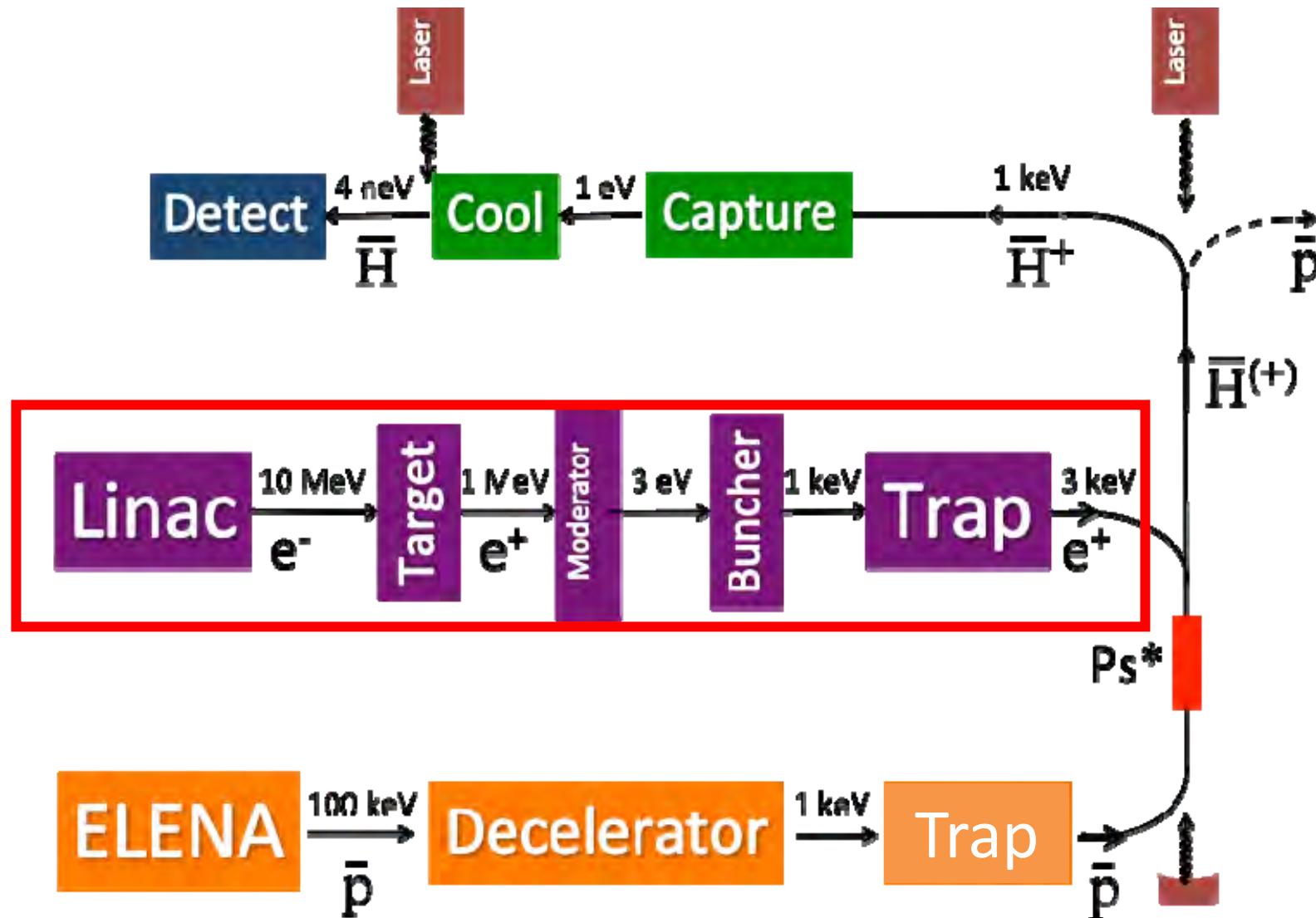
beams from ELENA:
 \bar{p} every 110 s
 H^- 5 s

2020: integrating the new antiproton trap

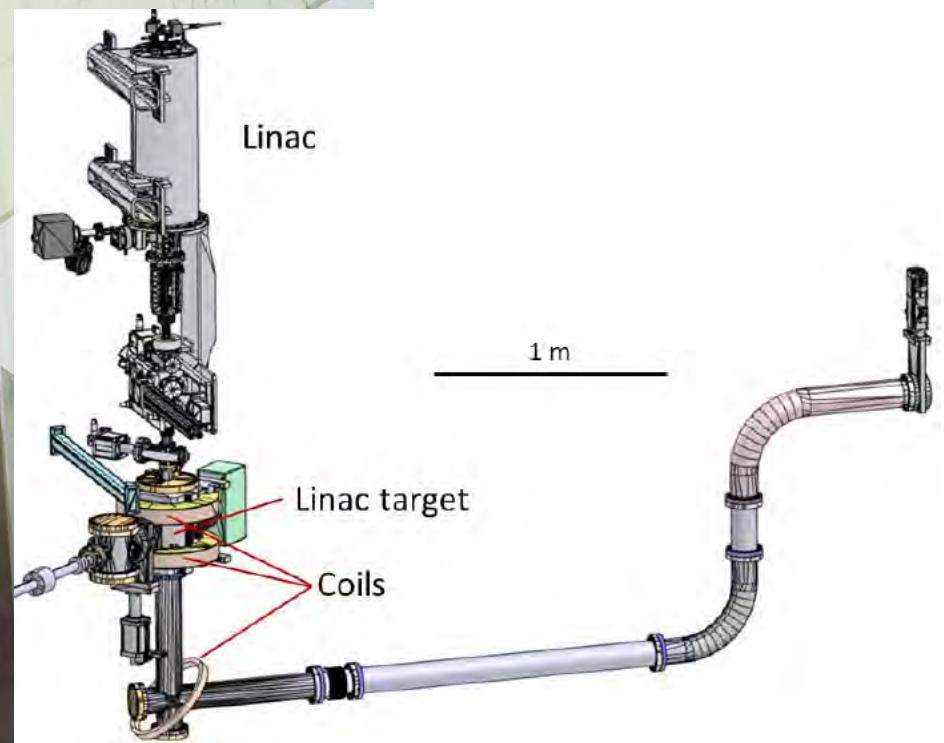


K.-H. Park, B.-C. Lee, B.-H. Kim, S.-K. Kim (Seoul) K.-H. Yoo (Ulsan) + J. Harrington (IJCLab/IRFU) + C. Roumegou (IJCLab)

GBAR Schematic



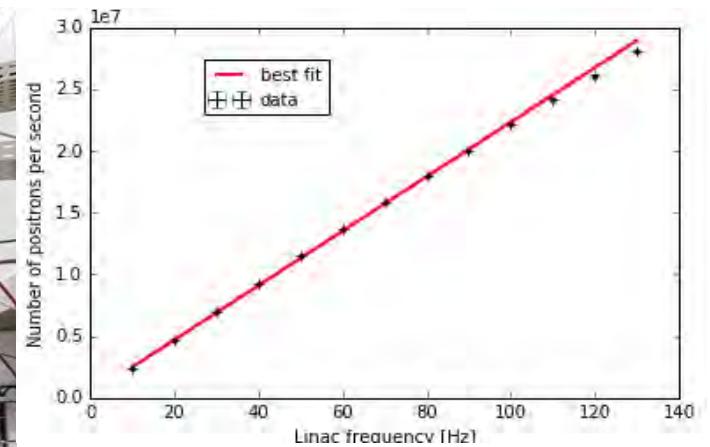
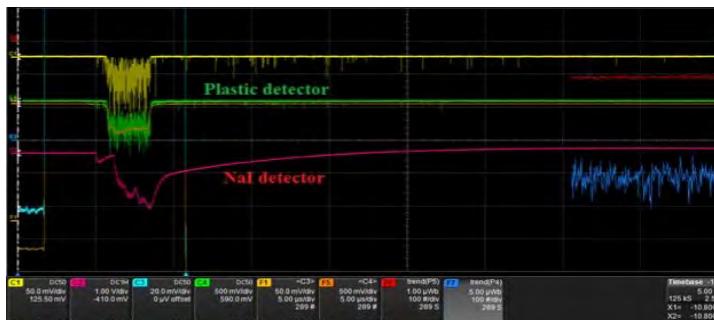
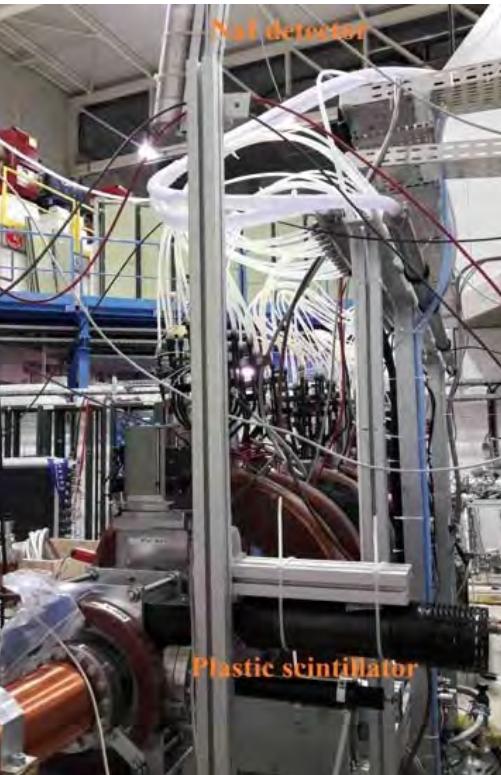
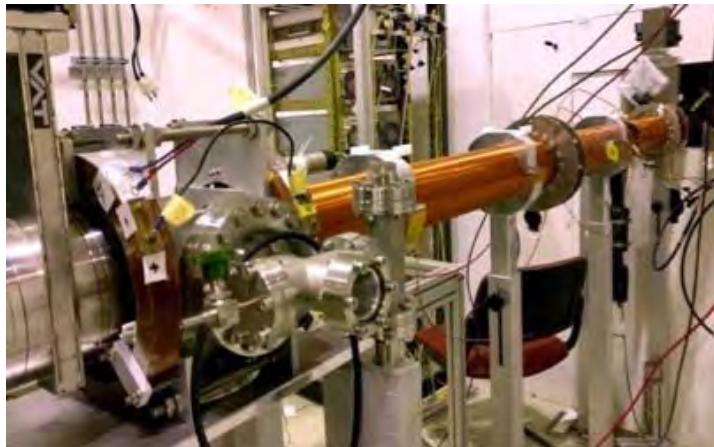
9 MeV, 300 Hz linac from NCBJ (Swierk, Poland)



L. Liszkay et al. (IRFU)
NIMA 985, 164657 (2021)

Measuring positron flux from linac

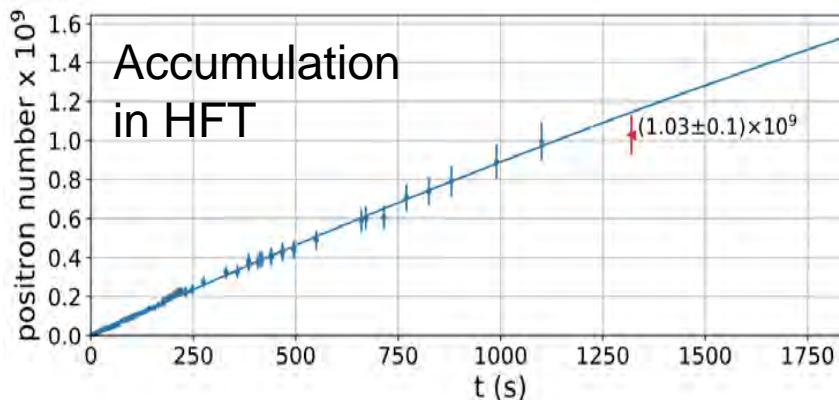
e^+ beam line exiting the bunker



- Extrapolation to 300 Hz
 $\rightarrow 6 \times 10^7 e^+ / s$
- Goal $3 \times 10^8 e^+ / s$

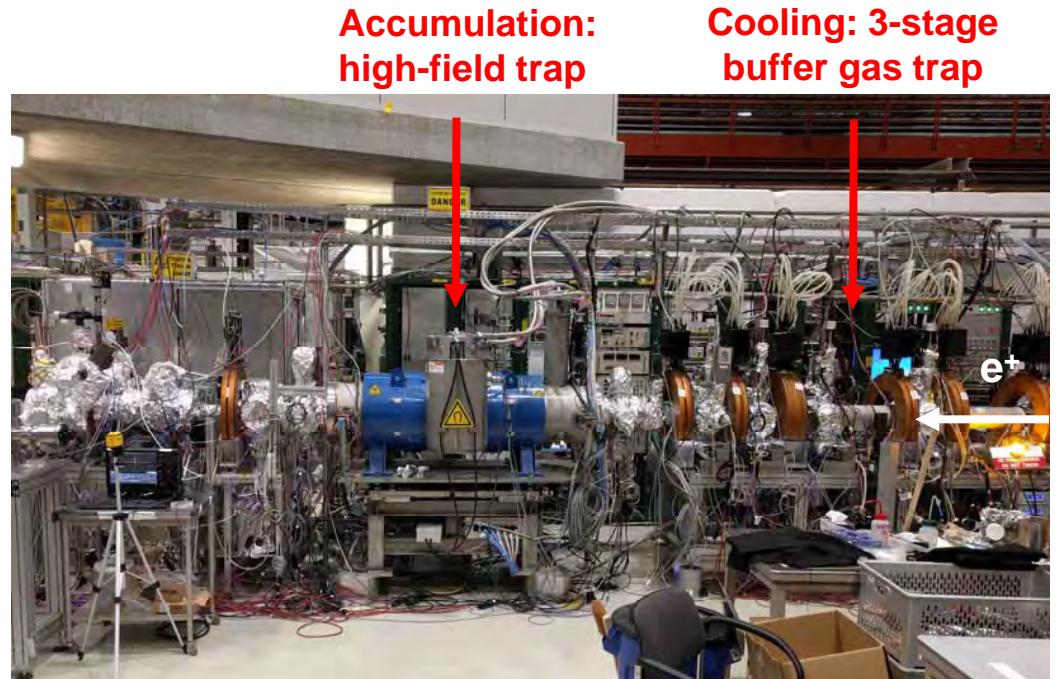
2020: positron accumulation record

positron beam:
rotating-wall
compression
in BGT



With linac at 200 Hz
 $\rightarrow 1 \times 10^9 e^+$ in 1100 s (some kind of record!)
 Goal: at least $10^{10} e^+$ in 110 s

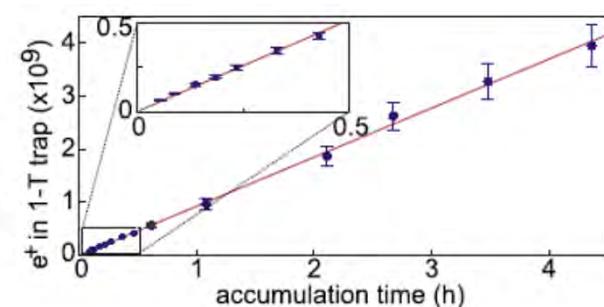
S. Niang, IRFU/U. Paris-Saclay, PhD (2020)



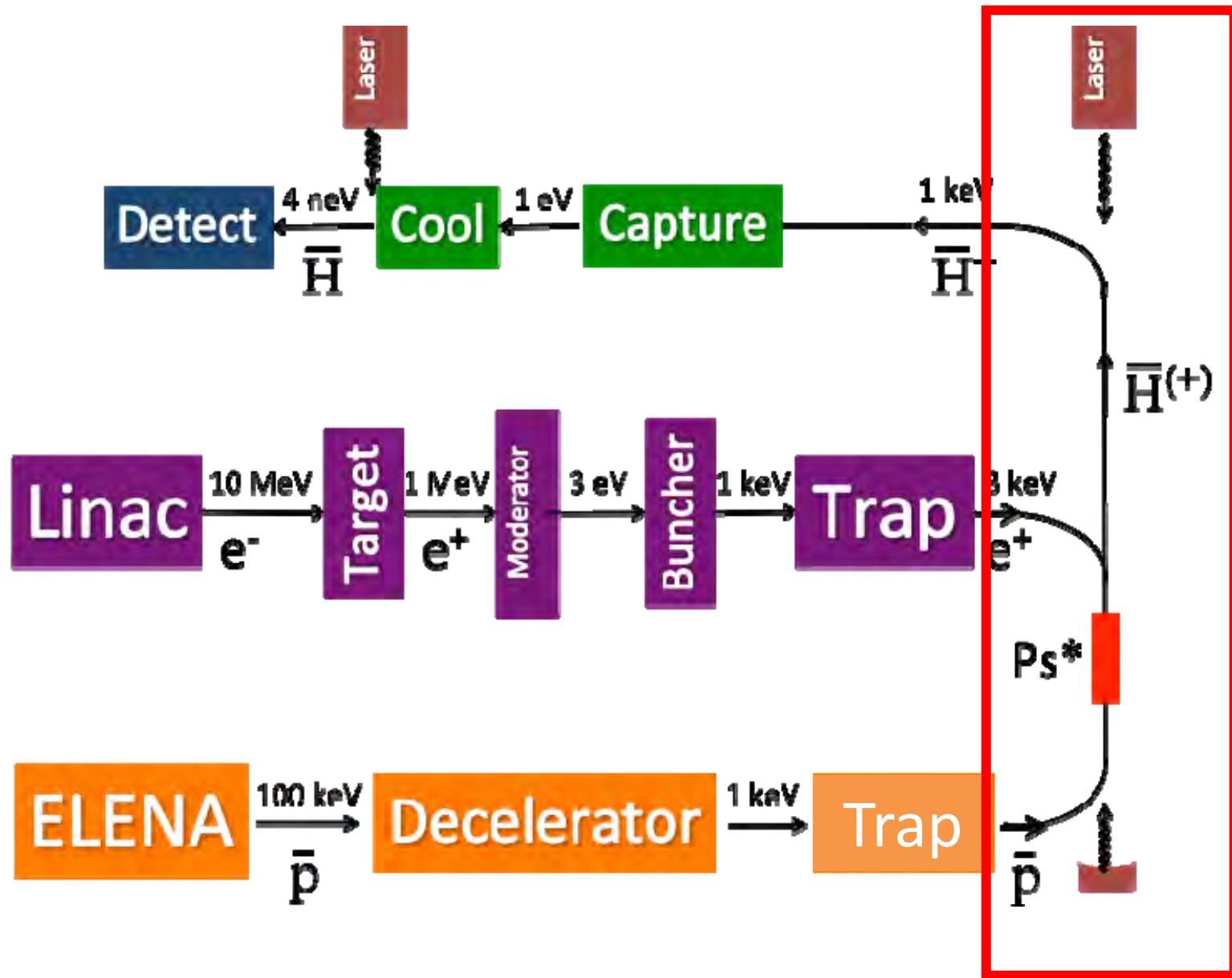
IOP Publishing
 J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 064001 (6pp)
 doi:10.1088/0953-4075/49/6/064001

Electron-cooled accumulation of 4×10^9 positrons for production and storage of antihydrogen atoms

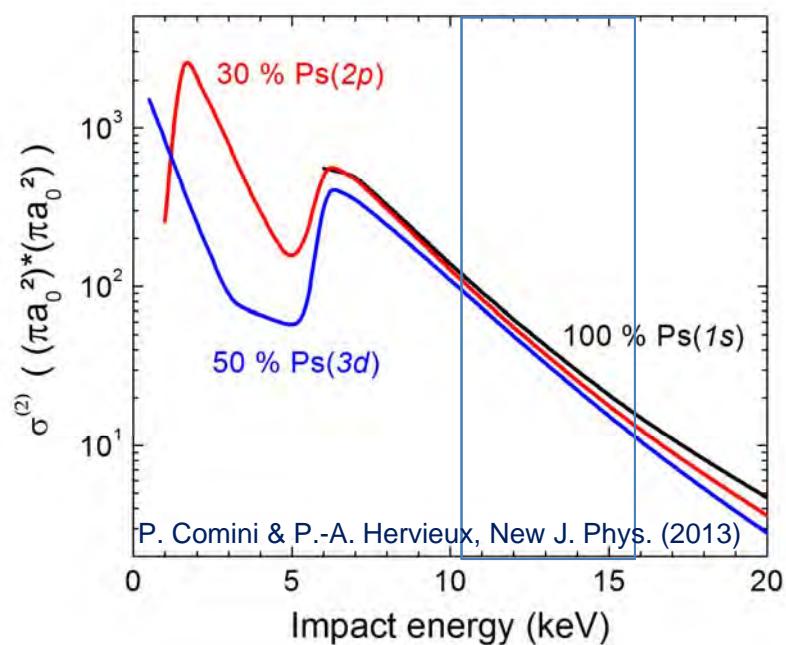
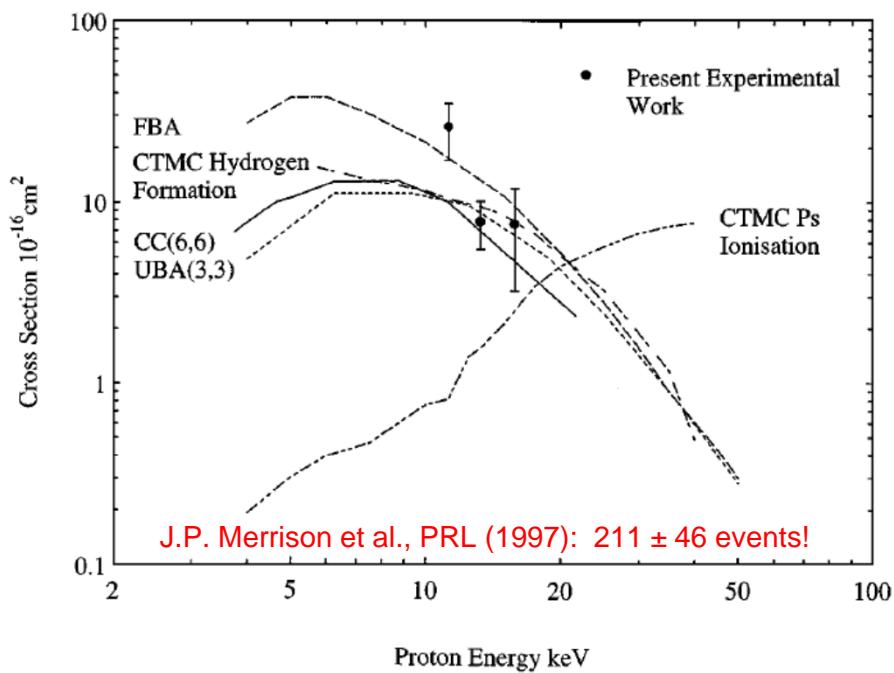
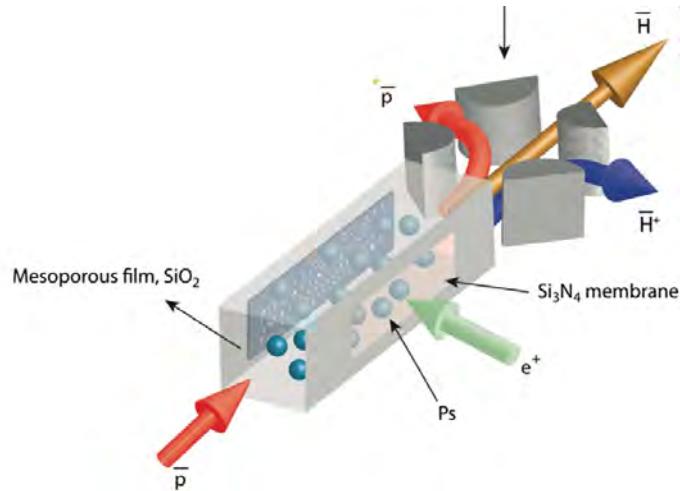
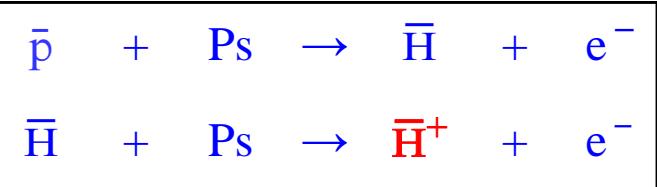
D W Fitzakerley¹, M C George¹, E A Hessels¹, T D G Skinner¹, C H Storry¹,
 M Weel¹, G Gabrielse^{2,3}, C D Hamley¹, N Jones¹, K Marable⁴, E Tardiff²,
 D Grzonka³, W Oelert⁴ and M Zielinski³ (ATRAP Collaboration)



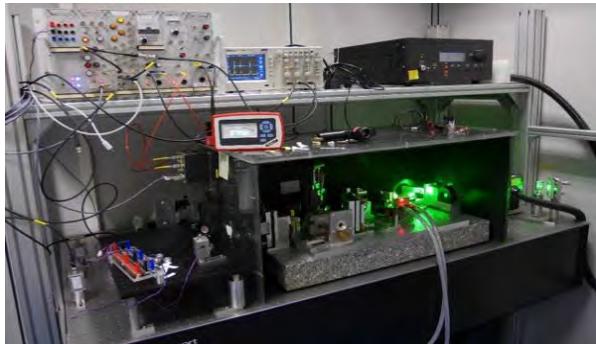
GBAR Schematic



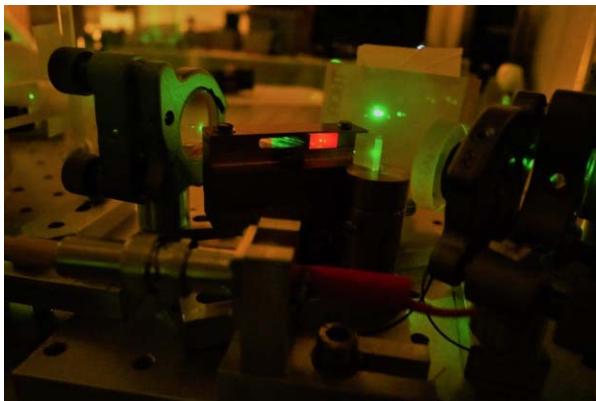
Antihydrogen ion production



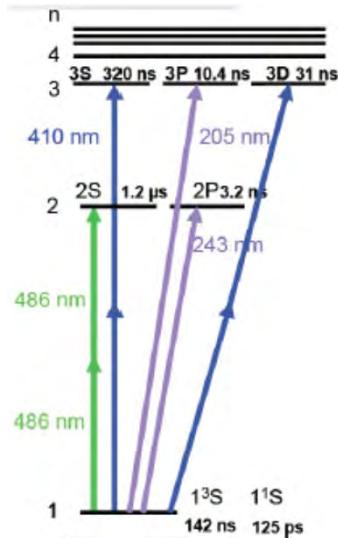
Ps excitation laser



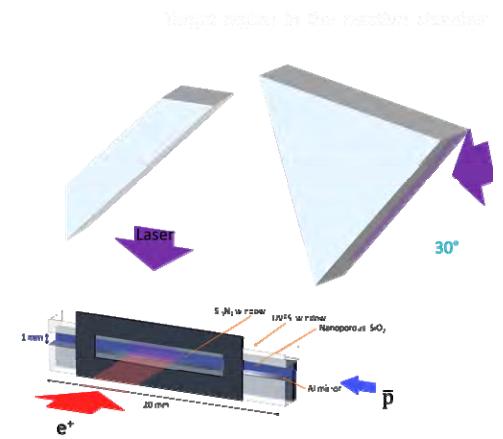
CW TiSa seeder, 260 mW at 820 nm



TiSa oscillator, >5 mJ at 820 nm
9 mJ obtained at 410 nm (with TiSa ampli)

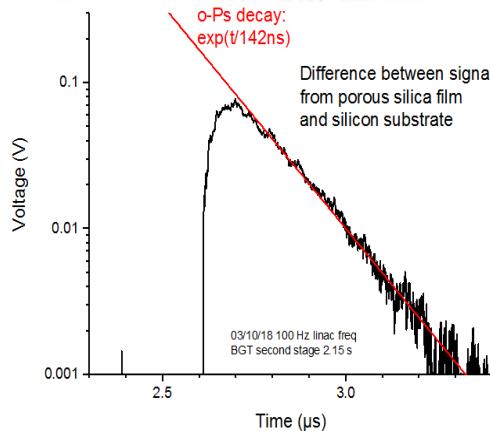
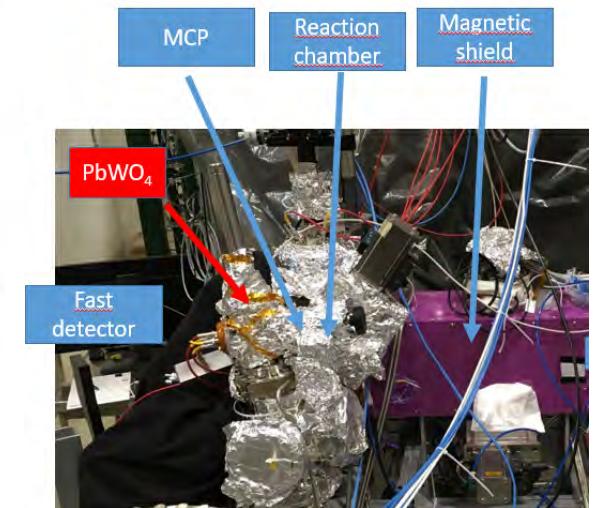
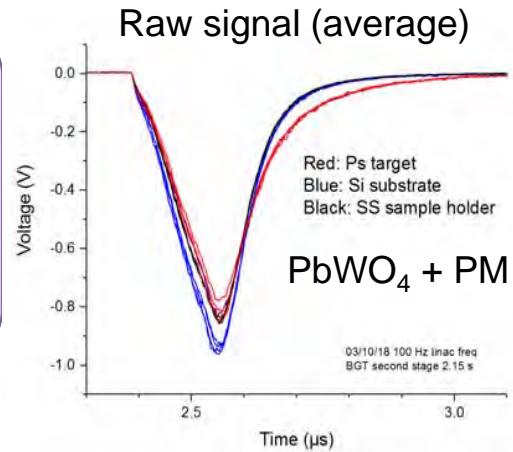
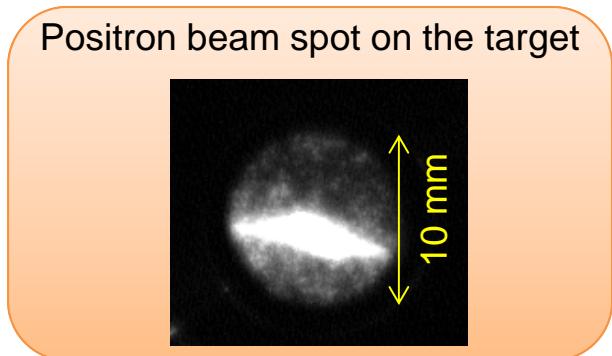
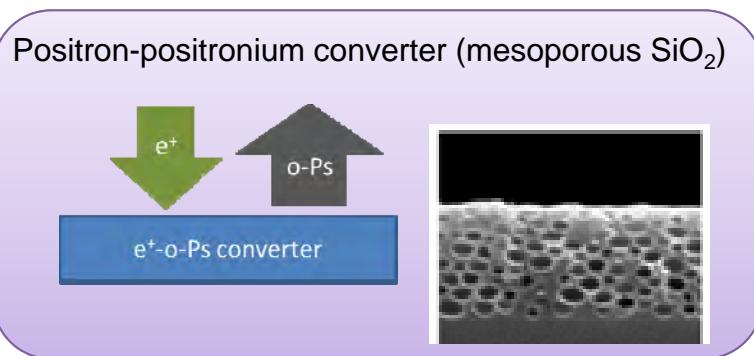


sample holder, MCP, mirror



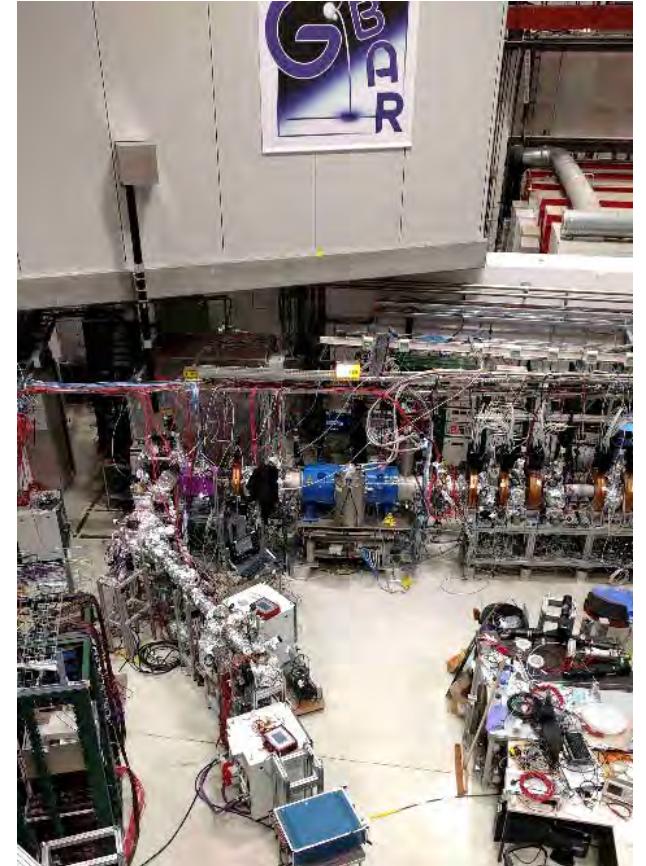
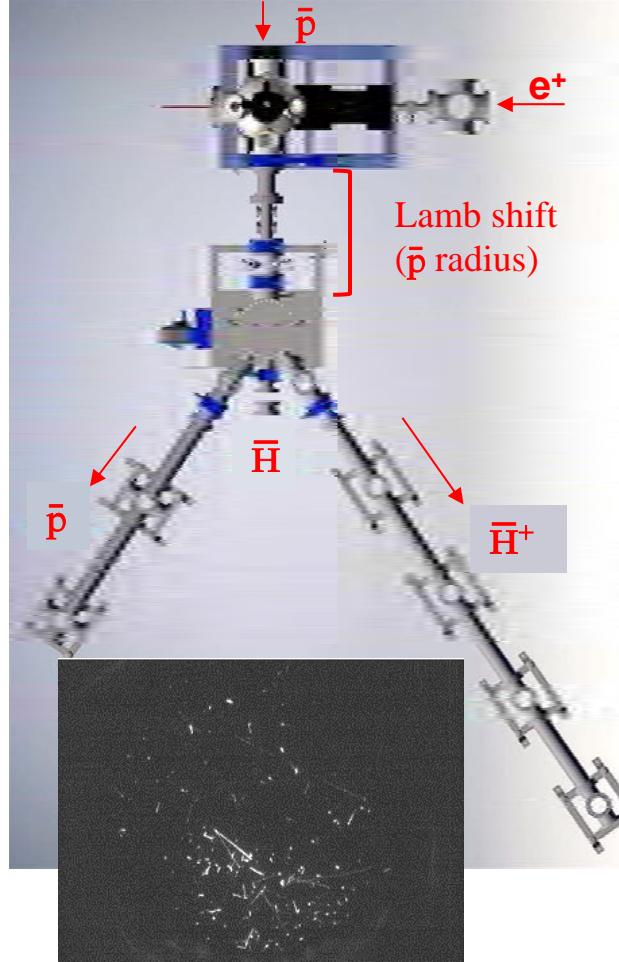
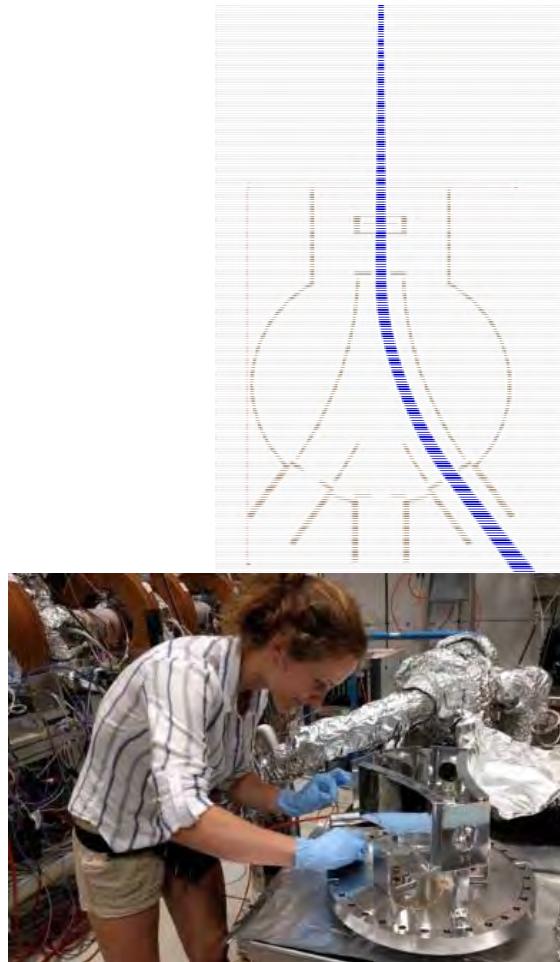
beam paths to Ps target

First ortho-positronium signal for GBAR@CERN



11 November 2018: GBAR attempts Antihydrogen!

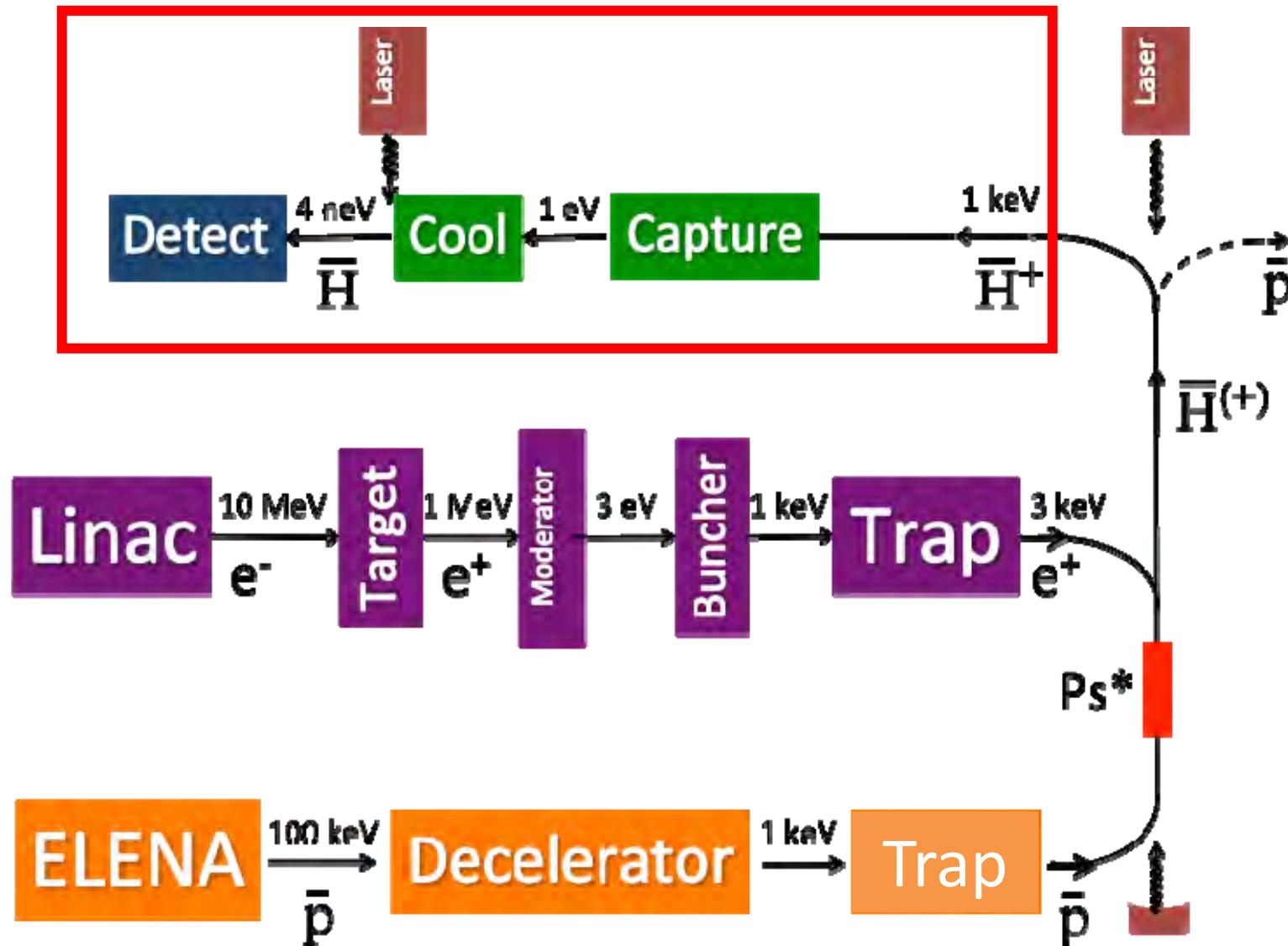
Included ELENA commissioning and debugging diagnostics...



B. Latacz (IRFU) PhD. (2019)

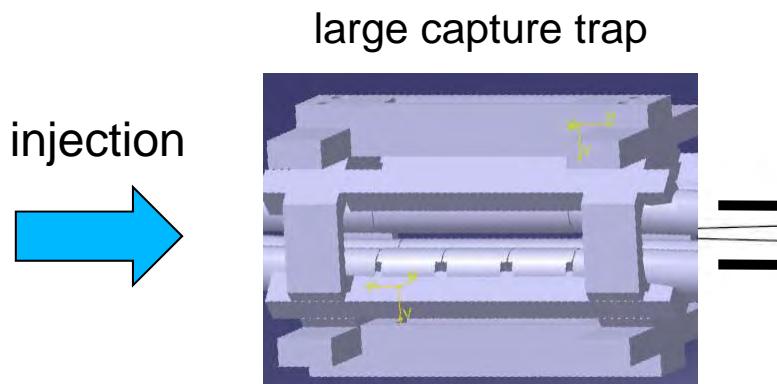
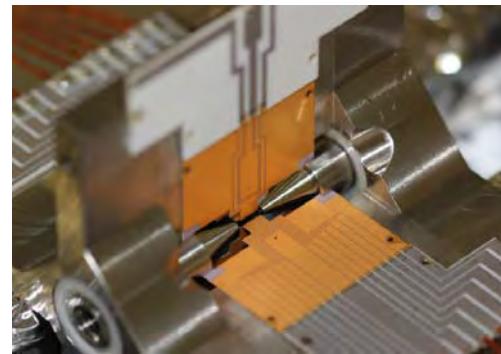
antiprotons in MCP
(no $\bar{H} \odot$)

GBAR Schematic



Sympathetic cooling of trapped \bar{H}^+ ions

No transition to laser cool \bar{H}
→ sympathetic cooling
transitions known for ${}^9\text{Be}$
But Δm with ${}^1\text{H}$ still large

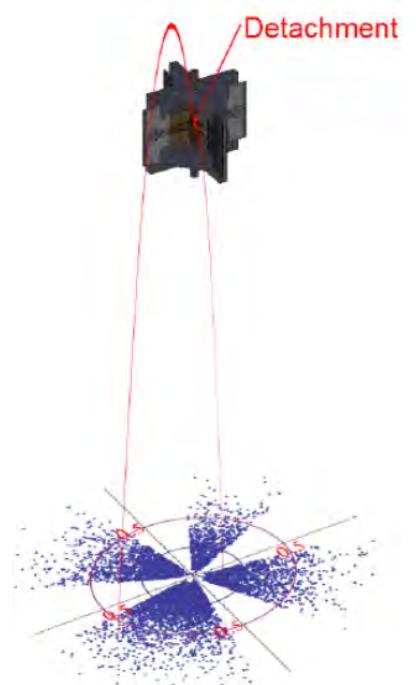
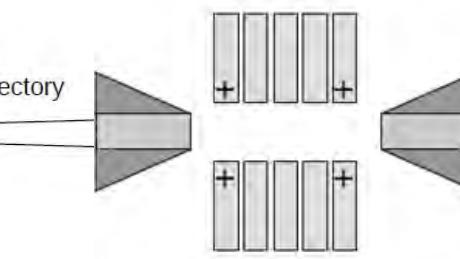


precision (56-MHz) μ trap



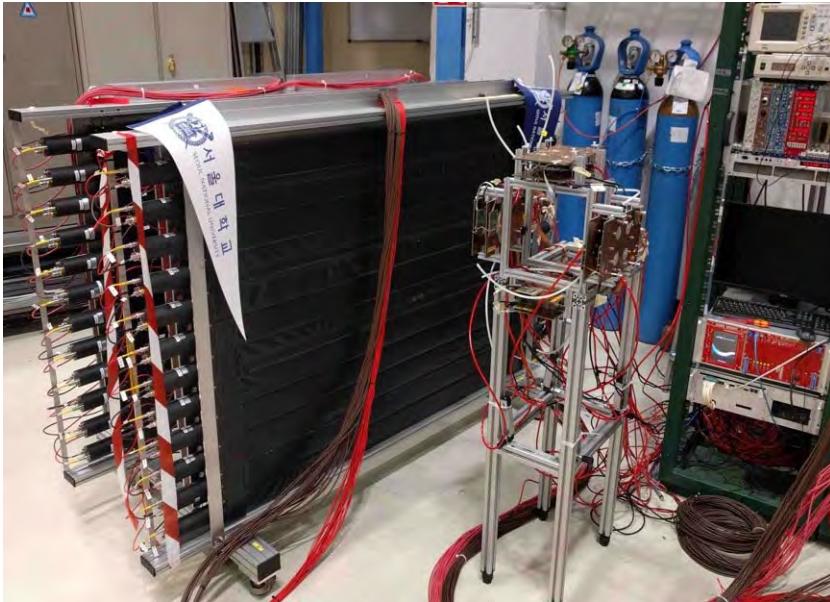
dark ion in capture trap (H_2^+ or H_3^+)
L. Hilico, J.-Ph. Karr et al. (LKB-Paris)

\bar{H}^+ cooled by Be “ice cubes”



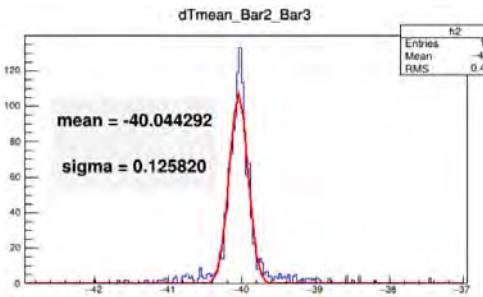
First results (using Ca ions)
S. Wolf, F. Schmidt-Kaler (Mainz)

The ultimate (drop) step



1.7 m TOF planes

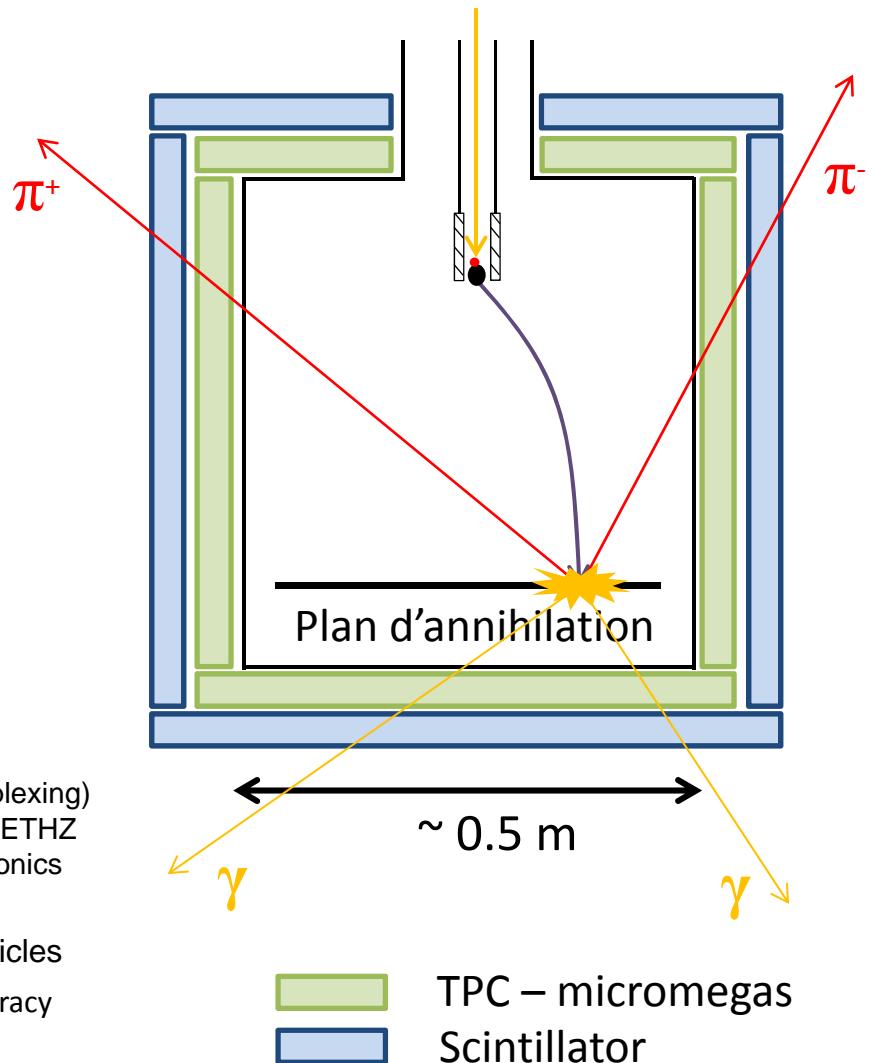
S.-K. Kim and team
(Seoul National University)



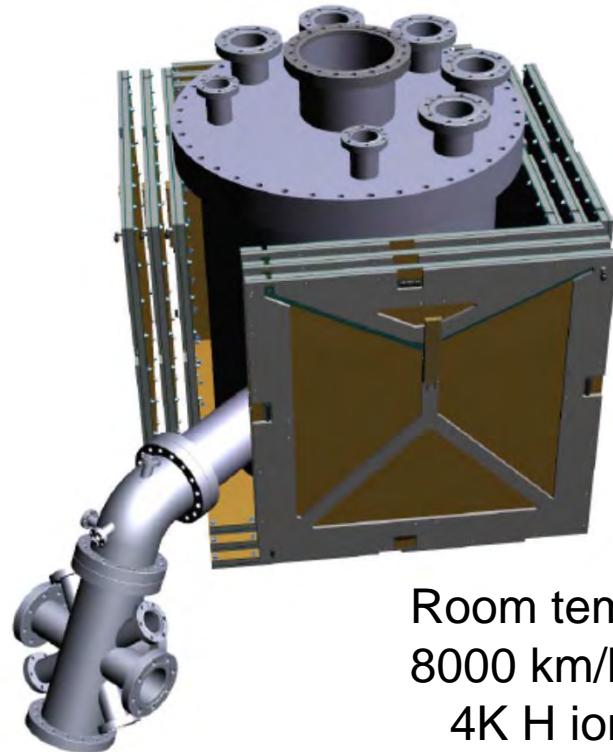
test micromegas tracker

P. Crivelli and team (ETH)
B. Vallage, S. Procureur & team (IRFU)

Test micromegas from ETHZ (x5 multiplexing)
19 planes 50 cm x 50 cm from IrFU and ETHZ
tested successfully with DREAM electronics
→ 80 ps resolution
allows to distinguish up-down particles
Aim: 1-mm vertex reconstruction accuracy



The ultimate (drop) step



Free-fall chamber
IRFU/ETH and
LKB (Nancy Paul)

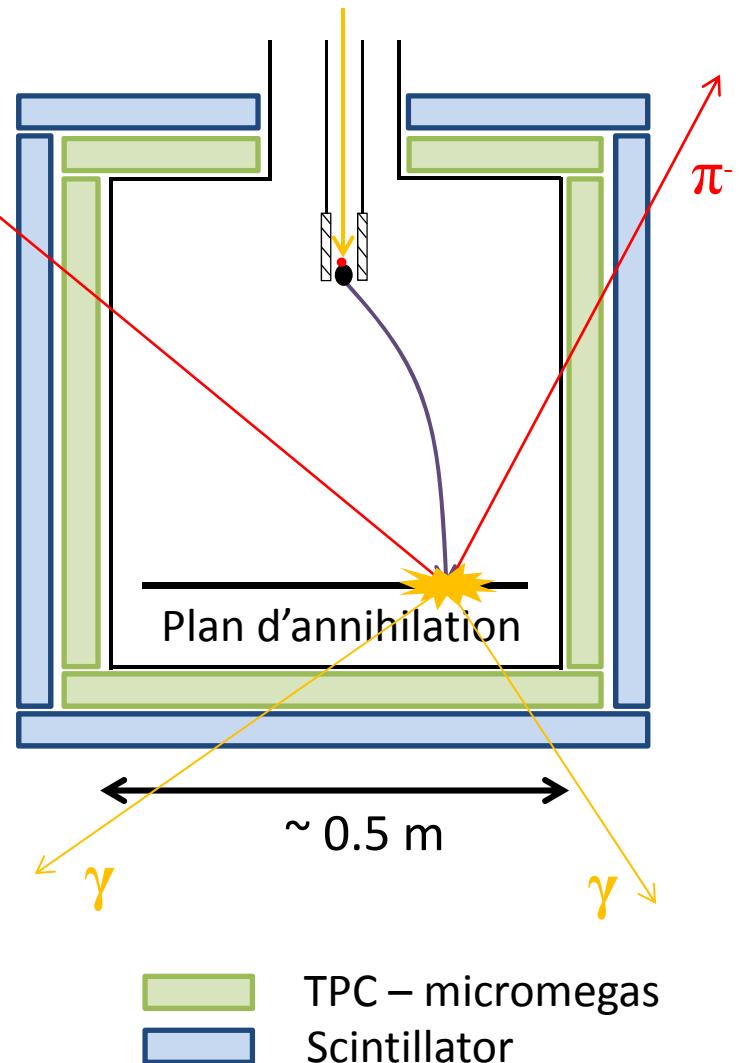
Room temperature \bar{p} ion:
 8000 km/h \rightarrow 2200 m/s!
 4K H ions: 500 m/s
 100 uK: 1 m/s
 1 uK: 0.1 m/s

For 1 \bar{H}^+ :

Need $10^7 \bar{p}$
 10^{12} Ps/cm^2
 $(10^{10} e^+)$
 in 1 AD cycle
 (110 s)

\bar{H} ions ($10 \mu\text{K}$)	$\Delta g/g$
10^3	0.02
10^4	0.006
5×10^5	0.001

$$y = y_0 + v_0 t + \frac{1}{2} g t^2$$



GBAR Timeline

Letter of Intent SPSC-2007-038	Research Board AD-7	CERN MoU	GBAR off-line commissioning
-----------------------------------	------------------------	-------------	--------------------------------

2007

2011

2012

2014

2016

Proposal
SPSC-P-342

CERN
FRC

GBAR on-line
commissioning

p-work
FF chamber

Cross-
Sections

Free-fall
chamber

2018

LS2 (Covid...)

2021

2022

2023

2024 (LS3)

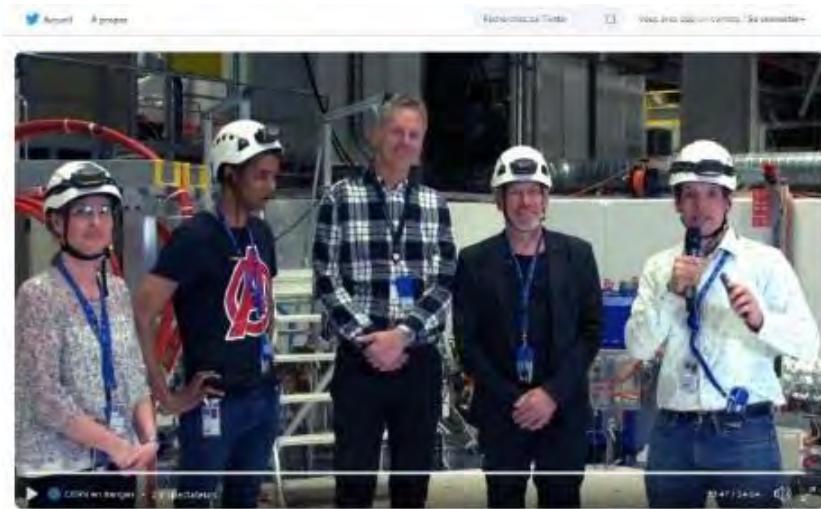
ELENA
commissioning

Anti-H
Lamb shift

antimatter in the (social) media



Au Grand Rex (mais pas tout à fait live du CERN...)



Dossier Cosmologie

EXPÉRIENCE

Gbar va traquer le comportement de l'antihydrogène

La quête récente des antiparticules

1932 Découverte Un an après sa prédiction théorique par Paul Dirac, Carl Anderson observe le positron (anti-electron).

1995 Lear Des atomes d'antihydrogène sont isolés pour la première fois dans l'anneau du Lear, au Cern.

2002 Athena Ces scientifiques parviennent à produire 50 000 atomes d'antihydrogène de basse énergie.

2011 Alpha Les atomes d'antihydrogène sont stabilisés pendant plus de 16 minutes.

2016 Gbar L'antimatière chute-t-elle comme l'hydrogène ? Gbar va tenter d'y répondre.

N° 636 - Octobre 2016 - Sciences et Avenir - 33

Summary

The screenshot shows the 'nature' journal website. At the top, there is a search bar with a 'Go' button. Below the search bar, the text 'International weekly journal of science' and 'Advanced search' are visible. A navigation menu includes 'Home', 'News & Comment', 'Research', 'Careers & Jobs', 'Current Issue', 'Archive', 'Audio & Video', and 'For Authors'. The breadcrumb navigation shows 'Archive > Volume 548 > Issue 7665 > News Feature > Article'. The main title of the article is 'The race to reveal antimatter's secrets'. Below the title, a subtitle reads: 'In the shadow of the Large Hadron Collider, six teams are competing to answer one of the Universe's deepest existential questions.' The author's name, 'Elizabeth Gibney', is listed at the bottom.

- ❖ Interesting and deep-rooted physics goal
- ❖ ...intense competition!
- ❖ Intersection of many disciplines
- ❖ GBAR first to receive ELENA antiproton beam
- ❖ Next: antihydrogen production studies
- ❖ Installation of free-fall chamber (2022)
- ❖ Long-term experiment!

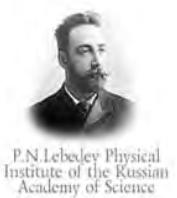


"Sir, I don't make the laws of gravity, I just enforce them."

GBAR Collaboration (70 authors; 17 institutes)



Swansea University
Prifysgol Abertawe



서 울 대 학 교
SEOUL NATIONAL UNIVERSITY



B. Argence¹, P. Blumer², M. Charlton³, J. Choi⁴, M. Chung⁵, P. Cladé¹, P. Comini⁶, P. Crivelli², P-P. Crépin¹, O. Dalkarov⁷, P. Debu⁶, L. Dodd³, A. Douillet^{1,8}, P. Froelich⁹, J. Gafriller¹⁰, N. Garoum¹¹, S. Guellati¹, J. Heinrich¹, P-A. Hervieux¹², L. Hilico^{1,8}, P. Indelicato¹, G. Janka², S. Jonsell⁹, J-P. Karr^{1,8}, B. Kim⁴, S. Kim⁴, E-S. Kim¹³, A. Kleyheeg¹⁰, Y. Ko¹⁴, T. Kosinski¹⁵, N. Kuroda¹⁶, B. Latacz⁶, H. Lee⁴, J. Lee¹⁴, A. Leite⁶, E. Lim¹³, L. Liszkay⁶, T. Louvradoux¹, D. Lunney¹⁷, K. Lévêque¹², G. Manfredi¹², B. Mansoulié⁶, M. Matusiak¹⁵, G. Mornacchi¹⁰, V. Nesvizhevsky¹⁸, F. Nez¹, S. Niang⁶, R. Nishi¹⁶, S. Nourbaksh¹⁰, B. Ohayon², K. Park⁴, N. Paul¹, P. Pérez⁶, B. Radics², C. Regenfus², S. Reynaud¹, C. Roumegou¹⁷, O. Rousselle¹, J-Y. Roussé⁶, A. Rubbia², J. Rzadkiewicz¹⁵, Y. Sacquin⁶, F. Schmidt-Kaler¹⁹, M. Staszczak¹⁵, T. Takumi¹⁶, B. Tuchming⁶, B. Vallage⁶, D.P. Van der Werf³, A. Voronin⁷, A. Welker¹⁰, S. Wolf¹⁹, D. Won⁴, S. Wronka¹⁵, Y. Yamazaki²⁰, K-H. Yoo⁵

Et pourquoi pas le



Merci !