GRAVITY AND ANTIMATTER: THE AEGIS EXPERIMENT AT CERN

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THE WEAK EQUIVALENCE PRINCIPLE

- **Universality of free fall** (UFF) established by Galileo and Newton

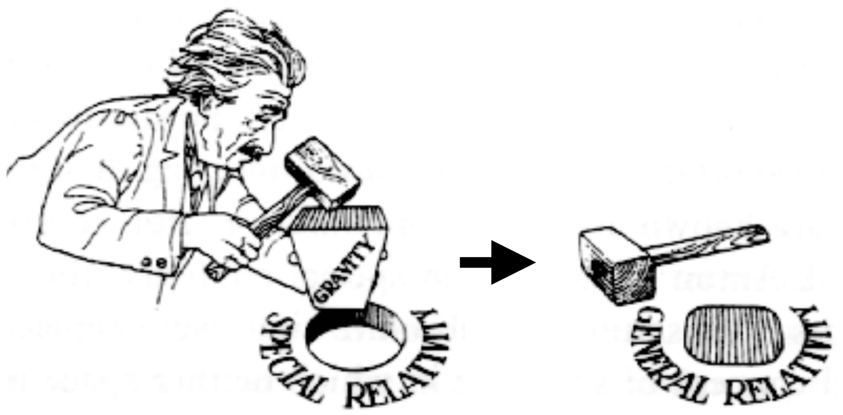
$$m_i = m_g$$

Weak equivalence principle (WEP)

- Unique behavior:

electric field:	gravitational field:
$\mathbf{F} = q \cdot \mathbf{E}$	$\mathbf{F} = m \cdot \mathbf{G}$
$\lvert\mathbf{E}\rvert \propto \frac{Q}{r^2}$	$\lvert\mathbf{G}\rvert \propto \frac{M}{r^2}$
$\lvert\mathbf{a}\rvert \propto q$	$\lvert\mathbf{a}\rvert$ = const

- **Einstein Equivalence Principle**:
  - WEP
  - Local Lorentz Invariance (LLI)
  - Local Position Invariance (LPI)



TEST OF THE EEP

- EEP is the *“heart and soul”* of **General Relativity (GR)**:
  - EEP valid → gravity is governed by a *“metric theory of gravity”*

R. Dicke, **Les Houches Summer School of Theoretical Physics: Relativity, Groups and Topology**, pp. 165–313, CNUM: C63-07-01 (1964)

C. Will, **Living Rev. Relativity** 17 (2014)

- EEP extensively tested experimentally:

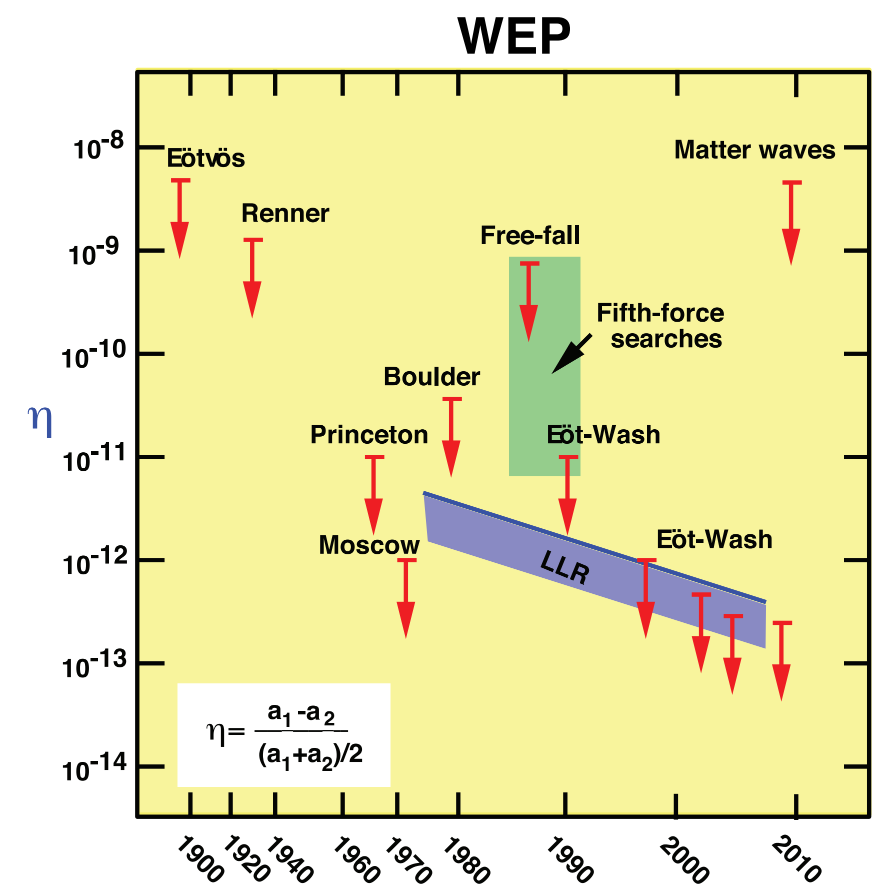
LLI Isotropy of atomic energy levels: $\delta = |c^{-2} - 1| > 10^{-23}$

LPI Gravitational red shift:

$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2} > 10^{-6}$$

WEP Torsion balance:

$$\eta = \frac{a_1 - a_2}{(a_1+a_2)/2} > 10^{-13}$$



WEP FOR ANTIMATTER: THE CURRENT PICTURE

- Some arguments *would* suggest the WEP holds for antimatter

- Strong theoretical arguments only apply to the idea of *antigravity*
  - **Morrison (1958), Schiff (1958), Good (1961), etc…**
  - **none of them *necessarily* requires** $m_i^{antimatter} = m_g^{matter}$

- On the experimental side:

- neutrinos detected from Supernova 1987A

  S. Pakvasa *et al.*, **Phys. Rev. Lett. D.** 39, 6 (1989)

  - **Shapiro delay of relativistic particles not a test for the EEP**

  G. T. Gillies, **Class. Quantum Grav.** 29 (2012)

- p-p̄ cyclotron frequency comparisons: $\frac{\omega_c - \bar{\omega_c}}{\omega_c} < 9 \times 10^{-11}$

  G. Gabrielse *et al.*, **PRL** 82 (3198) (1999)

  - **Model dependent, CPT assumption, absolute potentials, …**

- and others…but none of them is conclusive

WEP FOR ANTIMATTER: WHY TO TEST IT?

- Our attempts for a quantum theory of gravity typically result into new interactions which violate the WEP (ex. **KK theory**)

Int. J. Mod. Phys. D18, 251–273 (2009)

- Some open questions (like *dark matter* and *baryogenesis*) could benefit from a direct measurement

Astrophys. Space Sci. 334, 219–223 (2011)

JHEP 1502, 076 (2015)

- Because *it's possible* and no direct measurements are available

- Previous attempts:
  - **1967**: **Fairbank** and **Witteborn** tried to use positrons

    Phys. Rev. Lett. 19, 1049 (1967)
  - **1989**: PS-200 experiment at CERN tried to use (4 K) $\bar{p}$

    Nucl. Instr. and Meth. B, 485 (1989)
- **Problem** with charged particles: stray E and B fields
  - **2013**: ALPHA experiment at CERN set limit on m_g/m_i for $\bar{H}$

    Nature Communications 4, 1785 (2013)
    - m_g/m_i > 110 excluded at 95% CL

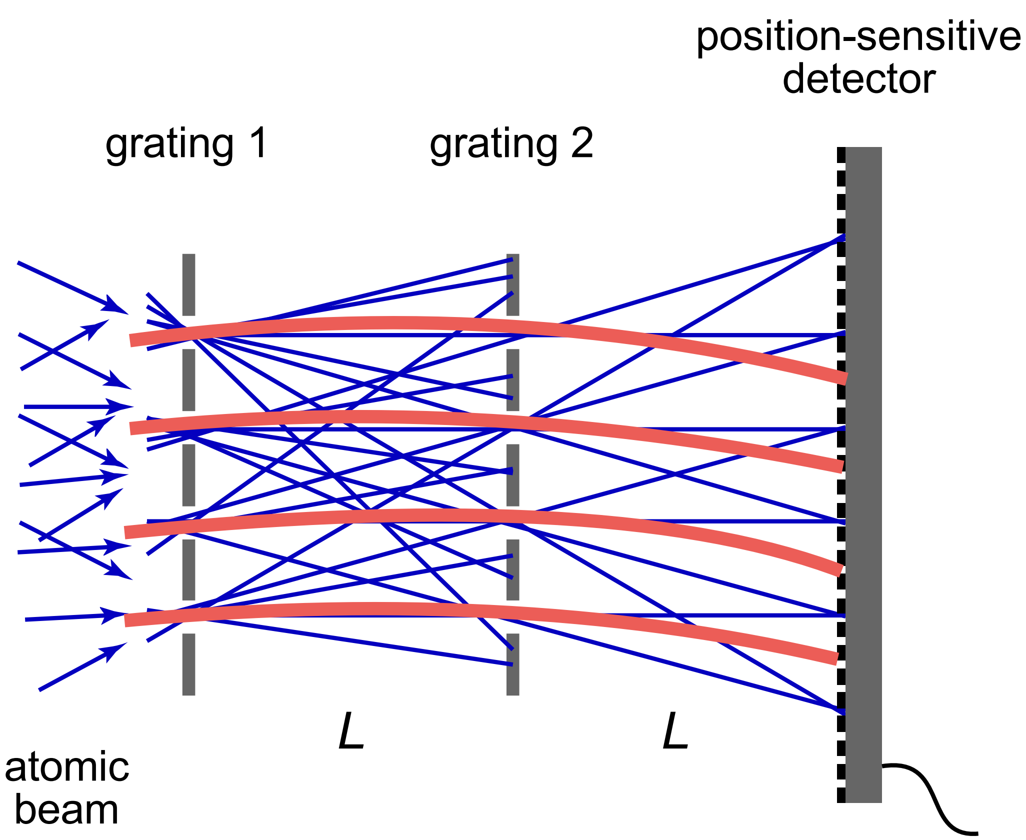
AEGIS COLLABORATION

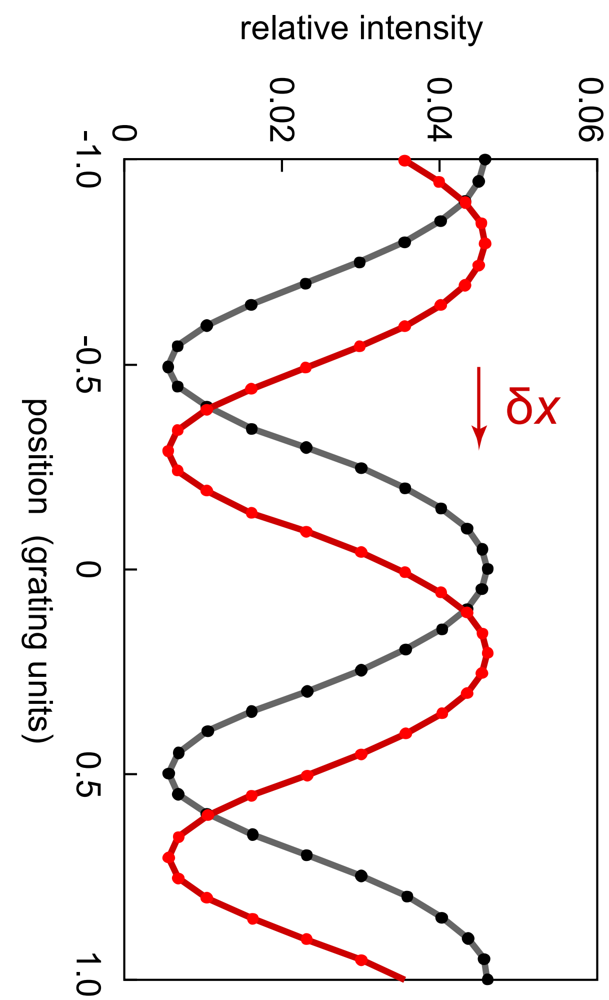
19 institutes and ~80 people

- University of Bergen
- University of Brescia
- CERN, Geneva
- University of Genova
- Heidelberg University
- Max Planck Institute for Nuclear Physics, Heidelberg
- University College London
- University of Lyon 1
- University of Milano
- Politecnico di Milano
- Institute of Nuclear Research of the Russian Academy of Science, Moscow
- University of Oslo
- University Paris-Saclay and CNRS
- University of Pavia
- Czech Technical University, Prague
- University of Trento
- Stefan Meyer Institute, Vienna
- ETH Zurich
- INFN Sections of Genova, Milano, Padova, Pavia, Trento

GRAVITY MEASUREMENT WITH AE$\bar{g}$IS EXPERIMENT

- The main goal of AEgIS is a direct measurement of the Earth’s local gravitational acceleration **g** on “cold” beam of $\overline{\mathrm{H}}$ atoms using a **moiré deflectometer**

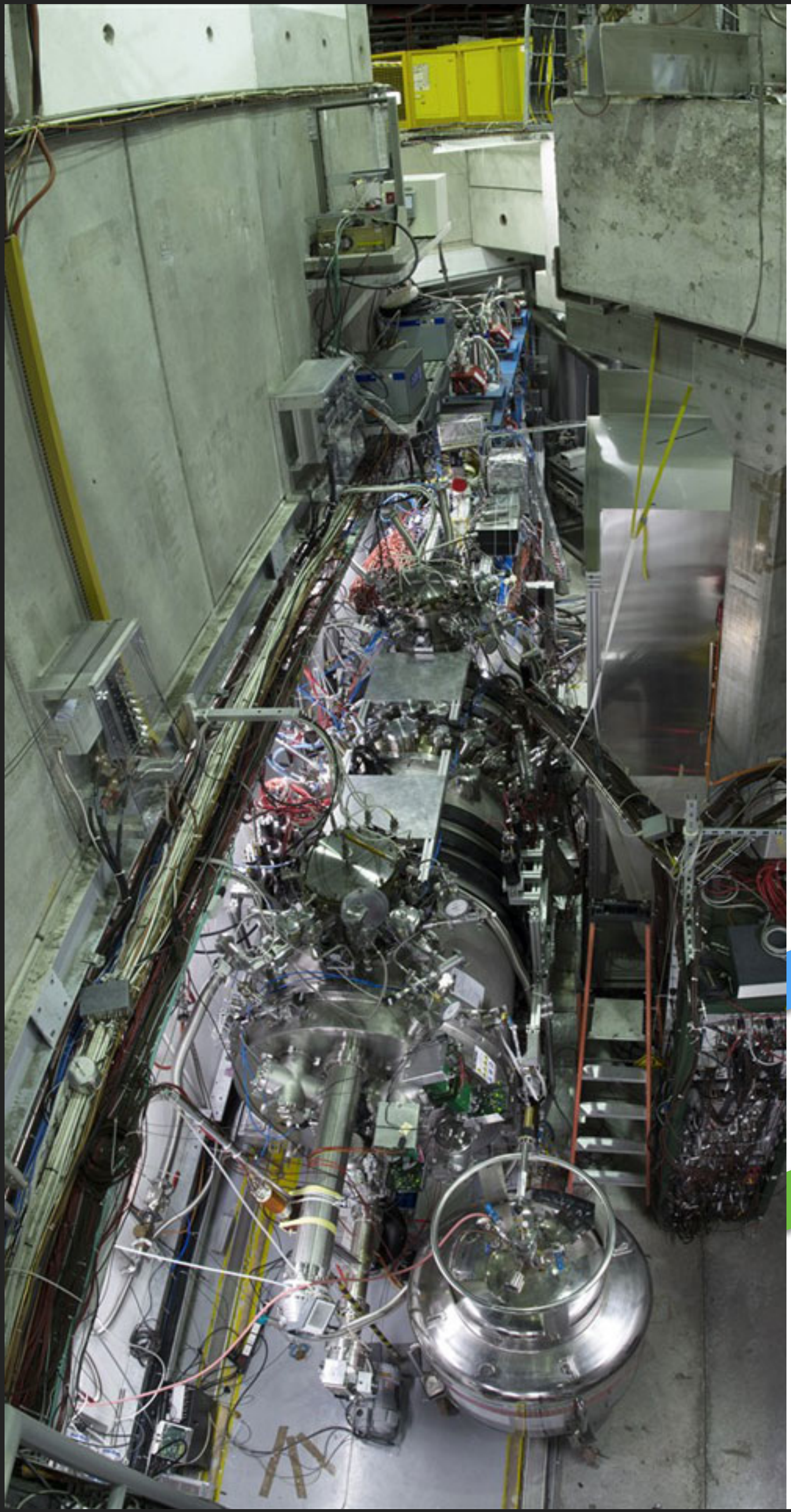




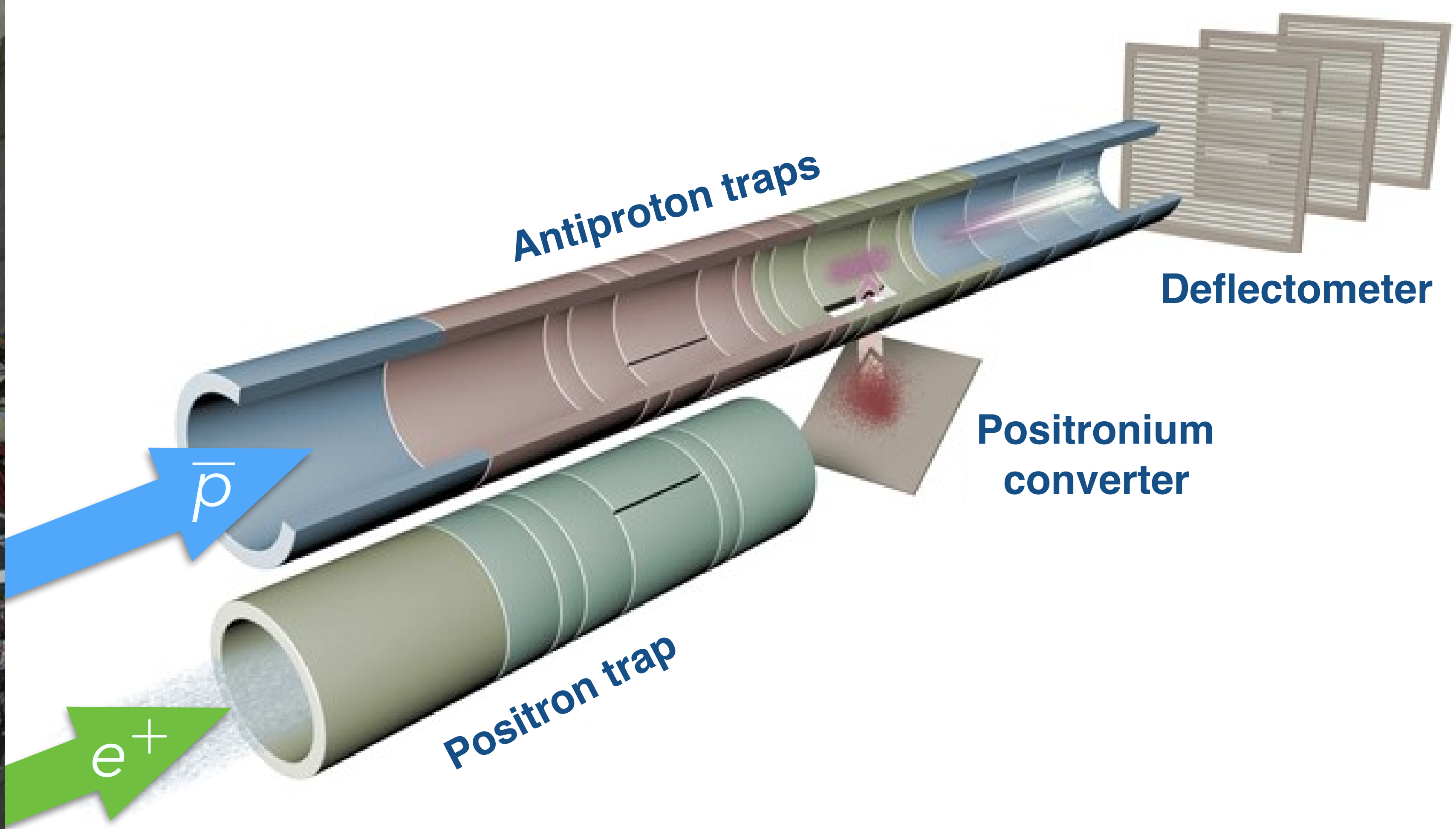
$$\delta x = -g\left(\frac{L}{v}\right)^2$$

- For $\overline{\mathrm{H}}$ at very low temperature a precision of the order of few percent can be reached

AEḡIS APPARATUS



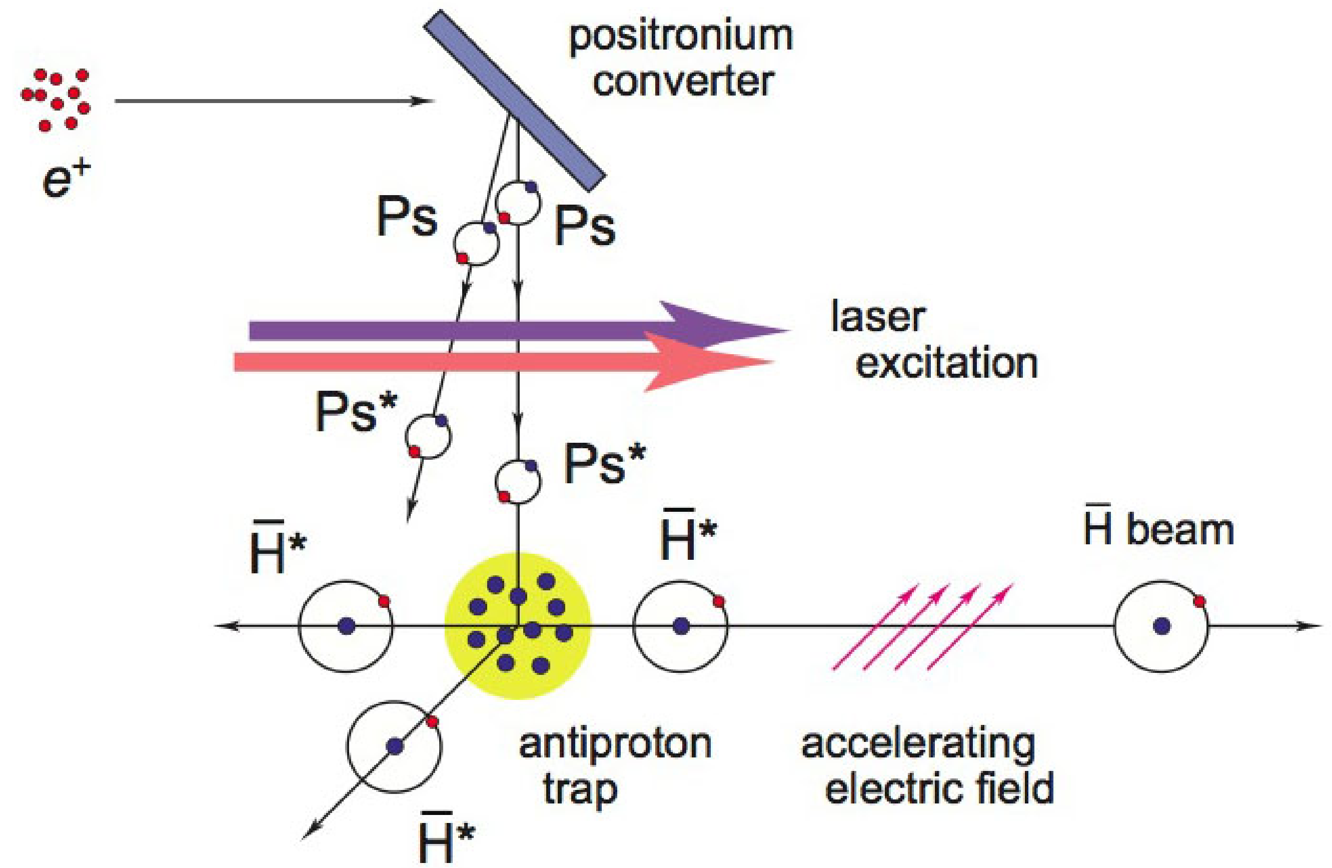
(Over)Simplification of the experimental setup



ANTIHYDROGEN PRODUCTION STRATEGY

- *Cold* Rydberg H̄* atoms can be produced via **charge exchange**

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



- $\sigma \propto n_{Ps}^4 \longrightarrow n_{Ps}$ ~ 20 - 30

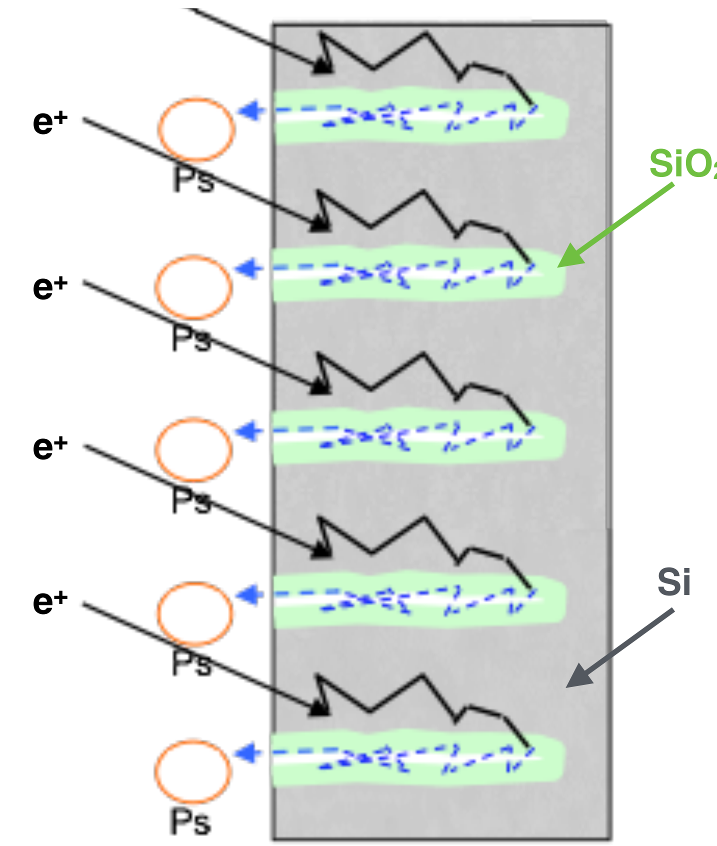
- Temperature of H̄ given by the temperature of p̄

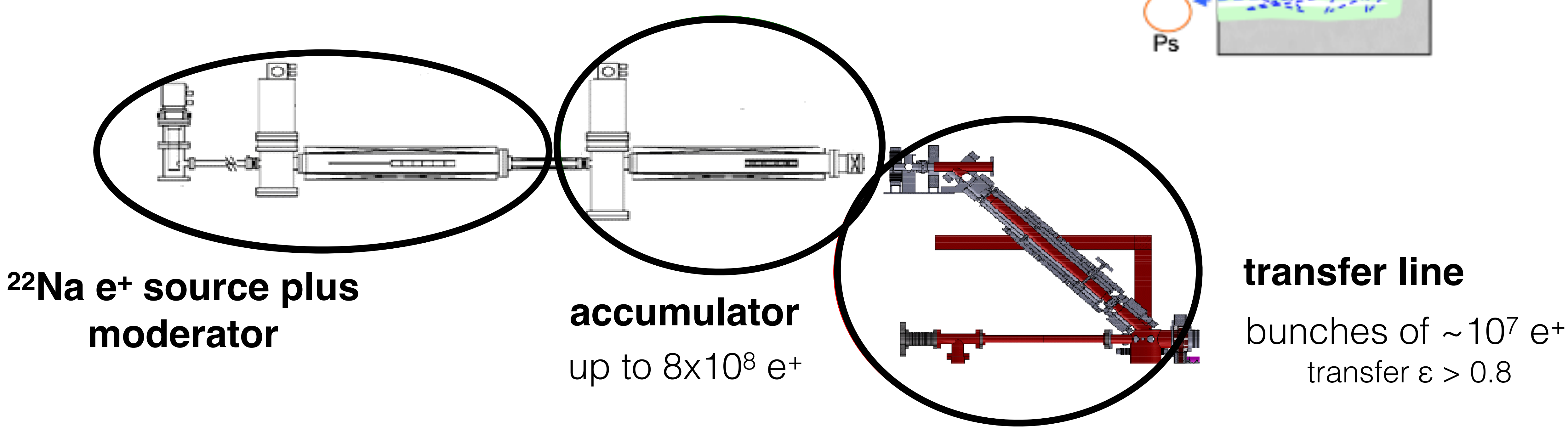
- Rydberg H̄: strong dipole moment → **Stark acceleration**

- p̄ are provided from the **Antiproton Decelerator (AD)** at CERN and are cooled down (electron cooling) in electromagnetic traps

POSITRONIUM FORMATION AND EXCITATION

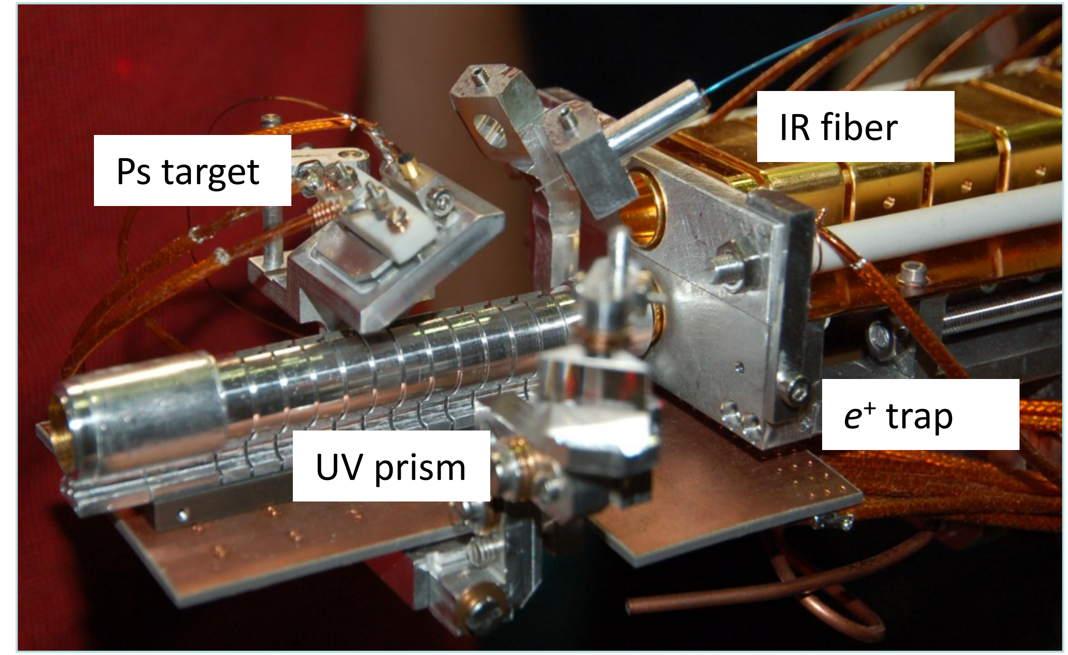
- The second ingredient for our $\overline{H}$ recipe is the Rydberg **positronium** which is an exotic atom composed by an e^- and a e^+
- **para-Ps**(125 ps) and **ortho-Ps**(142 ns)
- Ps produced via electron capture of e^+ within a nanoporous silica target

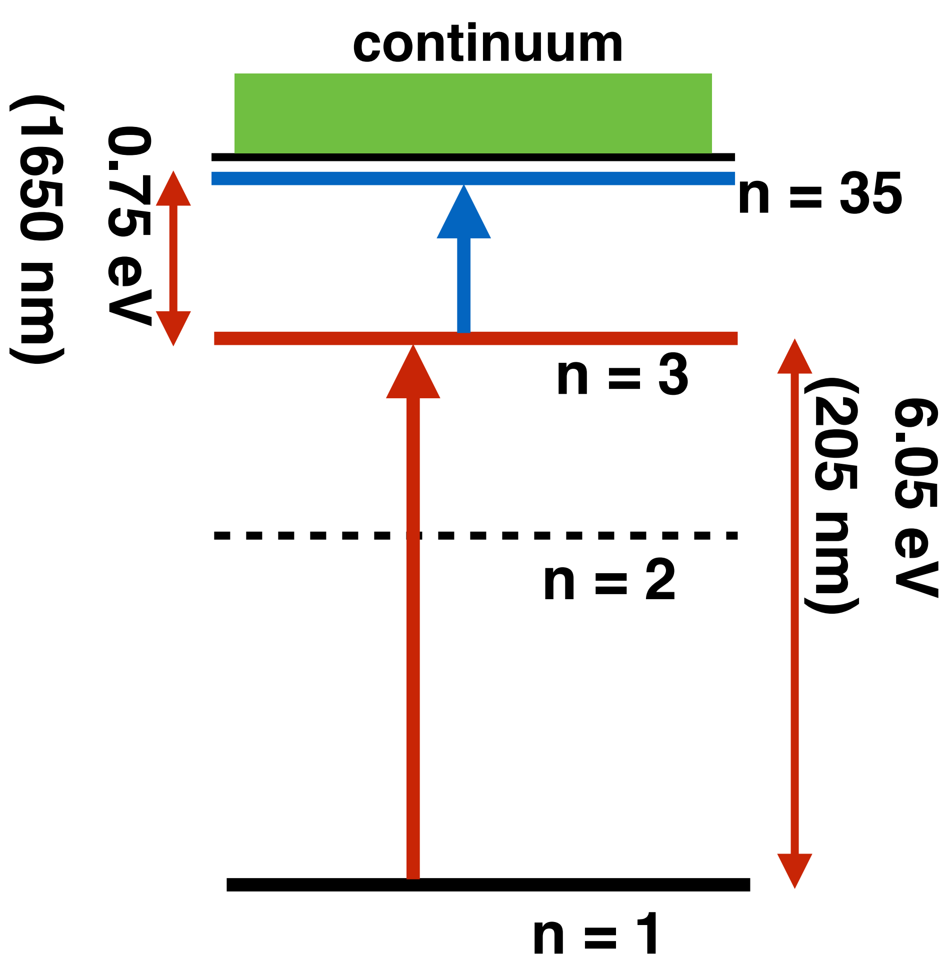




POSITRONIUM FORMATION AND EXCITATION

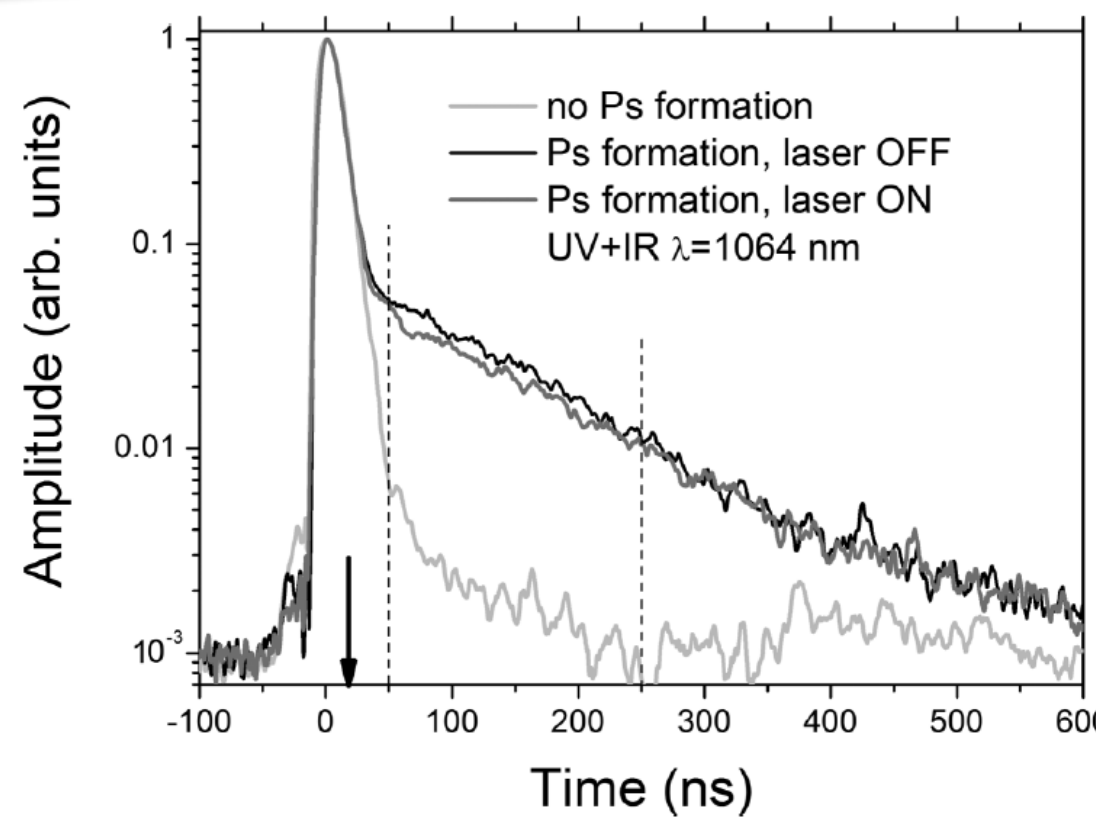
- Two-step excitation of Ps:
  - UV   n = 1 ⟶ 3
  - IR   n = 3 ⟶ Rydberg



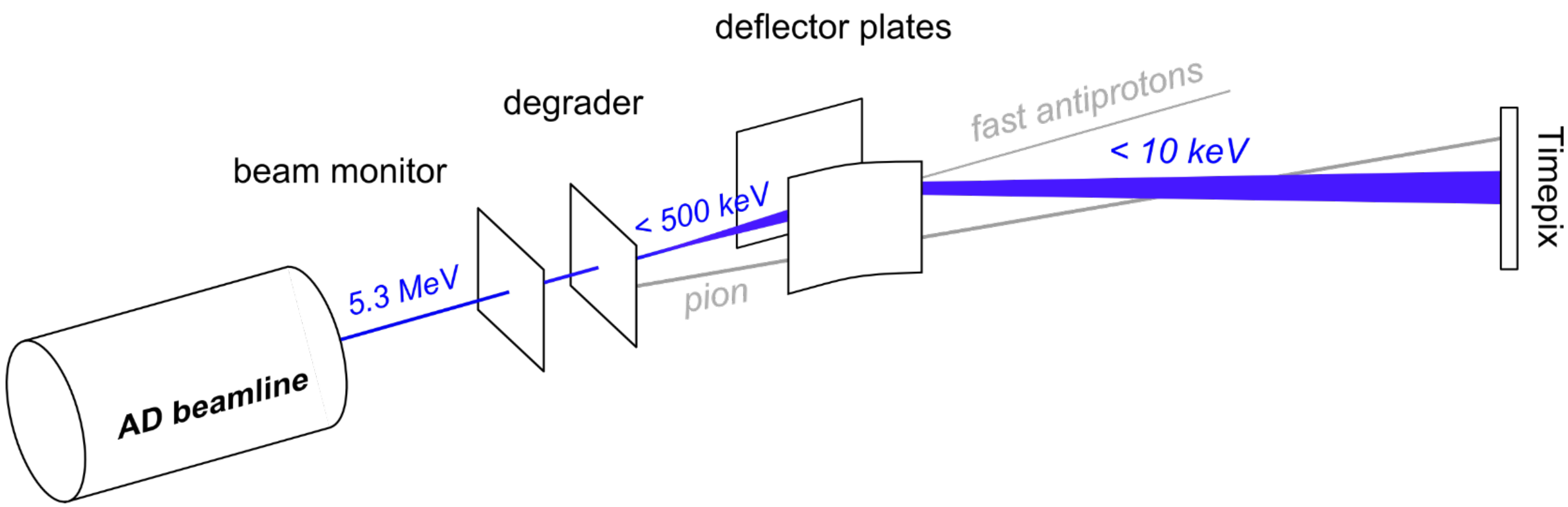


PHYSICAL REVIEW A **94**, 012507 (2016)

Laser excitation of the $n = 3$ level of positronium for antihydrogen production



DETECTOR TESTS



- Two candidates detectors are currently under investigation: **nuclear emulsions**[1] and **Timepix**[2] (from Medipix collaboration)

[1] S. Aghion *et al.*, JINST 12 (2017) P04021

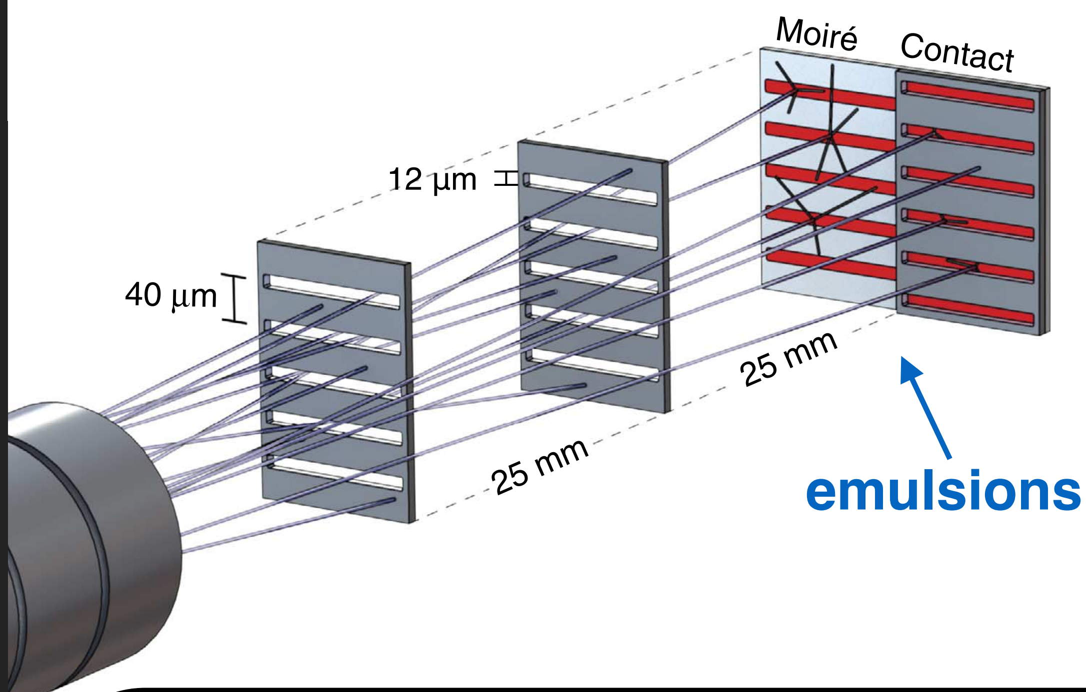
[2] N. Pacifico *et al.*, NIM A 831 (2016) 12–17

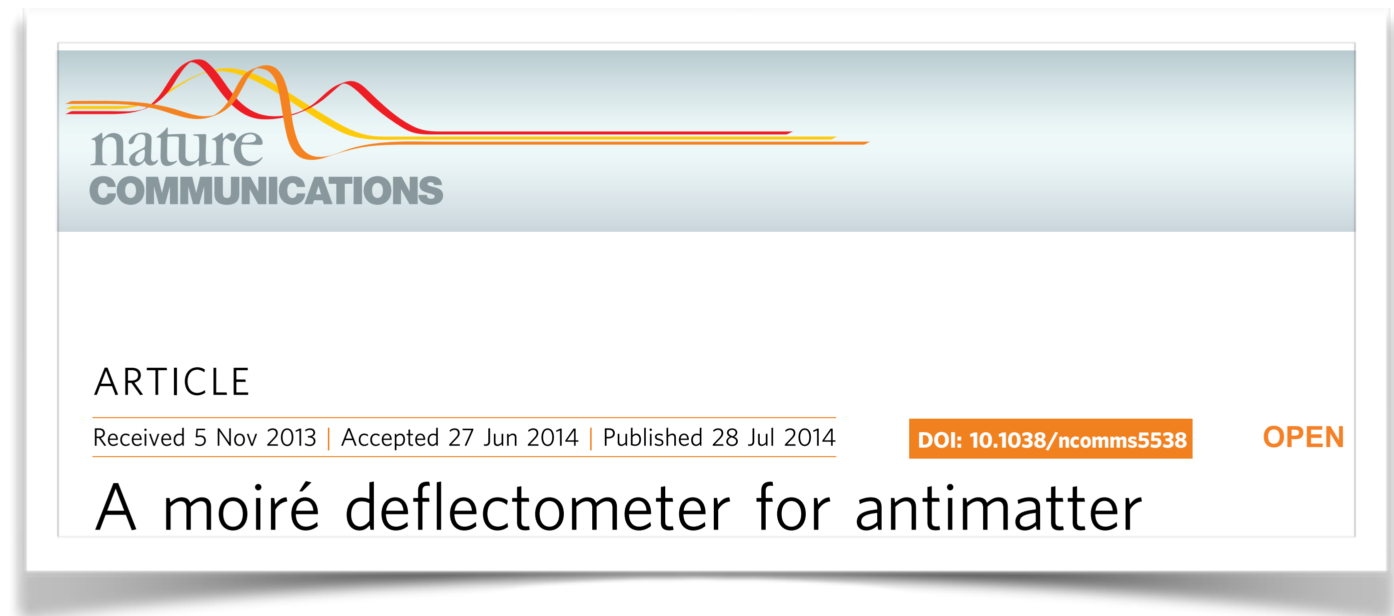
- Nuclear emulsions provide excellent position resolution (~2 μm) but require a very long time to be processed

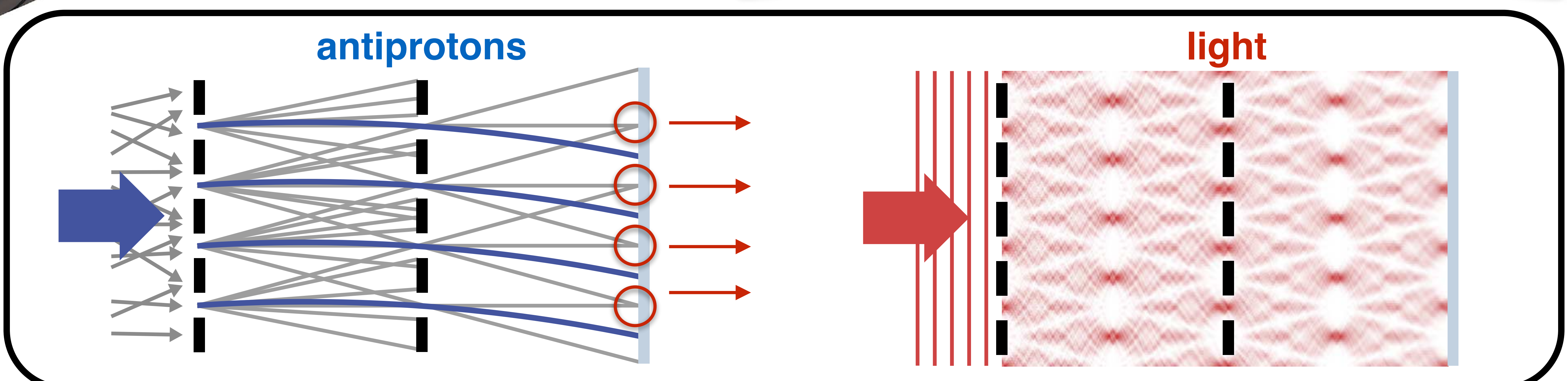
- Timepix is a silicon detector composed a matrix of 256 by 256 pixels which allows a spatial resolution of ~25 μm

RESULTS: (MINI) MOIRÉ TEST WITH ANTIPROTONS

- AEgIS experiment is taking data ($\overline{H}$ production expected in 2017)
- Small-scale test of the Moiré deflectometer with $\overline{p}$ was performed

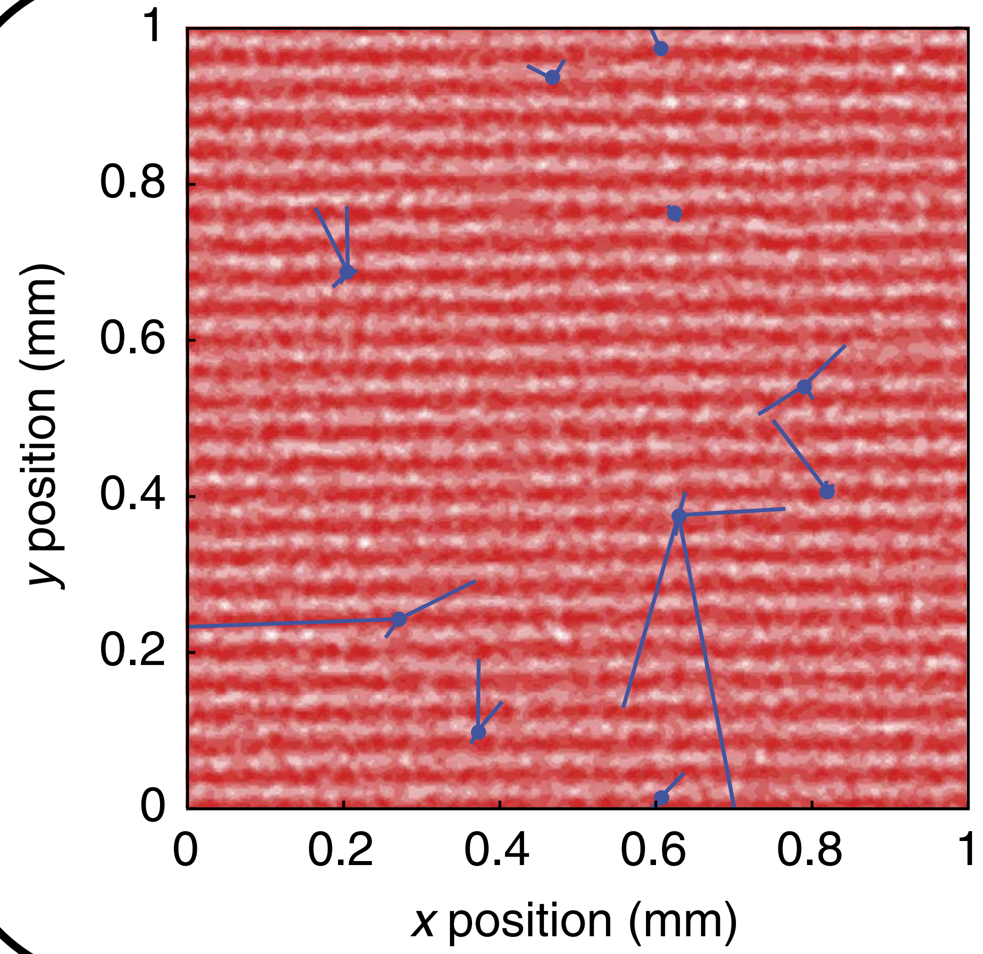


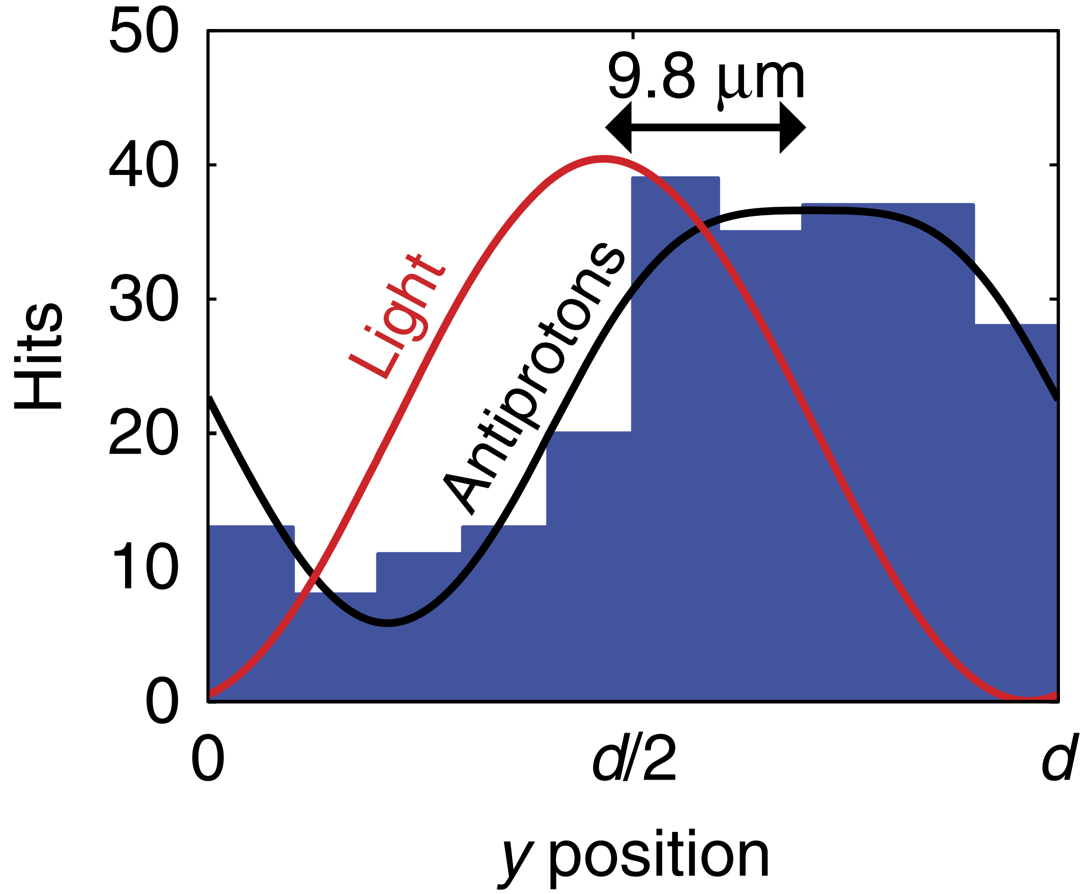

nature COMMUNICATIONS
ARTICLE
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014
DOI: 10.1038/ncomms5538
OPEN
A moiré deflectometer for antimatter



RESULTS: (MINI) MOIRÉ TEST WITH ANTIPROTONS

- 146 antiprotons recorded





$\Delta y = 9.8 \pm 0.9(\text{stat}) \pm 6.4(\text{syst})\ \mu m$

- $F = 530 \pm 50\,\text{aN}\ (\text{stat.}) \pm 350\,\text{aN}\ (\text{syst.})$
- consistent with a B ~ 7.4 G

B ~ 10 G measured at the Moiré position

CONCLUSIONS AND FUTURE PLANS

Goal

- AEgIS aims at probing the WEP on antimatter
  - No direct measurement so far

Results

- AEgIS is taking data
- The working principle tested using antiprotons
  - Stray B field → no gravity measurement possible on $\bar{p}$

Future plans

- $\bar{H}$ production expected to be achieved later this year
- First gravity measurements planned for the next years
- Longer term plans also include H-$\bar{H}$ spectroscopy