Testing the Equivalence Principle with antimatter

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INFN
Istituto Nazionale di Fisica Nucleare

Fellini
Fellowship for Innovation at INFN

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Galileo/Newton's (Weak) Equivalence Principle

The free-fall is independent of free-falling body masses

$$\begin{cases} \boldsymbol{F} = m_i \boldsymbol{a} \\ \boldsymbol{F}_g = m_g \boldsymbol{g} \end{cases} \longrightarrow m_i = m_g$$

Einstein's Equivalence Principle

The result of any local non-gravitational experiment is independent from the velocity of an observer in free-fall and his position and time in the universe

~ the Equivalence Principle is at the heart of any metric ~ theory of gravity

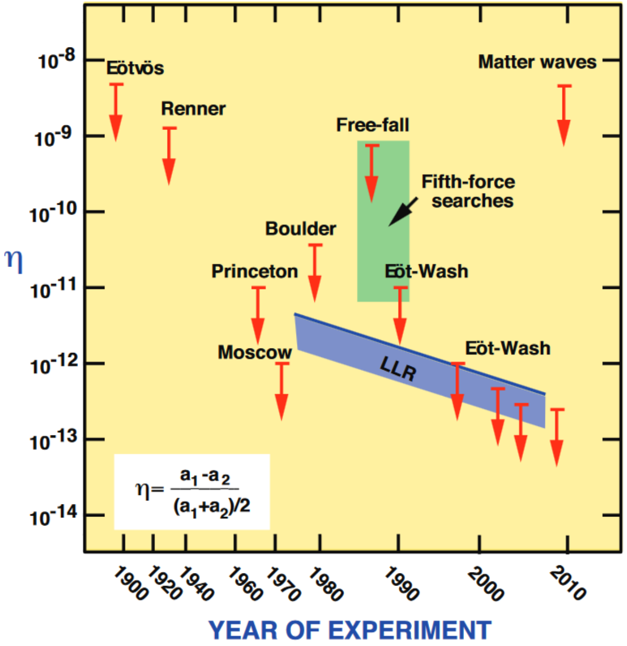
~ testing it means probing our paradigm in ~ understanding gravitation

Clifford M. Will, *Theory and experiment in gravitational physics* (1993)

Tests of the Weak Equivalence Principle

Extremely accurate with normal matter

- MICROSCOPE satellite reached 2 part in 10^{14}
- Eötvös torsion balances reached 2 part per 10^{13}
- Lunar laser ranging reached 3 part per 10^{12}
- Cold atoms interferometry reached 3 part per 10^{8}



With antimatter?

- Failed attempts with charged positrons ~ 1967
- Failed attempts with charged antiprotons ~ 1985
- Some questioned indirect limits 1987 - 2000
- Very rough limit set the ALPHA collaboration with antihydrogen in 2014

WEP tests with antimatter are a young active line of research

Any deviation from the expected perfect equality would be an indication of new physics

Will C. M., Living Rev. Rel. 9 (2006) 3

A topic open to anti-gravity speculation due to lack of experimental constraints

1. Morrison's argument: *antigravity would violate conservation of energy*
2. Schiff's (Dvali's) argument: *Standard Model and gravitational repulsion are incompatible*
3. Good's argument: *antigravity would cause an unobserved CP violation in kaons oscillations*
4. Karshenboim's argument: *EP cannot stand for light, matter and antimatter at the same time in case of antigravity – WEP on antimatter must be valid at the level we can verify deflection of light in GR*

Does it constraint quantum gravity models?

New scalar and vector fields are allowed in some models, and such fields may mediate interactions violating the weak equivalence principle:

attractive/repulsive vector gravitons → $ae^{-r/v}$; attractive scalar gravitons → $be^{-r/s}$

$$V = -\frac{G_\infty}{r} m_1 m_2 (1 \mp a e^{-r/v} + b e^{-r/s})$$

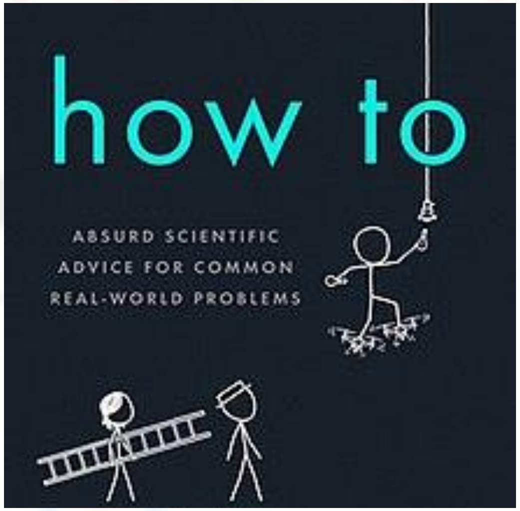
with cancellation effects occuring in matter experiments if a ~ b and v ~ s.

Does it constraint extra force models?

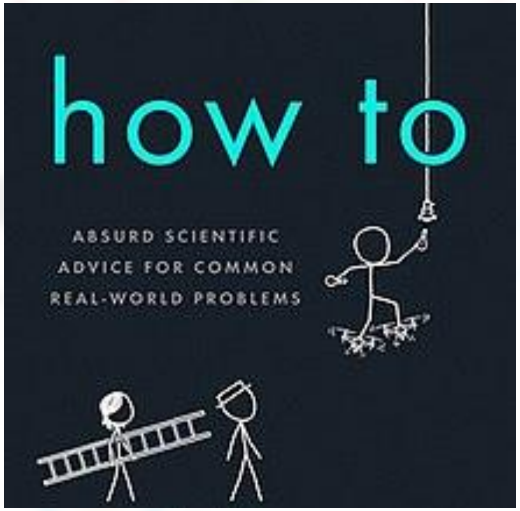
Antimatter WEP tests can constraint fifth force models and dark photons models.

Karshenboim, S. G., talk to 2° Workshop on Antimatter and Gravity (2013)
M. Nieto and T. Goldman, Phys. Rep. 205,5 221-281 (1992)
Phys. Rev. D 33 (1986) 2475
Fayet P., Phys. Rev. D 99 (2019) 055043
Fischbach E. et al. (2020), arXiv:2012.02862v1
Caldwell, A. Dvali G. (2019), arXiv:1903.09096

Testing the WEP with antimatter



1. **Charged antiparticles - plan A**
    - Take some artificial cold charged antiparticles
    - Drop them
    - Measure their free-fall in a field-free environment.
2. **Charged antiparticles - plan B**
    - Take some artificial cold charged antiparticles
    - Build with them a very precise clock
    - Use it to observe the gravitational redshift
3. **Neutral antiparticles – plan C**
    - ~~Take some artificial cold neutral antiparticles~~ no way
4. **Neutral antiparticles - plan D**
    - Take a naturally pulsed source of neutral antiparticles
    - wait for them pass in a gravitational field …
    - … and observe their Shapiro delay compared to light
5. **Neutral antiparticles – plan E**
    - Take some artificial cold charged antiparticles
    - Take counterparts of the opposite charge
    - Put them together to form a neutral atom
    - Drop it before it self-annihilates
    - Measure its free-fall



1. ~~Charged antiparticles - plan A~~
   - ~~Take some artifici~~ … ~~iparticles~~
   - …
   - ~~easure their free fall in a field free environment.~~

   unununderstood and very difficult

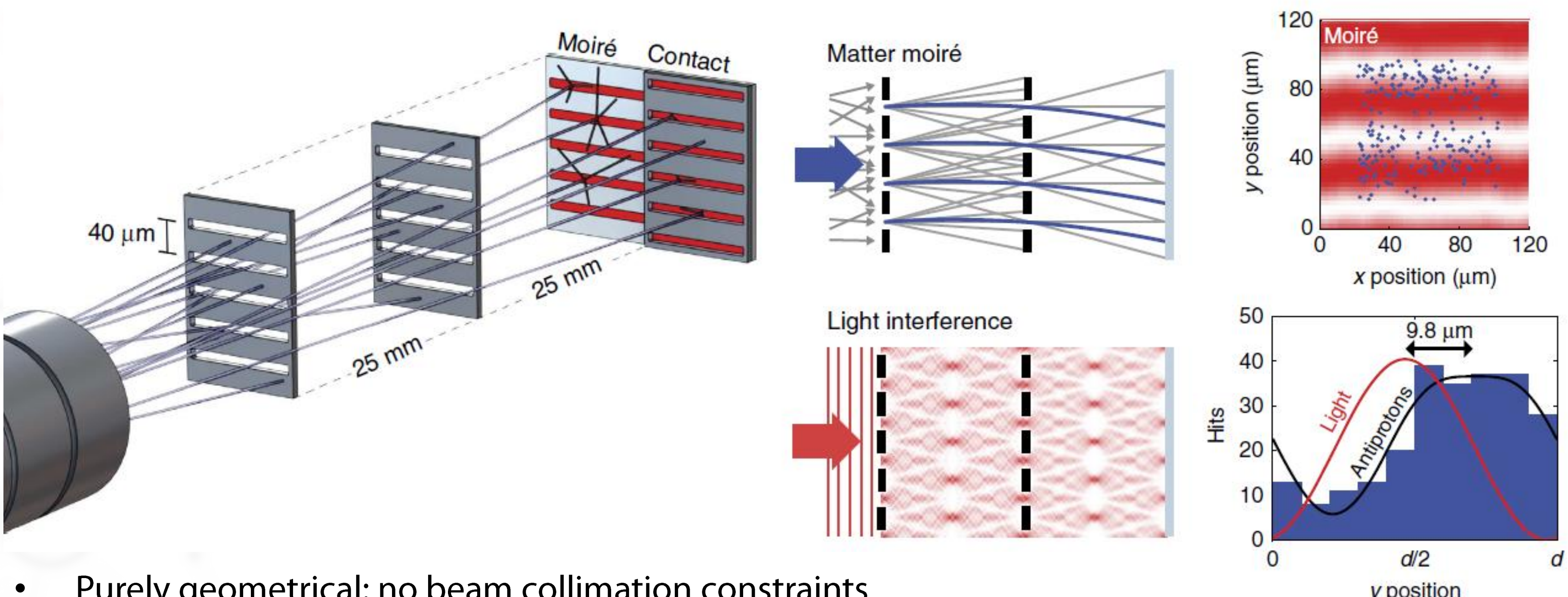
2. ~~Charged antiparticles - plan B~~
   - ~~Take some artificial cold~~ … ~~articles~~
   - …
   - ~~to observe the gravitational redshift~~

   doesn't provide a clean WEP test?

3. **Neutral antiparticles – plan C**
   - ~~Take some artificial cold neutral antiparticles~~ no way
4. ~~Neutral antiparticles - plan D~~
   - ~~Take a naturally~~ … ~~eutral antiparticles~~
   - ~~wa~~ … ~~al field …~~
   - ~~… and observe their Shapiro delay compared to light~~

   neutrinos are way too fast

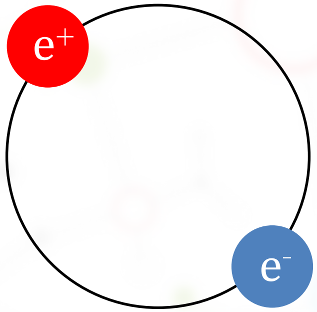
5. **Neutral antiparticles – plan E**
   - Take some artificial cold charged antiparticles
   - Take counterparts of the opposite charge
   - Put them together to form a neutral atom
   - Drop it before it self-annihilates
   - Measure its free-fall



- Purely geometrical: no beam collimation constraints
- Near-field diffraction of light as a tool for gratings alignment in all three spatial directions
- Atoms' time-of-flight knowledge required

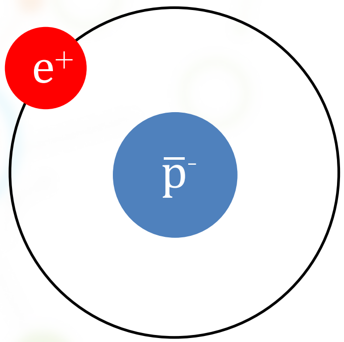
$$\Delta y = \frac{F_{\parallel}}{m}\tau^2 \longrightarrow F_{min} \approx 5 \cdot 10^{-16}\,\mathrm{N}$$

Pulsed sources of neutral antiatoms – available options



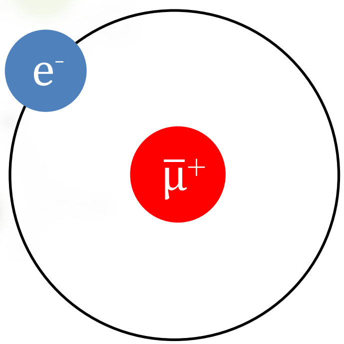
Positronium (Ps) Plan 1

- short lifetime only in GS (142 ns)
- 50% of mass is antimatter
- first generation elementary system
- produced in large numbers @ CERN, University of California, INFN, UCL



Antihydrogen ($\bar{\mathrm{H}}$)

- only stable candidate
- 99.95% mass is in form of QCD binding E
- first generation, non-elementary system
- produced in small amounts only @ CERN



Muonium (Mu)

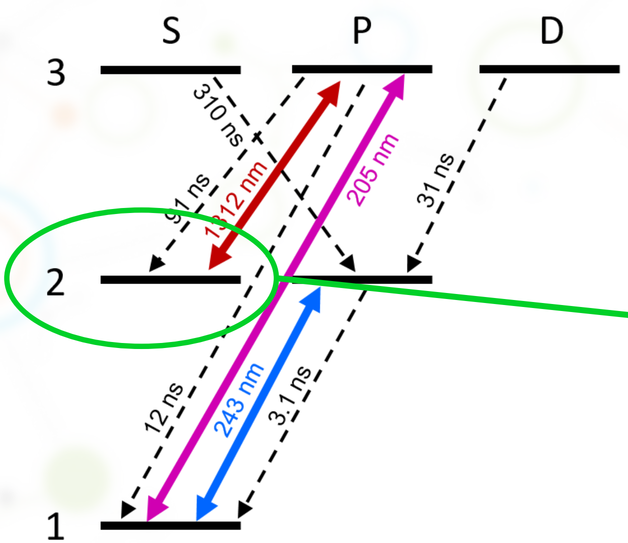
- short lifetime in all levels (2.2 us)
- 99.5% of mass is antimatter
- second generation elementary system
- produced in large numbers @ PAUL SCHERRER INSTITUT PSI

1) http://moriond.in2p3.fr/2019/Gravitation/transparencies/6_friday/1_morning/3_soter.pdf

Producing a pulsed source of 2^3S long-lived Ps

Several methods already explored in literature

1. 1^3S-2^3P single photon laser + 2^3P-2^3S microwaves (1975, Mills et al.)
2. 1^3S-2^3S two-photon laser (1984 Chu, Mills et al; 1993, Fee, Mills et al.)
3. 1^3S-2^3P single photon laser + mixing electric field (2017, Alonso, Hogan, Cassidy)



2^3S Ps state

- Optically metastable
- 2.2 us self-annihilation lifetime
- S-wave (no electric dipole)
- Reachable with today lasers

➢ Need a source with sufficient flux (> 1 atom detected/shot) and collimation (< 1 mrad)

Novel method: 1^3S-3^3P-2^3S two-step laser excitation

➢ 205nm deep UV pulsed laser driving 1^3S-3^3P
➢ 1312nm laser for stimulated 3^3P-2^3S decay

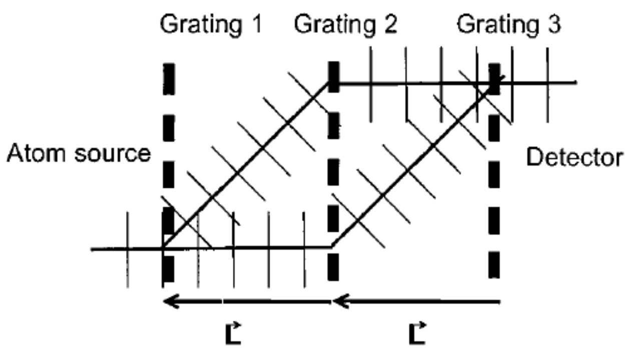
Amsler C. et al (AEgIS collaboration), Phys. Rev. A (2019) 033405

Physics perspectives from 2^3S Ps inertial sensing

PHYSICAL REVIEW A VOLUME 54, NUMBER 4 OCTOBER 1996

Inertial sensing with classical atomic beams

Mach-Zehnder Interferometer



Beam params.

$\Phi = 0.0014\ \mathrm{s}^{-1}$

$\delta\theta = 17\ \mathrm{mrad}$

$\delta v / v = 13\,\%$

Interferometer

$C = 0.2$

$d = 656\,\mathrm{nm}$

$\tau = 2.0\,\mu\mathrm{s}$

$$S = \frac{1}{C\sqrt{N_0}}\,\frac{d}{2\pi}\,\frac{1}{\tau^2} \approx 4000\,\mathrm{m/s^2}\ \ (200\,\mathrm{hours})$$

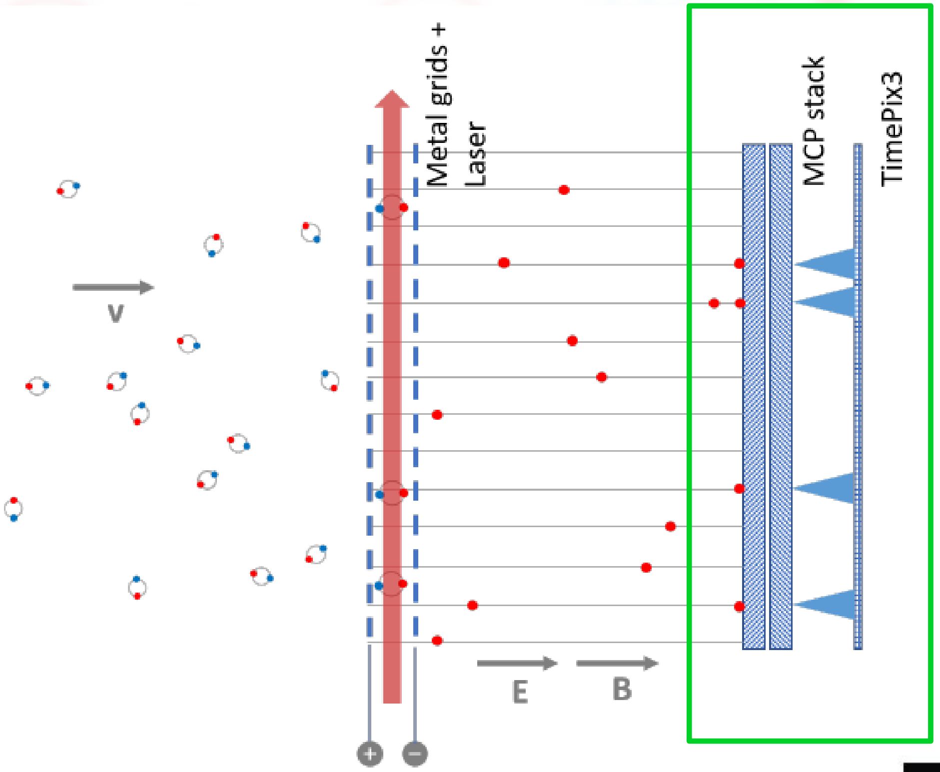
Physics within reach with this sensitivity

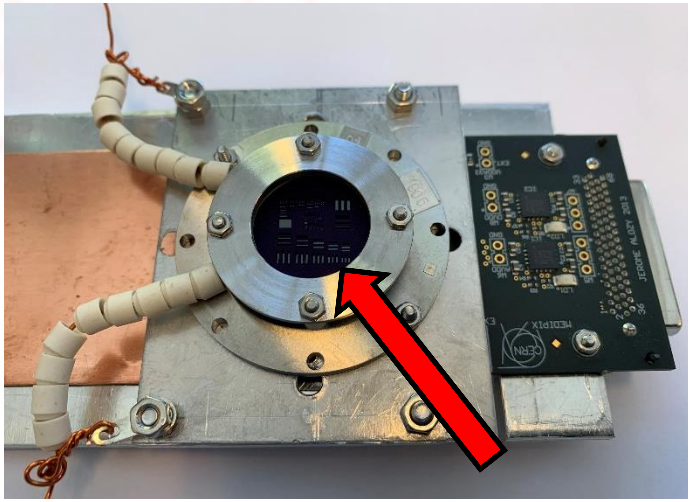
1. First detection of optical forces on Ps atoms (comparison with Rydberg Ps)
2. First detection of the Casimir-Polder force on antimatter

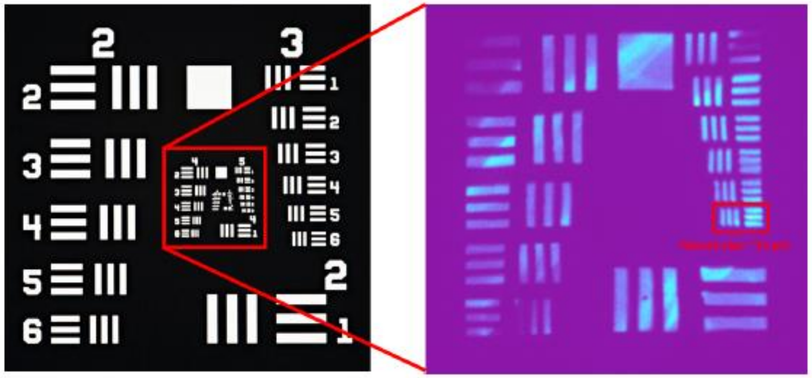
Next steps towards intertial sensing with positronium

1. **Improve detection:** high resolution imaging MCP for 2^3S Ps (up to x6 solid angle) ongoing
2. **Improve laser excitation efficiency:** test beam with 1312 nm stimulated decay (x3)
3. **Improve source directionality:** target nanofabrication for forward emission in press
4. **Improve beam collimation**: 1s-2p Doppler cooling ongoing

High resolution imaging and timing detector



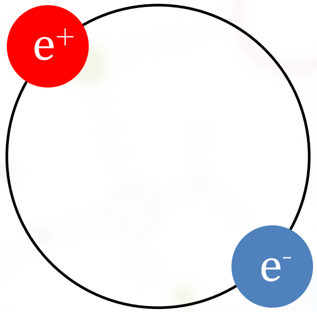




Work in progress

- Concept tested at TN-AML e^+ beamline
- Spatial resolution of 12 um
- Timing resolution of 1.5 ns
- Detection efficiency e^+ of 40 %

Pulsed sources of neutral antiatoms – available options



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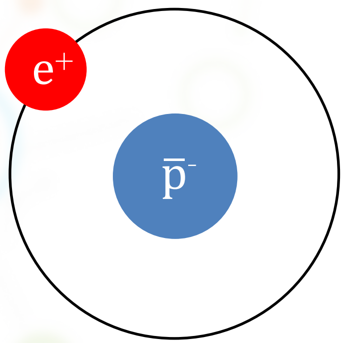
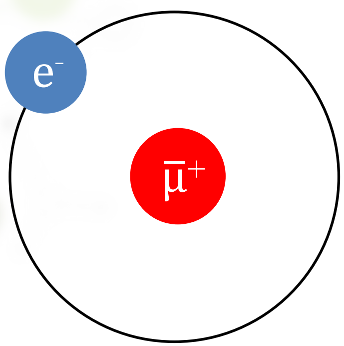


Antihydrogen ($\bar{H}$) Plan 2

- only stable candidate
- 99.95% mass is in form of QCD binding E
- first generation, non-elementary system
- produced in small amounts only @



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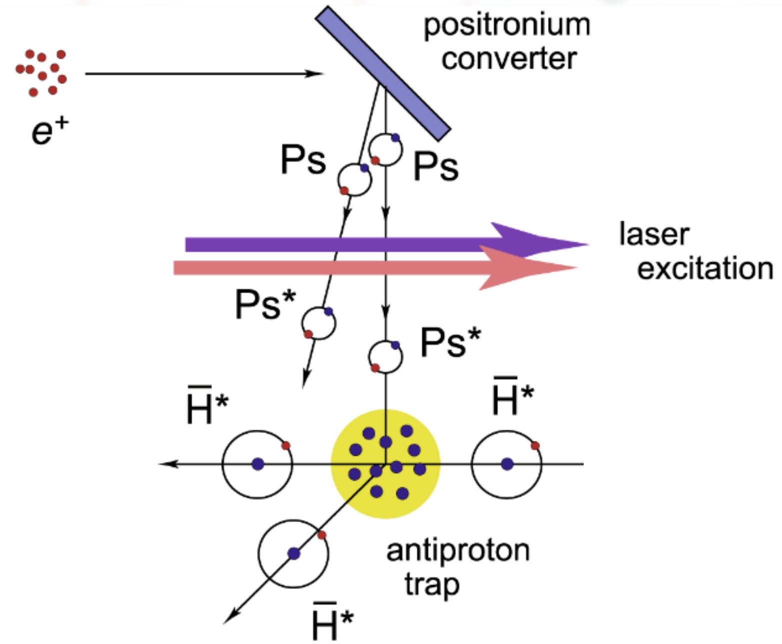
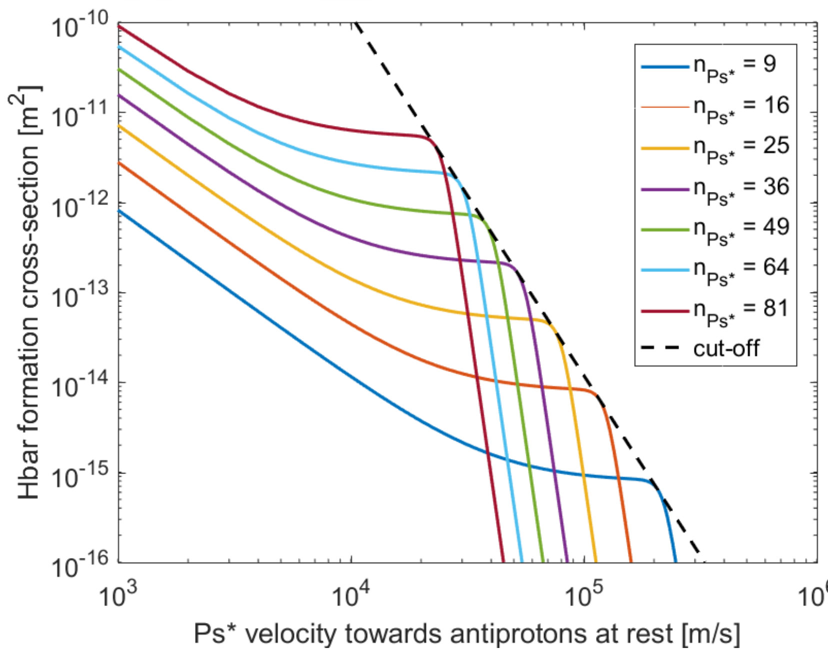
Conceptual scheme for pulsed antihydrogen production



1) Preparation of a cold antiproton plasma in a Penning trap
2) Pulsed production of cold Ps from e^+ conversion in mesoporous silica
3) Two-step laser excitation of Ps to Rydberg levels



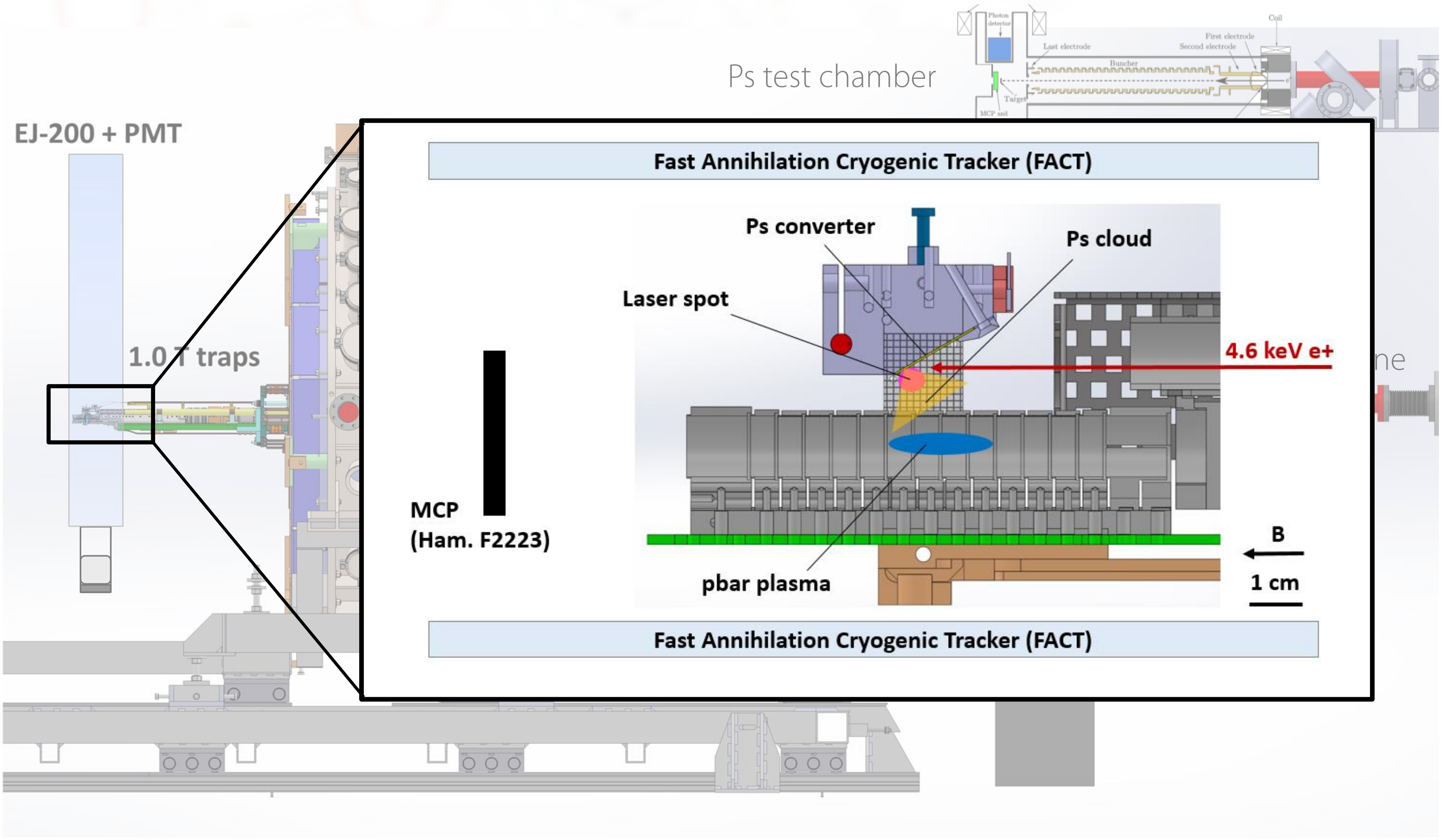
4) Charge-exchange with antiprotons

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

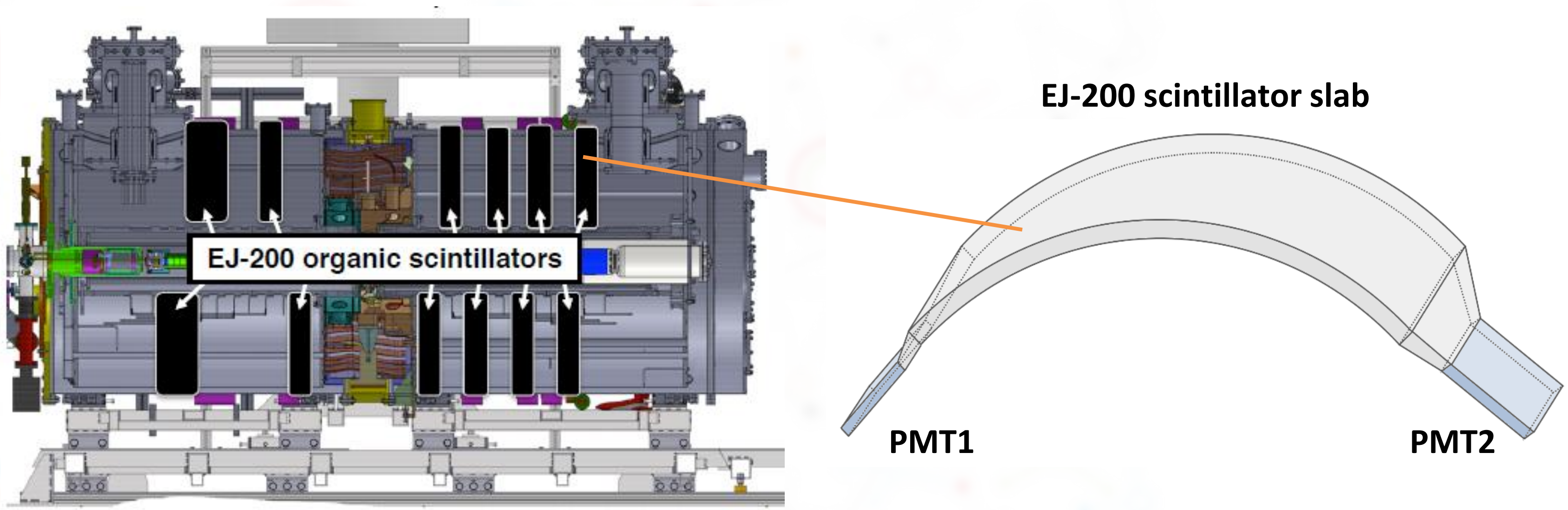
5) Detection of the annihilation products after collision with the trap walls

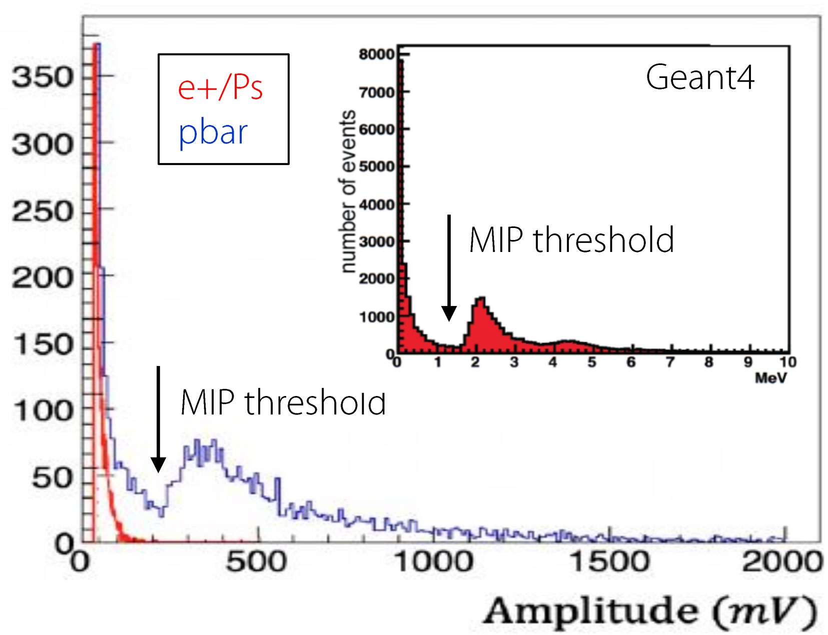
Doser M. et al., Class. Quantum Grav. 29, 184009 (2012).

The AEgIS experimental complex



Antihydrogen detection – scintillator array





Scintillator array for MIP detection

- 8 x EJ-200 scintillator slabs
- Scintillators are read at both ends with photomultipliers
- Each PMT is digitized at 250 MHz
- software **coincidence** between the signals is performed

Pulsed production of antihydrogen

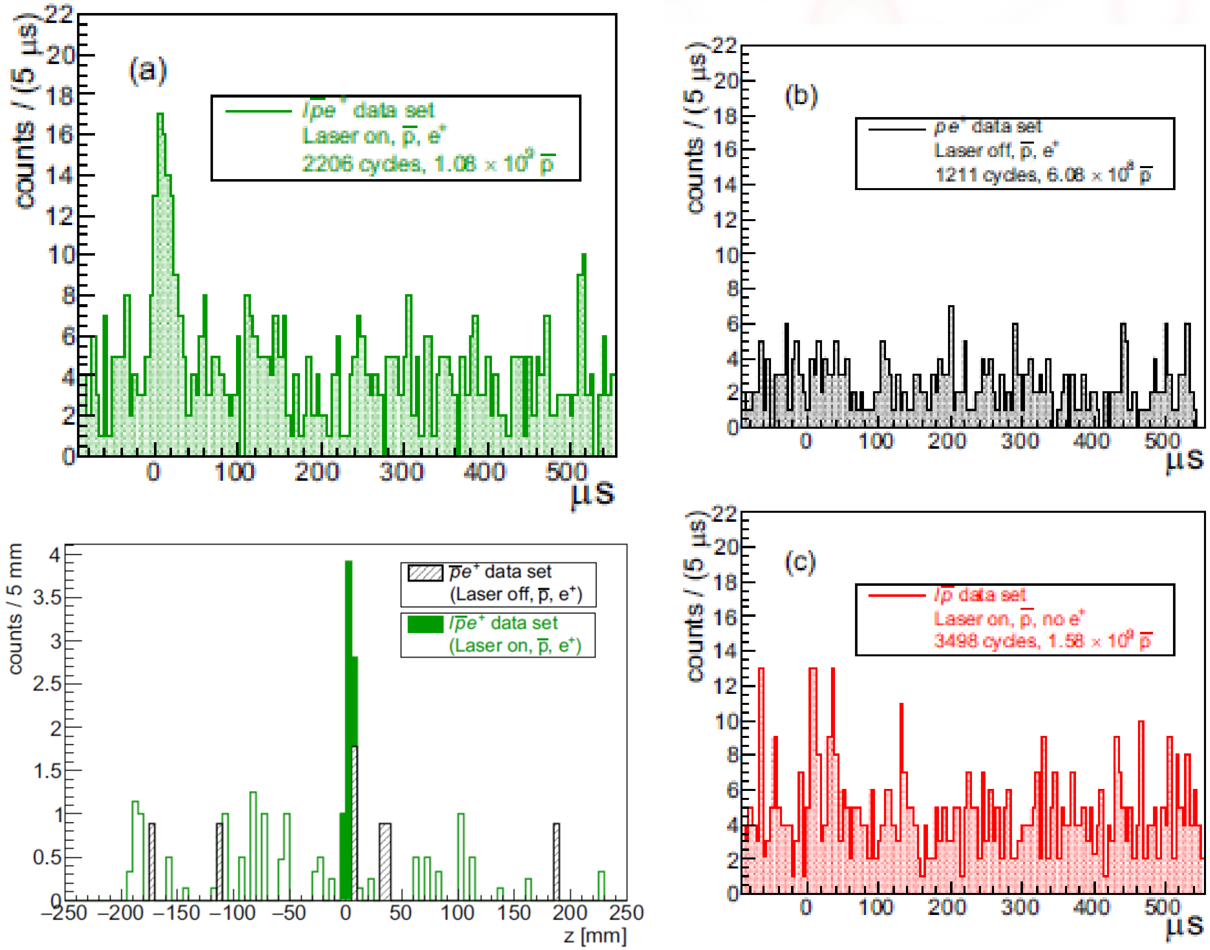
Hbar detection

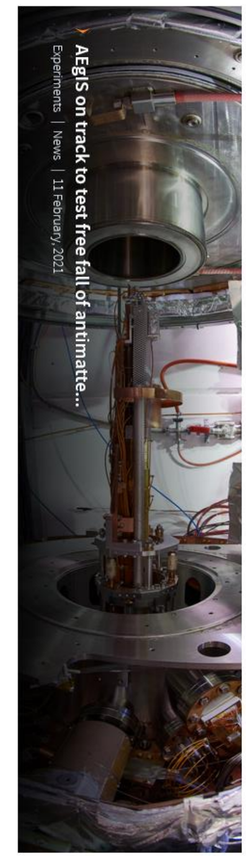
ARTICLE

https://doi.org/10.1038/s42005-020-00494-z OPEN

Check for updates

Pulsed production of antihydrogen





LATEST NEWS

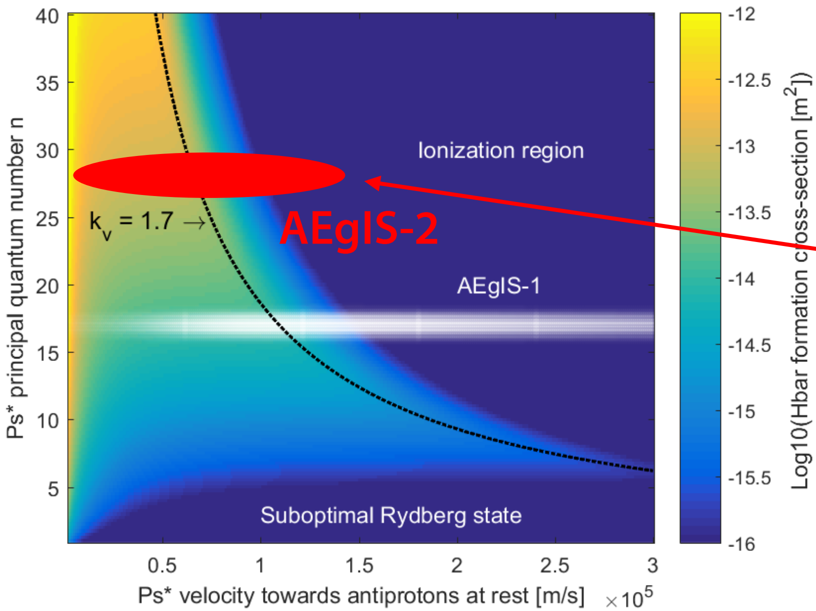
First-ever pulsed source of antihydrogen just demonstrated – 100 events in 2200 trials

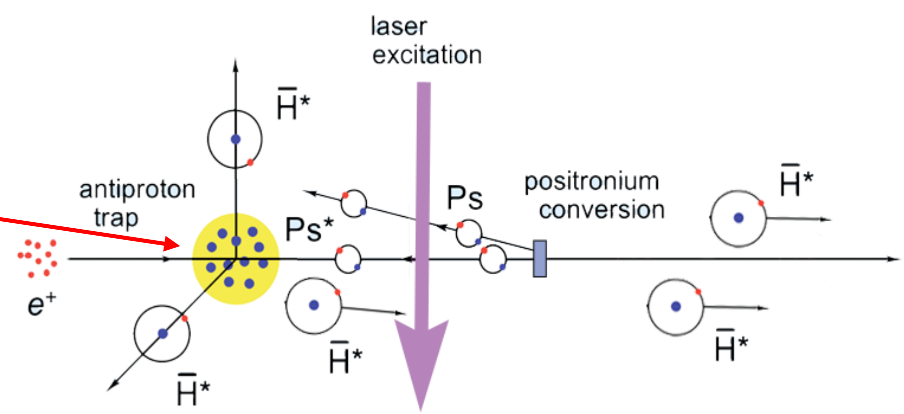
Hbar beam?

Probing the Weak Equivalence Principle with antihydrogen

1. Proof-of-concept pulsed antihydrogen source
2. Increase of produced antihydrogen atoms by a factor of 10
3. Demonstrate a forward pulsed beam of antihydrogen
4. First free-fall tests using a moiré deflectometer!

AEgIS-2: collinear scheme for boosted antihydrogen production





Expected an order of magnitude flux increase