Quantum gases, Fundamental interactions and Cosmology

Gravity tests with antimatter: the AEgIS experiment

Fiodor Sorrentino
INFN sez. Genova
Italy
On behalf of the AEgIS collaboration

Outline

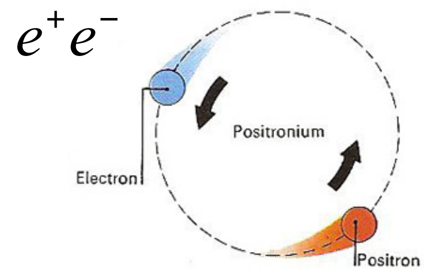
- Precision measurements on antimatter systems
- Motivations of the AEgIS experiment
- Overview of AEgIS
  - anti-H production
    - Antiproton cooling
    - Positron system
    - Charge exchange reaction with positronium
  - Anti-H detection
  - Gravity measurement with moiré deflectometer
- Recent results and perspectives

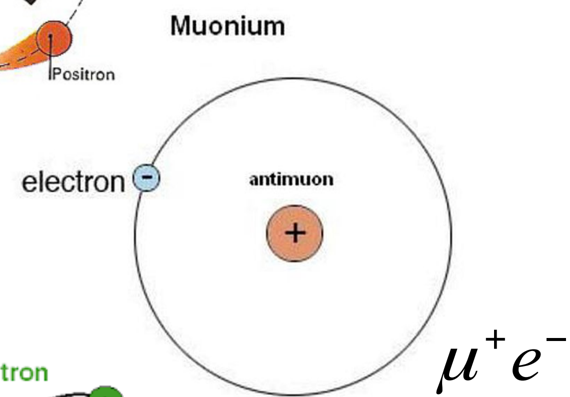
AEgIS Collaboration

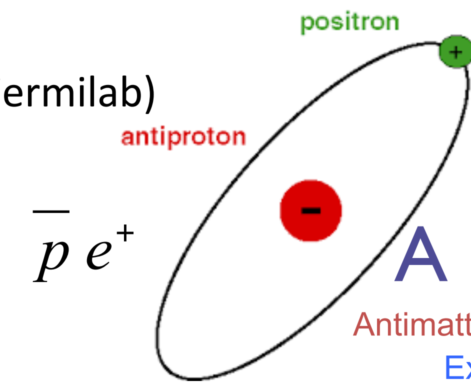
University of Bergen	University of Brescia	CERN, Geneva	University of Genova
Heidelberg University	Max Planck Institute for Nuclear Physics, Heidelberg	University College London	Lyon 1 University of Lyon 1
University of Milano	Politecnico di Milano	Institute of Nuclear Research of the Russian Academy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

Experimental physics with antimatter

- Charged antimatter
  - 1932 positrons e^+ in cosmic rays (Anderson 1932)
  - 1955 antiprotons $\bar{p}$ (Segré, Chamberlain, Wiegand)
- Neutral antimatter
  - Positronium
    - 1951 Discovery (Deutsch)
    - A. Mills (Univ. California Riverside)
    - P. Crivelli te al. (Univ. Zurich)
    - S. Hogan & S. Cassidy (ETH-London)
    - Tokyo University
    - AEgIS
  - Muonium
    - K. Kirch (ETH-PSI)
  - Antihydrogen
    - 1991 High-energy anti-H (CERN, Fermilab)
    - 2002 Cold anti-H (ATHENA)
    - 2011 Anti-H trapping (ALPHA)
    - 2013 Anti-H beam (ASACUSA)



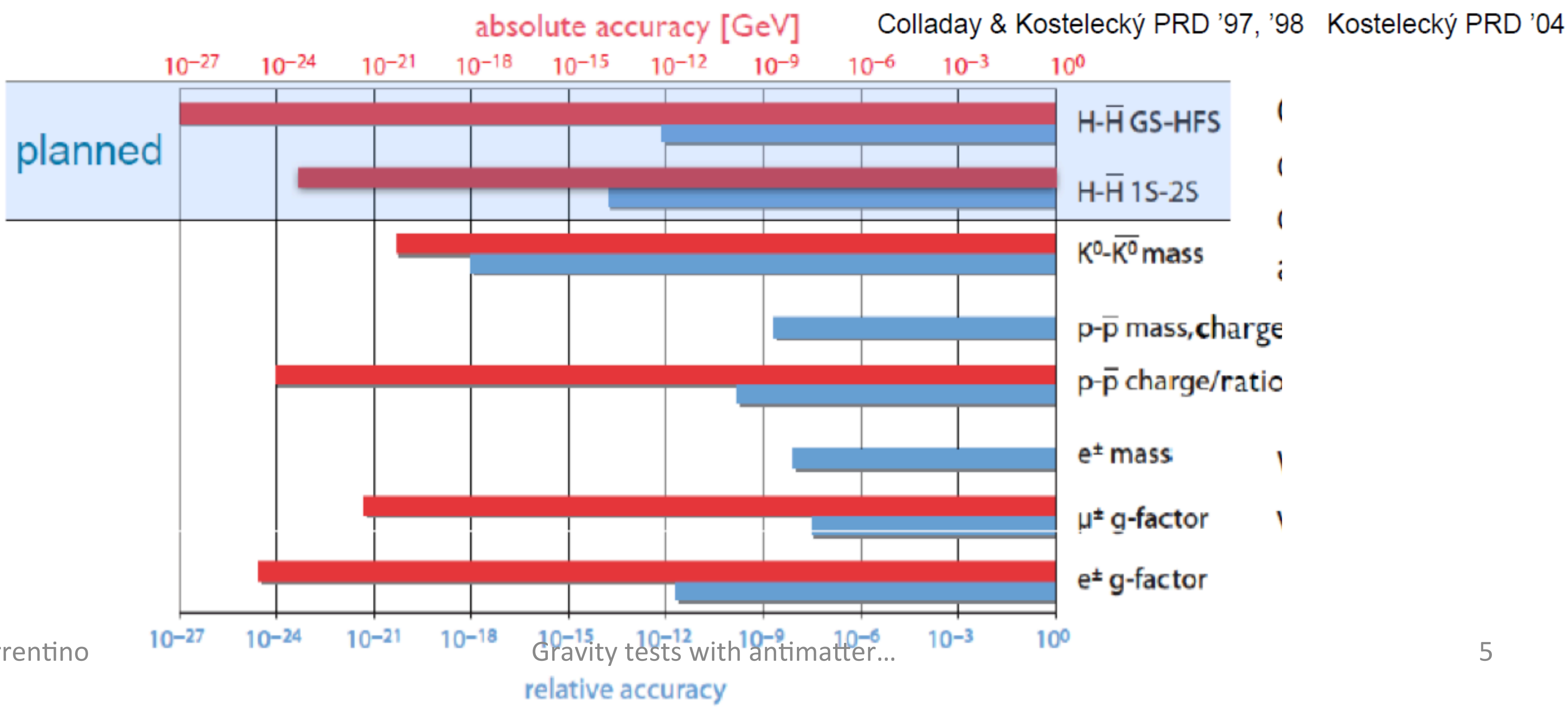




A E $\bar{g}$ I S
Antimatter Experiment Gravity Interferometry Spectroscopy

Precision measures on neutral antimatter

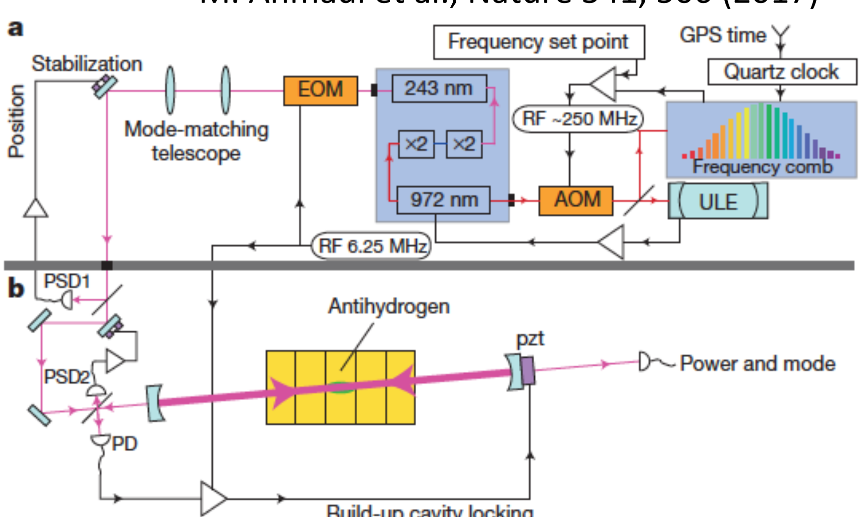
- spectroscopy
  - Local, unitary and Lorentz-invariant quantum field theories must respect CPT
  - mass, magnetic moment, transition frequency in matter-antimatter system must be equal
  - Breaking of Lorentz invariance appears in theories beyond the Standard Model
  - Standard-Model extension (SME): low energy framework to describe effects of a theory at Planck scale: effective theory which contains General Relativity (GR) & Standard Model (SM), covariant, aribitrary coordinate independent CPT & Lorentz violating terms (LV)



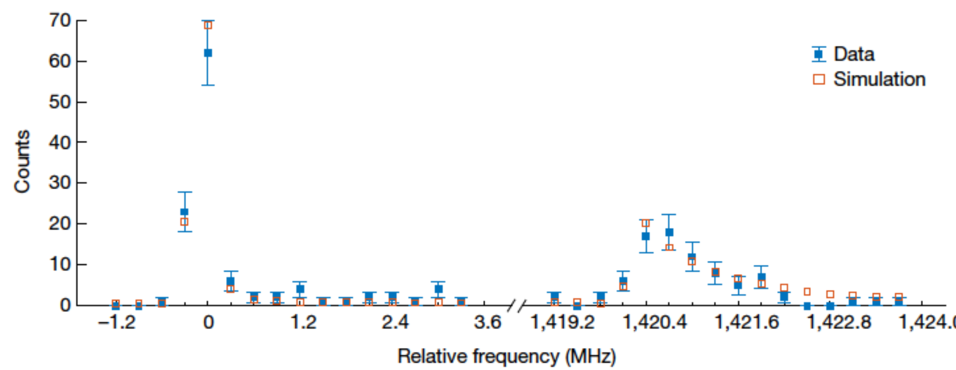
Precision measures on neutral antimatter

- spectroscopy
  - Local, unitary and Lorentz-invariant quantum field theories must respect CPT
  - mass, magnetic moment, transition frequency in matter-antimatter system must be equal
  - Breaking of Lorentz invariance appears in theories beyond the Standard Model
  - Standard-Model extension (SME): low energy framework to describe effects of a theory at Planck scale: effective theory which contains General Relativity (GR) & Standard Model (SM), covariant, aribitrary coordinate independent CPT & Lorentz violating terms (LV)
  - Recent results from ALPHA experiment: 1S-2S spectroscopy and GS-HFS in anti-hydrogen

M. Ahmadi et al., Nature 541, 506 (2017)

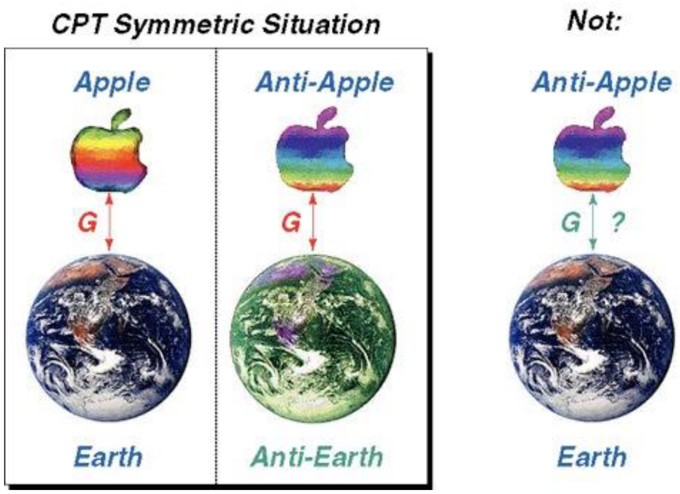


M. Ahmadi et al., Nature 548, 66 (2017)



Precision measures on neutral antimatter

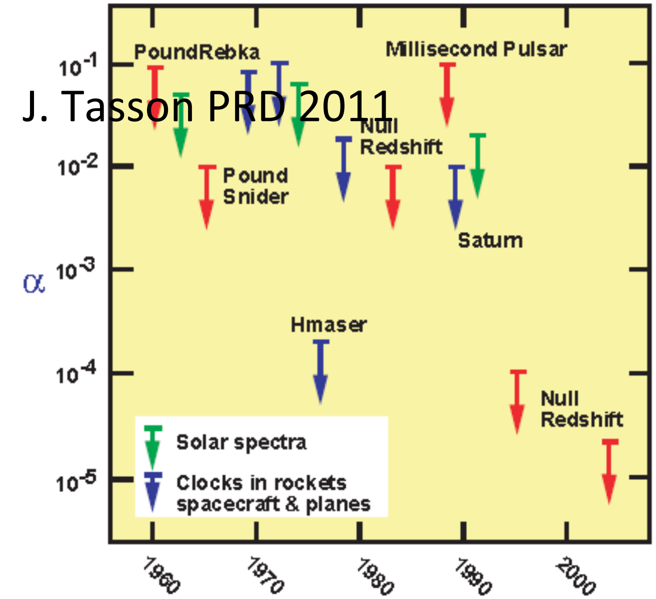
- *g* measurement
  - WEP test
    - e.g. in SME: WEP violations results from Lorentz and CPT violations
  - no direct measurements so far on antimatter:
    - e+ e- dominated by sistematic effects [PRL **19**, 1049, 1967]
    - proposal for repeating it in space [Gen. rel. Grav. **36**, (2004)]
    - experimental bound |gbar|<100 g from proof of principle (ALPHA)



Precision measures on neutral antimatter

- *g* measurement
  - WEP test
    - e.g. in SME: WEP violations results from Lorentz and CPT violations
  - no direct measurements so far on antimatter:
    - e+ e- dominated by sistematic effects [PRL **19**, 1049, 1967]
    - proposal for repeating it in space [Gen. rel. Grav. **36**, (2004)]
    - experimental bound |gbar|<100 g from proof of principle (ALPHA)

J. Tasson PRD 2011



Adapted from J. Tasson WAG 2013

a subset of the SME lagrangian with gravity[1]

$$L_{\text{fermion}} = \tfrac{1}{2} i e^{\mu}{}_{a}\, \overline{\psi}(\gamma^{a} - c_{\nu\lambda} e^{\nu a} e^{\lambda}{}_{b}\gamma^{b} - e_{\nu} e^{\nu a}) \overleftrightarrow{D}_{\mu}\psi - \overline{\psi}(m + a_{\mu} e^{\mu}{}_{a}\gamma^{a})\psi + \ldots$$

coefficients for Lorentz violation
- particle-species dependent

- vierbein – gravitational effects

evades constraints

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

J. Tasson PRD 2011

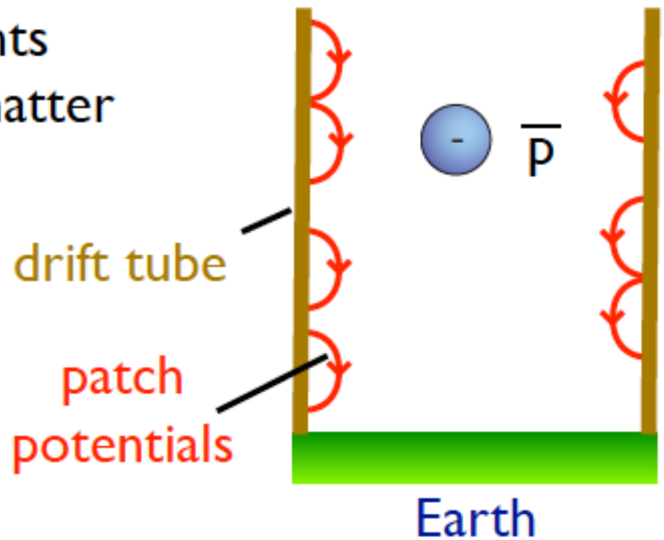
matter $m_{\text{i,eff}} = m_{\text{g,eff}}$, $\text{a} = g$

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

2/3/2012 Y. Sacquin IRFU/SPP CEA Saclay 4

Why anti-Hydrogen?

Free-fall experiments with charged antimatter (e+, $\bar{p}$) failed:



$F_{gravity} << F_{electromagnetic}$

Requires:

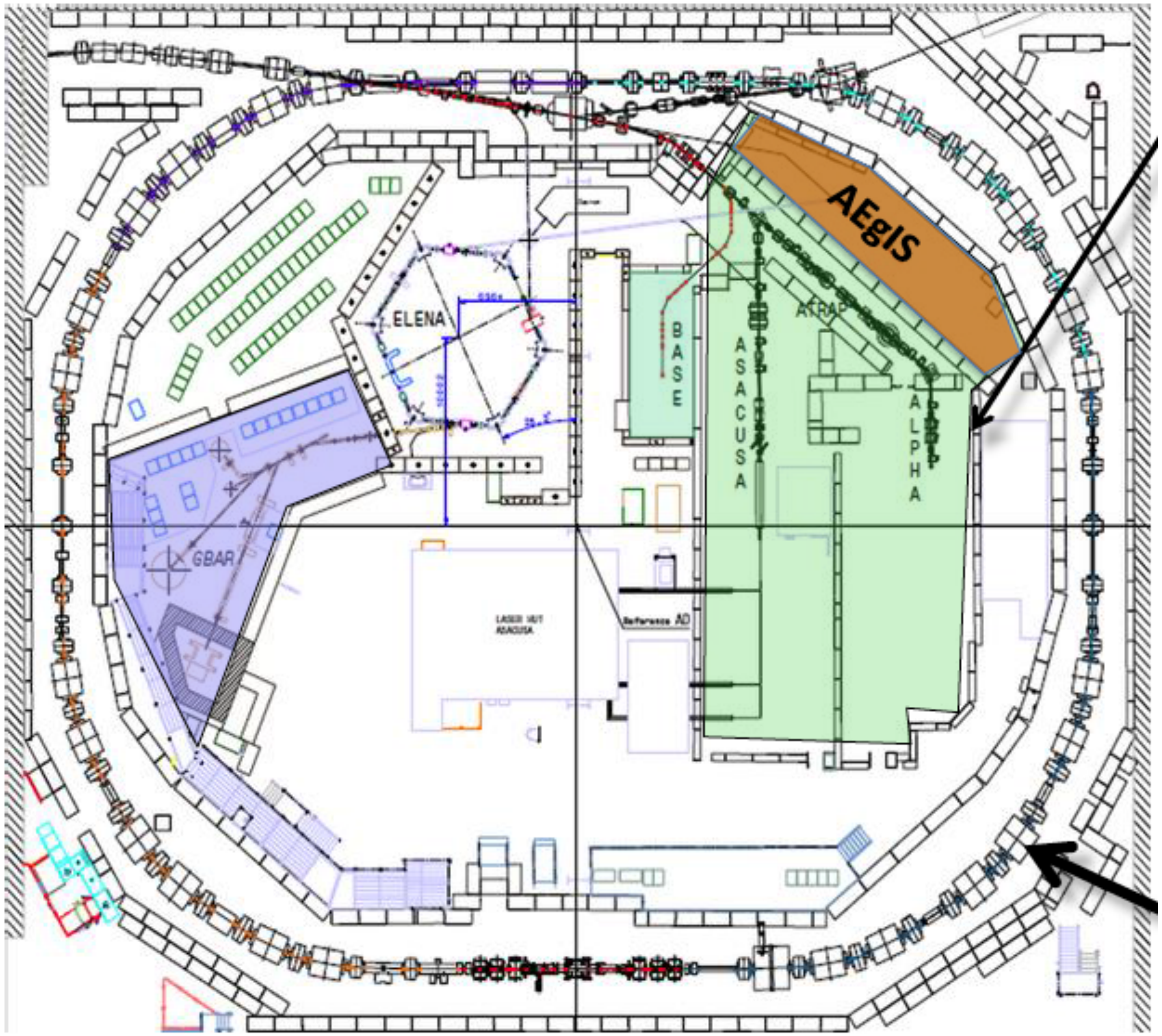
e^+ $E < 10^{-12}$ V/m

$\bar{p}$ $E < 10^{-7}$ V/m

Not possible: due to patch effect.

- AntiH and Ps are among the simplest neutral systems of antimatter
- Ps low mass -> large RMS velocity -> hard to make precision acceleration measurements

Antimatter experiments @ CERN: AD

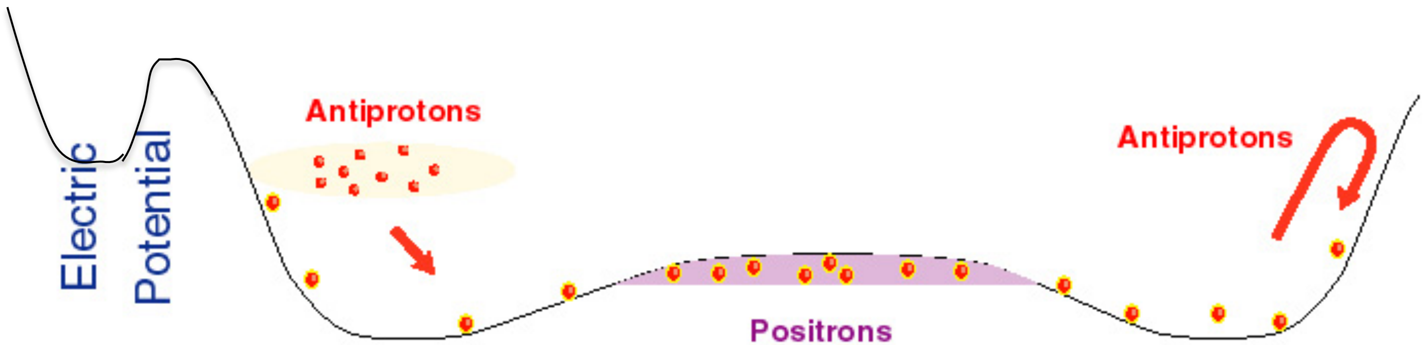


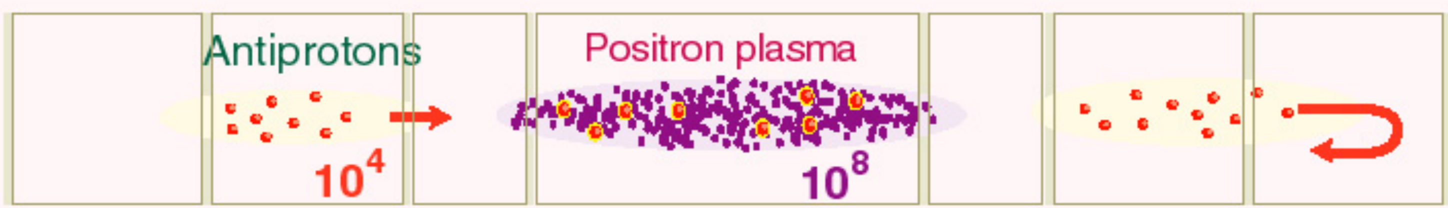
Experiments @ AD

- ACE
- **AEgIS**
- ALPHA
- ASACUSA
- ATRAP
- BASE
- More in the future (GBAR)

AD beam specs:
~ 3×10^7 anti-protons/shot
~ 5 MeV
~200 ns bunch length
~100 s repetition
From 2017: ELENA
~100 keV, 4 bunches

Hbar production: ATHENA





Mixing Trap Electrodes

a) Radiative recombination

$$\bar{p} + e^{+} \rightarrow \bar{H} + h\nu$$

Populate low n (n<10)

$$R \propto n_{e^{+}} T_{eff}^{-1}$$

b) 3 body recombination

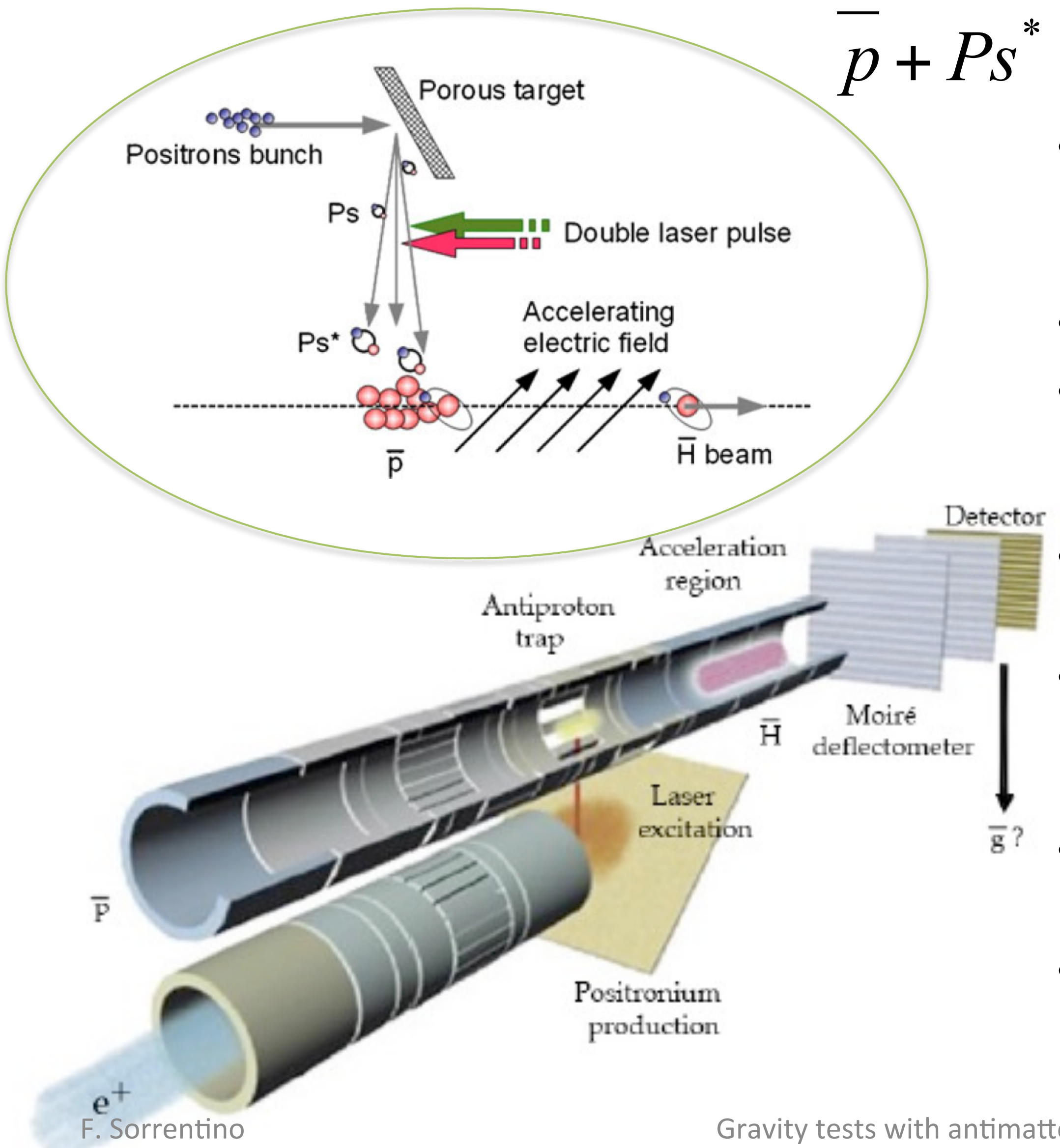
$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$

Populate high n, ionization by collisions and field ionization

$$R \propto n_{e^{+}}^{2} T_{eff}^{-9/2}$$

10^4-10^5 antiprotons
10^7-10^8 e+
10^4 K
15% of the pbar recombines

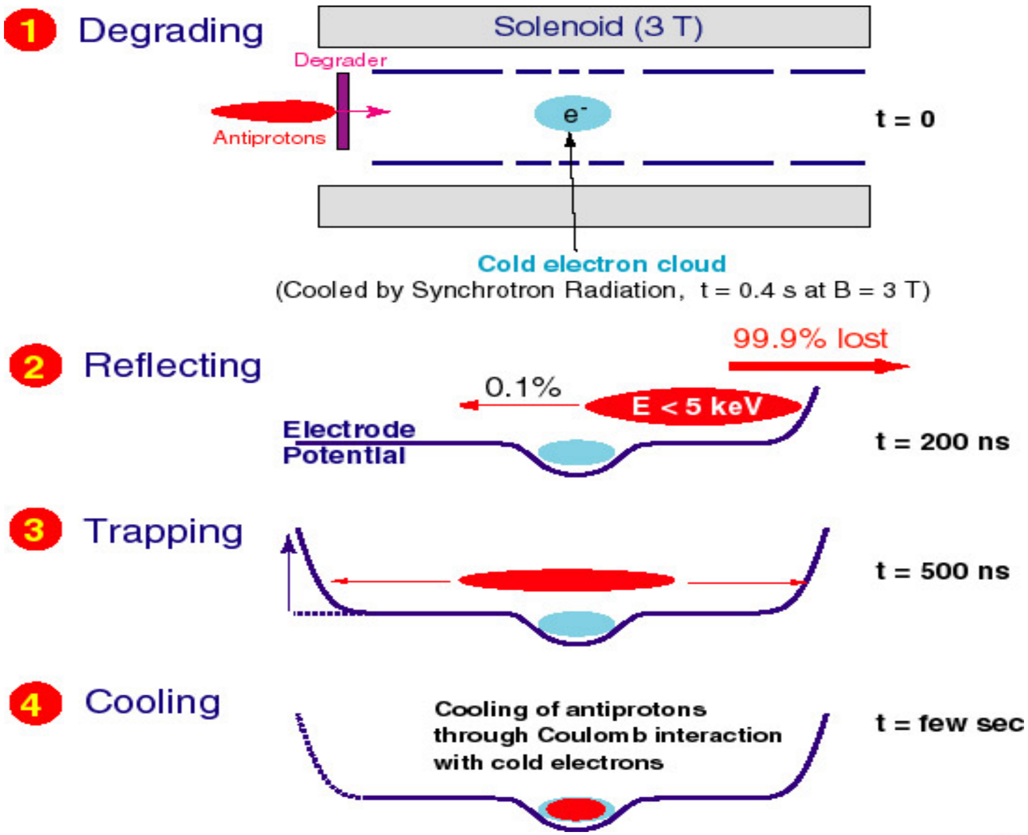
High flux, cold Hbar: the AEgIS recipe

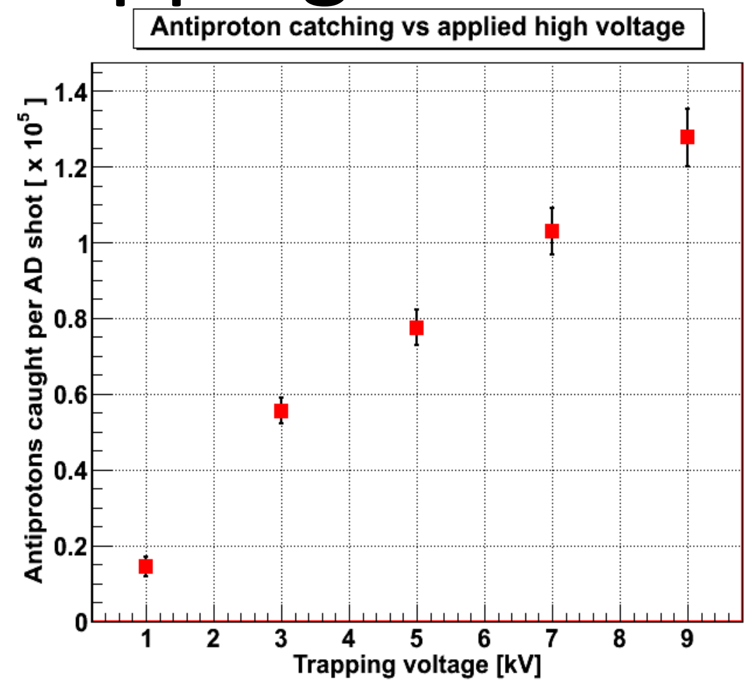


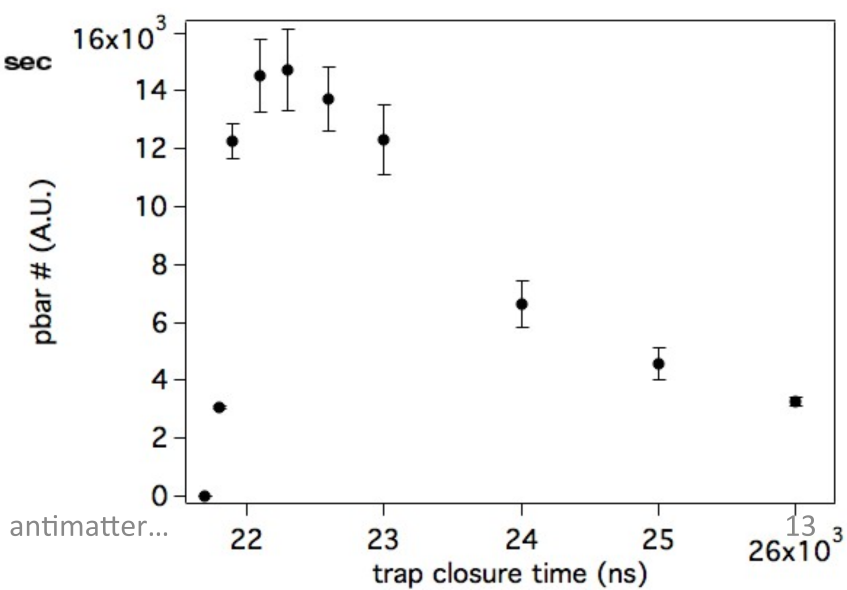
$$\bar{p} + Ps^* \rightarrow \overline{H}^* + e^-$$

- 1) Catch pbar from AD (CERN), cool, store
  - Pbar ultracooling
- 2) Accumulate e+;
- 3) Form Ps
  - launch e+ toward a e+ to Ps converter (nanoPorous target);
- 4) Excite Ps to Rydberg states
  - laser pulses
- 5) Produce Rydberg Hbar
  - Pbar + Ps charge transfer reaction
  - pulsed production
- 6) Form the beam
  - electric field gradient
- 7) Measure gravity
  - moiré deflectometer
  - time-position sensitive detector

AEgIS: pbar trapping



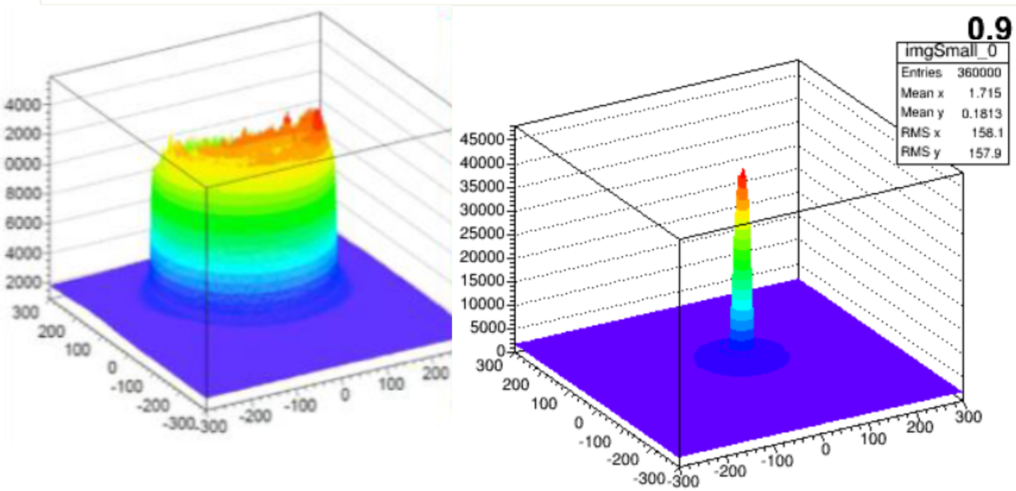


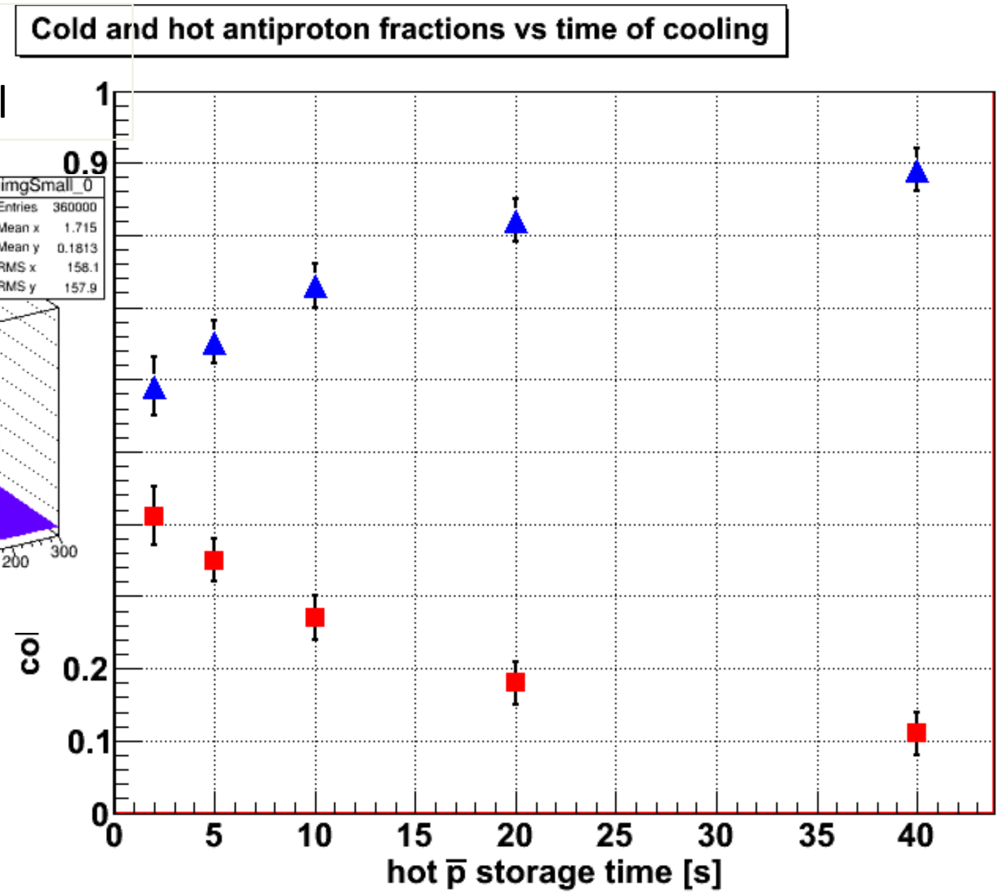


Trap in flight after traversing a degrader
Pulsed electrodes (several KV) in few tens ns

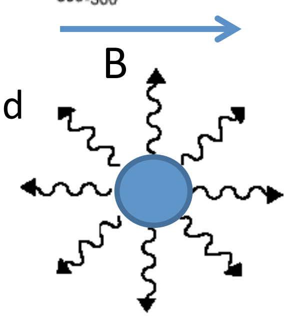
AEgIS: pbar compression & cooling

Radial compression of the
Trapped plasma with RF field: Rotating Wall





e- (and also positrons)
Radiation in high magnetic field
(cyclotron cooling)



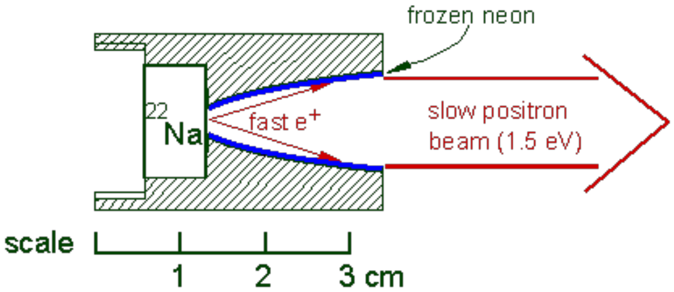
$$T = T_{iniz} e^{-t/\tau_{rad}} + T_{trap}$$

$$\tau_{rad} \propto \frac{m^3}{B^2}$$

e^-, e^+	$\tau_{rad} \cong 0.1 \sec @ 5T$
$\overline{p}$	$\tau_{rad} \cong 10^9 \sec @ 5T$

Cyclotron radiation + Coulomb collisions
= thermal equilibrium for e- and pbar
Final energy estimation: about 100 K
Further cooling methods: resistive cooling, sympathetic cooling with negative ions

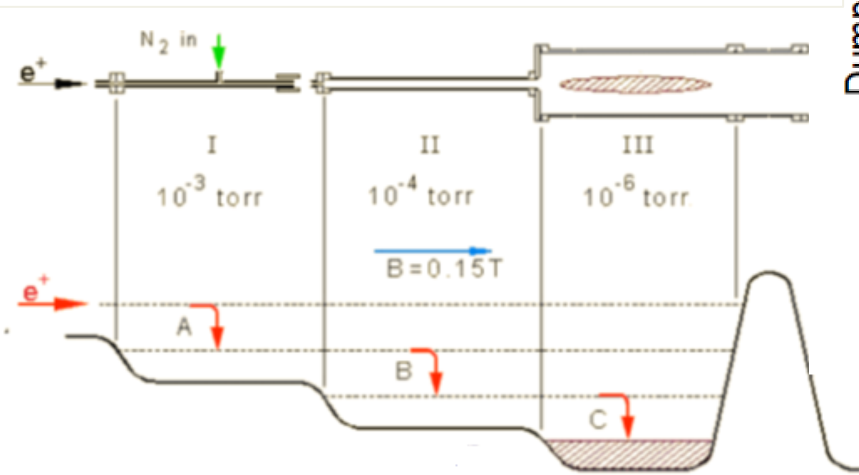
AEgIS: positrons



^{22}Na source

Continuous e^+ emission with high energy

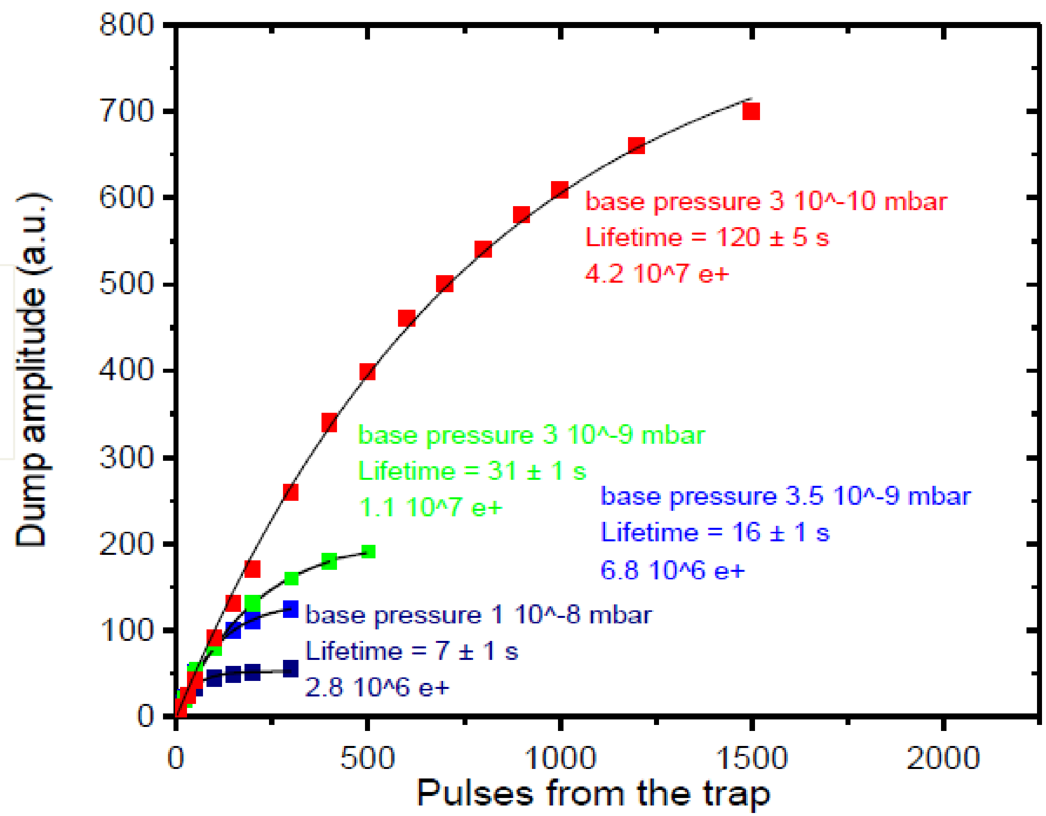
Moderation through solid neon



Buffer gas cooling plus transfer in UHV trap

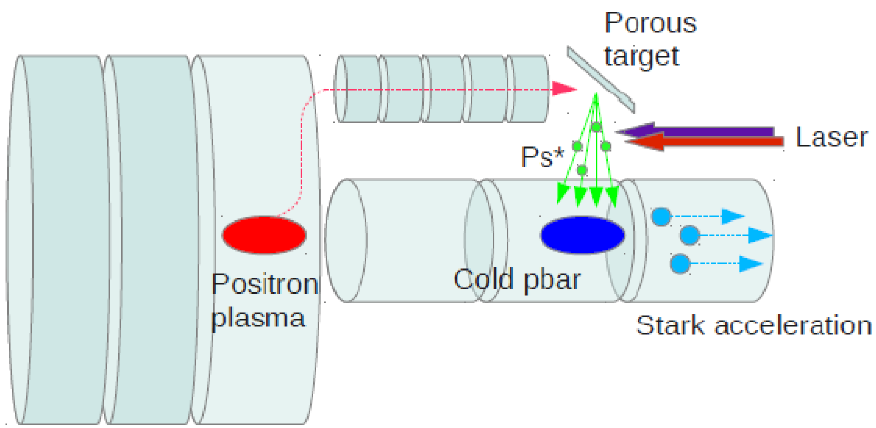
Accumulation in a trap in UHV with B=0.1-0.15 T

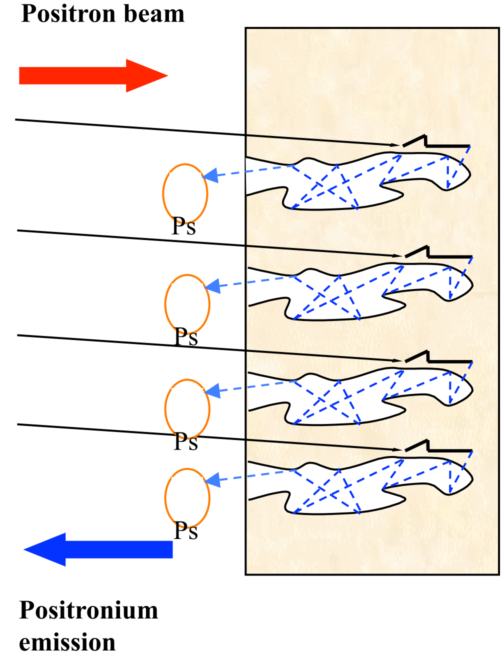
Radial compression of the cloud (RW)



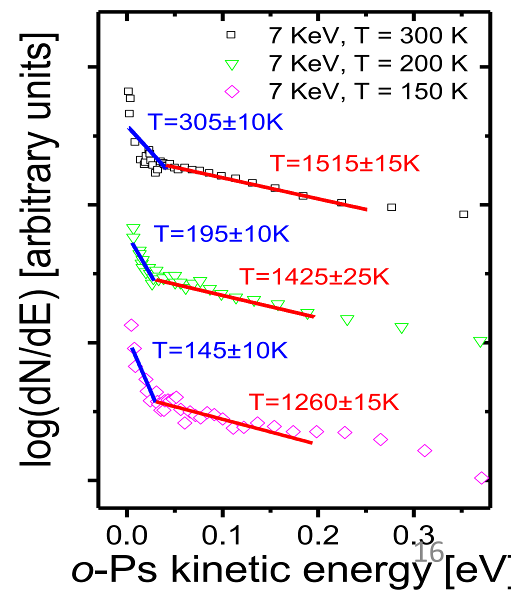
- Source activity ≈ 14 mCi
- Up to 1.2 10^8 e+ with 50 mCi source

AEgIS: Ps formation





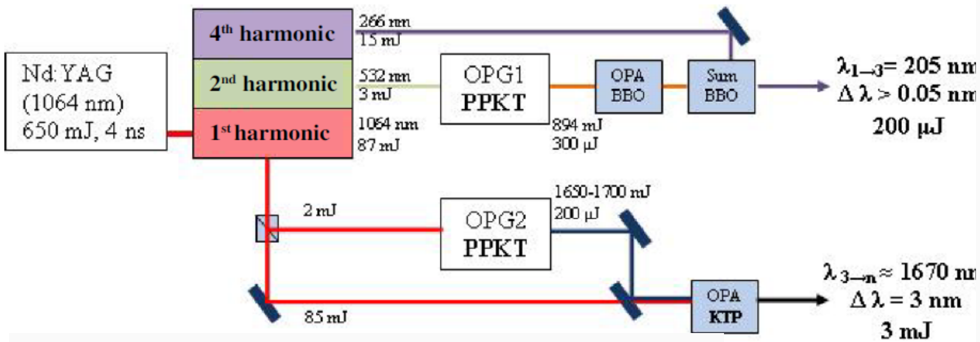
- Implantation of e+ in a nanoporous material (converter) SiO_2 on Si substrate
- Tunable nanochannel size: few nm to few tens ns
- Formation of Ps (eV energy)
- Cooling inside the pore and the channels
- at 7 keV 27 % of implanted positrons escape into the vacuum as *o*-Ps
- Ordered and disordered channels studied in AEgIS

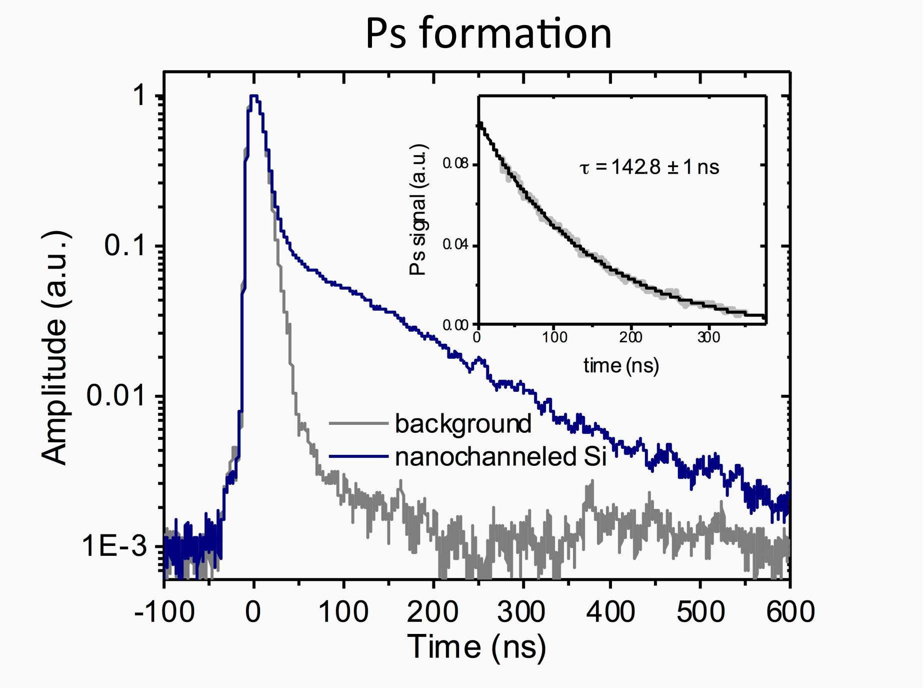


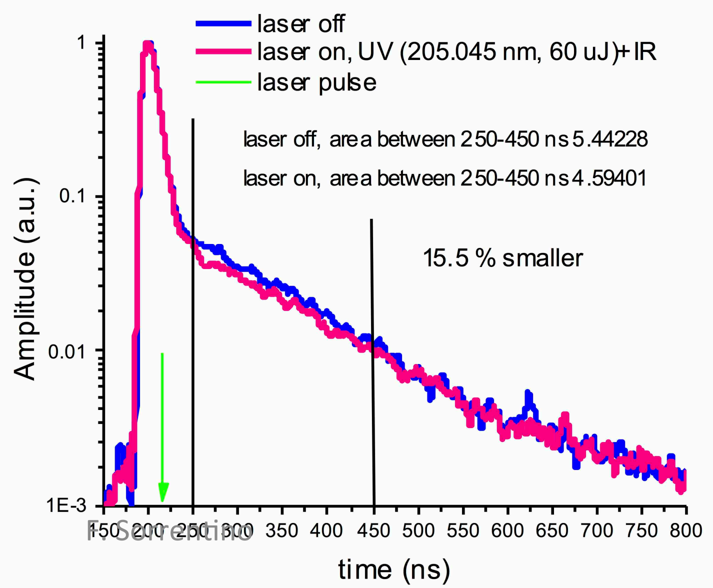
Observed cooling by collisions with pore walls
5-8 nm channels, 2-3% Ps thermalized with the target
[Mariazzi S. et al., Positronium cooling and emission (...), PRL 104 (2010) 243401]

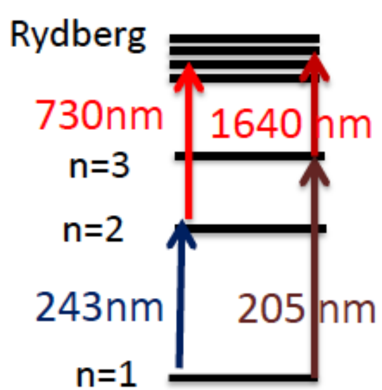
AEgIS: Ps excitation tests

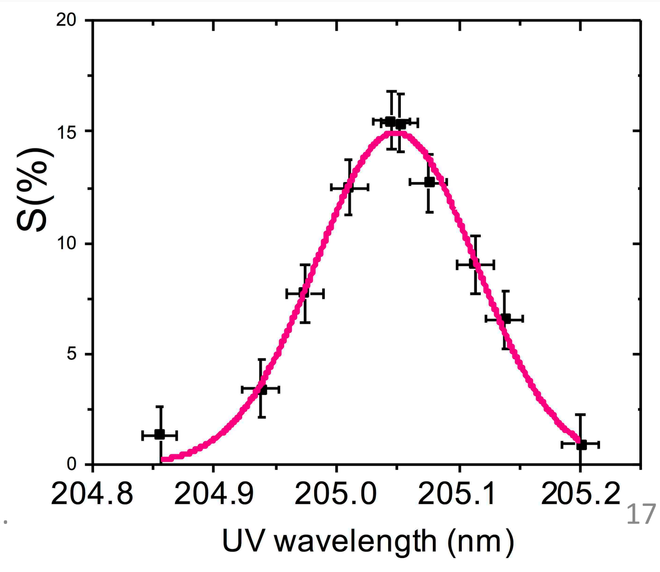
- Test on Ps formation & excitation
- Laser excitation to n=3 demonstrated by photoionization measurements



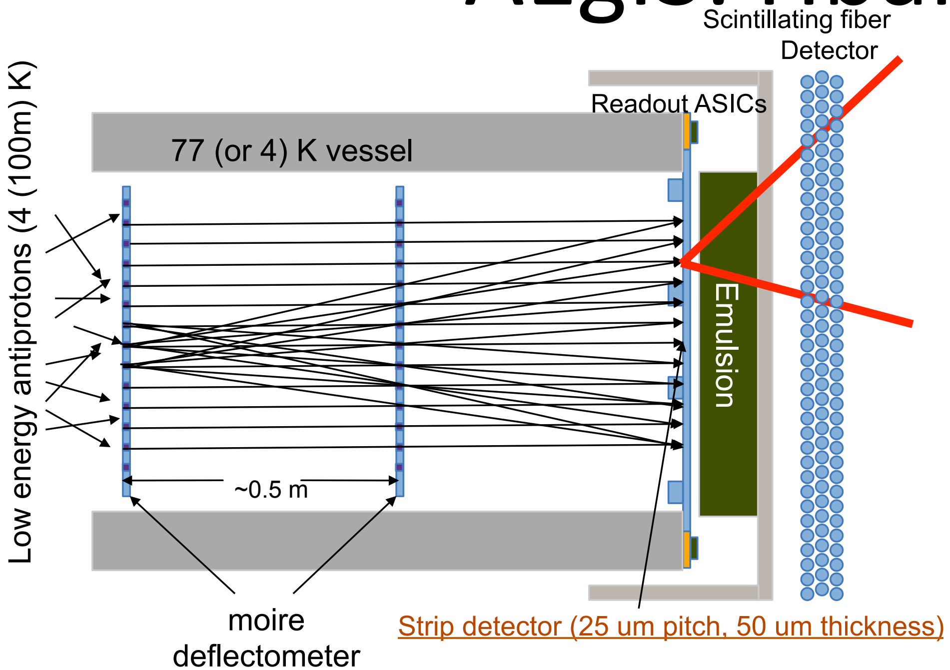


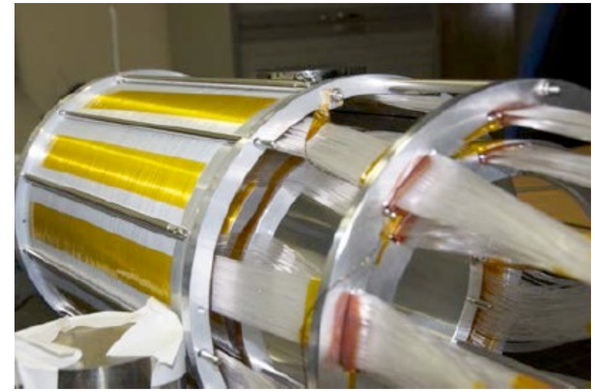






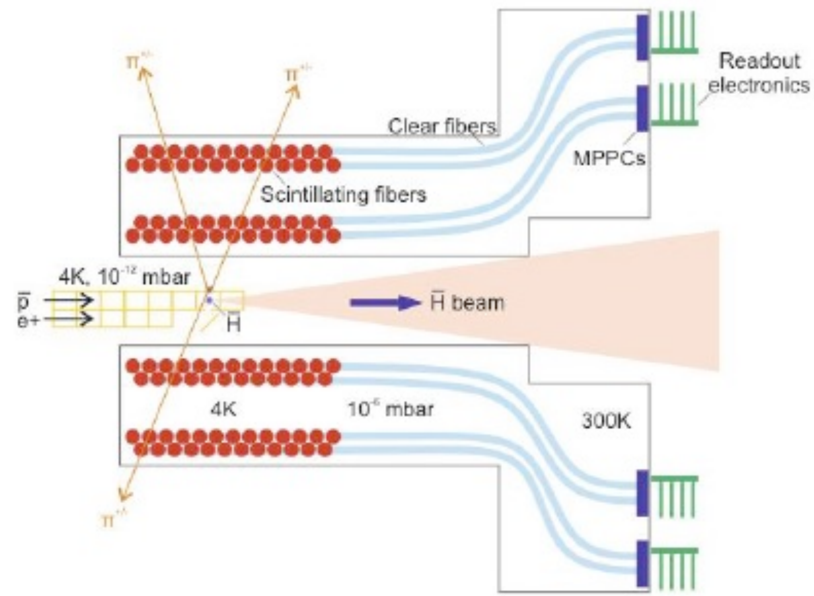
AEgIS: Hbar detector





Fast Annihilation Cryogenic Tracker (FACT)
Particle Tracking resolution ≈ 2 mm

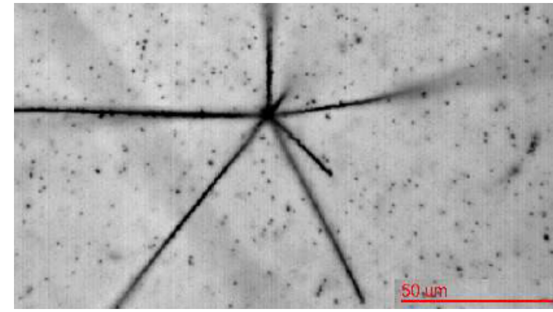
- 4 K operating temperature, in high vacuum @1 T
- power dissipation < 10 W.
- 800 scintillating fibers (4 layers 1mm diameter)
- coupled to clear fibers
- z sensitivity (beam formation): 2.1 mm resolution
- Read out by Multi Pixel Photon Counters (MPPC)
- Operated at 4 K, 1 Tesla, dissipation 10W
- Volume with vacuum separated from the main trap vacuum
- Counts thousands annihilations in about 1ms



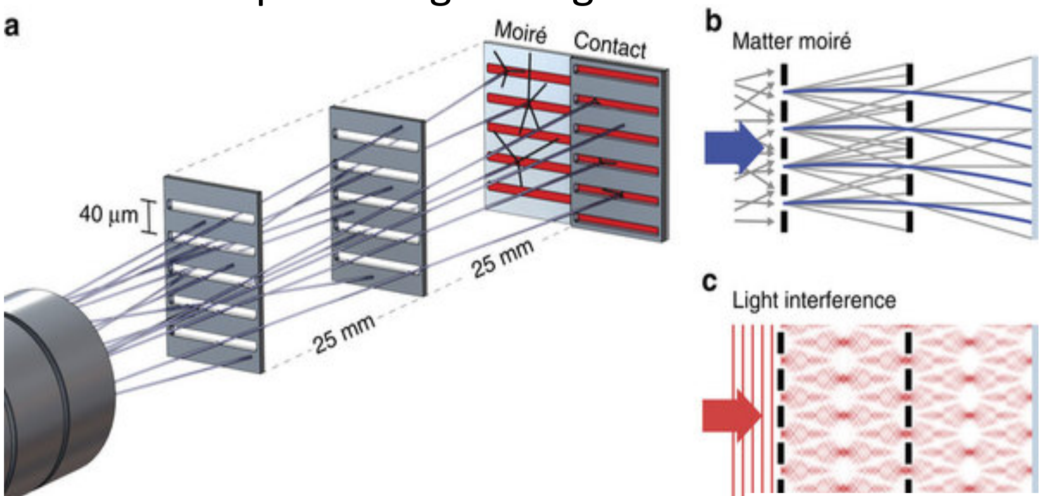
J. Storey et al (AEgIS Coll.) NIMA 732 437 (2013)

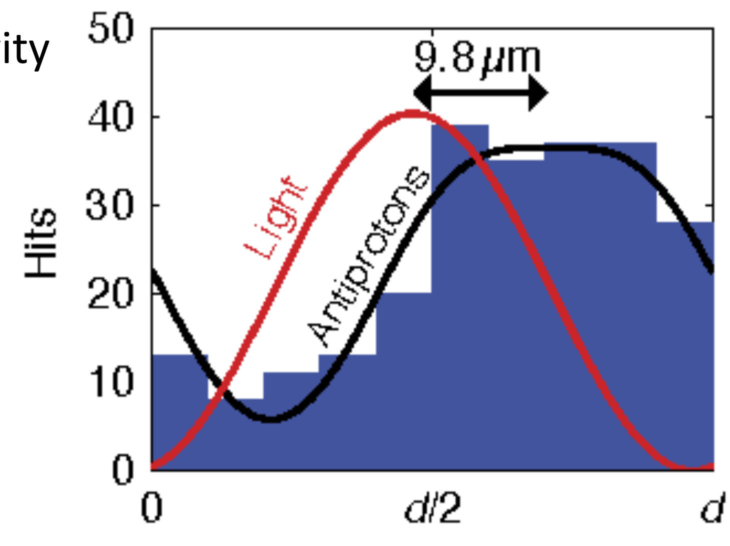
AEgIS: moiré deflectometer

- Direct g measurement with light-pulse atom interferometry would require sub-mK temperatures
- In AEgIS g will be measured with a moiré deflectometer
  - grating period: few tens of μm
  - high resolution position detector: few μm
  - shift of periodic pattern due to vertical forces (gravity)
- Tested with“slow” antiprotons (~ 100 keV)
  - deflectometer prototype on small distances, using emulsions for detecting antiprotons
  - shift of pbar vs light fringes: ~500 aN force sensitivity



J Instr. 9 (2014) C01061





ARTICLE
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014
DOI: 10.1038/ncomms5538

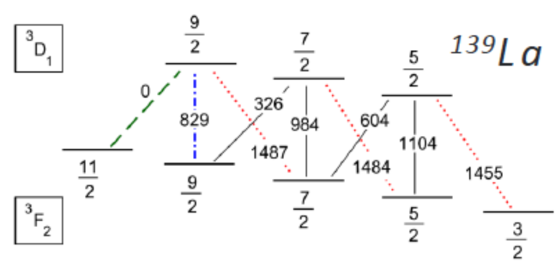
A moiré deflectometer for antimatter

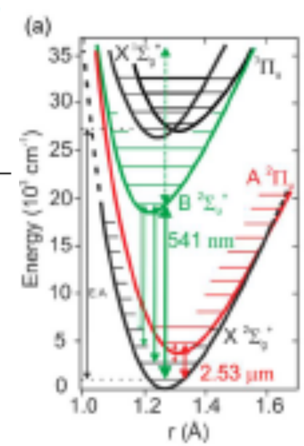
Medium- and long-term perspectives

- Improved antiproton source: ELENA
- Ps generation in transmission targets
- Ultracold anti-hydrogen
  - Antiproton cooling
  - Laser cooling of positronium
  - Laser cooling of anti-hydrogen

Antiproton cooling

- Cold antiprotons to maximize flux
- Final goal: T ~100 mK, 1stphase T ~ 7 K
- Cooling mechanisms
  - Radiative electron cooling
  - Evaporative / adiabatic antiproton cooling
  - Sympathetic resistive cooling of antiprotons with electrons cooled by resistive cooling
- Sympathetic laser cooling with negative ions
  - E. Jordan et al., PRL 115 113001 (2015)]





- Sympathetic cooling with C_2^-
  - P. Yzombard et al., PRL 114 213001 (2015)

Conclusions

- Exciting tests of fundamental physics expected from precision measurements on Hbar
- AEgIS commissioning
  - pbar trapping & cooling achieved
  - e+ trapping achieved
  - Ps produced on nanoporous materials
  - preliminary work on Ps excitation
  - Hbar detector ready
  - moiré deflectometer tested on pbar
  - cold Hbar at reach in the near future