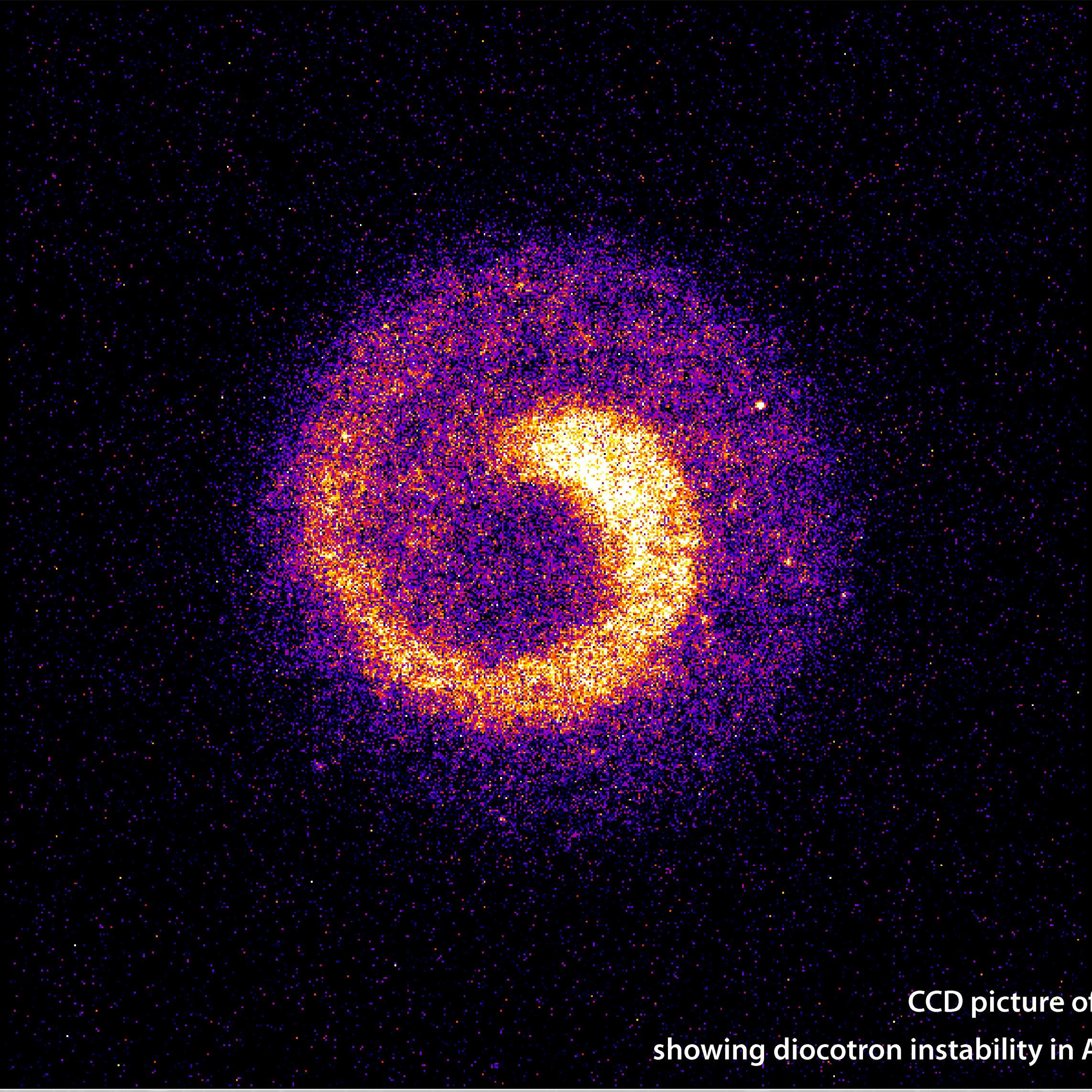
# Advances in Ps manipulation and laser studies in the AEgIS experiment

**Ruggero Caravita, PhD**

*INFN, Genova and CERN, on behalf of the AEgIS collaboration



CCD picture of a cold antiproton plasma showing diocotron instability in AEgIS final trap (Sep 2016)

# Outline

- Intro: gravity on antimatter
- The AEgIS experiment
- Producing Ps in AEgIS
- Laser studies on Ps in AEgIS

# Universality of the free-fall

## Galileo's  Pisa leaning tower thought experiment

*free-fall is independent of a body mass*

$$\begin{cases} \mathbf{F} = m_i \mathbf{a} \\ \mathbf{F_g} = m_g \mathbf{g} \end{cases} \xrightarrow{UFF} m_i = m_g$$

## 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*

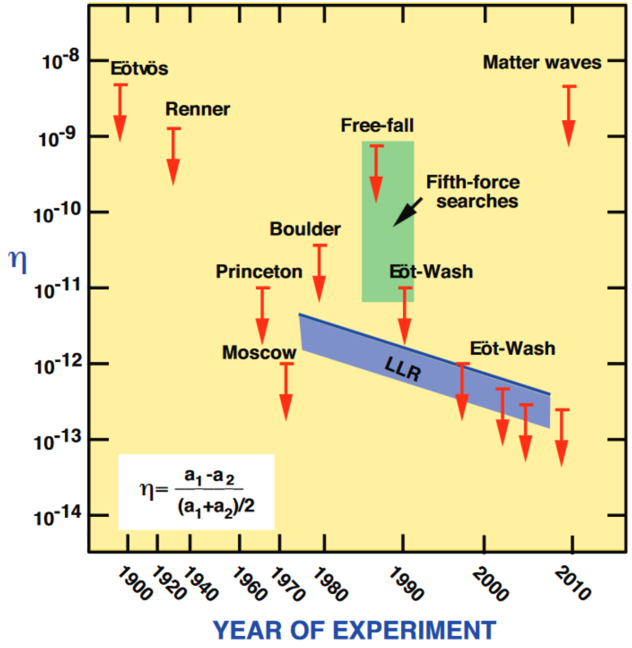
**EP** = **UFF** (universality of the free fall)
+ **LLI** (local Lorentz invariance)
+ **LPI** (local position invariance)

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

# Direct tests of the Equivalence Principle

## With normal matter

- Eötvös-like torsion balances (2 part per $10^{13}$)
- Lunar laser ranging (3 part per $10^{4}$)
- Cold atoms interferometry (3 part per $10^{8}$)

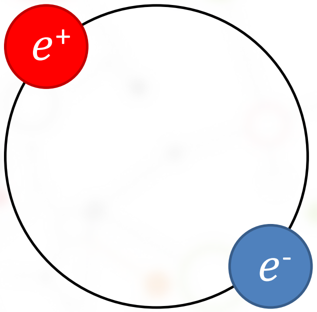



## With antimatter

- Attempts with charged positrons ~ 1967
- Attempts with charged antiprotons ~ 1985
- Some criticized indirect limits ~ 1987 - 2000
- Antihydrogen by ALPHA collab., 2014 (rough, sensitivity ~ 100 g)

**any deviation from the expected acceleration of 9.806 $m/s^2$ would be an indication of new physics**

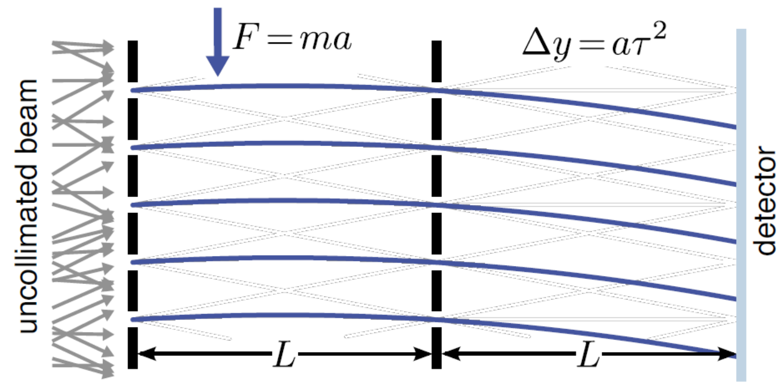
# Measuring gravity on neutral antimatter systems

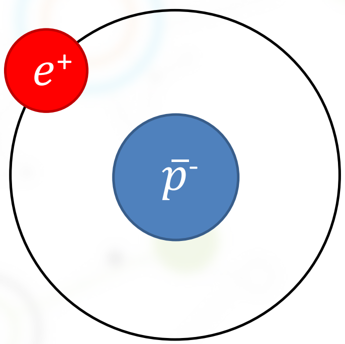



**Positronium** (Ps)

142 ns lifetime

from $\beta^+$ sources




**Antihydrogen** ($\overline{\mathrm{H}}$)

stable

only @ CERN A.D.

**Moiré deflectometer/Talbot-Lau interferometer**

- $g$ from $\Delta y = g\tau^2$
- reference with light
- requires **pulsed** production scheme
- 1% of $g$ with 1000 detected $\overline{\mathrm{H}}$ at 0.1 K


Aghion S. et al (AEgIS collaboration), *Nature communications (2013)* DOI: 10.1038/ncomms5538
Aghion S. et al (AEgIS collaboration), *JINST* 8 (2013) P08013

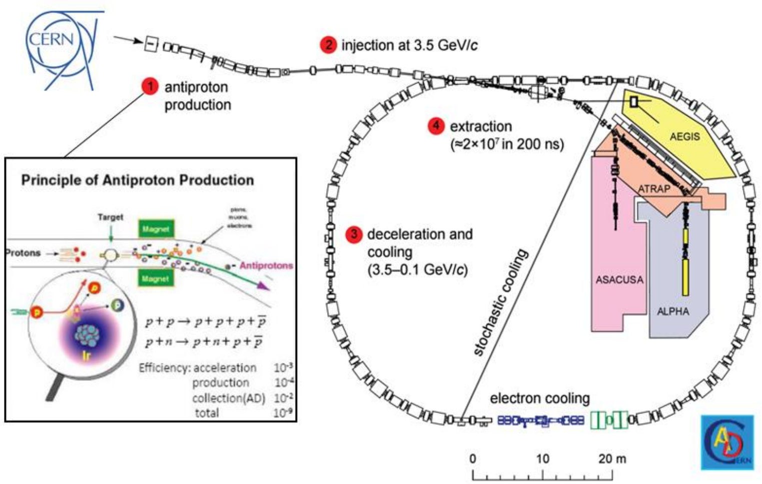
# The AEgIS experiment

**A**ntihydrogen **E**xperiment:

**G**ravity, **I**nterferometry, **S**pectroscopy

- CERN-based collaboration of ~ 80 collaborators and 18 institutes
- Aims to perform the first gravity measurement on antihydrogen


AEGIS zone at the AD




- Located inside the Antiproton Decelerator
- Working with antiprotons since 2012

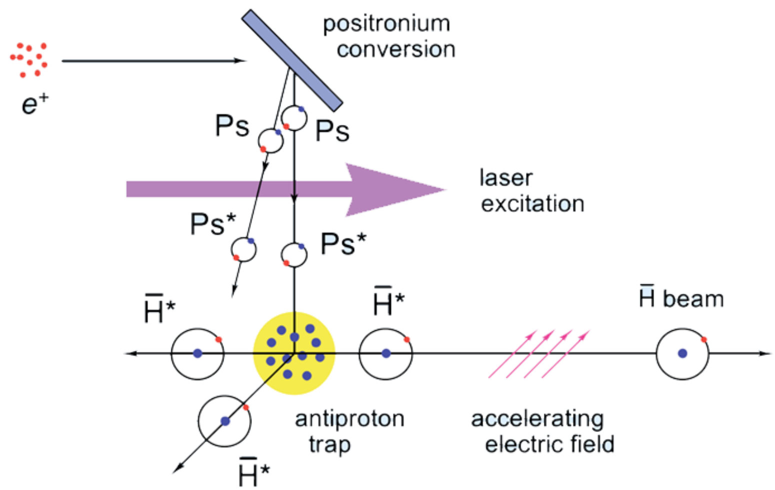
# AEgIS in extreme synthesis

**Pulsed antihydrogen sinthesys**

- Charge-exchange between $\bar{\mathrm{p}}$ and Ps
- $\bar{\mathrm{H}}$ temperature fixed to the $\bar{\mathrm{p}}$ temperature
- Cross-section $\sigma \propto n_{Ps}^4$

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

$$\sigma \simeq 10^{-10}\ \mathrm{cm}^2 \qquad n_{Ps} = 18$$

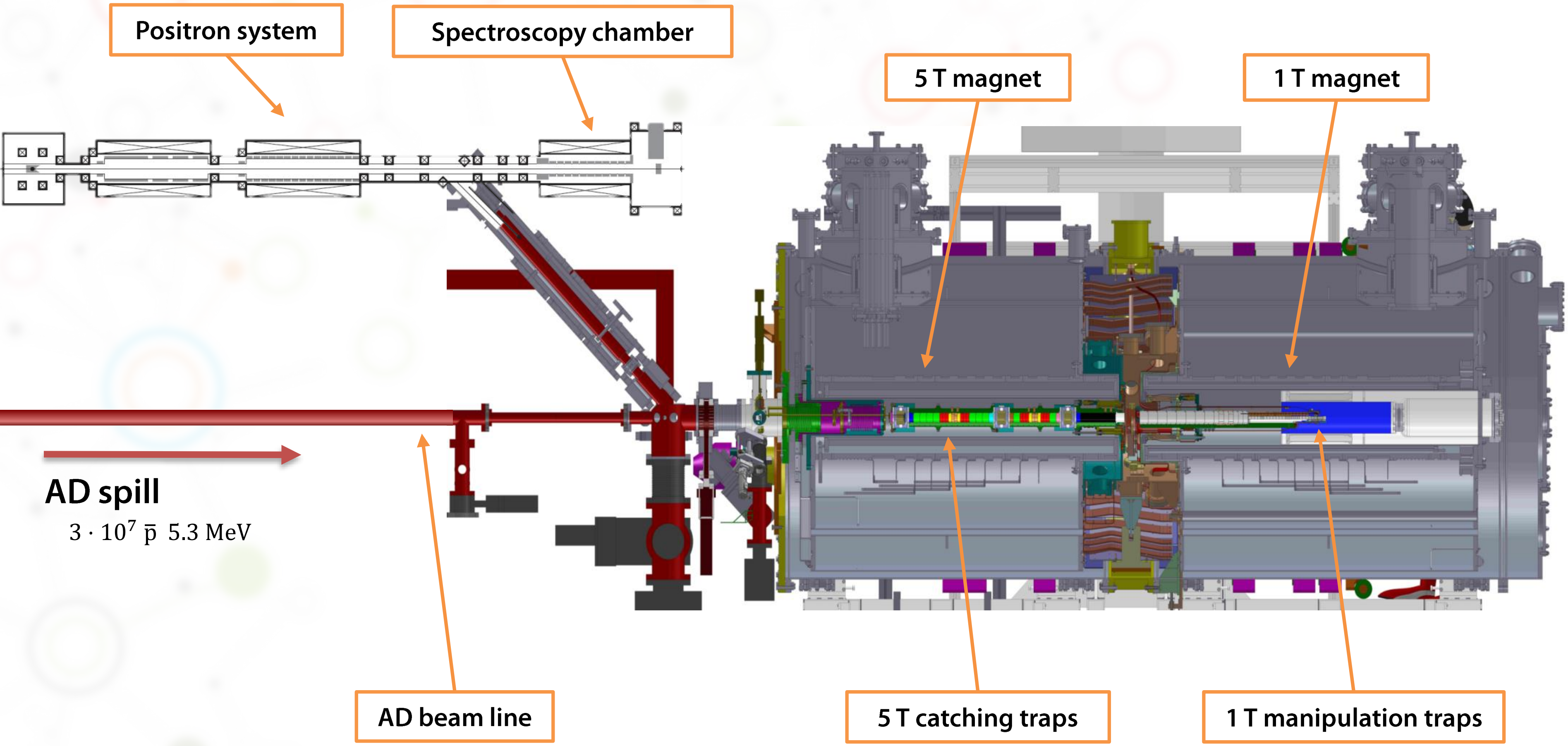



**Experimental scheme**

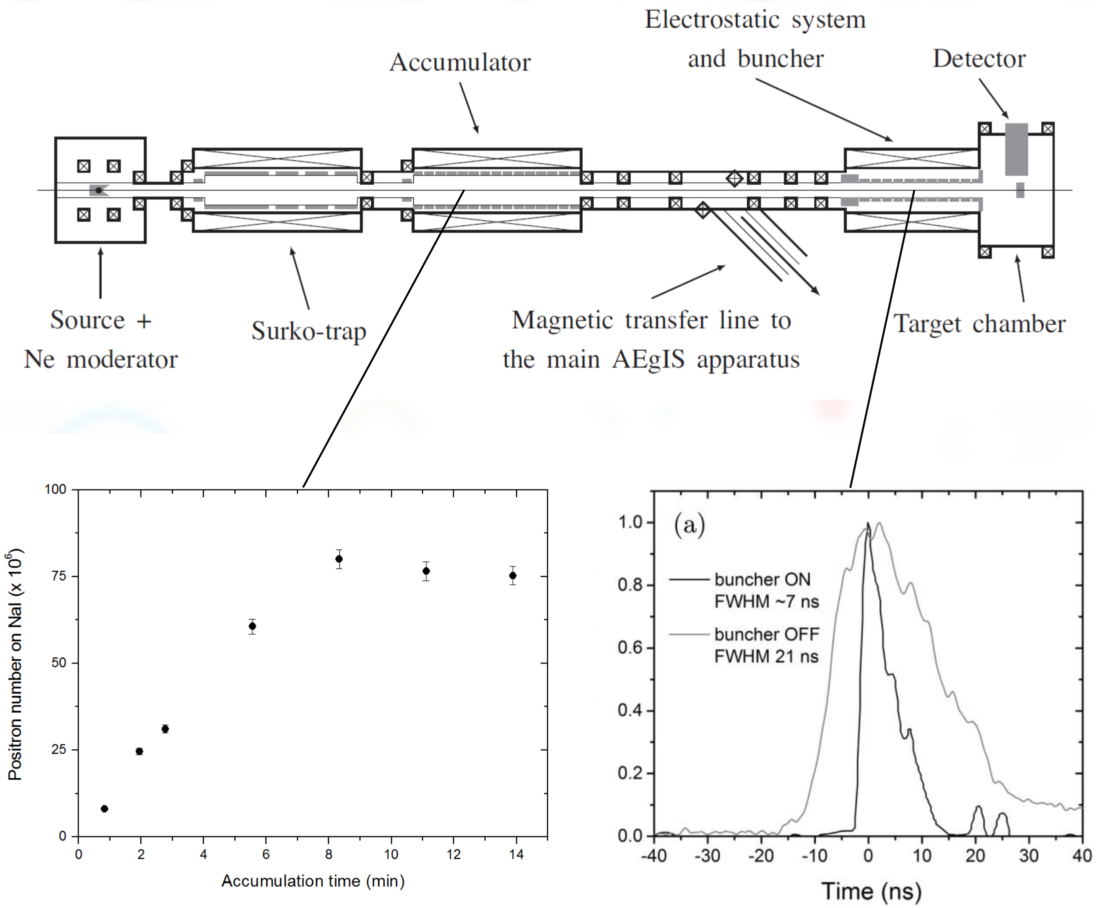
1) Preparation of cold antiprotons
2) Positrons implantation in converter
3) Formation of positronium
4) Laser Rydberg excitation of positronium
5) Charge-exchange with antiprotons


Kellerbauer A. et al (AEgIS collaboration), *NIM B* 266 (2008) 351-356
Krasnicky D., Caravita R., Canali C., Testera G., *PRA* 94 (2016) 022714

# The AEgIS experimental complex



# Positrons preparation in AEgIS




## AEgIS positron source

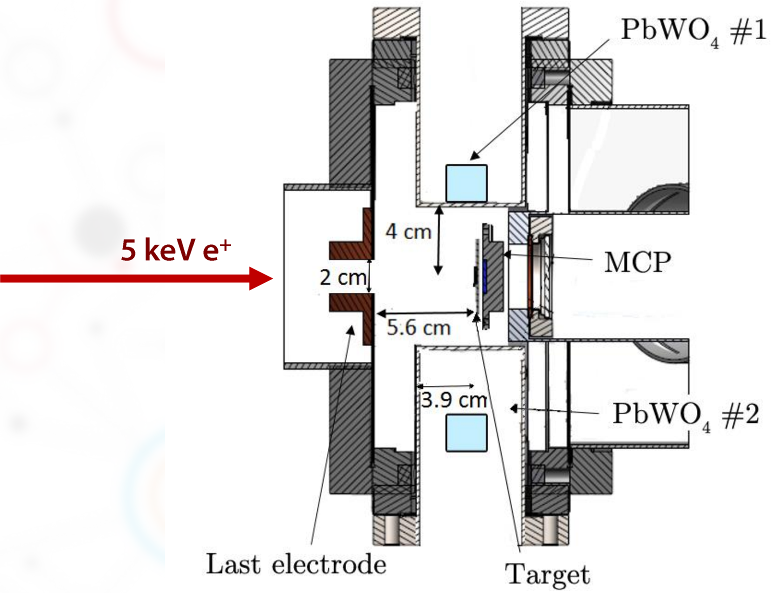
- $^{22}$Na radioactive source with solid Ne energy moderator
- Buffer-gas cooling and accumulation
- Delivers spills of ~10 million $e^+$ every 2 min

## Transport to Ps chamber

- Magnetic/electrostatic transfer line for field free
- 24 electrodes buncher for keV acceleration and bunching
- < 8 ns time spread

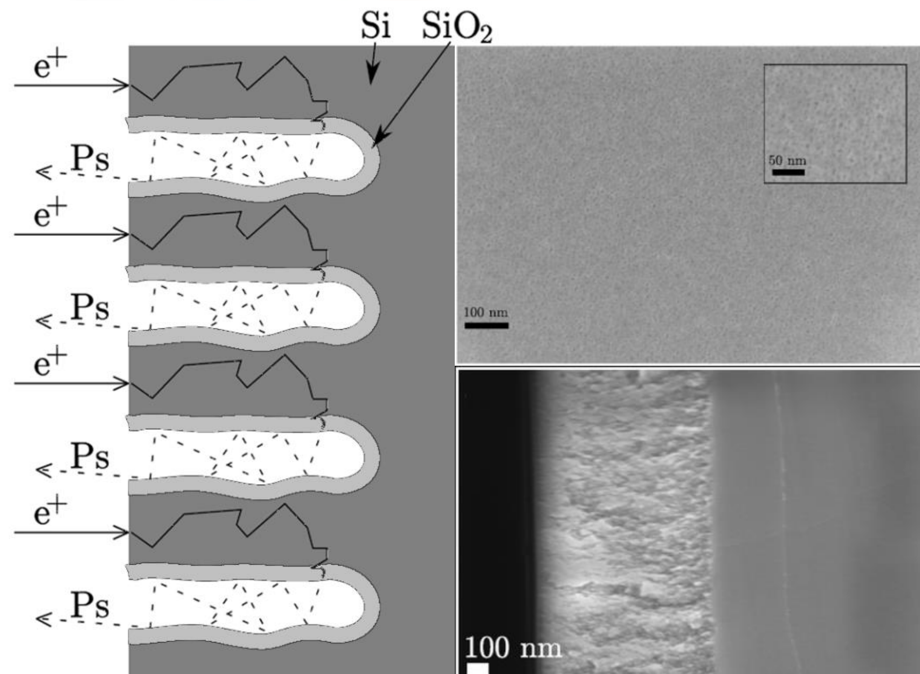
Aghion S. et al (AEgIS collaboration), *NIM B 362 (2015) 86-92*

# Positronium experimental chamber




## Positronium nanoporous silica converter

- $e^+$ implanted in the Si bulk @ keV
- Ps forms on the nanopores surface
- p-Ps annihilates, o-Ps cools by collisions
- o-Ps emitted in vacuum (35% overall eff.)




## Experimental chamber

- Room temperature
- Two $PbWO_4$ + Ham. R11265 detectors
- Side optical access for laser experiments

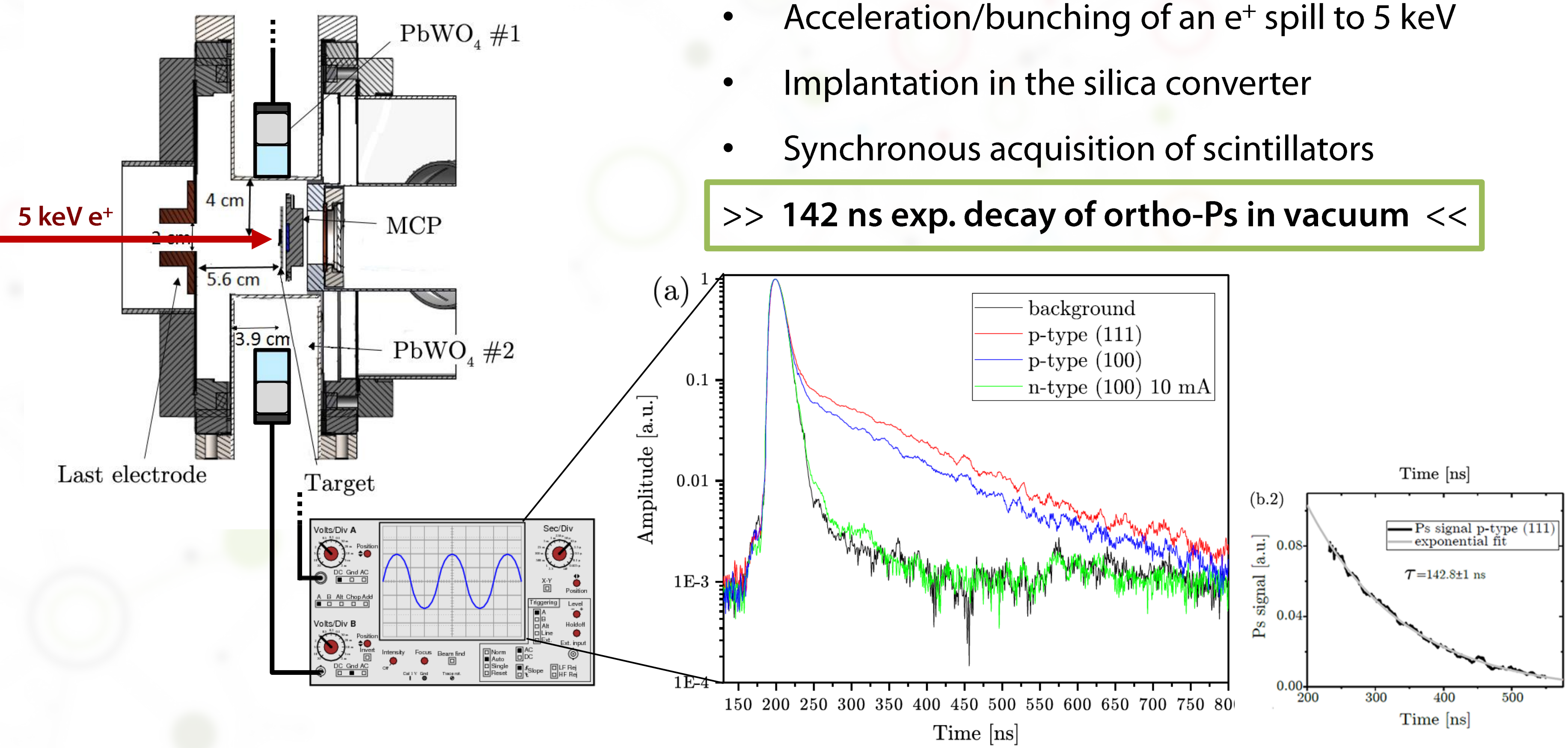
Mariazzi S. Bettotti P. Brusa R. S., *PRL 104 (2010) 243401*
Aghion S. et al (AEgIS collaboration), *NIM B 362 (2015) 86-92* 1

# Positronium formation and detection

## Experimental methodology

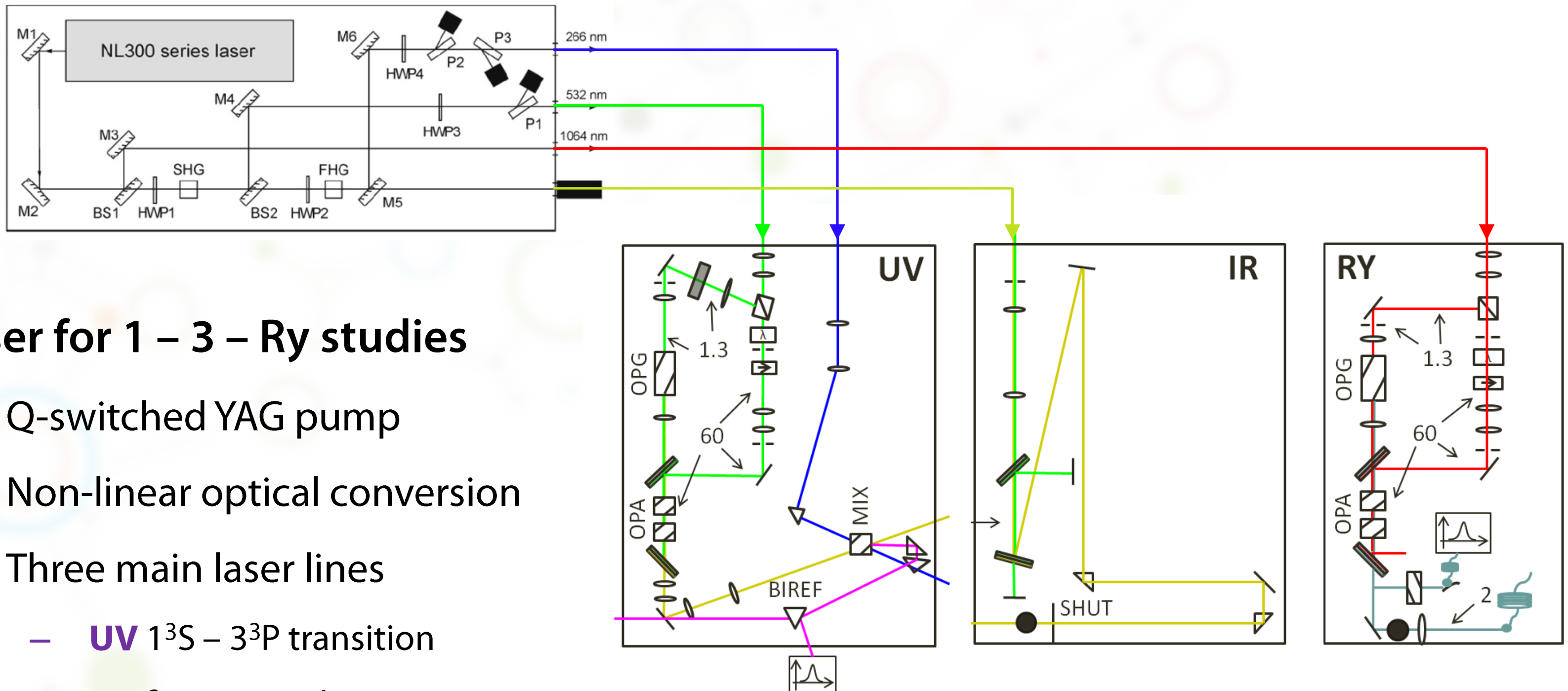
- Acceleration/bunching of an $e^+$ spill to 5 keV
- Implantation in the silica converter
- Synchronous acquisition of scintillators

**>> 142 ns exp. decay of ortho-Ps in vacuum <<**




Aghion S. et al (AEgIS collaboration), *NIM B 362 (2015) 86-92*

# Laser system for positronium studies




## Laser for 1 – 3 – Ry studies

- Q-switched YAG pump
- Non-linear optical conversion
- Three main laser lines
  - **UV** $1^3S – 3^3P$ transition
  - **IR** $3^3P$ – ionized
  - **RY** $3^3P$ – 15/23 transitions (tunable)

205 nm

1064 nm

1650-1720 nm


Cialdi S. Boscolo I. Castelli F. Villa F. Ferrari G. and Giammarchi M. G., *NIM B 269 (2011) 1527-1533*
Castelli F. Boscolo I. Cialdi S. Giammarchi M. D. and Comparat D., *PRA 78 (2008) 052512*

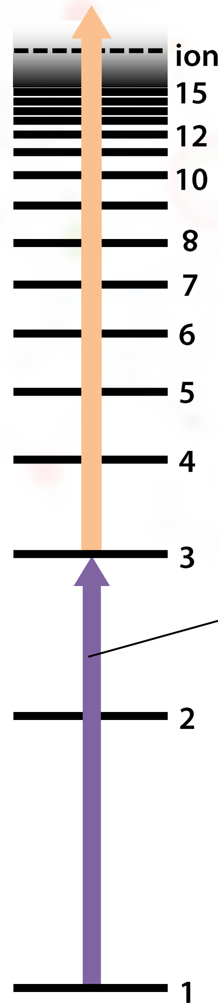
# Spectroscopy of Ps $1^3S - 3^3P$ transition

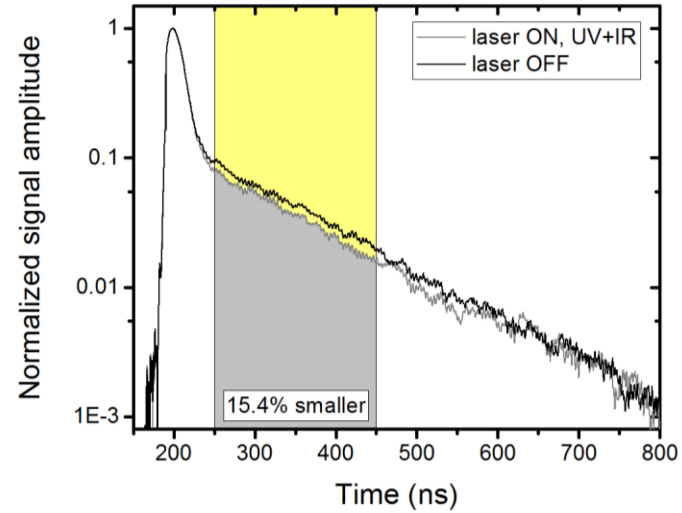
## Methodology

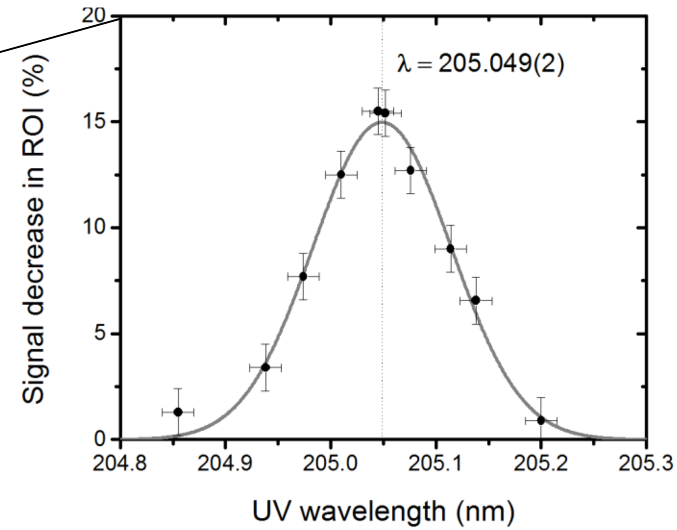
- Excite the $1^3S - 3^3P$ transition (**UV**)
- Photoionize $3^3P$ atoms (**IR**)
- Signal reduction after excitation

## Results

- First spectroscopy of Ps n = 3
- Doppler temperature ~1200K
- 16 % max. excitation efficiency
  - 20 % Doppler coverage
  - 80 % geometrical efficiency




Aghion S. et al (AEgIS collaboration), *Physical Review A 94 (2016) 012507*

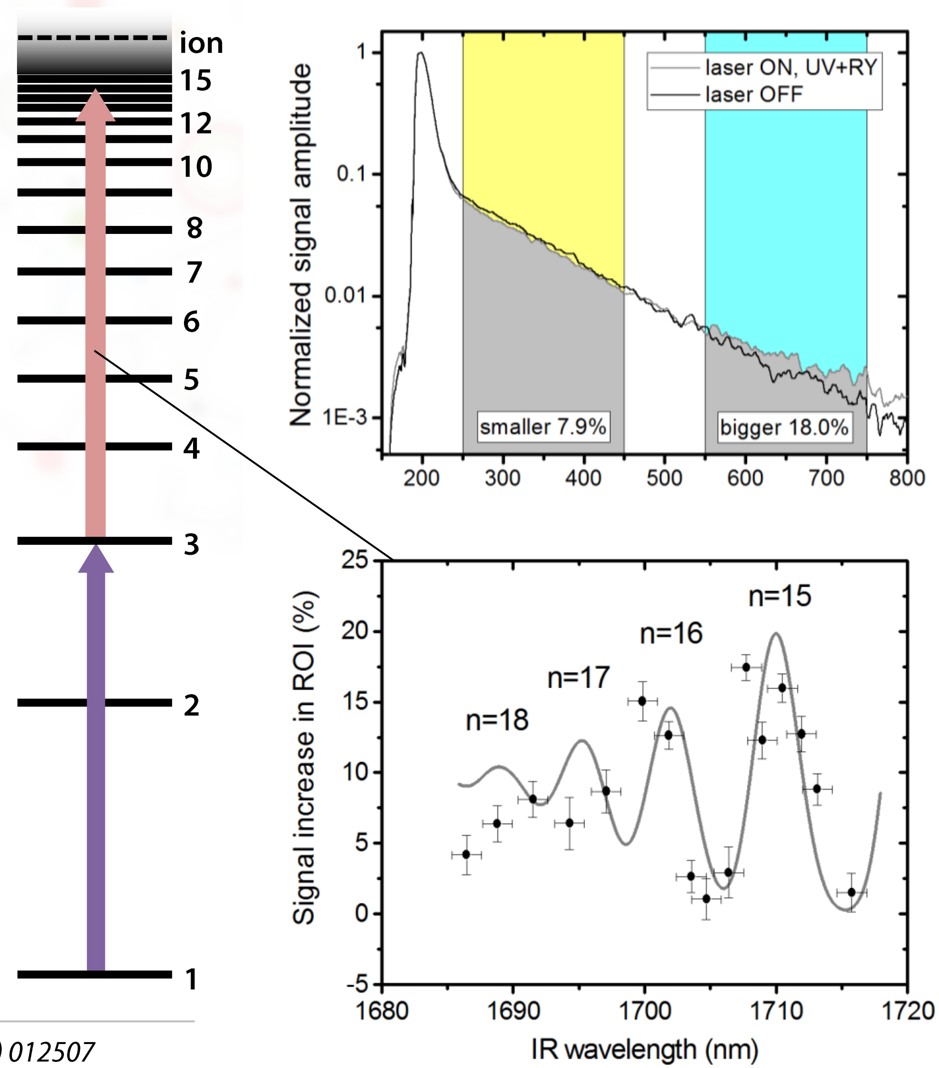
# Spectroscopy of Ps $3^3P$ – 15/18 transition

## Methodology

- Excite the $1^3S$ – $3^3P$ transition (**UV**)
- Excite the $3^3P$ – Ryd transition (**RY**)
- Signal increase at later times

## Results

- First spectroscopy of Ps Rydberg levels using n = 3 as intermediate
- Milestone for AEgIS - confirms the proof-of-concept




Aghion S. et al (AEgIS collaboration), *Physical Review A 94 (2016) 012507*

# Evidence of long-lived metastable $2^3S$ sublevel

## Ps $2^3S$ metastable sublevel

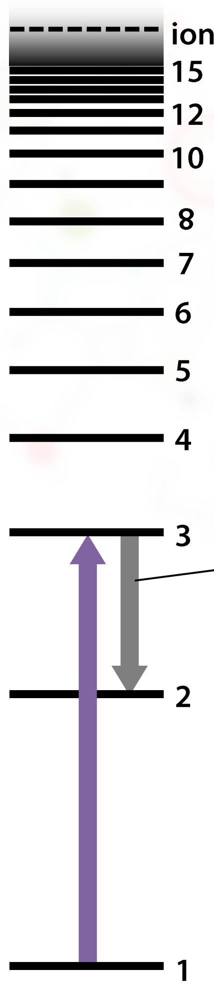
- Cannot decay to $1^3S$ (dipole sel. rules)
- Lifetime x8 with respect to o-Ps
- Interesting for atom interferometry (gravity) on Ps

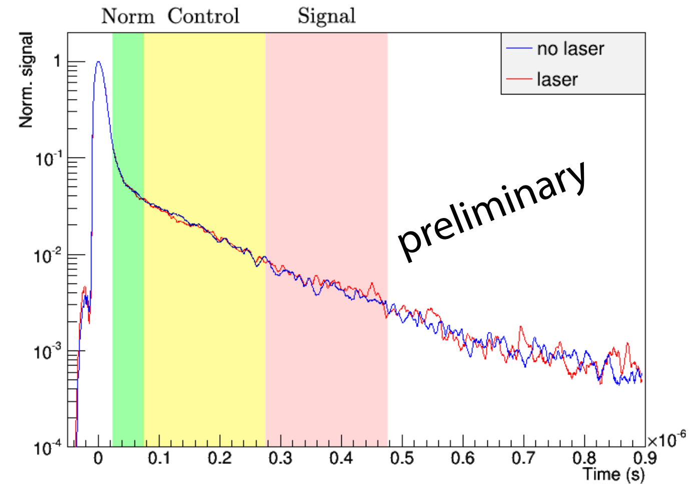
## Methodology

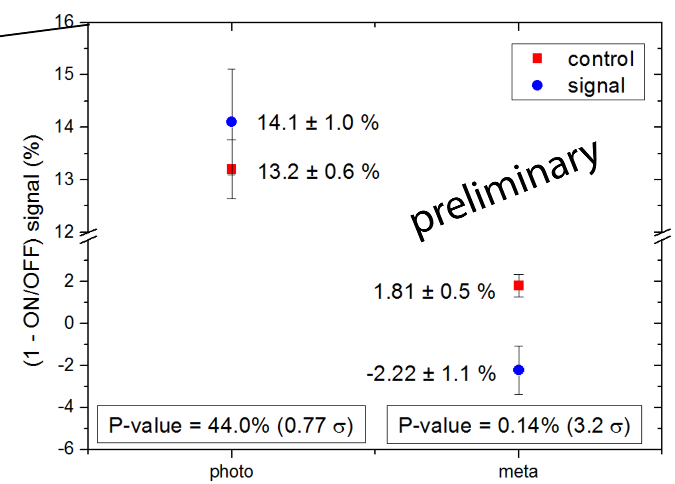
- Excite the $1^3S$ – $3^3P$ transition (**UV**)
- Spontaneous decay to $2^3S$ (10 % eff.)
- Signal increase at later times

## Results (work in progress)

- Observed a 3.2 σ excess
- Compatible with 0.6 - 1% production



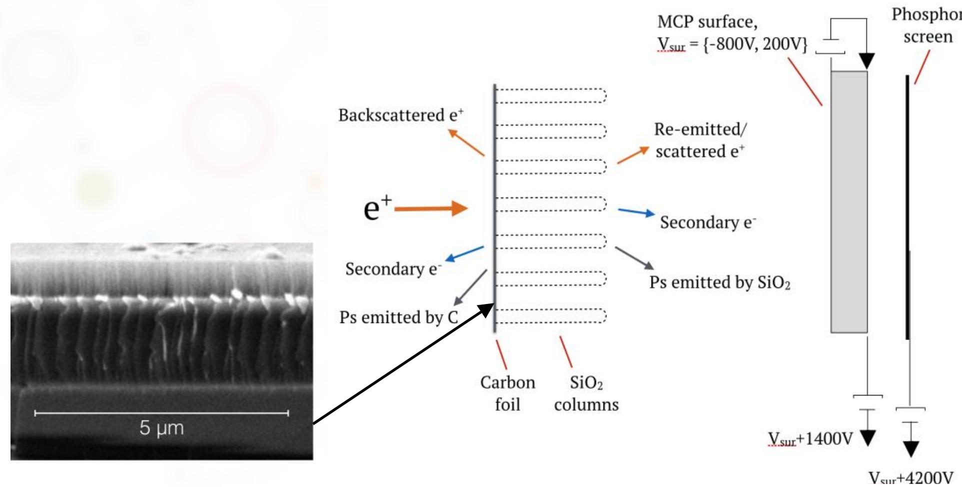




Oberthaler, M. K., *Antimatter inteferometry with Ps*, NIM B 192 (2002) 129

# Ps formation from transmission targets

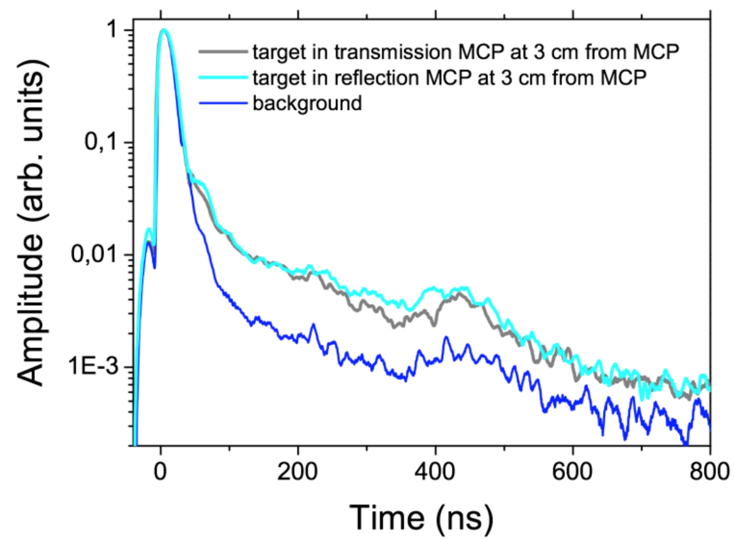
## Methodology

- Nanoporous $SiO_2$ evaporated on 20 nm carbon foil
- o-Ps tail on $PbWO_4$ scintillators
- Forward $e^+$ and $e^-$ on MCP




## Preliminary results

- Emission of o-Ps observed both in transmission and reflection
- ~ 10% o-Ps formed in transmission
- ~ 10% of positron cross the target and are forward emitted
- ~ 16 % of secondary electrons are forward emitted




Aghion S. et al (AEgIS collaboration), *accepted from NIM B (2017)*

# Summary

- AEgIS – measuring gravity on antihydrogen
- Positronium experiments in AEgIS
  - Spectroscopy of $1^3S$ – $3^3P$ transition
  - Spectroscopy of $3^3P$ – 15/18 transition
  - Observation of $2^3S$ metastable state
  - Development of transmission targets

# Future trends

- Positronium spectroscopy in AEgIS 1T field
- First pulsed antihydrogen production
- Efficient $2^3S$ positronium production ?