A Metastable Positronium Inertial Sensor (AMPIS)

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and colleagues of the AEgIS collaboration

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Fellini
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H2020 MSCA COFUND G.A. 754496

Who I am

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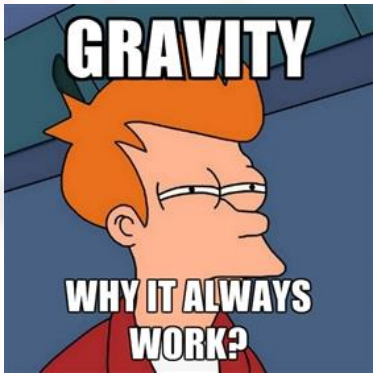
Education and research experience

- Bachelor degree in Physics
  University of Milano (Italy)
  massively parallel simulation of near-field speckle fields
- Master degree in Physics
  University of Milano (Italy)
  Laser apparatus for exciting positronium in the AEgIS experiment
- Ph.D. in Physics
  University of Genova (Italy) and CERN
  Towards measuring gravity on neutral antimatter
- CERN Research Fellow
  Positronium manipulations for pulsed antihydrogen production

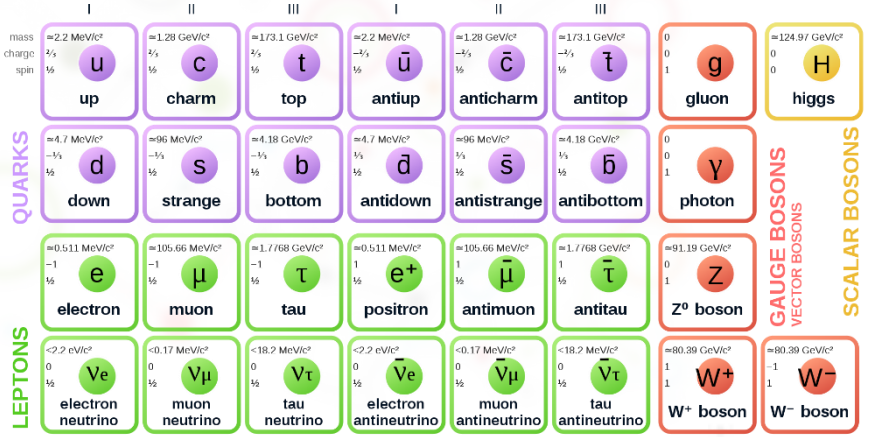
Main interests

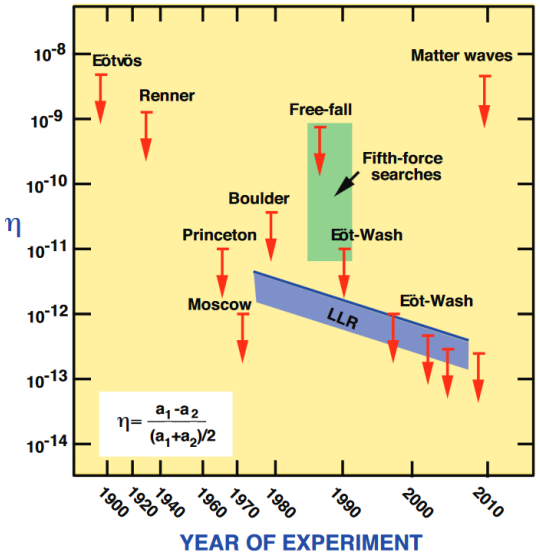
- Experimental antimatter physics
- Computational physics and computer science
- Applied laser physics
- Gravitation
- Atomic physics
- Complex systems

Gravity with antimatter – scientific case



Measuring the gravitational coupling of Standard Model (anti-) particles



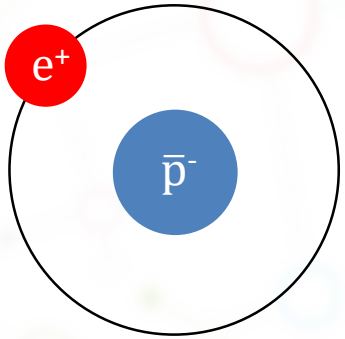


Searches for violations of the Universality of the Free-Fall

- Very accurate UFF tests with matter
- Attempts with charged positrons ~ 1967
- Attempts with charged antiprotons ~ 1985
- Some indirect limits ~ 1987 - 2000
- Limit on antihydrogen by ALPHA (2014)

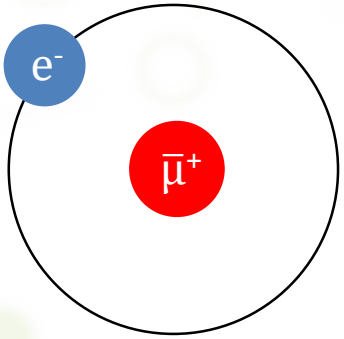
A deviation from *g* would be an indication of new physics

Gravity on antimatter – candidate neutral systems



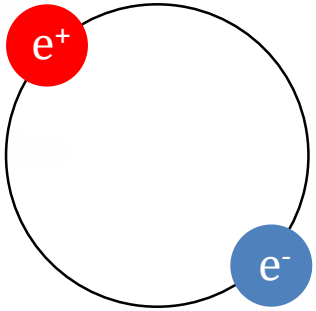
Antihydrogen ($\bar{H}$)

- 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 with accelerators (PSI)



Positronium (Ps)

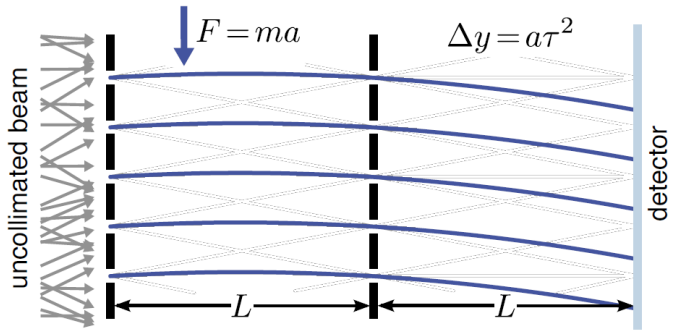
- short lifetime only in GS (142 ns)
- 50% of mass is antimatter
- first generation elementary system
- produced in large numbers table-top

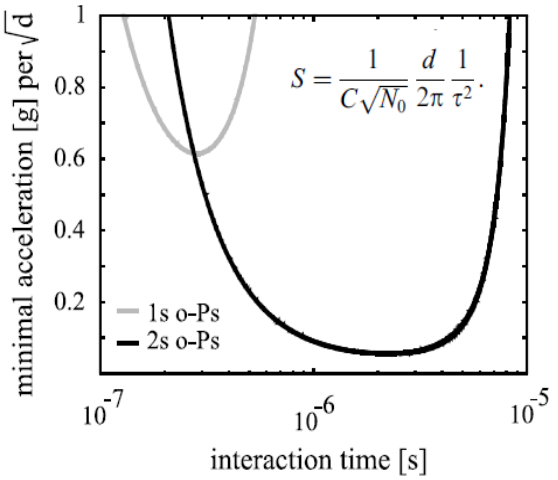
2^3S Ps as a tool for atom interferometry with Ps

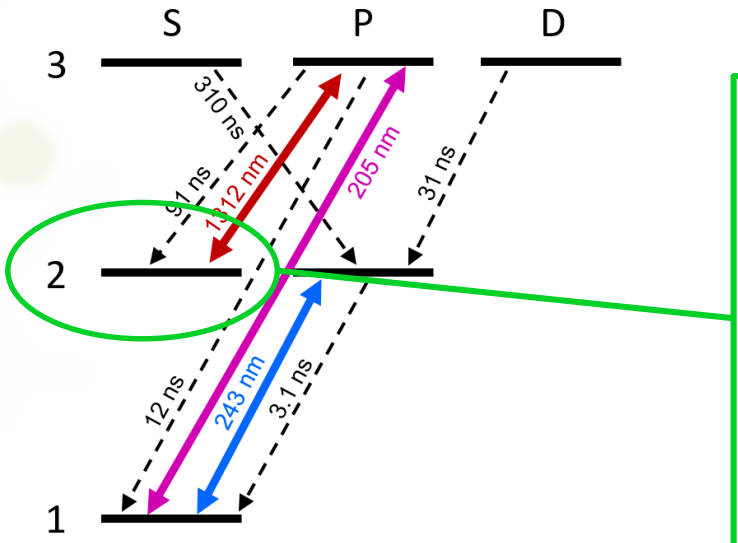
Nuclear Instruments and Methods in Physics Research B 192 (2002) 129–134

Anti-matter wave interferometry with positronium

M.K. Oberthaler







2^3S Ps state

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

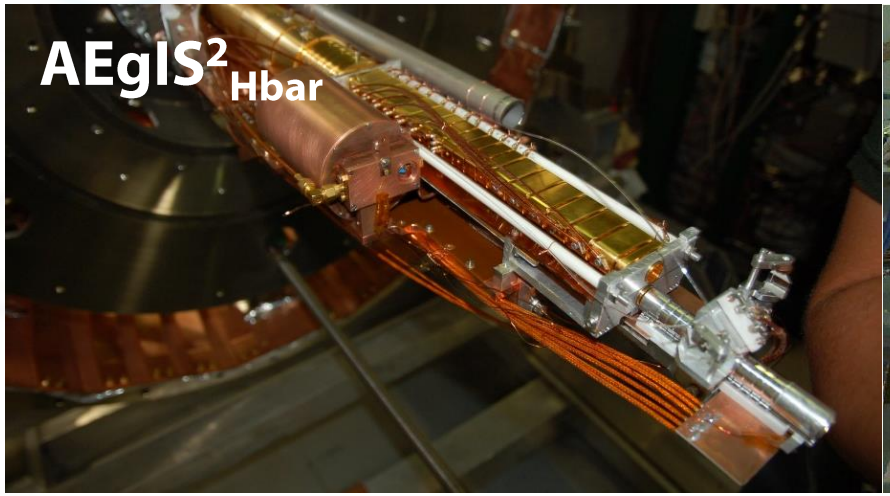
➢ Need a source with sufficient flux (> 1 atom detected/shot) and collimation (< 1 mrad)

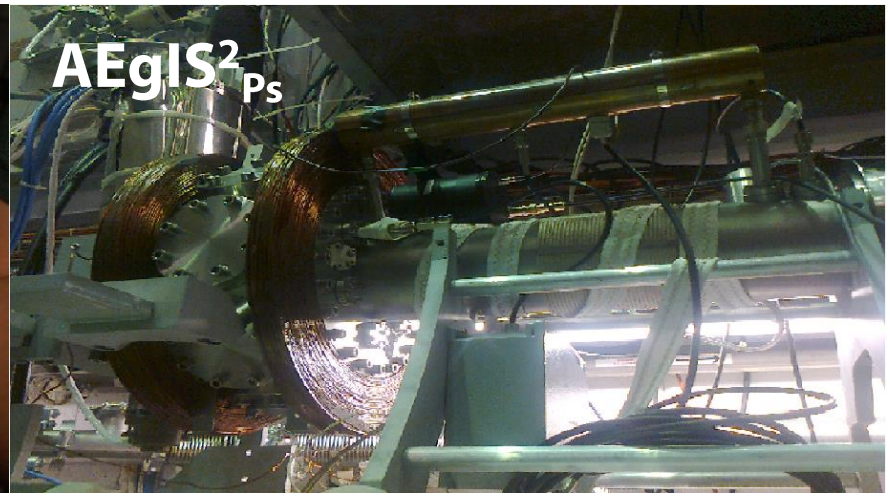
Research context: the AEgIS collaboration

AEgIS

(**A**ntimatter **E**xperiment: **G**ravity, **I**nterferometry, **S**pectroscopy)

- CERN-based collaboration
- Aims to perform the first direct free-fall measurement of gravity on antimatter
- Recently completed phase1: establishing pulsed Hbar production
- Now towards phase2: first proof-of-concept gravity on antimatter





Physics Coordinator of AEgIS phase2 since October, 2019

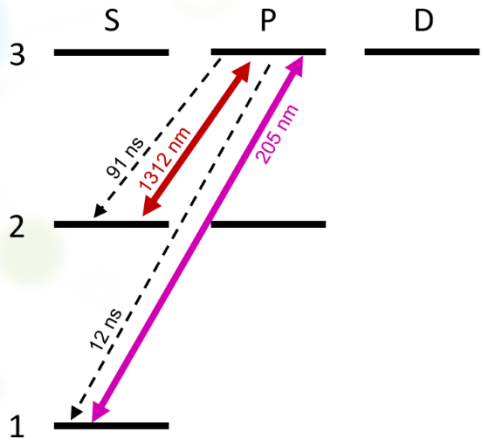
Producing a pulsed source of 2^3S Ps

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)

Novel method: 1^3S-3^3P single-photon laser excitation

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

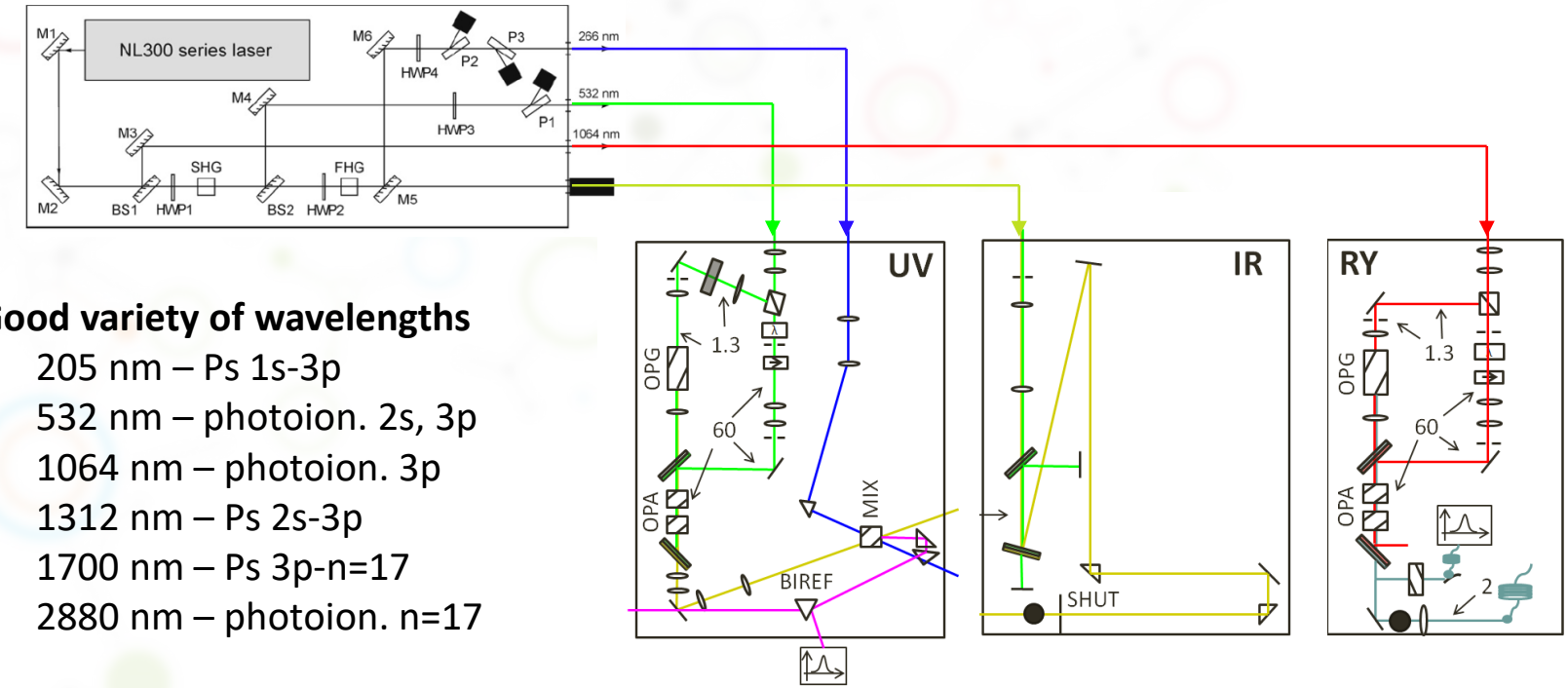


- Simple method, only one laser beam
- No relevant multi-photon ionization
- Provides naturally longitudinal (TOF) and transverse (Doppler) velocity selection of the atoms

➢ Need 205nm deep UV pulsed laser system
➢ Optionally 1312nm laser for stimulated 3^3P-2^3S decay

AEgIS pulsed laser system

EKSPLA pulsed YAG



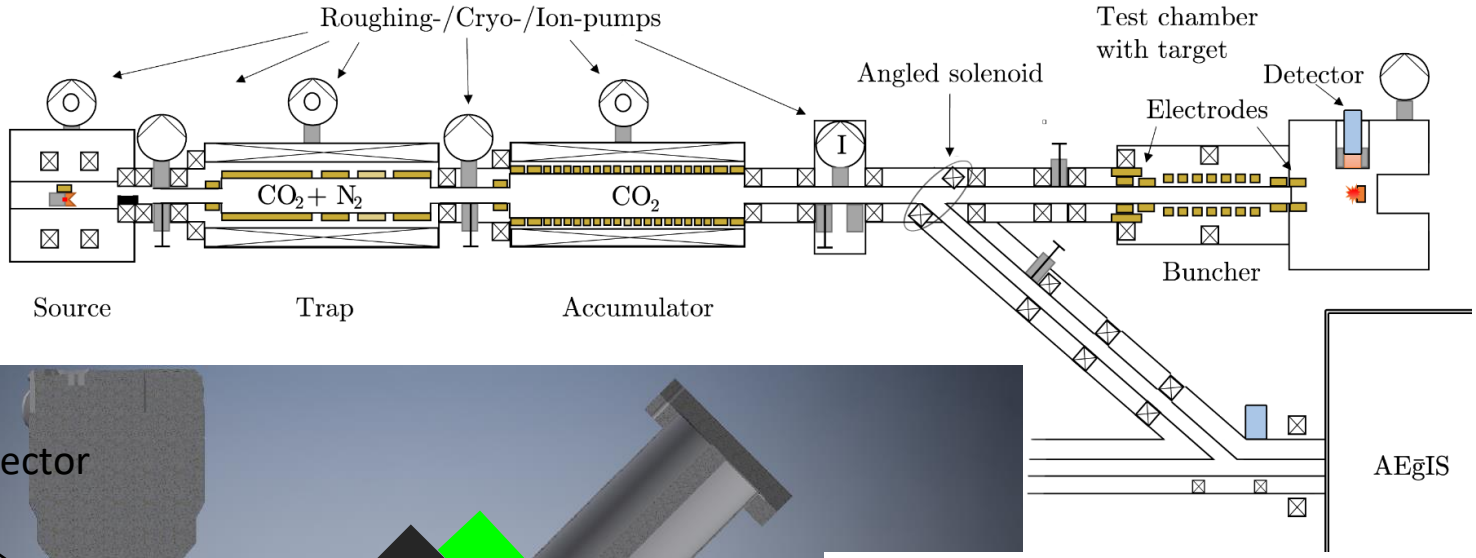
Good variety of wavelengths

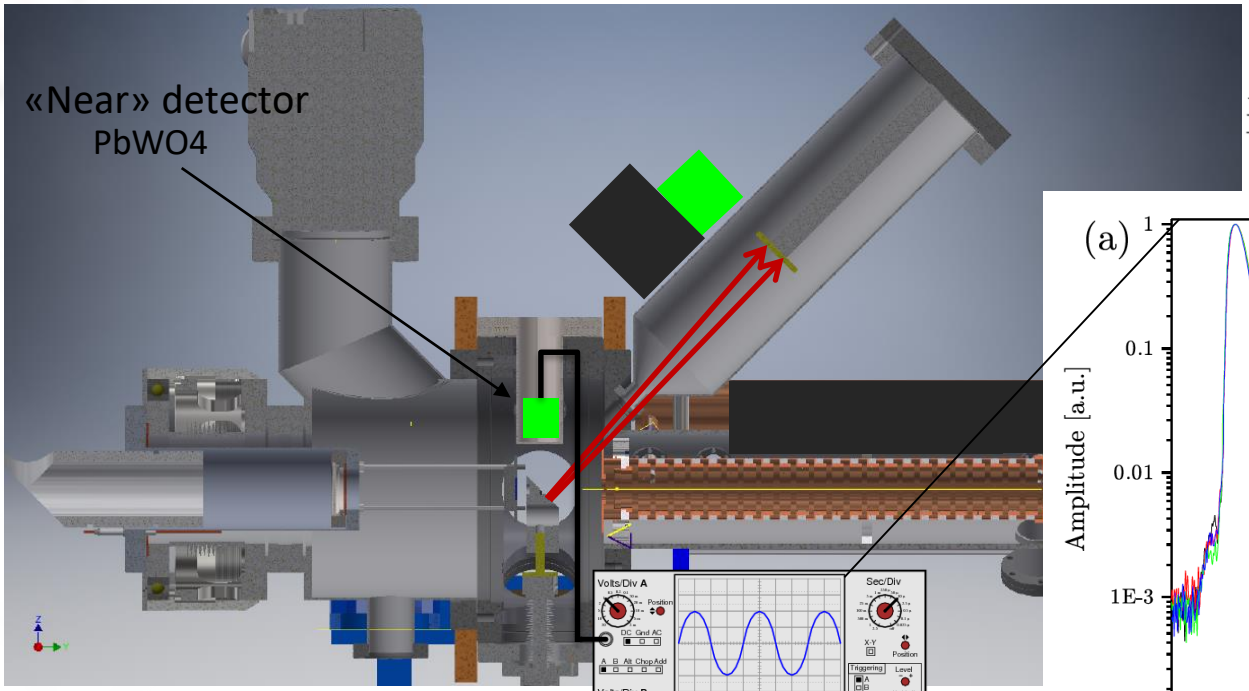
- 205 nm – Ps 1s-3p
- 532 nm – photoion. 2s, 3p
- 1064 nm – photoion. 3p
- 1312 nm – Ps 2s-3p
- 1700 nm – Ps 3p-n=17
- 2880 nm – photoion. n=17

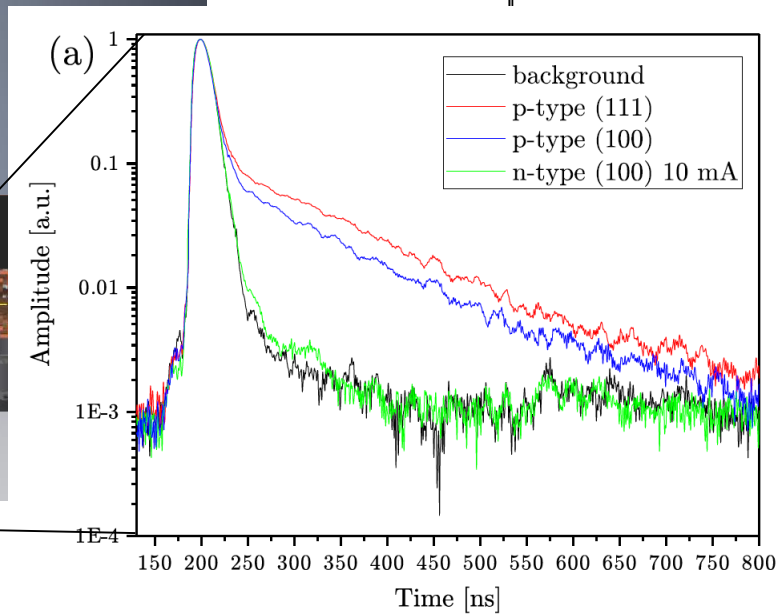
$$
\begin{aligned}
532\,\mathrm{nm}_{(o)} &\longrightarrow 894\,\mathrm{nm}_{(o)} + 1314\,\mathrm{nm}_{(o)} \quad \text{OPG, type II} \\
532\,\mathrm{nm}_{(e)} &\longrightarrow 894\,\mathrm{nm}_{(o)} + 1314\,\mathrm{nm}_{(o)} \quad \text{OPA, type I} \\
894\,\mathrm{nm}_{(o)} + 266\,\mathrm{nm}_{(o)} &\longrightarrow 205\,\mathrm{nm}_{(e)} \quad \text{SFG, type II}\ .
\end{aligned}
$$

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*

AEgIS pulsed positronium beam



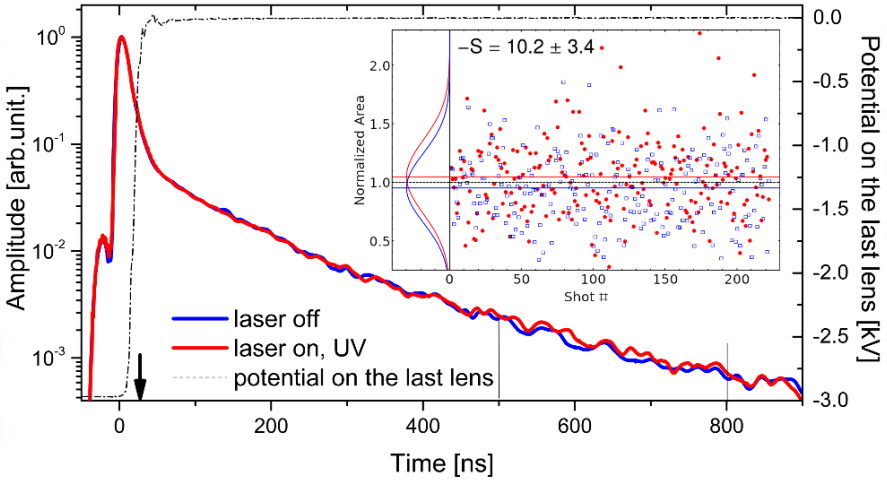


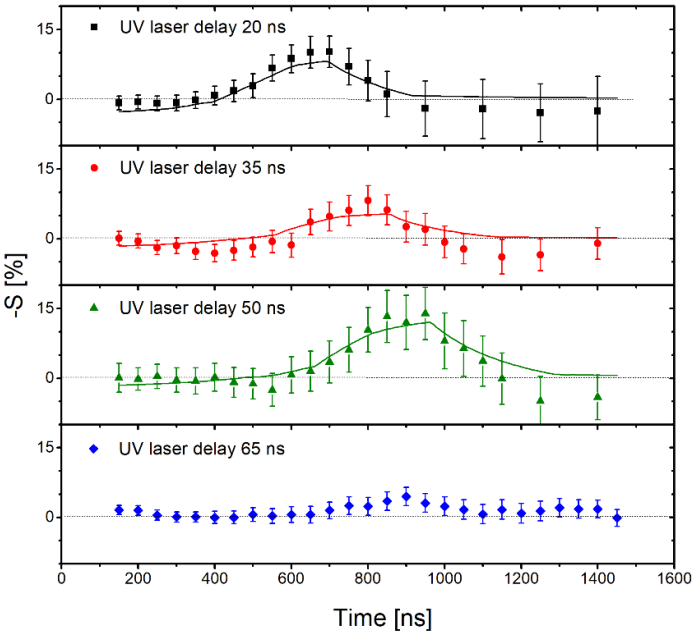


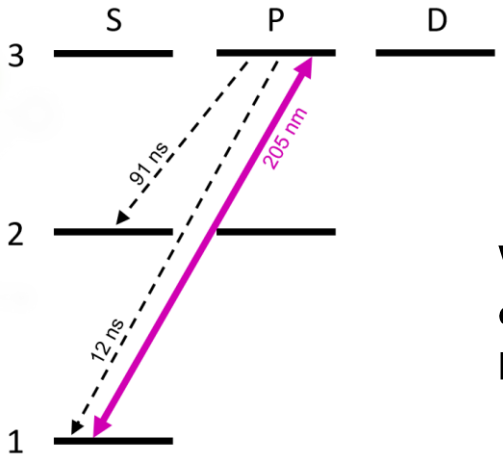
A pulsed source of 2^3S Ps with tunable velocity

PHYSICAL REVIEW A 99, 033405 (2019)

Velocity-selected production of 2^3S metastable positronium

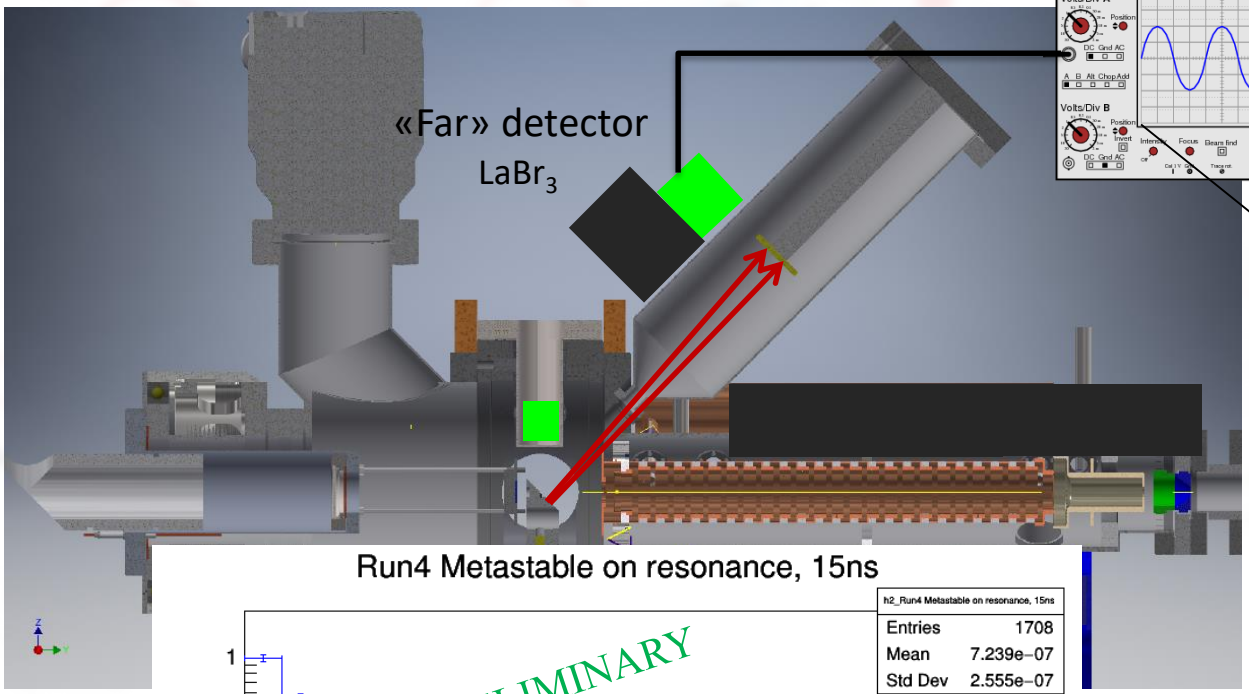


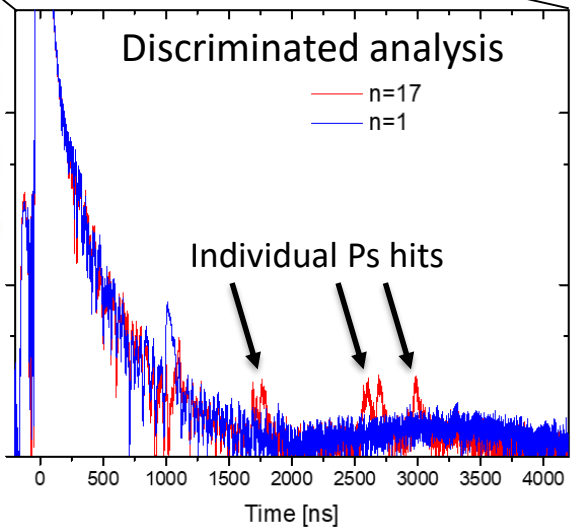


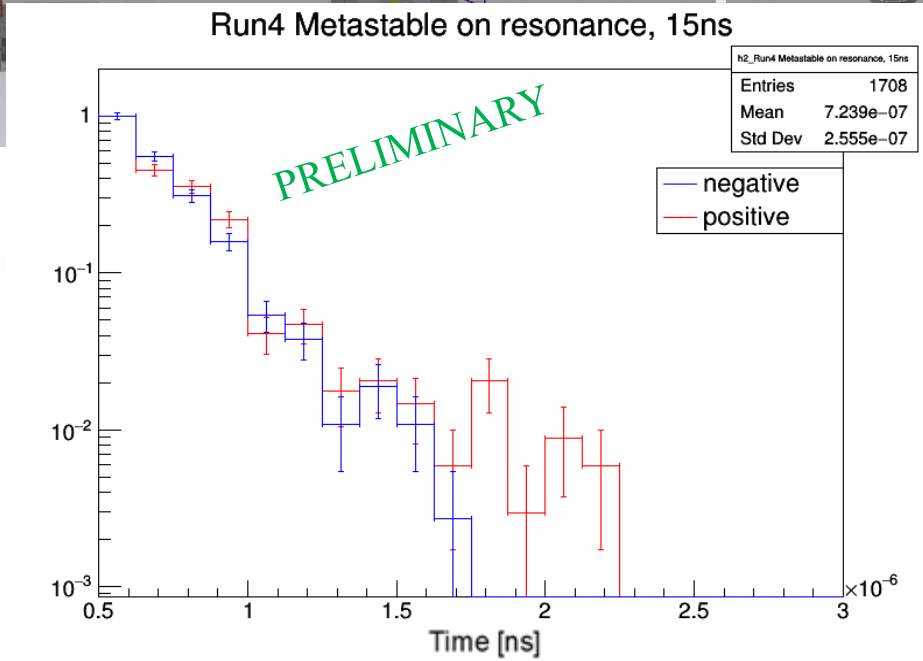


Velocity selected 2^3S Ps source with ~1.4 % production efficiency (0.8 x 10^4 2^3S Ps atoms every minute), ~13% longitudinal velocity spread.

Pulsed 2^3S Ps single events detection







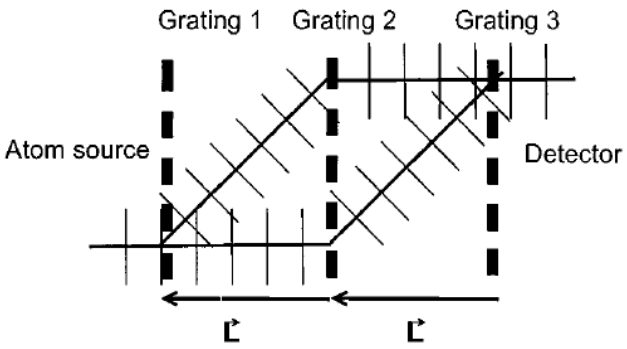
21 2^3S events detected in 170 shots (4.2 h) with 30 cm free-flight and 17 mrad collimator

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

$C = 0.2$

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

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

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

Goals within reach

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

~ and maybe sooner or later direct gravity on the positron ~

Next possible steps towards a high sensitivity intertial sensing experiment

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

Summary and conclusions

Take-home messages

- Demonstrated a novel method to produce an intense source of 2^3S Ps through 1s-3p single-photon laser-excitation;
- Demonstrated the possibility to produce a beam of 2^3S Ps with ~13% longitudinal velocity spread, 17mrad divergence at 30cm from the source
- Roadmap for first inertial measurements with Ps

Interesting connections (occasions of secondment?)

- Run coordination of AEgIS2 (CERN)
- Galactic and cosmological constraints on positron/positronium gravity via a complex system, SD-modelling approach (Univ. Napoli, dept. Agraria)
- Logic-learning machine learning methodology applied to highly voxelized detectors for events reconstruction (RULEX inc., Genova)
- Measurement of multi-partite entanglement of gamma rays from polarized 2^3S^0, 2^3S^1 and 2^3S^{-1} annihilations (Jag. University, Krakow)
- Fine structure $2^3S - 2^3P$ Ps measurements

Open collective points

Major questions

- Is secondment obligatory, or is it not?

> project that the fellow has started. It should also cover the scope of the eventual secondment it foresees and the expectations that the fellow has in terms of training and formation and possible implications on his/her future career. If outreach activities are already planned we would be very interested to also hear about them.

- Procedures for the so-far obligatory secondment:
  - In what italian private/public insitutions/companies can it be done?
  - Is there going to be a salary integration during the secondment?
  - Does that integration change according to the country where the secondment is taken (problem for CERN)?
- Open questions about the salary raised by the FELLINI winners collectively;

Minor questions

- It was said that no fund transfer from mission to equipment funds on fellows' money was possible by LM, stated wrong by former PM;
- It was said no missions could be done on any other money but the fellows' by LM, stated wrong by former PM;
- It was said once that fellows' money does not transfer to the next year budget by LM, then that it does by former PM;

As the PM resigned (without any communication to the fellows), are these words still actual?
Who is the new PM – or contact person for the fellows?

Open personal points

Questions

- Submitted project integration for approval on November the 14°, 2019 – was it approved?

Comments

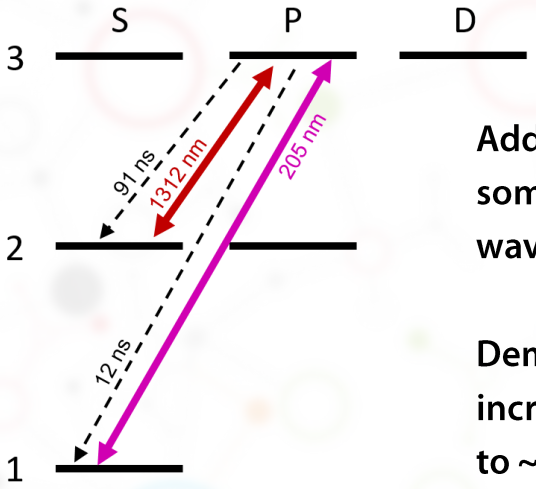
- Contract conditions were not communicated until 3 days before contract signature, only after a solicited request;
- No support received for the tax exemption request from local admininistration, request elevated to the former Project Manager, no answer yet obtained;
- No payment of mobility allowance for Sep/Oct/Nov/Dec 19 – had to make explicit request through local administration, processed by AC, payment received, to be verified.

Completing the Career Development Plan is difficul before:

- Project modification is approved;
- Clarification of secondment conditions;
- Processing of personal requests (tax exemption, mobility allowance).

BACKUP

Improving the beam: stimulated decay of 3^3P Ps to 2^3S



Added the 1312 nm laser (with some 205 detuning to adjust the wavelengths).

Demonstrated that is possible to increase efficiency from ~1.5 % to ~4.0 % (x 2.8 gain)