Positronium for fundamental studies

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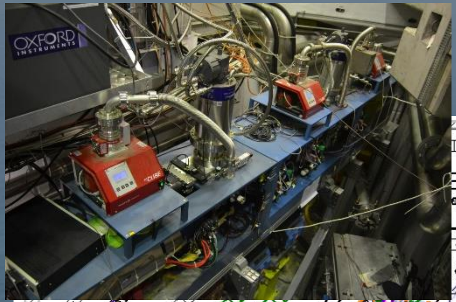
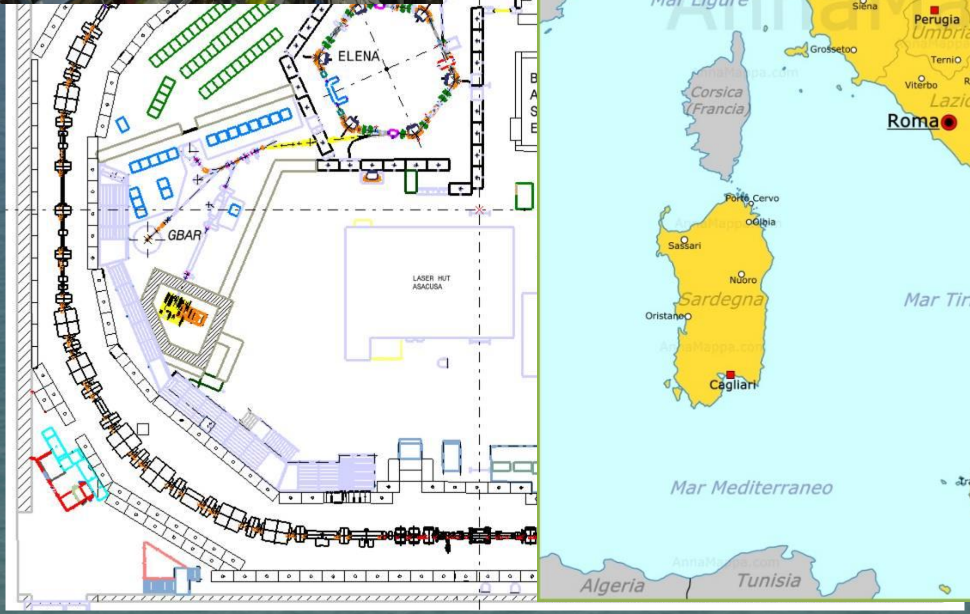
3° Jagiellonian Symposium on Fundamental and Applied Subatomic Physics
Collegium Maius – Kraków – 23-28 June 2019

CERN


OXFORD INSTRUMENTS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Outline

- How to obtain cooled Ps in vacuum
- Many positron bunched beams for many Ps in vacuum
- Ps excitation – long lived Ps
- Ps for Antihydrogen formation
- Metastable Ps
- metastable Ps beam -planned experiments
- Many positron polarized bunched beams planned experiments

Positronium

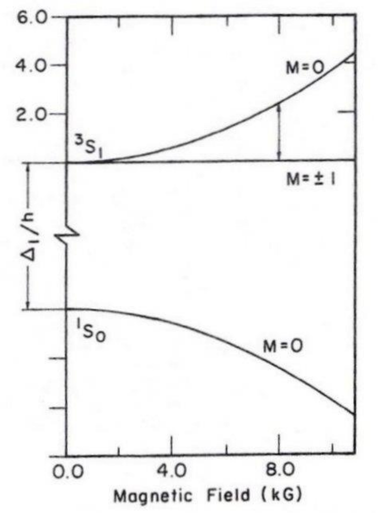
Hydrogen-like bound state of an electron and a positron

IN VACUUM

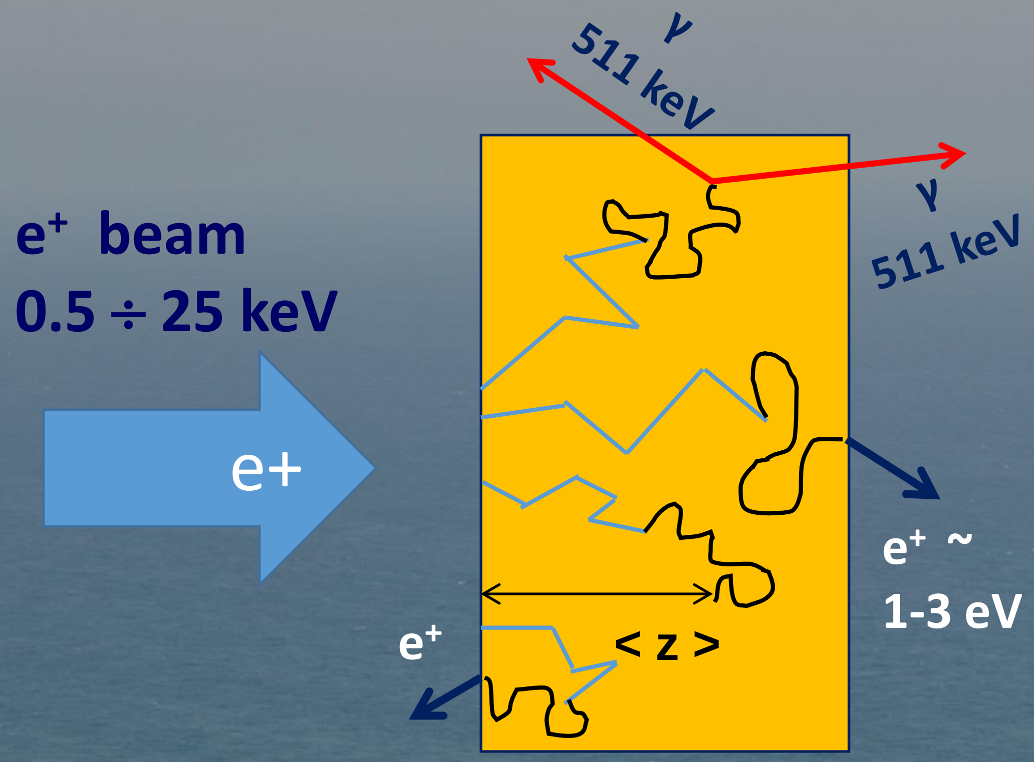
Orto-Ps mean lifetime τ 142 ns annihilation in 3 γ

Para-Ps mean lifetime τ 120 ps annihilation in 2 γ

In magnetic field the M=0 state of pPs and oPs mix togheter (Zeeman effect)
State M=+1; -1 are not affected



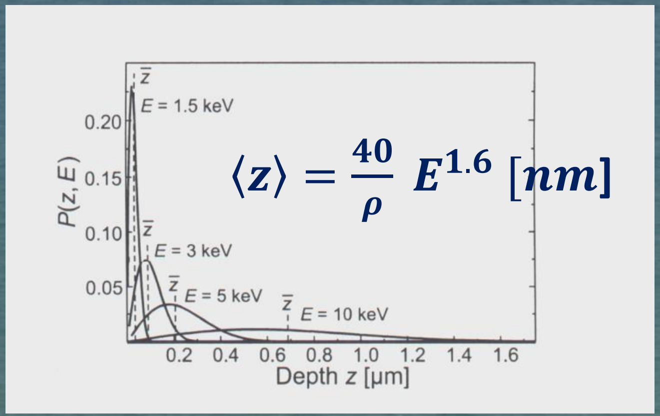
Interaction of positrons with matter and Ps formation



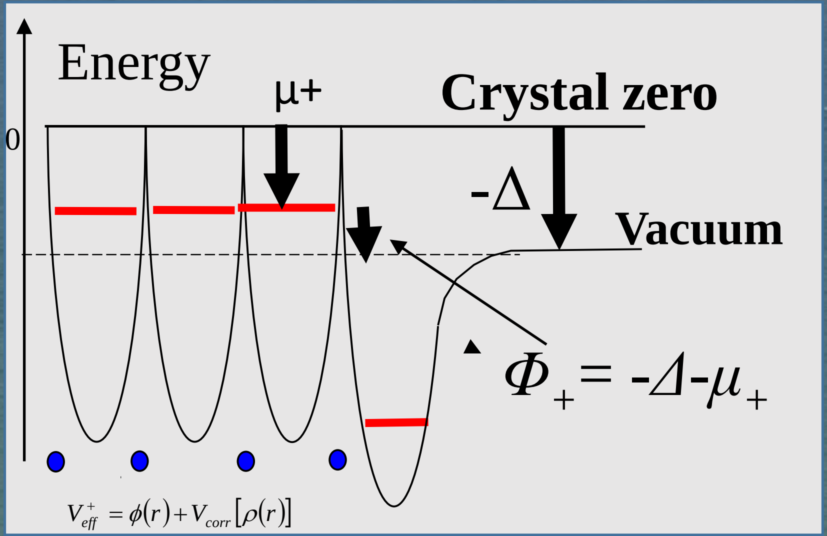
1. **Slowing down (0<t<10^{-12} s)**
From energy E to thermal energy: ionization, phonon scattering

2. **Diffusion motion (0<t<10^{-10} s)**

3. **Emission if negative work function**



$$\langle z \rangle = \frac{40}{\rho} E^{1.6}\ [nm]$$



Ps formation in metals and semiconductors

Ps is formed at the surfaces because in the bulk positron is screened by electrons can be a competitive process with e+ emission

Ps from backscattered e+

Ps from epithermal e+

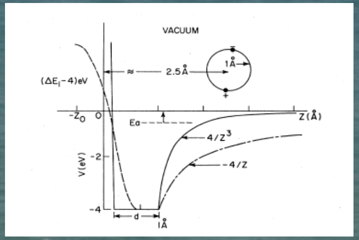
Ps from thermal e+

«Fast» Ps

Energy eV or fraction of eV

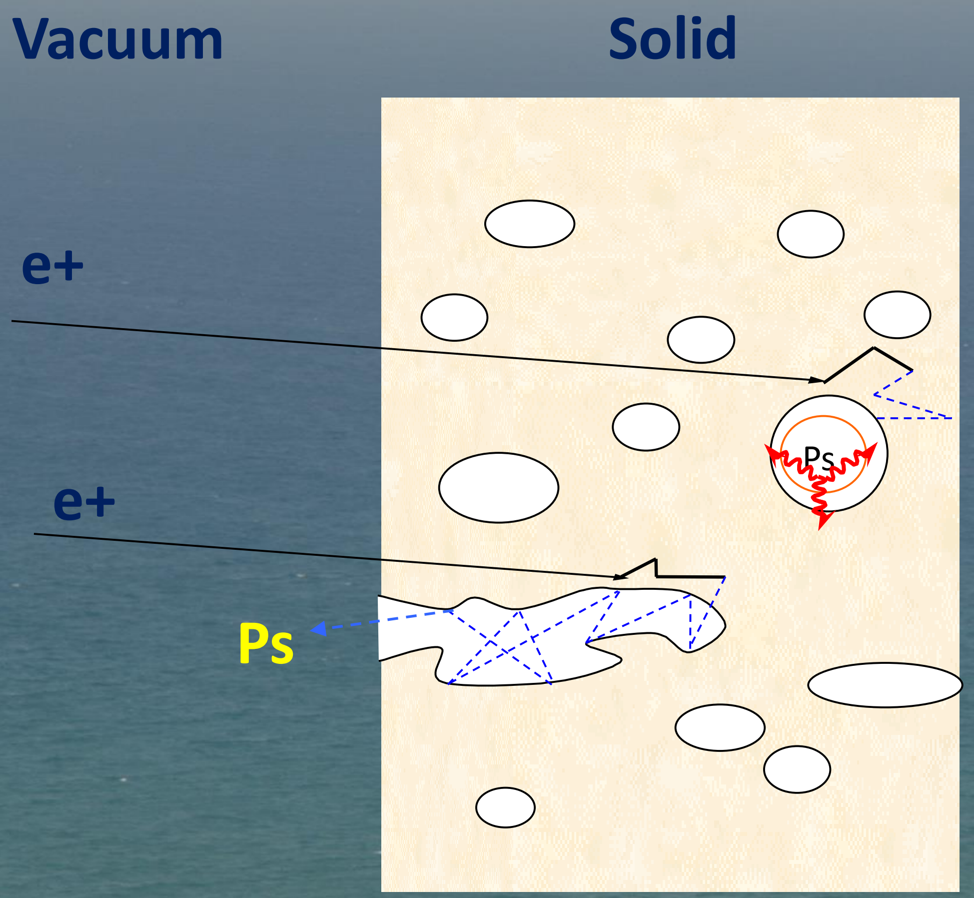
Ps emissionn in metals and semiconductors is a thermal activate process

a) e+ trapped in a surface state pick an electron



Positronium formation in porous materials

collisional cooling mechanism



Formation Mechanisms:

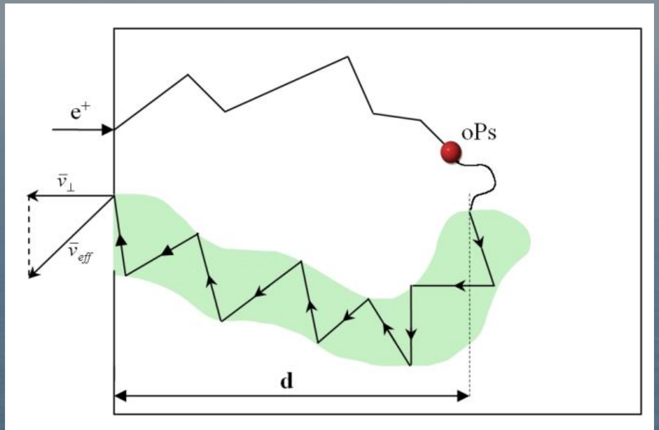
If Ps is formed in the bulk and thermalize, to be emitted in open volumes requieres a **negative work function**

$$\varphi_{Ps} = \varphi_{+} + \varphi_{-} - E_{gap} + E_{b} - 6.8\ eV < 0$$

Ps can be formed at the surface when a positron pick up an electron

Ps from nanochannelled silicon converters

avoiding quantum confinement

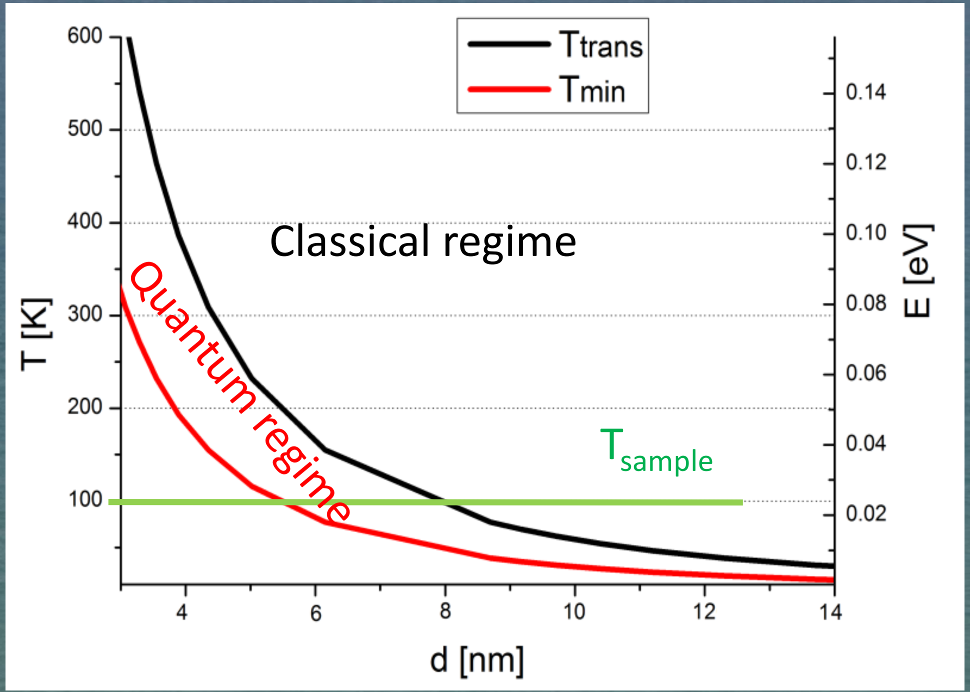


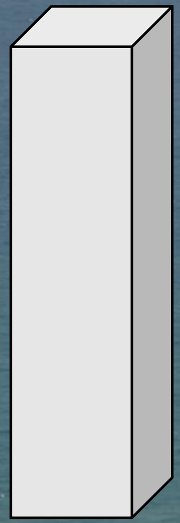
Classical regime

$$\lambda_{Ps} = \frac{h}{\sqrt{4m_0 E_{Ps}}} \ll a$$

Quantum regime

$$\lambda_{Ps} \sim a$$



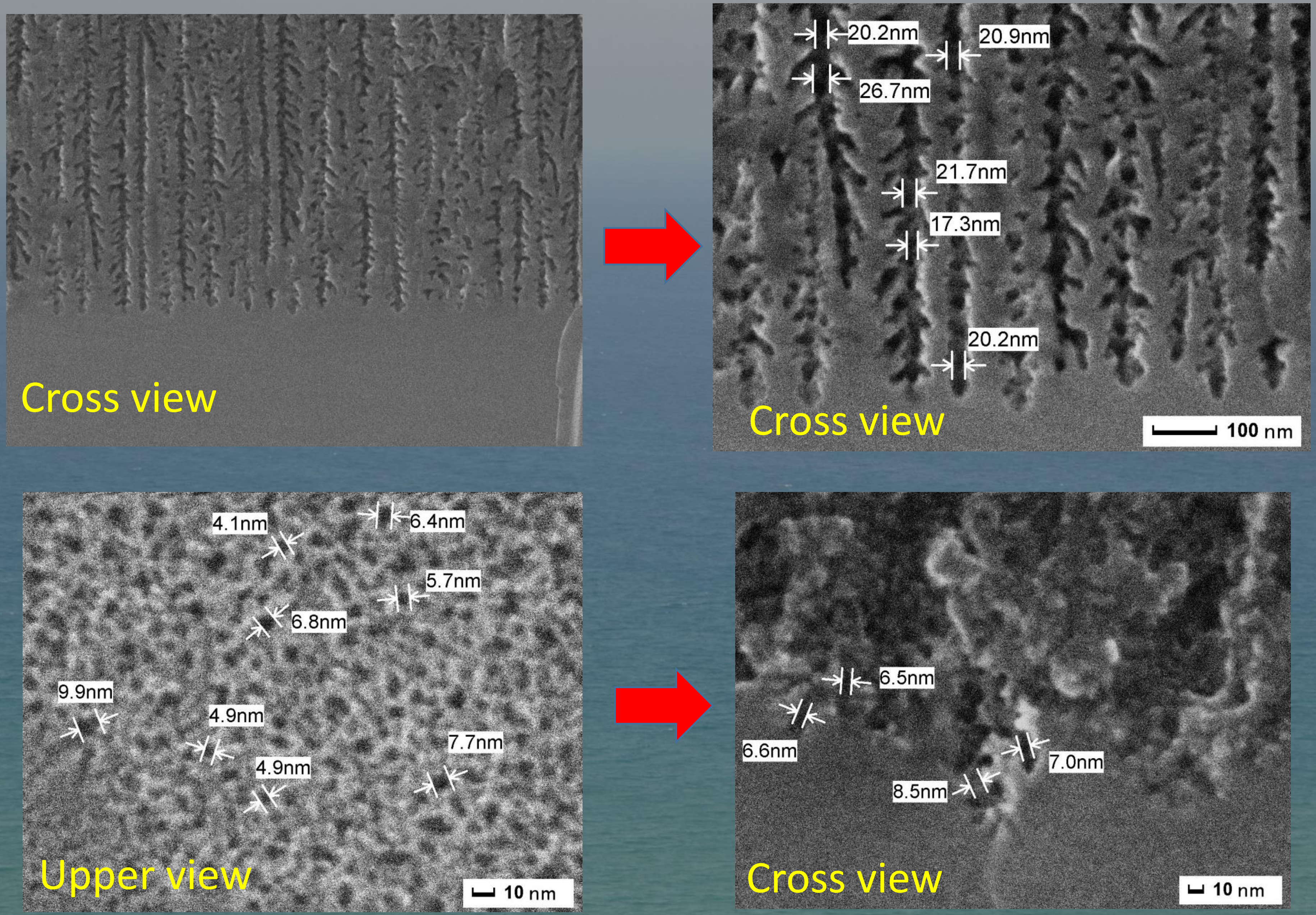


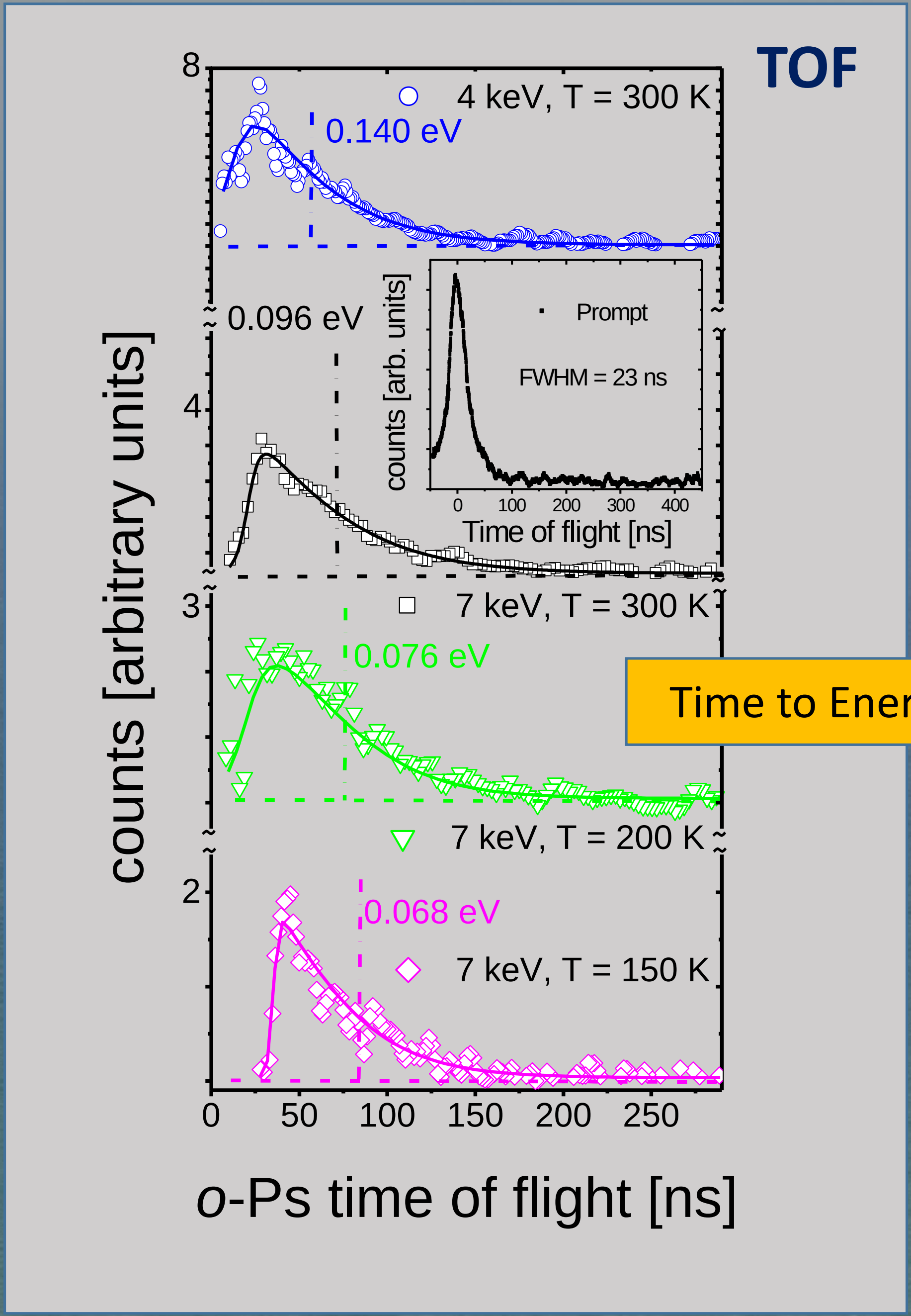
$$E = \frac{\hbar^2\pi^2}{2m}\left(\frac{n_m}{a}\right)^2$$

$$T = \frac{2}{3k_B}E = \frac{\hbar^2\pi^2}{3k_B m}\left(\frac{n_m}{a}\right)^2$$

Brusa-Dupasquier -Varenna School 2009

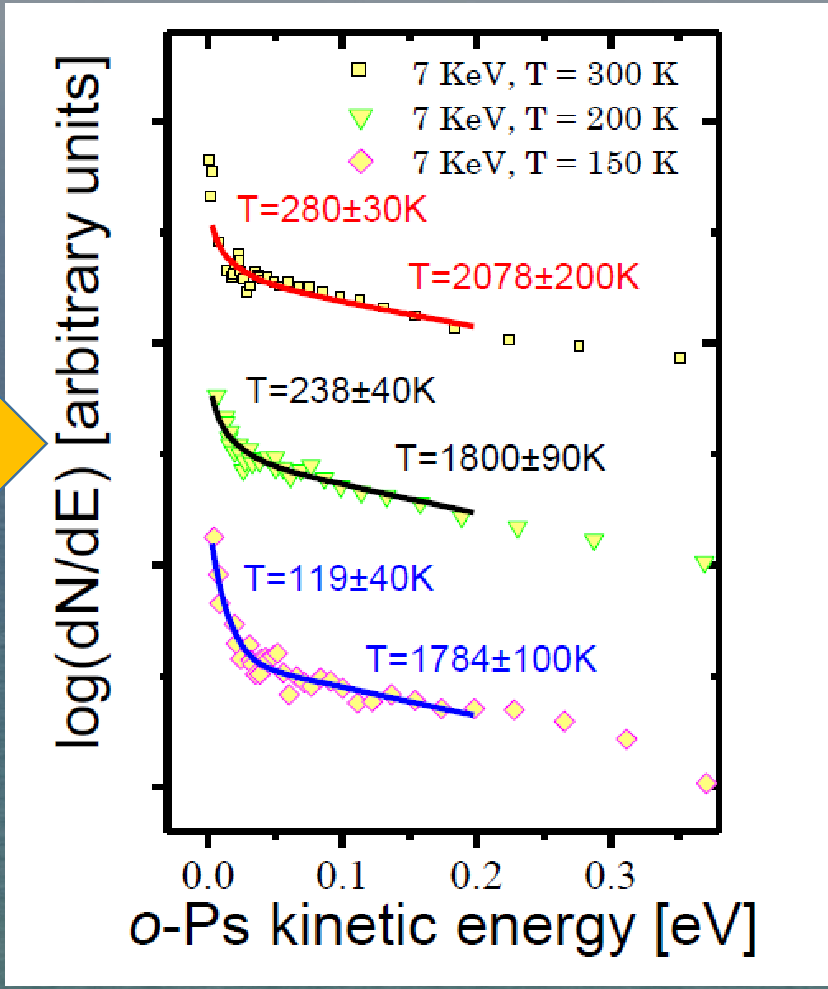
tunable nanochannels in silicon





Time to Energy

ENERGY SPECTRA



300 K

~20% of emitted Ps thermal

~5% of implanted e$^+$

250 K

~15% emitted Ps thermal

~4% of implanted e$^+$

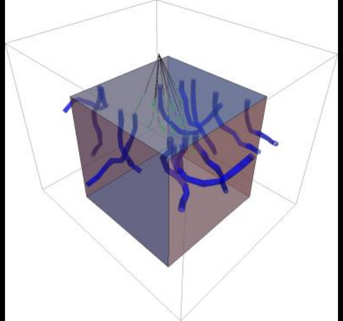
150 K

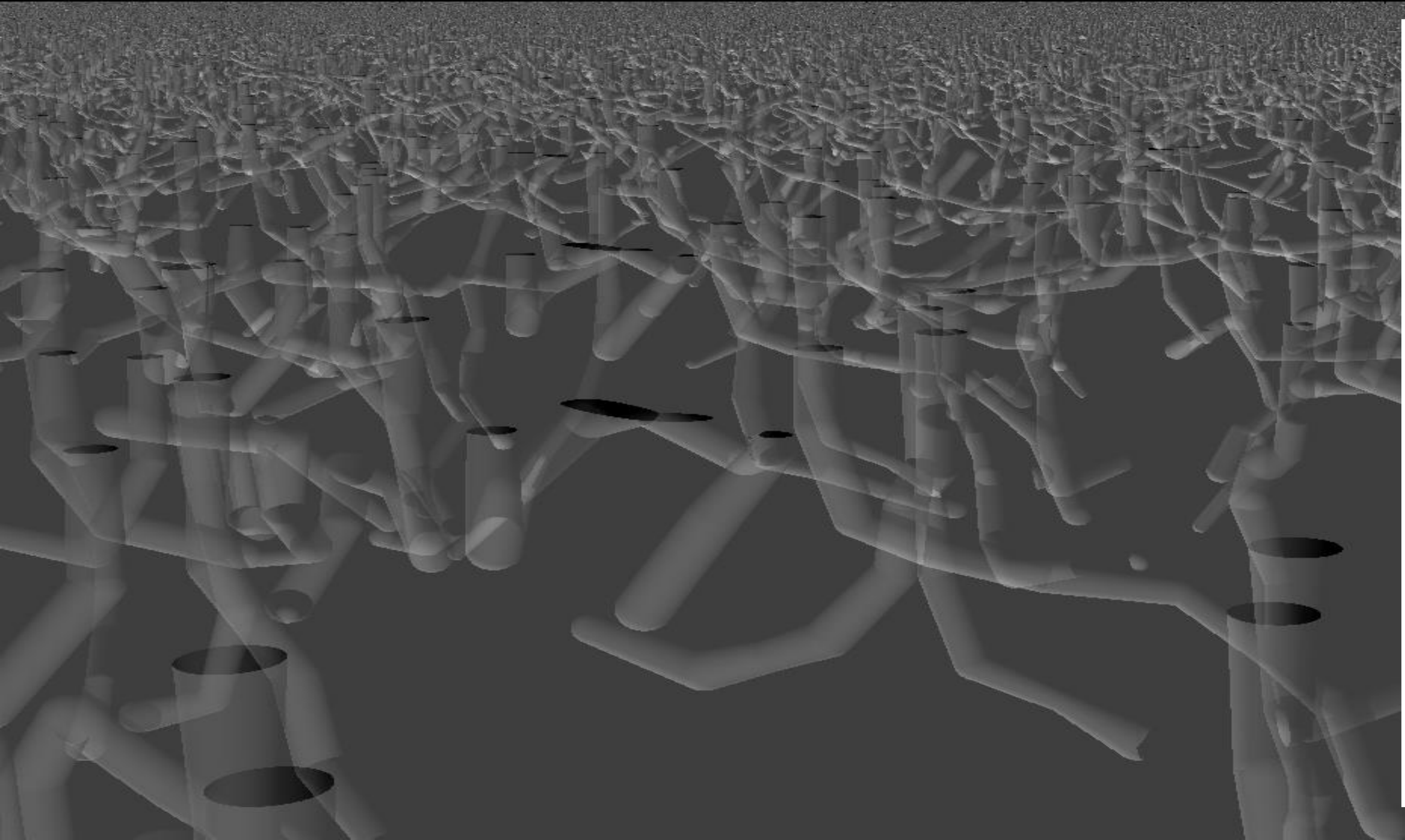
~10% emitted Ps thermal

~3% of implanted e$^+$

Mariazzi S, Brusa R S et al., *Phys. Rev. Lett.* **104** 243401 (2010)

Nanochannelled silicon simulation and Montecarlo Ps cooling





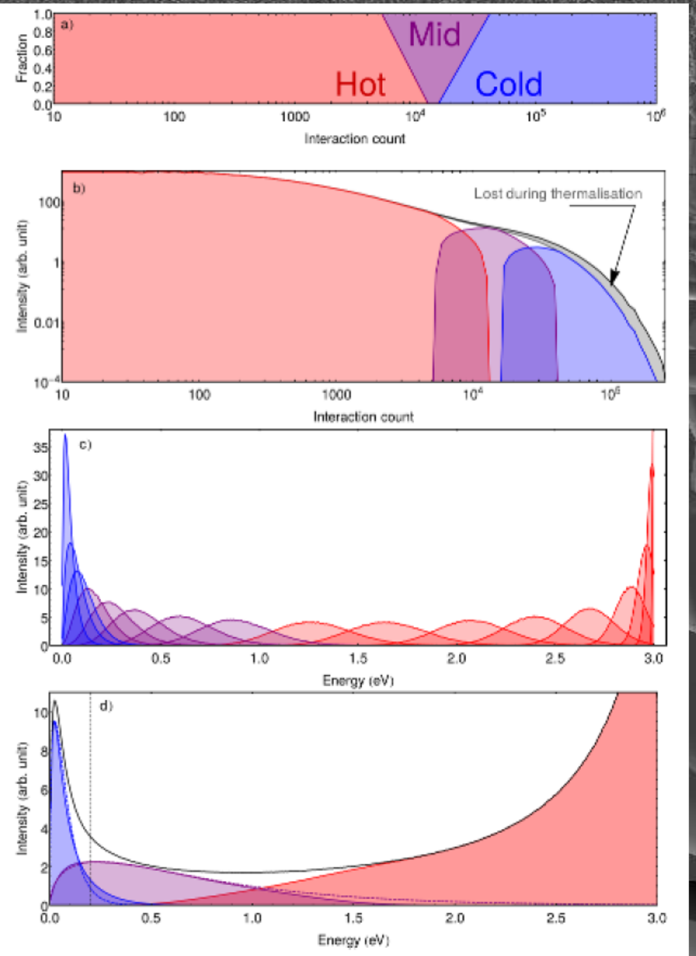


Figure 1.24: Illustration of the mechanism that leads to the positronium spectrum to show two thermal distribution. Please refer to section 1.10 for a detailed description.

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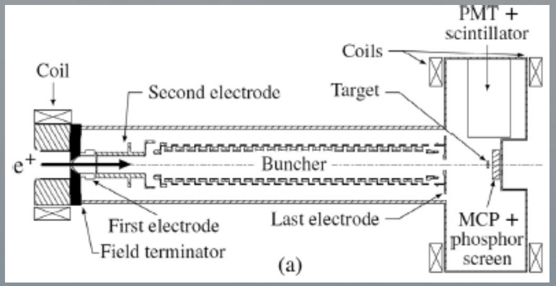
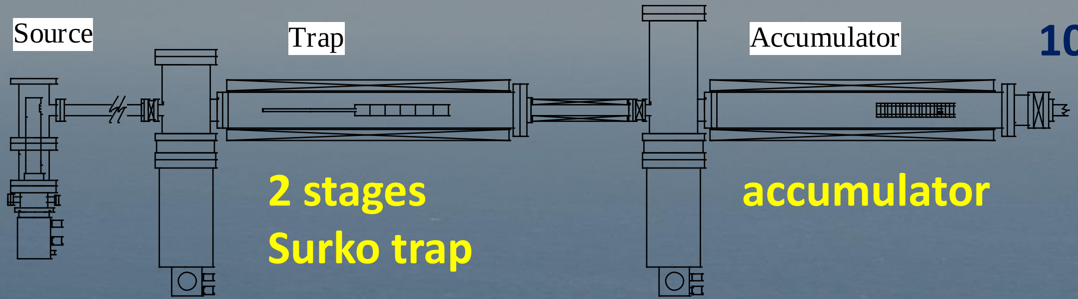
system characteristics



Na22 source
Ne moderator



2 stages
Surko trap

accumulator

20 ns
100 V
10^7-10^8 e+

re bunching

3-7 kV
10^7 e+

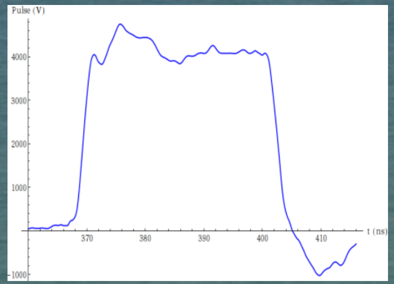
Field
terminator

In magnetic field 700- 1000 G

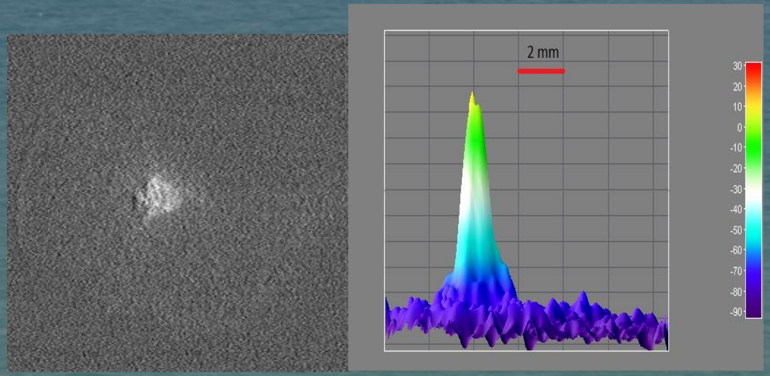
Electrostatic and then Free field

at the e+ -Ps converter

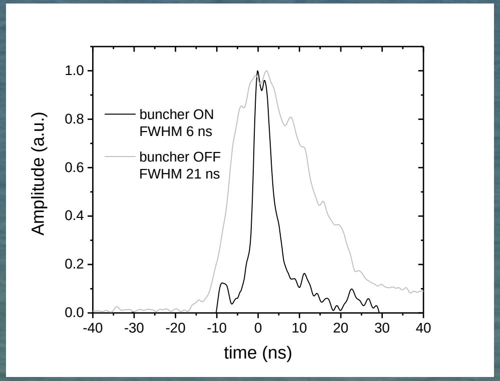
kV pulse, rise 3 ns
Duration 30 ns



Spot at MCP



Bunching
(PbF_2+PMT)



Mariazzi et al. NIMB 362,86 (2015)

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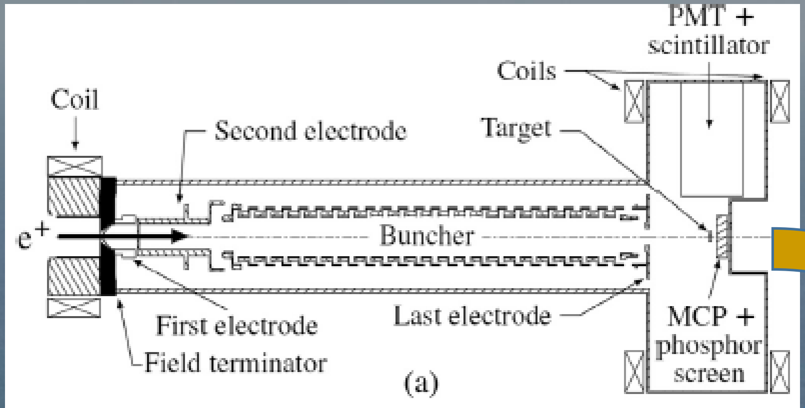
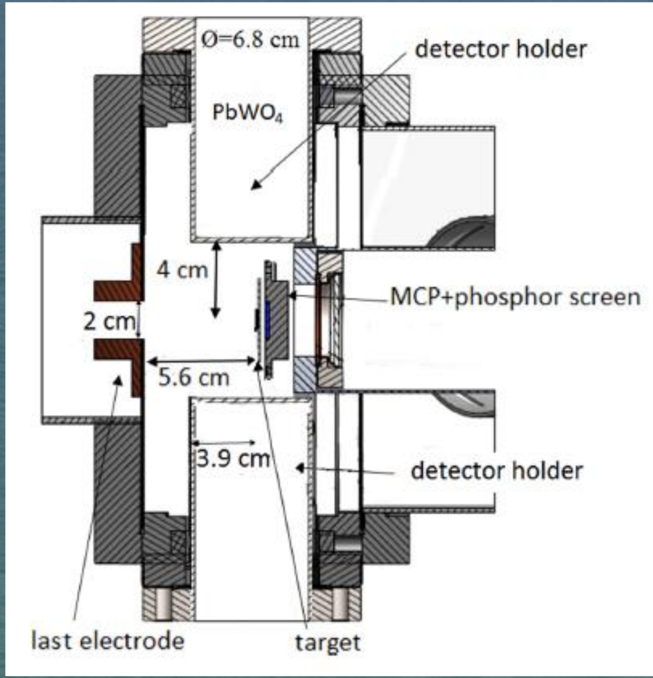
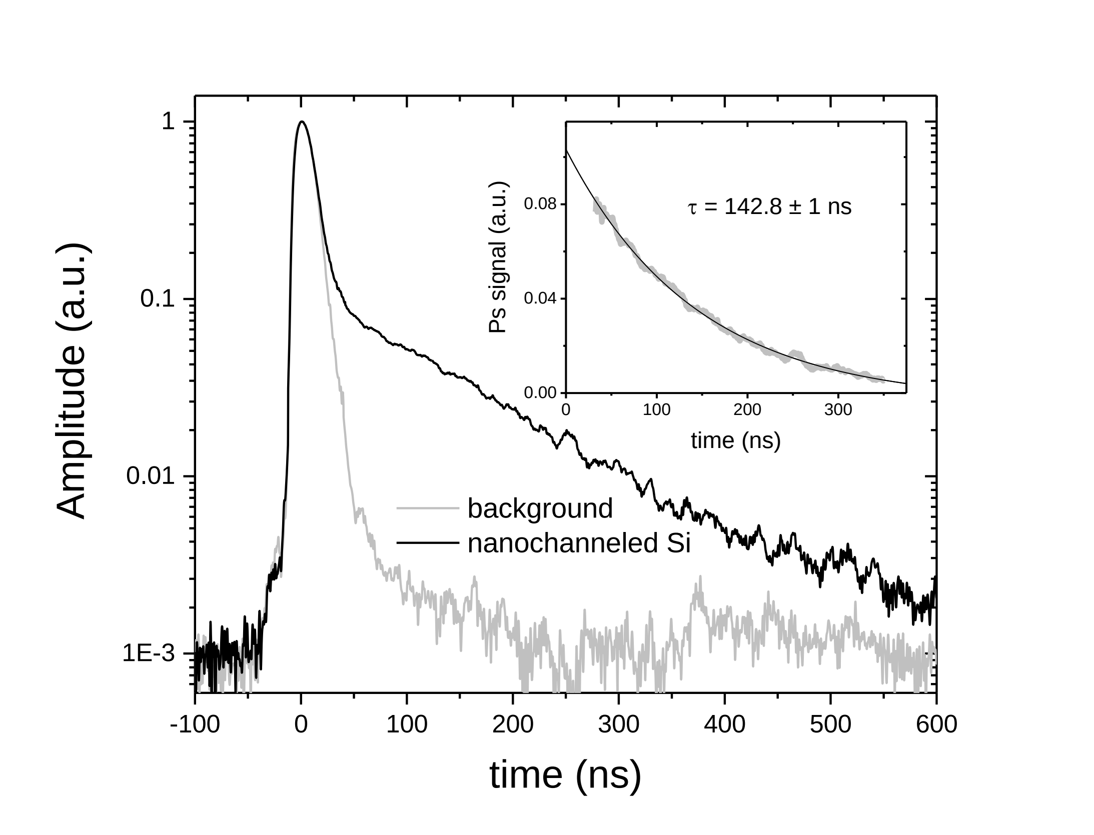
Detecting Ps flying in vacuum

SSPALS (Single Shot Positron Annihilation Lifetime Spectroscopy) Techniques, firstly introduced by Cassidy & Mills







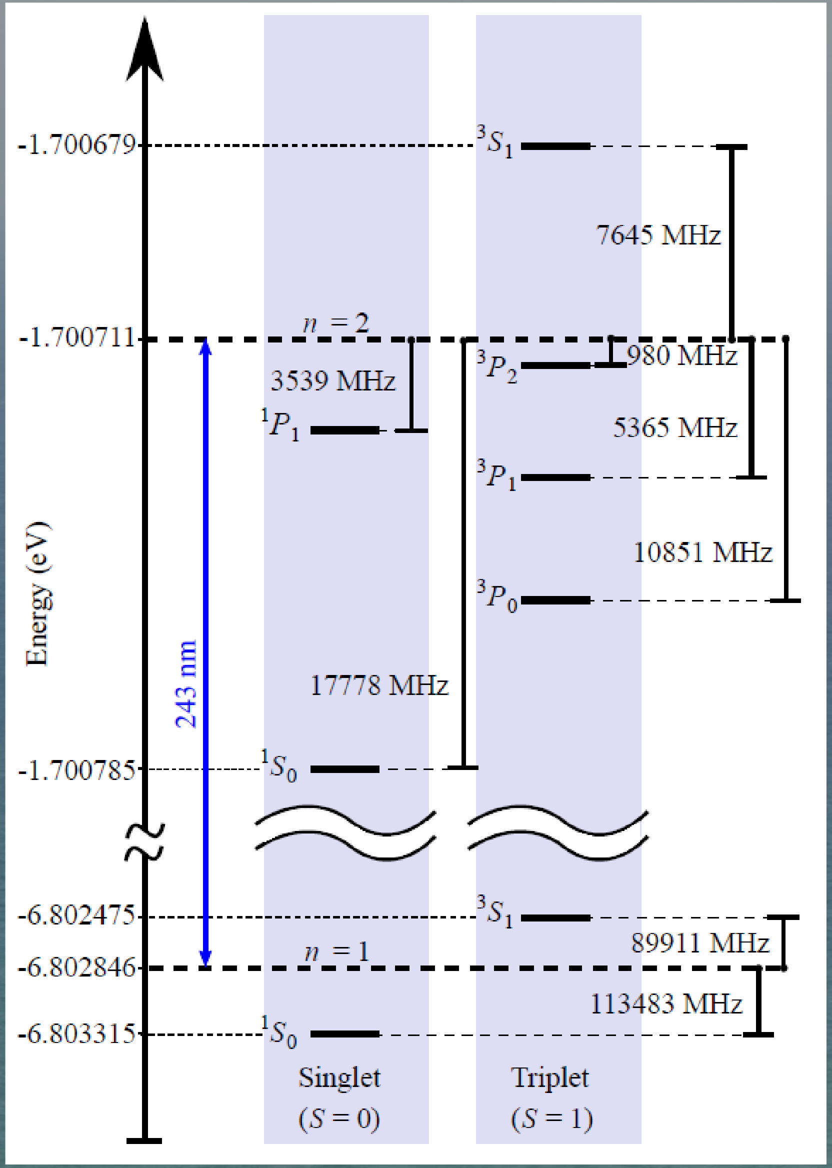
10^6 Ps atoms in vacuum for shot

Detector : $PbWO_4$ scintillator + Hamamatsu R11265-100 PMT

Time decay about 15 ns

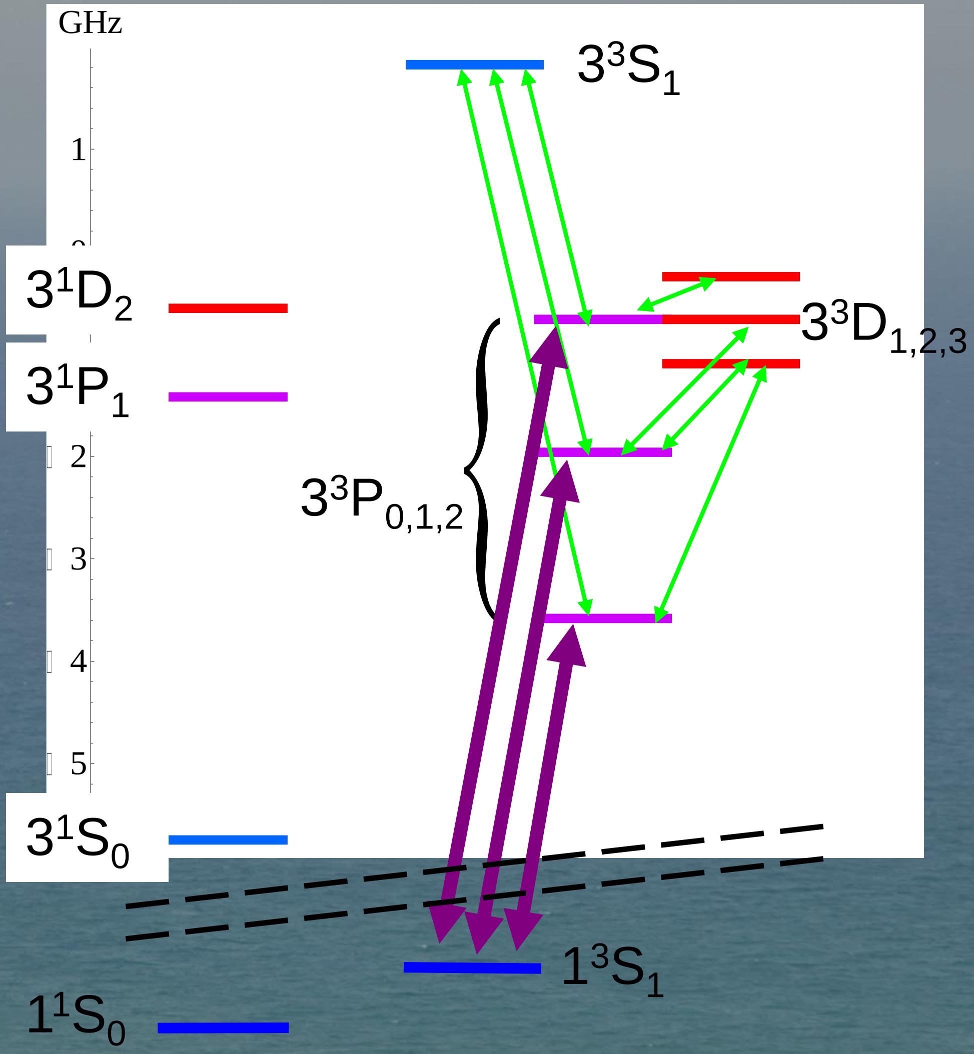
Long lived Ps

Route n=2



From Cassidy Eur. Phys. J. D (2018) 72: 53

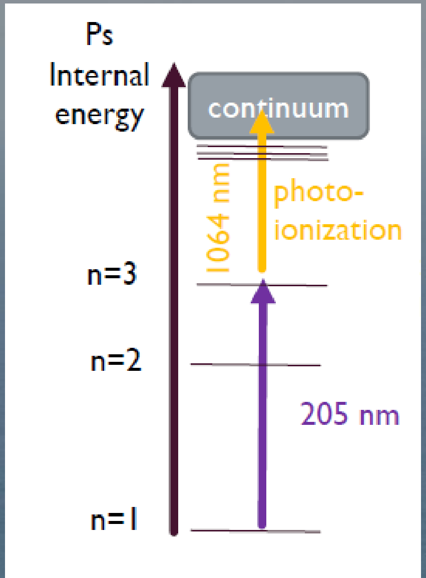
Route n=3

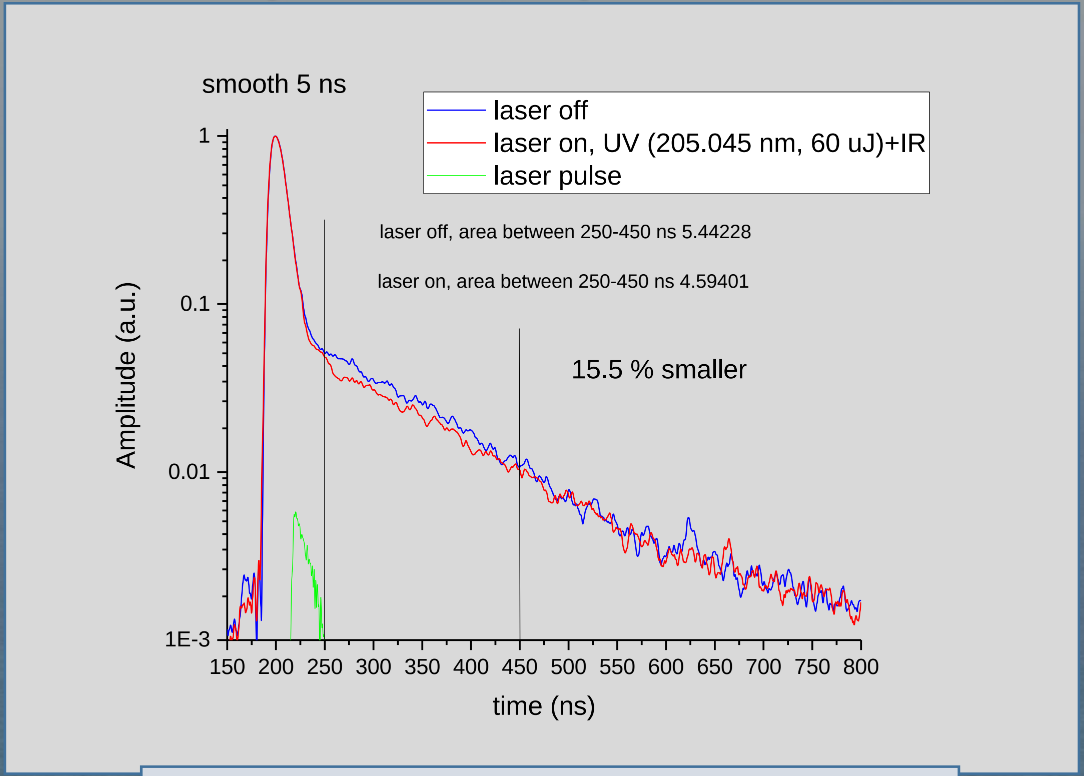


Para Ps
singlet

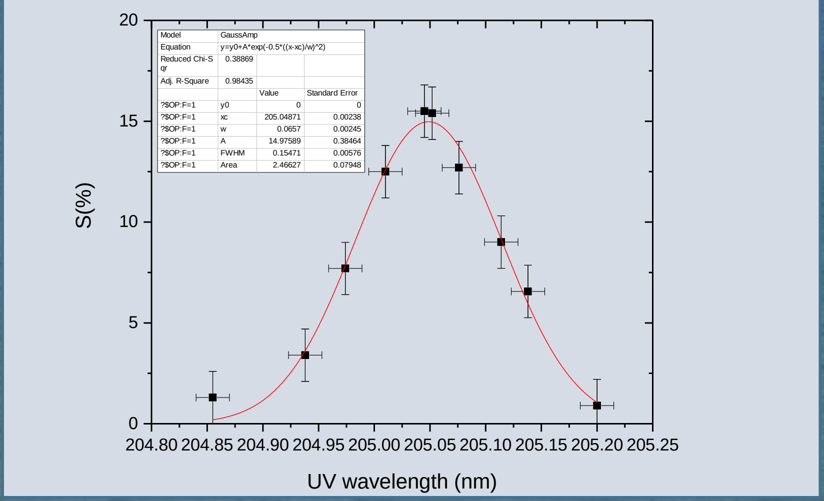
Orto Ps
triplet

n=3 Ps excitation (1^3S - 3^3P)





S(%)=(Area laser OFF-Area laser ON)/Area laser OFF



$$S = \frac{A_{\text{off}} - A_{\text{on}}}{A_{\text{off}}},$$

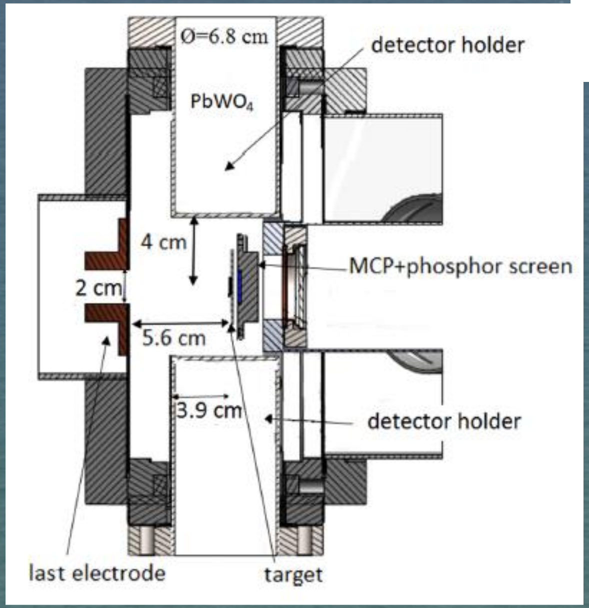
-3P excitation line centered at 205.05±0.02 nm

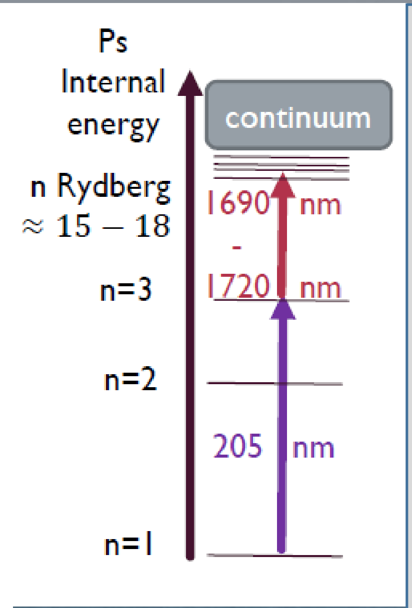
-excitation-ionization efficiency ~15%

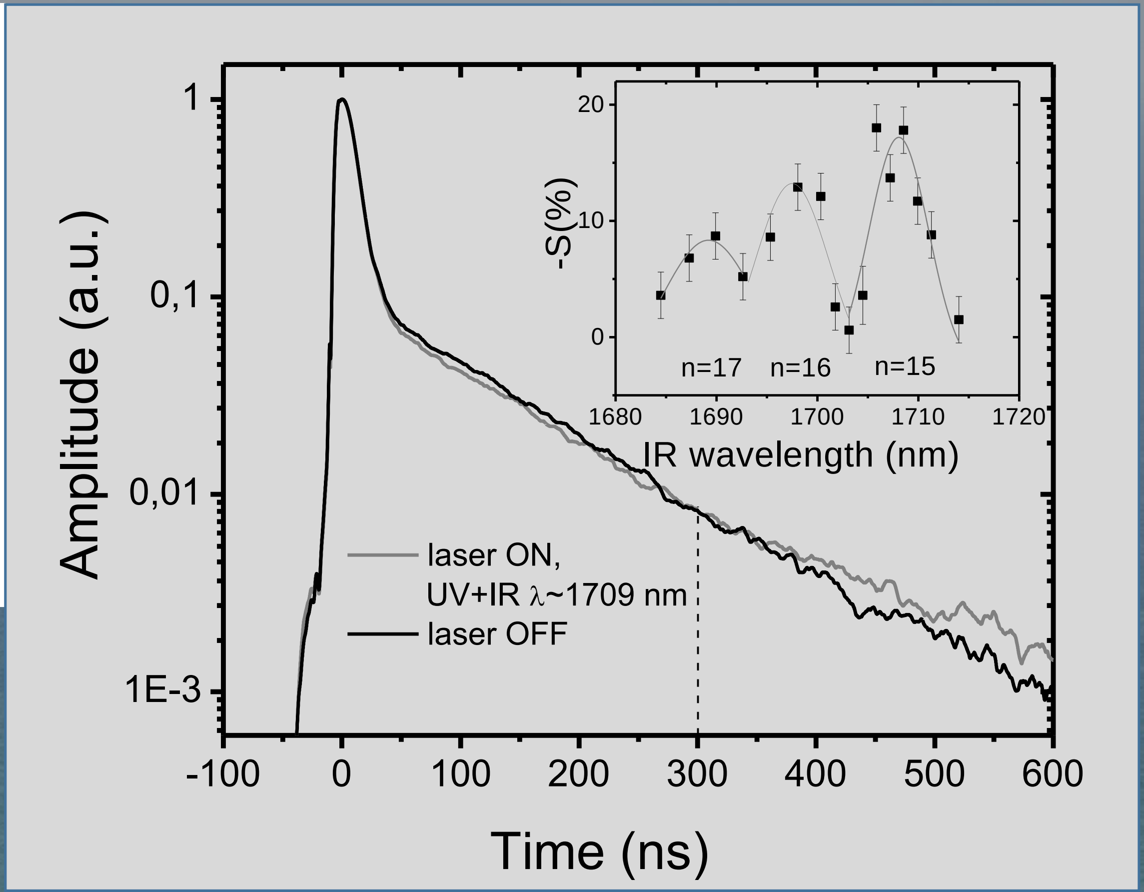
Energy : 54 μJ UV; 1.1 mJ IR

Aghion et al. Phys. Rev. A **94**, 012507 (2016)

Ps excitation n3 - Rydberg







S(%)=(Area laser OFF-Area laser ON)/Area laser OFF

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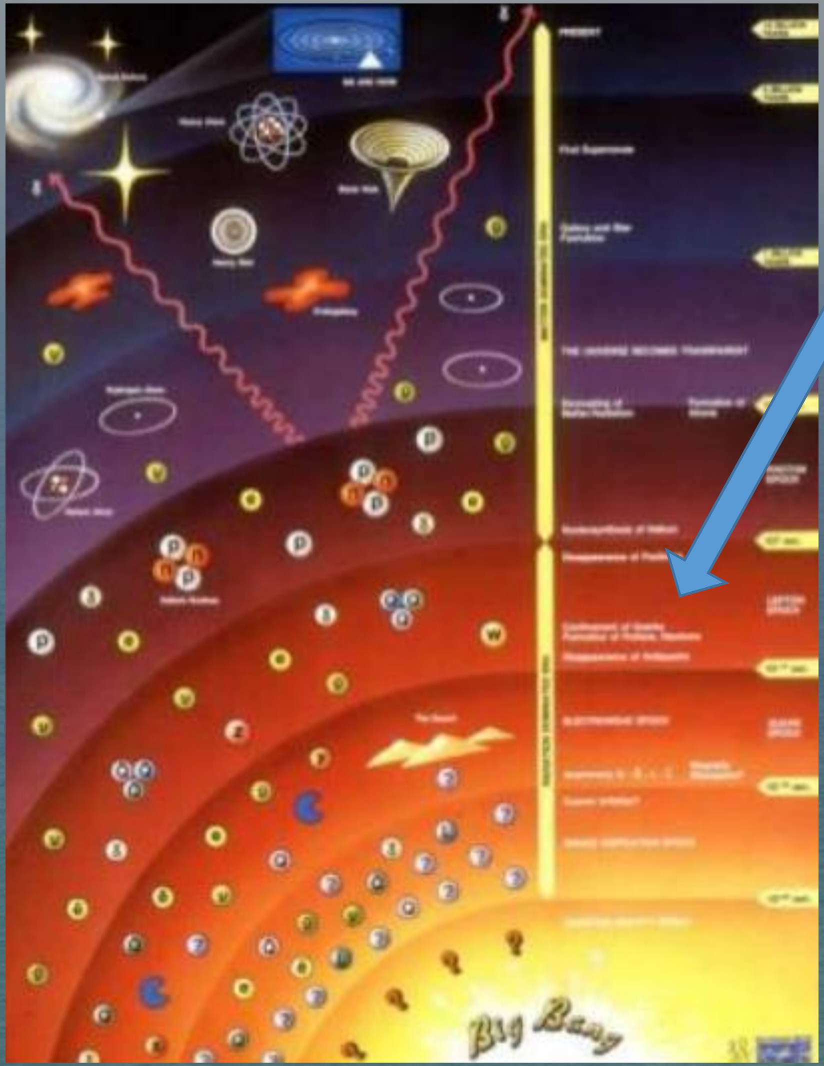
  planned experiments

Motivation

Disappearance of antimatter

Violation of CPT or WEP ?

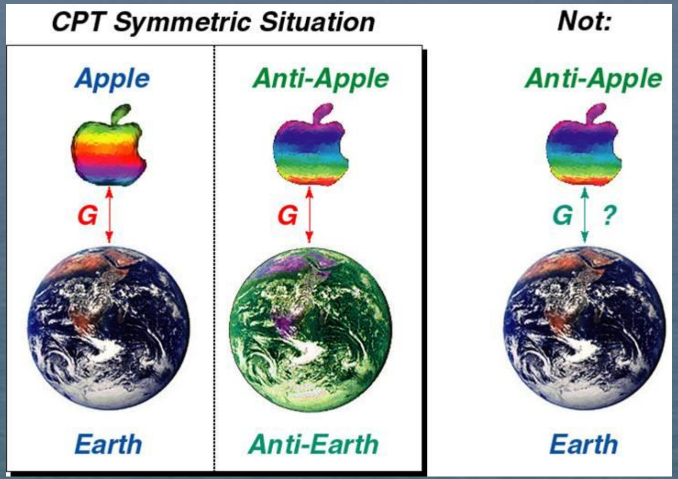


CERN-image

Tests of universality free fall (UFF)

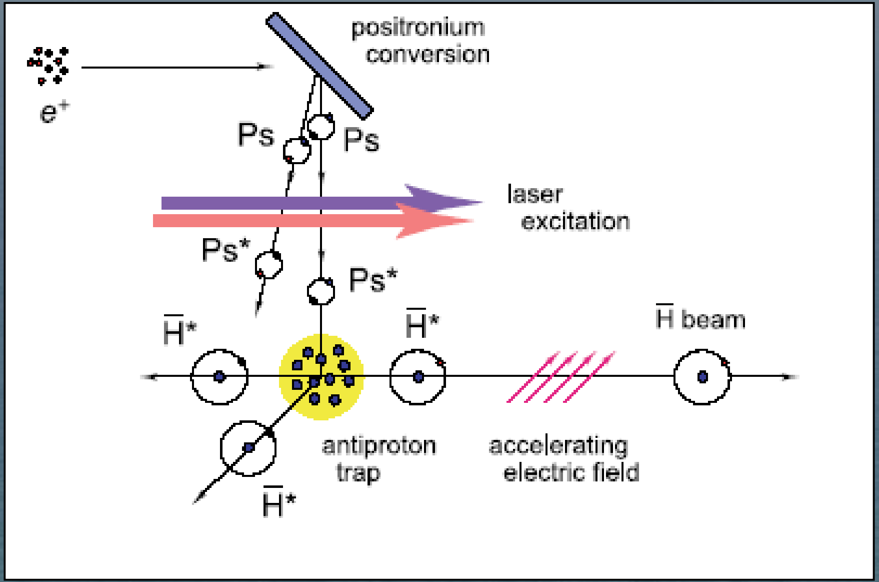
Luigi Catani 1816- Firenze Palazzo Pitti

"cascai in opinione che se si levasse totalmente la resistenza del mezzo, tutte le materie discenderebbero con eguali velocità".
Galileo Galilei (1564-1642)



AEgIS (Antihydrogen experiment: gravity, interferomentry, spectroscopy) at CERN

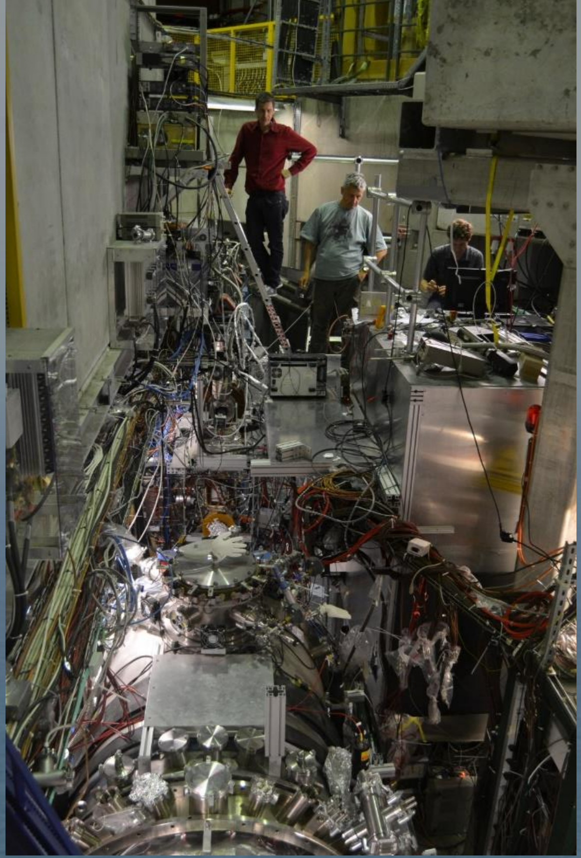
$\bar{H}$ production by charge exchange



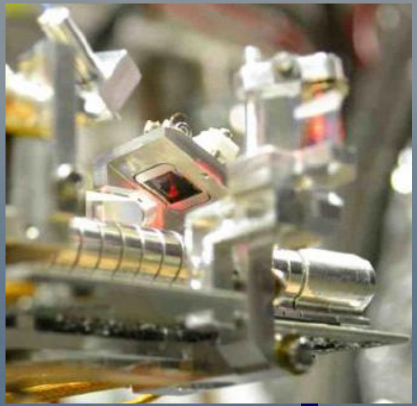
$$\bar{p} + (Ps)^* \rightarrow \bar{H}^* + e^-$$

- Large cross section $\sigma \approx \pi a_0 n^4$ for Ps cold
- Ps needed in Rydberg state for increasing the lifetime and cross section
- Quantum states of antihydrogen related to Ps quantum number
- Antiprotons T determines antihydrogen T (cold antiprotons!)

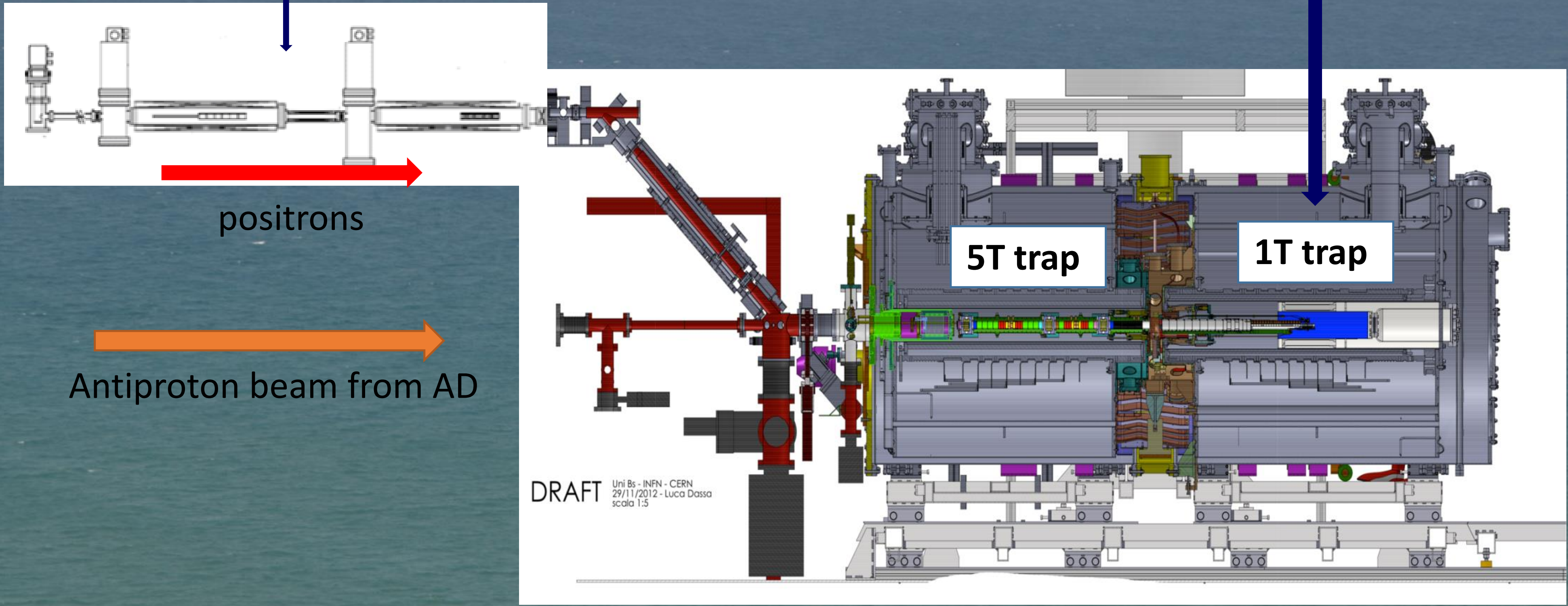
AEgIS apparatus



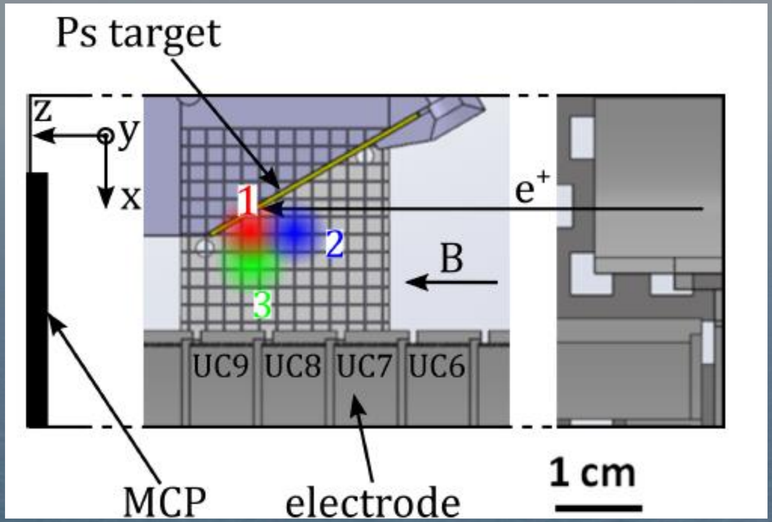
Ps cooling & converter

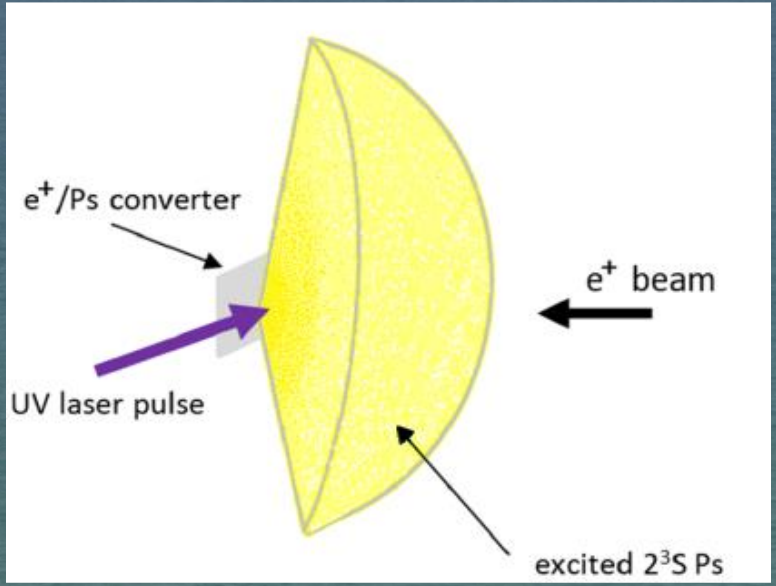


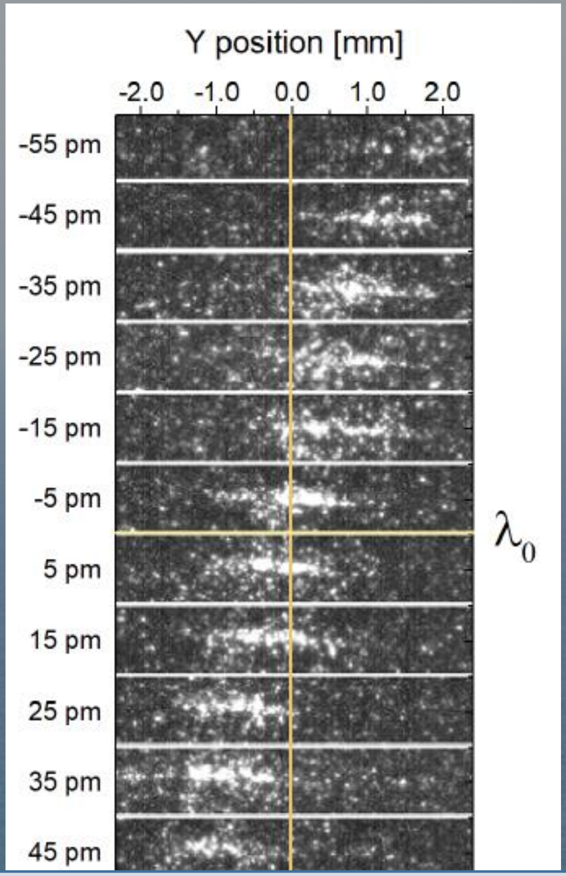
e+ bunched beam



Ps * towards the pbar trap







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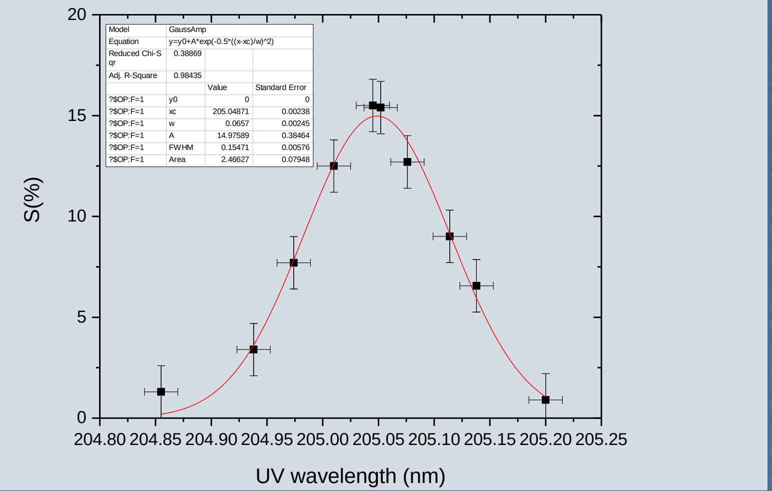
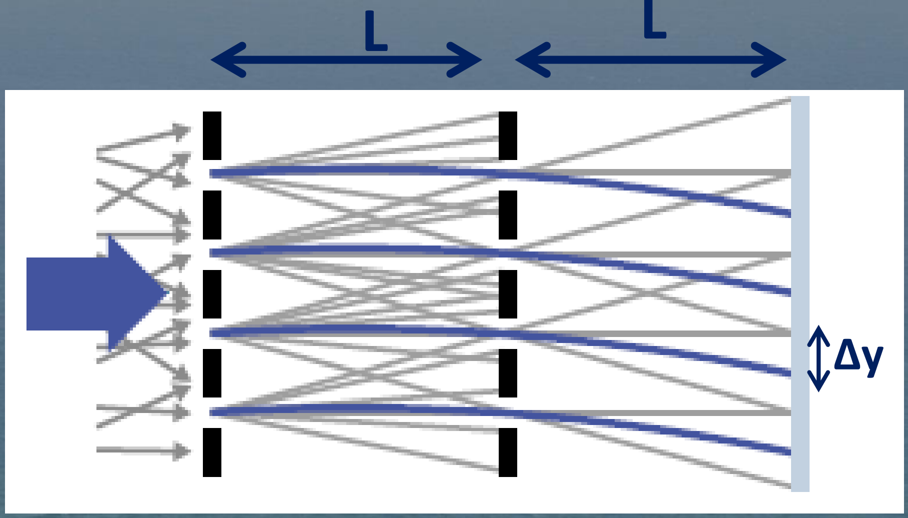


$\bar{H}$ free fall measurement

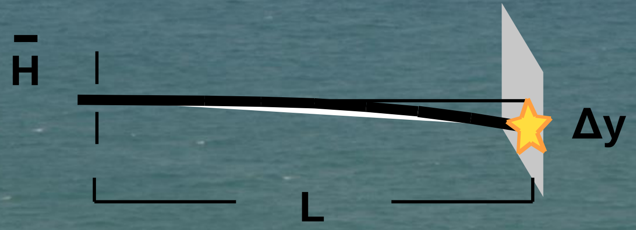
Moirè deflectometer

2 gratings L~ 50 cm
Φ=100 mm, slit 12 µm, pitch 40 µm
Δy≤ 10 µm

pulsed $\bar{H}$ beam , Stark acceleration $v \approx 400\ m/s$



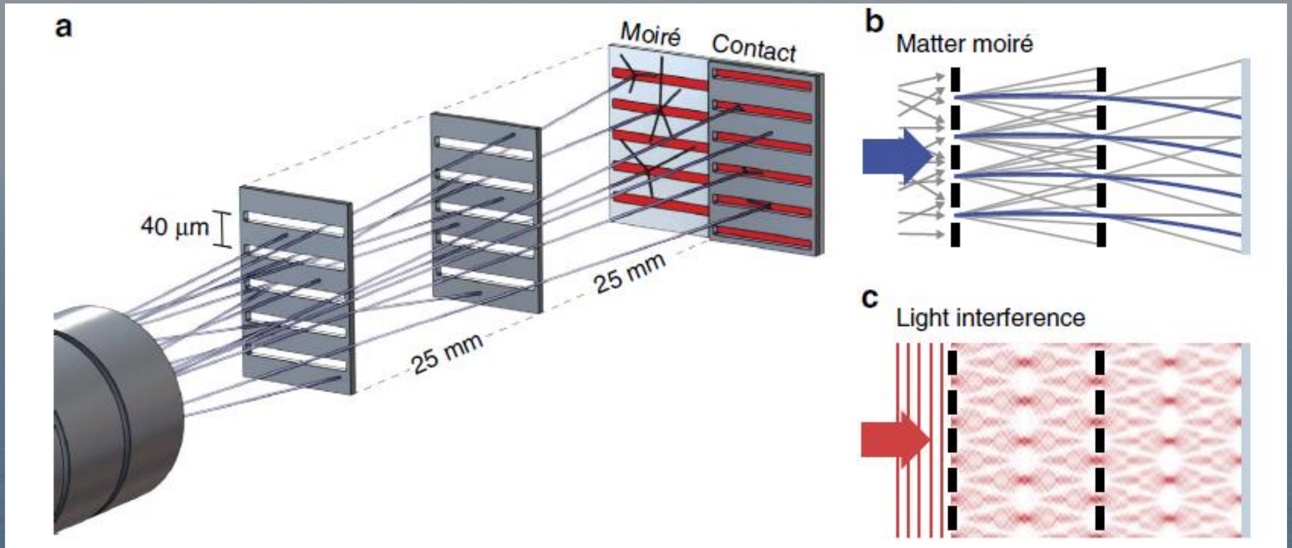
M.K. Oberthaler et al. PRA 54, 3165 (1996)



$$\Delta y = \frac{1}{2} g T^2 \left(\frac{L}{v}\right)^2$$

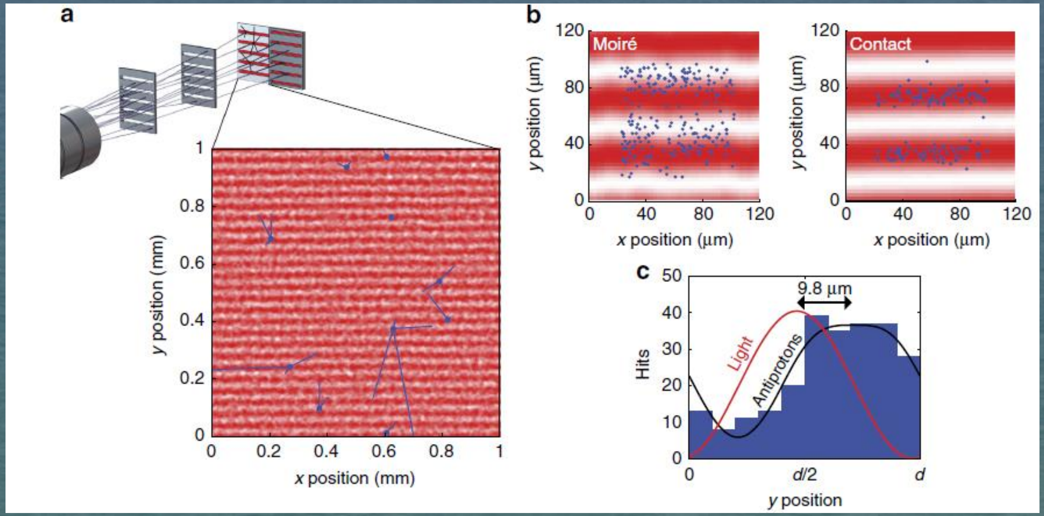
Aghion et al. (AEgIS) Nature Comm. 5, 4538 (2014)

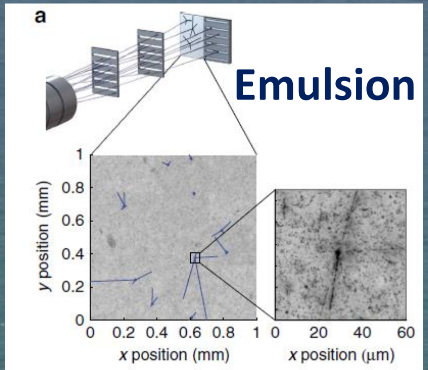
Test with a Mini-moiré



Antiproton E=100±150 keV

slit arrays in 100-µm thick silicon by ion etching
slit width of 12 µm
periodicity of d=40 µ m
Reference measuerement with light (Talbot –Lau)





Compatible with a force
530 ±50 (stat.) ± 350 (syst.) aN
Corresponding to an E=33 V/cm direction of the grating period
or a B= 7.4G perpendicular to the grating period and antiproton direction

With lower v ($\bar{H}$), L ~ 1m , sensitivity 11 order mag better

Δy=9.8±0.9 µm (stat.) ±6.4 µ m (syst.)

Aghion et al. (AEgIS) Nature Comm. 5, 4538 (2014)

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5 March 2019

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AEgIS makes positronium for antimatter gravity experiments

The AEgIS collaboration at CERN has found a new way of making long-lived positronium atoms for antimatter gravity experiments

5 MARCH, 2019 | By Ana Lopes

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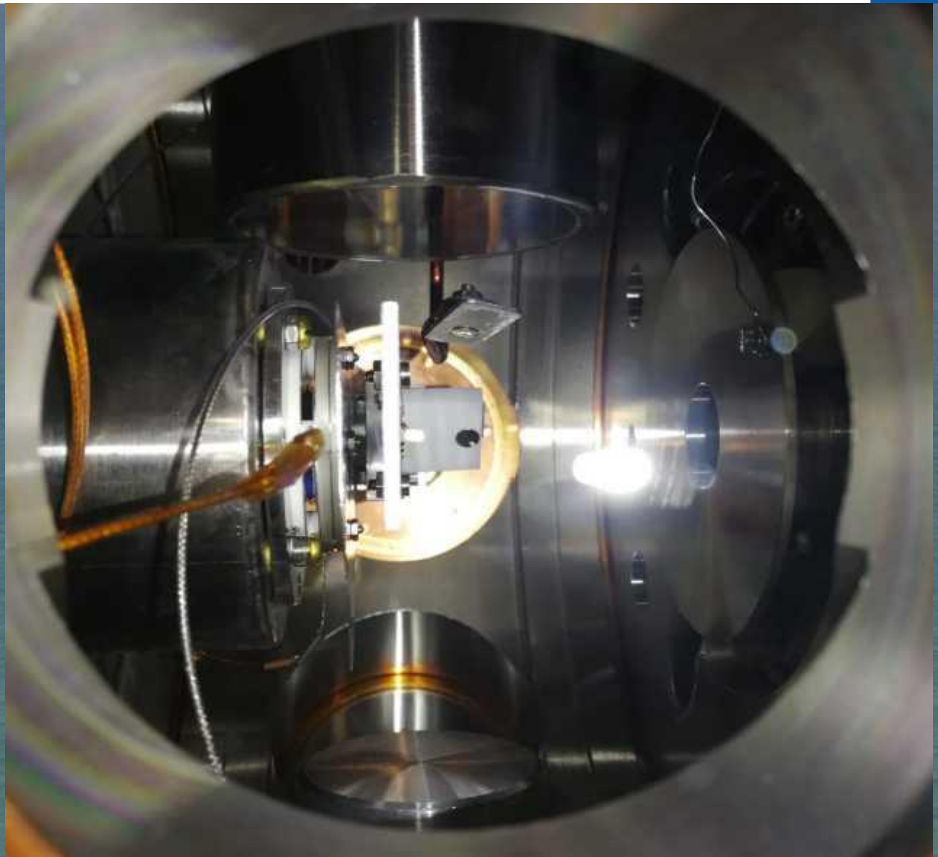
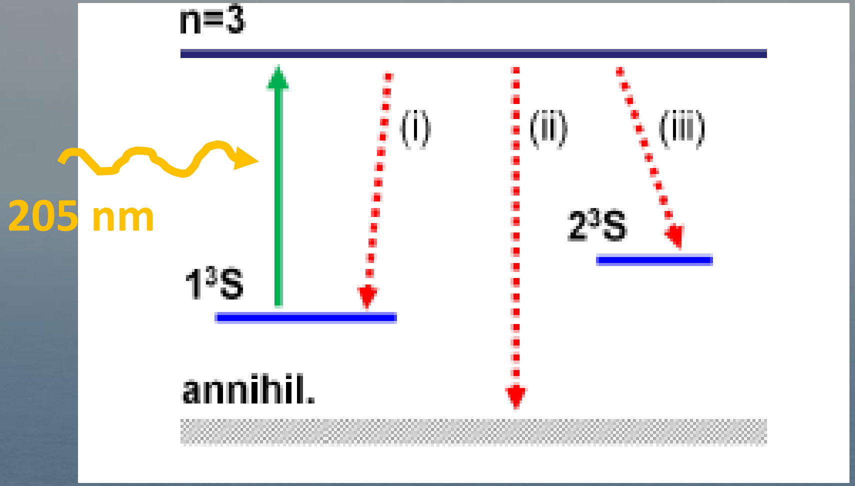
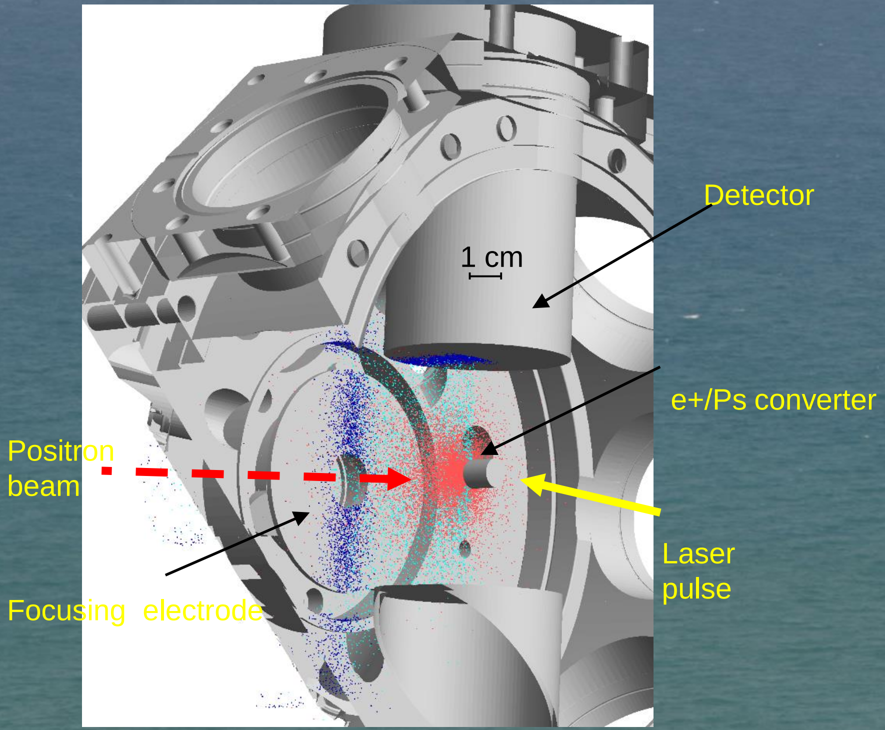
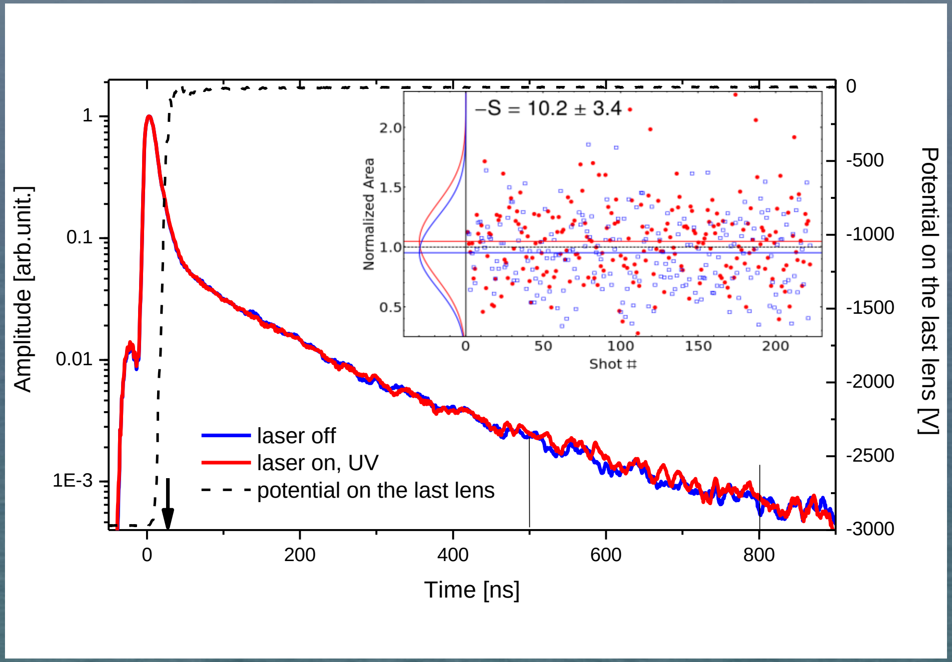


2^3S Ps ,metastable state 1140 ns, in FREE FIELD



In free field→lifetime 1140 ns

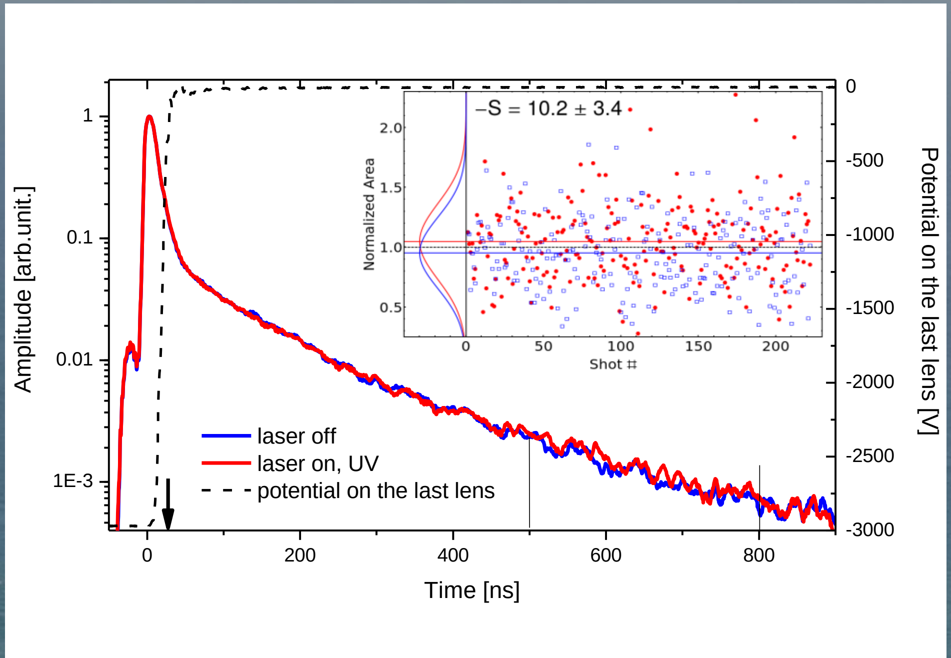


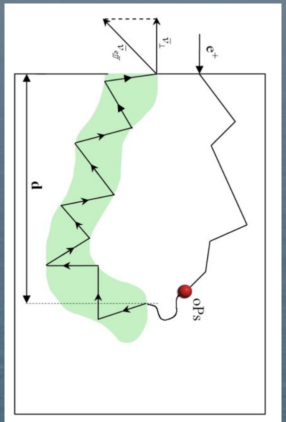


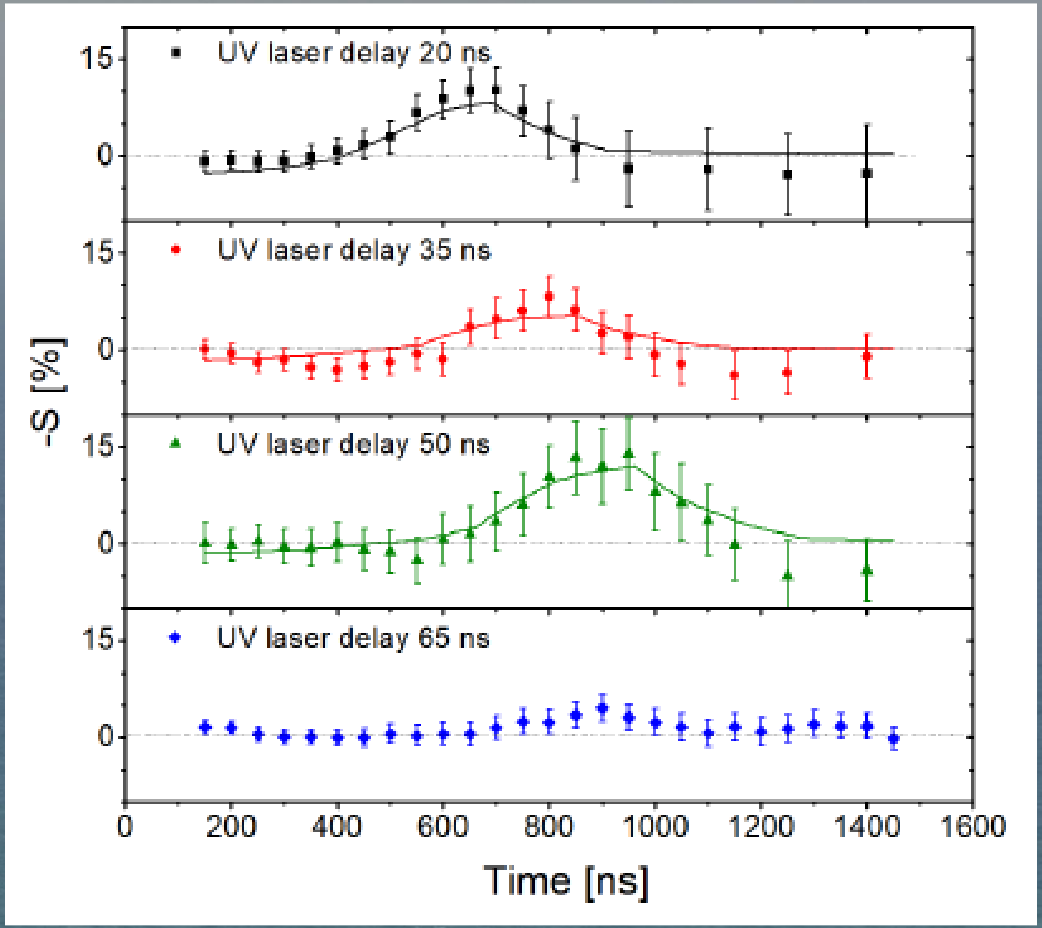
Aghion et al. Phys. Rev. A **99**, 033405 (2019)

Selecting velocities of 2^3S Ps by retarding the laser

Selection of different Ps population cooled from nanochannelled silicon convertres, i.e. population with different velocities
From $1x10^5$ m/s to $7x10^4$ m/s

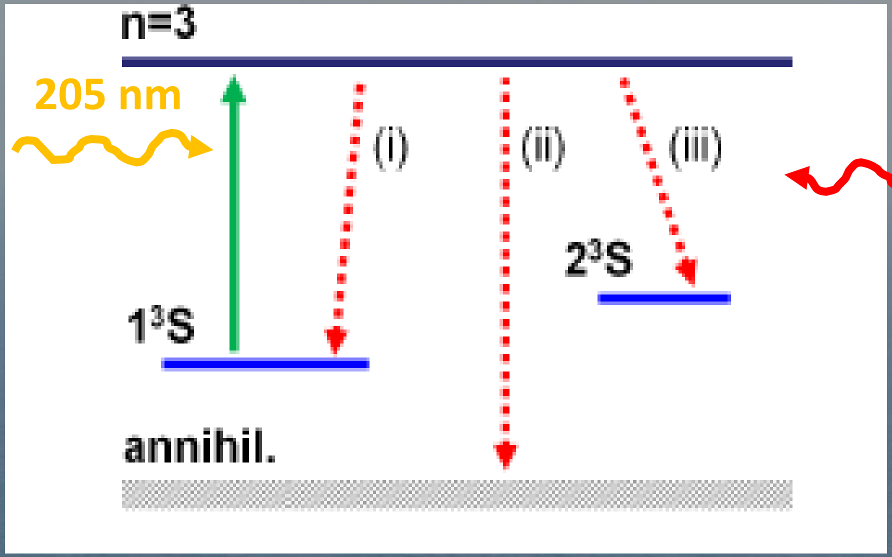


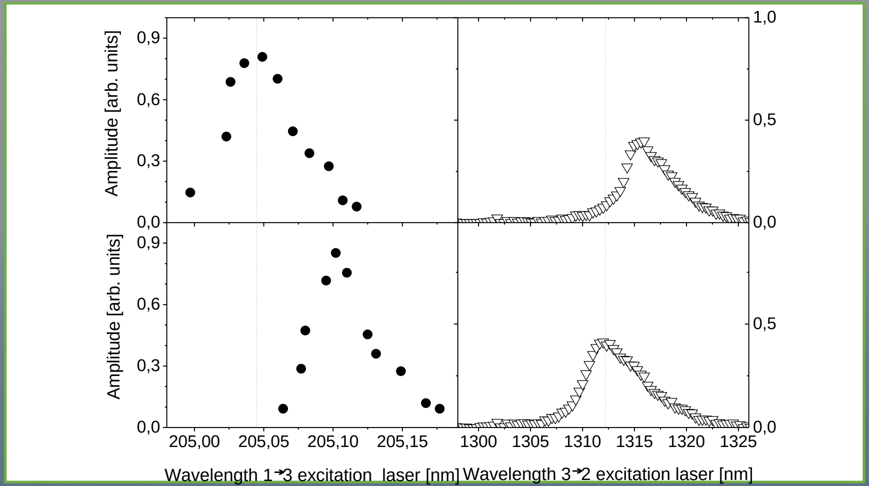




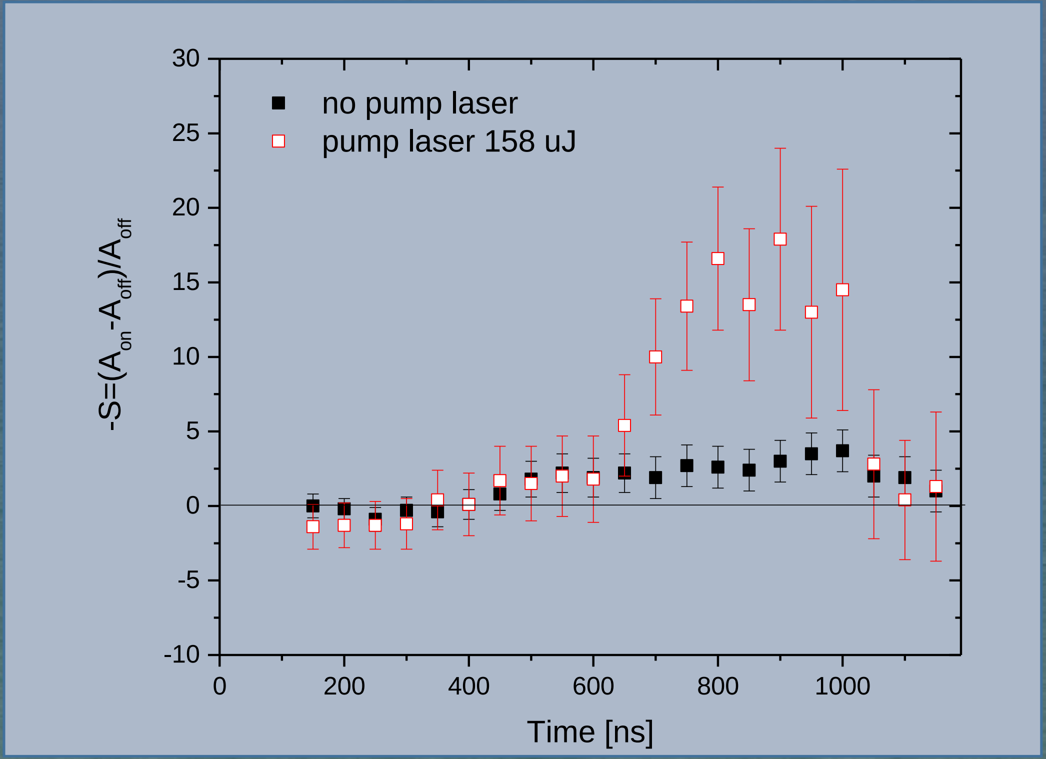
Laser delay	$1\,^3S \rightarrow 3\,^3P$ efficiency	$3\,^3P \rightarrow 2\,^3S$ efficiency	$2\,^3S$ average velocity
20 ns	$(13.8 \pm 2.2)\%$	$(9.7 \pm 2.7)\%$	$(1.0 \pm 0.1) \times 10^5$ ms^{-1}
35 ns	$(8.8 \pm 2.6)\%$	$(8.7 \pm 5.0)\%$	$(0.8 \pm 0.1) \times 10^5$ ms^{-1}
50 ns	$(6.8 \pm 2.9)\%$	$(10.1 \pm 6.2)\%$	$(0.7 \pm 0.1) \times 10^5$ ms^{-1}

2^3S Ps ,metastable state 1140 ns, stimulated production





preliminary

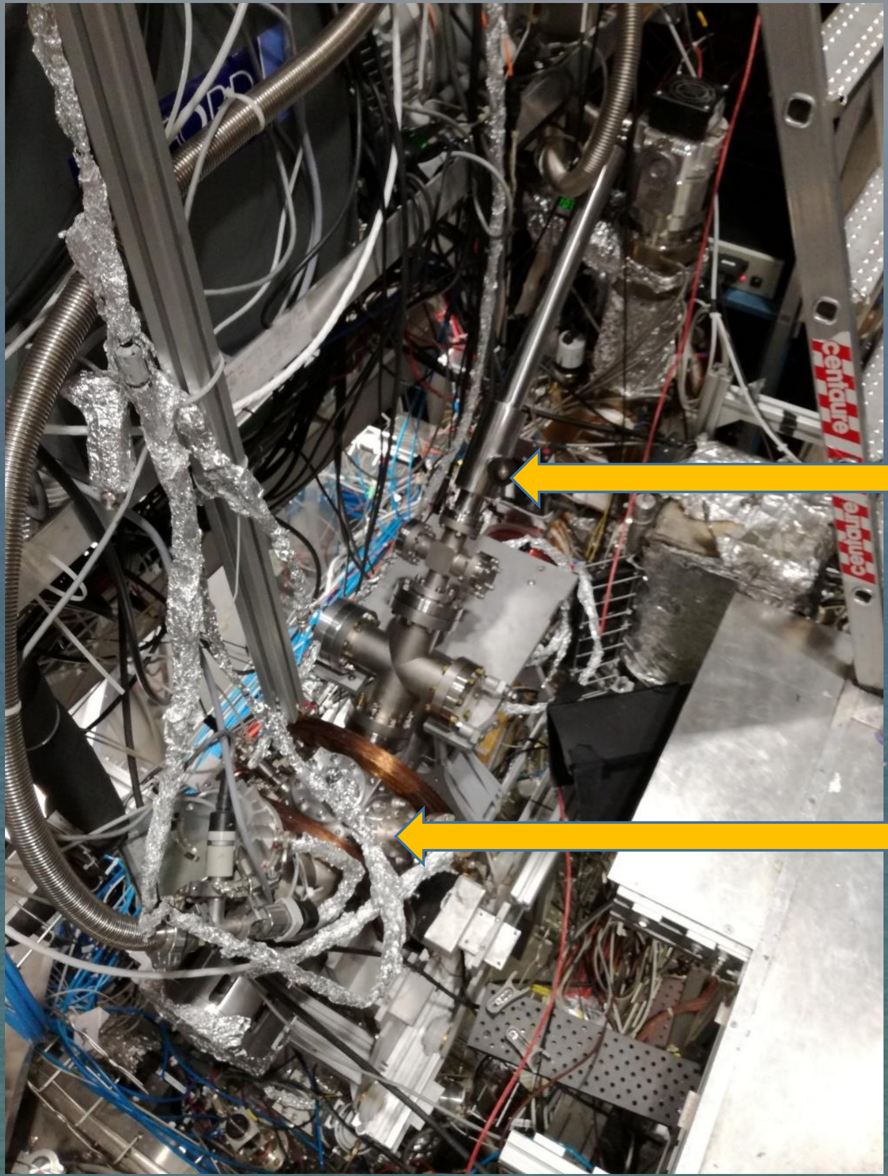


This give a 2^3S Ps yield of about 3 time more than spontaneous decay (with a tuned system we expect about 4.5 % of produced Ps in metastable state)

Outline

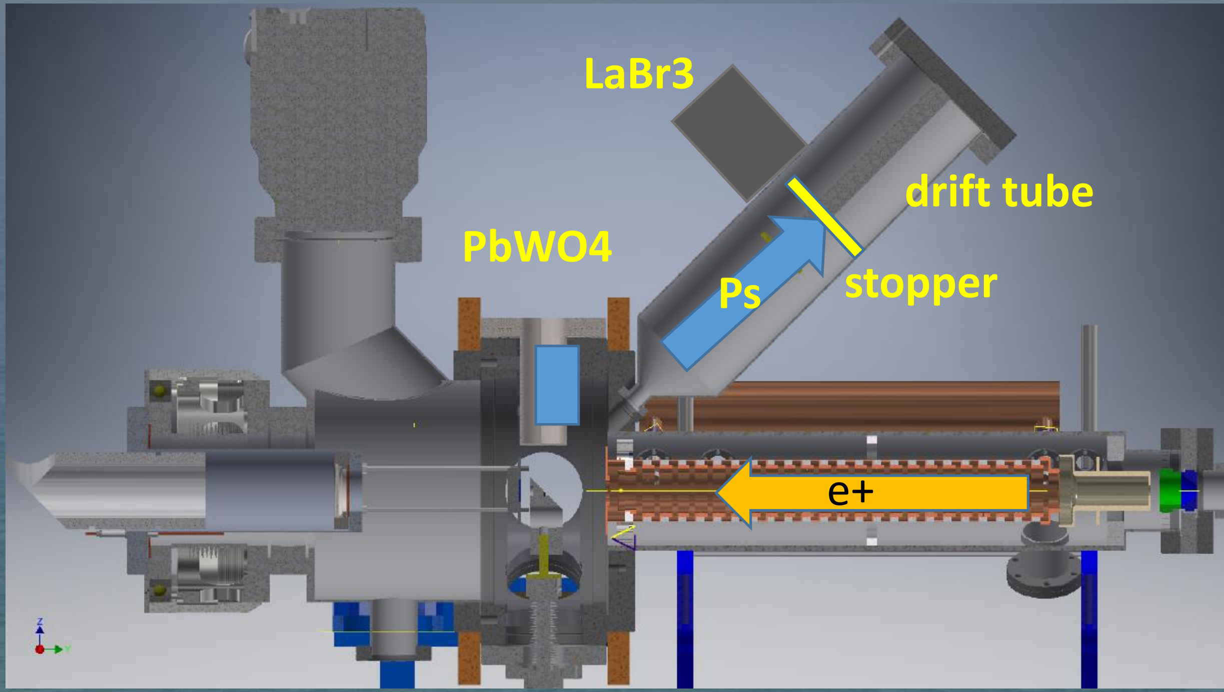
- How to obtain cooled Ps in vacuum
- Many positron bunched beams for many Ps in vacuum
- Ps excitation – long lived Ps
- Ps for Antihydrogen formation
- Metastable Ps
- metastable Ps beam - planned experiments
- Many positron polarized bunched beams
  planned experiments

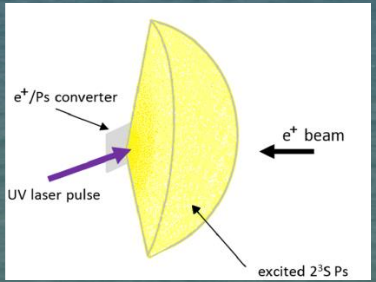
Ps metastable beam-apparatus



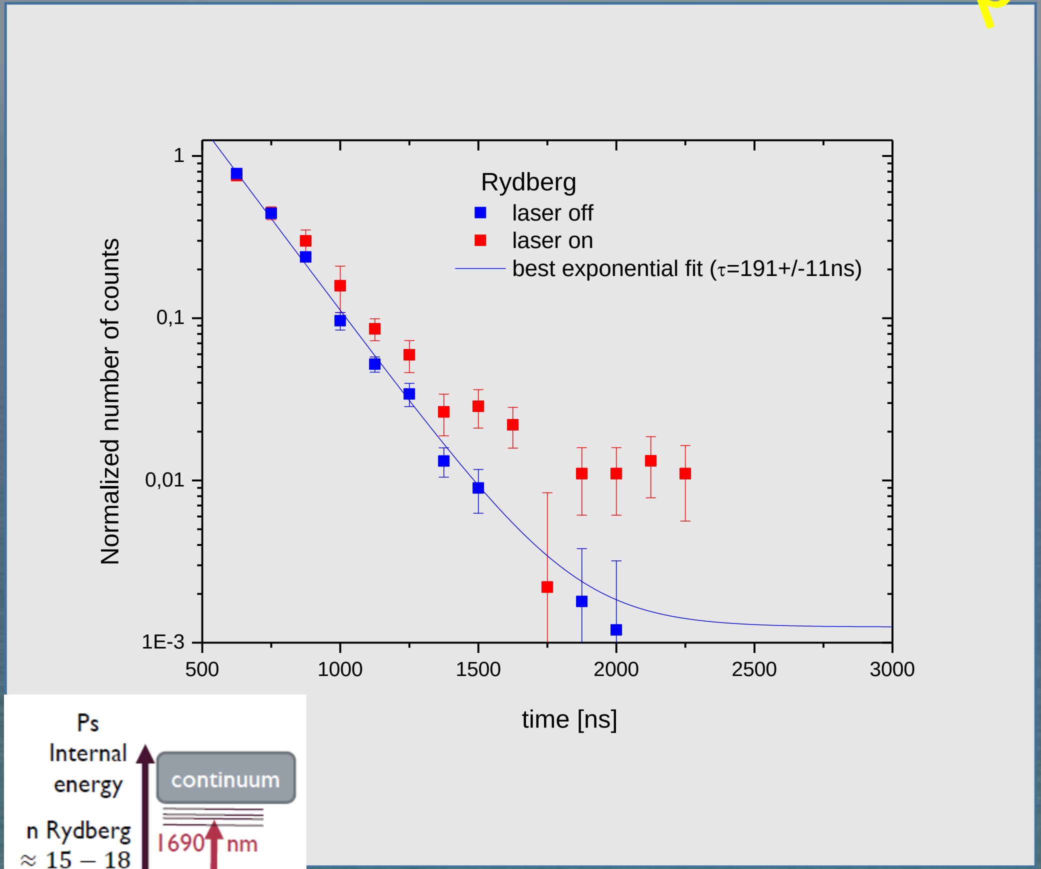
Metastable Ps drift tube

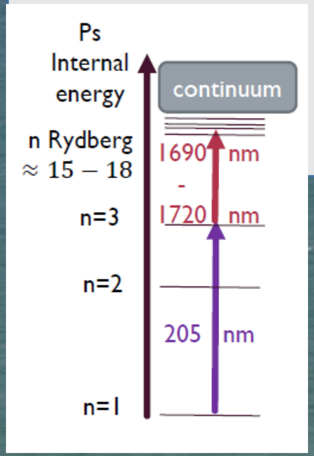
Ps chamber formation



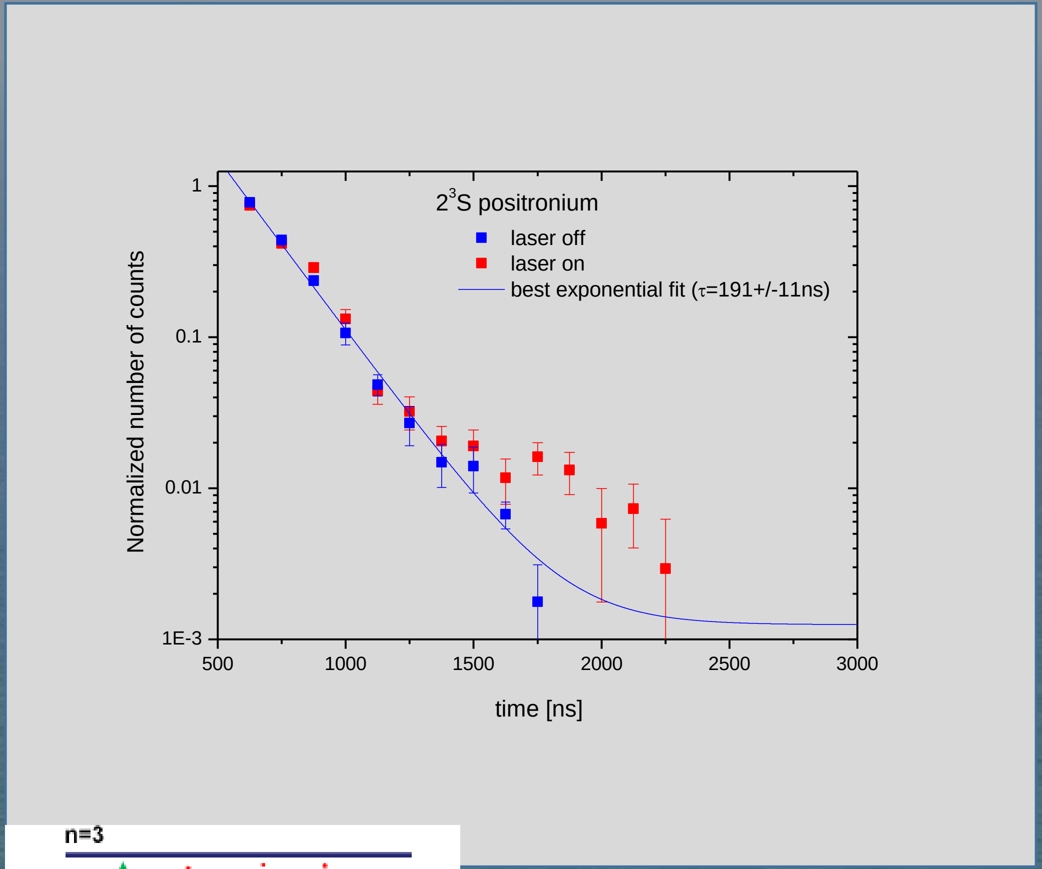


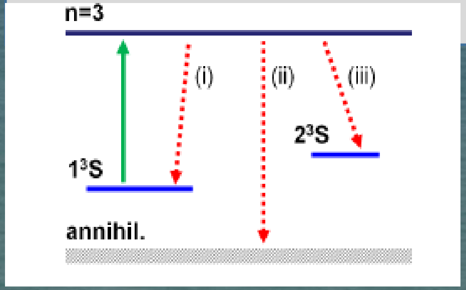
preliminary





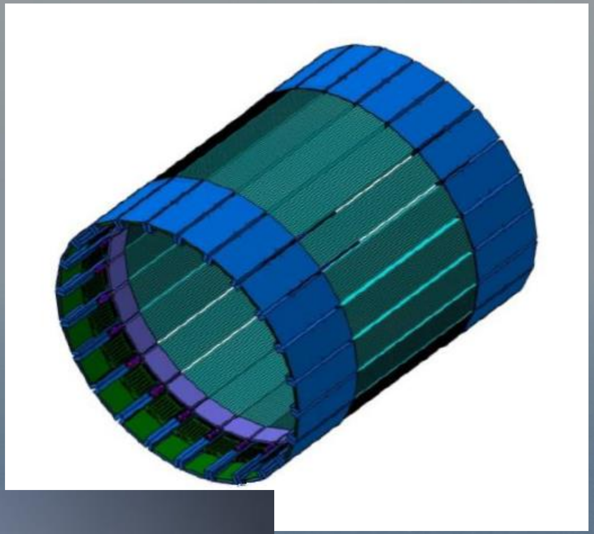
Ps Rydberg



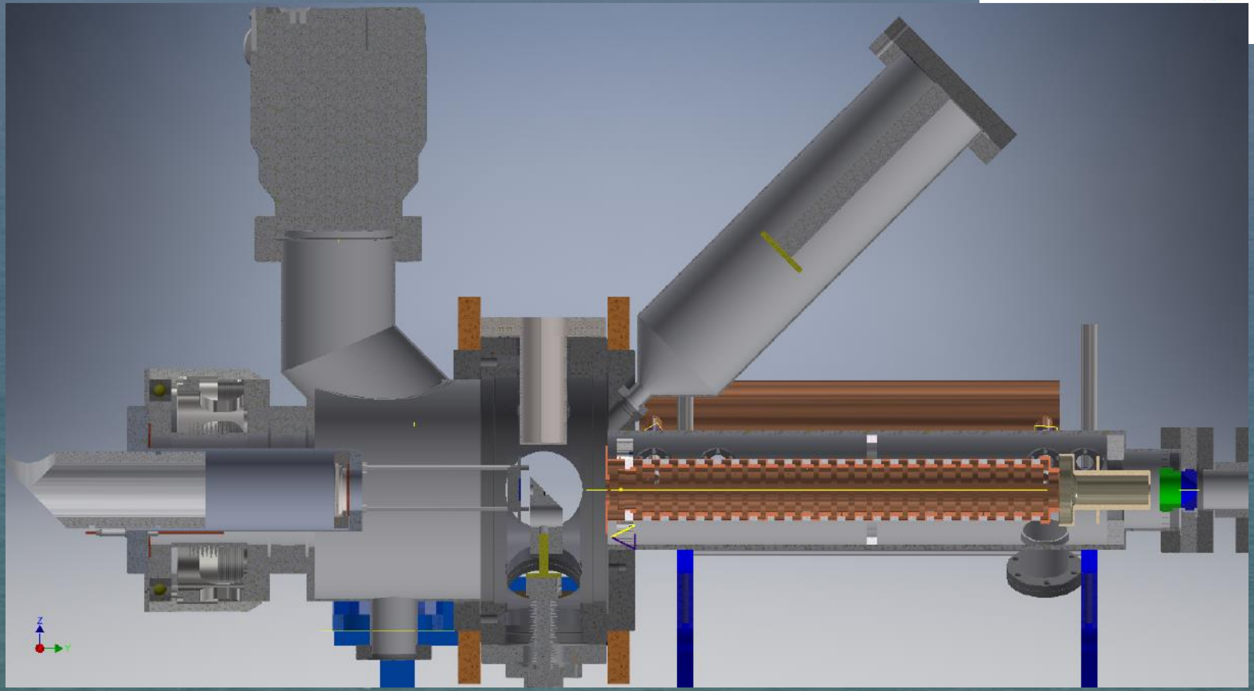


Ps Metastable

PLAN

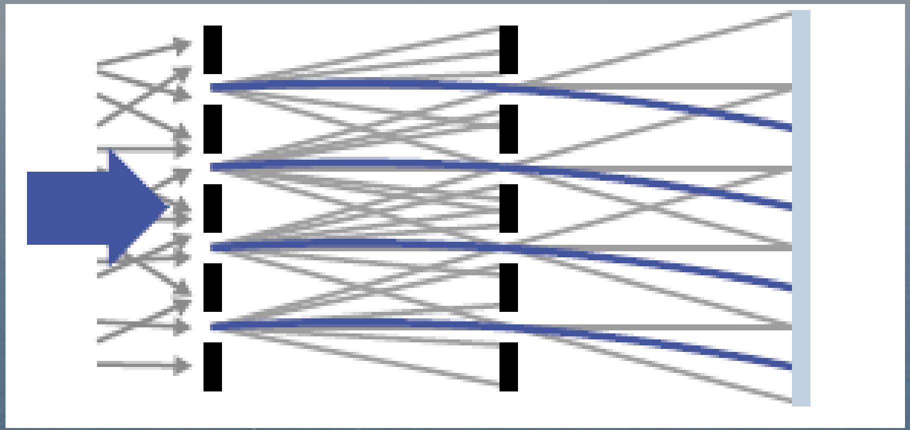


Determining the hitting position of the metastable Ps on the stopper, and
If possible its annihilation in flight
With a detector derived by J-PET



Jagiellonian Uni:
Pawel Moskal
Sushil Sharma

Towards measurement of g acting on Ps



Planned measurement with moire’ deflectometer or
Mach Zehnder interferometer
Measurement of dipole forces 100g -1000g (10%)

Outline

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- metastable Ps beam-planned experiments
- Many positron polarized bunched beams planned experiments

First stage of polarized e+ beam-source at Trento University

First Planned experiments

Study of entaglement of 3 photons of decaying Ps

Collaboration and tasks:

UNIVERSITÀ DEGLI STUDI DI TRENTO
Dipartimento di Fisica

INFN Istituto Nazionale di Fisica Nucleare

Trento Uni: Polarized Ps in vacuum and selection of oP states by laser or by solid state converters

universität wien

Vienna Uni: Beatrix C. Hiesmayr Theory

Marian Smoluchowski Institute of Physics
Jagiellonian University in Kraków

Jagiellonian Uni: Pawel Moskal
Detector System to measure momentum and spin of gammas


Detectors

J-PET's plastic revolution

A recently developed detector based on inexpensive plastic scintillators paves the way for whole-body PET imaging and precision measurements of fundamental symmetries.

CERNCOURIER

Conclusions

Manipulation of Long lived Positronium is shown to be possible, opening the route for interesting fundamental studies

Further improvements of quality of the metastable beam and of its intensity are possible developing techniques like Ps laser cooling and different schemes to bring Ps in the 2^3S state

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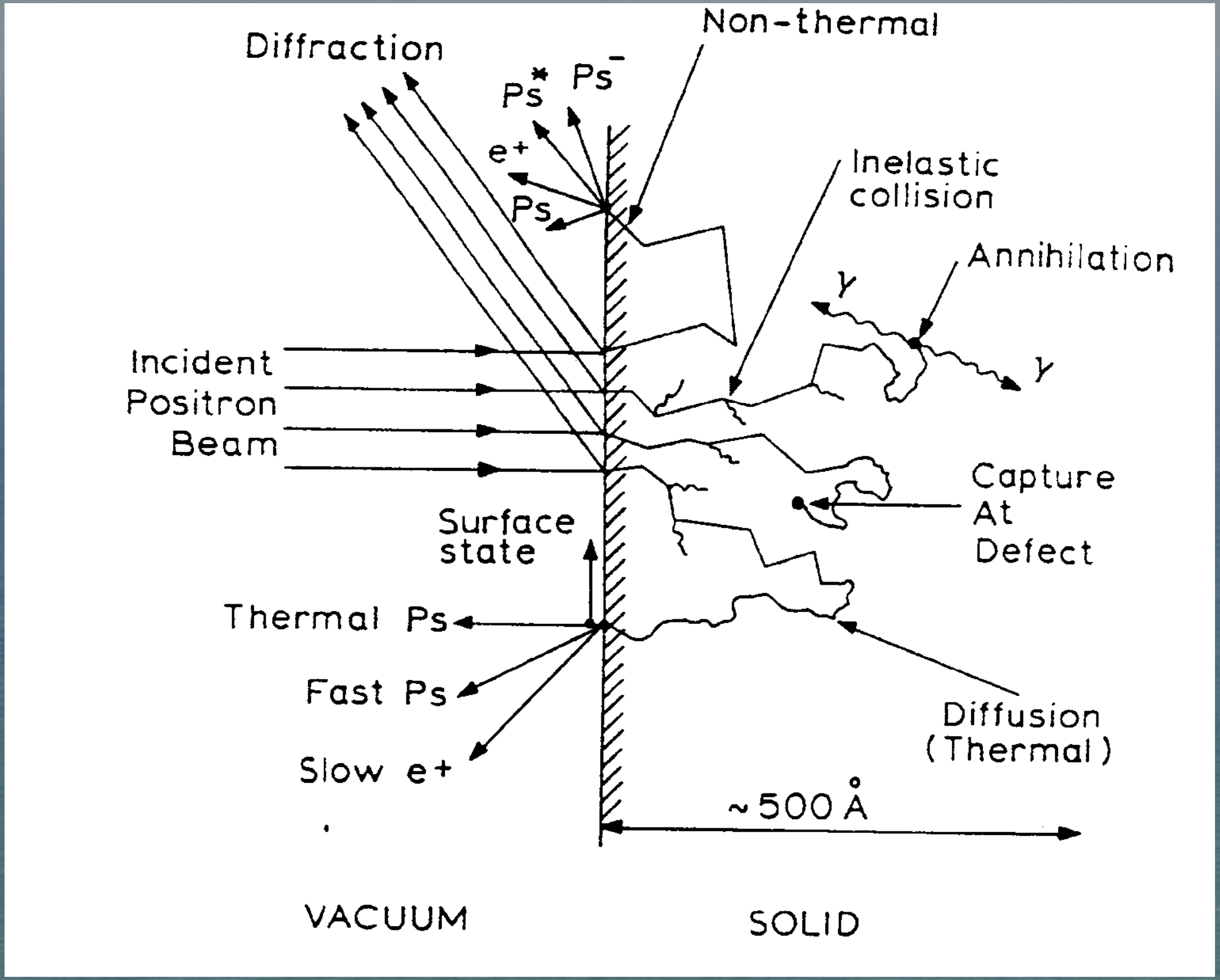
in particular laser-positron people
Ruggero Caravita
Benji Rienacker
Antoine Camper

New projects
Pawel Moskal
Sushil Sharma
Beatrix Hiesmayr

Thank you
for your attention!

Interaction of positrons with matter and moderation process



SLOWING DOWN to attain equilibrium

$0 < t < 10^{-12}\ s$

Energy loss : core excitation, plasmons, hole-electron, phonons

$$\frac{\partial f(\mathbf{r},\mathbf{p},t)}{\partial t} + \mathbf{v}(\mathbf{p})\cdot\nabla_{\mathbf{r}} f(\mathbf{r},\mathbf{p},t) + \mathbf{F}\cdot\nabla_{\mathbf{p}} f(\mathbf{r},\mathbf{p},t) = \left[\frac{\partial f(\mathbf{r},\mathbf{p},t)}{\partial t}\right]_s - (\lambda_b + \kappa) f(\mathbf{r},\mathbf{p},t) + f_i(\mathbf{r},\mathbf{p},t)$$

DIFFUSION

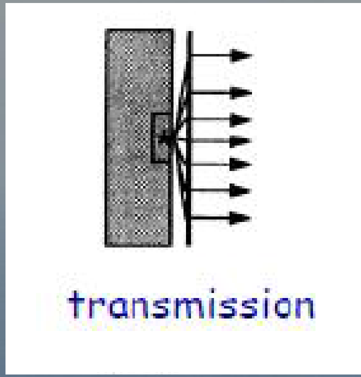
Free annihilation and trapping

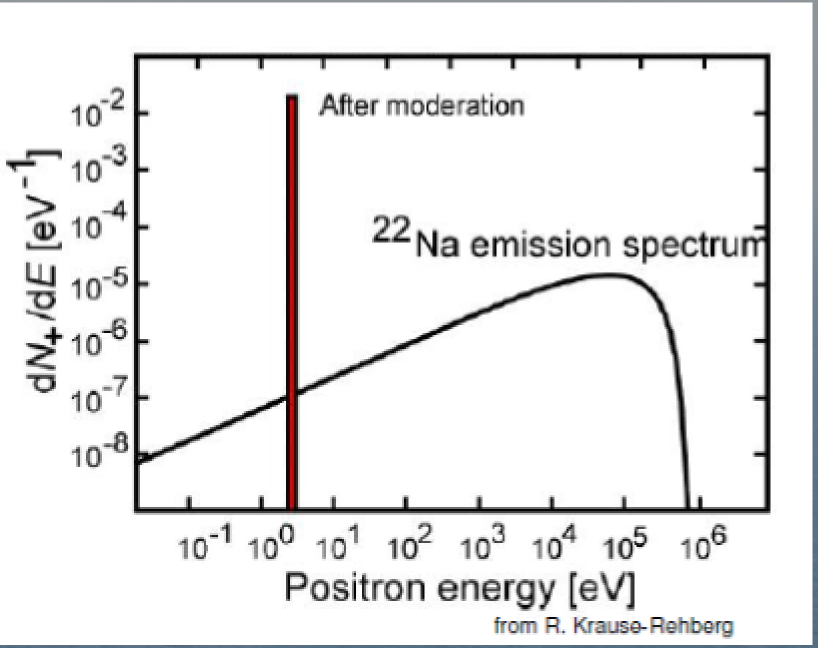
$$\frac{\partial f(\mathbf{r},t)}{\partial t} = D_+ \nabla^2 f(\mathbf{r},t) - [\lambda_b + \kappa(\mathbf{r})] f(\mathbf{r},t) - \nabla\cdot[\mathbf{v}_d(\mathbf{r}) f(\mathbf{r},t)] + f_i(\mathbf{r},t) ,$$

Steady state

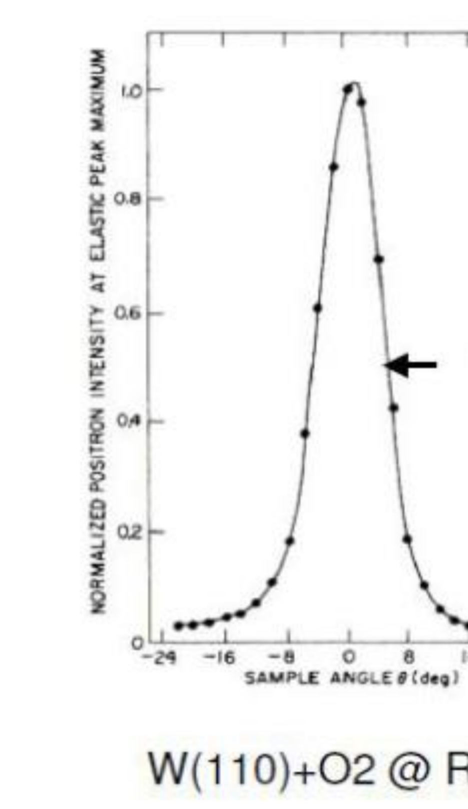
$$D_+ \nabla^2 f(\mathbf{r}) - [\lambda_b + \kappa(\mathbf{r})] f(\mathbf{r}) - \nabla\cdot[\mathbf{v}_d(\mathbf{r}) f(\mathbf{r})] + f_i(\mathbf{r}) = 0$$

Positron moderation

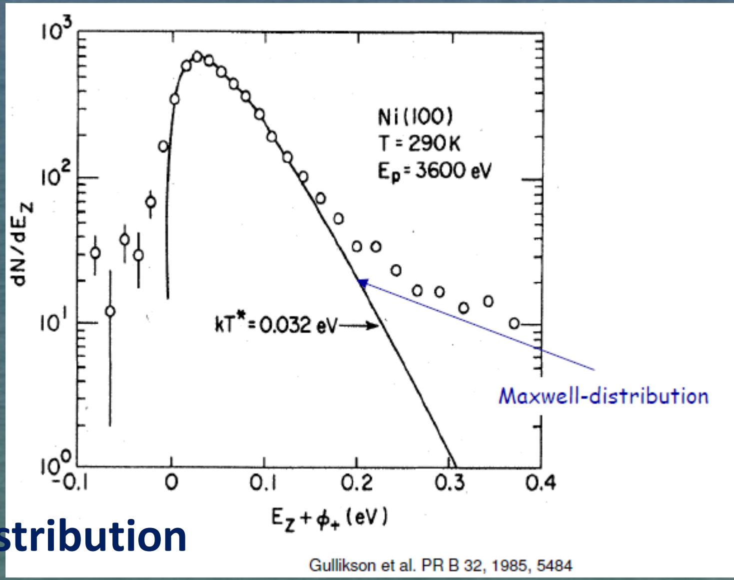




Angular distribution

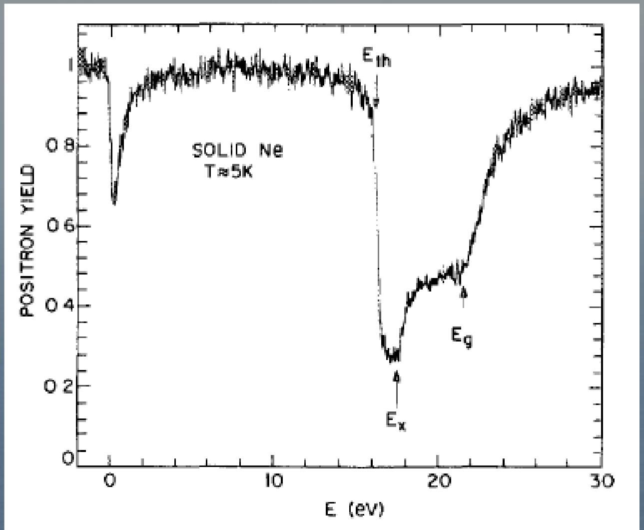


$$\theta^i_{1/2} \simeq \left[\frac{E_{prob}}{\phi^+}\right]^{1/2} = \left[\frac{kT}{\phi^+}\right]^{1/2}$$



Energy Distribution

Solid gas moderator



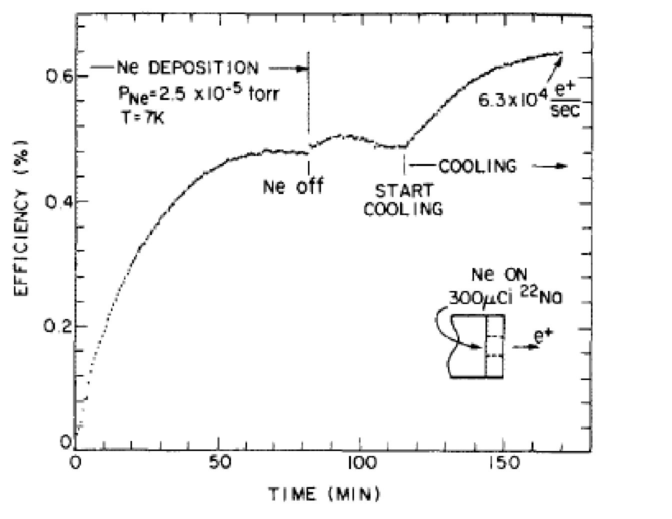
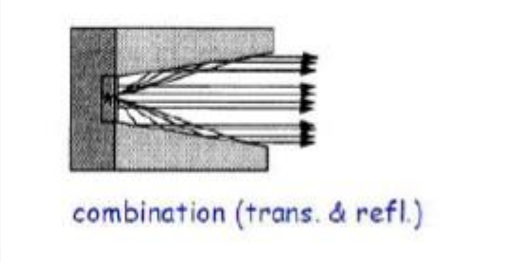
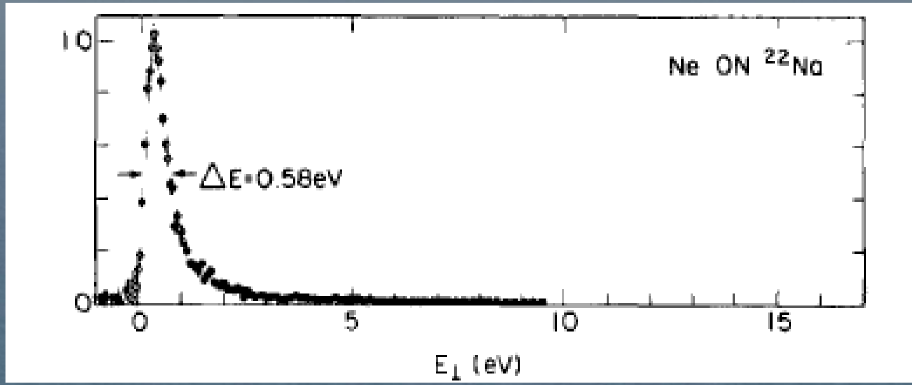


FIG. 4. Efficiency of the ^{22}Na plus solid Ne slow positron source vs time. Neon was condensed onto the ^{22}Na for the first 81 min. The efficiency increased to 0.64% when the source was cooled to ≃5 K. The inset shows the source deposit with the efficiency-enhancing cylinder in place.





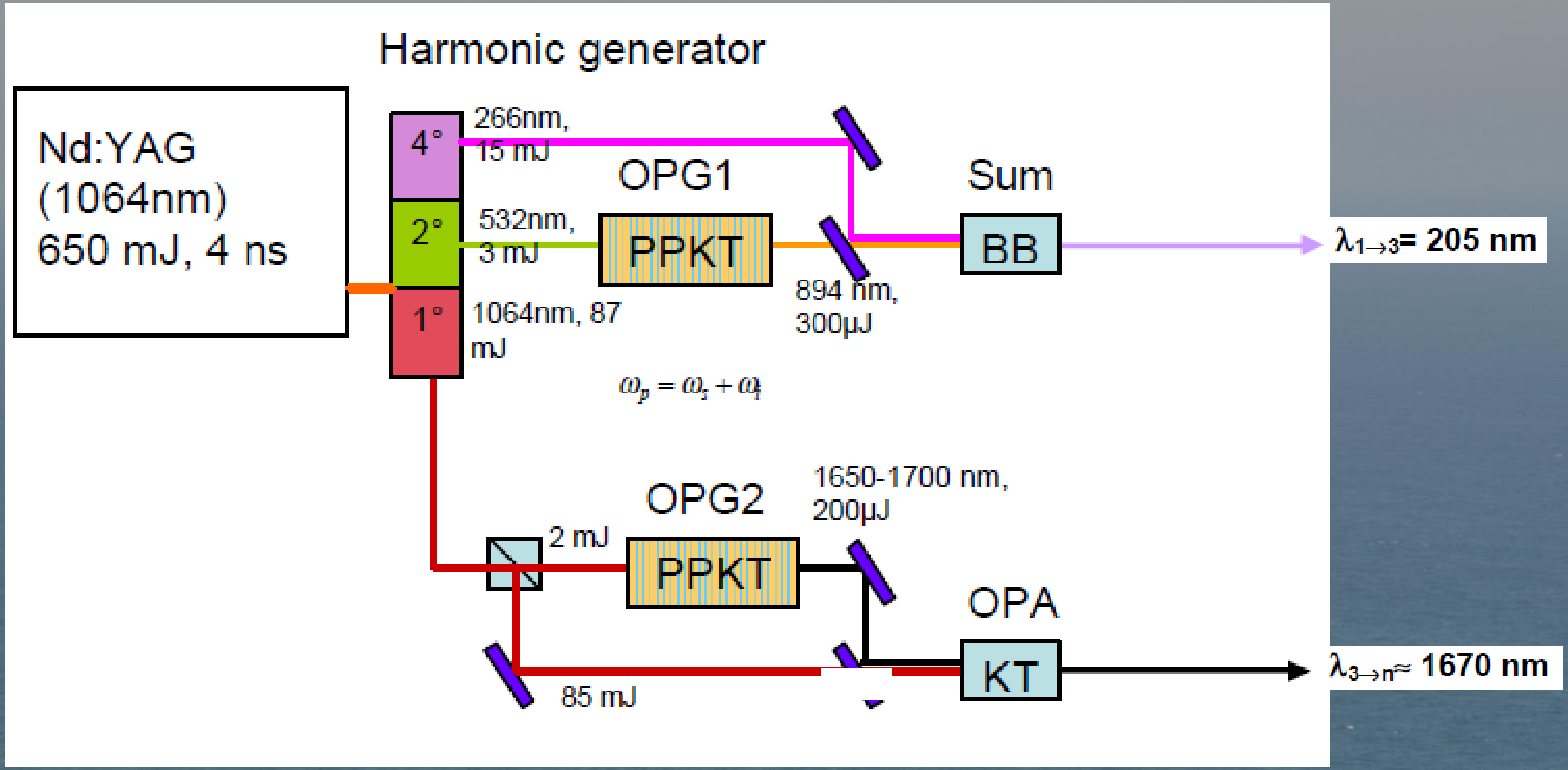
Energy spectrum of positron emitted by a thick Layer of Ne covering a Na22 source

TABLE I. Properties of rare gas solid moderators.

	Ne	Ar	Kr	Xe
Efficiency (%)	0.70(2)	0.13(2)	0.14(2)	0.13(2)
ΔE(eV)	0.58(5)	1.7(2)	1.8(2)	3.2(4)

A.P. Mills, E.M. Gullikson APL 49, 1121 (1986)

Ps excitation -laser system



OPG (Optical Parametric Generator) $\omega = \omega_1 + \omega_2$ Signal and Idler

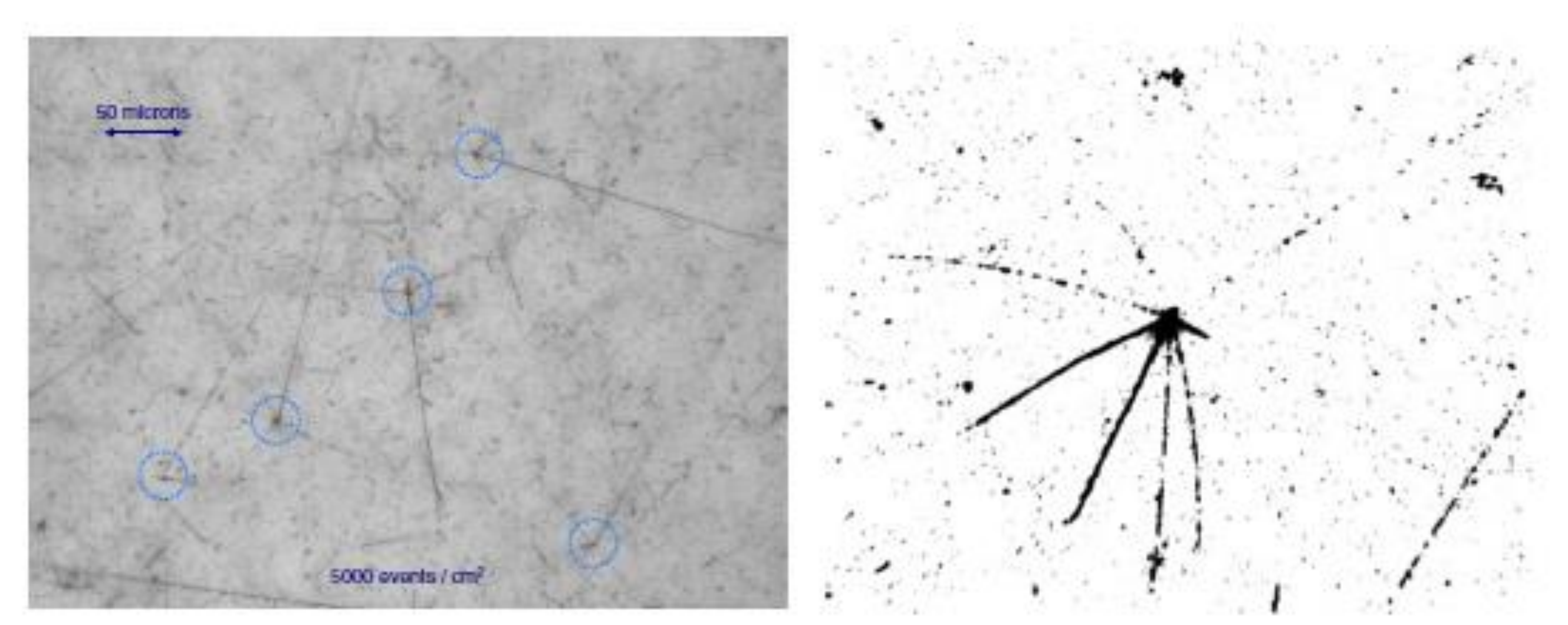
OPA (Optical Parametric Amplifier) after the OPG to match in SUM

SUM in a BBO (Barium Borate)crystal

Wavelength tuned by changing the OPG temperature

Cialdi et al. NIMB 269, 1527 (2011), Castelli et al. PRB 78, 052512 (2008))

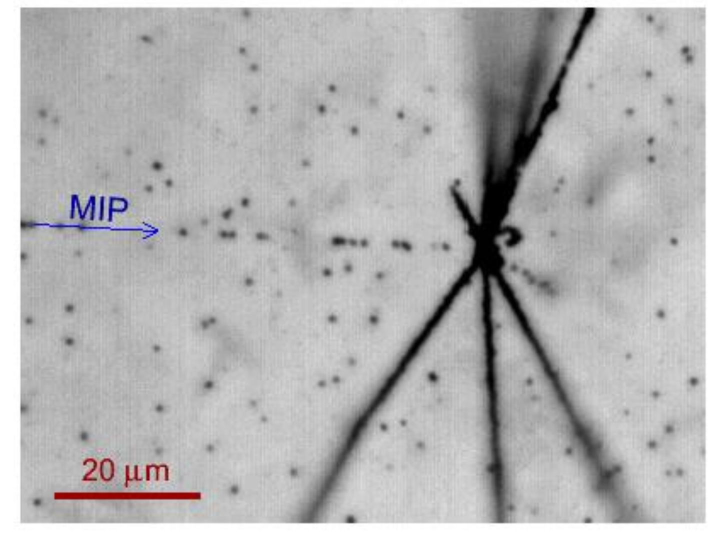
Detector: Emulsions



Gel developed by the University of Nagoya

Antiprotons 100 keV
Annihilation vertex and tracks.
Positions are found with 1-2 μm resolution

Tacks main pions, vertex proton and Heavy nuclear fragments.



Storey et al. Hyp. Inter . 228, 151 (2014), S. Aghion et al. JINST 2013