POSITRONIUM STUDIES WITHIN THE QUPLAS EXPERIMENT

Stefano AGHION[1,2] on behalf of the QUPLAS collaboration

[1] L-NESS, Dipartimento di Fisica, Politecnico di Milano
[2] Istituto Nazionale di Fisica Nucleare Sezione di Milano

AMDPP – October 2016

QUPLAS

QUPLAS

QUantum Interferometry, decoherence and gravitational studies with **P**ositrons and **LAS**ers

QUPLAS main goals are to:

- ✧ perform **positron interferometry** (QUPLAS - 0)
- ✧ perform **positronium (Ps) interferometry** (QUPLAS – I)
- ✧ measure the **gravitational acceleration** of a **Ps** beam (QUPLAS - II)

VEPAS

Variable **E**nergy **P**ositron **A**nnihilation **S**pectroscopy

Politecnico di Milano, Como

INFN Istituto Nazionale di Fisica Nucleare

POLITECNICO MILANO 1863

THE QUPLAS COLLABORATION

Università degli Studi di Milano and Infn Milano

F. Castelli, S. Cialdi, M. Giammarchi, M. Longhi, G. Maero, L. Miramonti, S. Olivares, M. Paris, M. Potenza, M. Romé, S. Sala

Politecnico di Milano (at Como)

S. Aghion, M. Bollani (IFN, CNR), M. Lodari, C. Evans, M. Leone, R. Ferragut

Albert Einstein Center – Laboratory for HEP – Bern University

A. Ariga, T. Ariga, A. Ereditato, C. Pistillo, P.Scampoli

Dept. of Chemistry, University of Bath

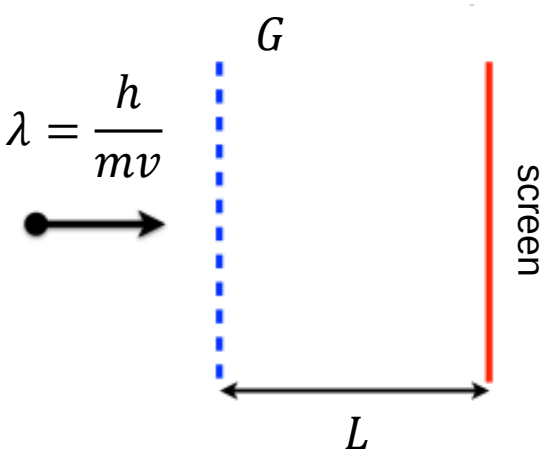
K. Edler

R. Greaves (Los Angeles, formerly at First Point Scientific)

OUTLINE

1) INTRODUCTION
2) MOTIVATIONS
3) THE QUPLAS PROJECT
    a) QUPLAS 0
    b) QUPLAS I
    c) QUPLAS II
4) CURRENT PROGRESS
5) CONCLUDING REMARKS

Particle interferometry



The particle probability density distribution:

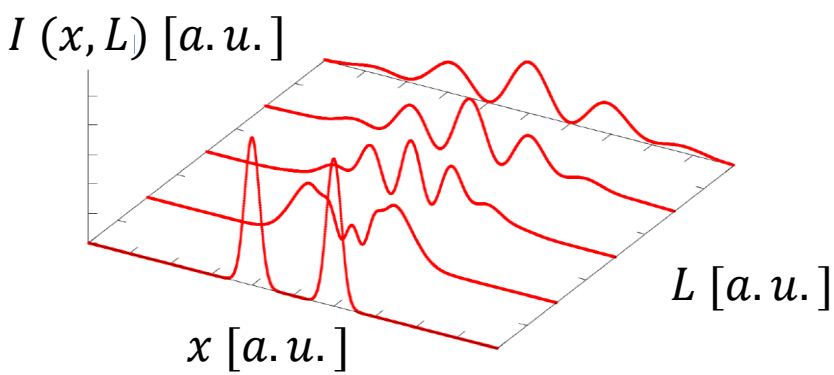
$$I(x) = |\psi^{(N)}(x, t = L/v)|^2$$

where:

$$\psi^{(N)}(x,t) = \frac{1}{\sqrt{\lambda L}} \int_{-\infty}^{+\infty} \exp\left[\mathrm{i}\frac{\pi}{\lambda L}(x - x')^2\right] \psi^{(N)}(x', 0)\, \mathrm{d}x'$$

analog to the Fresnel integral of classical optics.

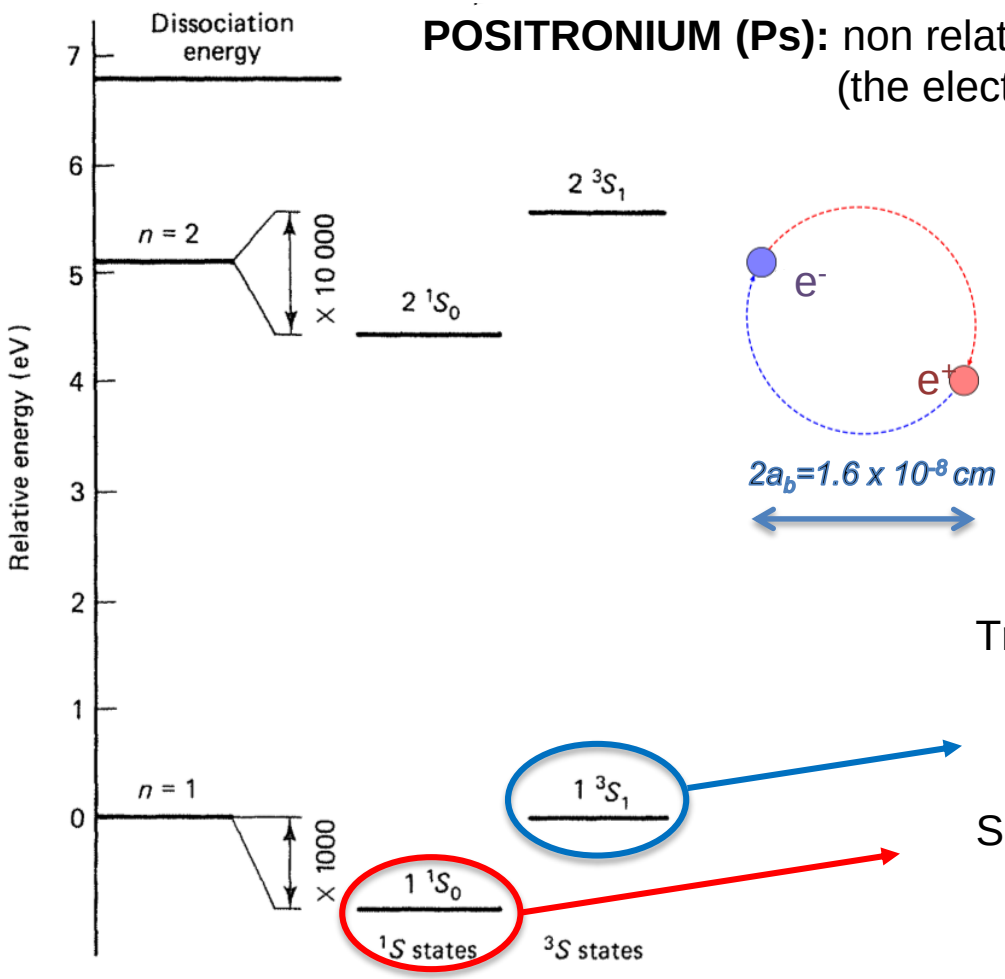
Ideal case of two slits in :



Interferometry can be a tool for:

- conducting quantum mechanical studies;
- measuring uniform forces acting on the particles in flight.

INTRODUCTION
Positronium



POSITRONIUM (Ps): non relativistic purely leptonic bound state of a particle (the electron) and its antiparticle (the positron)

Schrödinger equation:

$$\left(-\frac{\hbar^2}{2\mu_{Ps}}\nabla^2 - \frac{e^2}{r}\right)\psi_{Ps} = i\hbar\frac{\partial}{\partial t}\psi_{Ps}$$

Reduced mass:

$$\mu_{Ps} = \frac{m_e}{2}$$

Energy levels:

$$E_{n,Ps} = -\alpha^2 mc^2 \frac{1}{4n^2} = \frac{E_{n,H}}{2}$$

Triplet state, ortho-Ps mean lifetime

$$\boxed{\tau_{o-Ps} = 142\ ns}$$

Singlet state, para-Ps mean lifetime

$$\boxed{\tau_{p-Ps} = 125\ ps}$$

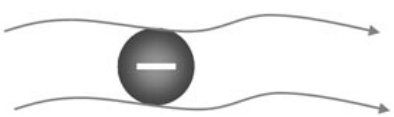
Antimatter interferometry

… never done before!

1. **Interferometry with positrons**

   - New type of CPT tests on fundamental fermions by comparison the matter wave interferometry properties of positrons and electrons

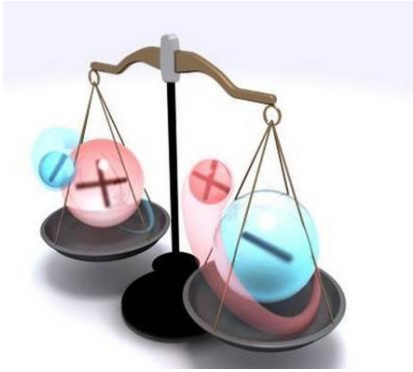
$$\lambda = \frac{h}{p}$$



Luis de Broglie 1892-1987

2. **Interferometry with positronium**

   - Quantum mechanical studies on Ps
   - **Measurement of the gravitational acceleration of positronium in the Earth gravitational field**



Gravity (I/II)

Still missing a Quantum Theory of Gravity, in many Quantum Gravity models (in the classical static limit):

$$V = \frac{-GmM}{r}\left(1 \mp ae^{-r/v} + be^{-r/s}\right)$$

Graviton

Gravi-Vector

Gravi-Scalar

The sign of the Gravi-Vector can be different for Matter and Antimatter

Matter-Matter experiments
$|a - b|$

Matter-Antimatter experiments
$|a + b|$

Weak **E**quivalence **P**rinciple (**WEP**) violation **?**

MOTIVATIONS
Gravity (II/II)

Dynamical meaning:

$$F = m_I a$$

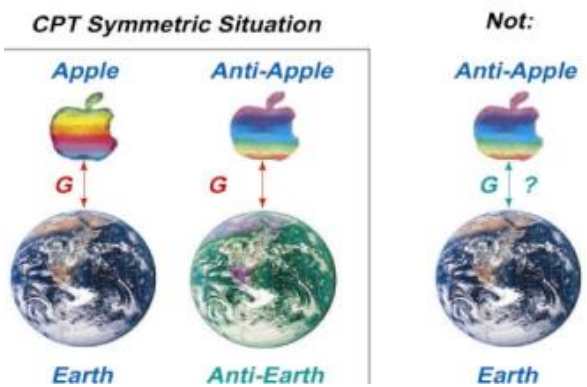
The gravitational "charge":

$$F = -G m_G M_G / r^2$$

According to the WEP: $m_I = m_G$

According to the CPT: $m_I = \bar{m}_I$

$$m_G = m_I = \bar{m}_I \ ? \ \bar{m}_G$$



$m_G \neq \bar{m}_G$ would not mean that CPT is broken !

Where do we stand?

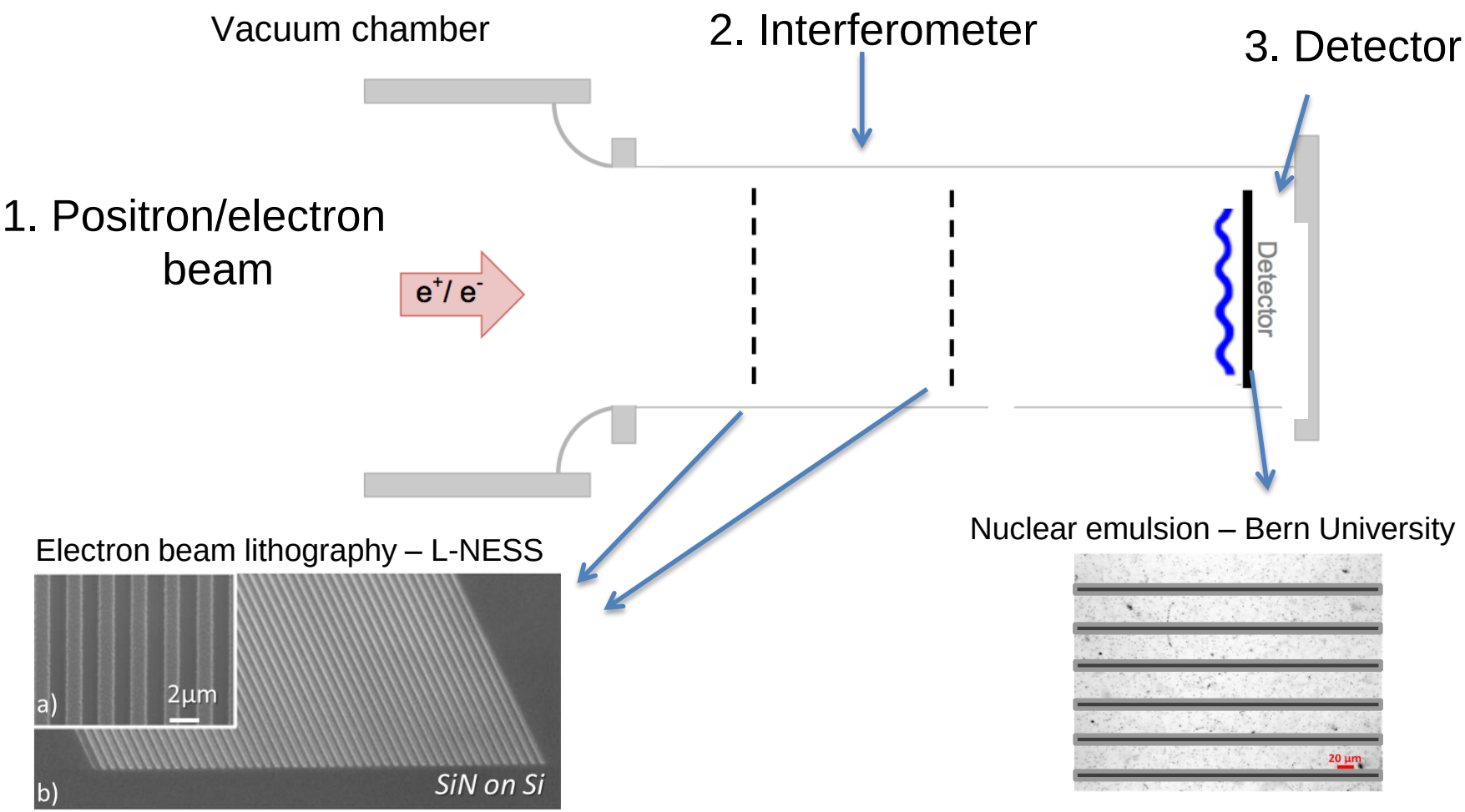
WEP for matter-matter systems: 10^{-13} of accuracy

WEP for matter-antimatter systems: ?

New physics!

OUTLINE

Positron interferometry



QUPLAS 0

VEPAS slow positron beam (I/II)

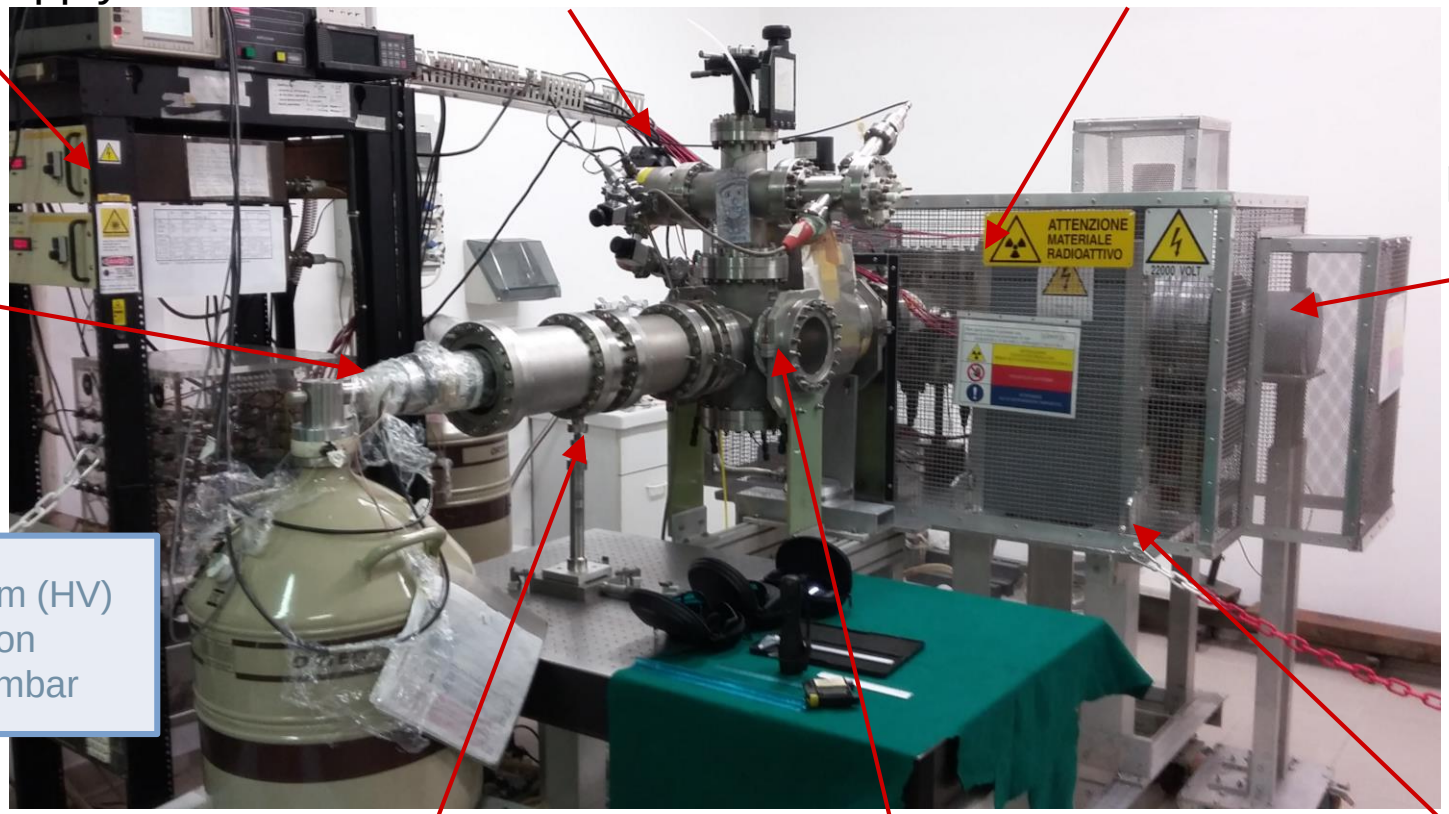
HV power supply

Turbo pump

Beam optics

^{22}Na positron source

Detector HPGe



High vacuum (HV) condition
10^{-7}-10^{-8} mbar

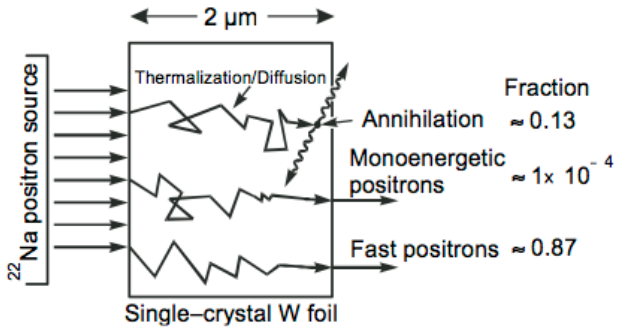
Interferometer tube

Sample chamber

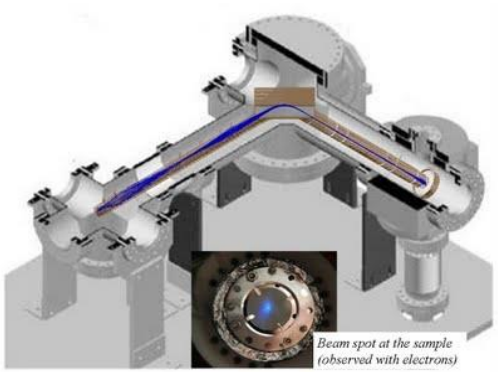
Faraday cage

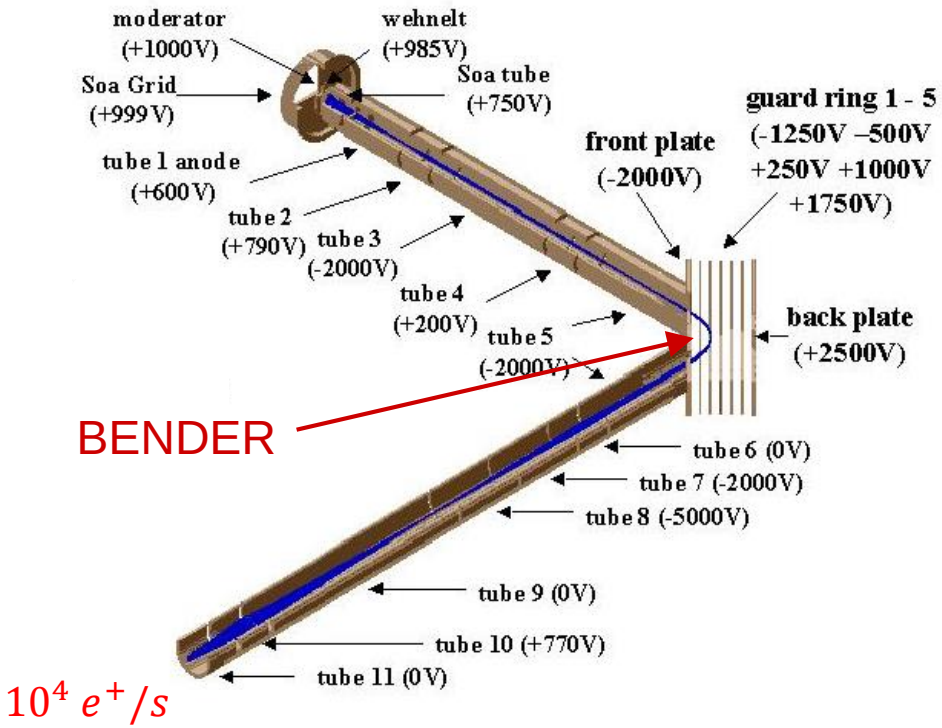
VEPAS slow positron beam (II/II)

Beam source ^{22}Na: current intensity ≈ 10 mCi



Beam energy: 0.1-20 keV



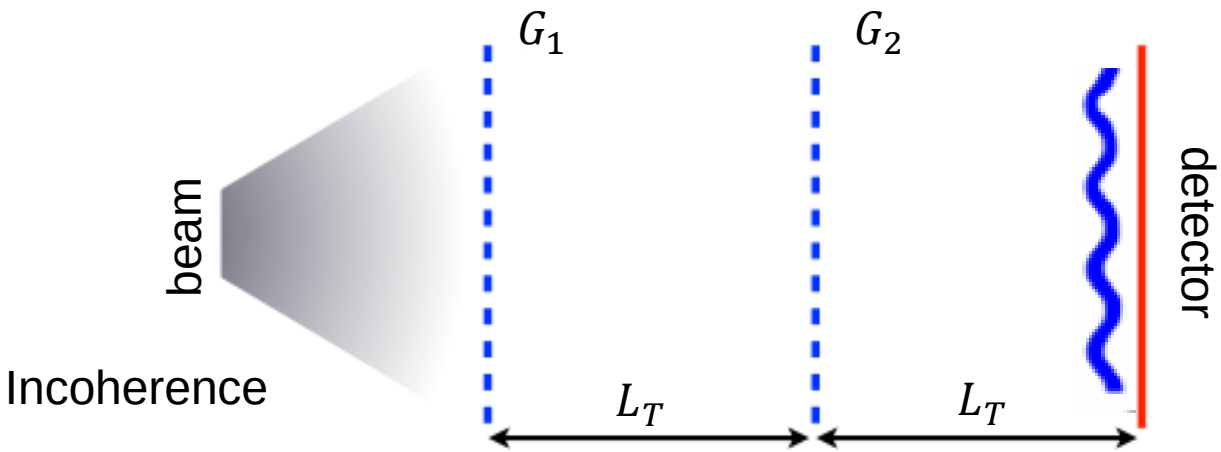


$10^4\ e^+/s$

Talbot Lau regime (I/II)

The **Talbot-Lau** regime in respect to the Fraunhofer (far field) regime:

- ✓ Minimization of the total length of the apparatus
- ✓ Robust to the incoherence of the source



Talbot length

$$L_T = \frac{D^2}{\lambda}$$

Generation of coherence

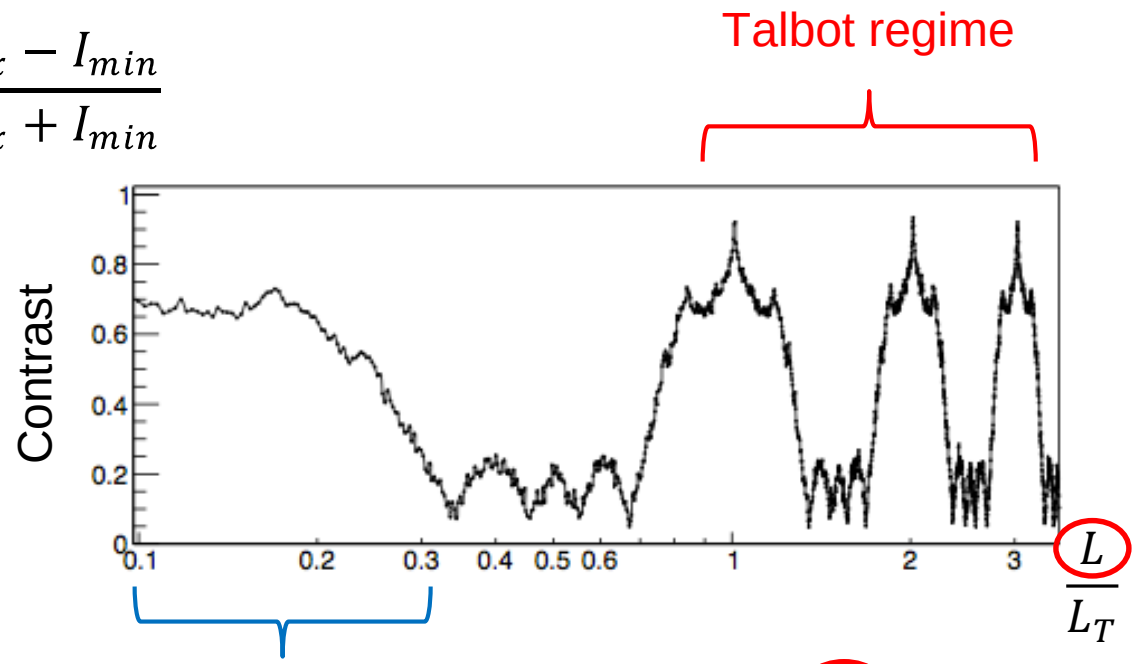
Interference

Fringe pattern with the same periodicity *D* of the gratings

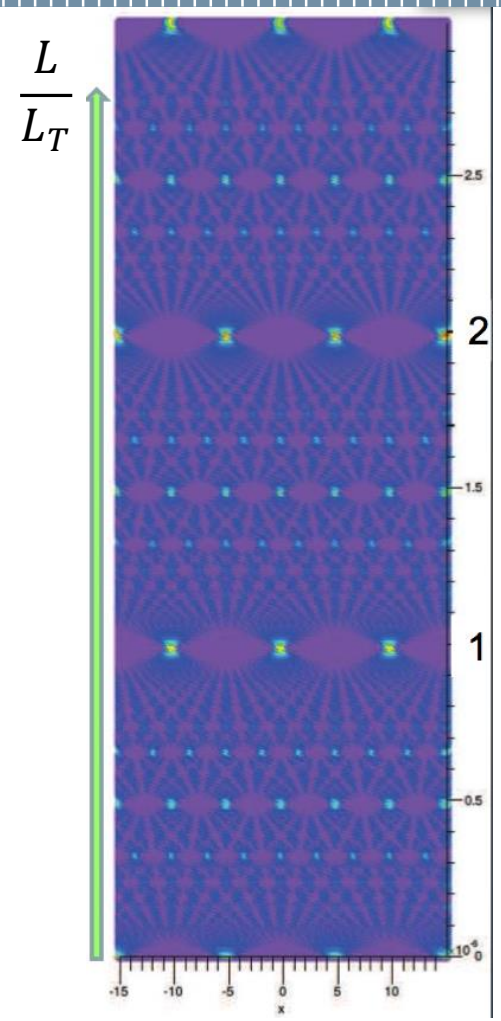
Talbot Lau regime (II/II)

Monte Carlo simulations [1]

$$c = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$



$$L_T = \frac{D^2}{\lambda}$$



[1] S. Sala *et al.*, J. of Phys. B 48 (2015) 195002

Numbers

Positron kinetic energy

$$T = 10\ keV$$

Positron velocity

$$v = 6 \times 10^{7}\ m/s$$

The de Broglie wavelength

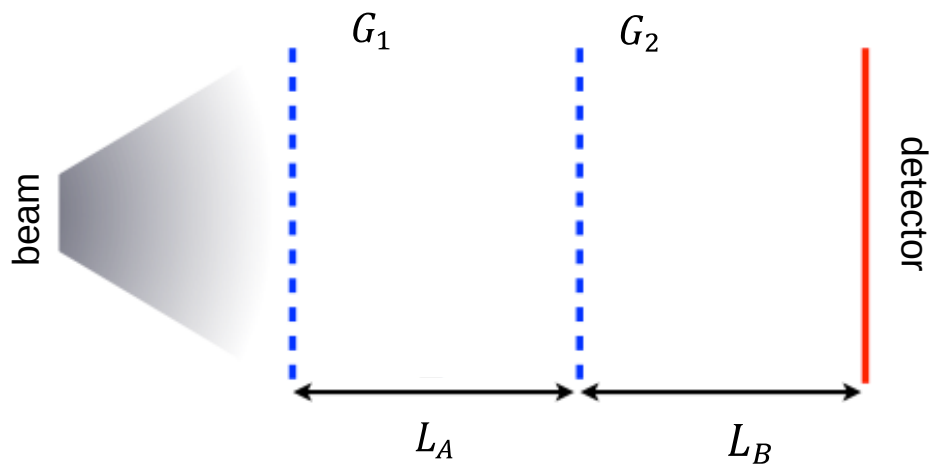
$$\lambda = \frac{h}{mv} = 1.2 \times 10^{-11}\ m$$

Periodicity of the grating

$$D = 2\ \mu m$$

Talbot Length

$$L_T = \frac{D^2}{\lambda} = 33\ cm$$

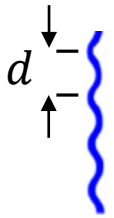


Therefore:

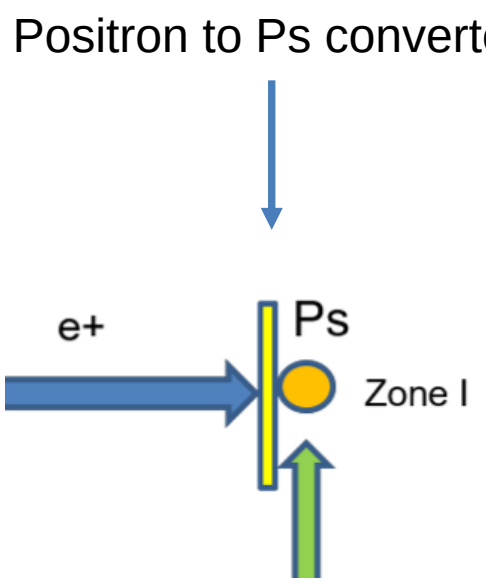
$$L_A = L_B = 33\ cm$$

and the periodicity pattern on the emulsion:

$$d = 2\ \mu m$$



…towards QUPLAS I

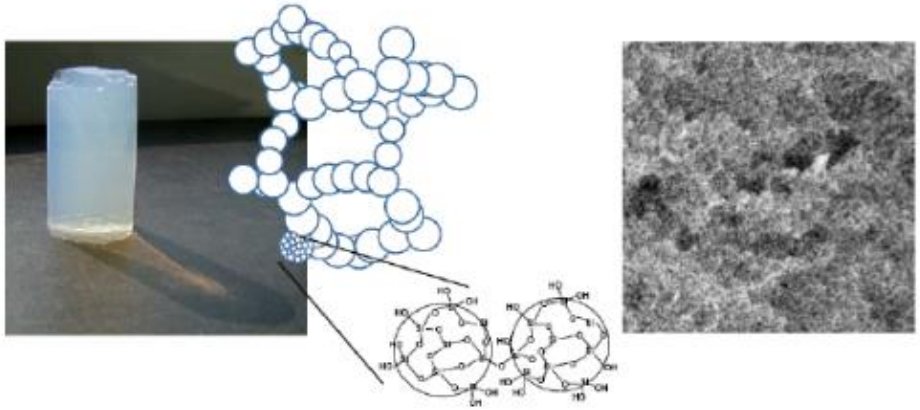


How to create a positronium beam?

Positron to Ps converters

Good e+/Ps converters: mesoporous silica samples
Ex: Aerogel 85/150

- 85/150 mg/cm^3
- 96/93 % porosity
- disorded porous material
- hydrophobic -> no ice



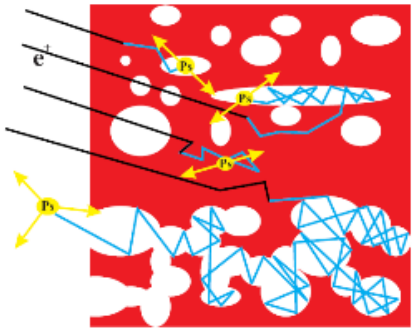
Ps formed inside:

$v \approx 4 - 7 \times 10^5$ m s^{-1}
(E ≈ 1-3 eV)

Ps emitted from the surface:

$v \approx 10^4$ m s^{-1} (E ≈ meV)

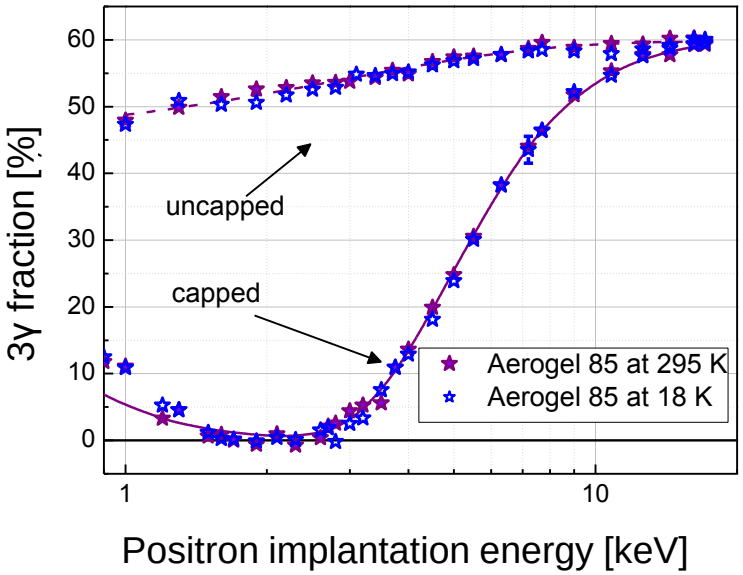
$$E_{th} \approx \frac{3}{2} K_B T$$



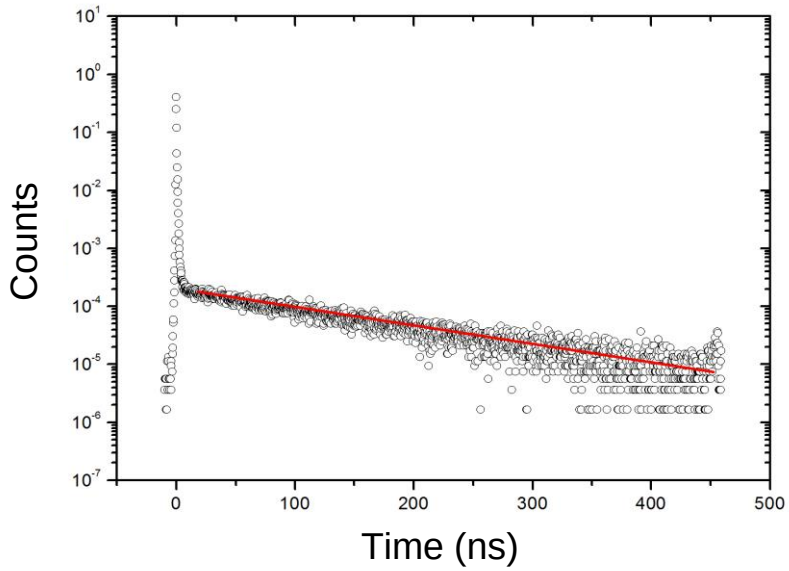
T [K]	$\langle v_{th} \rangle$ [m s^{-1}]
300	8×10^4
10	1×10^4

Positron to Ps converters: Ps yield and lifetime

Positronium yield



Positronium lifetime



Experimental evidences:

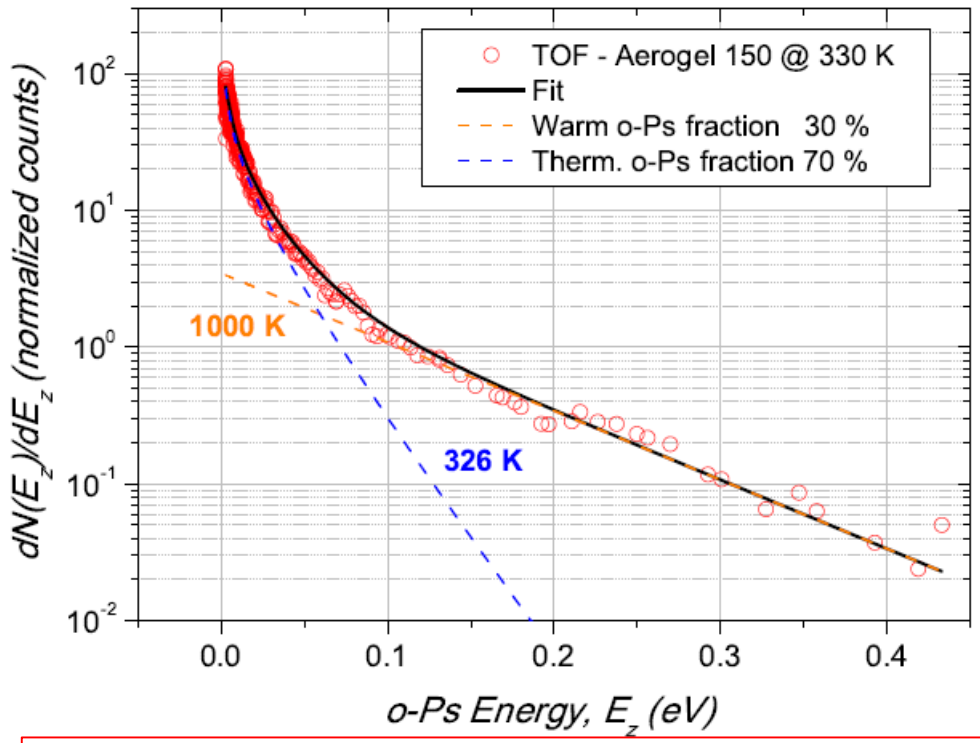
- High ortho-Ps yield ≈ 60%
- µm ortho-Ps diffusion length
- long ortho-Ps lifetime

T (K)	$L_{o\text{-}Ps}^{diff}$ *(µm)*	$\tau_{o\text{-}Ps}$ *(ns)*	*l (nm)*
295	2.30 (0.25)	129 (3)	32 (2)
18	2.25 (0.25)	128 (3)	30 (2)

G. Consolati *et al.*, Chem. Soc. Rev. 42, 3821 (2013)

Positron to Ps converters: Ps TOF

Aerogel 150 TOF spectrum



≈ 70 % of the o-Ps formed thermalizes inside the Aerogel!

Fitting model:

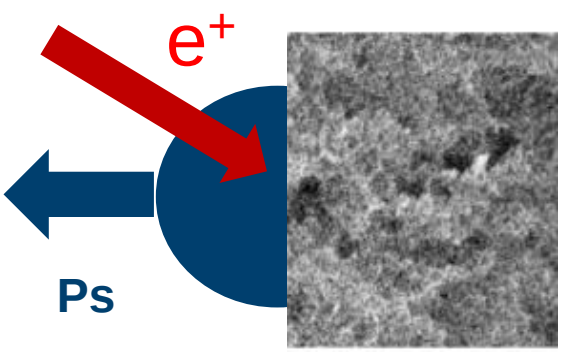
$$f(E_z) = \frac{\alpha}{k_B T_w} e^{-\frac{E_z}{k_B T_w}} + \frac{\beta}{\sqrt{\pi k_B T_{Th} E_z}} e^{-\frac{E_z}{k_B T_{Th}}}$$

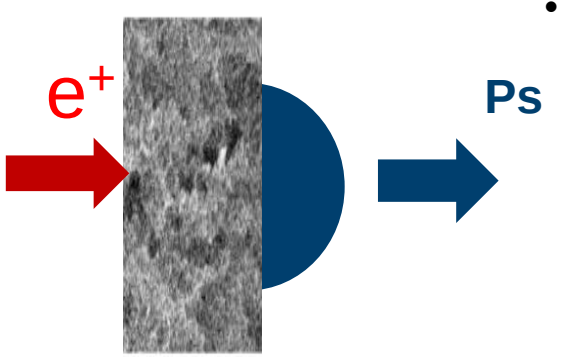
Results:

Parameter	Value
α	0.30 ± 0.05
T_w (K)	1000 ± 30
β	0.70 ± 0.05
T_{Th} (K)	326 ± 10

Positron to Ps converters: transmission

REFLECTION VS TRANSMISSION

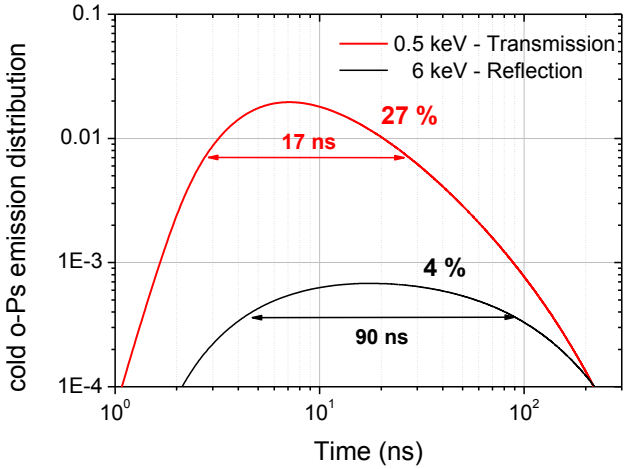




$\approx \mu m$

- GEOMETRY
  - + Solid angle
  - + Secondary electrons
  - + Backscattered positrons

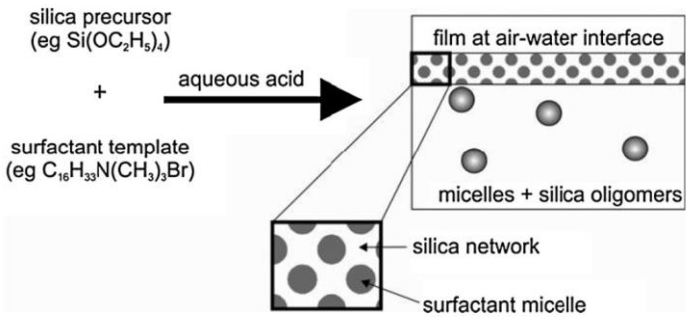
- Ps CLUOD FEATURES
  - + Monocromatic Ps beam
  - + **Higher termalized Ps fraction**



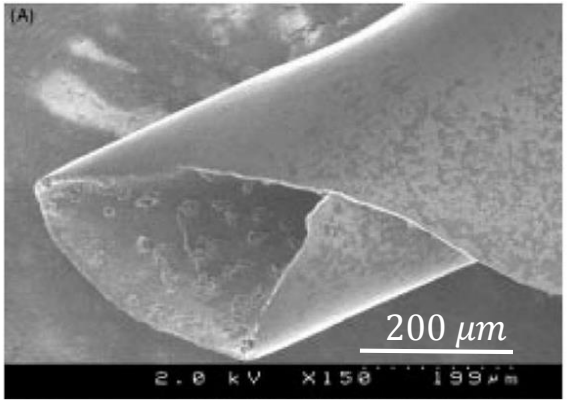
...but micrometric thickness required: difficult to produce and to handle!

Transmission targets development (I/II)

1) Synthesis route to growth free-standing surfactant-template films of silica (Chemistry Department, University of Bath, Claverton Down, Bath) [1]



Calcination (400ºC)



2)

..and

Chem. Mater. **2003**, *15*, 3619−3624 3619

Transferable Thin Films of Mesoporous Silica

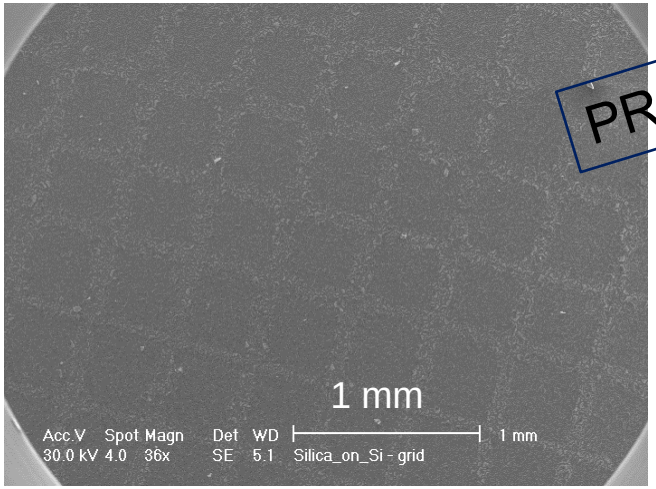
Rajdip Bandyopadhyaya,[†] Einat Nativ-Roth,[†] Rachel Yerushalmi-Rozen,[†,‡] and Oren Regev*[,†,‡,§]

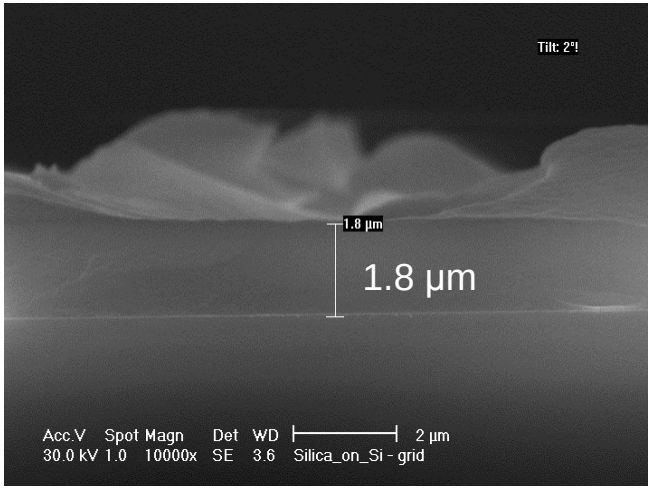
Department of Chemical Engineering and The Ilse Katz Center for Meso and Nano-Scale Science and Technology, Ben-Gurion University of the Negev, 84105 Beer-Sheva, Israel, and Laboratory of Polymer Chemistry, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

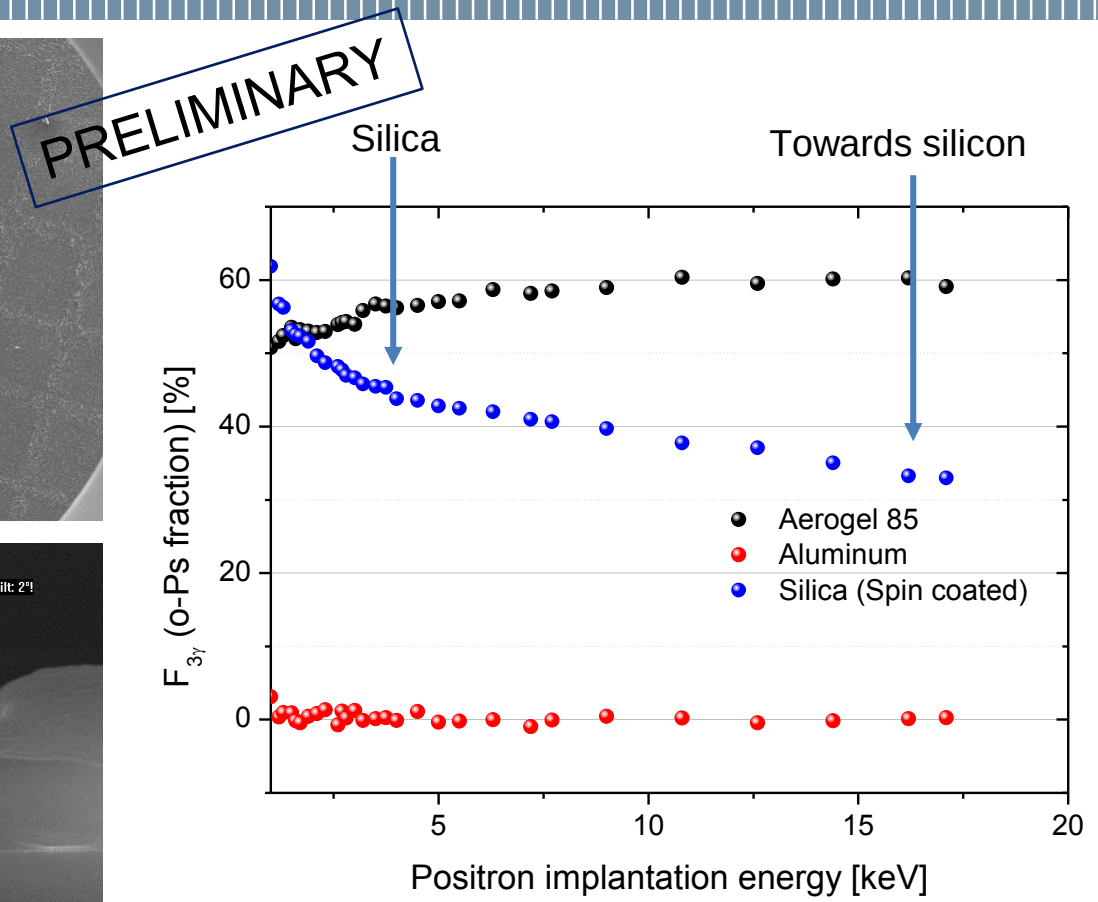
Received April 16, 2003. Revised Manuscript Received June 23, 2003

[1] K. J. Edler and B. Yang, Chem. Soc. Rev. 42, 3765 (2013)

Transmission targets development (II/II)







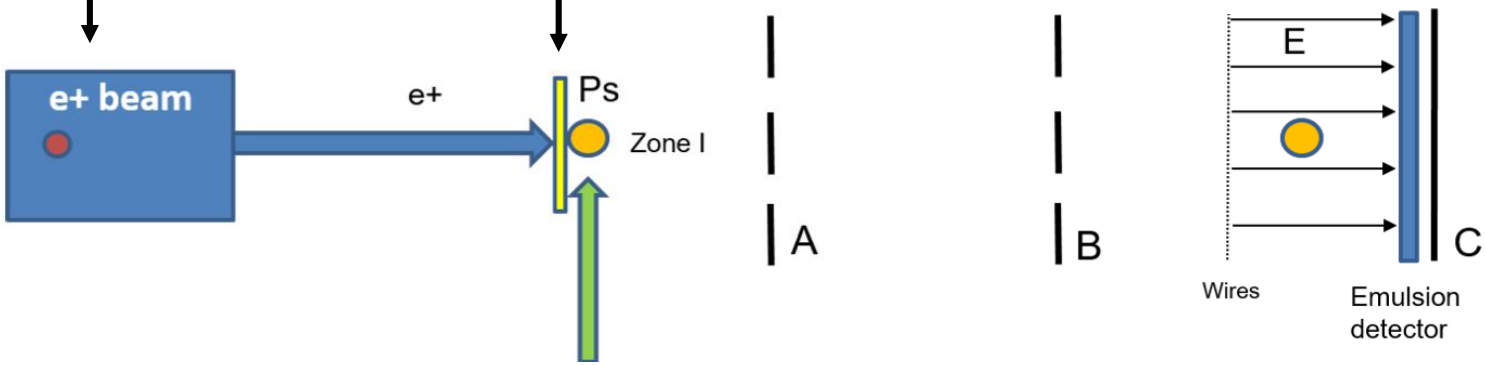
QUPLAS I

Ps interferometry

New source + new moderator

Positron to Ps converter at 10 K $\langle v_{Ps} \rangle \approx 10^4\ m\ s^{-1}$

Detection through ionization required



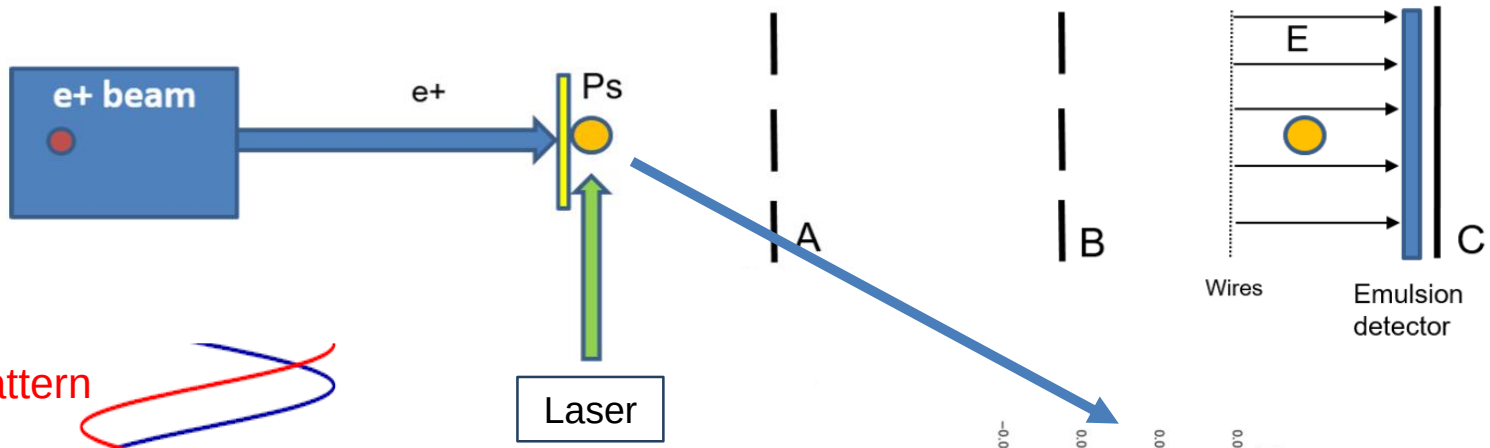
Excitation laser *n* 1->2-> Rydberg

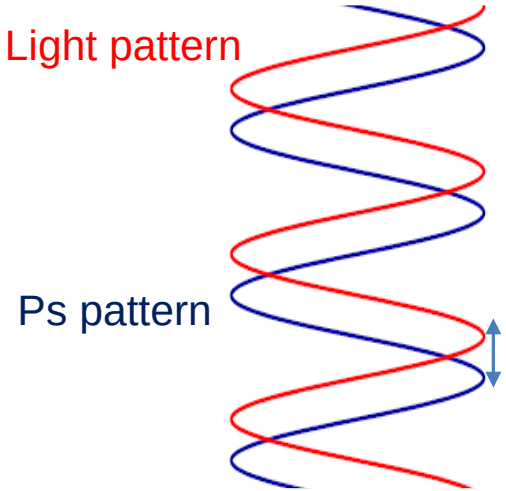
Mean Ps lifetime $\tau \approx n^3 l^2$

$142\ ns < \tau <$ hundreds of μs

$v\ [m\ s^{-1}]$	λ_{dB} [nm]	$D\ [\mu m]$	$L_T\ [cm]$	$TOF[\mu s]$
10^4	33.6	100.0	29.8	59.5

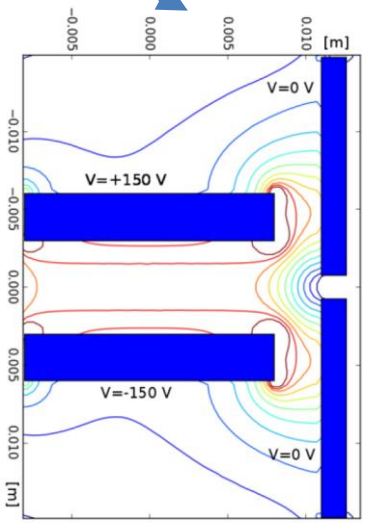
QUPLAS II
Positronium fall





$\bar{g}$ measurement

$$\Delta x = \frac{1}{2}\,\bar{g}\,(TOF)^2$$



Stark deceleration device under study to slow down Ps atoms from 10^4 to 10^3 m s^{-1}!

Gravity shift of 4 micron over the distance of a meter (for 10^3 m s^{-1} positronium)

QUPLAS II
Numbers

Gravity measurement count rate

Count rate for a typical experiment

50mCi source with RGM moderator (0.4 % efficiency) -> 7 x 10^6 e^+ s^{-1}

e+ -> Ps conversion (10%) and reemission (30%) by converters -> 2 x 10^5 s^{-1}

Ps solid angle of emission and interferometer geometry (0.1 %) -> 200 s^{-1}

Ps excitation efficiency is high but the spectral selection will introduce 10 % -> 20 s^{-1}

Trasparency of gratings 25 % -> 5 s^{-1}

Sensivity to g for Ps (only Talbot, interferometric methods)

Given 0.5 dots s^{-1} on the emulsion, one has, for a very realistic 50 % contrast, $D = 476\ \mu m$ $\Delta x = 4\mu m$

$$\frac{\sigma\,(\bar{g})}{\bar{g}} \cong \frac{1}{2\pi C}\frac{1}{\sqrt{N}}\frac{D}{\Delta x(g)}$$

(Only statistical error)

- 2 % in a WEEK
- 1 % in a MONTH
- <0.1 % in a YEAR

OUTLINE

CURRENT PROGRESS
Theoretical framework

Matter-wave interferometry: towards antimatter interferometers

Simone Sala[1,2], Fabrizio Castelli[1,2], Marco Giammarchi[2], Stefano Siccardi[1] and Stefano Olivares[1,2]

[1] Dipartimento di Fisica, Università degli Studi di Milano, I-20133 Milano, Italy
[2] INFN Sezione di Milano, I-20133 Milano, Italy

E-mail: stefano.olivares@fisica.unimi.it

Abstract. Starting from an elementary model and refining it to take into account more realistic effects, we discuss the limitations and advantages of matter-wave interferometry in different configurations. We focus on the possibility to apply this approach to scenarios involving antimatter, such as positrons and positronium atoms. In particular, we investigate the Talbot-Lau interferometer with material gratings and discuss in details the results in view of the possible experimental verification.

S. Sala *et al.*, J. of Phys. B 48 (2015) 195002

Asymmetric Talbot-Lau interferometry for inertial sensing

Simone Sala,[1,2] Marco Giammarchi,[2,3] and Stefano Olivares[1,*]

[1] *Dipartimento di Fisica, Università degli Studi di Milano, I-20133 Milano, Italy*
[2] *INFN Sezione di Milano, I-20133 Milano, Italy*
[3] *Albert Einstein Center for Fundamental Physics Laboratory for High Energy Physics University of Bern Sidlerstrasse, 5 CH-3012 Bern*

We study in detail a peculiar configuration of the Talbot-Lau matter wave interferometer, characterised by unequal distances between the two diffraction gratings and the observation plane. We refer to this apparatus as the "asymmetric Talbot-Lau setup". Particular attention is given to its capabilities as an inertial sensor for particle and atomic beams, also in comparison with the classical moiré deflectometer. The present analysis is motivated by possible experimental applications in the context of antimatter wave interferometry, including the measurement of the gravitational acceleration of antimatter particles. To support our findings, we have performed numerical simulations of realistic particle beams with varying speed distributions.

PACS numbers: 07.60.Ly,37.25.+k

S. Sala *et al.*, Phys Rev. A 94, 033625 (2016)

CURRENT PROGRESS

Building the interferometer

The interferometer coupled to the positron beam at the L-Ness Laboratory in Como

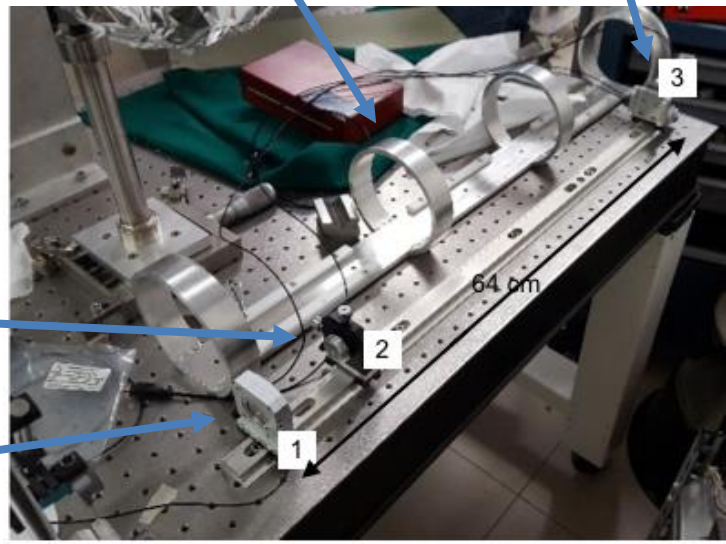
Inside: double layer μ-metal shielding

Emulsion holder

Interferometry frame

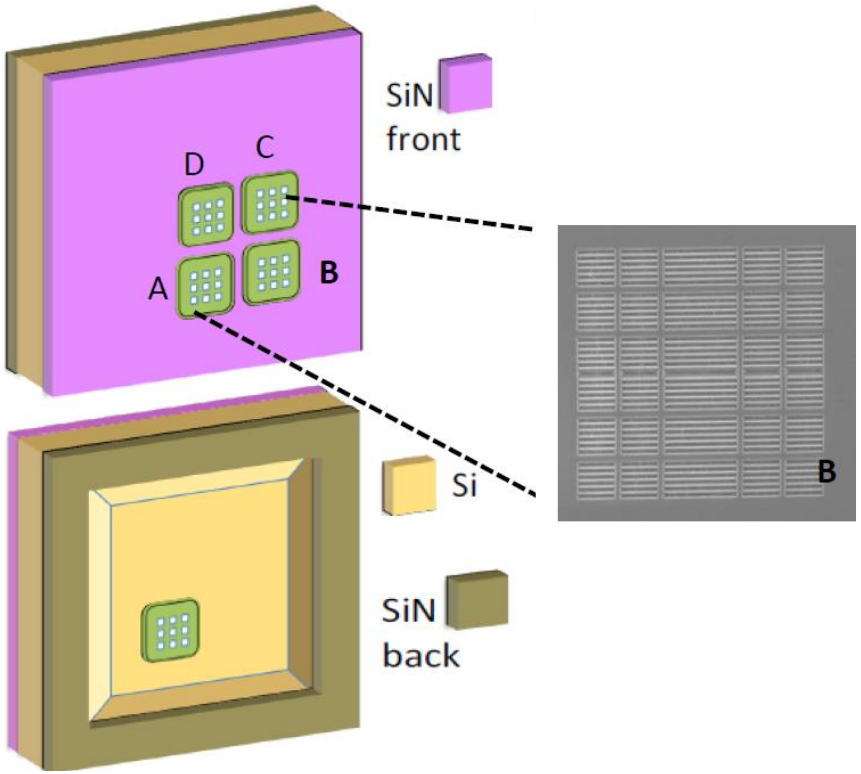
Second grating

First grating holder



CURRENT PROGRESS
Gratings

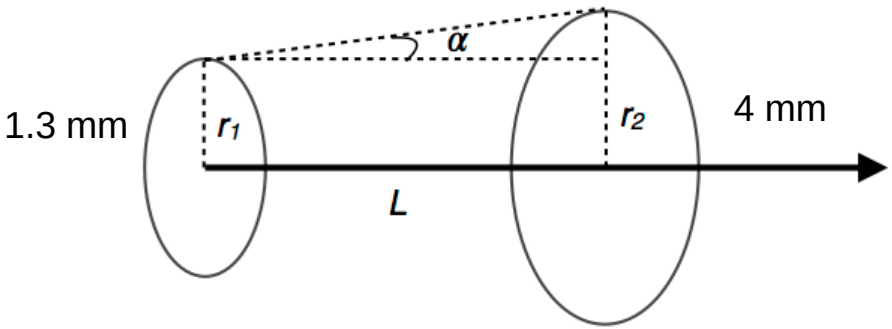
Electron Beam Lithography + Reactive Ion Etching



- Under developlment at L-NESS

  M. Bollani (IFN researcher, CNR),
  M. Lodari (PhD student, Politecnico di Milano)

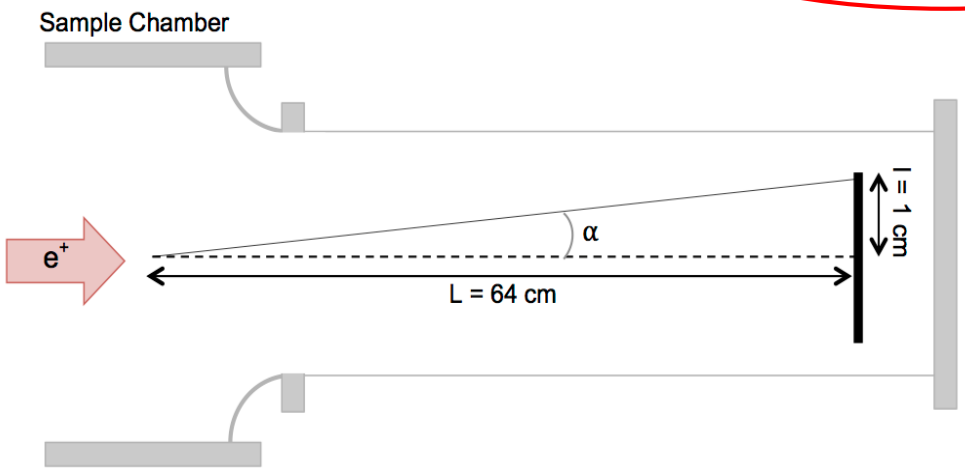
Beam characterization



Angle of divergence : α

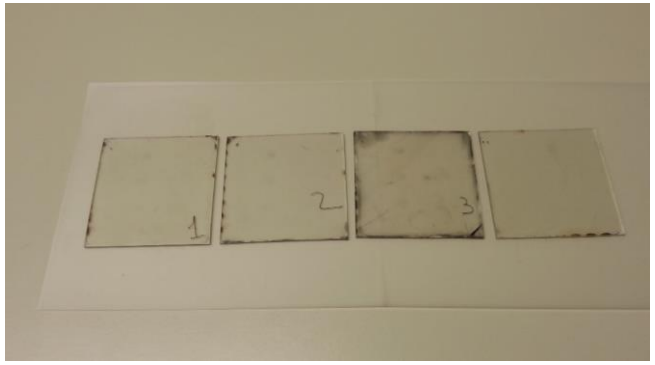
$$\alpha = \arctan\left(\frac{r_2 - r_1}{L}\right)$$

α_{max}=4,200(12) mrad

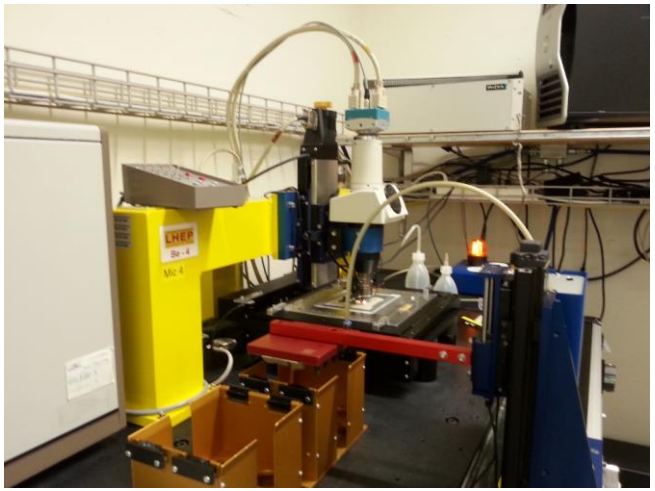


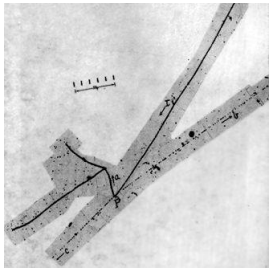
CURRENT PROGRESS

Emulsion exposure (I/III)



Laboratory of High
Energy Physics of the University of Bern





Nuclear emulsions :

AgBr crystals with diameter of 0.2 µm embedded in a gelatine matrix

↓

Latent image produced by a ionizing radiation

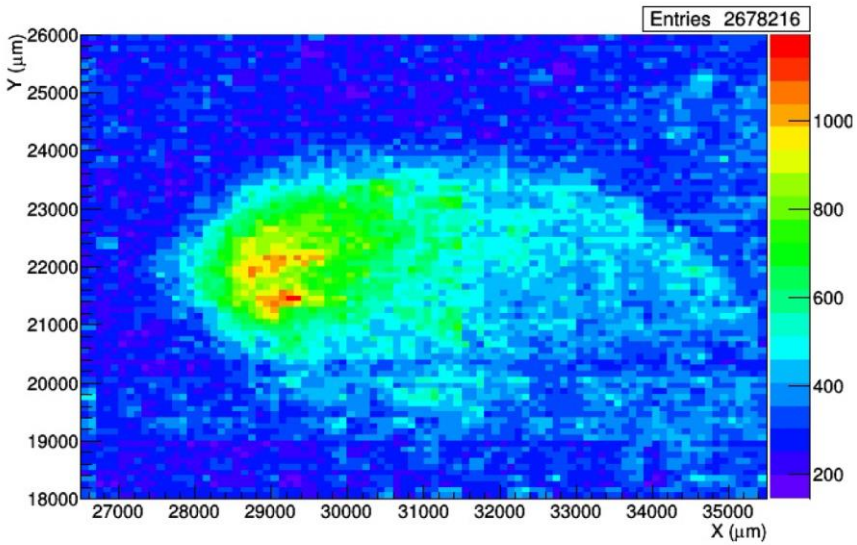
↓

Chemical development process: 1 µm silver grain visible by means of an optical microscope

↙

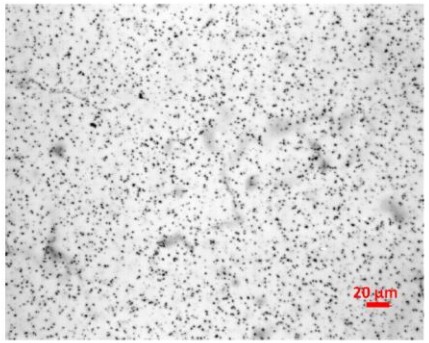
Scanning with the LHEP microcope drive by ad hoc software

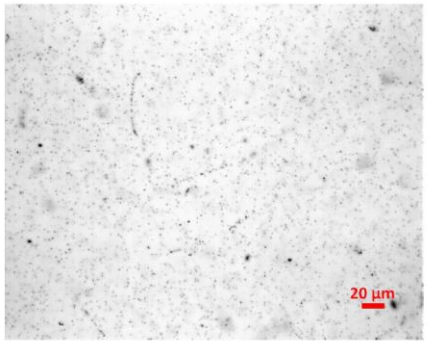
Emulsion exposure (II/III)



- Beam spot at 15 keV
- 120 s integration
- 10^4 μm^2 surface

BEAM

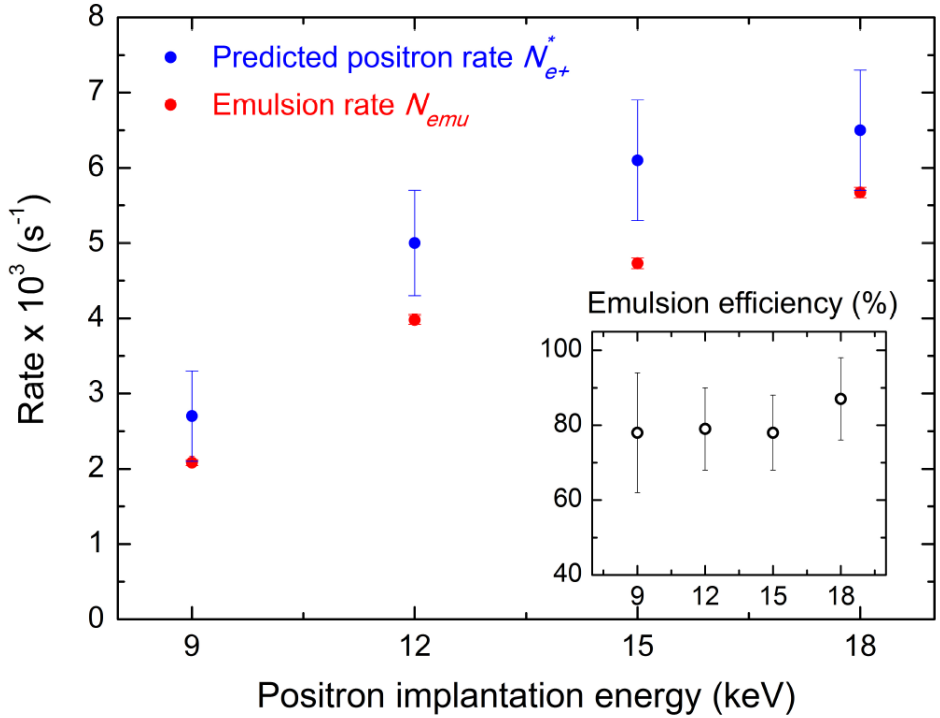




NO BEAM

S. Aghion *et al.*, J. Of Instr. 11 (2016) P0617

Emulsion exposure (III/III)



- Count rate as a function of the positron implantation energy
- Count normalization takes into account 1 μm thick protective layer
- High and energy independent (within the range considered) emulsion efficiency

S. Aghion *et al.*, J. Of Instr. 11 (2016) P0617

CONCLUDING REMARKS

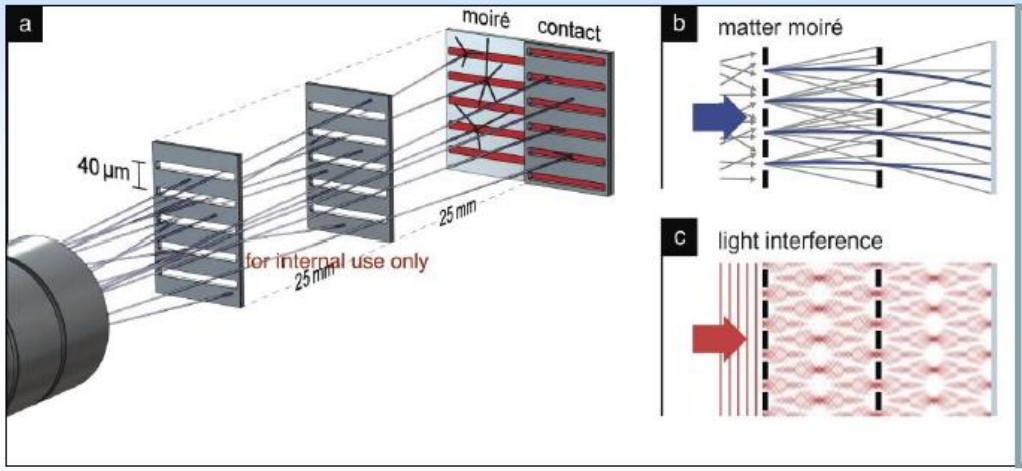
- Quantum Interference to explore new Physics with e+/e-/Ps
- QUPLAS is a staged project to tackle these subjects
- QUPLAS – 0: Positron and Electron quantum interference (CPT test)
  - Scheduled for January 2017
- QUPLAS – I: Positronium Quantum Interferometry
  - R&D in progress: transmission targets, stark decelerator device, etc.
- QUPLAS – II: Positronium Gravity as a test of the Weak Equivalence Principle

THANK YOU FOR THE KIND ATTENTION

Backup slides

Moirè deflectometry

Tested with antiprotons (in an inhomogeneous magnetic field) in the AEgIS experiment at CERN. Grating system followed by the emulsion detector.



Reference pattern obtained by light: Talbot-Laue interferometry (rephasing of light pattern at discrete distances after the grating)

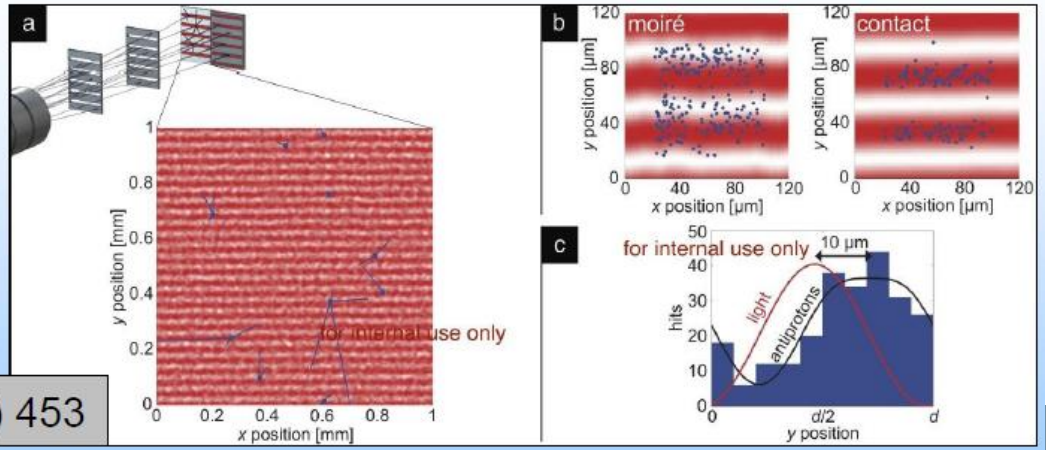
$$\Delta y = \frac{F_y}{m} t^2$$

$$L_T = \frac{2d^2}{\lambda}$$

$$\Delta y_{mean} = 10.0 \pm 0.9 \pm 6.3 \quad \mu m$$

$$v = 4.5 \times 10^6 \quad m/s$$

$$t = 5.6 \quad ns$$



S. Aghion et al, Nature Comm. 5 (2014) 453

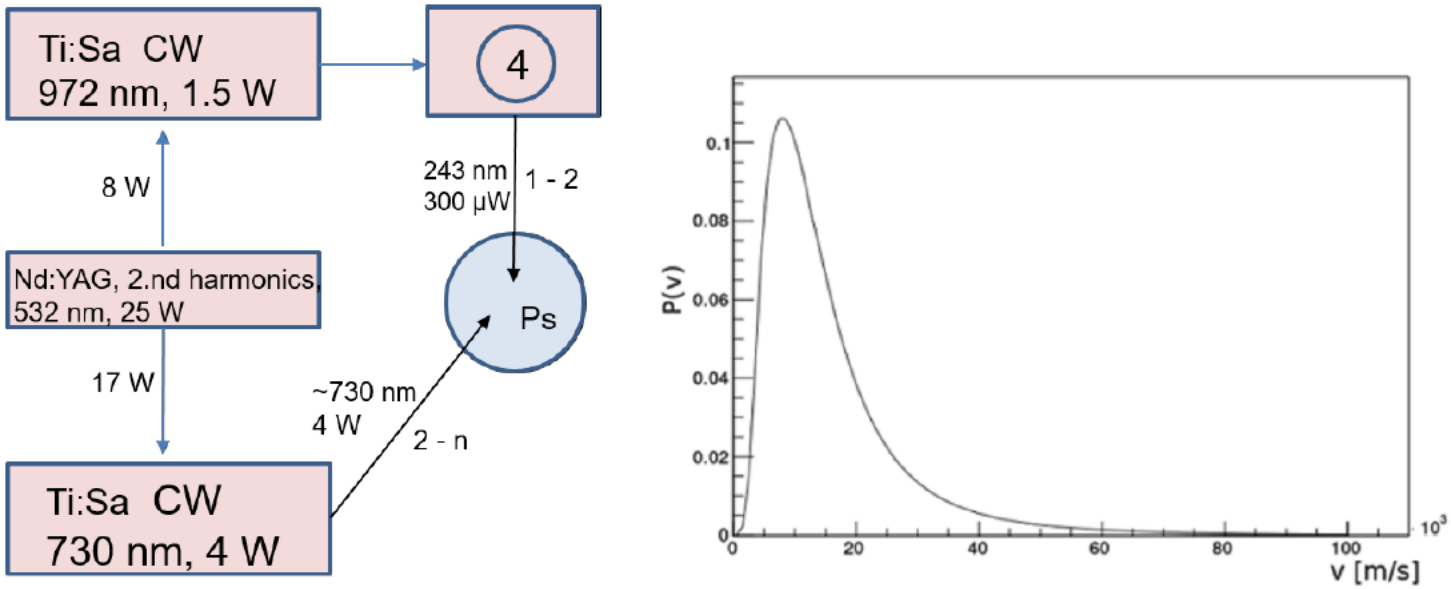


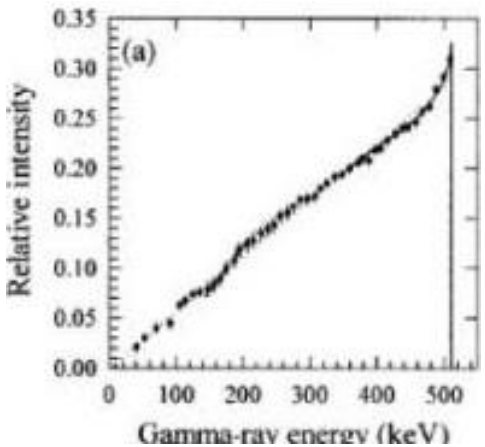
Figure 9. Left: concept of the proposed continuous laser system for Ps excitation to Rydberg states. Right: simulated Ps excitation probability for the configuration described in the text, having the maximum probability at a Ps velocity around 10^4 *m/s*.

POSITRONIUM (Ps) ANNIHILATION:

a) triplet spin state: *ortho-Ps*

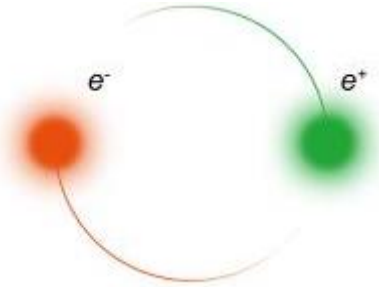
$$e^+ + e^- \rightarrow 3\gamma$$

- γ ray energy:



- mean lifetime in vacuum

$$< \tau >= 142\ ns$$



b) singlet spin state: *para-Ps*

$$e^+ + e^- \rightarrow 2\gamma$$

- γ ray energy:

$$E_{\gamma-ray} = m_0 c^2 = 511\ keV$$

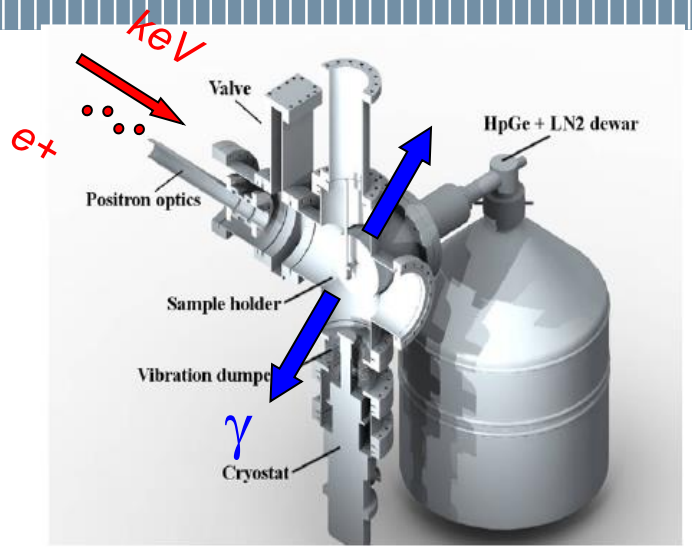
- mean lifetime in vacuum

$$< \tau >= 0.125\ ns$$

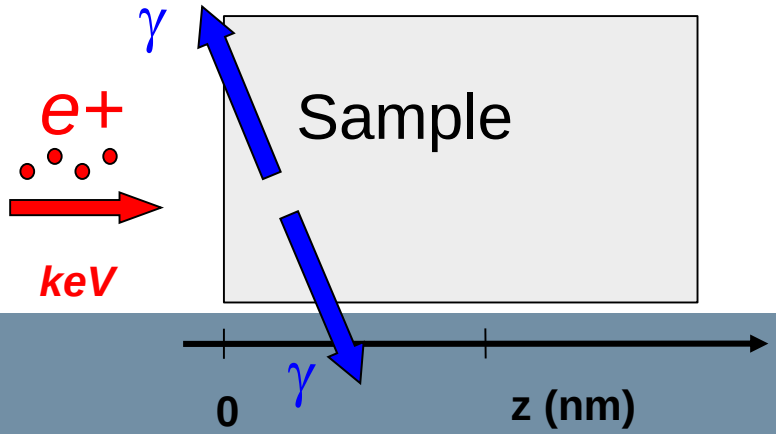
- **Experimental setup**:

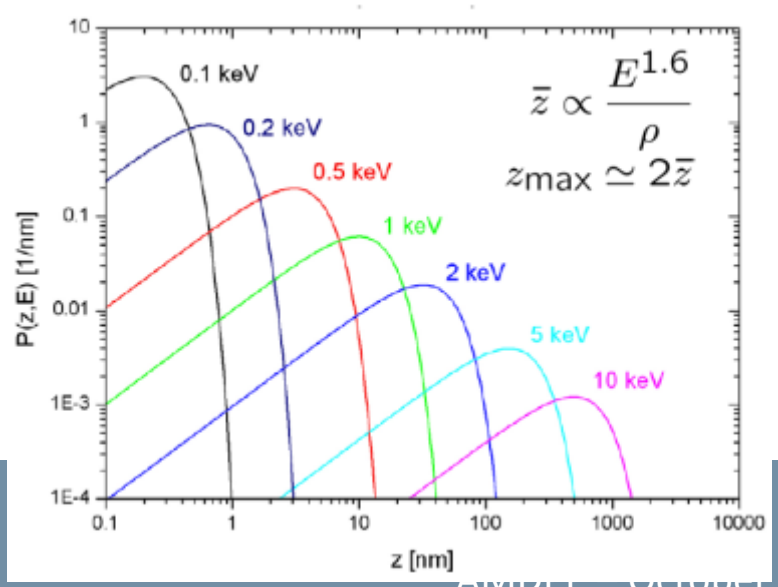
➢ Slow positron beam 0.1-20 keV

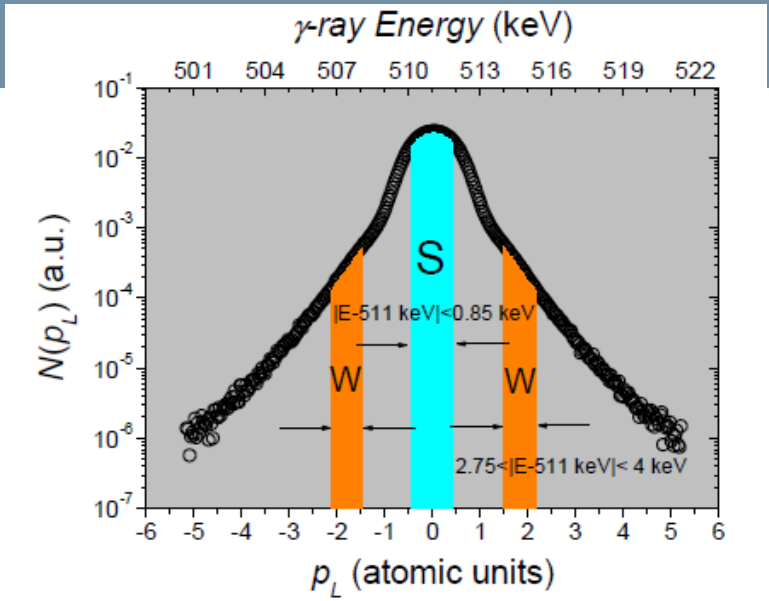
➢ HpGe detectors



- **Variable energy E: depth-profile**



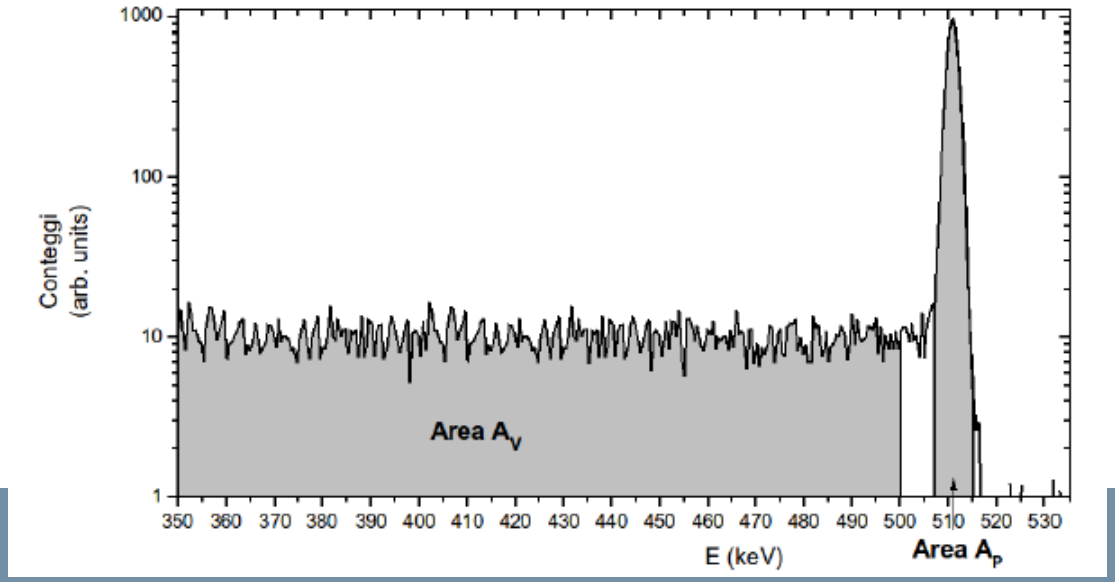


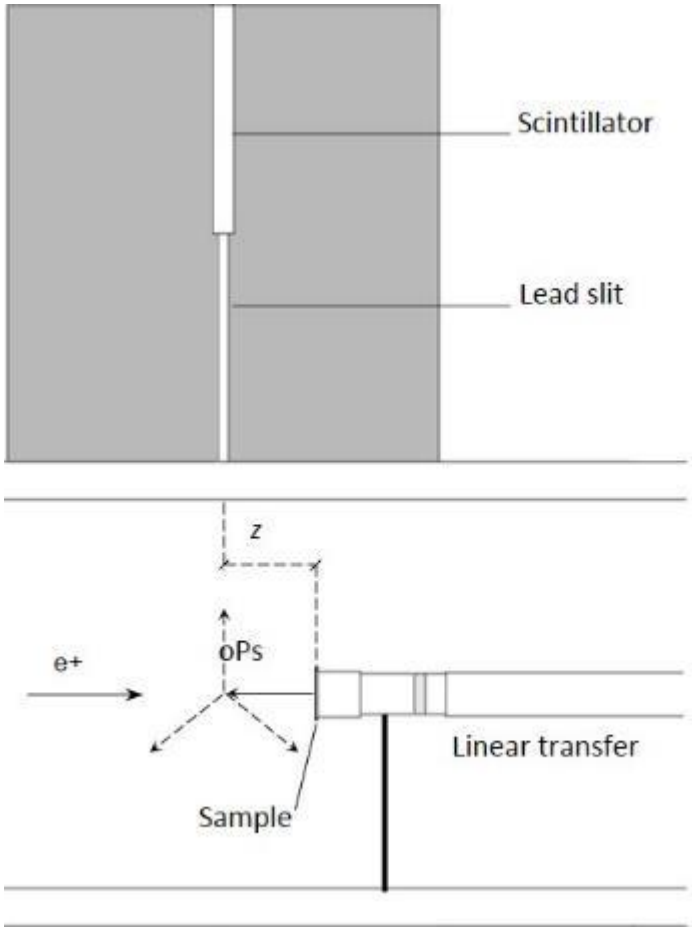


- **PAS parameters:**

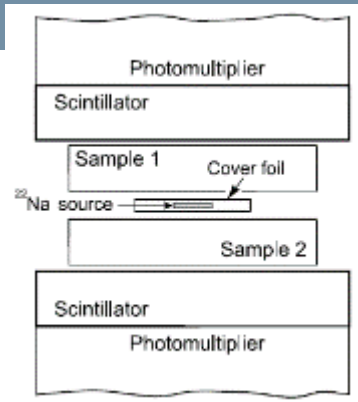
➢ Doppler Broadening (S-parameter)

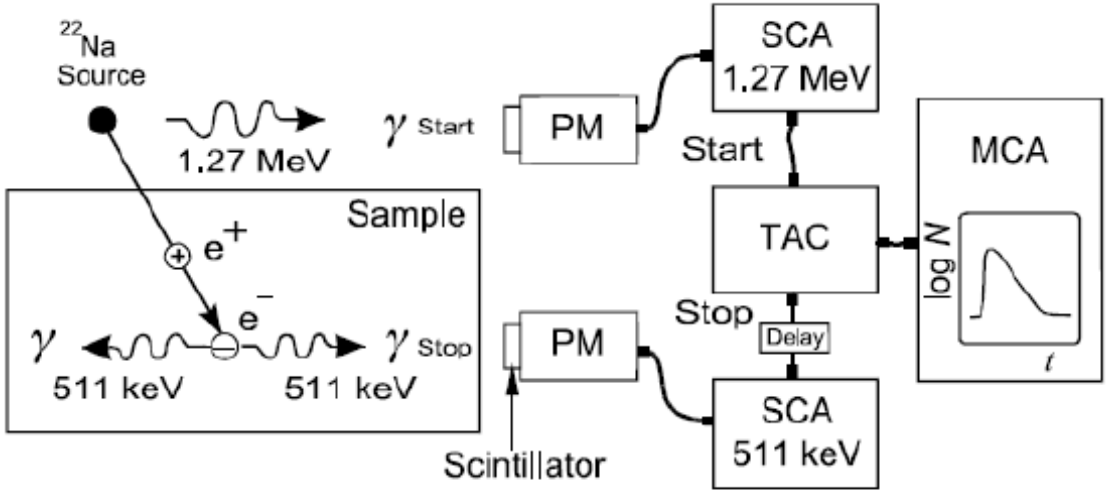
➢ ortho-Ps formation ($F_{3\gamma} = f\left(\frac{A_p}{A_v}\right)$)

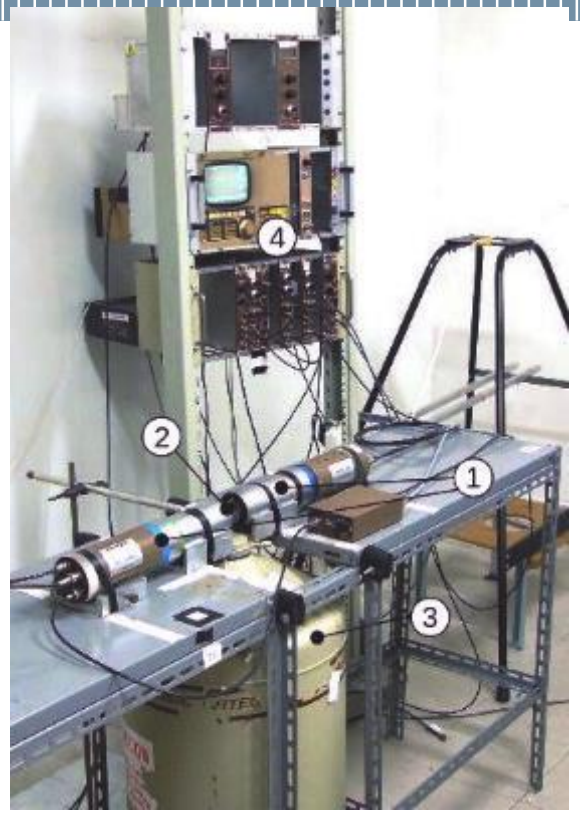




TOF experimental setup



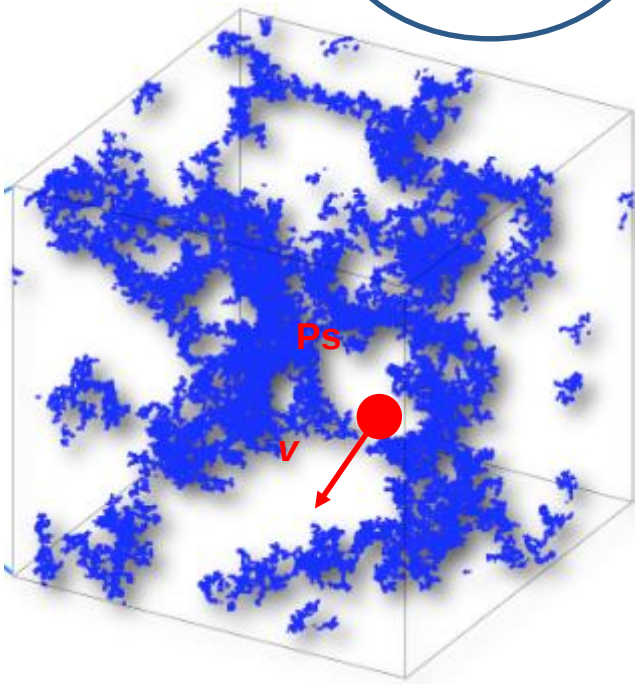




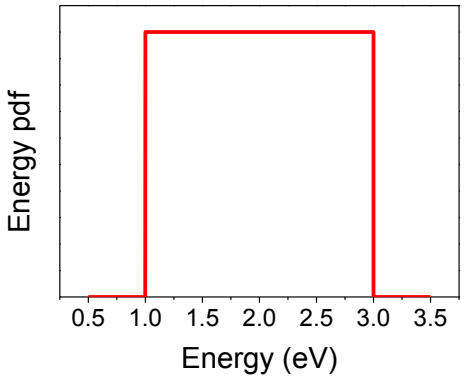
1. Scintillators and photomultipliers
2. Sample;
3. Liquid nitrogen Dewar;
4. Detector electronics

n-cycles

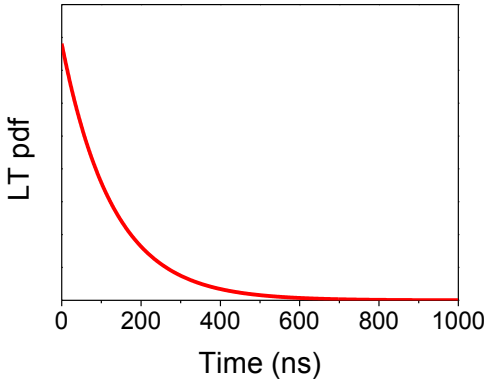
0. ortho-Ps in a Silica mesopore



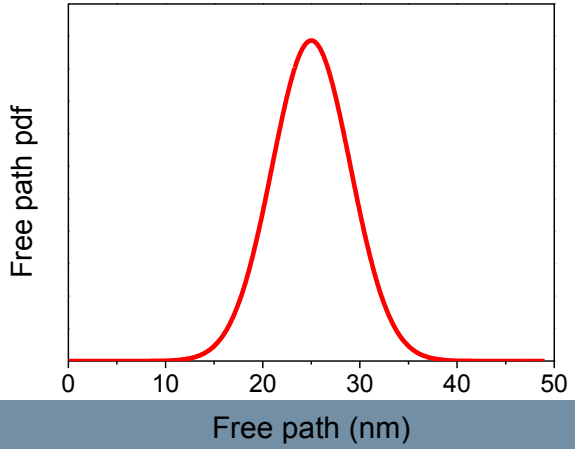
1. Sampling initial Energy:



2. Sampling Ps lifetime:



3. 3-D Random Walk



Energy loss [1]

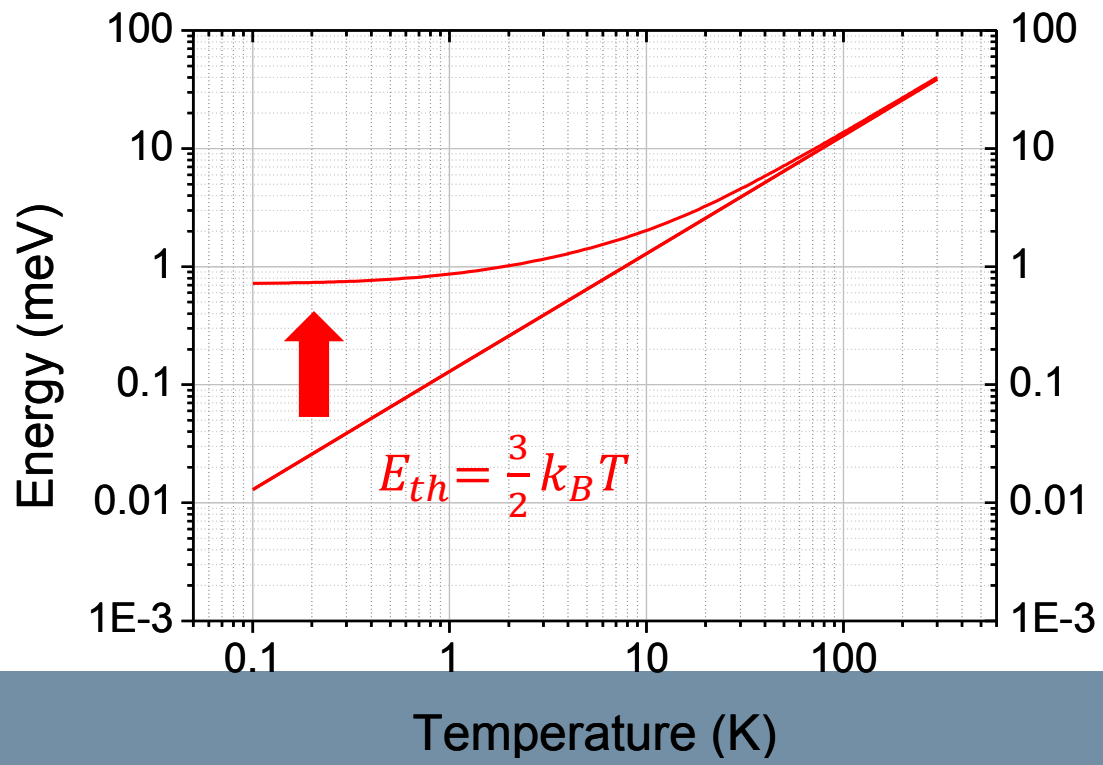
$$E_2 - E_1 = -\alpha(E_1 - E_{th})$$

$$\alpha = \frac{2m_{Ps}}{\overline{M_s}} = 8 \times 10^{-5}$$

$$Classical: E_{th} = \frac{3}{2} k_B T$$

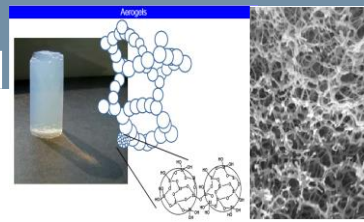
QM – particle in a cylinder E_{nm}

$$E_{nm} = \frac{k_B T}{2} + \frac{\hbar^2}{2m_{Ps}} \frac{Z_{nm}^2}{(R+\Delta)^2} \qquad E_{th} = \frac{\sum_{nm} E_{nm} e^{-E_{nm}/k_B T}}{\sum_{nm} e^{-E_{nm}/k_B T}}$$

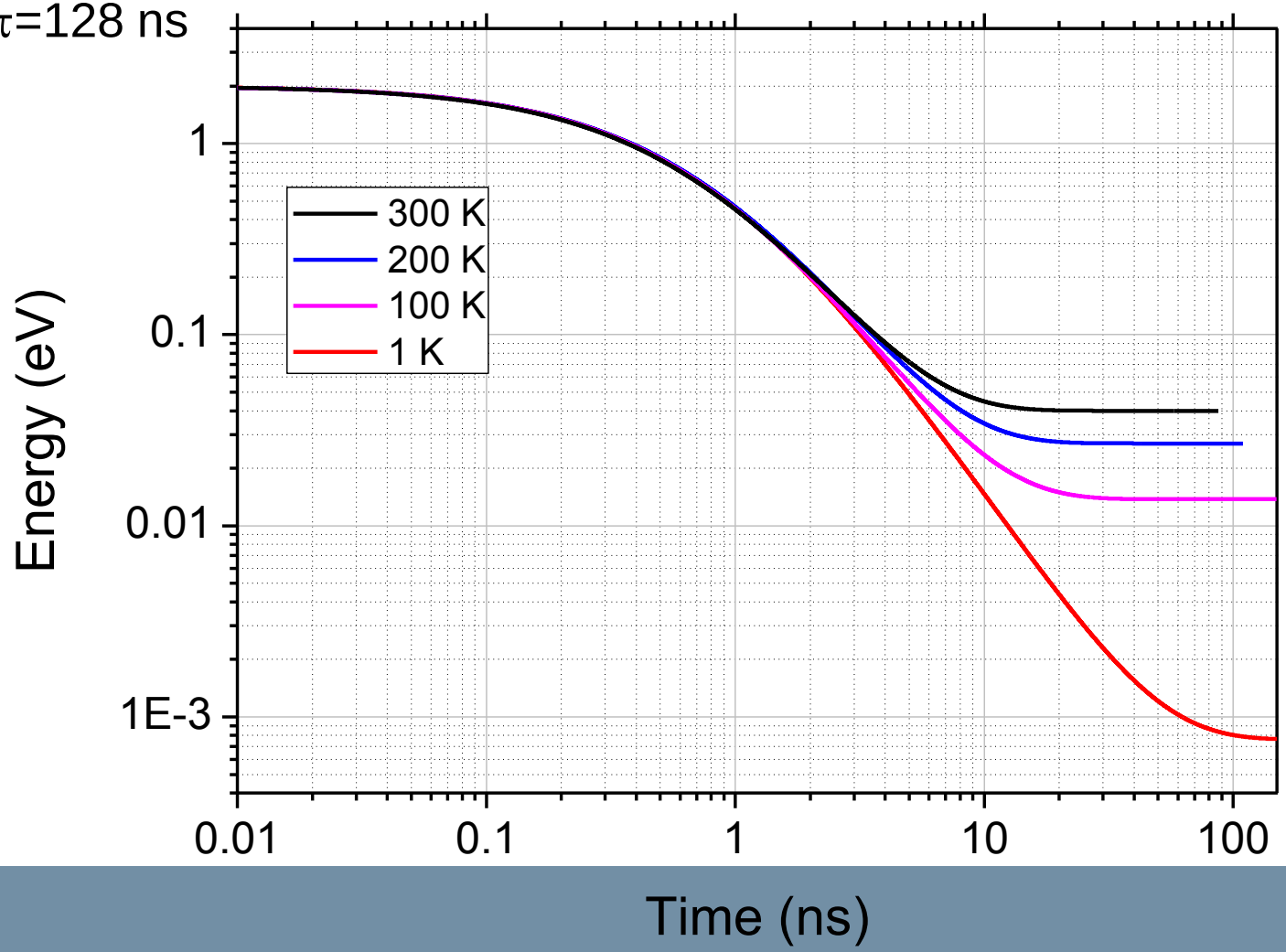


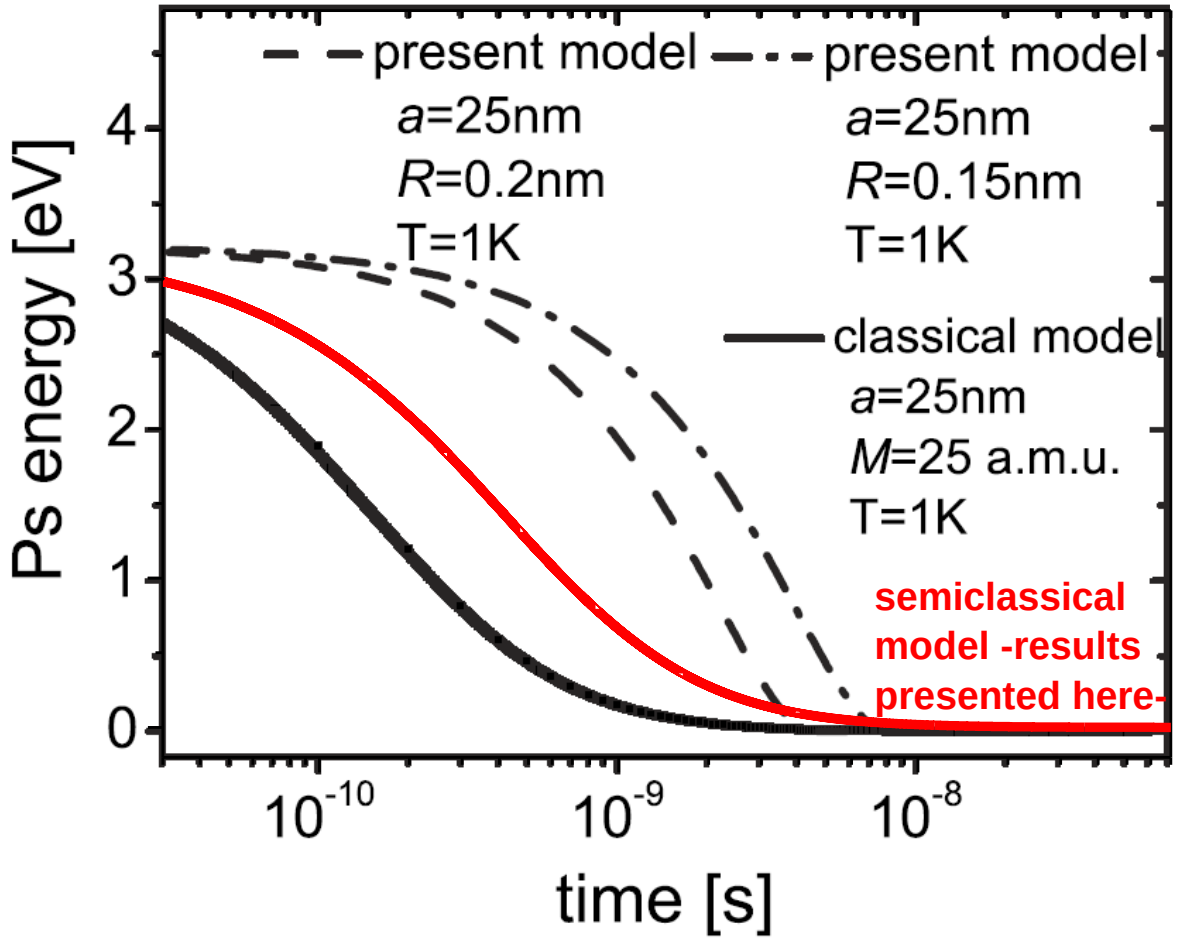
[1] Nagashima et al., Phys Rew A. **52**, 258

Ps cooling (Aerogel)



- Pore cylindrical geometry
- R=16 nm
- τ=128 ns





[1] Mariazzi *et al. Phys. Rev. B* **78**, 085428