Ps formation, cooling and emission into vacuum from porous materials

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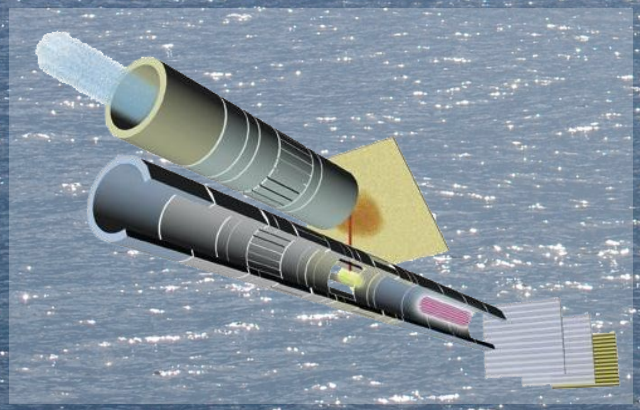
Positron in Astrophysics 19 march 2012 – Murren

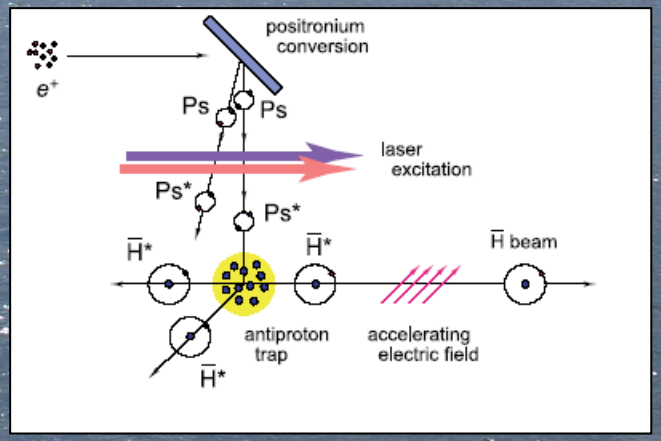
main motivation

Many experiments with positrons require high yield of cooled Ps

In particular we need cooled Ps for AEgIS Hbar experiment and Ps spectroscopy at CERN



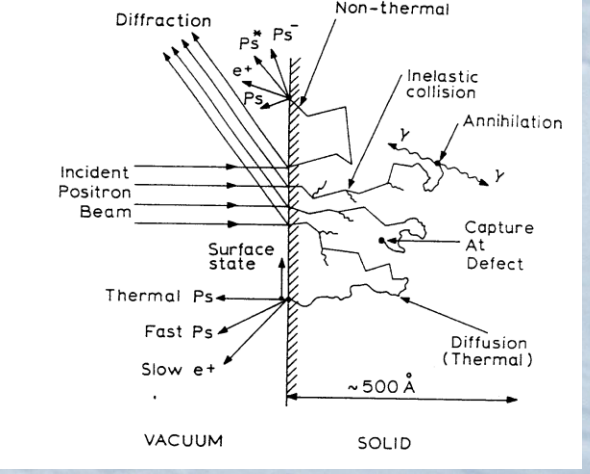
$$\overline{p} + (Ps)^{*} \rightarrow \overline{H}^{*} + e^{-}$$

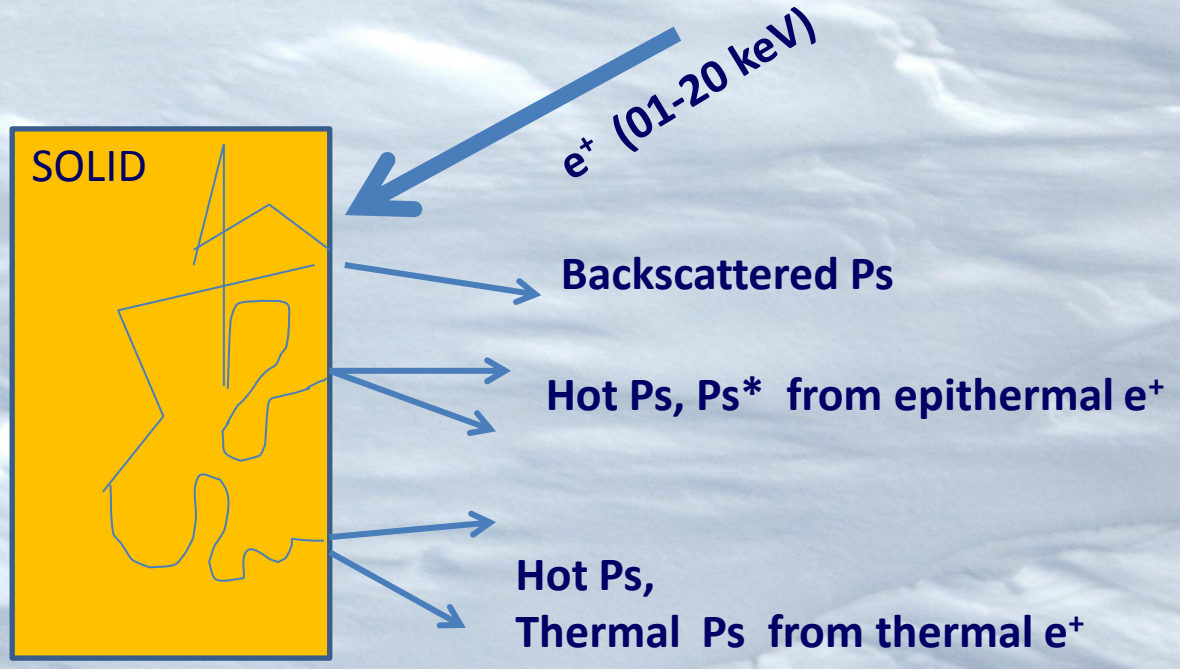


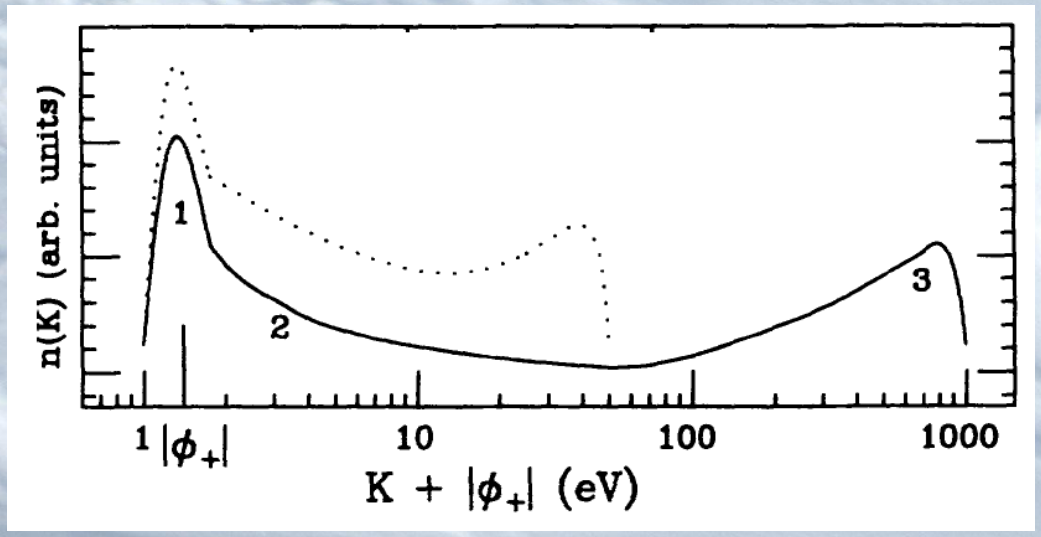
Outline

- Positronium emission from surface
- Ps collisional cooling and Ps thermalization in porous material

Ps at surfaces





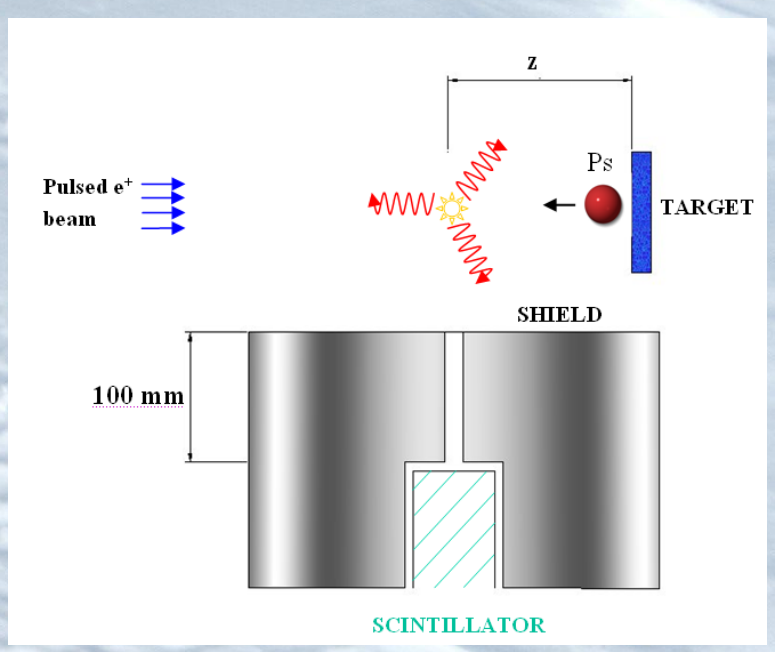


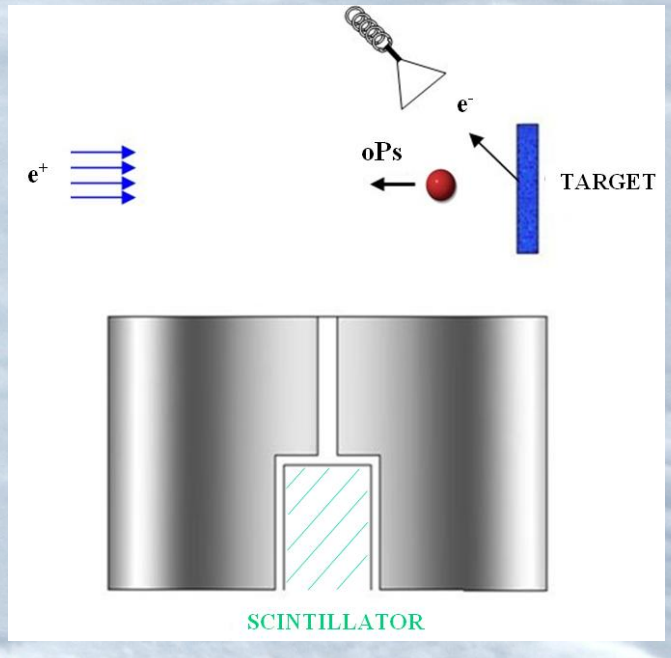
Calculated density of e+ returning at the Al surface, solid line 1keV e+ dashed line 50 eV e+

1 Thermal e+
2 Epithermal e+
3 Backscattered e+

After Steiger and Conti 1992

Time of flight measurement with e+ beams



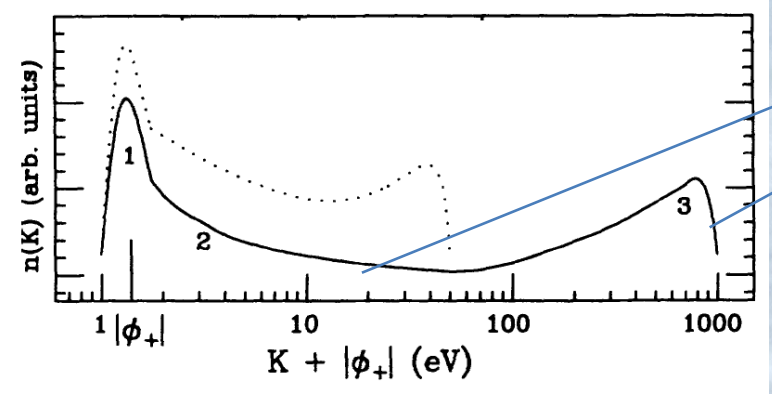


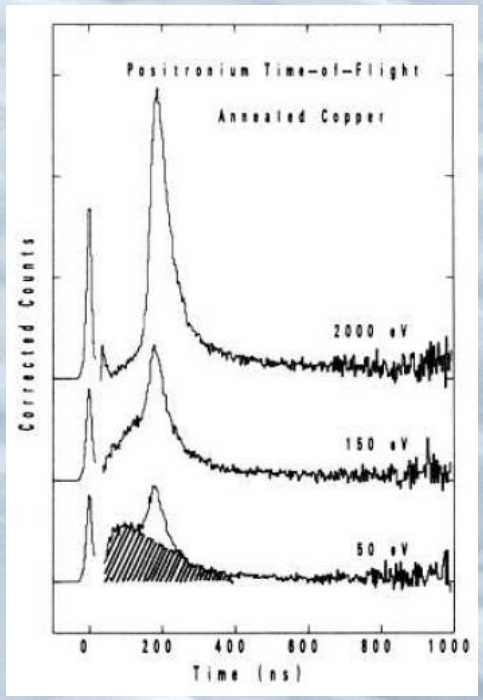
The perpendicular velocity is measured $v_\perp$

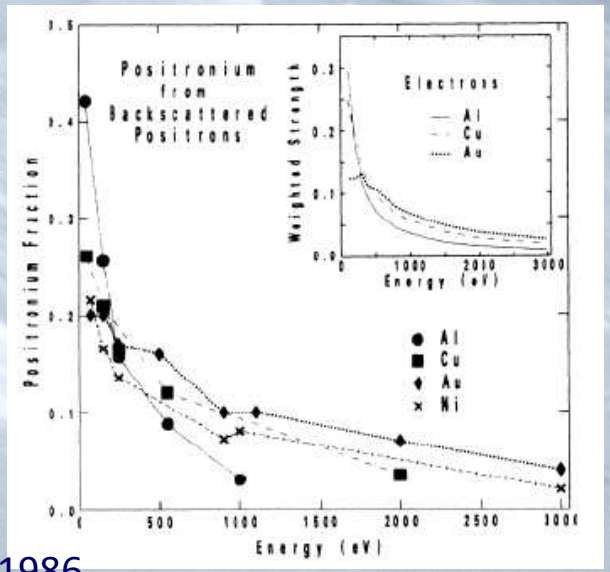
$$E_\perp = \frac{1}{2} m_{Ps} v_\perp^{\,2} = m_e \frac{z^2}{t^2}$$

Backscattered Ps and Ps by epithermal e^+

TOF spectra of Ps emitted from Cu
Hatched area , spectrum of Ps from epithermal e+



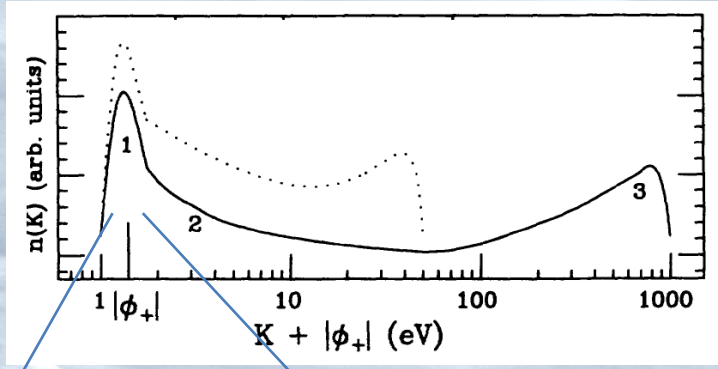




Backscattered Ps has a energy dependence approximately as E^{-1} where E is the e+ incident energy

After Howell 1986

Ps formation and emission by thermal e^+



Direct Ps formation

Ps formation by trapped positron at the surface

Direct Ps formation and emission by thermal e^+

Possible when the positronium formation potential is negative

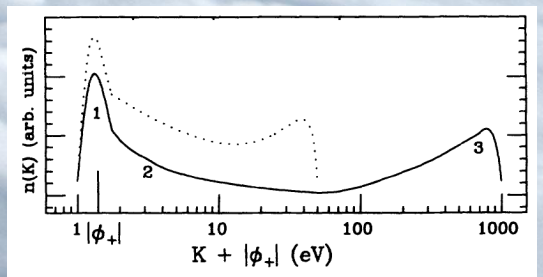
positronium formation potential (ε_{Ps})

$$\epsilon_{Ps} = \varphi_+ + \varphi_- - 6.8\ eV$$

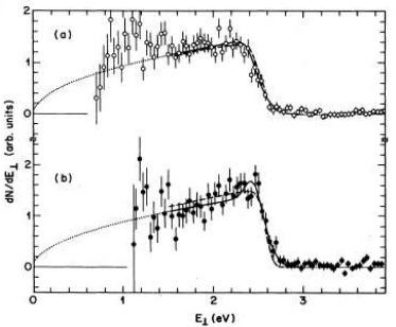
Li +0.56	Be -3.69												Al -2.39	Si +0.15
Na +0.32	Mg -0.62													
K +0.25	Ca -0.4	Sc -1.7	Ti -2.74	V -3.36	Cr -4.18	Mn -3.08	Fe -2.96	Co -2.62	Ni -2.34	Cu -1.99/ -2.5	Zn -1.56			Ge -0.11
Rb +0.18	Sr -0.39	Y -1.49	Zr -2.82	Nb -3.87	Mo -4.88	Tc -5.13	Ru -4.88	Rh -3.7	Pd -1.76	Ag -1.44	Cd -1.02			Sn +0.8
Cs +0.14	Ba -0.67	Lu -1.9	Hf -3.1	Ta -4.17	W -5.49	Re -5.83	Os -5.91	Ir -5.27	Pt -3.44	Au -2.21				Pb -1.24/ -0.73

Pink: No surface Ps emission $\varepsilon_{Ps} > 0$ -White : Ps emission $\varepsilon_{Ps} < 0$

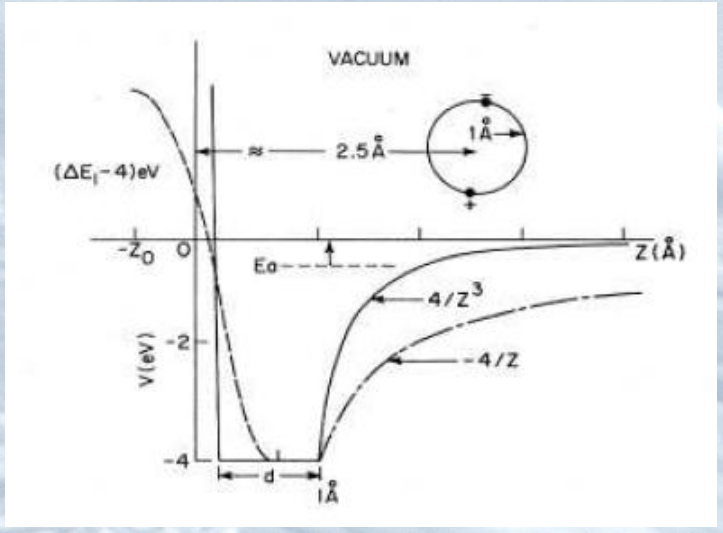
Blue: competition between Ps emission and e^+ emission



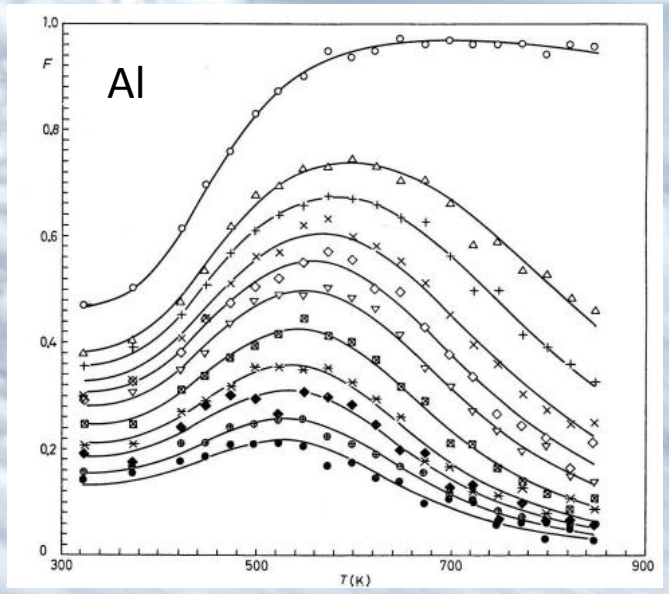
continuous energy spectrum up to the Fermi energy level in metals.



Thermal Ps emission- surface trapping



e+ can fall in a trapped state localized
In few Amstrong from the surface
e+ is strongly correlated with the electron cloud.
In figure two extreme:
image potential - bare positron
Van der Waals - virtual positronium-like



After Shultz and Lynn 1988

Ps emission require an energy E_a, and thermal activation is possible

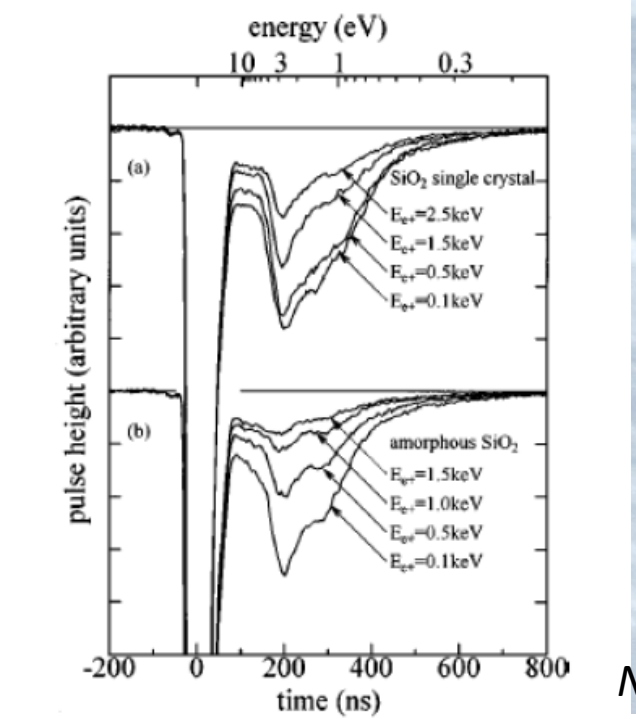
$$E_a = E_b + \phi_- - E_B$$

Ps emission from dielectrics

- Ps formation by thermal positron reaching the surface is, in most cases, energetically forbidden. The 6.8 eV energy gain of Ps formation is not enough to extract an electron

- Formation of Ps can occur in the bulk. Ps reaching the surface can be emitted If its work function is negative $\varphi_{Ps} = \varphi_+ + \varphi_- - E_{gap} + E_b - 6.8\ eV < 0$

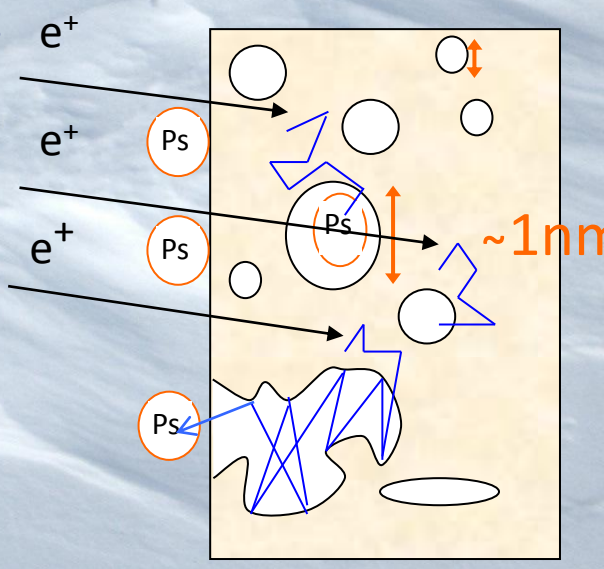
- Ps can form and be hosted by open volumes in dielectrics. If there is a open volume defect network , hopping diffusion may lead to Ps emission into vacuum



In quartz and amorphous SiO_2 two different Ps components were observed :

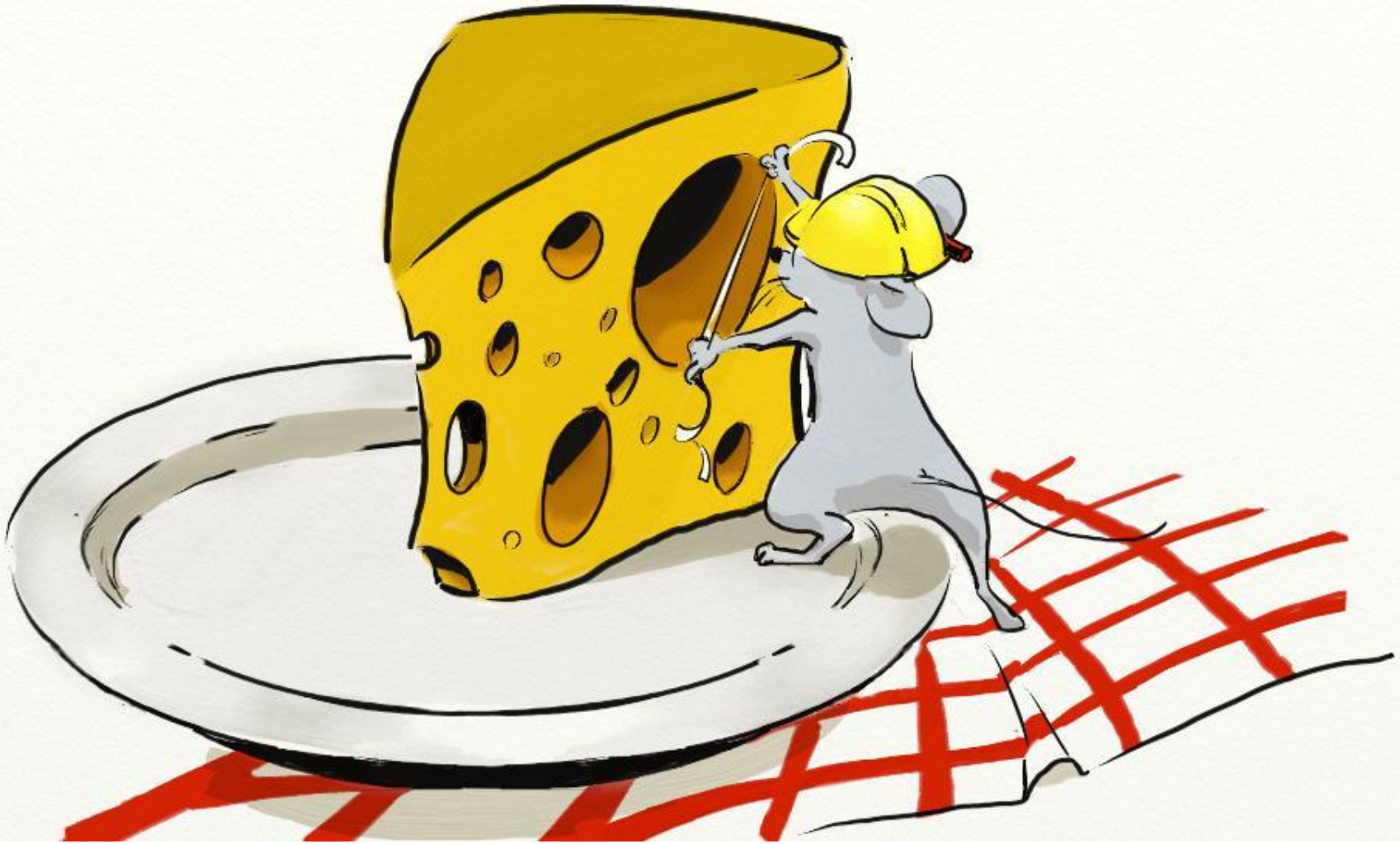
One around 1 eV attributed to Ps formed in the bulk

One around 3 eV by electron capture of an electron at The surface

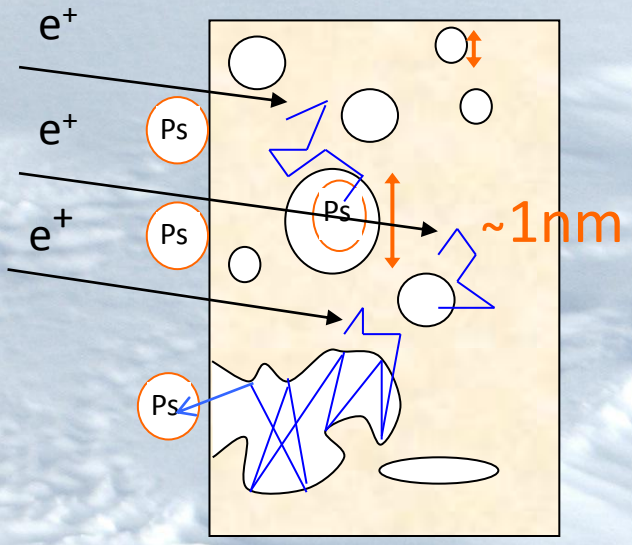


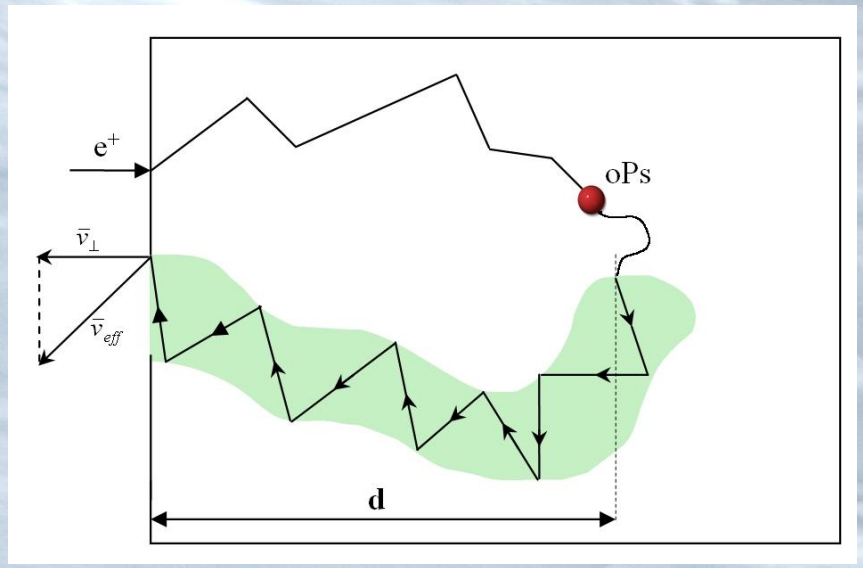
Nagashima et al. 1998

Ps cooling using porous SiO_2 based materials



Ps cooling by collisions



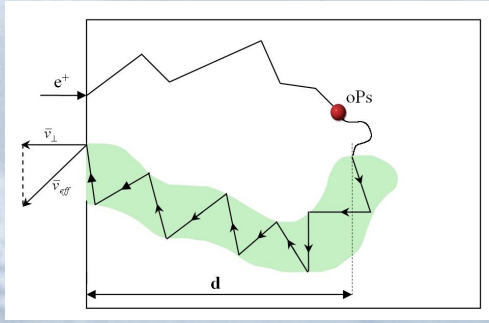


Ps is formed with eV energy but lose energy by collision with the walls of the connected porosities.

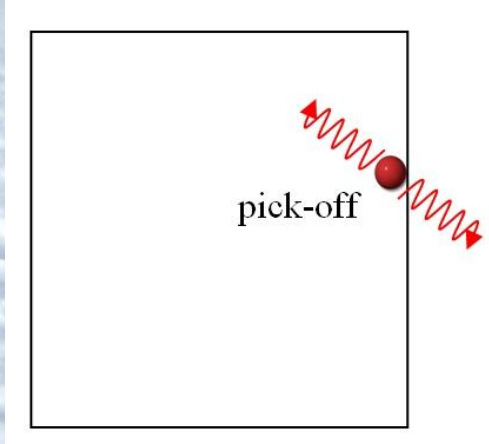
Ps energy is normally insufficient for electronic excitation, Ps lose energy by exciting atomic motion

A fraction of oPs can reach the surface and can be emitted cooled into the vacuum.

Competitive effect : Ps pick-off



oPs ⟶ 2γ



Pick off : when the e+ in Ps has an overlap with an e- of the walls in an interaction region R

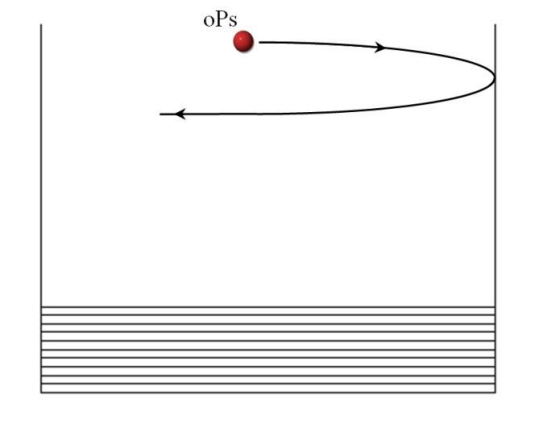
$$\lambda_{pick-off} \propto \frac{v_{Ps}}{L}$$

It is expected :

to depend from cooling time: ie. permanence in the excited states

Ps cooling and quantum confinement

Ps cooling process can be described in two regimes:



HIGH ENERGY LIMIT:

de Broglie wavelength is small respect to the dimension d of the cavity

$$E >> \frac{h^2}{4m_o d^2} \cong \left(\frac{6nm}{d}\right) 20\ meV$$

Ps can be considered a free object of size:

$$\lambda \cong 6\ nm \sqrt{\frac{20\ meV}{E}}$$

Ps collisions can be treated as a classical elastic scattering

(Sauder , *J. Res. Natl. Bur. Stand. § A* ,**72**, (1968) 91)

Ps cooling and quantum confinement

LOW ENERY REGIME $E < \frac{h^2}{4m_o d^2} \cong \left(\frac{6nm}{d}\right) 20\ meV$

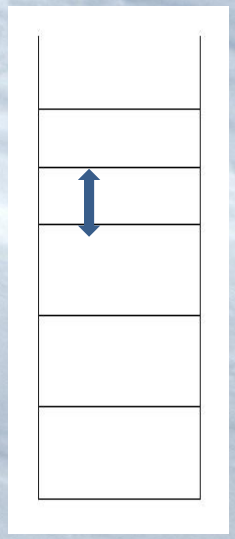
The interaction between the Ps atom and the walls can be described in terms of the contact between a confined Ps atom with the solid as a whole.

An estimation of the minimum T permitted for a Ps atom confined in nano-pores and nano-channels, when the temperature is lowered, can be made by modeling the Ps cooling by creation and destruction of phonons at the surface of the pores.

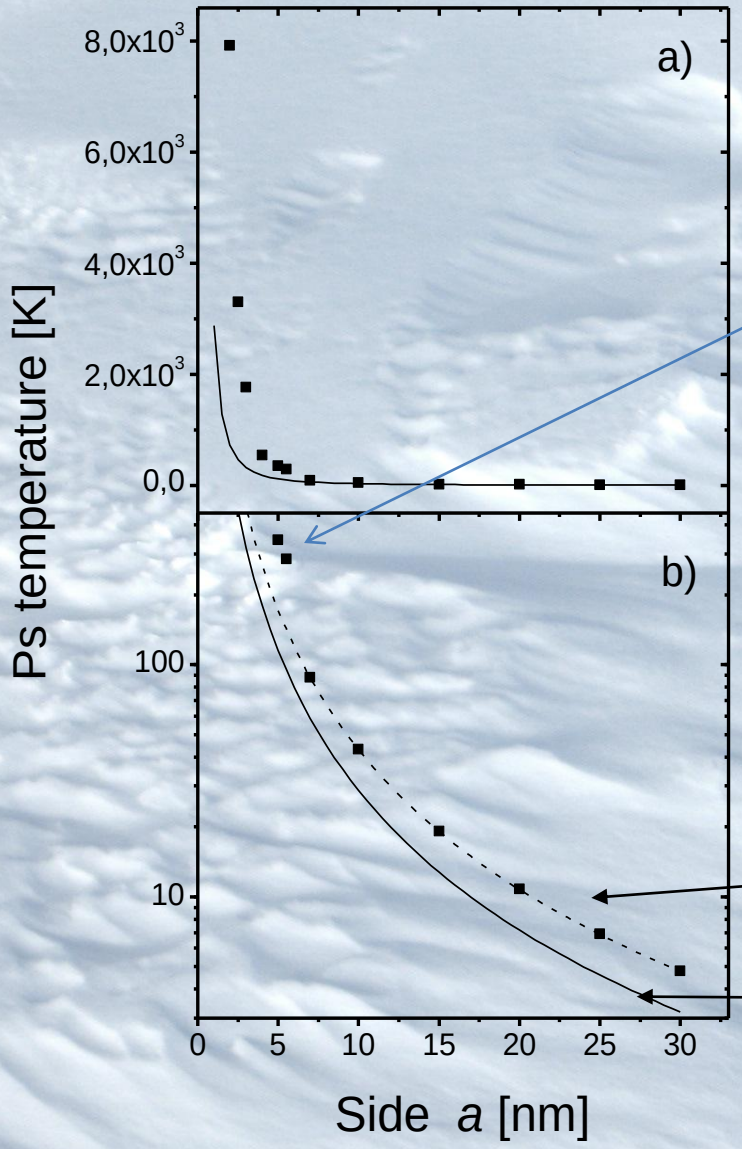
(Mariazzi ,Salemi, Brusa, PRB 2008).

the maximum variation of the momentum magnitude of Ps due to the exchange of a single phonon at the first order

$$\Delta k_{\max} = \left\| |k| - |k^I| \right\|_{\max} = \frac{2 v_s m}{\hbar} \approx 1.7 * 10^8 \,\mathrm{m}^{-1}$$



Ps cooling and quantum confinement



Minimum energy and minimum temperature of a Ps atom confined in a cubic box of size a

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

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

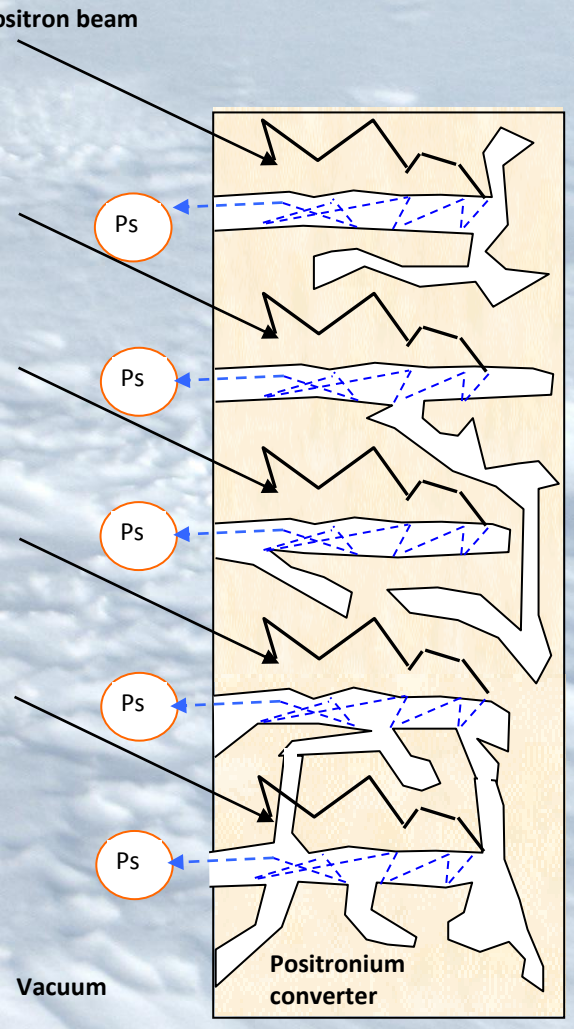
n_m **is the lower accessible level**

Dashed line :ground level in a cubic box

Continuous line : ground state = minimum level in Nano-channels (infinite well)

Mariazzi S, Salemi A and Brusa R S 2008 *Phys. Rev. B* **78** 085428

Nano-size and Ps thermalization

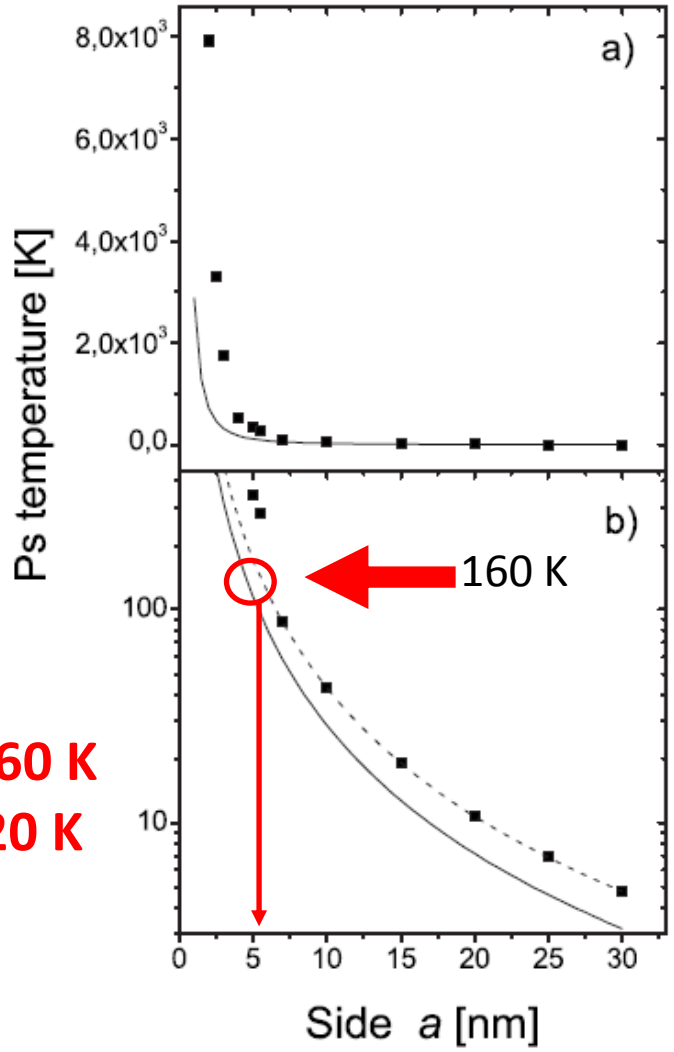


$$E_g = (\hbar^2 \pi^2)/(m\, a^2)$$

the minimum temperature is:

$$T = (2/3k_B)E_g$$

#0 (4-7 nm) mini T is 180-60 K
#1 (8-12 nm) min T is 45-20 K



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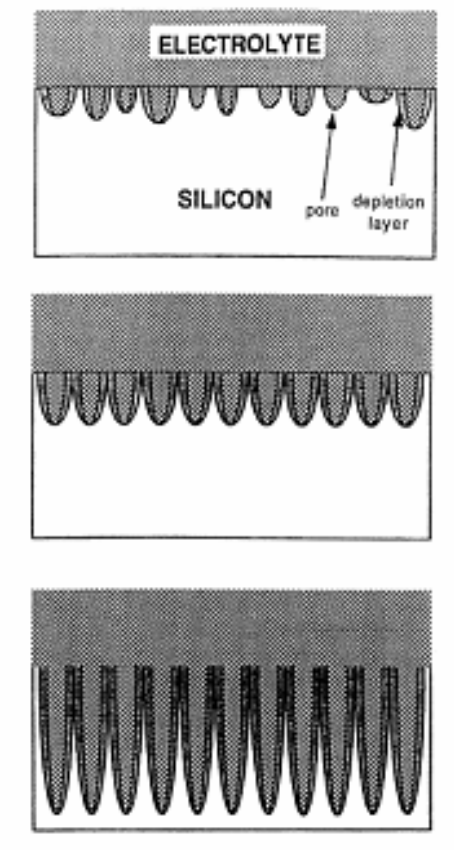
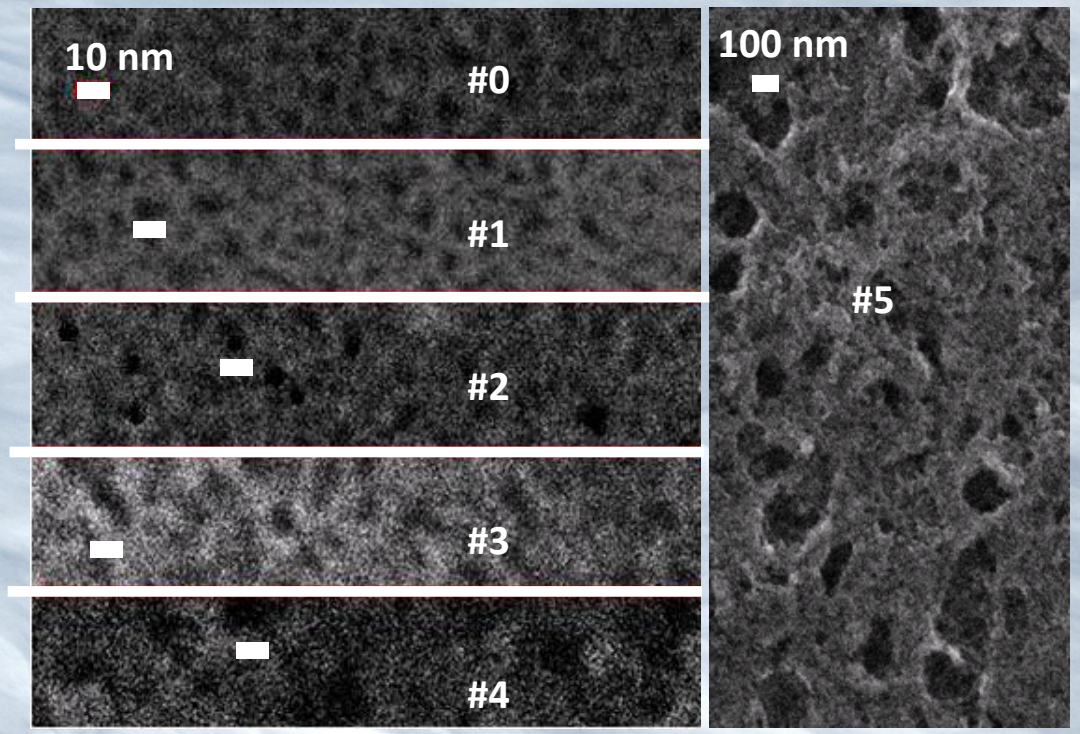
Tuning the size of nanochannels

produced by electrochemical etching, as for porous silicon but adapting times and current for obtaining nano- structures





Si p-type 0.15-0.21 Ohm/cm
current from 4-18 mA/cm^2 , 15'

Possibility of tuning: #0 = 4-7 nm
#1=8-12 nm #2= 8-14 nm
 # 3= 10-16 nm #4= 14-20 nm
#5= 80-120 nm

Mariazzi S, Brusa R S et al *Phys. Rev. B* **81, 235418** (2010)

Trento slow positron beam (50 eV-30 keV)

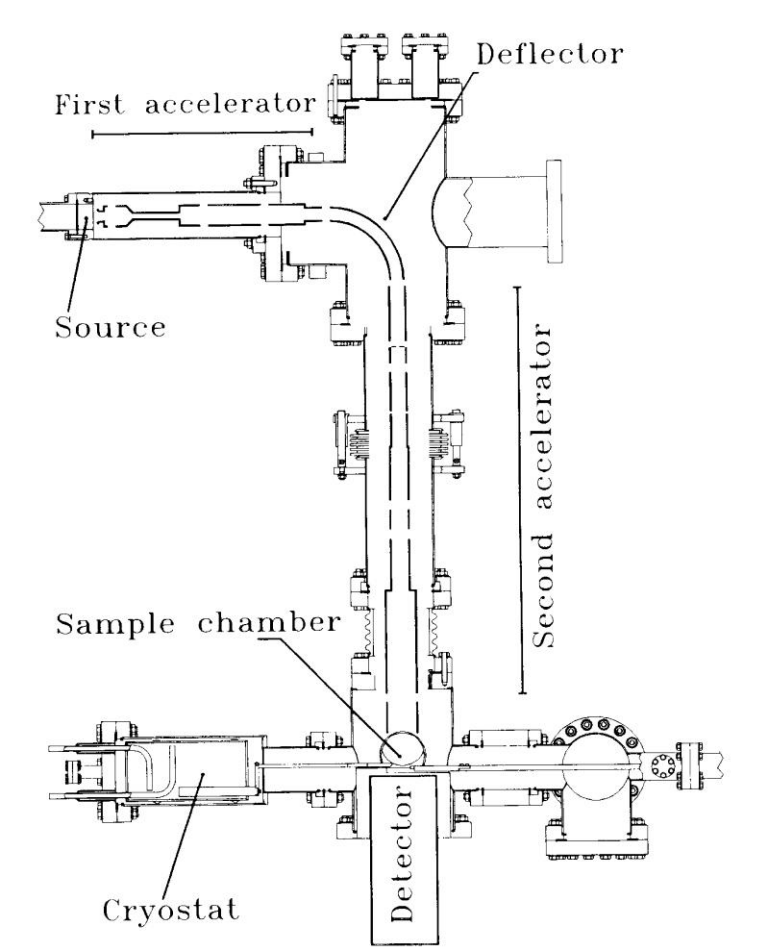
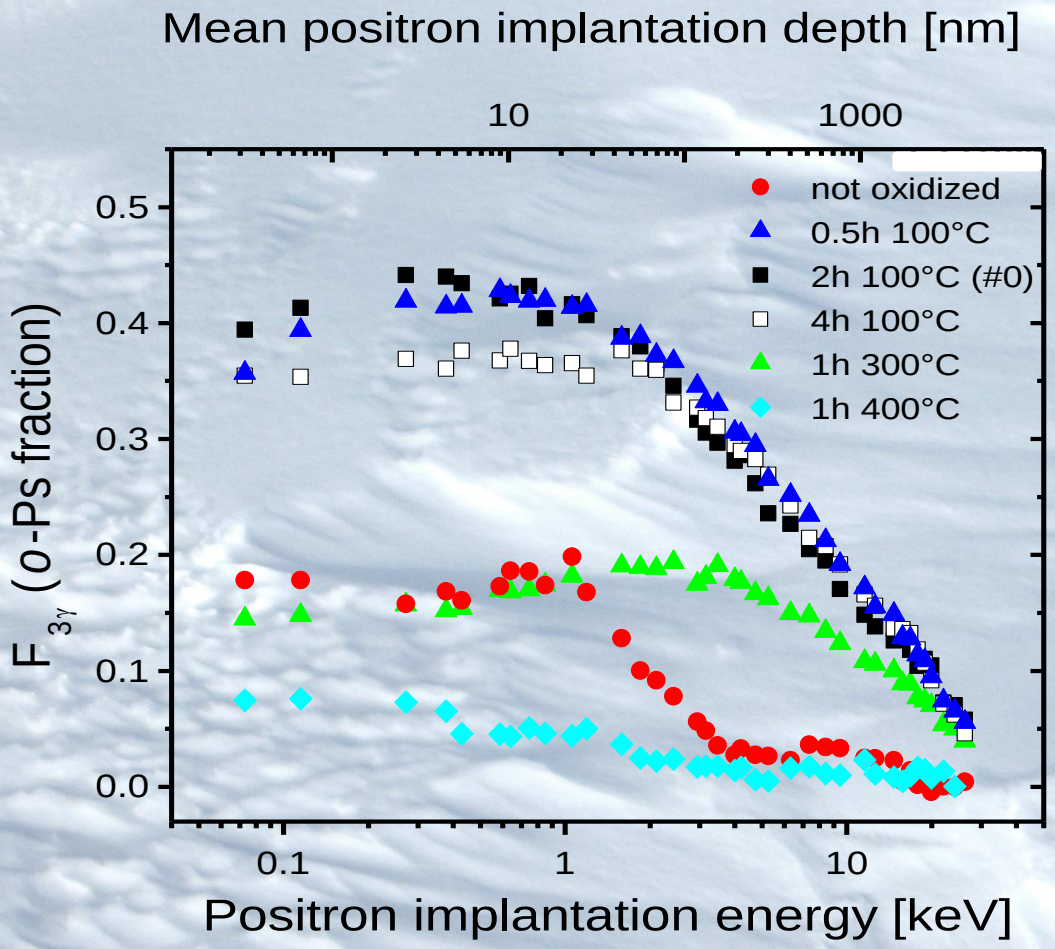
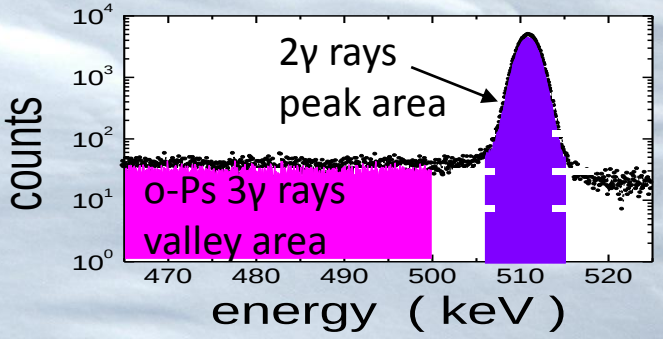


Fig. 1. A schematic layout of the electrostatic positron beam constructed in the Trento laboratory.

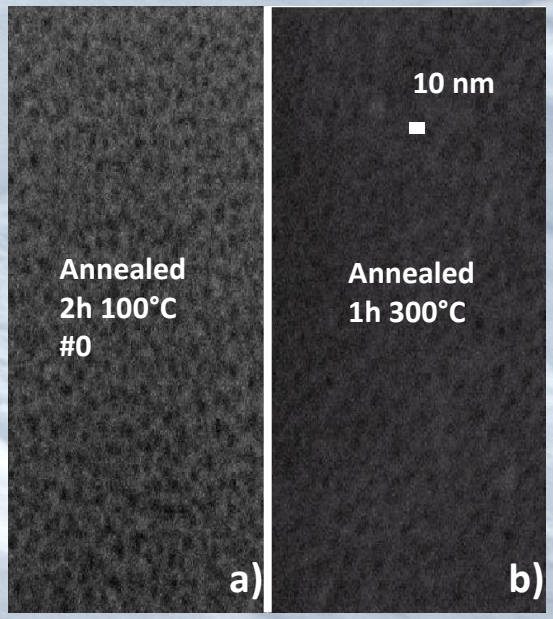
Optimum oxidation for the Ps yield



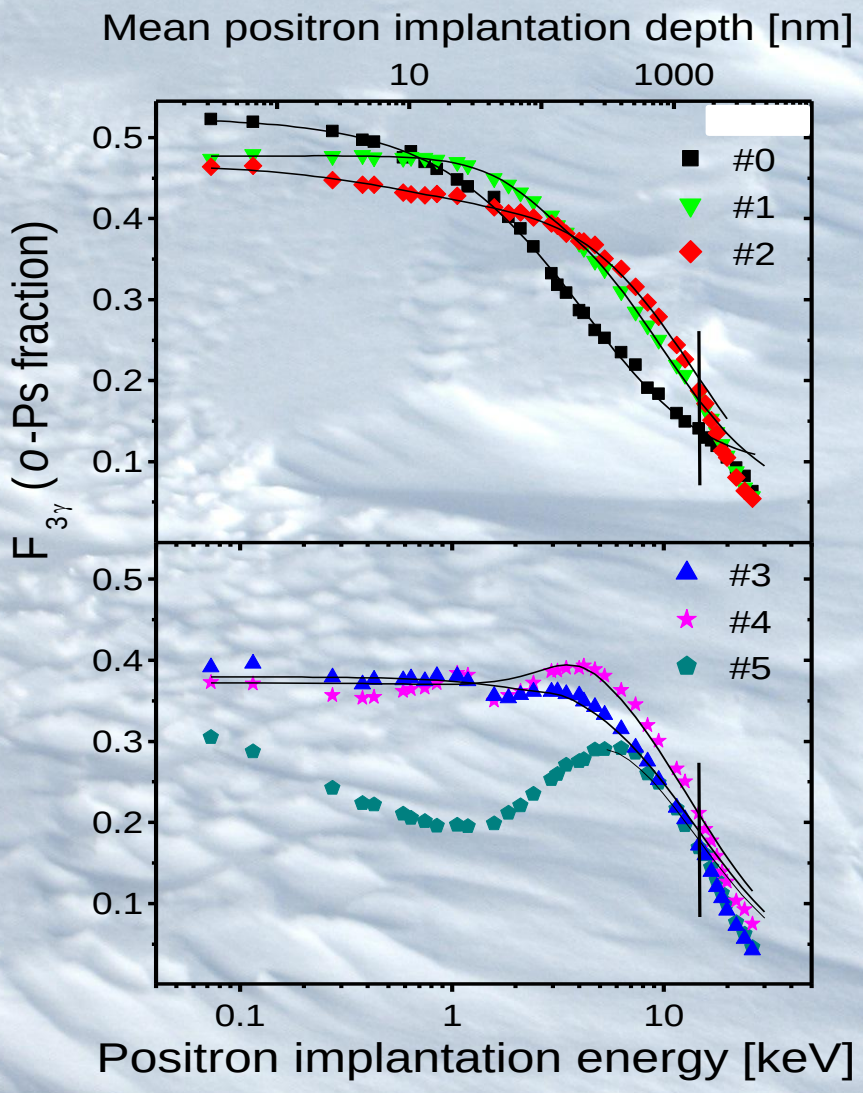


$$R(E) = V(E) / P(E)$$

$$F_{3\gamma}(E) = \frac{3}{4}\left\{1 + \frac{P_1[R_1 - R(E)]}{P_0[R(E) - R_0]}\right\}$$



Ps yield and channel size



$$F_{3\gamma}(E) = A(E)\cdot B(E) + C(E)$$

$$A(E) = F_1 + (F_2 - F_1)e^{-\frac{1}{2}\left(\frac{E}{E_1}\right)^{\beta}}$$

***o*-Ps formation**

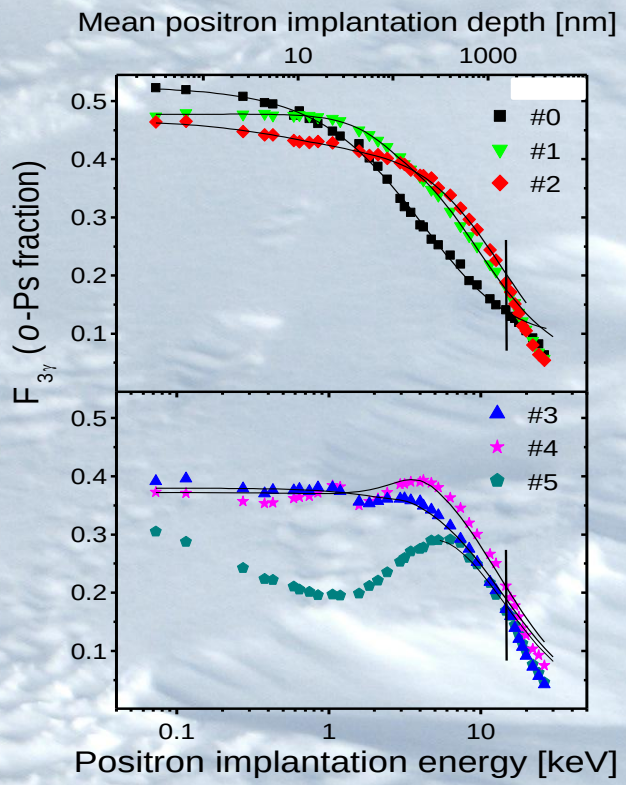
$$B(E) = \frac{1}{1+\left(\frac{E}{E_0}\right)^{1.6}}$$

***o*-Ps out diffusion probability**

$$C(E) = K\left[\frac{C_1 - C_2}{1+\left(\frac{E}{E_2}\right)} + C_2\right]$$

***o*-Ps annihilation via 3γ into pores**

#0 = 4-7 nm
#1=8-12 nm
#2= 8-14 nm
 # 3= 10-16 nm
#4= 14-20 nm
#5= 80-120 nm



Up to 42 % of implanted positrons at 1 keV emitted as o-Ps

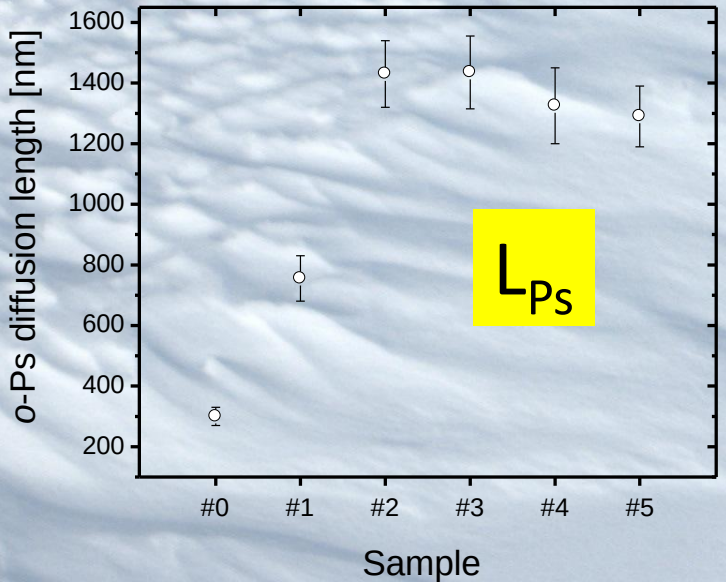
The *o*-Ps fraction out-diffusing at 10 keV positron implantation energy is still

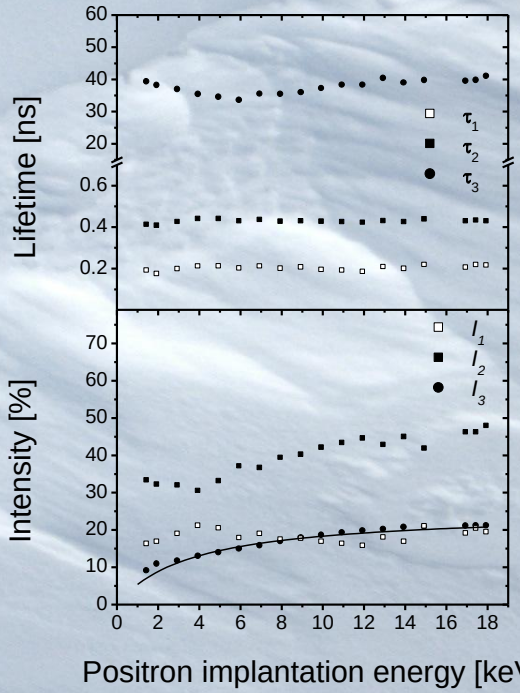
10 % in #0 = 4-7 nm

17 % in #1 = 8-12 nm

23-25 % in #2, #3, #4 and #5

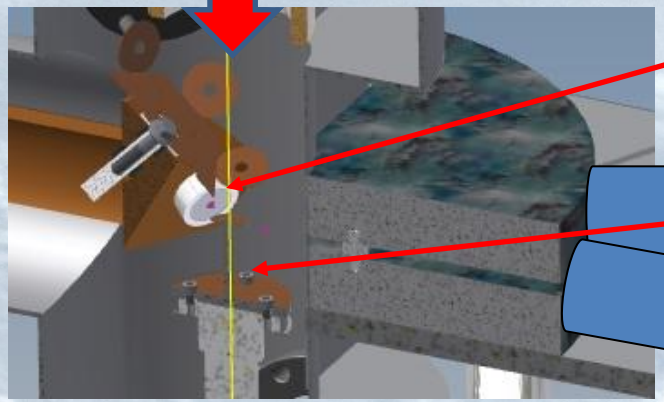
15 - 100nm





Trento TOF Apparatus

BEAM

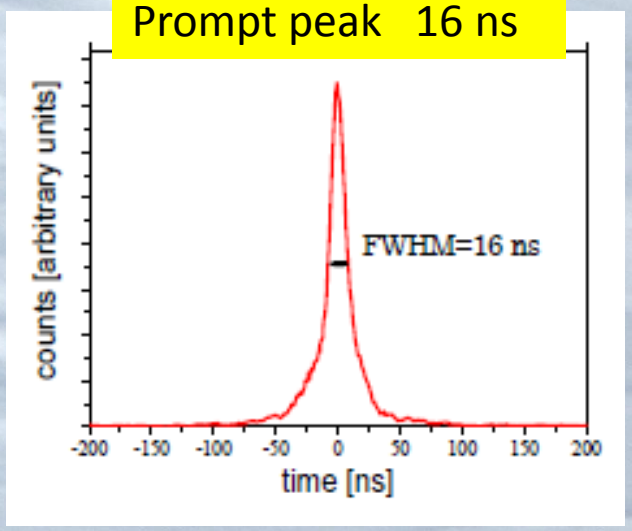


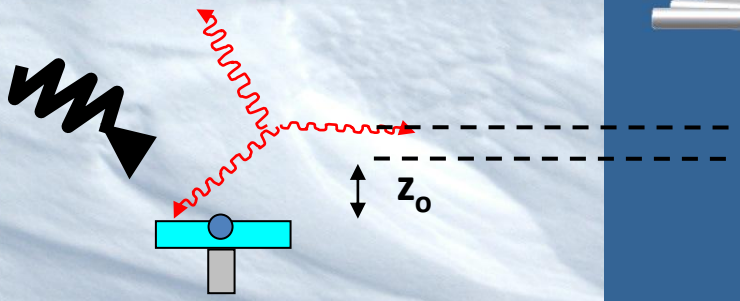
2 channeltrons

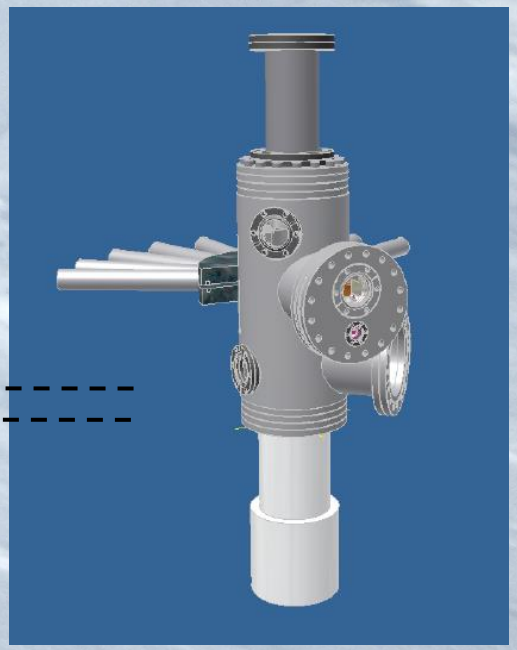
target position

5 NaI scintillators

Prompt peak 16 ns

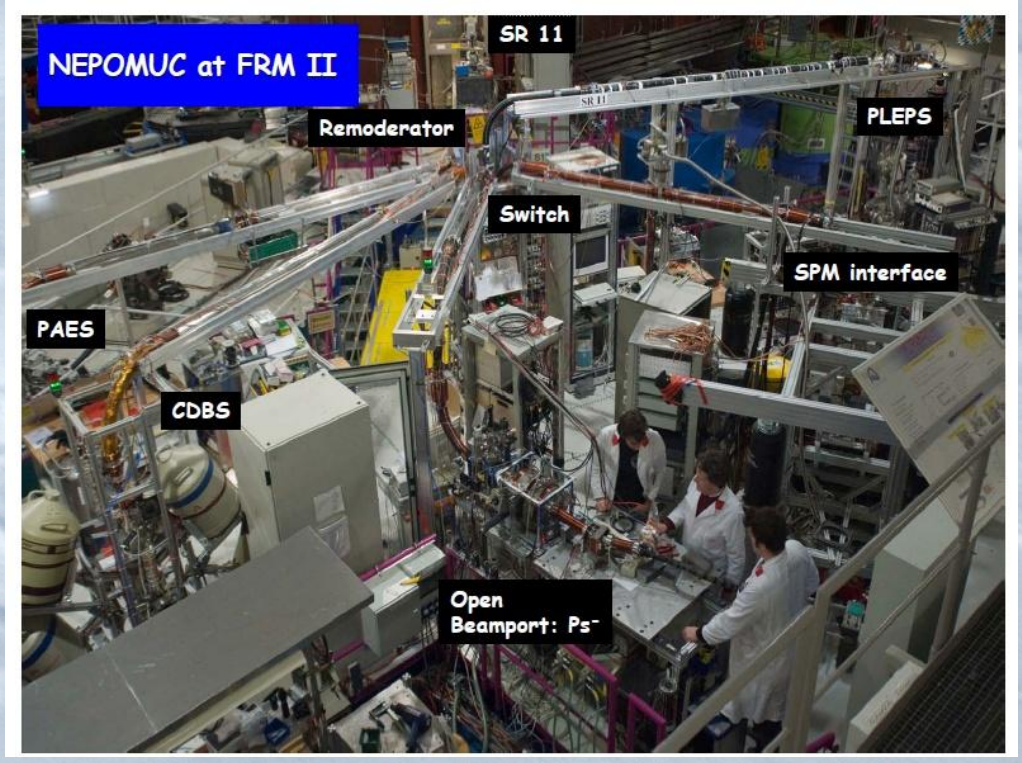




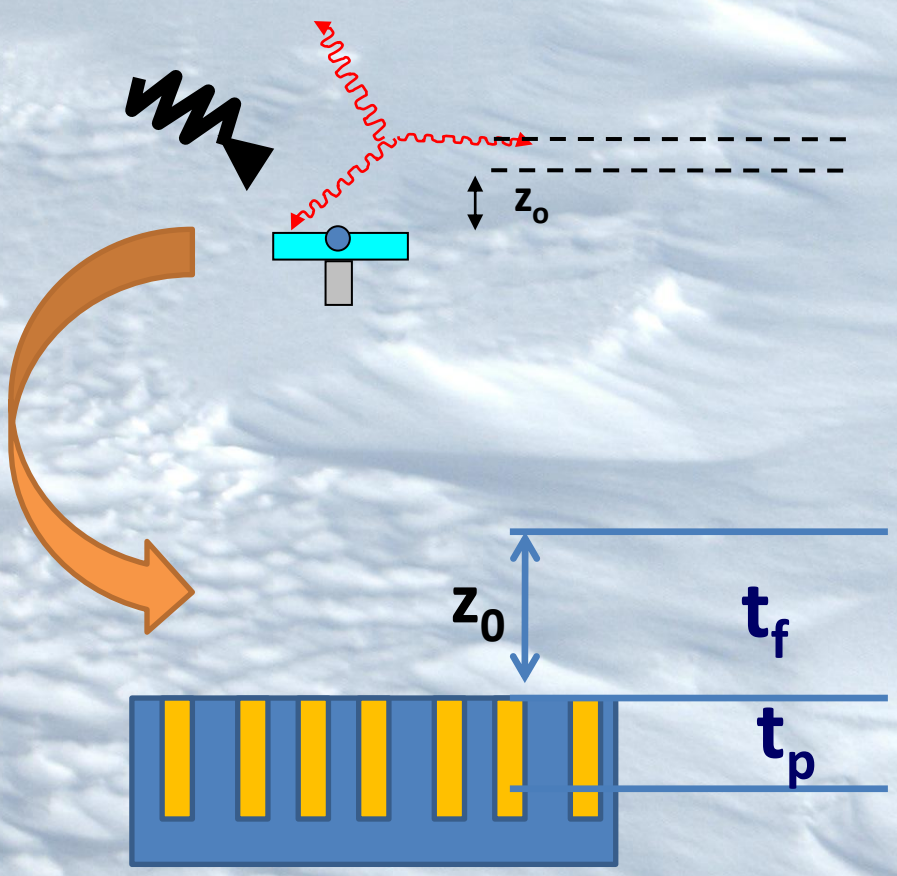


The TOF apparatus of Trento is now at the intense positron source NEPOMUC at the FRMII reactor in Munich and will be set up at the reactor hall in June-July.

NEPOMUC gives 10^{9} e+ /s



o-Ps Time of Flight measurements



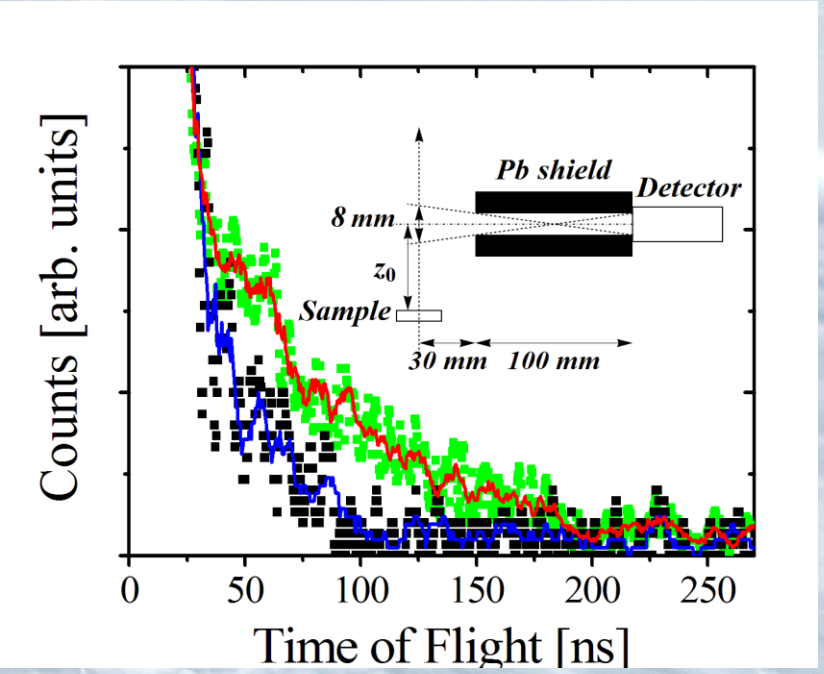
$$E_{\perp} = (m_0 z_0^2)/t_f^2$$

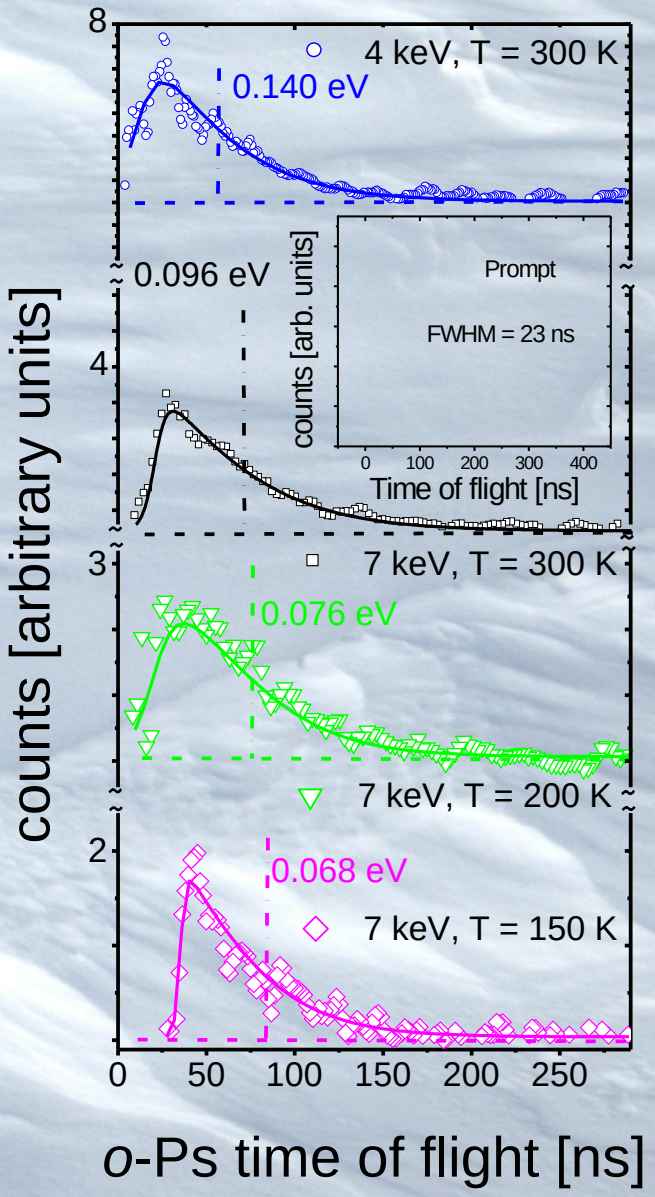
where $\langle t_m \rangle = \langle t_p \rangle + \langle t_f \rangle$

$$\langle t_m \rangle = \langle t_p \rangle + z_0/v_{\perp}$$

If $t_p \ll t_f$ $\quad t_m \cong t_f$

Ps cooling - 5-8 nm channels

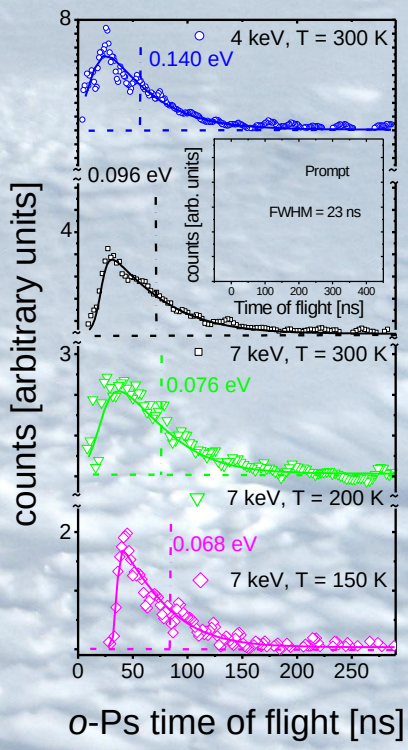




After smoothing, subtraction of the background, and correction by multiplying by $\left(1/t\right)\exp\left(t/142\right)$

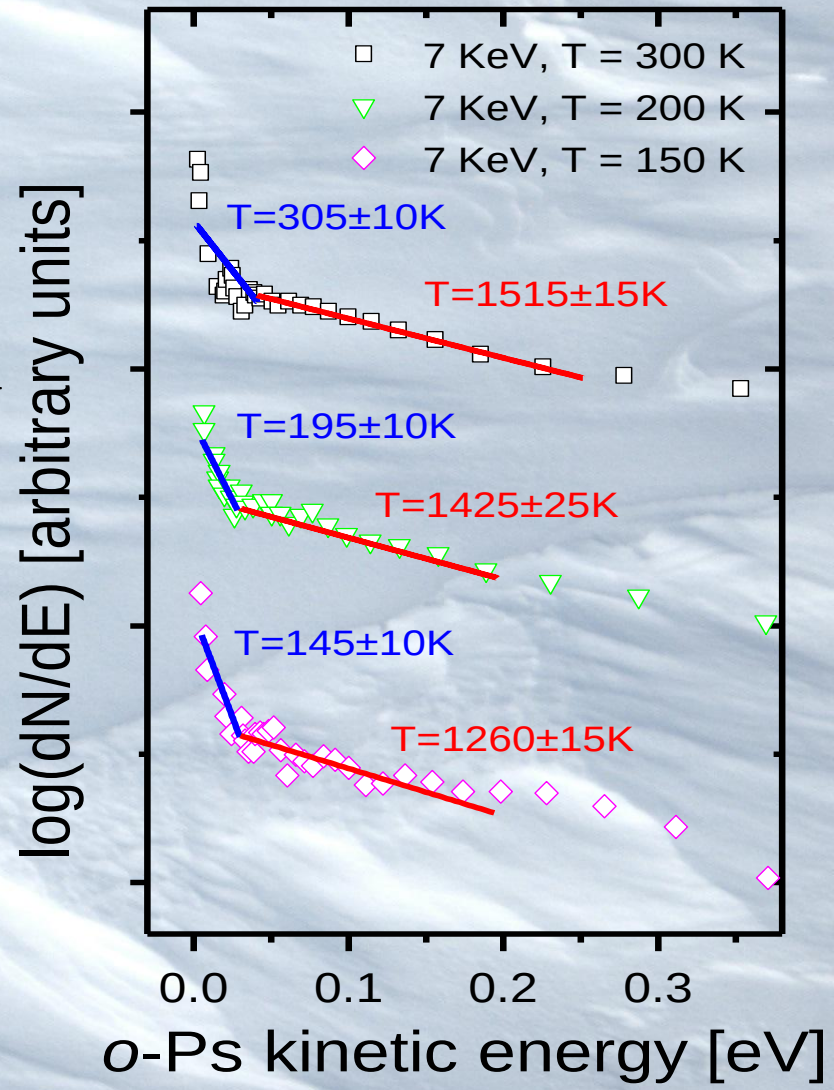
Mariazzi S, Brusa R S et al., *Phys. Rev. Lett.* **104** 243401 (2010)

Ps energy



$$\int N(t)dt = \int N(E)dE$$

$$N(E) \propto N(t)t^3$$



The two lines in log-lin graph are proportional to $e^{-\frac{E_\perp}{k_B T}}$

at two different T.

Mariazzi , Bettotti, Brusa, 2010 *Phys. Rev. Lett.* **104** 243401

Analysis of the Ps energy spectra

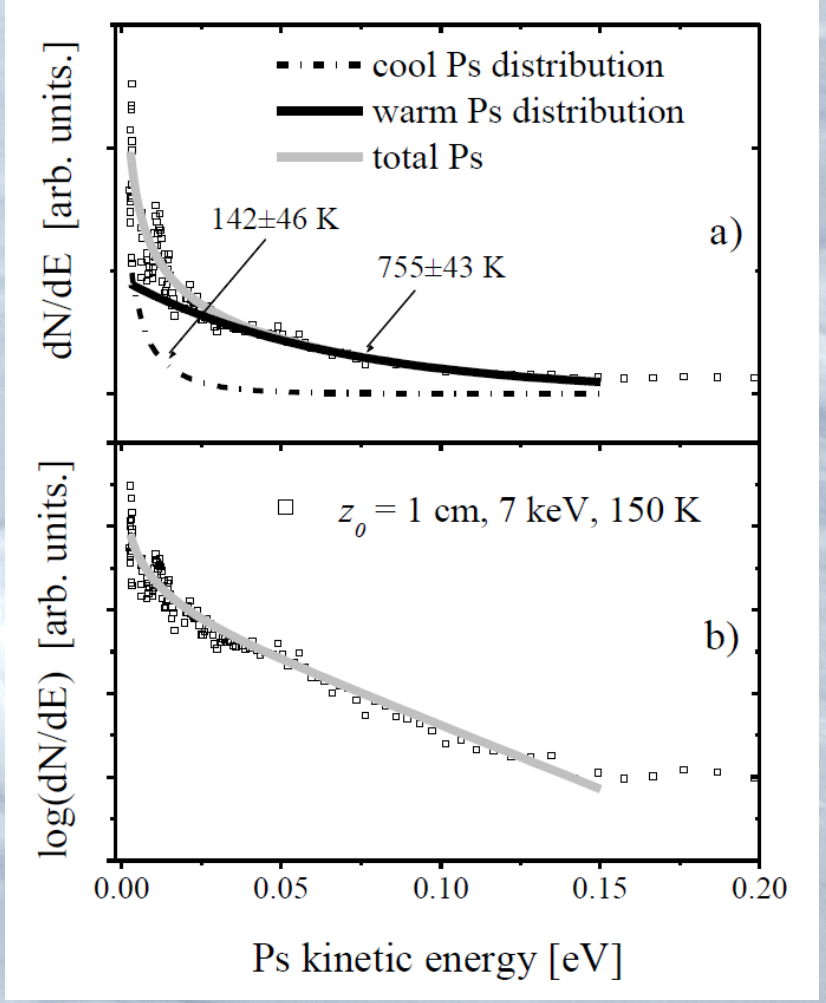
$$\ln\left(\frac{dN}{dE_\perp}\right) = \ln\left[\alpha \cdot E_\perp^m A(m,T_1) e^{-\frac{E_\perp}{k_B T_1}} + \beta \cdot E_\perp^n B(n,T_2) e^{-\frac{E_\perp}{k_B T_2}}\right]$$

With A and B , normalization factors

$$\int_0^\infty E_\perp^m A(m,T_1) e^{-\frac{E_\perp}{k_B T_1}} dE_\perp = 1$$

$$\int_0^\infty E_\perp^n B(n,T_2) e^{-\frac{E_\perp}{k_B T_2}} dE_\perp = 1$$

$$\alpha + \beta = 1$$



Cool distribution

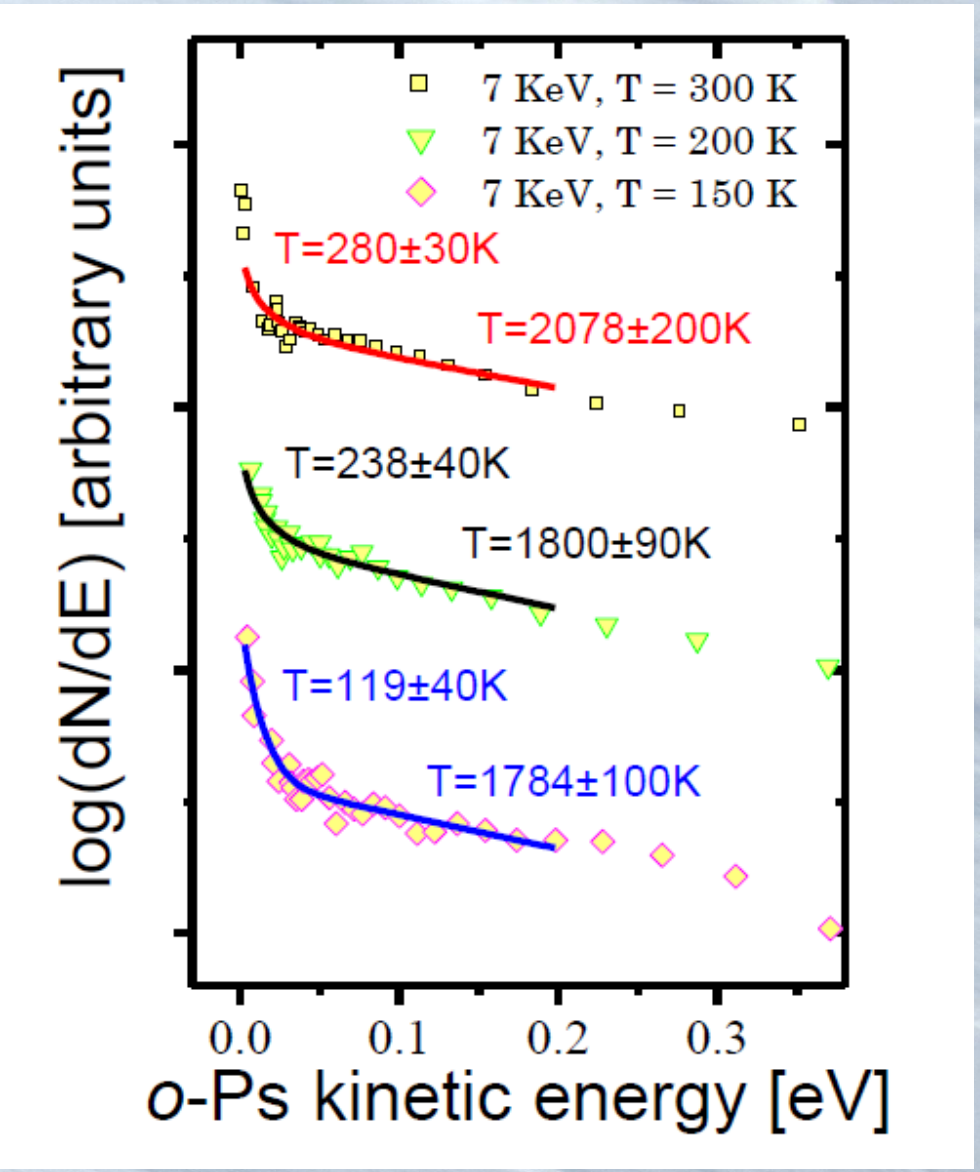
$$F(E_{c\perp}) = \frac{E_\perp^{-1/2}}{\sqrt{\pi k_B T_1}} e^{-\frac{E_\perp}{k_B T_1}}$$

$$\langle E_{c\perp} \rangle = \frac{T_1 k_B}{2}$$

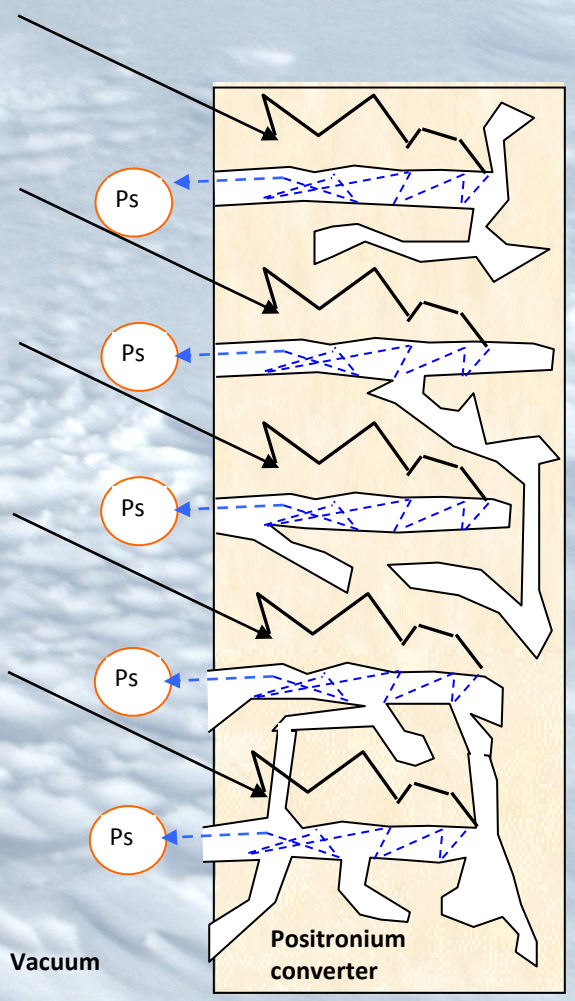
Warm distribution

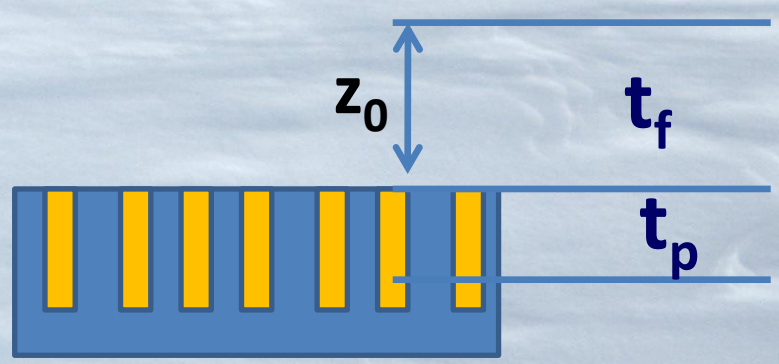
$$G(E_{w\perp}) = \frac{1}{k_B T_2} e^{-\frac{E_\perp}{k_B T_2}}$$

$$\langle E_{w\perp} \rangle = T_2 k_B$$



Permanence time of Ps in nano-channels before escaping into vacuum



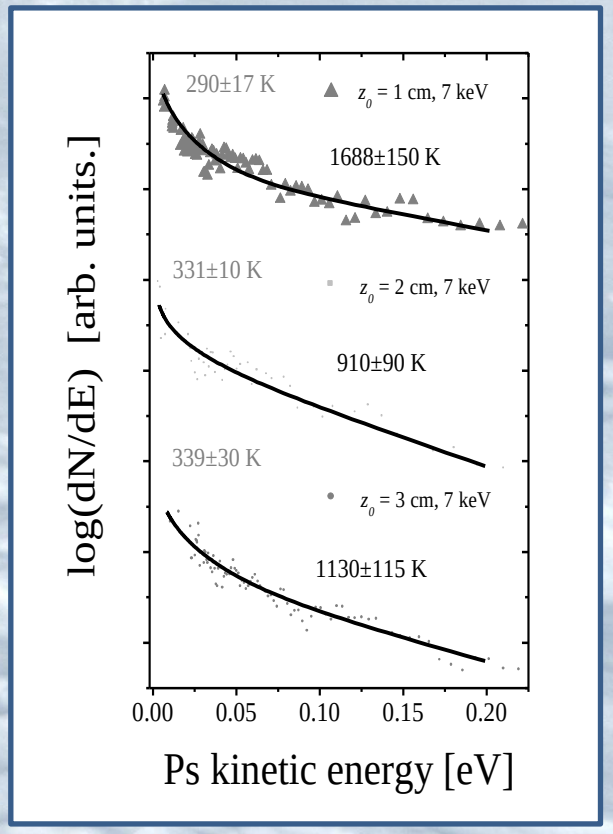


$$\langle t_m \rangle = \langle t_p \rangle + \langle t_f \rangle$$

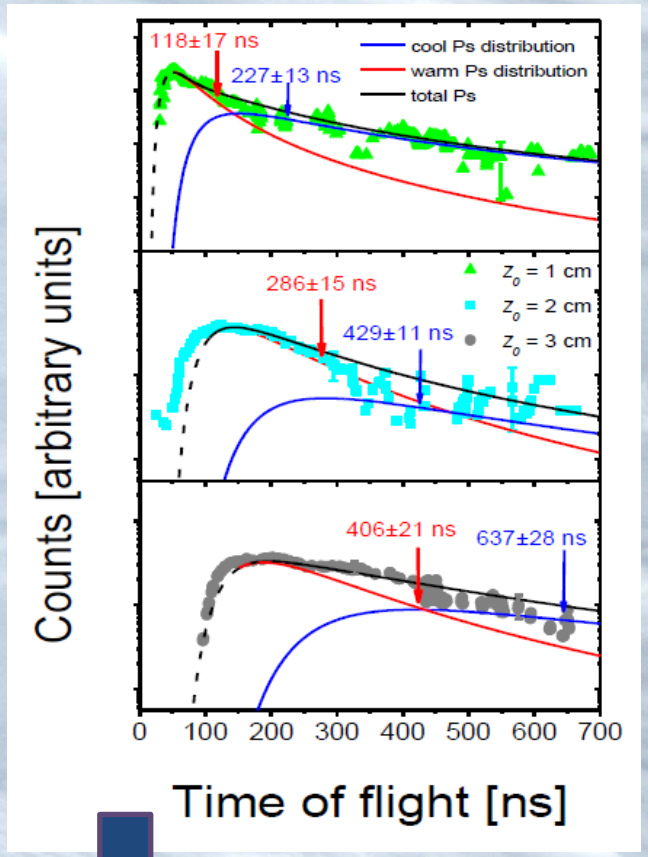
Measurements at three different distances z_0 allow to evaluate $\langle t_p \rangle$

Measurements were done at 7 keV e+ energy

Ps energy spectra



Ps energy spectra

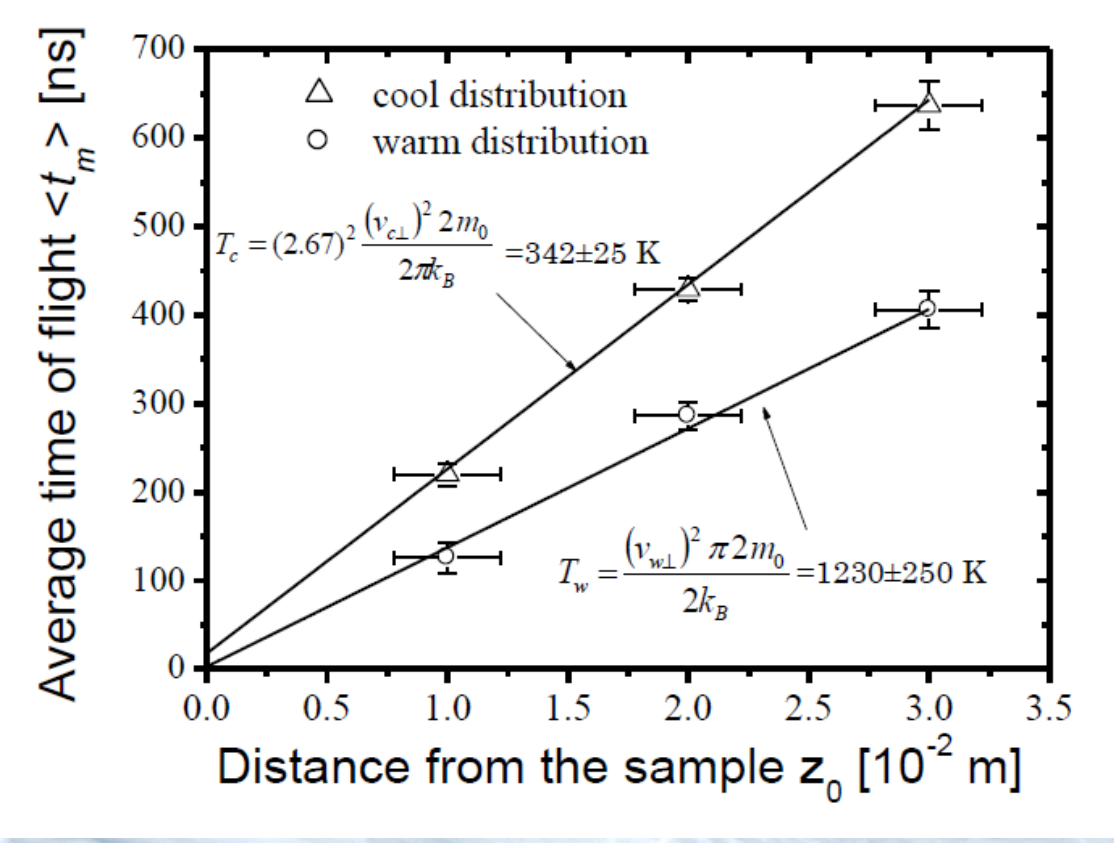


$$F(E_{c\perp}) = \frac{E_\perp^{-1/2}}{\sqrt{\pi k_B T_1}} e^{-\frac{E_\perp}{k_B T_1}}$$

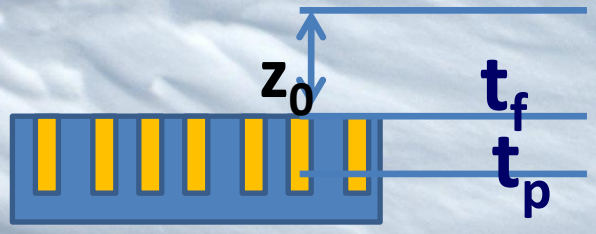
$$G(E_{w\perp}) = \frac{1}{k_B T_2} e^{-\frac{E_\perp}{k_B T_2}}$$

$\langle t_m \rangle$ of the cold and warm distribution

Cooling time of Ps



$\langle t_m \rangle = \langle t_p \rangle + z_0/v_\perp$



$\langle t_{cp} \rangle$ =18±6 ns

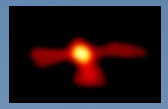
$\langle t_{cw} \rangle$ < 7 ns

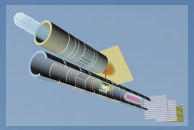
conclusion
with a question

Study of Ps formation and annihilation in complex materials and porous complex materials at low temperature are lacking

Could be more data useful for understanding signal of Ps annihilation in ISM ?

Thanks for listening and
Thanks to the organizers
for the invitation and
the wonderful workshop





From Schilthorn