Properties of positronium and its possible connection with imaging of the metabolic processes

LNGS SEMINAR

Assergi L'Aquila, 23 November 2016

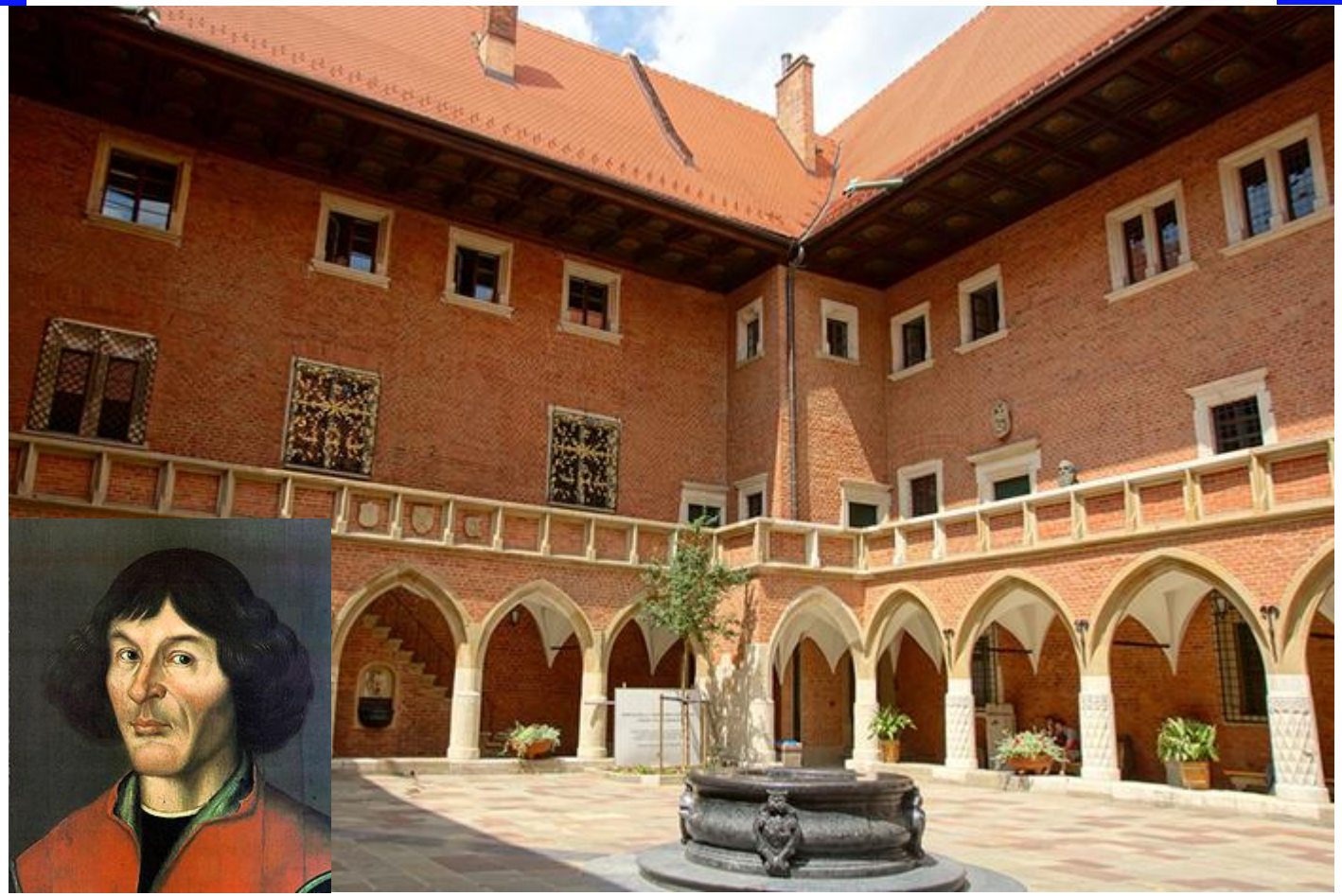
Paweł Moskal, Jagiellonian University

for and on behalf of the J-PET collaboration

http://koza.if.uj.edu.pl

Jagiellonian University

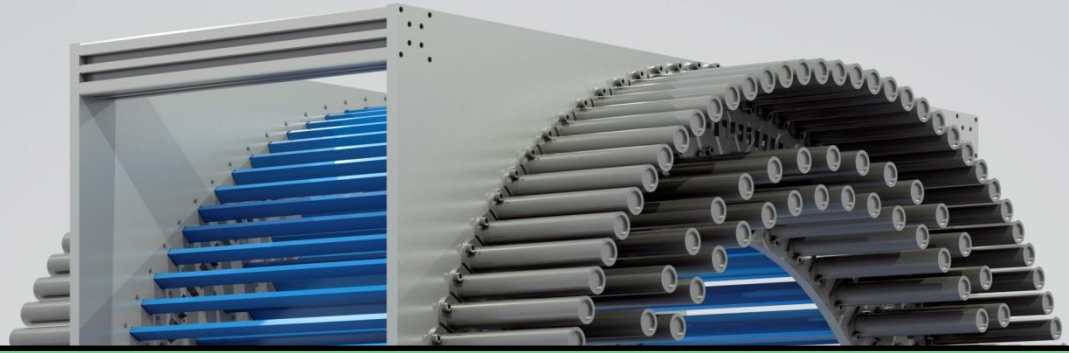
1364



Collegium Maius at the University since **1400**

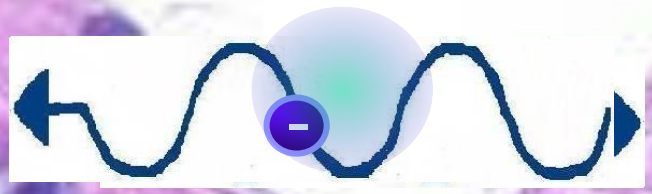
Jagiellonian PET

Jagiellonian PET



- **Jagiellonian PET**

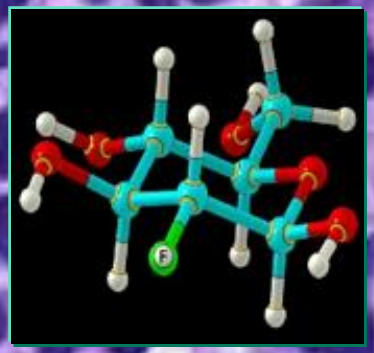
- **Positronium**
- **Discrete symmetries**
- **Quantum entanglement**
- **Morphometric imaging**



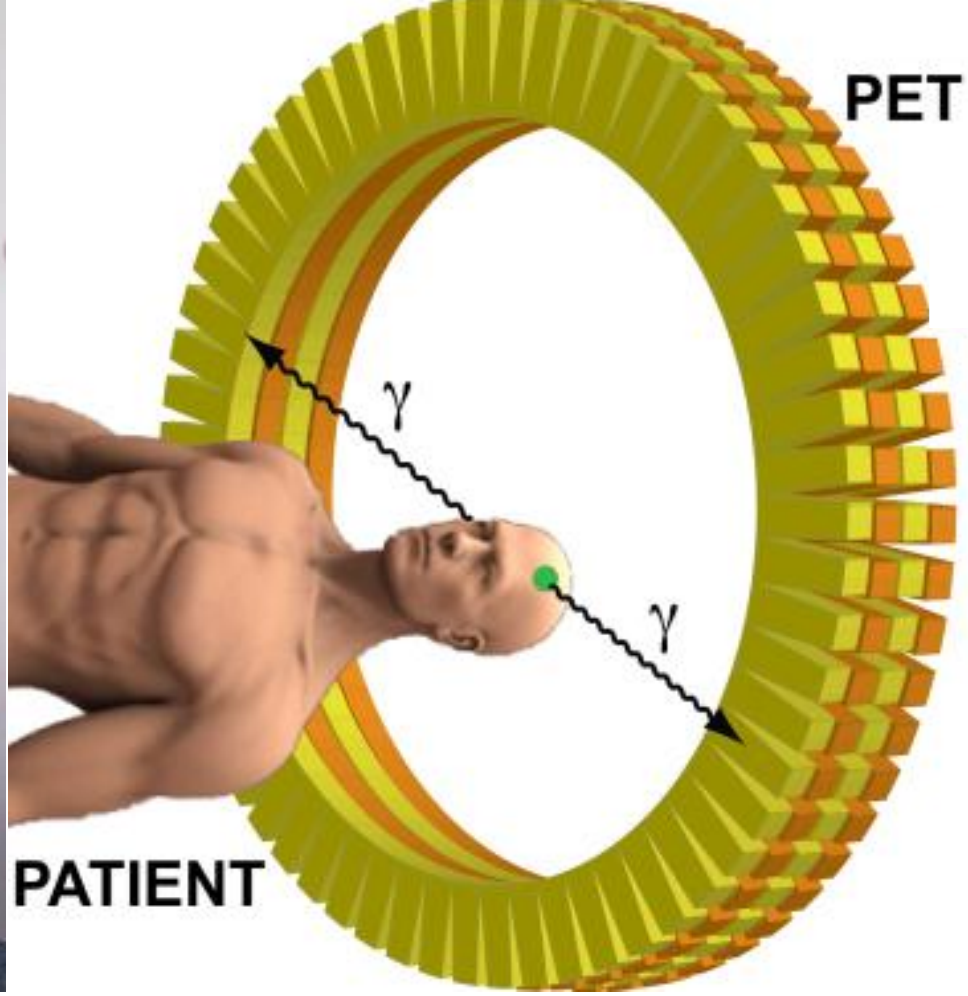
RADIOACTIVE SUGER

Fluoro–deoxy-glucose
(F-18 FDG)

~200 000 000
gamma per second



7 mSv PET/CT
~ 2.5 mSv PET
~3 mSv natural
background in Poland



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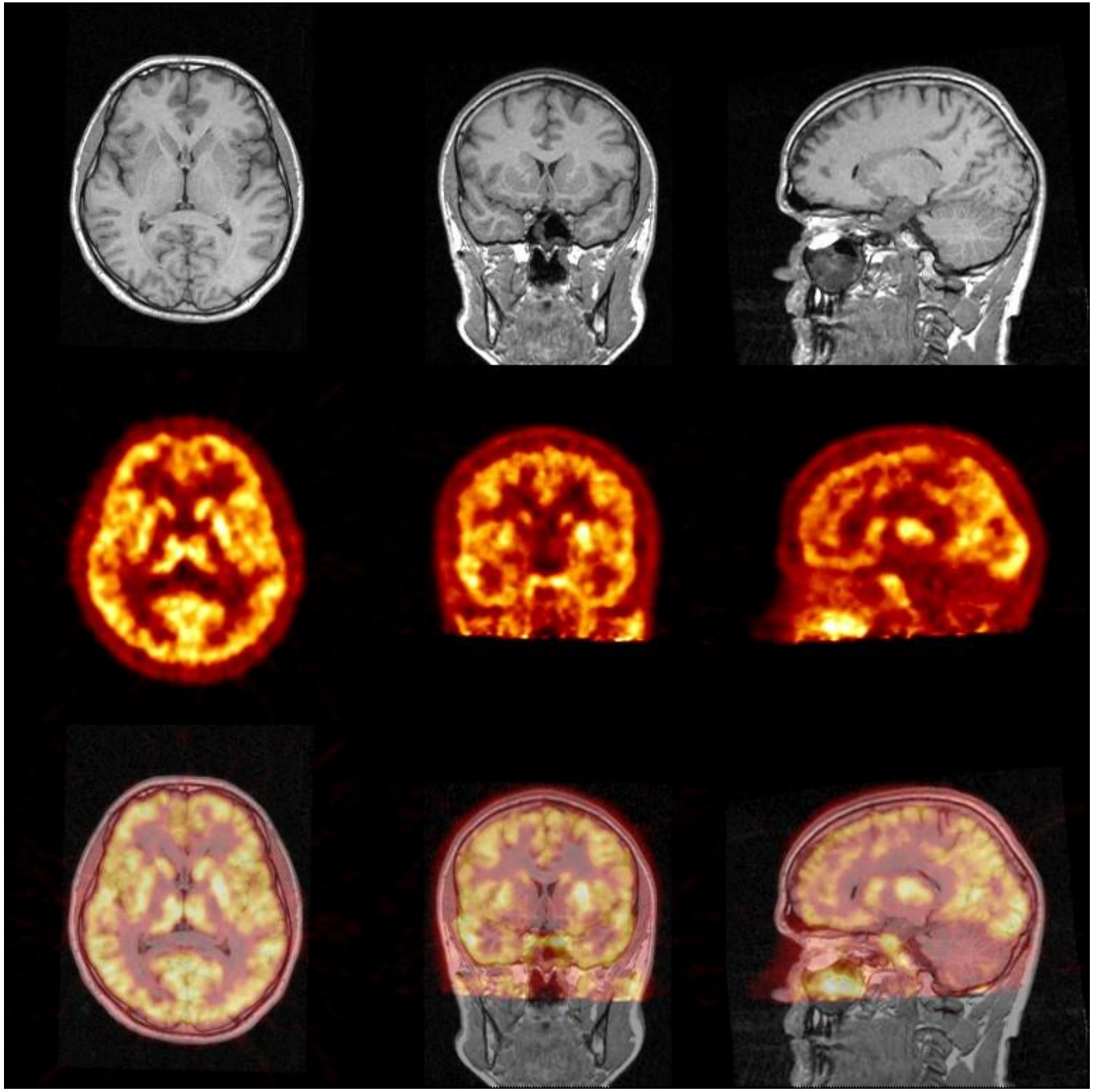
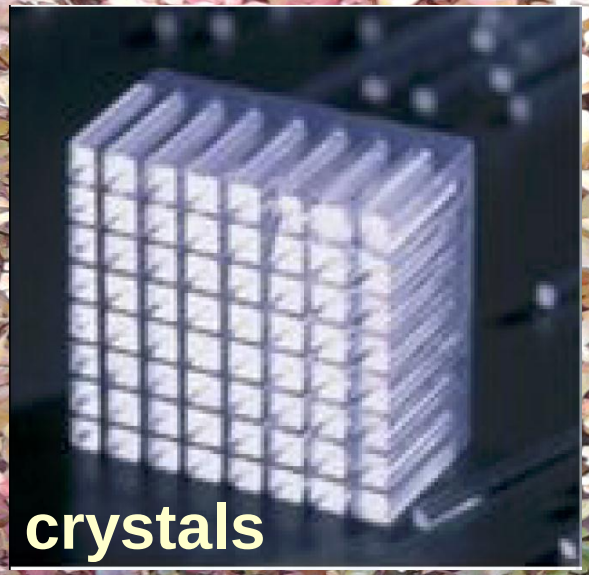
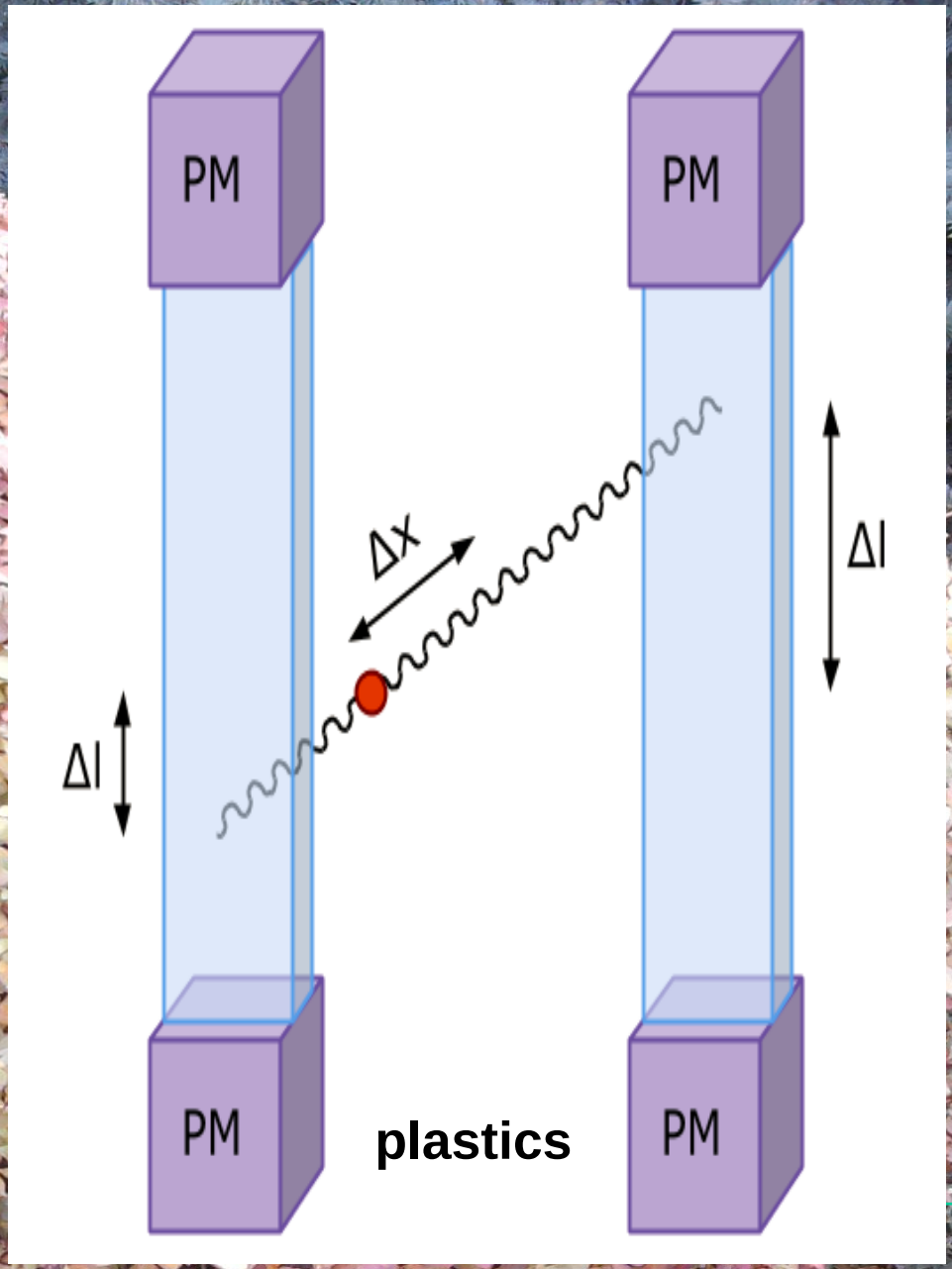
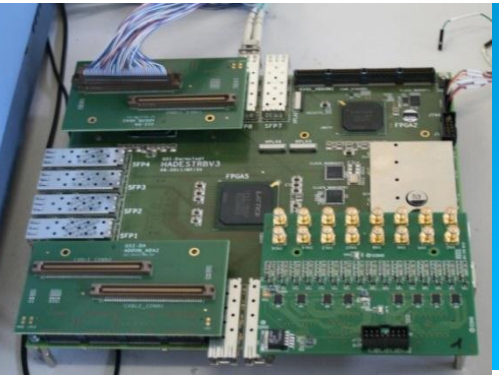



crystals


PM
PM
PM
PM
Δx
Δl
Δl
plastics



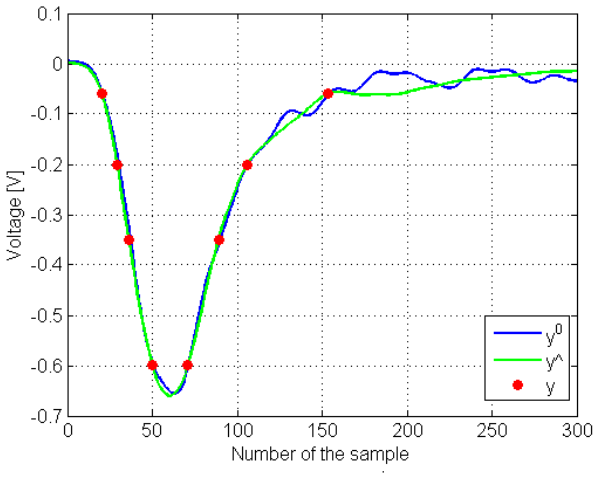
ONLY DIGITAL in triggerless mode

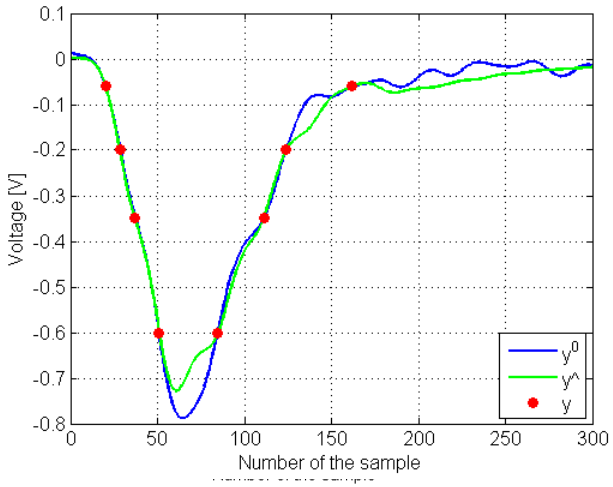
FFE sampling & Readout electronics

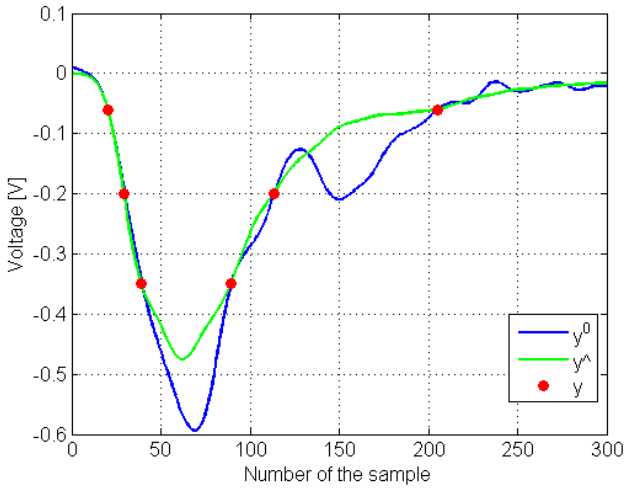
precision of 21ps (sigma) for 10 Euro per sample

M.Pałka, P.M., **PCT/EP2014/068367**

G. Korcyl, P. M., M. Kajetanowicz, M. Pałka, **PCT/EP2014/068352**







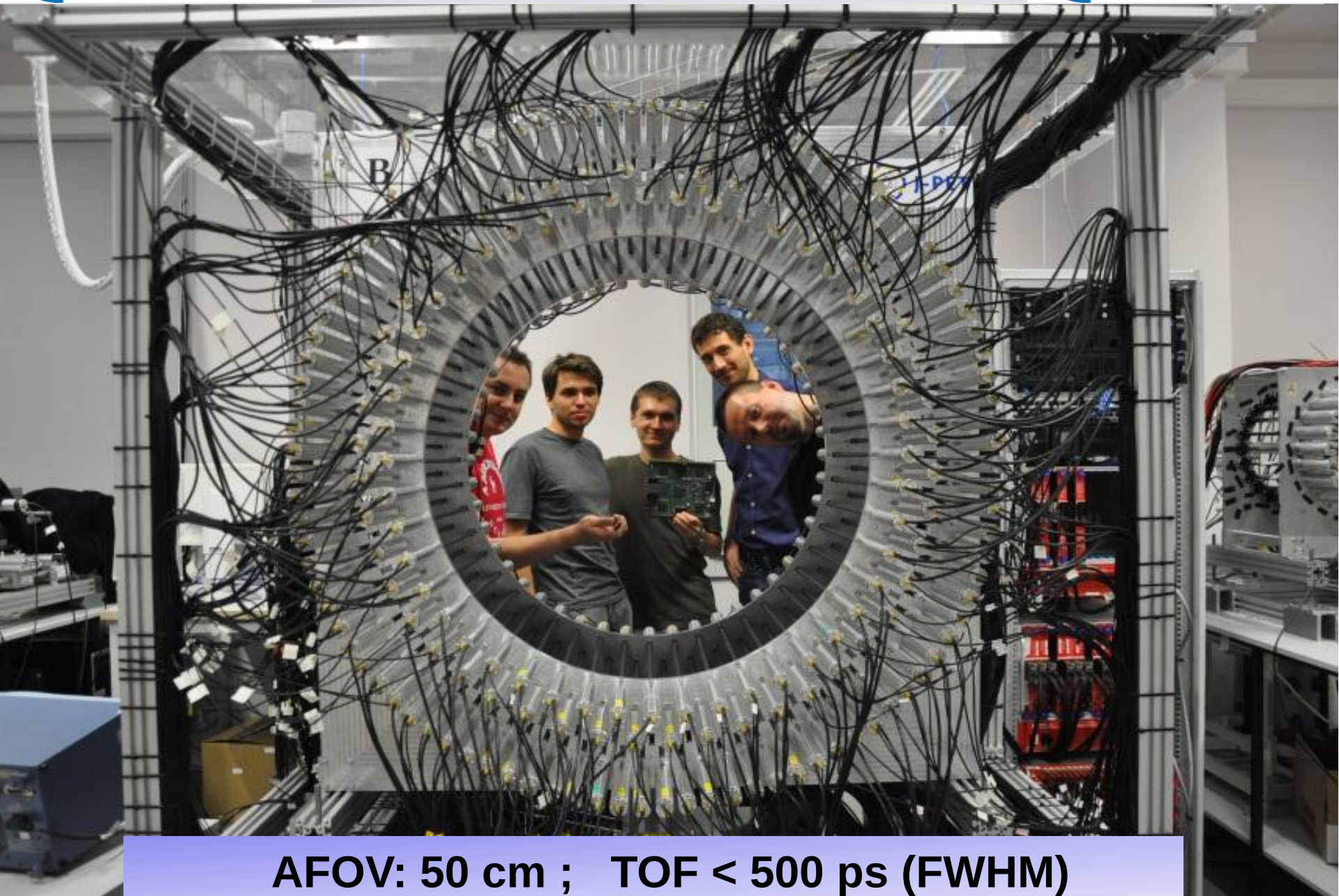
Library of signals; Principal Component Analysis; Compressive Sensing;
J-PET: L. Raczyński et al., Nucl. Instr. Meth. A786 (2015) 105
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54

Reconstruction

Detector | **FrontEnd electronics** | **Electronics controller** | **Hit along strip** | **Annihilation point** | **Image**

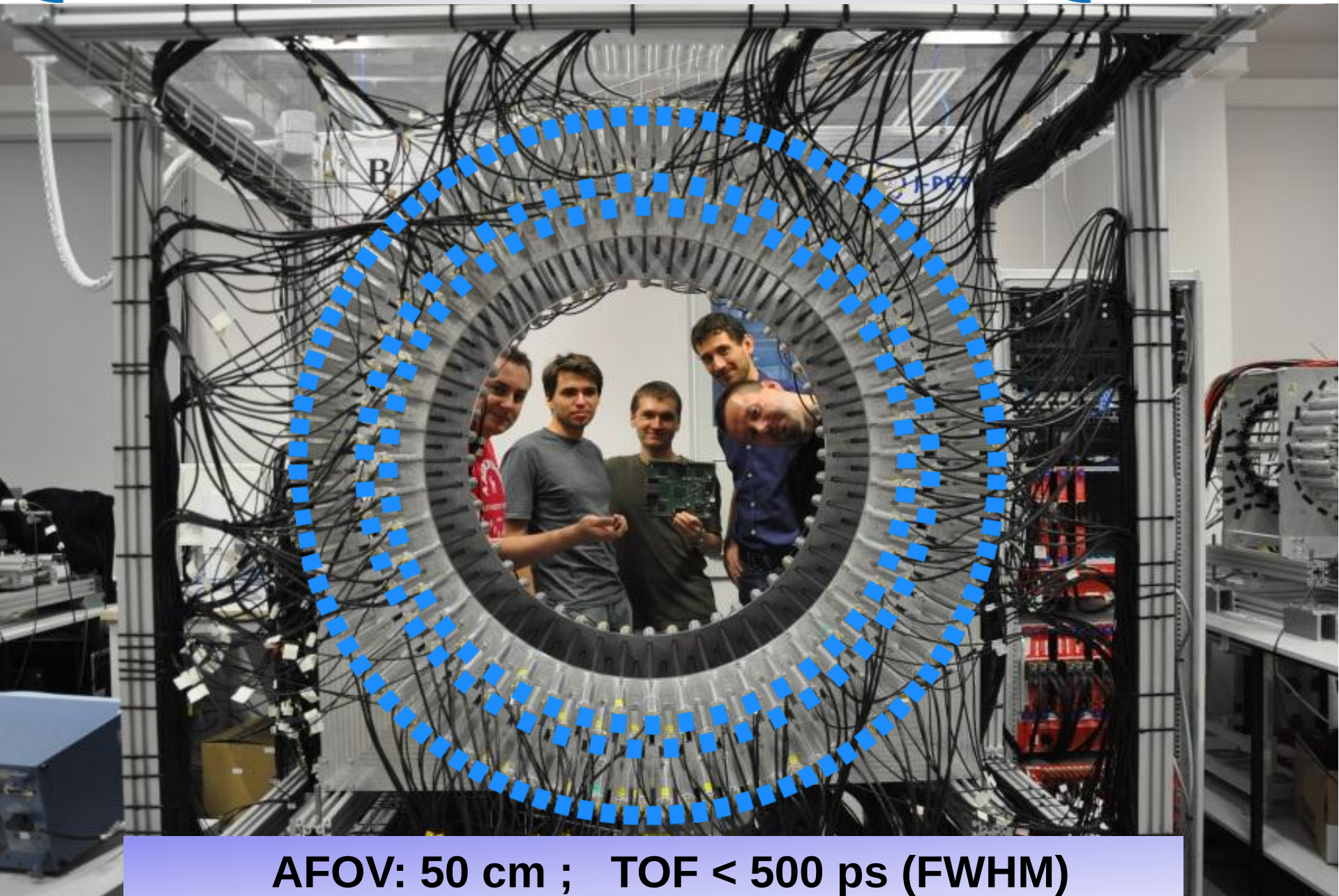
J-PET: W. Krzemień et al., Acta Phys. Pol. B47 (2016) 561

Jagiellonian PET



AFOV: 50 cm ; TOF < 500 ps (FWHM)

Jagiellonian PET



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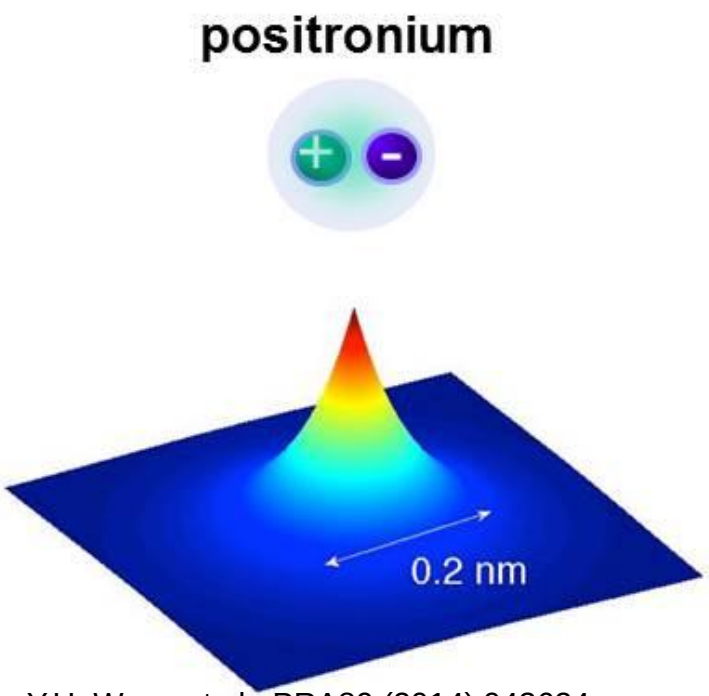
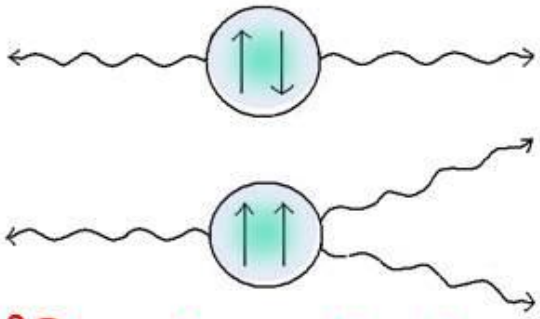


Y.H. Wang et al., PRA89 (2014) 043624+

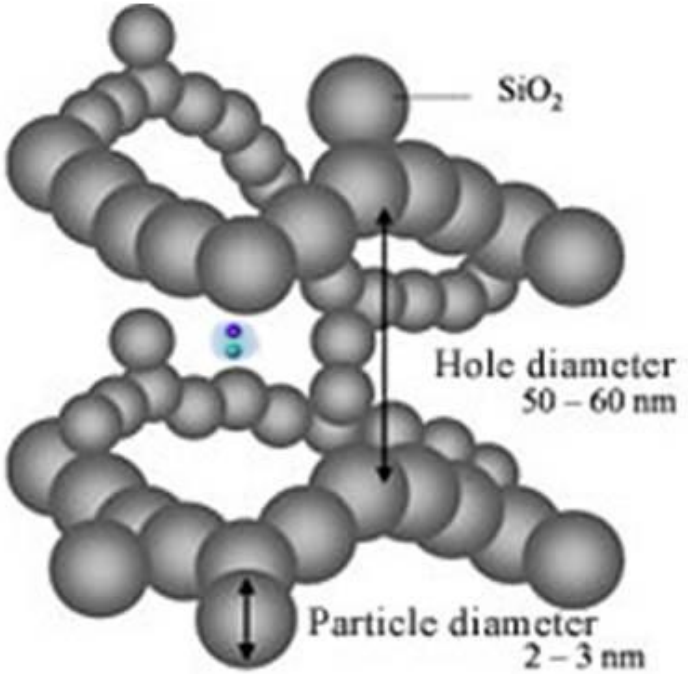
$\tau \approx 125$ ps

$^1S_0$ para-positronium p-Ps

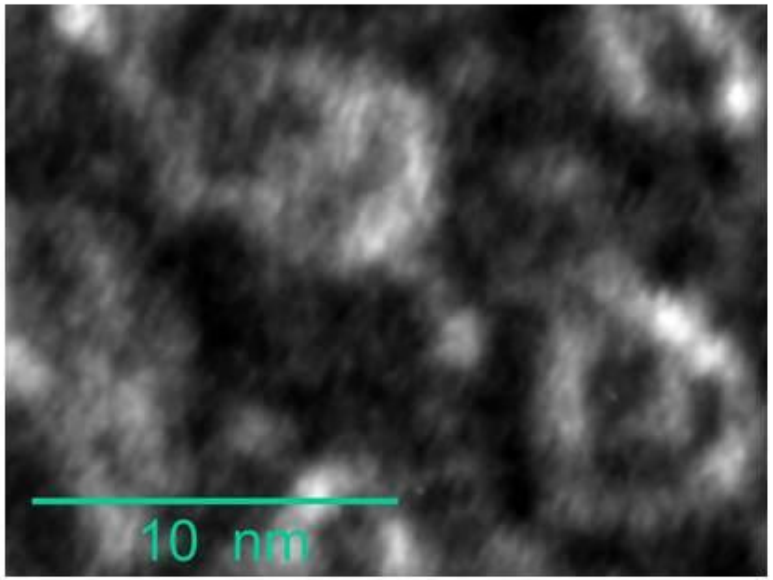


$^3S_1$ ortho-positronium o-Ps

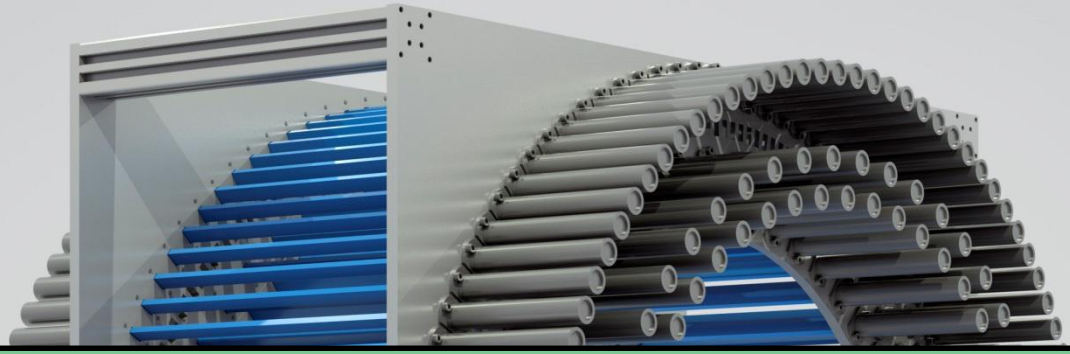
$\tau \approx 142$ ns



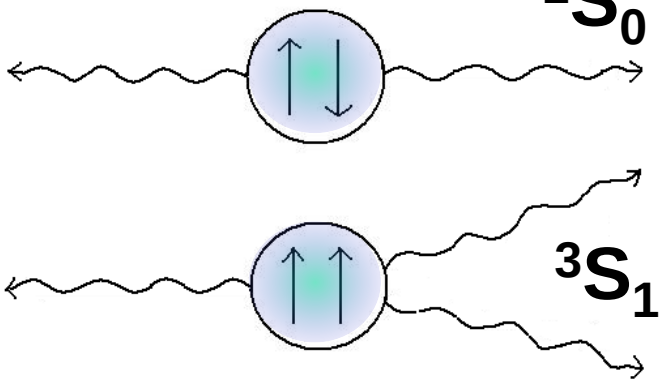
http://www.chem-eng.kyushu-u.ac.jp/e/research.html



Jagiellonian PET



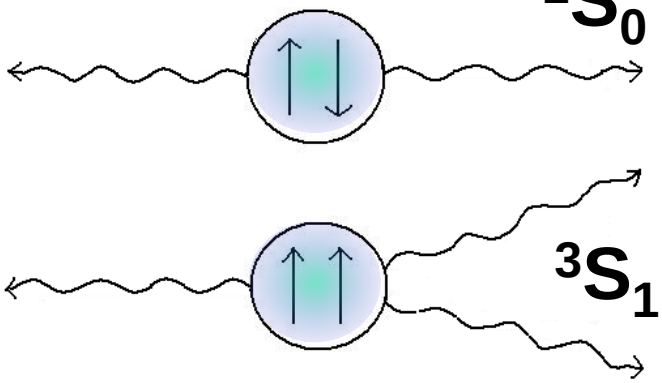
- Jagiellonian PET
- Positronium
- Discrete symmetries
- Quantum entanglement
- Morphometric imaging



$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

	$^1S_0$	$^3S_1$
L	0	0



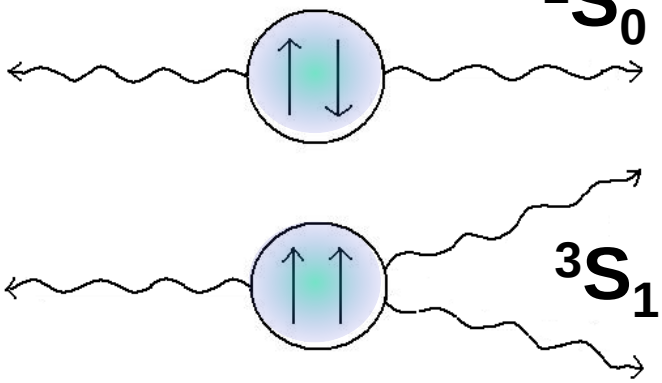
$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

	$^1S_0$	$^3S_1$
L	0	0
S	0	1

S = 0 $\downarrow\uparrow - \uparrow\downarrow$

S = 1 $\uparrow\uparrow + \downarrow\downarrow$



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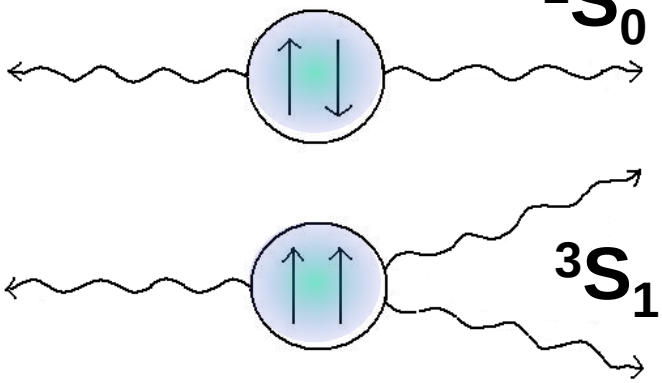
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-

S = 0 $\downarrow\uparrow - \uparrow\downarrow$

S = 1 $\uparrow\uparrow + \downarrow\downarrow$



$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

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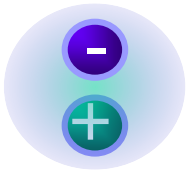
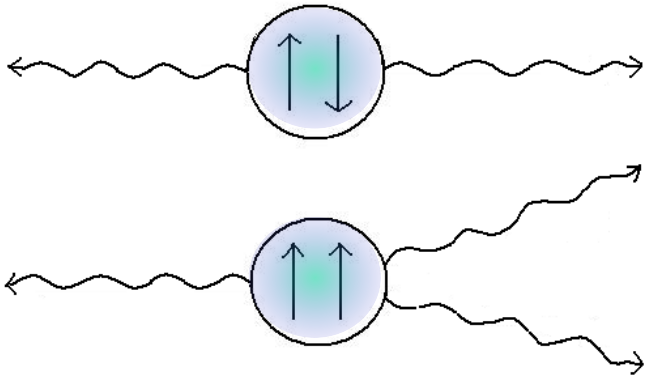
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-
L=0 -> P	-	-
CP	-	+

S = 0 $\downarrow\uparrow - \uparrow\downarrow$

S = 1 $\uparrow\uparrow + \downarrow\downarrow$

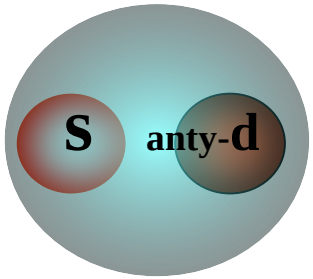


POSITRONIUM

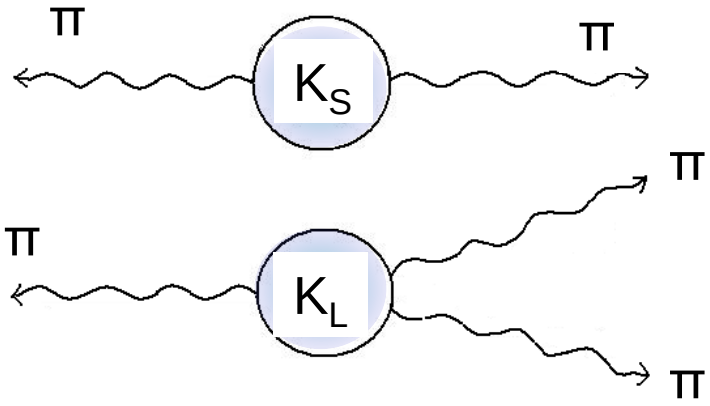


CP = + Para-positronium tau(p-Ps) ≈ 125 ps

CP = - Ortho-positronium tau(o-Ps) ≈ 142 ns



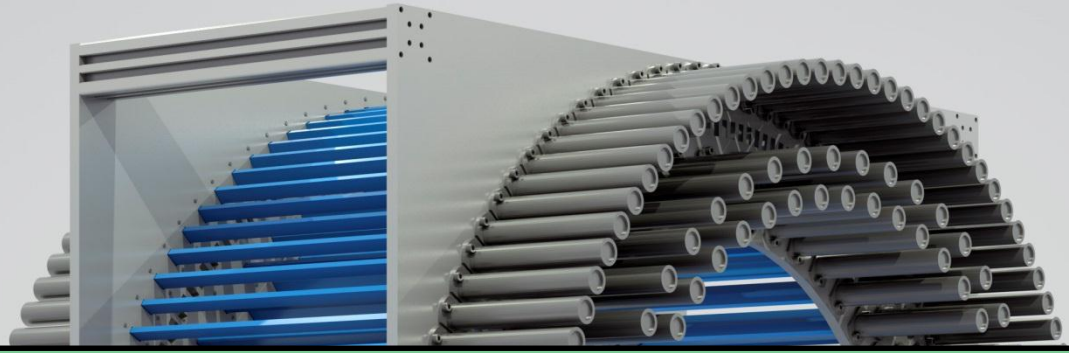
MESON K



CP ~= + tau(K_S) ≈ 90 ps

CP ~= - tau(K_L) ≈ 52 ns

Jagiellonian PET



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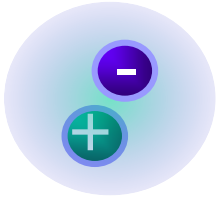
ODE TO POSITRONIUM

Eigen-state of Hamiltonian and P, C, CP operators



The lightest known atom and at the same time anti-atom which undergoes self-annihilation as flavor neutral mesons

The simplest atomic system with charge conjugation aigenstates.

Electrons and positron are the lightest leptons so they can not decay into lighter partilces via weak interactiom ...
effects due the weak interaction can lead to the violation at the order of 10^{-14}.
M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)

No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)
Light by light contributions to various correlations are small
B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988).
W. Bernreuther et al., Z. Phys. C 41, 143 (1988).

Purely Leptonic state !

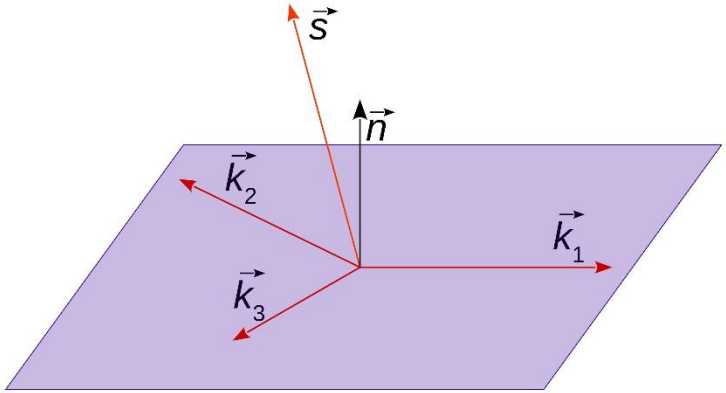
Breaking of T and CP was observed but only for processes involving quarks.
So far breaking of these symmetries was not observed for purely leptonic systems.

10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

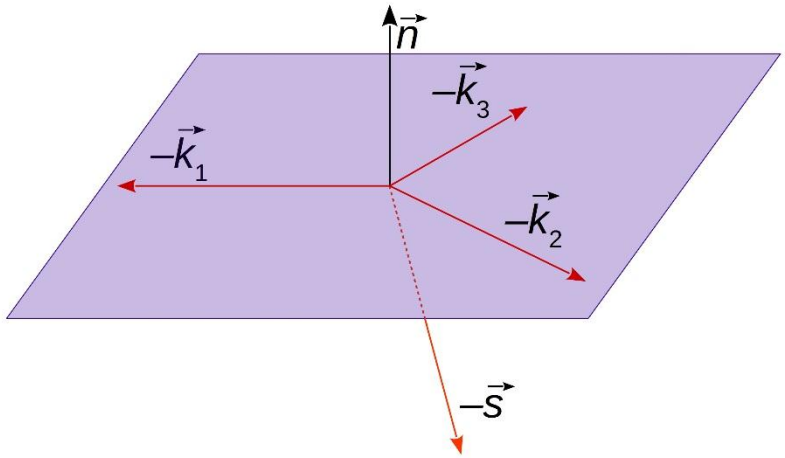
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)\left(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+

Operators for the o-Ps→3γ process, and their properties with respect to the C, P, T, CP and CPT symmetries.

$$|k_1| > |k_2| > |k_3|$$



T, CPT

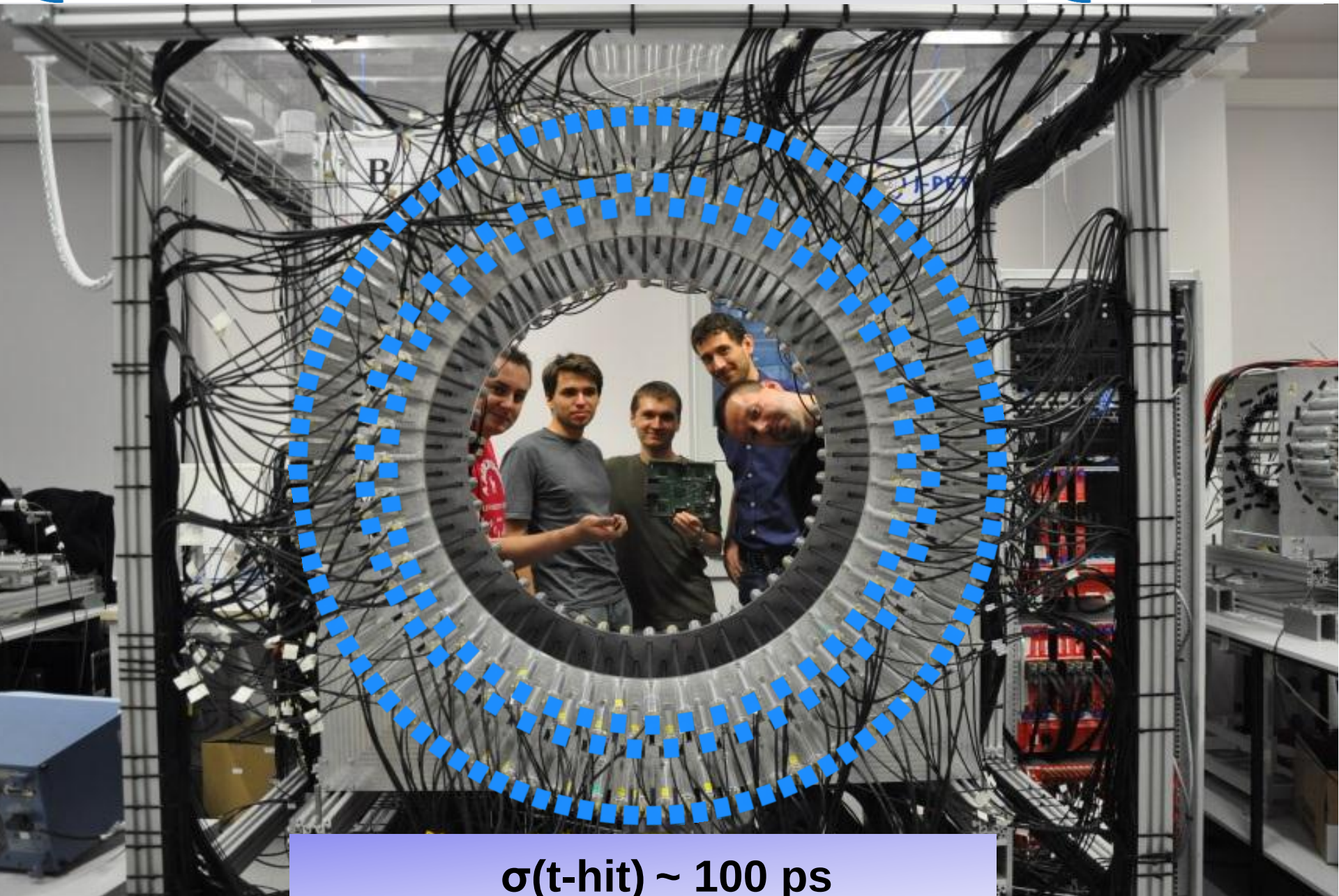


So far best accuracy for **CP and CPT violation** was reported by

-0.0023 < CP < 0.0049 at 90% CL T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

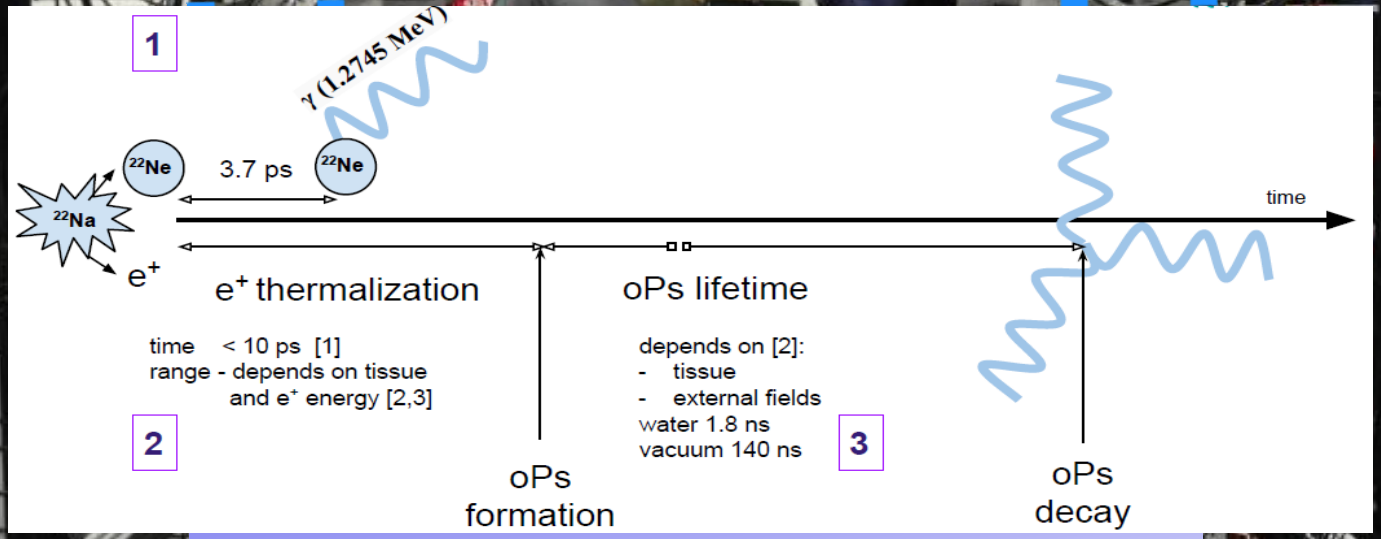
CPT = 0.0071 ± 0.0062 P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003).

Jagiellonian PET



σ(t-hit) ~ 100 ps

Jagiellonian PET



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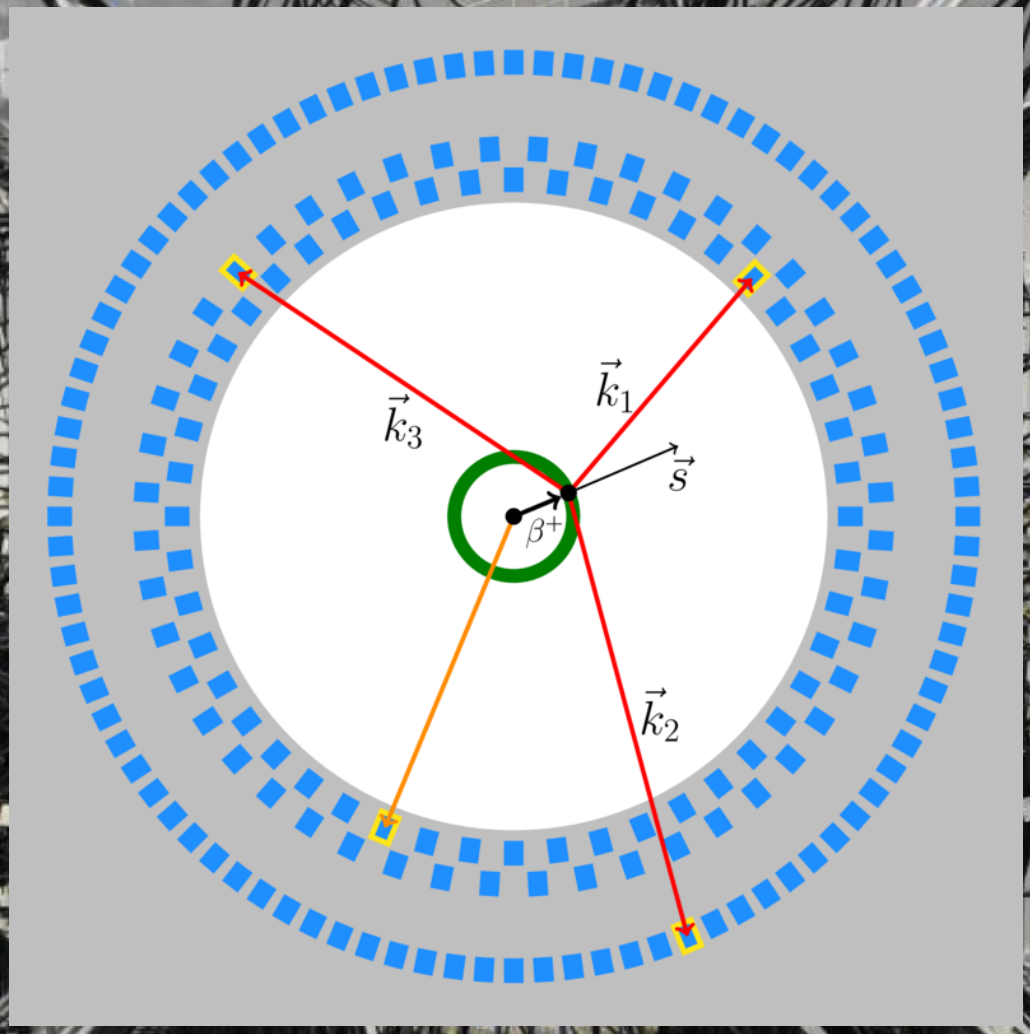

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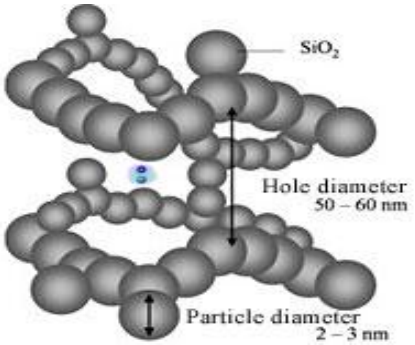
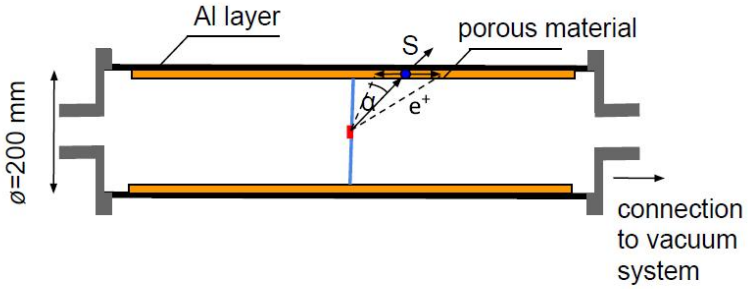
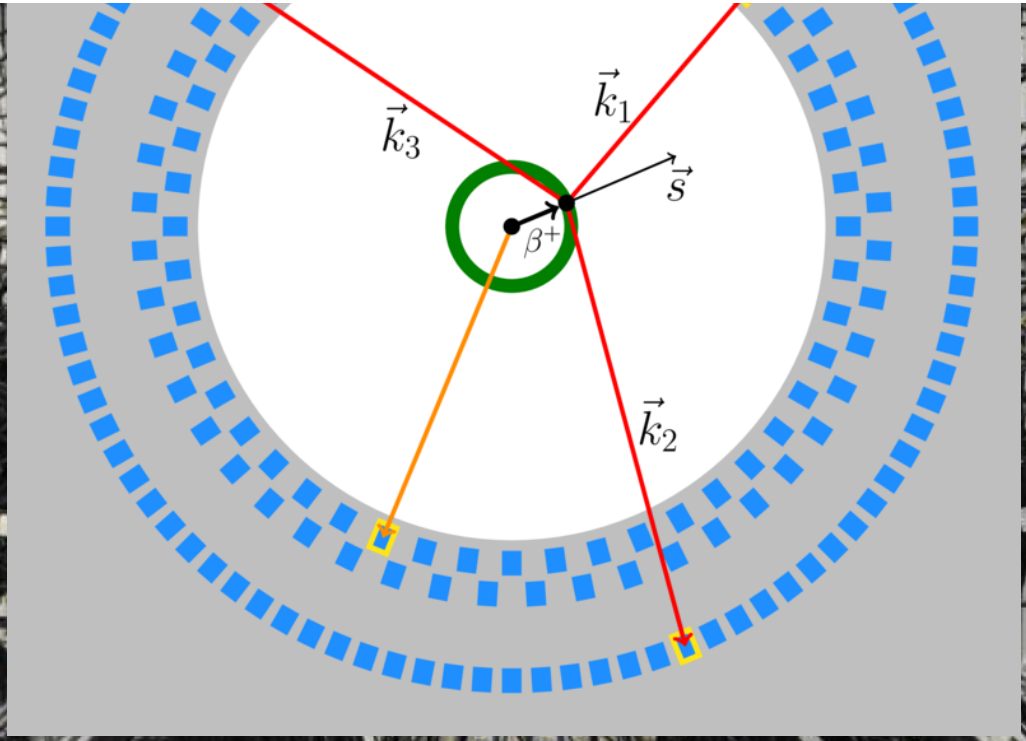


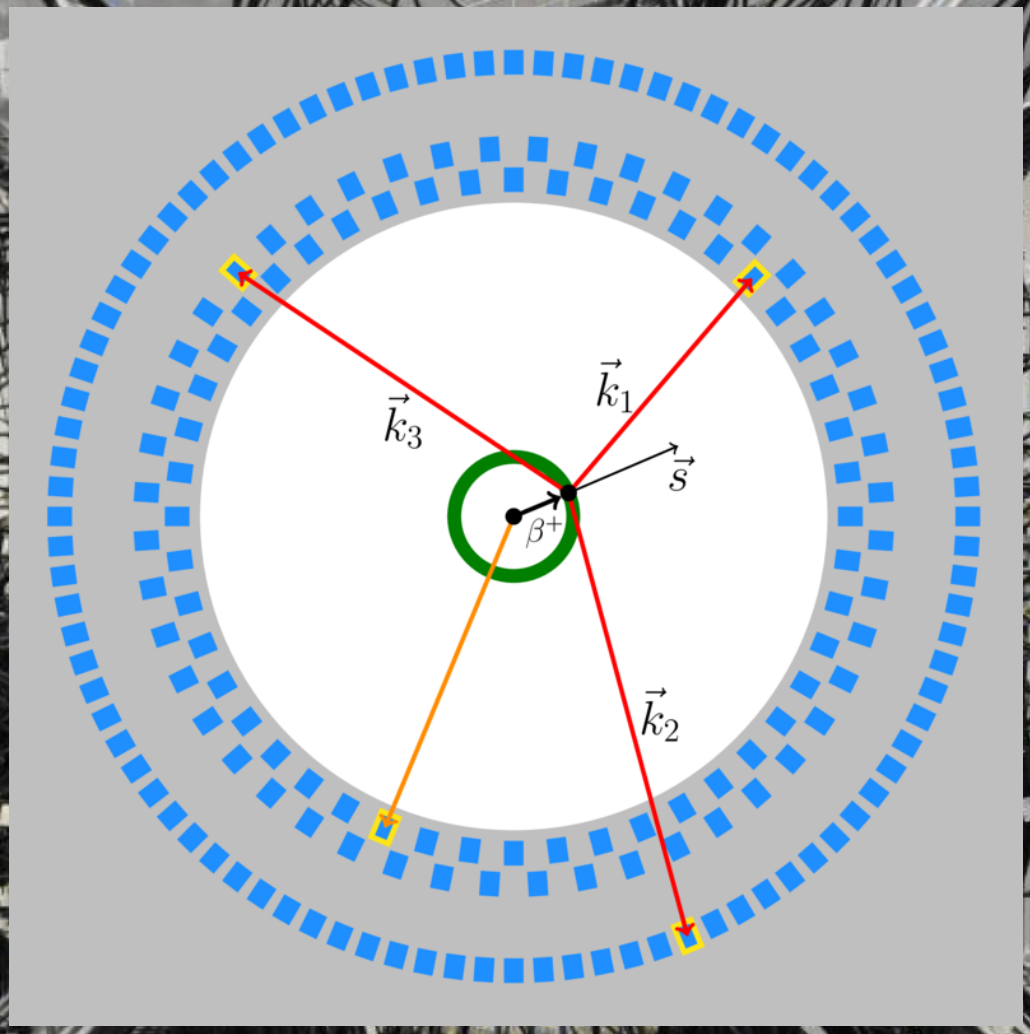


http://www.chem-eng.kyushu-u.ac.jp/e/research.html



σ(t-hit) ~ 100 ps

Jagiellonian PET



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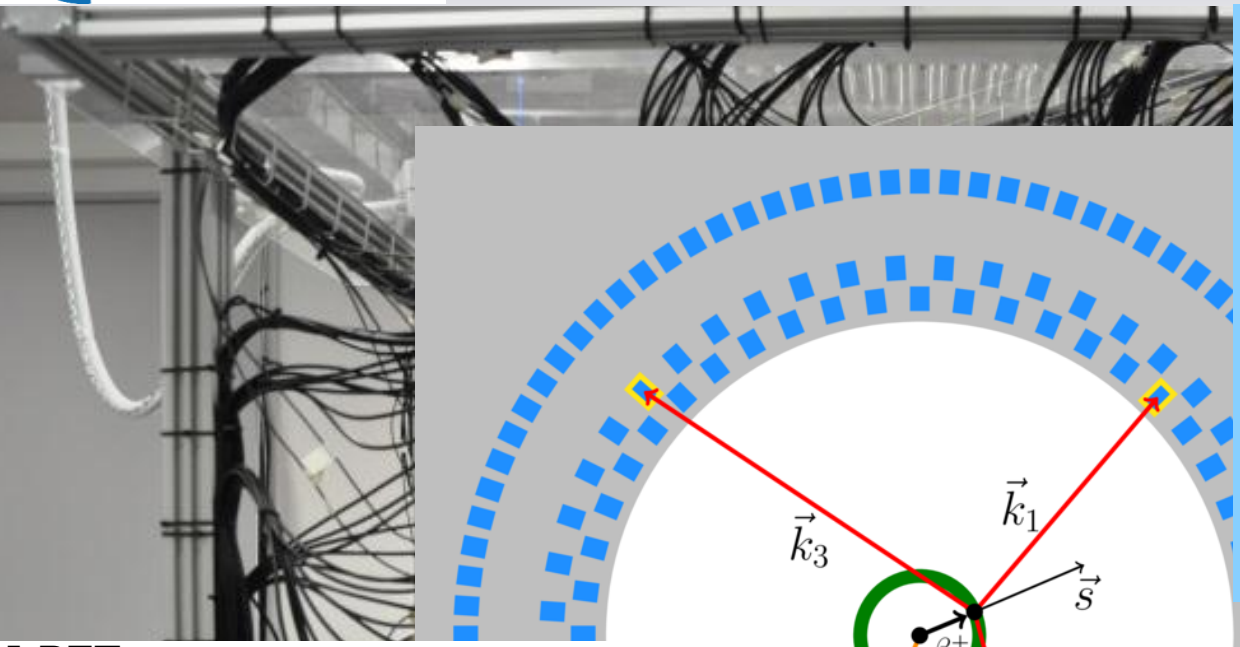
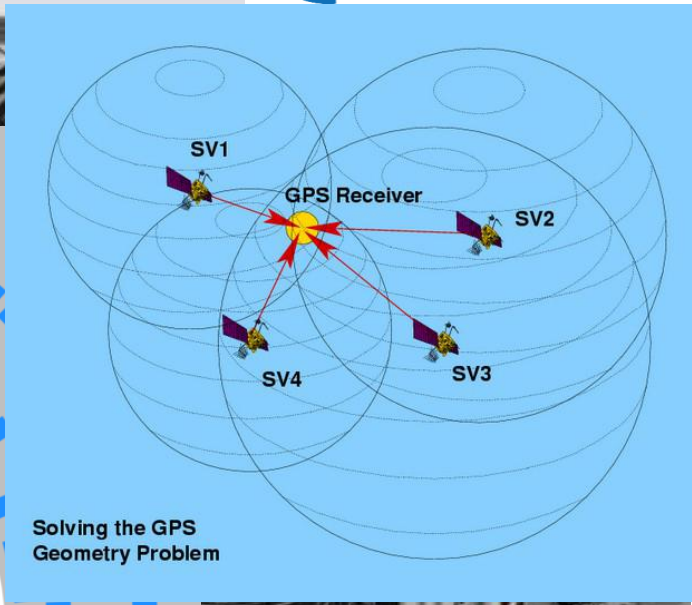
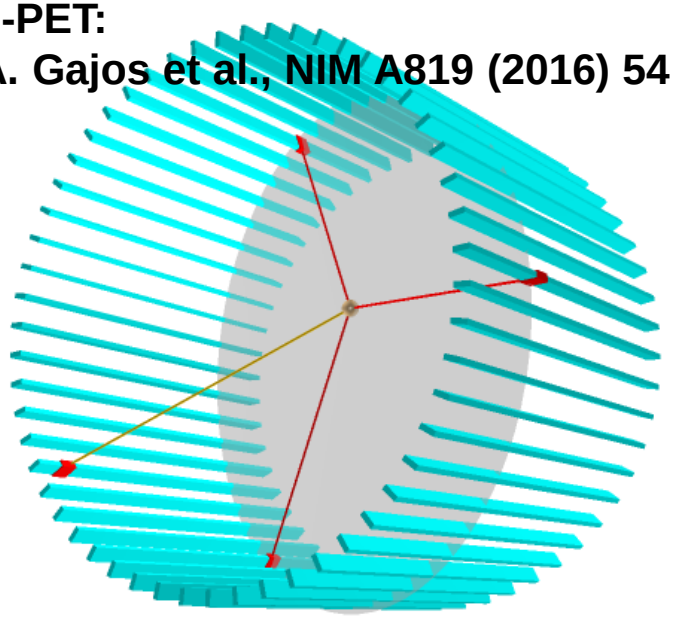




J-PET:
A. Gajos et al., NIM A819 (2016) 54



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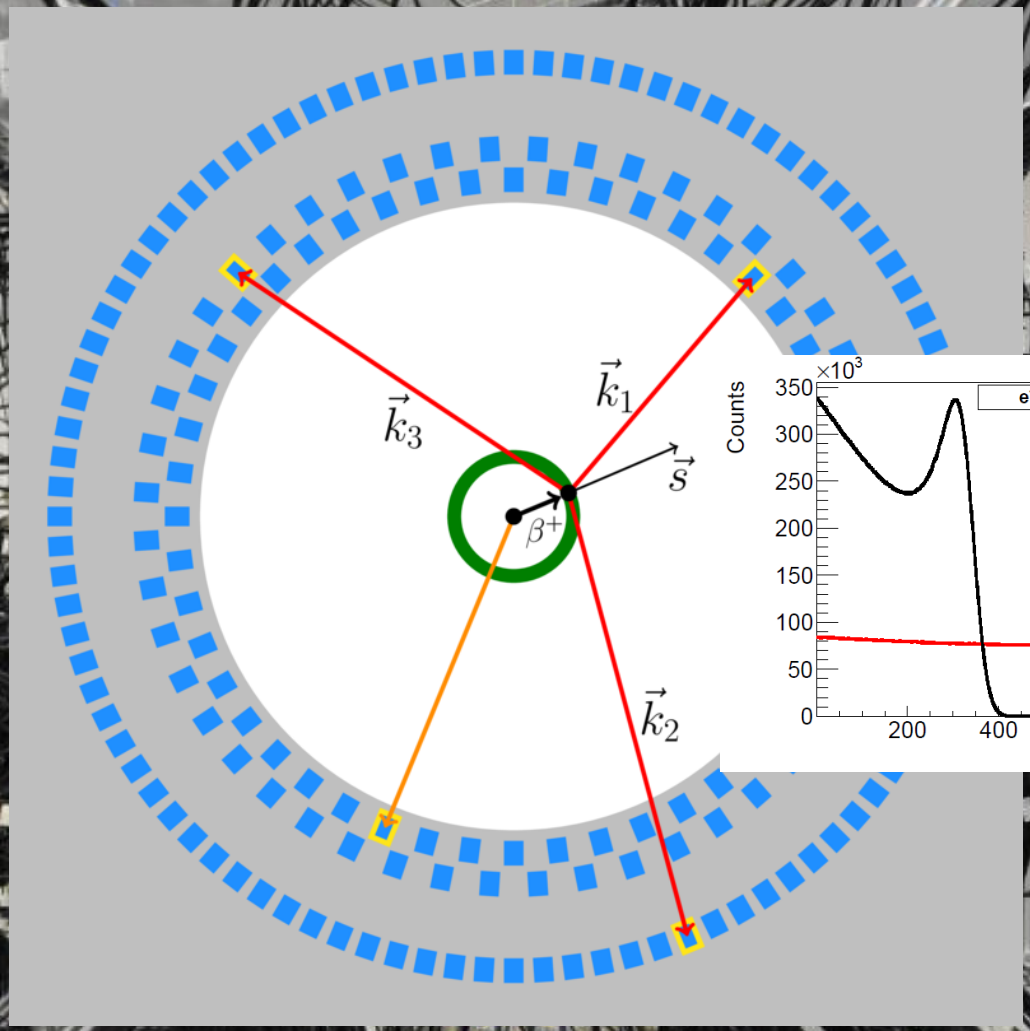

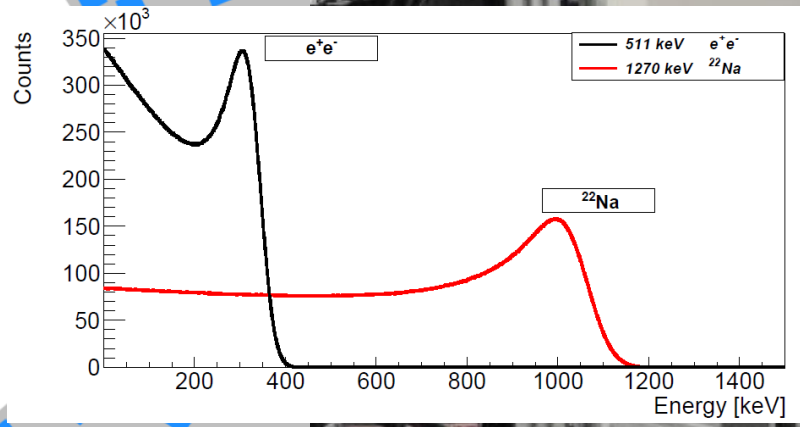

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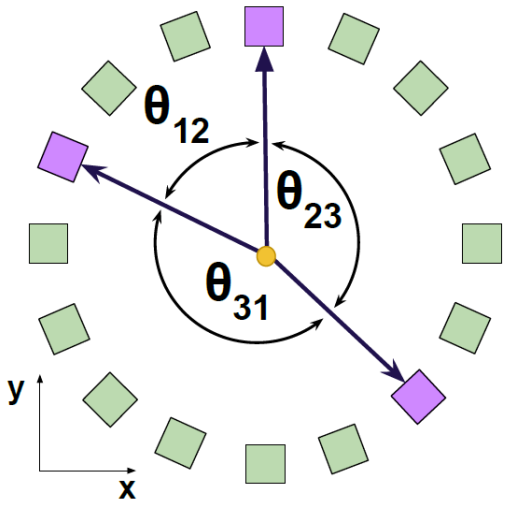
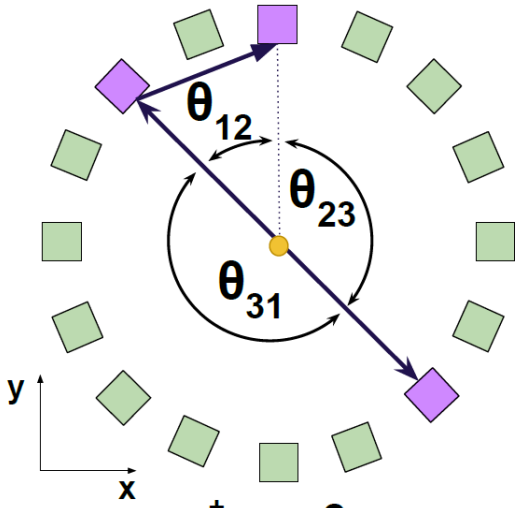


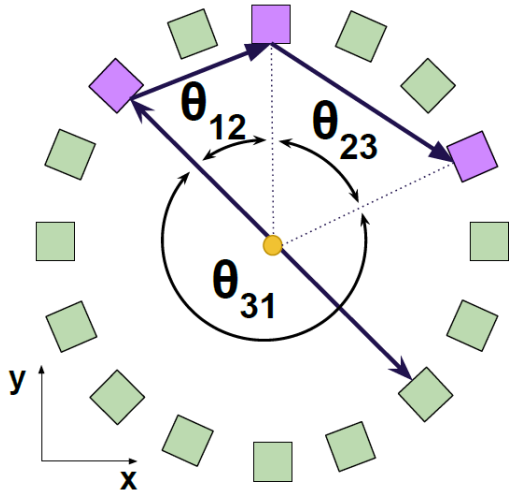
o-Ps → 3γ

$\theta_{23} > 180 - \theta_{12}$



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

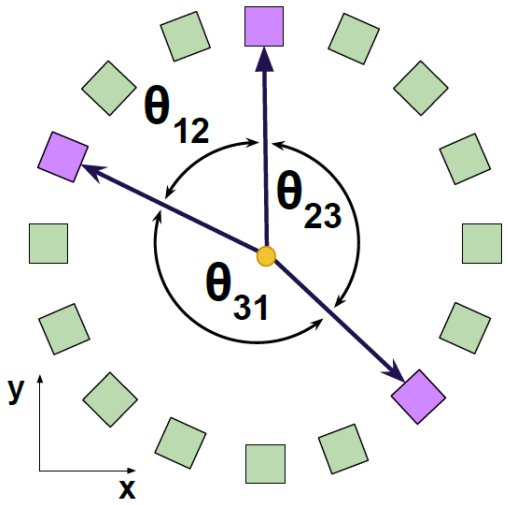
$\theta_{23} = 180 - \theta_{12}$



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

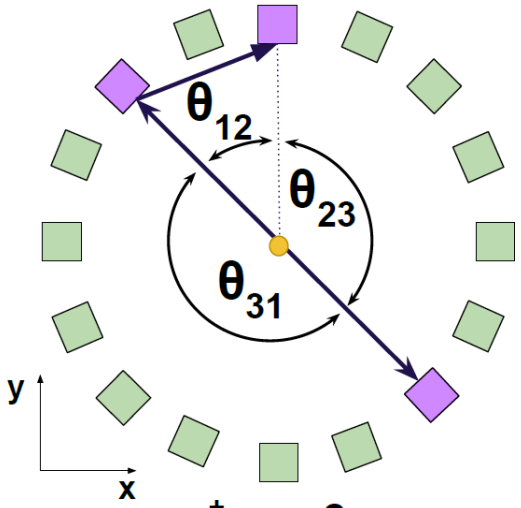
$\theta_{23} < 180 - \theta_{12}$

$$\theta_{12} < \theta_{23} < \theta_{31}$$



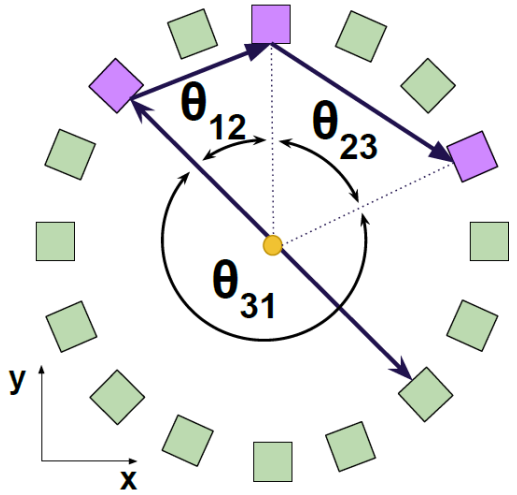
o-Ps → 3γ

$\theta_{23} < 180 - \theta_{12}$



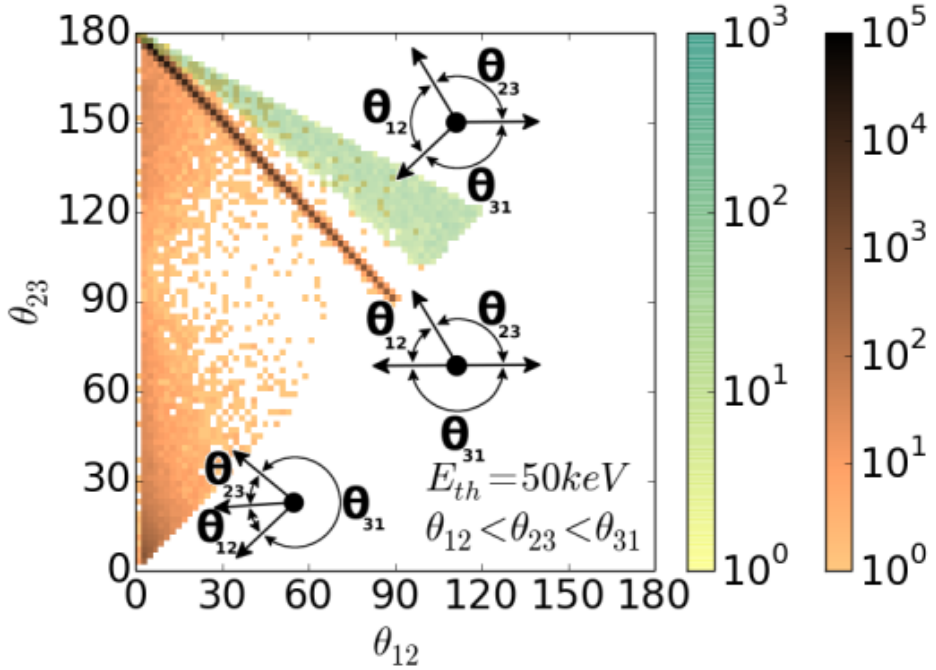
$e^+e^- \rightarrow 2\gamma$
single scattered

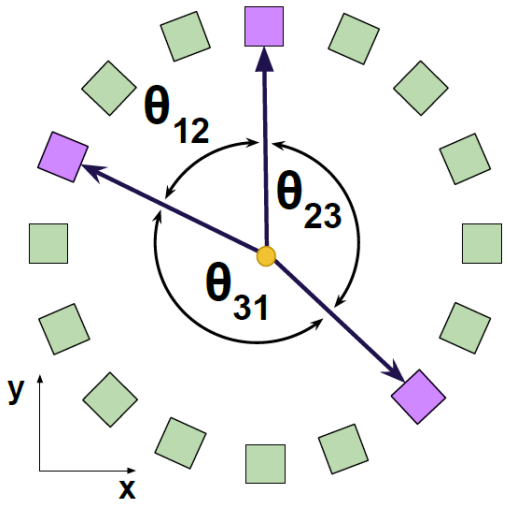
$\theta_{23} = 180 - \theta_{12}$



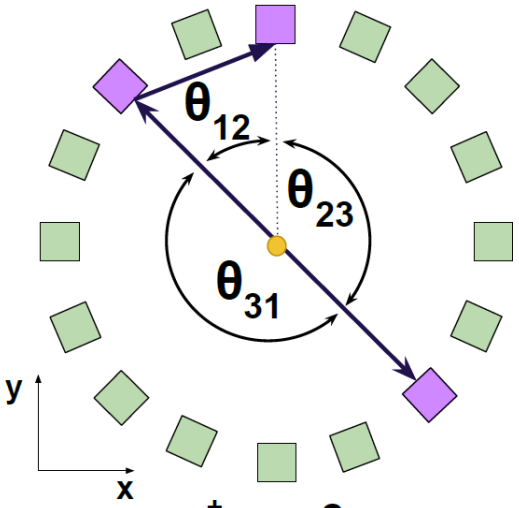
$e^+e^- \rightarrow 2\gamma$
double scattered

$\theta_{23} < 180 - \theta_{12}$

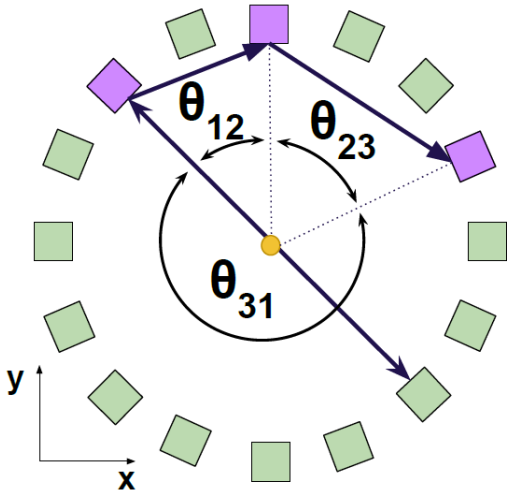




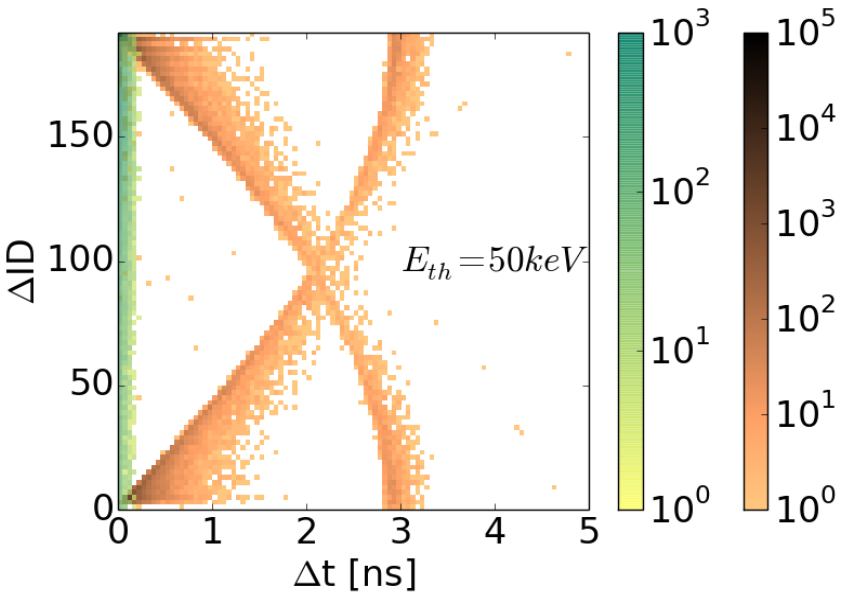
o-Ps → 3γ

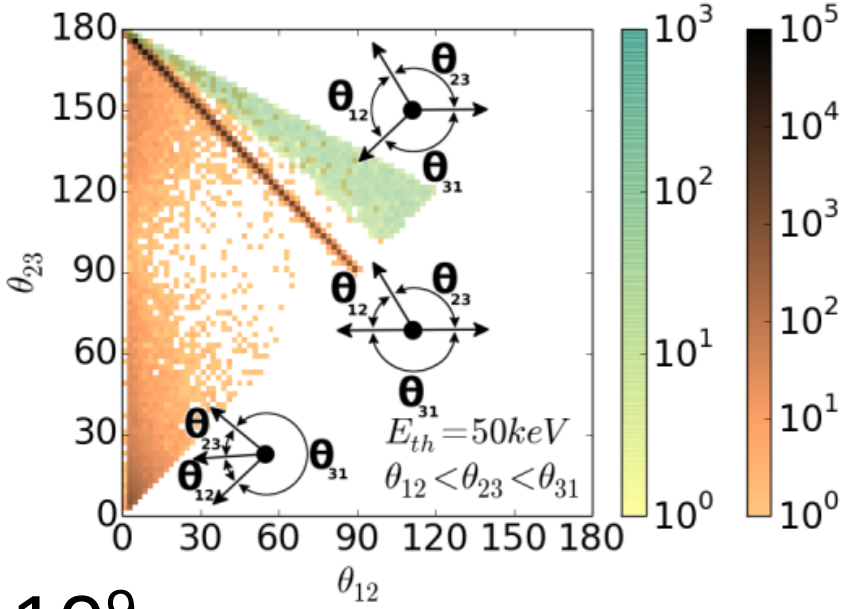


$e^+e^- \rightarrow 2\gamma$
single scattered



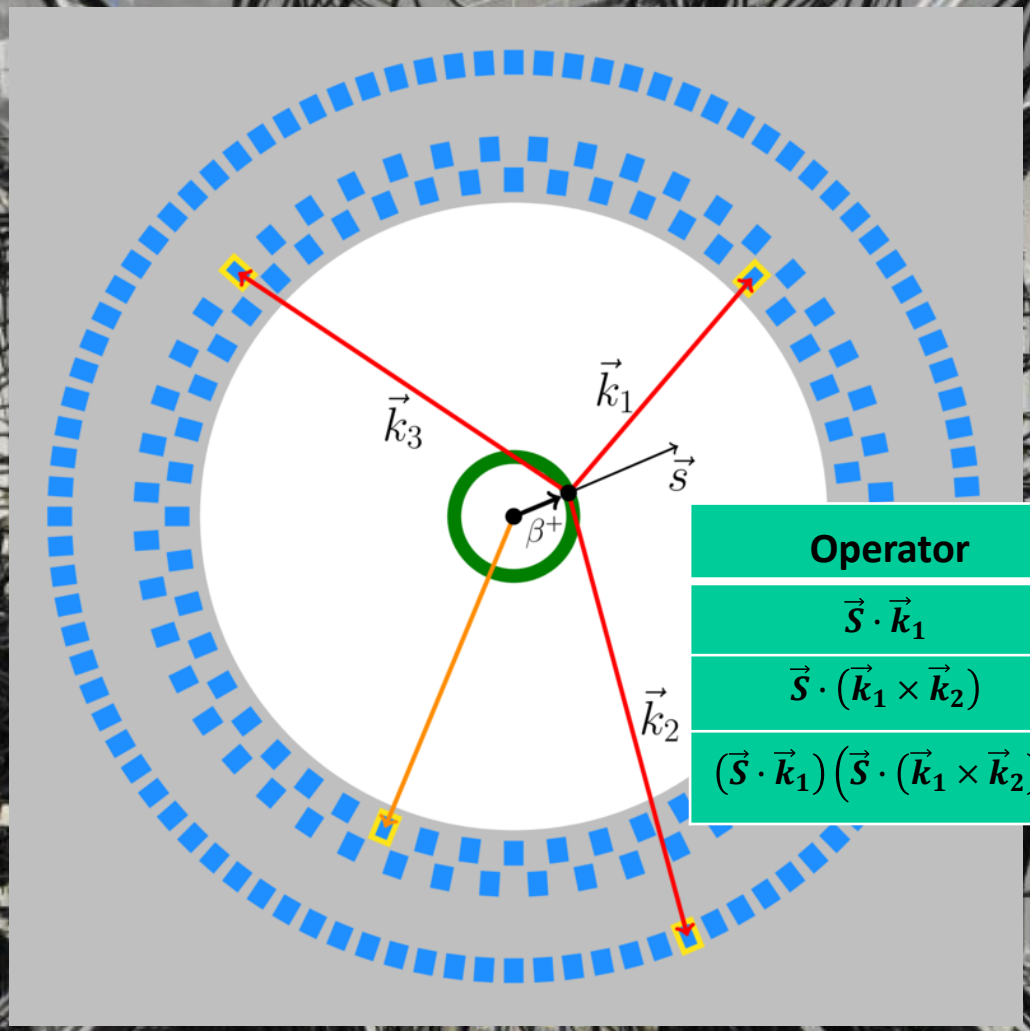
$e^+e^- \rightarrow 2\gamma$
double scattered





Reduction by factor 10^9

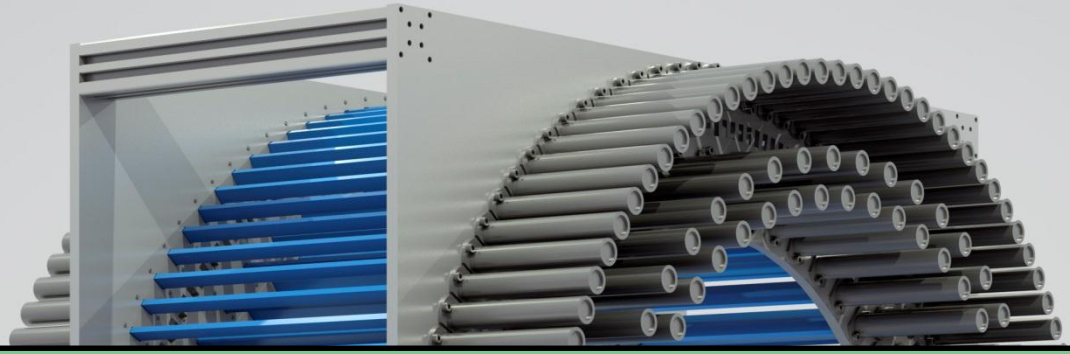
Jagiellonian PET



Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)\left(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+

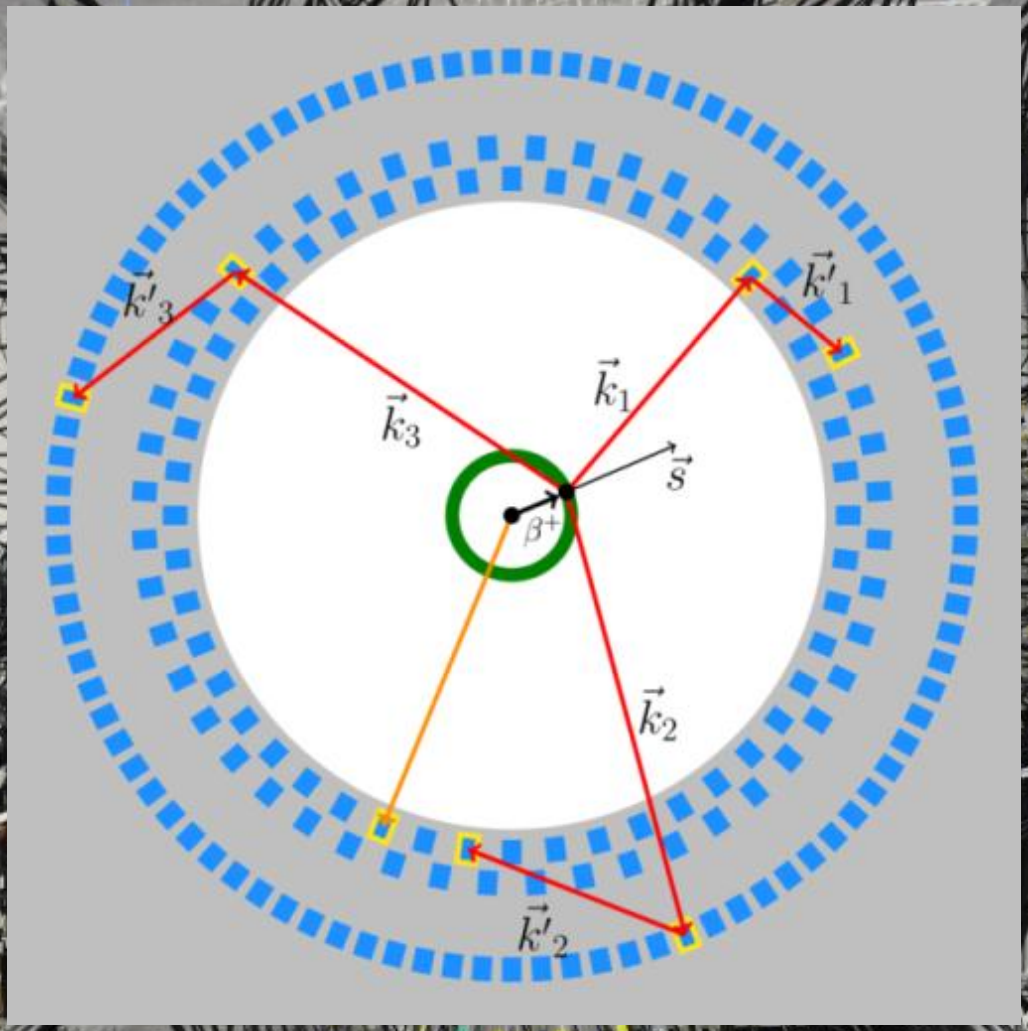
σ(t-hit) ~ 100 ps

Jagiellonian PET



- Jagiellonian PET
- Positronium
- Discrete symmetries NEW!
- Quantum entanglement
- Morphometric imaging

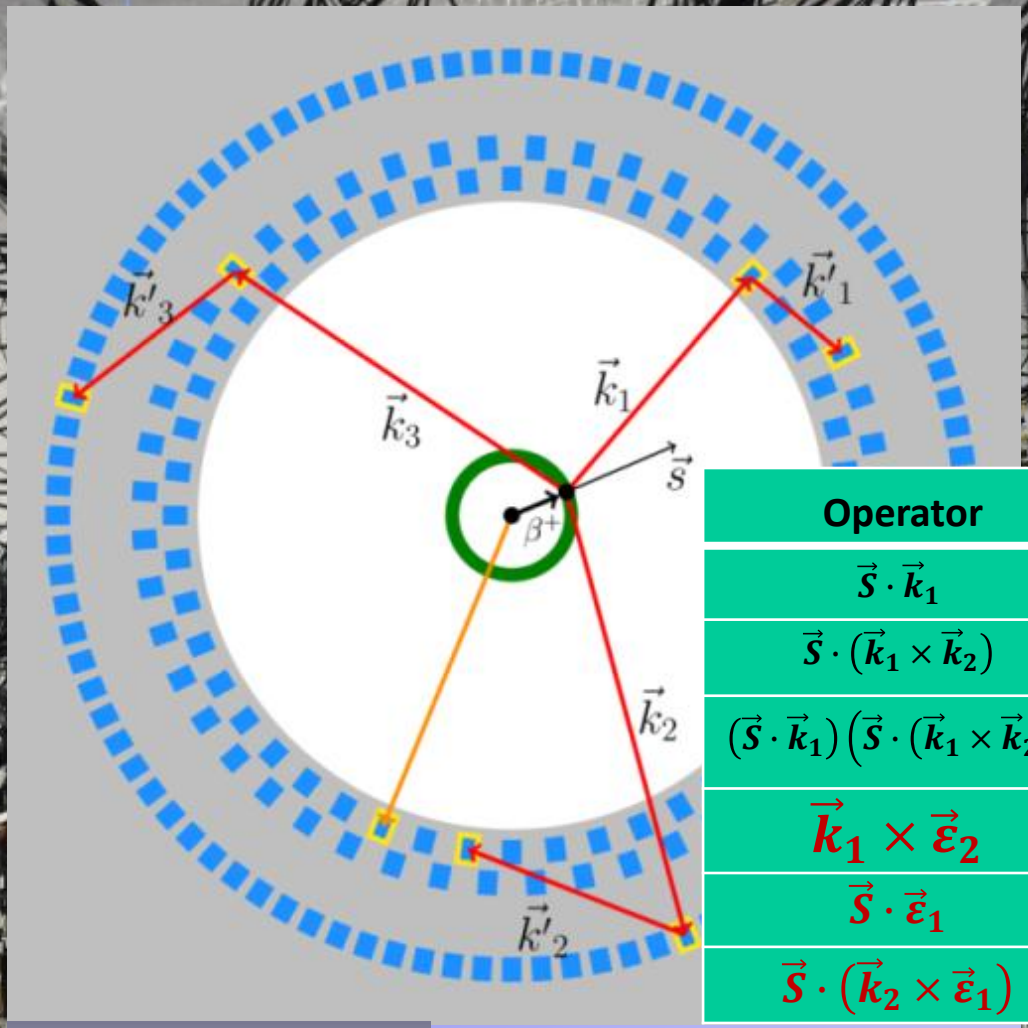
Jagiellonian PET



$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$

σ(t-hit) ~100 ps

Jagiellonian PET



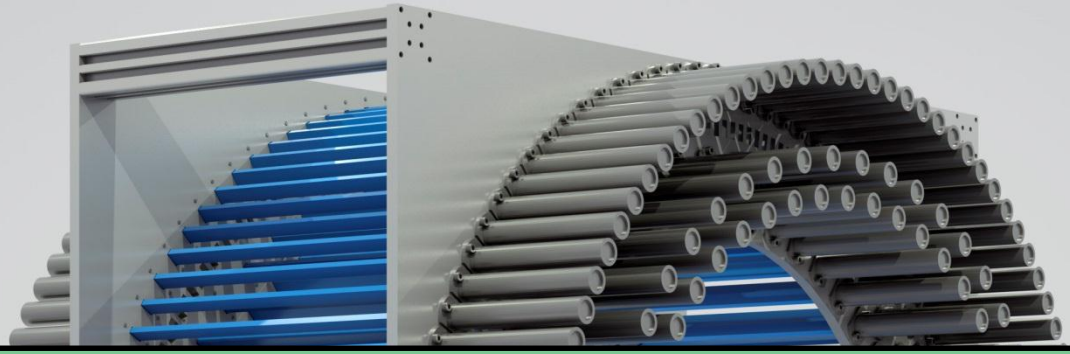
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)\left(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+
$\vec{k}_1\times\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	–	+	–	–

$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$

σ(t-hit) ~ 100 ps

SM 10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

Jagiellonian PET



- Jagiellonian PET
- Positronium
- Discrete symmetries NEW!
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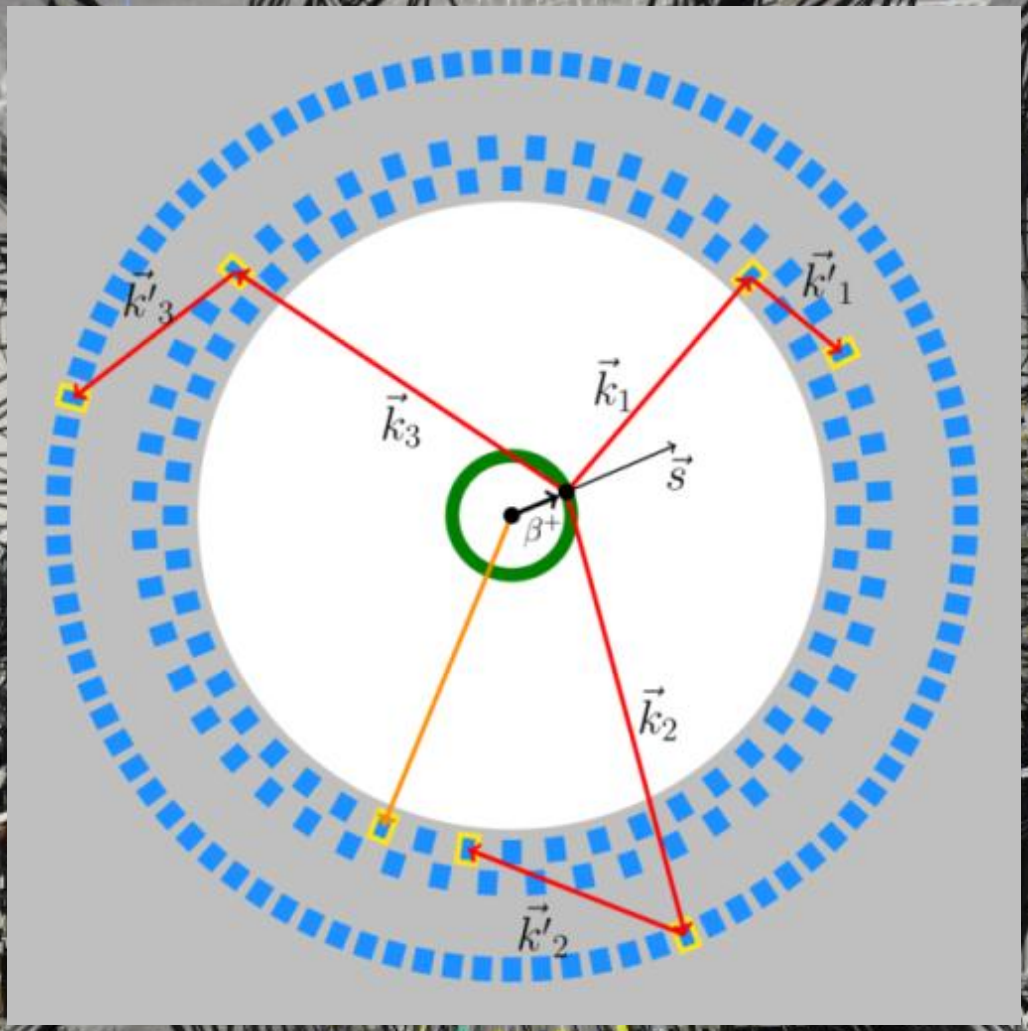
Jagiellonian PET

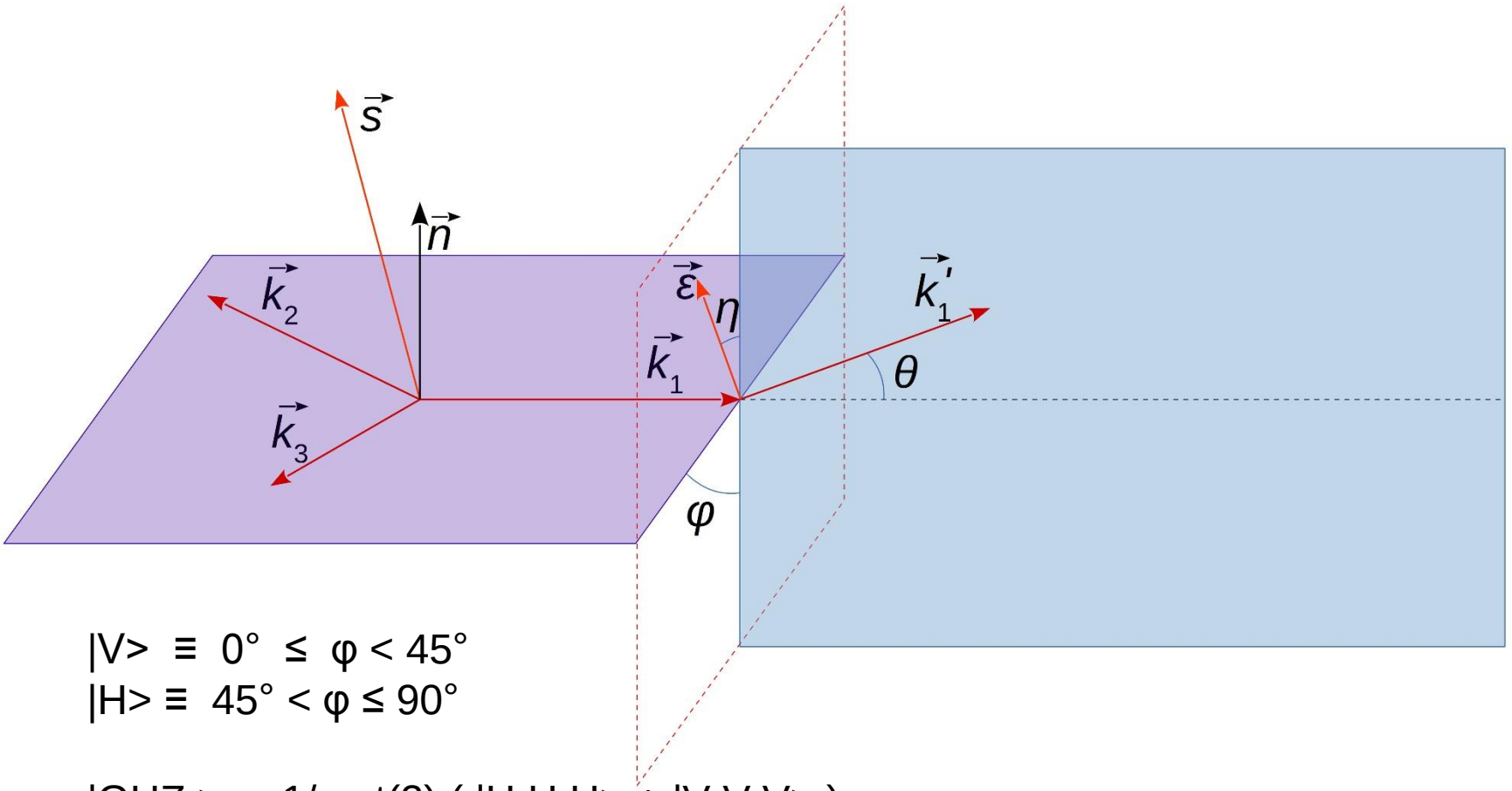


$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$

σ(t-hit) = 80 ps

Jagiellonian PET

J-PET



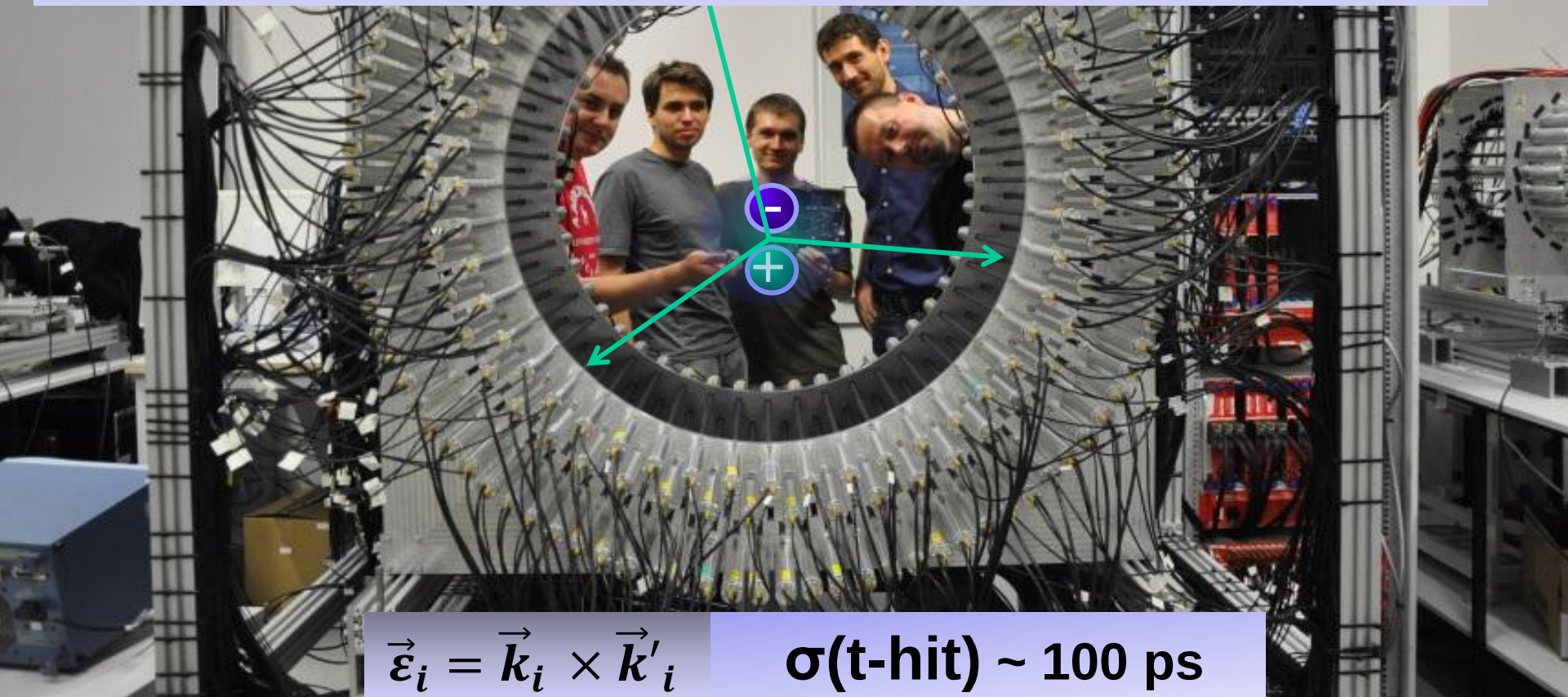
|V> ≡ 0° ≤ φ < 45°
|H> ≡ 45° < φ ≤ 90°

|GHZ > = 1/sqrt(2) (|H H H> + |V V V>)
| W > = 1/sqrt(3) (|H H V> + |H V H> + |V H H >)

Jagiellonian PET

It is an open question whether or not the three-photon entanglement can be reduced to the two-photon entanglement and decoherence of the two-photon states does imply decoherence in photon triplets. This hypothesis can be tested by comparison of measured two- and three-photon correlation functions. There exist three-photon states maximizing the Greenberger-Horn-Zeilinger (GHZ) entanglement and they can be used to test quantum local realism versus quantum mechanics.

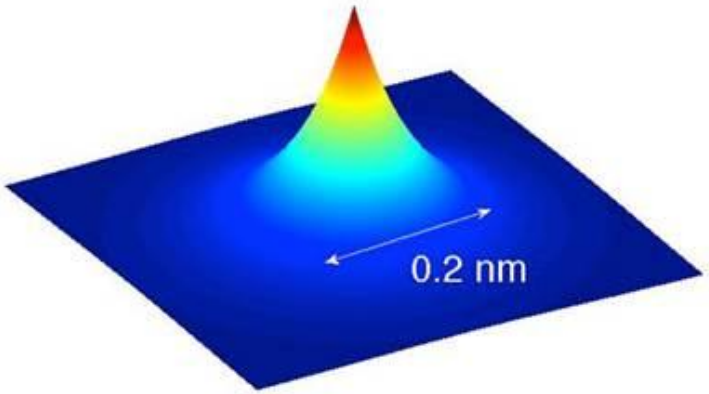
D.M. Greenberger et al., Am. J. Phys. 58(1990)1131
A. Acin et al., Phys. Rev. A63(2001) 042107; N.D. Mermin, Phys. Rev. Lett. 65 (1990)1838



$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$

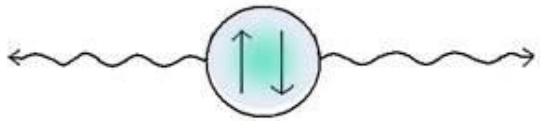
σ(t-hit) ~ 100 ps

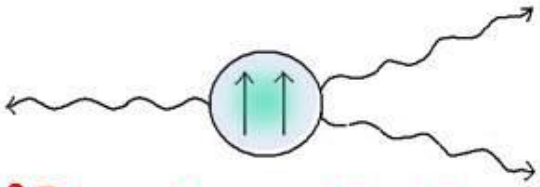
positronium



$\tau \approx 125$ ps

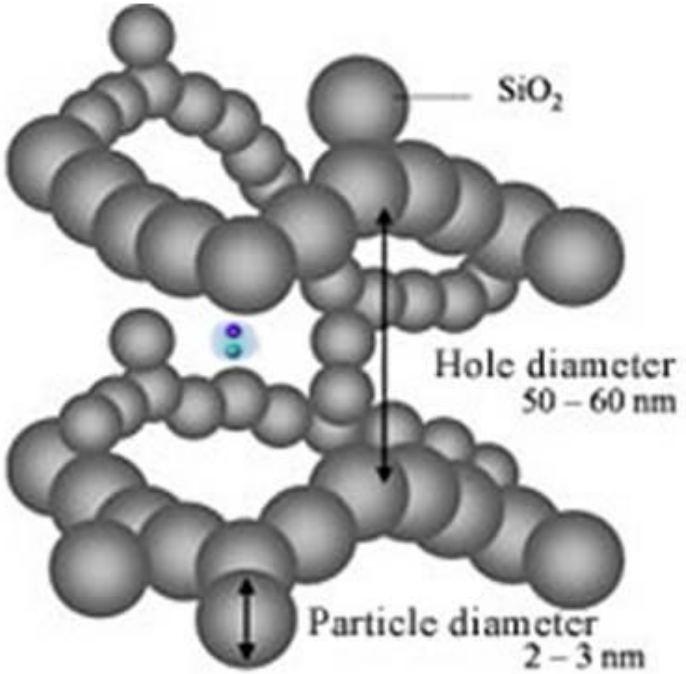
$^1S_0$ para-positronium p-Ps

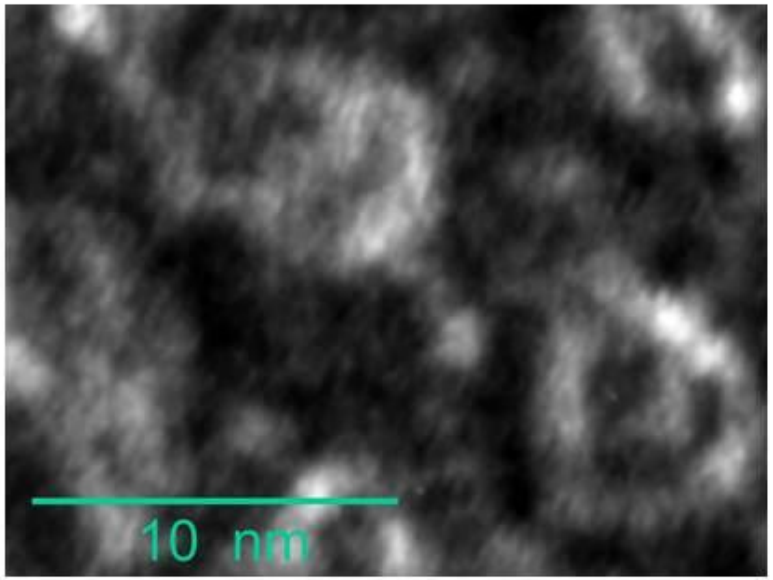




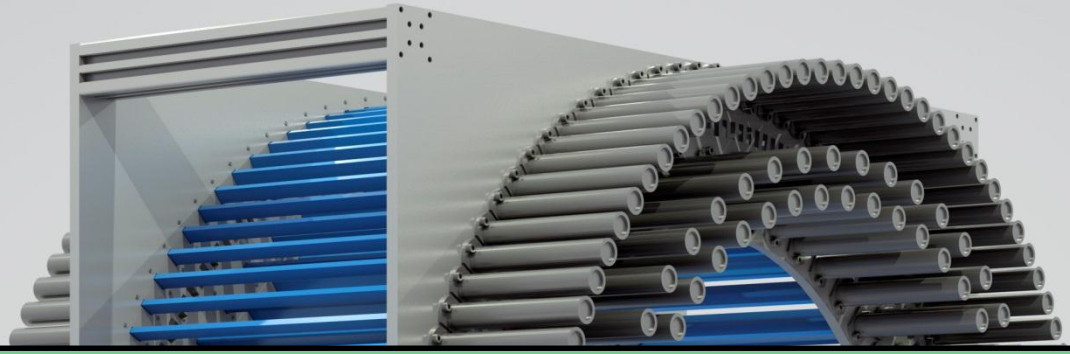
$^3S_1$ ortho-positronium o-Ps

$\tau \approx 142$ ns

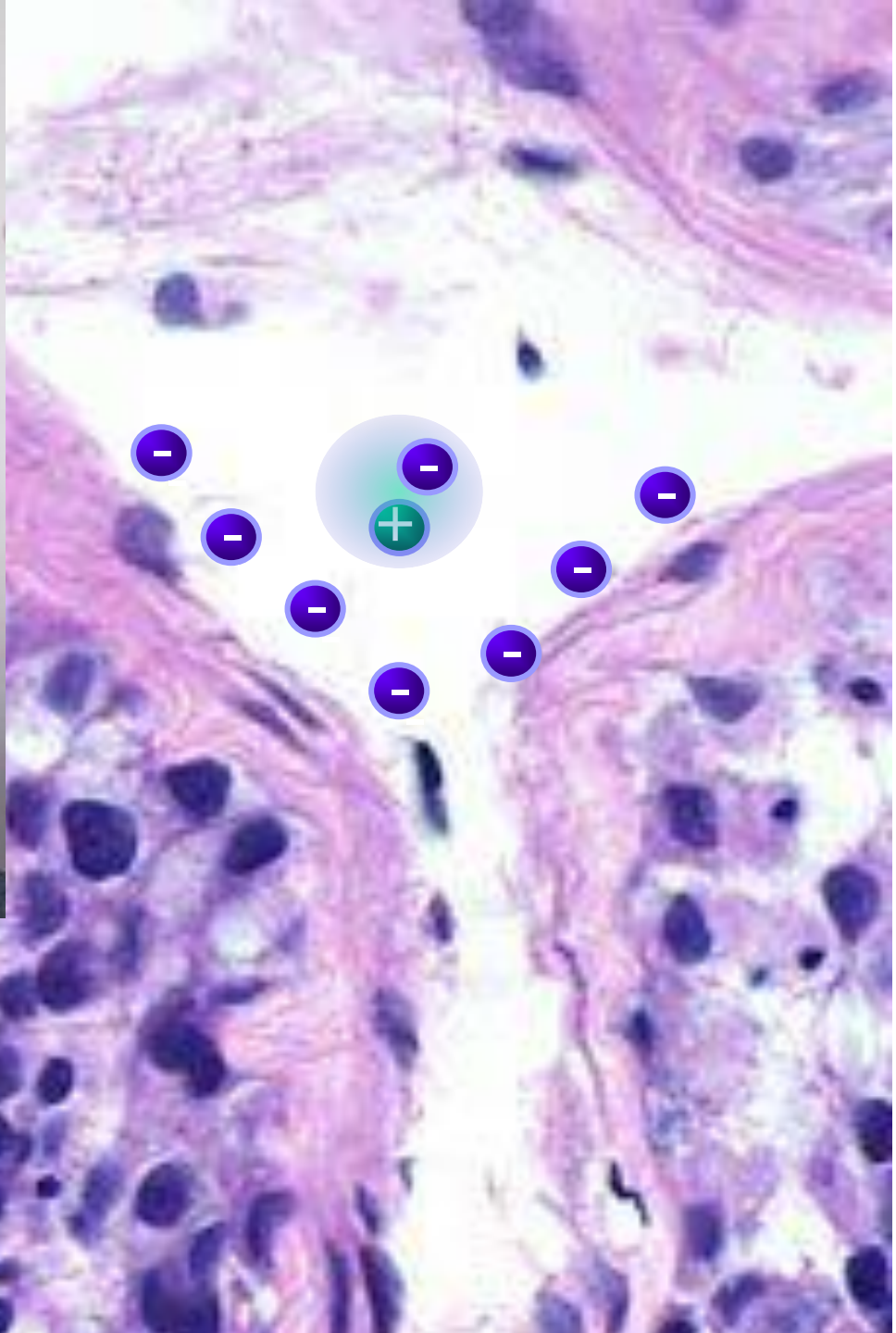


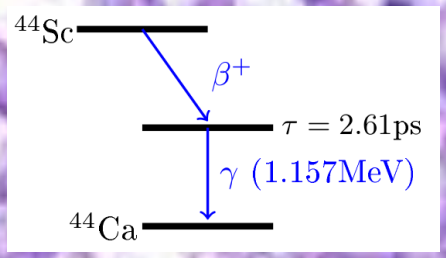


Jagiellonian PET

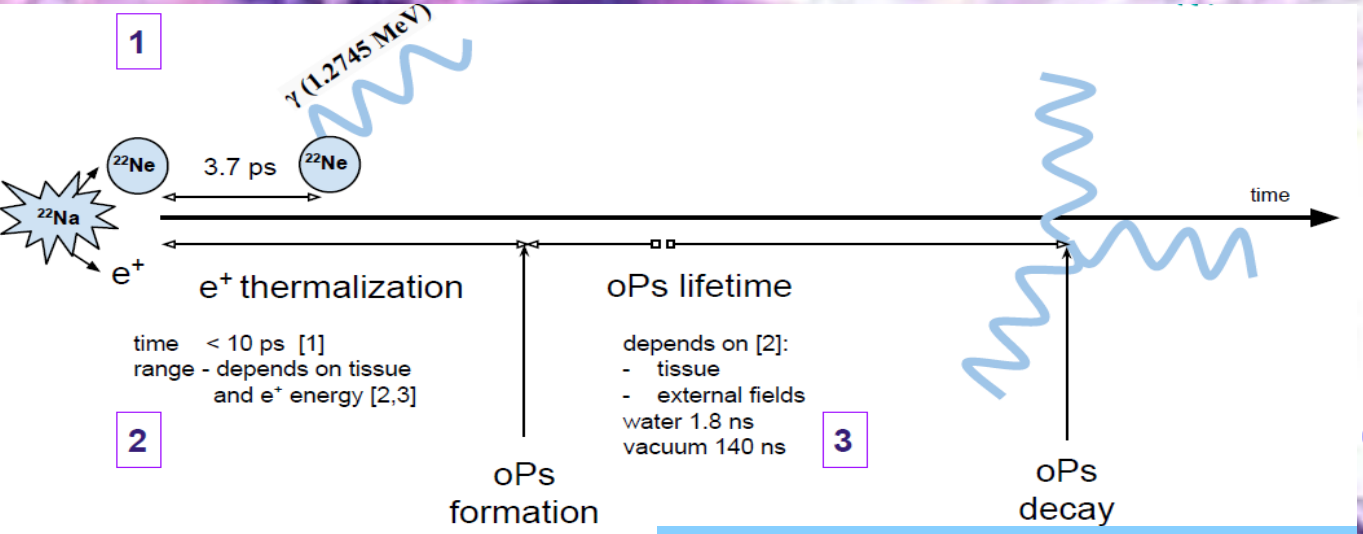


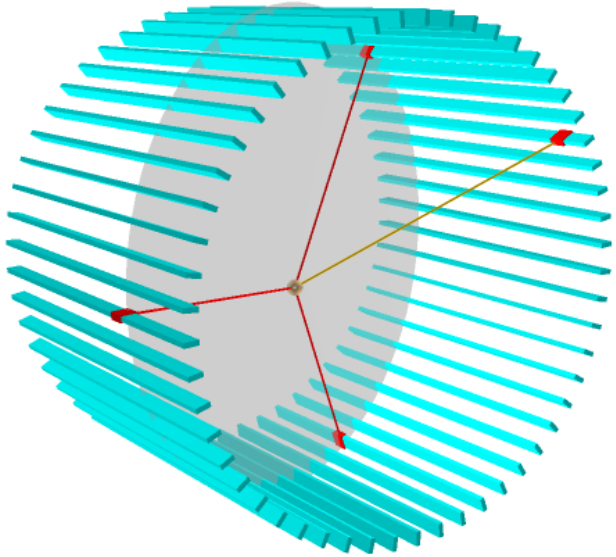
- Jagiellonian PET
- Positronium
- Discrete symmetries
- Quantum entanglement
- Morphometric imaging

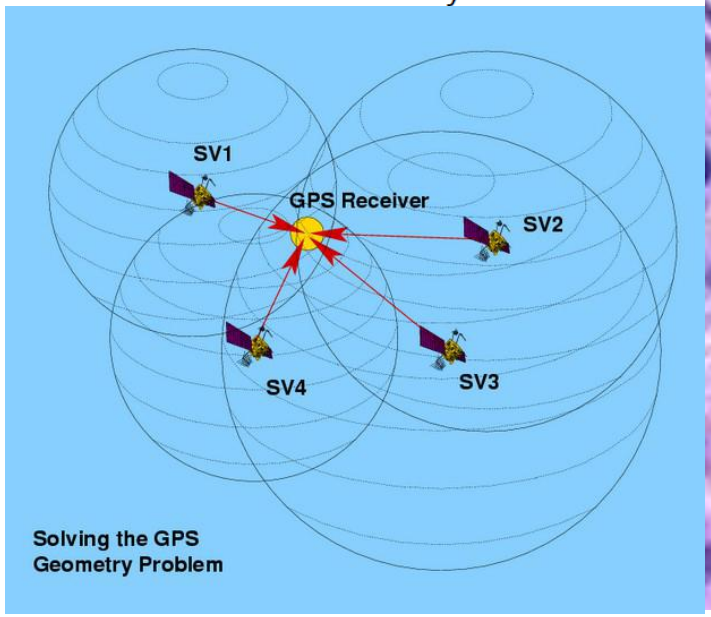


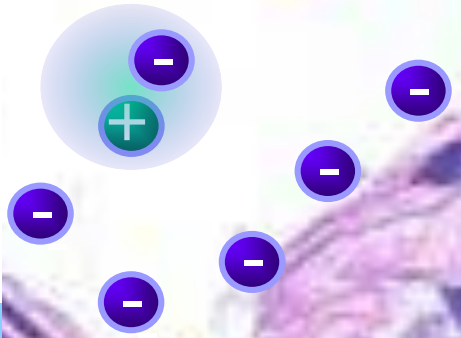

^{44}Sc
β^+
$\tau = 2.61$ps
γ (1.157MeV)
^{44}Ca

Ortho-positronium life-time tomography

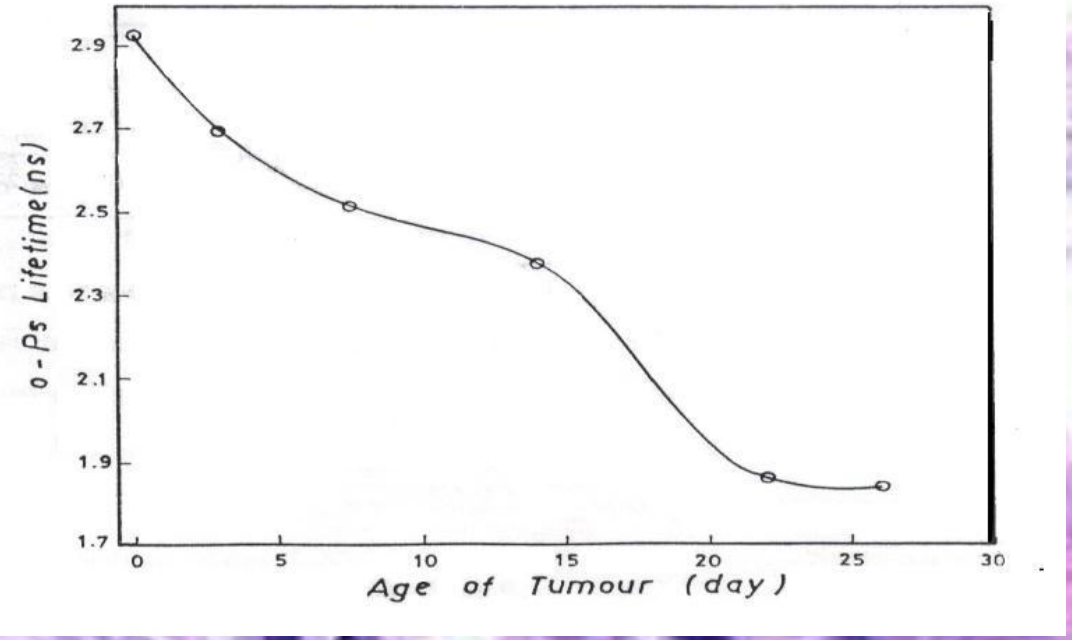




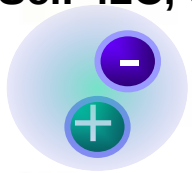


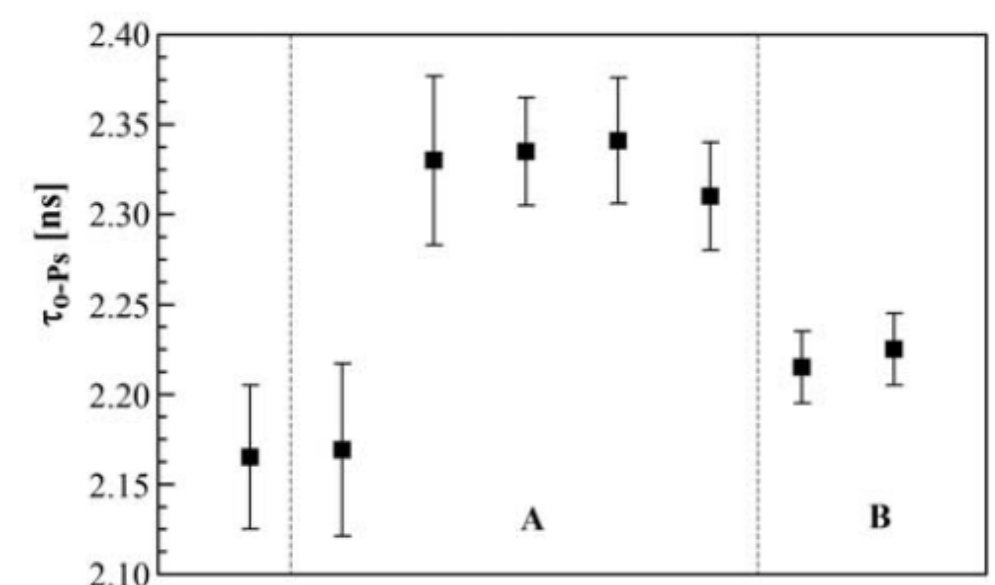


Patent applications: P. M., **PCT/EP2014/068374**; A. Gajos, E. Czerwiński, D. Kamińska, P. M., **PCT/PL2015/050038**

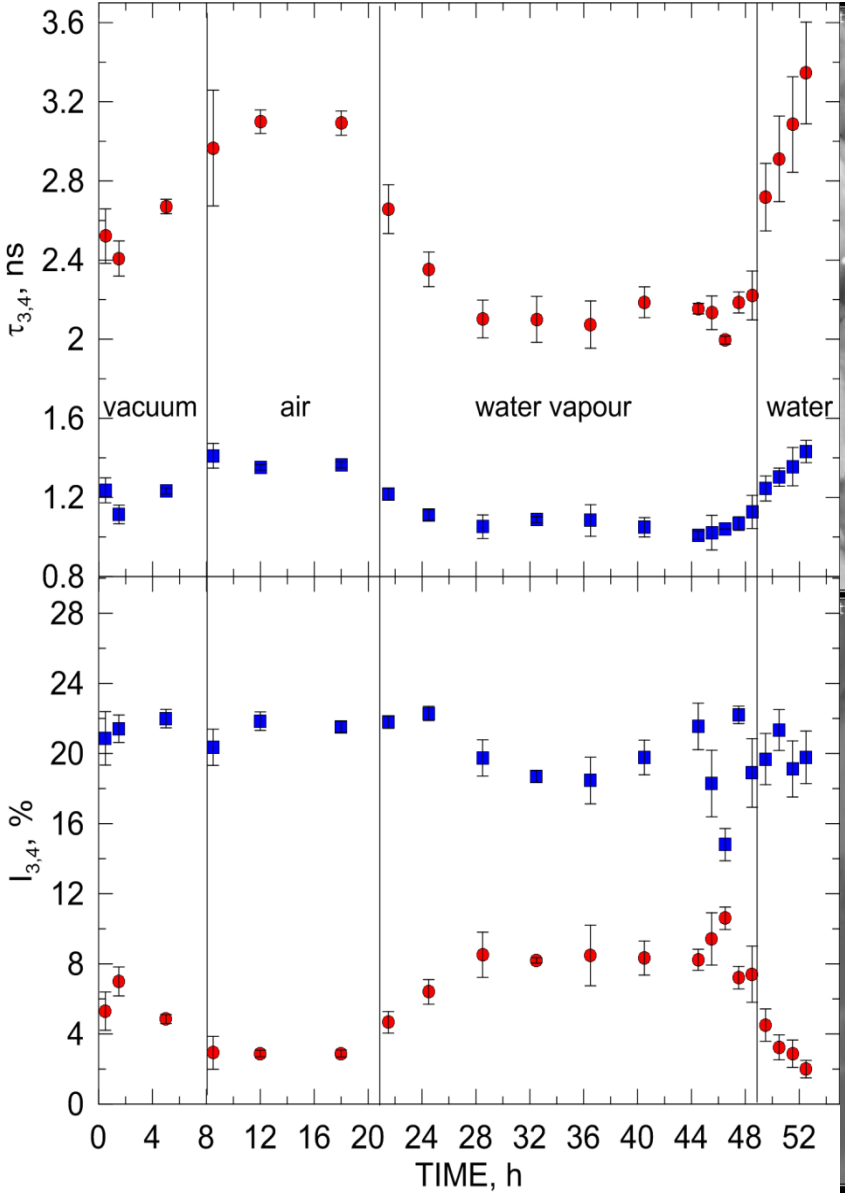


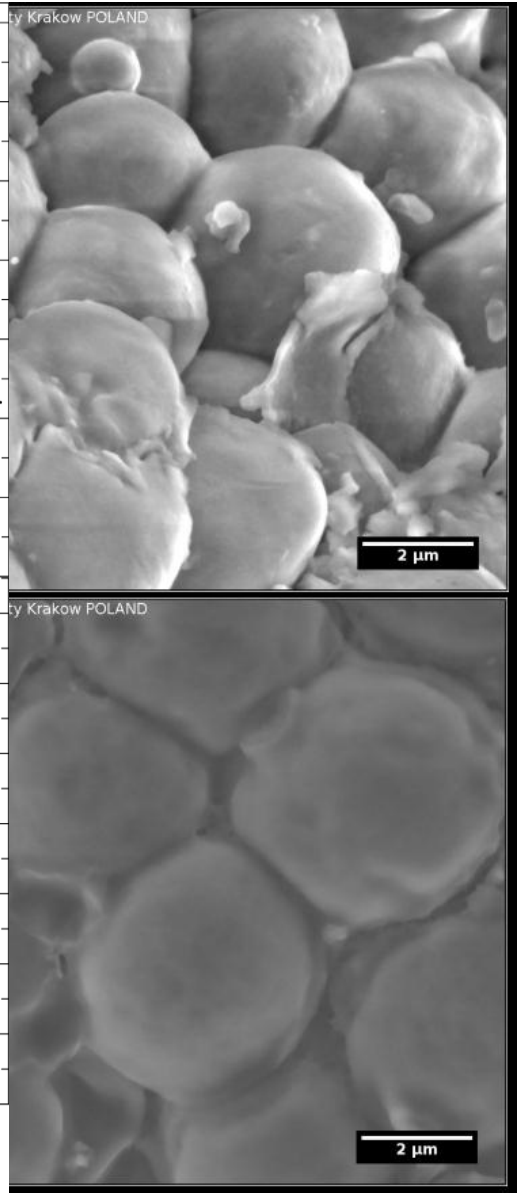
The age of mice's tumour with o-Ps lifetime
A.H. Al-Mashhadani et al., Iraqi J. Sci. 42C, 60 (2001) 3.





R. Pietrzak et al., NUKLEONIKA 58 (2013) 199



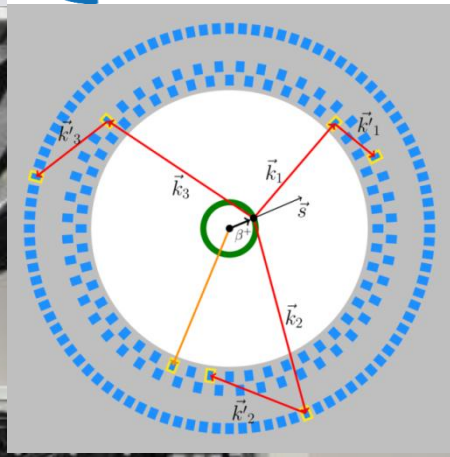


J-PET: E. Kubicz, et al., Nukleonika 60 (2015) 749.
Studies of unicellular micro-organisms Saccharomyces cerevisiae by means of positron annihillation lifetime spectroscopy

Environmental Scanning Electron Microscopy images of lyophilised yeasts (upper) and dried under normal conditions, after addition of water (bot-tom).

Jagiellonian PET

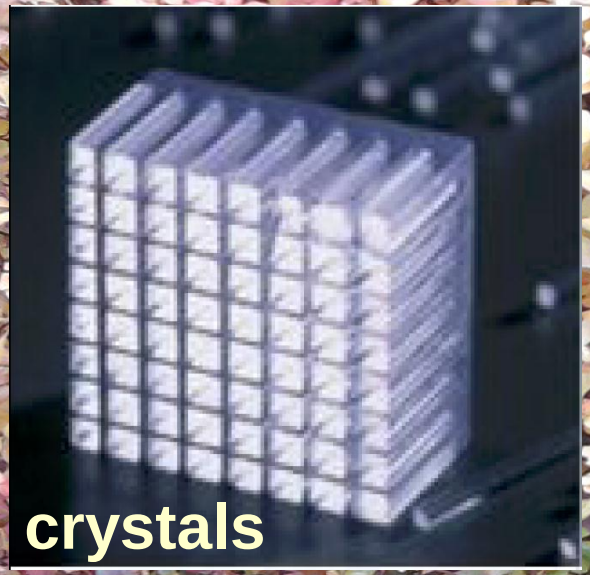
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)\left(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+
$\vec{k}_1\times\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	–	+	–	–

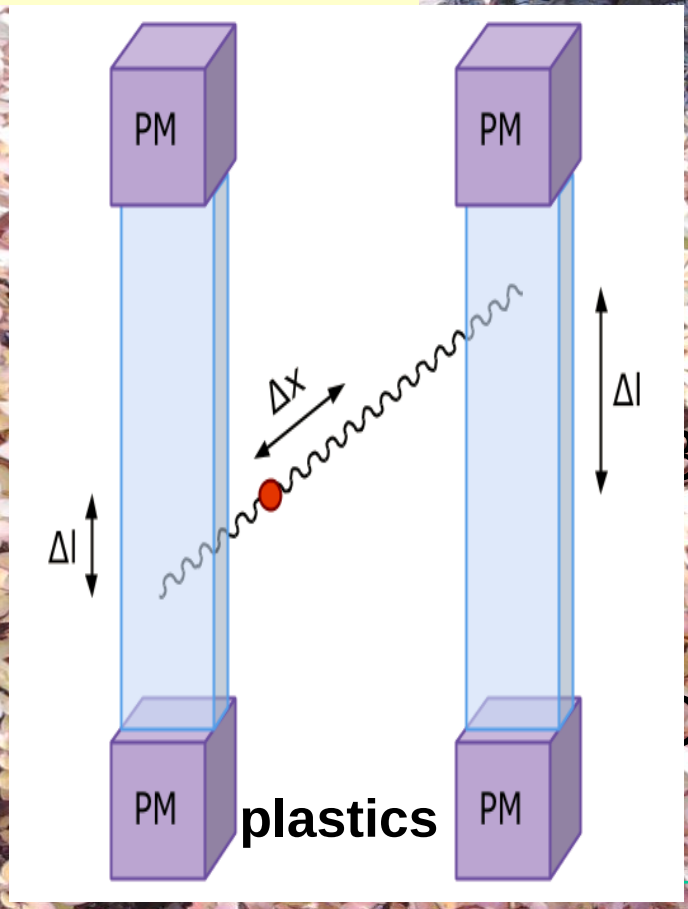


SM 10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

….
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A764 (2014) 186
J-PET: P. M. et al., Nucl. Instrum. Meth. A764 (2014) 317
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A786 (2015) 105
J-PET: P. M. et al., Phys. Med. Biol. 61 (2016) 2025
J-PET: A. Gajos et al., Nucl. Instrum. Meth 819 (2016) 54
J-PET: P. M. et al., Acta Phys. Pol. B 47 (2016) 509
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445

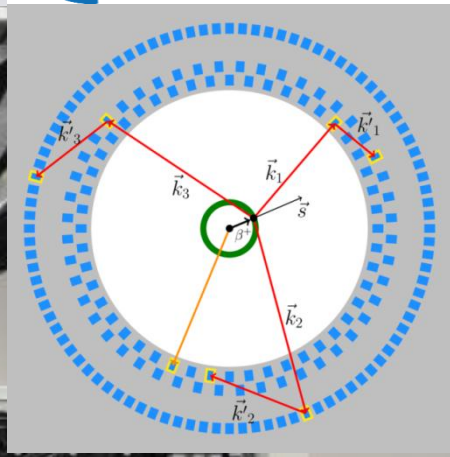
Over 50 articles and 16 international patent applications

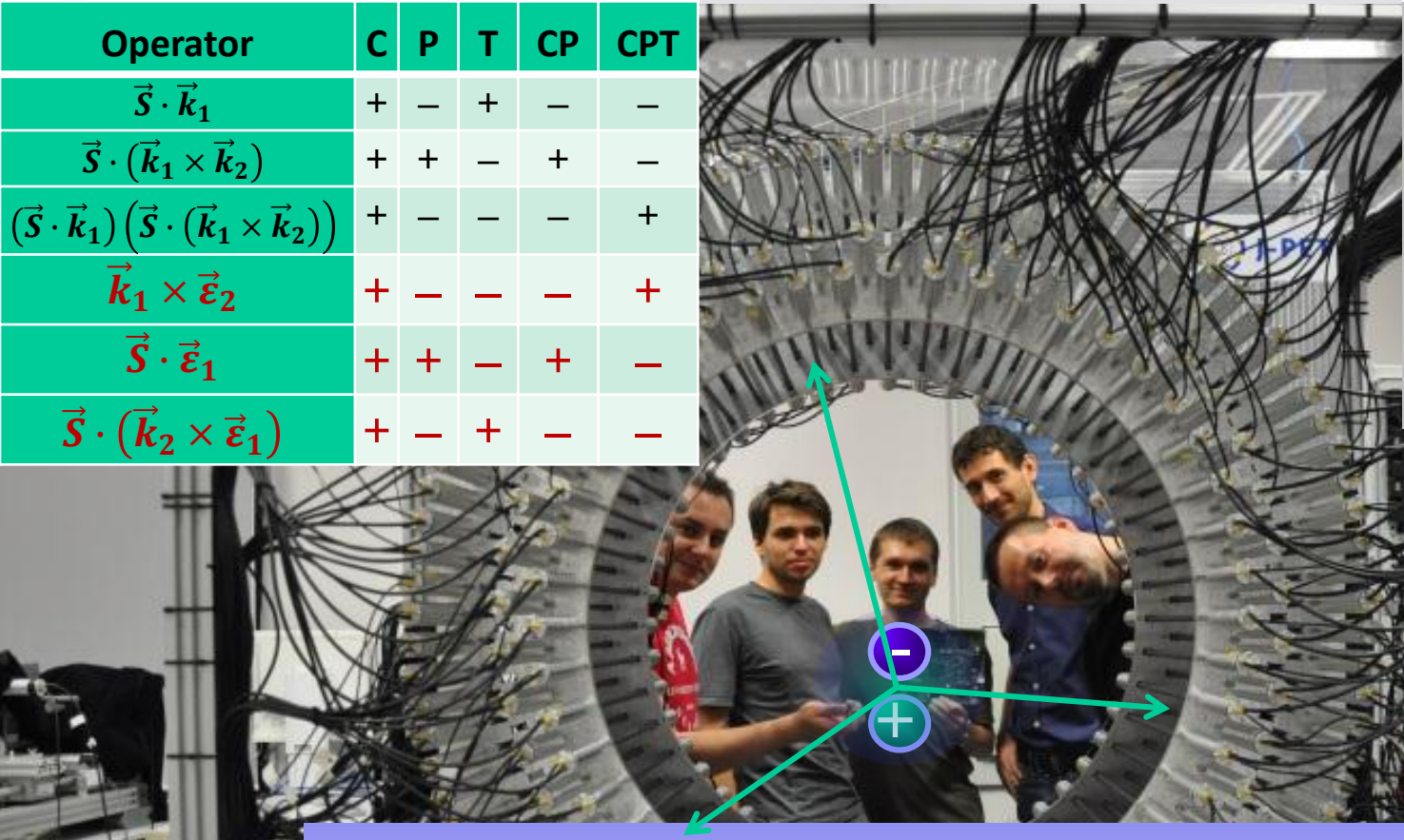




Jagiellonian PET

Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)\left(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+
$\vec{k}_1\times\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	–	+	–	–



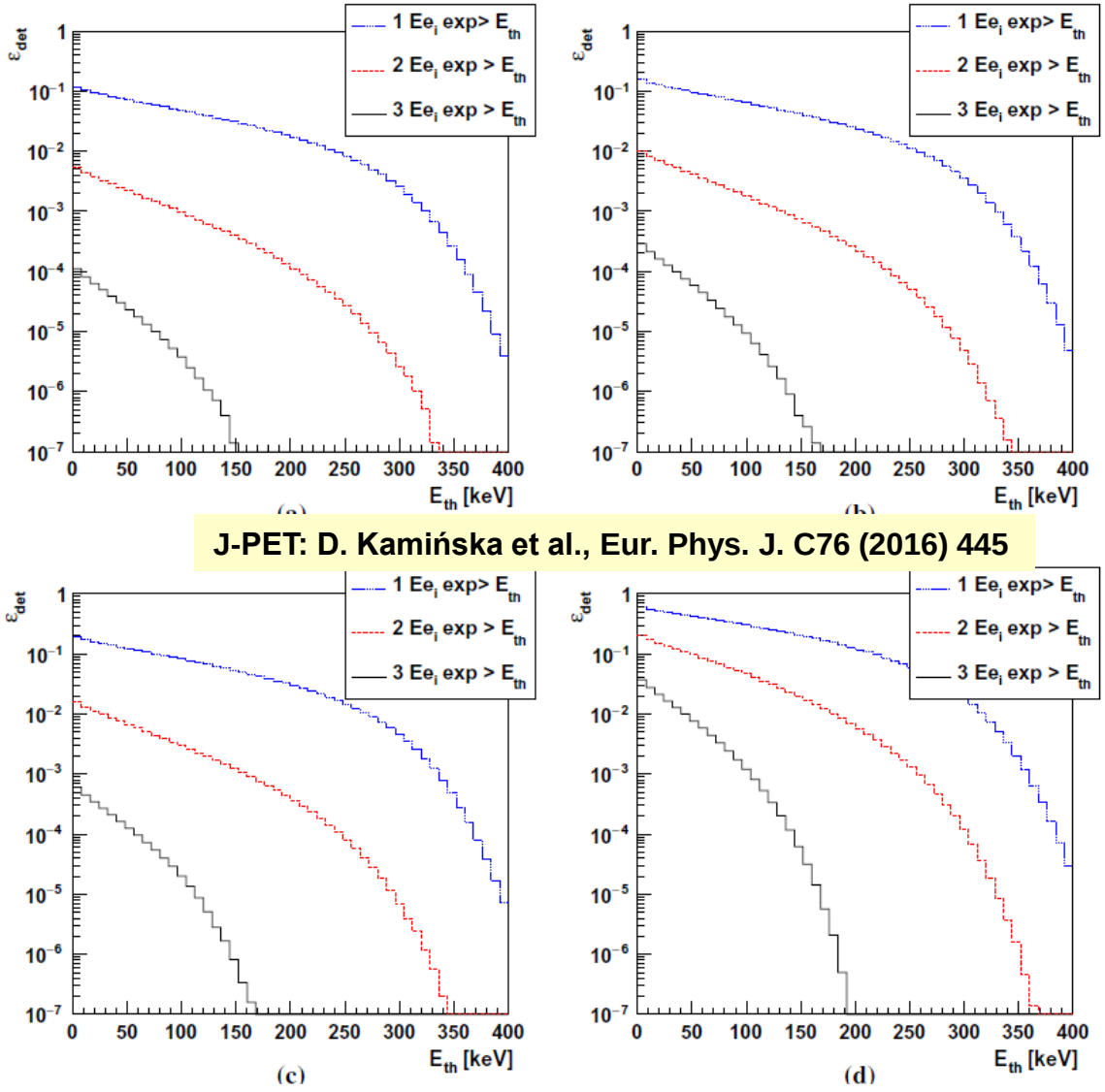


THANK YOU
FOR YOUR ATTENTION

SM 10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

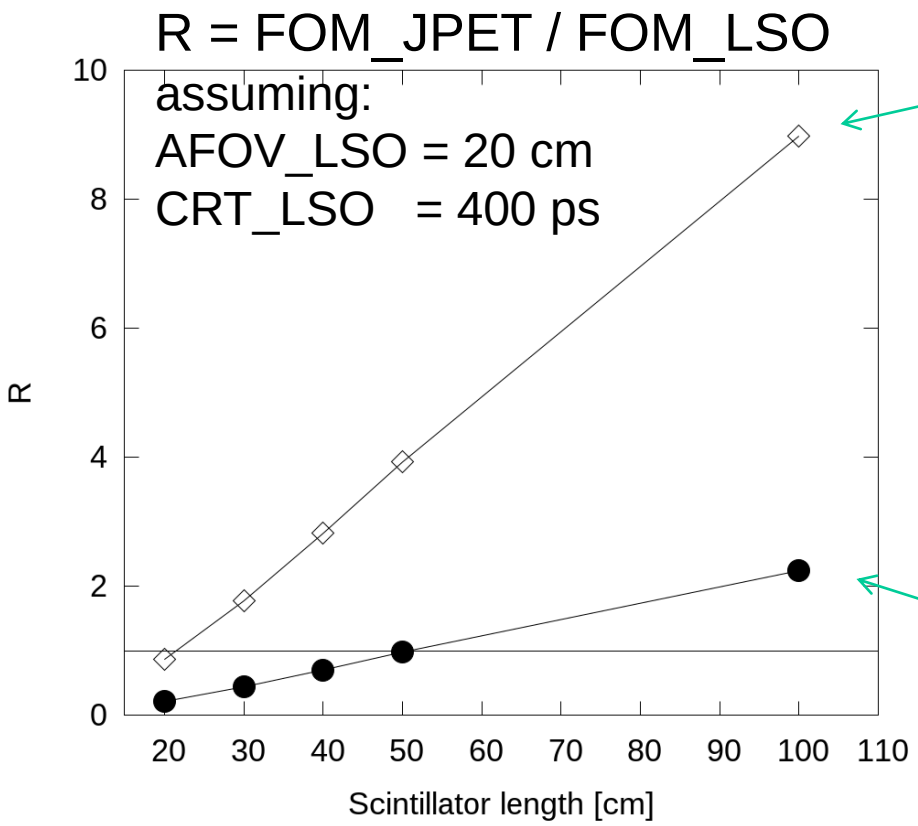
Jagiellonian PET

Cracow, July 2016

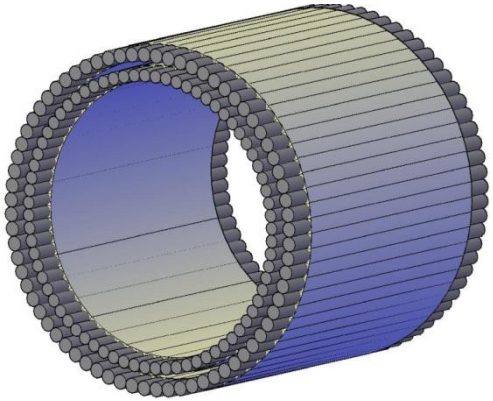


J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445

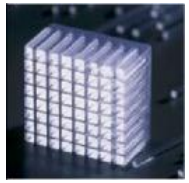
Target material	Rate of registered o-Ps $\rightarrow 3\gamma$ events (s^{-1})			
	J-PET	J-PET+1	J-PET+2	J-PET-full
IC3100	15	70	130	10600
XAD-4	25	115	230	18300



N_JPET_layers = 2



$$R = \frac{FOM\_JPET}{FOM\_LSO}$$



LSO

N_JPET_layers = 1

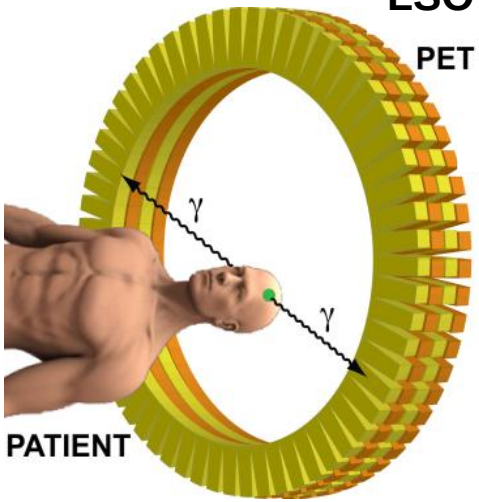


Figure of Merit for whole body imaging (FOM):

$$FOM \cong \frac{(\text{detection effi.})^2 \cdot (\text{selection effi.})^2 \cdot \text{acceptance}}{CRT \cdot \text{Number\_of\_bed\_positions}}$$

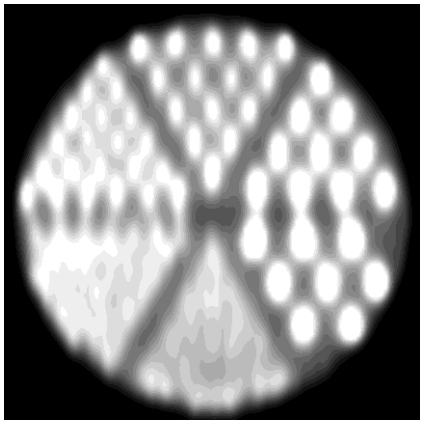
J-PET: P.M. et al., Phys. Med. Biol. 61 (2016) 2025; arXiv:1602.02058

J-PET: P. Bialas, J. Kowal, A. Strzelecki et al. Acta Phys. Pol. A127 (2015) 1500
Adam Strzelecki, PhD thesis, 2016

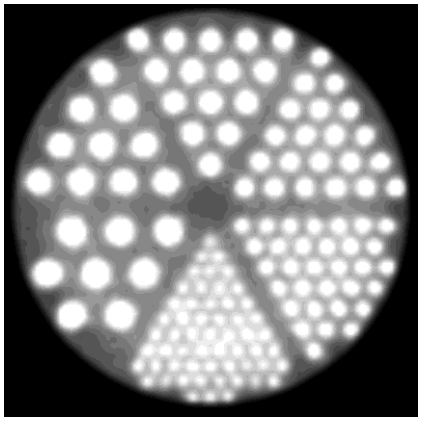
384 strips, diameter 85 cm, 50 cm AFOV, 10^8 events, 50 iterations,

J-PET: image reconstracted from simulated data

rotated (coronal)



axially arranged



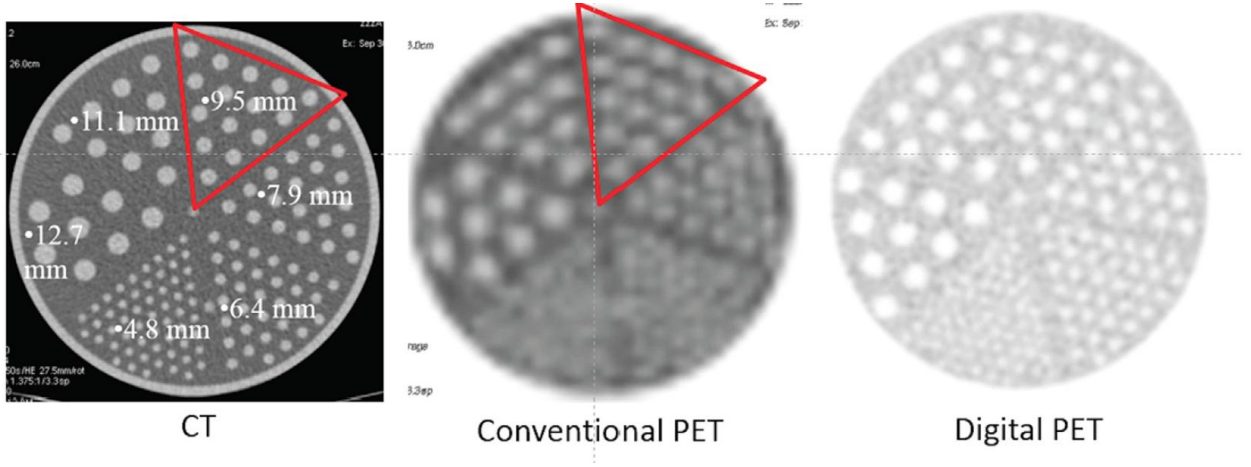


Figure from P. Slomka, T. Pan, G. Germano, Semin. Nucl. Med. 46 (2016) 46

Digital PET, courtesy of Jun Zhang (PhD), Michael V. Knopp (MD, PhD), The Ohio State University