From tests of discrete symmetries to medical imaging with J-PET detector

PANIC 2021

22nd Particle and Nuclei International Conference

08.09.2021

P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

From tests of discrete symmetries to medical imaging with J-PET detector

J-PET: Nature Communications (2021) in press

Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography 10^{-4}

J-PET: Science Advances (2021) in press

Positronium imaging with the novel multi-photon PET scanner

PANIC 2021
22nd Particle and Nuclei International Conference
08.09.2021

P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

From tests of discrete symmetries to medical imaging with J-PET detector

J-PET: Nature Communications (2021) in press

Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography 10^{-4}

J-PET: Science Advances (2021) in press

Positronium imaging with the novel multi-photon PET scanner

14:50 W. Krzemien: Test of new operators of discrete symmetries with J-PET

N. Chug: Poster: CPT symmetry test in positronium annihilations with the J-PET detector

PANIC 2021
22nd Particle and Nuclei International Conference
08.09.2021

P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

From tests of discrete symmetries to medical imaging with J-PET detector

- Jagiellonian-PET (J-PET)
- Positronium imaging
- Discrete symmetries
- Quantum entanglement

PANIC 2021
22nd Particle and Nuclei International Conference
08.09.2021

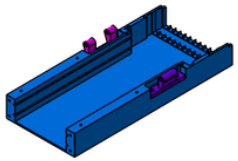
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**


Jagiellonian PET
Frascati 2019

Kraków 2019

P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

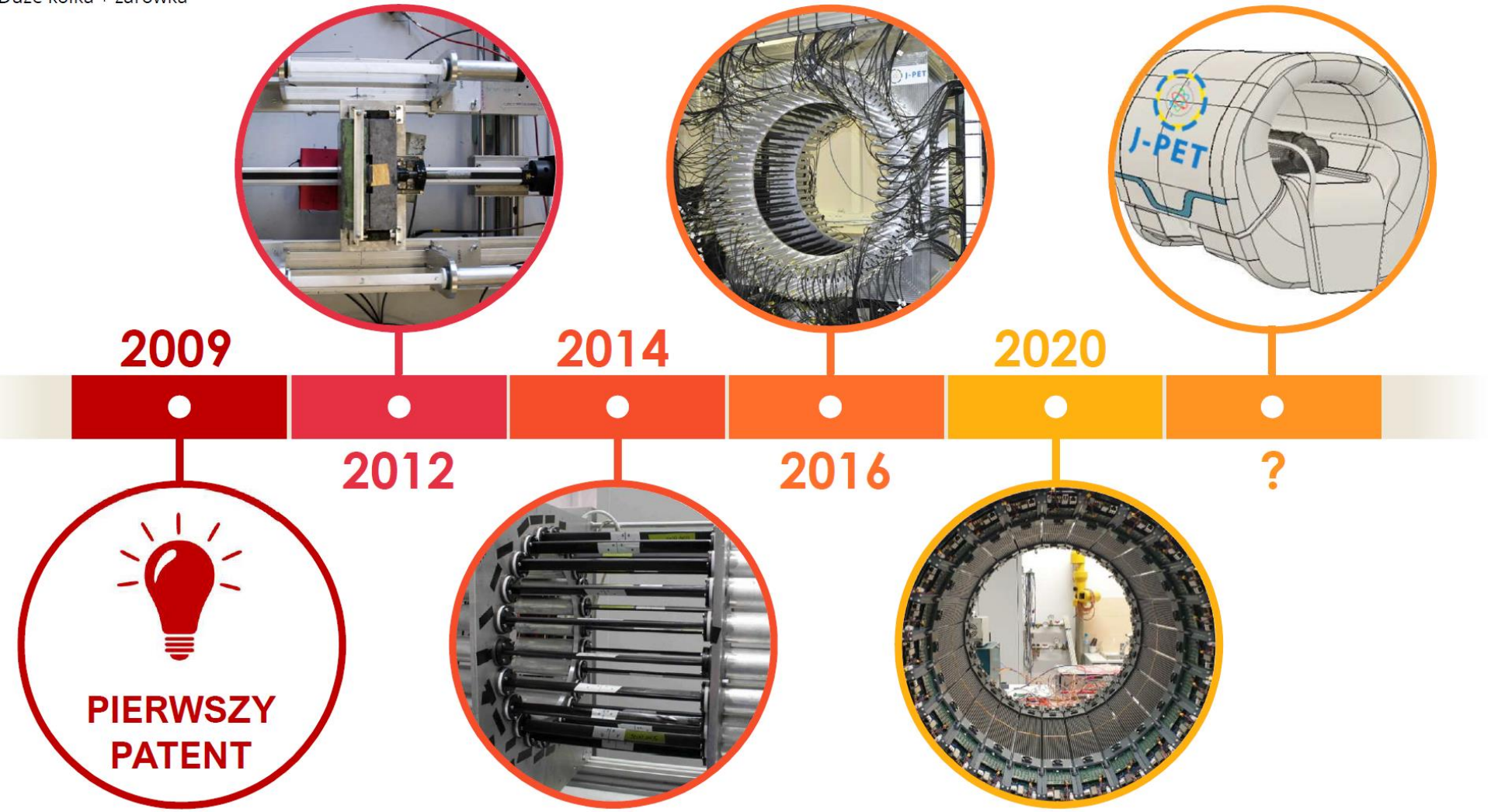
Development of cost-effective total-body PET



Aim:

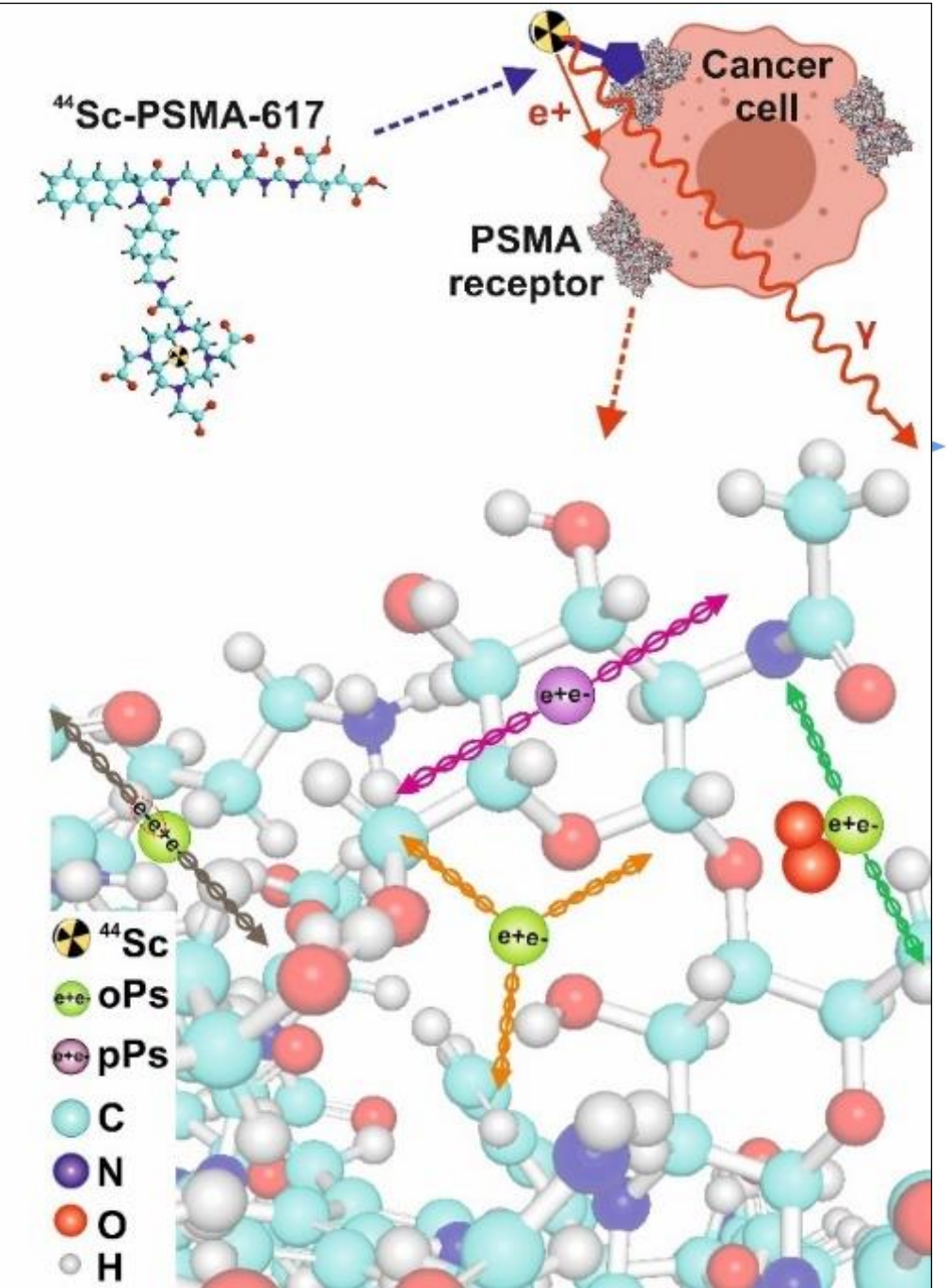
- Cost effective total-body PET
- Light, modular, configurable and portable

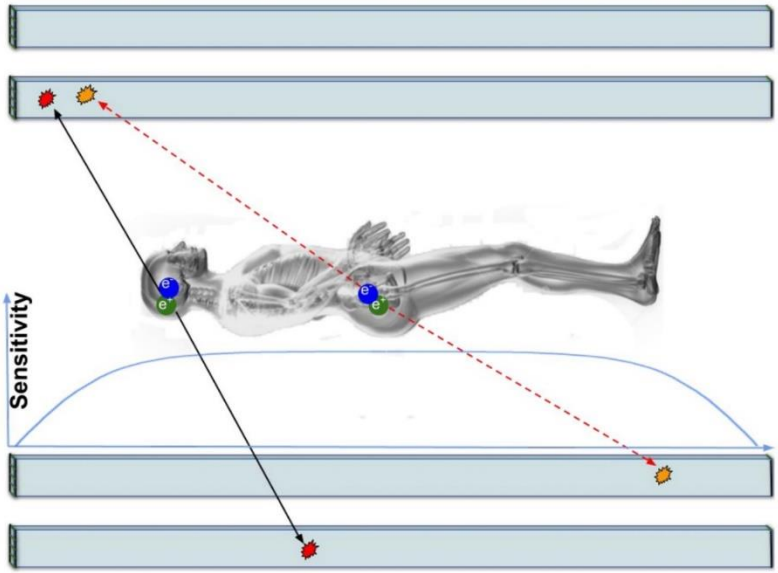
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**



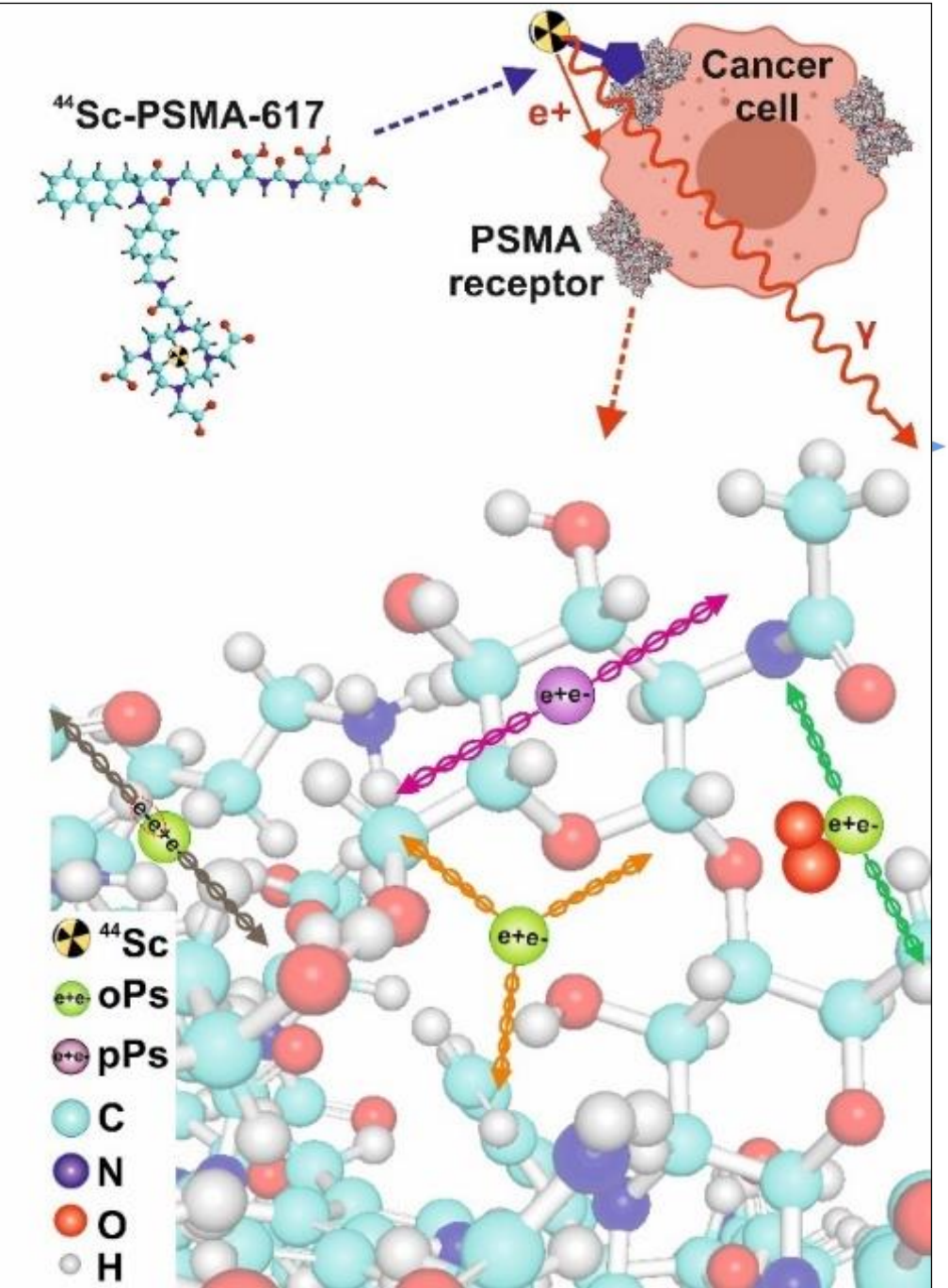
Financed by:
Ministry of Science and Higher Education
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes)

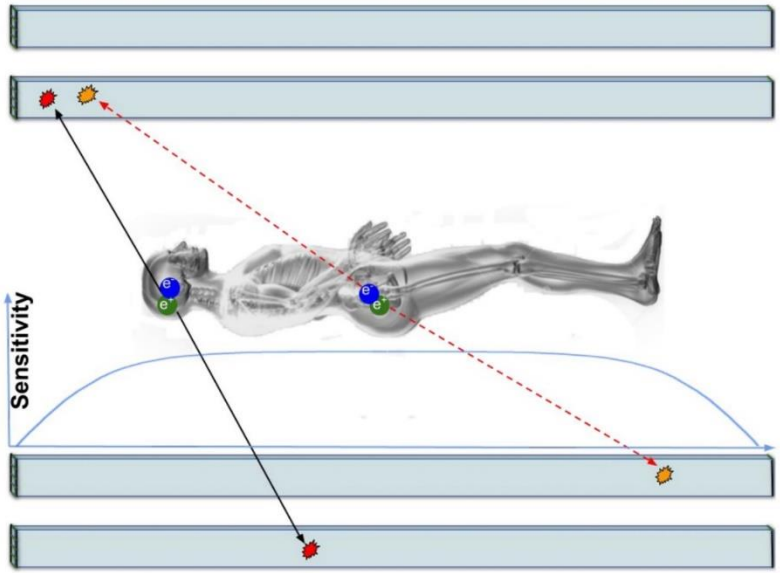
P. Moskal, E. Ł. Stępień, PET Clinics 15 (2020) 439





P. Moskal, E. Ł. Stępień, PET Clinics 15 (2020) 439





P. Moskal, B. Jasińska, E. Ł. Stępień, S. Bass,
Nature Reviews Physics 1 (2019) 527

30% – 40%

From tests of discrete symmetries to medical imaging with J-PET detector

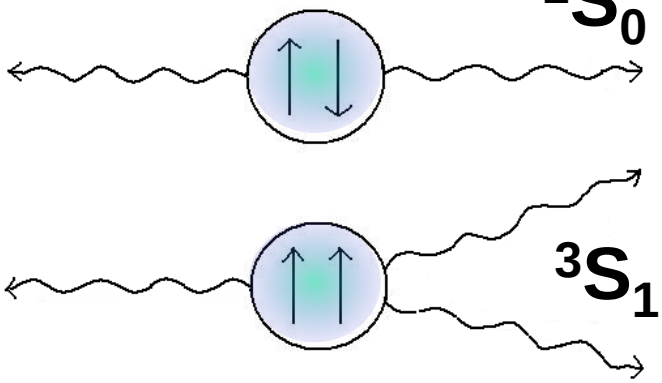
- Jagiellonian-PET (J-PET)
- Positronium imaging
- Discrete symmetries
- Quantum entanglement

PANIC 2021

22nd Particle and Nuclei International Conference

08.09.2021

P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**



$^1S_0$ **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
C	+	-
L=0 -> P	-	-
CP	-	+

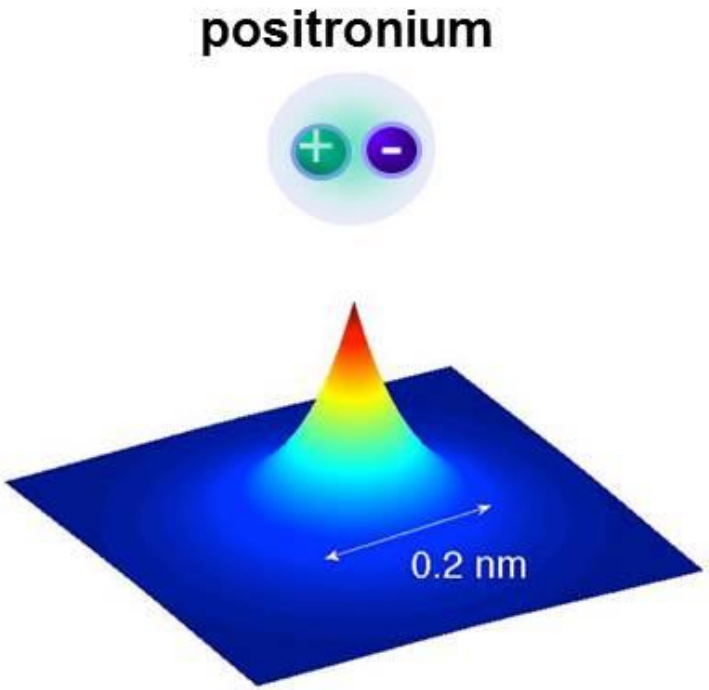
S = 0 $\downarrow\uparrow - \uparrow\downarrow$

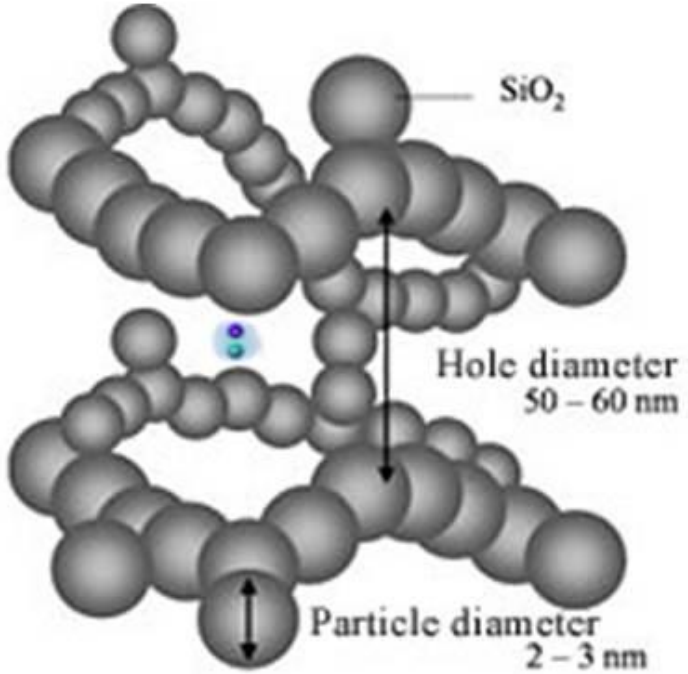
$\uparrow\uparrow$

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

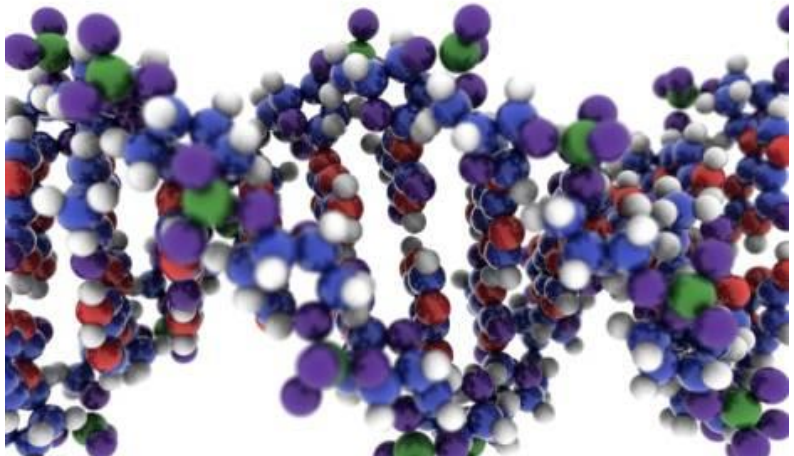
$\downarrow\downarrow$

S. Bass, QED and Fundamental Symmetries in Positronium Decays
Acta Phys. Pol. B 50, 7 (2019)



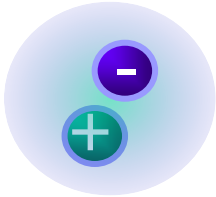


Y.H. Wang et al., Phys. Rev. A 89 (2014) 043624,
http://www.chem-eng.kyushu-u.ac.jp/e/research.html



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).

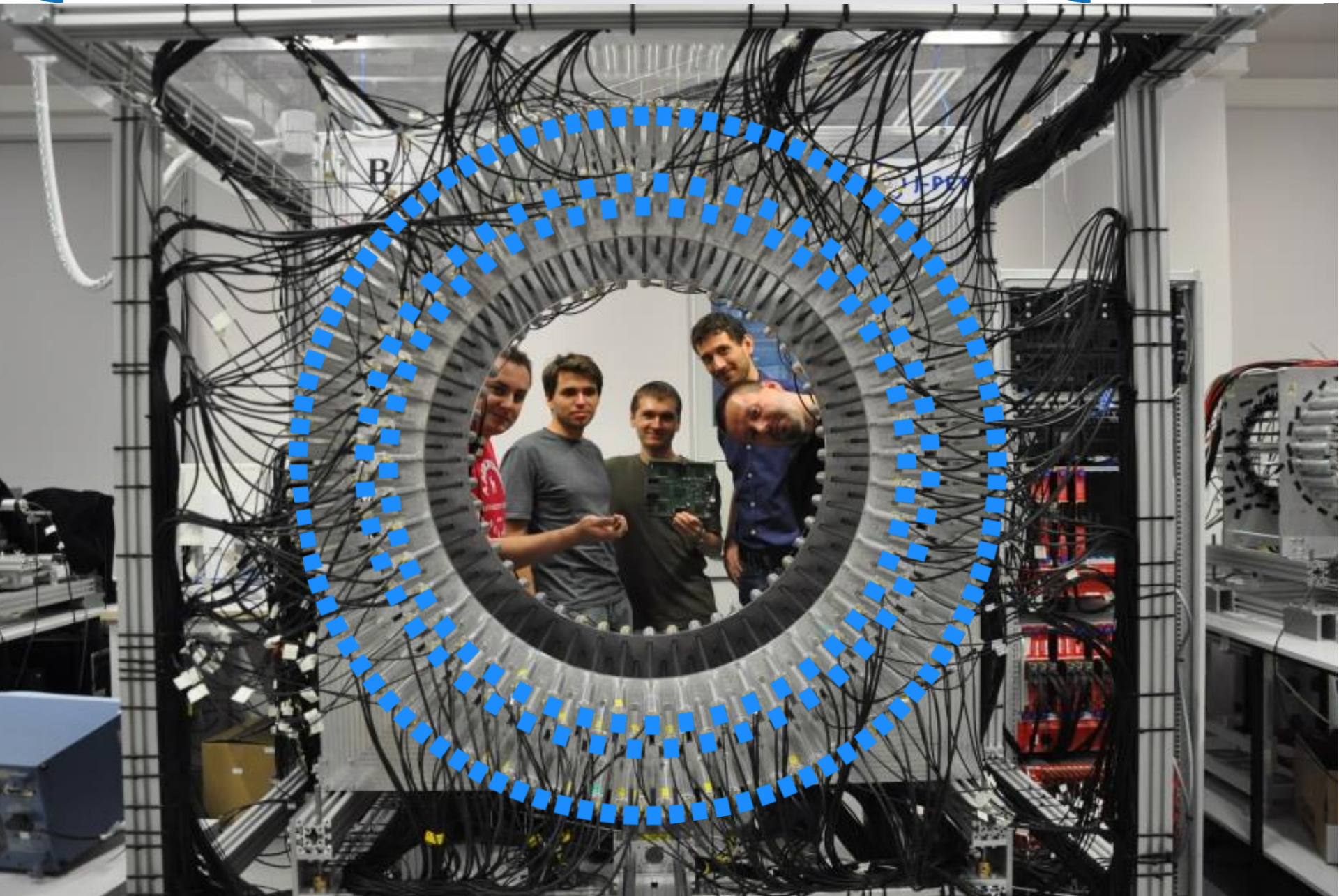
Purely Leptonic state !

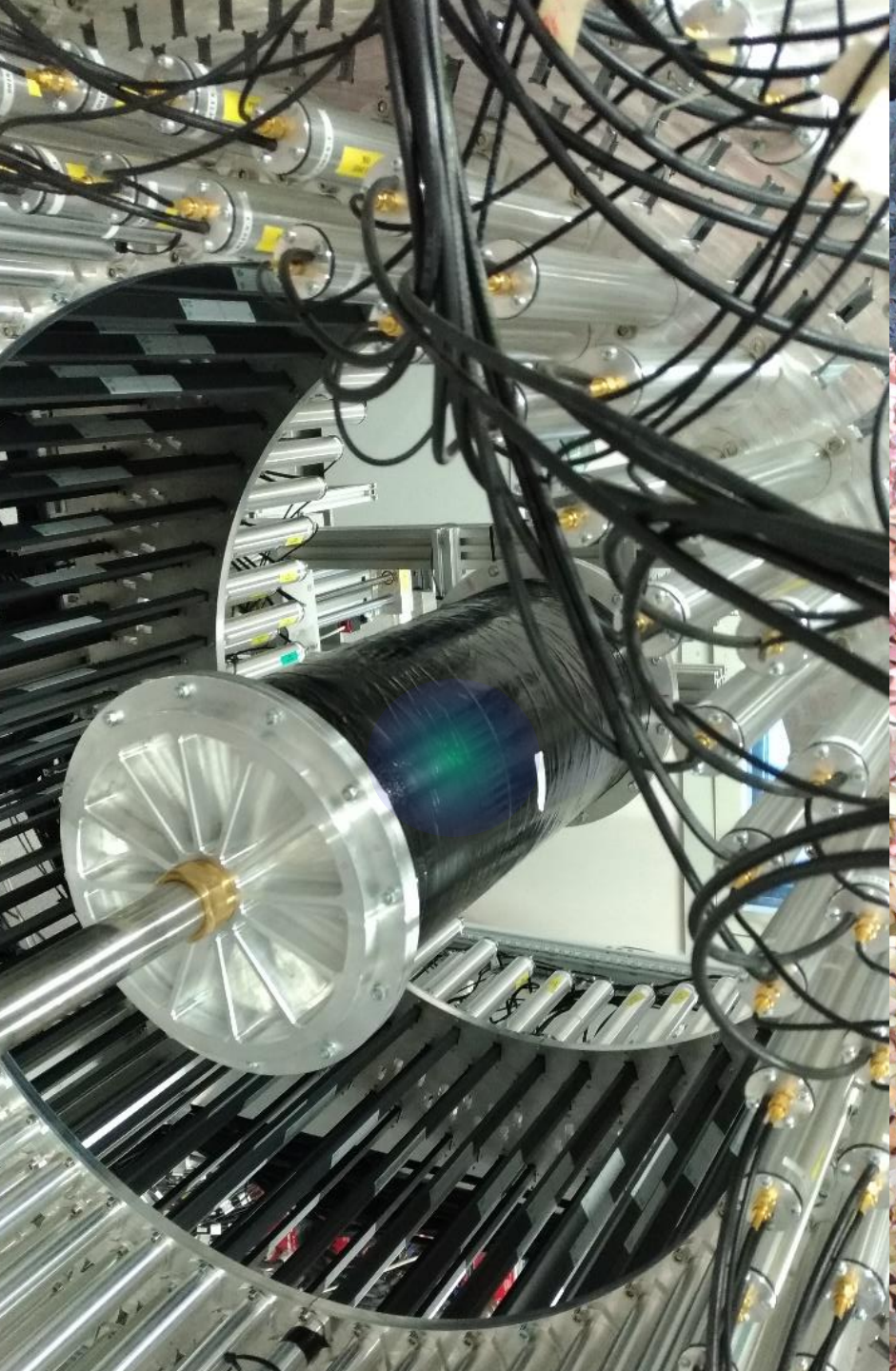
Breaking of T and CP was observed but only for processes involving quarks.
So far breaking of these symmetries was not observed for purely leptonic systems.

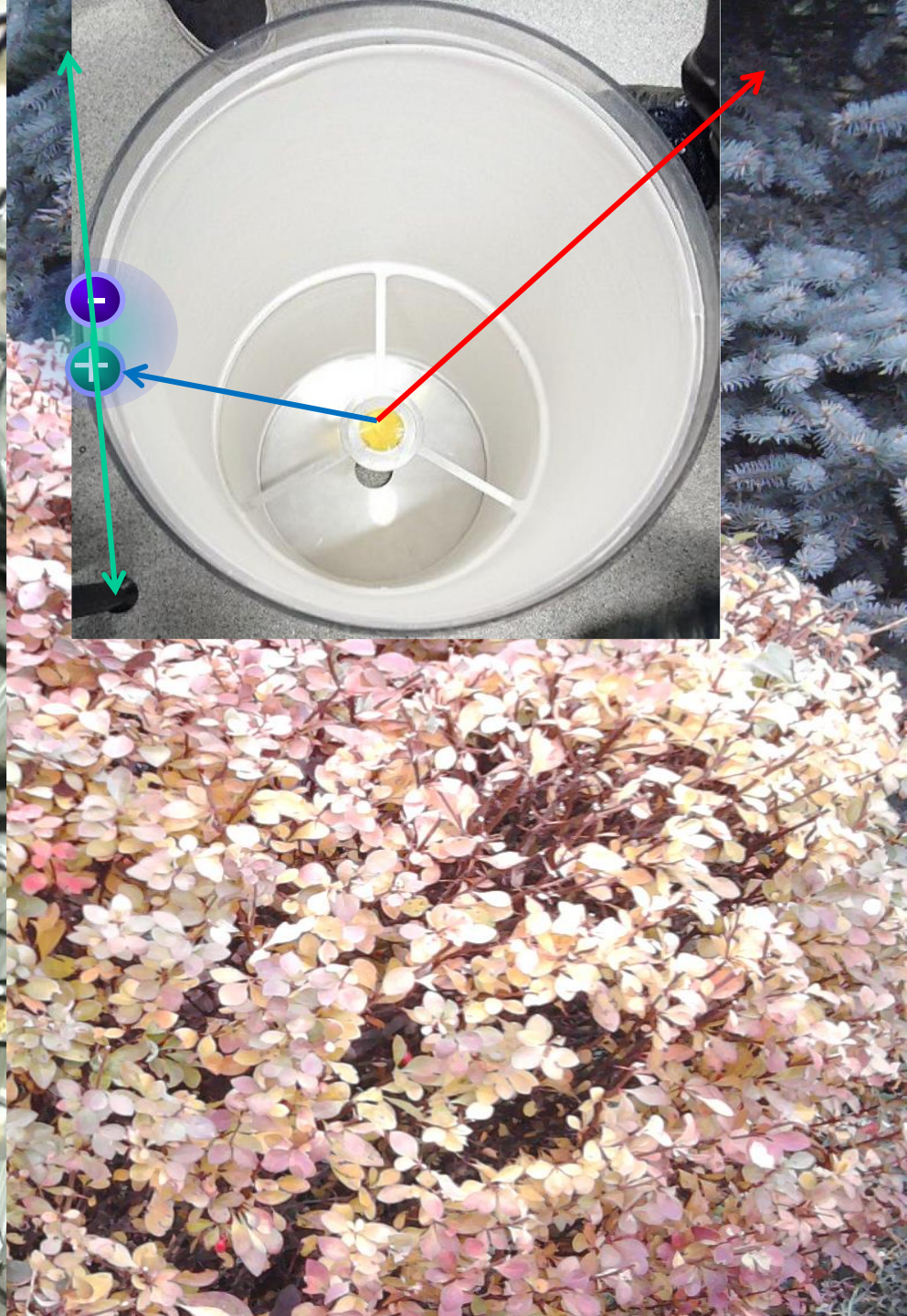
10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

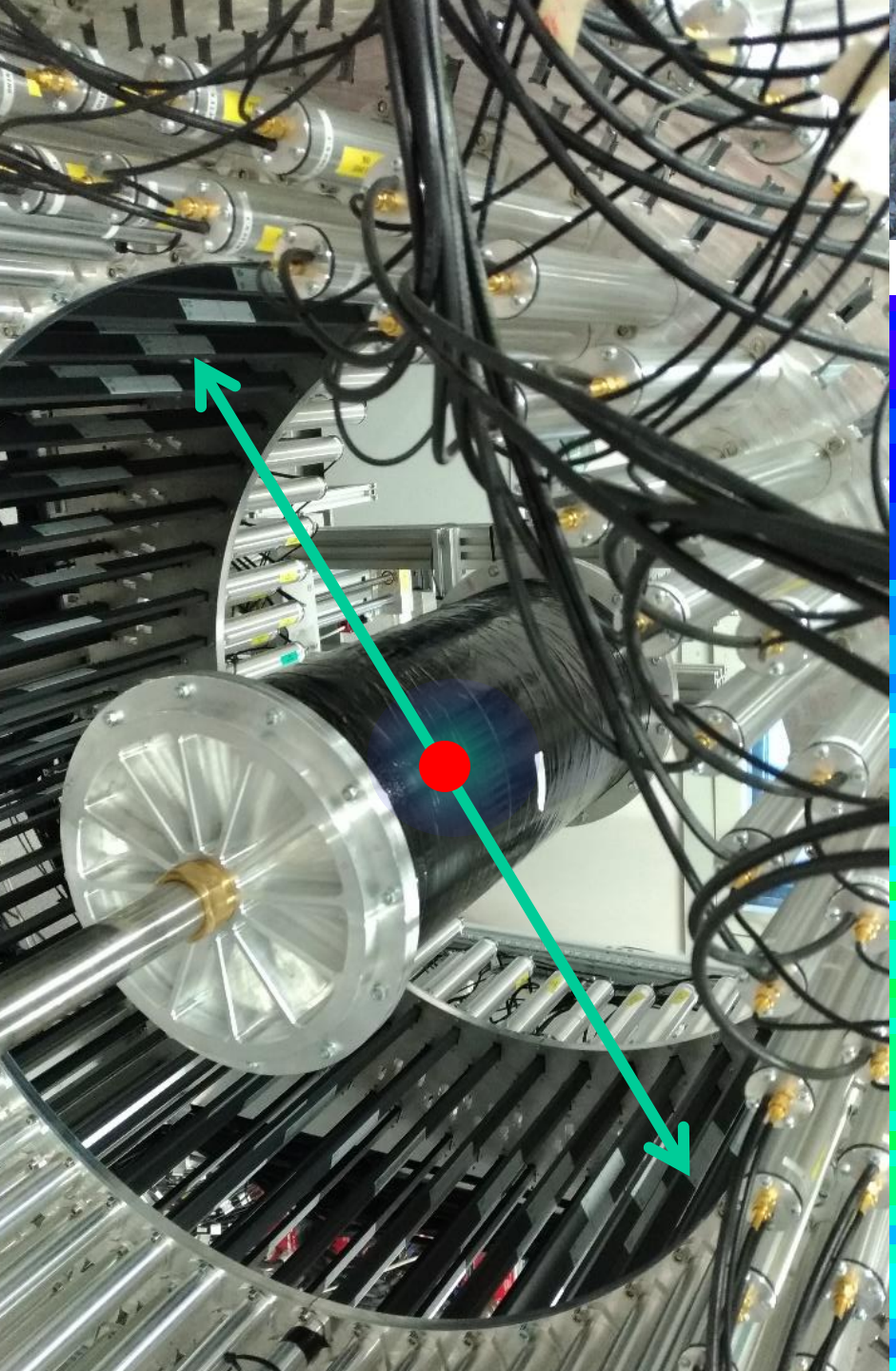
P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003)
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

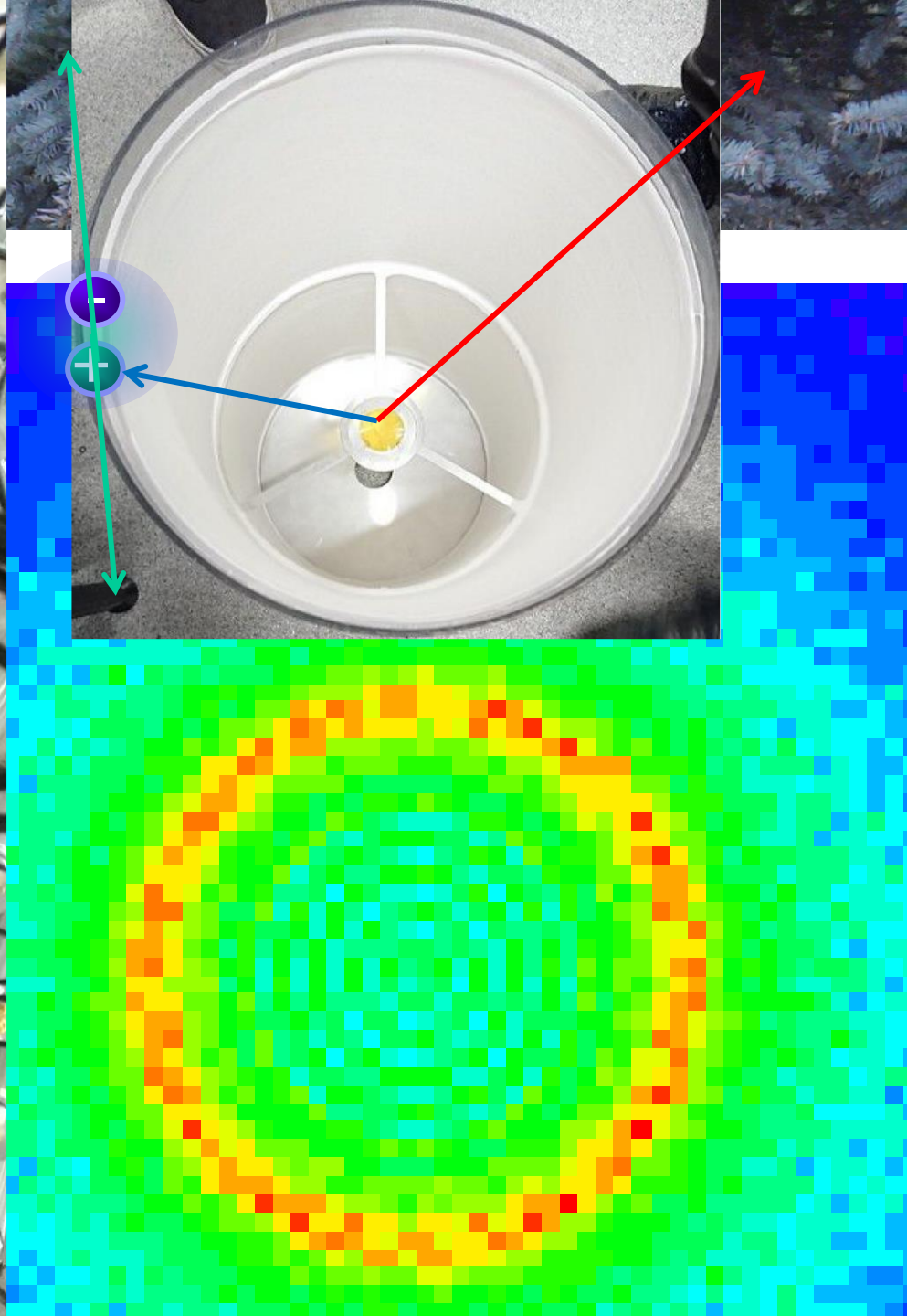
Jagiellonian PET

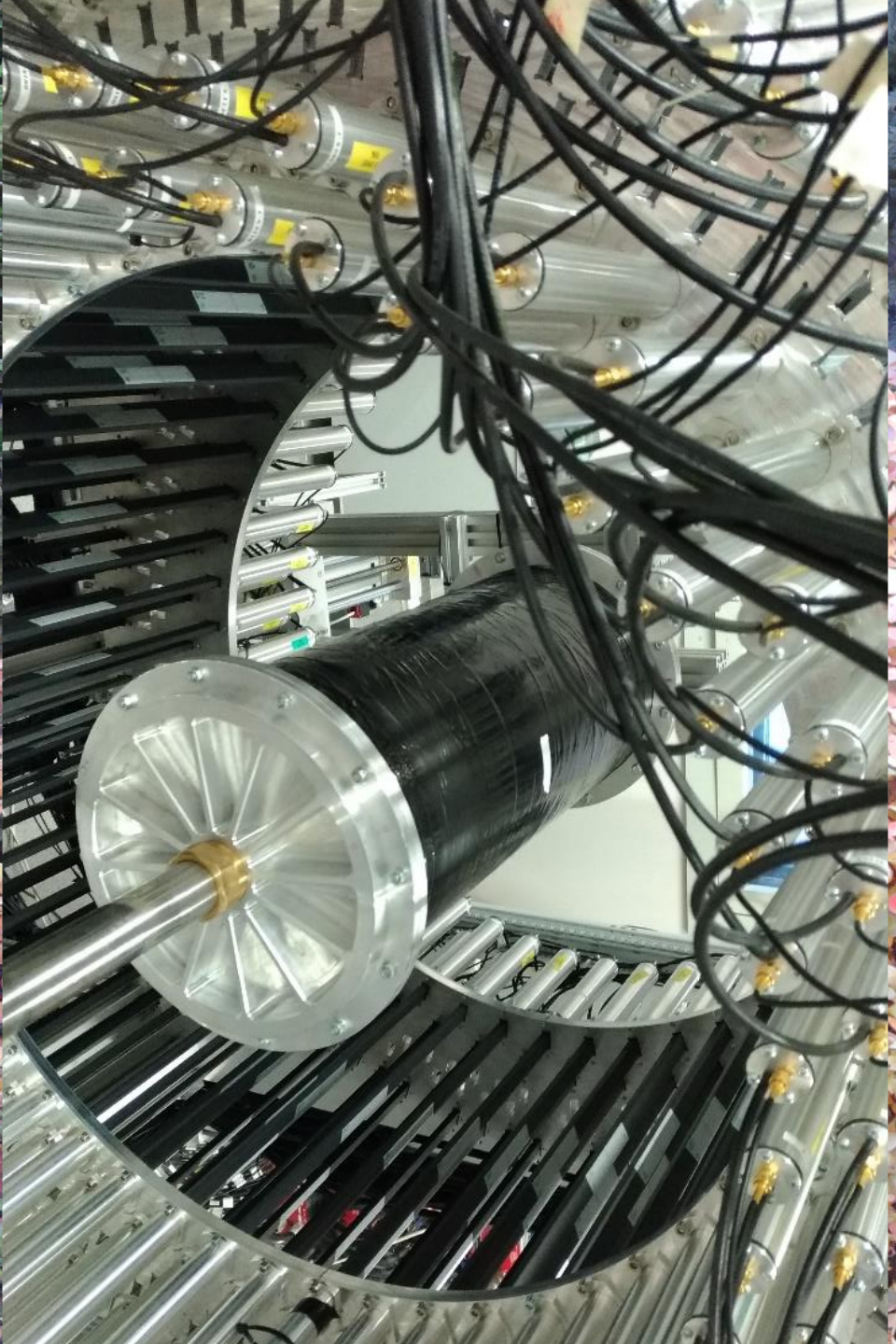


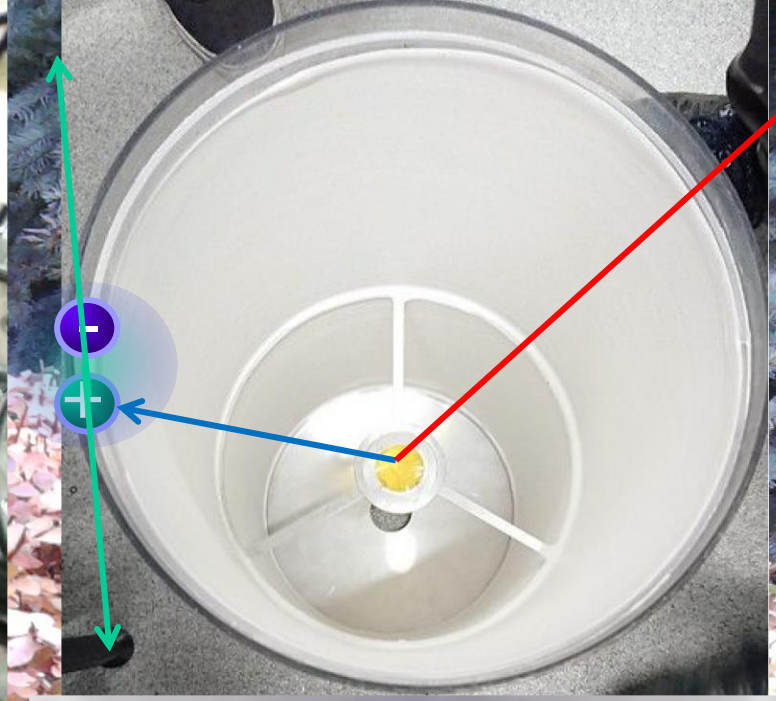


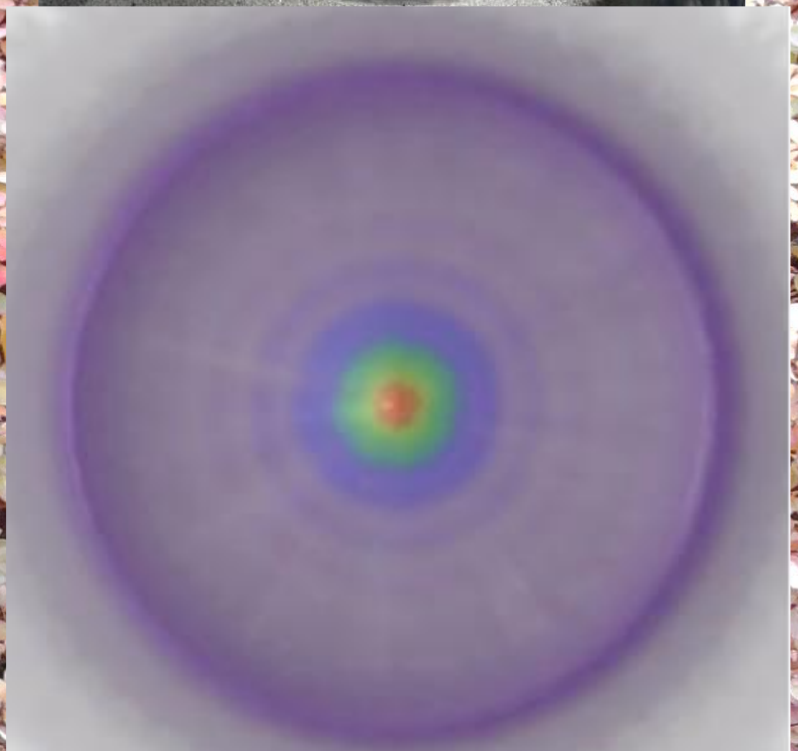






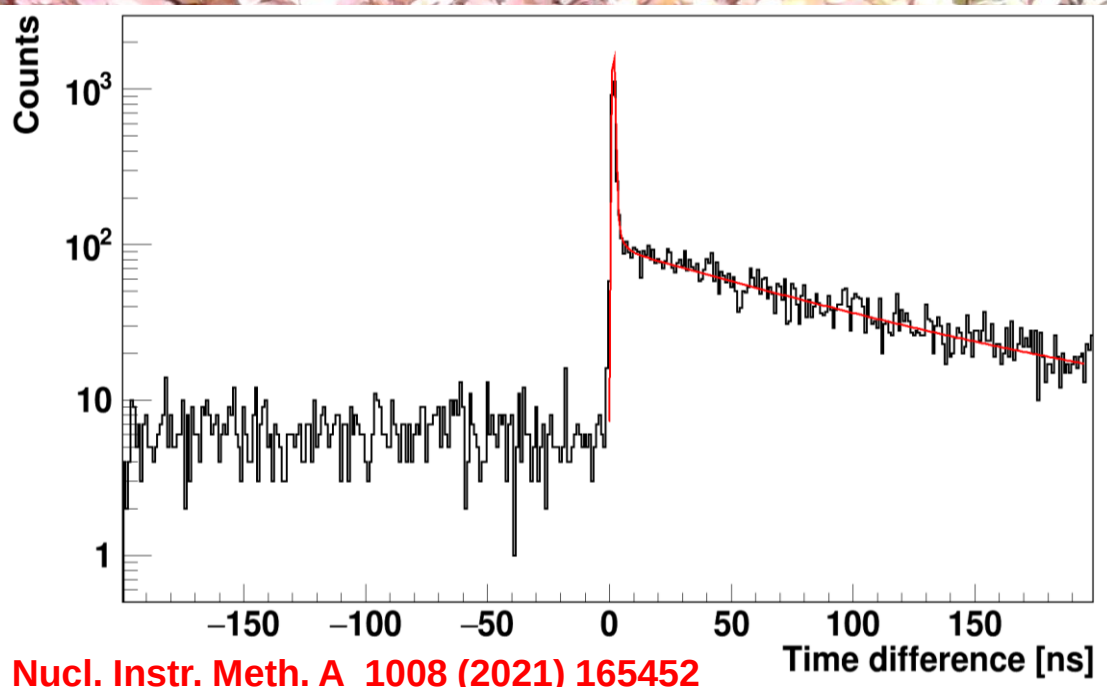




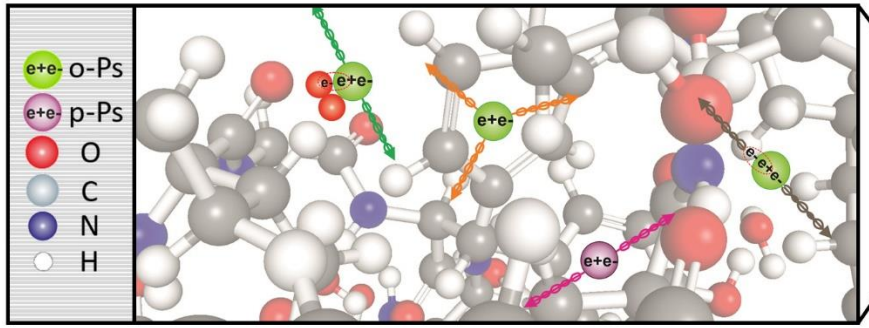


$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$

$^{22}Ne + \gamma$



J-PET: K. Dulski et al., Nucl. Instr. Meth. A 1008 (2021) 165452



Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

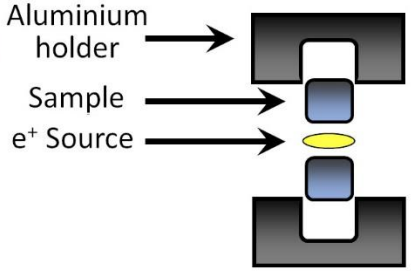
Patient 1 1 1

Patient 2 2 2

Aluminium holder

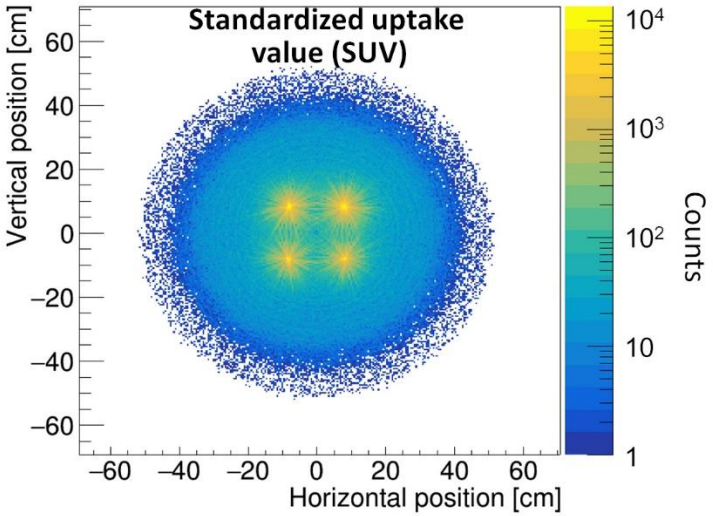
Sample

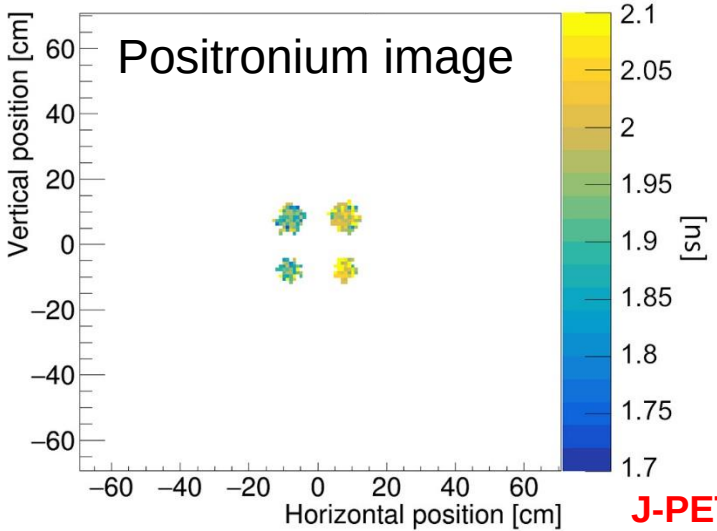
e^+ Source

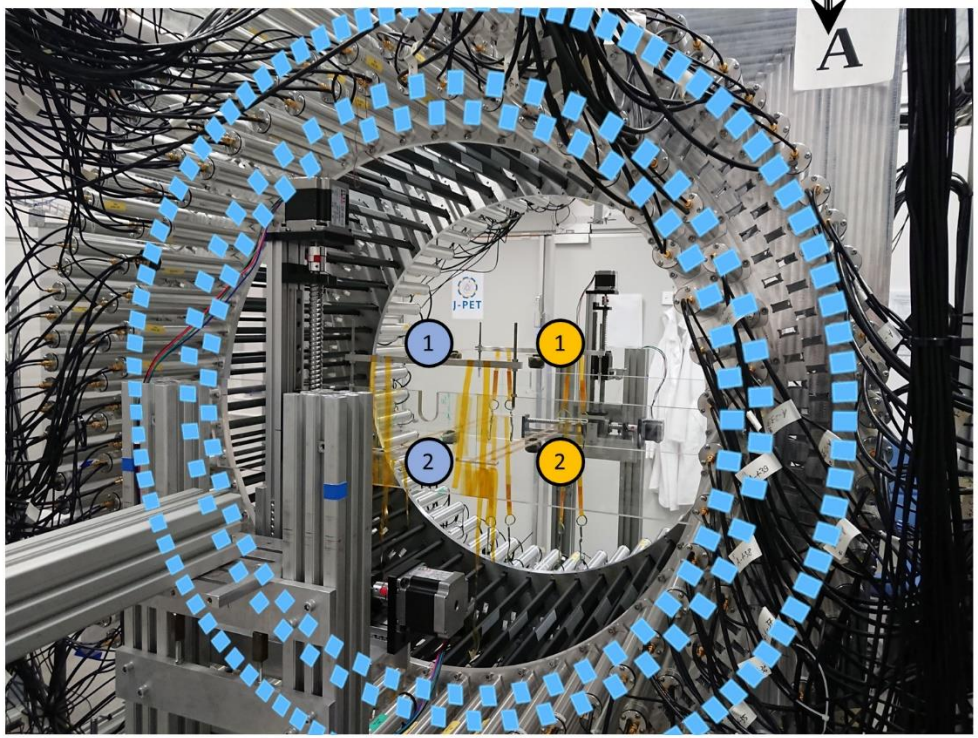


Placing samples in the chambers

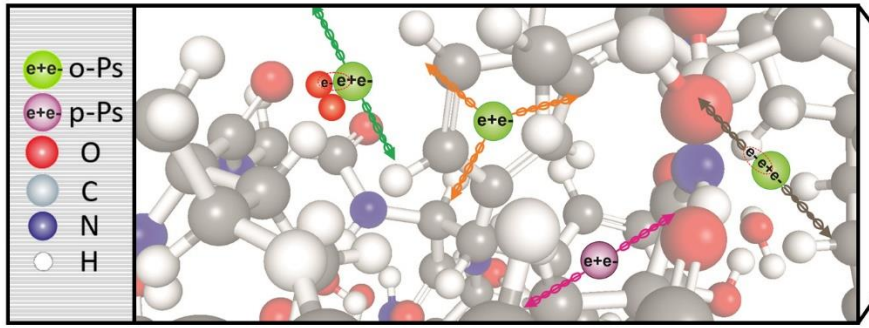
Inserting setup to the detector







J-PET: P. Moskal, K. Dulski et al., Science Advances (2021) in press



Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

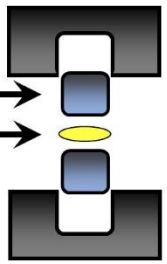
Patient 1 1 1

Patient 2 2 2

Aluminium holder

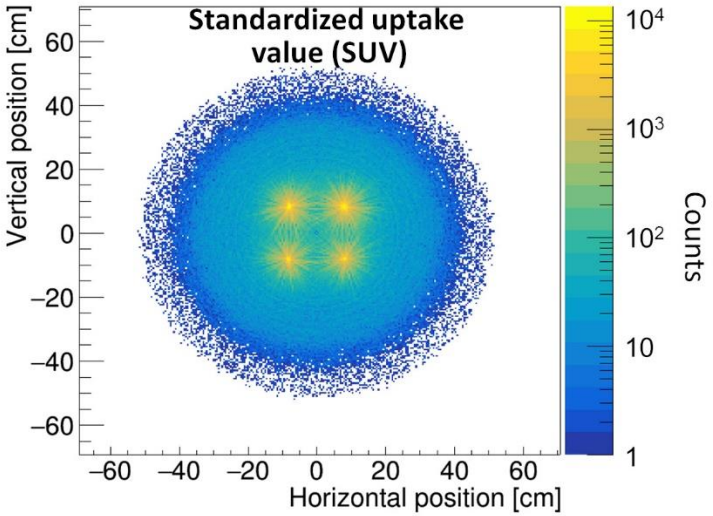
Sample

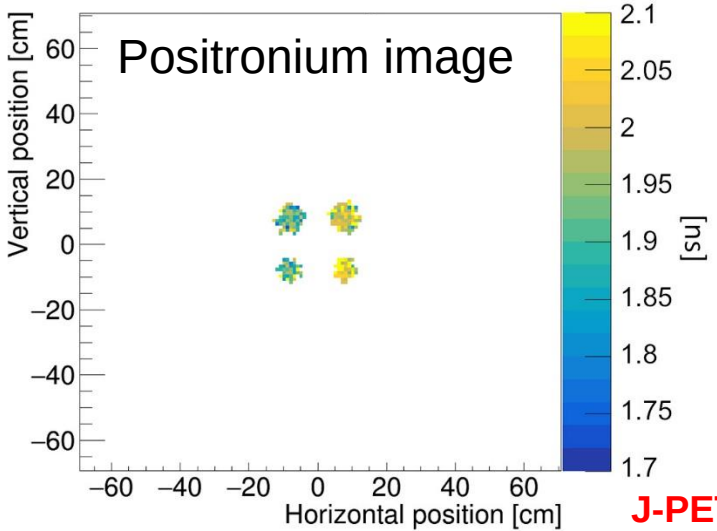
e^+ Source

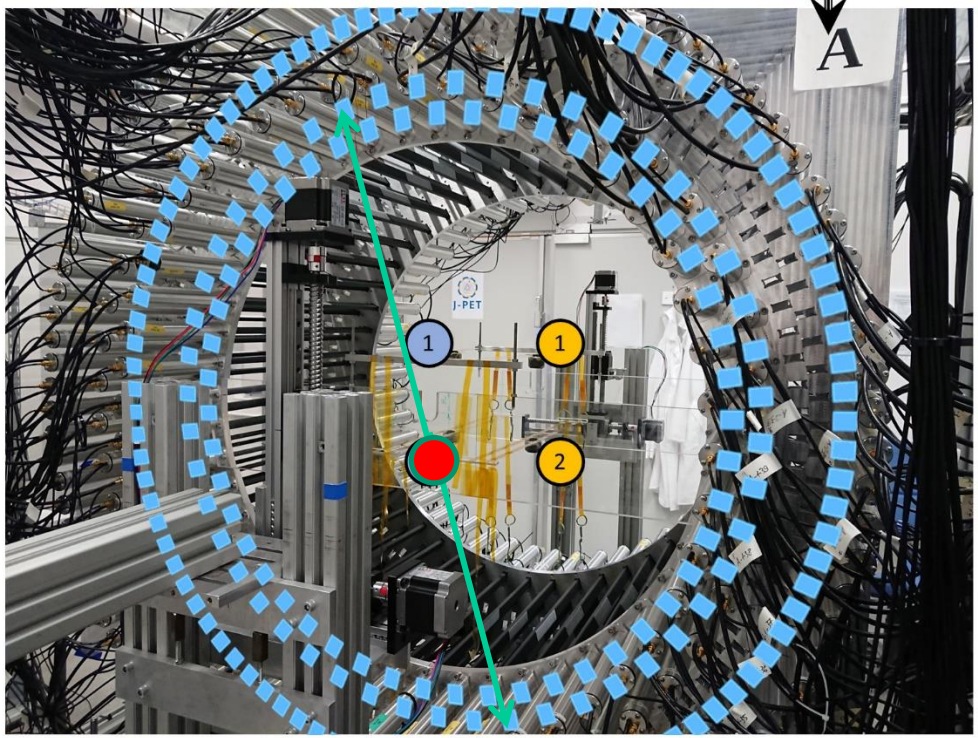


Placing samples in the chambers

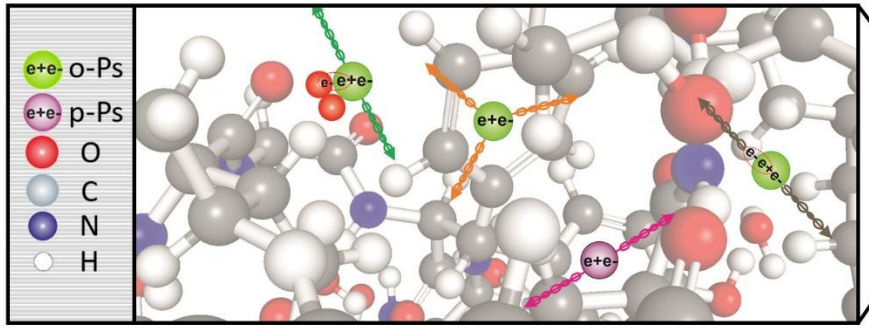
Inserting setup to the detector







J-PET: P. Moskal, K. Dulski et al., Science Advances (2021) in press



Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

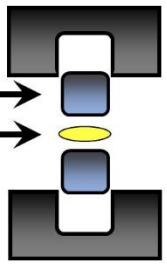
Patient 1 1 1

Patient 2 2 2

Aluminium holder

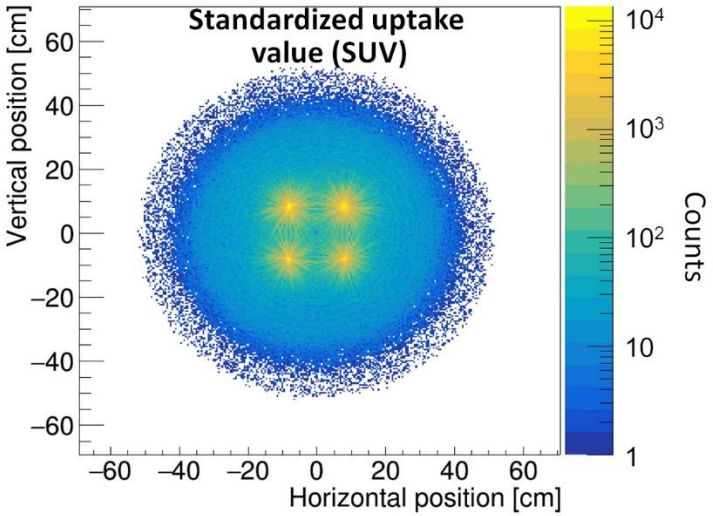
Sample

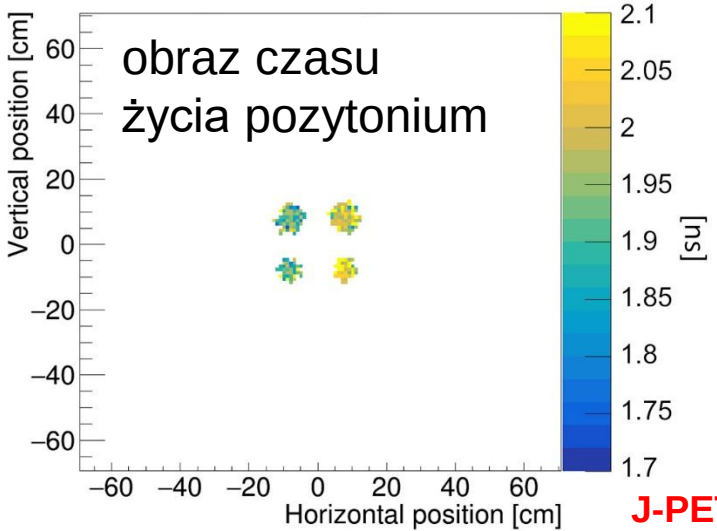
e^+ Source

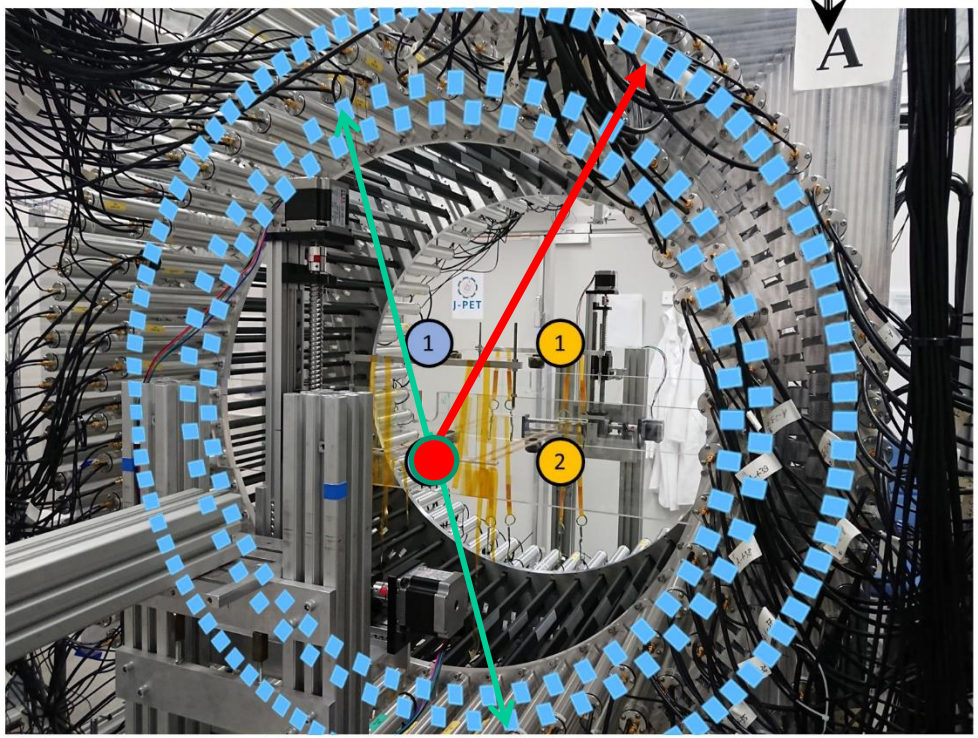


Placing samples in the chambers

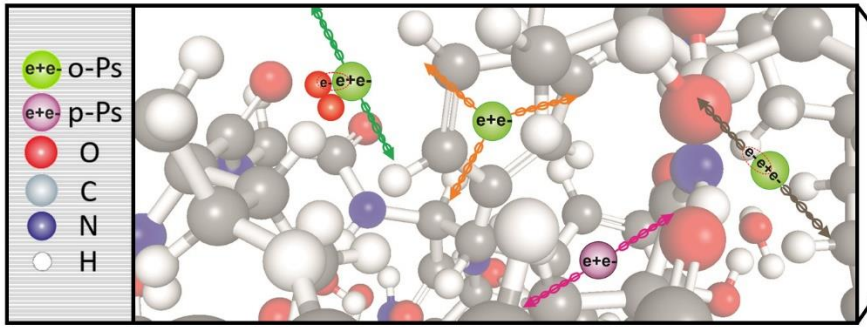
Inserting setup to the detector







J-PET: P. Moskal, K. Dulski et al., Science Advances (2021) in press



Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

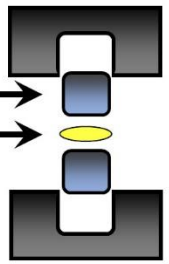
Patient 1 1 1

Patient 2 2 2

Aluminium holder

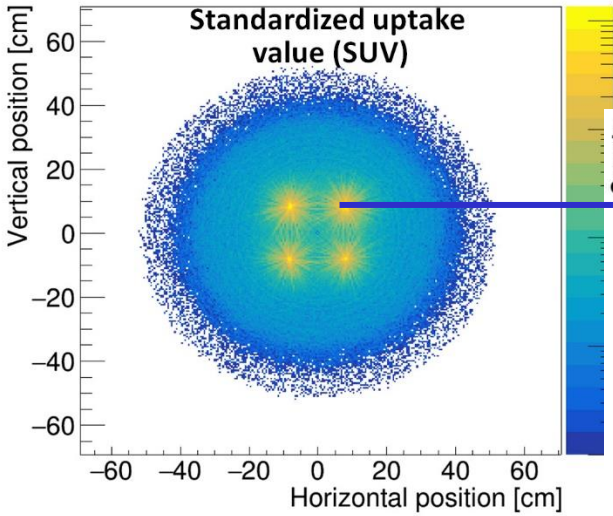
Sample

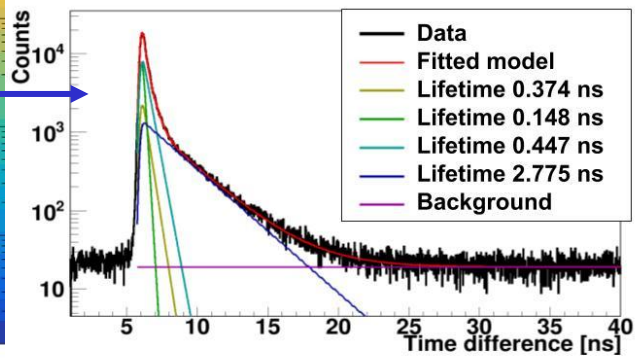
e^+ Source

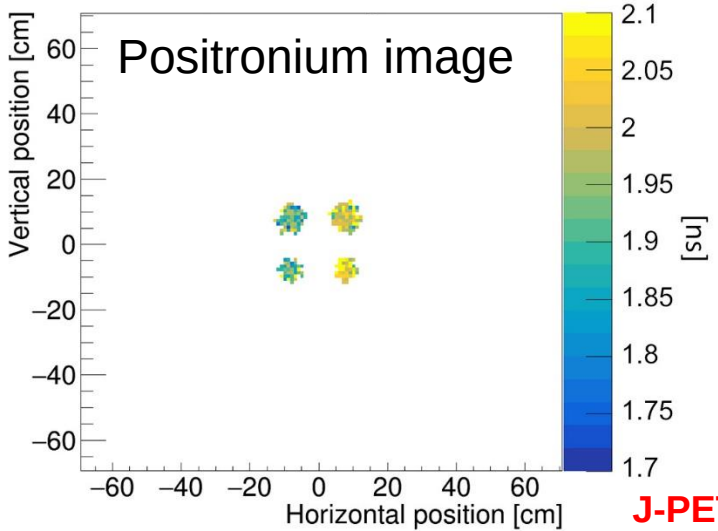


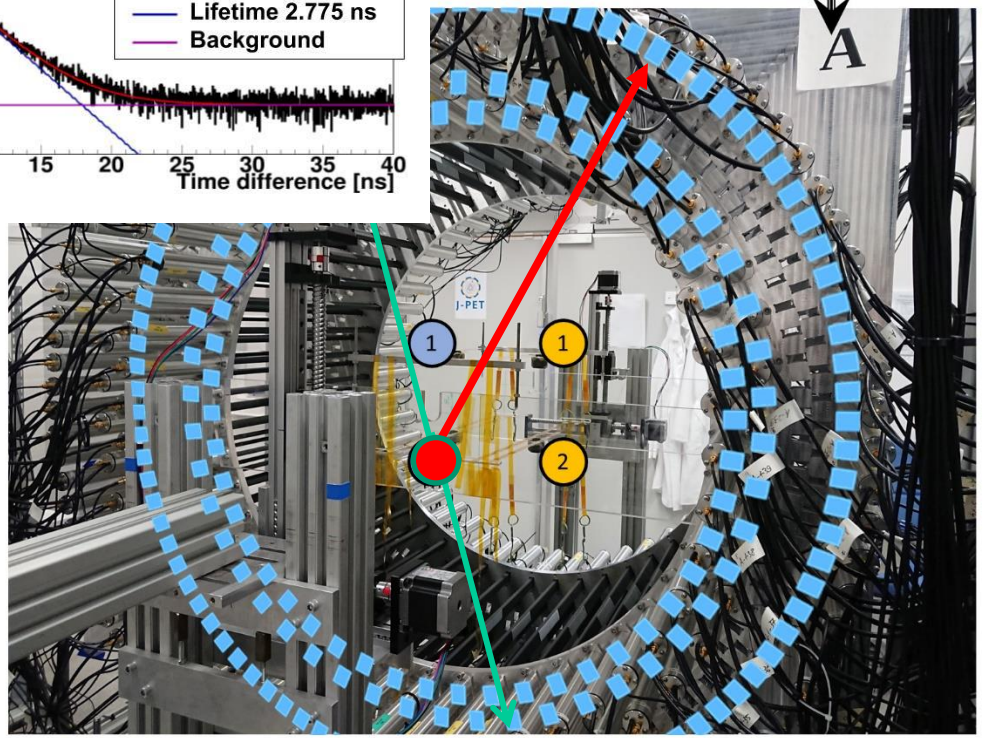
Placing samples in the chambers

Inserting setup to the detector





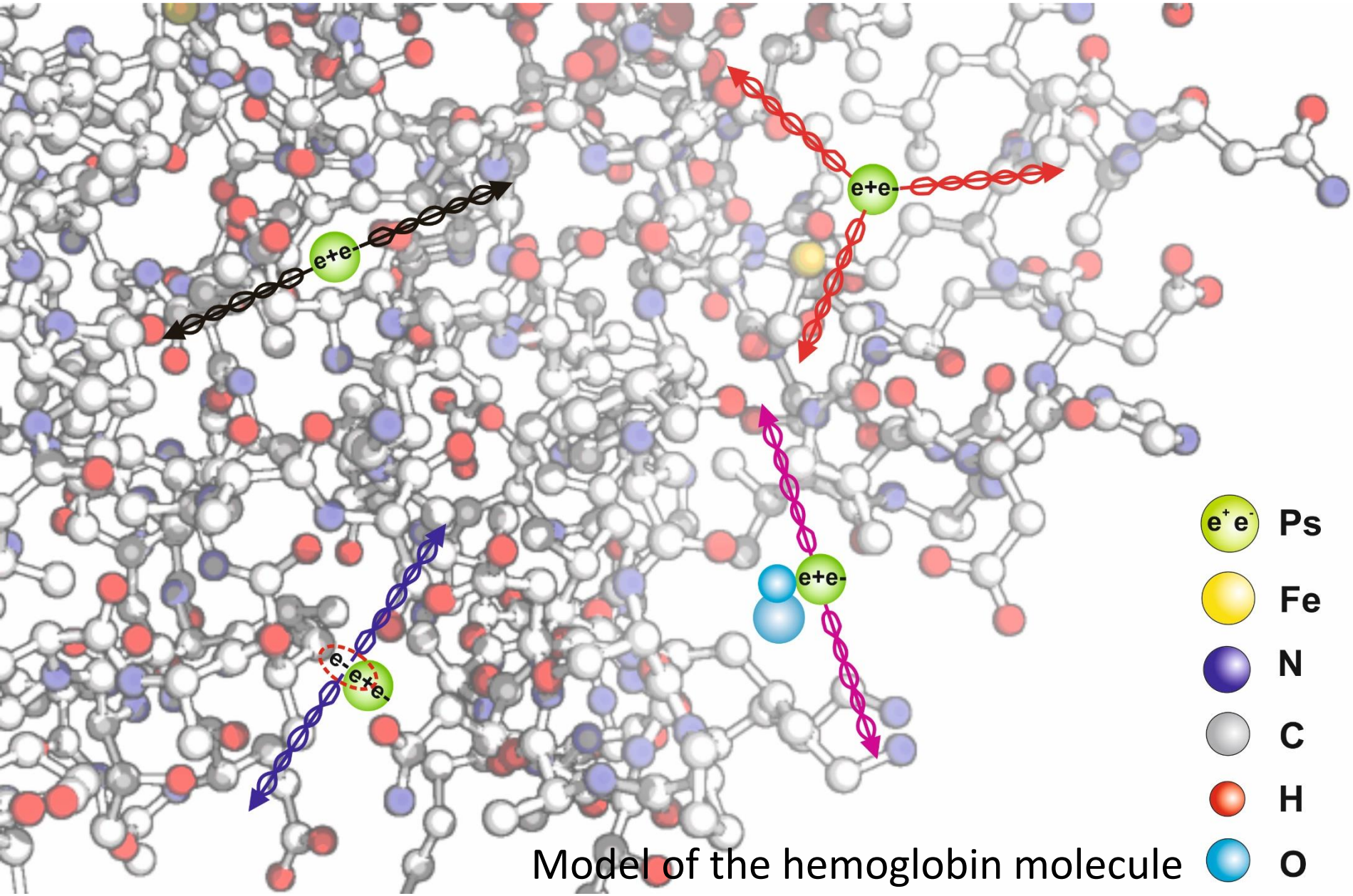




J-PET: P. Moskal, K. Dulski et al., Science Advances (2021) in press

Positronium imaging

P. M., B. Jasińska, E. Ł. Stępień, S. Bass, Nature Reviews Physics 1 (2019) 527



Model of the hemoglobin molecule

From tests of discrete symmetries to medical imaging with J-PET detector

- Jagiellonian-PET (J-PET)
- Positronium imaging
- Discrete symmetries
- **Quantum entanglement**

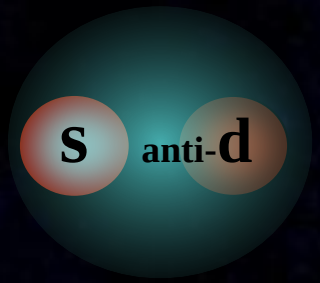
PANIC 2021

22nd Particle and Nuclei International Conference

08.09.2021

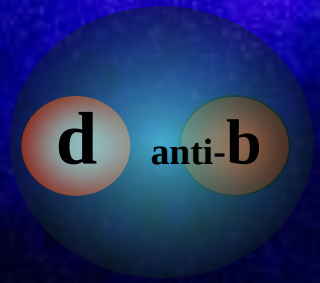
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

Violation of CP and T
confirmed experimentally
for hadrons only



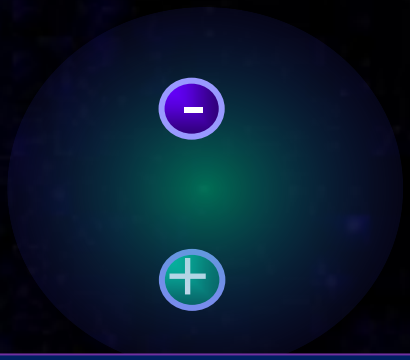
meson K

1964



meson B

2012



positronium

?

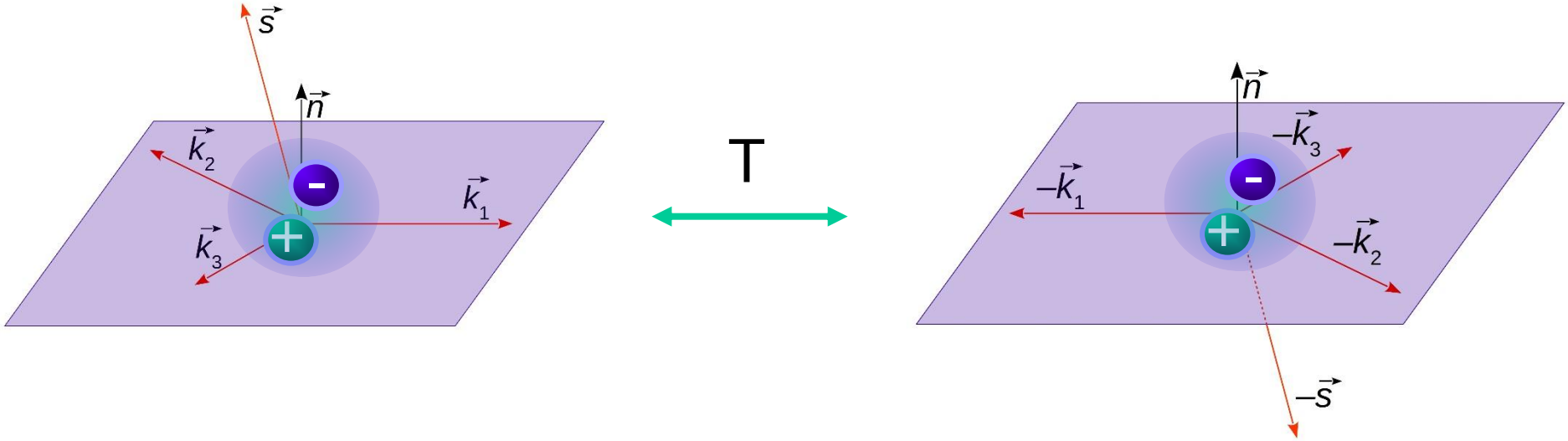
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	–	+	–	–
$\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)$	+	+	–	+	–
$\left(\vec{S} \cdot \vec{k}_1\right)\left(\vec{S}$	+	–	–	–	+

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

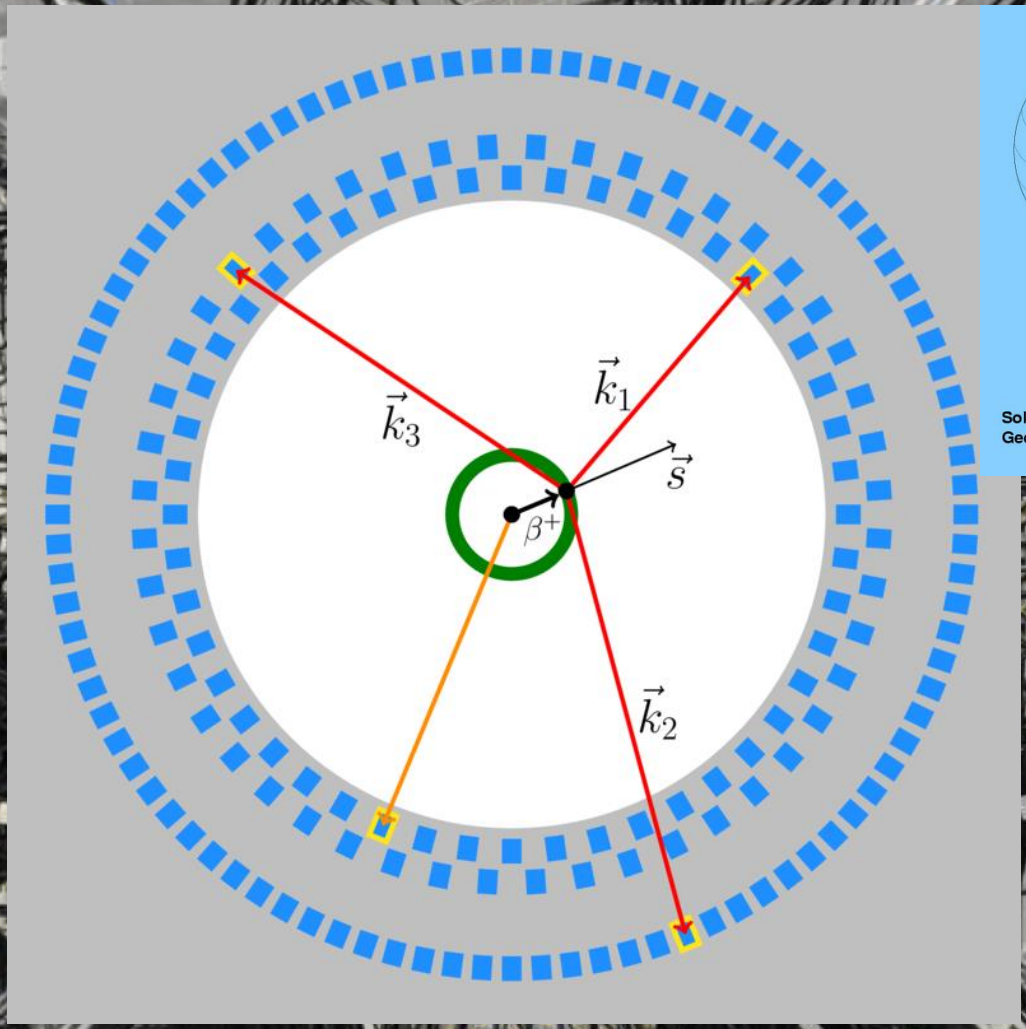
Operators for the o-Ps→3γ process, and their properties with respect to the C, P, T, CP and CPT symmetries.

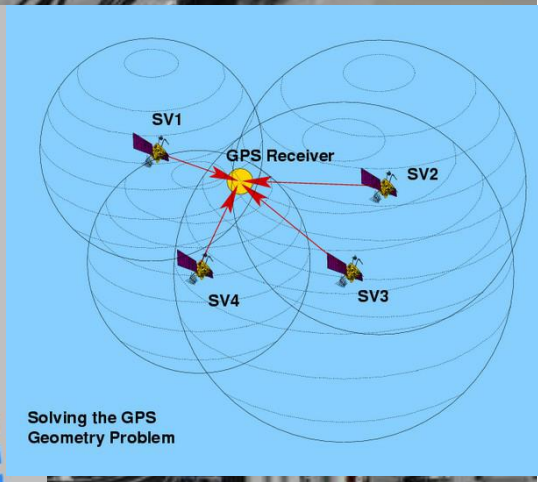
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	–	+	–	–
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	–	+	–
$(\vec{S} \cdot \vec{k}_1)(\vec{S}$	+	–	–	–	+

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



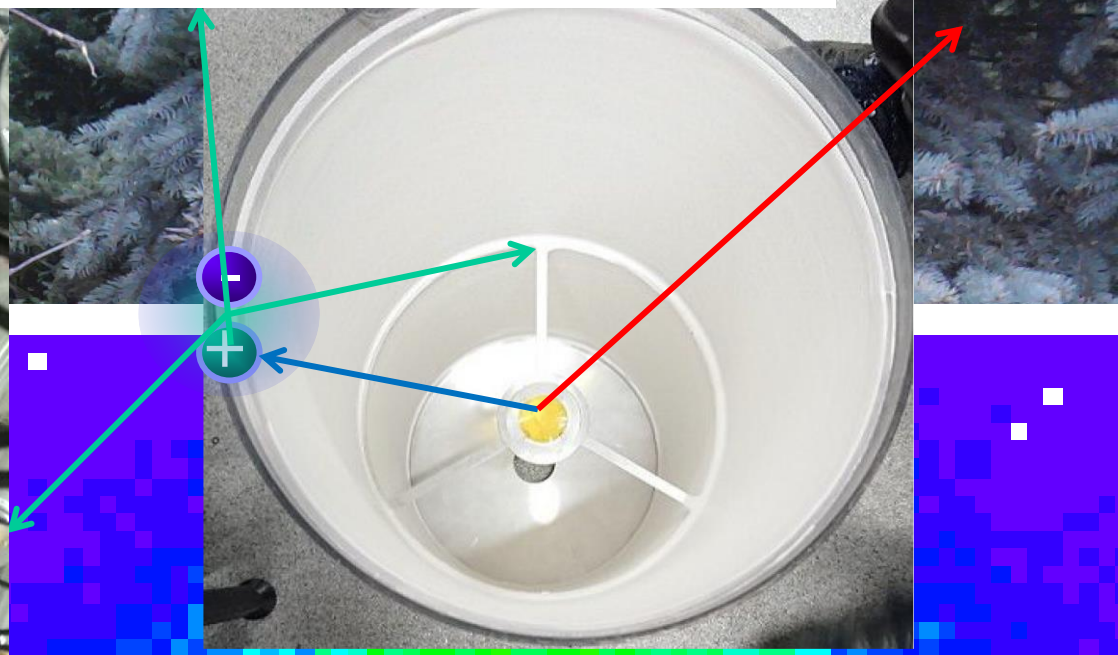
Jagiellonian PET

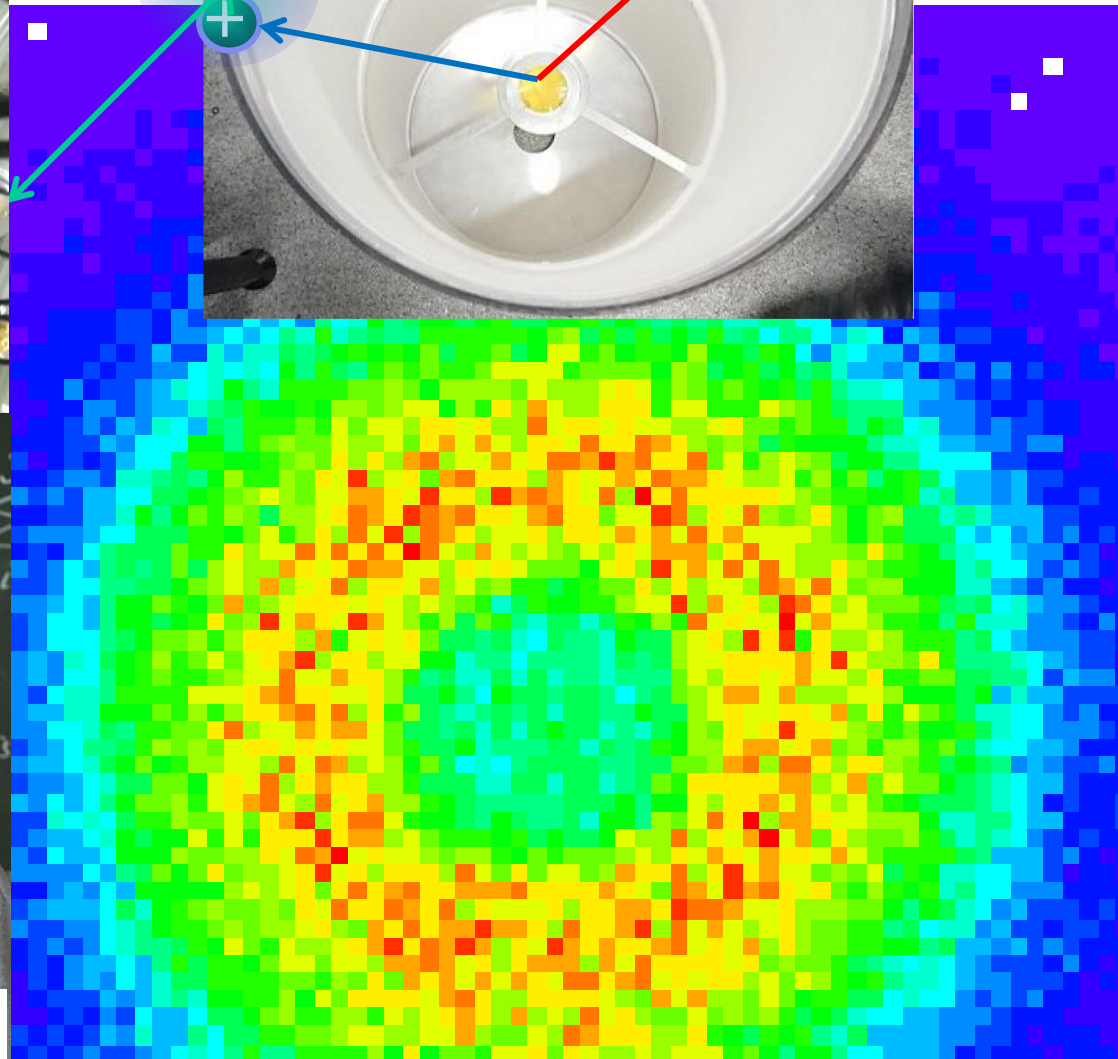


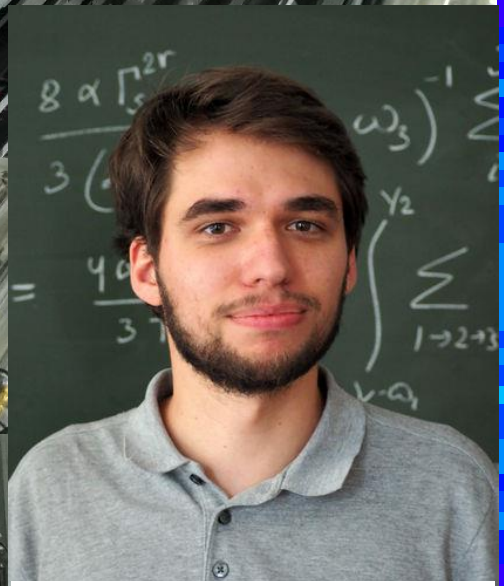


P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509

J-PET: P. Moskal, A. Gajos et al., Nature Communications (2021) in press





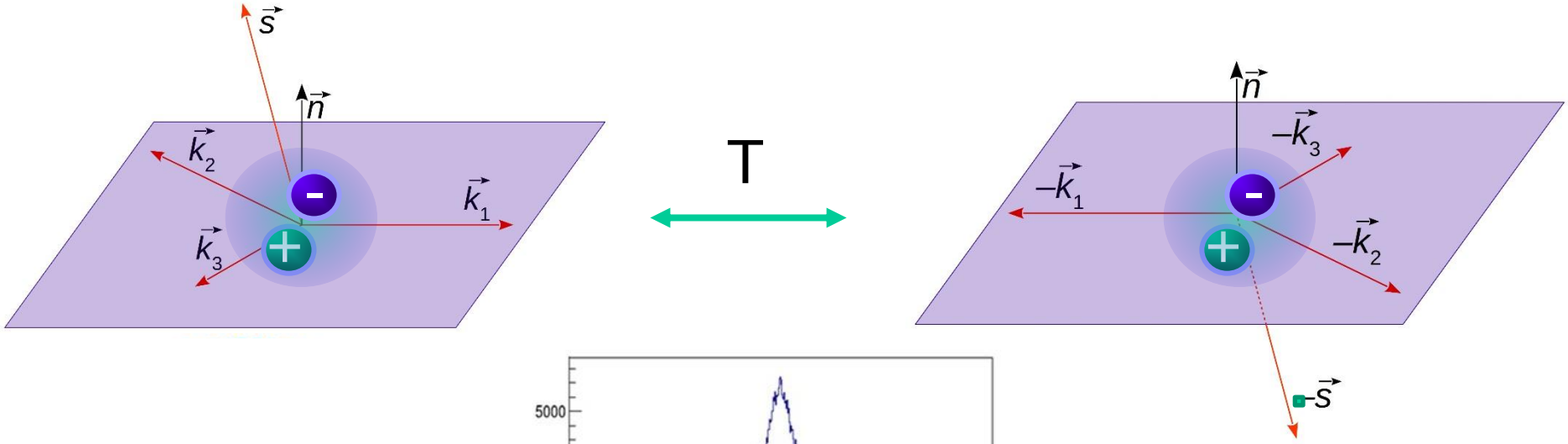


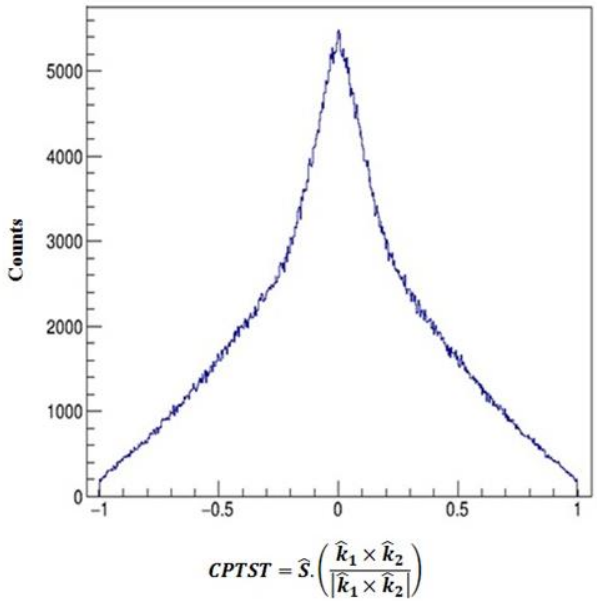
Aleksander Gajos

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

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

J-PET: P. Moskal, A. Gajos et al., Nature Communications (2021) in press

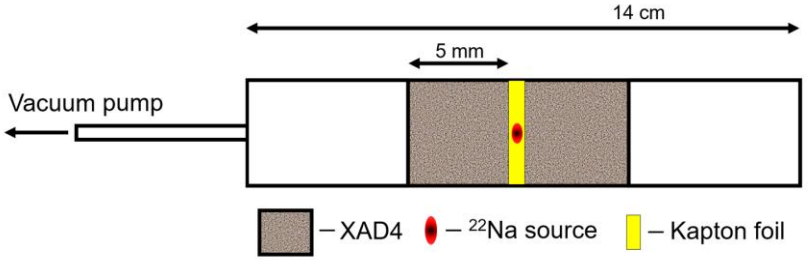


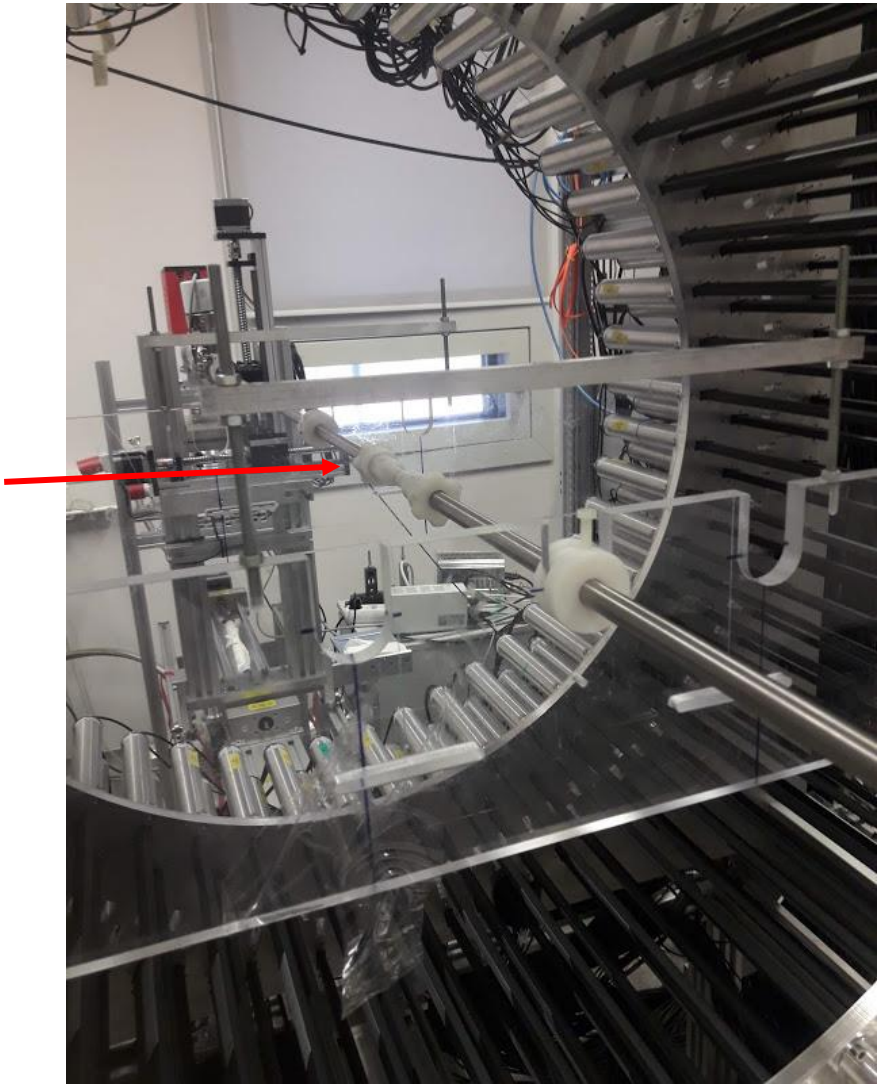


10^{-4}

J-PET detector overview

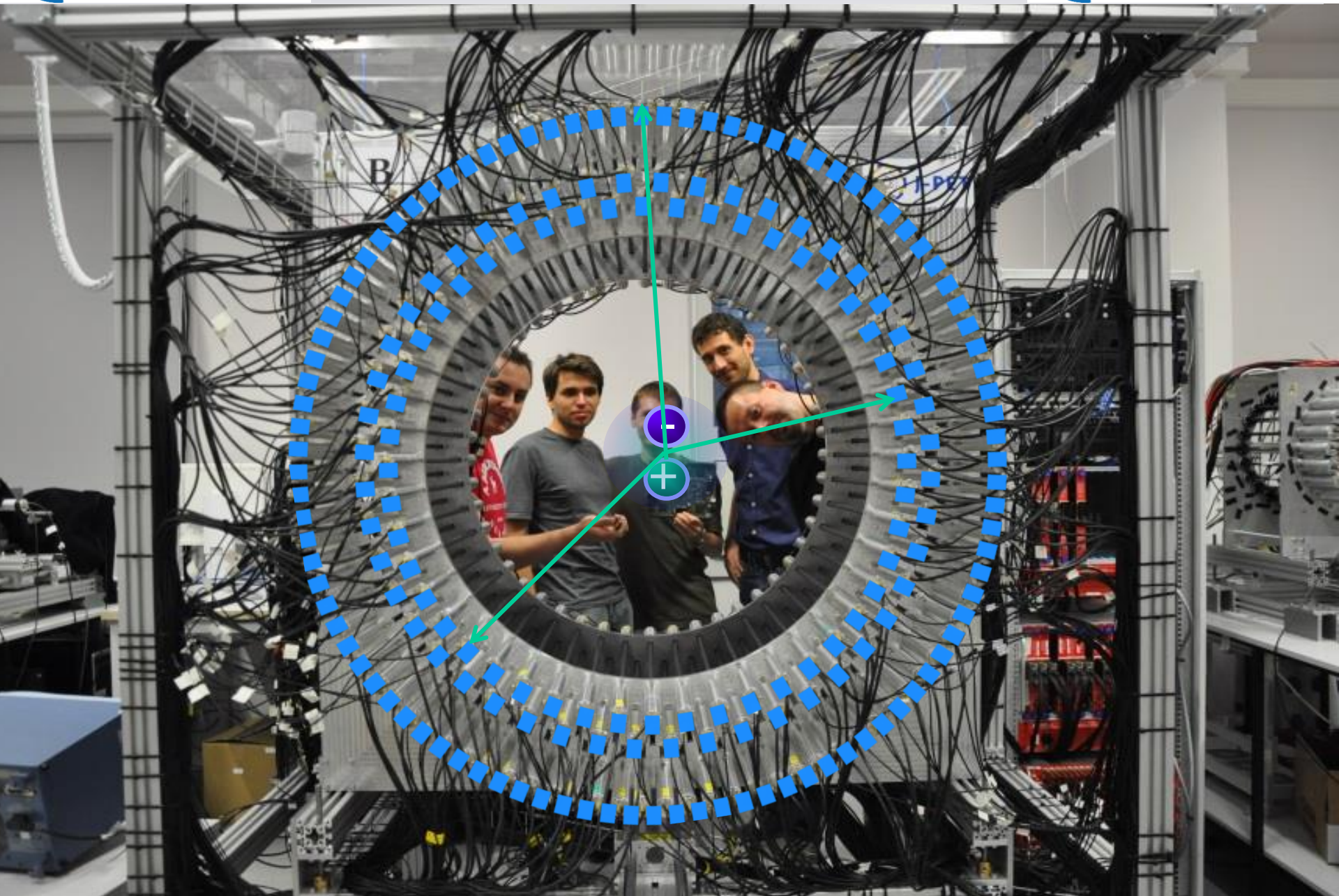
Small annihilation chamber used for production of positronium:



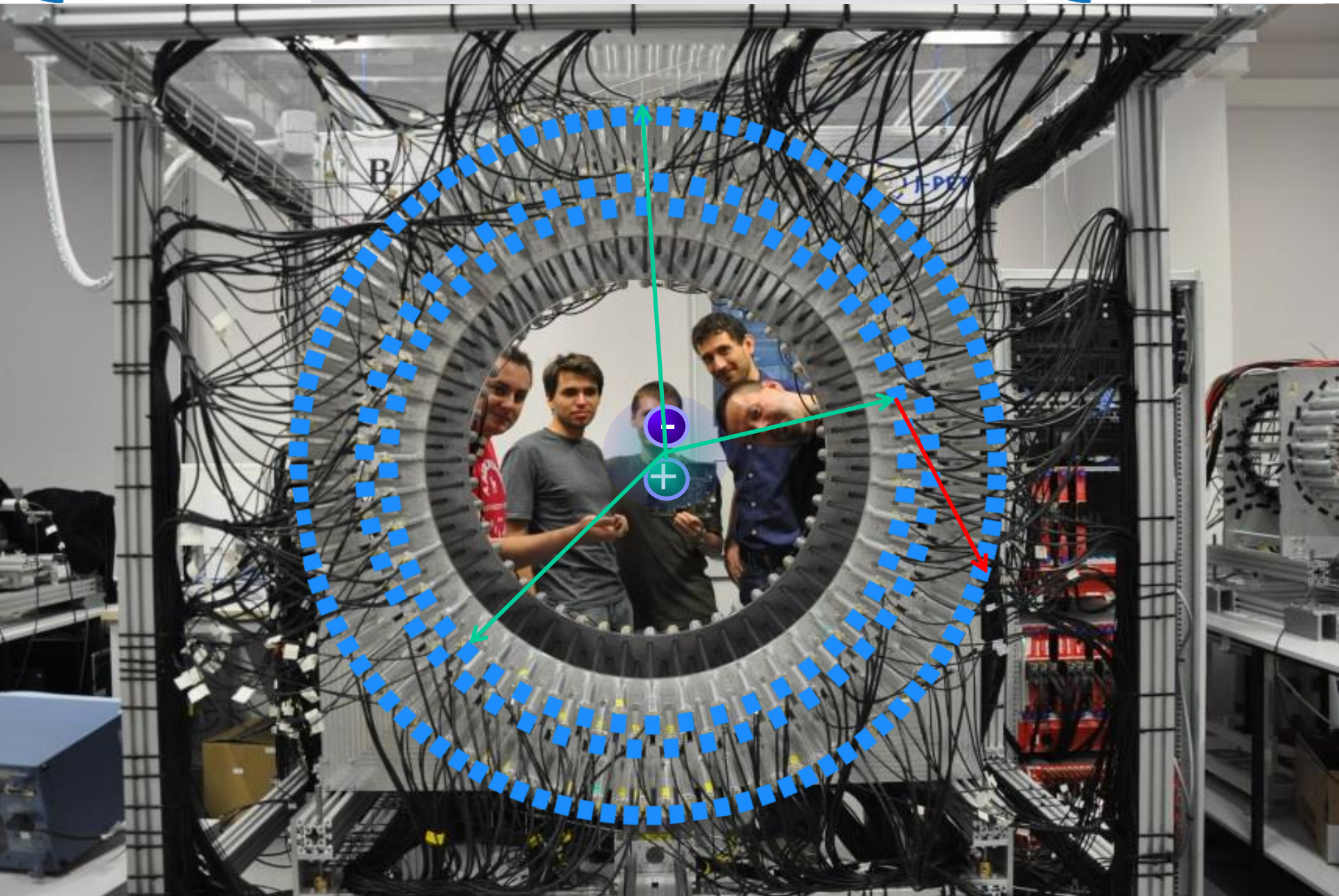



B
SIDE B
WARNING
KEEP HANDS
OUT OF
MACHINERY

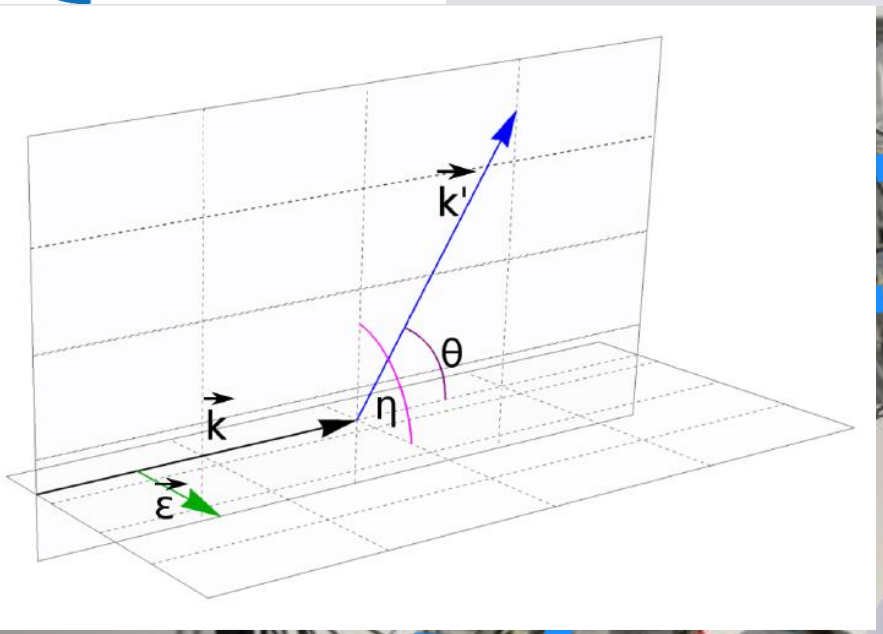
Jagiellonian PET

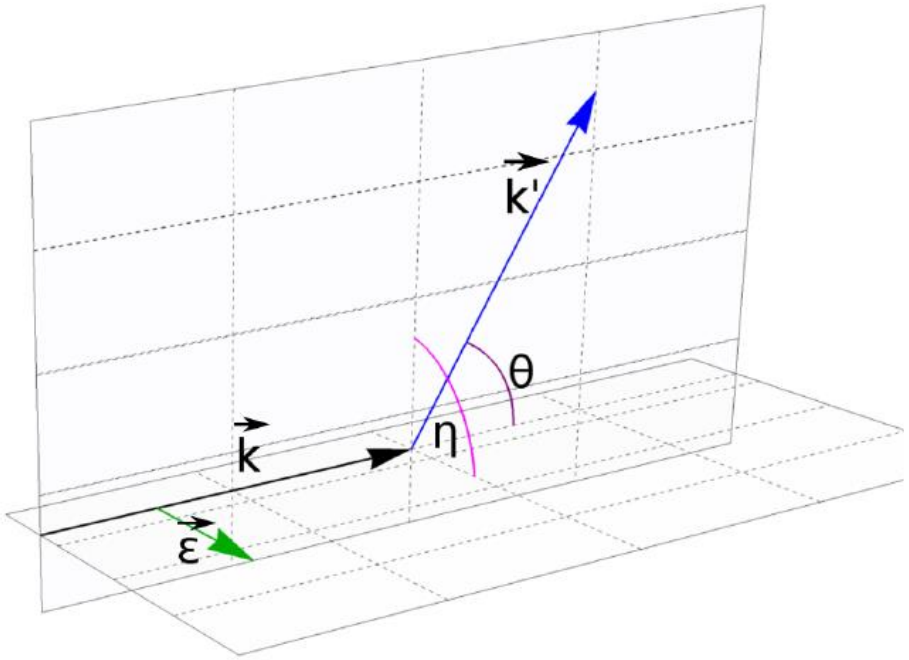


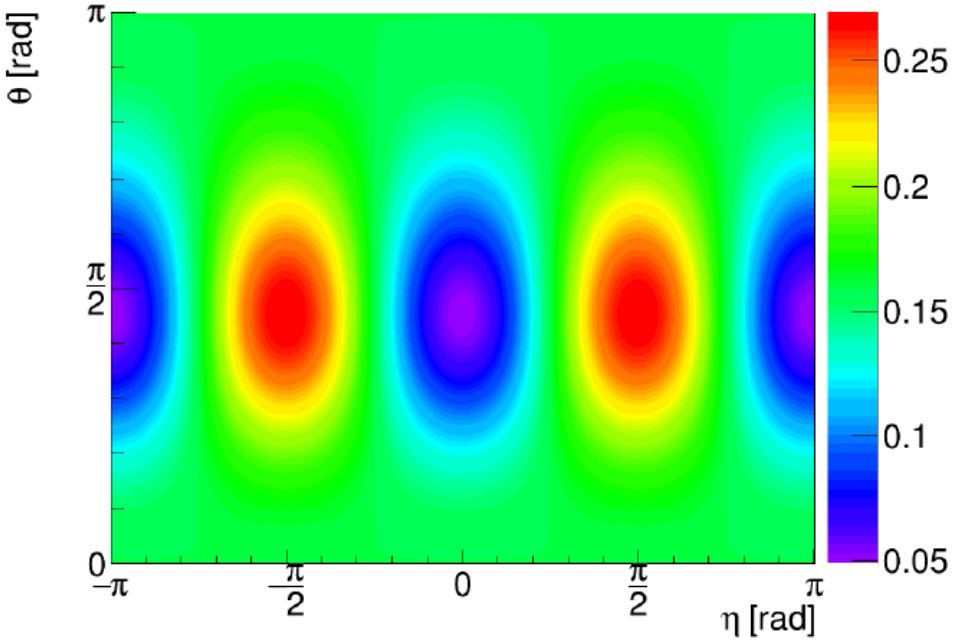
Jagiellonian PET



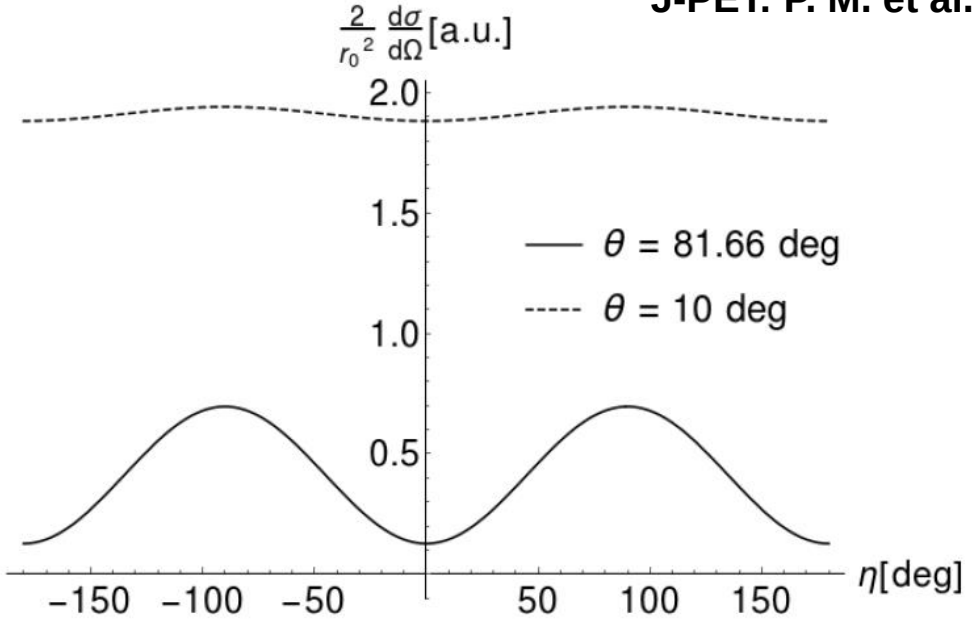
Jagiellonian PET



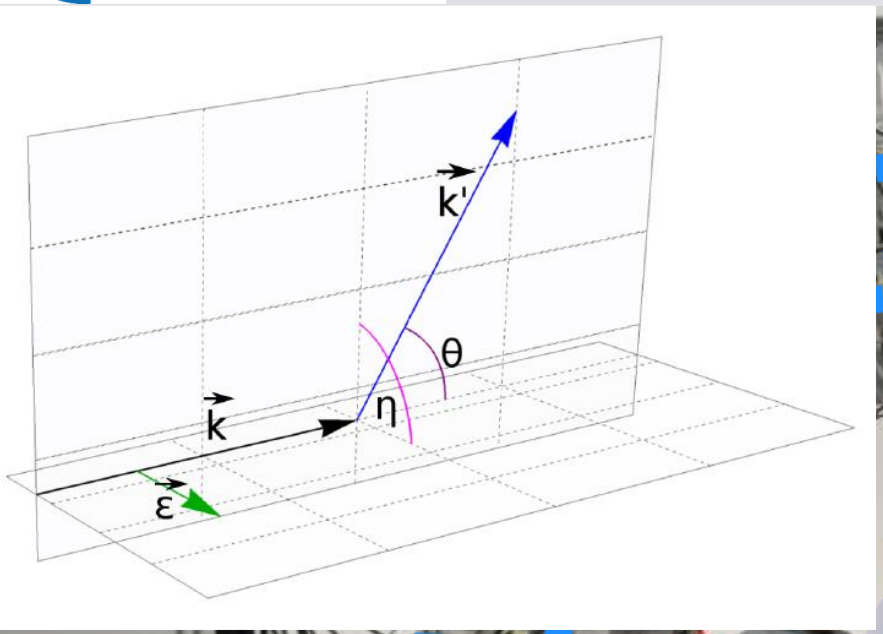




J-PET: P. M. et al., Eur. Phys. J. C 78 (2018) 970



Jagiellonian PET



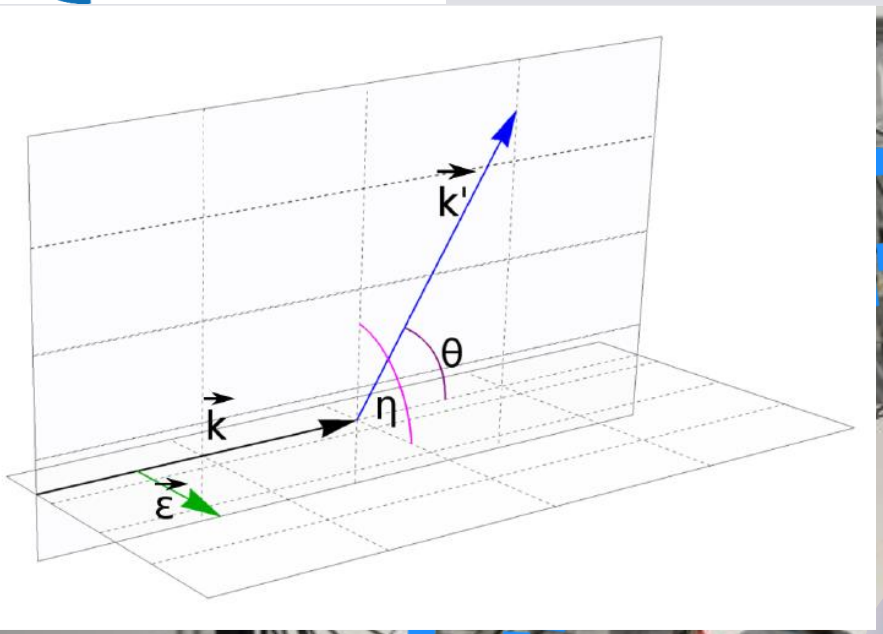
$$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$$

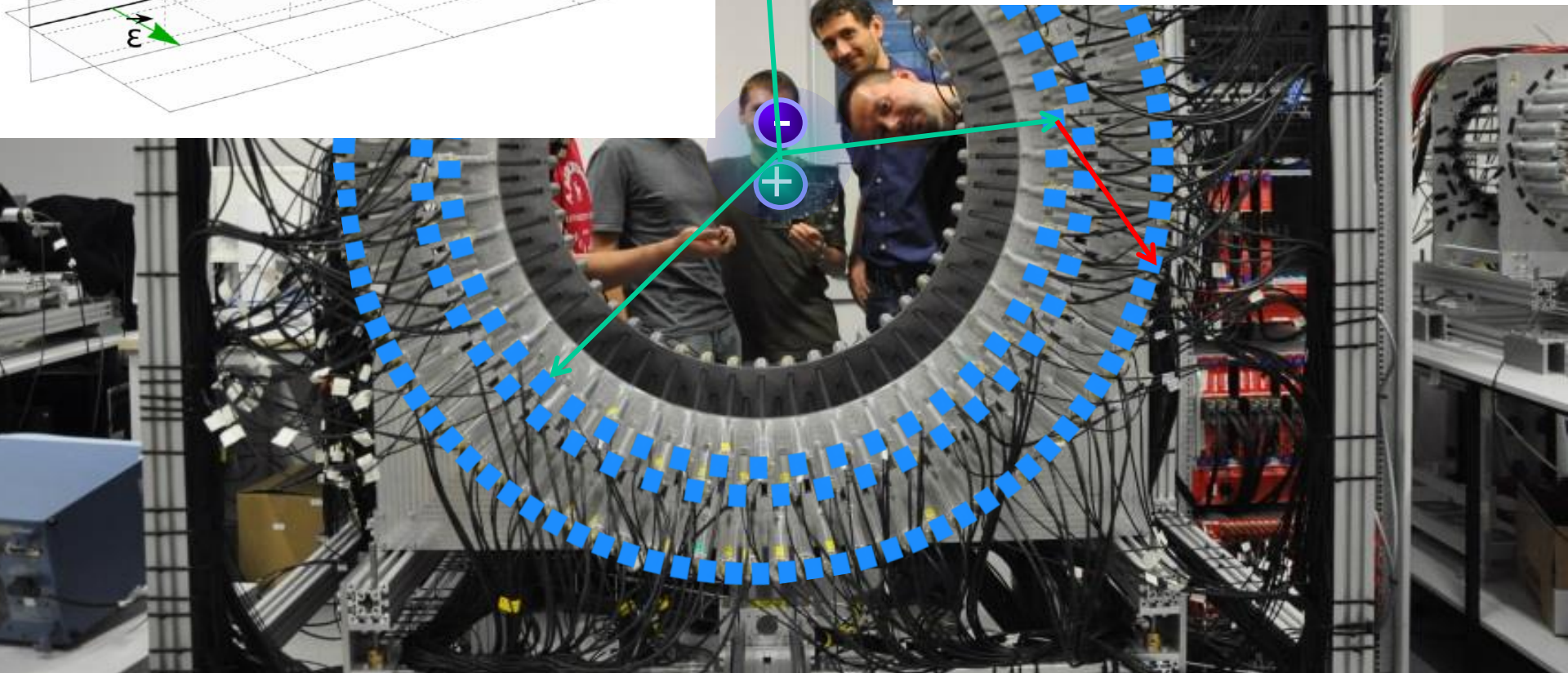
P. M. et al., Acta Phys. Pol. B 47 (2016) 509

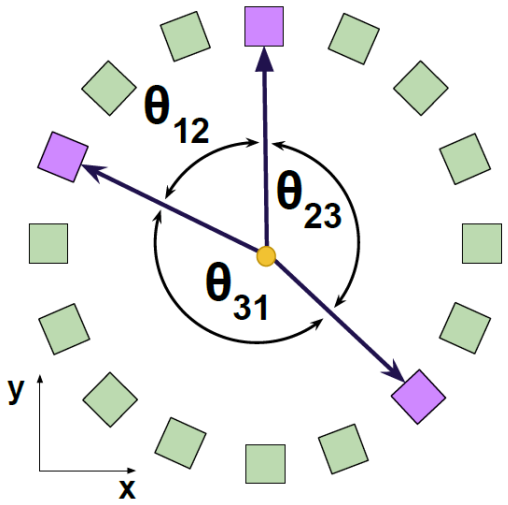
J-PET Jagiellonia

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

P. M. et al., Acta Phys. Pol. B 47 (2016) 509

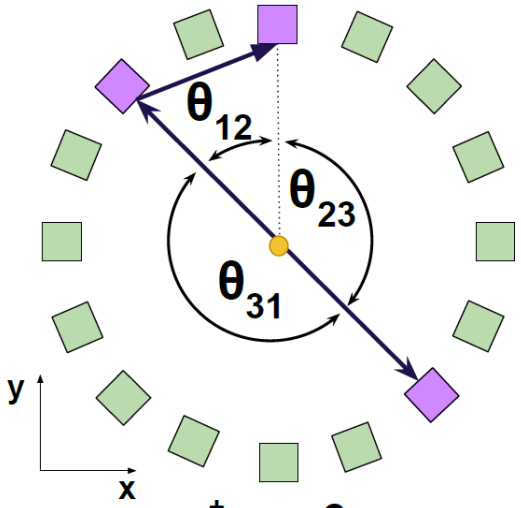






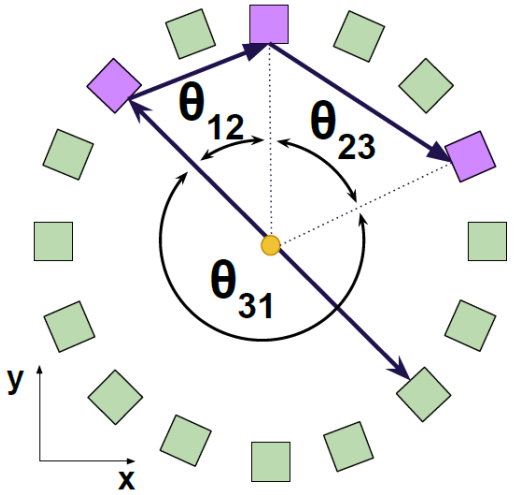
o-Ps → 3γ

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



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

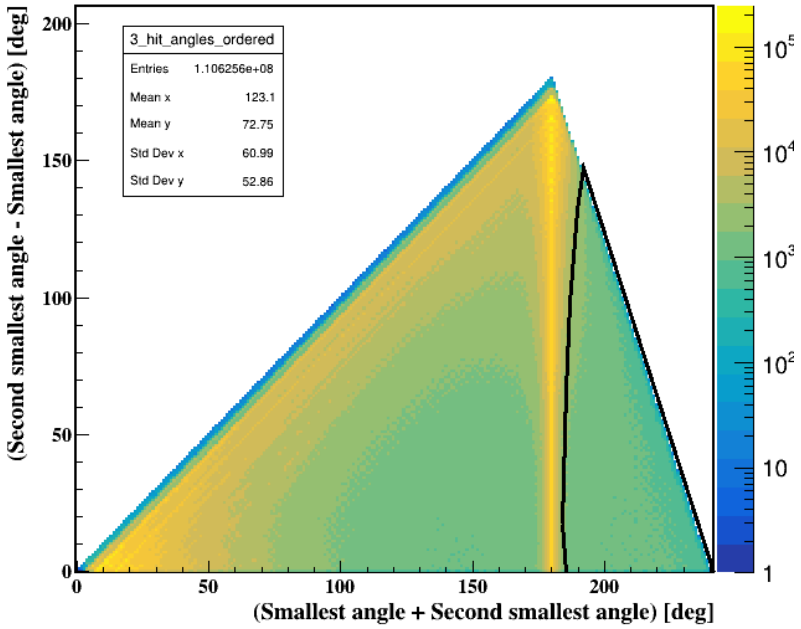
$\theta_{23} + \theta_{12} = 180$

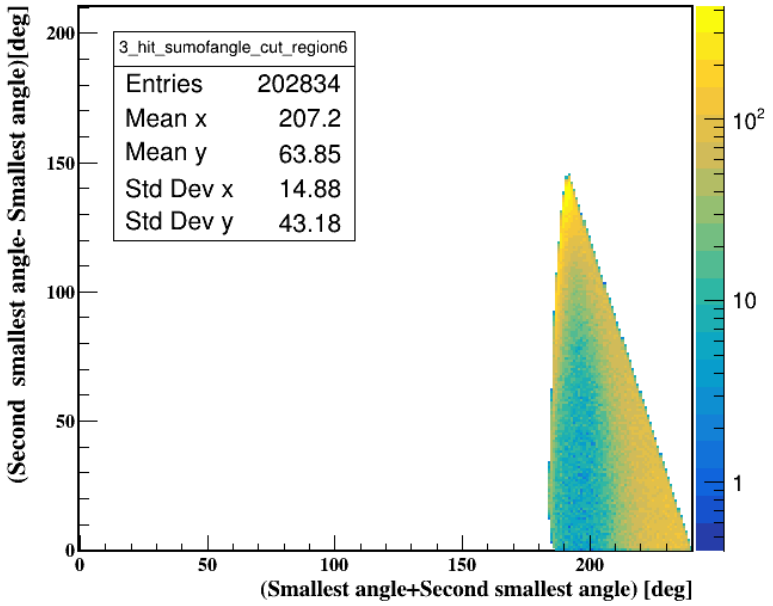


$e^+e^- \rightarrow 2\gamma$
double scattered

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

3 Hit angles

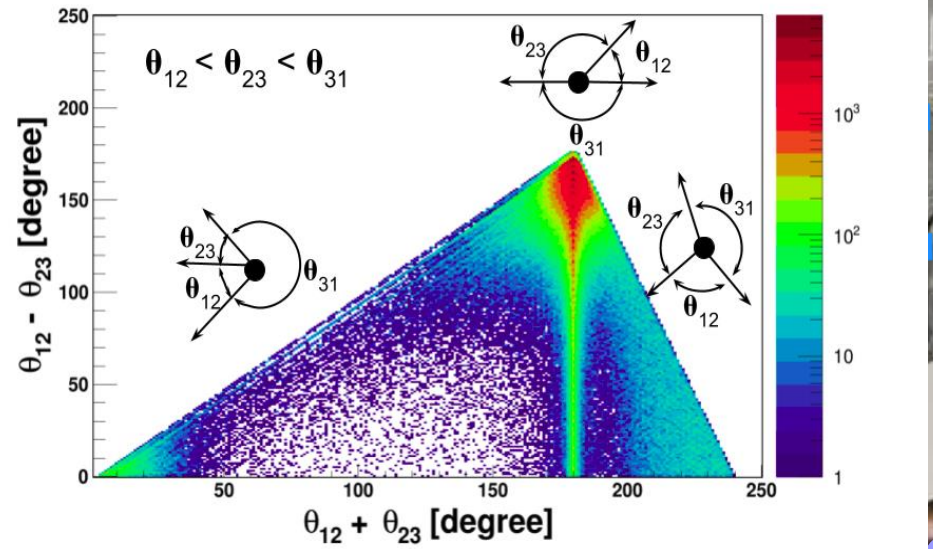




J-PET Jagiellonia

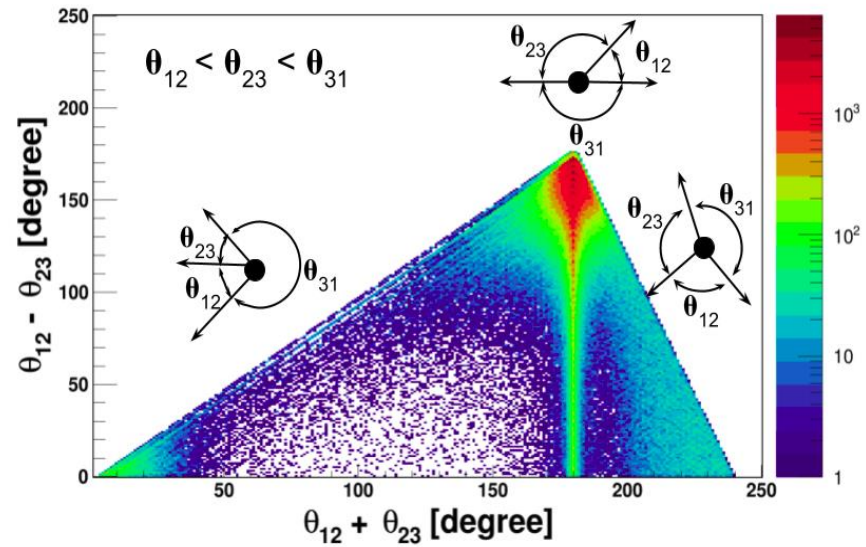
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	−	+	−	−
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	−	+	−
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	−	−	−	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	−	−	−	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	−	+	−
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$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

P. M. et al., Acta Phys. Pol. B 47 (2016) 509

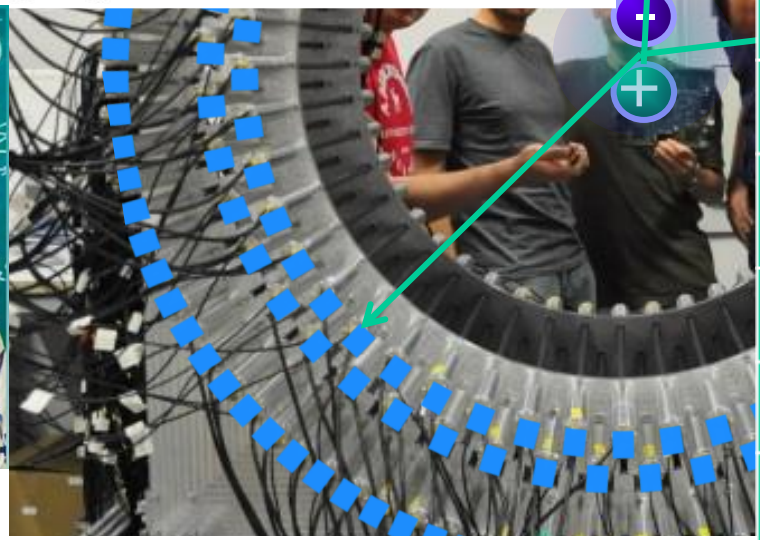


Juhi Raj

J-PET Jagiellonia



Juhi Raj



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

P. M. et al., Acta Phys. Pol. B 47 (2016) 509

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

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

Expectation Value = 0.0003 +/- 0.0003
PRELIMINARY

From tests of discrete symmetries to medical imaging with J-PET detector

- Jagiellonian-PET (J-PET)
- Positronium imaging
- Discrete symmetries
- Quantum entanglement

PANIC 2021

22nd Particle and Nuclei International Conference

08.09.2021

P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

Jagiellonian PET

THANK YOU
FOR YOUR ATTENTION