# Test of discrete symmetries in positronium decays using J-PET tomograph

**Bialasówka, AGH, Kraków, 08.10.2021**

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

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**J-PET: Nature Communications 12 (2021) 5658**

***Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography***

***$10^{-4}$***

**J-PET: Science Advances 7 (2021) eabh4394**

***Positronium imaging with the novel multi-photon PET scanner***

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

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Jagiellonian PET
Frascati 2019


Kraków 2019


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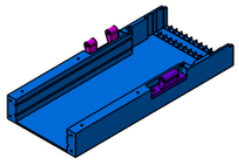
# Development of cost-effective total-body PET



Aim:

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

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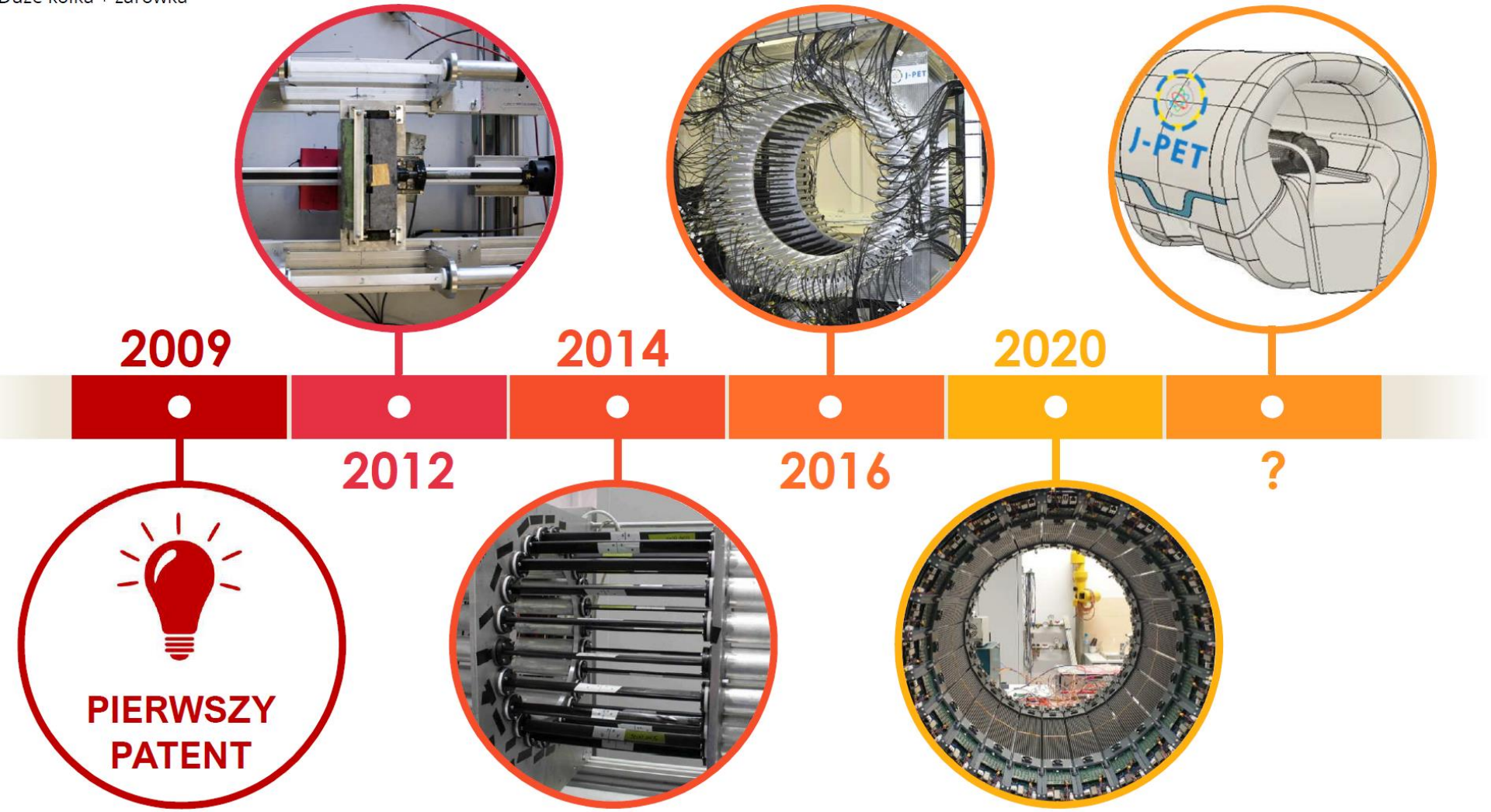
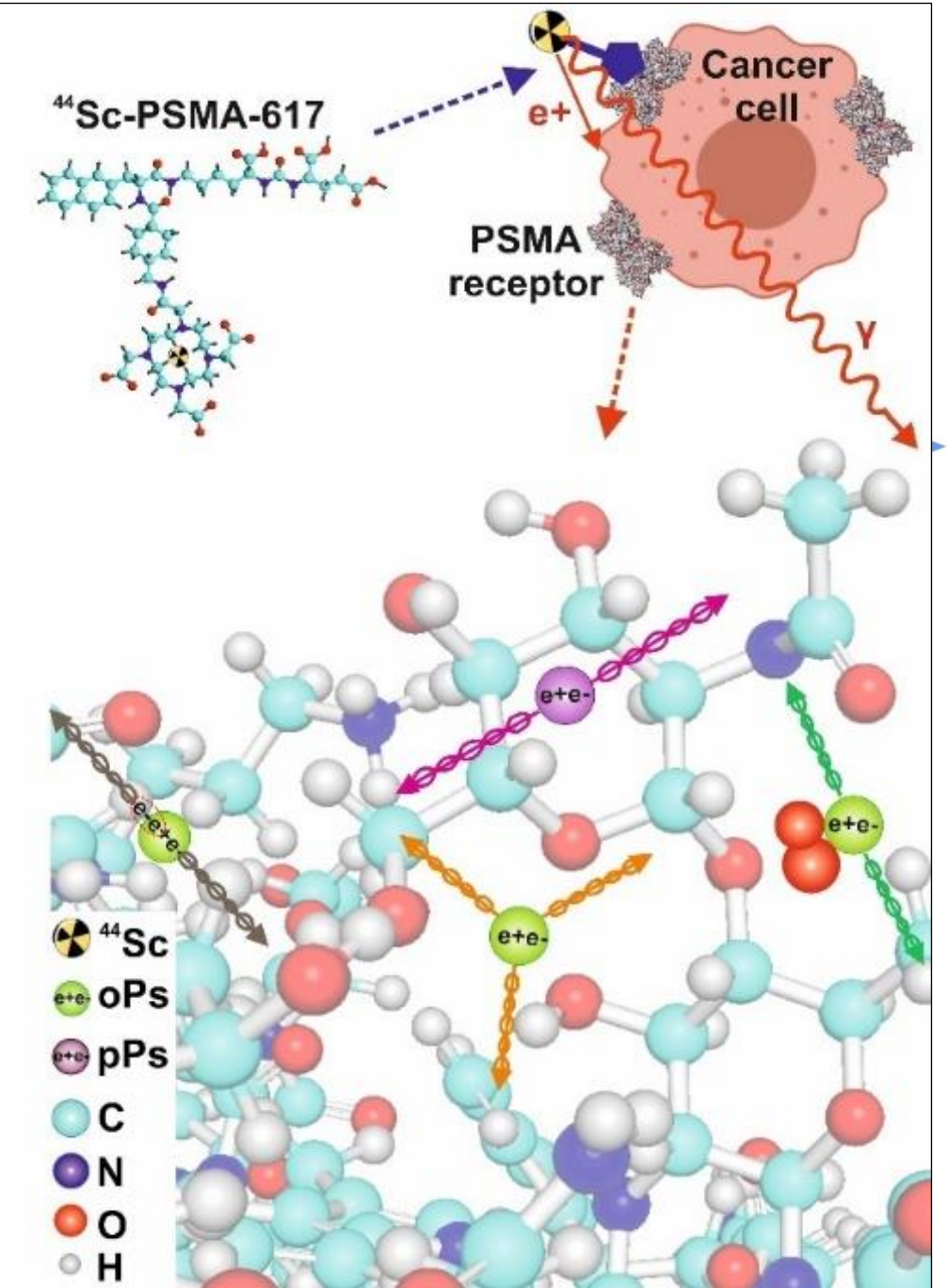
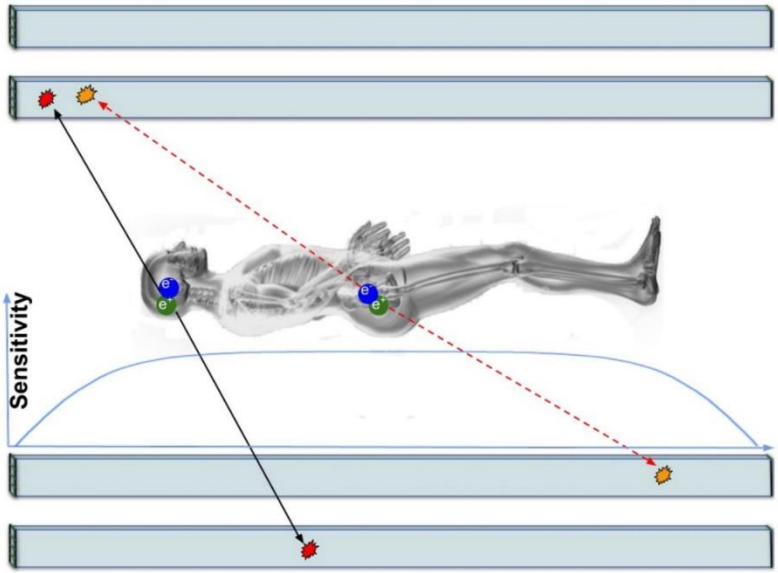


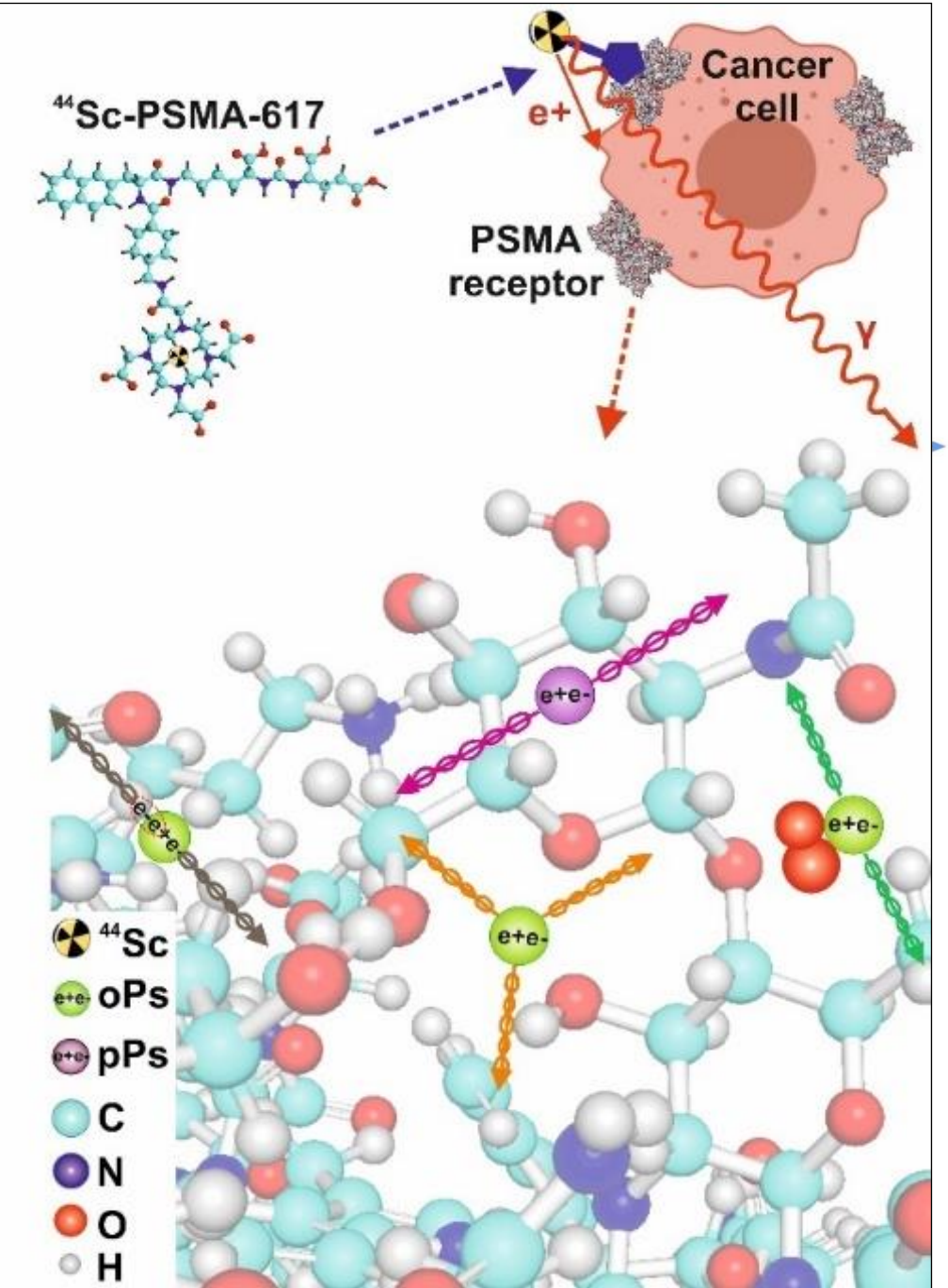

Financed by:
Ministry of Science and Higher Education
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes)

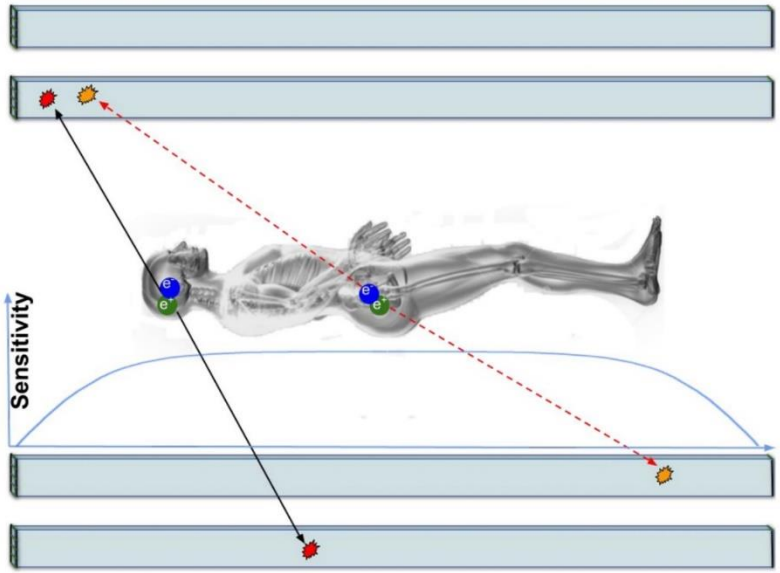
# P. Moskal, E. Ł. Stępień, PET Clinics 15 (2020) 439



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%

# Test of discrete symmetries in positronium decays using J-PET tomograph

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- Positronium imaging
- Discrete symmetries
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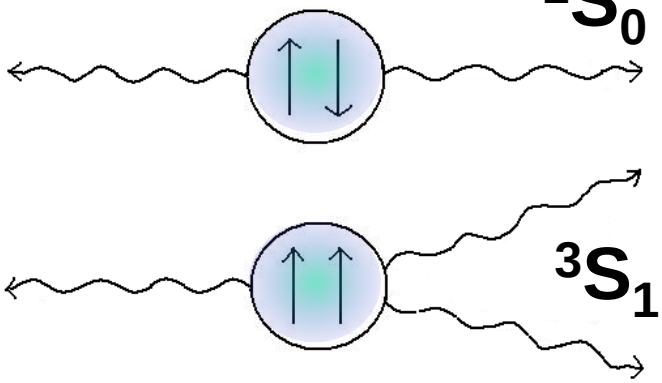


$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

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

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

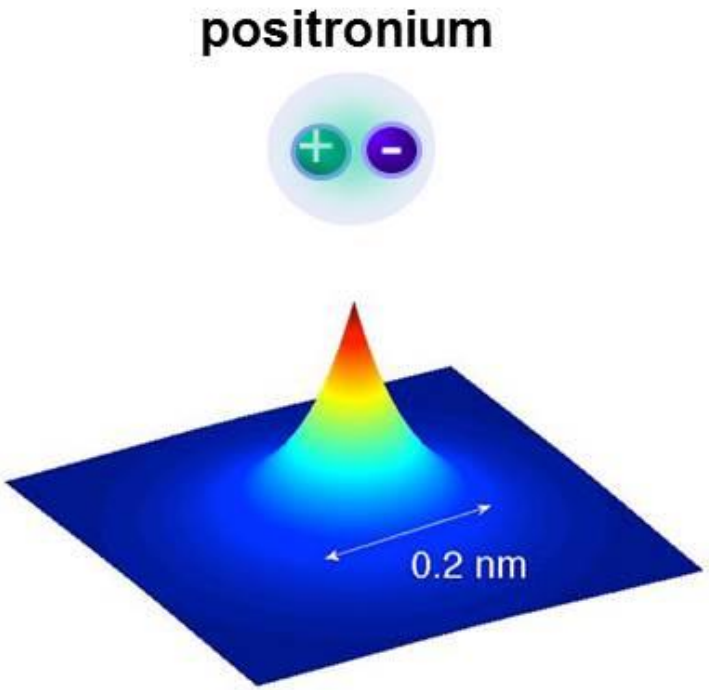
S = 0 $\downarrow\uparrow - \uparrow\downarrow$

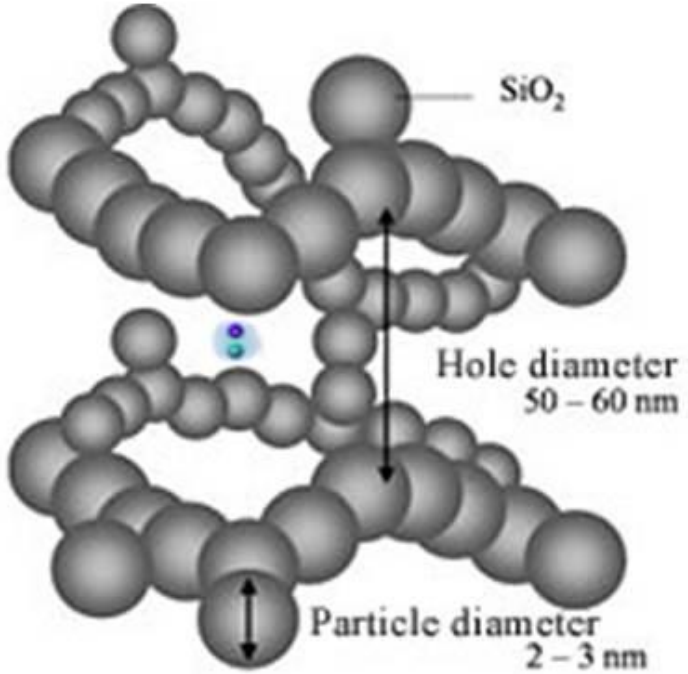
$\uparrow\uparrow$

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

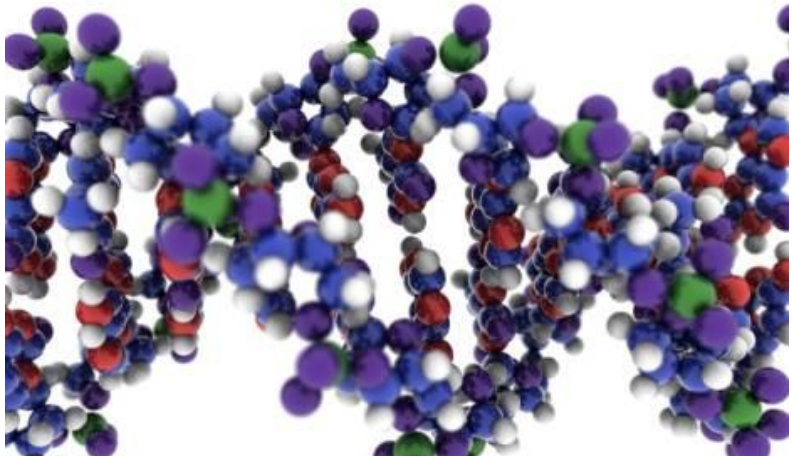
$\downarrow\downarrow$

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



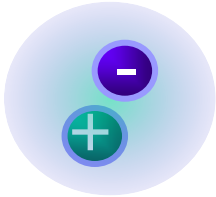




Y.H. Wang et al., Phys. Rev. A 89 (2014) 043624,
http://www.chem-eng.kyushu-u.ac.jp/e/research.html



# 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)**

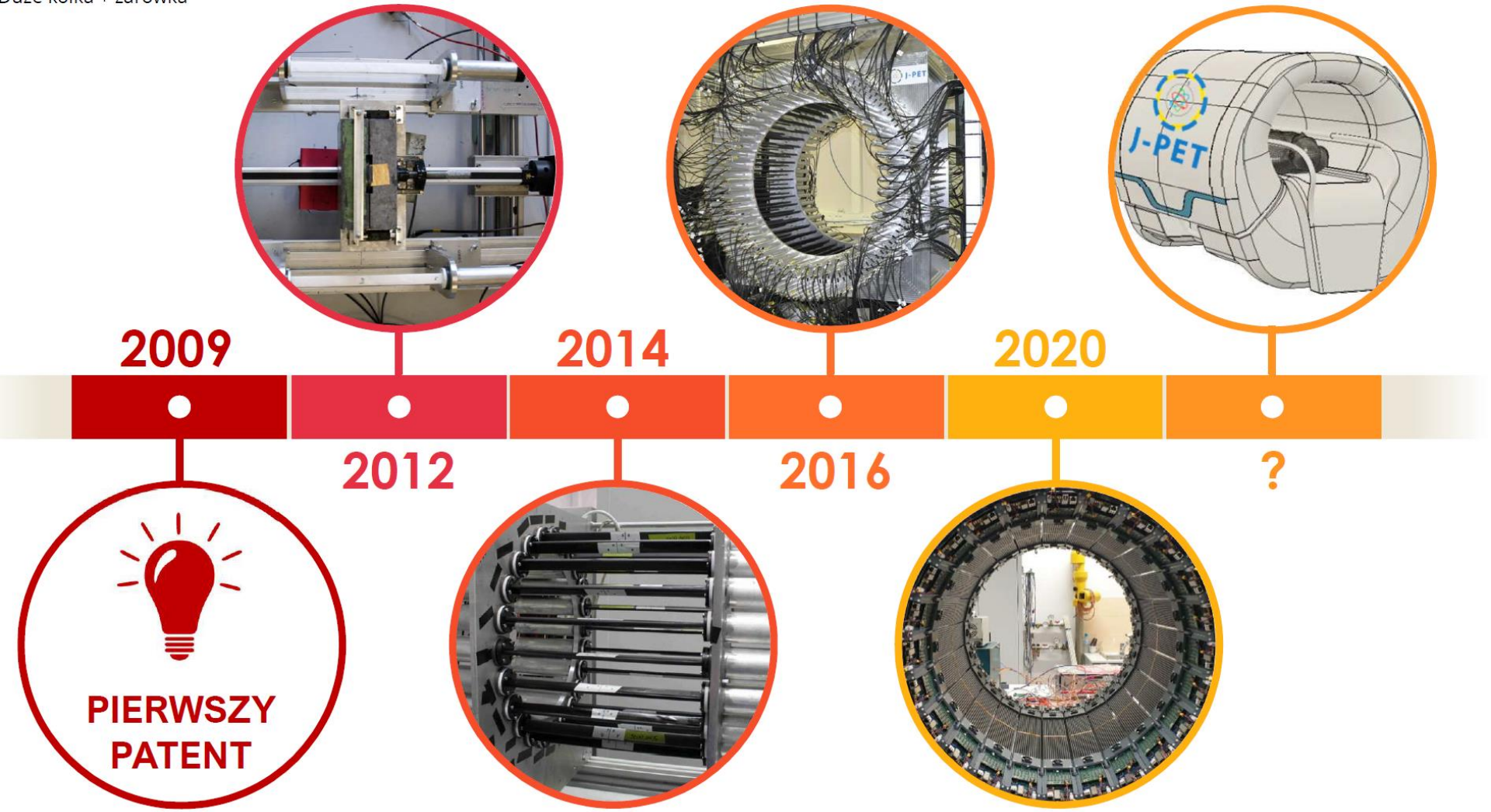
**No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)**
**Light by light contributions to various correlations are small**
**B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988).**
**W. Bernreuther et al., Z. Phys. C 41, 143 (1988).**

## 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

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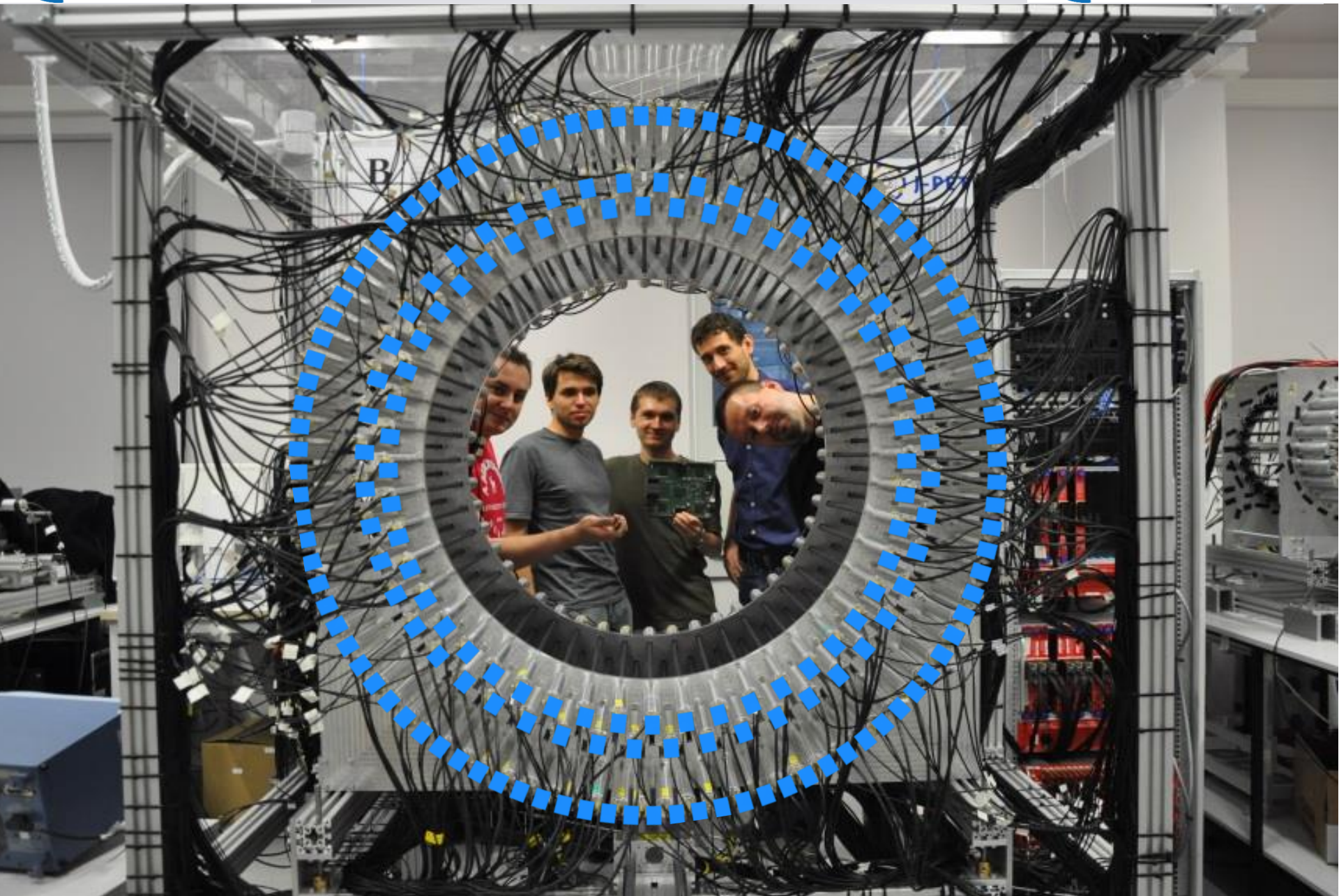
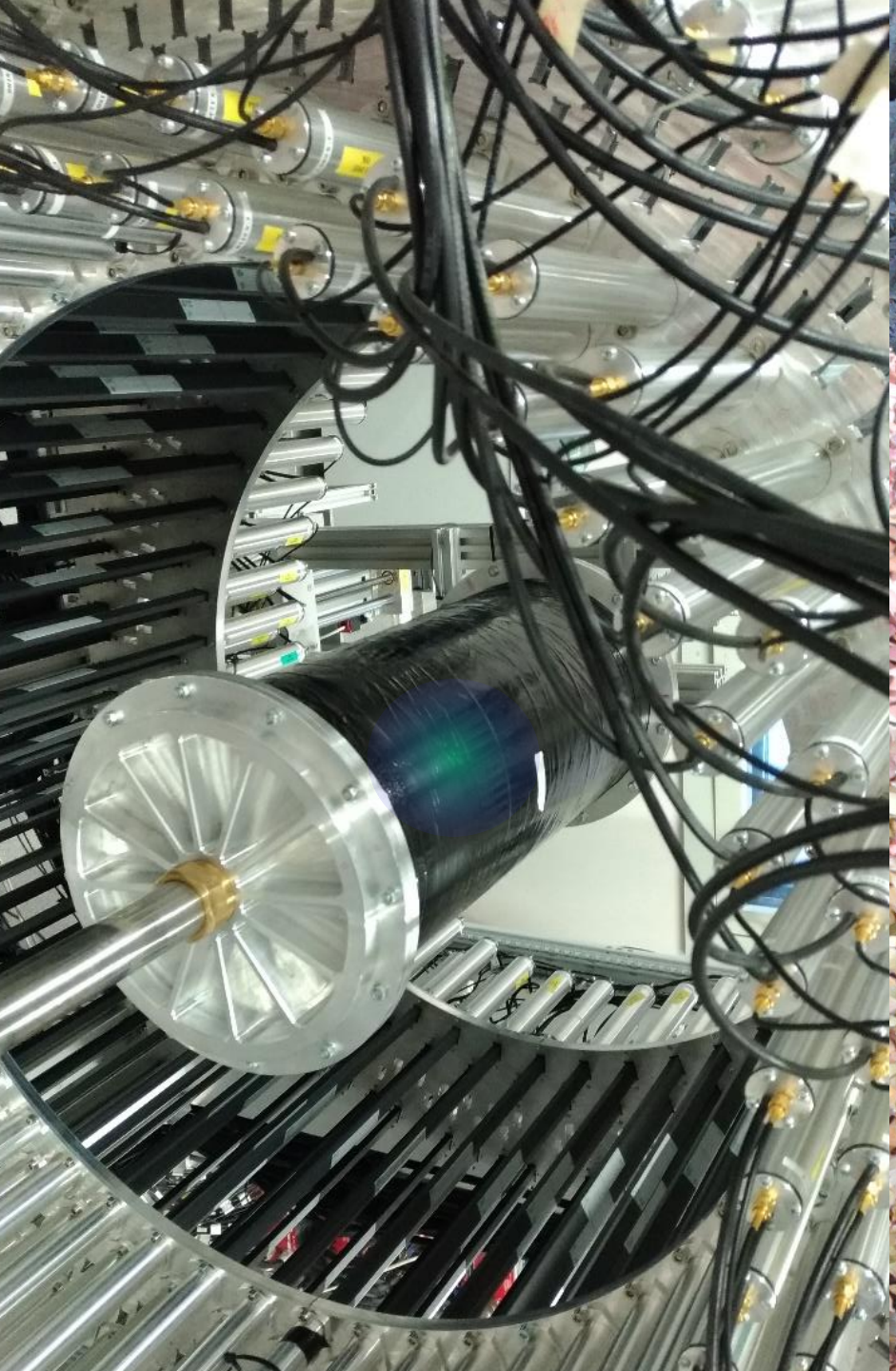
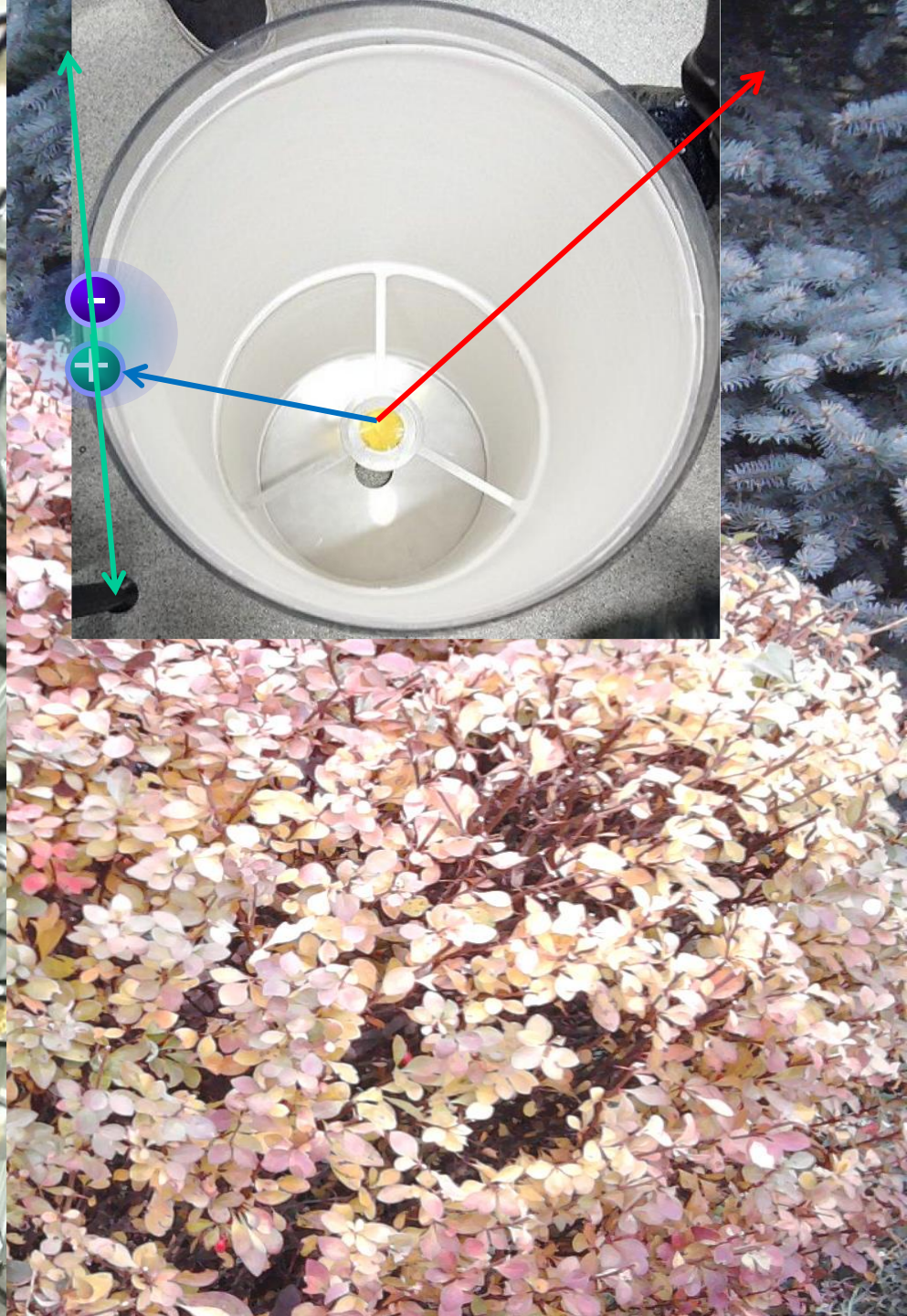
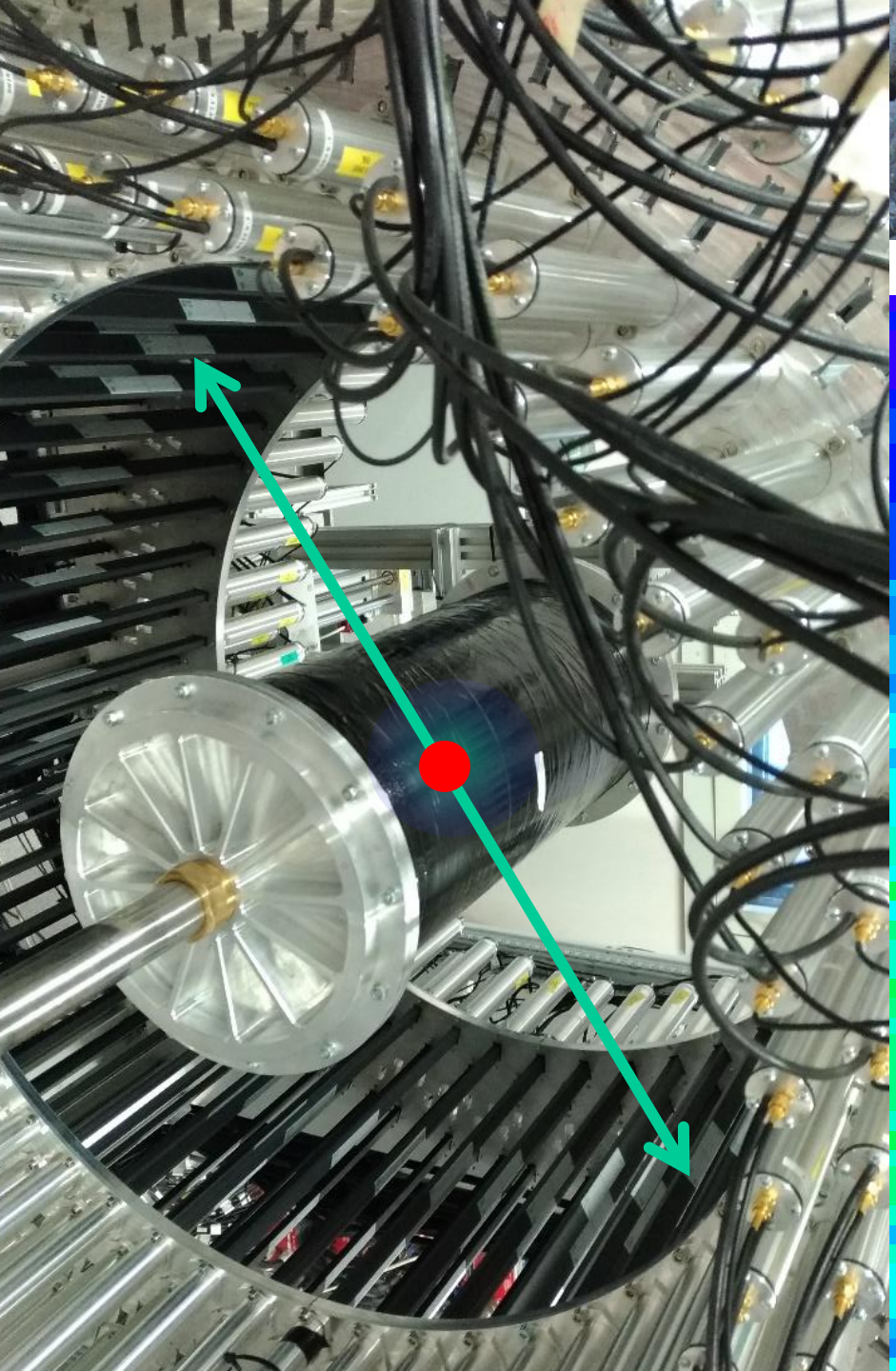
National Science Center (OPUSes)

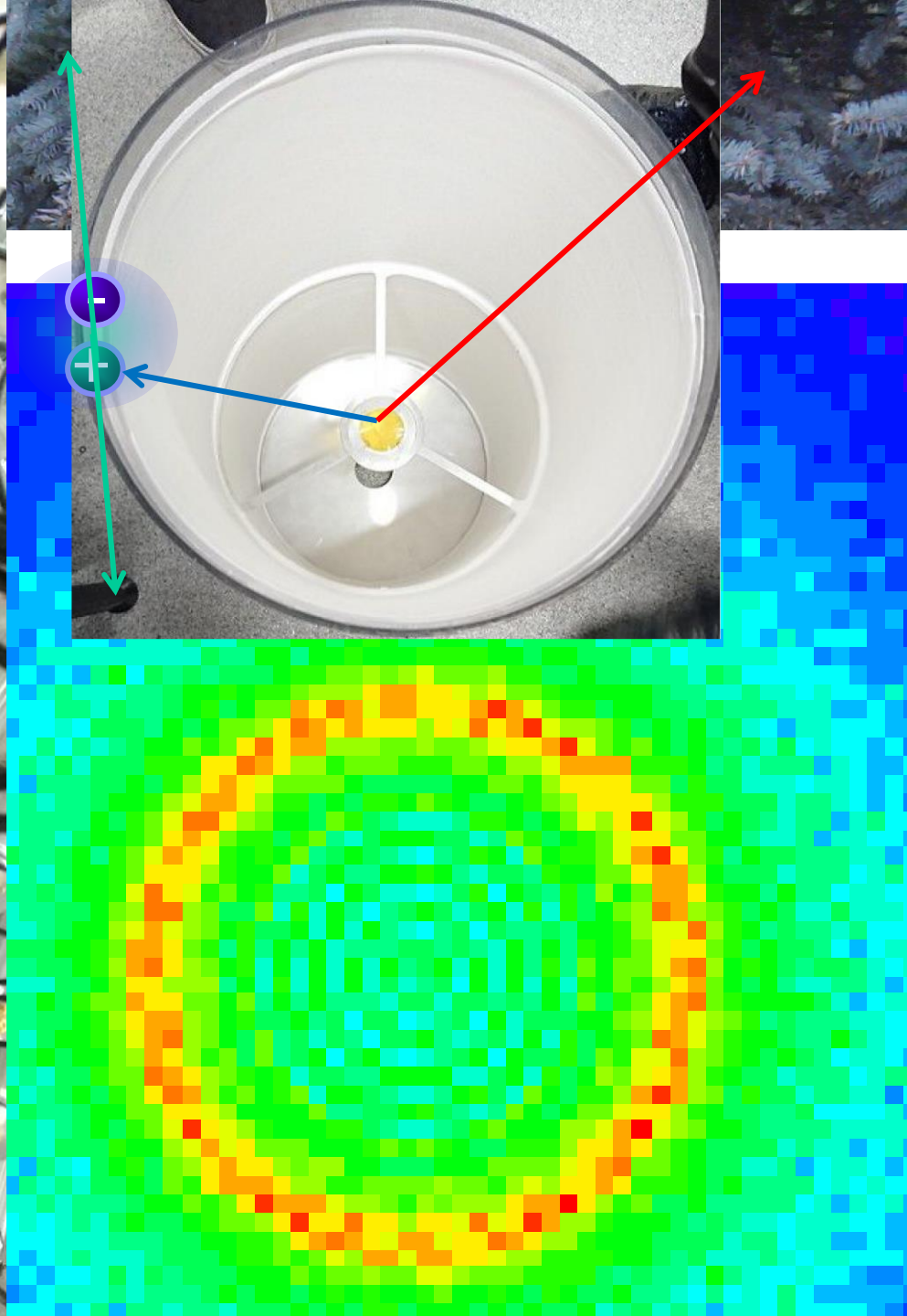
# Jagiellonian PET

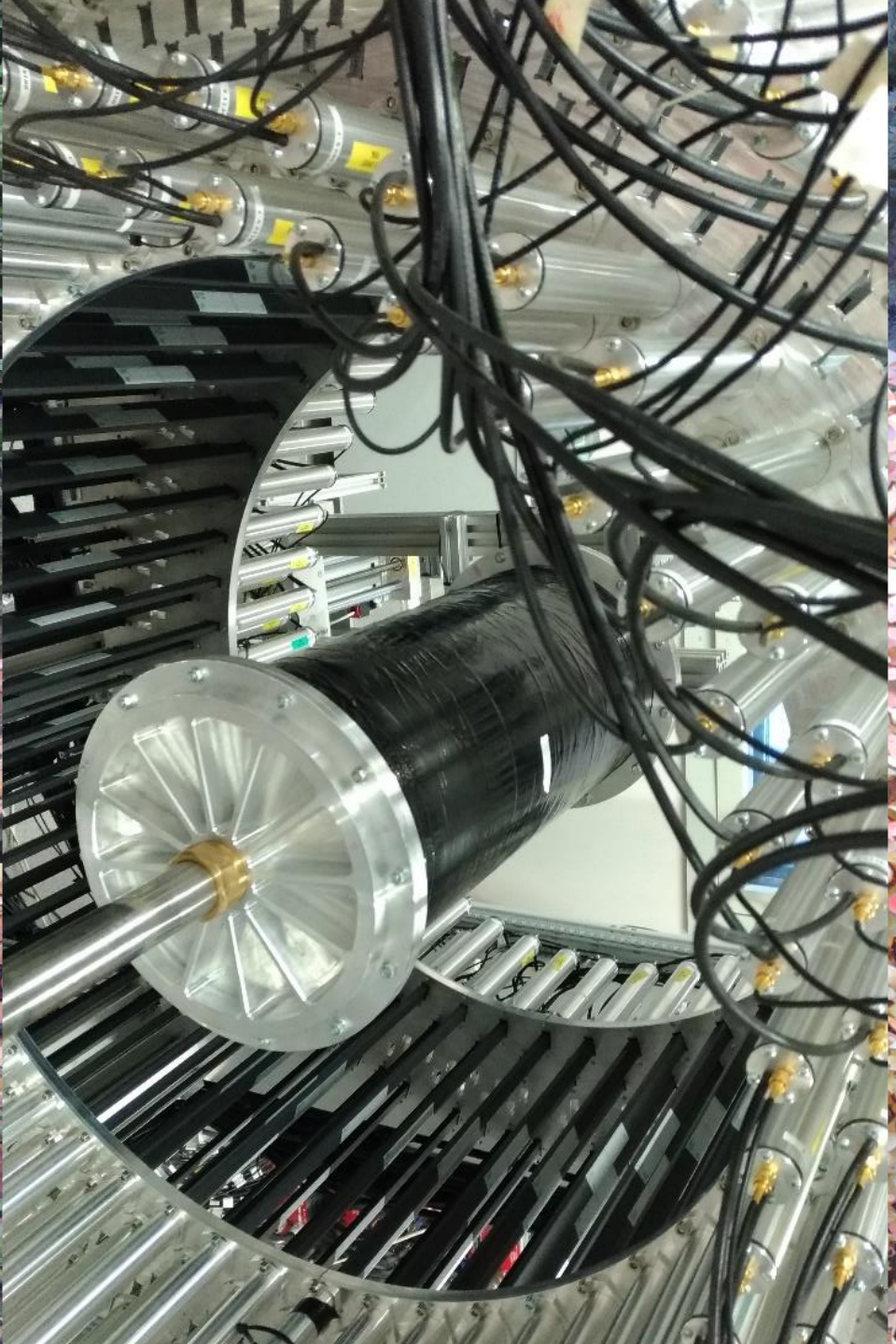


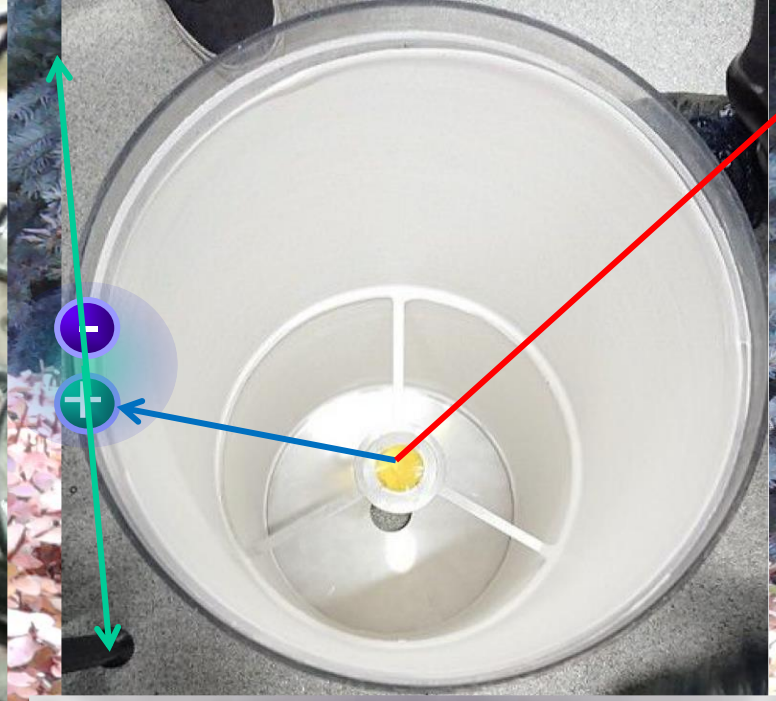


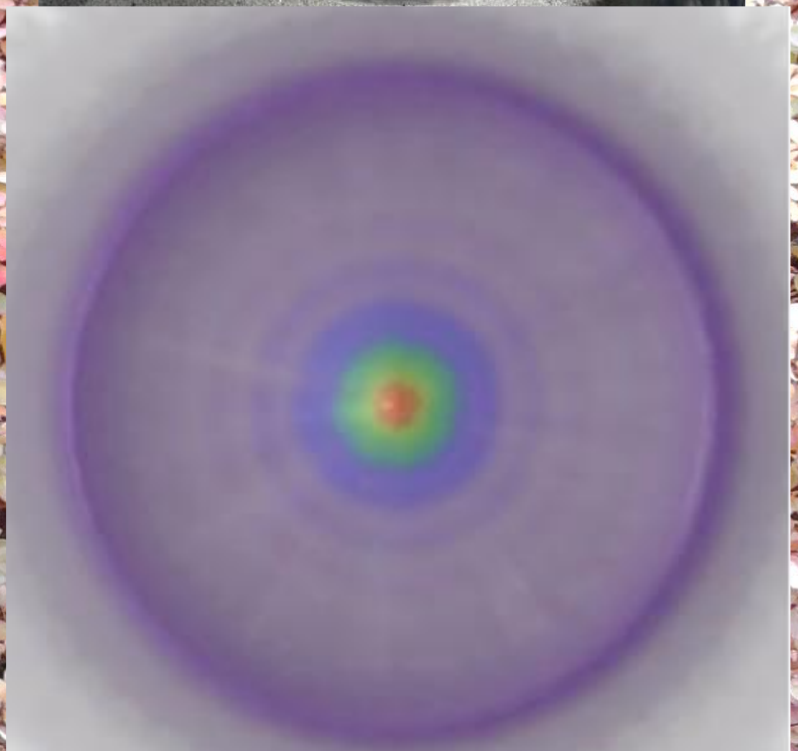






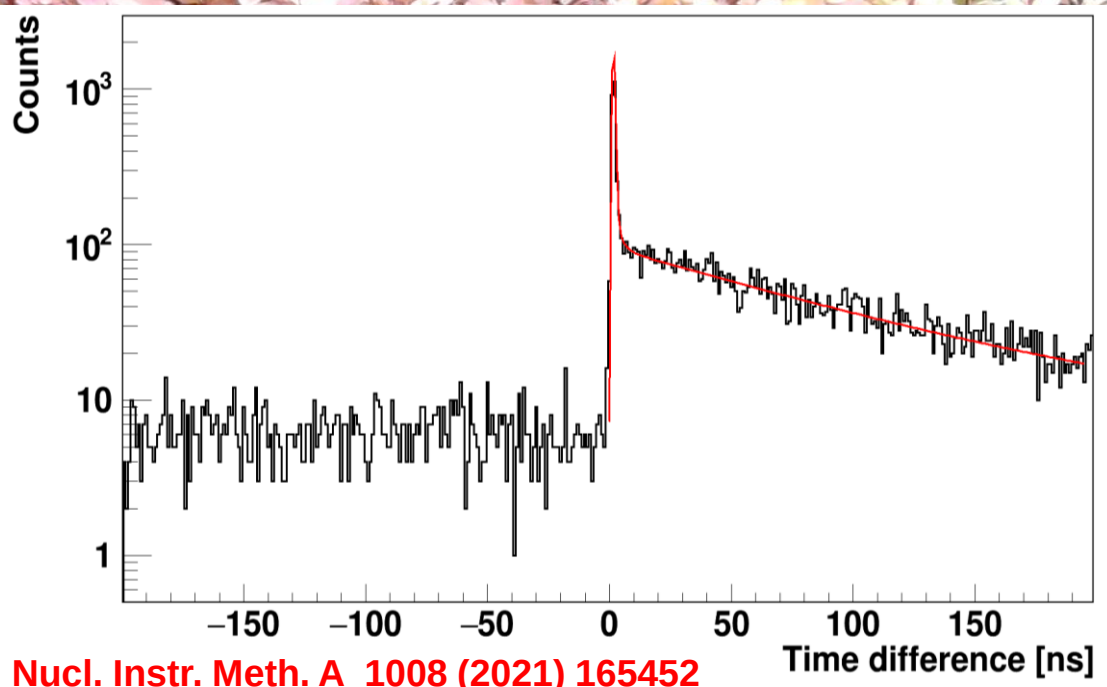




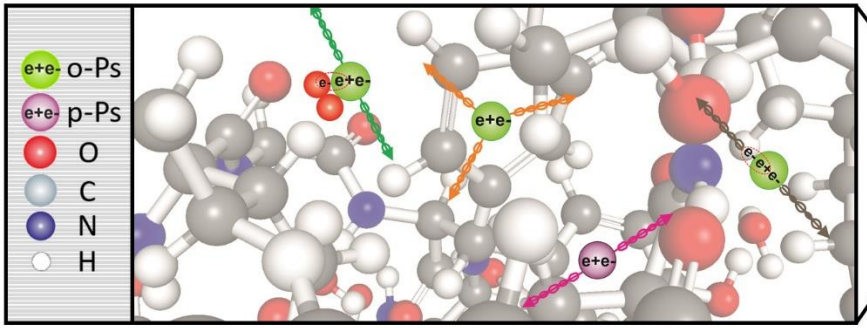


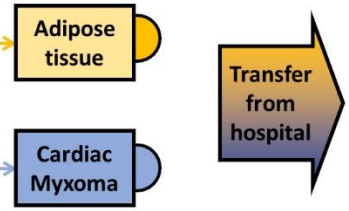
$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$

$^{22}Ne + \gamma$



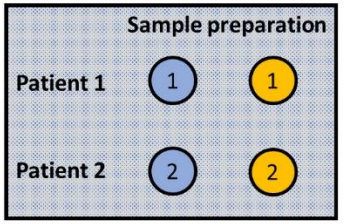

J-PET: K. Dulski et al., Nucl. Instr. Meth. A 1008 (2021) 165452

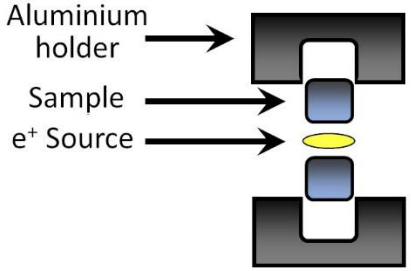




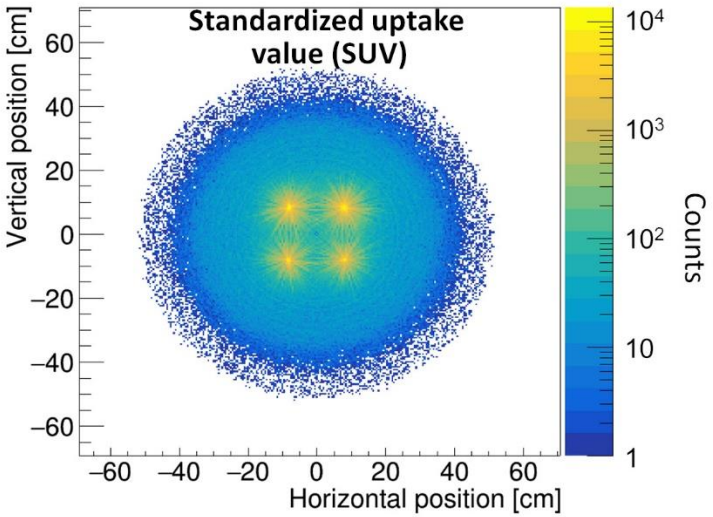


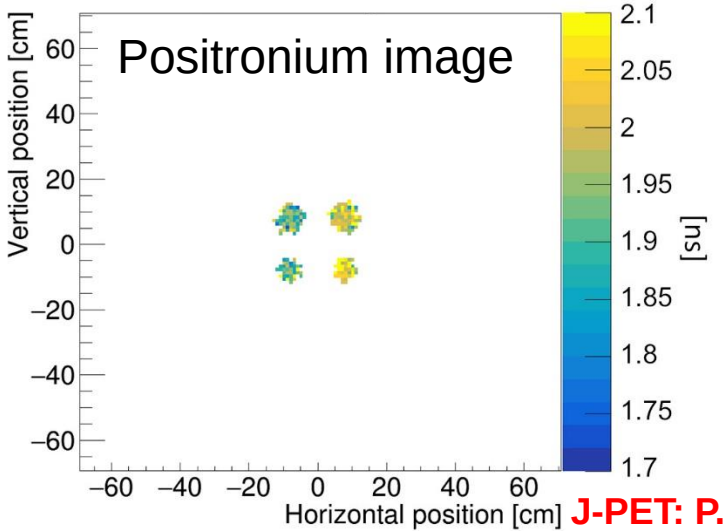


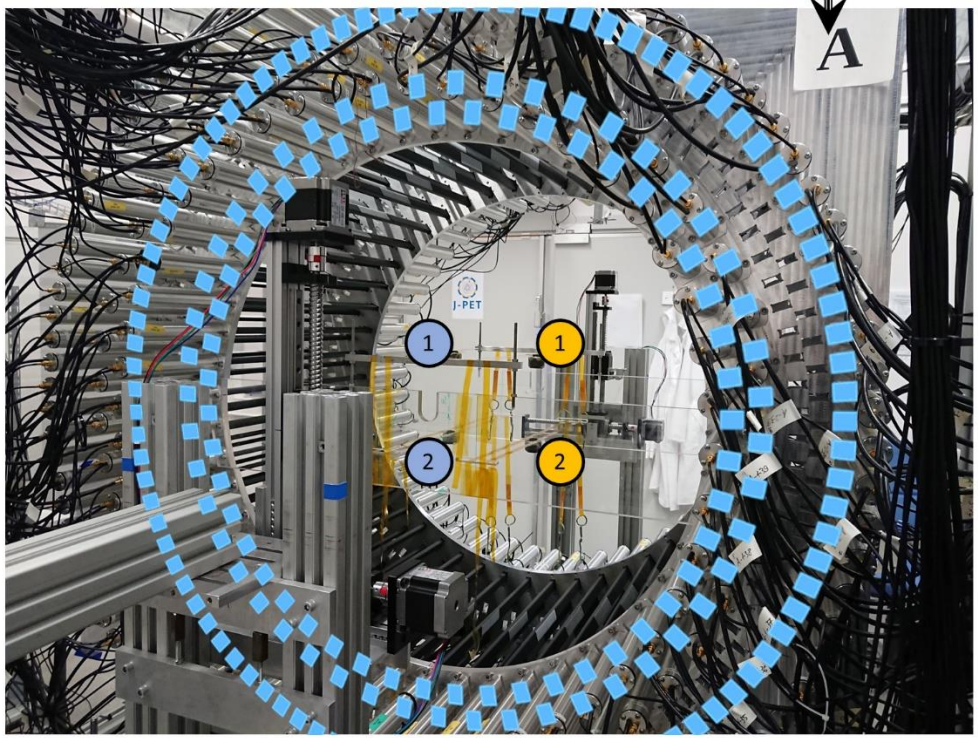




Placing samples in the chambers

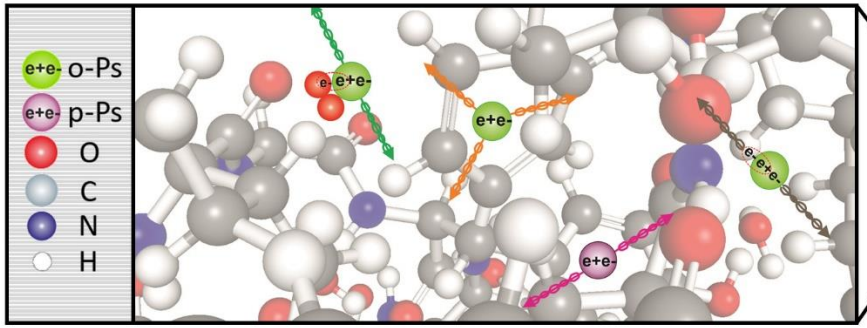
Inserting setup to the detector

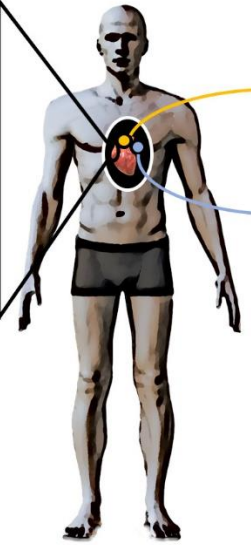


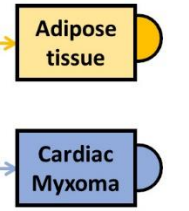



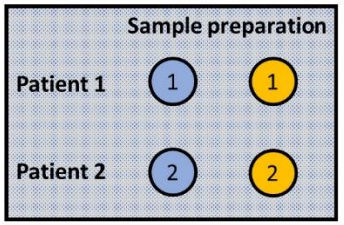

J-PET: P. Moskal, K. Dulski et al., Science Advances 7 (2021) eabh4394

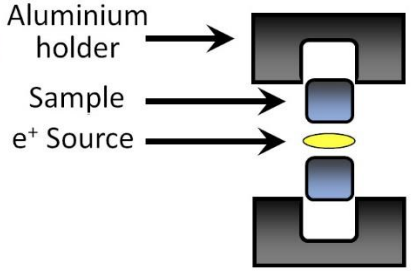




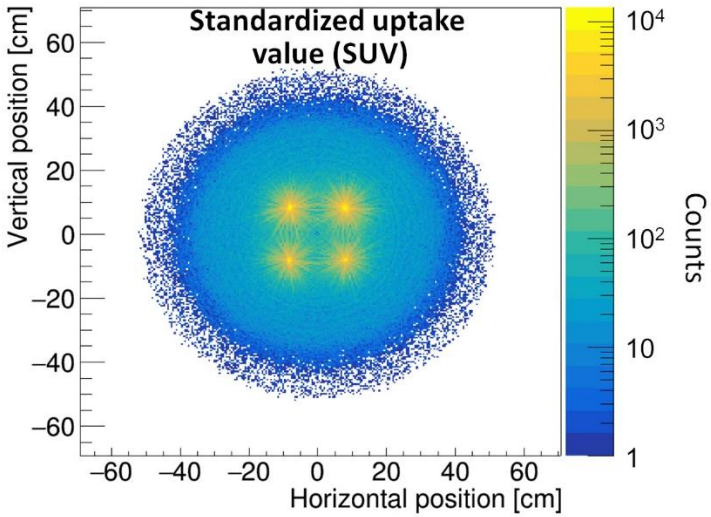


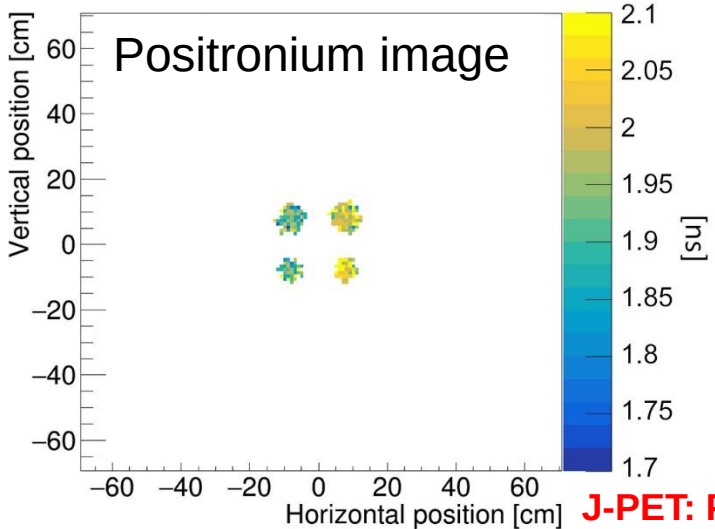


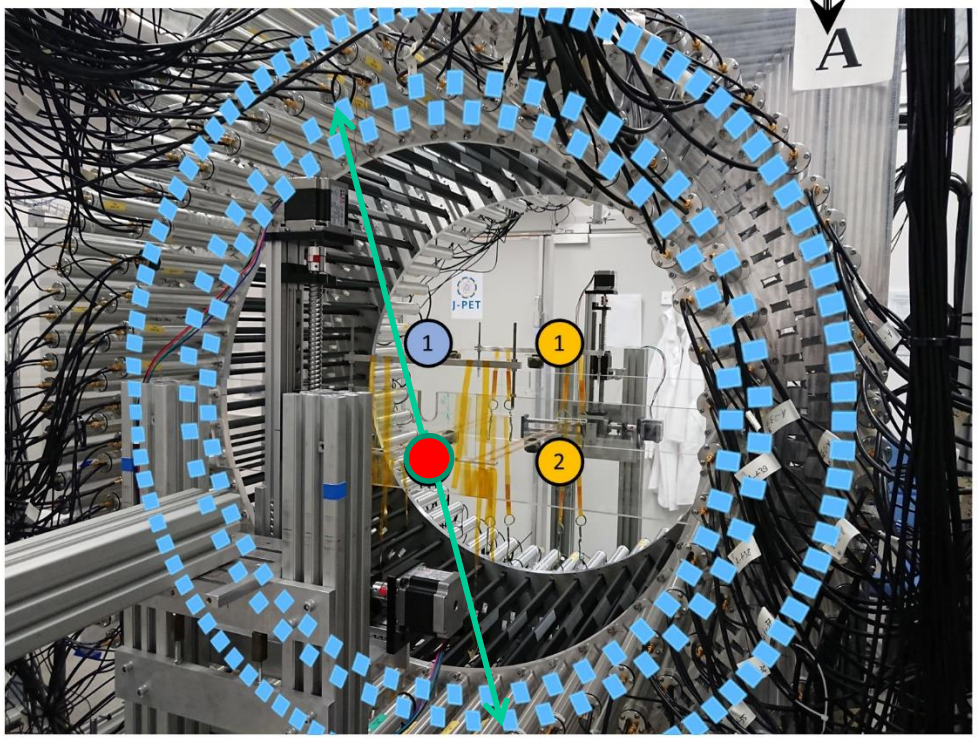




Placing samples in the chambers

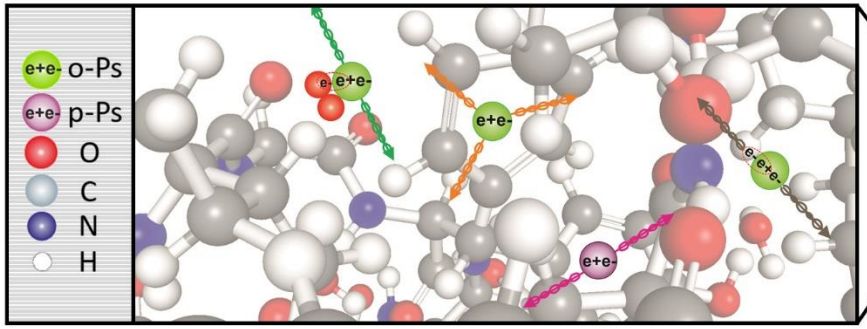
Inserting setup to the detector

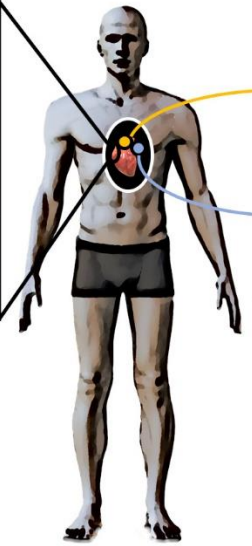


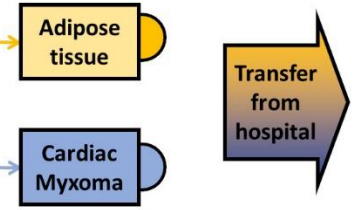




J-PET: P. Moskal, K. Dulski et al., Science Advances 7 (2021) eabh4394

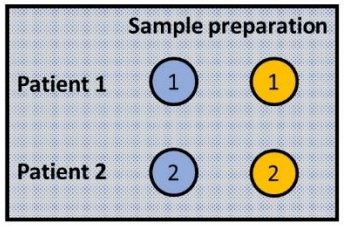


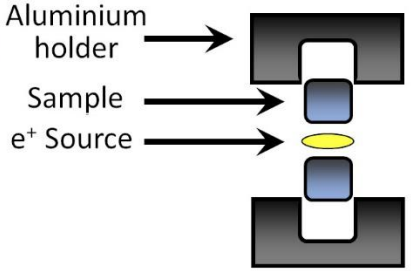







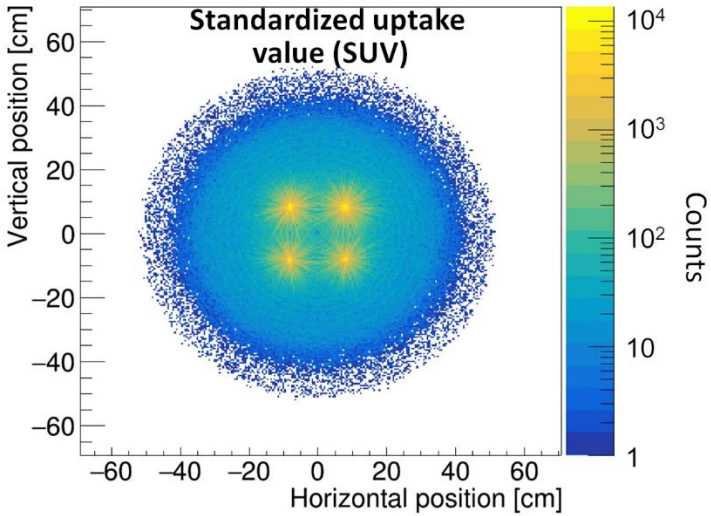


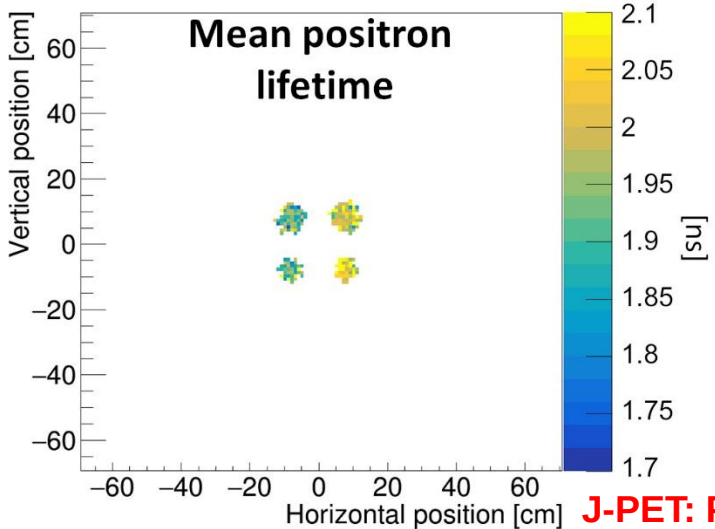


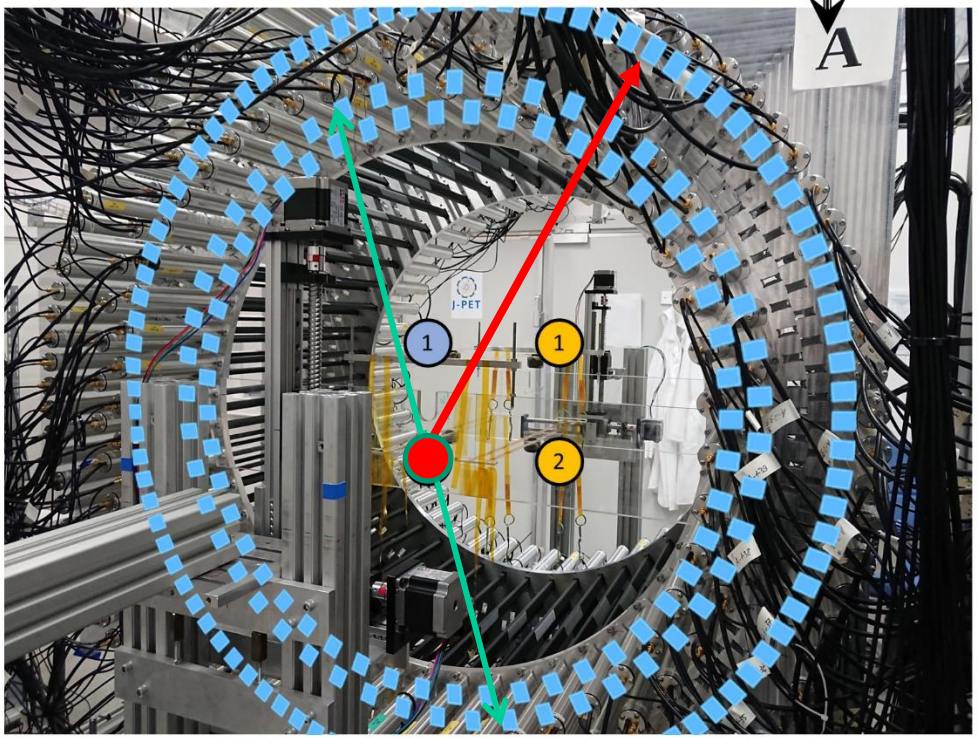




Placing samples in the chambers

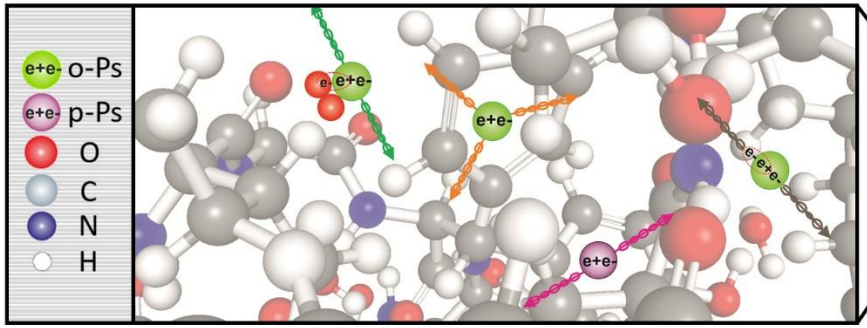
Inserting setup to the detector




J-PET: P. Moskal, K. Dulski et al., Science Advances 7 (2021) eabh4394




Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

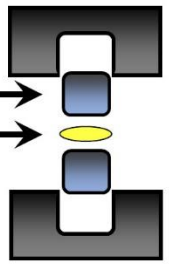
Patient 1 1 1

Patient 2 2 2

Aluminium holder

Sample

$e^+$ Source



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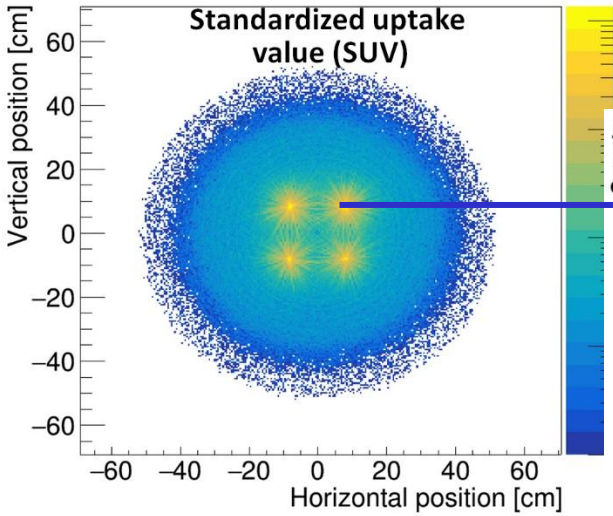
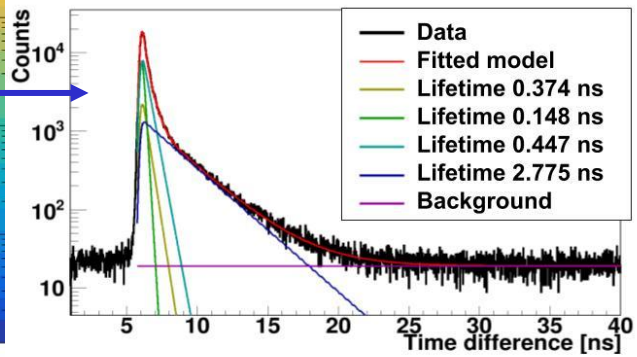
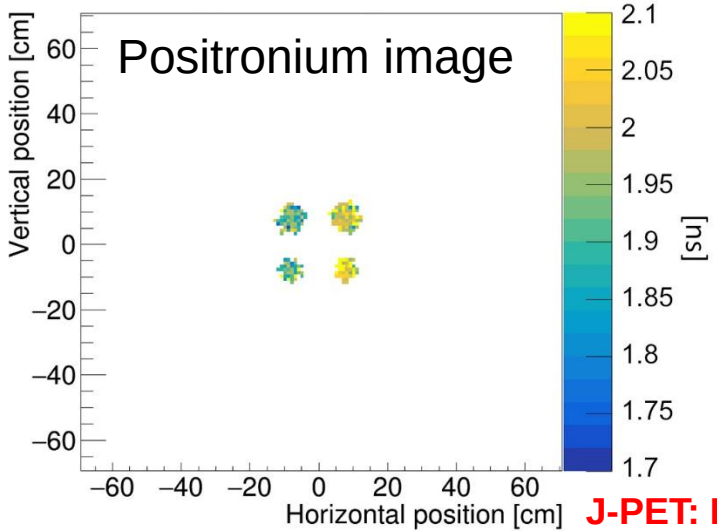
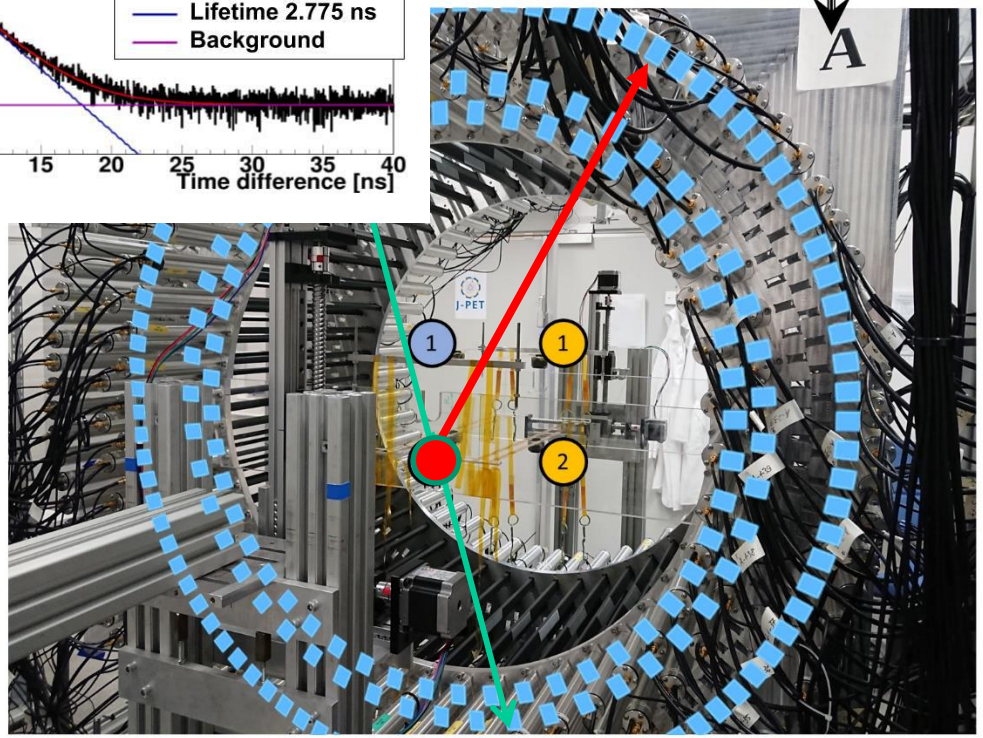
Inserting setup to the detector



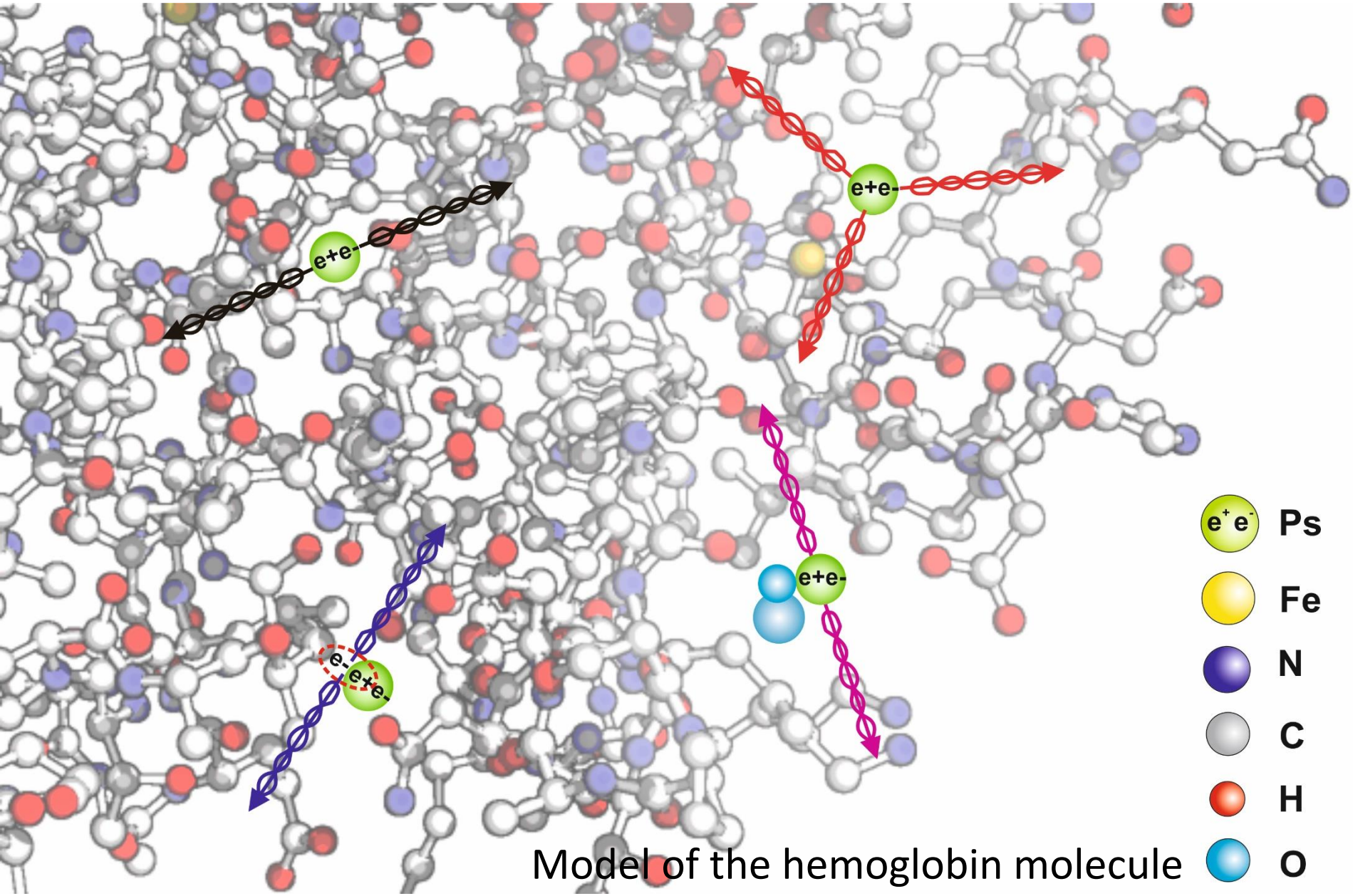




J-PET: P. Moskal, K. Dulski et al., Science Advances 7 (2021) eabh4394

# Positronium imaging

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




Model of the hemoglobin molecule

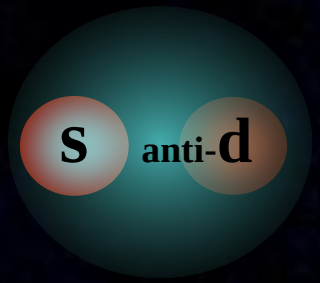
# Test of discrete symmetries in positronium decays using J-PET tomograph

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

**Bialasówka, AGH, Kraków, 08.10.2021**

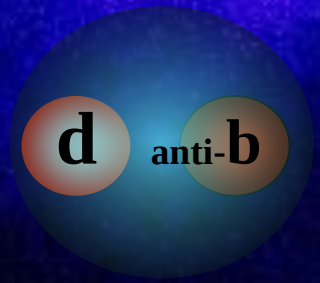
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

Violation of CP and T
confirmed experimentally
for hadrons only



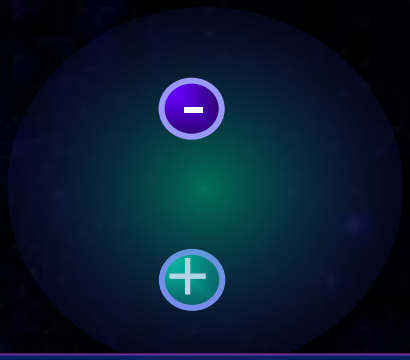

meson K

1964




meson B

2012




positronium

?

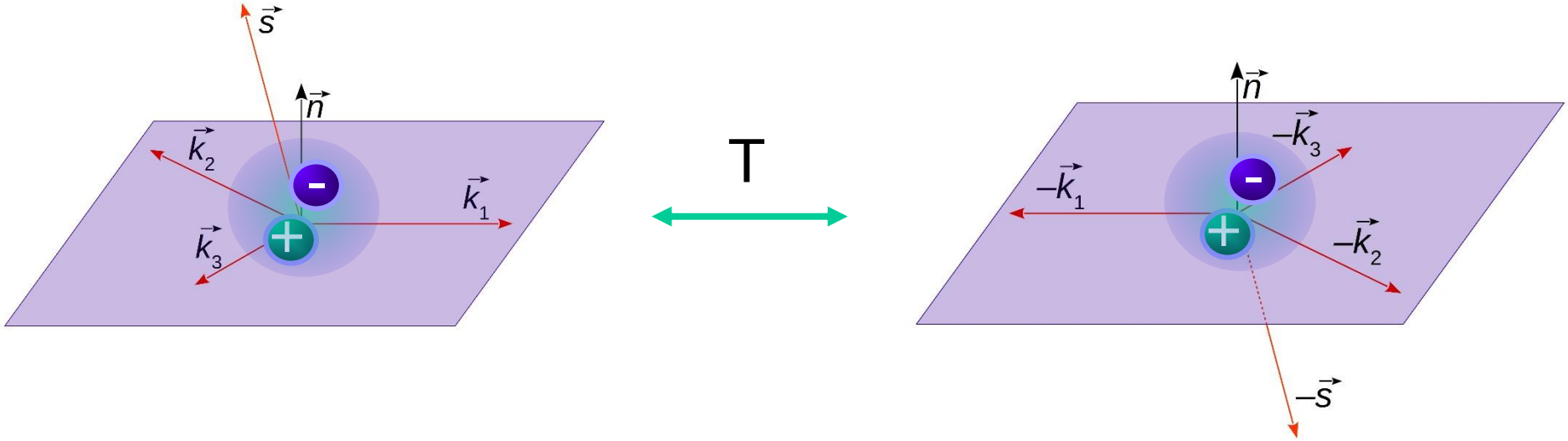
| Operator | C | P | T | CP | CPT |
|---|---|---|---|---|---|
| $\vec{S} \cdot \vec{k}_1$ | + | – | + | – | – |
| $\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)$ | + | + | – | + | – |
| $\left(\vec{S} \cdot \vec{k}_1\right)\left(\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)\right)$ |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

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

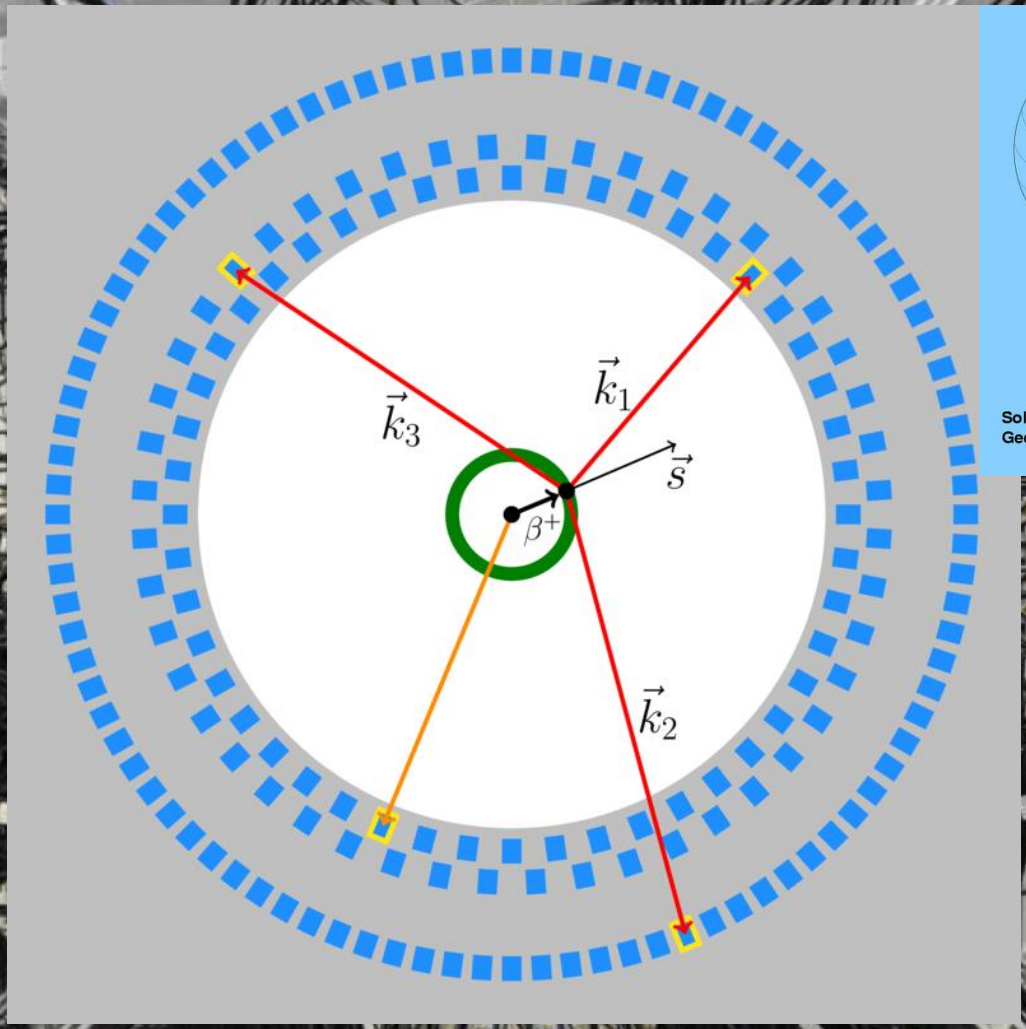
Operators for the o-Ps→3γ process, and their properties with respect to the C, P, T, CP and CPT symmetries.

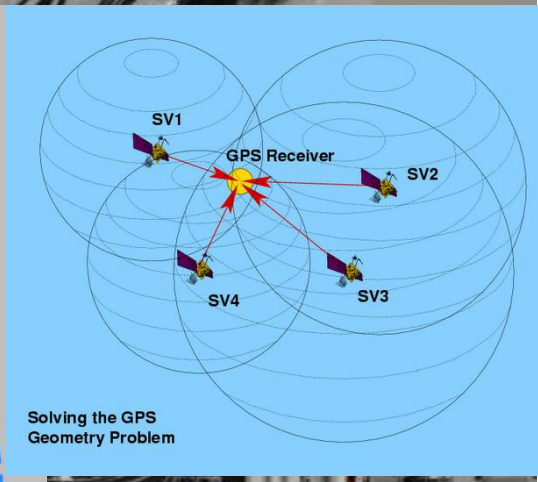
| Operator | C | P | T | CP | CPT |
|---|---|---|---|---|---|
| $\vec{S} \cdot \vec{k}_1$ | + | – | + | – | – |
| $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ | + | + | – | + | – |
| $(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$ | + | – | – | – | + |

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



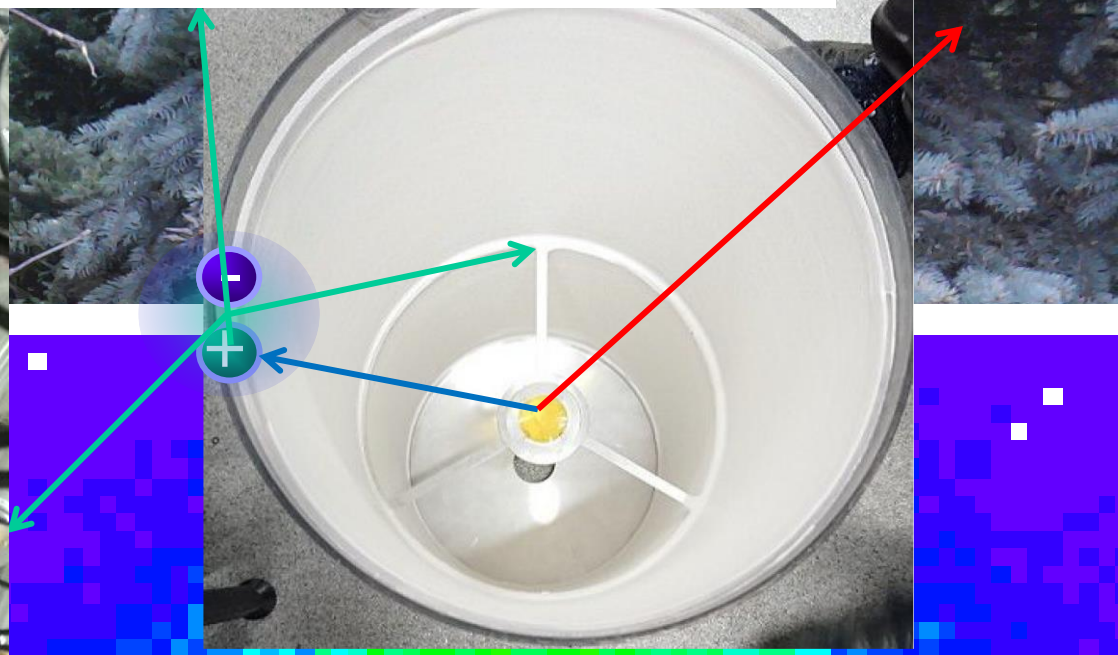
# Jagiellonian PET

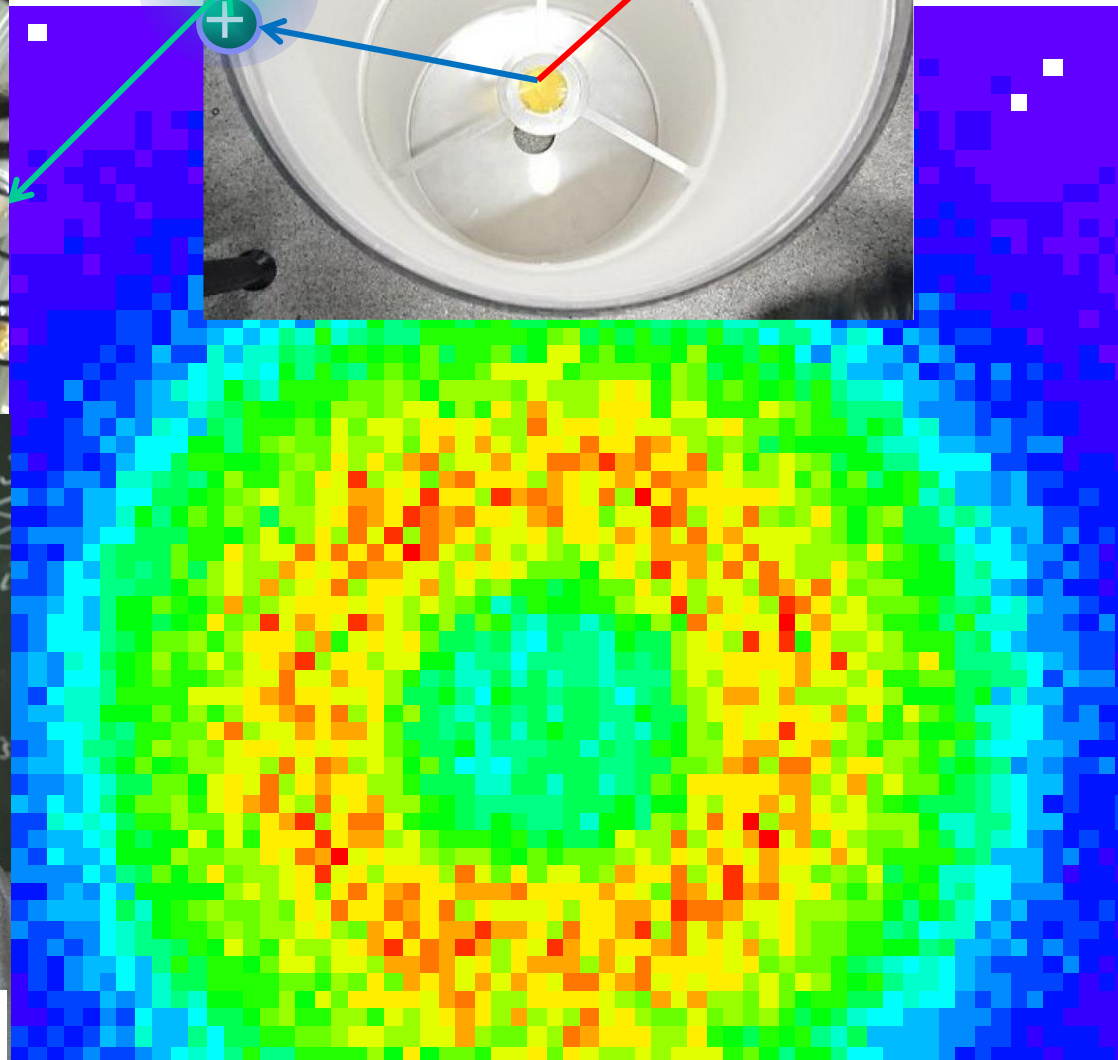


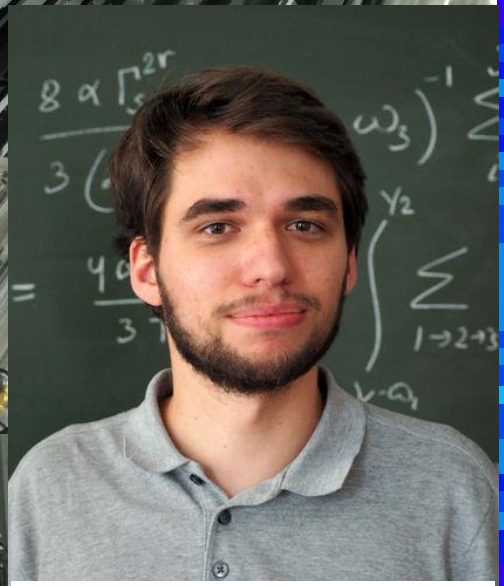




P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509

J-PET: P. Moskal, A. Gajos et al., Nature Communications 7 (2021) 5658





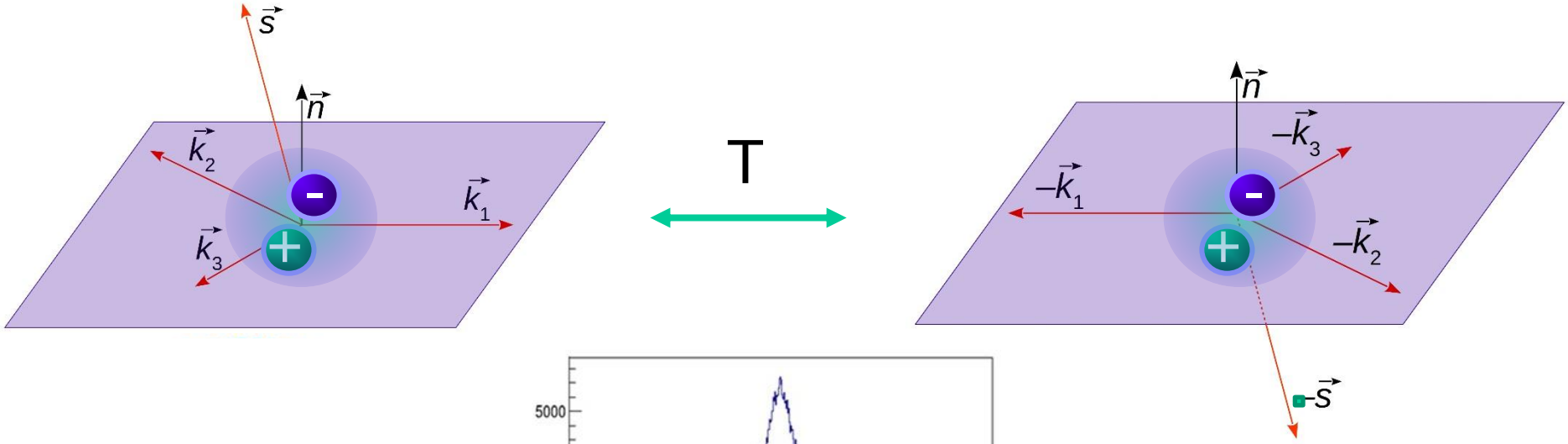


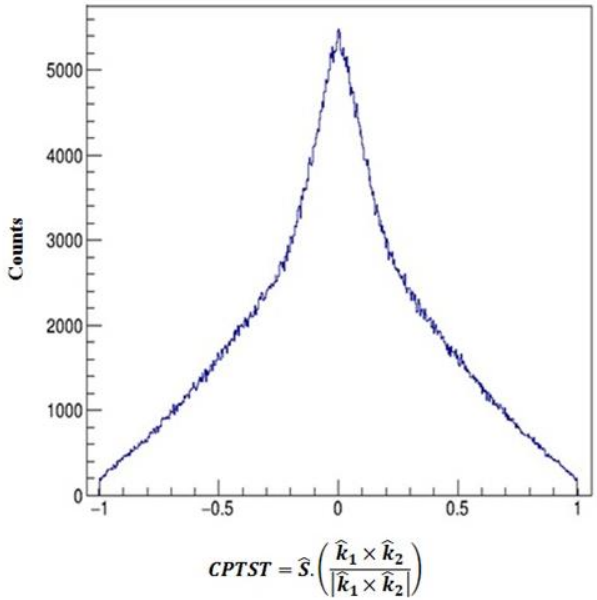
Aleksander Gajos

| 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 7 (2021) 5658

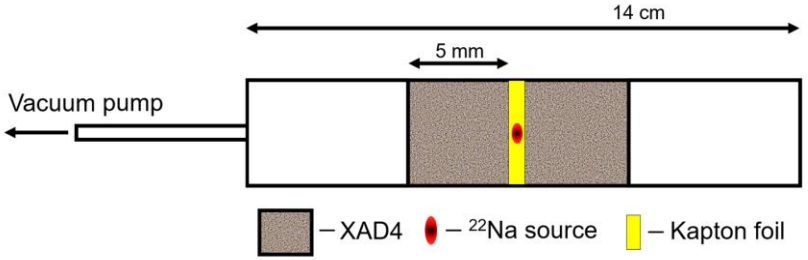


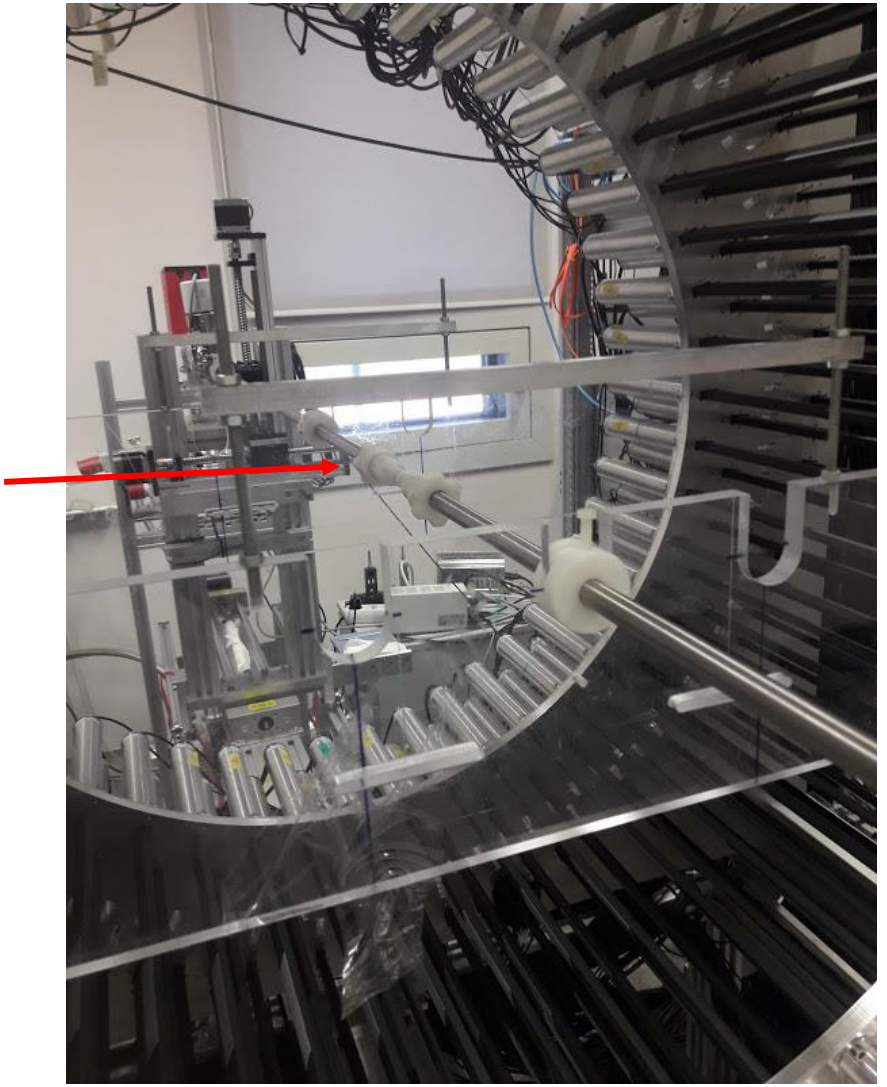




$10^{-4}$

# J-PET detector overview

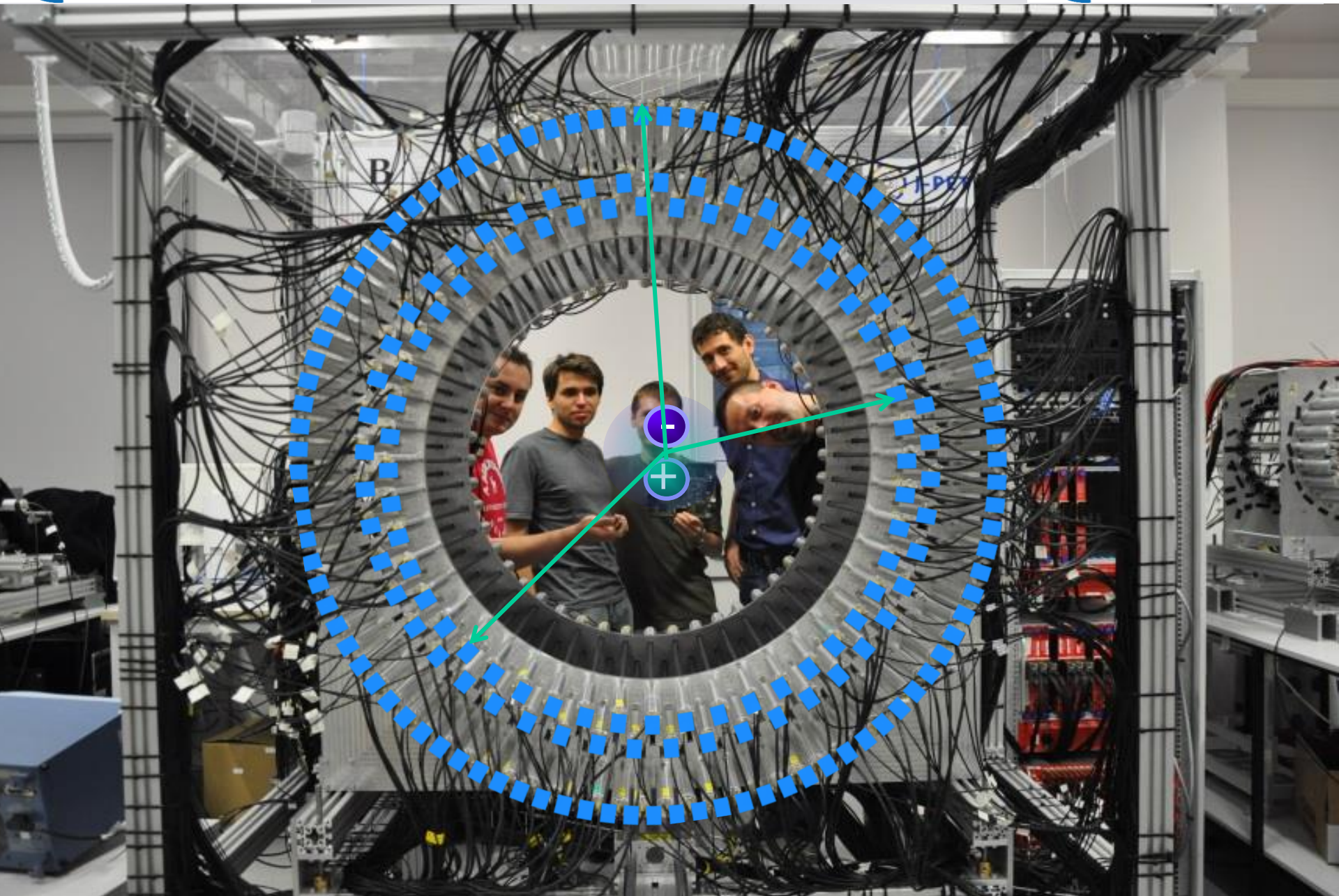
Small annihilation chamber used for production of positronium:



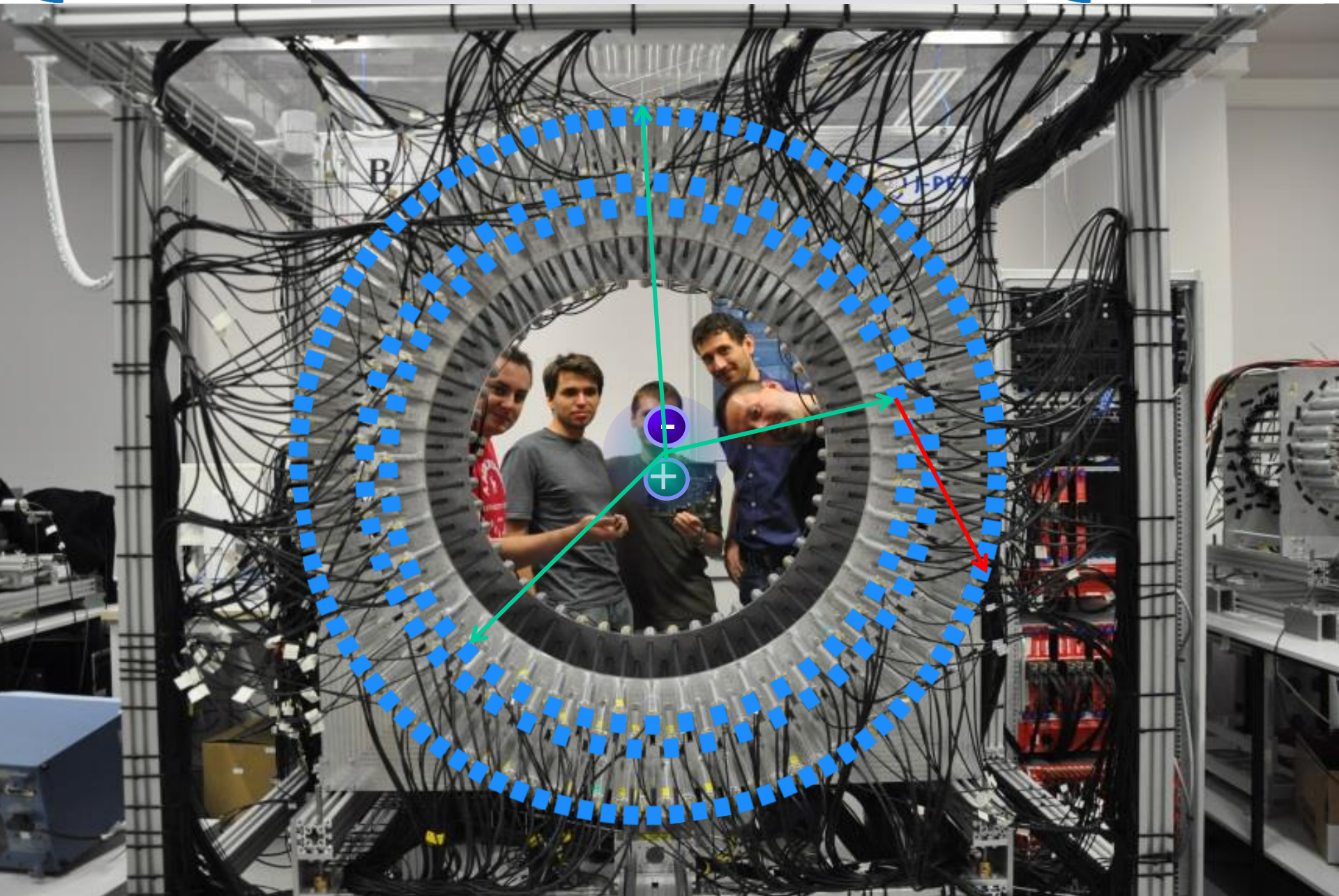




B
SIDE B
WARNING
KEEP HANDS
OUT OF
MACHINERY

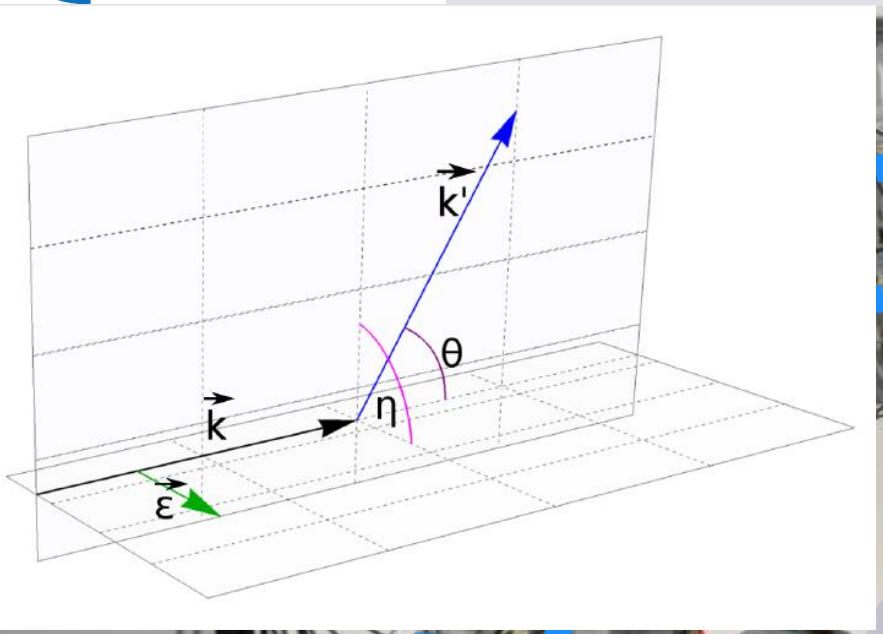
# Jagiellonian PET

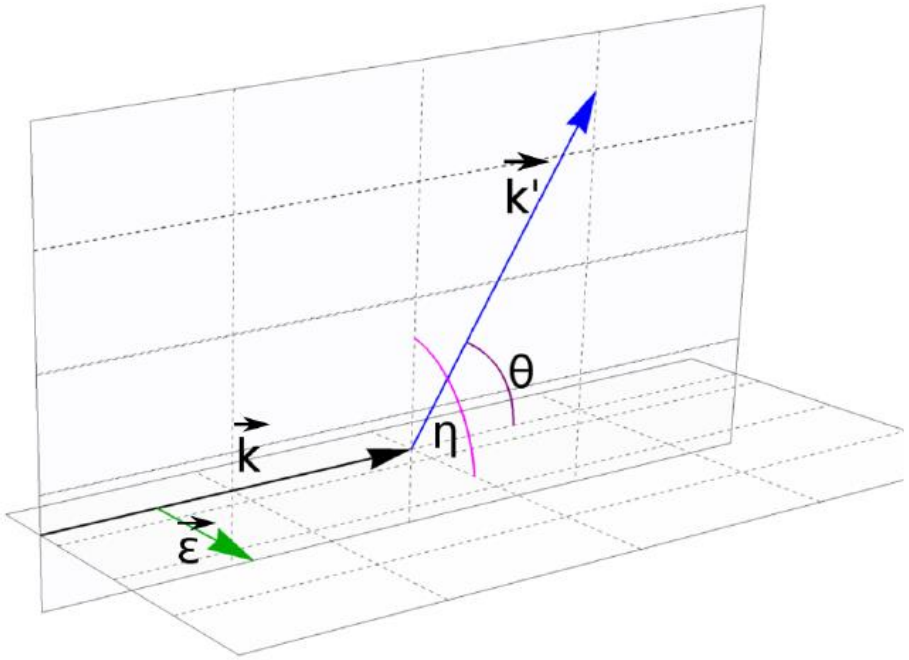


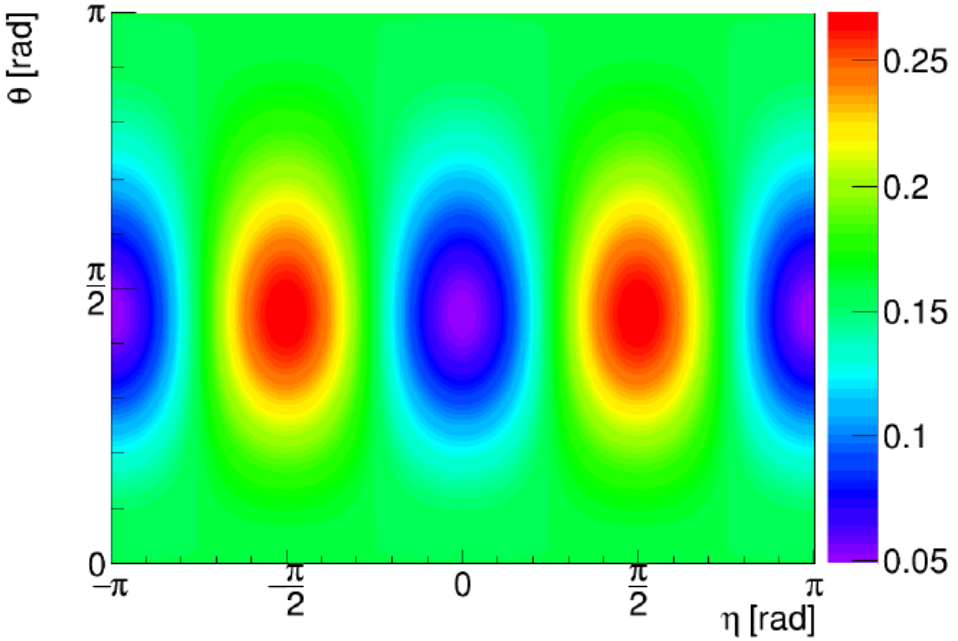
# Jagiellonian PET



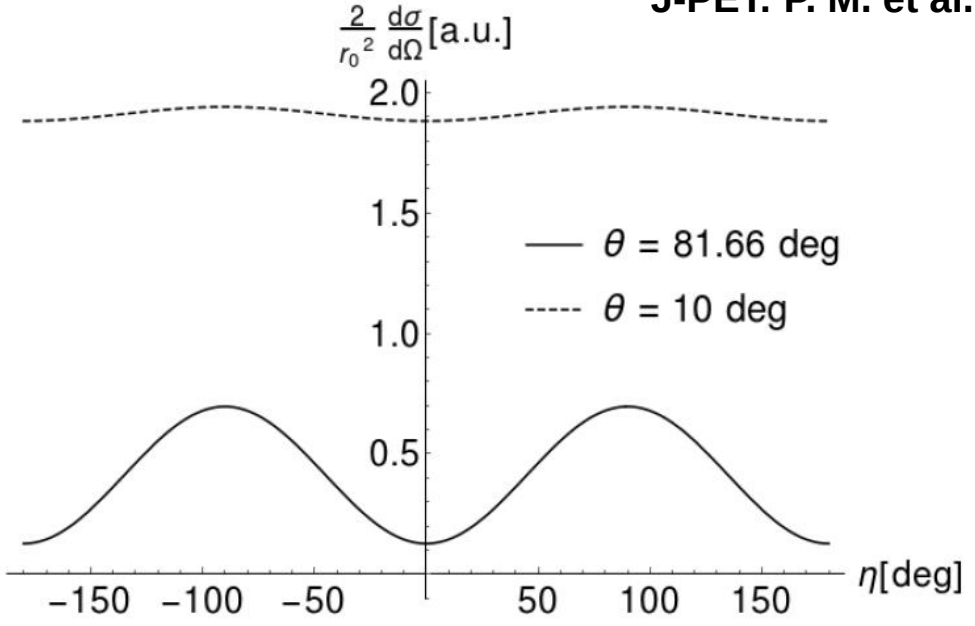
# Jagiellonian PET



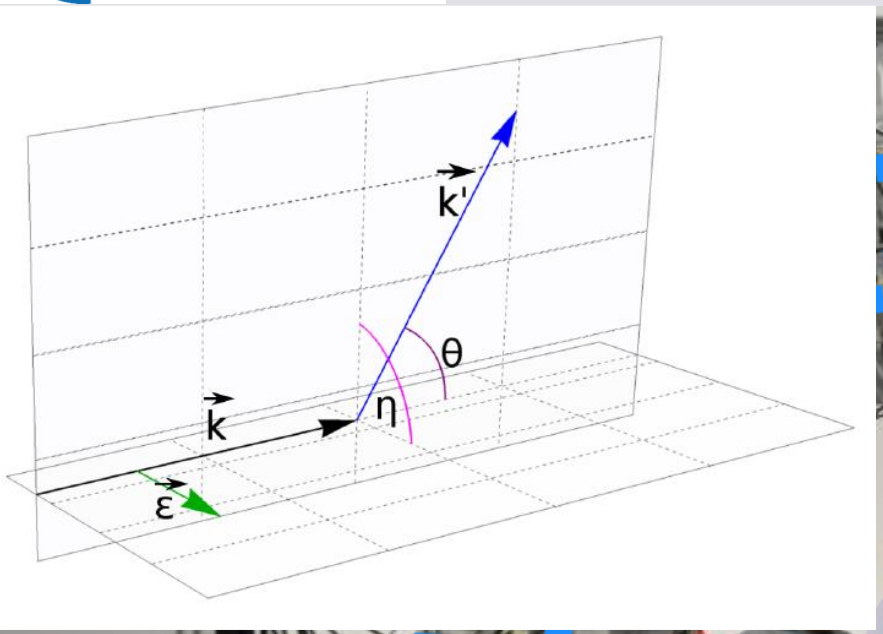



**J-PET: P. M. et al., Eur. Phys. J. C 78 (2018) 970**



# Jagiellonian PET



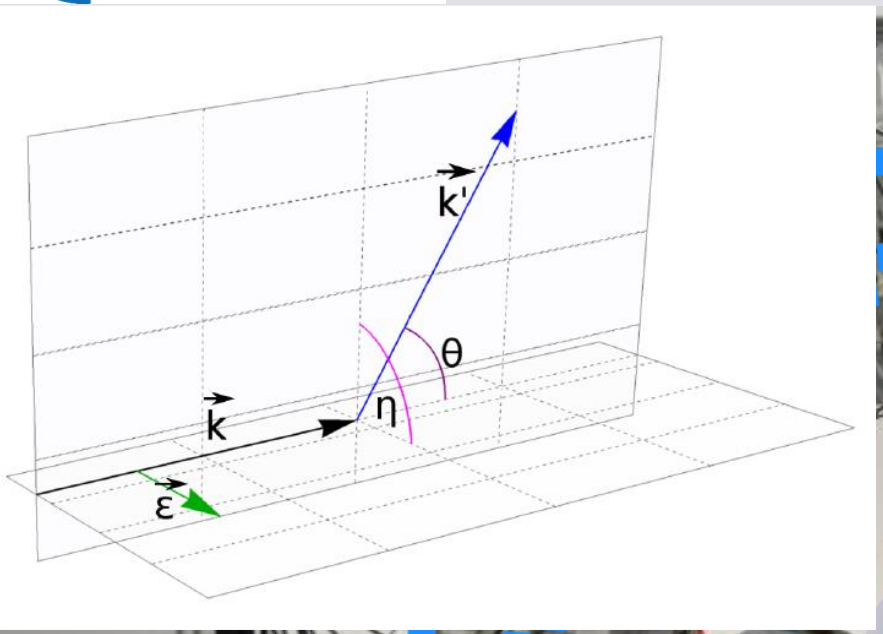

$$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$$

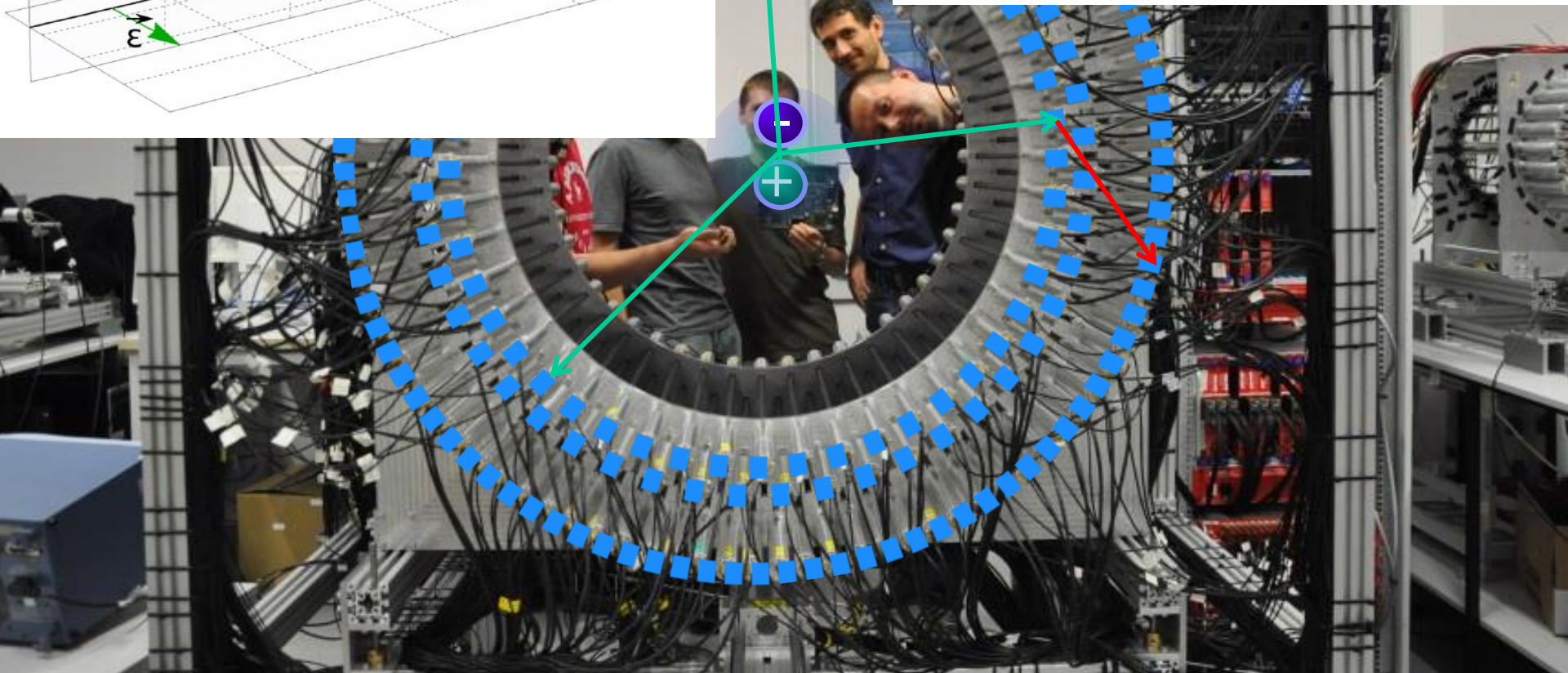
P. M. et al., Acta Phys. Pol. B 47 (2016) 509

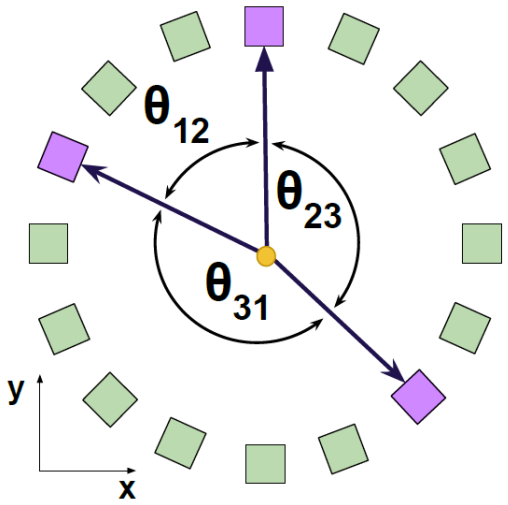
# J-PET Jagiellonia

| 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

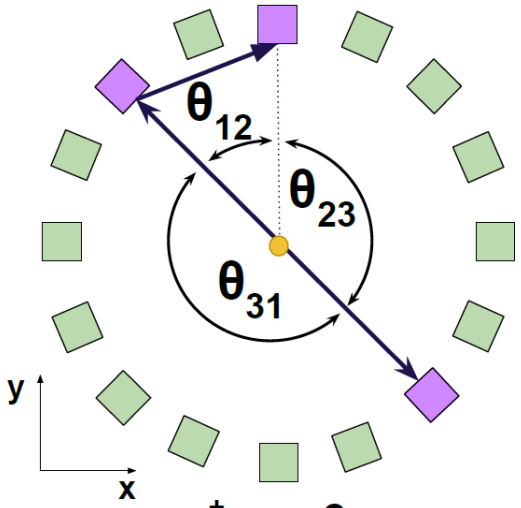




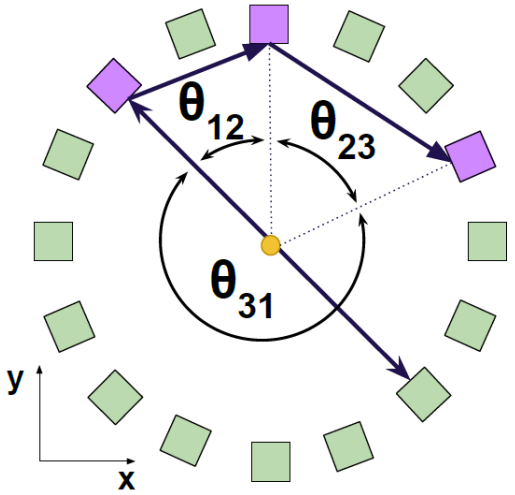

o-Ps → 3γ

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




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

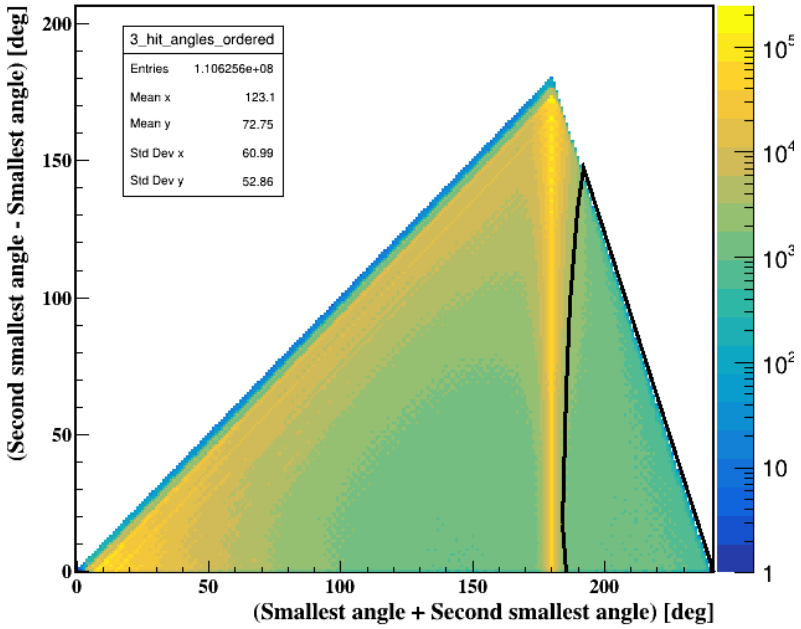
$\theta_{23} + \theta_{12} = 180$

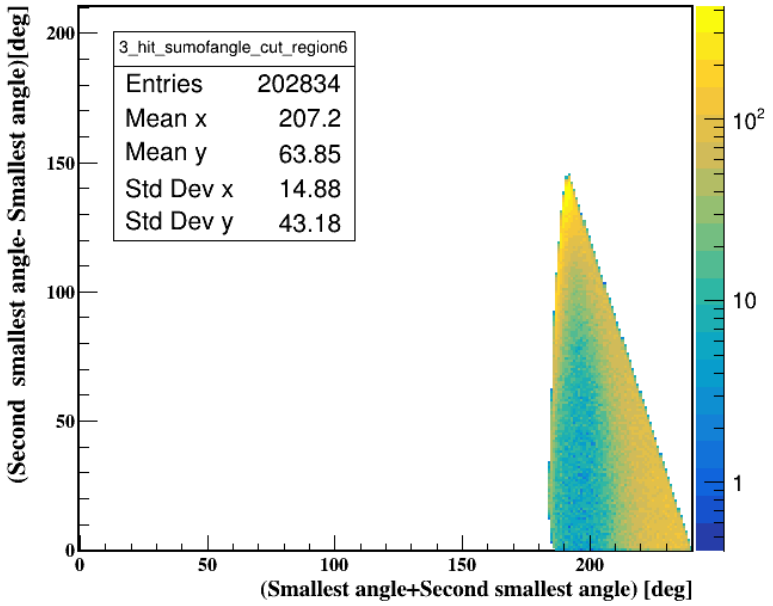



$e^+e^- \rightarrow 2\gamma$
double scattered

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

3 Hit angles

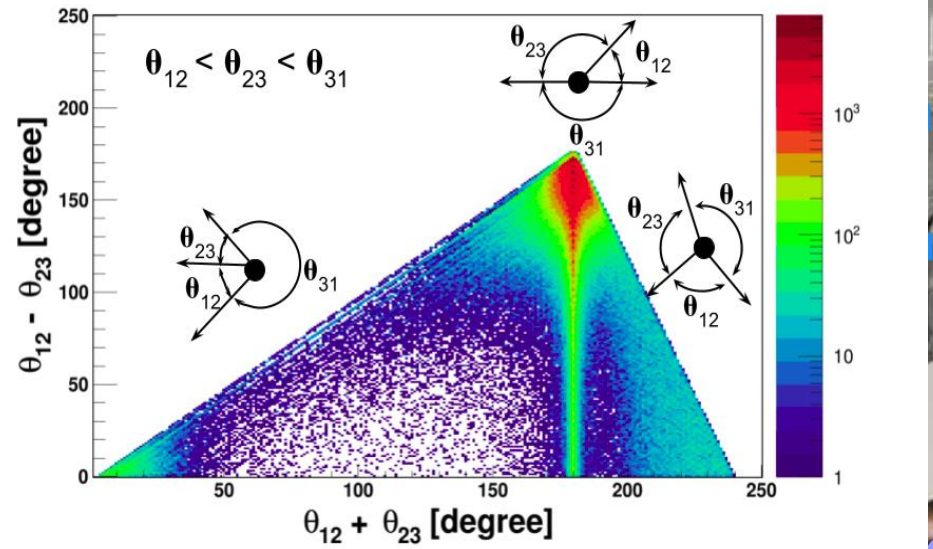


# J-PET Jagiellonia

| 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

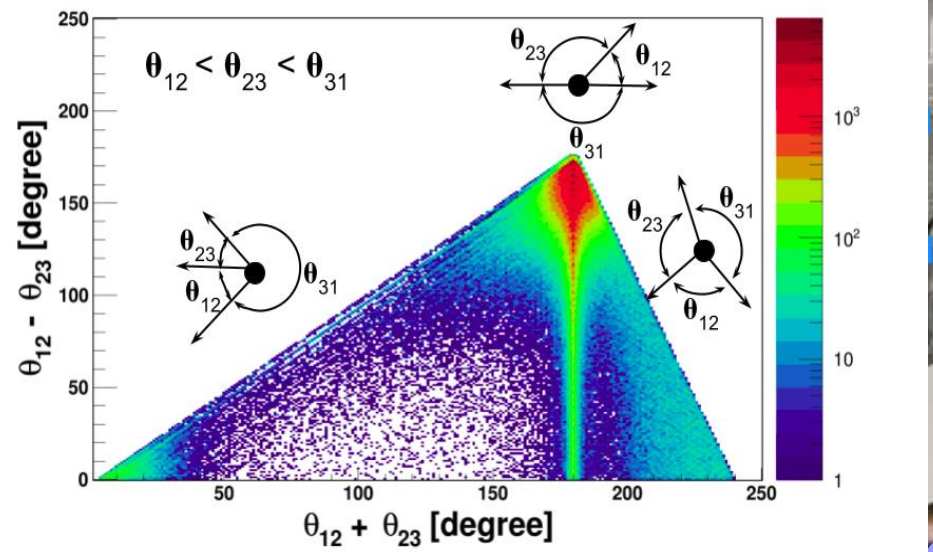



Juhi Raj

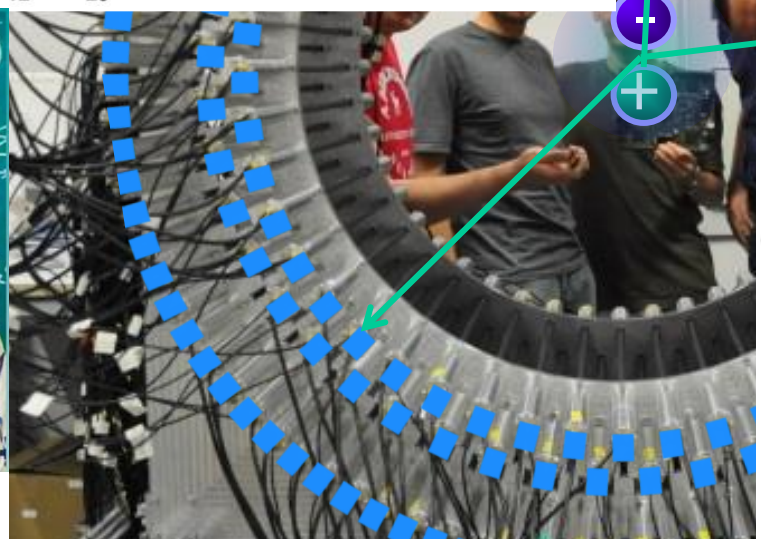
# J-PET Jagiellonia

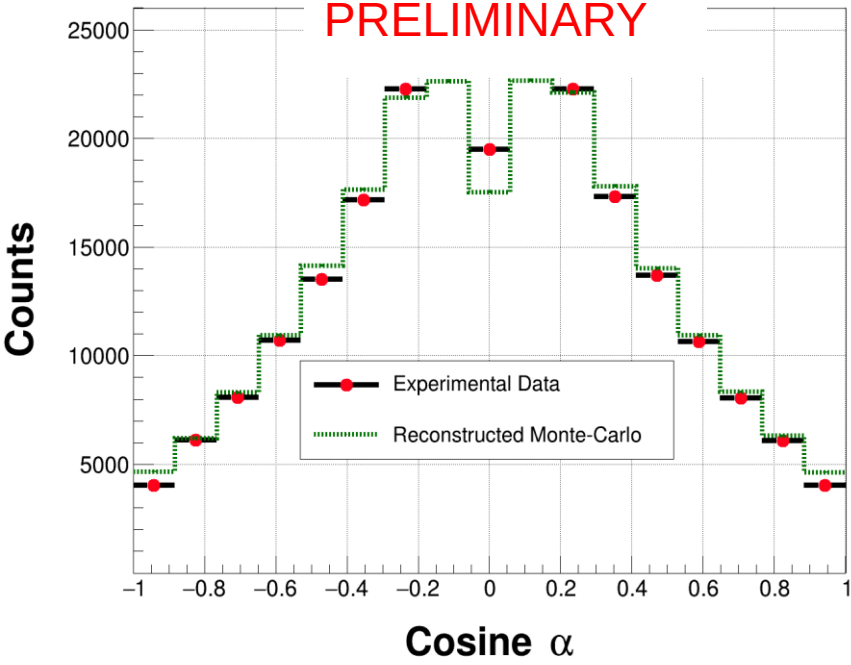
| Operator | C | P | T | CP | CPT |
|---|---|---|---|---|---|
| $\vec{S}\cdot\vec{k}_1$ | + | – | + | – | – |
| $\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$ | + | + | – | + | – |
| $(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$ | + | – | – | – | + |
| $\vec{k}_1\cdot\vec{\varepsilon}_2$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

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




Juhi Raj





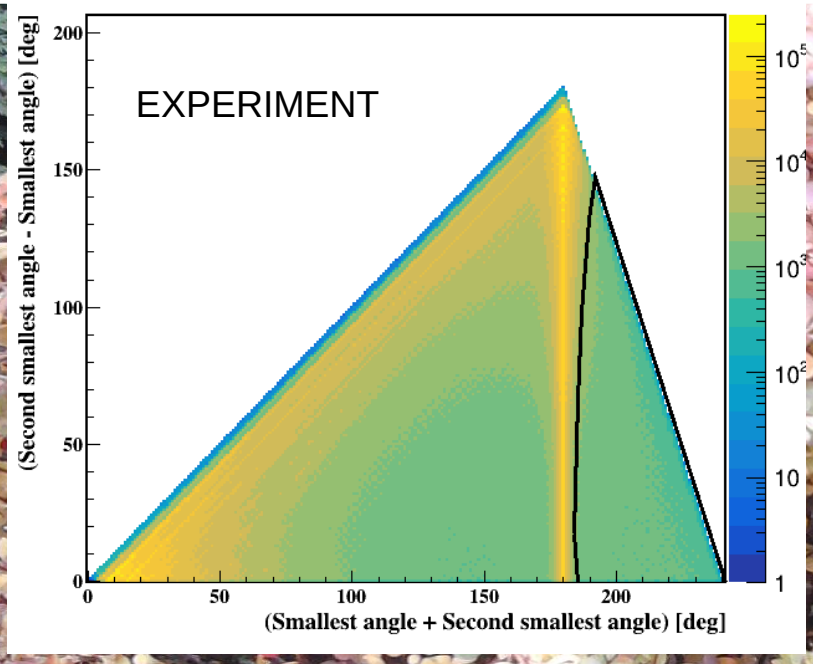

**Expectation Value** = 0.0003 +/- 0.0003

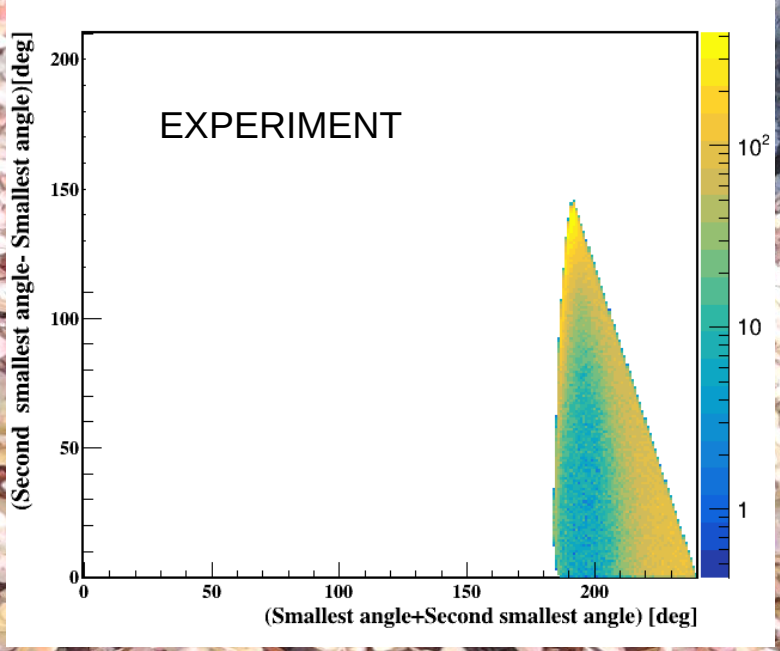
PRELIMINARY

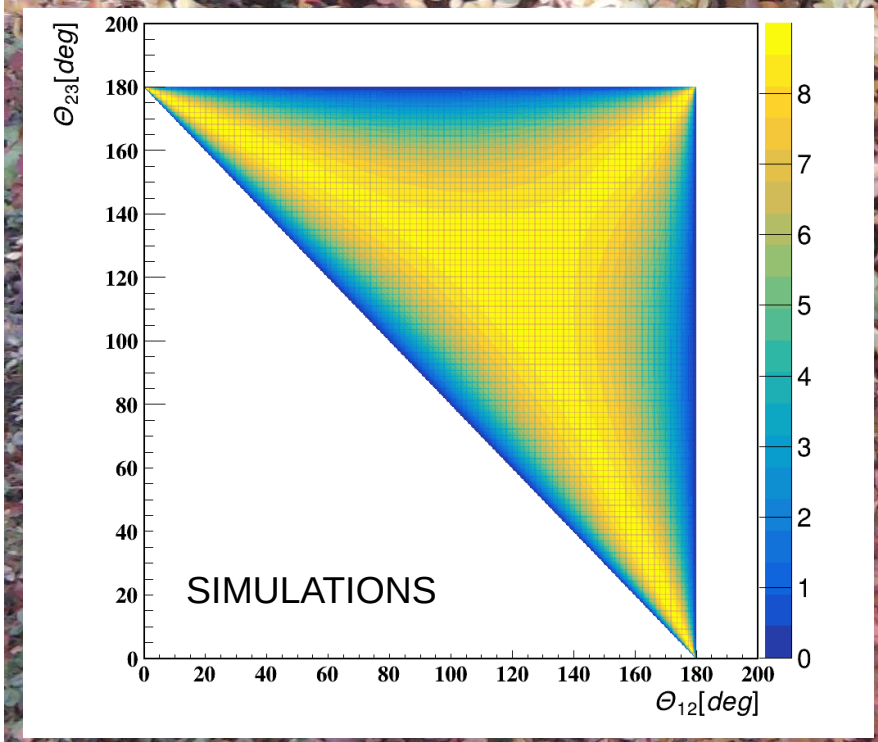
**Best so far:**

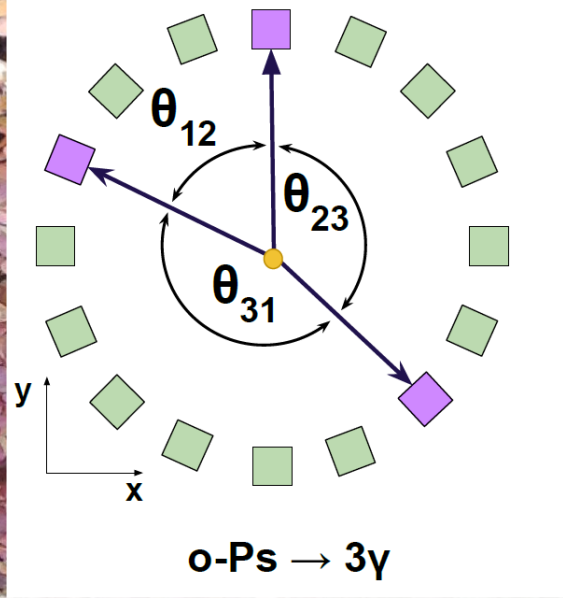
**-0.0023 < CP < 0.0049 at 90% CL**

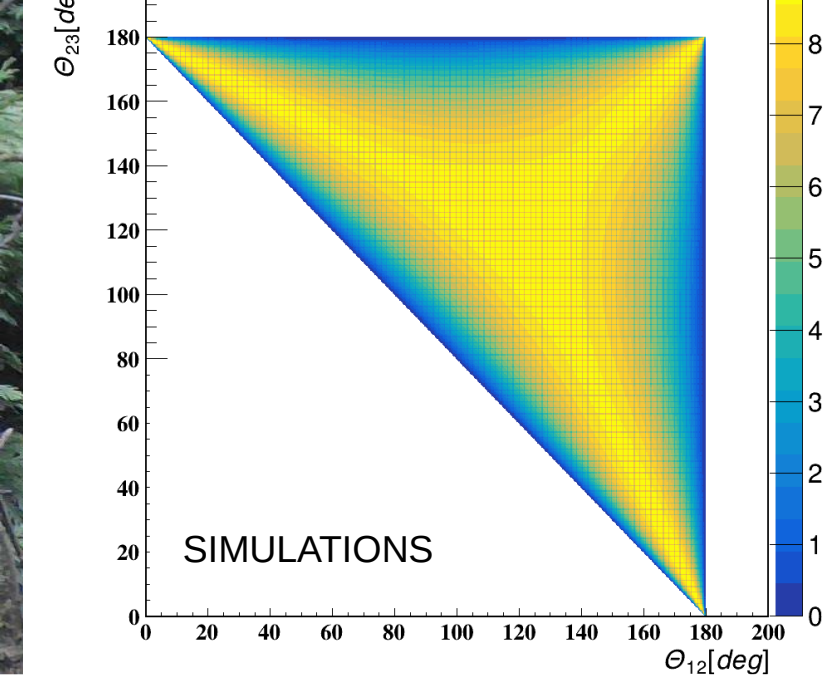
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

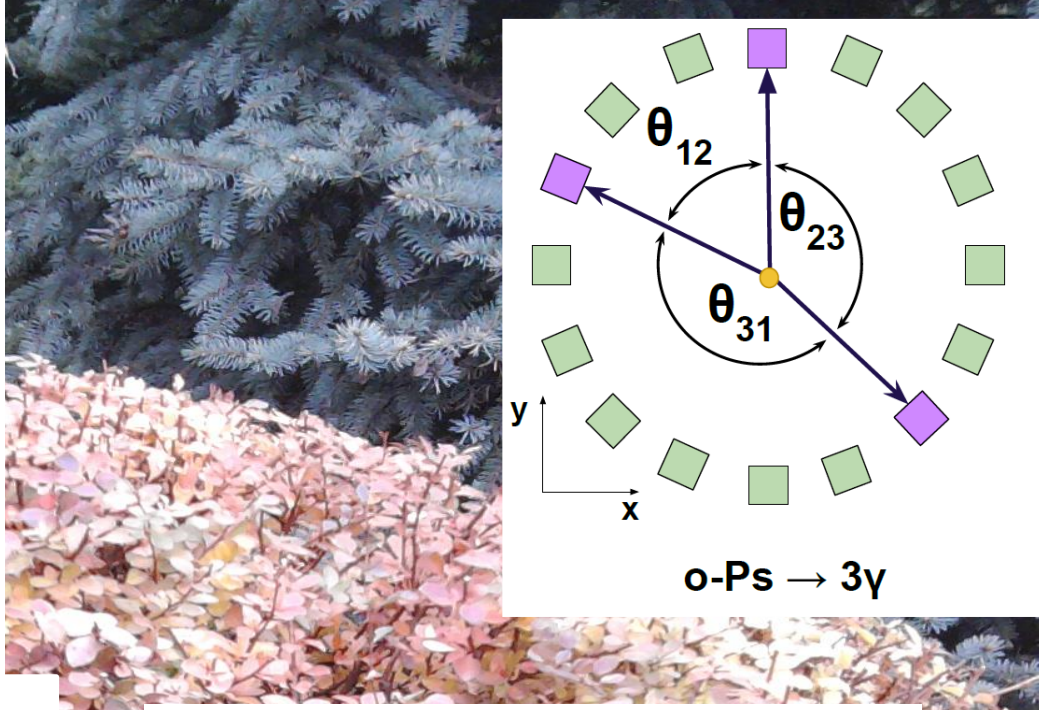

EXPERIMENT
(Second smallest angle - Smallest angle) [deg]
(Smallest angle + Second smallest angle) [deg]

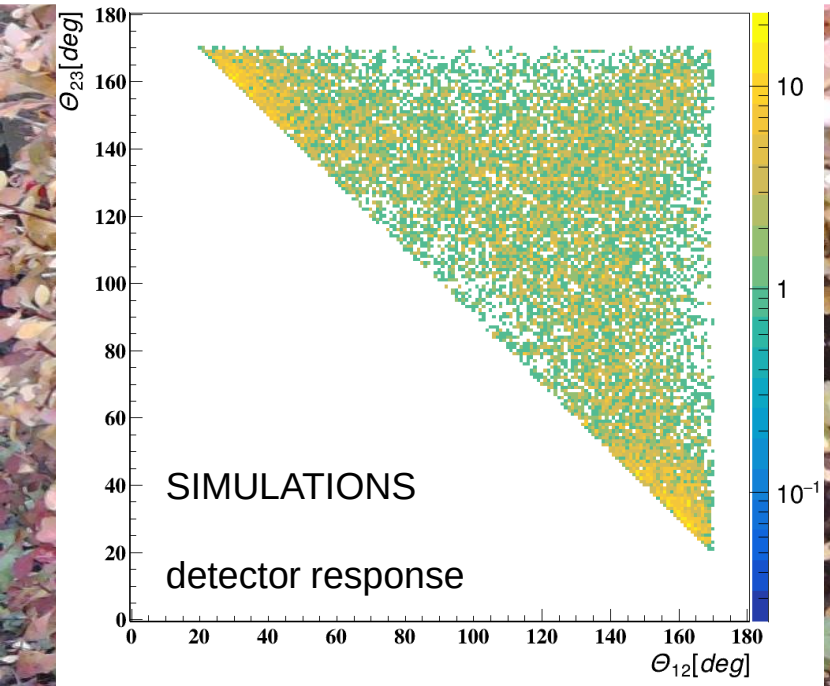

EXPERIMENT
(Second smallest angle- Smallest angle)[deg]
(Smallest angle+Second smallest angle) [deg]

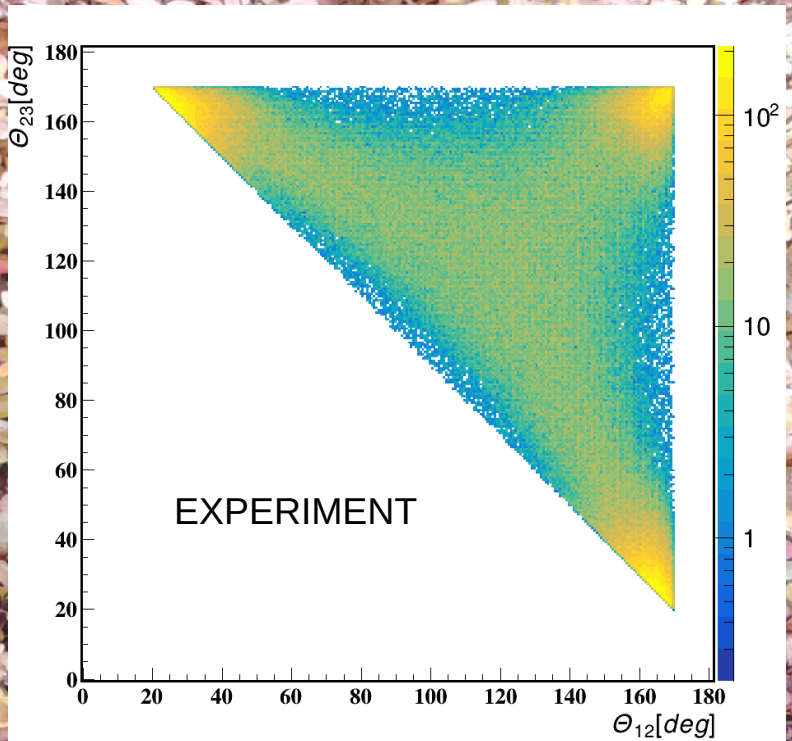

SIMULATIONS
Θ23[deg]
Θ12[deg]

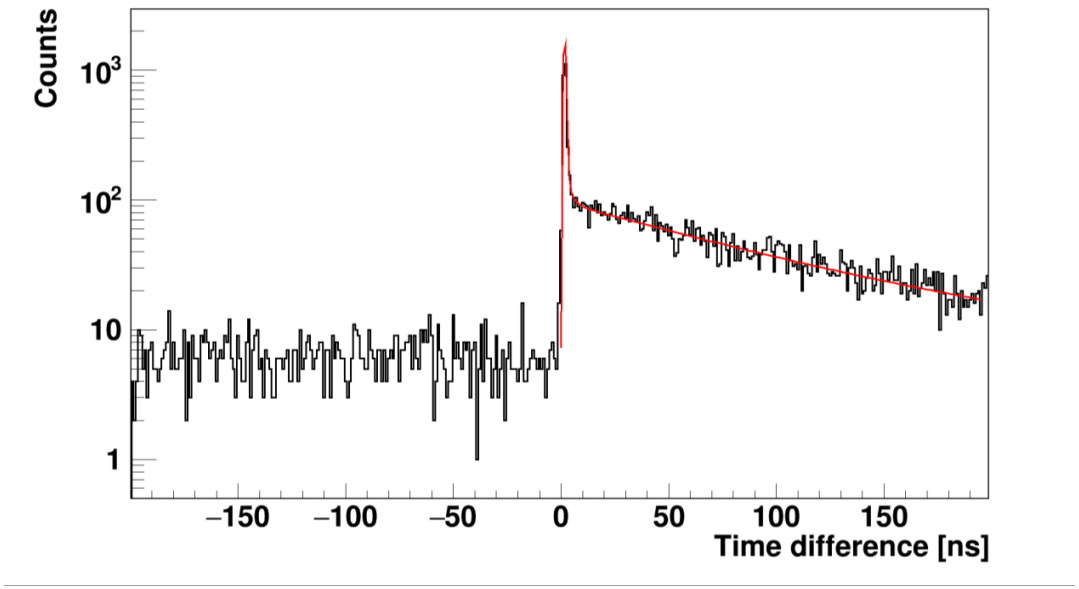

θ12
θ23
θ31
y
x
o-Ps → 3γ

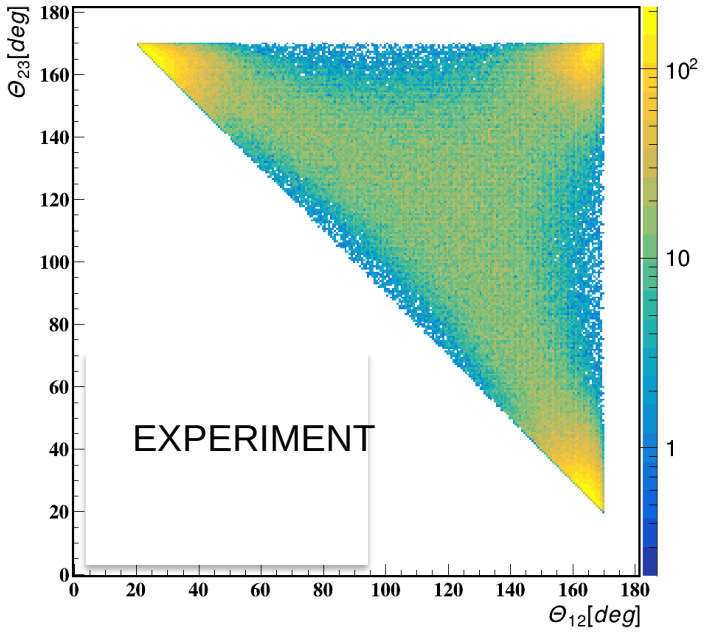

SIMULATIONS
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$

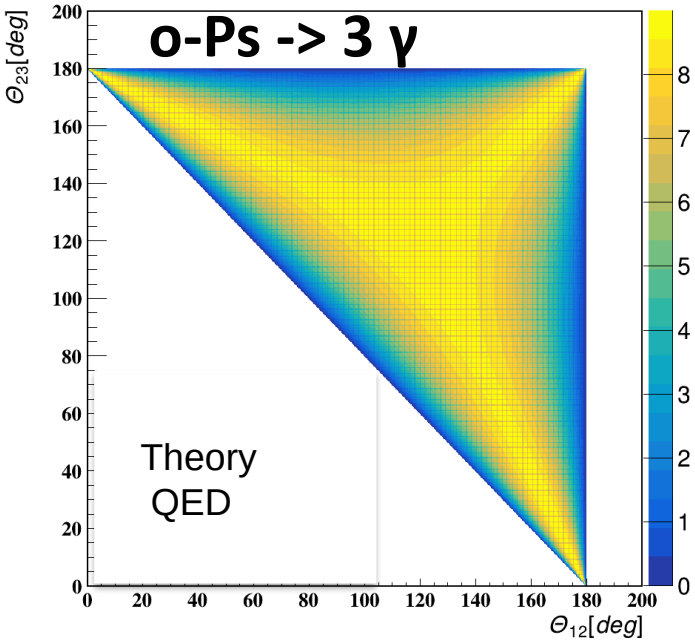

θ12
θ23
θ31
y
x
o-Ps → 3γ

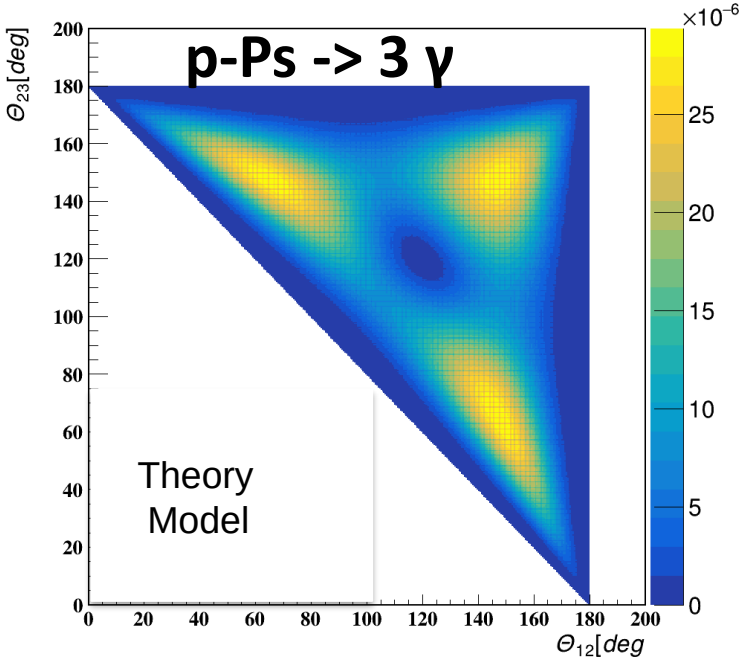

SIMULATIONS
detector response
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$

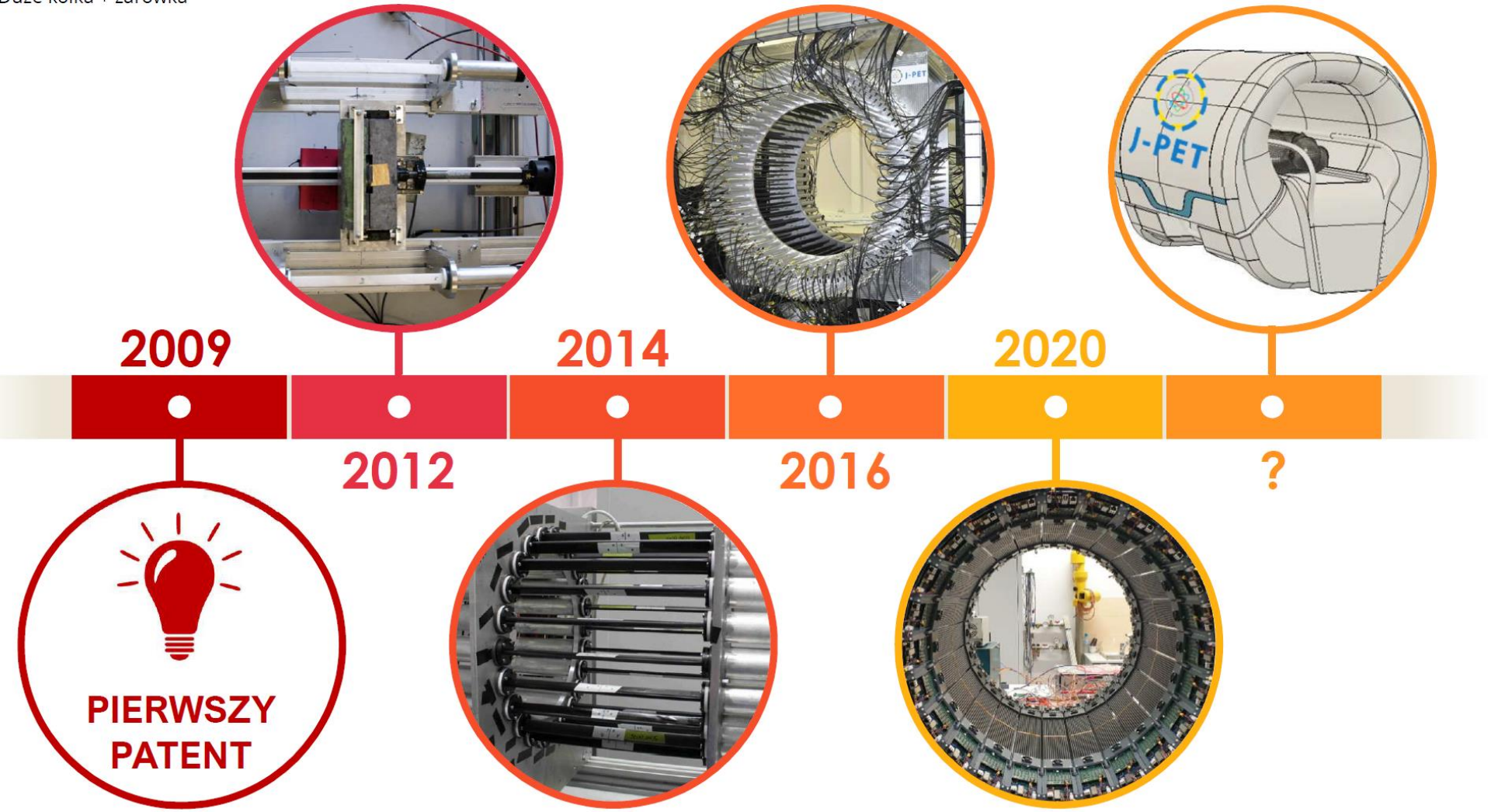

EXPERIMENT
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$


Counts
$10^3$
$10^2$
10
1
−150
−100
−50
0
50
100
150
Time difference [ns]


$\Theta_{23}[deg]$
$\Theta_{12}[deg]$
EXPERIMENT
$10^2$
10
1


o-Ps -> 3 γ
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$
Theory
QED


p-Ps -> 3 γ
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$
Theory
Model
$\times 10^{-6}$

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Ministry of Science and Higher Education
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National Center for Research and Development (Innotech)
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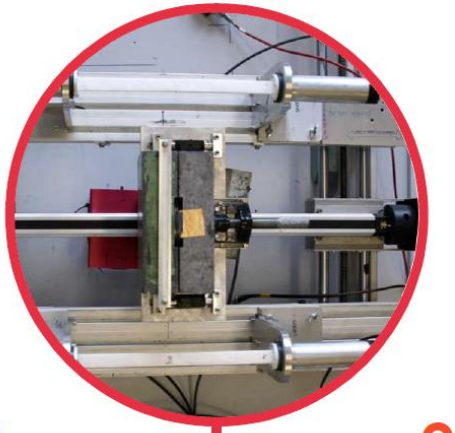



2009

2012

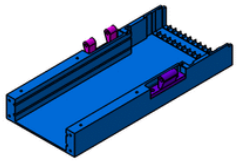
2014

2016

2020

?

PIERWSZY PATENT



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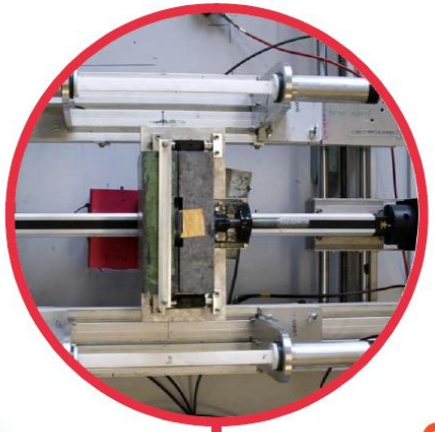
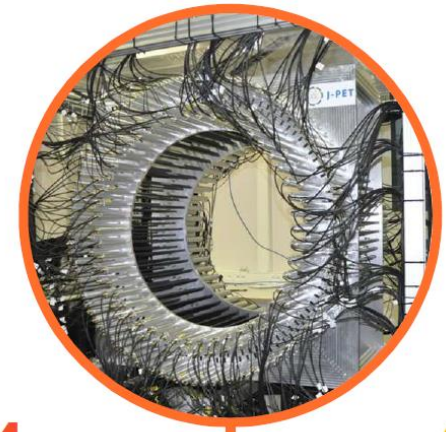
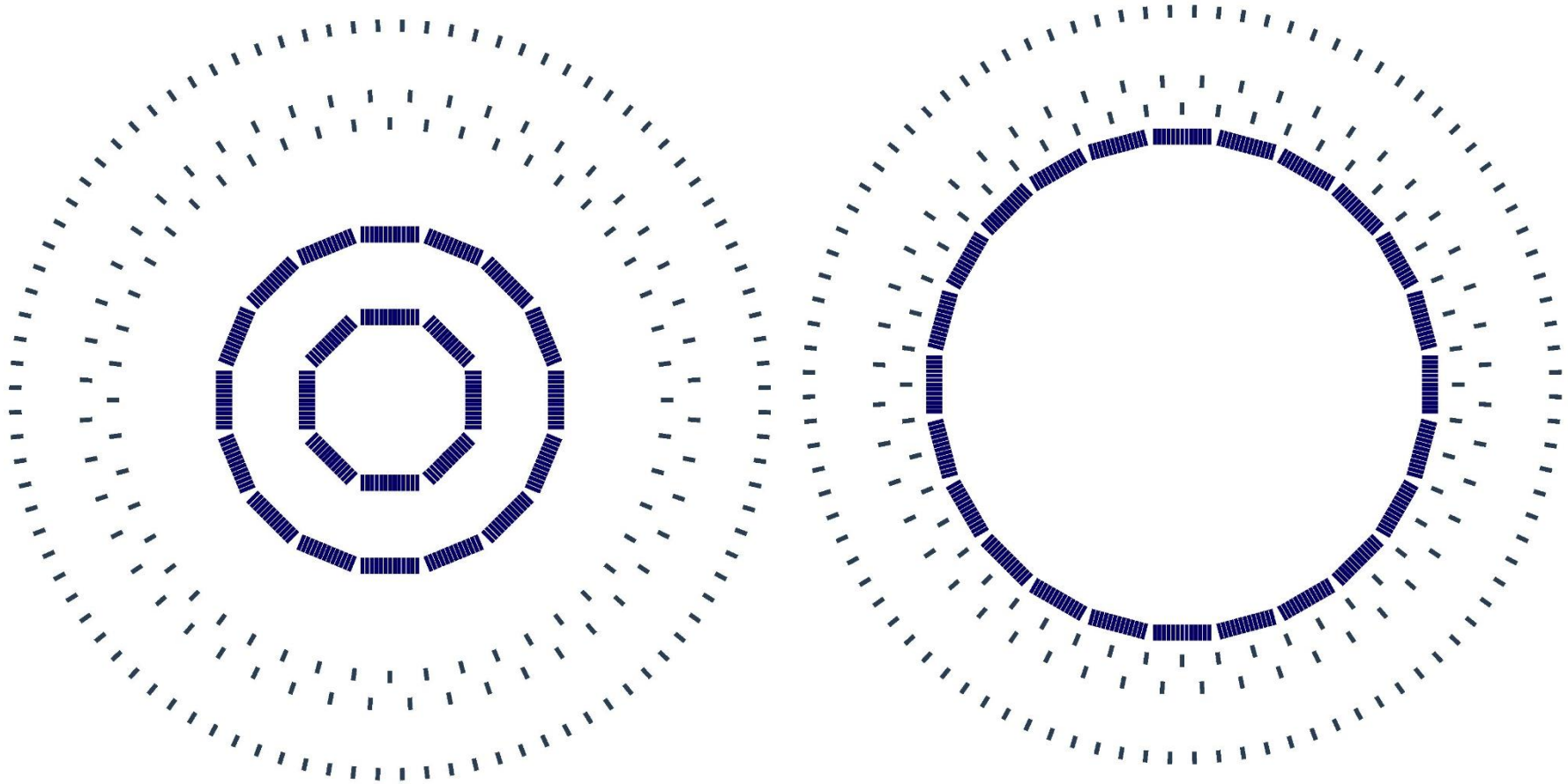
Duże kółka + żarówka







2009 2014 2020



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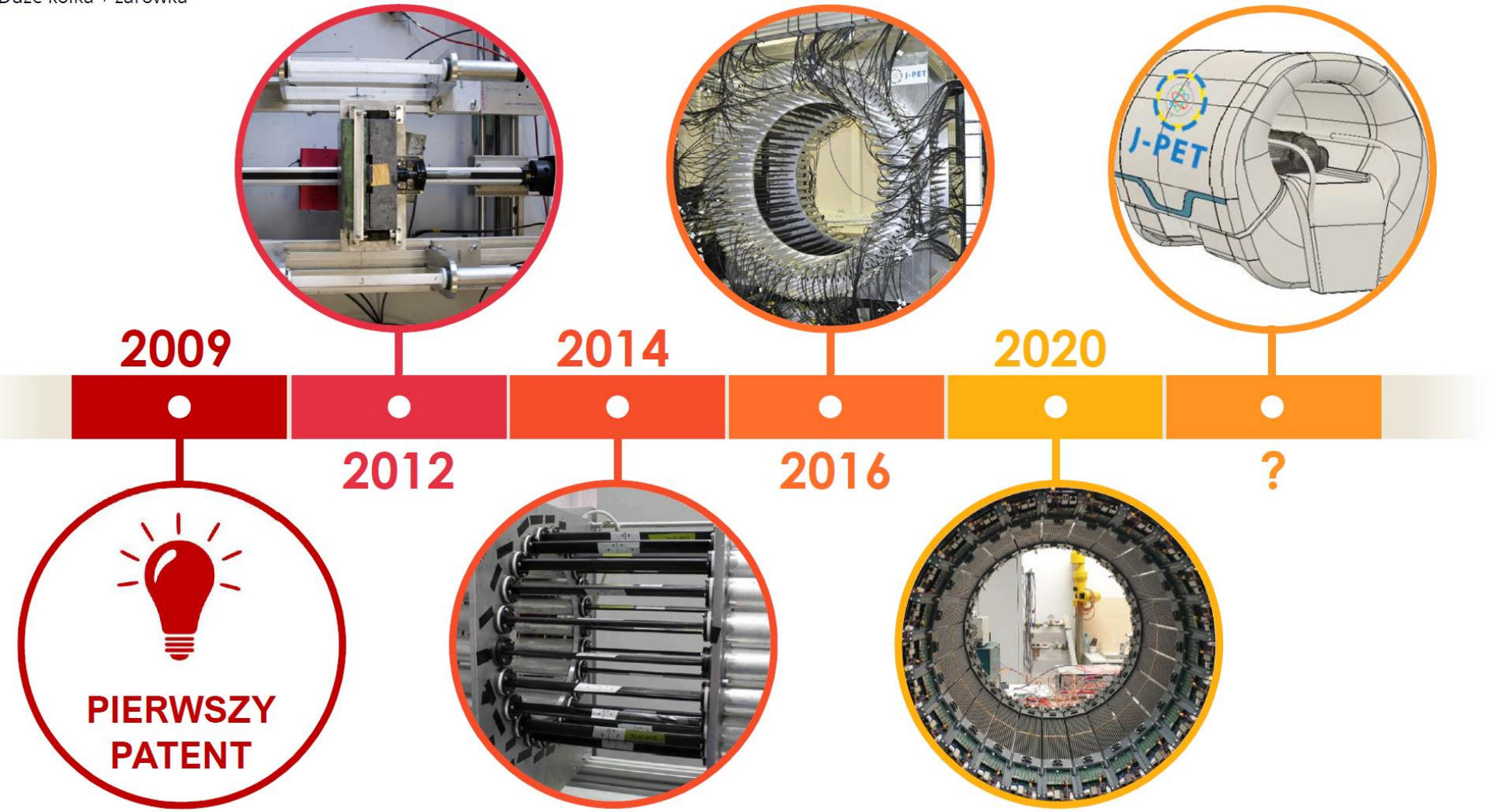


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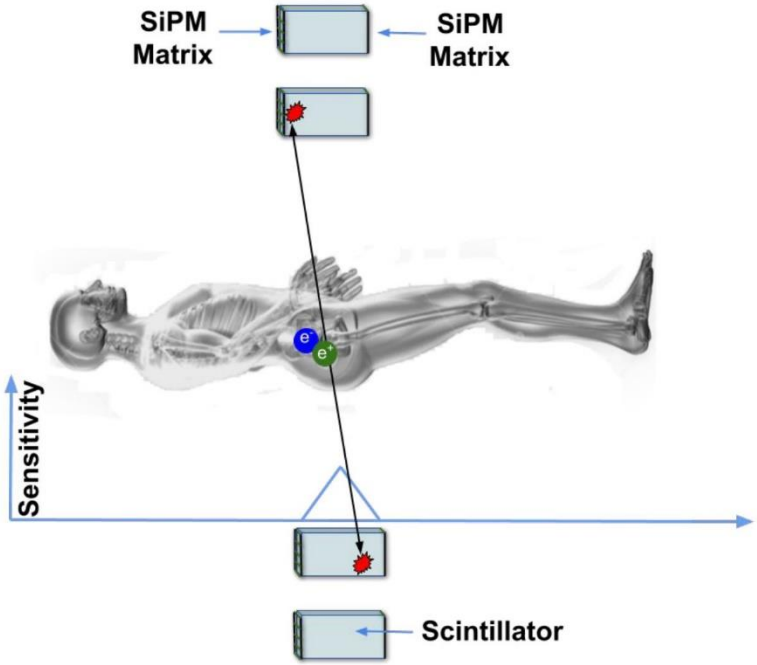
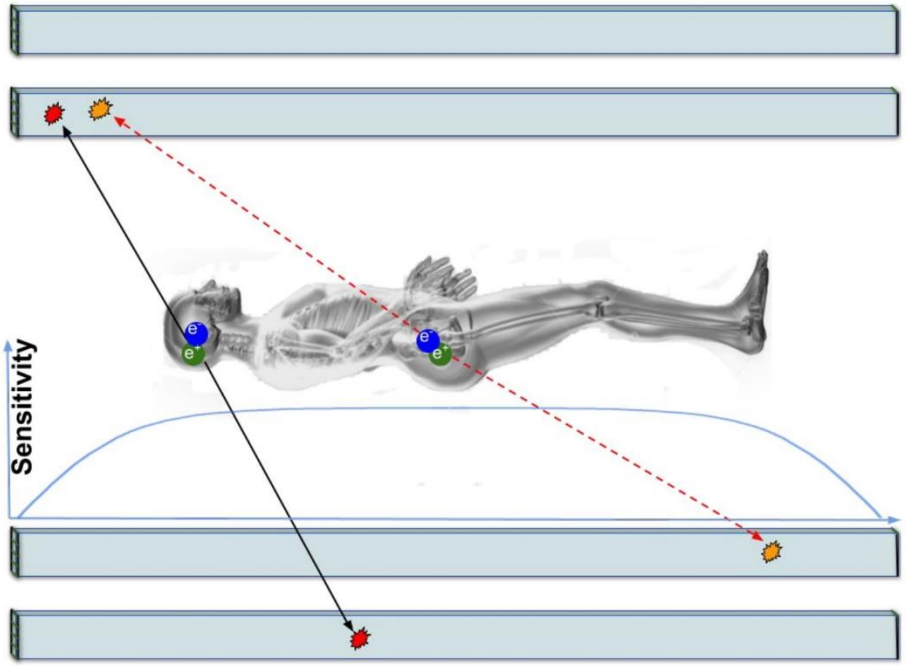
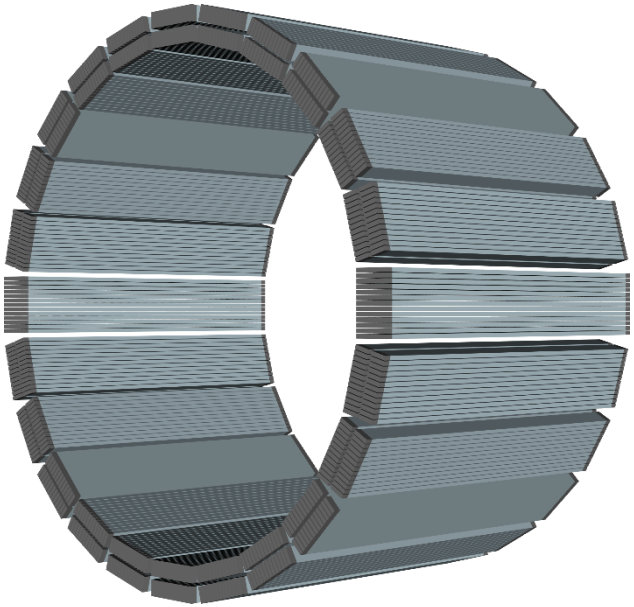
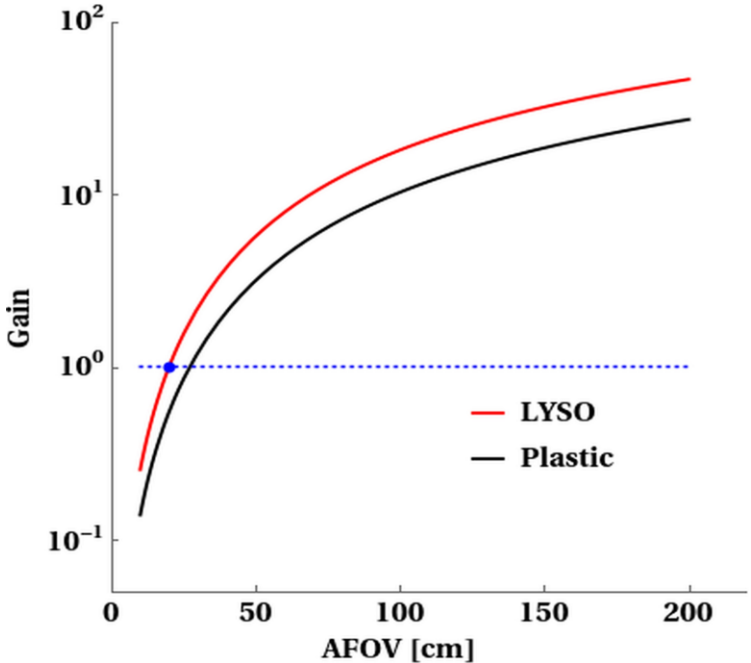
# P. Moskal, E. Ł. Stępień, PET Clinics 15 (2020) 439





# Test of discrete symmetries in positronium decays using J-PET tomograph

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

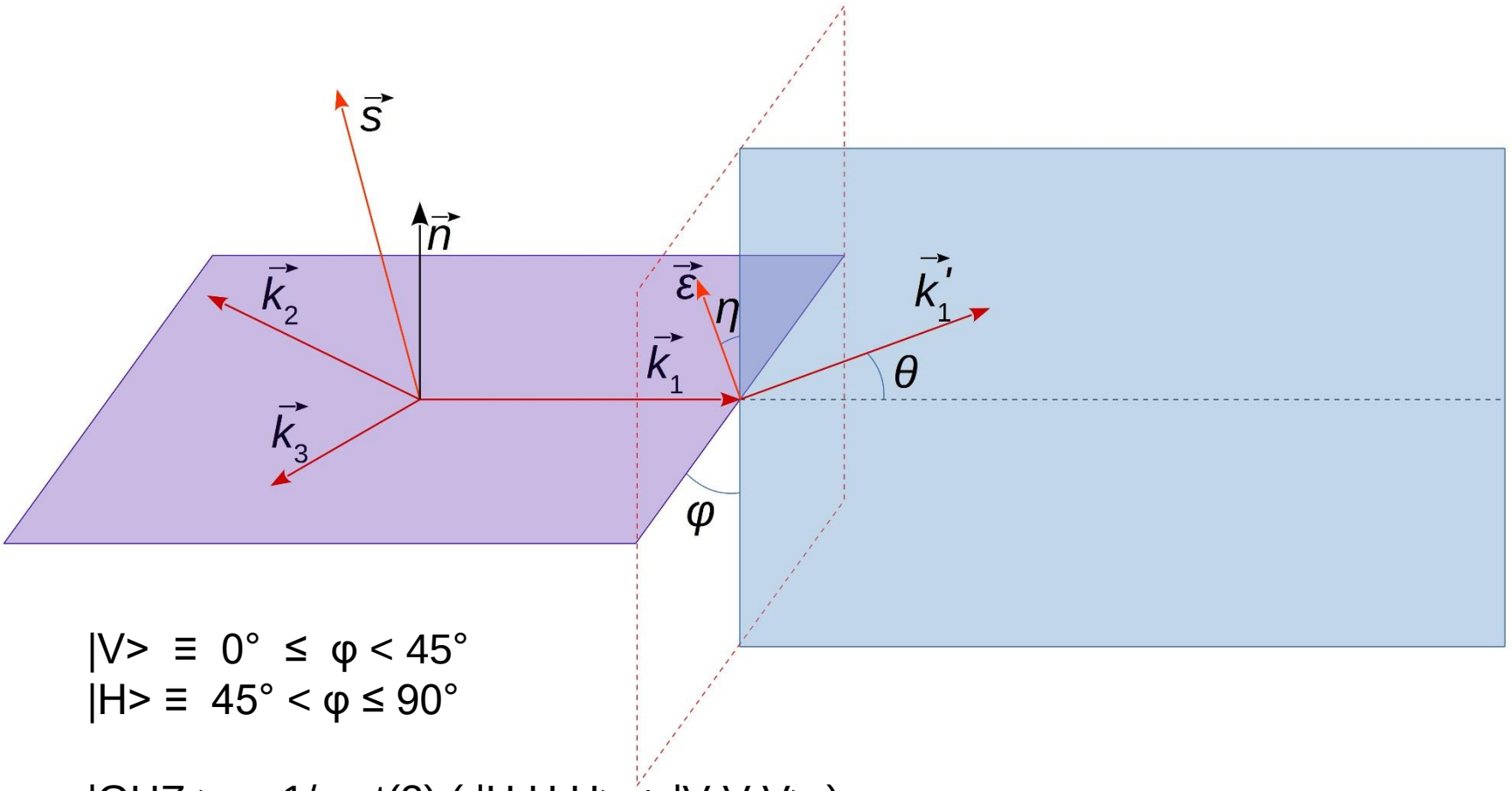
**Bialasówka, AGH, Kraków, 08.10.2021**

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

# Jagiellonian PET

THANK YOU
FOR YOUR ATTENTION

# Jagiellonian PET




$|V\rangle \equiv 0° \leq \varphi < 45°$

$|H\rangle \equiv 45° < \varphi \leq 90°$

$|GHZ\rangle = 1/\sqrt{2}\,(|H\,H\,H\rangle + |V\,V\,V\rangle)$

$|W\rangle = 1/\sqrt{3}\,(|H\,H\,V\rangle + |H\,V\,H\rangle + |V\,H\,H\rangle)$

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# Genuine Multipartite Entanglement in the 3-Photon Decay of Positronium

Received: 23 June 2017
Accepted: 25 October 2017
Published online: 10 November 2017

Beatrix C. Hiesmayr[1] & Pawel Moskal[2]

The electron-positron annihilation into two photons is a standard technology in medicine to observe e.g. metabolic processes in human bodies. A new tomograph will provide the possibility to observe not only direct $e^+e^-$ annihilations but also the 3 photons from the decay of ortho-positronium atoms formed in the body. We show in this contribution that the three-photon state with respect to polarisation degrees of freedom depends on the angles between the photons and exhibits various specific entanglement features. In particular genuine multipartite entanglement, a type of entanglement involving all degrees of freedom, is subsistent if the positronium was in a definite spin eigenstate. Remarkably, when all spin eigenstates are mixed equally, entanglement –and even stronger genuine multipartite entanglement– survives. Due to a "*symmetrization*" process, however, *Dicke*-type or W-type entanglement remains whereas *GHZ*-type entanglement vanishes. The survival of particular entanglement properties in the mixing scenario may make it possible to extract quantum information in the form of distinct entanglement features, e.g., from metabolic processes in human bodies.

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SCIENTIFIC REPORTS

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# Witnessing Entanglement In Compton Scattering Processes Via Mutually Unbiased Bases

Received: 21 August 2018
Accepted: 20 May 2019
Published online: 03 June 2019

Beatrix C. Hiesmayr[1] & Pawel Moskal[2]

We present a quantum information theoretic version of the Klein-Nishina formula. This formulation singles out the quantity, the *a priori* visibility, that quantifies the ability to deduce the polarisation property of single photons. The Kraus-type structure allows a straightforward generalisation to the multiphoton cases, relevant in the decay of positronium which is utilized e.g. for metabolic PET-imaging (Positron- Emission- Tomograph). Predicted by theory but never experimentally proven, the two- or three-photon states should be entangled. We provide an experimentally feasible method to