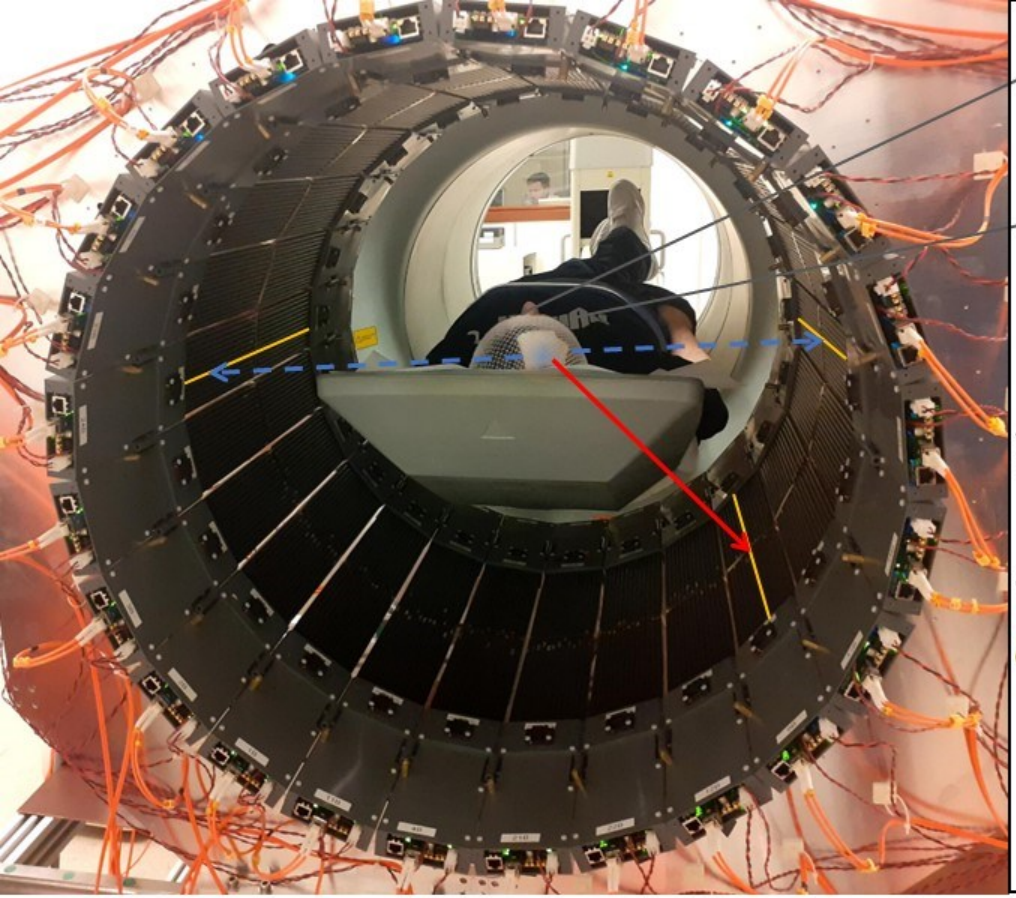
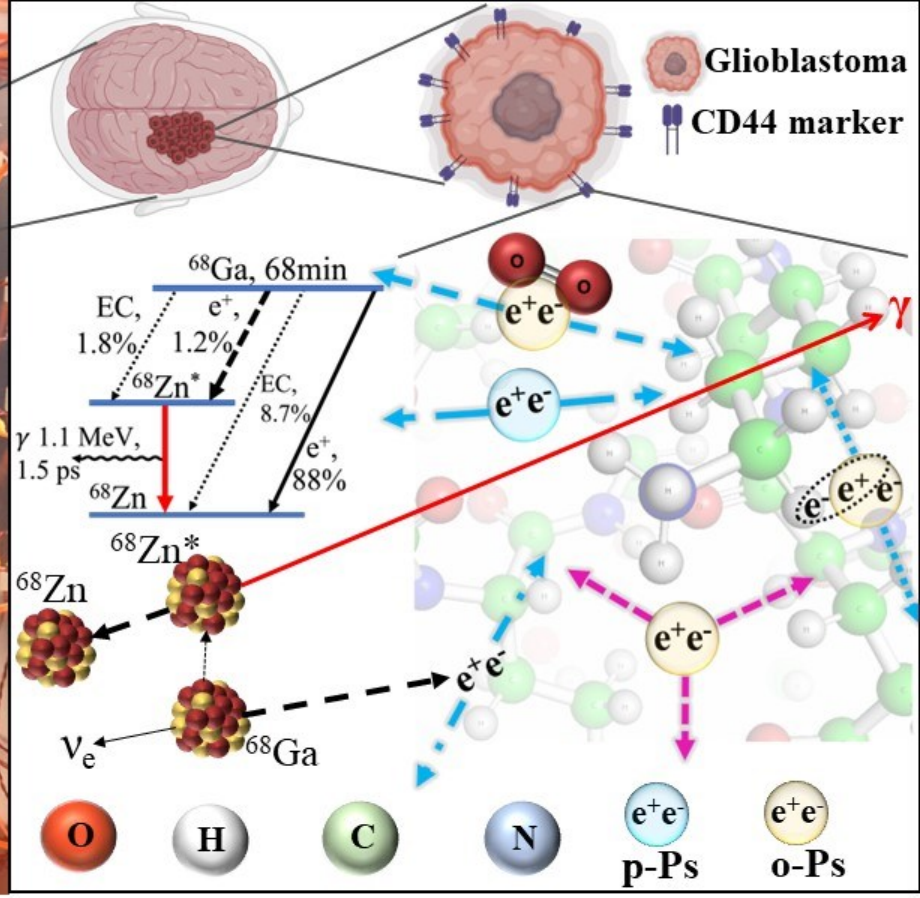
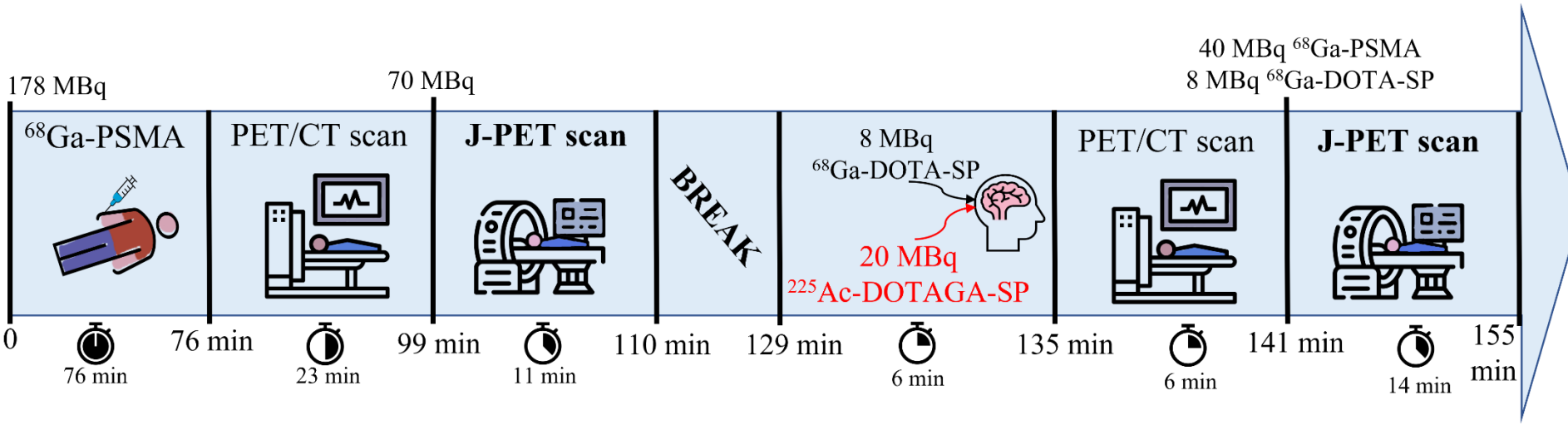
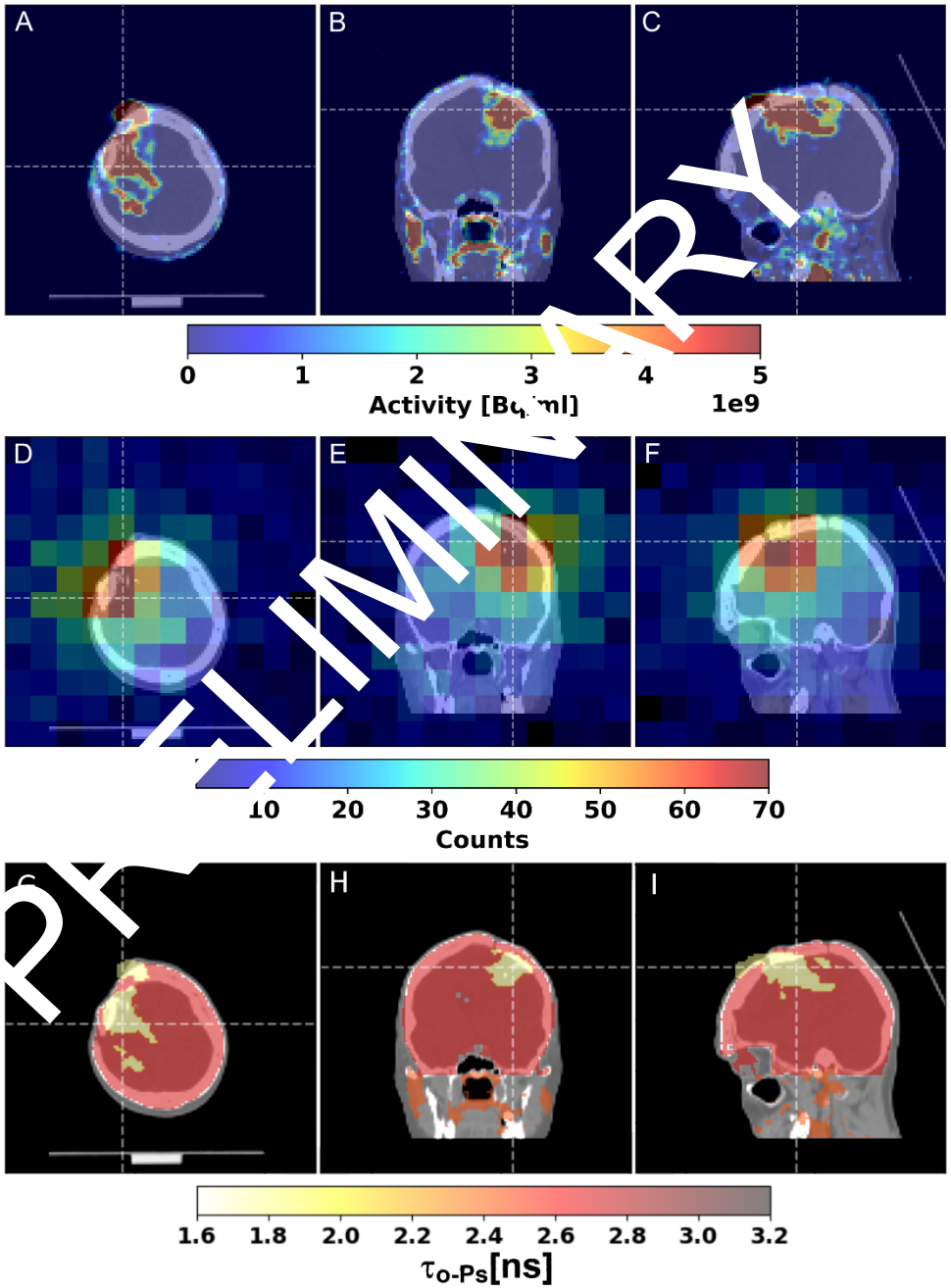



Glioblastoma
CD44 marker
^{68}Ga, 68min
EC, 1.8%
e$^+$, 1.2%
^{68}Zn*
EC, 8.7%
e$^+$, 88%
γ 1.1 MeV, 1.5 ps
^{68}Zn
^{68}Zn*
^{68}Zn
^{68}Ga
ν$_e$
e$^+$e$^-$
γ
O
H
C
N
p-Ps
o-Ps


178 MBq
^{68}Ga-PSMA
70 MBq
PET/CT scan
J-PET scan
BREAK
8 MBq
^{68}Ga-DOTA-SP
20 MBq
^{225}Ac-DOTAGA-SP
40 MBq ^{68}Ga-PSMA
8 MBq ^{68}Ga-DOTA-SP
PET/CT scan
J-PET scan
0
76 min
76 min
23 min
99 min
11 min
110 min
129 min
6 min
135 min
6 min
141 min
14 min
155 min

First clinical positronium imaging of patients



PRELIMINARY

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**

Imaging the decay of positronium atoms using the J-PET tomograph

Bialasówka, AGH, Kraków, 17.05.2024

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

PET from plastic scintillators

P. Moskal et al., Nature Communications 12 (2021) 5658

Testing CPT symmetry in ortho-positronium decays with PET

P. Moskal et al., Physics in Medicine and Biology 66 (2021) 175015

Simulating NEMA characteristics of the modular total-body J-PET scanner

P. Moskal et al., Nature Communications 15 (2024) 78

Discrete symmetries tested at 10−4 precision using linear polarization of photons

POSITRONIUM IMAGING

P. Moskal et al., Nature Reviews Physics 1 (2019) 527

Positronium in physics and biology

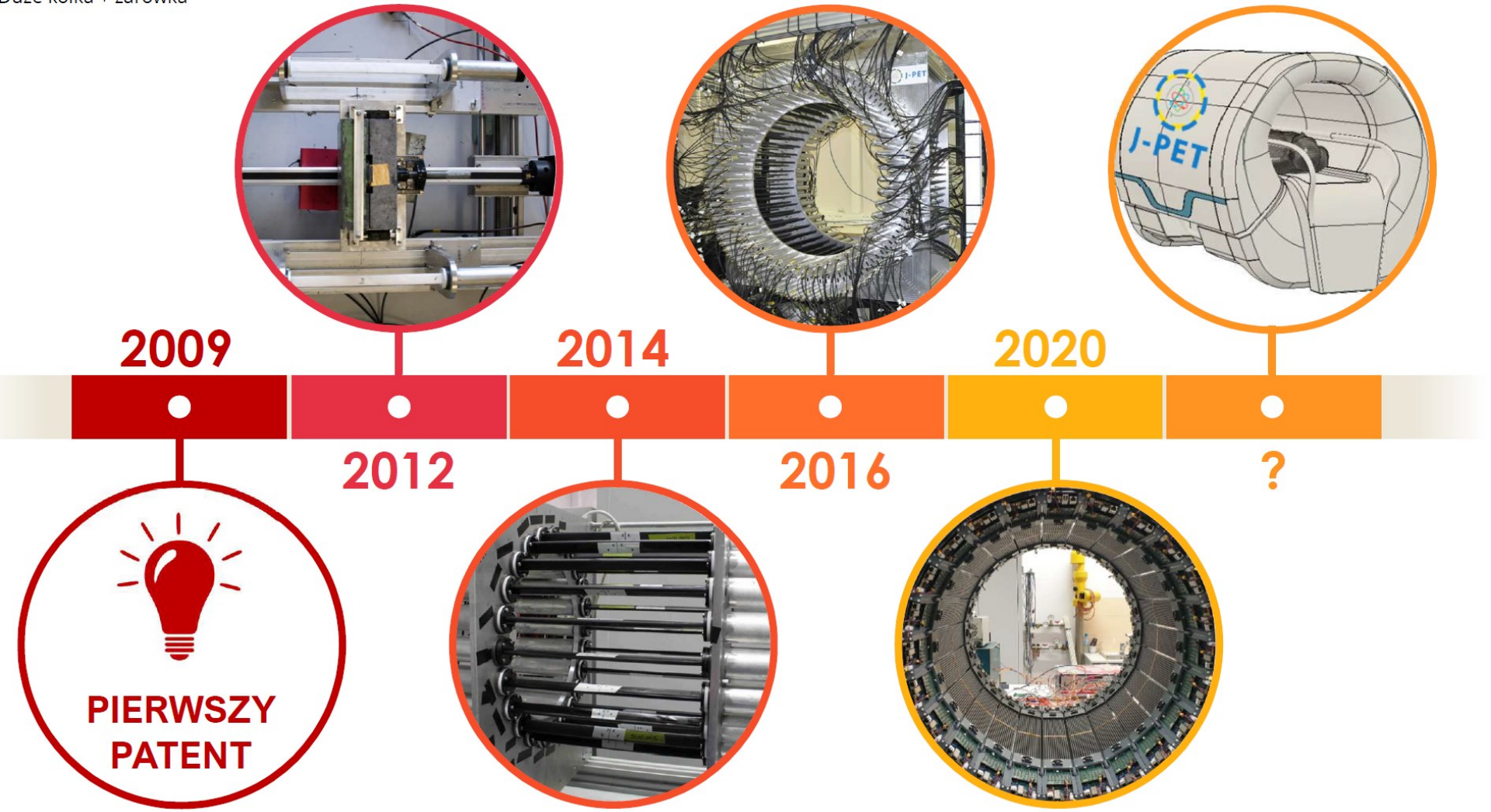
P. Moskal et al., Science Advances 7 (2021) eabh4394

Positronium imaging with the novel multi-photon PET scanner

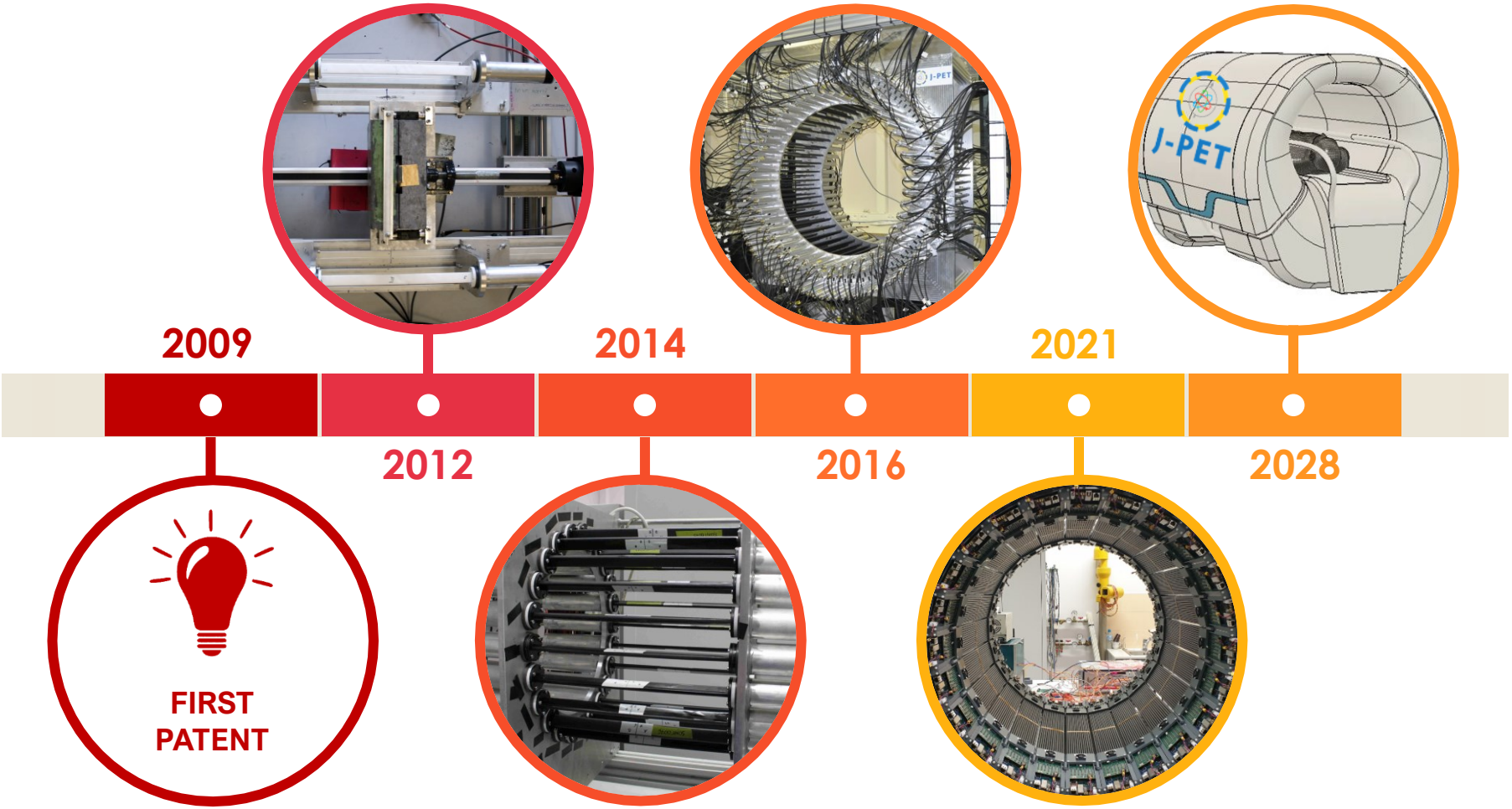
P. Moskal, E. Stępień et al., EJNMMI Physics 10 (2023) 22

Developing a Novel Positronium Biomarker for Cardiac Myxoma Imaging

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)



Financed by:
Ministry of Science and Higher Education
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National Center for Research and Development (Innotech)
National Science Center (OPUSes, MAESTRO)

Imaging the decay of positronium atoms using the J-PET tomograph

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

Bialasówka, AGH, Kraków, 17.05.2024

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

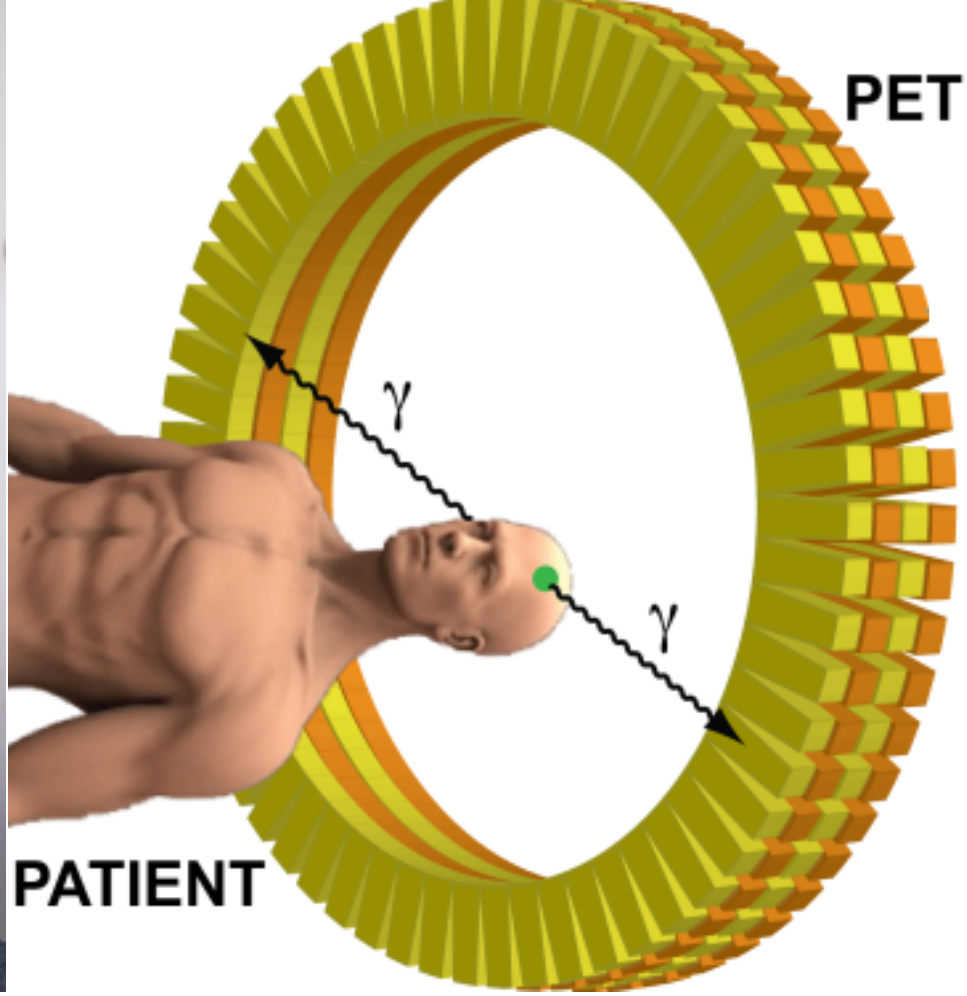
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

J-PET

CENTER FOR THERANOSTICS

J-PET

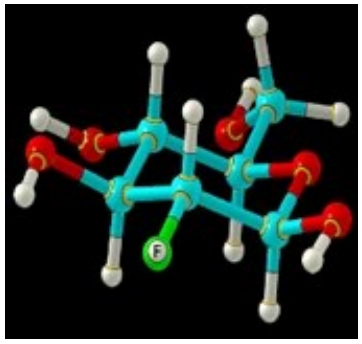
Kraków March 2024



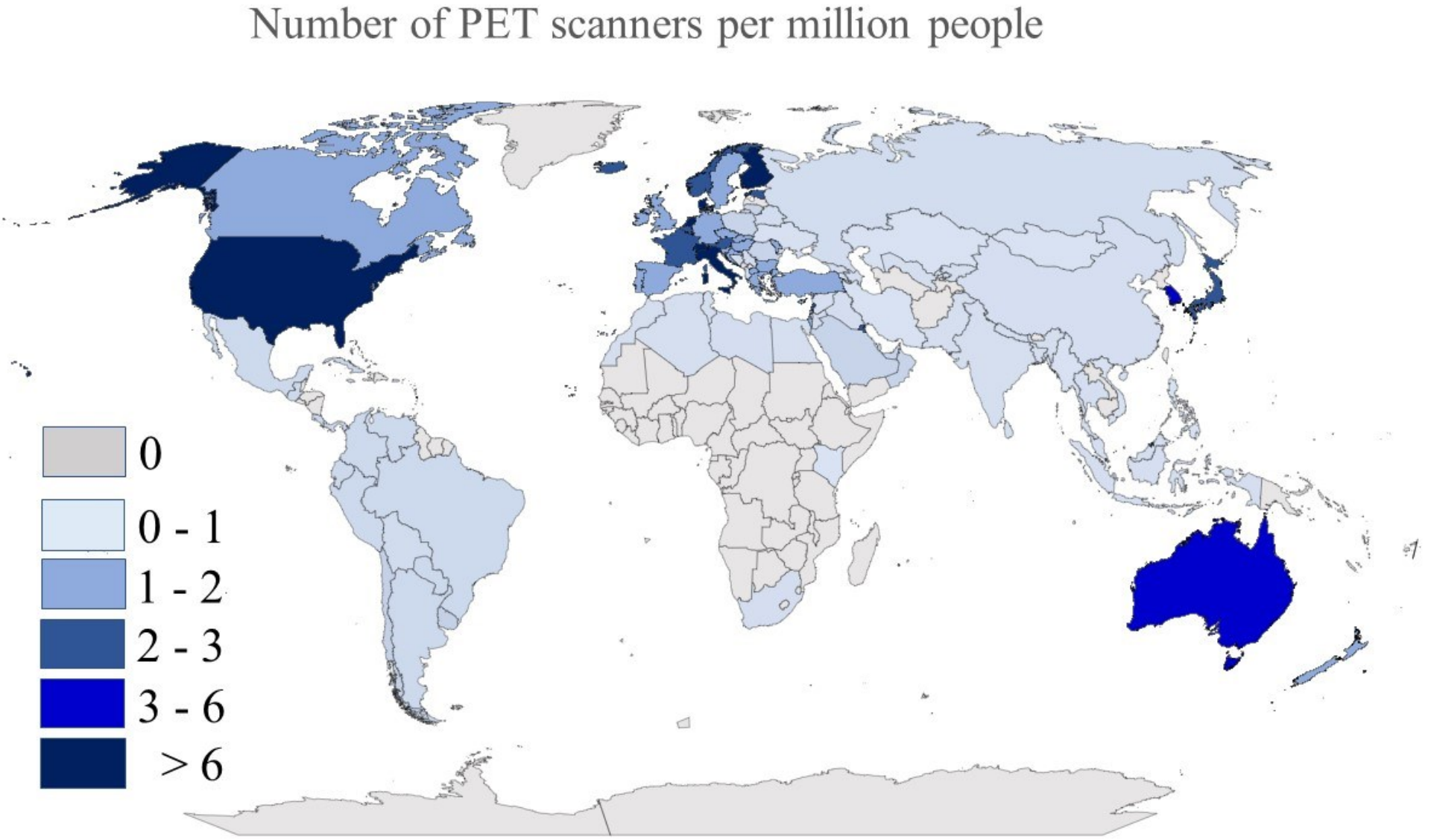
RADIOACTIVE SUGAR

Fluoro–deoksy-glucose
(F-18 FDG)

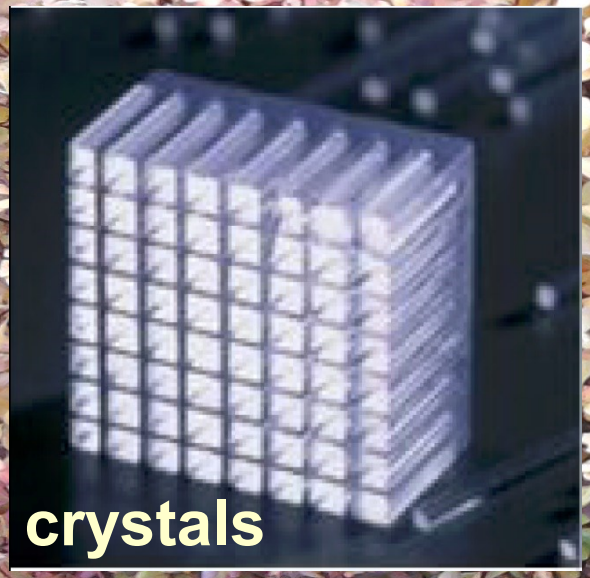
~200 000 000
gamma rays per second

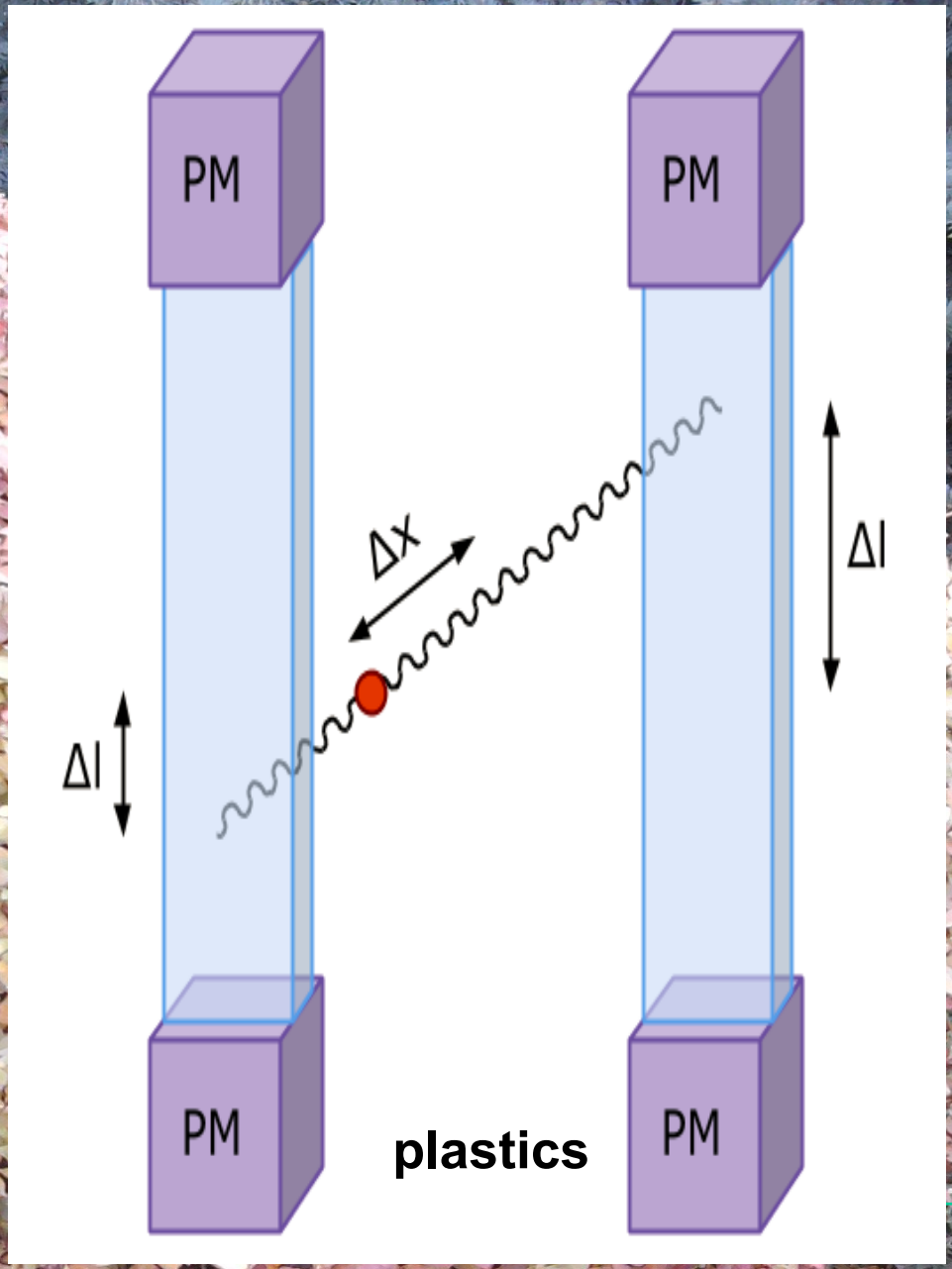


7 mSv PET/CT
~ 2.5 mSv PET
~3 mSv yearly
dose of natural radiation



IAEA Medical imAGIng and Nuclear mEdicine (IMAGINE) database developed by the International Atomic Energy Agency (IAEA) available at: https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINE.html


crystals


PM
PM
PM
PM
Δx
Δl
Δl
plastics

Nowa metoda w tomografii PET !

KAPITAŁ LUDZKI
NARODOWA STRATEGIA SPÓJNOŚCI

Projekt współfinansowany przez Unię Europejską
w ramach Programu Operacyjnego Kapitał Ludzki

UNIA EUROPEJSKA
EUROPEJSKI
FUNDUSZ SPOŁECZNY

numer umowy: Umowa nr CITTRU/061023/01/10/2009
płatne ze środków: budżetu projektu Kompas innowacji (PSP:S/FS0/0023)
jednostka organizacyjna: CITTRU

Warszawa, dnia 17 listopada 2009 roku.

Recenzja wniosku patentowego nr 9534/09

„Urządzenie matrycowe i sposób do wyznaczania miejsca i czasu reakcji kwantów gamma oraz zastosowanie urządzenia do wyznaczania miejsca i czasu reakcji kwantów gamma w emisyjnej tomografii pozytonowej"

Kierując się obecnym stanem wiedzy, zarówno z zakresu dostępnych technologii, jaki i podstaw fizyki uważam, że proponowane rozwiązanie nie nadaje się do zastosowania w praktyce. Przedłożony wniosek przedstawia ogólną definicję tomografii pozytonowo emisyjnej, natomiast w dalszym jego części proponuje rozwiązania, które świadczą o niezrozumieniu zasady działania układu detekcyjnego będącego fizyczną podstawą dyskutowanej metody obrazowania, czyli detekcji kwantów anihilacji gamma o energii 511 keV.

Nowa metoda w tomografii PET !

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Warszawa, dnia 17 listopada 2009 roku.

P. Moskal, Patents: EP2454612B1 (2014), US 8,969,817 (2015), JP 5824773 (2015)

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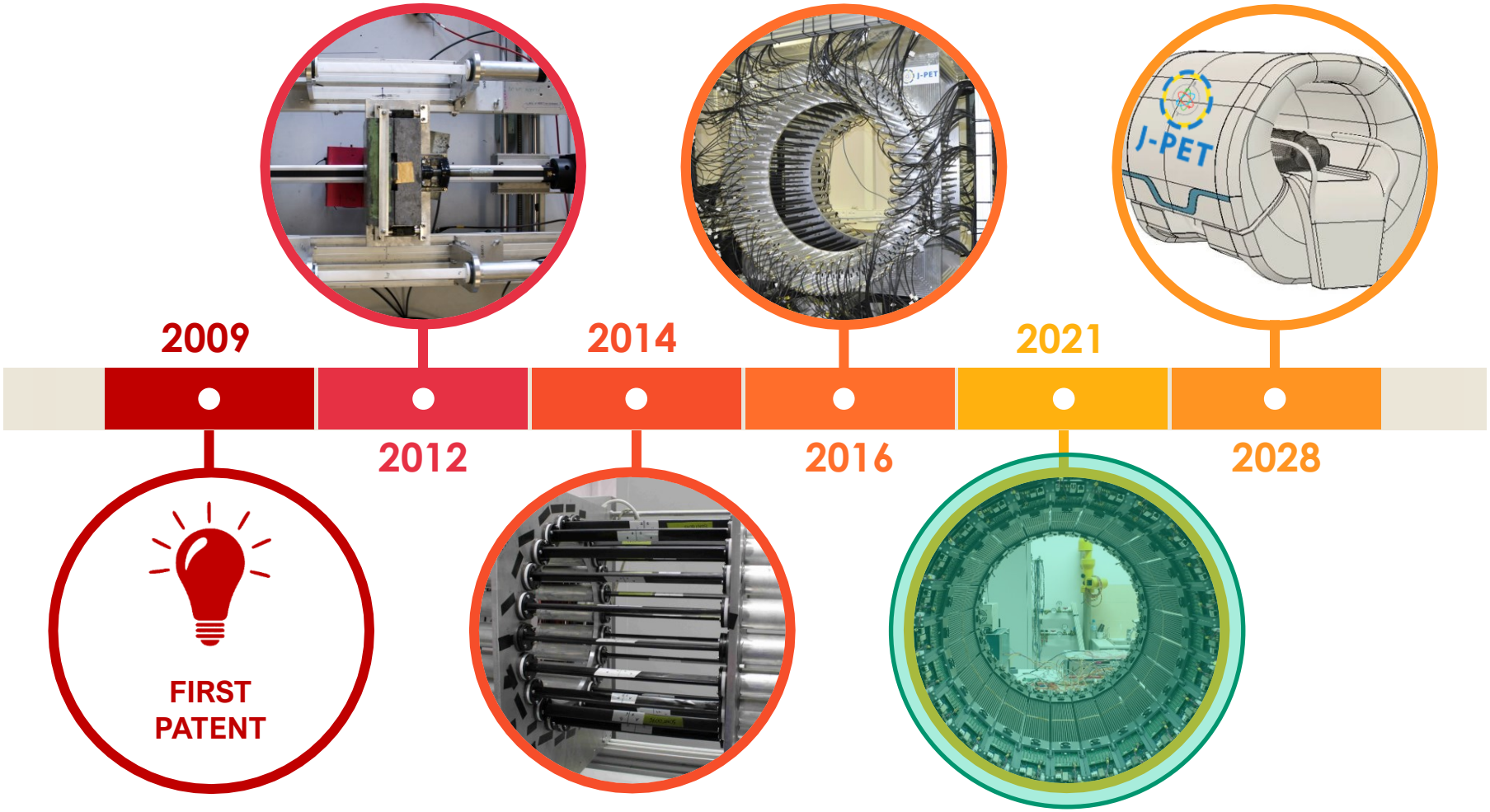
DISCLAIMER

Poland: PL 218733, PL 229380, PL 227657, PL 228457, PL 227660, PL 223751, PL 228483, PL 227658, PL 227661, PL 228119, PL 227659, PL 225474, PL 227854, PL 228003, PL 233378

Europe: EP 2454611, EP 2454612, EP 3039456, EP 3039453, EP 3189356, EP 3189523, EP 3 323 001, EP 3347742, EP 3513221

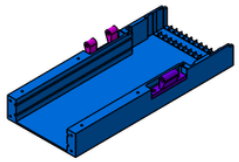
USA: US 8,969,817, US 8,859,973, US 10,007,011, US 9,804,206, US 9,804,279, US 9,804,274, US 10,520,568, US 9,798,021, US 9,851,456, US 10,042,058, US 10,088,581, US 10,126,257, US 10,329,481, US 10,339,676

Japan: JP 5824773, JP 5824774, JP 6580675



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

Development of cost-effective total-body PET

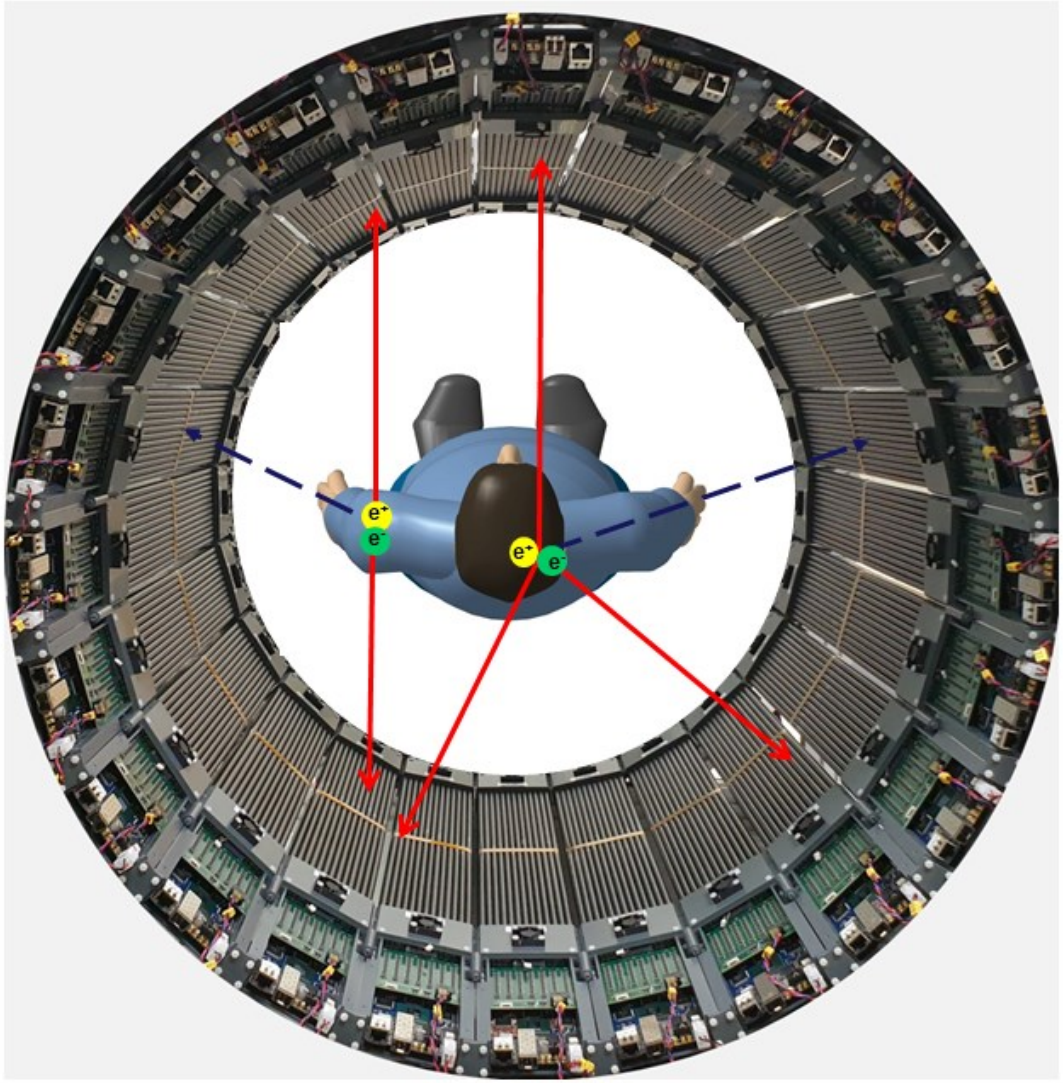


Aim:

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

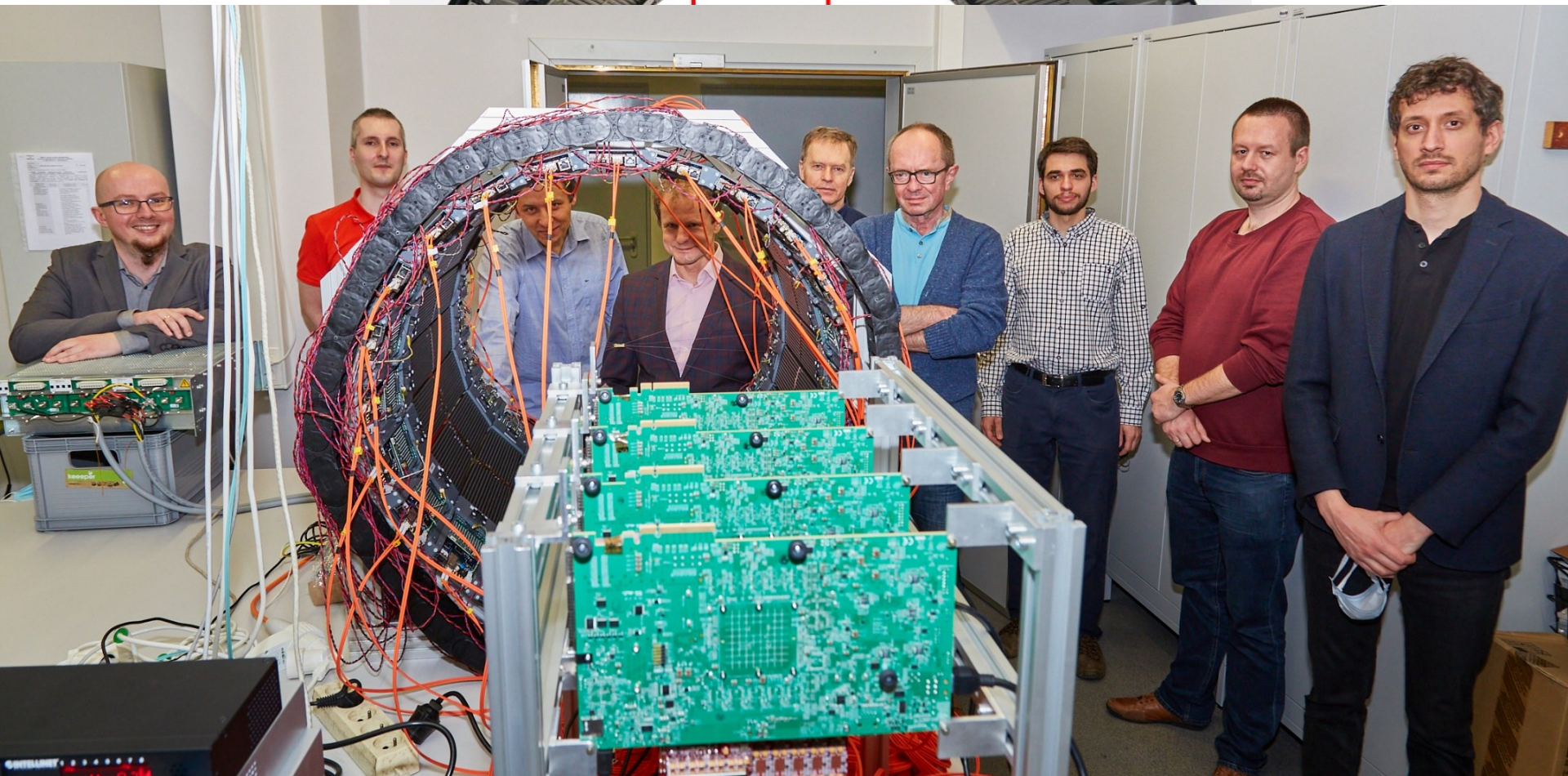
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

Modular J-PET scanner



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

Modular J-PET scanner



Modular J-PET scanner

IEEE TIM 2021

IEEE TNS 2020

SoftwareX 2020

JINST 2017

Adv. HEP 2018

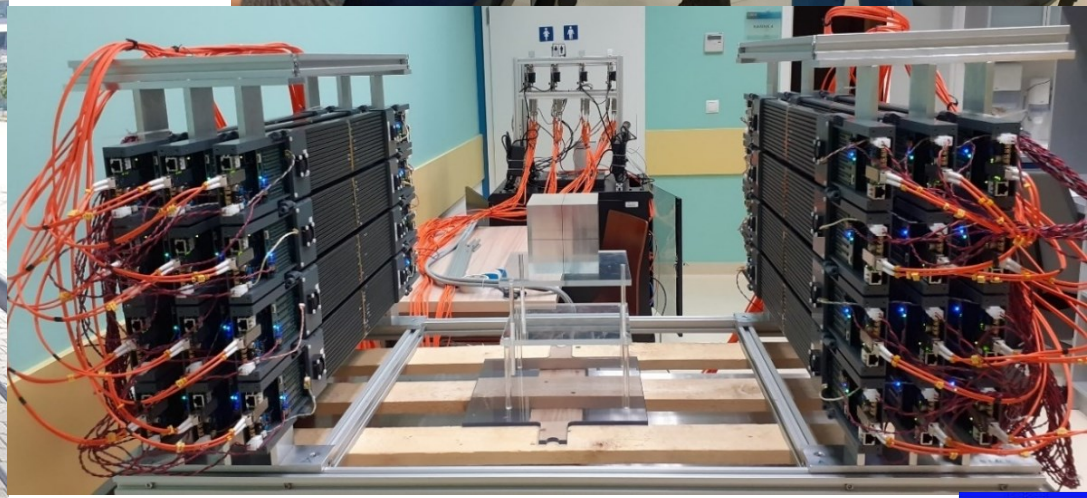
NIM 2016

IEEE TMI 2018

https://www.thebraintumourcharity.org/media-centre/news/research-news/pencil-beam-scanning-proton-therapy-could-spare-me/

Proton beam range monitoring using modular J-PET scanner

Proton beam range monitoring using modular J-PET scanner



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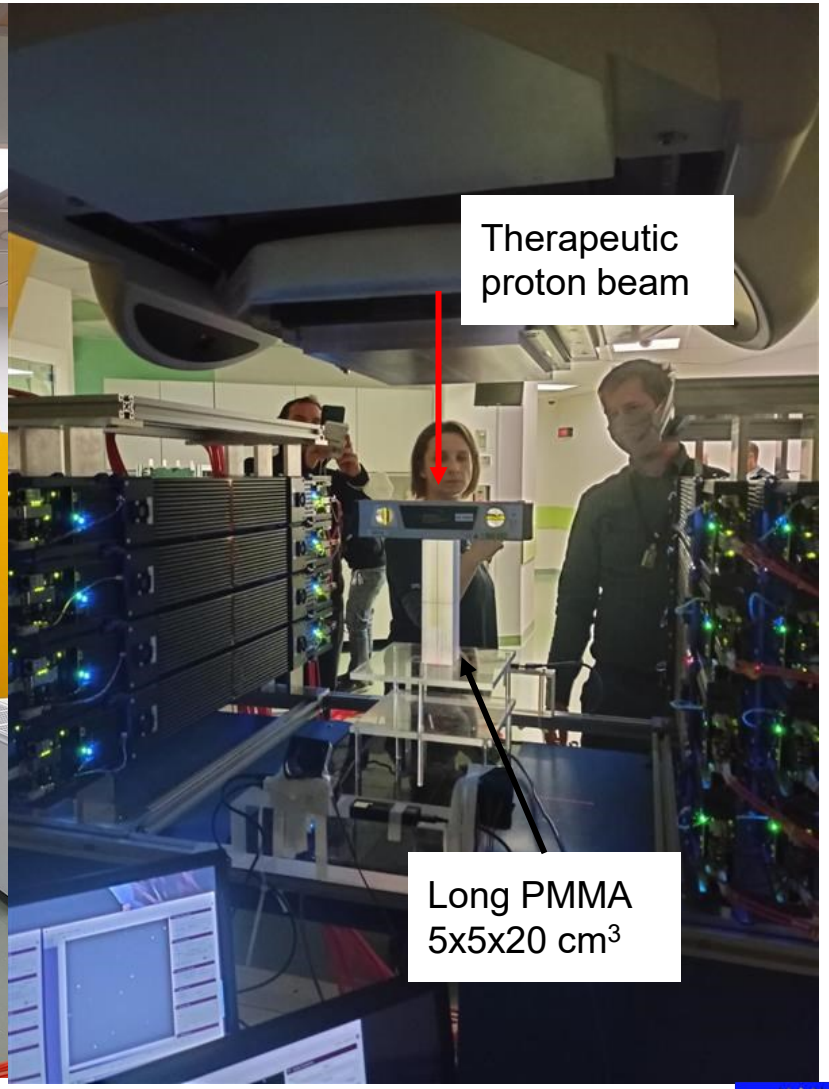
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

Proton beam range monitoring using modular J-PET scanner



P. Moskal, Jagiellonian University
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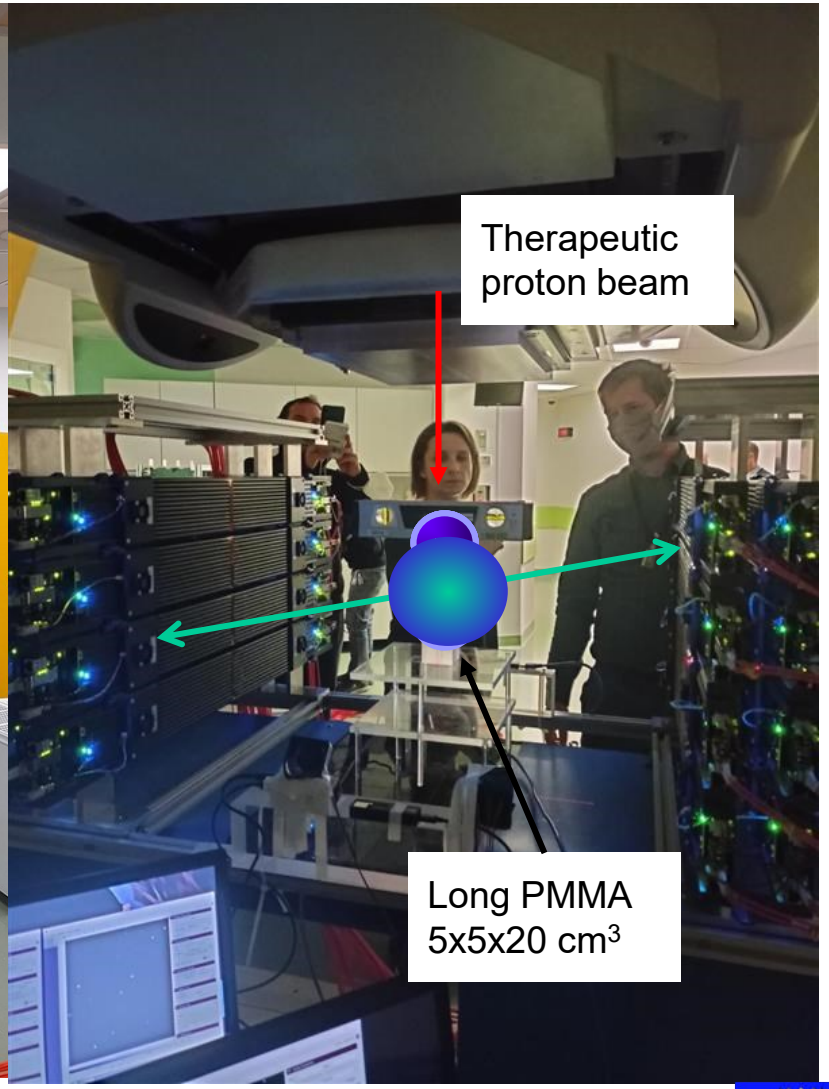
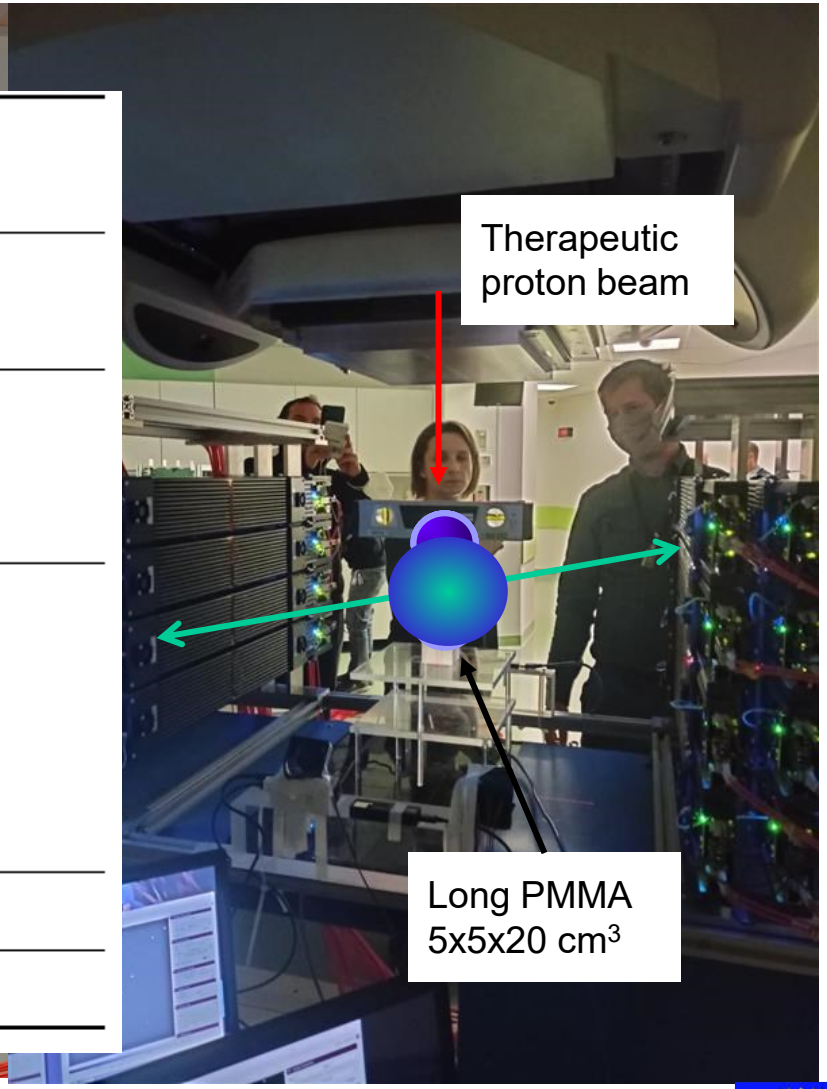
Proton beam range monitoring using modular J-PET scanner



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

Proton beam range monitoring using modular J-PET scanner

TARGET	NUCLEAR REACTION CHANNELS	β^+ ISOTOPES	HALF-LIFE
C	$^{12}C(p,pn)^{11}C$, $^{12}C(p,p2n)^{10}C$	^{10}C, ^{11}C	19.29 s, 20.33 min
N	$^{14}N(p,2p2n)^{11}C$, $^{14}N(p,pn)^{13}N$, $^{14}N(p,pn)^{14}O$	^{13}N	9.96 min
O	$^{16}O(p,pn)^{15}O$, $^{16}O(p,3p3n)^{11}C$, $^{16}O(p,2p2n)^{13}N$, $^{16}O(p,p2n)^{14}O$, $^{16}O(p,3p4n)^{10}C$	^{14}O, ^{15}O	70.61 s, 122.24 s
P	$^{31}P(p,pn)^{30}P$	^{30}P	2.50 min
Ca	$^{40}Ca(p,2pn)^{38}K$	^{38}K	7.64 min

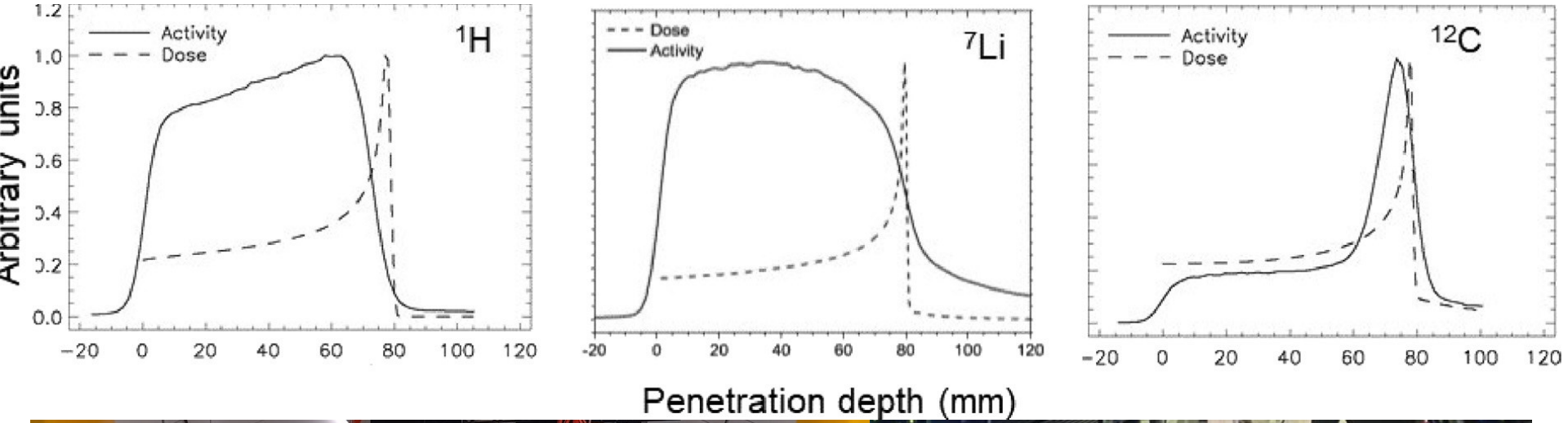


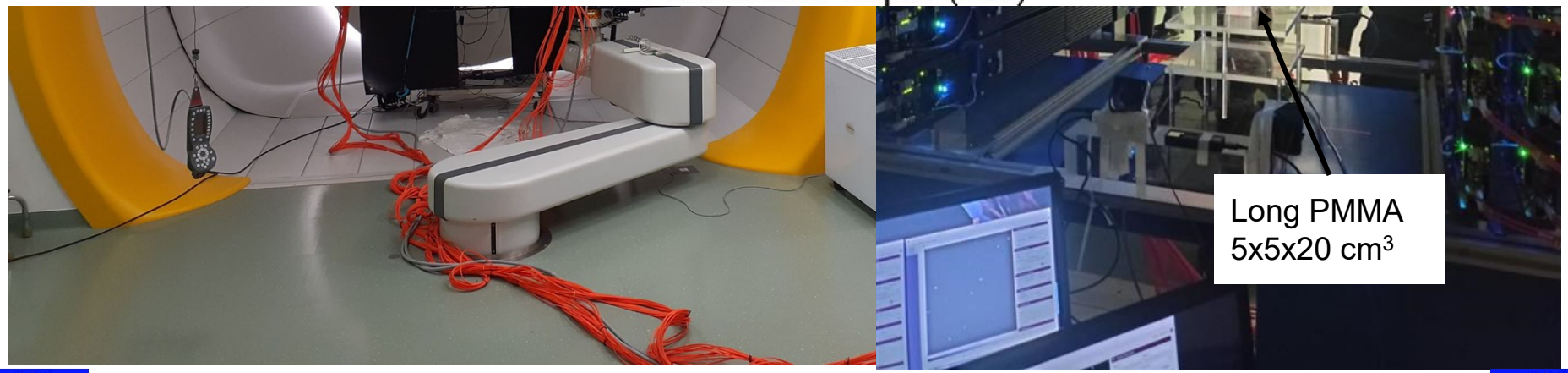
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

Proton beam range monitoring using modular J-PET scanner

K.Parodi, T. Yamaya, P. Moskal, Z Med Phys 33 (2023) 22–34

Experience and new prospects of PET imaging for ion beam therapy monitoring





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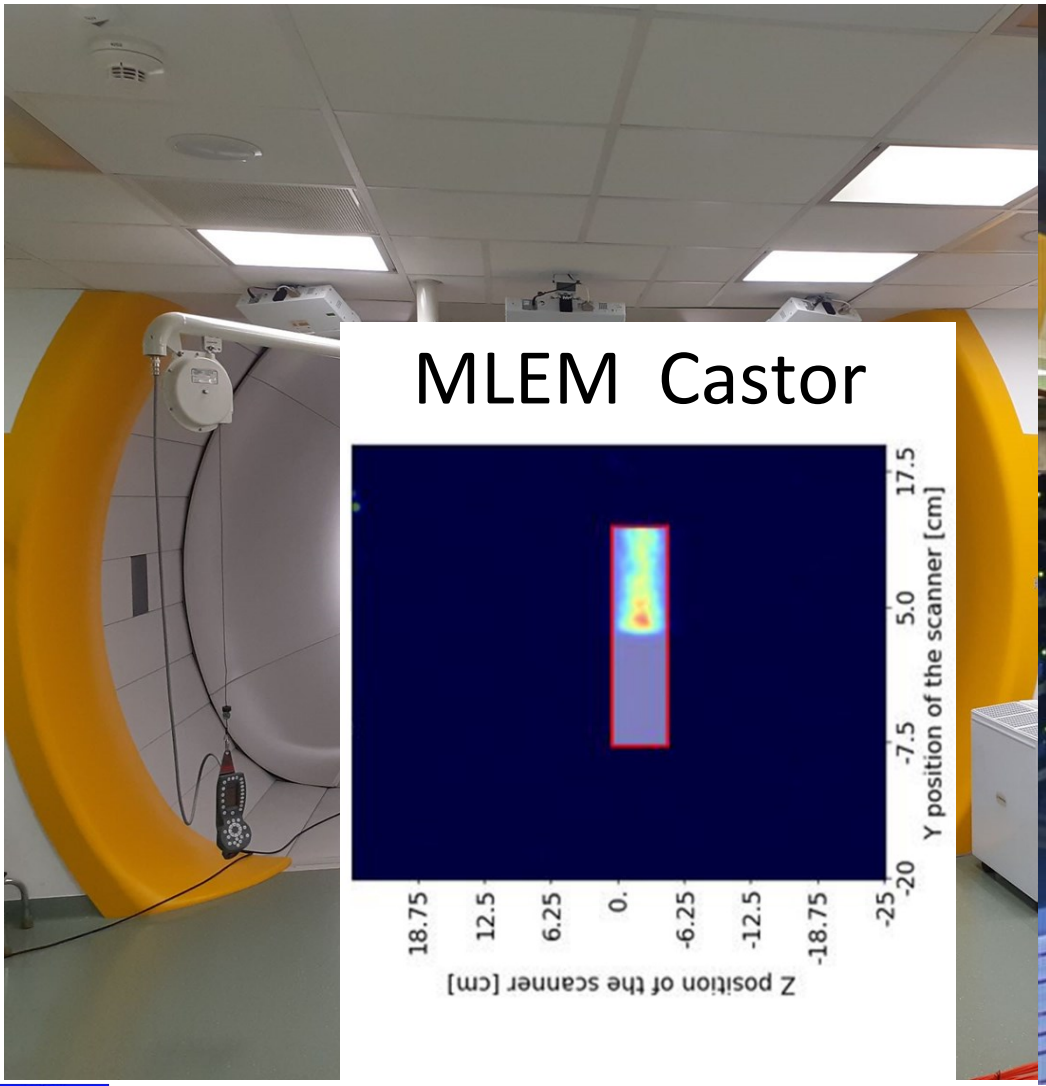
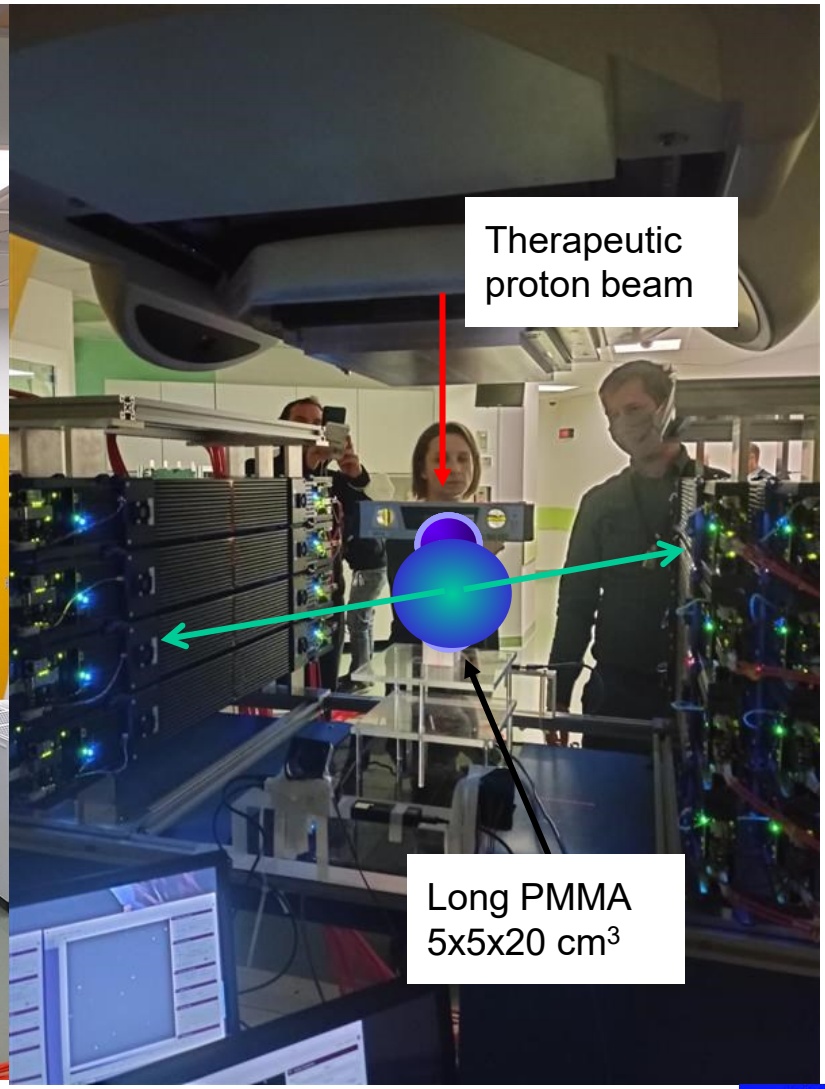
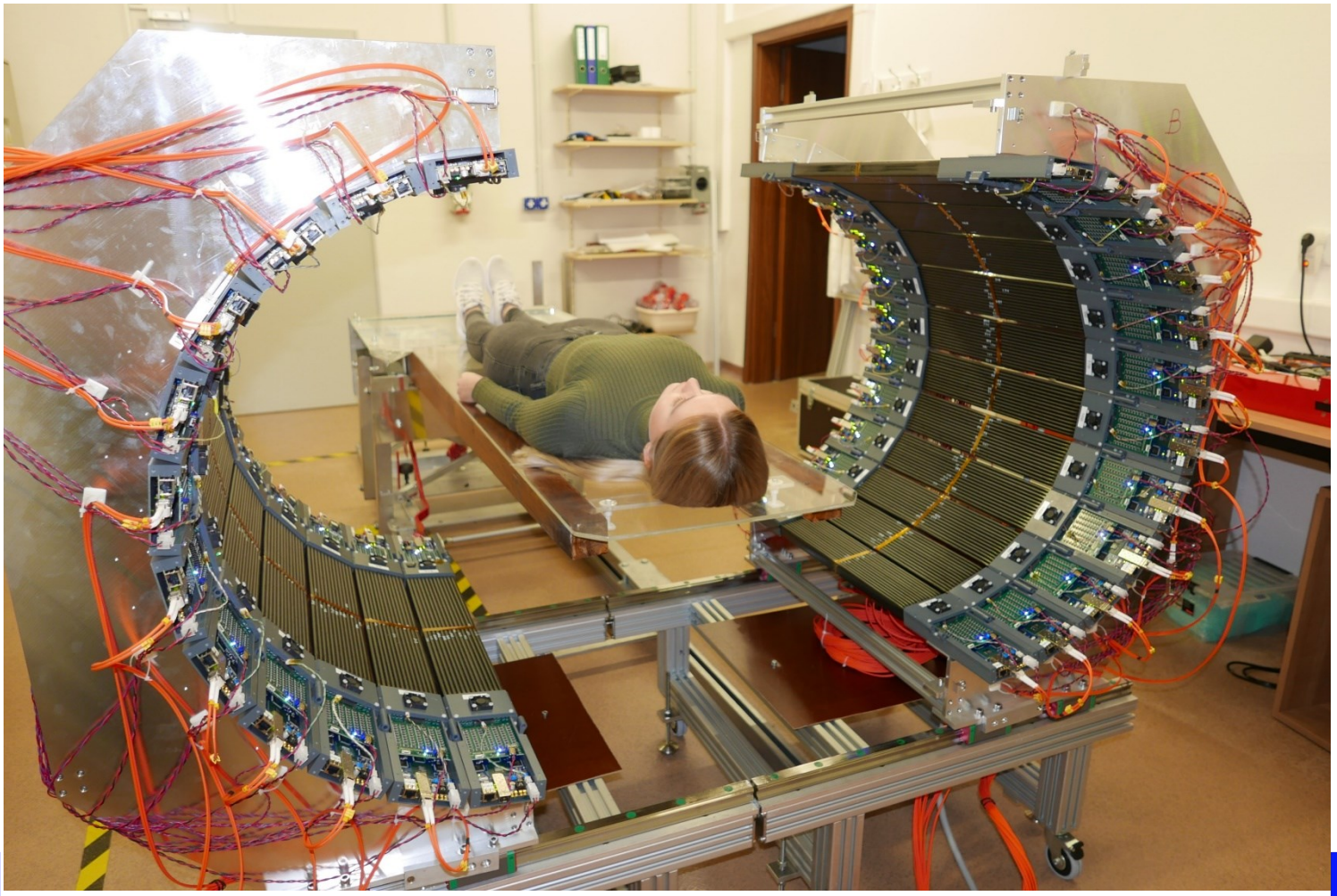
Proton beam range monitoring using modular J-PET scanner





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

First clinical positronium imaging of patients



P. Moskal, Jagiellonian University
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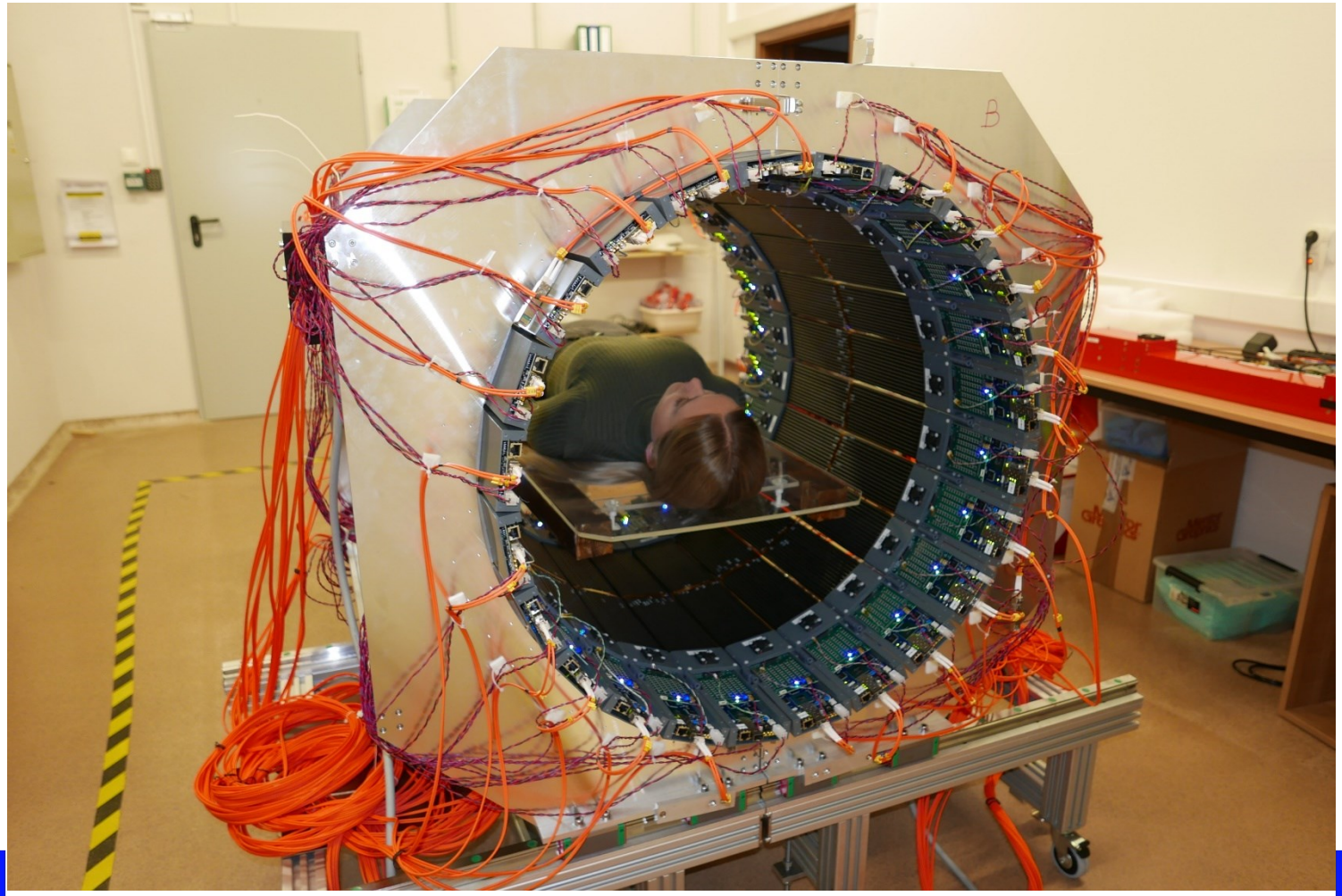
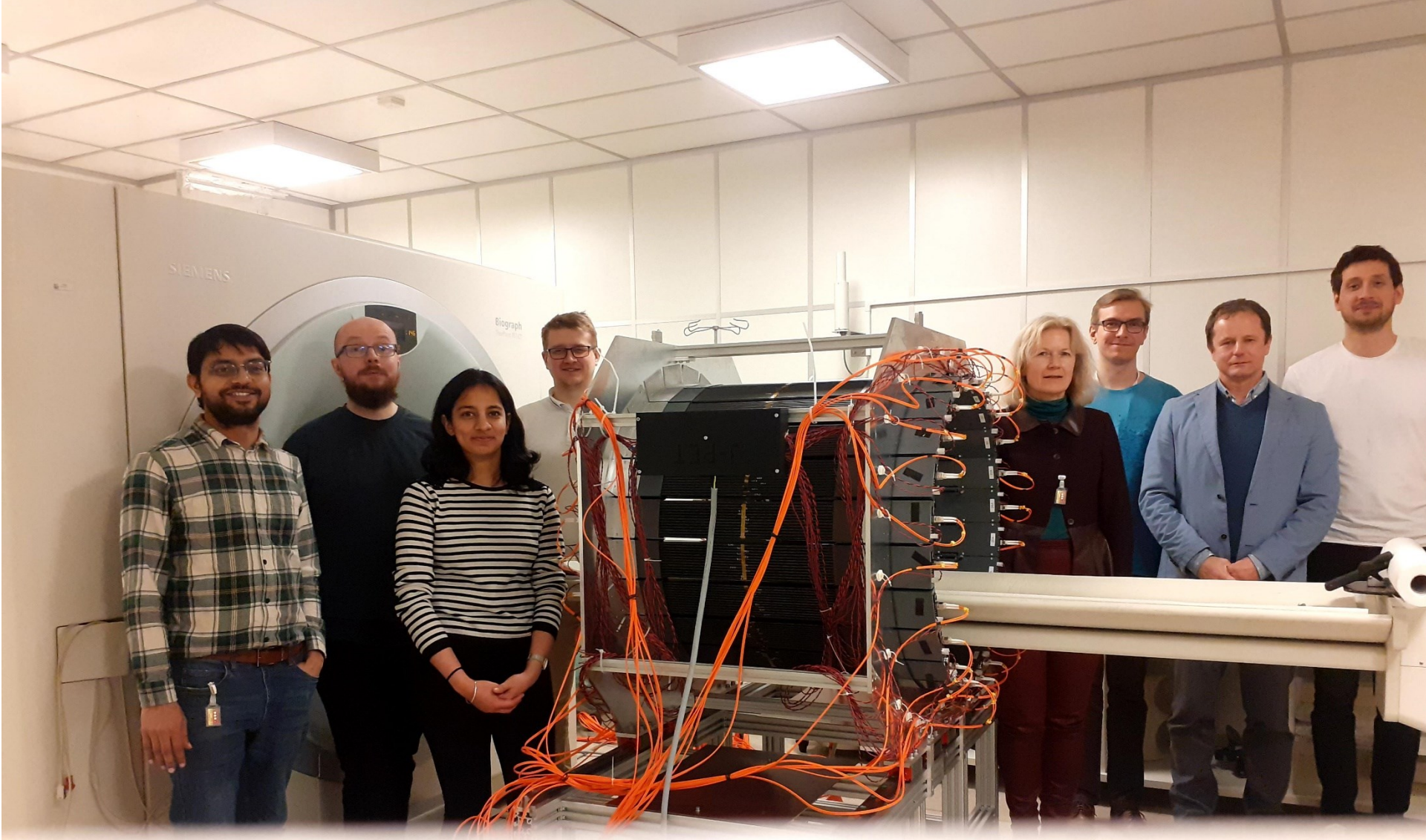
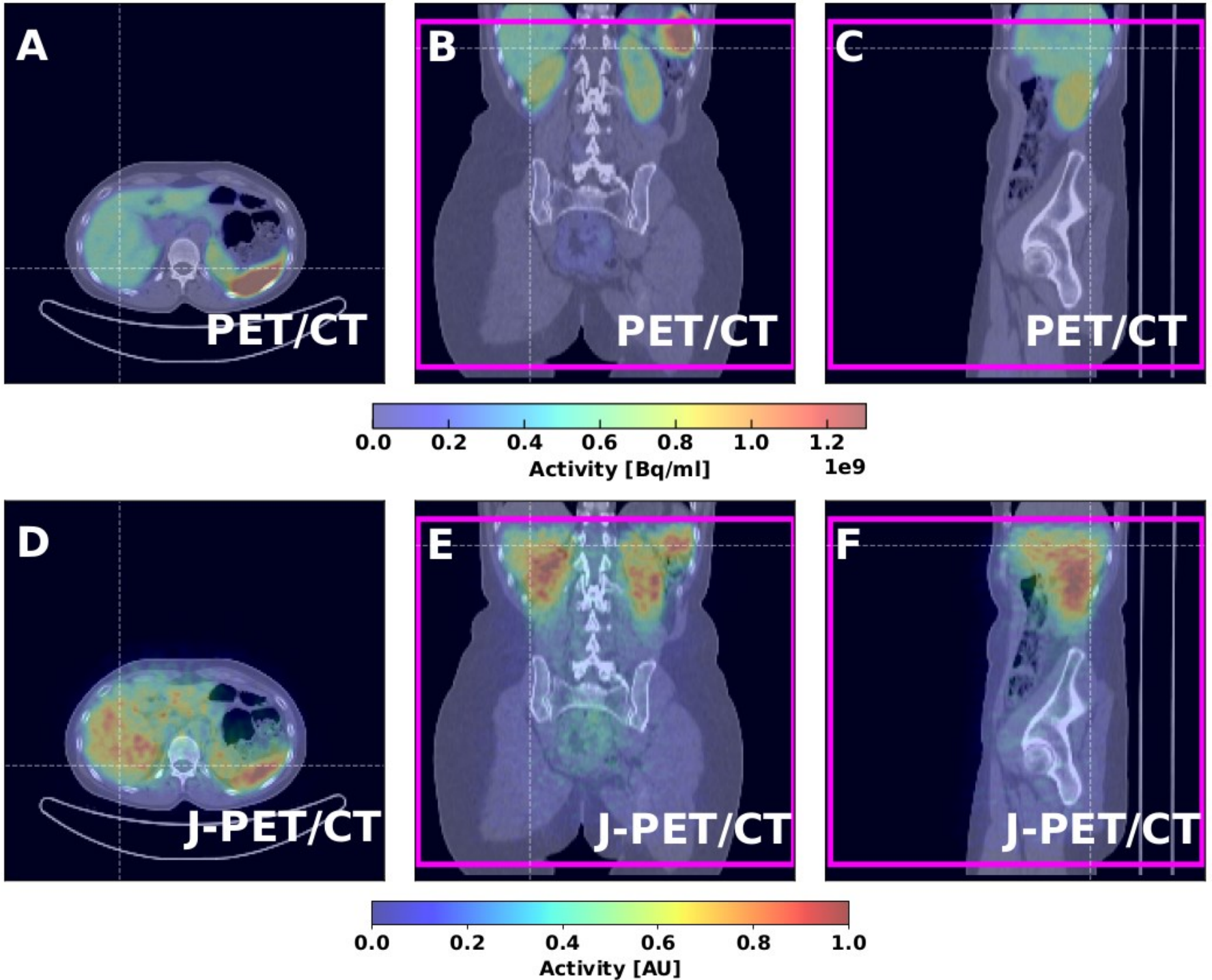
First clinical positronium imaging of patients



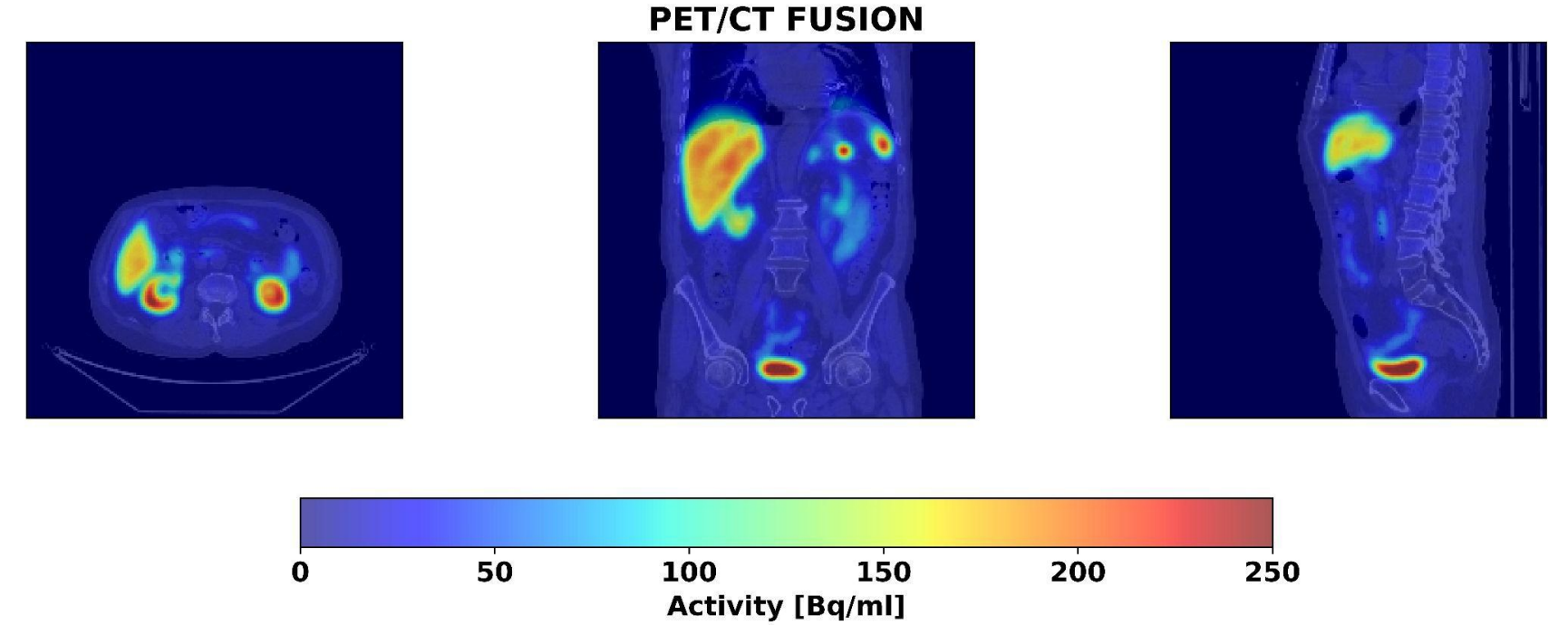
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

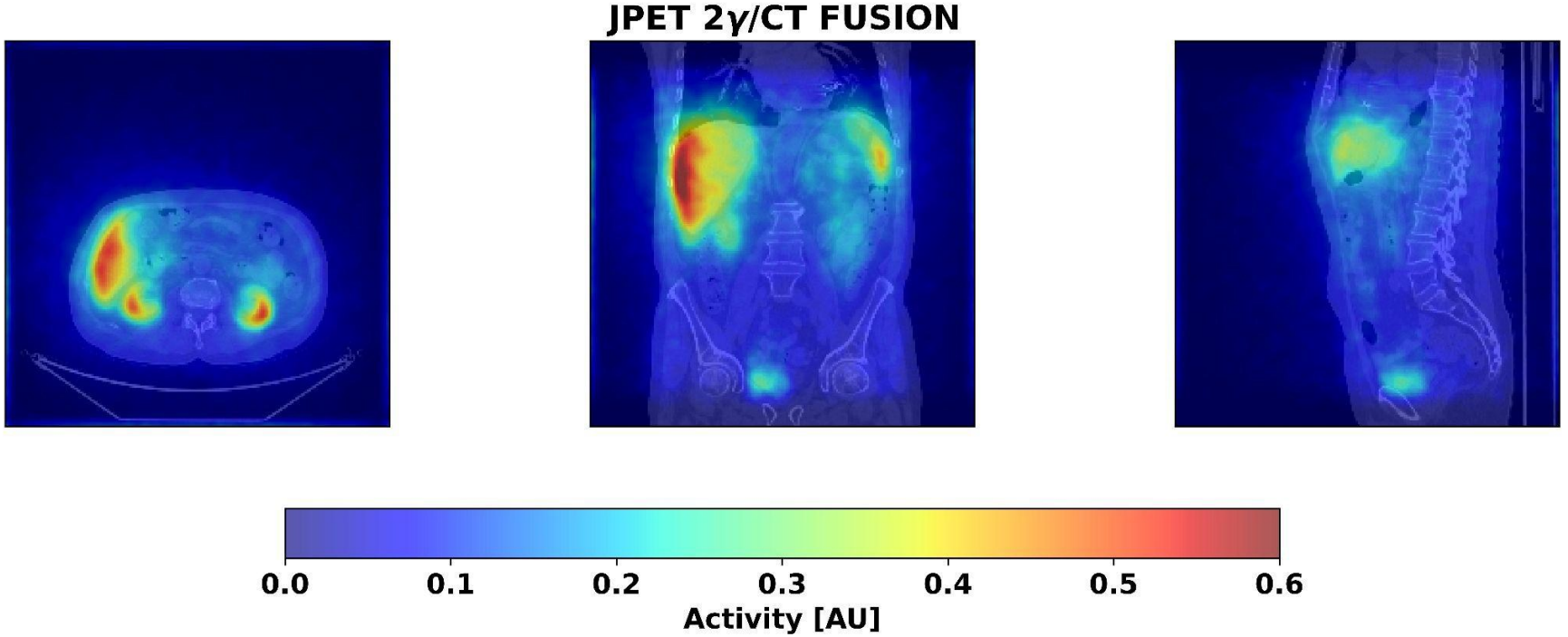

SIEMENS
Biograph

First clinical PET and positronium imaging of patients with J-PET
Biograph
J-PET: P. Moskal et al., 2022


A
PET/CT
B
PET/CT
C
PET/CT
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1e9
Activity [Bq/ml]
D
J-PET/CT
E
J-PET/CT
F
J-PET/CT
0.0
0.2
0.4
0.6
0.8
1.0
Activity [AU]

4935


PET/CT FUSION
0
50
100
150
200
250
Activity [Bq/ml]

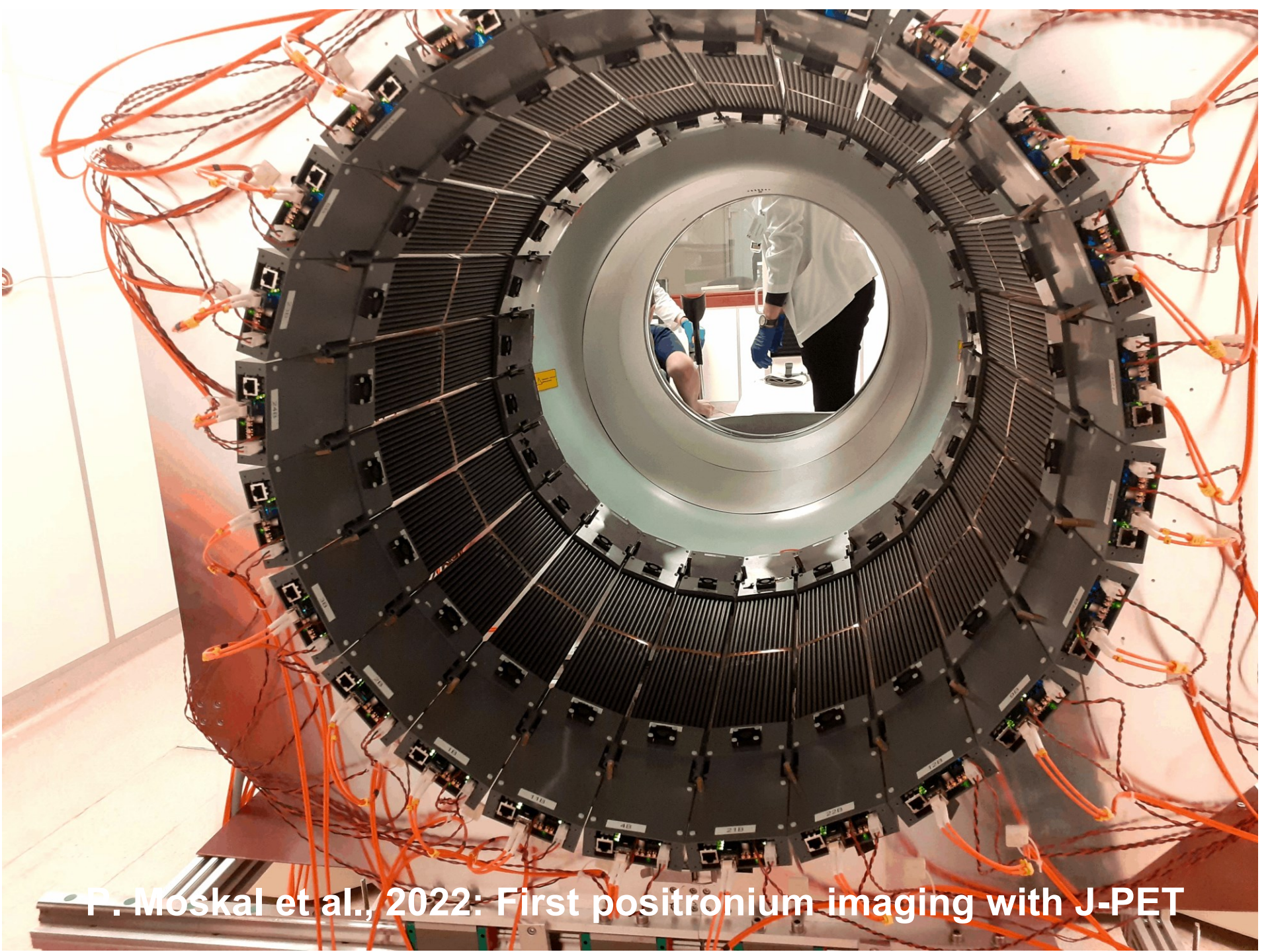

JPET 2γ/CT FUSION
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Activity [AU]

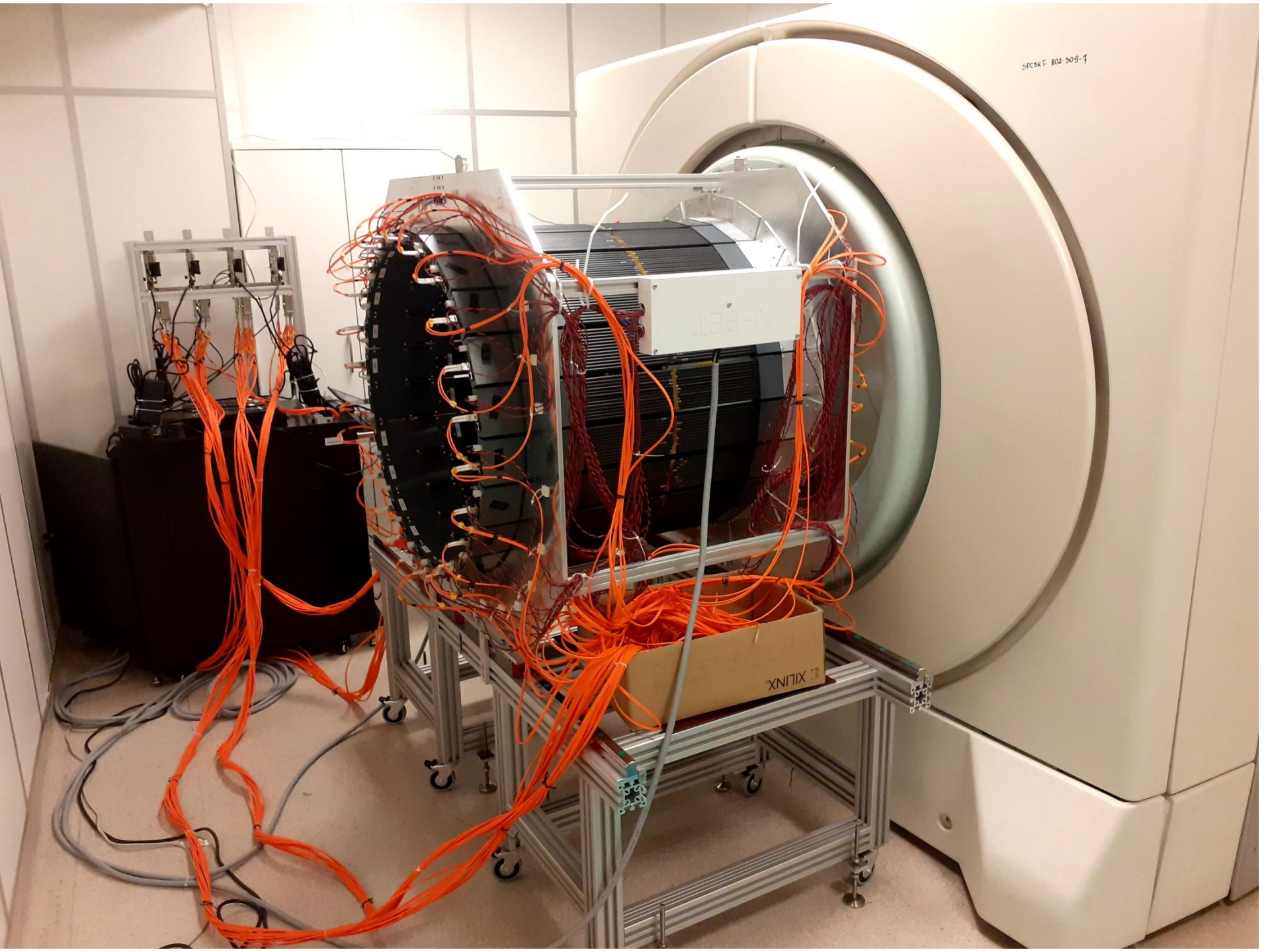
Imaging the decay of positronium atoms using the J-PET tomograph

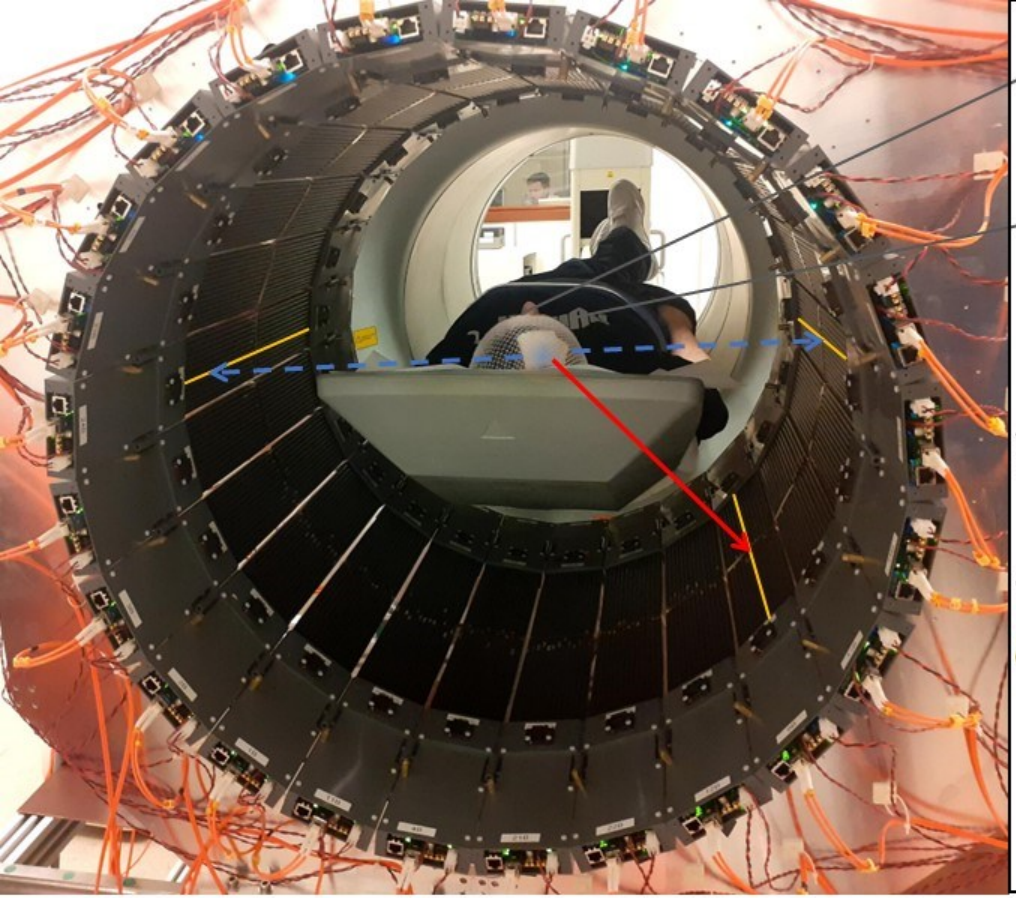
- Jagiellonian-PET (J-PET)
- Positronium imaging
- Discrete symmetries

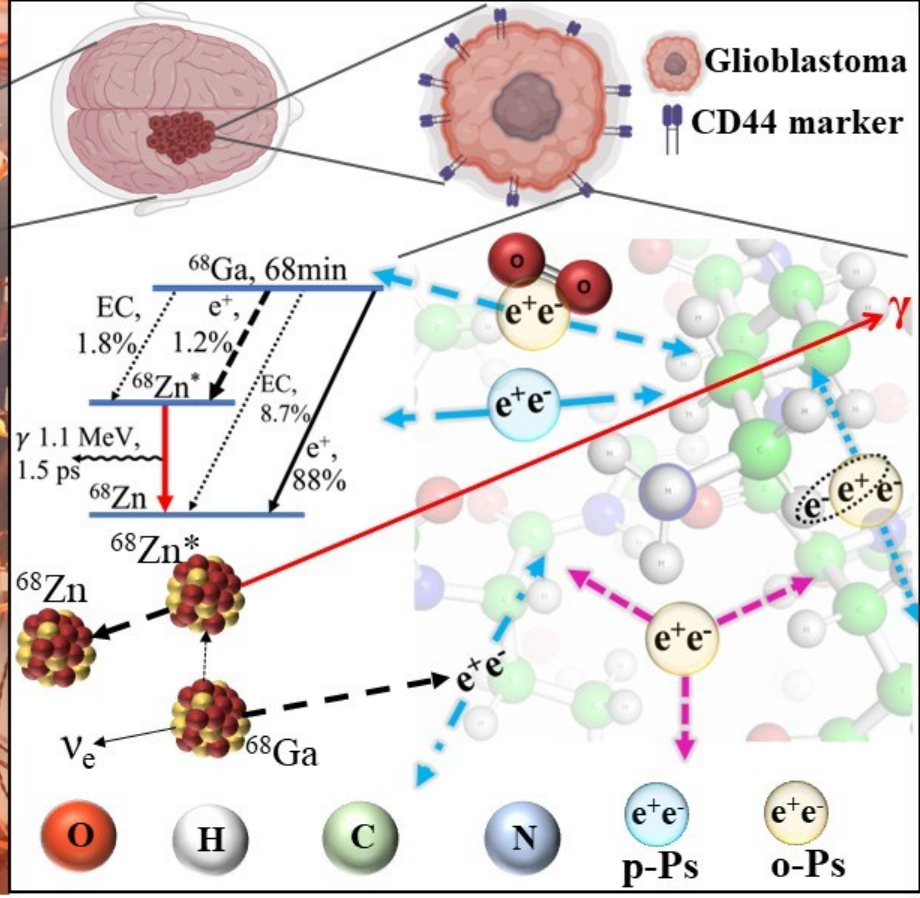
Bialasówka, AGH, Kraków, 17.05.2024

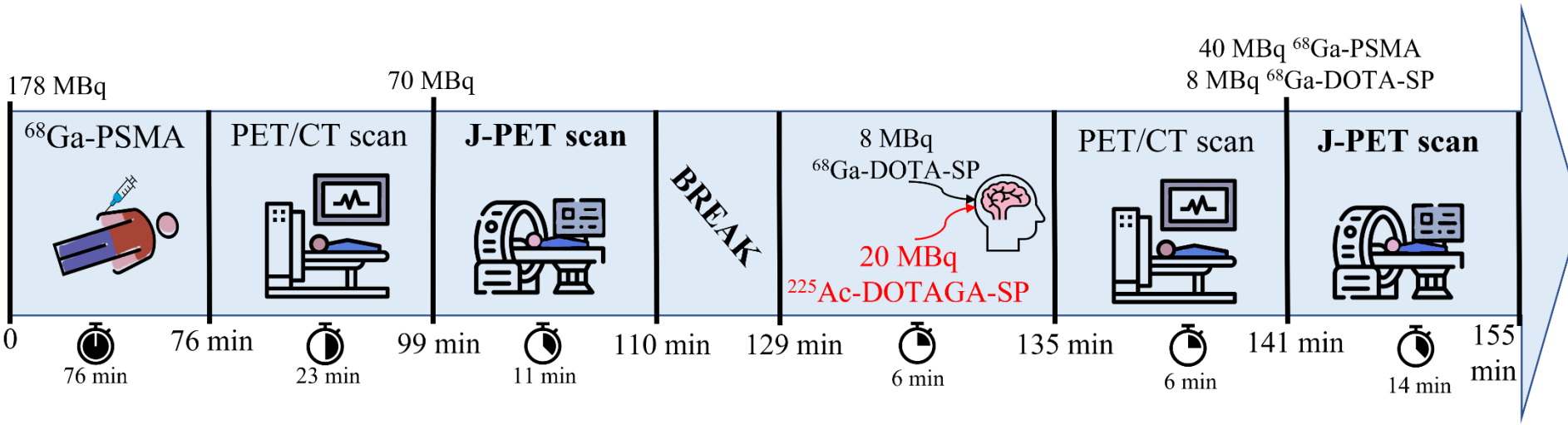
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**


P. Moskal et al., 2022: First positronium imaging with J-PET

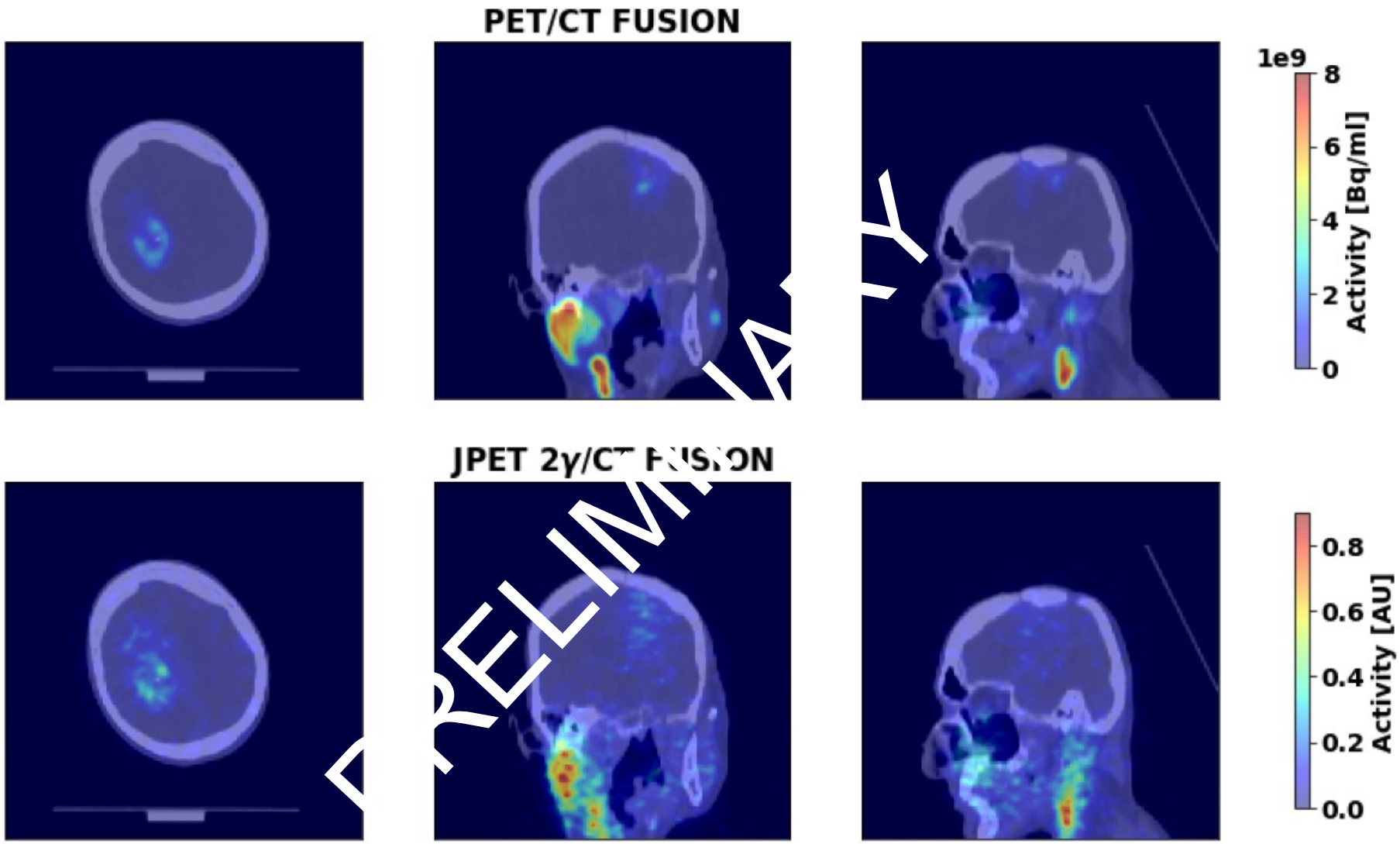

XILINX




Glioblastoma
CD44 marker
^{68}Ga, 68min
EC, 1.8%
e$^+$, 1.2%
^{68}Zn*
EC, 8.7%
e$^+$, 88%
γ 1.1 MeV, 1.5 ps
^{68}Zn
^{68}Zn*
^{68}Zn
^{68}Ga
ν$_e$
e$^+$e$^-$
γ
O
H
C
N
p-Ps
o-Ps

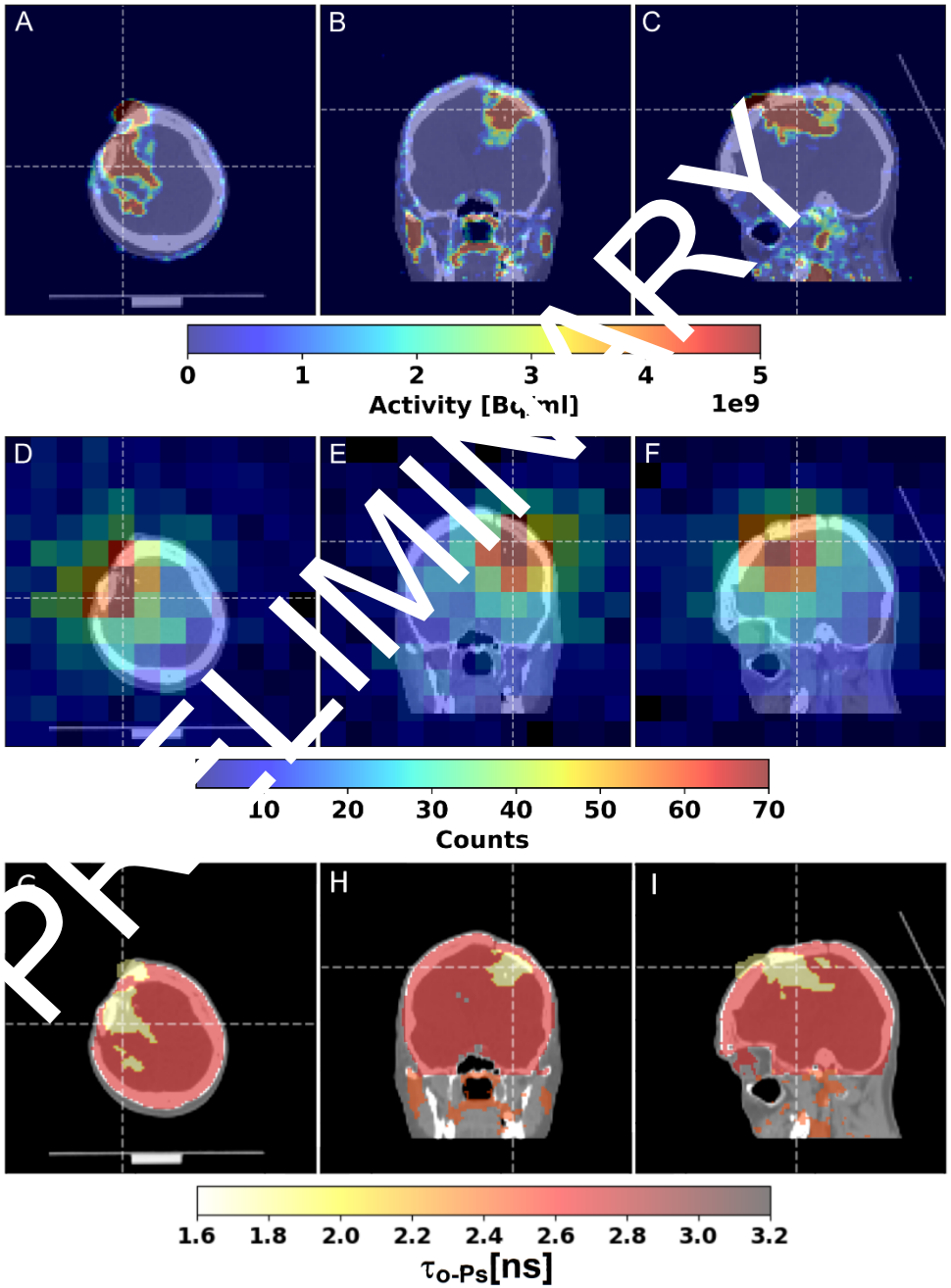

178 MBq
^{68}Ga-PSMA
70 MBq
PET/CT scan
J-PET scan
BREAK
8 MBq
^{68}Ga-DOTA-SP
20 MBq
^{225}Ac-DOTAGA-SP
40 MBq ^{68}Ga-PSMA
8 MBq ^{68}Ga-DOTA-SP
PET/CT scan
J-PET scan
0
76 min
76 min
23 min
99 min
11 min
110 min
129 min
6 min
135 min
6 min
141 min
14 min
155 min

First clinical PET imaging of patients with J-PET



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

First clinical positronium imaging of patients



PRELIMINARY

First clinical positronium imaging of patients

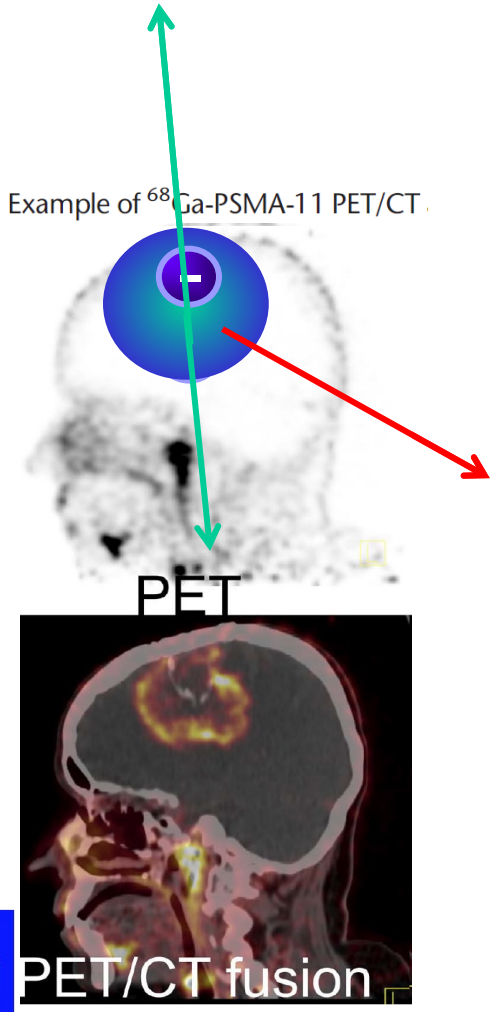
Clinical Nuclear Medicine • Volume 45, Number 1, January 2020 www.nuclearmed.com | 11

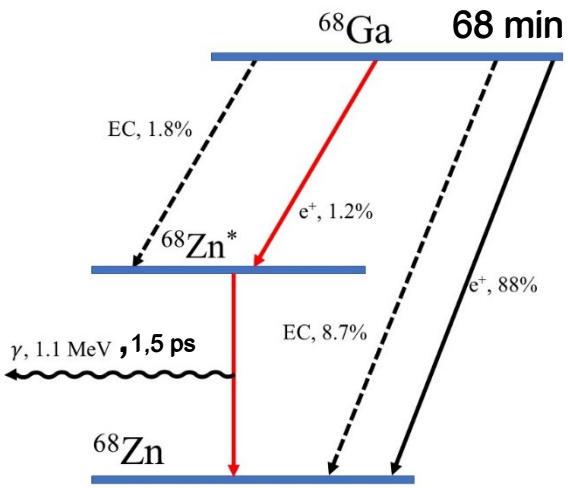
^{68}Ga–Prostate-Specific Membrane Antigen-11 PET/CT

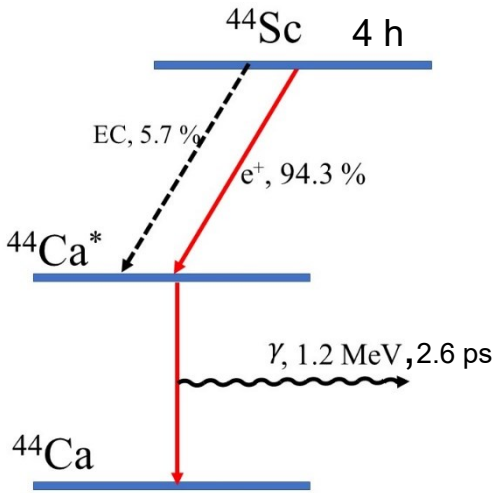
A New Imaging Option for Recurrent Glioblastoma Multiforme?

Jolanta Kunikowska, MD, PhD, Radosław Kuliński, MSc,* Kristoff Muylle, MD,† Henryk Koziara, MD,‡ and Leszek Królicki, MD, PhD**

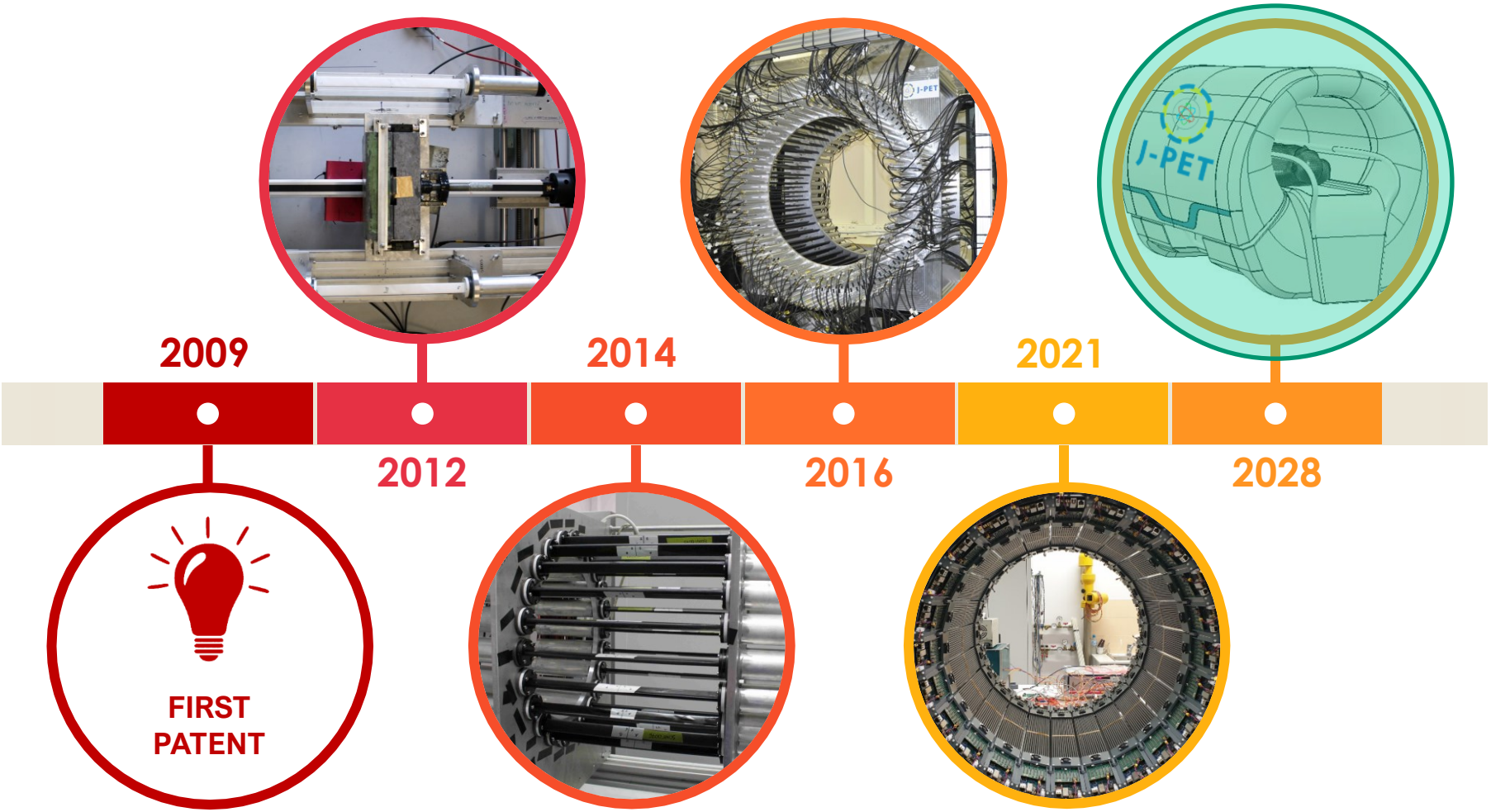
Example of ^{68}Ga-PSMA-11 PET/CT



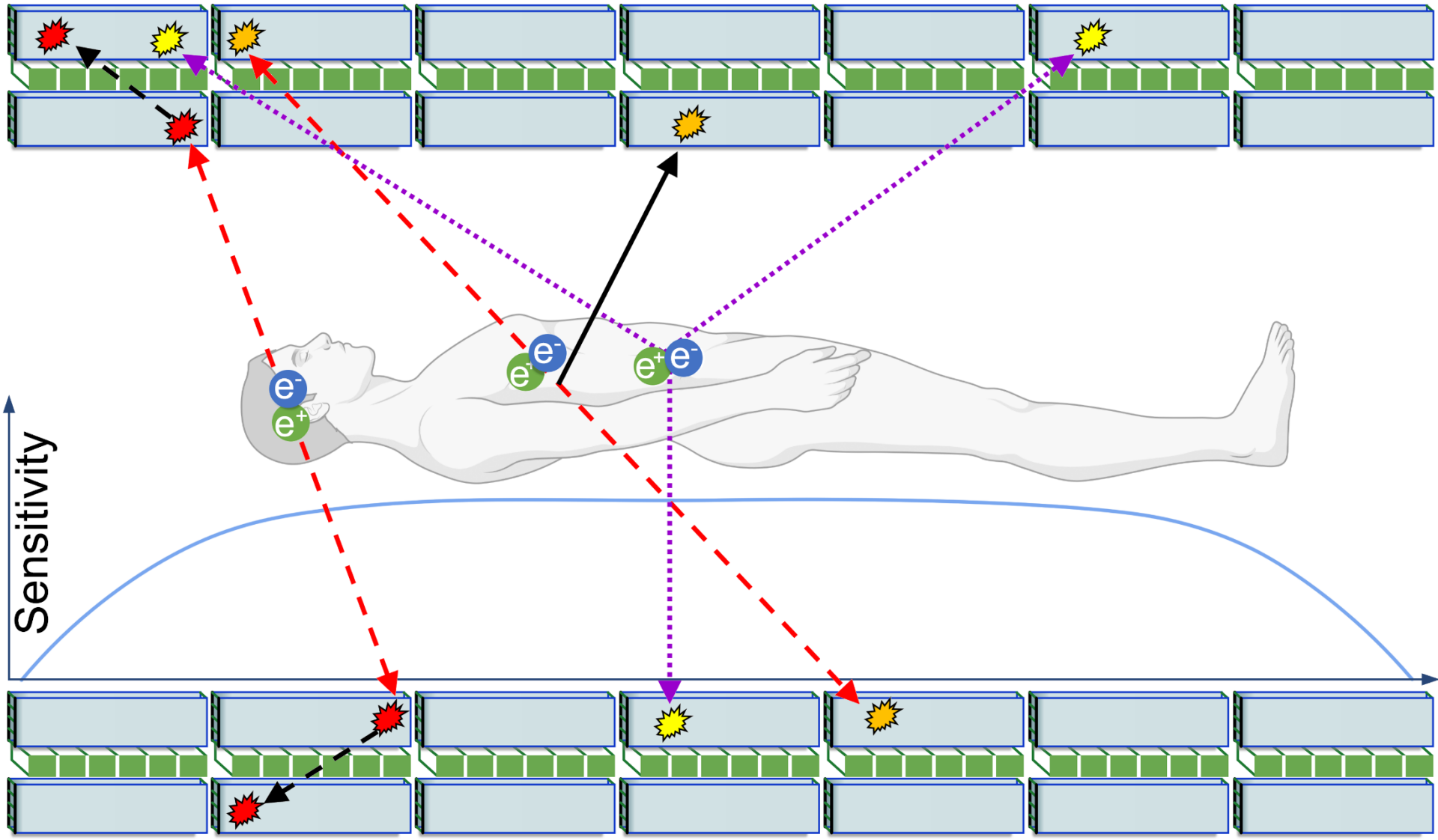




P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**



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



S. D. Bass, S. Mariazzi, P. Moskal, E. Stepien,

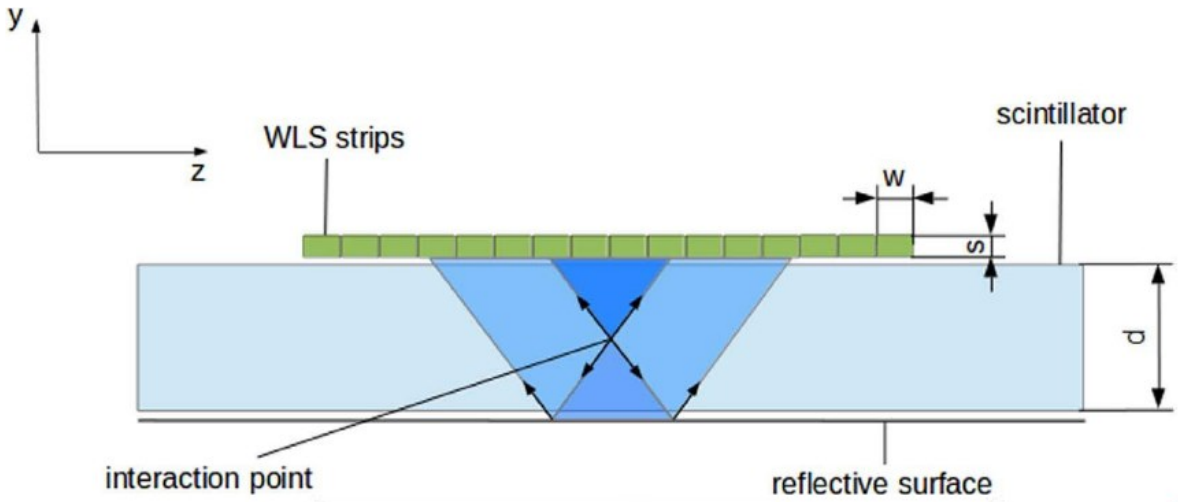
Rev. Mod. Phys. 95 (2023) 021002

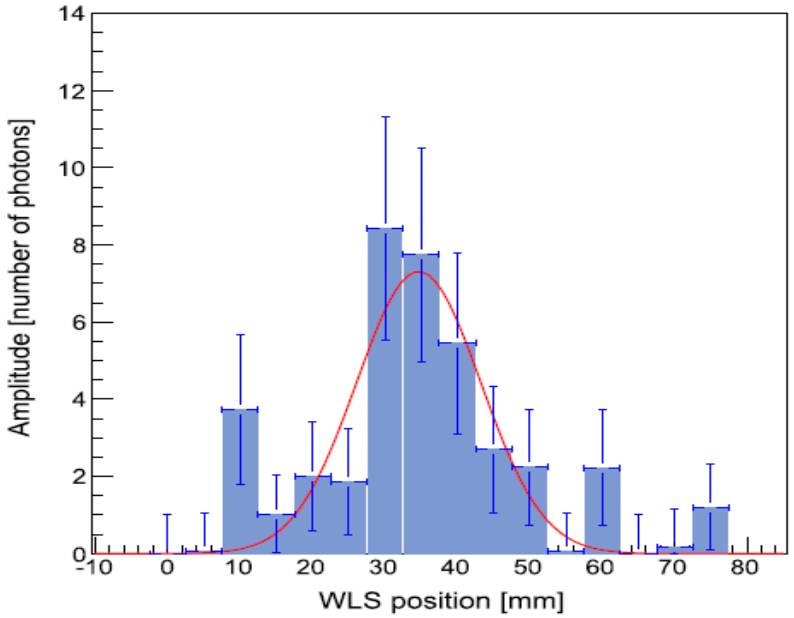
CENTER FOR THERANOSTICS

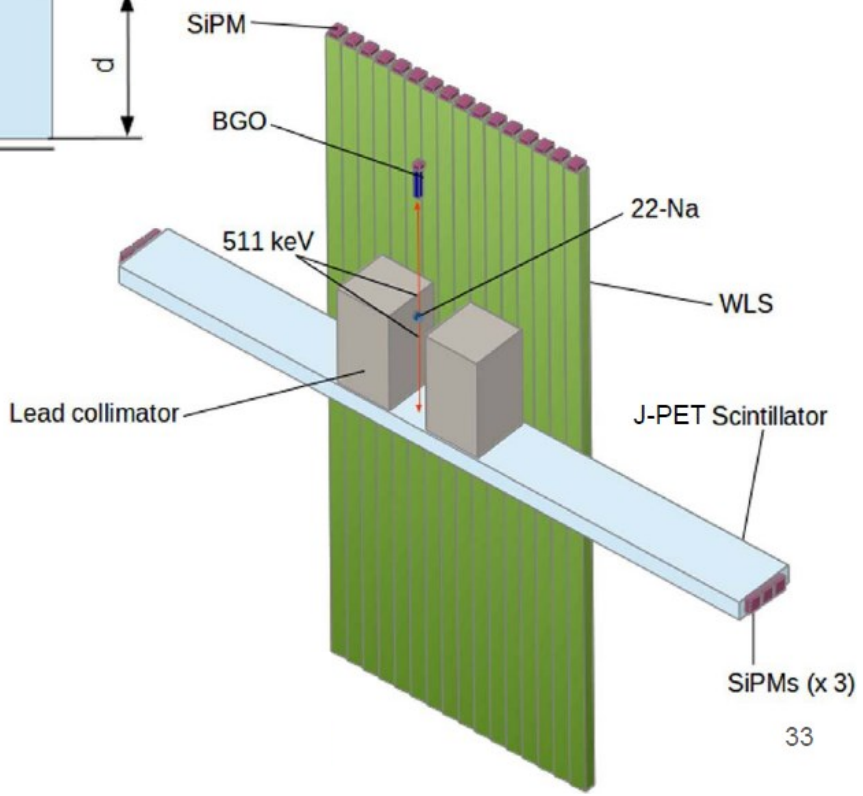
Positronium physics and biomedical applications

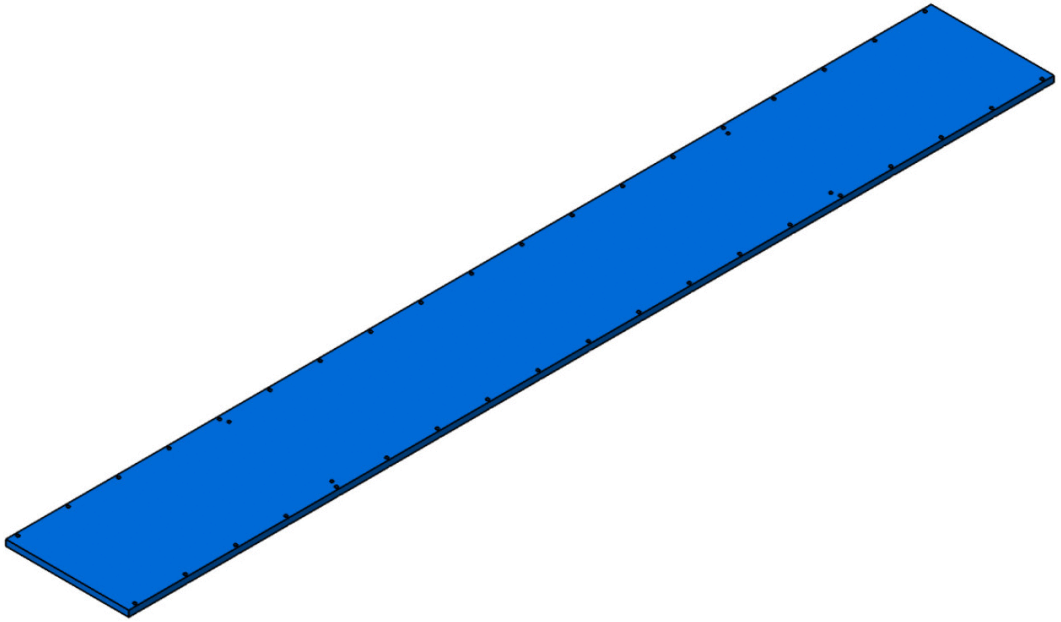
WLS

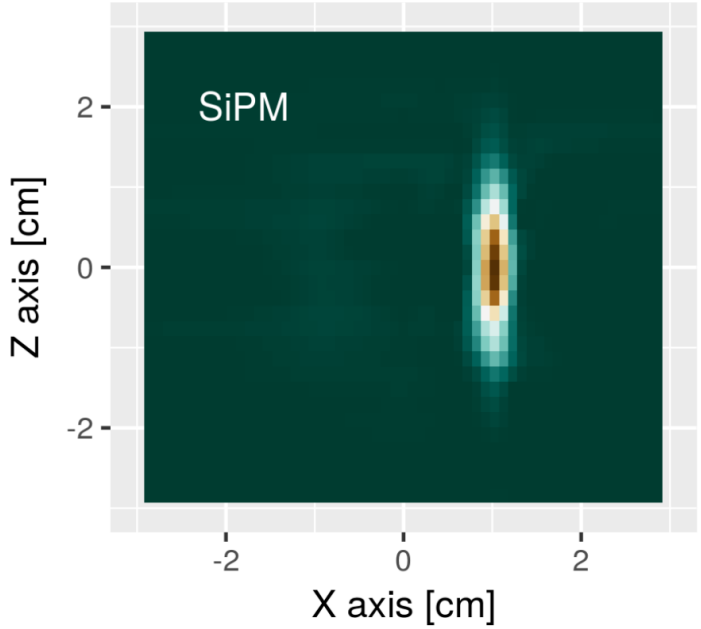
J-PET: J. Smyrski et al., Nucl. Instr. Meth A 851 (2017) 39



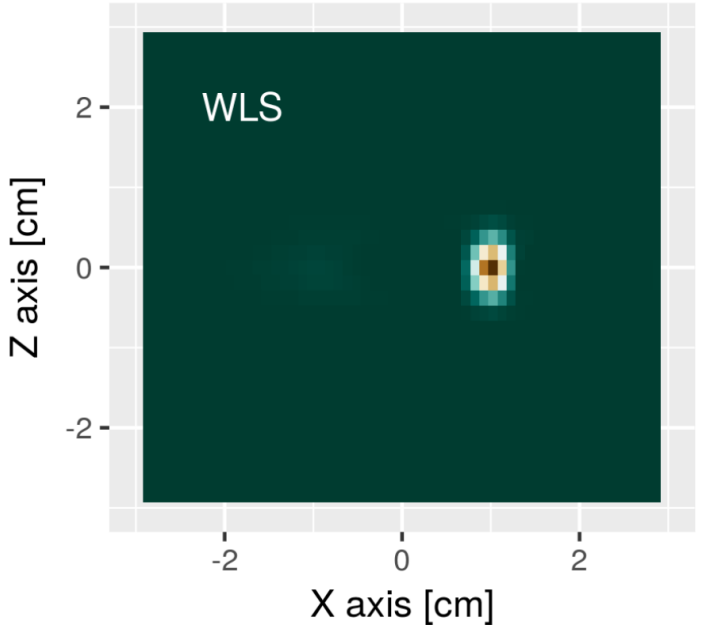


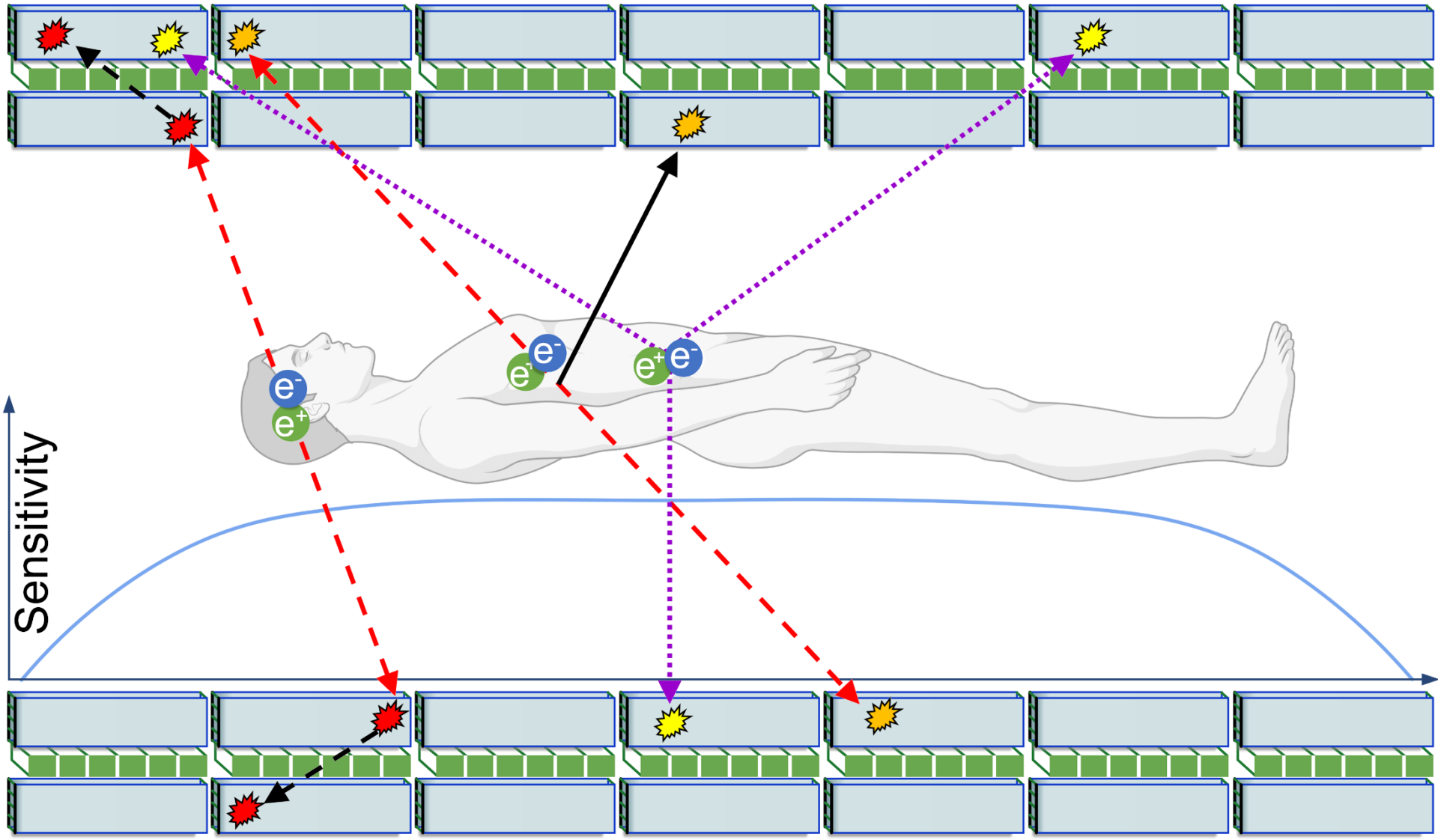






GATE Simulations: **P. Kowalski et al., Phys. Med. Biol. 63 (2018) 165008**
P. Moskal et al., Phys. Med. Biol. 66 (2021) 175015





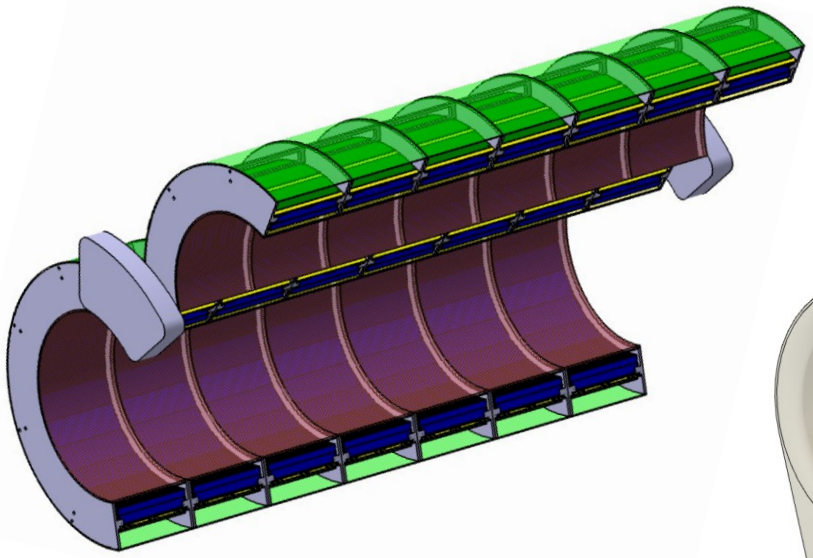
S. D. Bass, S. Mariazzi, P. Moskal, E. Stepien,

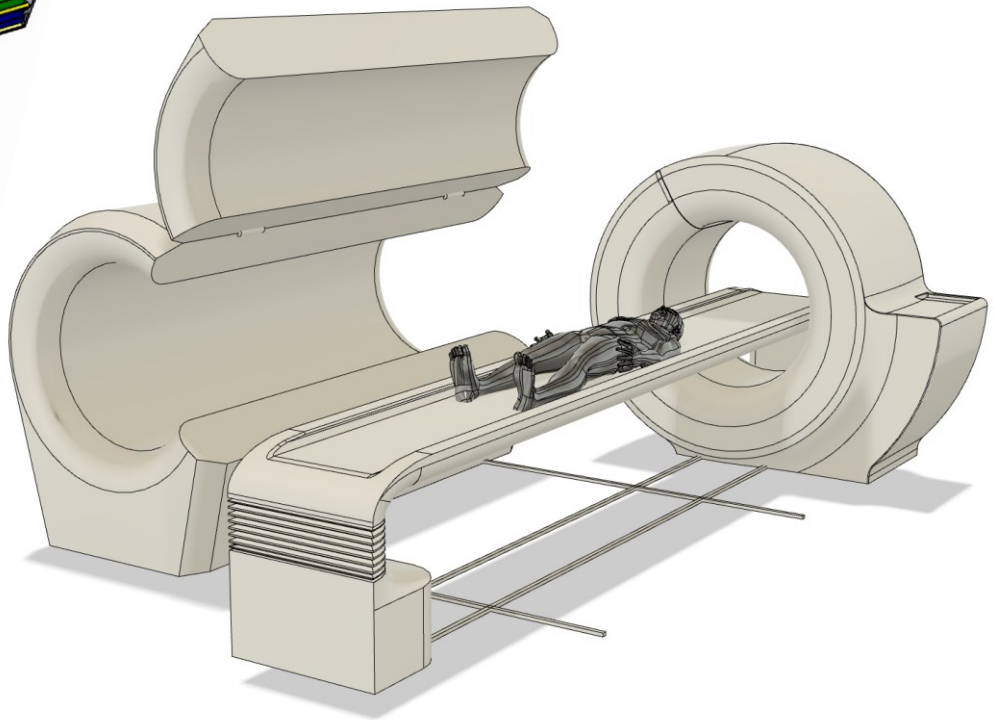
Rev. Mod. Phys. 95 (2023) 021002

CENTER FOR THERANOSTICS

Positronium physics and biomedical applications

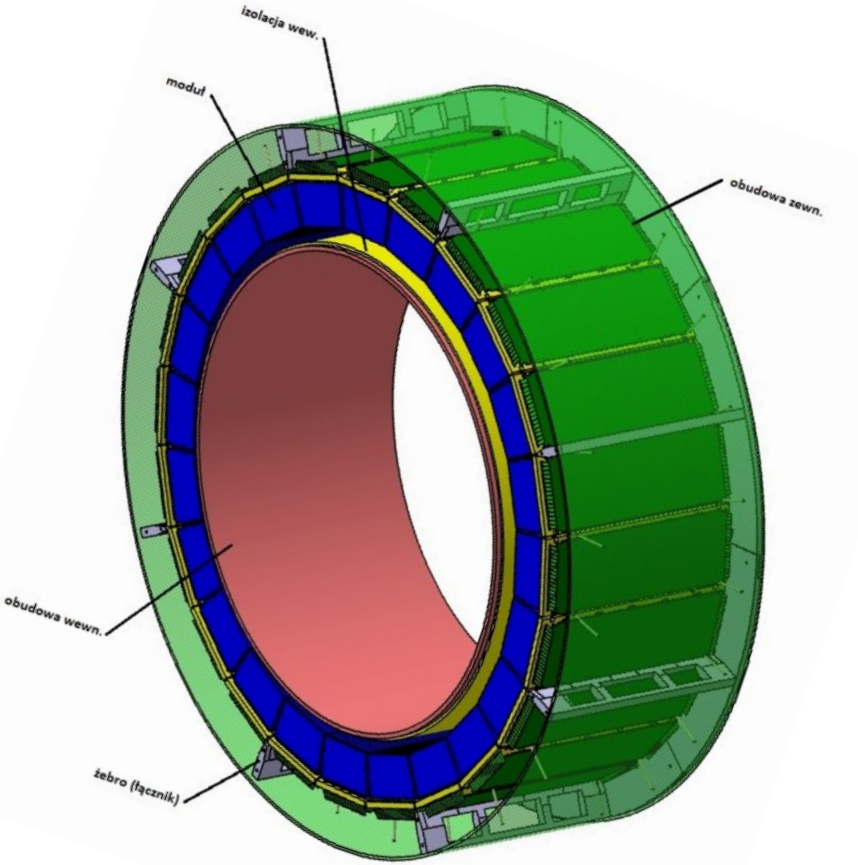
Total body J-PET

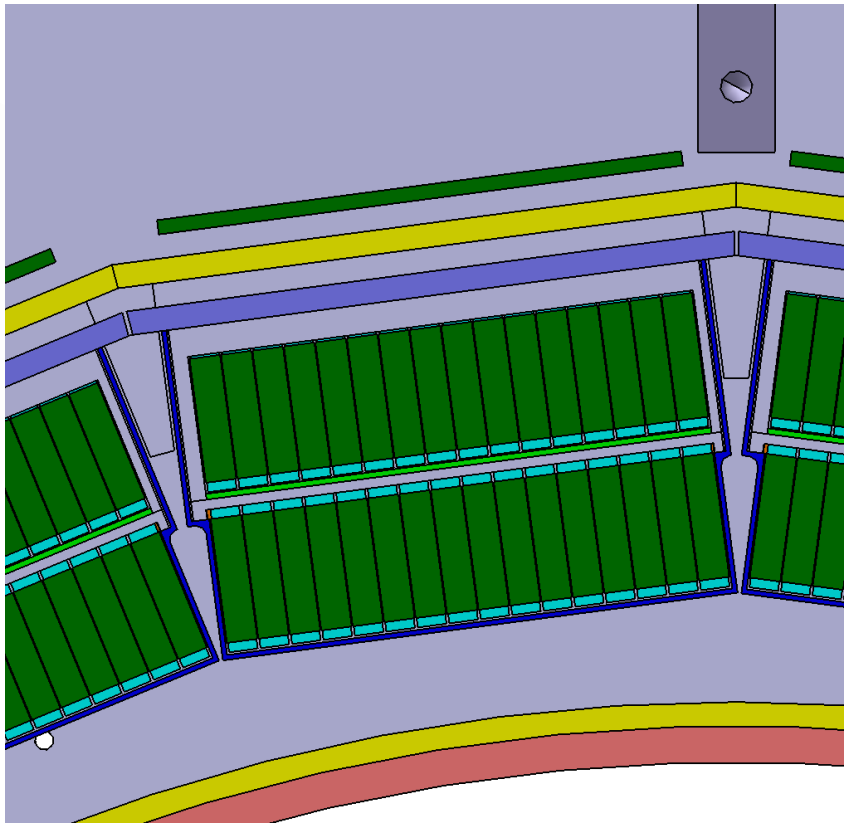




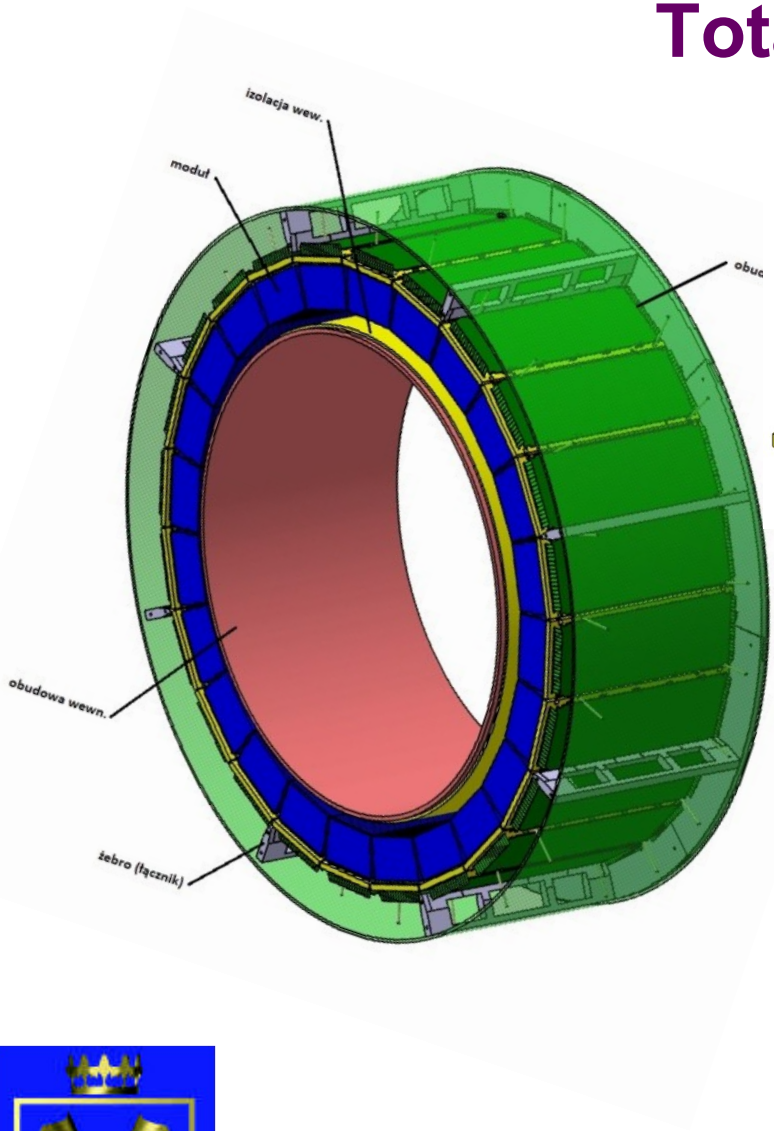
Pawel Moskal, Jagiellonian University

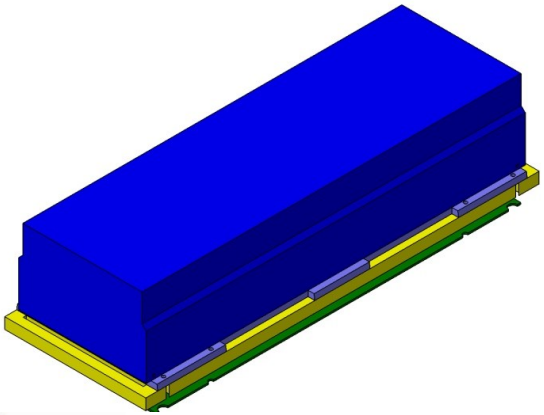
Total body J-PET

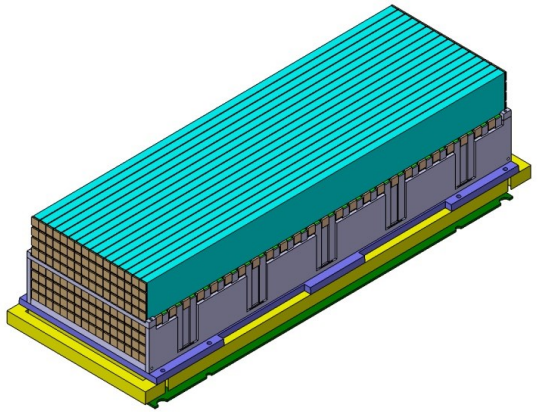


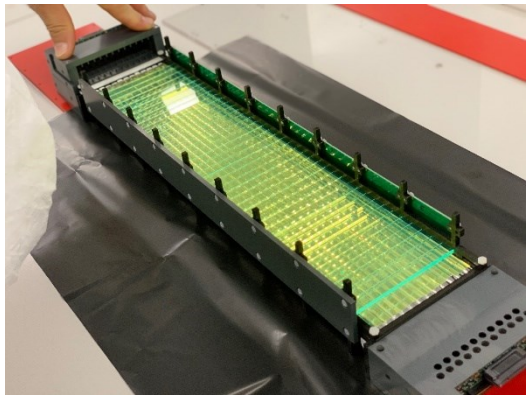


Total body J-PET

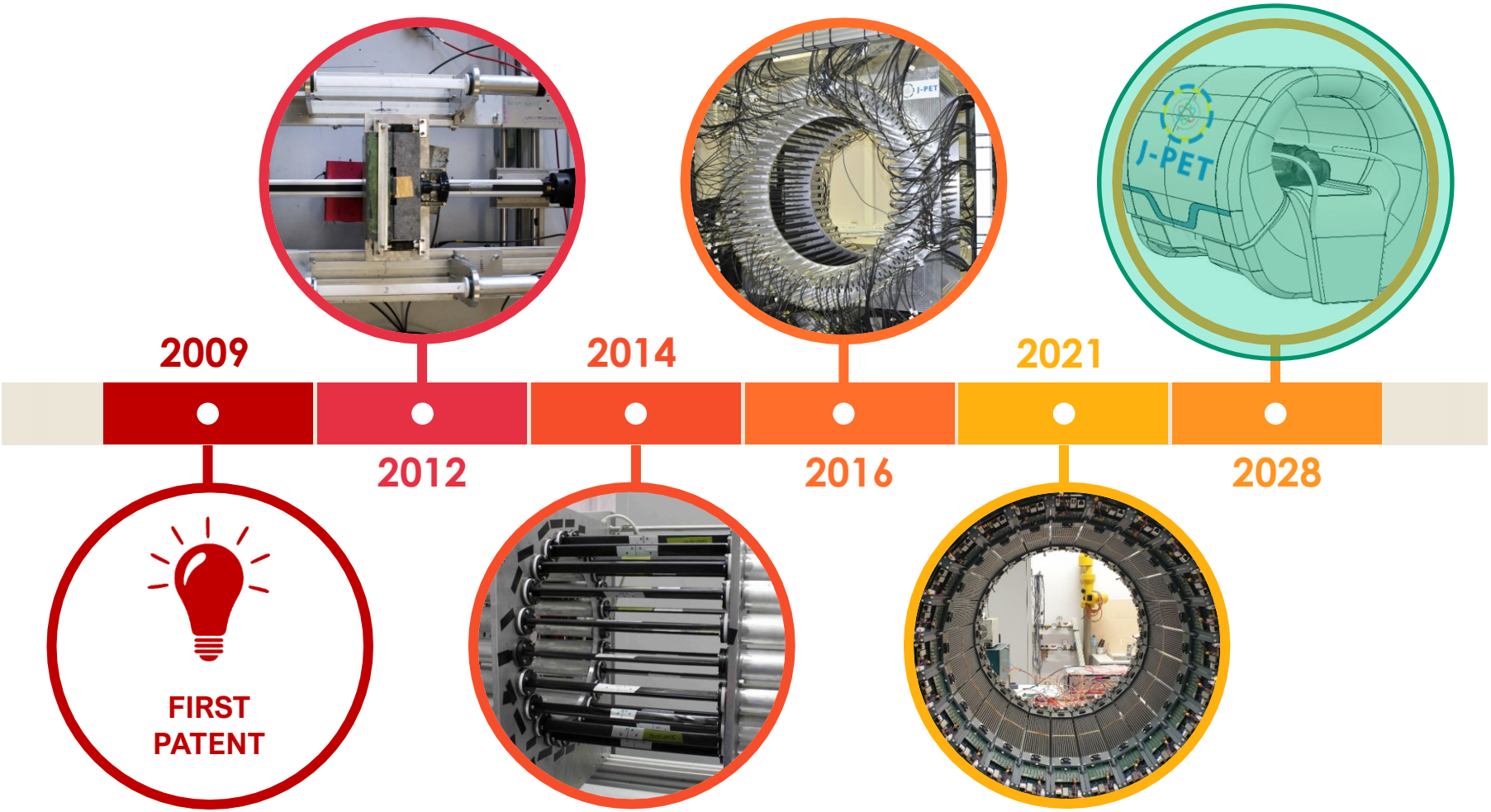








Pawel Moskal, Jagiellonian University



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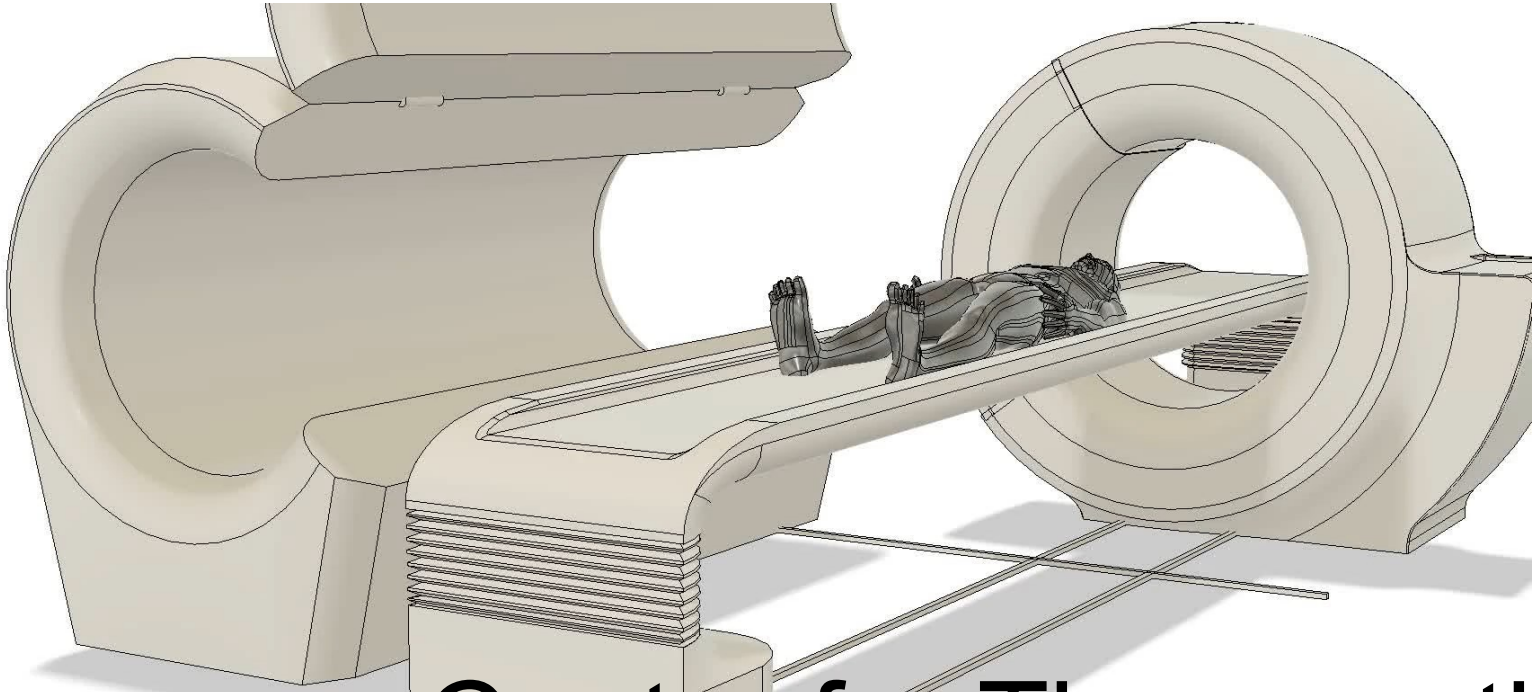
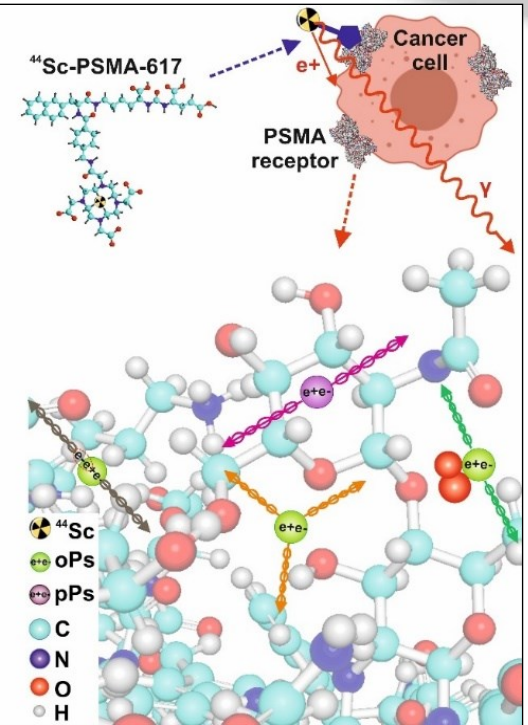
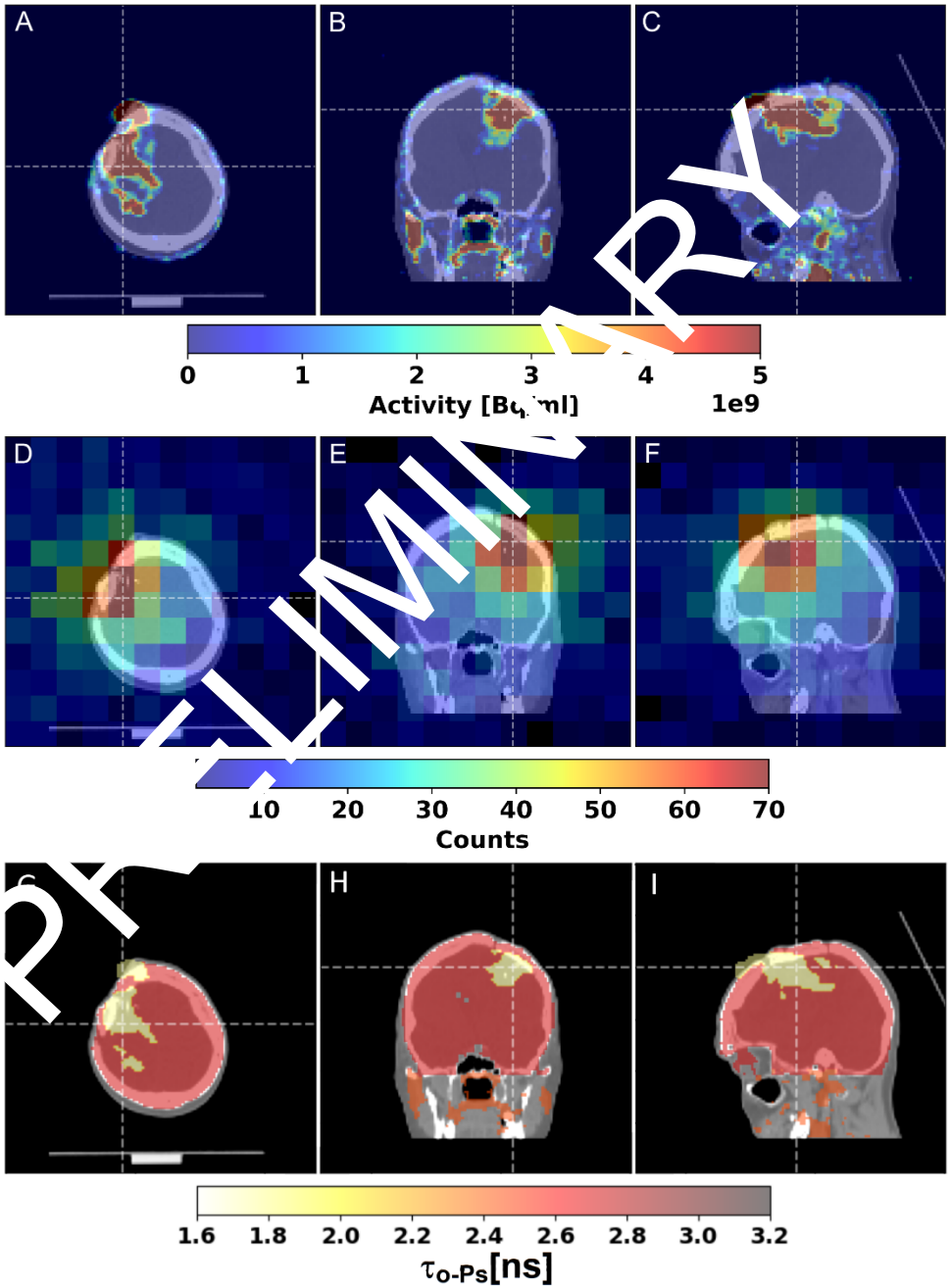


Center for Theranostics
Jagiellonian University



First clinical positronium imaging of patients

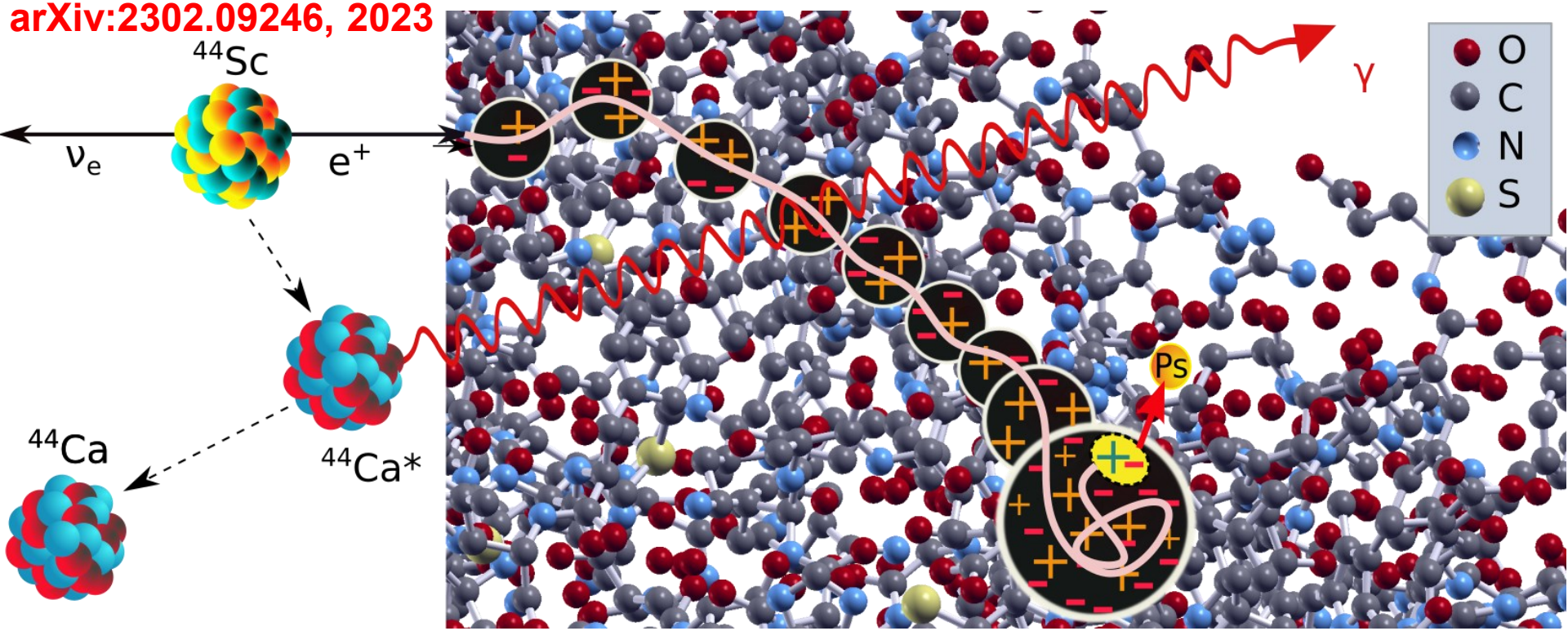


PRELIMINARY

First positronium imaging of humans using modular J-PET scanner

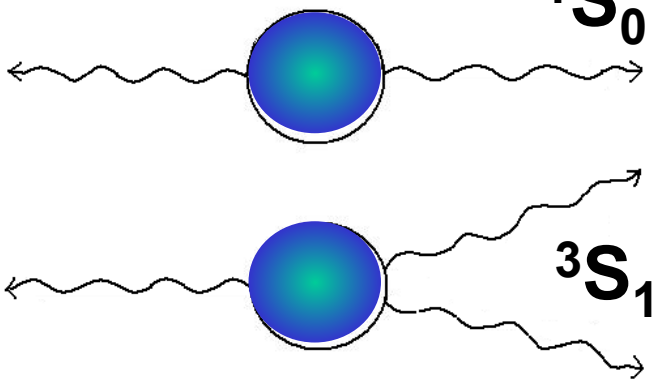
S. Bass, S. Mariazzi, P. Moskal, E. Stepien,

Reviews of Modern Physics 95 (2023) 021002
arXiv:2302.09246, 2023



P. Moskal, E. Ł. Stępień, Bio-Algorithms and Med.-Systems 17 (2021) 311

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	-	+

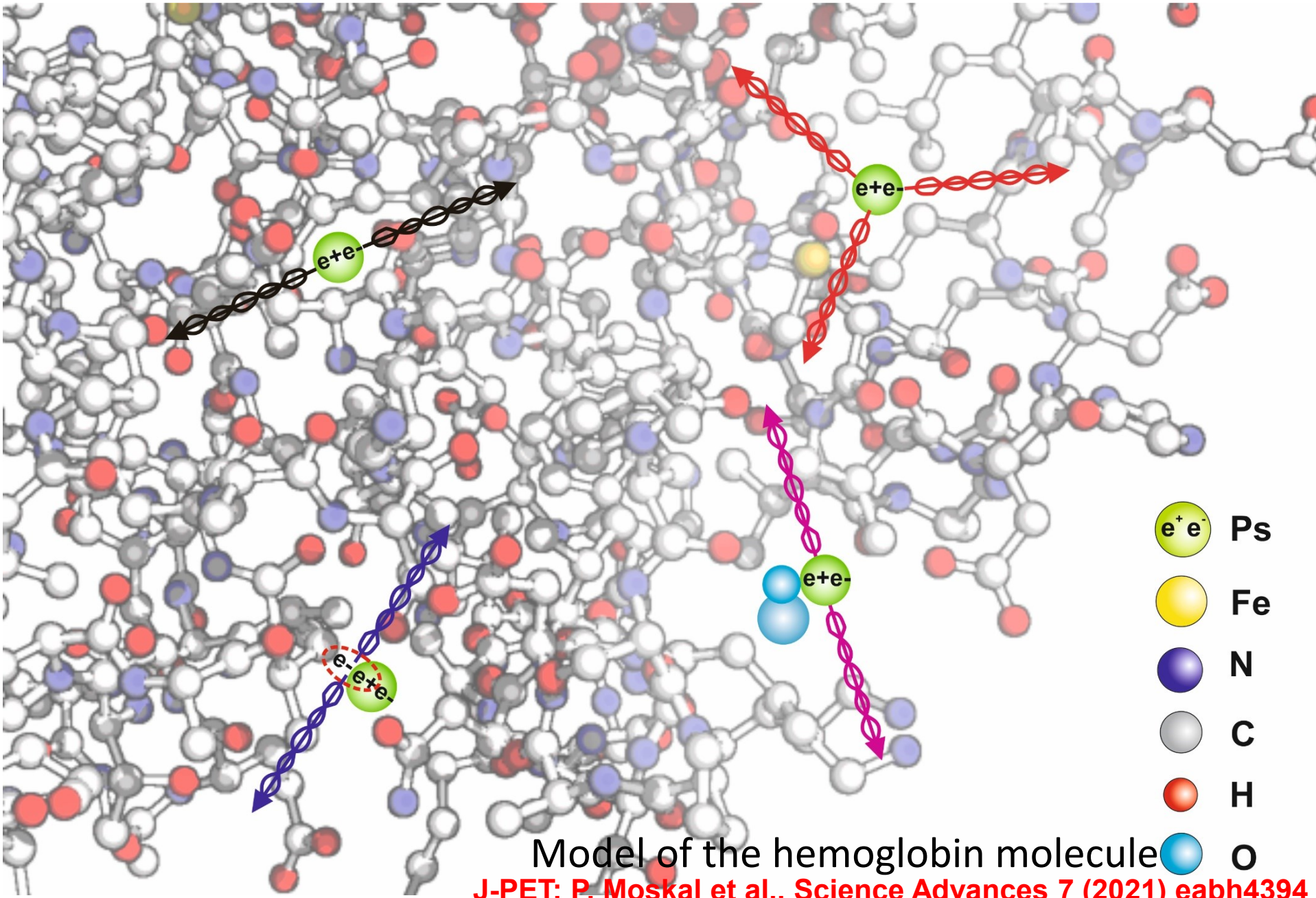
S = 0 $\downarrow\uparrow - \uparrow\downarrow$

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

S. Bass, S. Mariazzi, P. Moskal, E. Stepien,
Reviews of Modern Physics 95 (2023) 021002 arXiv:2302.09246, 2023

Positronium imaging

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

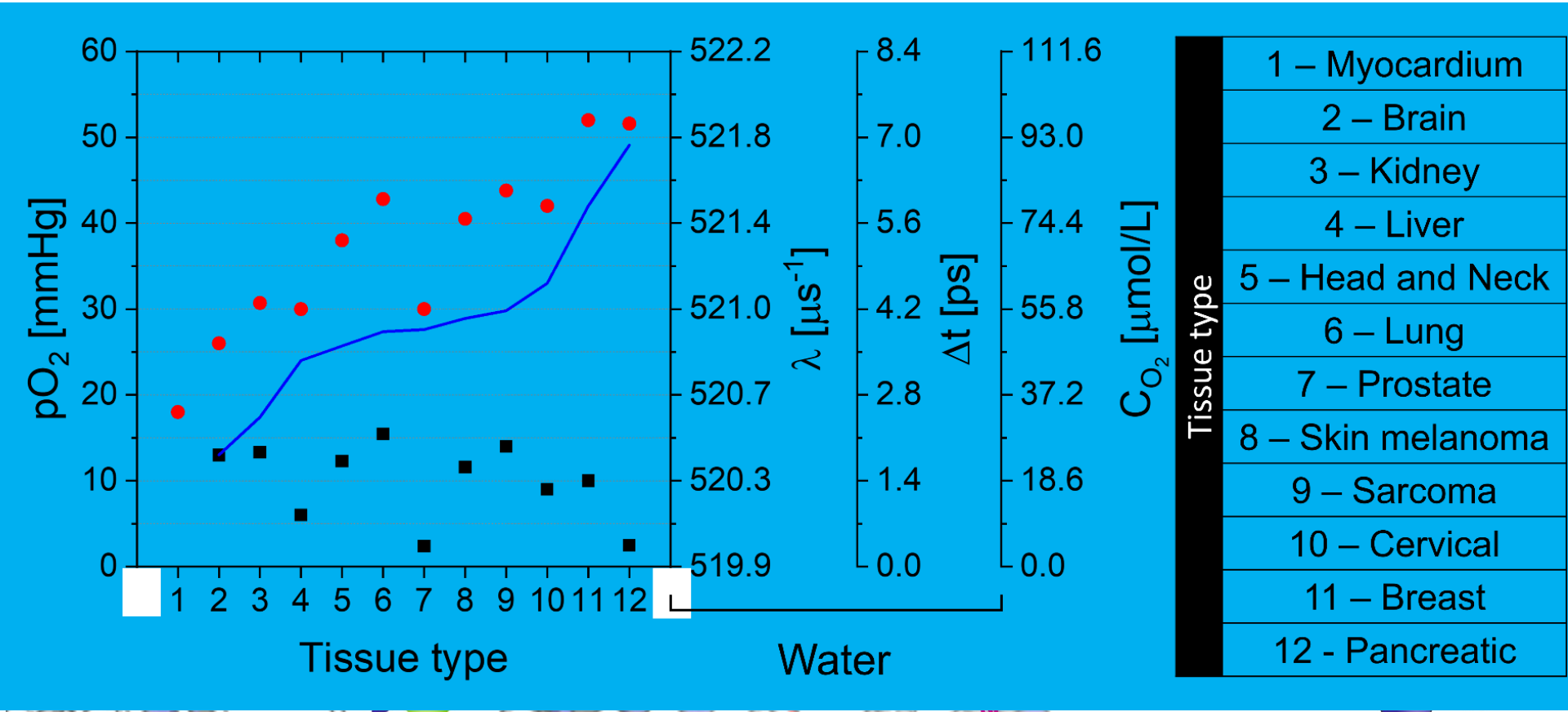


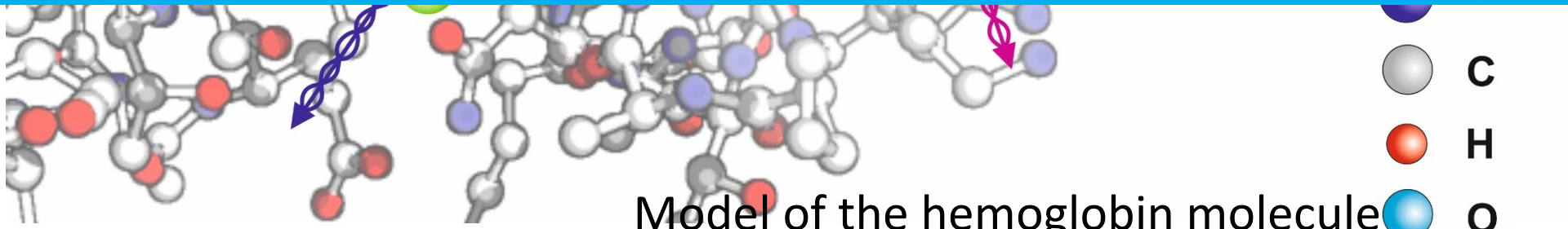
Model of the hemoglobin molecule

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

Positronium imaging

P. Moskal, E. Stępień., Bio-Algorithms and Med-Systems 17 (2021) 311
„Positronium as a biomarker of hypoxia"





Model of the hemoglobin molecule

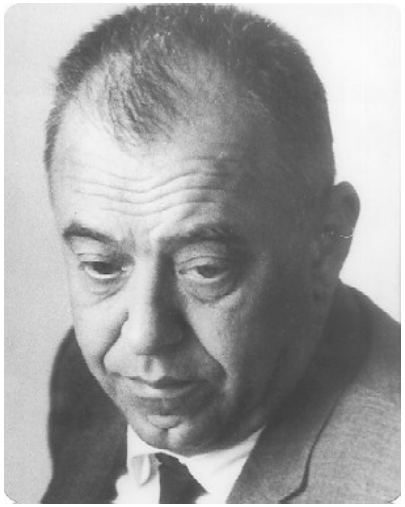
J-PET: P. Moskal, Science Advances 7 (2021) eabh4394

Radiological
Laboratory in Warsaw

Nature 1934;133:564–5,

„An Artificial Radioelement from Nitrogen”

https://lnkd.in/di246kY2



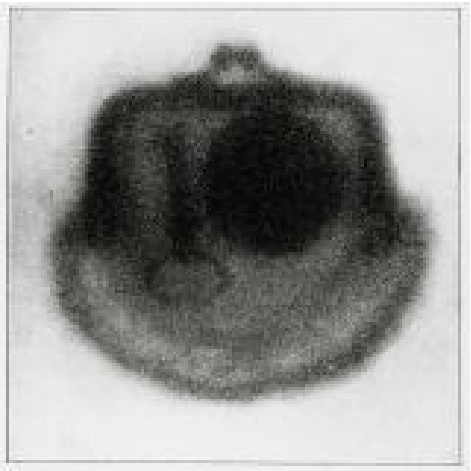
Prof. Ludwik Wertenstein
Marian Danysz

$$^{4}He + {}^{14}N \rightarrow {}^{17}F + n$$

$$^{17}F \rightarrow {}^{18}O + e^{+} + \nu$$

Formal leader of the Radiological Laboratory in Warsaw

A girl from Warsaw

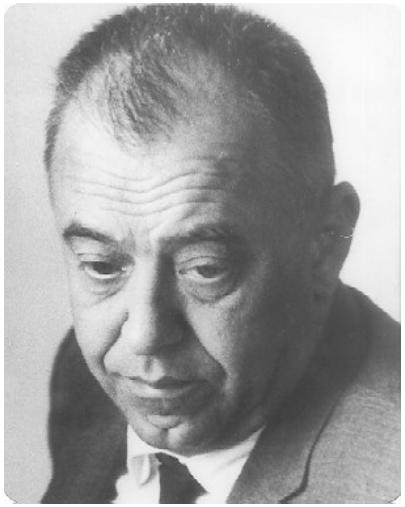


„Radiograph”
taken by
Maria Curie
by exposing
a purse to radium.

http://www.galloimages.co.za/

R.F. Mould, The British Journal of Radiology, **71**, 1229 (1998)

Radiological
Laboratory in Warsaw
Nature 1934;133:564–5,
„An Artificial Radioelement from Nitrogen”
https://lnkd.in/di246kY2



Prof. Ludwik Wertenstein
Marian Danysz

$$^{4}He + {}^{14}N \rightarrow {}^{17}F + n$$

$$^{17}F \rightarrow {}^{18}O + e^{+} + \nu$$

Irene and Frederic Joliot-Curie
Nature 1934;133:201–2,
„Artificial Production of
a New Kind of Radio-Element”
https://lnkd.in/dRtzeZJD
Nobel Prize in Chemistry in 1935

$$^{4}He + {}^{10}B \rightarrow {}^{13}N + n$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

Imaging the decay of positronium atoms using the J-PET tomograph

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

Bialasówka, AGH, Kraków, 17.05.2024

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

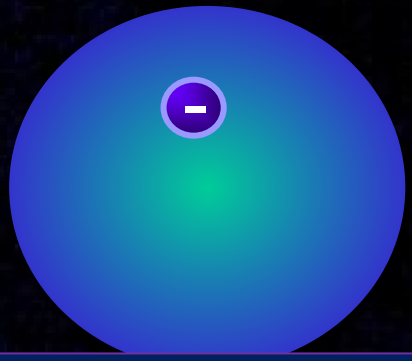
Violation of CP and T
confirmed experimentally
for hadrons only

meson K

1964

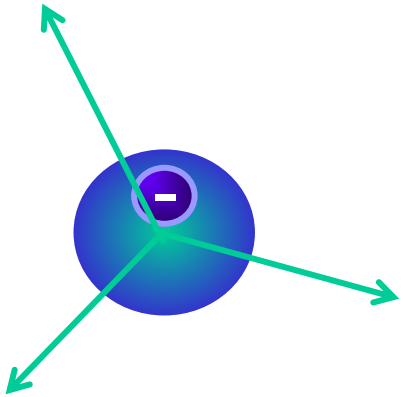
meson B

2012



positronium

?



$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$
PRL 104 (2010) 083401

6 OOM of
unexplored precision

Physical sensitivity limit:
false asymmetries from
$\gamma\gamma$ interactions in the final state

$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$
PRL. 91 (2003) 263401

J-PET

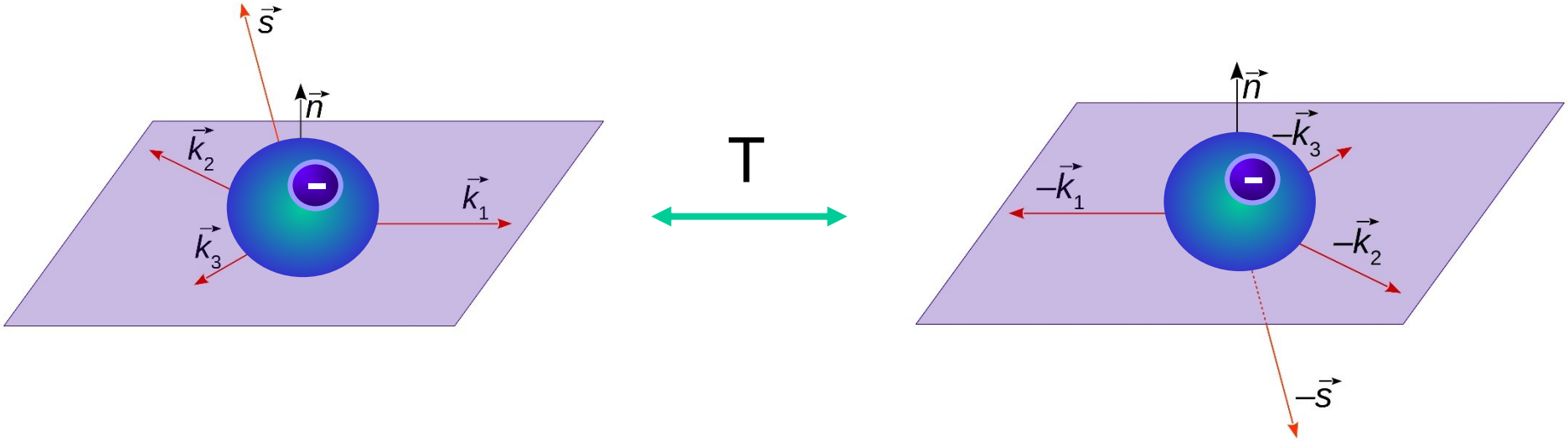
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	–	+	–	–
$\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)$	+	+	–	+	–
$\left(\vec{S} \cdot \vec{k}_1\right)\left(\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)\right)$	+	–	–	–	+

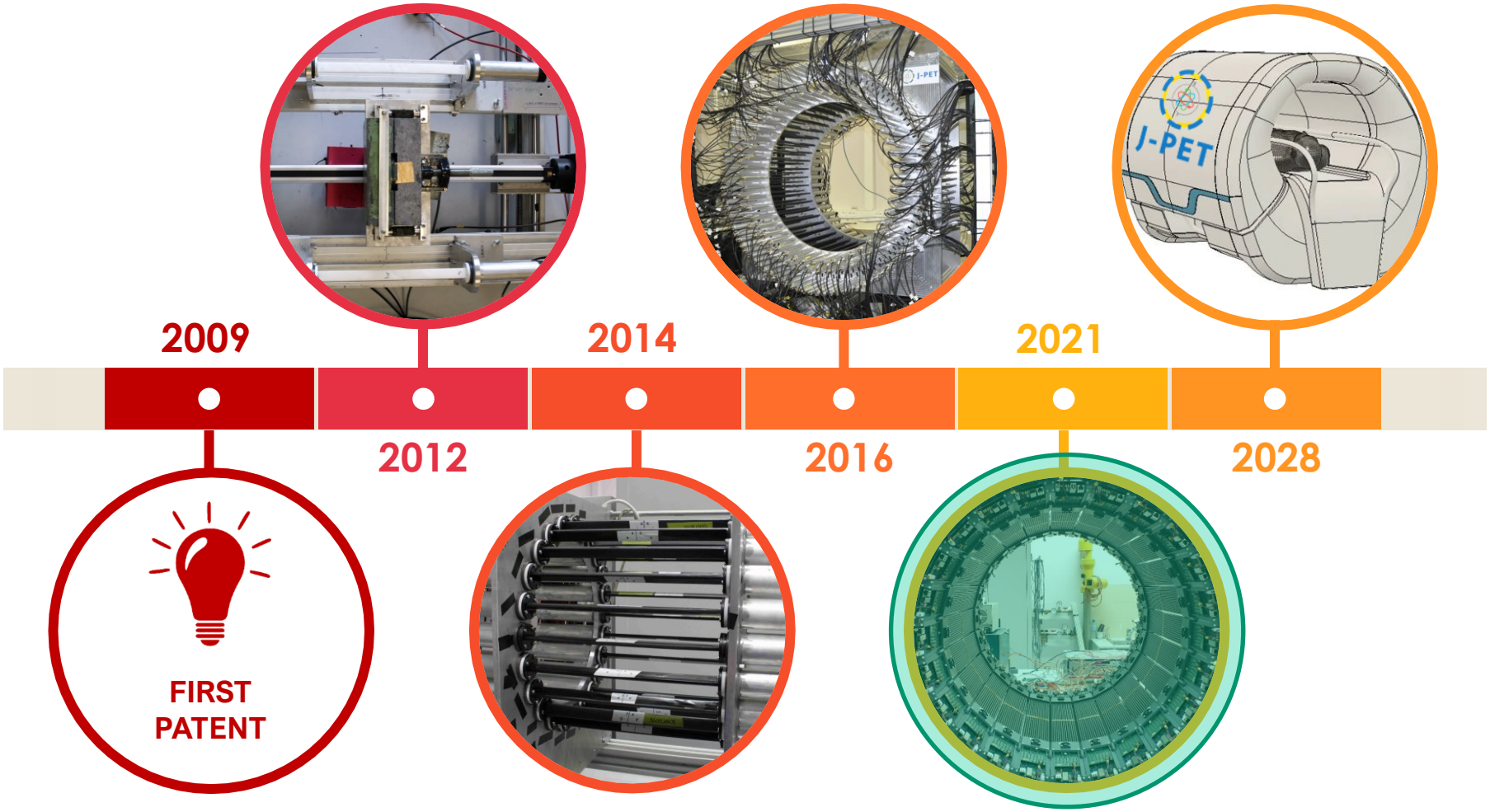
$$|k_1| > |k_2| > |k_3|$$

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
$\vec{S} \cdot \vec{k}_1$	+	–	+	–	–
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	–	+	–
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	–	–	–	+

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





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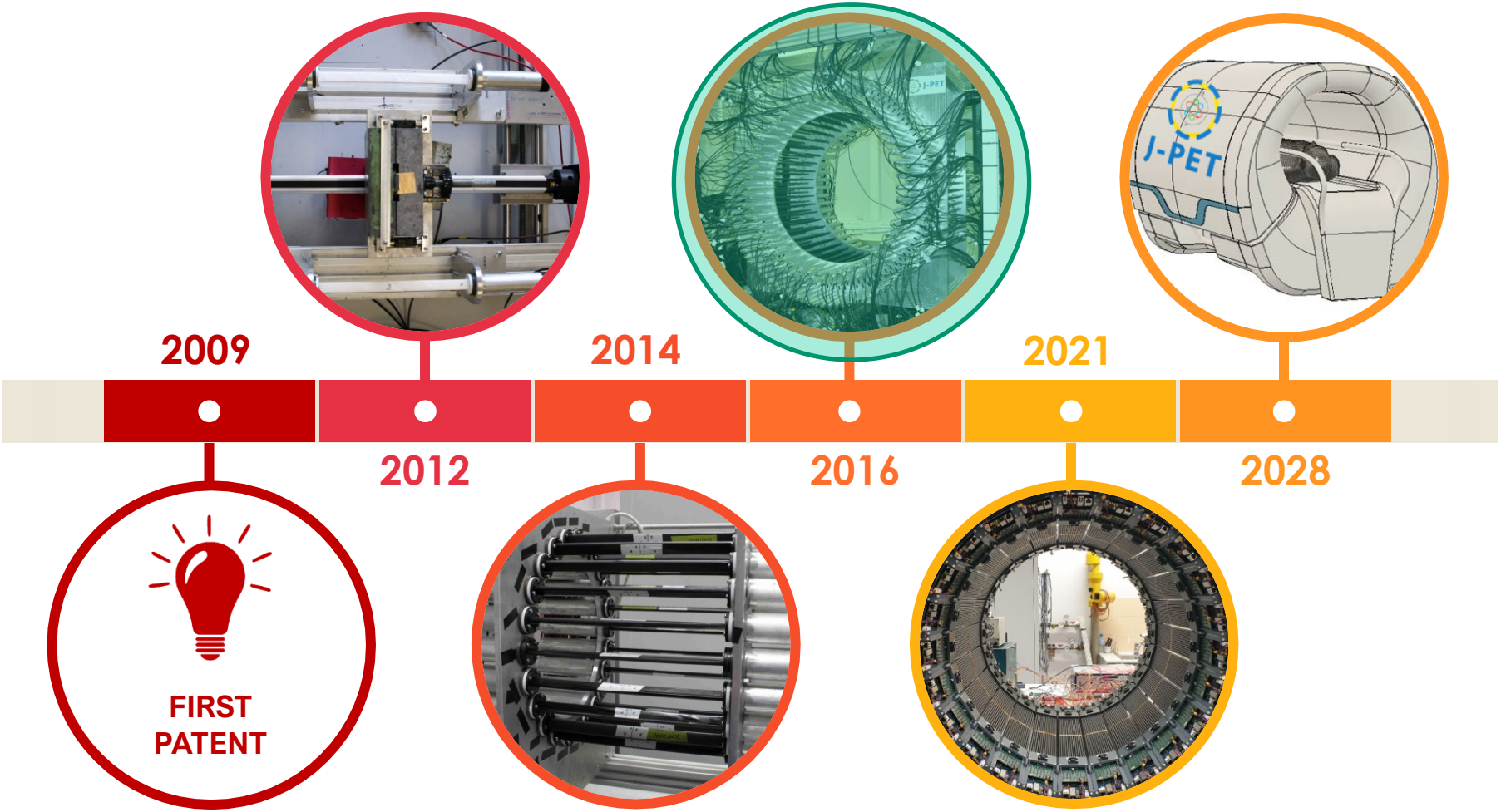

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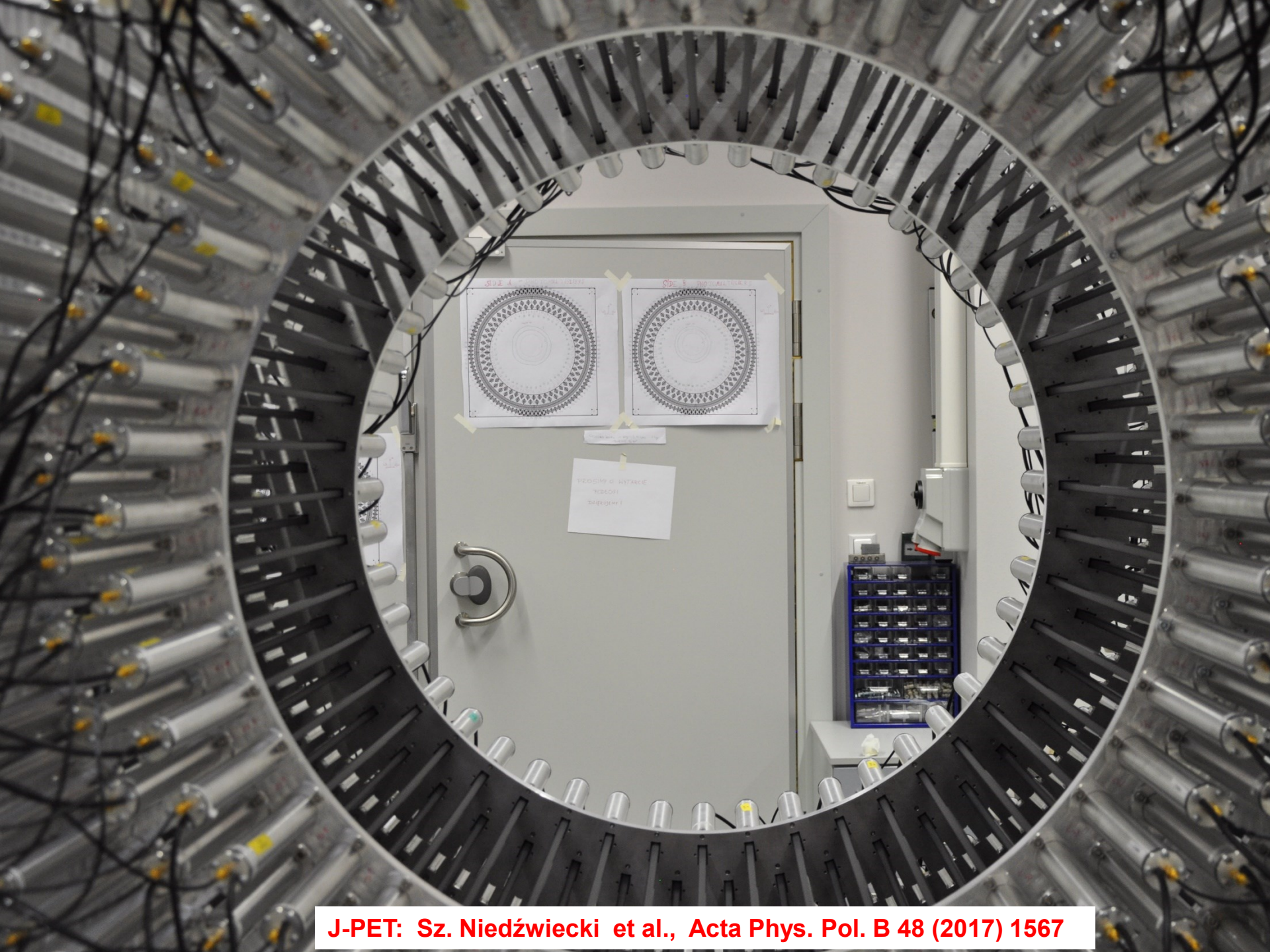
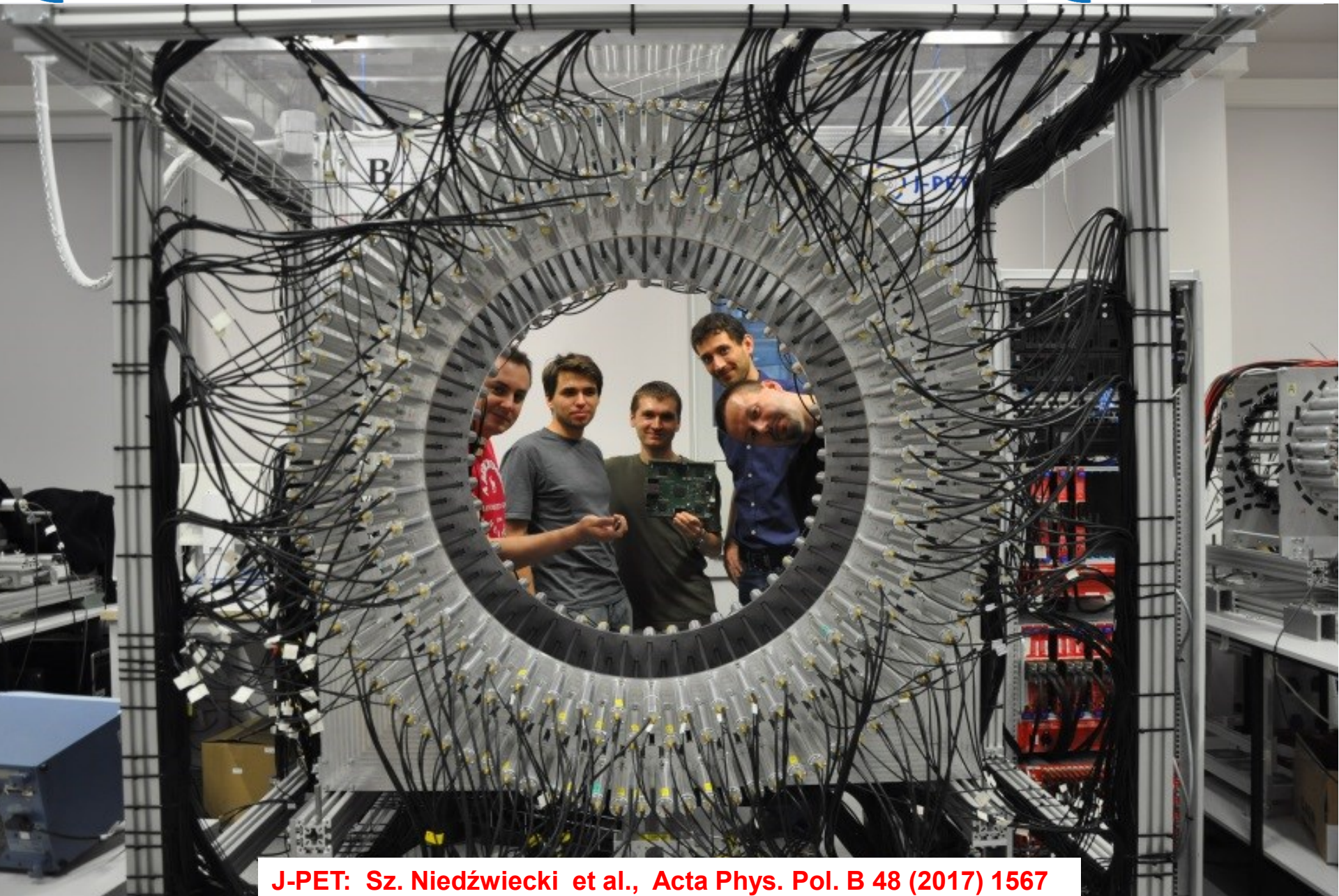


J-PET: Sz. Niedźwiecki et al., Acta Phys. Pol. B 48 (2017) 1567

Jagiellonian PET



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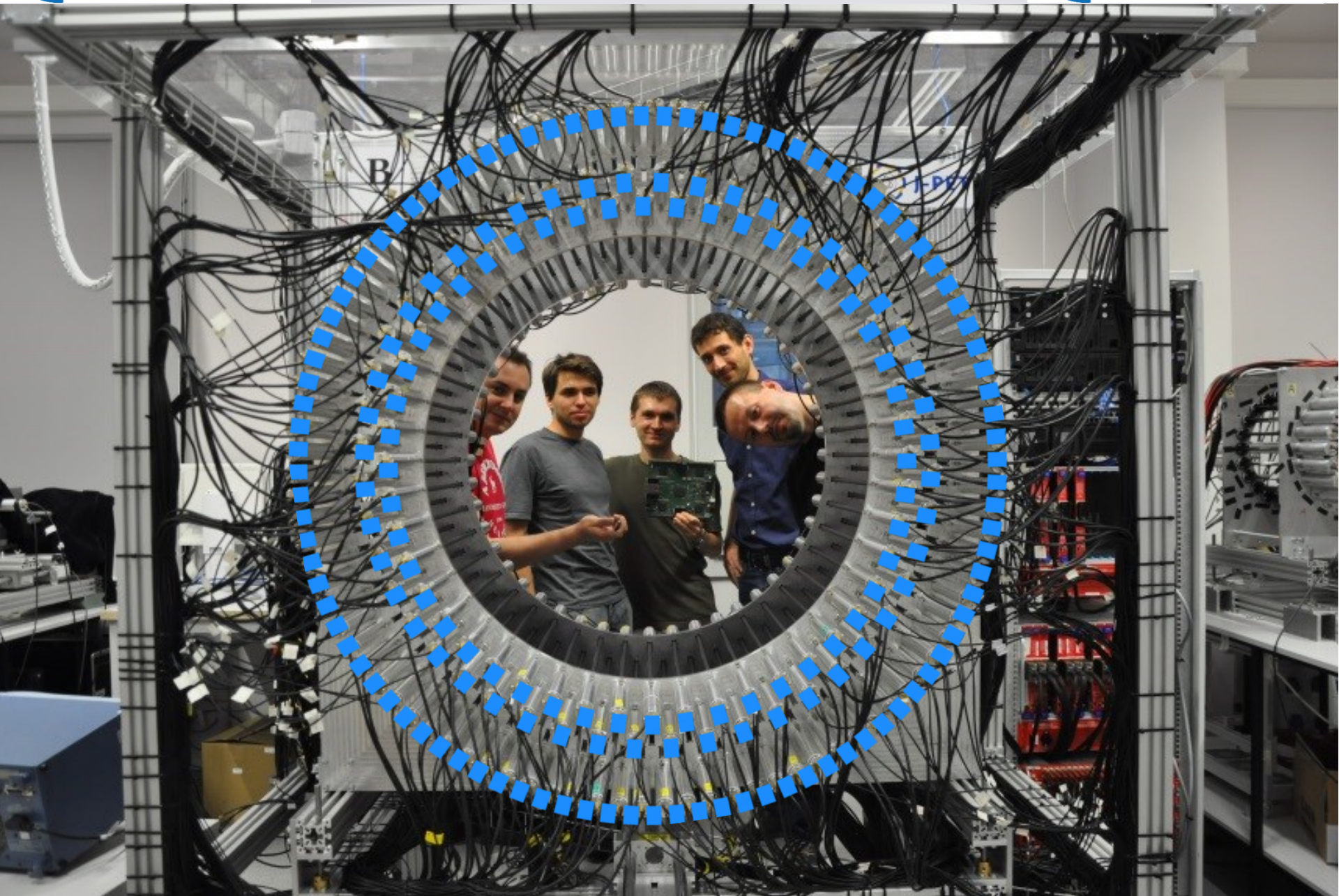

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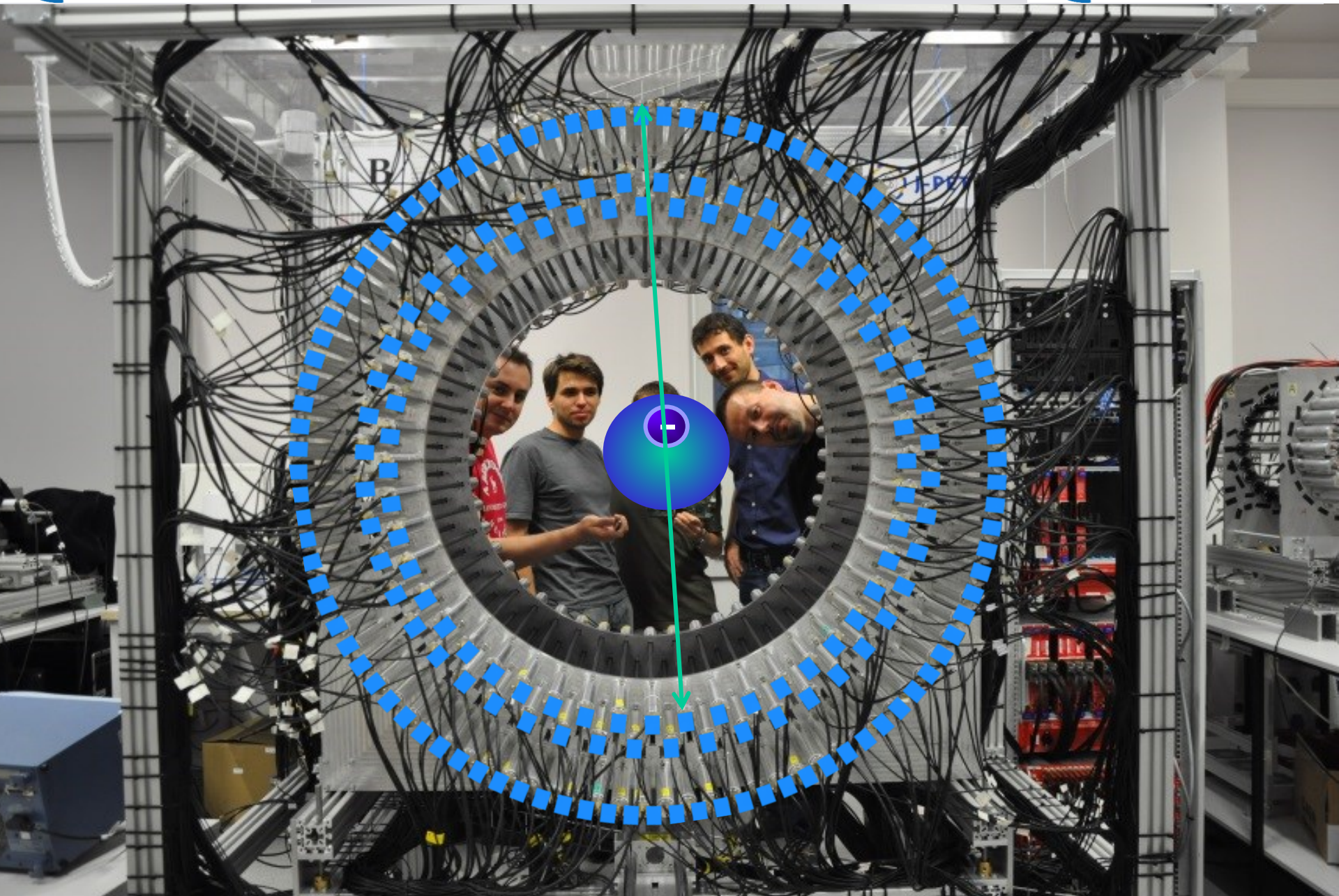

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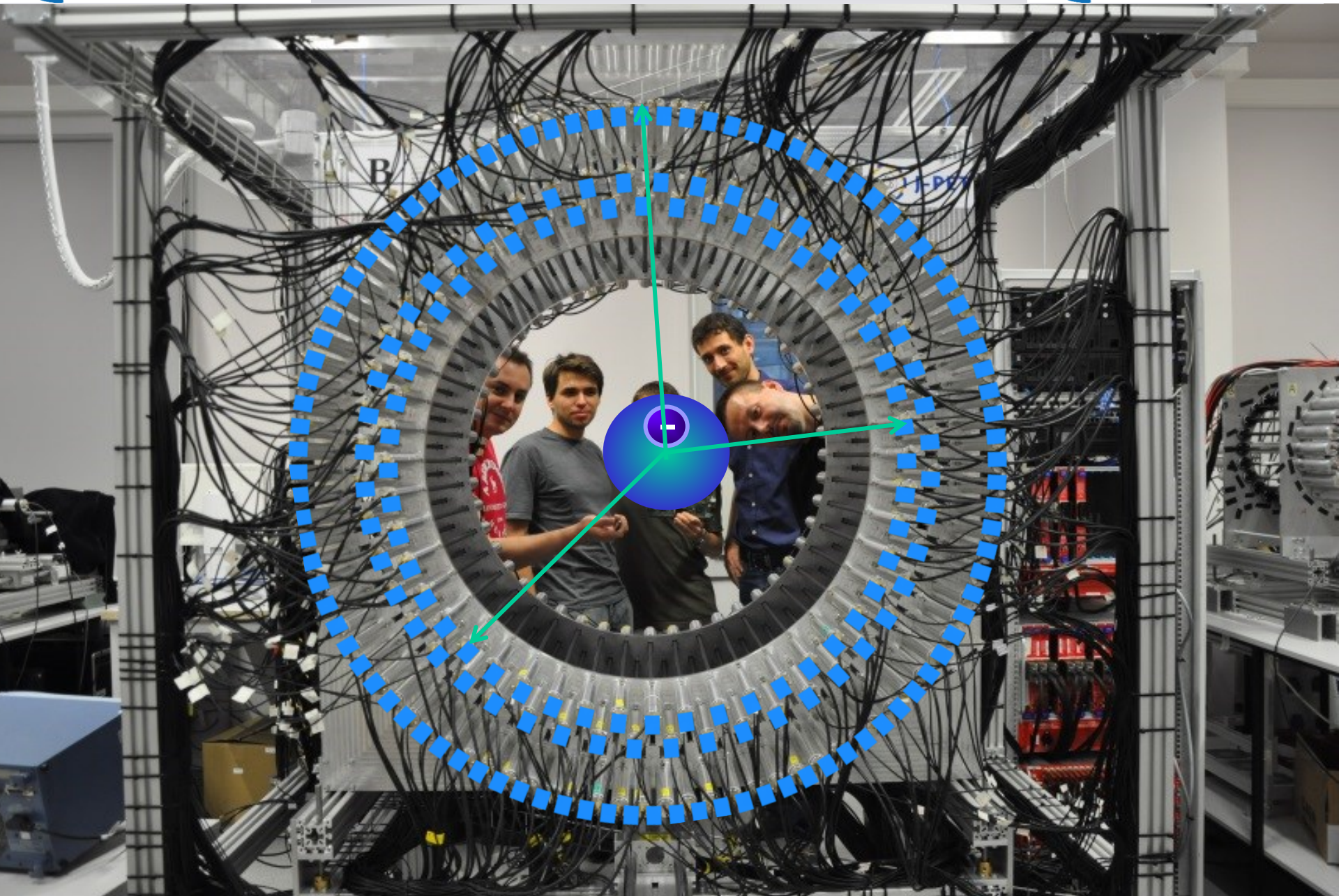
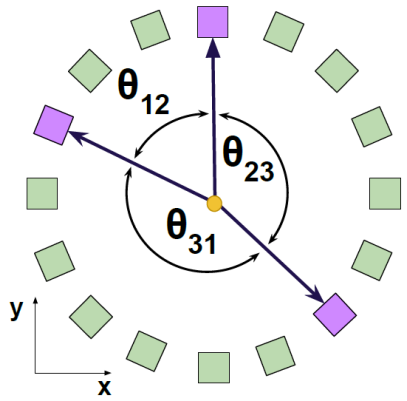
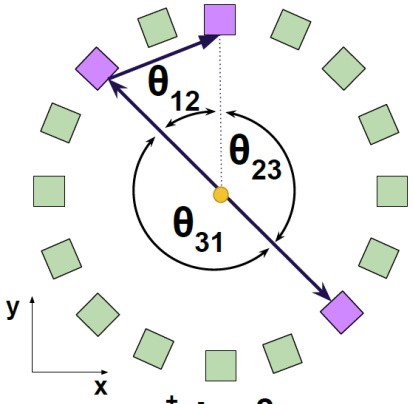




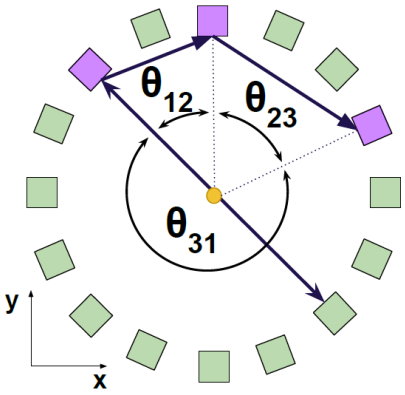
o-Ps → 3γ

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



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

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



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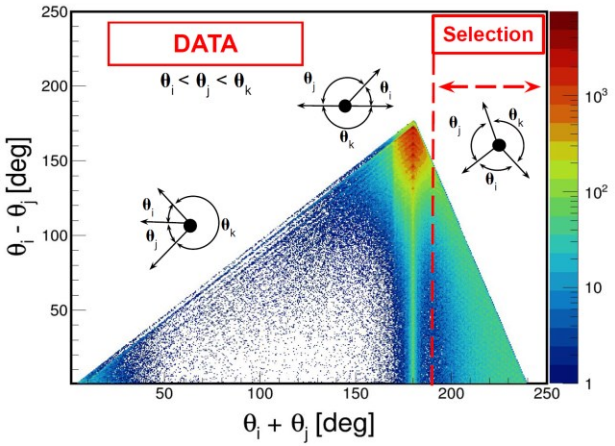

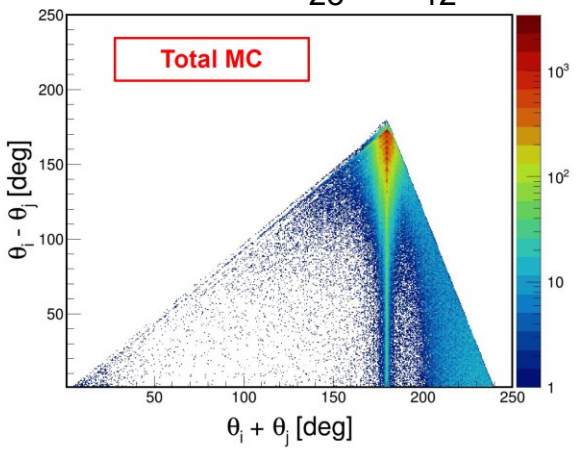

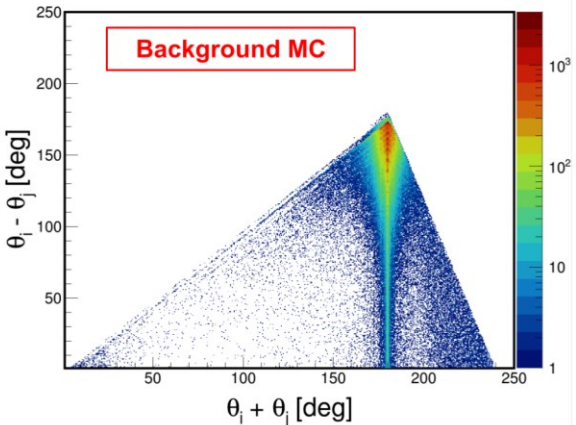

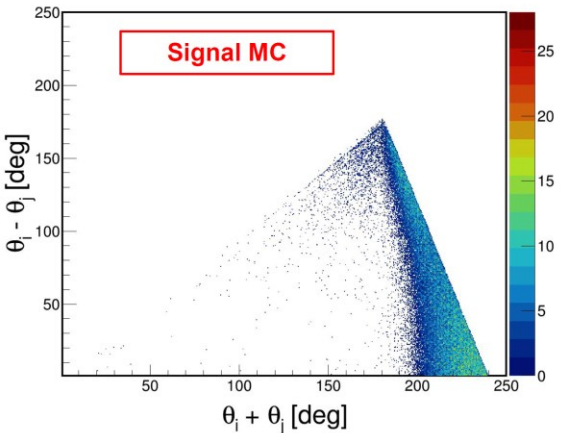

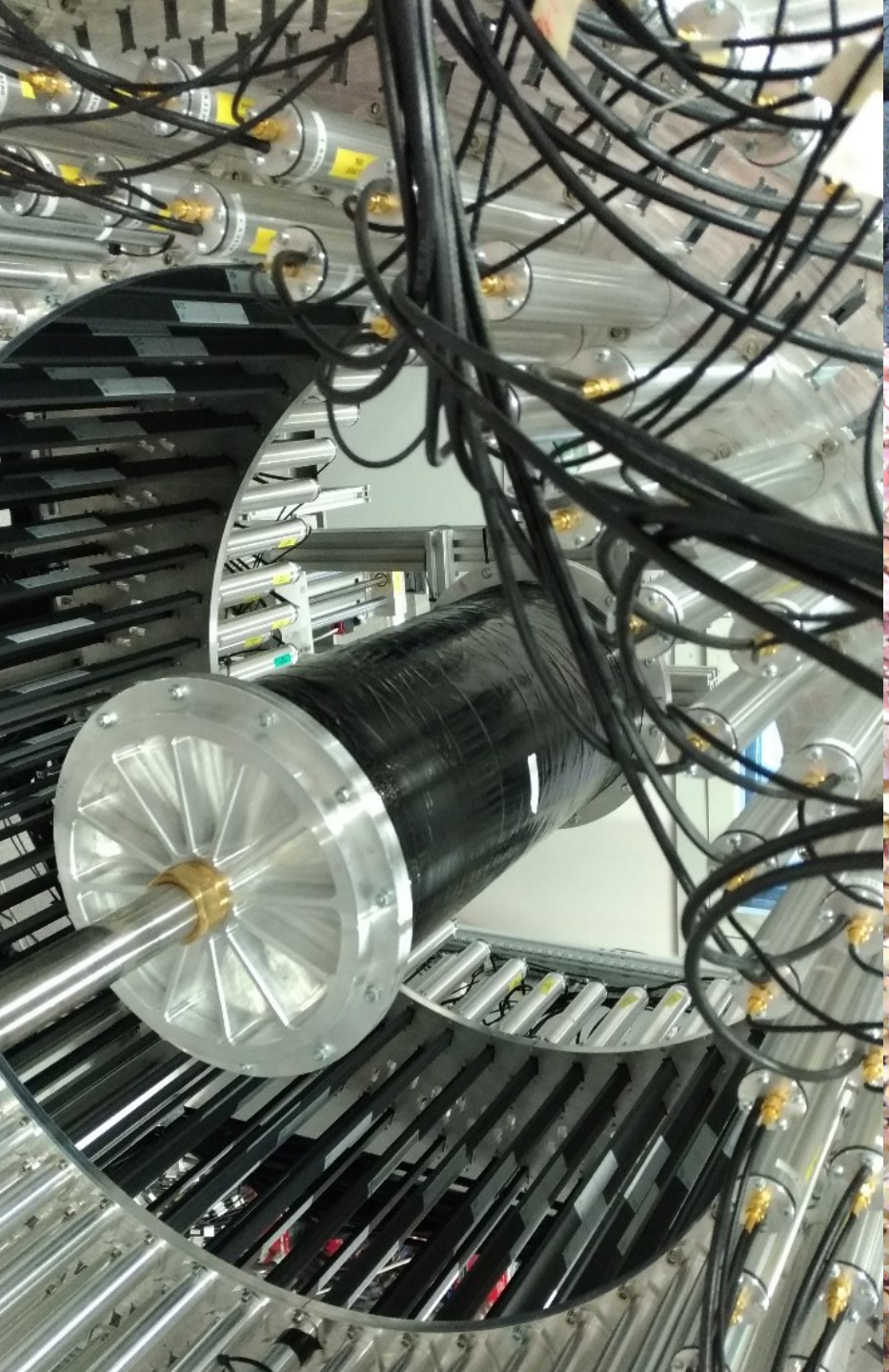

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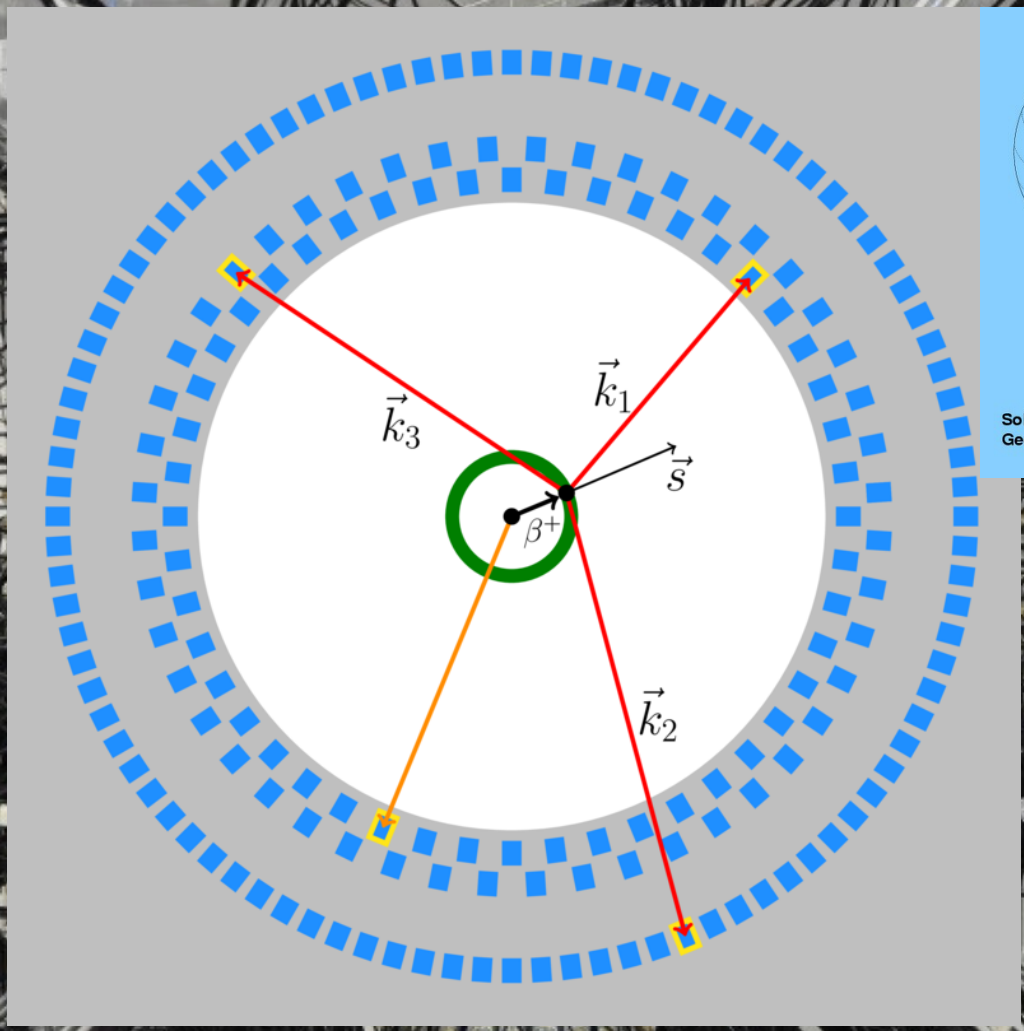
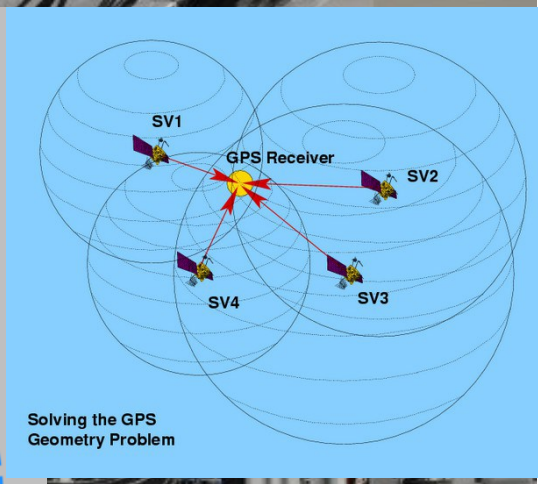
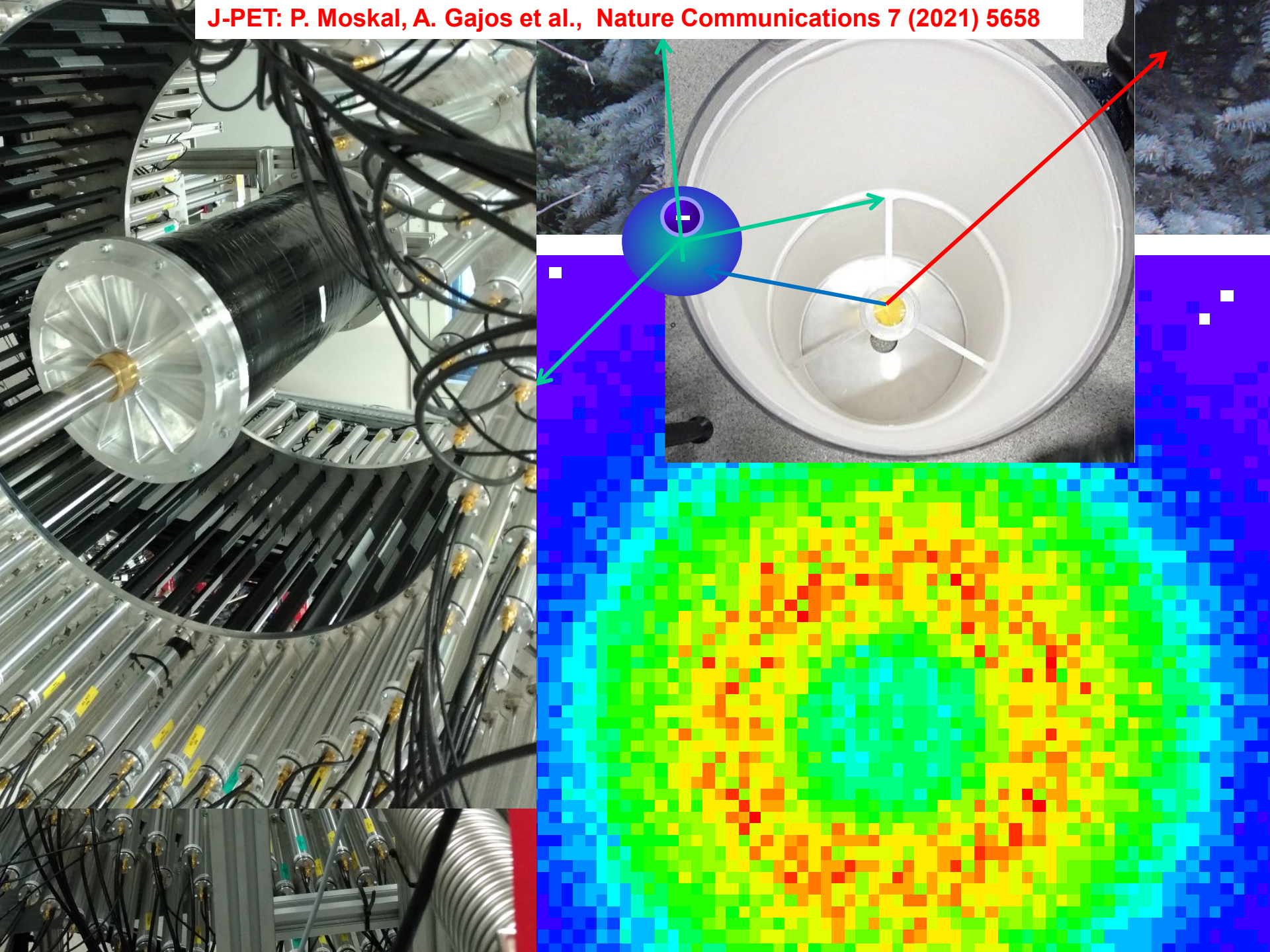




P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509

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



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

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

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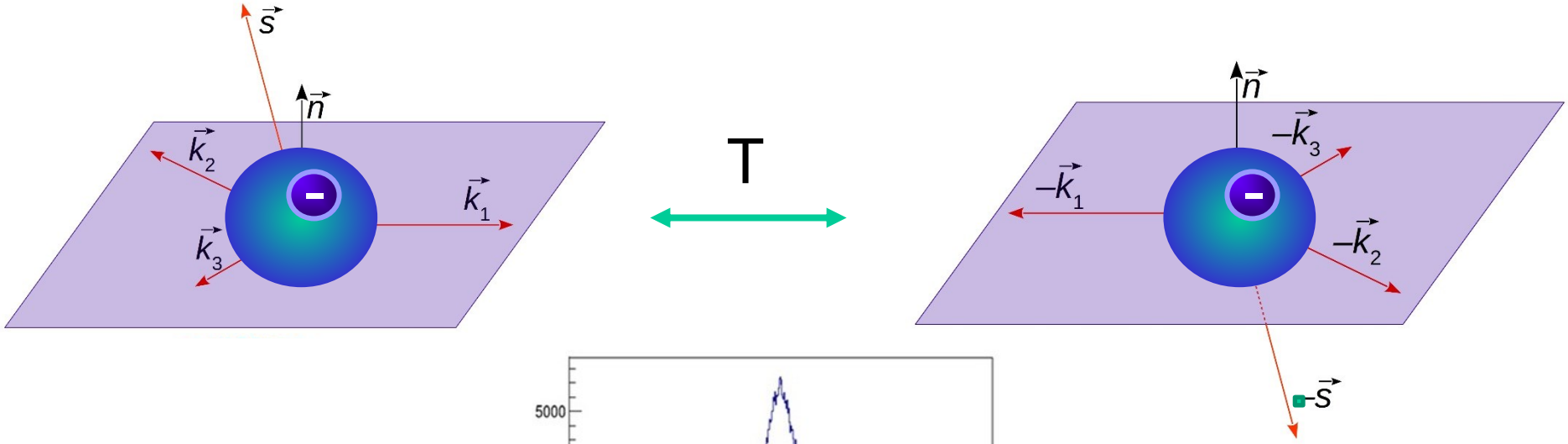
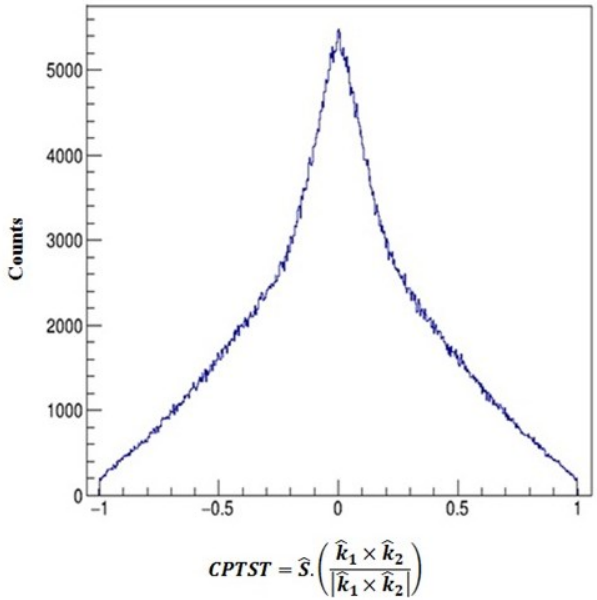
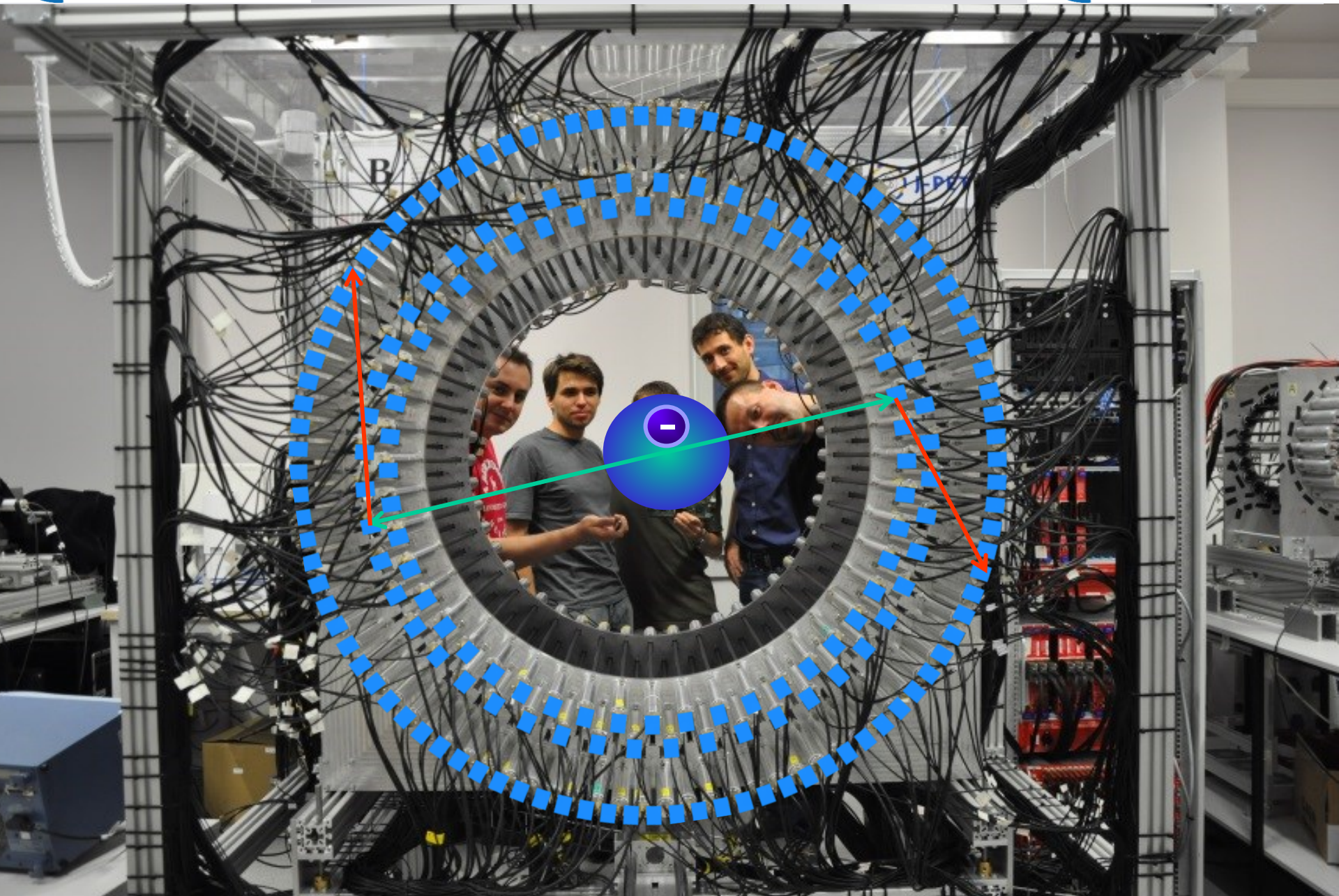




10^{-4}

Jagiellonian PET



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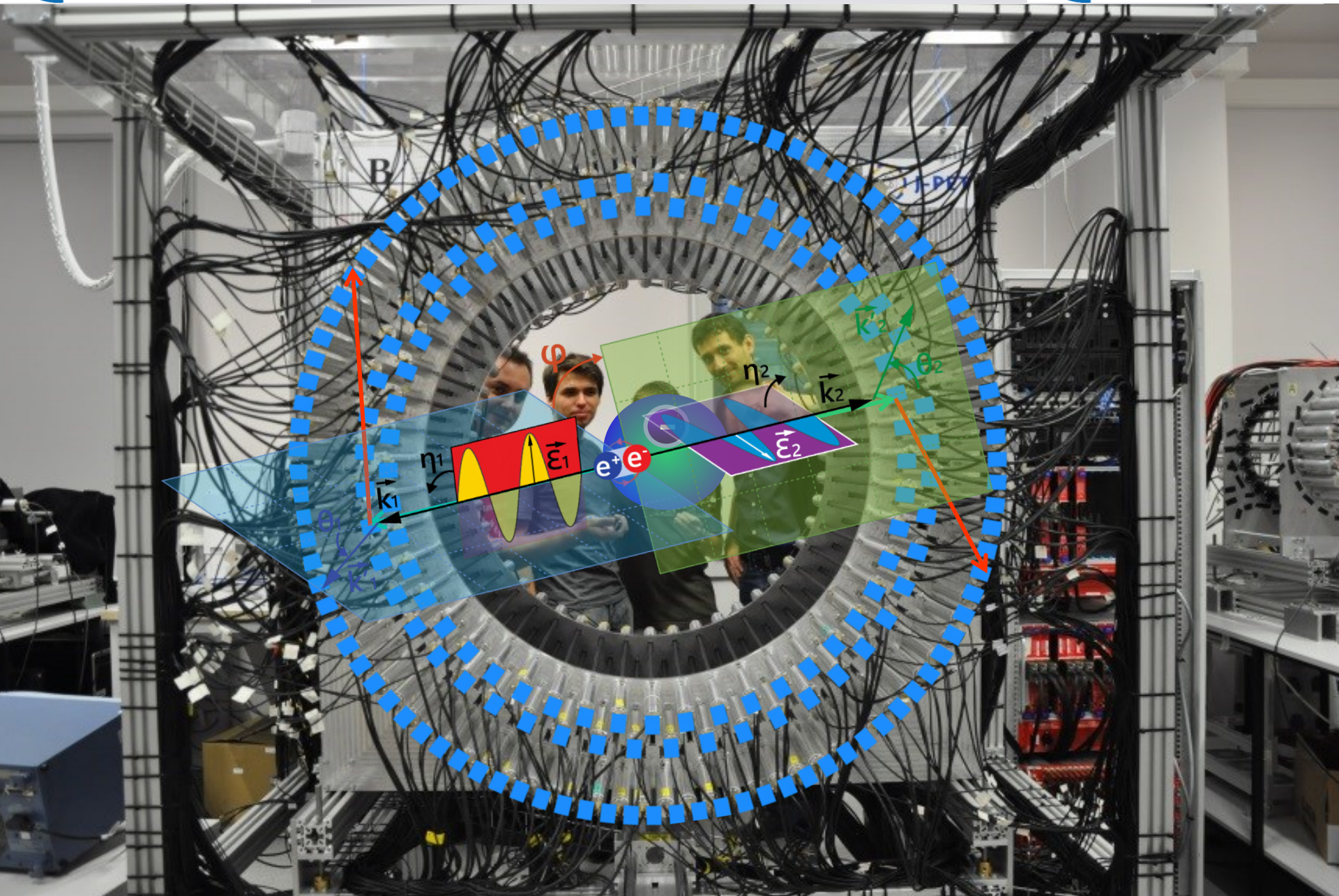

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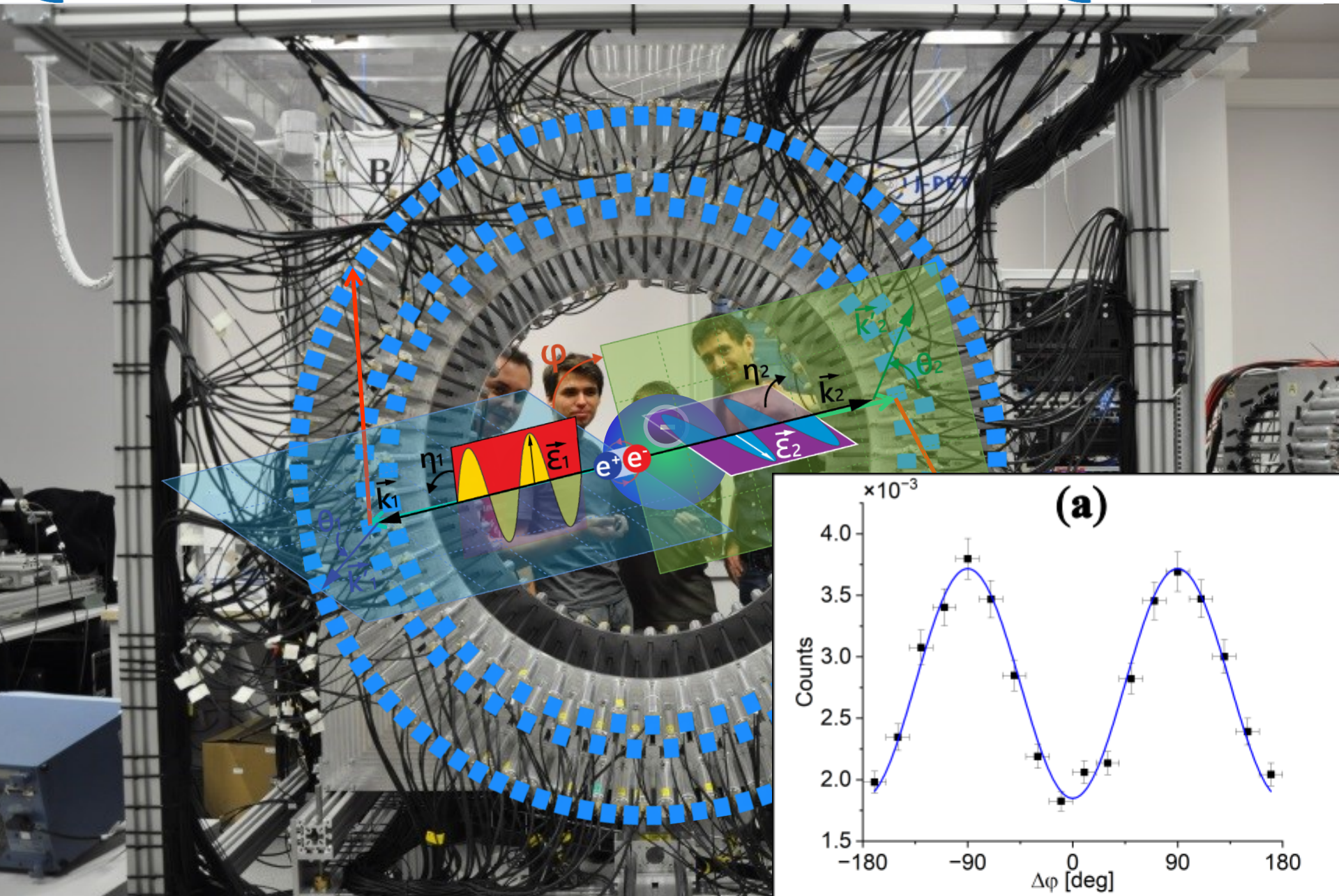
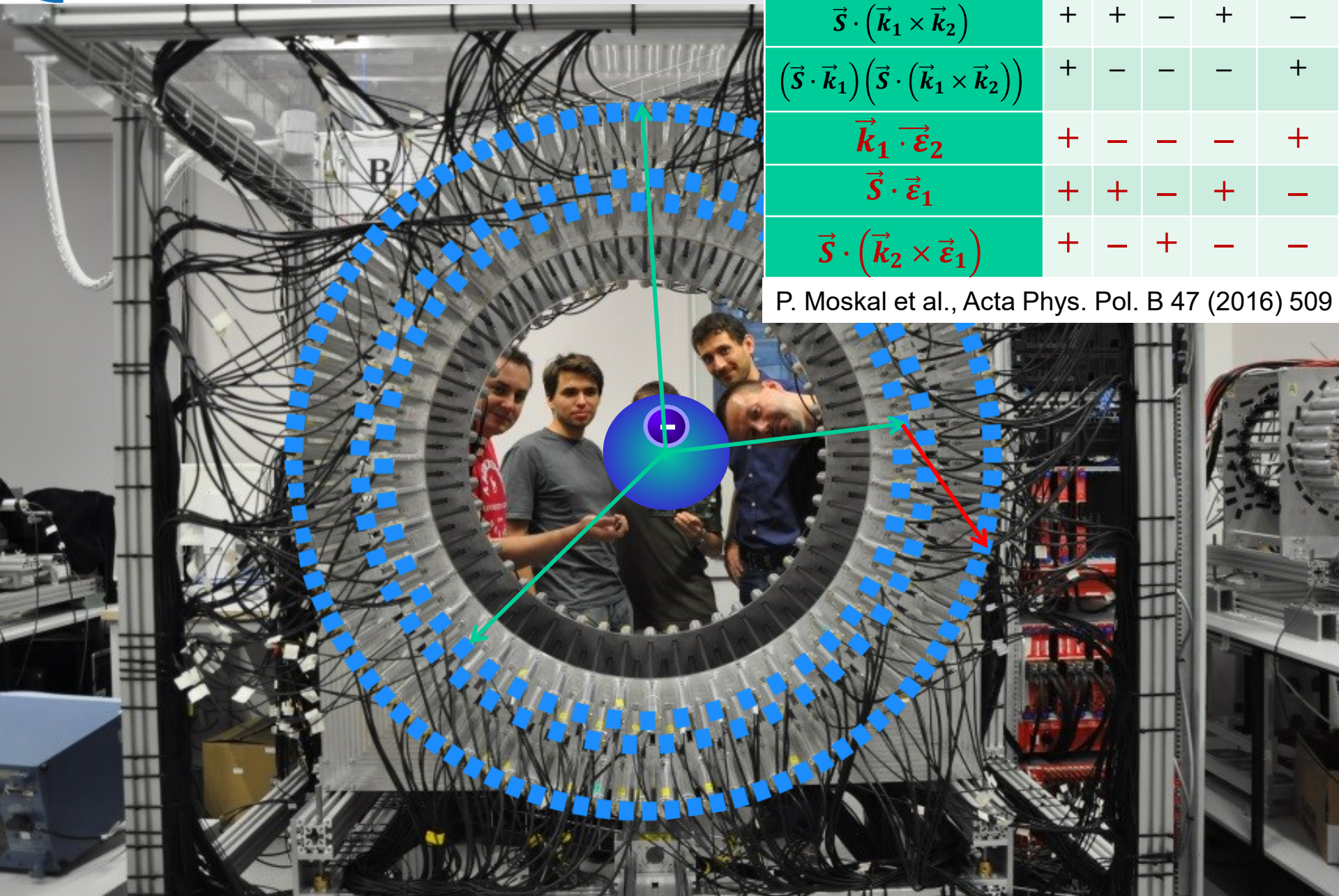


J-PET Jagiellonia

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



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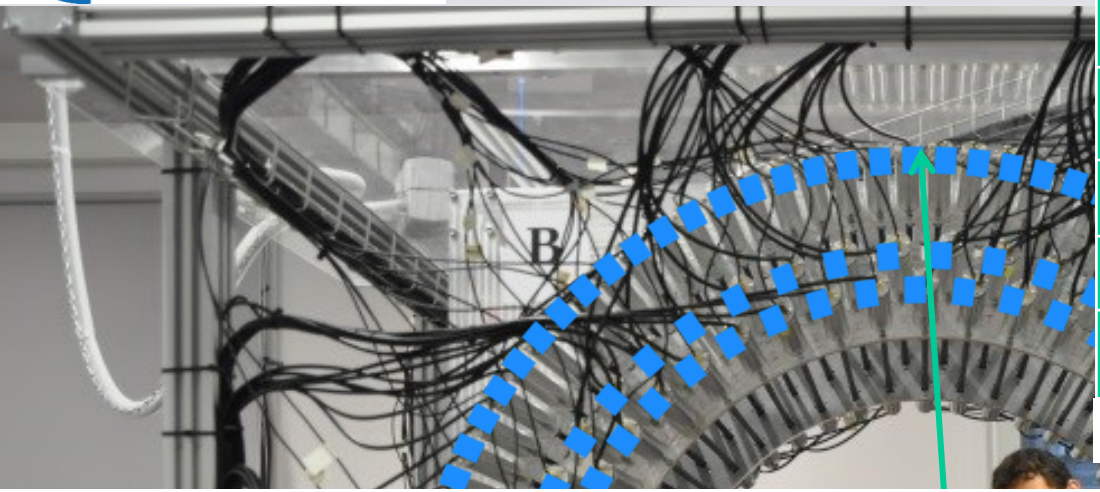

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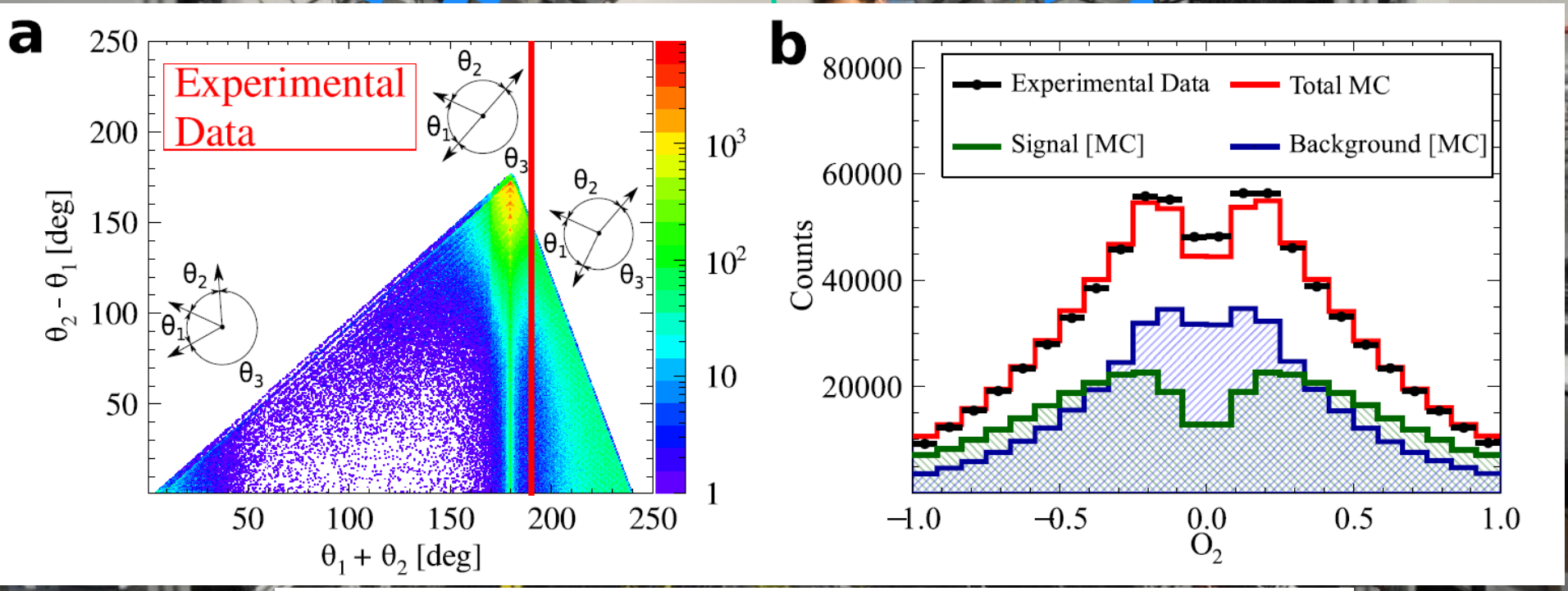

J-PET: P. Moskal et al., Nature Communications 15 (2024) 78

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$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	−	−	−	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	−	−	−	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	−	+	−
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	−	+	−	−

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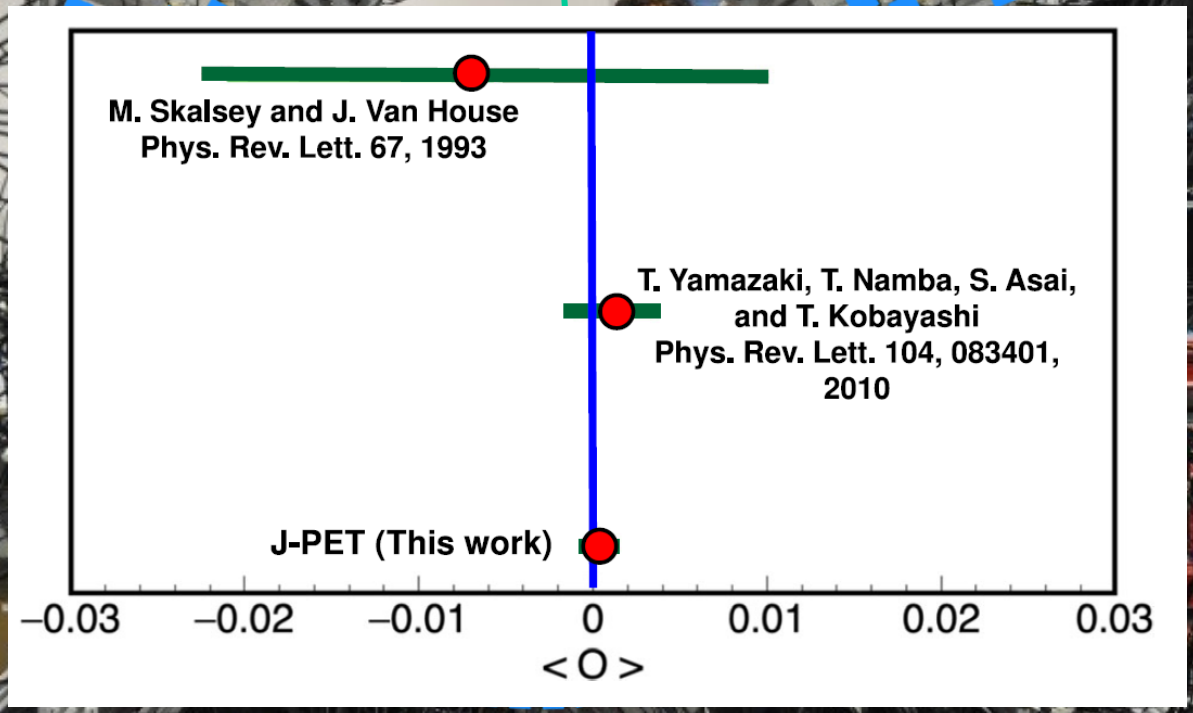

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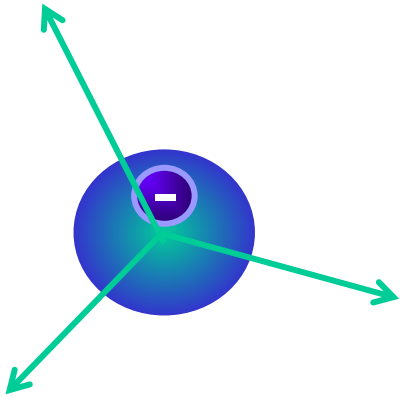

$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$
PRL 104 (2010) 083401

6 OOM of
unexplored precision

Physical sensitivity limit:
false asymmetries from
$\gamma\gamma$ interactions in the final state

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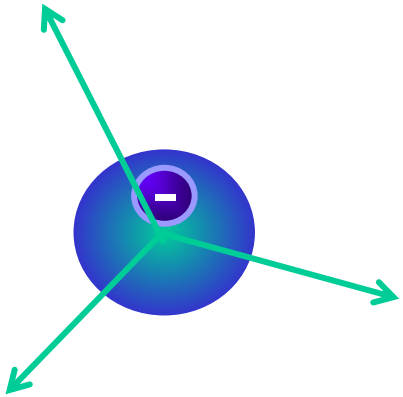
PRL. 91 (2003) 263401

J-PET



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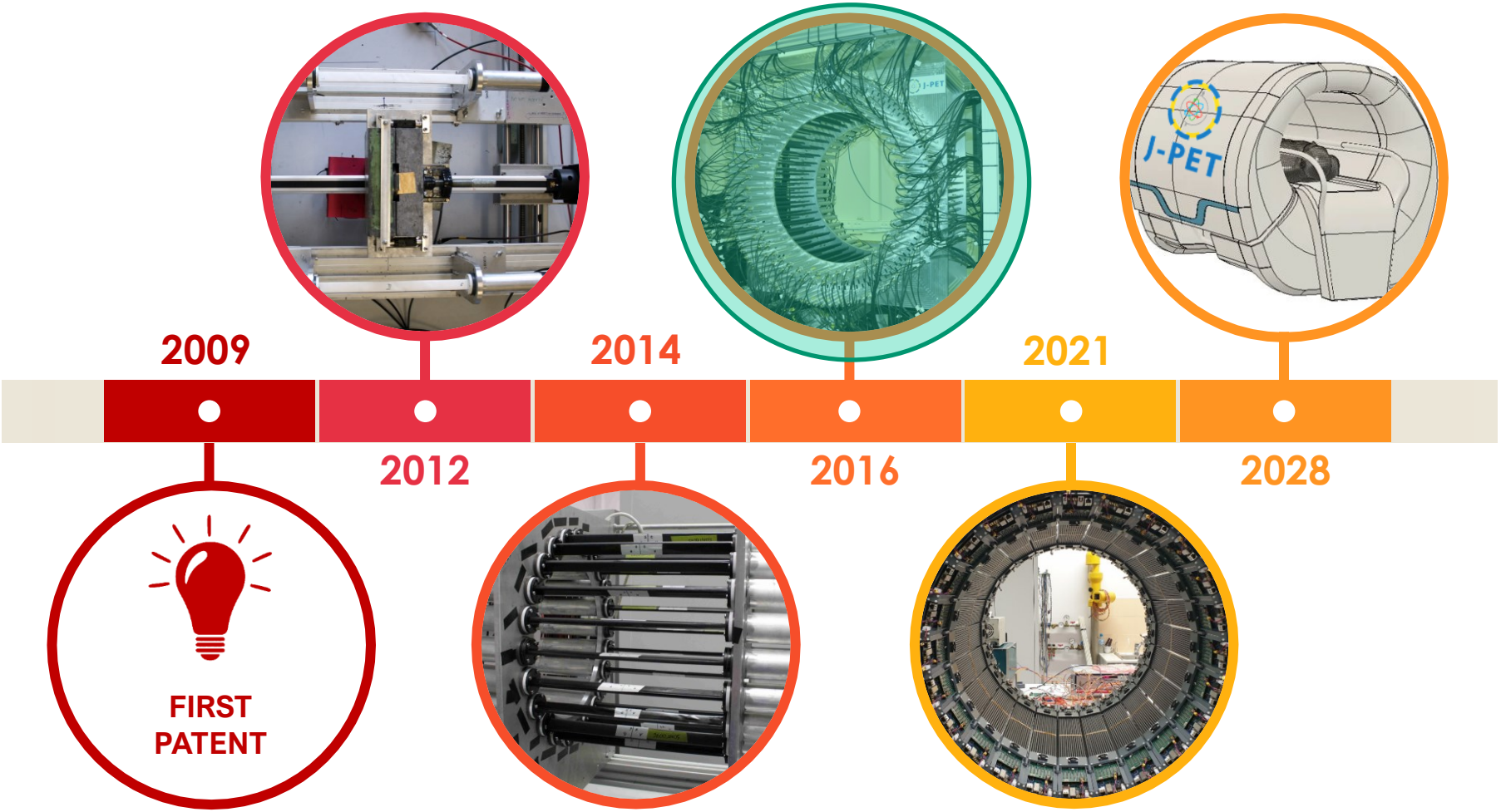

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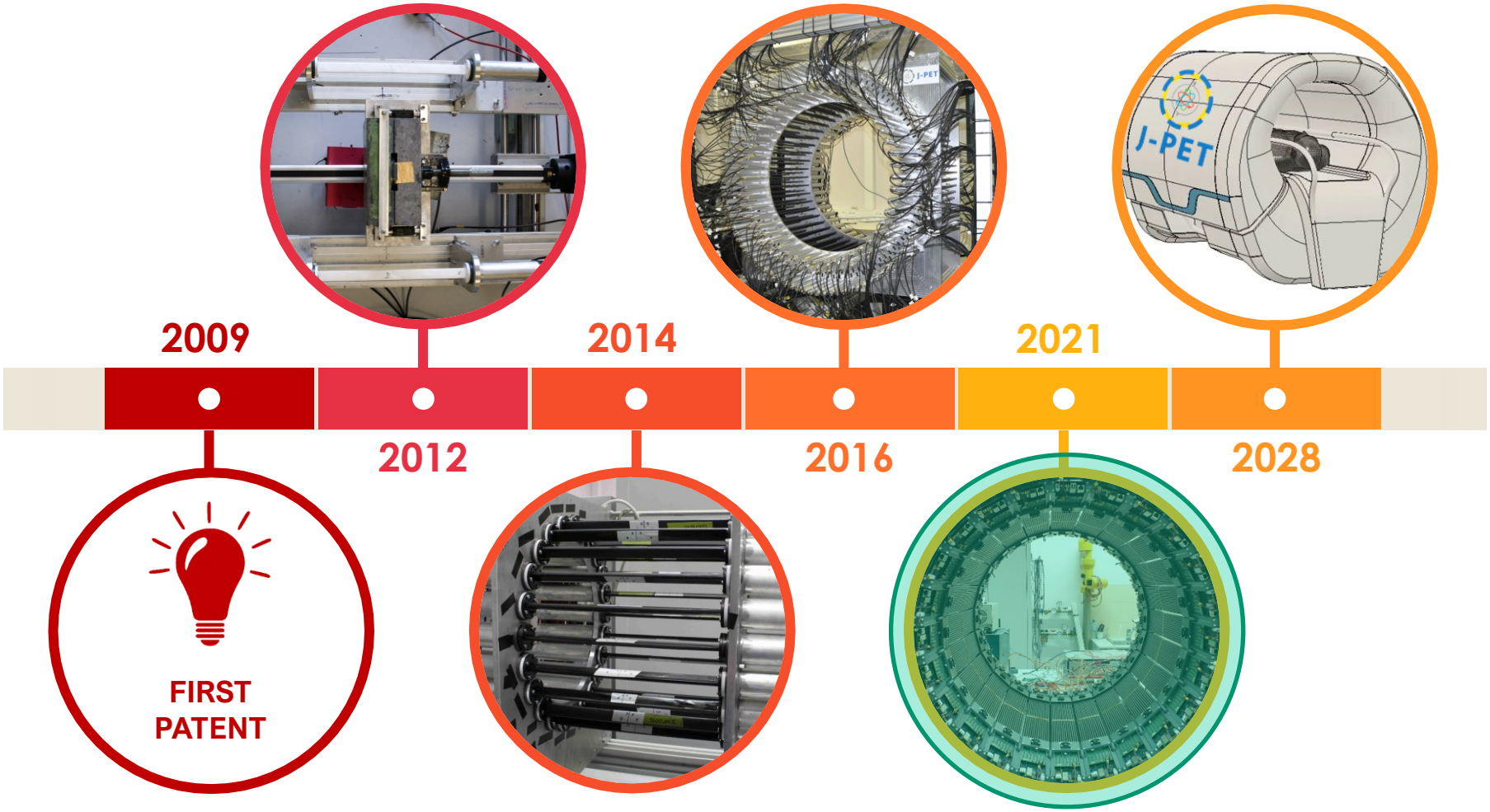

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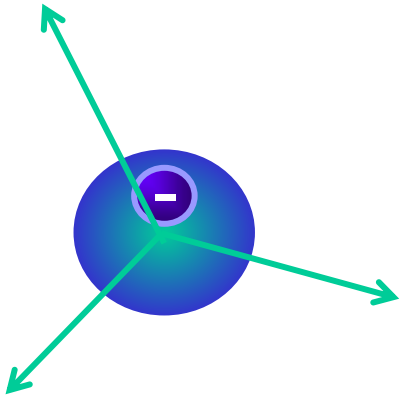

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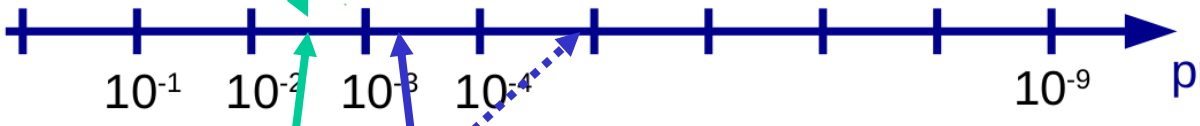

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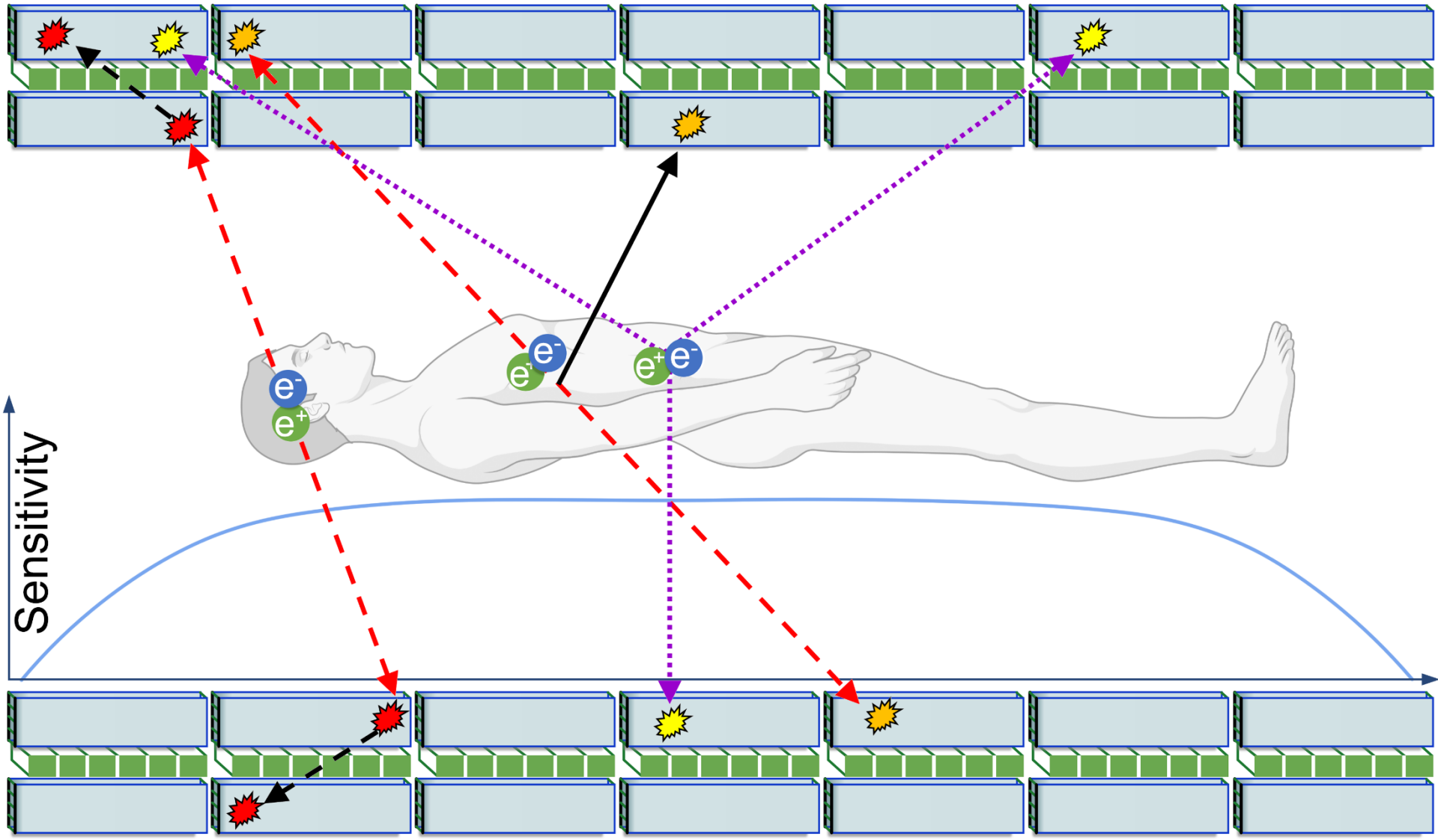
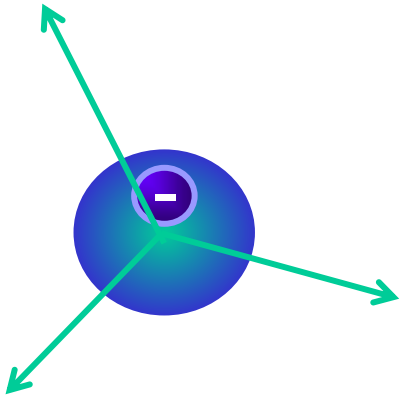


S. D. Bass, S. Mariazzi, P. Moskal, E. Stepien,

Rev. Mod. Phys. 95 (2023) 021002

CENTER FOR THERANOSTICS

Positronium physics and biomedical applications



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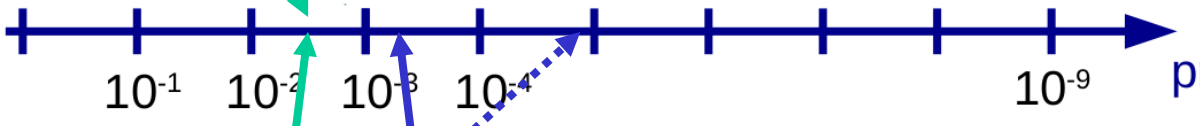

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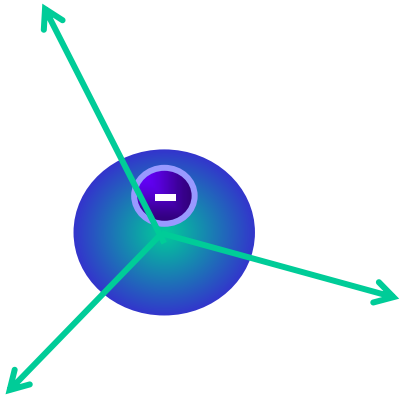

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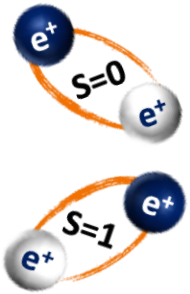
Ortho-positronium decay rate by measuring lifetime of Ps

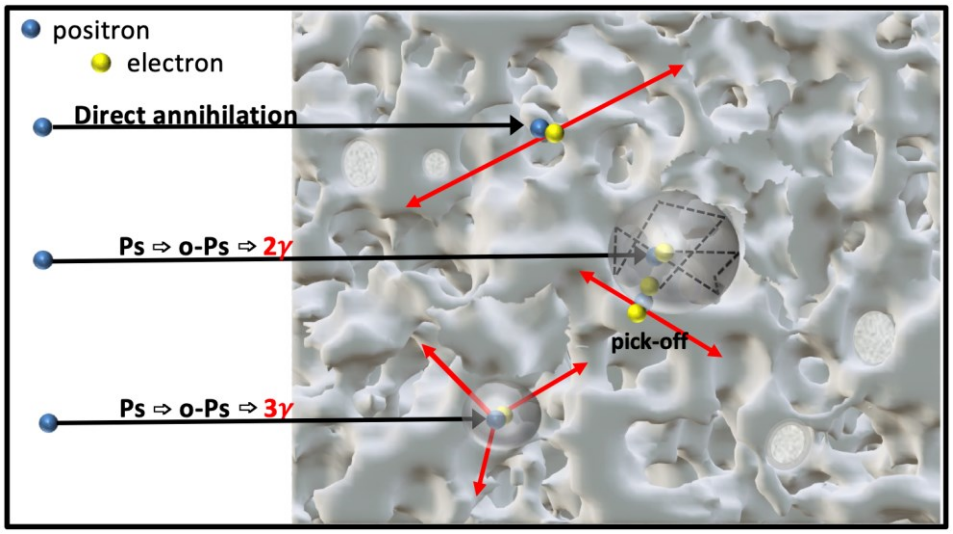


Ps ground states	Charge conjugation invariance	Lifetime (τ)
para-Positronium ($^1S_0$)	$(-1)^{l+s} = 1$ => *even no. of photons*	0.125 ns
ortho-Positronium ($^3S_1$)	$(-1)^{l+s} = -1$ => *odd no. of photons*	142 ns

Ortho-positronium lifetime in porous material :

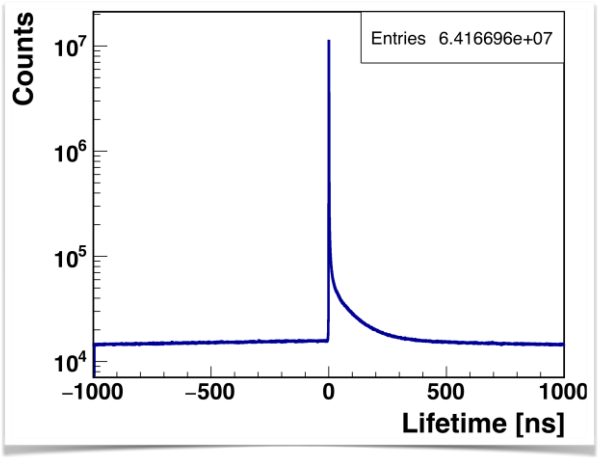
In matter, o-Ps lifetime can be shortened due to the interaction of the positron with electrons from the material (pick-off process) or para-magnetic molecule (conversion).

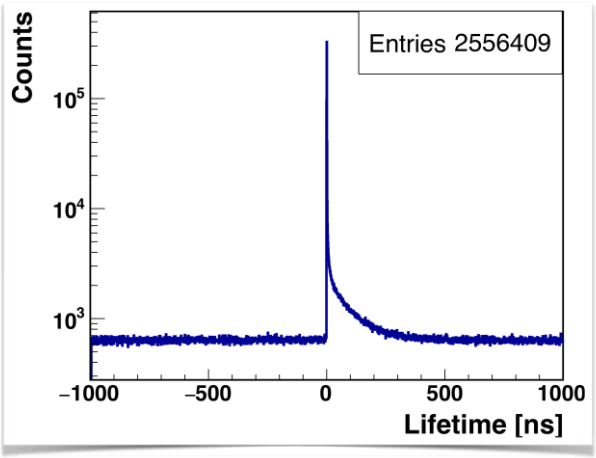
$$\lambda_{exp}(t) = \lambda_{o-Ps} + \lambda_{pick-off}(t)$$



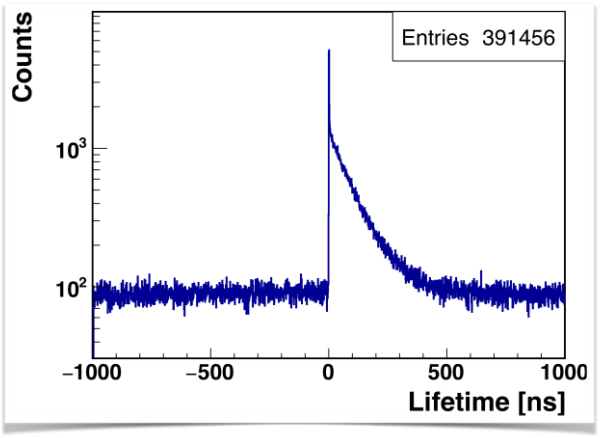
Lifetime spectra

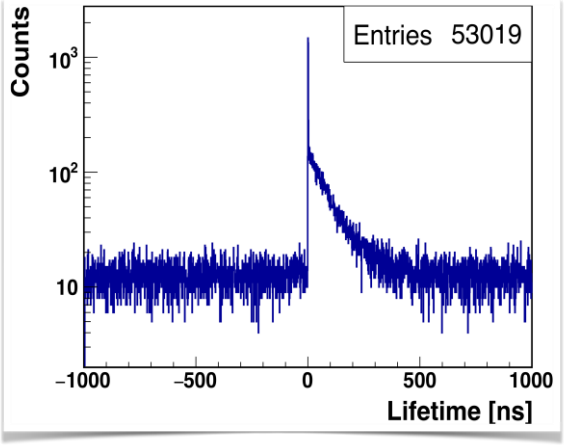
3-hit events
1 Prompt +
2 annihilations (B2B)
LT (2g)





4-hit events
1 Prompt +
3 annihilations (o-Ps)
LT (3g)





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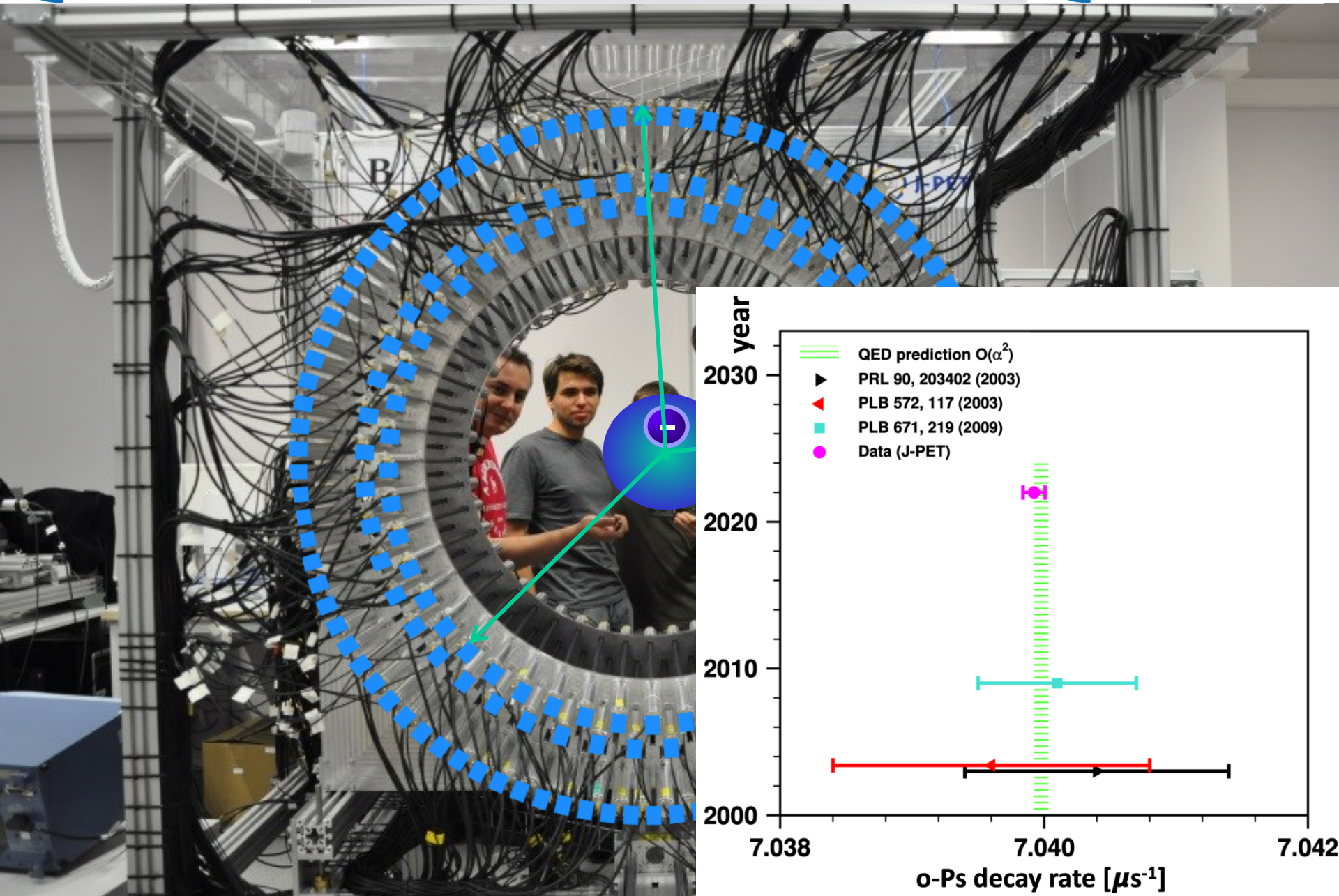

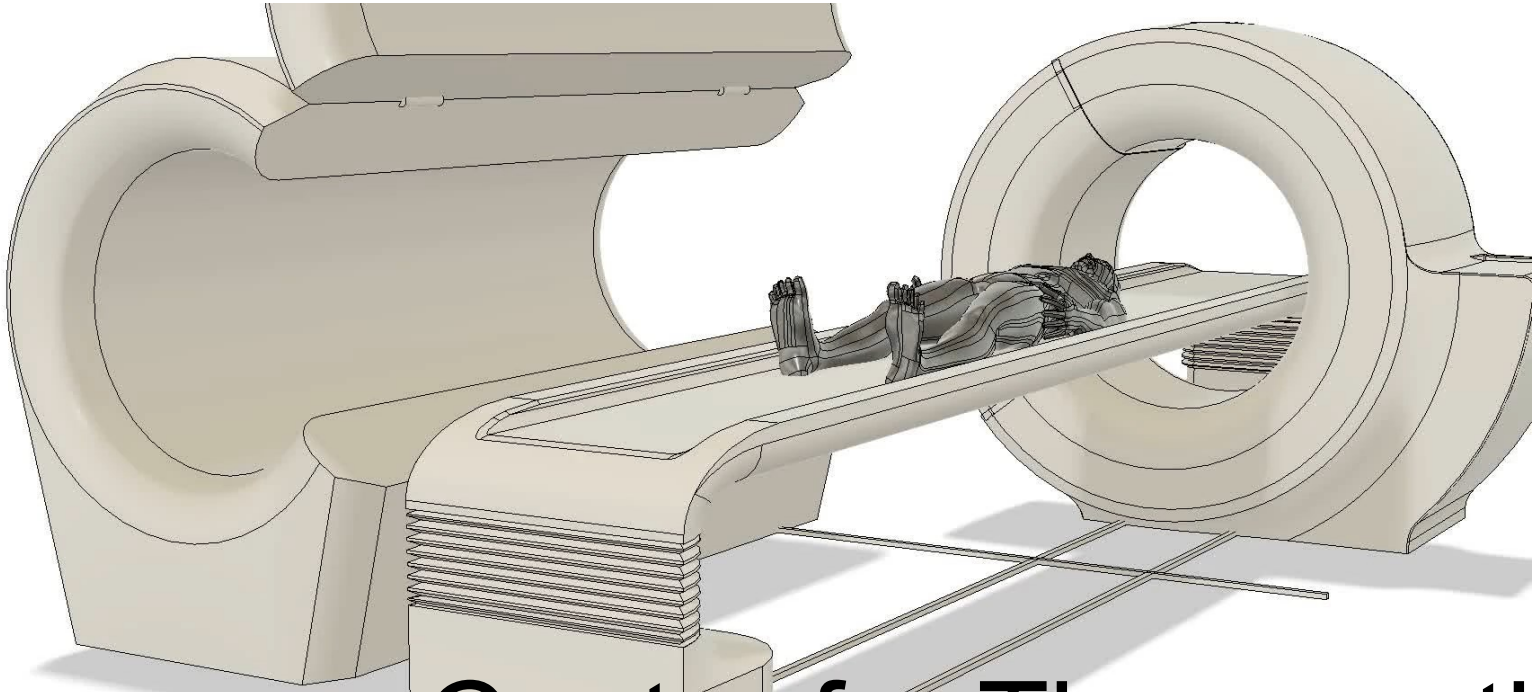
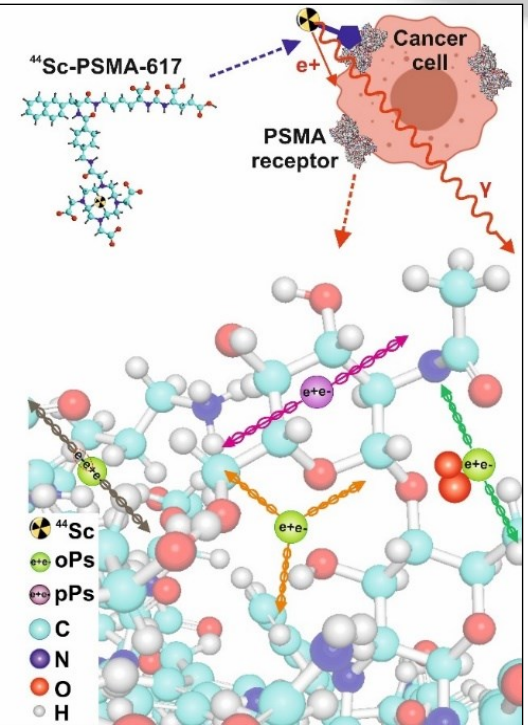
Center for Theranostics
Jagiellonian University