Advancement in positronium and quantum entanglement imaging with J-PET

Workshop on Fundamental Physics with Exotic Atoms
24.06.2025, LNF FRASCATI

P. Moskal, Jagiellonian University
http://koza.if.uj.edu.pl

J-PET

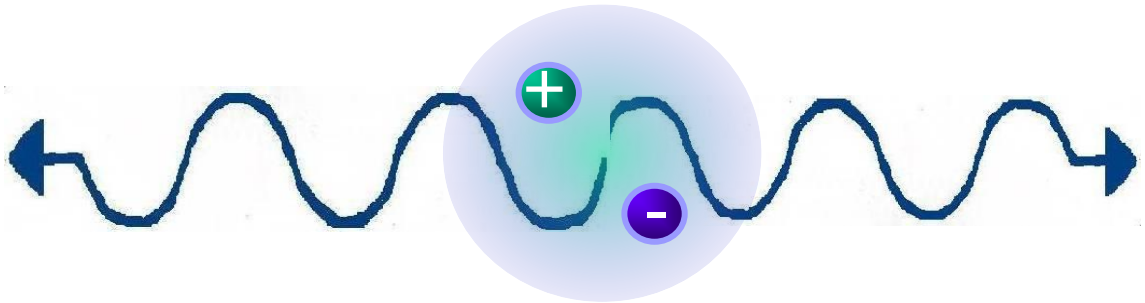
CENTER FOR THERANOSTICS

J-PET

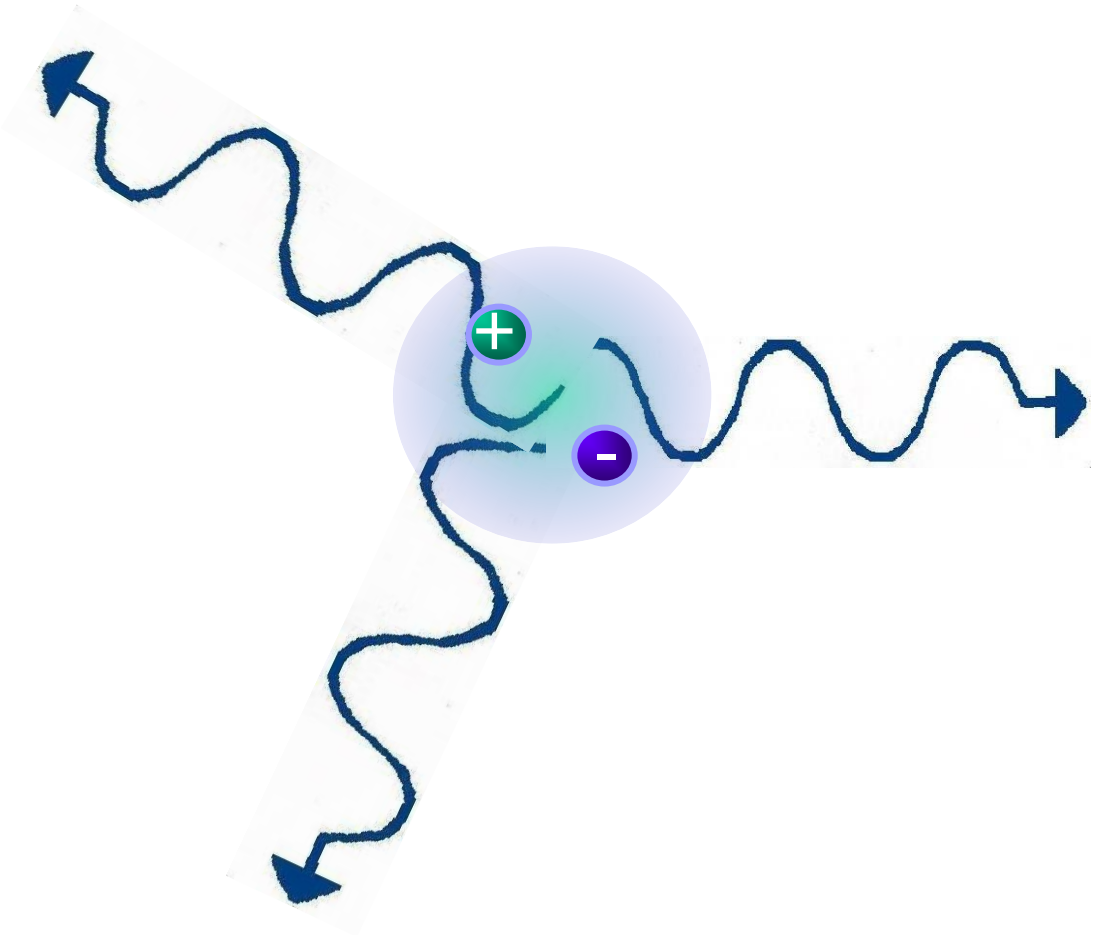
Jagiellonian – PET (J-PET)

Jagiellonian University, Poland

POSITRONIUM



POSITRONIUM



Pawel Moskal, Jagiellonian University

POSITRONIUM

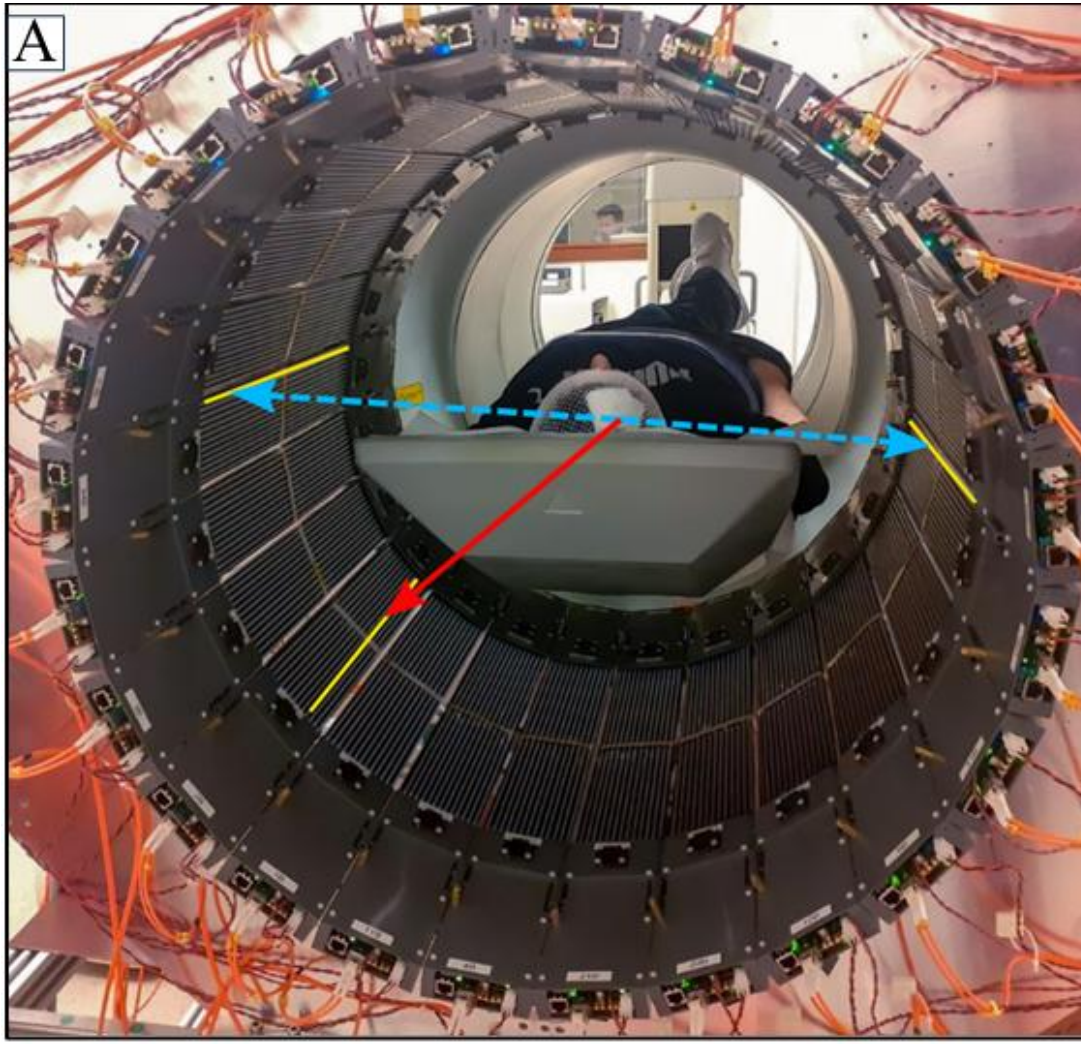
POSITRONIUM in MEDICINE

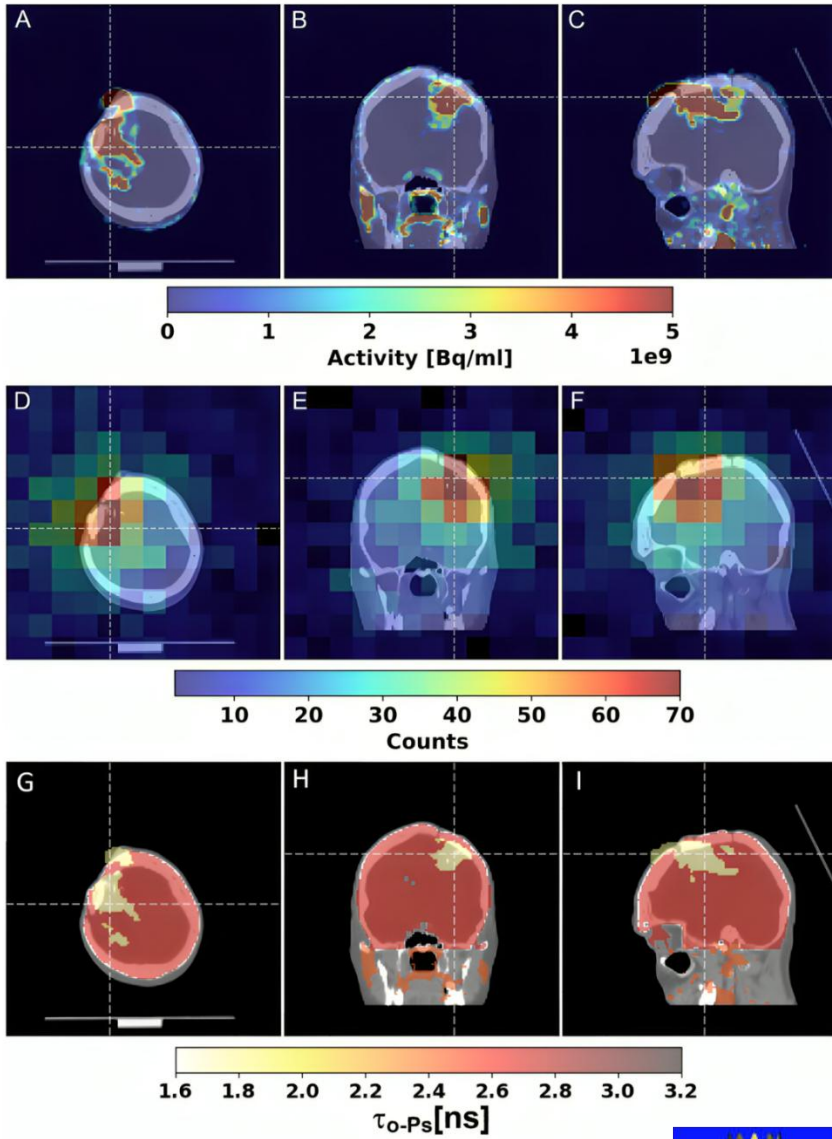
PALS and PET

=>

POSITRONIUM IMAGING

First clinical positronium imaging of patients

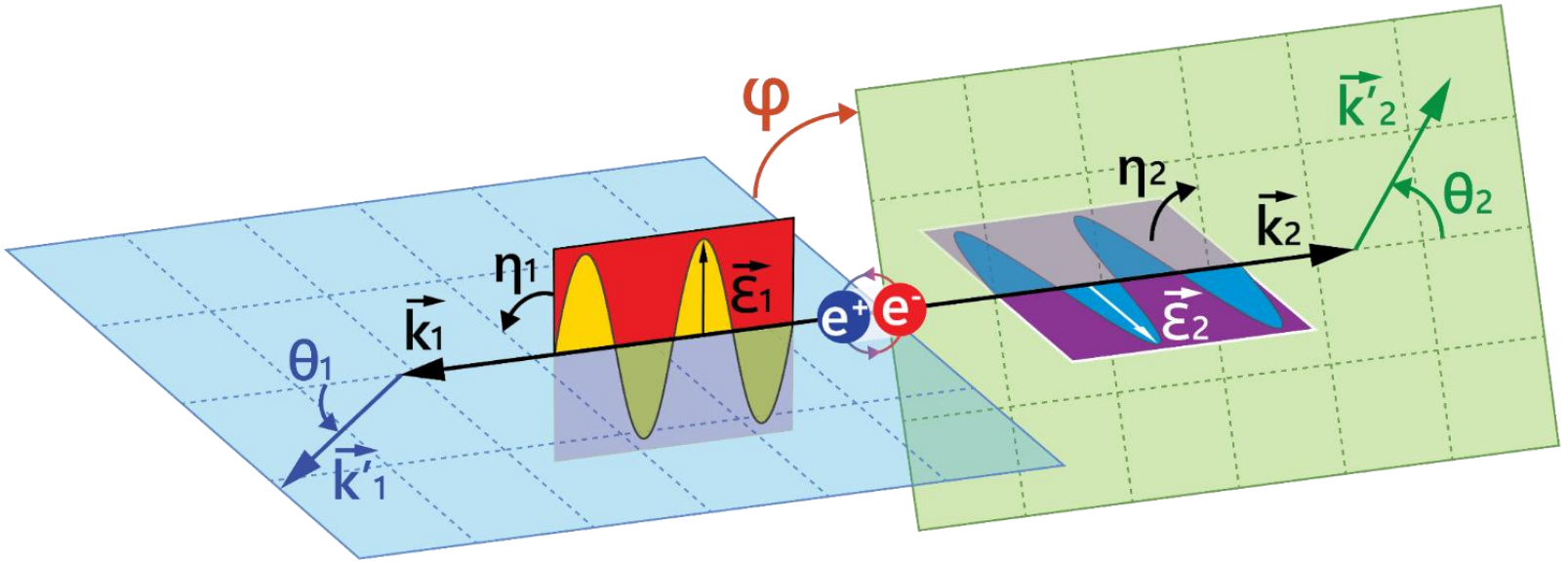




P. Moskal, …, E. Stepień, Science Advances 10 (2024) eadp2840

Positronium image of the human brain in vivo

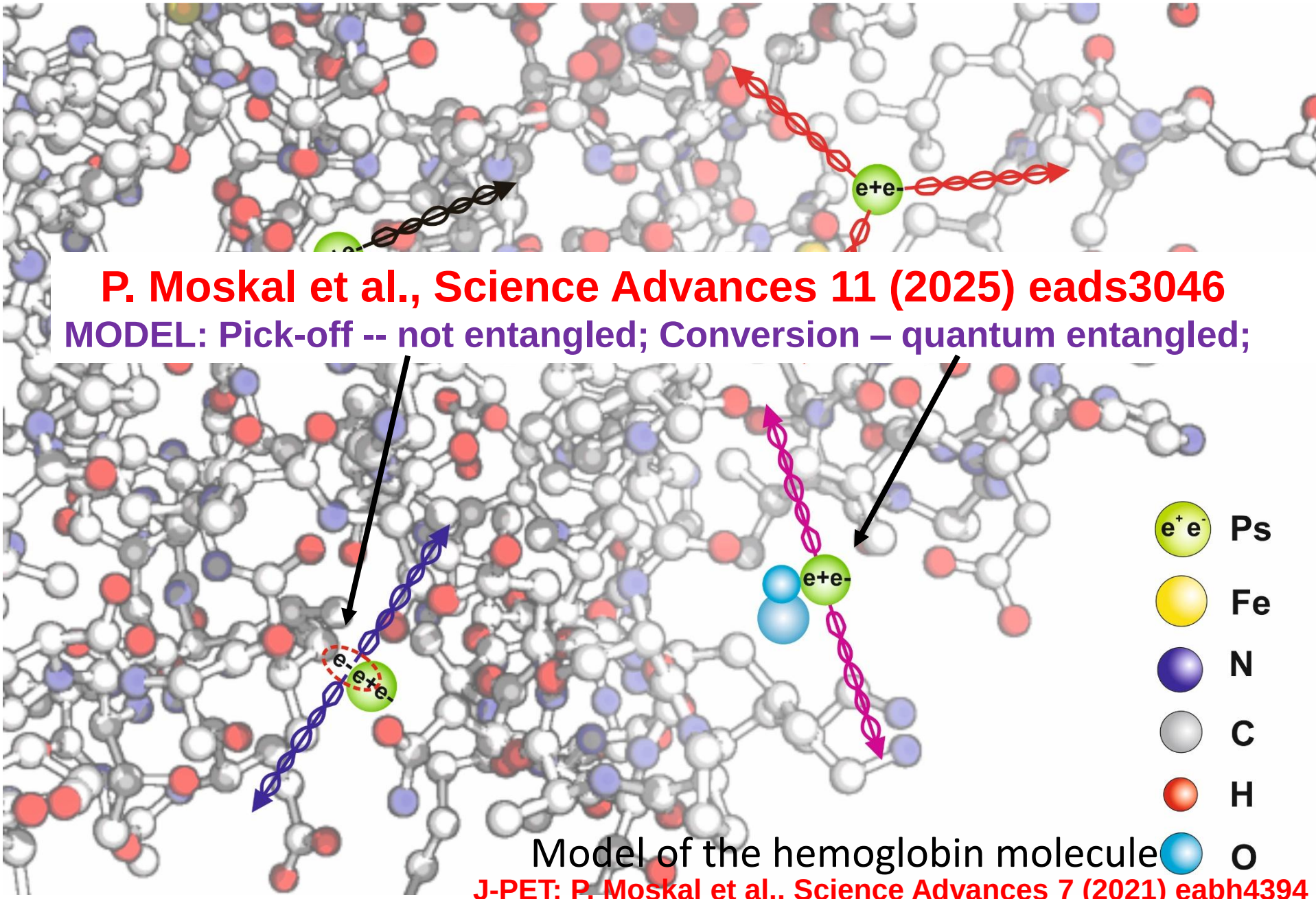
Pawel Moskal, Jagiellonian University



quantum entangled photons

Pawel Moskal, Jagiellonian University

QUANTUM ENTANGLEMENT IMAGING

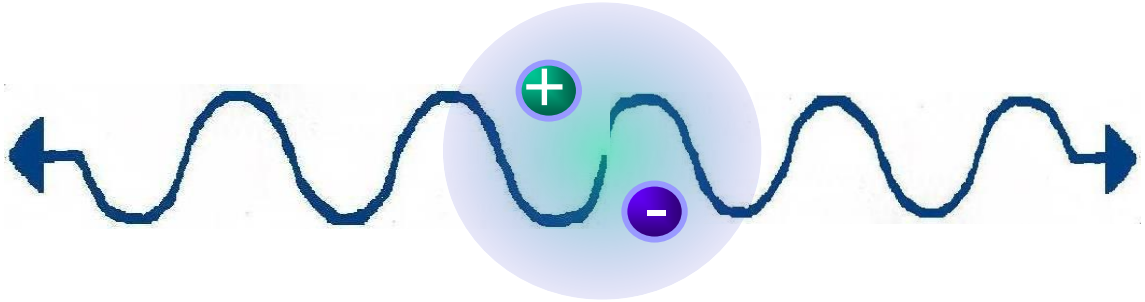


P. Moskal et al., Science Advances 11 (2025) eads3046

MODEL: Pick-off -- not entangled; Conversion – quantum entangled;

Model of the hemoglobin molecule

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



P. Moskal, …, E. Stępień, Nature Review Physics 1 (2019)
P. Moskal, …, E. Stępień, Science Advances 7 (2021) eabh4394
P. Moskal et al., Nature Communications 12 (2021) 5658
P. Moskal, …, E. Stępień, Science Advances 10 (2024) eadp2840
P. Moskal et al., Nature Communications 15 (2024) 78
P. Moskal et al., Science Advances 11 (2025) eads3046

PET from PLASTIC SCINTILLATORS

POSITRONIUM IMAGING

DISCRETE SYMMETRIES

QUANTUM ENTANGLEMENT IMAGING

P. Moskal, Jagiellonian University
http://koza.if.uj.edu.pl

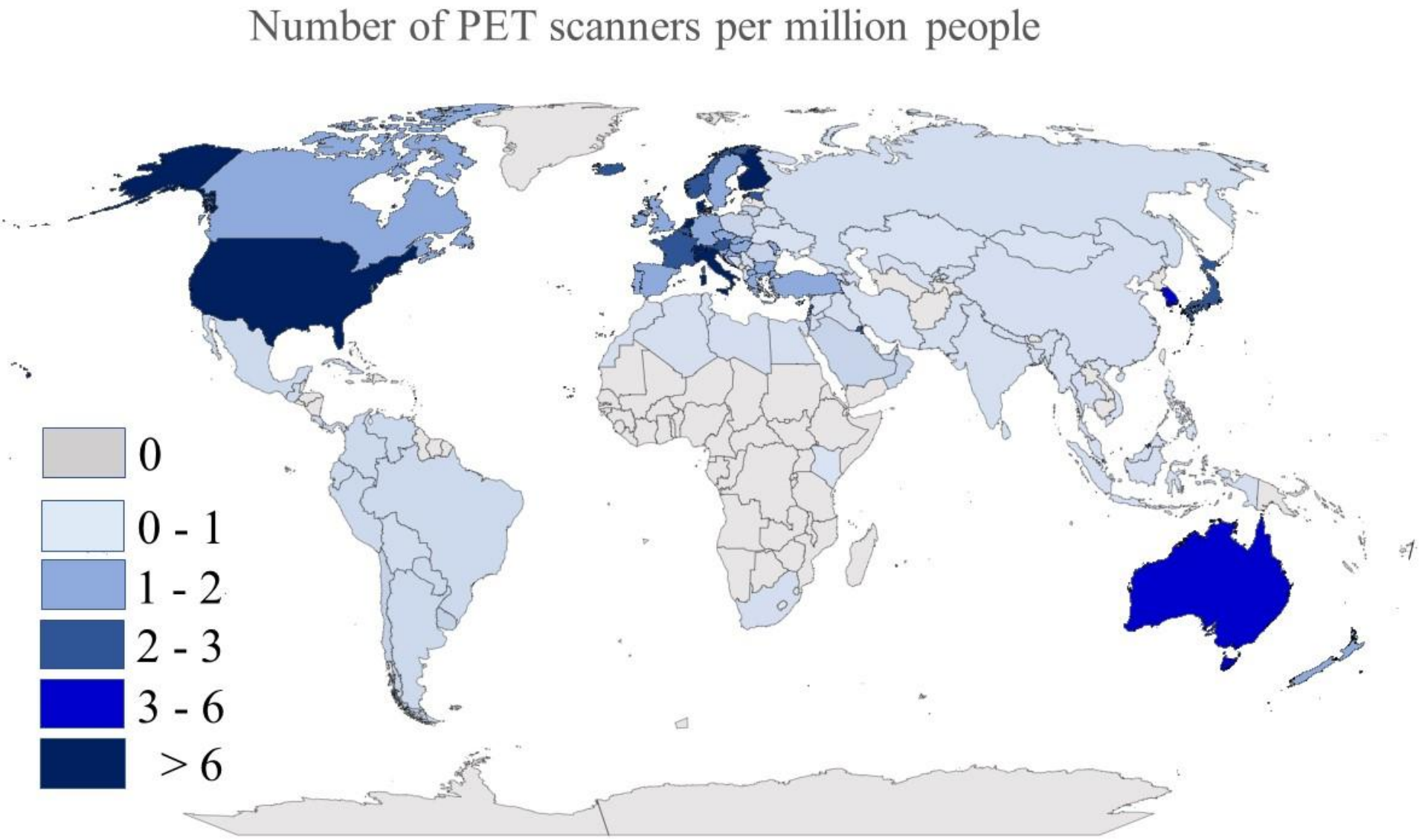
PET from PLASTIC SCINTILLATORS

POSITRONIUM IMAGING

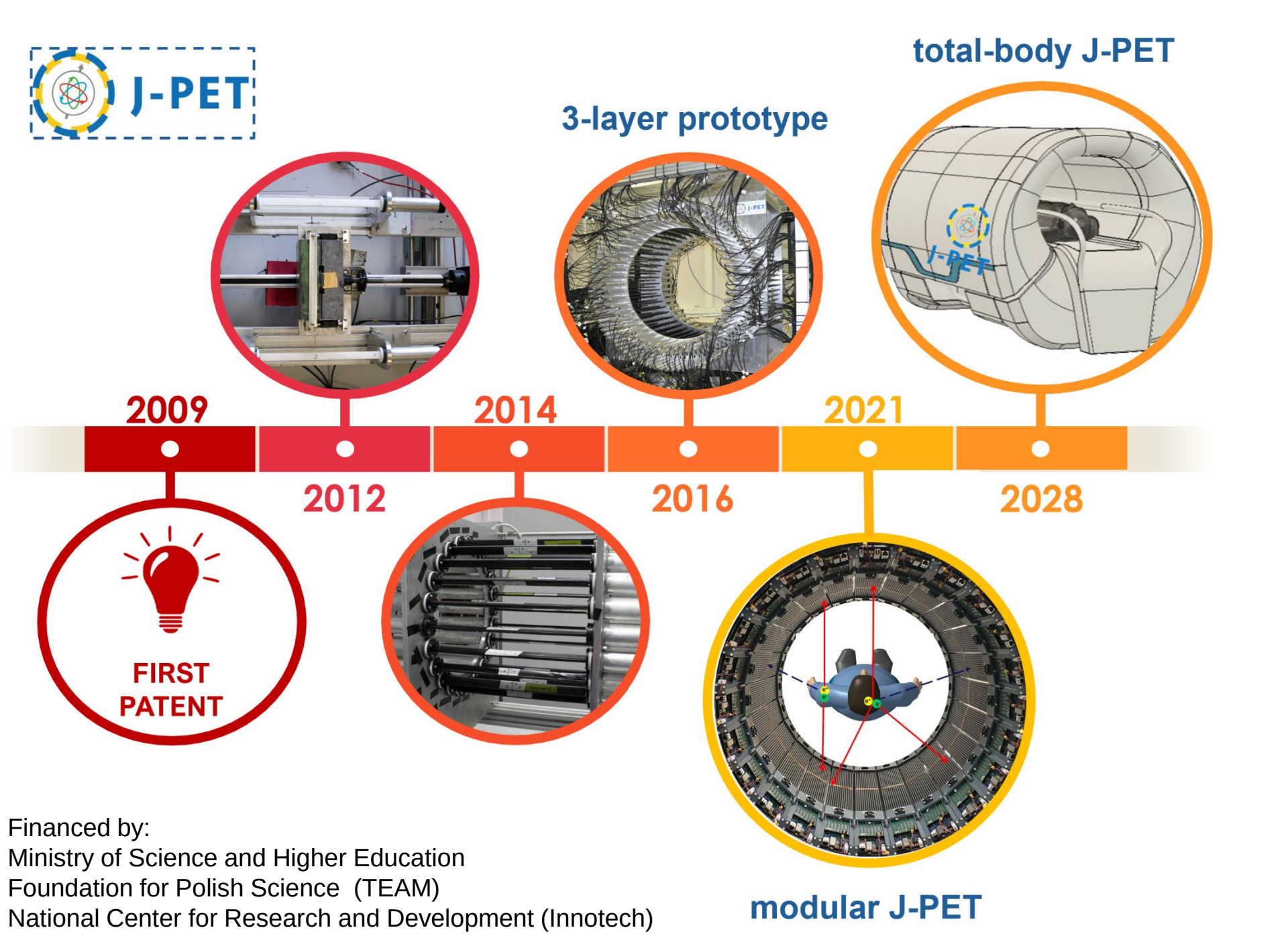
DISCRETE SYMMETRIES

QUANTUM ENTANGLEMENT IMAGING

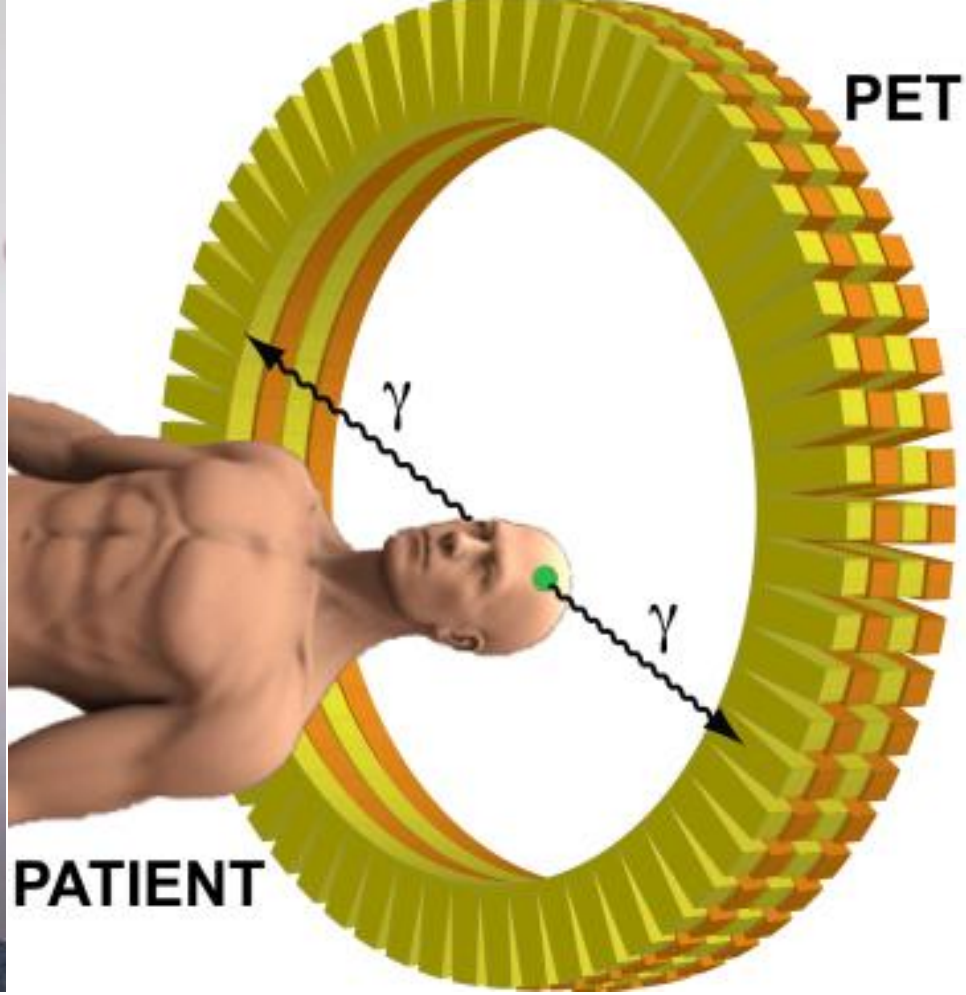
P. Moskal, Jagiellonian University
http://koza.if.uj.edu.pl



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



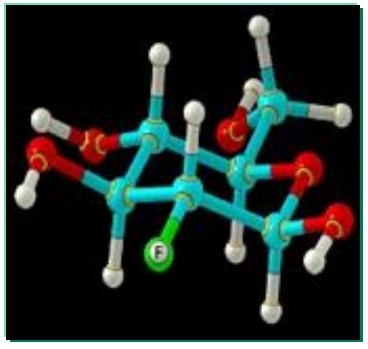
Financed by:
Ministry of Science and Higher Education
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes, MAESTRO)



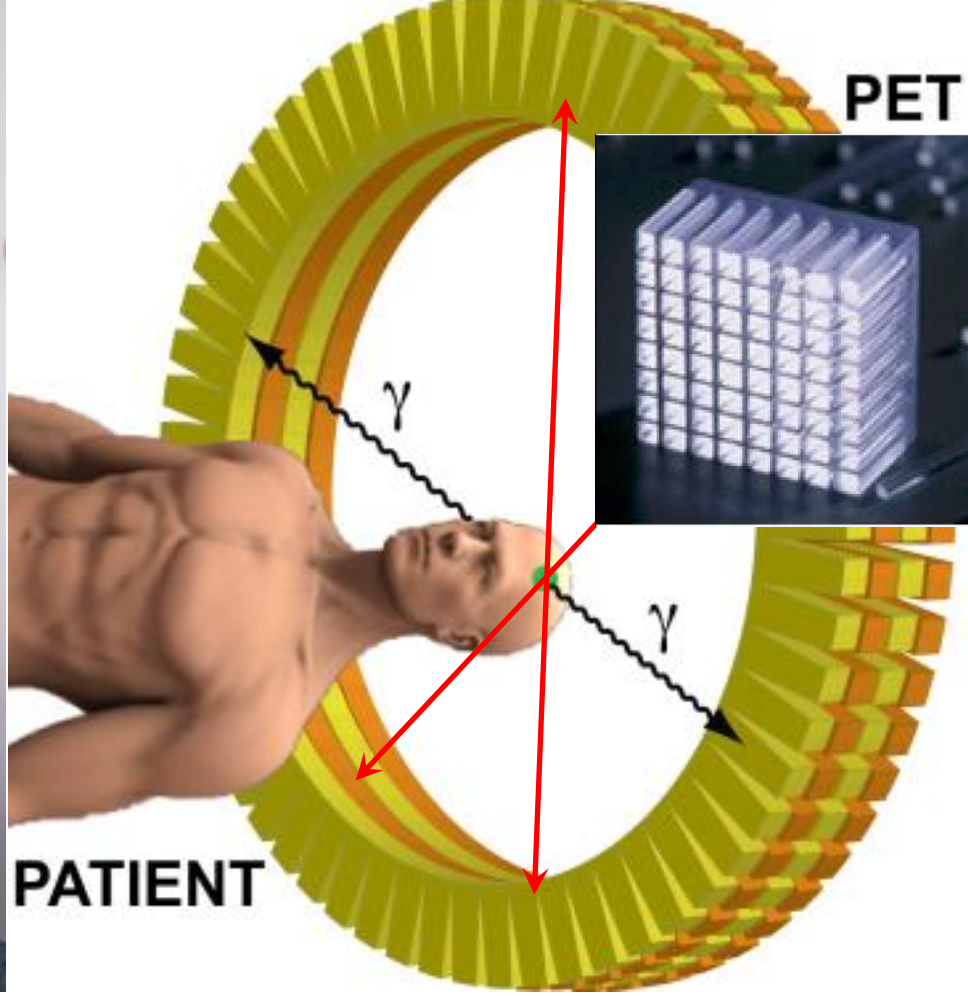
RADIOACTIVE SUGAR

Fluoro–deoksy-glucose
(F-18 FDG)

~200 000 000
gamma rays per second

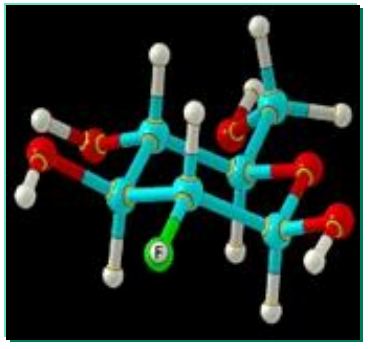


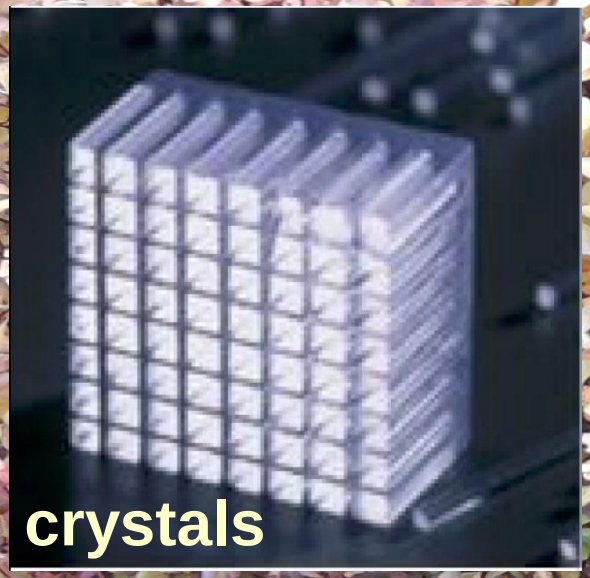
7 mSv PET/CT
~ 2.5 mSv PET
~3 mSv yearly
dose of natural radiation

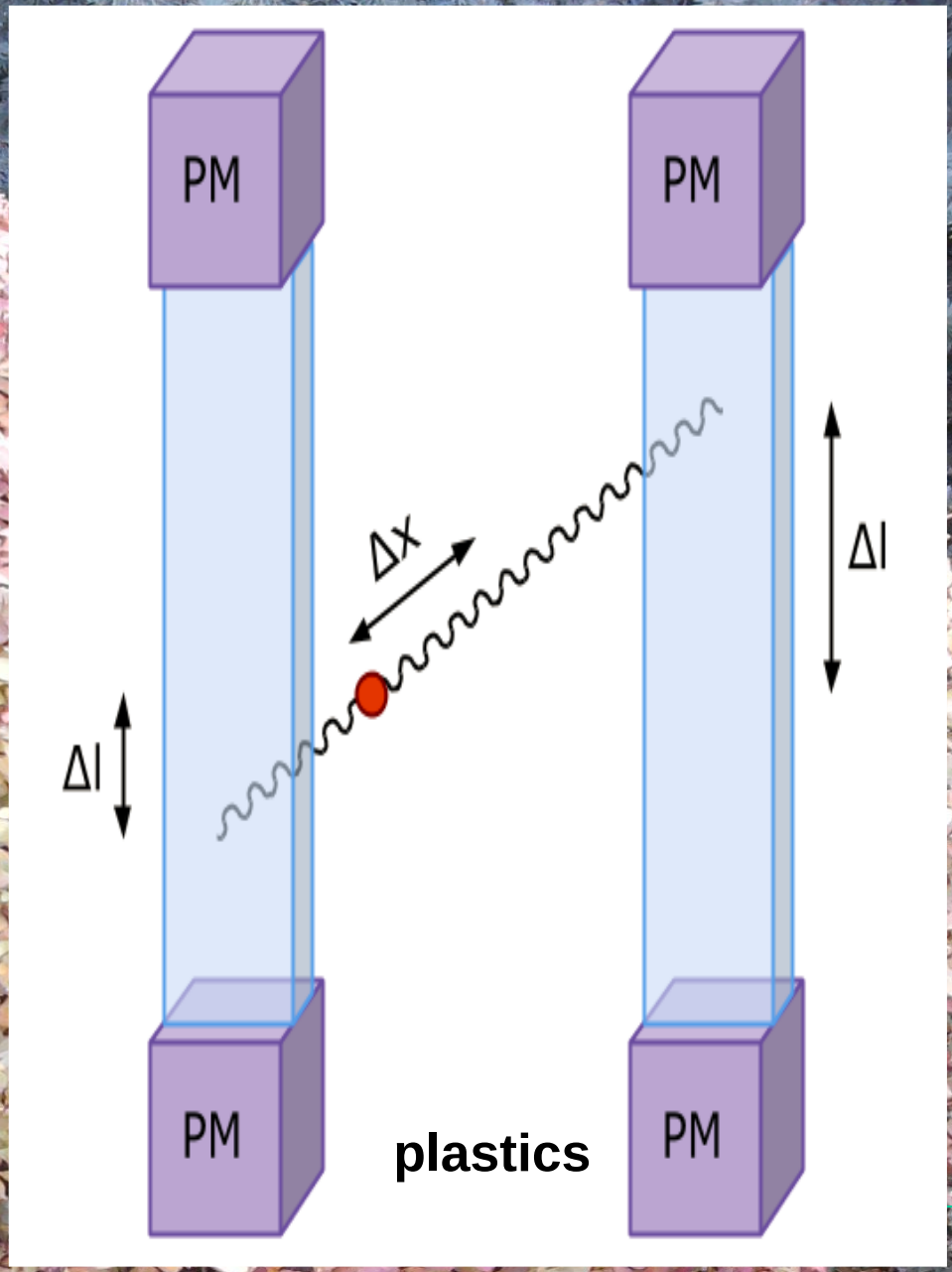


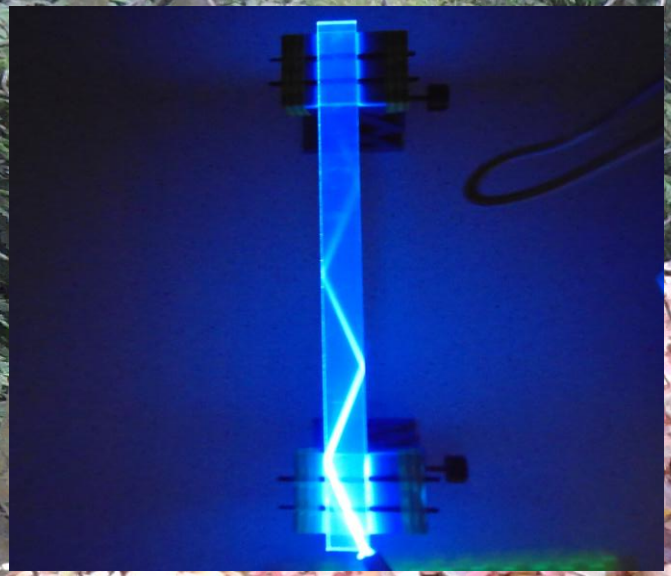
RADIOACTIVE SUGAR

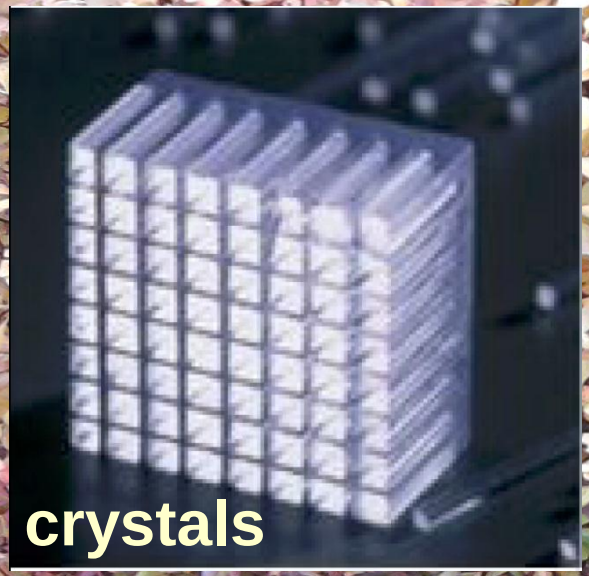
Fluoro–deoksy-glucose
(F-18 FDG)

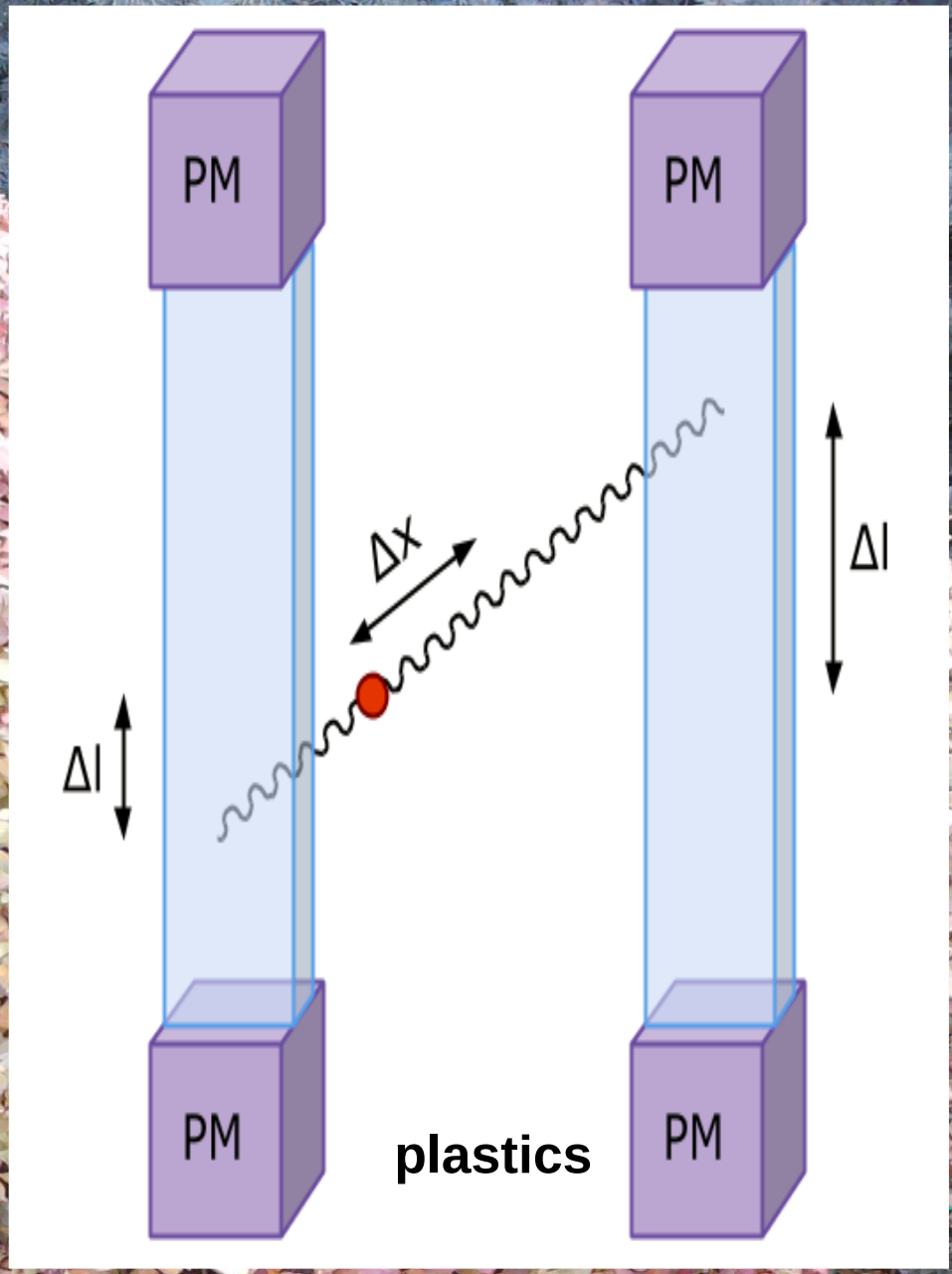



crystals

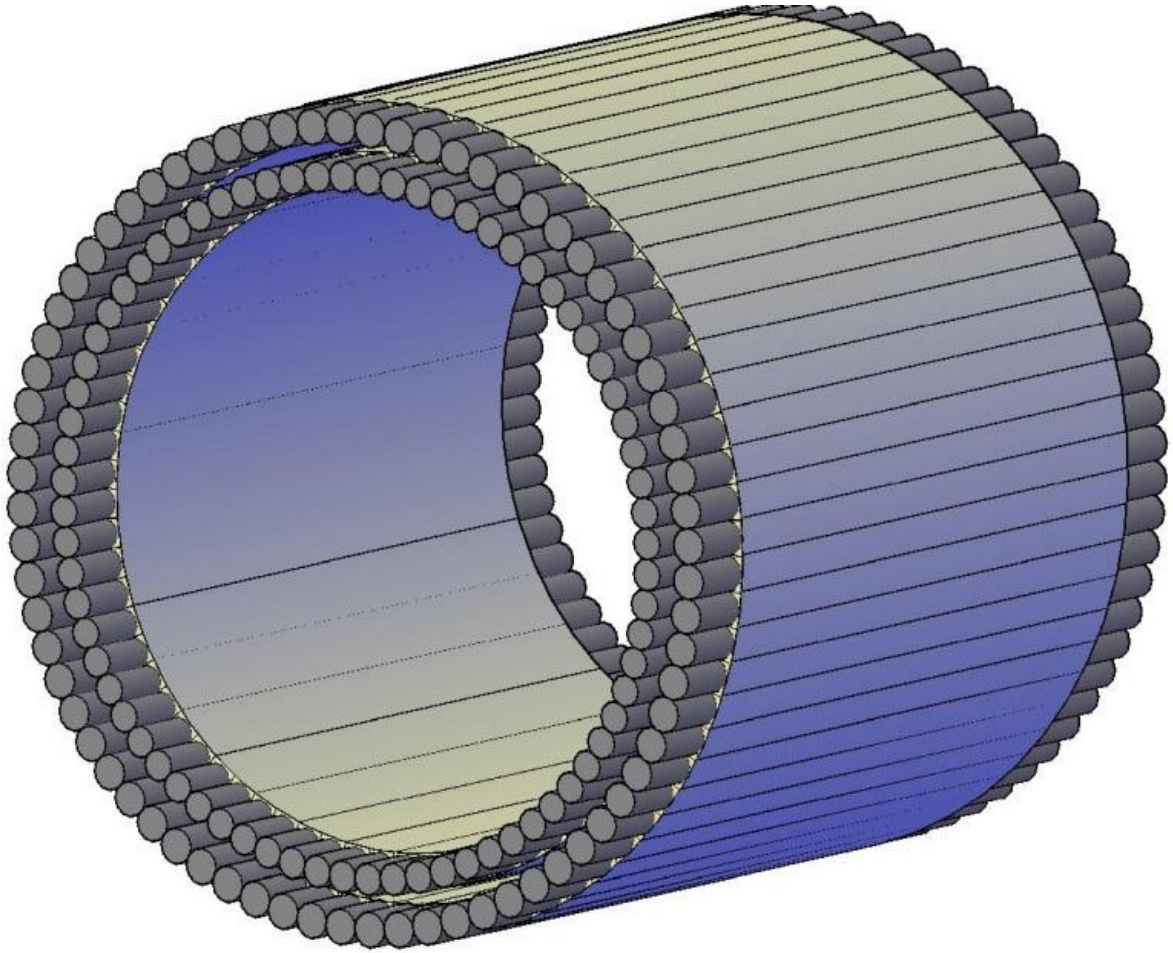

PM
PM
PM
PM
Δx
Δl
Δl
plastics




crystals


PM
PM
PM
PM
Δx
Δl
Δl
plastics

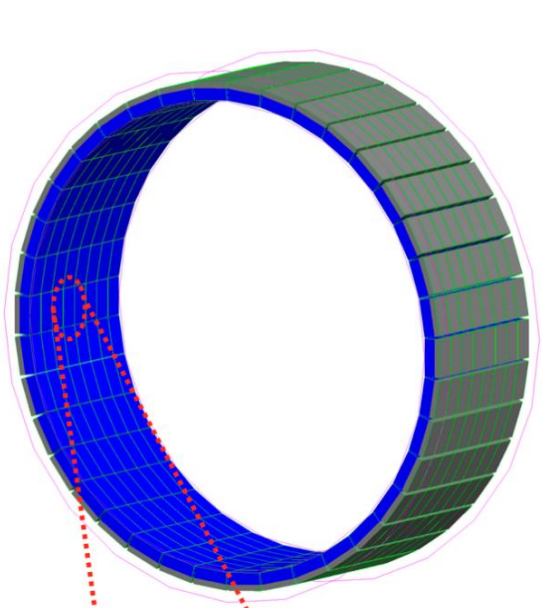
Development of cost-effective total-body PET

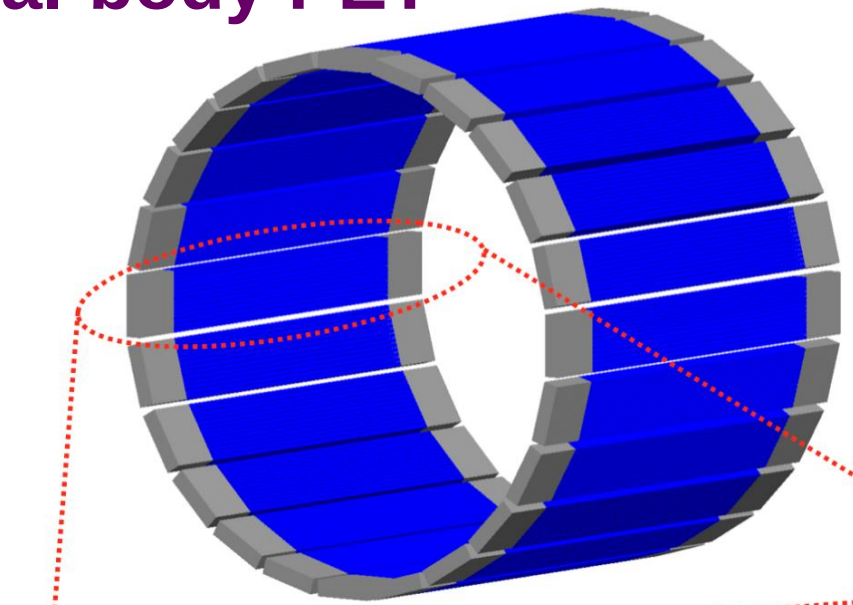


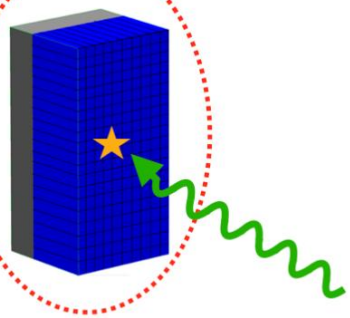
P. Moskal et al., Phys. Med. Biol. 66 (2021) 175015

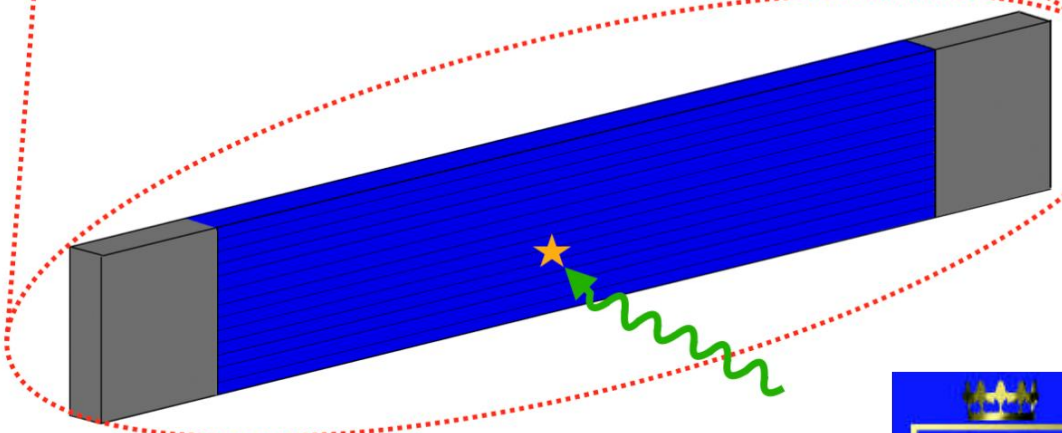
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

Development of cost-effective total-body PET









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

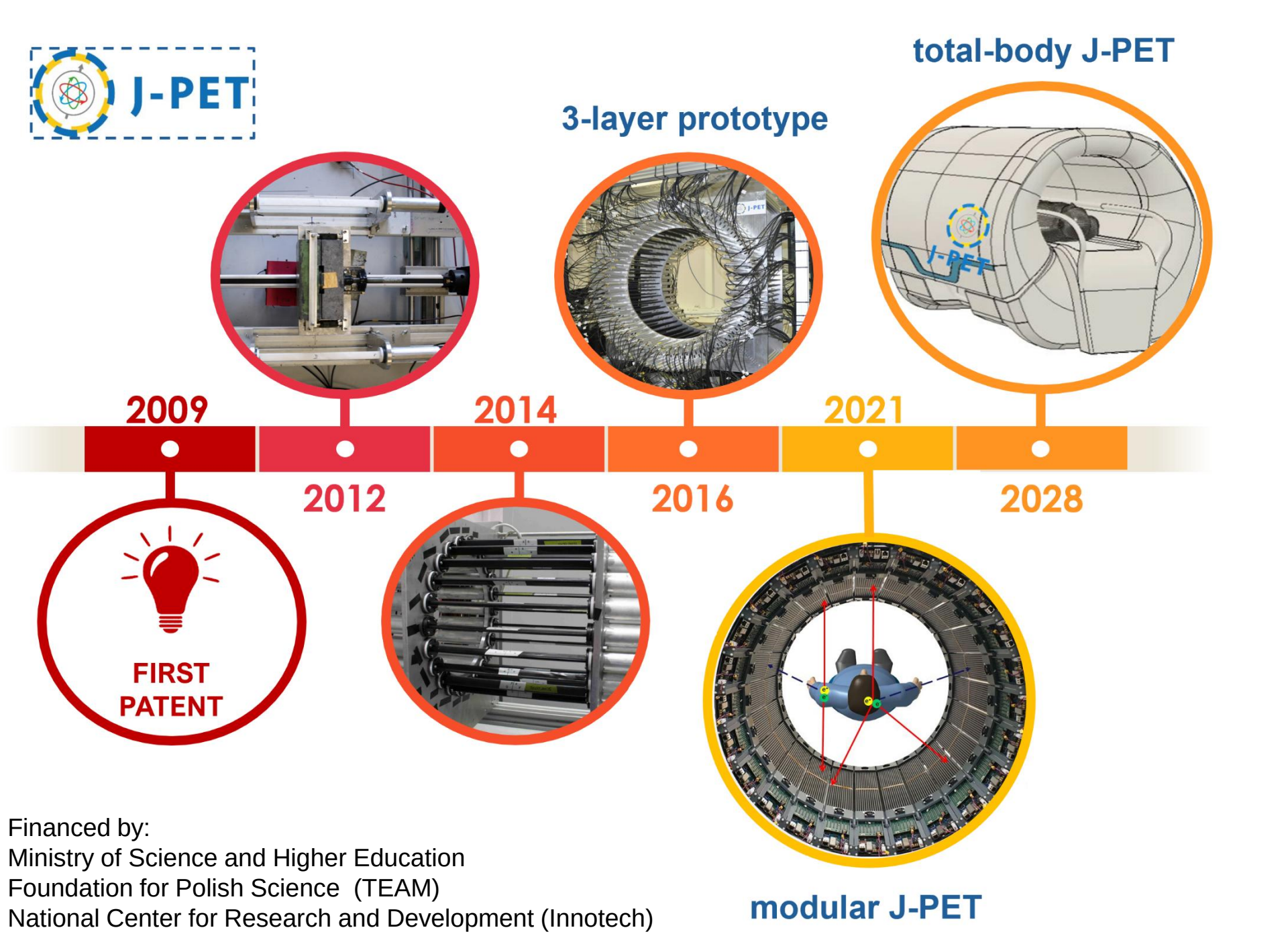
DISCLAIMER

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

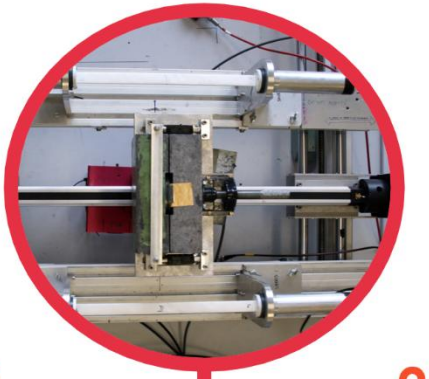


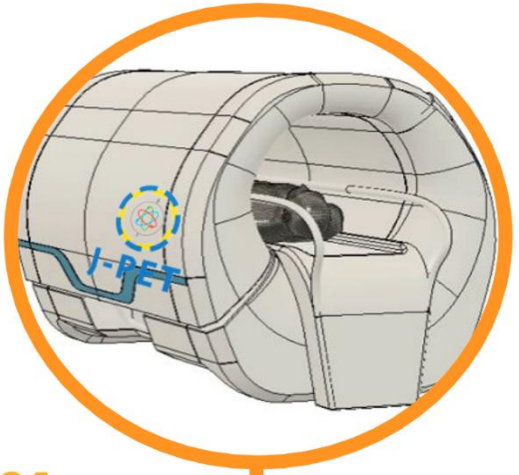
Financed by:
Ministry of Science and Higher Education
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes, MAESTRO)

J-PET

total-body J-PET

3-layer prototype





2009

2012

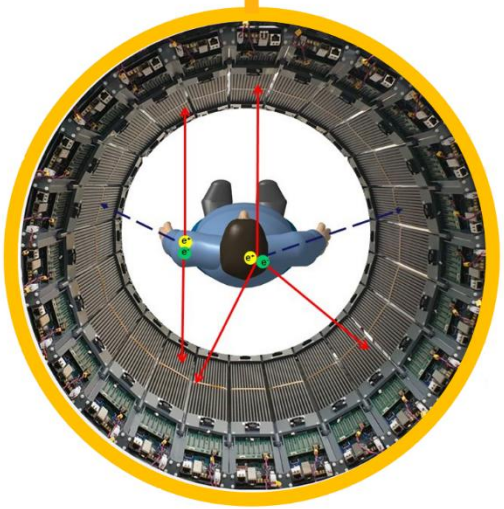
2014

2016

2021

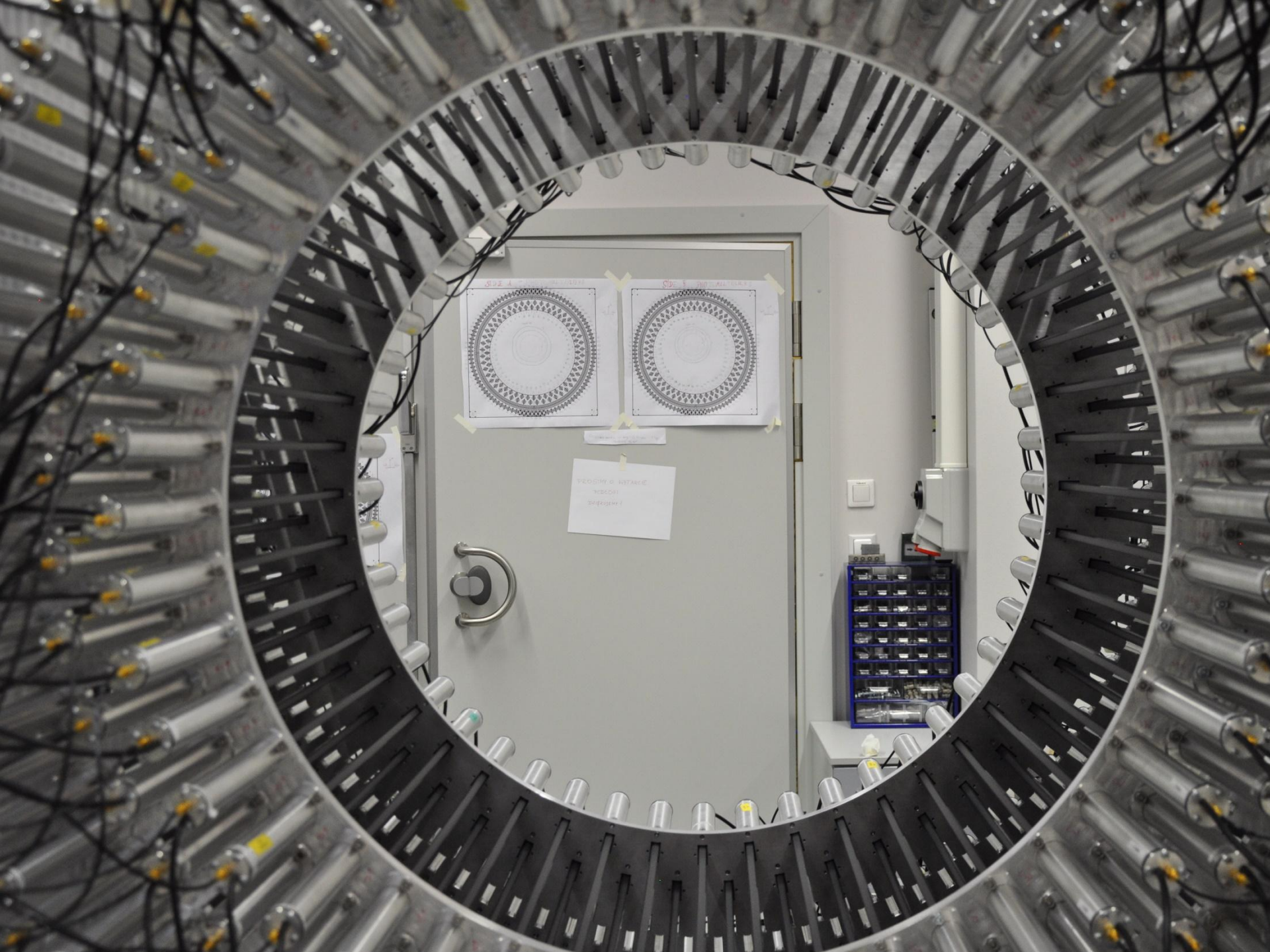
2028

FIRST PATENT

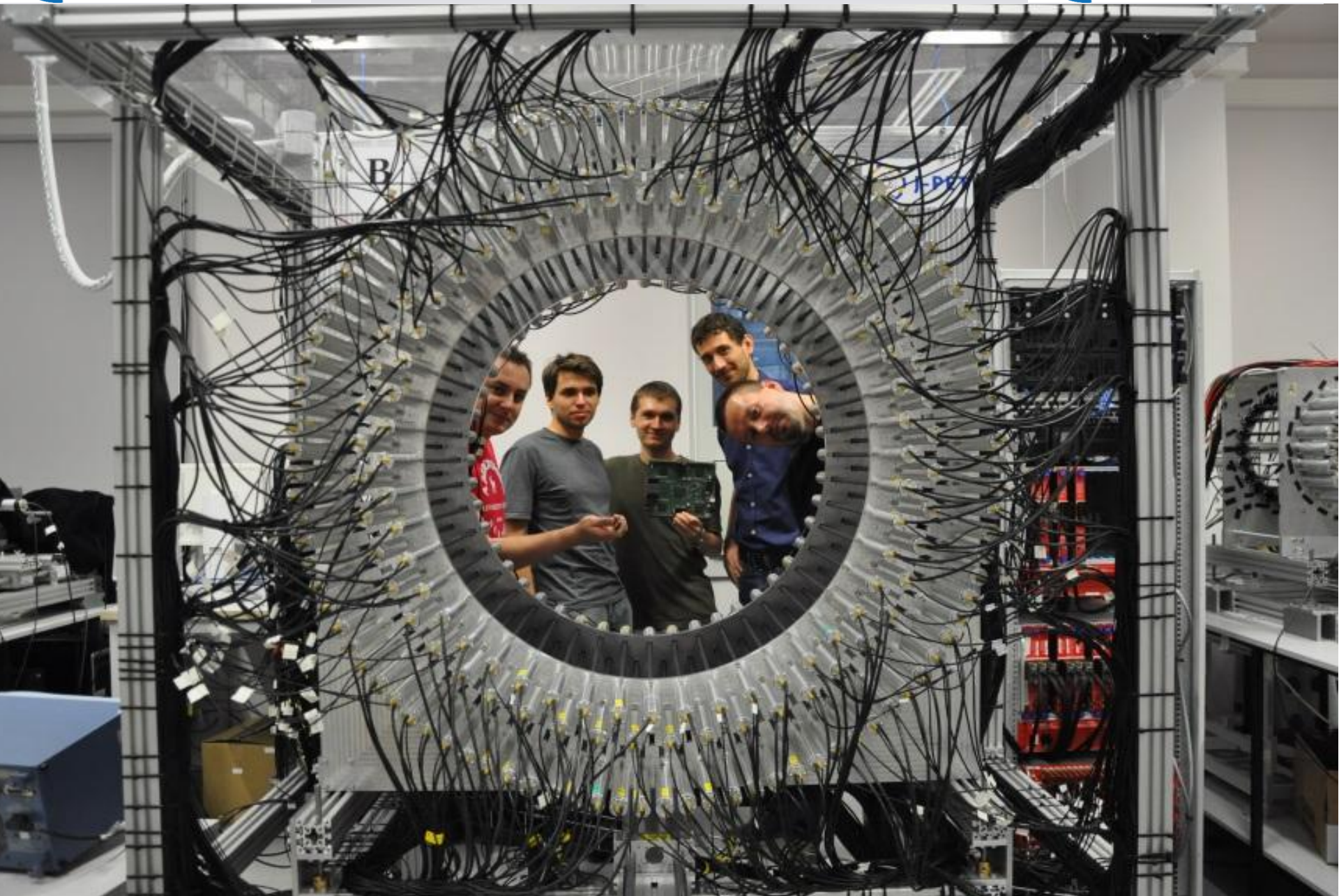


modular J-PET

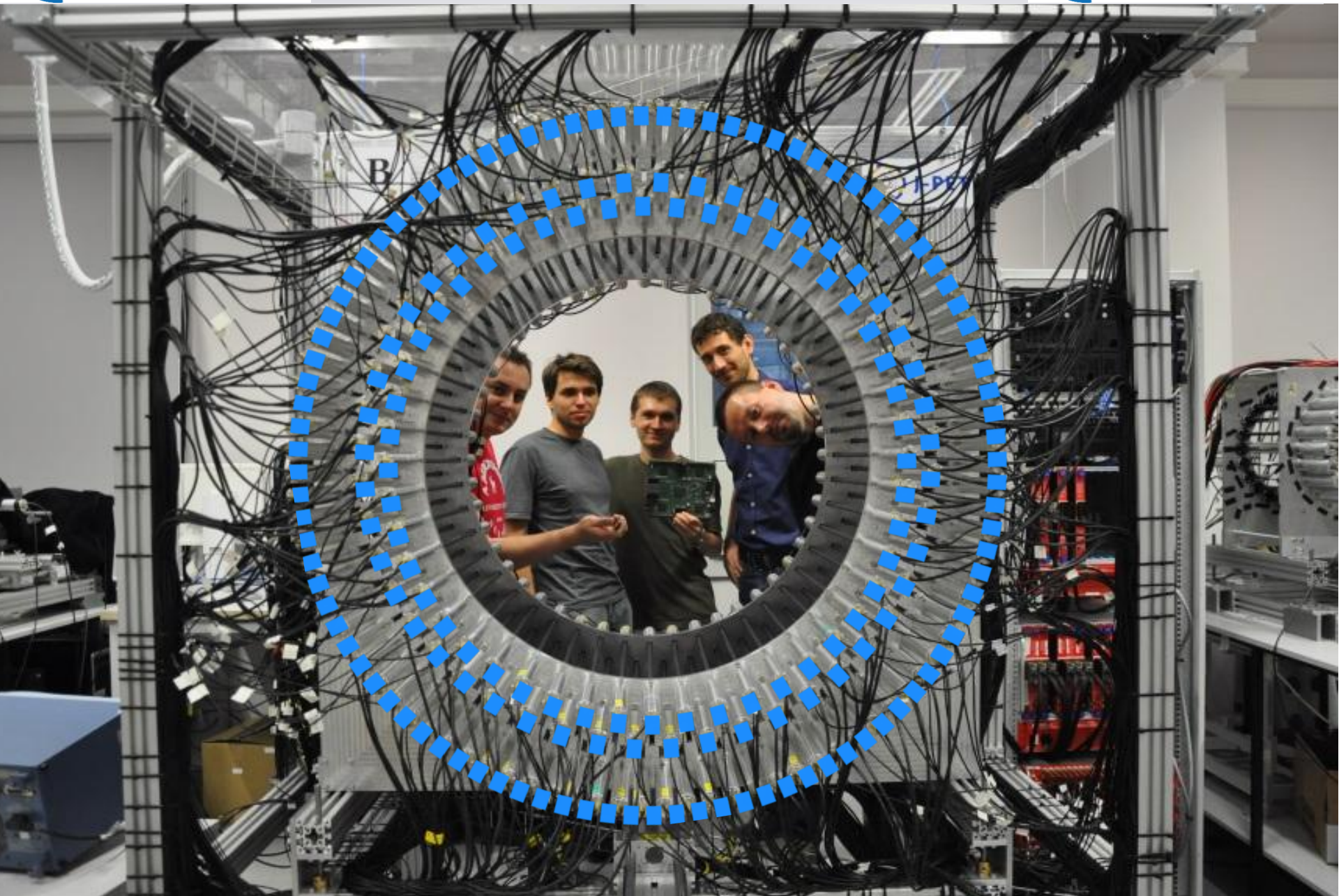
Financed by:
Ministry of Science and Higher Education
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes, MAESTRO)



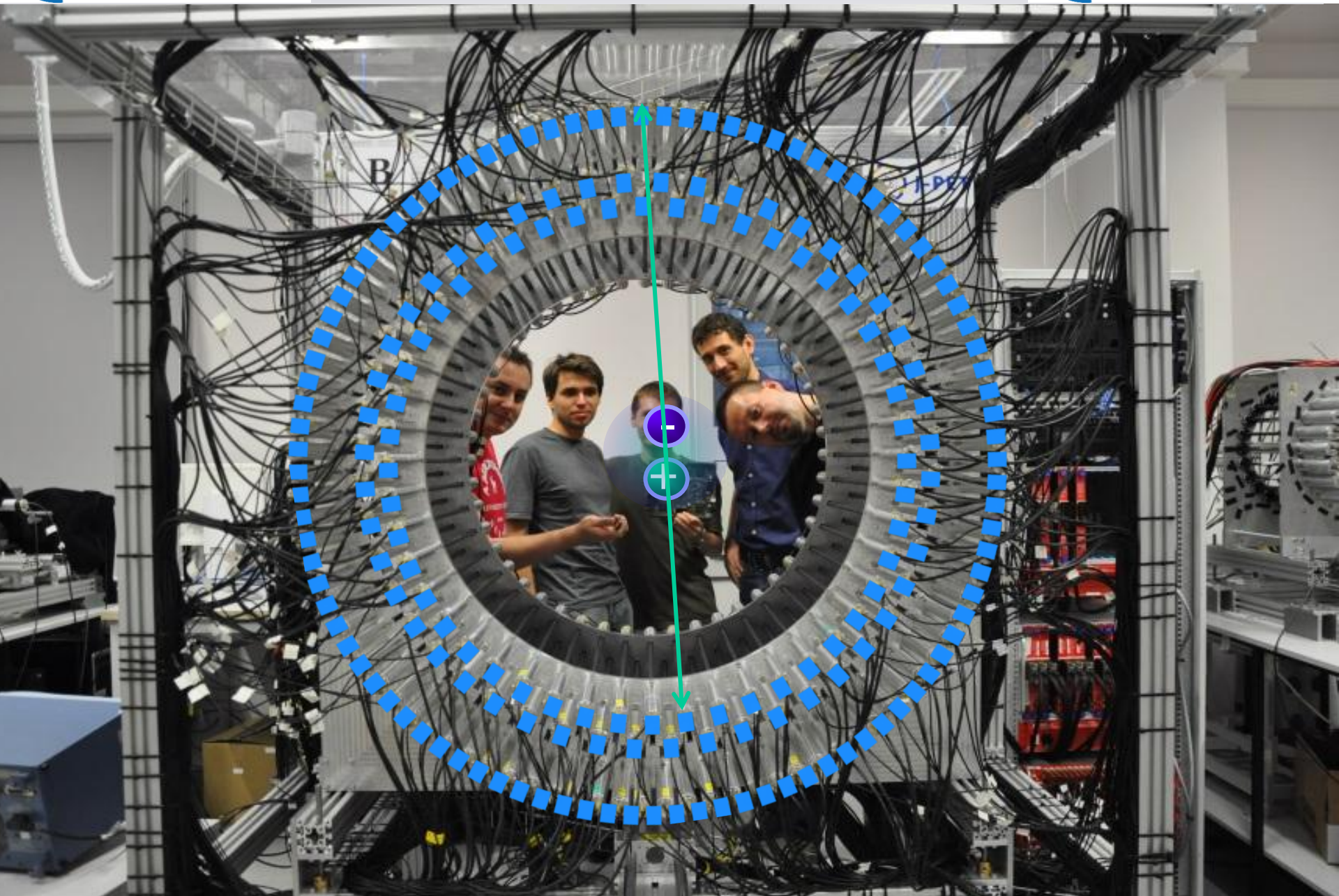
Jagiellonian PET



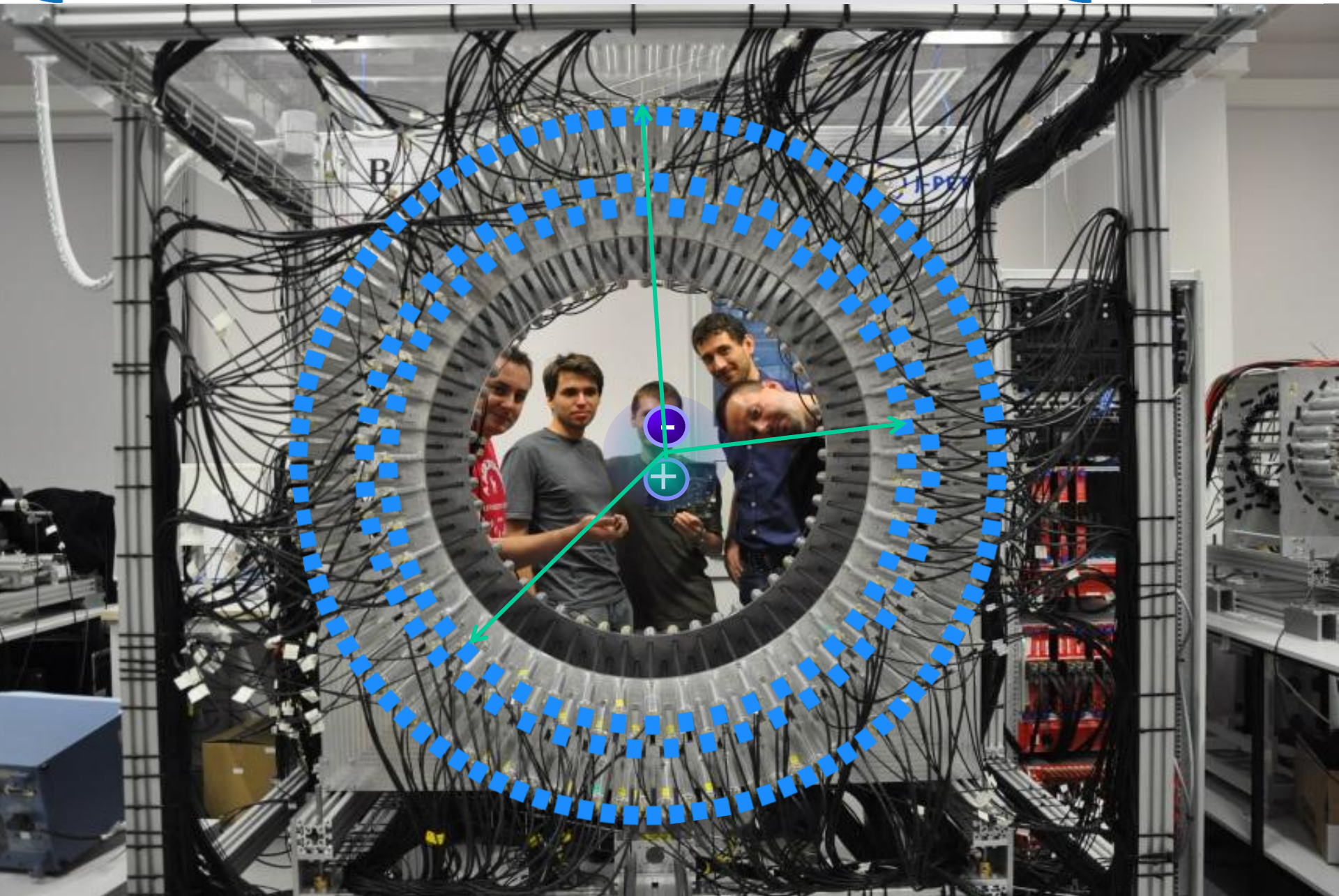
Jagiellonian PET

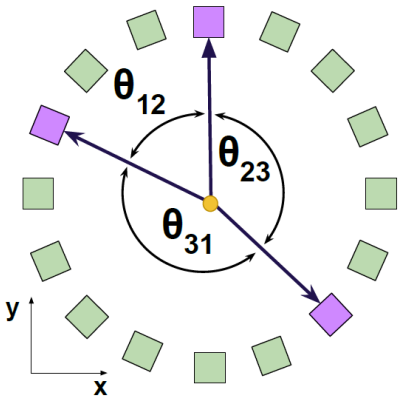


Jagiellonian PET



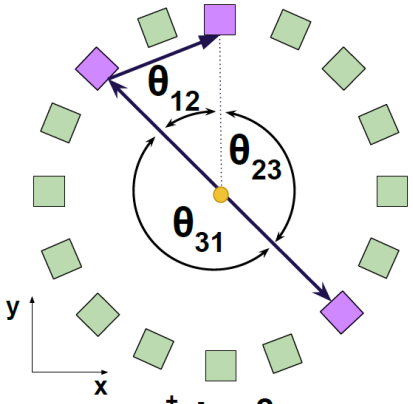
Jagiellonian PET





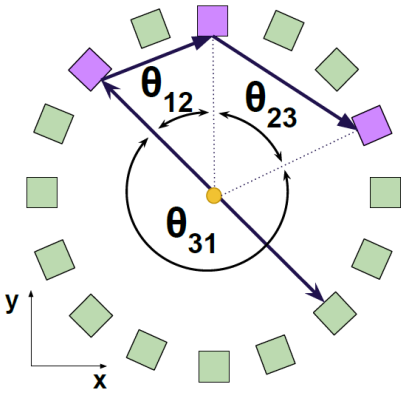
o-Ps → 3γ

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



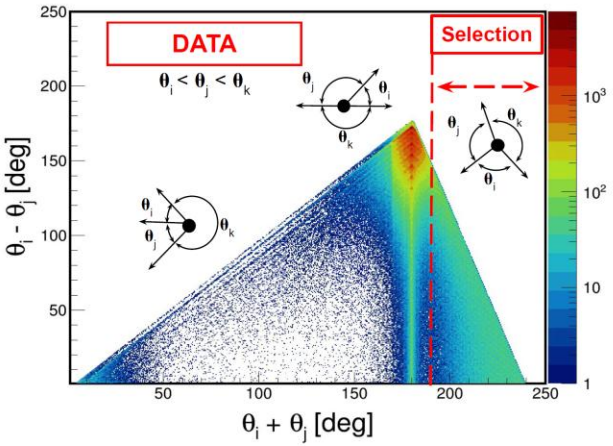
$e^+e^- \rightarrow 2\gamma$
single scattered

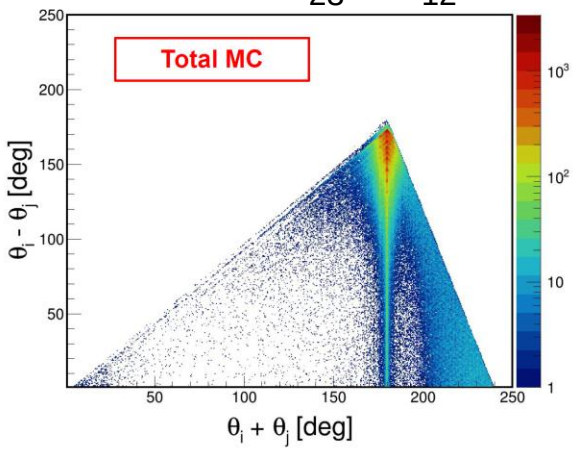
$\theta_{23} + \theta_{12} = 180$

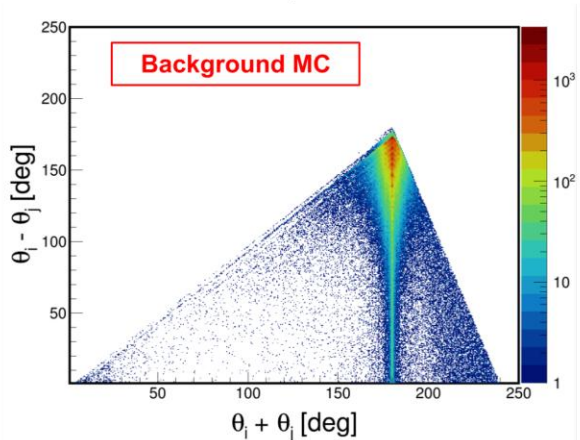


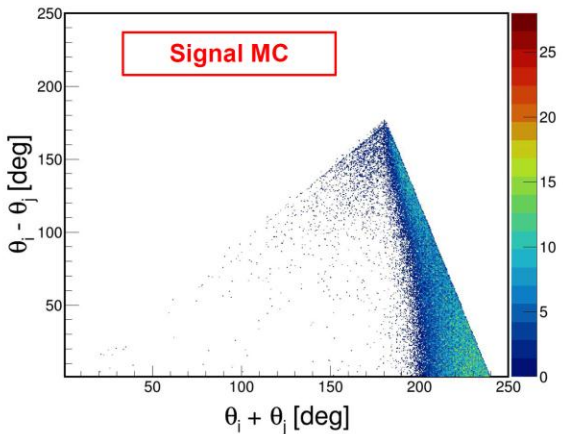
$e^+e^- \rightarrow 2\gamma$
double scattered

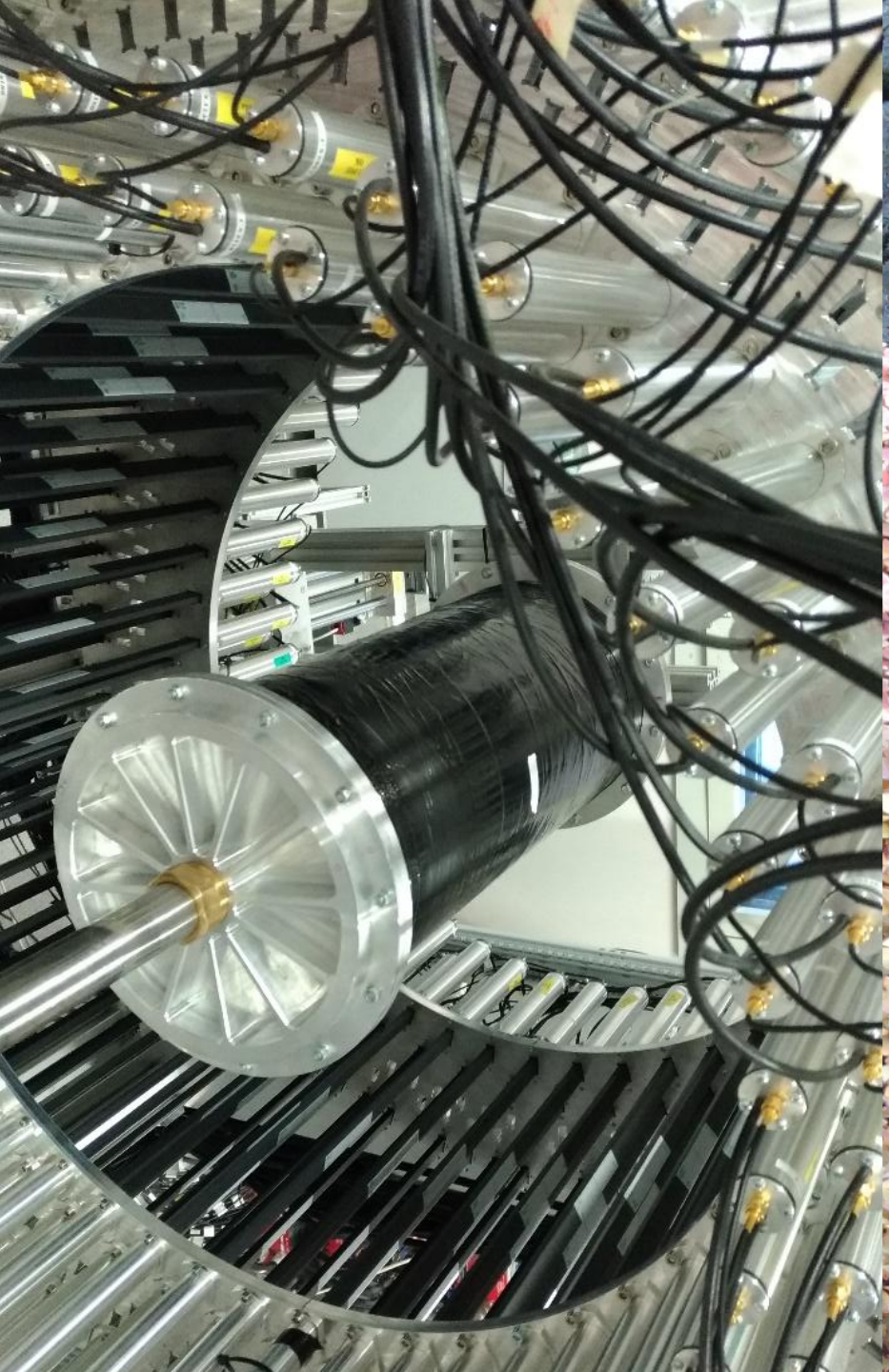
$\theta_{23} + \theta_{12} < 180$

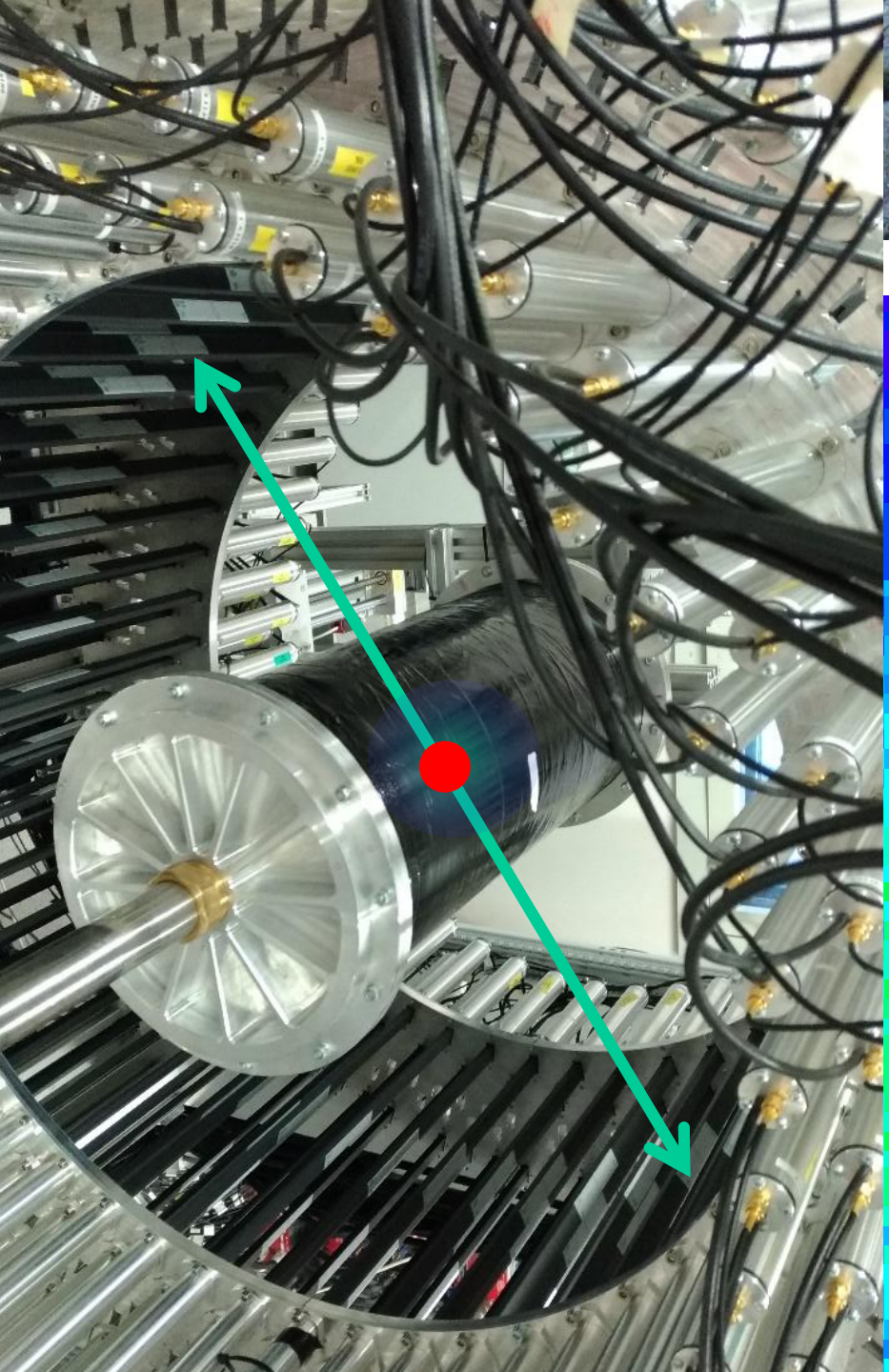


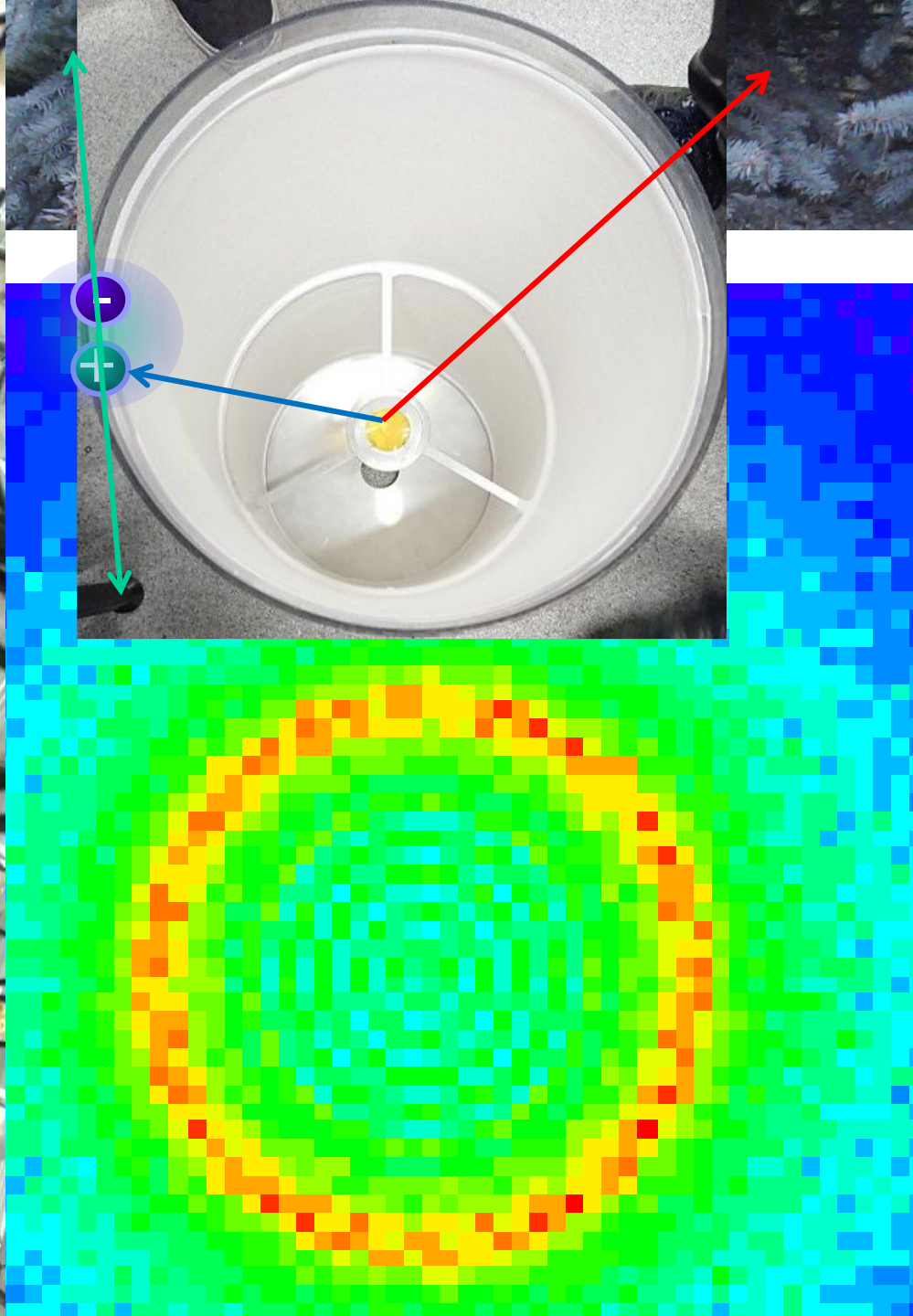


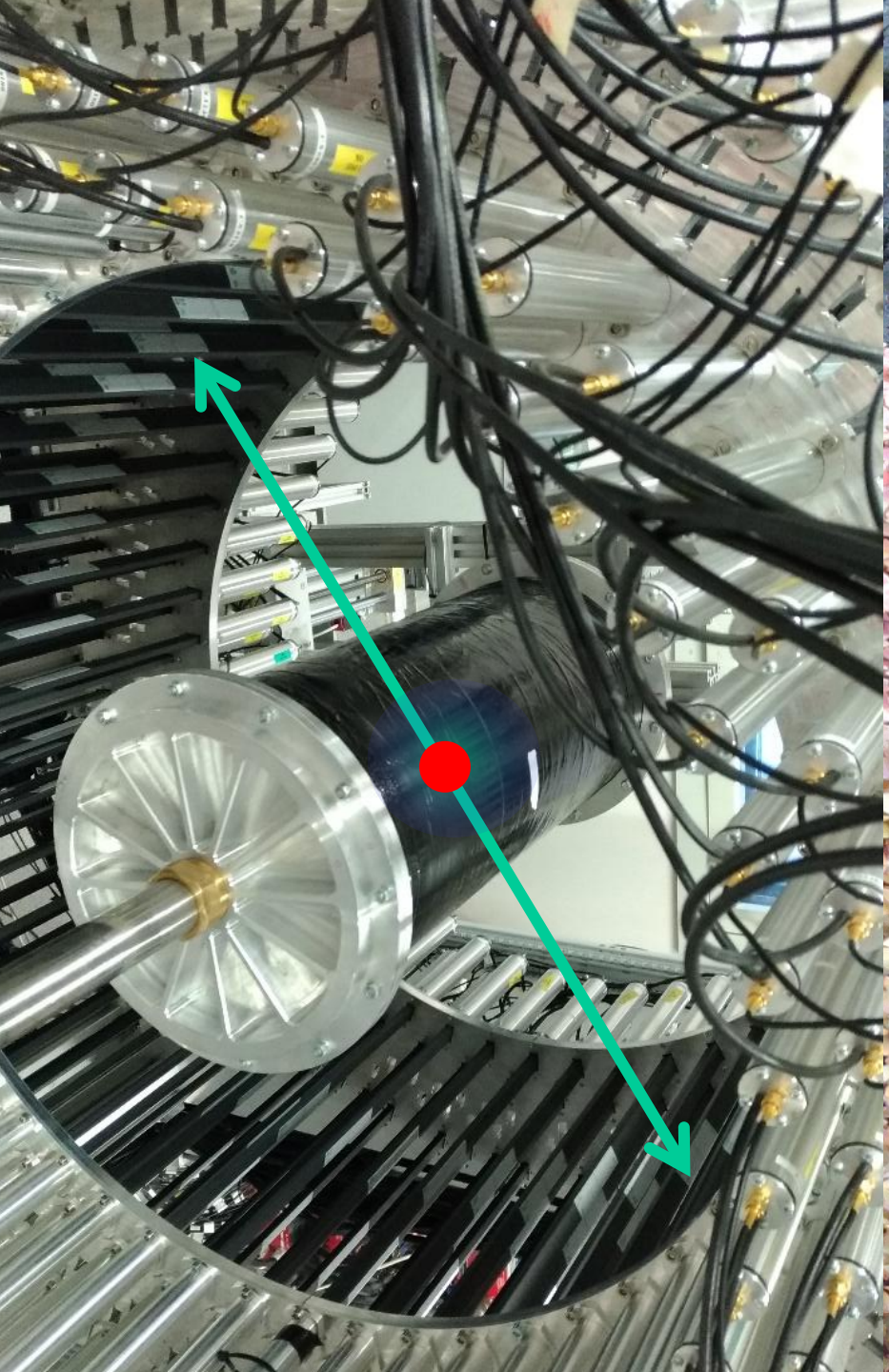


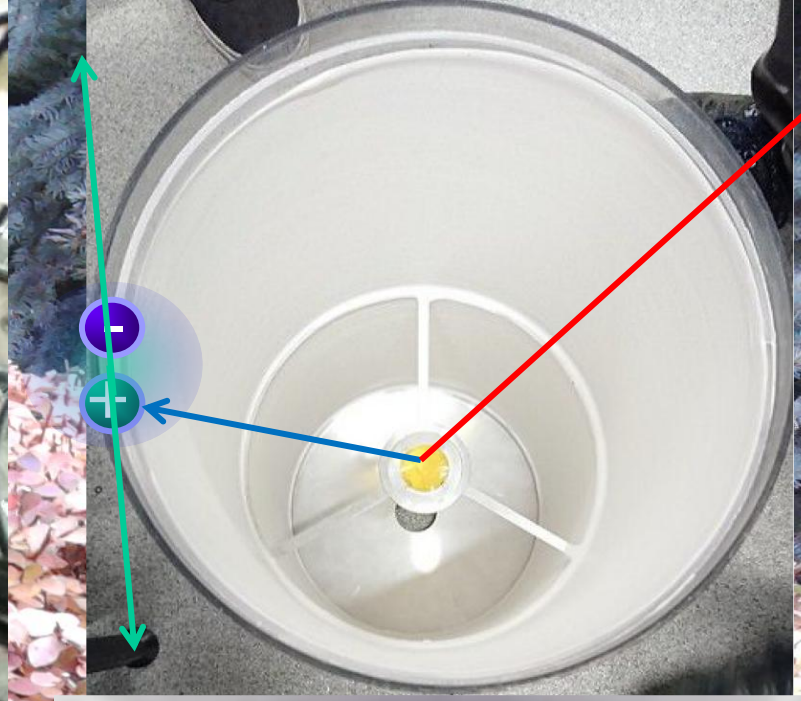


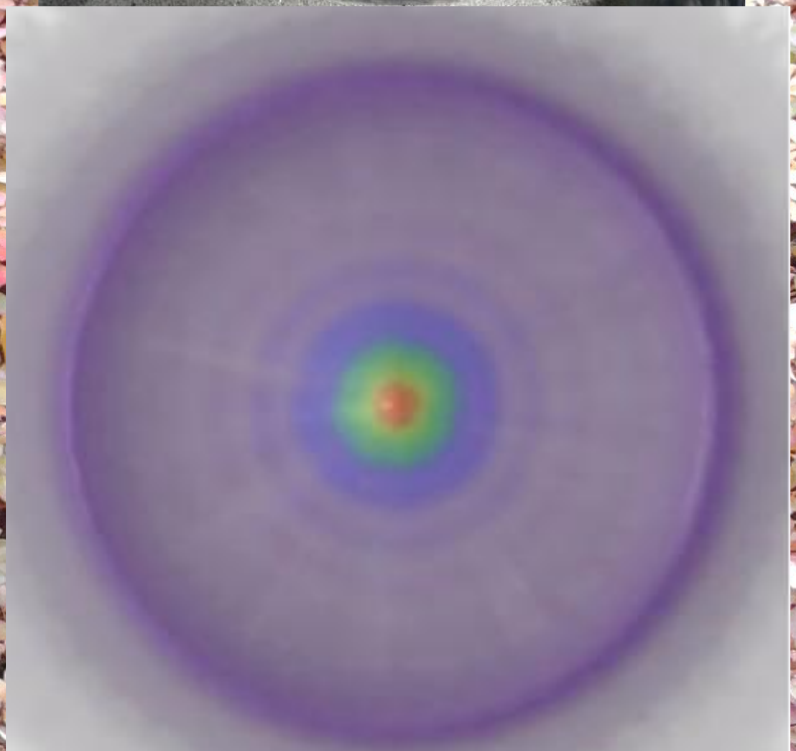




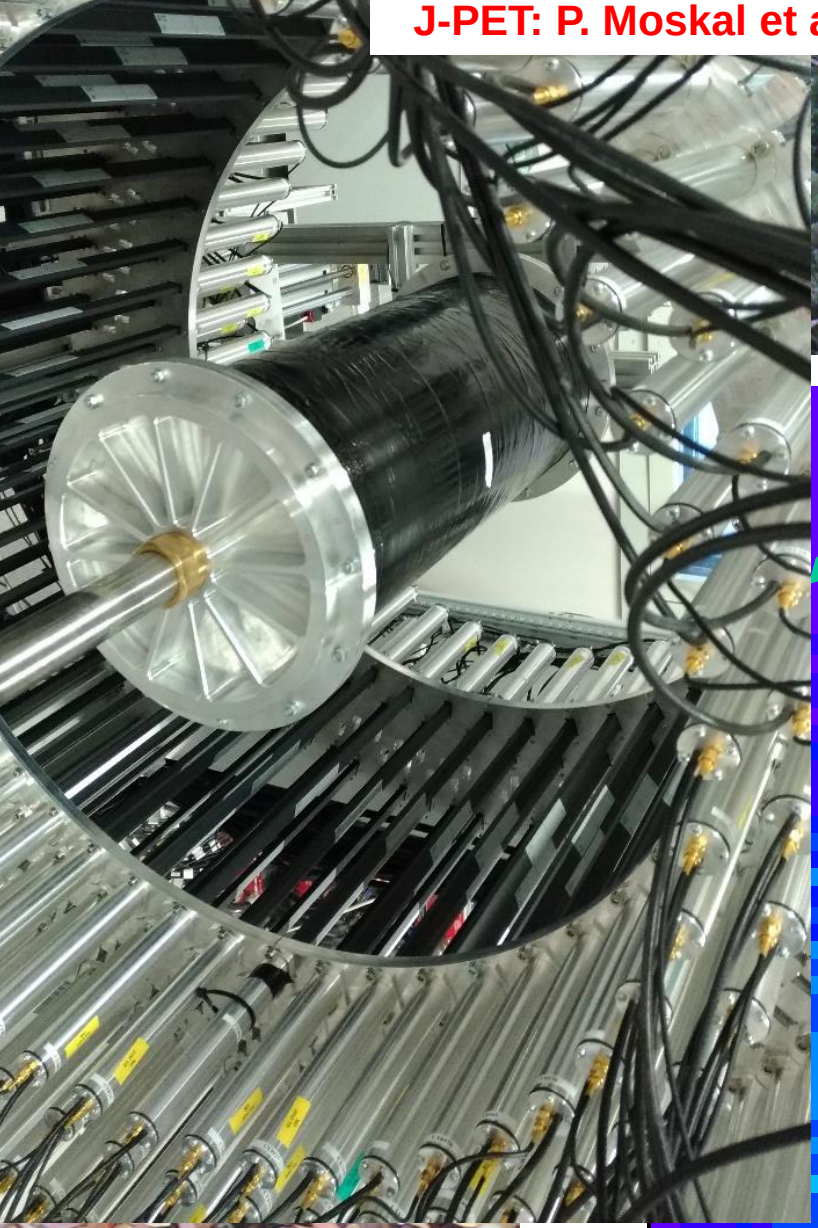


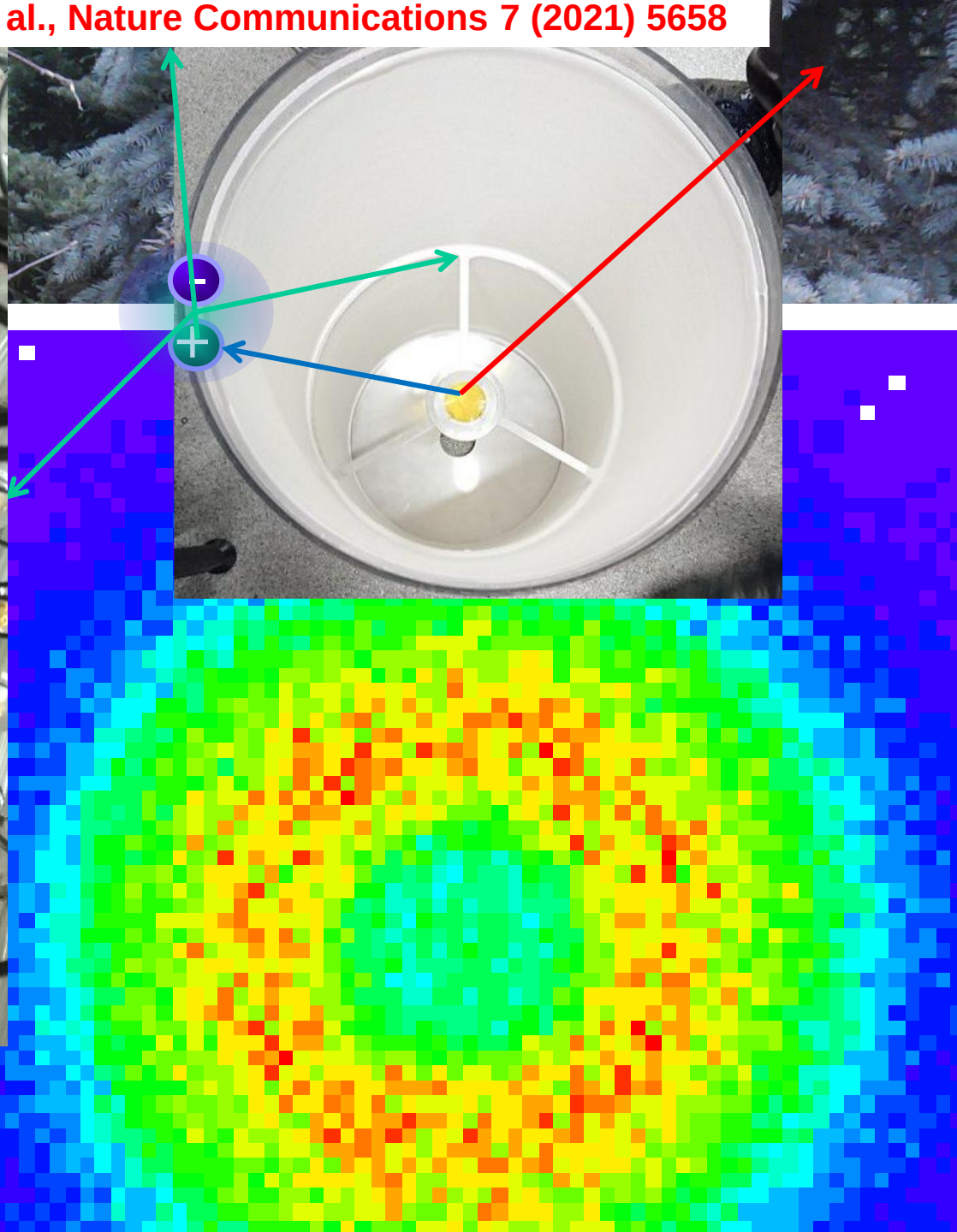




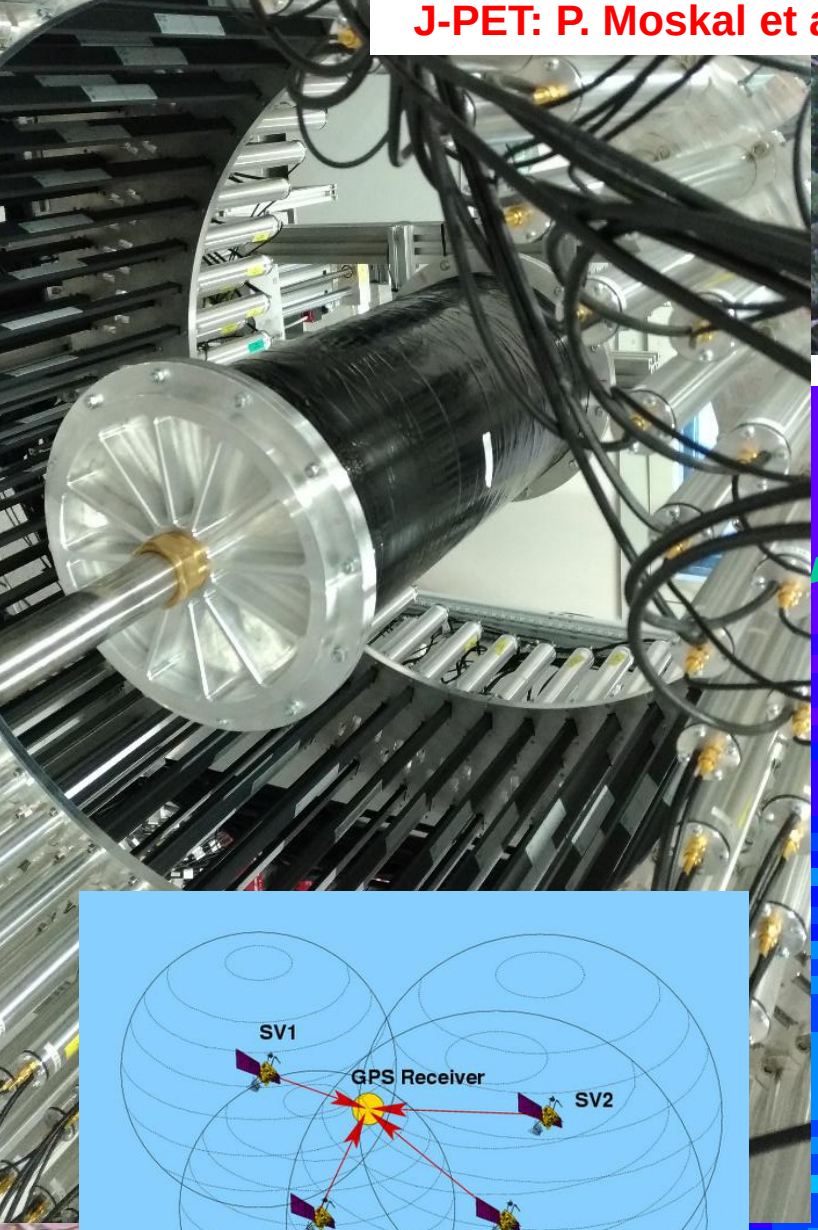


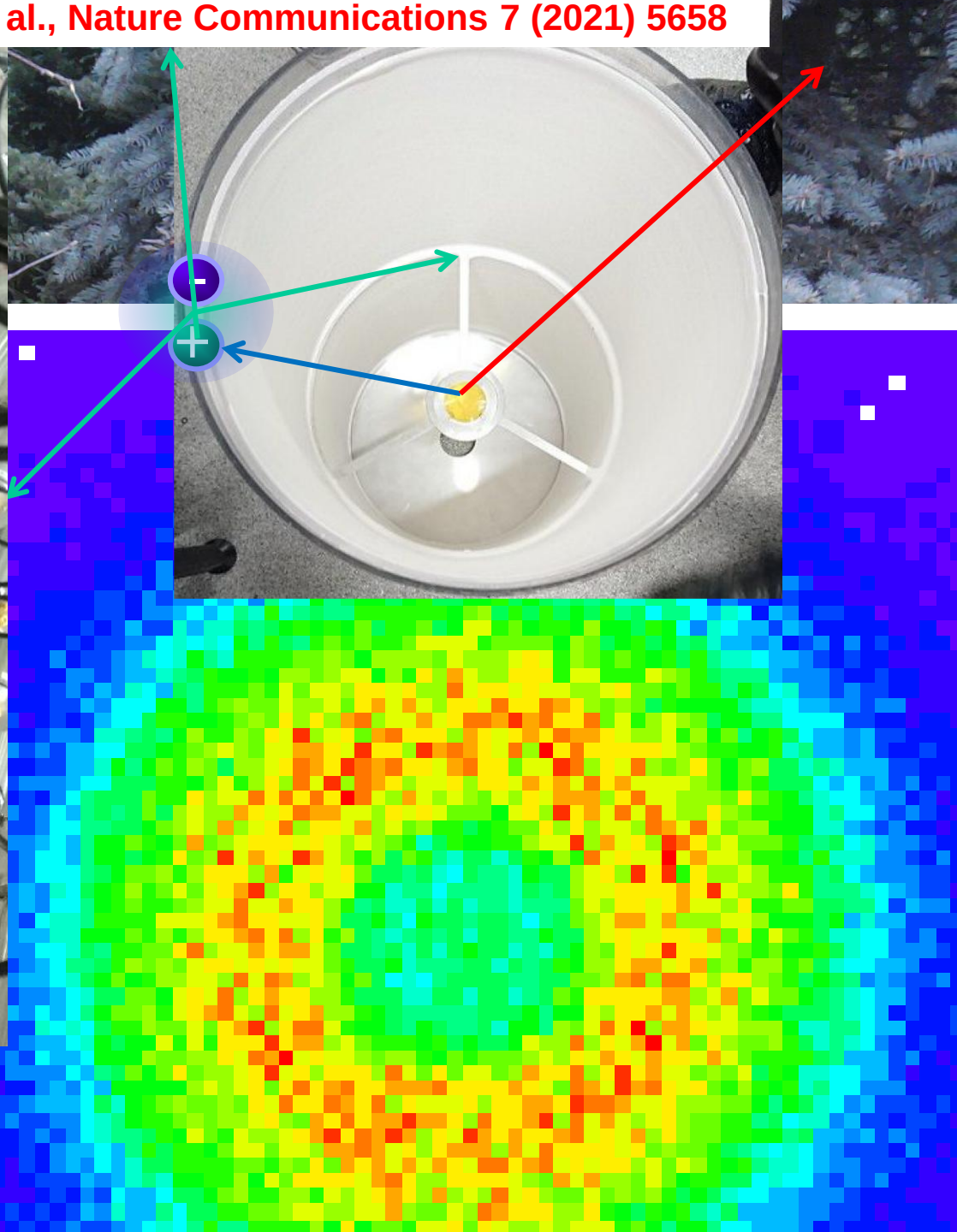
J-PET: P. Moskal et al., Nature Communications 7 (2021) 5658

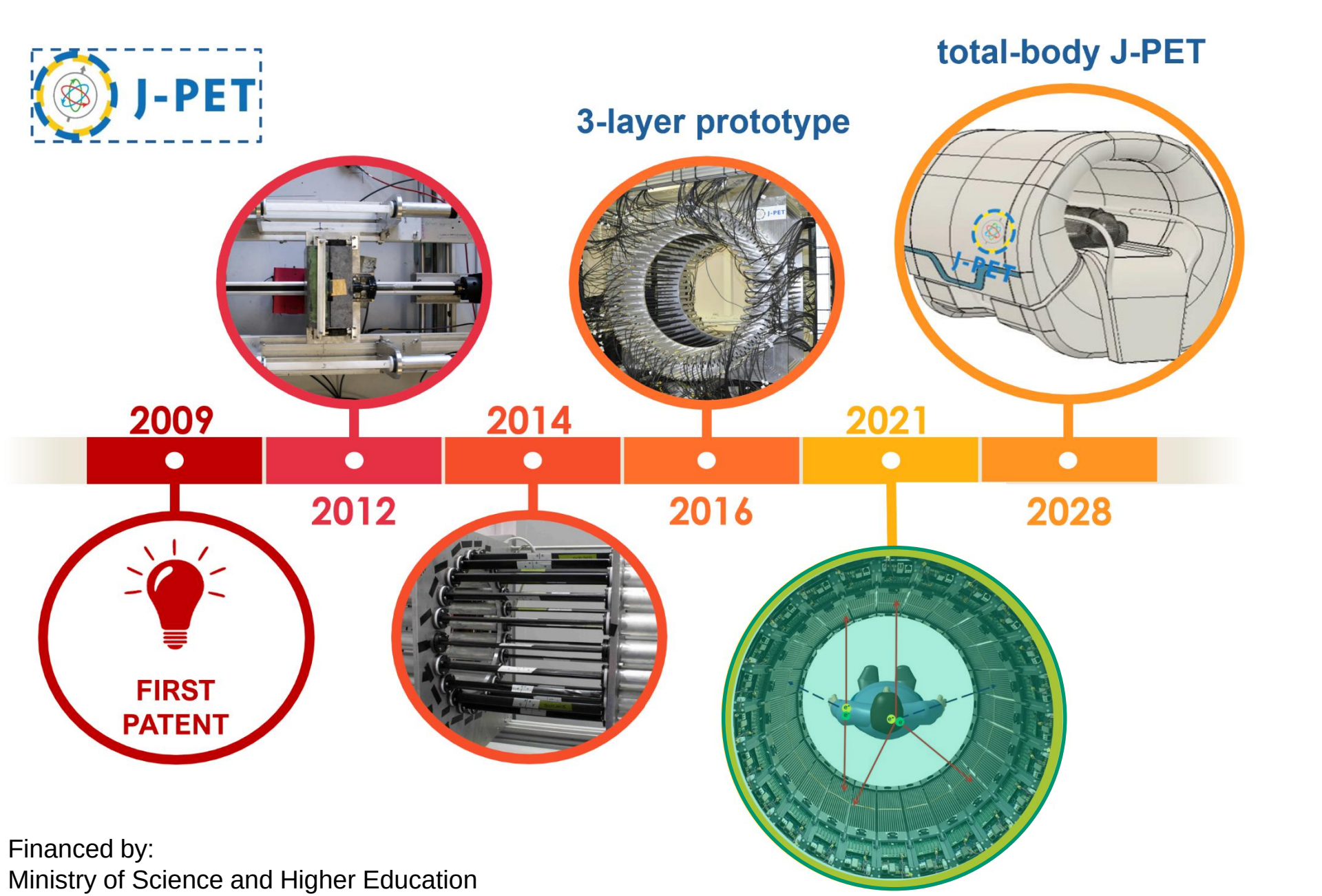




J-PET: P. Moskal et al., Nature Communications 7 (2021) 5658

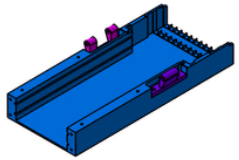






Financed by:
Ministry of Science and Higher Education
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes, MAESTRO)

Development of cost-effective total-body PET

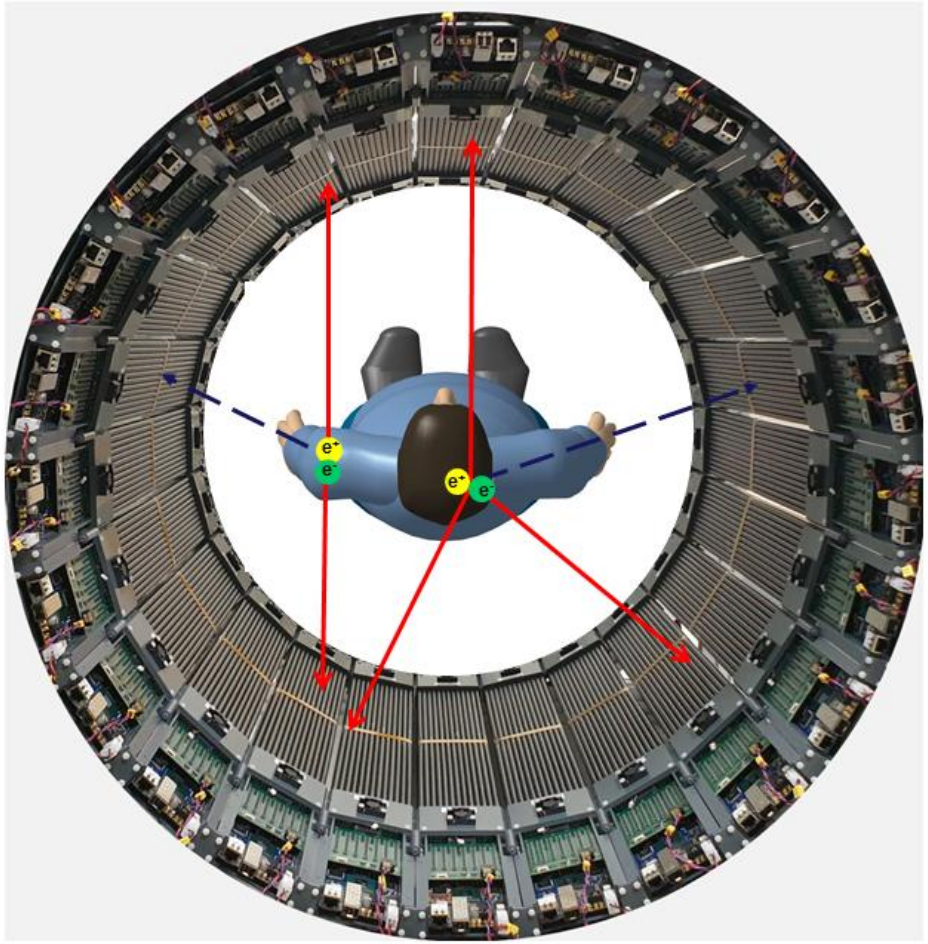


Aim:

- 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**

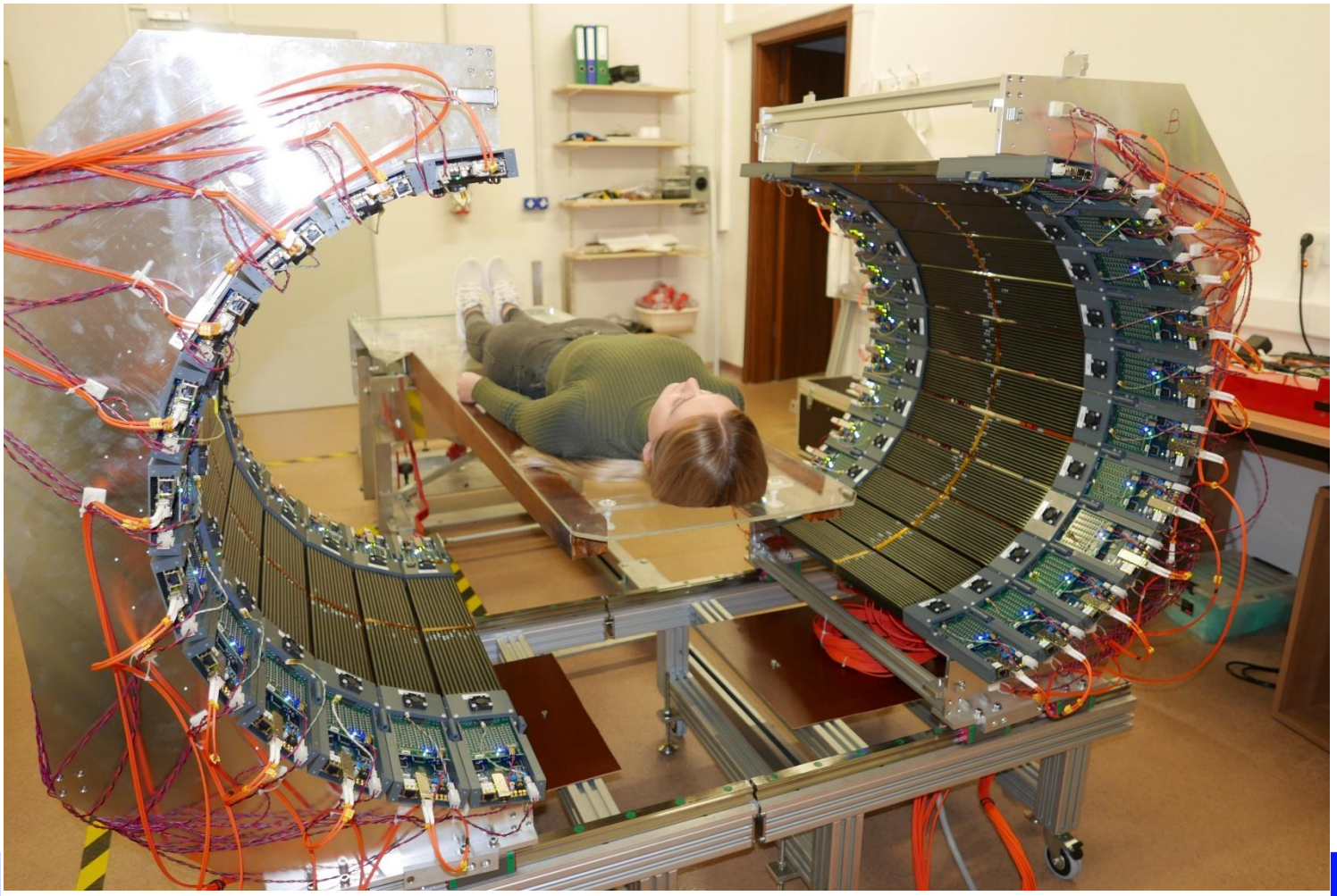
Modular J-PET scanner
MULTI-PHOTON PET



P. Moskal et al., Nature Communications 12 (2021) 5658
P. Moskal et al., Nature Communications 15 (2024) 78

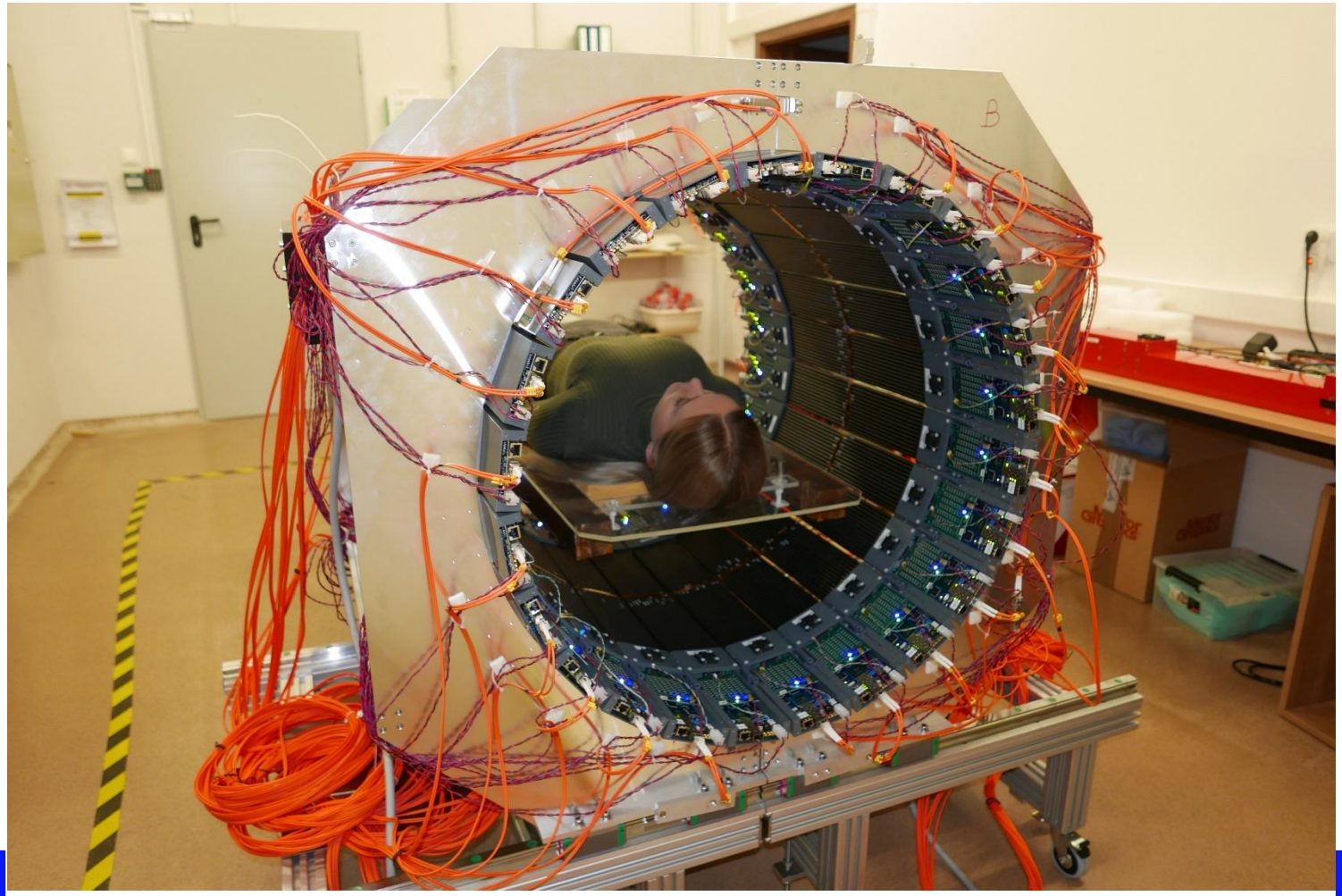
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

First clinical PET and positronium imaging of patients



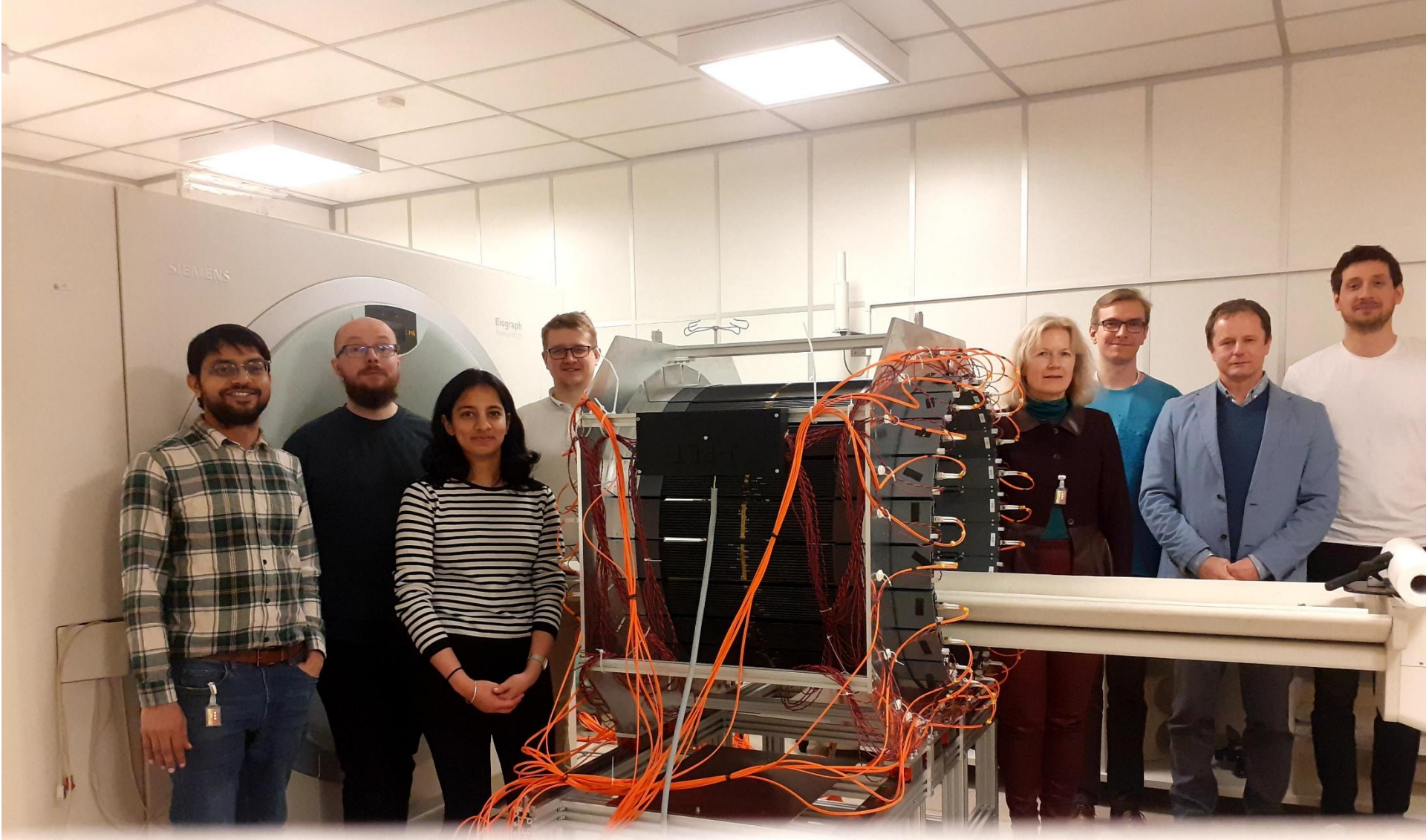
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

First clinical positronium imaging of patients

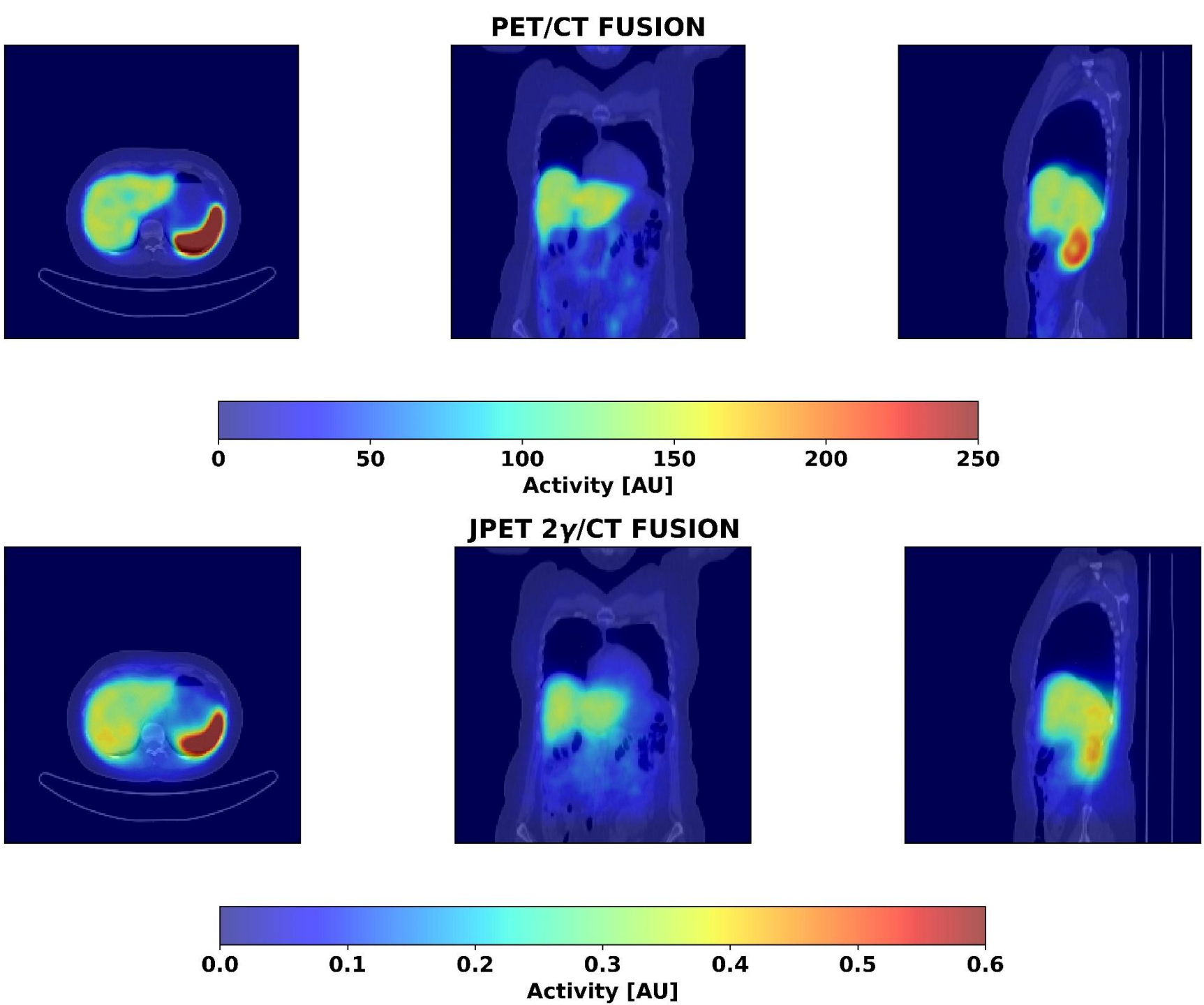


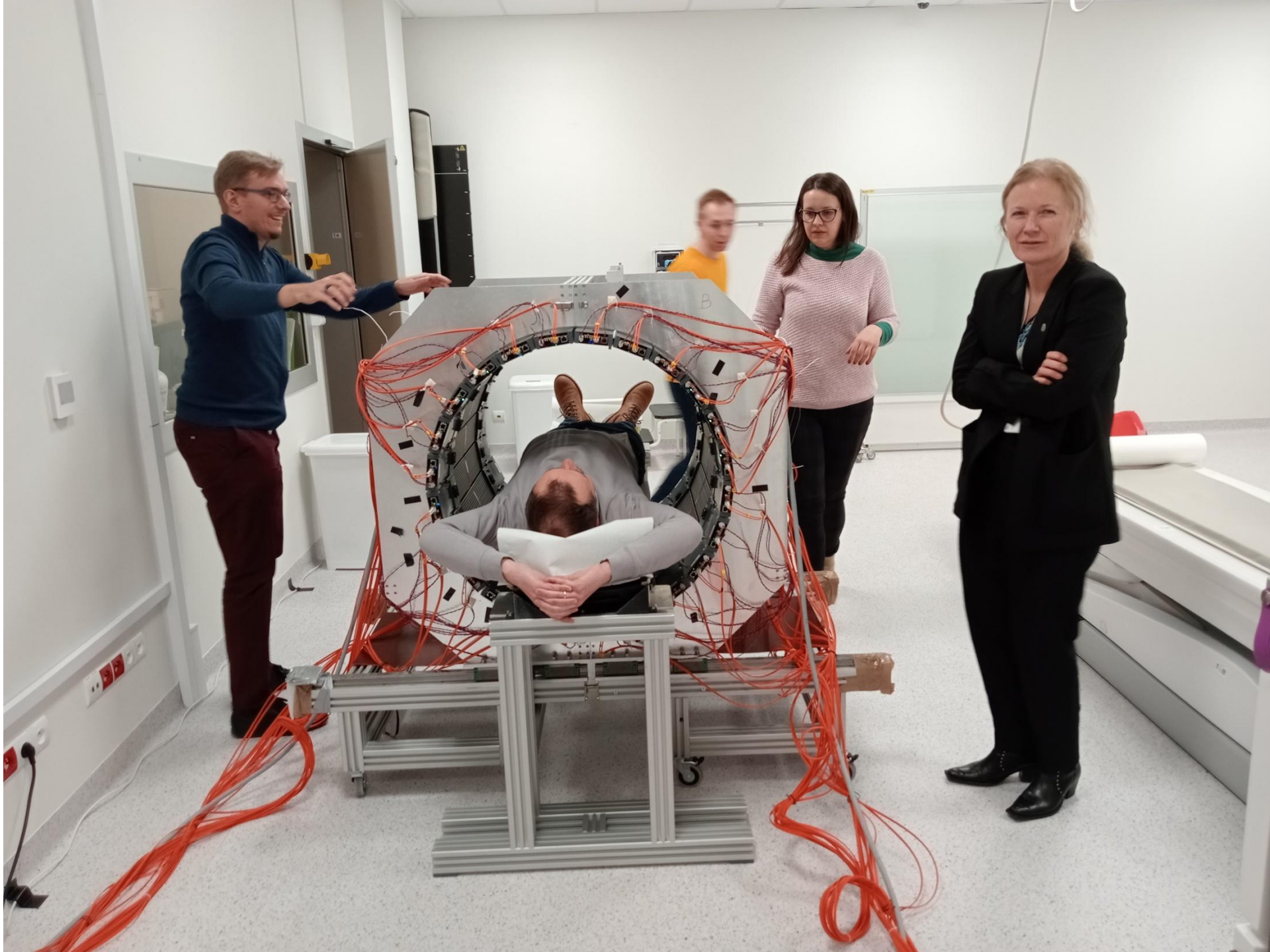
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

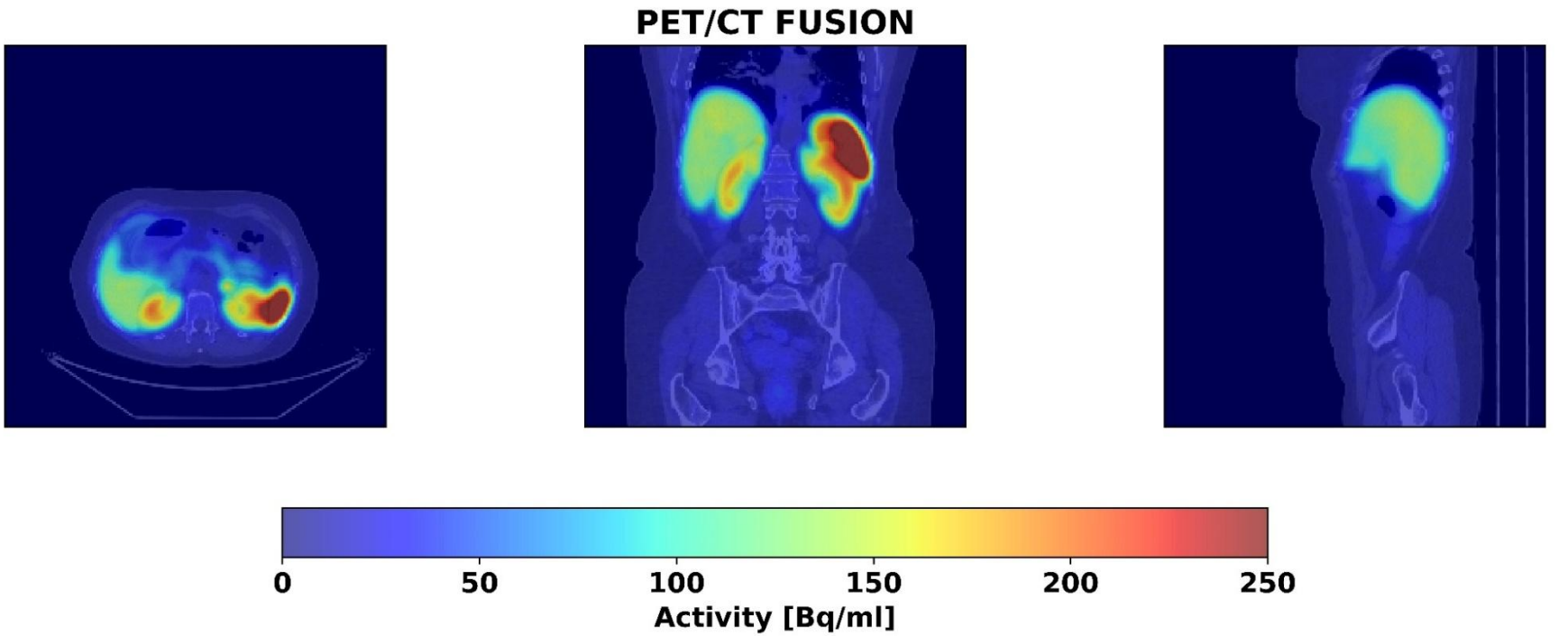


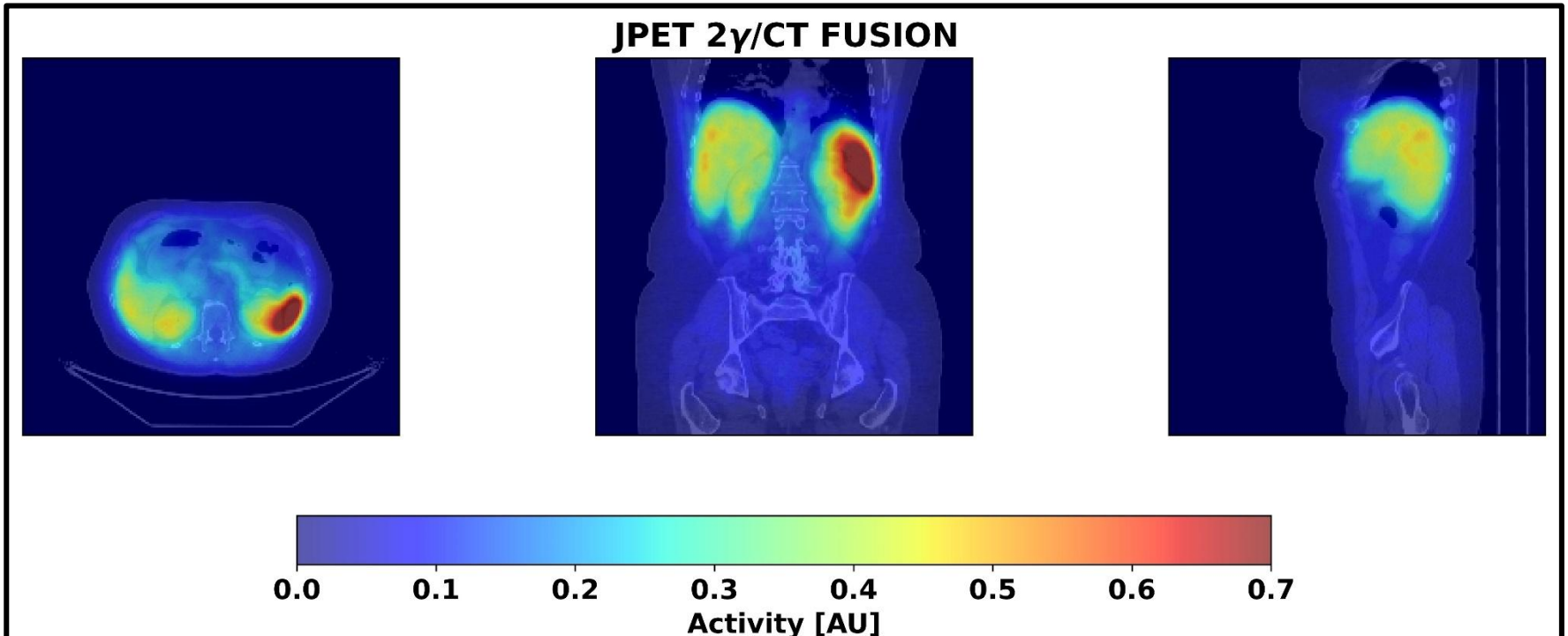


SIEMENS
Biograph


First clinical PET and positronium imaging of patients with J-PET
Biograph
P. Moskal, …, E. Stepien, Science Advances 10 (2024) eadp2840


PET/CT FUSION
0
50
100
150
200
250
Activity [AU]
JPET 2γ/CT FUSION
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Activity [AU]



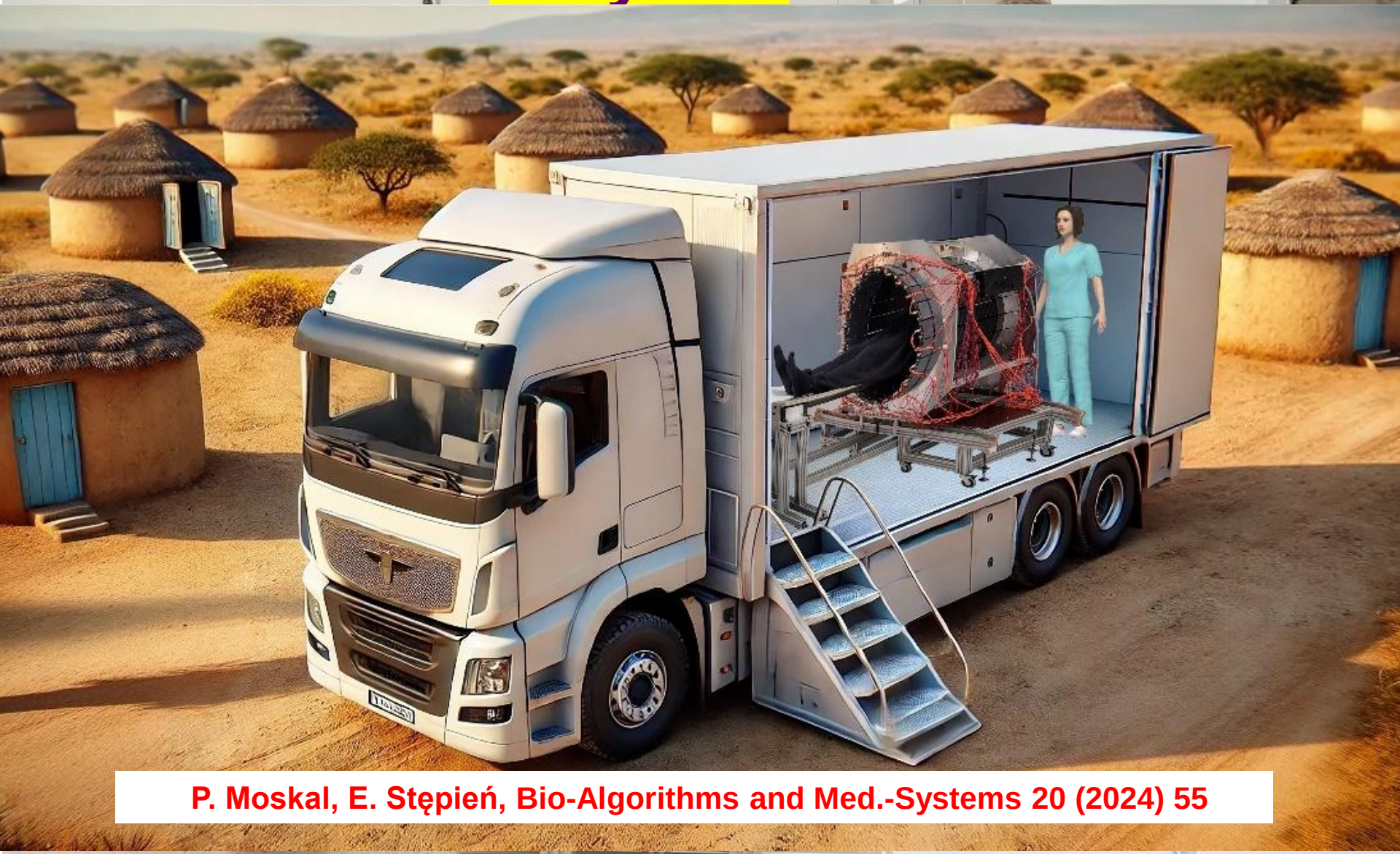

PET/CT FUSION
0
50
100
150
200
250
Activity [Bq/ml]


JPET 2γ/CT FUSION
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Activity [AU]

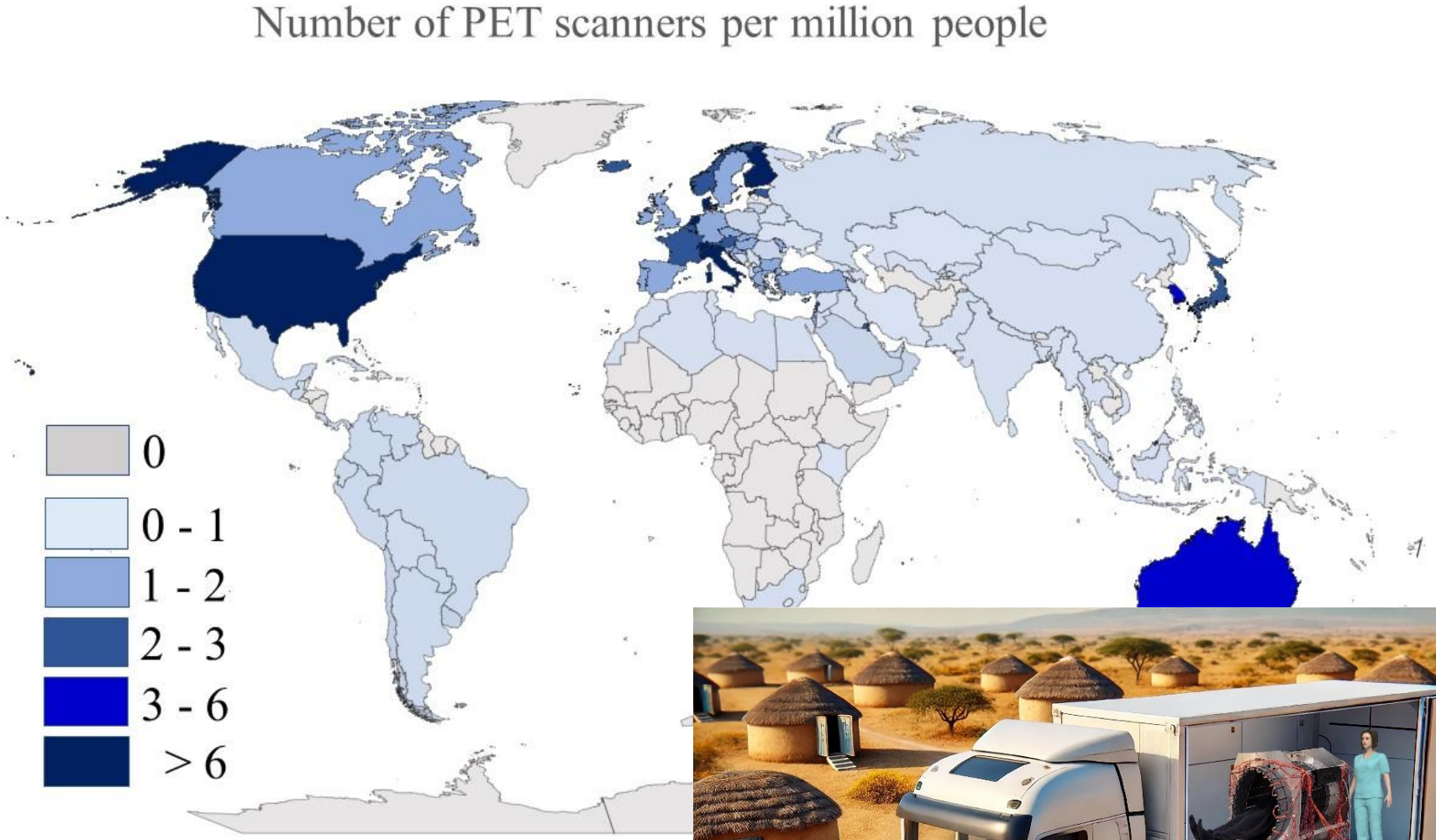

^{44}Ti / ^{44}Sc
60 years
HCl
Polymer
O
OH
N
R
^{44}Ti
^{44}Sc
^{44}Sc
^{44}Sc

Modular J-PET + ^{44}Ti / ^{44}Sc

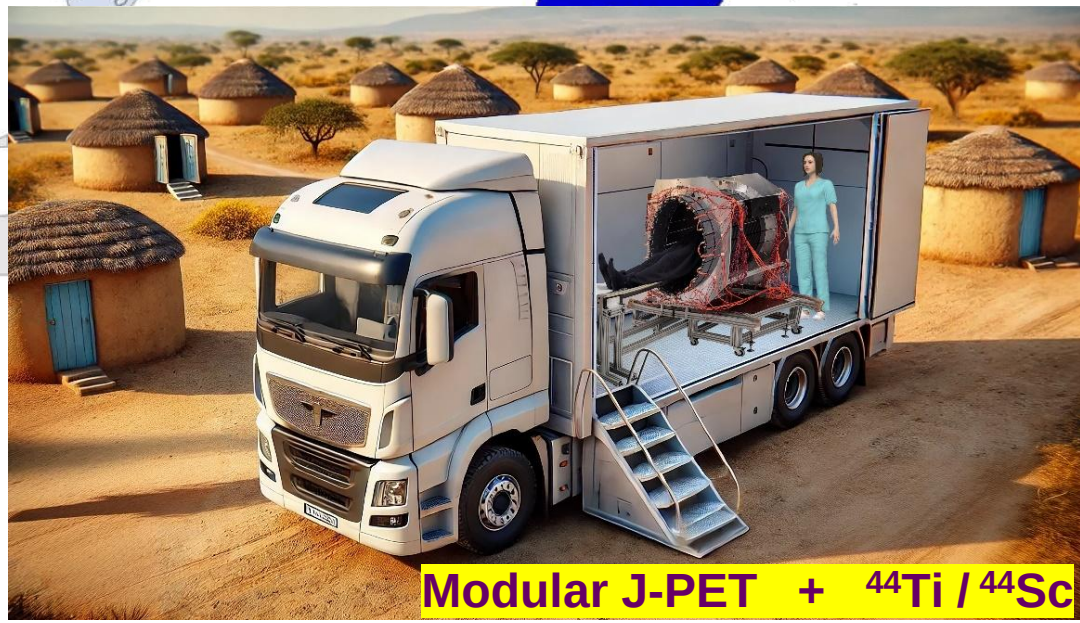
60 years



P. Moskal, E. Stępień, Bio-Algorithms and Med.-Systems 20 (2024) 55



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



P. Moskal, E. Stępień, Bio-Algorithms and Med-Systems 20 (2024) 55

PET from PLASTIC SCINTILLATORS

POSITRONIUM IMAGING

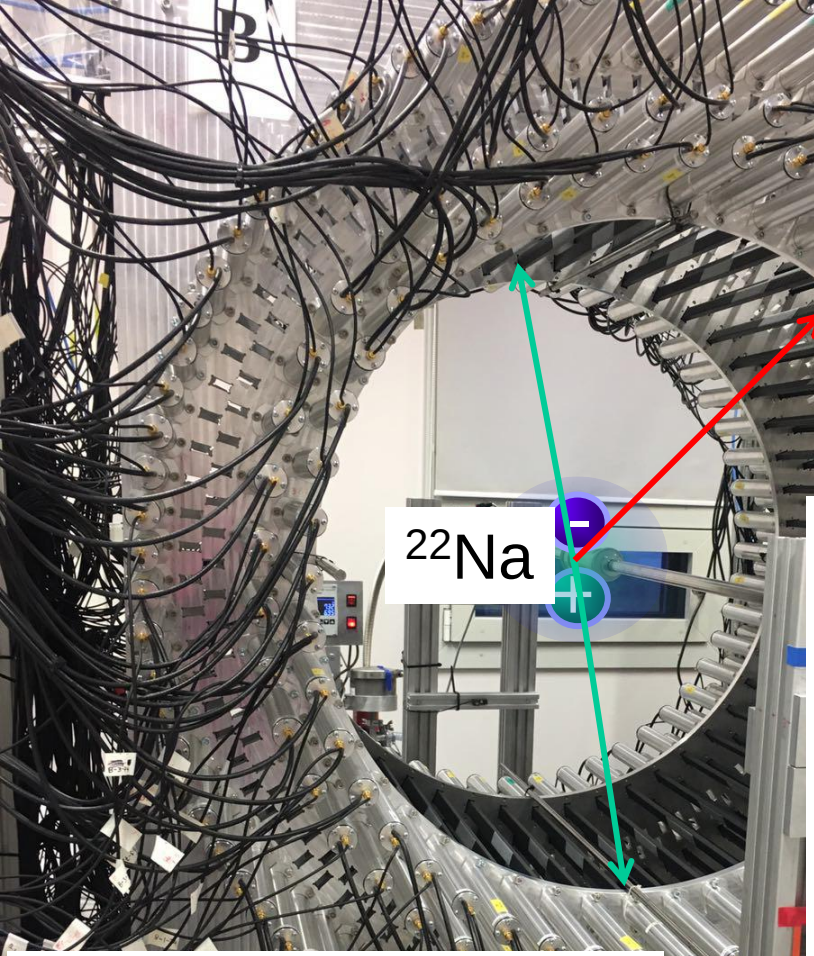
DISCRETE SYMMETRIES

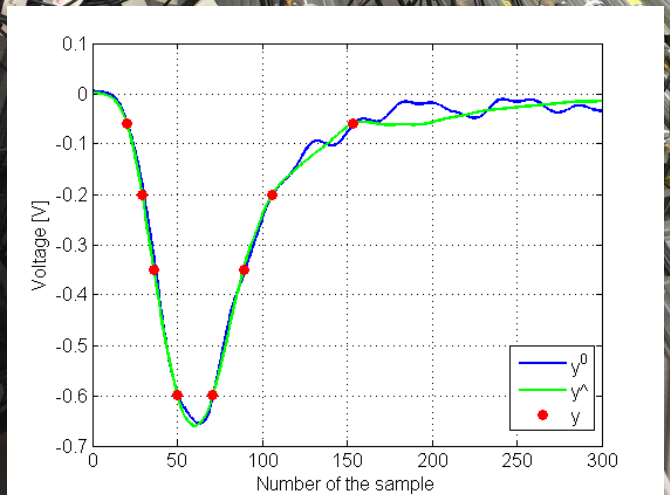
QUANTUM ENTANGLEMENT IMAGING

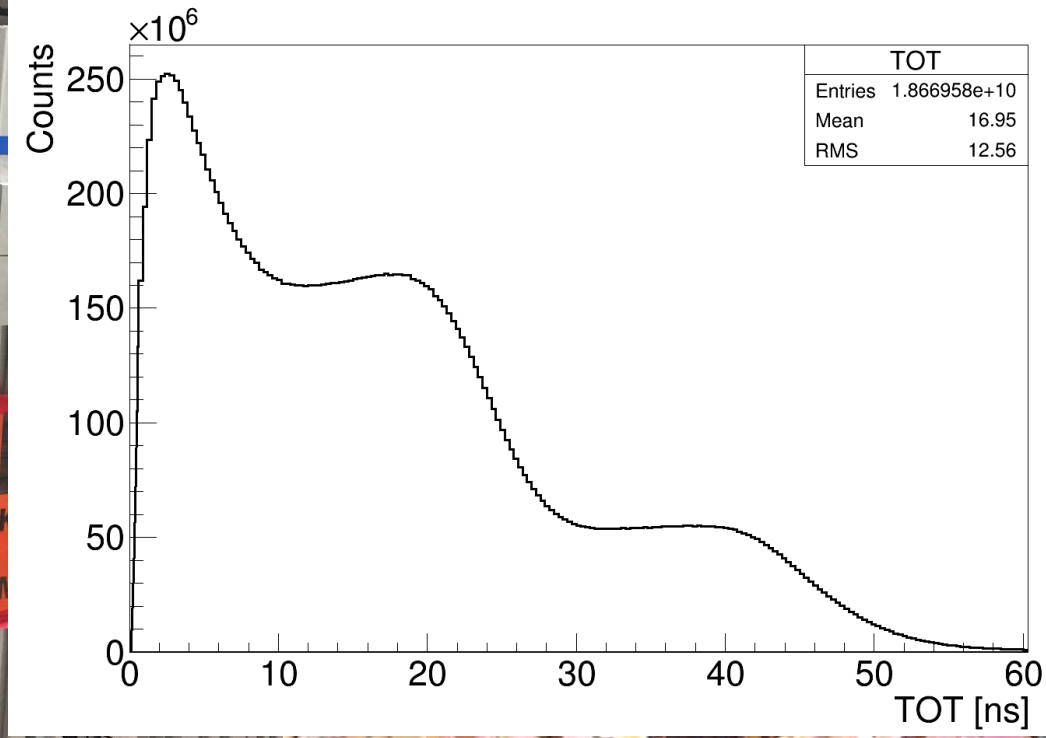
P. Moskal, Jagiellonian University
http://koza.if.uj.edu.pl

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

$^{22}Ne + \gamma$





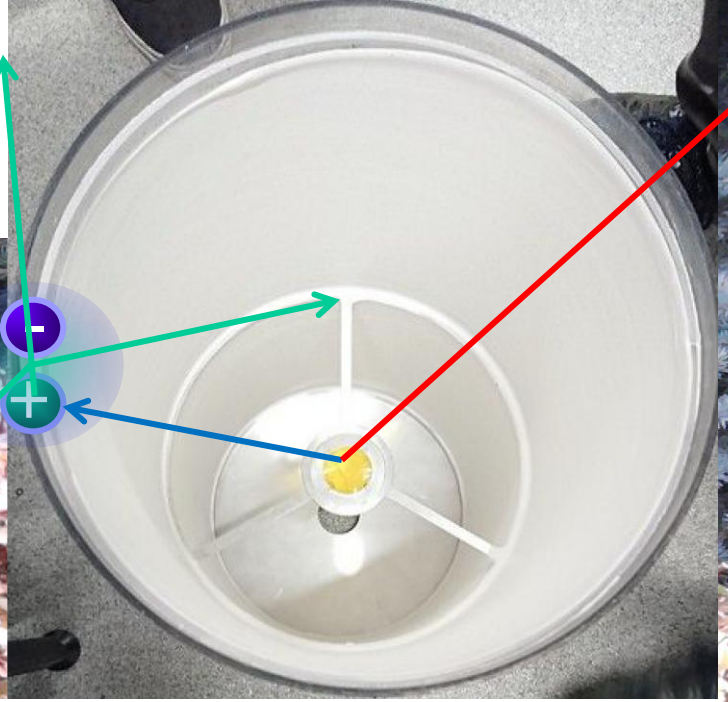


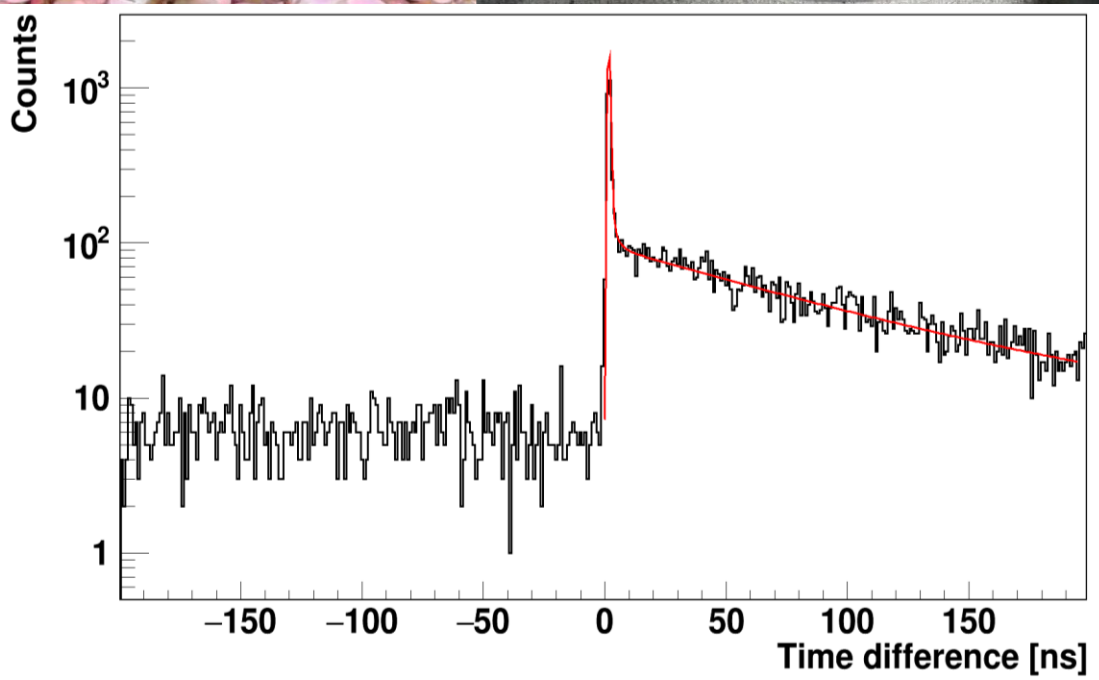
J-PET: S. Sharma et al., EJNMMI Phys. 7 (2020) 39

J-PET: S. Sharma et al., EJNMMI Phys. 10 (2023) 28

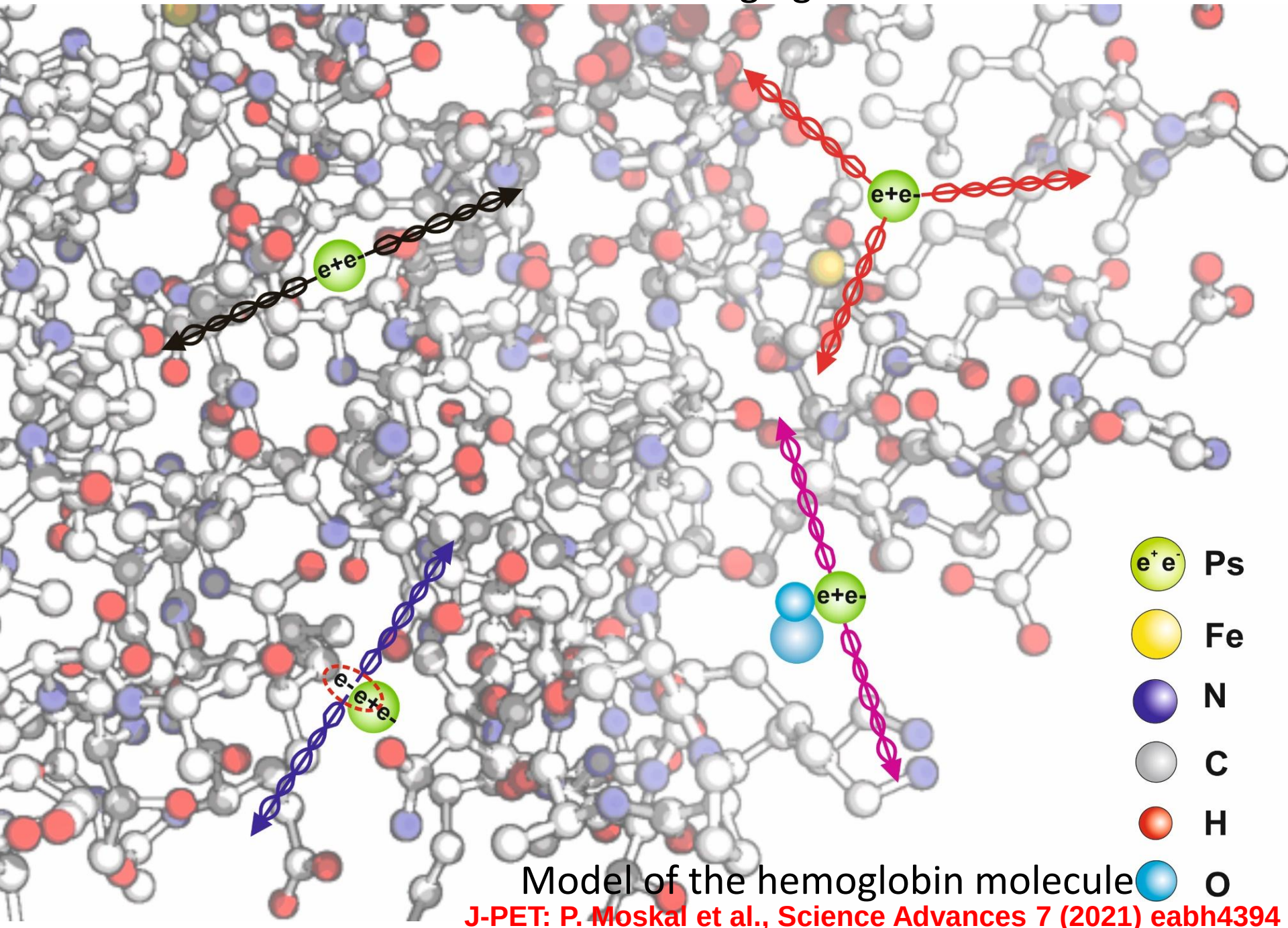
$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$

$^{22}Ne + \gamma$



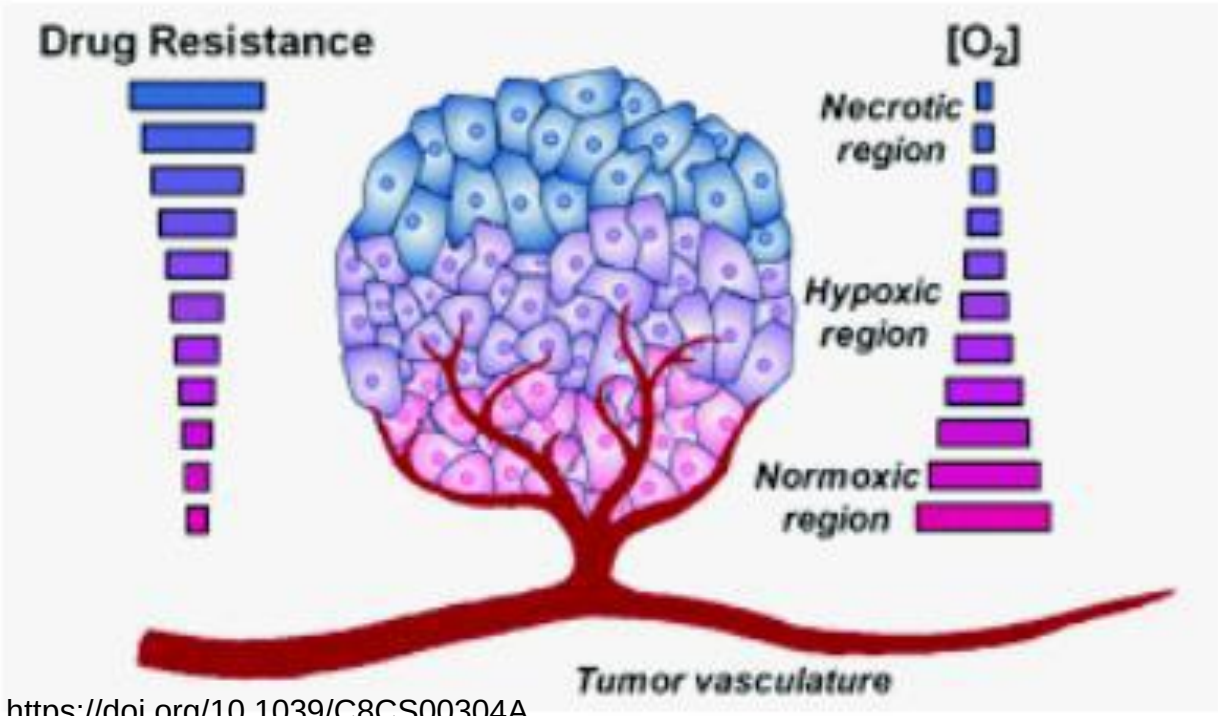


Positronium imaging



Model of the hemoglobin molecule

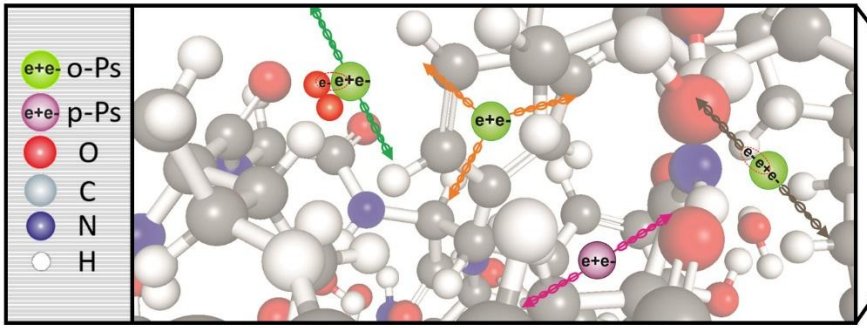
J-PET: P. Moskal et al., Science Advances 7 (2021) eabh4394



https://doi.org/10.1039/C8CS00304A

Hypoxia ≡ deficit in tissue oxidation

Hypoxia is a good cancer prognostic indicator,
it is associated with tumor aggressiveness,
and increased occurrence of metastases and resistance to treatment



Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

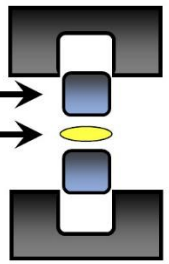
Patient 1 1 1

Patient 2 2 2

Aluminium holder

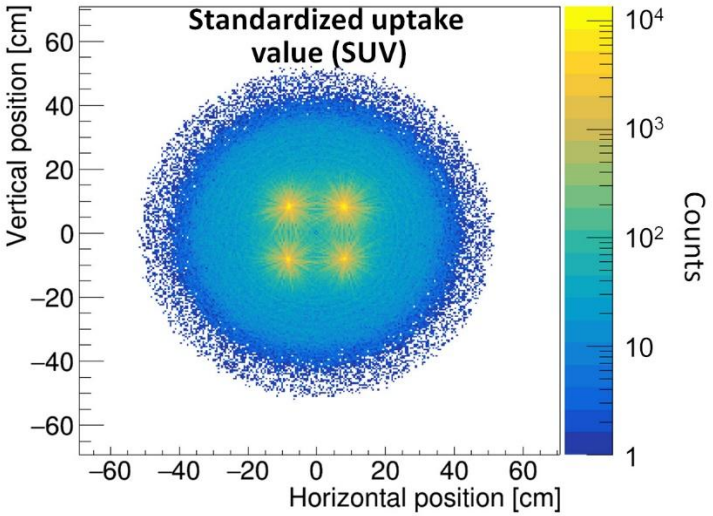
Sample

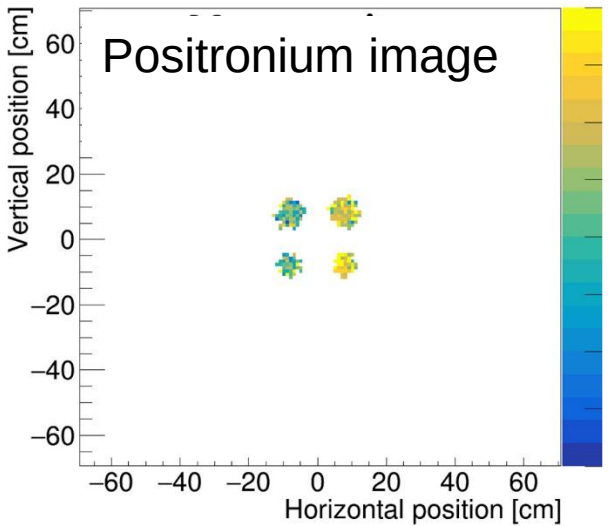
e^+ Source



Placing samples in the chambers

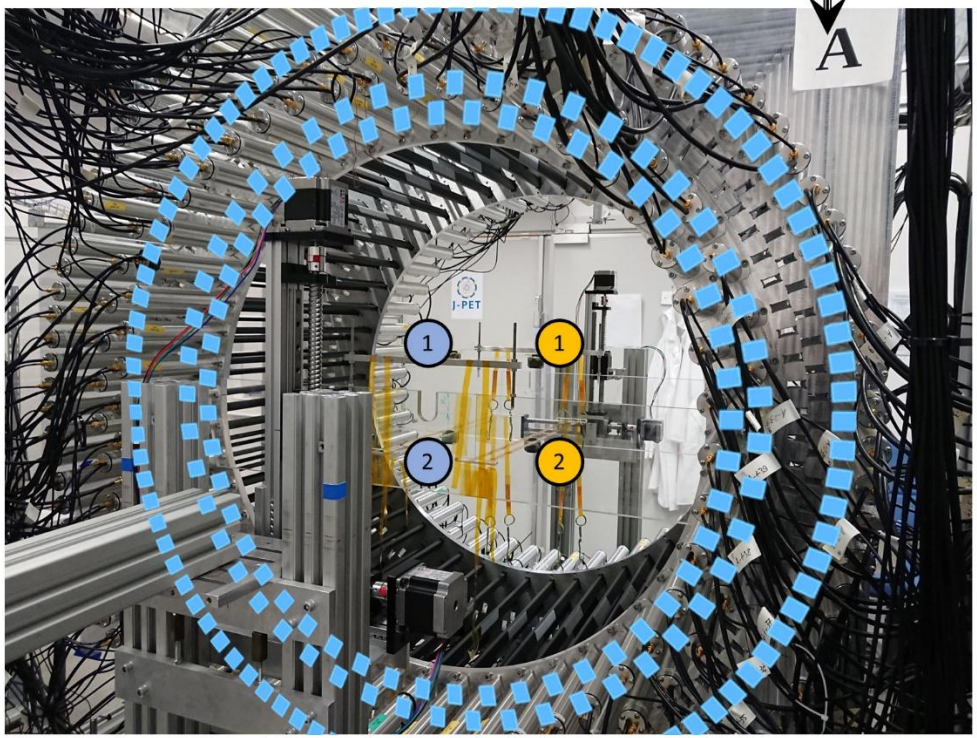
Inserting setup to the detector



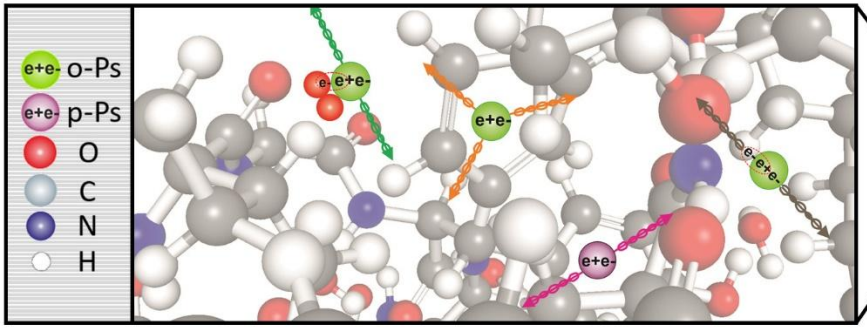


3 ns

1.7 ns



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



Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

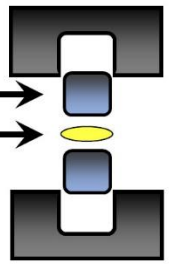
Patient 1 1 1

Patient 2 2 2

Aluminium holder

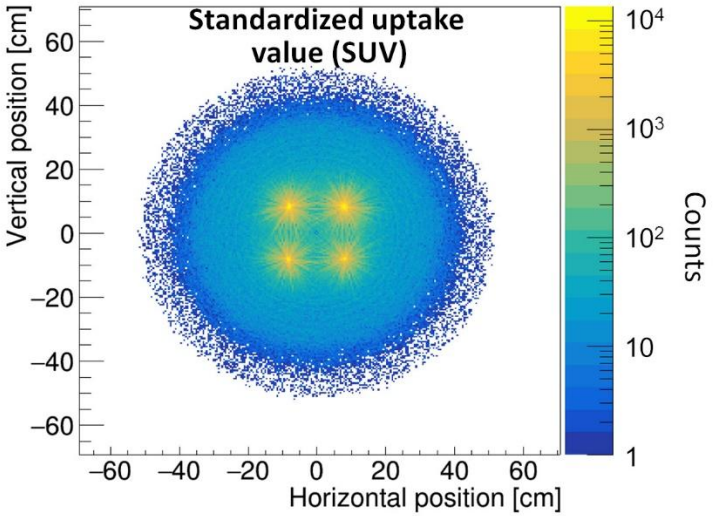
Sample

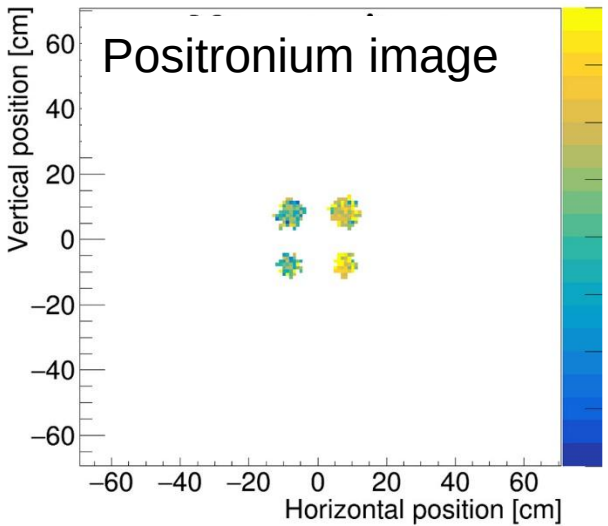
e^+ Source



Placing samples in the chambers

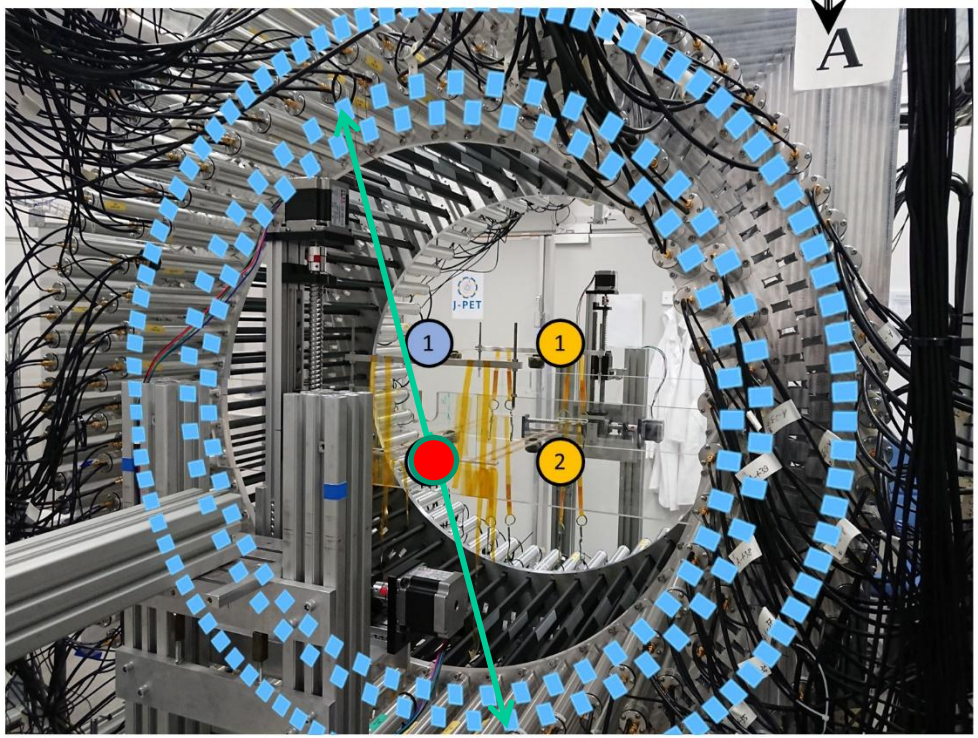
Inserting setup to the detector



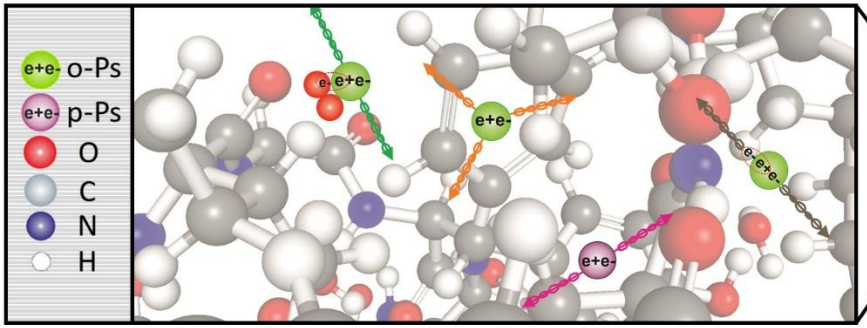


3 ns

1.7 ns



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



Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

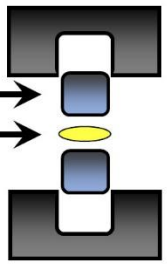
Patient 1 1 1

Patient 2 2 2

Aluminium holder

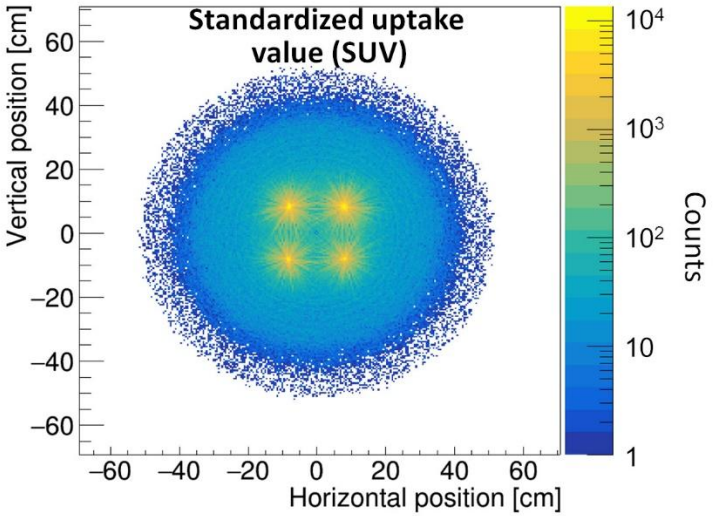
Sample

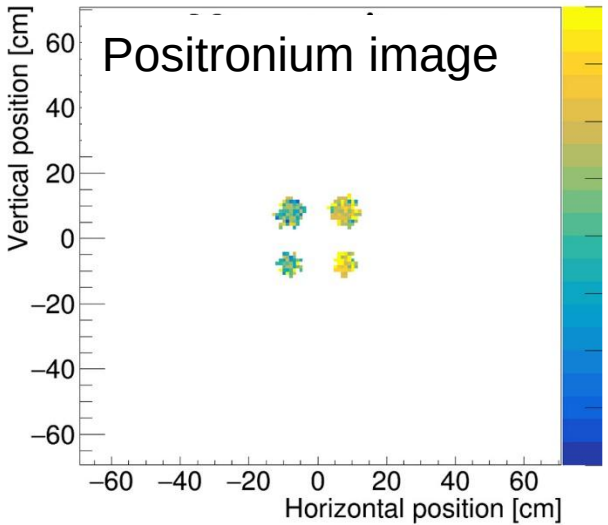
e^+ Source



Placing samples in the chambers

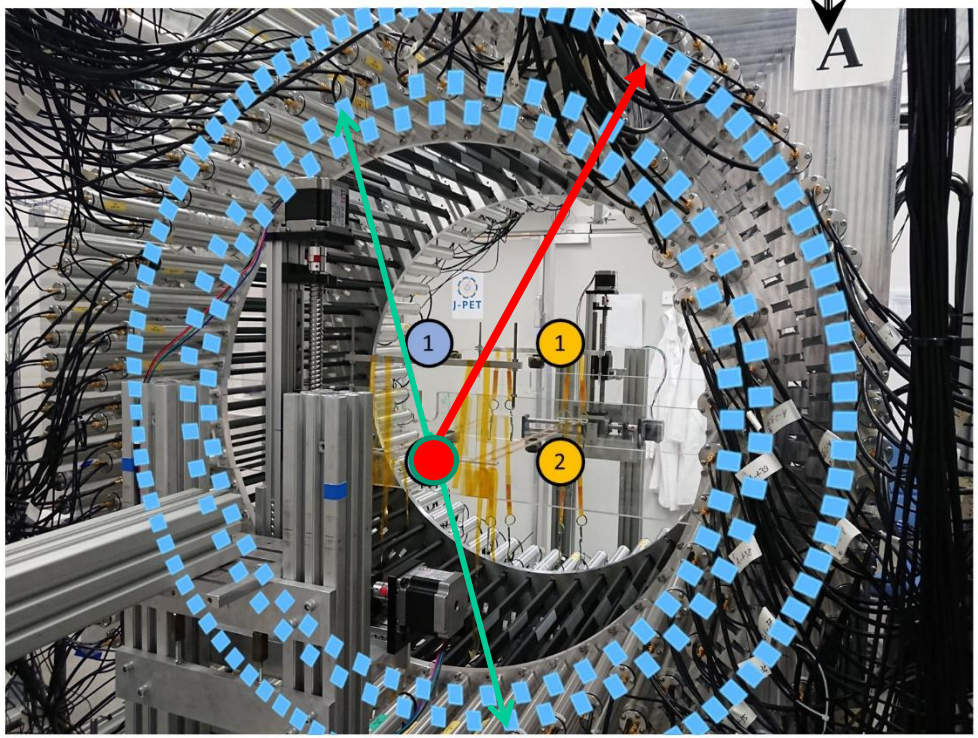
Inserting setup to the detector



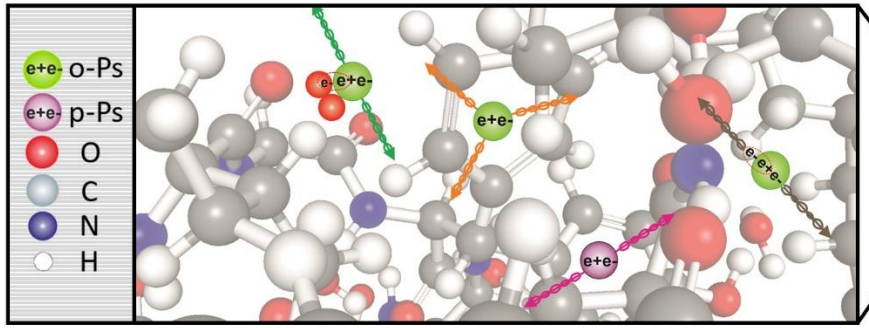


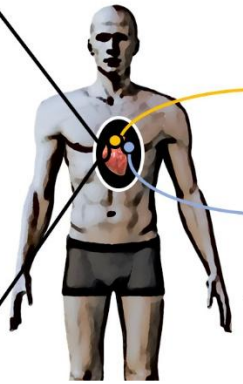
3 ns

1.7 ns



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





Adipose tissue

Cardiac Myxoma

Transfer from hospital

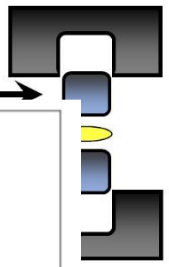
Sample preparation

Patient 1 1 1

Patient 2 2 2

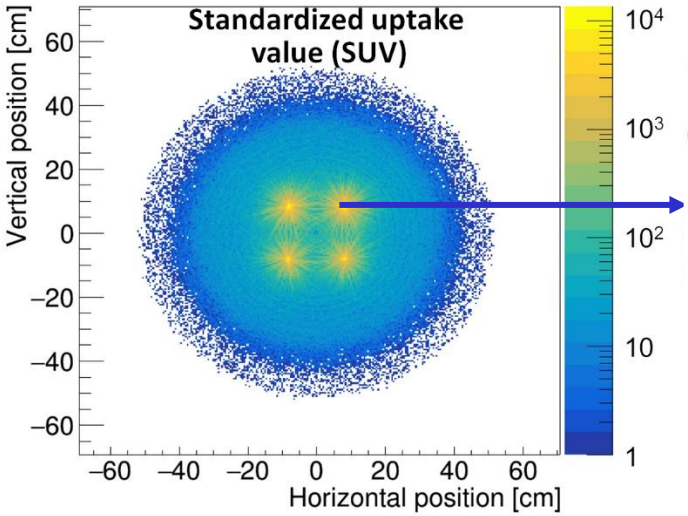
Aluminium holder

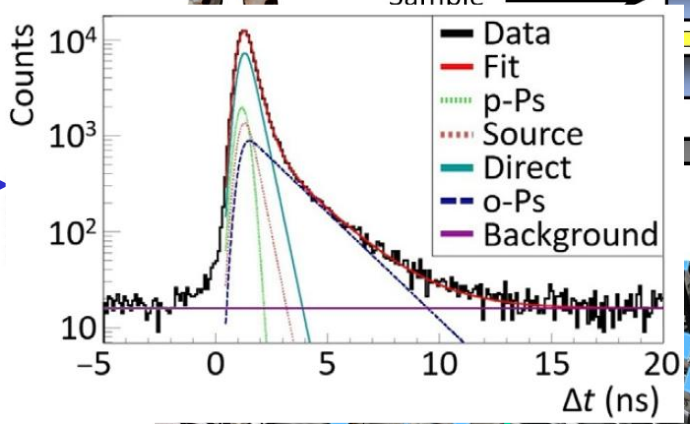
Sample

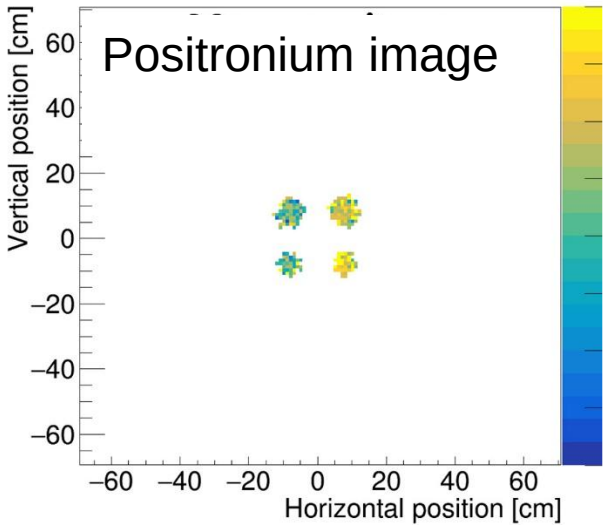


Placing samples in the chambers

Inserting setup to the detector

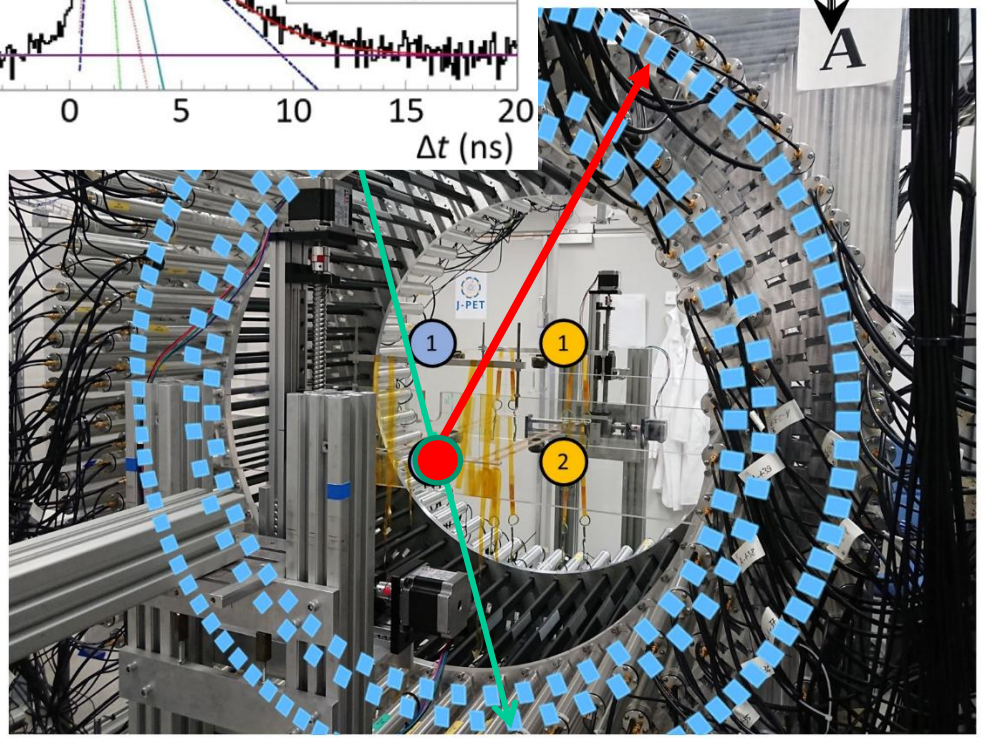






3 ns

1.7 ns

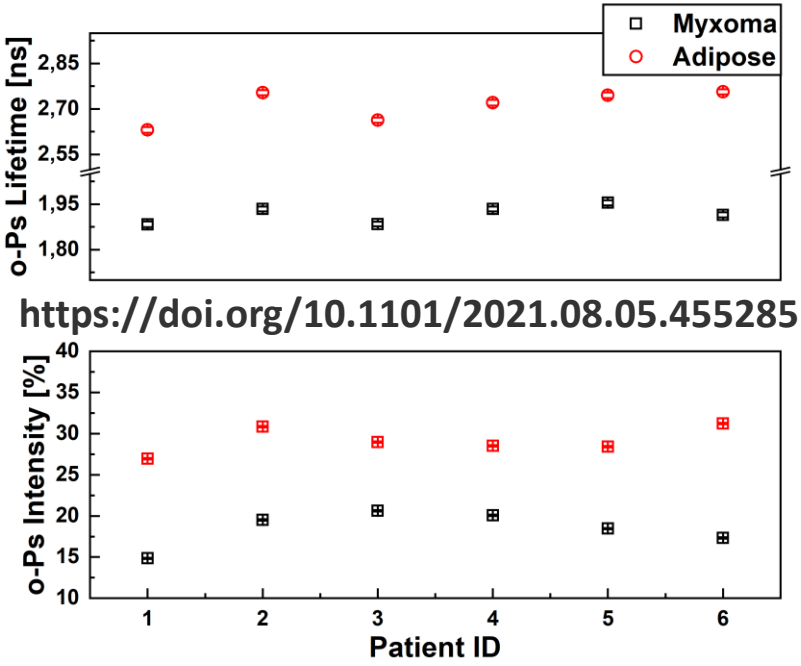


J-PET: P. Moskal et al., Science Advances 7 (2021) eabh4394

Ex-vivo human tissues studies

o-Ps as a biomarker in cancer diagnostic:

- Cardiac myxoma
- Colon cancer
- Breast cancer
- Uterine cancer



Prof. dr Ewa Stępień
Jagiellonian University

Dr n. med. Grzegorz Grudzień
Oddział Kliniczny Chirurgii Serca, Naczyń i Transplantologii
Szpital JP2 Kraków

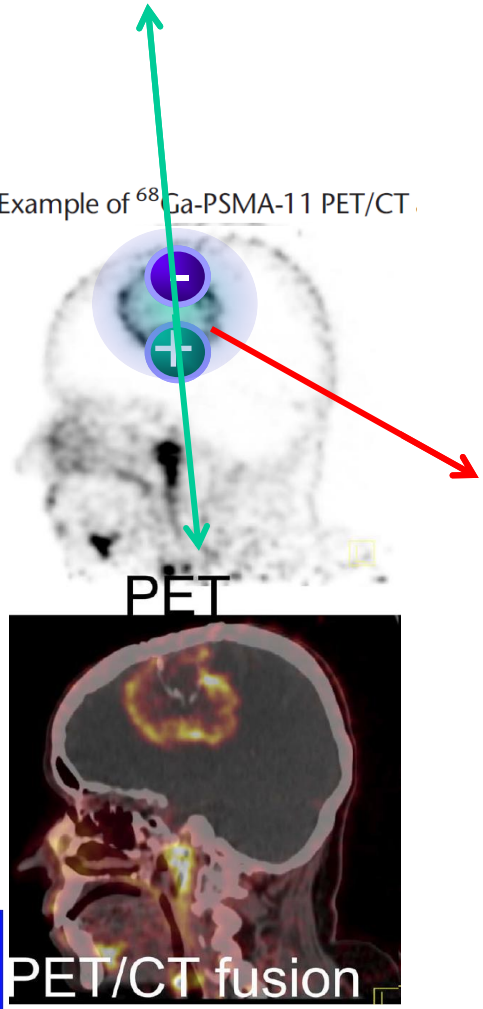
Prof. dr n. med. Michał Pędziwiatr
Chirurgii Endoskopowej, Metabolicznej i Nowotworów Tkanek Miękkich
Szpital Uniwersytecki

Dr hab. n. med. Elżbieta Łuczyńska
Kierownik Zakładu Elektroradiologii
WNoZ UJCM

First clinical positronium imaging of patients

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

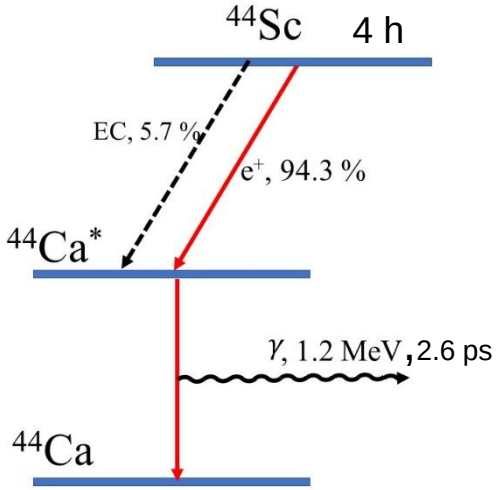
Example of ^{68}Ga-PSMA-11 PET/CT



^{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**

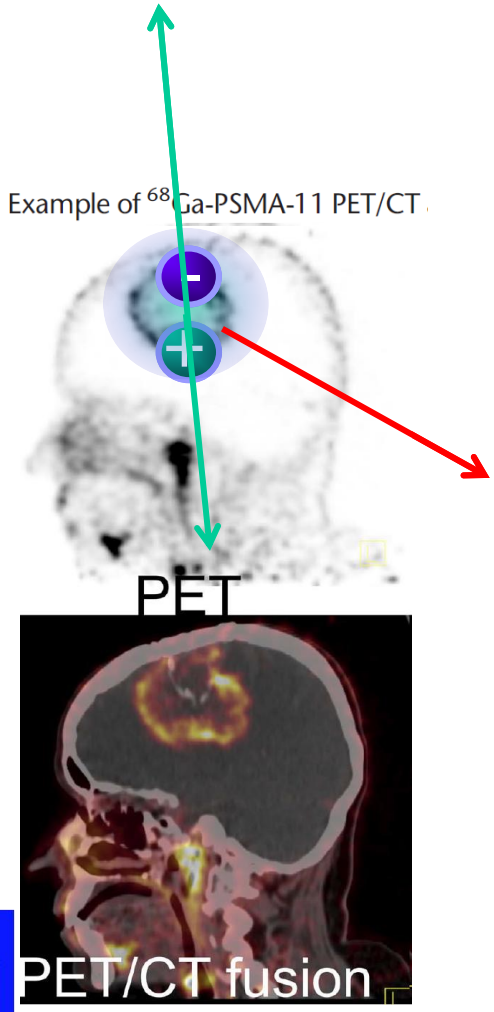


P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

First clinical positronium imaging of patients

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

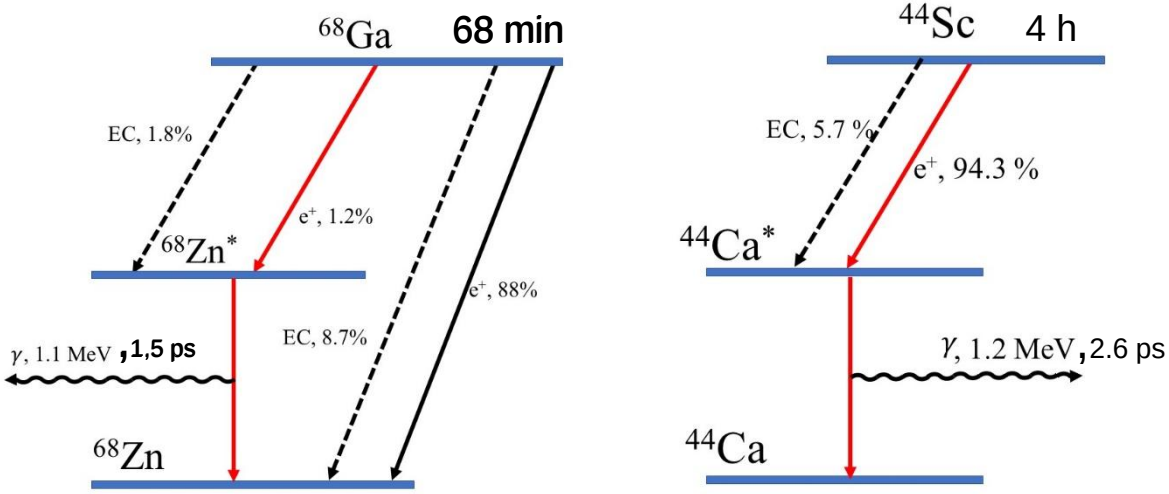
Example of ^{68}Ga-PSMA-11 PET/CT



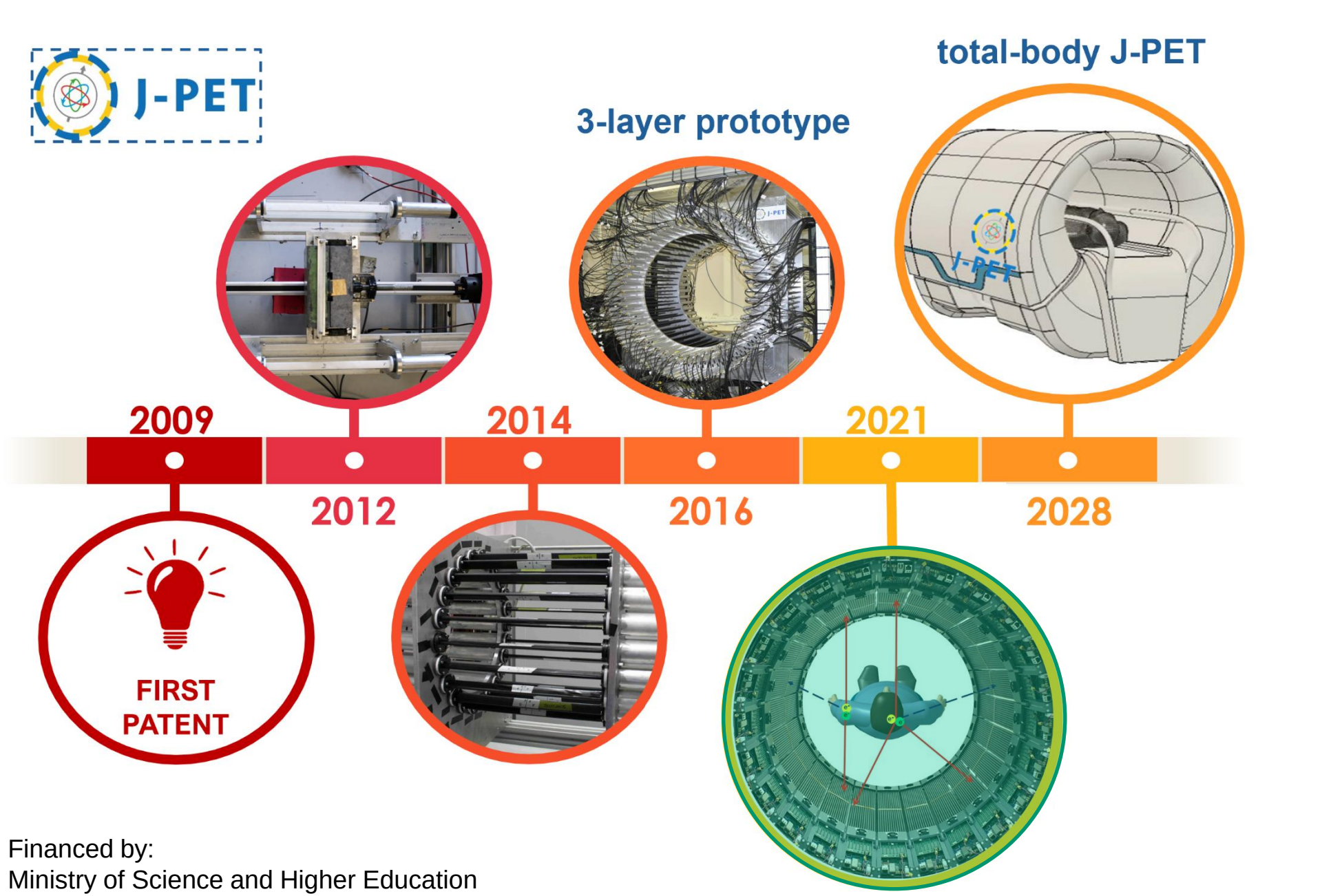
^{68}Ga–Prostate-Specific Membrane Antigen-11 PET/CT

A New Imaging Option for Recurrent Glioblastoma Multiforme?

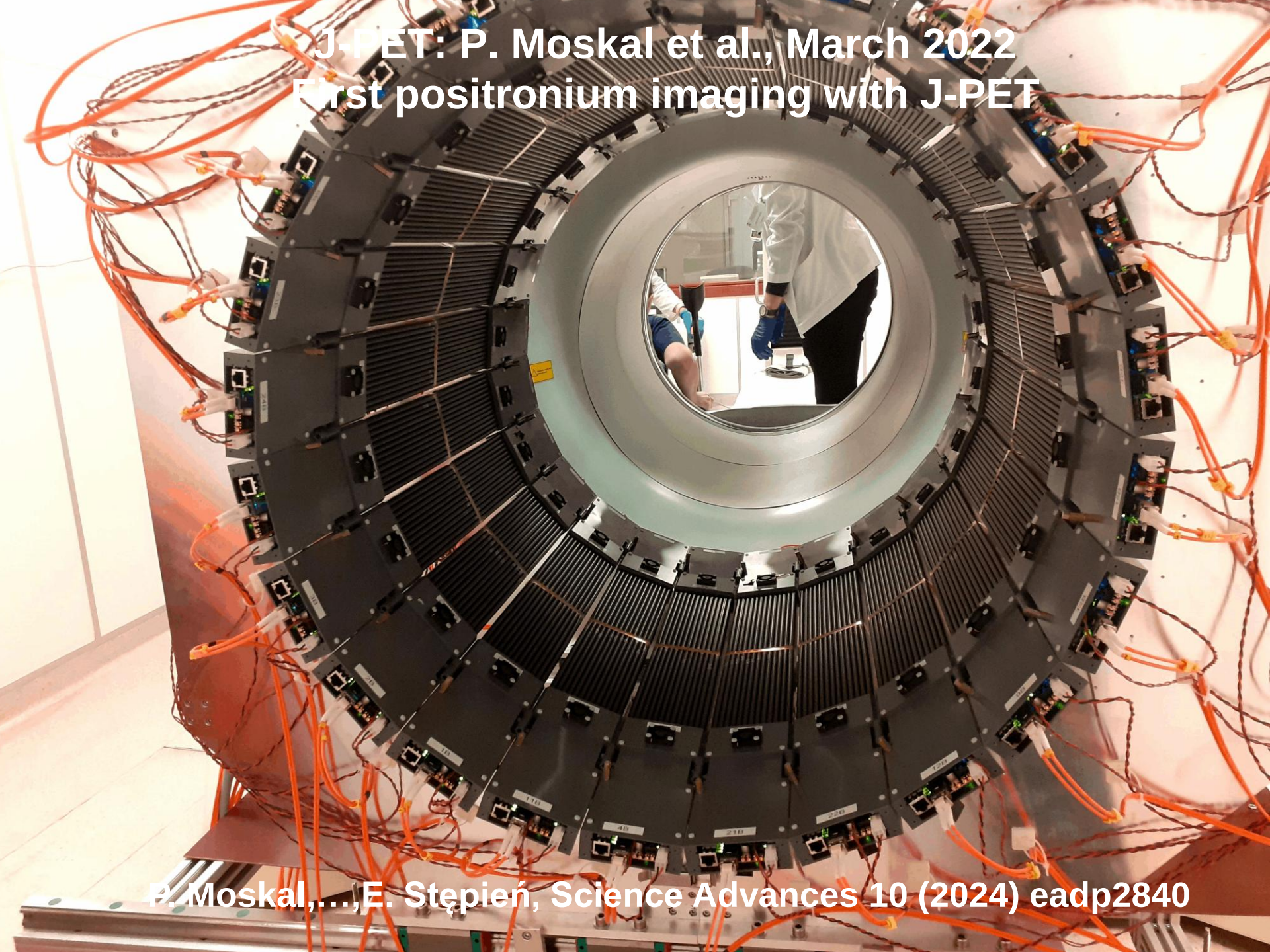
Jolanta Kunikowska, MD, PhD, Radosław Kuliński, MSc,* Kristoff Muylle, MD,† Henryk Koziara, MD,‡ and Leszek Królicki, MD, PhD**

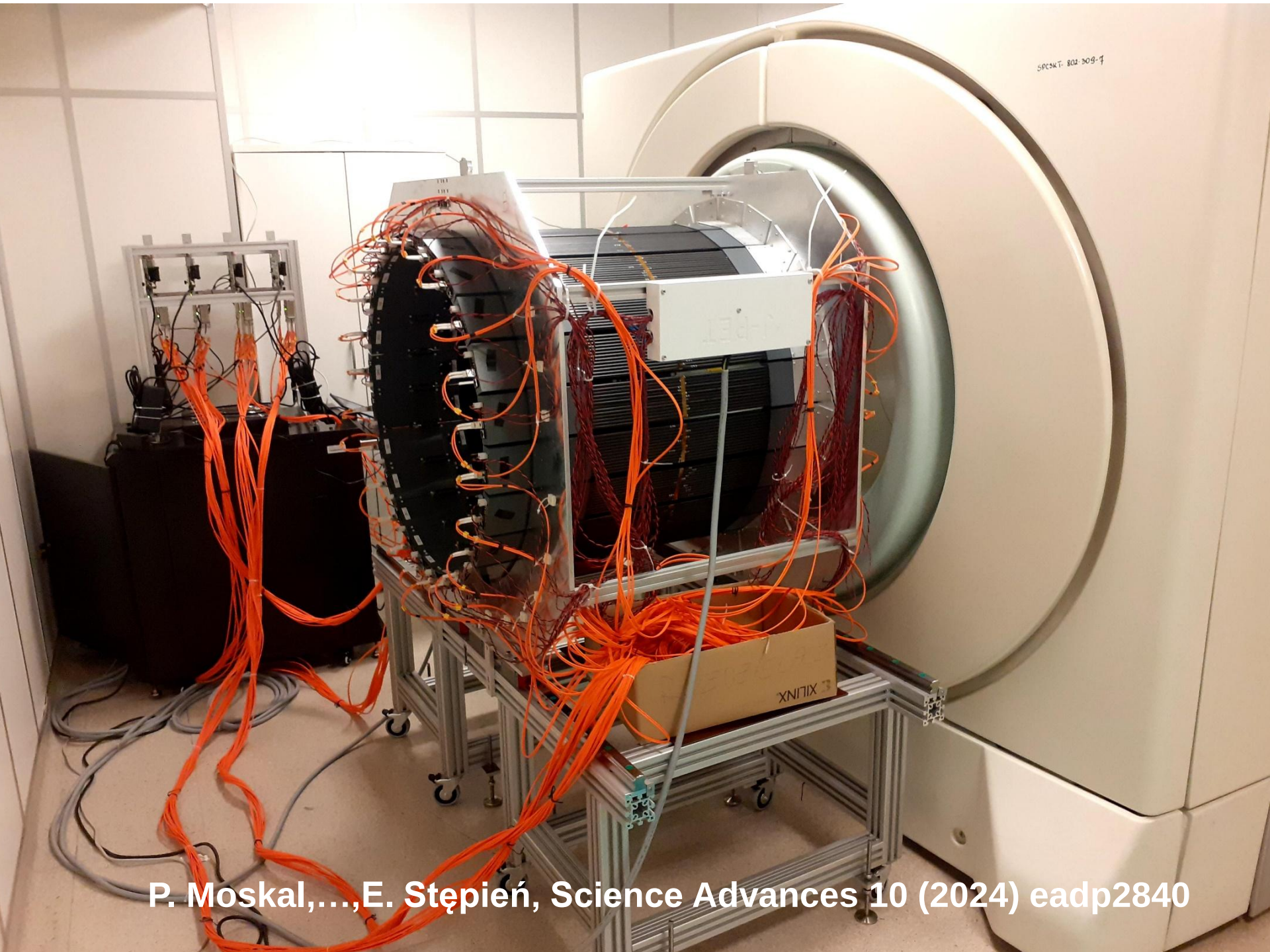


P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**

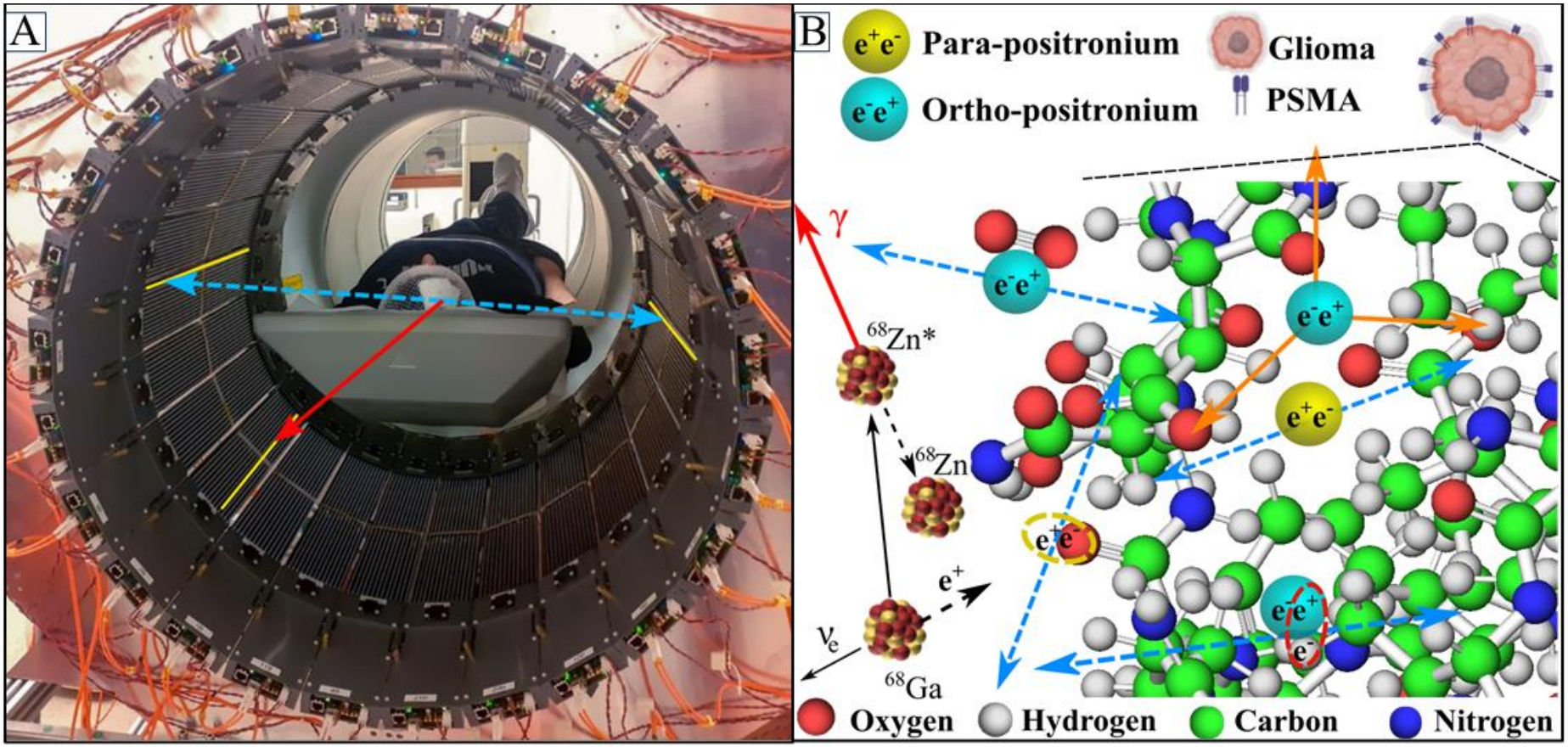


Financed by:
Ministry of Science and Higher Education
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes, MAESTRO)

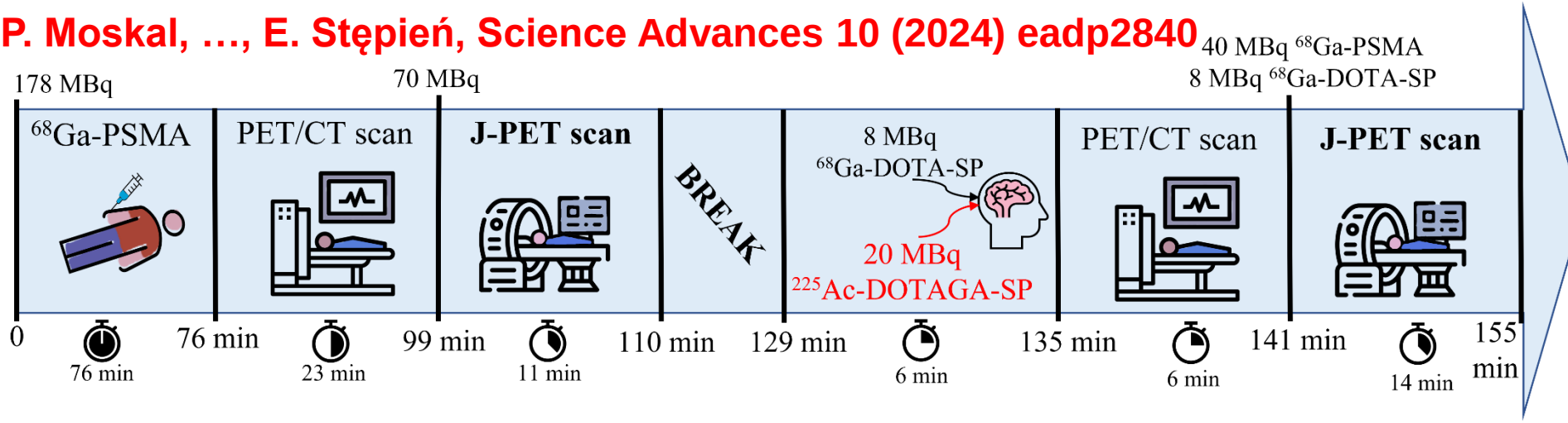

J-PET: P. Moskal et al., March 2022
First positronium imaging with J-PET
P. Moskal,…,E. Stępień, Science Advances 10 (2024) eadp2840

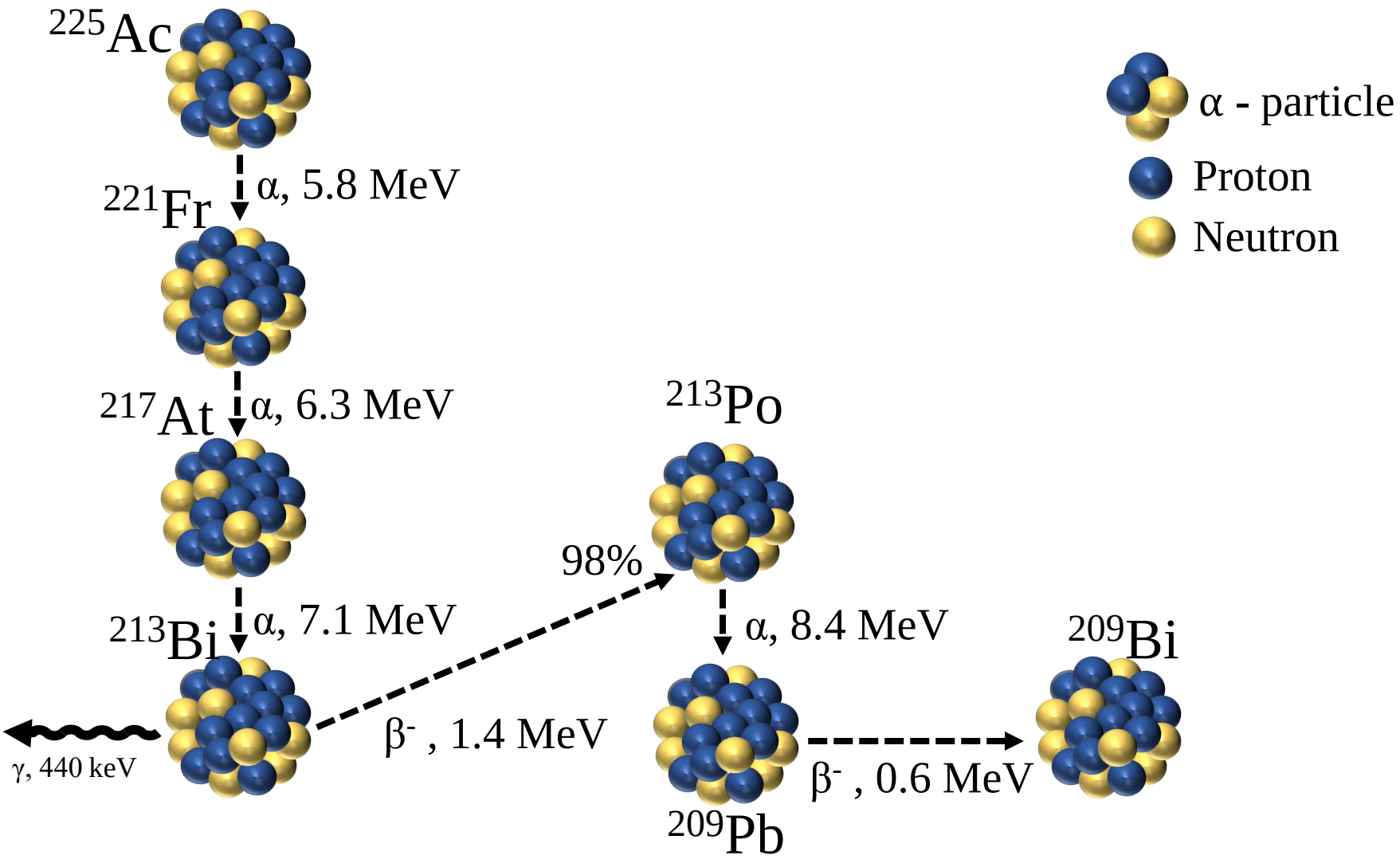


P. Moskal,…,E. Stępień, Science Advances 10 (2024) eadp2840

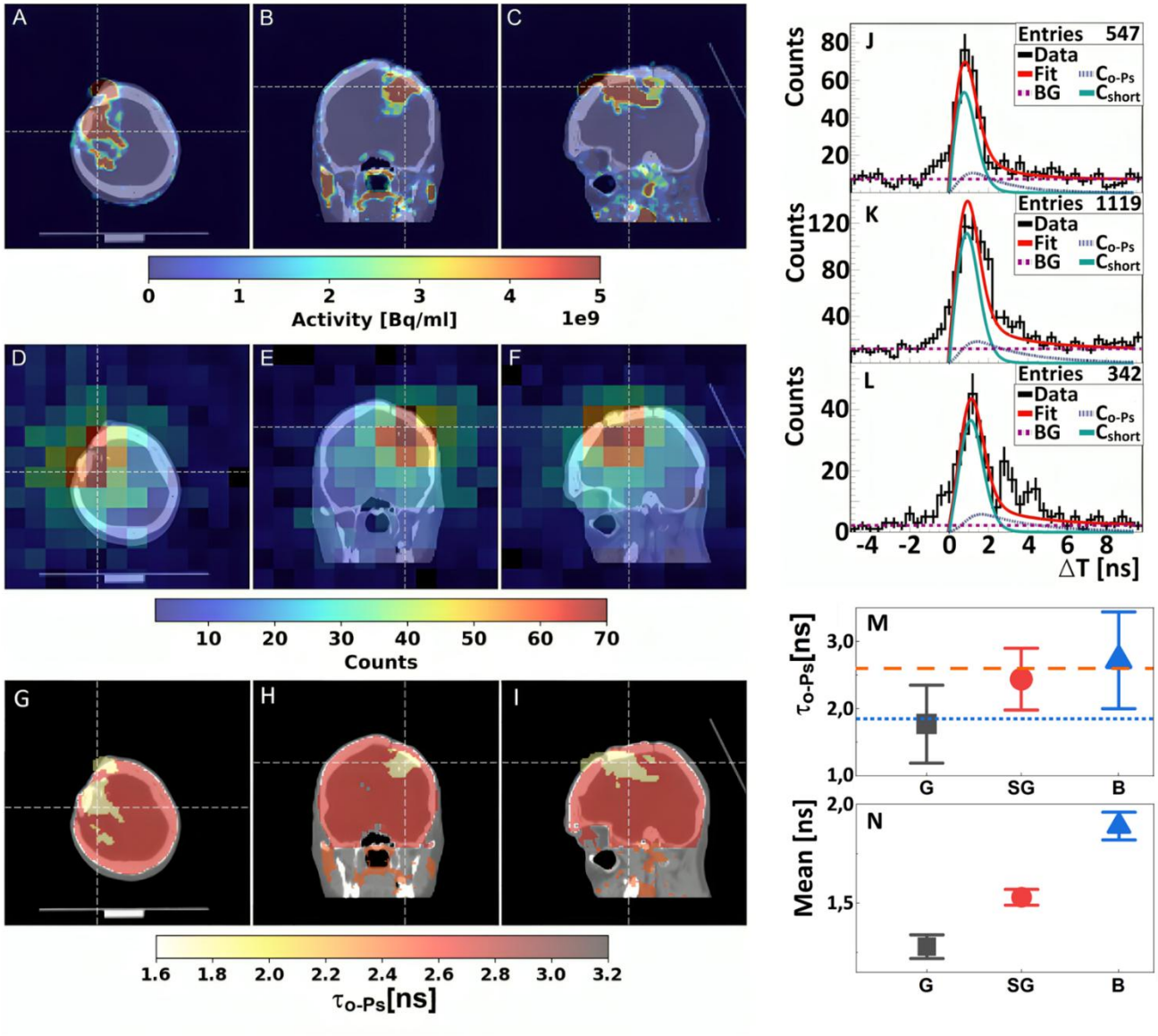


P. Moskal, …, E. Stępień, Science Advances 10 (2024) eadp2840



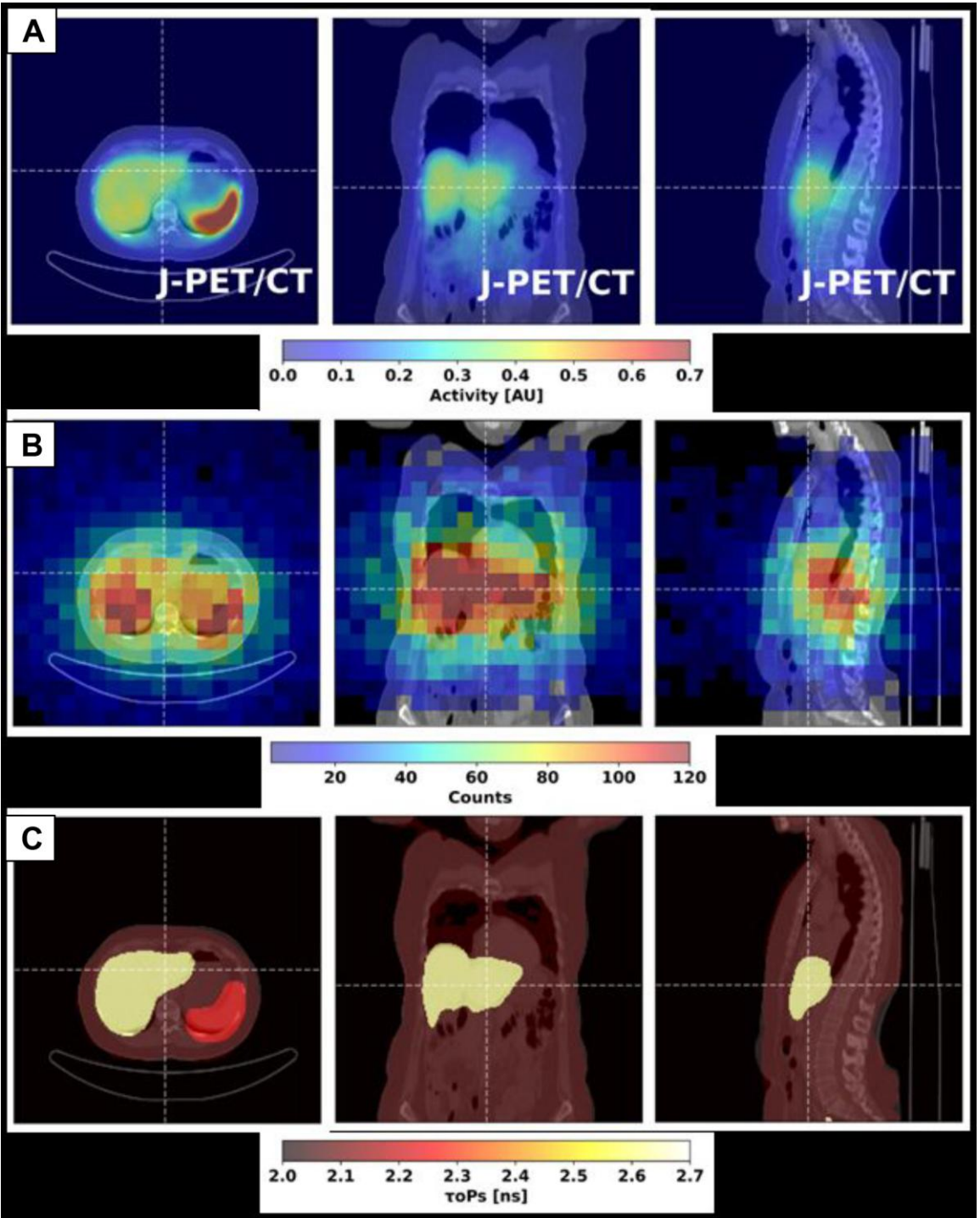

225Ac
α, 5.8 MeV
221Fr
217At
α, 6.3 MeV
213Bi
α, 7.1 MeV
γ, 440 keV
213Po
98%
α, 8.4 MeV
β- , 1.4 MeV
209Pb
β- , 0.6 MeV
209Bi
α - particle
Proton
Neutron

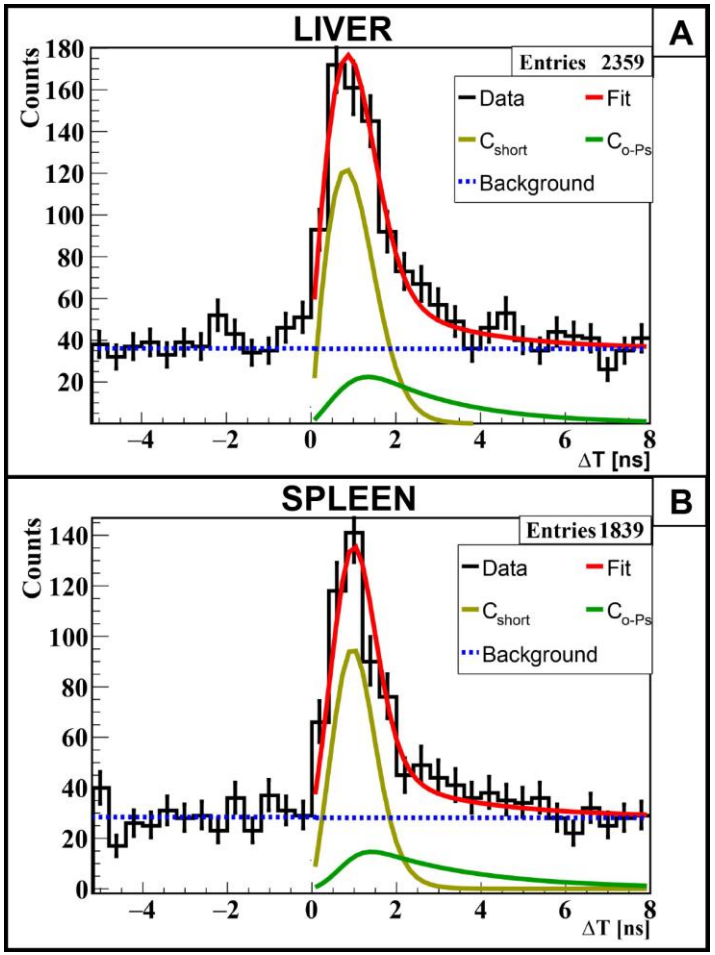
First clinical positronium imaging of patients



P. Moskal, …, E. Stępień, Science Advances 10 (2024) eadp2840

Positronium image of the human brain in vivo

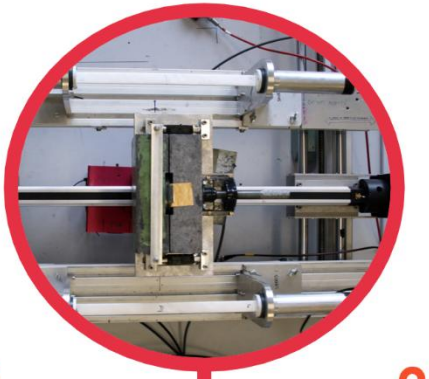

A
J-PET/CT
J-PET/CT
J-PET/CT
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
Activity [AU]
B
20 40 60 80 100 120
Counts
C
2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7
τoPs [ns]

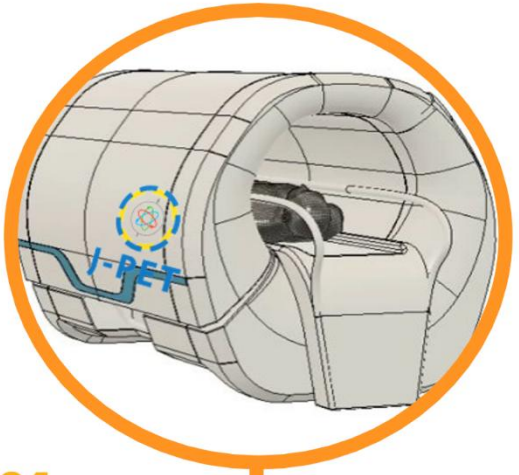

LIVER
A
Entries 2359
Data
Fit
C_short
C_o-Ps
Background
Counts
ΔT [ns]
SPLEEN
B
Entries 1839
Data
Fit
C_short
C_o-Ps
Background
Counts
ΔT [ns]

J-PET

total-body J-PET

3-layer prototype





2009

2012

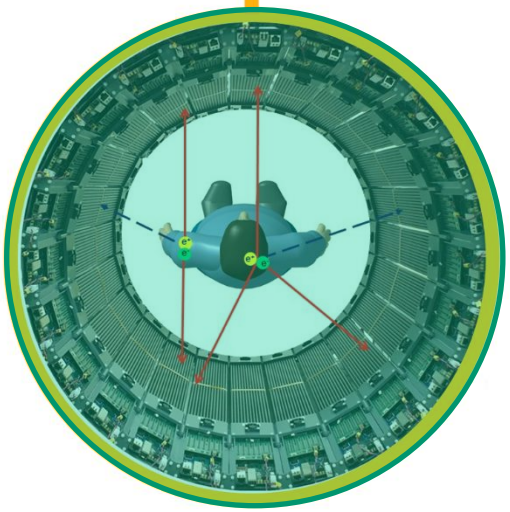
2014

2016

2021

2028

FIRST PATENT

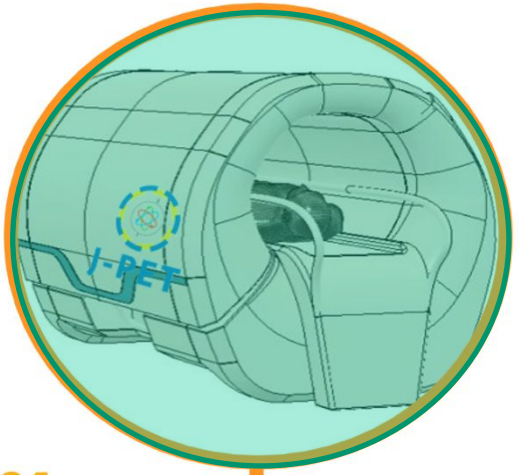


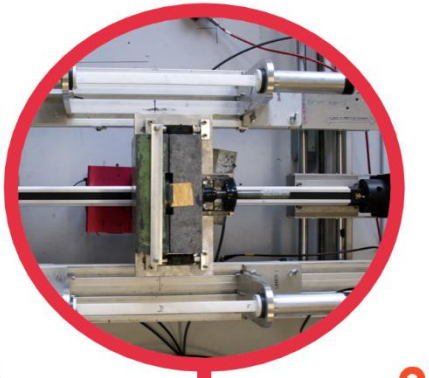
modular J-PET

J-PET

total-body J-PET

3-layer prototype





2009

2012

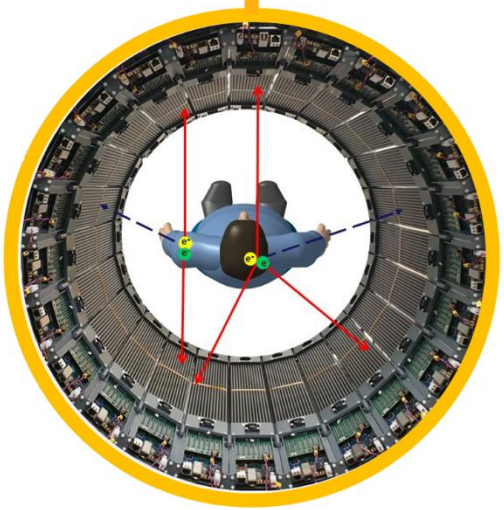
2014

2016

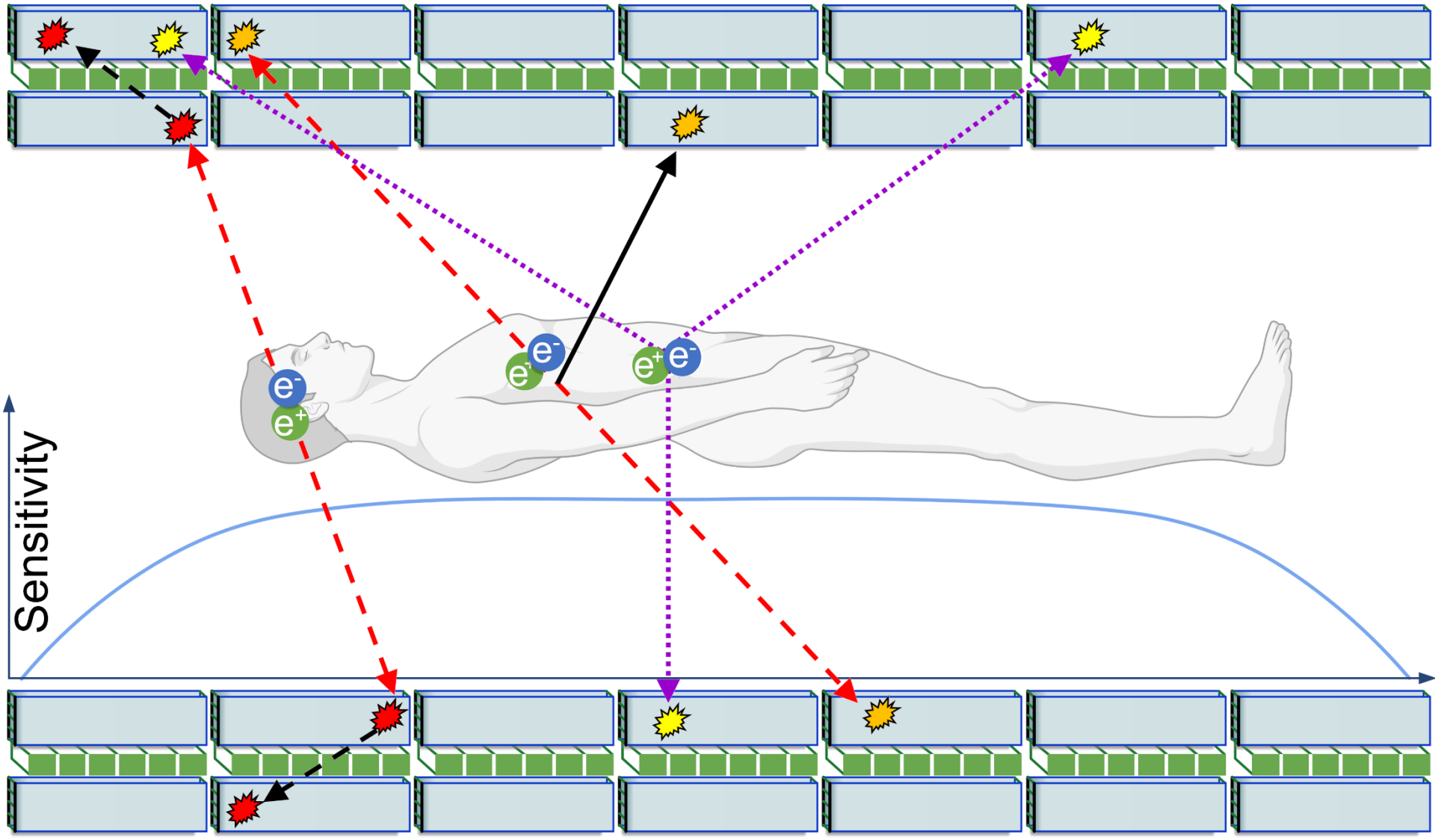
2021

2028

FIRST PATENT



modular J-PET



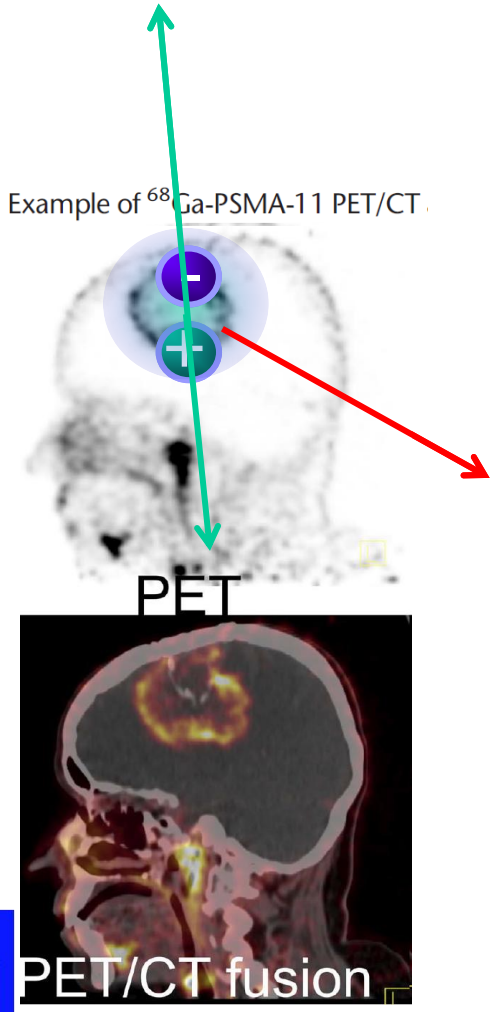
P. Moskal et al., Phys. Med. Biol. 66 (2021) 175015

CENTER FOR THERANOSTICS

First clinical positronium imaging of patients

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

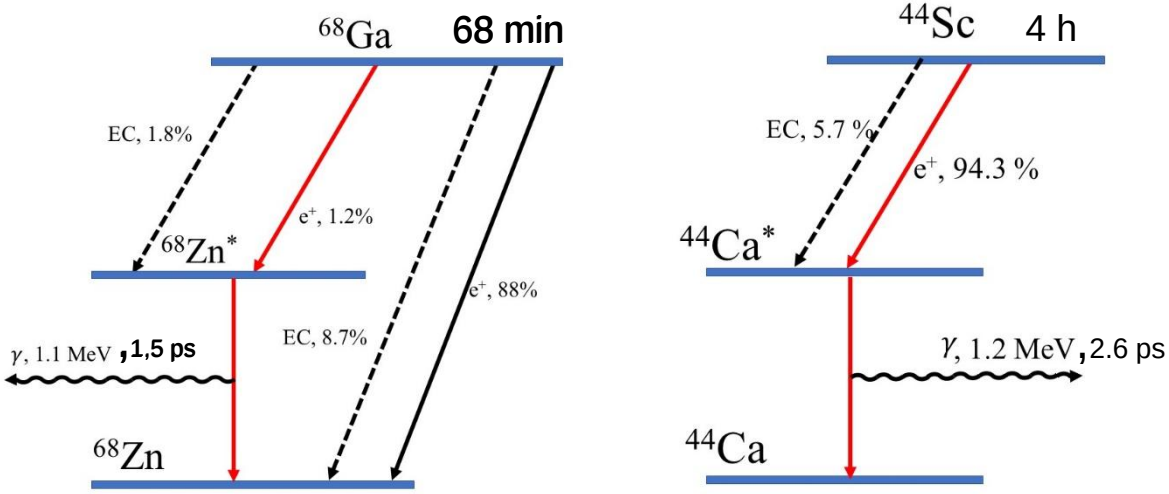
Example of ^{68}Ga-PSMA-11 PET/CT



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

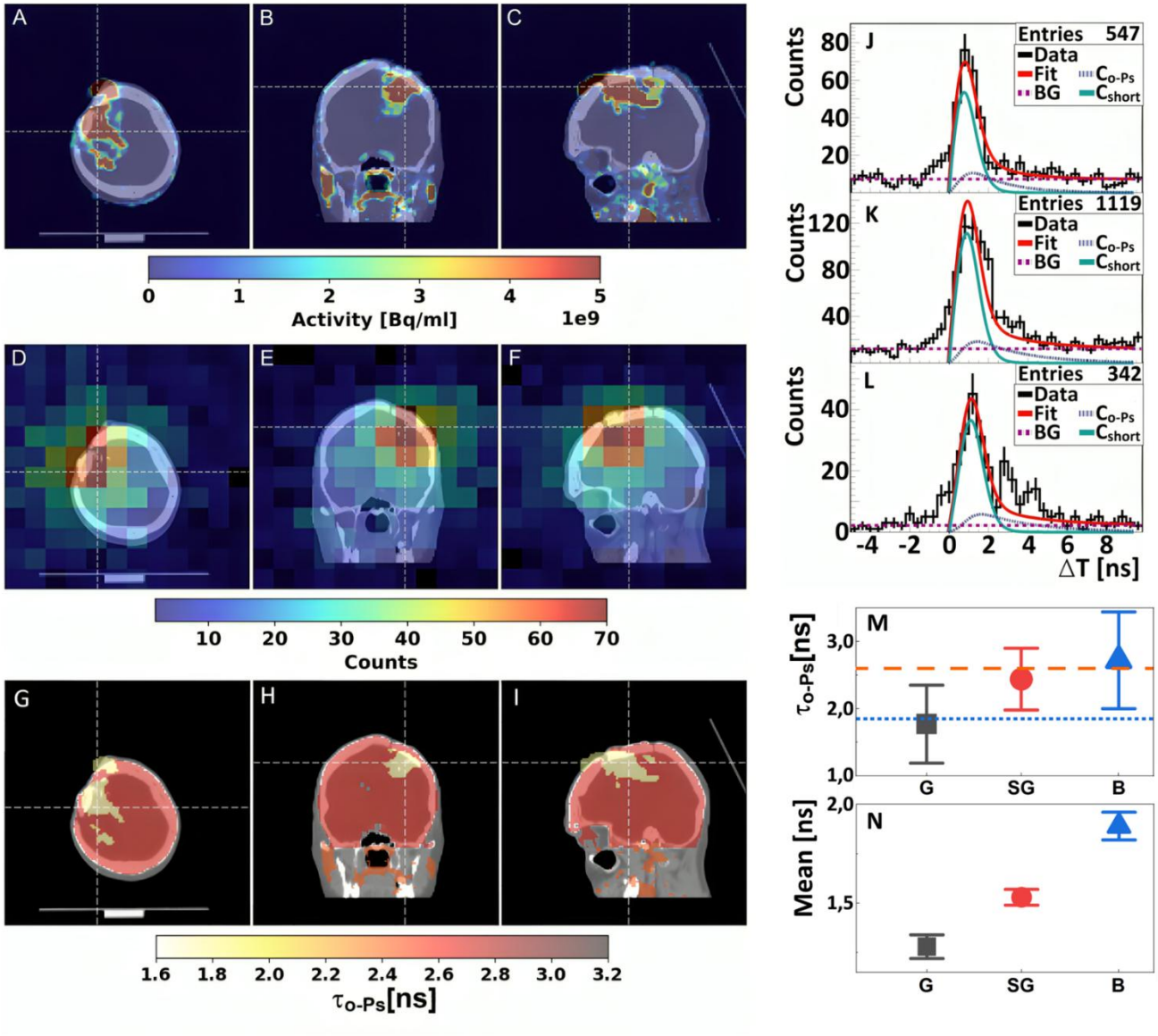
A New Imaging Option for Recurrent Glioblastoma Multiforme?

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



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

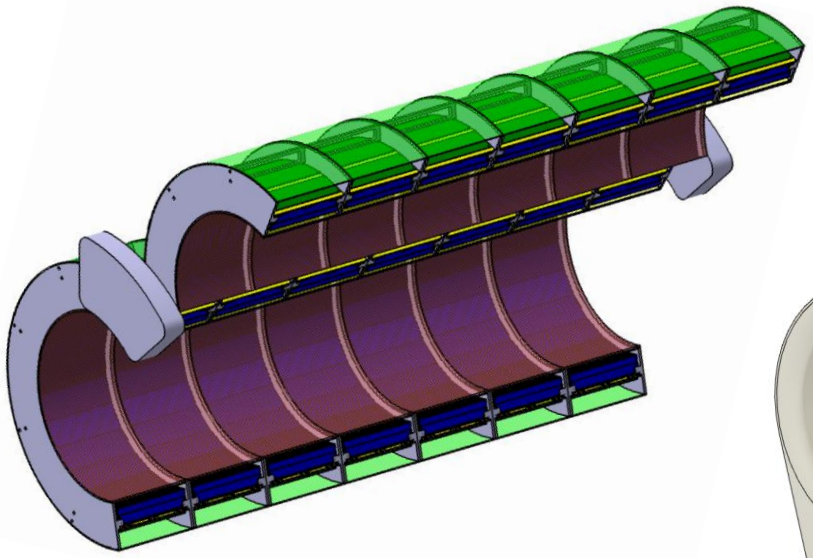
First clinical positronium imaging of patients

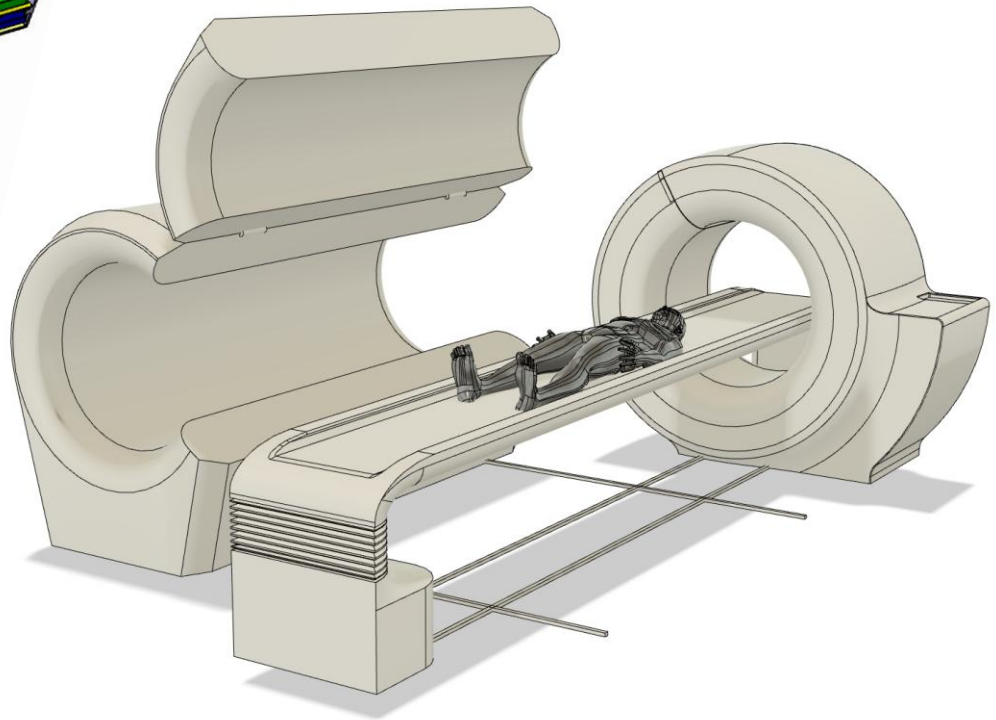


P. Moskal, …, E. Stępień, Science Advances 10 (2024) eadp2840

Positronium image of the human brain in vivo

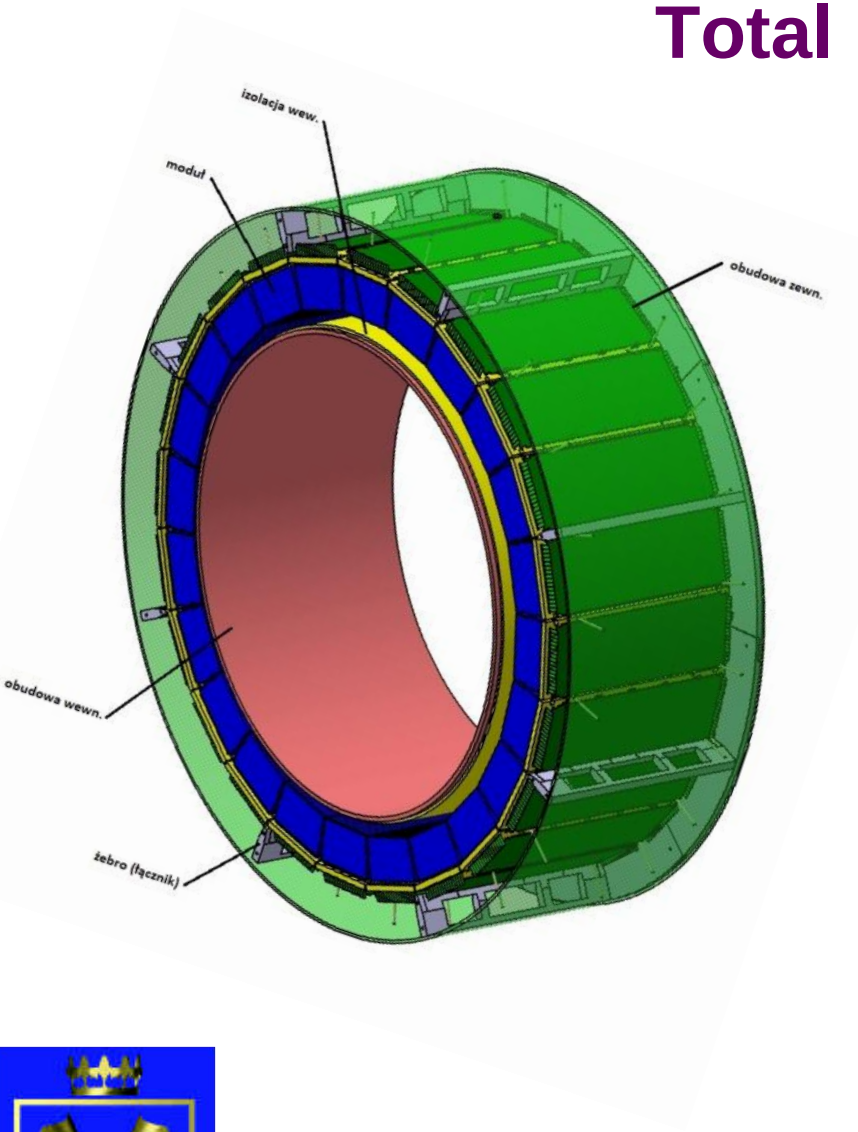
Total body J-PET

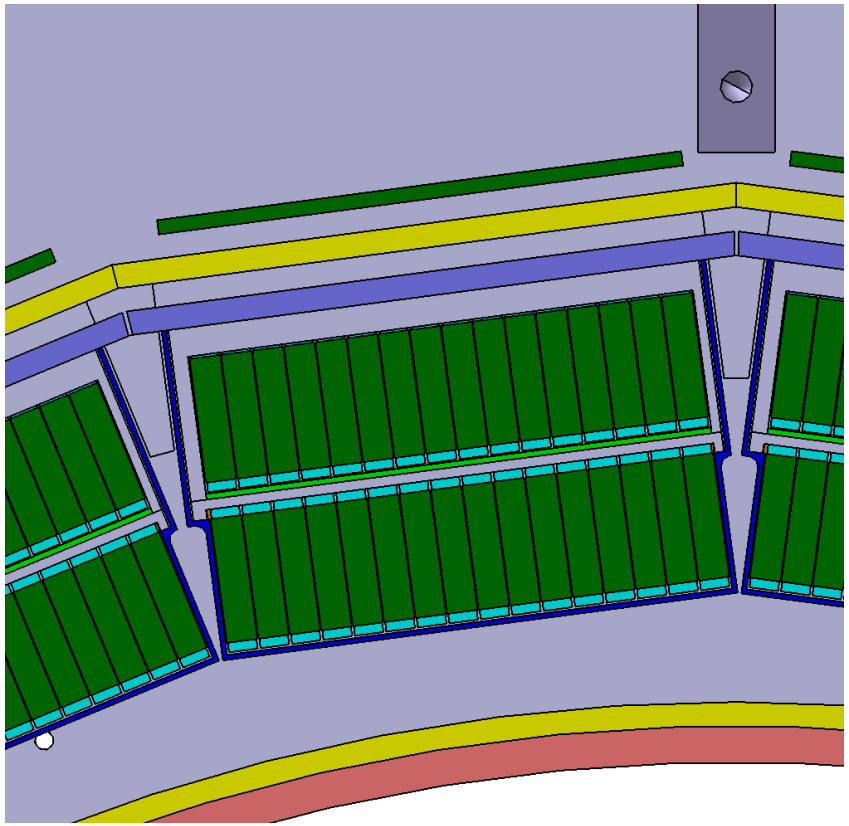




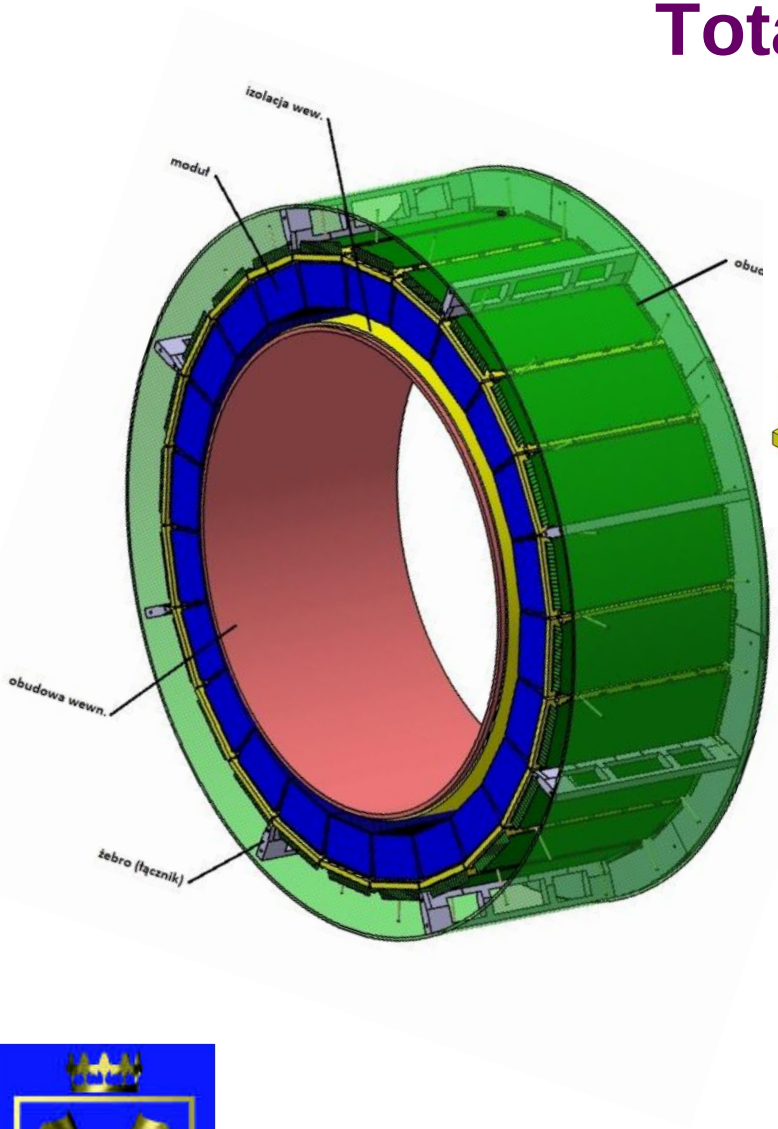
Pawel Moskal, Jagiellonian University

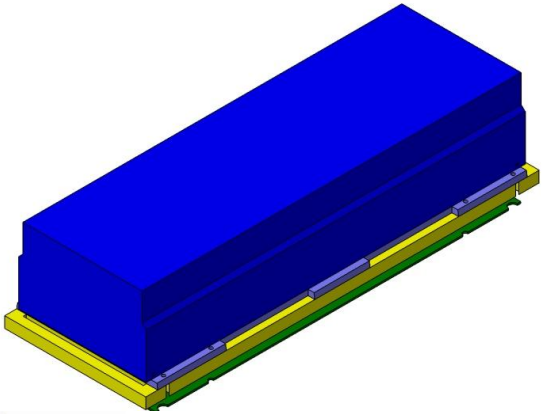
Total body J-PET

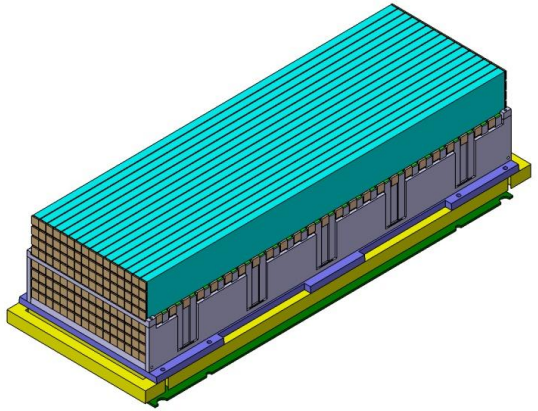


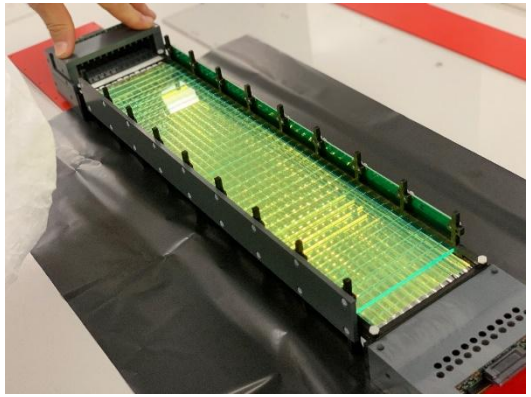


Total body J-PET

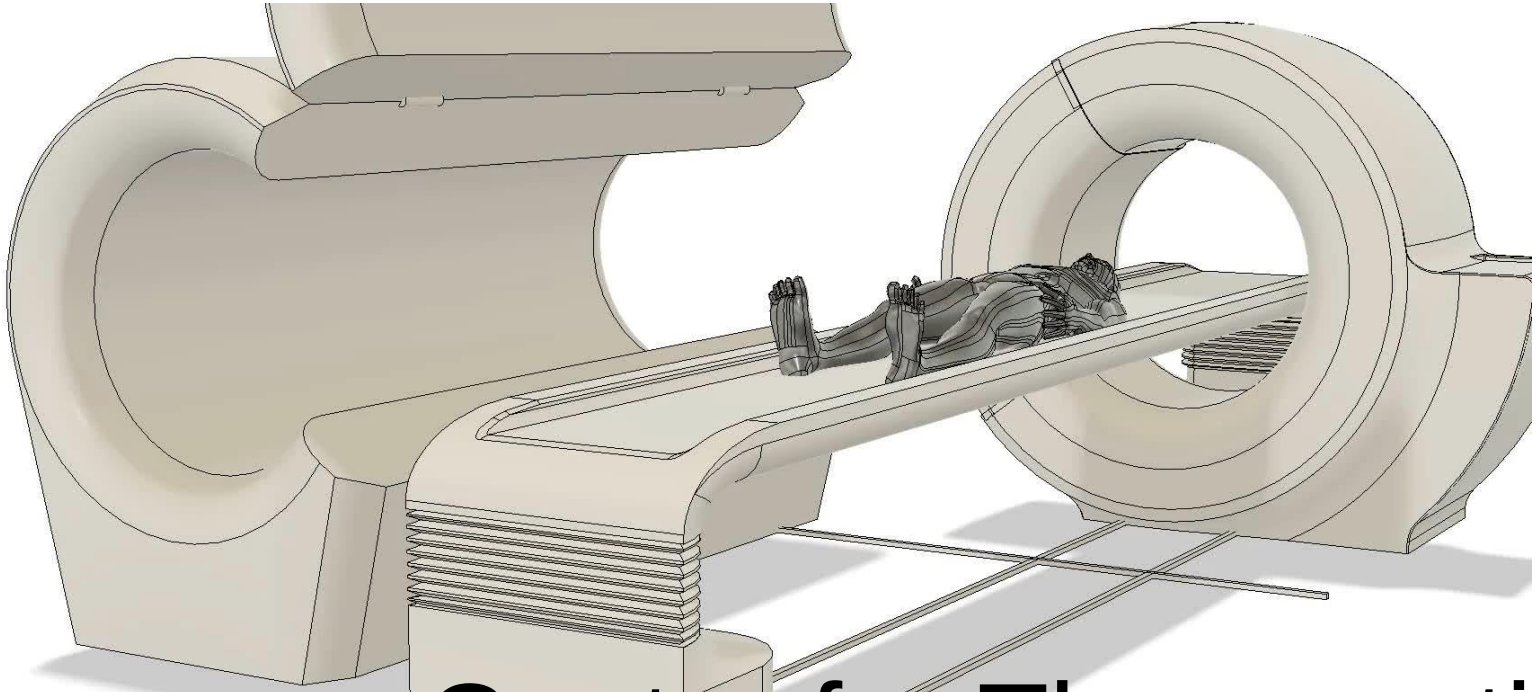




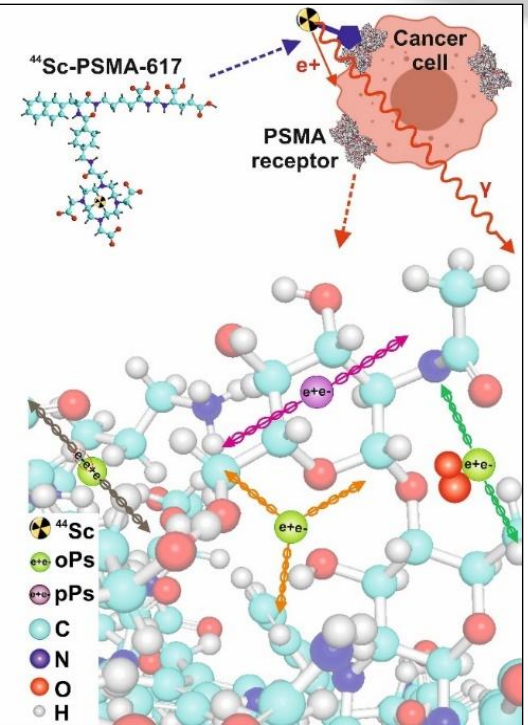




Pawel Moskal, Jagiellonian University

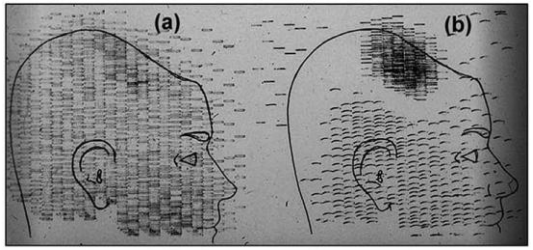


Center for Theranostics
Jagiellonian University



1932
Positron
C.D. Anderson

1953
Positron imaging
Brain positron image
G. L. Brownell , W. H. Sweet



1970
PET
M. Phelps
E. J. Hoffman
N. A. Mullani
M. Ter-Pogossian

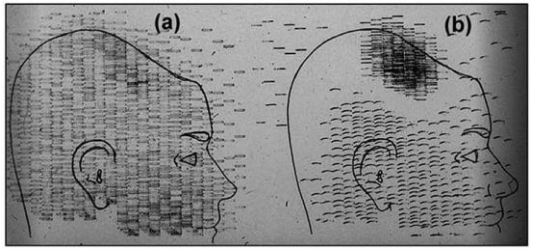
1991
PET/CT
D. Townsend

2019
Total-Body PET
S. Cherry, R. Badawi

POSITRON in MEDICINE

1932
Positron
C.D. Anderson

1953
Positron imaging
Brain positron image
G. L. Brownell , W. H. Sweet



1970
PET
M. Phelps
E. J. Hoffman
N. A. Mullani
M. Ter-Pogossian

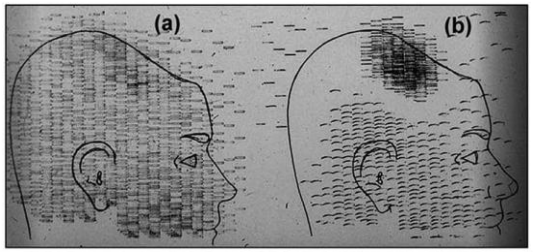
1991
PET/CT
D. Townsend

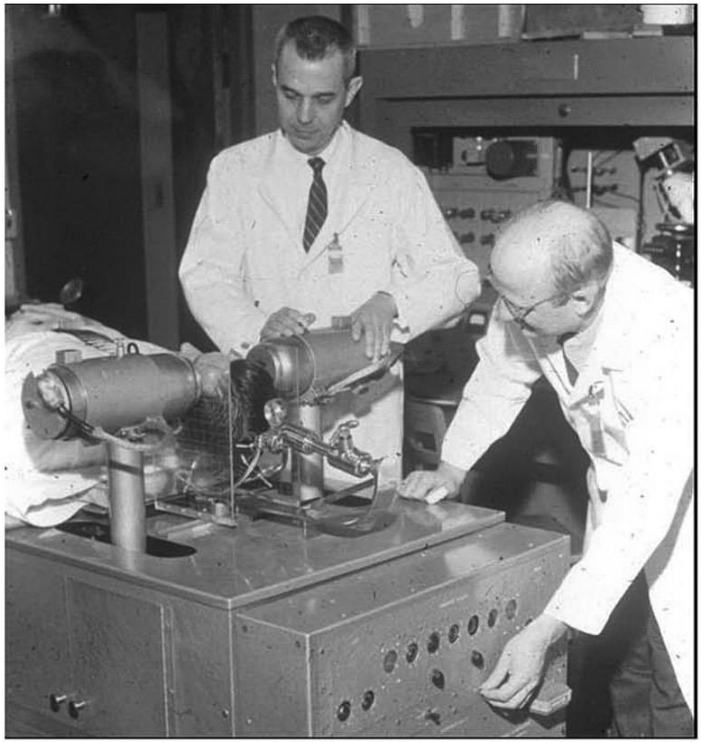
2019
Total-Body PET
S. Cherry, R. Badawi

POSITRON in MEDICINE

1932
Positron
C.D. Anderson

1953
Positron imaging
Brain positron image
G. L. Brownell , W. H. Sweet





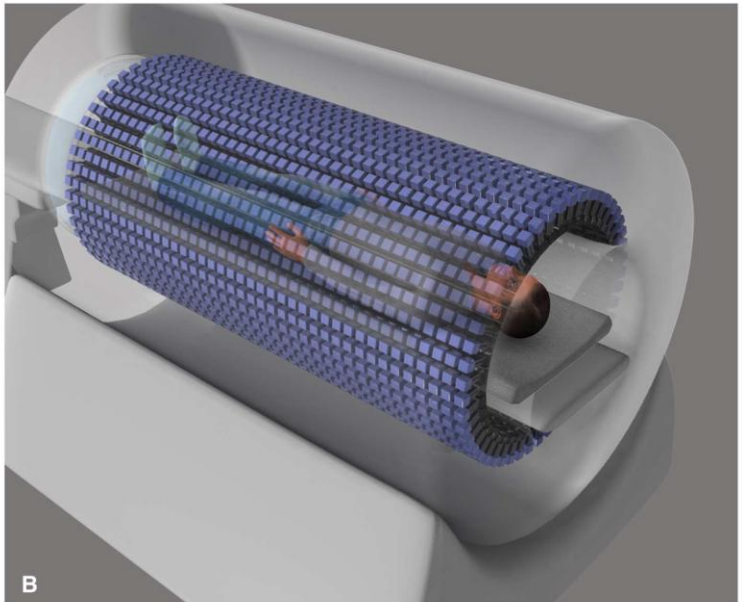
2 detectors

1970
PET
M. Phelps
E. J. Hoffman
N. A. Mullani
M. Ter-Pogossian

1991
PET/CT
D. Townsend

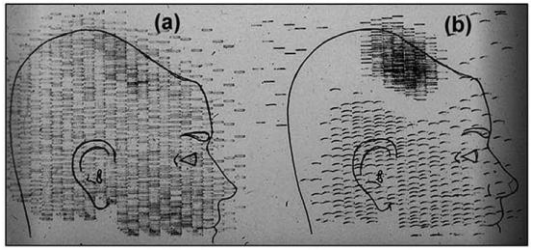
2019
Total-Body PET
S. Cherry, R. Badawi

560 000 detectors



1932
Positron
C.D. Anderson

1953
Positron imaging
Brain positron image
G. L. Brownell , W. H. Sweet



1970
PET
M. Phelps
E. J. Hoffman
N. A. Mullani
M. Ter-Pogossian

1991
PET/CT
D. Townsend

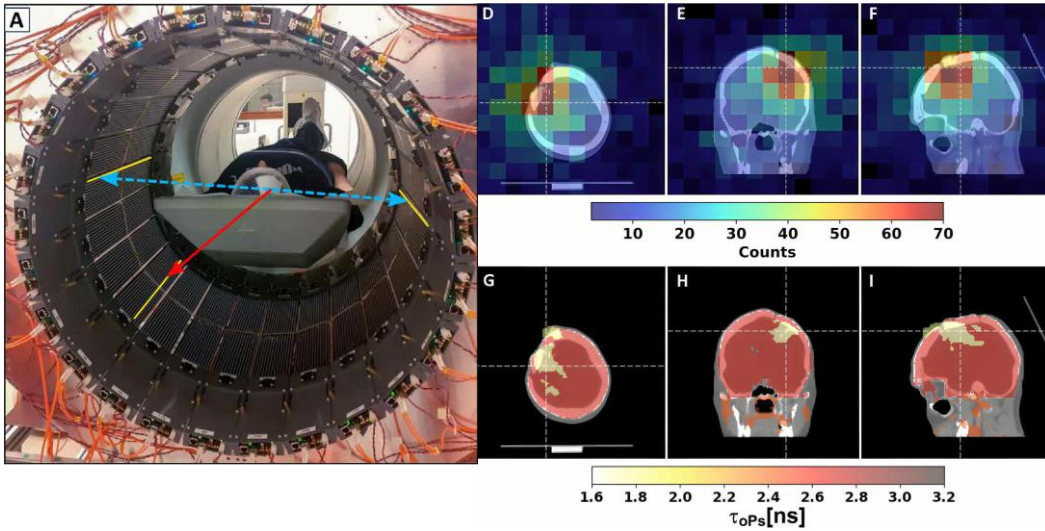
2019
Total-Body PET
S. Cherry, R. Badawi

0 min 0 sec

1951
Positronium
M. Deutch

2024
Positronium imaging
Brain positronium image

POSITRONIUM in MEDICINE



PET from PLASTIC SCINTILLATORS

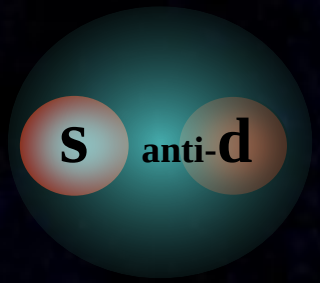
POSITRONIUM IMAGING

DISCRETE SYMMETRIES

QUANTUM ENTANGLEMENT IMAGING

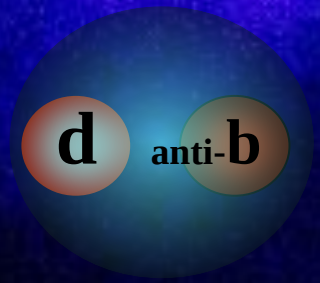
P. Moskal, Jagiellonian University
http://koza.if.uj.edu.pl

Violation of CP and T
confirmed experimentally
for hadrons only



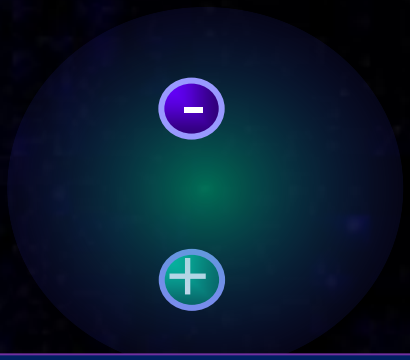
meson K

1964



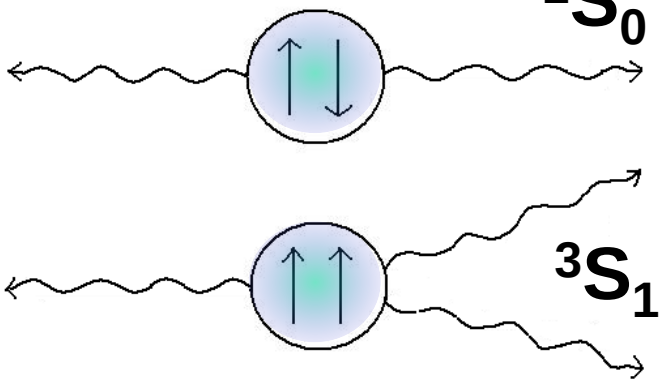
meson B

2012



positronium

?



$^1S_0$ **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	-	+

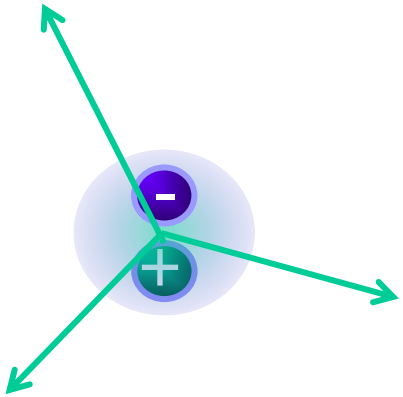
S = 0 $\downarrow\uparrow - \uparrow\downarrow$

$\uparrow\uparrow$

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

$\downarrow\downarrow$

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



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

6 OOM of
unexplored precision

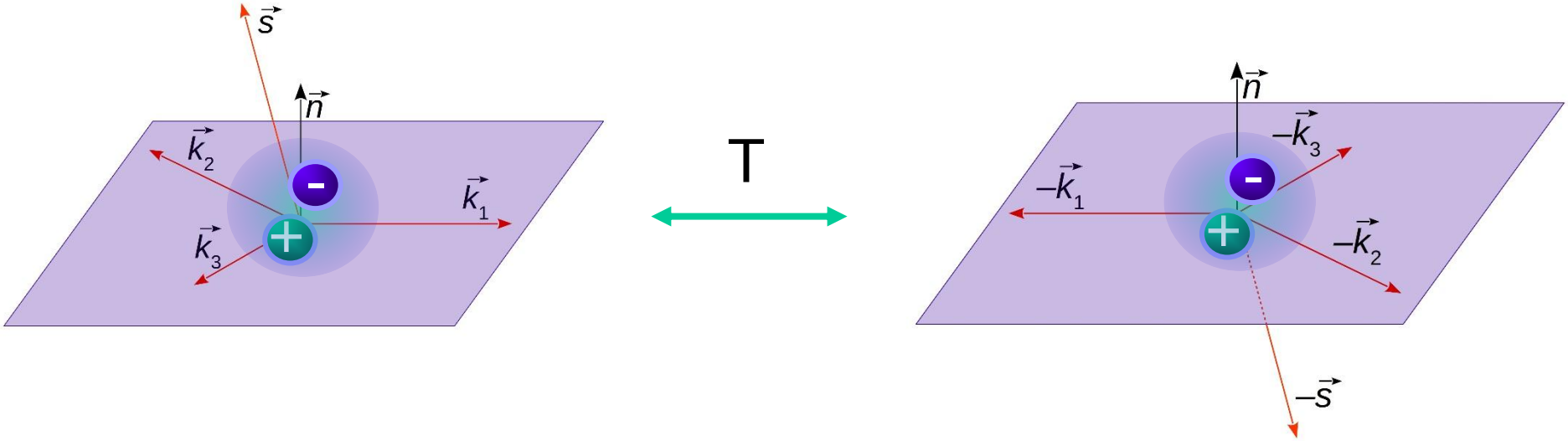
Physical sensitivity limit:
false asymmetries from
$\gamma\gamma$ interactions in the final state

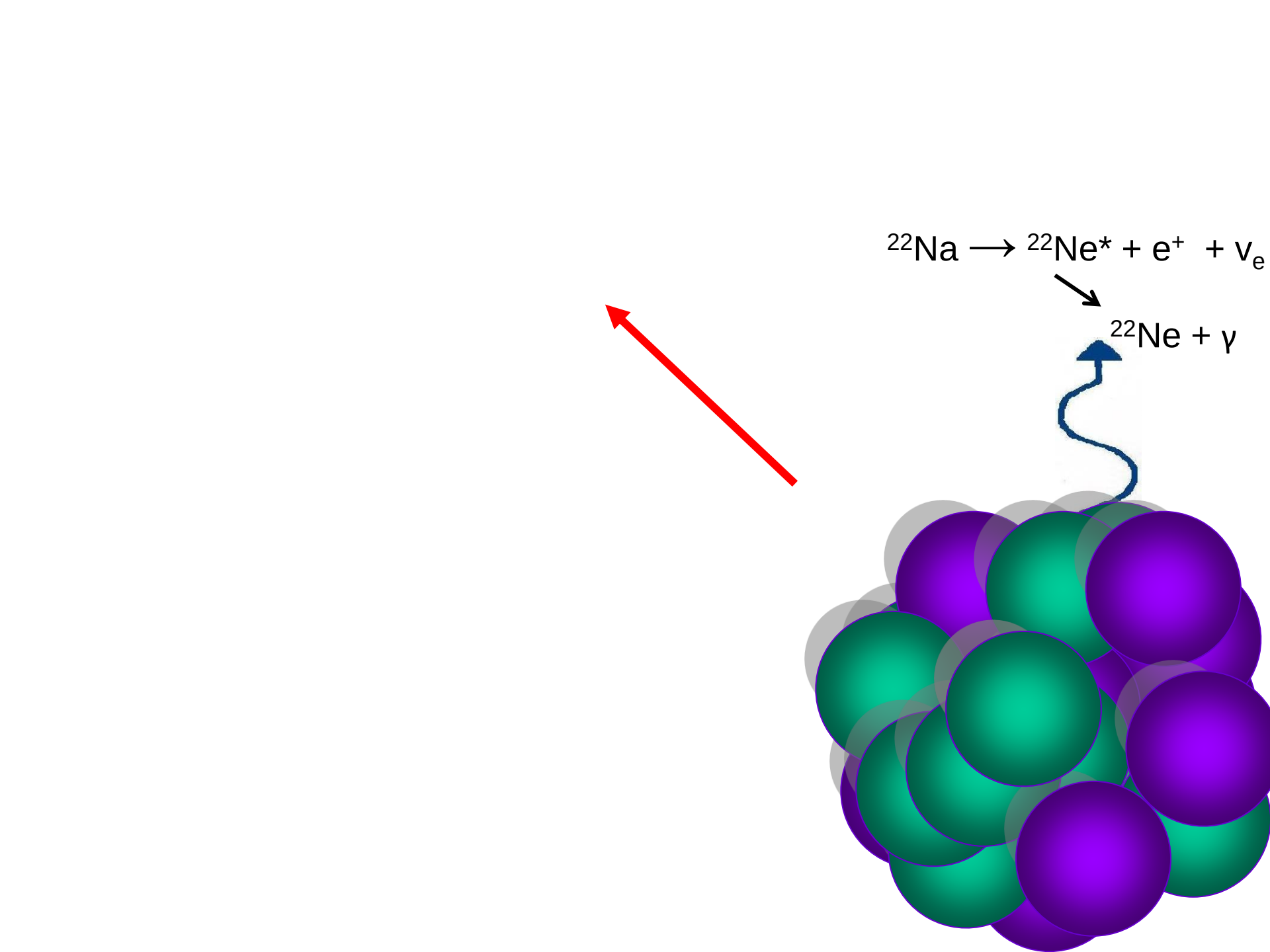
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-9} precision

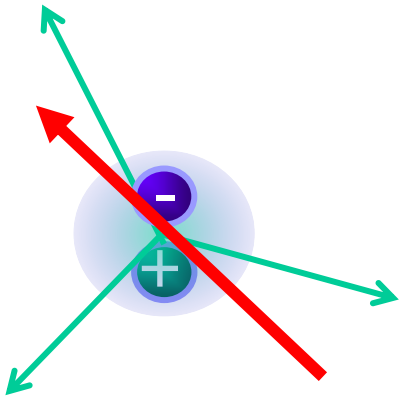
$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$
PRL. 91 (2003) 263401

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

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

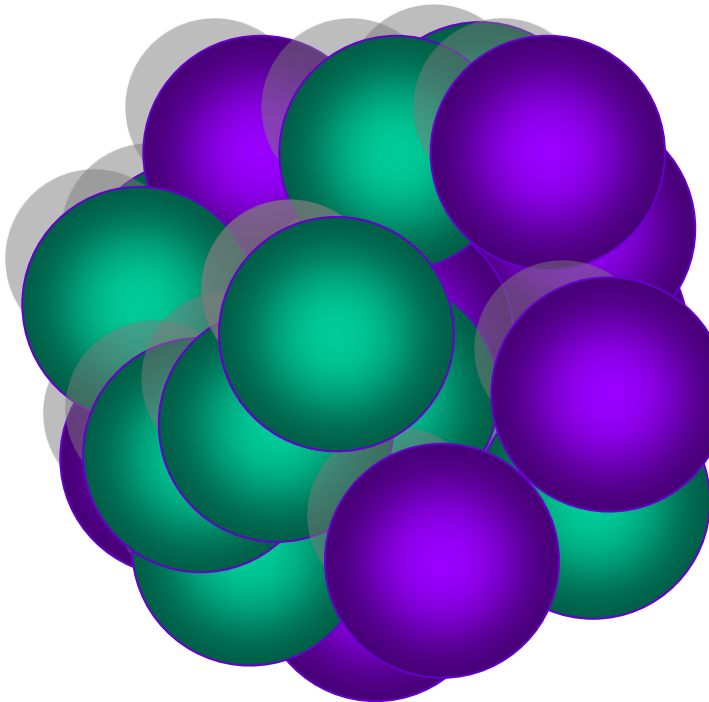



$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$
$^{22}Ne + \gamma$

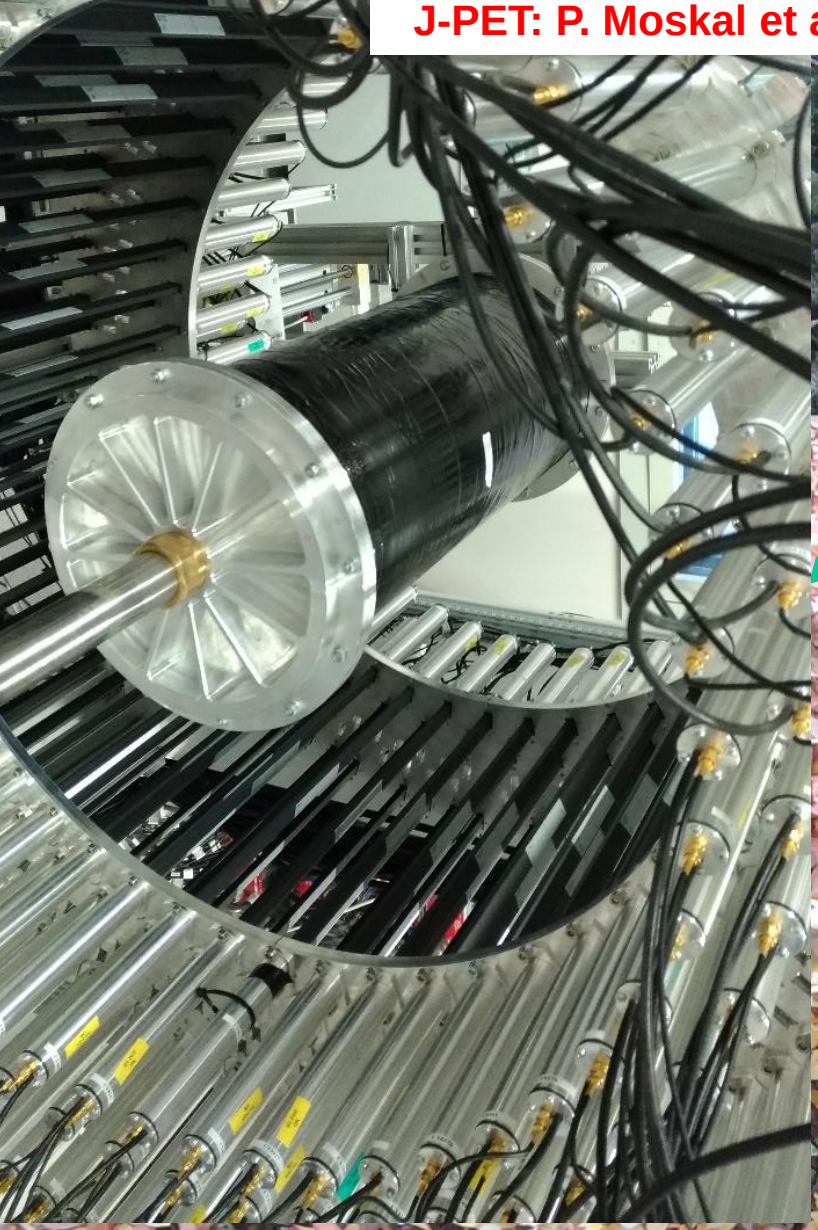


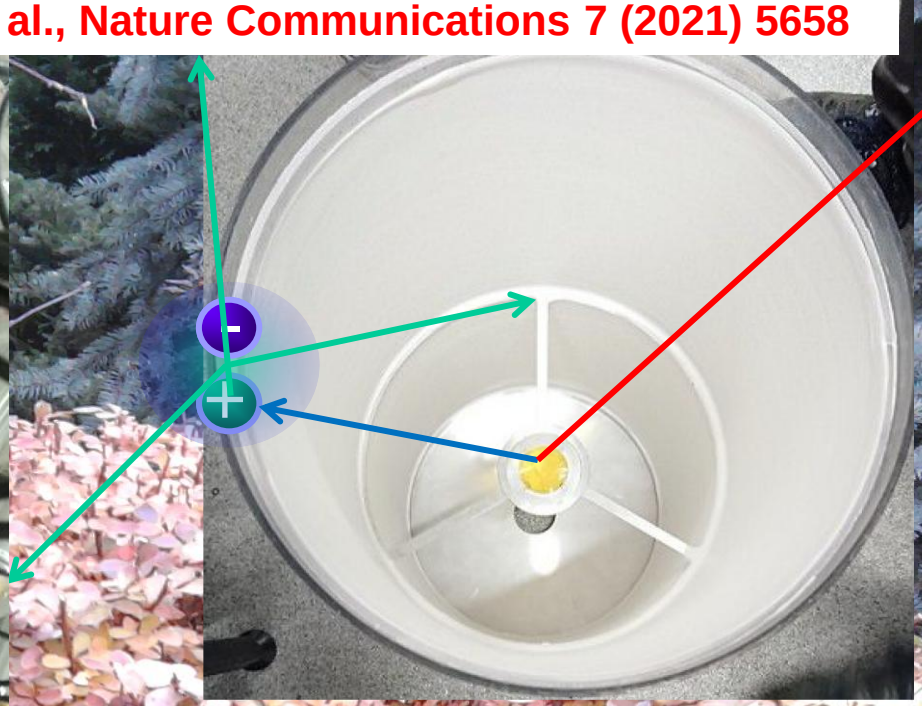
$$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$$

$$^{22}Ne^{*} \searrow {}^{22}Ne + \gamma$$

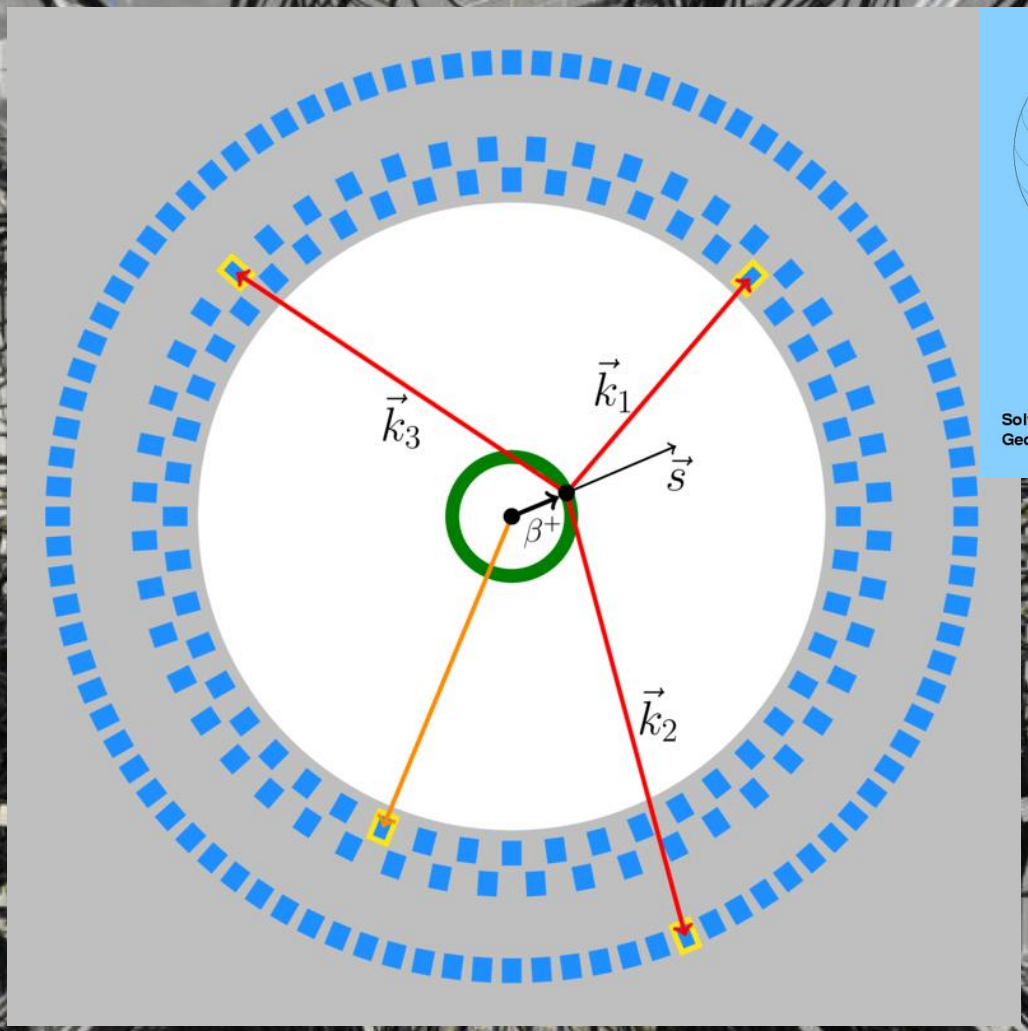


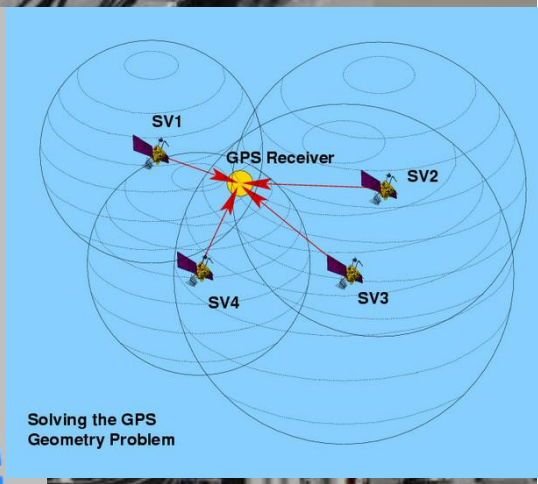
J-PET: P. Moskal et al., Nature Communications 7 (2021) 5658





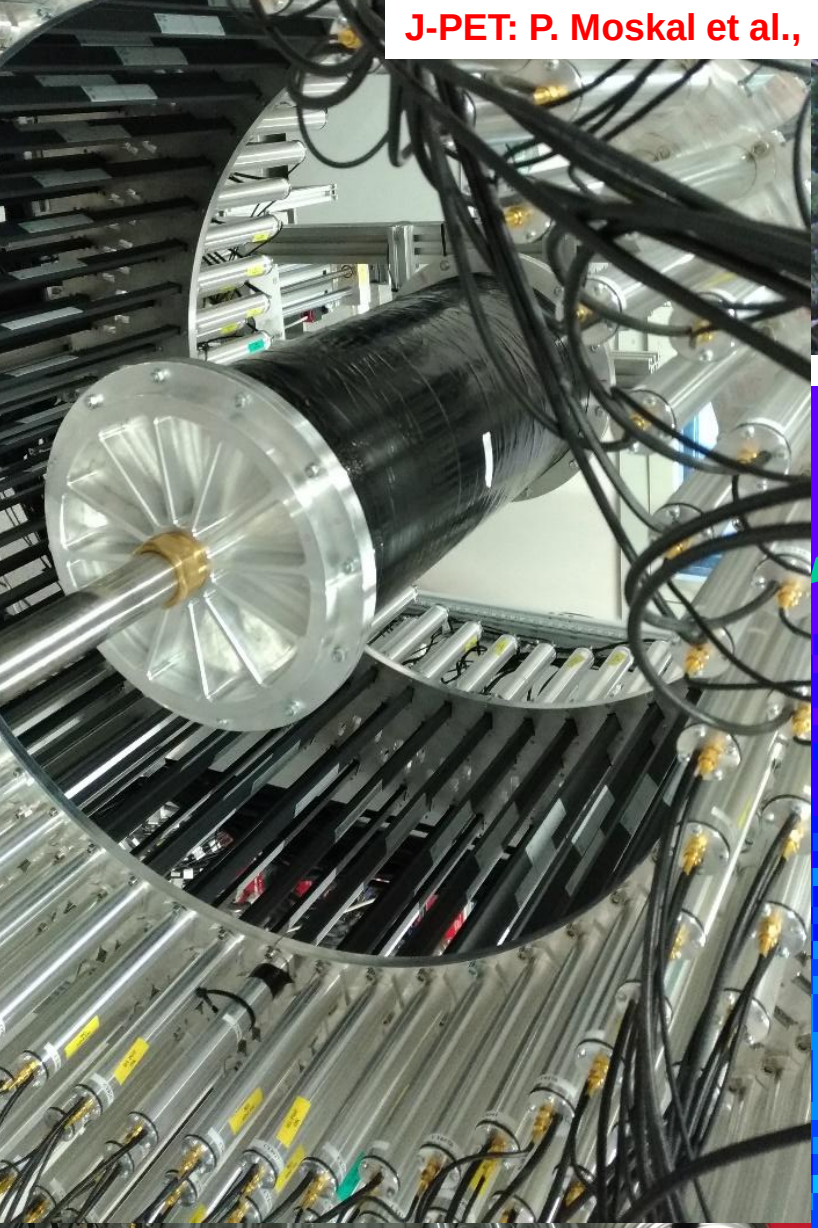
Jagiellonian PET

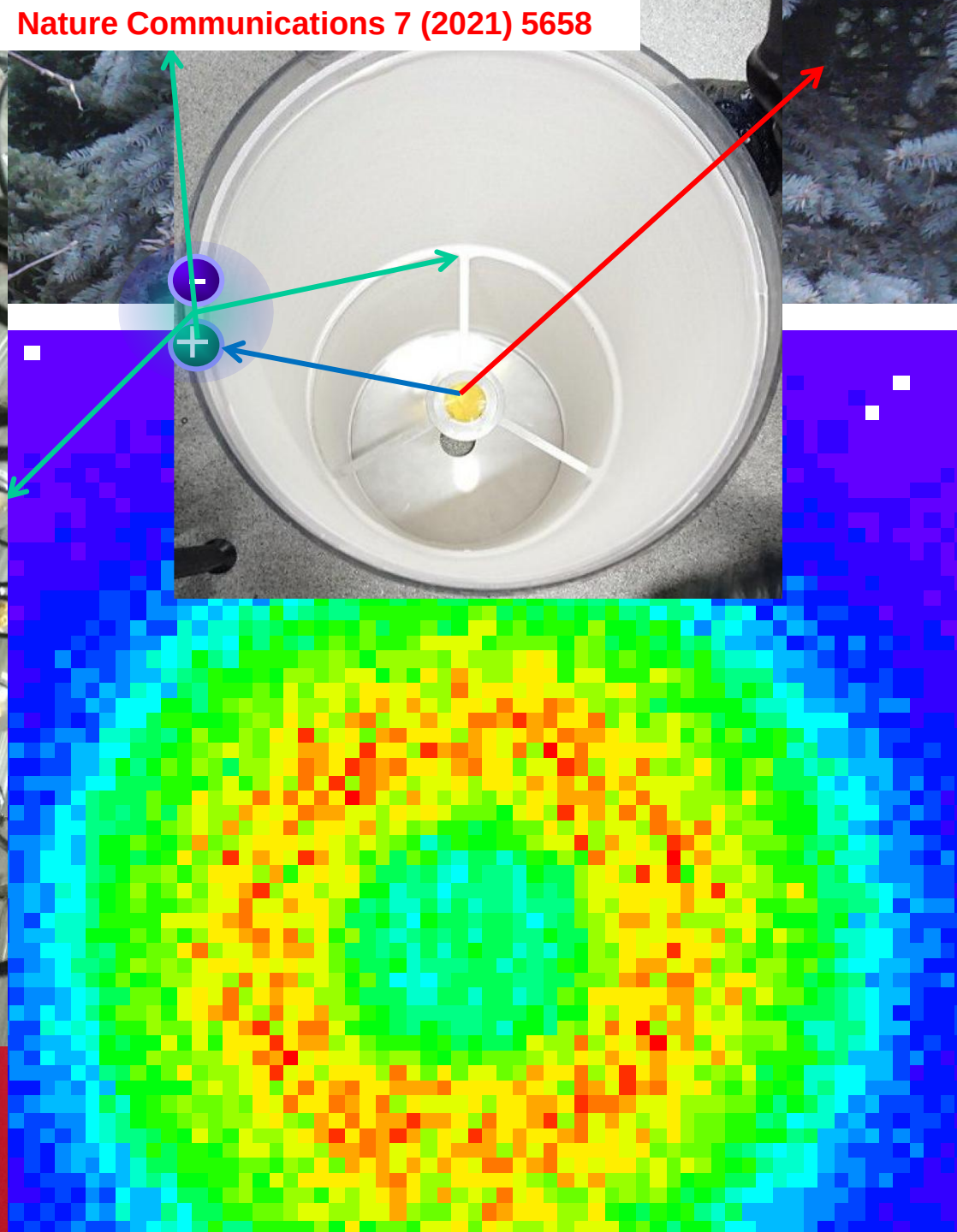




P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509

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

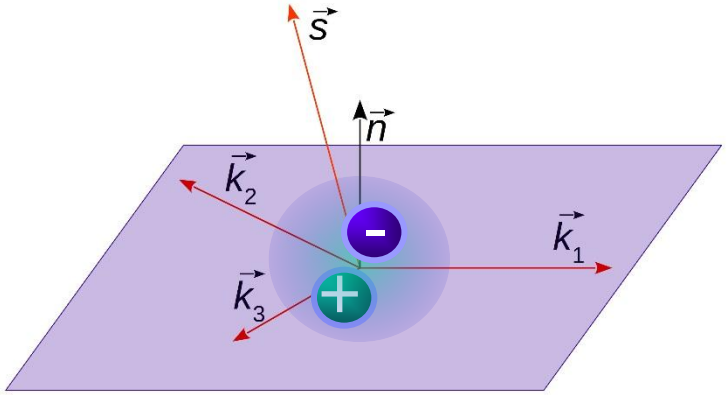




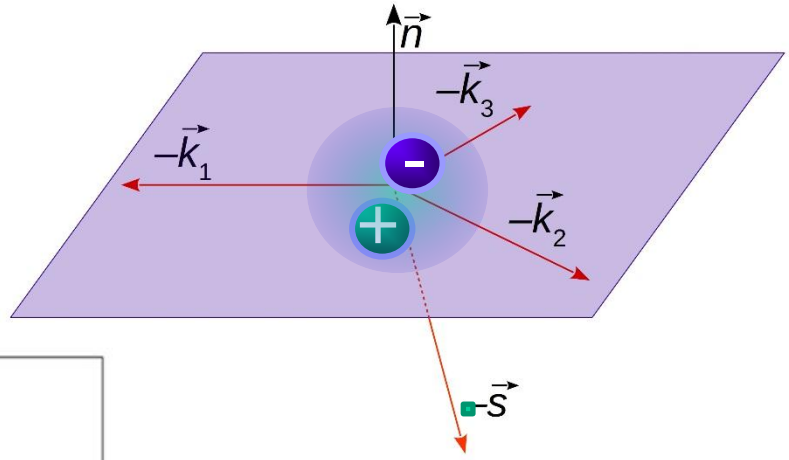
Operator	C	P	T	CP	CPT
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	–	+	–

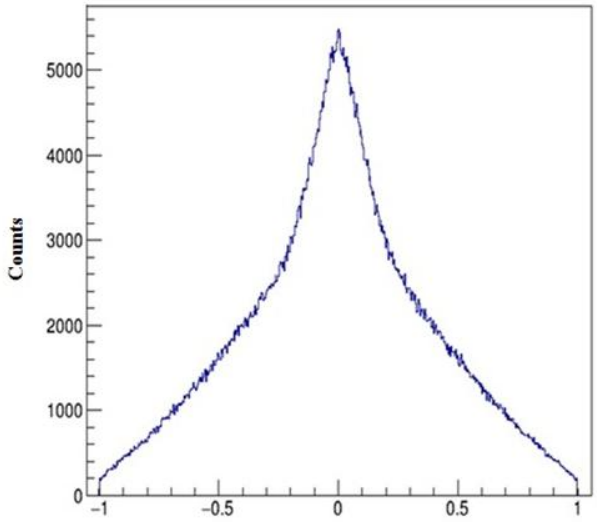
$|k_1| > |k_2| > |k_3|$

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

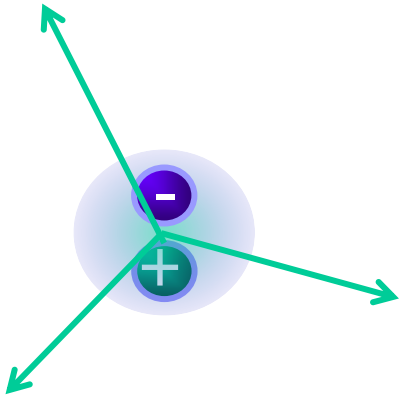


T, CPT





+- 0.00095



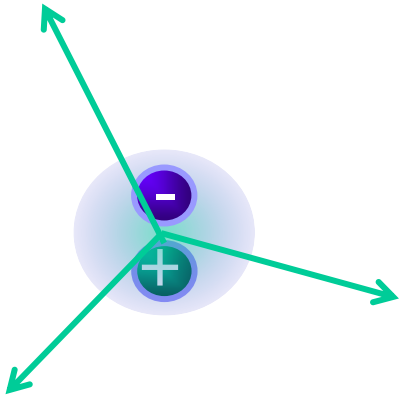
$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$
PRL 104 (2010) 083401

6 OOM of
unexplored precision

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

10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-9} precision

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



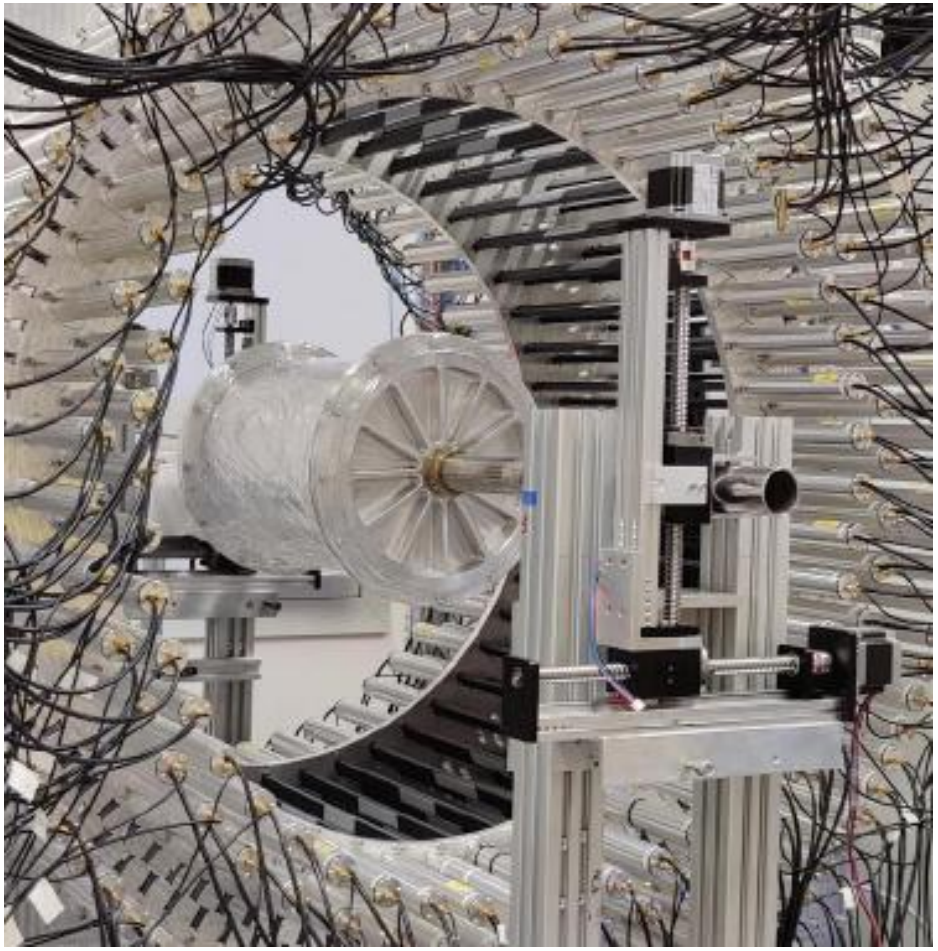
$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$
PRL 104 (2010) 083401

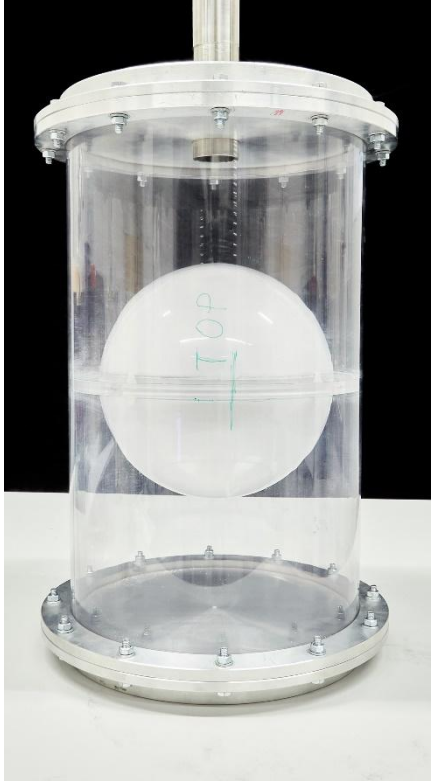
6 OOM of
unexplored precision

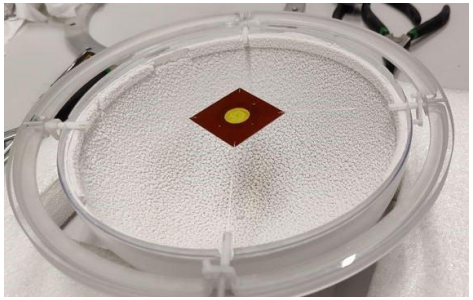
Physical sensitivity limit:
false asymmetries from
$\gamma\gamma$ interactions in the final state

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

J-PET



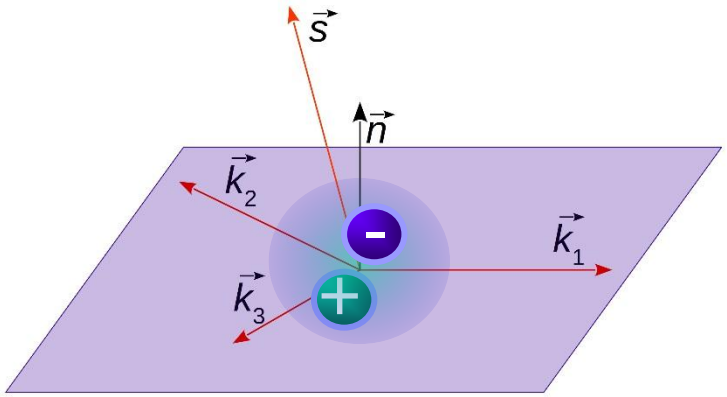




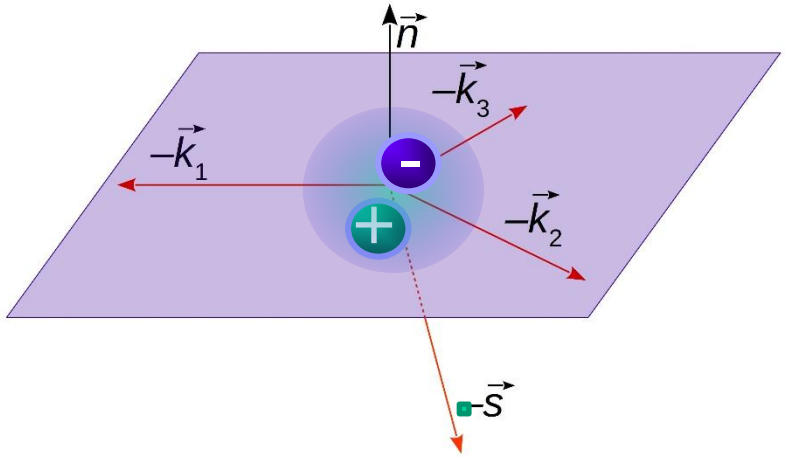
B. Jasińska,
M. Gorgol,
R. Zaleski et al.,
UMCS
Lublin, Poland

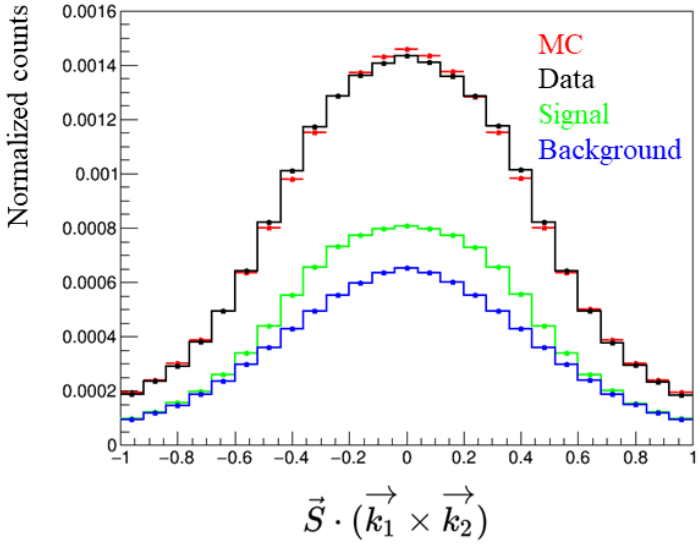
Operator	C	P	T	CP	CPT
$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$	+	+	–	+	–

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



T, CPT

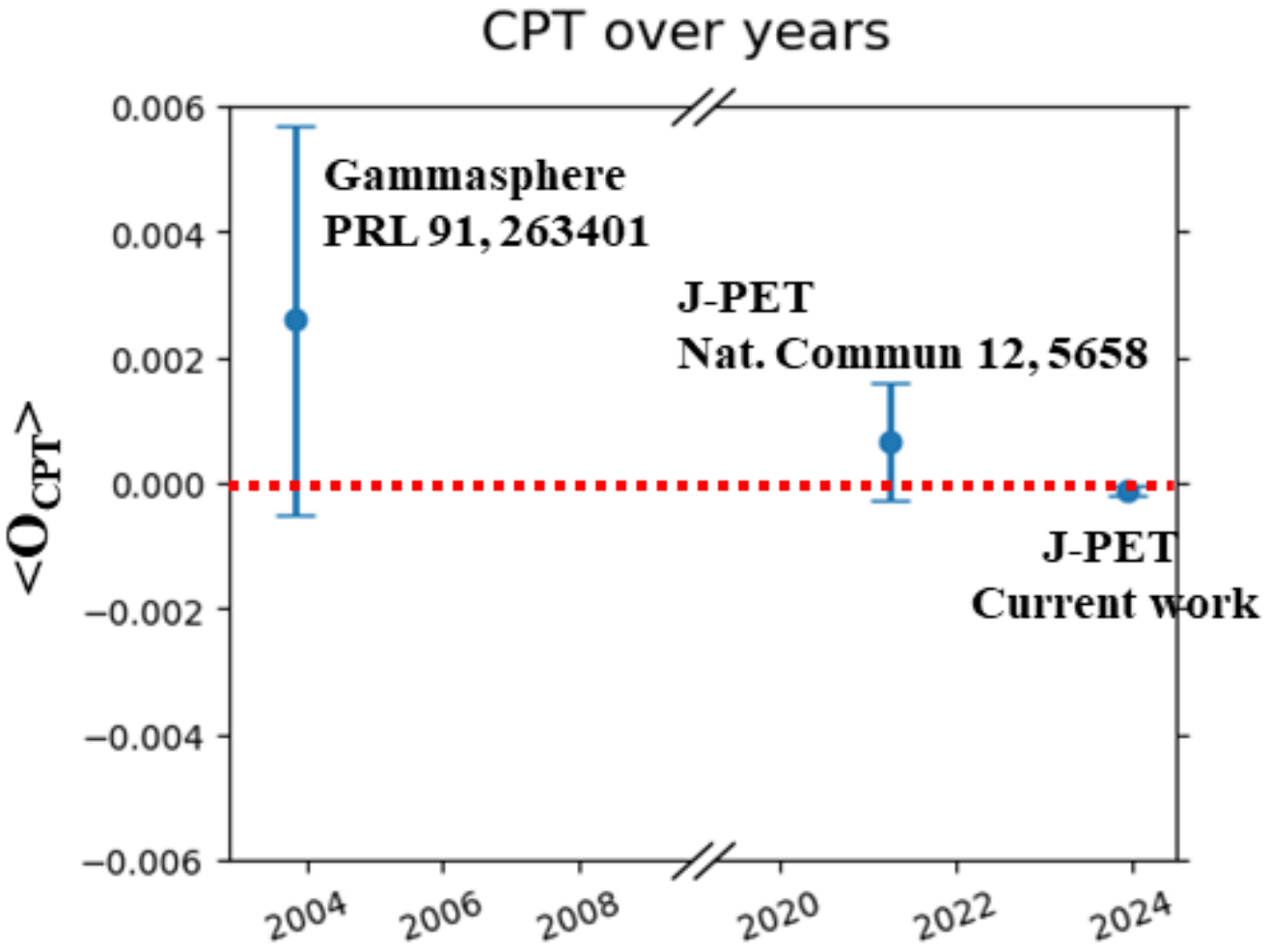


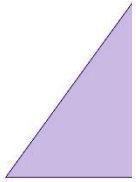


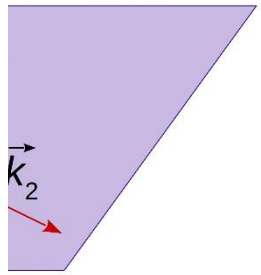
+- 0.0002

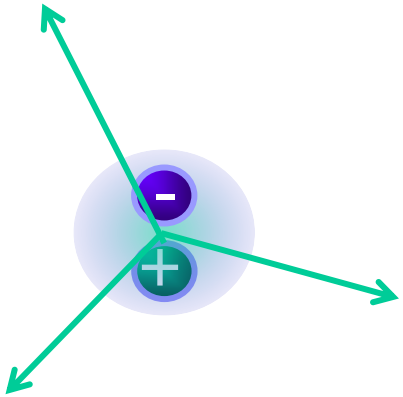
Operator	C	P	T	CP	CPT
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	–	+	–

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









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

6 OOM of
unexplored precision

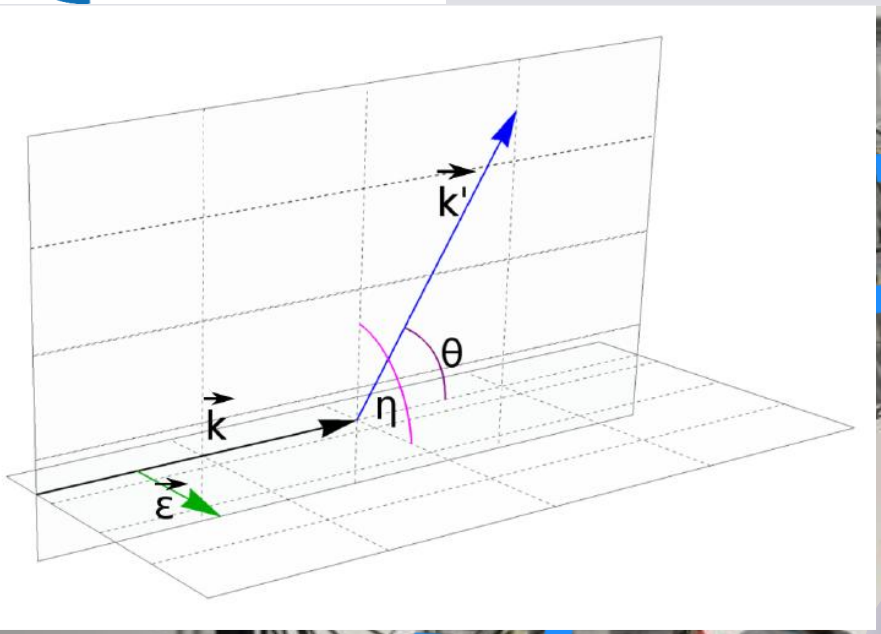
Physical sensitivity limit:
false asymmetries from
$\gamma\gamma$ interactions in the final state

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

J-PET

CPT

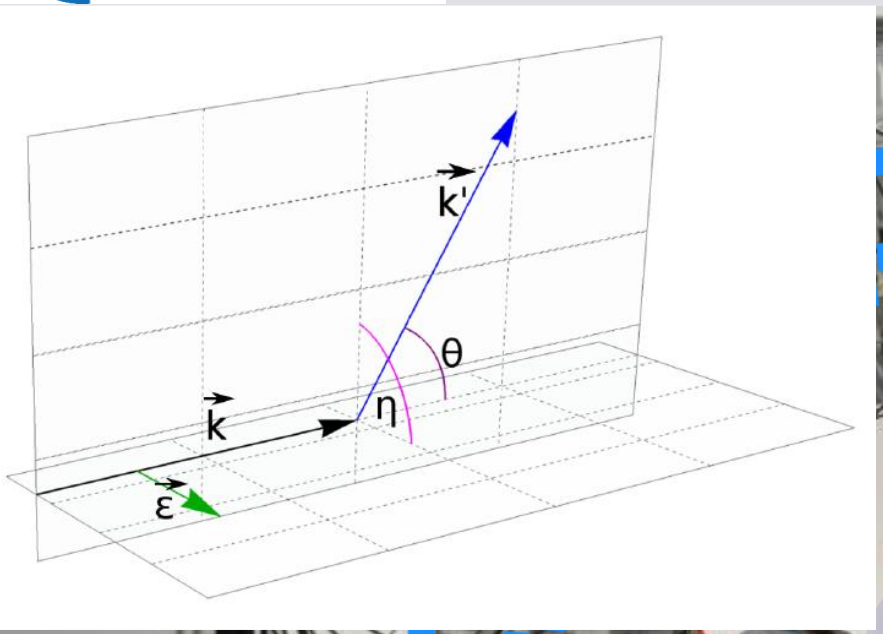
Jagiellonian PET



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

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

J-PET Jagiellonia



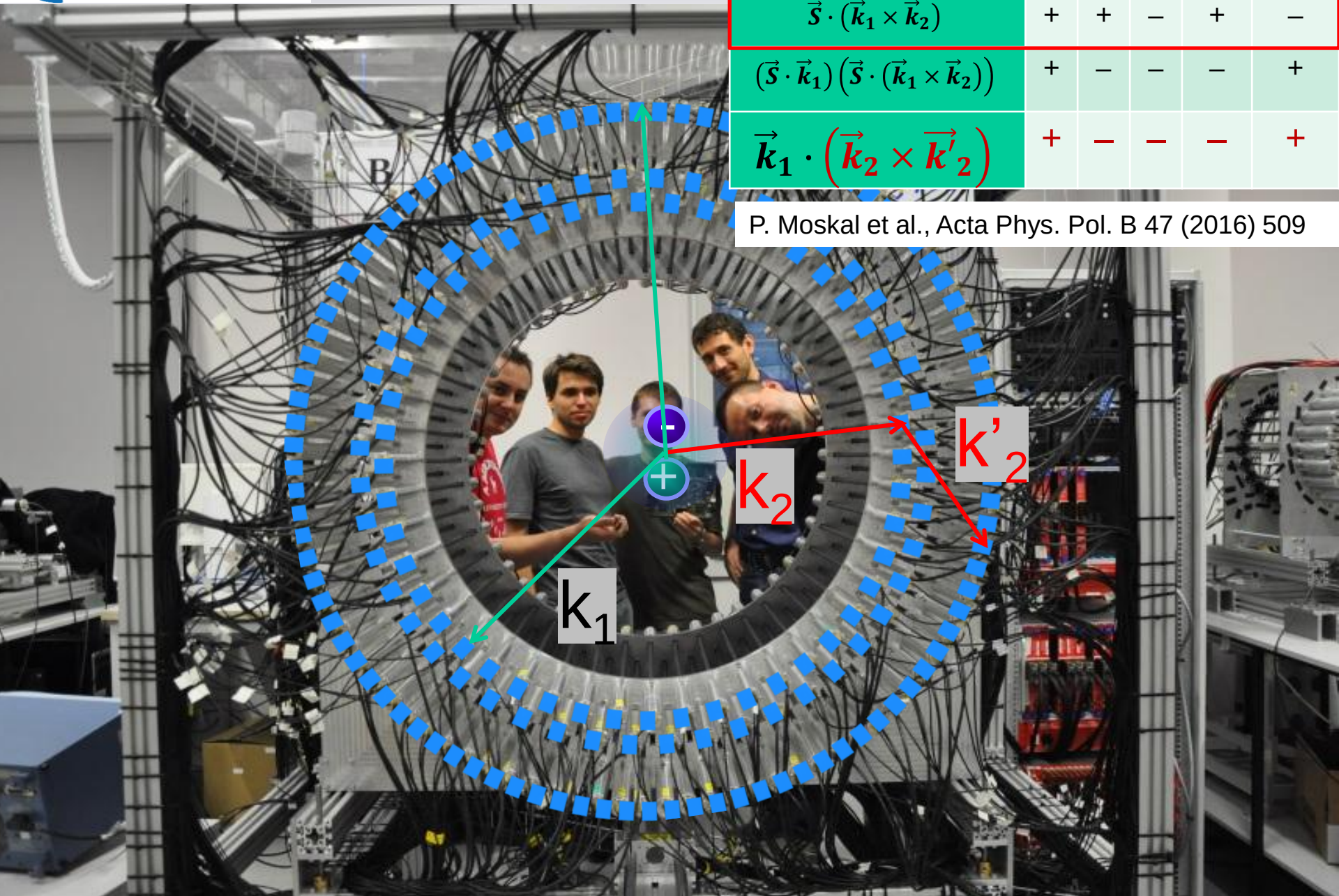
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)\left(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$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

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

J-PET Jagiellonia

Operator	C	P	T	CP	CPT
$\vec{s}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{s}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{s}\cdot\vec{k}_1)\left(\vec{s}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+
$\vec{k}_1\cdot\left(\vec{k}_2\times\vec{k'}_2\right)$	+	–	–	–	+

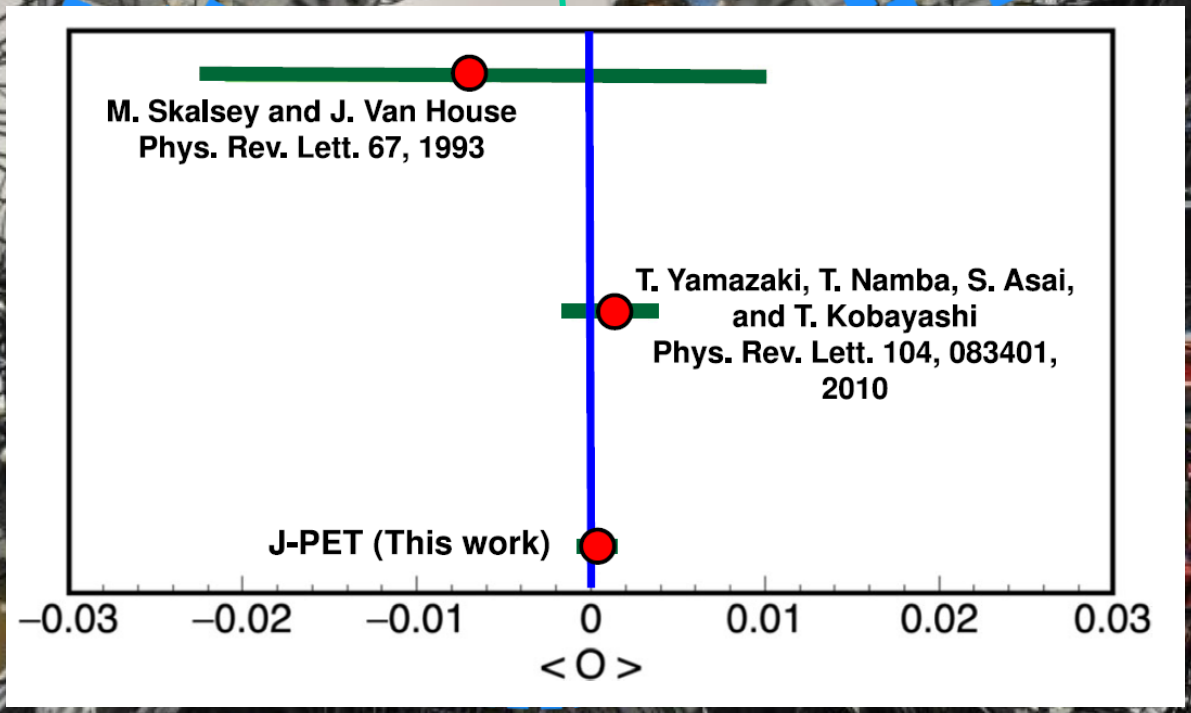
P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509



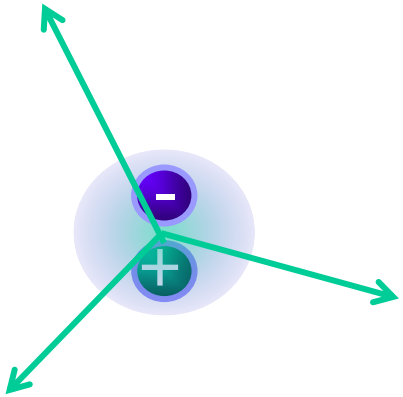
J-PET Jagiellonia

Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)\left(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\right)$	+	–	–	–	+
$\vec{k}_1\cdot\left(\vec{k}_2\times\vec{k'}_2\right)$	+	–	–	–	+

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



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



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

6 OOM of
unexplored precision

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

10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-9} precision

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

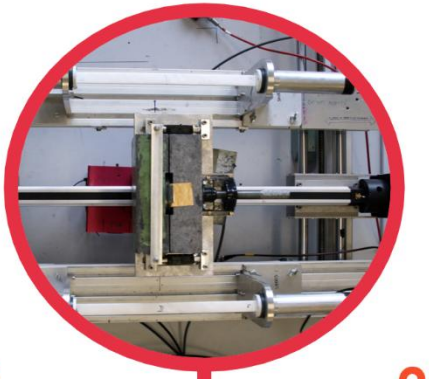
J-PET

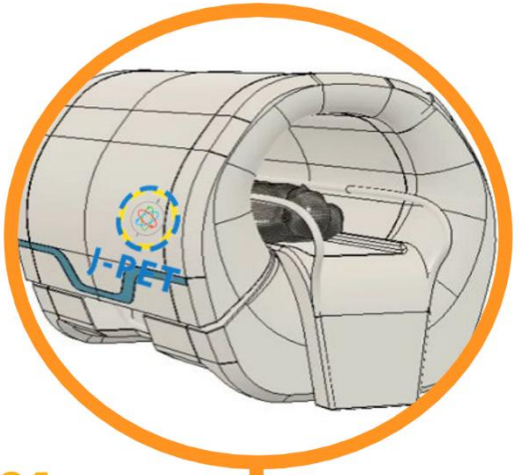
CP

J-PET

total-body J-PET

3-layer prototype





2009

2012

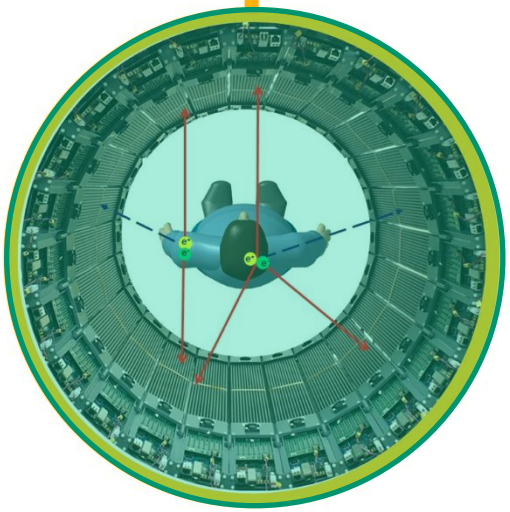
2014

2016

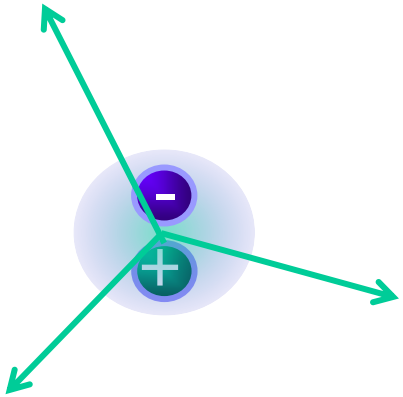
2021

2028

FIRST PATENT



modular J-PET



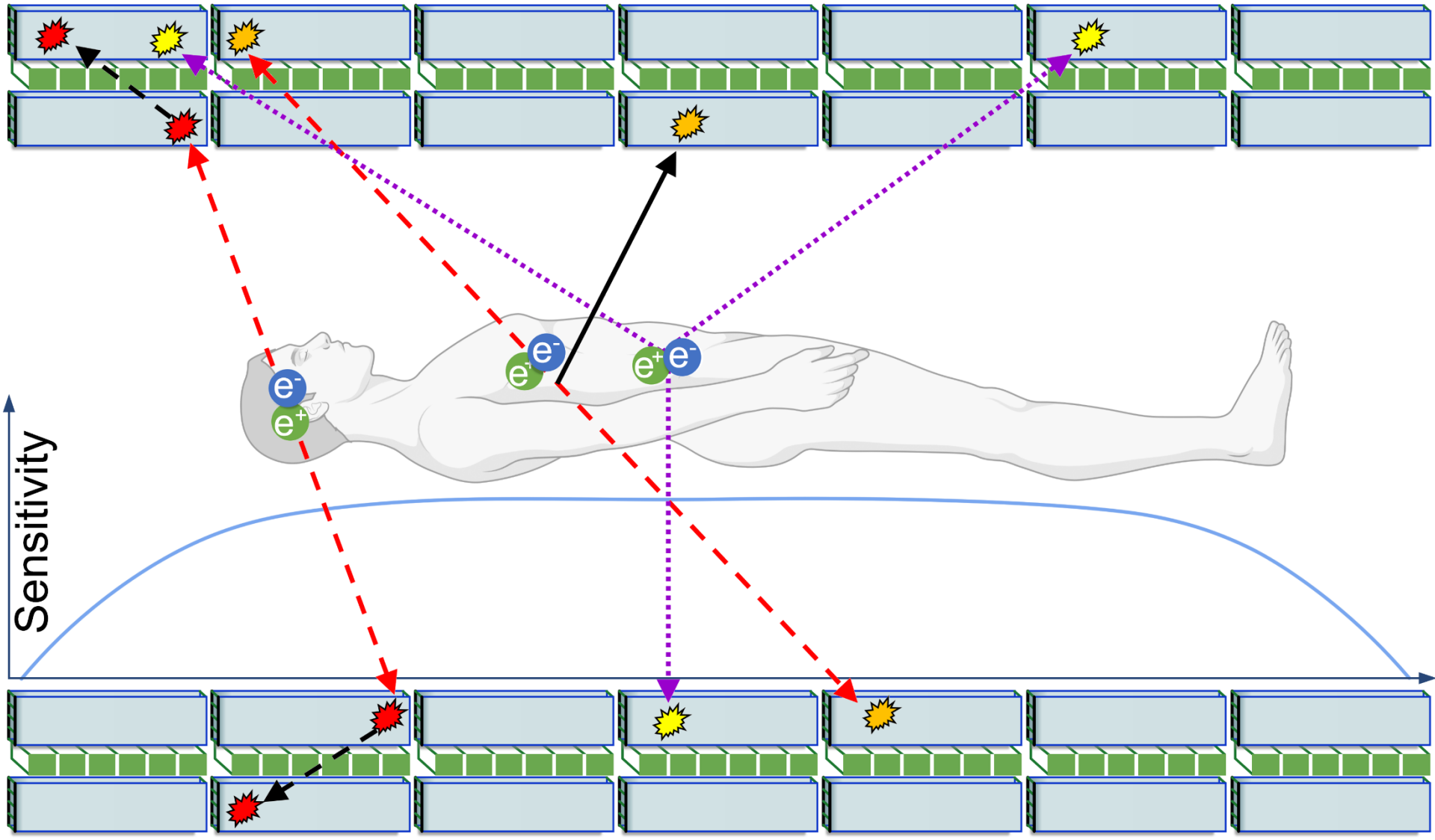
$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$
PRL 104 (2010) 083401

6 OOM of
unexplored precision

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

10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-9} precision

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

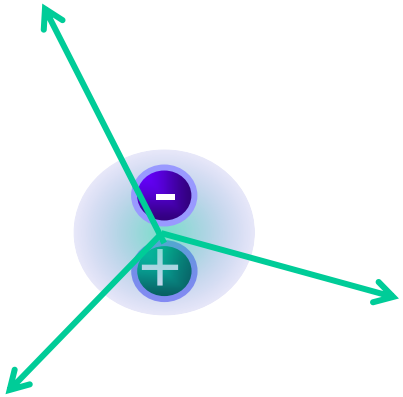


S. D. Bass, S. Mariazzi, P. Moskal, E. Stepien,

Rev. Mod. Phys. 95 (2023) 021002

CENTER FOR THERANOSTICS

Positronium physics and biomedical applications



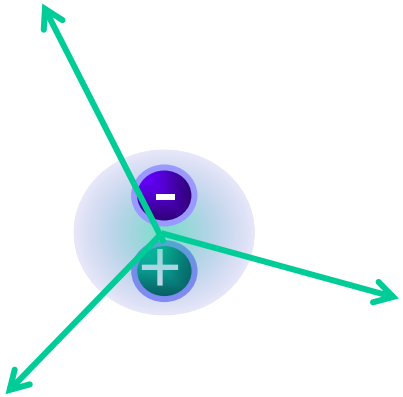
$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$
PRL 104 (2010) 083401

6 OOM of
unexplored precision

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

10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-9} precision

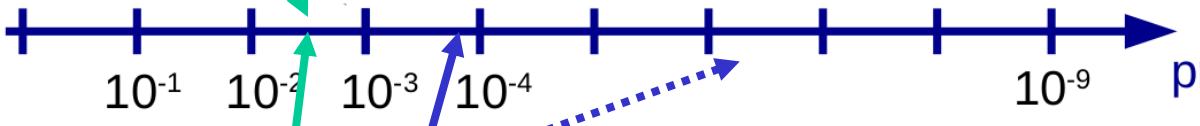
$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$
PRL. 91 (2003) 263401



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

PET from PLASTIC SCINTILLATORS

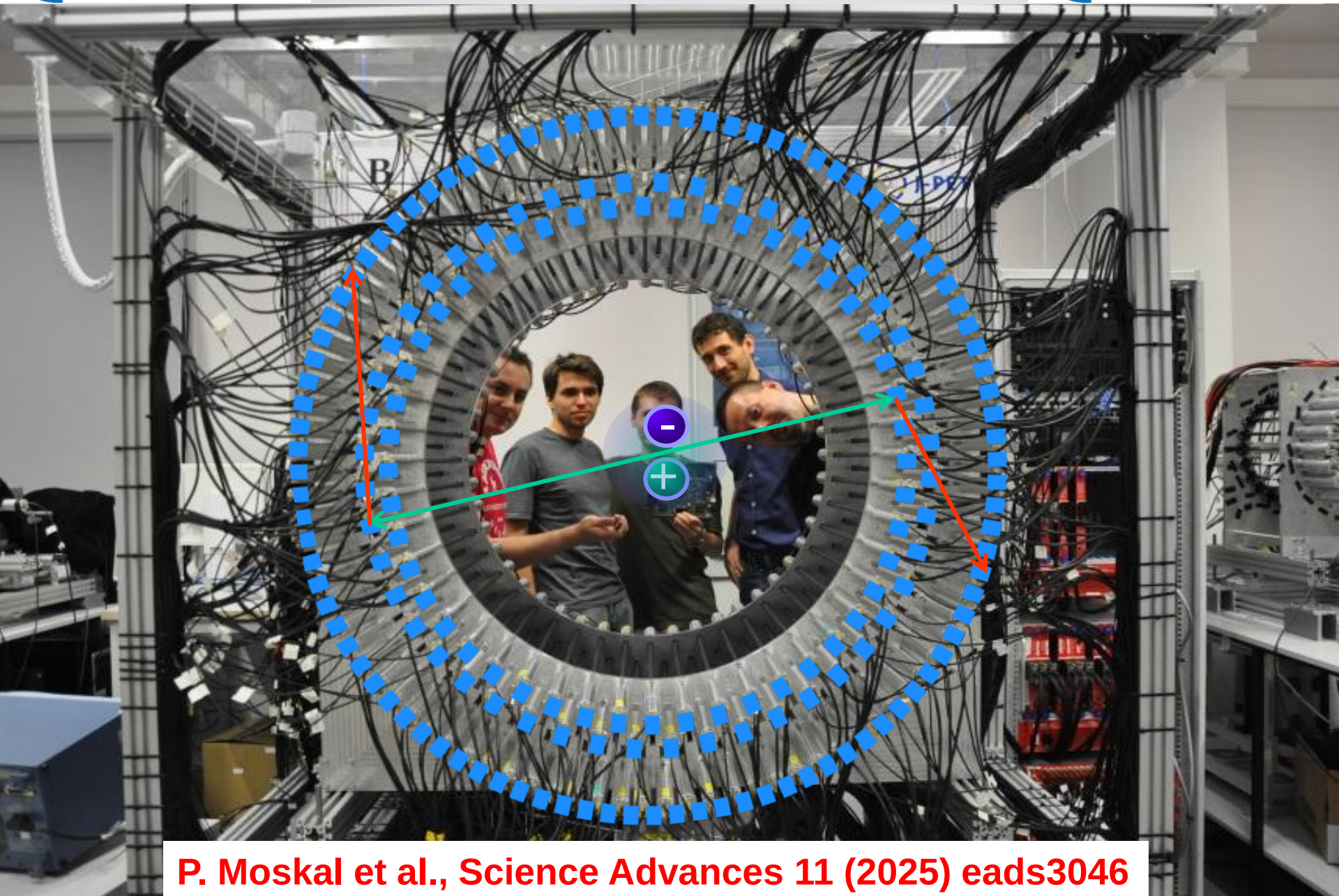
POSITRONIUM IMAGING

DISCRETE SYMMETRIES

QUANTUM ENTANGLEMENT IMAGING

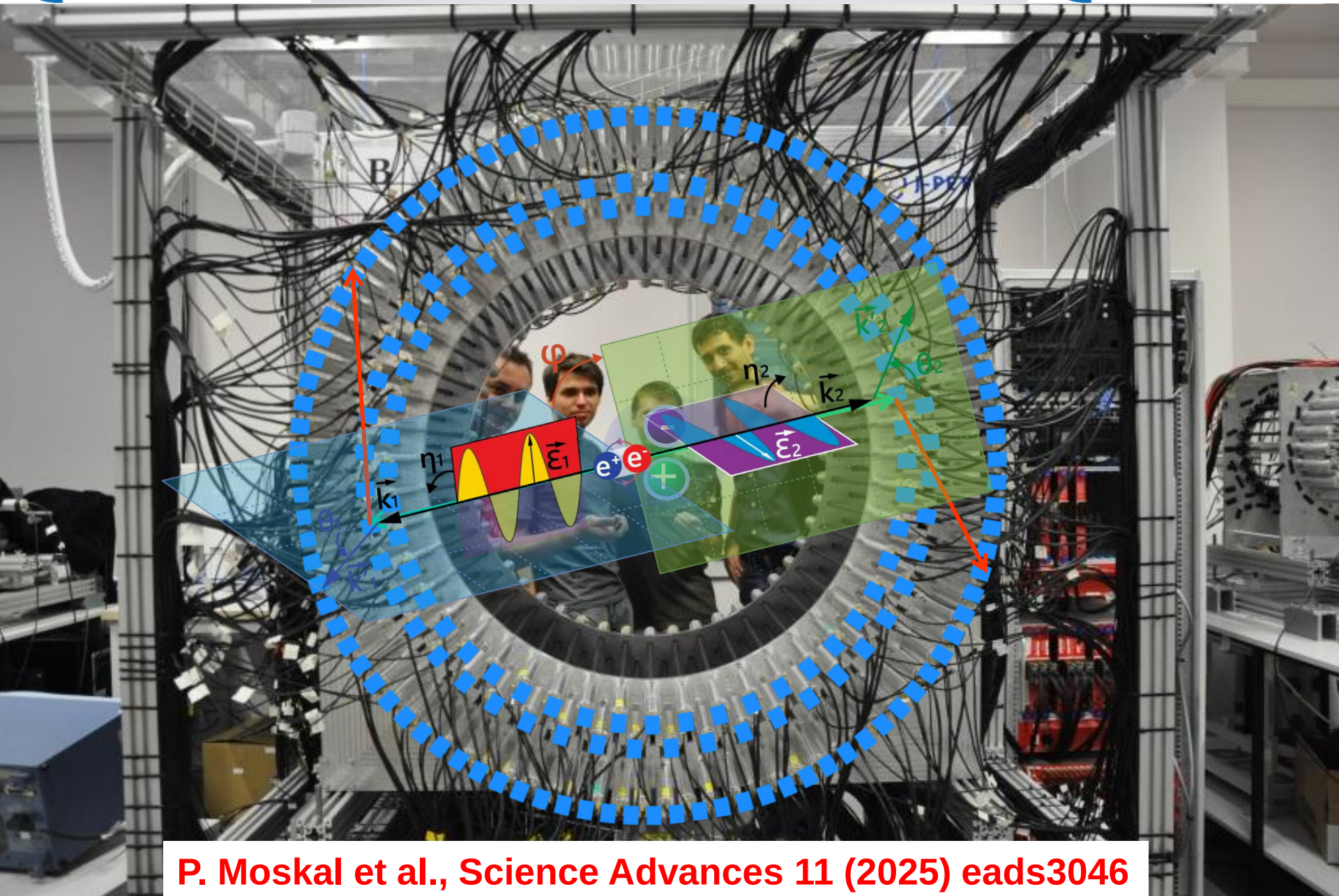
P. Moskal, Jagiellonian University
http://koza.if.uj.edu.pl

Jagiellonian PET

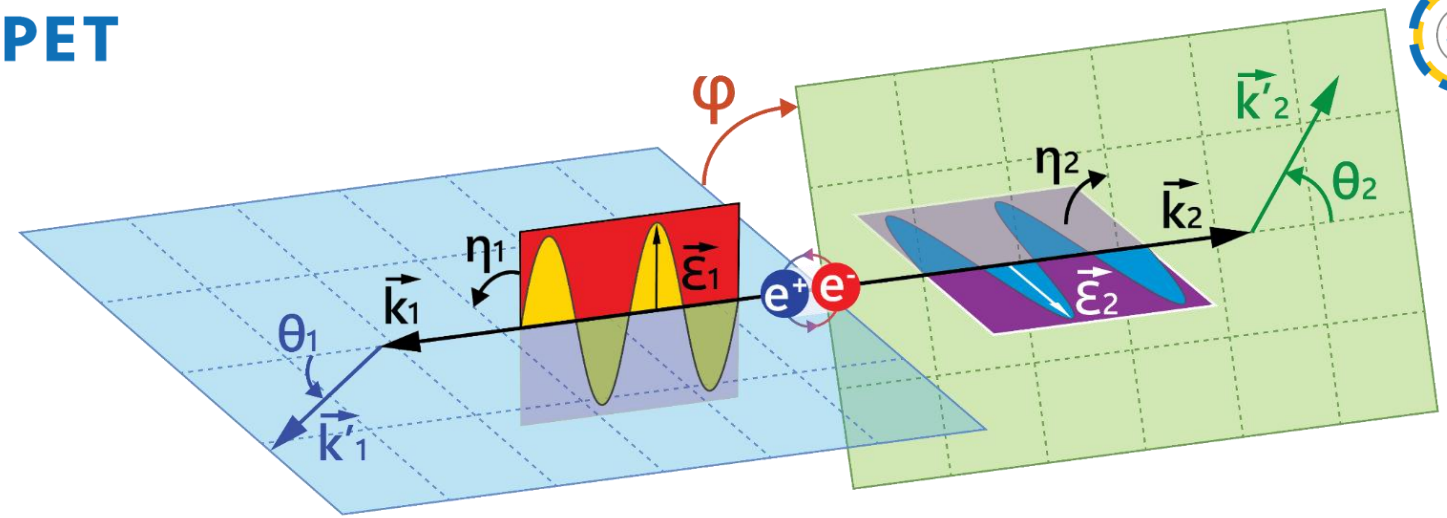


P. Moskal et al., Science Advances 11 (2025) eads3046

Jagiellonian PET

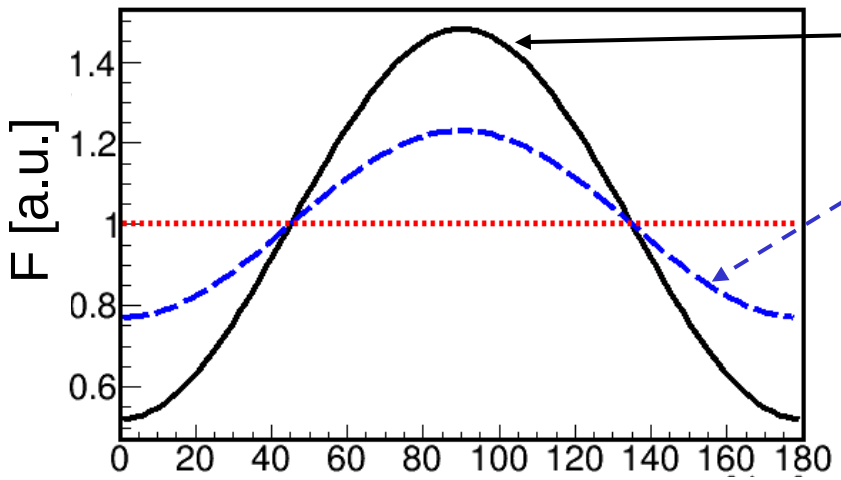


P. Moskal et al., Science Advances 11 (2025) eads3046



P. Moskal et al., Science Advances 11 (2025) eads3046

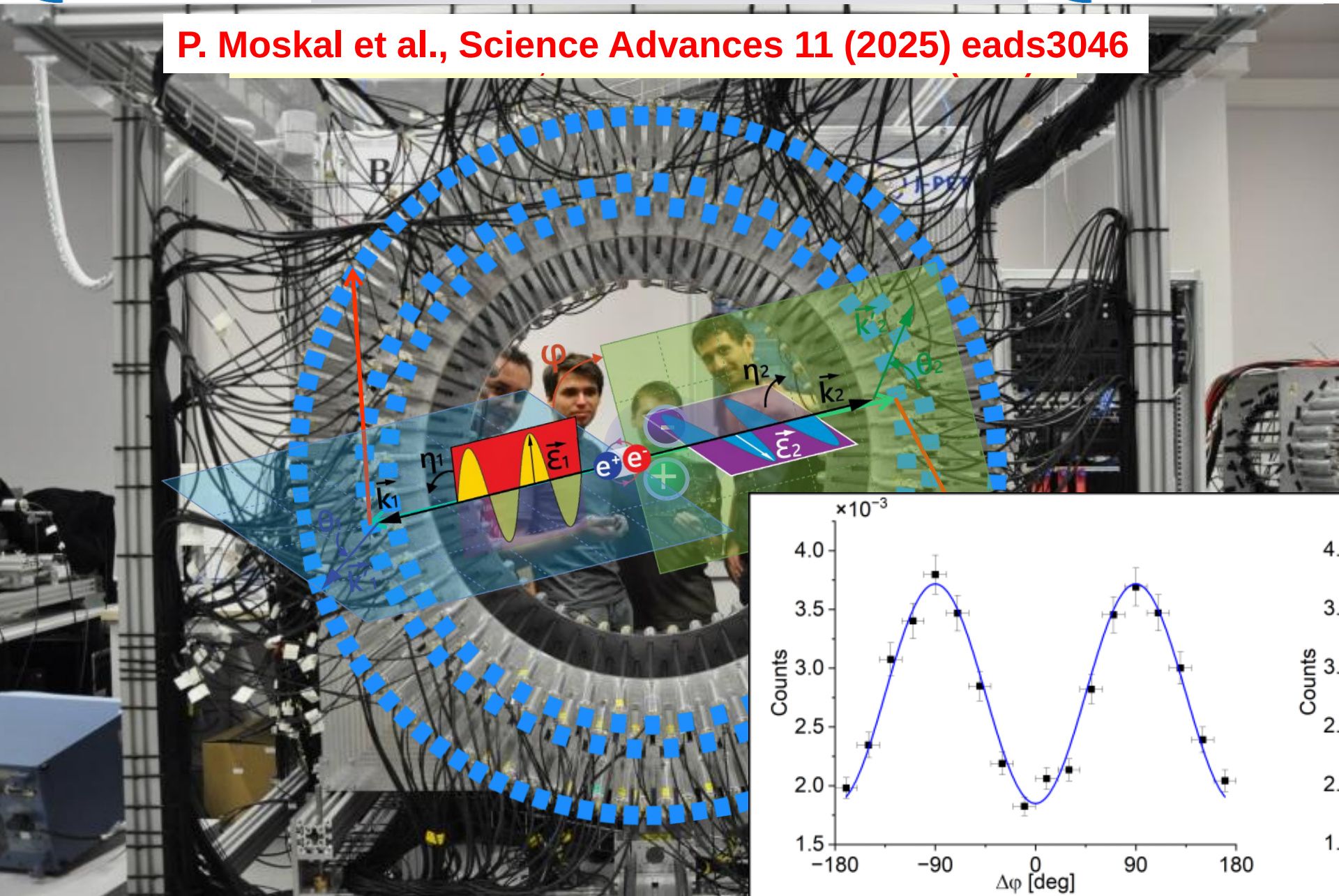
$F = A - B\cos(2\varphi)$



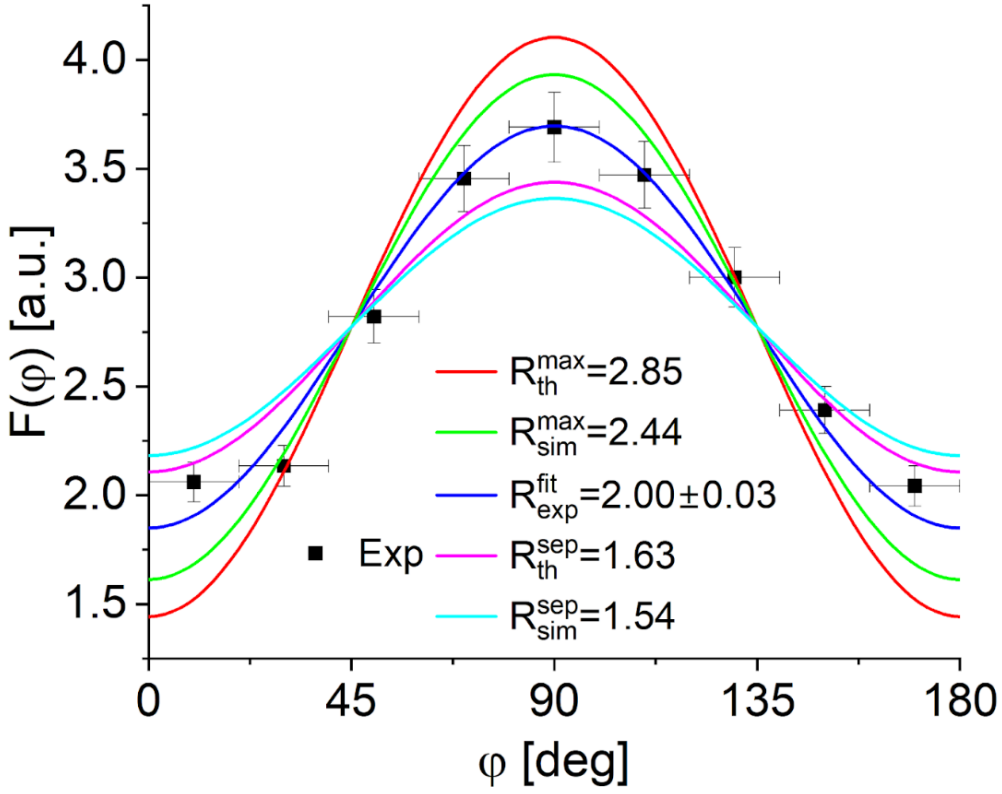
$$R = \frac{F_{max}}{F_{min}}$$

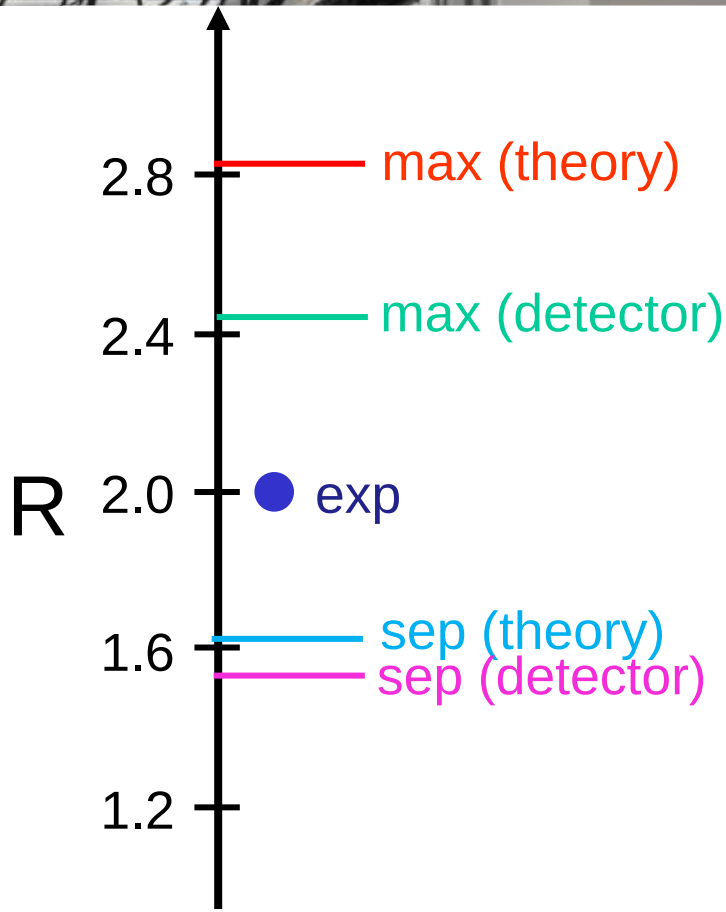
Jagiellonian PET

P. Moskal et al., Science Advances 11 (2025) eads3046



Jagiellonian PET



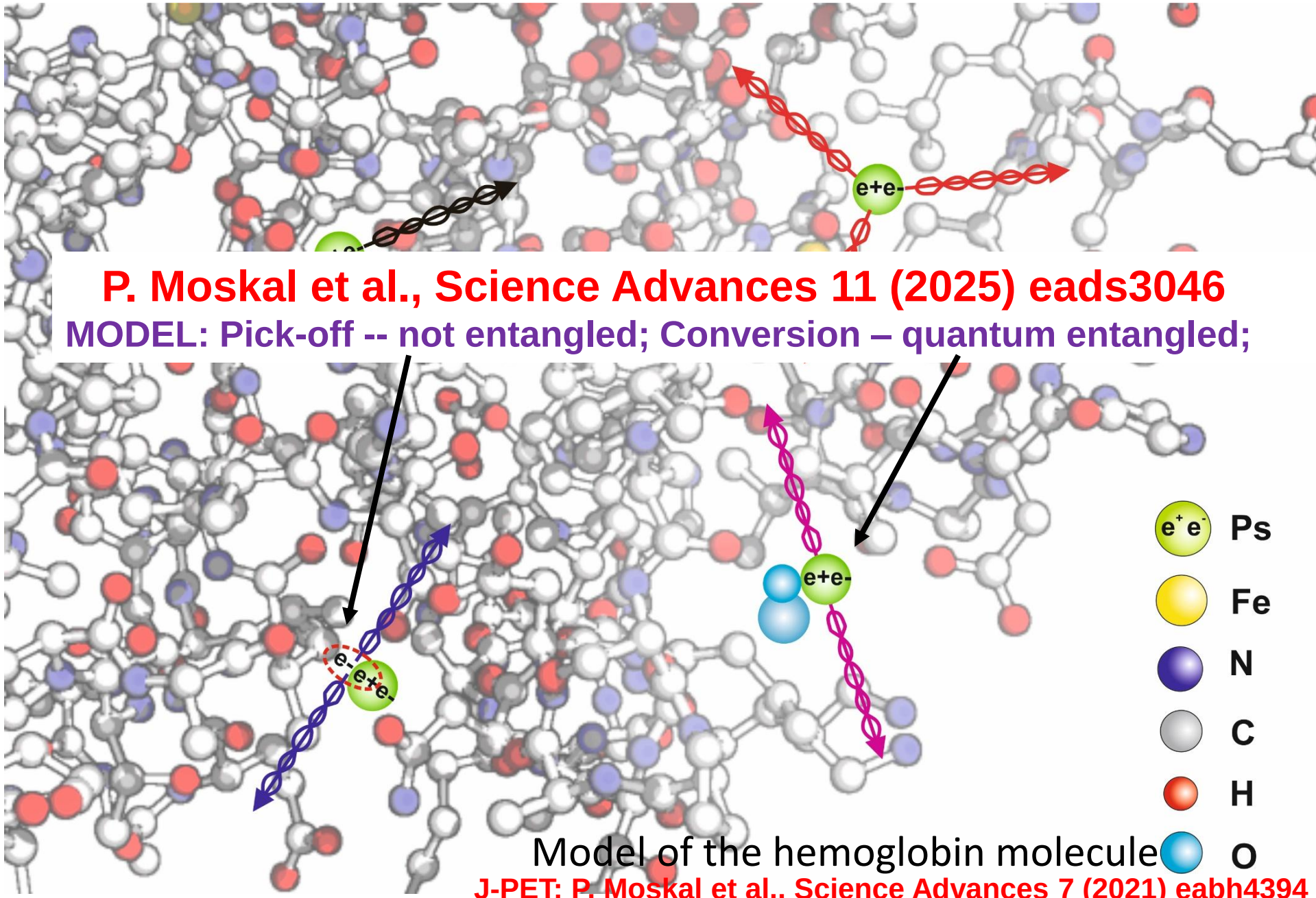


P. Moskal et al., Science Advances 11 (2025) eads3046

Non-maximal entanglement of photons from positron-electron annihilation demonstrated using a plastic PET scanner

Positronium imaging

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



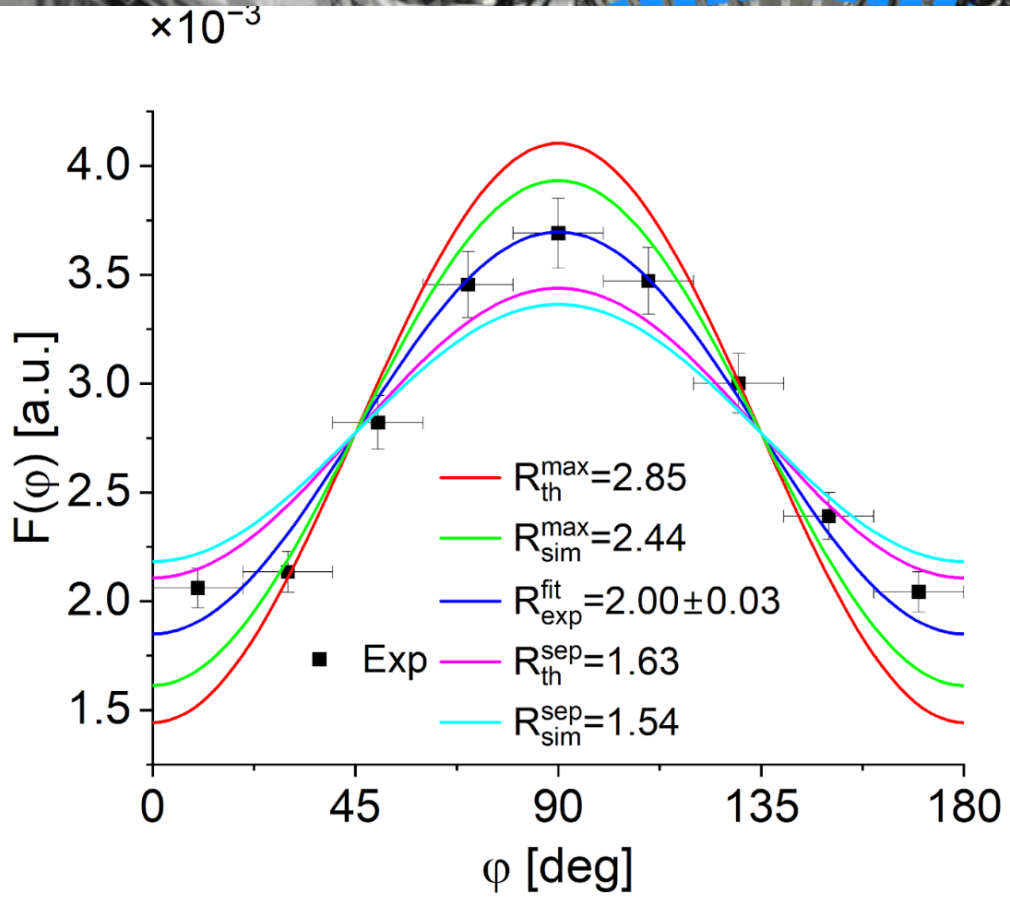
P. Moskal et al., Science Advances 11 (2025) eads3046

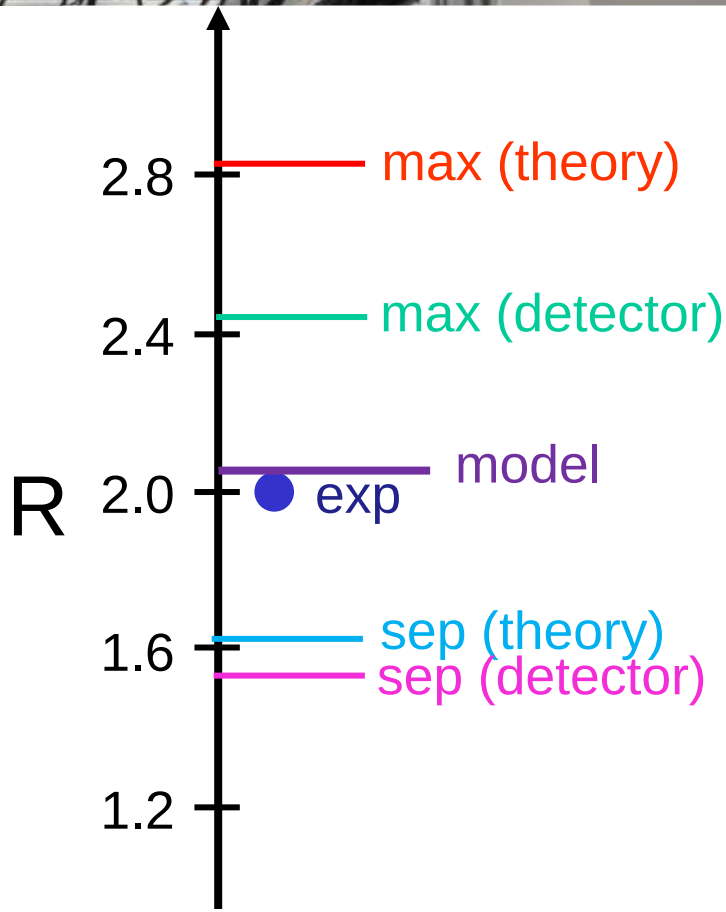
MODEL: Pick-off -- not entangled; Conversion – quantum entangled;

Model of the hemoglobin molecule

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

Jagiellonian PET





P. Moskal et al., Science Advances 11 (2025) eads3046

Non-maximal entanglement of photons from positron-electron annihilation demonstrated using a plastic PET scanner

JAGIELLONIAN-PET (J-PET)

PET from PLASTIC SCINTILLATORS

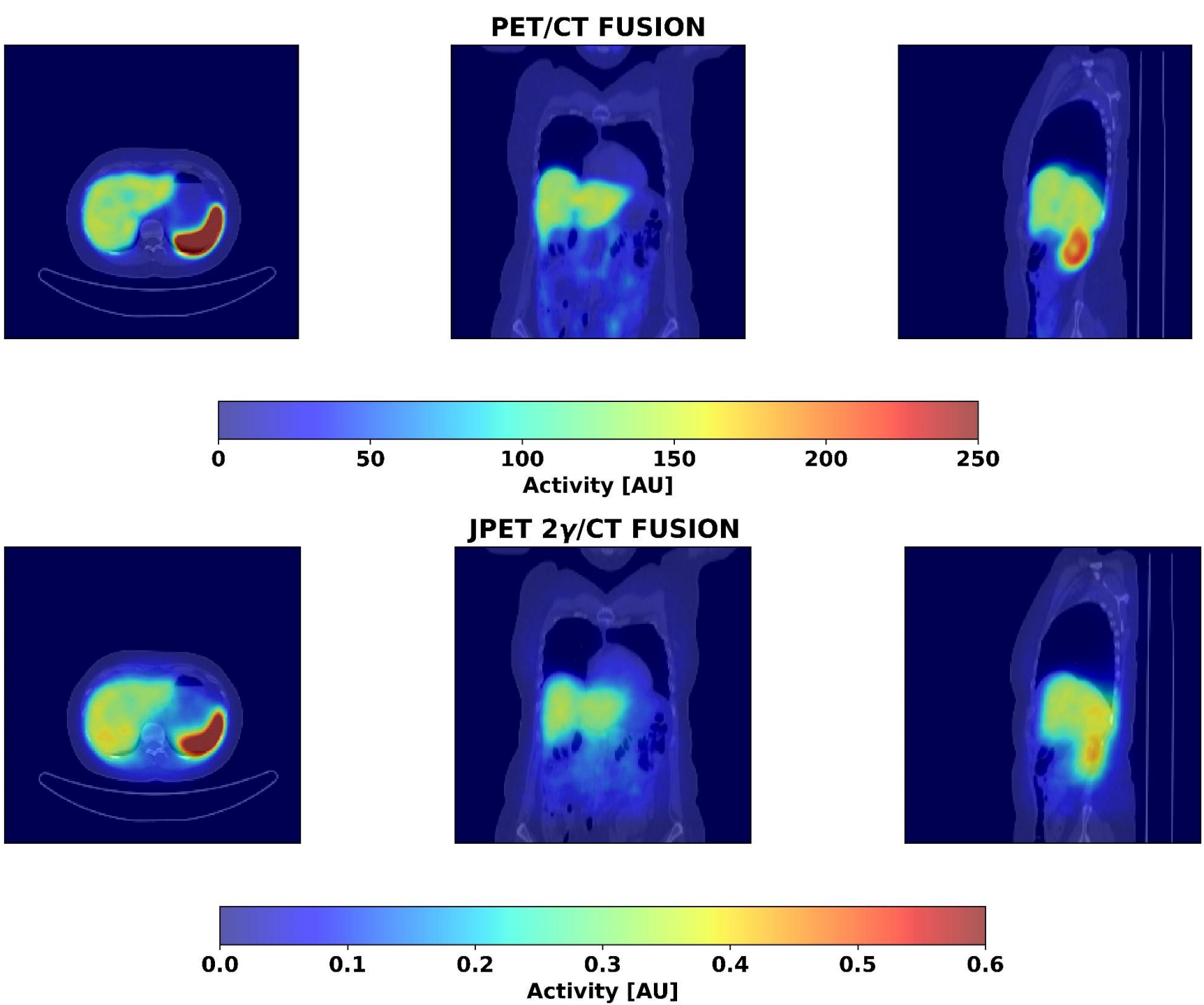
POSITRONIUM IMAGING

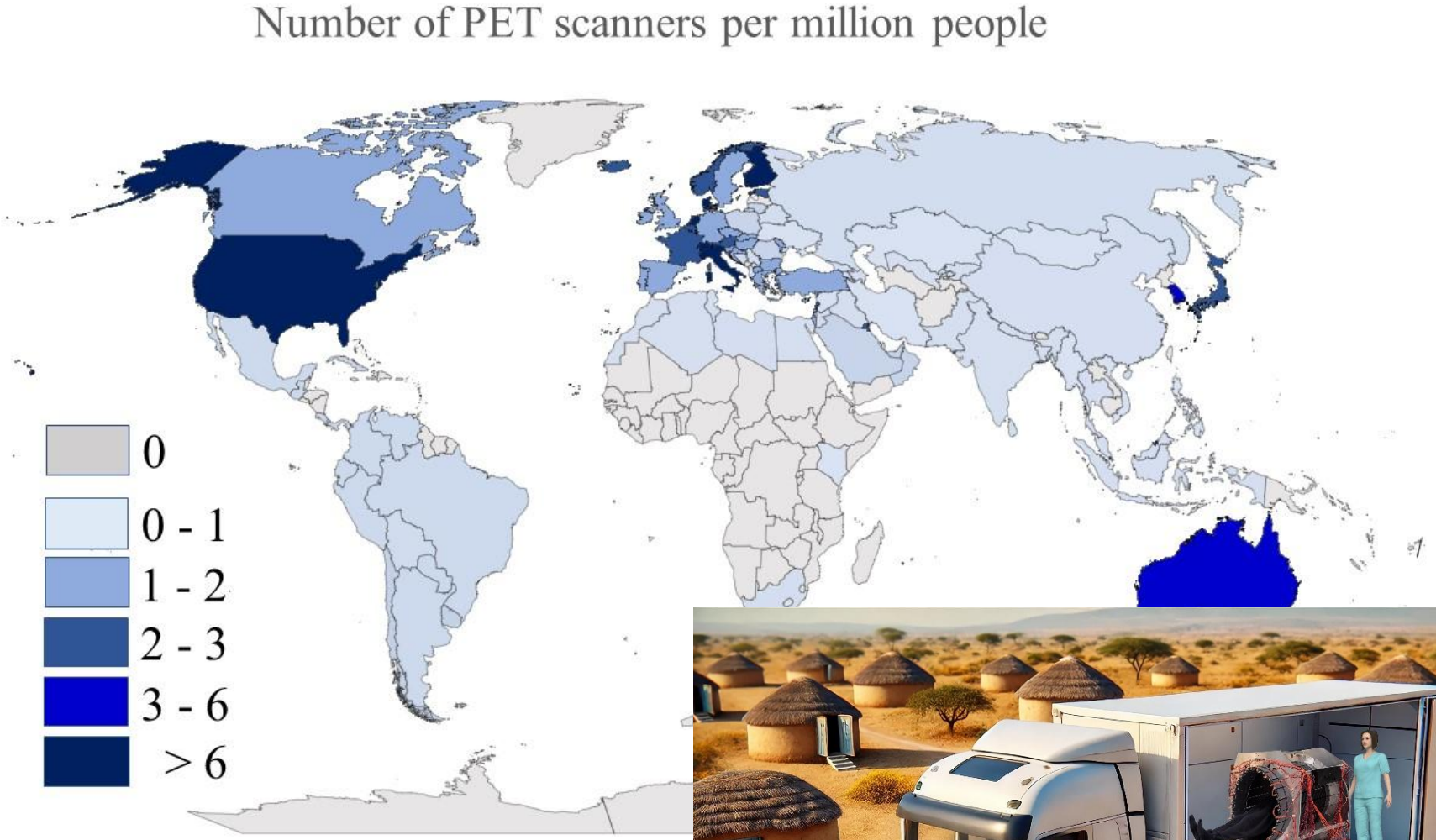
DISCRETE SYMMETRIES

QUANTUM ENTANGLEMENT IMAGING

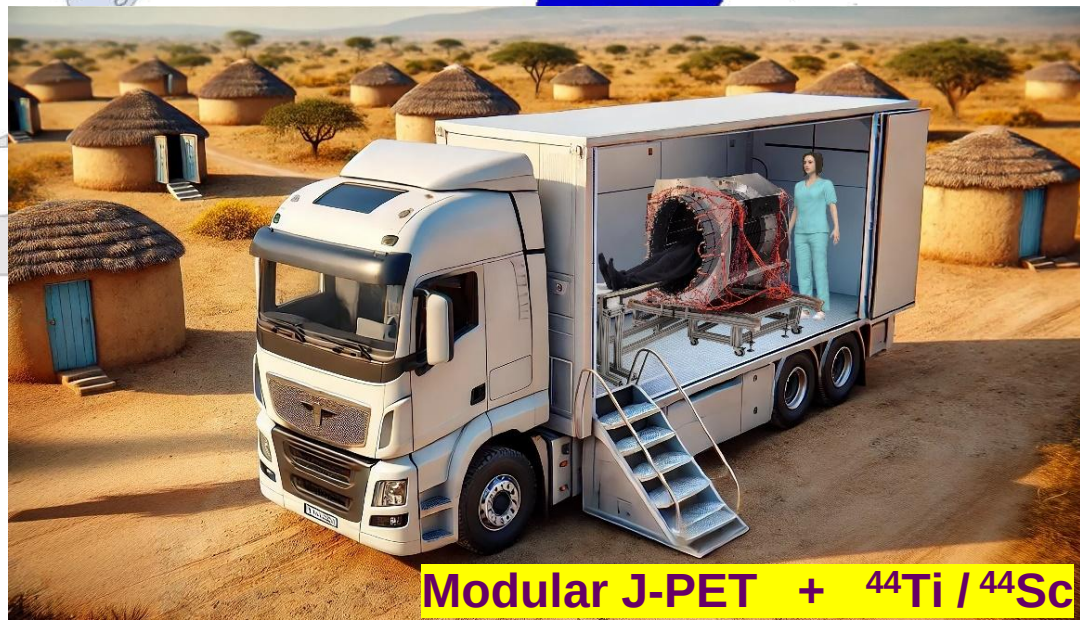
P. Moskal, Jagiellonian University
http://koza.if.uj.edu.pl


First clinical PET and positronium imaging of patients with J-PET
Biograph
P. Moskal, …, E. Stepien, Science Advances 10 (2024) eadp2840


PET/CT FUSION
0
50
100
150
200
250
Activity [AU]
JPET 2γ/CT FUSION
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Activity [AU]

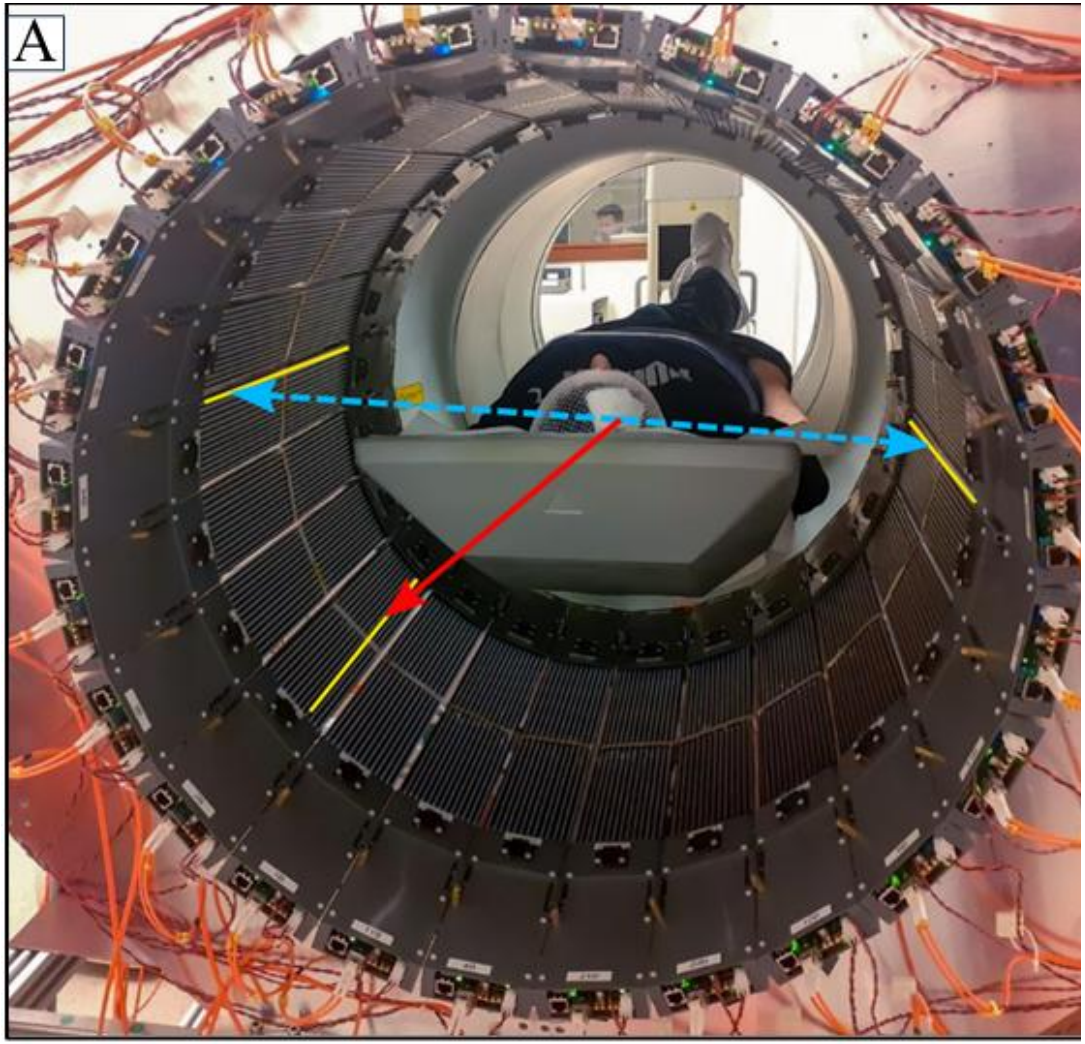


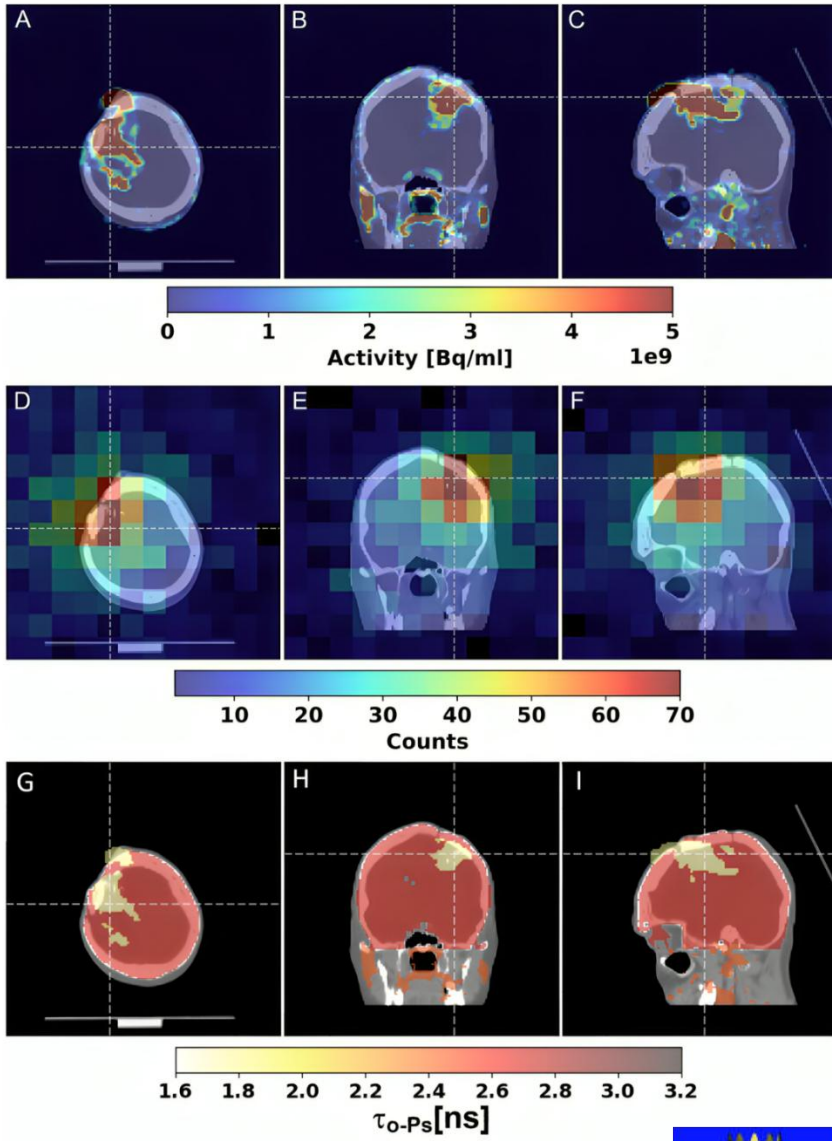
IAEA Medical imAGIng and Nuclear mEdicine (IMAGINE) database developed by the International Atomic Energy Agency (IAEA) available at: https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINE.html



P. Moskal, E. Stępień, Bio-Algorithms and Med-Systems 20 (2024) 55

First clinical positronium imaging of patients

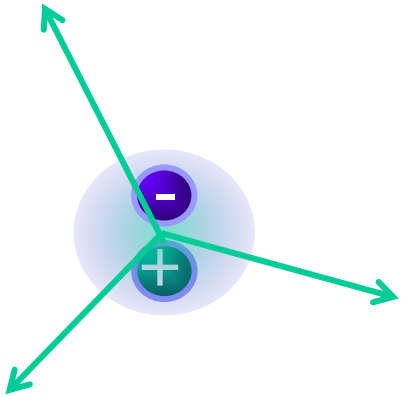




P. Moskal, …, E. Stepień, Science Advances 10 (2024) eadp2840

Positronium image of the human brain in vivo

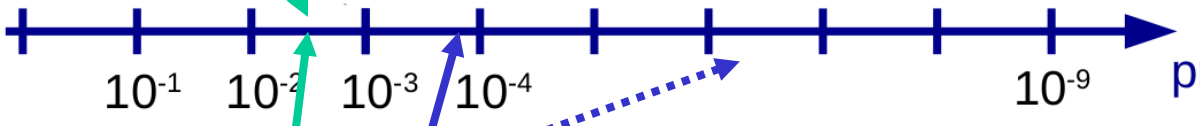
Pawel Moskal, Jagiellonian University



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

6 OOM of
unexplored precision

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



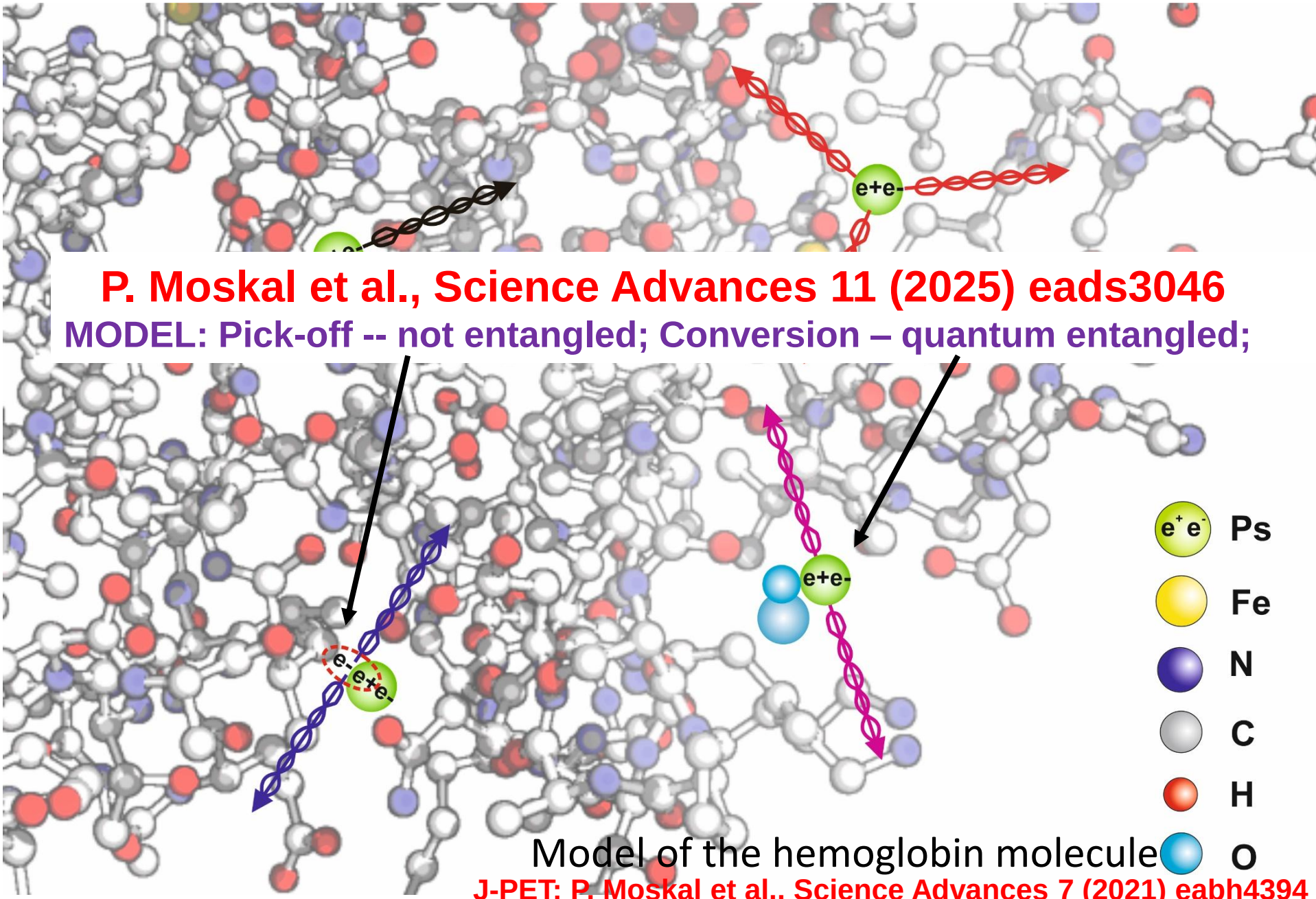
$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$
PRL. 91 (2003) 263401

J-PET

P. Moskal et al., Nature Communications 12 (2021) 5658
P. Moskal et al., Nature Communications 15 (2024) 78

Positronium imaging

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

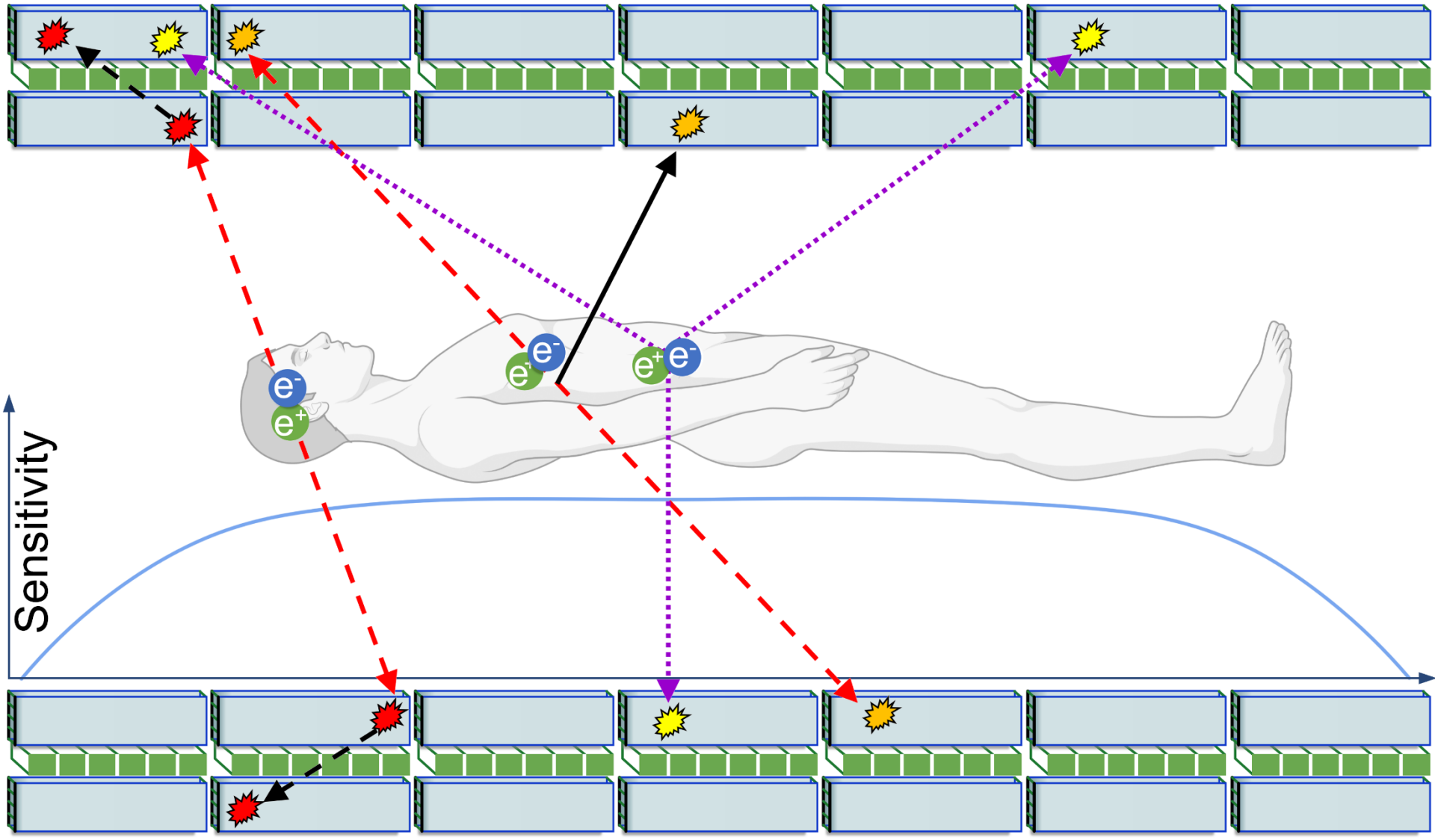


P. Moskal et al., Science Advances 11 (2025) eads3046

MODEL: Pick-off -- not entangled; Conversion – quantum entangled;

Model of the hemoglobin molecule

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

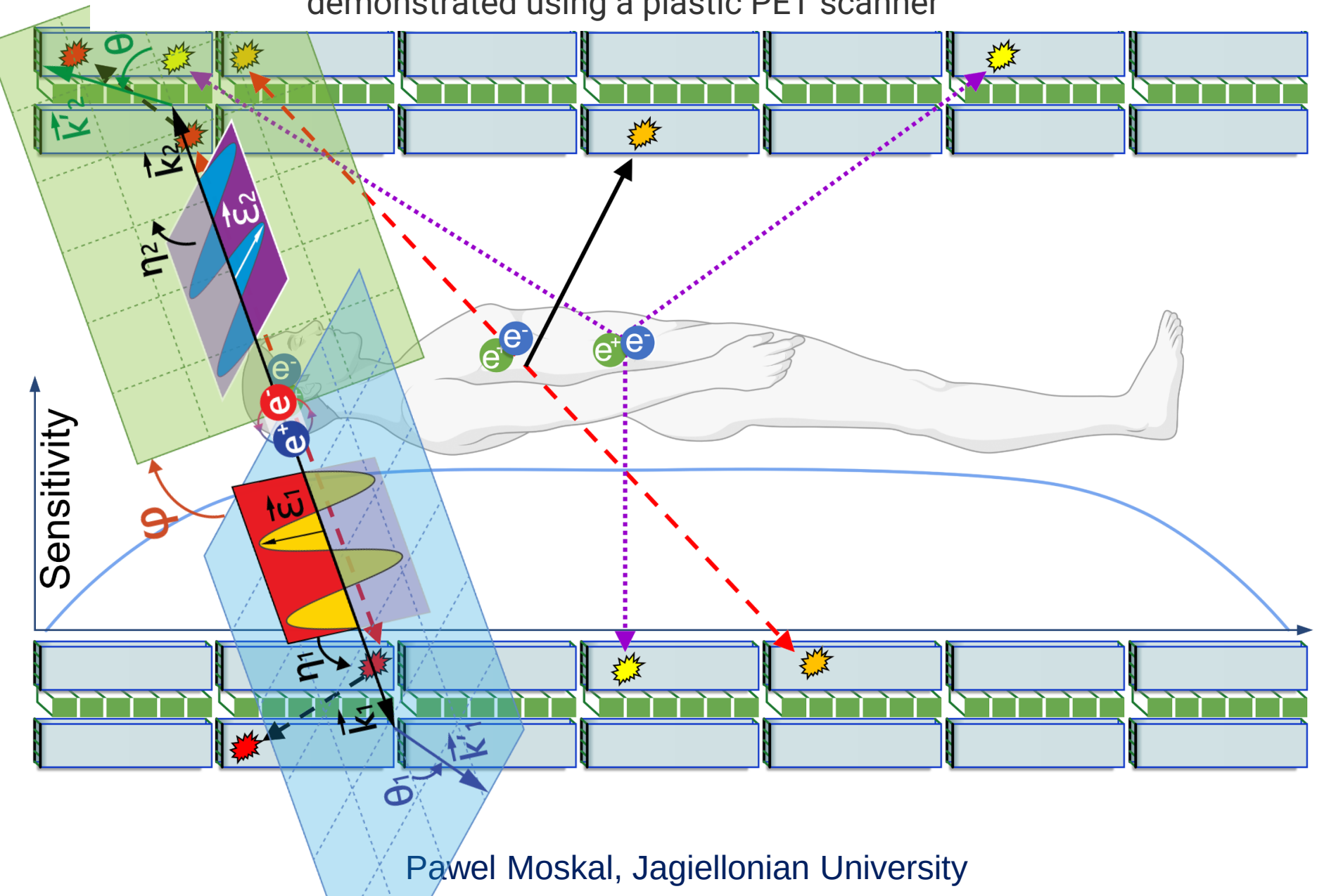


P. Moskal et al., Phys. Med. Biol. 66 (2021) 175015

CENTER FOR THERANOSTICS

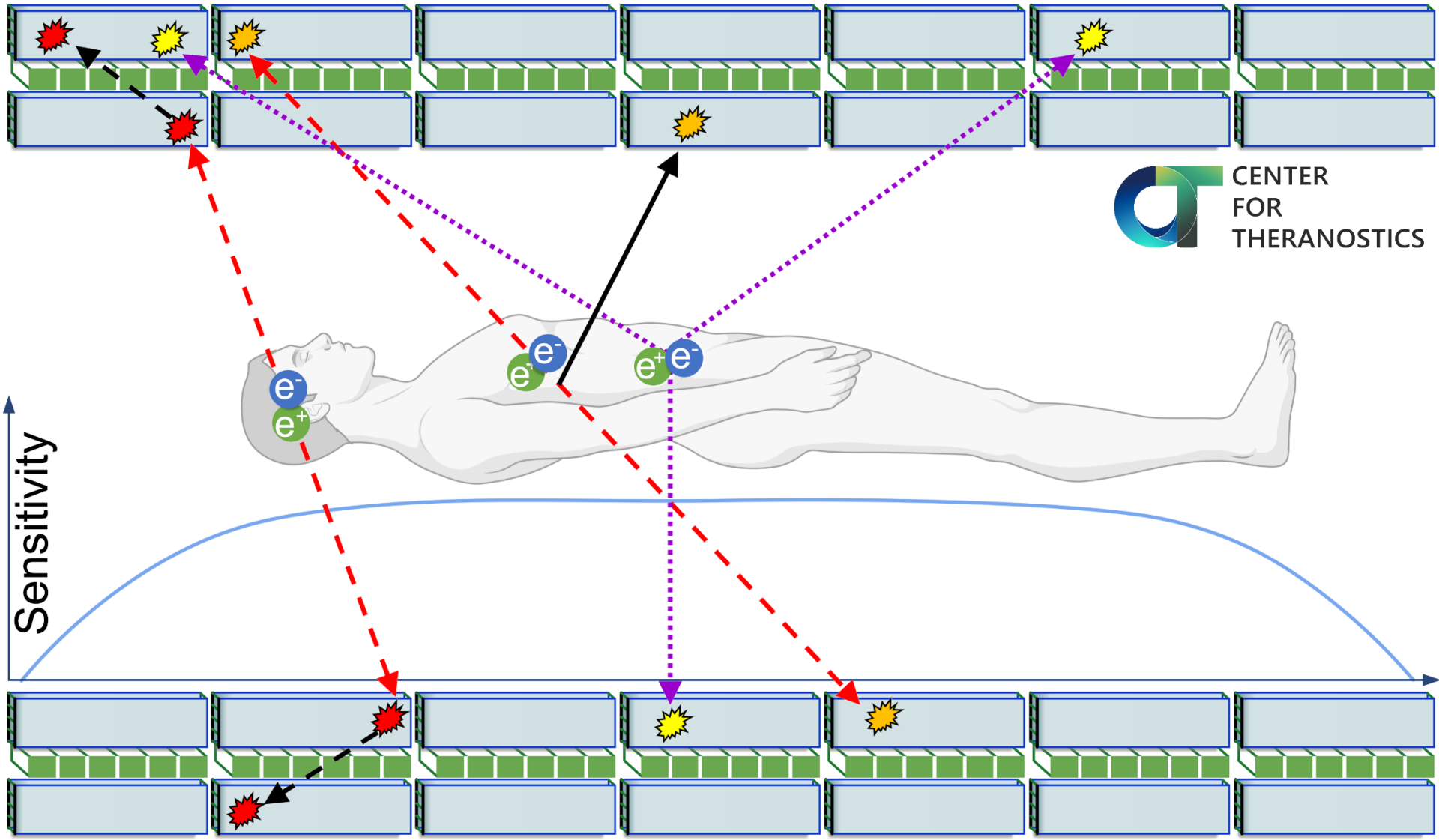
P. Moskal et al., Science Advances 11 (2025) eads3046

Non-maximal entanglement of photons from positron-electron annihilation demonstrated using a plastic PET scanner



Pawel Moskal, Jagiellonian University

FIRST TOTAL-BODY PET for DYNAMIC POSITRONIUM and QUANTUM ENTAGLEMET IMAGING

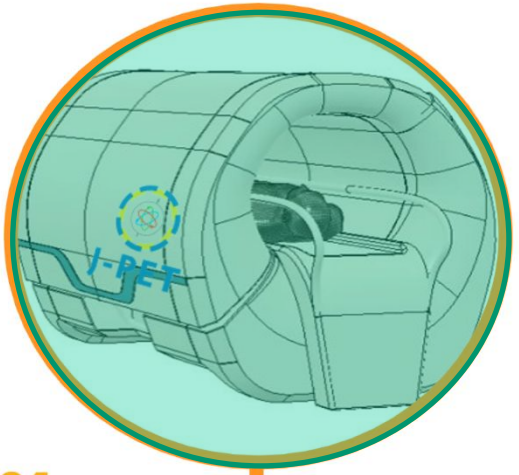


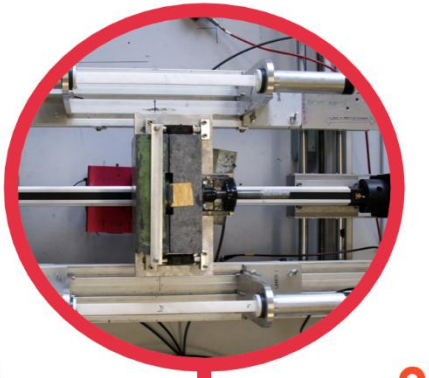
MULTI-PHOTON PALS SPECTROMETER QUANTUM ENTAGLEMENT SPETROMETER

J-PET

total-body J-PET

3-layer prototype





2009

2012

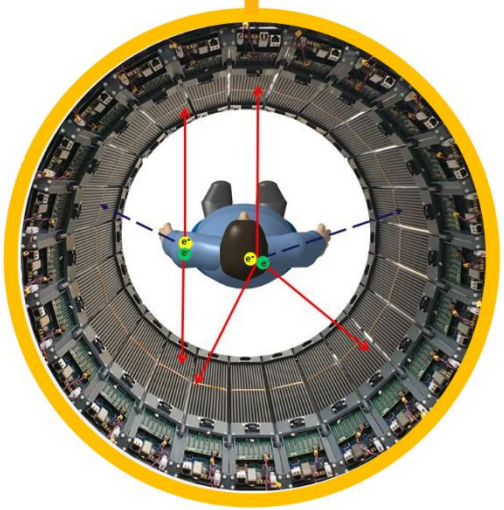
2014

2016

2021

2028

FIRST PATENT



modular J-PET

6th Jagiellonian Symposium
5 – 11 July 2026
CRACOW, POLAND
Positronium in PHYSICS
Positronium in MEDICINE