Demonstrating the first positronium image of the human brain in vivo.

International day of Medical Physics
07.11.2024, University of Padua, Italy

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


ARCTIC OCEAN
Greenland
Svalbard (Nor.)
ARCTIC OCEAN
United States of America
Canada
Iceland
Norway
Sweden
Finland
Russia
United Kingdom
Denmark
Ireland
Neth.
Ger.
Pol.
Estonia
Latvia
Belarus
Ukraine
Kazakhstan
Mongolia
France
Italy
Rom.
Georgia
Bulgaria
Azer.
Uzb.
Turkm.
Kyrgyzstan
Tajikistan
Spain
Portugal
Turkey
Greece
Tunisia
Lebanon
Syria
Iraq
Iran
Afg.
Pakistan
China
N. Korea
S. Korea
Japan
Nepal
Bhutan
India
Laos
Taiwan
Vietnam
Philippines
Thailand
Cambodia
Bangl.
Burma
Sri Lanka
Malaysia
Indonesia
Papua New Guinea
Solomon Islands
Fiji
Australia
New Zealand
ATLANTIC OCEAN
PACIFIC OCEAN
INDIAN OCEAN
Morocco
Western Sahara
Algeria
Libya
Egypt
Israel
Jordan
Kuwait
Saudi Arabia
U.A.E.
Oman
Yemen
Mauritania
Mali
Niger
Chad
Eritrea
Djibouti
Sudan
Ethiopia
Somalia
Senegal
Guinea-Bissau
Sierra Leone
Liberia
Cote d' Ivoire
Ghana
Nigeria
Cam.
C.A.R.
Togo
Gabon
Dem. Rep. of Congo
Uganda
Kenya
Tanzania
Rep. of the Congo
Angola
Zambia
Malawi
Madagascar
Namibia
Zimbabwe
Mozambique
Botswana
Swaziland
Lesotho
South Africa
Mexico
Guatemala
Honduras
Nicaragua
Costa Rica
Panama
Colombia
Ven.
Guyana
French Guiana
Suriname
Ecuador
Peru
Brazil
Bolivia
Paraguay
Chile
Argentina
Uruguay

Cracow

Jagiellonian University

1364

Collegium Maius at the University since **1400**

Jagiellonian University

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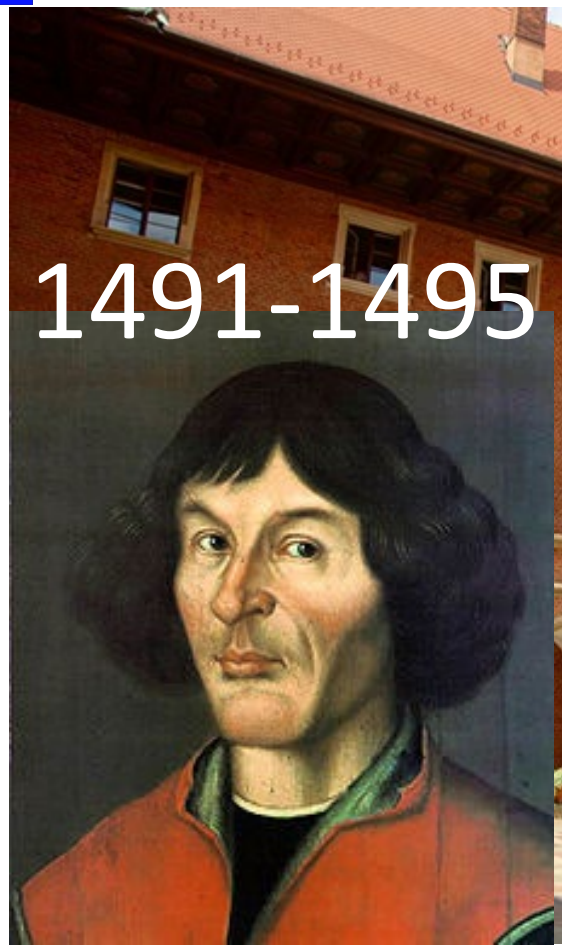

Collegium Maius at the University since **1400**

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Collegium Maius at the University since **1400**

Jagiellonian PET

Kraków May 2022

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

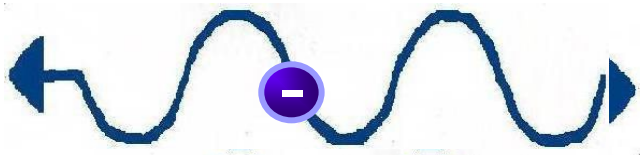
J-PET

CENTER FOR THERANOSTICS

J-PET

Kraków March 2024

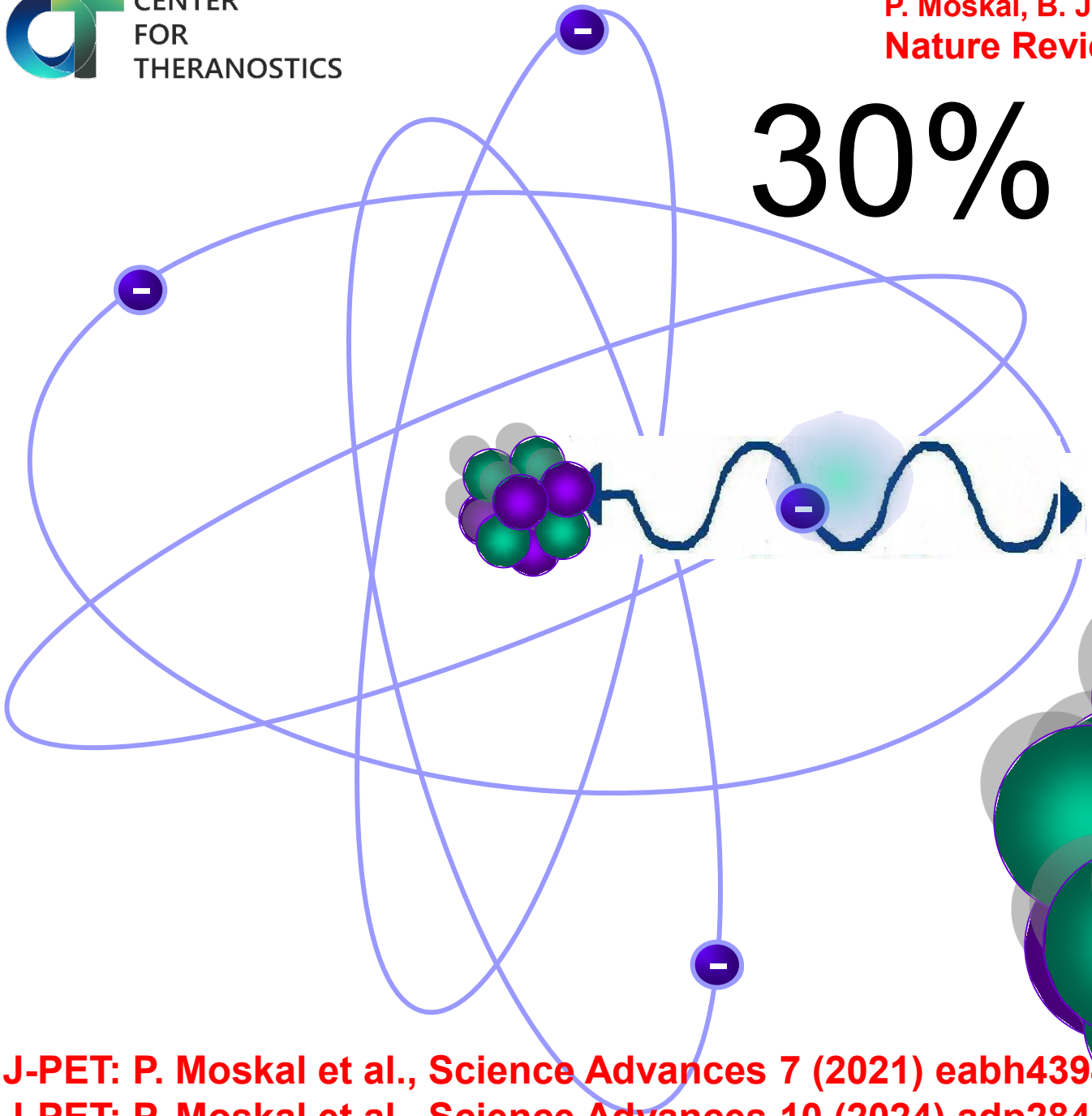
P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration **http://koza.if.uj.edu.pl**



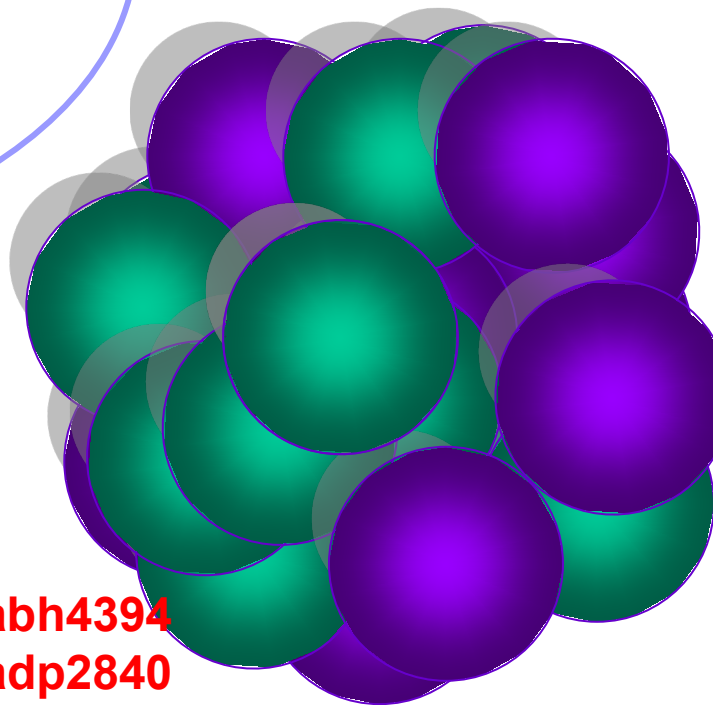
CENTER
FOR
THERANOSTICS

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

30% – 40%



$$^{18}F \longrightarrow {}^{18}O + e^{+} + \nu_e$$



J-PET: P. Moskal et al., Science Advances 7 (2021) eabh4394
J-PET: P. Moskal et al., Science Advances 10 (2024) adp2840

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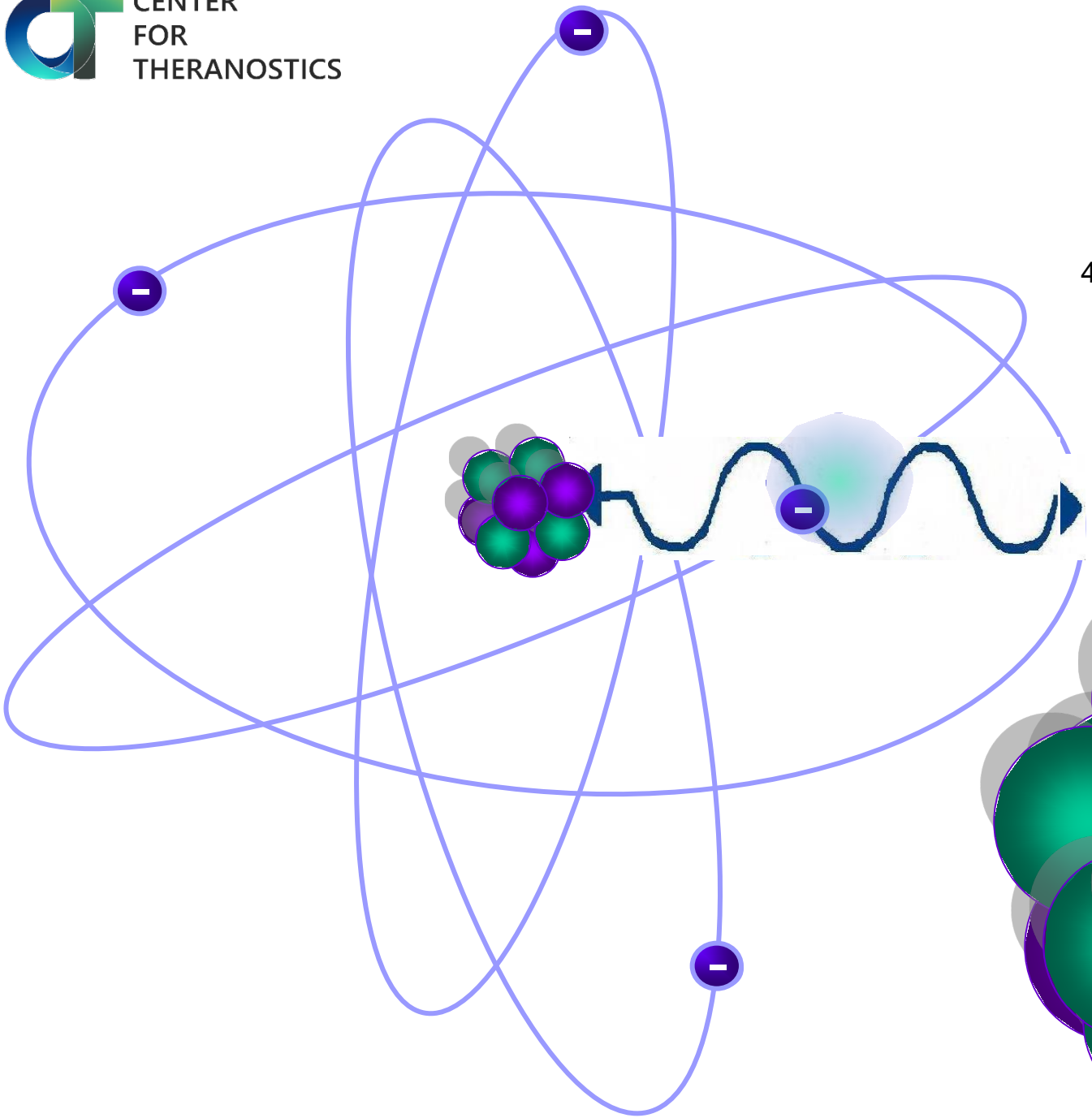
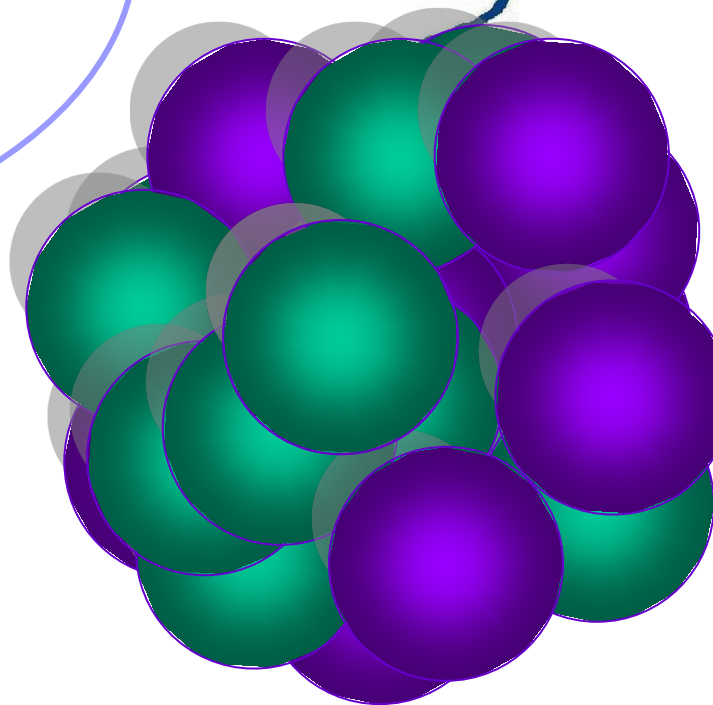
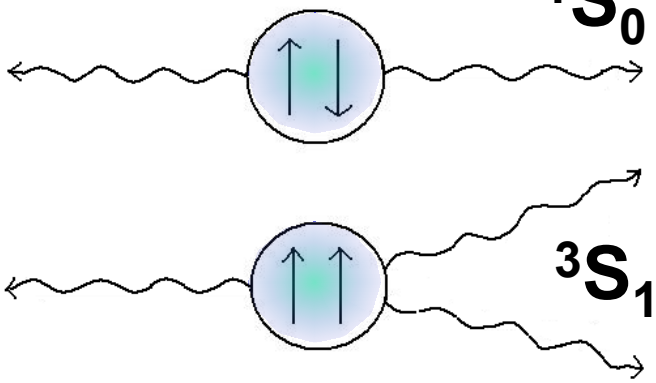


$$^{44}Sc \longrightarrow {}^{44}Ca^{*} + e^{+} + \nu_e$$

$$^{44}Ca^{*} \longrightarrow {}^{44}Ca + \gamma$$





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

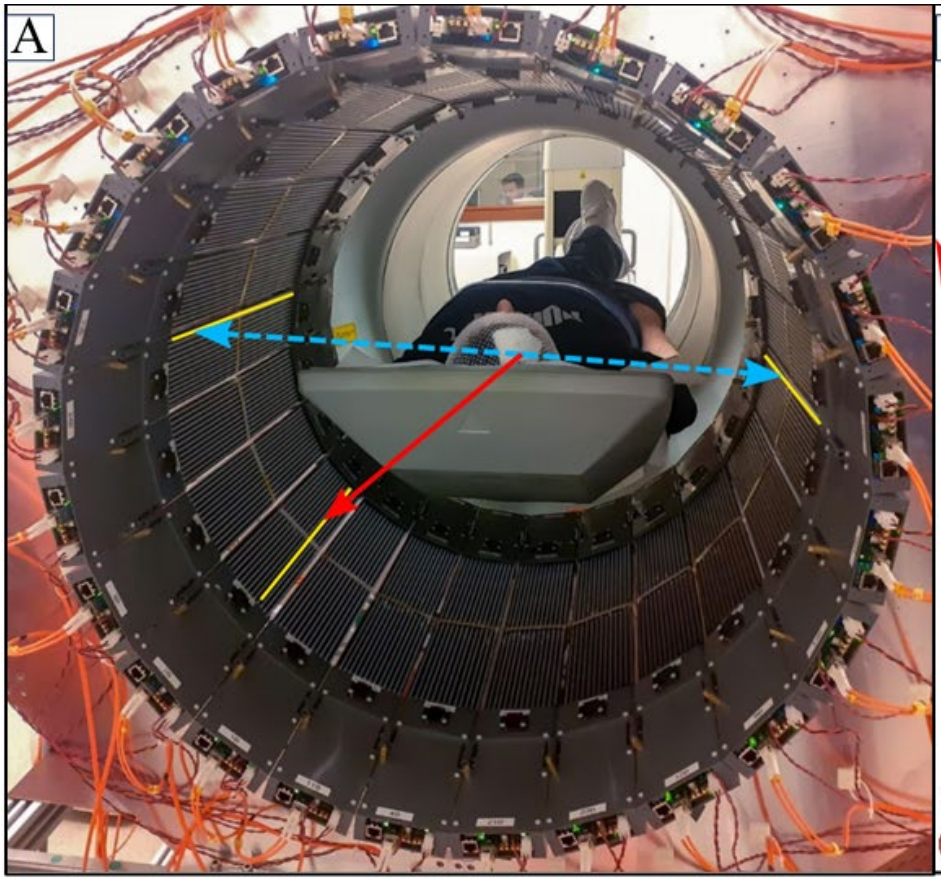
$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

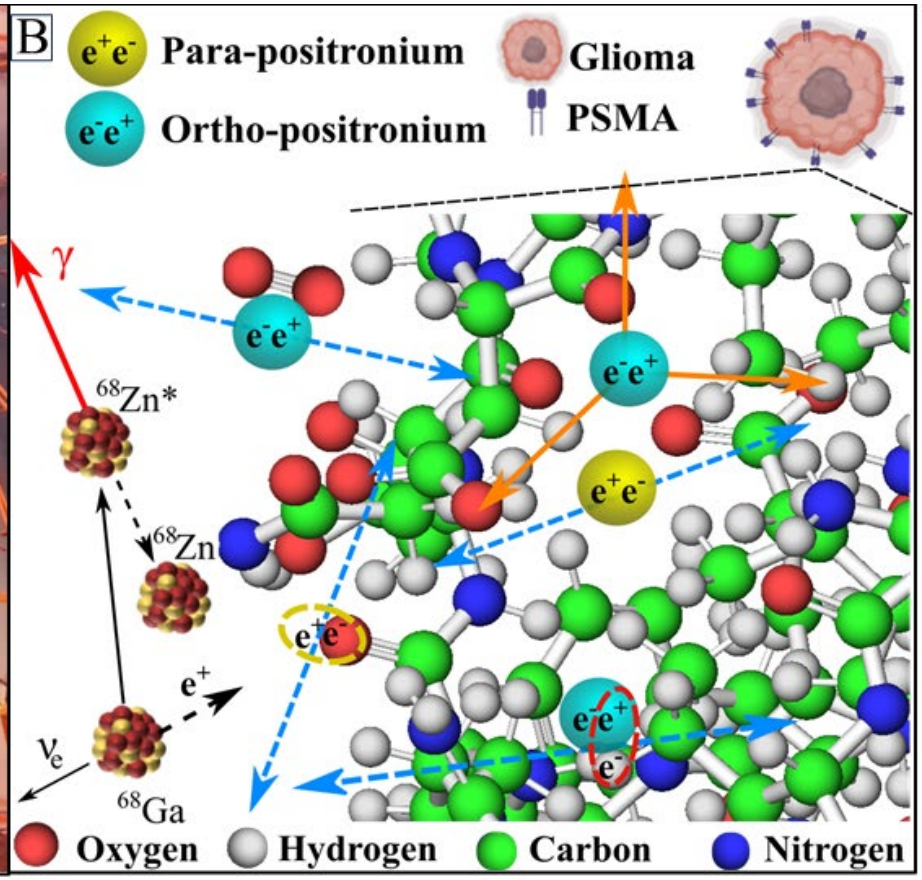
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-
L=0 -> P	-	-
CP	-	+

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

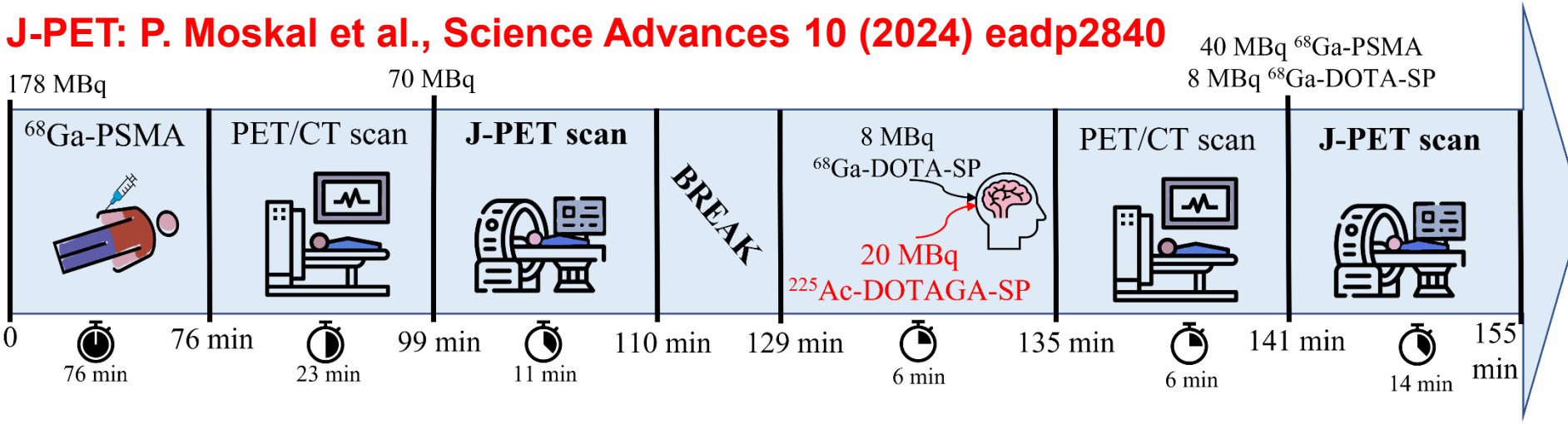
S = 1 $\uparrow\uparrow$ $\downarrow\uparrow + \uparrow\downarrow$ $\downarrow\downarrow$

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

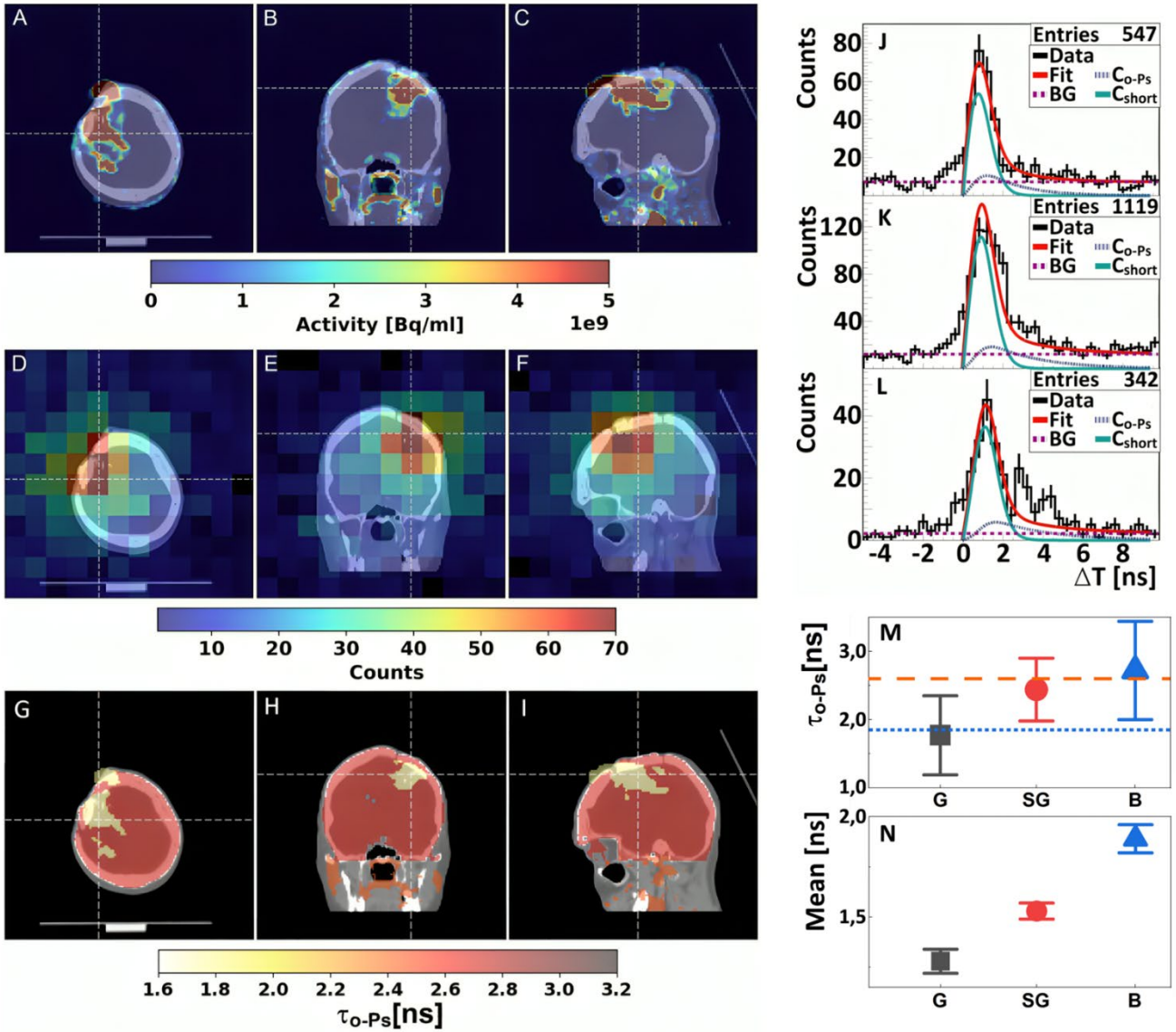




J-PET: P. Moskal et al., Science Advances 10 (2024) eadp2840



First clinical positronium imaging of patients



P. Moskal et al., Science Advances 10 (2024) eadp2840

Positronium image of the human brain in vivo

https://www.medrxiv.org/content/10.1101/2024.02.01.23299028v1

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

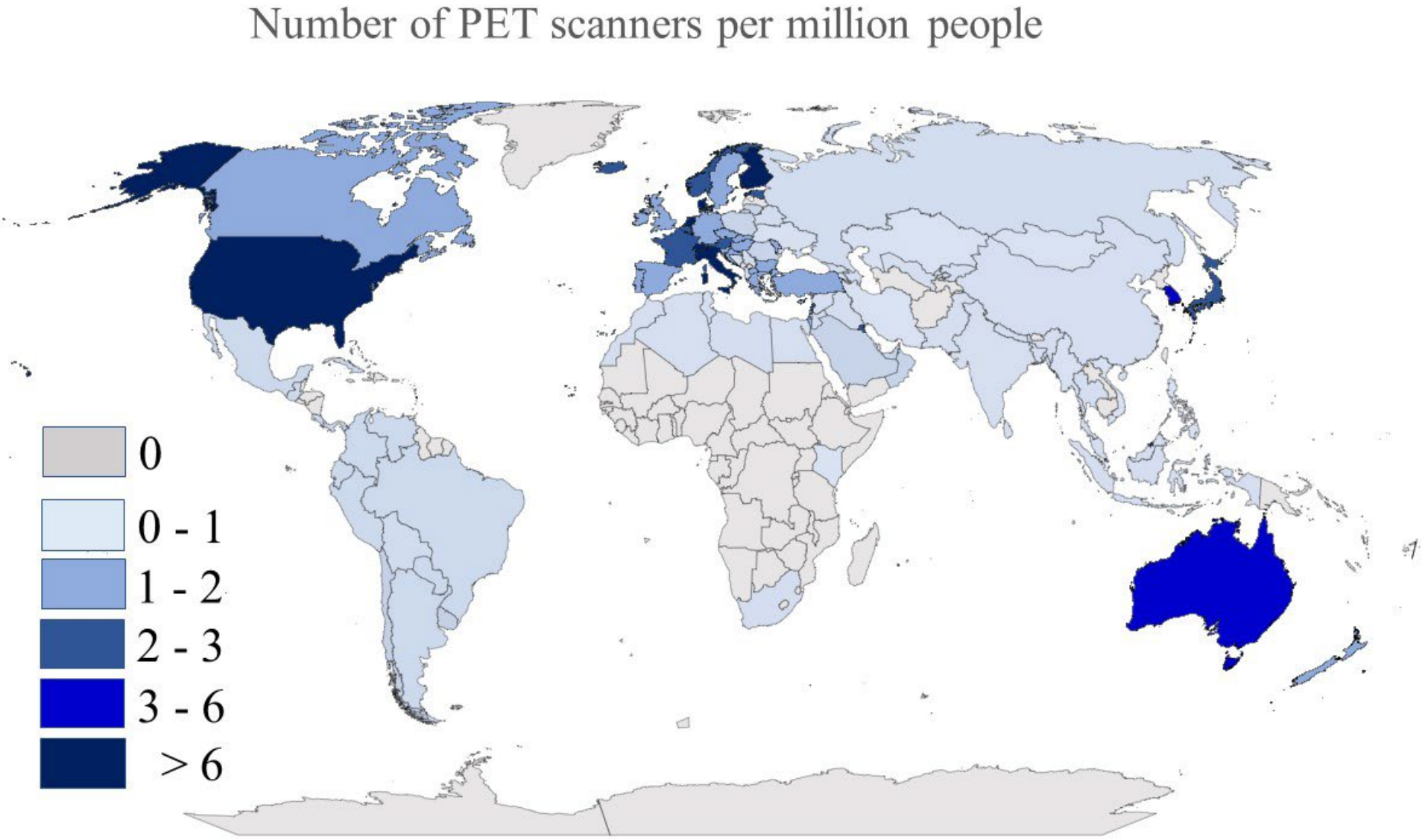
P. Moskal et al., Science Advances 7 (2021) eabh4394

Positronium imaging with the novel multi-photon PET scanner

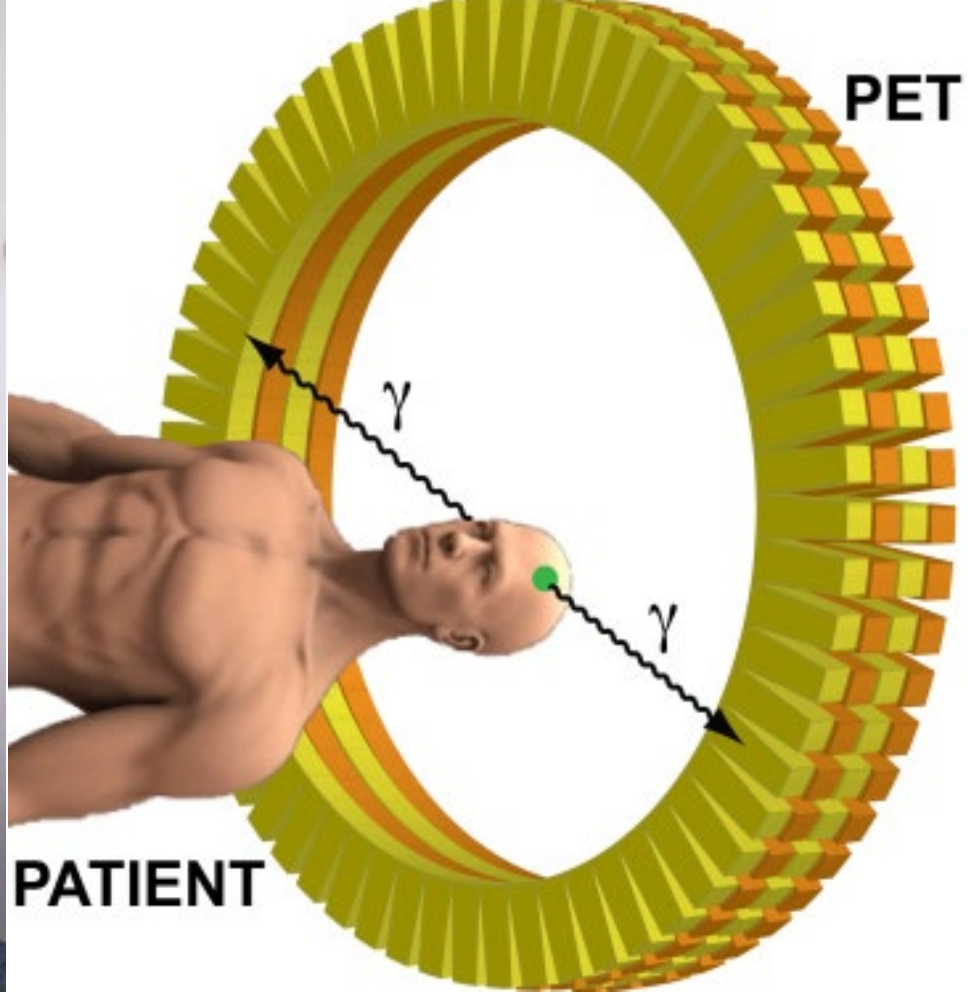
P. Moskal et al., Science Advances 10 (2024) adp2840

Positronium image of the human brain in vivo

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



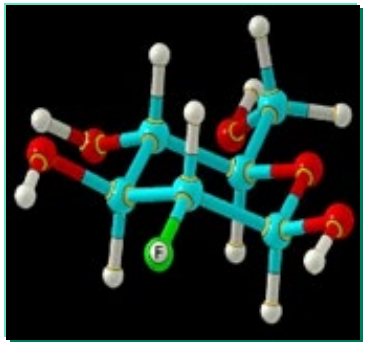
IAEA Medical imAGIng and Nuclear mEdicine (IMAGINE) database developed by the International Atomic Energy Agency (IAEA) available at: https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINE.html



RADIOACTIVE SUGAR

Fluoro–deoksy-glucose
(F-18 FDG)

~200 000 000
gamma rays per second



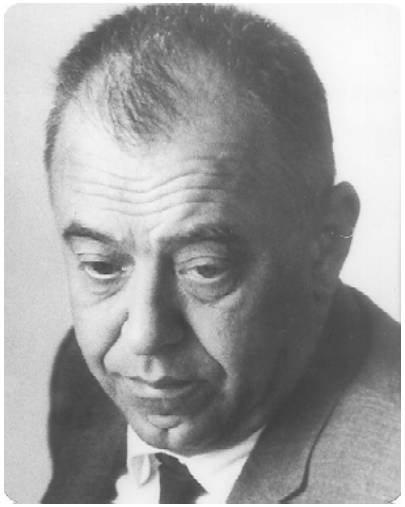
7 mSv PET/CT
~ 2.5 mSv PET
~3 mSv yearly
dose of natural radiation

Radiological
Laboratory in Warsaw

Nature 1934;133:564–5,

„An Artificial Radioelement from Nitrogen”

https://lnkd.in/di246kY2



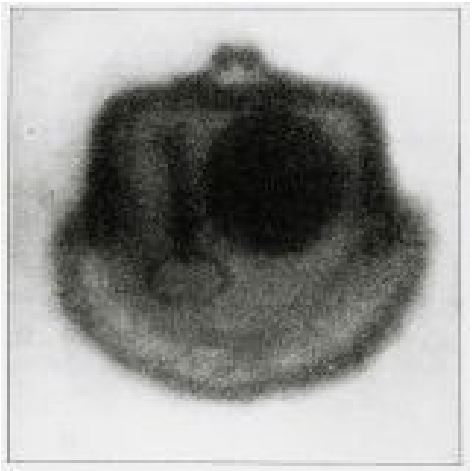
Prof. Ludwik Wertenstein
Marian Danysz

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

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

Formal leader of the Radiological Laboratory in Warsaw

A girl from Warsaw

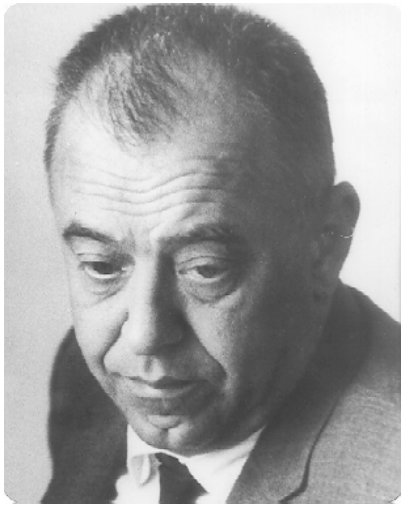


„Radiograph”
taken by
Maria Curie
by exposing
a purse to radium.

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

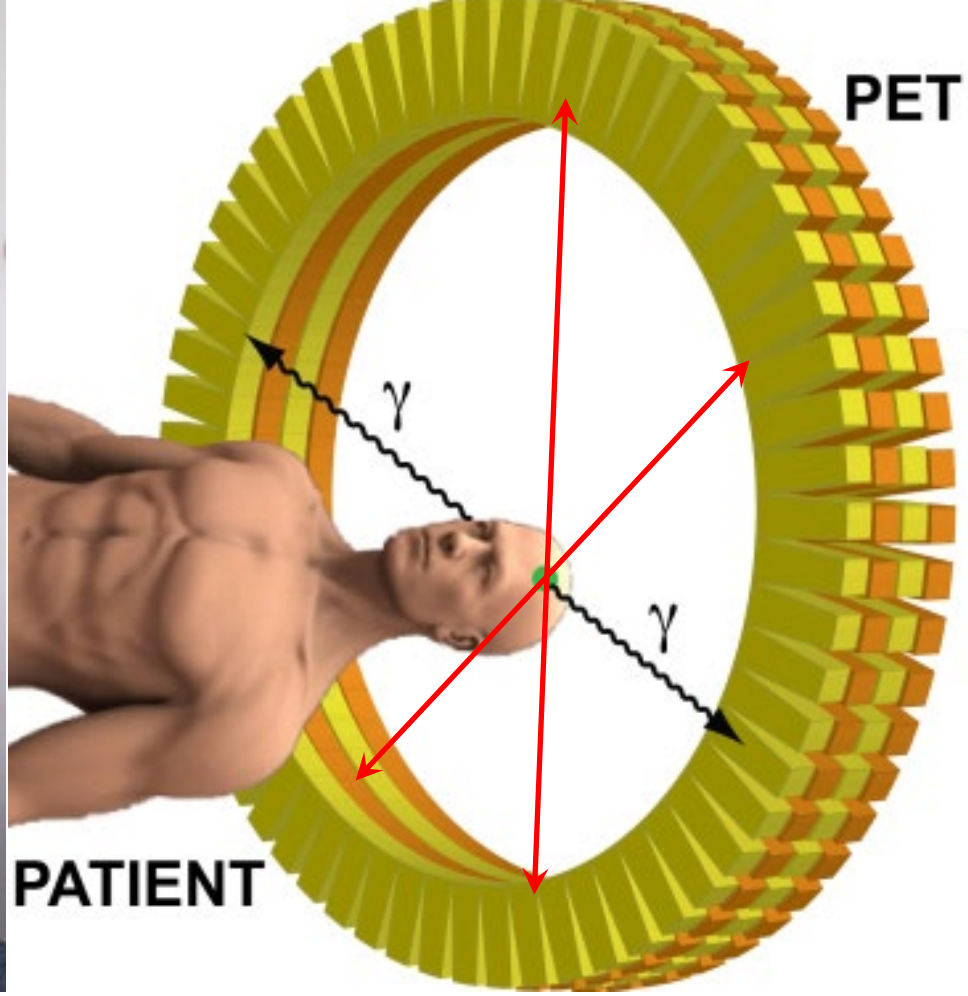
$$^{4}He + {}^{14}N \rightarrow {}^{17}F + n$$

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

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

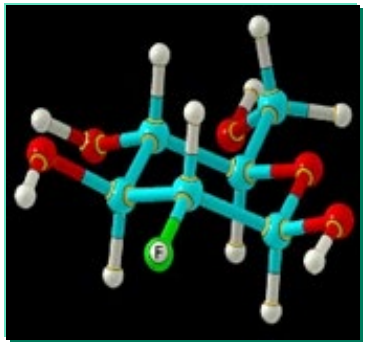
$$^{4}He + {}^{10}B \rightarrow {}^{13}N + n$$

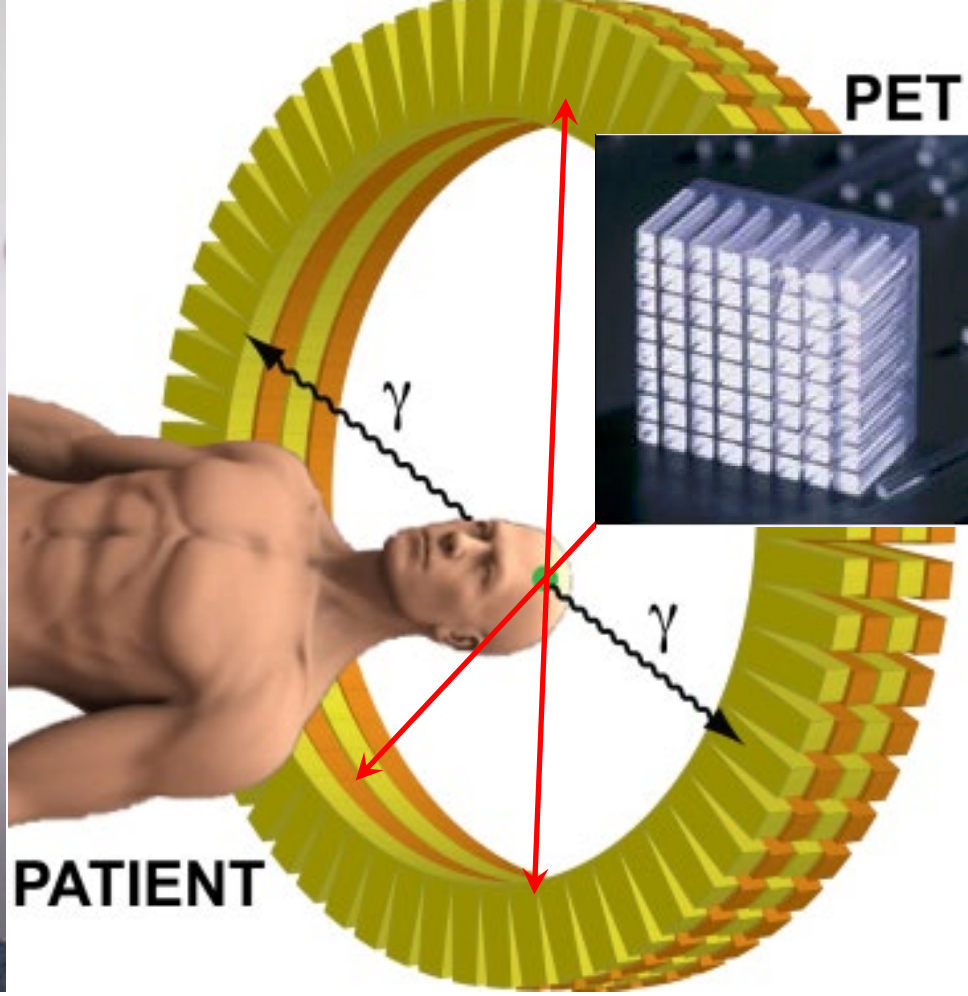
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$



RADIOACTIVE SUGAR

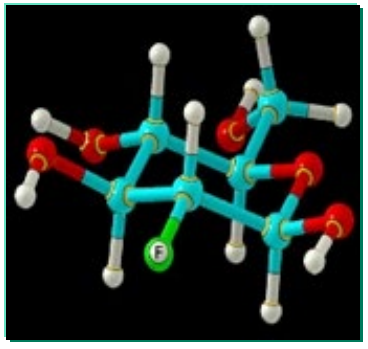
Fluoro–deoksy-glucose
(F-18 FDG)

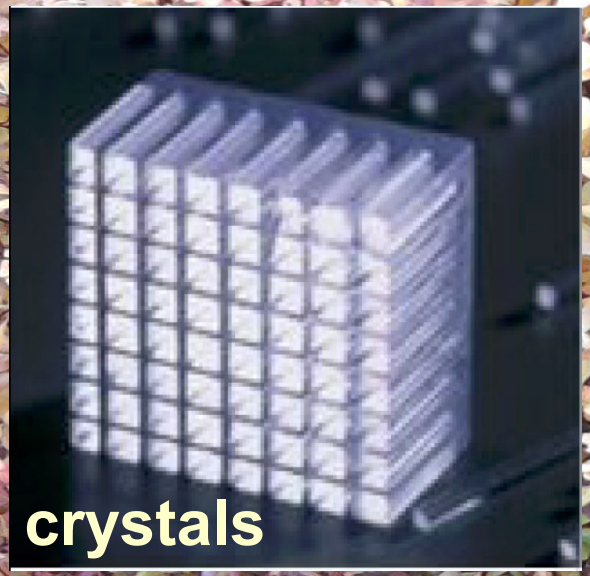


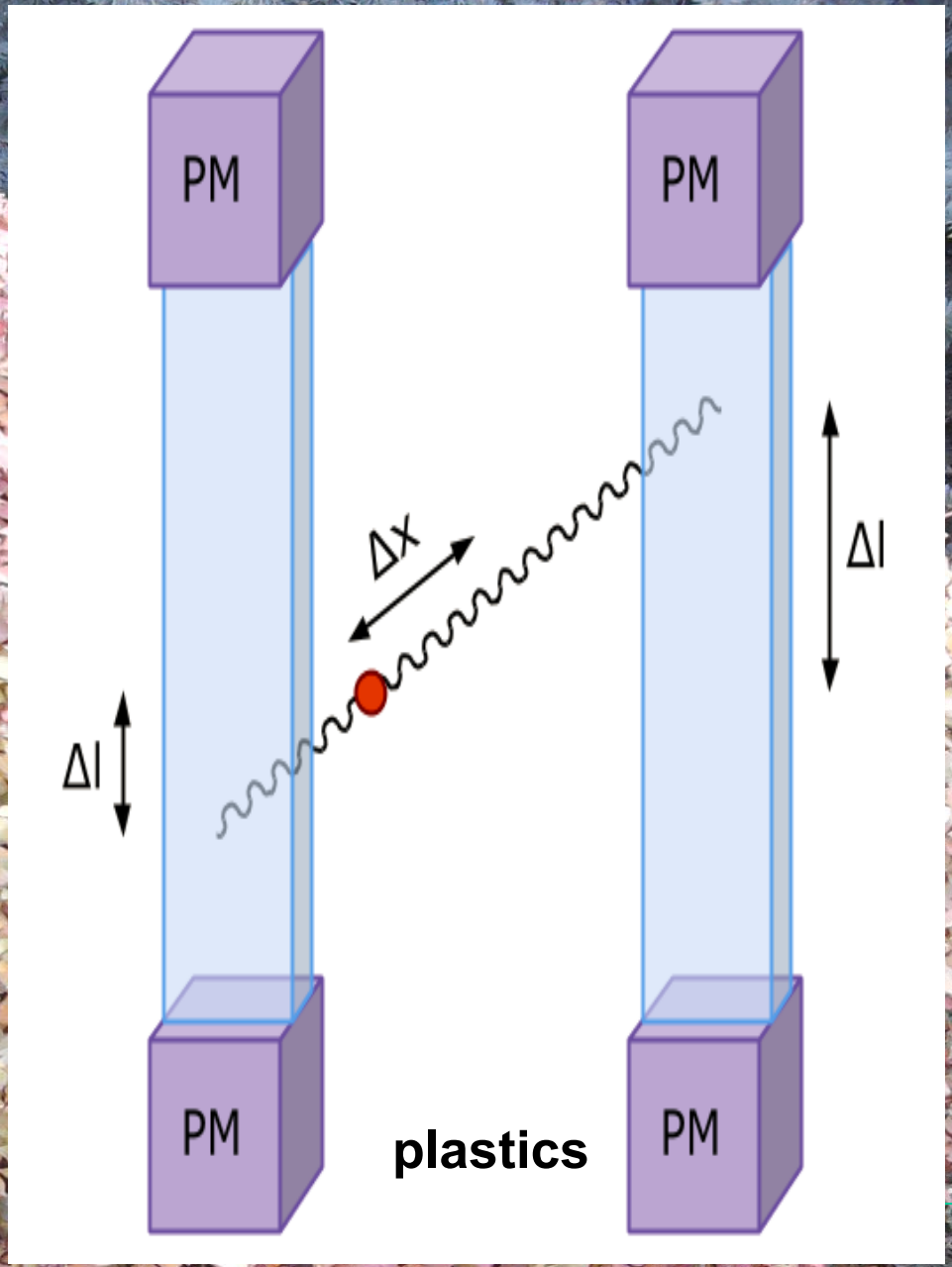


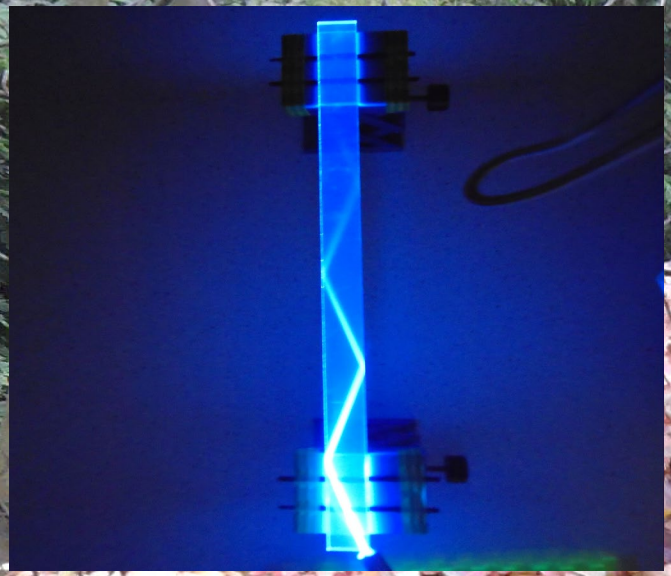
RADIOACTIVE SUGAR

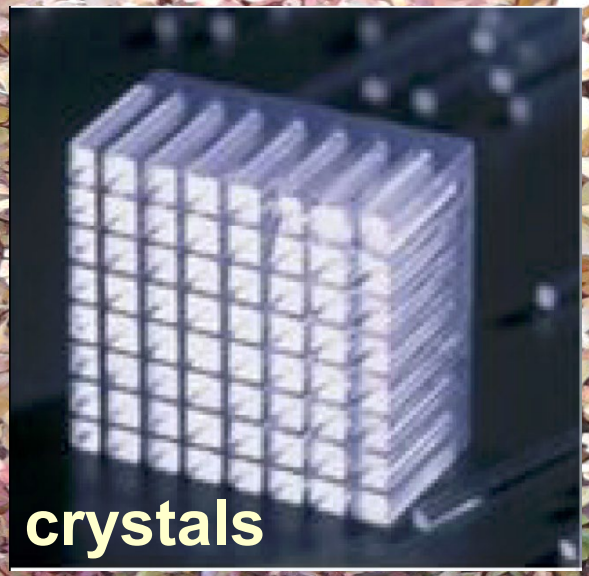
Fluoro–deoksy-glucose
(F-18 FDG)

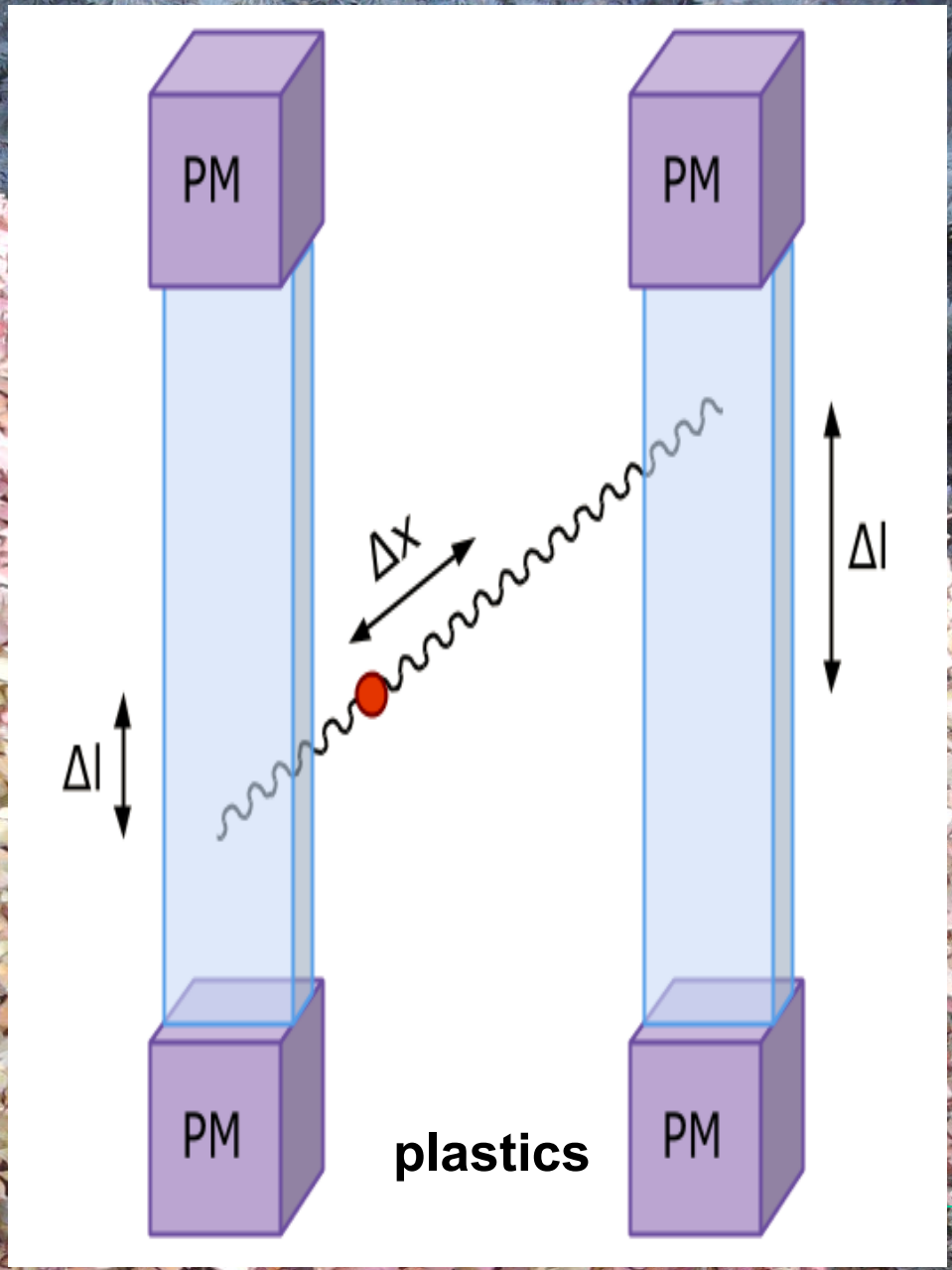



crystals

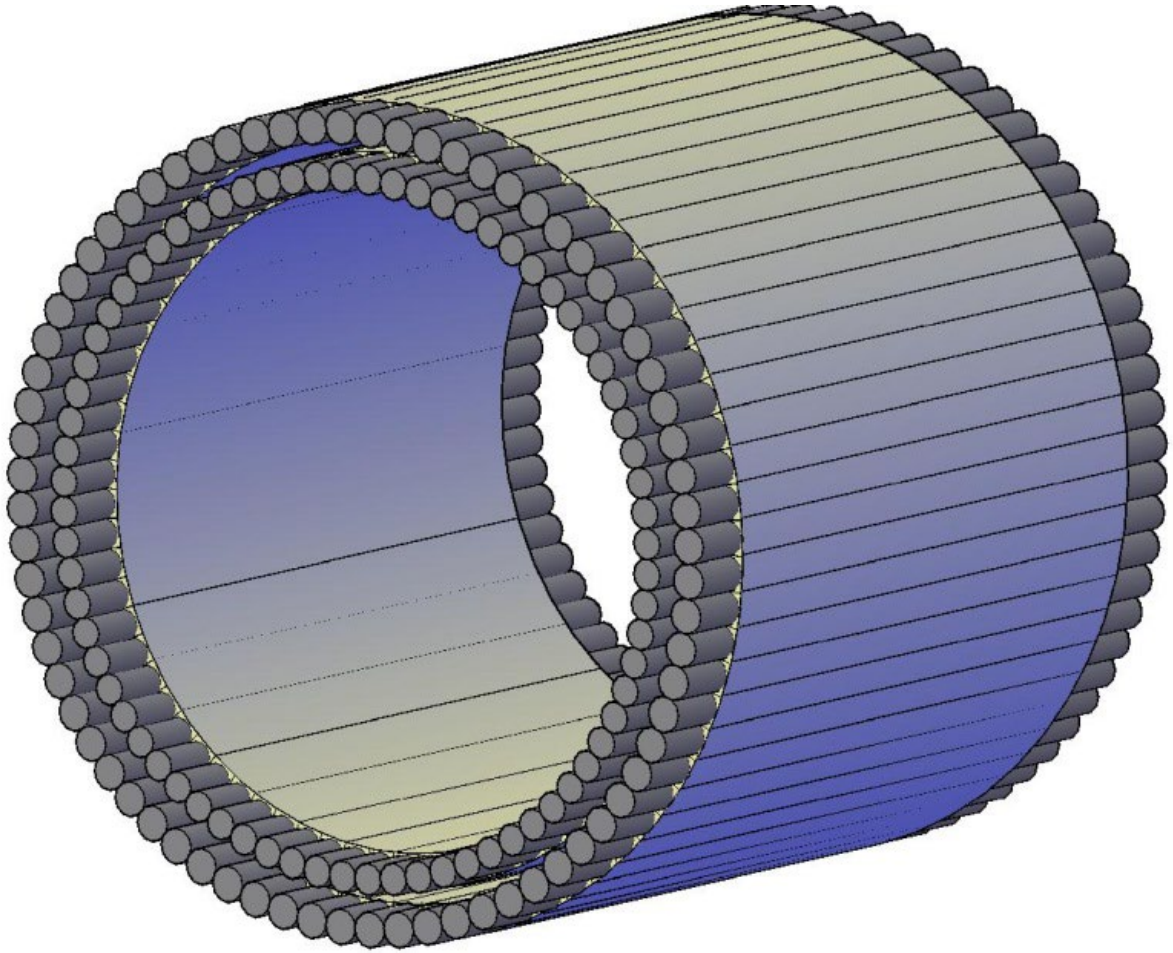

PM
PM
PM
PM
Δx
Δl
Δl
plastics




crystals


PM
PM
PM
PM
Δx
Δl
Δl
plastics

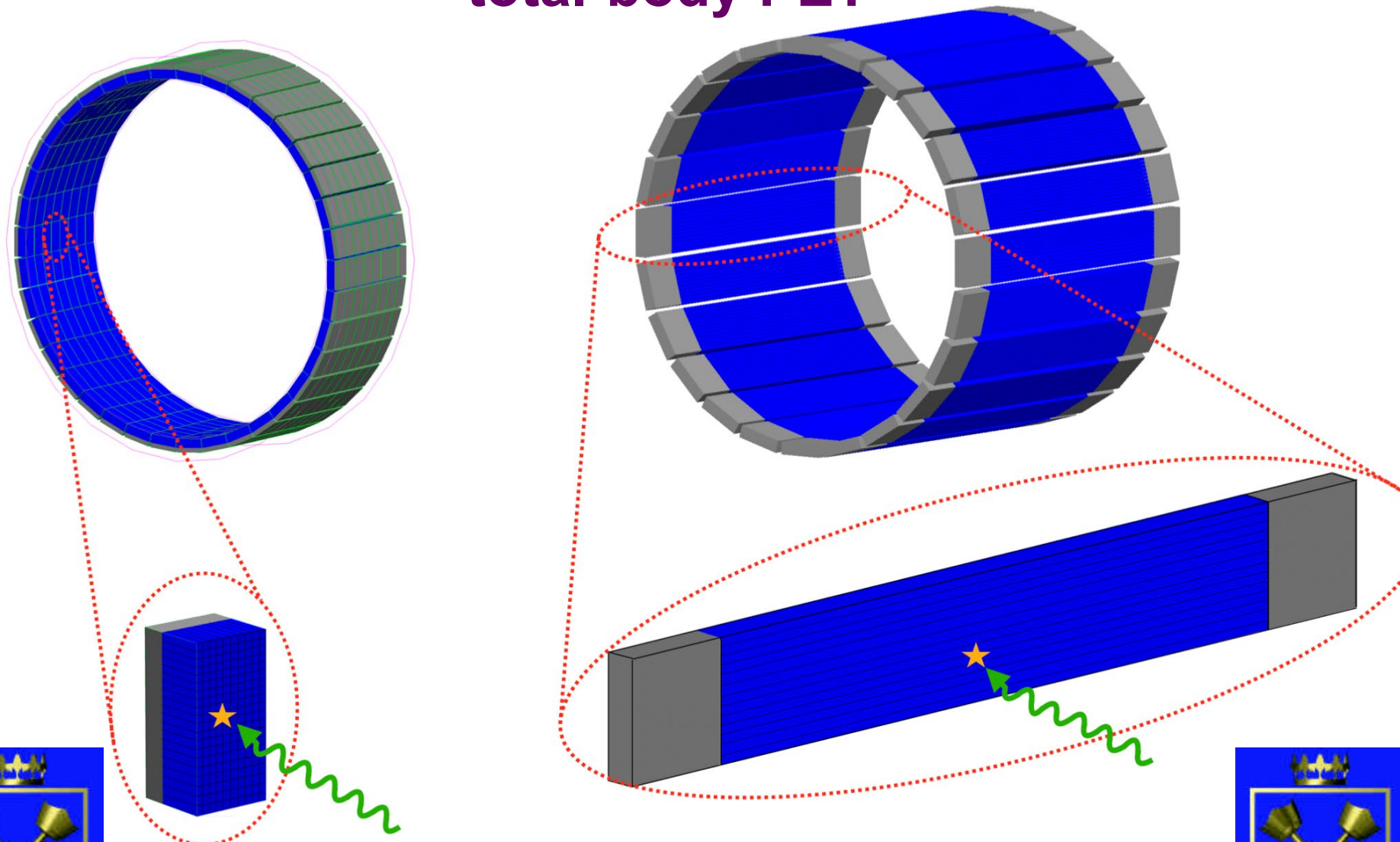
Development of cost-effective total-body PET



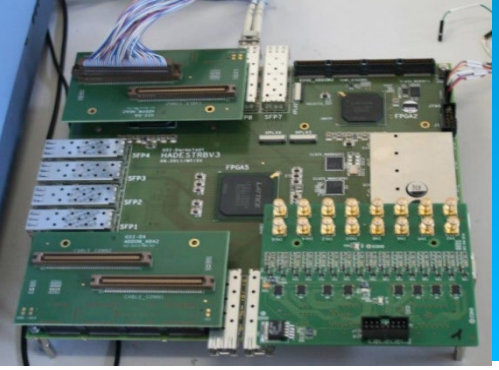
P. Moskal et al., Phys. Med. Biol. 66 (2021) 175015

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**



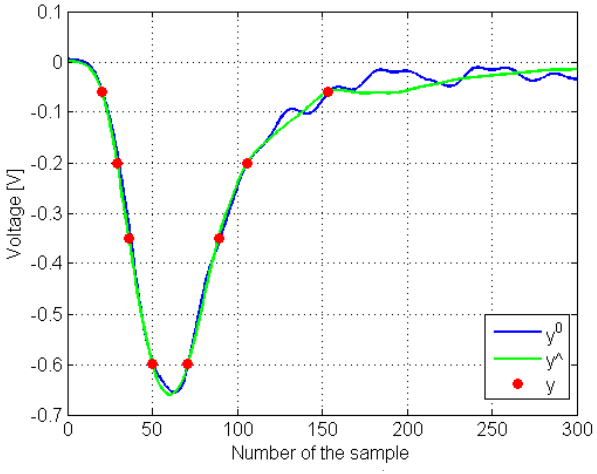
ONLY DIGITAL in triggerless mode

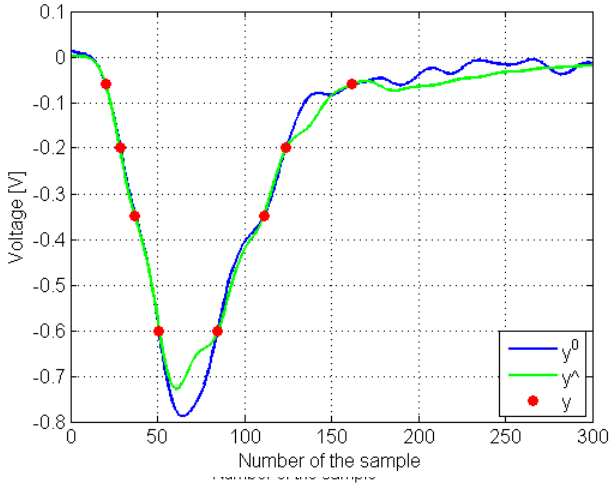
FFE sampling & Readout electronics

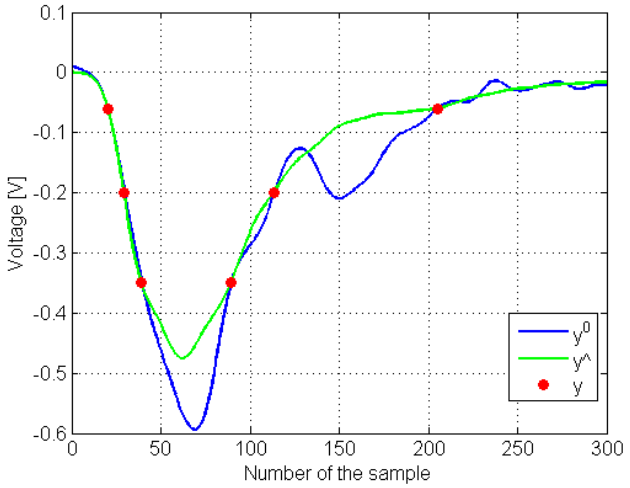
precision of 20ps (sigma) for 10 Euro per sample

M.Pałka, P.M., **PCT/EP2014/068367**

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







Library of signals; Principal Component Analysis; Compressive Sensing;

J-PET: L. Raczyński et al., Nucl. Instr. Meth. A786 (2015) 105

J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54

J-PET: L. Raczyński et al., Phys. Med. Biol. 62 (2017) 5076

Reconstruction

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

J-PET: M.Palka et al., JINST 12 (2017) P08001

J-PET: G. Korcyl et al., IEEE TMI 37 (2018) 2526

J-PET: W. Krzemień et al., SoftwareX 11 (2020) 100487

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

J-PET: P. Bialas et al., Bio-Alg. and Med-Sys. 10 (2014) 12

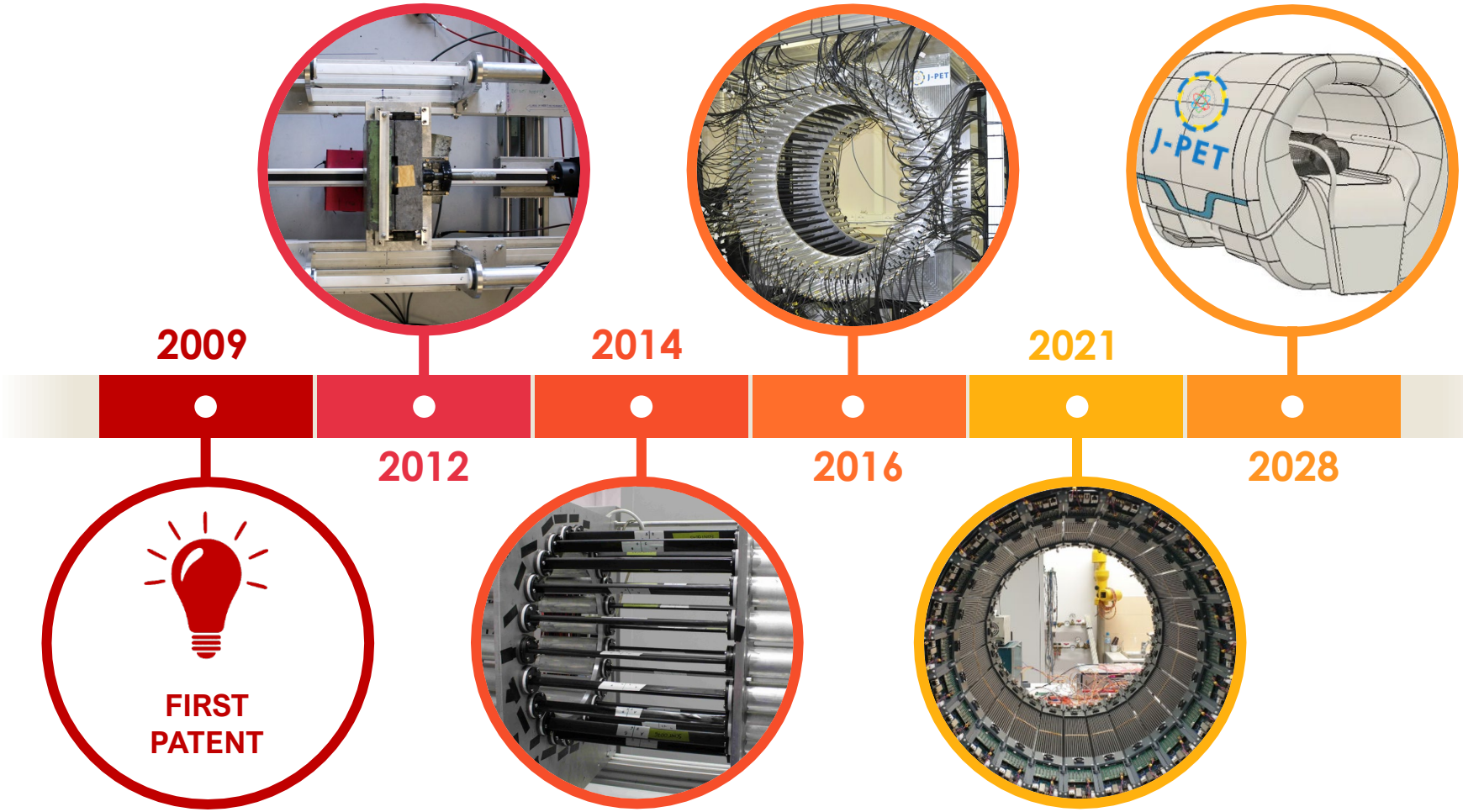
DISCLAIMER

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

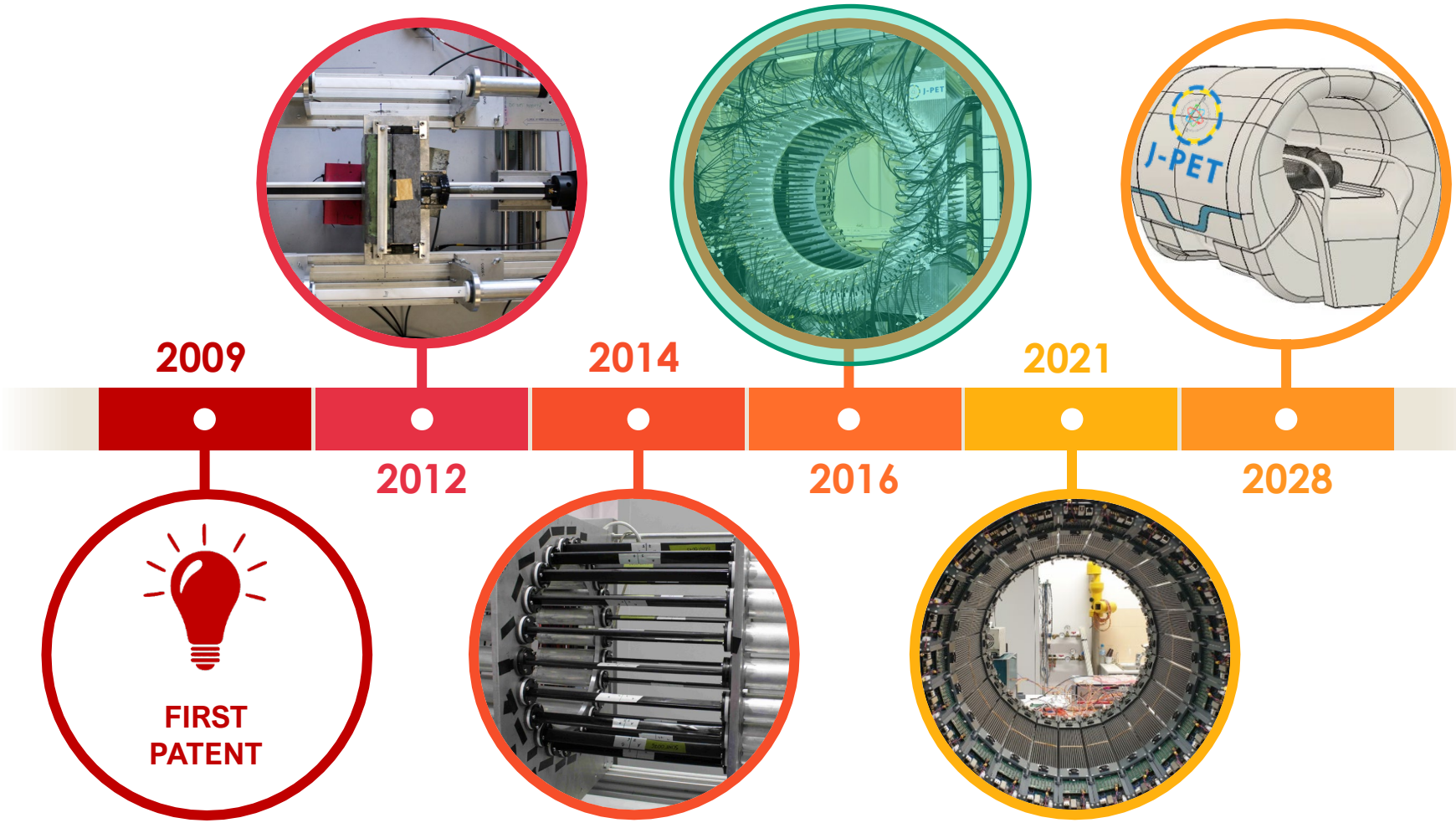
Europe: EP 2454611, EP 2454612, EP 3039456, EP 3039453, EP 3189356, EP 3189523, EP 3 323 001, EP 3347742, EP 3513221

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)



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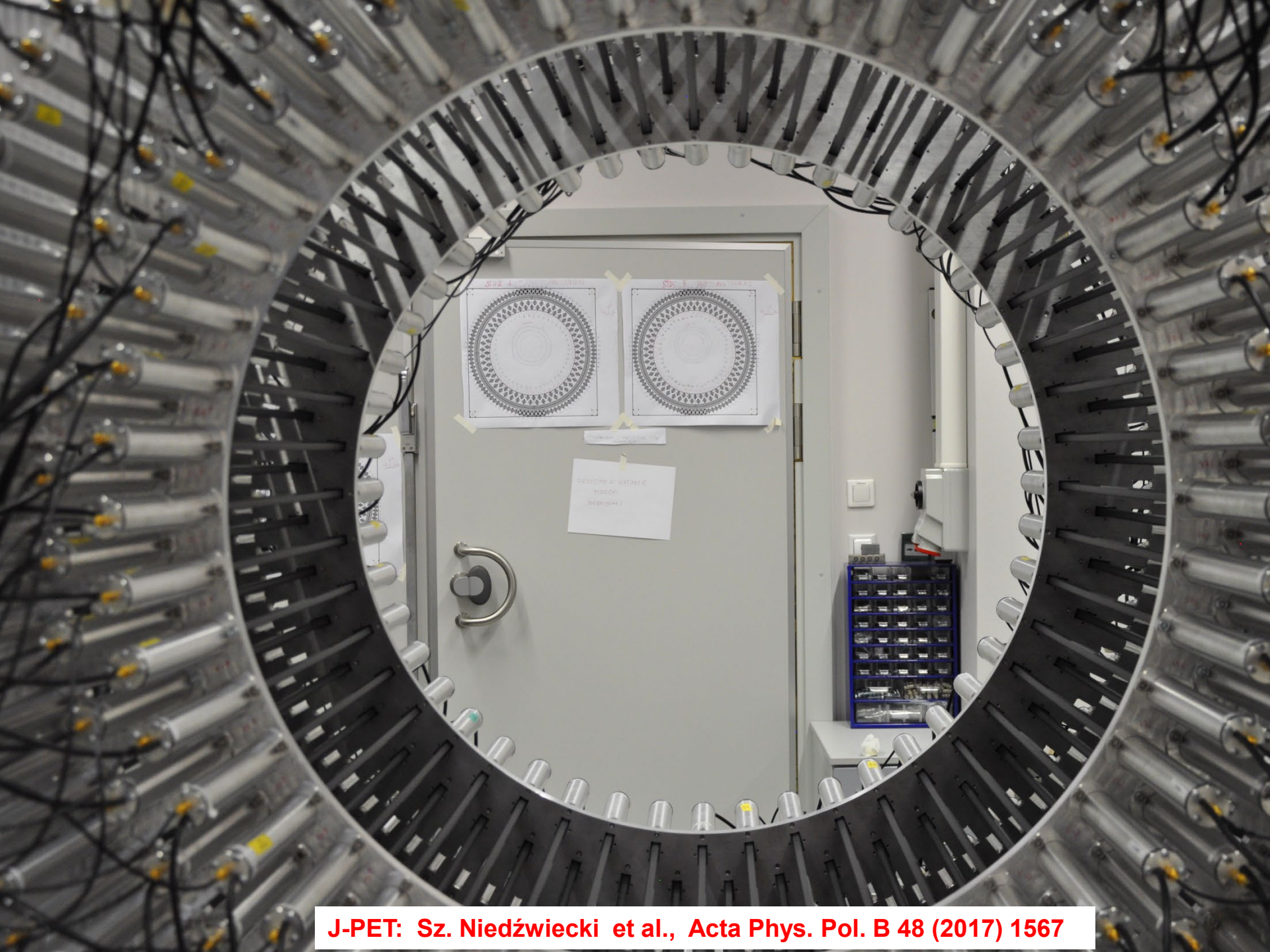
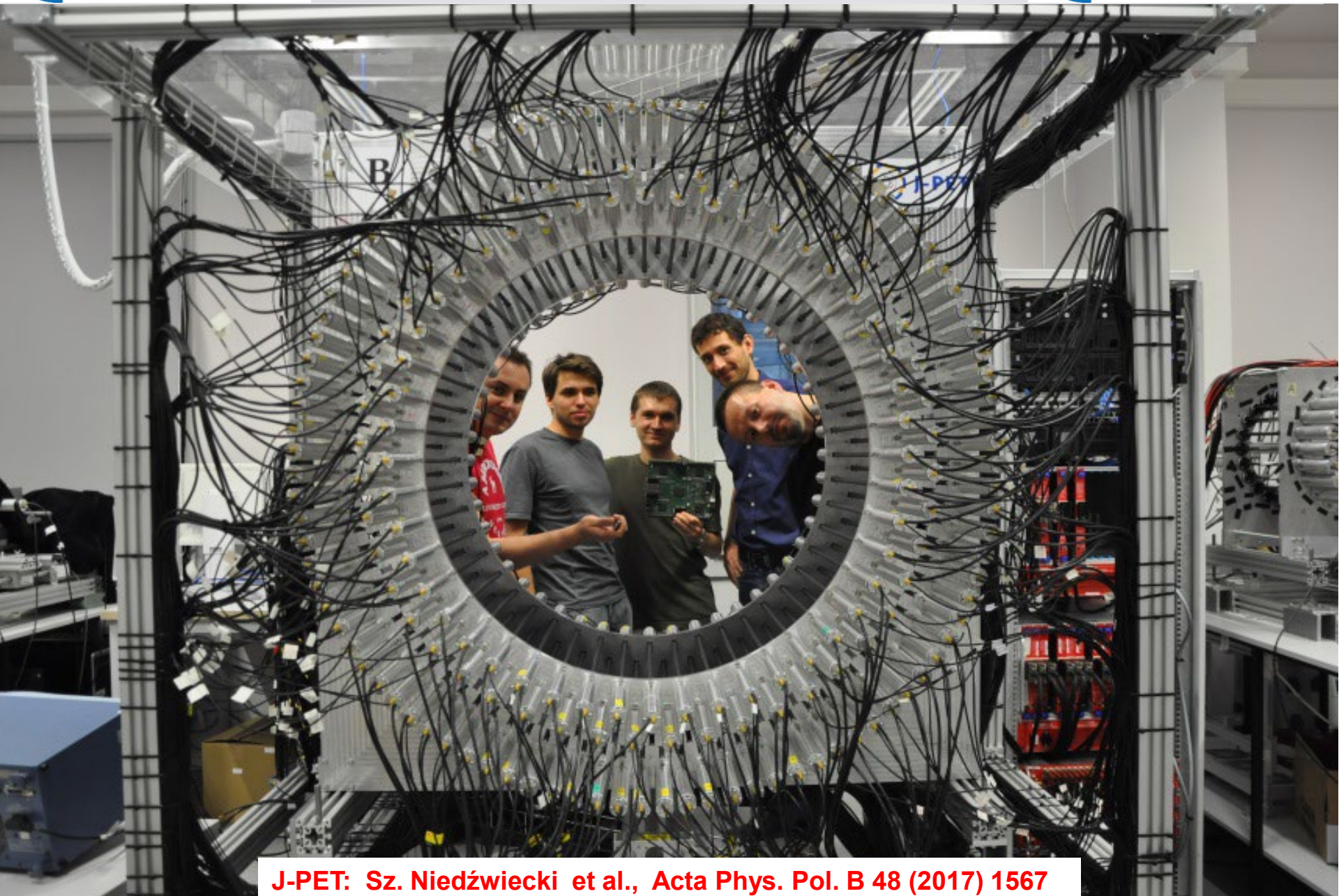
Foundation for Polish Science (TEAM)
National Center for Research and Development (Innotech)
National Science Center (OPUSes, MAESTRO)



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

Jagiellonian PET



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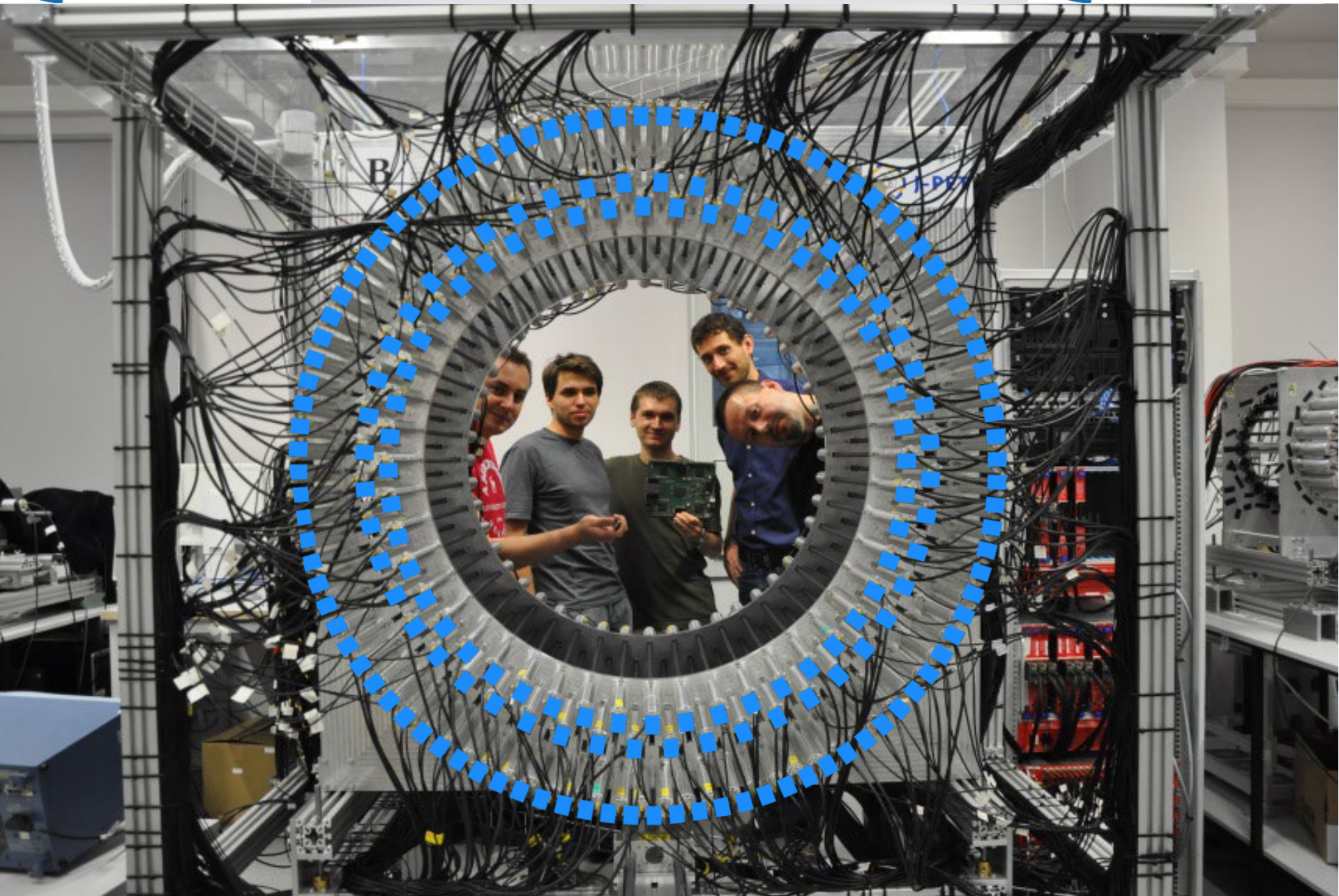
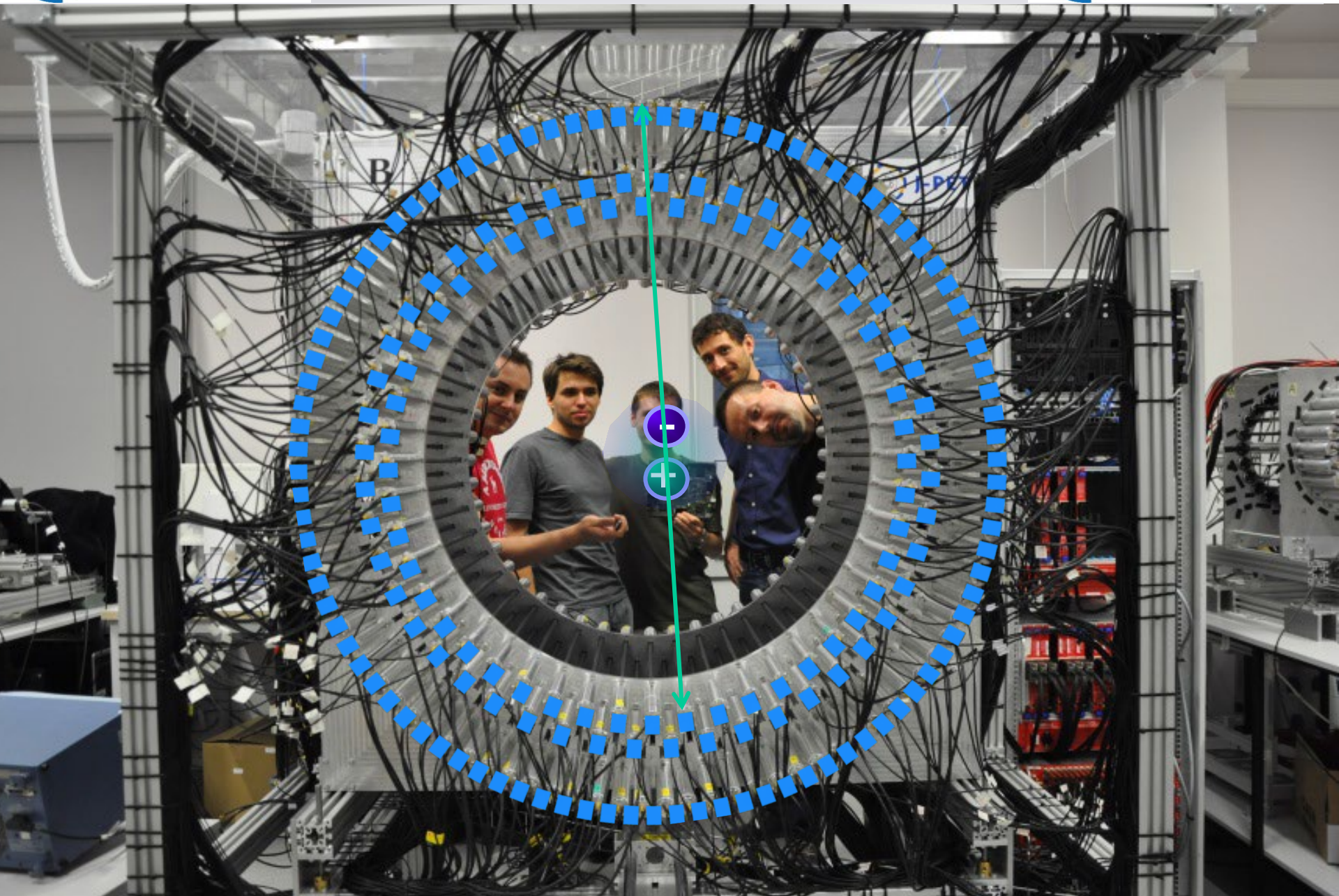
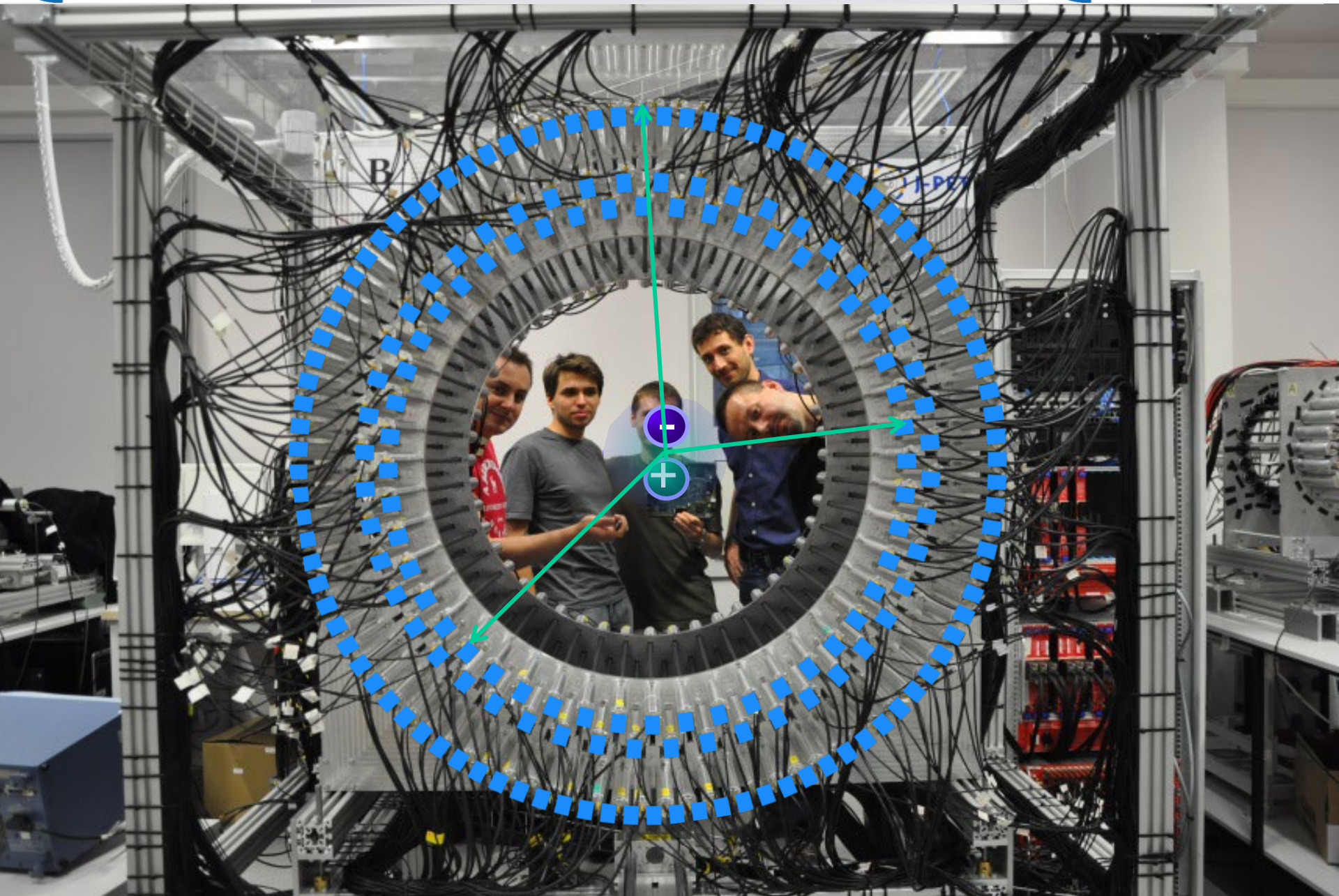
Jagiellonian PET

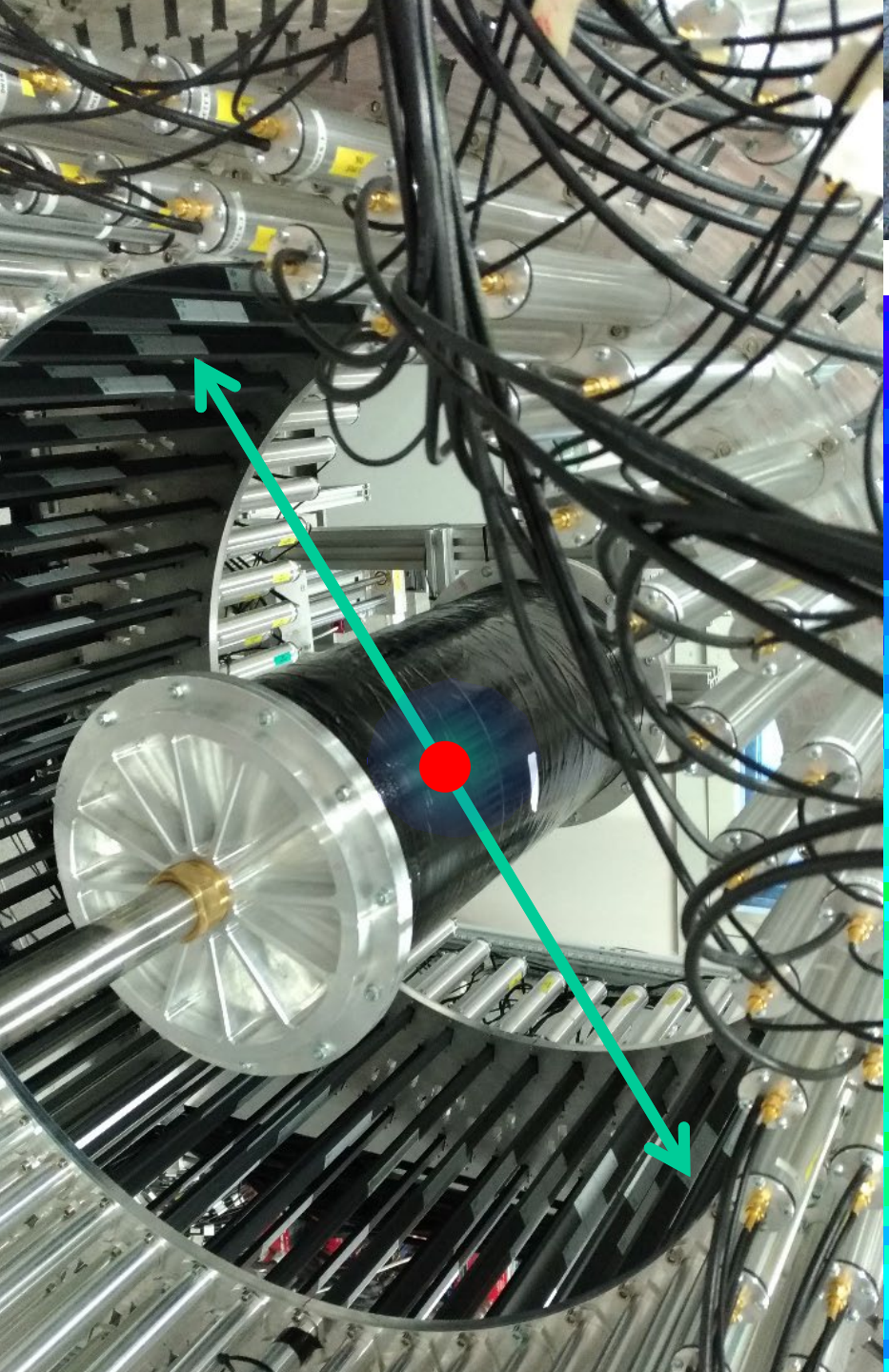


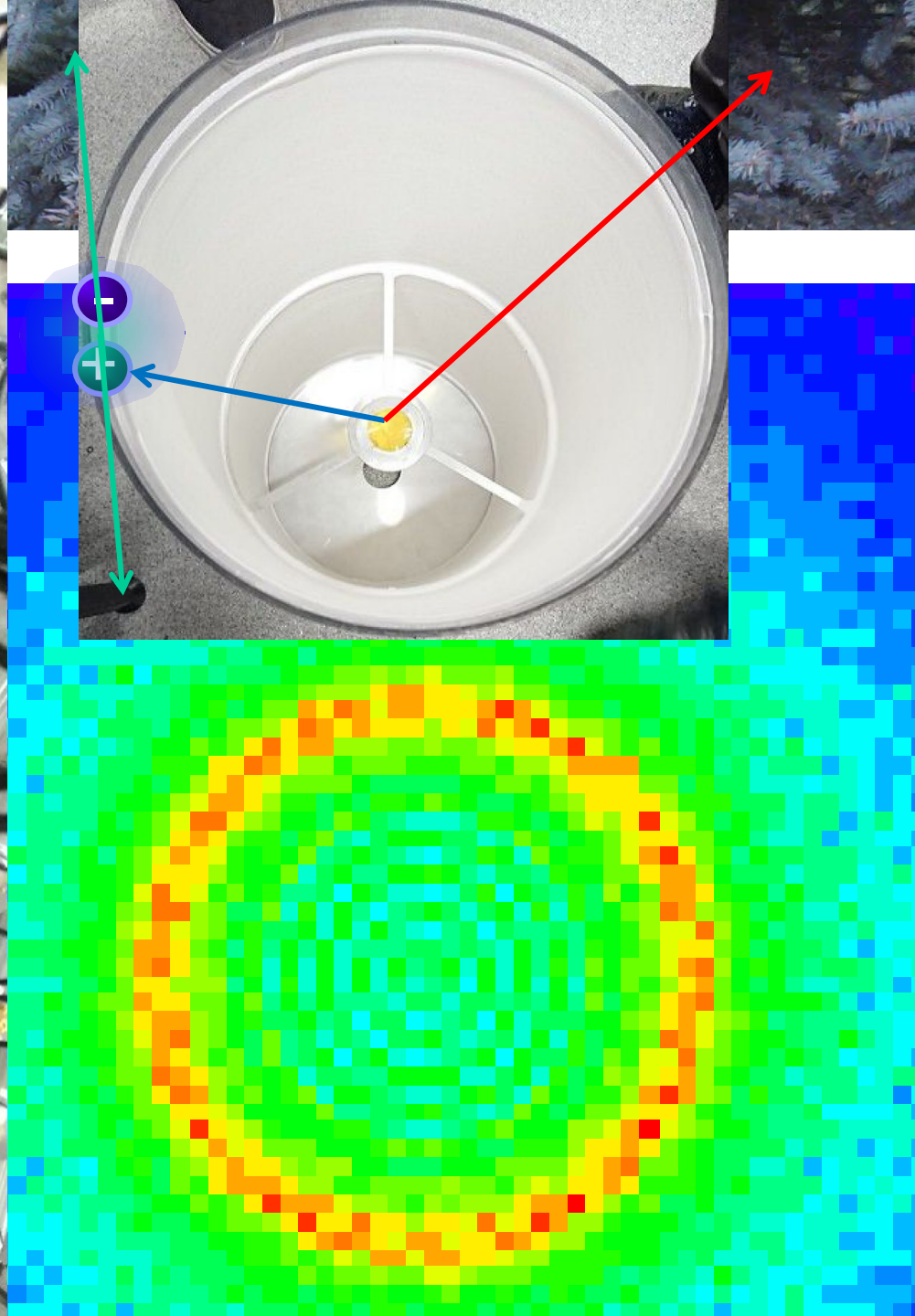
Jagiellonian PET

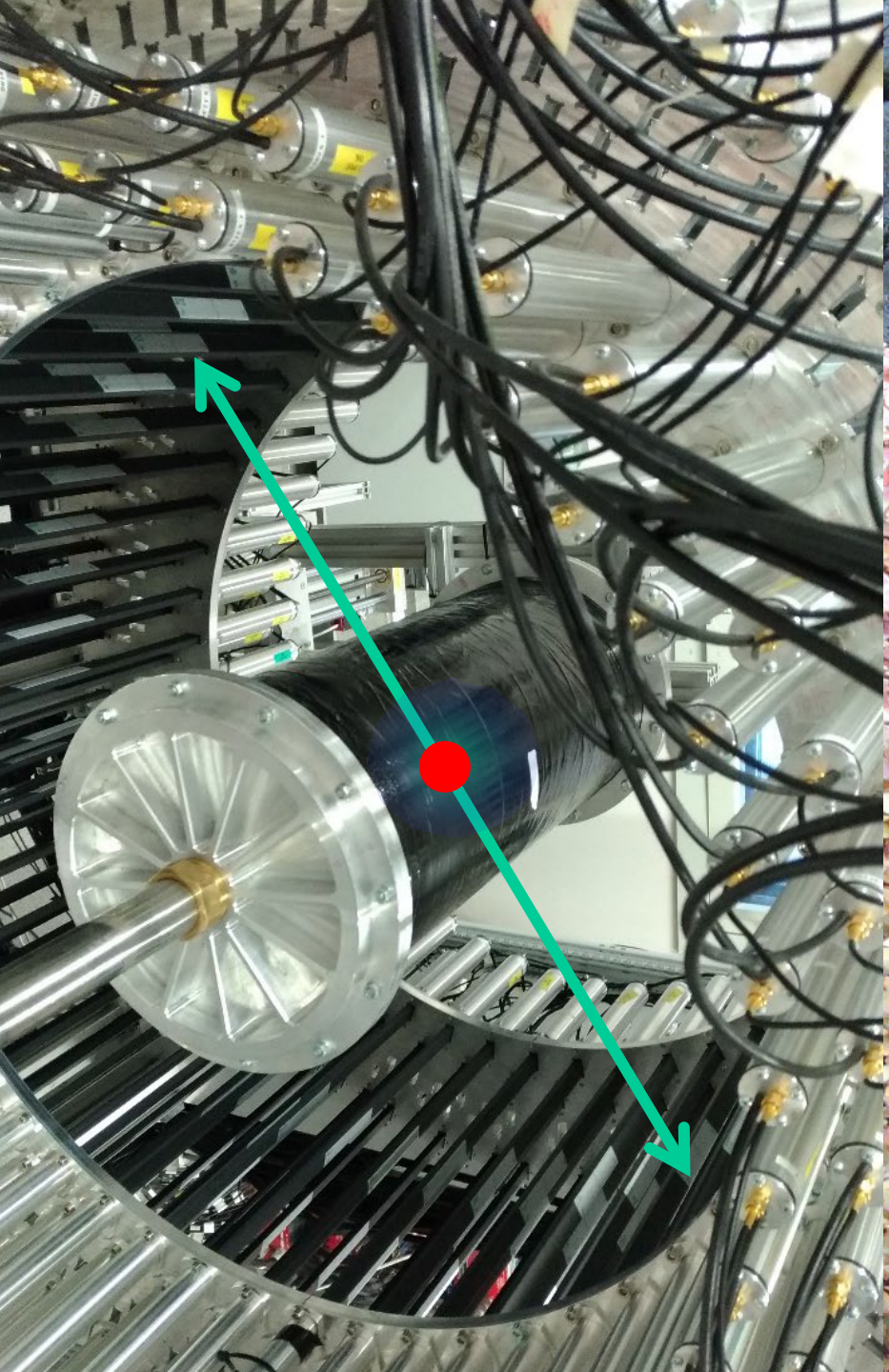


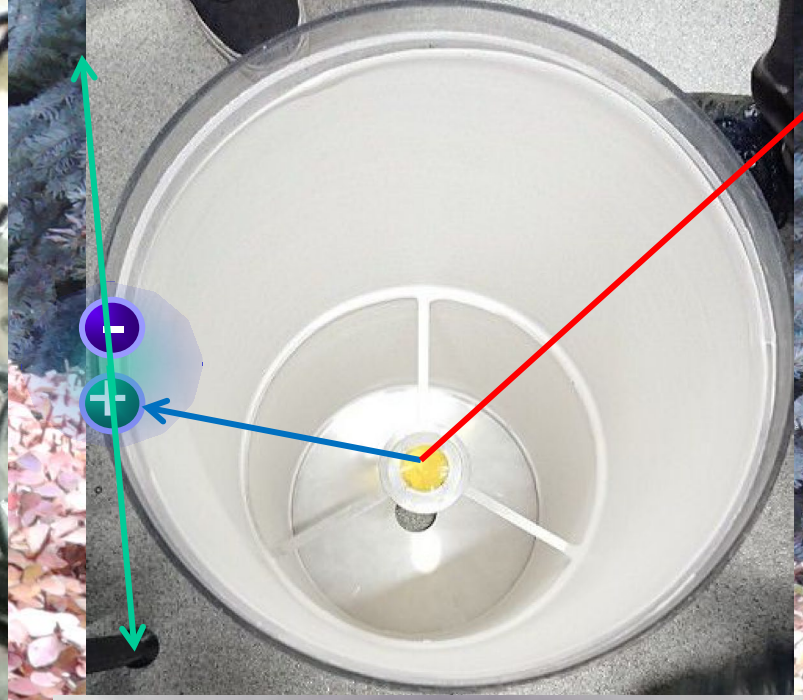
Jagiellonian PET

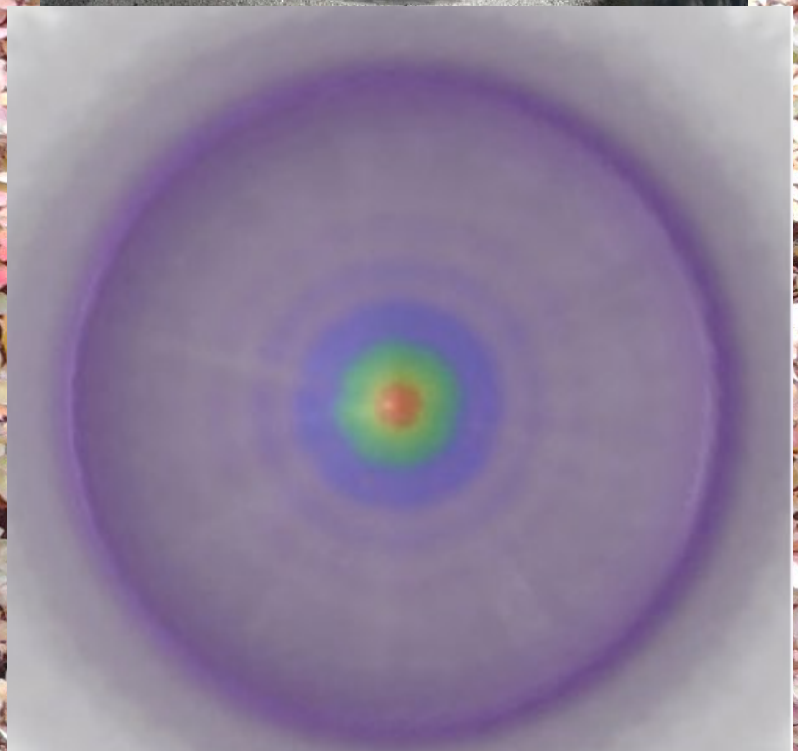




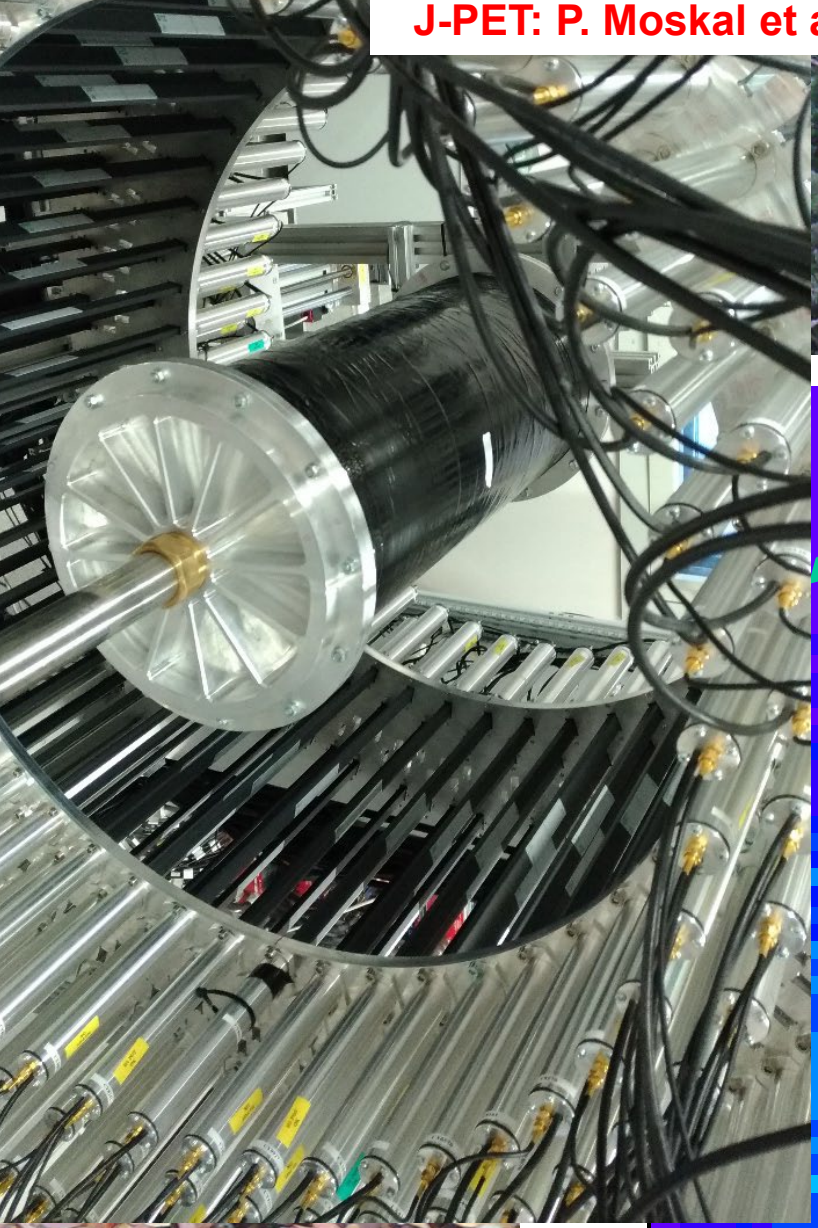


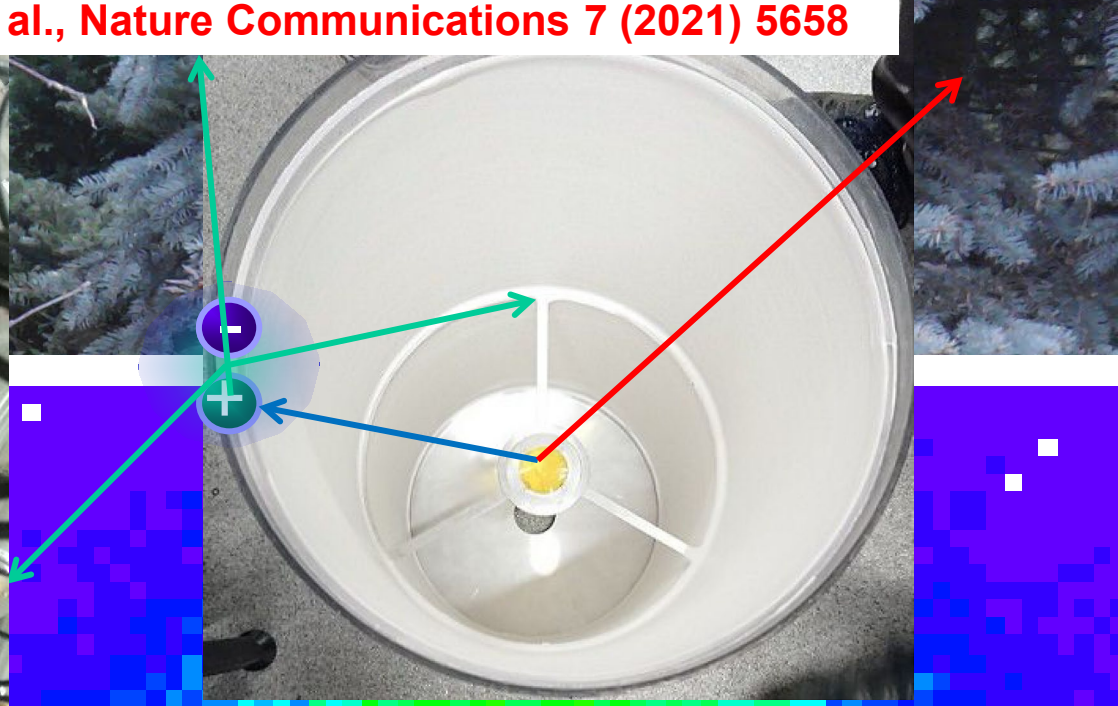


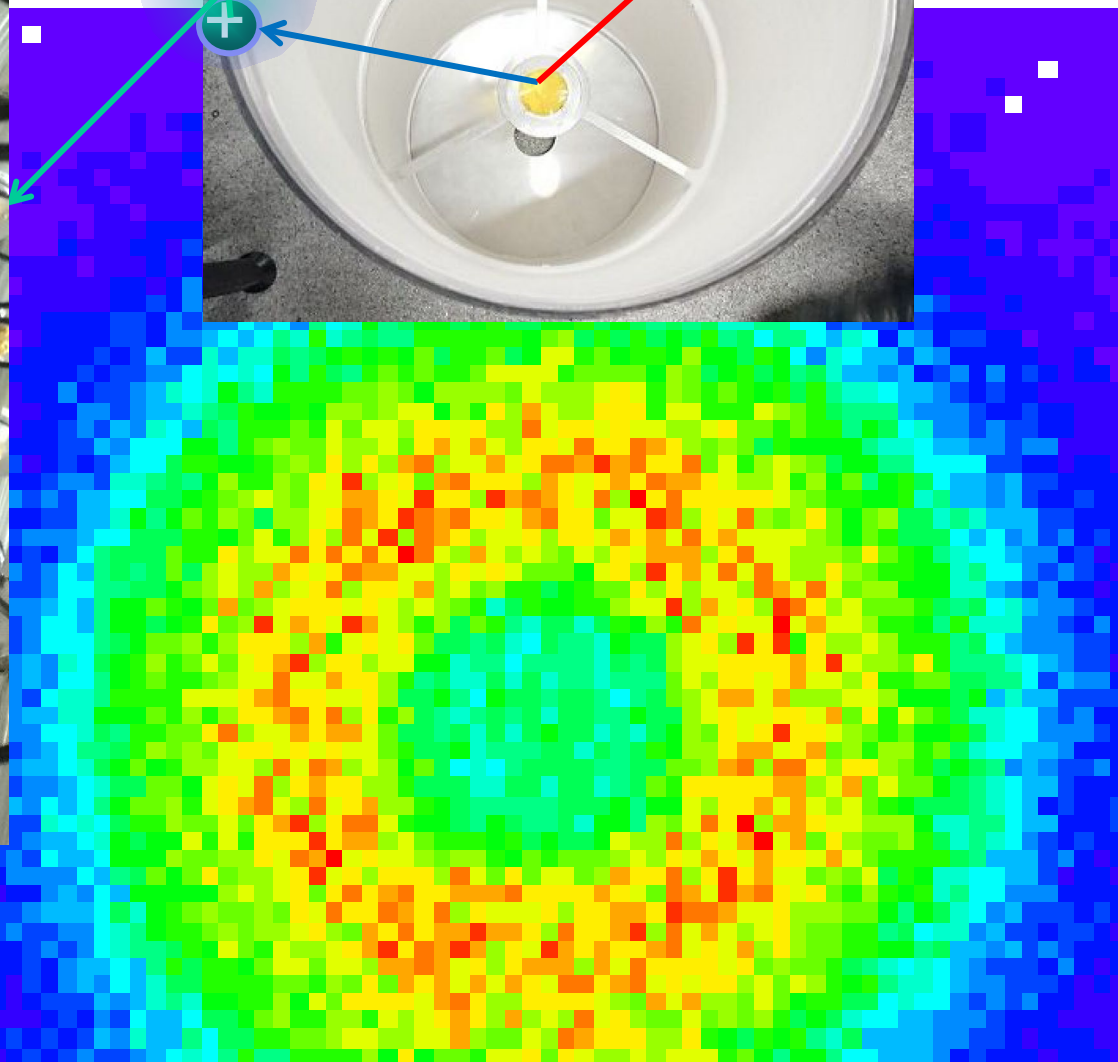




J-PET: P. Moskal et al., Nature Communications 7 (2021) 5658



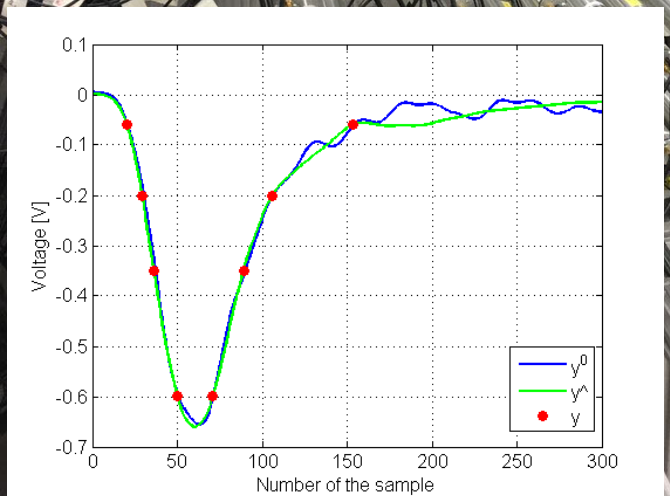


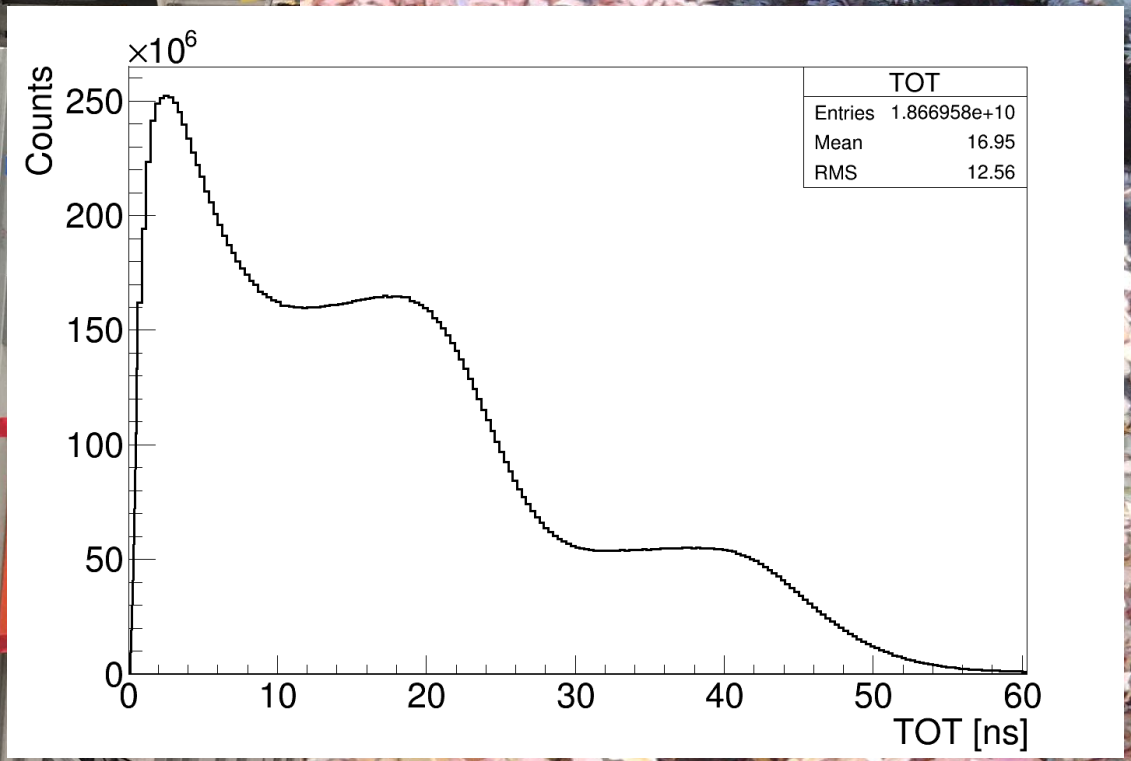


$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$

$^{22}Ne + \gamma$

^{22}Na





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

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

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

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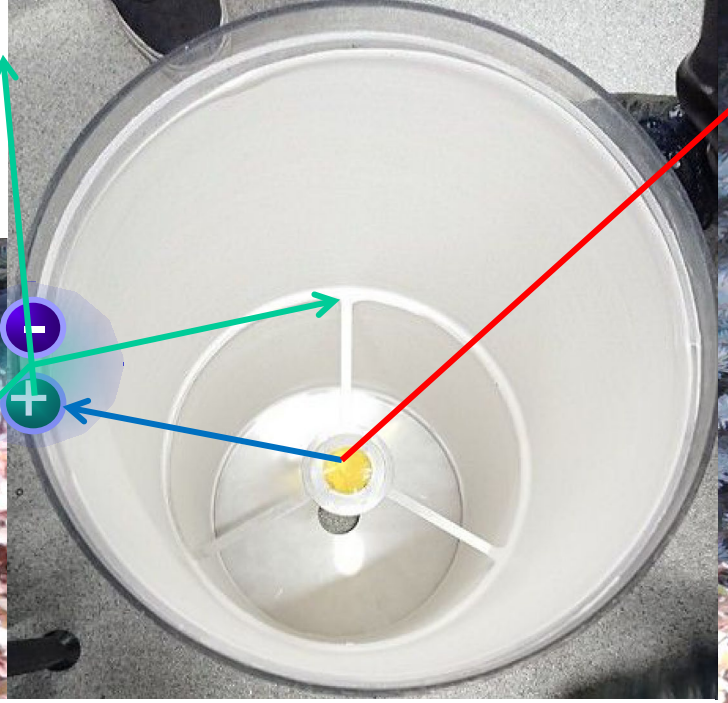
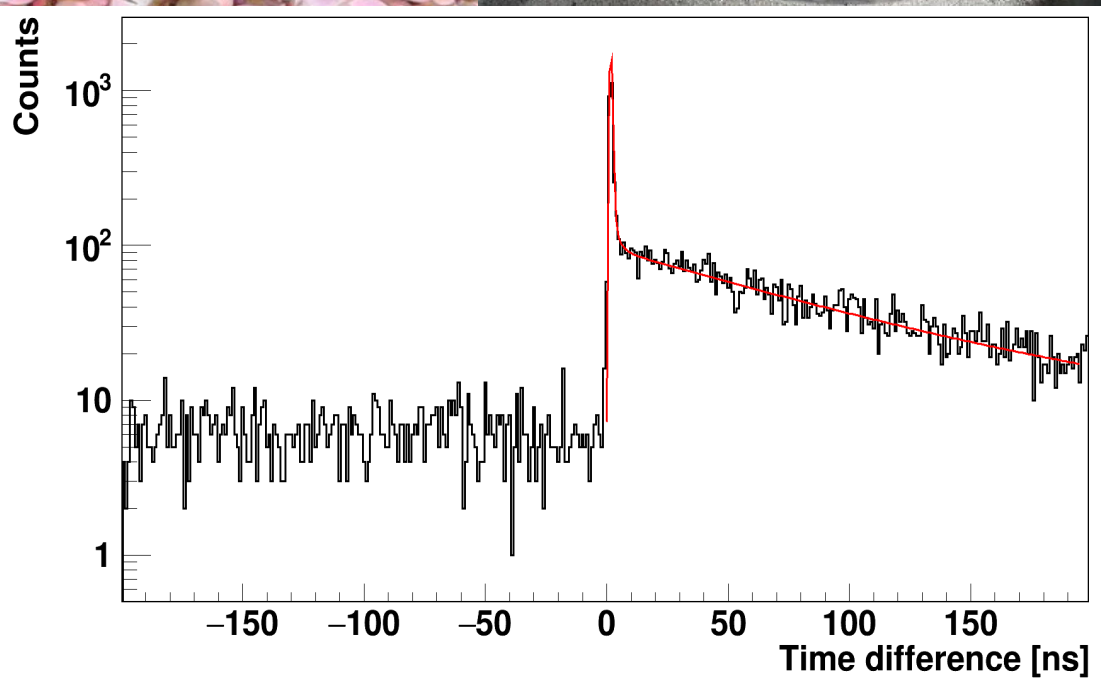
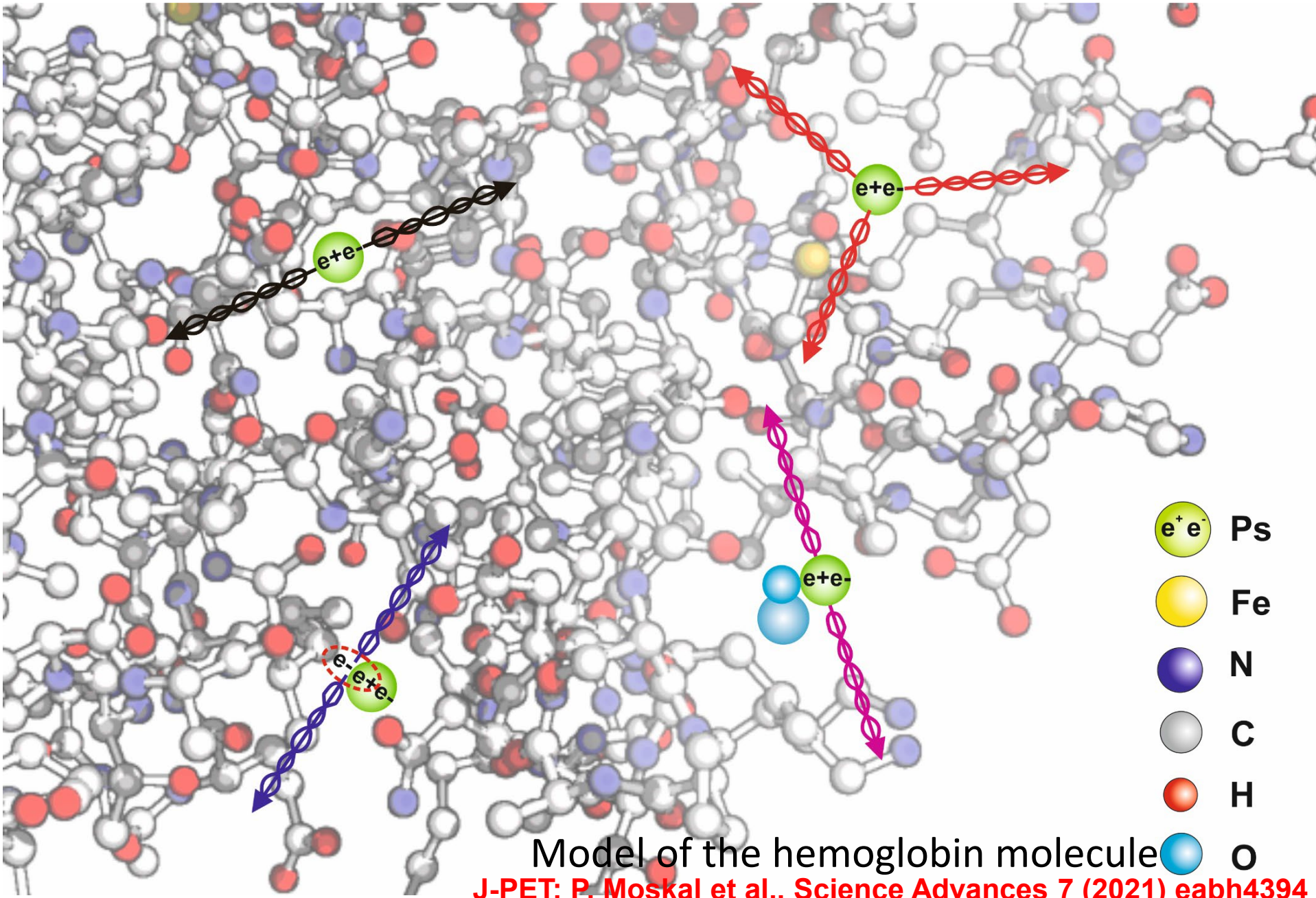




J-PET: K. Dulski et al., Nucl. Instr. Meth. A 1008 (2021) 165452

Positronium imaging

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

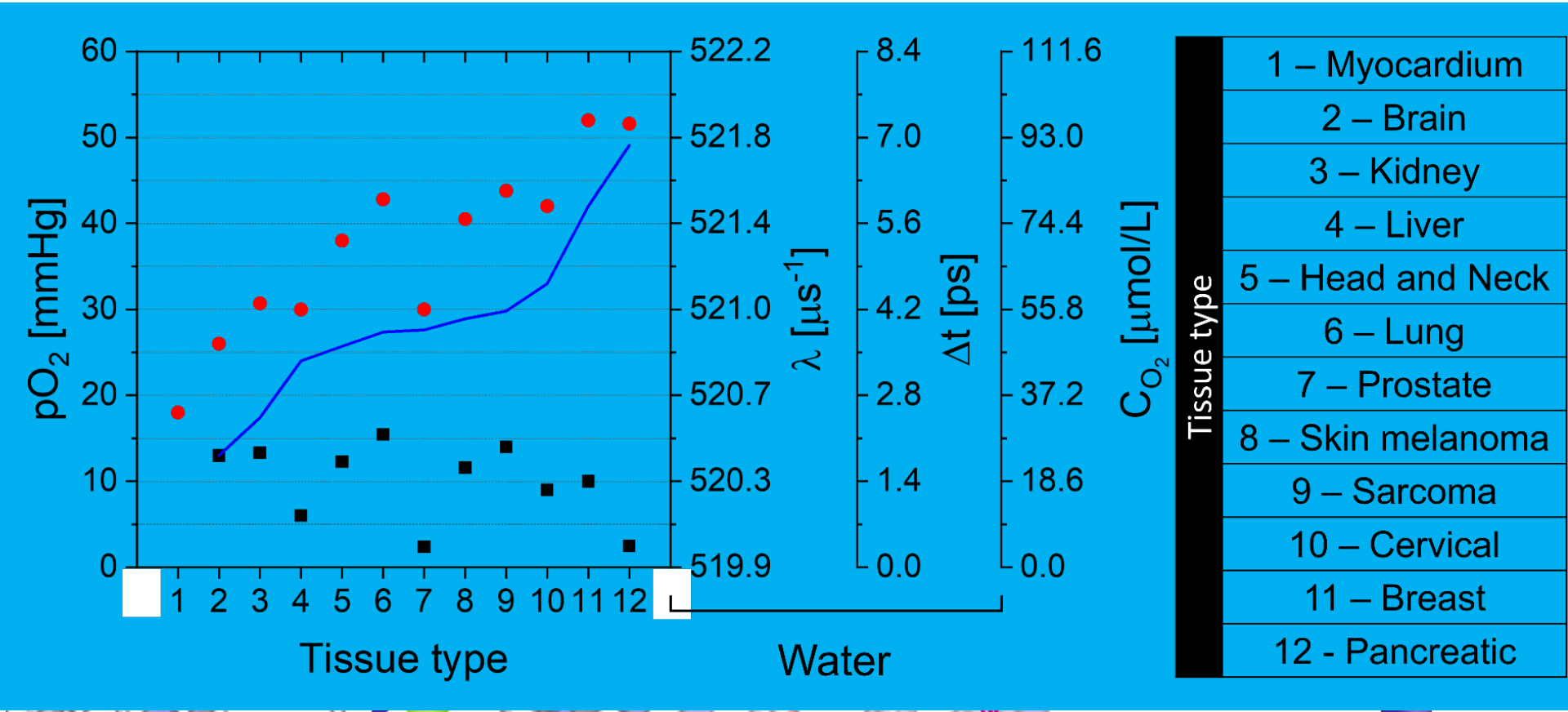


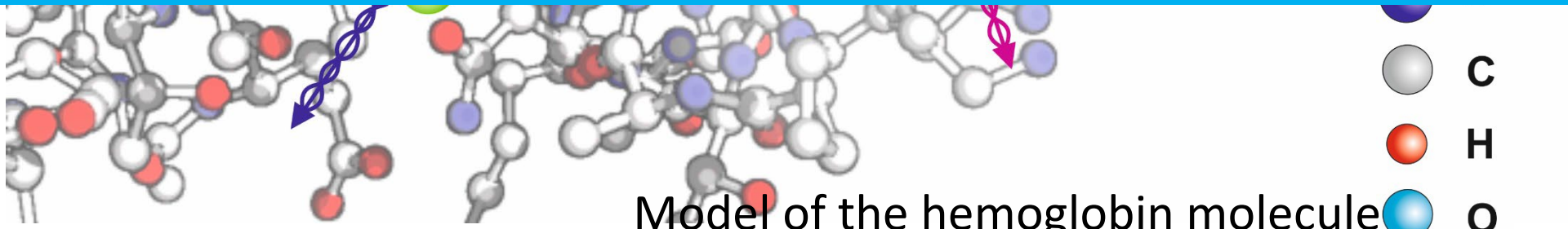
Model of the hemoglobin molecule

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"





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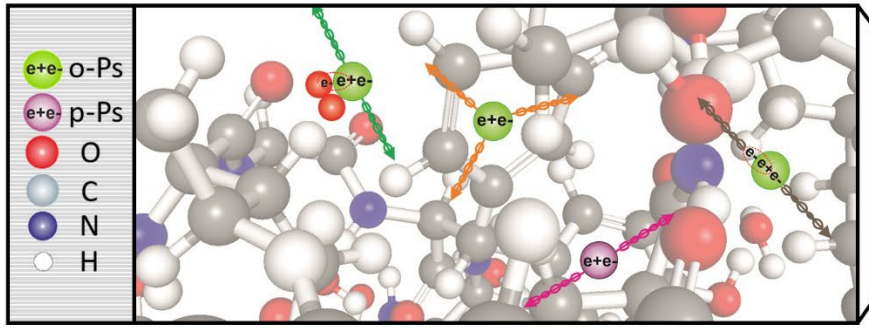
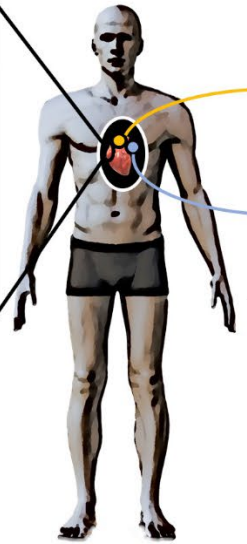
J-PET: P. Moskal, Science Advances 7 (2021) eabh4394





Adipose tissue

Cardiac Myxoma

Transfer from hospital

Sample preparation

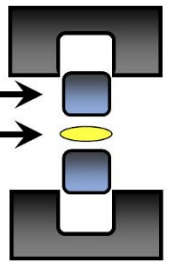
Patient 1 1 1

Patient 2 2 2

Aluminium holder

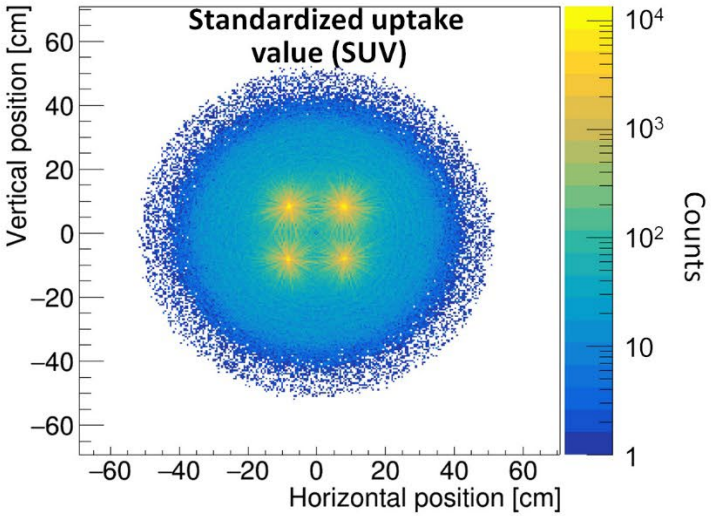
Sample

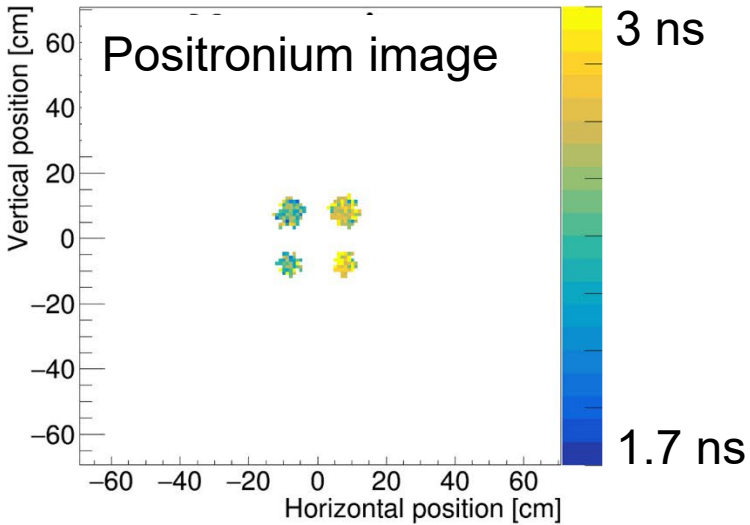
e^+ Source

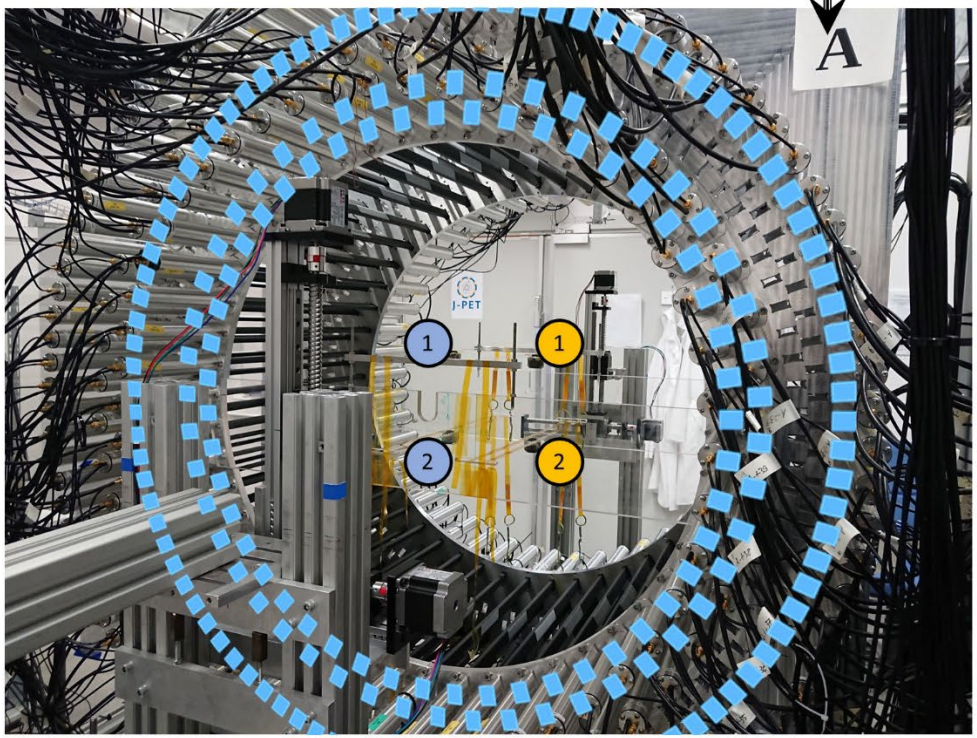


Placing samples in the chambers

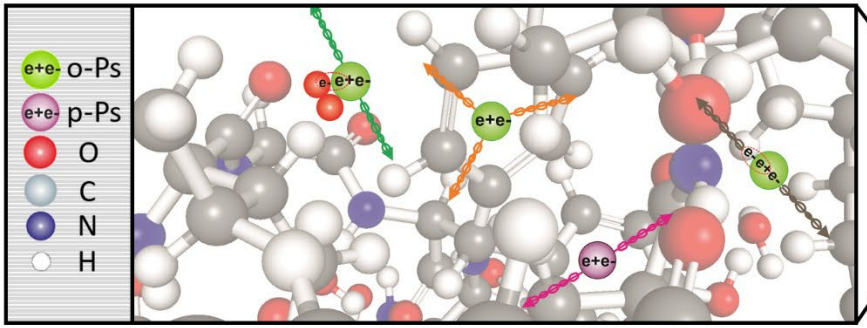
Inserting setup to the detector

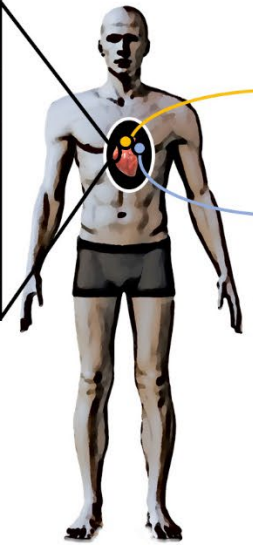






J-PET: P. Moskal et al., Science Advances 7 (2021) eabh4394





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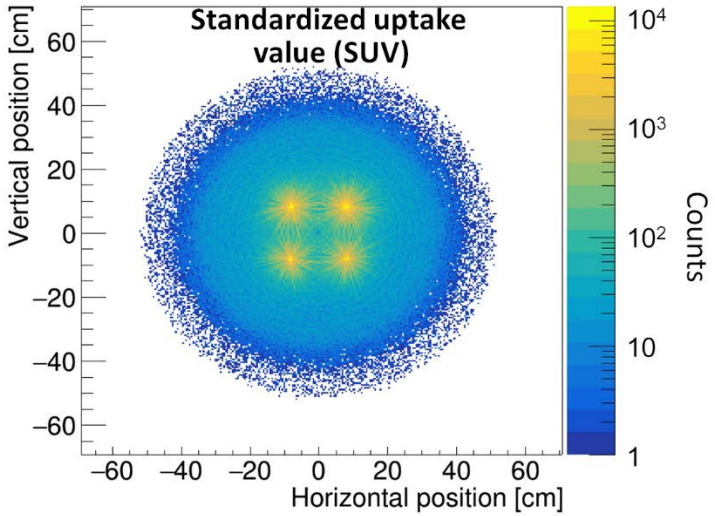
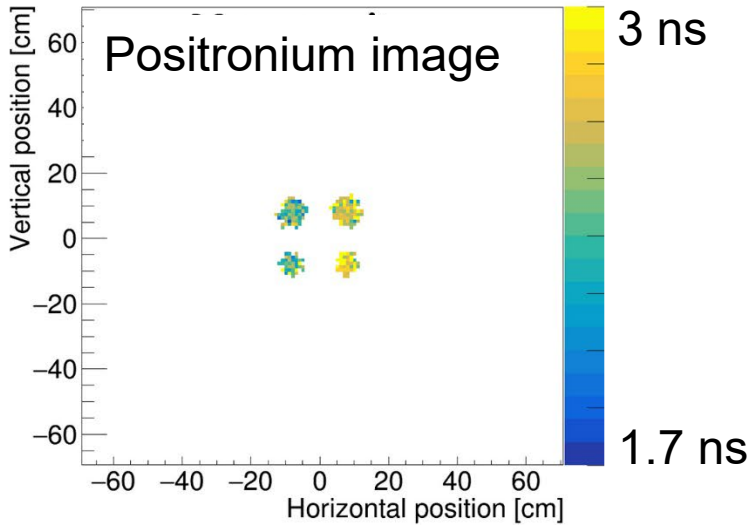
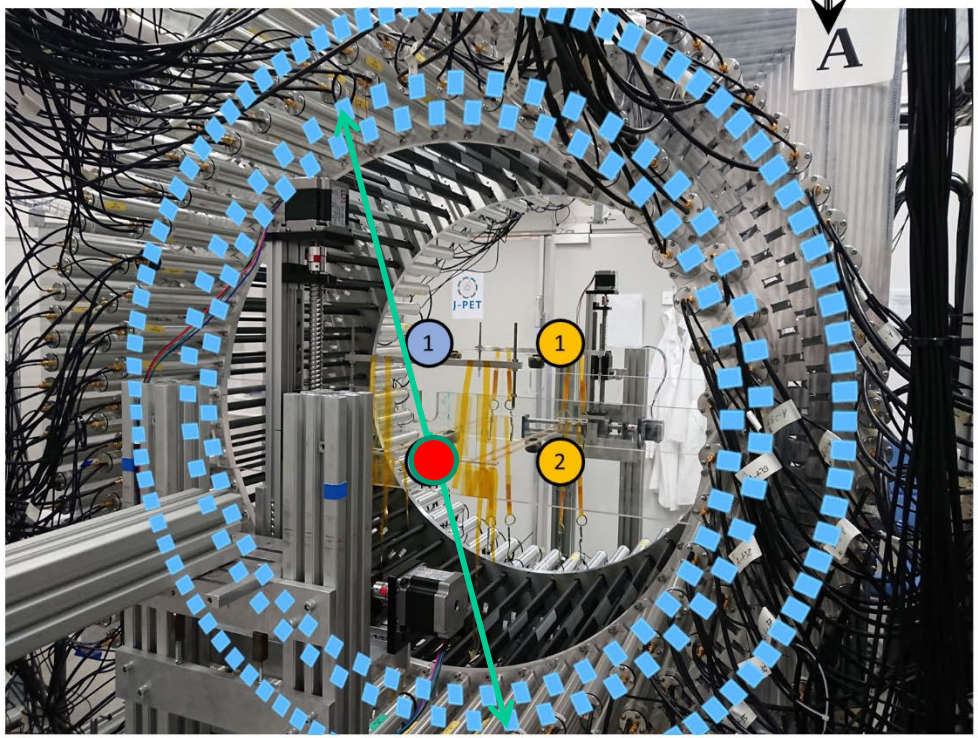


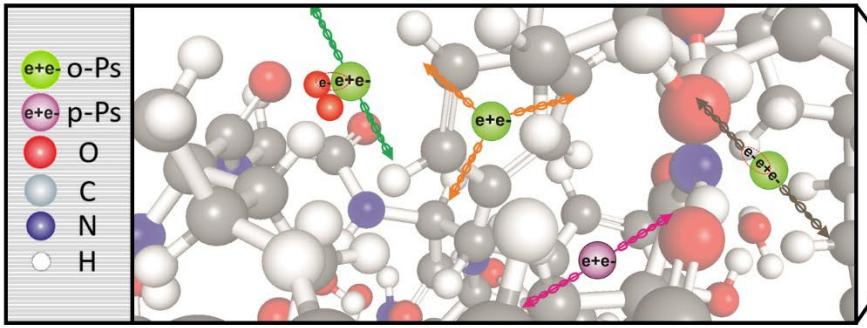


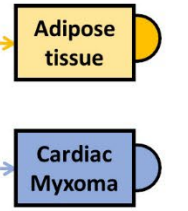
Placing samples in the chambers

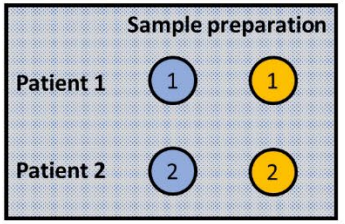
Inserting setup to the detector

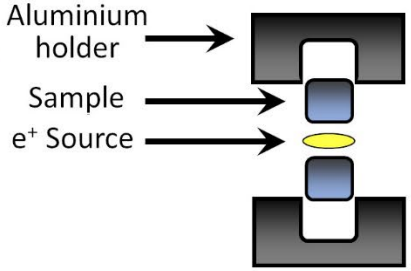


J-PET: P. Moskal et al., Science Advances 7 (2021) eabh4394



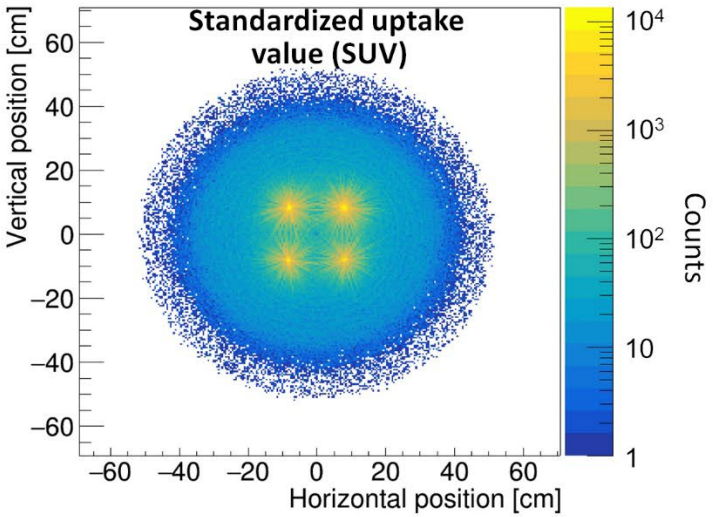


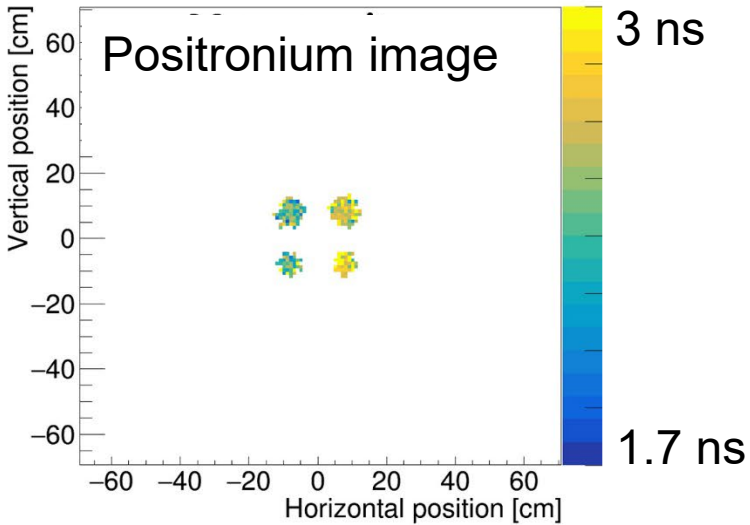


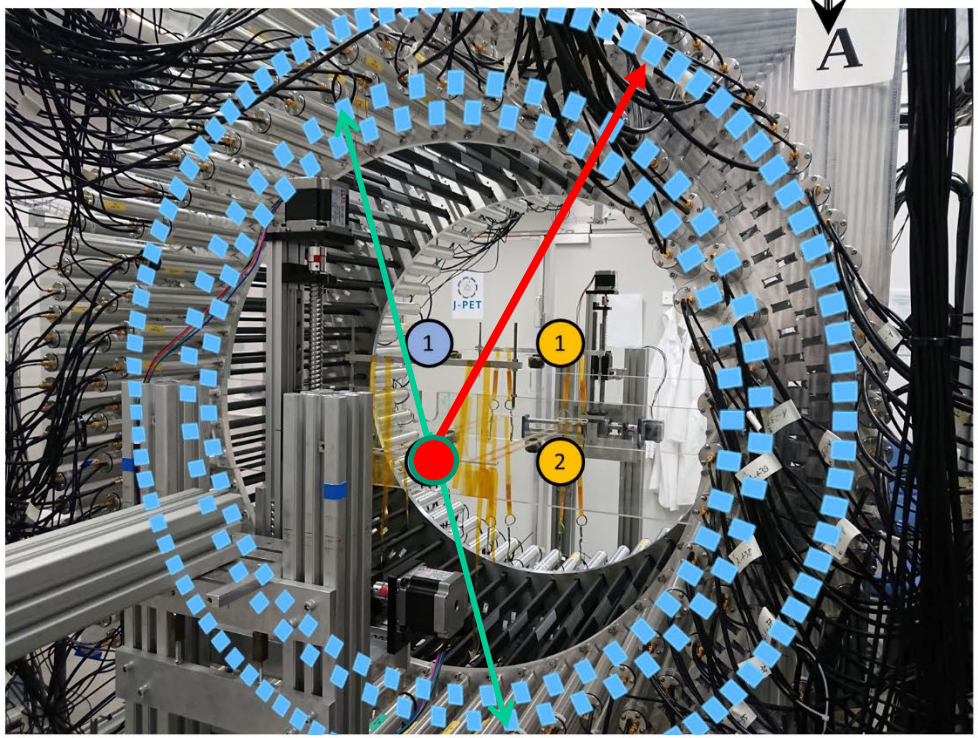


Placing samples in the chambers

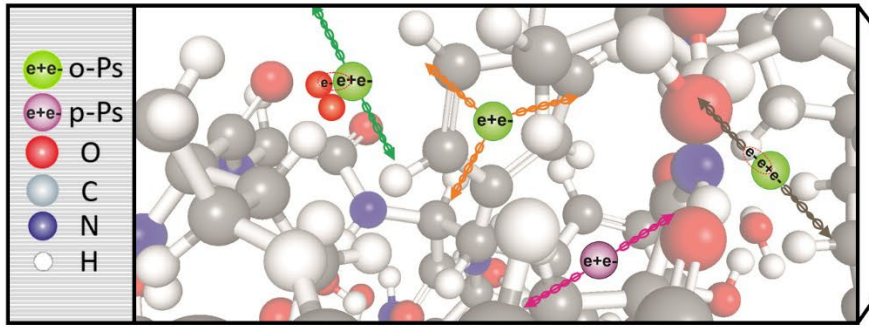
Inserting setup to the detector

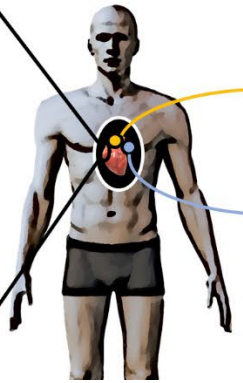






J-PET: P. Moskal et al., Science Advances 7 (2021) eabh4394

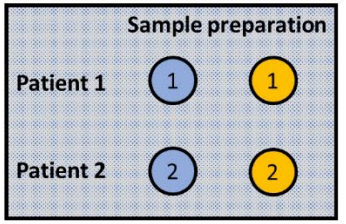




Adipose tissue

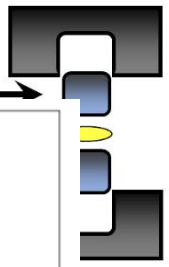
Cardiac Myxoma

Transfer from hospital



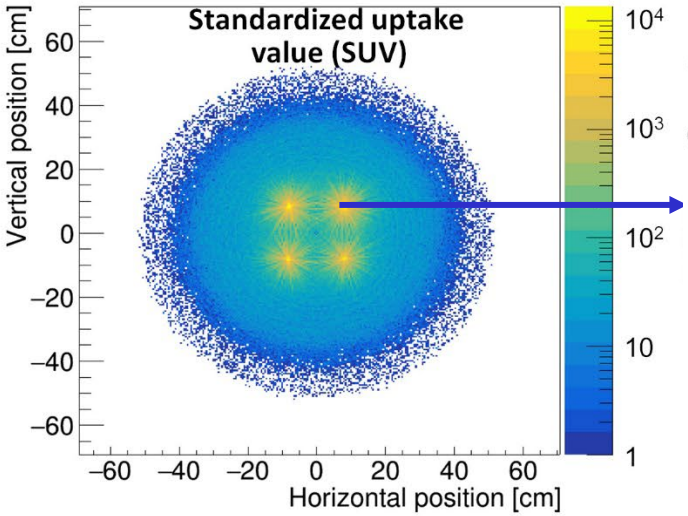
Aluminium holder

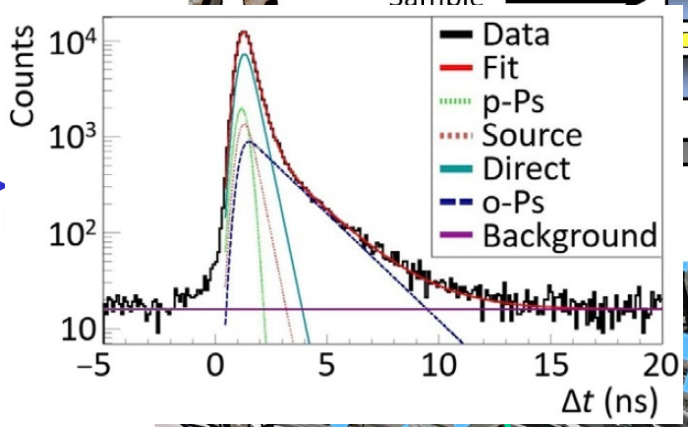
Sample

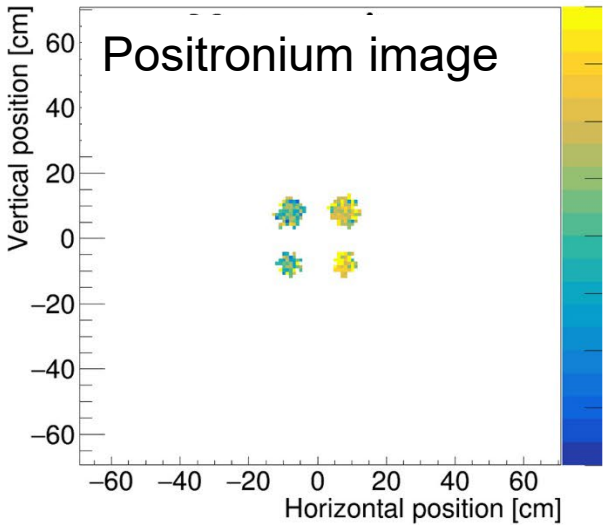


Placing samples in the chambers

Inserting setup to the detector

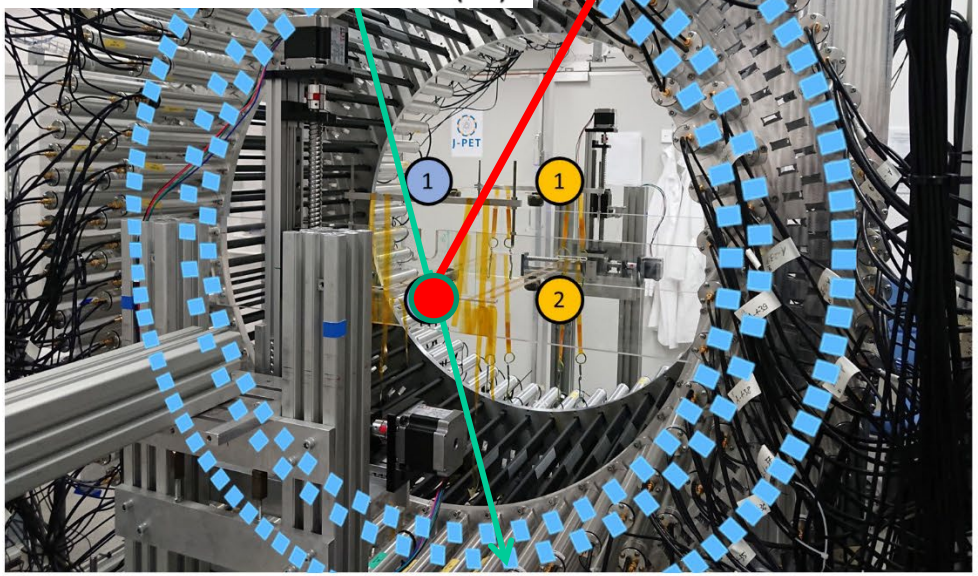






3 ns

1.7 ns

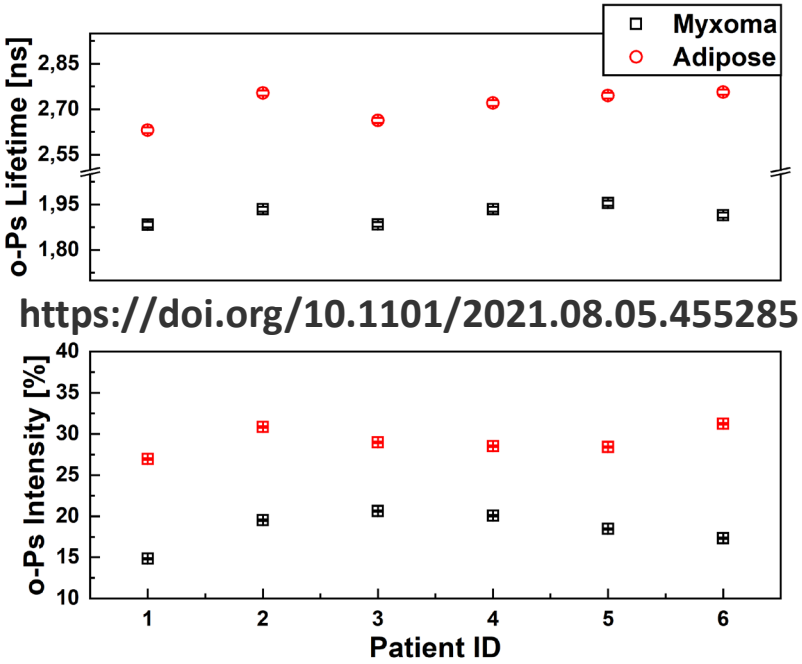


J-PET: P. Moskal et al., Science Advances 7 (2021) eabh4394

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

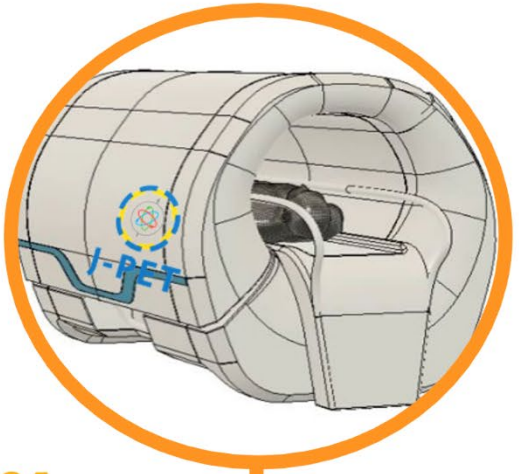
Prof. dr n. med. Michał Pędziwiatr
Chirurgii Endoskopowej, Metabolicznej i Nowotworów Tkanek Miękkich
Szpital Uniwersytecki

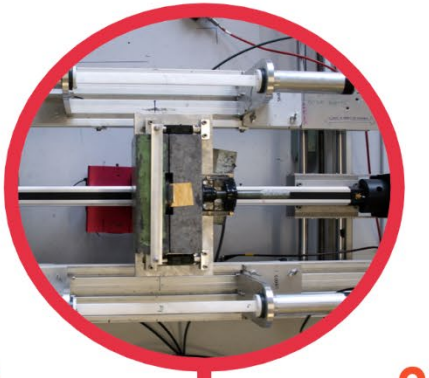
Dr hab. n. med. Elżbieta Łuczyńska
Kierownik Zakładu Elektroradiologii
WNoZ UJCM

J-PET

total-body J-PET

3-layer prototype





2009

2012

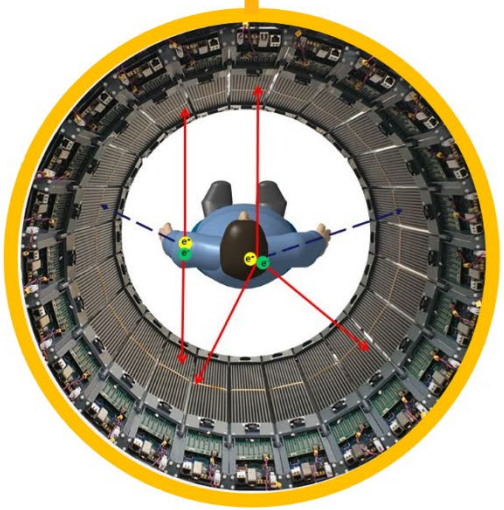
2014

2016

2021

2028

FIRST PATENT

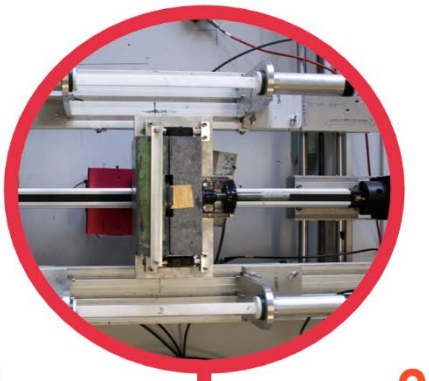


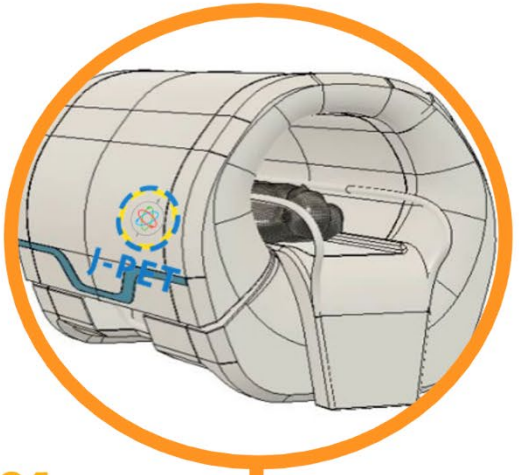
modular J-PET

J-PET

total-body J-PET

3-layer prototype





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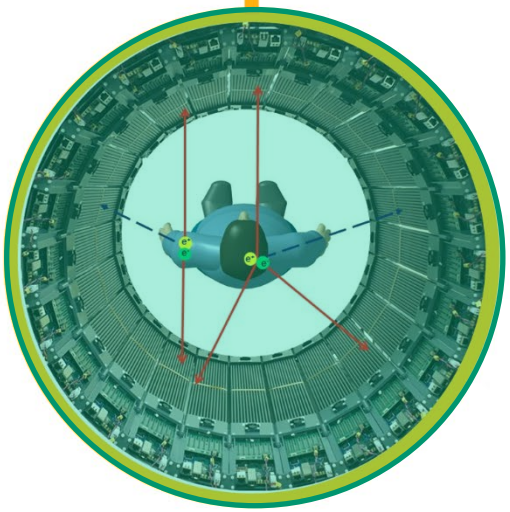
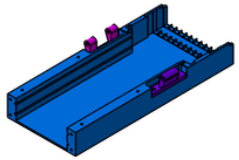


modular J-PET

Development of cost-effective total-body PET

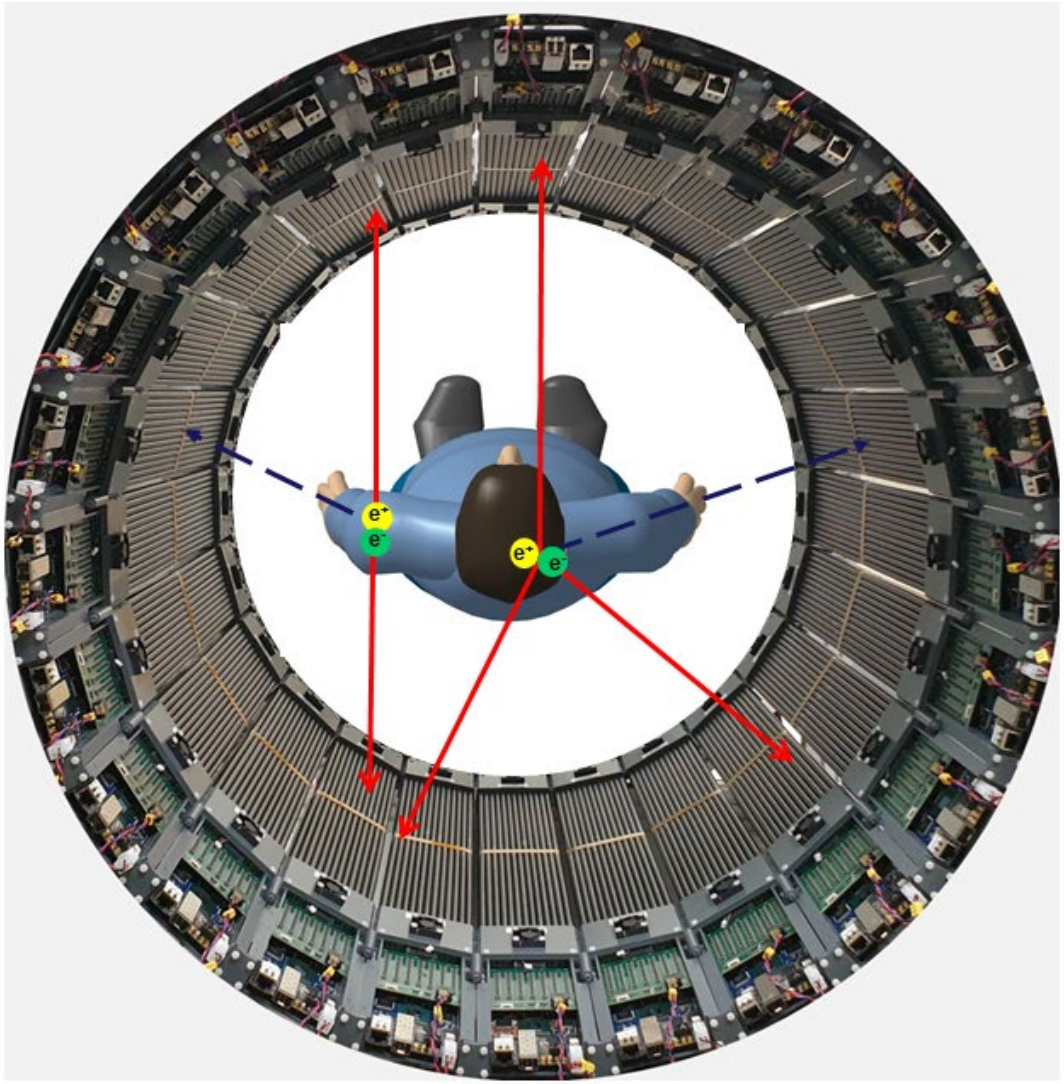


Aim:

- 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



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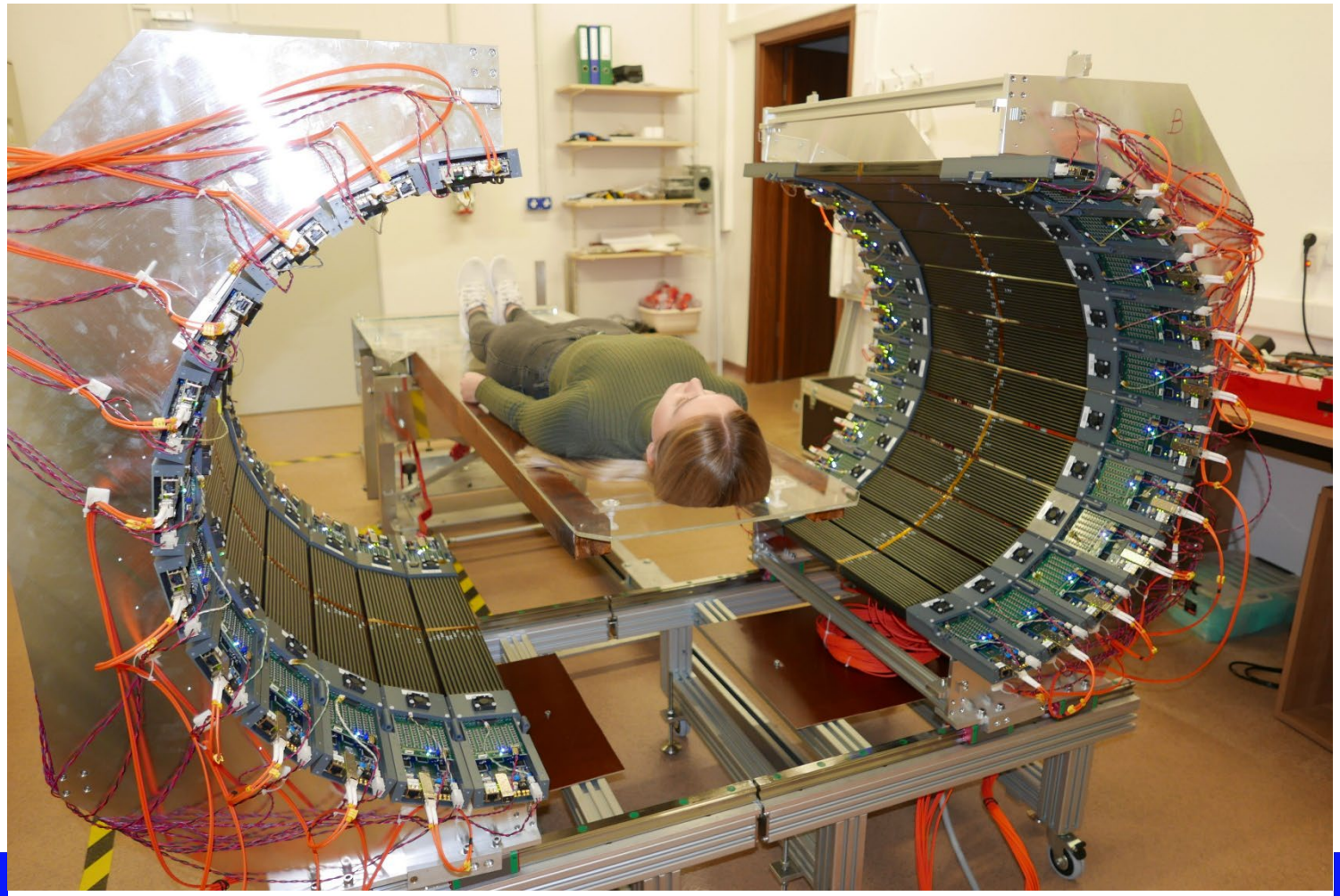
First clinical positronium imaging of patients



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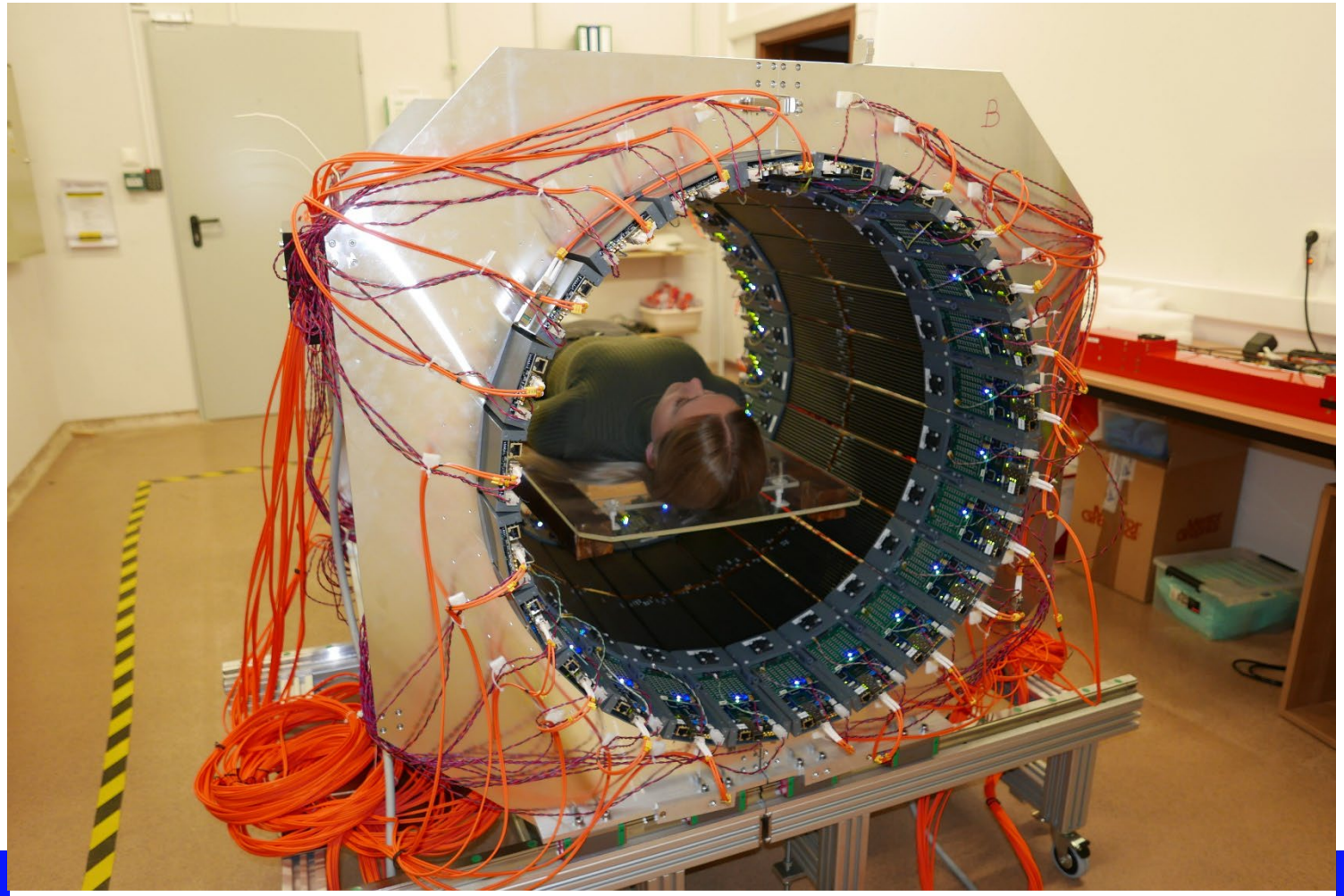

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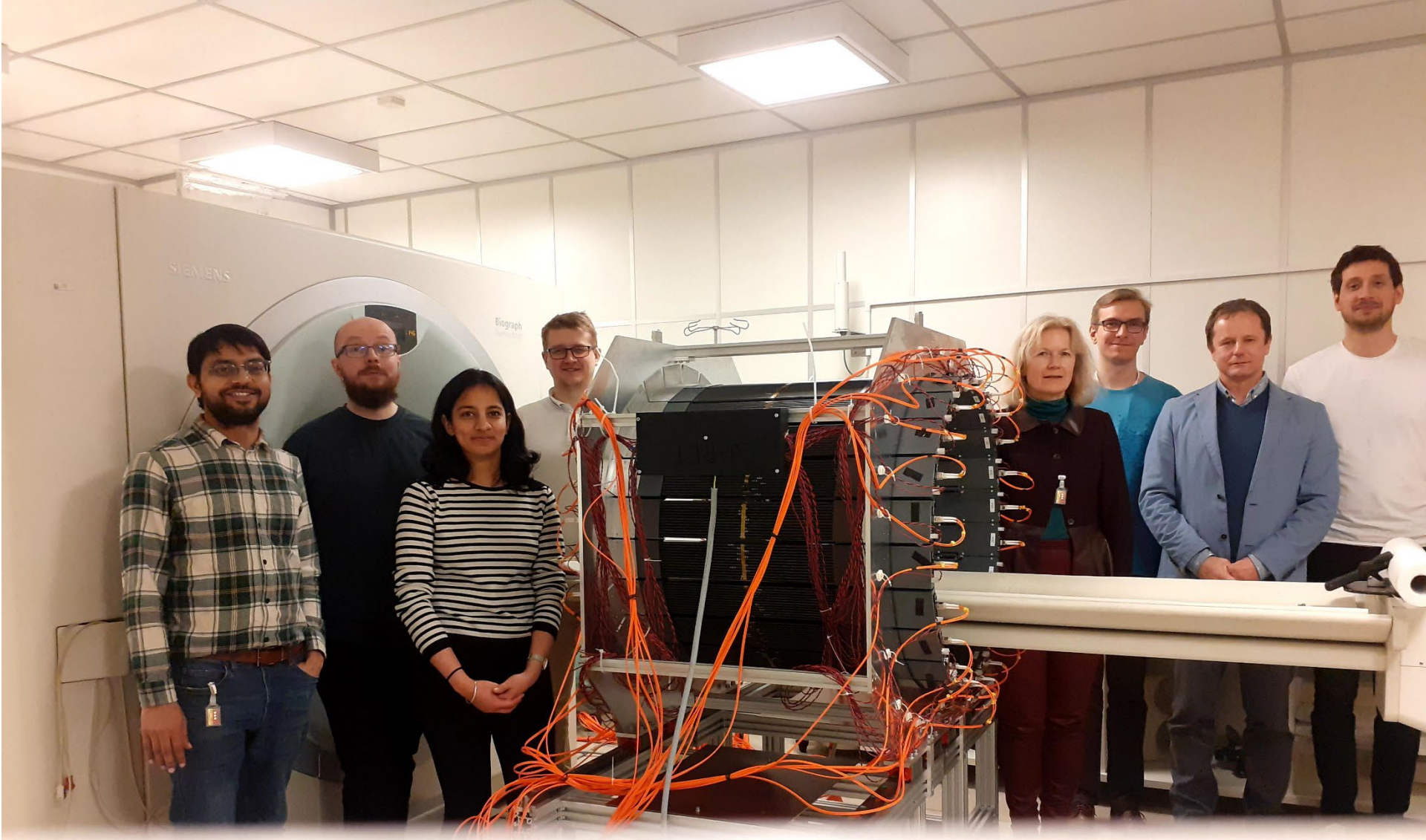
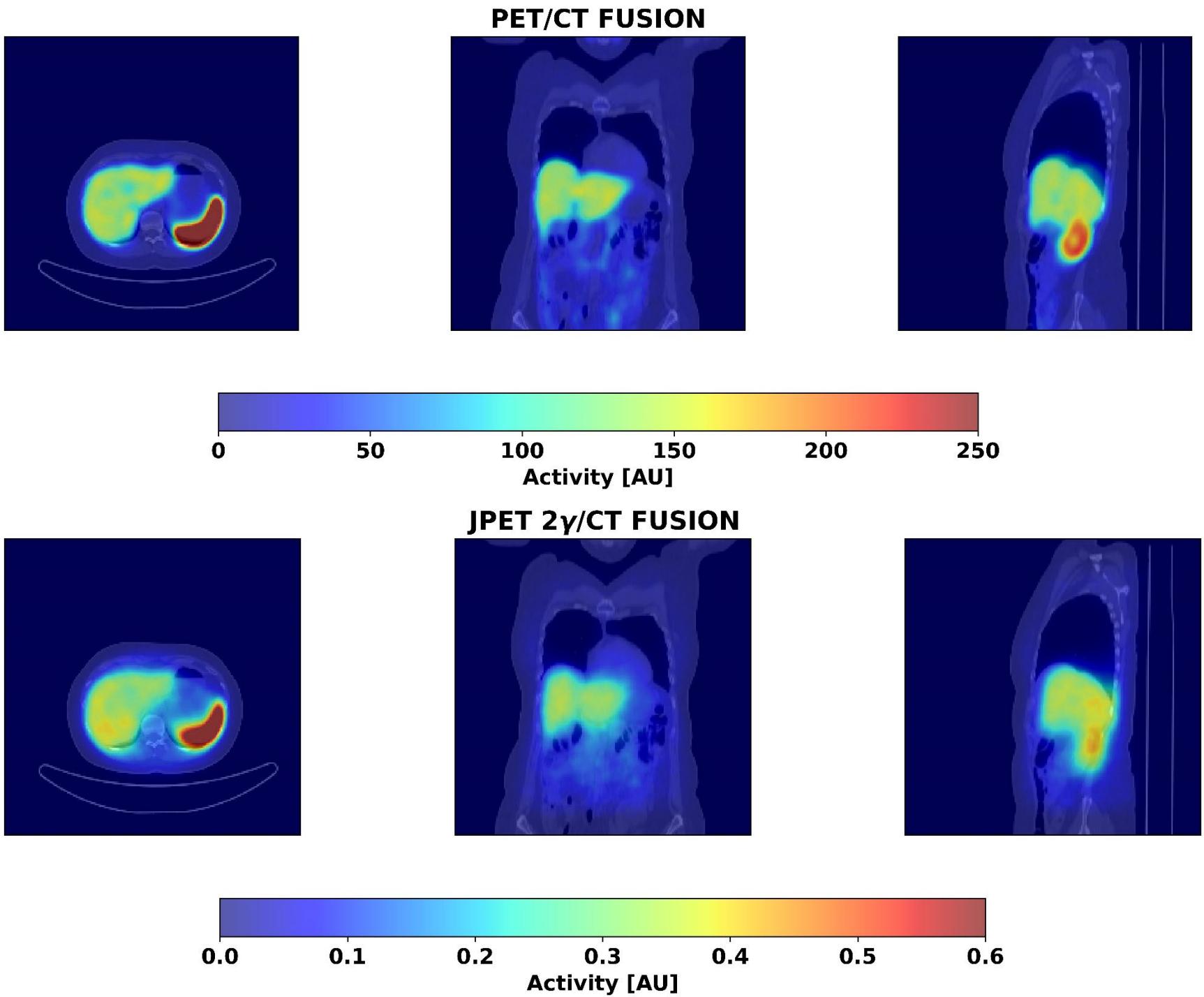
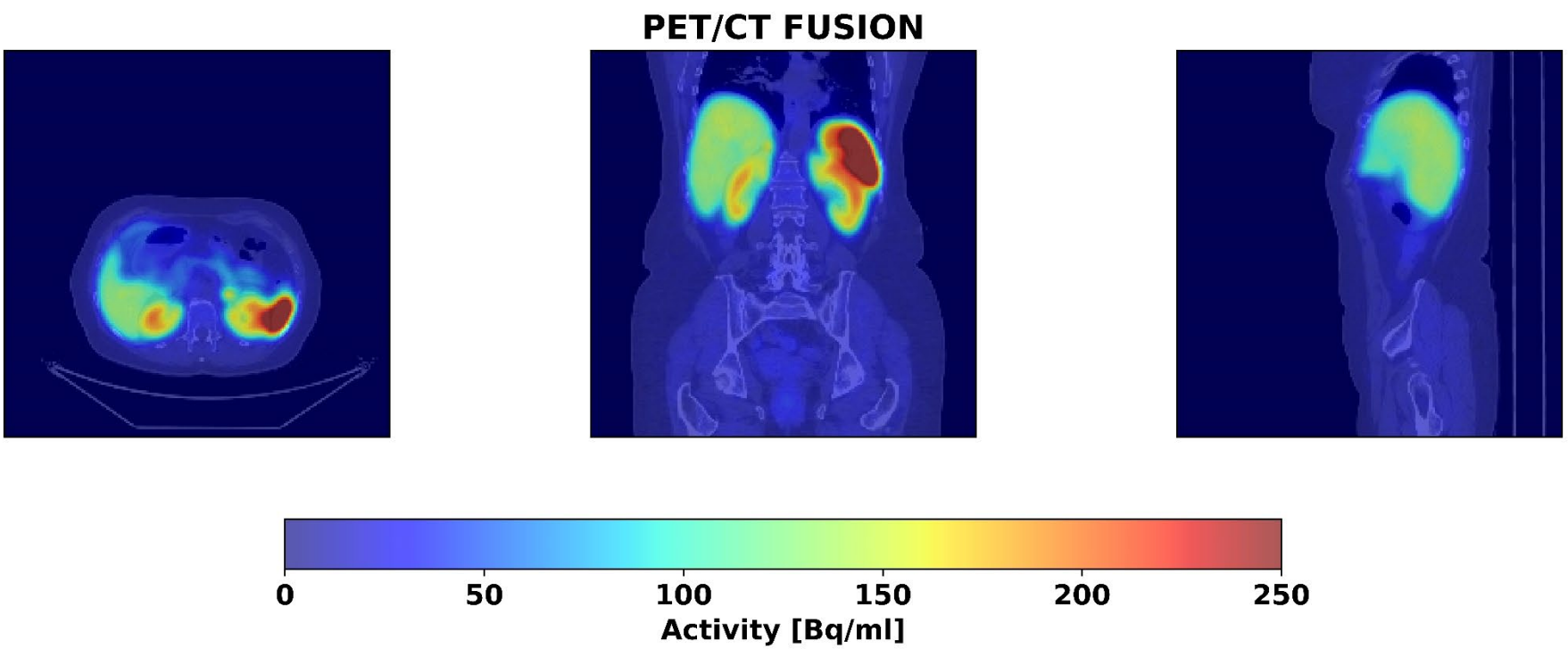
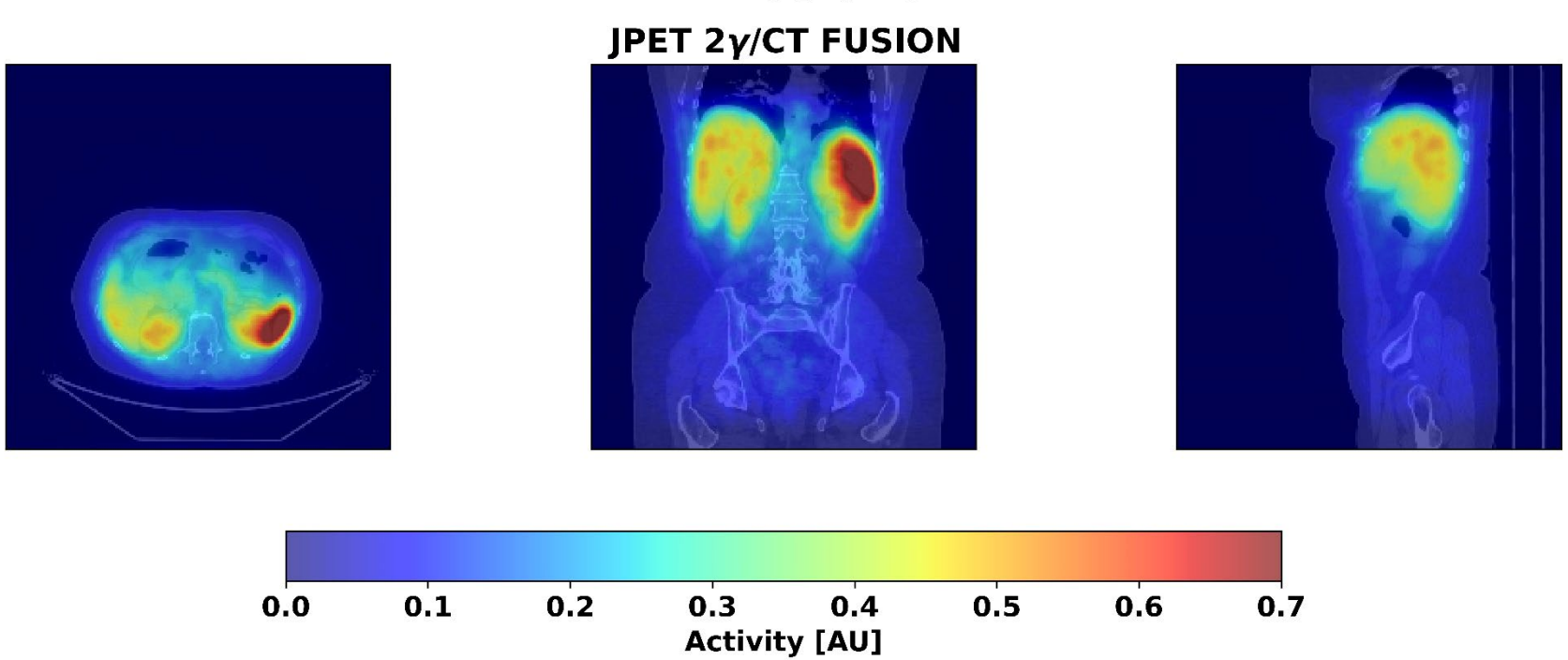

SIEMENS
Biograph


First clinical PET and positronium imaging of patients with J-PET
P. Moskal, …, E. Stepien, Science Advances 10 (2024) eadp2840
P. Moskal,…, E. Stępień, https://www.medrxiv.org/content/10.1101/2024.02.01.23299028v1


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]


4935

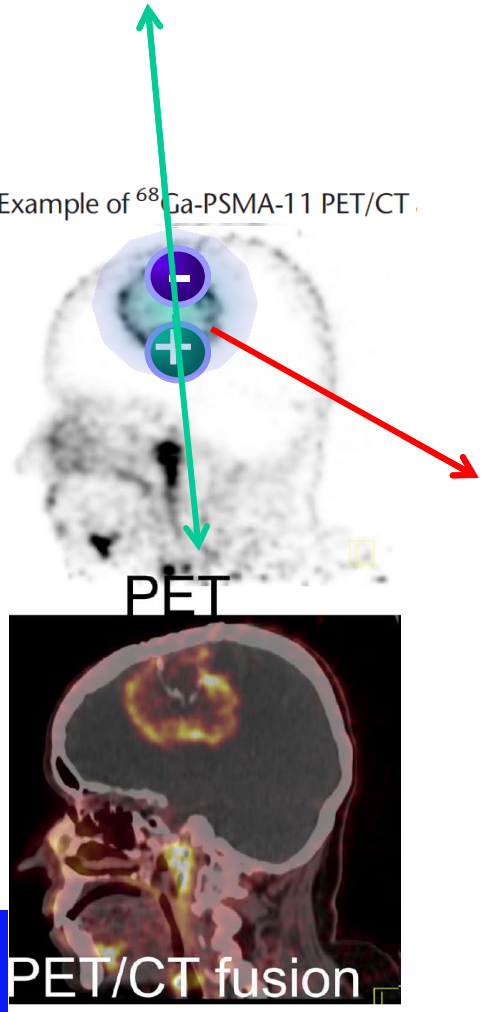

PET/CT FUSION
0
50
100
150
200
250
Activity [Bq/ml]


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

First clinical positronium imaging of patients

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

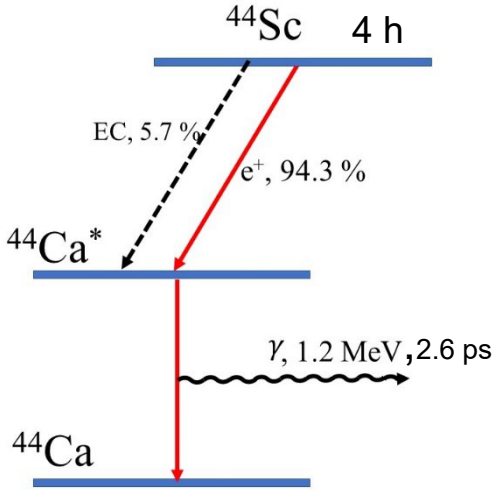
Example of ^{68}Ga-PSMA-11 PET/CT



^{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**

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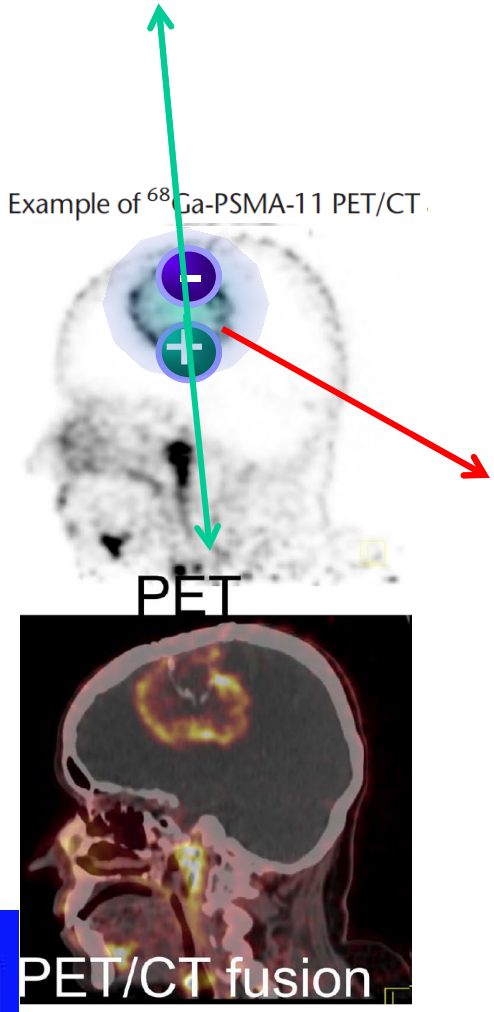

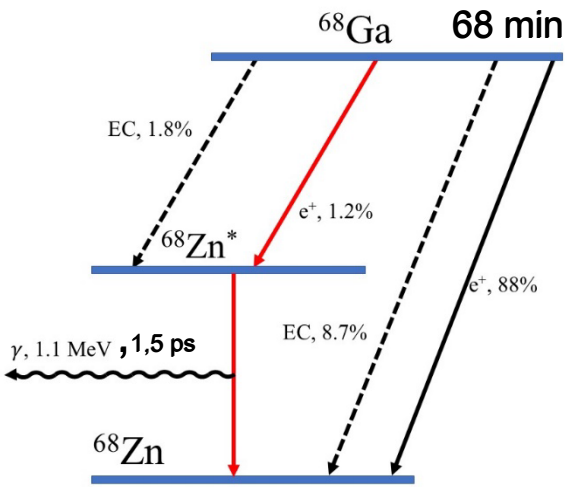

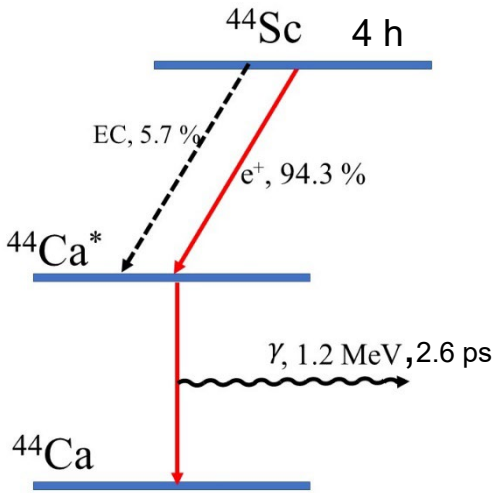

P. Moskal, Jagiellonian University
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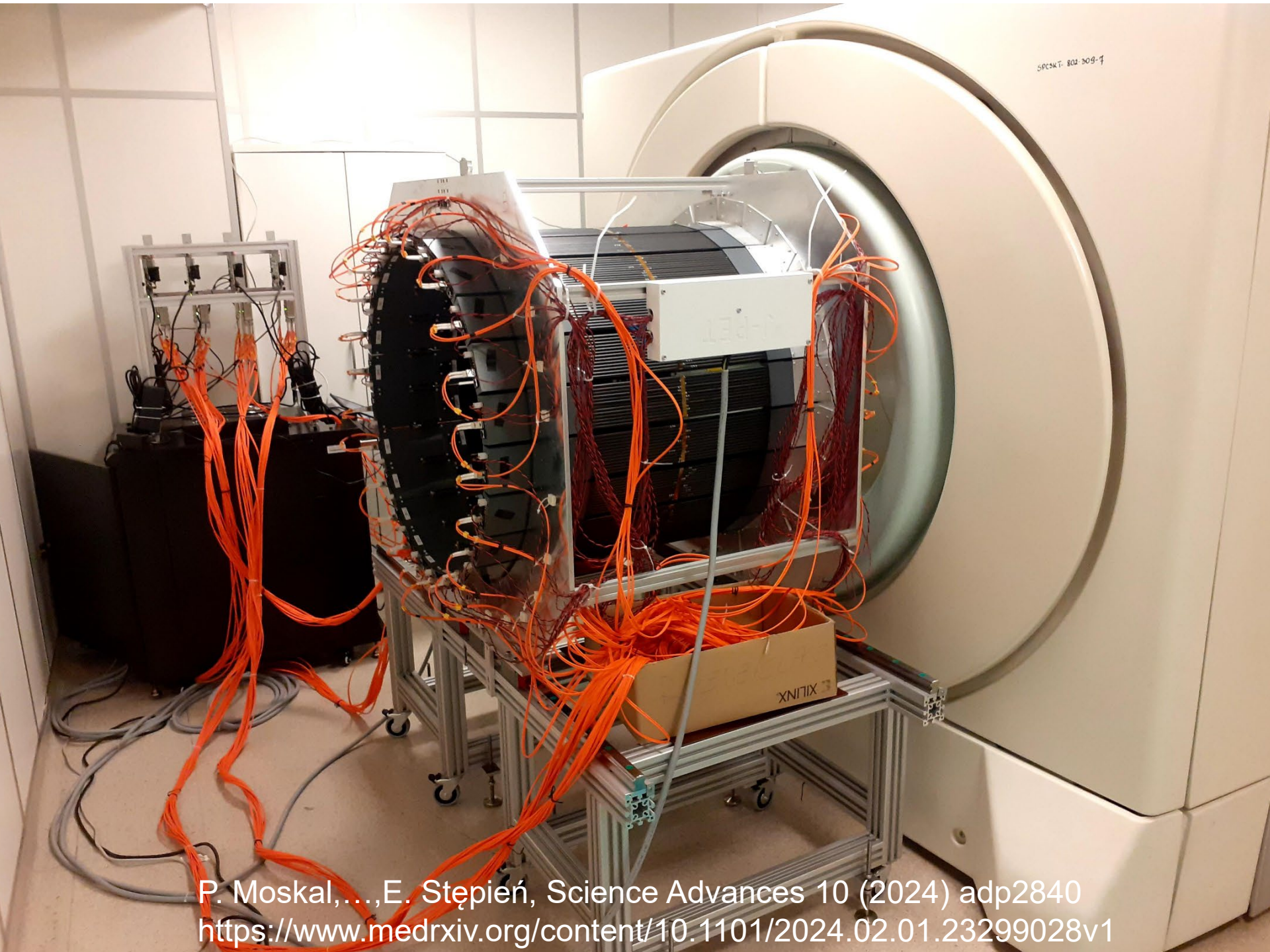
J-PET: P. Moskal et al., March 2022
First positronium imaging with J-PET
P. Moskal,...,E. Stępień, Science Advances 10 (2024) adp2840
https://www.medrxiv.org/content/10.1101/2024.02.01.23299028v1



P. Moskal,…,E. Stępień, Science Advances 10 (2024) adp2840
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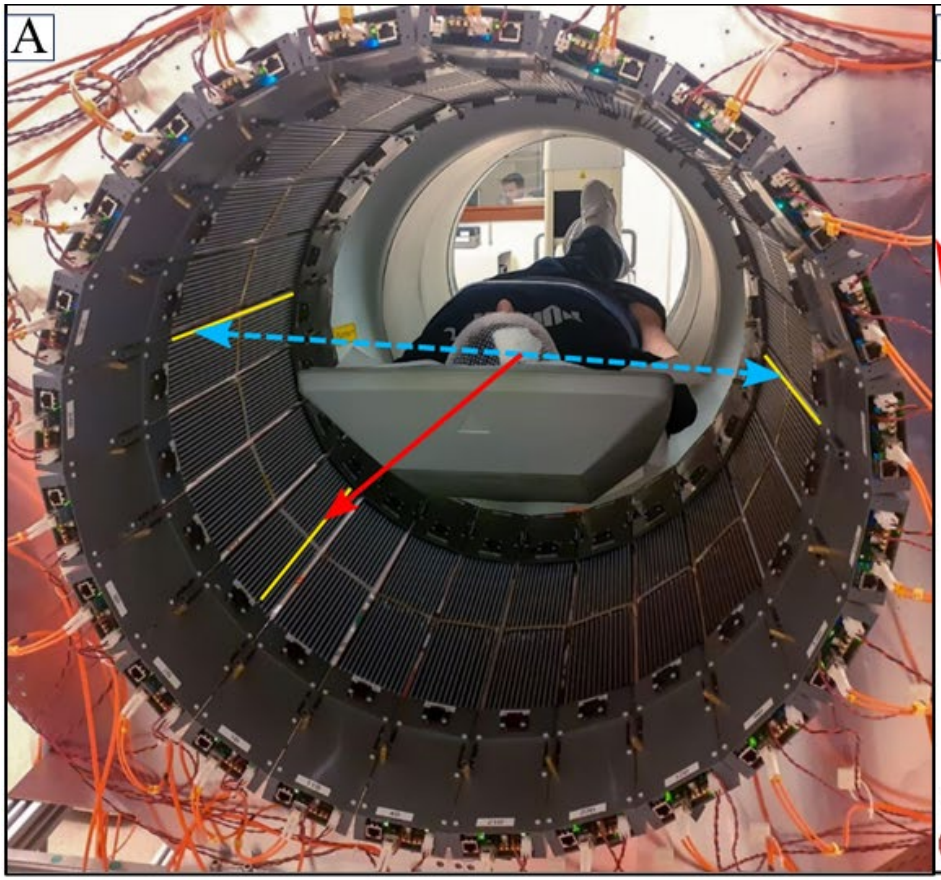
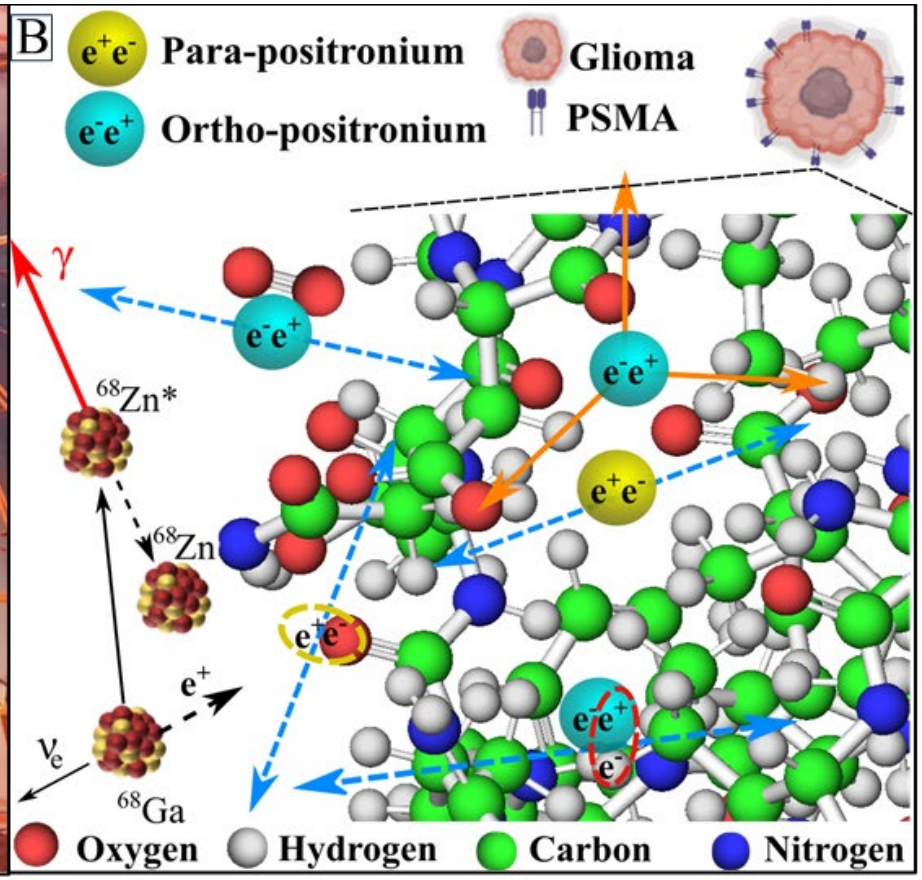
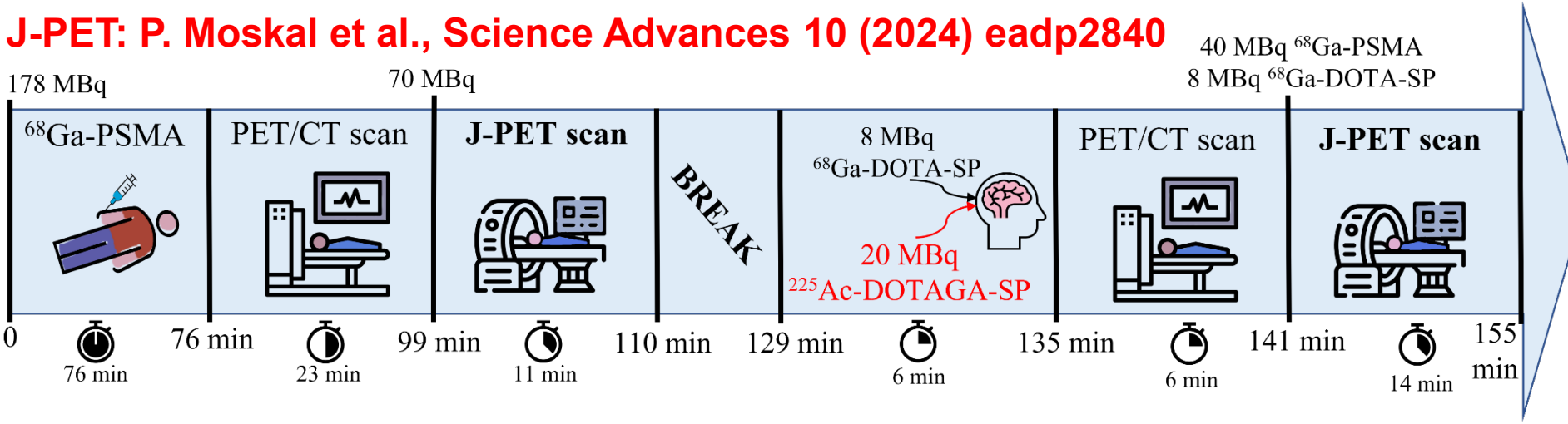
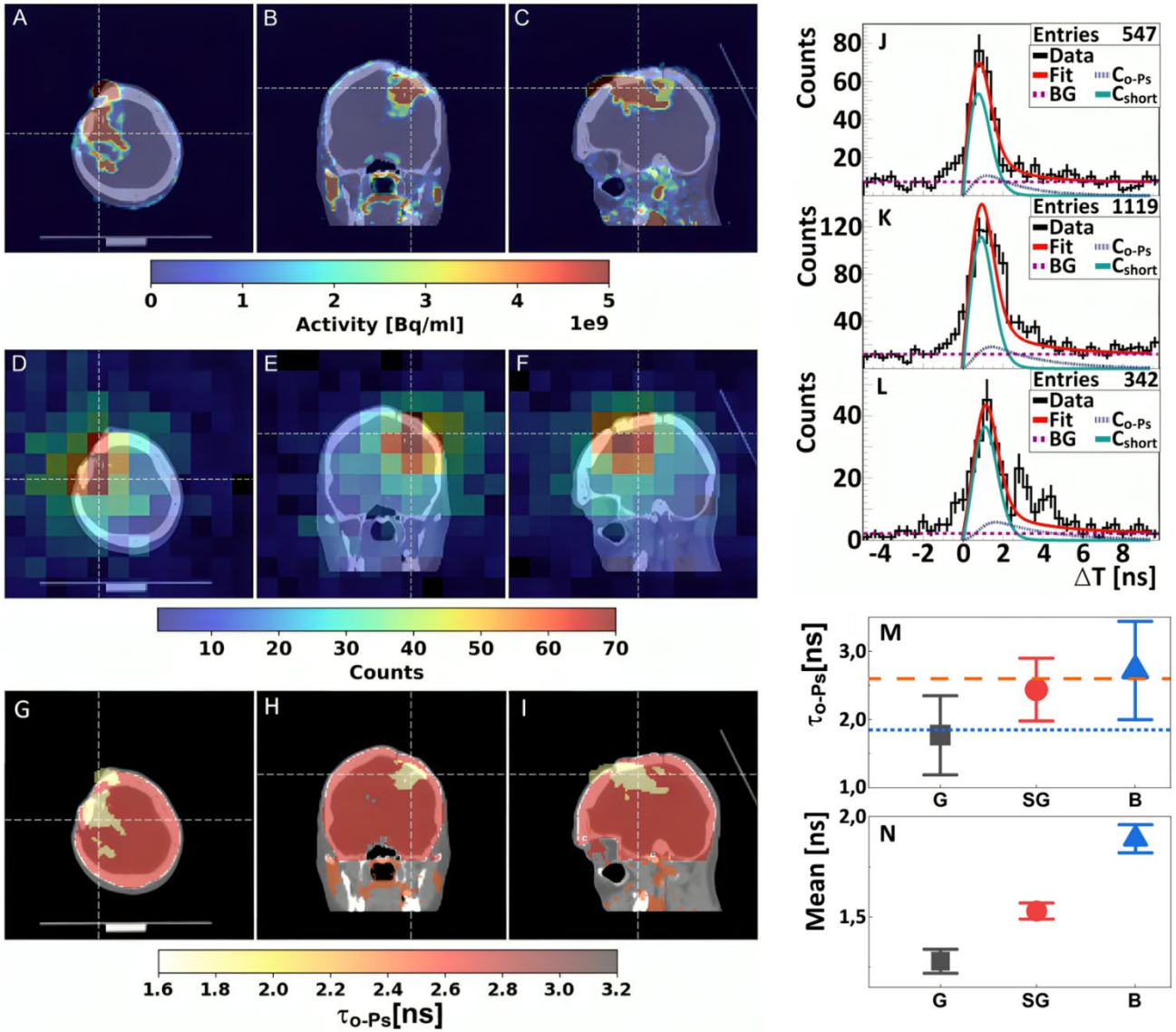




J-PET: P. Moskal et al., Science Advances 10 (2024) eadp2840



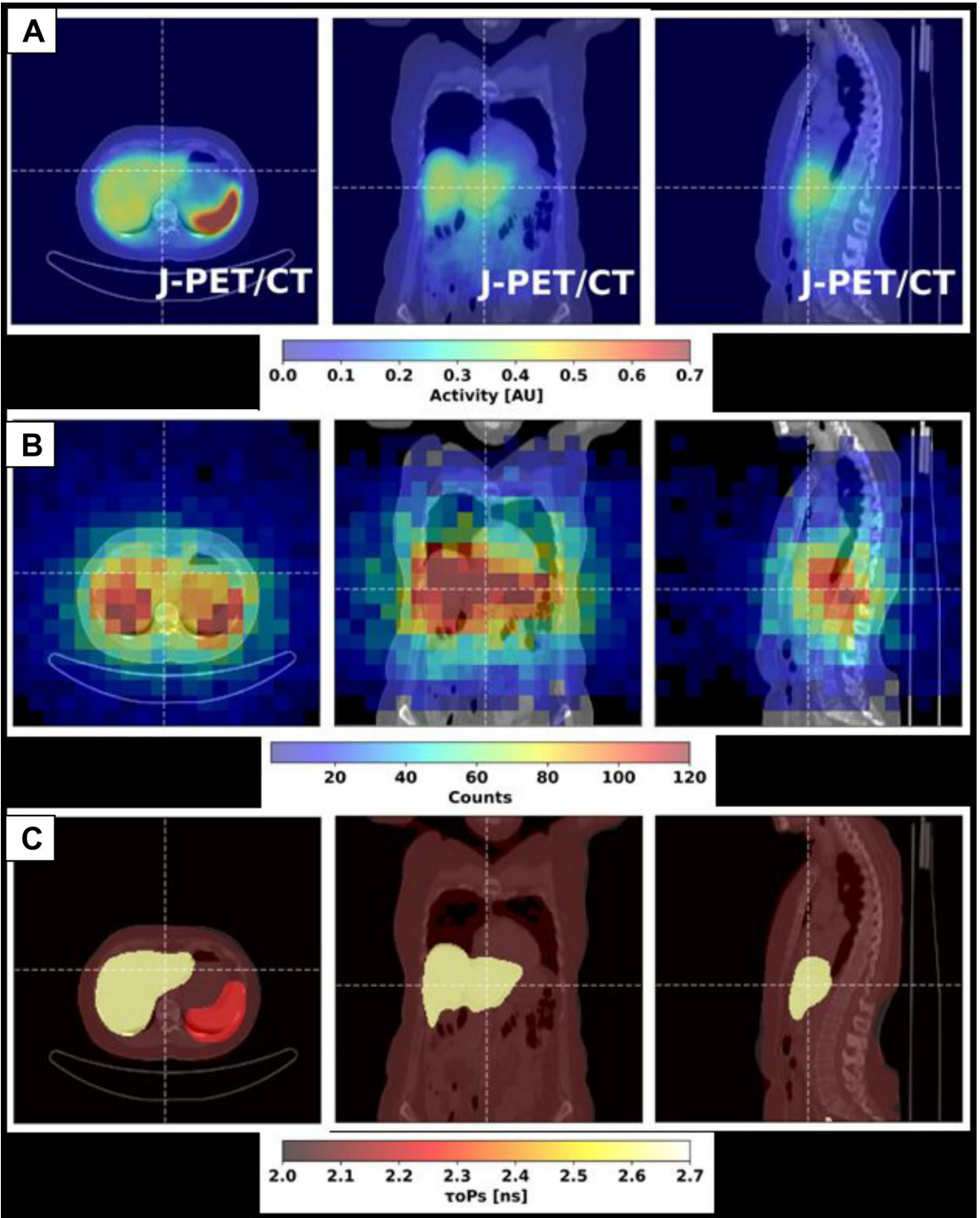
First clinical positronium imaging of patients

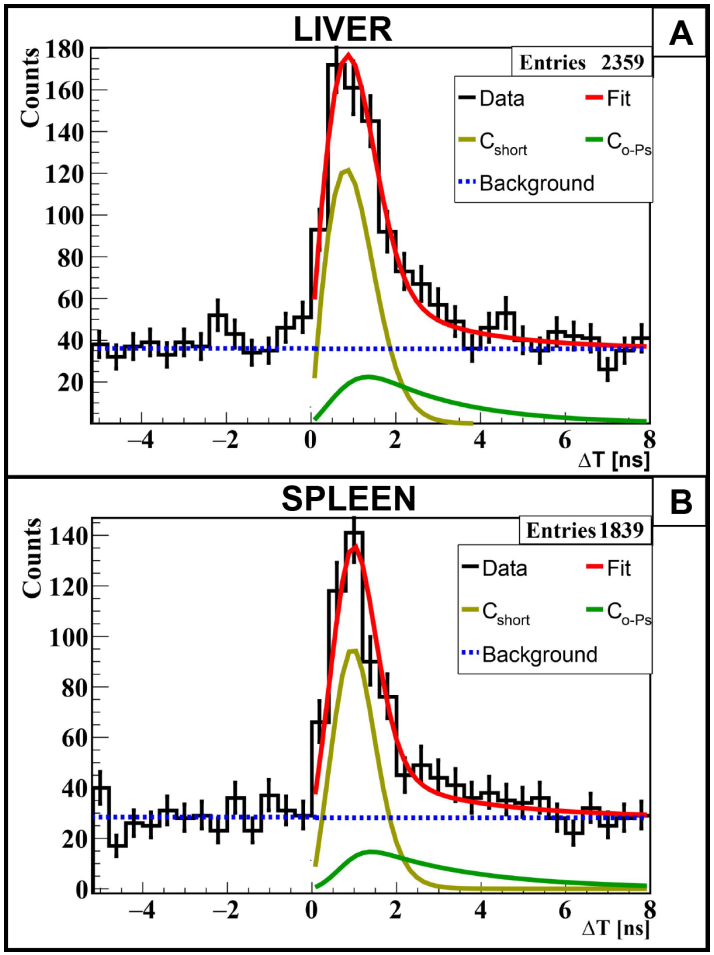


P. Moskal et al., Science Advances 10 (2024) eadp2840

Positronium image of the human brain in vivo

https://www.medrxiv.org/content/10.1101/2024.02.01.23299028v1

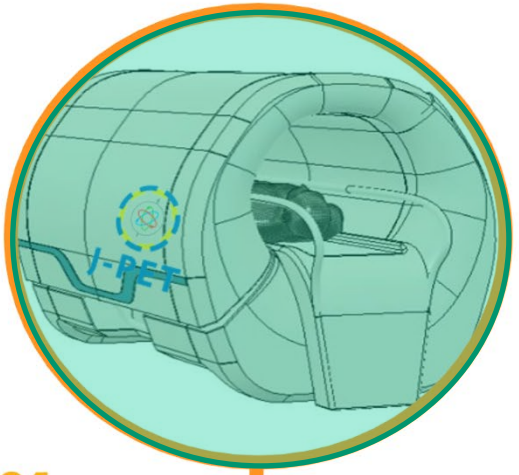

A
J-PET/CT
J-PET/CT
J-PET/CT
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
Activity [AU]
B
20 40 60 80 100 120
Counts
C
2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7
τoPs [ns]

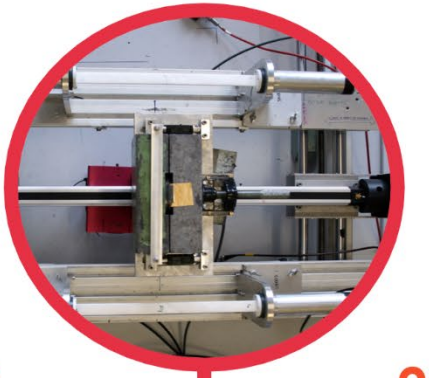

LIVER
A
Entries 2359
Data
Fit
C_short
C_o-Ps
Background
Counts
ΔT [ns]
SPLEEN
B
Entries 1839
Data
Fit
C_short
C_o-Ps
Background
Counts
ΔT [ns]

J-PET

total-body J-PET

3-layer prototype





2009

2012

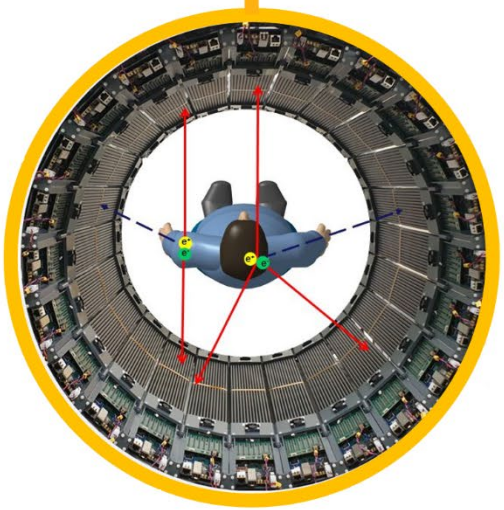
2014

2016

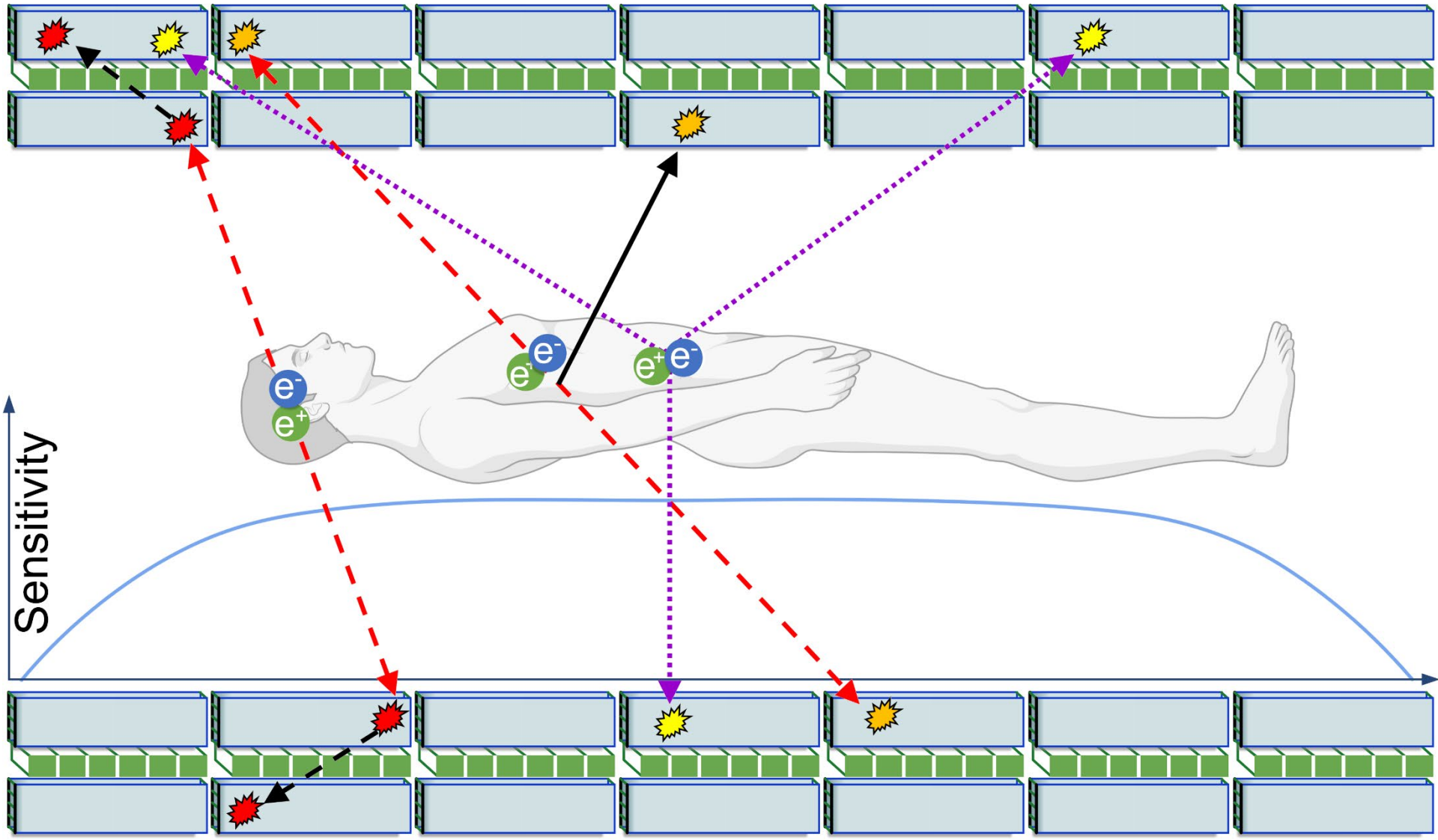
2021

2028

FIRST PATENT



modular J-PET



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

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Positronium physics and biomedical applications