

using a multi-photon J-PET scanner

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

**Seminarium Fizyki Jądra Atomowego,
Uniwersytet Warszawski
28.11.2024**

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





J-PET

Studies of discrete symmetries, quantum entanglement and positronium imaging with the J-PET tomograph



J-PET

Seminar of atomic nucleus physics

Heavy Ion Laboratory,

Department of Nuclear Physics, University of Warsaw

Warsaw, 21 March 2019

P. Moskal, Jagiellonian University, Poland

<http://koza.if.uj.edu.pl>





- **PET**
- **Jagiellonian-PET (J-PET)**
- **Positronium imaging (PET & PALS)**
- **Discrete symmetries**
- **Quantum Entanglement Tomography**
- **Hadrontherapy beam monitoring**

Positronium imaging with the J-PET tomograph



Nuclear Physics Division, University of Warsaw

19.05.2022

P. Moskal, Jagiellonian University

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Positronium imaging with the J-PET tomograph

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using a multi-photon J-PET scanner

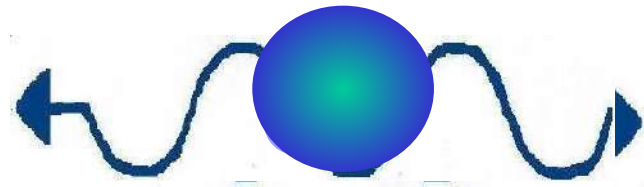
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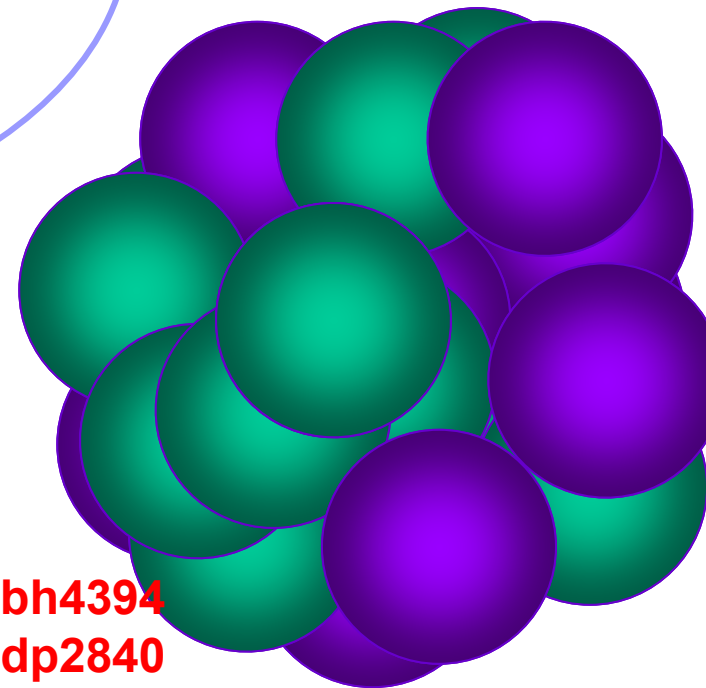
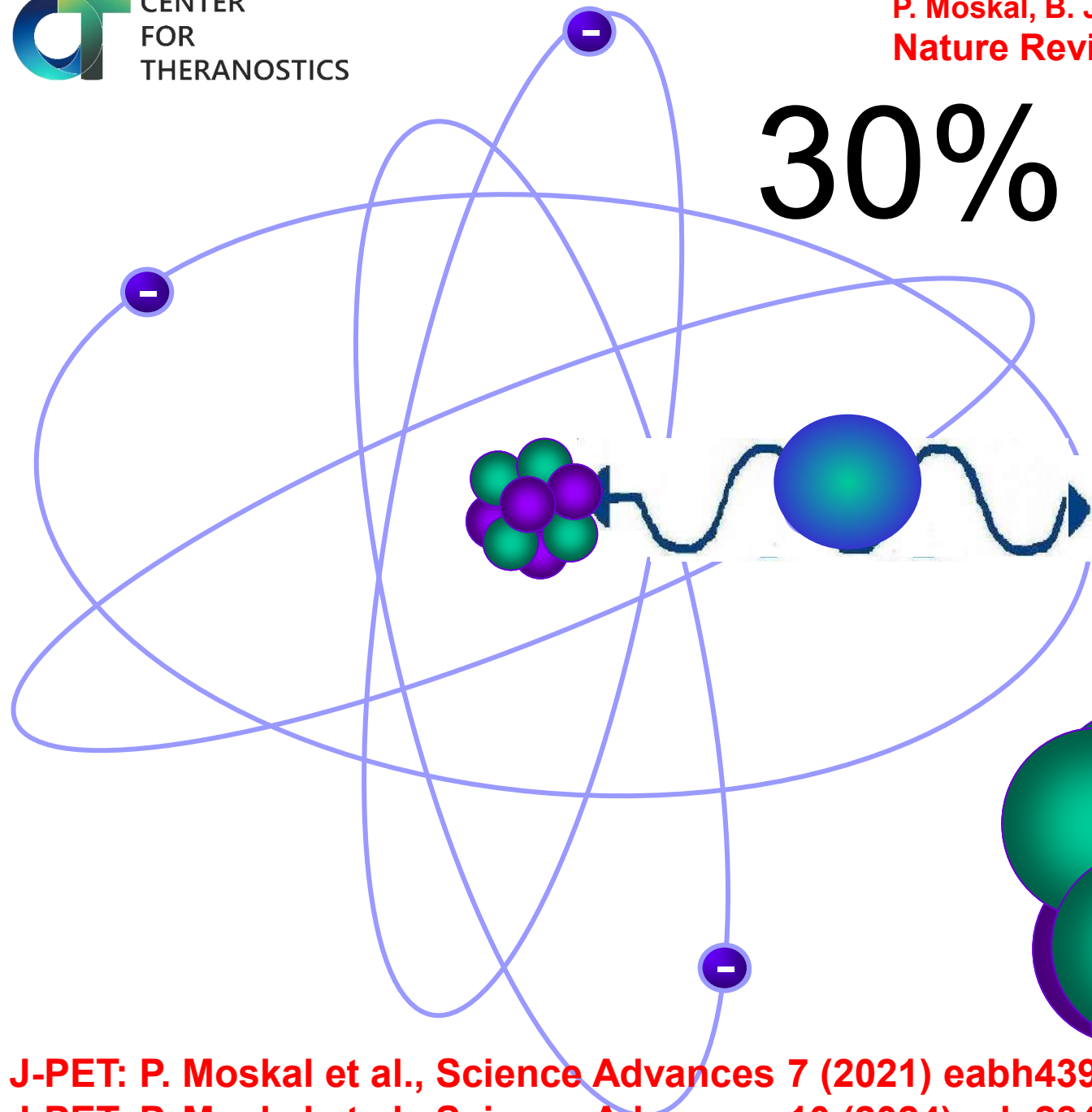
P. Moskal, Jagiellonian University
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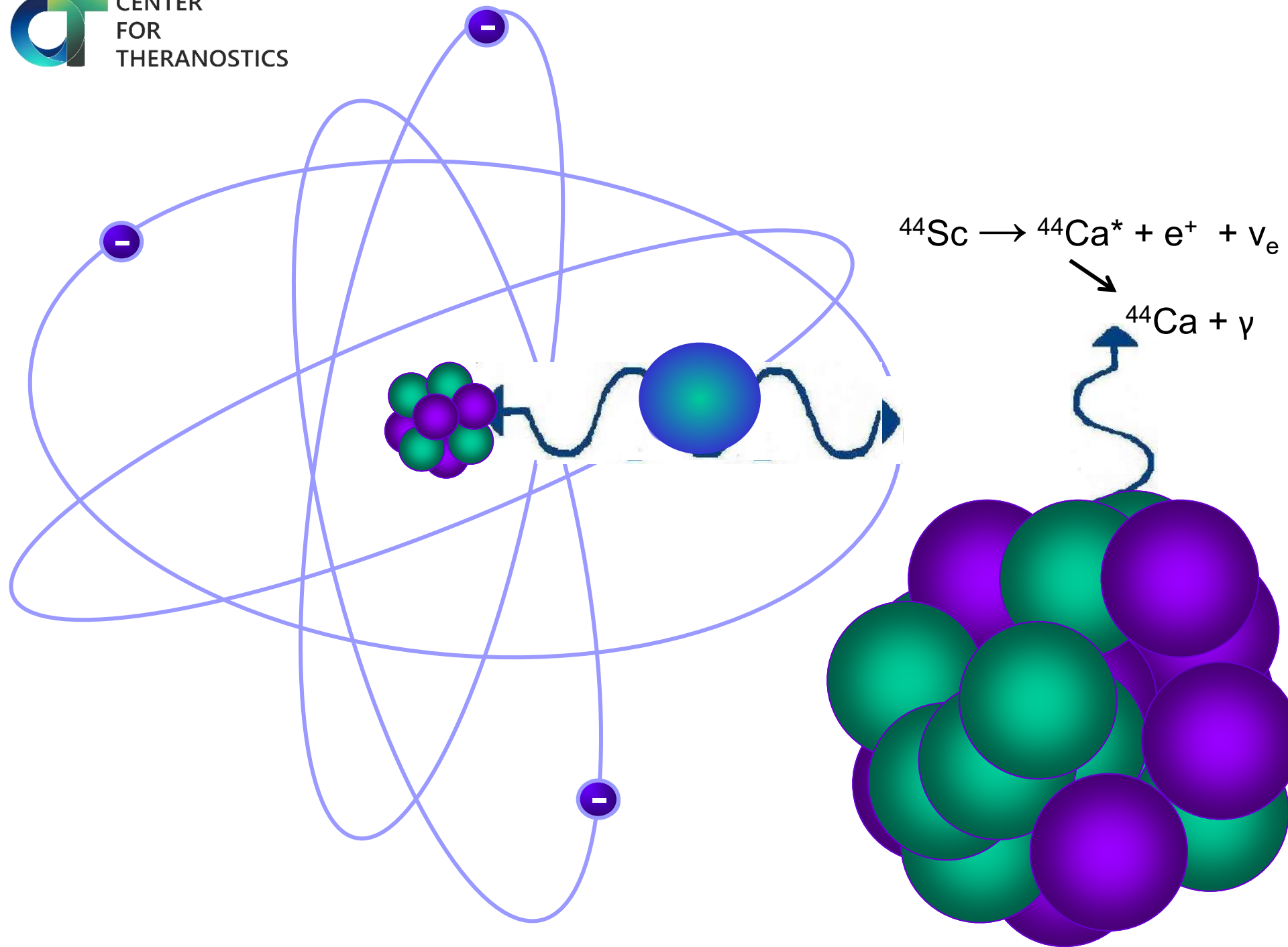


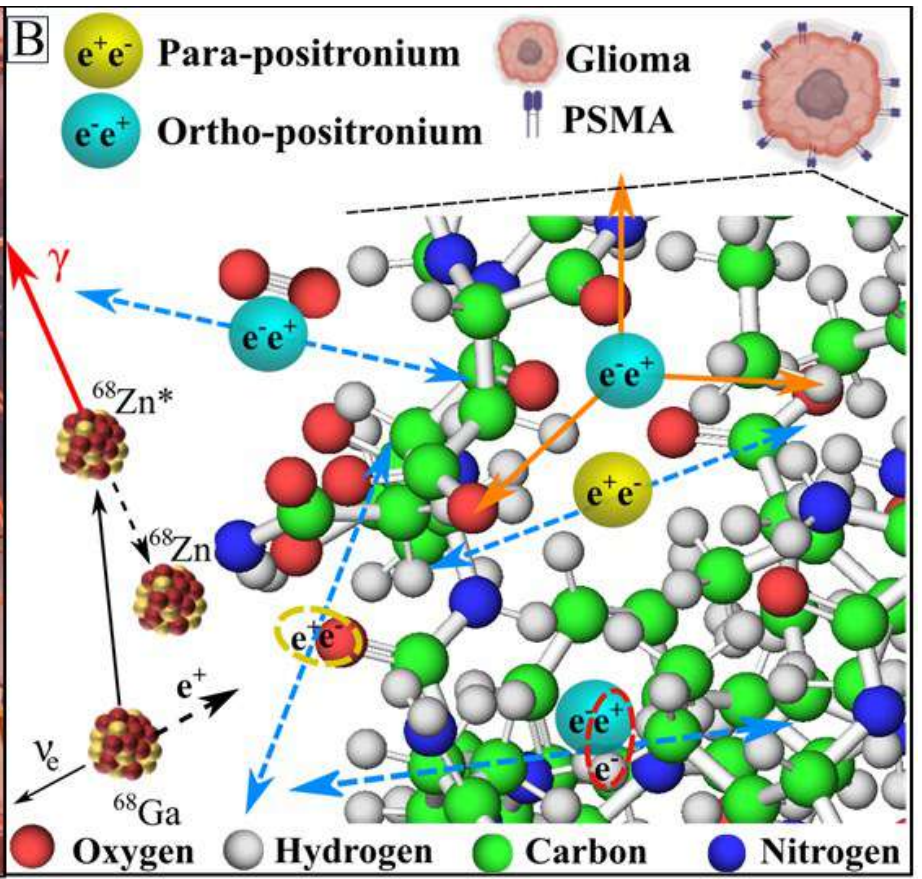
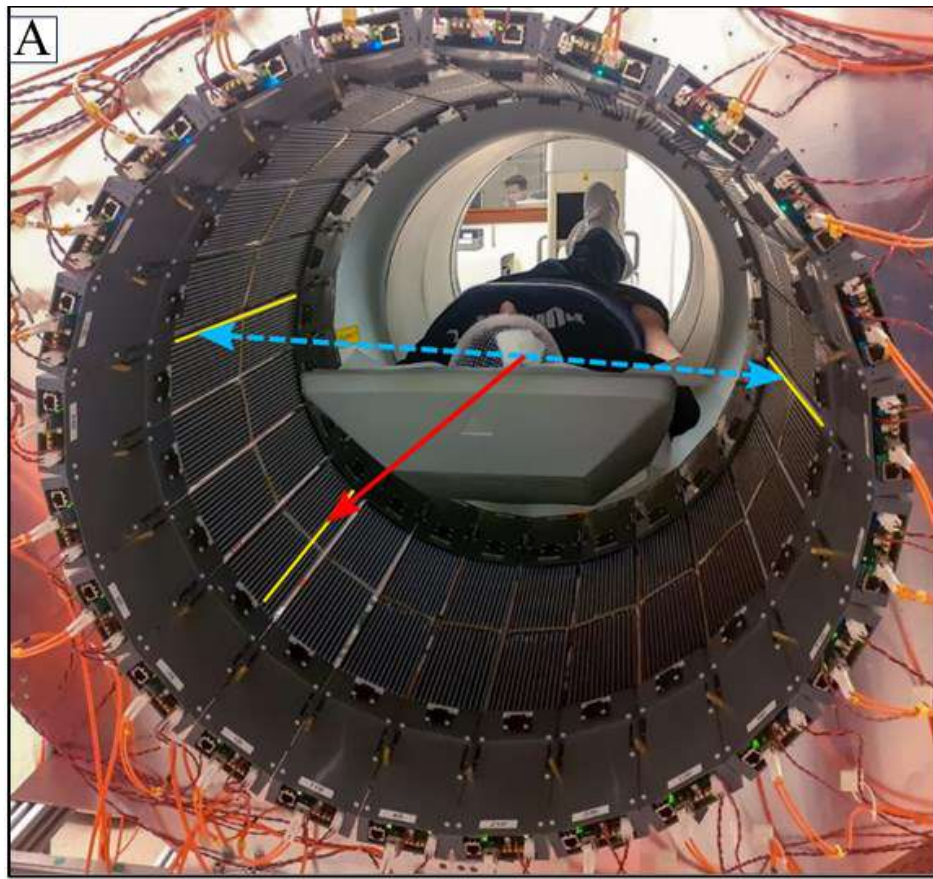




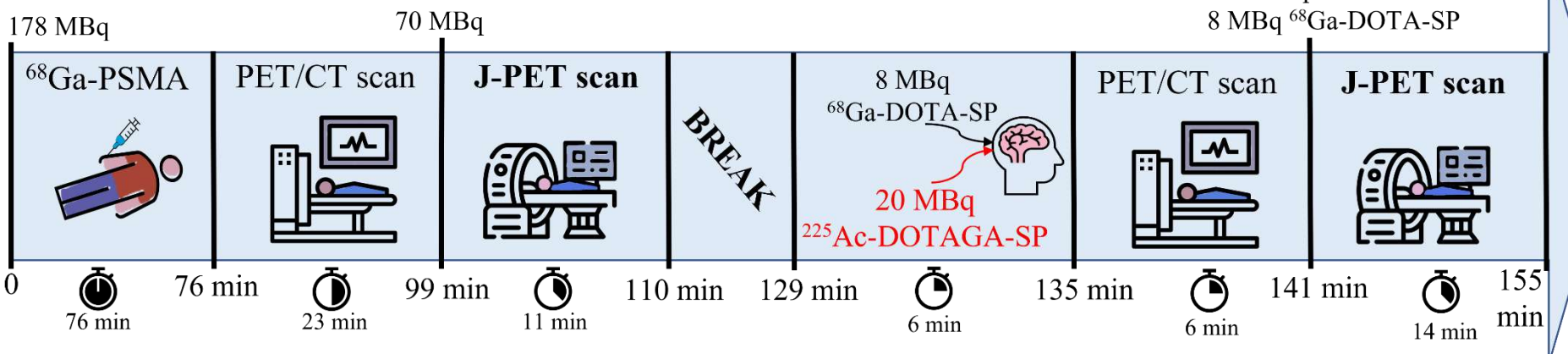
30% – 40%



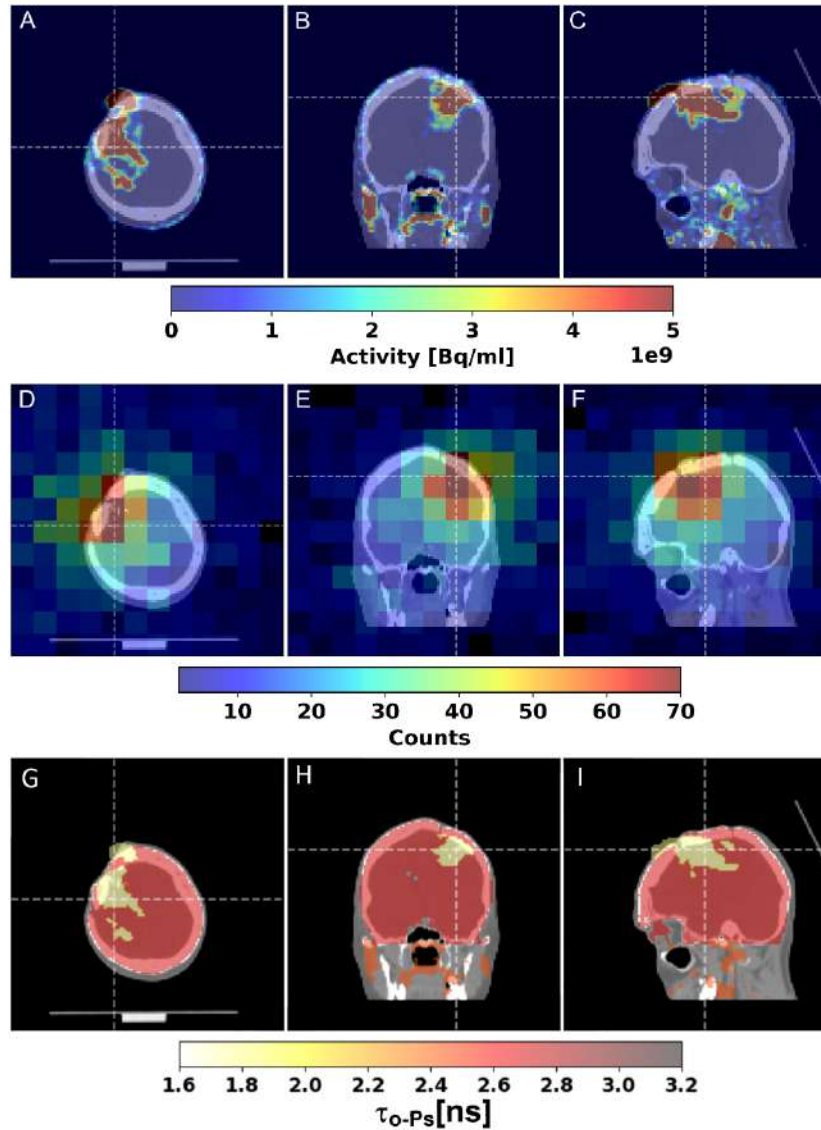




J-PET: P. Moskal et al., Science Advances 10 (2024) adp2840



First clinical positronium imaging of patients



P. Moskal et al., Science Advances 10 (2024) adp2840
Positronium image of the human brain in vivo

using a multi-photon J-PET scanner

- **Jagiellonian-PET (J-PET)**
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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

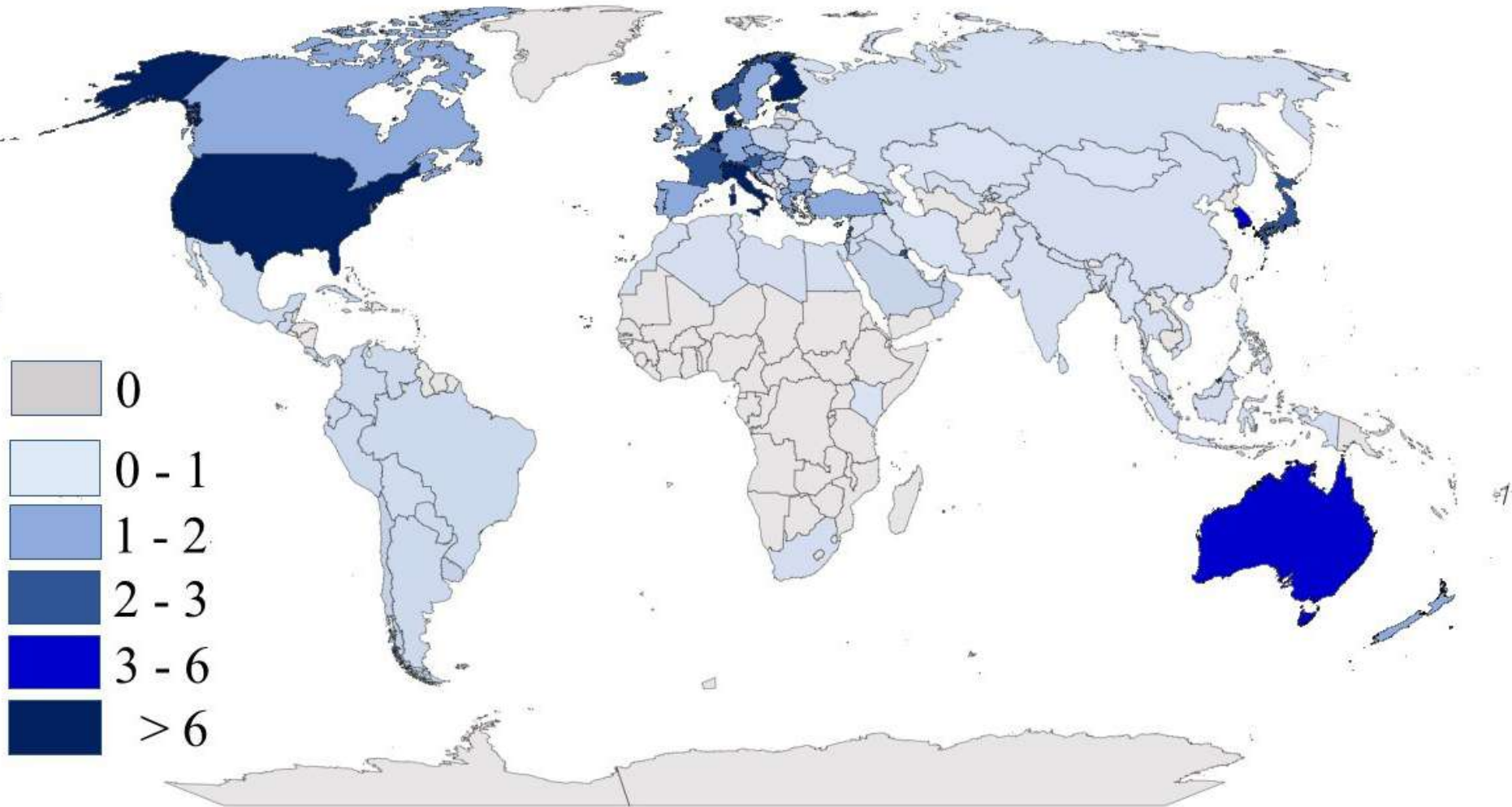
Positronium imaging with the novel multi-photon PET scanner

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

Positronium image of the human brain in vivo



Number of PET scanners per million people

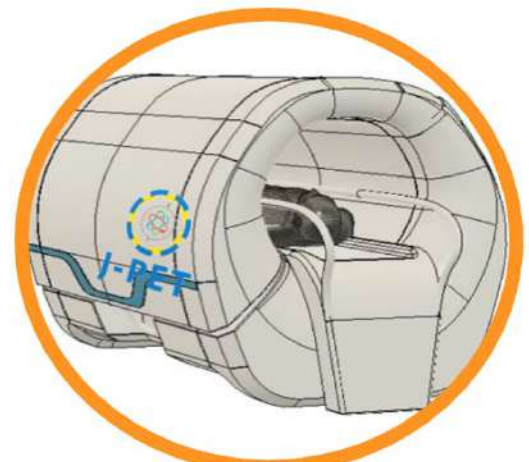


IAEA Medical imAGIng and Nuclear mEdicine (IMAGINE) database developed by the International Atomic Energy Agency (IAEA) available at: <https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINE.html>



total-body J-PET

3-layer prototype



2009

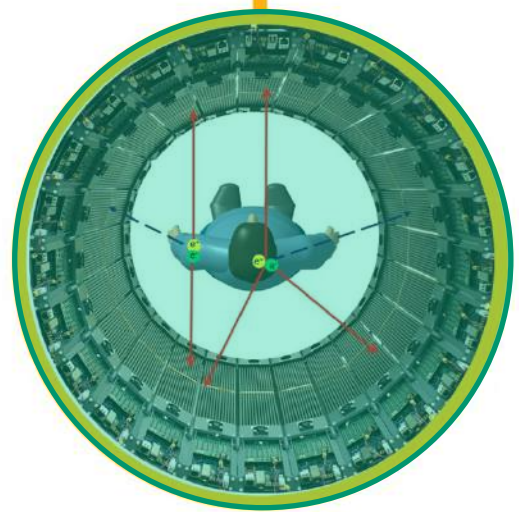
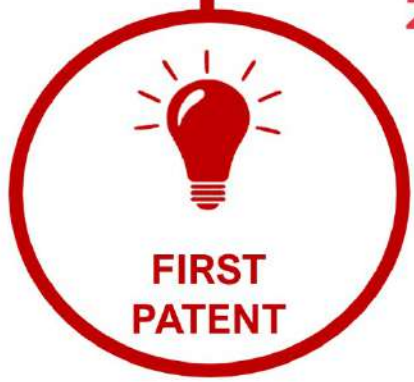
2014

2021

2012

2016

2028



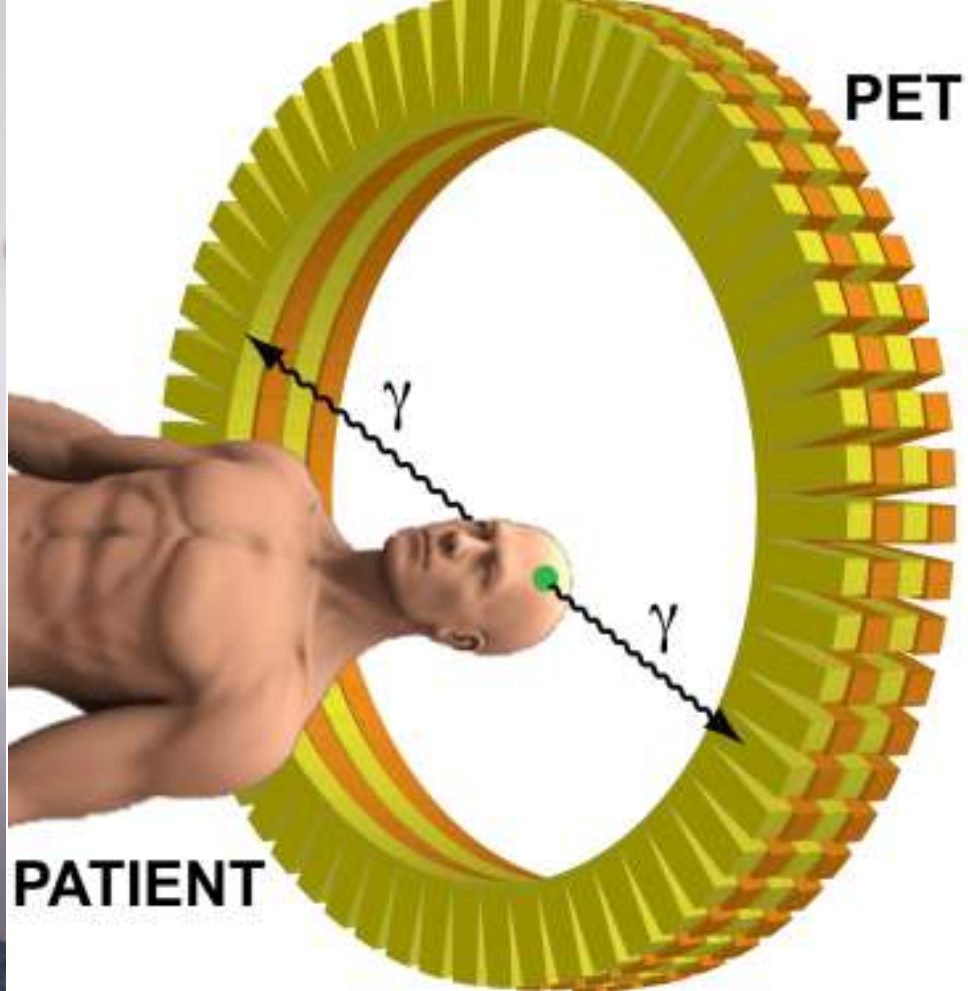
modular J-PET

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)

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- **Quantum Entanglement**



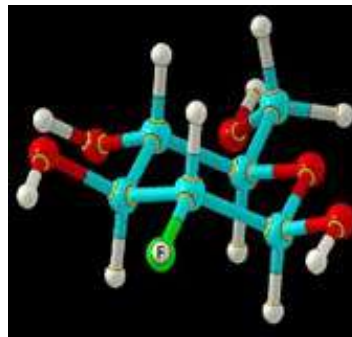




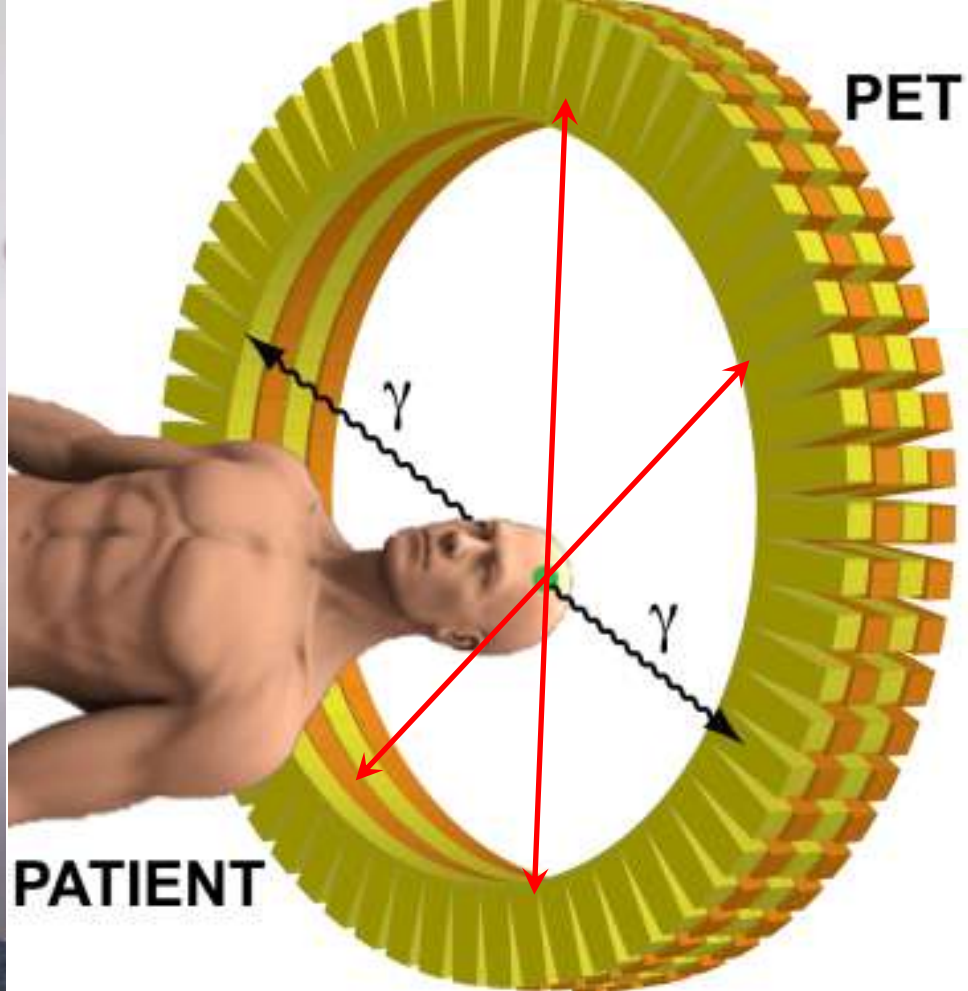
RADIOACTIVE SUGAR

Fluoro-deoksy-glucose
(F-18 FDG)

~200 000 000
gamma rays per second

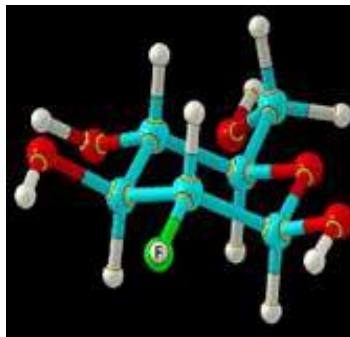


7 mSv PET/CT
~ 2.5 mSv PET
~3 mSv yearly
dose of natural radiation



RADIOACTIVE SUGAR

Fluoro-deoksy-glucose
(F-18 FDG)



Radiological

Laboratory in Warsaw

Nature 1934;133:564–5,

„An Artificial Radioelement from Nitrogen”

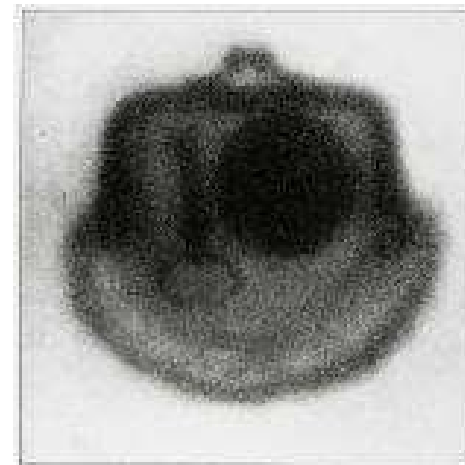
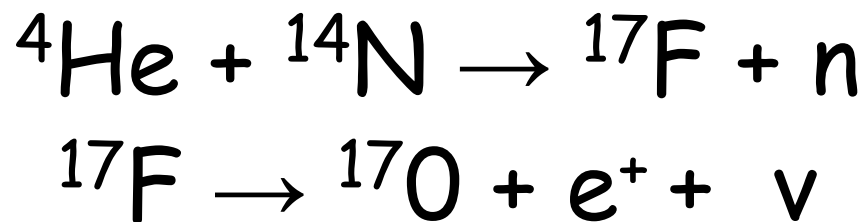
<https://lnkd.in/di246kY2>

Formal leader of the Radiological
Laboratory in Warsaw



A girl from Warsaw

Prof. Ludwik Wertenstein
Marian Danysz



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

[http://www.galloim
ages.co.za/](http://www.galloim
ages.co.za/)

Radiological

Laboratory in Warsaw

Nature 1934;133:564–5,

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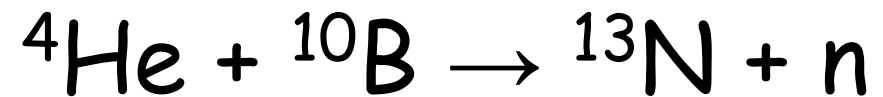
Irene and Frederic Joliot-Curie

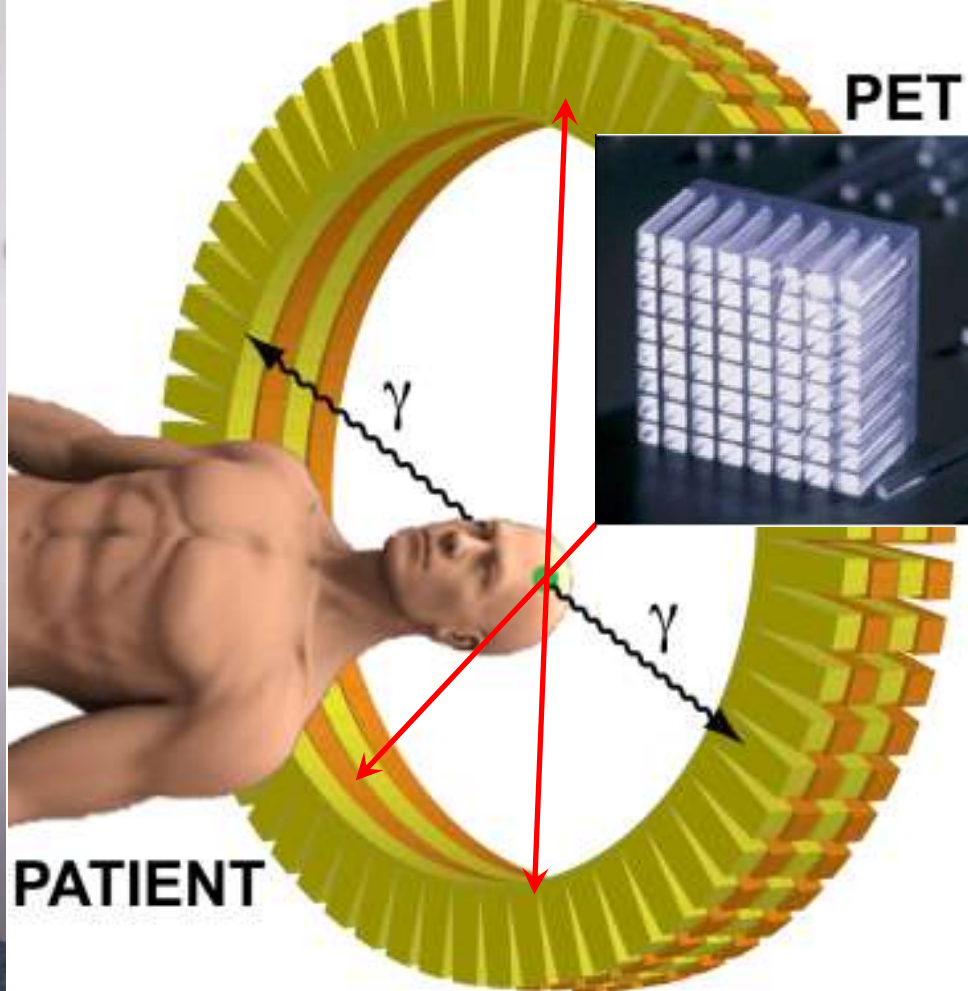
Nature 1934;133:201–2,

„Artificial Production of
a New Kind of Radio-Element”

<https://lnkd.in/dRtzeZJD>

Nobel Prize in Chemistry in 1935

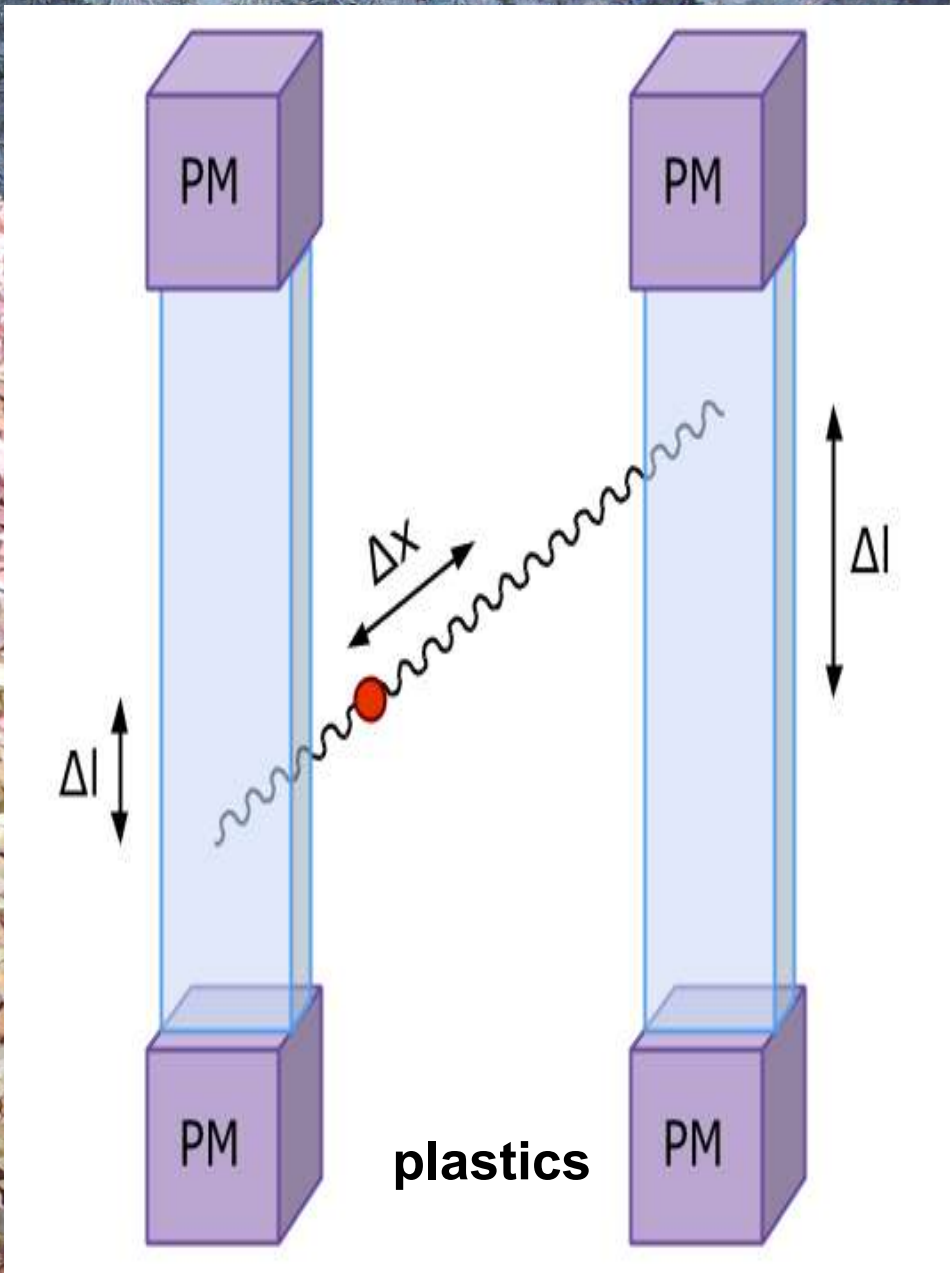




RADIOACTIVE SUGAR

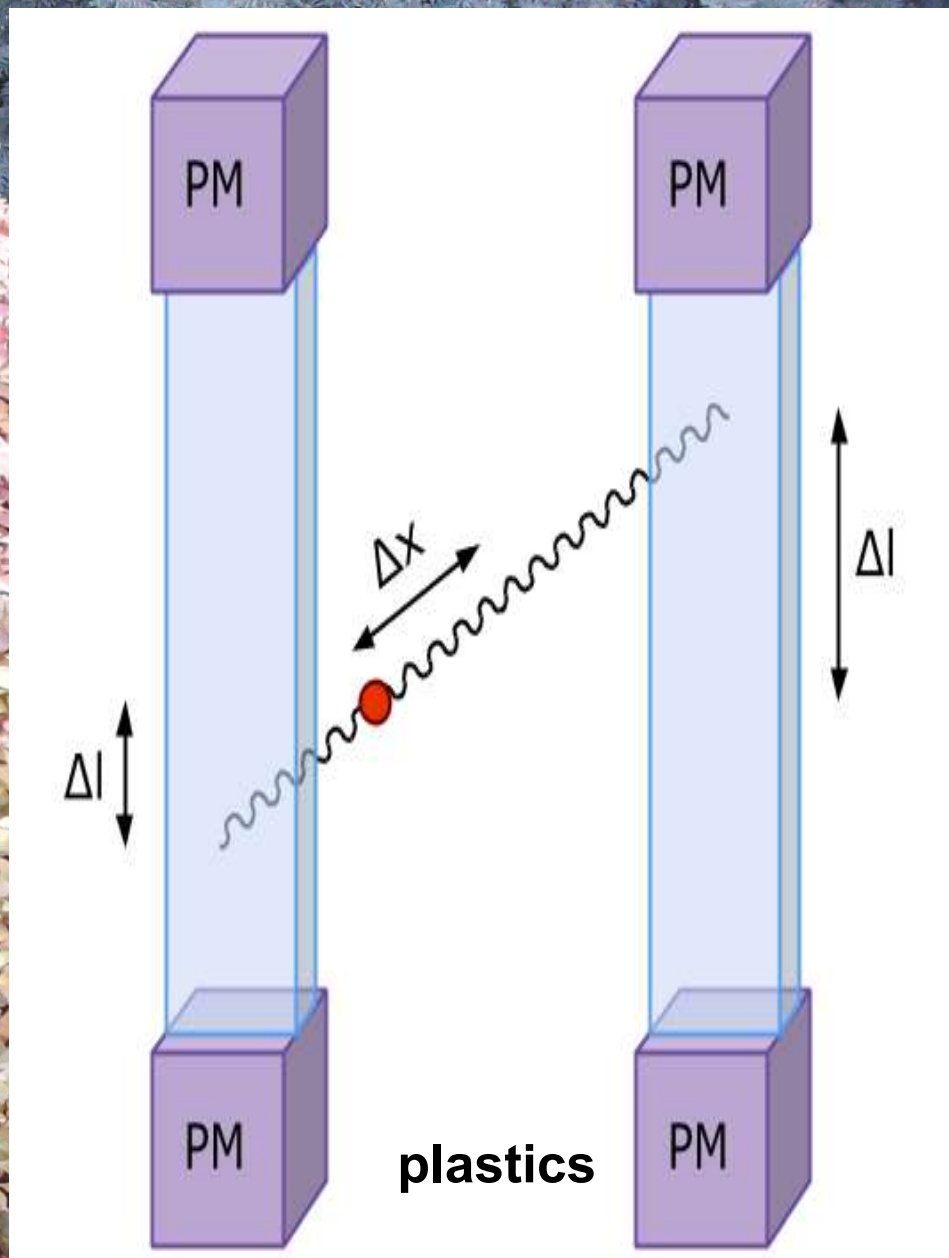
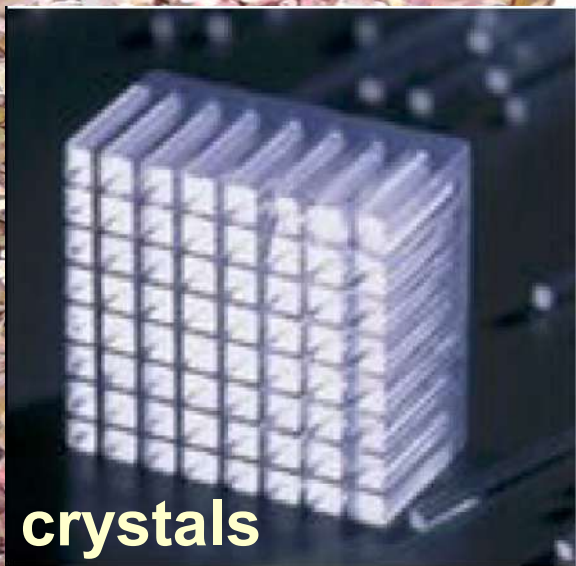
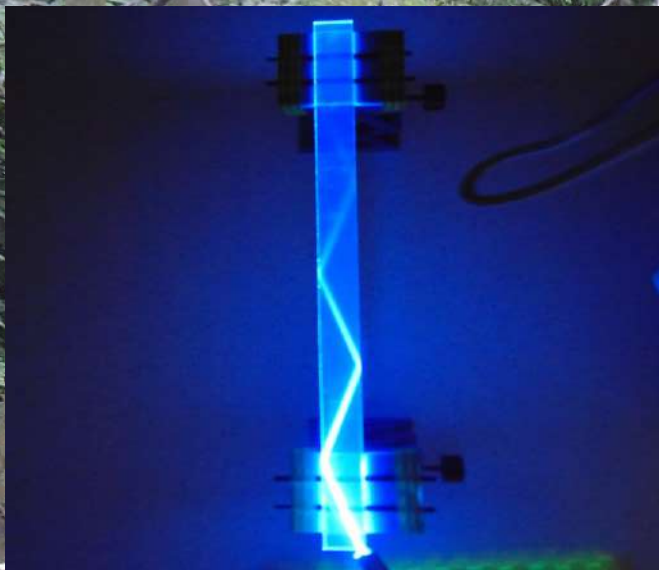
Fluoro-deoksy-glucose
(F-18 FDG)



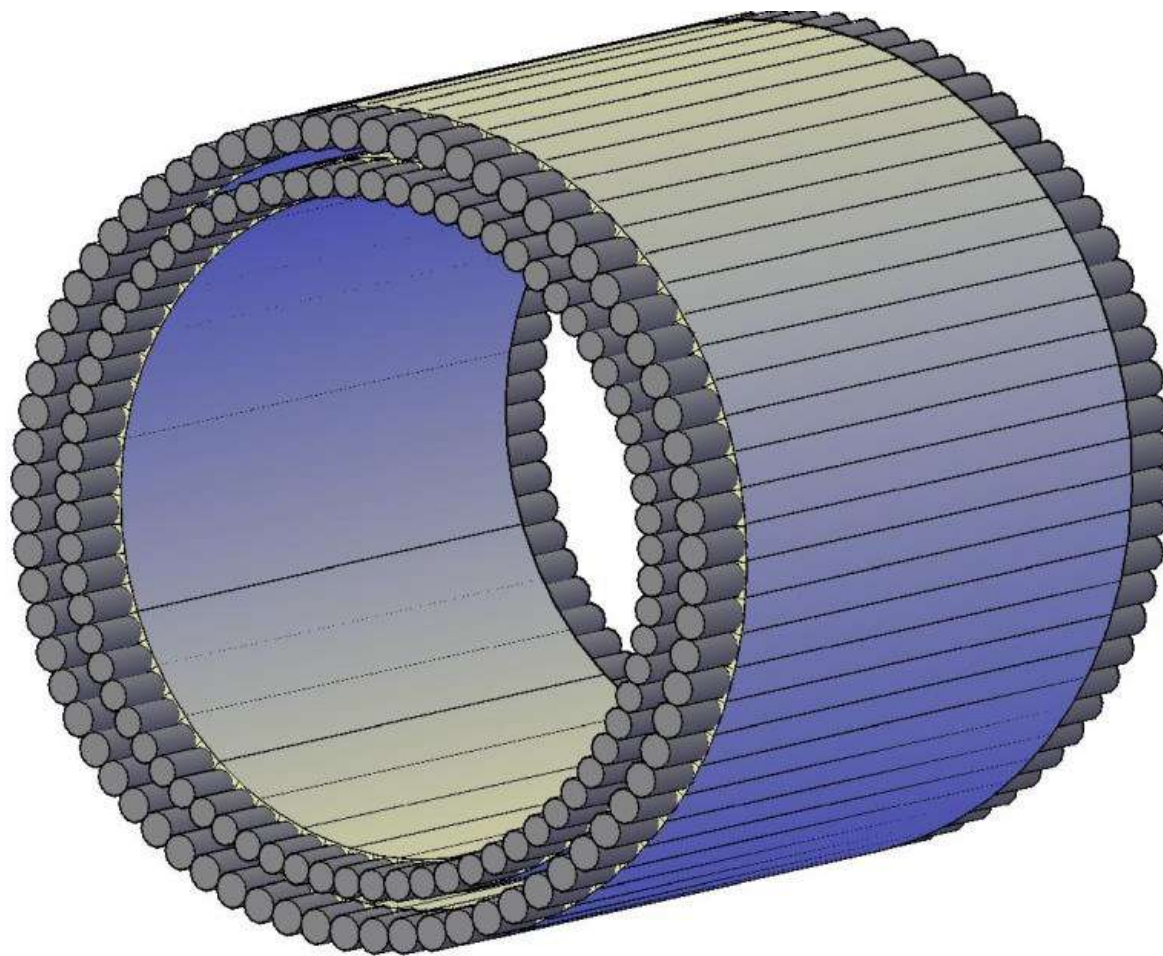


crystals

plastics



Development of cost-effective total-body PET

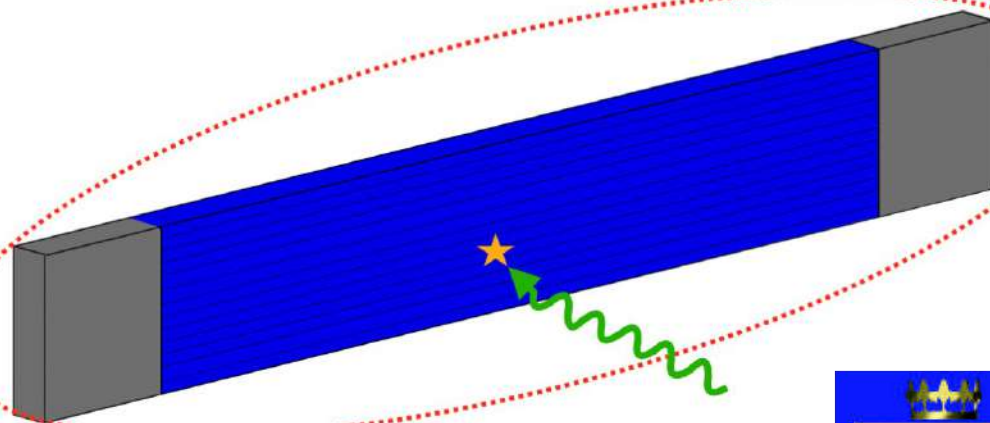
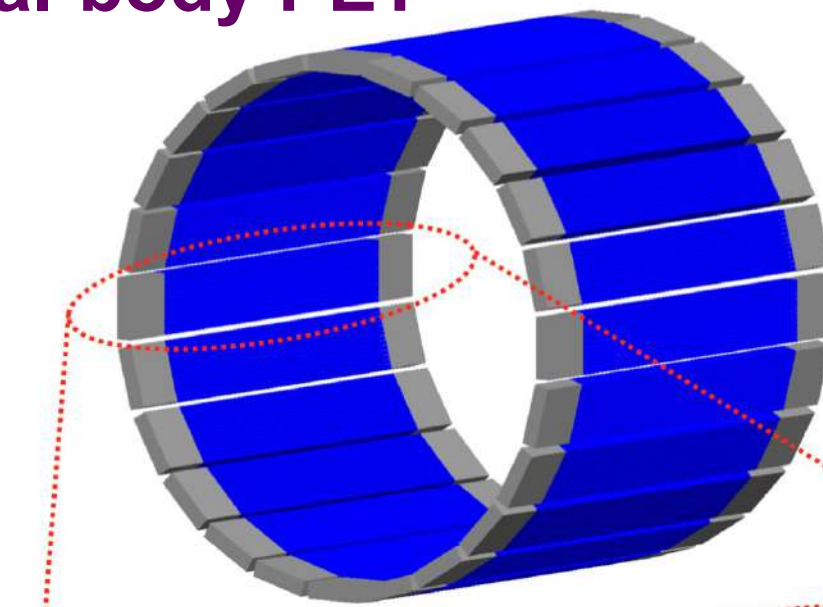
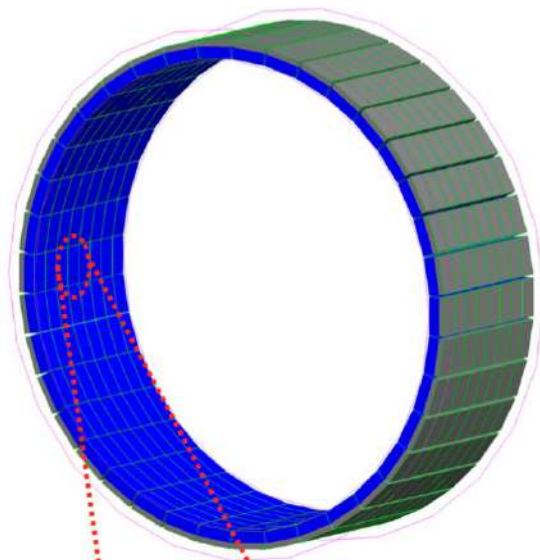


P. Moskal et al., Phys. Med. Biol. 66 (2021) 175015

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Development of cost-effective total-body PET



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

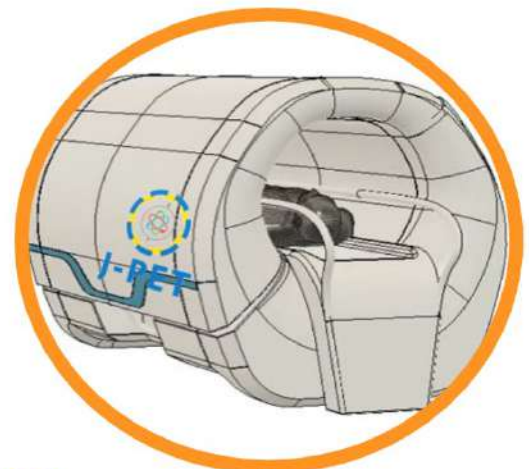
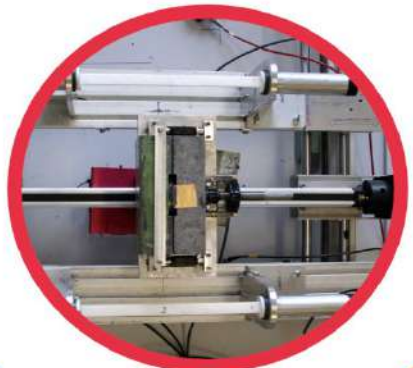
Japan: JP 5824773, JP 5824774, JP 6580675





total-body J-PET

3-layer prototype



2009

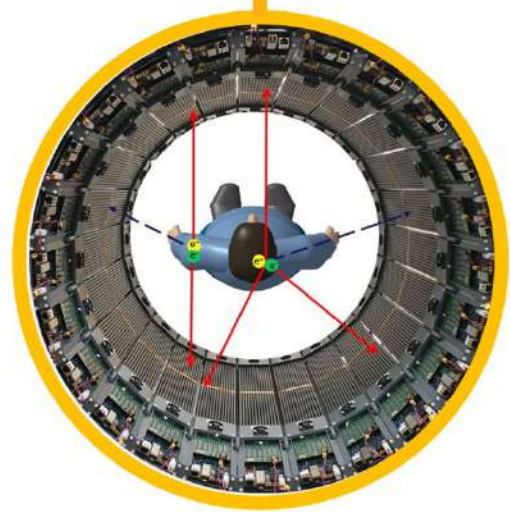
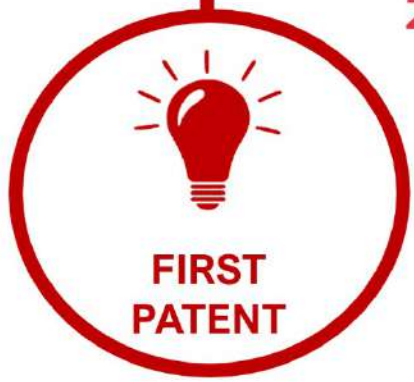
2014

2021

2012

2016

2028



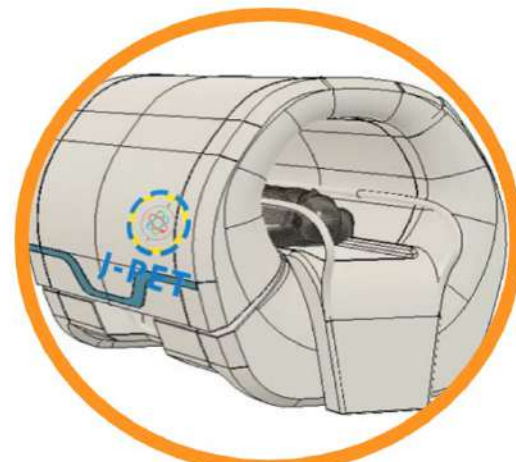
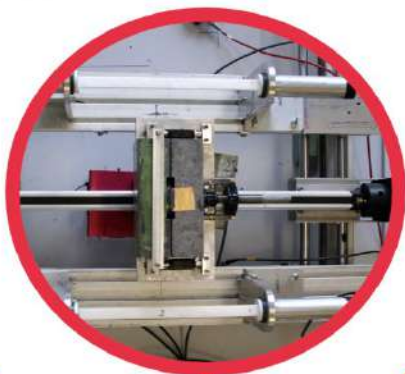
modular J-PET

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total-body J-PET

3-layer prototype



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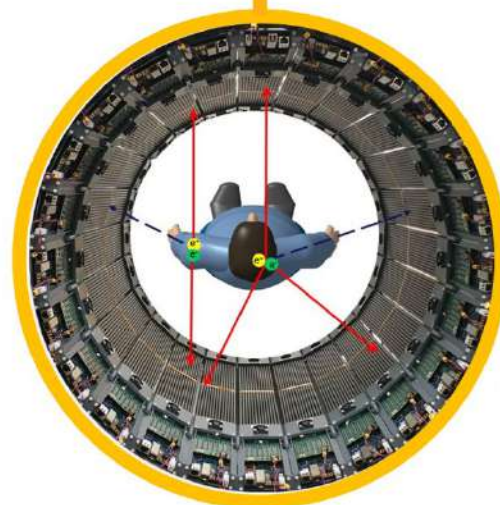
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modular J-PET

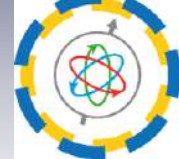
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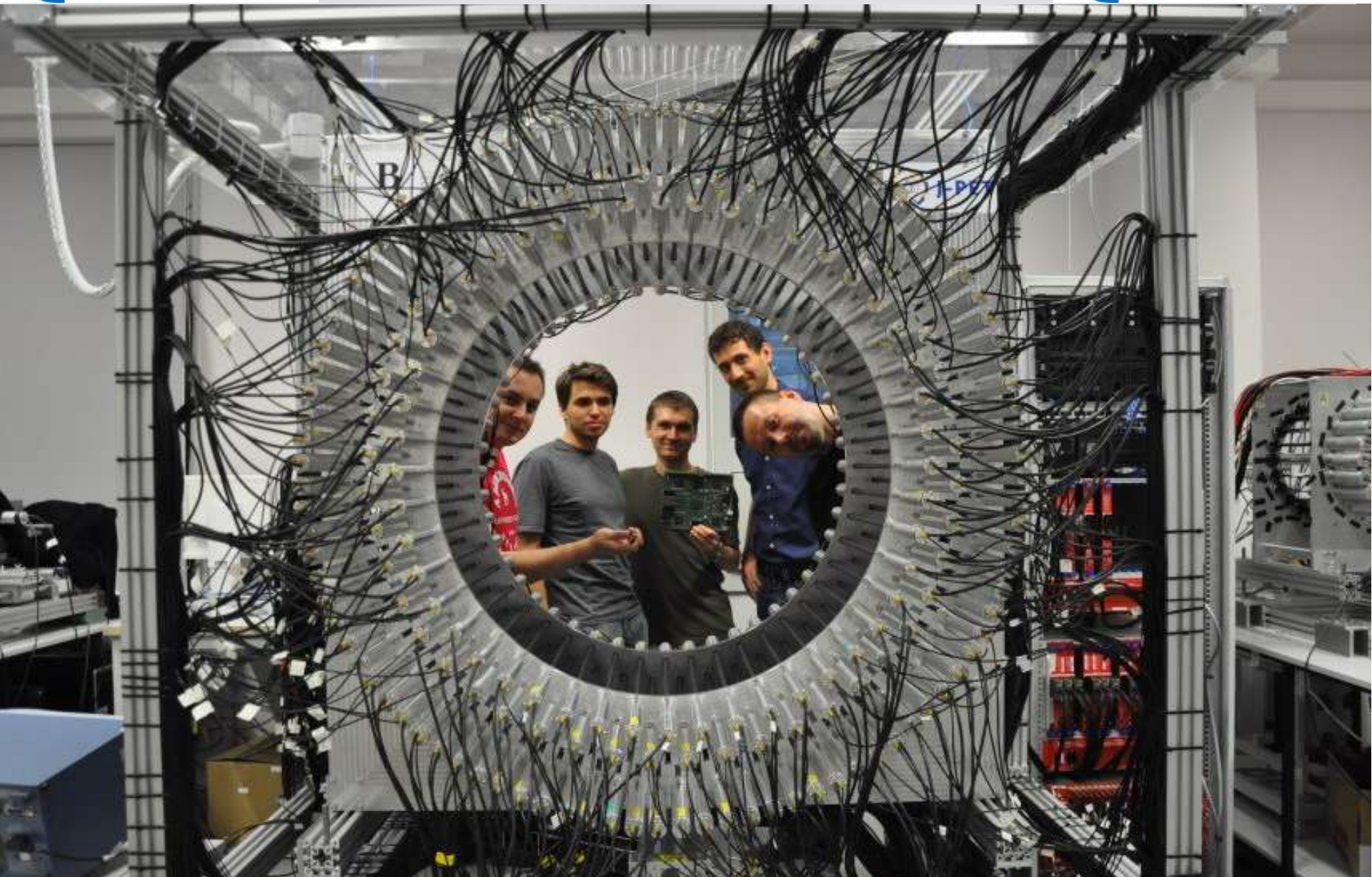


J-PET

Jagiellonian PET



J-PET



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

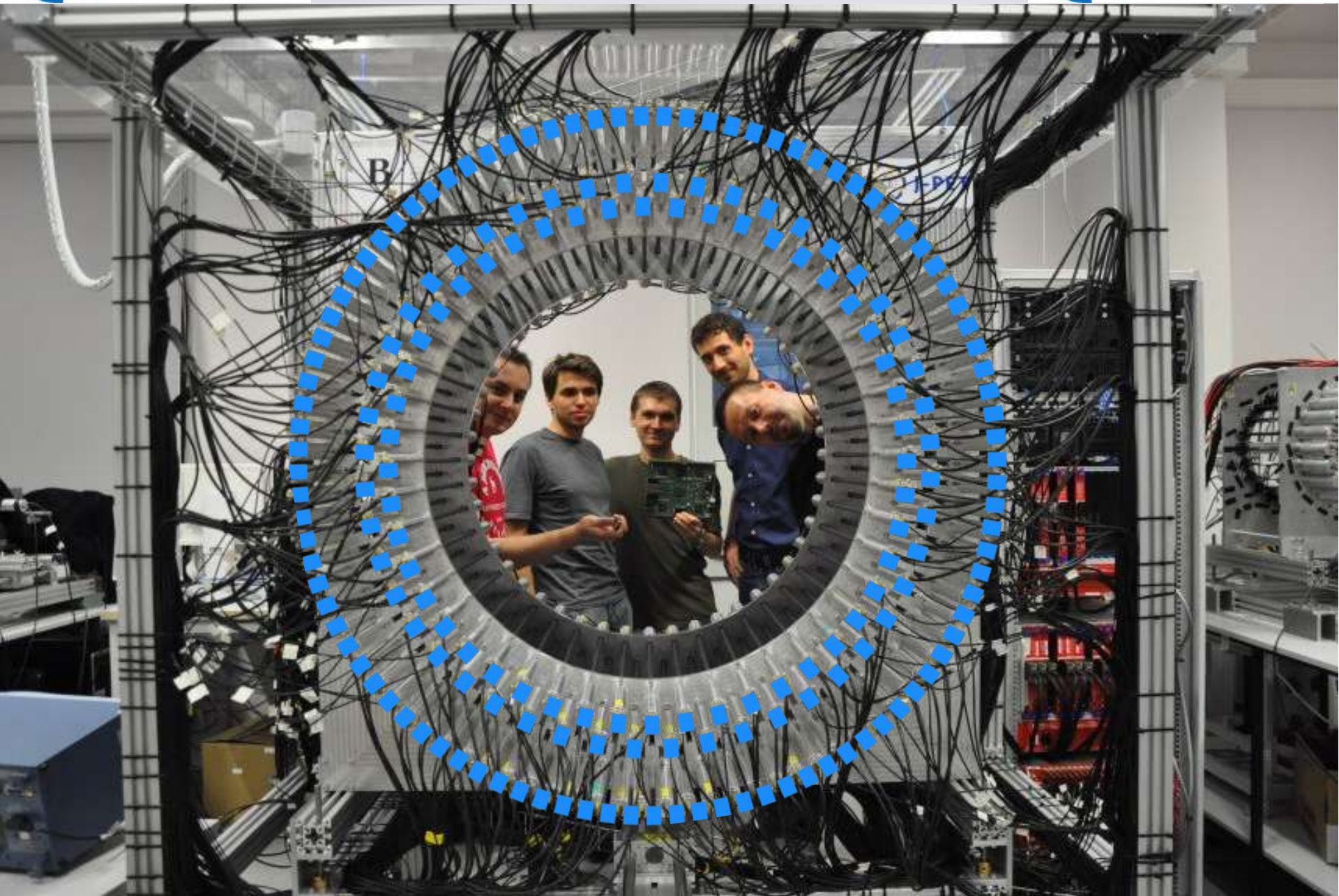


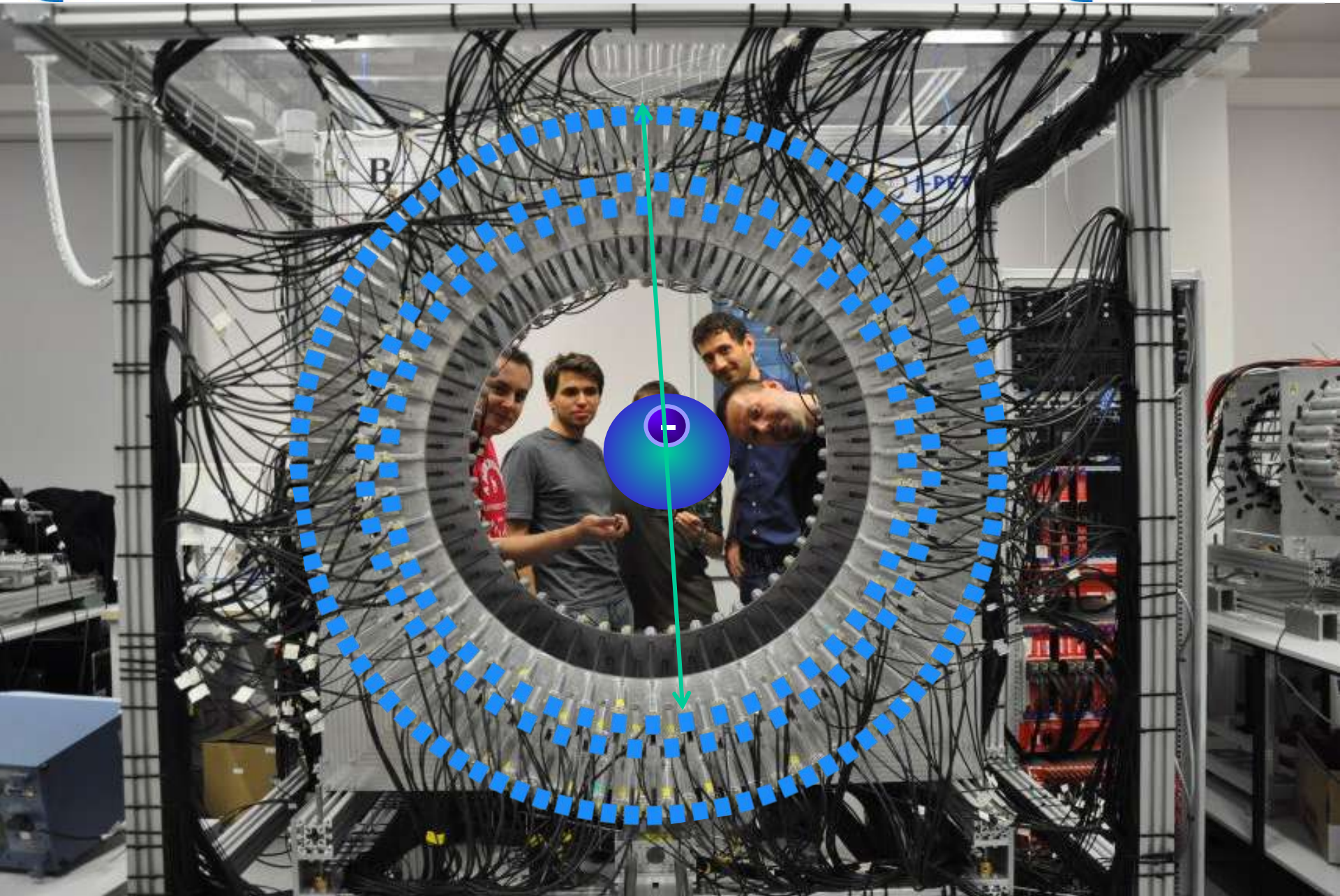
J-PET

Jagiellonian PET



J-PET





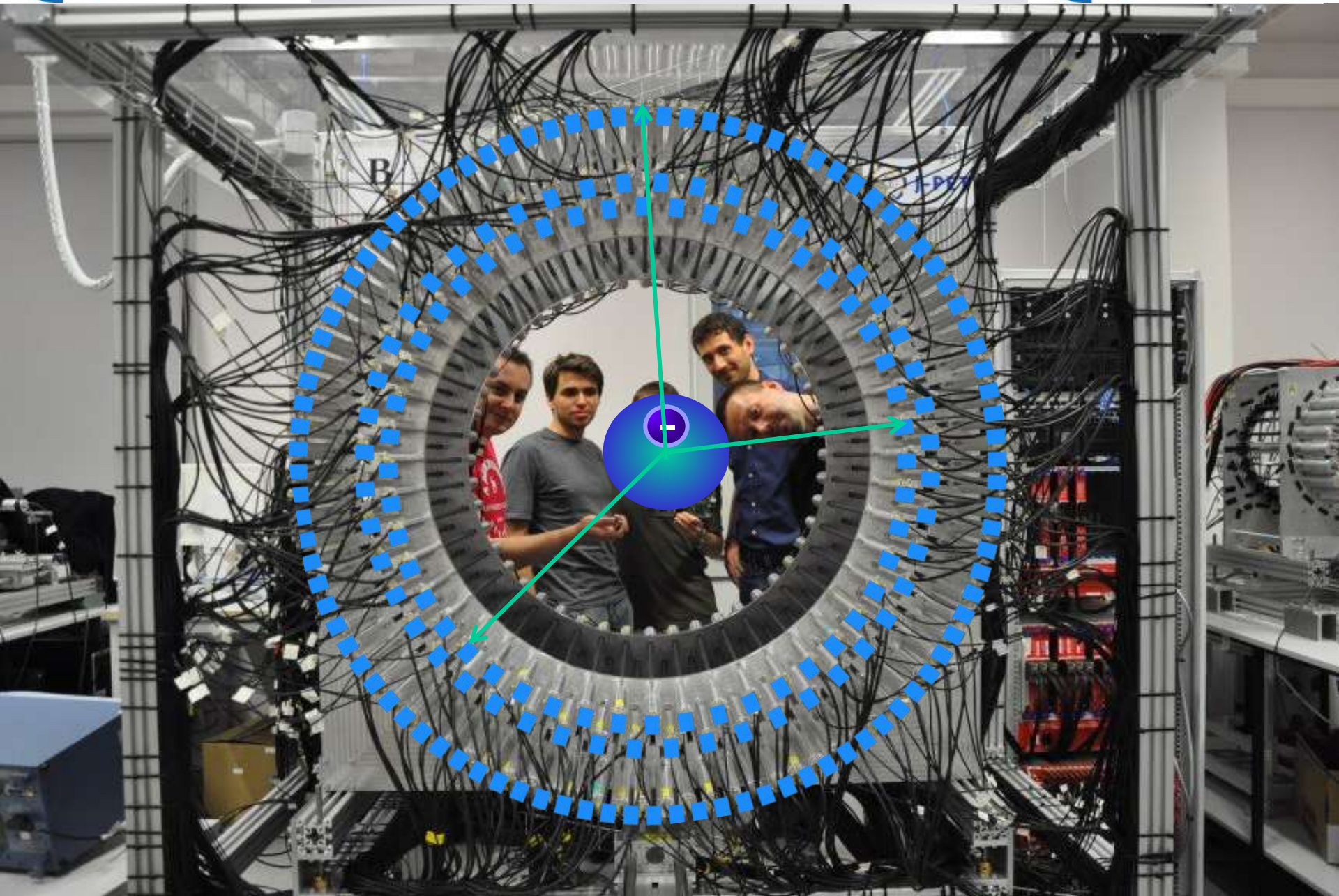


J-PET

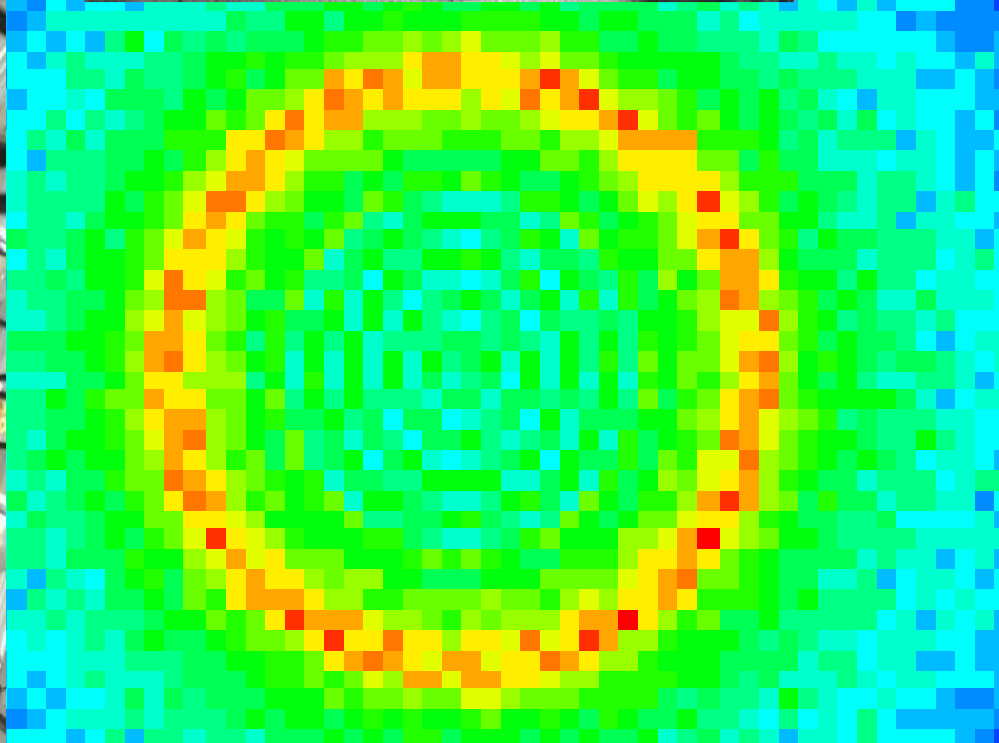
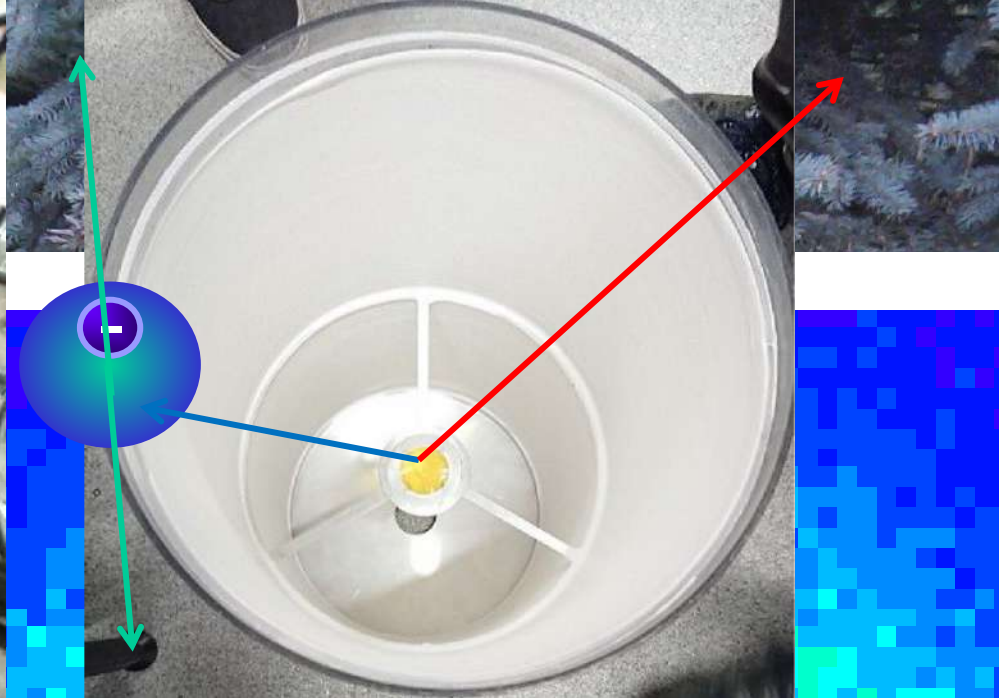
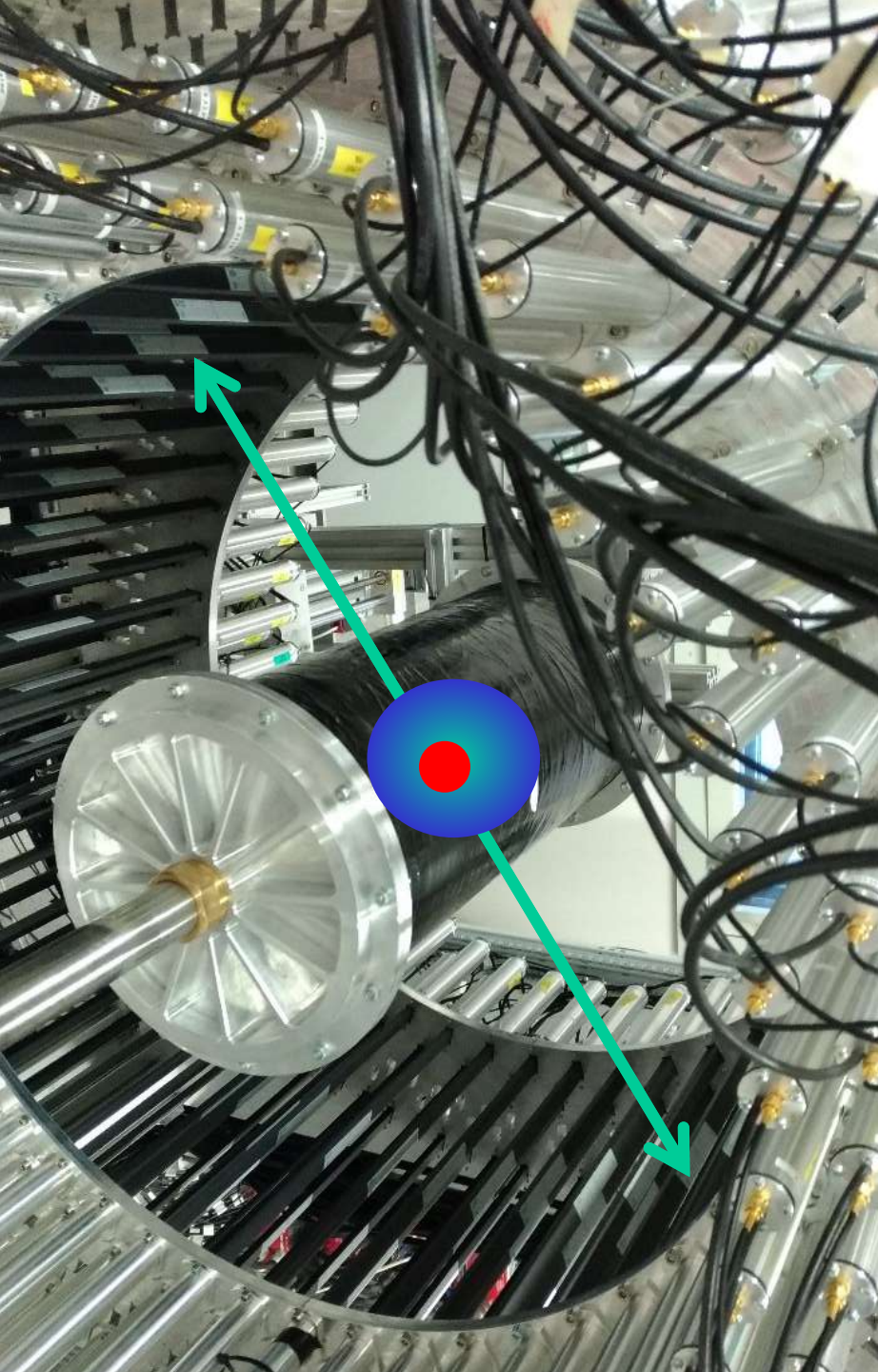
Jagiellonian PET

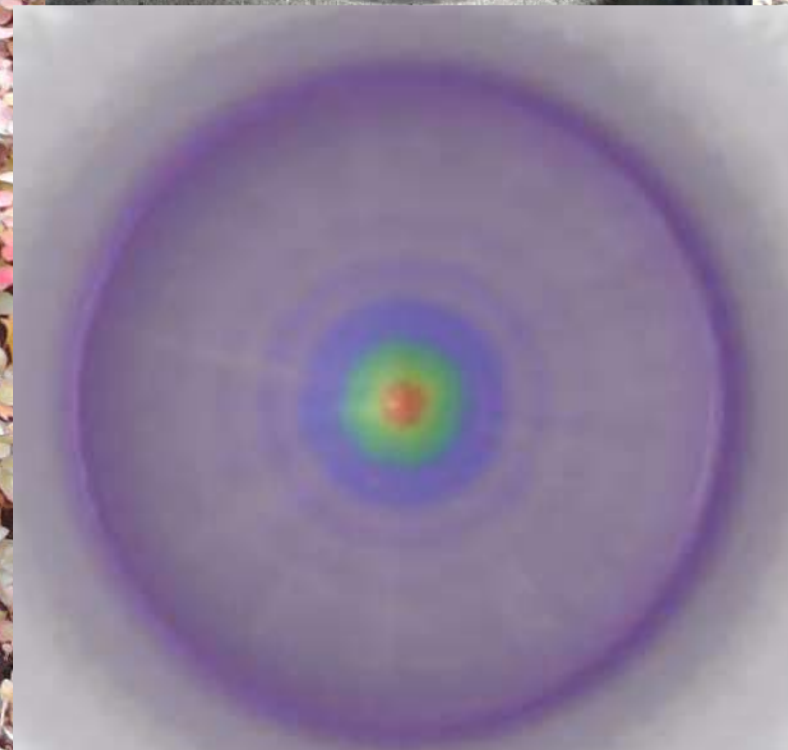
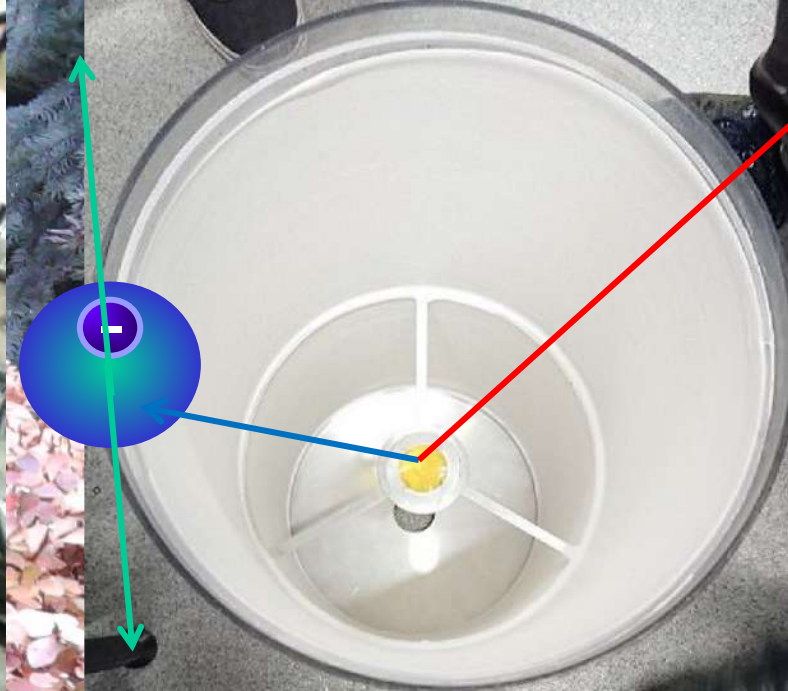
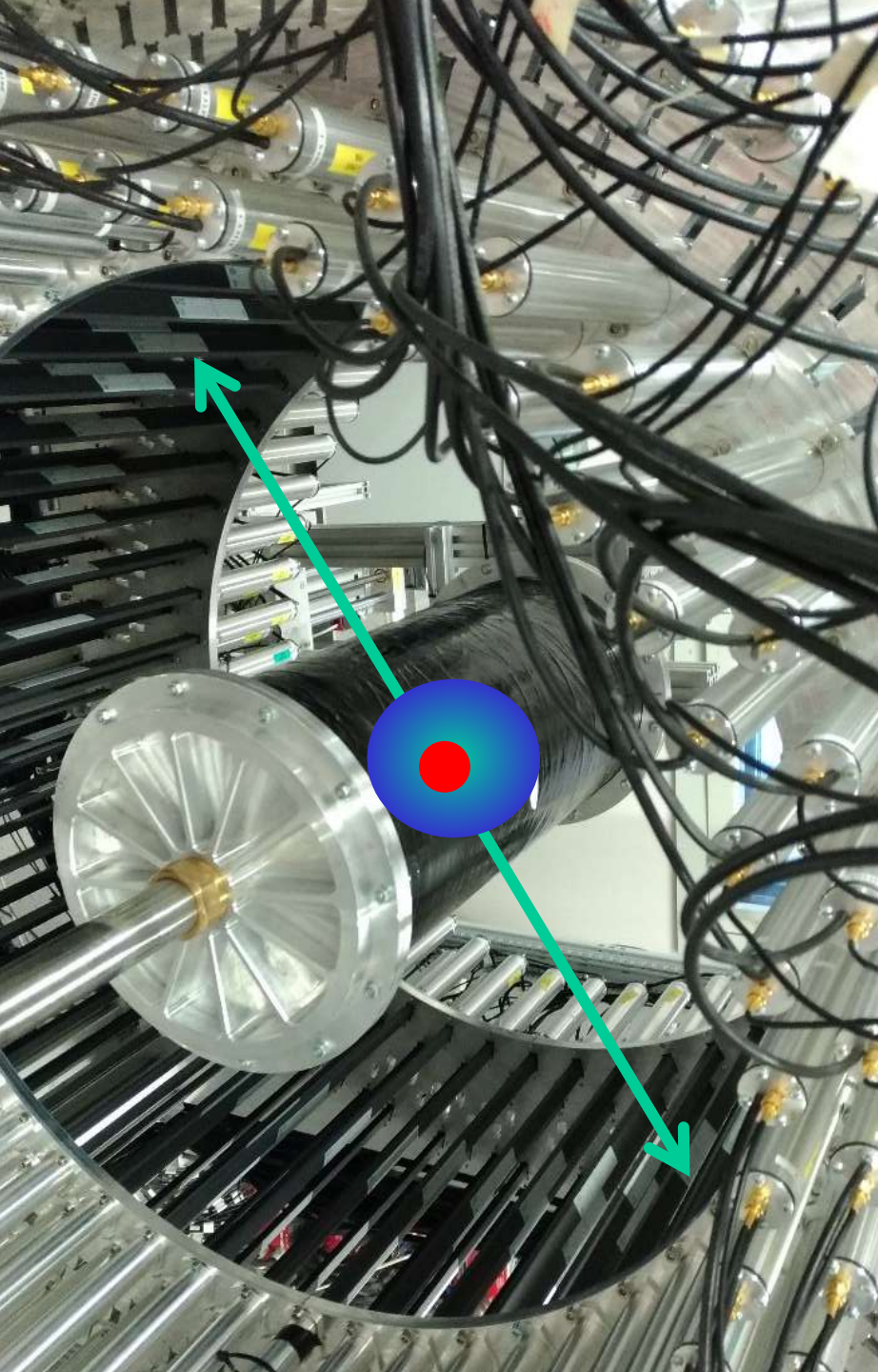


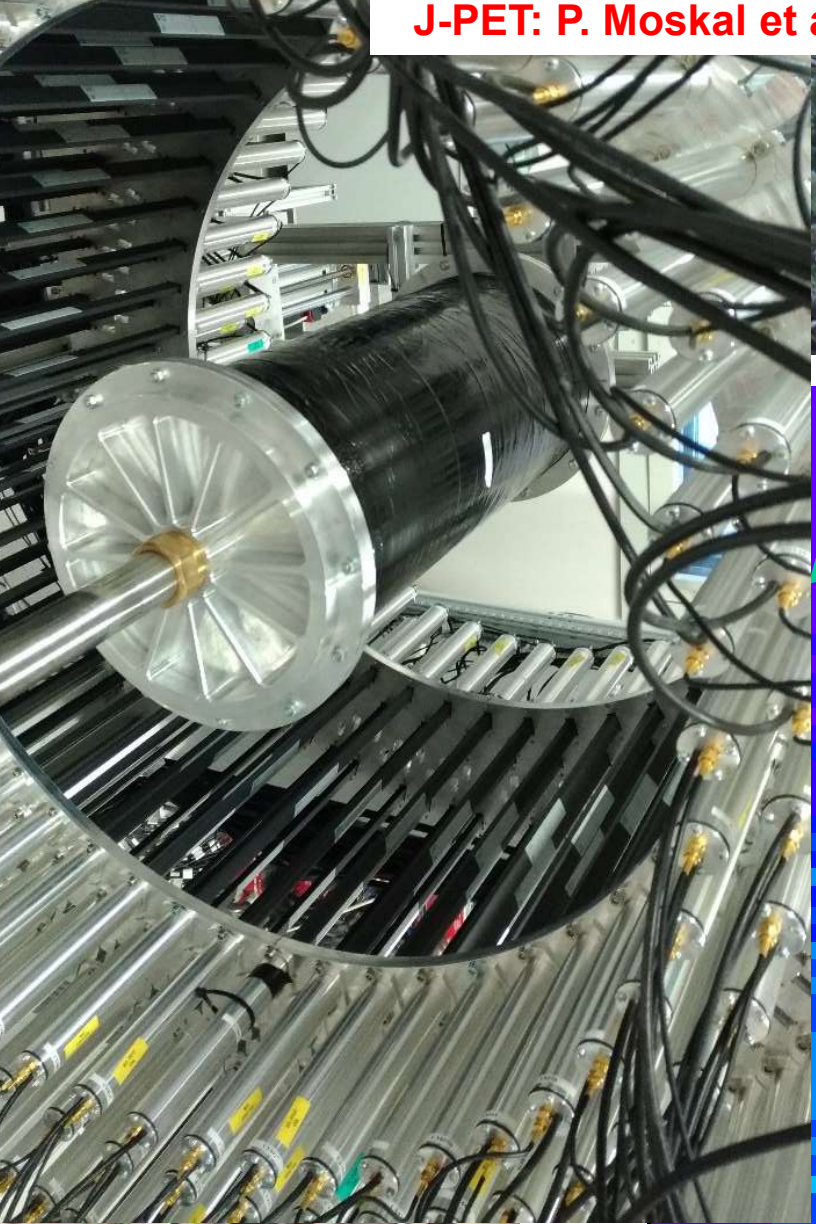
J-PET



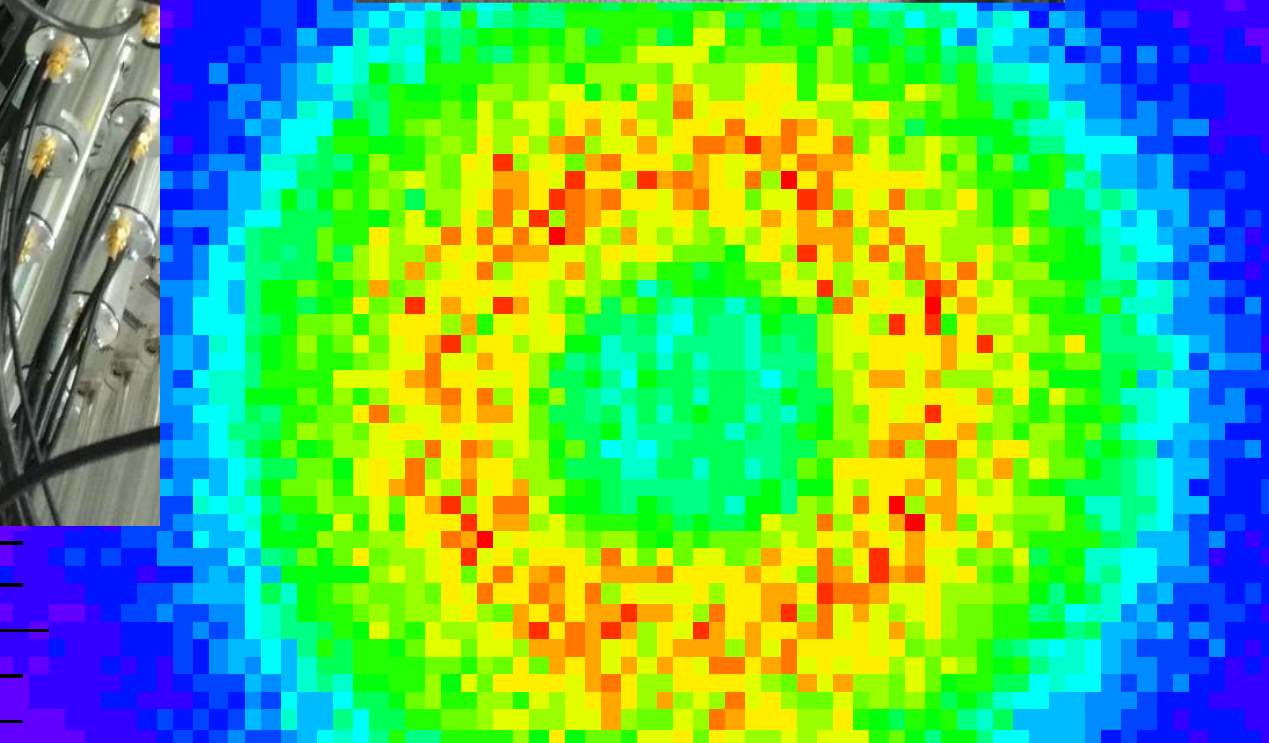






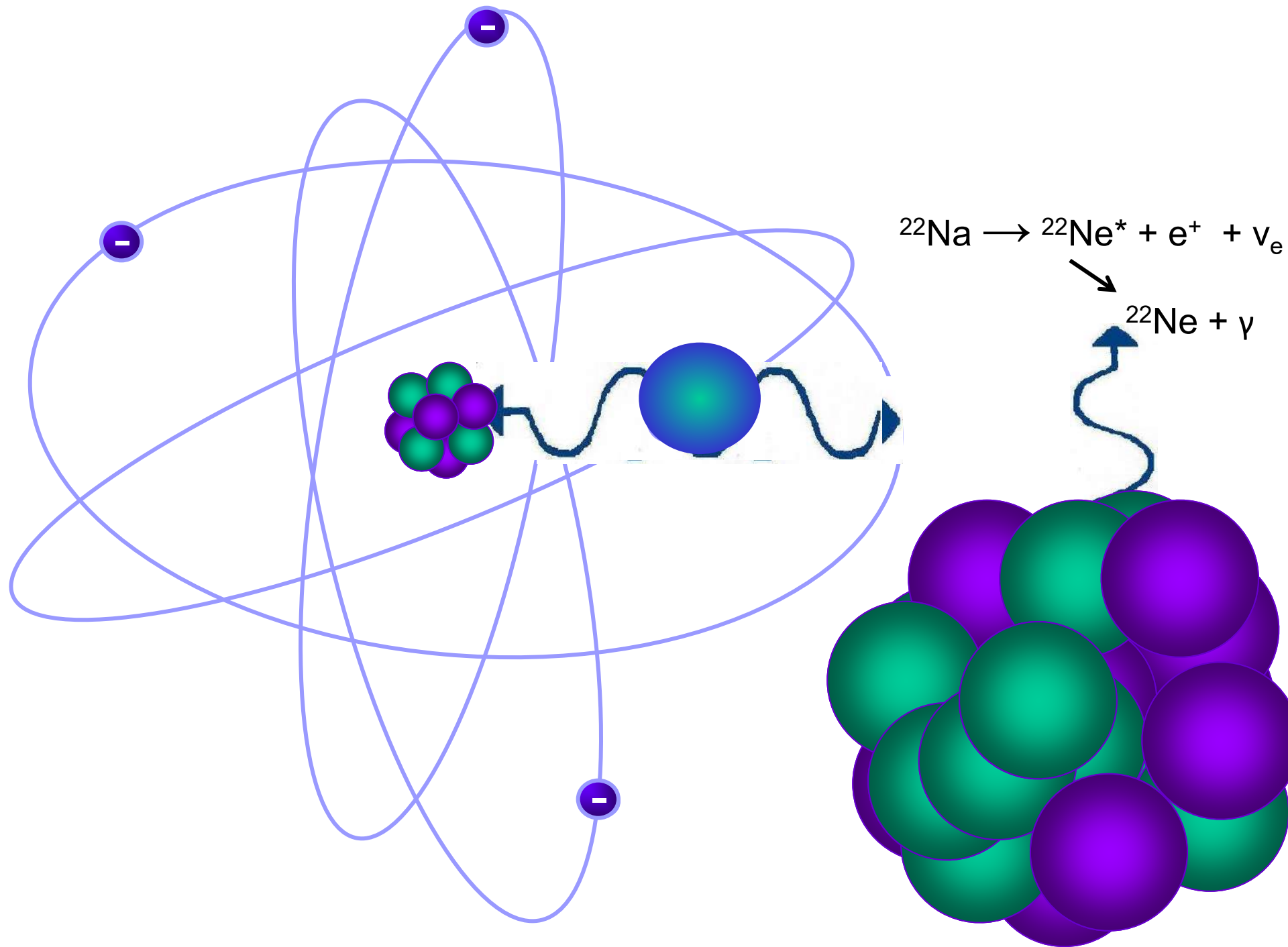


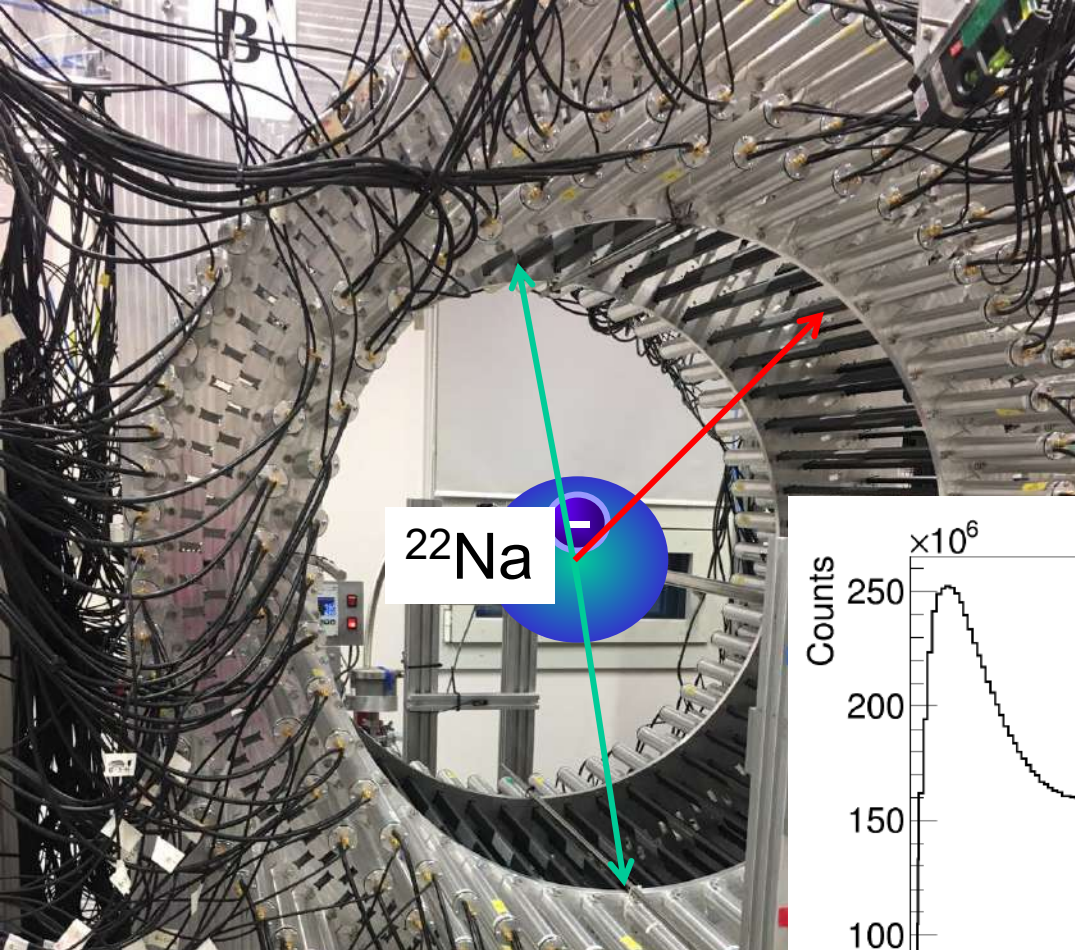
-10




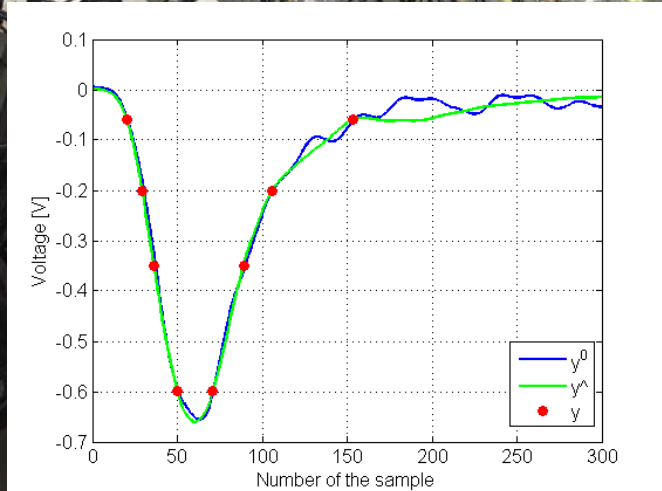
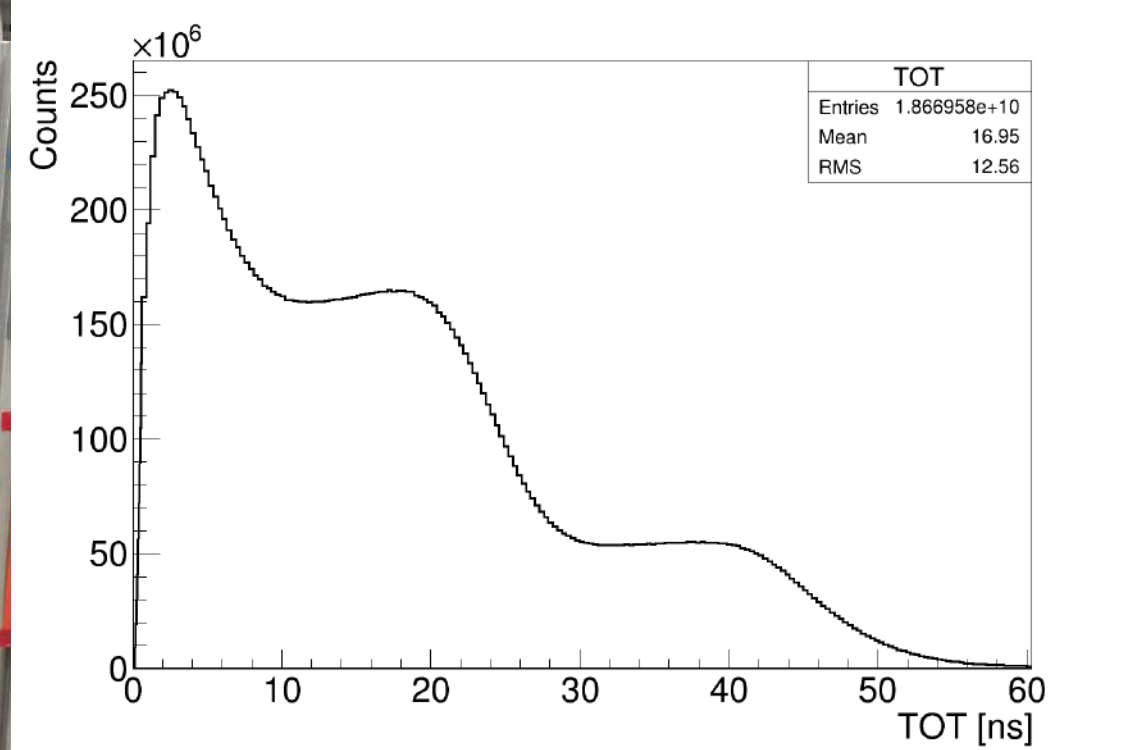
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- Positronium imaging
- Discrete symmetries
- Quantum Entanglement





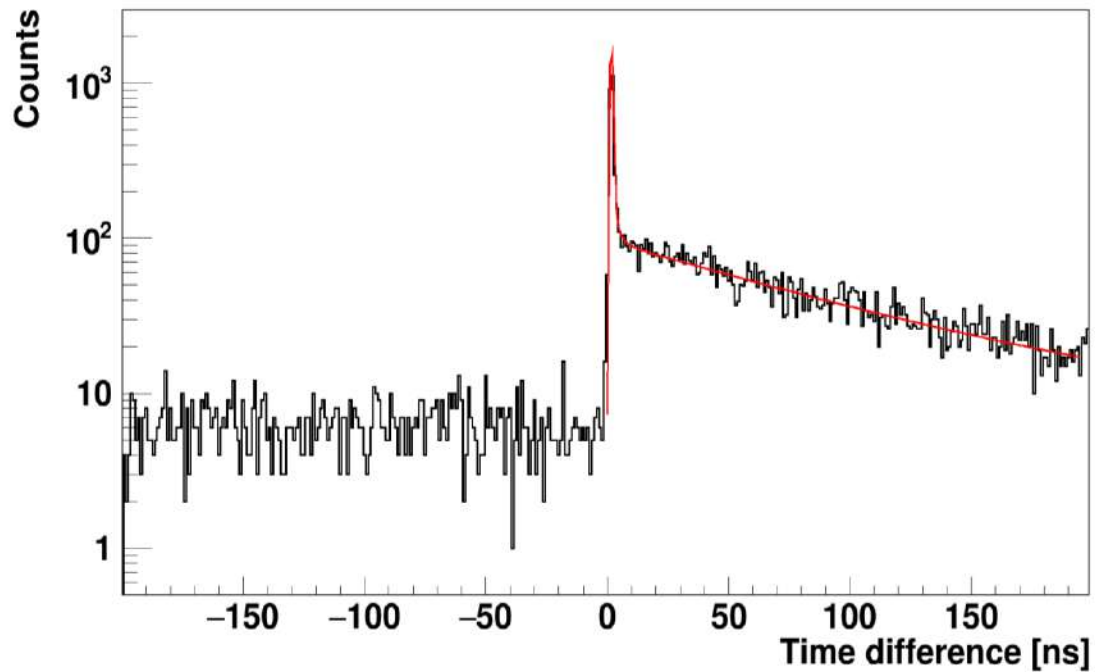


^{22}Na 



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

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

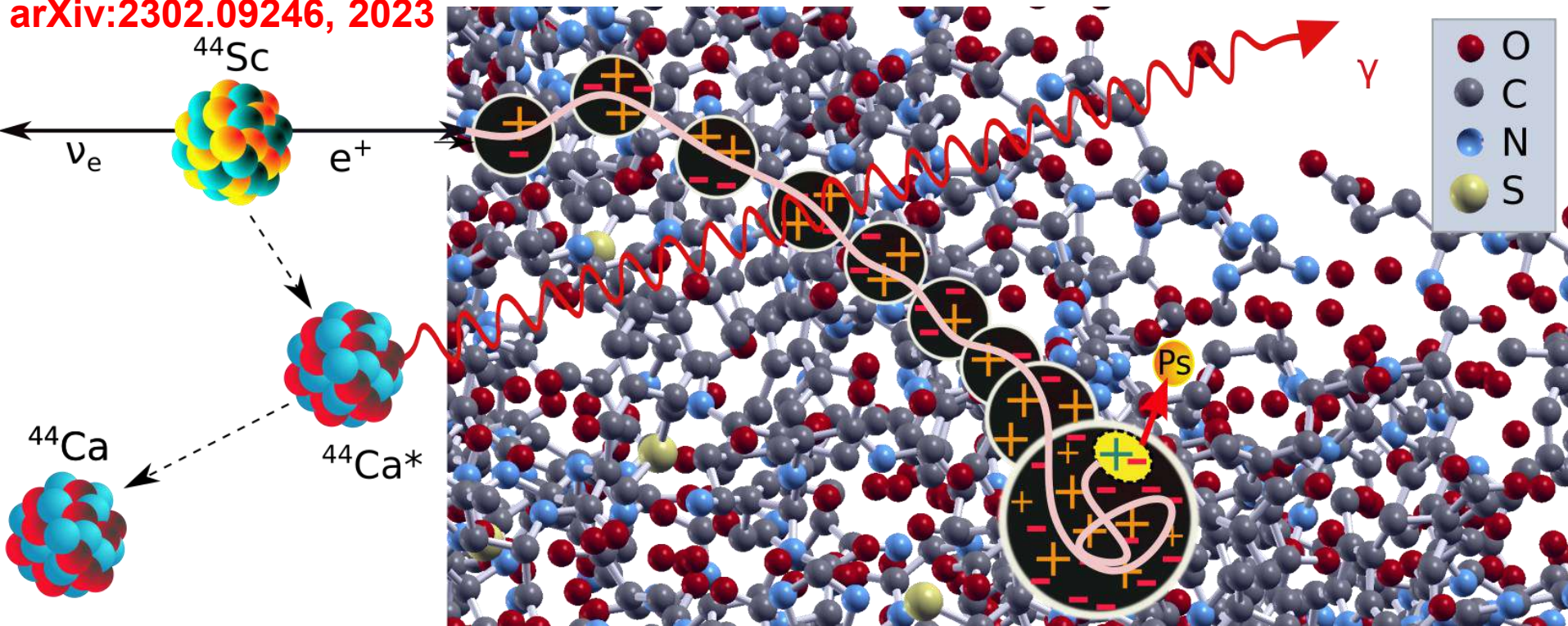




J-PET First positronium imaging of humans using modular J-PET scanner



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

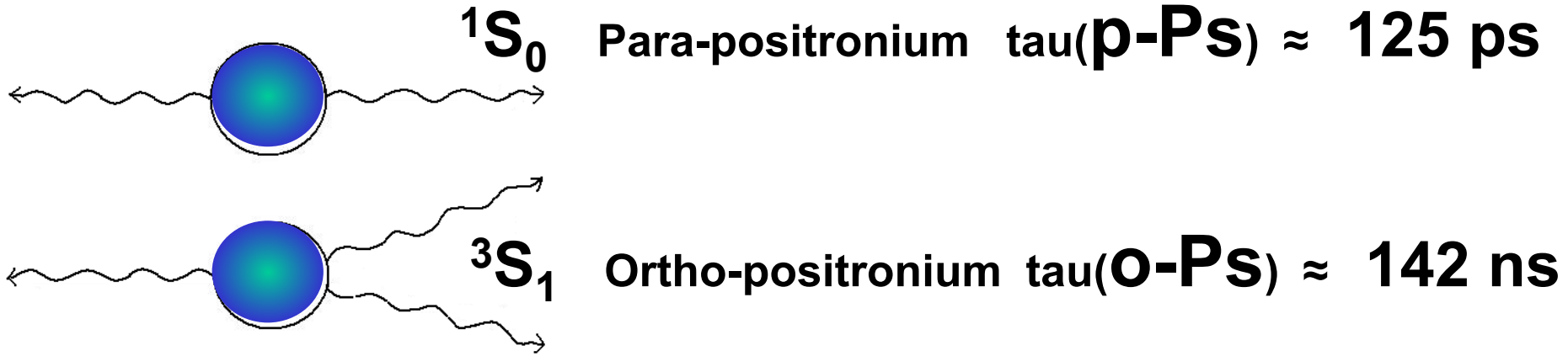


P. Moskal, E. Ł. Stępień, Bio-Algorithms and Med.-Systems 17 (2021) 311



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

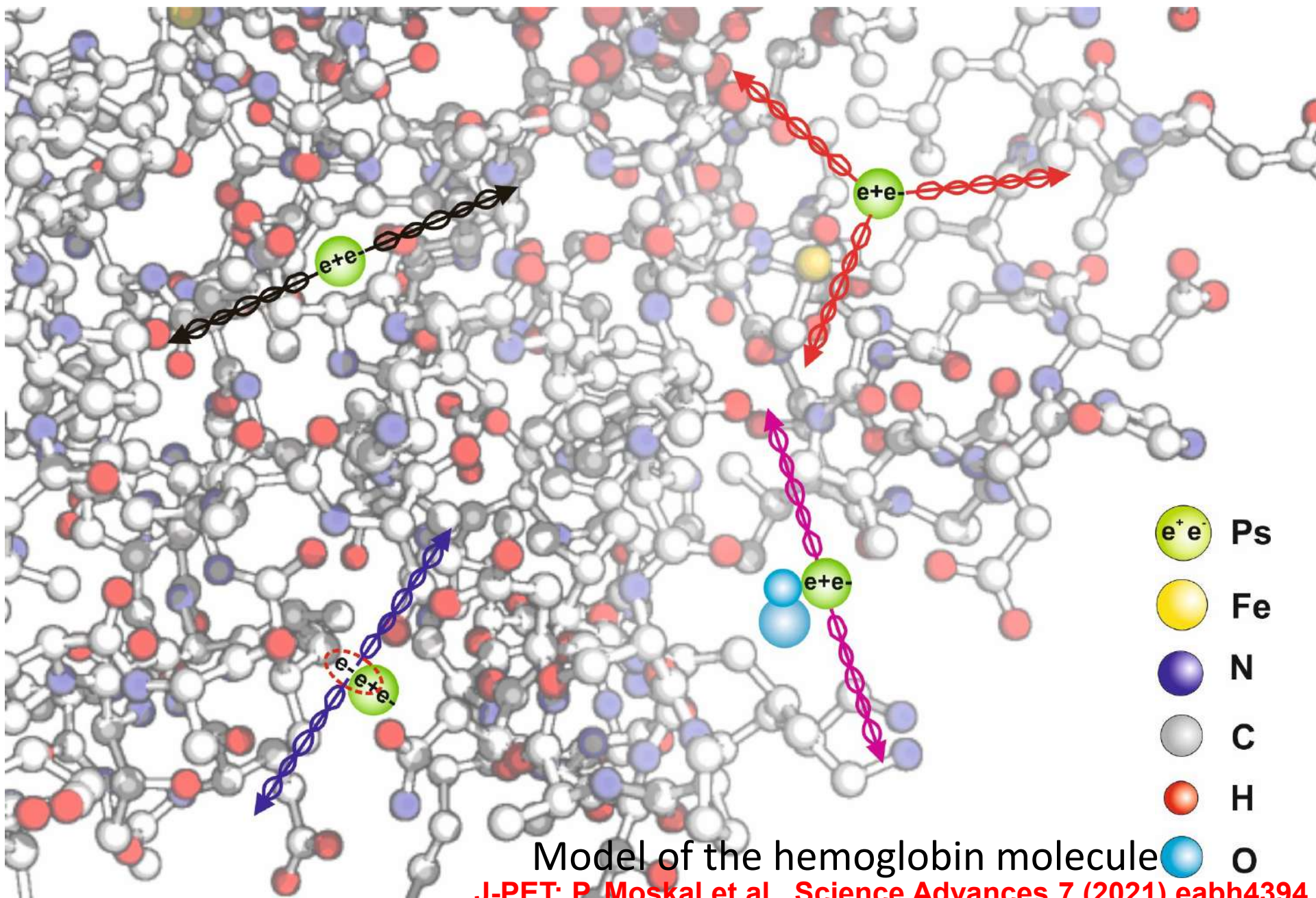




	1S_0	3S_1	
L	0	0	$S = 0$ $\downarrow\uparrow - \uparrow\downarrow$
S	0	1	$\uparrow\uparrow$
C	+	-	$S = 1$ $\downarrow\uparrow + \uparrow\downarrow$
$L=0 \rightarrow$ P	-	-	$\downarrow\downarrow$
CP	-	+	

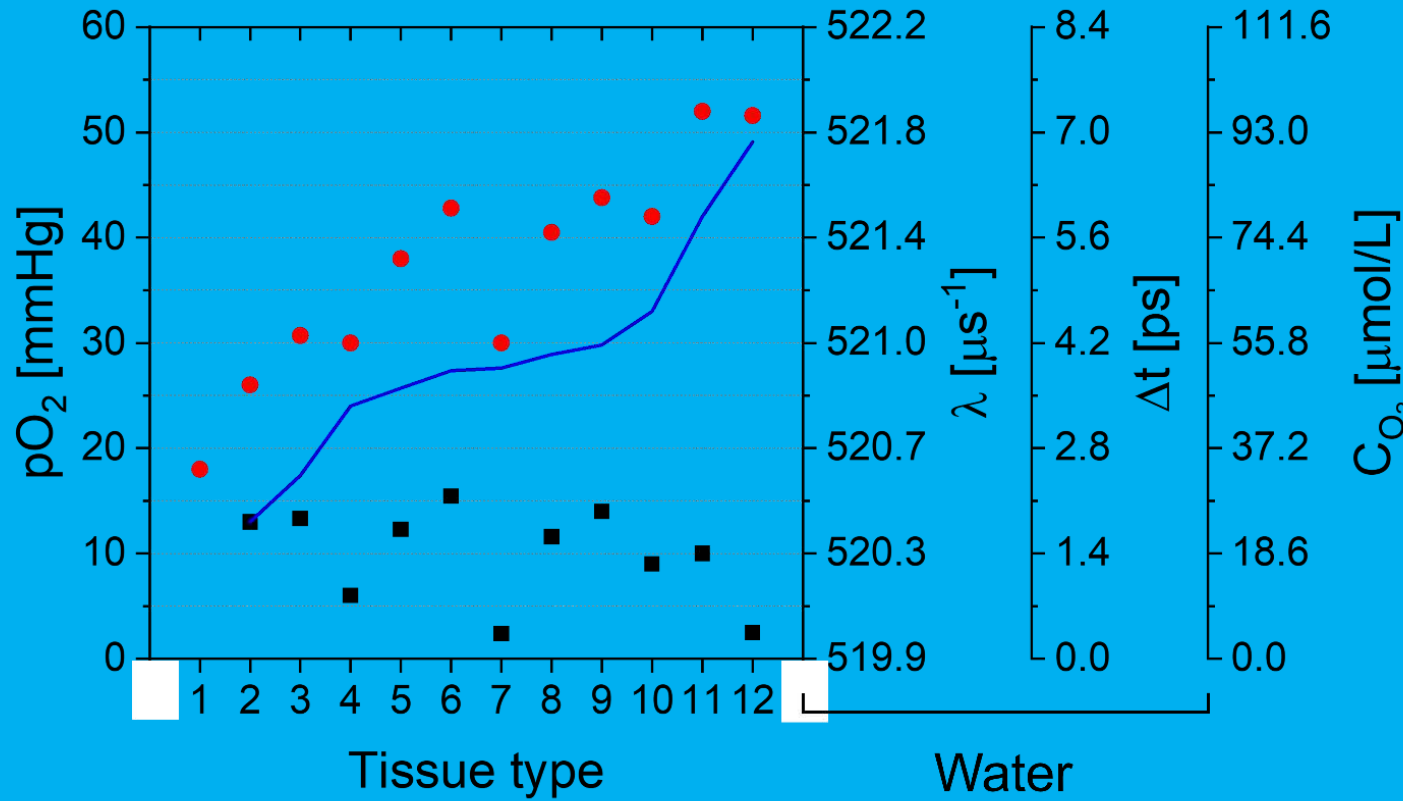
Positronium imaging

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

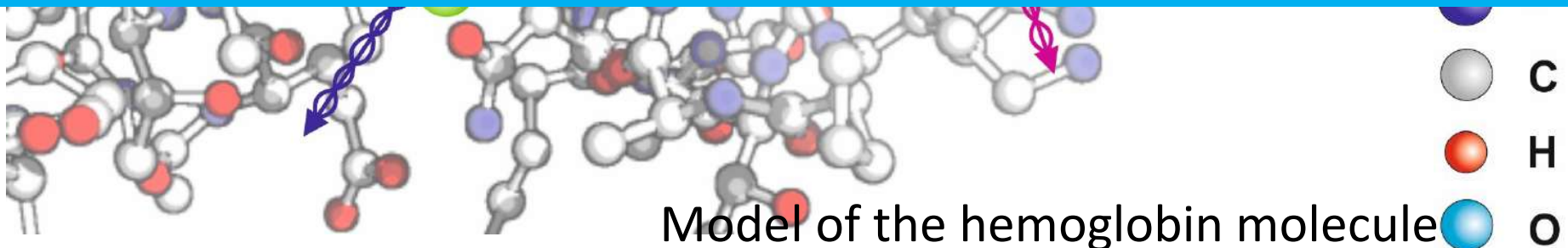


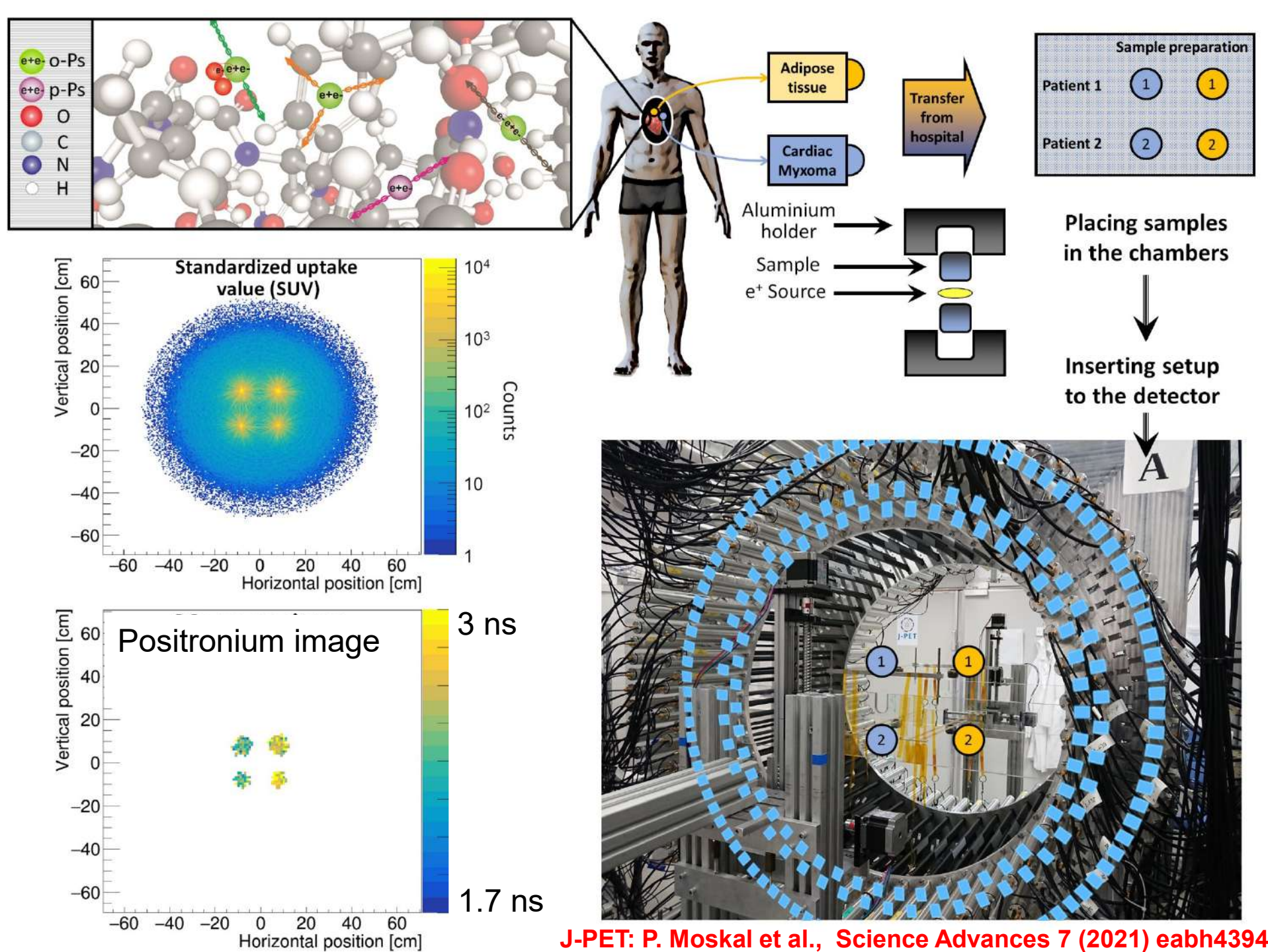
Positronium imaging

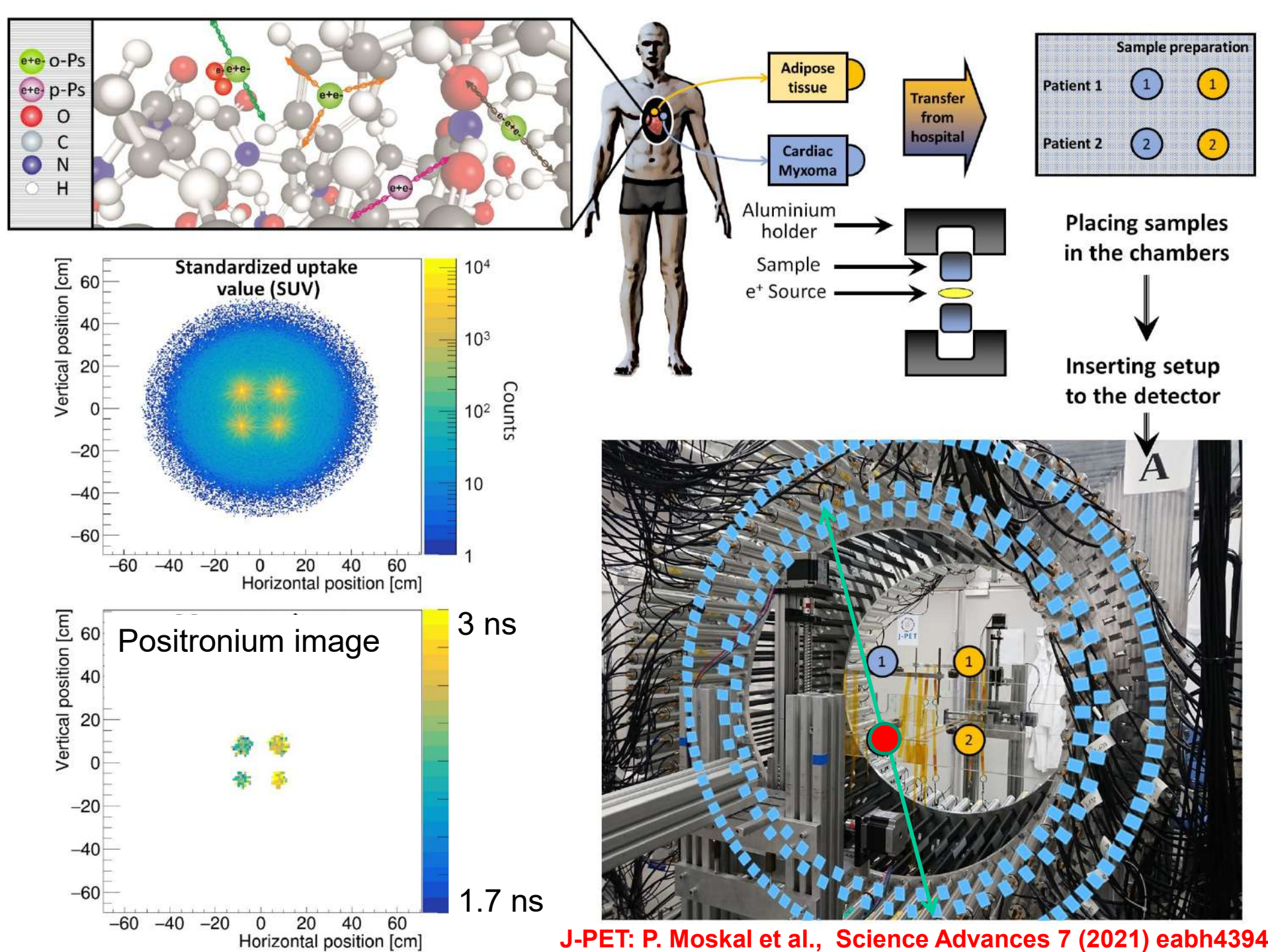
P. Moskal, E. Stępień., *Bio-Algorithms and Med-Systems* 17 (2021) 311
 „Positronium as a biomarker of hypoxia”

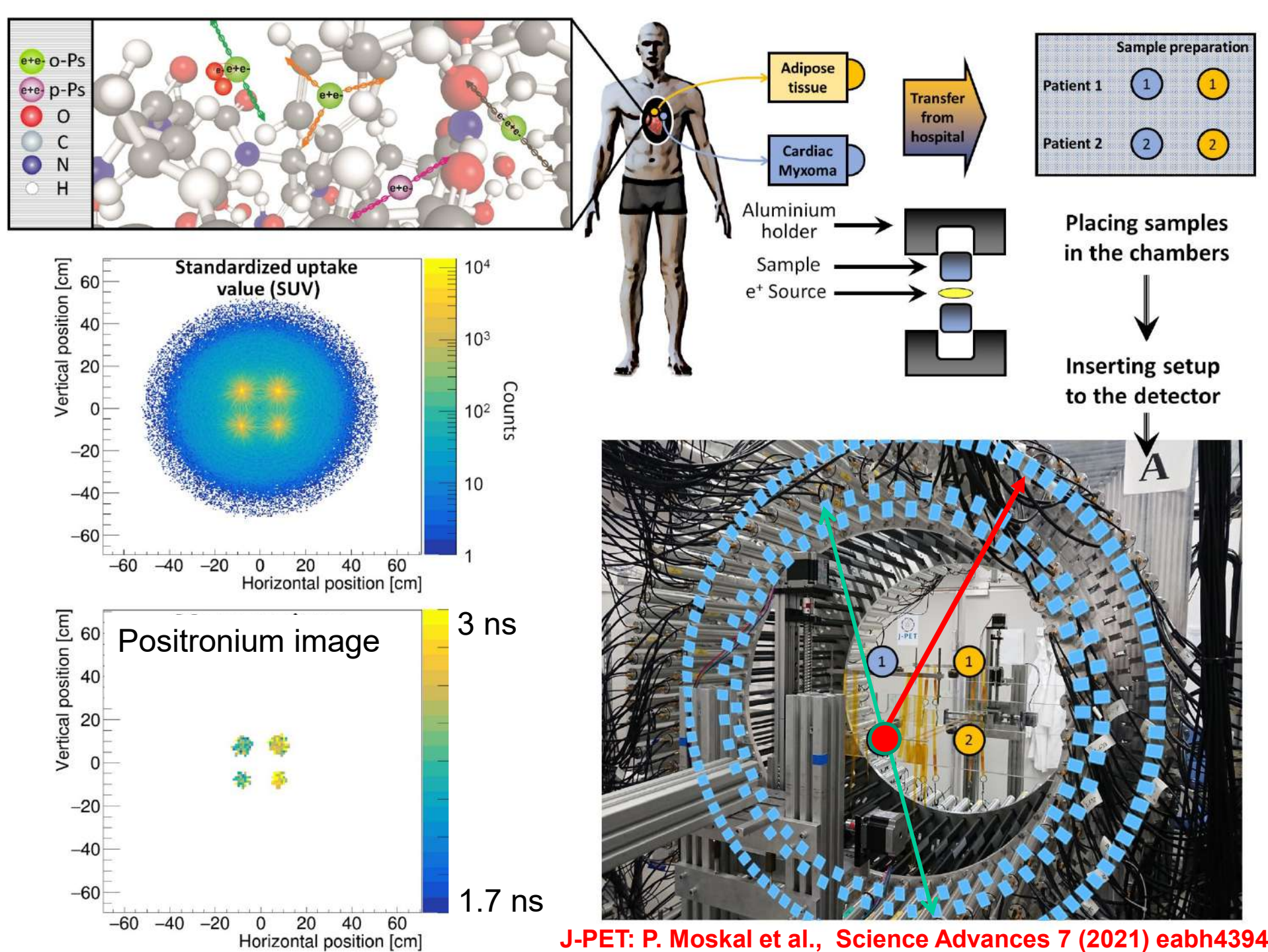


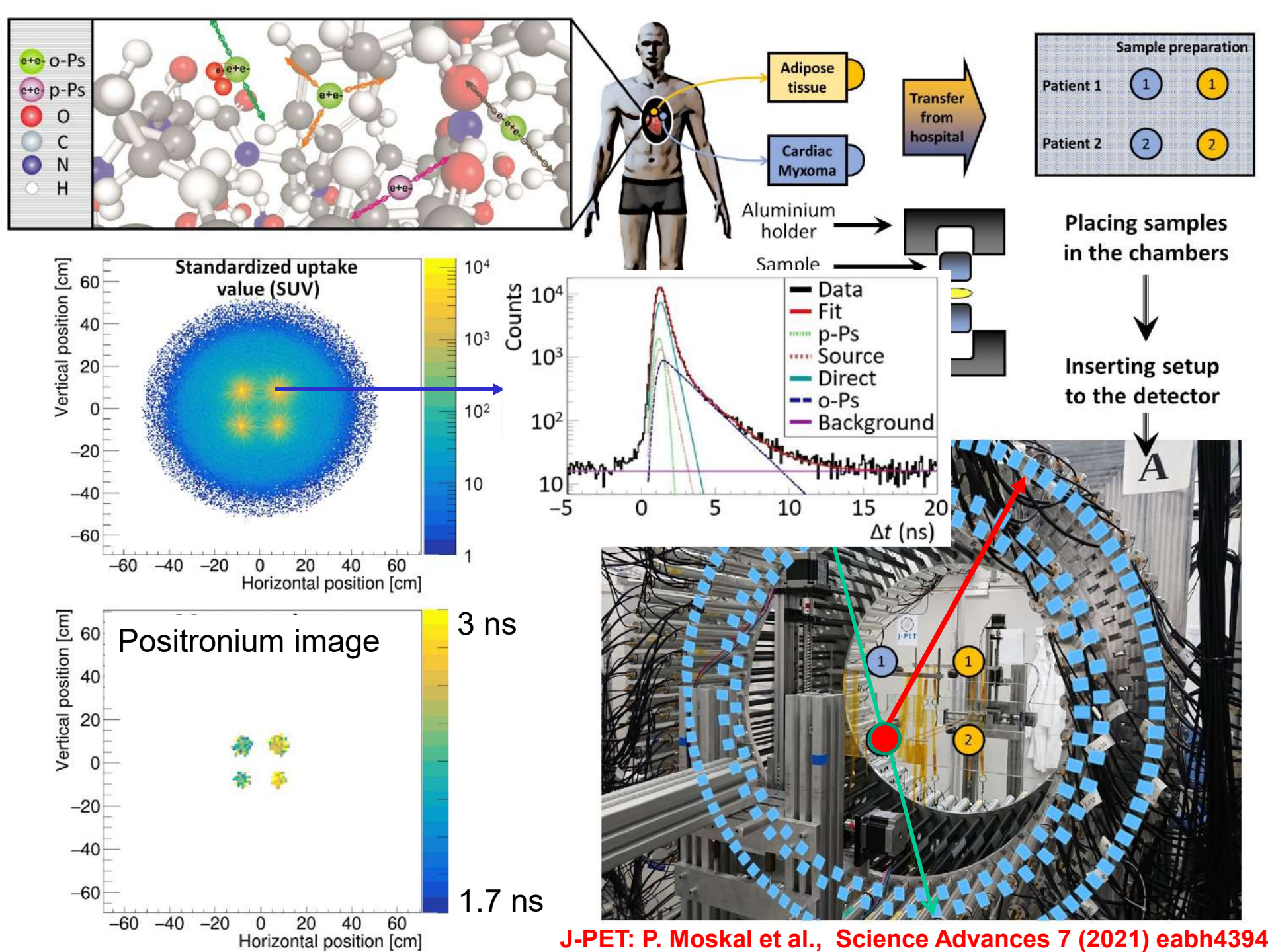
Tissue type	Description
1	Myocardium
2	Brain
3	Kidney
4	Liver
5	Head and Neck
6	Lung
7	Prostate
8	Skin melanoma
9	Sarcoma
10	Cervical
11	Breast
12	Pancreatic







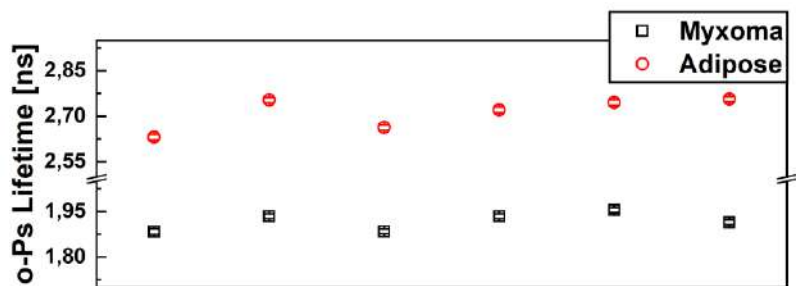




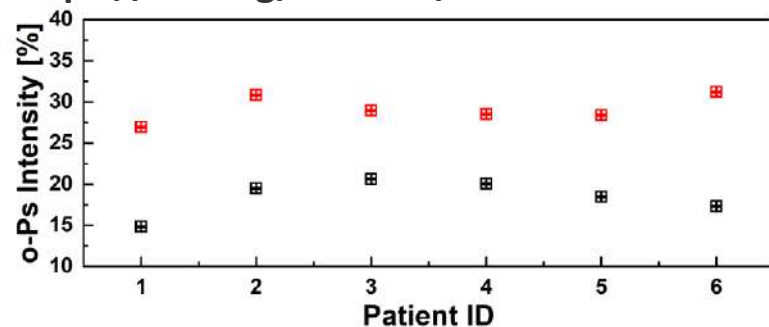
Ex-vivo human tissues studies

o-Ps as a biomarker in cancer diagnostic:

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



<https://doi.org/10.1101/2021.08.05.455285>



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



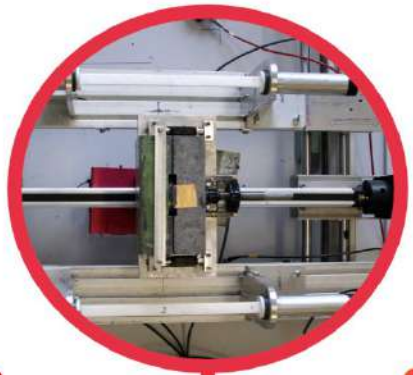
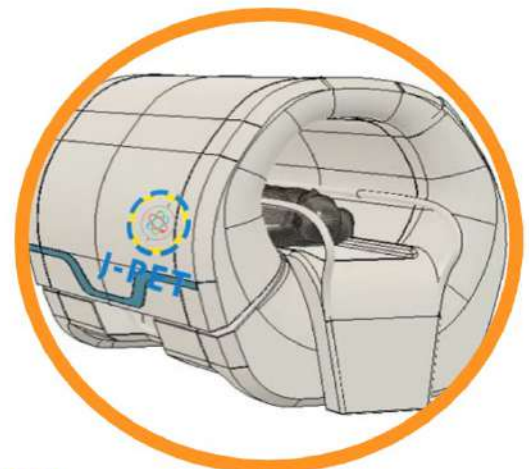
Dr hab. n. med.
 Elżbieta Łuczyńska
 Kierownik Zakładu
 Elektroradiologii
 WN0Z UJCM





total-body J-PET

3-layer prototype



2009

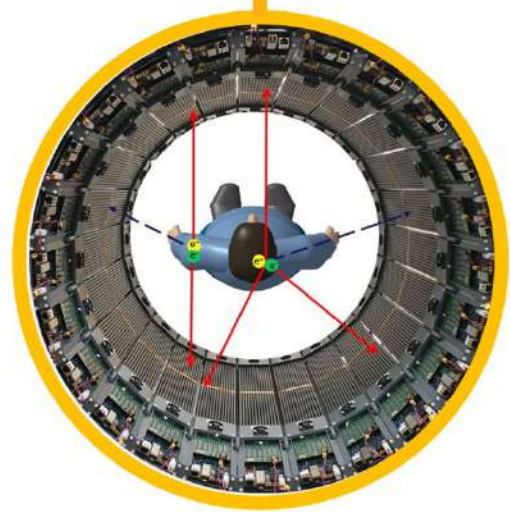
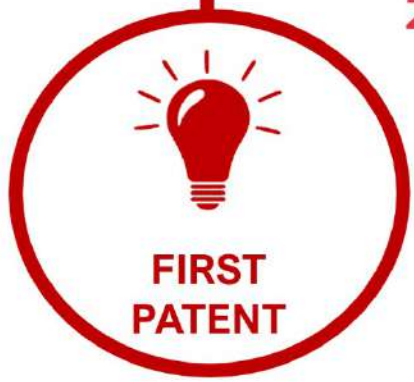
2014

2021

2012

2016

2028



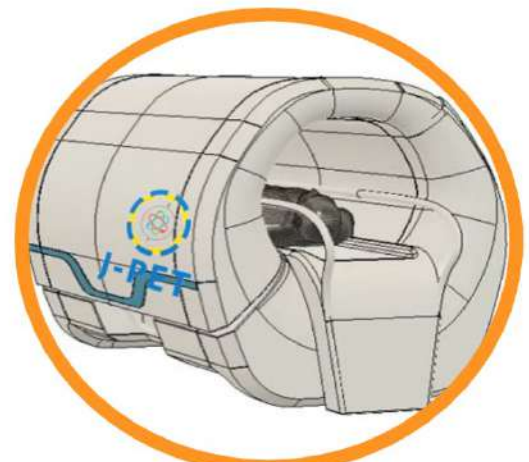
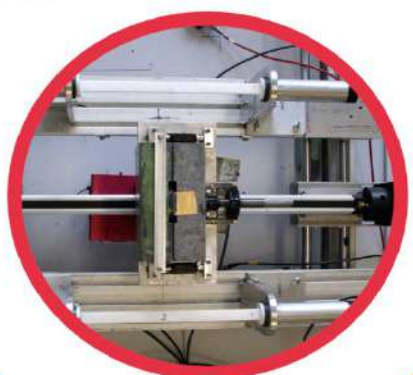
modular J-PET

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)



total-body J-PET

3-layer prototype



2009

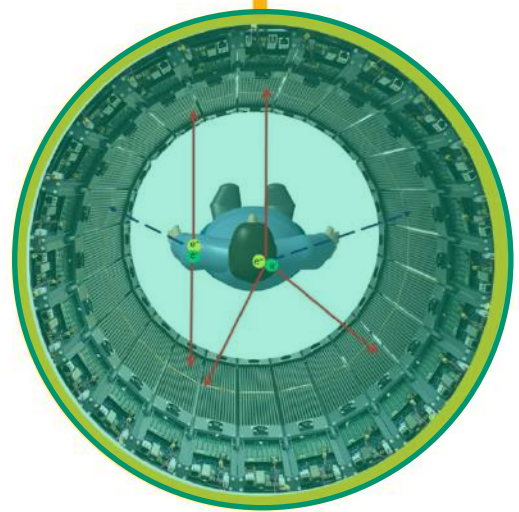
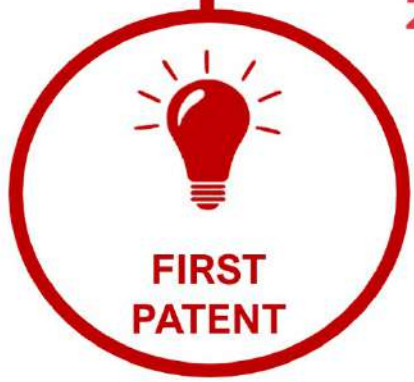
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2028

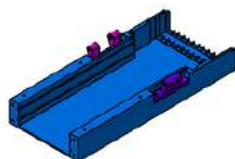


modular J-PET

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

Development of cost-effective total-body PET

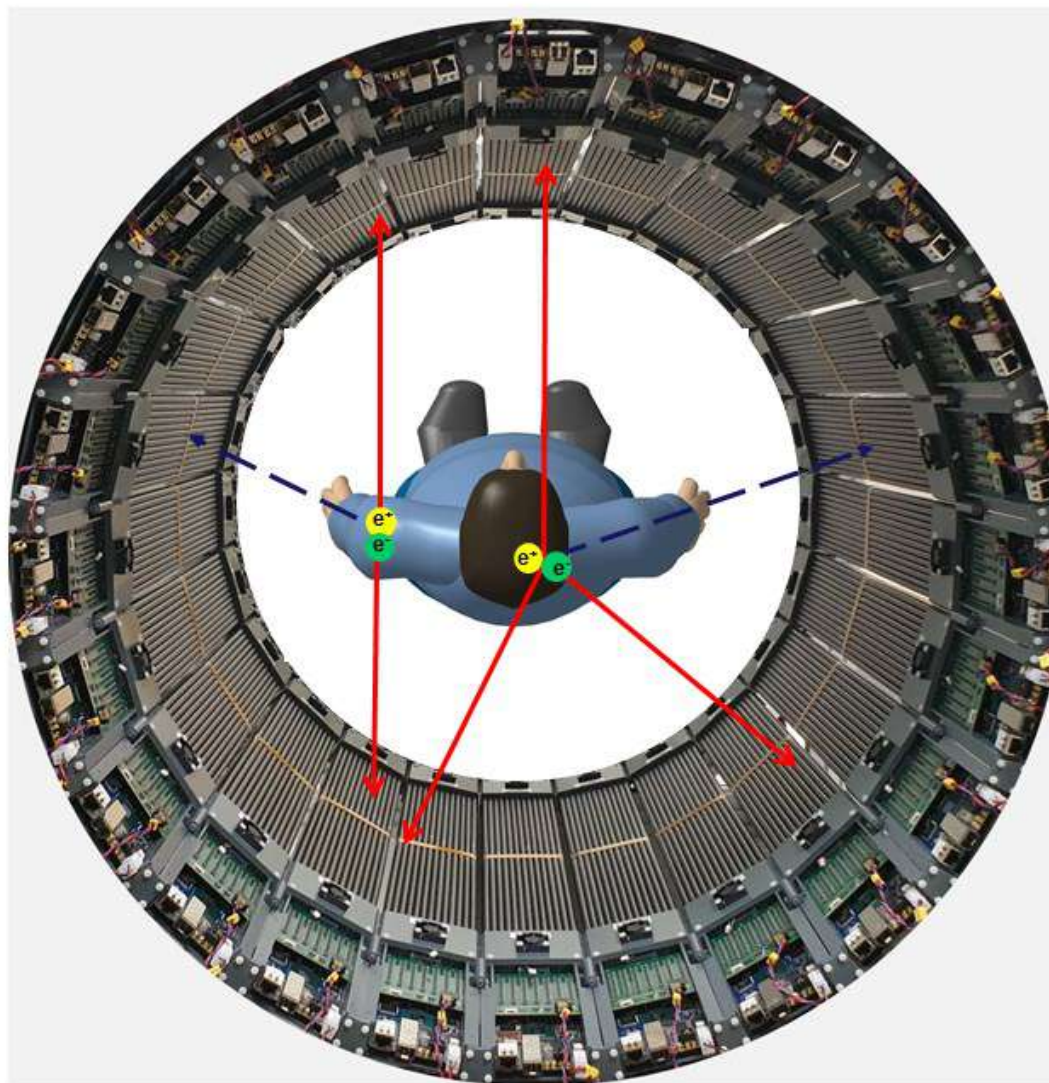
20.11



Aim:

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

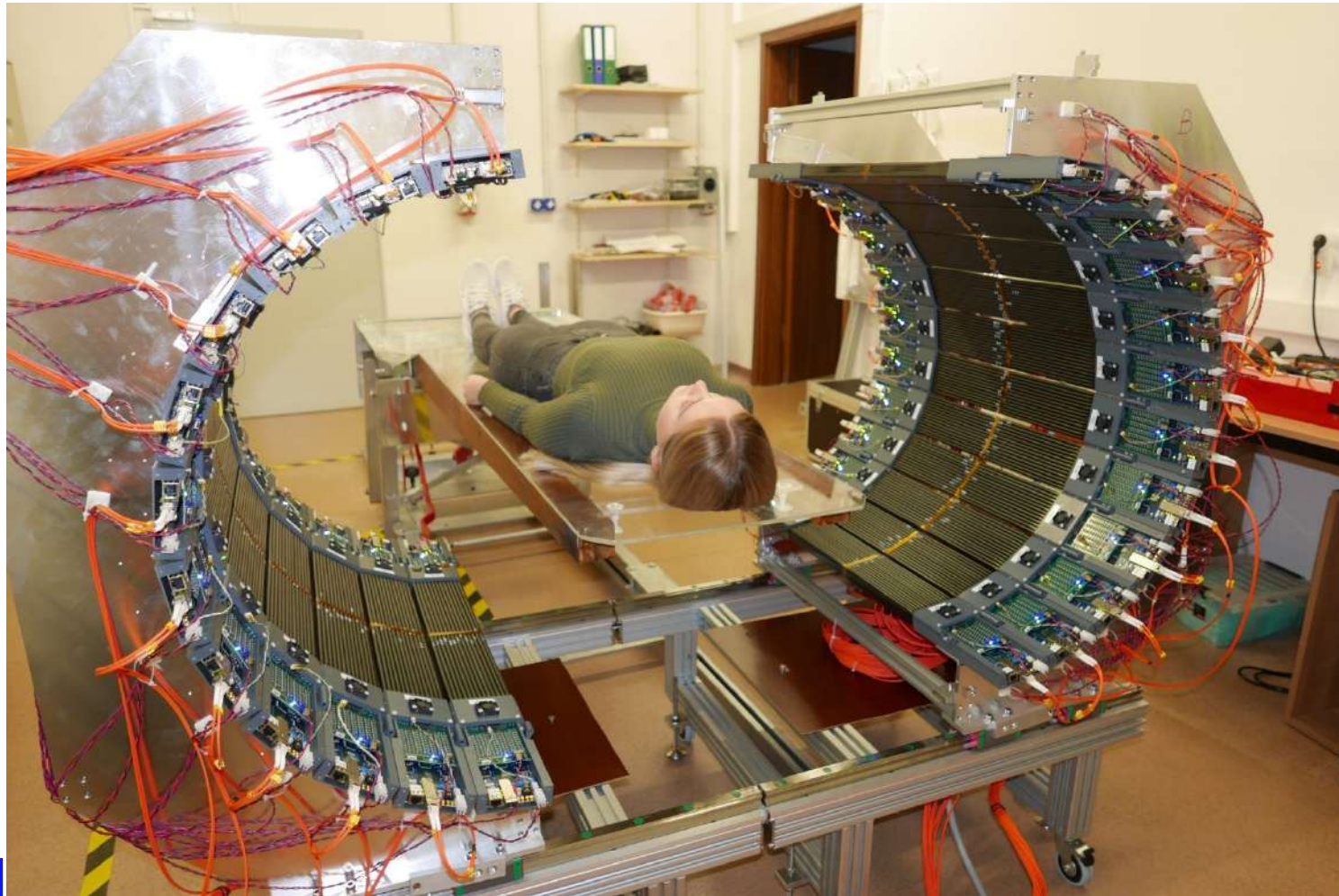




P. Moskal, Jagiellonian University
on behalf of the J-PET Collaboration <http://koza.if.uj.edu.pl>



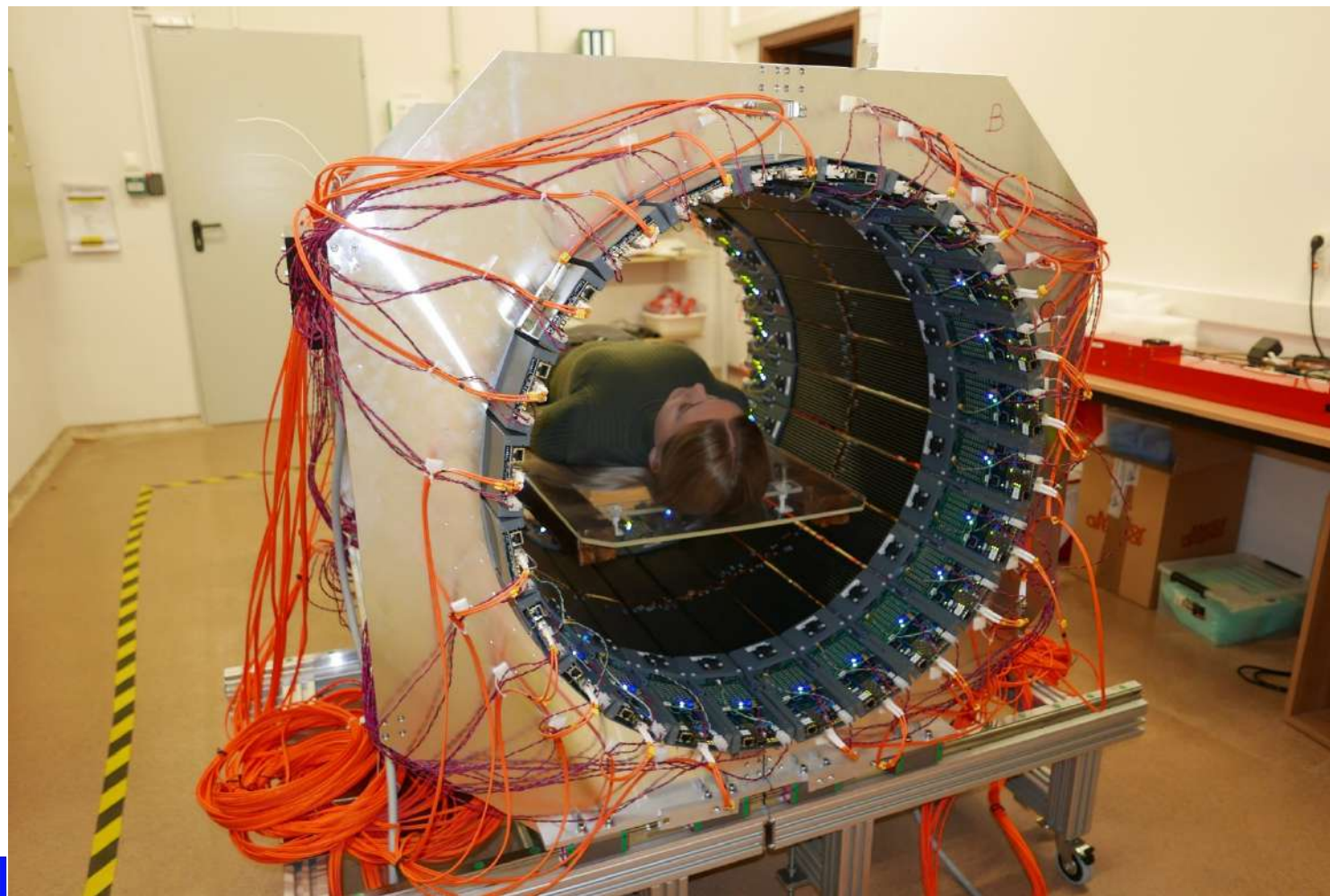
First clinical positronium imaging of patients



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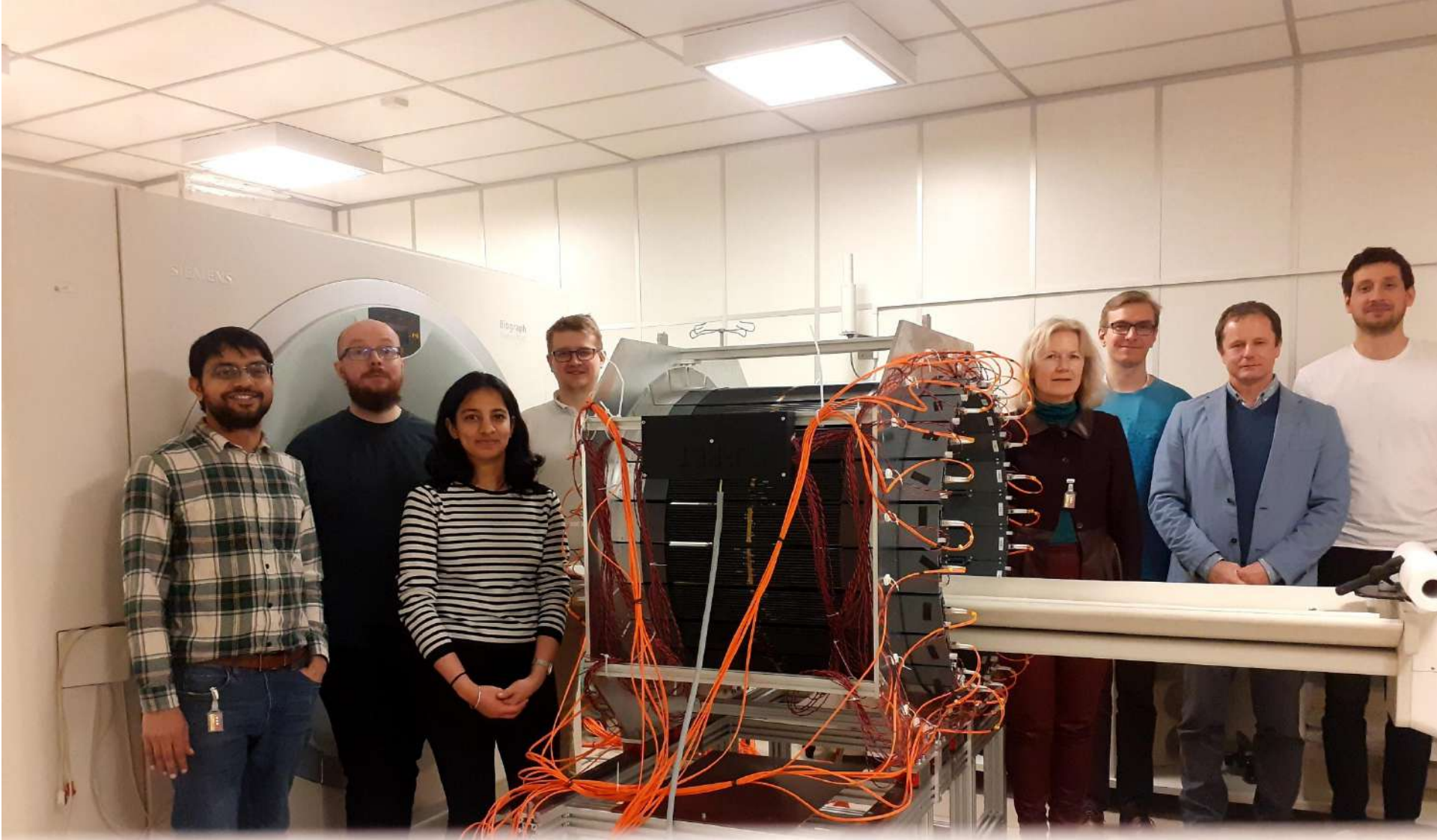
First clinical positronium imaging of patients



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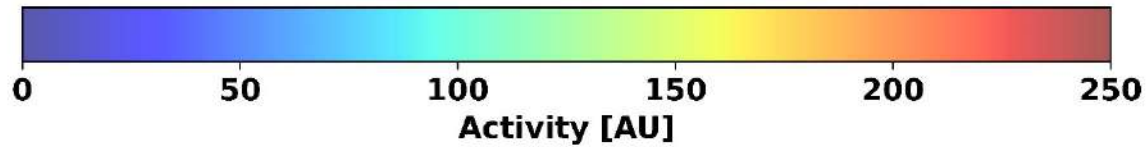
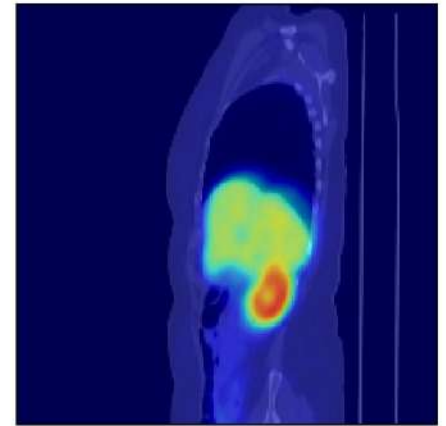
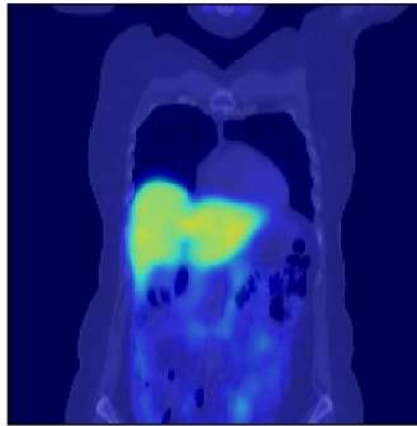
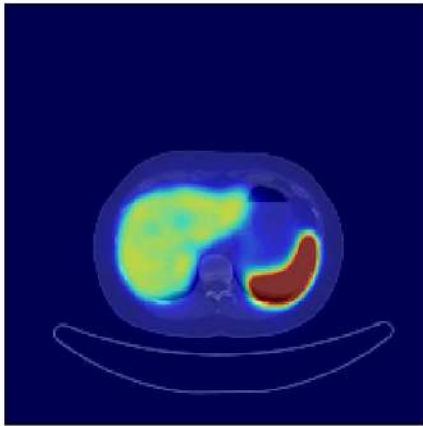
First clinical PET and positronium imaging of patients with J-PET



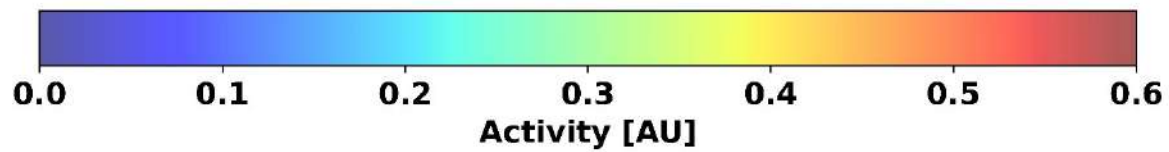
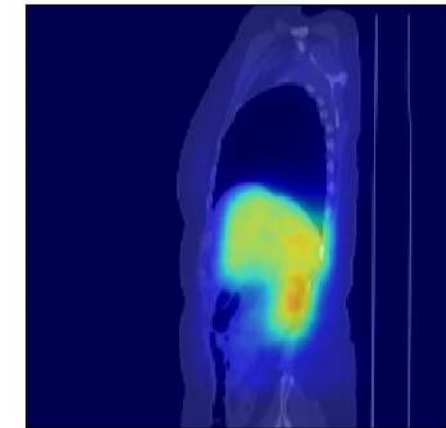
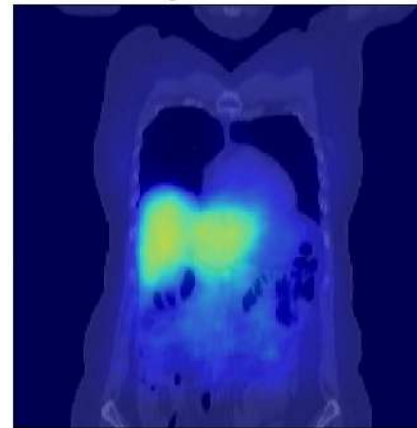
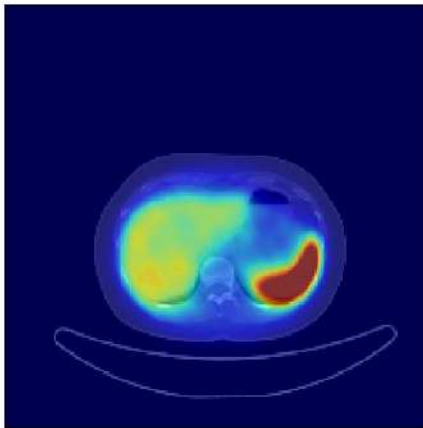
P. Moskal, ..., E. Stepien, *Science Advances* 10 (2024) eadp2840

P. Moskal, ..., E. Stępień, <https://www.medrxiv.org/content/10.1101/2024.02.01.23299028v1>

PET/CT FUSION



JPET 2 γ /CT FUSION

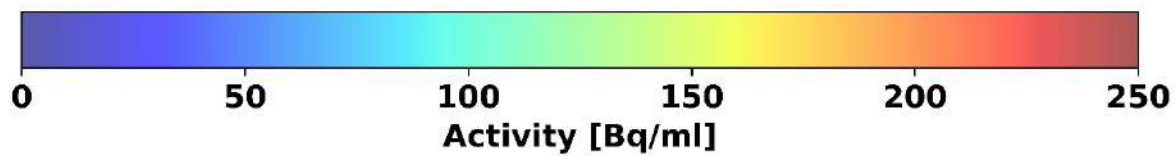
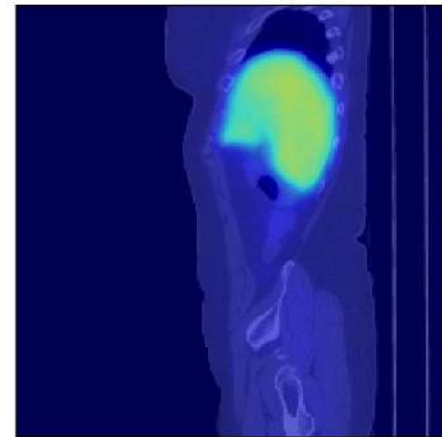
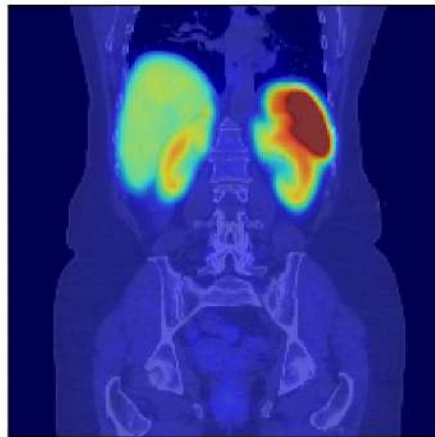
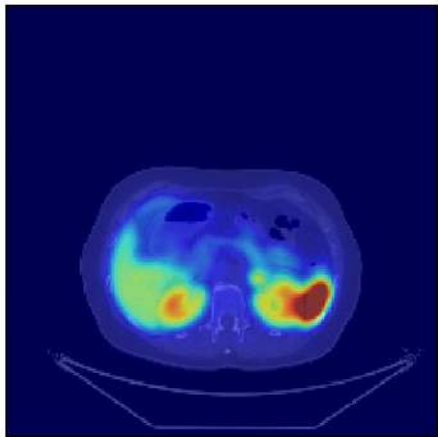




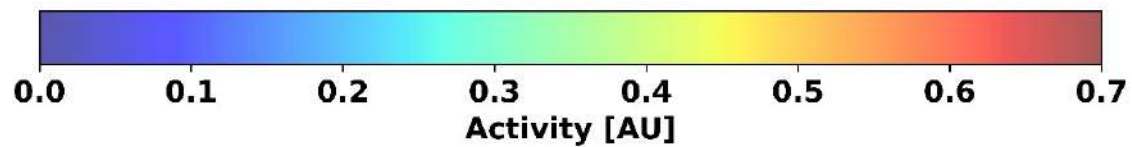
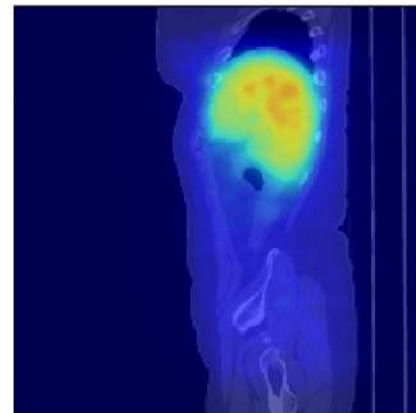
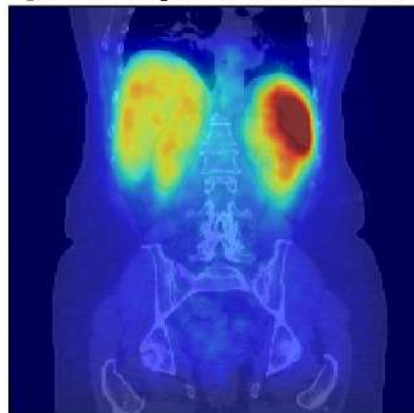
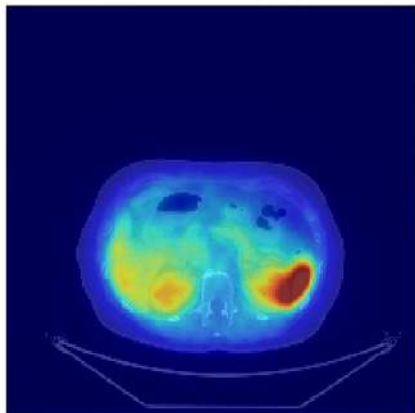




PET/CT FUSION

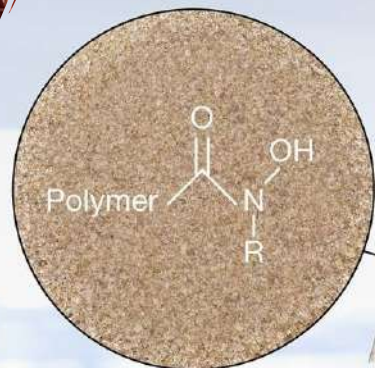


JPET 2 γ /CT FUSION



$^{44}\text{Ti} / ^{44}\text{Sc}$

60 years



HCl

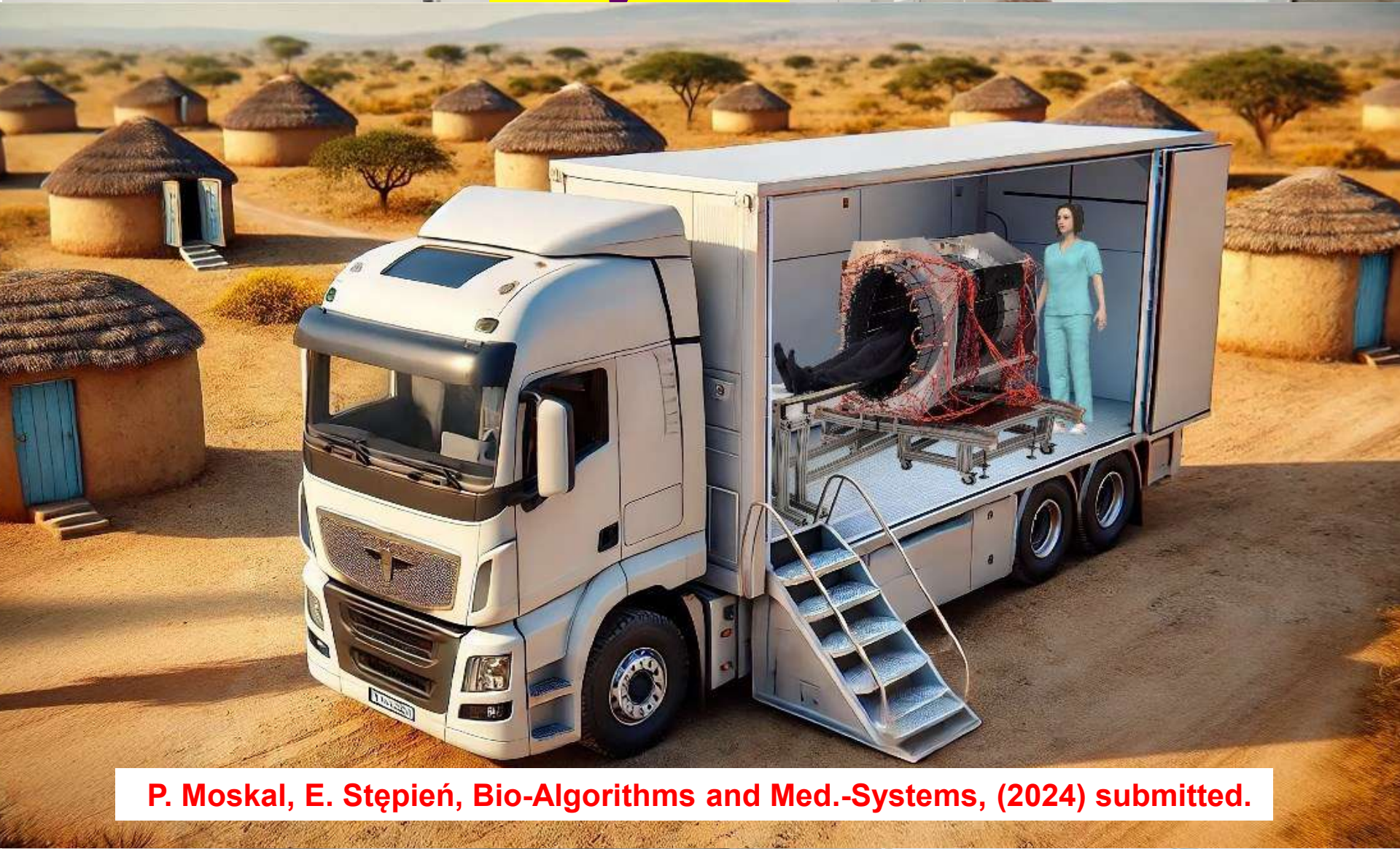


^{44}Sc



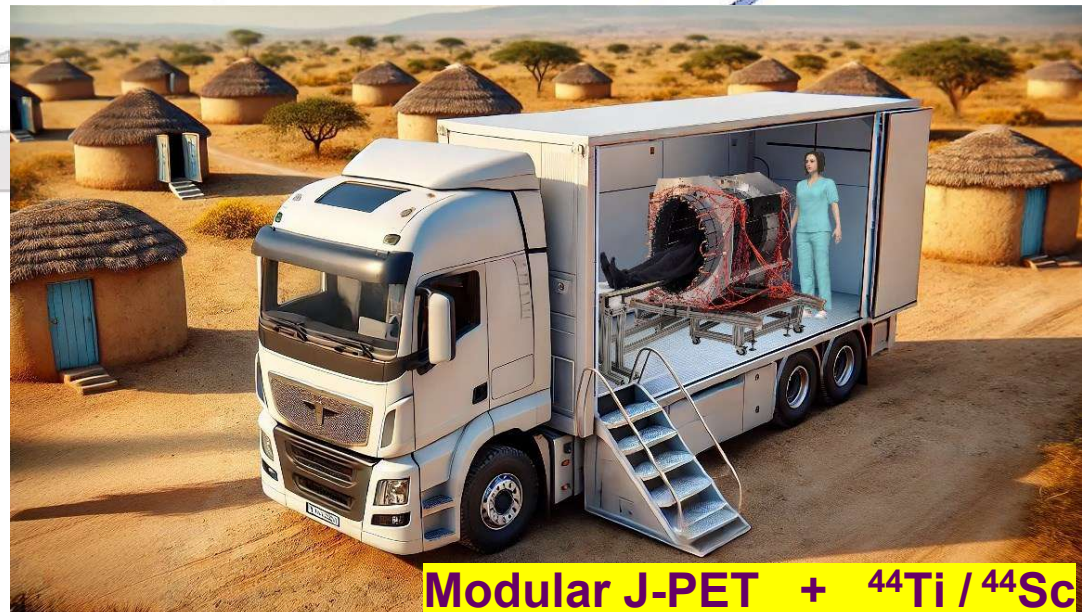
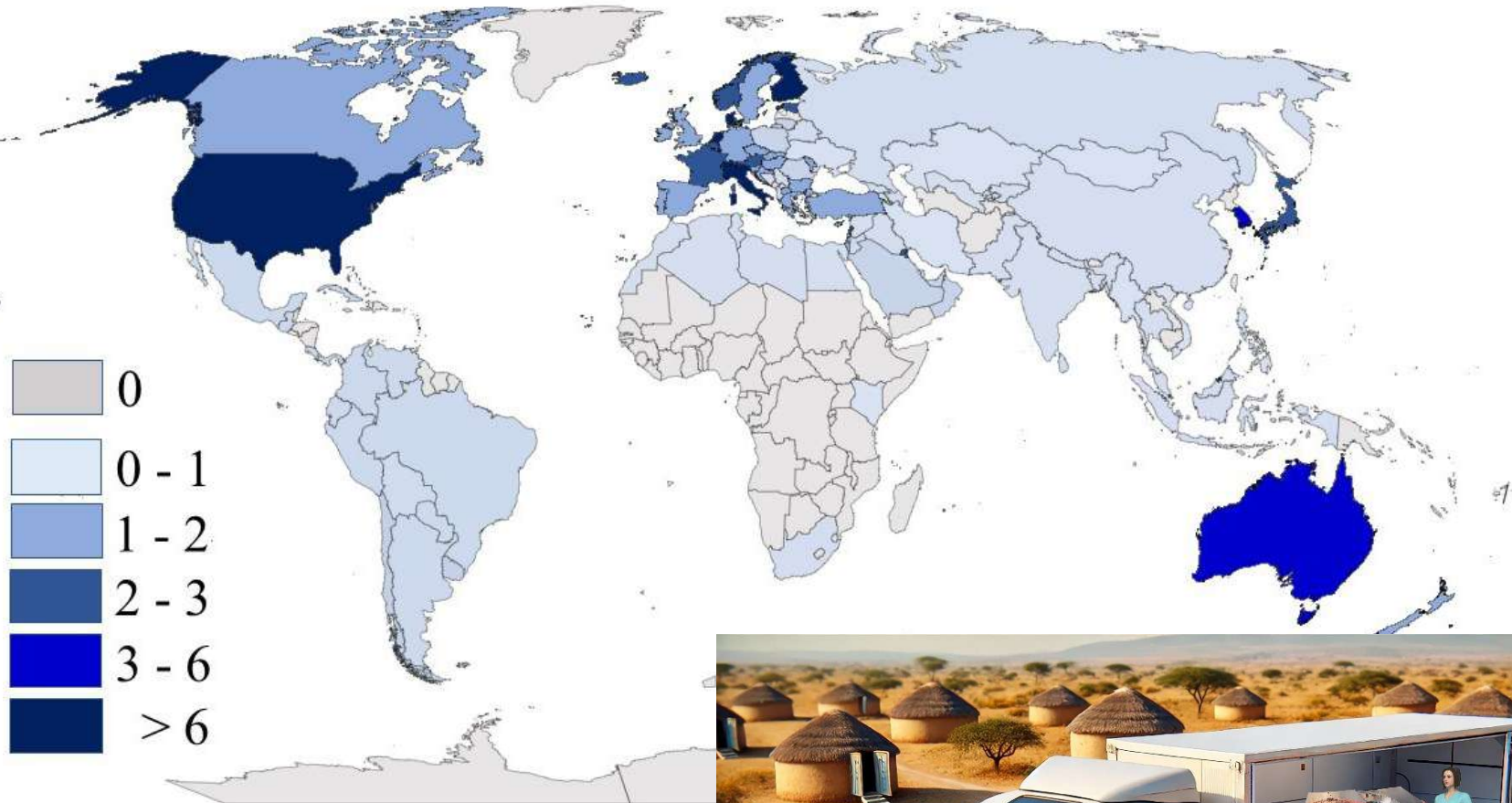
Modular J-PET + $^{44}\text{Ti} / ^{44}\text{Sc}$

60 years



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

Number of PET scanners per million people

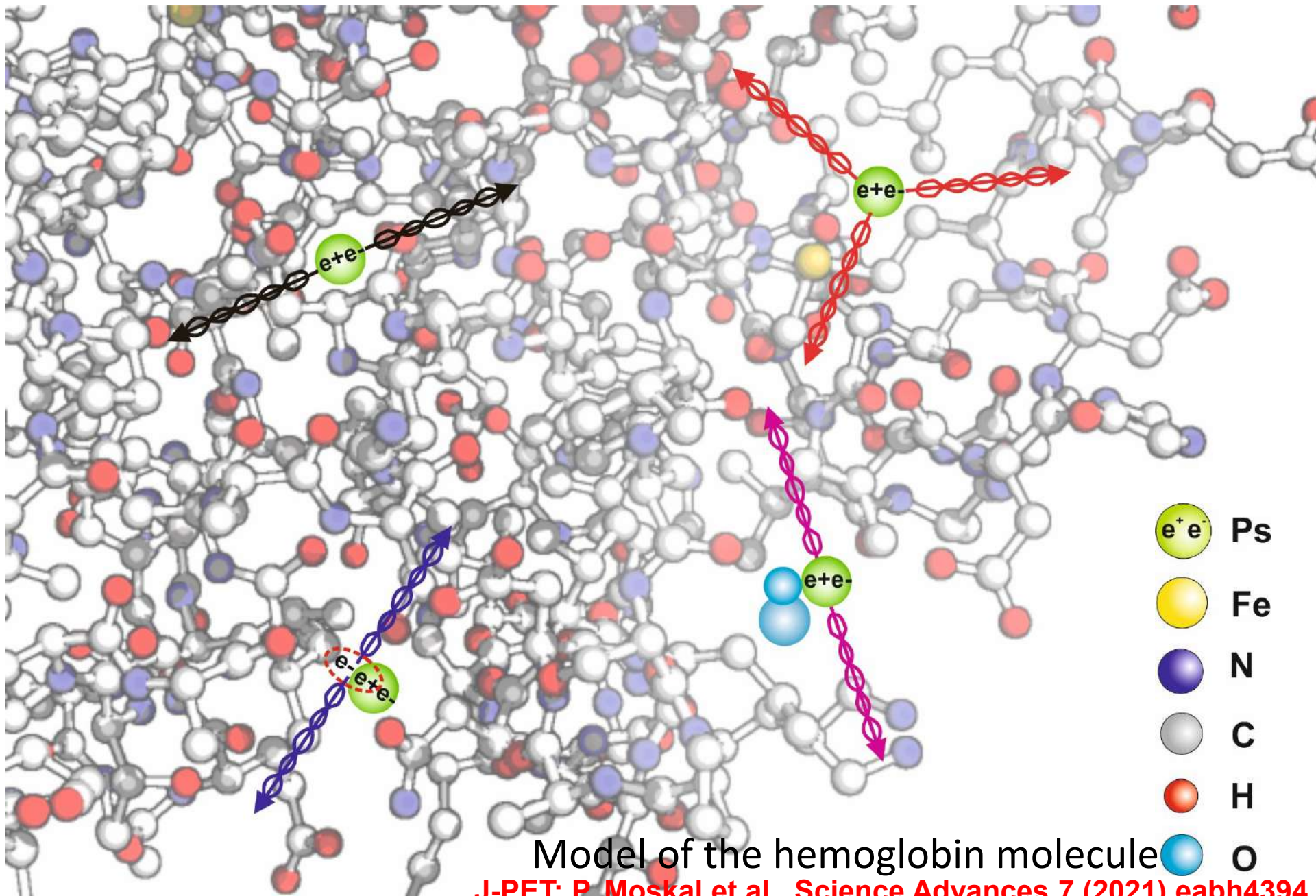


IAEA Medical imAGing and Nuclear mEdicine (IMAGINE) database developed by the International Atomic Energy Agency (IAEA) available at: <https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINE.html>

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

Positronium imaging

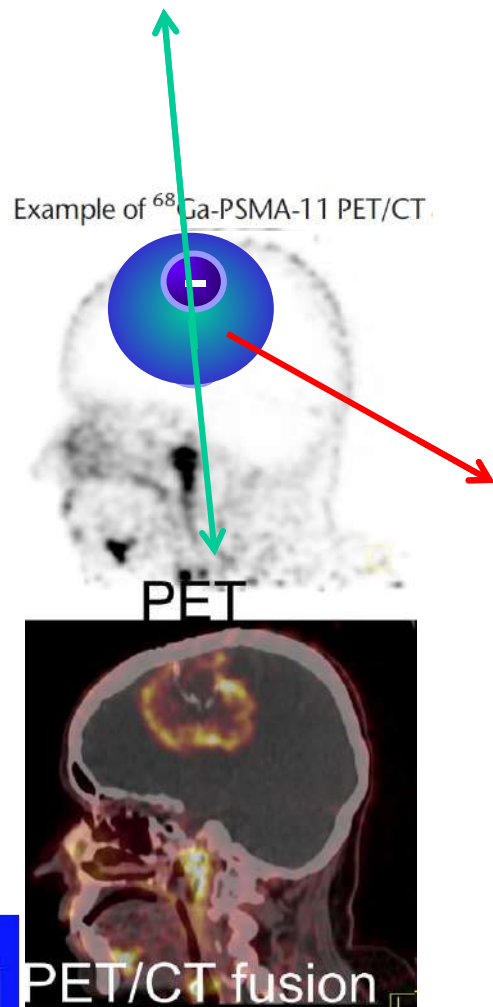
P. Moskal, B. Jasińska, E. Ł. Stępień, S. Bass, *Nature Reviews Physics* 1 (2019) 527



First clinical positronium imaging of patients

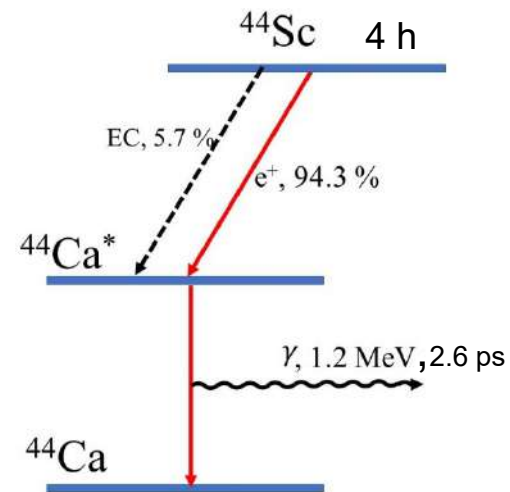
Clinical Nuclear Medicine • Volume 45, Number 1, January 2020

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^{68}Ga -Prostate-Specific Membrane Antigen-11 PET/CT A New Imaging Option for Recurrent Glioblastoma Multiforme?

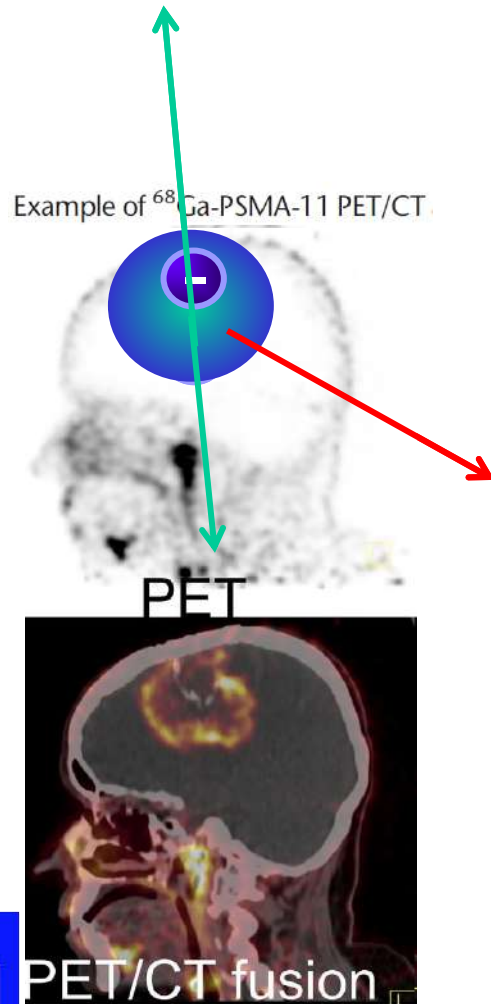
Jolanta Kunikowska, MD, PhD, Radosław Kuliński, MSc,* Kristoff Muylle, MD,†
Henryk Koziara, MD,‡ and Leszek Króllicki, MD, PhD**



First clinical positronium imaging of patients

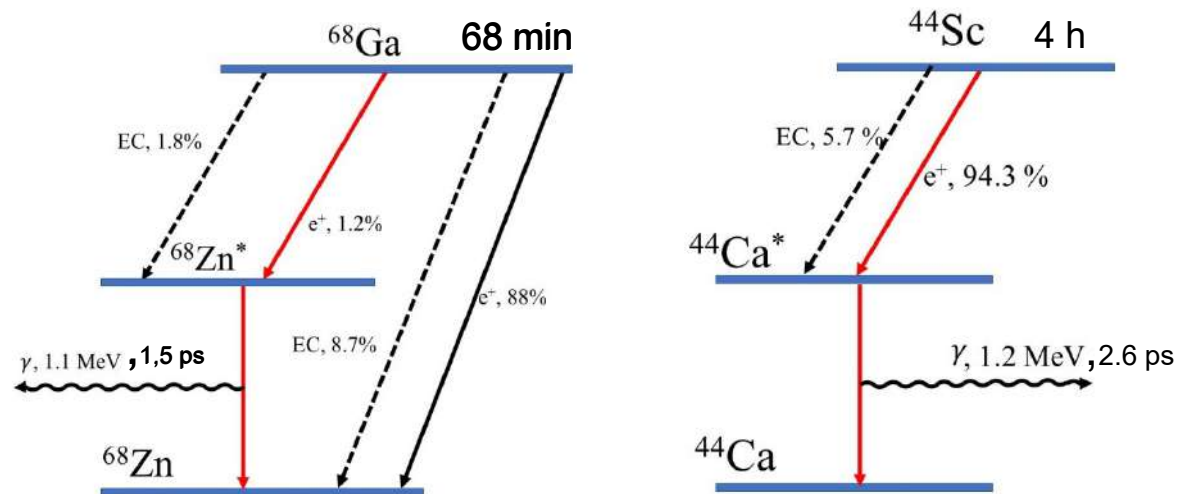
Clinical Nuclear Medicine • Volume 45, Number 1, January 2020

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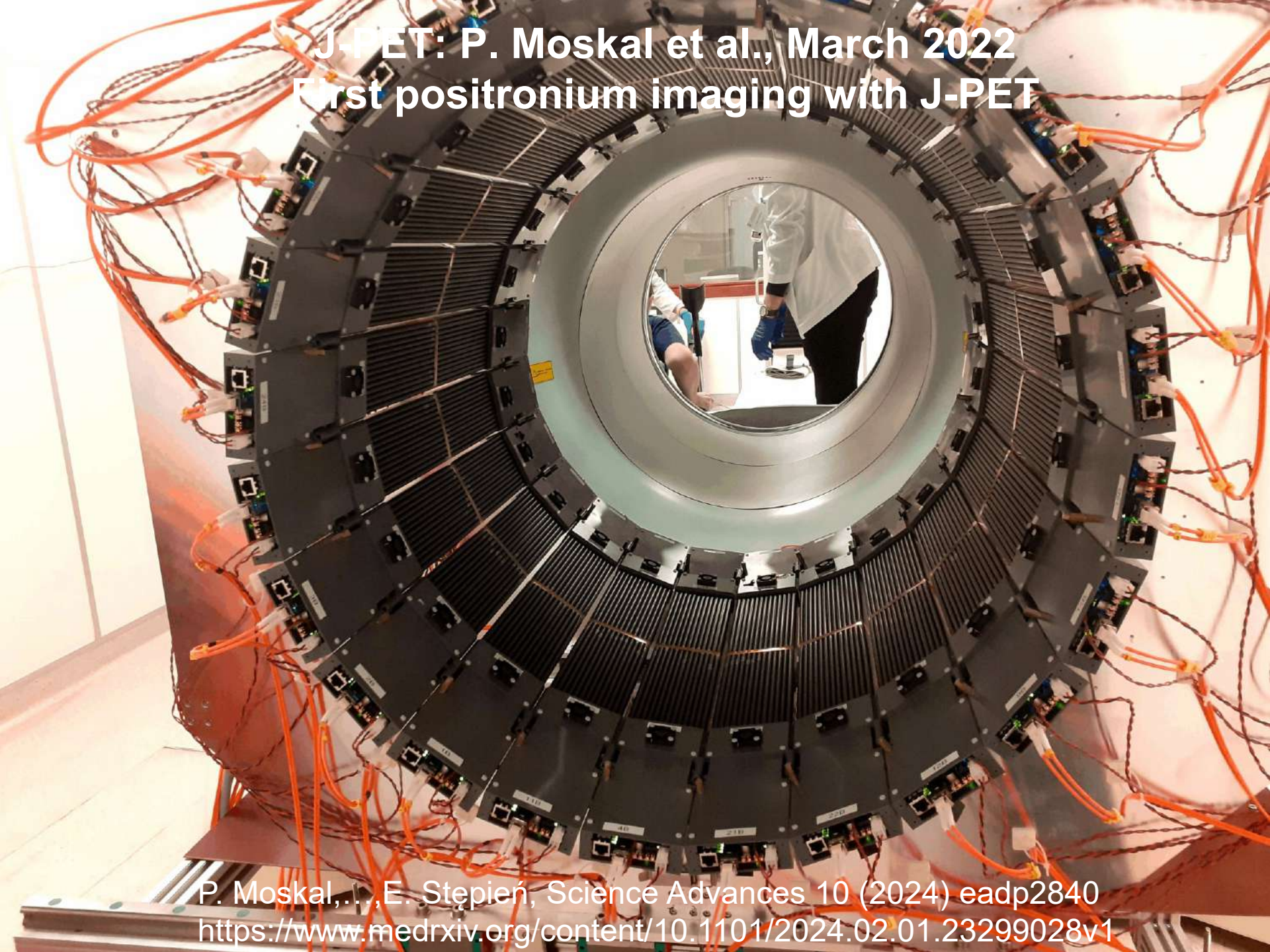


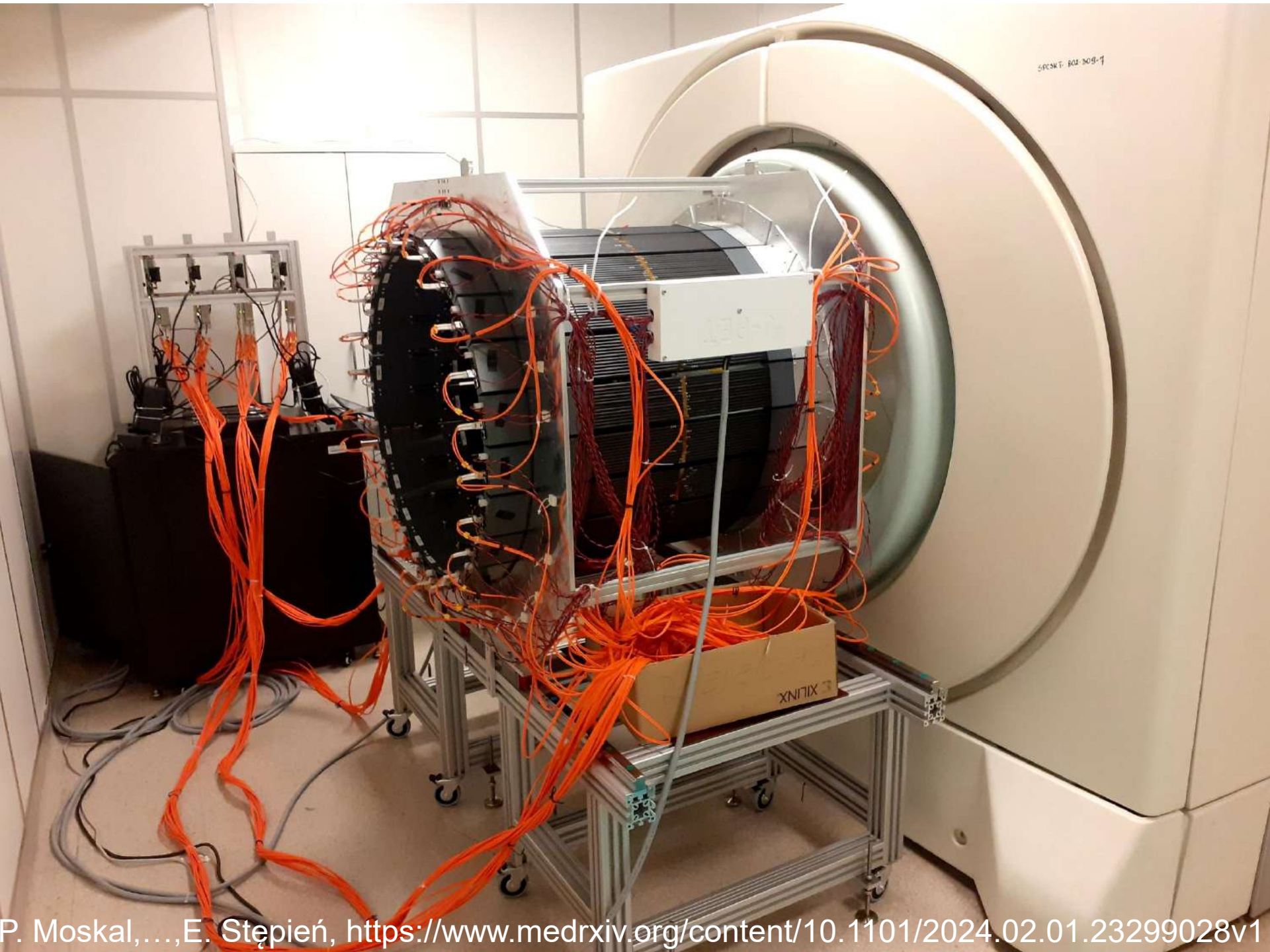
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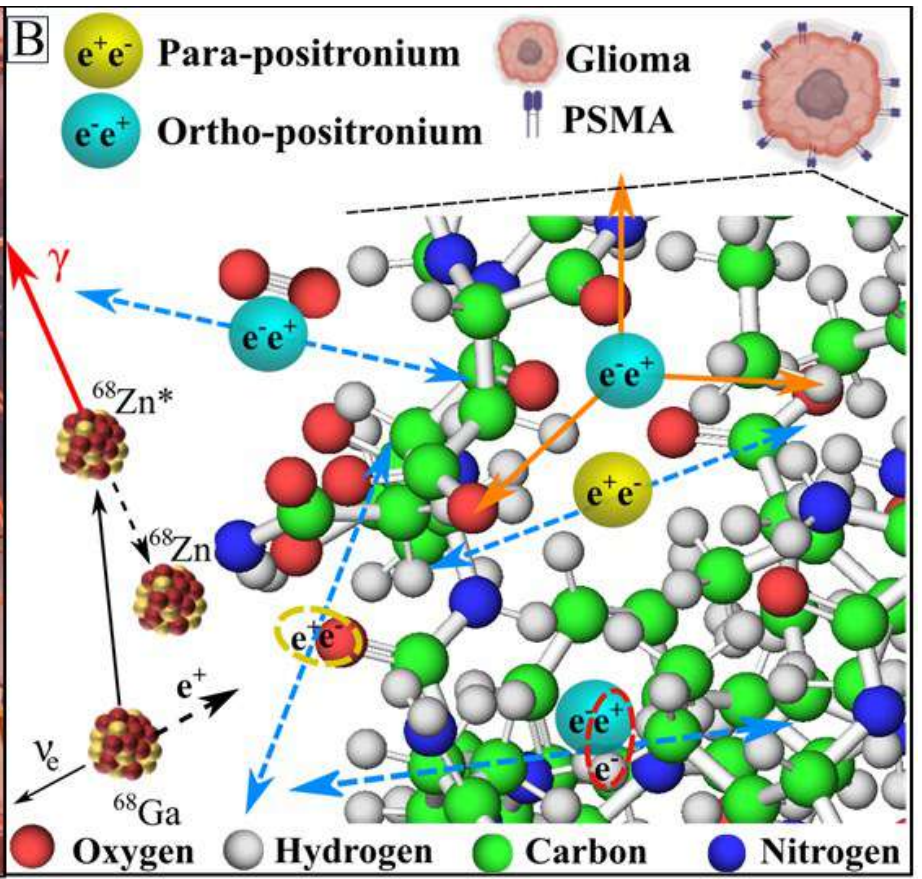
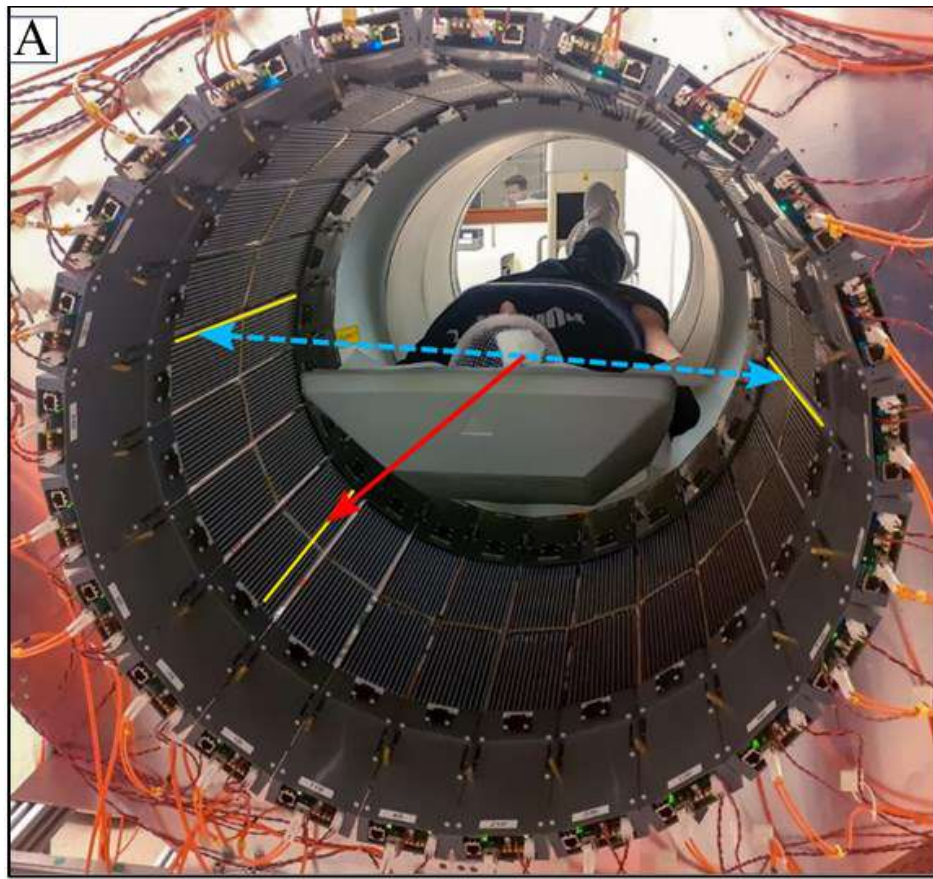
Jolanta Kunikowska, MD, PhD,* Radosław Kuliński, MSc,* Kristoff Muylle, MD,†
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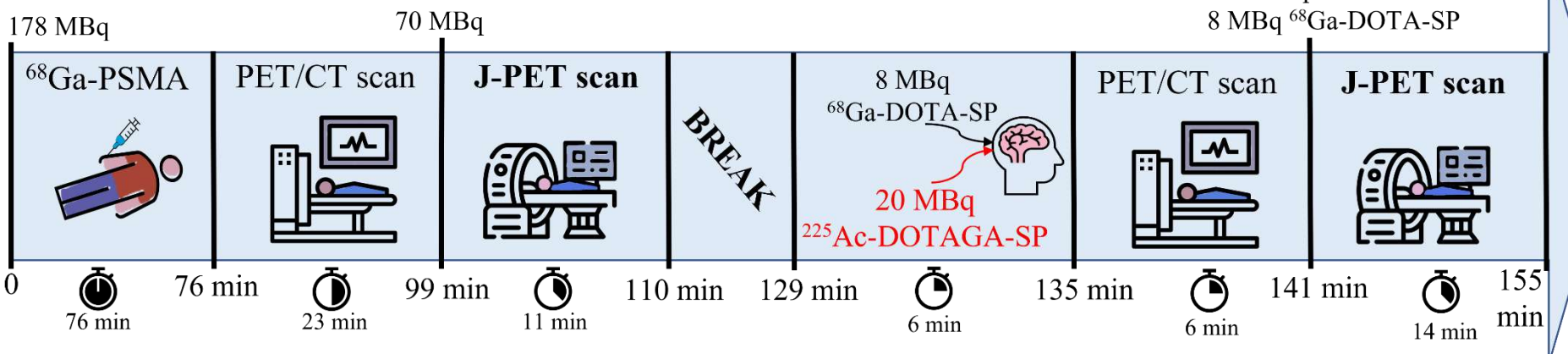
J-PET: P. Moskal et al., March 2022
First positronium imaging with J-PET



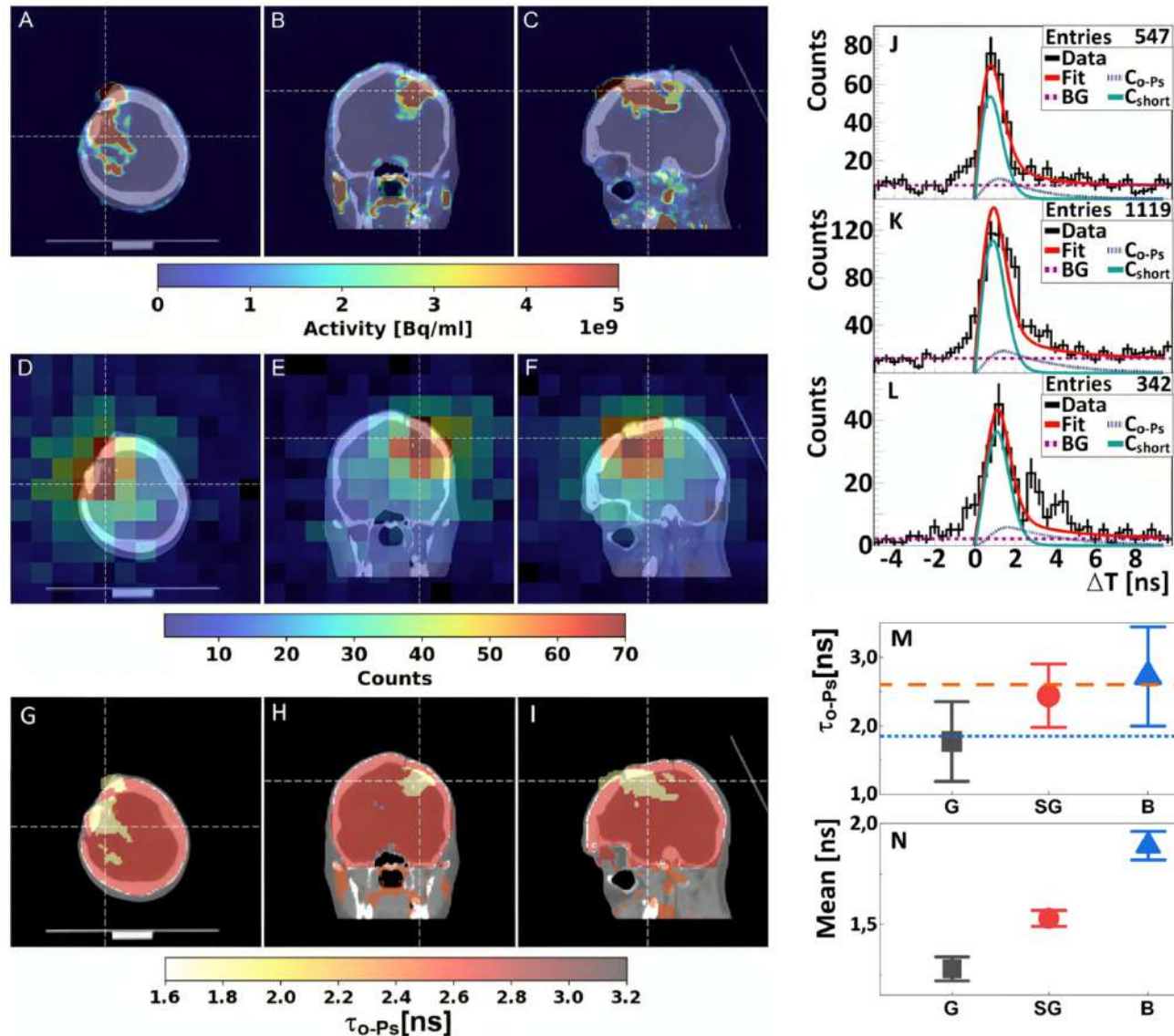




J-PET: P. Moskal et al., Science Advances 10 (2024) adp2840



First clinical positronium imaging of patients

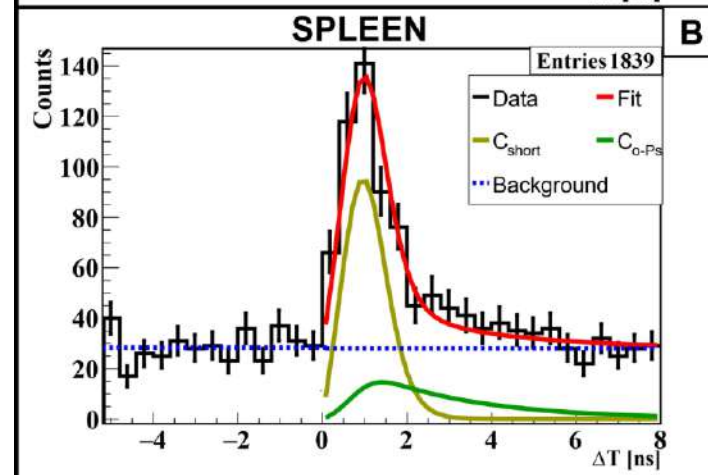
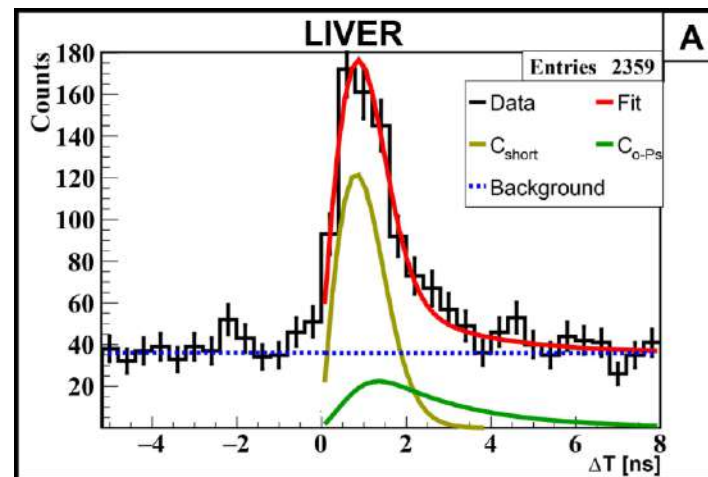
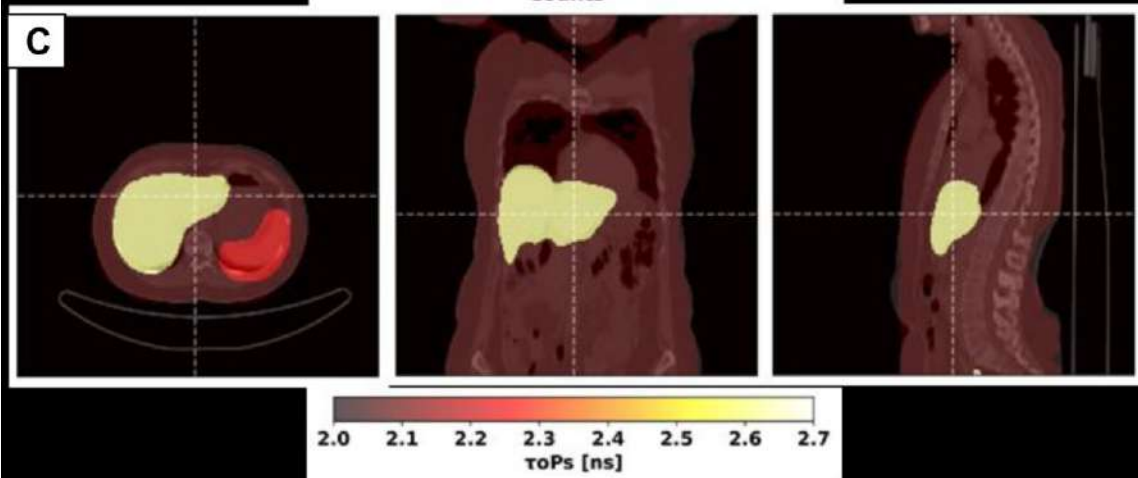
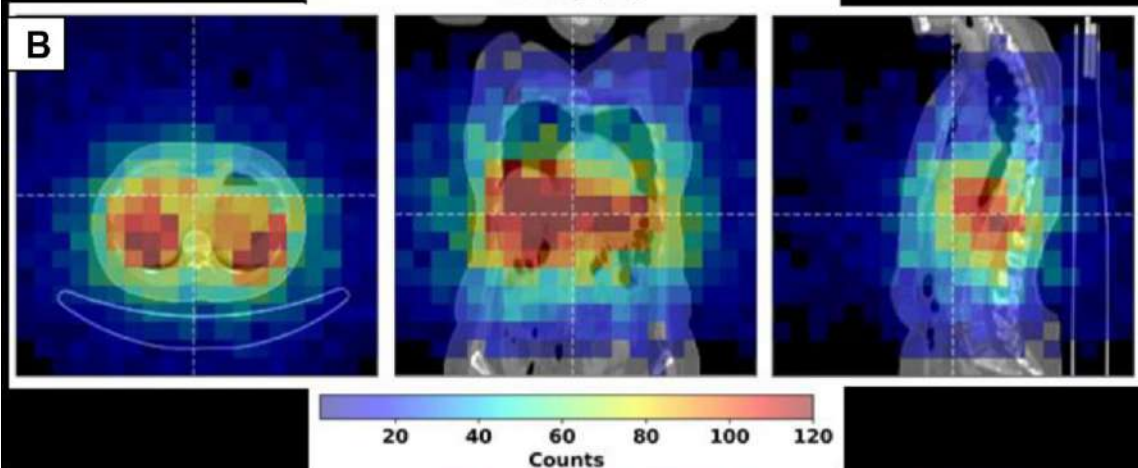
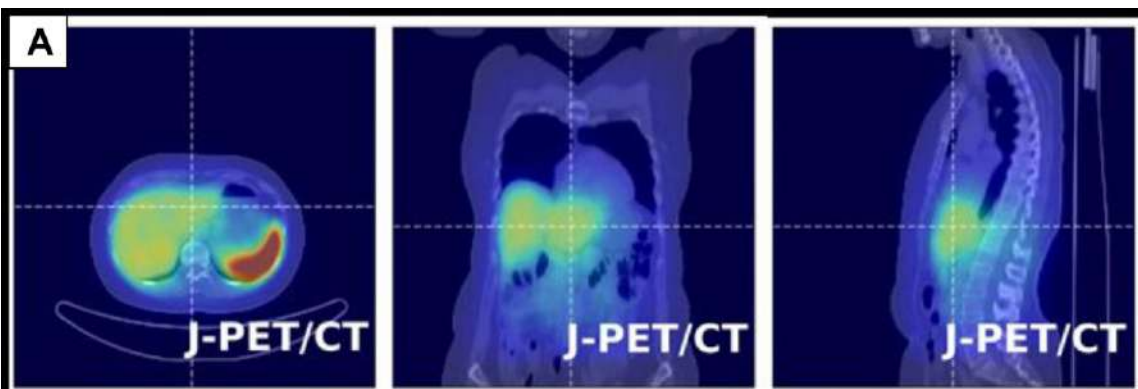


P. Moskal et al., Science Advances 10 (2024) eadp2840

Positronium image of the human brain in vivo

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

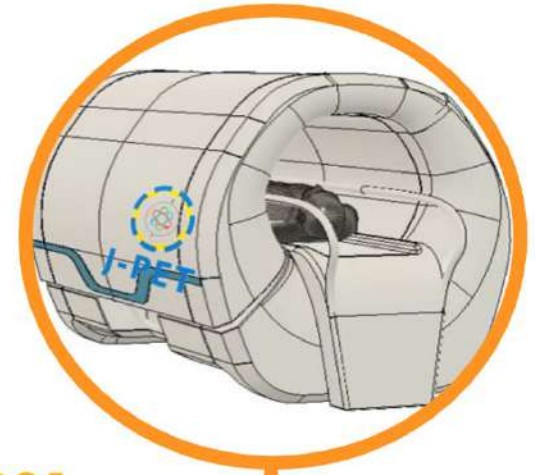
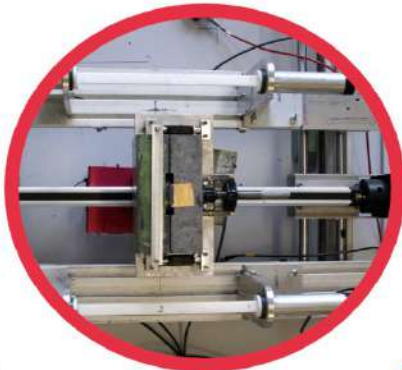






total-body J-PET

3-layer prototype



2009

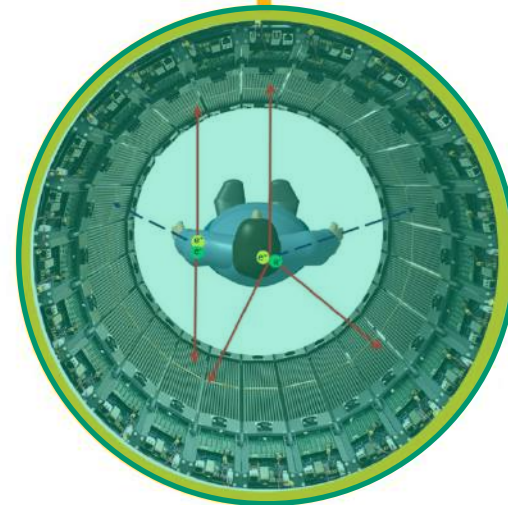
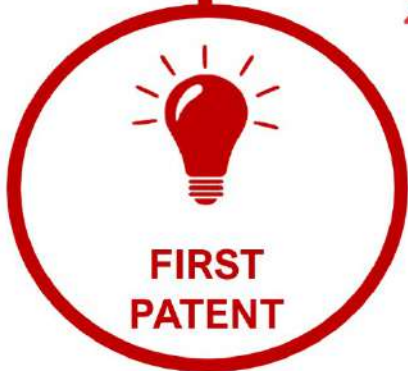
2014

2021

2012

2016

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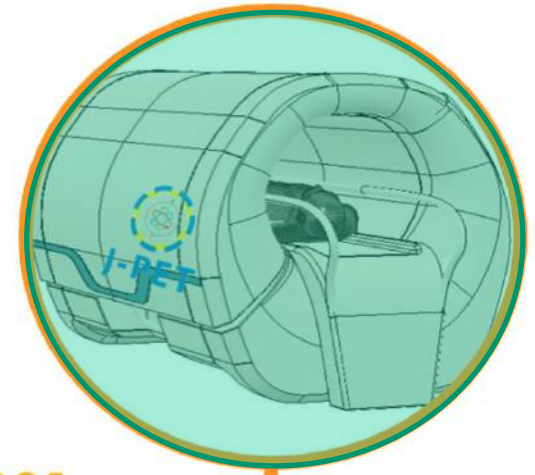
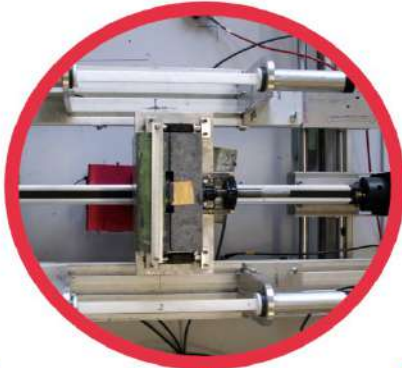


modular J-PET



total-body J-PET

3-layer prototype



2009

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2021

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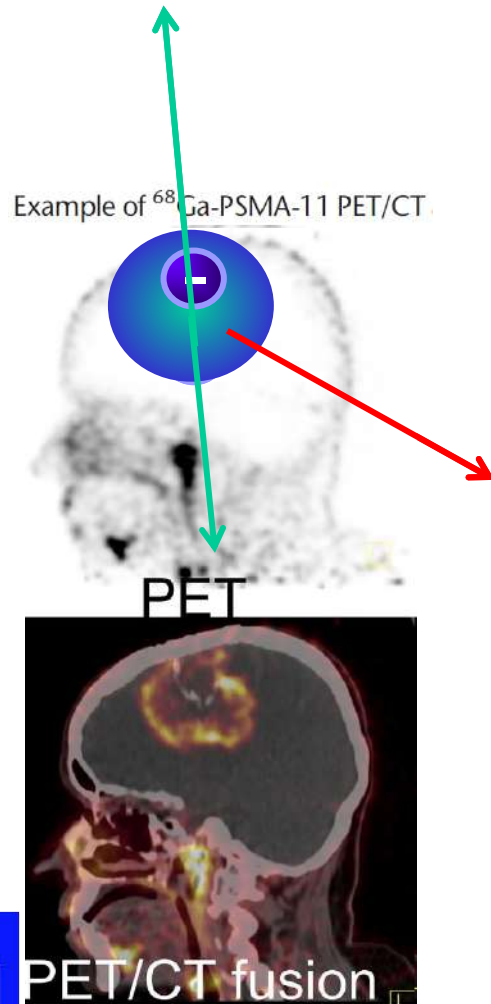


modular J-PET

First clinical positronium imaging of patients

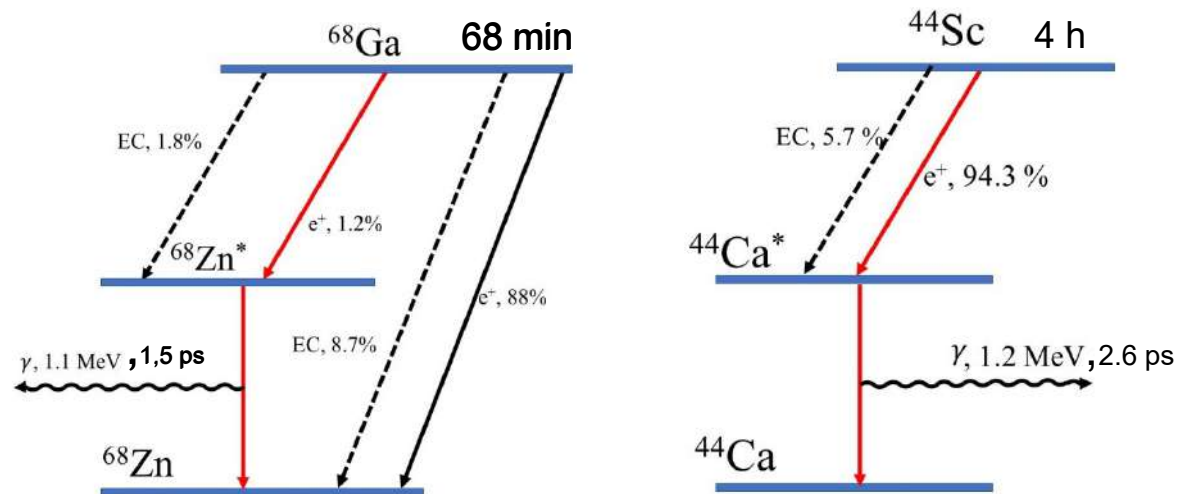
Clinical Nuclear Medicine • Volume 45, Number 1, January 2020

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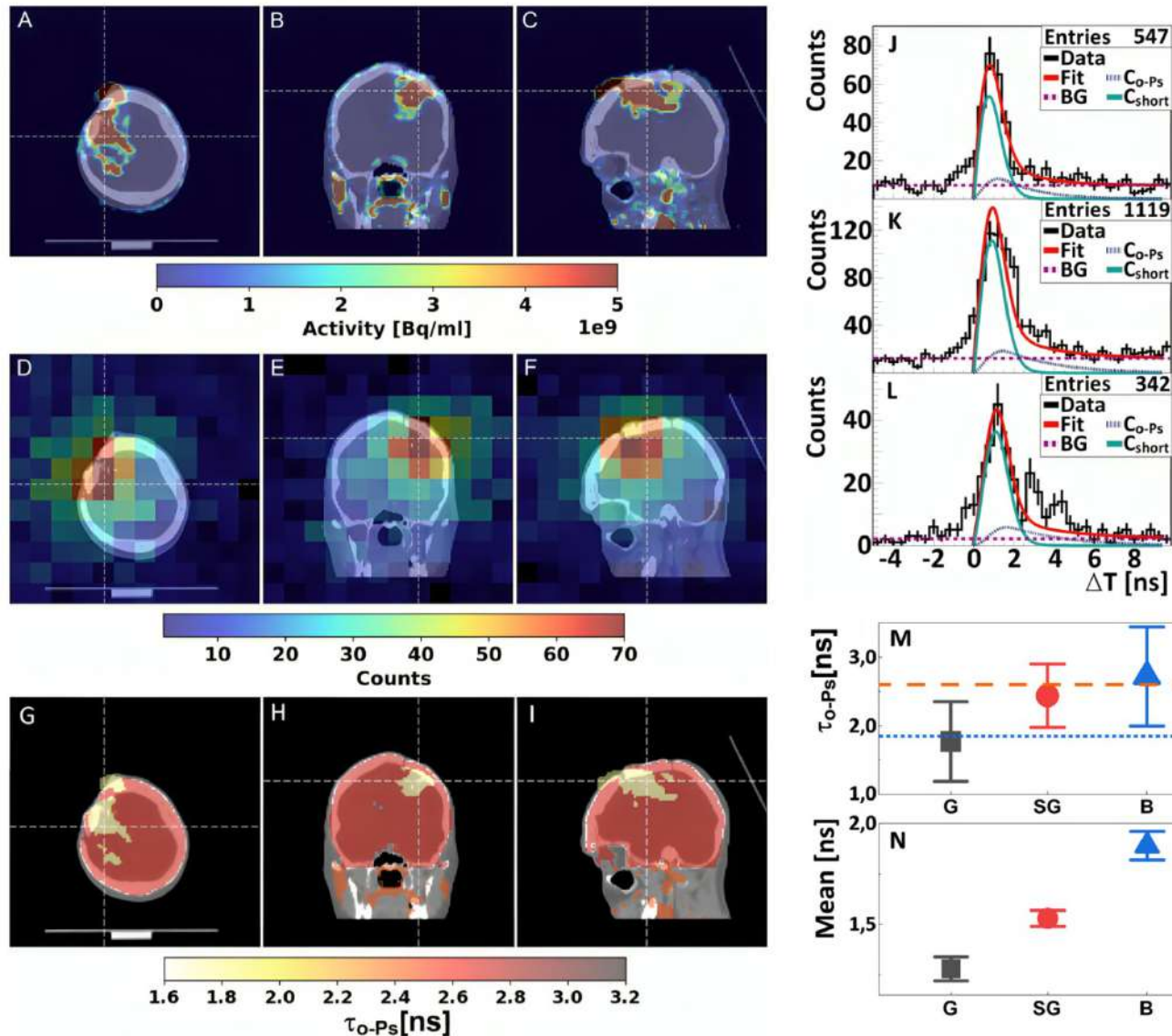


^{68}Ga -Prostate-Specific Membrane Antigen-11 PET/CT A New Imaging Option for Recurrent Glioblastoma Multiforme?

Jolanta Kunikowska, MD, PhD,* Radosław Kuliński, MSc,* Kristoff Muylle, MD,†
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First clinical positronium imaging of patients



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

Positronium image of the human brain in vivo

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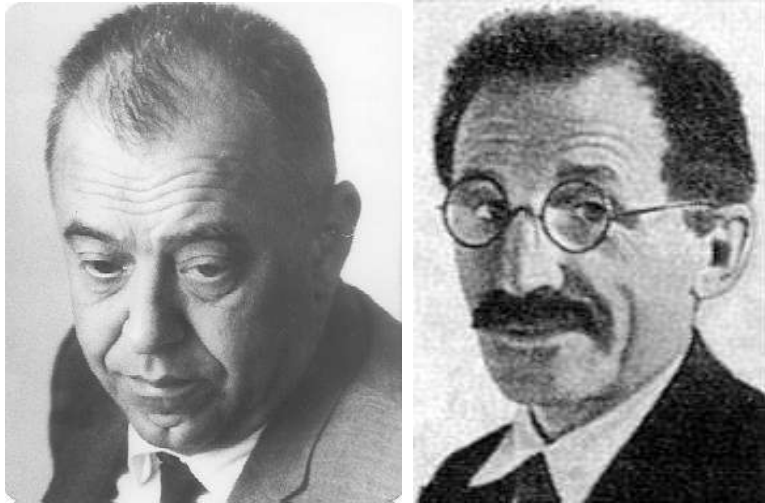
Radiological

Laboratory in Warsaw

Nature 1934;133:564–5,

„An Artificial Radioelement from Nitrogen”

<https://lnkd.in/di246kY2>



Prof. Ludwik Wertenstein

Marian Danysz



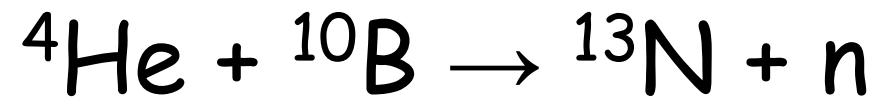
Irene and Frederic Joliot-Curie

Nature 1934;133:201–2,

„Artificial Production of
a New Kind of Radio-Element”

<https://lnkd.in/dRtzeZJD>

Nobel Prize in Chemistry in 1935

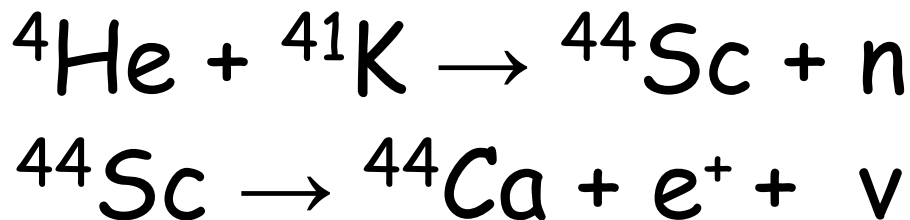


Radiological
Laboratory in Warsaw
Nature 1934;133:564–5,

Michał (Mojsej) Żyw
Induced radioactivity of potassium.
Nature 1934;134: 64–5



Prof. Ludwik Wertenstein



Induced Radioactivity of Potassium

I HAVE bombarded potassium chloride with the α -rays of radium C of 55 mm. effective range and found that it acquires a greater radioactivity than that due to the natural activity of potassium. The effect is due to potassium, because no similar effect was exhibited by sodium chloride irradiated in the same conditions. In order to measure exactly the amount of induced radioactivity, all counting experiments were done by taking the difference between the number of impulses due to two identical samples of potassium chloride, one of which has been irradiated.

Irradiating potassium chloride for 12 hours with 30 millicuries of radon, I have found that the corrected initial activity amounts to about 50 impulses per minute, while the non-irradiated sample gave an effect of 17 impulses per minute. The induced activity decays exponentially with a half-period of 3 hours. I have found that the radiation consists of positrons and is completely absorbed by a sheet of lead of 0.27 gm./cm.². No positron emission takes place when the range of α -rays is reduced to 45 mm.

The probable reactions are :

- (1) ${}_{19}\text{K}^{41} + {}_2\text{He}^4 = {}_{21}\text{Sc}^{44} + \text{neutron} ;$
- (2) ${}_{21}\text{Sc}^{44} = {}_{20}\text{Ca}^{44} + \text{positron}$

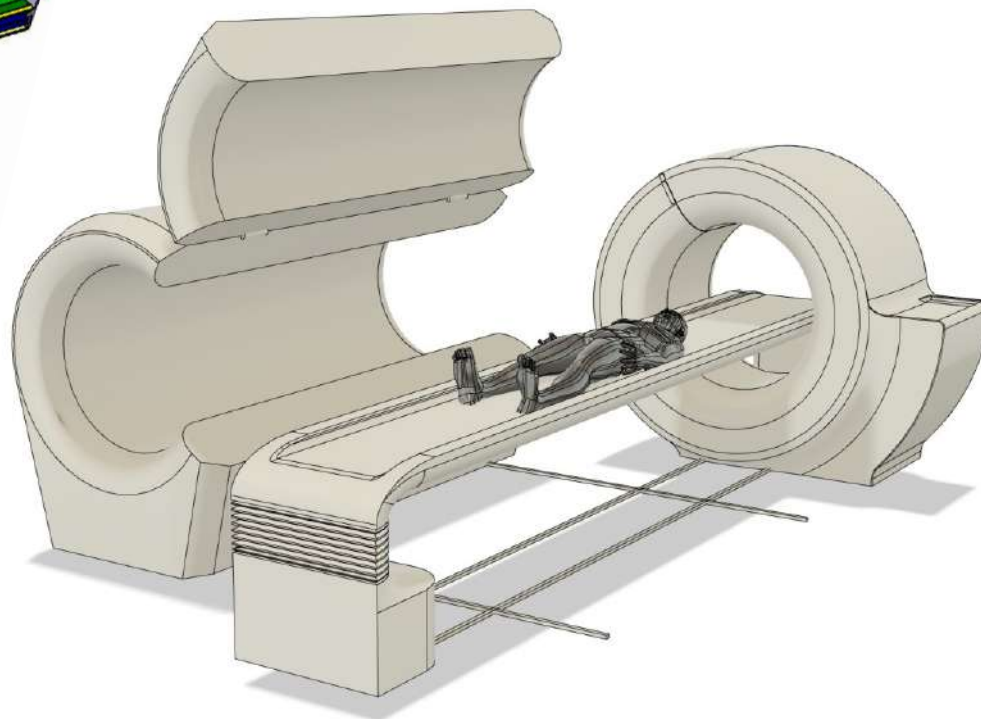
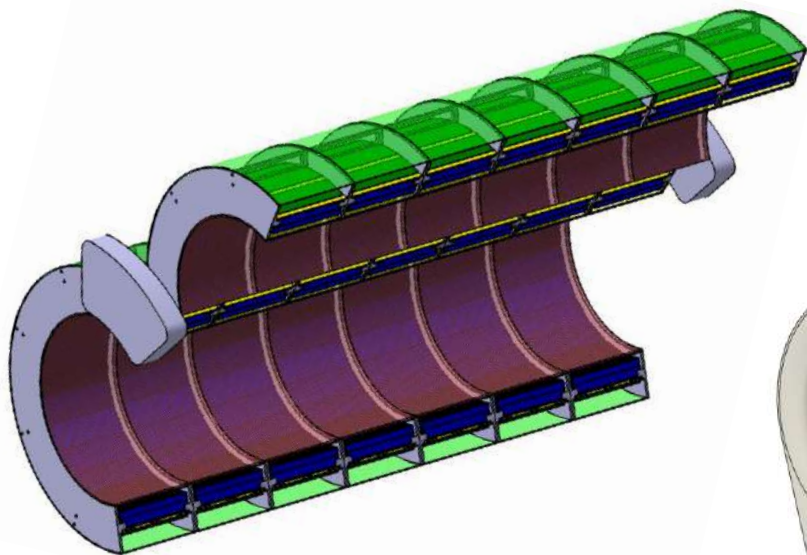
or analogous reactions due to the 39 potassium isotope.

In order to test this possibility, I have tried to separate chemically the assumed scandium isotope, with the help of Mr. A. Wroncberg, to whom my best thanks are due. Irradiated potassium chloride was dissolved in slightly acidulated water, a few milligrams of scandium chloride (ScCl_3) added to the solution and precipitated by an excess of ammonia. The precipitate exhibited an activity of the same character and comparable in amount with that emitted by irradiated potassium chloride.

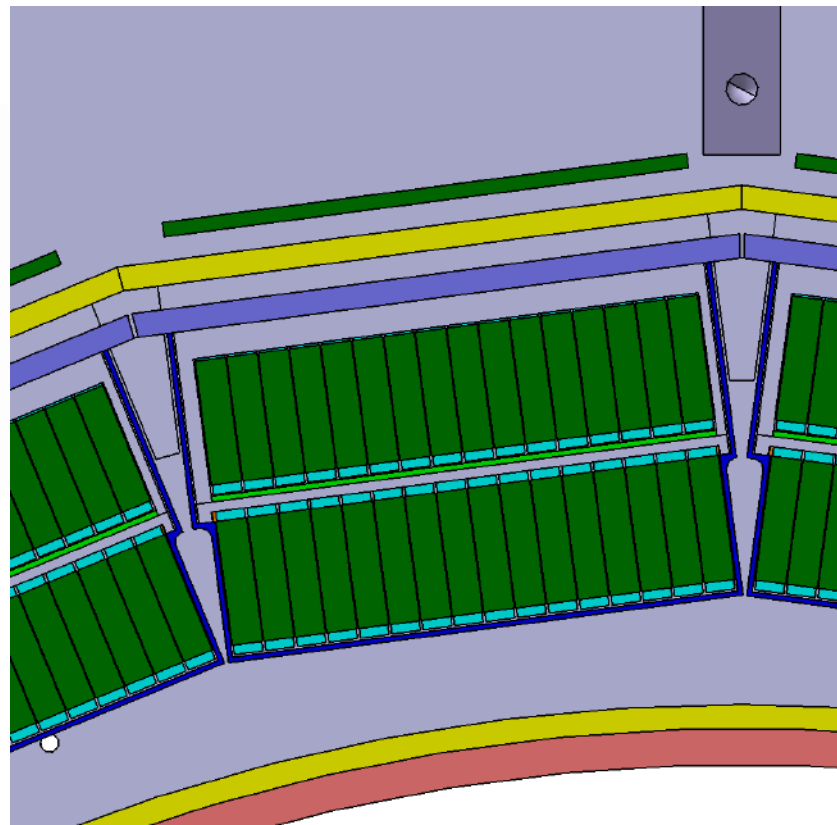
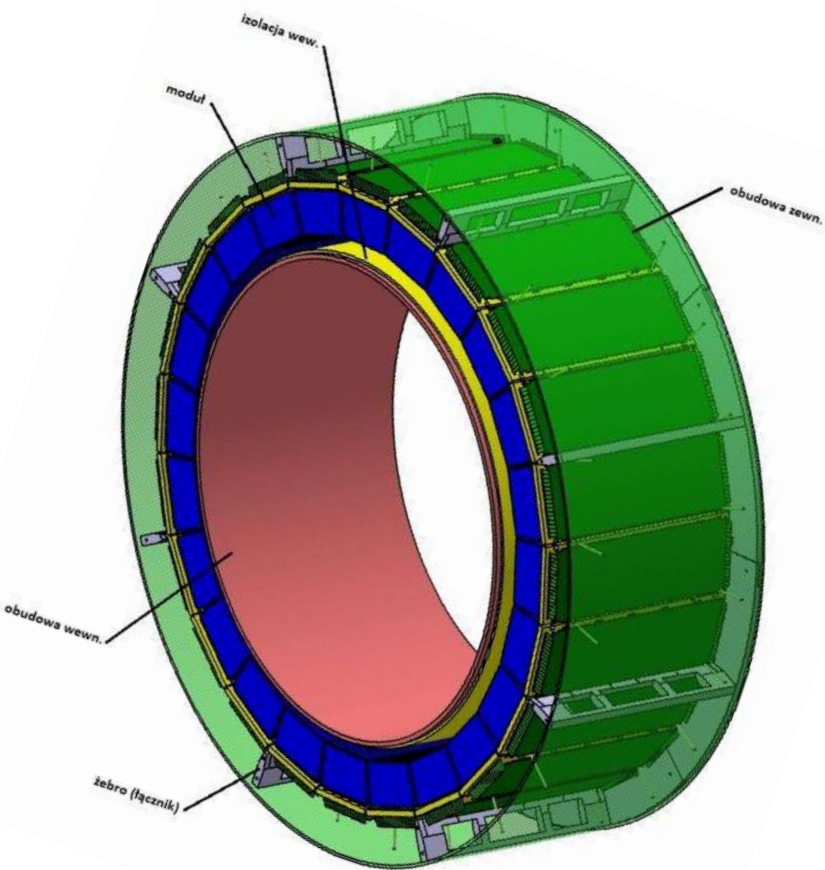
M. ŻYW.

Mirosław Kernbaum Radiological
Laboratory,
Warsaw Society of Sciences.
June 14.

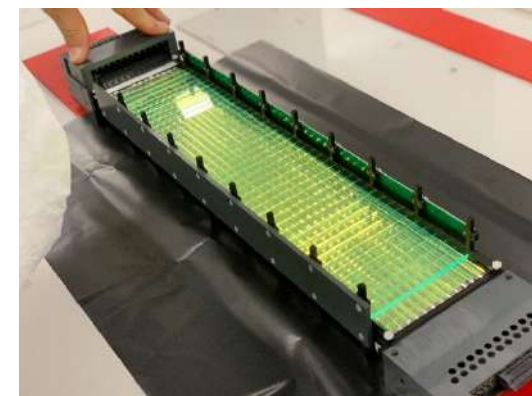
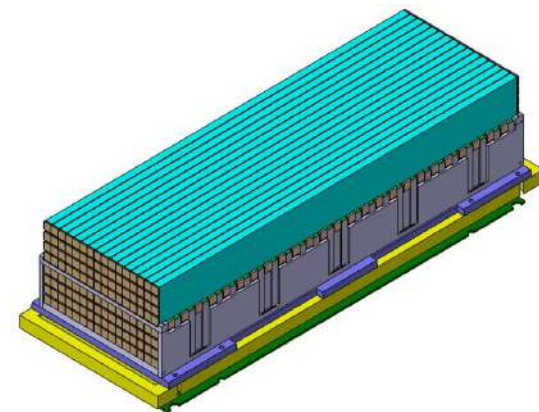
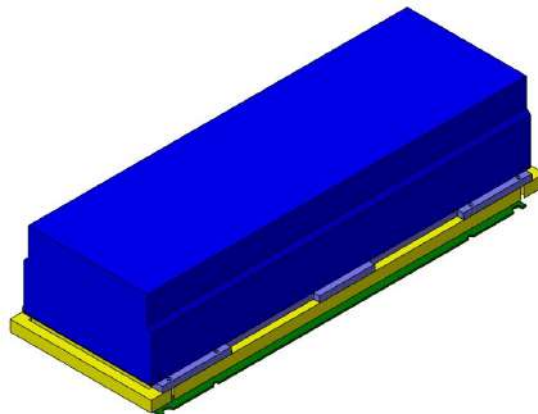
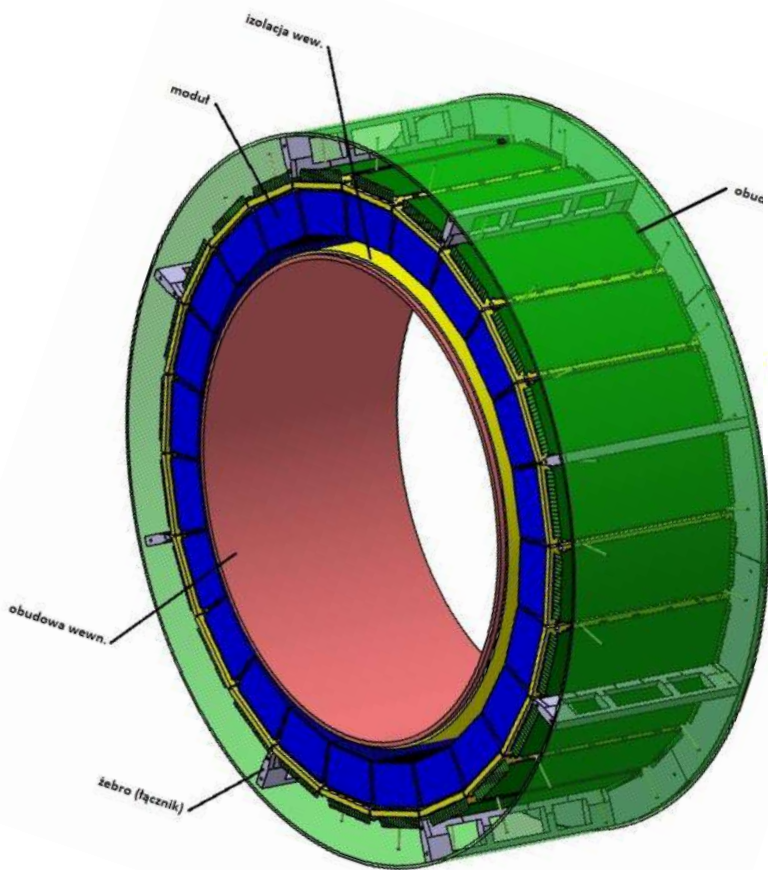
Total body J-PET



Total body J-PET



Total body J-PET



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



Violation of CP and T
confirmed experimentally
for hadrons only

S anti-**d**

meson K

1964

d anti-**b**

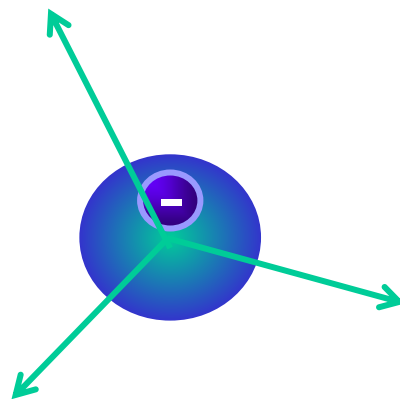
meson B

2012

-

positronium

?

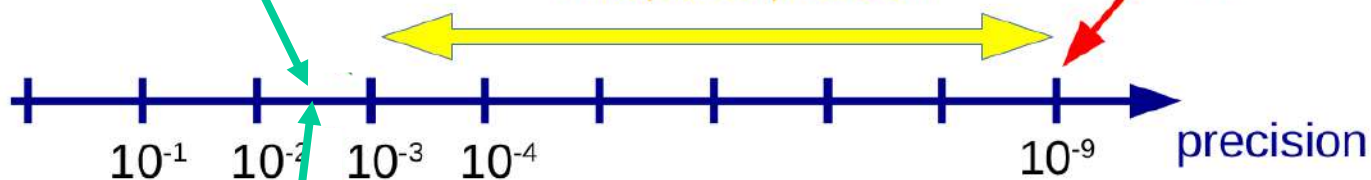


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

PRL 104 (2010) 083401

6 OOM of
unexplored precision

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



$$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$$

PRL. 91 (2003) 263401



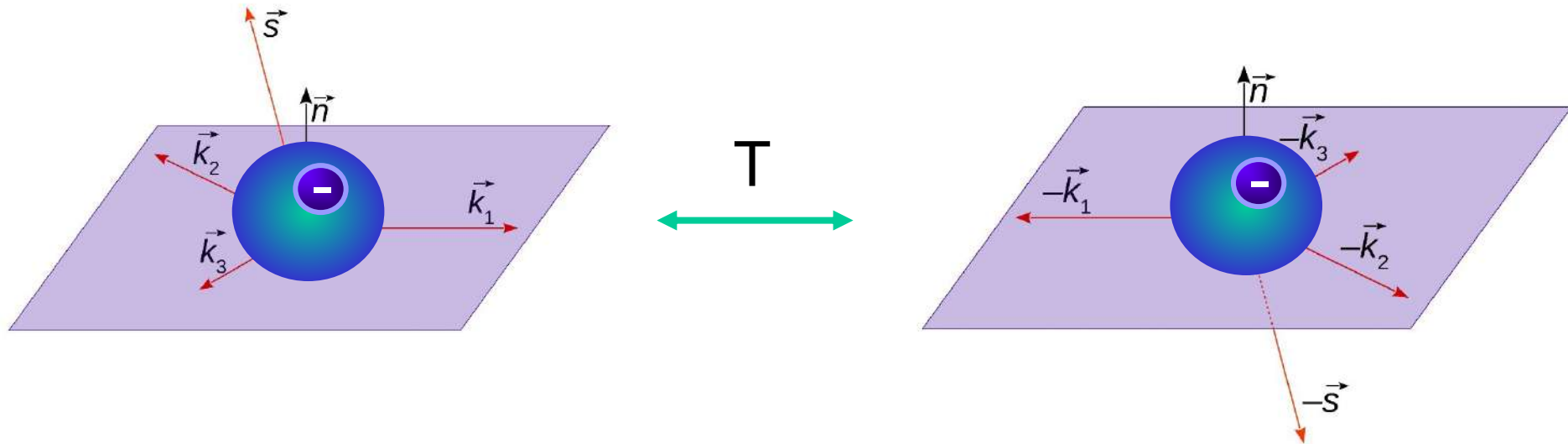
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1) (\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+

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

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

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

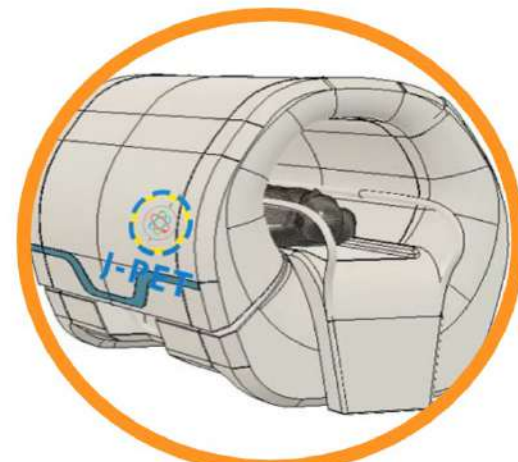
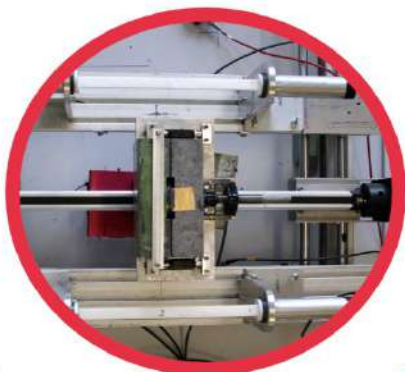
$$|k_1| > |k_2| > |k_3|$$





total-body J-PET

3-layer prototype



2009

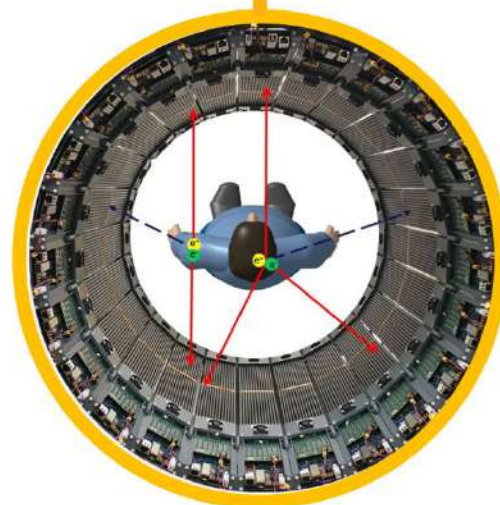
2014

2021

2012

2016

2028



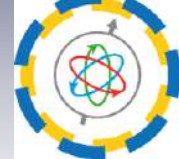
modular J-PET

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)

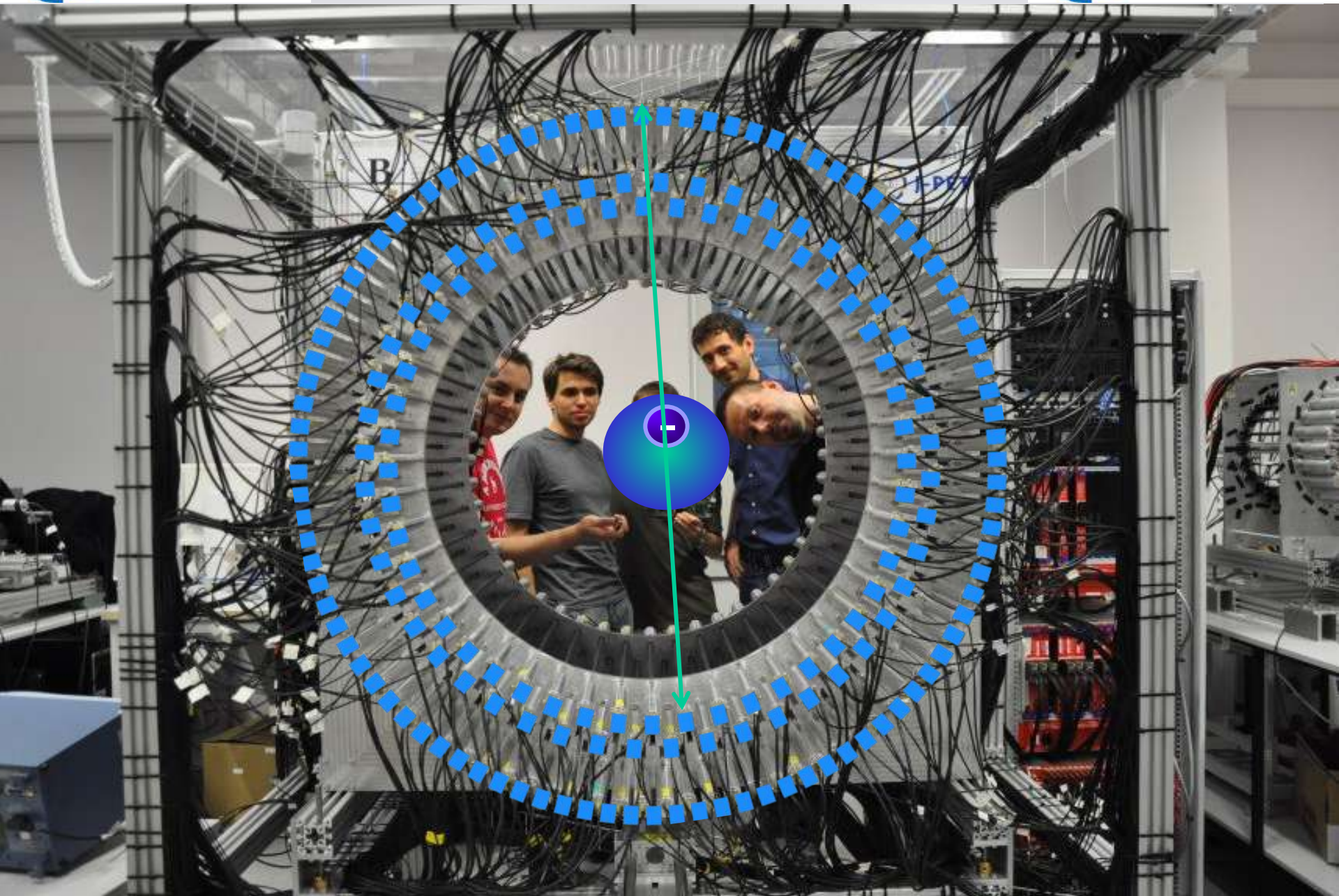


J-PET

Jagiellonian PET



J-PET



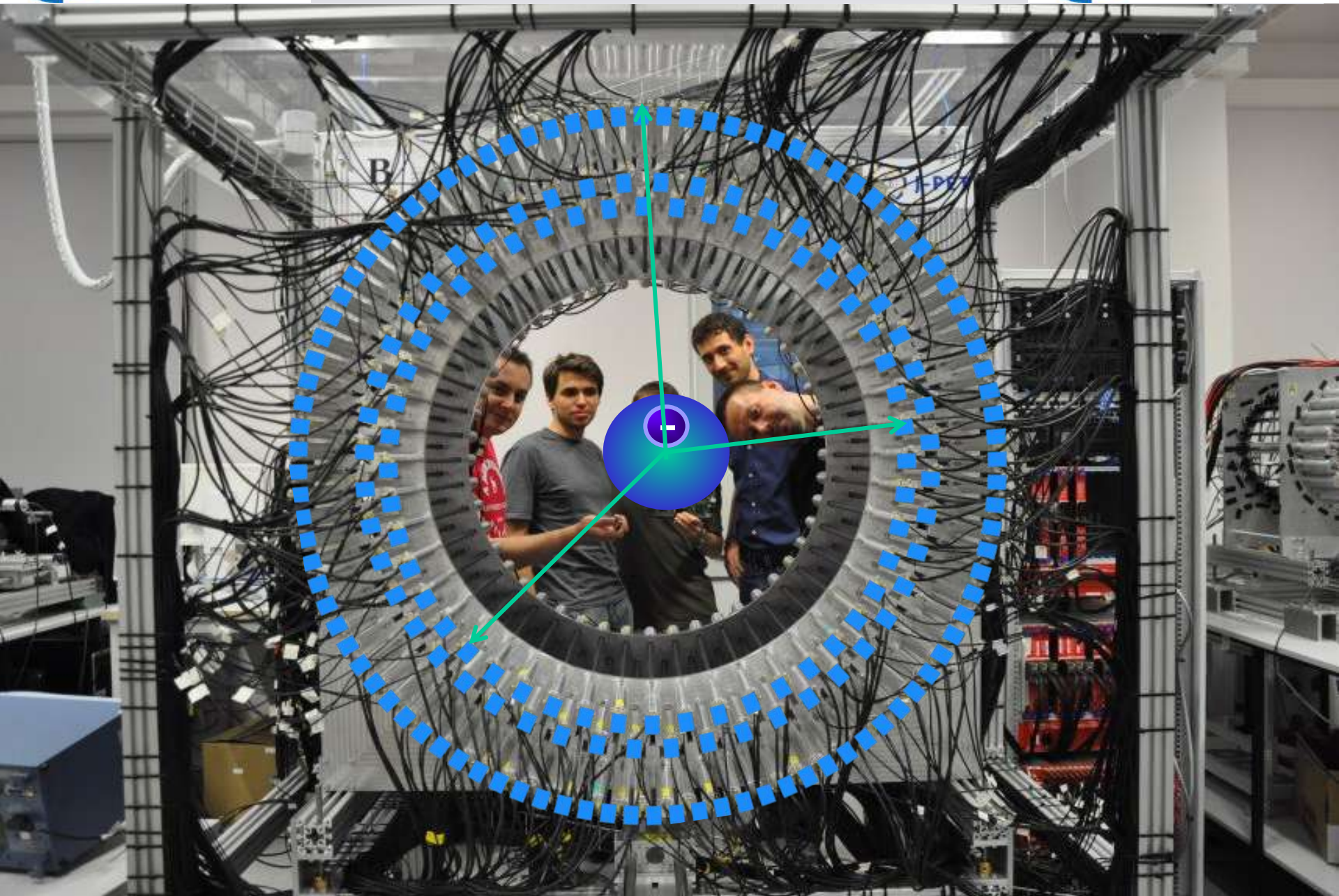


J-PET

Jagiellonian PET



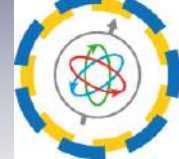
J-PET



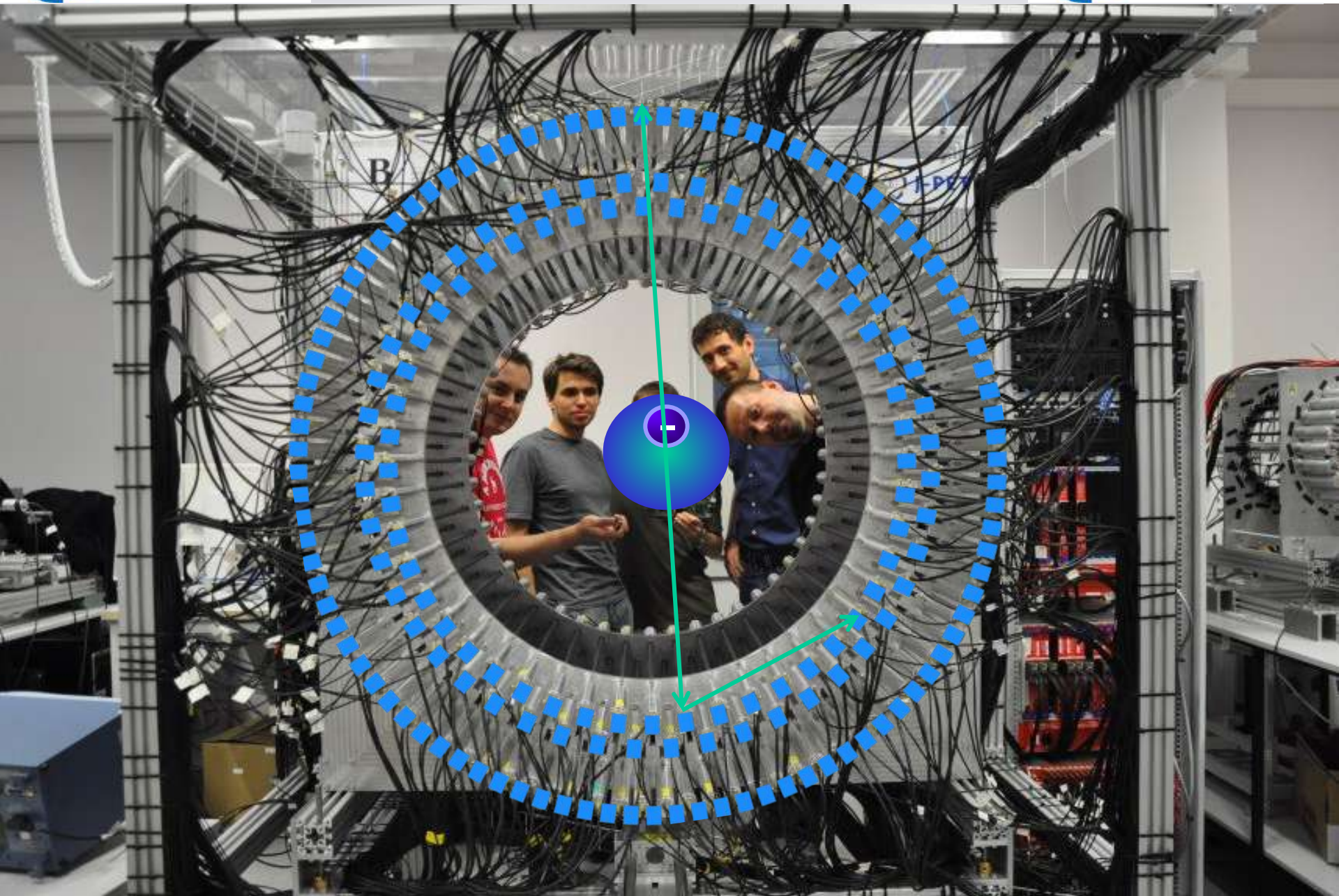


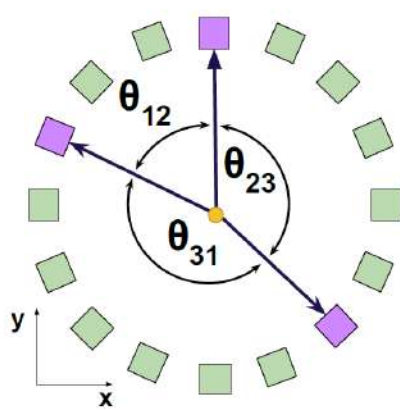
J-PET

Jagiellonian PET



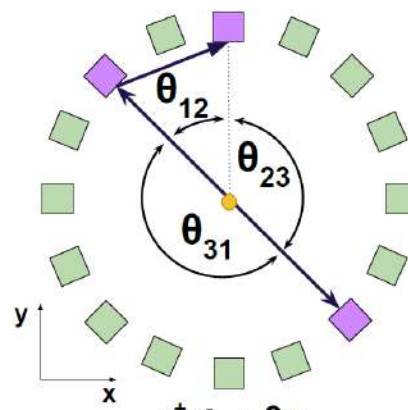
J-PET





$o\text{-Ps} \rightarrow 3\gamma$

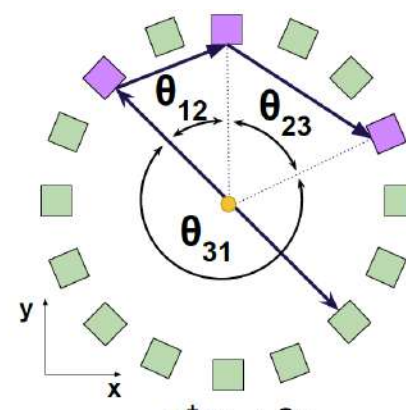
$$\theta_{23} + \theta_{12} > 180$$



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

single scattered

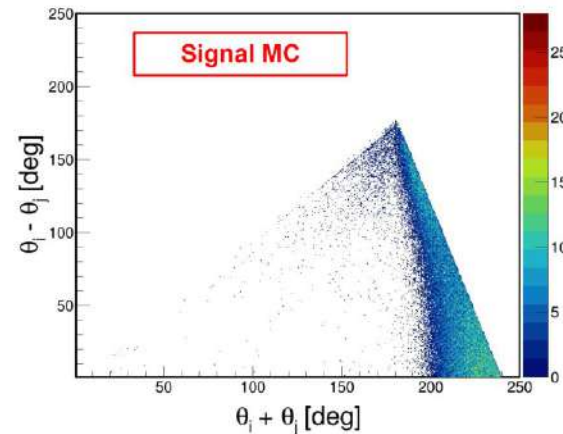
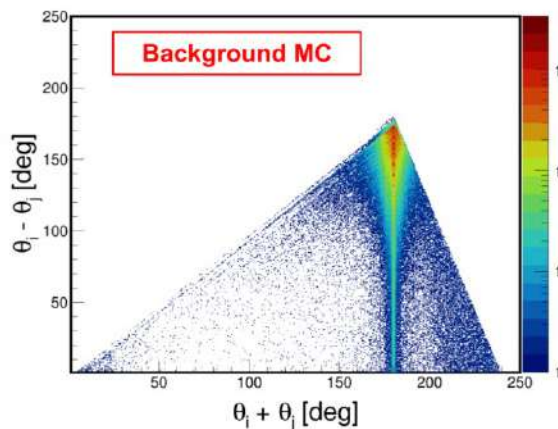
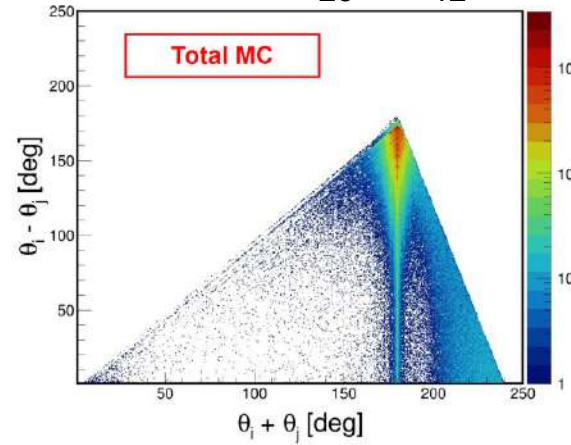
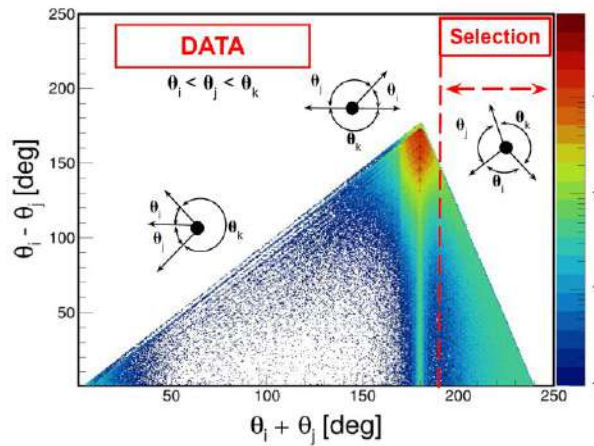
$$\theta_{23} + \theta_{12} = 180$$



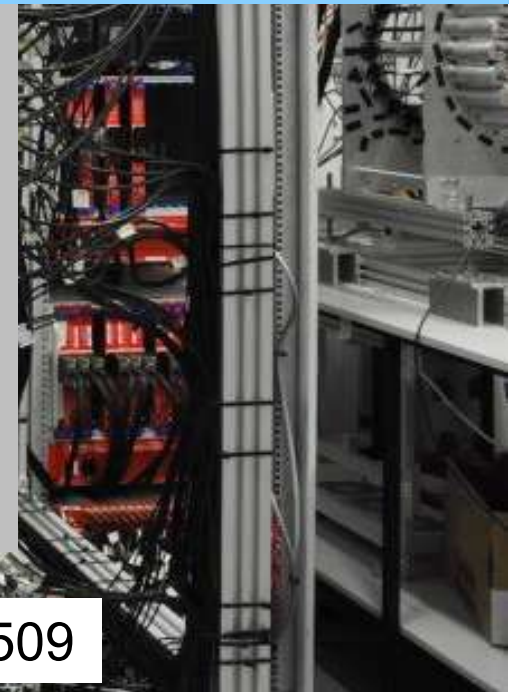
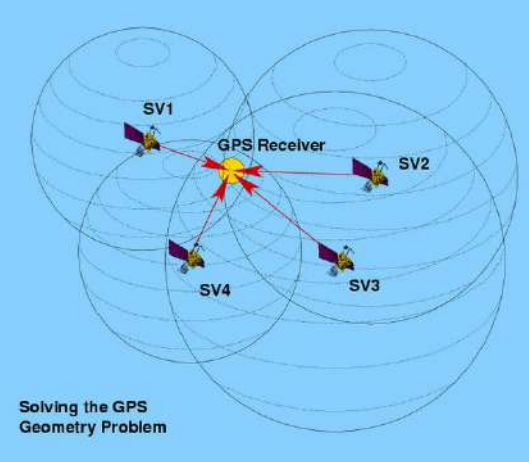
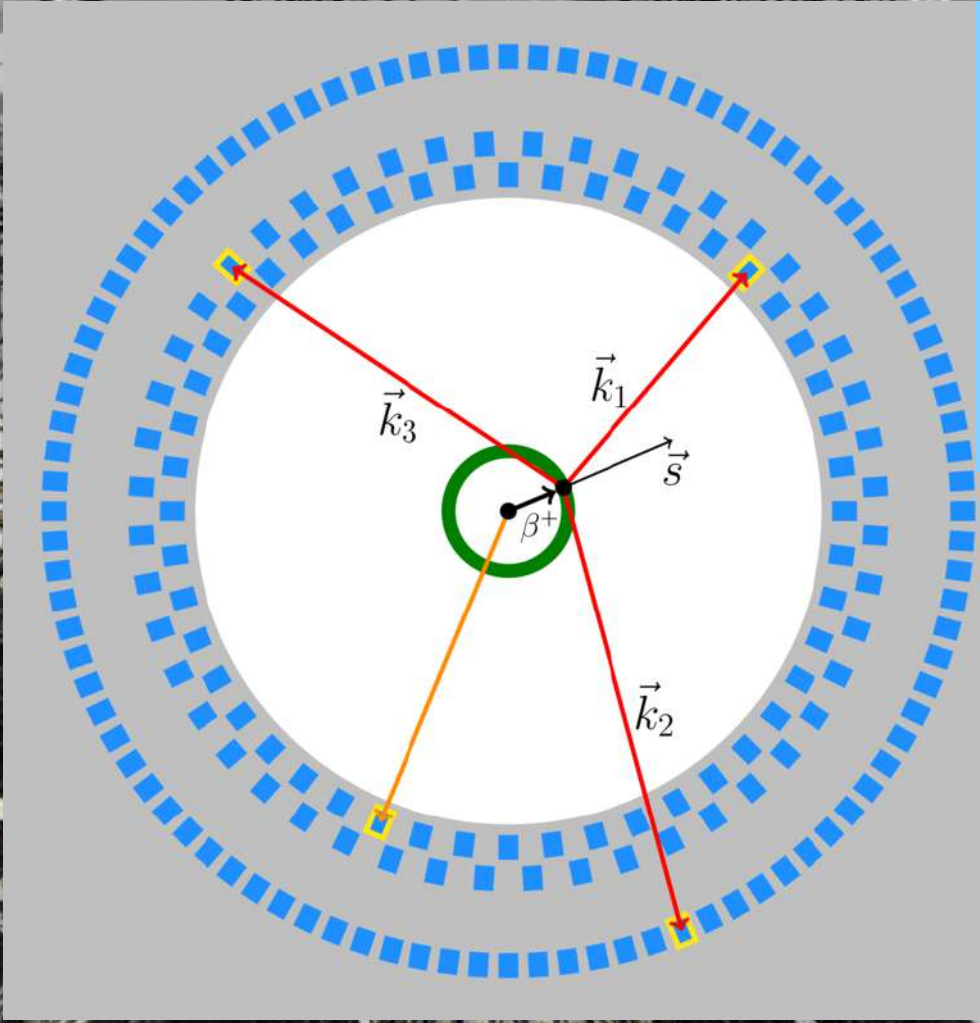
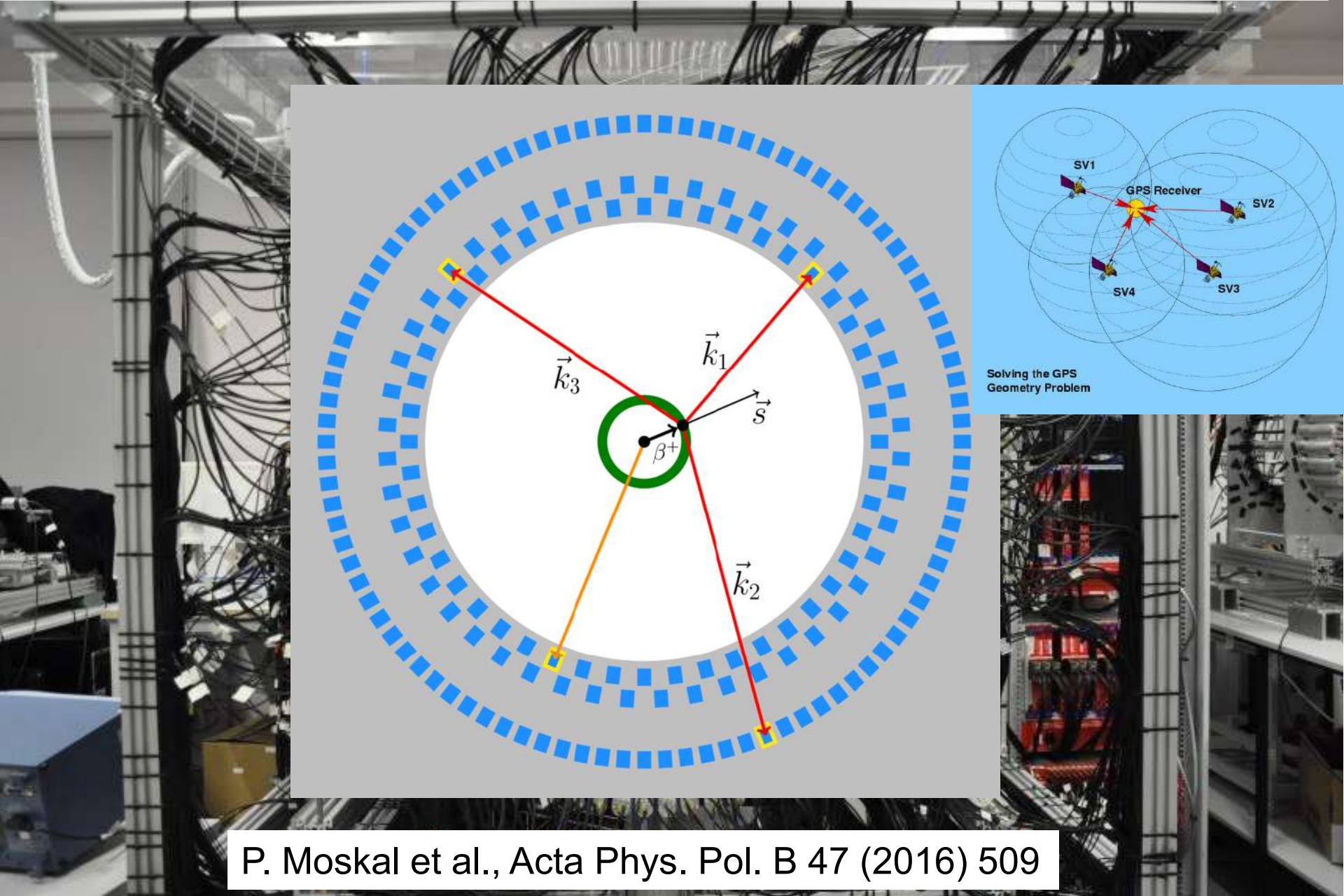
$e^+e^- \rightarrow 2\gamma$

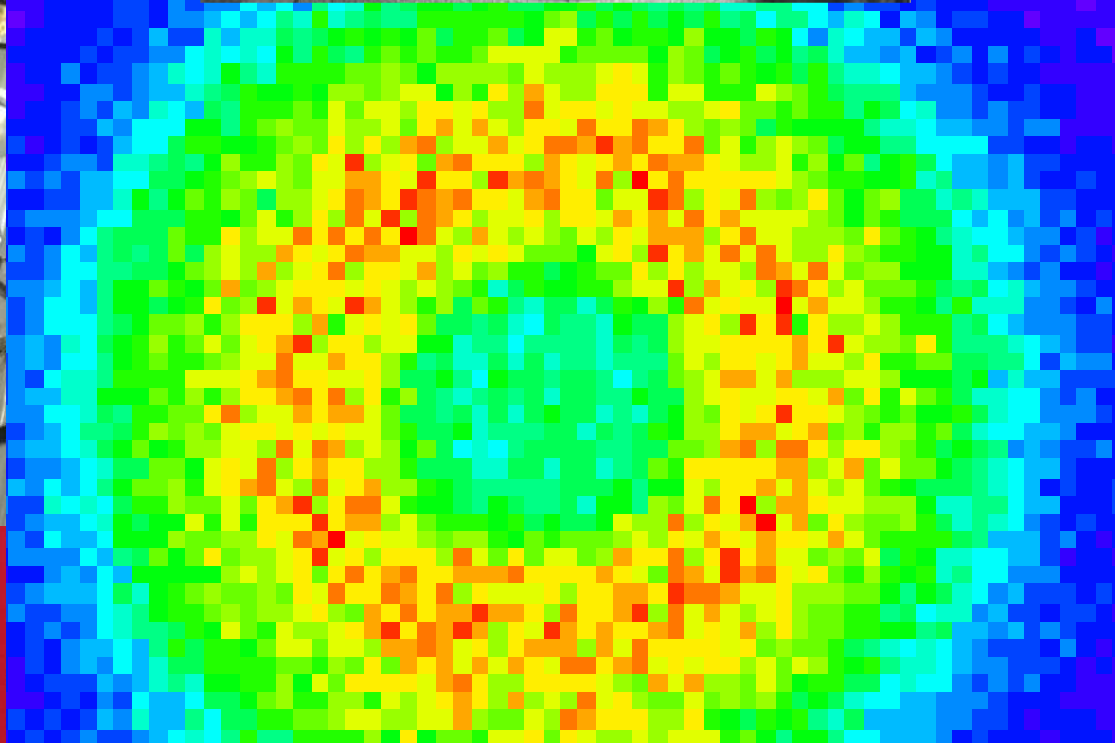
double scattered

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









Operator

C

P

T

CP

CPT

$$\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2)$$

+

+

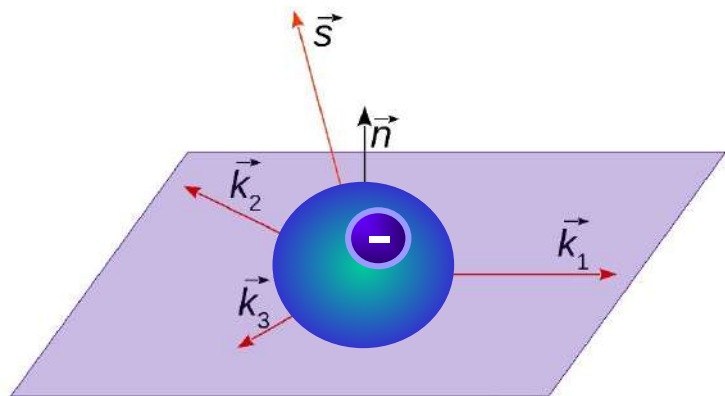
-

+

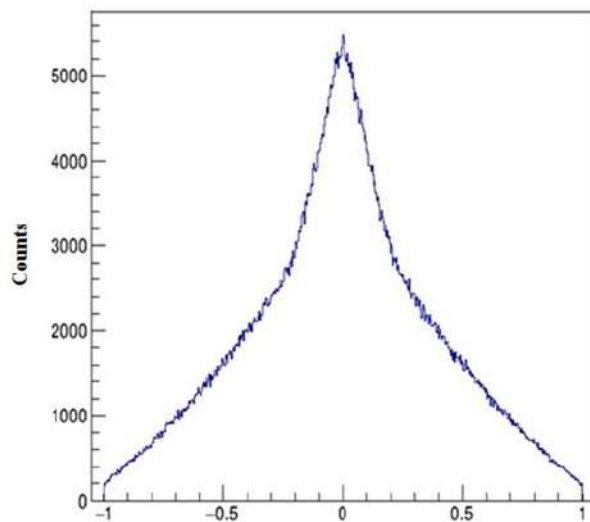
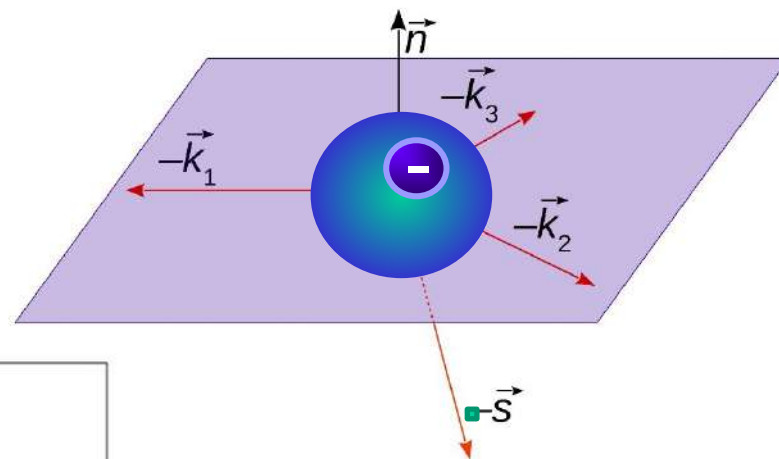
-

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

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

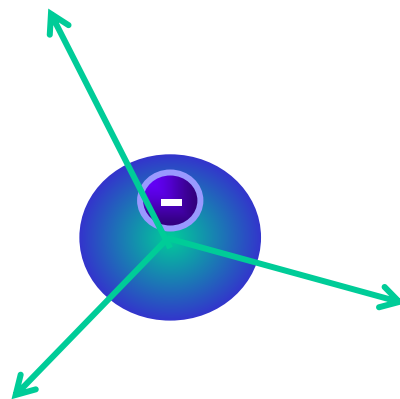


T, CPT



$$CPTST = \vec{s} \cdot \frac{\hat{k}_1 \times \hat{k}_2}{|\hat{k}_1 \times \hat{k}_2|}$$

+ - 0.00095

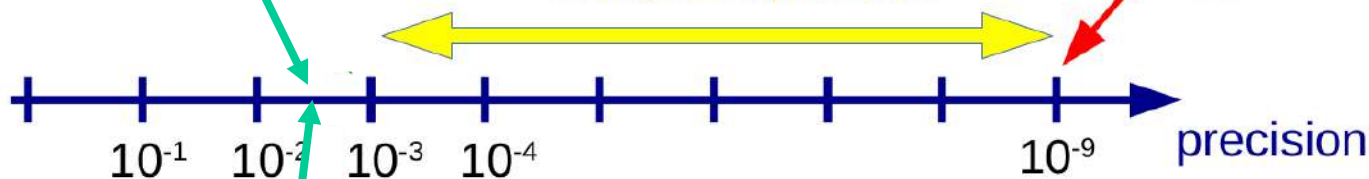


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

PRL 104 (2010) 083401

6 OOM of unexplored precision

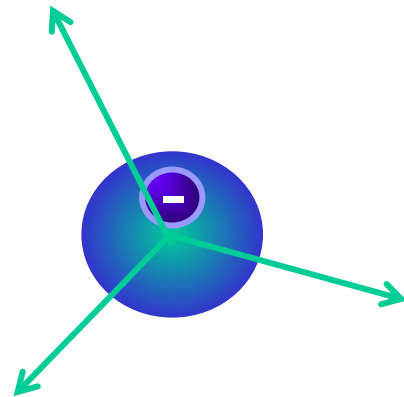
Physical sensitivity limit:
false asymmetries from $\gamma\gamma$ interactions in the final state



$$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$$

PRL. 91 (2003) 263401



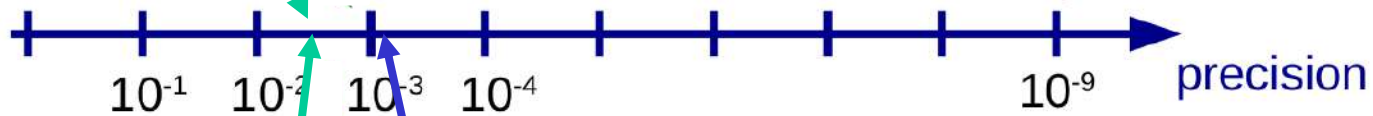


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

PRL 104 (2010) 083401

6 OOM of
unexplored precision

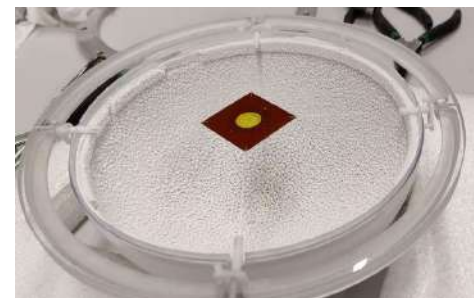
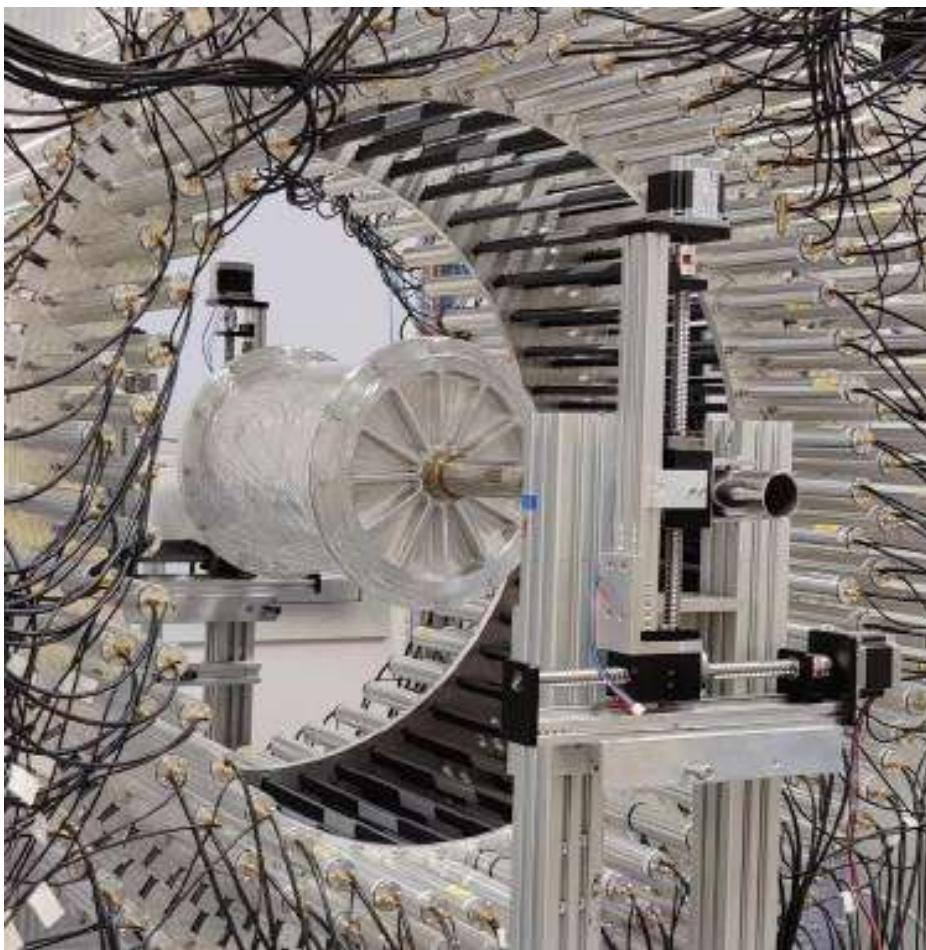
Physical sensitivity limit:
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$$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$$

PRL. 91 (2003) 263401





Operator

C

P

T

CP

CPT

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

+

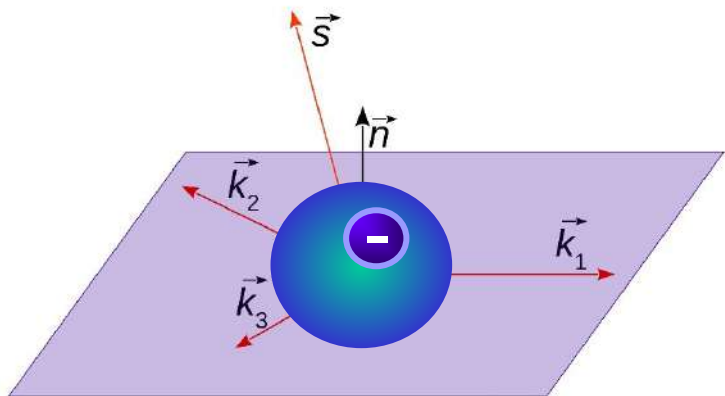
+

-

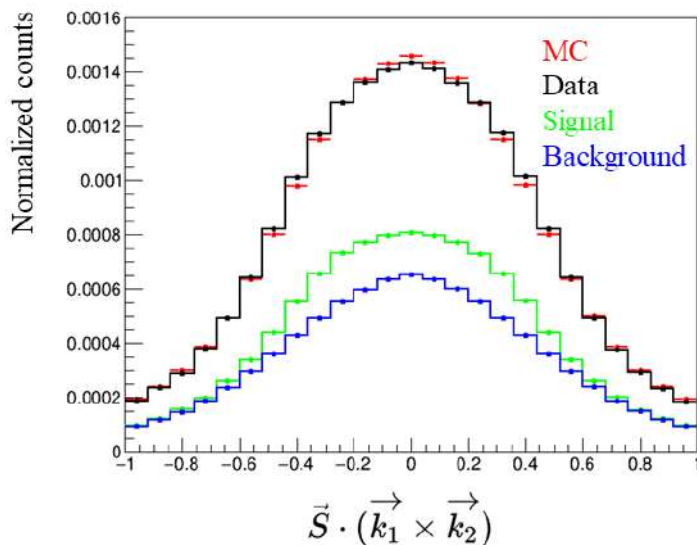
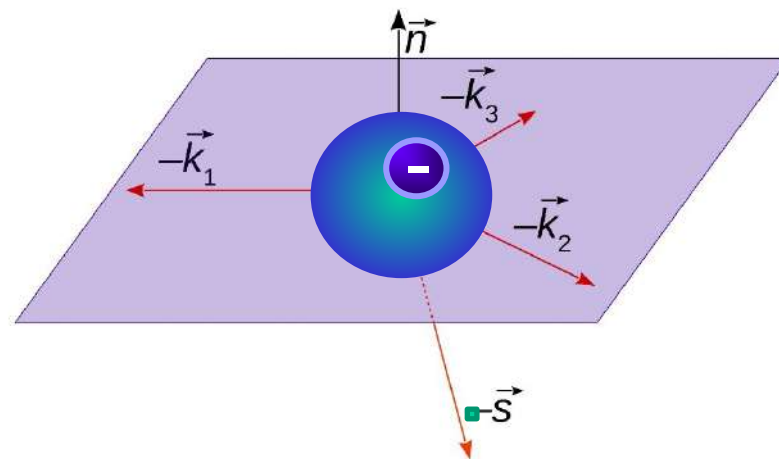
+

-

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



T, CPT



+ - 0.0002

Operator

C

P

T

CP

CPT

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

+

+

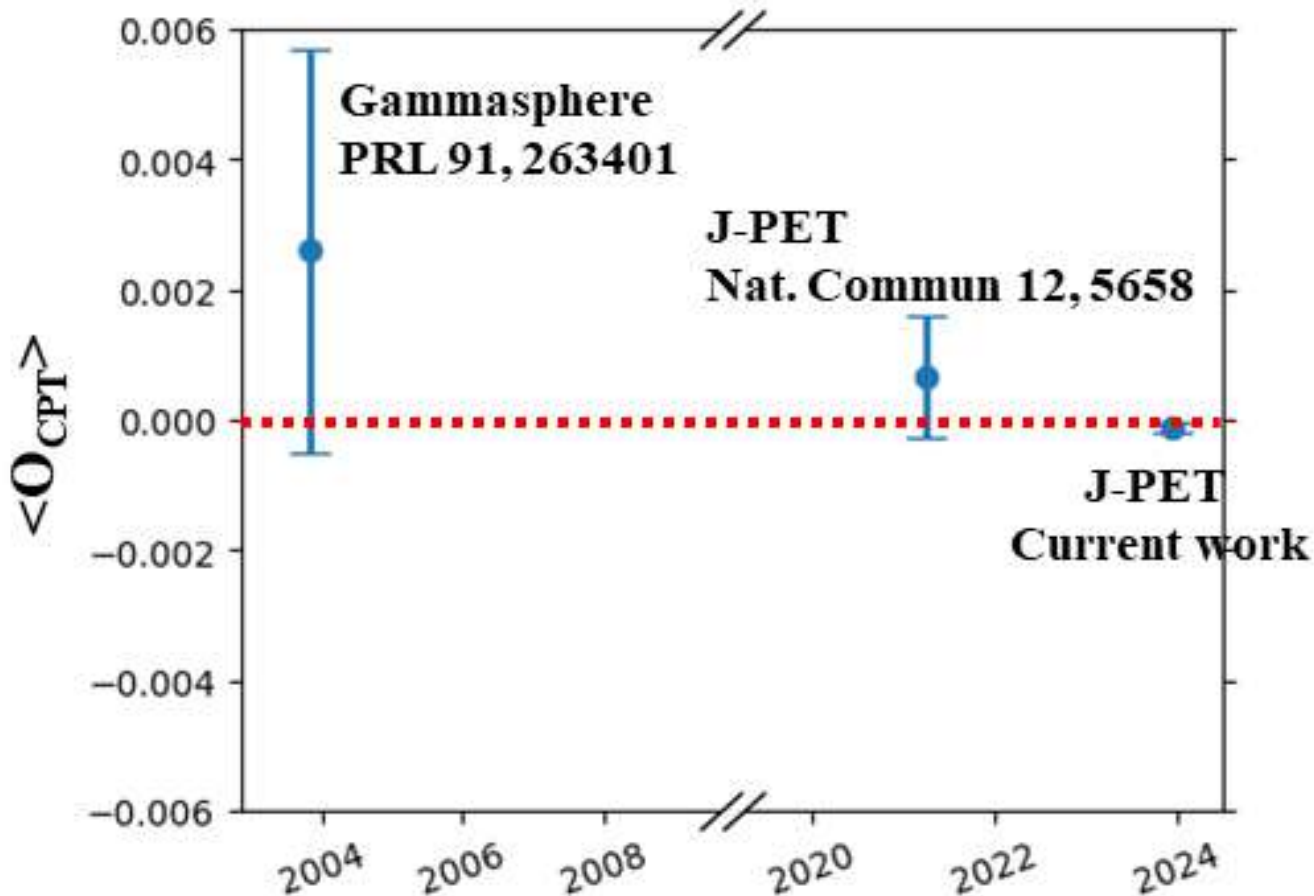
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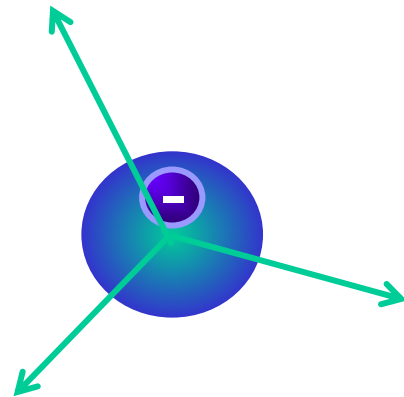
+

-

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

CPT over years



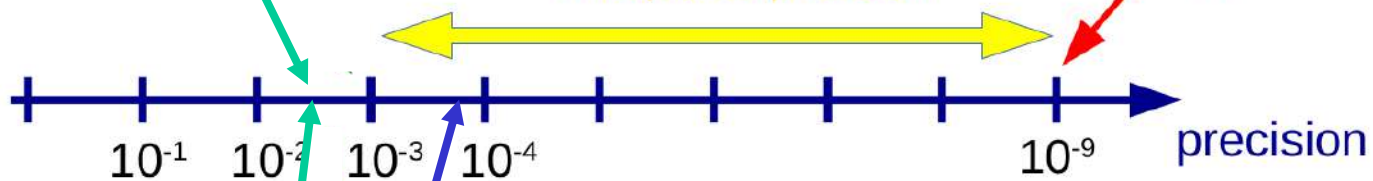


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

PRL 104 (2010) 083401

6 OOM of
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$$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$$

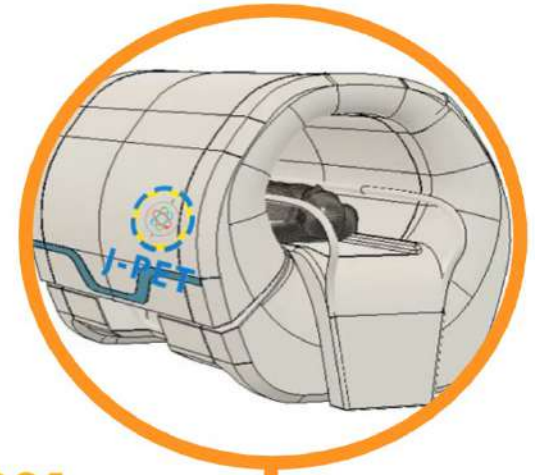
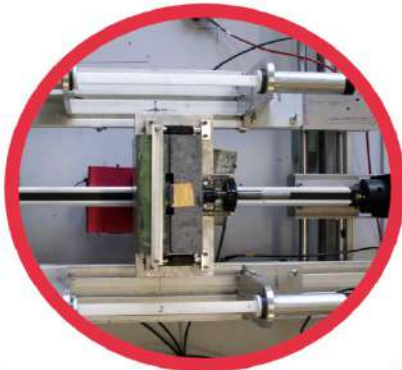
PRL. 91 (2003) 263401





total-body J-PET

3-layer prototype



2009

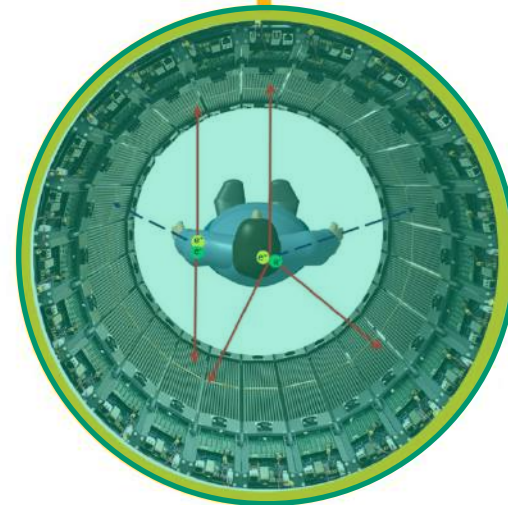
2014

2021

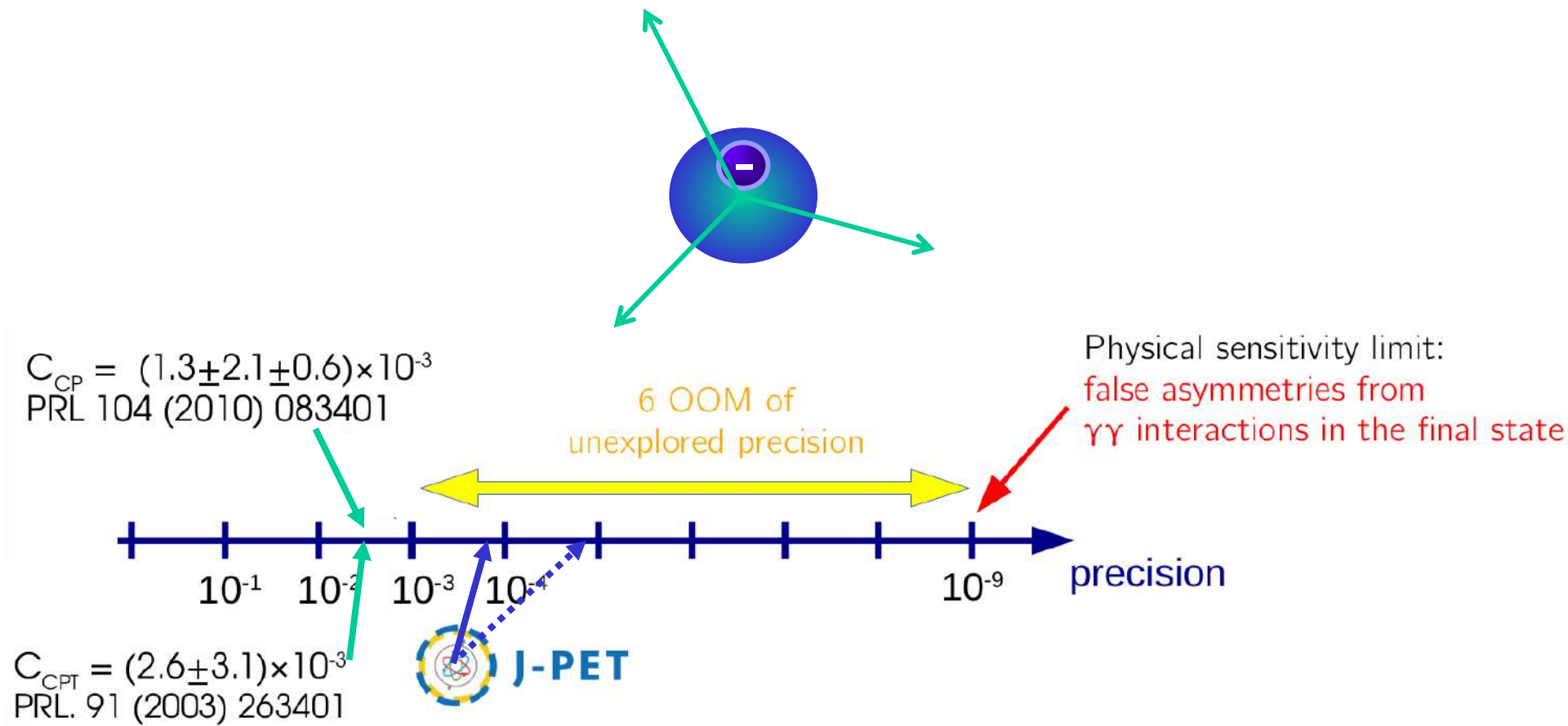
2012

2016

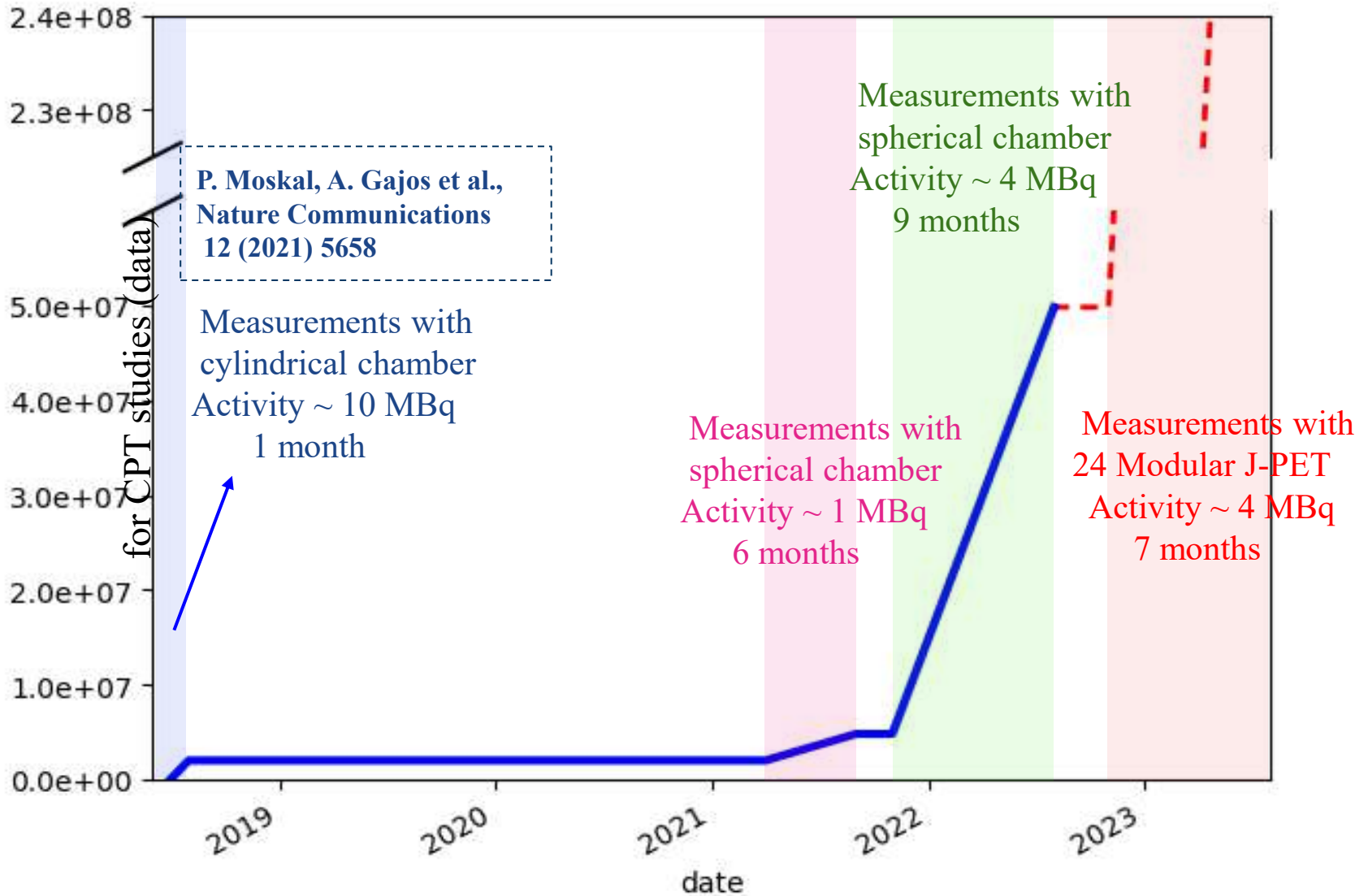
2028

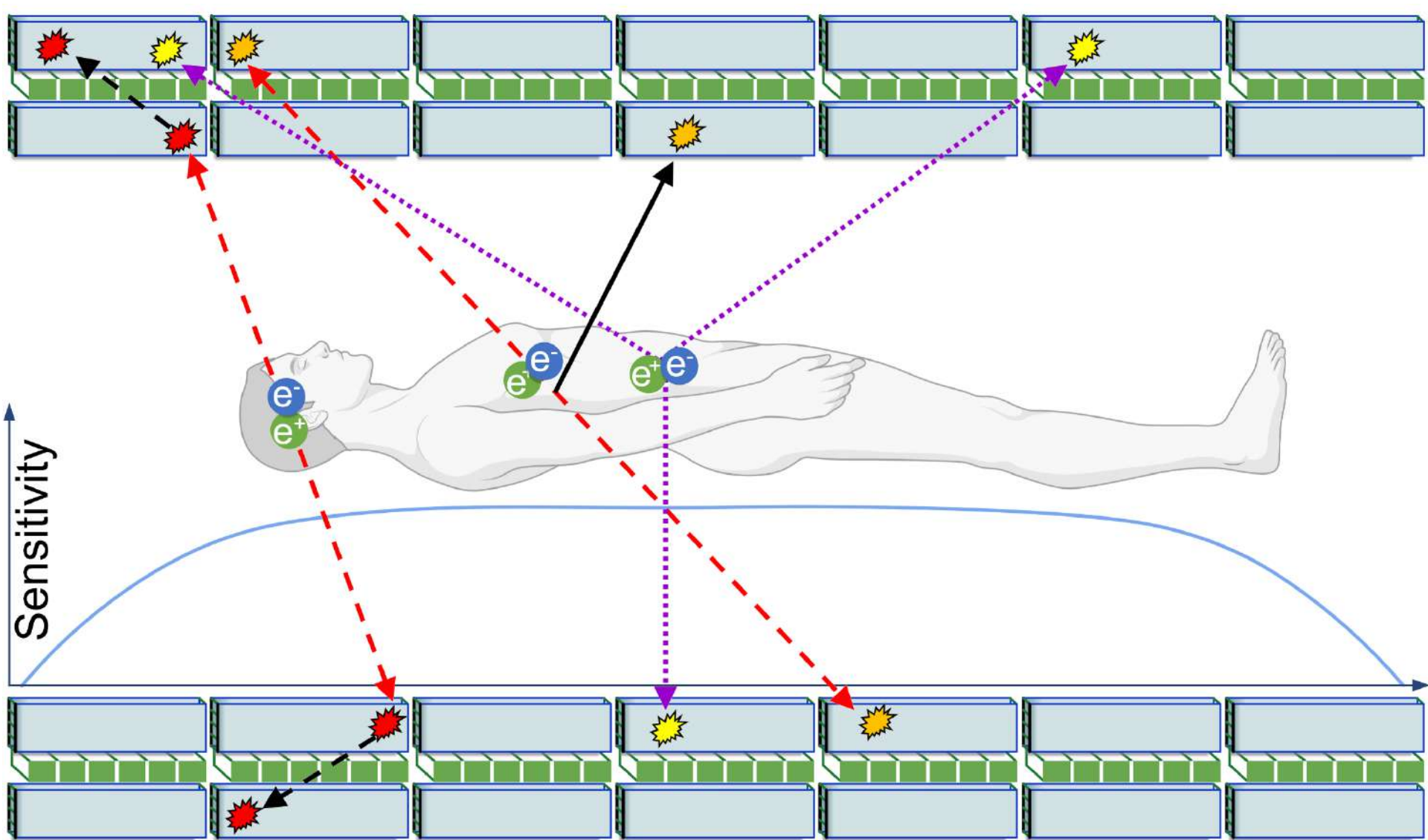


modular J-PET



No. of o-Ps events recorded in J-PET



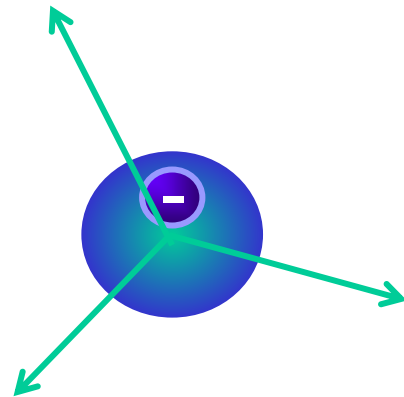


S. D. Bass, S. Mariazzi, P. Moskal, E. Stepien,

Rev. Mod. Phys. 95 (2023) 021002



Positronium physics and biomedical applications

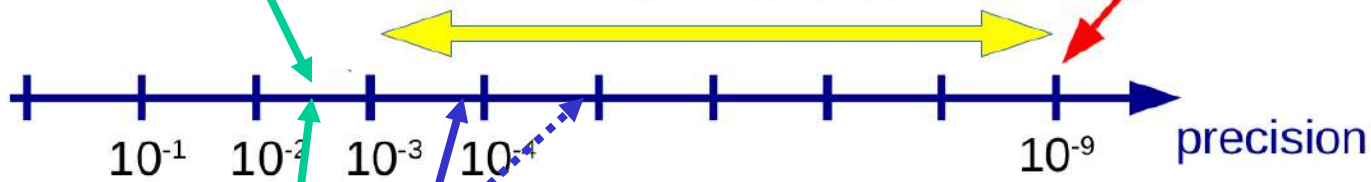


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

PRL 104 (2010) 083401

6 OOM of unexplored precision

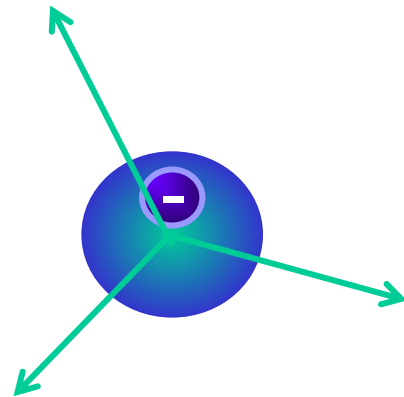
Physical sensitivity limit:
false asymmetries from $\gamma\gamma$ interactions in the final state



$$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$$

PRL. 91 (2003) 263401



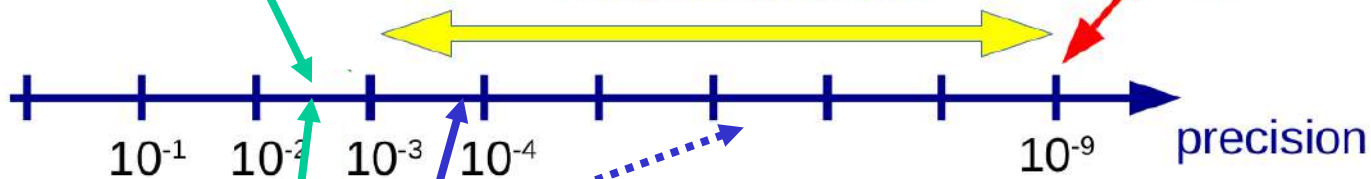


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

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



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



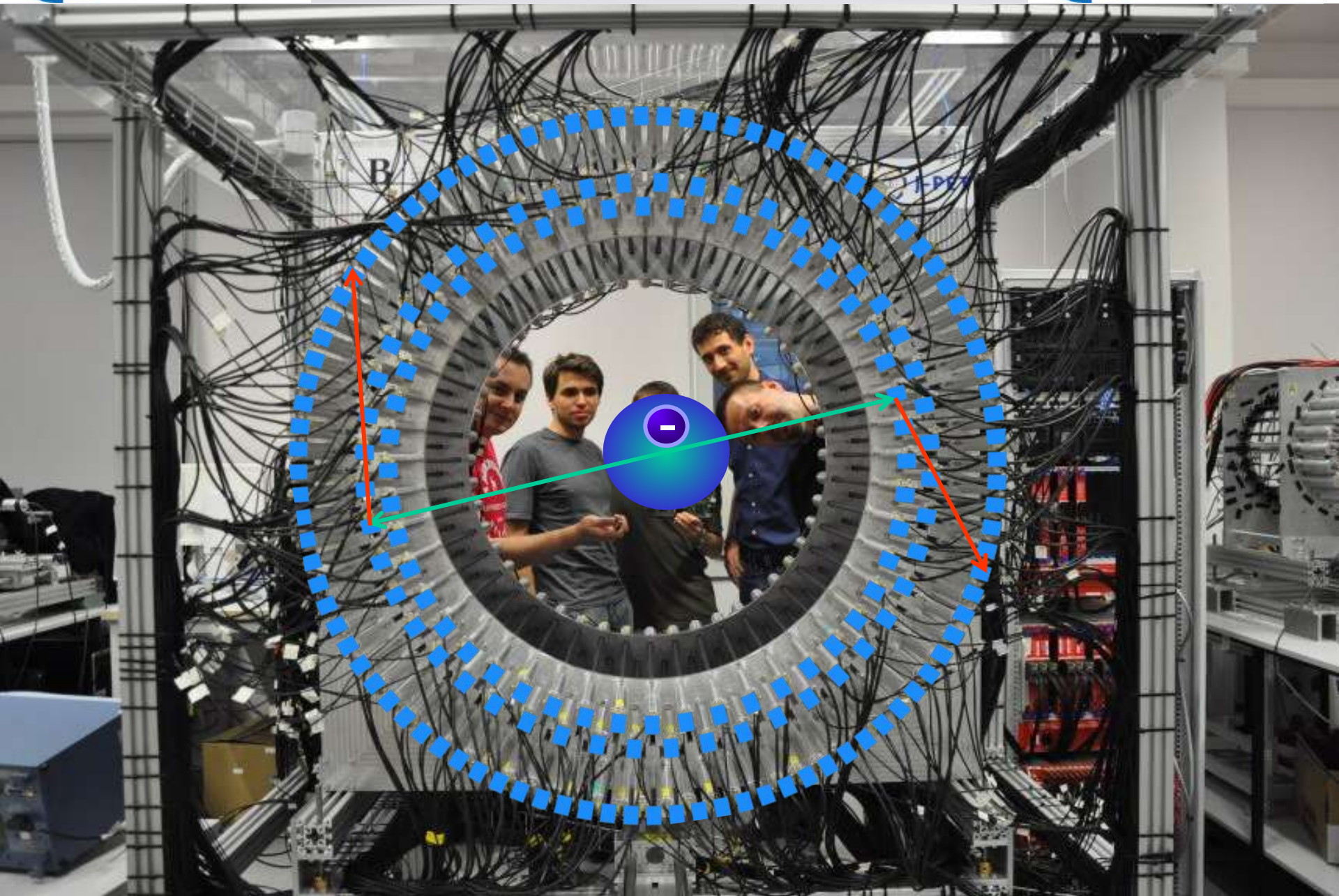


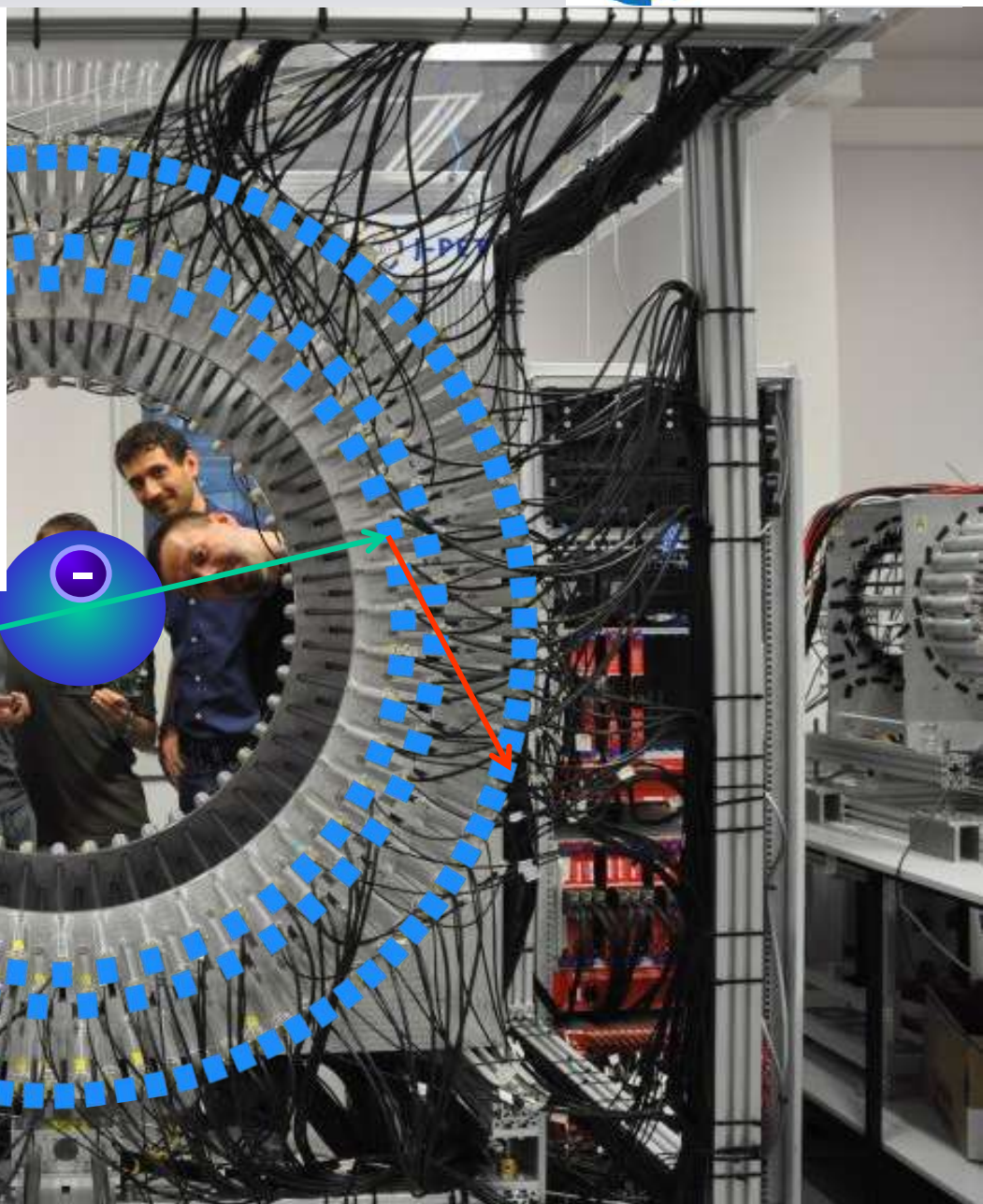
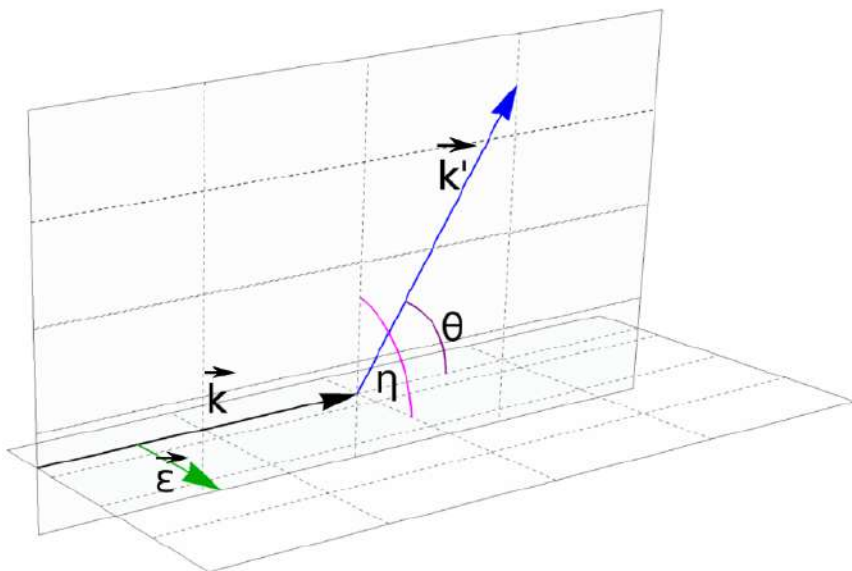
J-PET

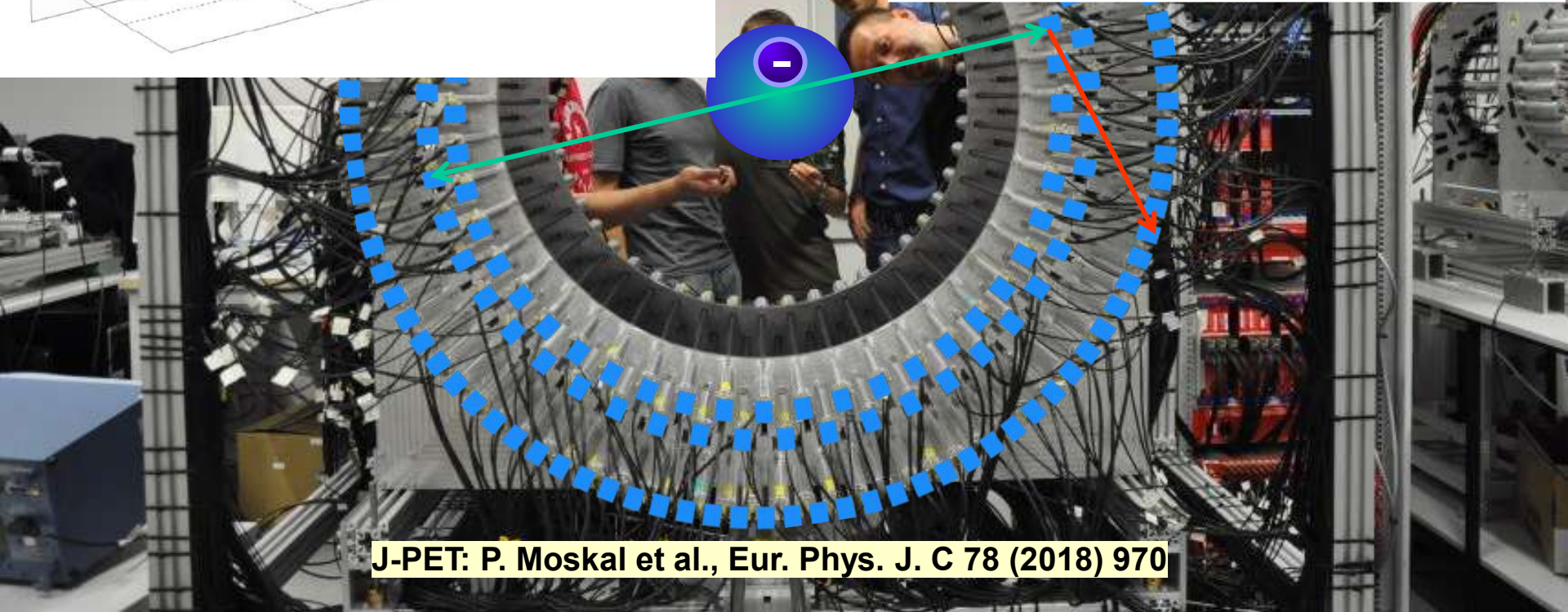
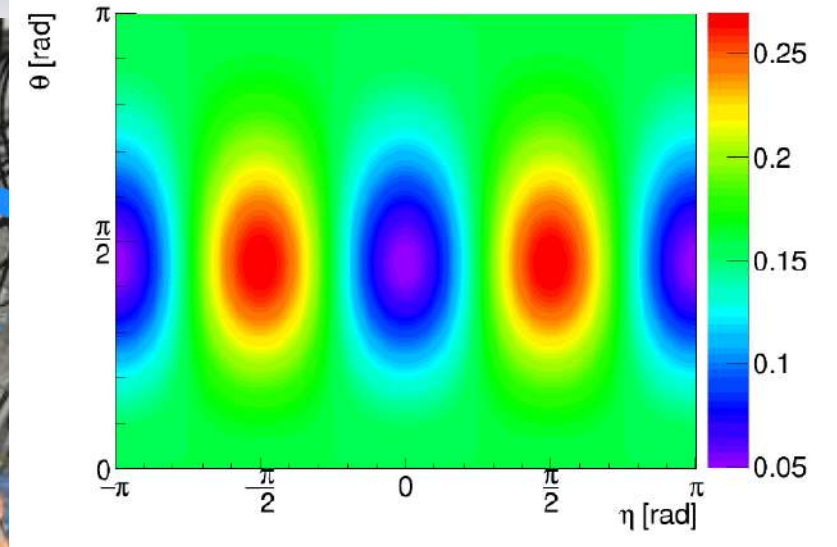
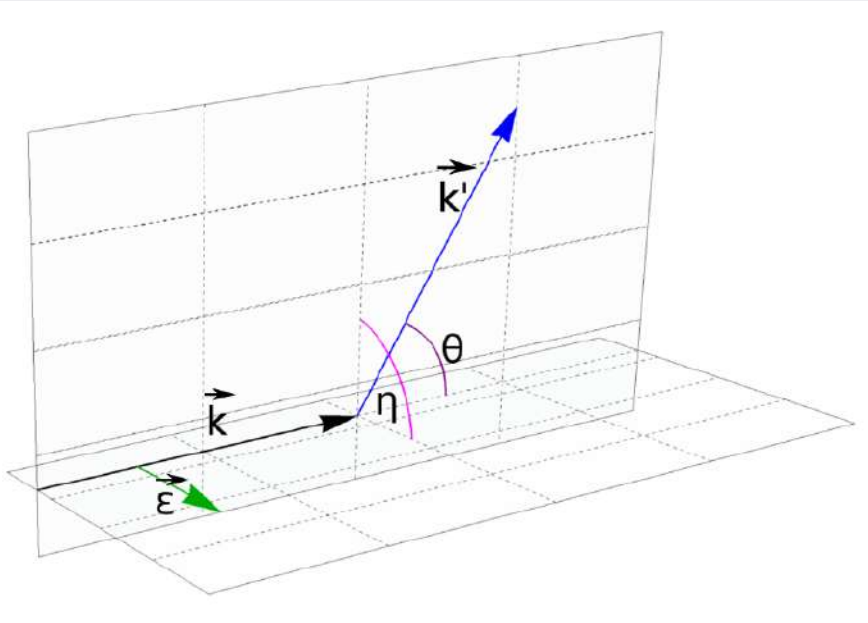
Jagiellonian PET



J-PET



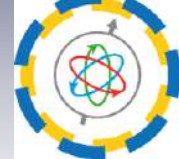




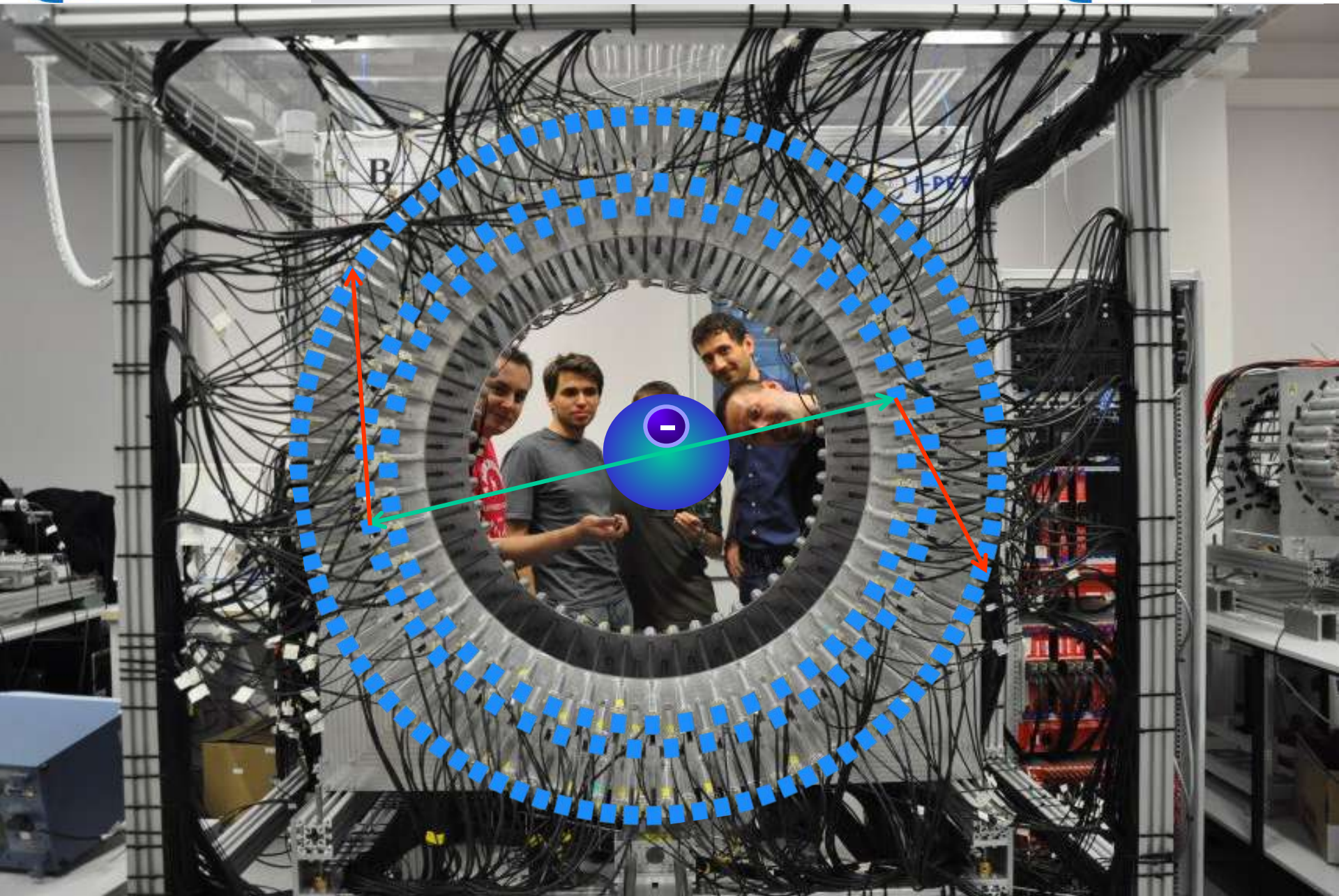


J-PET

Jagiellonian PET



J-PET



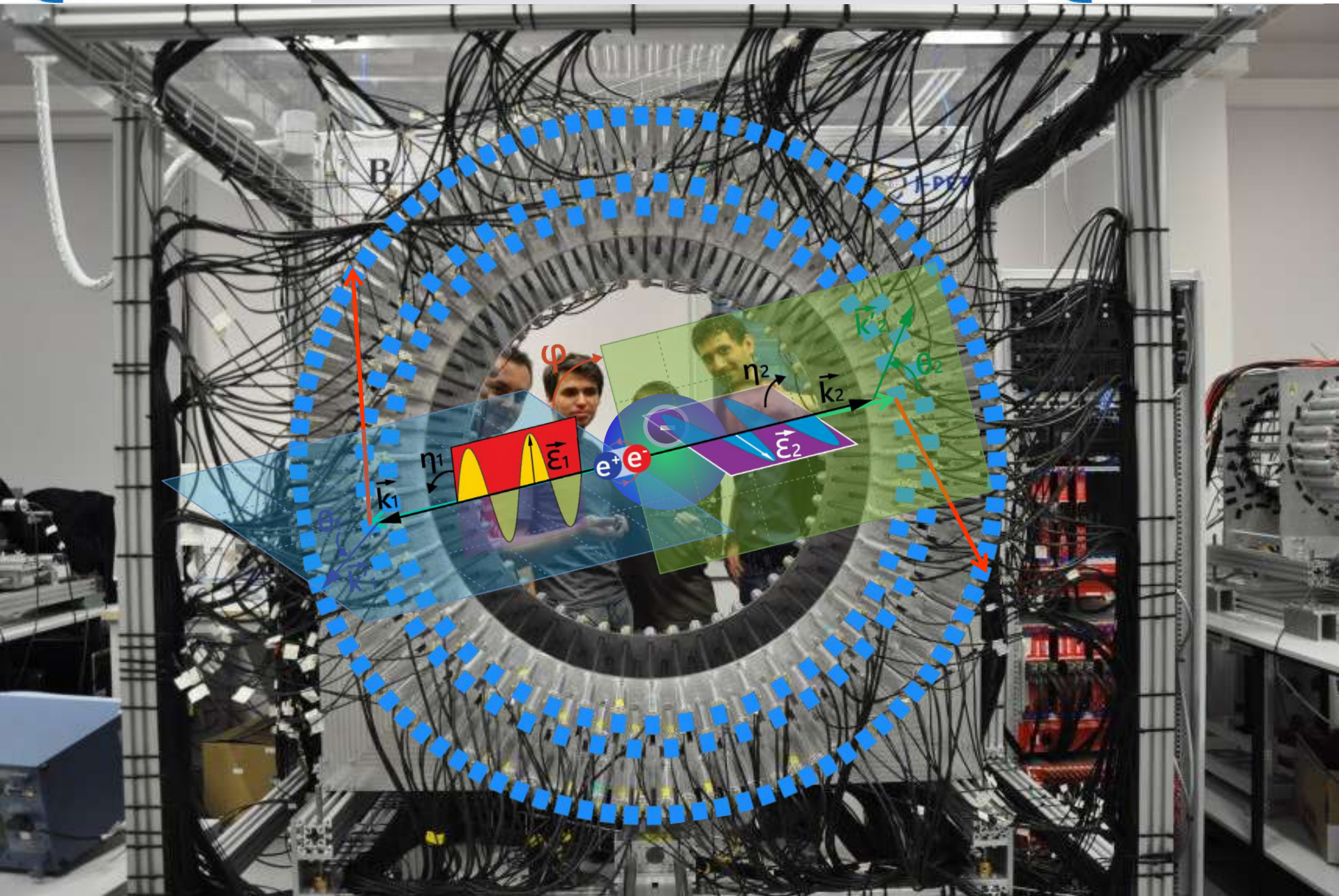


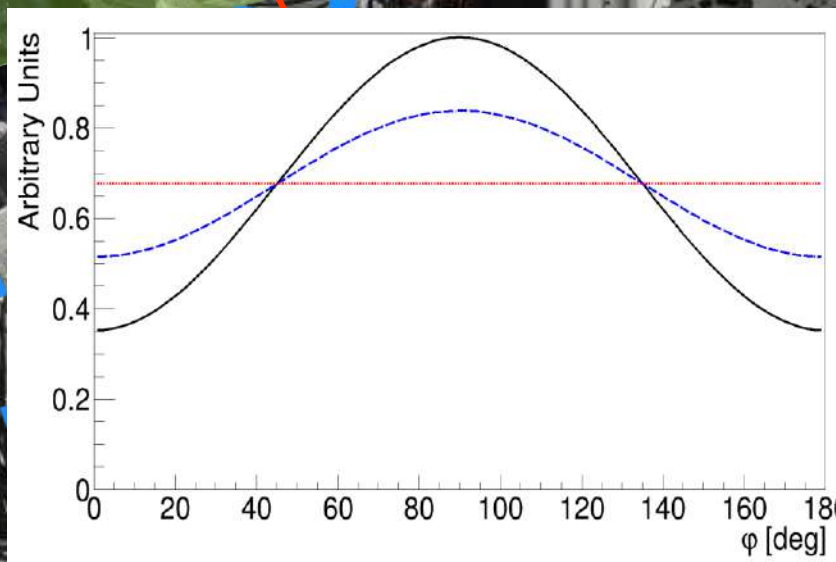
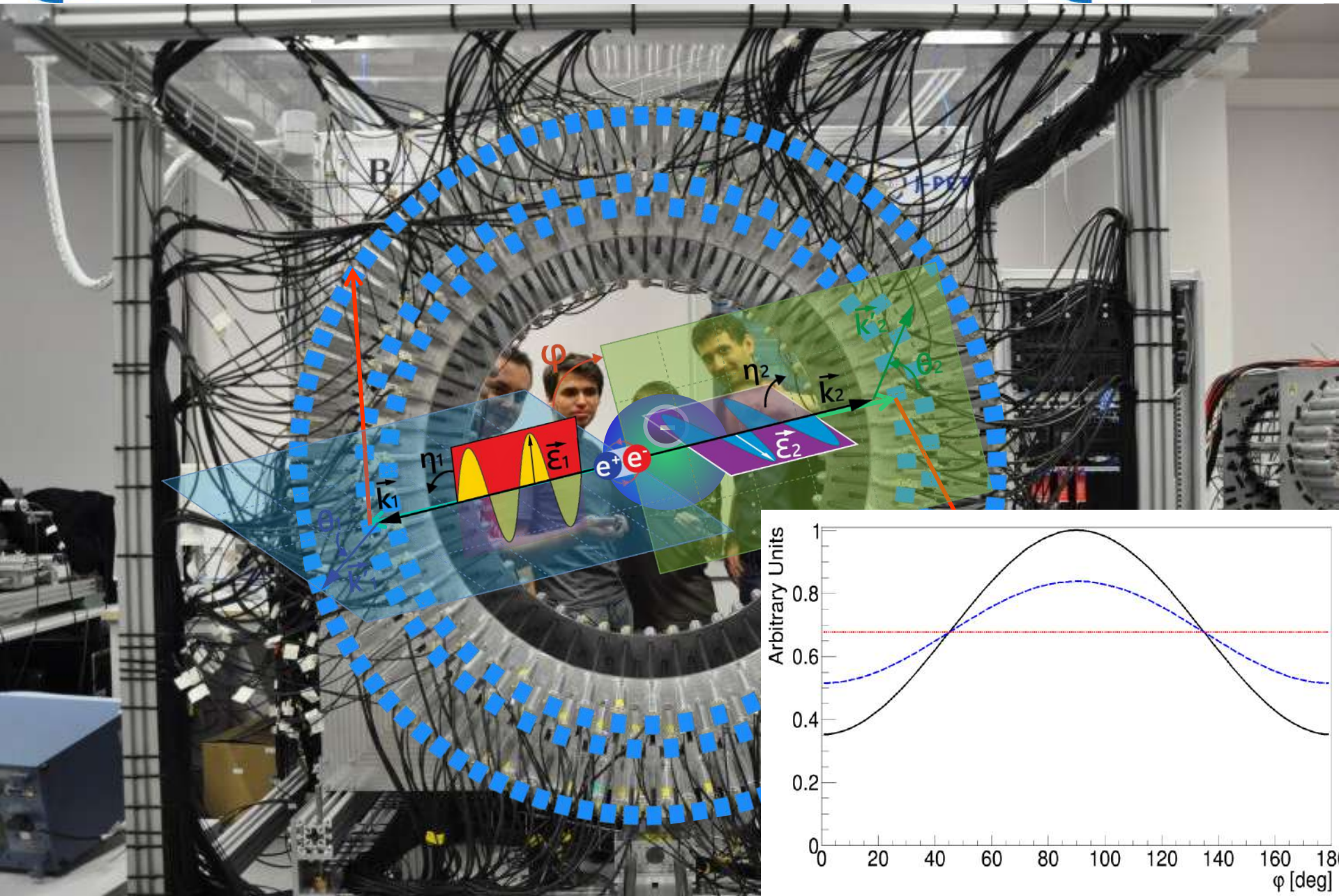
J-PET

Jagiellonian PET



J-PET







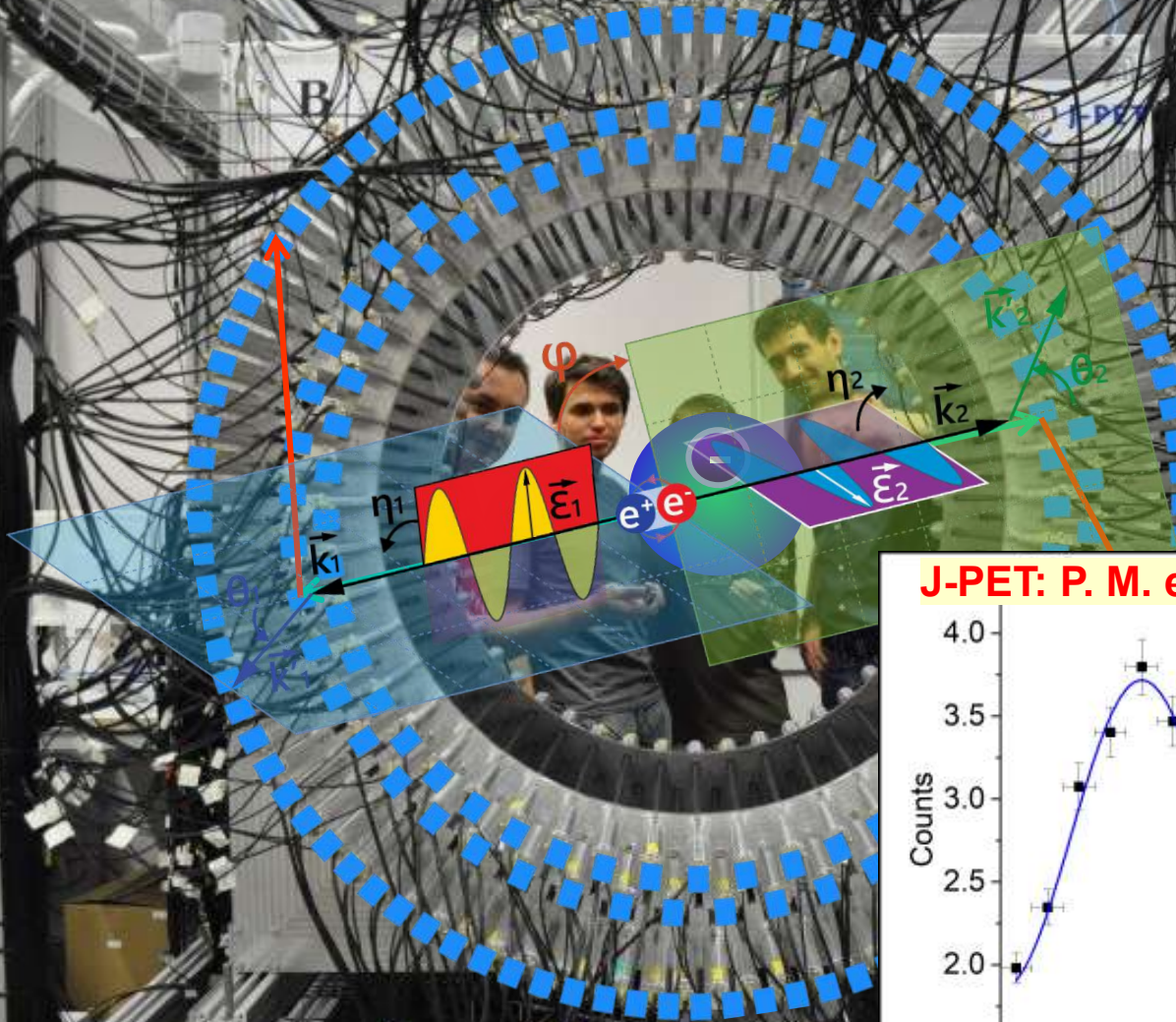
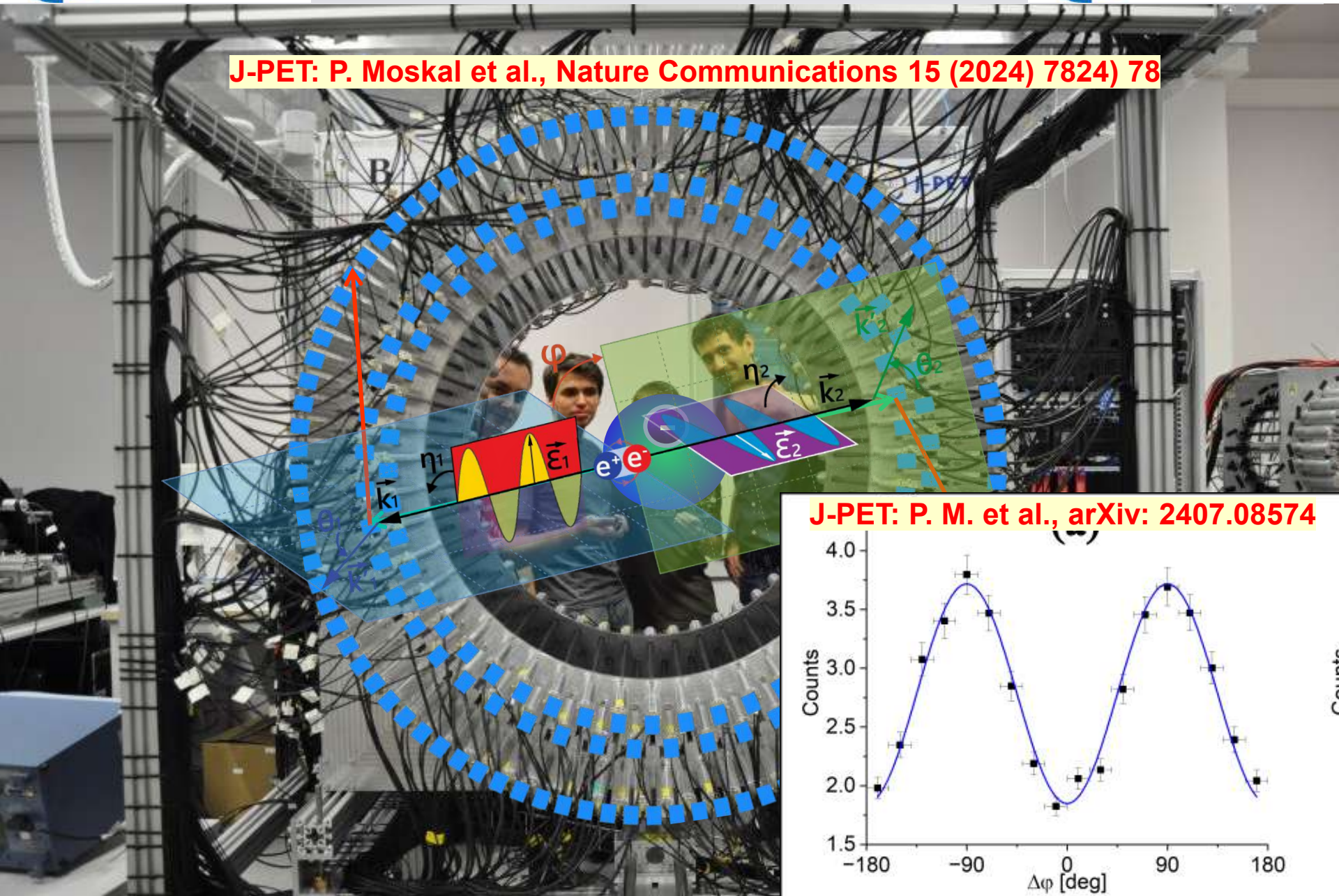
J-PET

Jagiellonian PET

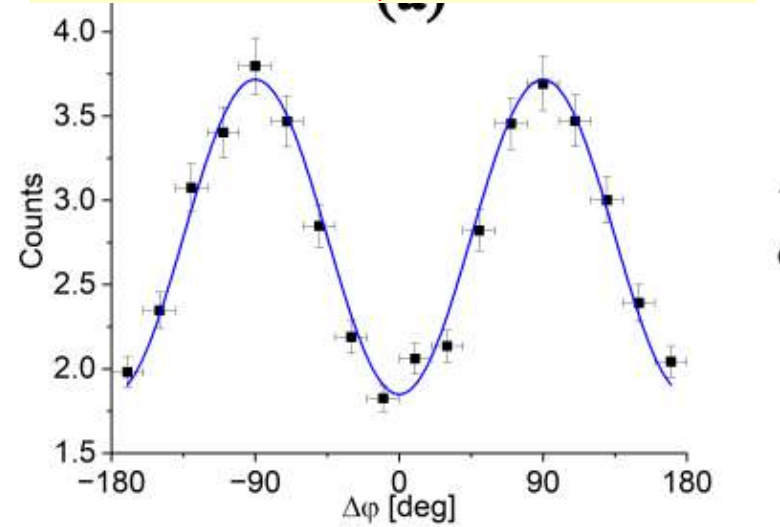


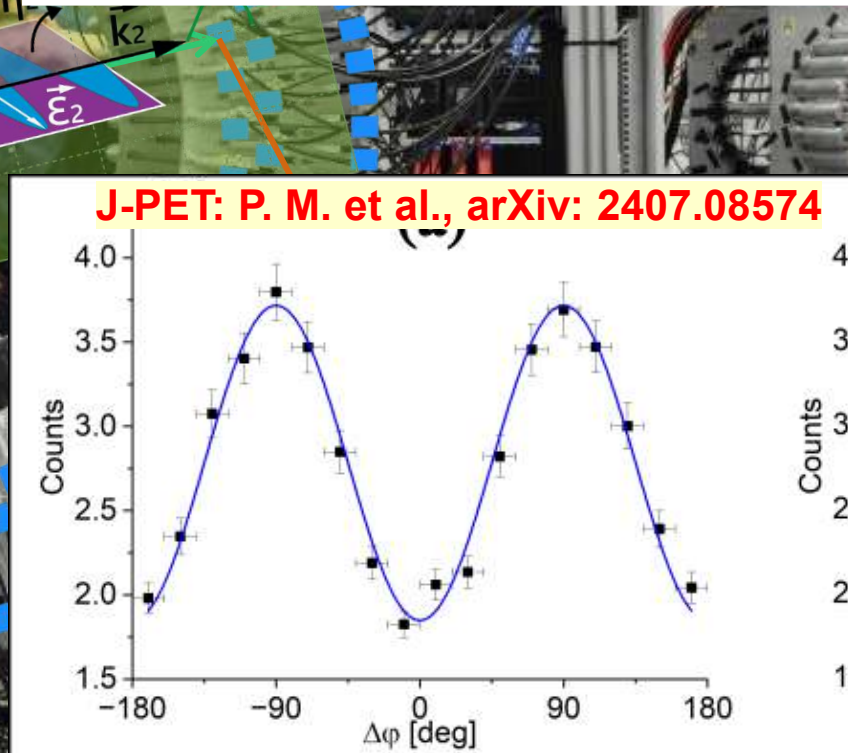
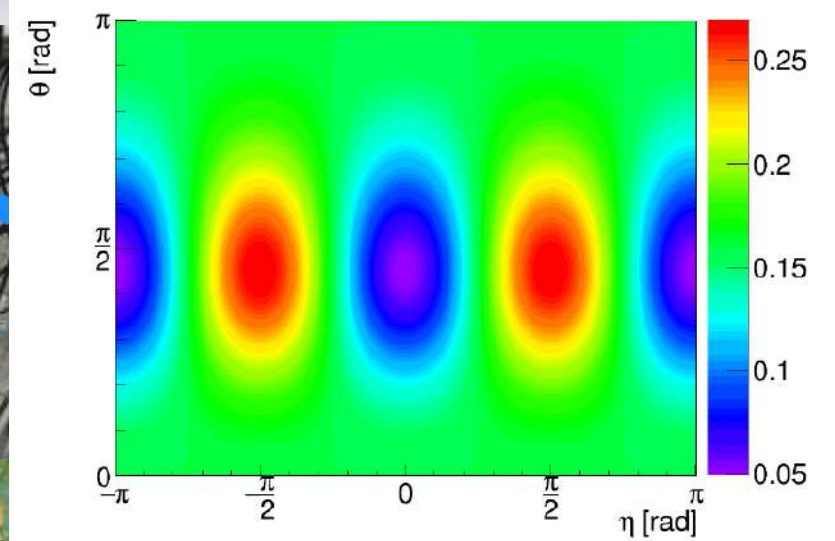
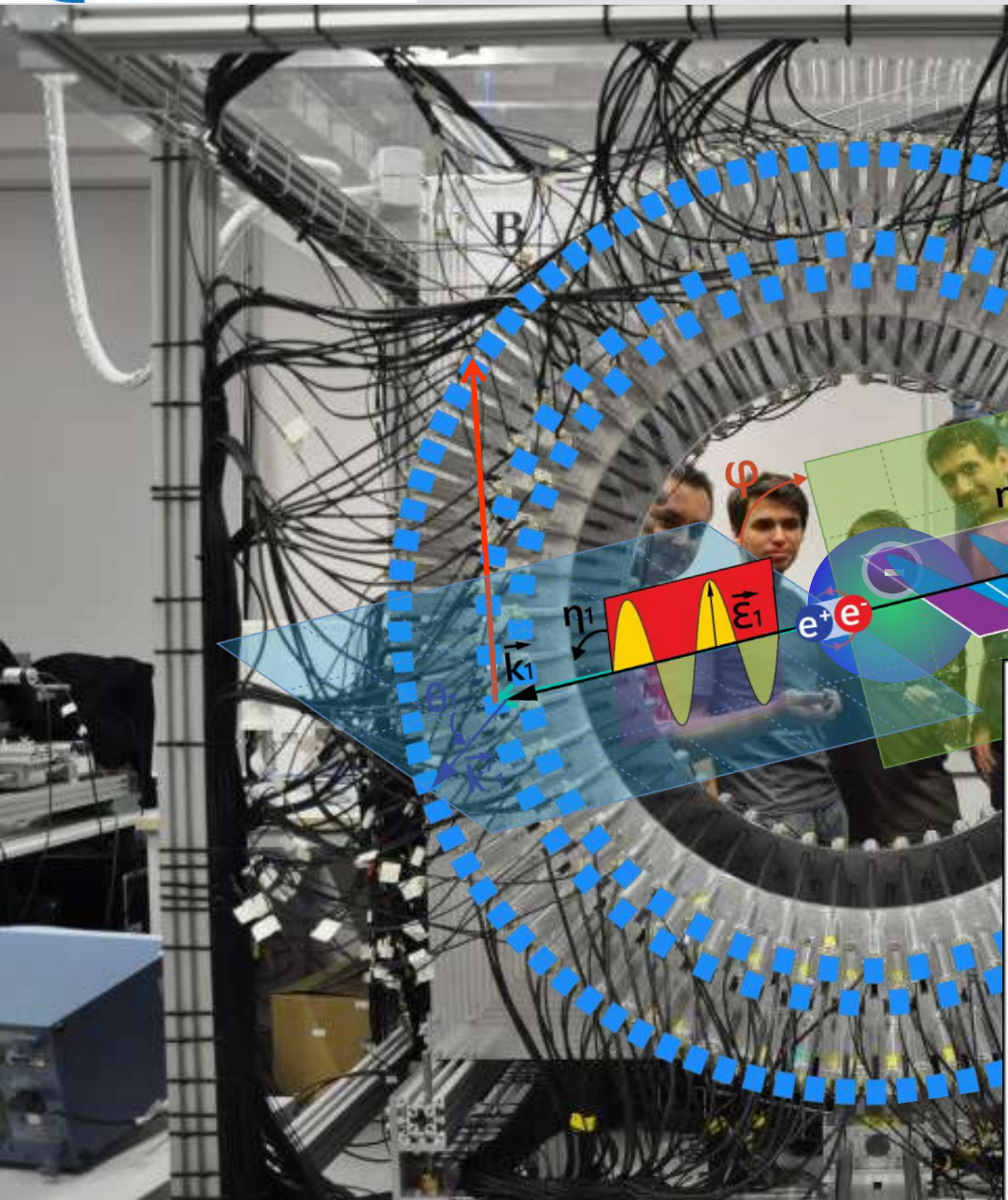
J-PET

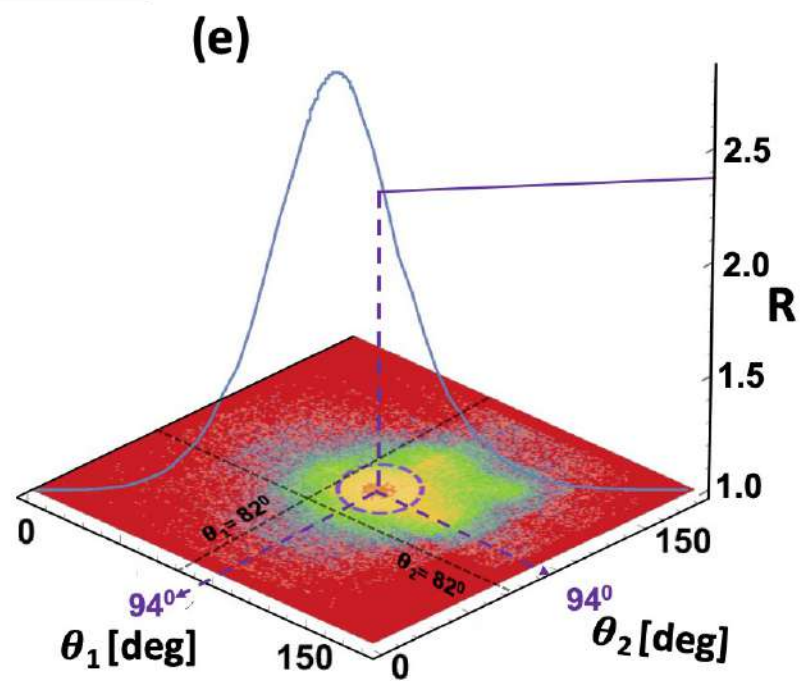
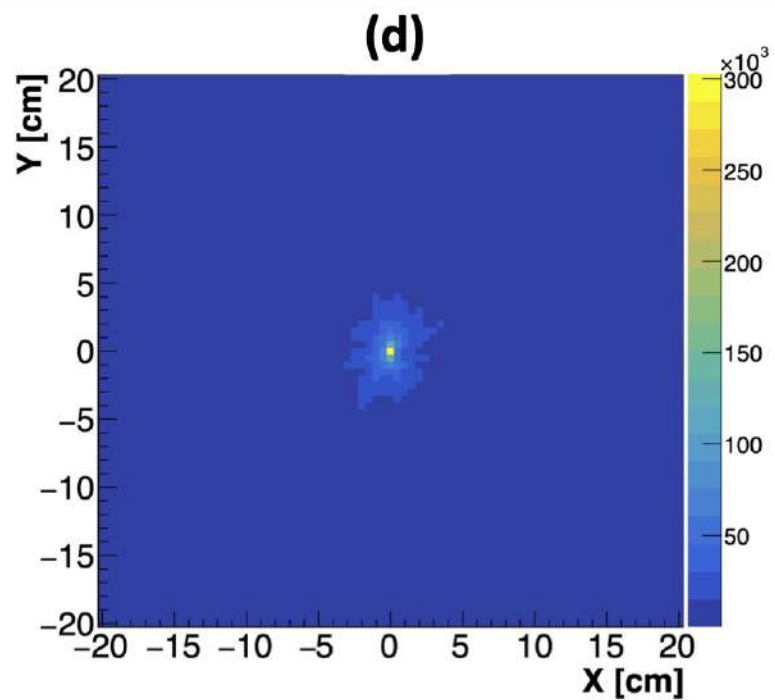
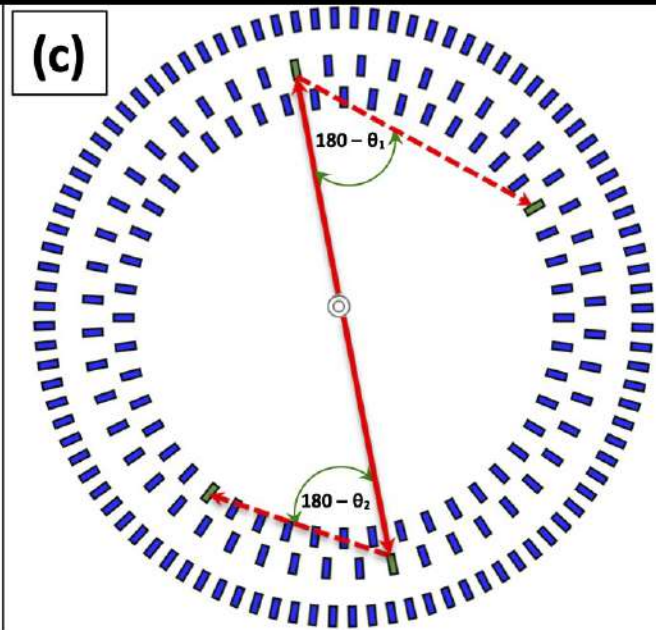
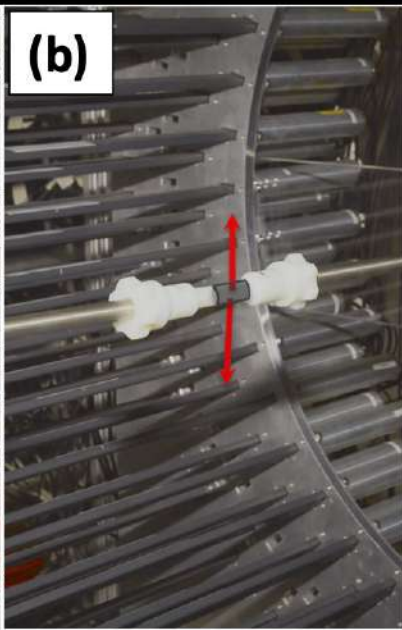
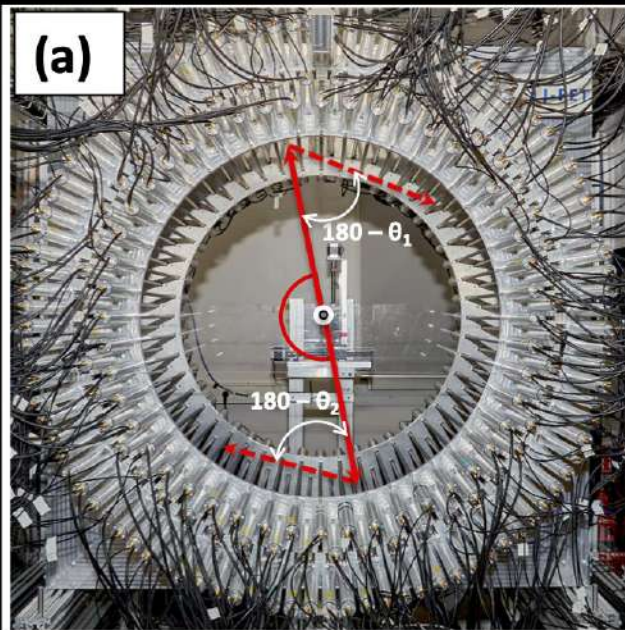
J-PET: P. Moskal et al., Nature Communications 15 (2024) 7824) 78

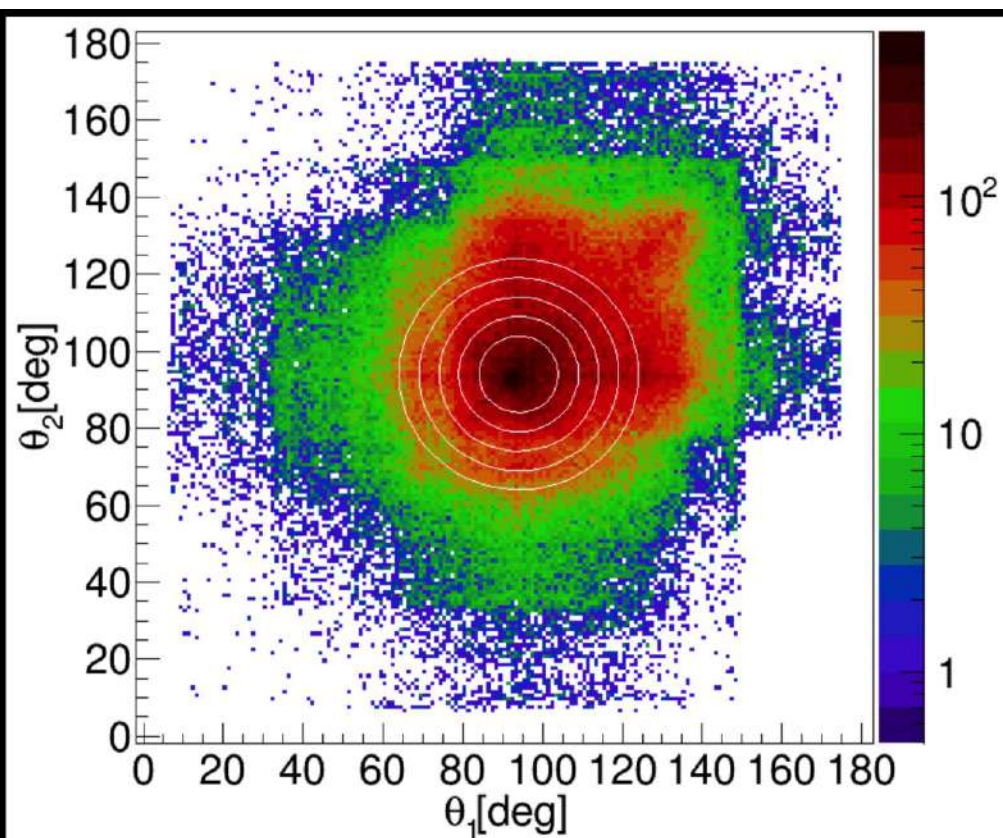
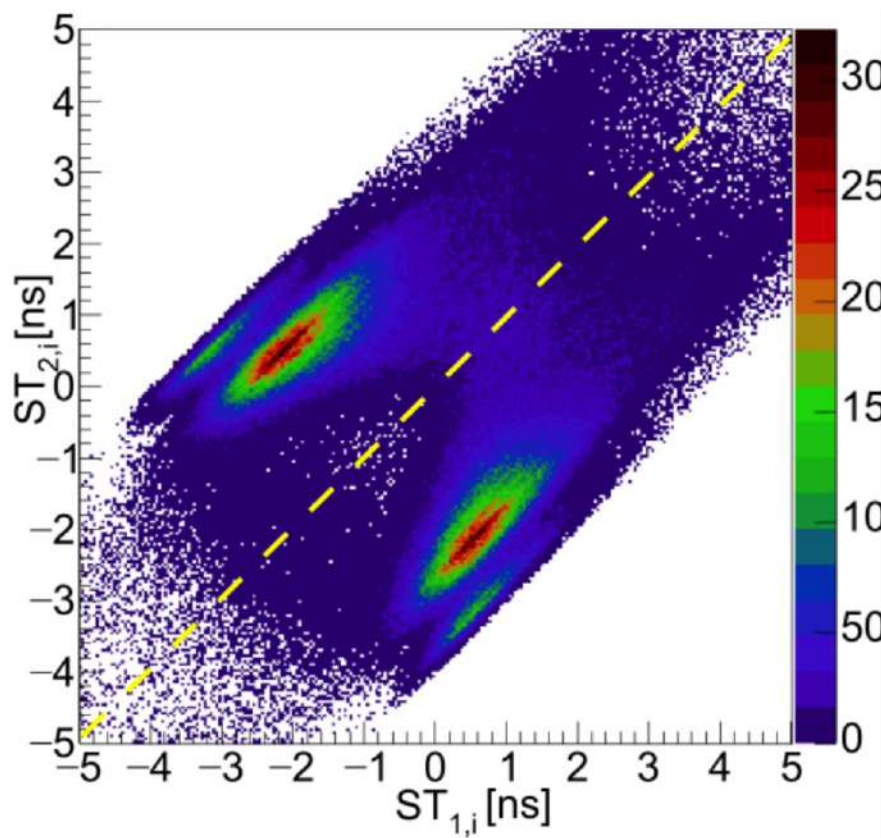


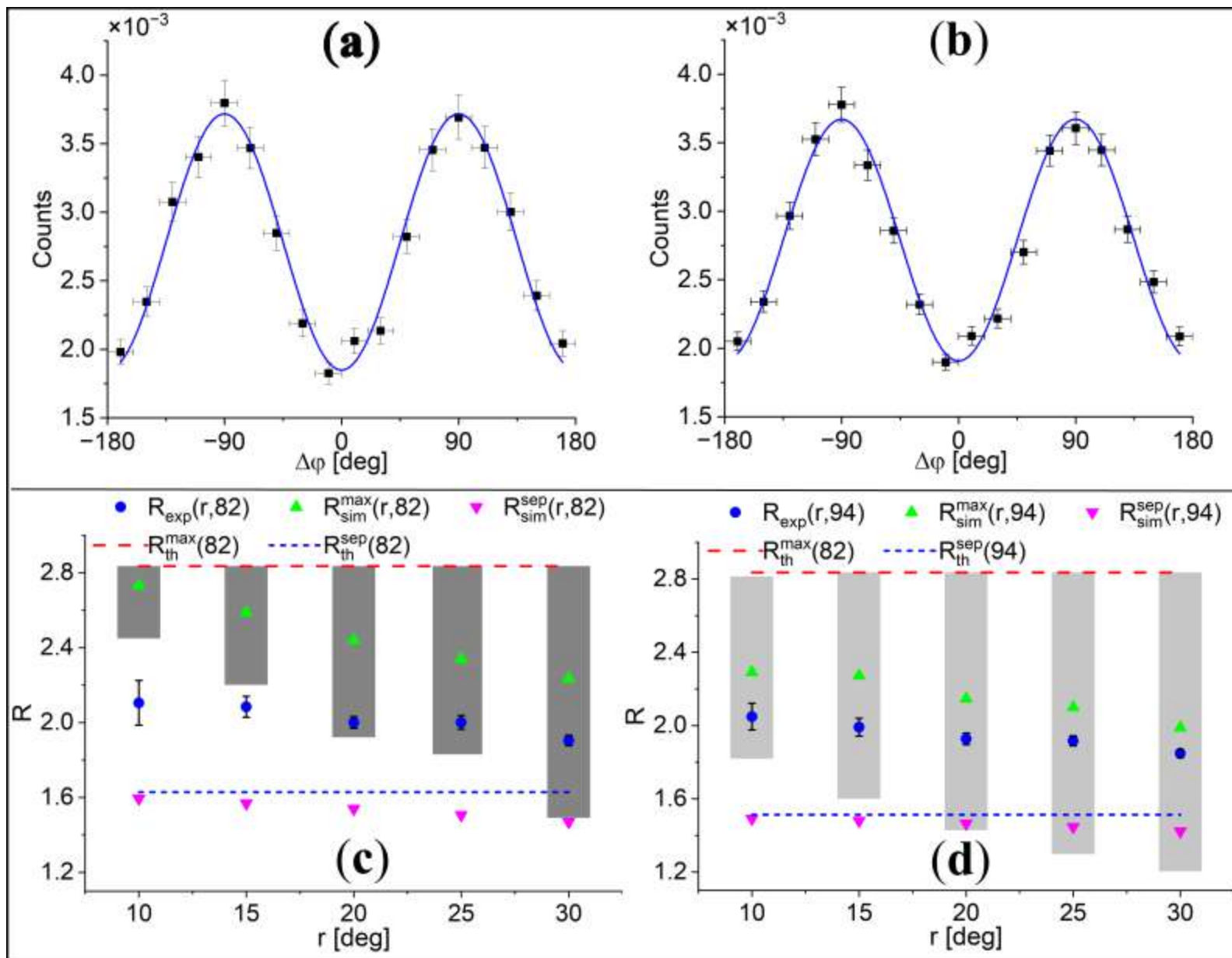
J-PET: P. M. et al., arXiv: 2407.08574





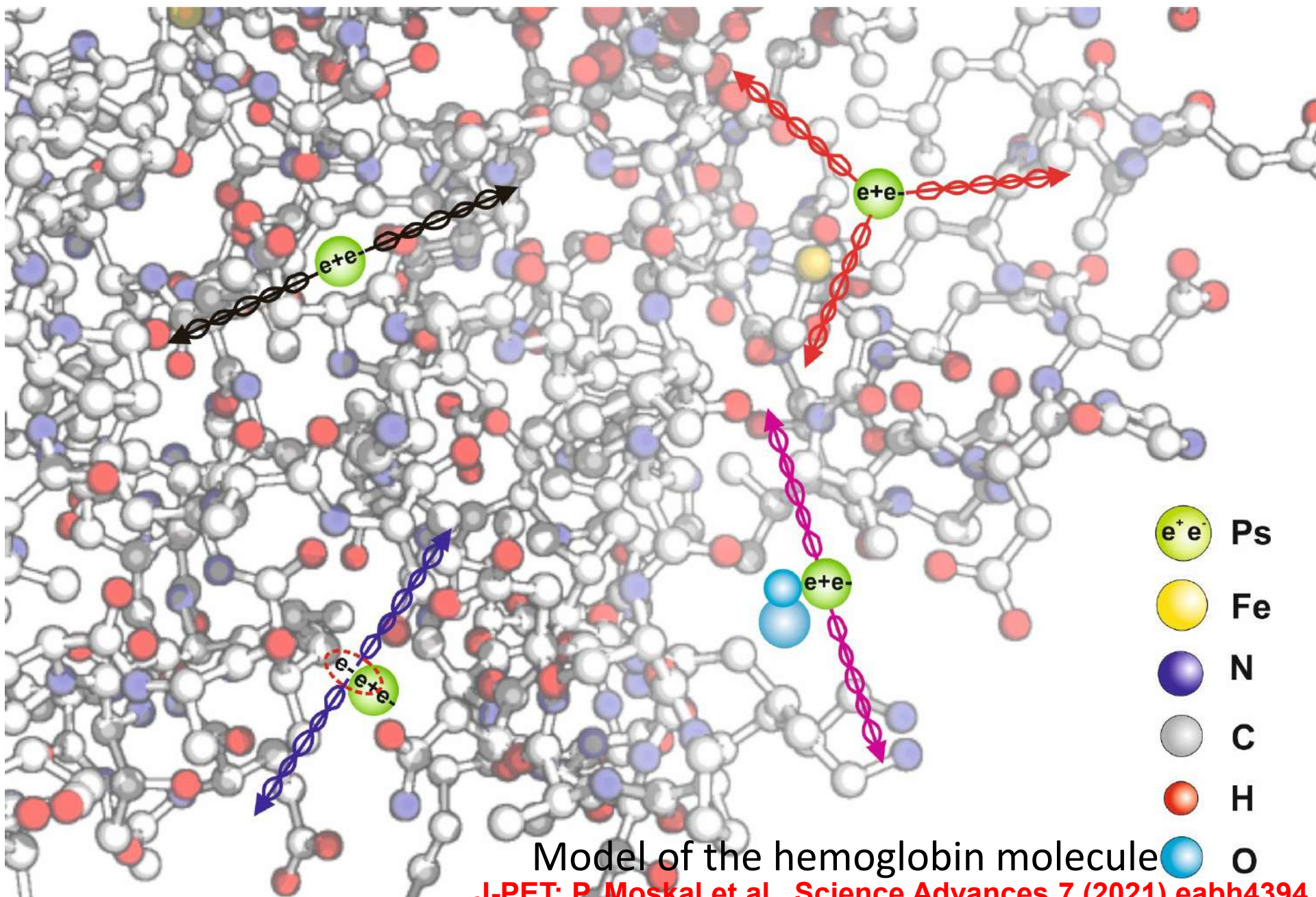




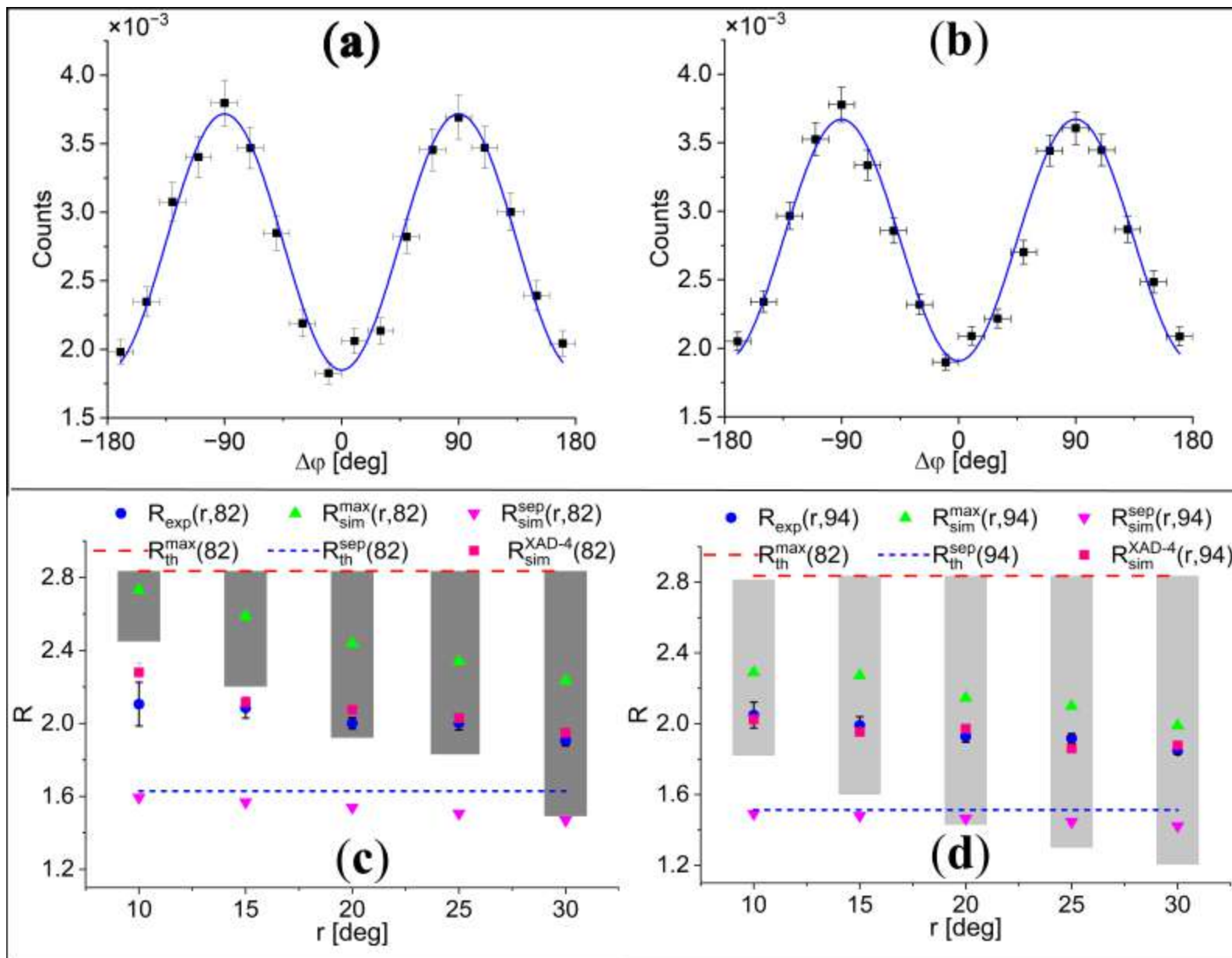


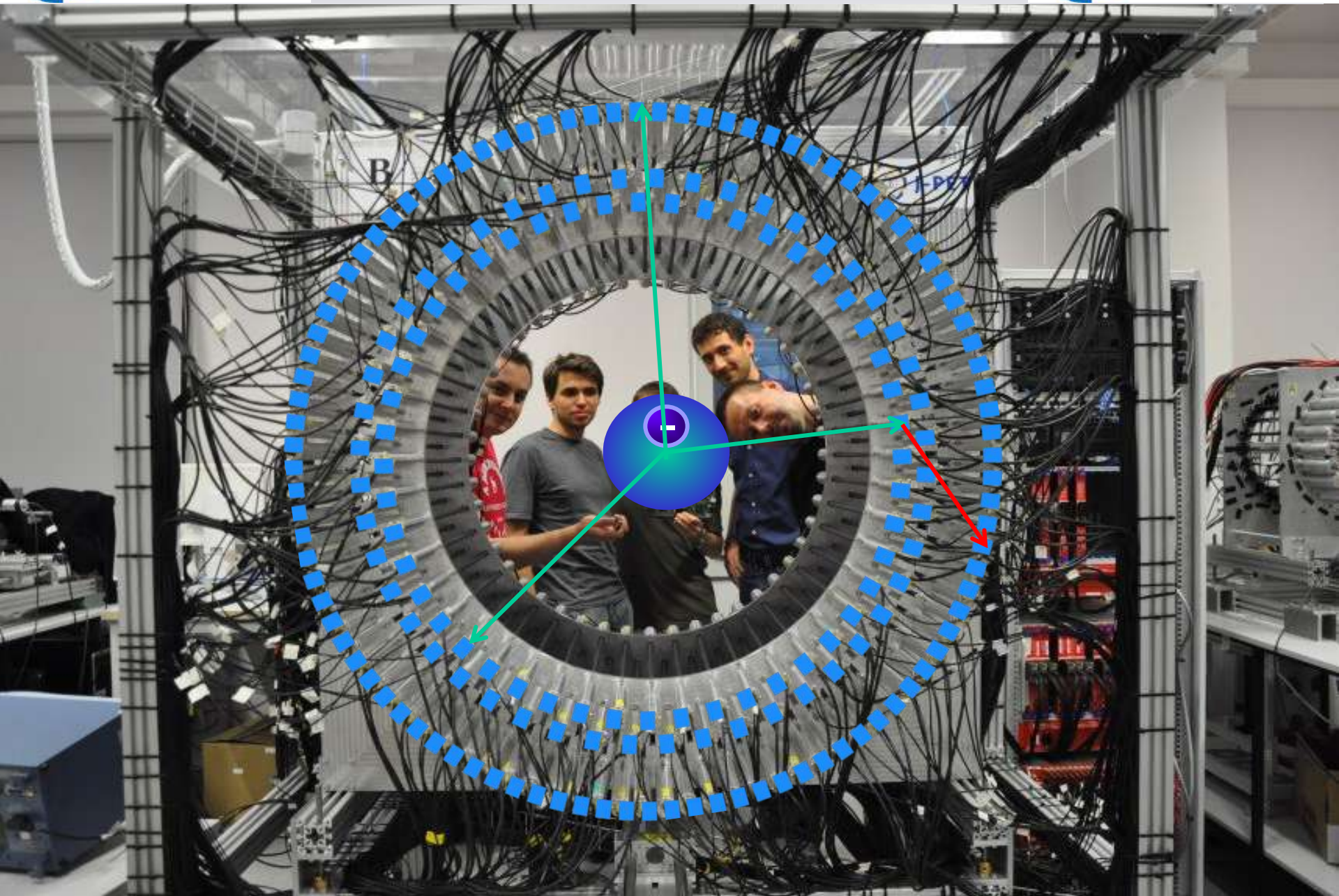
Positronium imaging

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



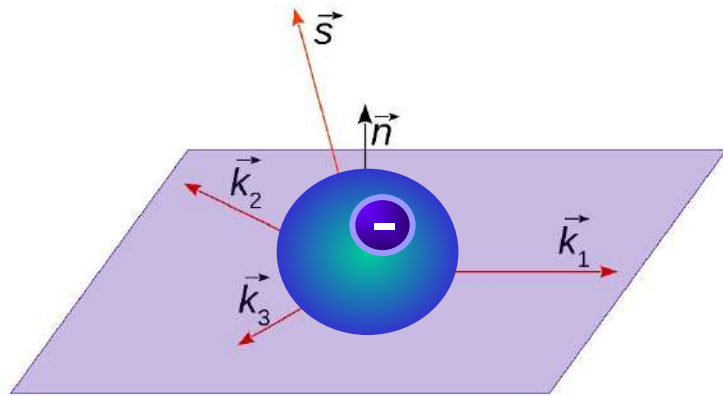
J-PET: P. Moskal et al., *Science Advances* 7 (2021) eabh4394





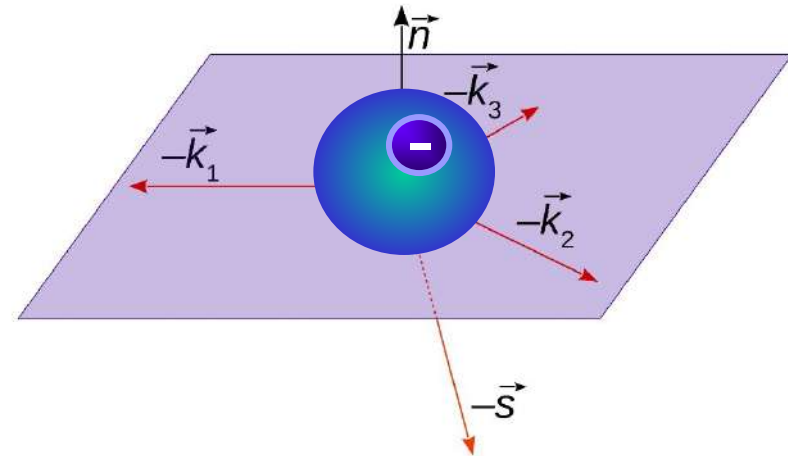
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1) (\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+

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



T, CPT

↔



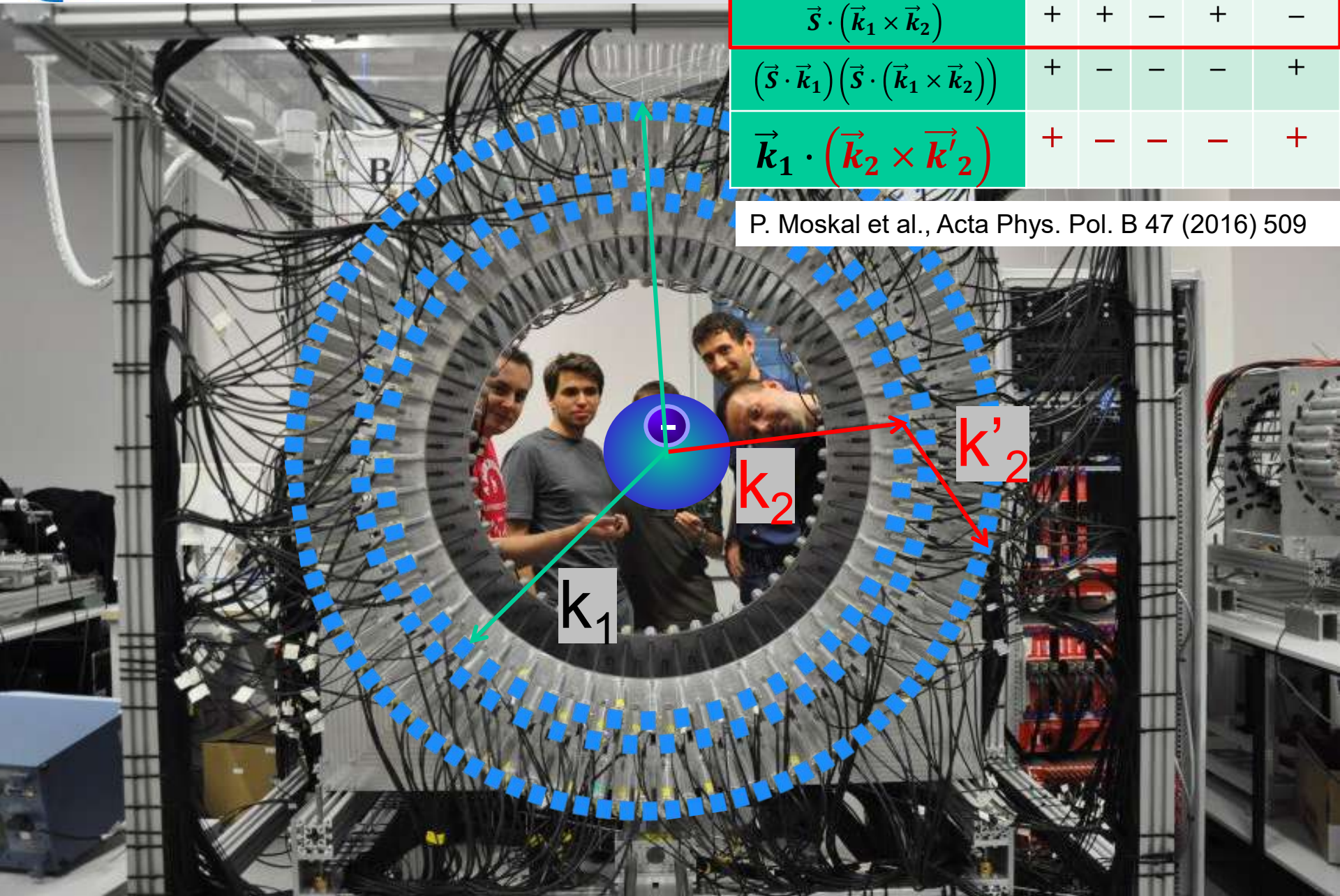


J-PET

Jagielloni

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

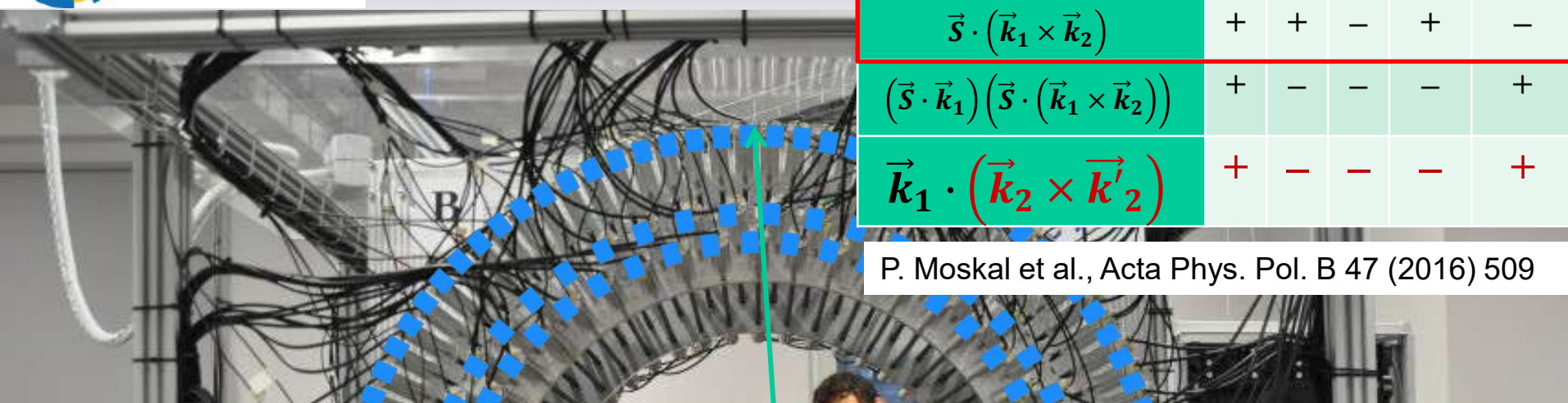
P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509





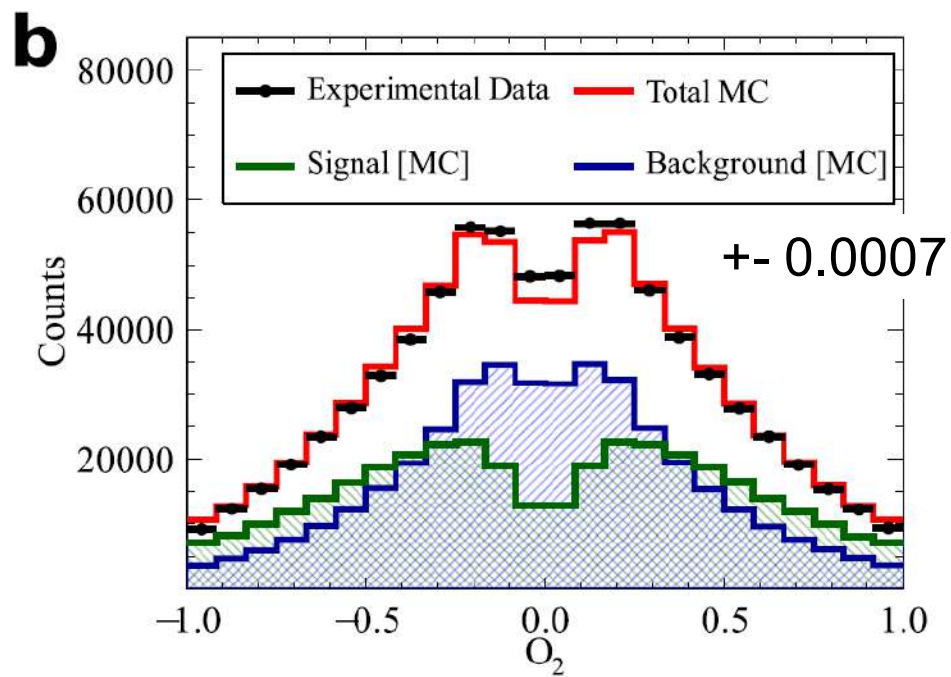
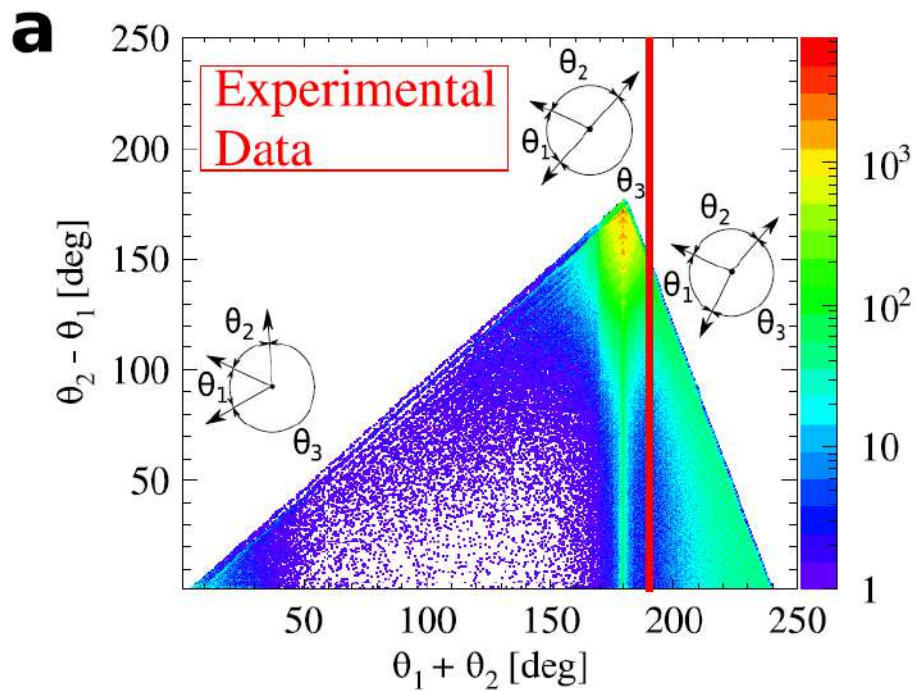
J-PET

Jagielloni



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

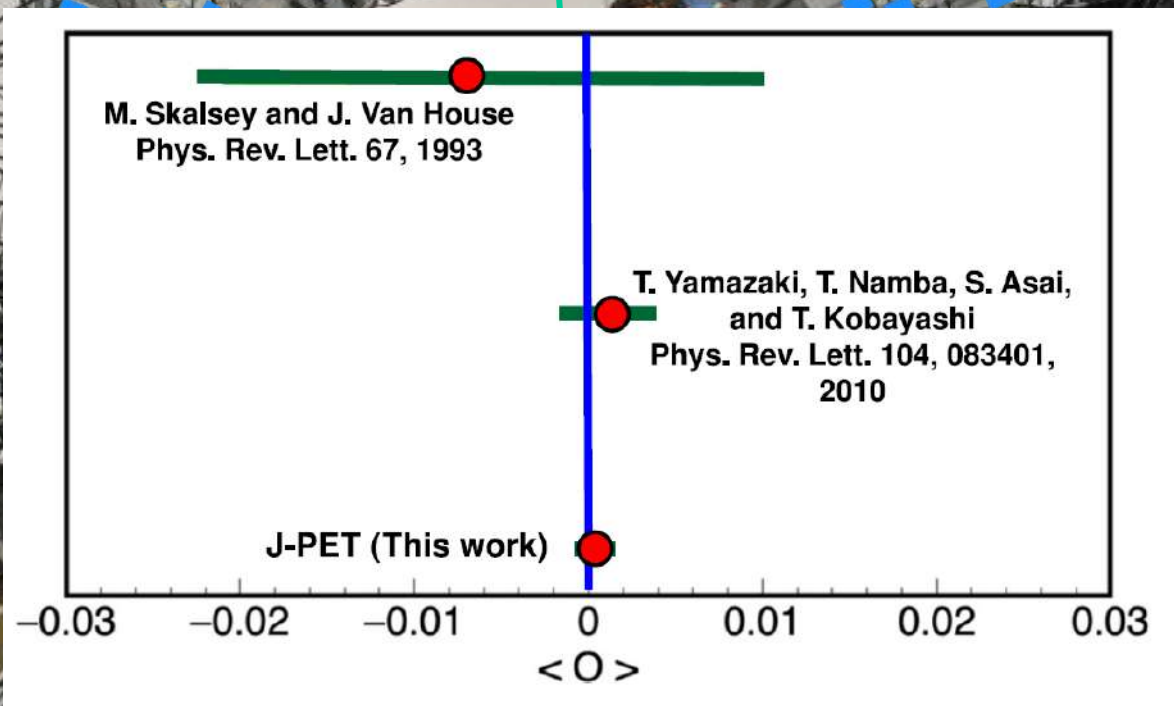
P. Moskal et al., Acta Phys. Pol. B 47 (2016) 509

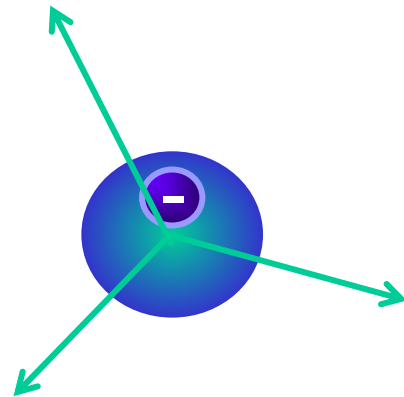


J-PET: P. Moskal et al., Nature Communications 15 (2024) 78

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

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



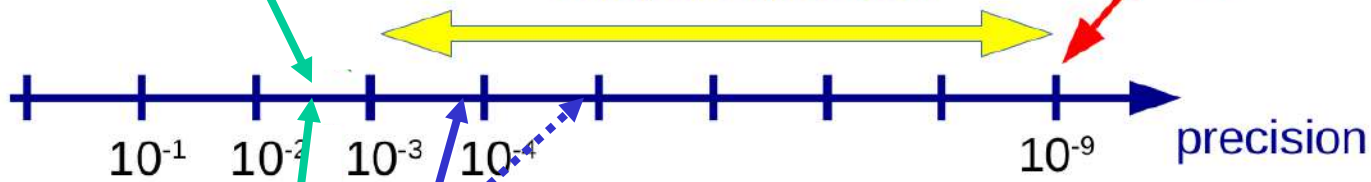


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

PRL 104 (2010) 083401

6 OOM of unexplored precision

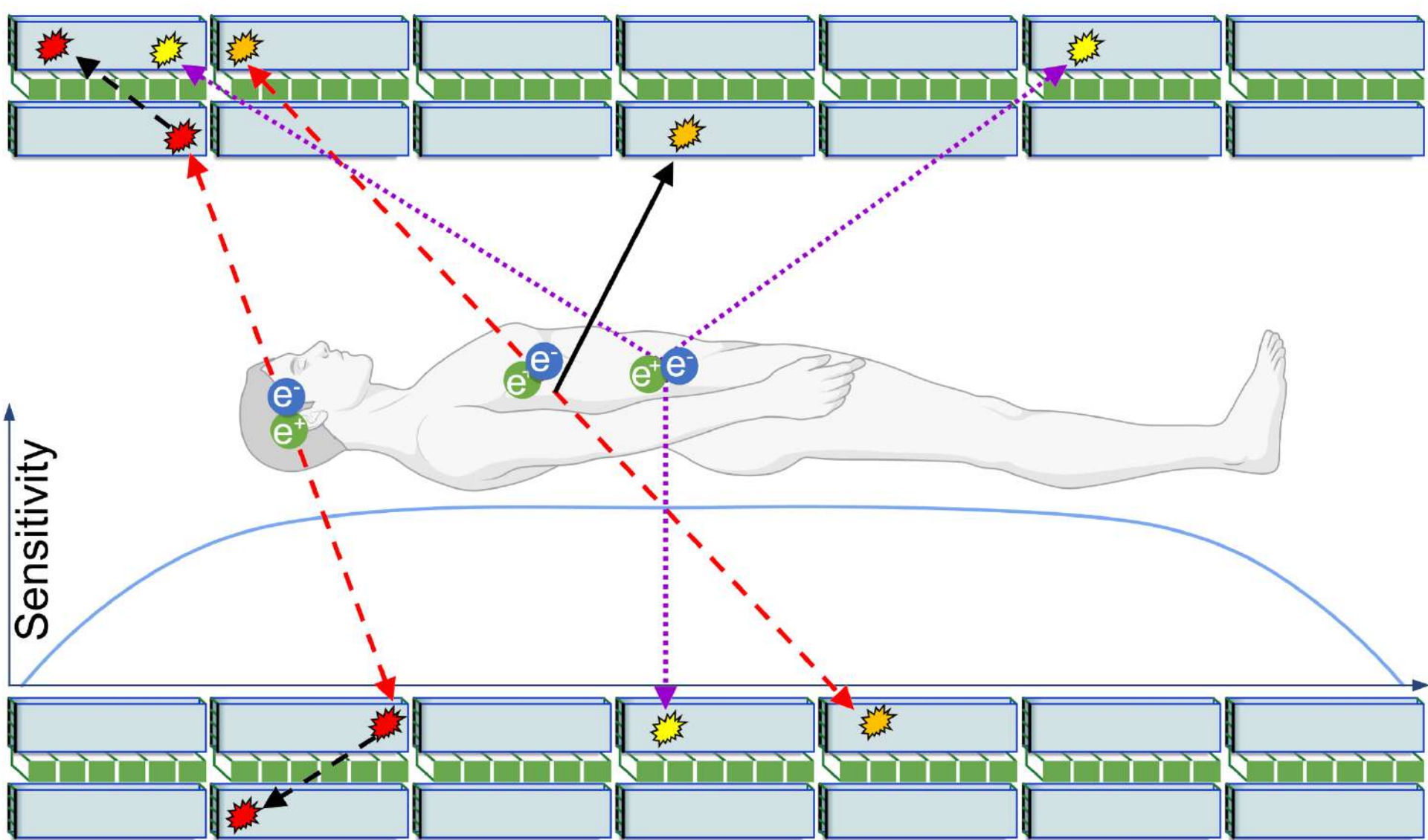
Physical sensitivity limit:
false asymmetries from $\gamma\gamma$ interactions in the final state



$$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$$

PRL. 91 (2003) 263401



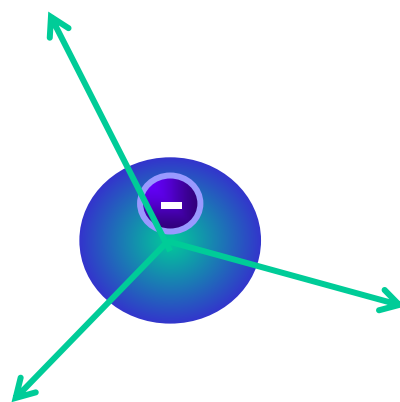


S. D. Bass, S. Mariazzi, P. Moskal, E. Stepien,

Rev. Mod. Phys. 95 (2023) 021002



Positronium physics and biomedical applications

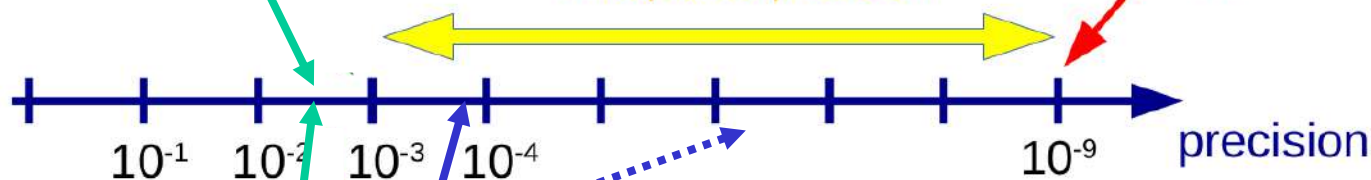


$$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$$

PRL 104 (2010) 083401

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$$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$$

PRL. 91 (2003) 263401



