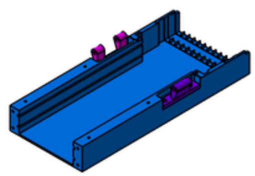
Positronium
in physics and medicine

Seminar at University of Geneva
Geneva, 15 May 2019

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

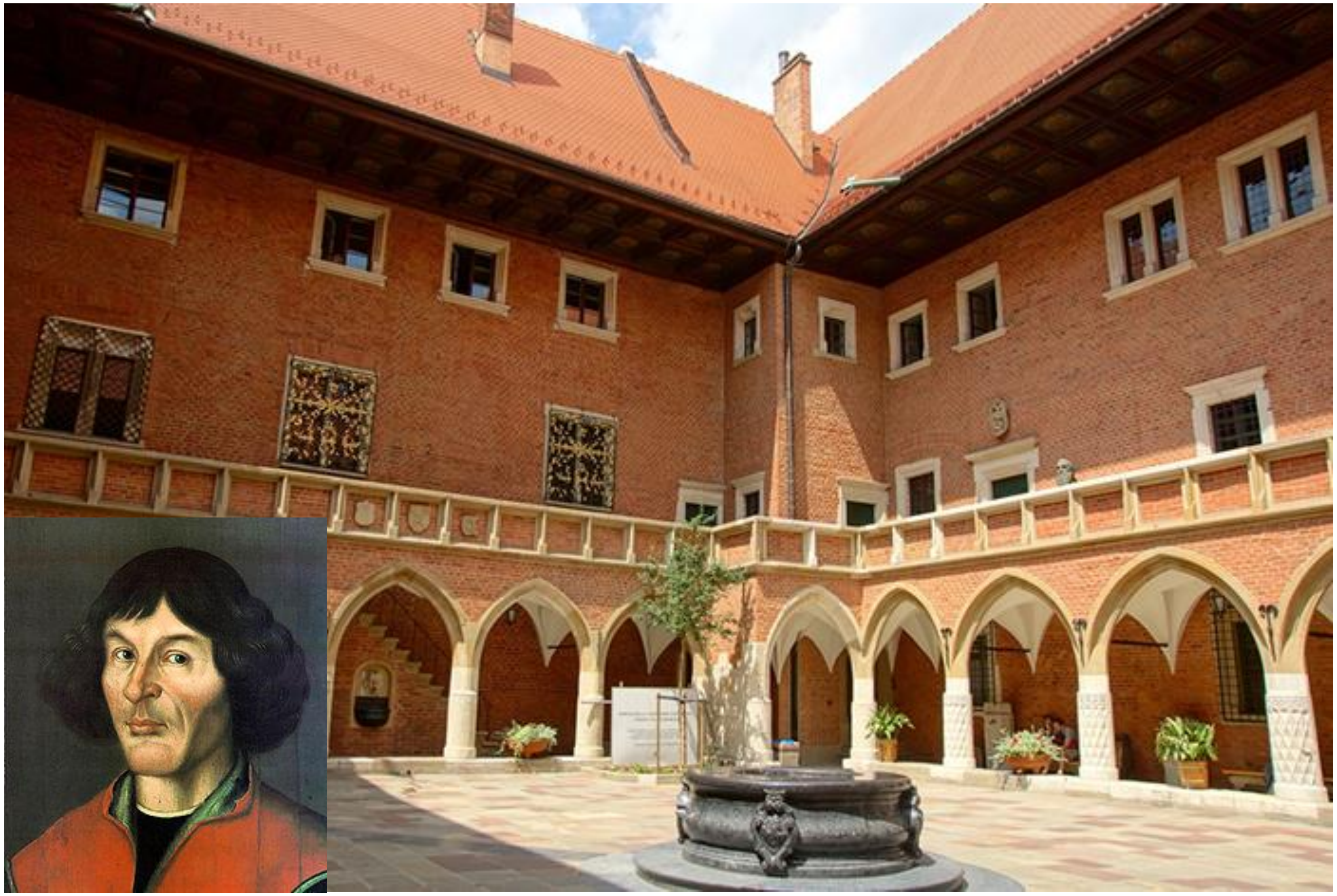
Positronium
in physics and medicine



Seminar at University of Geneva
Geneva, 15 May 2019

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

Jagiellonian University
1364



Collegium Maius at the University since **1400**

Jagiellonian PET

Collegium Maius 2015

J-PET: First PET based on plastic scintillators

Jagiellonian-PET Collaboration:

P. Moskal[1], C. Curceanu[2], E. Czerwiński[1], K. Dulski[1], A. Gajos[1], M. Gorgol[3], B. Hiesmayr[4], B. Jasińska[3], D. Kisielewska[1], G. Korcyl[1], P. Kowalski[5], T. Kozik[1], W. Krzemień[5], E. Kubicz[1], N. Krawczyk[1] M. Mohammed[1], M. Pawlik-Niedźwiecka[1], Sz. Niedźwiecki[1], M. Pałka[1], L. Raczyński[5], J. Raj[1], N. Sharma[1], S. Sharma[1], Shivani[1], M. Silarski[1], M. Skurzok[1], W. Wiślicki[5], B. Zgardzińska[3]

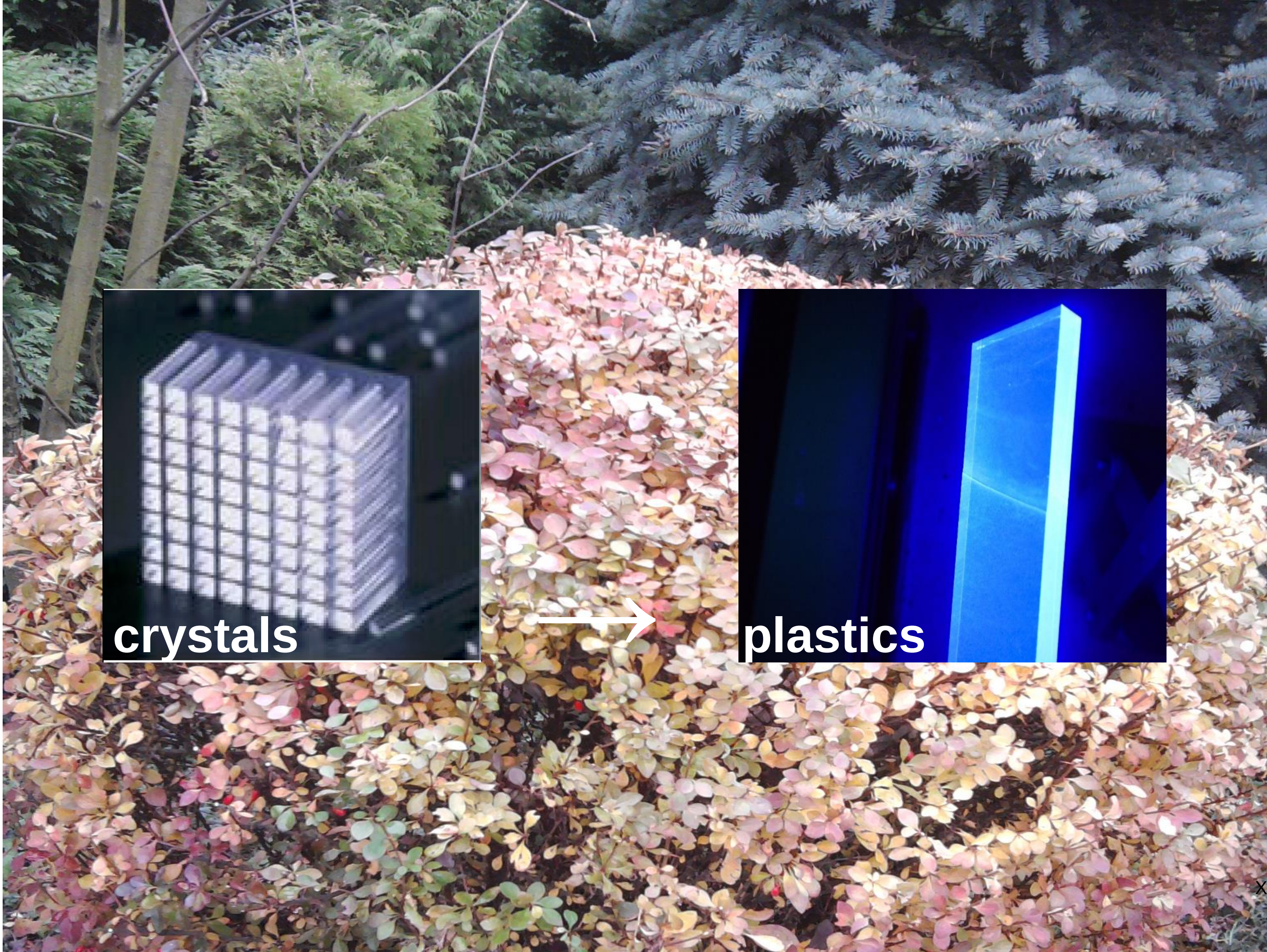
[1]Jagiellonian University, Poland; [2]LNF INFN, Italy; [3]Maria Curie-Skłodowska University, Poland; [4]University of Vienna, Austria; [5]National Centre for Nuclear Research, Poland;

Aim:

- Cost effective total-body PET
- Light, modular, configurable and portable
- For large animals
- MR and CT compatible PET insert

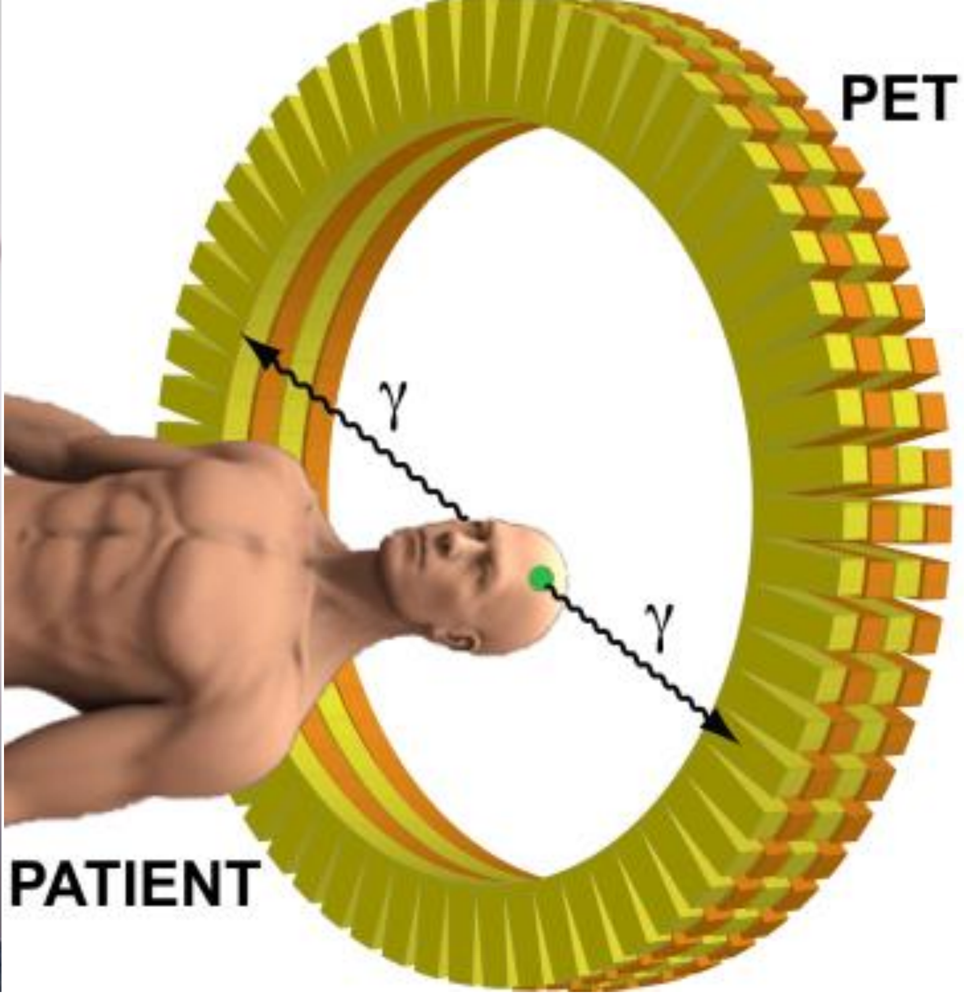
Jagiellonian PET

Cracow, July 2016


crystals
plastics

J-PET

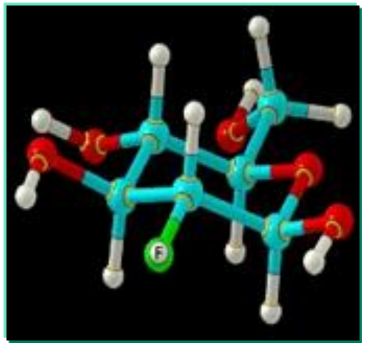
- **PET**
- **Jagiellonian-PET (J-PET)**
- **Positronium imaging (PET & PALS)**
- **Discrete symmetries**
- **Quantum Entanglement Tomography**
- **Hadrontherapy beam monitoring**



RADIOACTIVE SUGER

Fluoro–deoxy-glucose (F-18 FDG)

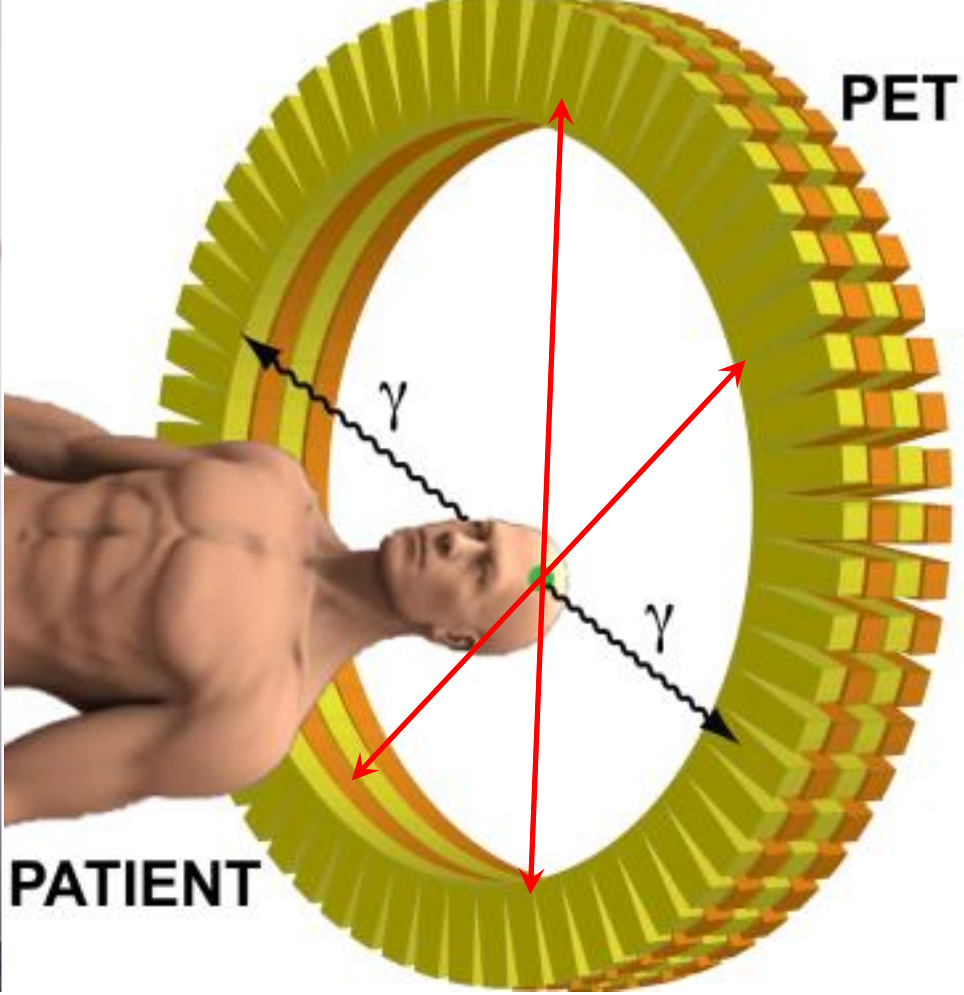
~200 000 000 gamma per second



7 mSv PET/CT

~ 2.5 mSv PET

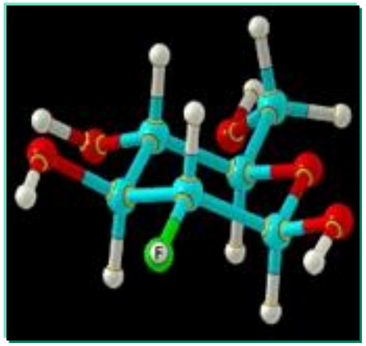
~3 mSv natural background in Poland



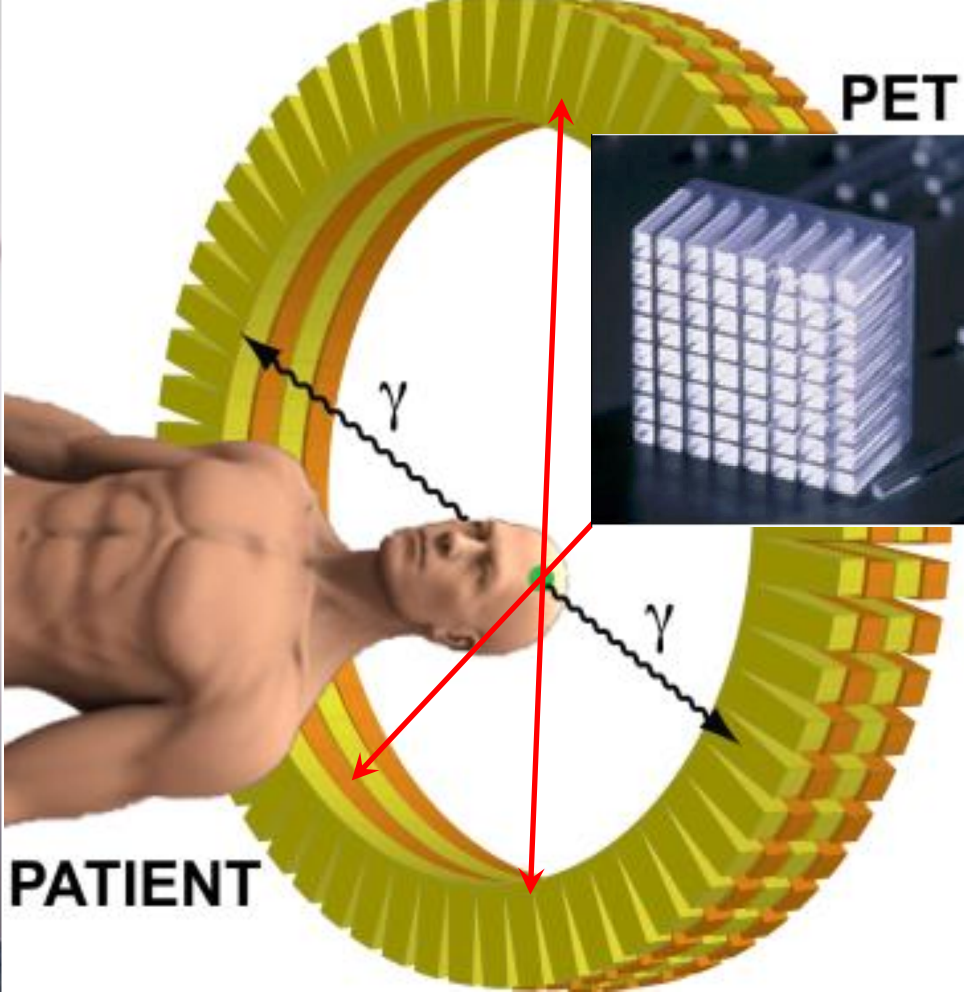
RADIOACTIVE SUGER

Fluoro–deoxy-glucose
(F-18 FDG)

~200 000 000
gamma per second



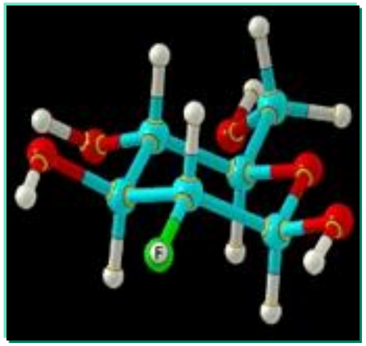
7 mSv PET/CT
~ 2.5 mSv PET
~3 mSv natural
background in Poland



RADIOACTIVE SUGER

Fluoro–deoxy-glucose (F-18 FDG)

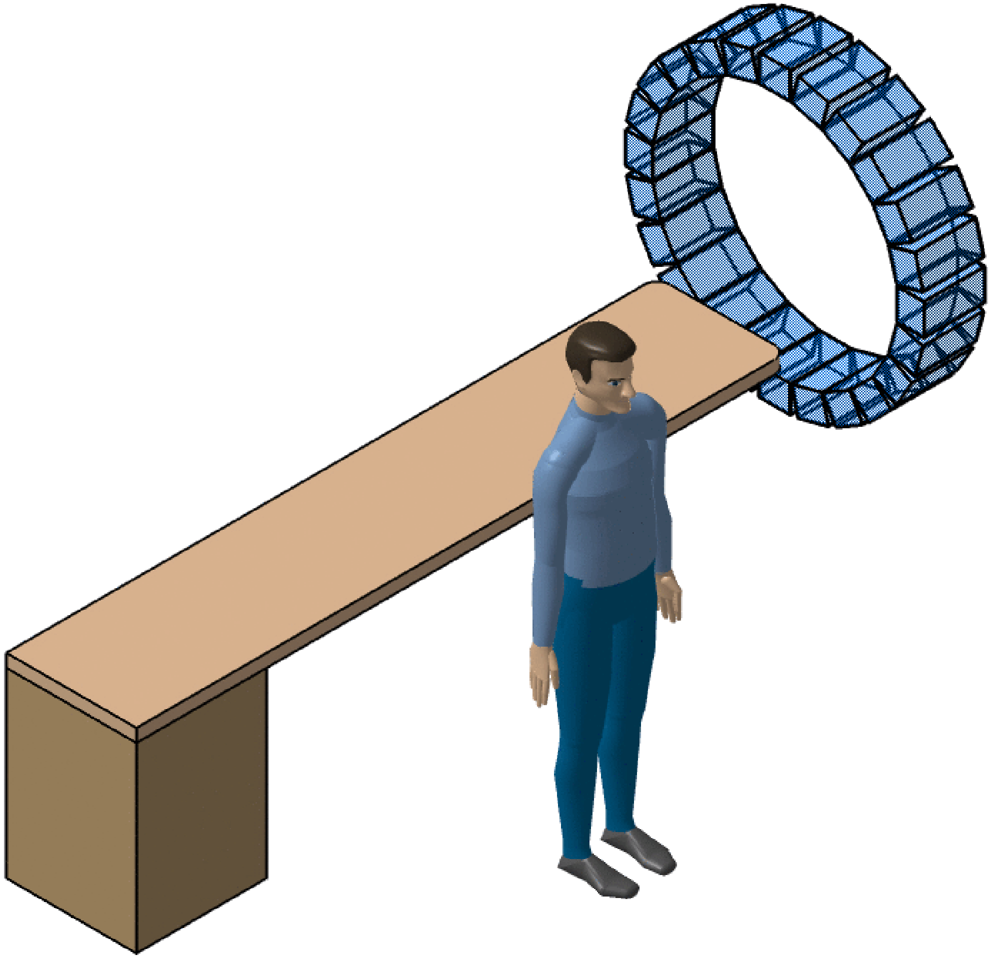
~200 000 000 gamma per second



7 mSv PET/CT

~ 2.5 mSv PET

~3 mSv natural background in Poland



EXPLORER PROJECT

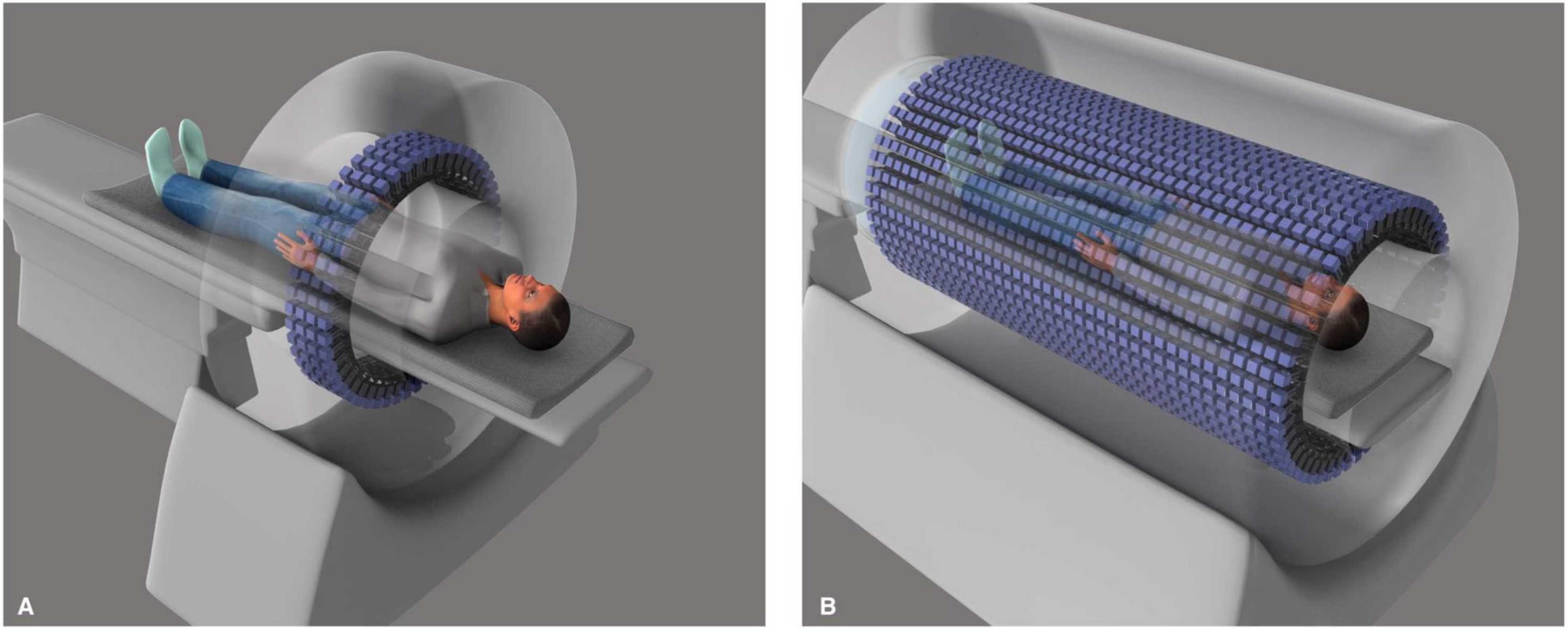


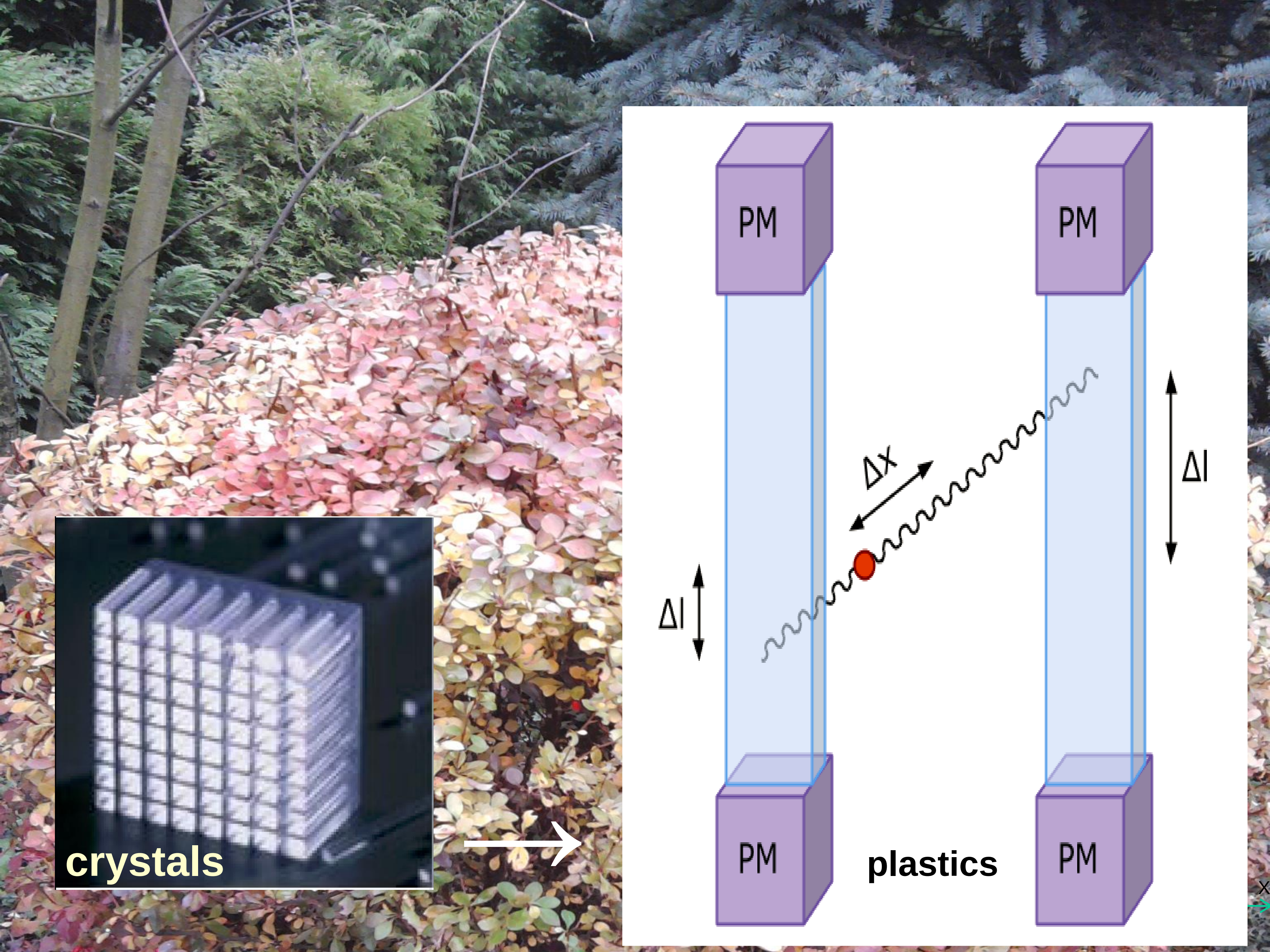
Fig. 1. Seeing into our future. Illustration depicting (**A**) a conventional PET scanner and (**B**) total-body PET (TB-PET) scanner. An x-ray computed tomography (CT) scanner will be mounted on the front of the TB-PET gantry for anatomical coregistration to ensure optimal integration of anatomical imaging with molecular imaging.

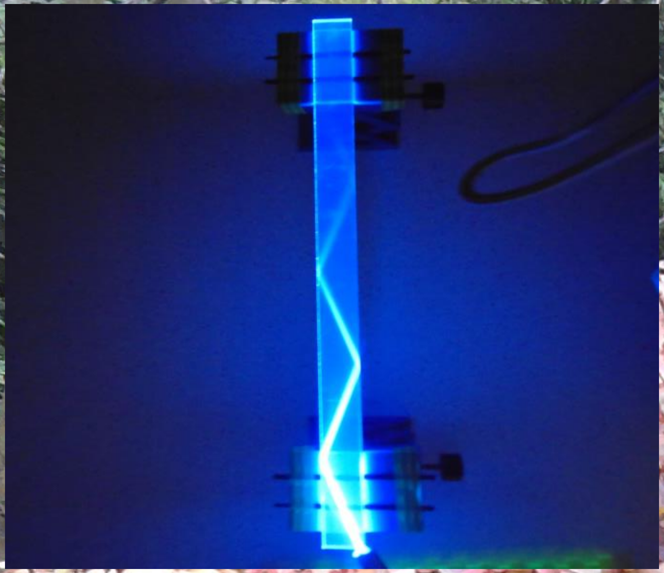
Simon R. Cherry,[1]* Ramsey D. Badawi,[1] Joel S. Karp,[2] William W. Moses,[3] Pat Price,[4] Terry Jones[1]

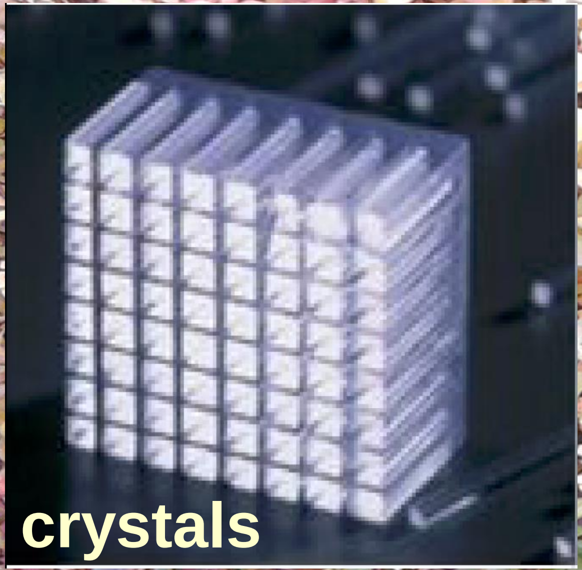
Cherry *et al., Sci. Transl. Med.* **9**, eaaf6169 (2017)

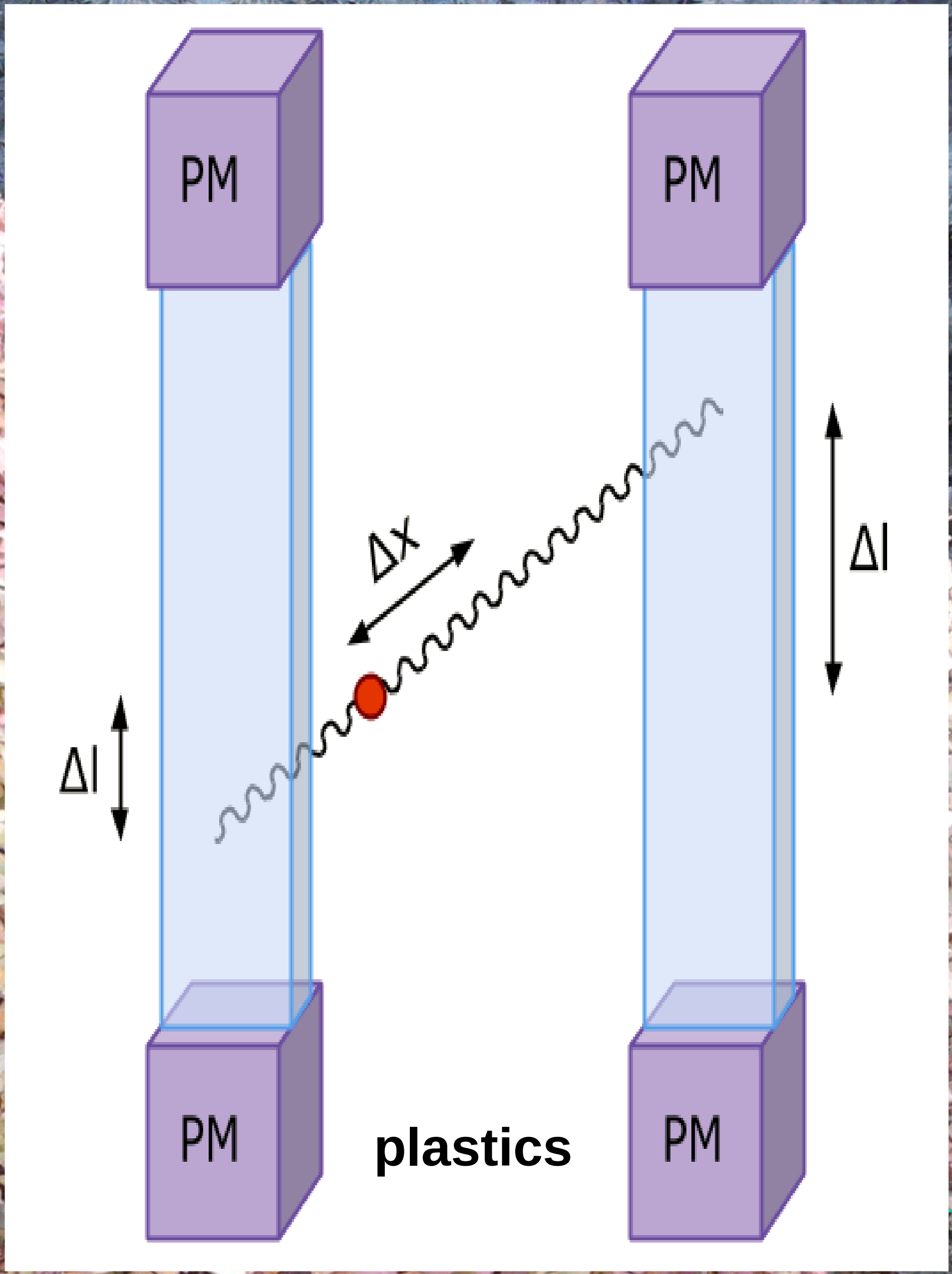
[1]University of California, Davis, Davis, CA 95616, USA. [2]University of Pennsylvania, Philadelphia, PA 19104, USA. [3]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA. [4]Hammersmith Hospital, Imperial College London, London W12 0NN, U.K.

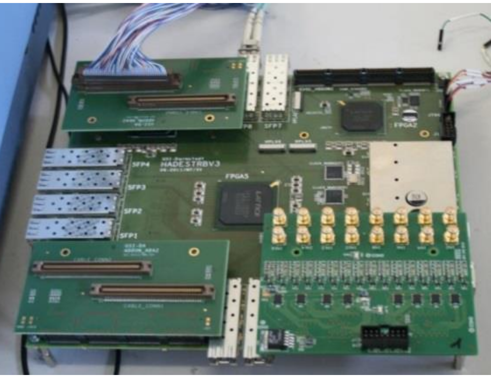
- PET
- Jagiellonian-PET (J-PET)
- Positronium imaging (PET & PALS)
- Discrete symmetries
- Quantum Entanglement Tomography
- Hadrontherapy beam monitoring


crystals
PM
PM
PM
PM
ΔX
ΔI
ΔI
plastics




crystals


PM
PM
Δx
Δl
Δl
PM
plastics
PM



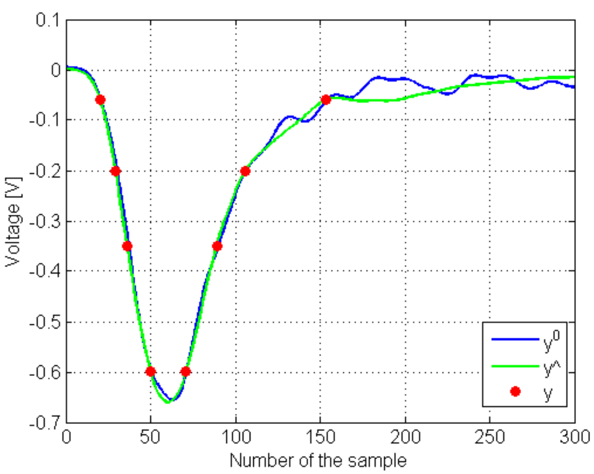
ONLY DIGITAL in triggerless mode

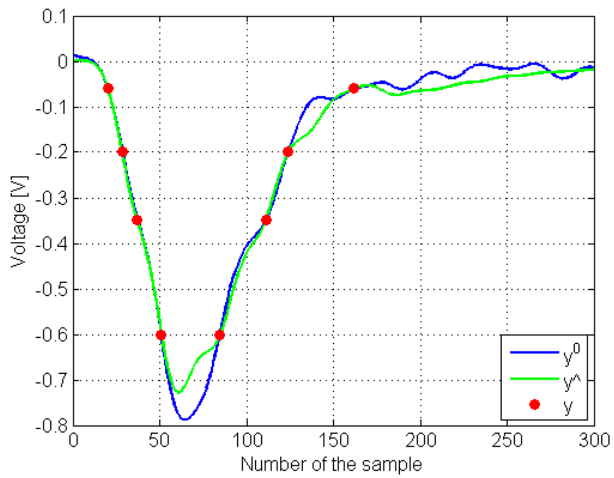
FFE sampling & Readout electronics

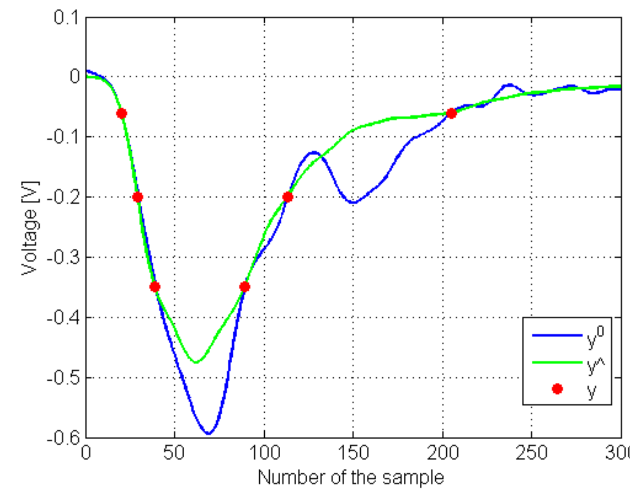
precision of 21ps (sigma) for 10 Euro per sample

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

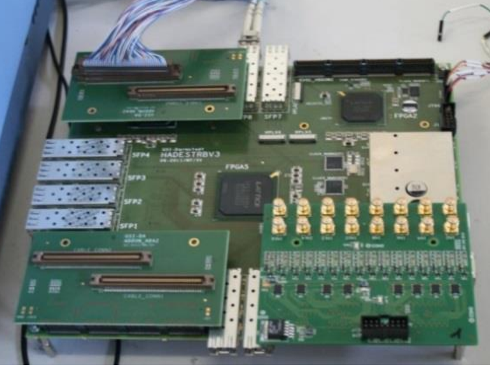
Detector	FrontEnd electronics	Electronics controller	Hit along strip	Annihilation point	Image

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., Acta Phys. Pol. B47 (2016) 561

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



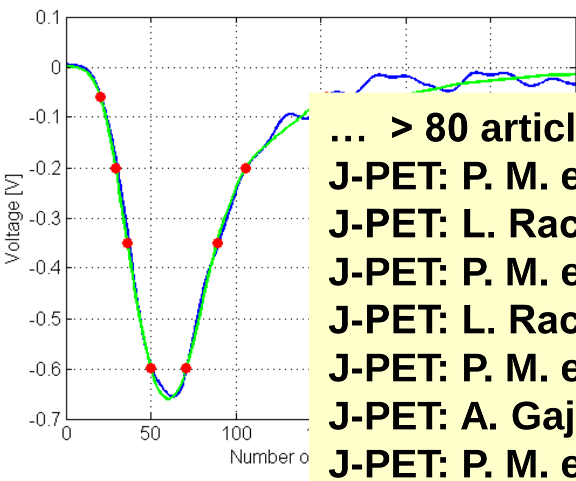
ONLY DIGITAL in triggerless mode

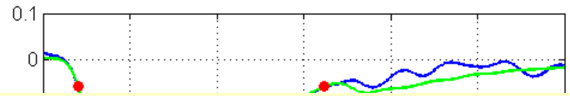
FFE sampling & Readout electronics

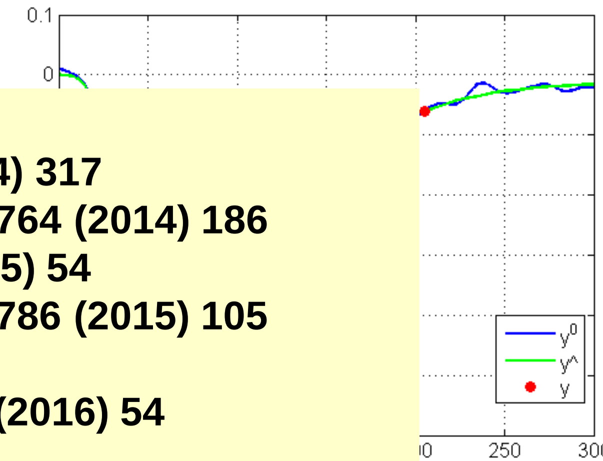
precision of 20ps (sigma) for 10 Euro per sample

M.Pałka, P.M., **PCT/EP2014/068367**

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







… > 80 articles …

J-PET: P. M. et al., Nucl. Instrum. Meth. A764 (2014) 317
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A764 (2014) 186
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A786 (2015) 105
J-PET: P. M. et al., Phys. Med. Biol. 61 (2016) 2025
J-PET: A. Gajos et al., Nucl. Instrum. Meth. B 819 (2016) 54
J-PET: P. M. et al., Acta Phys. Pol. B 47 (2016) 509
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445
J-PET: J. Smyrski et al., Nucl. Instrum. Meth. A851 (2017) 39
J-PET: L. Raczyński et al., Phys. Med. Biol. 62 (2017) 5076
J-PET: M. Pałka et al., JINST 12 (2017) P08001
J-PET: P. Kowalski et al., Phys. Med. Biol. 63 (2018) 165008
J-PET: G. Korcyl et al., IEEE Trans. Med. Imaging 37 (2018) 2526
J-PET: A. Gajos et al., Adv. High Energy Phys. 2018 (2018) 8271280
J-PET: P. M. et al., Eur. Phys. J. C 78 (2018) 970
J-PET: P. M. et al., Phys. Med. Biol. 64 (2019) 055017

and 17 patents

Library of signal
J-PET: L. Raczyń
J-PET: P. M. et al
J-PET: L. Raczyń

Detector

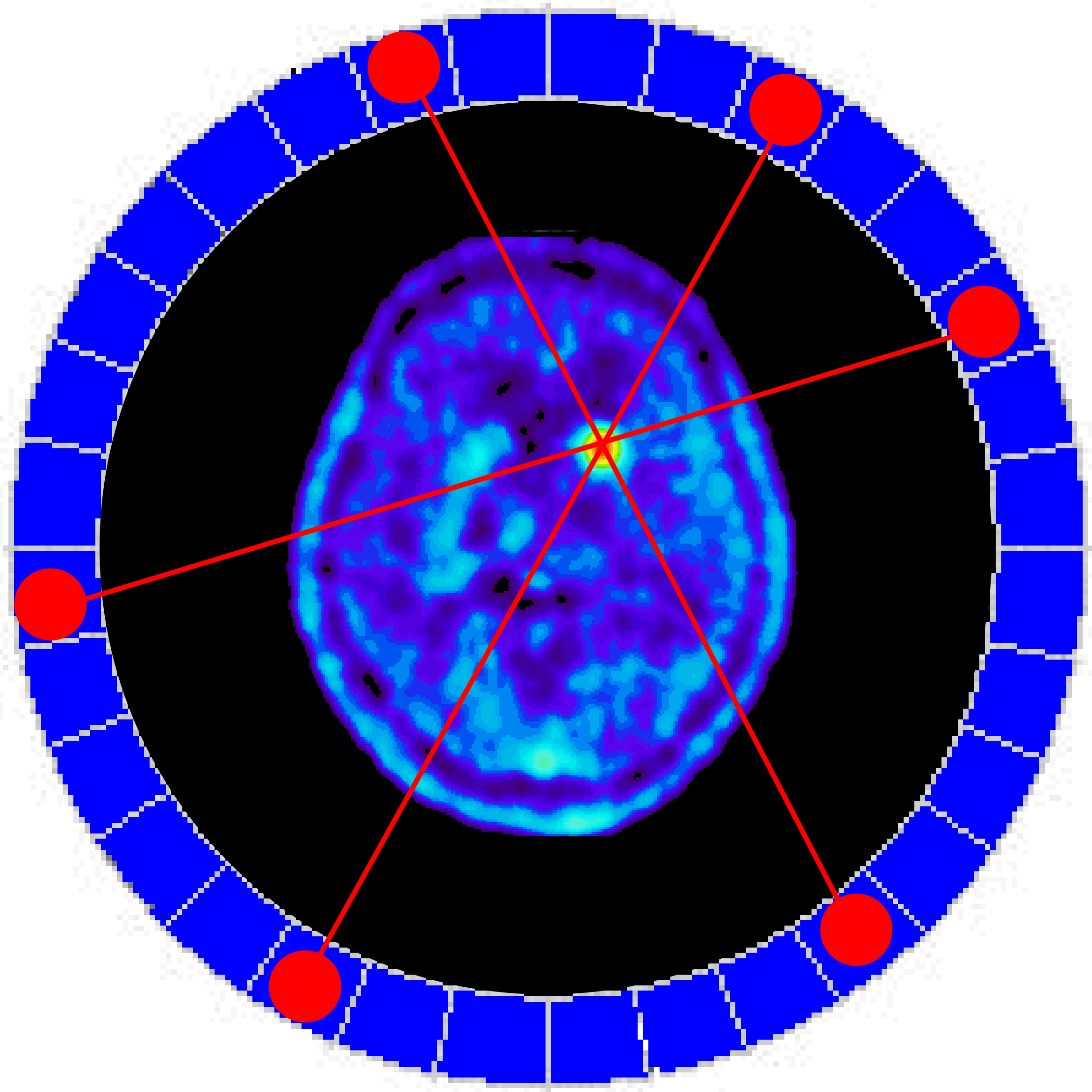
mage

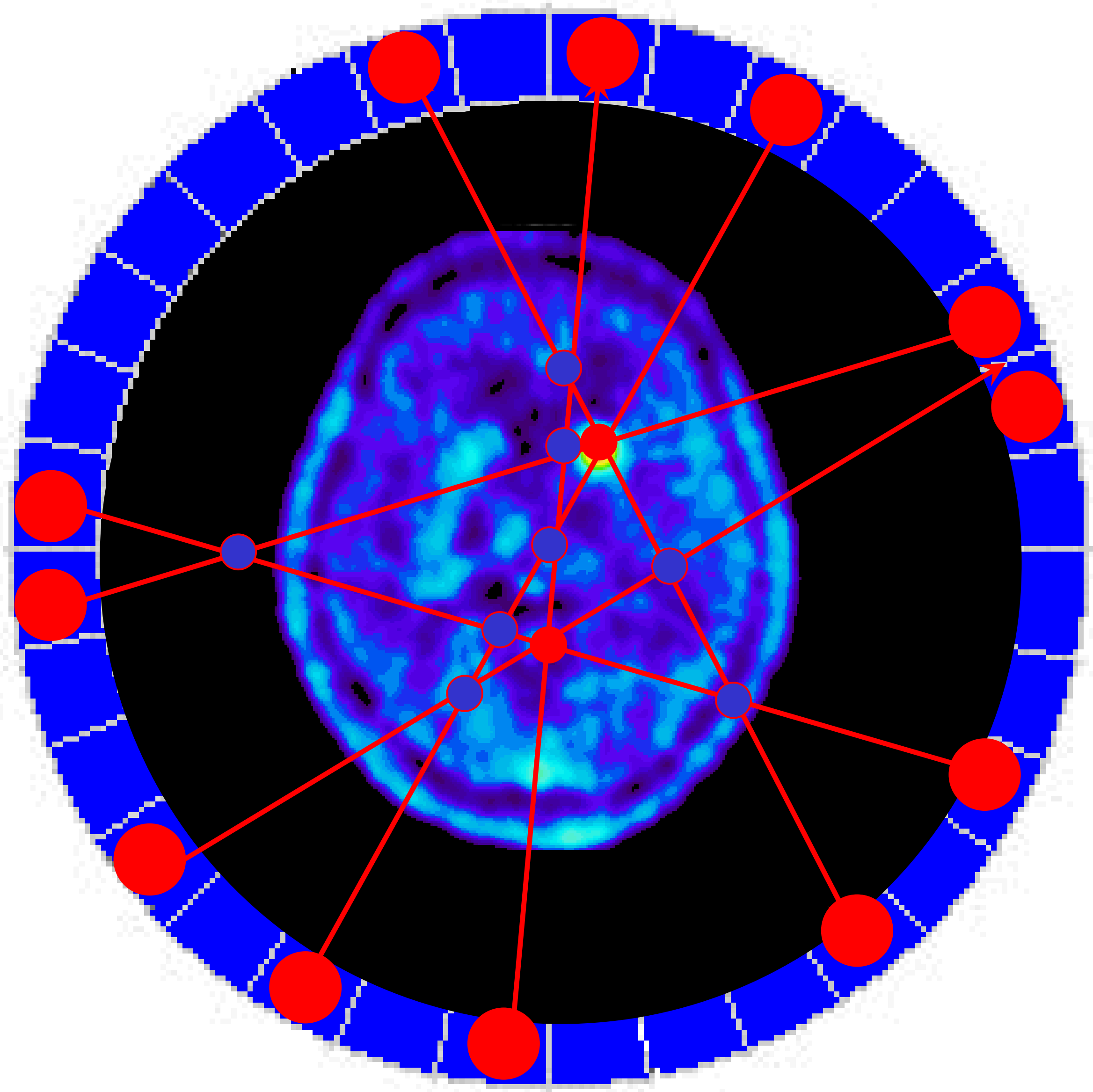
J-PET: M.Palka e … **(2016) 561**
J-PET: G. Korcyl … **0 (2014) 12**

for the 2.5 cm layer the efficiency for the registration of events selected
to reconstruct the image is for the plastic scintillator by

a factor of about 20 smaller in relation to the BGO crystals and about 40 times less compared to the LSO crystals

name	type	density [g/cm^3]	decay time [ns]	photons/ MeV	mean free path [cm]	light Attenuation length [cm]
BGO	crystal	7.13	300	6000	1.04	7.1
GSO	crystal	6.71	50	10000	1.49	6.7
LSO	crystal	7.40	40	29000	1.15	7.4
BC420	polymer	1.032	1.5	10000	10.2	110
BC404	polymer	1.032	1.8	10000	10.2	160
BC408	polymer	1.032	2.1	10000	10.2	380

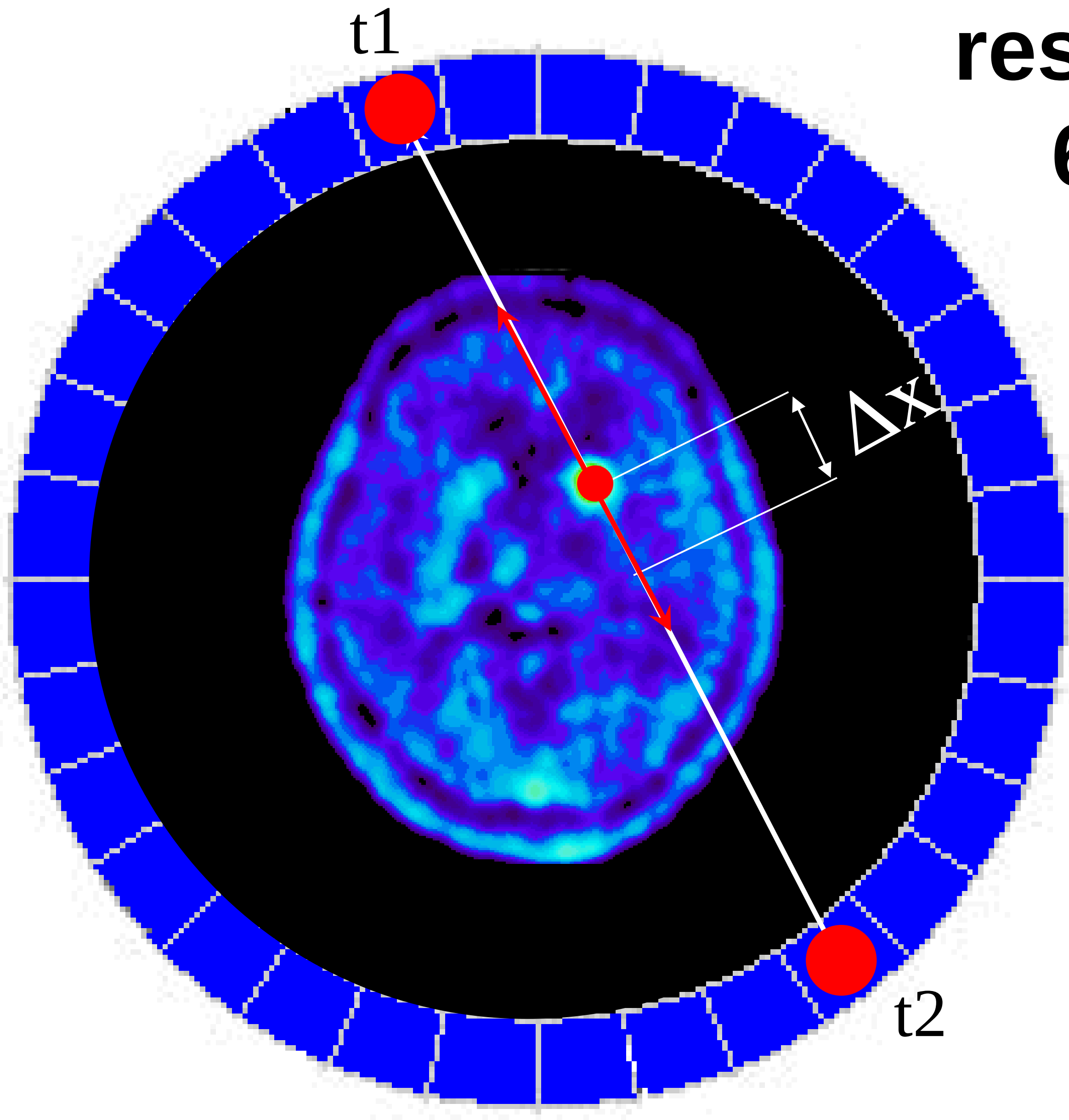


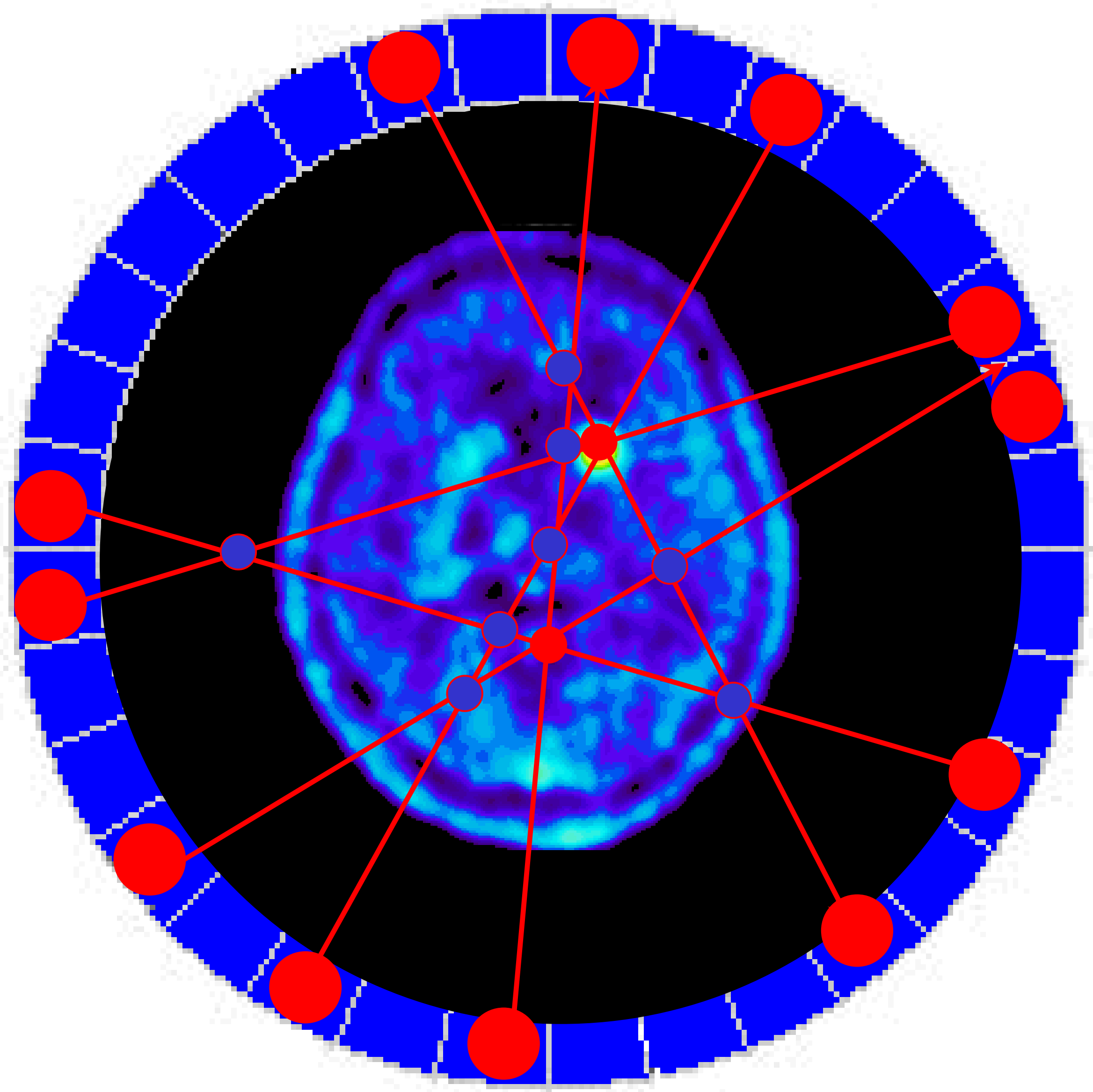


PET-TOF

$$\Delta x = (t2 - t1)\, c / 2$$

resolution 600ps CRT

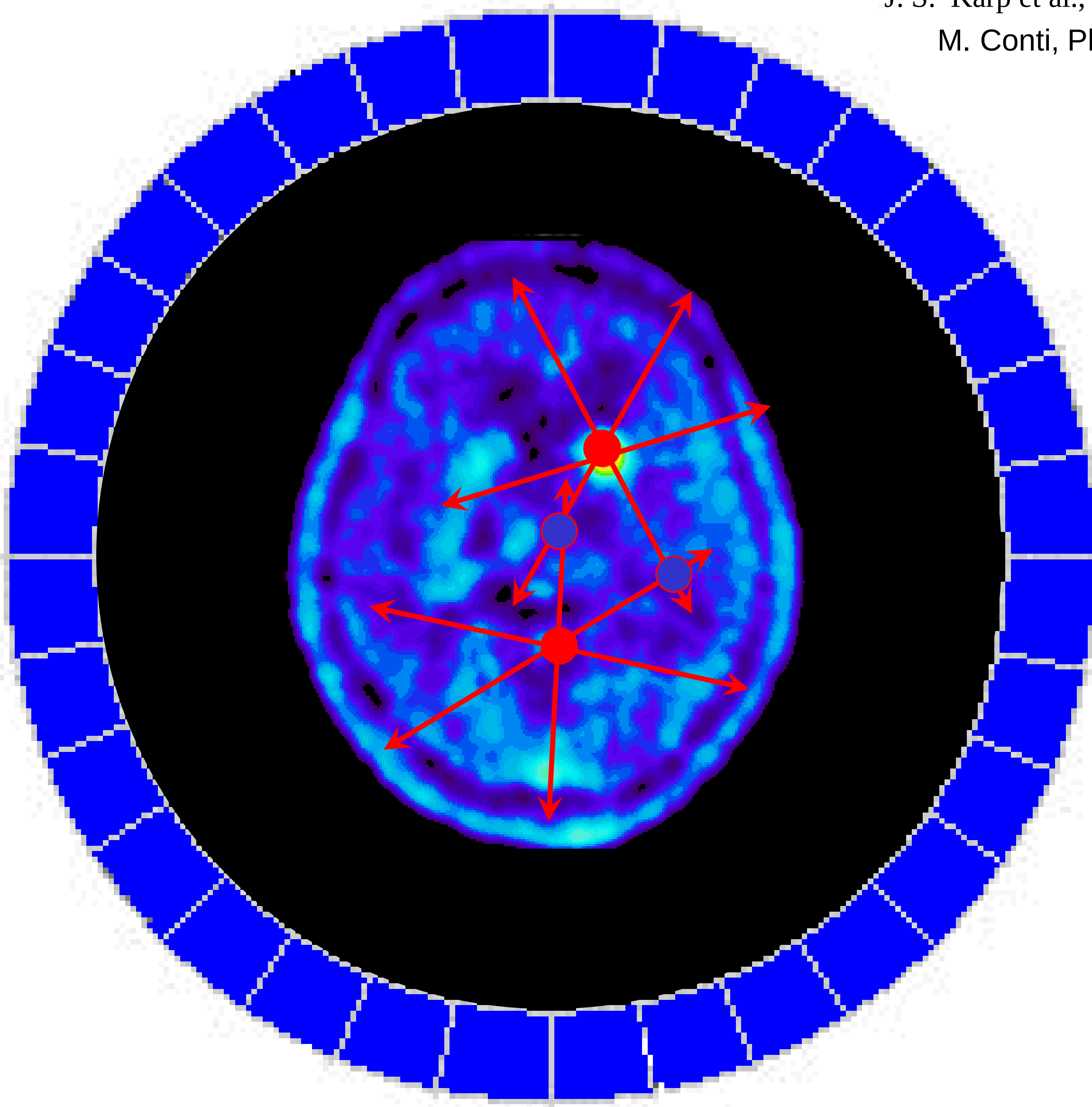




signal/noise
$\sim D / \Delta t$

40cm/600ps improvement by factor of 4

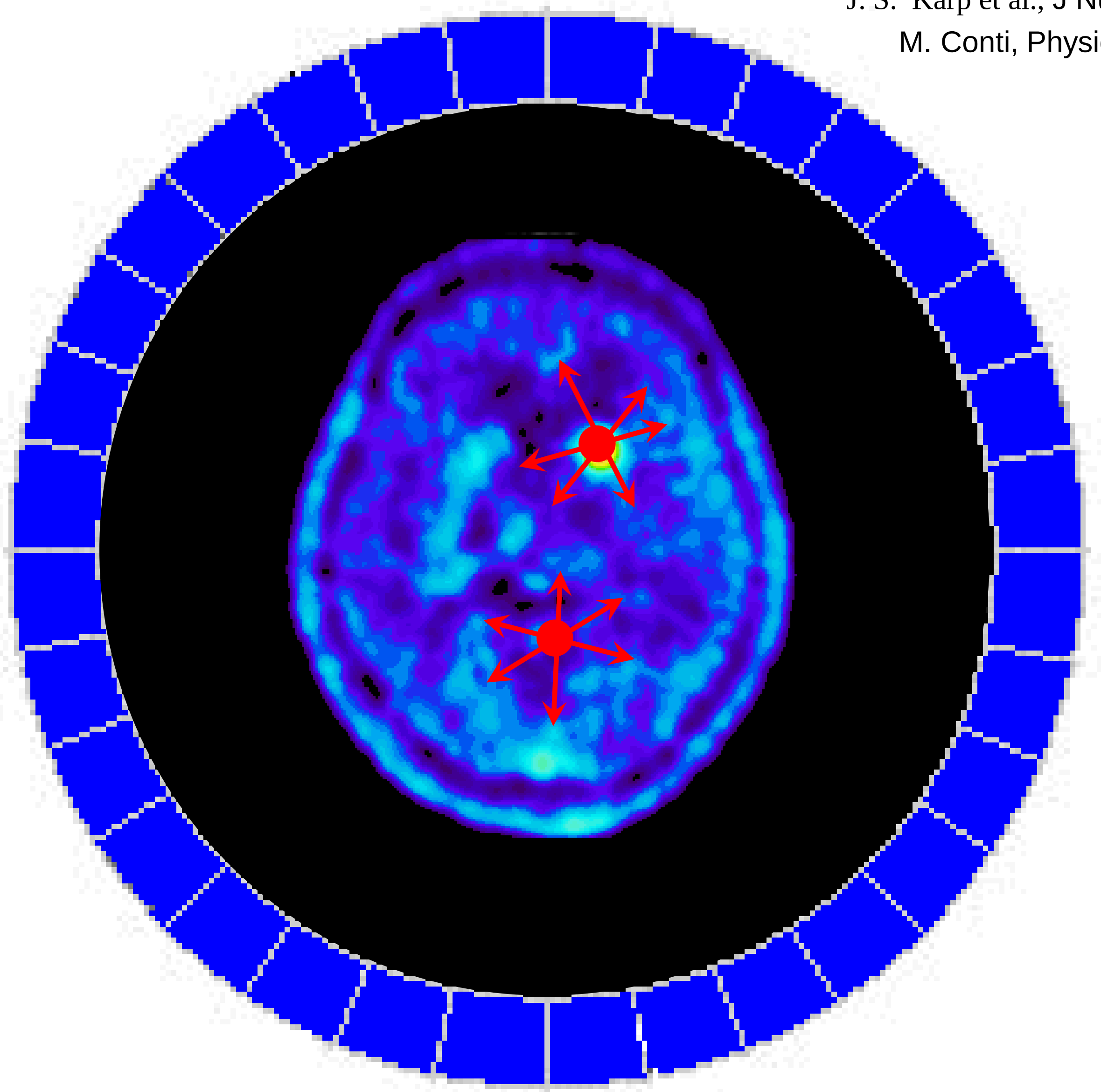
J. S. Karp et al., J Nucl Med 2008; 49: 462
M. Conti, Physica Medica 2009; 25: 1.



signal/background ~ D / Δt

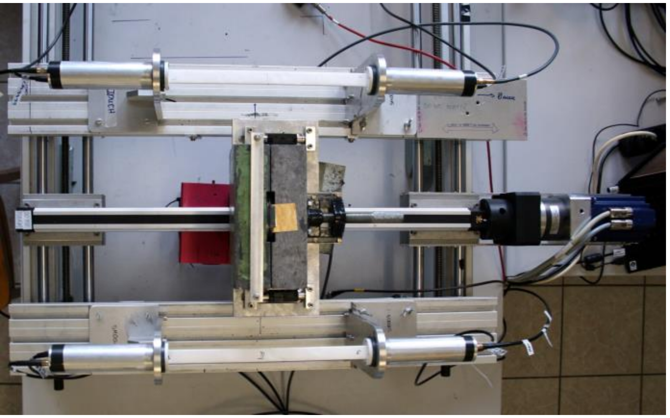
40cm/200ps improvement by factor of 12

J. S. Karp et al., J Nucl Med 2008; 49: 462
M. Conti, Physica Medica 2009; 25: 1.



2012

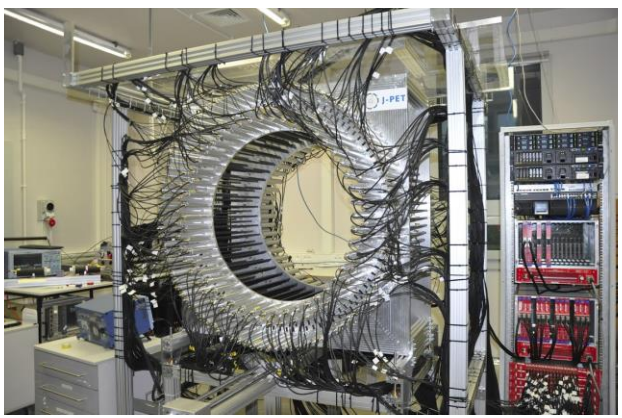
2 strips



2014

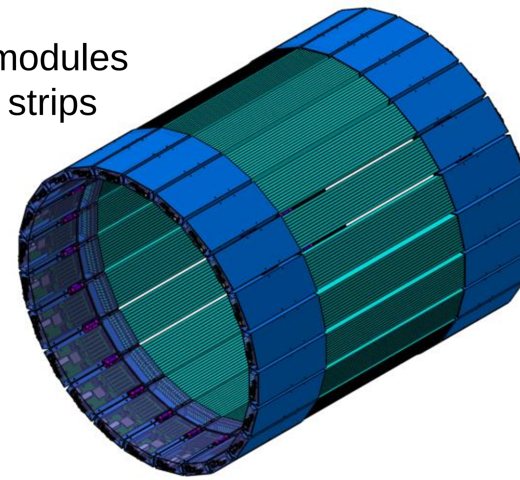
48 plastic strips

192 plastic strips



2016

24 modules
312 strips

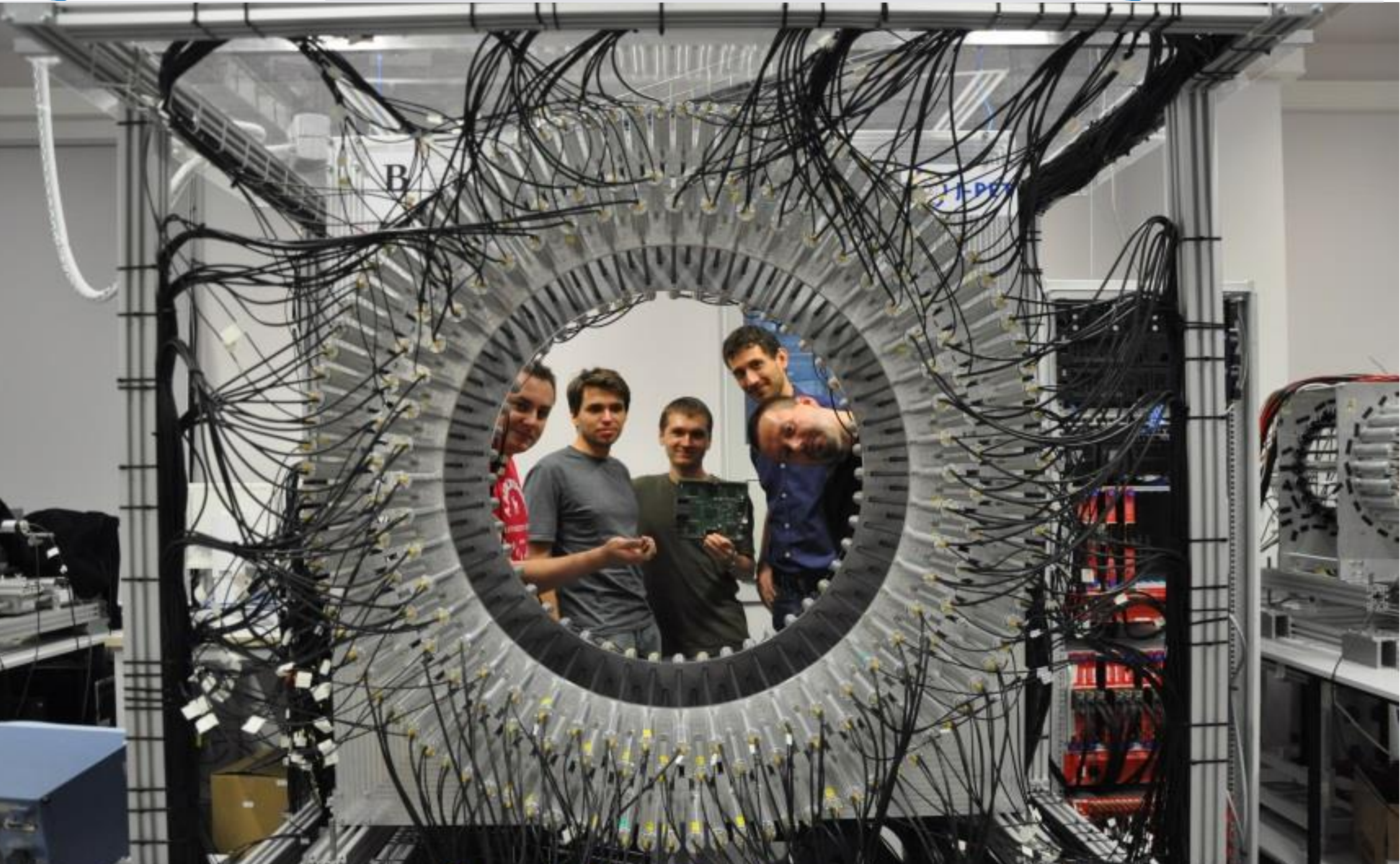


MODULAR

2019

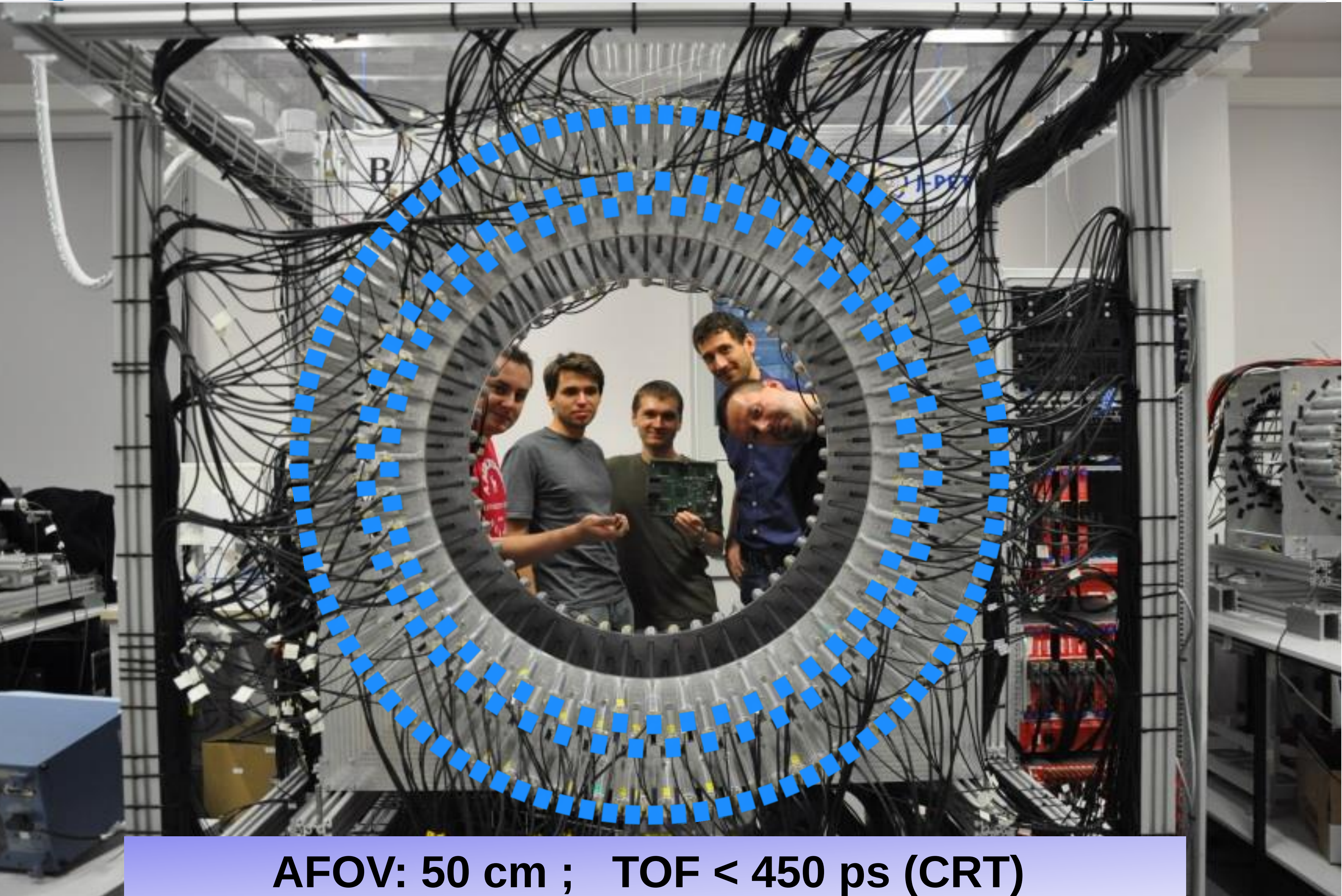
Funding:
Foundation for Polish Science (TEAM)
Polish National Centre for Development and Research
Polish Ministry for Science and Higher Education

Jagiellonian PET

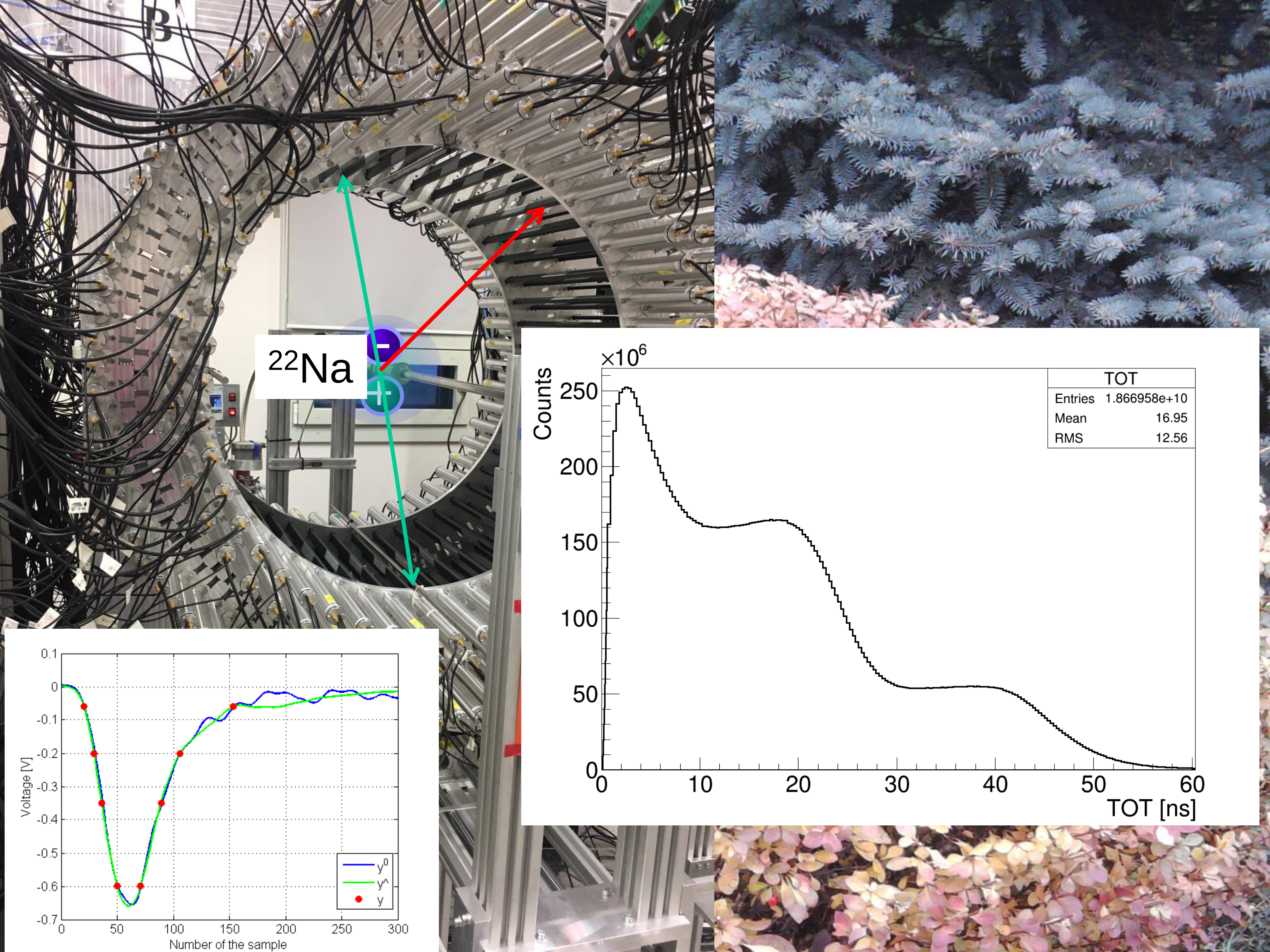


AFOV: 17 cm → 50 cm ;   TOF < 450 ps

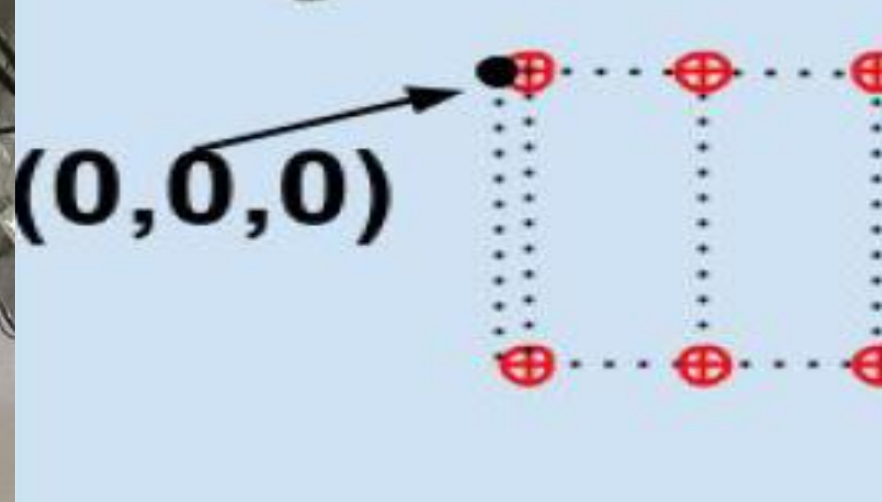
Jagiellonian PET

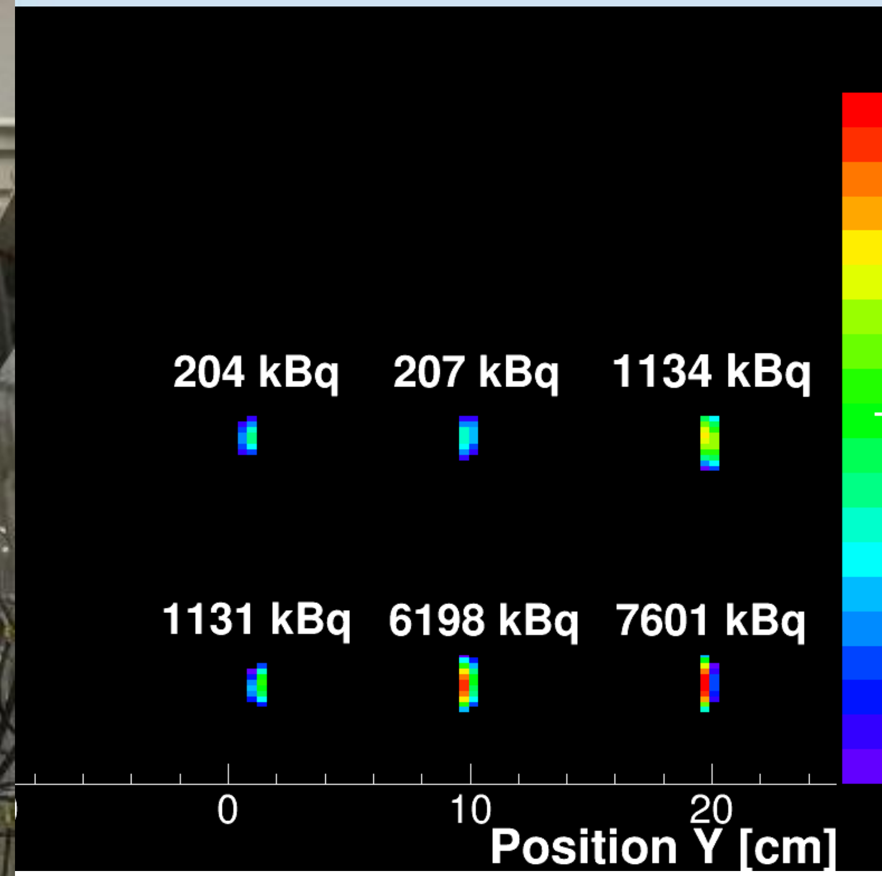


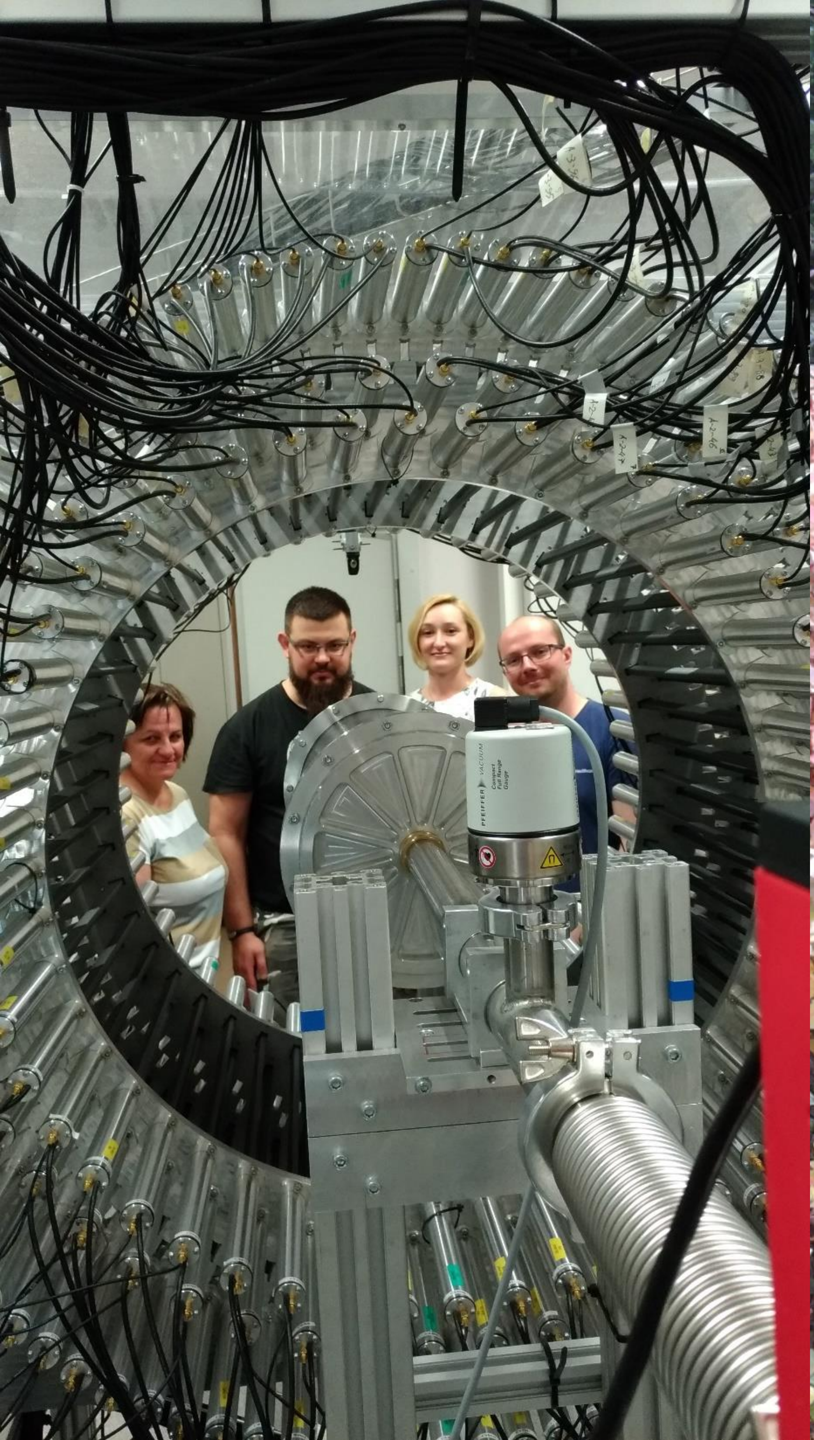
AFOV: 50 cm ;   TOF < 450 ps (CRT)

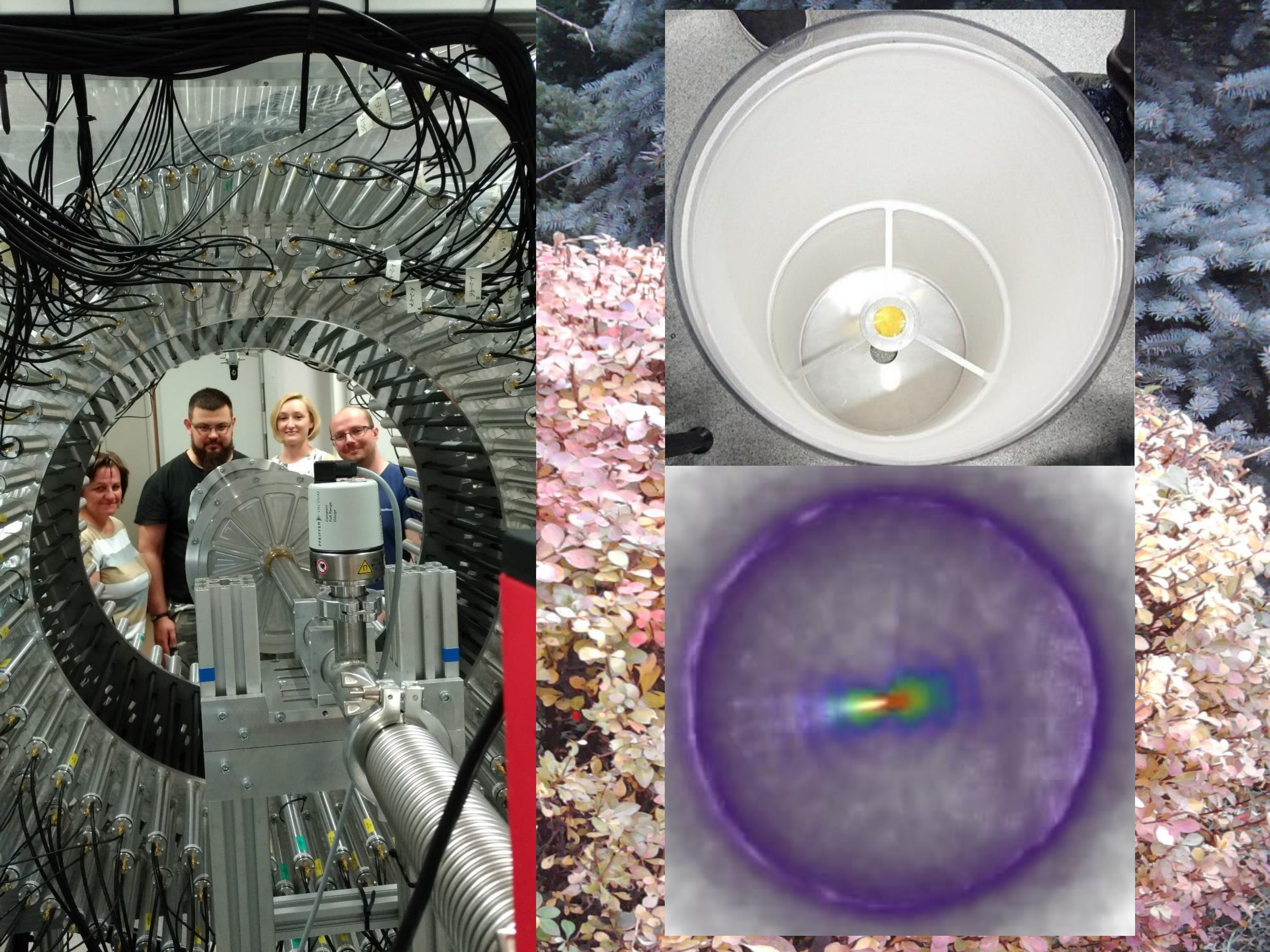


22Na
×10^6
Counts
TOT
Entries 1.866958e+10
Mean 16.95
RMS 12.56
0
50
100
150
200
250
0
10
20
30
40
50
60
TOT [ns]
Voltage [V]
Number of the sample
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0
50
100
150
200
250
300
y0
y^
y

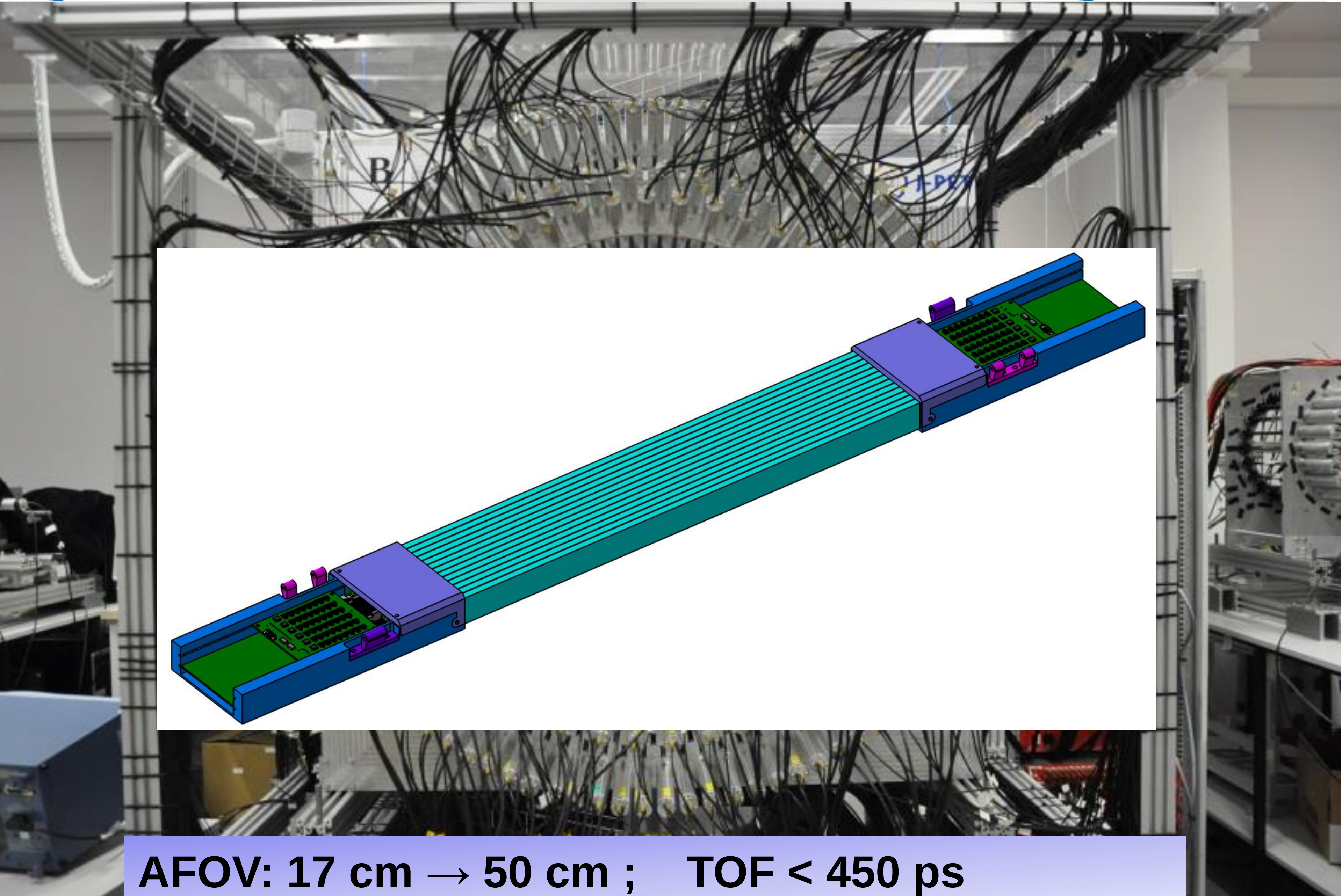

(0,0,0)


204 kBq
207 kBq
1134 kBq
1131 kBq
6198 kBq
7601 kBq
0
10
20
Position Y [cm]



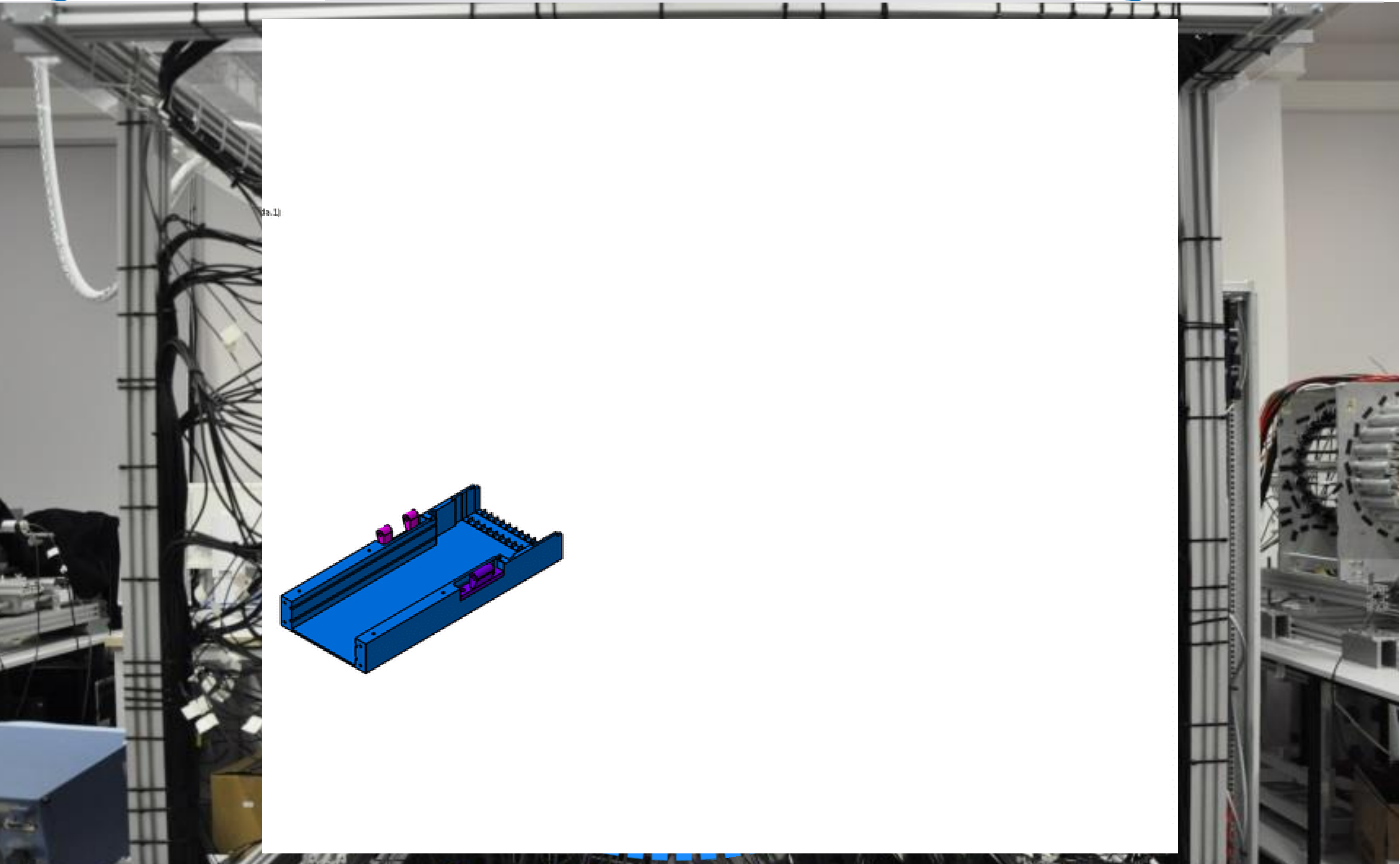


Jagiellonian PET



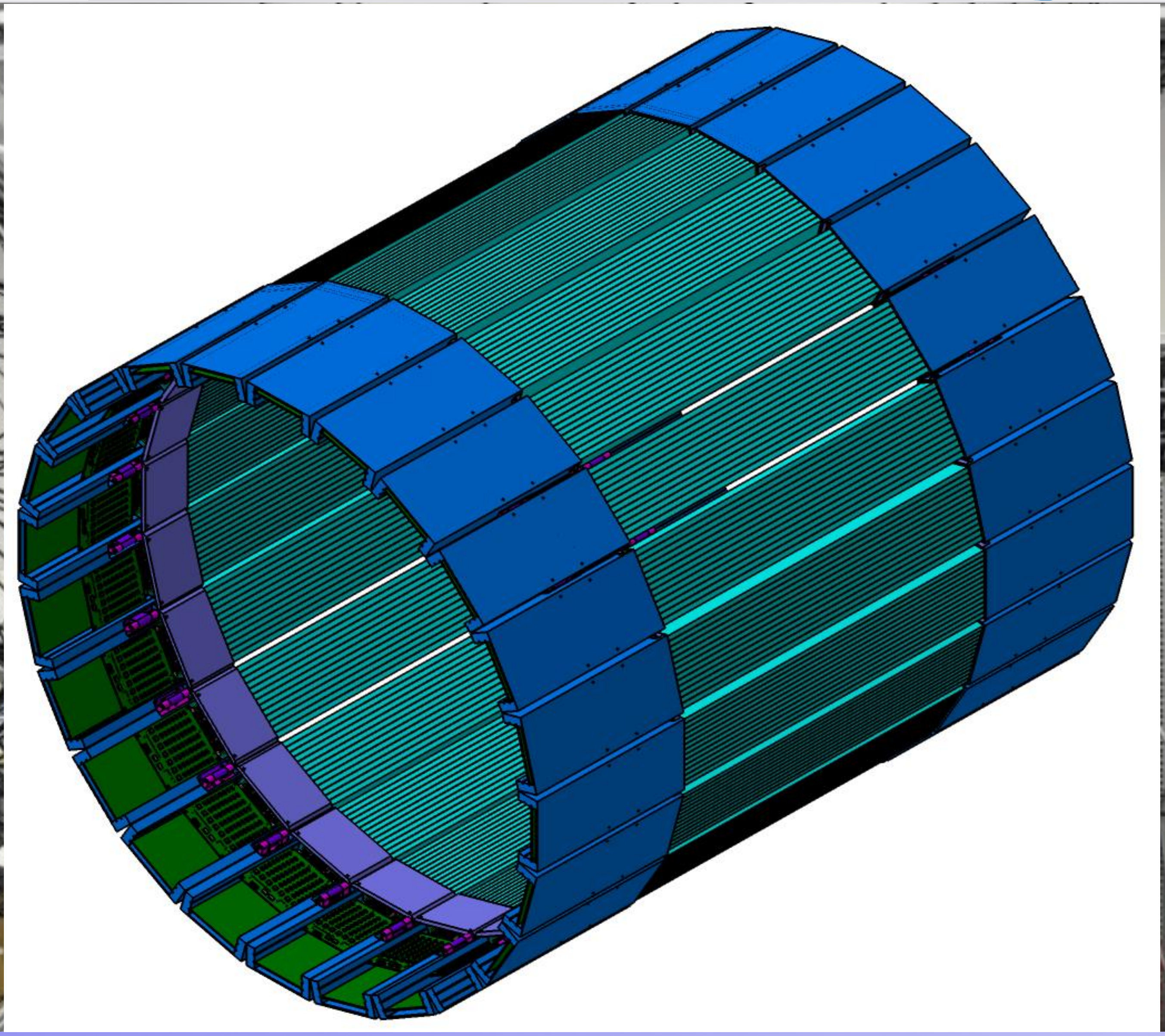
AFOV: 17 cm → 50 cm ;   TOF < 450 ps

Jagiellonian PET



AFOV: 50 cm ;   TOF < 450 ps (FWHM)

Jagiellonian PET

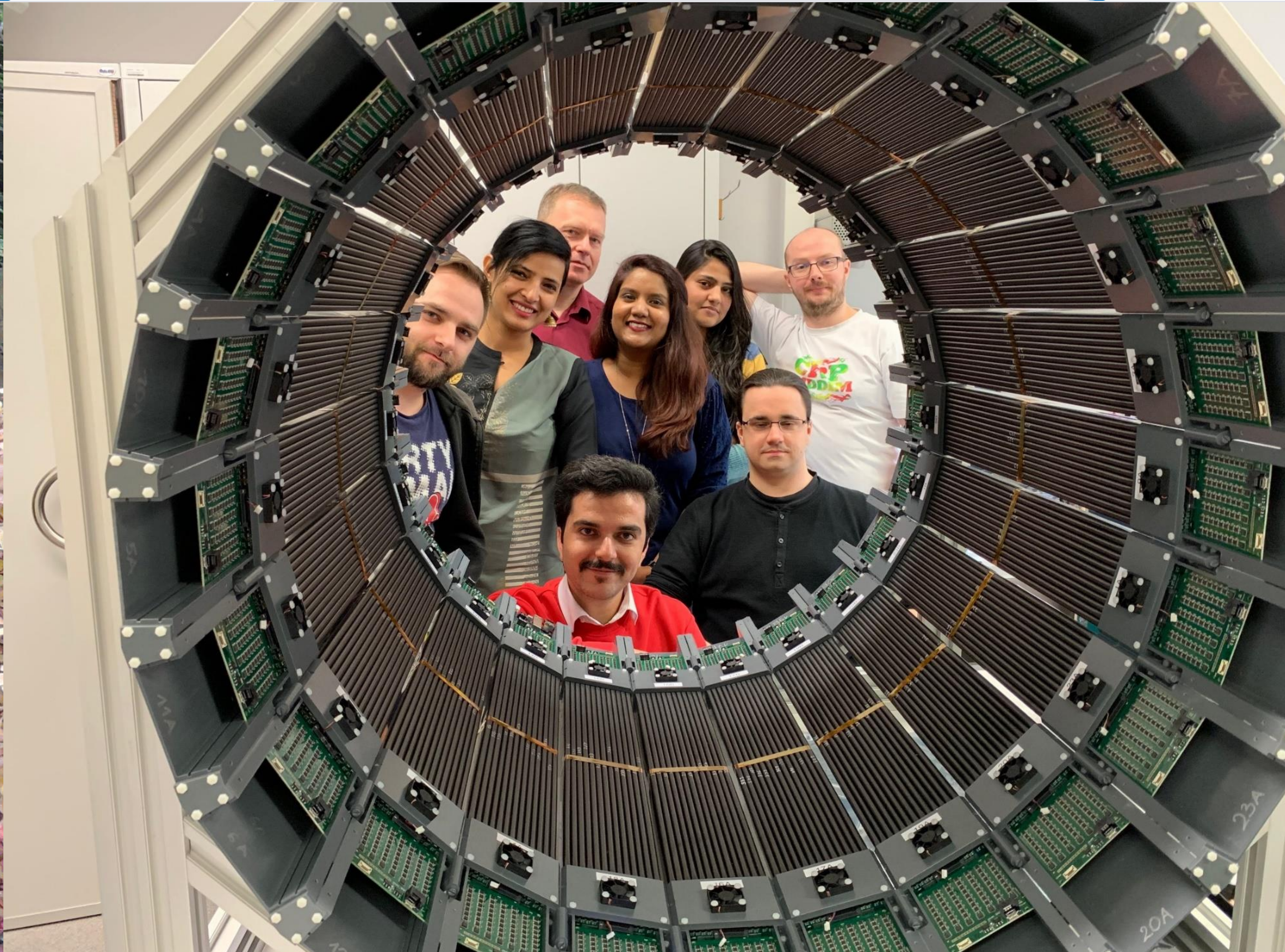


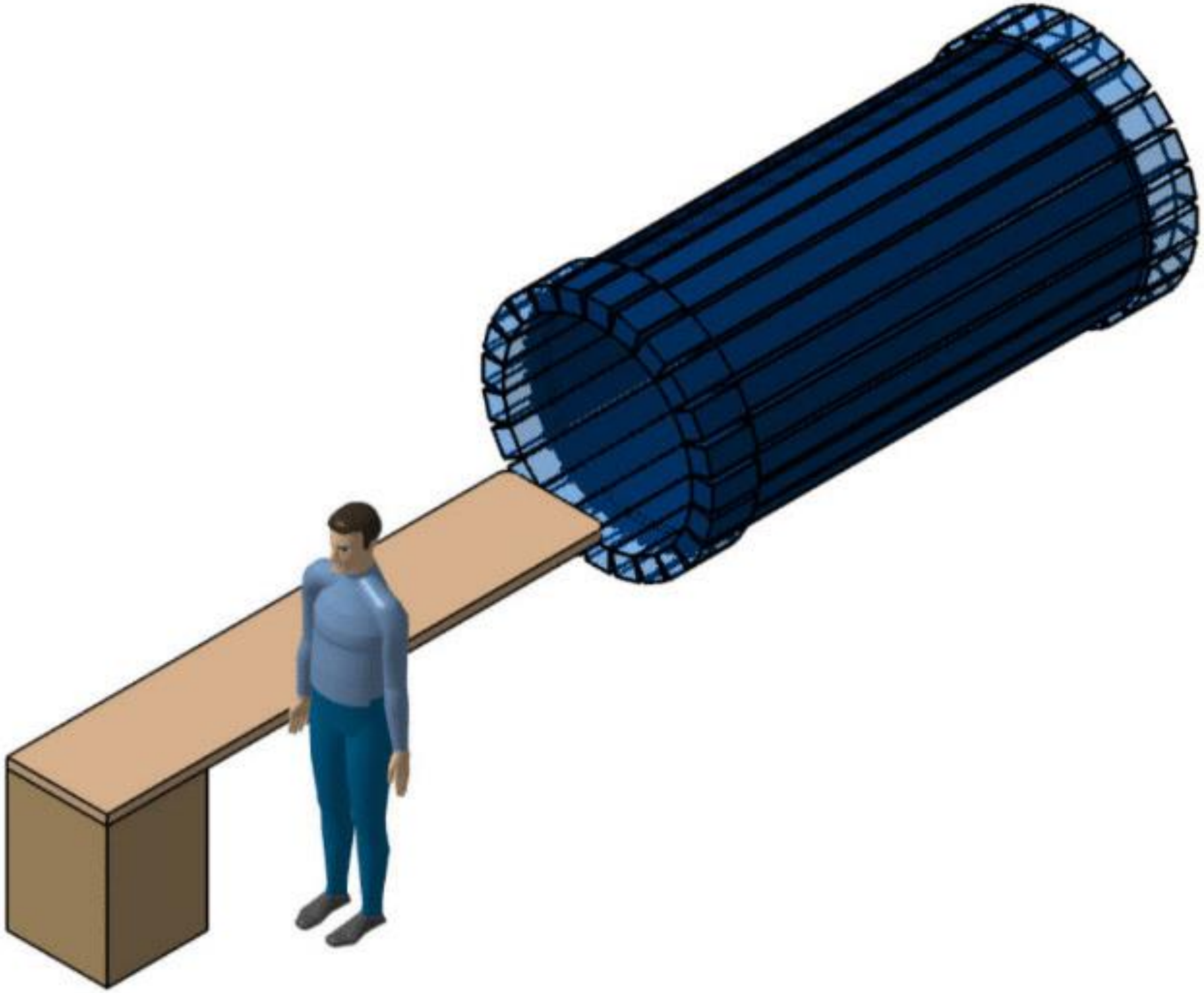
AFOV: 50 cm ; TOF < 450 ps (FWHM)

J-PET

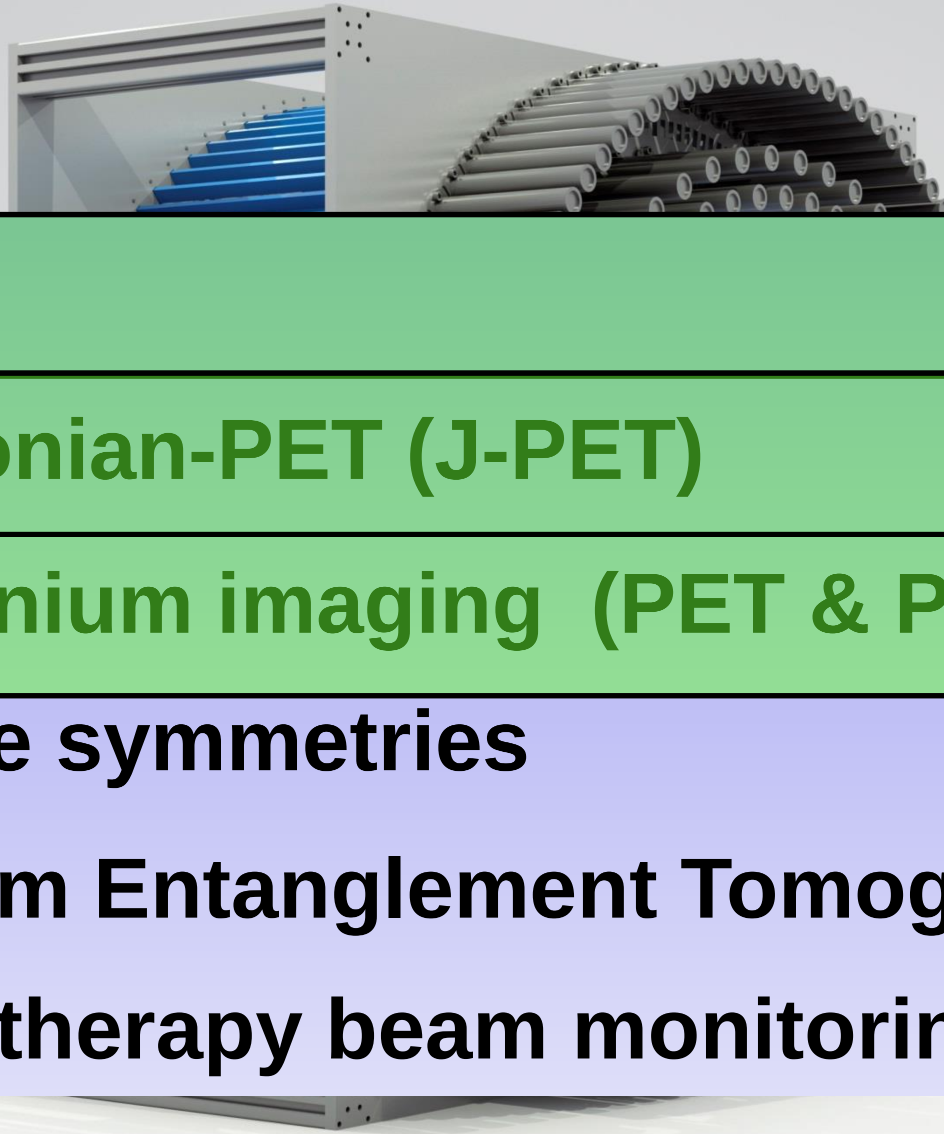
Jagiellonian PET

J-PET

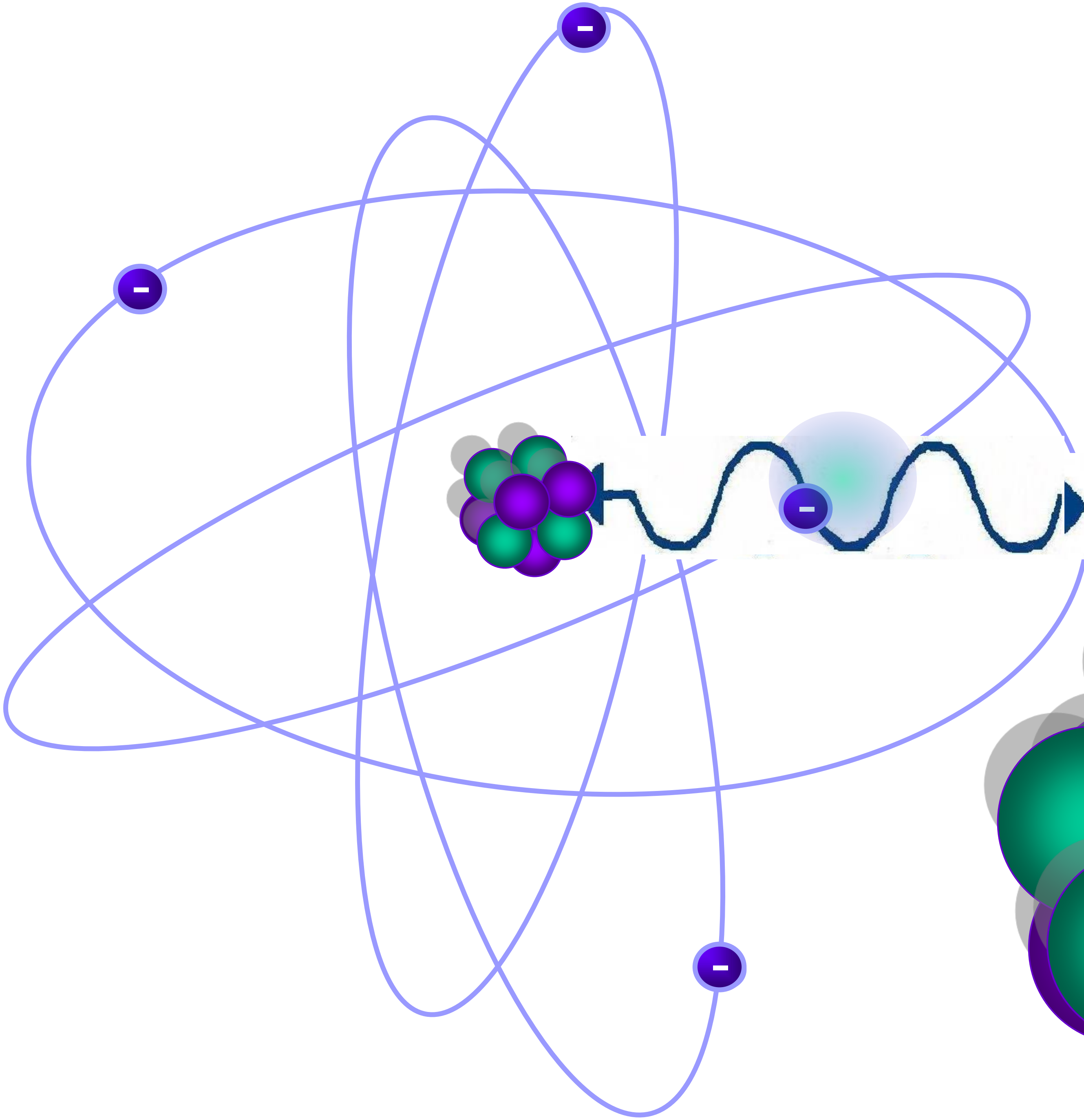




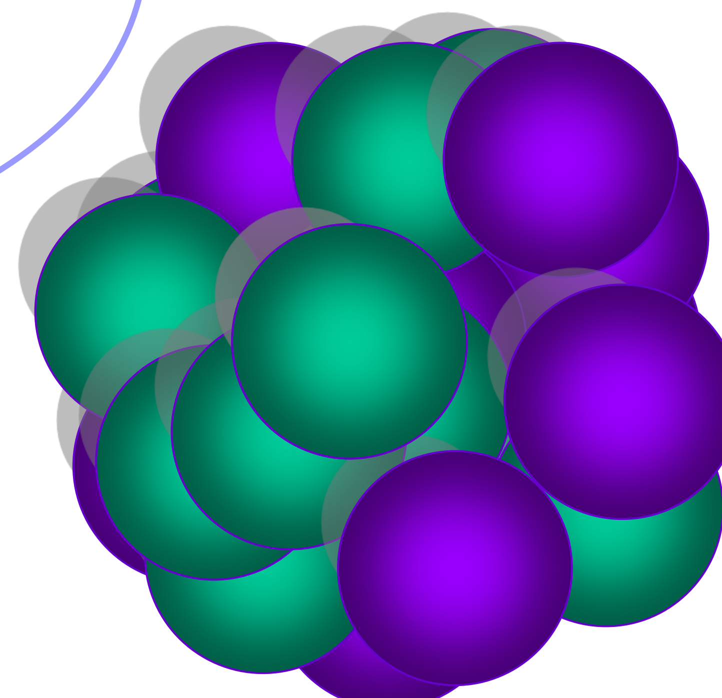
J-PET



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

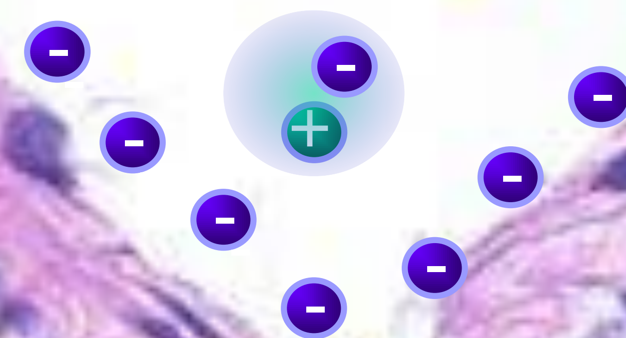


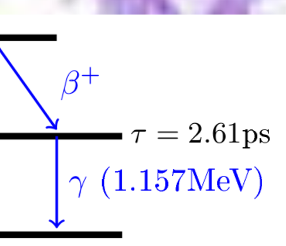
$$^{18}F \longrightarrow {}^{18}O + e^{+} + \nu_e$$



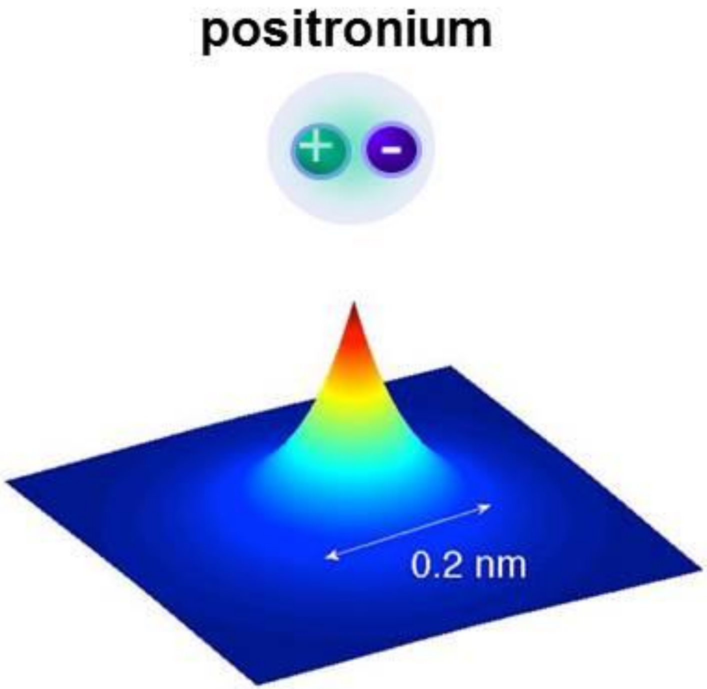
P. M., Patent US 9,851,456, PCT/EP2014/068374

30% – 40%

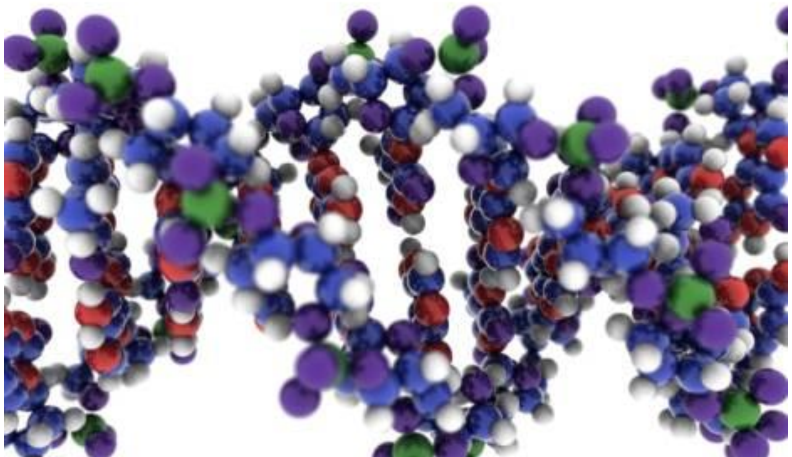


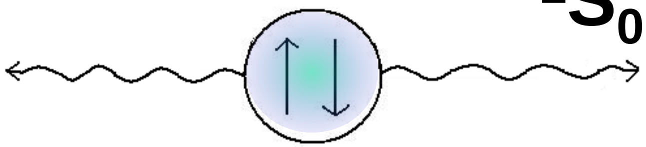


J-PET: P. M et al., Phys. Med. Biol. 64 (2019) 055017
https://arxiv.org/pdf/1805.11696.pdf

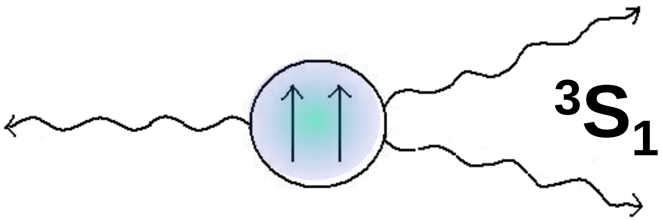


Y.H. Wang et al., Phys. Rev. A 89 (2014) 043624,
http://www.chem-eng.kyushu-u.ac.jp/e/research.html



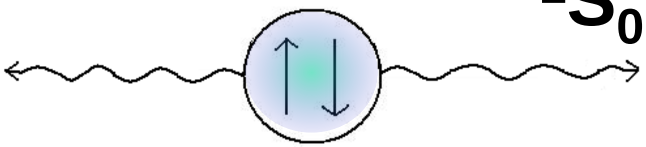


$^1S_0$ Para-positronium tau(p-Ps) ≈ 125 ps

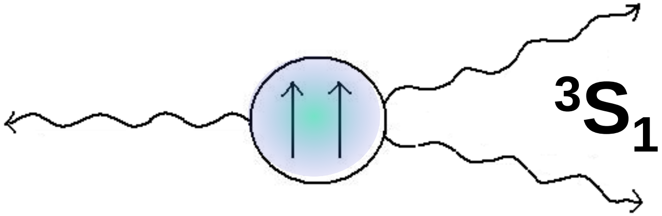


$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

	$^1S_0$	$^3S_1$
L	0	0



$^{1}S_{0}$ Para-positronium tau(p-Ps) ≈ 125 ps



$^{3}S_{1}$ Ortho-positronium tau(o-Ps) ≈ 142 ns

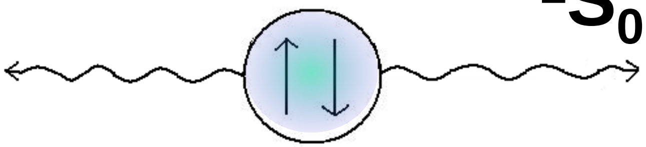
	$^{1}S_{0}$	$^{3}S_{1}$
L	0	0
S	0	1

S = 0 ↓↑ − ↑↓

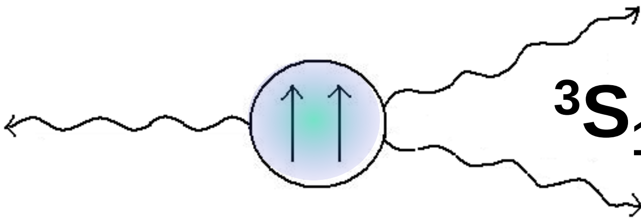
↑↑

S = 1 ↑↓ + ↓↑

↓↓



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



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

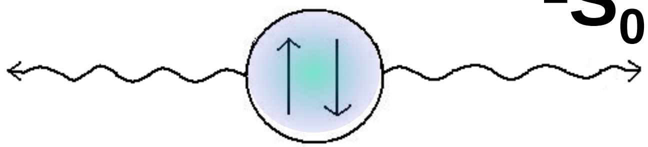
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-

S = 0 ↓↑ − ↑↓

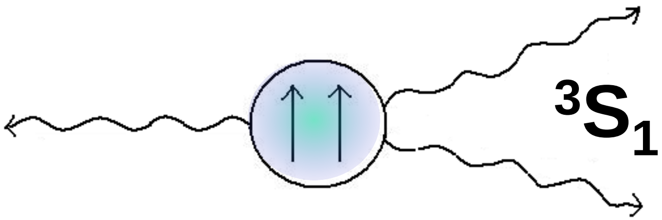
↑↑

S = 1 ↓↑ + ↑↓

↓↓



$^1S_0$ **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	-	+

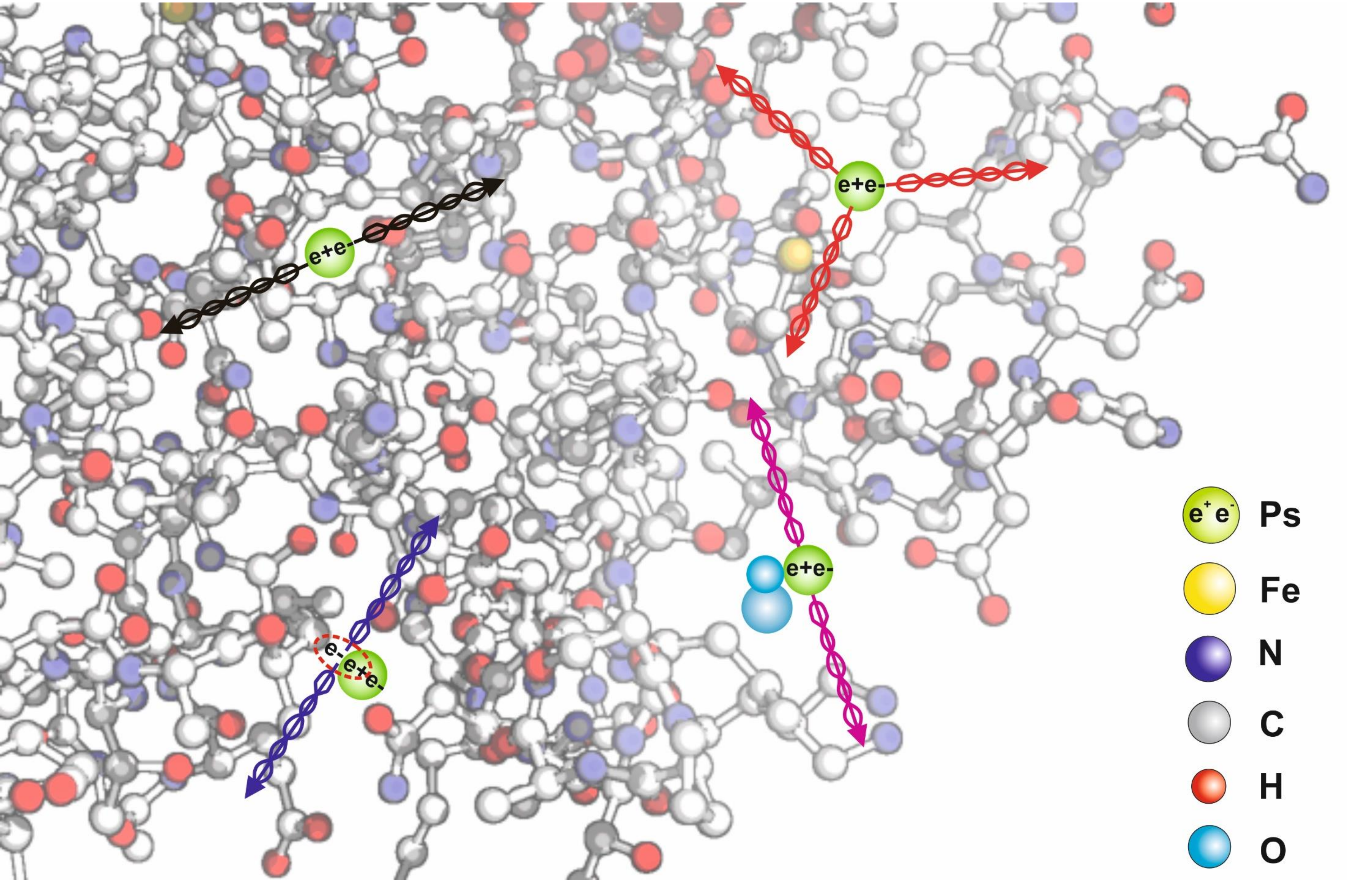
S = 0 ↓↑ − ↑↓

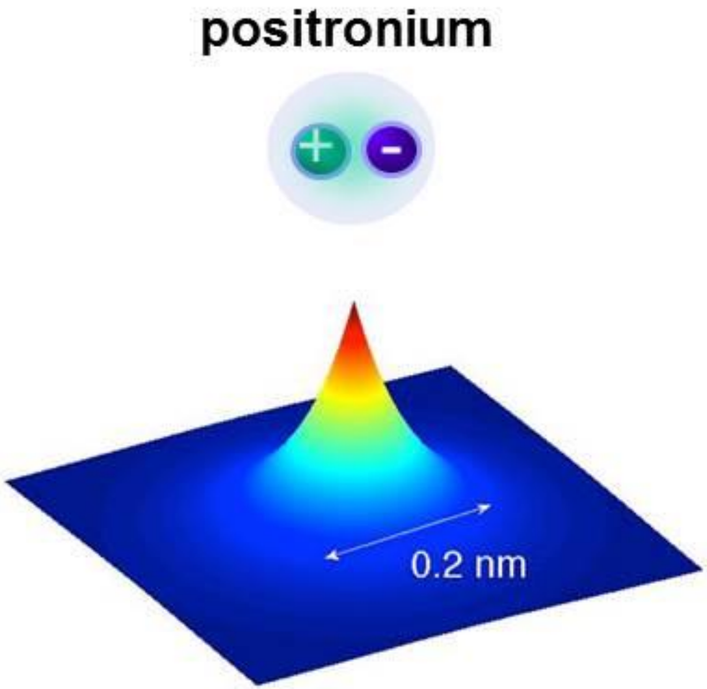
↑↑

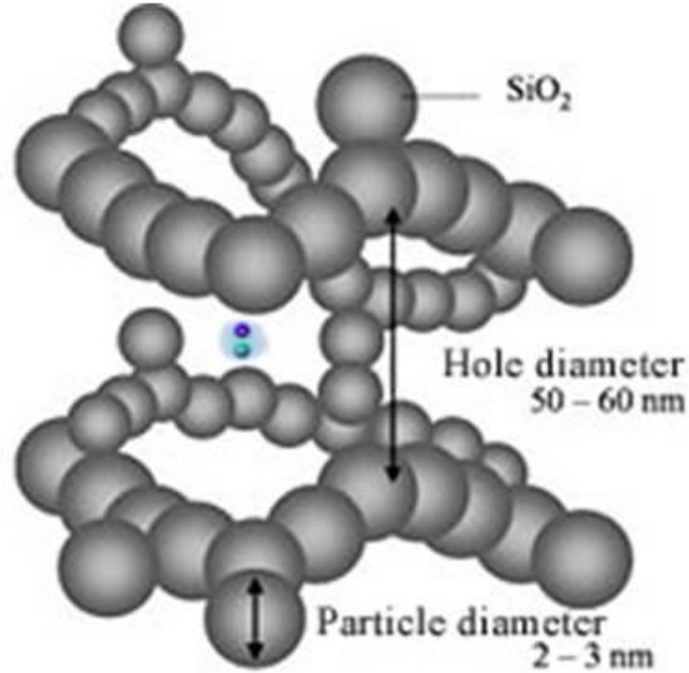
S = 1 ↓↑ + ↑↓

↓↓

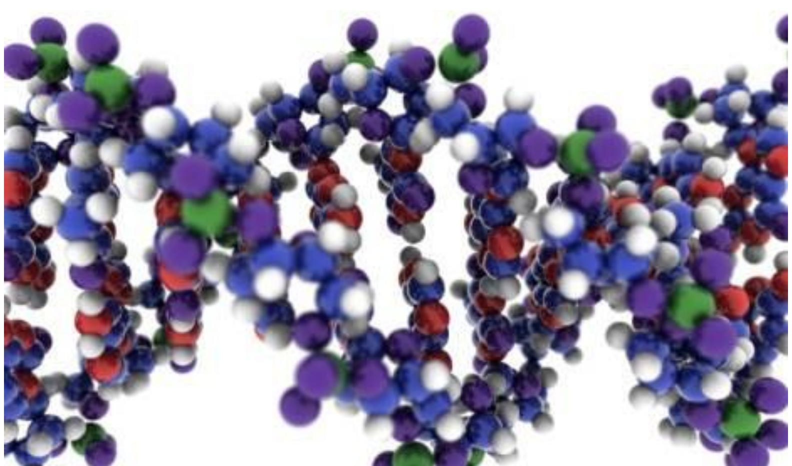
Model of the hemoglobin molecule



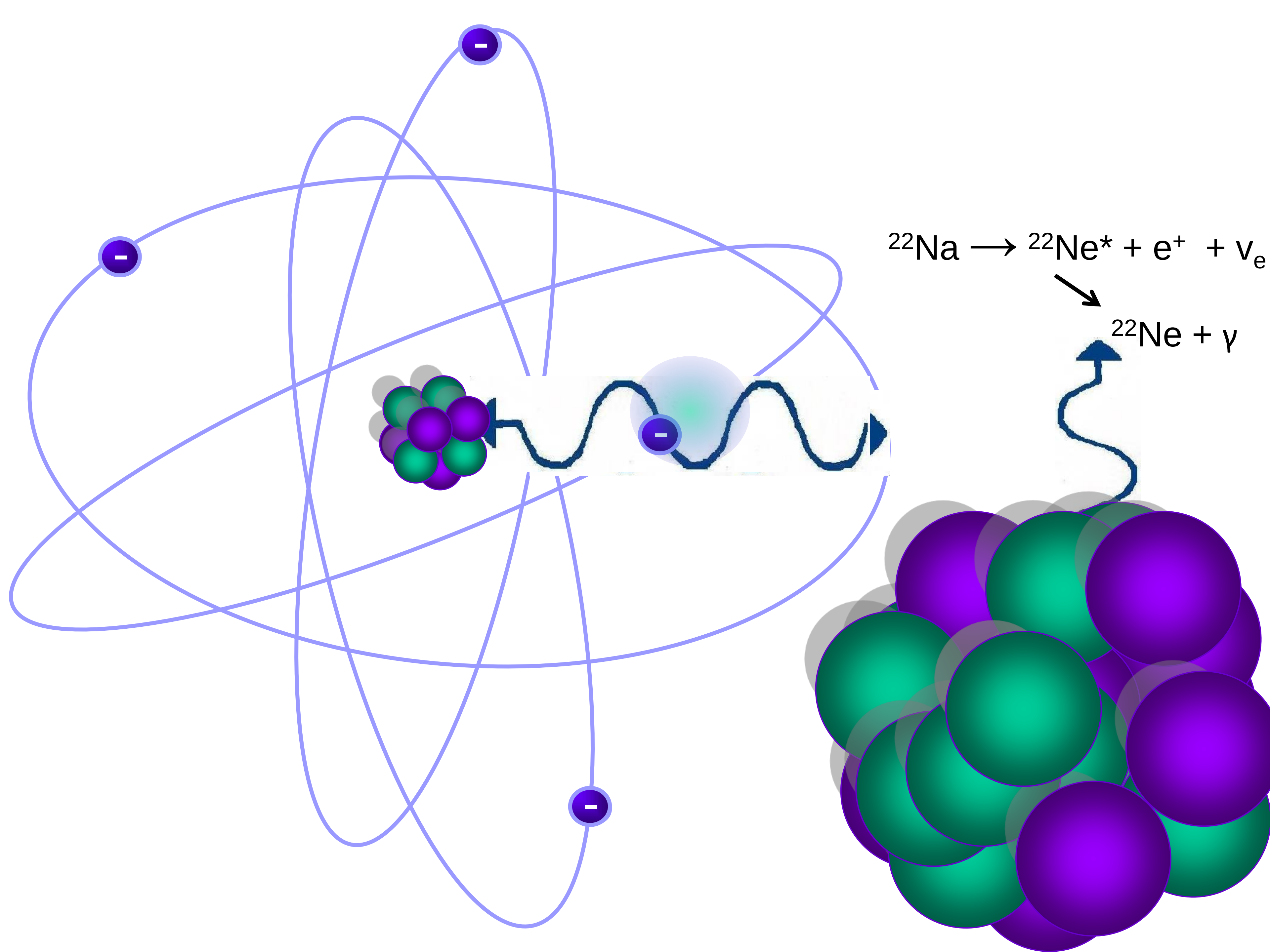




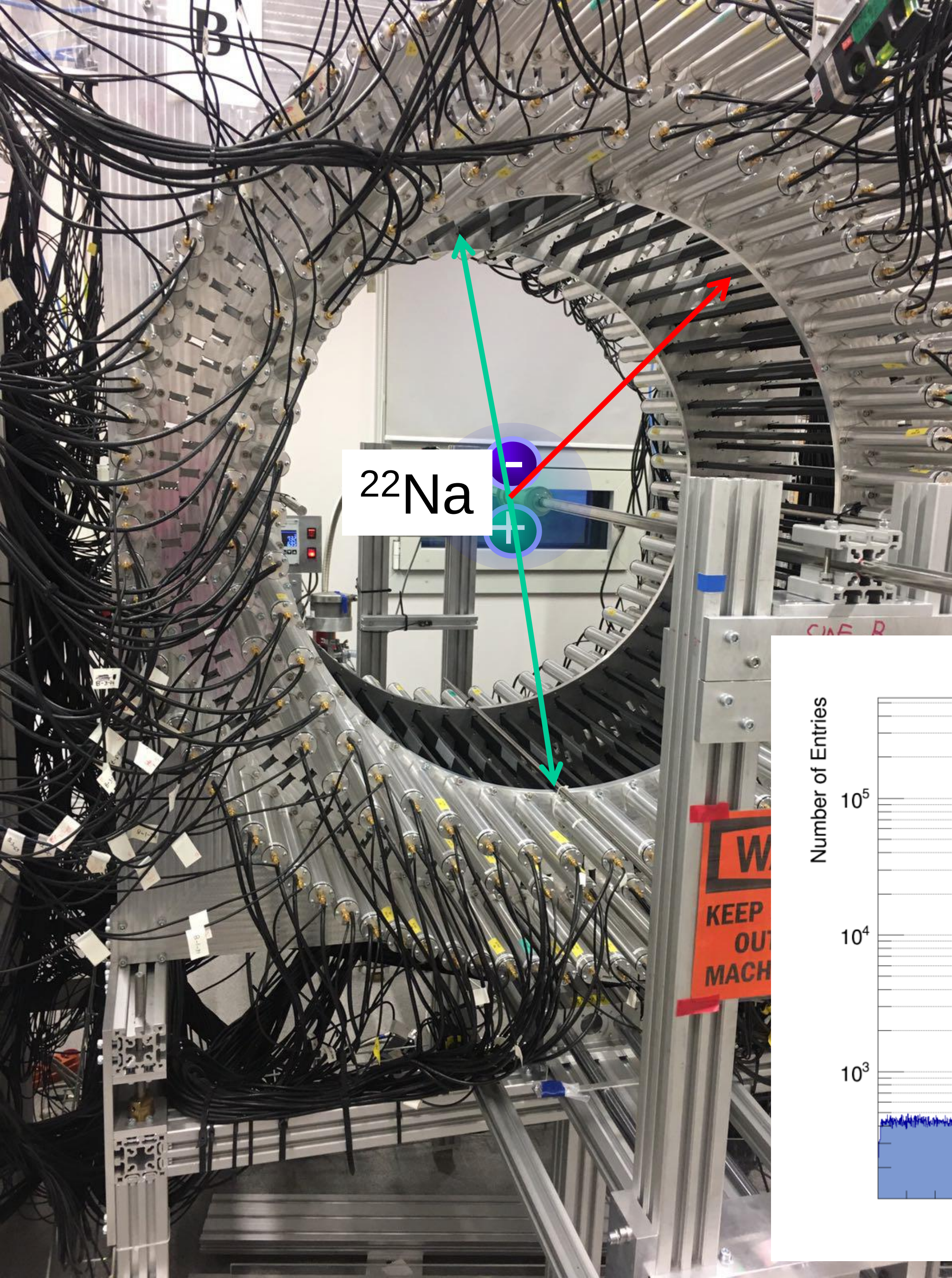
Y.H. Wang et al., Phys. Rev. A 89 (2014) 043624,
http://www.chem-eng.kyushu-u.ac.jp/e/research.html



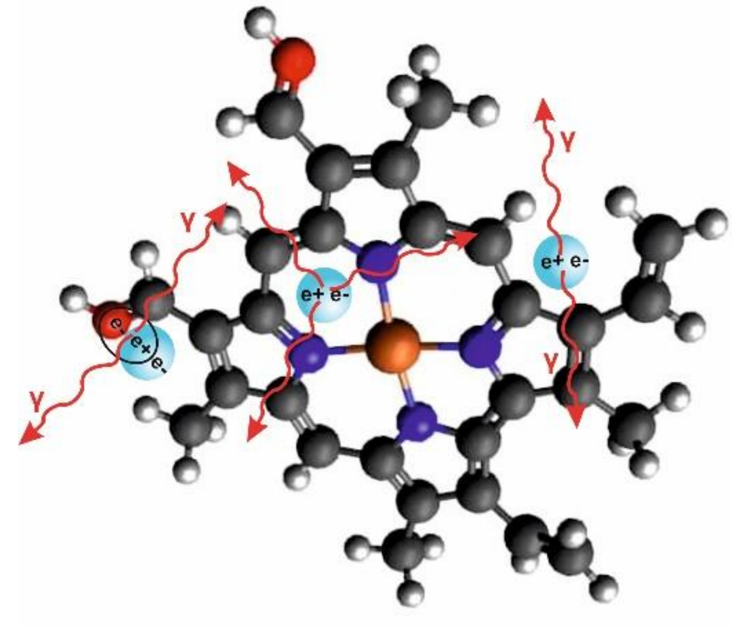

B
SIDE B
WARNING
KEEP HANDS OUT OF MACHINERY



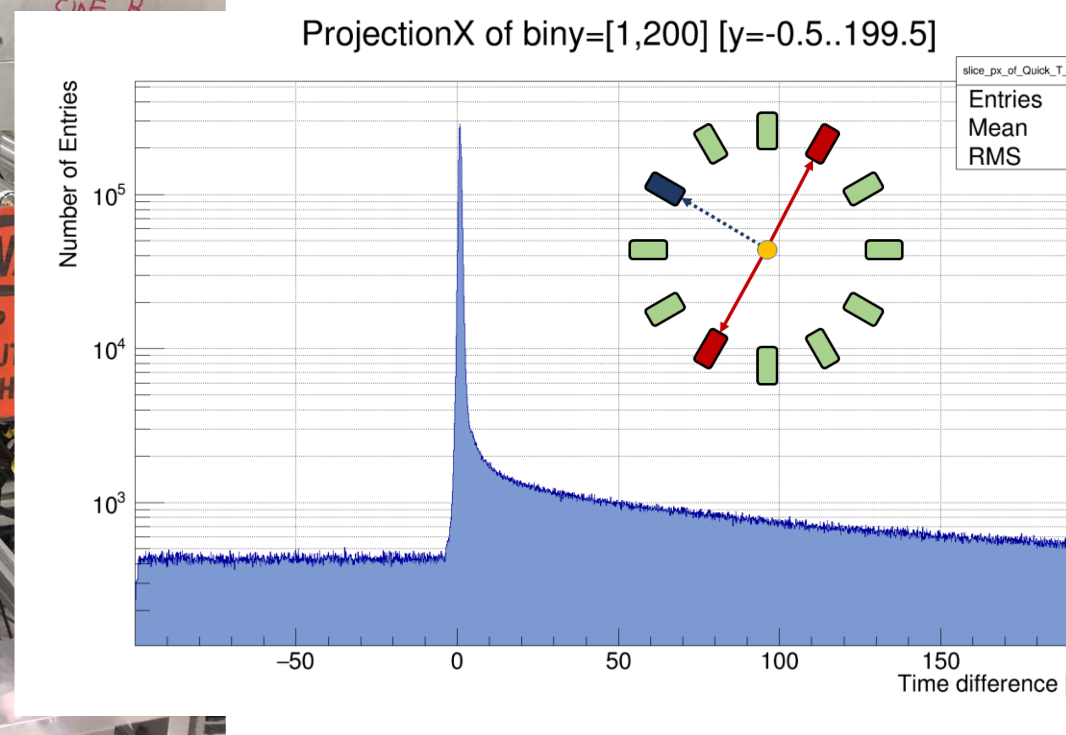
$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$
$^{22}Ne + \gamma$



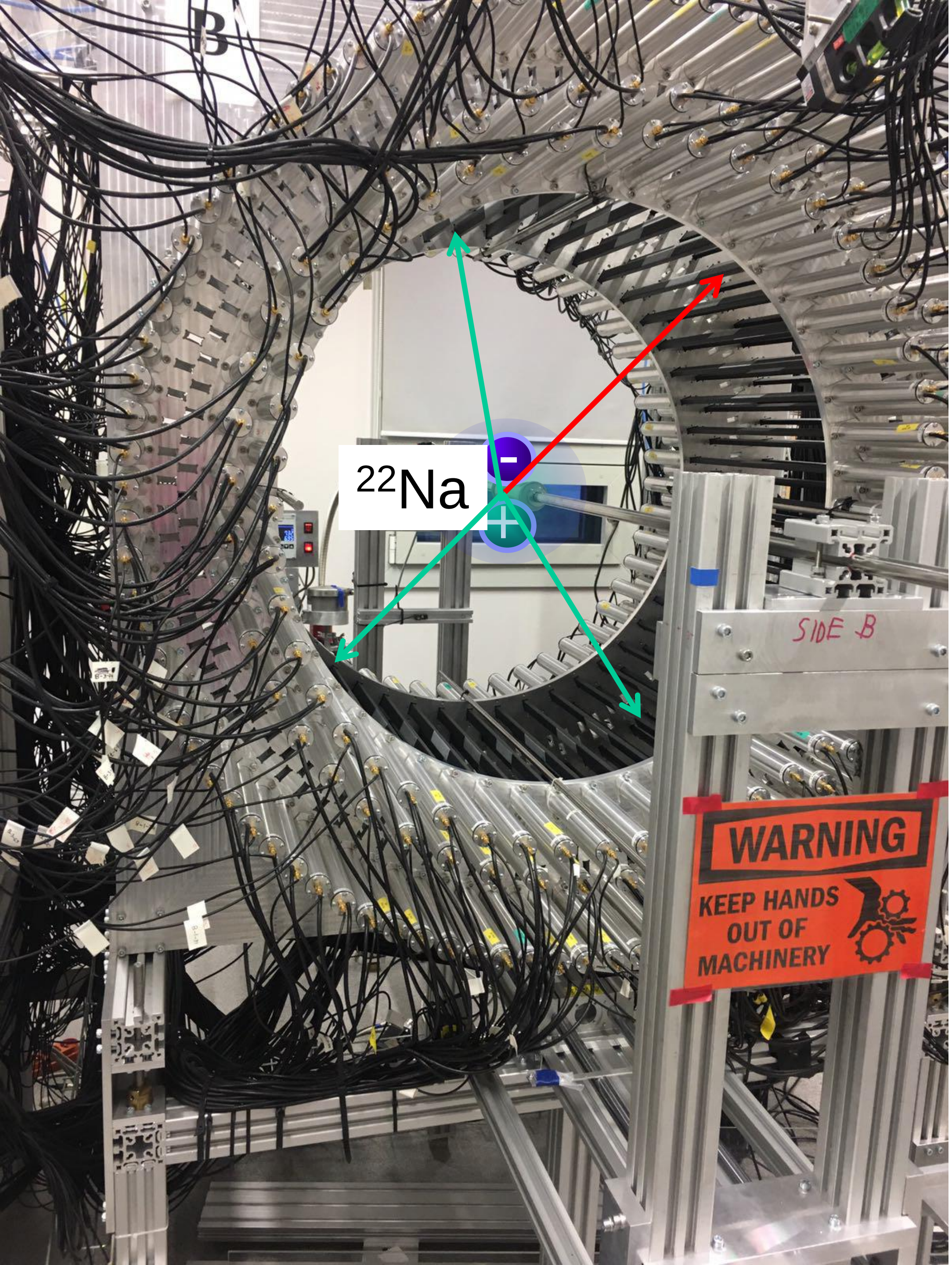
^{22}Na
KEEP

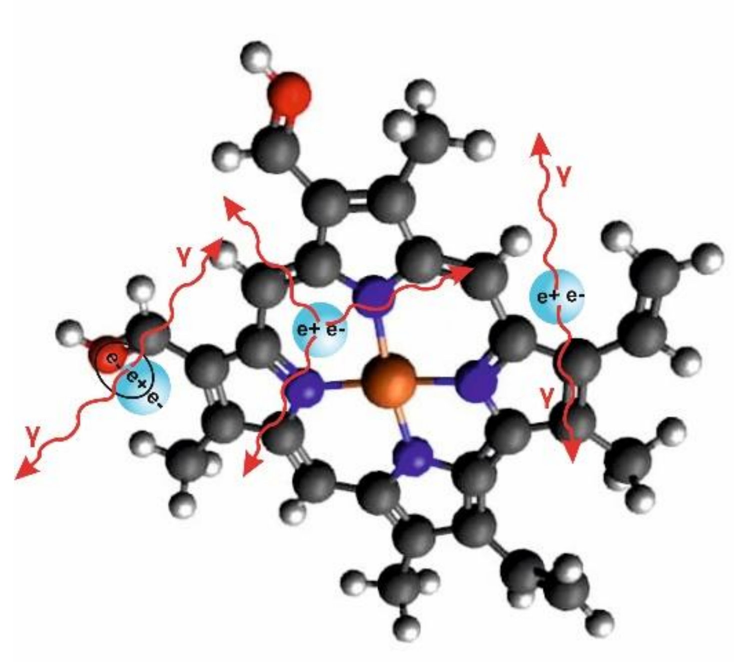


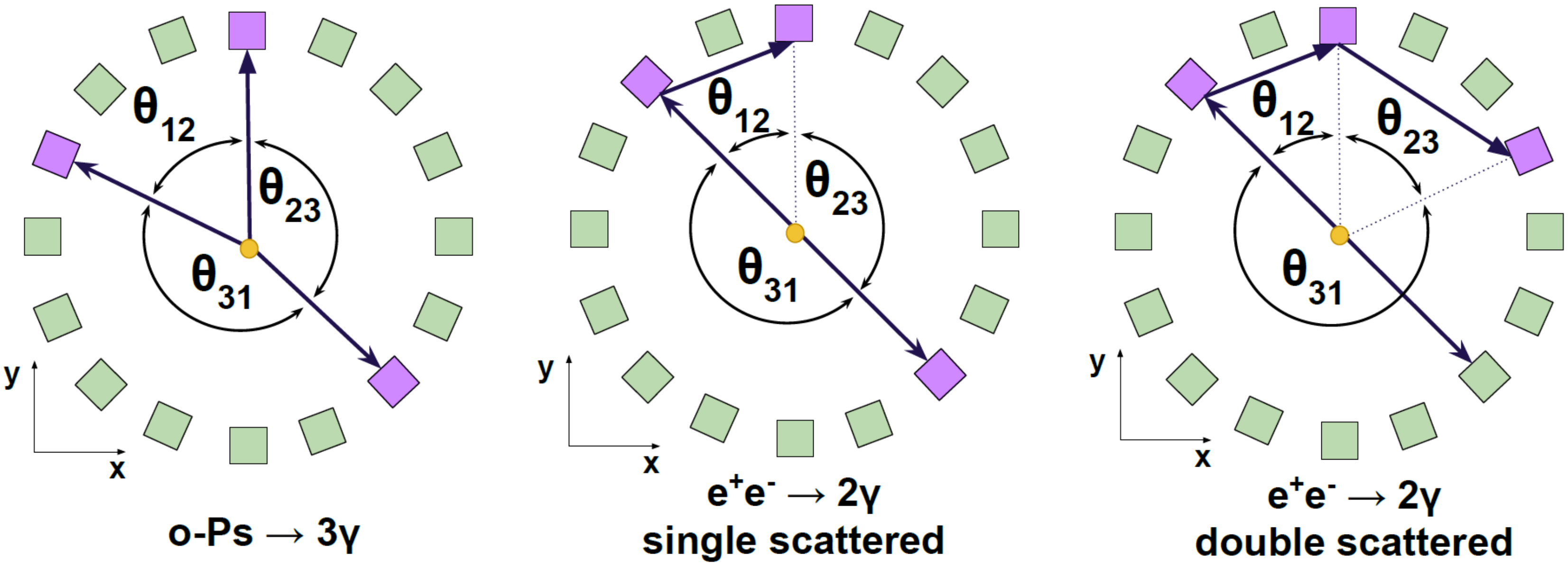
γ
e+ e-



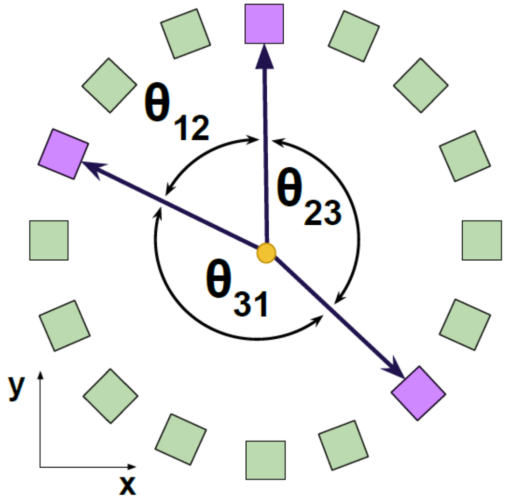
ProjectionX of biny=[1,200] [y=-0.5..199.5]
Number of Entries
Time difference
Entries
Mean
RMS
10^5
10^4
10^3
-50
0
50
100
150


B
^{22}Na
SIDE B
WARNING
KEEP HANDS OUT OF MACHINERY


γ
e+ e-

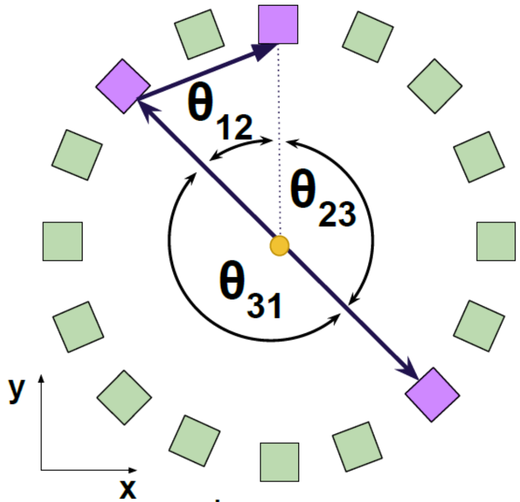


$$\theta_{23} + \theta_{12} > 180 \qquad \theta_{23} + \theta_{12} = 180 \qquad \theta_{23} + \theta_{12} < 180$$



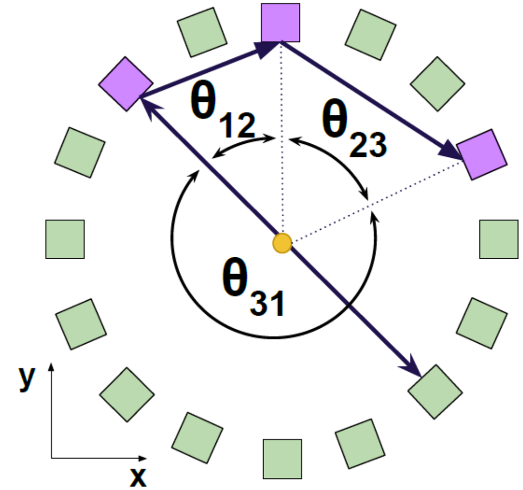
o-Ps → 3γ

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



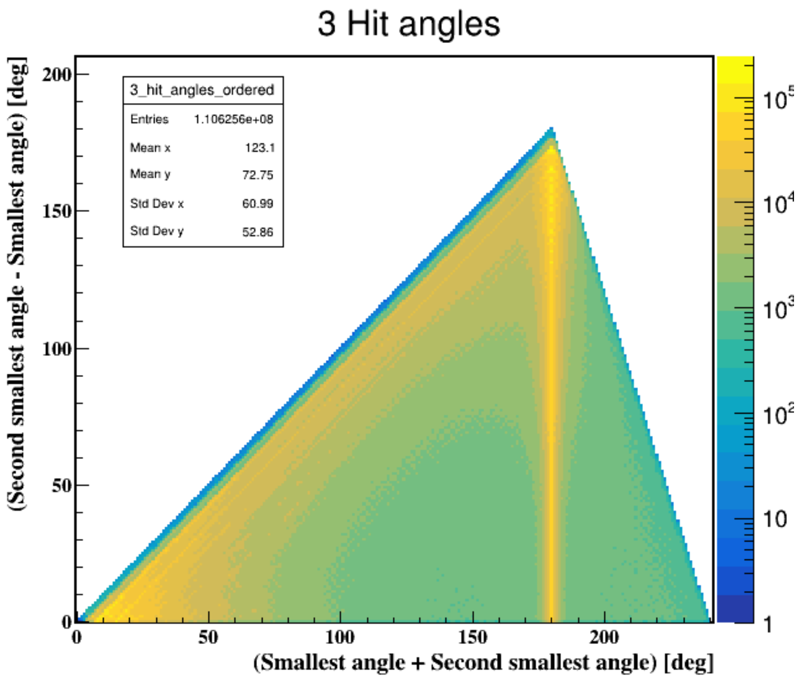
$e^+e^- \rightarrow 2\gamma$
single scattered

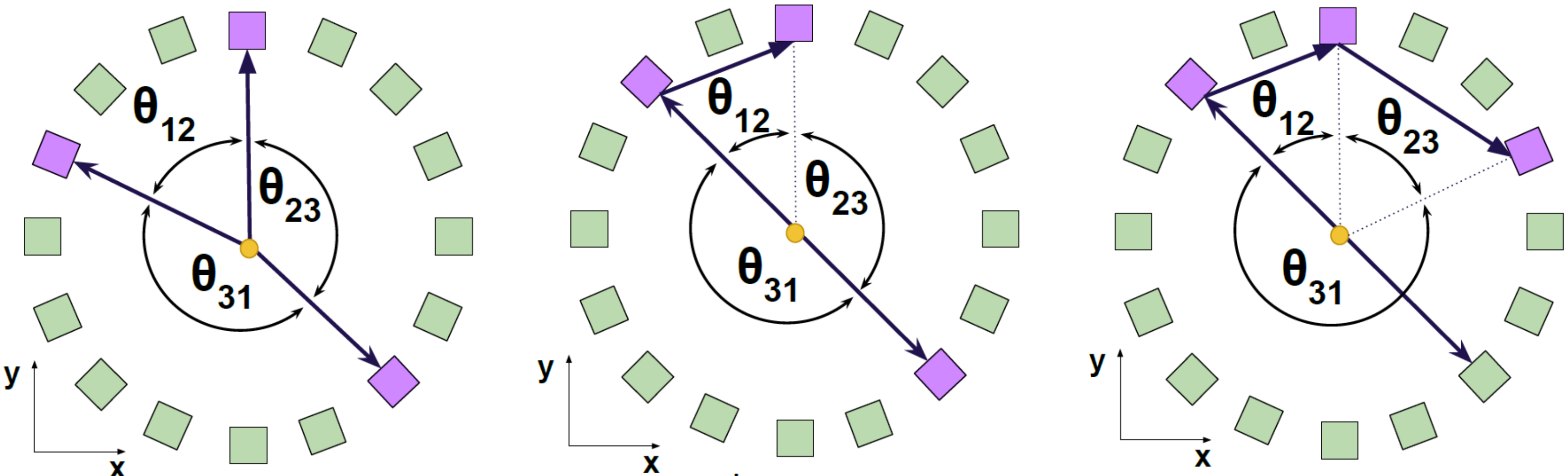
$\theta_{23} + \theta_{12} = 180$



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

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





o-Ps → 3γ

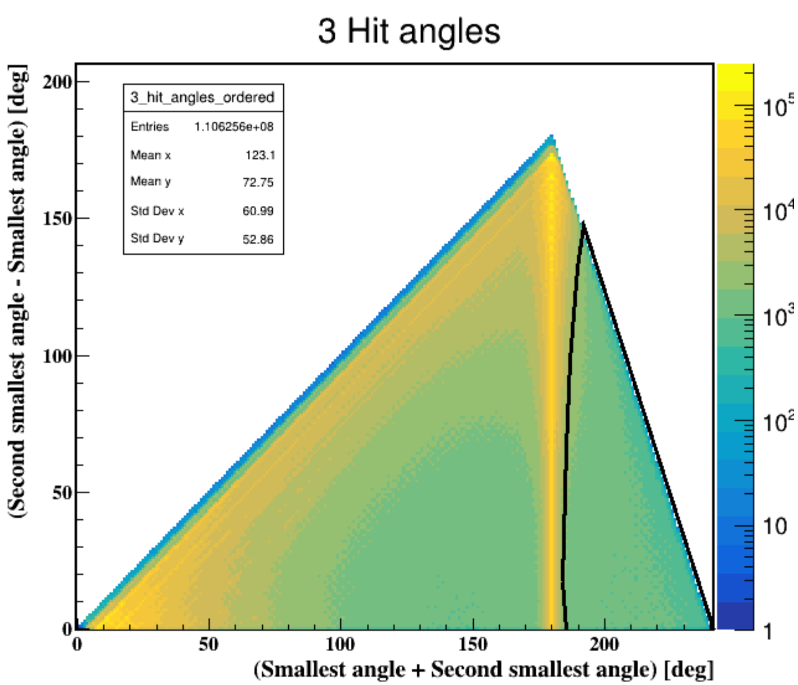
$\theta_{23} + \theta_{12} > 180$

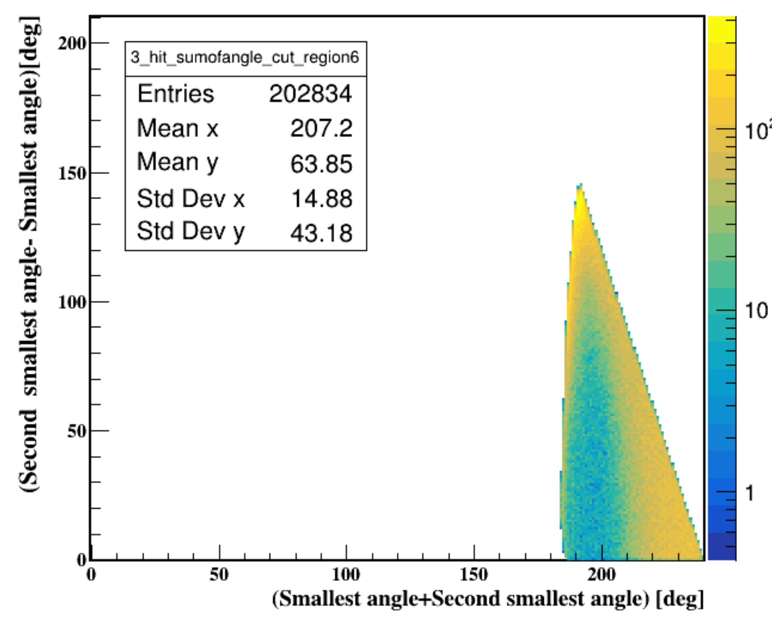
$e^+e^- \rightarrow 2\gamma$
single scattered

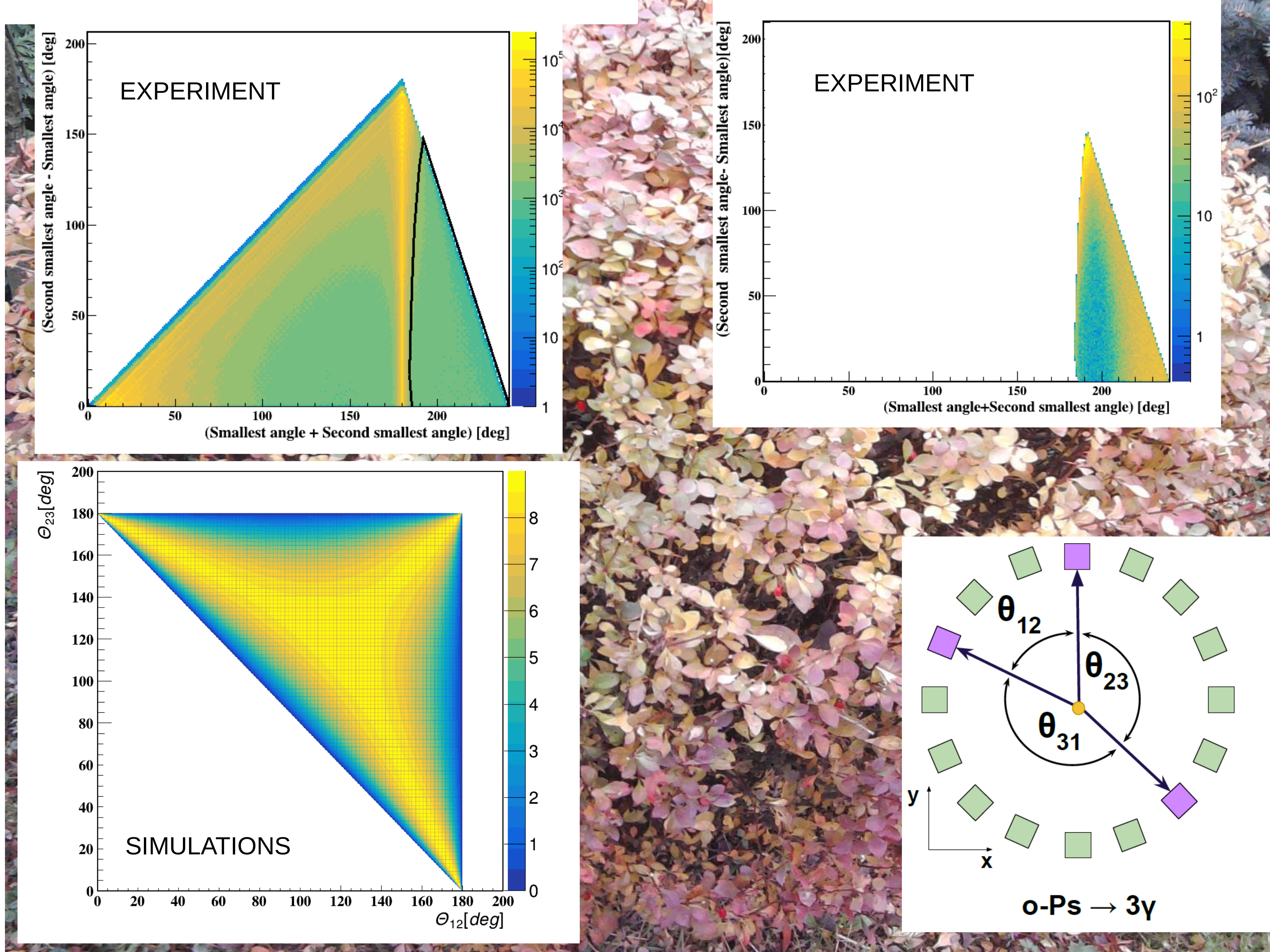
$\theta_{23} + \theta_{12} = 180$

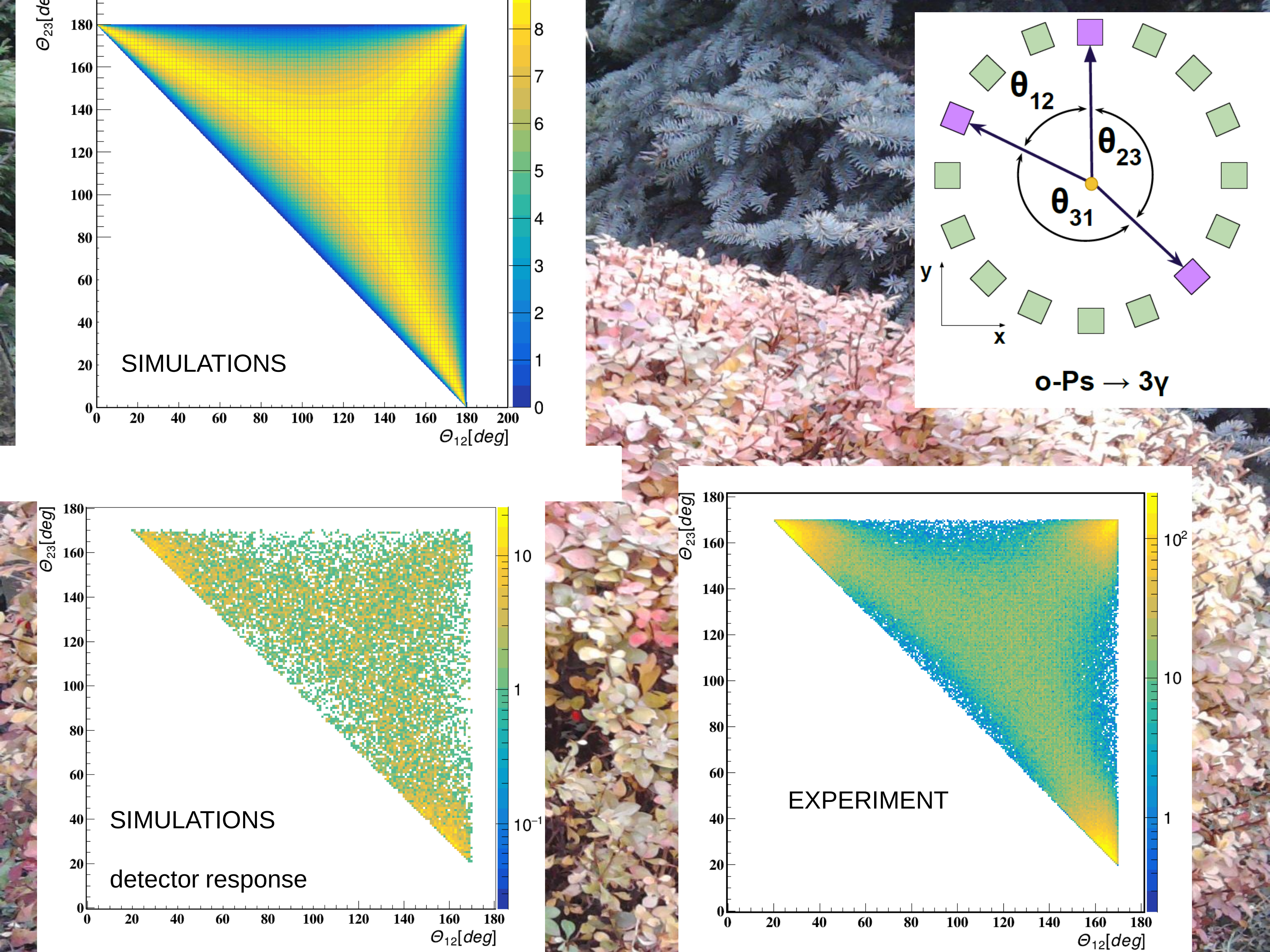
$e^+e^- \rightarrow 2\gamma$
double scattered

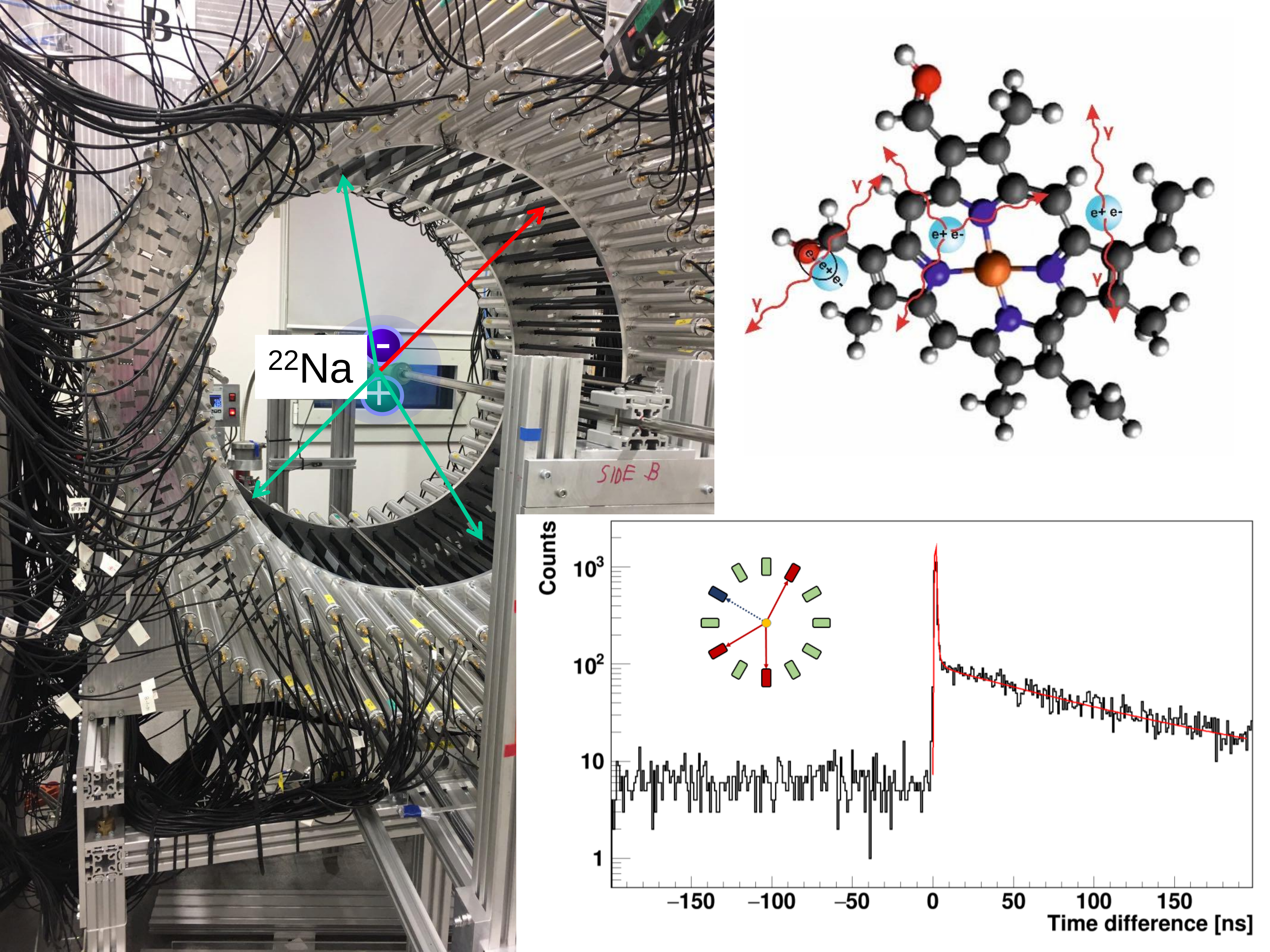
$\theta_{23} + \theta_{12} < 180$






EXPERIMENT
(Second smallest angle - Smallest angle) [deg]
(Smallest angle + Second smallest angle) [deg]
EXPERIMENT
(Second smallest angle- Smallest angle)[deg]
(Smallest angle+Second smallest angle) [deg]
SIMULATIONS
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$
θ_{12}
θ_{23}
θ_{31}
y
x
o-Ps → 3γ

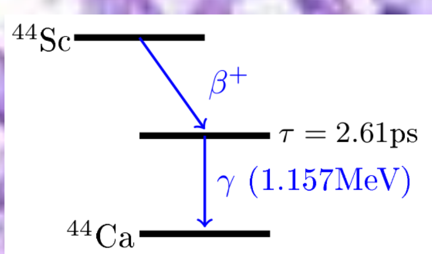

SIMULATIONS
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$
o-Ps → 3γ
θ12
θ23
θ31
x
y
SIMULATIONS
detector response
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$
EXPERIMENT
$\Theta_{23}[deg]$
$\Theta_{12}[deg]$



B
22Na
SIDE B
γ
e+ e-
Counts
10³
10²
10
1
−150
−100
−50
0
50
100
150
Time difference [ns]

P. M., Patent US 9,851,456, PCT/EP2014/068374

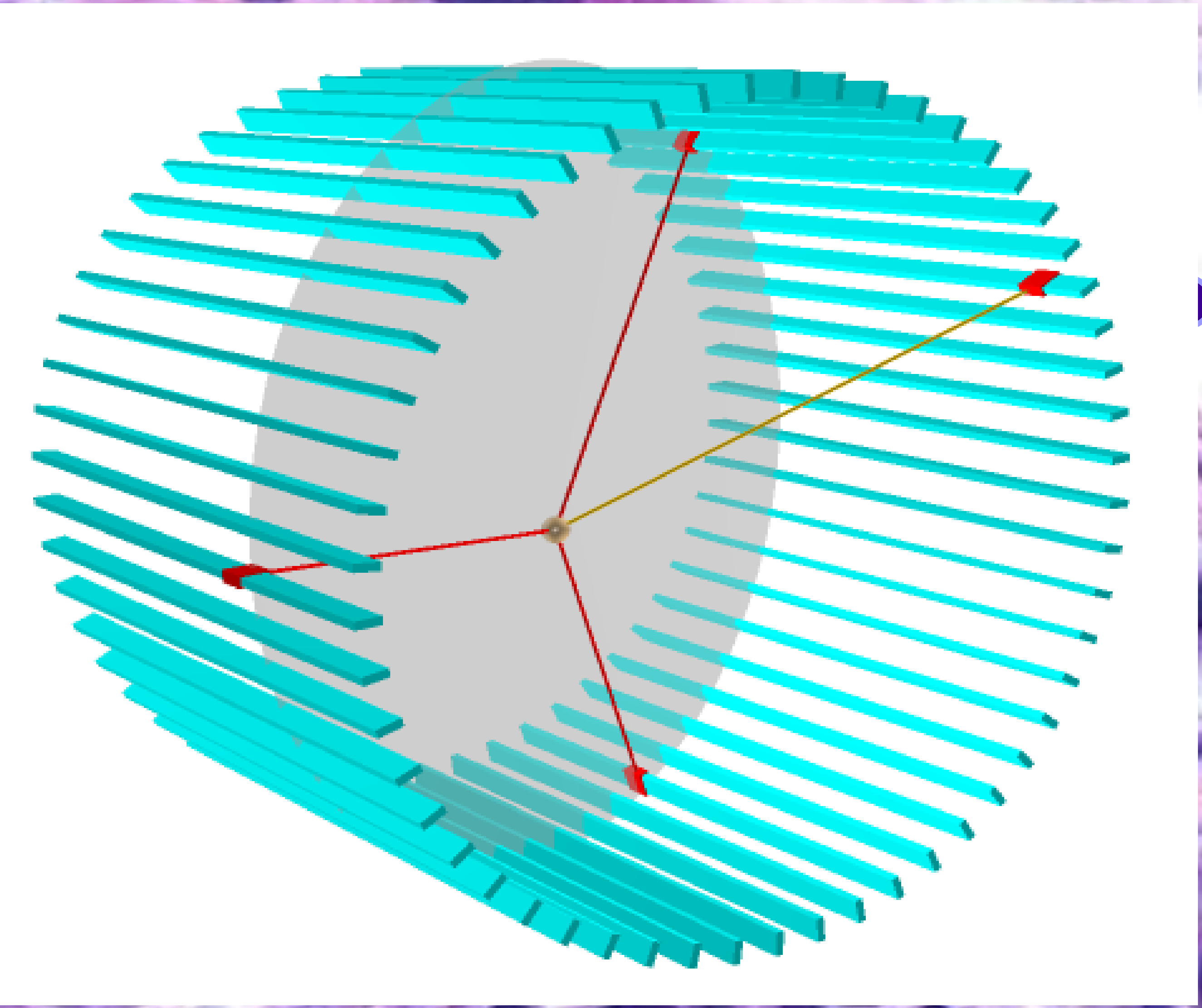
30% – 40%

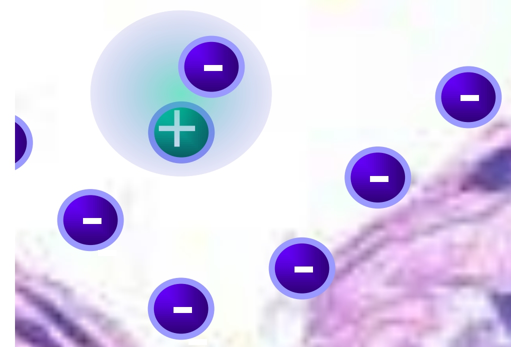


J-PET: P. M et al., Phys. Med. 64 (2019) 055017
https://arxiv.org/pdf/1805.11696.pdf

Ortho-positronium life-time tomography

P. M., Patent US 9,851,456, PCT/EP2014/068374

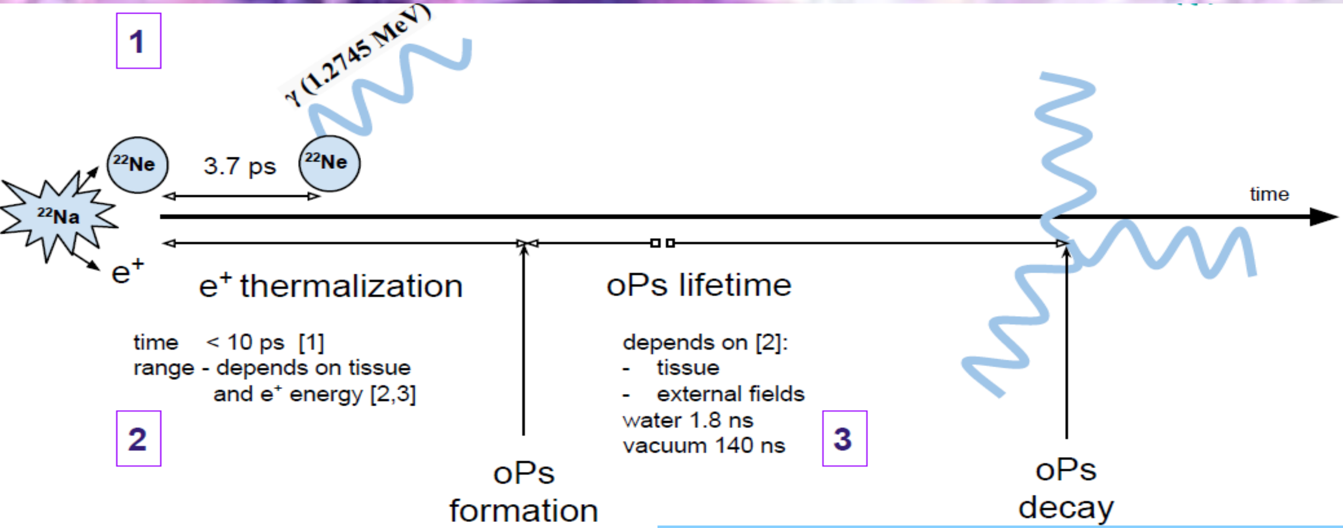


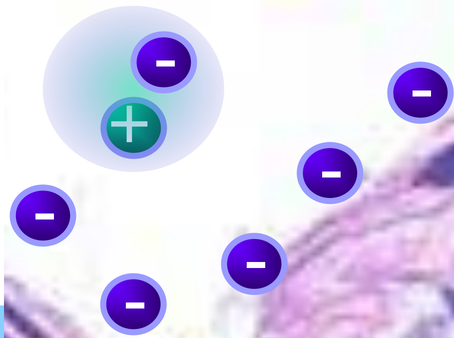


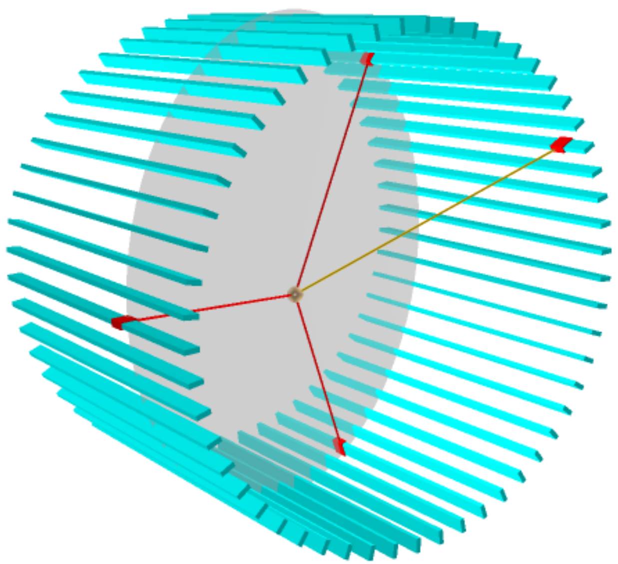
Ortho-positronium life-time tomography

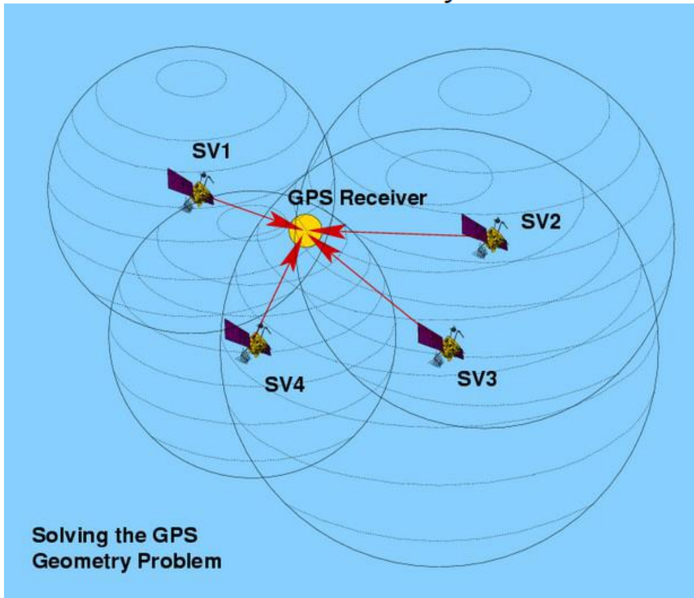
J-PET: P. M et al., Phys. Med. Biol. 64 2019 055017

https://arxiv.org/pdf/1805.11696.pdf



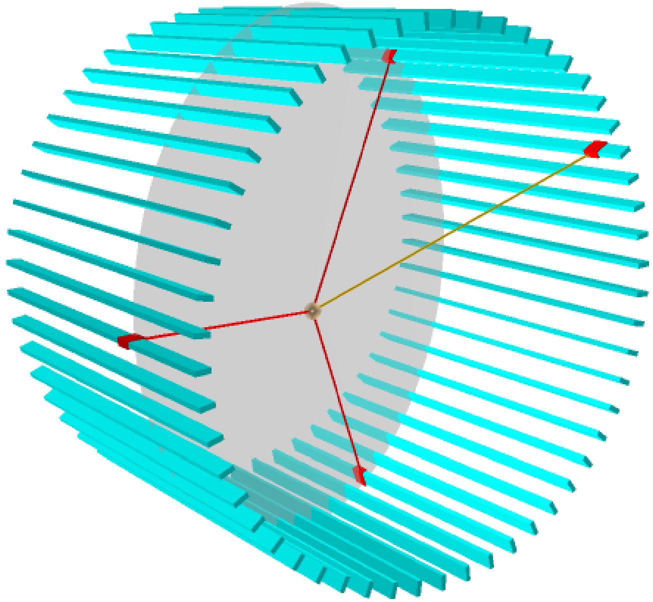


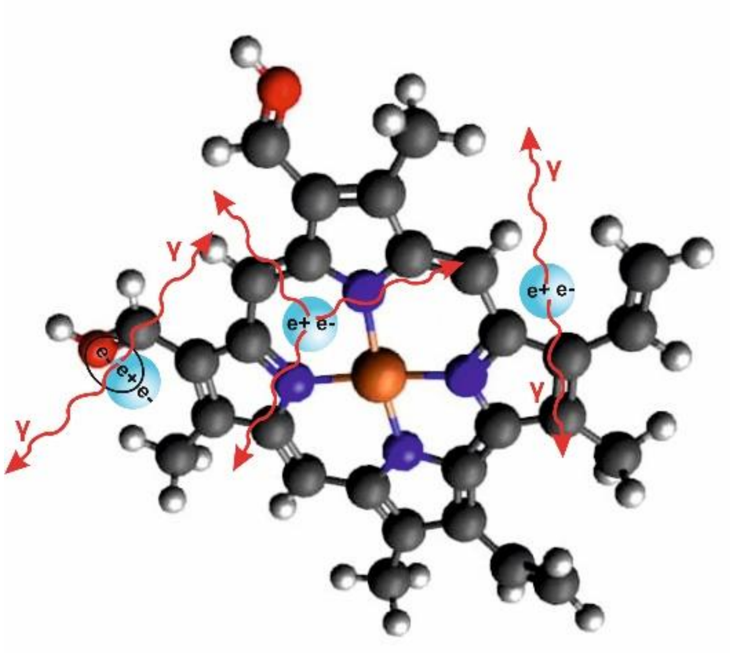




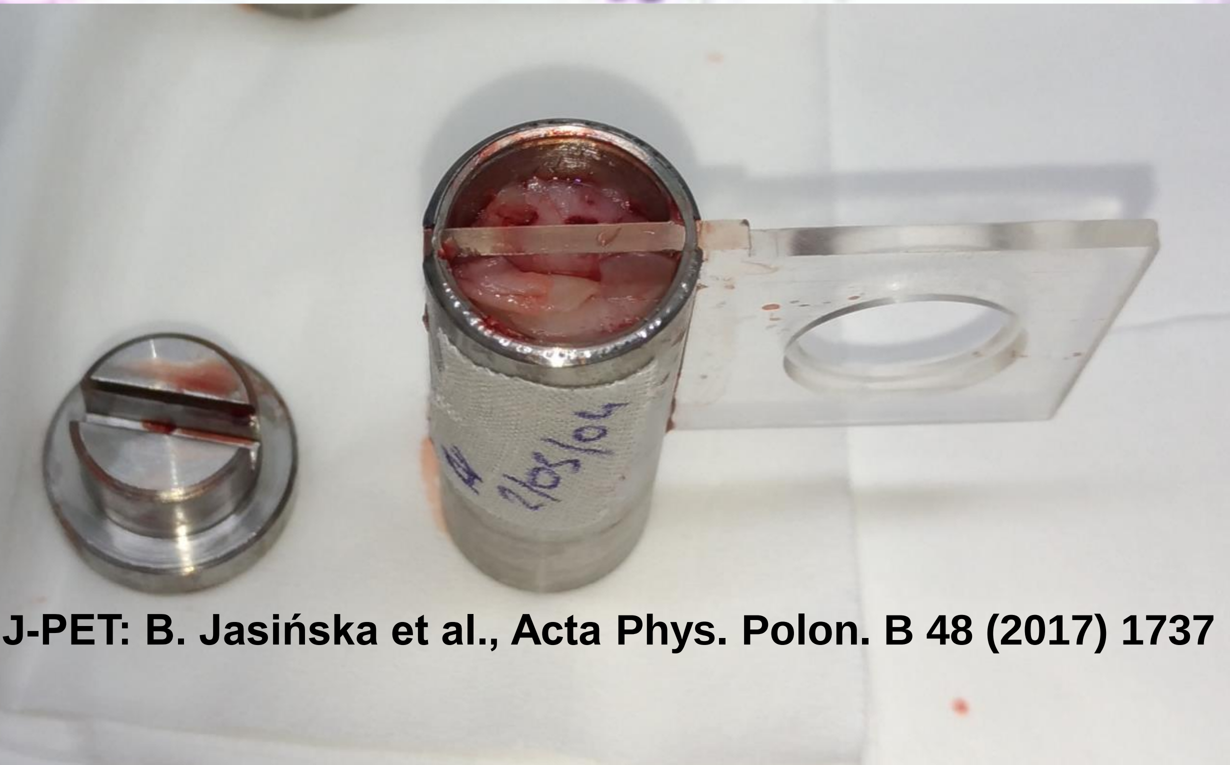
J-PET: A. Gajos et al., Nucl. Instr. Meth. A 819 (2016) 54; D. Kaminska et al., Eur. Phys. J. C (2016) 76:445

3g/2g tomography

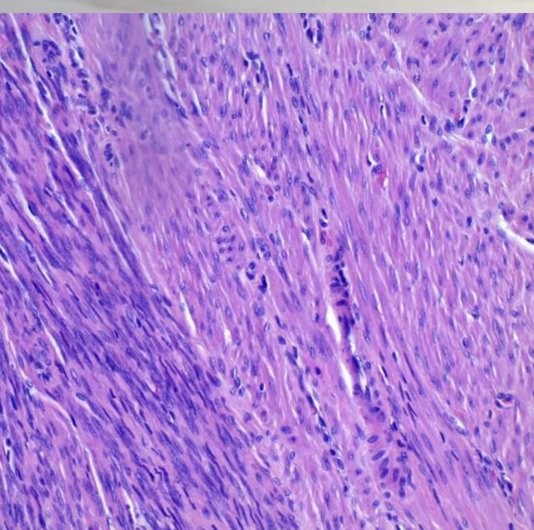


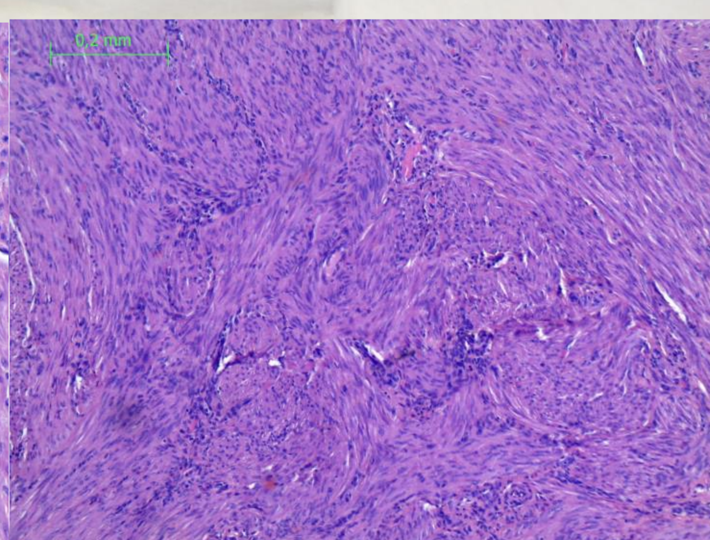


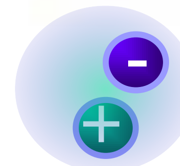
B. Jasińska, P. M. , Acta Physica Polonica B48 (2017) 1577

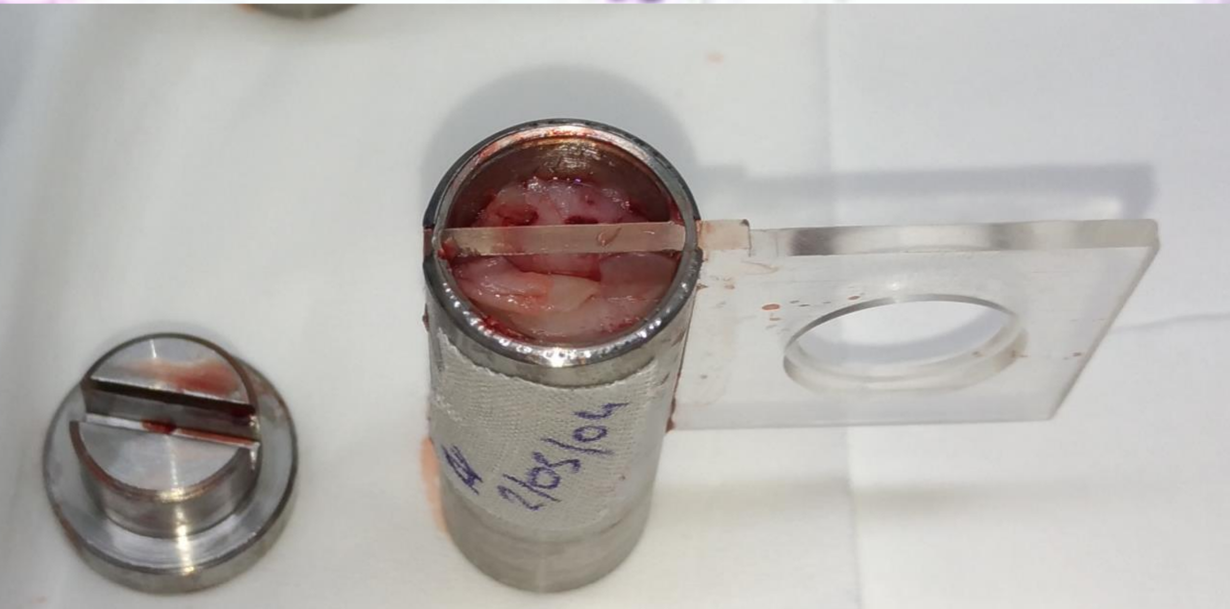


J-PET: B. Jasińska et al., Acta Phys. Polon. B 48 (2017) 1737

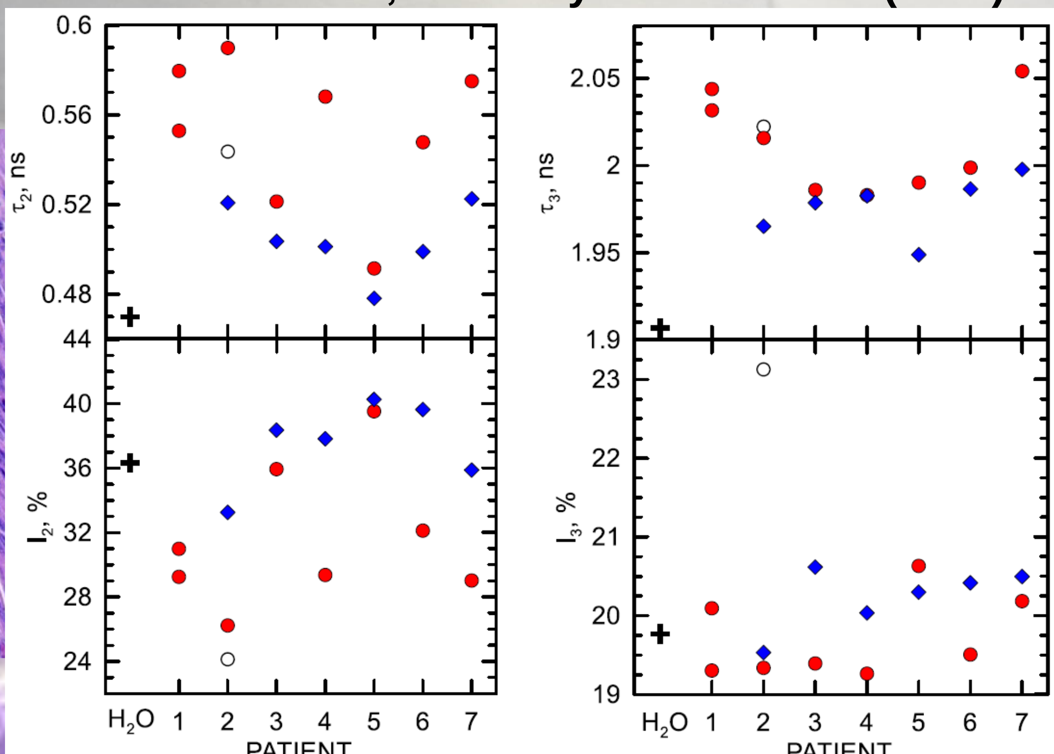


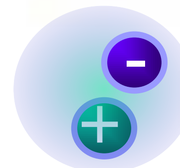




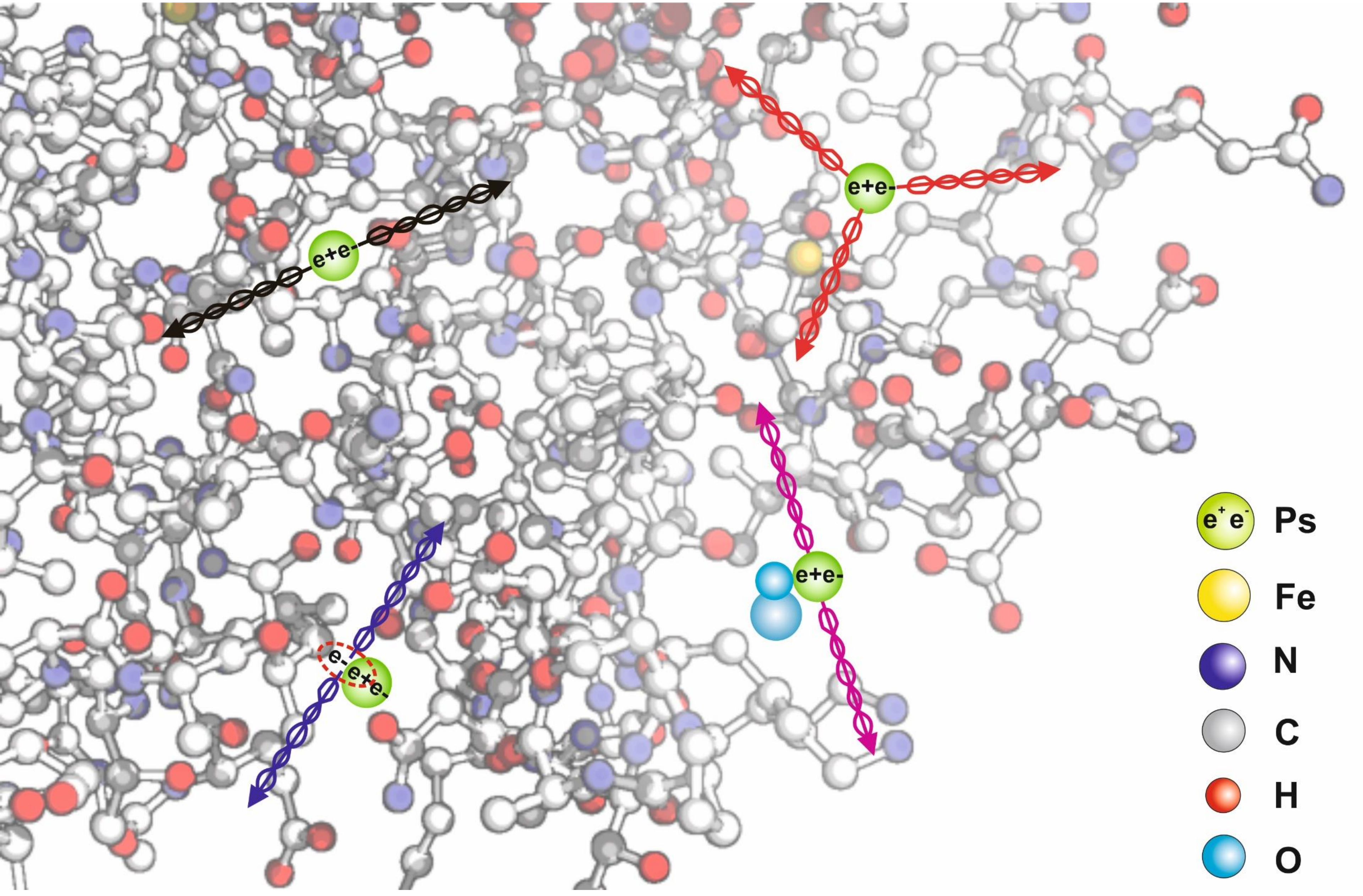


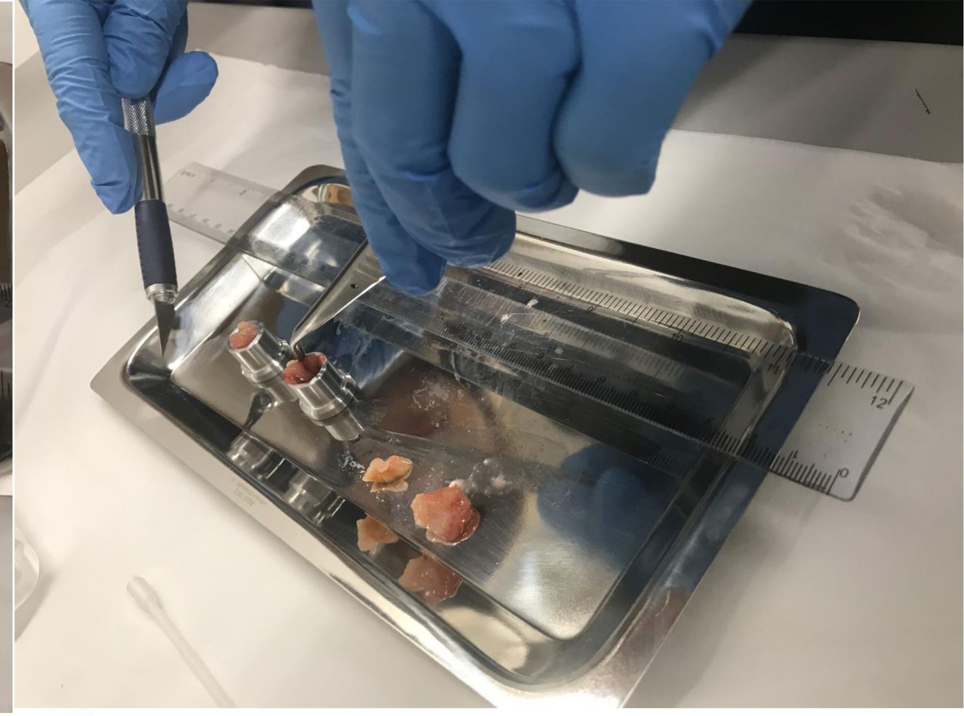
J-PET: B. Jasińska et al., Acta Phys. Polon. B 48 (2017) 1737

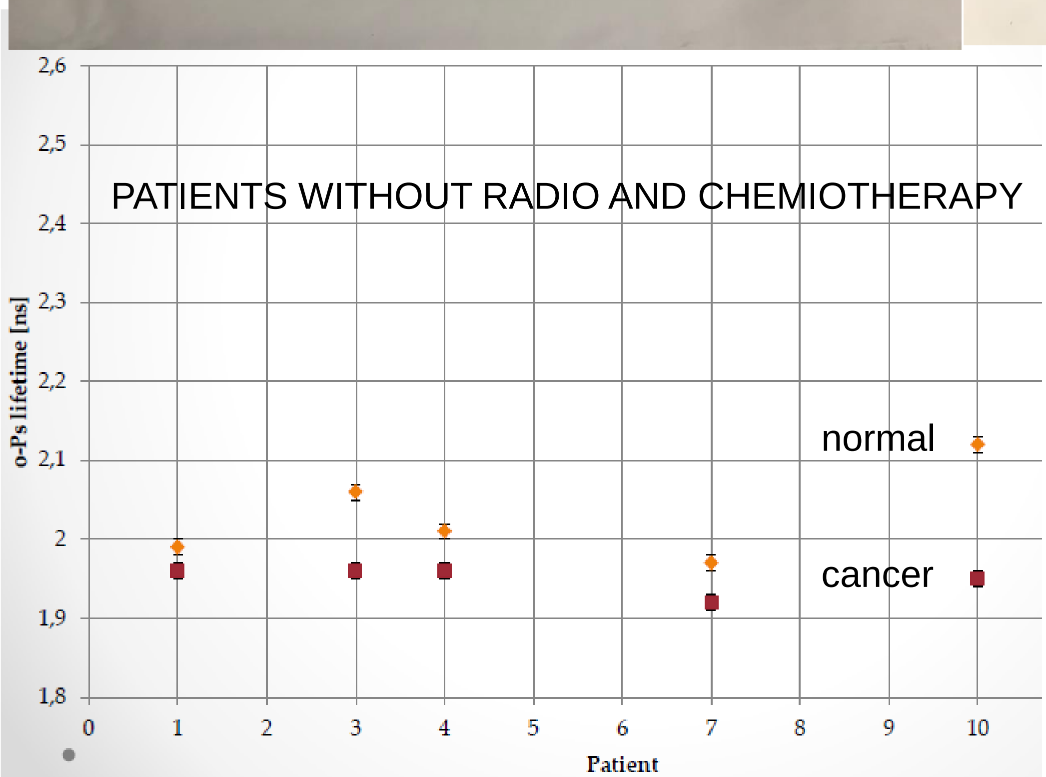




Model of the hemoglobin molecule







COLON CANCER
(CANCER OF LARGE INTENSTINE)

J-PET

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

Discrete symmetries

P reflection in space (x,y,z $\rightarrow$ -x,-y-z)

C charge conjugation (particles $\rightarrow$ anti-particle)

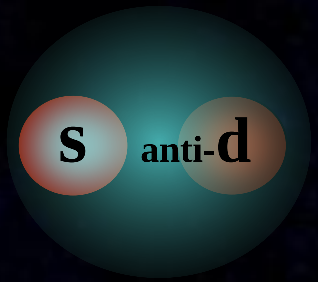
T reversal in time (A $\rightarrow$ B => B $\rightarrow$ A)

CP

CPT

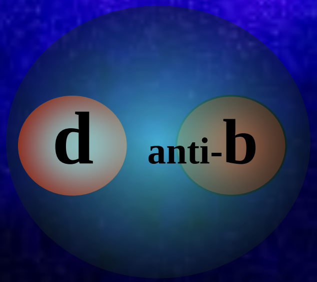
[redacted]

Violation of CP and T
confirmed experimentally
for hadrons only



meson K

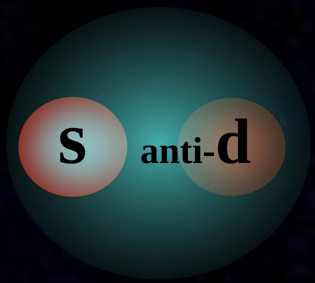
1964



meson B

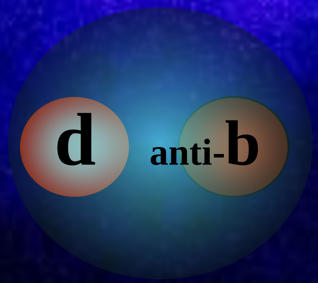
2012

Violation of CP and T confirmed experimentally for hadrons only



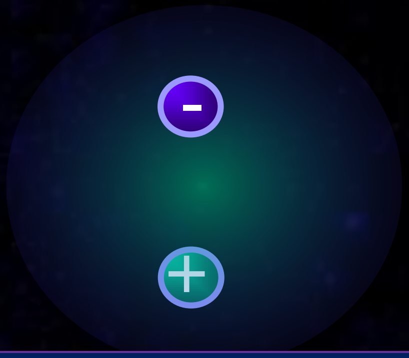
meson K

1964



meson B

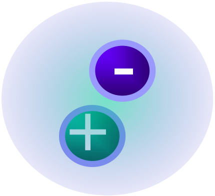
2012



positronium

?

ODE TO POSITRONIUM



Eigen-state of Hamiltonian and P, C, CP operators

The lightest known atom and at the same time anti-atom which undergoes self-annihilation as flavor neutral mesons

The simplest atomic system with charge conjugation aigenstates.

Electrons and positron are the lightest leptons so they can not decay into lighter partilces via weak interactiom ...
effects due the weak interaction can lead to the violation at the order of 10^{-14}.
M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)

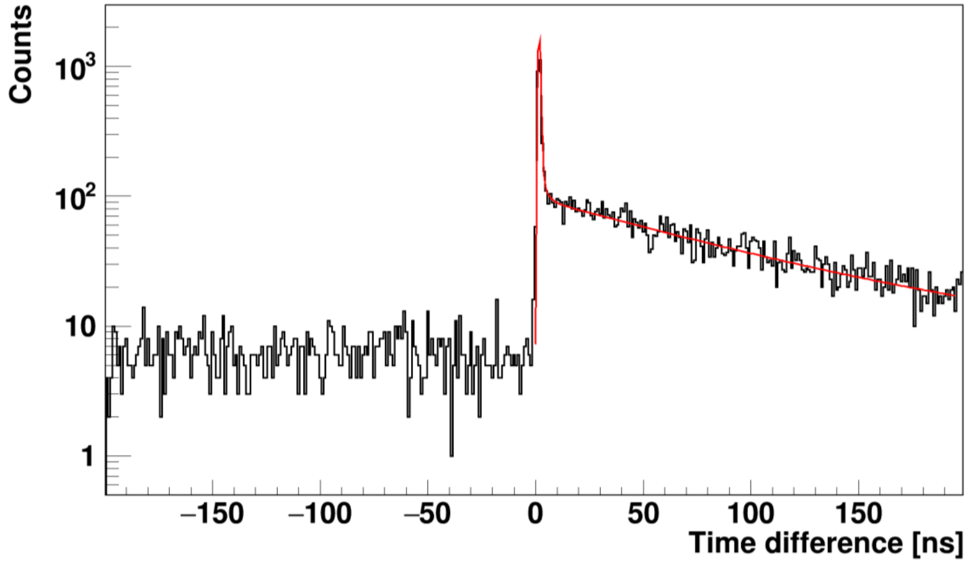
No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)
Light by light contributions to various correlations are small
B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988).
W. Bernreuther et al., Z. Phys. C 41, 143 (1988).

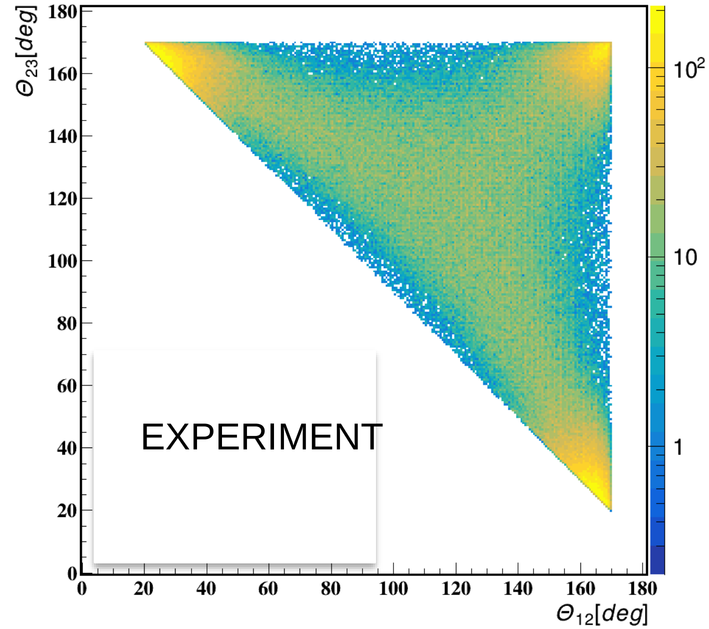
Purely Leptonic state !

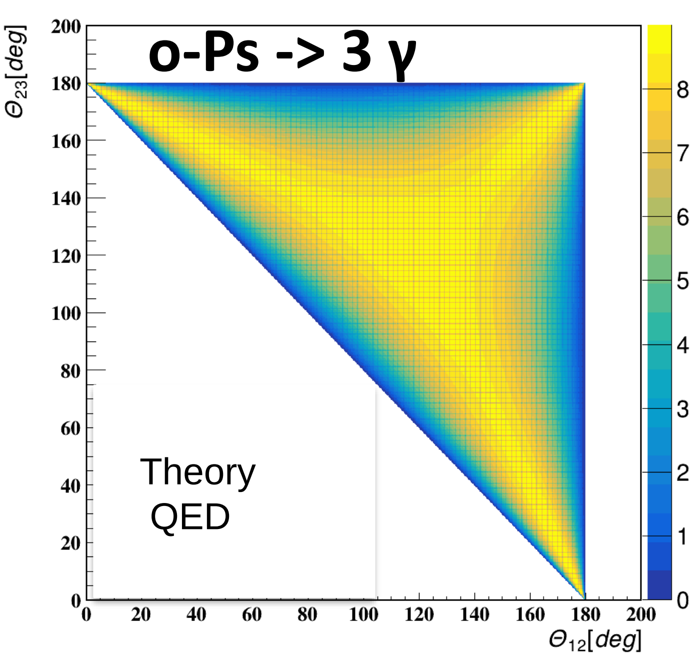
Breaking of T and CP was observed but only for processes involving quarks.
So far breaking of these symmetries was not observed for purely leptonic systems.

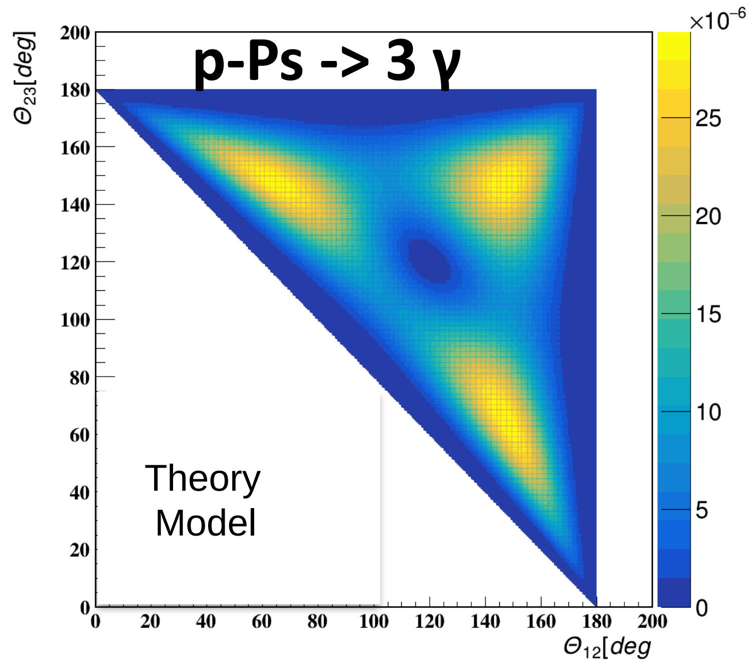
10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003)
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401


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


Θ23[deg]
Θ12[deg]
EXPERIMENT
10^2
10
1

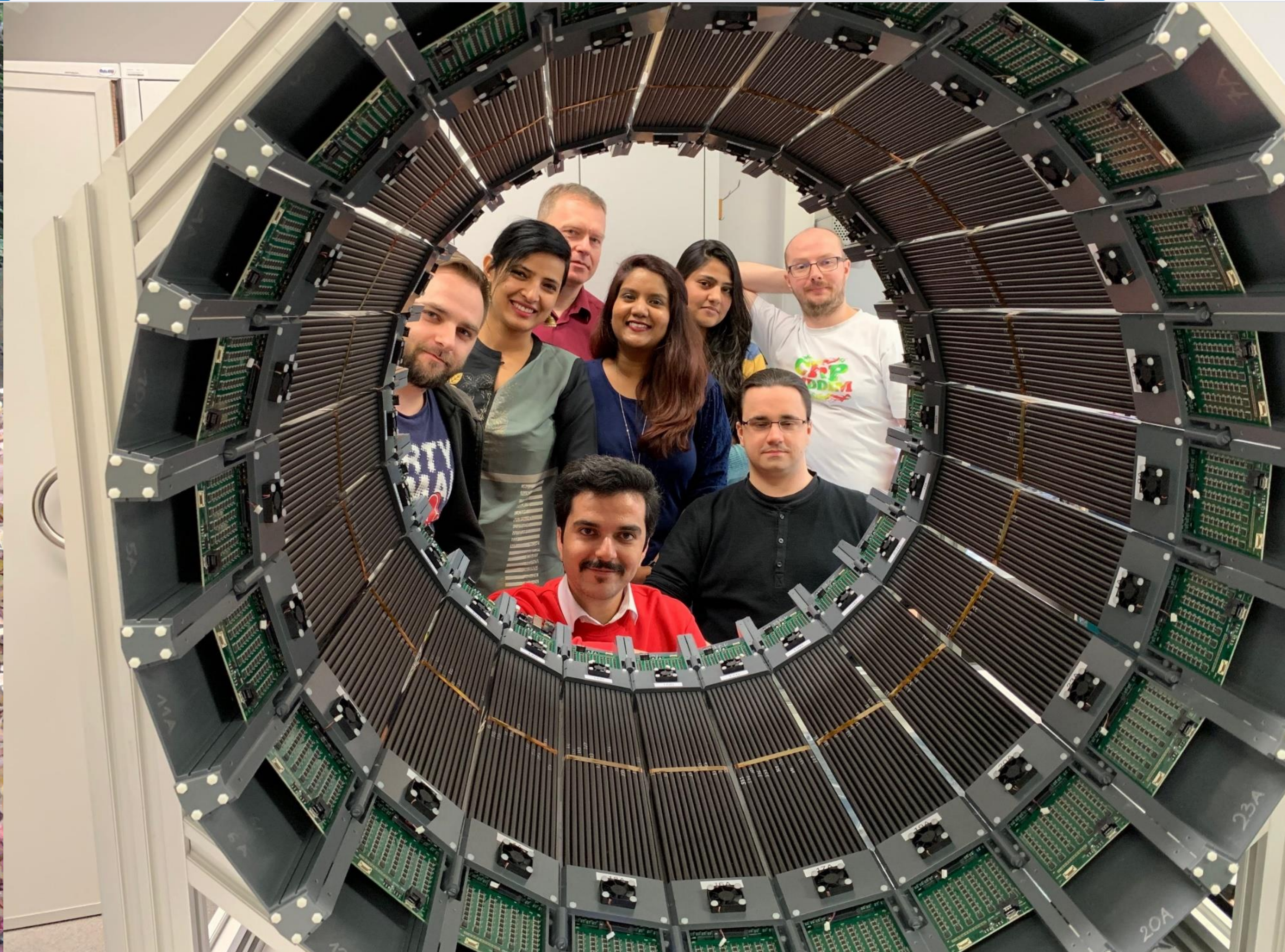

o-Ps -> 3 γ
Θ23[deg]
Θ12[deg]
Theory
QED

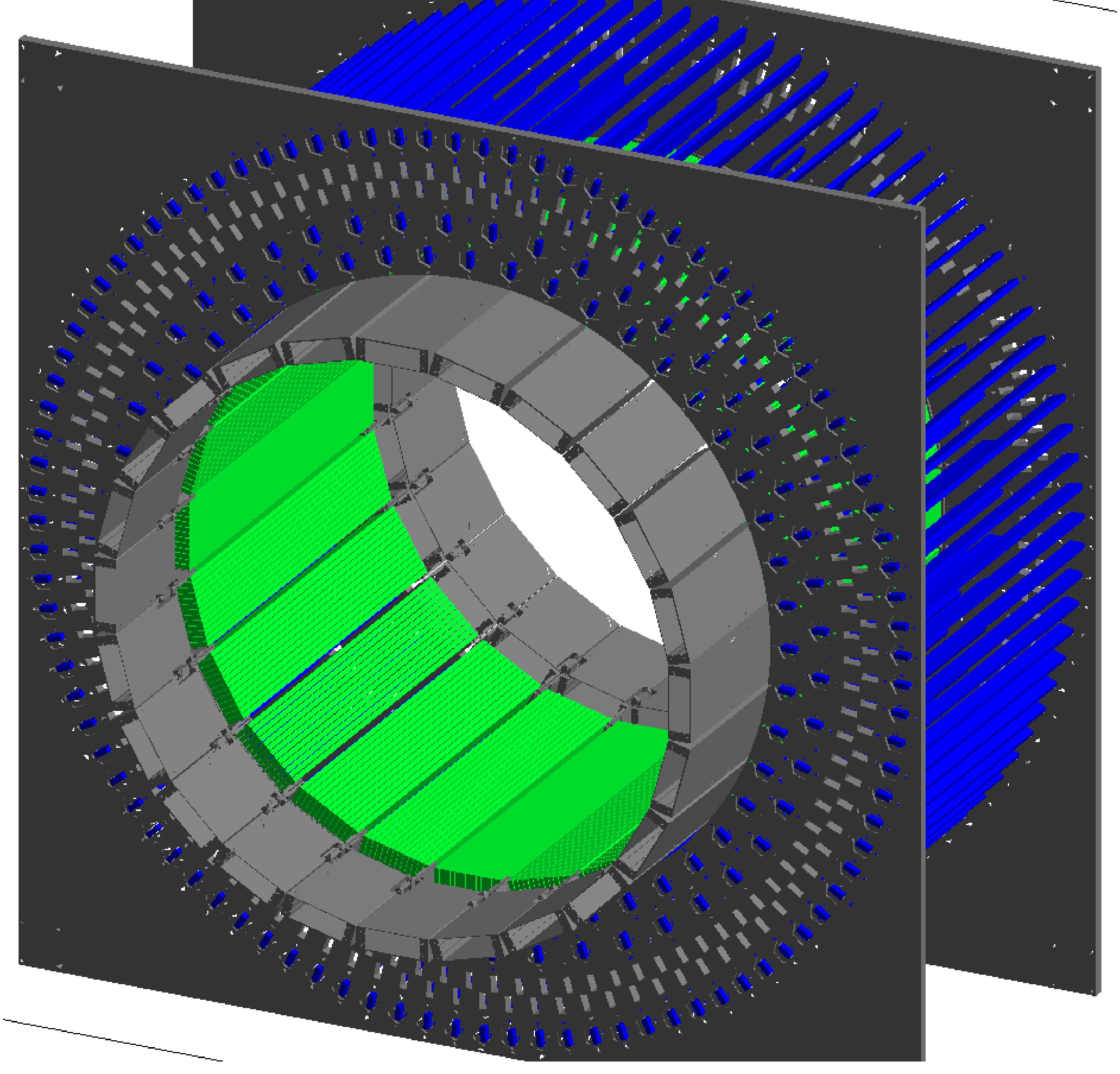

p-Ps -> 3 γ
Θ23[deg]
Θ12[deg
×10^−6
Theory
Model

J-PET

Jagiellonian PET

J-PET

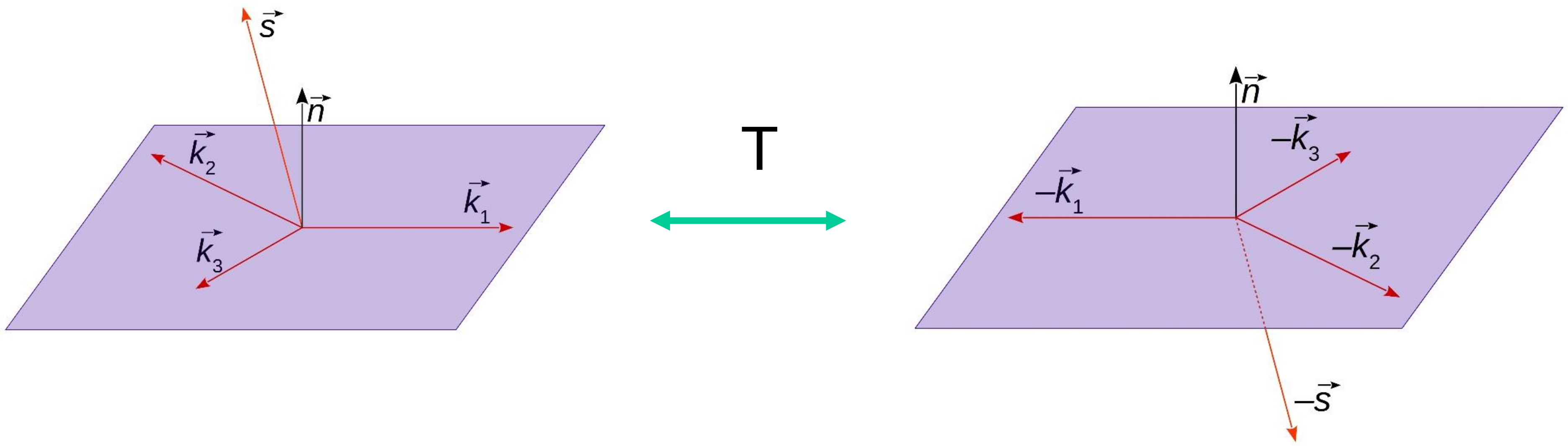




Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	–	–	–	+

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

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



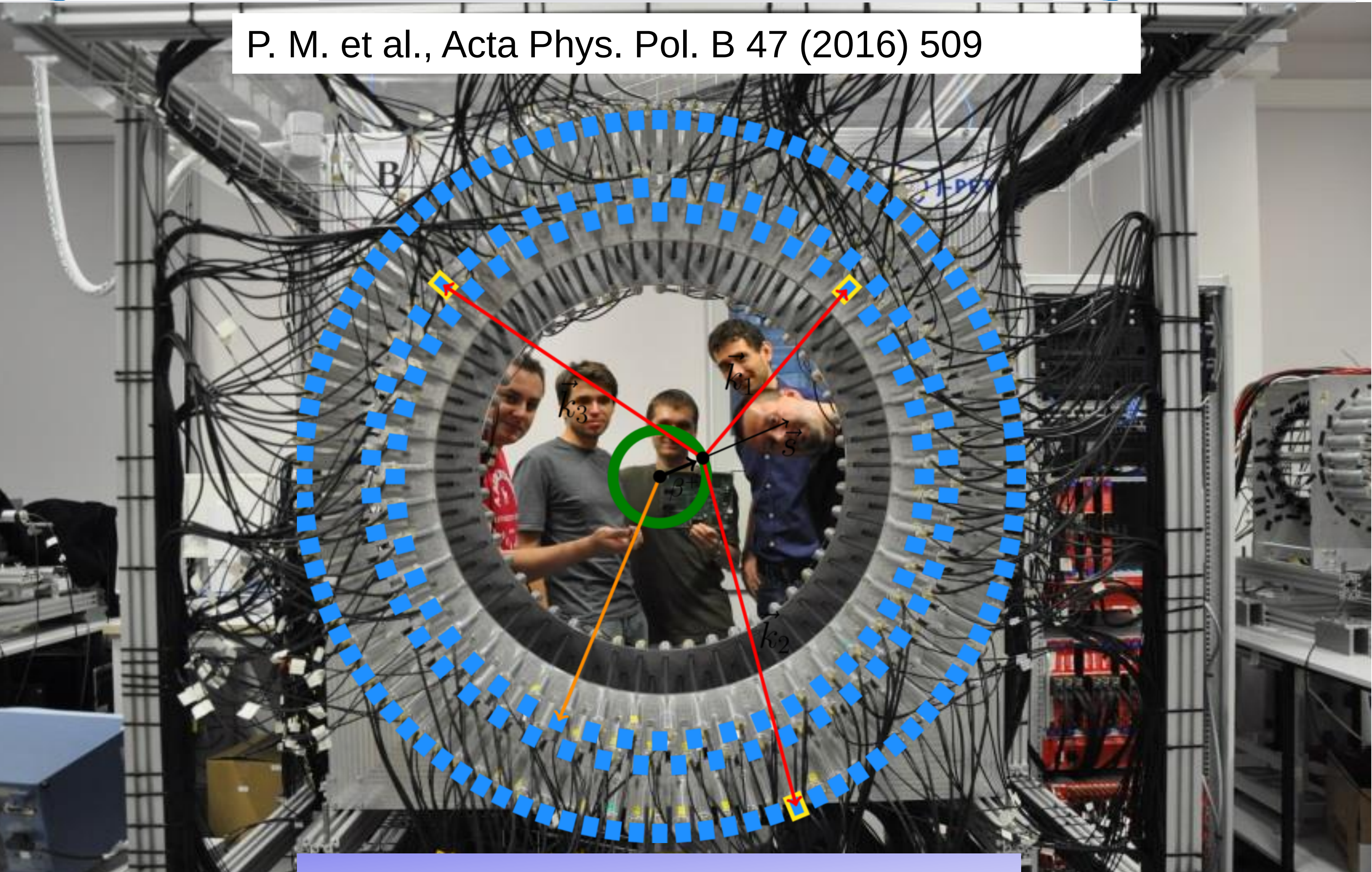
So far best accuracy for tests of **CP and CPT violation** was reported by

-0.0023 < CP < 0.0049 at 90% CL T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

CPT = 0.0071 ± 0.0062 P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003).

Jagiellonian PET

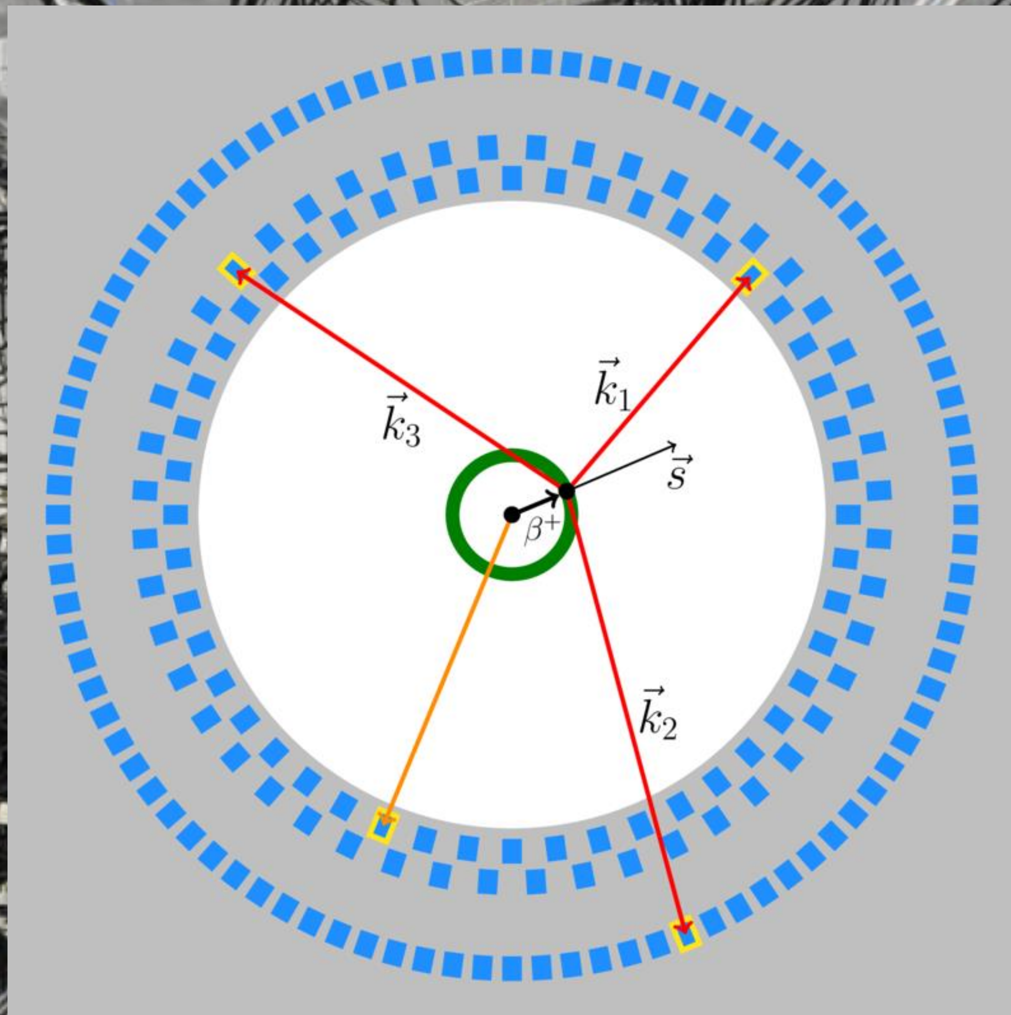
P. M. et al., Acta Phys. Pol. B 47 (2016) 509



σ(t-hit) ~ 100 ps

Jagiellonian PET

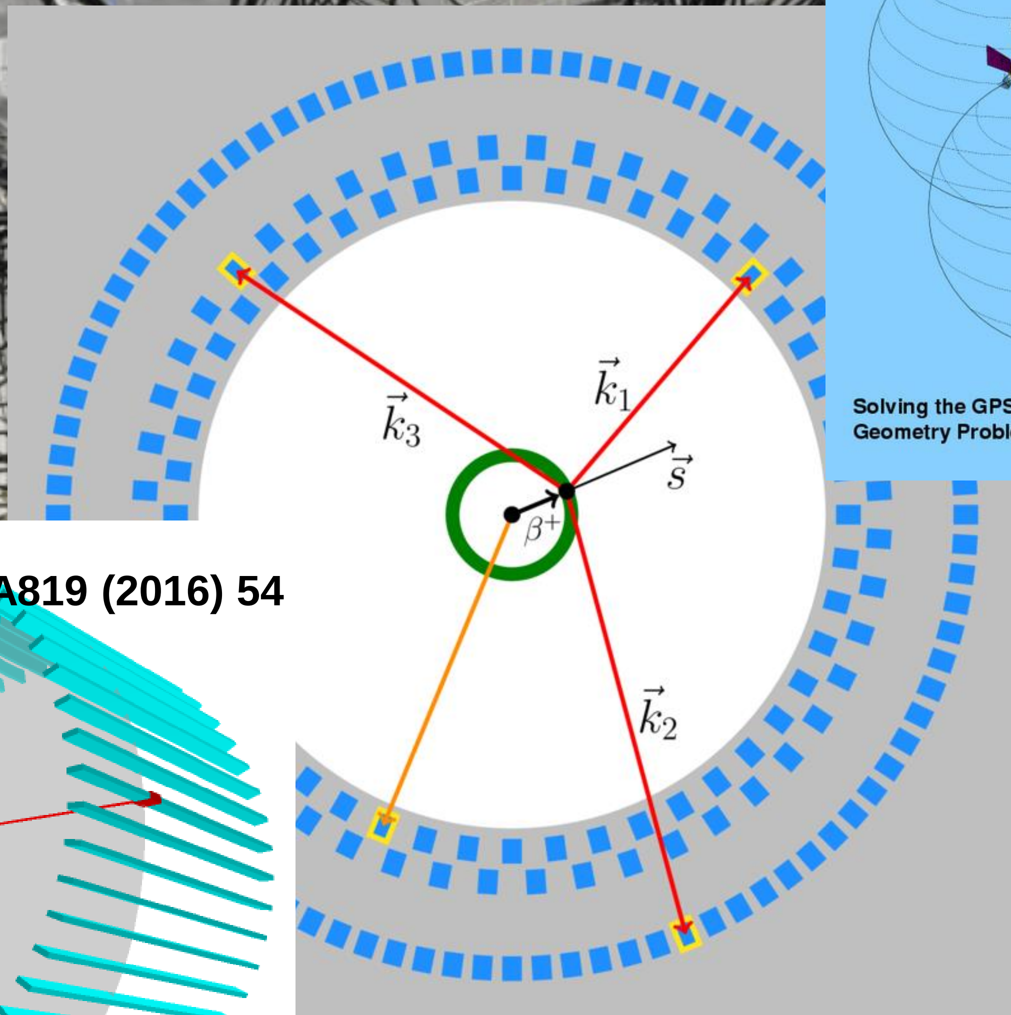
P. M. et al., Acta Phys. Pol. B 47 (2016) 509

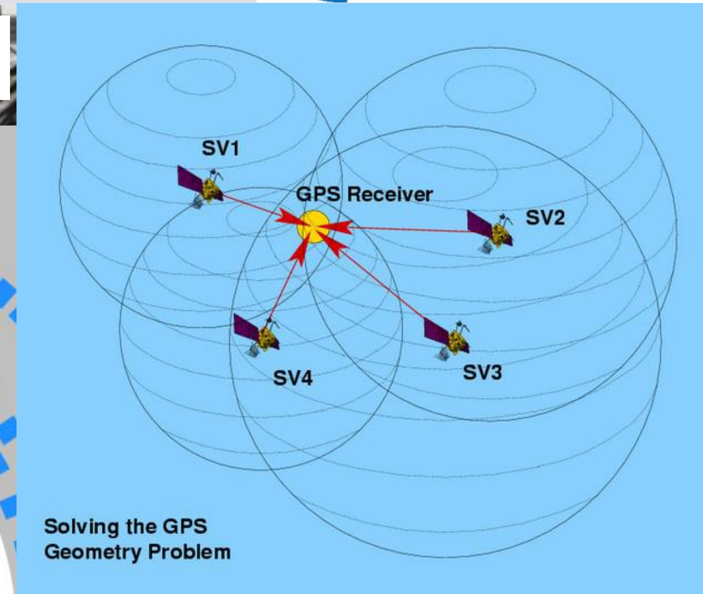


σ(t-hit) ~ 100 ps

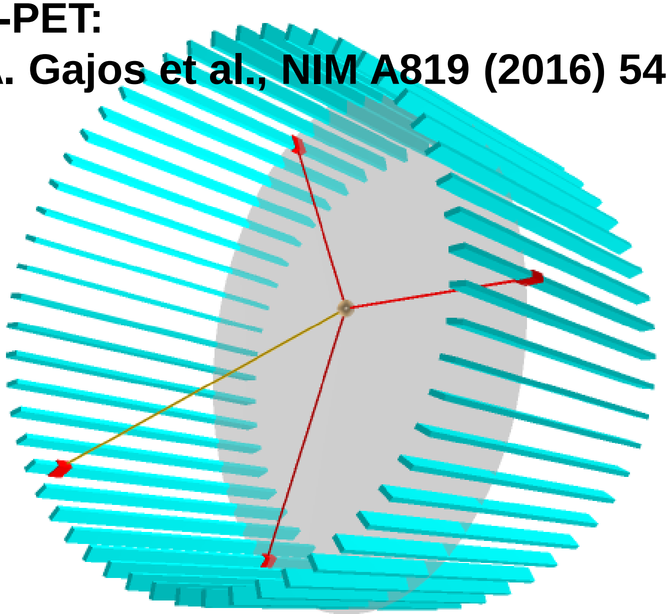
Jagiellonian PET

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

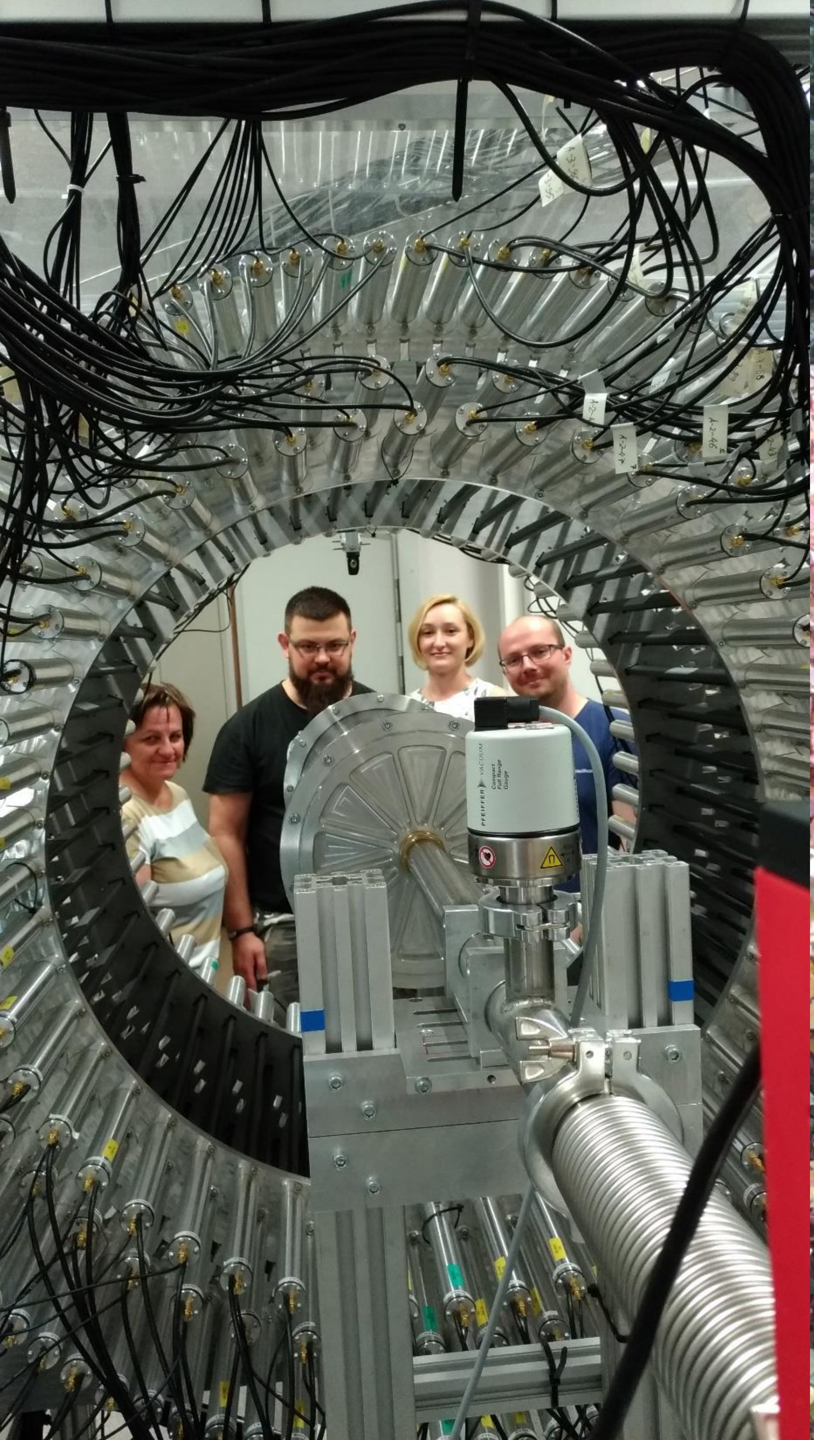


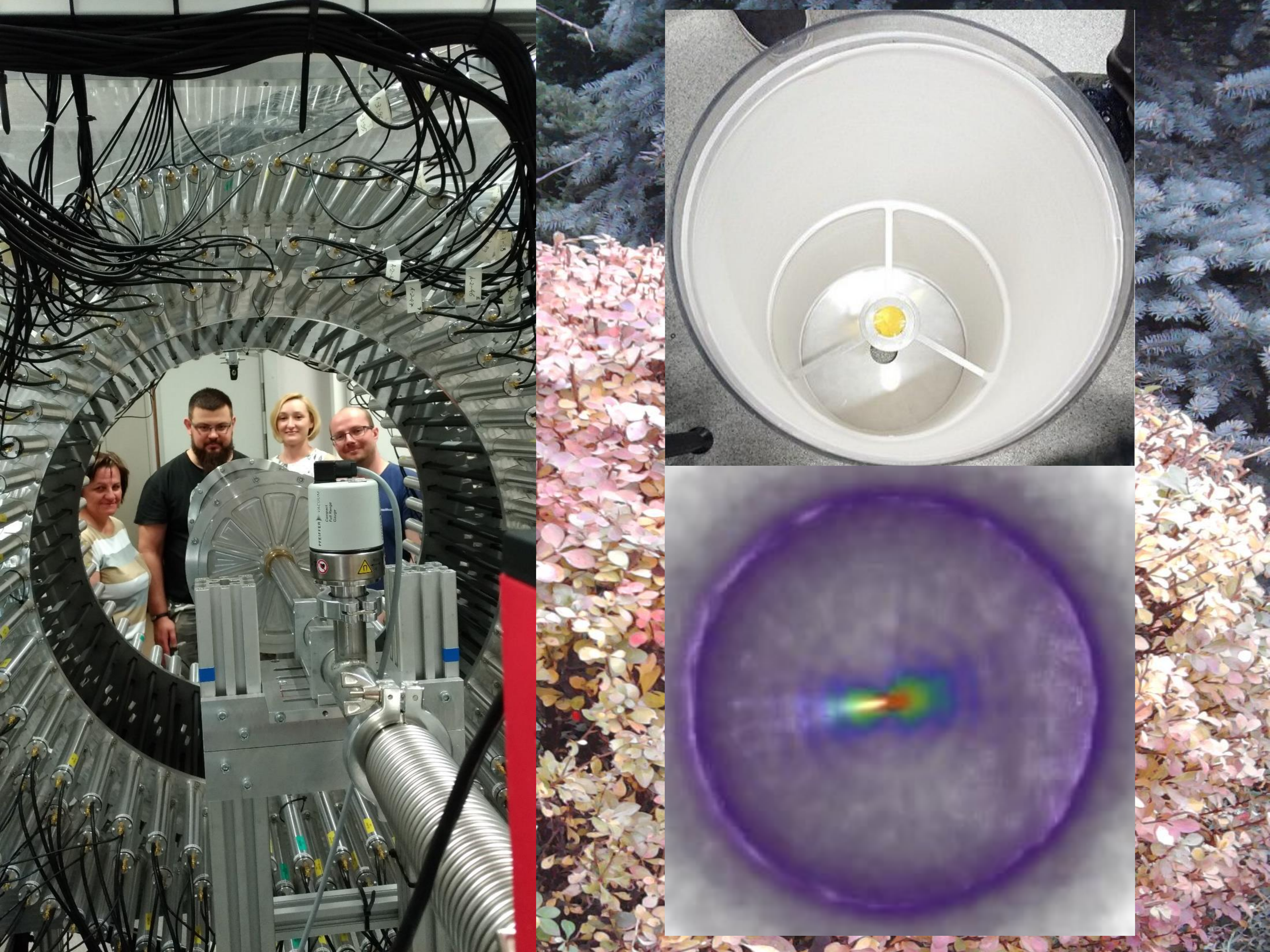


J-PET:
A. Gajos et al., NIM A819 (2016) 54



σ(t-hit) ~ 100 ps

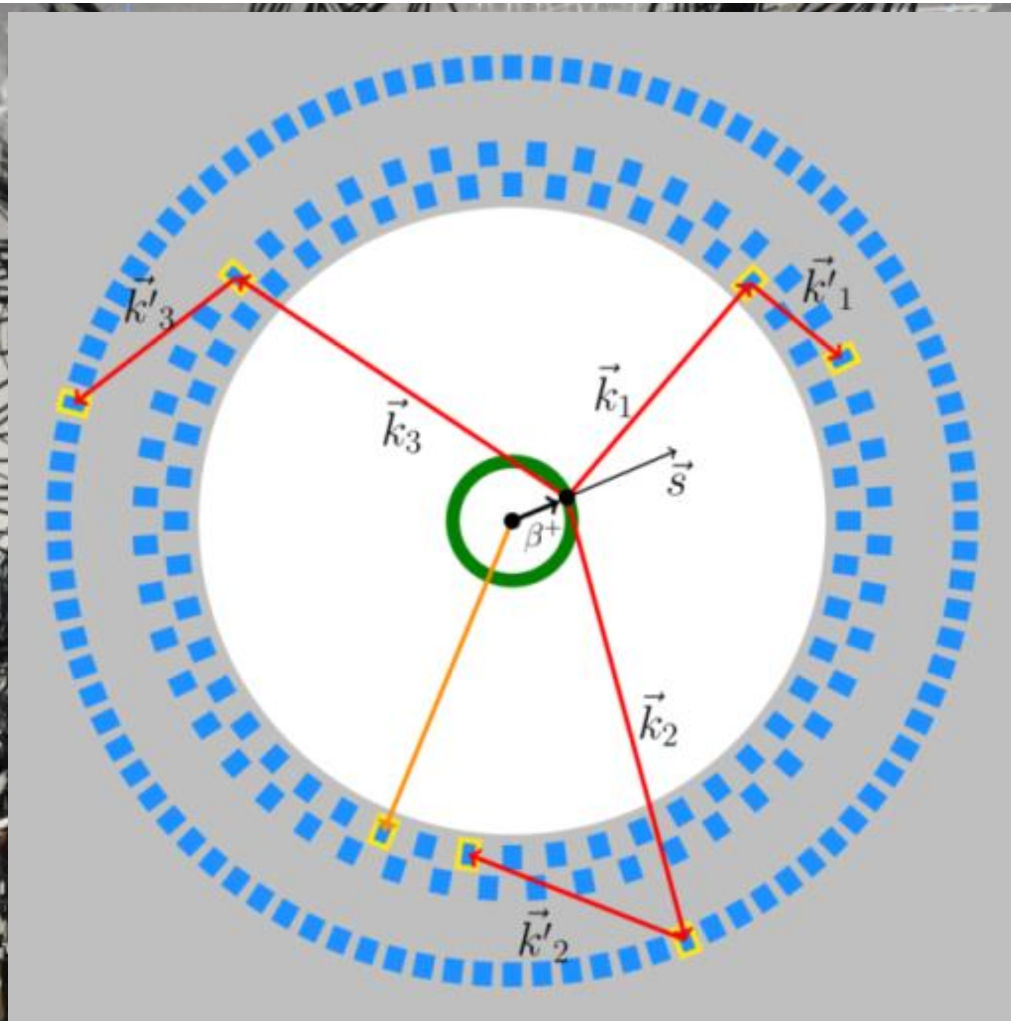




Jagiellonian PET

J-PET

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

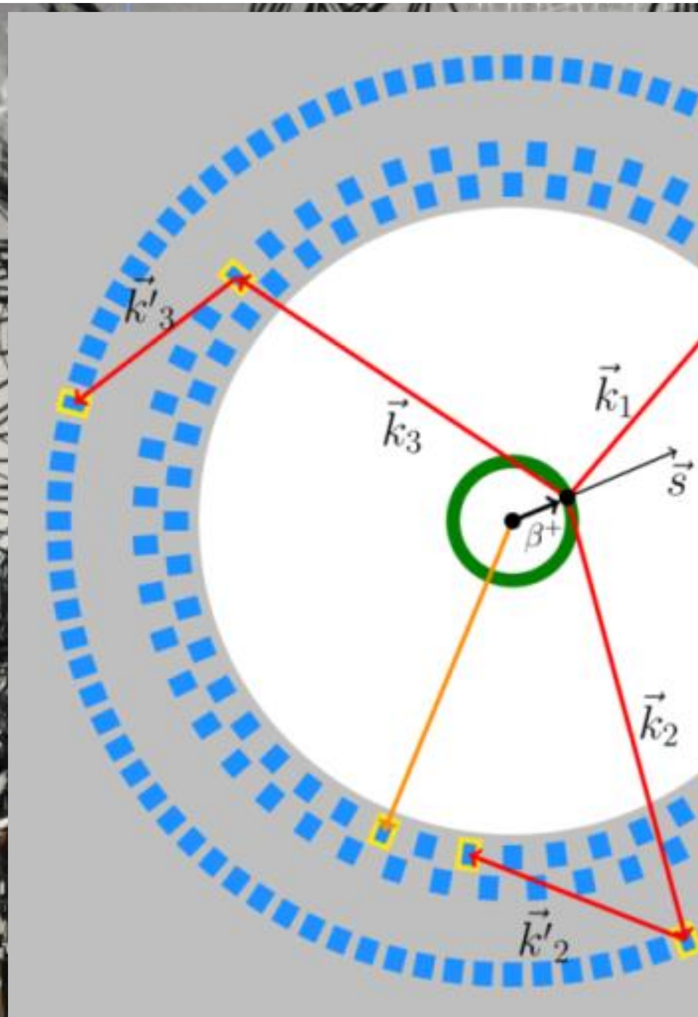


$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$

σ(t-hit) ~100 ps

Jagiellonian PET

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



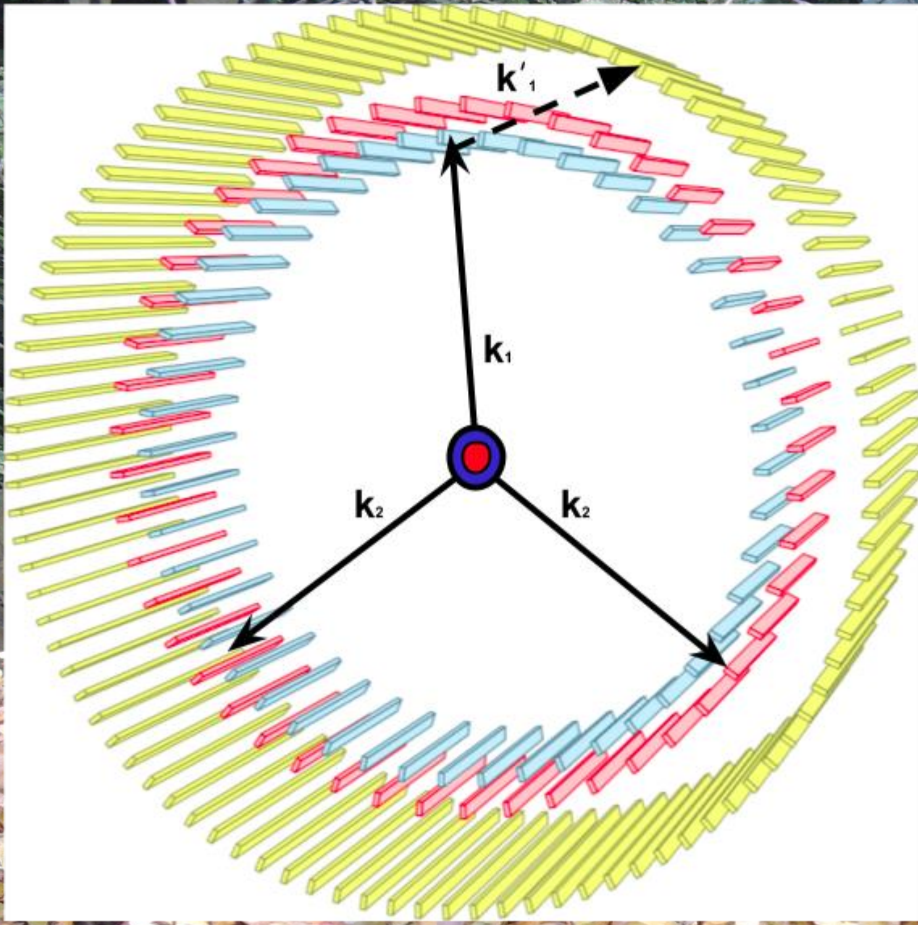
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	–	–	–	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$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

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

σ(t-hit) ~ 100 ps

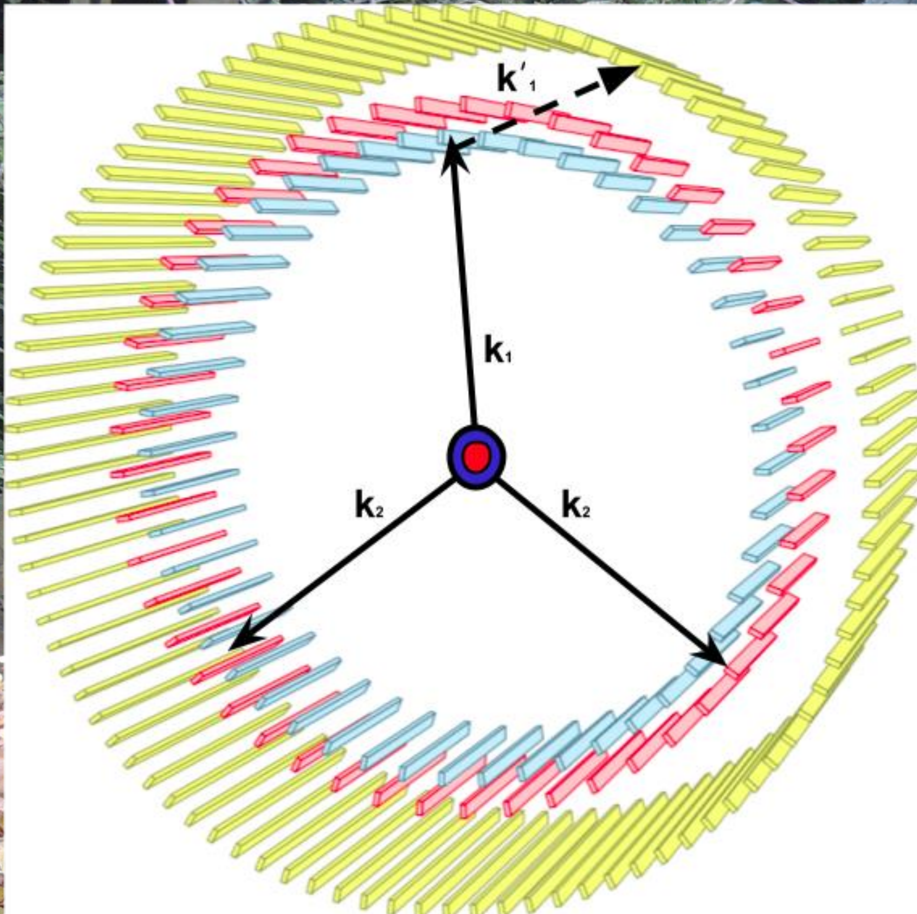
SM 10^{-9} vs upper limits of 3 10^{-3} for T, CP, CPT


B
SIDE B
WARNING
KEEP HANDS OUT OF MACHINERY



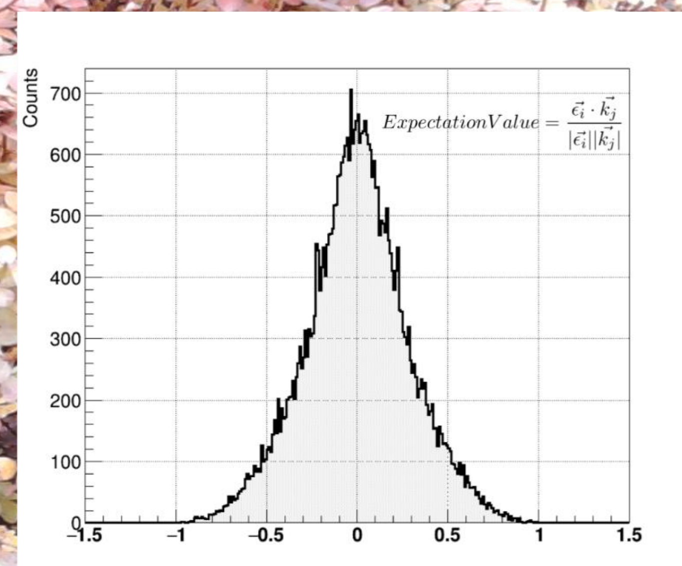
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	–	–	–	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$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

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



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

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



Best so far:

-0.0023 < CP < 0.0049 at 90% CL

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

Total No. of Entries = 39816

Expectation Value = 0.0005 +/- 0.0014

PRELIMINARY from 5% of data

J-PET

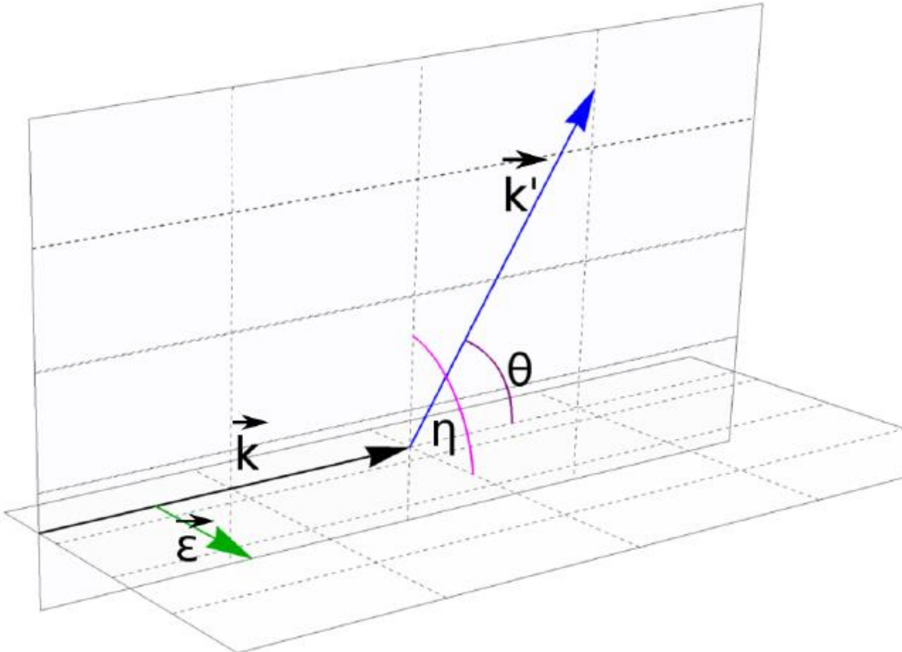
Jagiellonian PET

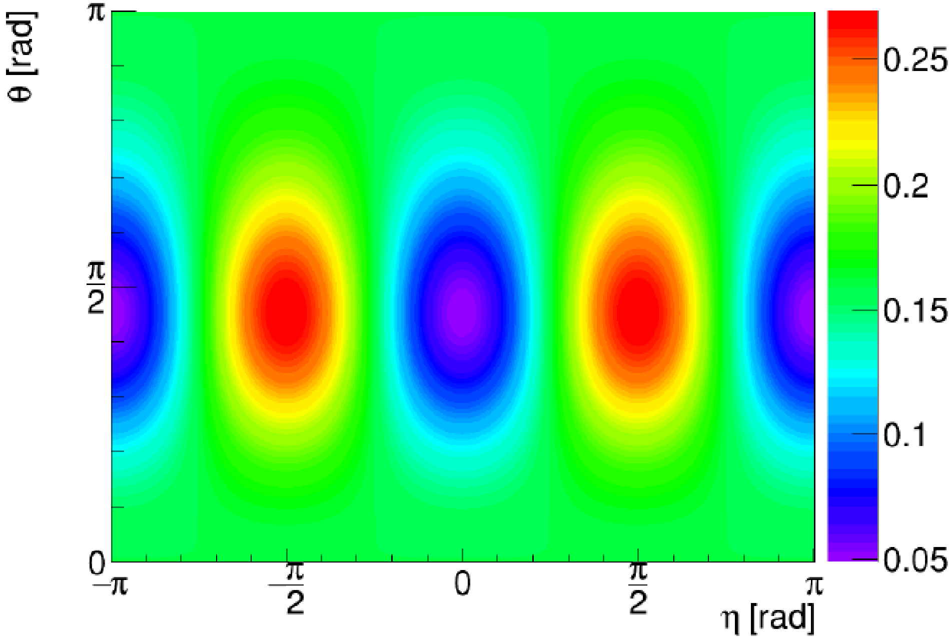
J-PET

THANK YOU
FOR YOUR ATTENTION

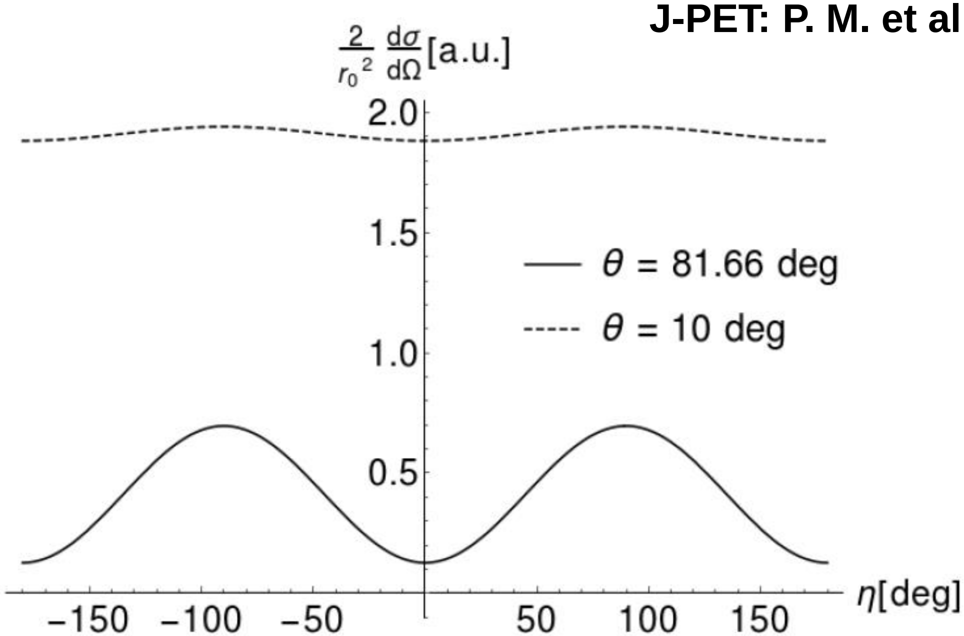
J-PET

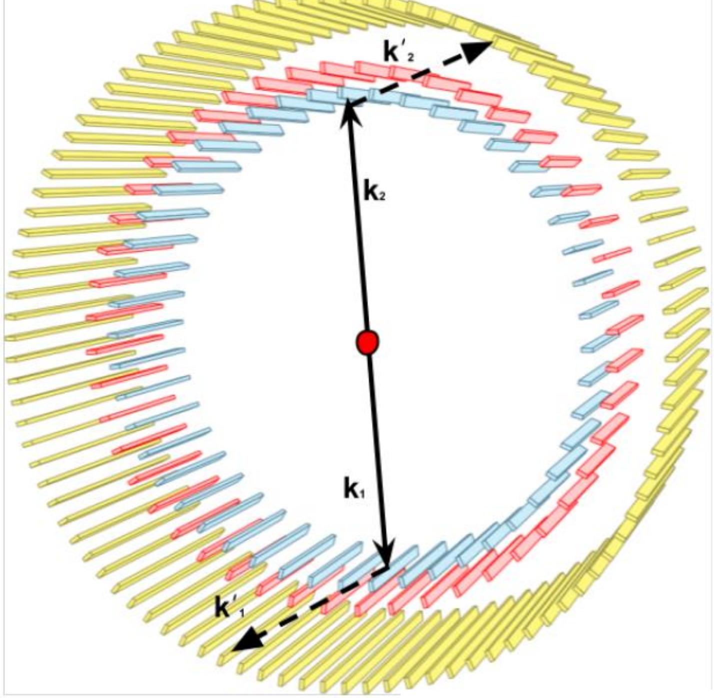
- PET
- Jagiellonian-PET (J-PET)
- Positronium imaging (PET & PALS)
- Discrete symmetries
- Quantum Entanglement Tomograph
- **Hadrontherapy beam monitoring**

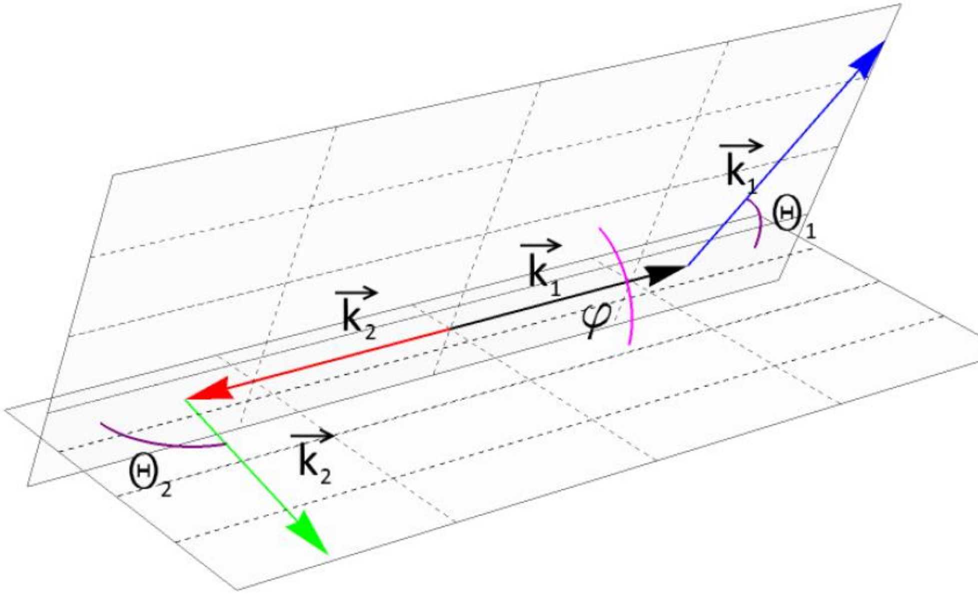




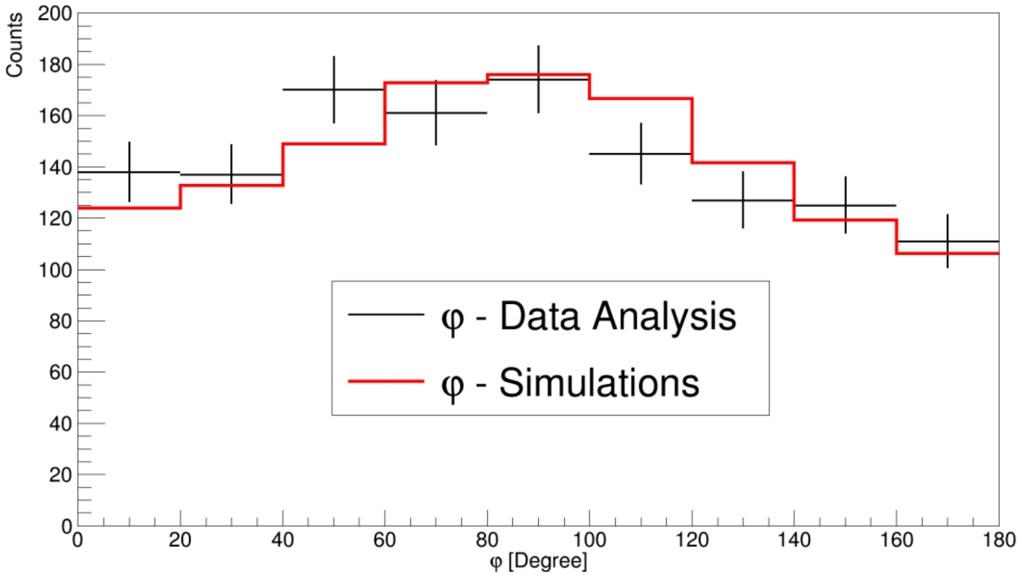
J-PET: P. M. et al., Eur. Phys. J. C 78 (2018) 970

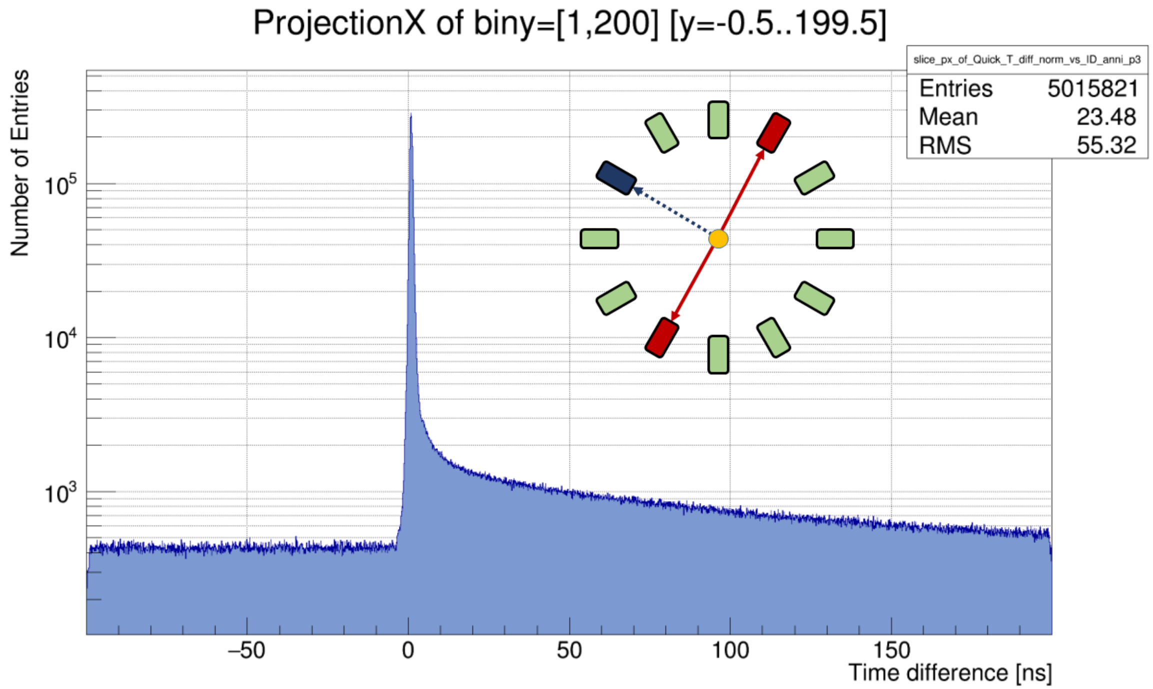


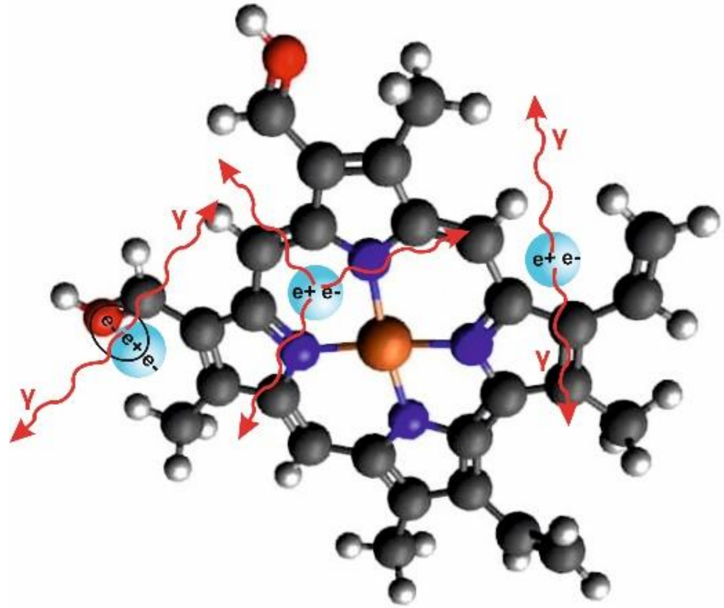




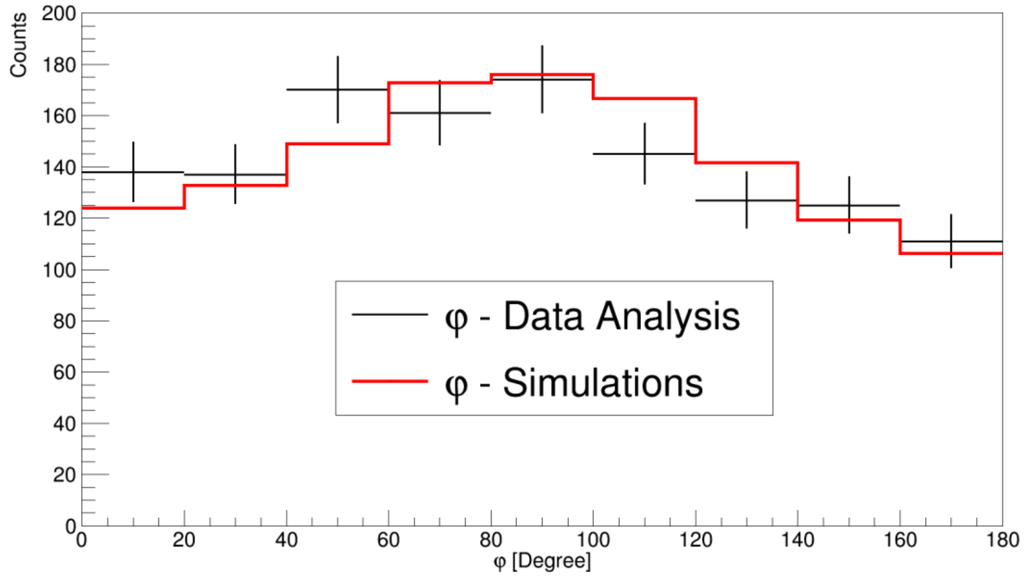
QUANTUM PALS

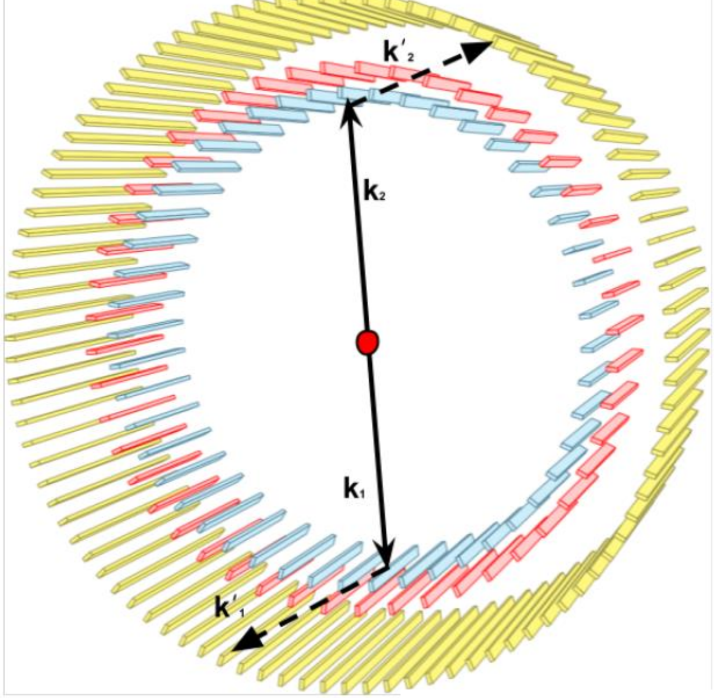


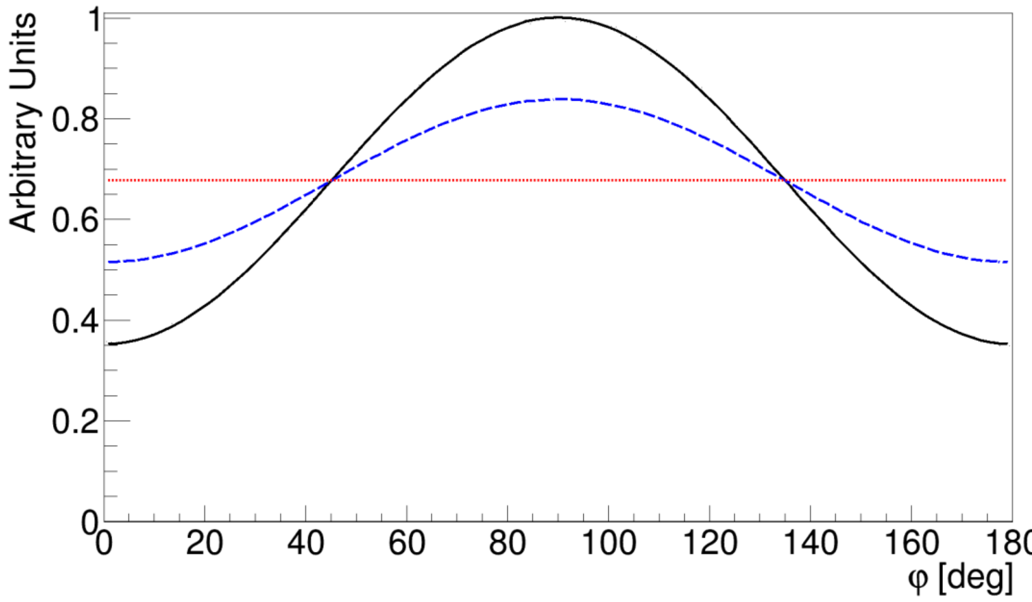




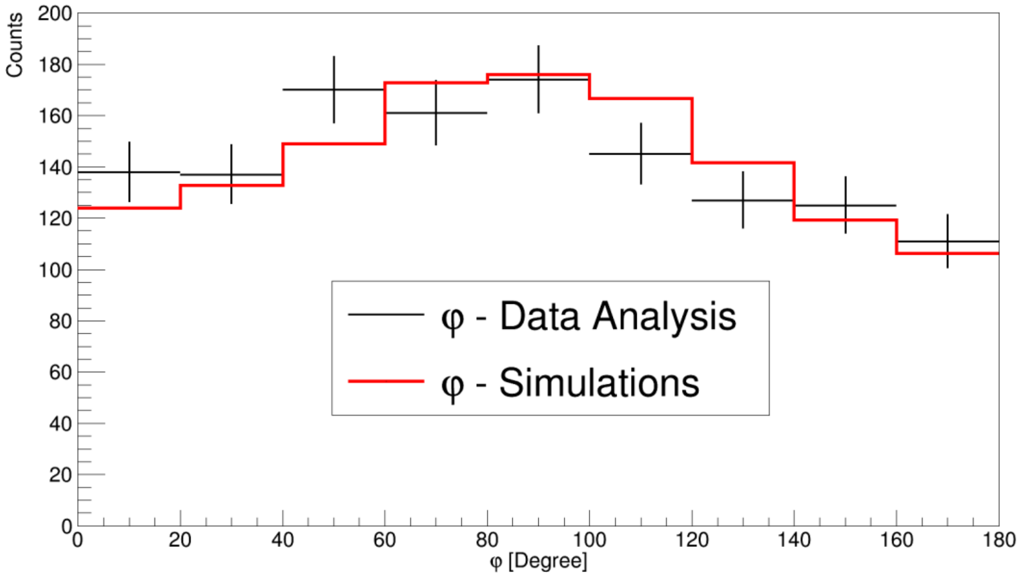
QUANTUM PALS







QUANTUM PALS



www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN

Genuine Multipartite Entanglement in the 3-Photon Decay of Positronium

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

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

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

B. Hiesmayr P.M., Scientific Reports 7 (2017) 15349

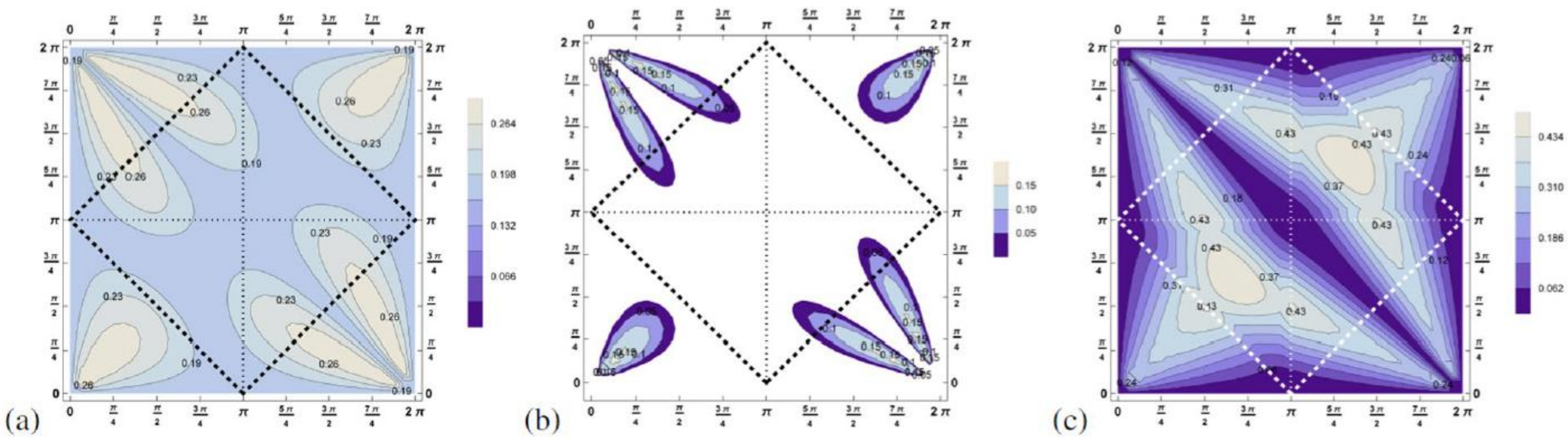
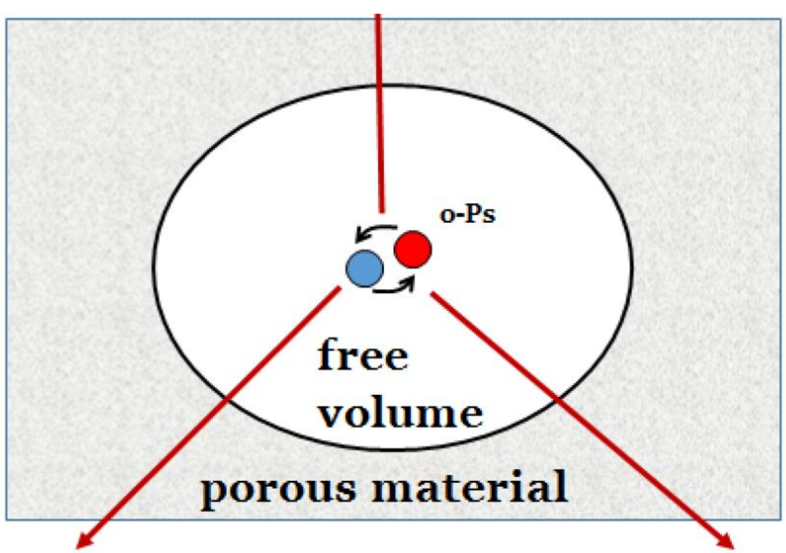
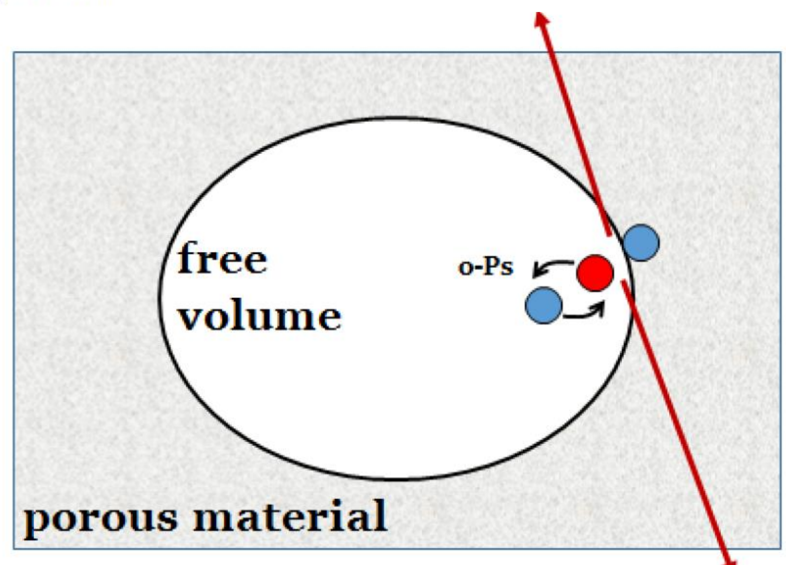


Figure 5. These three contour plots show (**a**) Q_{SEP}, (**b**) Q_{GHZ} and (**c**) Q_W for the state mixed equally between all three possible quantum states $s_{\hat{n}} = 0, +1, -1$, equation 17. Still genuine multipartite entanglement is revealed for some scenarios ($\widetilde{\Theta}_{ab}$, $\widetilde{\Theta}_{bc}$). The criterion Q_W detecting W-type of genuine multipartite entanglement is by far more sensitive to reveal genuine multipartite entanglement.





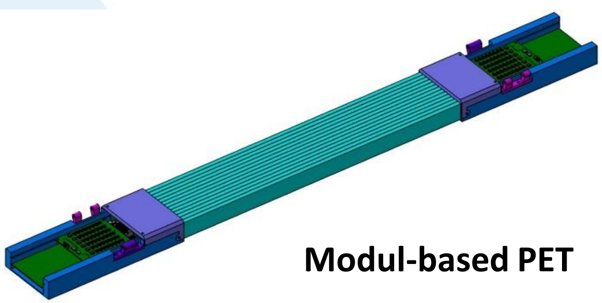
J-PET

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

Plastic-scintillator based PET detector:
Proton beam therapy range monitoring strategies

Characterization of the detector performance and optimization of the detector acceptance for in-room PET-gamma based range monitoring strategies:

- Off-beam
- Inter-spill
- In-beam

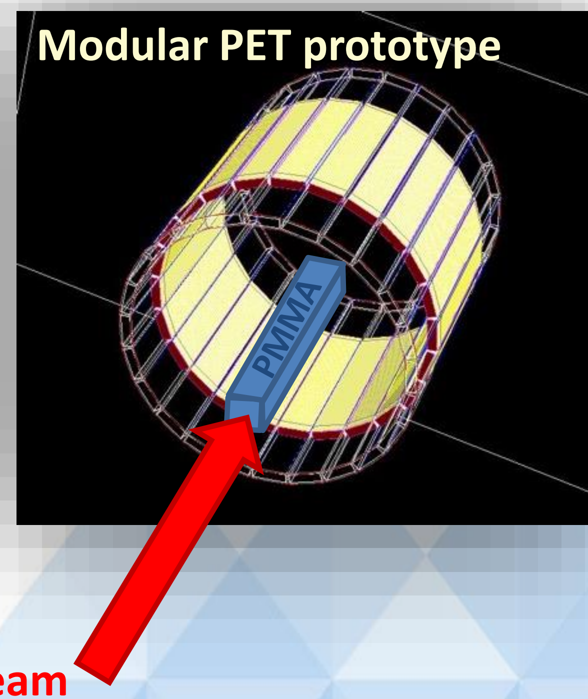


Modul-based PET

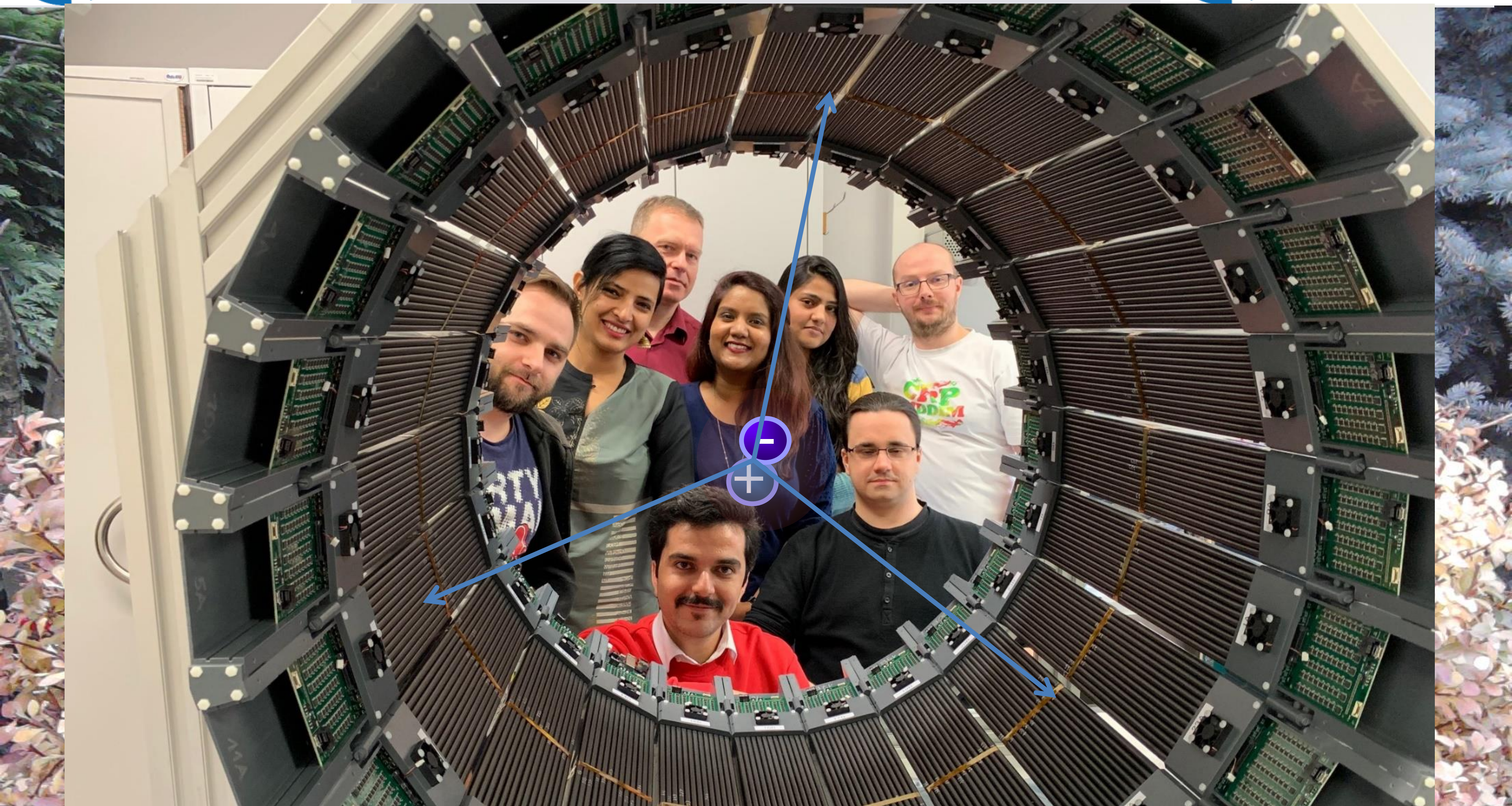
Gantry treatment room of IFJ PAN Krakow PBT centre

Monte Carlo simulations

GATE software toolkit is currently used to investigate the proton beam induced β^+ signal that can be detected by the plastic scintillator based diagnostic PET detector prototype.



Jagiellonian PET



THANK YOU
FOR YOUR ATTENTION