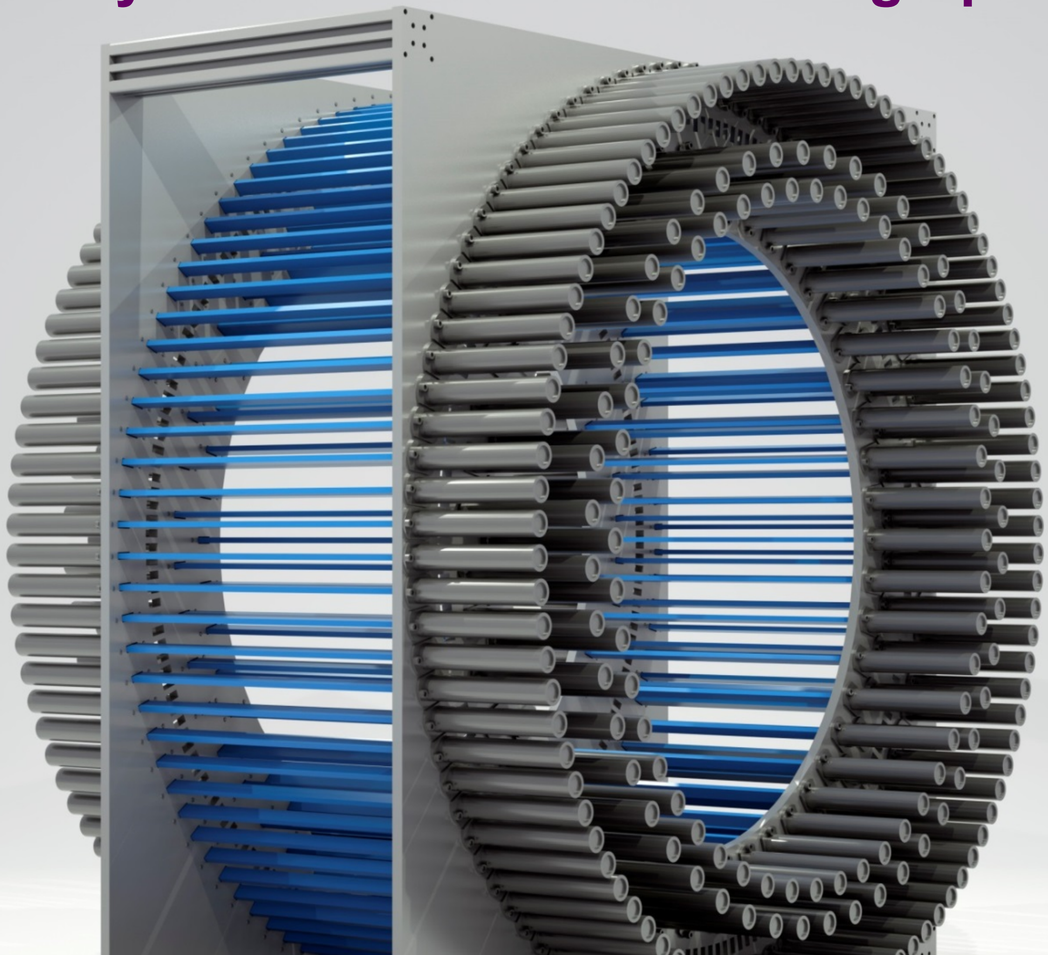
Studies of discrete symmetries in Nature by means of the J-PET tomograph



Quantum Foundation Workshop
LNF Frascati, 24 May 2017

Paweł Moskal, Jagiellonian University

for and on behalf of the J-PET collaboration

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

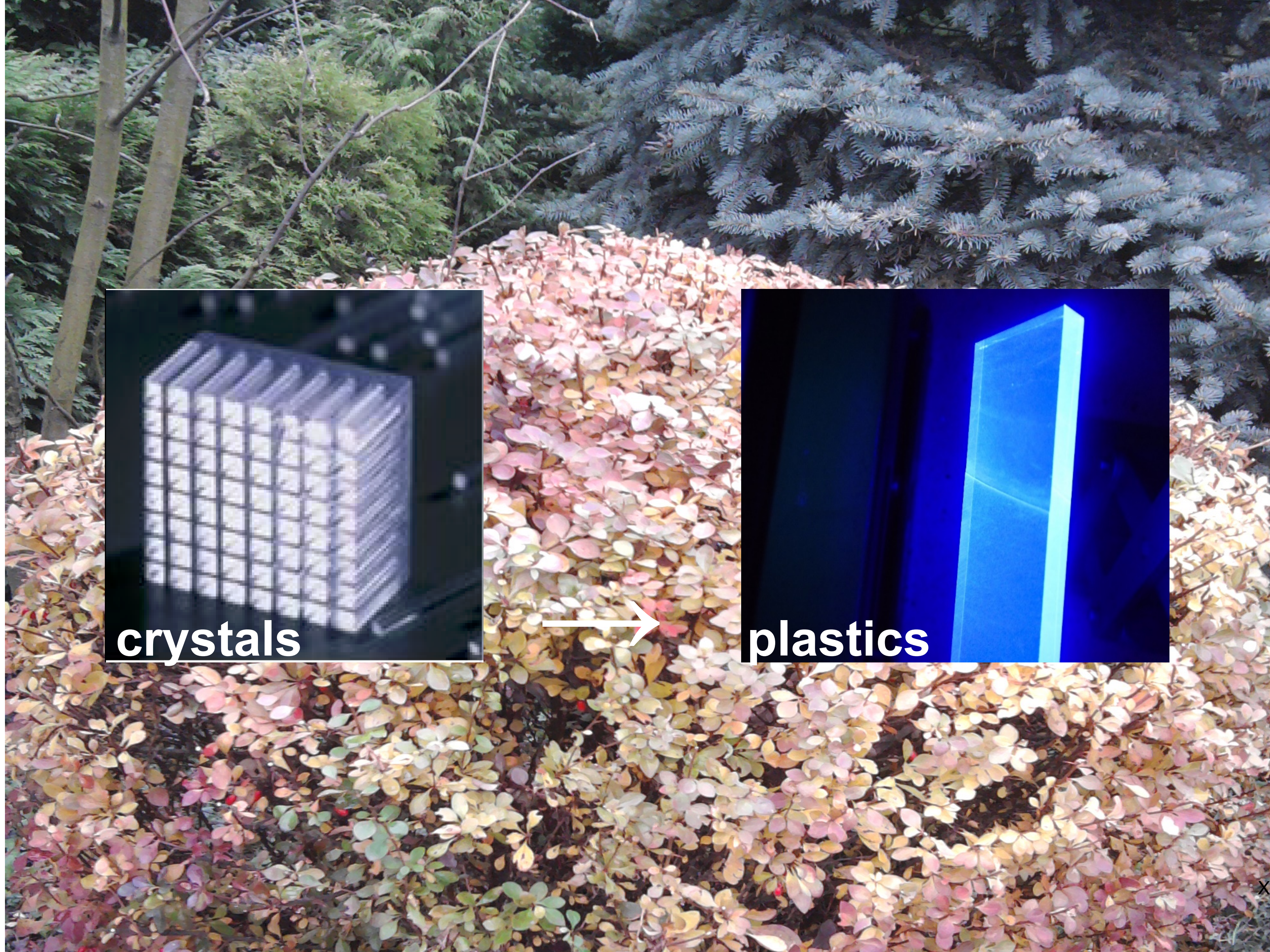
Jagiellonian-PET Collaboration:

P. Moskal[1], D. Alfs[1], T. Bednarski[1], P. Białas[1], C. Curceanu[2], E. Czerwiński[1], K. Dulski[1], A. Gajos[1], B. Głowacz[1], M. Gorgol[3], B. Hiesmayr[4], B. Jasińska[3], D. Kamińska[1], G. Korcyl[1], P. Kowalski[5], T. Kozik[1], W. Krzemień[5], E. Kubicz[1], M. Mohammed[1], M. Pawlik-Niedźwiecka[1], Sz. Niedźwiecki[1], M. Pałka[1], L. Raczyński[5], Z. Rudy[1], O. Rundel[1], N. Sharma[1], M. Silarski[1], J. Smyrski[1], A. Strzelecki[1], A. Wieczorek[1], W. Wiślicki[5], B. Zgardzińska[3], M. Zieliński[1]

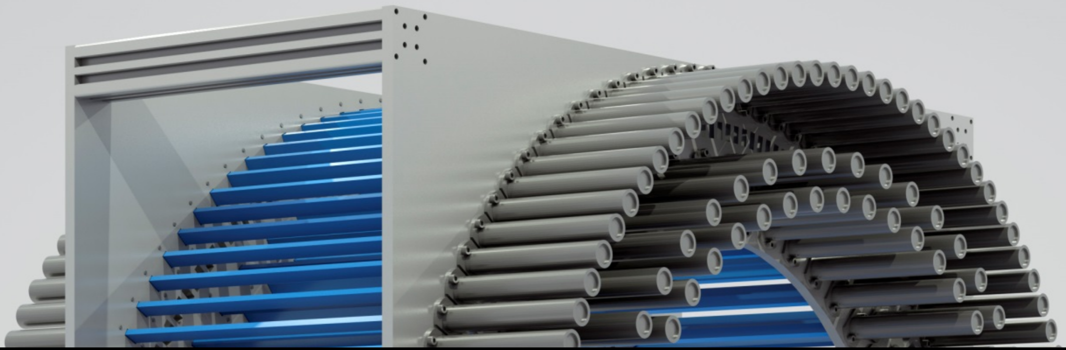
[1]Jagiellonian University, Poland; [2]LNF INFN, Italy; [3]Maria Curie-Skłodowska University, Poland; [4]University of Vienna, Austria; [5]National Centre for Nuclear Research, Poland;

Aim:

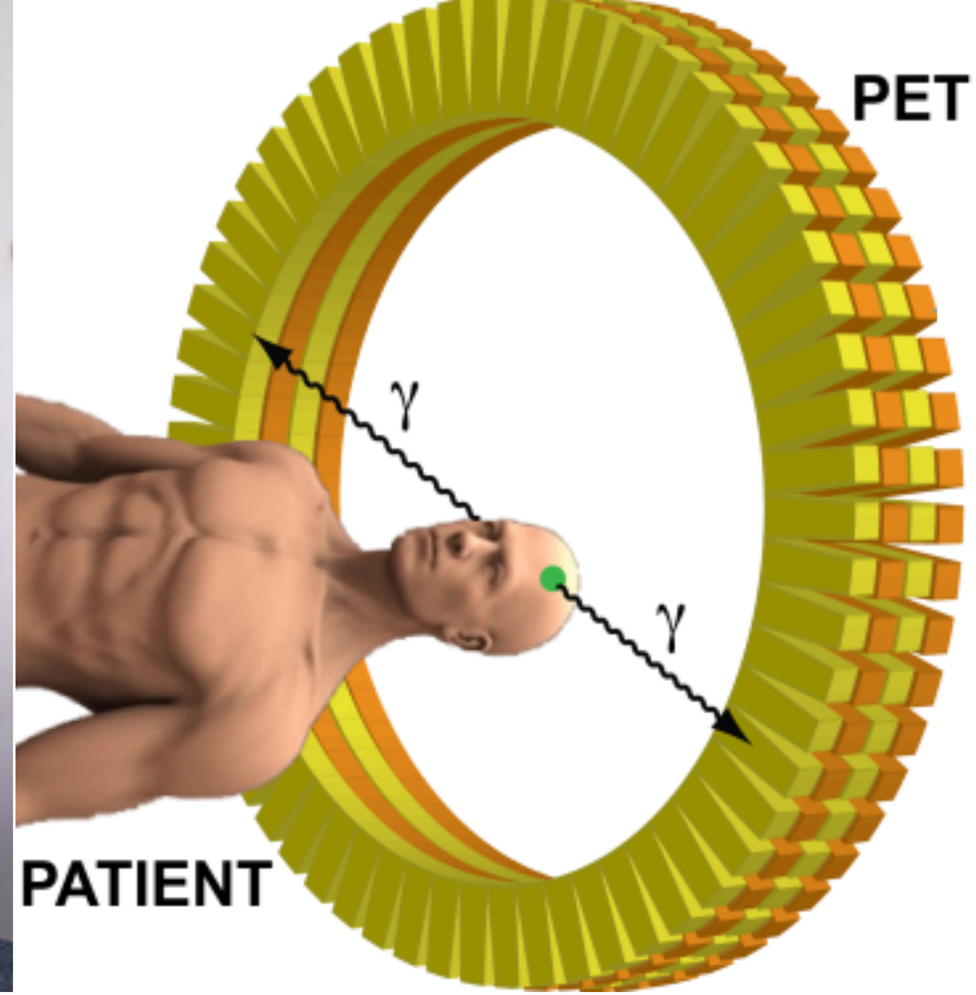
- Cost effective whole-body PET
- MR and CT compatible PET insert


crystals
plastics

Jagiellonian PET



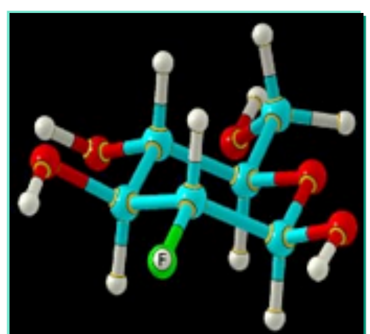
- Jagiellonian PET
- Positronium
- Discrete symmetries
- Morphometric imaging
- Quantum entanglement



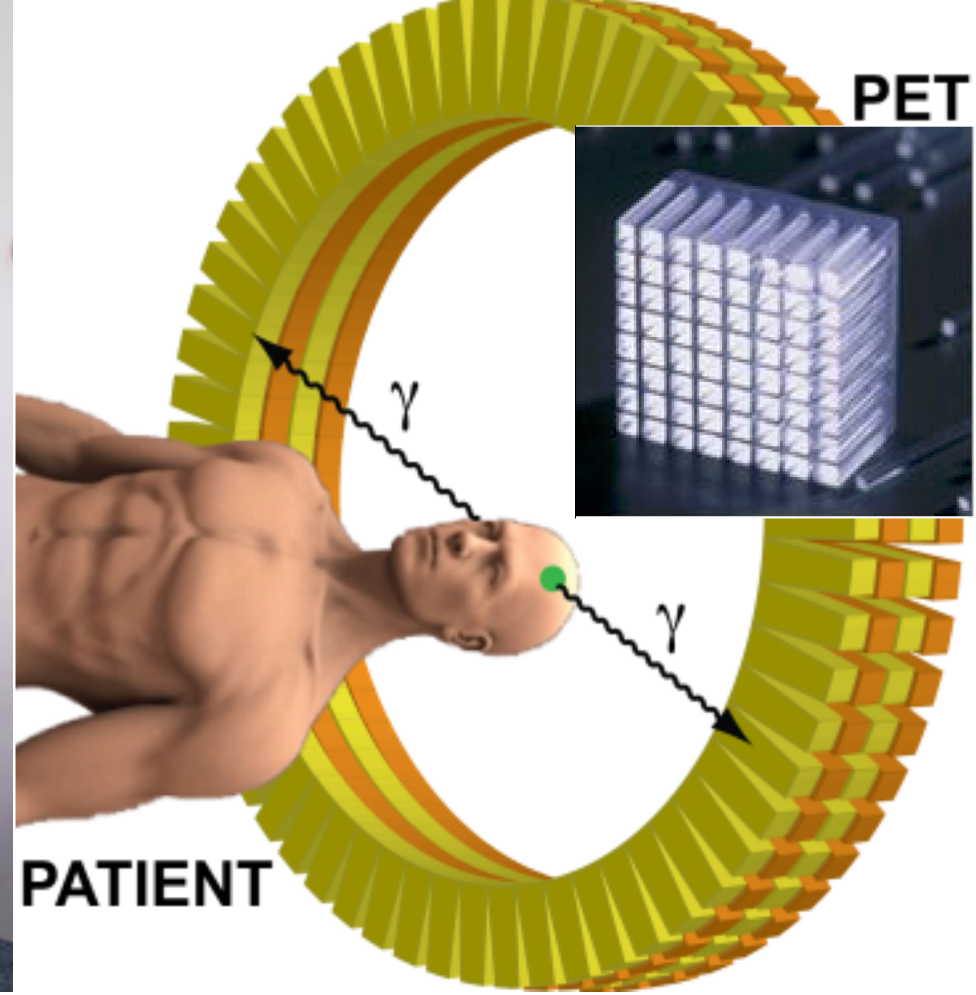
RADIOACTIVE SUGER

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
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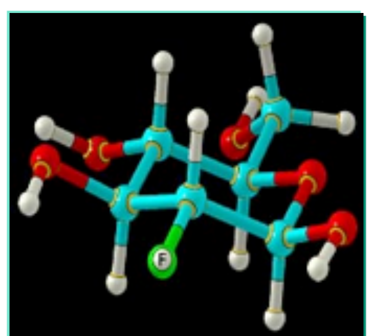

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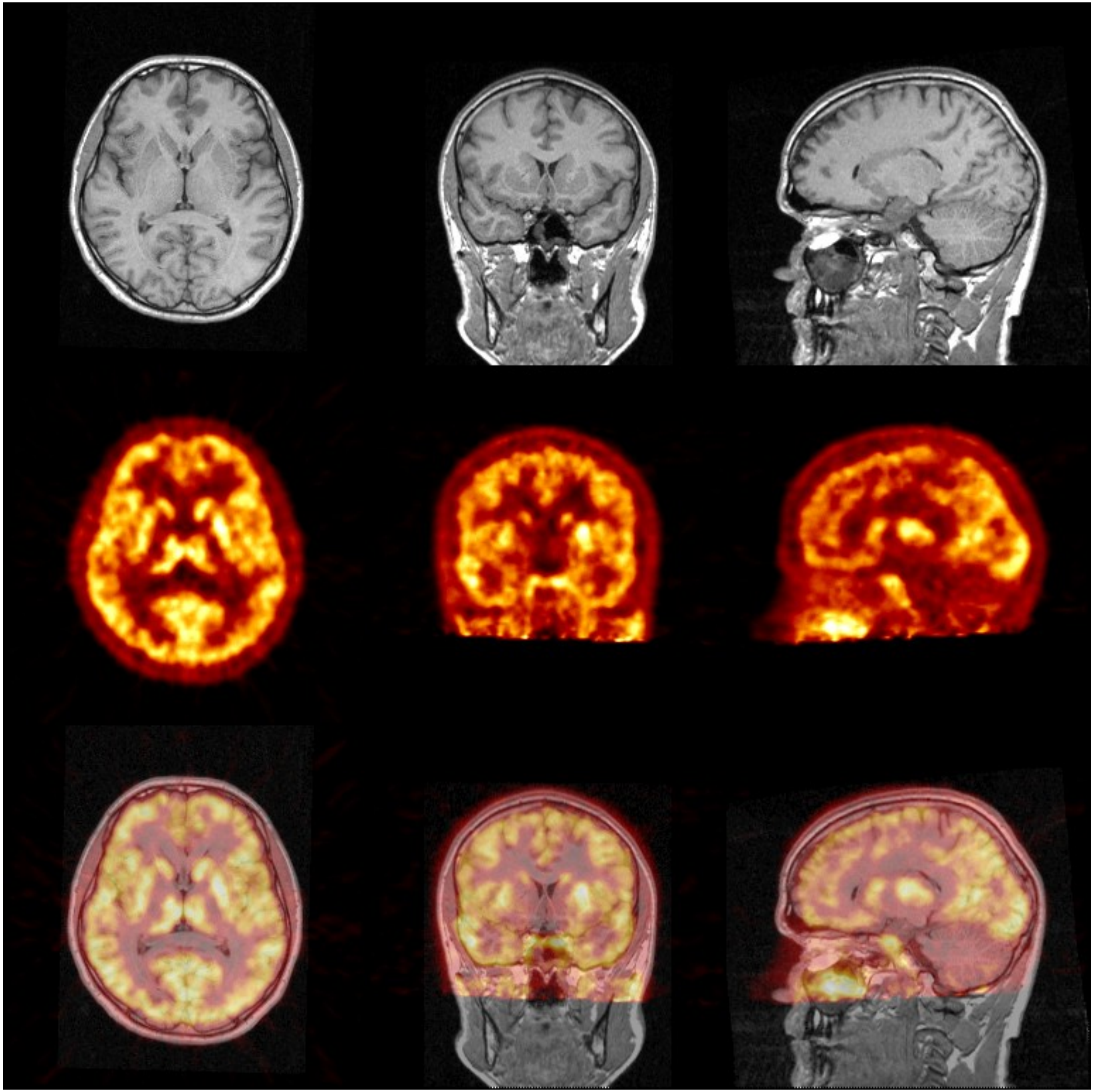
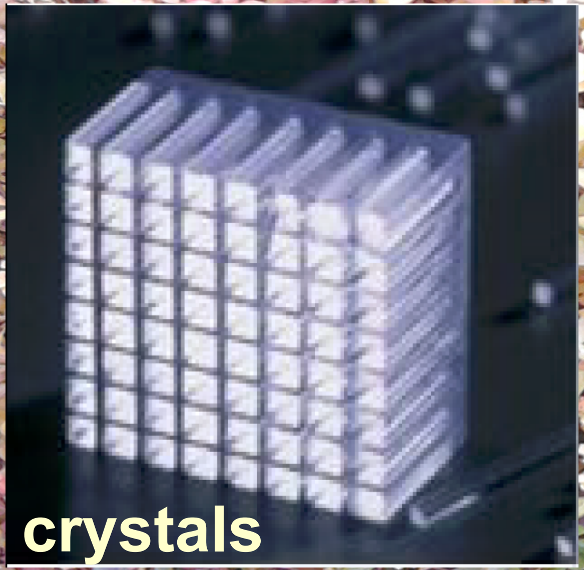
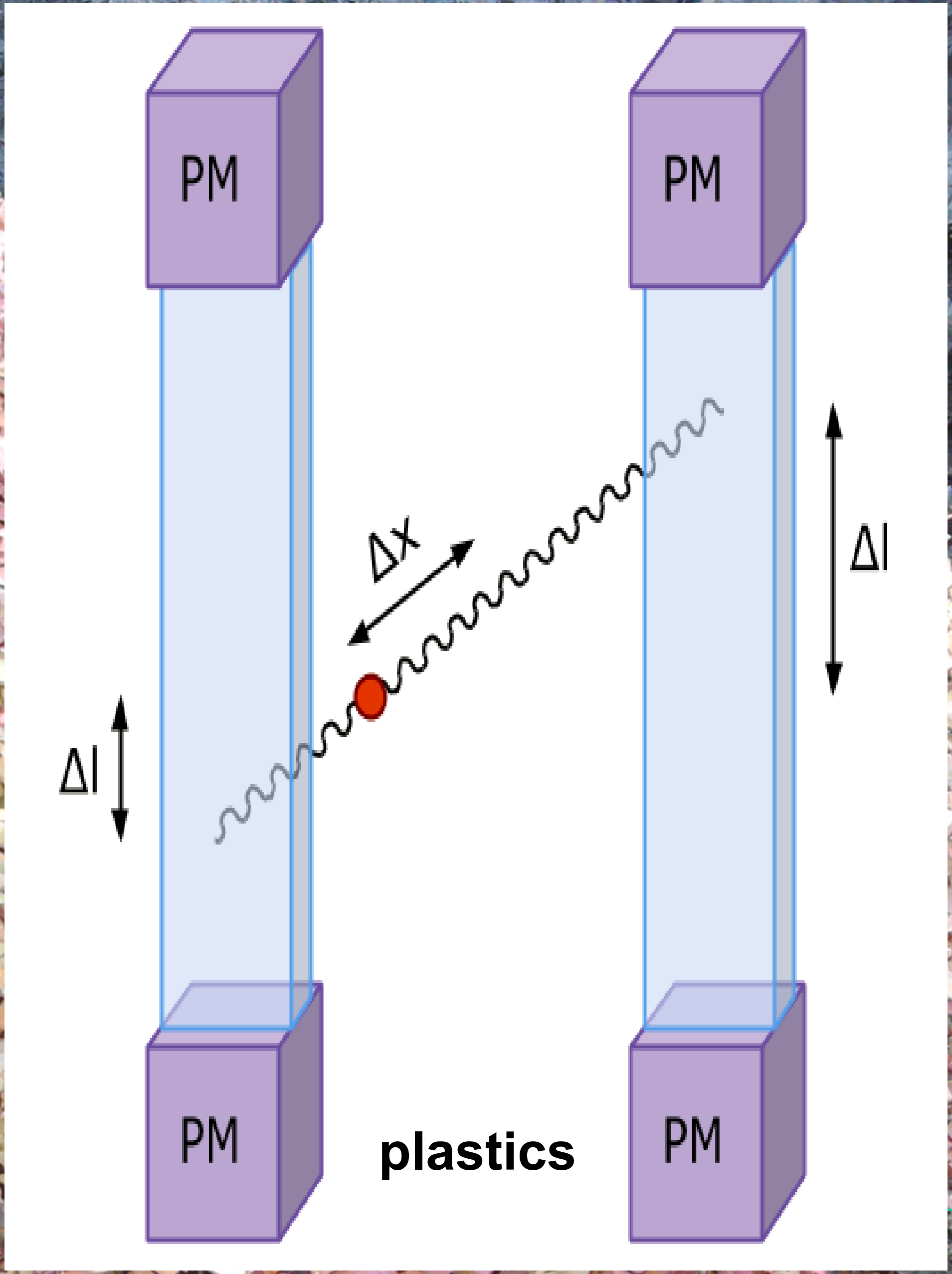
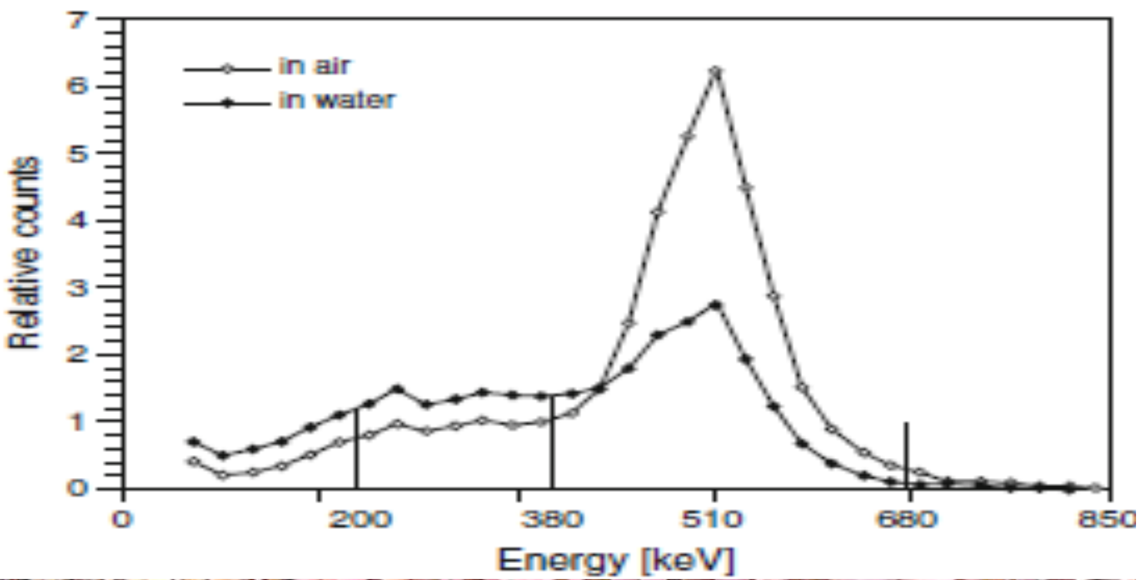
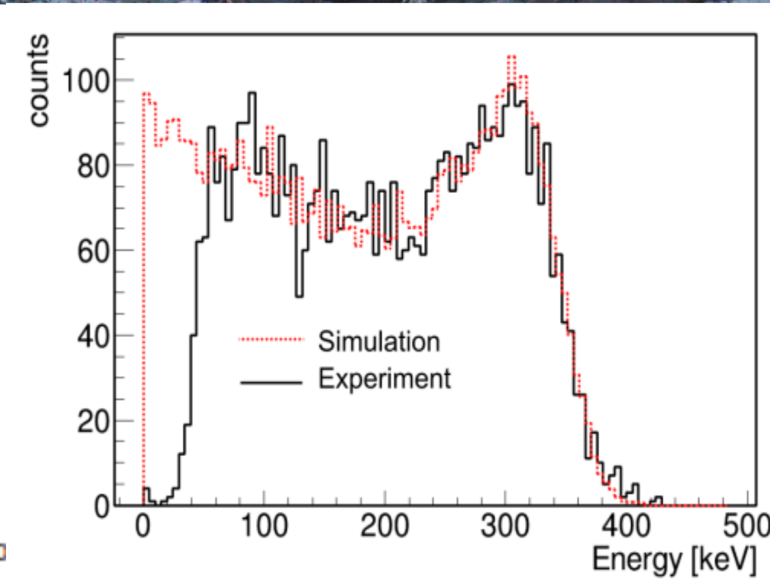



crystals

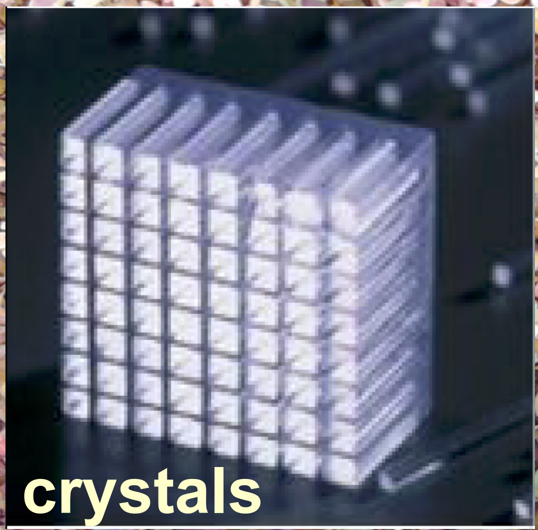

PM
PM
Δx
Δl
Δl
PM
plastics
PM



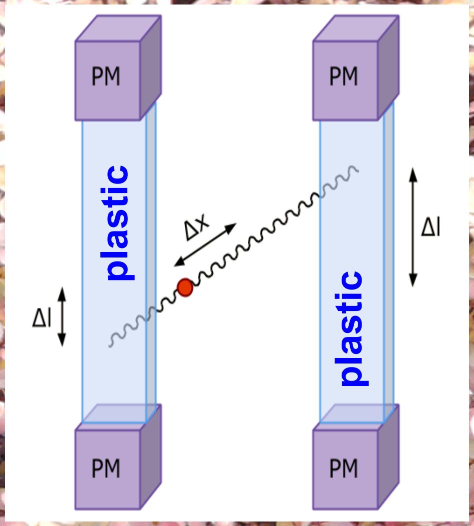
in air
in water
Relative counts
0
1
2
3
4
5
6
7
0
200
380
510
680
850
Energy [keV]



counts
0
20
40
60
80
100
Simulation
Experiment
0
100
200
300
400
500
Energy [keV]

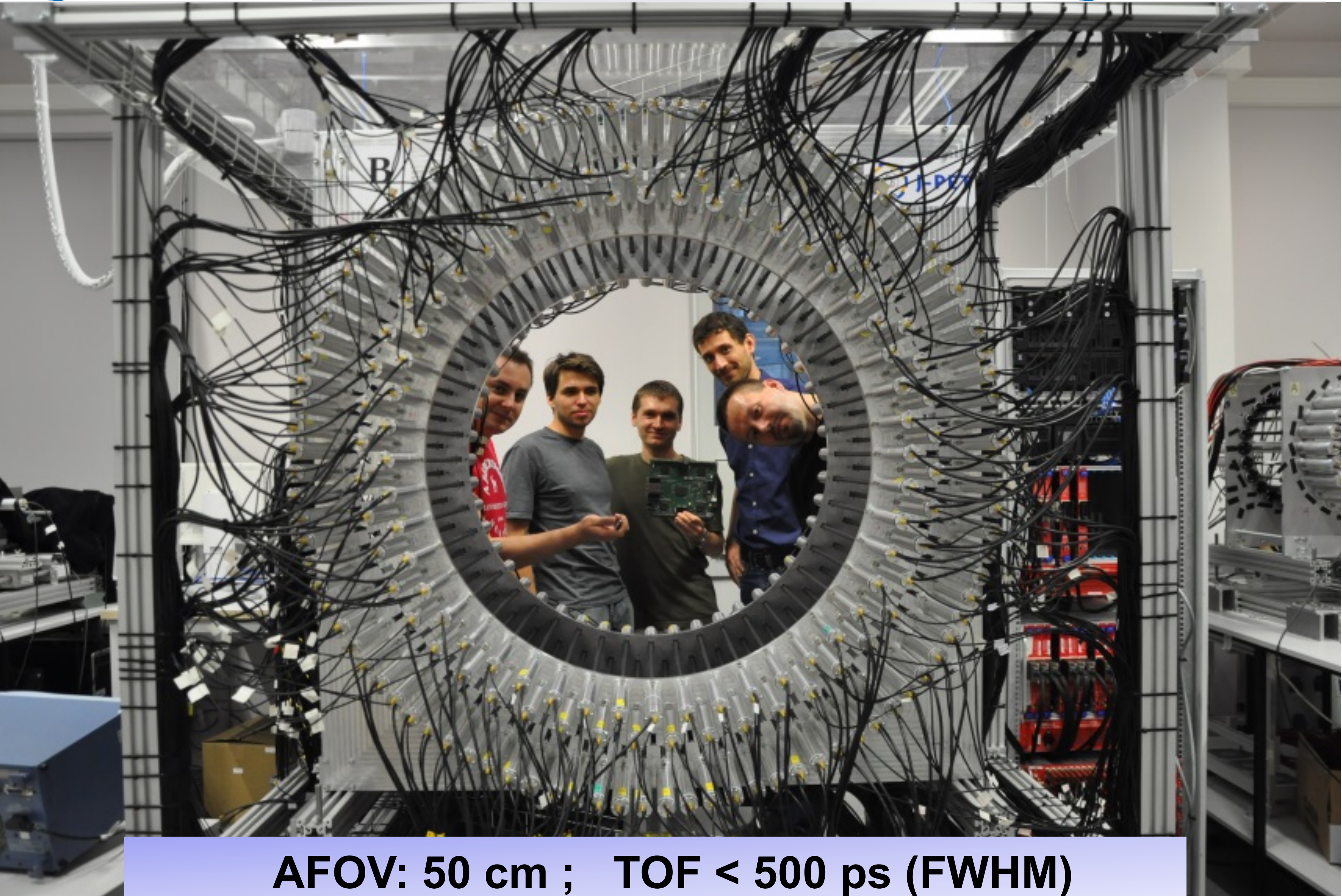


crystals



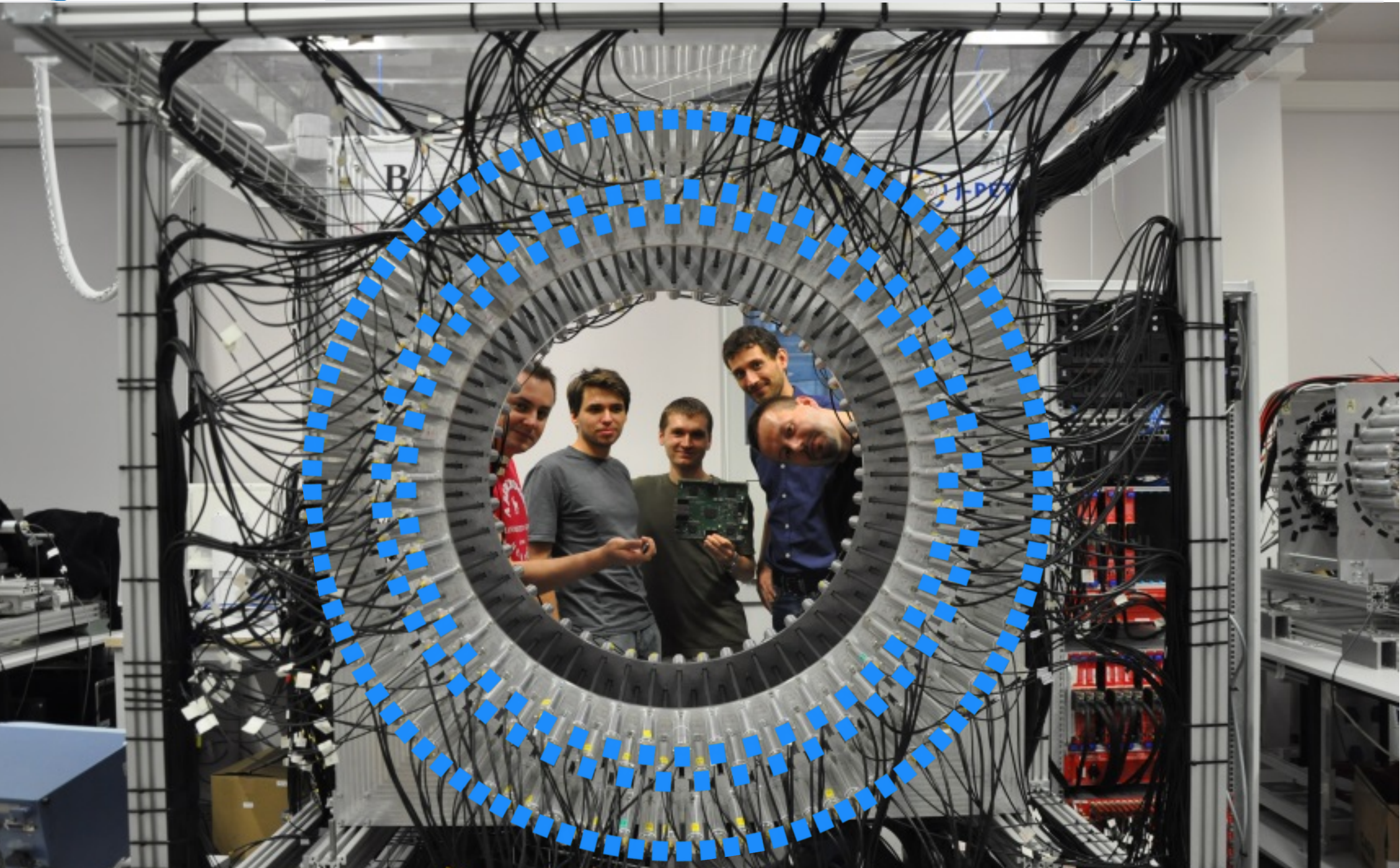
PM
PM
plastic
plastic
Δx
Δl
Δl
PM
PM

Jagiellonian PET



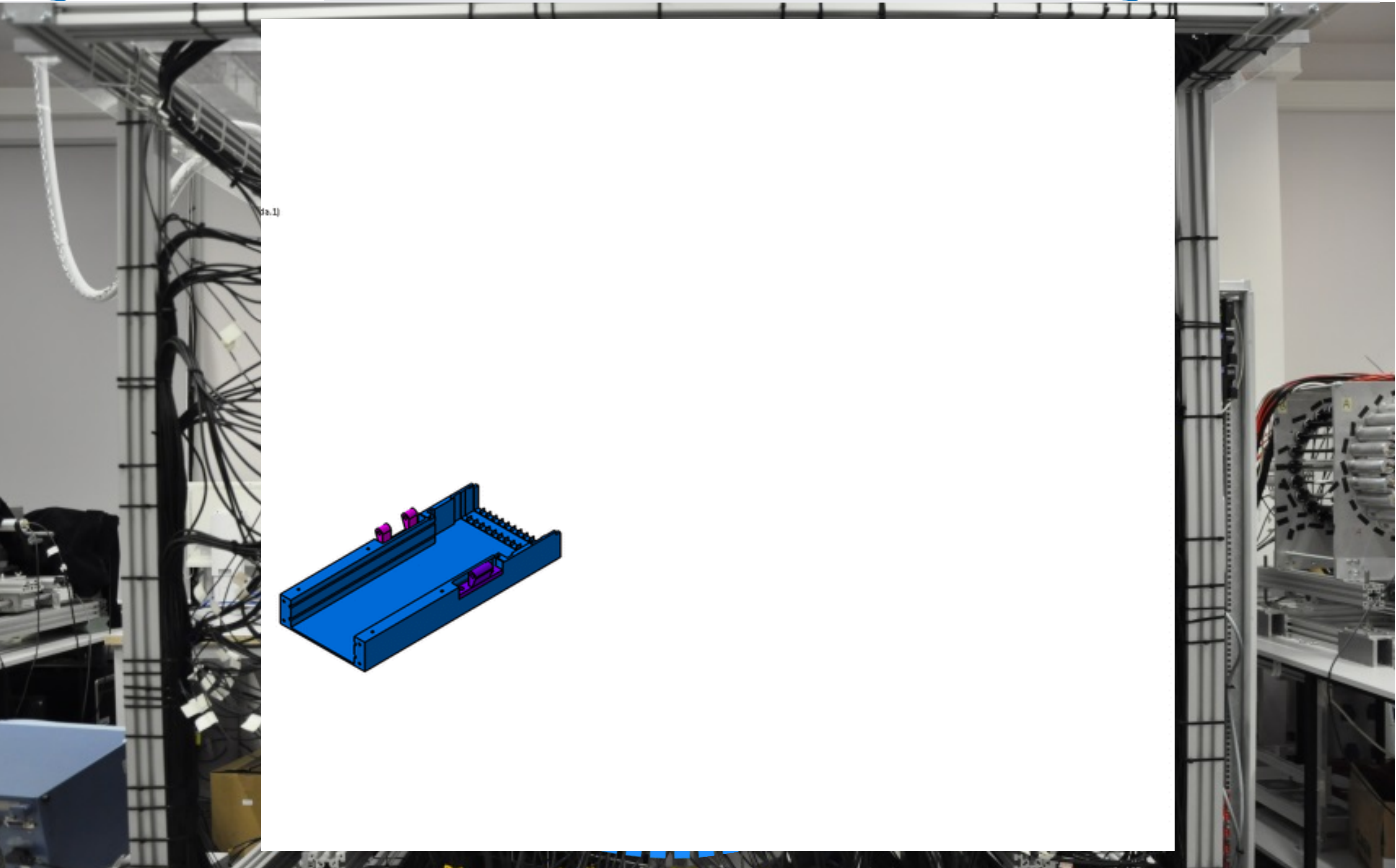
AFOV: 50 cm ;   TOF < 500 ps (FWHM)

Jagiellonian PET



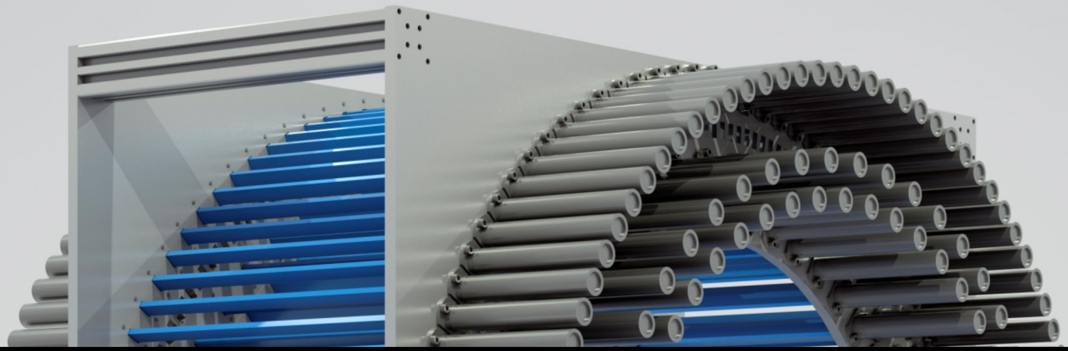
AFOV: 50 cm ;   TOF < 500 ps (FWHM)

Jagiellonian PET



AFOV: 50 cm ;   TOF < 500 ps (FWHM)

Jagiellonian PET



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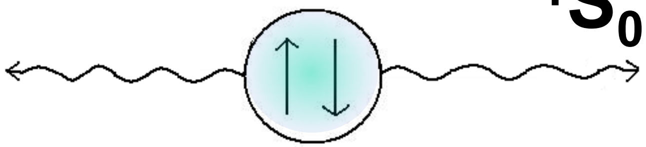
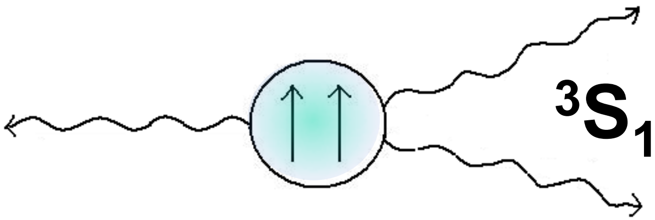
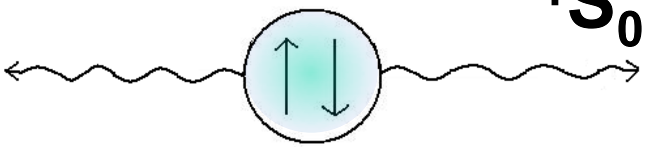


$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

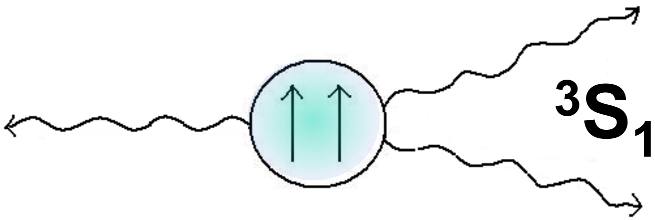


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

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



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

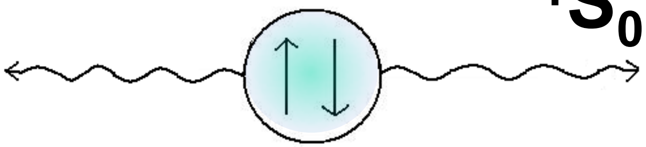


$^3S_1$ Ortho-positronium tau(**o-Ps**) ≈ 142 ns

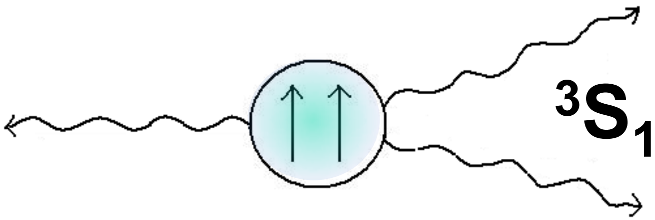
	$^1S_0$	$^3S_1$
L	0	0
S	0	1

S = 0 ↓↑ − ↑↓

S = 1 ↑↑ + ↓↓



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

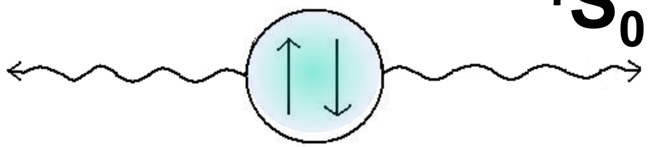


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

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

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

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



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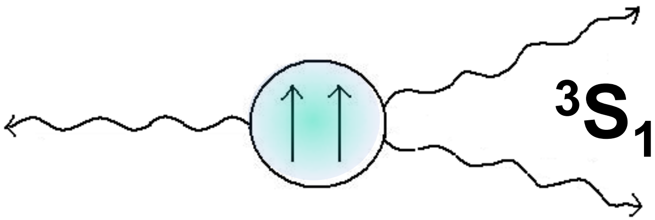
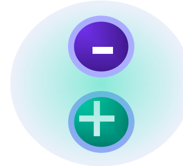


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

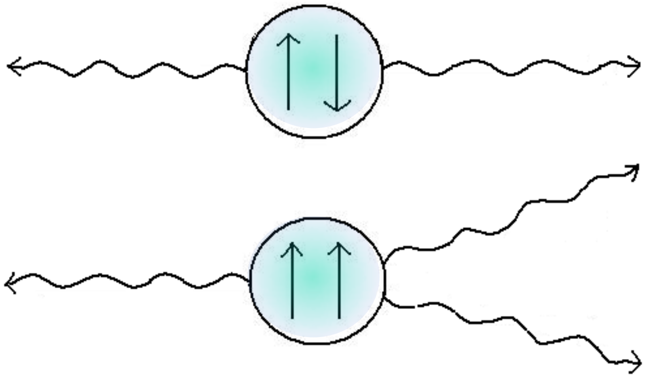
		$^1S_0$	$^3S_1$
	L	0	0
	S	0	1
	C	+	-
L=0 ->	P	-	-
	CP	-	+

S = 0 ↓↑ − ↑↓

S = 1 ↑↑ + ↓↓

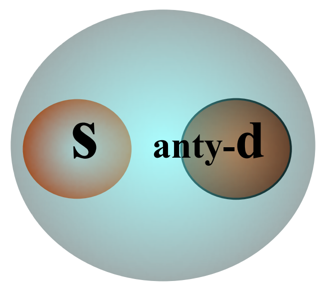


POSITRONIUM

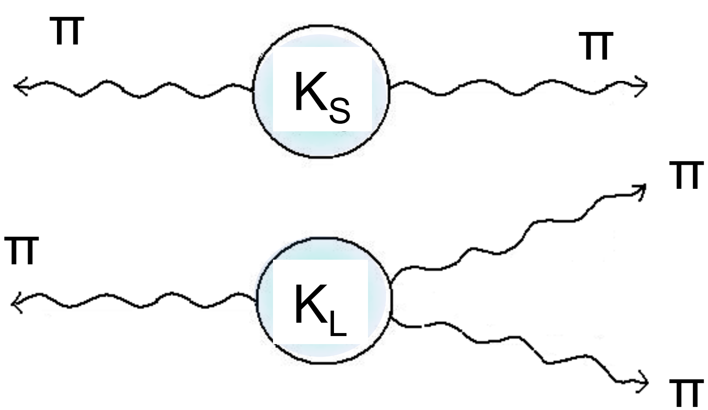


CP = + Para-positronium tau(p-Ps) ≈ 125 ps

CP = - Ortho-positronium tau(o-Ps) ≈ 142 ns



MESON K



CP ~= + tau(K_S) ≈ 90 ps

CP ~= - tau(K_L) ≈ 52 ns

50 year later ....

V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.

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

$$\nu_\mu \rightarrow \nu_e \qquad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

50 year later ....

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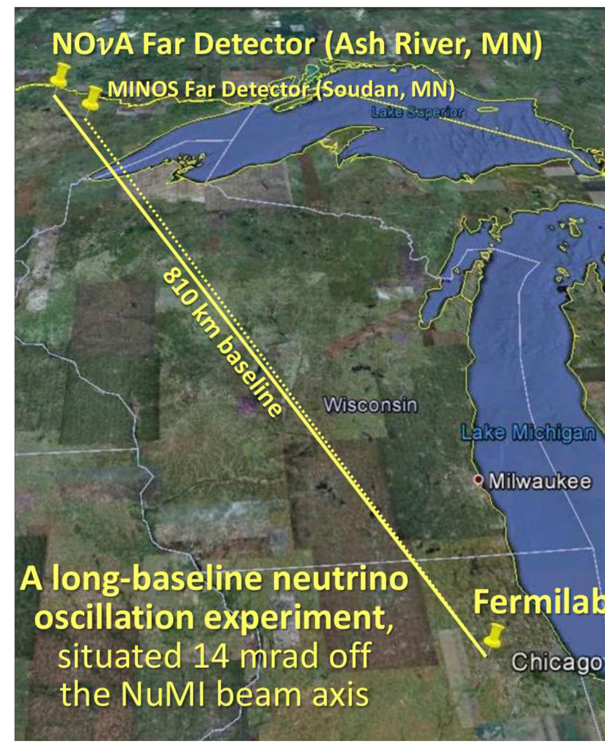
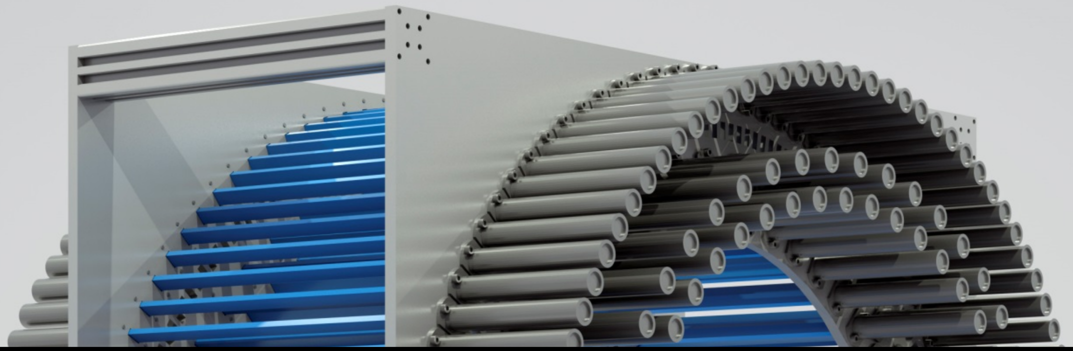
$$\nu_\mu \to \nu_e \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

T2K Tokai to Kamioka



Jagiellonian PET



- Jagiellonian PET
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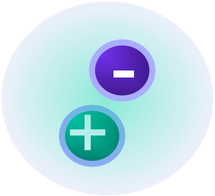
ODE TO POSITRONIUM



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 !

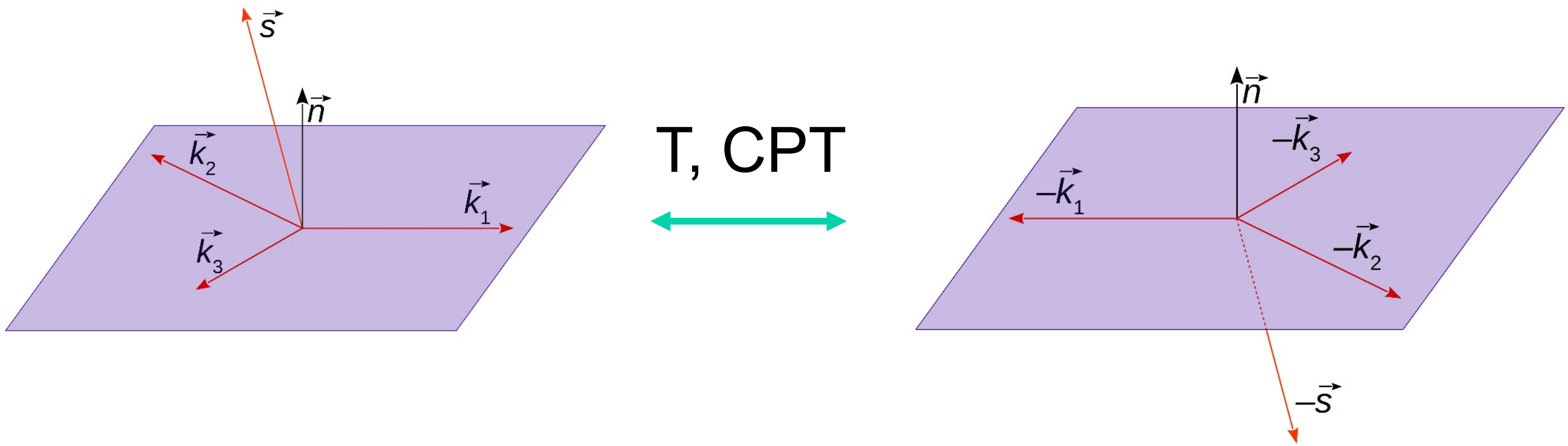
Breaking of T and CP was observed but only for processes involving quarks.
So far breaking of these symmetries was not observed for purely leptonic systems.

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

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

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

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

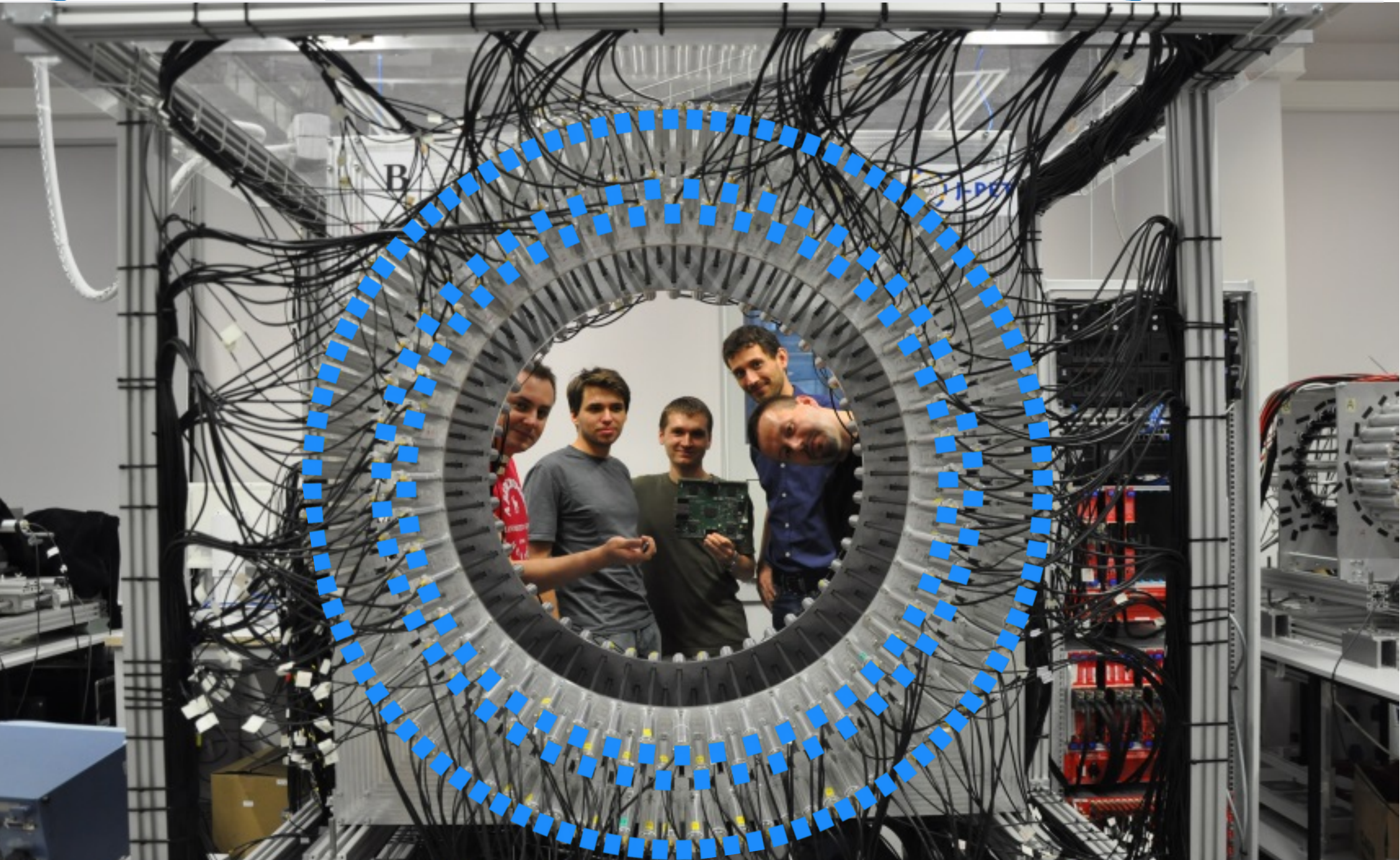


So far best accuracy for **CP and CPT violation** was reported by

-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

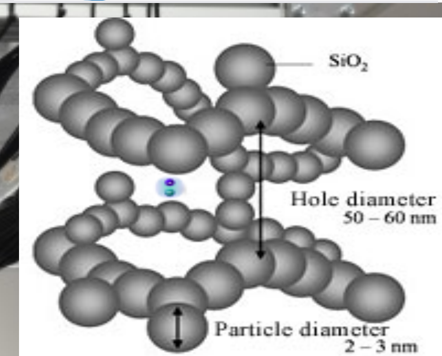


σ(t-hit) ~ 100 ps

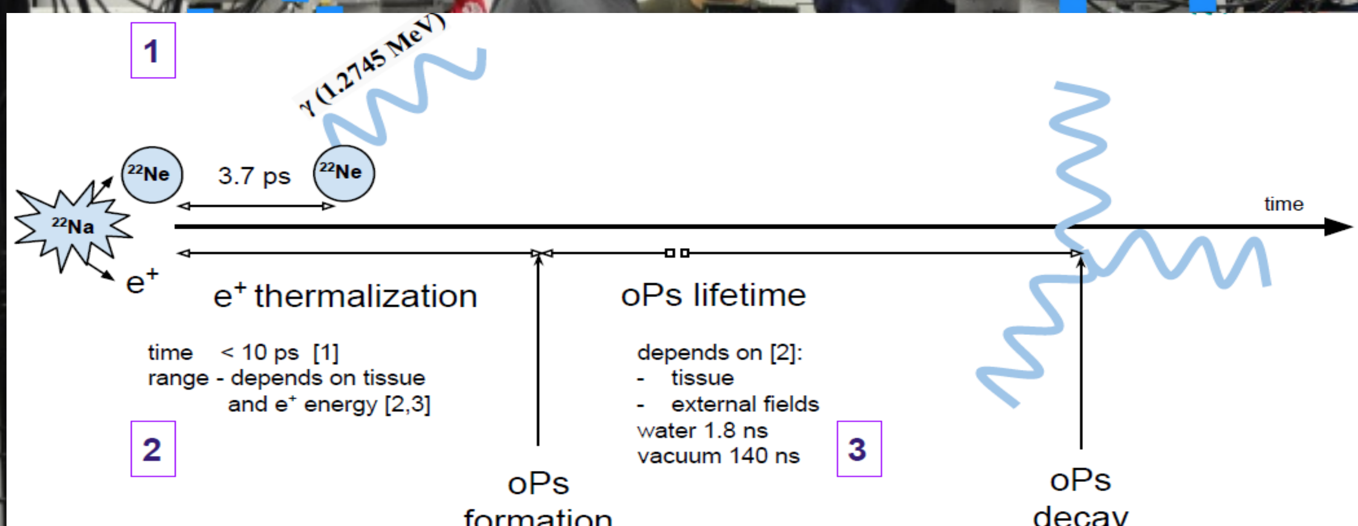
Jagiellonian PET

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

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

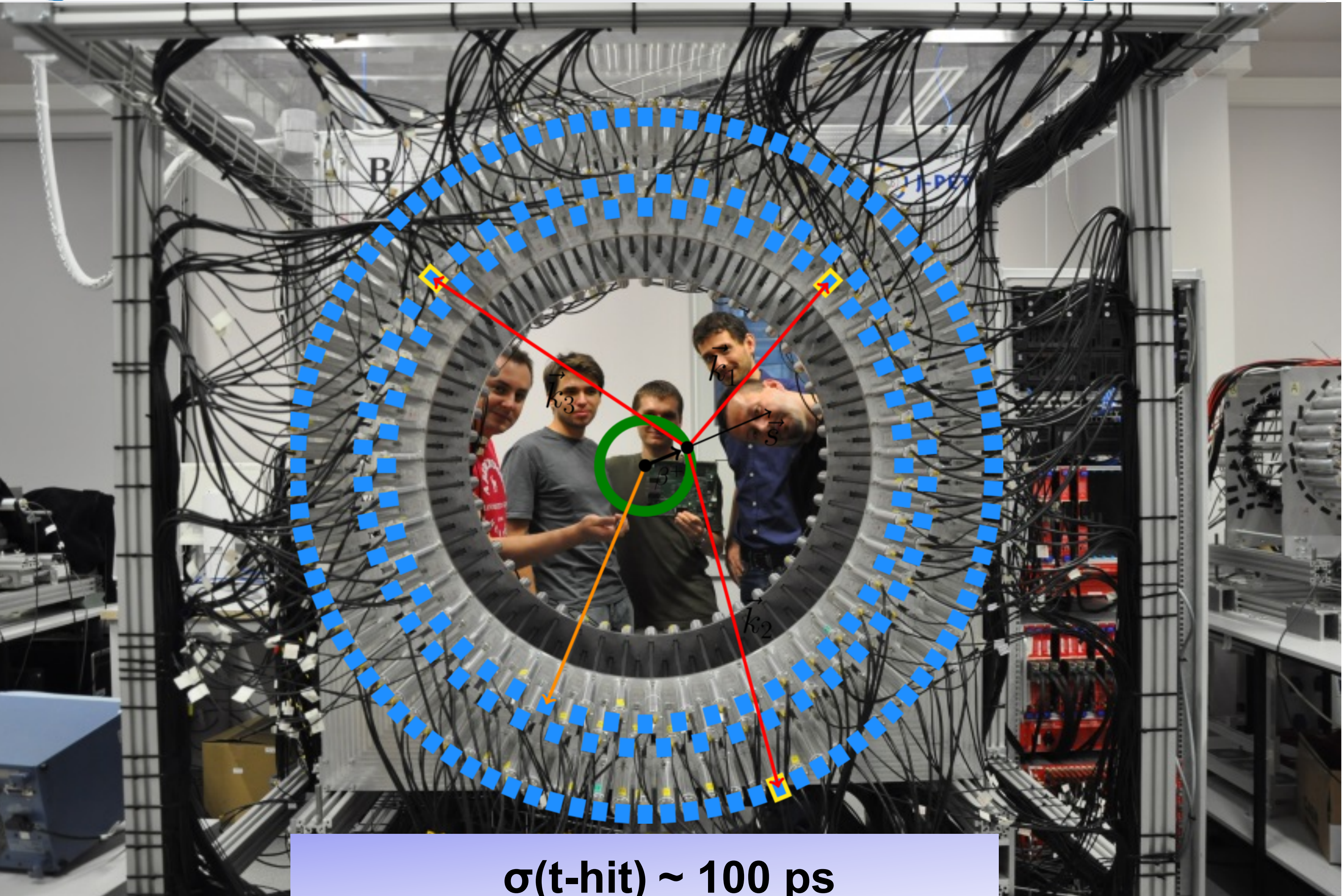


http://www.chem-eng.kyushu-u.ac.jp/e/research.html



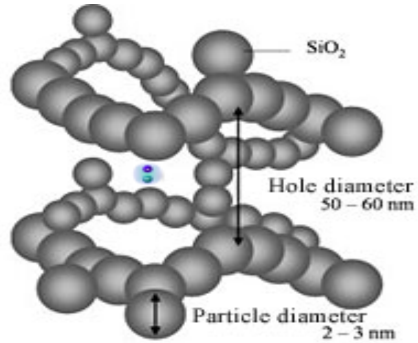
σ(t-hit) ~ 100 ps

Jagiellonian PET

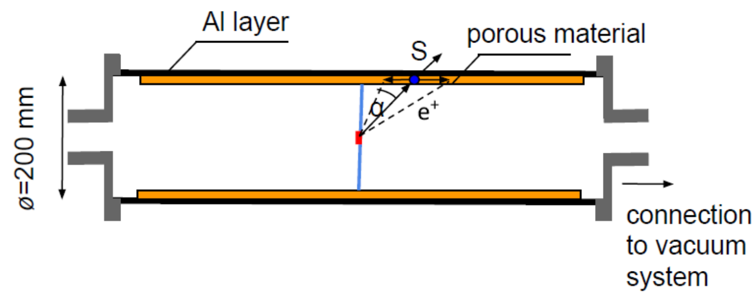


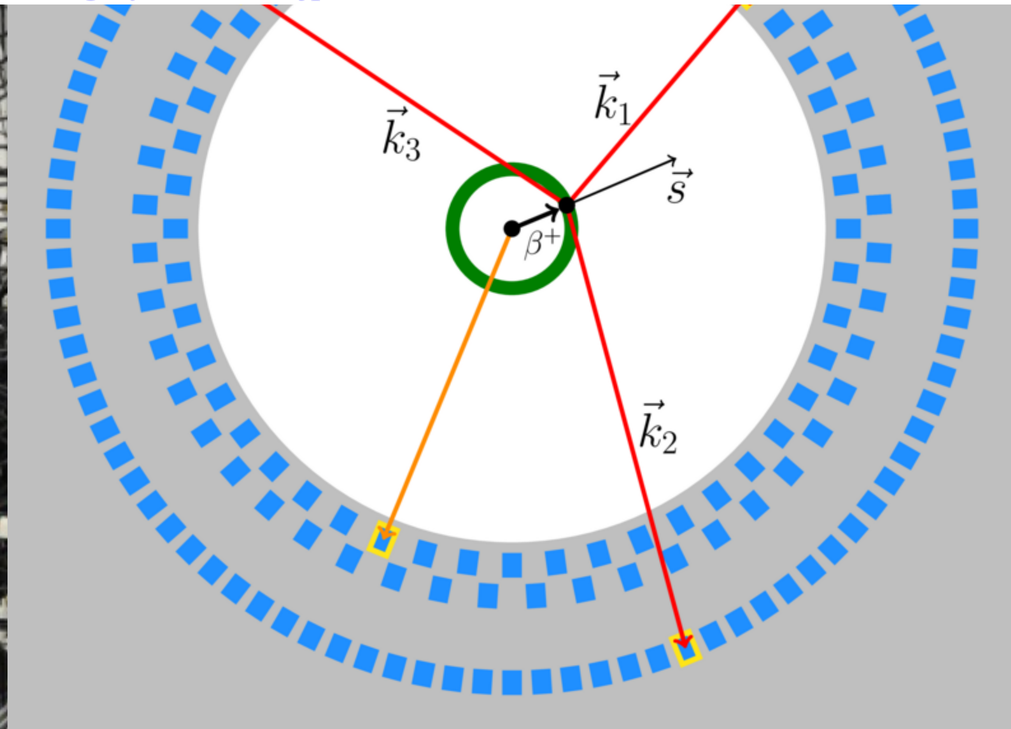
σ(t-hit) ~ 100 ps

Jagiellonian PET



http://www.chem-eng.kyushu-u.ac.jp/e/research.html



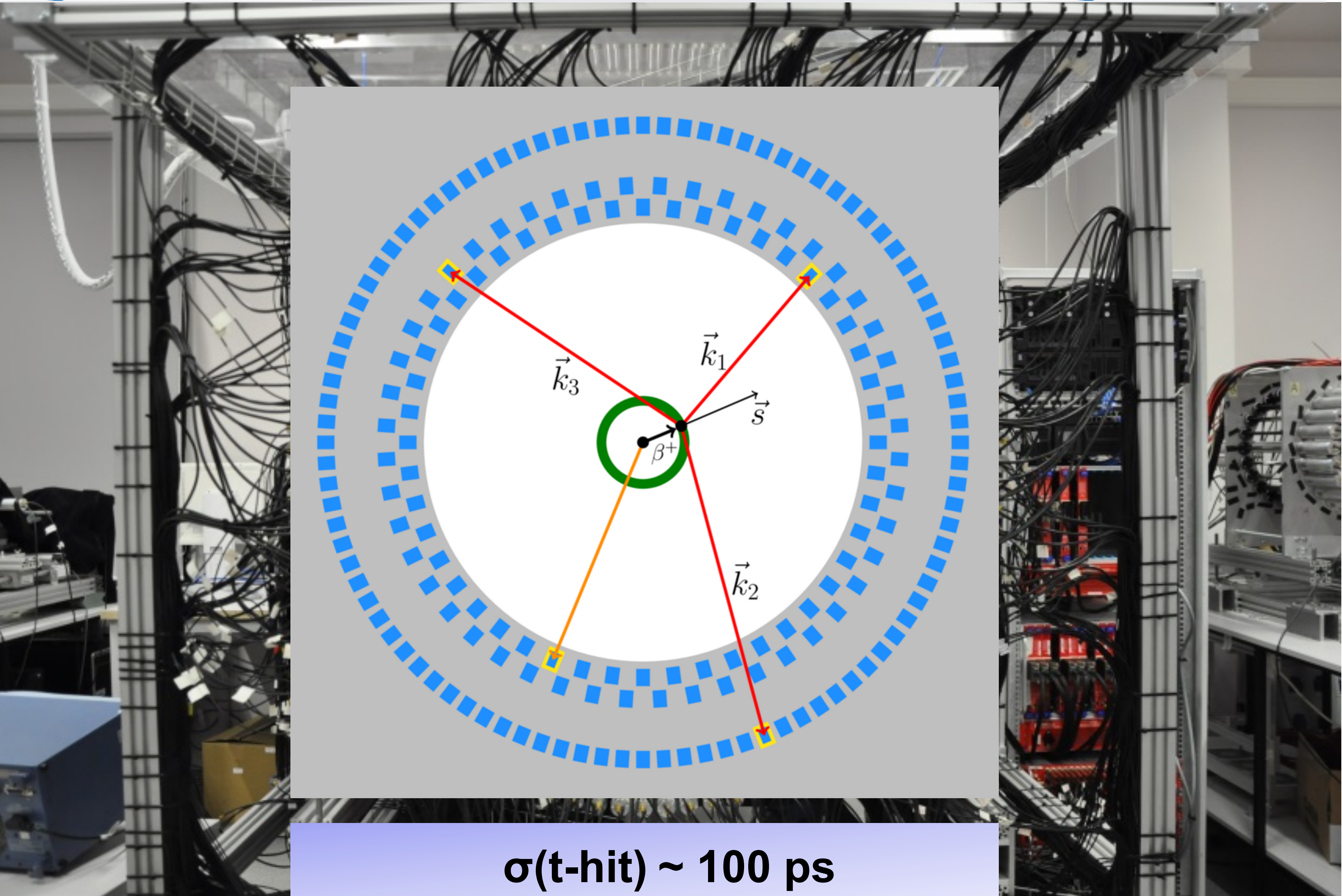


σ(t-hit) ~ 100 ps

J-PET

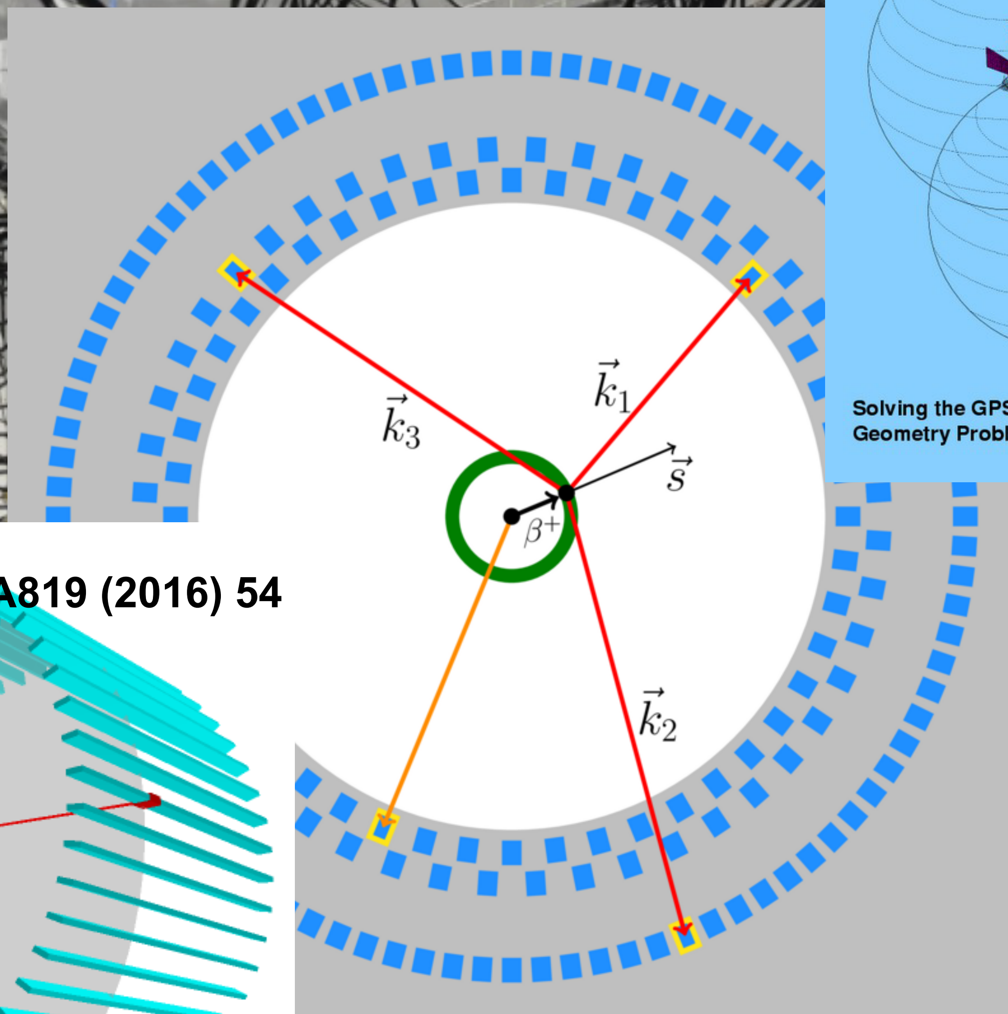
First cylindrical porous target by Prof. J. Goworek from UMCS

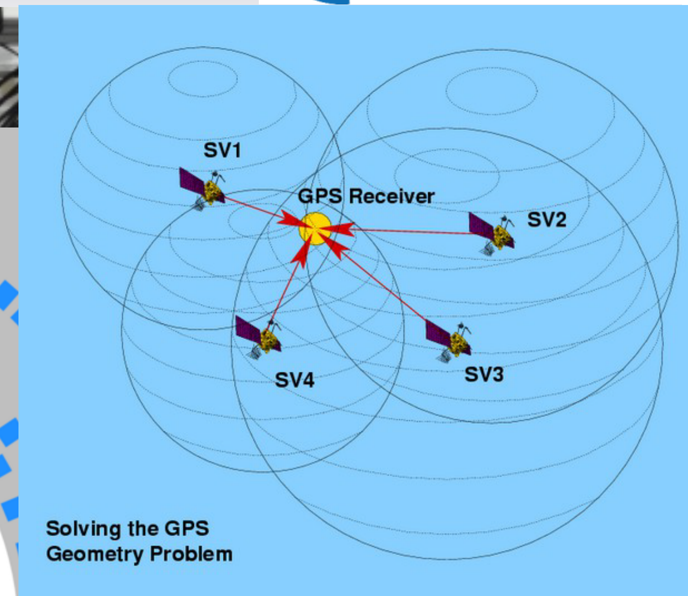
Jagiellonian PET



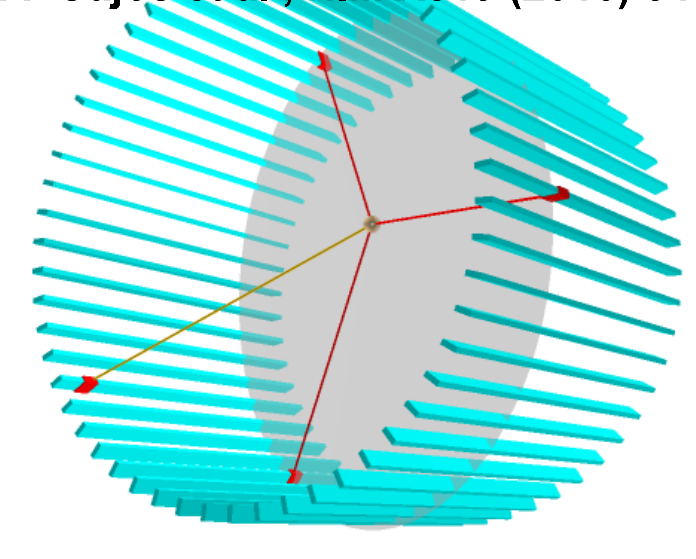
σ(t-hit) ~ 100 ps

Jagiellonian PET



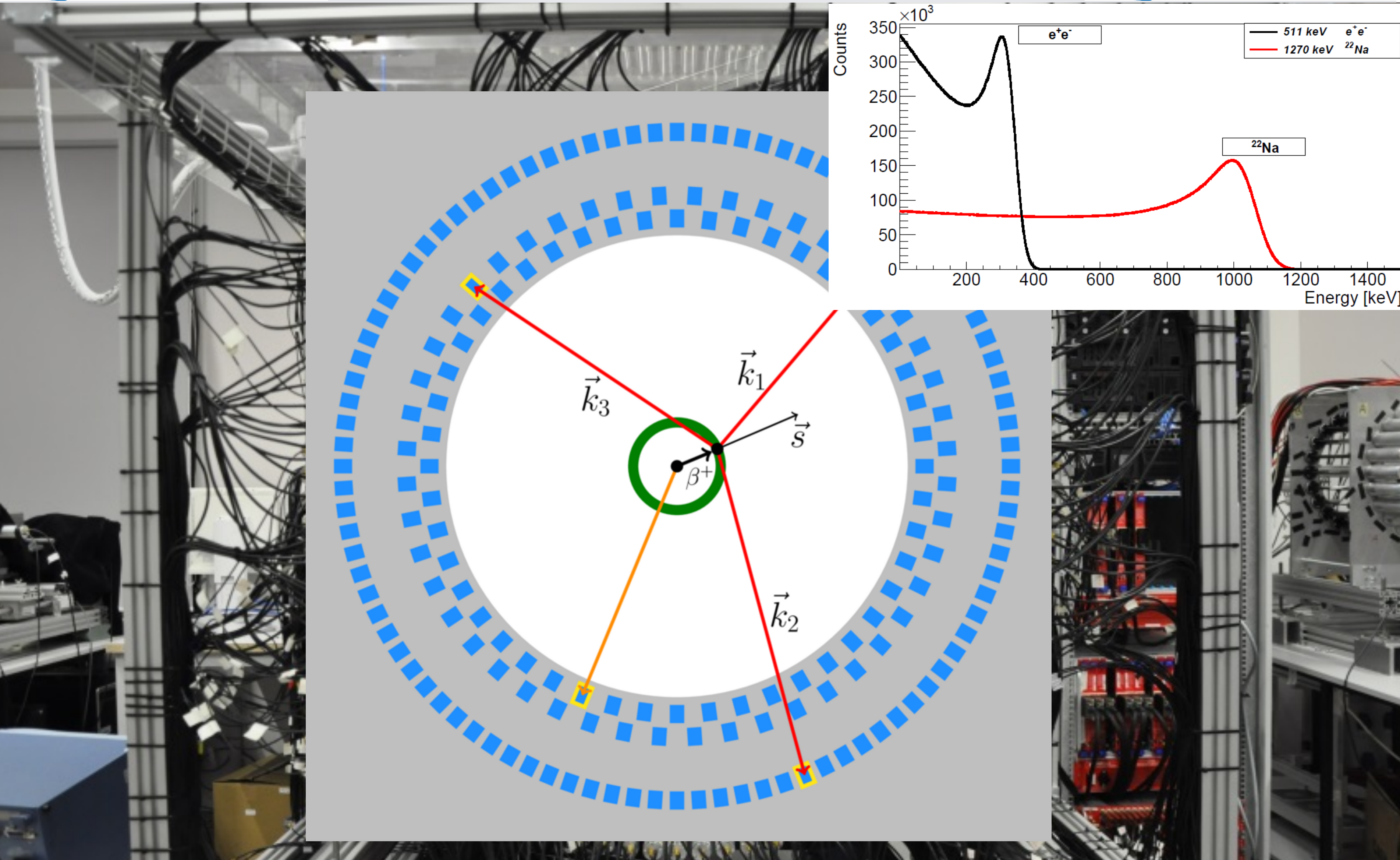


J-PET:
A. Gajos et al., NIM A819 (2016) 54

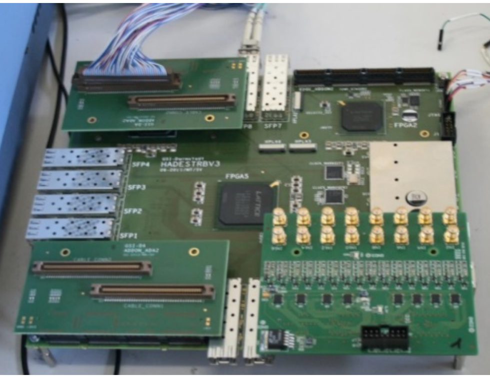


σ(t-hit) ~ 100 ps

Jagiellonian PET



σ(t-hit) ~ 100 ps



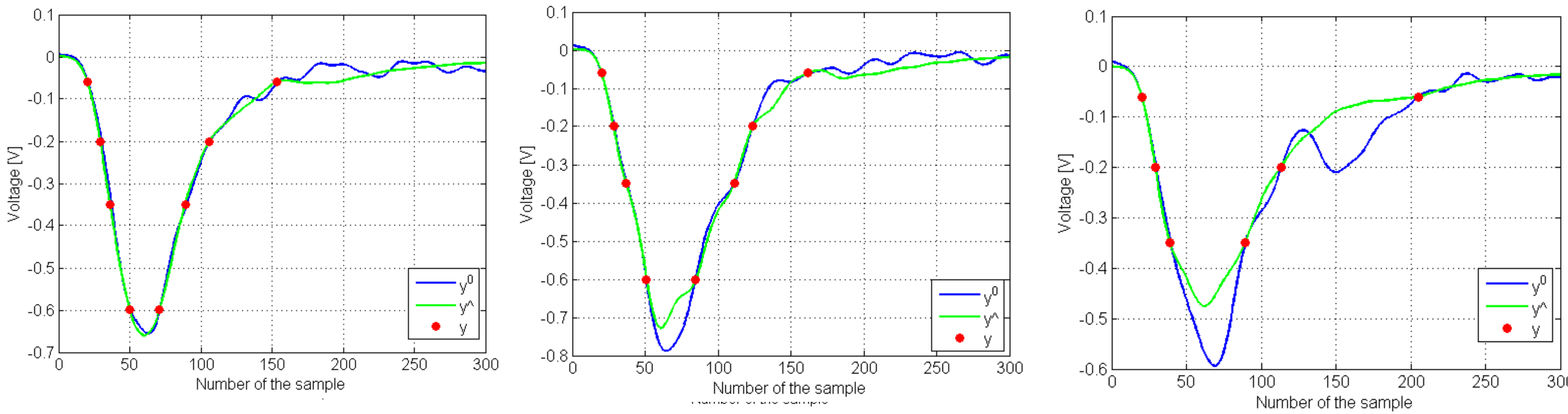
ONLY DIGITAL in triggerless mode

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**



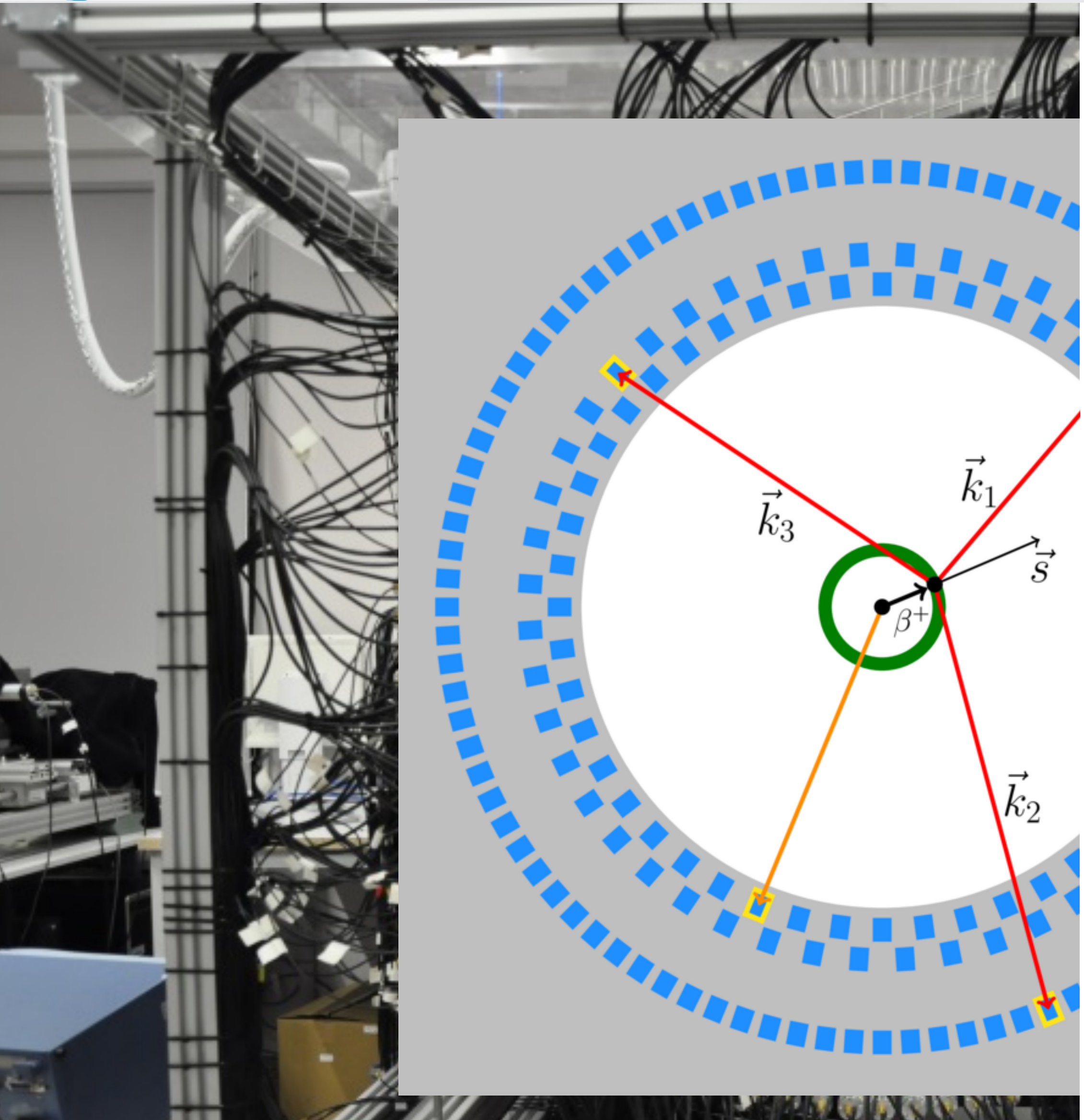
Library of signals; Principal Component Analysis; Compressive Sensing;
J-PET: L. Raczyński et al., Nucl. Instr. Meth. A786 (2015) 105
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54

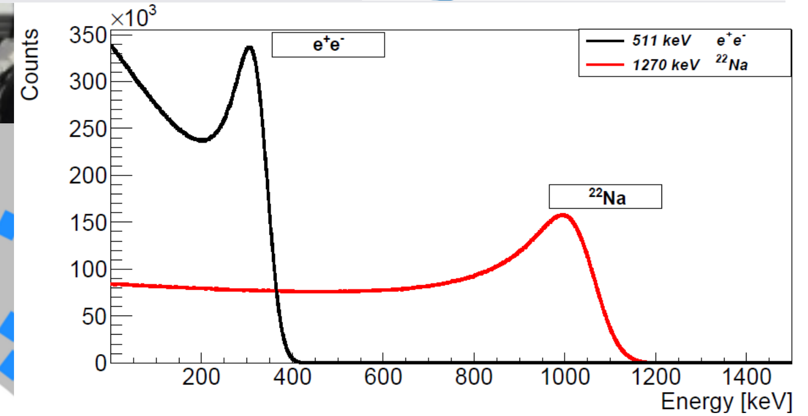
Reconstruction

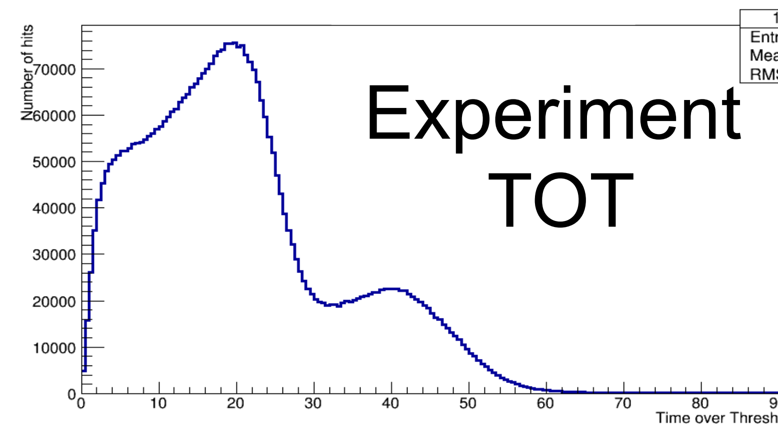
Detector → **FrontEnd electronics** → **Electronics controller** → **Hit along strip** → **Annihilation point** → **Image**

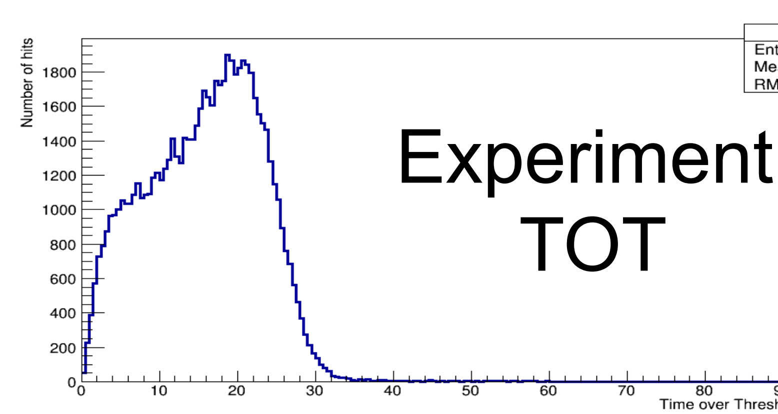
J-PET: W. Krzemień et al., Acta Phys. Pol. B47 (2016) 561

Jagiellonian PET

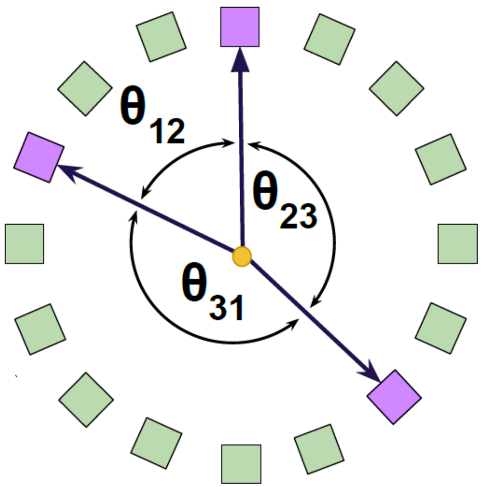




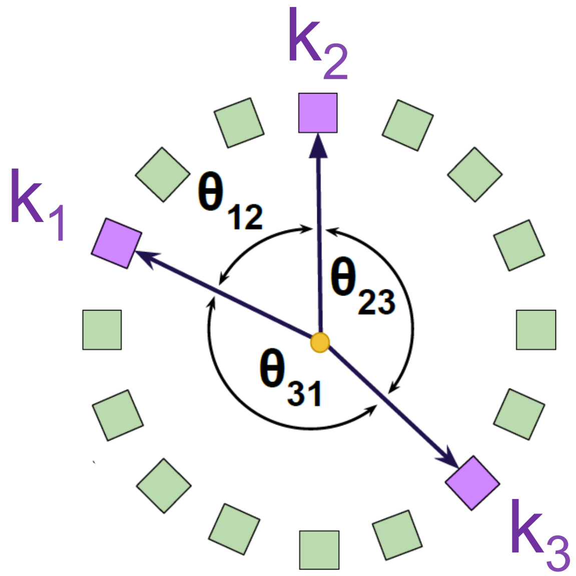




σ(t-hit) ~ 100

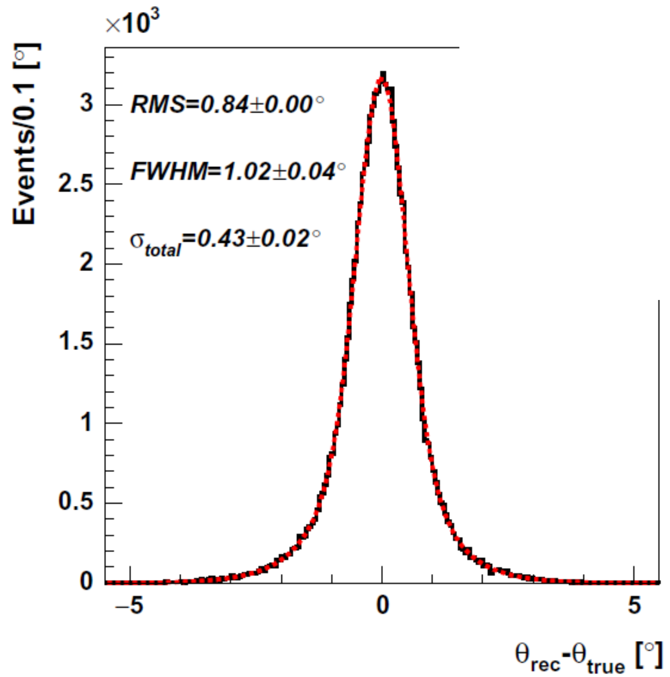


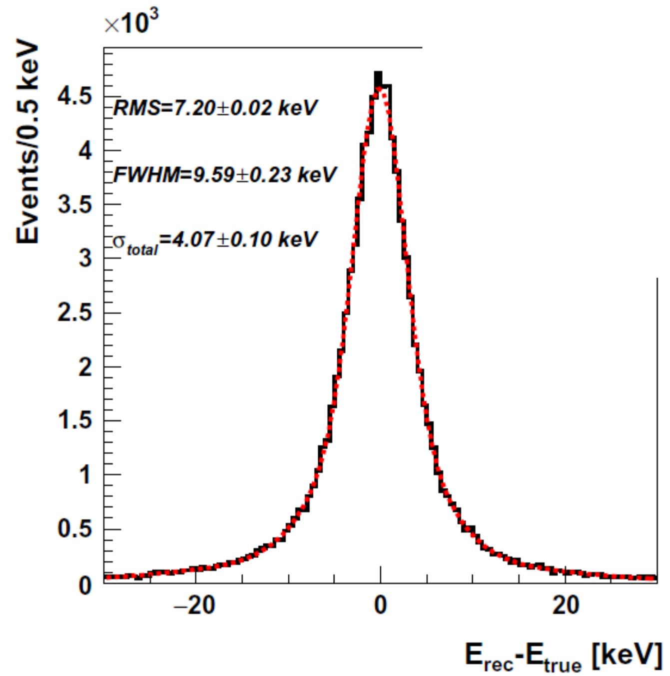
o-Ps → 3γ

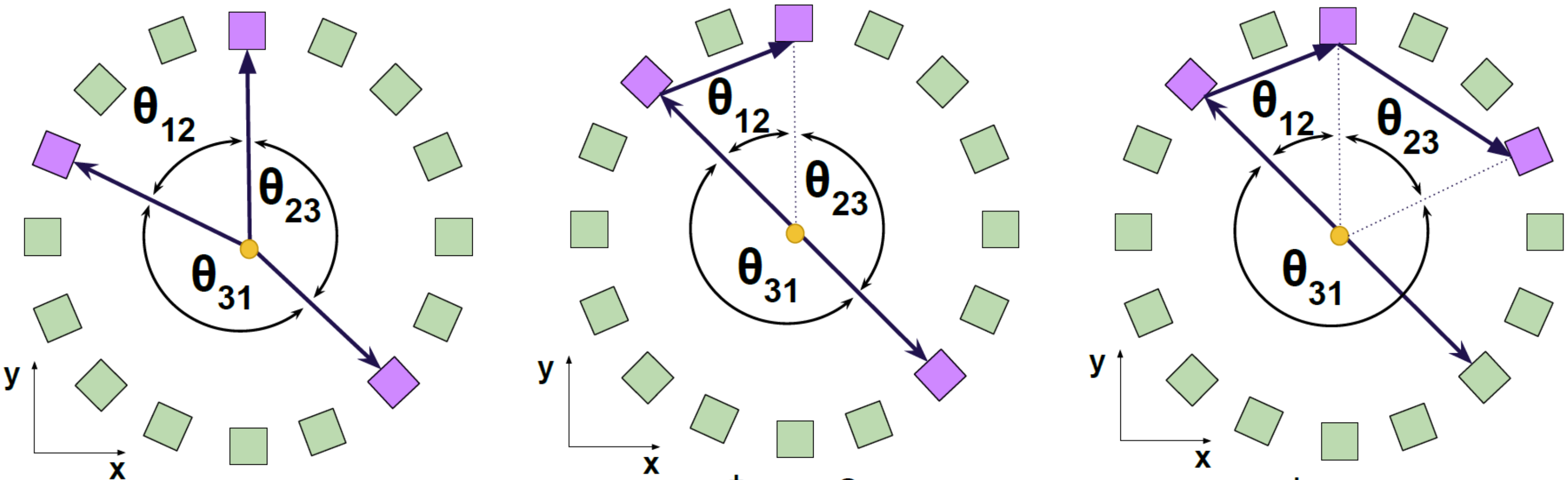


o-Ps → 3γ

J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445







o-Ps → 3γ

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

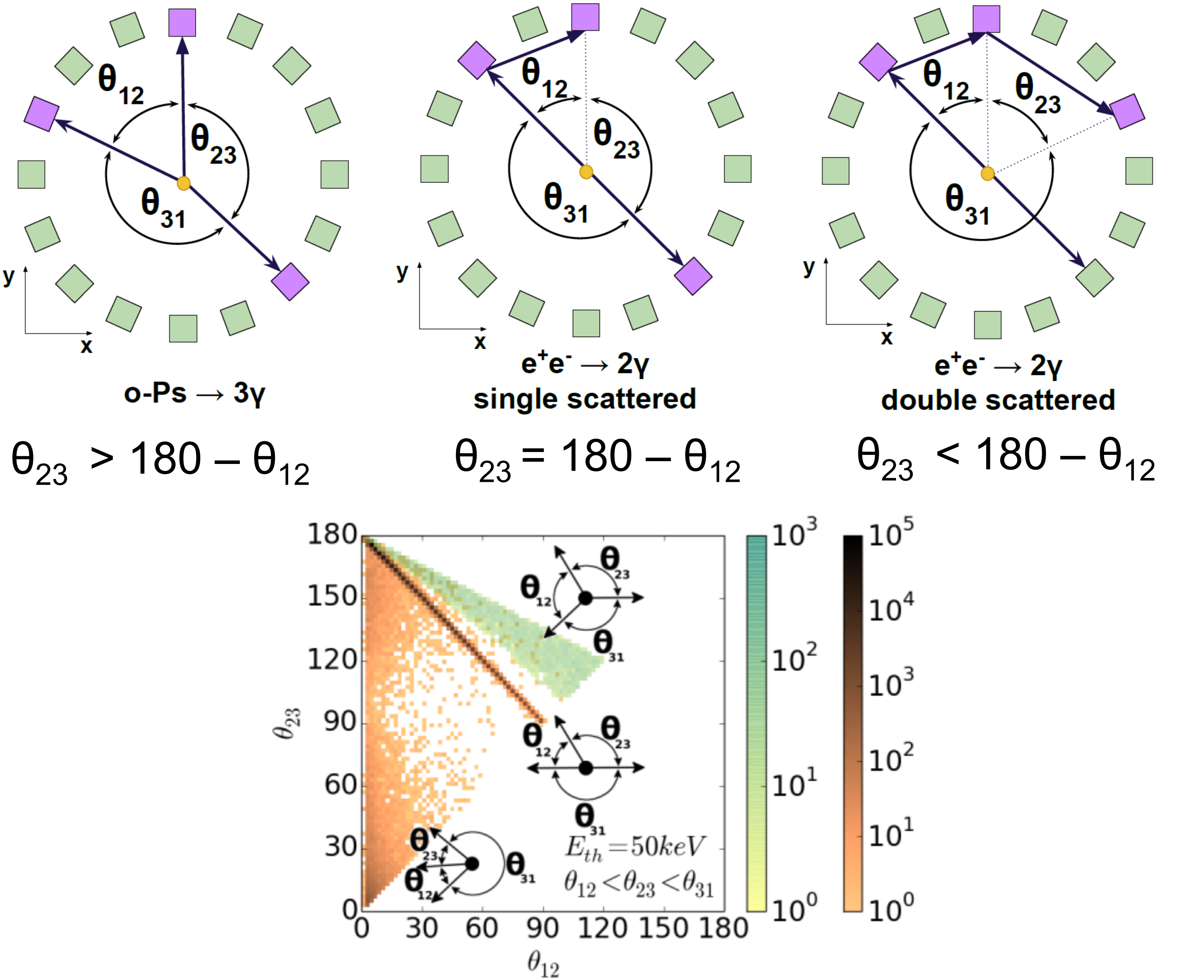
$e^+e^- \rightarrow 2\gamma$
single scattered

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

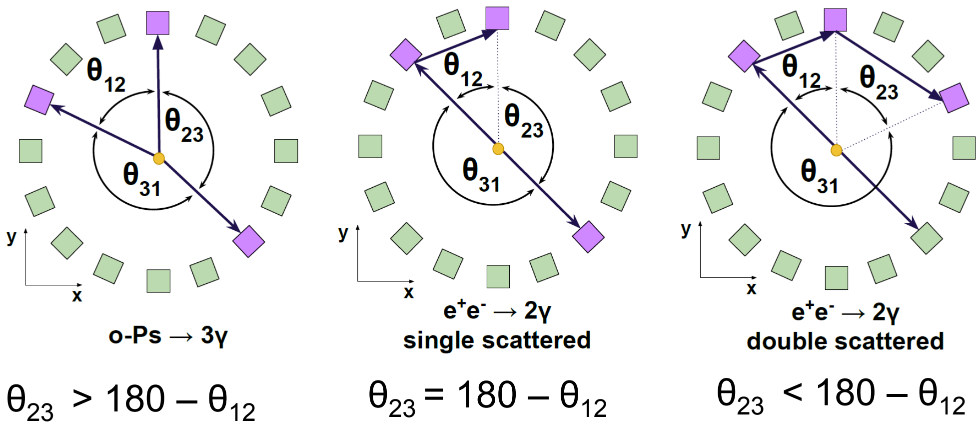
$e^+e^- \rightarrow 2\gamma$
double scattered

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

$$\theta_{12} < \theta_{23} < \theta_{31}$$



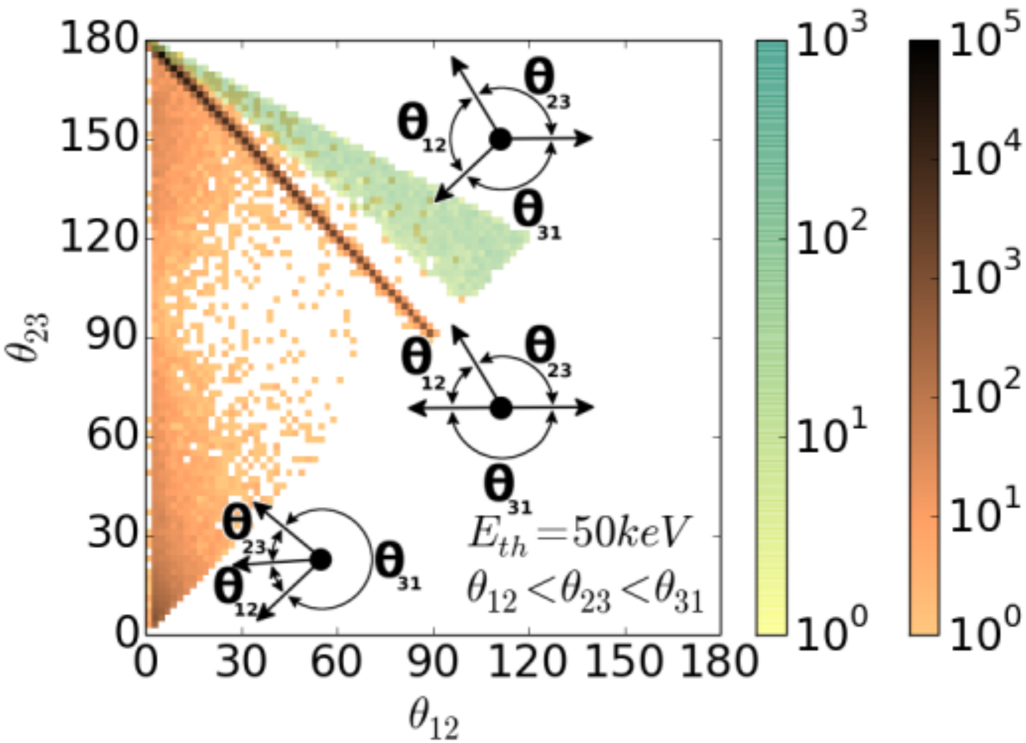
θ12
θ23
θ31
y
x
o-Ps → 3γ
e+e- → 2γ
single scattered
e+e- → 2γ
double scattered
θ23 > 180 – θ12
θ23 = 180 – θ12
θ23 < 180 – θ12
θ23
θ12
E_th = 50keV
θ12 < θ23 < θ31



J-PET

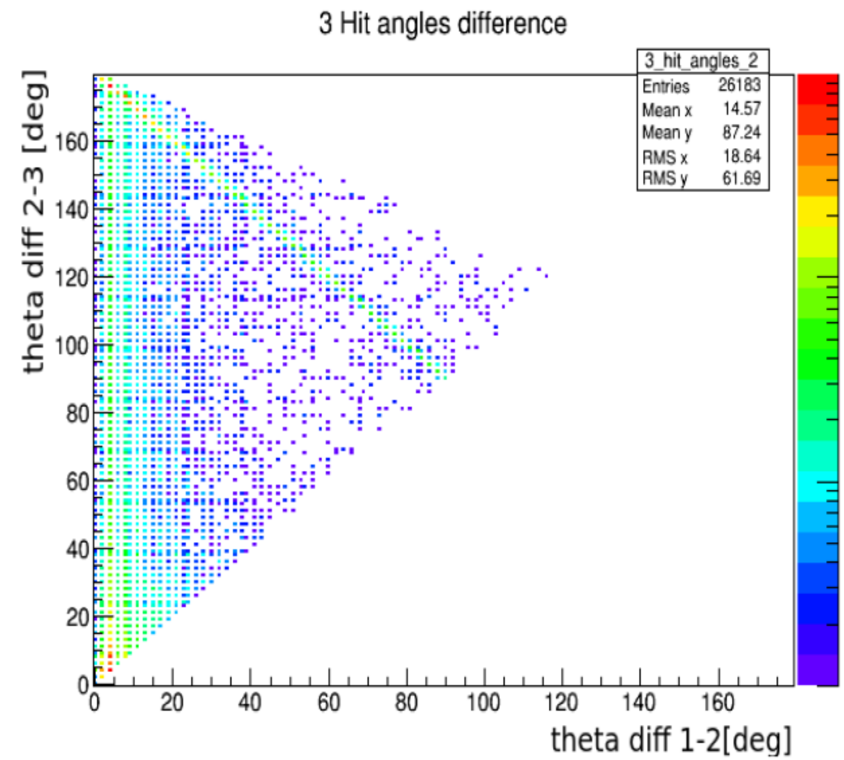
Simulations

Eur. Phys. J. C76 (2016) 445

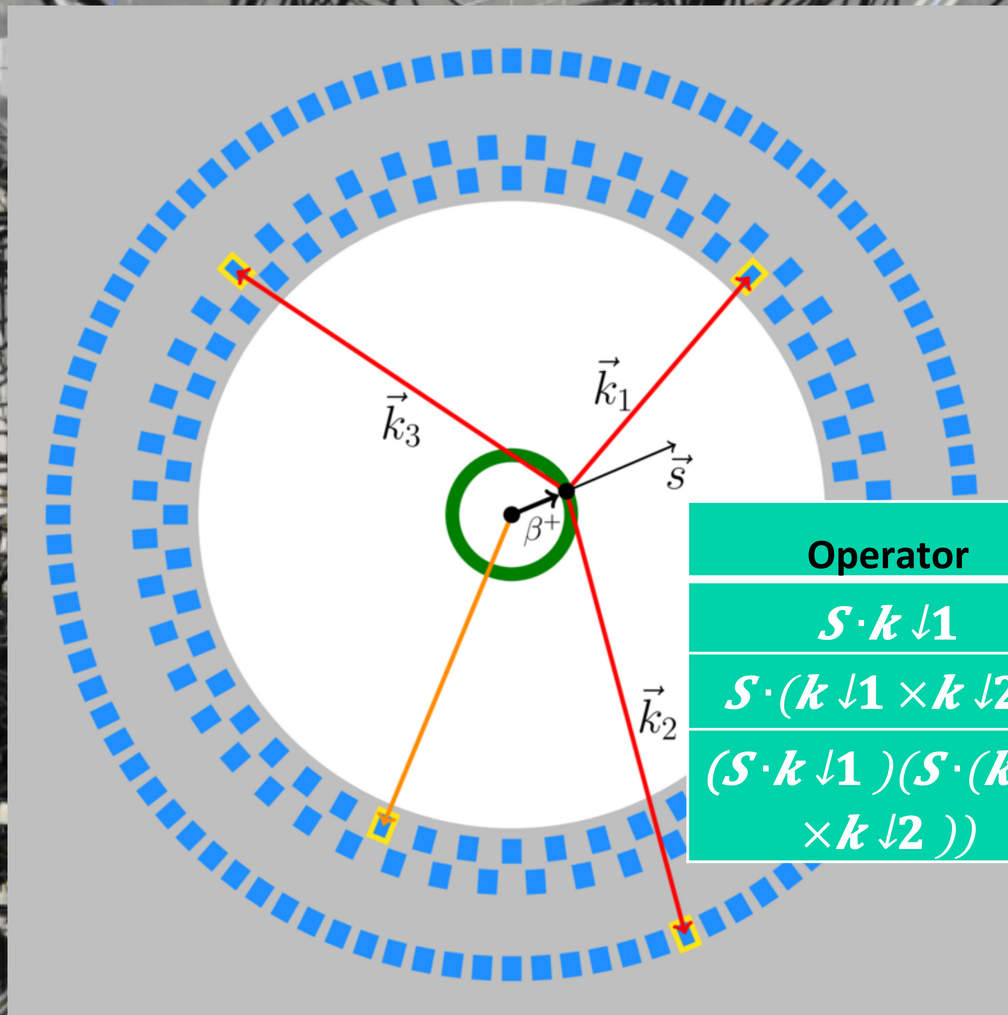


EXPERIMENT Run-1

analysed by K. Kacprzak



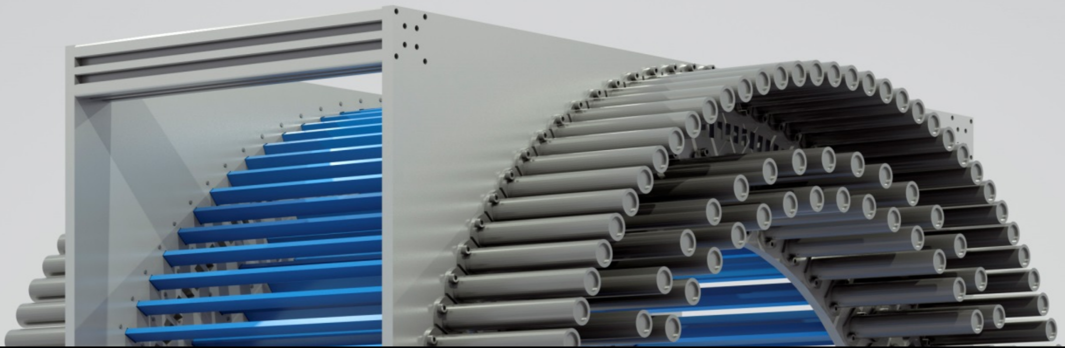
Jagiellonian PET



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

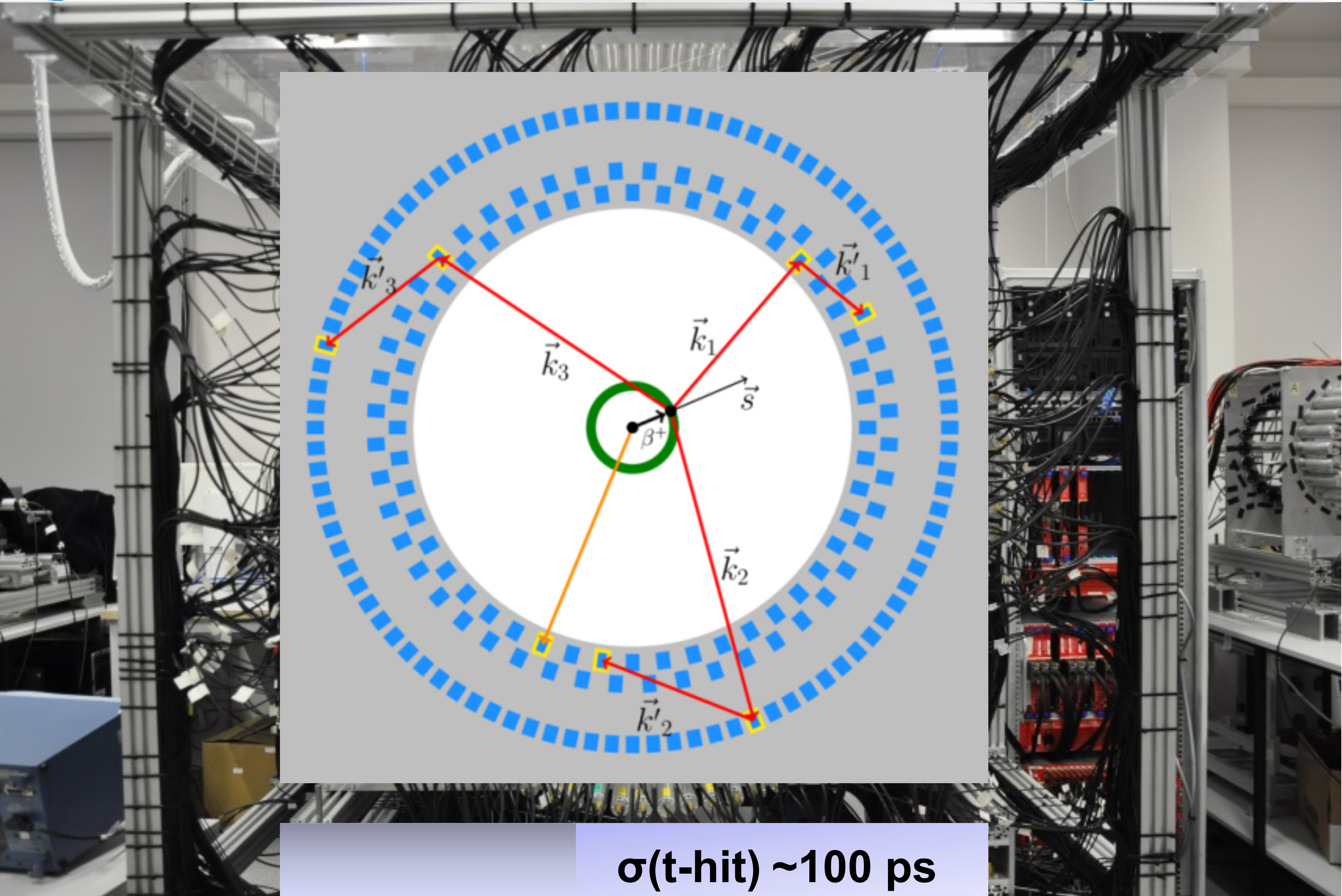
σ(t-hit) ~ 100 ps

Jagiellonian PET



- Jagiellonian PET
- Positronium
- Discrete symmetries NEW!
- Morphometric imaging
- Quantum entanglement

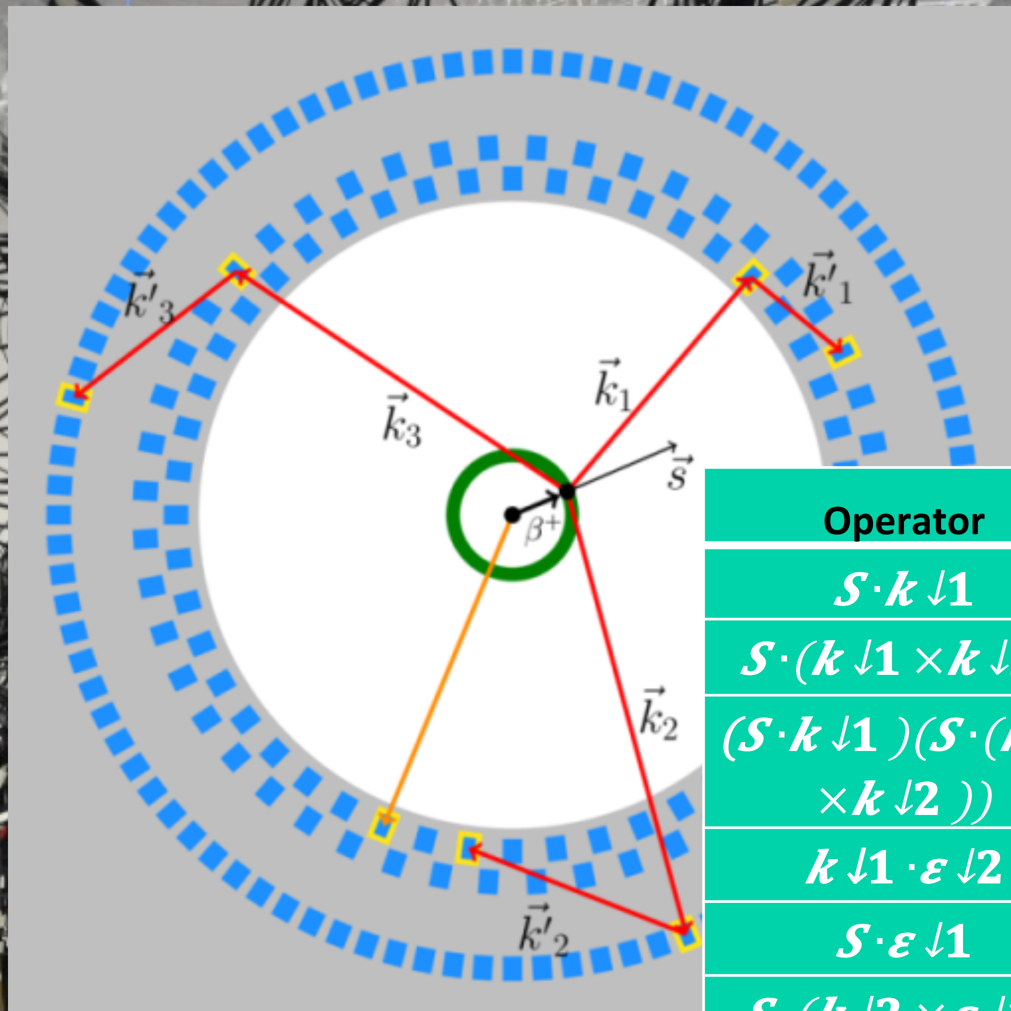
Jagiellonian PET



σ(t-hit) ~100 ps

Jagiellonian PET

J-PET



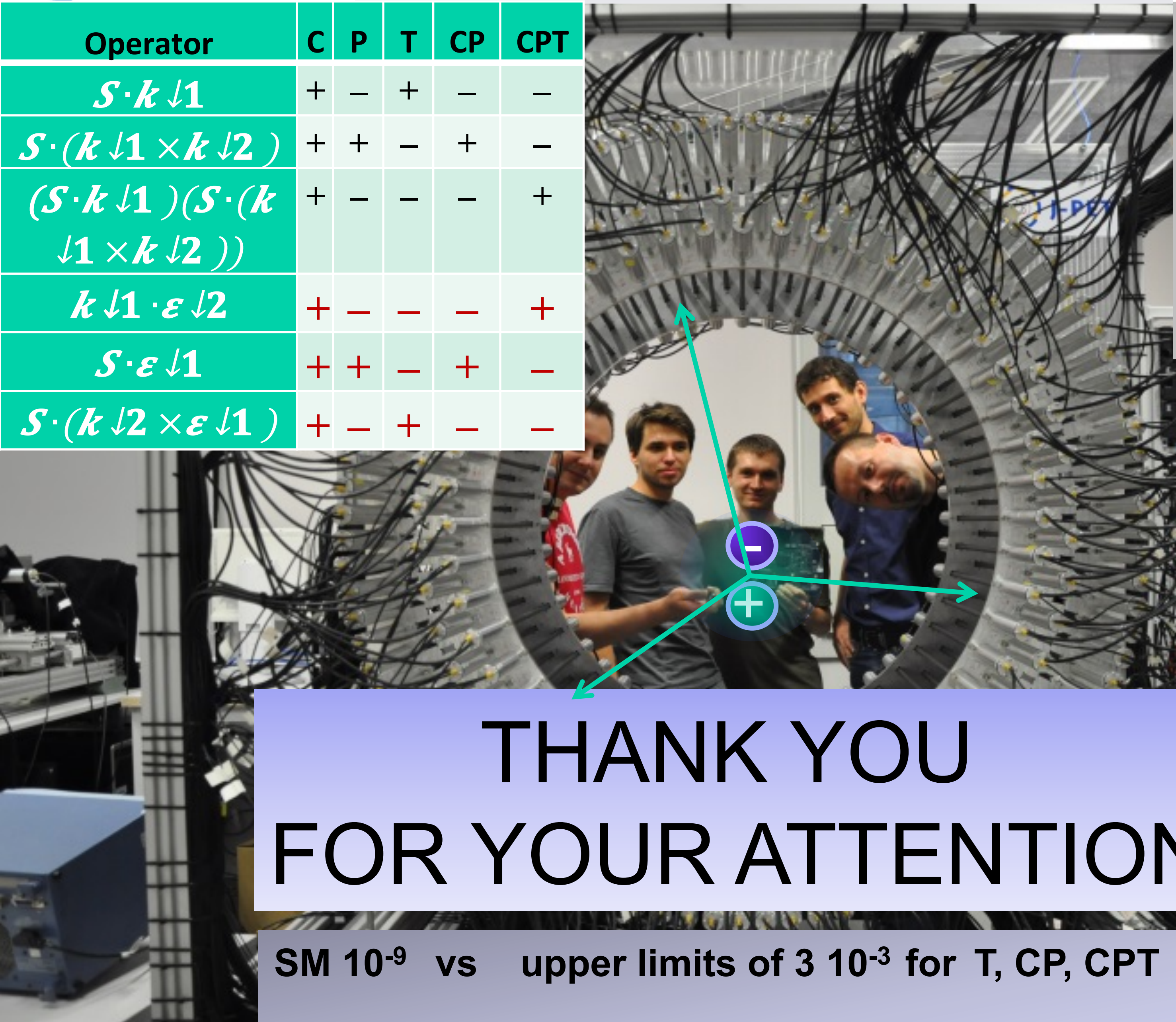
Operator	C	P	T	CP	CPT
$S \cdot k_1$	+	–	+	–	–
$S \cdot (k_1 \times k_2)$	+	+	–	+	–
$(S \cdot k_1)(S \cdot (k_1 \times k_2))$	+	–	–	–	+
$k_1 \cdot \varepsilon_2$	+	–	–	–	+
$S \cdot \varepsilon_1$	+	+	–	+	–
$S \cdot (k_2 \times \varepsilon_1)$	+	–	+	–	–

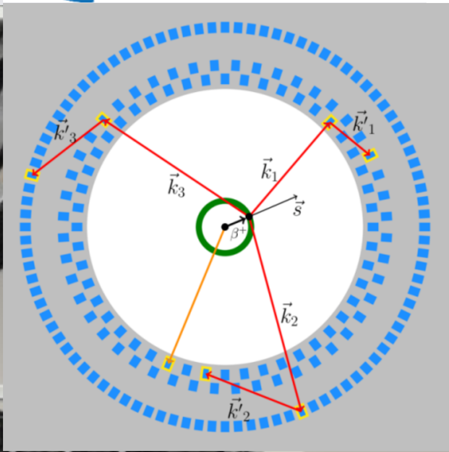
σ(t-hit) ~ 100

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

Jagiellonian PET

Operator	C	P	T	CP	CPT
$S \cdot k_1$	+	–	+	–	–
$S \cdot (k_1 \times k_2)$	+	+	–	+	–
$(S \cdot k_1)(S \cdot (k_1 \times k_2))$	+	–	–	–	+
$k_1 \cdot \varepsilon_2$	+	–	–	–	+
$S \cdot \varepsilon_1$	+	+	–	+	–
$S \cdot (k_2 \times \varepsilon_1)$	+	–	+	–	–





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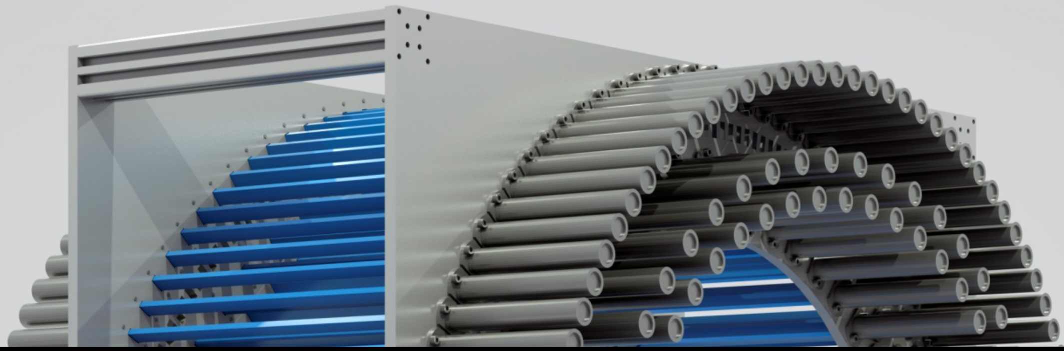
SM 10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

Jagiellonian PET



- Jagiellonian PET
- Positronium
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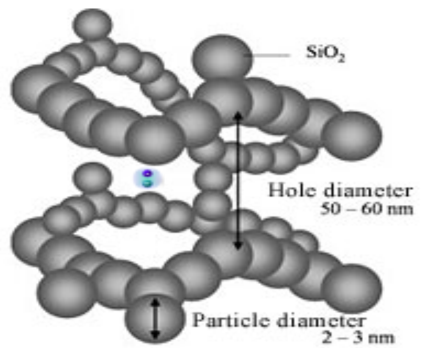
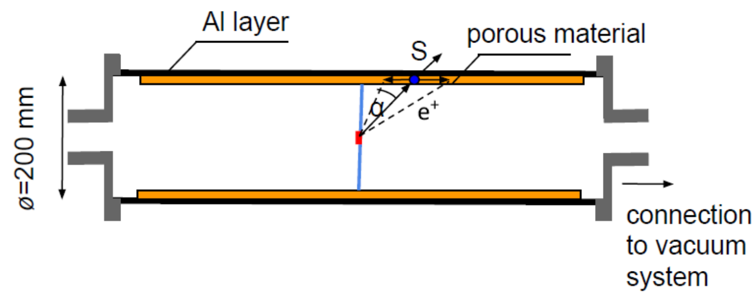
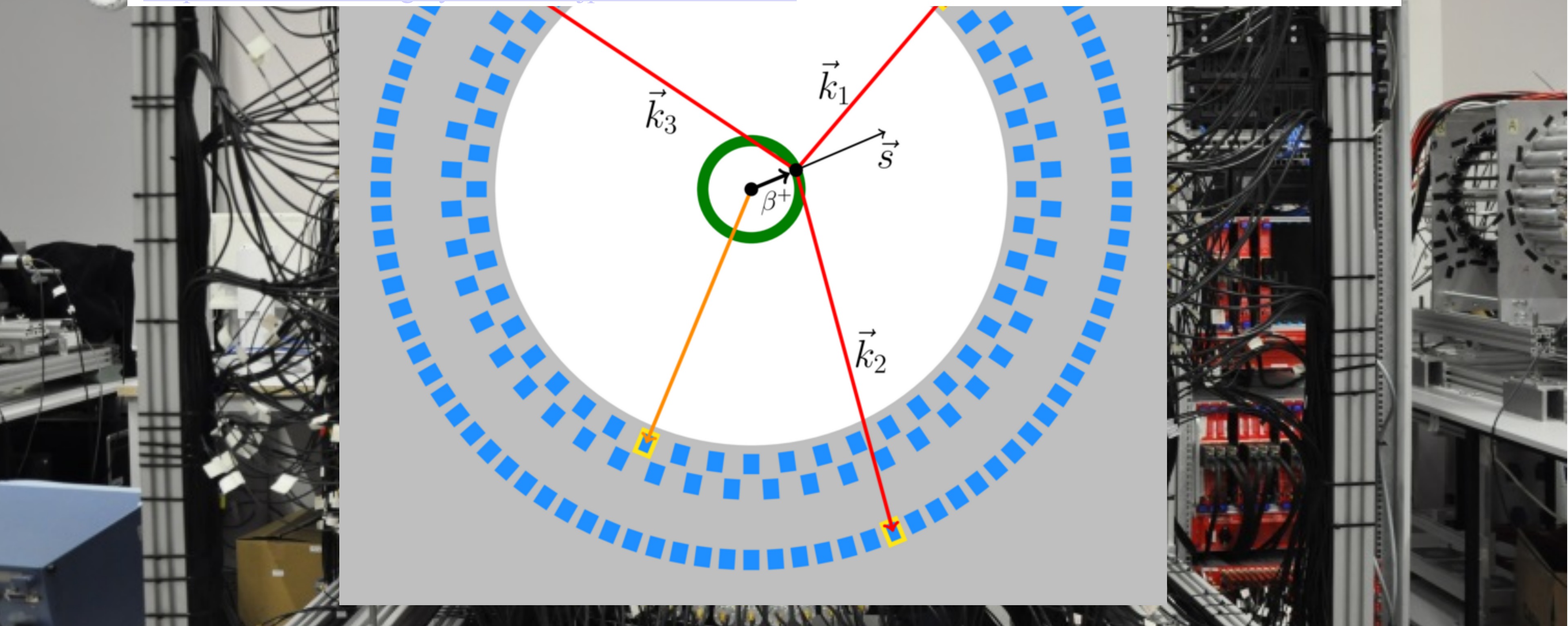
Jagiellonian PET

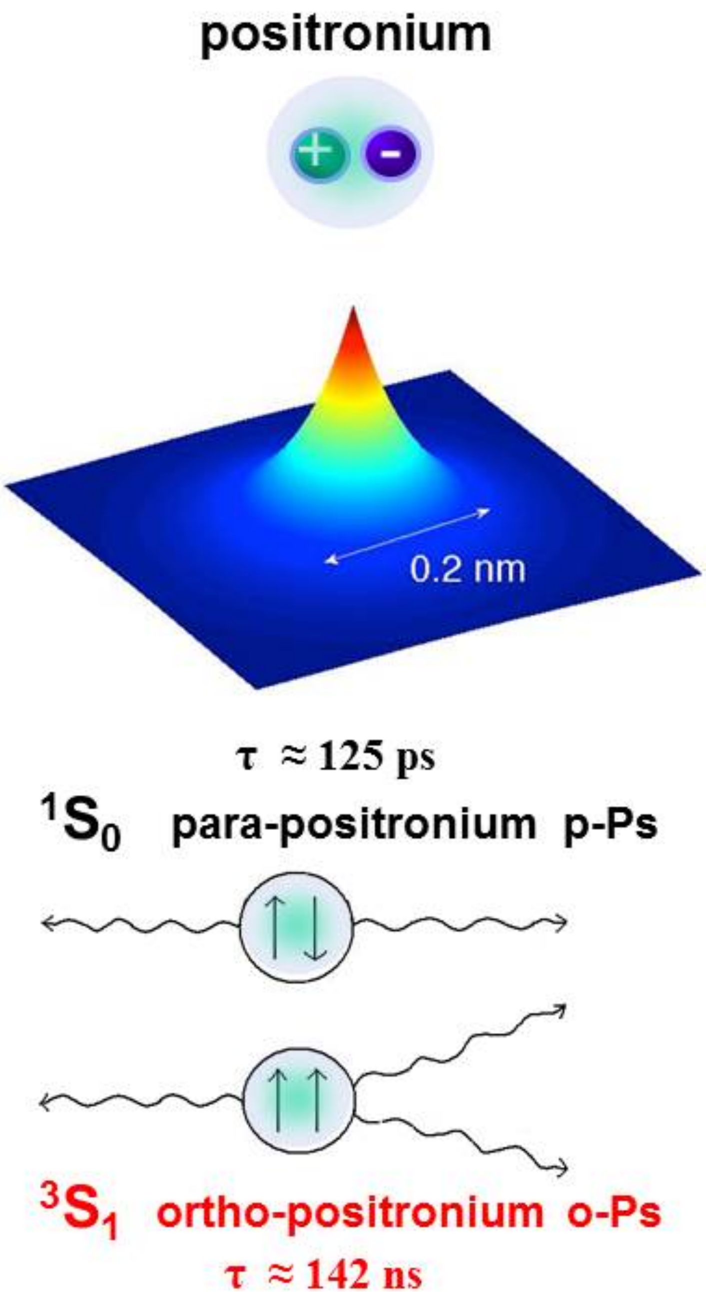


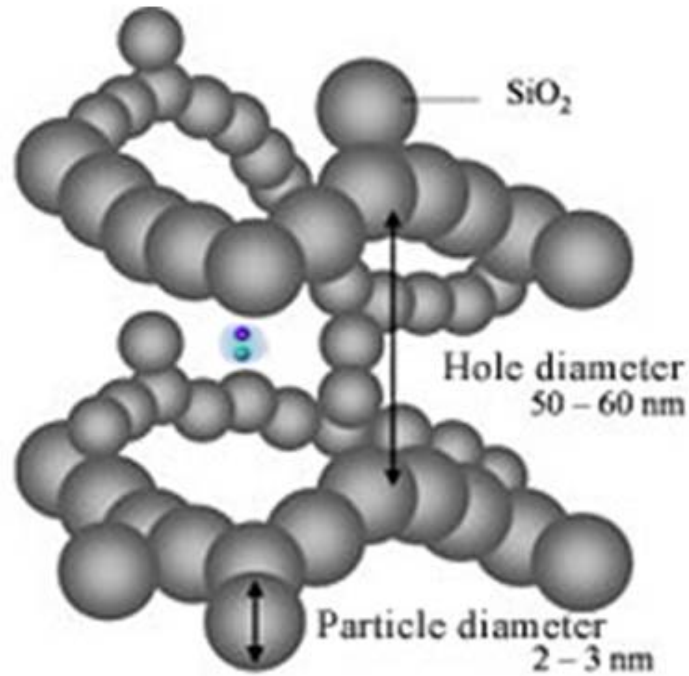
http://www.chem-eng.kyushu-u.ac.jp/e/research.html

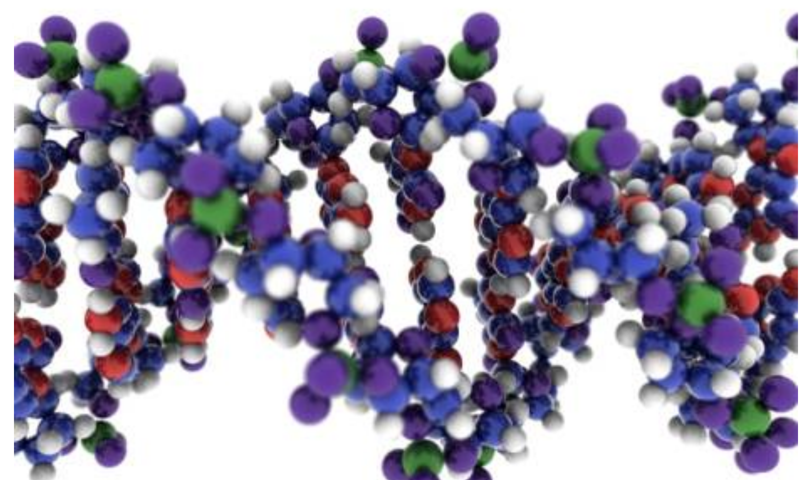




σ(t-hit) ~ 100 ps

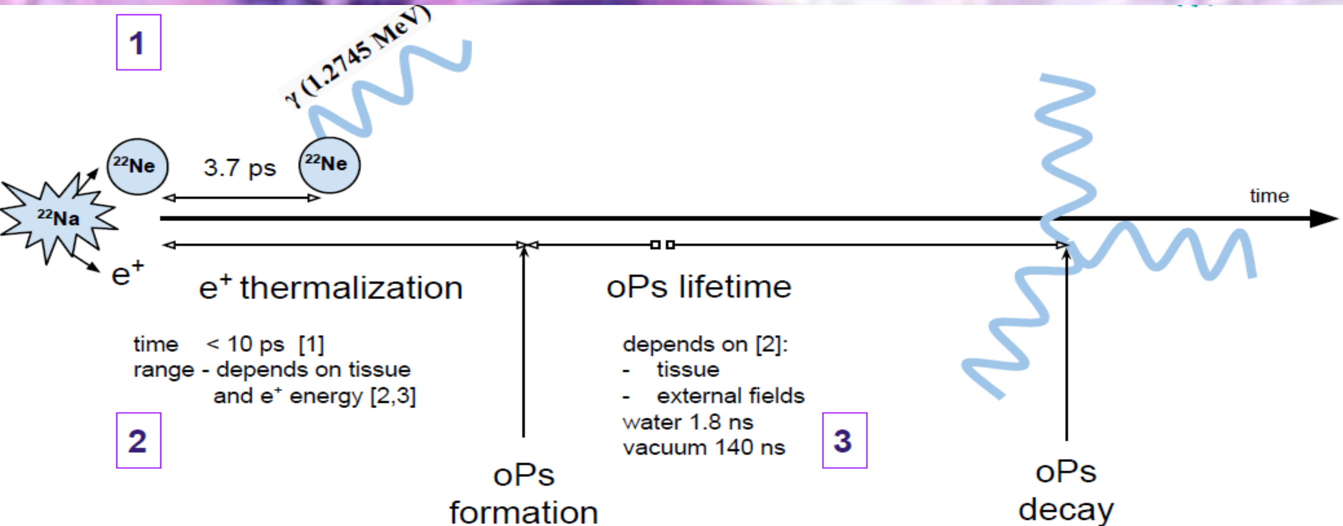

positronium
0.2 nm
τ ≈ 125 ps
¹S₀ para-positronium p-Ps
³S₁ ortho-positronium o-Ps
τ ≈ 142 ns

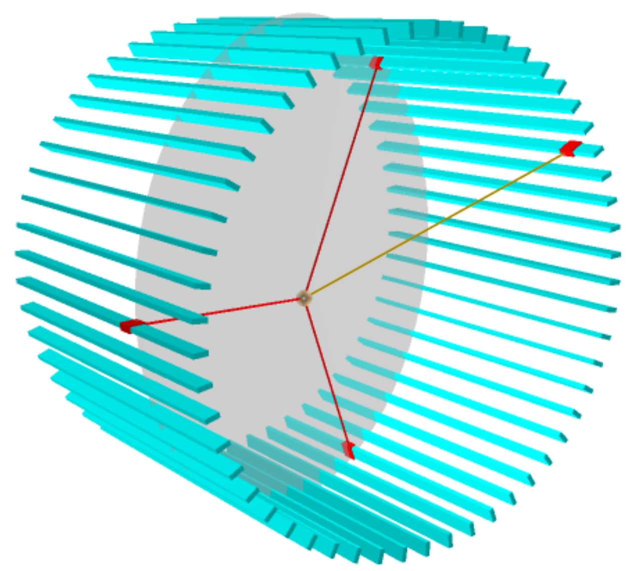

SiO₂
Hole diameter
50 – 60 nm
Particle diameter
2 – 3 nm

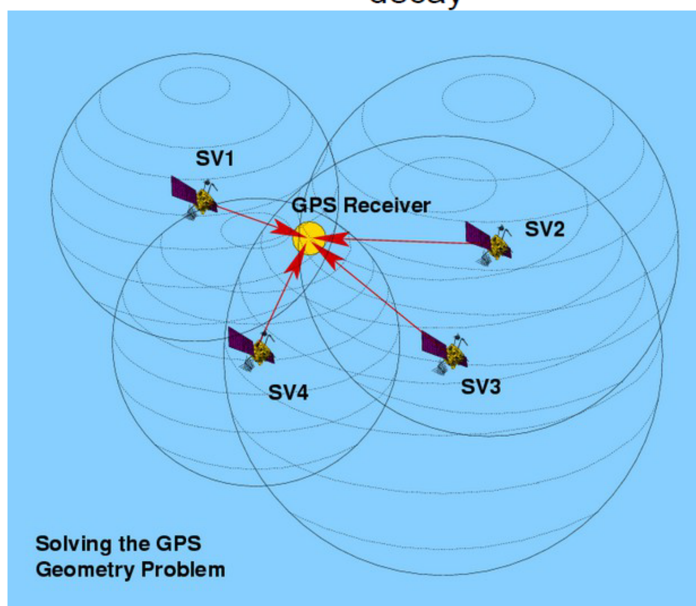



^{44}Sc
β^+
$\tau = 2.61$ps
γ (1.157MeV)
^{44}Ca

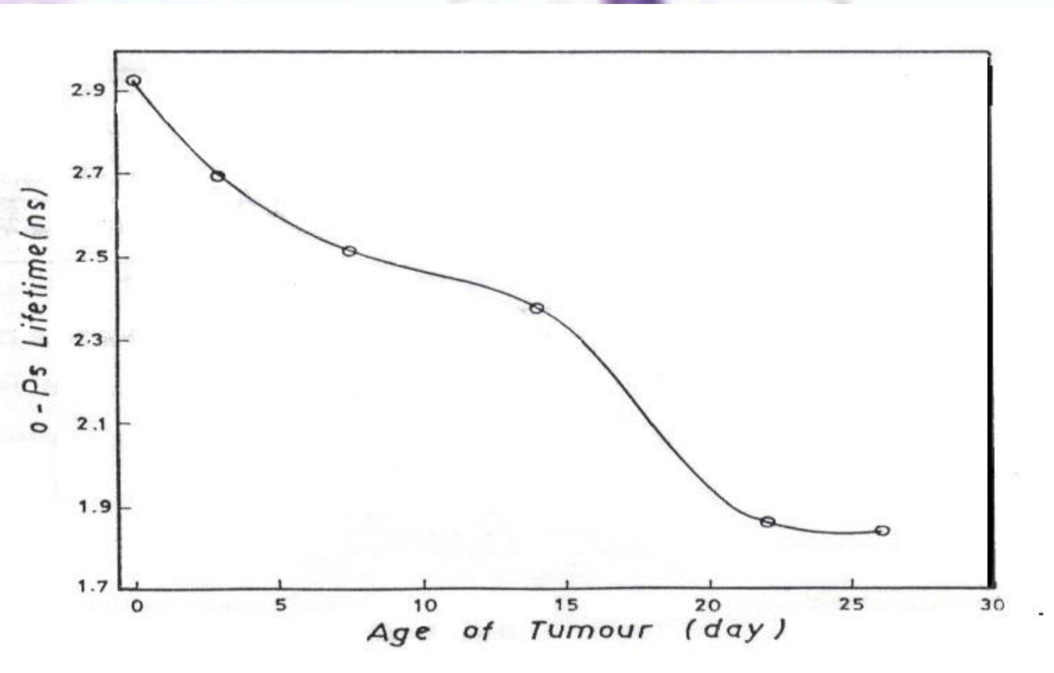
Ortho-positronium life-time tomography



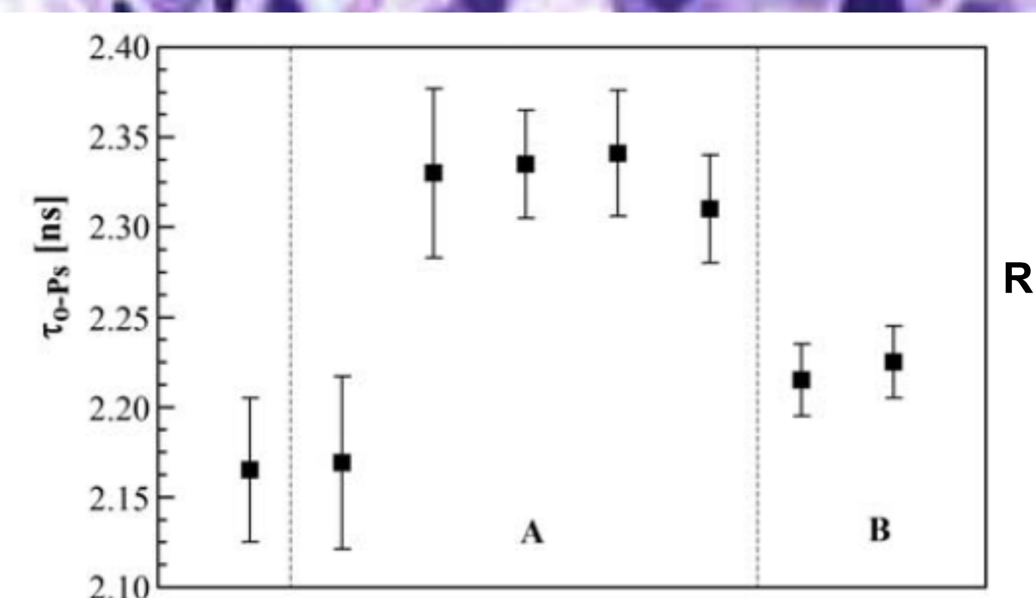




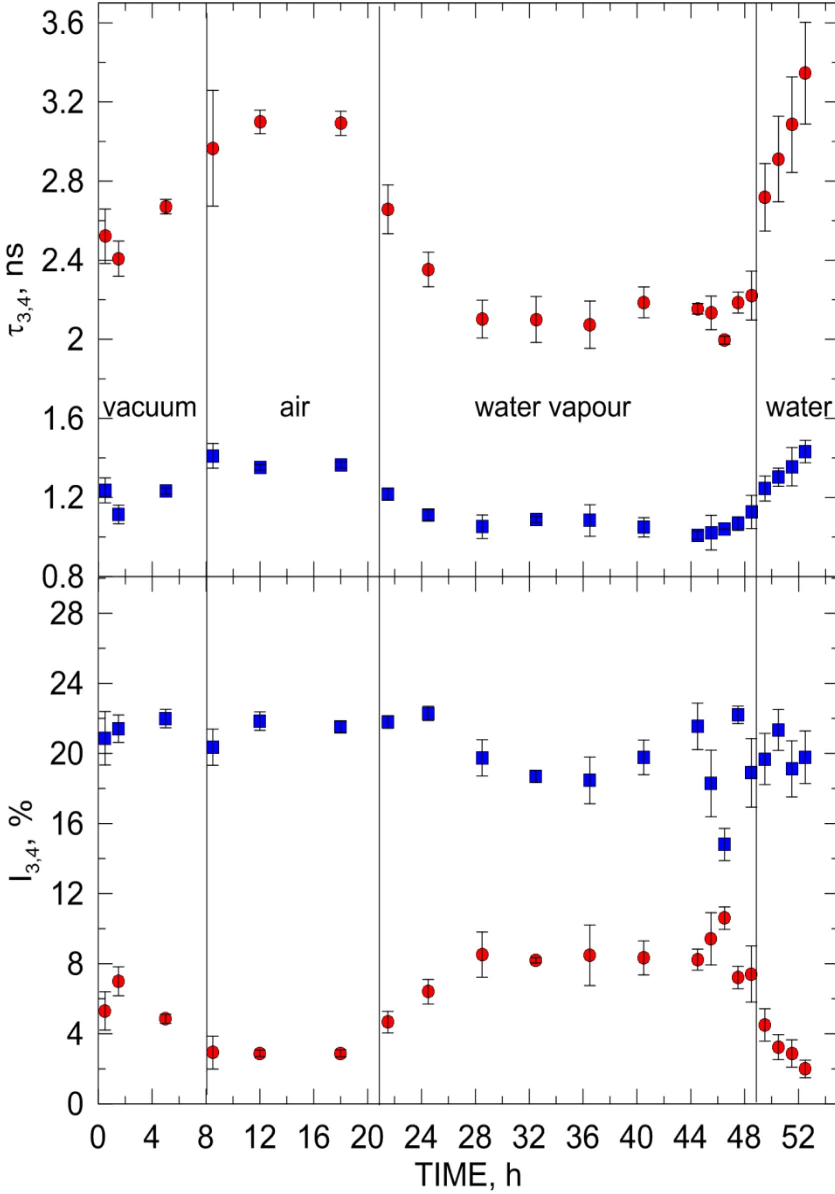
Patent applications: P. M., **PCT/EP2014/068374**; A. Gajos, E. Czerwiński, D. Kamińska, P. M., **PCT/PL2015/050038**

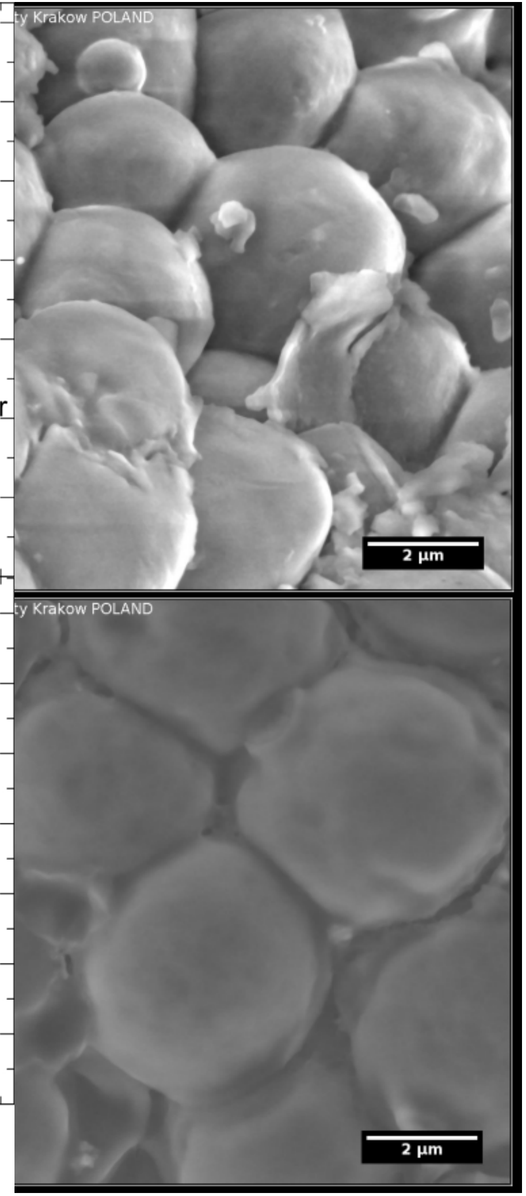


The age of mice's tumour with o-Ps lifetime
A.H. Al-Mashhadani et al., Iraqi J. Sci. 42C, 60 (2001) 3.



R. Pietrzak et al., NUKLEONIKA 58 (2013) 199





J-PET: E. Kubicz, et al., Nukleonika 60 (2015) 749.
Studies of unicellular micro-organisms Saccharomyces cerevisiae by means of positron annihillation lifetime spectroscopy

Environmental Scanning Electron Microscopy images of lyophilised yeasts (upper) and dried under normal conditions, after addition of water (bot-tom).

J-PET

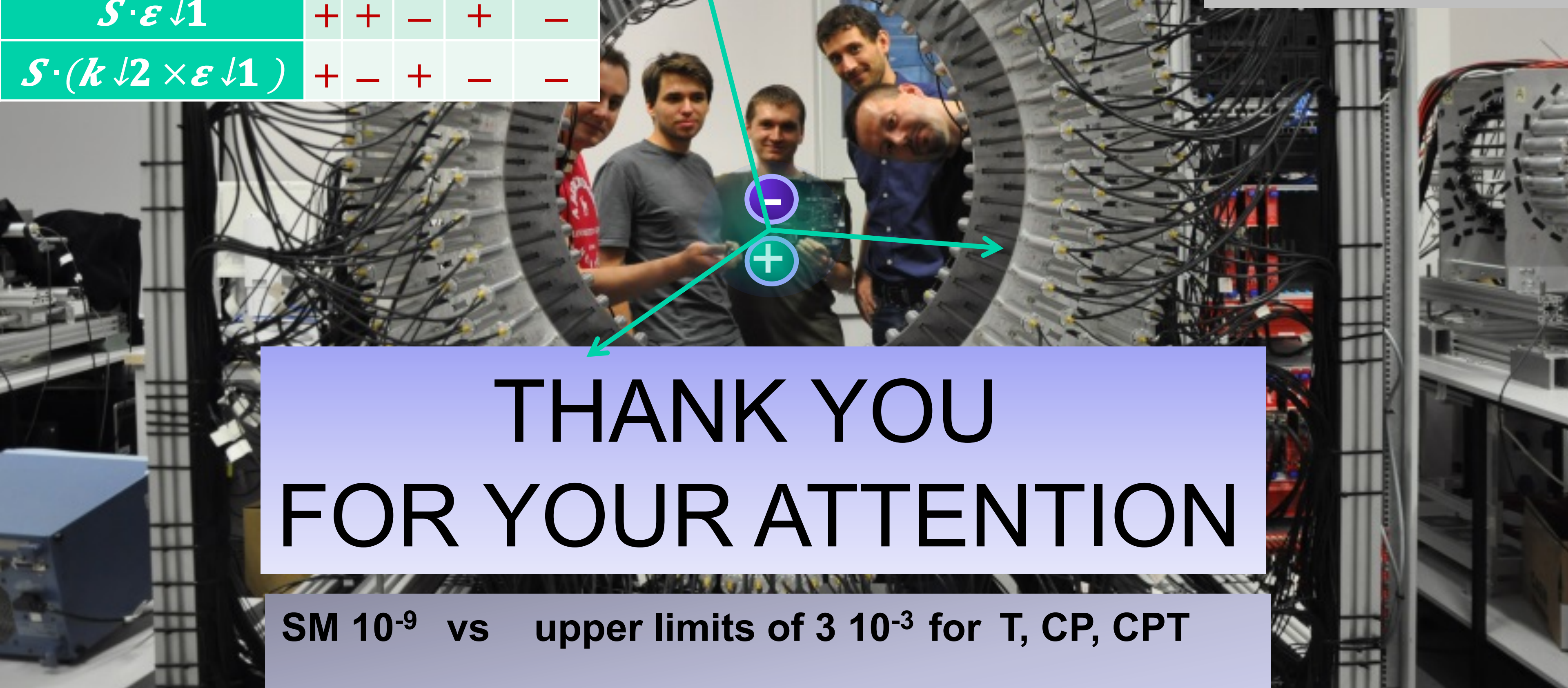
Jagiellonian PET

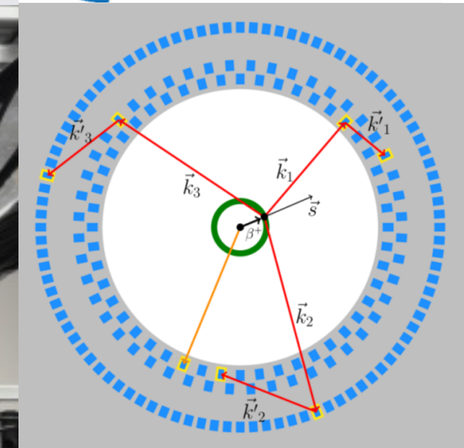
J-PET

Cracow, July 2016

Jagiellonian PET

Operator	C	P	T	CP	CPT
$S \cdot k_1$	+	–	+	–	–
$S \cdot (k_1 \times k_2)$	+	+	–	+	–
$(S \cdot k_1)(S \cdot (k_1 \times k_2))$	+	–	–	–	+
$k_1 \cdot \varepsilon_2$	+	–	–	–	+
$S \cdot \varepsilon_1$	+	+	–	+	–
$S \cdot (k_2 \times \varepsilon_1)$	+	–	+	–	–





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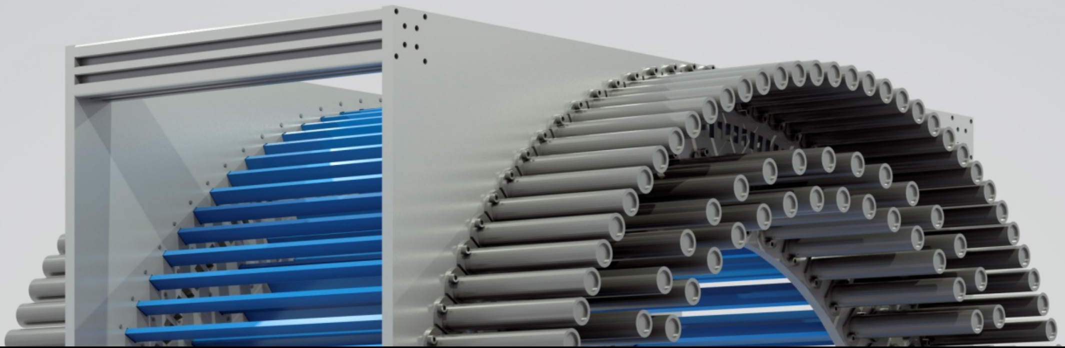
SM 10^{-9} vs upper limits of 3 10^{-3} for T, CP, CPT

Jagiellonian PET



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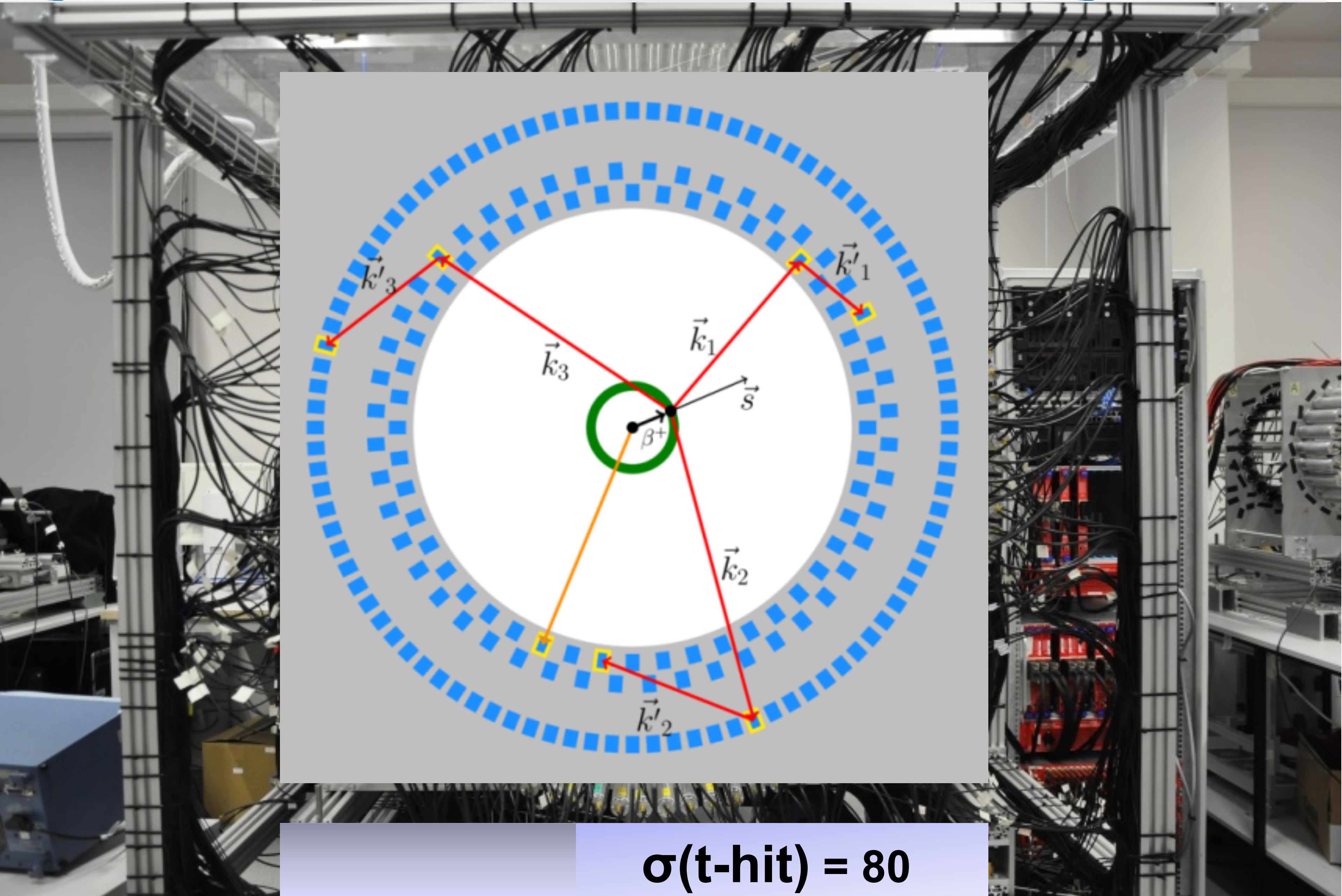
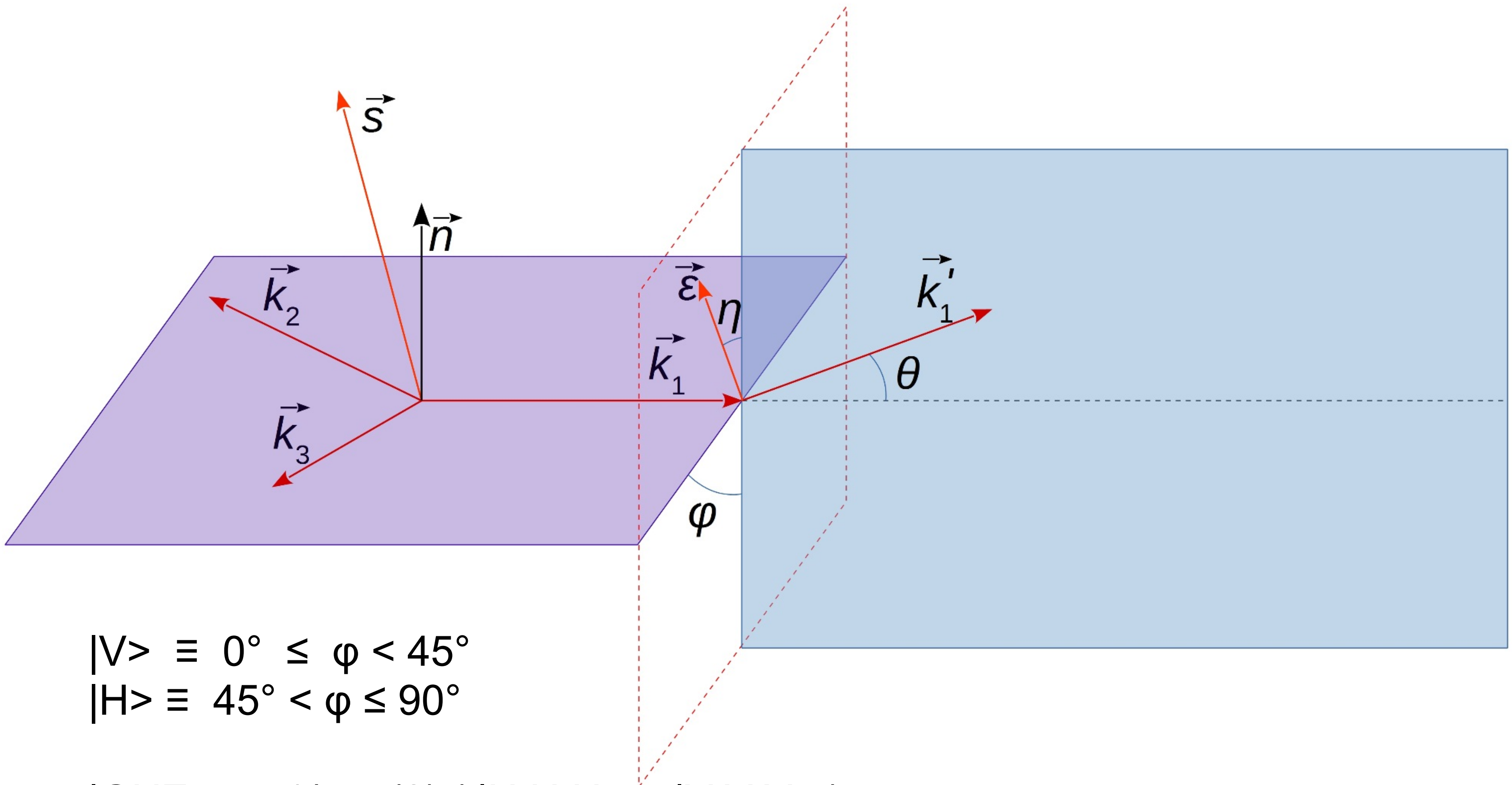


σ(t-hit) = 80

Jagiellonian PET



|V> ≡ 0° ≤ φ < 45°
|H> ≡ 45° < φ ≤ 90°

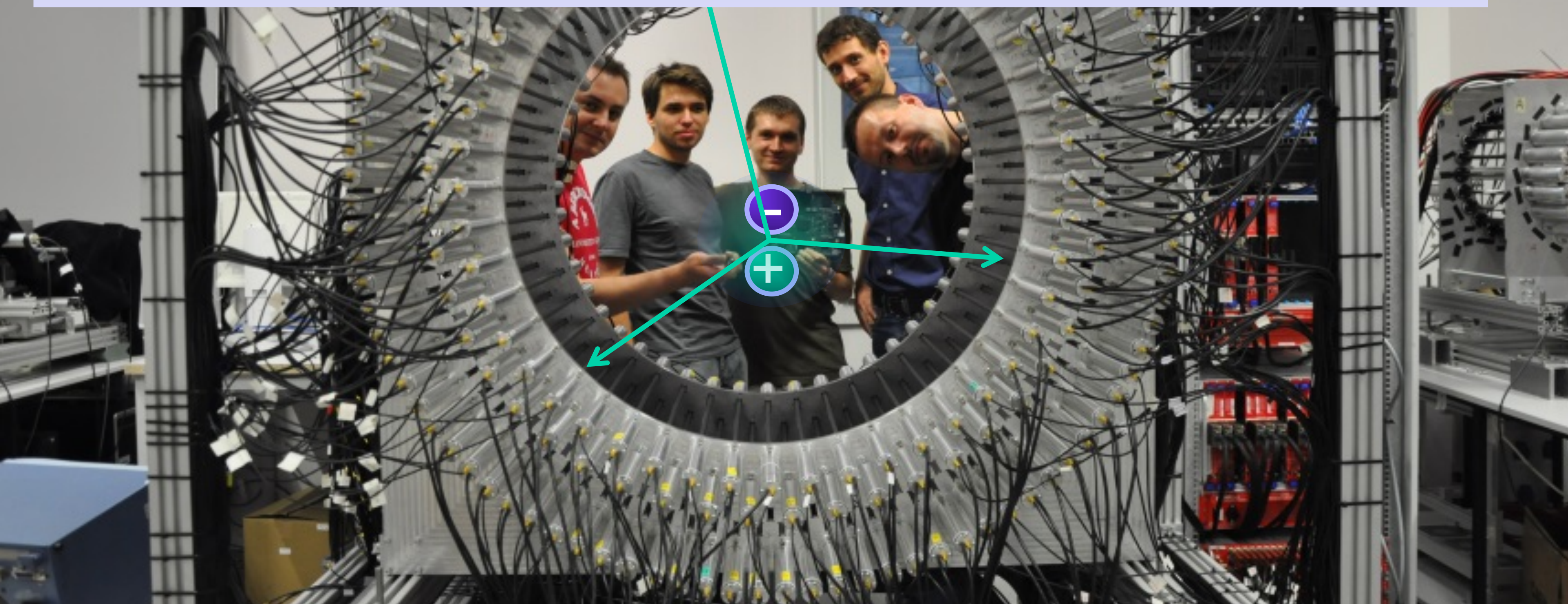
|GHZ > = 1/sqrt(2) (|H H H> + |V V V>)
| W > = 1/sqrt(3) (|H H V> + |H V H> + |V H H >)

Jagiellonian PET

It is an open question whether or not the three-photon entanglement can be reduced to the two-photon entanglement and decoherence of the two-photon states does imply decoherence in photon triplets. This hypothesis can be tested by comparison of measured two- and three-photon correlation functions. There exist three-photon states maximizing the Greenberger-Horn-Zeilinger (GHZ) entanglement and they can be used to test quantum local realism versus quantum mechanics.

D.M. Greenberger et al., Am. J. Phys. 58(1990)1131

A. Acin et al., Phys. Rev. A63(2001) 042107; N.D. Mermin, Phys. Rev. Lett. 65 (1990)1838



σ(t-hit) ~ 100 ps

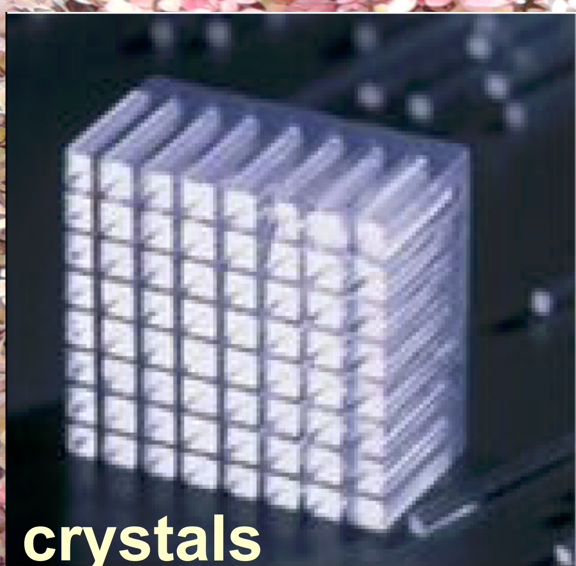
Jagiellonian PET

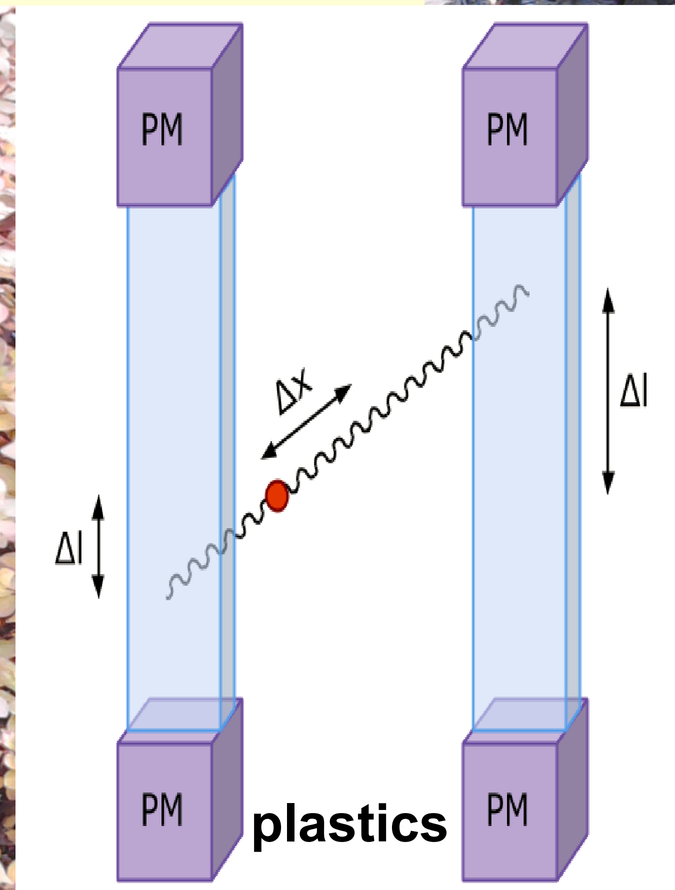
Cracow, July 2016

....

J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A764 (2014) 186
J-PET: P. M. et al., Nucl. Instrum. Meth. A764 (2014) 317
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 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

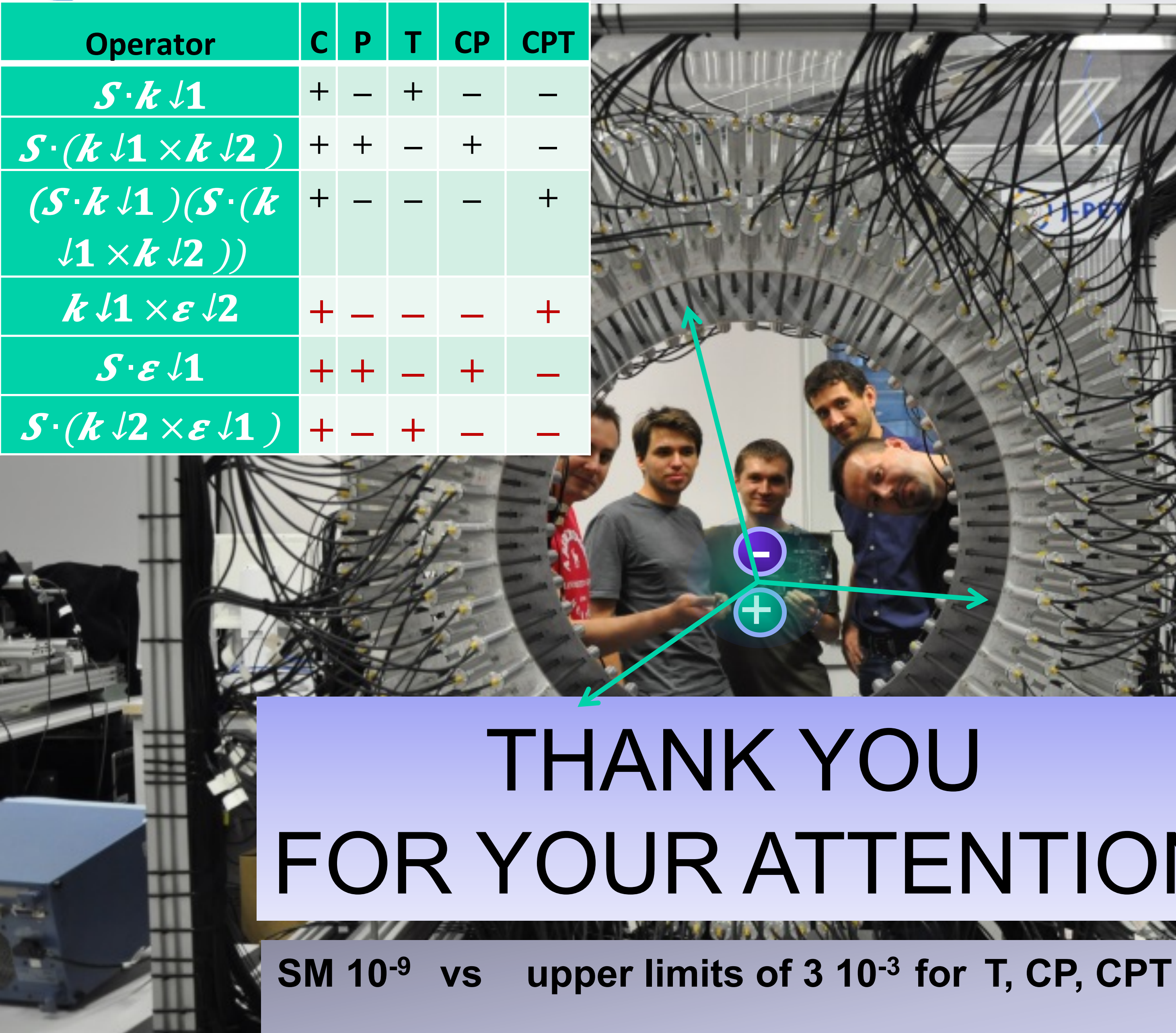
Over 50 articles and 16 international patent applications

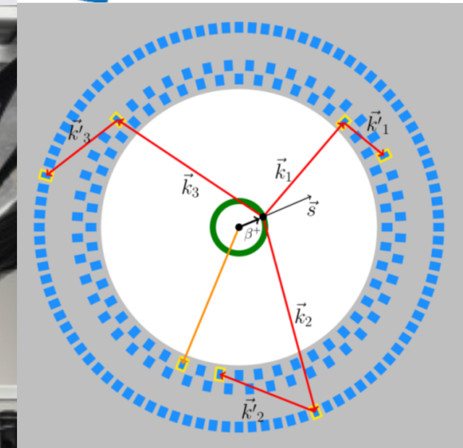




Jagiellonian PET

Operator	C	P	T	CP	CPT
$S\cdot k_1$	+	–	+	–	–
$S\cdot(k_1\times k_2)$	+	+	–	+	–
$(S\cdot k_1)(S\cdot(k_1\times k_2))$	+	–	–	–	+
$k_1\times\varepsilon_2$	+	–	–	–	+
$S\cdot\varepsilon_1$	+	+	–	+	–
$S\cdot(k_2\times\varepsilon_1)$	+	–	+	–	–





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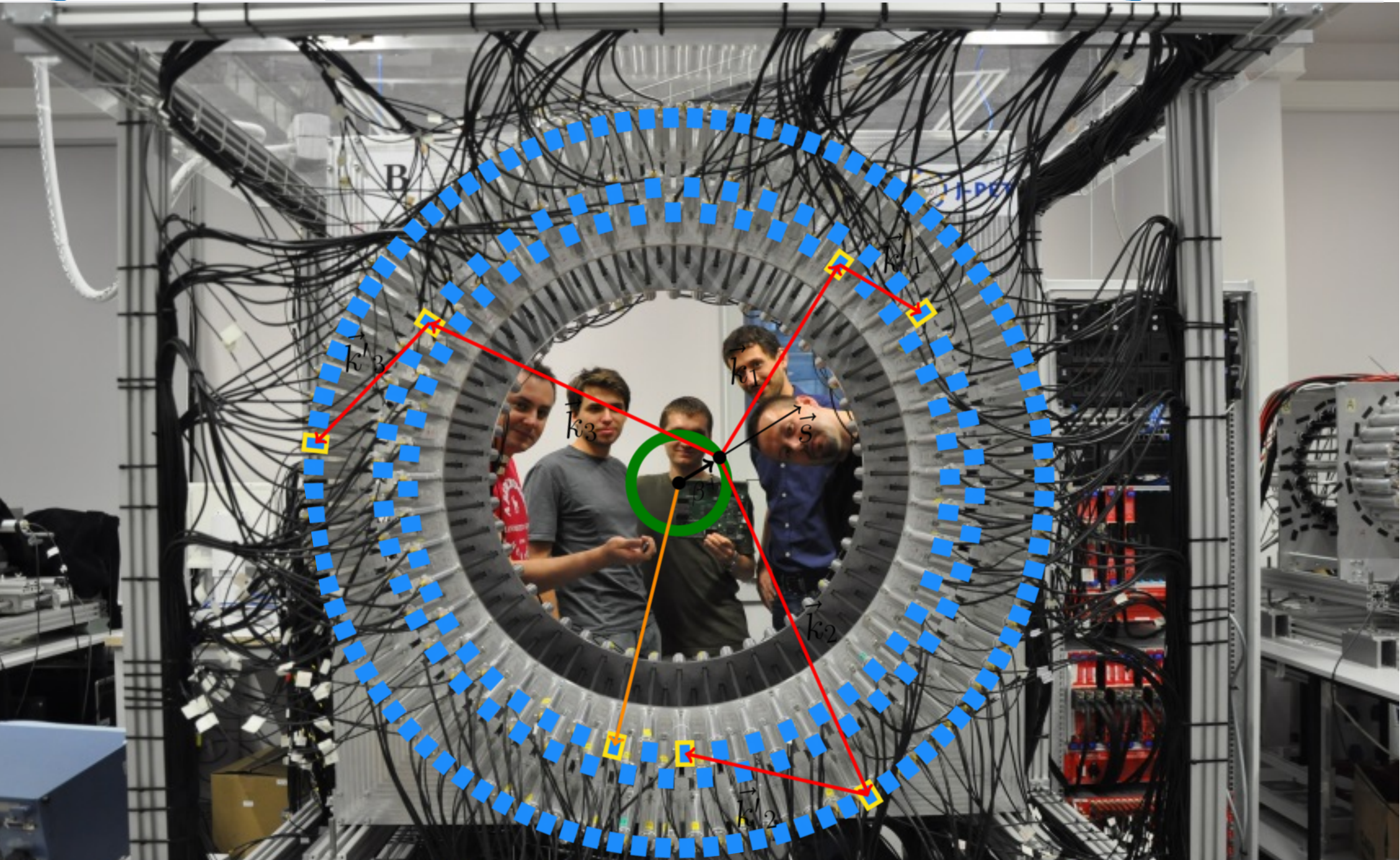
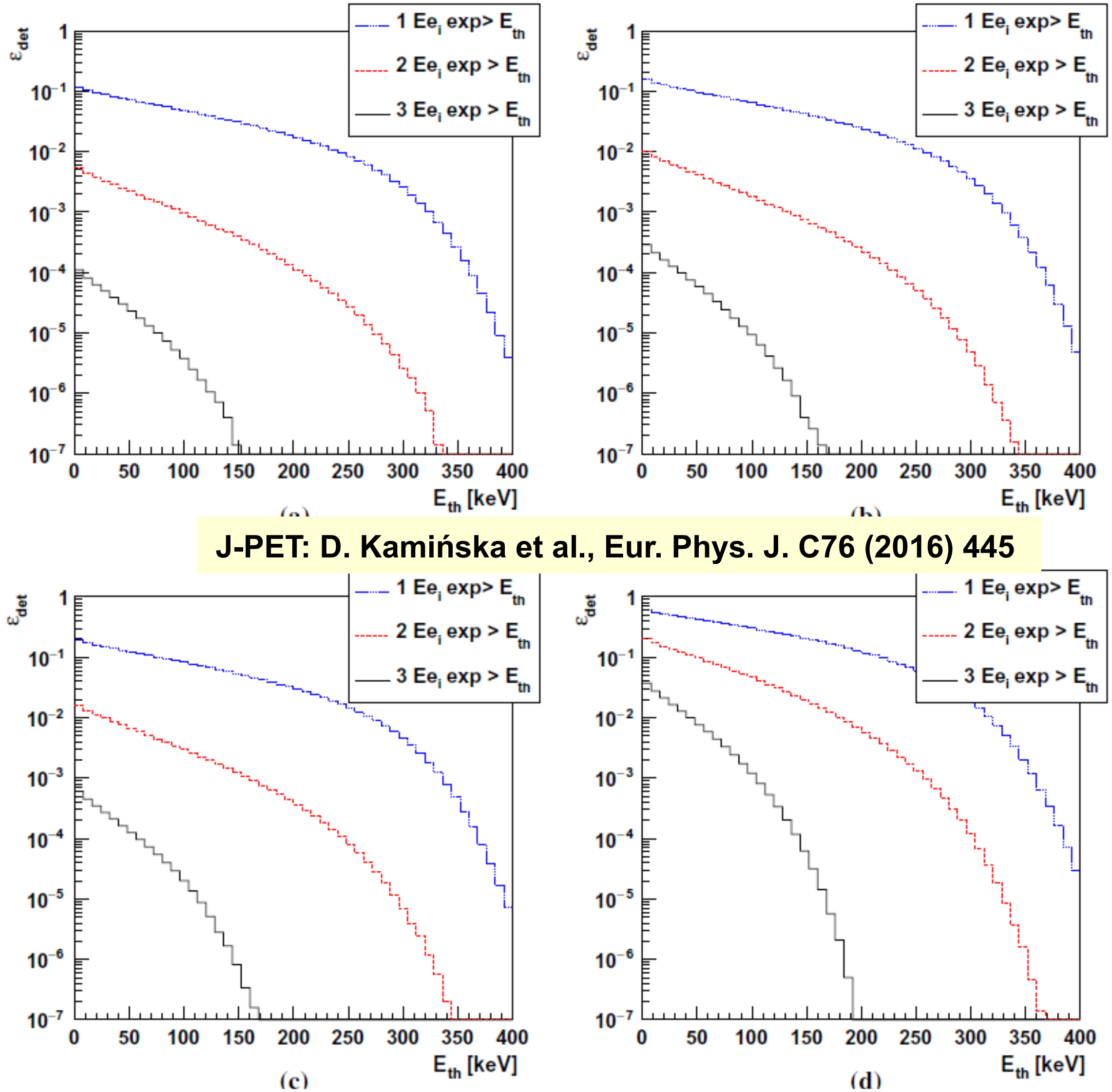
SM 10^{-9} vs upper limits of 3 10^{-3} for T, CP, CPT

Jagiellonian PET

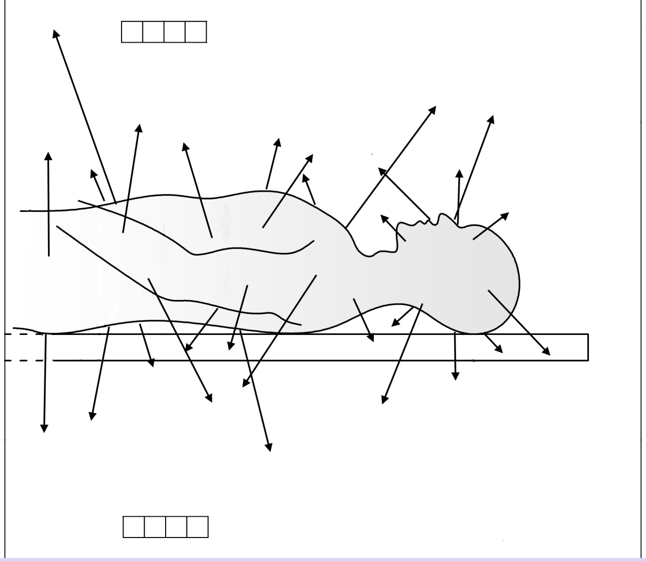


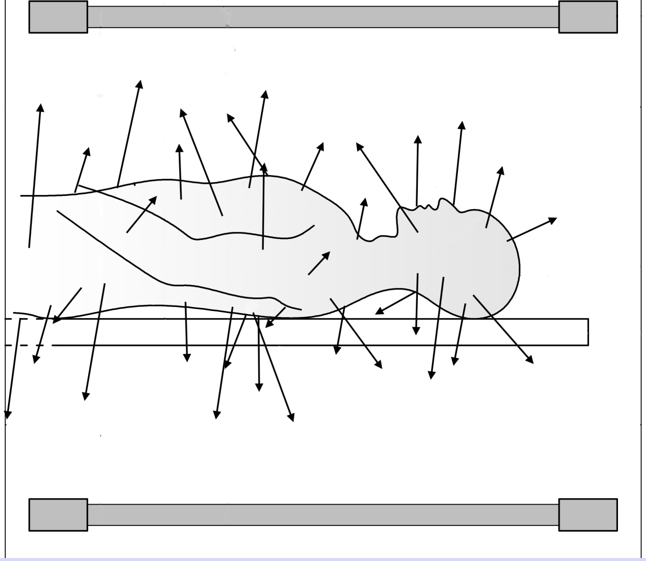
σ(t-hit) ~ 100 ps



J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445

Target material	Rate of registered o-Ps $\rightarrow 3\gamma$ events (s^{-1})			
	J-PET	J-PET+1	J-PET+2	J-PET-full
IC3100	15	70	130	10600
XAD-4	25	115	230	18300

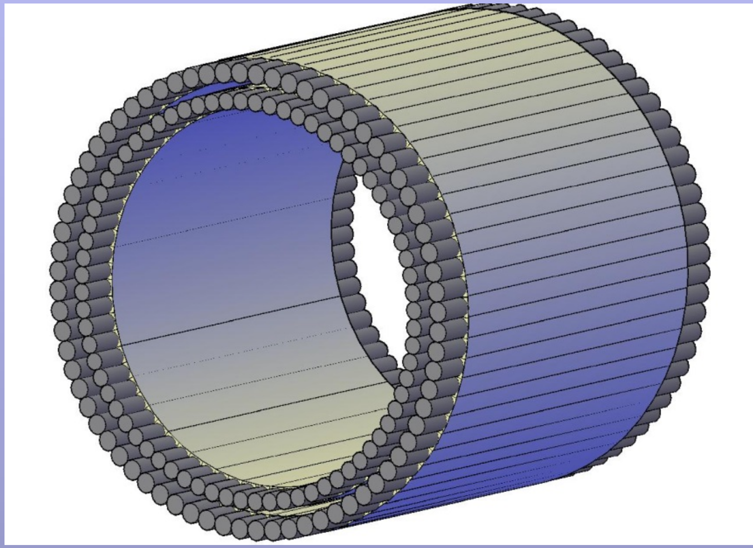




It is important to note that the cost of J-PET does not increase with the increase of the FOV

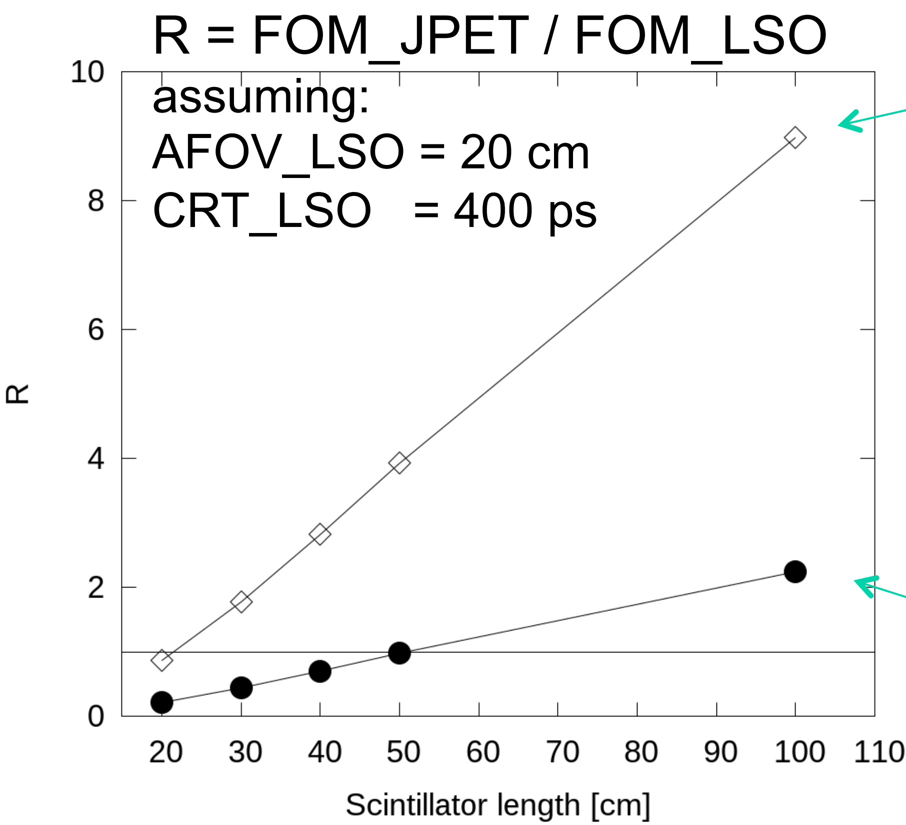
epsilon^2 = 20 to 40 smaller efficiency

But

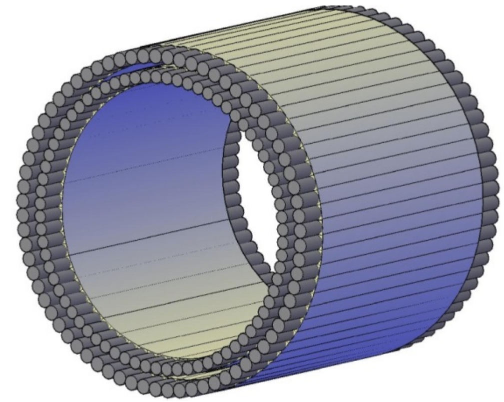


Solid angle -------------------- > factor of ~5
600 ps --> 200ps – 300ps --> factor of 3 -- 2
1m instead of ~17 cm ---------> factor of 10
N layers in the strip-PET ----> factor **N^2**

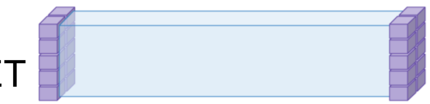
Conservatively:
for N=1 ----> total factor of ~ 100
Lower dose by factor of 3 (100 better / 30 worse)

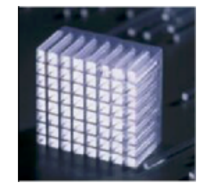


N_JPET_layers = 2



$$R = \frac{\text{FOM\_JPET}}{\text{FOM\_LSO}}$$





LSO

N_JPET_layers = 1

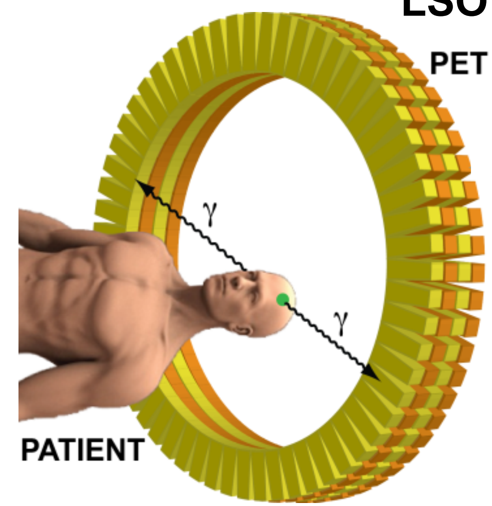
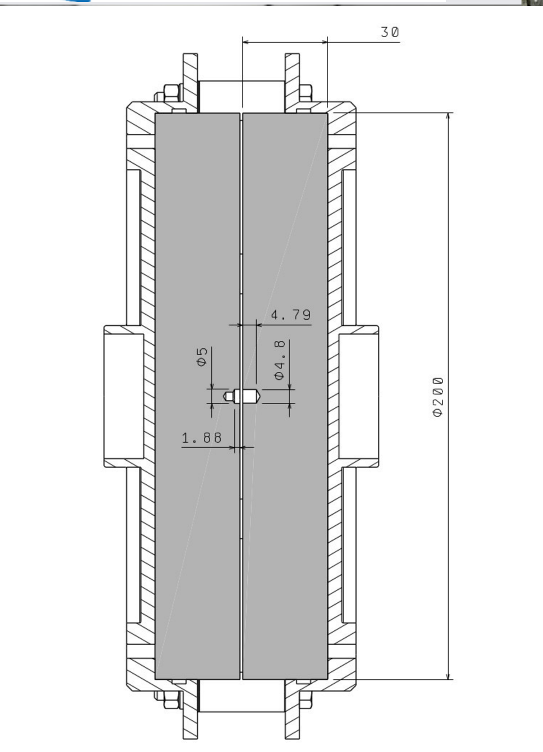
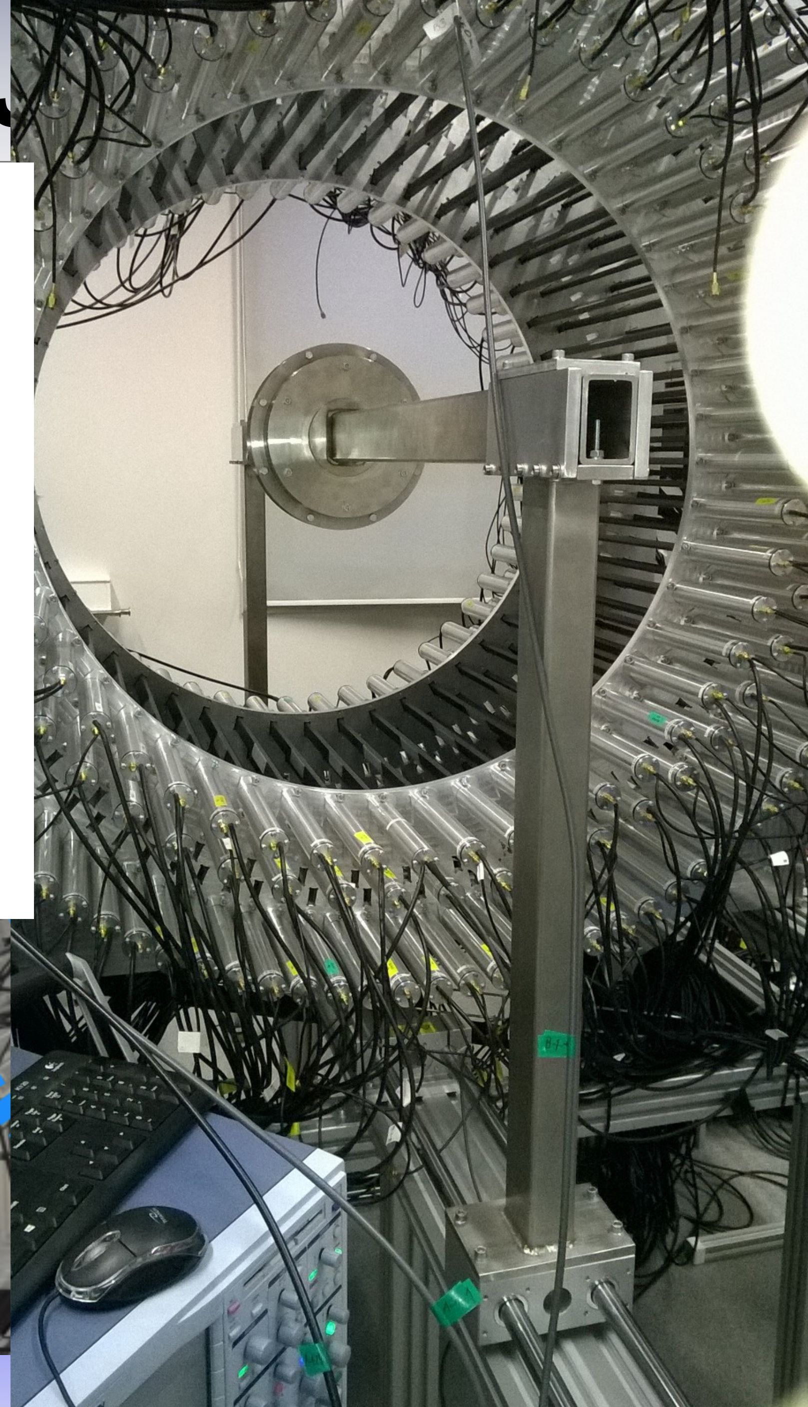


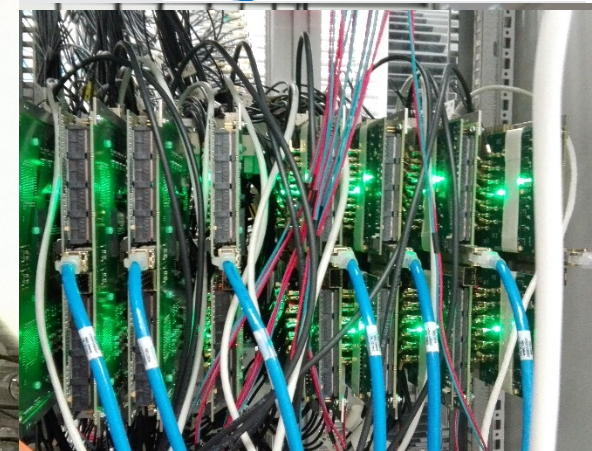
Figure of Merit for whole body imaging (FOM):

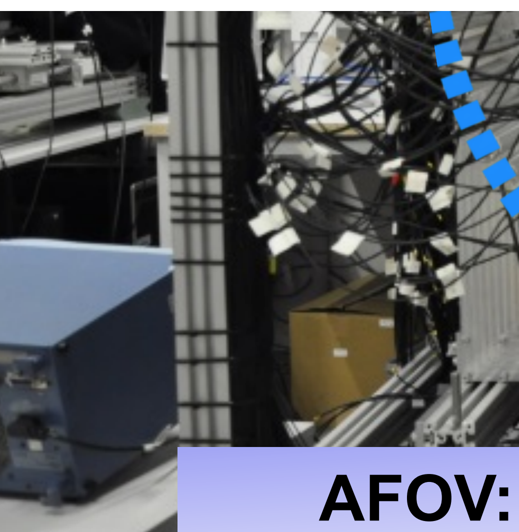
$$\textbf{FOM} \cong \frac{(\text{detection effi.})^2 \cdot (\text{selection effi.})^2 \cdot \text{acceptance}}{\text{CRT} \cdot \text{Number\_of\_bed\_positions}}$$

J-PET: P.M. et al., Phys. Med. Biol. 61 (2016) 2025; arXiv:1602.02058







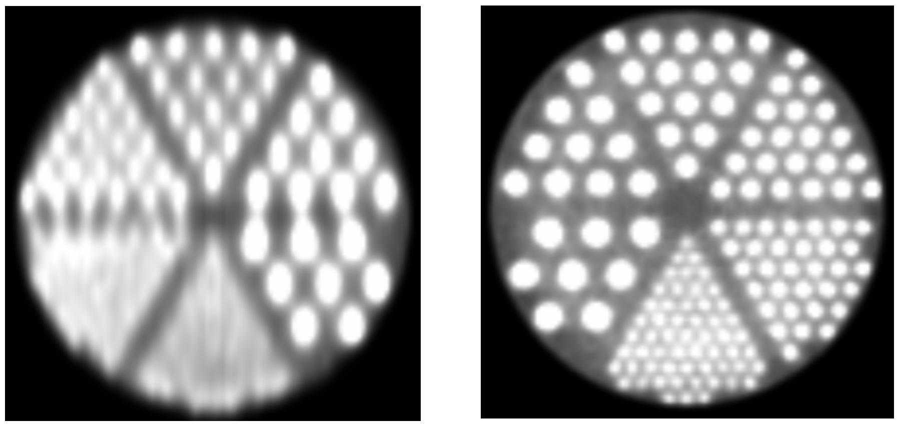


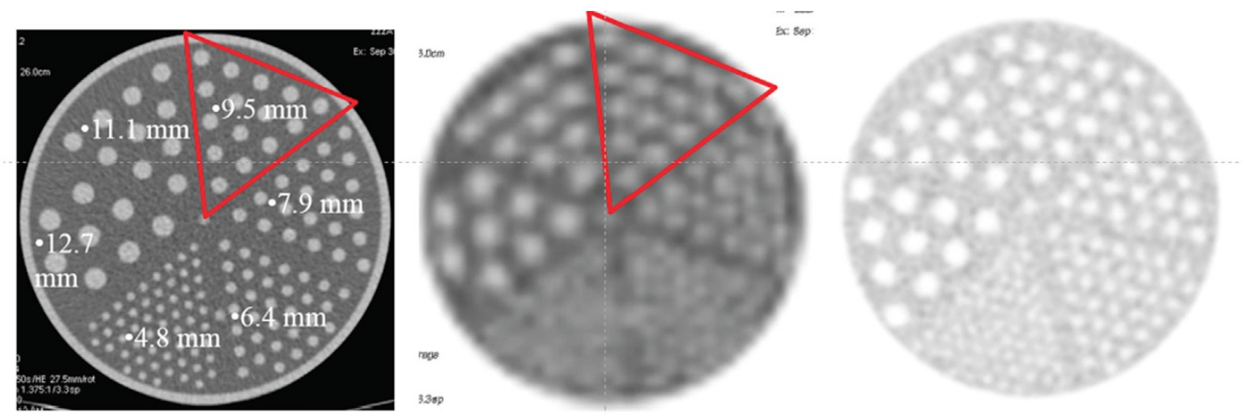
AFOV: 500 ps

J-PET: P. Bialas, J. Kowal, A. Strzelecki et al. Acta Phys. Pol. A127 (2015) 1500
Adam Strzelecki, PhD thesis, 2016

384 strips, diameter 85 cm, 50 cm AFOV, 10^8 events, 50 iterations,

J-PET: image reconstracted from simulated data
rotated (coronal) axially arranged

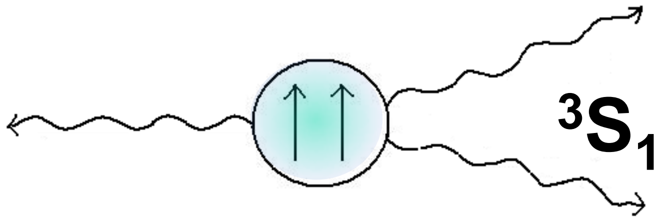




CT Conventional PET Digital PET

Figure from P. Slomka, T. Pan, G. Germano, Semin. Nucl. Med. 46 (2016) 46

Digital PET, courtesy of Jun Zhang (PhD), Michael V. Knopp (MD, PhD), The Ohio State University

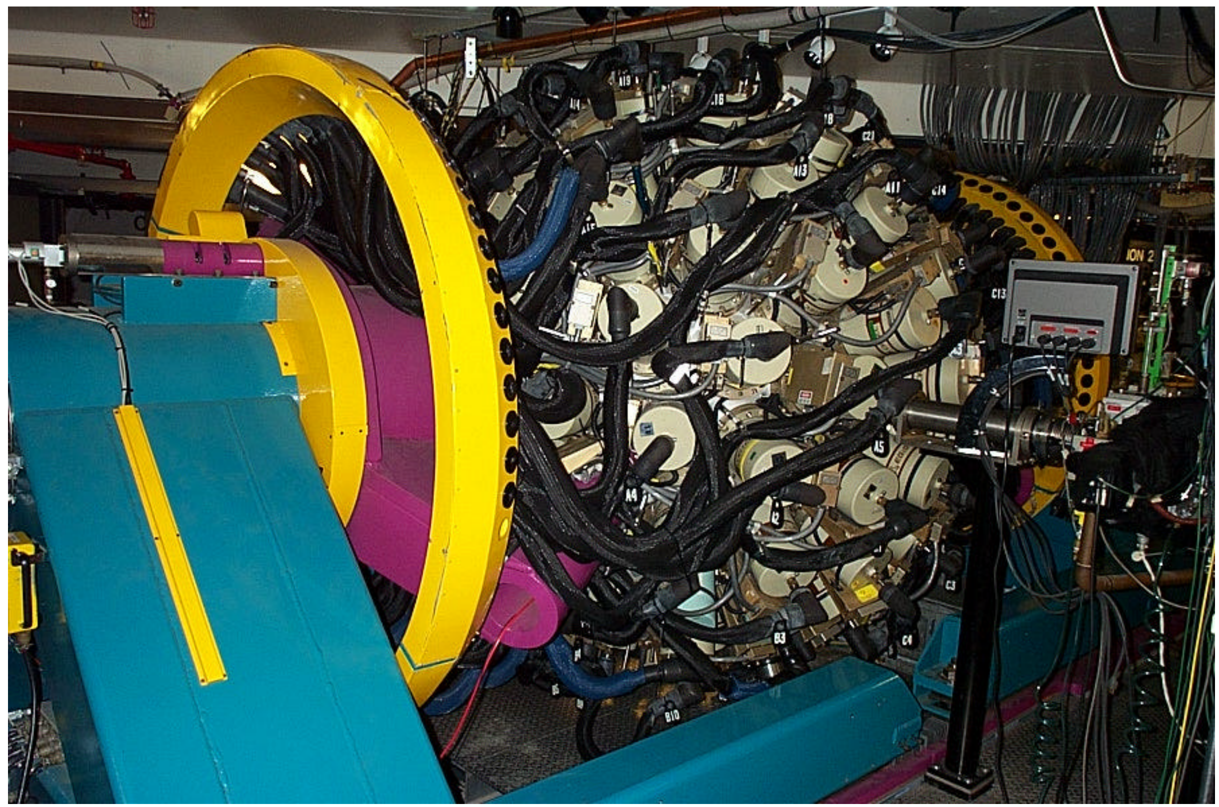


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

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

P.A. Vetter and S.J. Freedman,
Phys. Rev. Lett. 91, 263401 (2003).

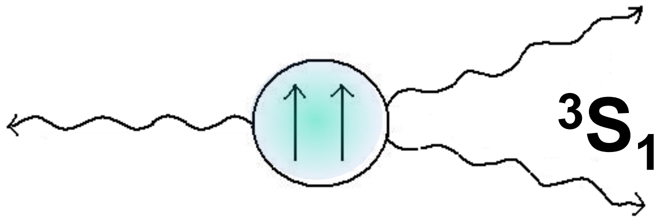
C_CPT = 0.0071 ± 0.0062



SM $10^{-10} - 10^{-9}$

photon-photon interactions

Figure taken form the presentation of P. Vetter, INT UW Seattle, November, 2002



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

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

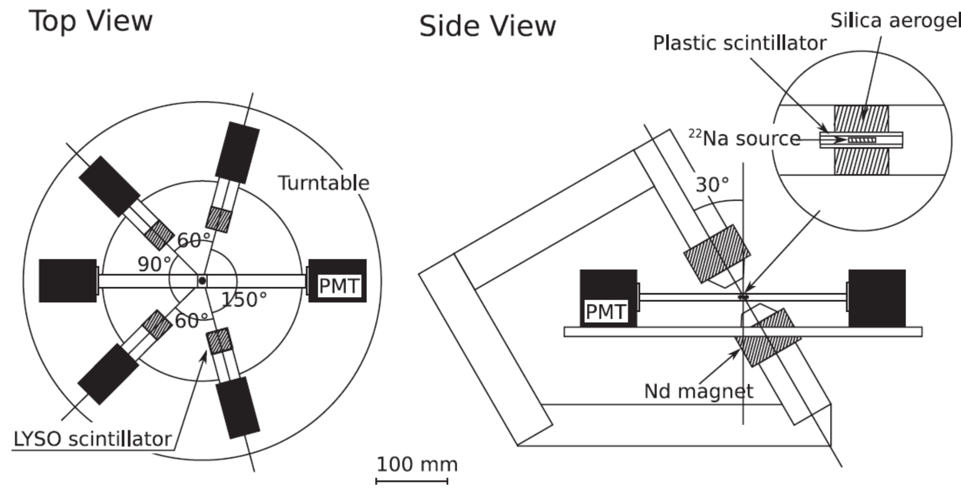
So far best accuracy for
CP violation was reported by
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

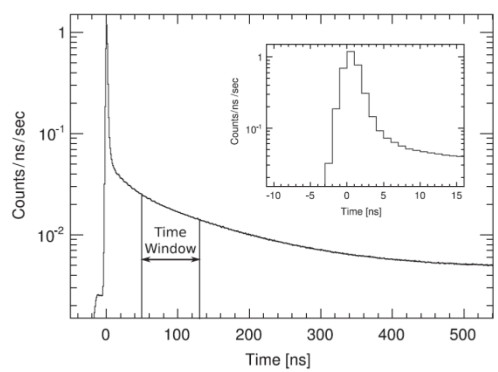
-0.0023 < C_CP < 0.0049 at 90% CL

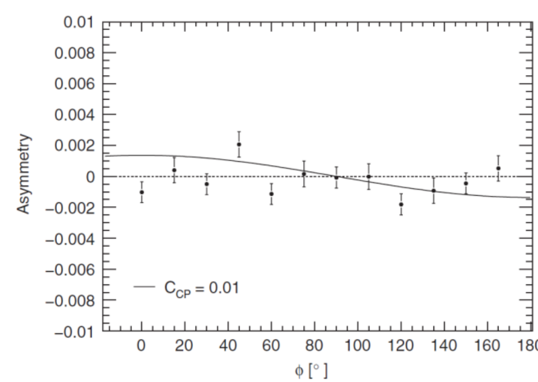
vs

SM $10^{-10} – 10^{-9}$
W. Bernreuther et al., Z. Phys. C 41, 143 (1988)
This is due to photon-photon interactions in the final state caused by the creation of virtual charged particle pairs)

$$P_2 = \frac{N_{+1} - 2N_0 + N_{-1}}{N_{+1} + N_0 + N_{-1}}$$

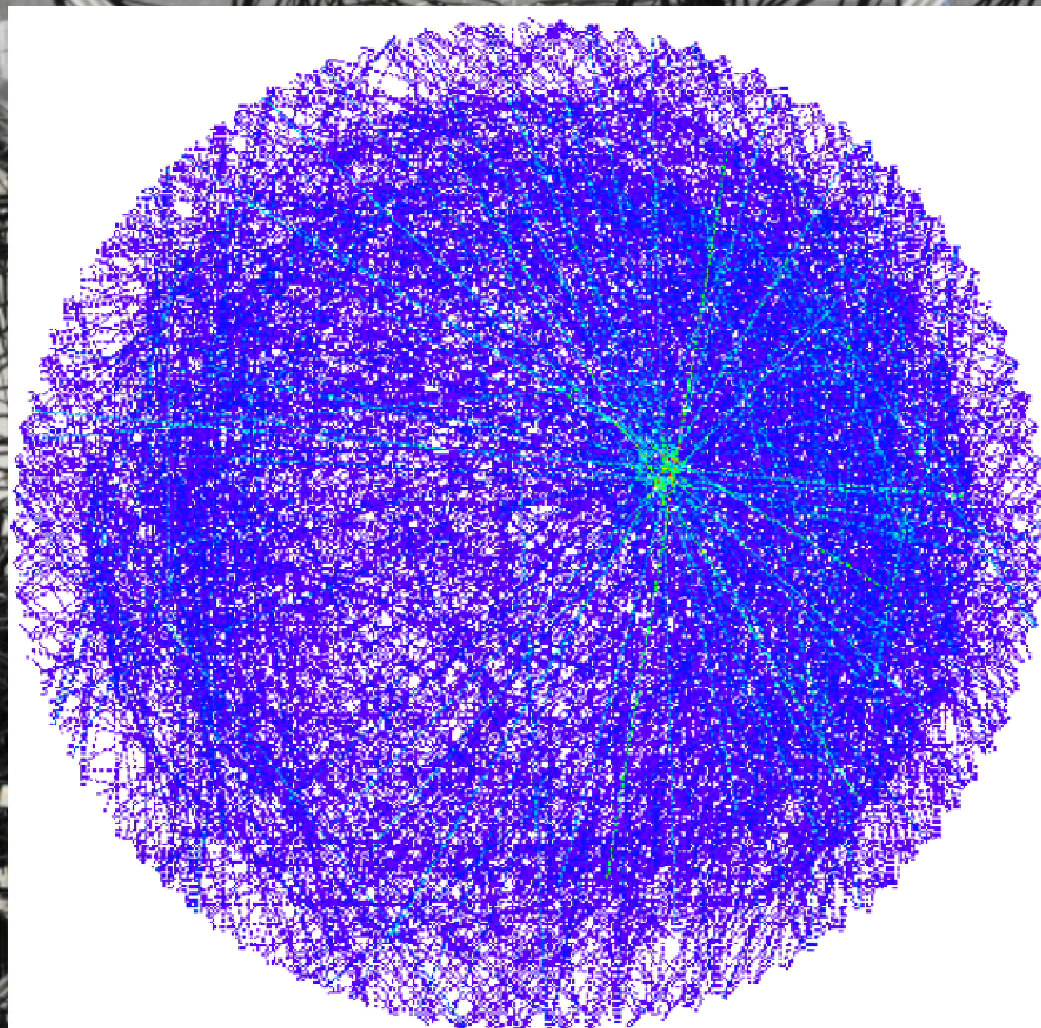




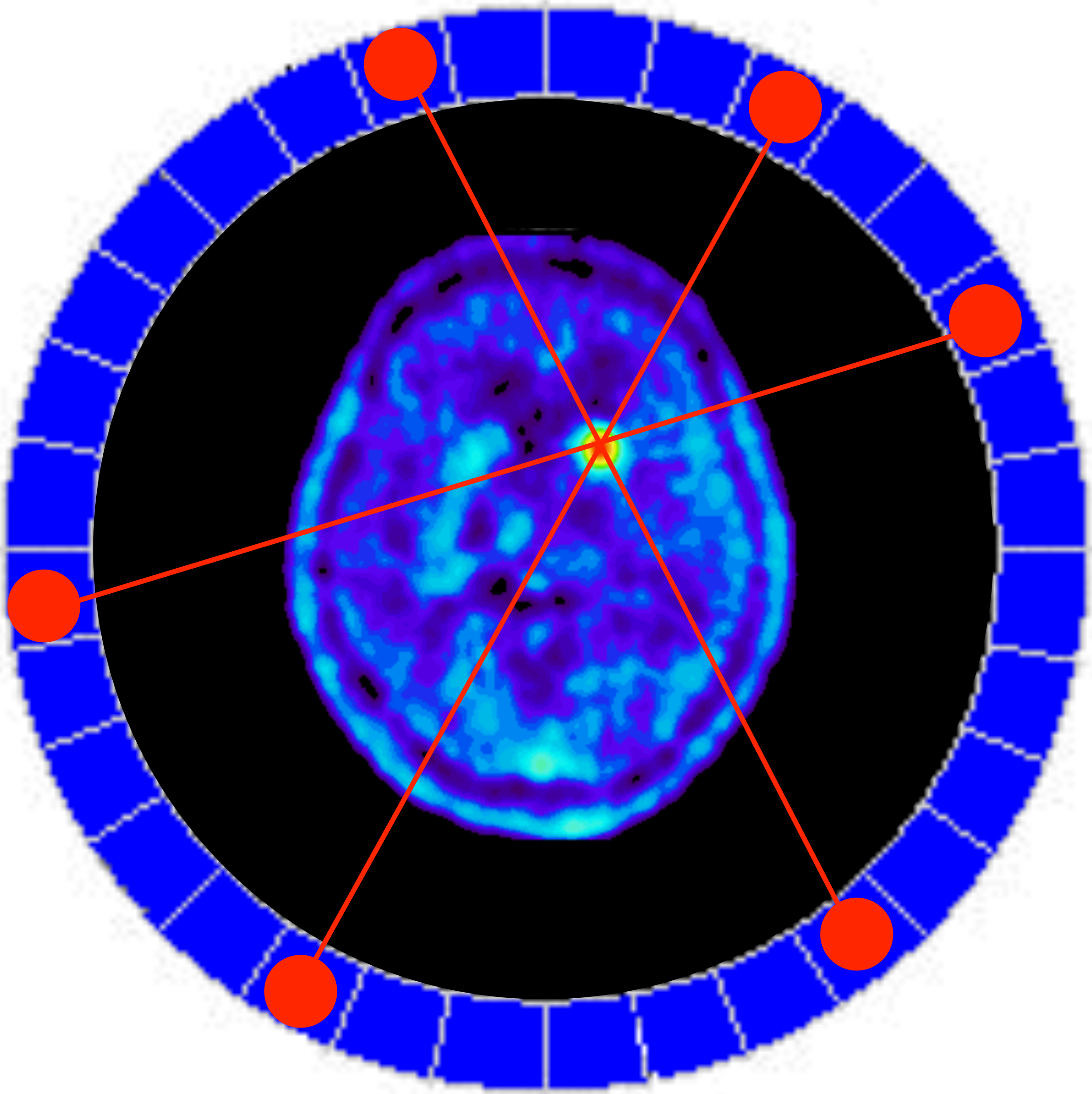


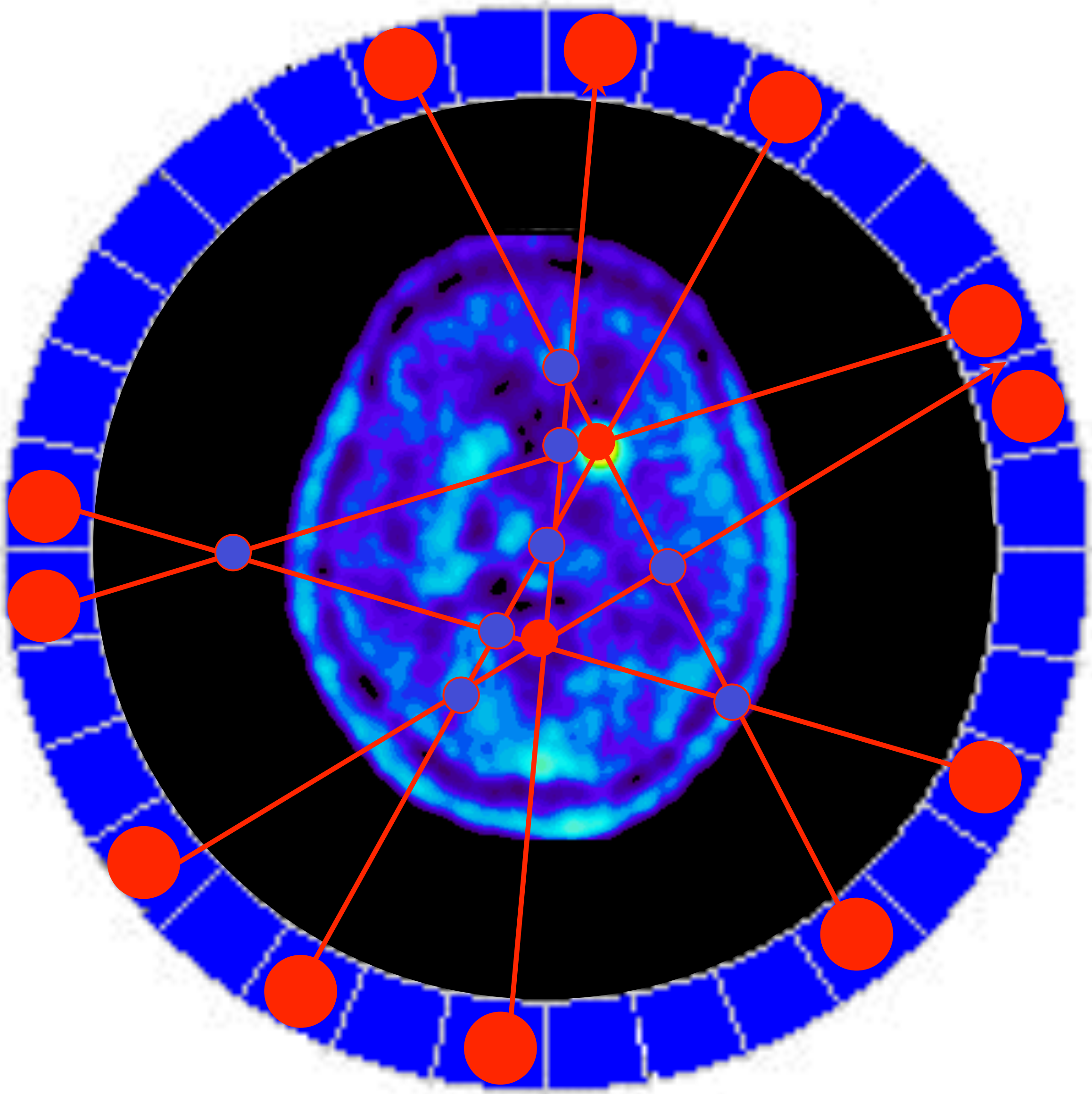
Jagiellonian PET

Reconstruction of point-like image in real time done by Grzegorz



AFOV: 50 cm ; TOF < 500 ps (FWHM)

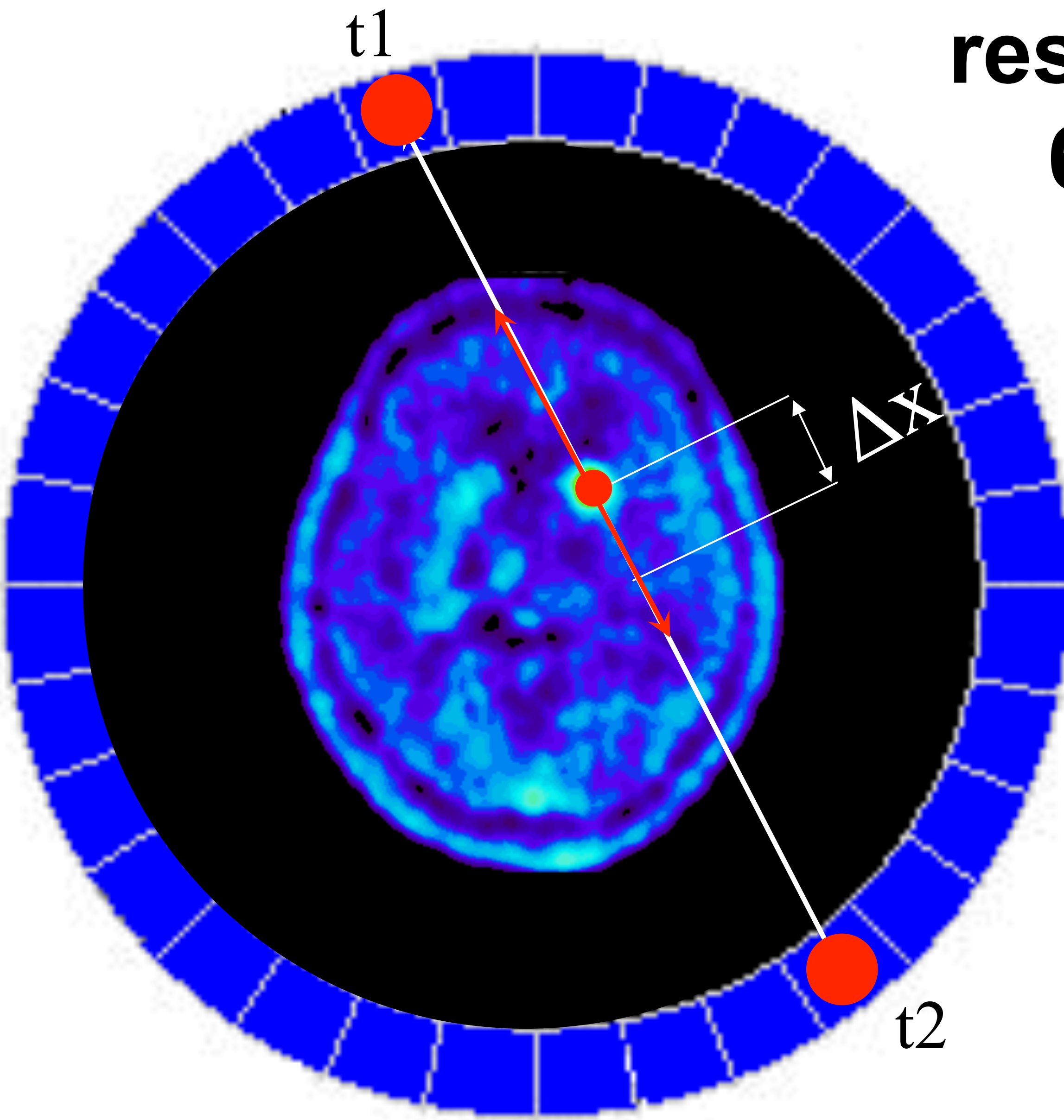


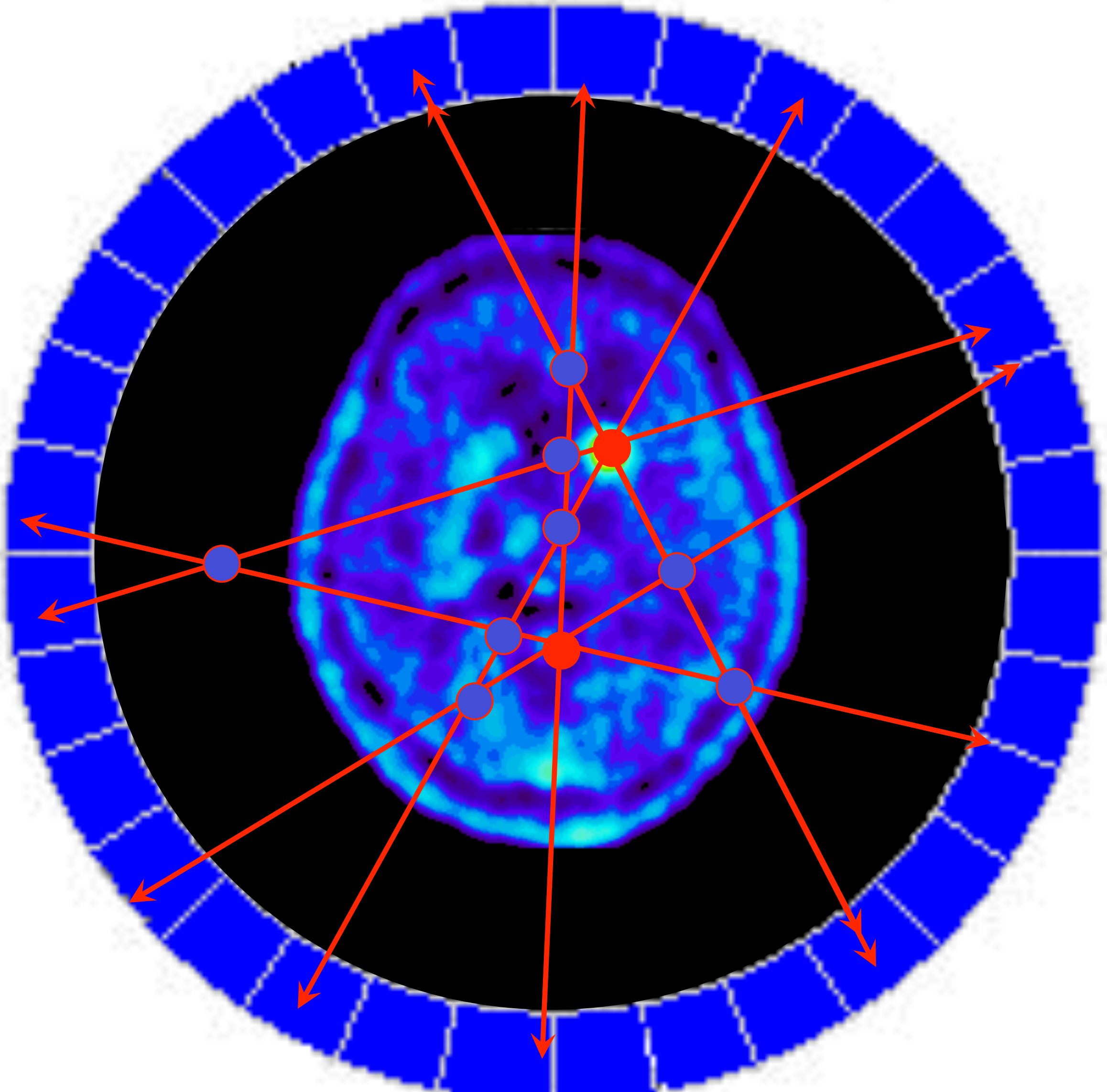


PET-TOF

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

resolution 600ps



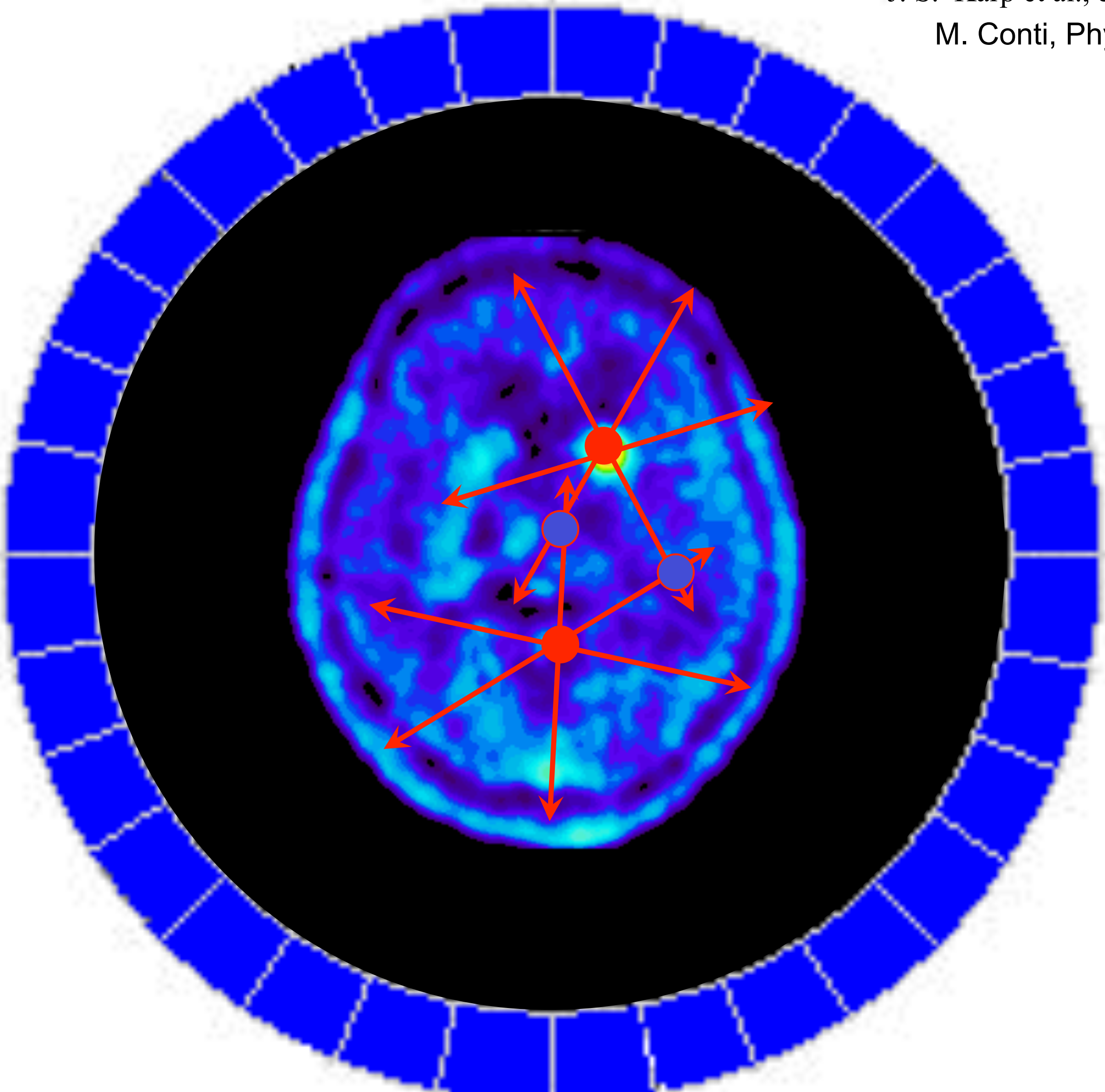


signal/noise
$\sim D / \Delta t$

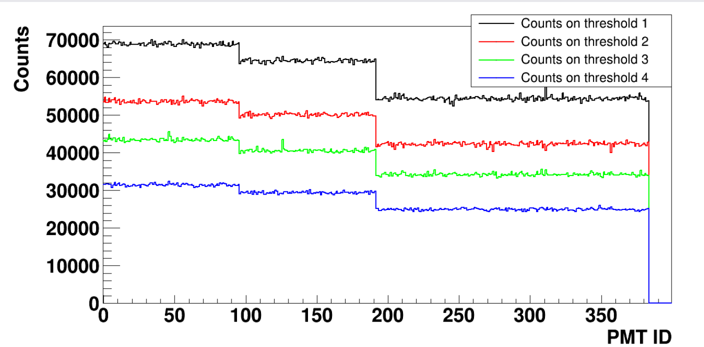
40cm/600ps

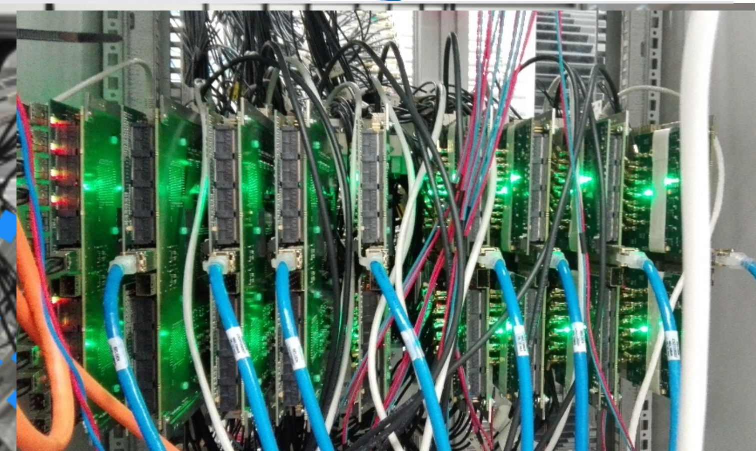
czterokrotna poprawa

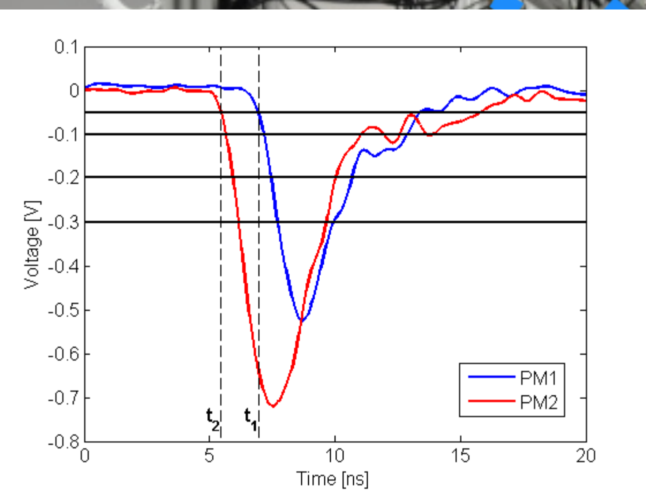
J. S. Karp et al., J Nucl Med 2008; 49: 462
M. Conti, Physica Medica 2009; 25: 1.

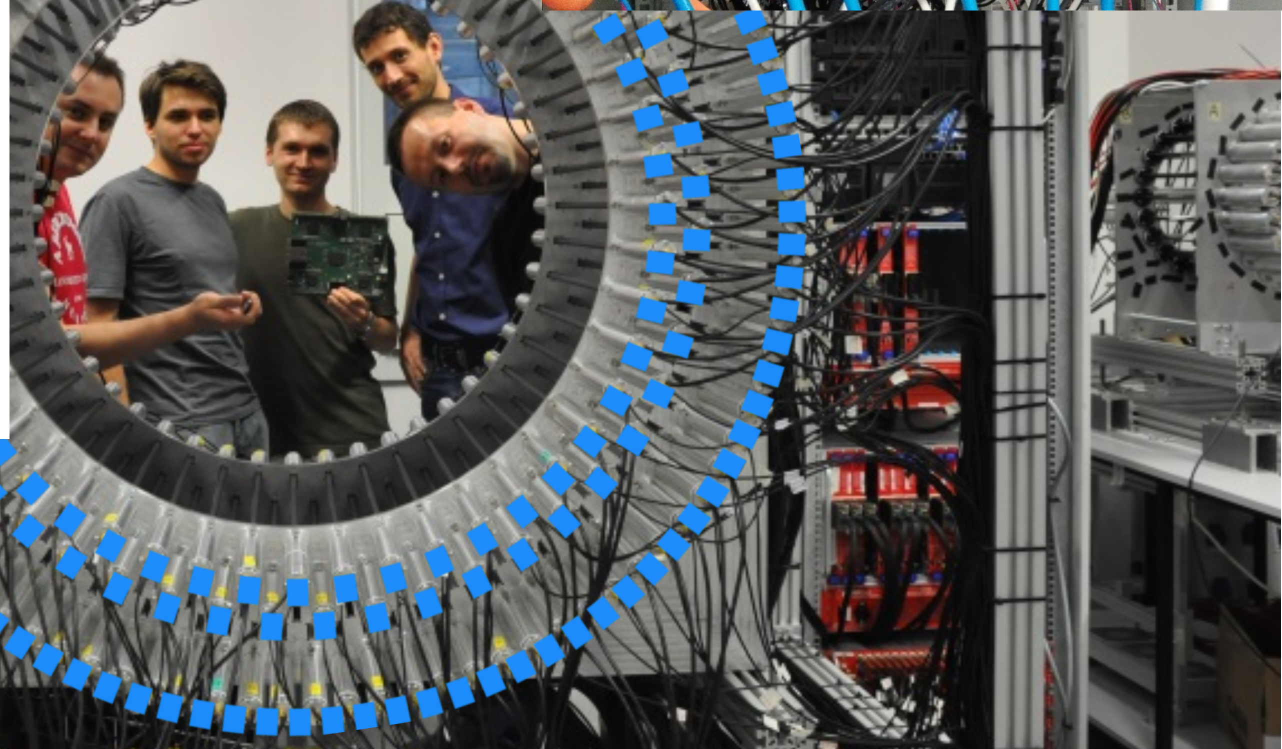


Jagiellonian PET



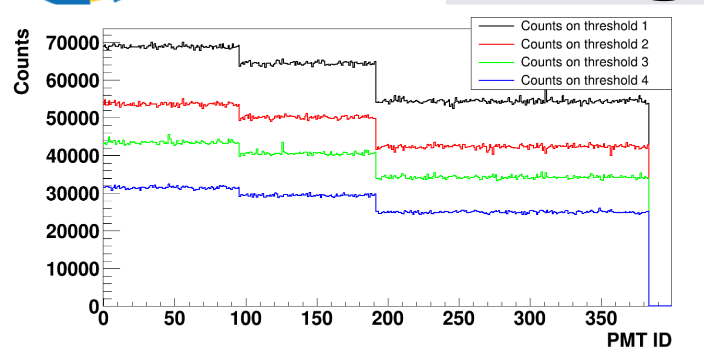


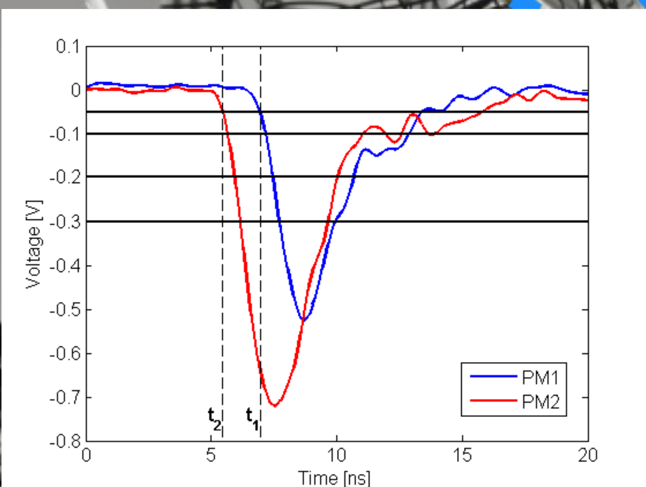


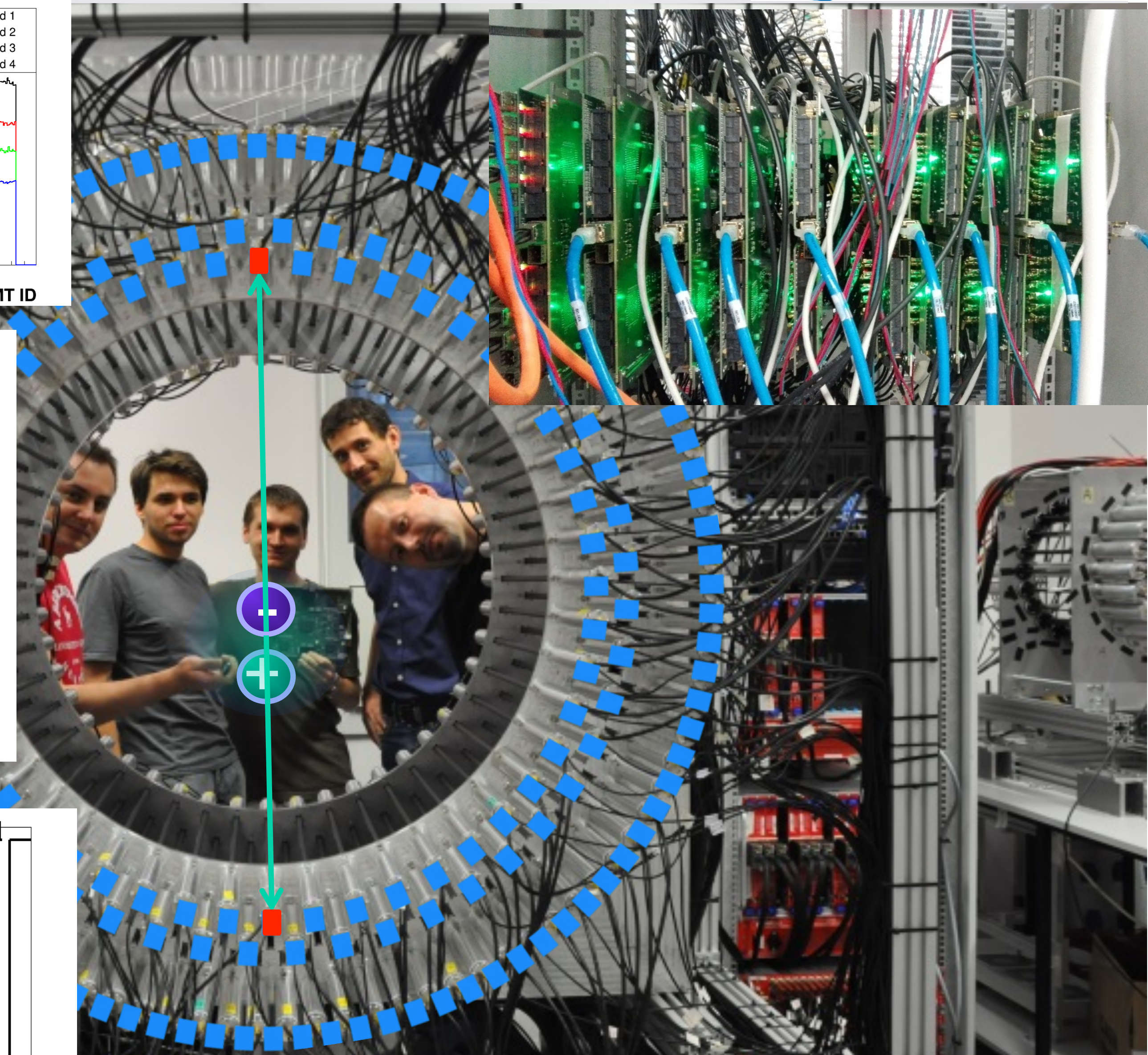


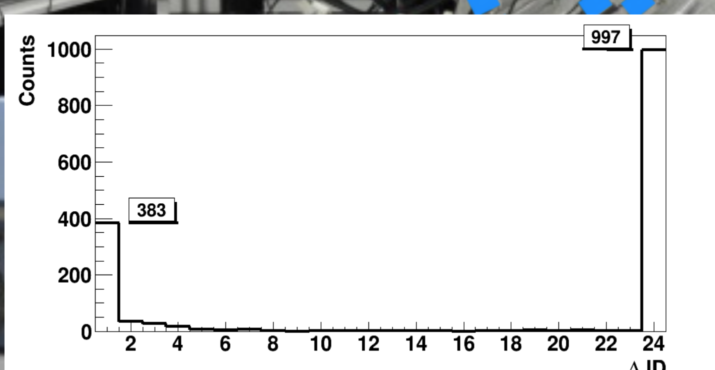
AFOV: 50 cm ;   TOF < 500 ps

Jagiellonian PET



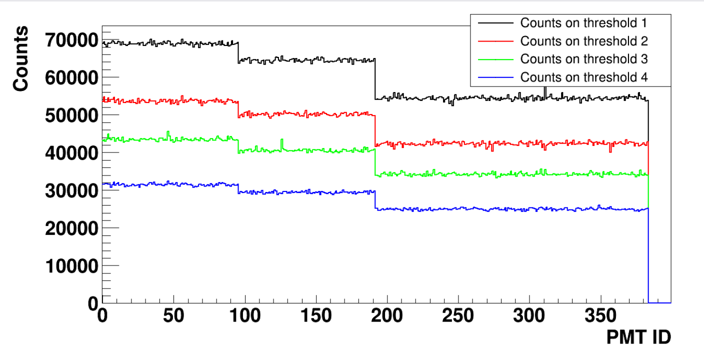


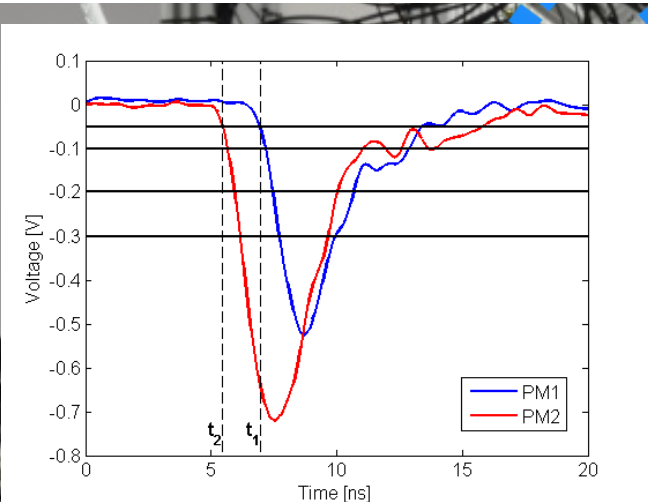


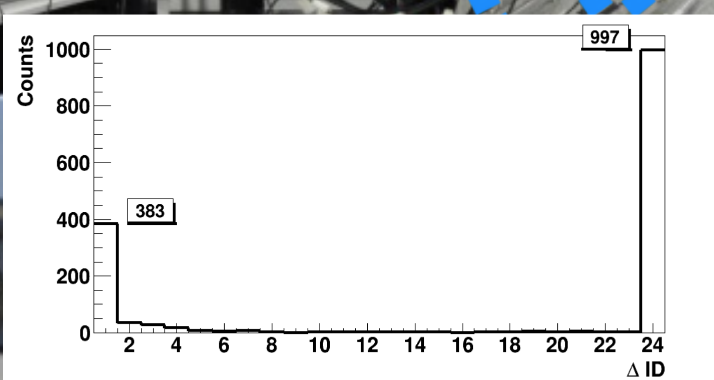


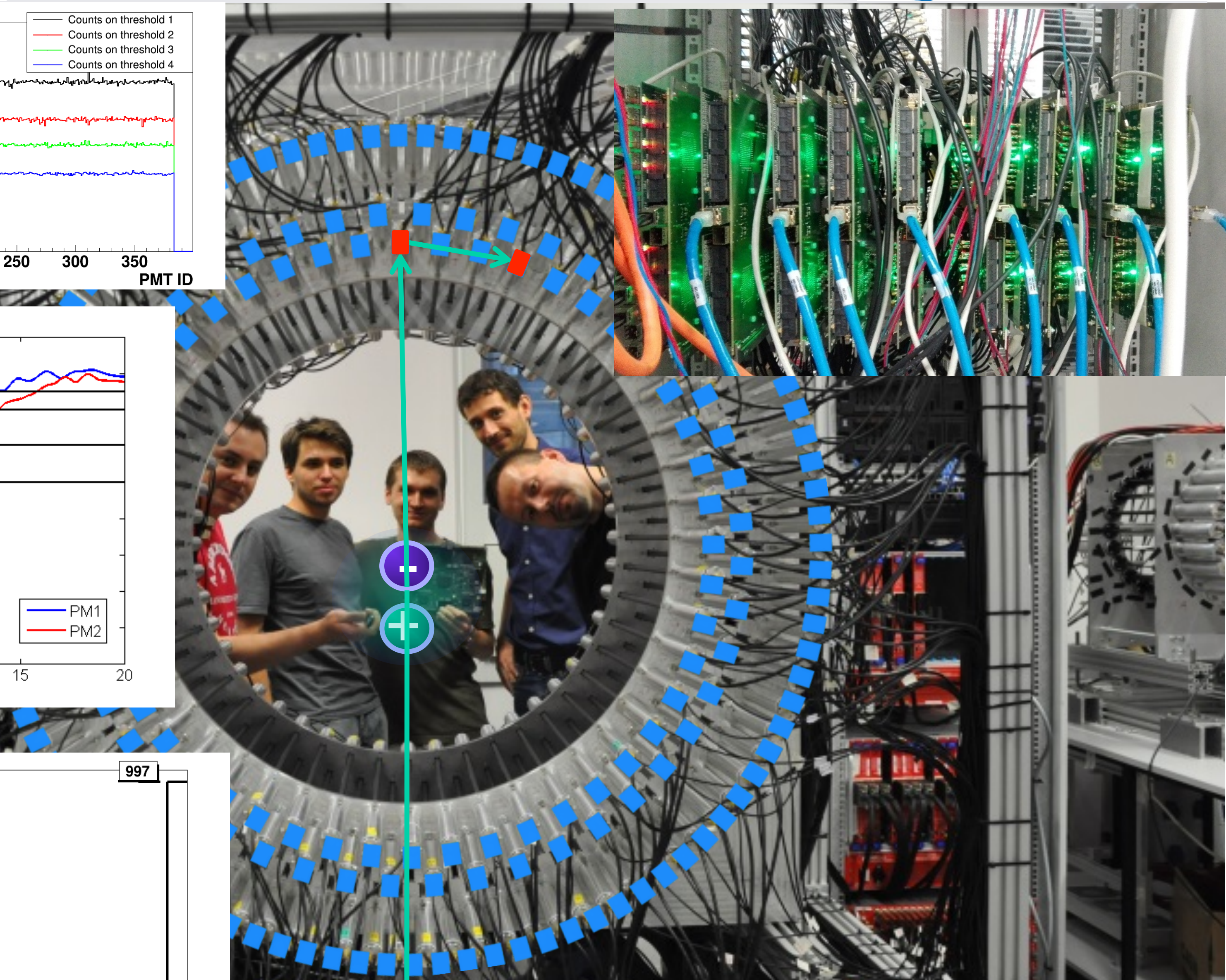
→ 50 cm ; TOF < 500 ps

Jagiellonian PET

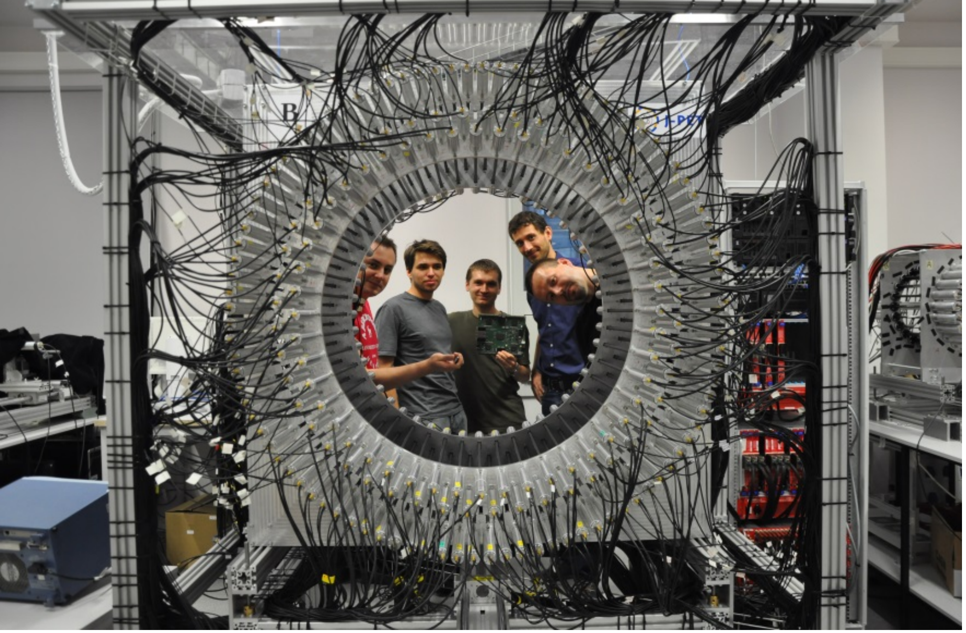


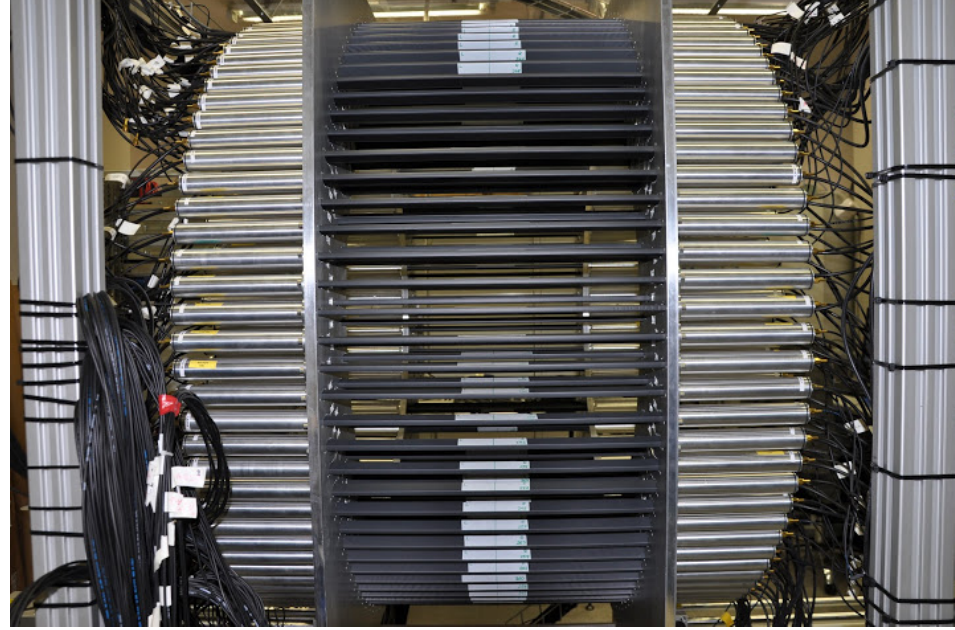


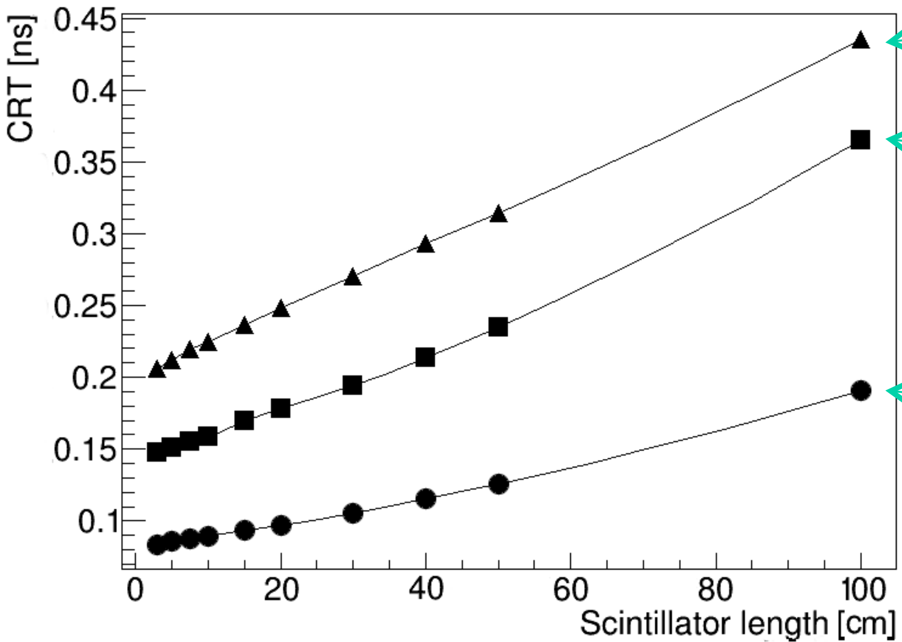


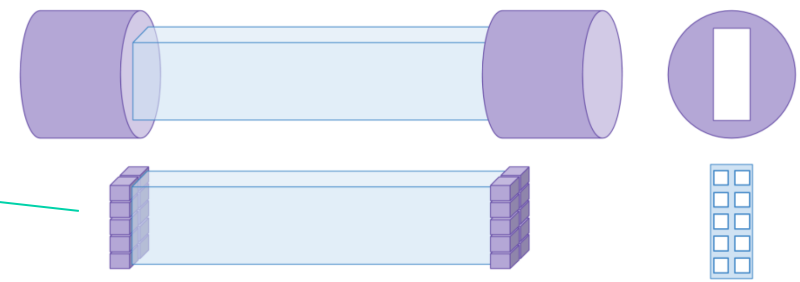


n → 50 cm ; TOF < 500 ps



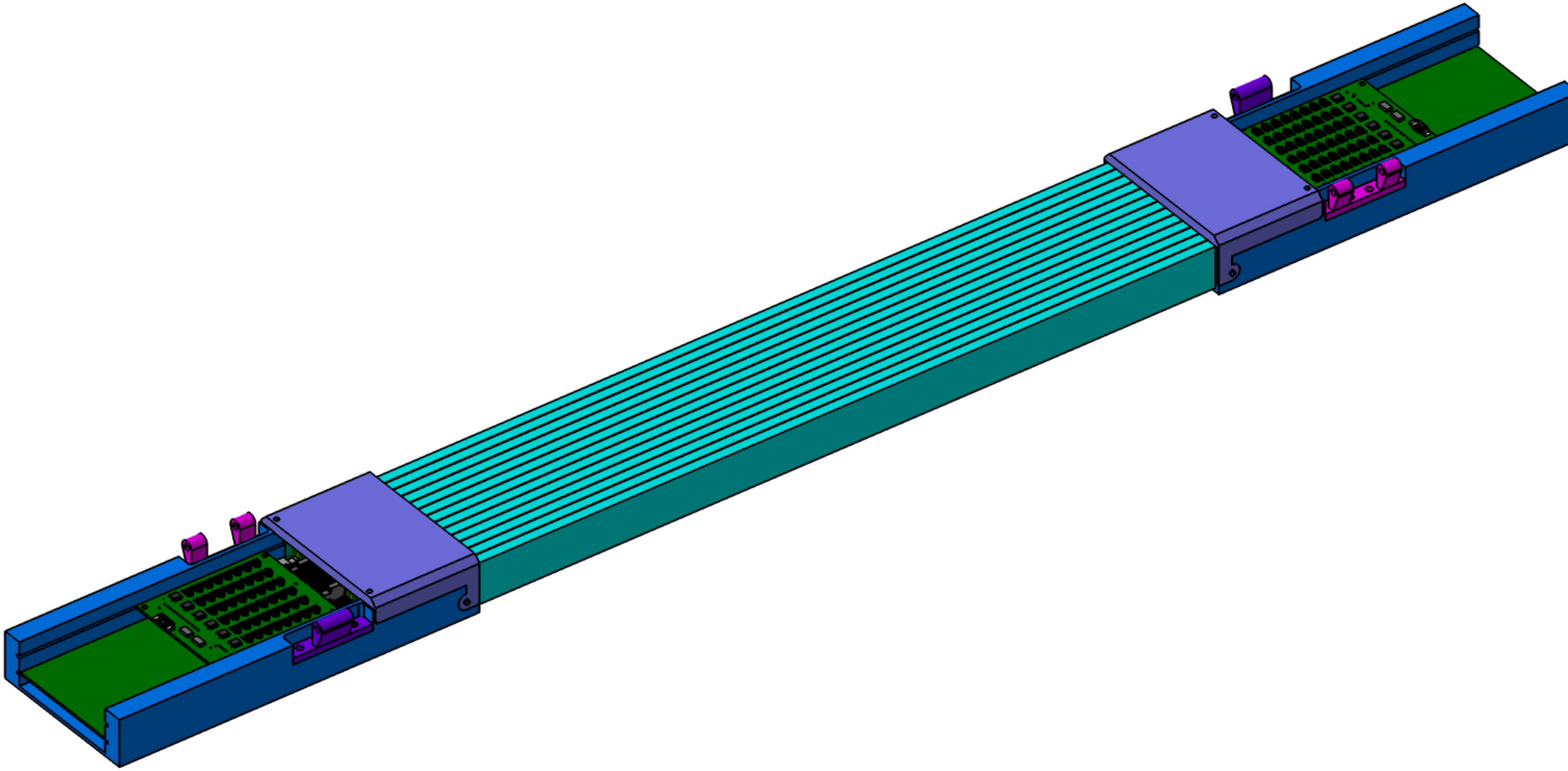


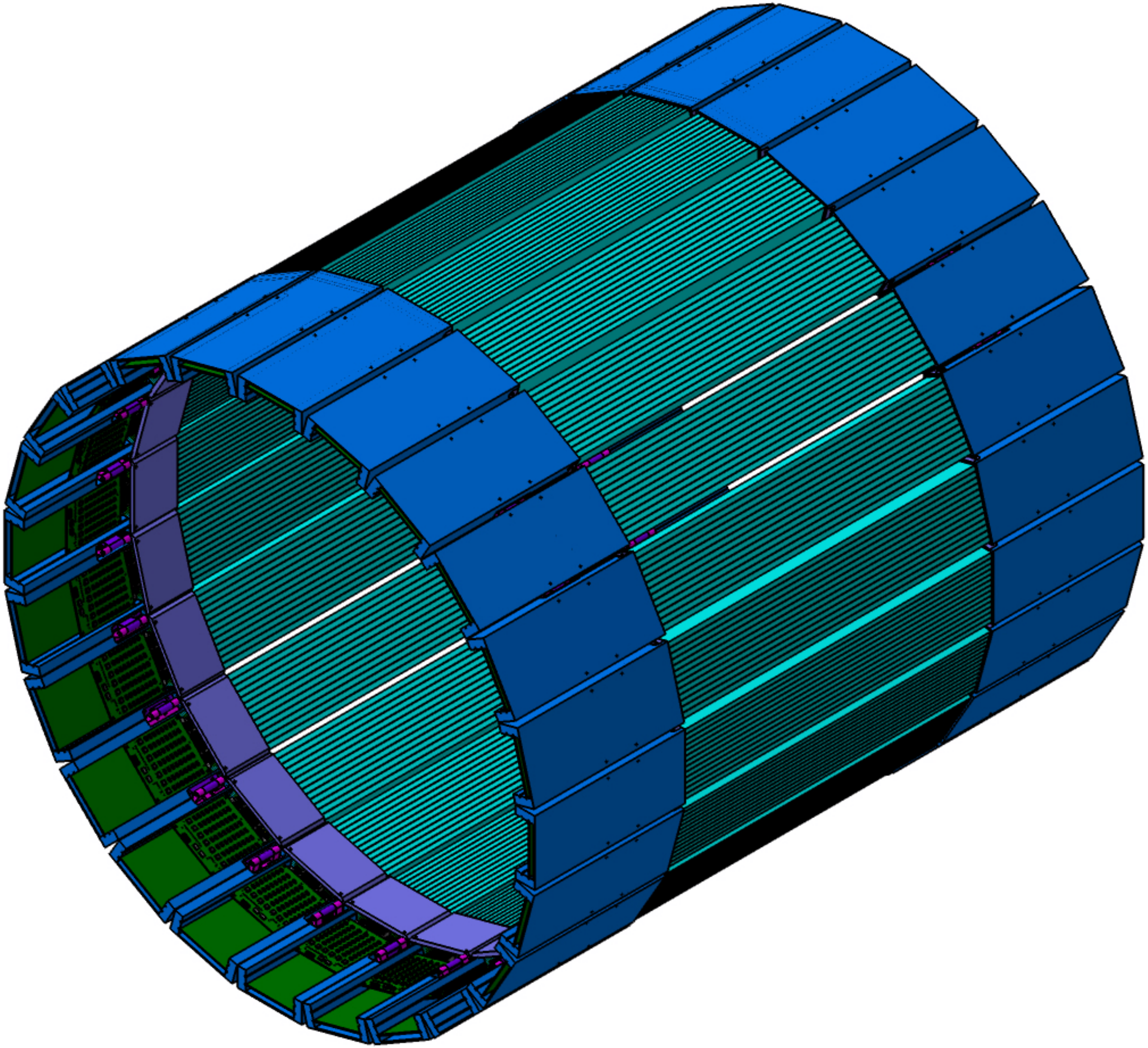




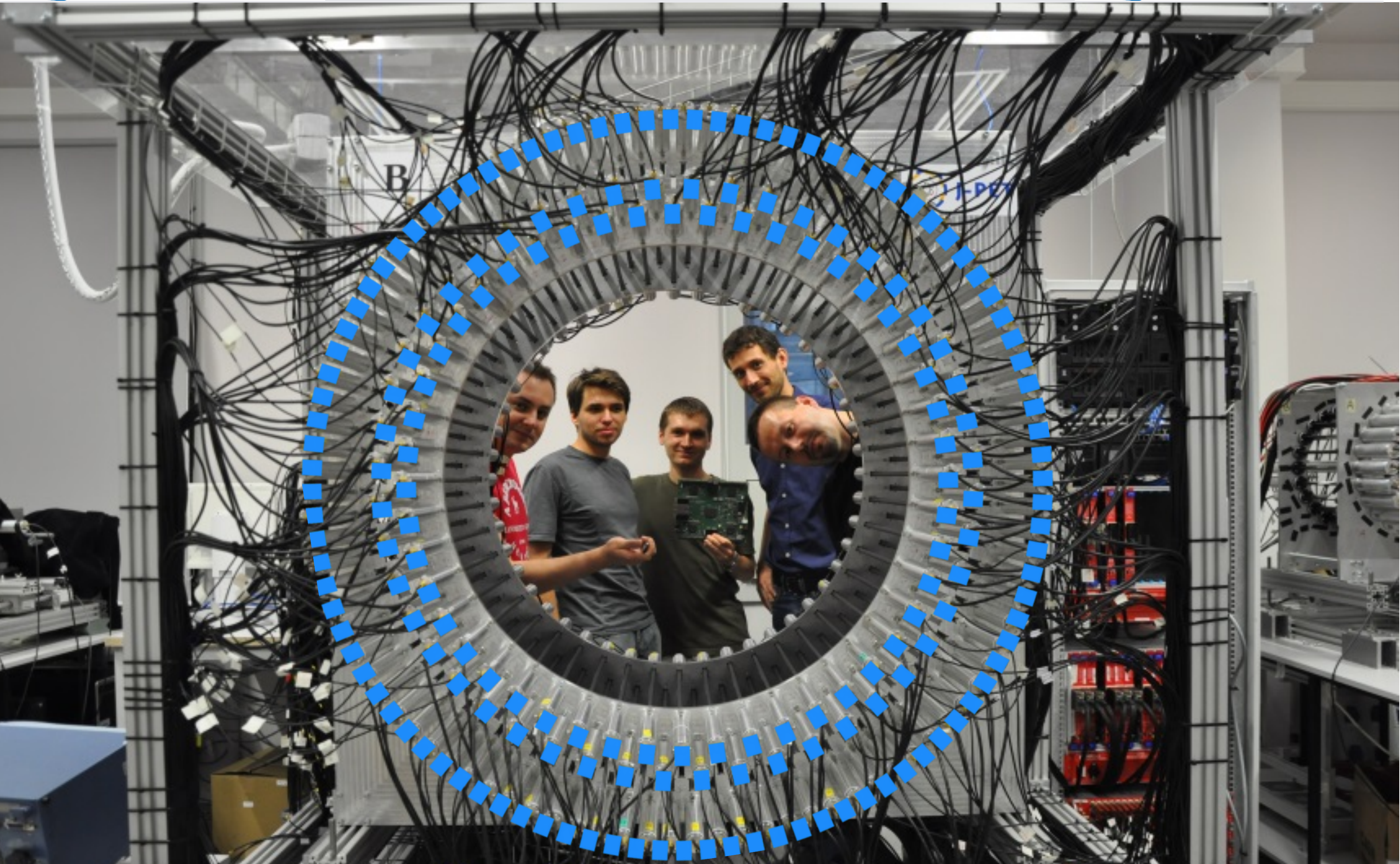
J-PET: P.M. et al., Phys. Med. Biol. 61 (2016) 2025

Limit of the J-PET

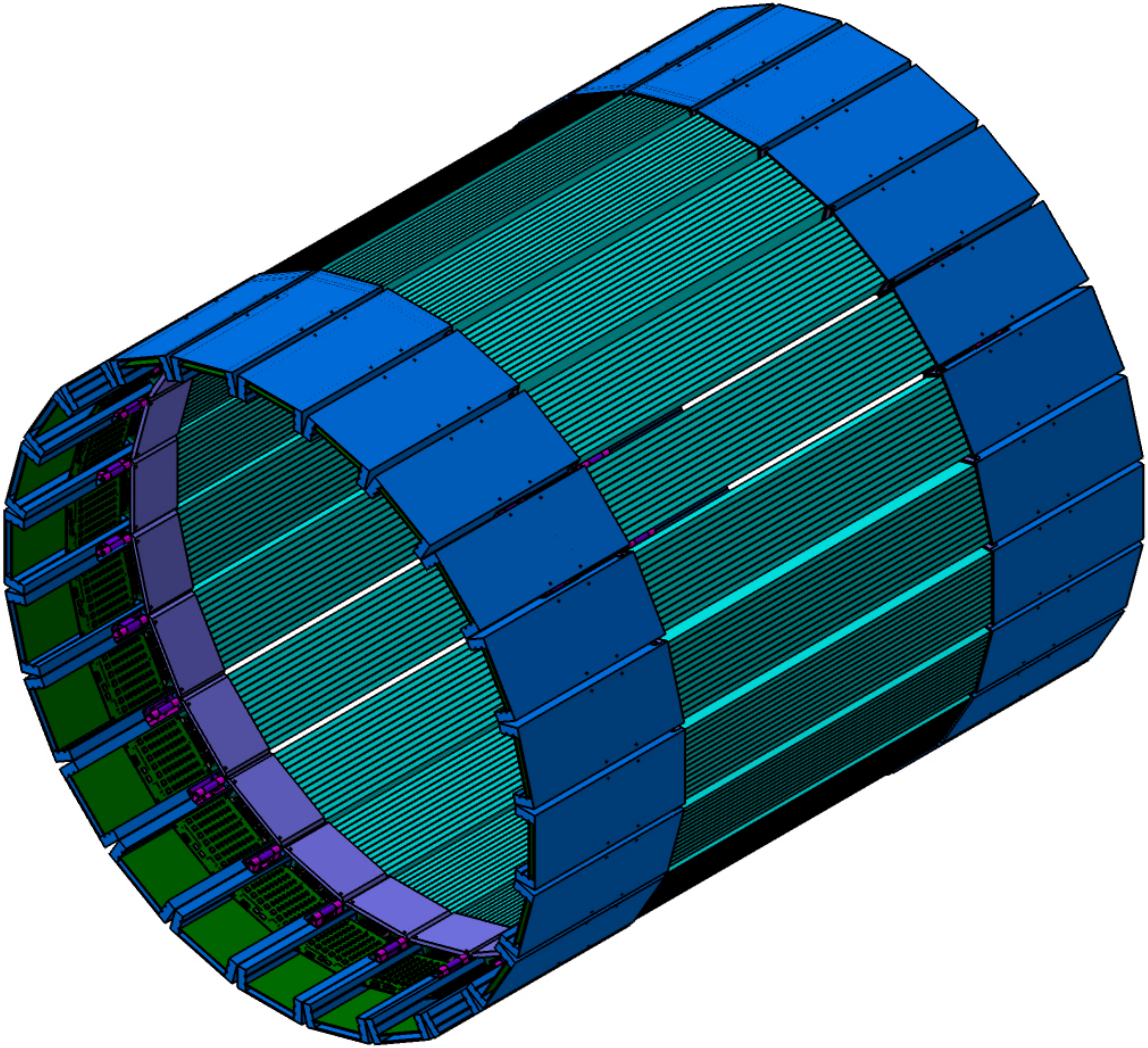




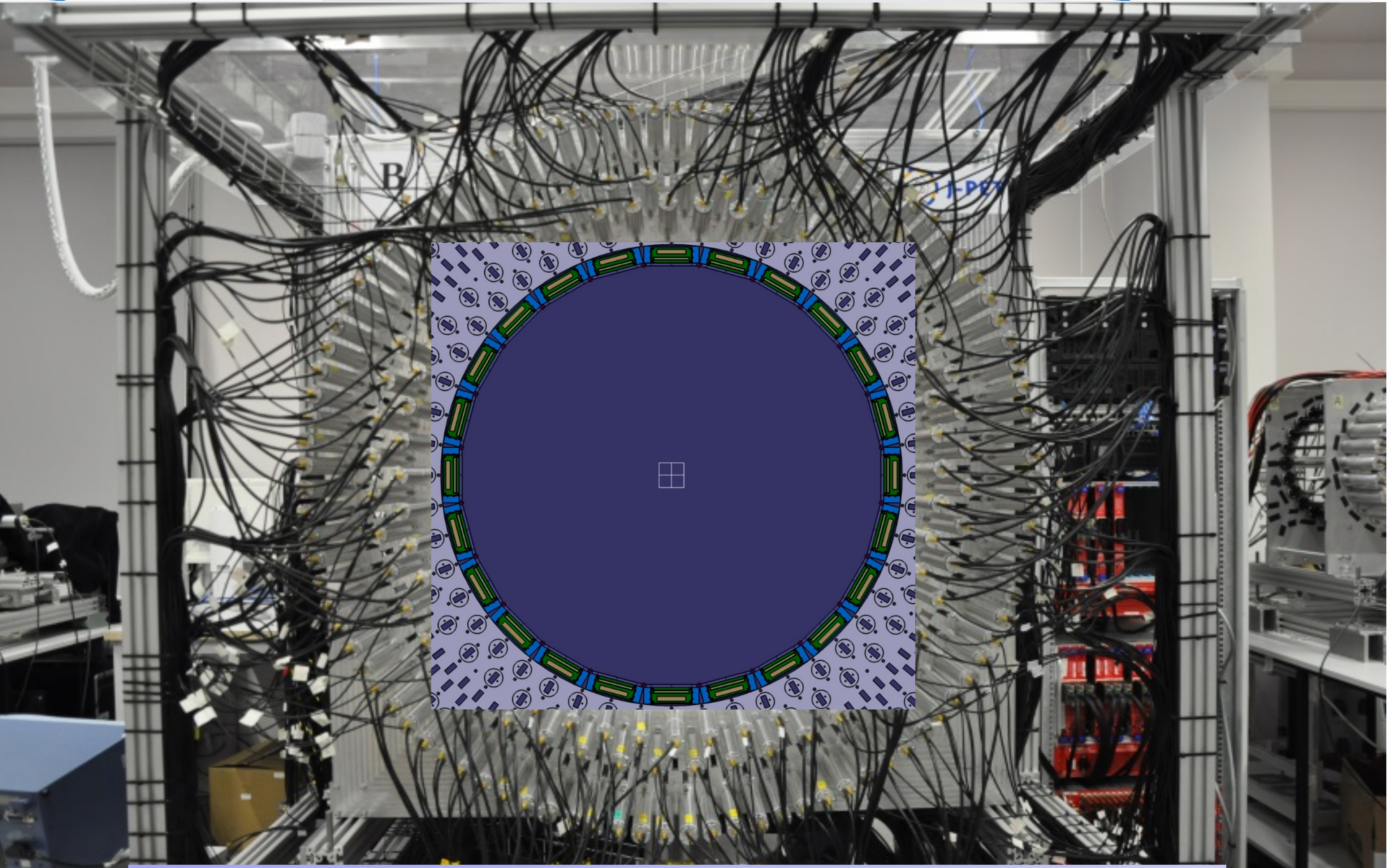
Jagiellonian PET



AFOV: 50 cm ;   TOF < 500 ps (FWHM)

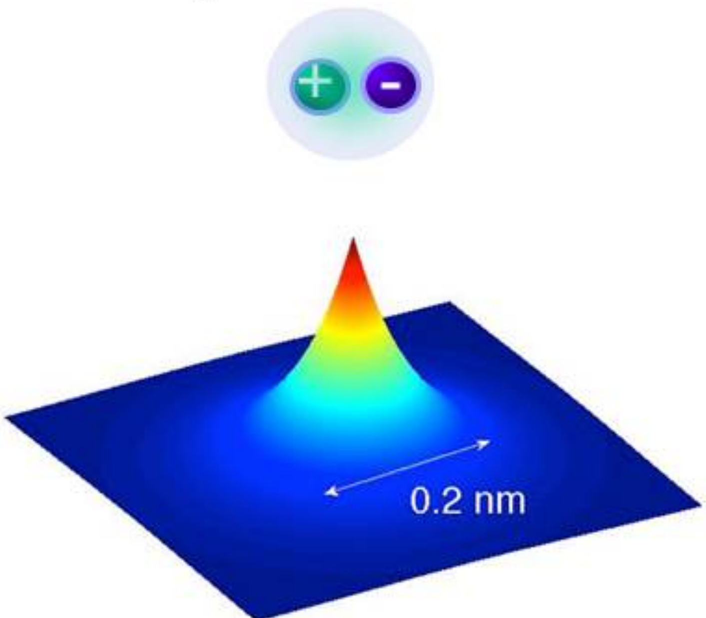


Jagiellonian PET



AFOV: 17 cm → 50 cm ;   TOF < 500 ps

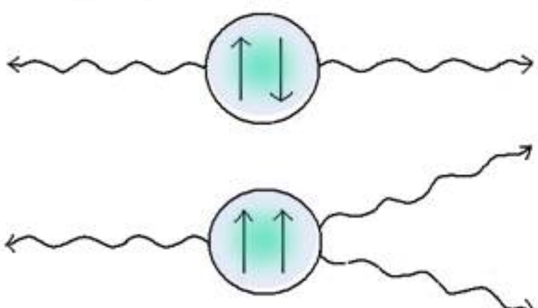
positronium



Y.H. Wang et al., PRA89 (2014) 043624+

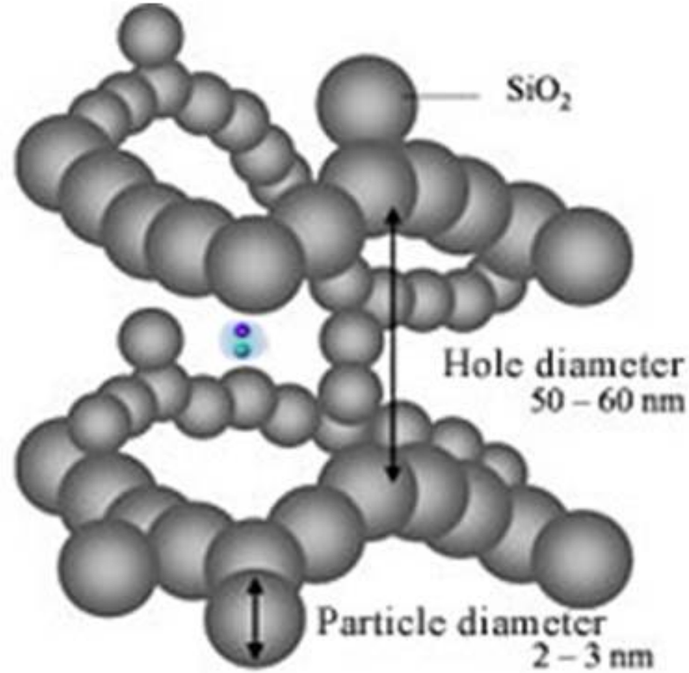
$\tau \approx 125$ ps

$^1S_0$ **para-positronium p-Ps**

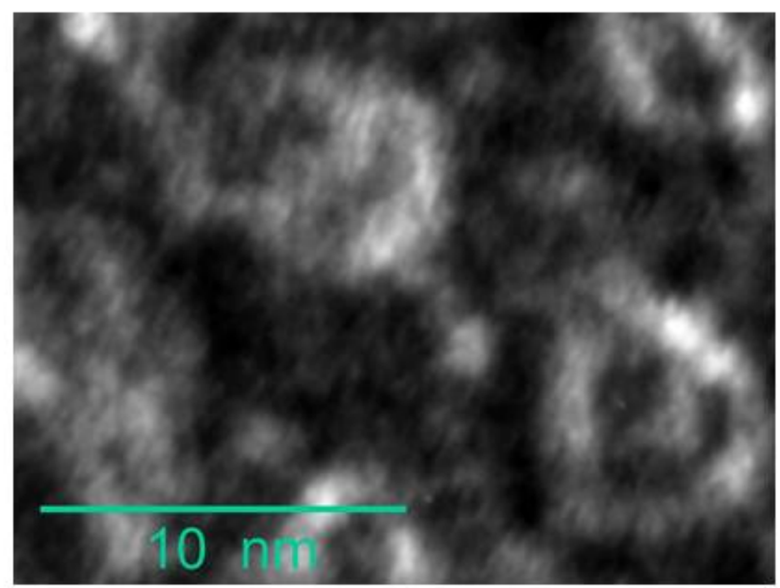


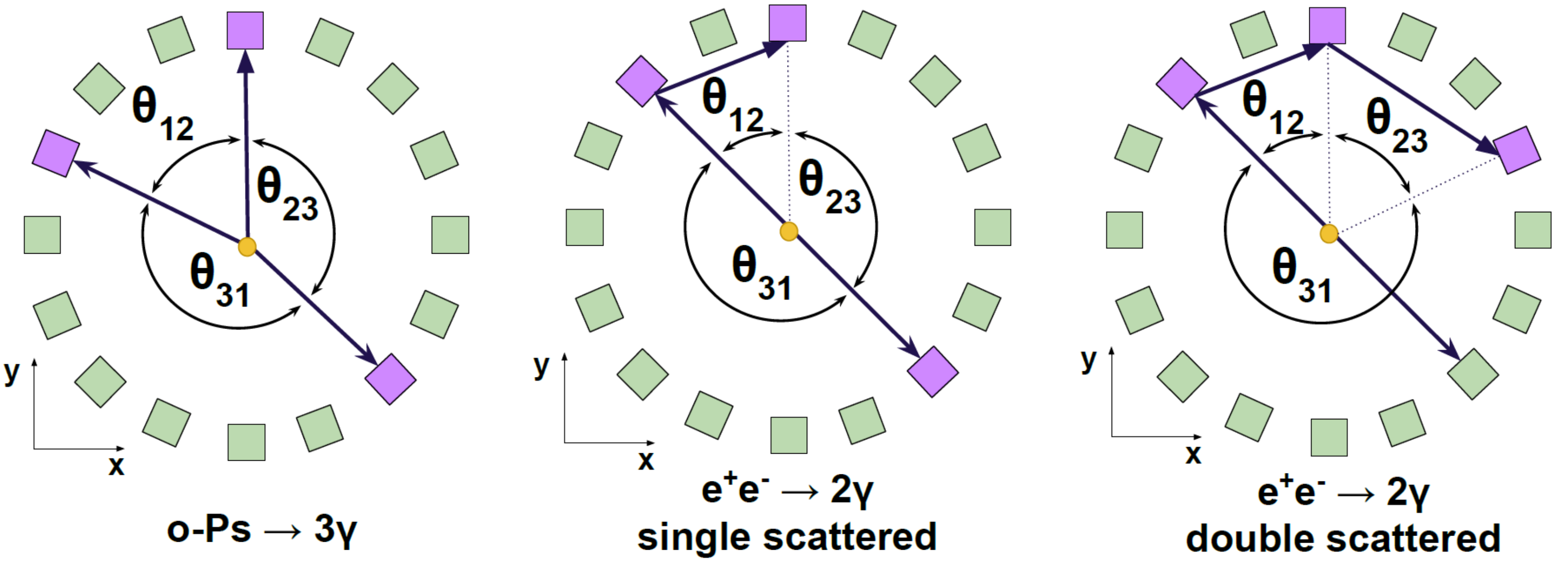
$^3S_1$ **ortho-positronium o-Ps**

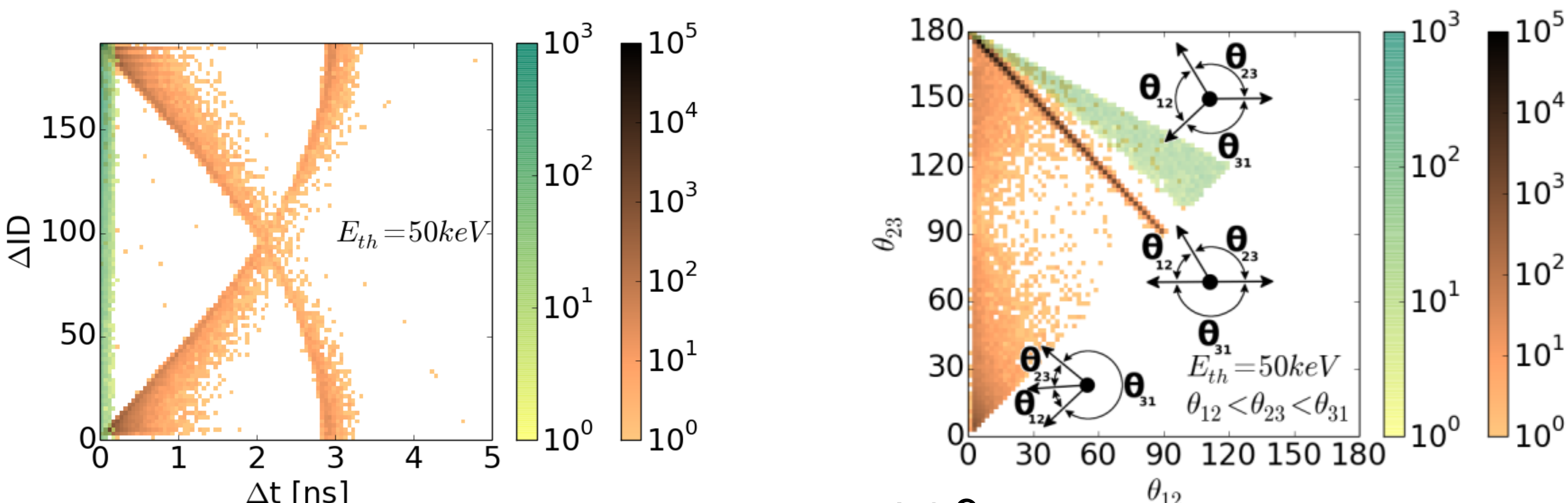
$\tau \approx 142$ ns



http://www.chem-eng.kyushu-u.ac.jp/e/research.html



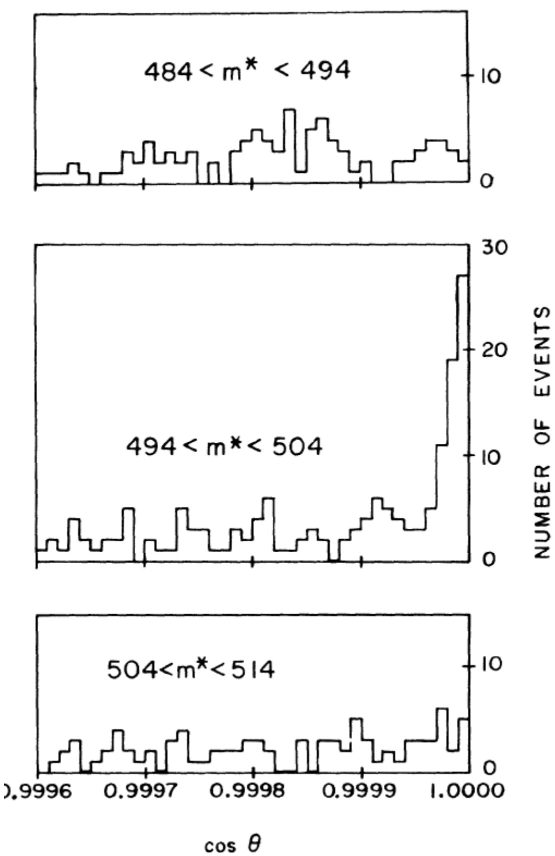


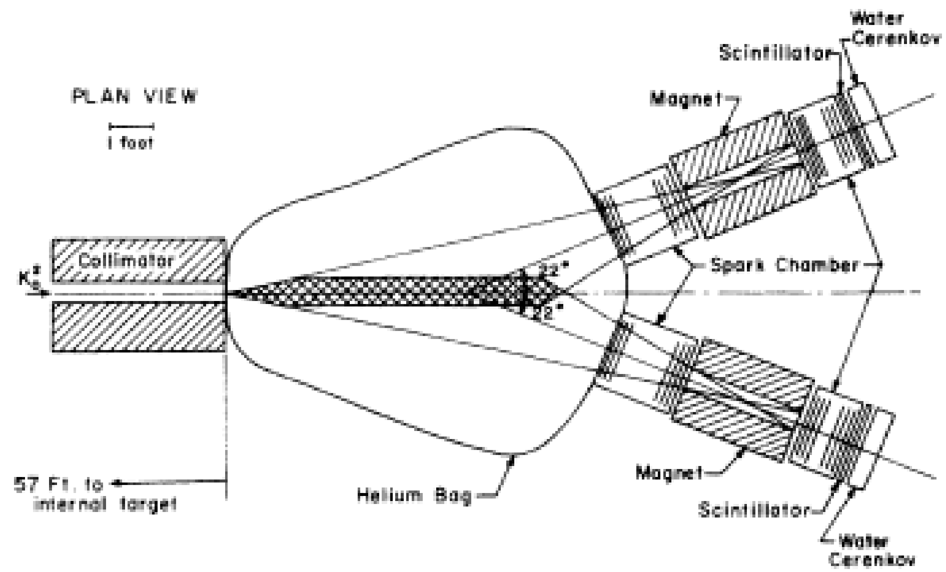


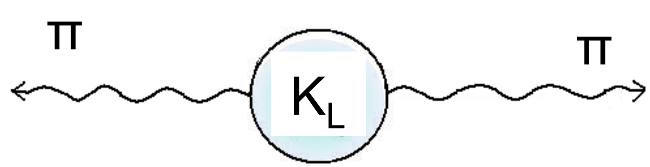
Reduction by factor 10^9

V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.







50 year ....

V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.

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

$$\nu_\mu \to \nu_e \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

50 year later ....

V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

Phys. Rev. Lett. 13 (1964) 138.

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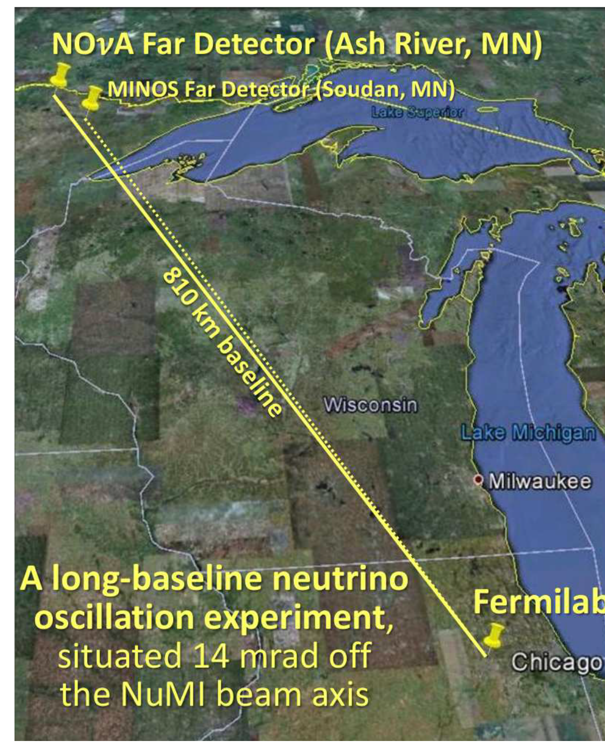
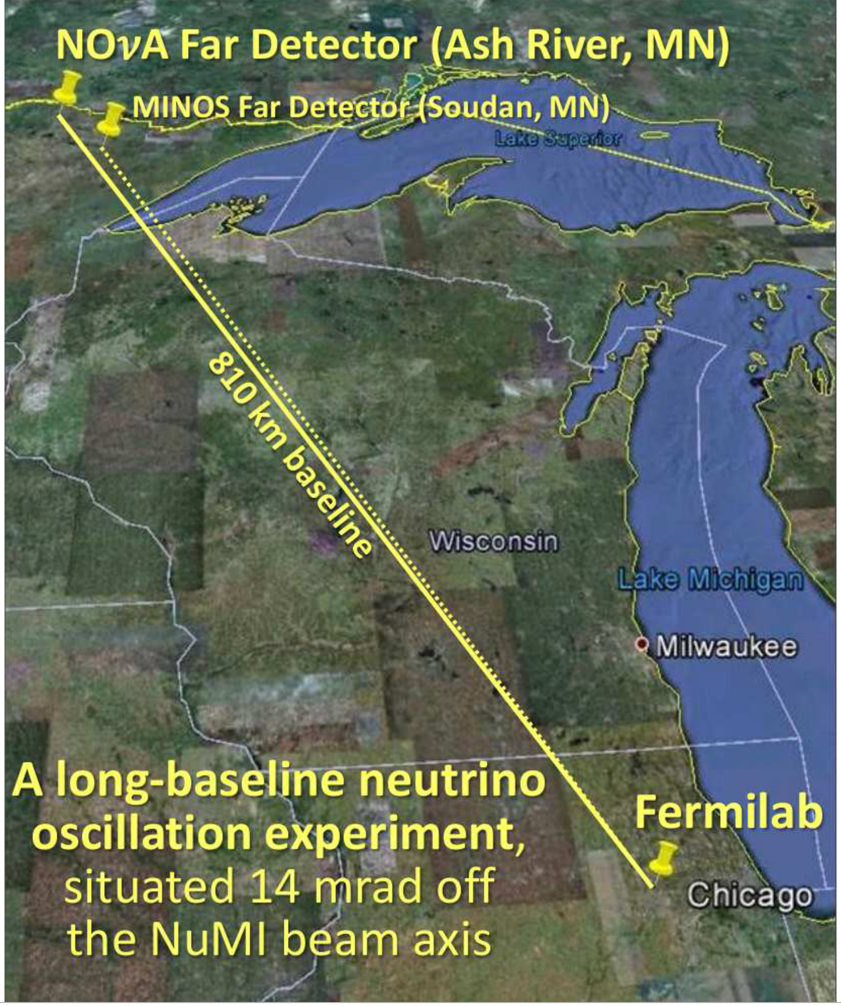
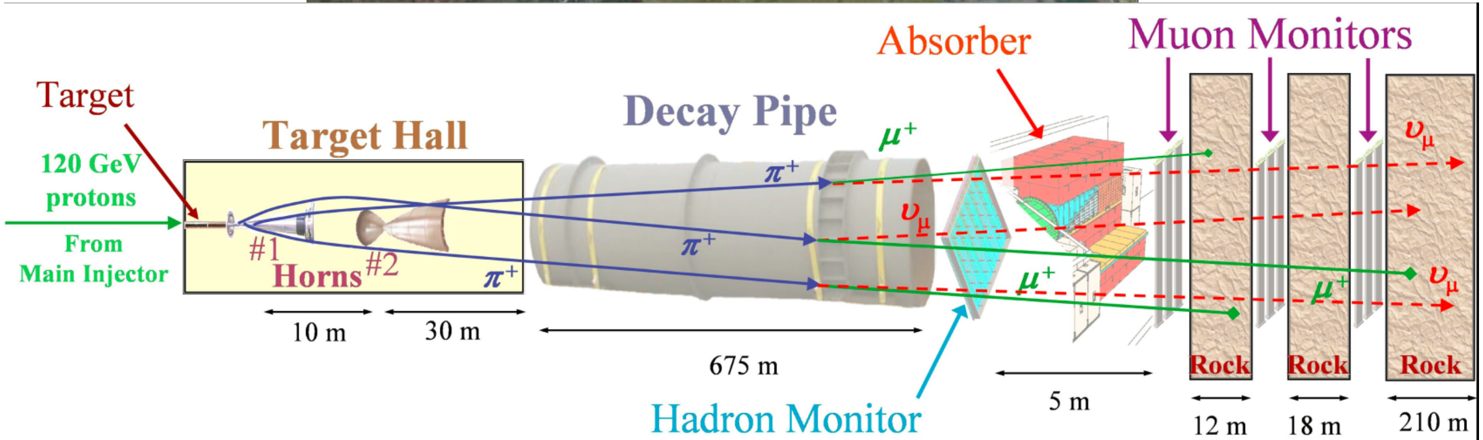
So far breaking of these symmetries was not observed for purely leptonic systems.

$$\nu_\mu \rightarrow \nu_e \qquad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

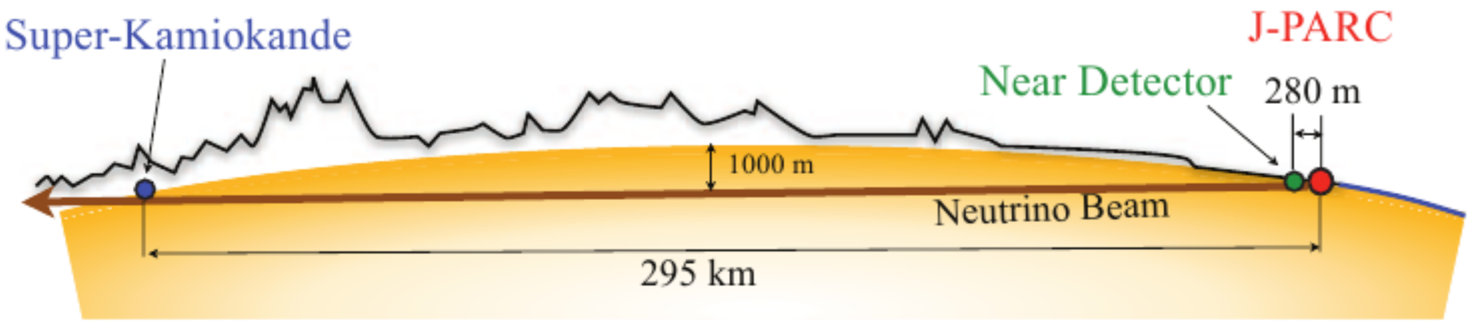


$\nu_\mu \to \nu_\mu \qquad \bar{\nu}_\mu \to \bar{\nu}_\mu$





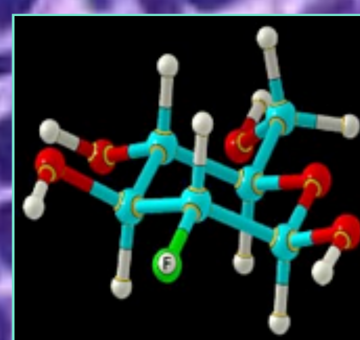
T2K Tokai to Kamioka



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