Searches for discrete symmetries violation in ortho-positronium decay

Workshop on Testing Fundamental Physics Principles

Corfu, Greece, 24 September 2017

Paweł Moskal, Jagiellonian University

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

Searches for discrete symmetries violation in ortho-positronium decay using Jagiellonian Positron Emission Tomograph

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Discrete symmetries

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

C charge conjugation (particles → anti-particle)

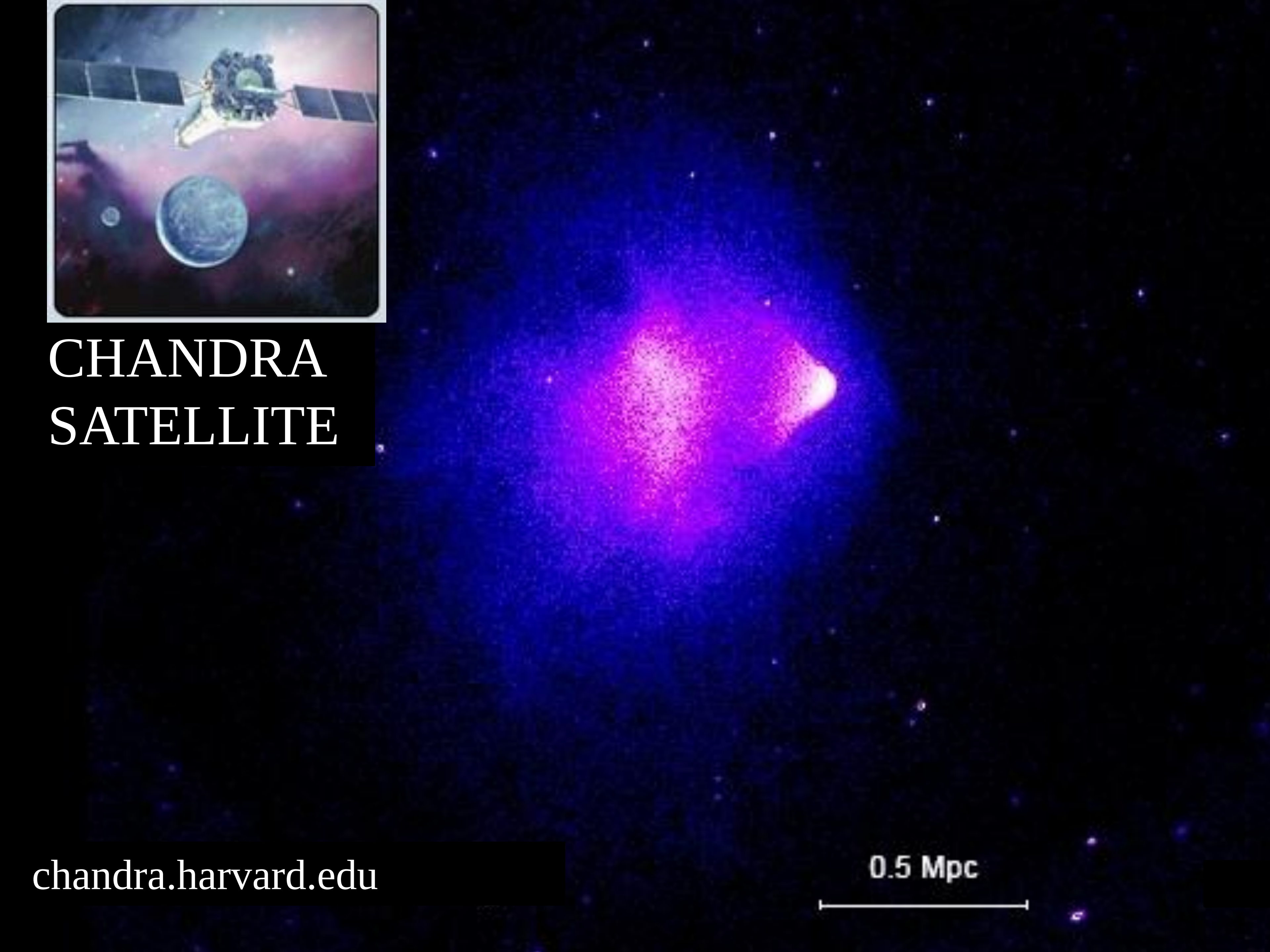
T reversal in time $(A \rightarrow B \Rightarrow B \rightarrow A)$

CP

CPT

[redacted]

CHANDRA
SATELLITE



chandra.harvard.edu

Discrete symmetries

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

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CPT

Lorentz and unitarity and locality => CPT

G. Lüders, Ann. Phys. 2 (1957) 1.; Ann. Phys. 281 (2000) 1004 „Proof of the TCP theorem"

~CPT => ~Lorentz

O. W. Greenberg Phys. Rev. Lett. 89 (2002) 231602.

1595 ?

1604 ?

1609 ?

Michelangelo Merisi da Caravaggio, self-portraits

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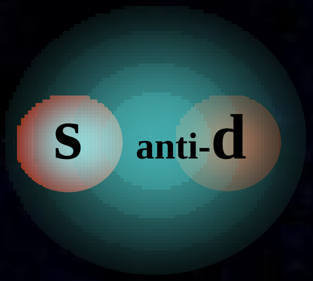
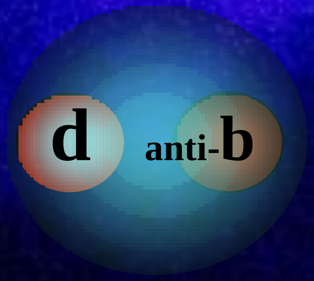
time →

Violation of CP and T confirmed experimentally for mesons only

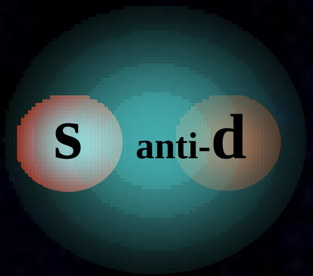


meson K



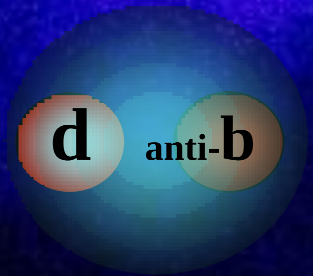
meson B

Violation of CP and T confirmed experimentally for mesons 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)

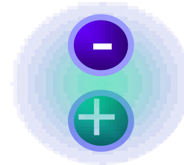
No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)
Light by light contributions to various correlations are small
B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988).
W. Bernreuther et al., Z. Phys. C 41, 143 (1988).

Purely Leptonic state !

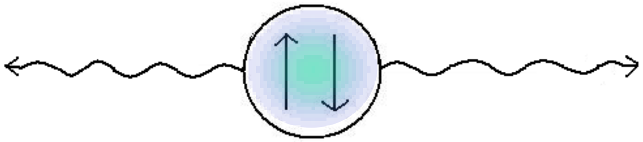
Breaking of T and CP was observed but only for processes involving quarks.
So far breaking of these symmetries was not observed for purely leptonic systems.

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

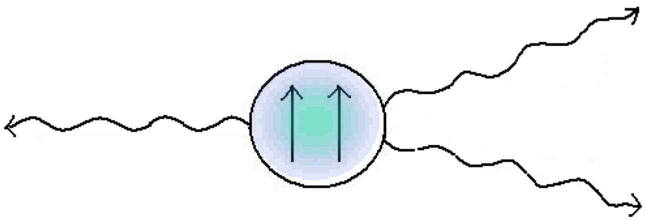
P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003)
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401



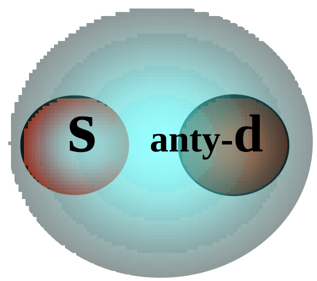
POSITRONIUM



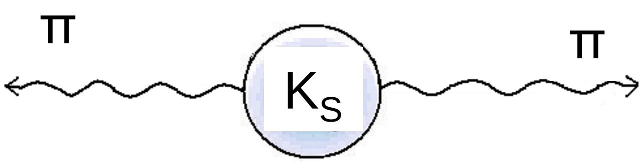
CP = + Para-positronium tau(p-Ps) ≈ 125 ps



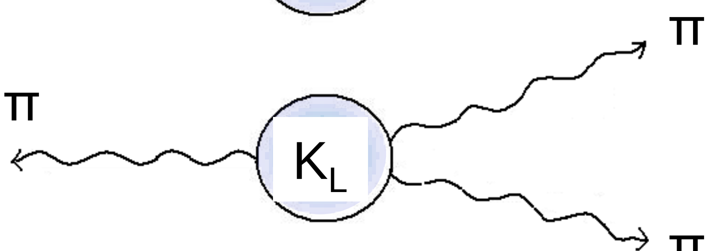
CP = - Ortho-positronium tau(o-Ps) ≈ 142 ns



MESON K



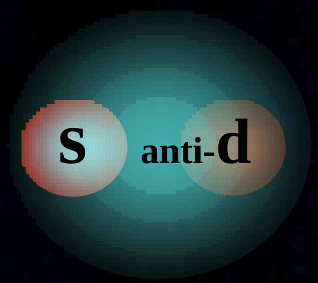
CP ~= + tau(K_S) ≈ 90 ps



CP ~= - tau(K_L) ≈ 52 ns

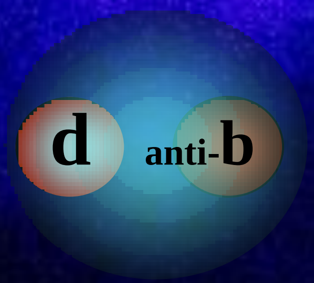
T symmetry violation

- $A \longrightarrow B \qquad B \longrightarrow A$
- T symmetry odd operators
- Particle mixing



meson K

1964



meson B

2012

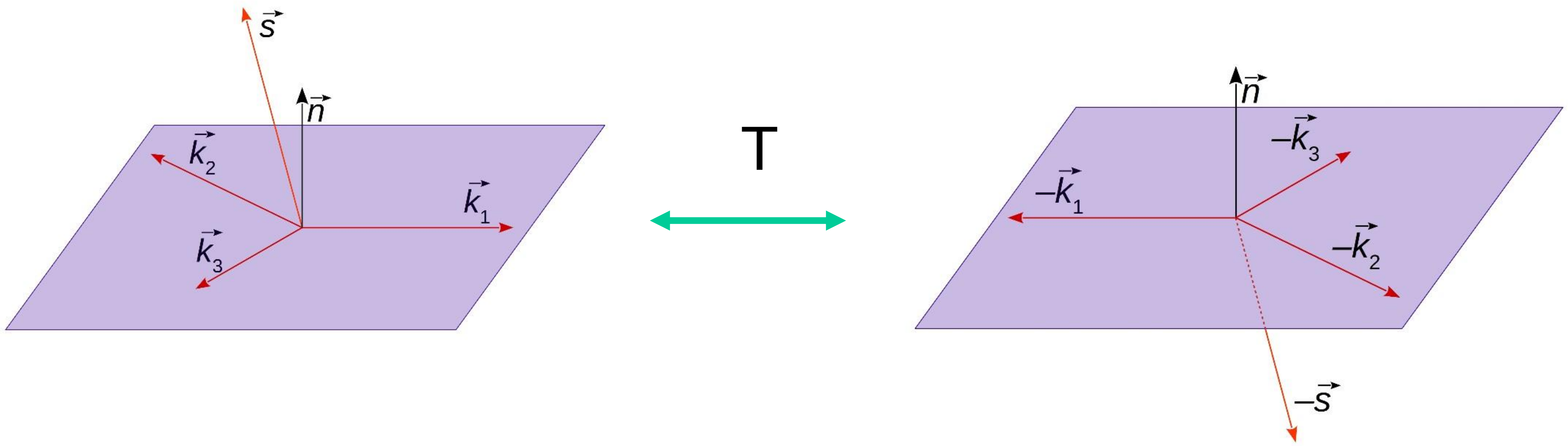
positronium

?

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.

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

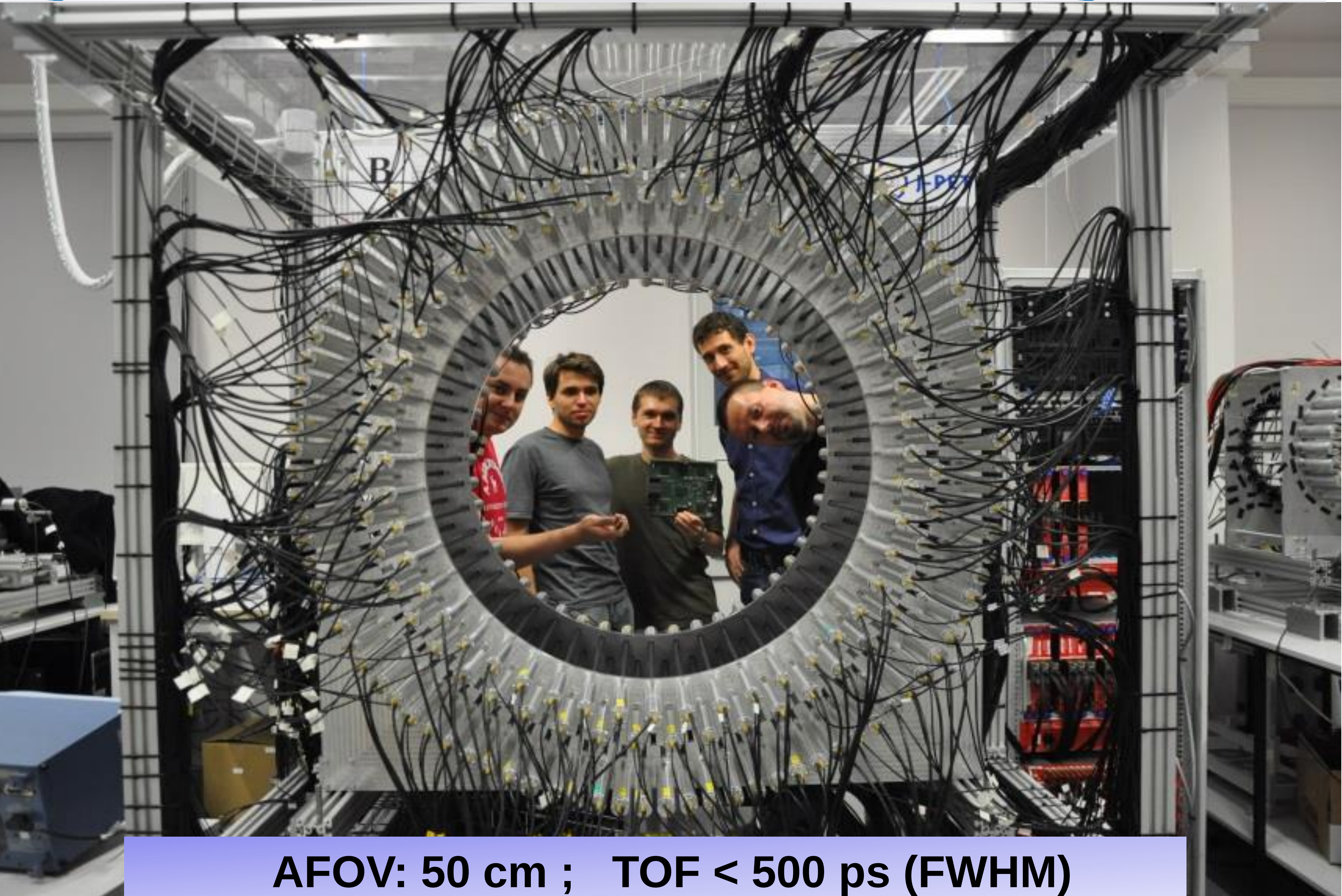


So far best accuracy for tests of **CP and CPT violation** was reported by

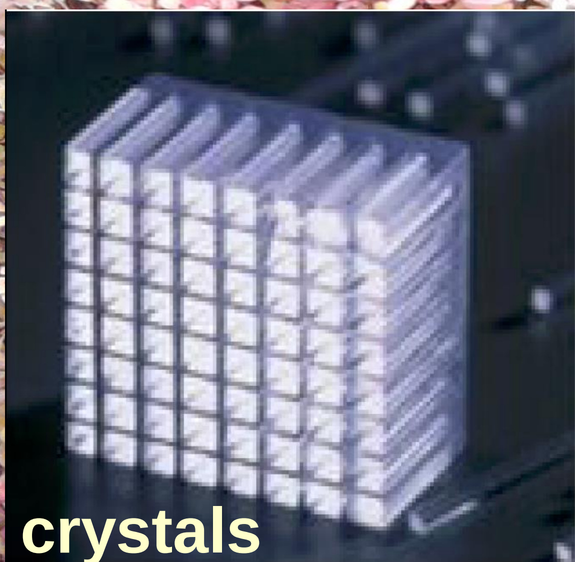
-0.0023 < CP < 0.0049 at 90% CL T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

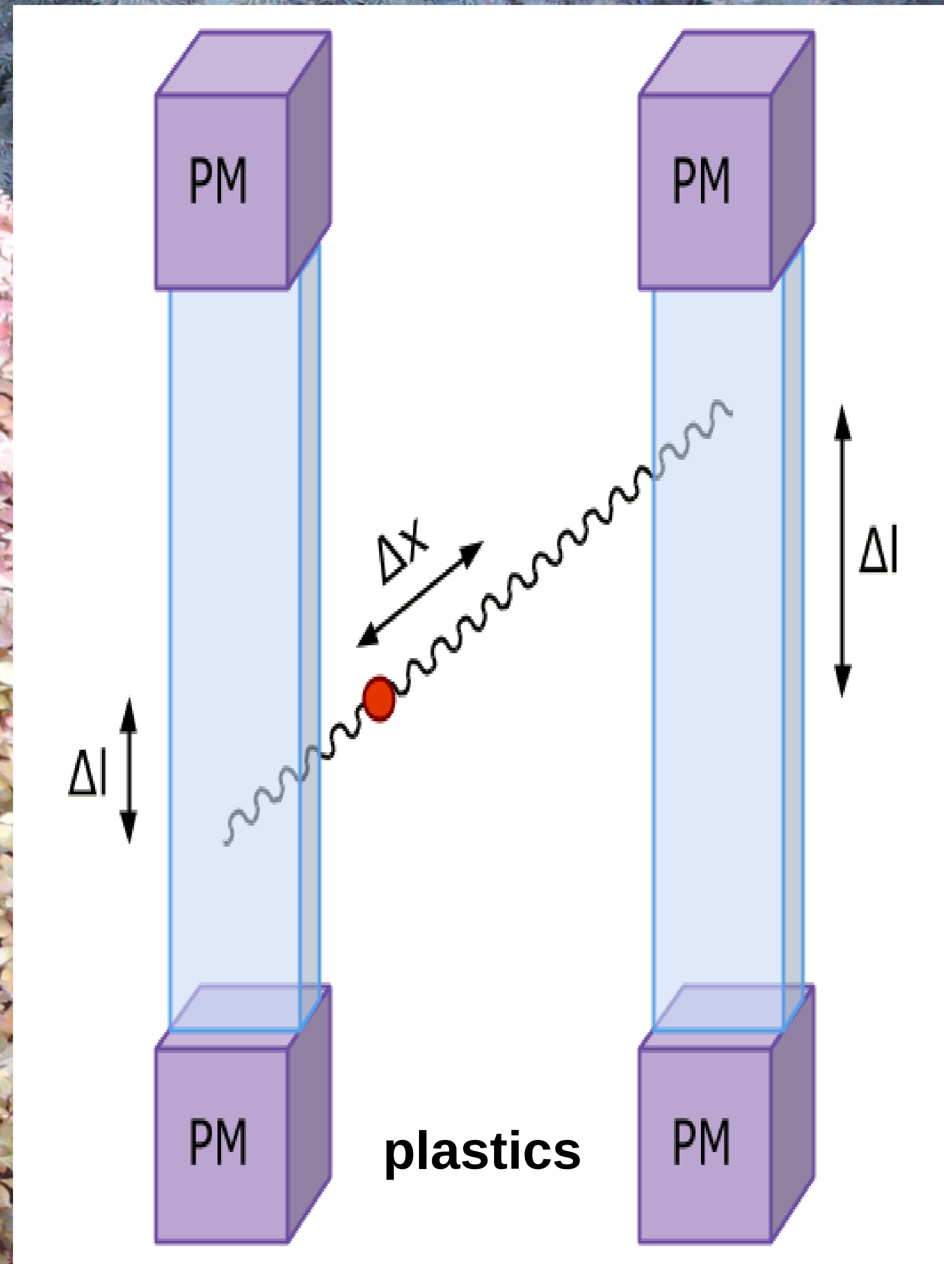
CPT = 0.0071 ± 0.0062 P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003).

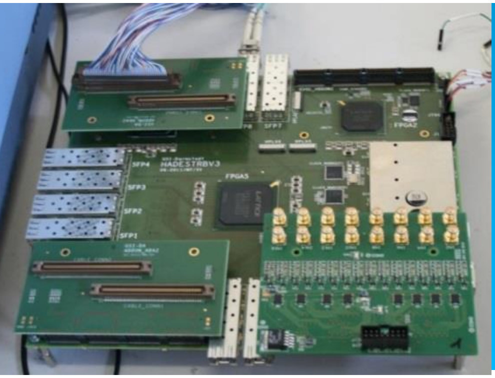
Jagiellonian PET



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


crystals


PM
PM
Δx
Δl
Δl
PM
plastics
PM



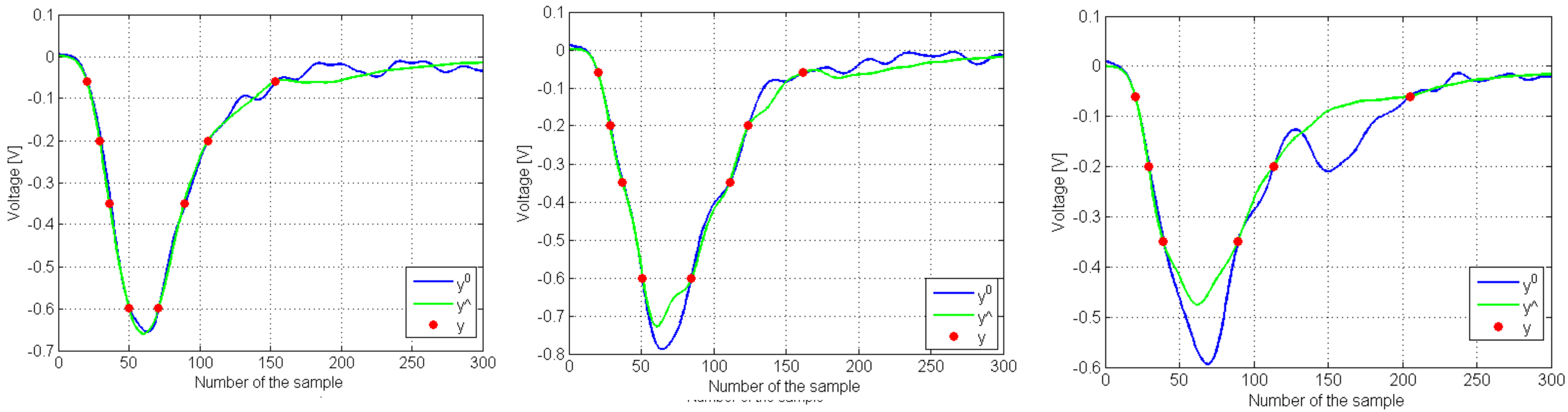
ONLY DIGITAL in triggerless mode

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**

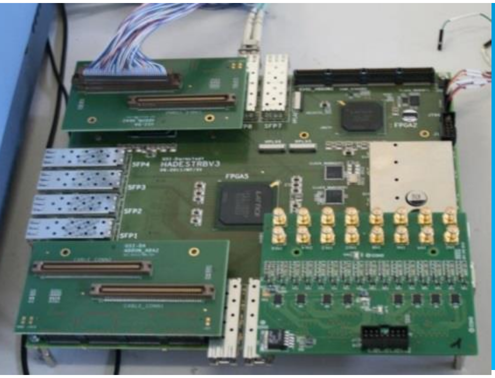


Library of signals; Principal Component Analysis; Compressive Sensing;
J-PET: L. Raczyński et al., Nucl. Instr. Meth. A786 (2015) 105
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54

Reconstruction

Detector	FrontEnd electronics	Electronics controller	Hit along strip	Annihilation point	Image

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



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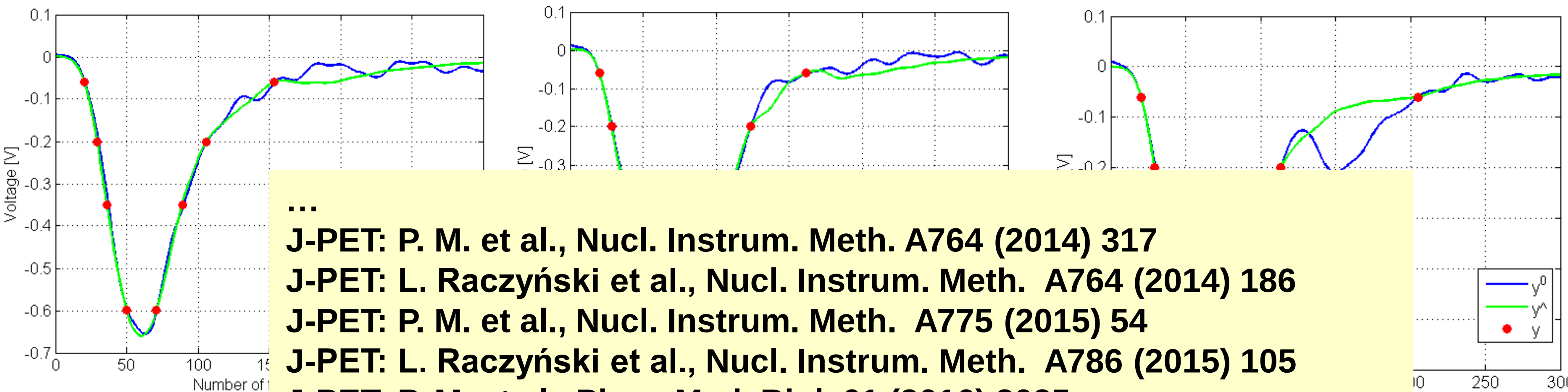


Library of signals
J-PET: L. Raczyń
J-PET: P. M. et al.

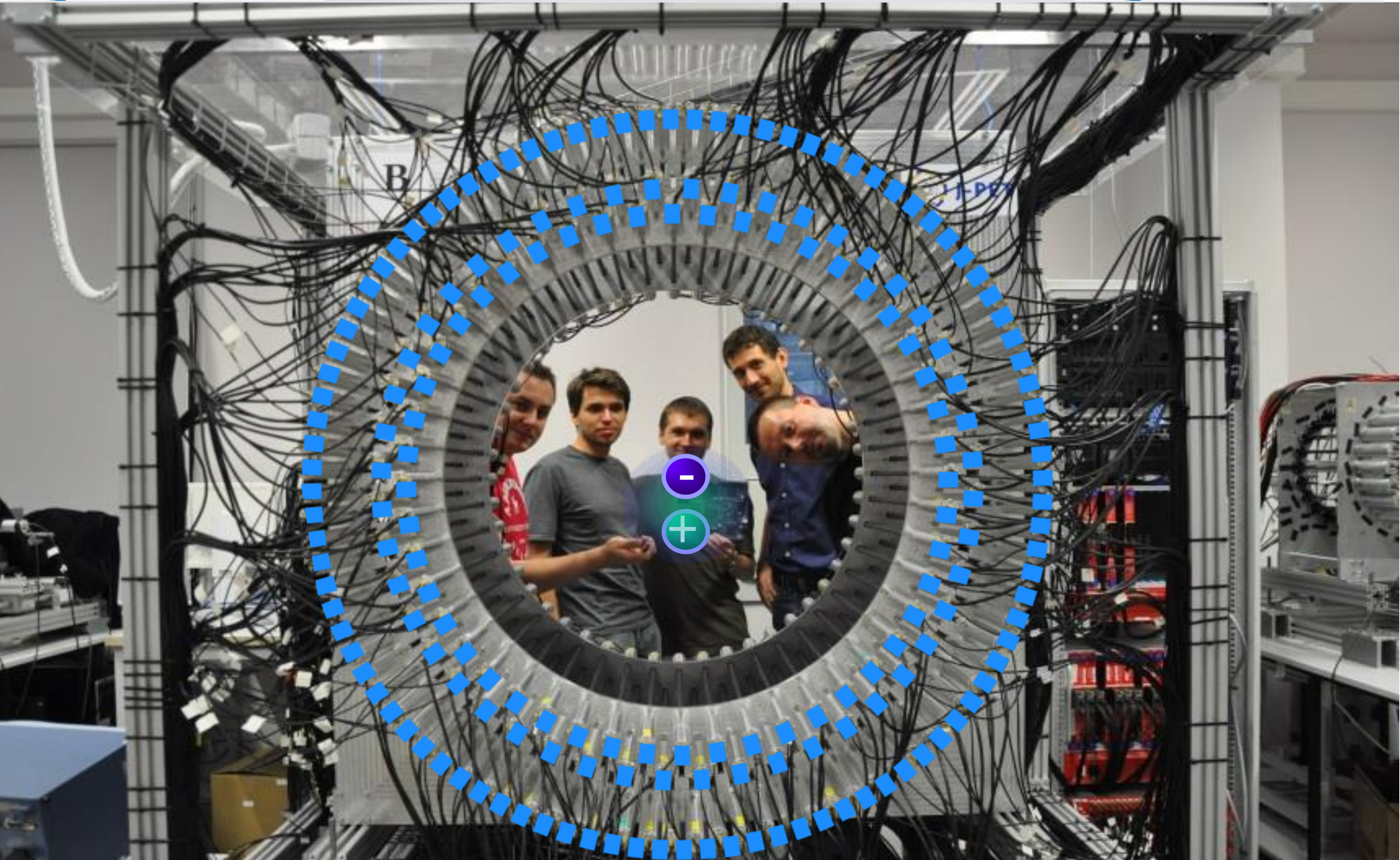
…
J-PET: P. M. et al., Nucl. Instrum. Meth. A764 (2014) 317
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A764 (2014) 186
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54
J-PET: L. Raczyński et al., Nucl. Instrum. Meth. A786 (2015) 105
J-PET: P. M. et al., Phys. Med. Biol. 61 (2016) 2025
J-PET: 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

~60 articles and 17 international patent applications

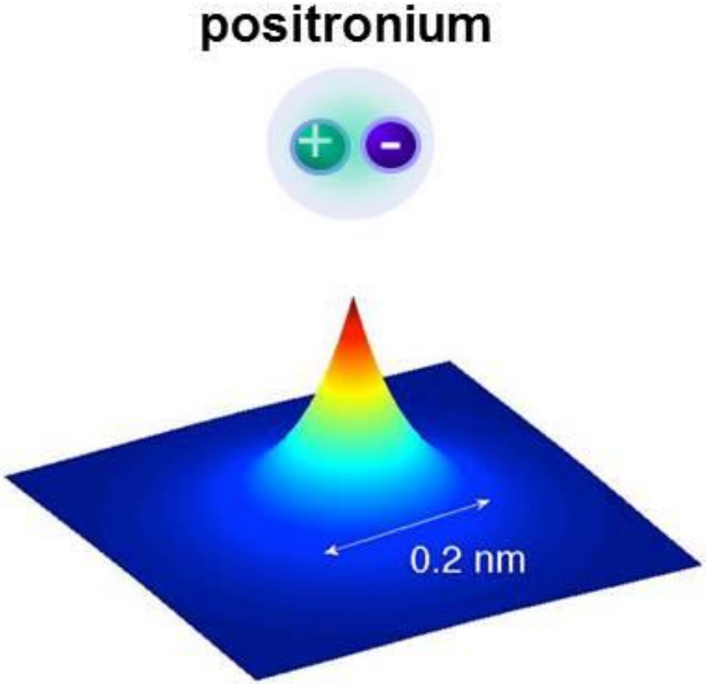
Detector **mage**

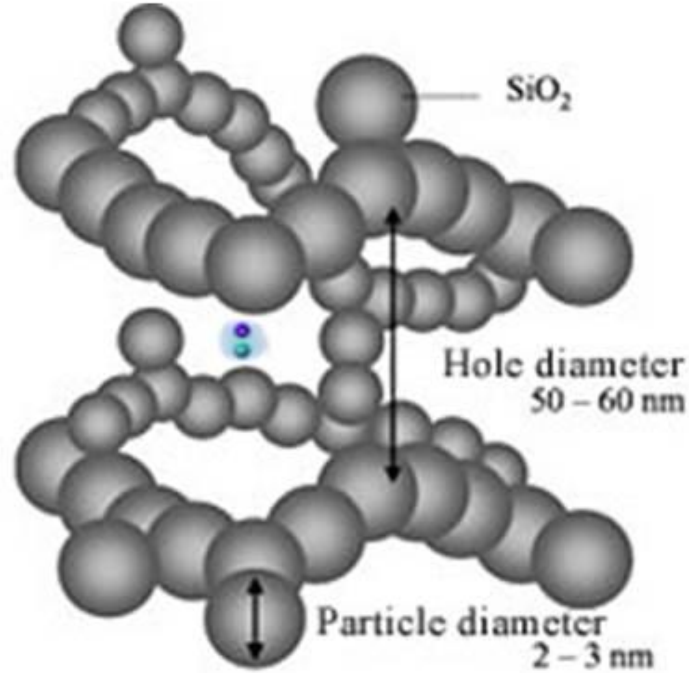
J-PET: W. Krzemień et al., Acta Phys. Pol. B47 (2016) 561

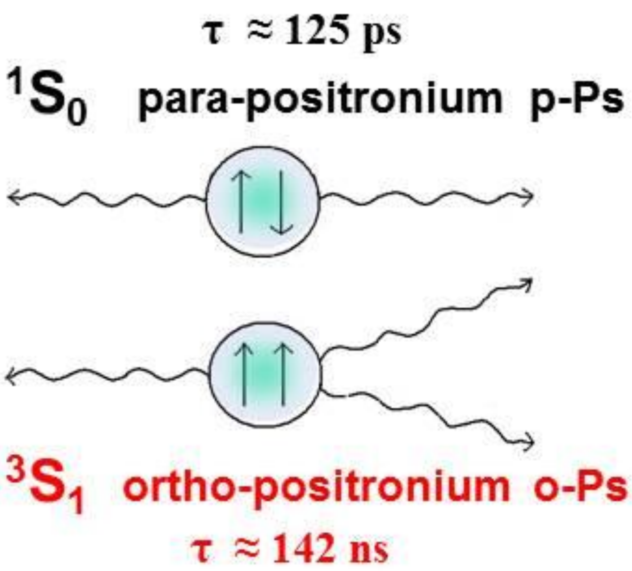
Jagiellonian PET

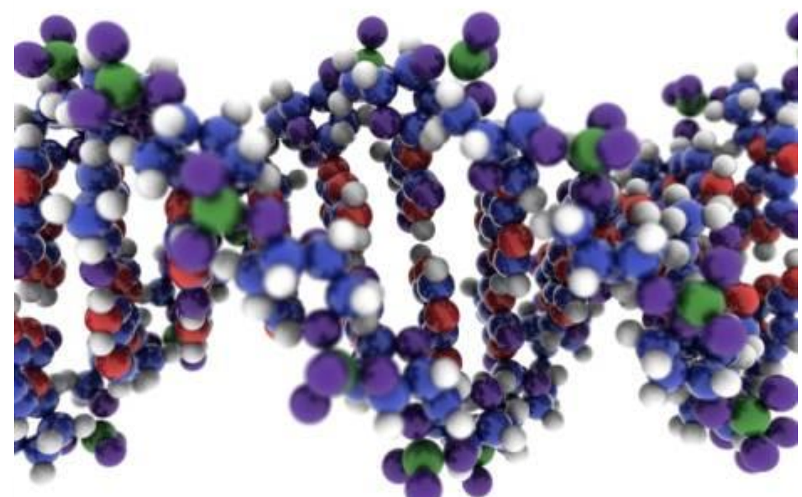


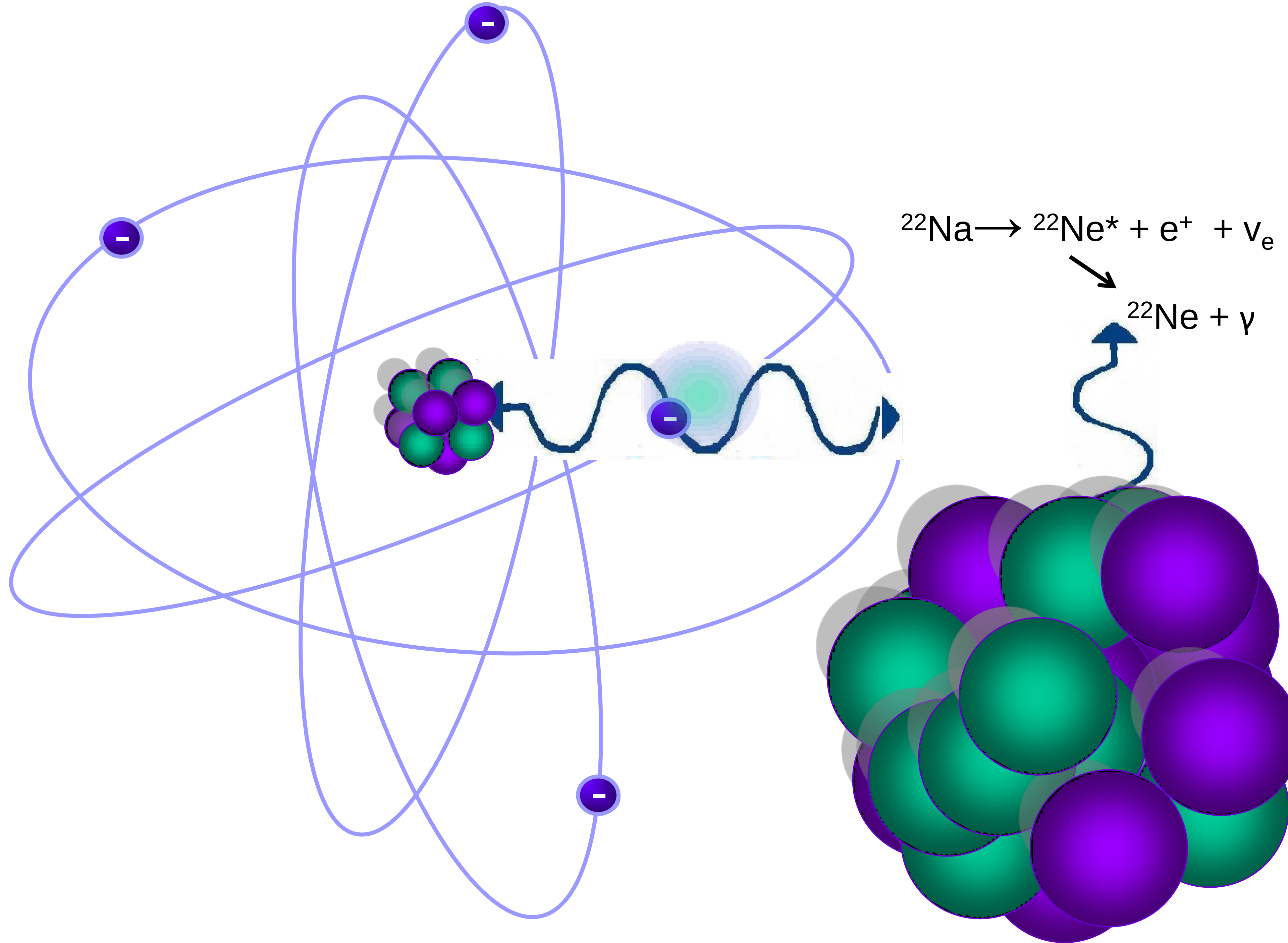
σ(t-hit) ~ 100 ps


positronium
0.2 nm

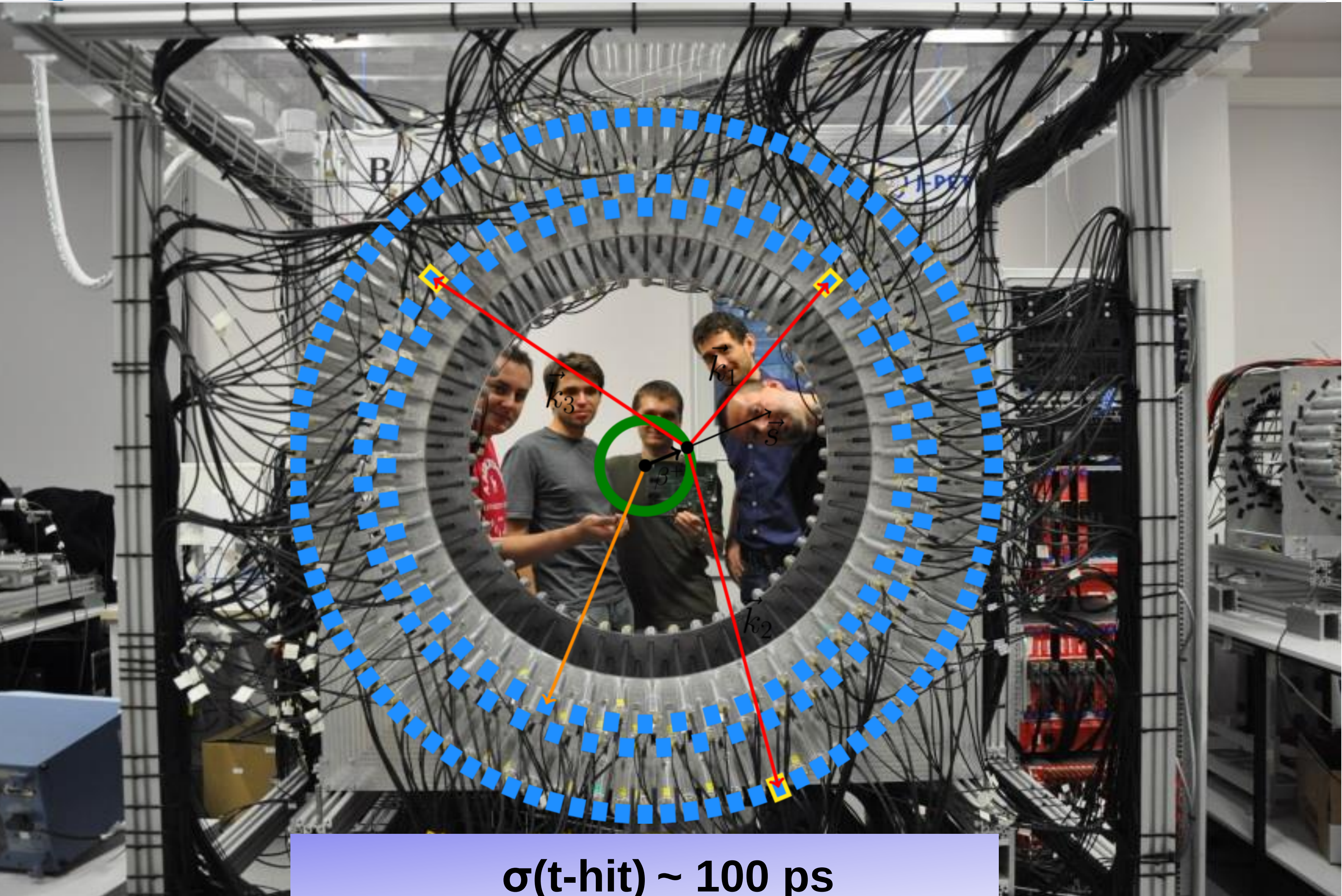

SiO$_2$
Hole diameter
50 – 60 nm
Particle diameter
2 – 3 nm


τ ≈ 125 ps
$^1S_0$ para-positronium p-Ps
$^3S_1$ ortho-positronium o-Ps
τ ≈ 142 ns



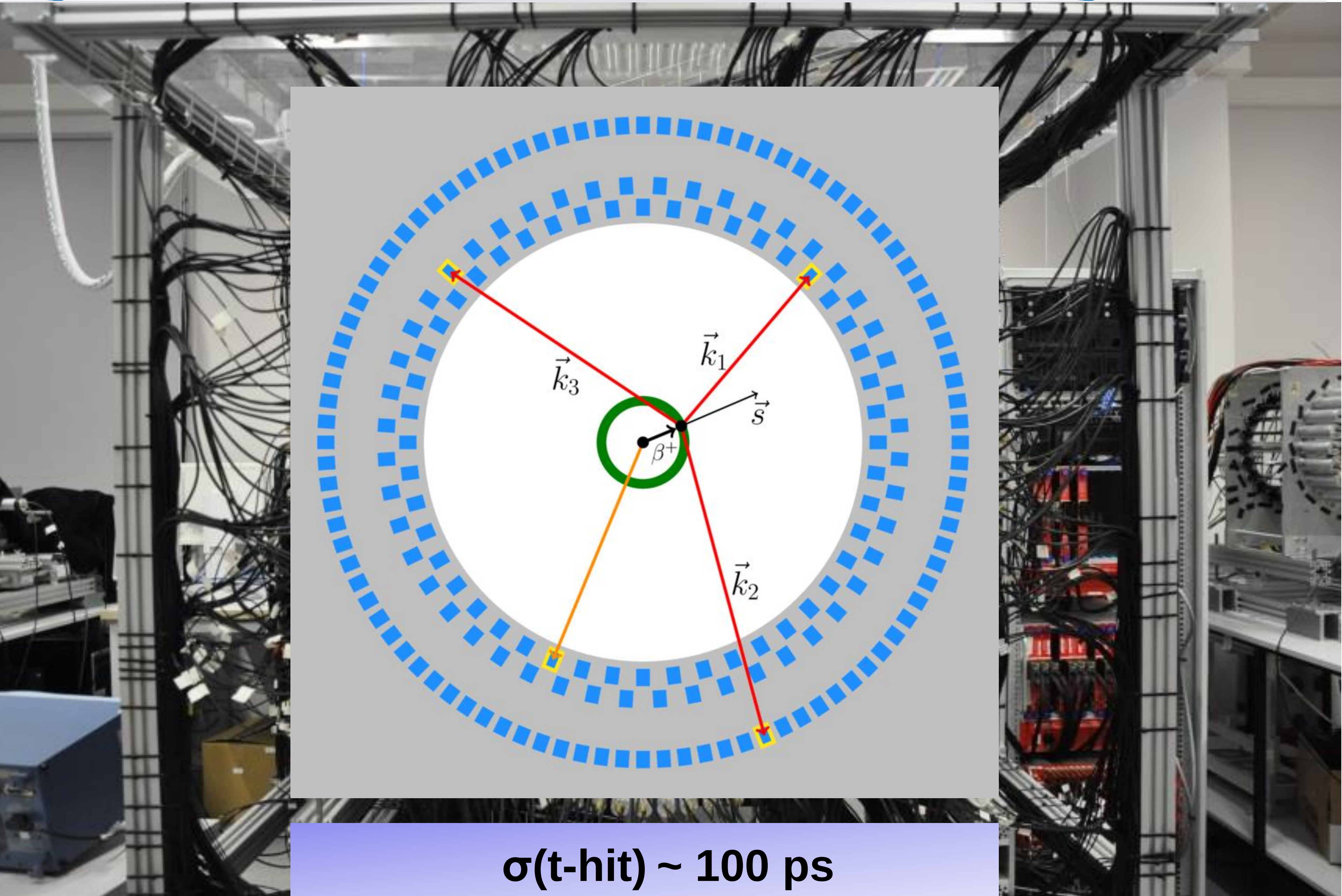

$^{22}Na \longrightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$
$^{22}Ne + \gamma$

Jagiellonian PET



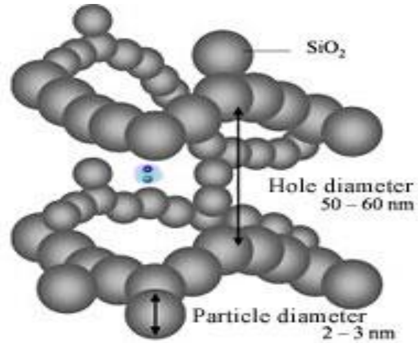
σ(t-hit) ~ 100 ps

Jagiellonian PET

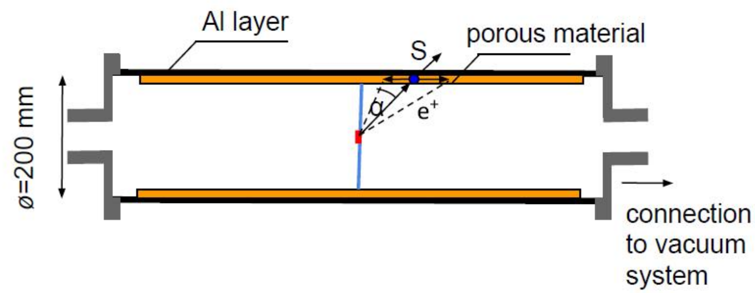


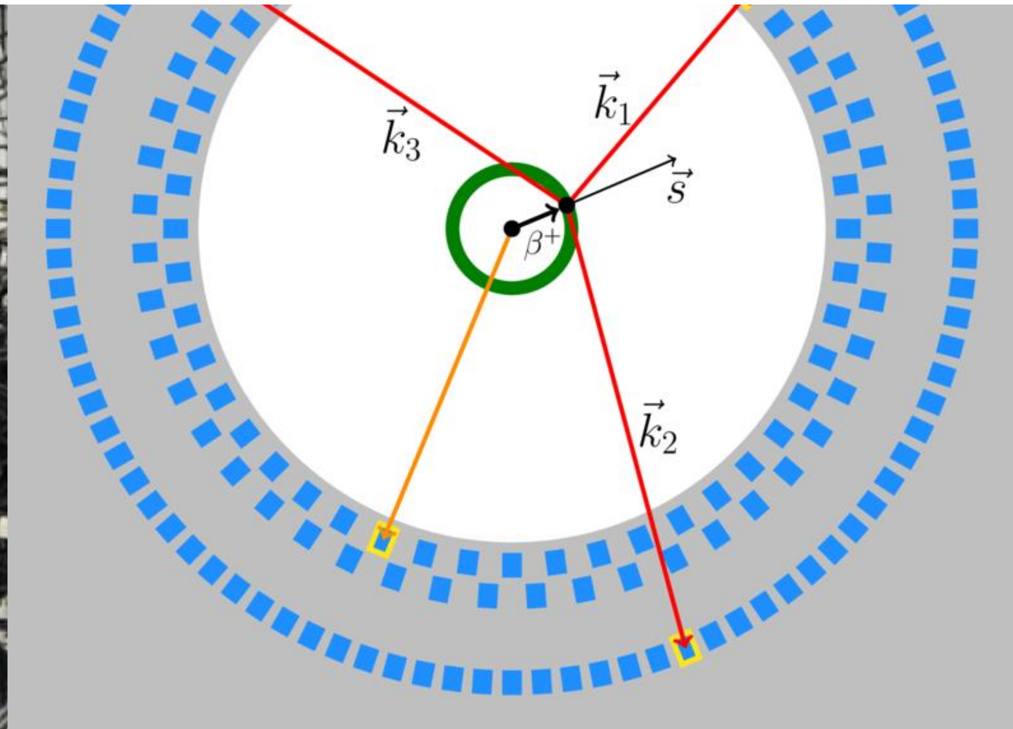
σ(t-hit) ~ 100 ps

Jagiellonian PET



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



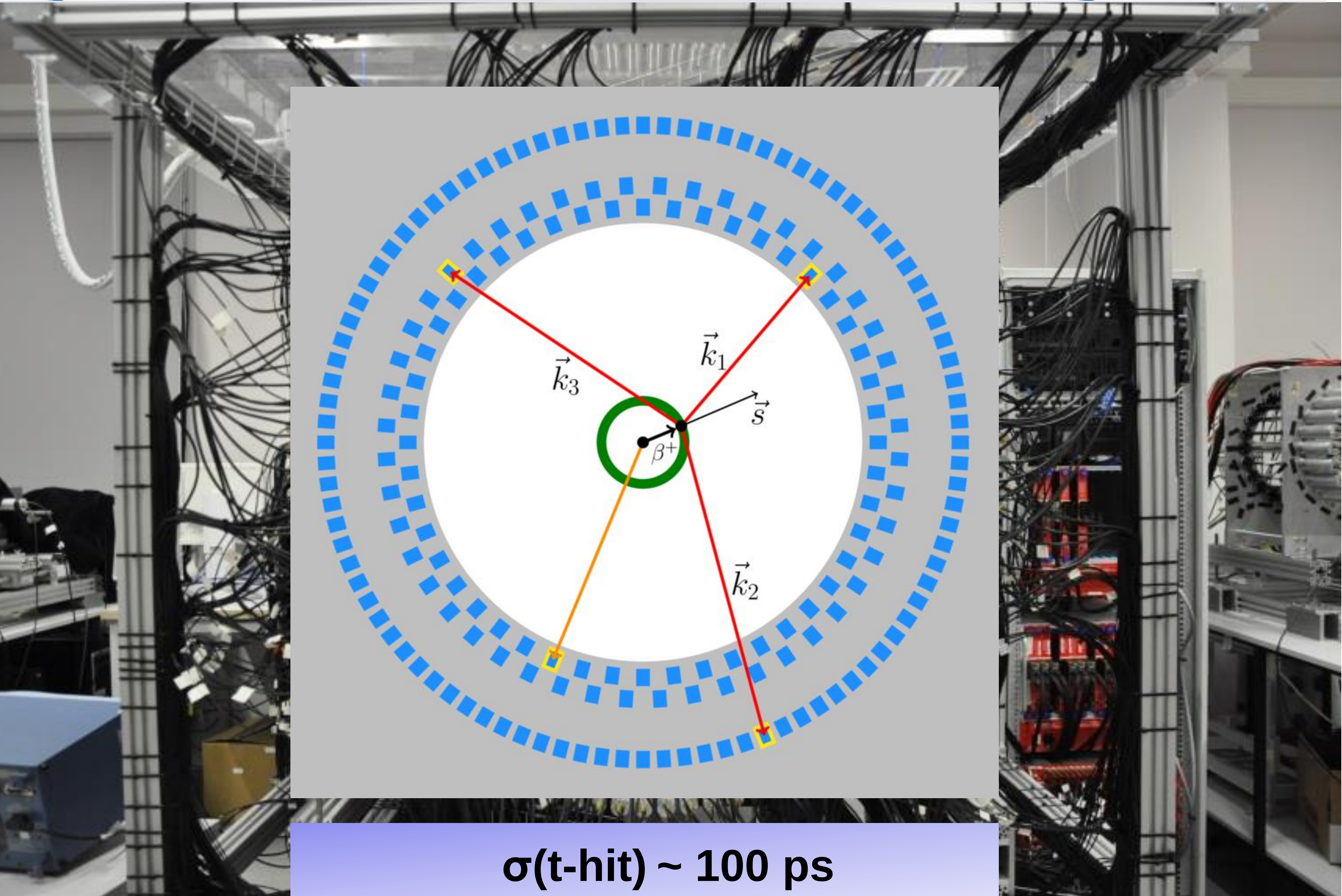


σ(t-hit) ~ 100 ps

J-PET

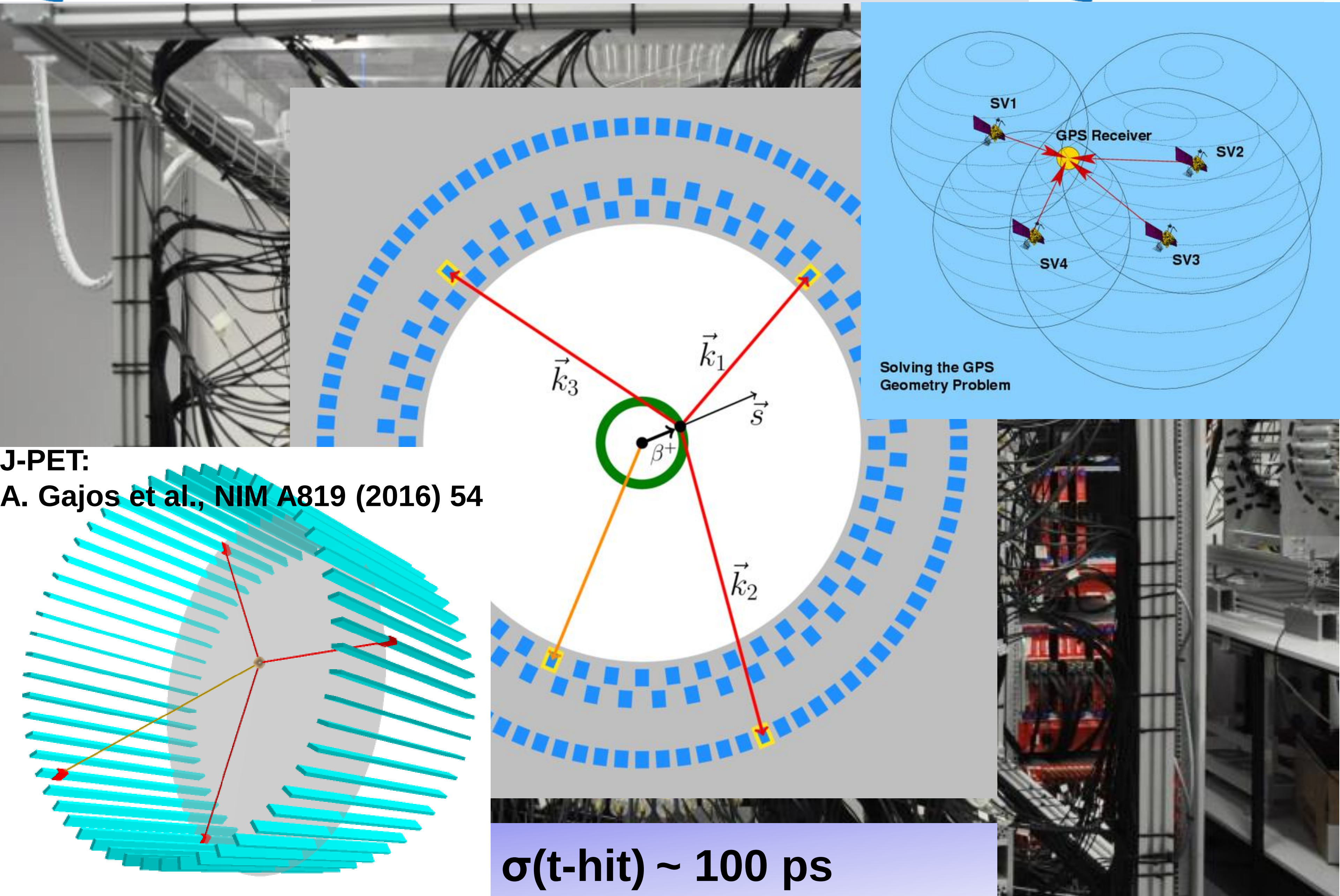
First cylindrical porous target by Prof. J. Goworek from UMCS in Lublin

Jagiellonian PET



σ(t-hit) ~ 100 ps

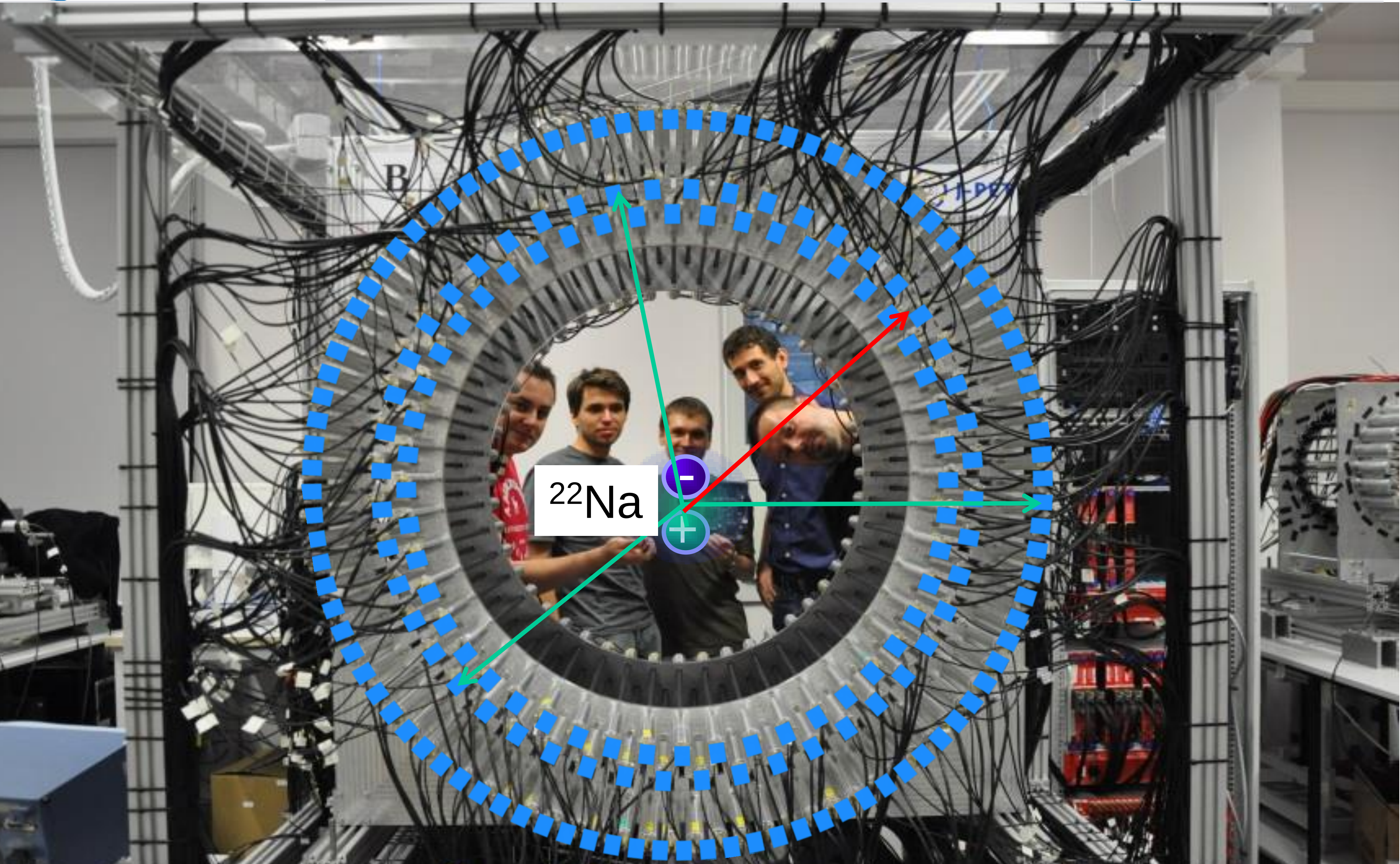
Jagiellonian PET



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

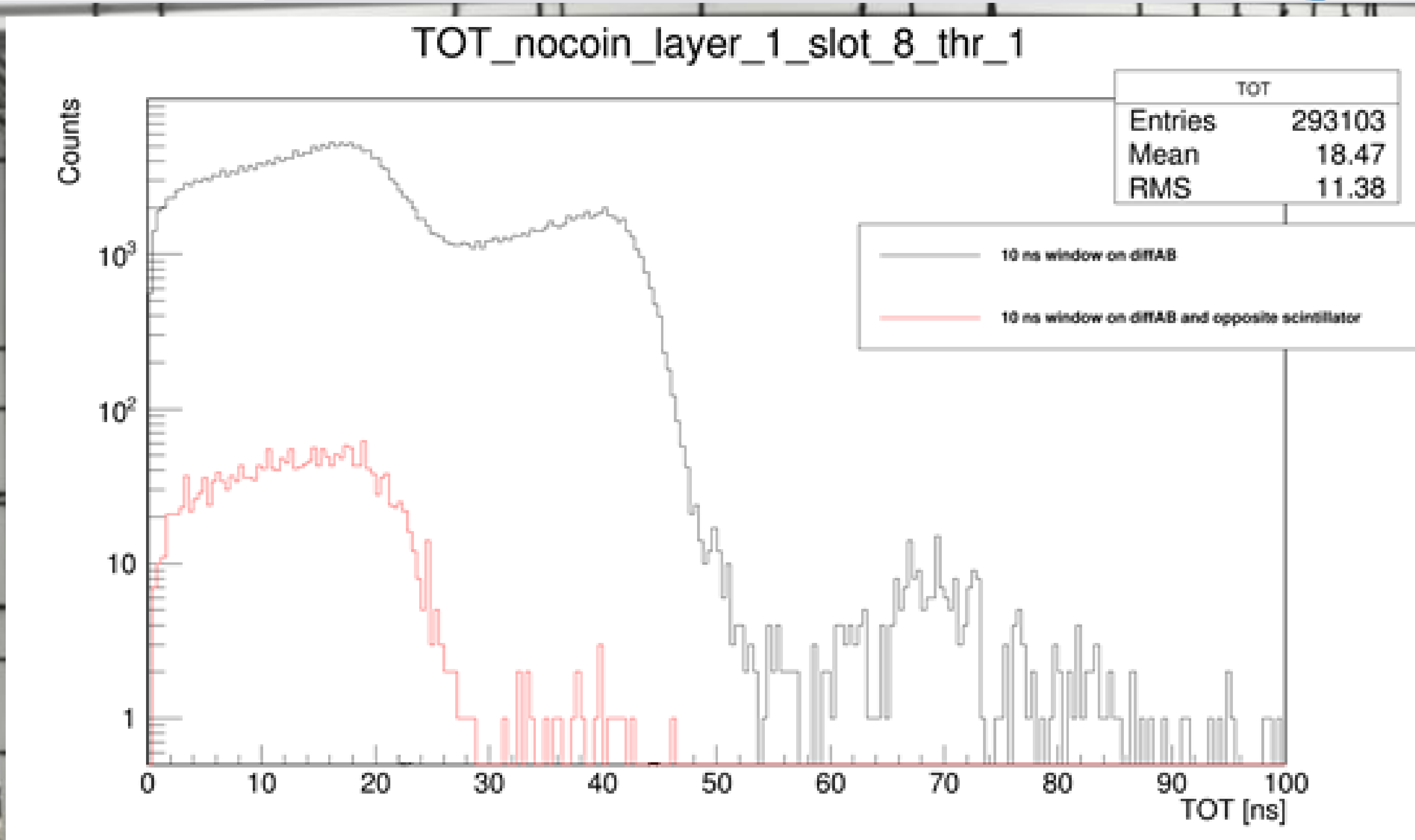
σ(t-hit) ~ 100 ps

Jagiellonian PET



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

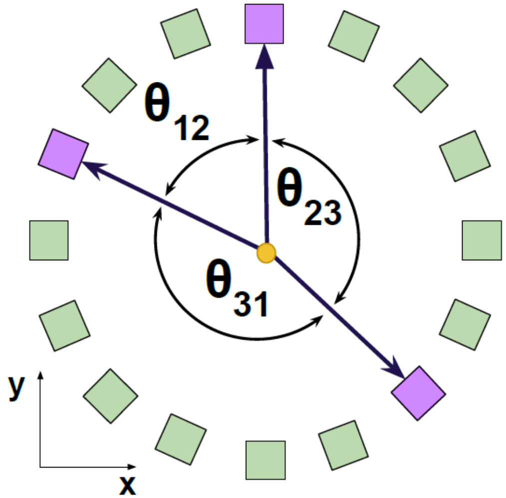
Jagiellonian PET



$$e^+ + e^- \rightarrow \gamma\,\gamma \text{ (511 keV)}$$

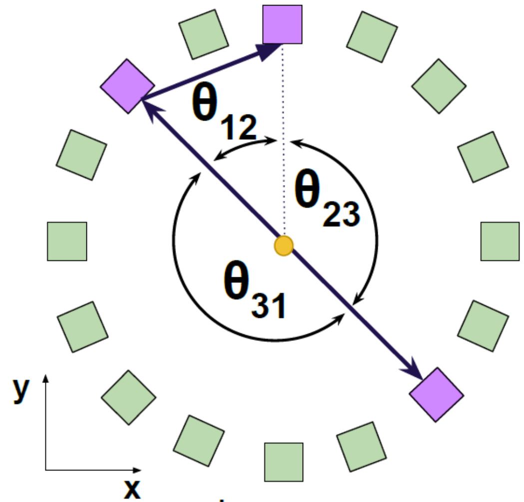
$$^{22}Na \longrightarrow {}^{22}Ne^* + e^+ + \nu_e$$

$$^{22}Ne + \gamma \text{ (1270 keV)}$$



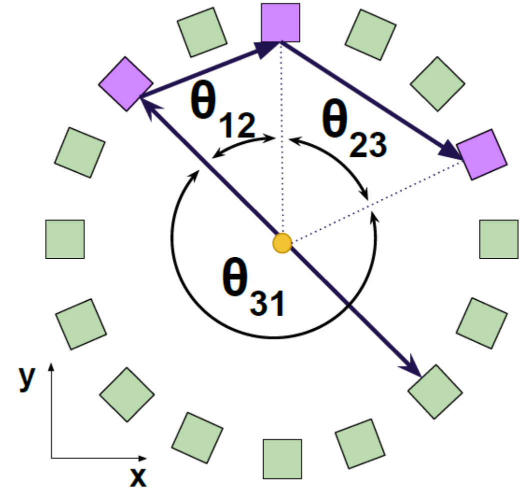
o-Ps → 3γ

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



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

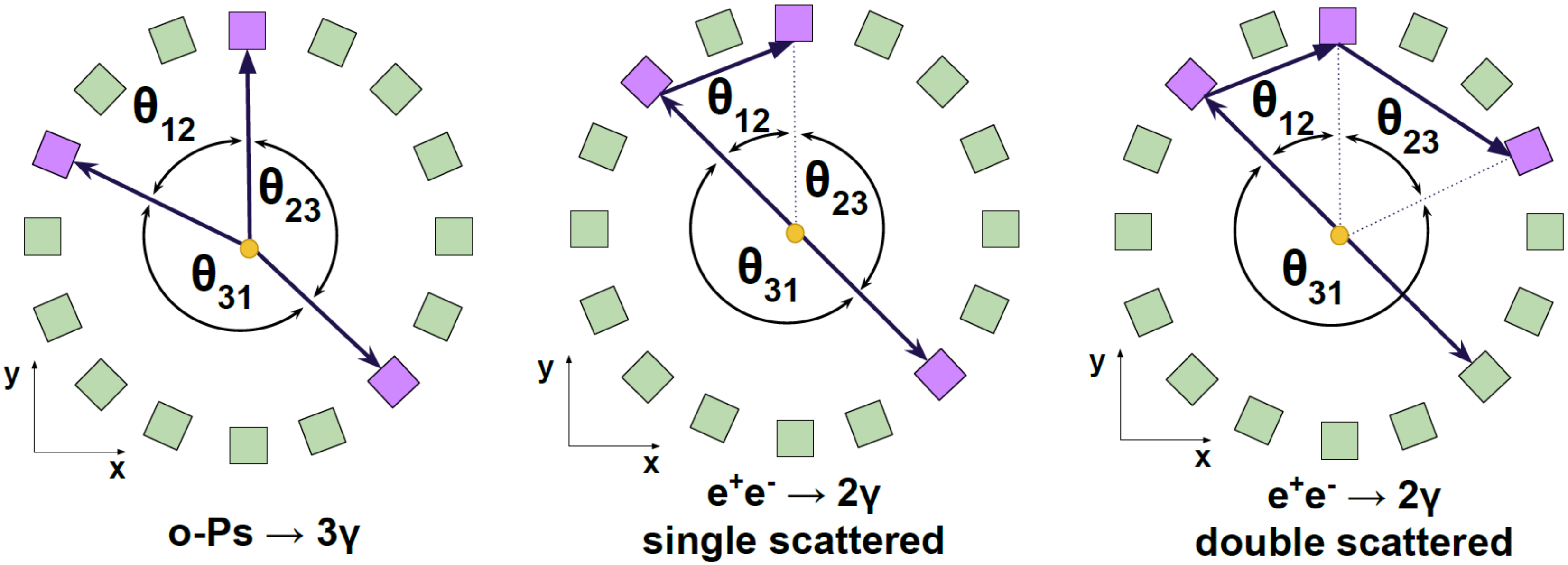
$\theta_{23} = 180 - \theta_{12}$



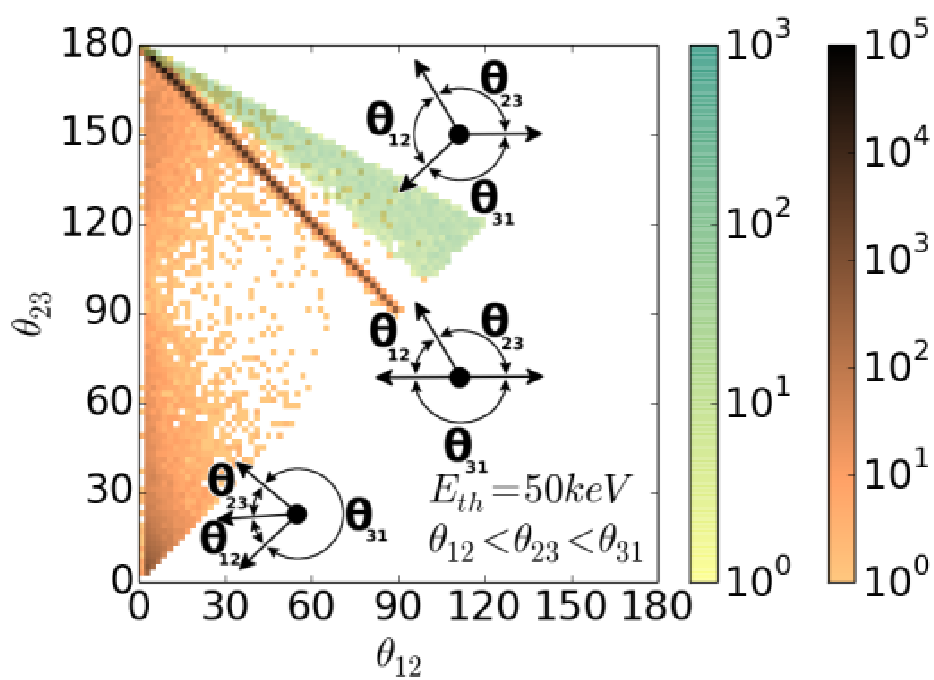
$e^+e^- \rightarrow 2\gamma$
double scattered

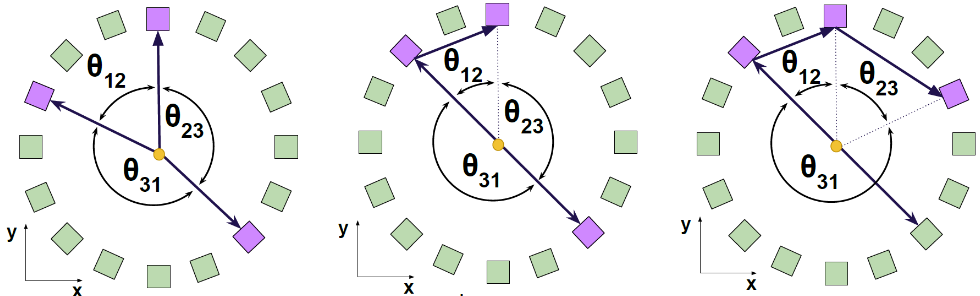
$\theta_{23} < 180 - \theta_{12}$

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



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





o-Ps → 3γ

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

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

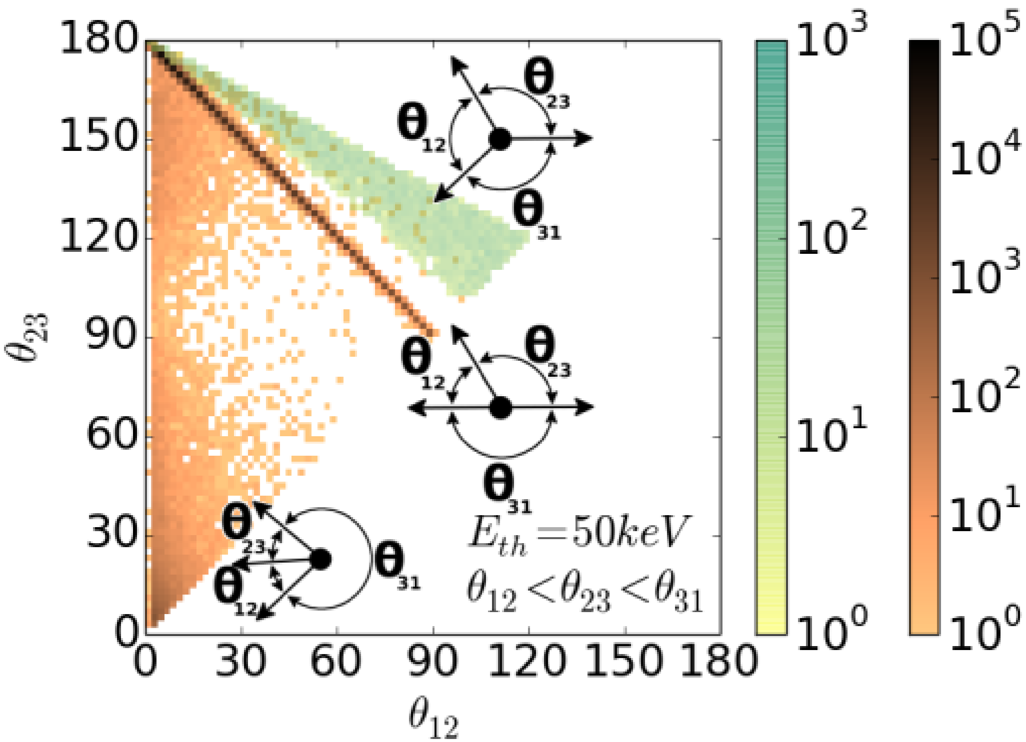
$\theta_{23} > 180 - \theta_{12}$

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

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

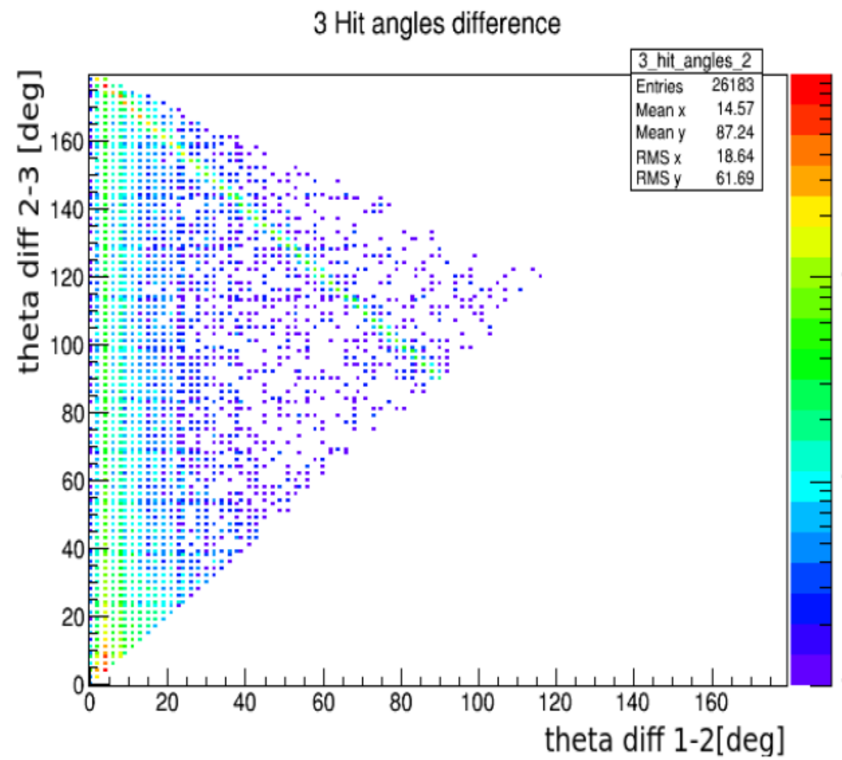
Simulations

Eur. Phys. J. C76 (2016) 445

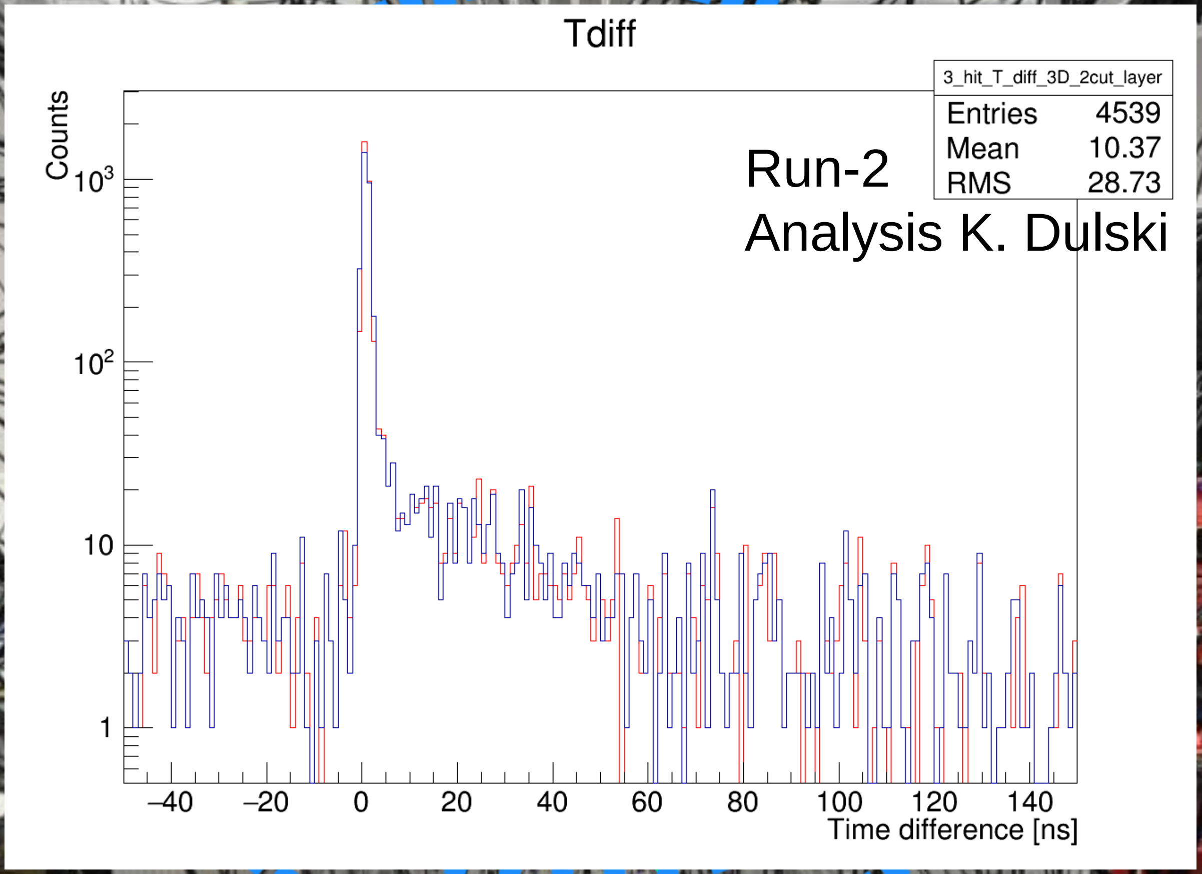


EXPERIMENT Run-1

analysed by K. Kacprzak

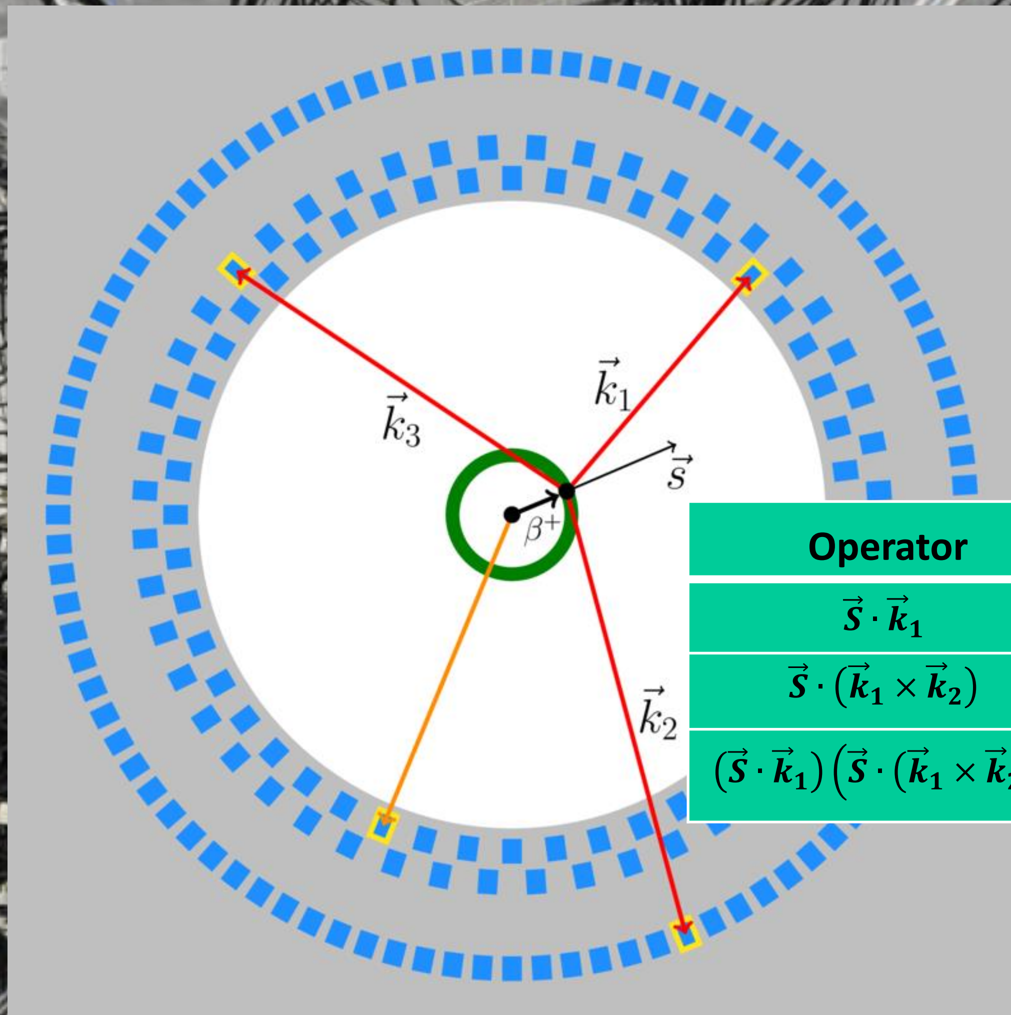


Jagiellonian PET



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

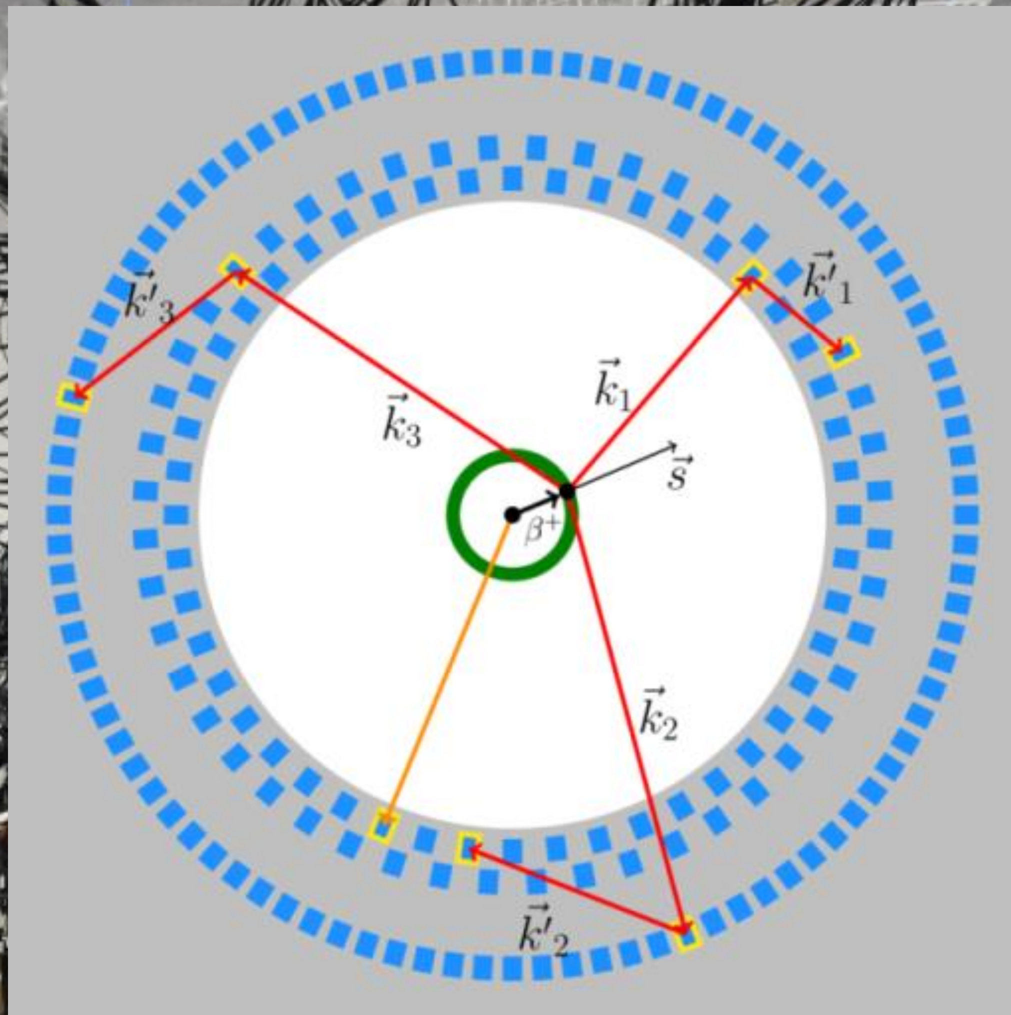
Jagiellonian PET



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

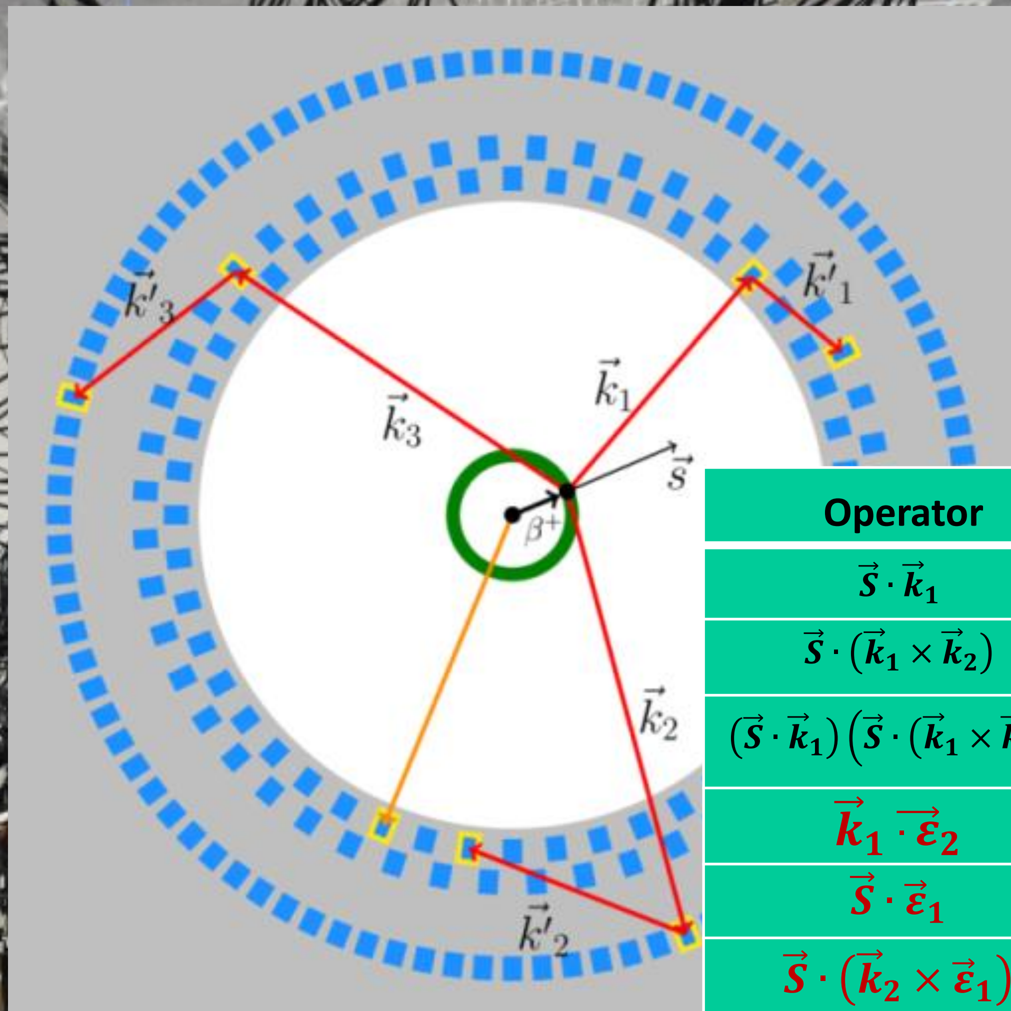
σ(t-hit) ~ 100 ps

Jagiellonian PET



$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$ **σ(t-hit) ~100 ps**

Jagiellonian PET



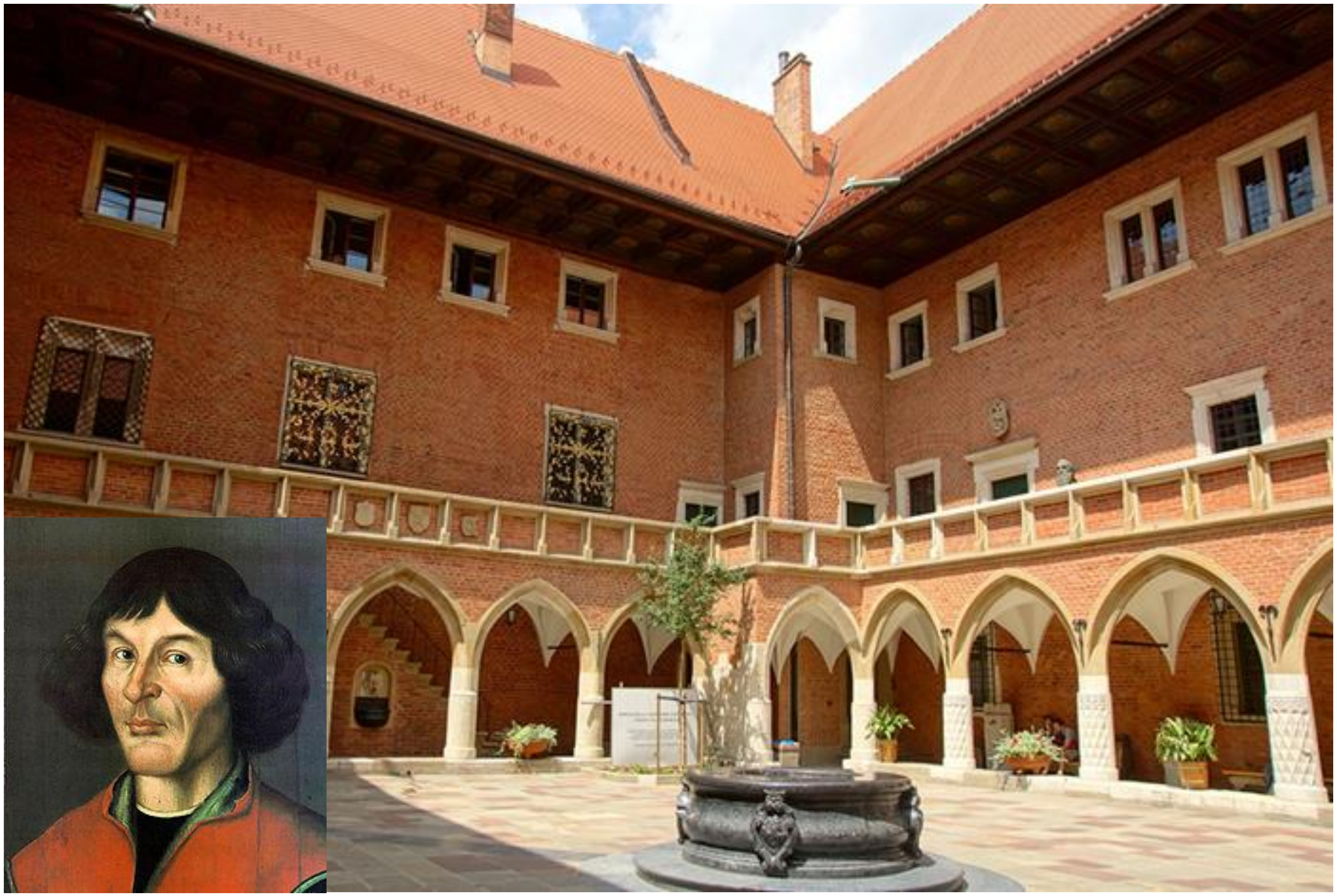
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	–	+	–	–
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	–	+	–
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	–	–	–	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$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

$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$ σ(t-hit) ~ 100 ps

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

Jagiellonian University

1364



Collegium Maius at the University since **1400**

Jagiellonian PET

Collegium Maius 2015

Jagiellonian PET

Cracow, July 2016

J-PET: First PET based on plastic scintillators

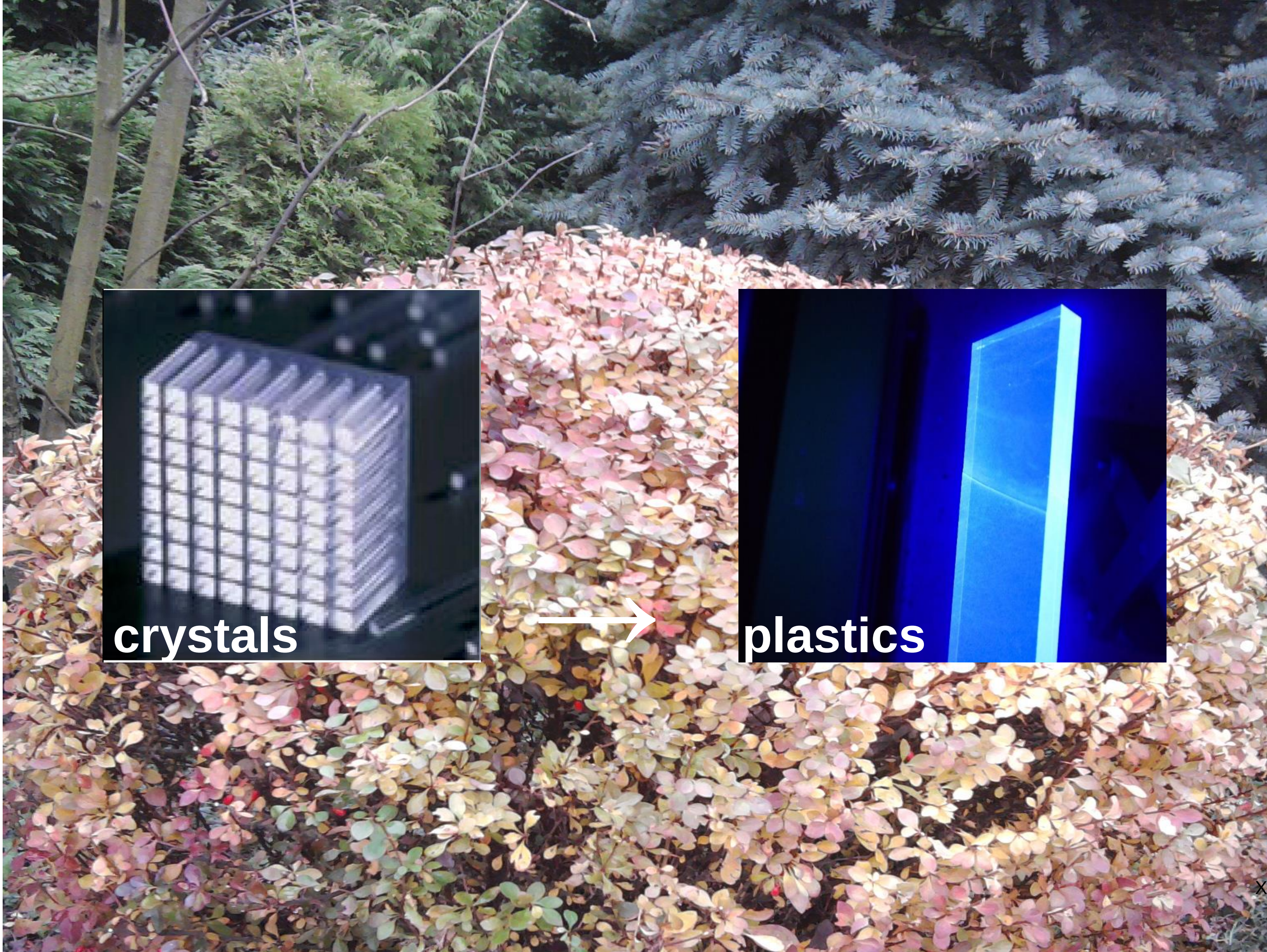
Jagiellonian-PET Collaboration:

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]

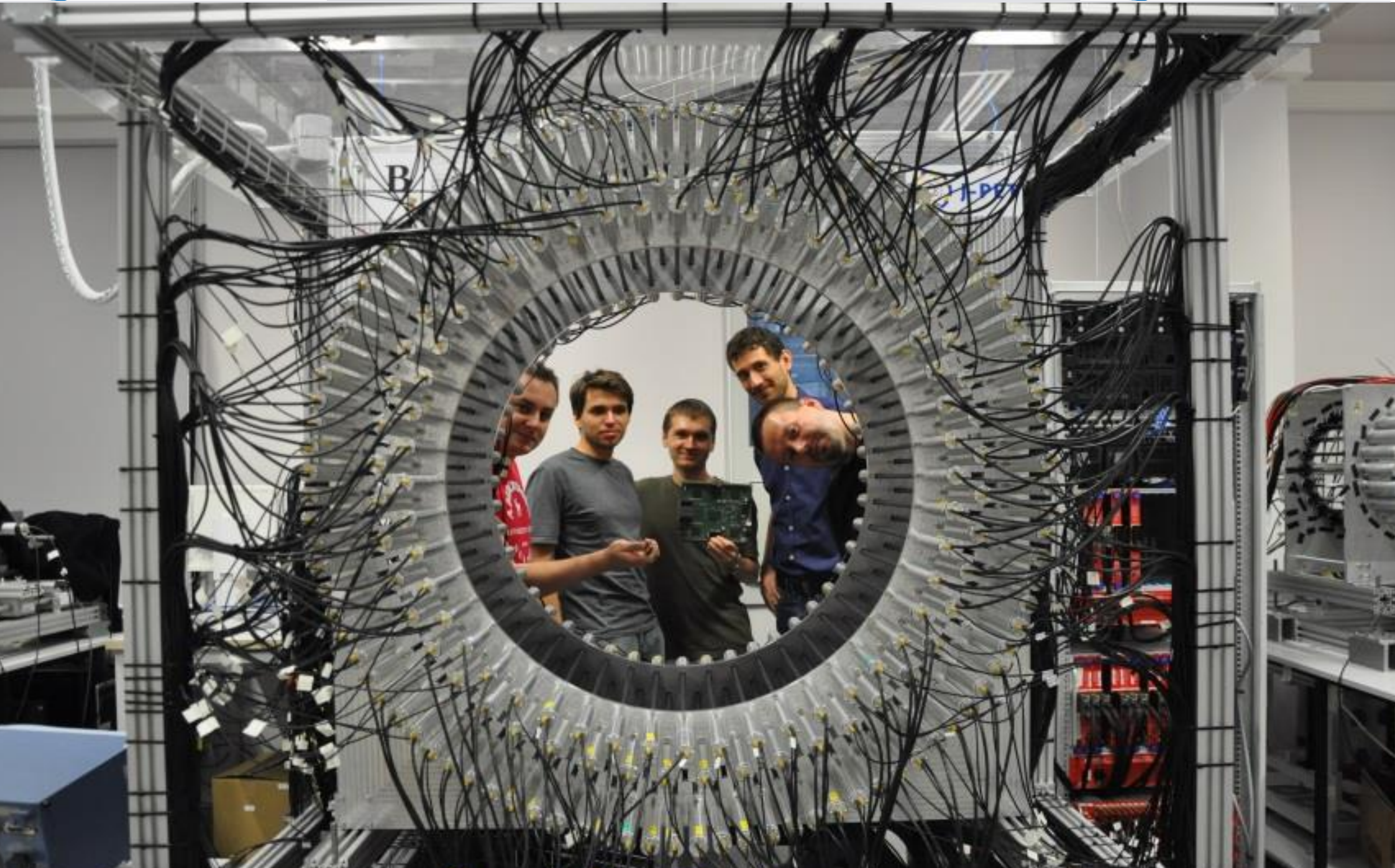
[1]Jagiellonian University, Poland; [2]LNF INFN, Italy; [3]Maria Curie-Skłodowska University, Poland; [4]University of Vienna, Austria; [5]National Centre for Nuclear Research, Poland;

Aim:

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

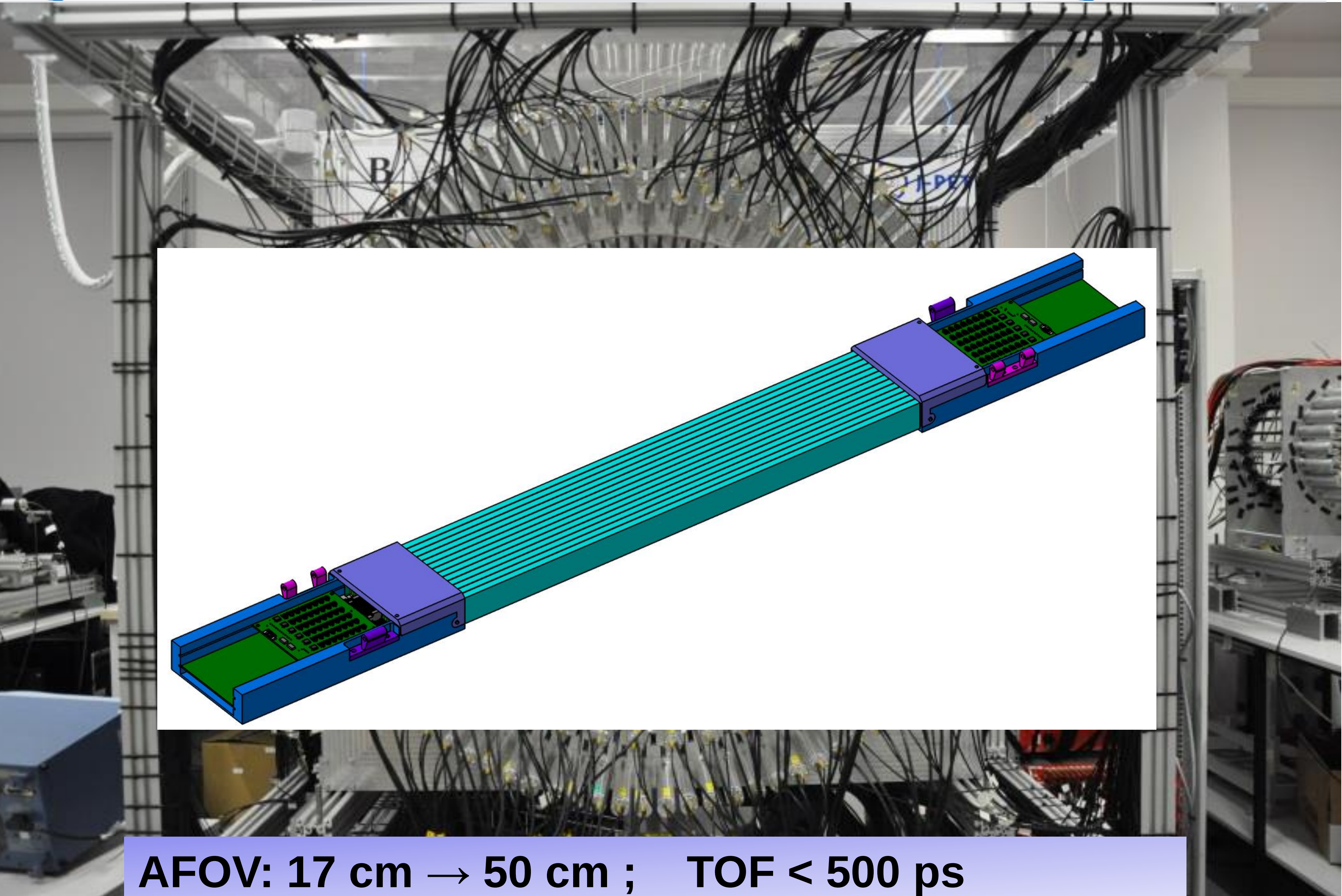

crystals
plastics

Jagielloński PET



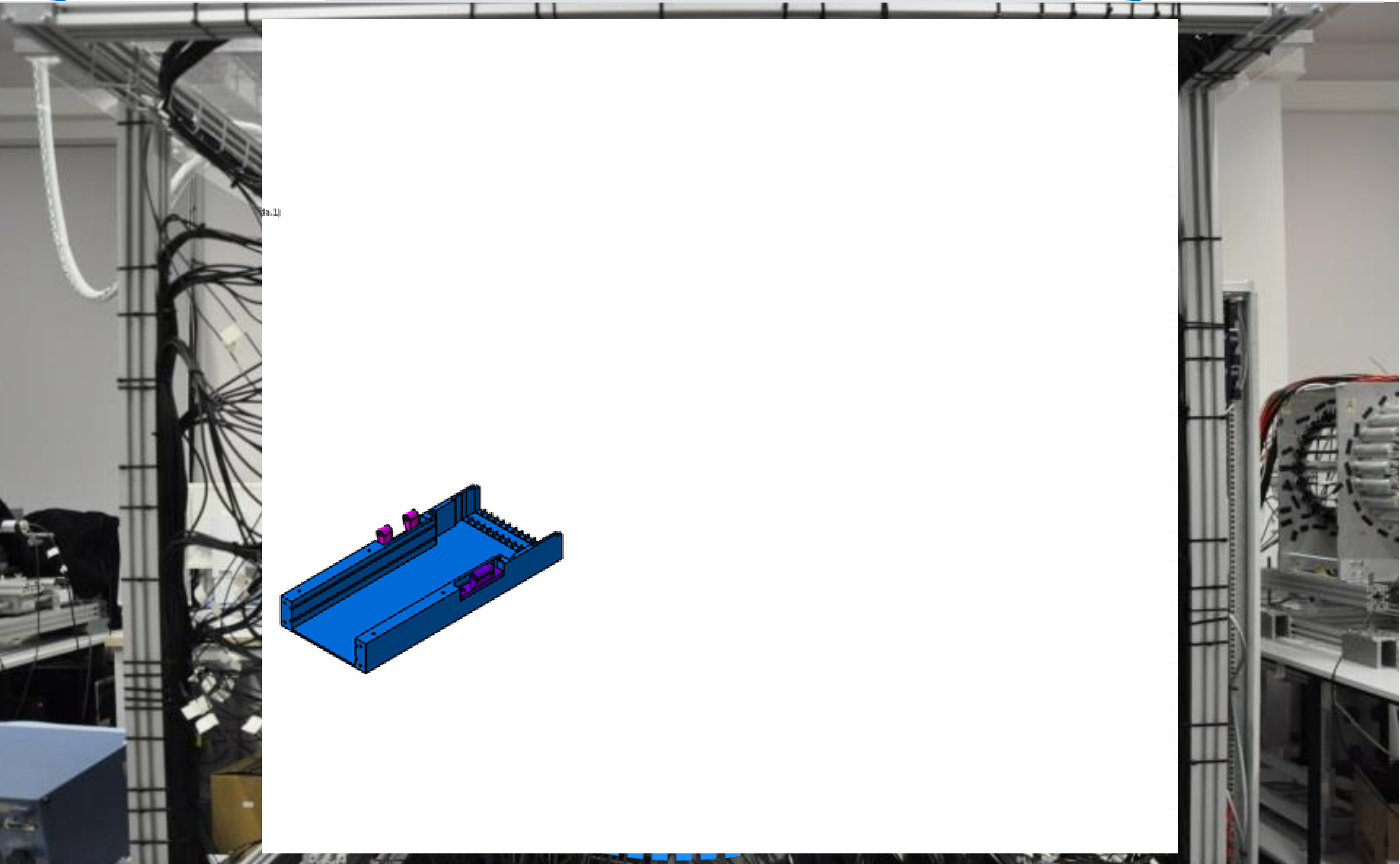
AFOV: 17 cm → 50 cm ;   TOF < 500 ps

Jagielloński PET

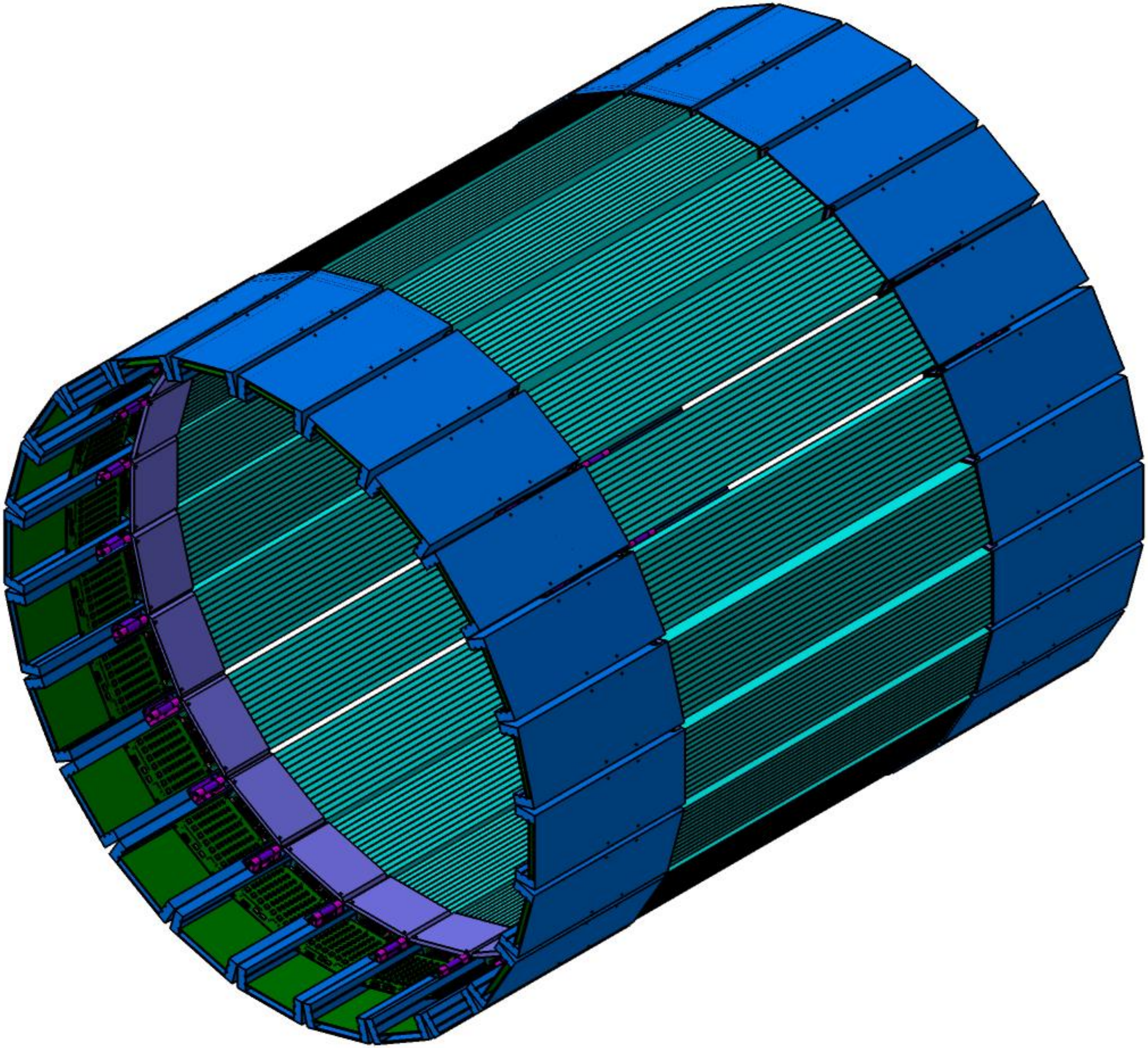


AFOV: 17 cm → 50 cm ;   TOF < 500 ps

Jagiellonian PET

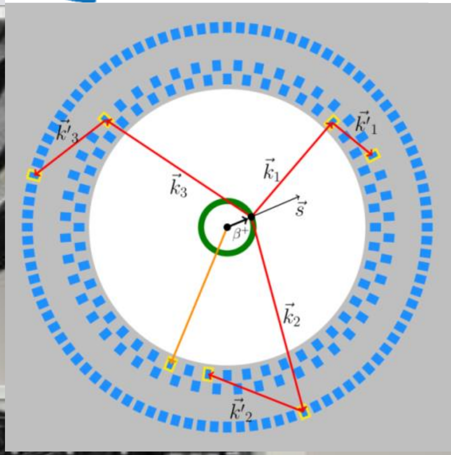


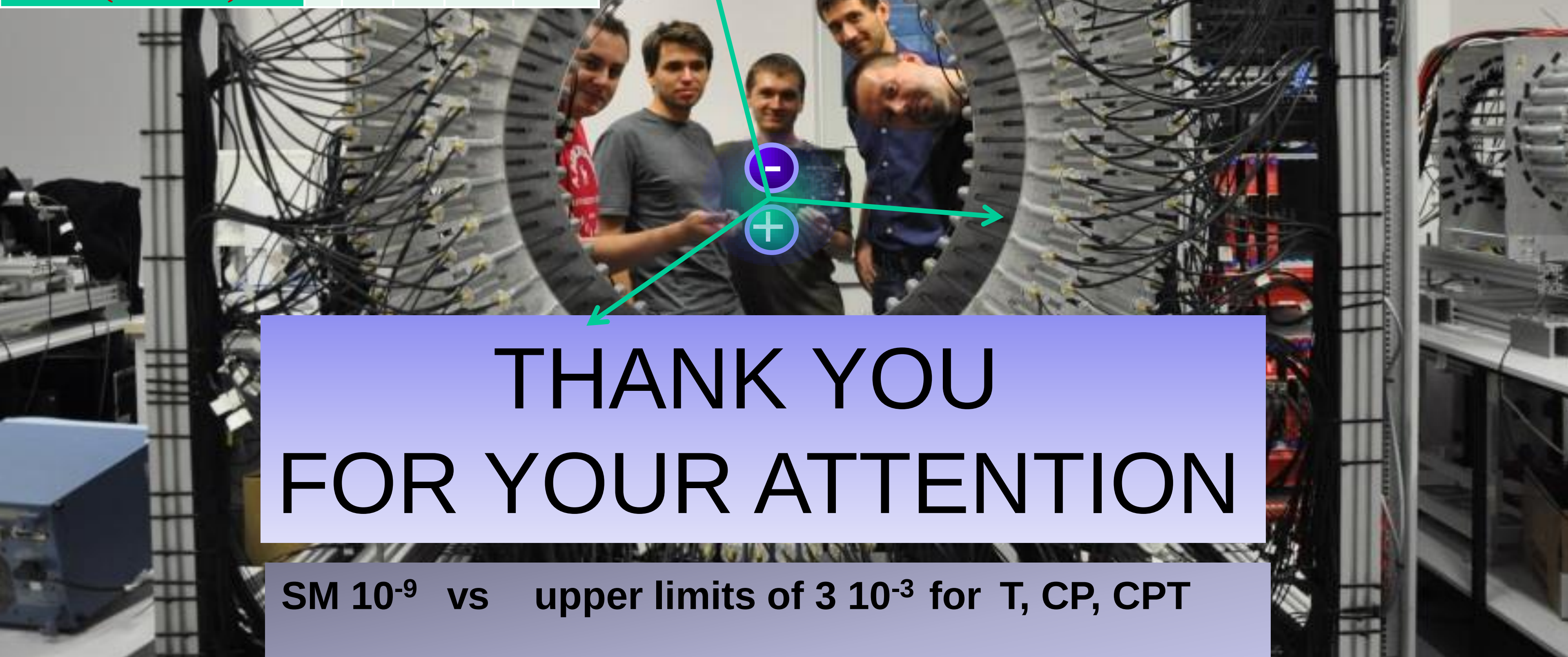
AFOV: 50 cm ;   TOF < 500 ps (FWHM)



Jagiellonian PET

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

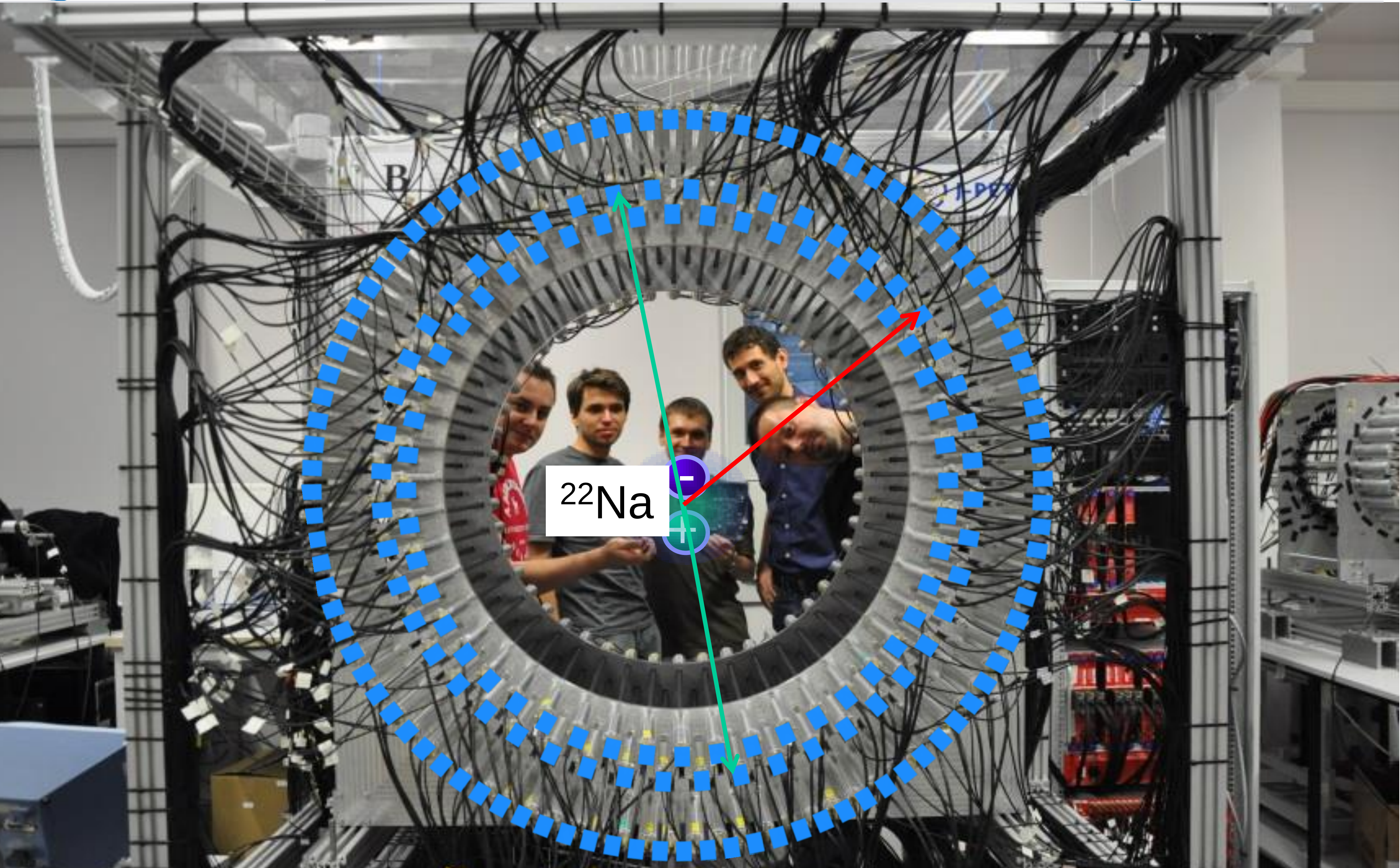




THANK YOU
FOR YOUR ATTENTION

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

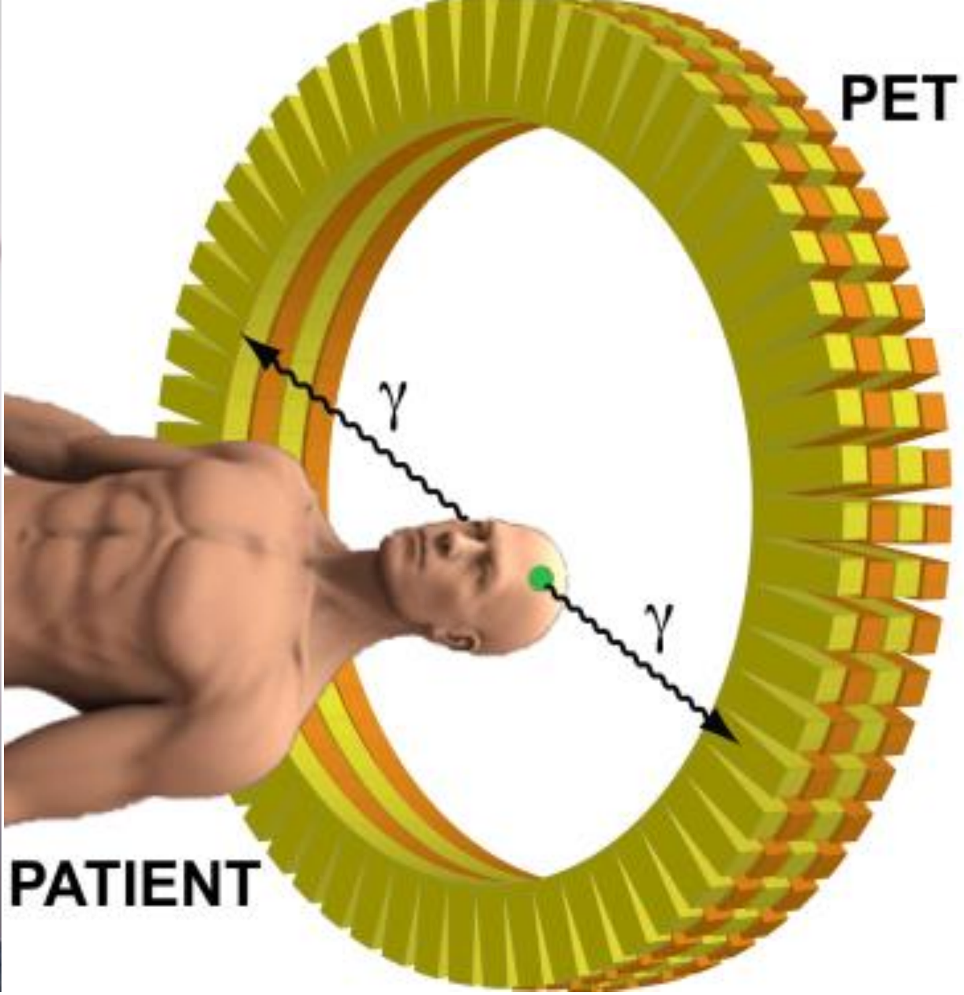
Jagiellonian PET



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

- Jagiellonian PET
- Positronium
- Discrete symmetries
- First J-PET runs

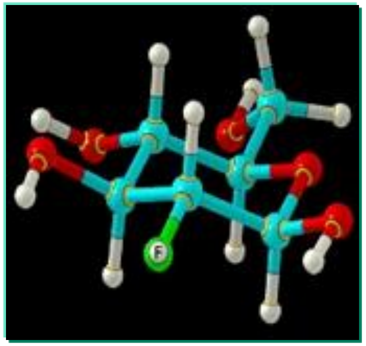
- **Jagiellonian PET**
- **Positronium**
- **Discrete symmetries**
- **First J-PET runs**



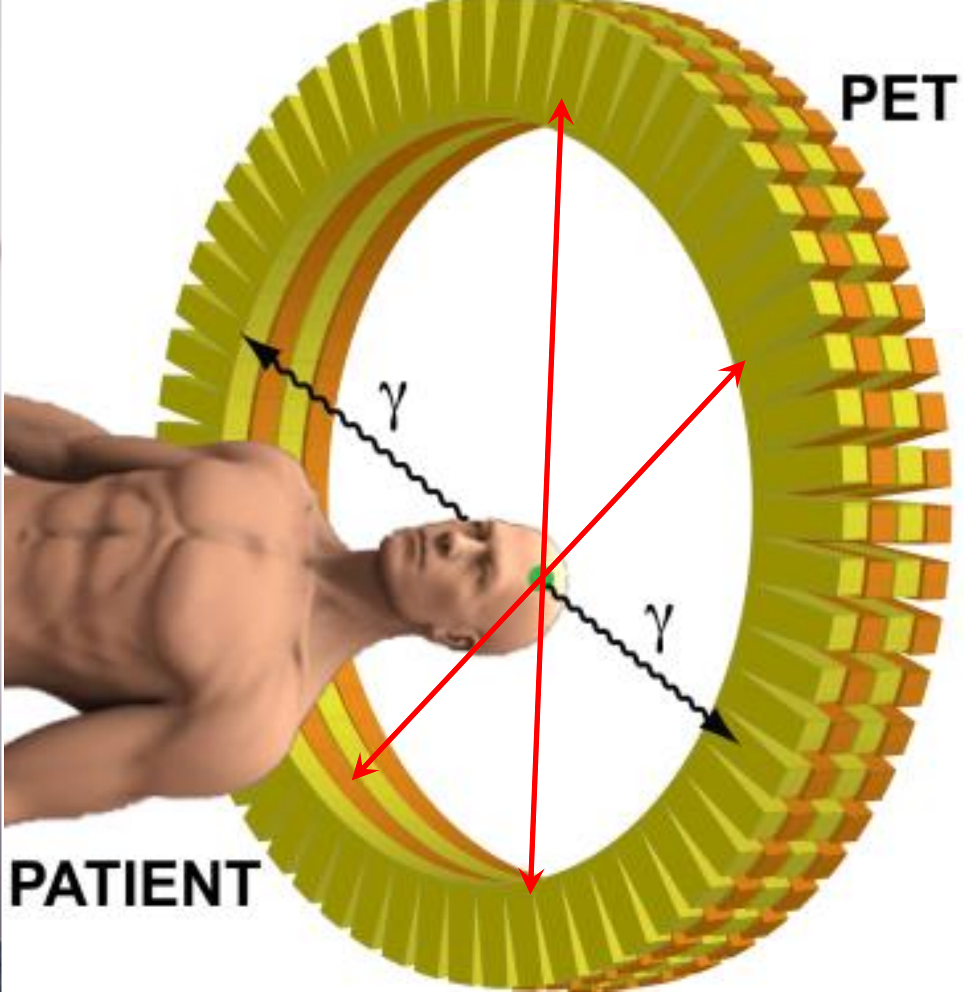
RADIOACTIVE SUGER

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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~200 000 000
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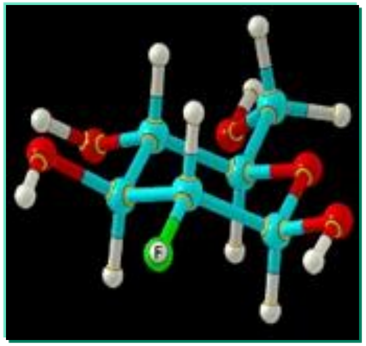

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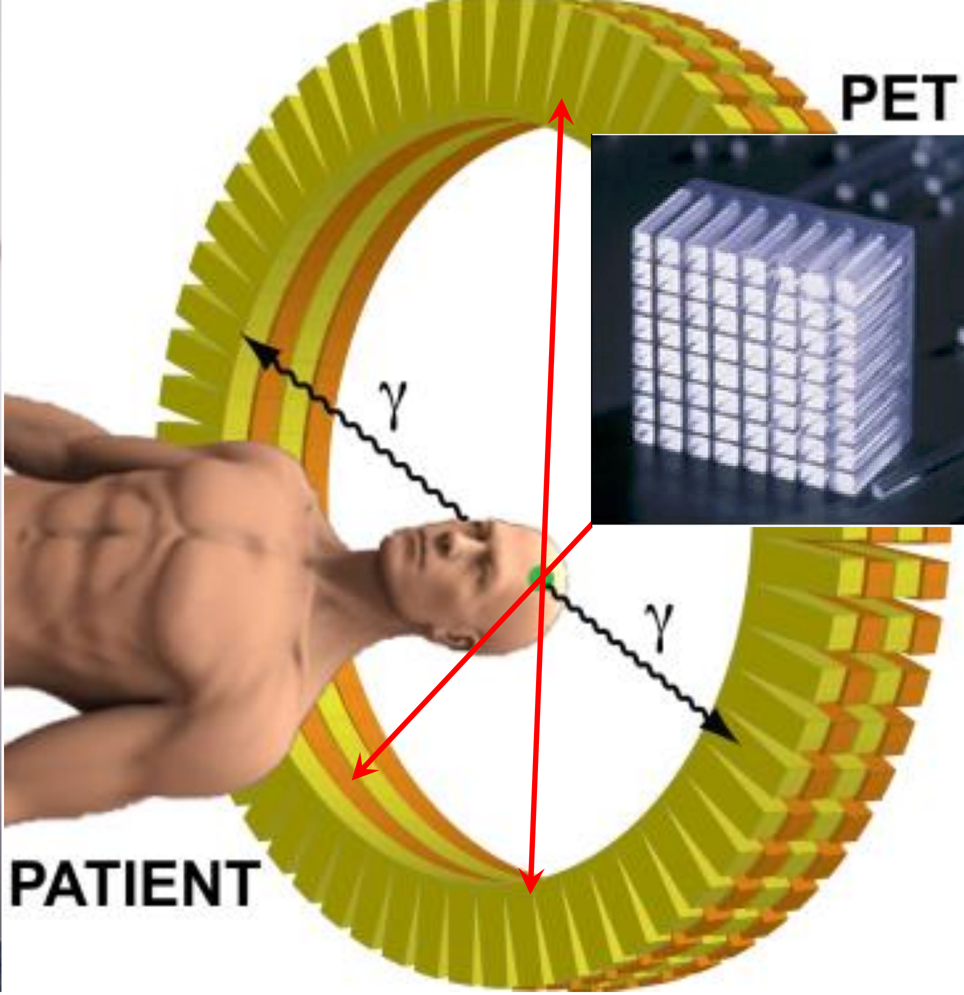
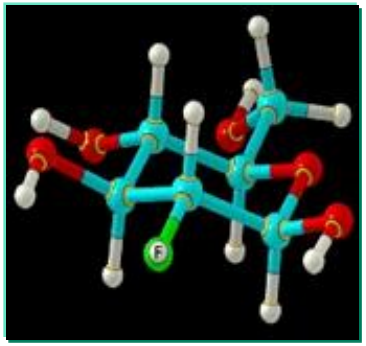


RADIOACTIVE SUGER

Fluoro–deoxy-glucose (F-18 FDG)

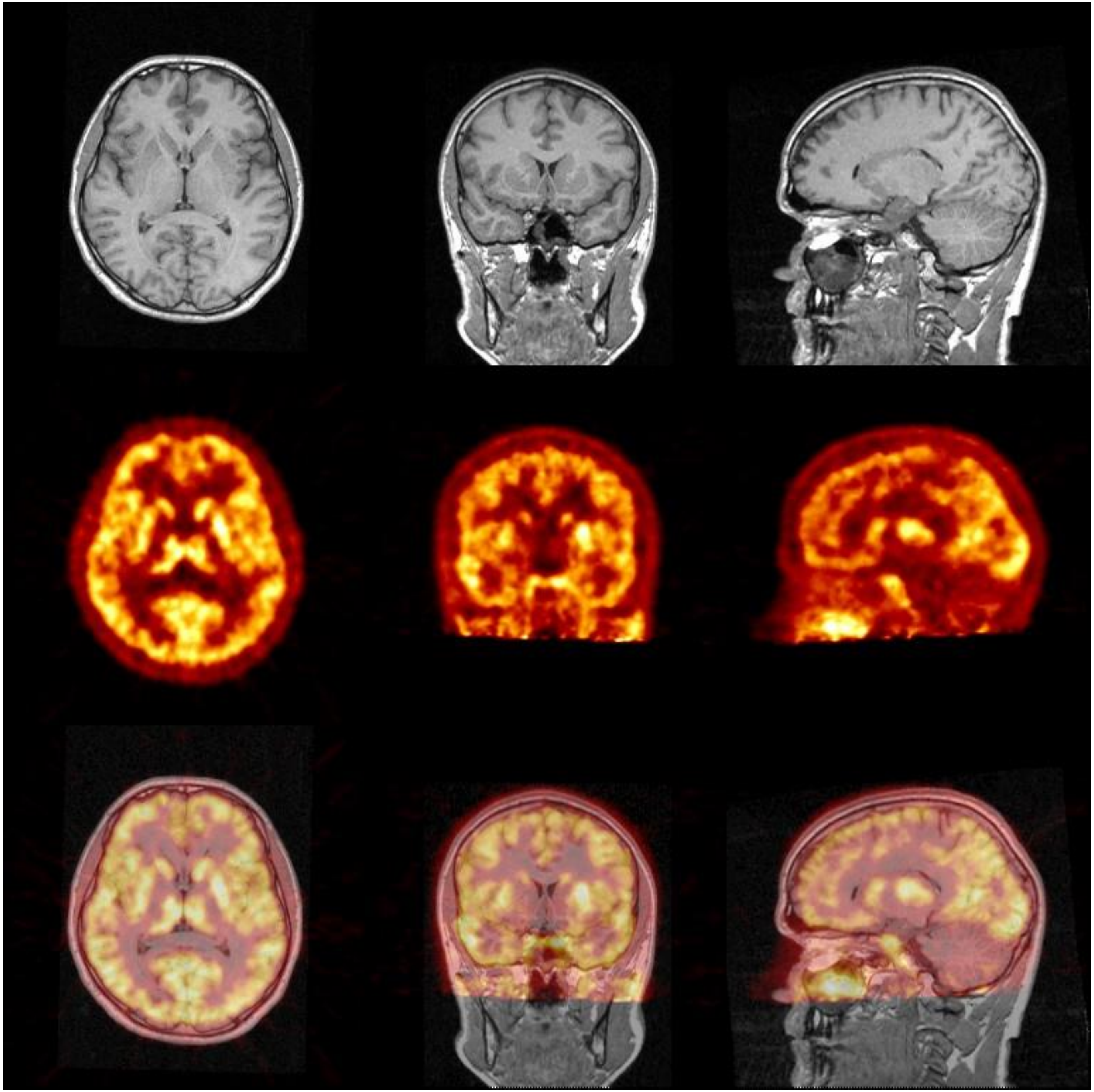
~200 000 000 gamma per second

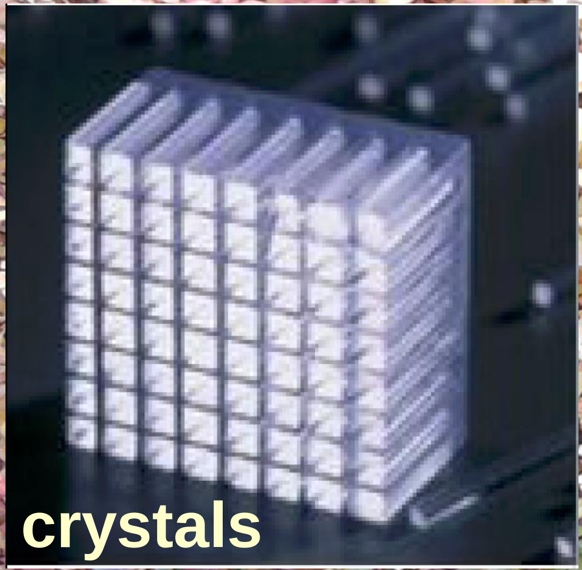


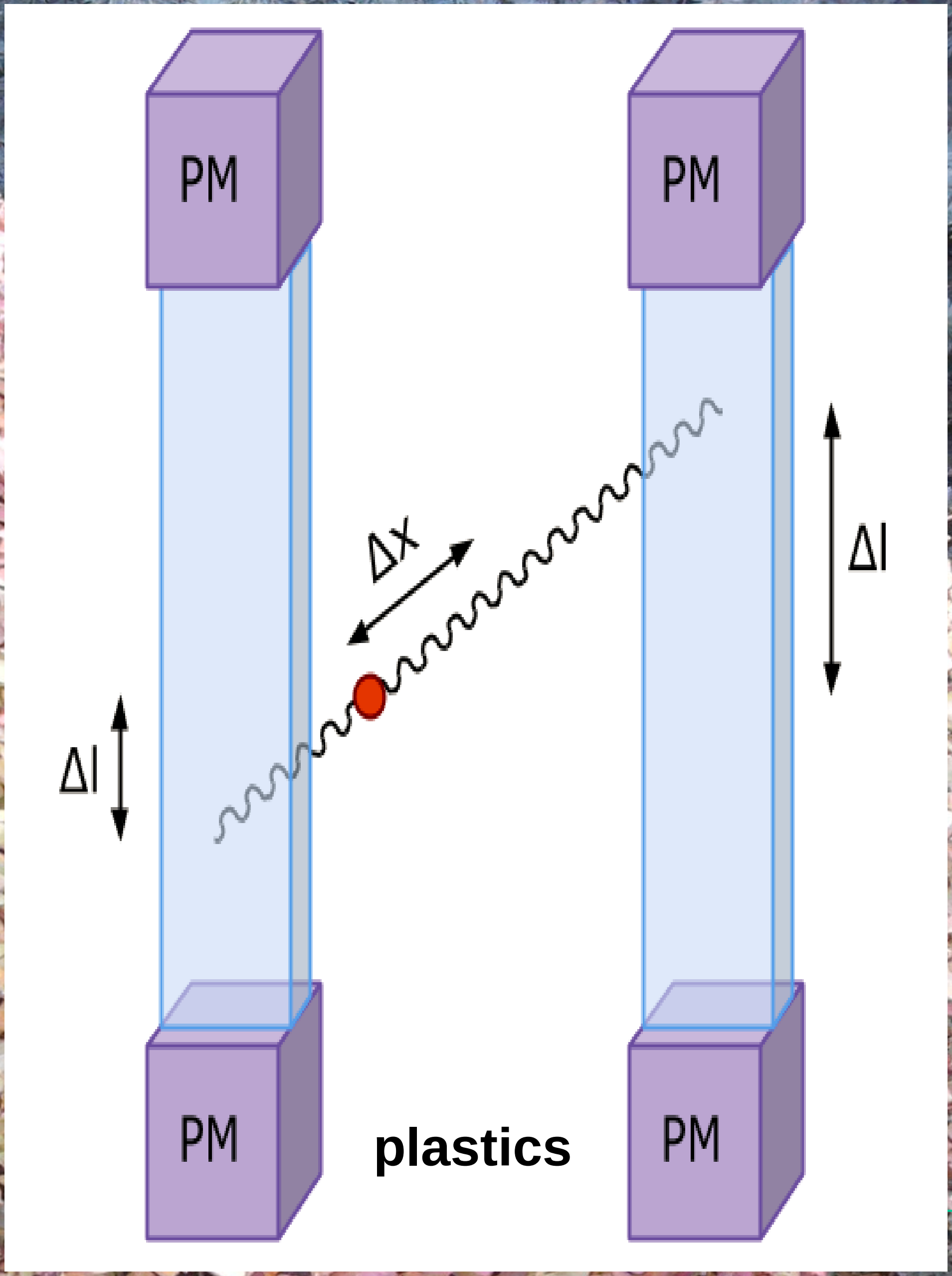
7 mSv PET/CT

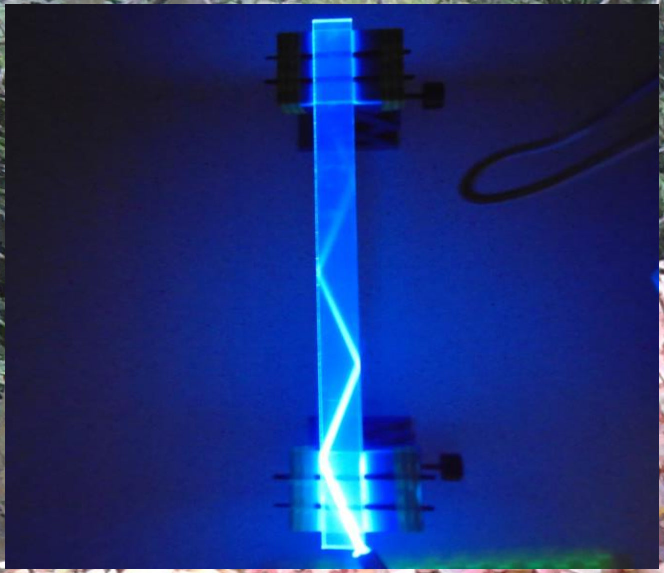
~ 2.5 mSv PET

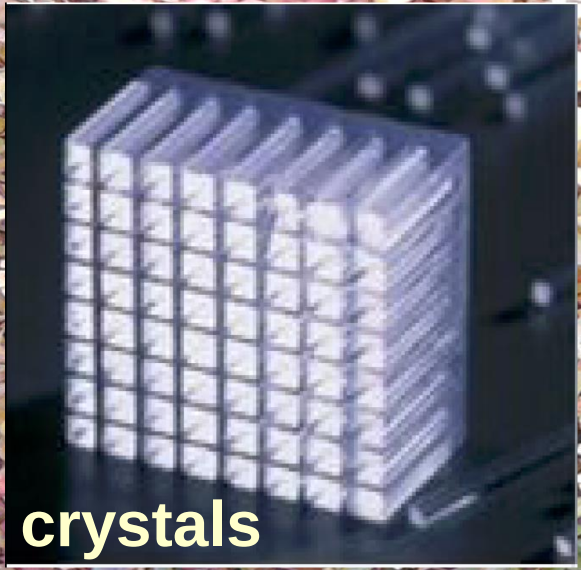
~3 mSv natural background in Poland

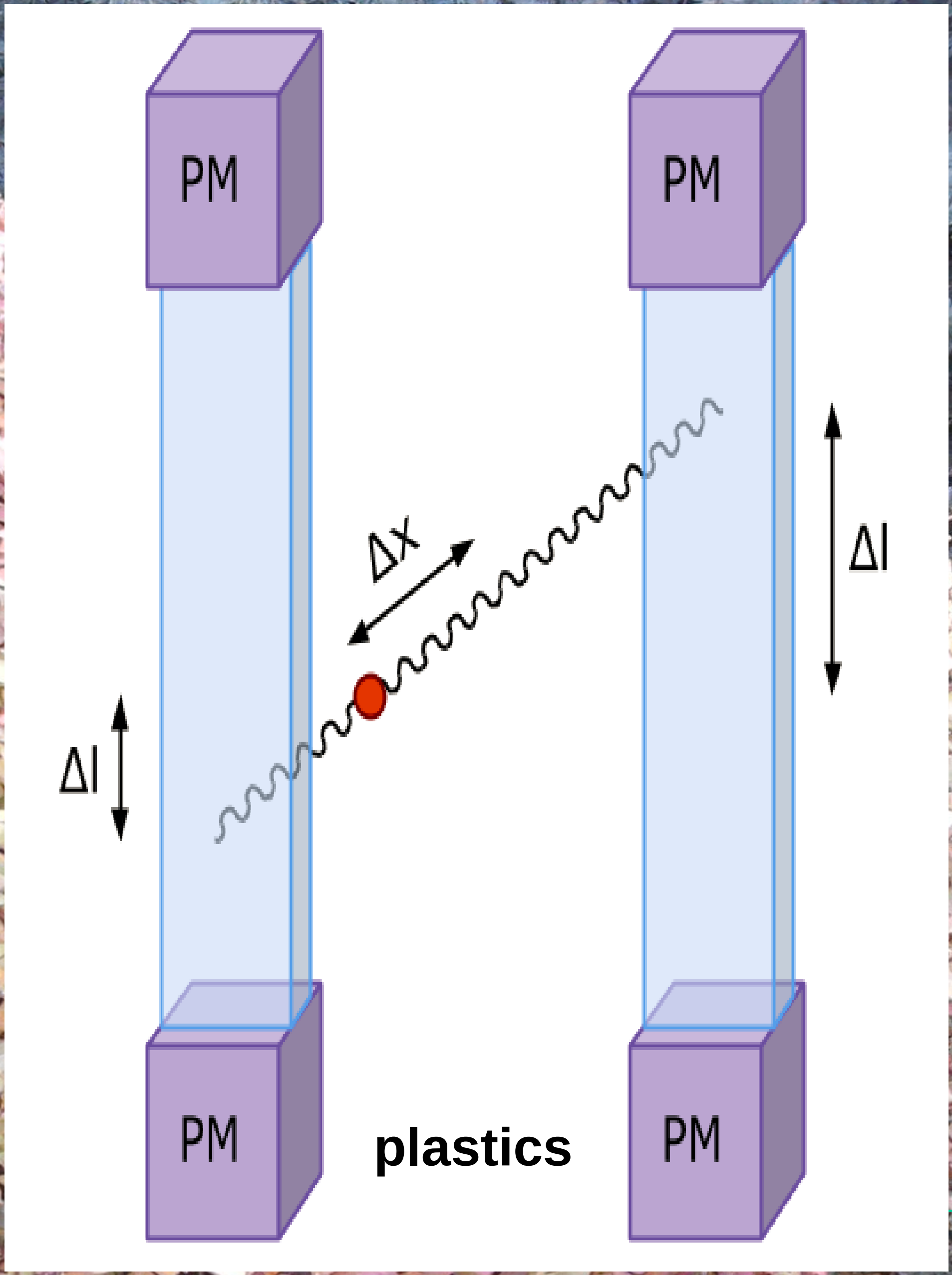



crystals

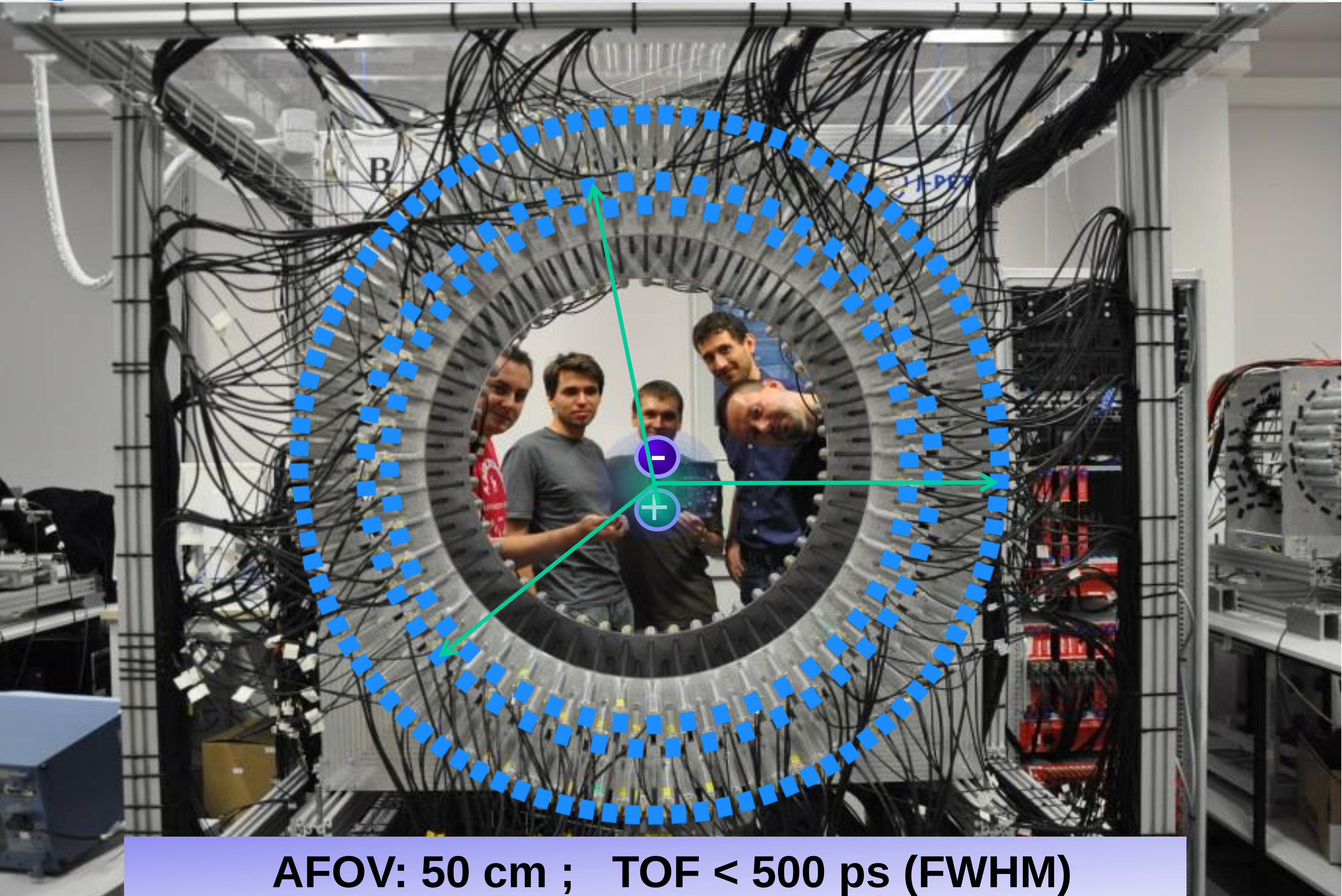

PM
PM
Δx
Δl
Δl
PM
plastics
PM



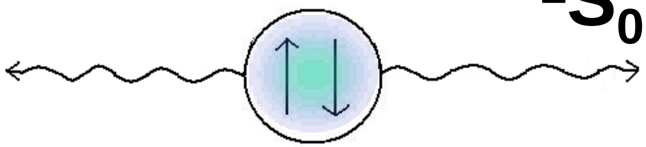

crystals


PM
PM
Δx
Δl
Δl
PM
plastics
PM

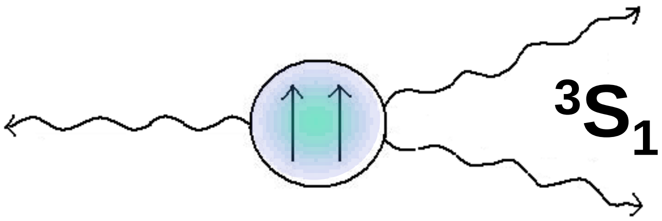
Jagiellonian PET



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

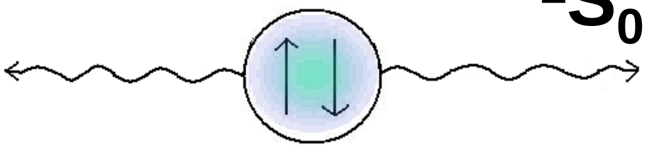


$^1S_0$ Para-positronium tau(p-Ps) ≈ 125 ps

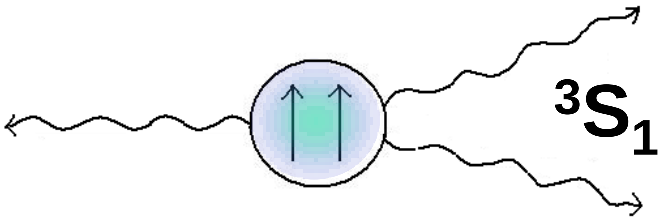


$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

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



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



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

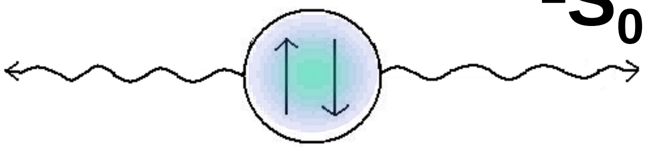
	$^1S_0$	$^3S_1$
L	0	0
S	0	1

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

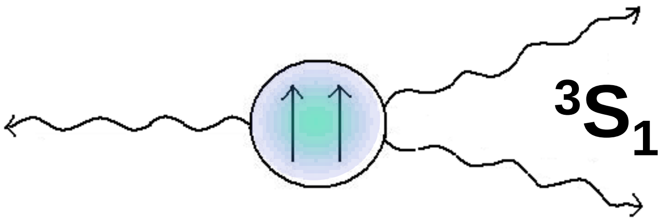
$\uparrow\uparrow$

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

$\downarrow\downarrow$



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



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

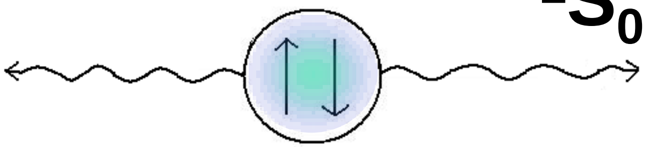
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-

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

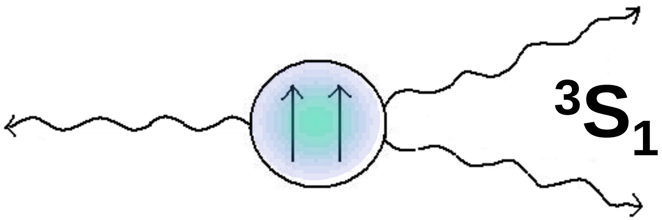
$\uparrow\uparrow$

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

$\downarrow\downarrow$



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



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

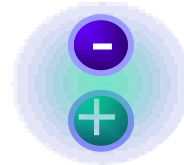
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-
L=0 -> P	-	-
CP	-	+

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

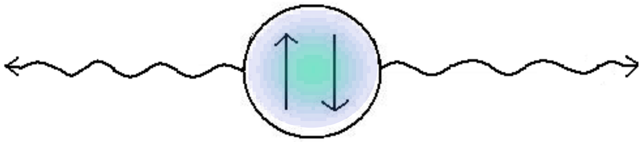
$\uparrow\uparrow$

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

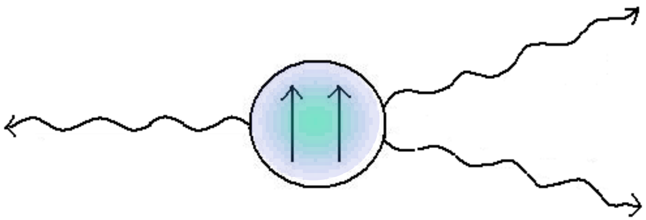
$\downarrow\downarrow$



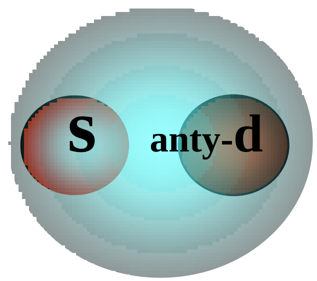
POSITRONIUM



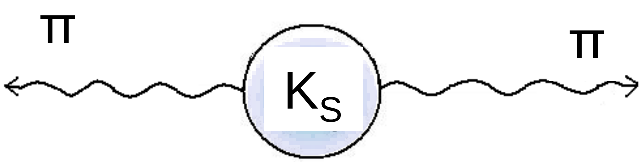
CP = + Para-positronium   tau(p-Ps) ≈ 125 ps



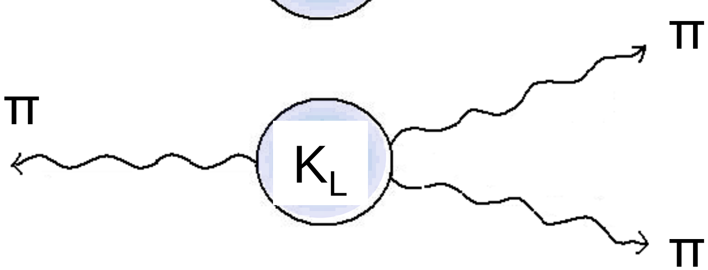
CP = - Ortho-positronium tau(o-Ps) ≈ 142 ns



MESON K

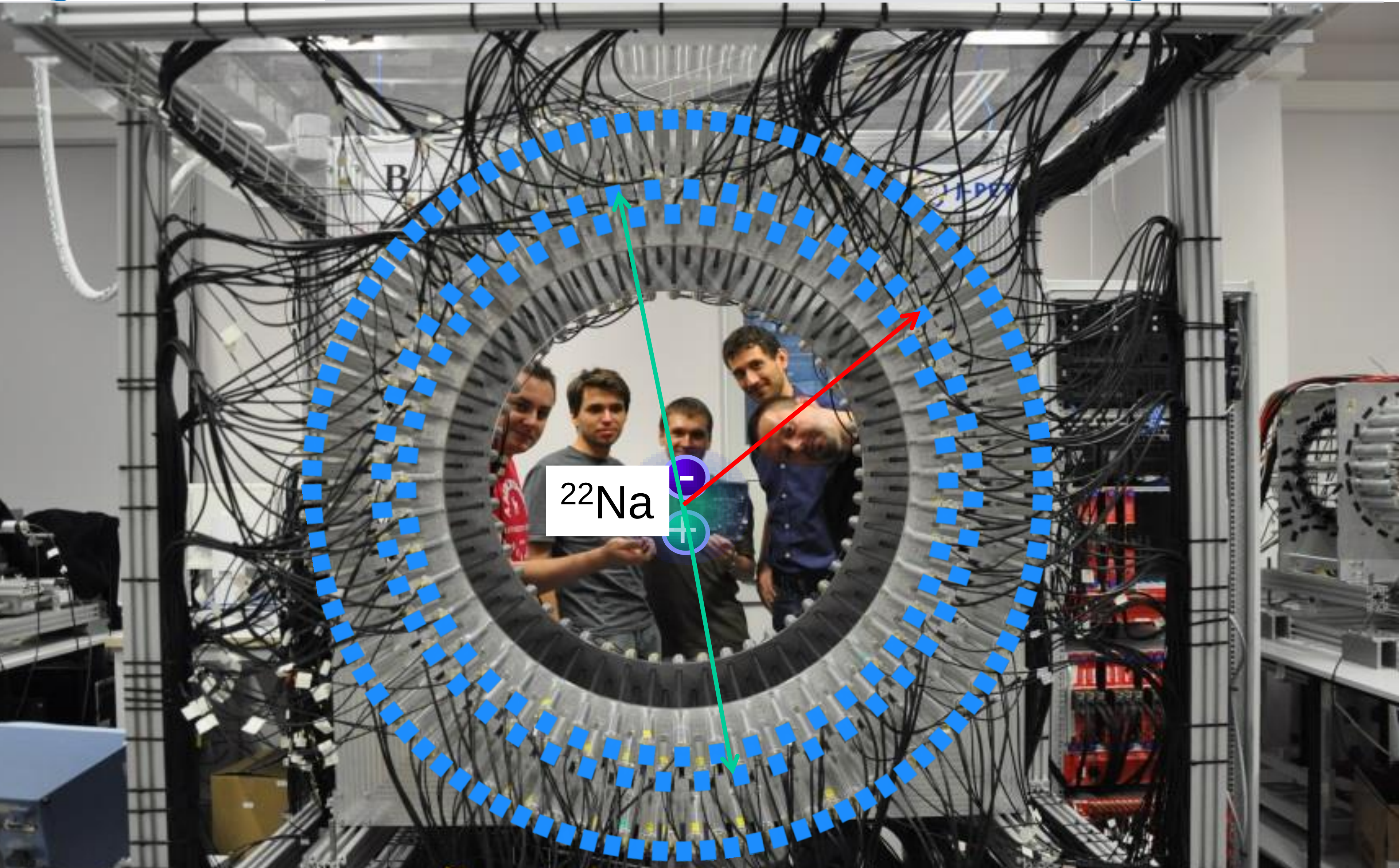


CP ~= +   tau(K_S) ≈ 90 ps

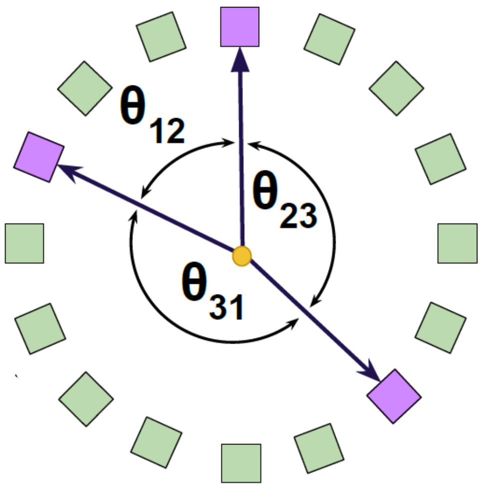


CP ~= -   tau(K_L) ≈ 52 ns

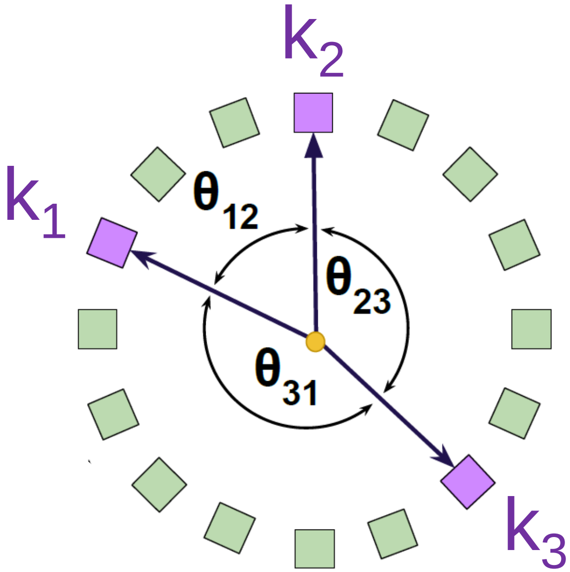
Jagiellonian PET



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

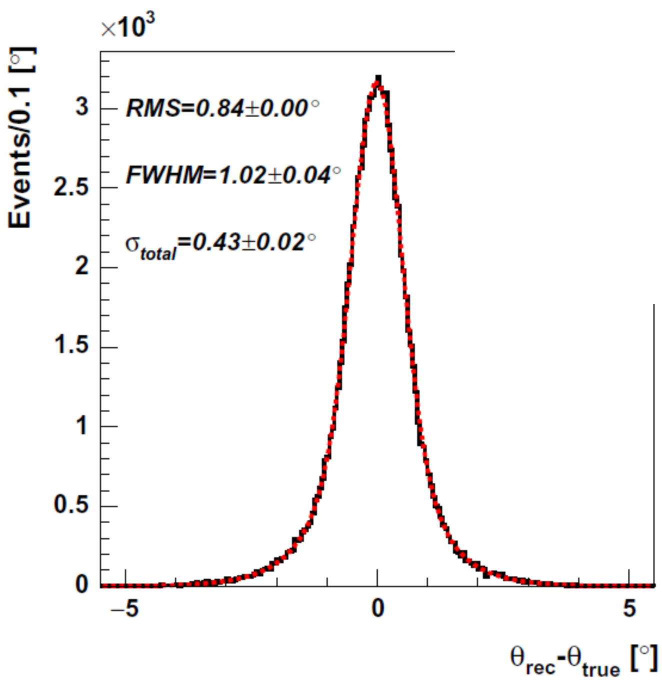


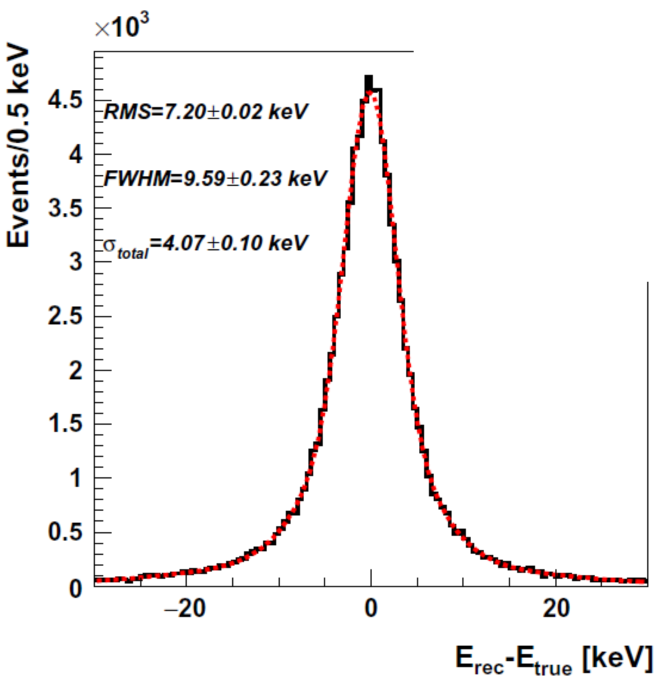
o-Ps → 3γ



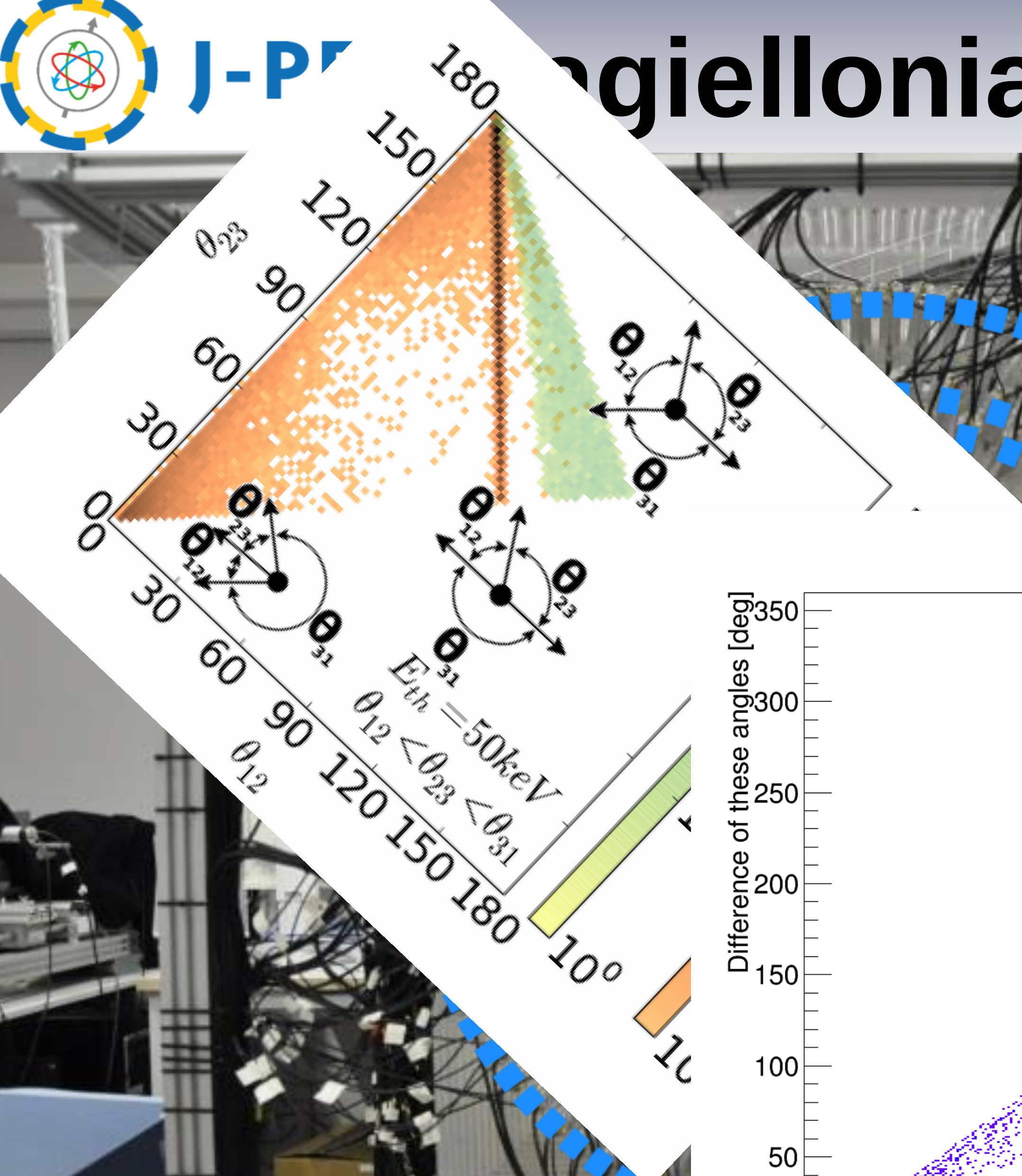
o-Ps → 3γ

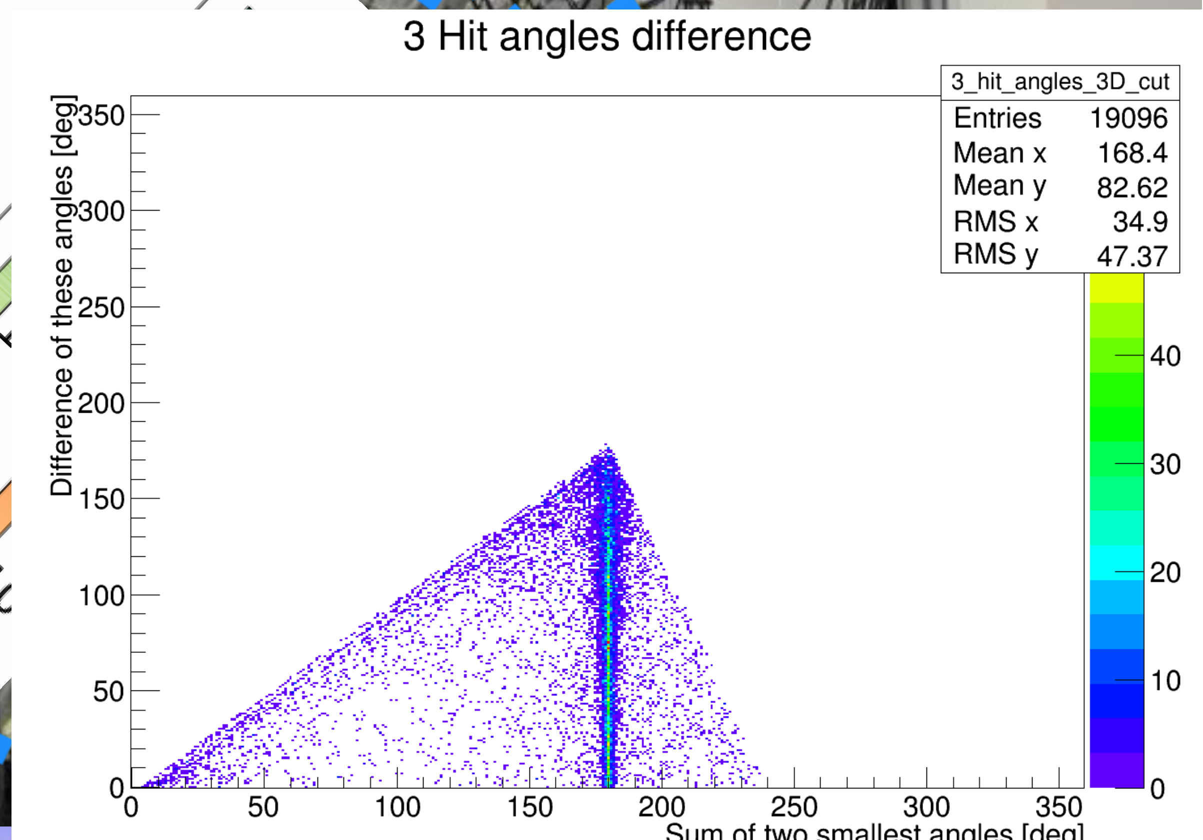
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445





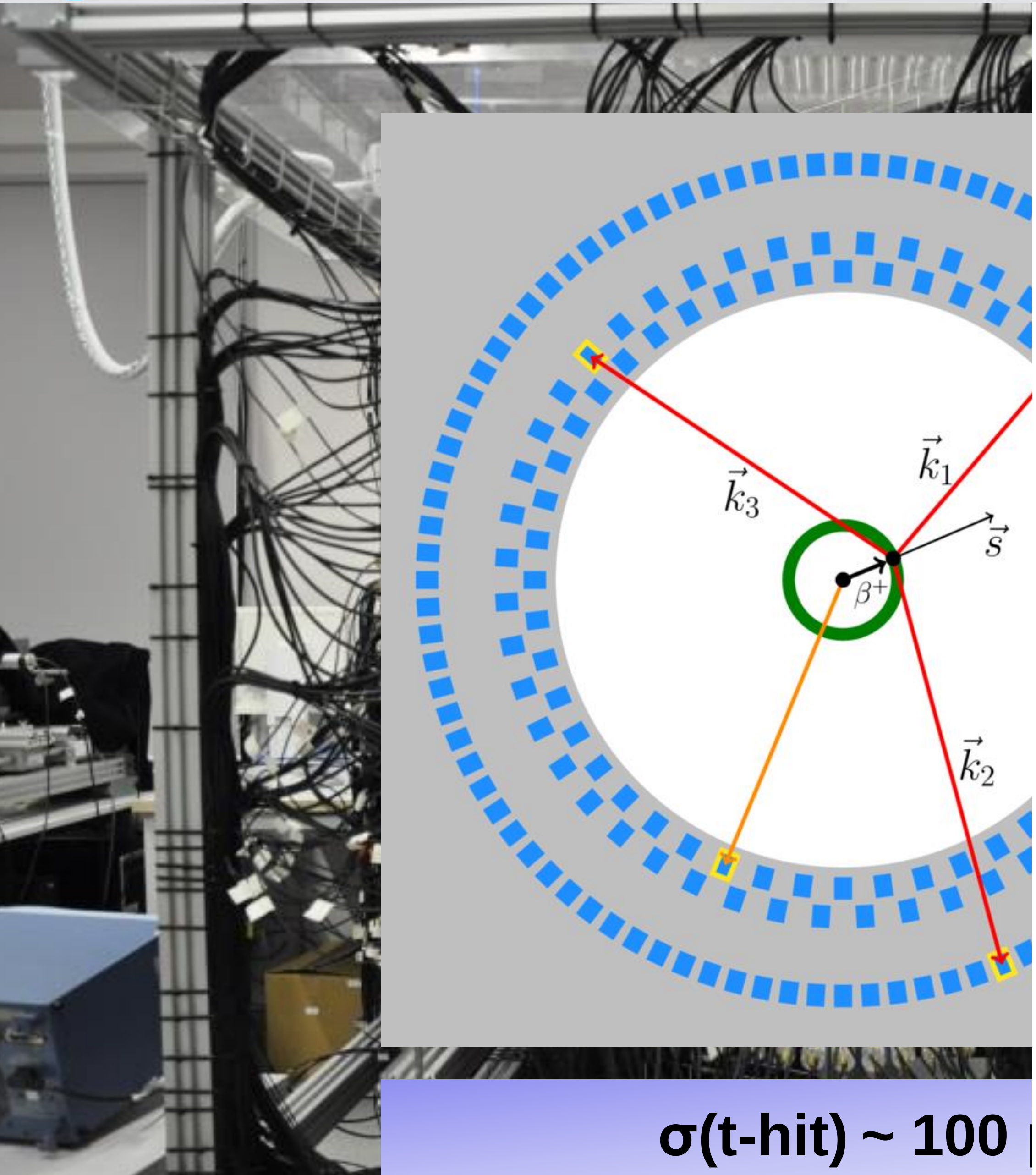
giellonian PET

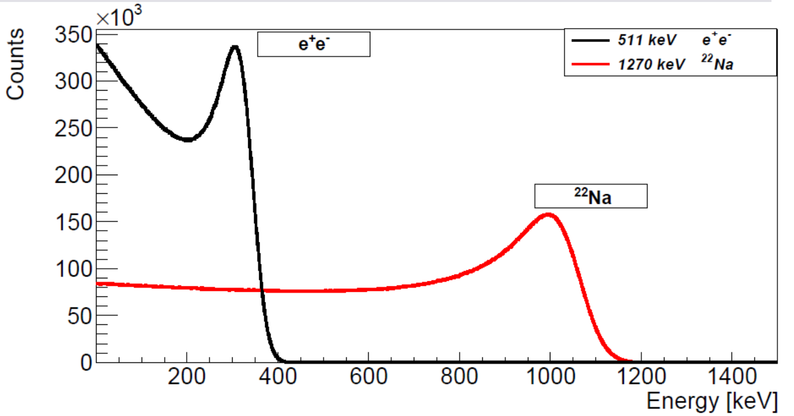


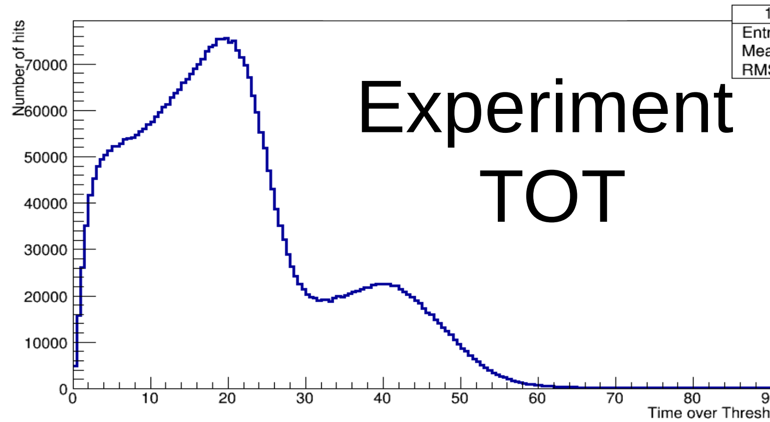


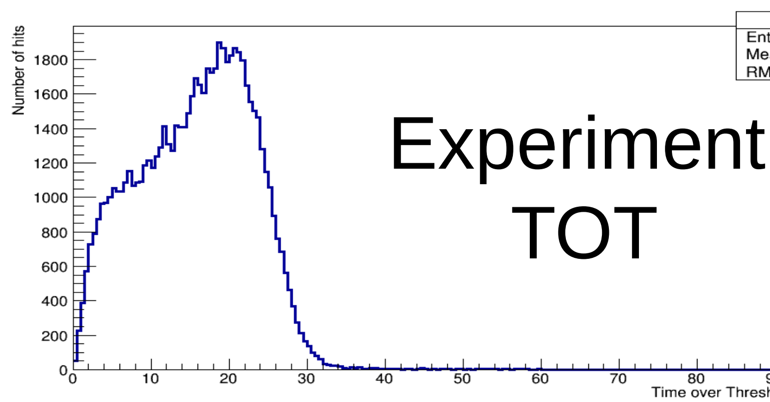
AFOV: 50 cm ; TOF < 500 ps (FWHM)

Jagiellonian PET



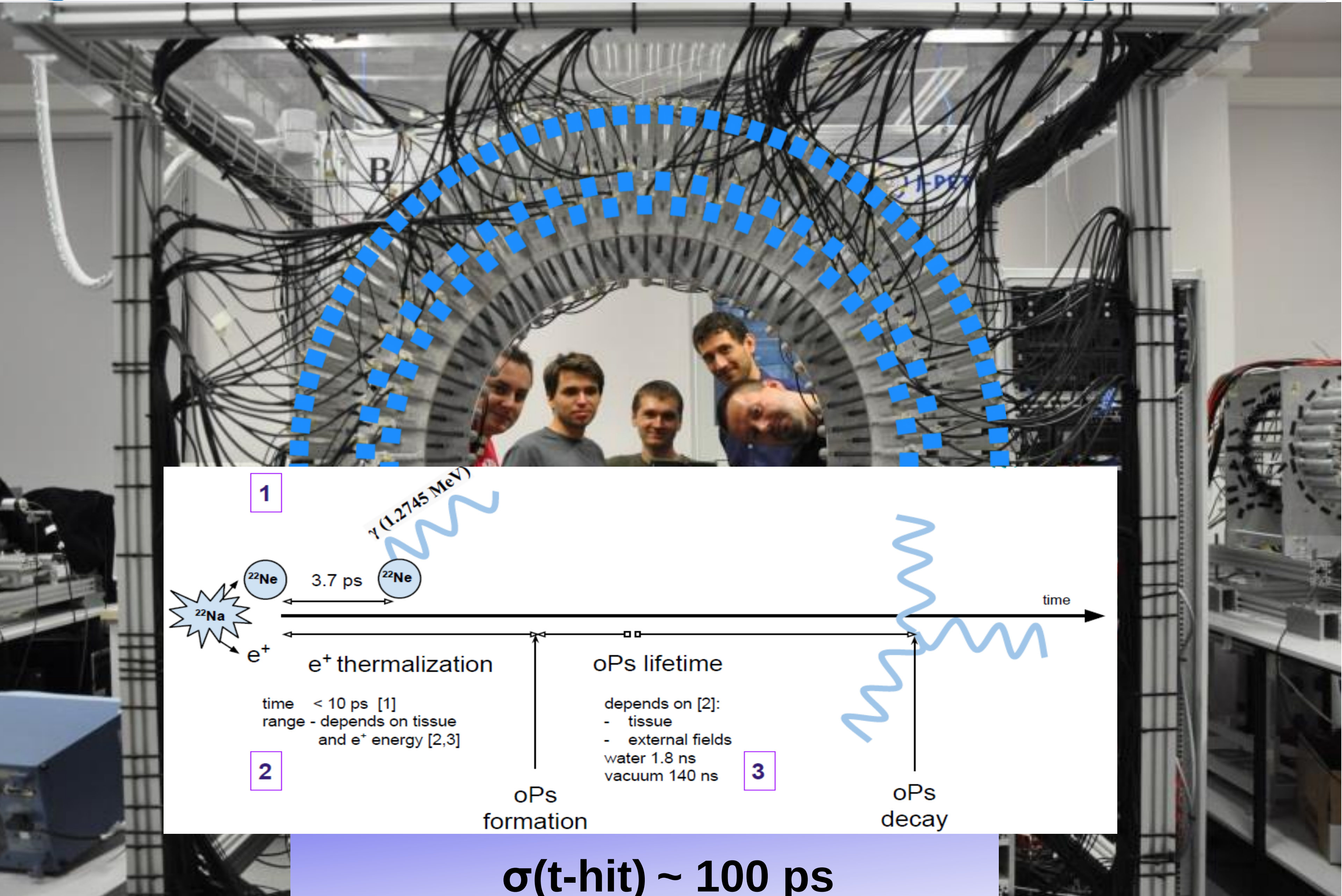




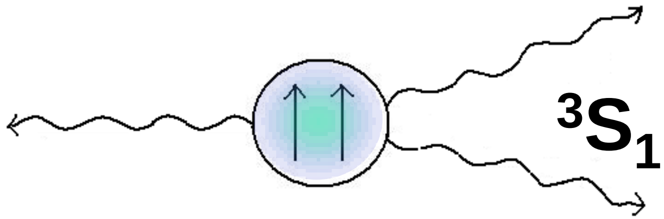


σ(t-hit) ~ 100

Jagiellonian PET



σ(t-hit) ~ 100 ps



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

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

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

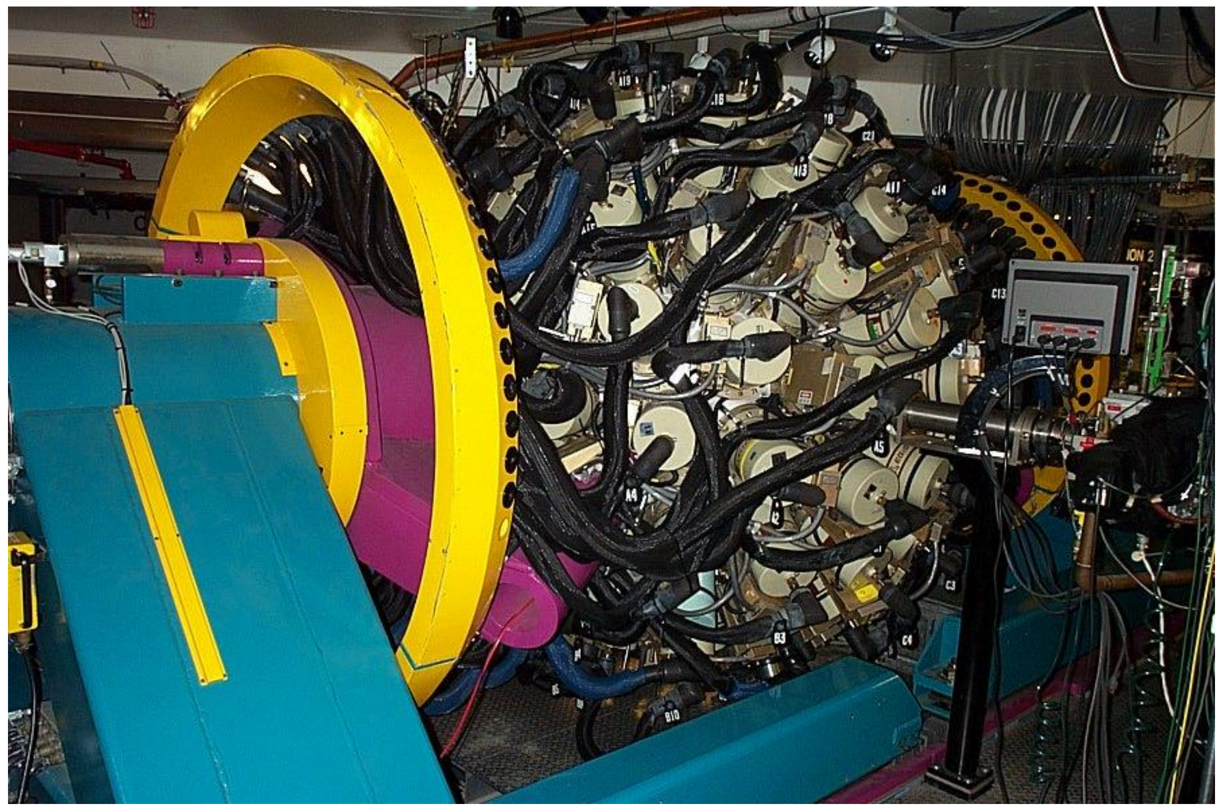
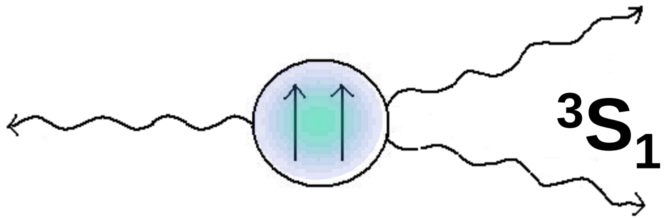


Figure taken form the presentation of P. Vetter, INT UW Seattle, November, 2002



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

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

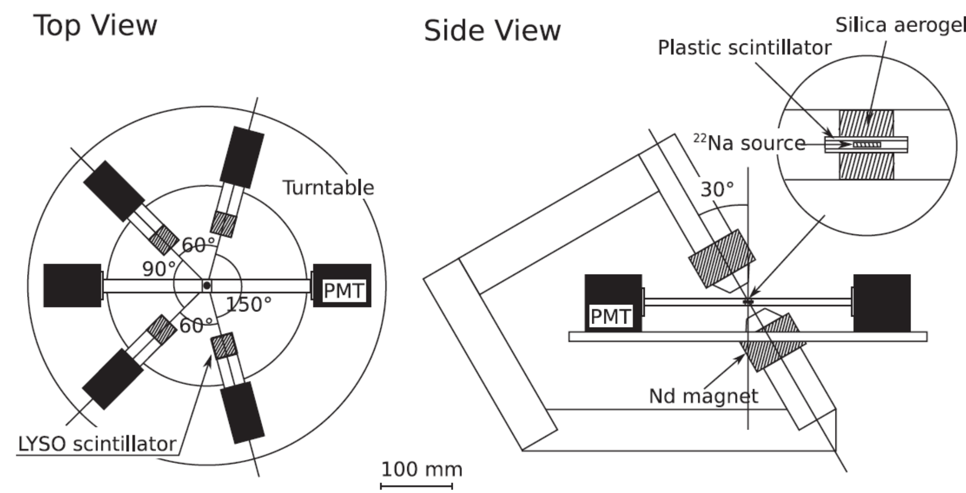
So far best accuracy for
CP violation was reported by
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

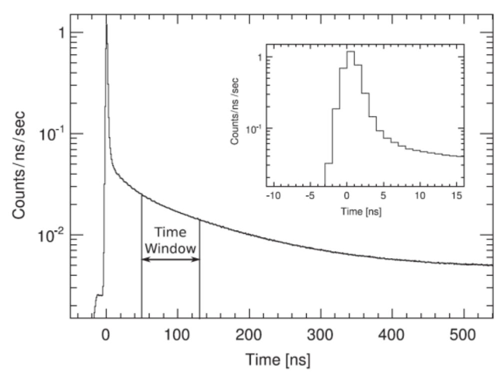
-0.0023 < C_CP < 0.0049 at 90% CL

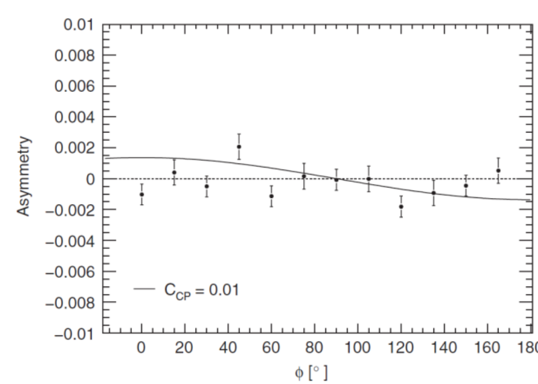
vs

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)

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

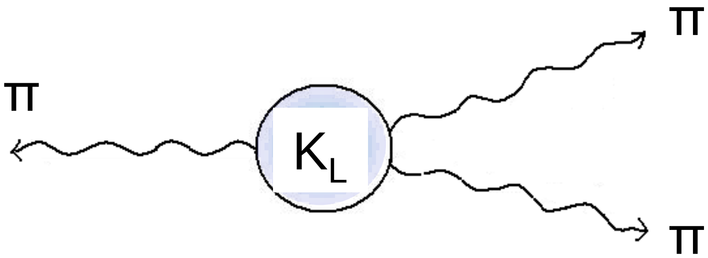


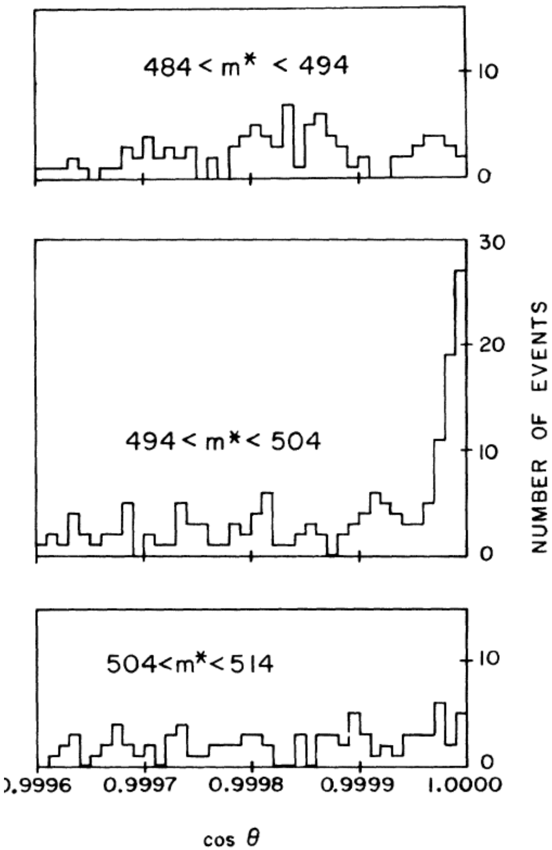


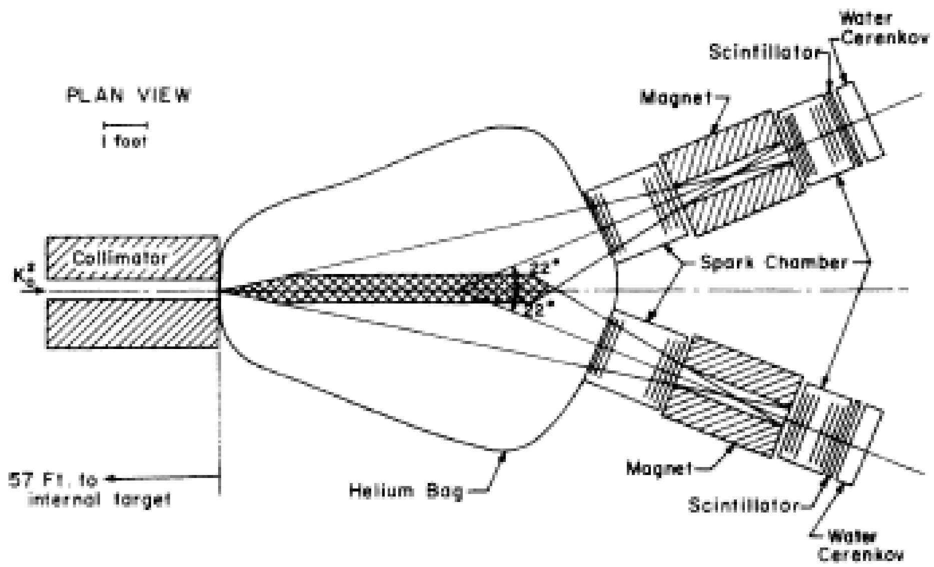


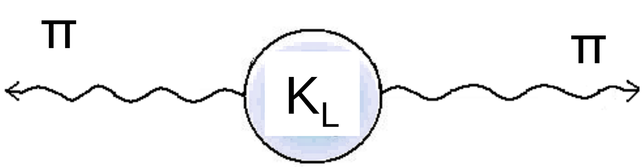
V.L.Fitch, R.Turlay, J.W.Cronin , J.H.Christenson

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









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

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

53 years later ....

Breaking of T and CP observed but only for processes involving quarks
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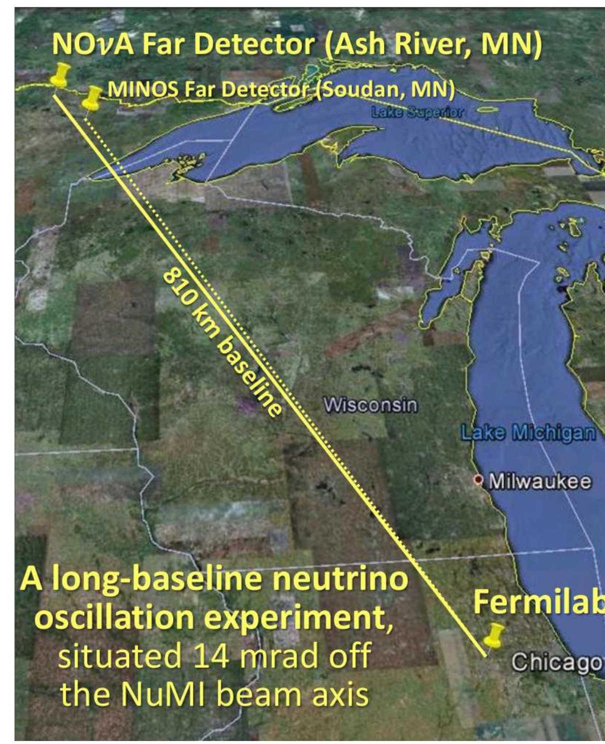
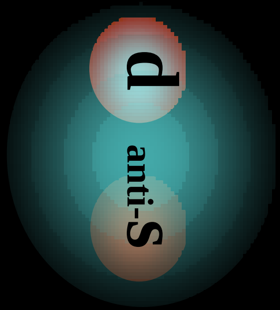
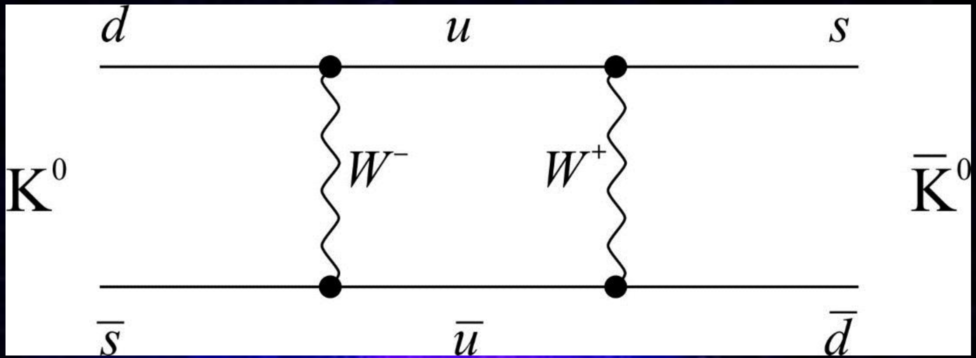
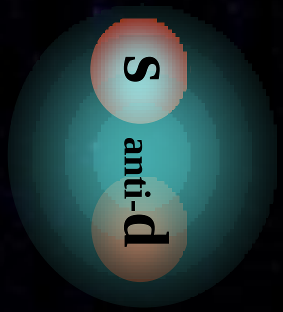




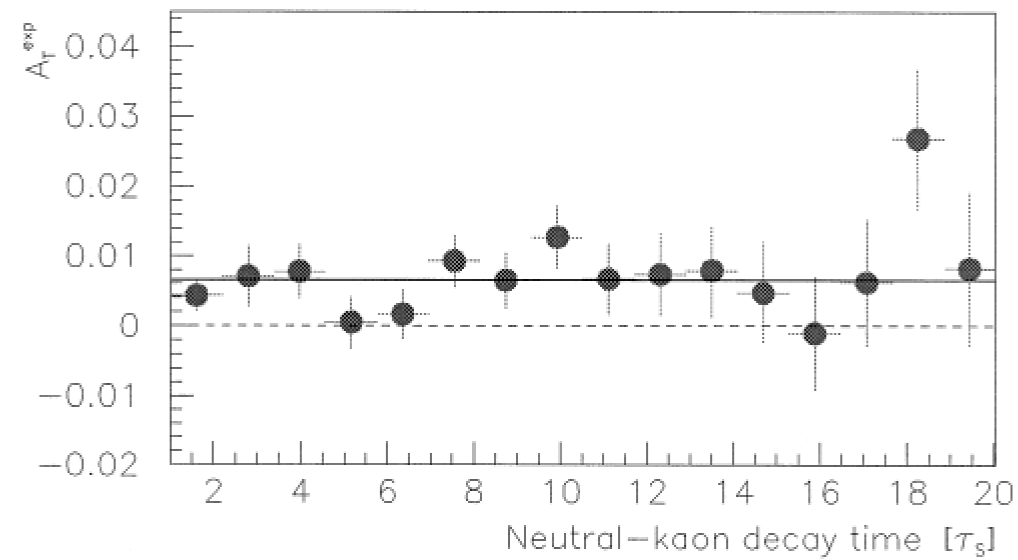


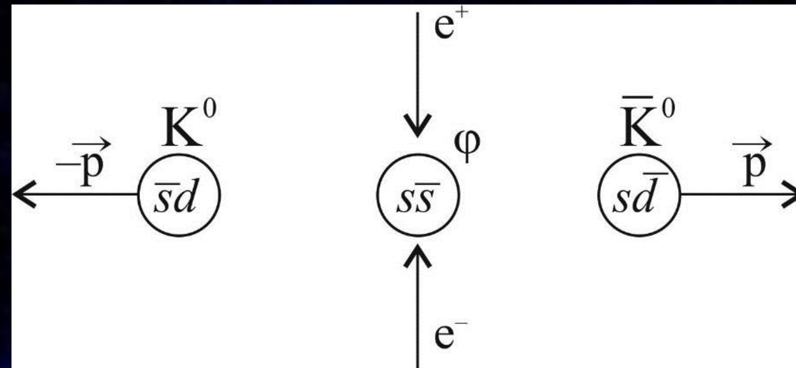


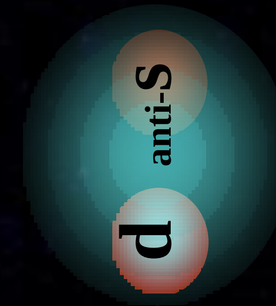
symetria T

$$K^0 \xrightarrow[\tau]{} \bar{K}^0 \Longleftrightarrow \bar{K}^0 \xrightarrow[\tau]{} K^0$$

A. Angelopoulos et al. / Physics Letters B 444 (1998) 43–51







Pairs of quantum entangled neutral mesons

$$\varphi : J^{CP} = 1^{--} \quad e^+e^- \rightarrow \varphi \rightarrow |K^0, p\rangle |K^0, -p\rangle - |K^0, p\rangle |K^0, -p\rangle$$

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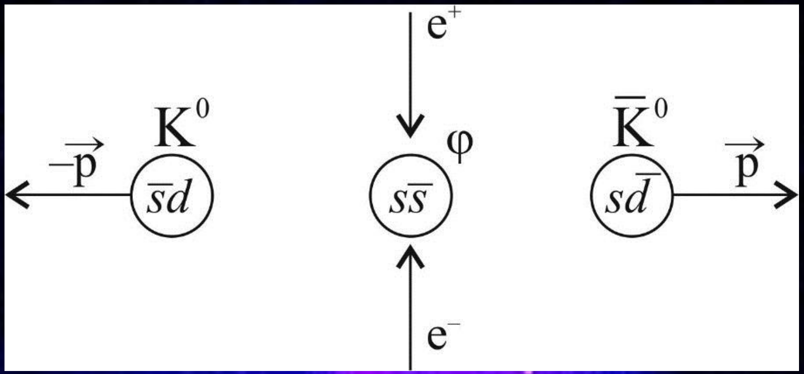

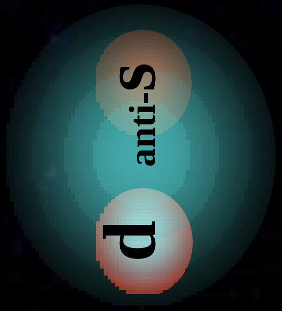

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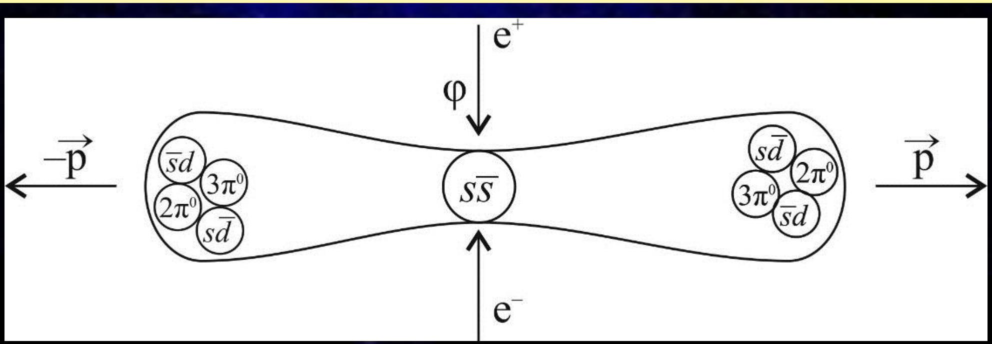
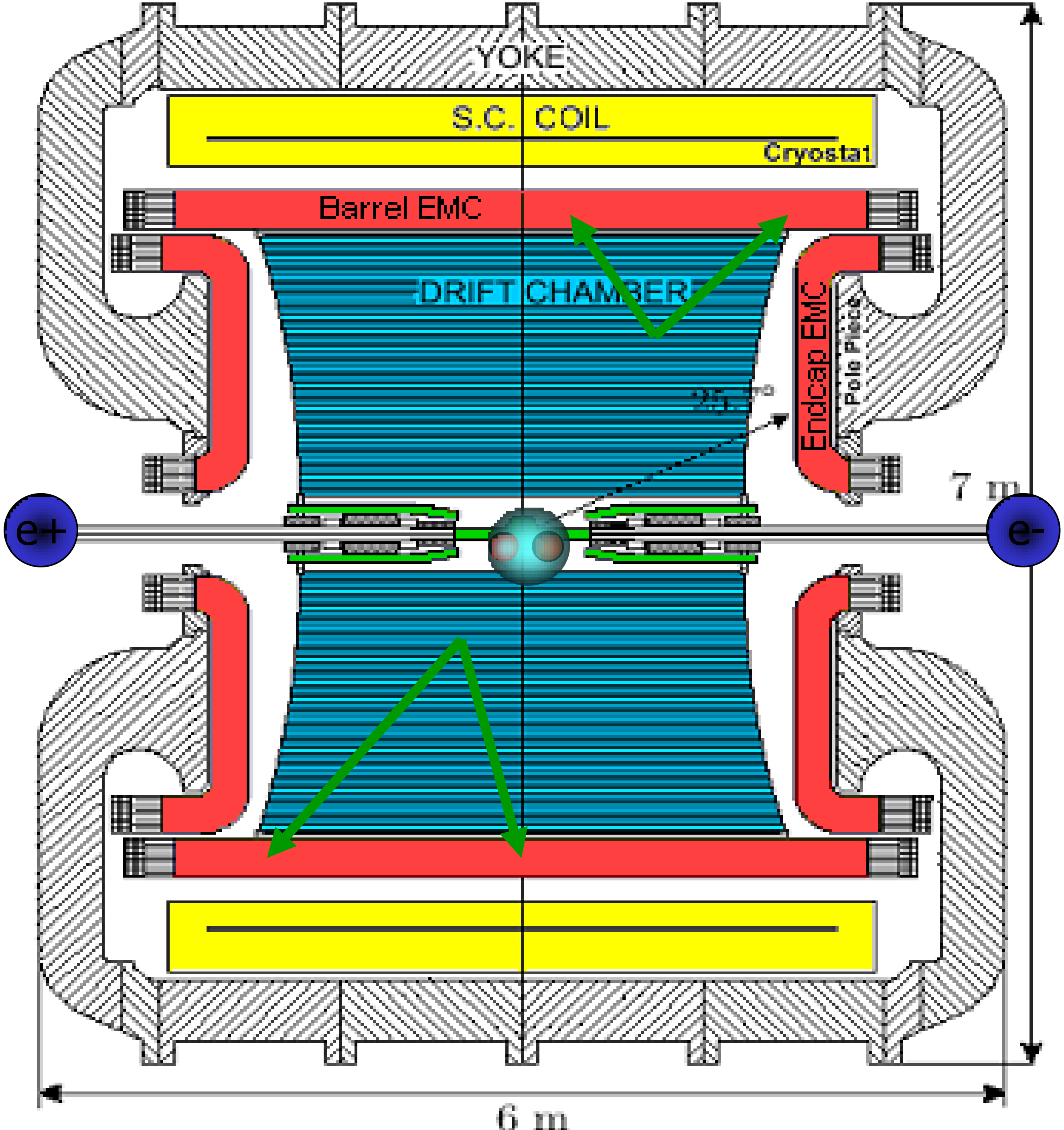
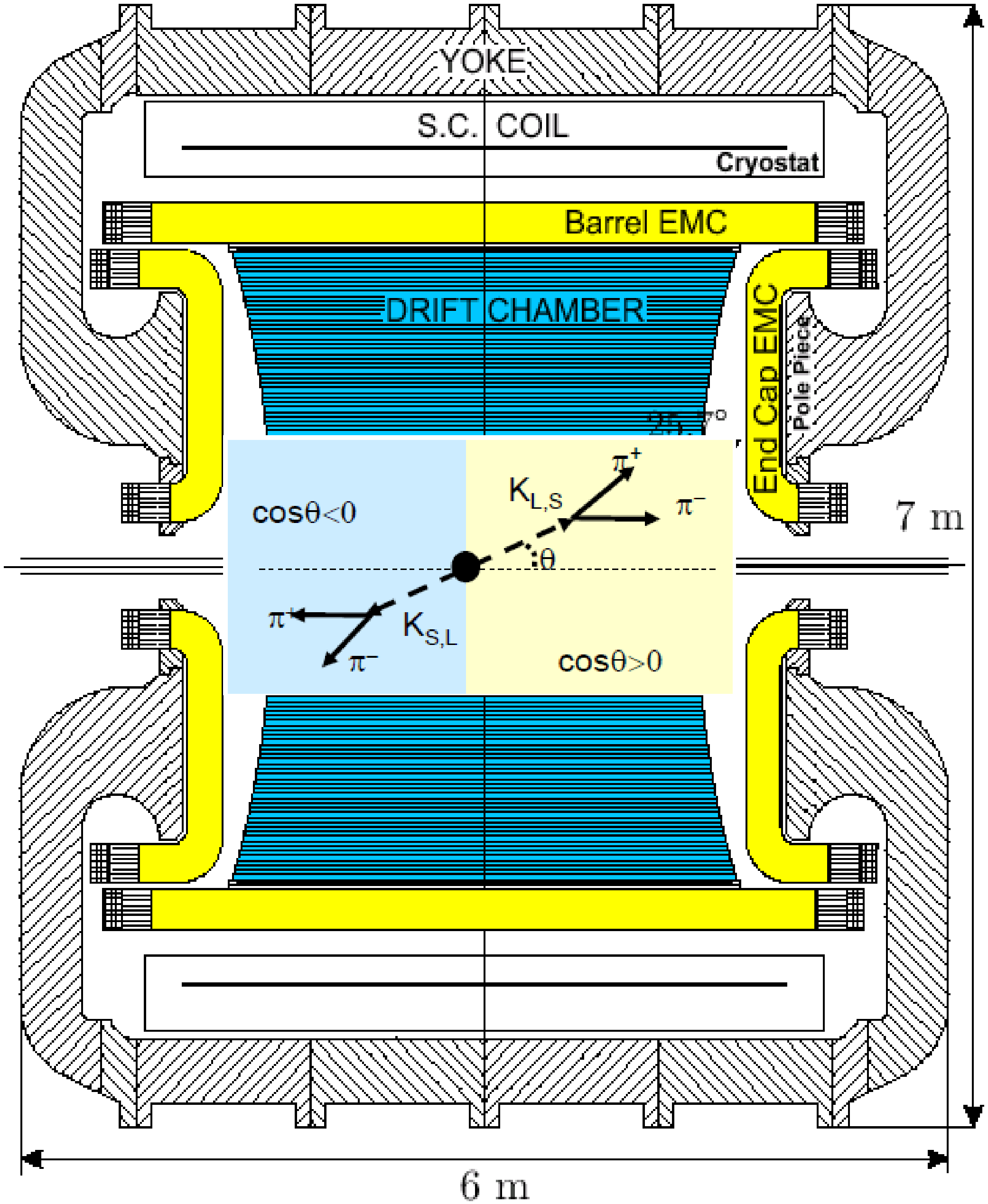


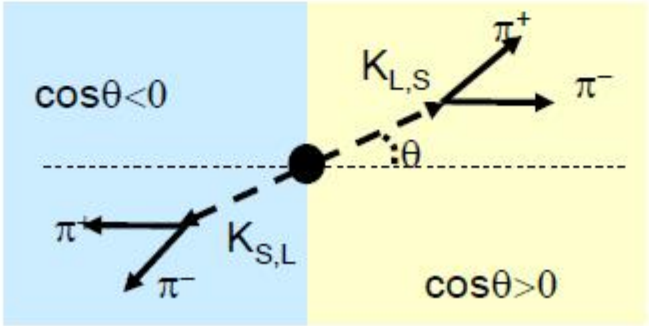
KLOE

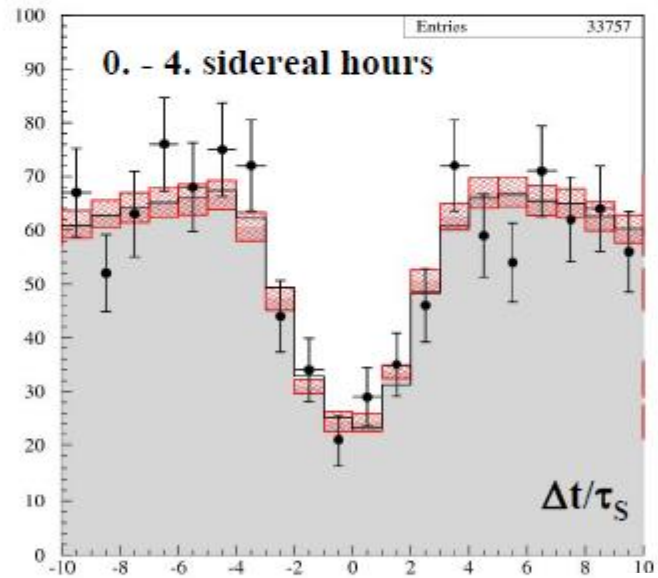
K LOng Experiment



Interferometria kwantowa neutralnych mezonów K

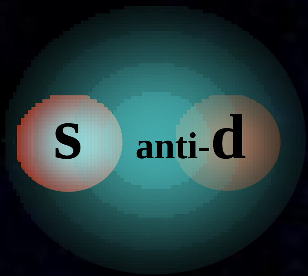






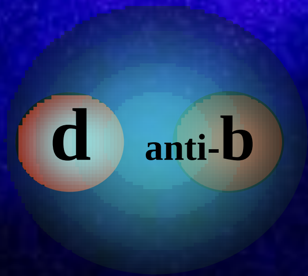
T symmetry violation

- $A \longrightarrow B \qquad B \longrightarrow A$
- T symmetry odd operators
- Particle mixing



meson K

1964



meson B

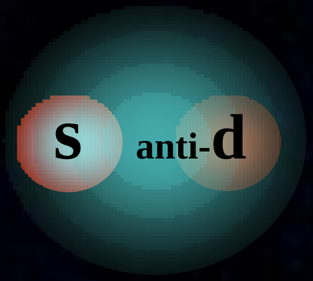
2012

positronium

?

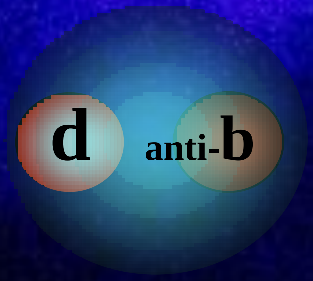
T symmetry violation

anti-K0 $\rightarrow K_+$ $K_+ \rightarrow$ anti-K0



meson K

1964



meson B

2012

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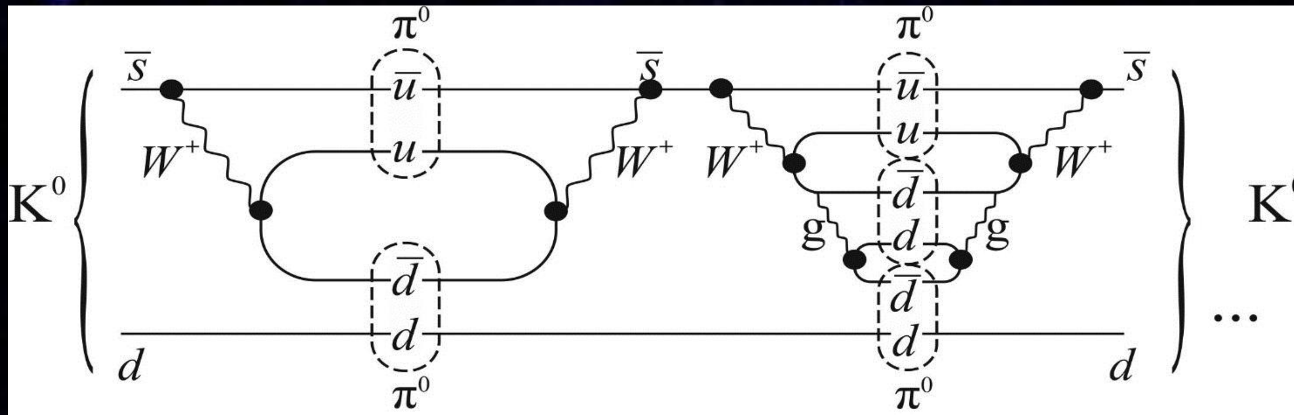

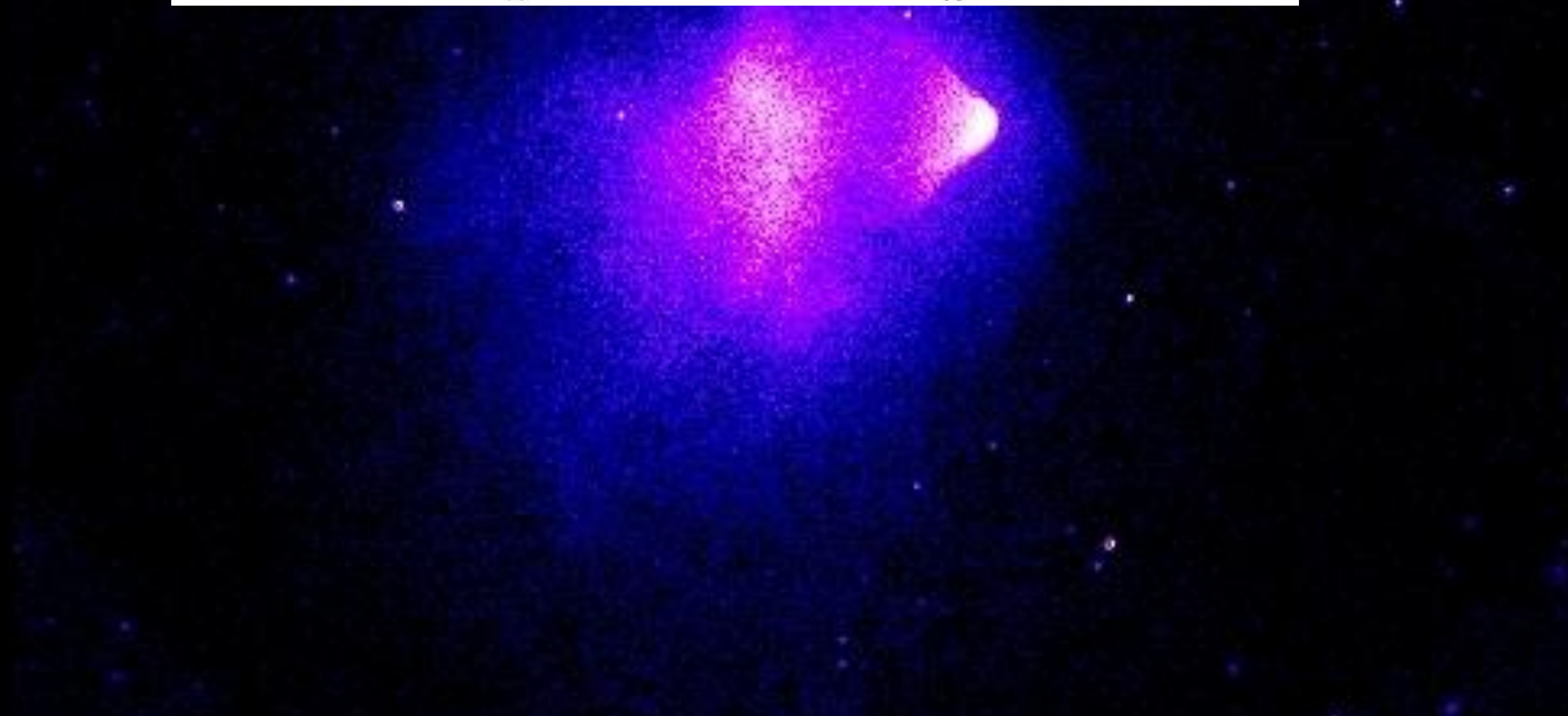

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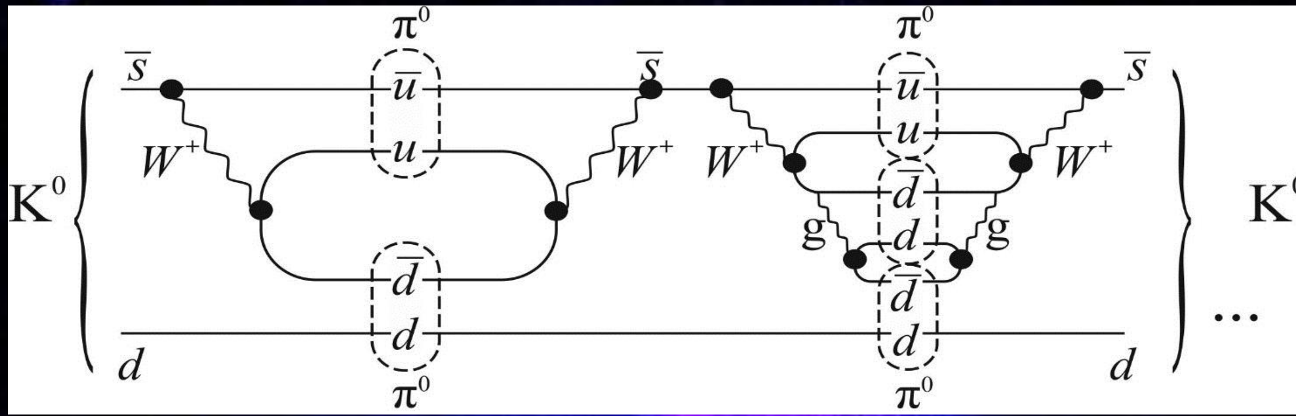
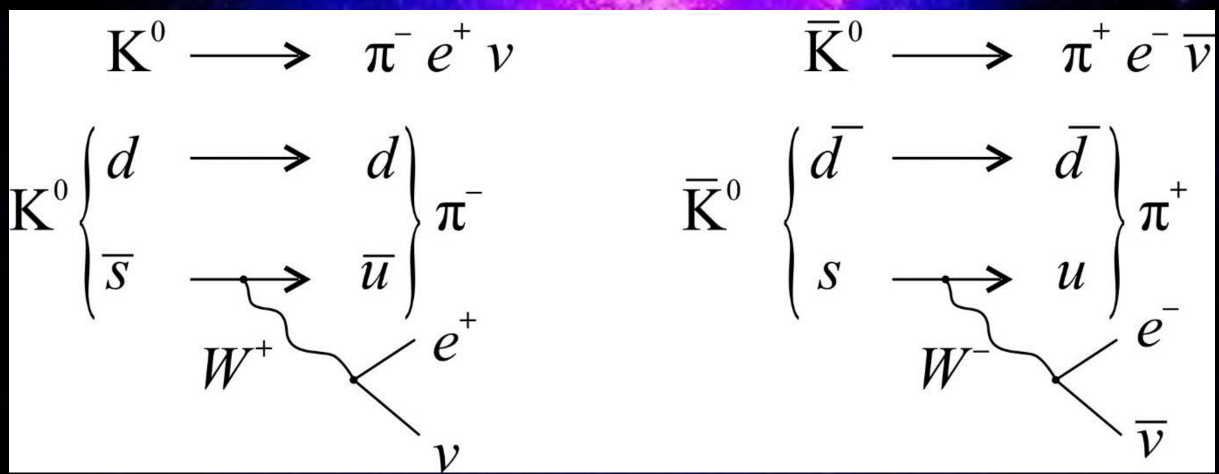
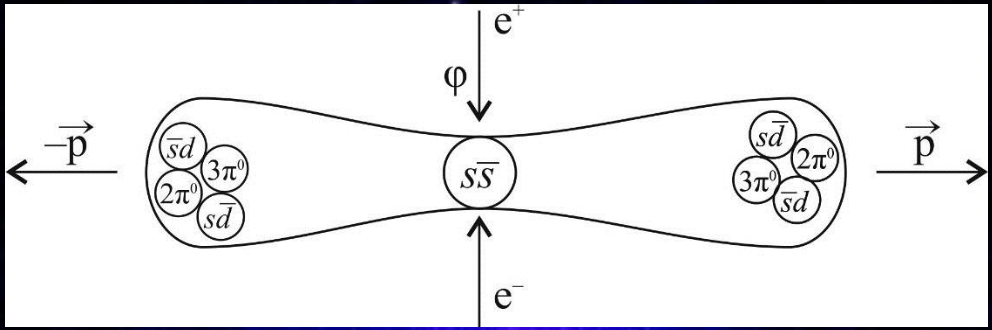
anti-S
d

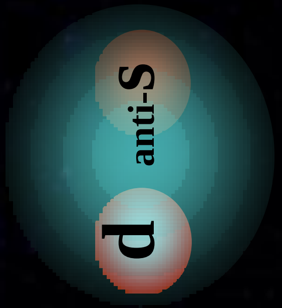

π^0
$\bar{s}$
$\bar{u}$
u
W^+
K^0
$\bar{d}$
d
g
π^0
K^0
...


anti-S
d


$K^0 \longrightarrow \pi^- e^+ \nu$
$\bar{K}^0 \longrightarrow \pi^+ e^- \bar{\nu}$
π^-
π^+
W^+
W^-
e^+
ν
e^-
$\bar{\nu}$

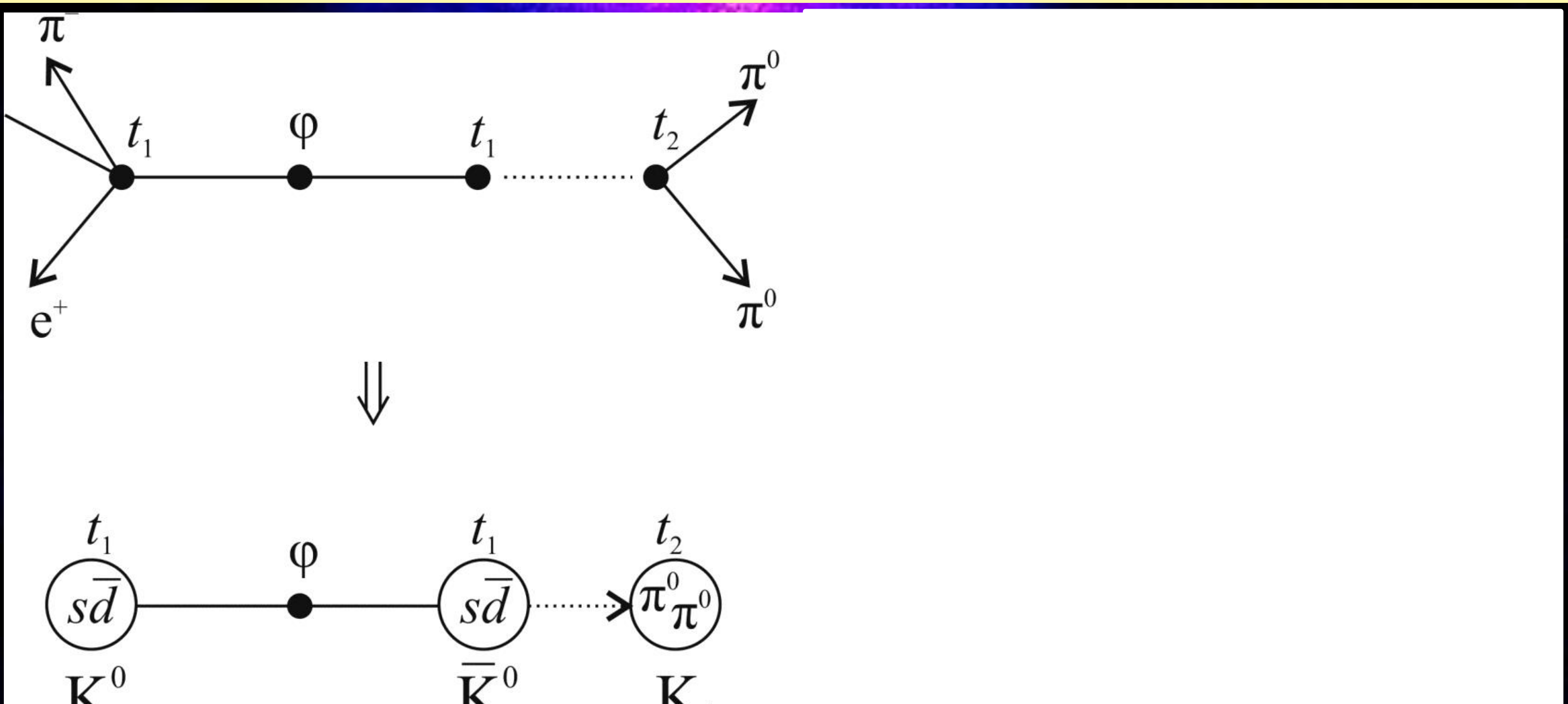
[redacted]

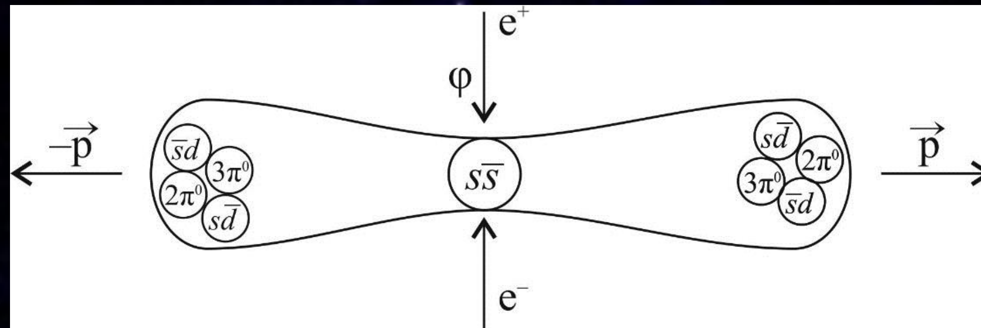




Pairs of quantum entangled neutral mesons

φ:$J^{CP} = 1^{--}$ $e^+e^- \rightarrow \varphi \rightarrow |K^0,p>|K^0,-p> - |K^0,p>|K^0, -p>$





Pairs of quantum entangled neutral mesons

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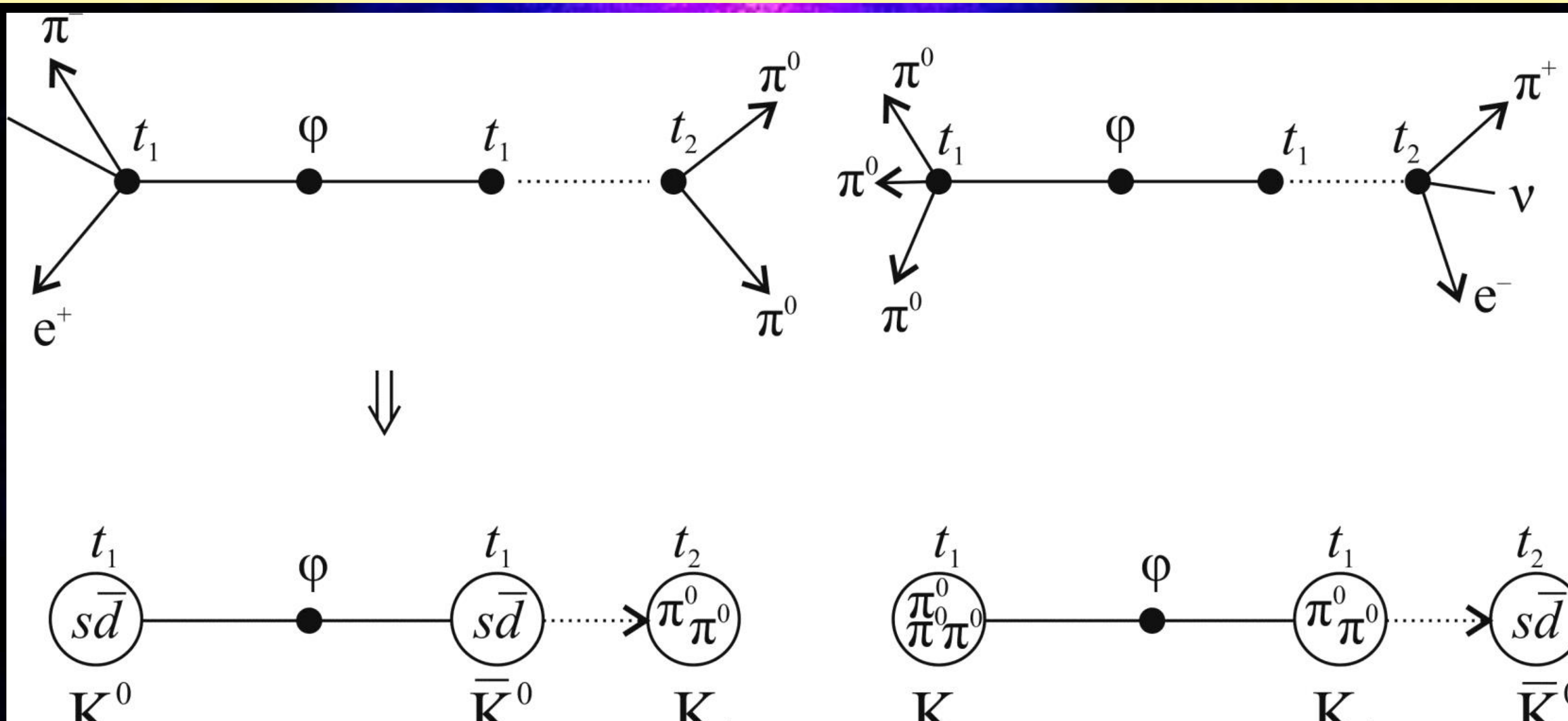


Pairs of quantum entangled neutral mesons

$\varphi: J^{CP} = 1^{--}$

$e^+e^- \rightarrow \varphi \rightarrow |K^0, p\rangle |\bar{K}^0, -p\rangle - |\bar{K}^0, p\rangle |K^0, -p\rangle$

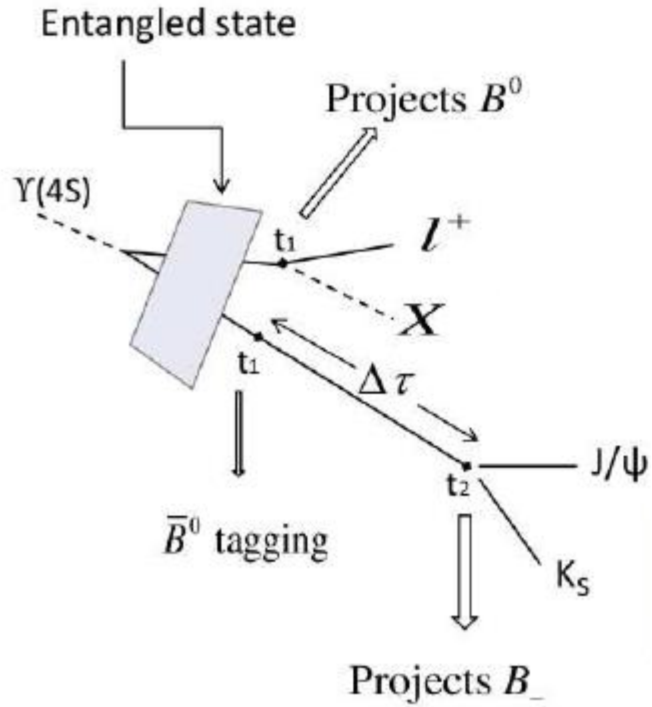
$e^+e^- \rightarrow \Upsilon(4s) \rightarrow |B^0, p\rangle |\bar{B}^0, -p\rangle - |\bar{B}^0, p\rangle |B^0, -p\rangle$

$\Upsilon(4S)$: $J^{CP} = 1^{--}$

$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow |B^0, p\rangle|\overline{B}^0, -p\rangle - |\overline{B}^0, p\rangle|B^0, -p\rangle$$

$B_- \equiv B^0 \dashrightarrow J/\psi\ K_+ \dashrightarrow J/\psi\ \pi\pi$

$B_+ \equiv B^0 \dashrightarrow J/\psi\ K_- \dashrightarrow J/\psi\ \pi^0\pi^0\pi^0$



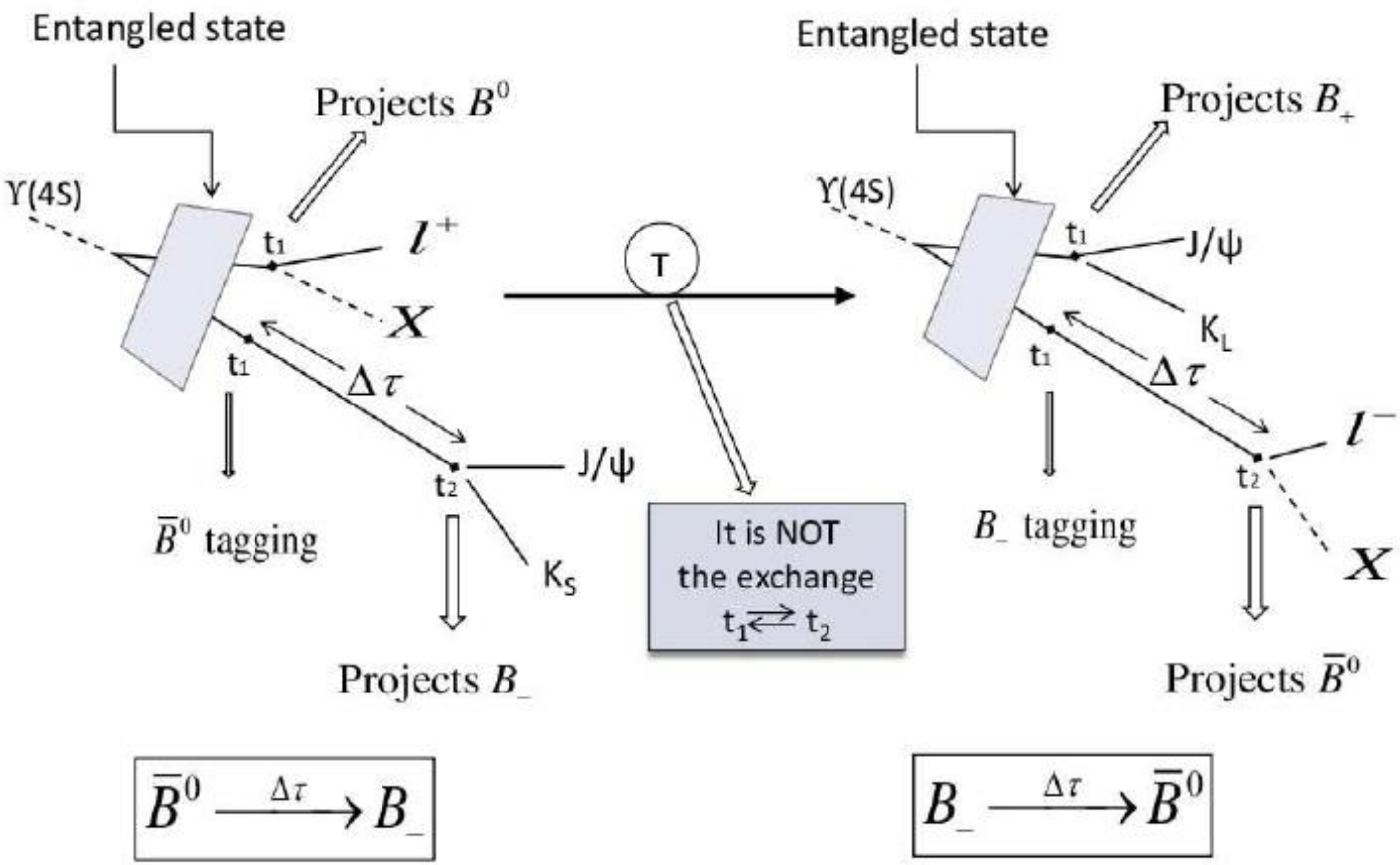
$$\boxed{\overline{B}^0 \xrightarrow{\Delta\tau} B_-}$$

J. Barnabeu et al., JHEP08 (2012) 064

$$e^+e^- \to \Upsilon(4s) \to |B^0, p\rangle|\bar{B}^0, -p\rangle - |\bar{B}^0, p\rangle|B^0, -p\rangle$$

$B_- \equiv B^0 \dashrightarrow J/\psi\ K_+ \dashrightarrow J/\psi\ \pi\pi$

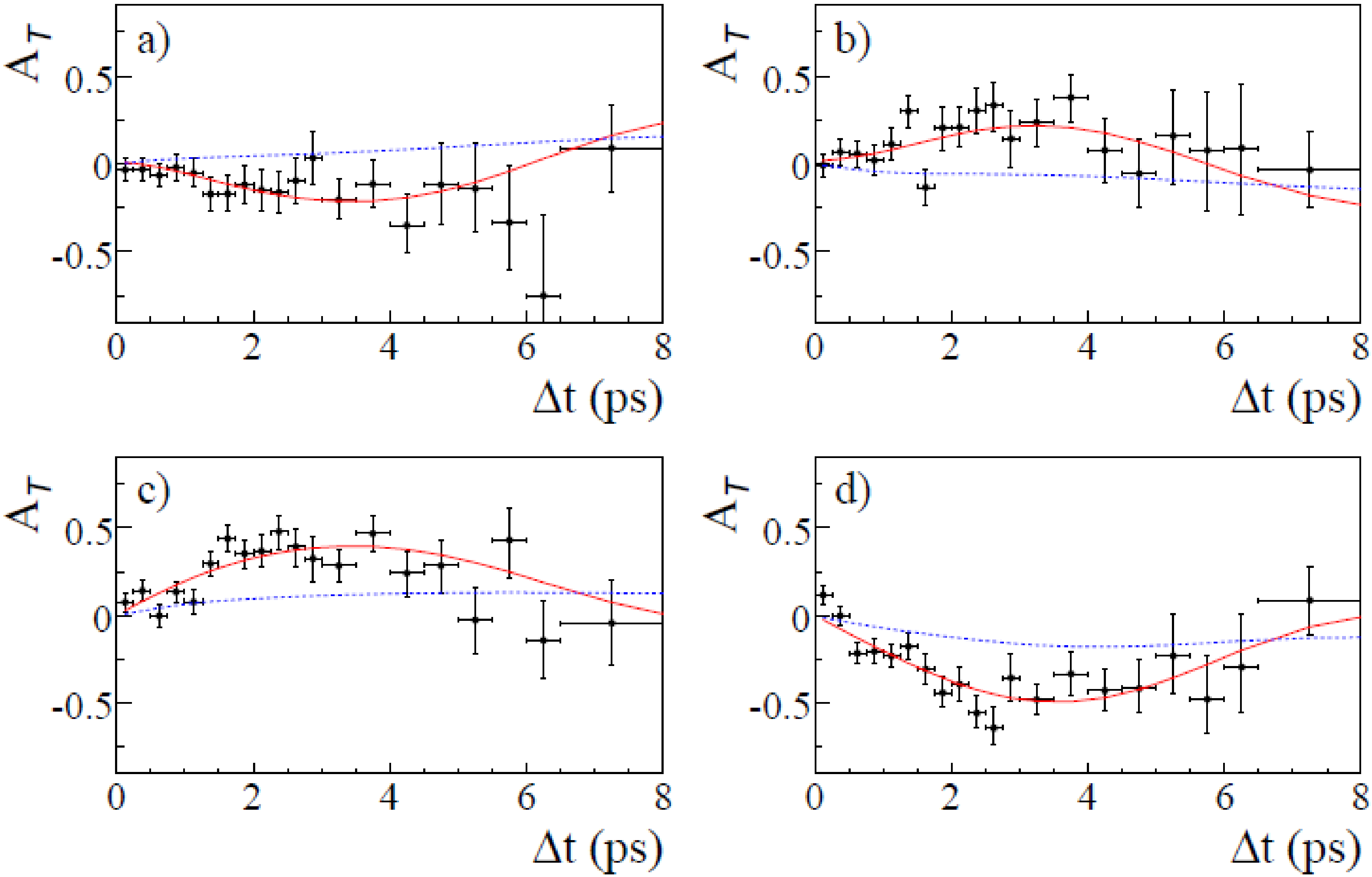
$B_+ \equiv B^0 \dashrightarrow J/\psi\ K_- \dashrightarrow J/\psi\ \pi^0\pi^0\pi^0$



J. Barnabeu et al., JHEP08 (2012) 064

Results of BABAR experiment

$$A_T(\Delta t_+) \approx \frac{\Delta C_T^+}{2}\cos\Delta m\Delta t_+ + \frac{\Delta S_T^+}{2}\sin\Delta m\Delta t_+.$$



Phys. Rev. Lett. 109 (2012) 211801

$B_- \equiv B^0 \dashrightarrow J/\psi\ K_+ \dashrightarrow J/\psi\ \pi\pi$

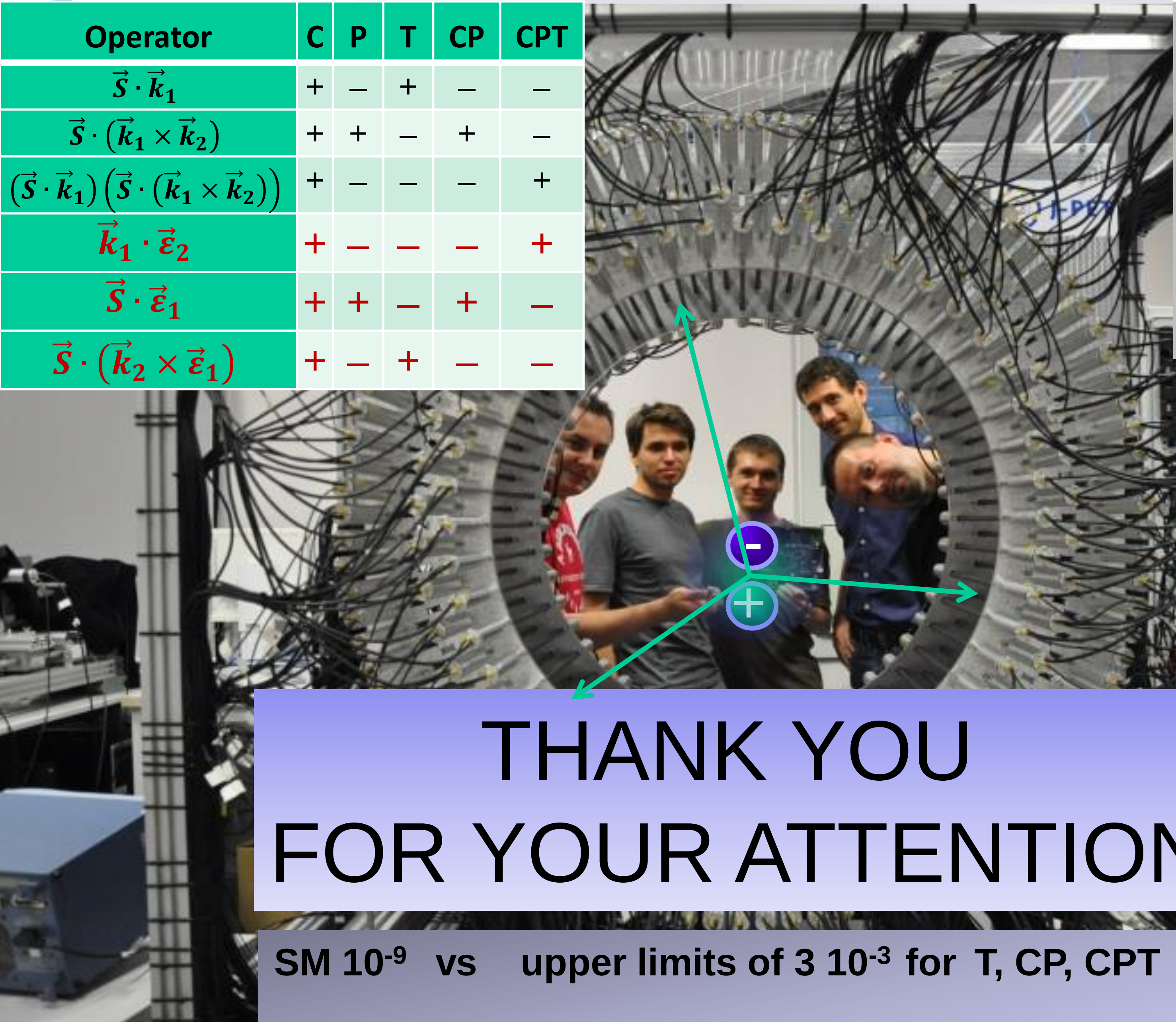
$B_+ \equiv B^0 \dashrightarrow J/\psi\ K_- \dashrightarrow J/\psi\ \pi^0\pi^0\pi^0$

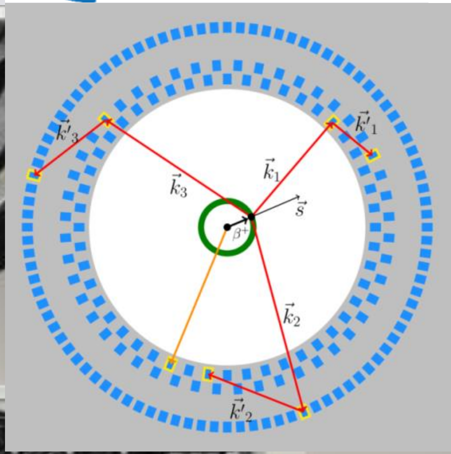
$\frac{B_+ \to B^0}{(J/\Psi\ K_S,\ \ell^+)}$	CP	CPT	T
Transition	$B_+ \to \bar{B}^0$	$\bar{B}^0 \to B_+$	$B^0 \to B_+$
(X, Y)	$(J/\Psi\ K_S,\ \ell^-)$	$(\ell^+,\ J/\Psi\ K_L)$	$(\ell^-,\ J/\Psi\ K_L)$

time

Jagiellonian PET

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

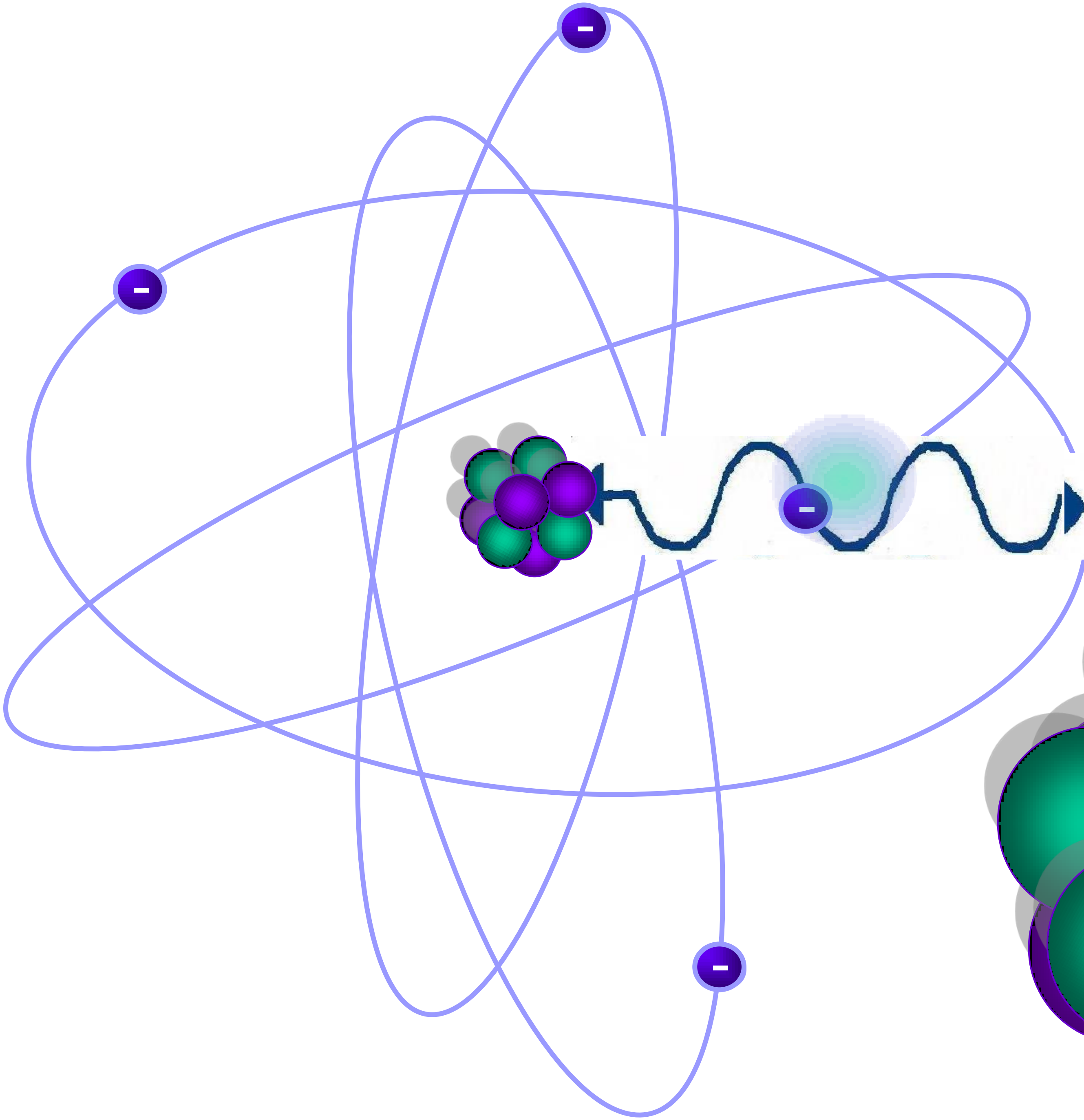




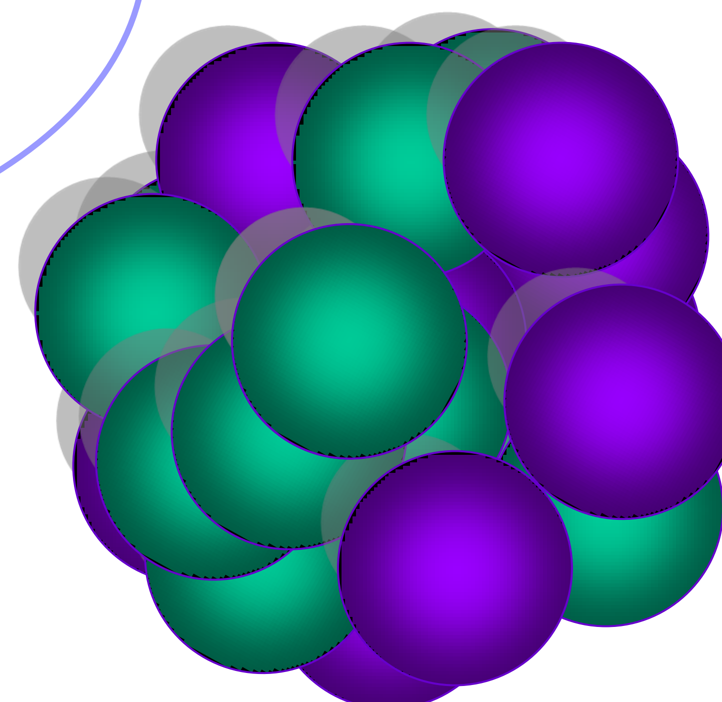
THANK YOU
FOR YOUR ATTENTION

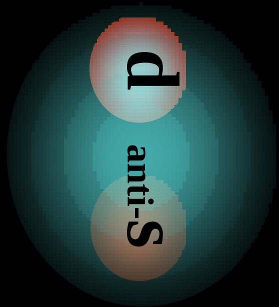
SM 10^{-9} vs upper limits of $3\ 10^{-3}$ for T, CP, CPT

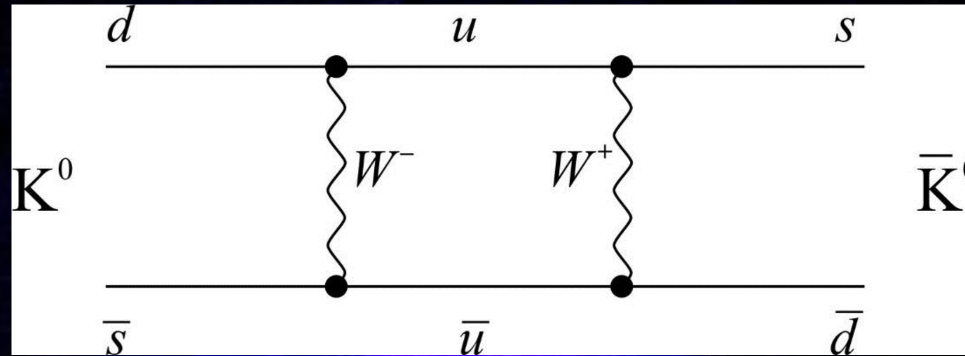
- **CPLEAR: A. Angelopoulos et al., Phys. Lett. B 444 (1998) 43**
- **L. Wolfenstein, Phys. Rev. Lett. 83 (1999) 911**
- **J. Barnabeu et al., JHEP08 (2012) 064**
- **BABAR: J. P. Lees et al., Phys. Rev. Lett. 109 (2012) 211801**

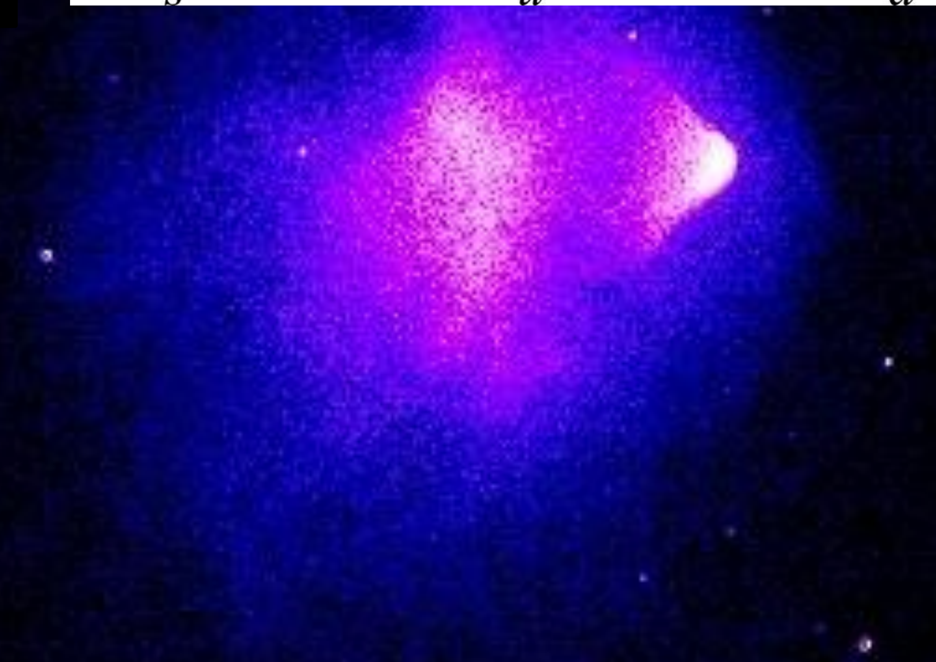


$$^{18}F \longrightarrow {}^{18}O + e^{+} + \nu_e$$









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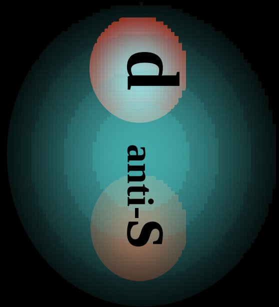
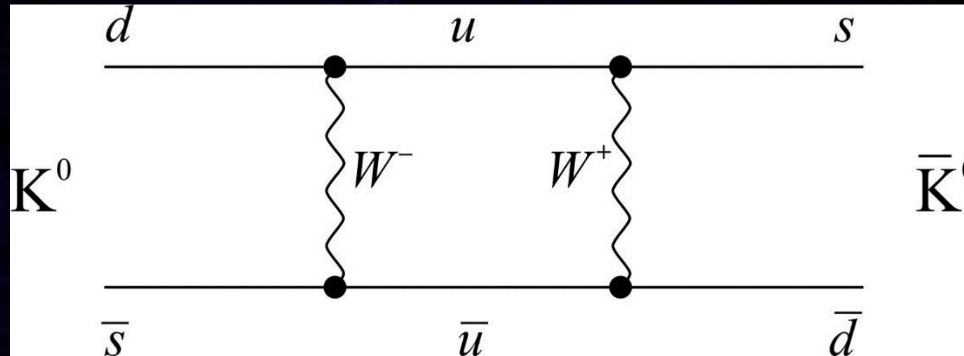
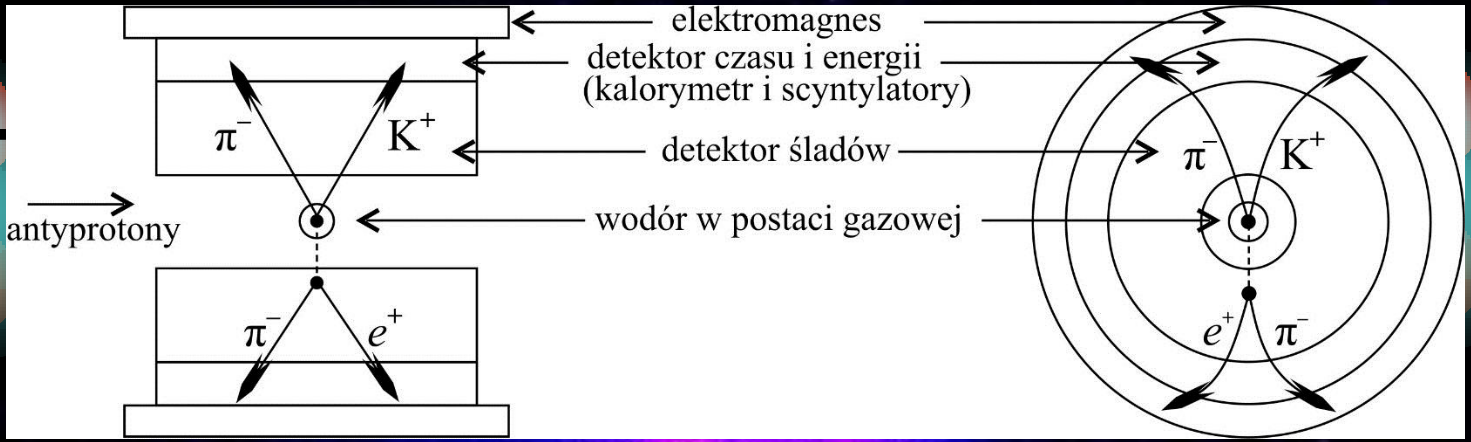




T symmetry

$$K^0 \xrightarrow[\tau]{} \bar{K}^0 \iff \bar{K}^0 \xrightarrow[\tau]{} K^0$$



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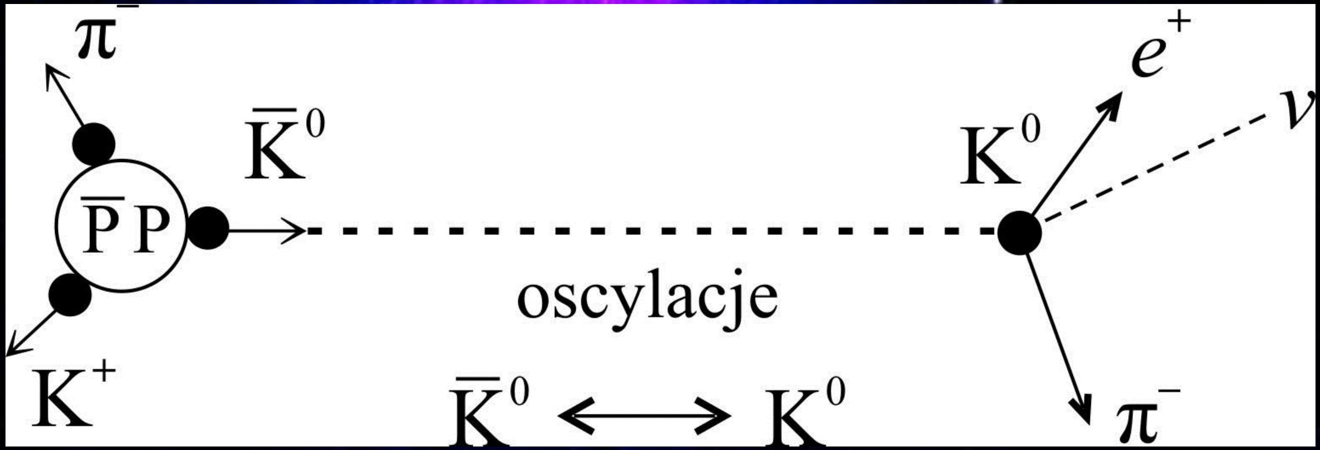

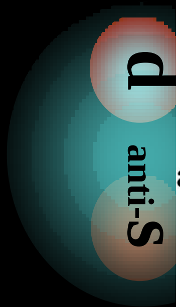

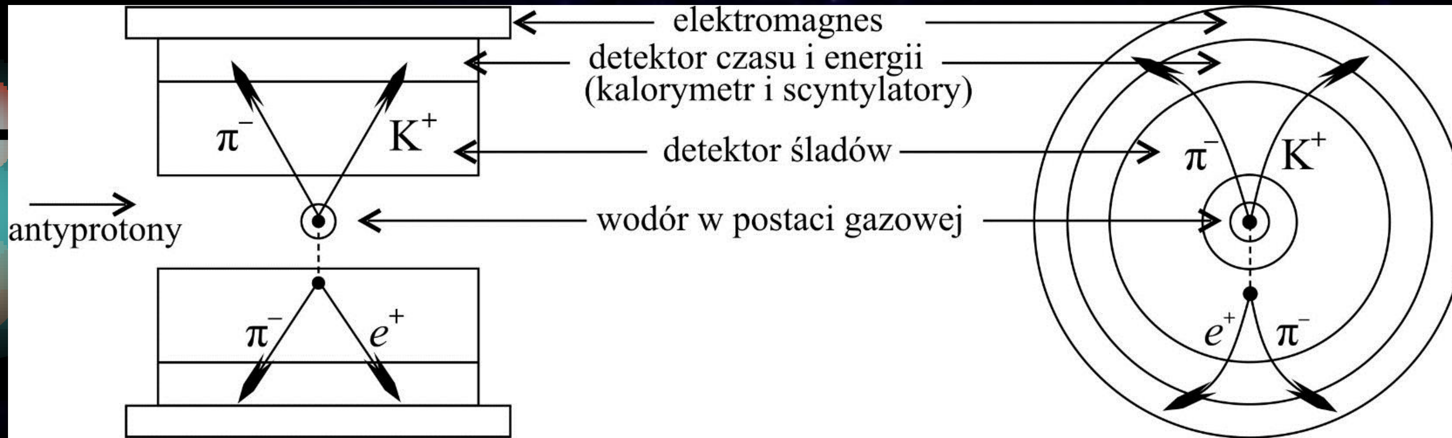

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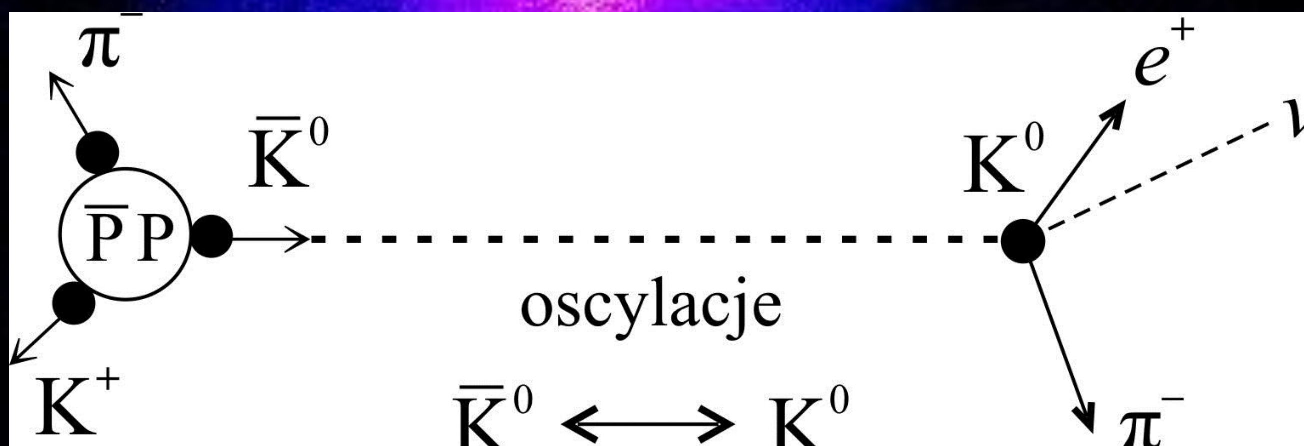

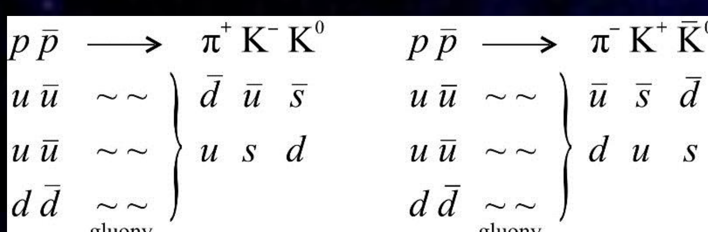

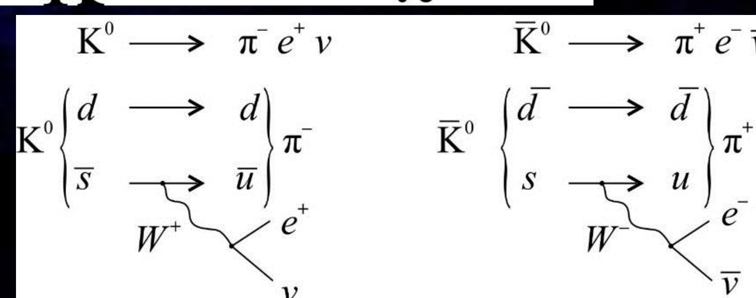

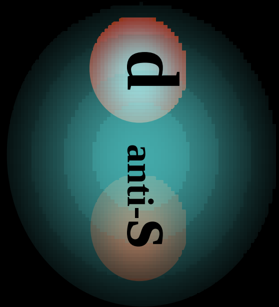

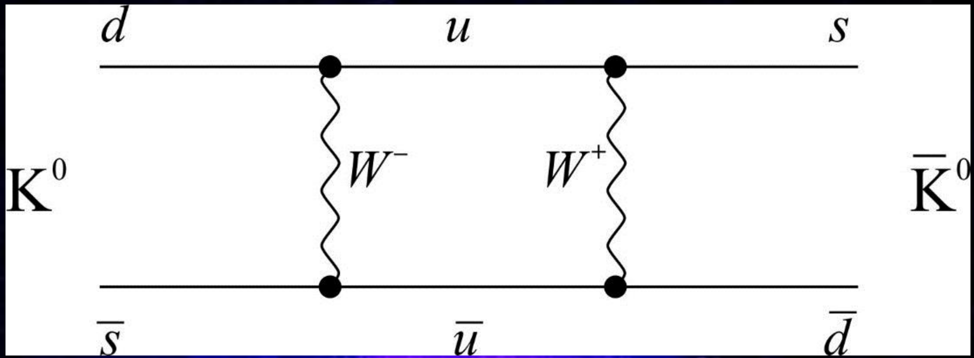

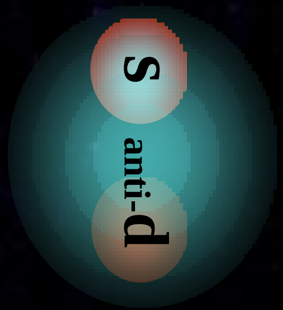

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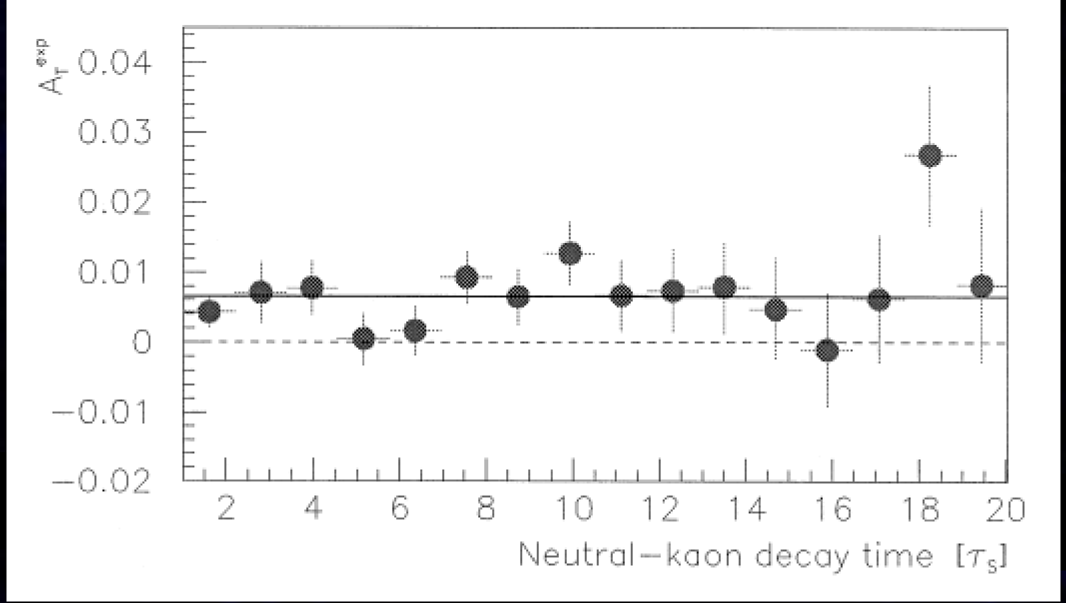
A. Angelopoulos et al. / Physics Letters B 444 (1998) 43–51

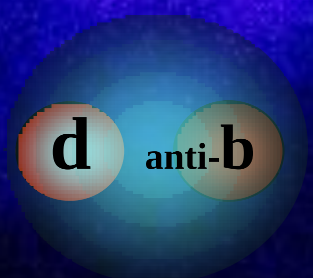


T symmetry violation

- A ⟶ B   B ⟶ A
- T symmetry odd operators
- Particle mixing

meson K

1964

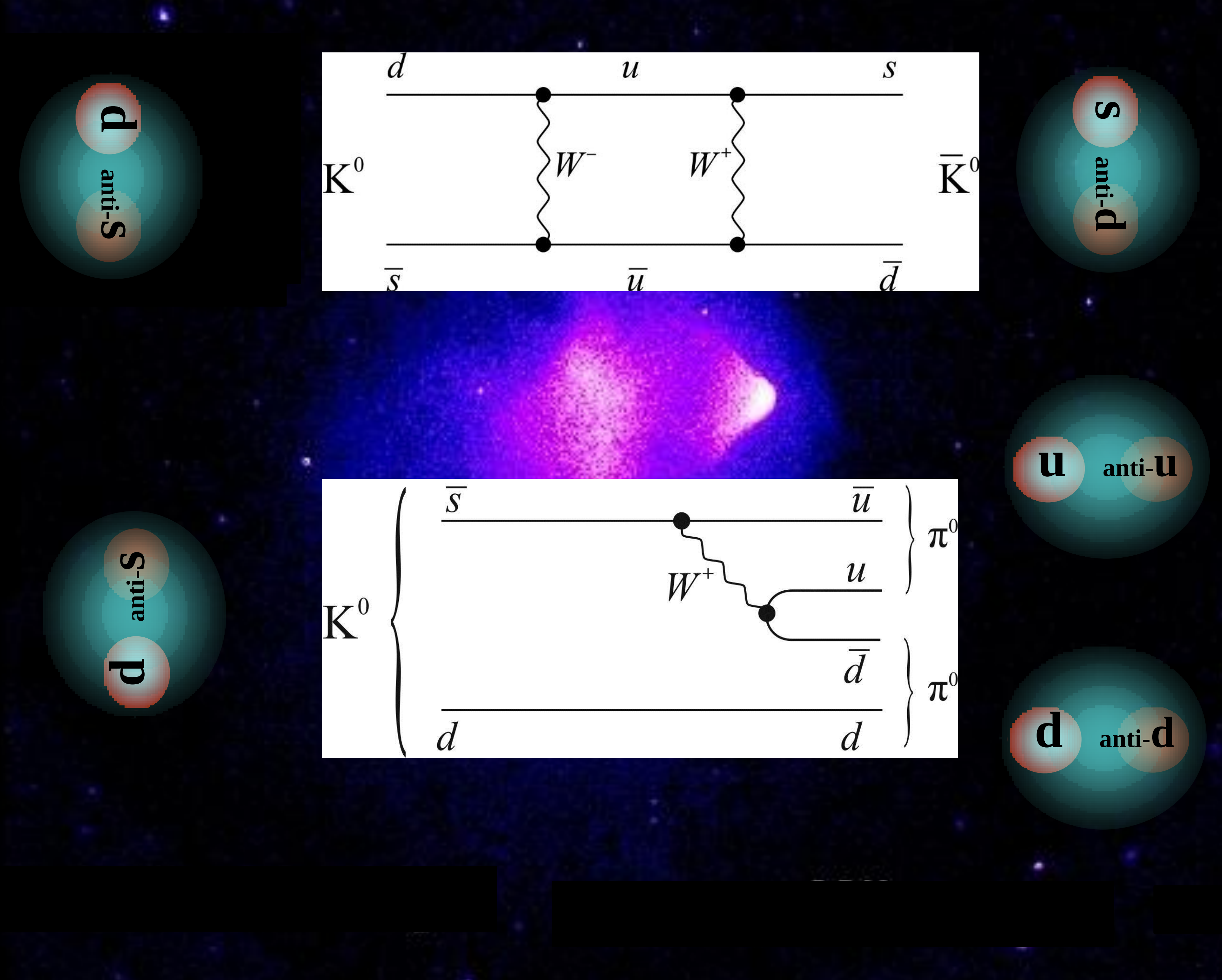


meson B

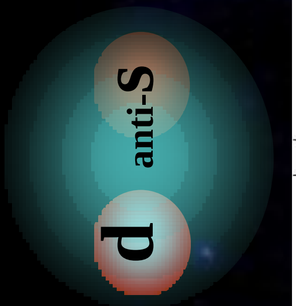
2012

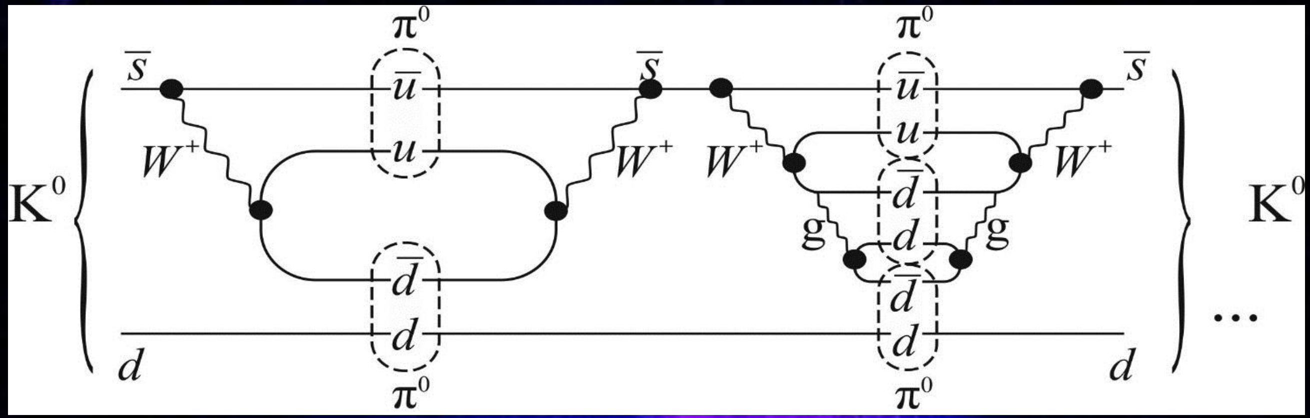
positronium

?

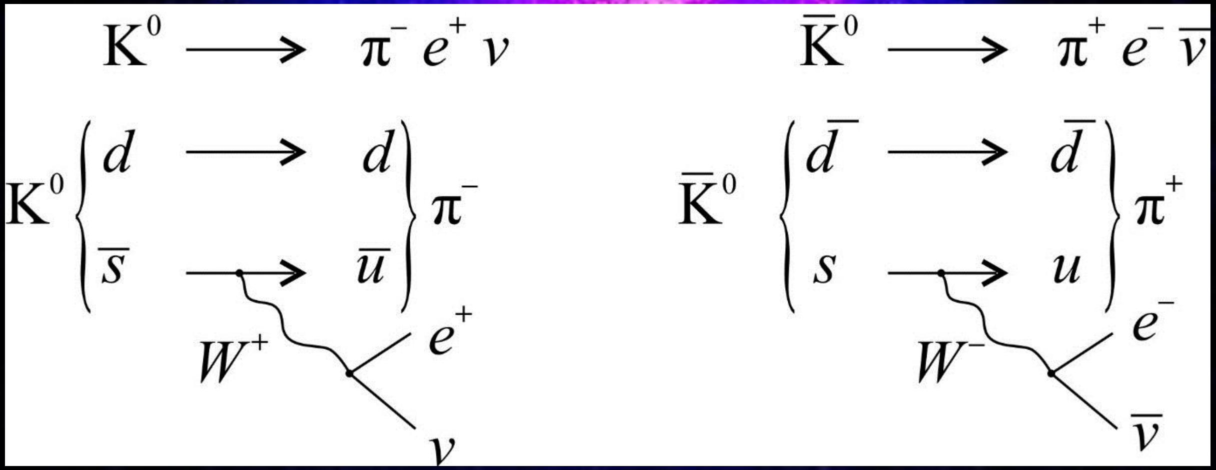

d
anti-S
d
u
s
K0
W−
W+
K̄0
s̄
ū
d̄
s
anti-d
s̄
ū
π0
u
W+
d̄
d
d
K0
π0
anti-S
d
u
anti-u
d
anti-d

[redacted]


d
anti-S


π^0
$\bar{s}$
$\bar{u}$
u
W^+
K^0
$\bar{d}$
d
g
π^0
...

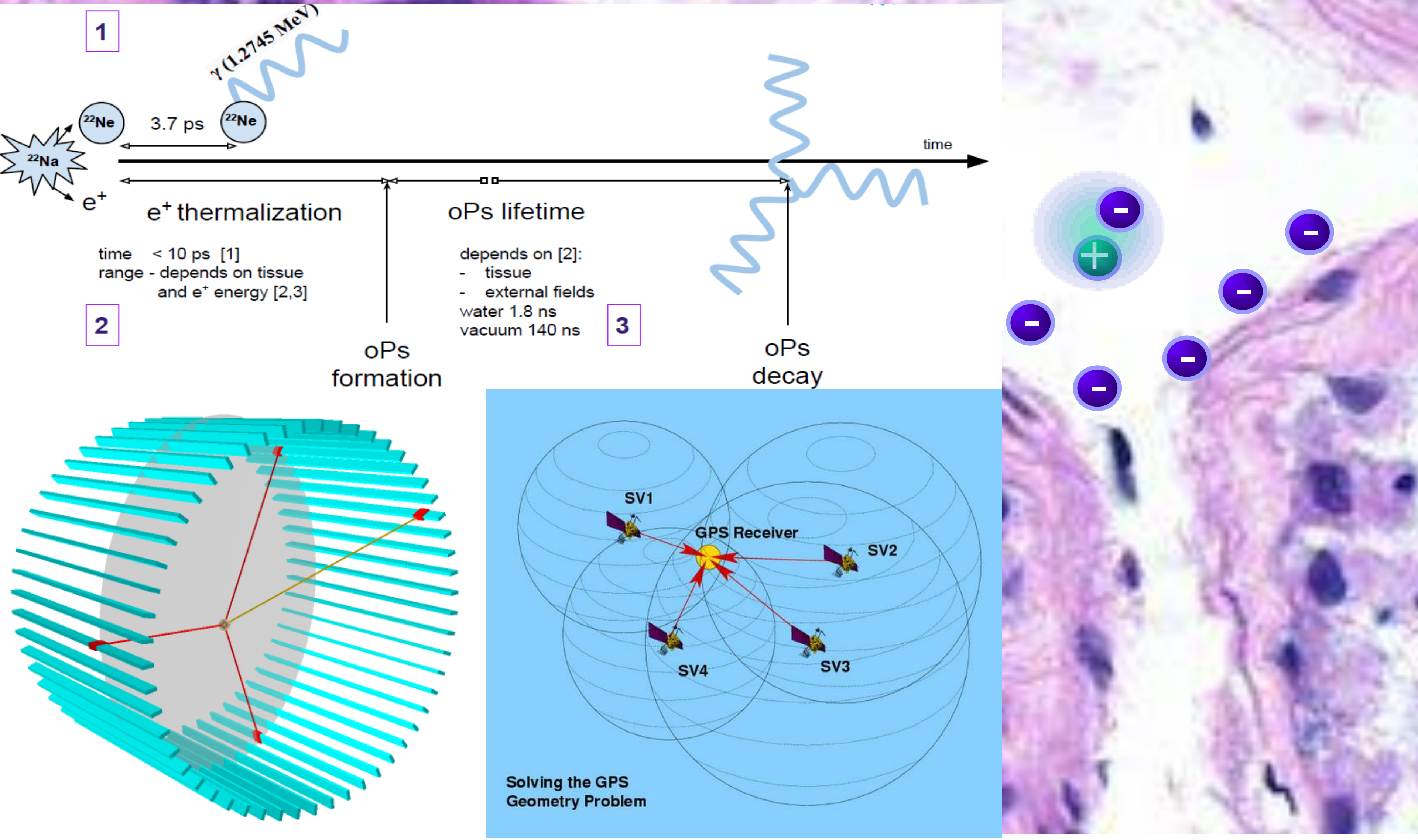

d
anti-S


$K^0 \longrightarrow \pi^- e^+ \nu$
$\bar{K}^0 \longrightarrow \pi^+ e^- \bar{\nu}$
K^0
$d \longrightarrow d$
$\bar{s} \longrightarrow \bar{u}$
π^-
W^+
e^+
ν
$\bar{K}^0$
$\bar{d} \longrightarrow \bar{d}$
$s \longrightarrow u$
π^+
W^-
e^-
$\bar{\nu}$

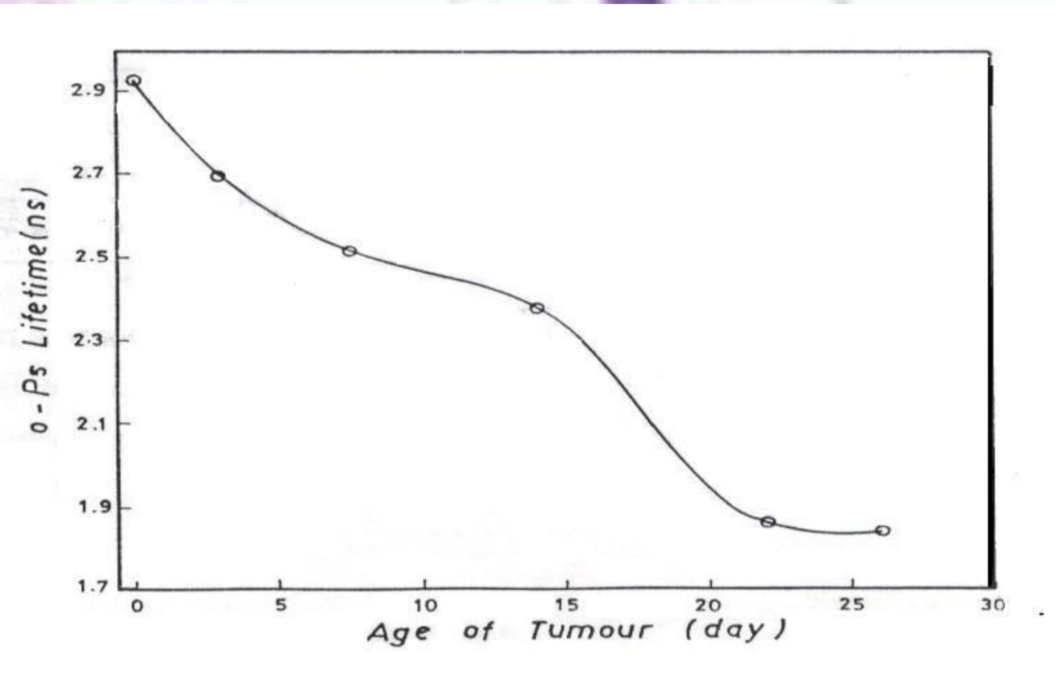
[redacted]


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

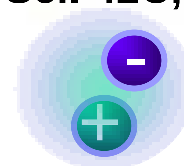
Ortho-positronium life-time tomography

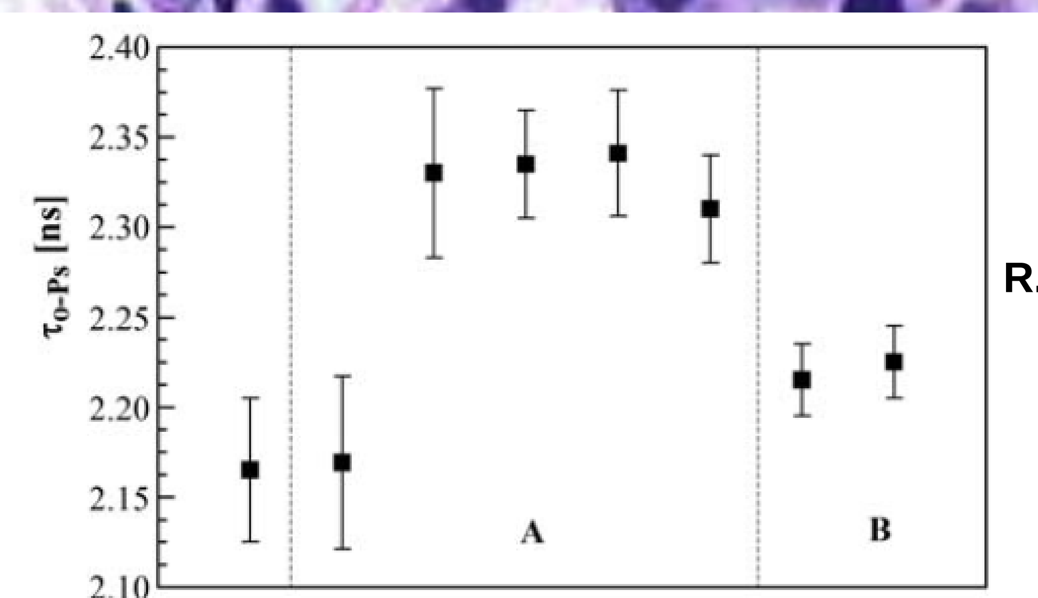


Patent applications: P. M., **PCT/EP2014/068374**; A. Gajos, E. Czerwiński, D. Kamińska, P. M., **PCT/PL2015/050038**

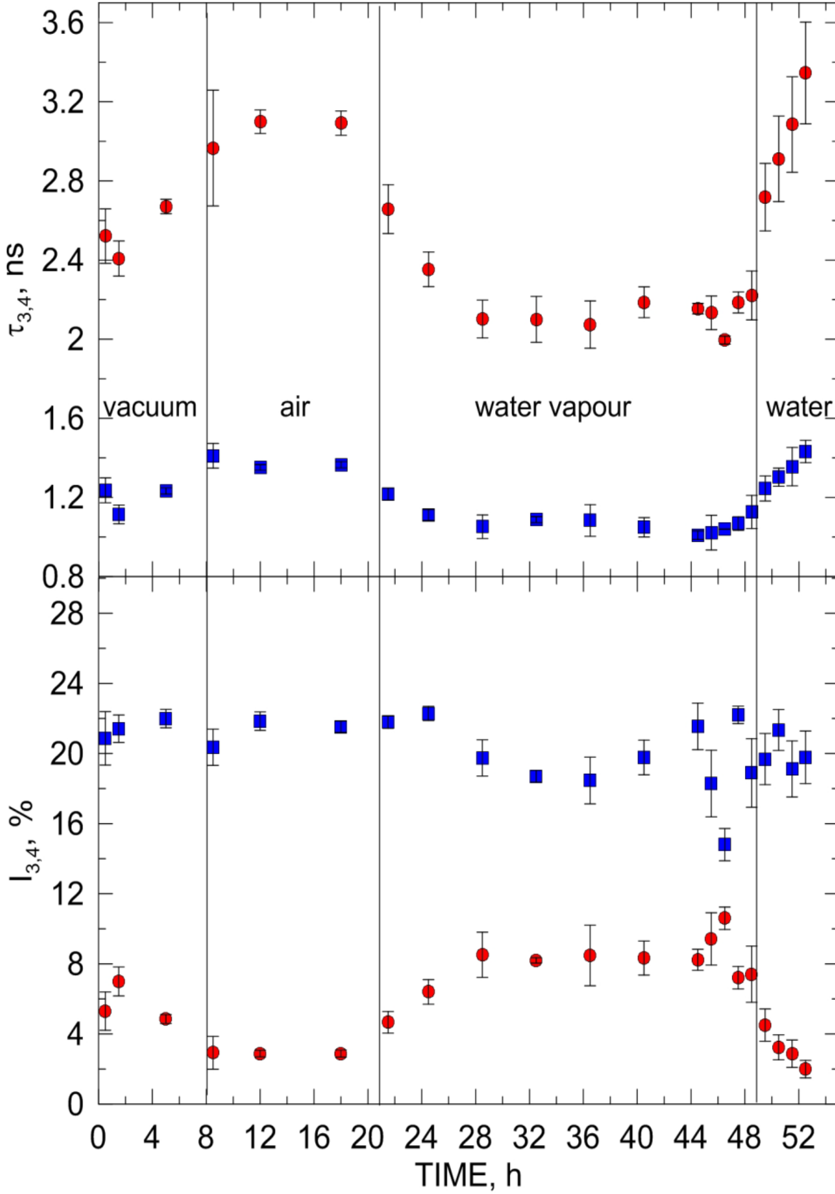


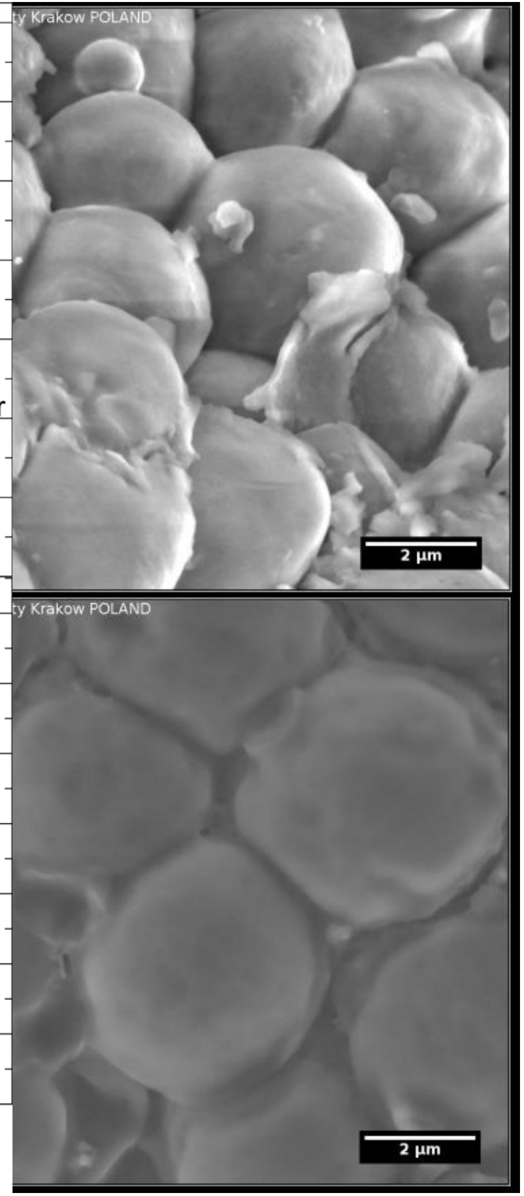
The age of mice’s tumour with o-Ps lifetime
A.H. Al-Mashhadani et al., Iraqi J. Sci. 42C, 60 (2001) 3.





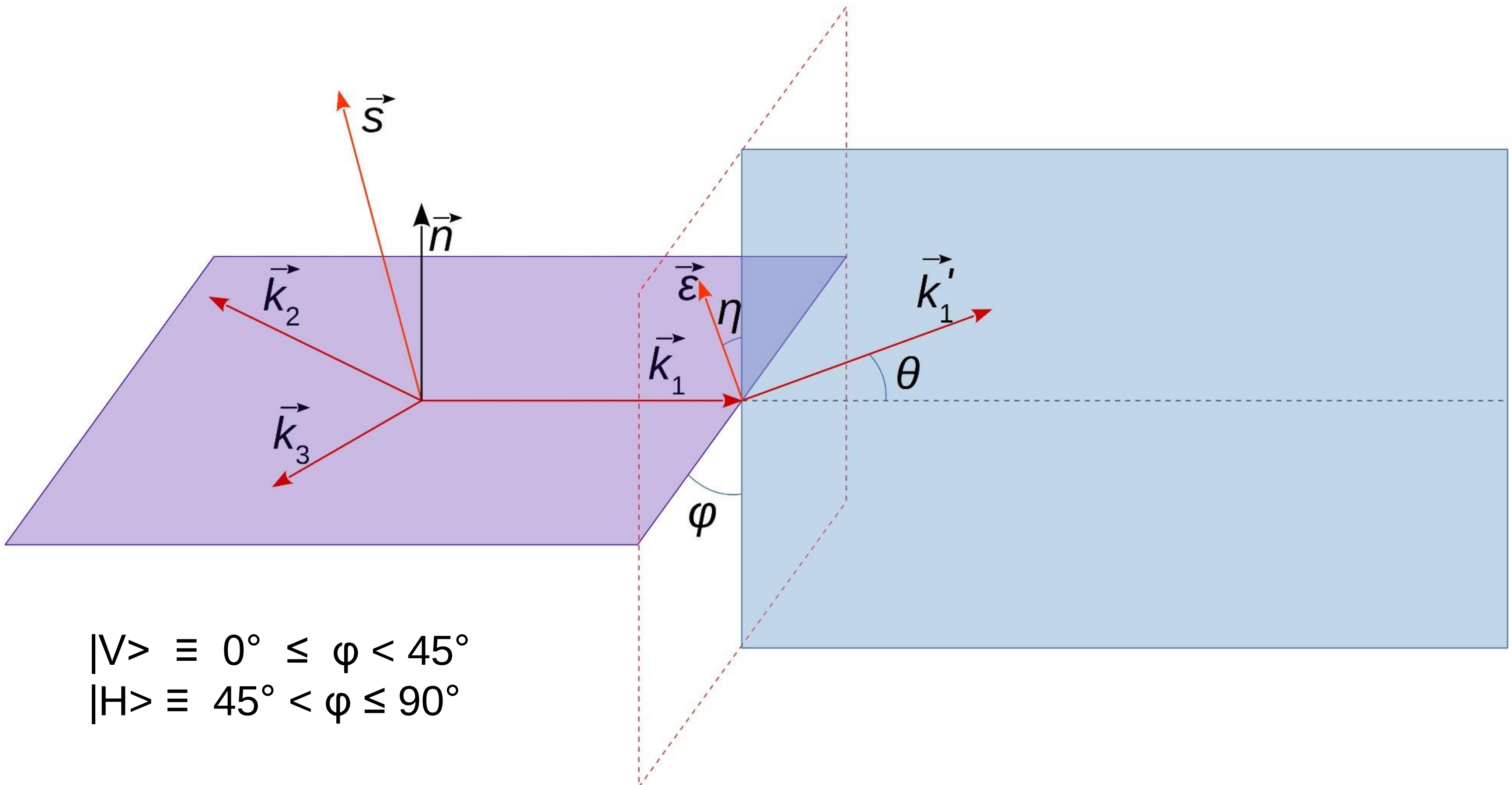
R. Pietrzak et al., NUKLEONIKA 58 (2013) 199





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).



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

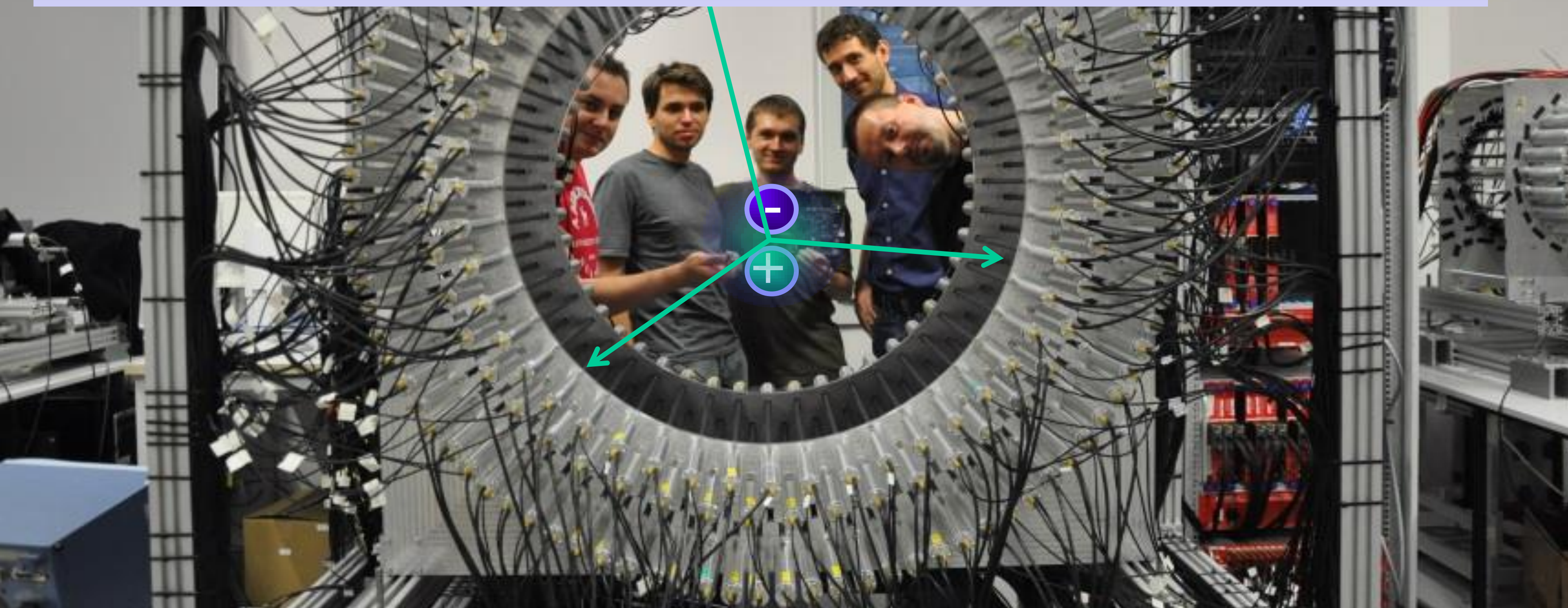
|GHZ > = 1/sqrt(2) (|H H H> + |V V V>)
| W > = 1/sqrt(3) (|H H V> + |H V H> + |V H H >)

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.

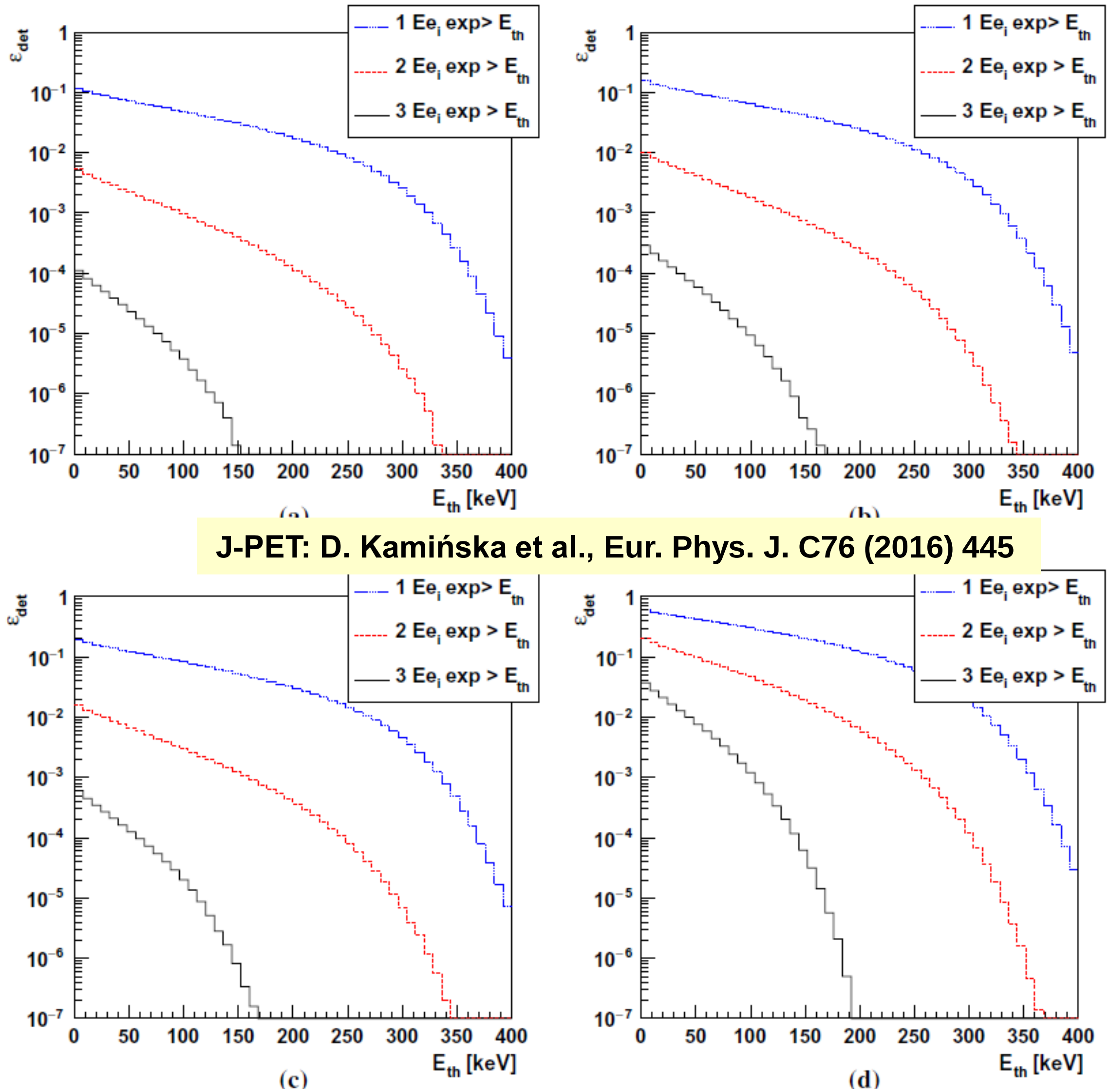
D.M. Greenberger et al., Am. J. Phys. 58(1990)1131

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



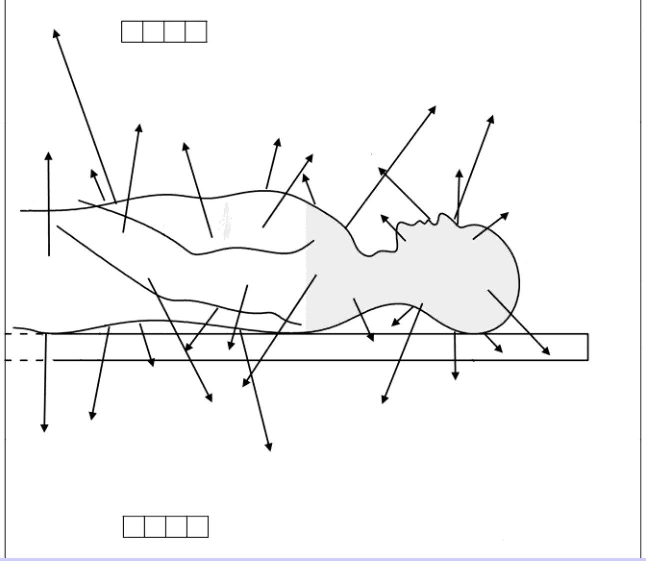
$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$

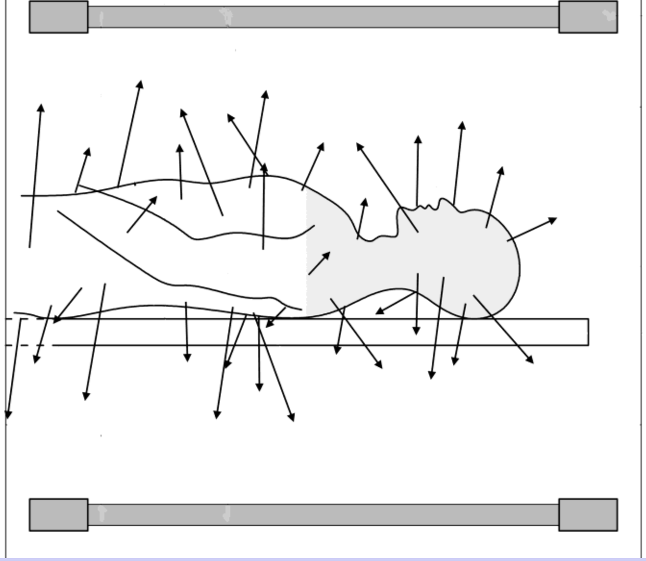
σ(t-hit) ~ 100 ps



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

Target material	Rate of registered o-Ps $\to 3\gamma$ 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

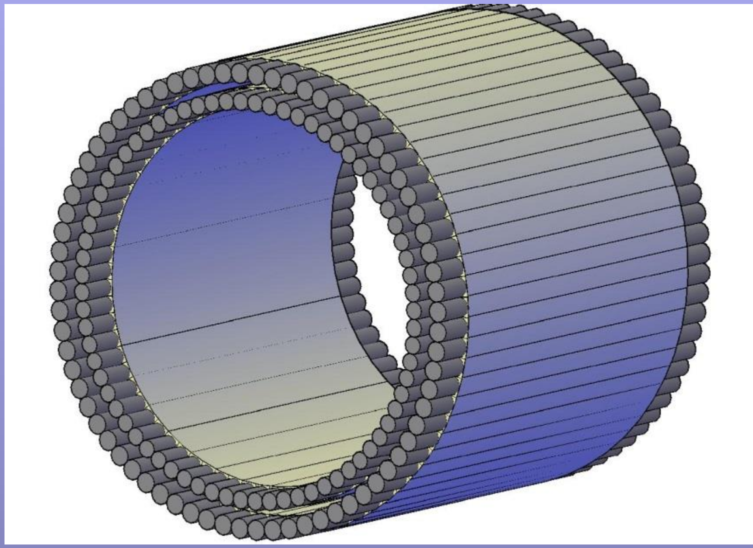




It is important to note that the cost of J-PET does not increase with the increase of the FOV

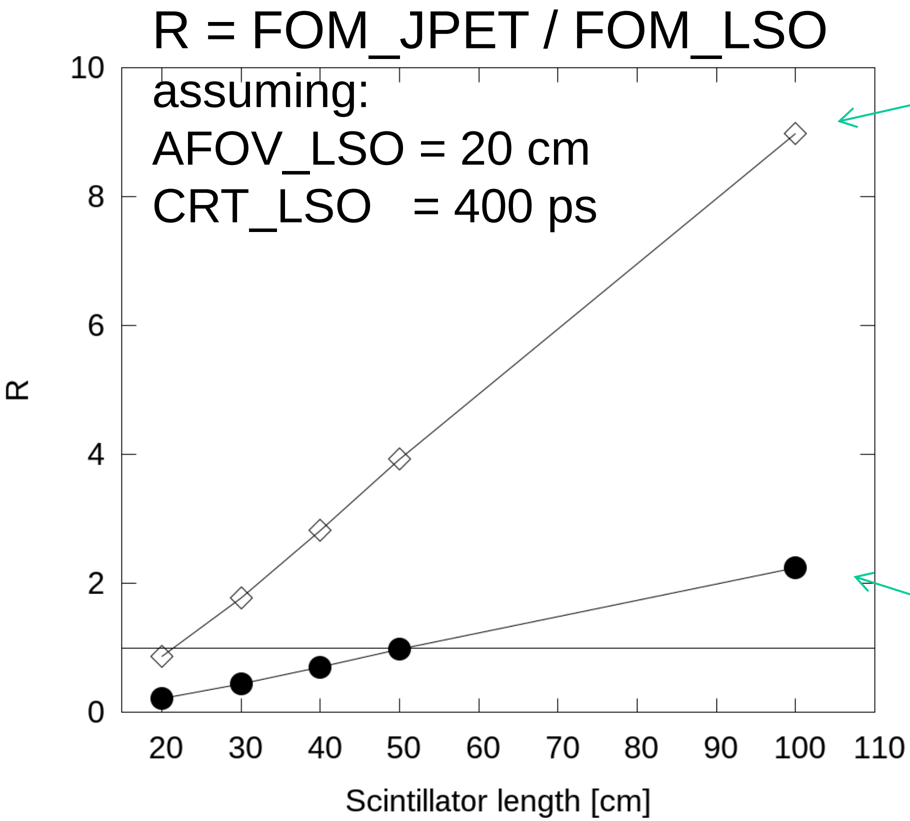
epsilon^2 = 20 to 40 smaller efficiency

But



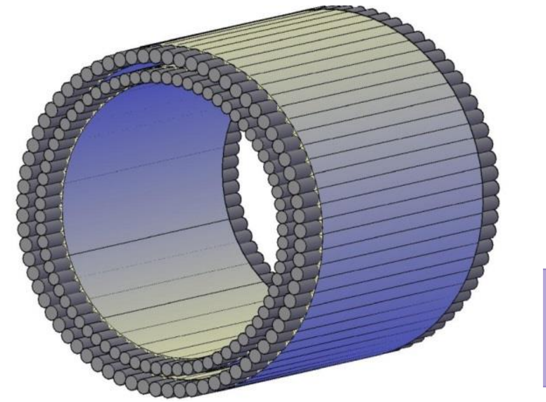
Solid angle --------------------- > factor of ~5
600 ps --> 200ps – 300ps --> factor of 3 -- 2
1m instead of ~17 cm ---------> factor of 10
N layers in the strip-PET ----> factor **N^2**

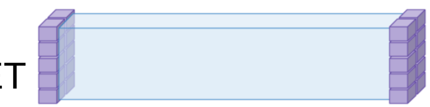
Conservatively:
for N=1 ----> total factor of ~ 100
Lower dose by factor of 3 (100 better / 30 worse)



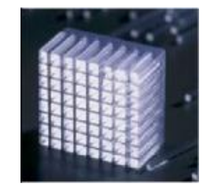
N_JPET_layers = 2

N_JPET_layers = 1





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



LSO

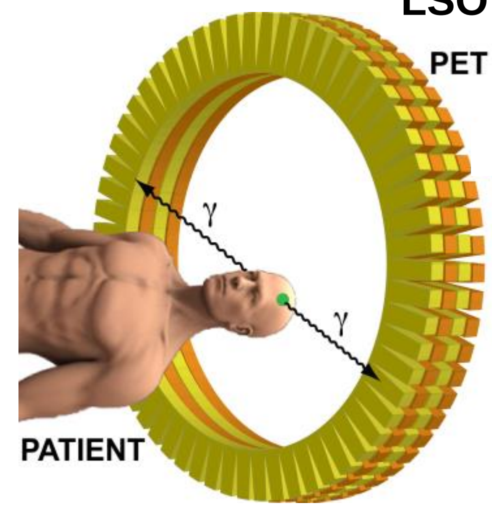
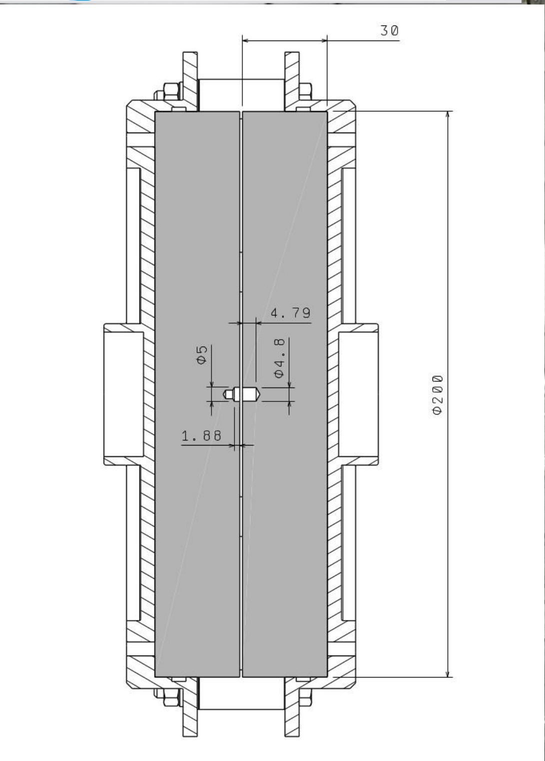
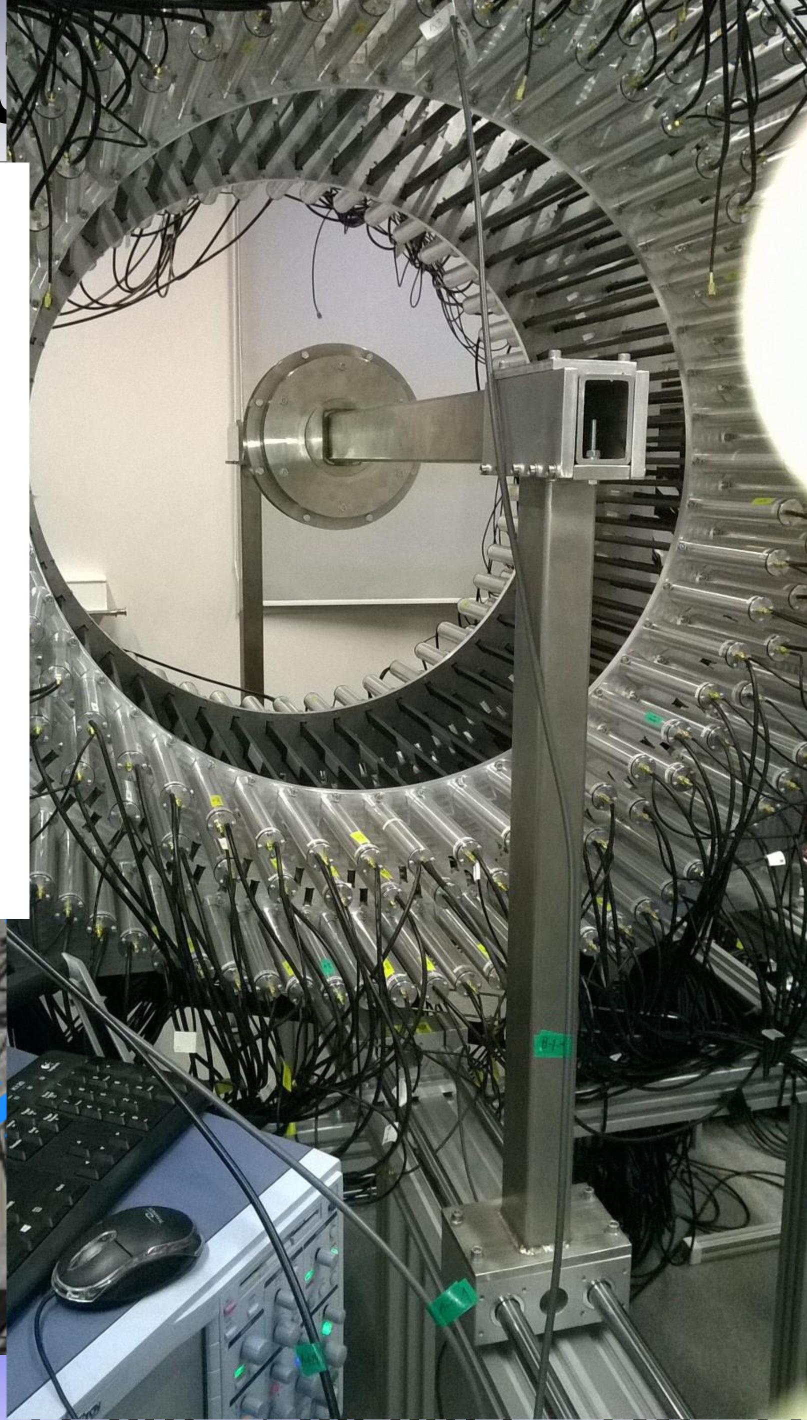


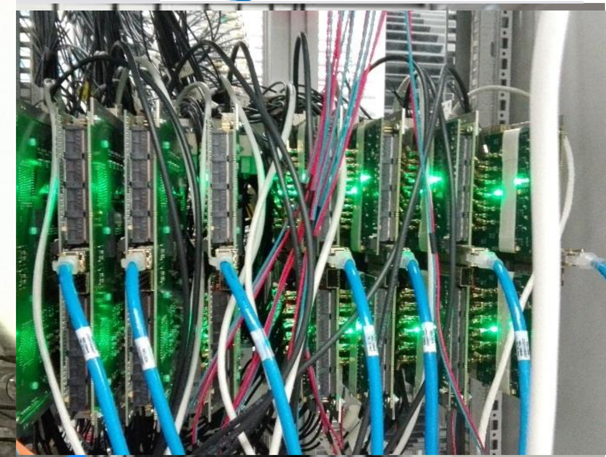
Figure of Merit for whole body imaging (FOM):

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

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







AFOV:

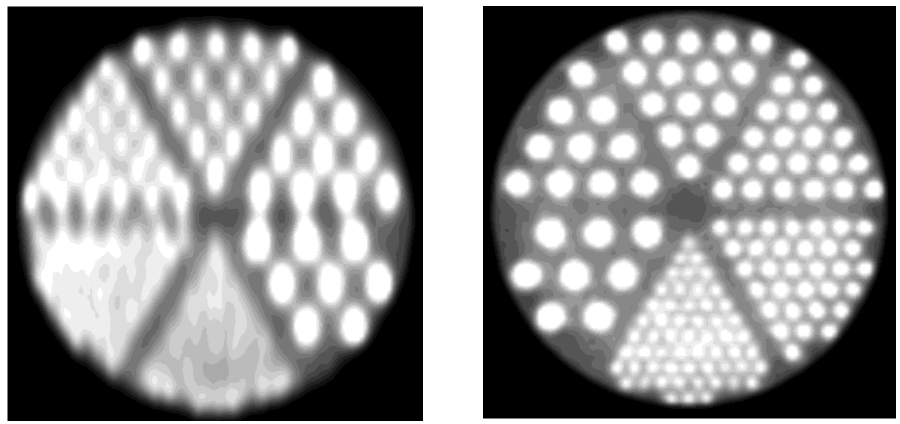
500 ps

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



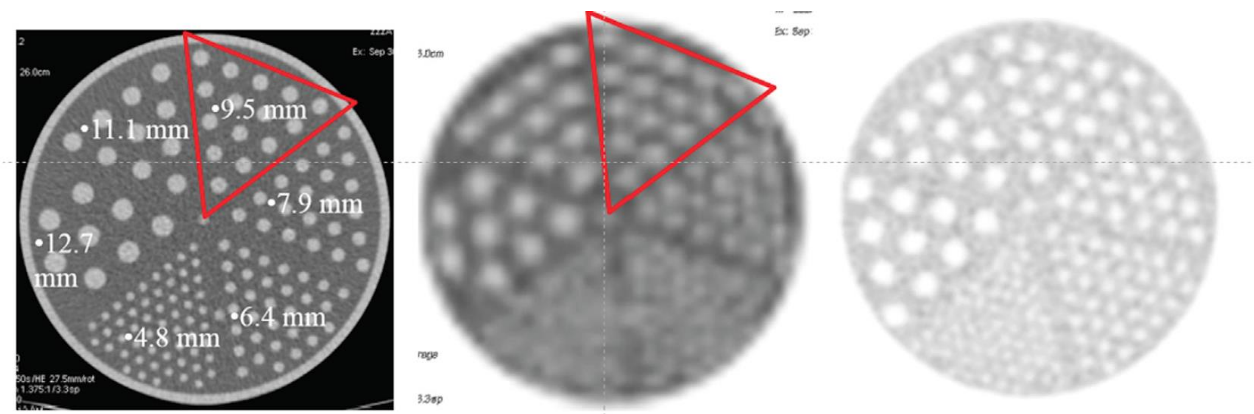
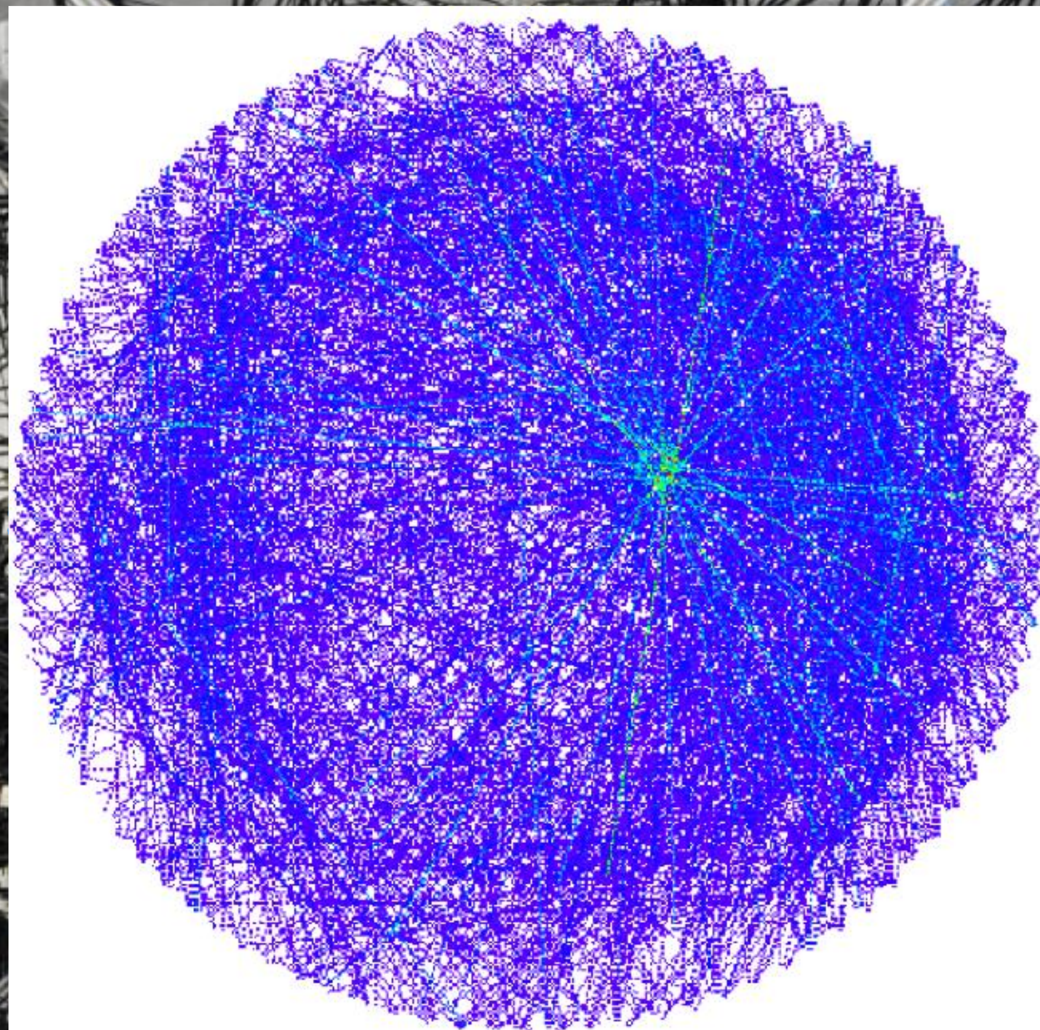


Figure from P. Slomka, T. Pan, G. Germano, Semin. Nucl. Med. 46 (2016) 46

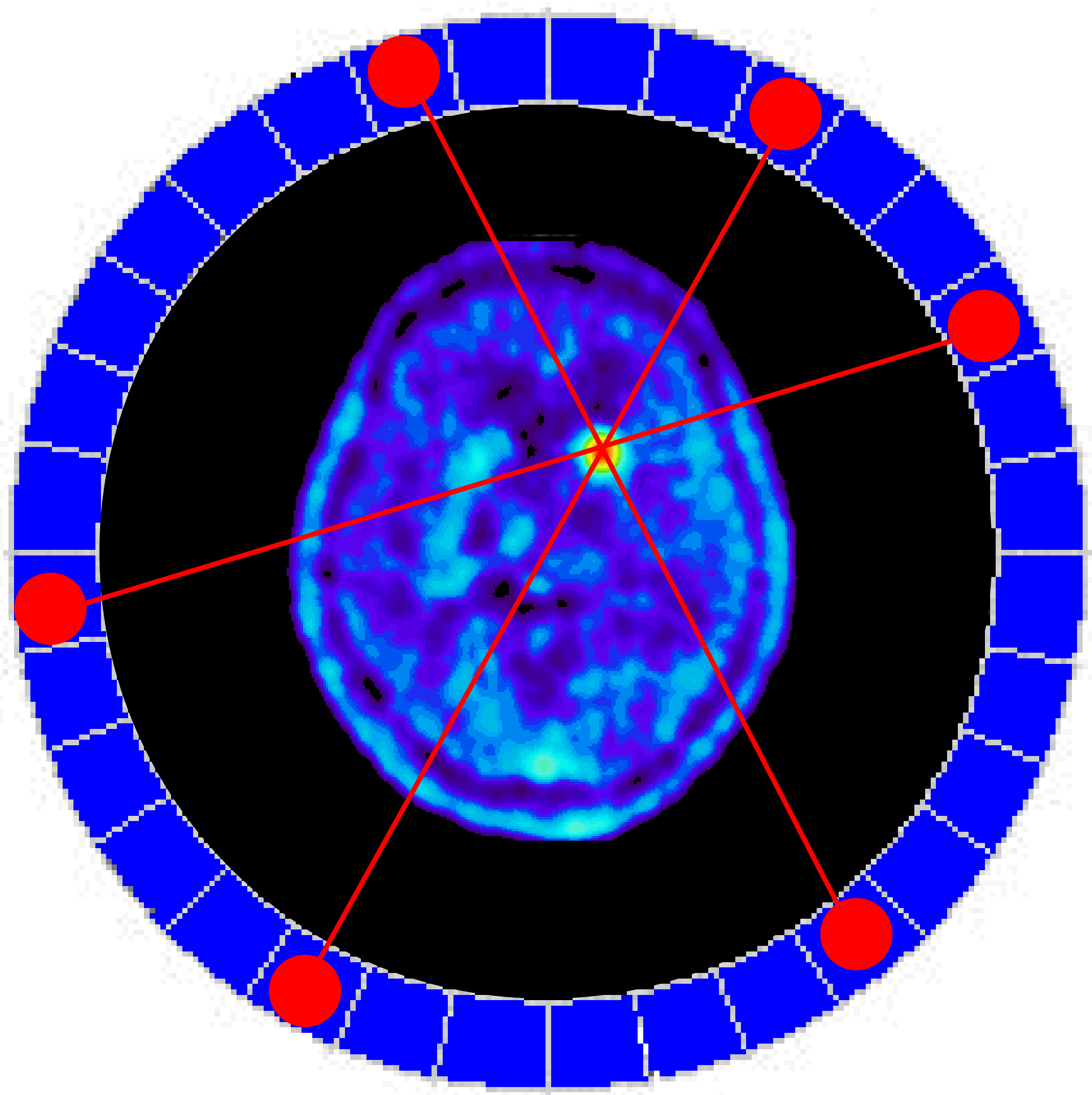
Digital PET, courtesy of Jun Zhang (PhD), Michael V. Knopp (MD, PhD), The Ohio State University

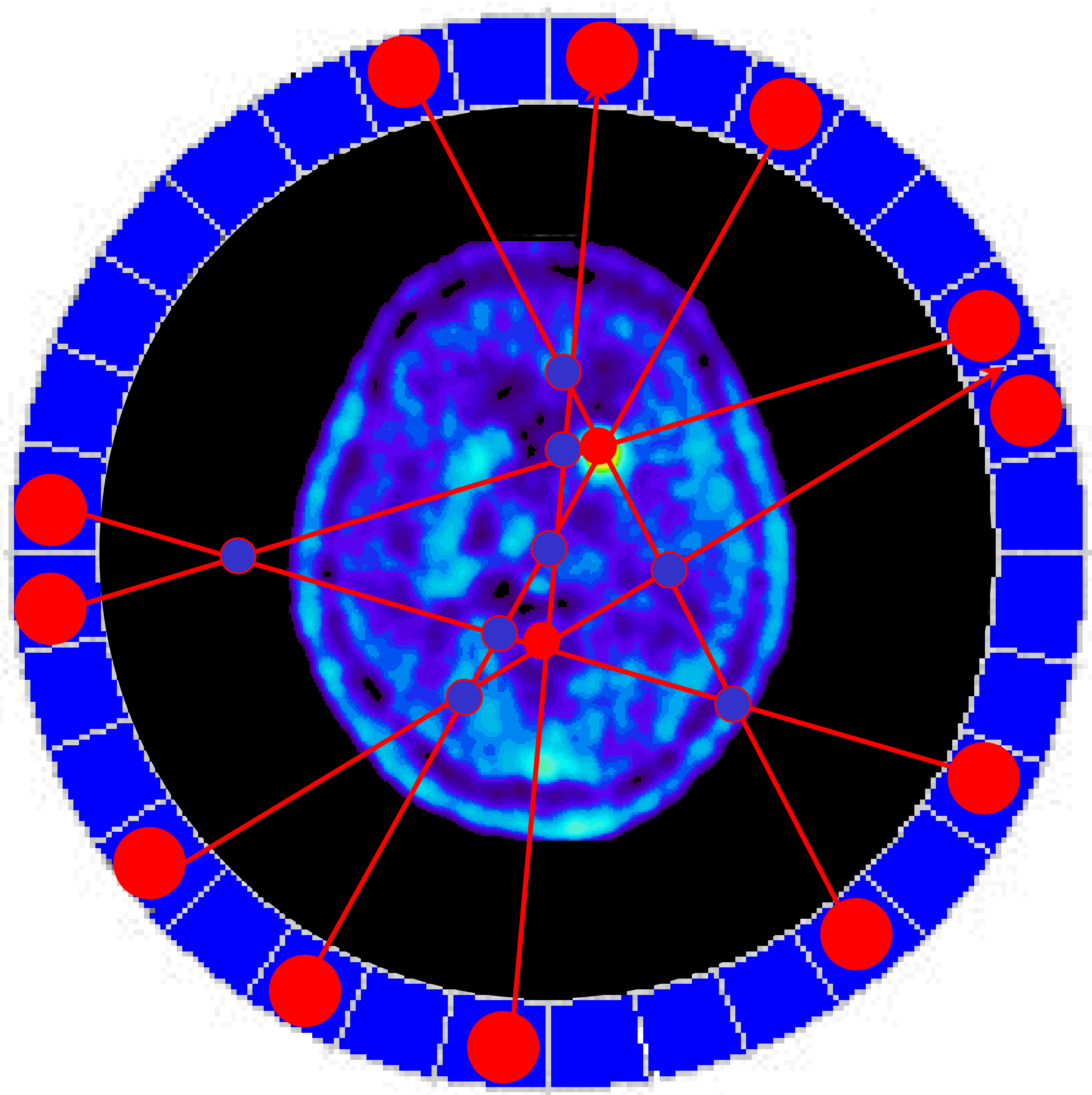
Jagiellonian PET

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



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

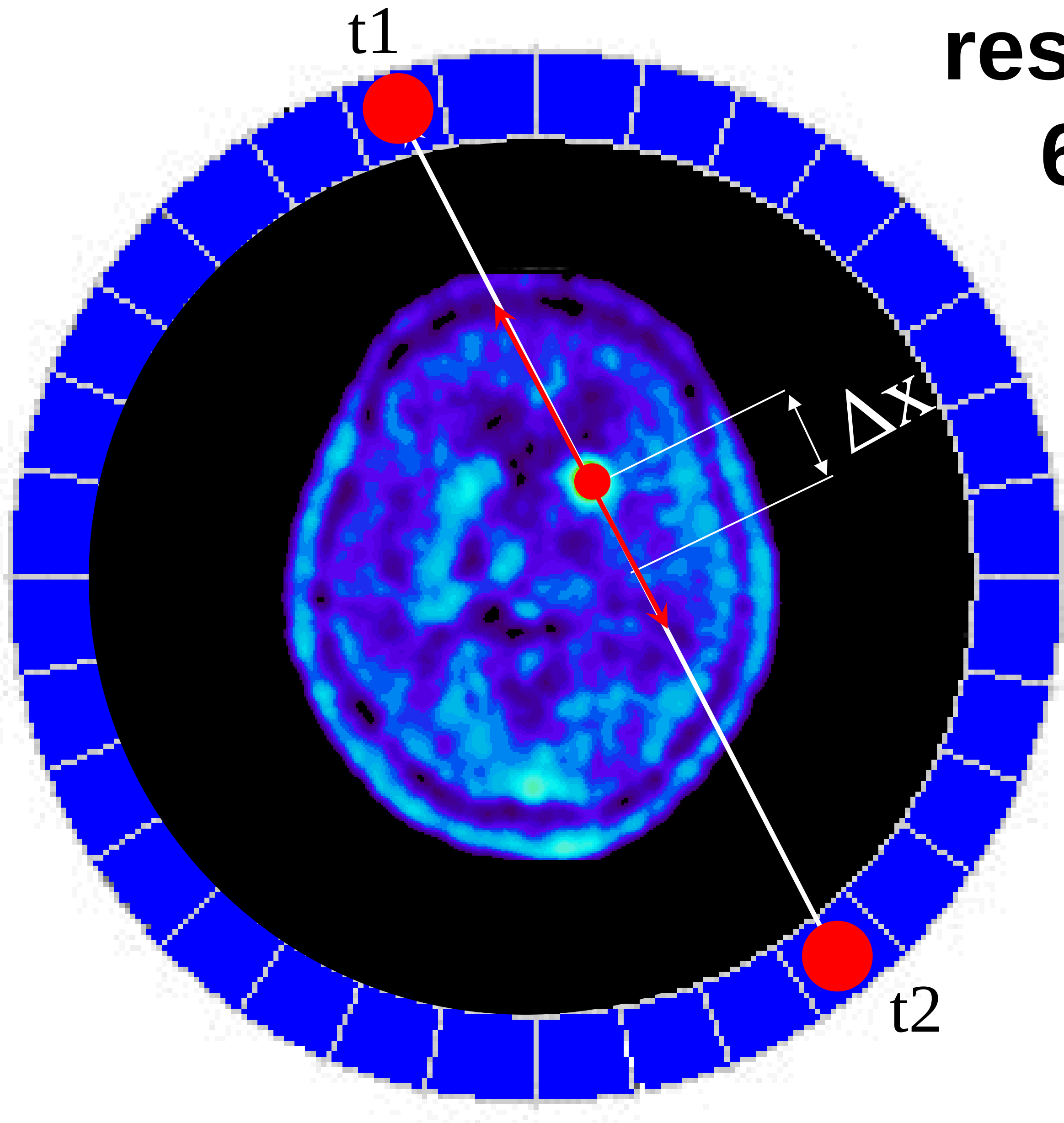


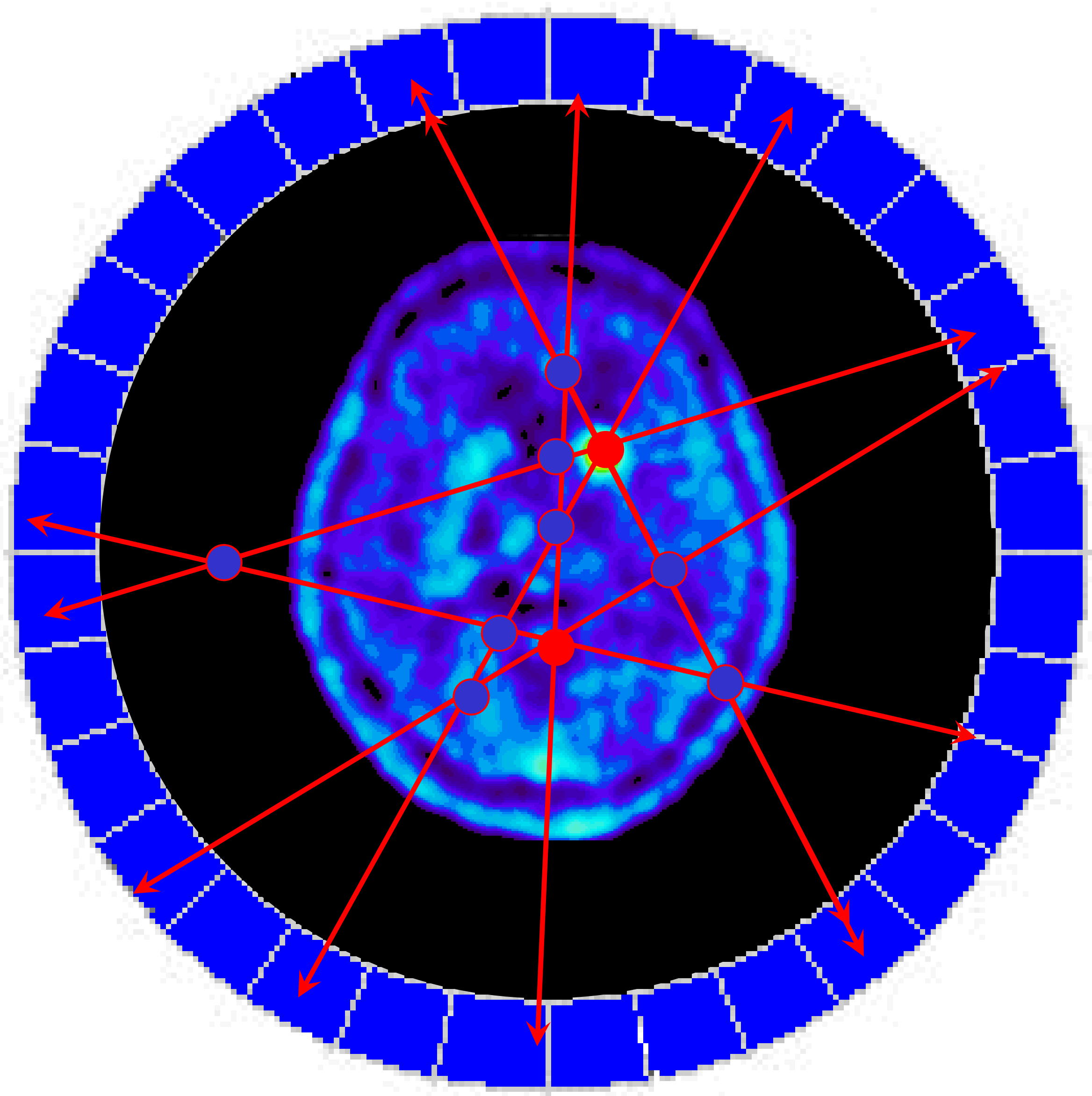


PET-TOF

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

resolution 600ps



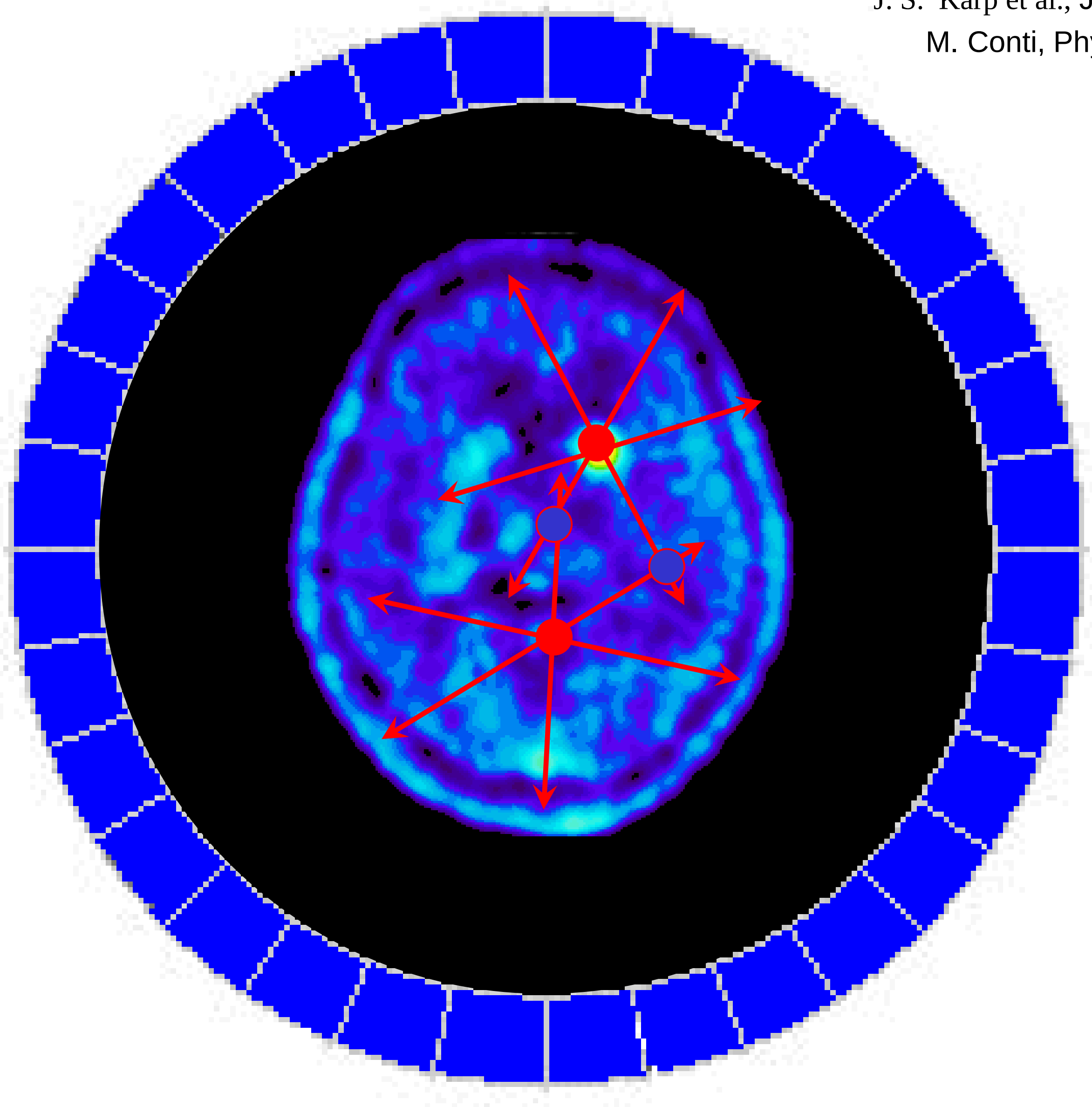


signal/noise
$\sim D / \Delta t$

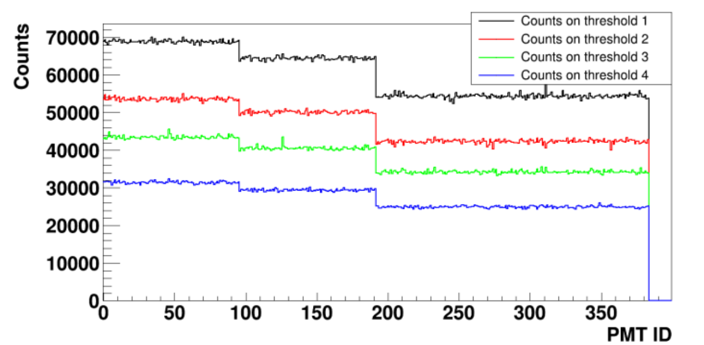
40cm/600ps

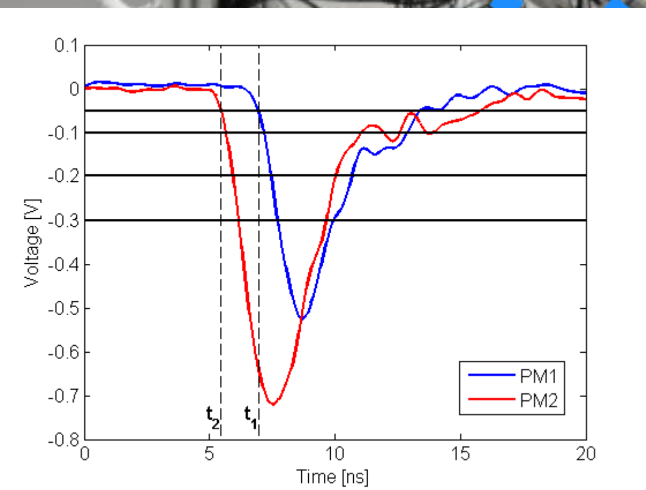
czterokrotna poprawa

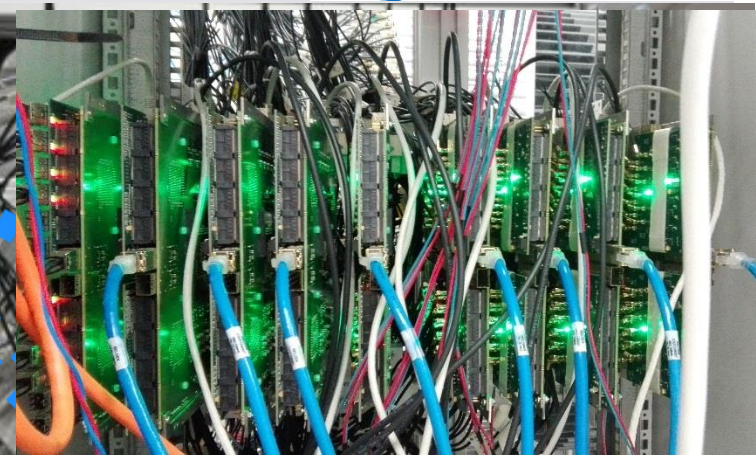
J. S. Karp et al., J Nucl Med 2008; 49: 462
M. Conti, Physica Medica 2009; 25: 1.

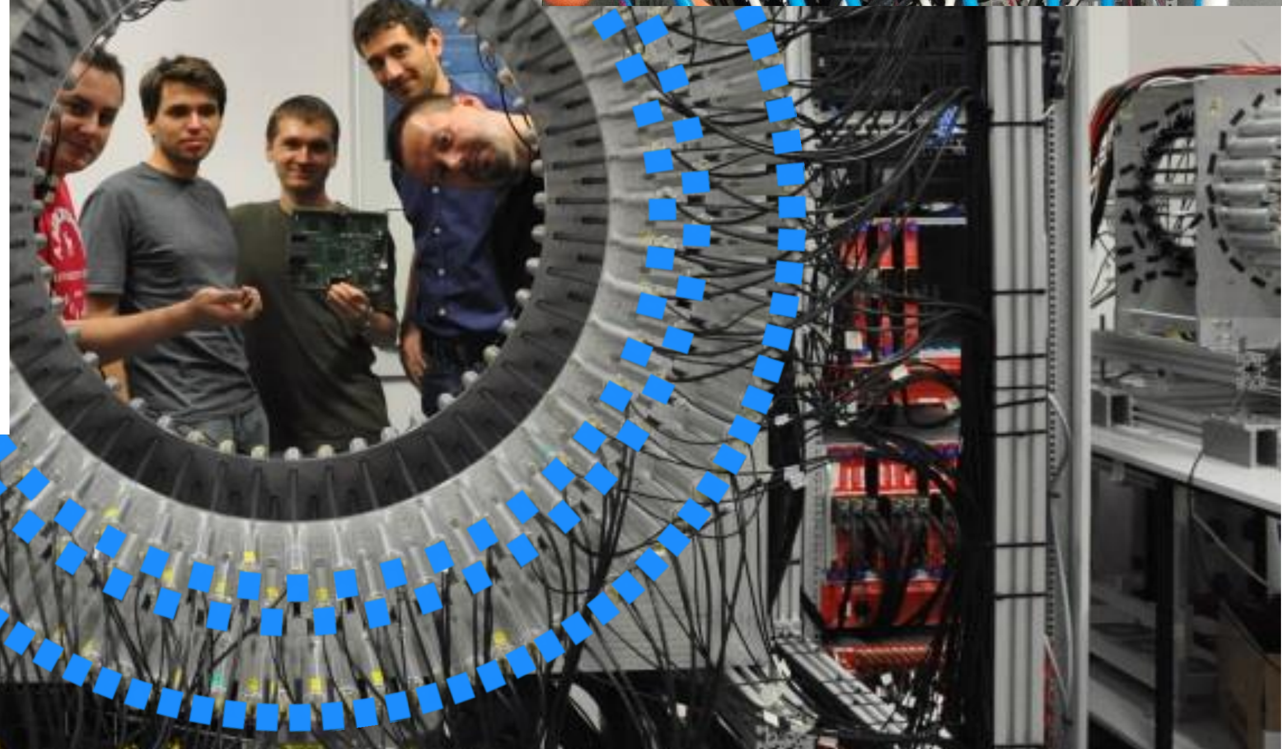


Jagiellonian PET



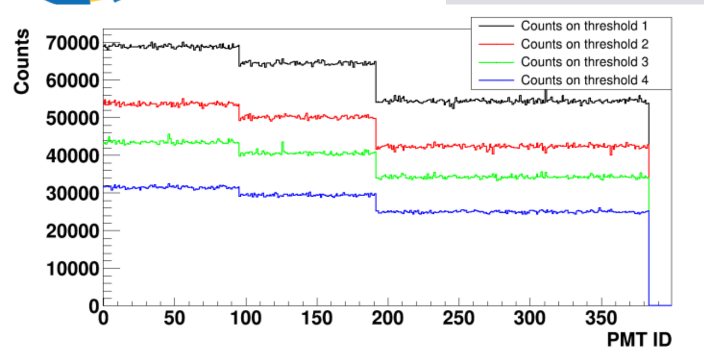


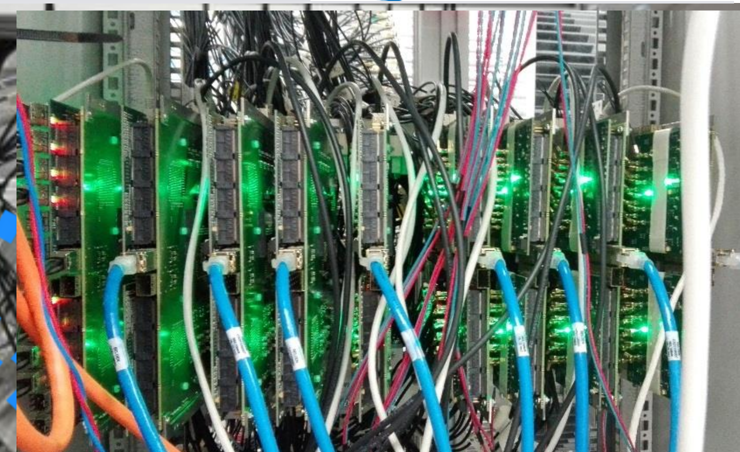


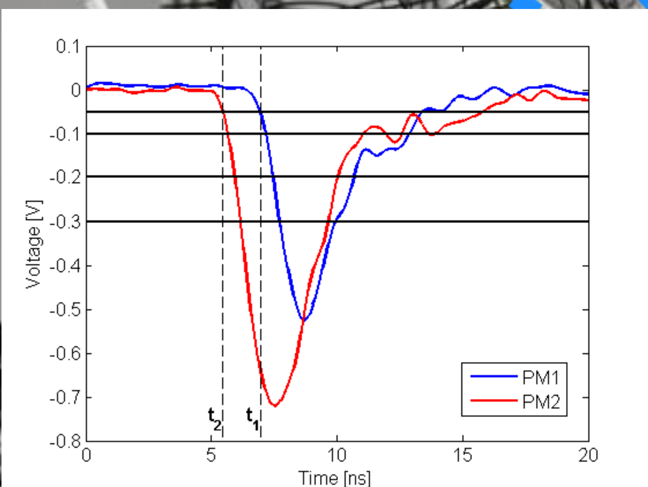


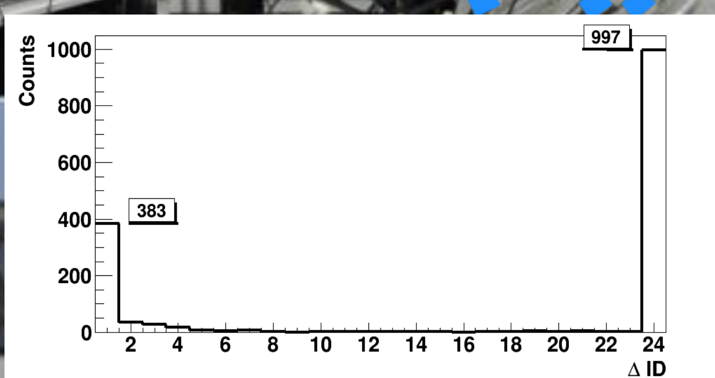
AFOV: 50 cm ; TOF < 500 ps

Jagiellonian PET



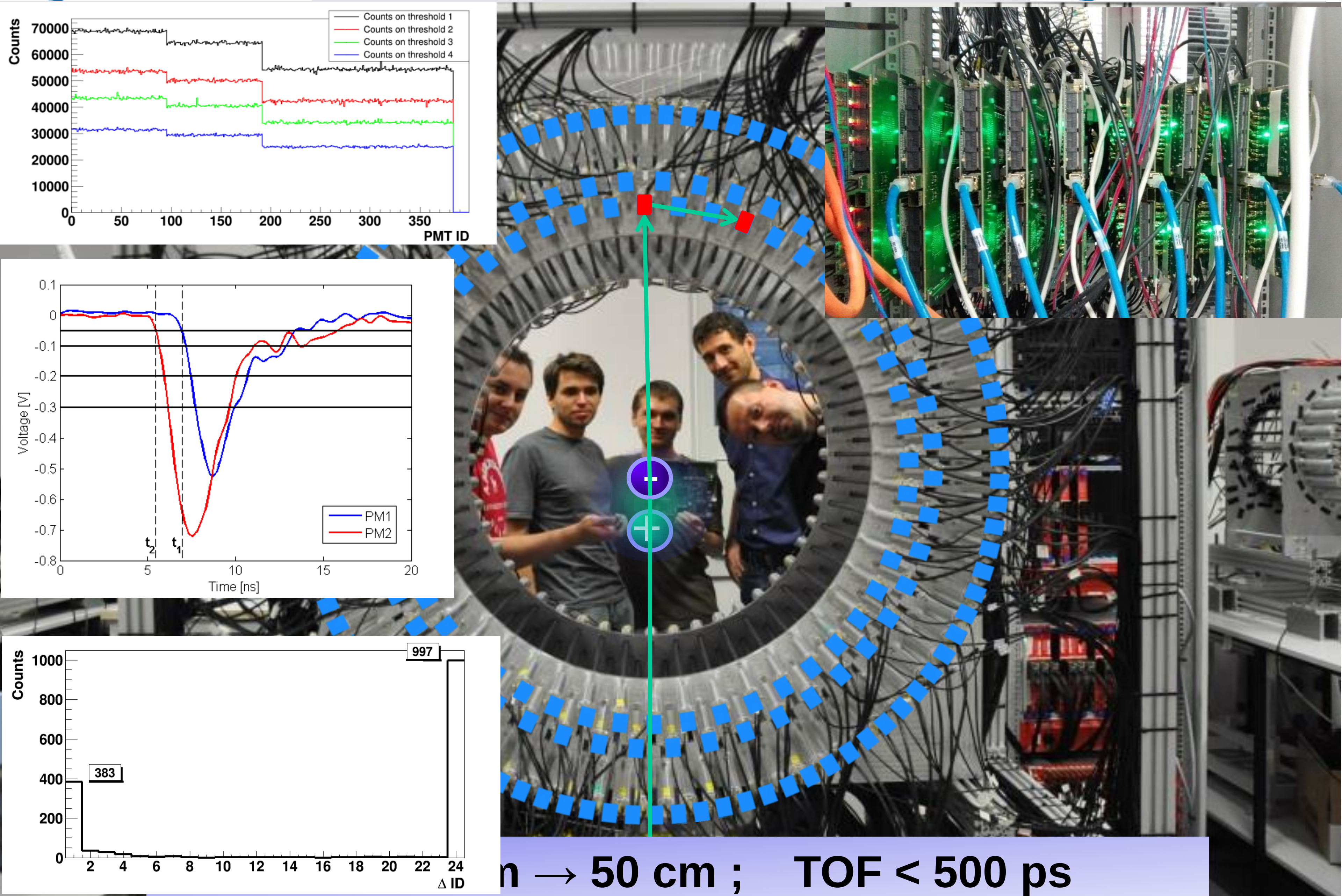




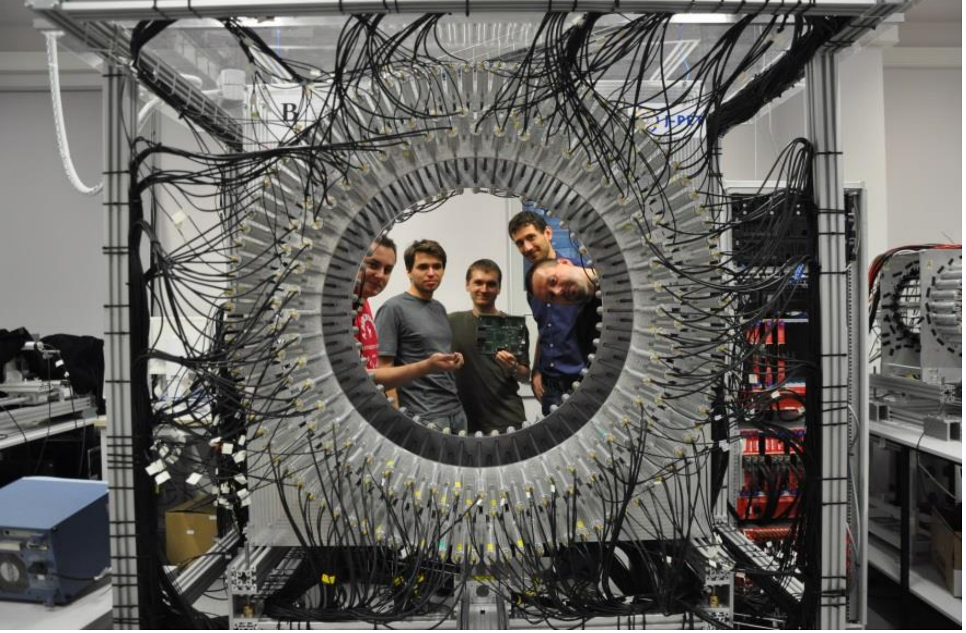


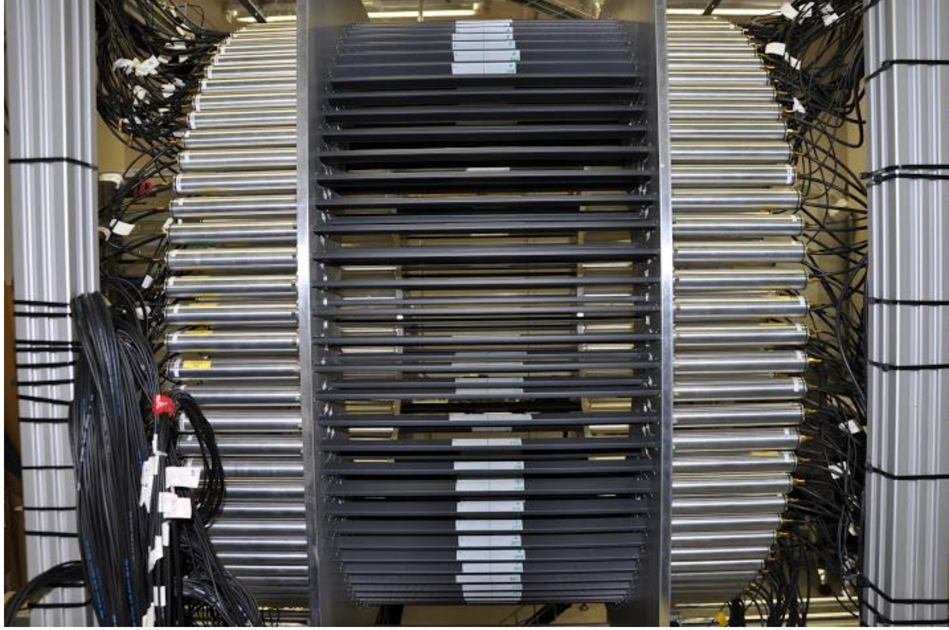
→ 50 cm ;   TOF < 500 ps

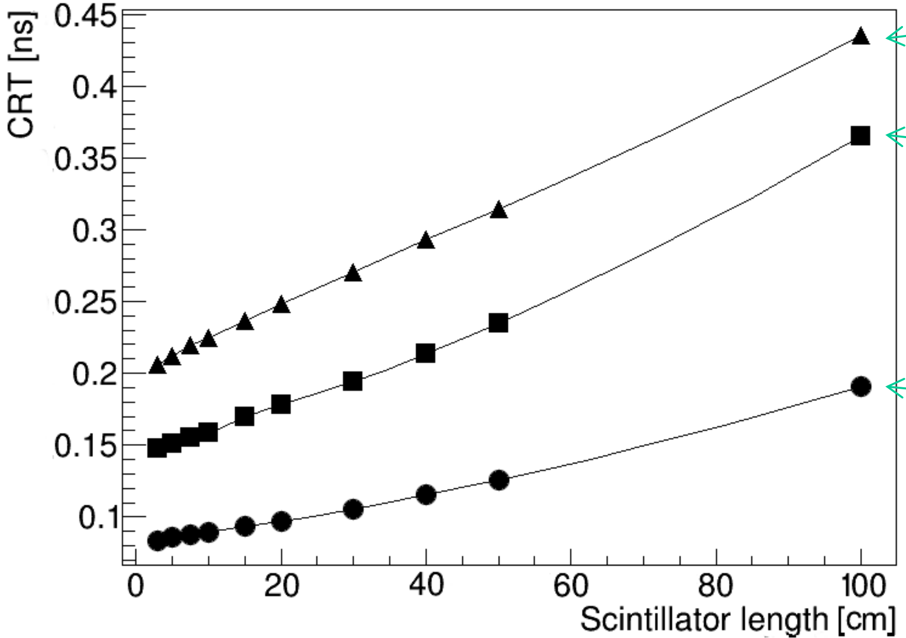
Jagiellonian PET

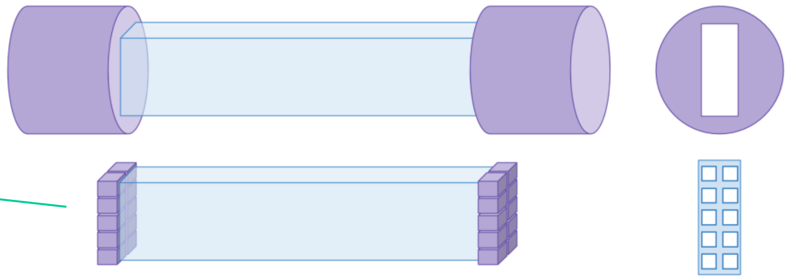


n → 50 cm ; TOF < 500 ps





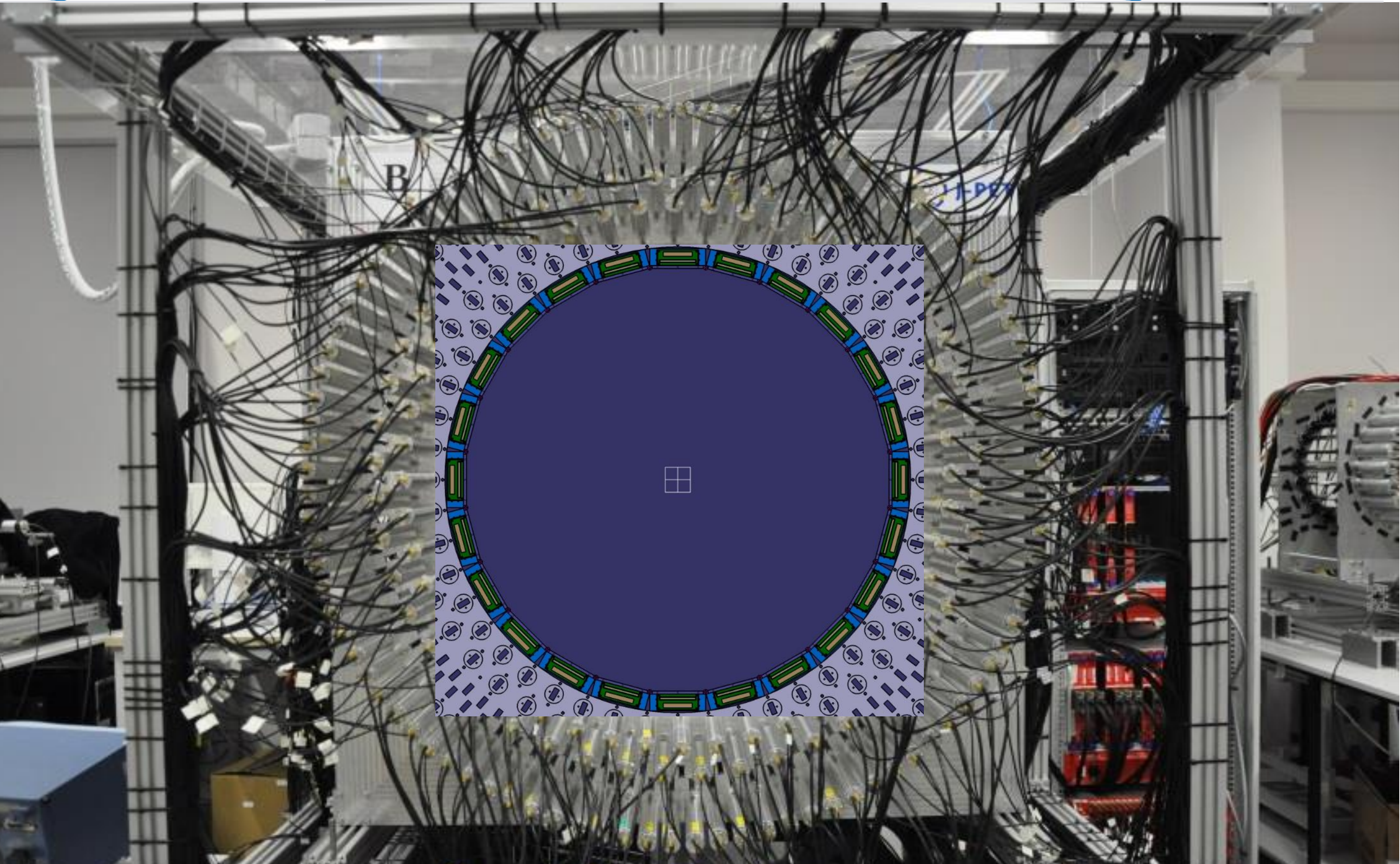




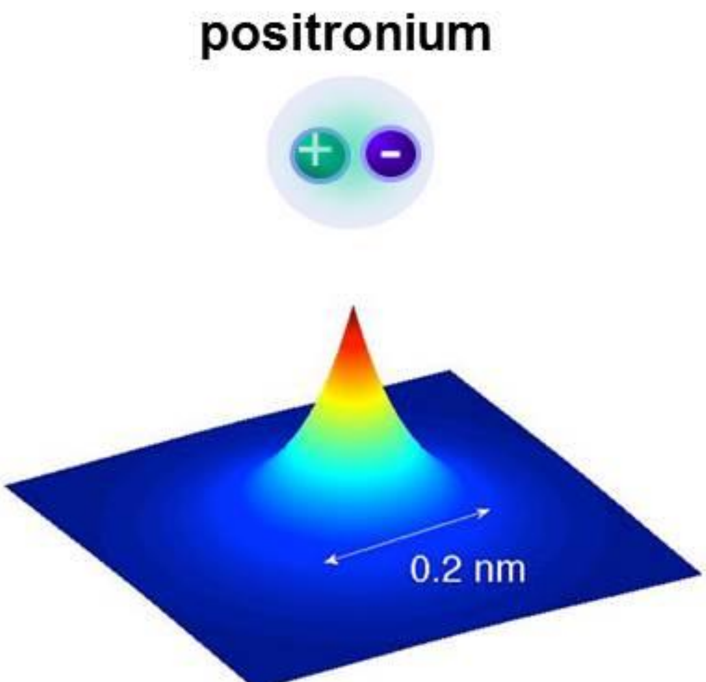
J-PET: P.M. et al., Phys. Med. Biol. 61 (2016) 2025

Limit of the J-PET

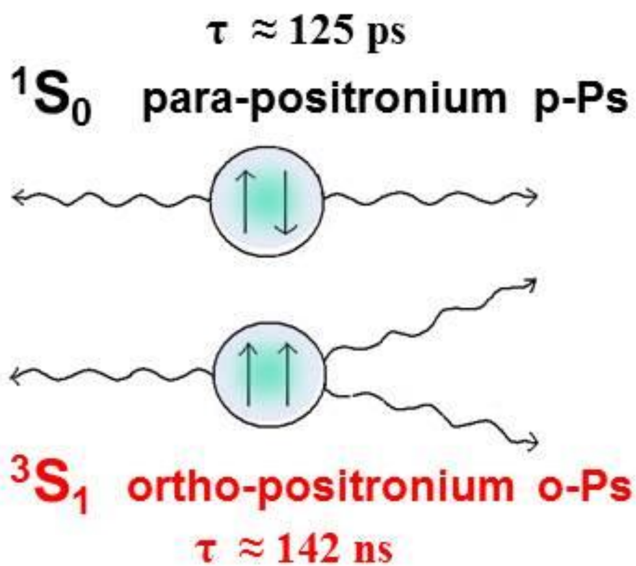
Jagiellonian PET

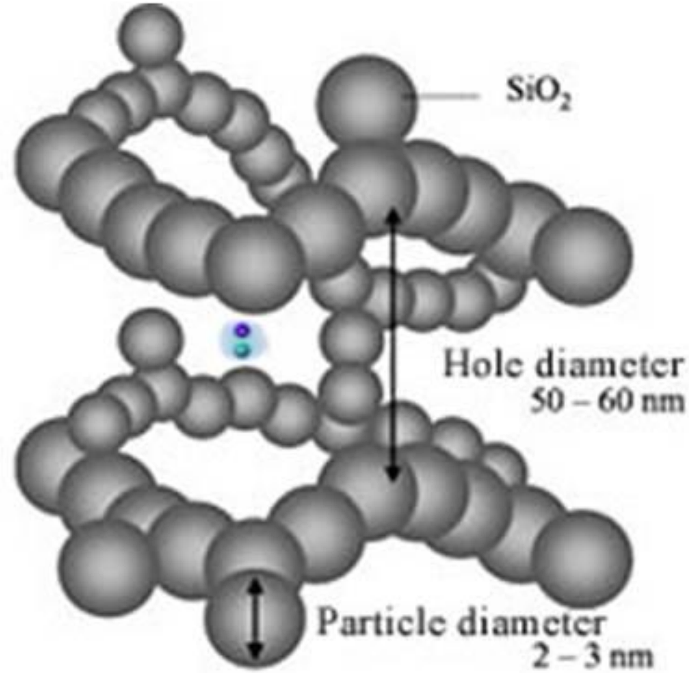


AFOV: 17 cm → 50 cm ;   TOF < 500 ps

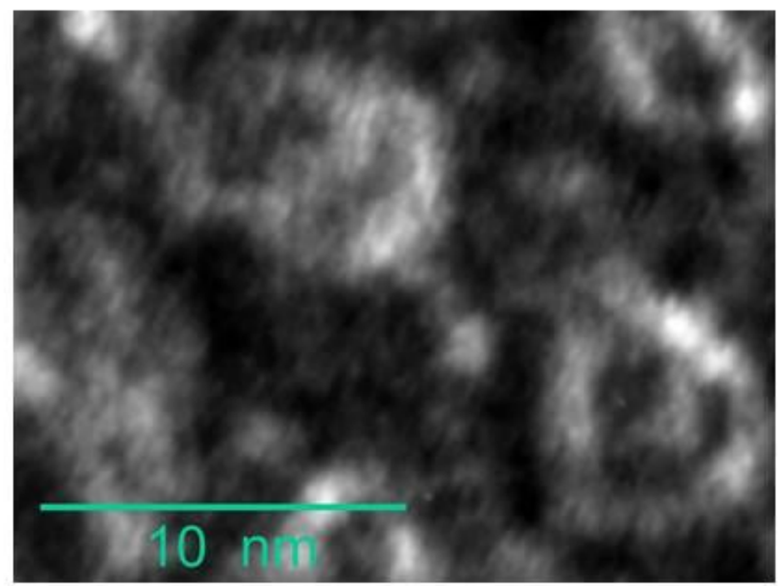


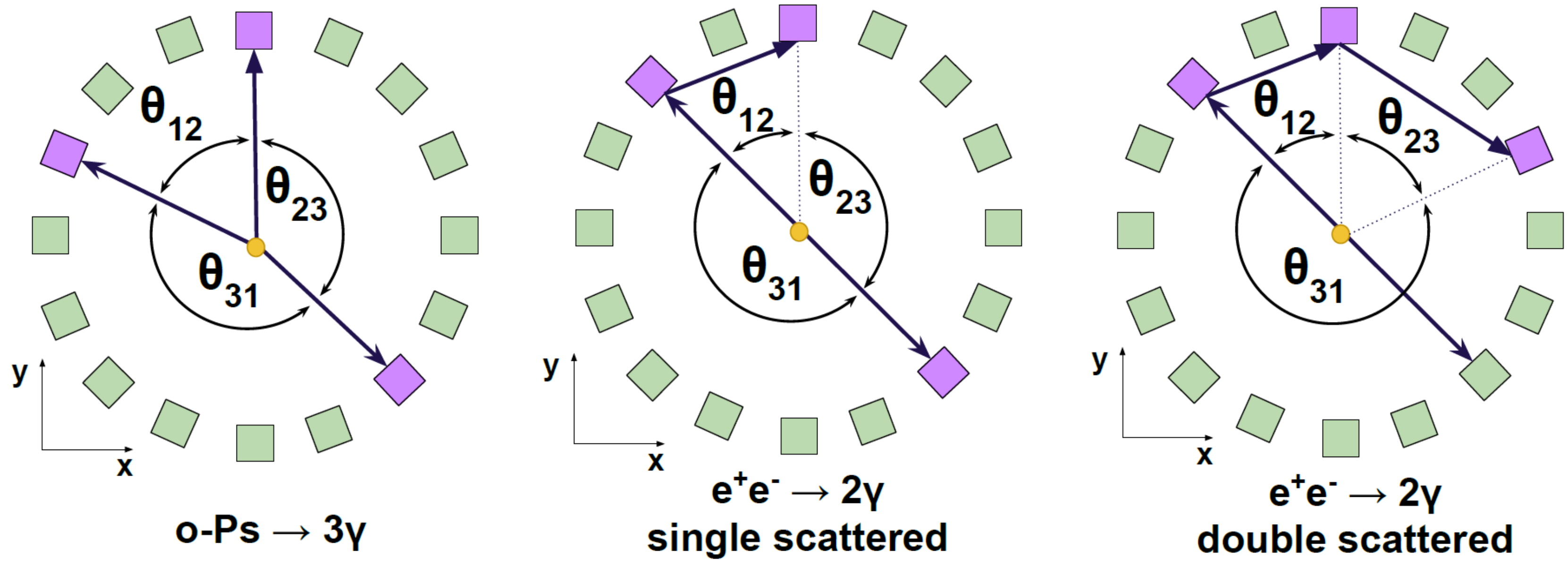
Y.H. Wang et al., PRA89 (2014) 043624+

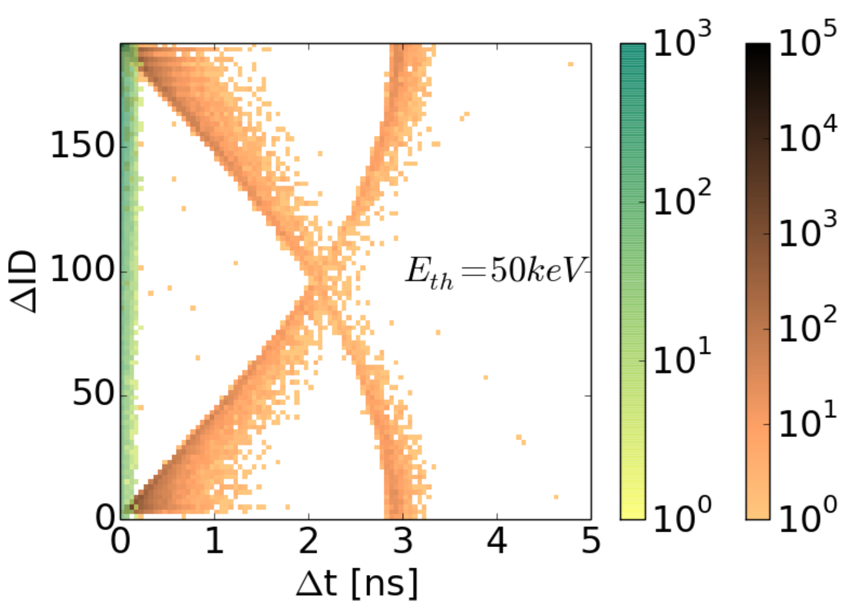


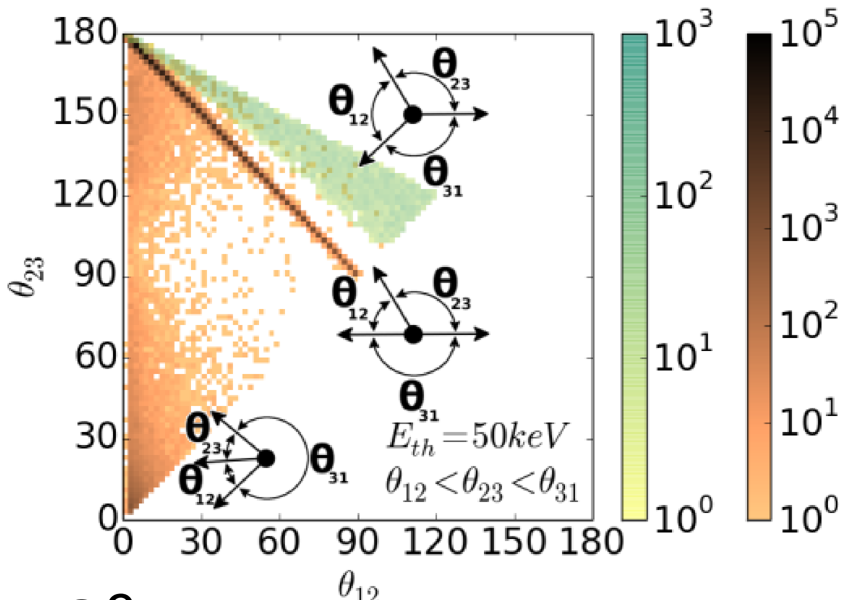


http://www.chem-eng.kyushu-u.ac.jp/e/research.html



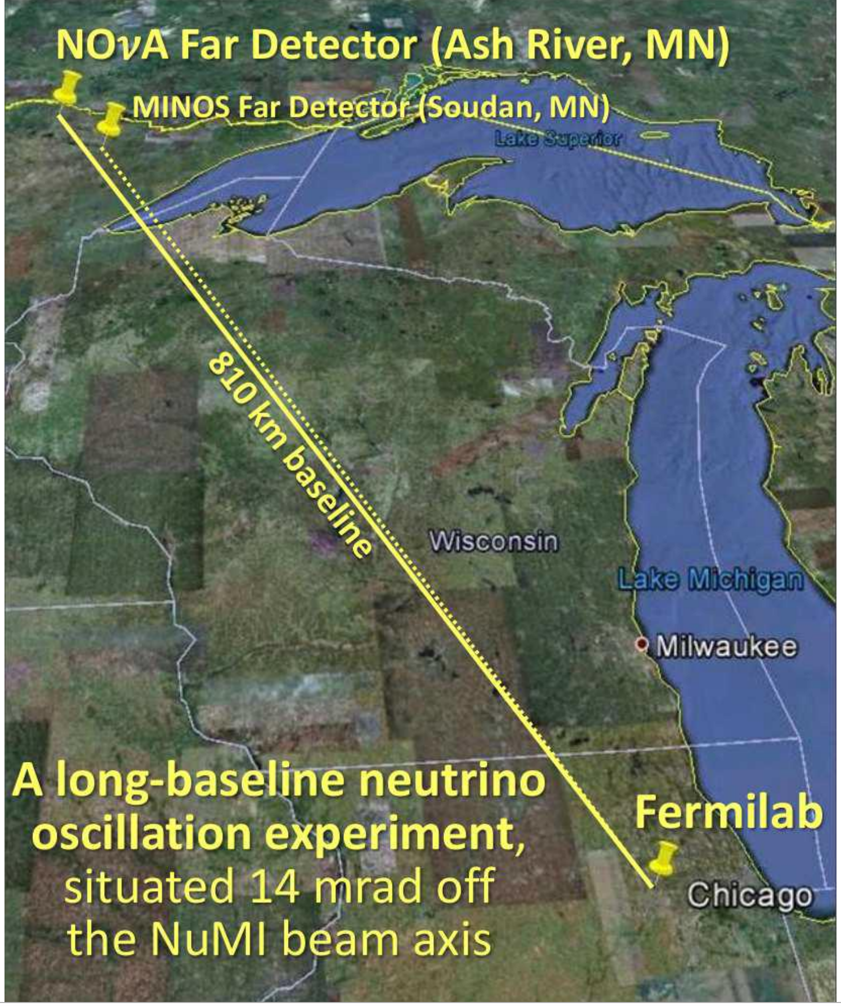


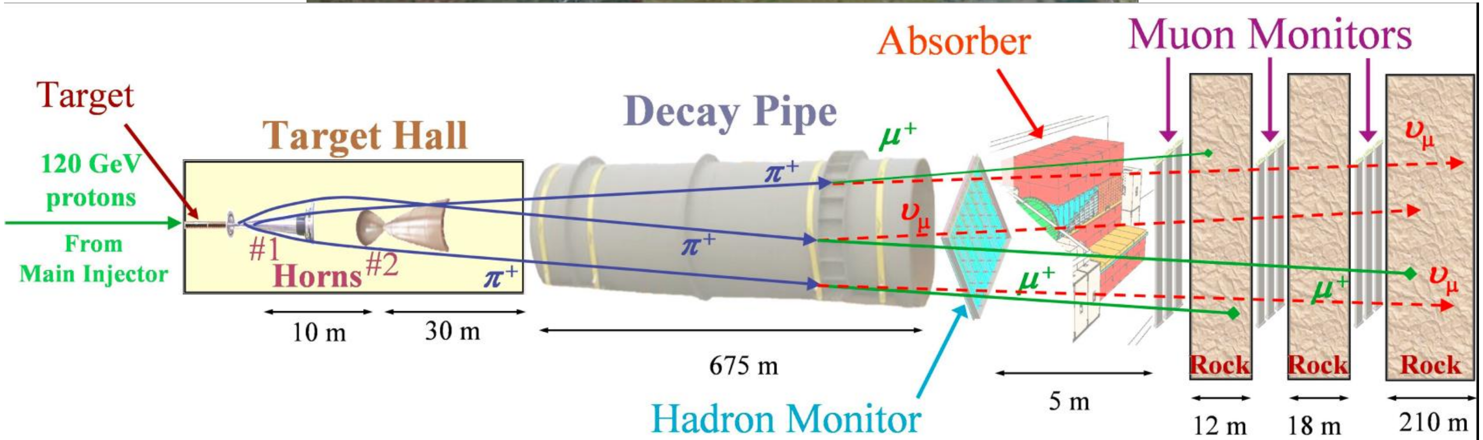




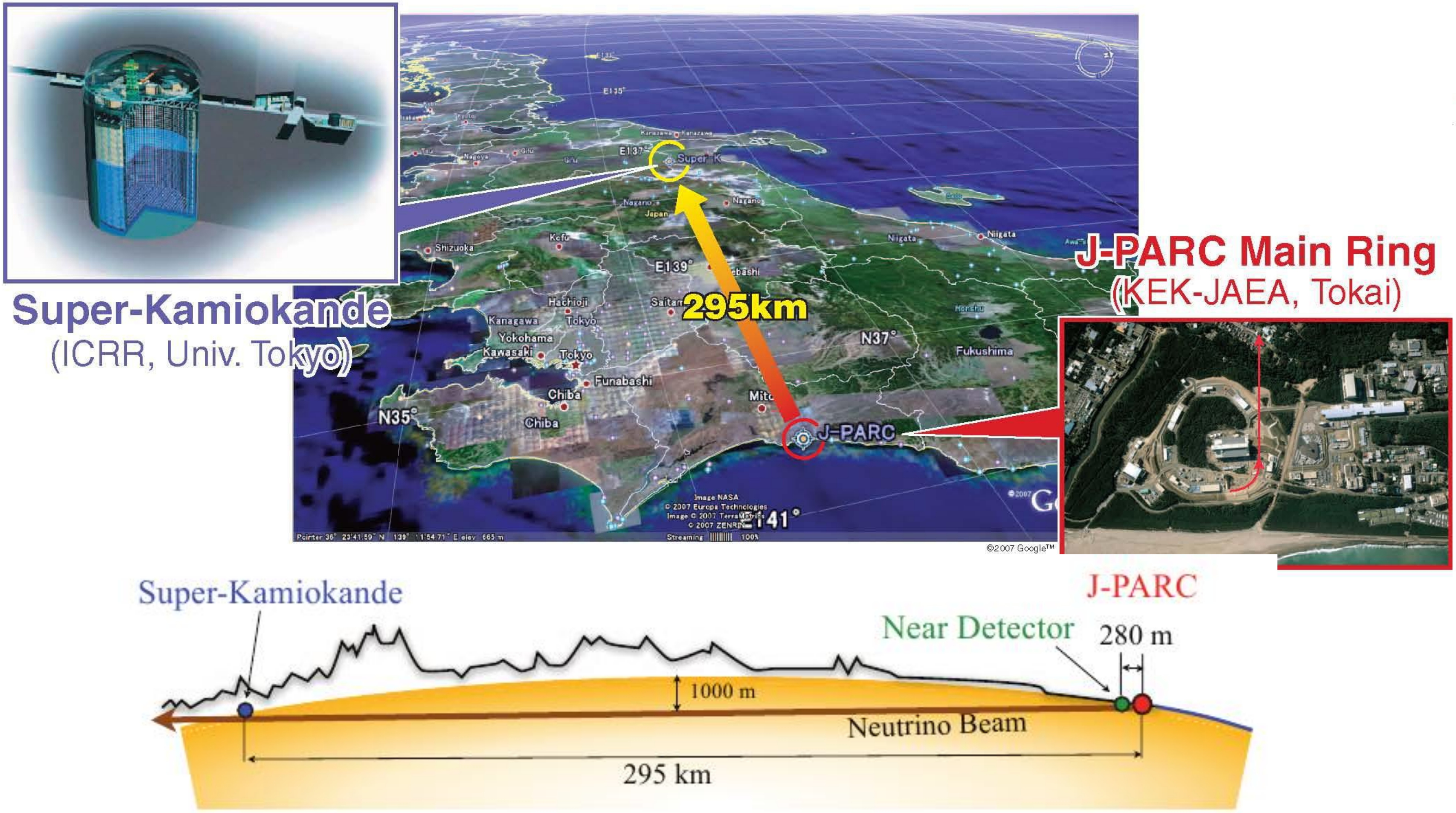
Reduction by factor 10^9

$\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$





T2K Tokai to Kamioka



RADIOACTIVE SUGER

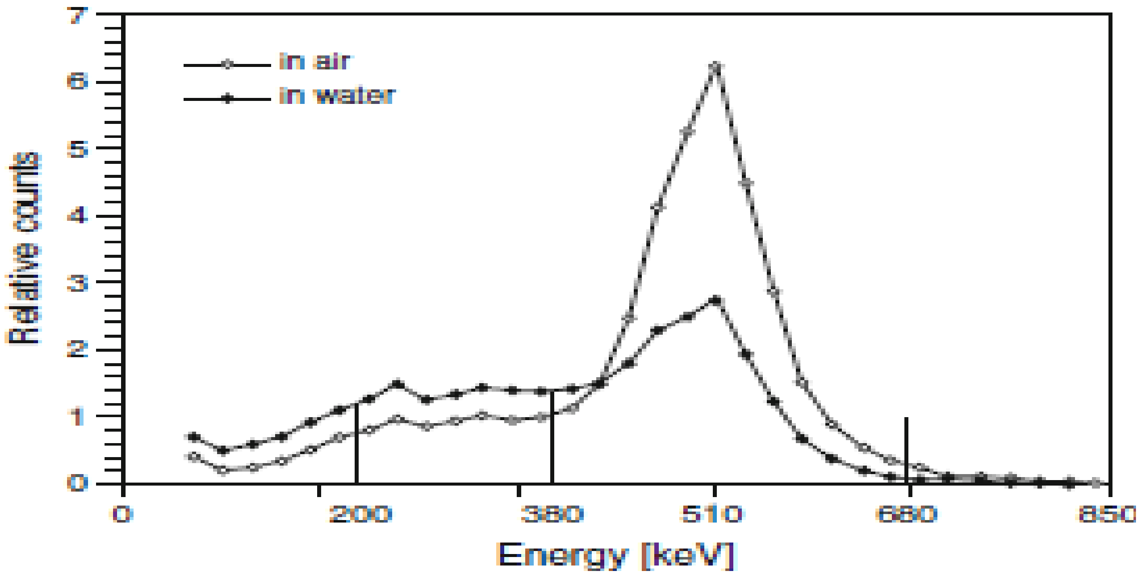
Fluoro–deoxy-glucose (F-18 FDG)

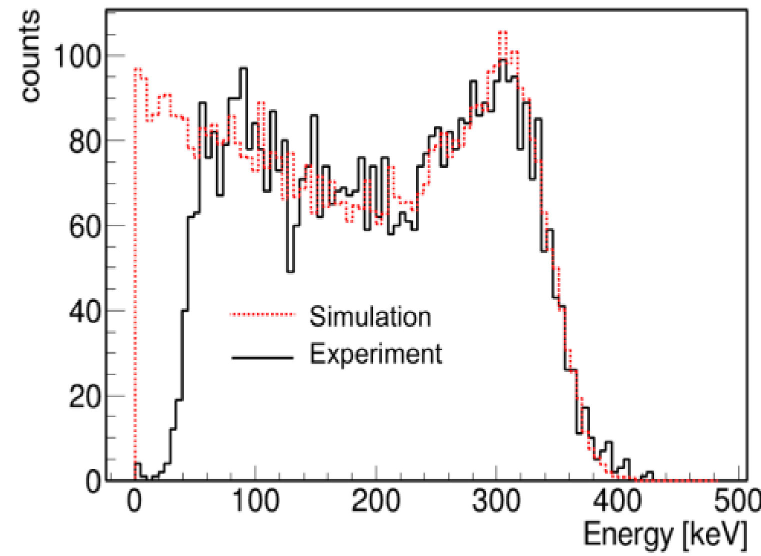
~200 000 000 gamma per second

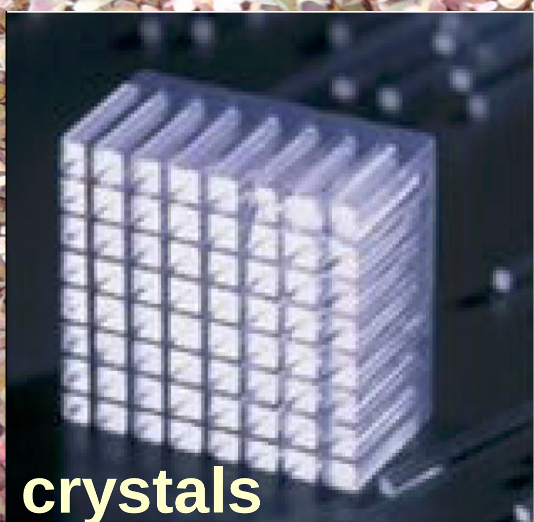
7 mSv PET/CT

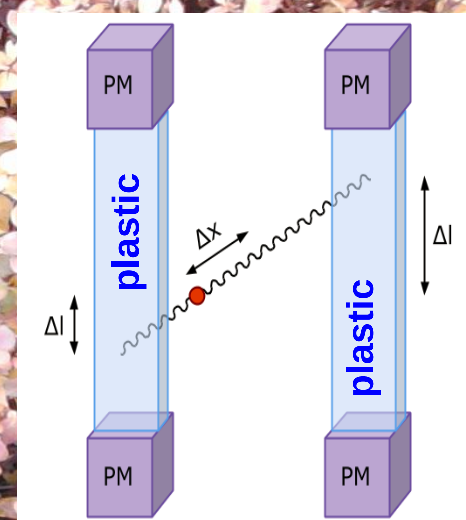
~ 2.5 mSv PET

~3 mSv natural background in Poland


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


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

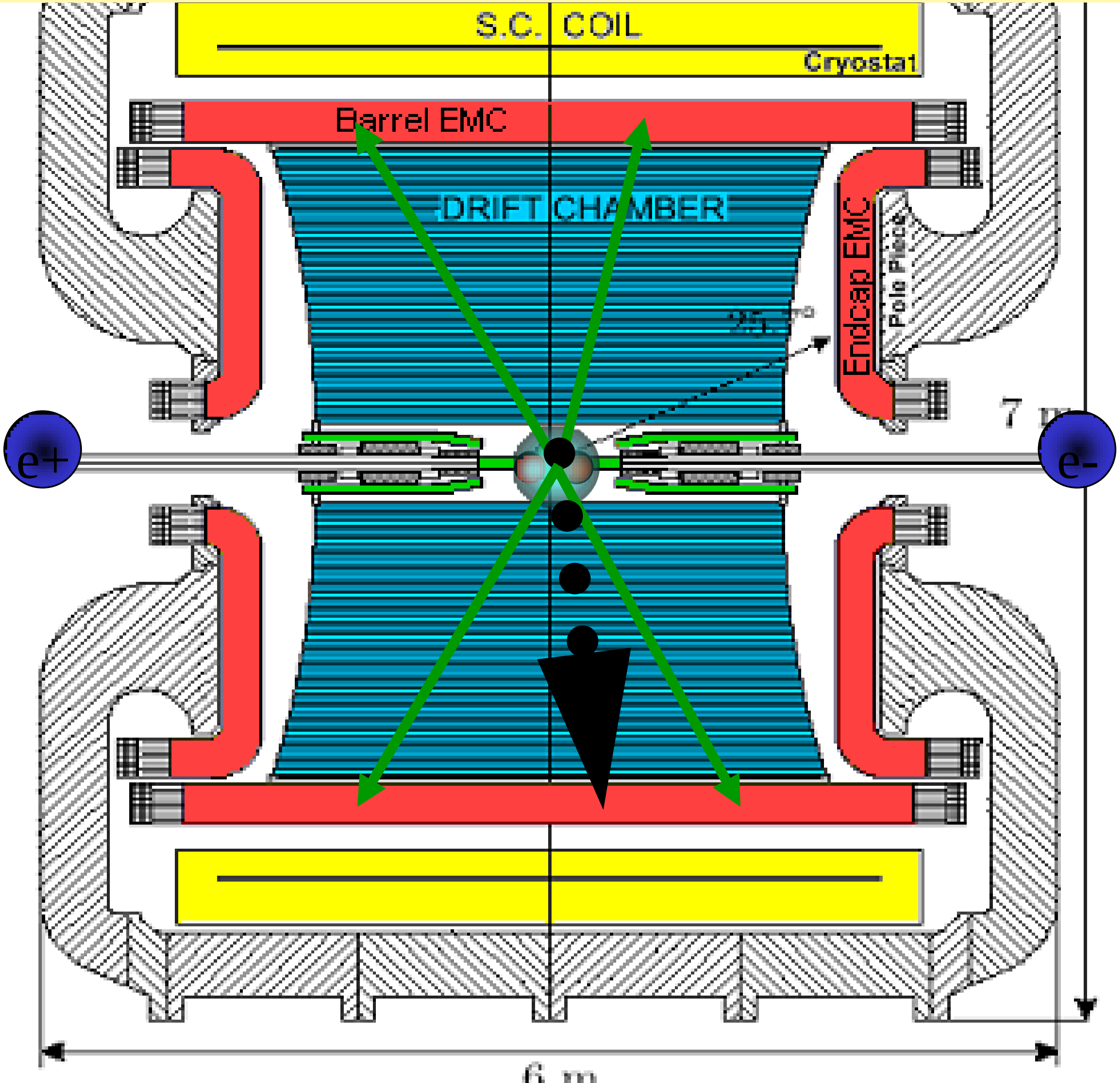

crystals


PM
PM
plastic
plastic
Δx
Δl
Δl
PM
PM

$e^+e^- \to \varphi \to \eta\gamma \qquad \eta \to \pi^+\pi^- e^+e^-$

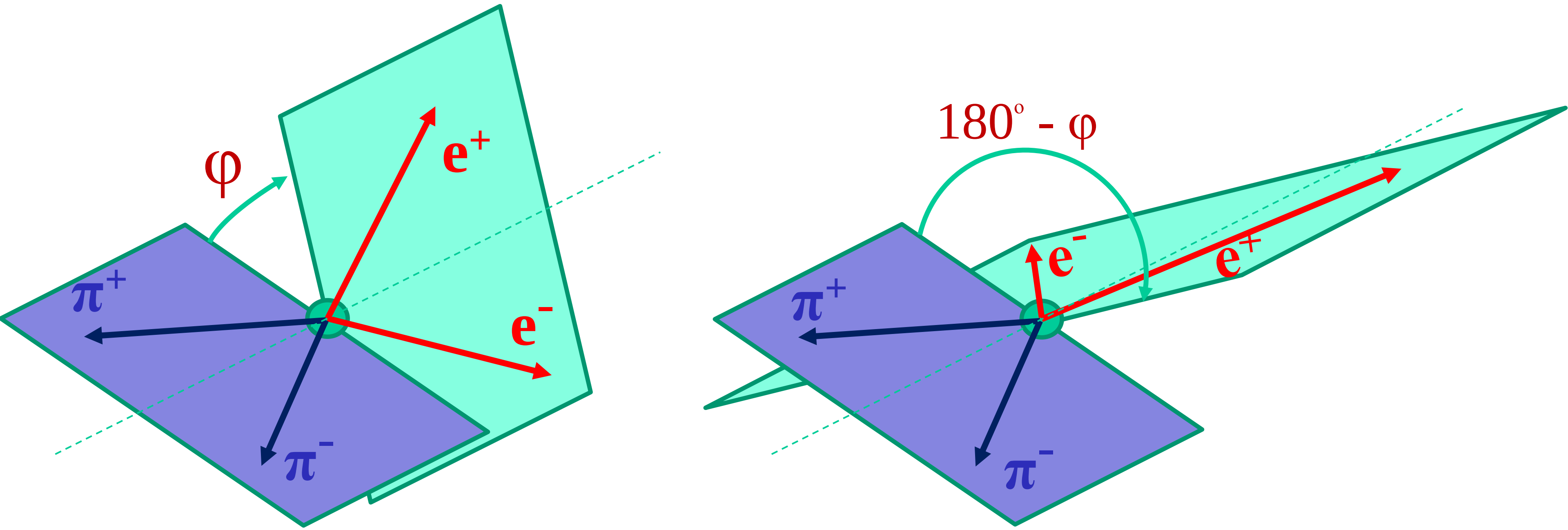
KLOE

K LOng Experiment



$\eta \rightarrow \pi^+\pi^- e^+e^-$

łamanie CP bez zmiany zapachu ?



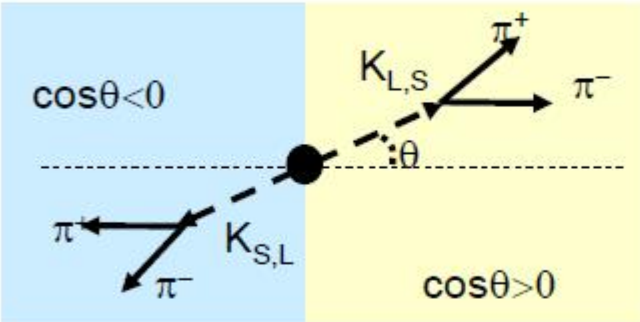
symetria CP implikuje N(φ) = N(180 – φ)

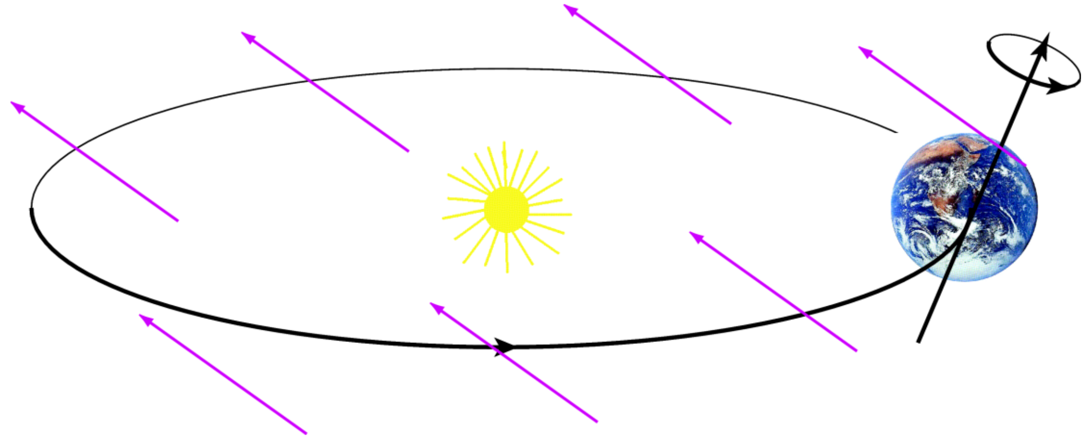
$$A_\phi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$

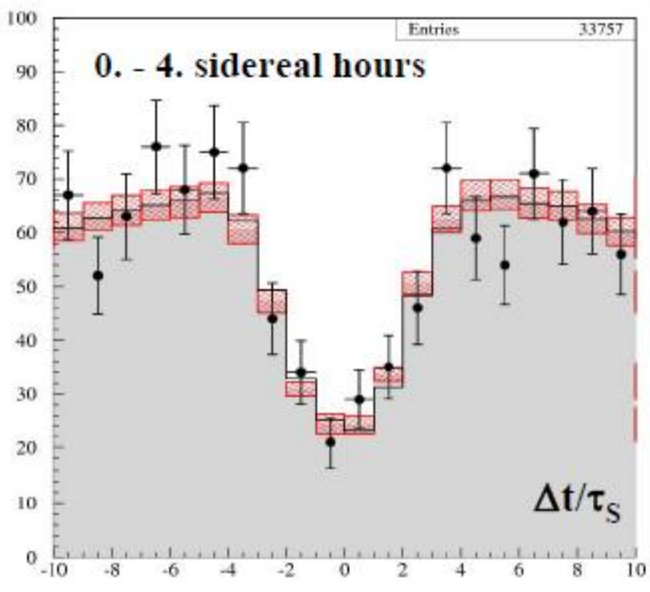
Prof. Neelima Kelkar

24.07.2017

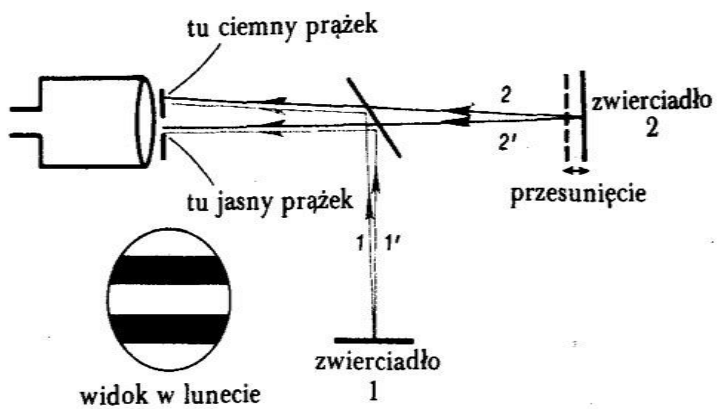
„Yes, you can talk about J-PET”

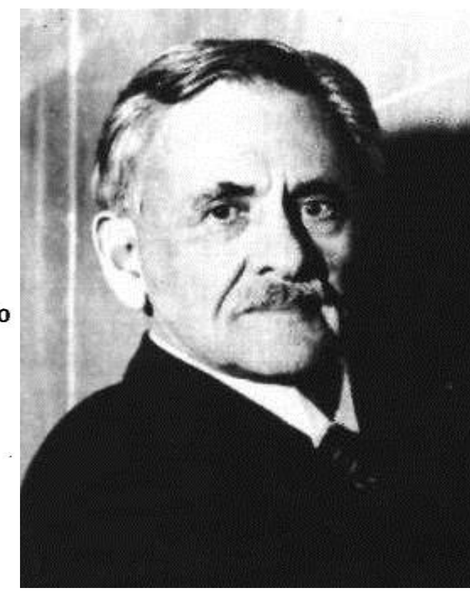






A . A. Michelson, Am. J. Sci. 22 (1881) 120.





Strzelno 1852

10^{-20} ← PRECYZJA → 0.01