



**Kyiv National Taras Shevchenko University,
1 September 2016**

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





Jagiellonian University

1364

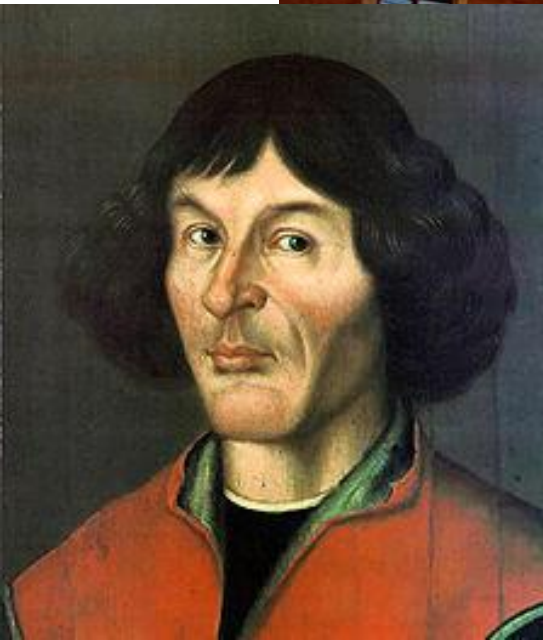


Collegium Maius at the university since **1400**



Jagiellonian University

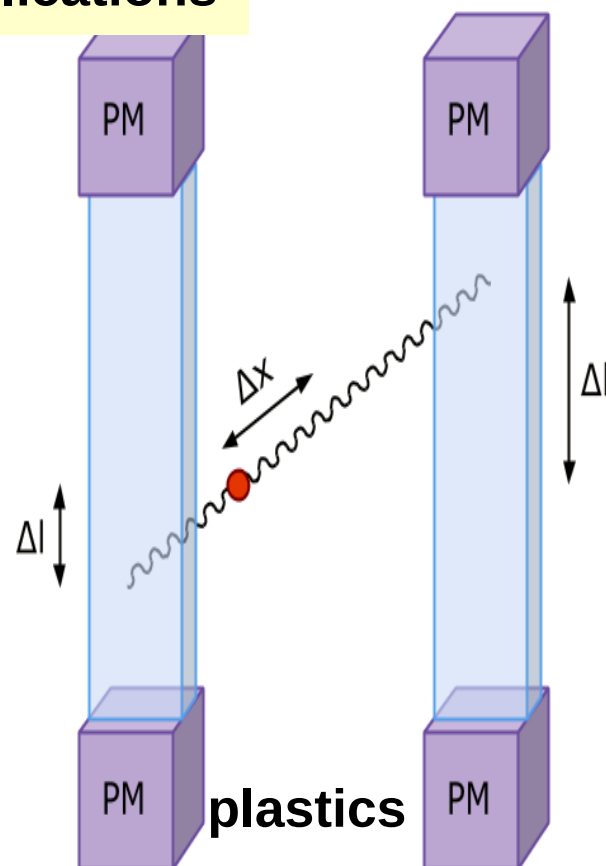
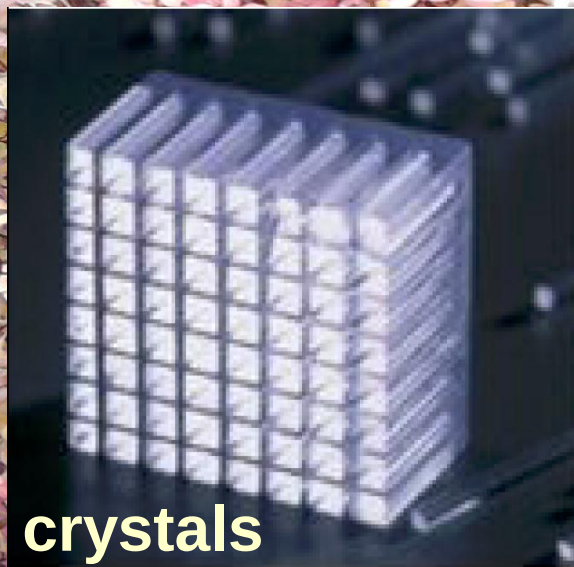
1364

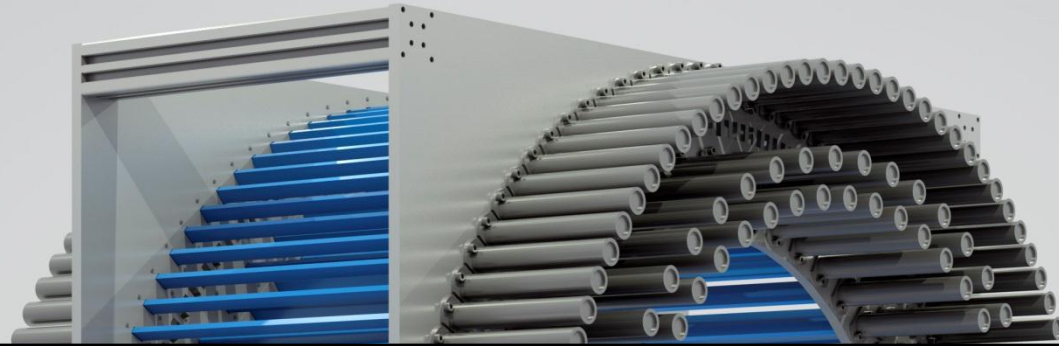


Collegium Maius at the University since **1400**



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
50 articles and 16 international patent applications





- **Jagiellonian PET**
- **Positronium**
- **Nanostructure of cells**
- **Discrete symmetries**
- **Quantum entanglement ...**



- **Jagiellonian PET**

WHOLE BODY

LARGE ANIMAL

COST EFFECTIVE

CONFIGURABLE

MRI COMPATIBLE

...

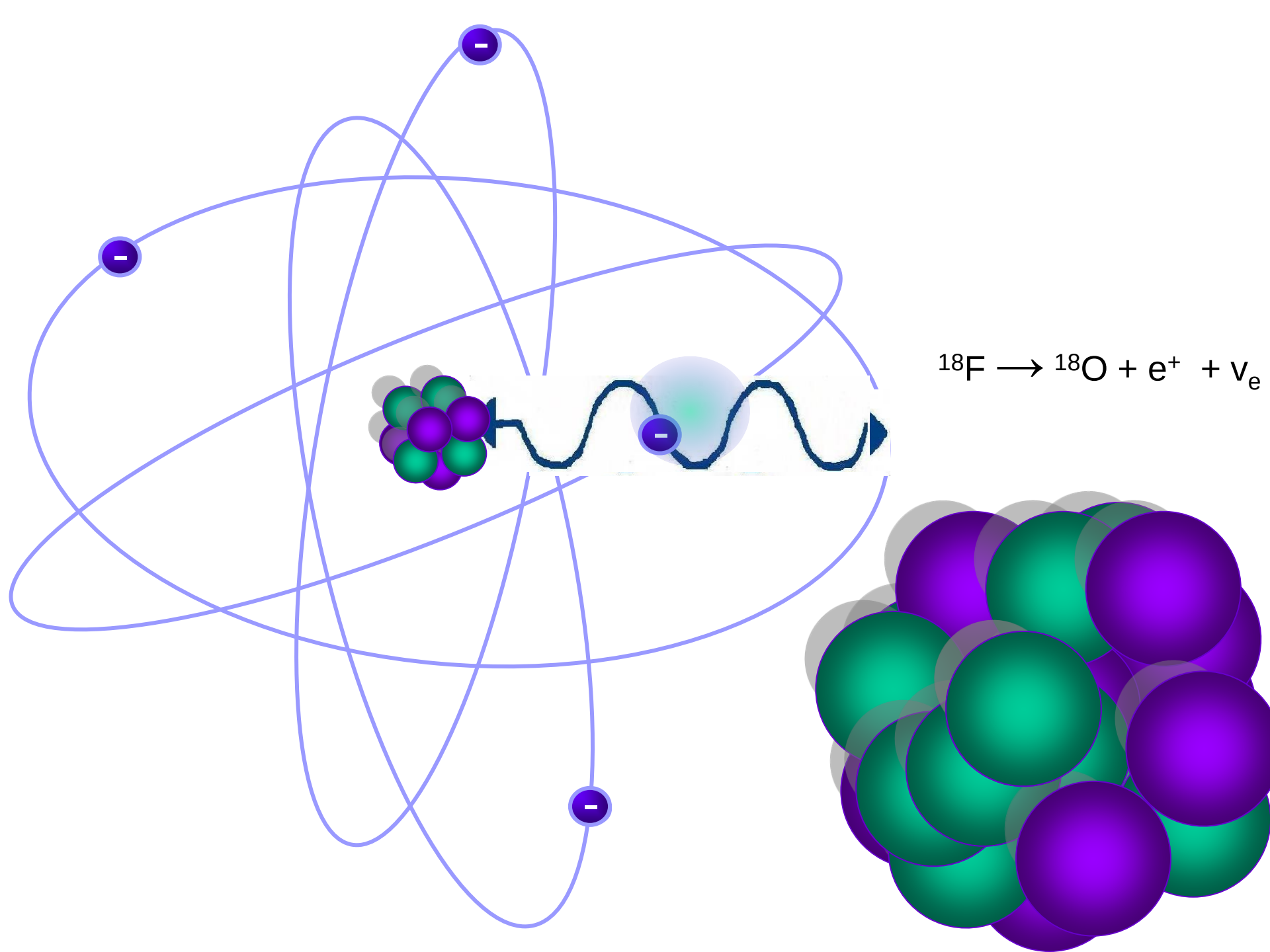


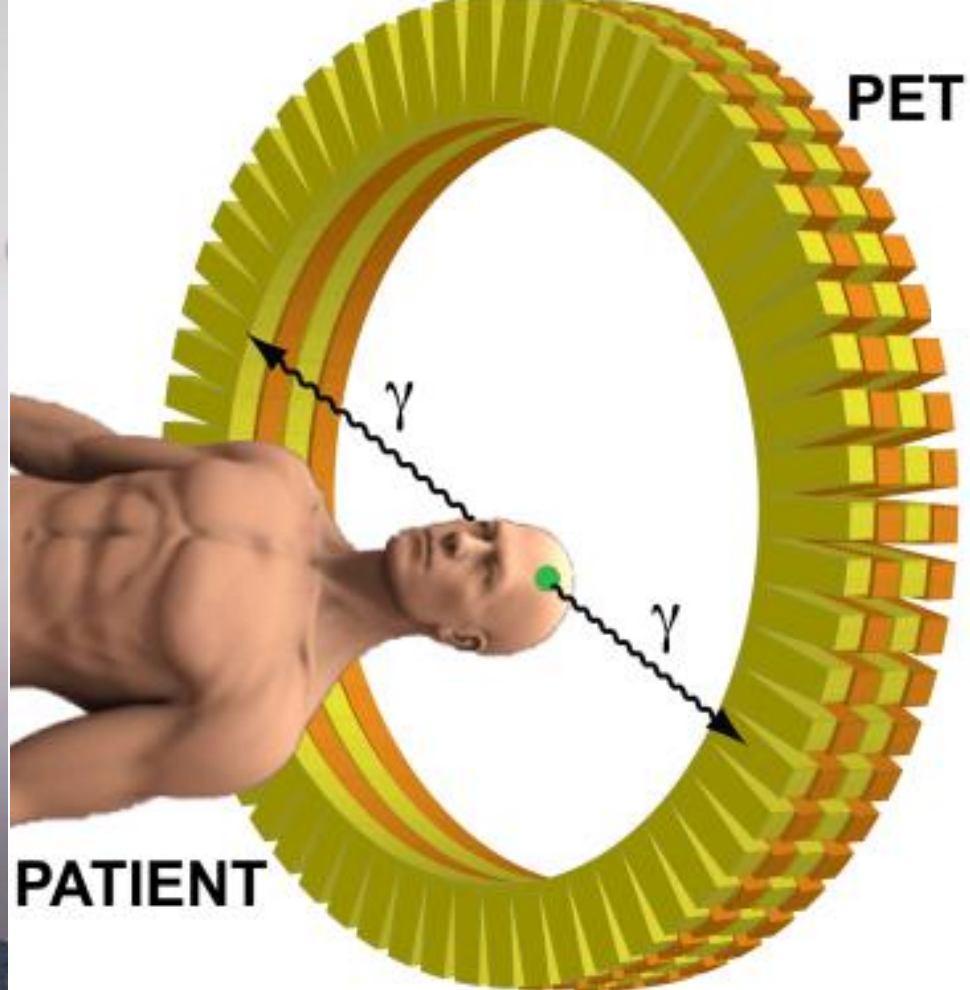
Increased glycolysis in tumor cells
-Warburg phenomenon-
20-30 time higher glucose metabolism
and FDG is trapped in malignant cells.

RADIOACTIVE SUGER

Fluoro-deoxy-glucose
(F-18 FDG)



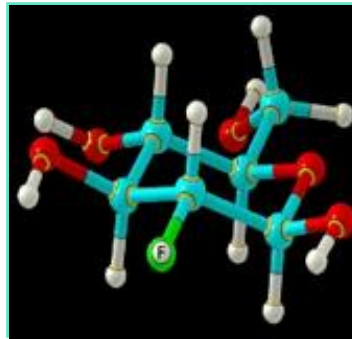




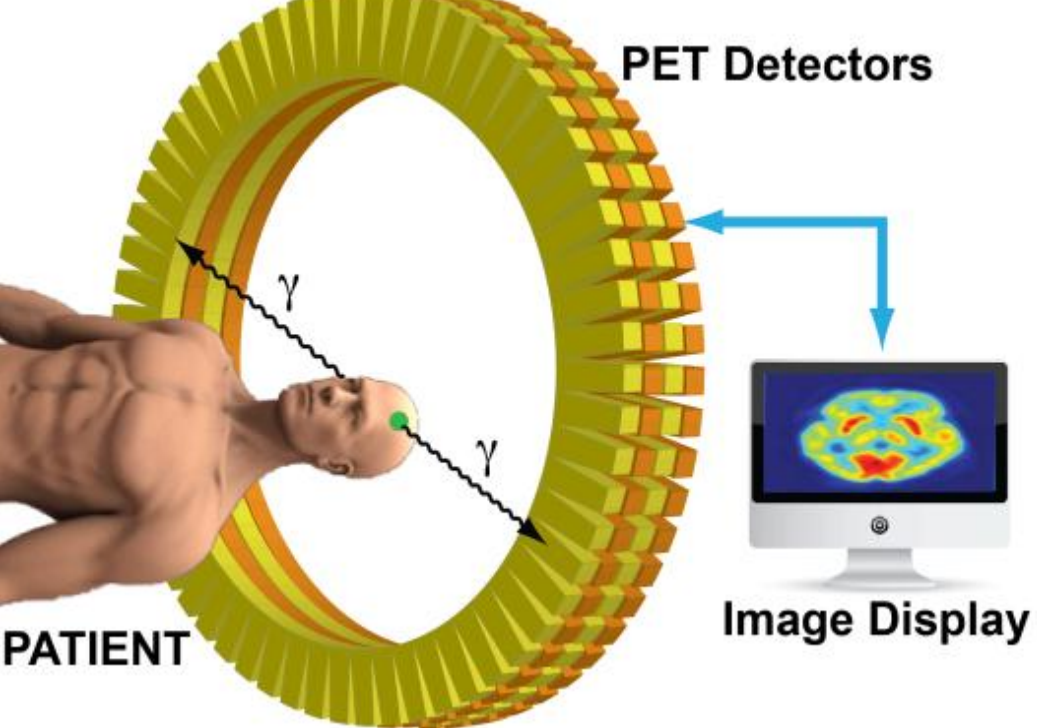
RADIOACTIVE SUGER

Fluoro-deoxy-glucose
(F-18 FDG)

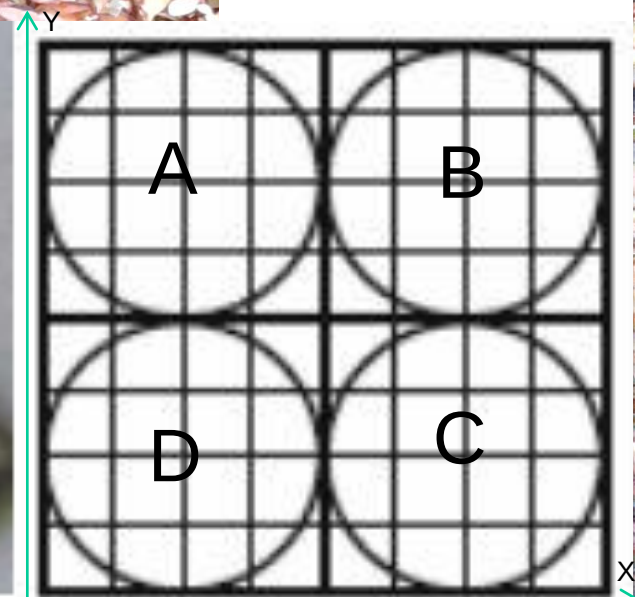
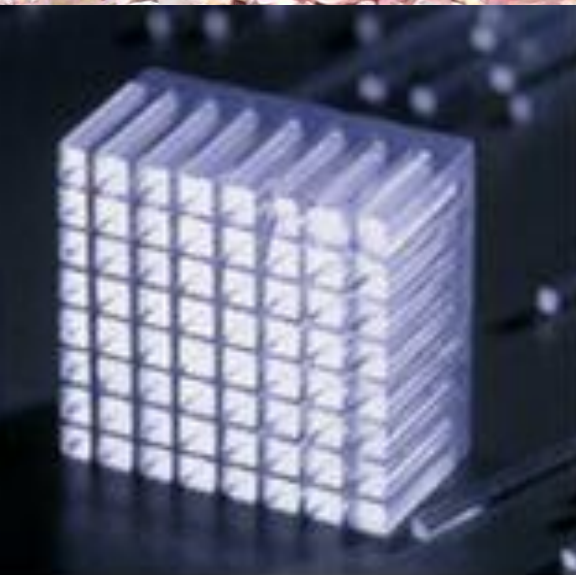
~200 000 000
gamma per second

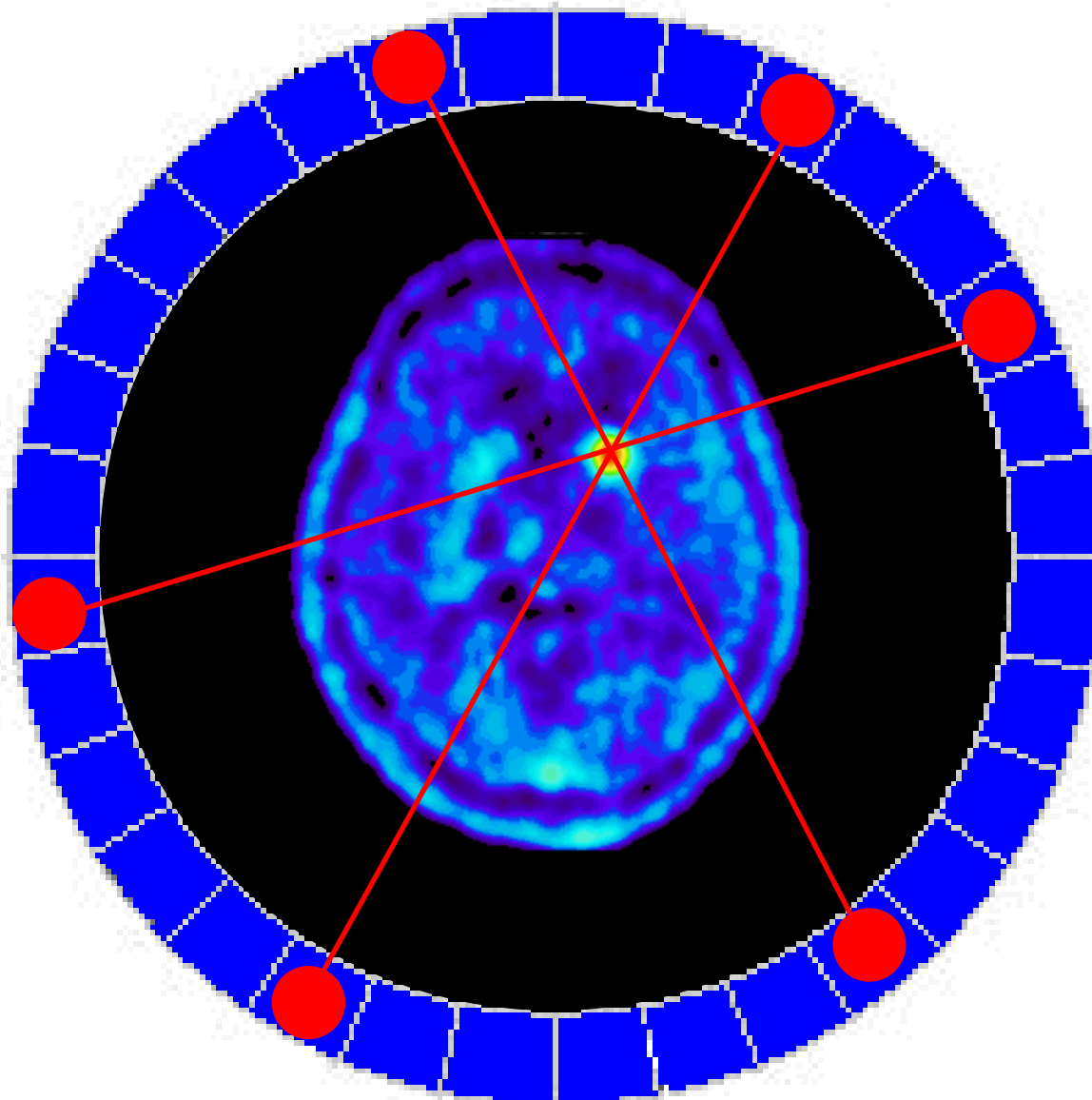


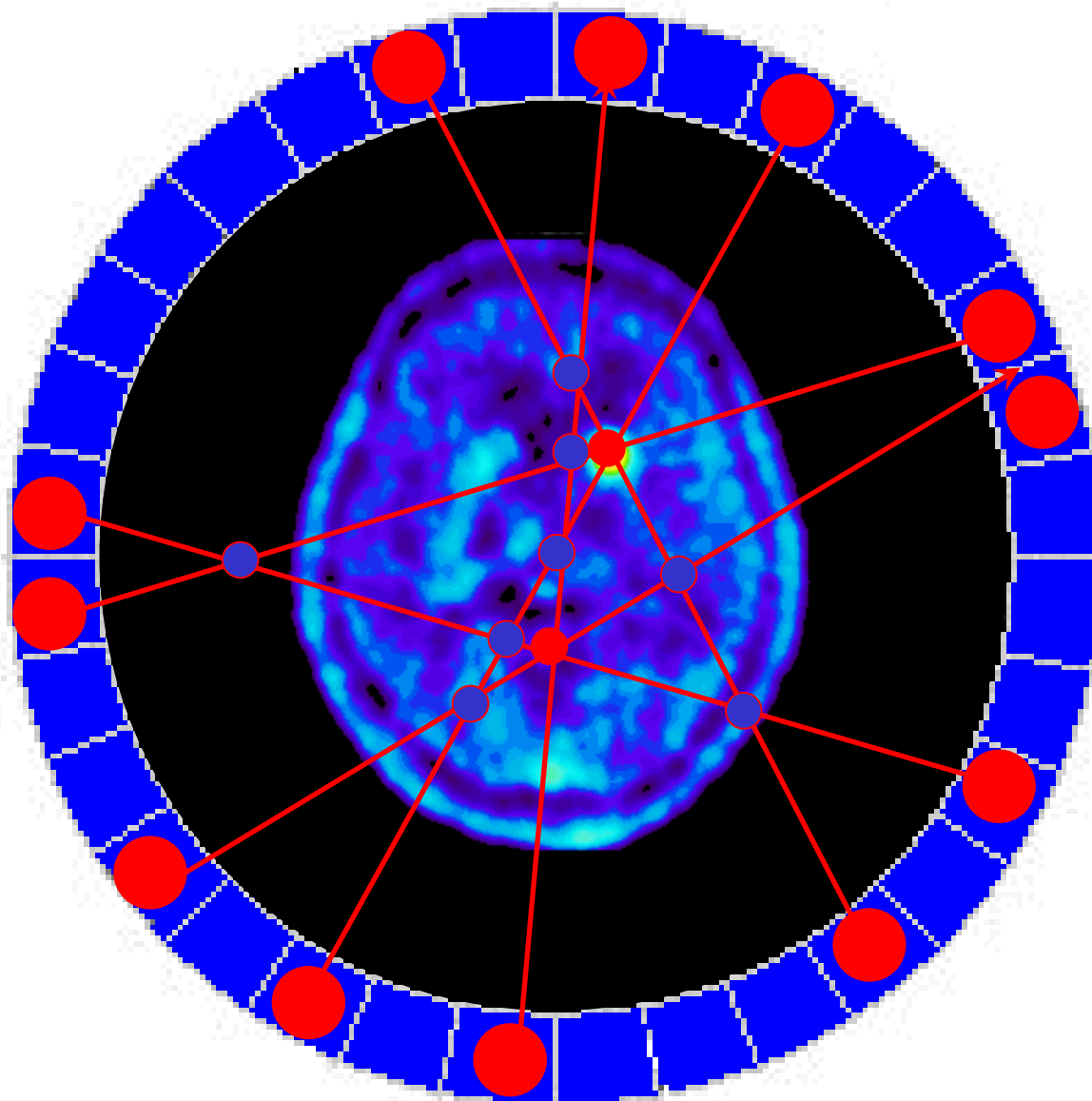
7 mSv PET/CT
~3 mSv natural
background in Poland

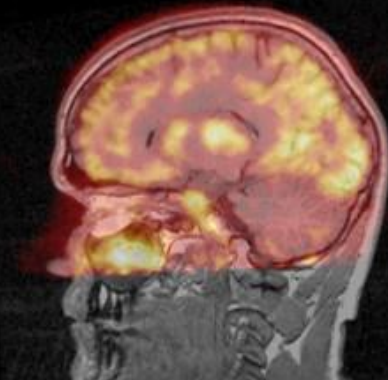
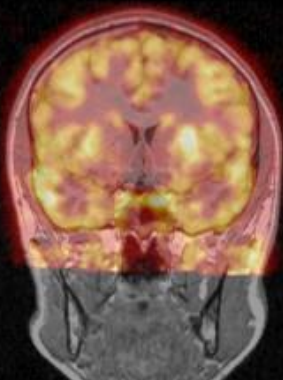
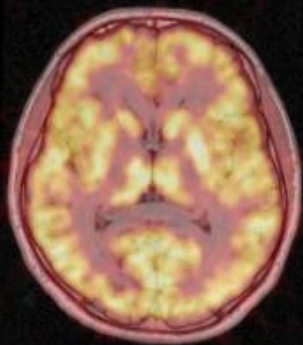
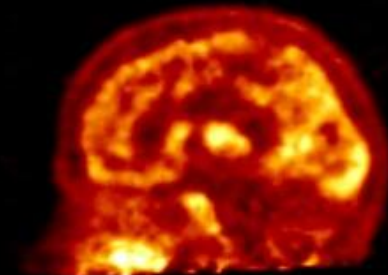
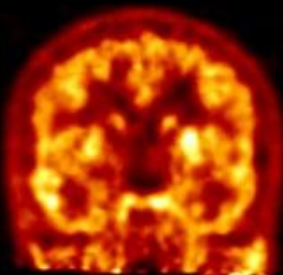
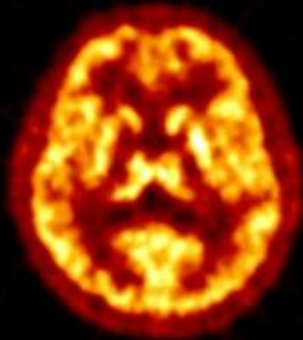
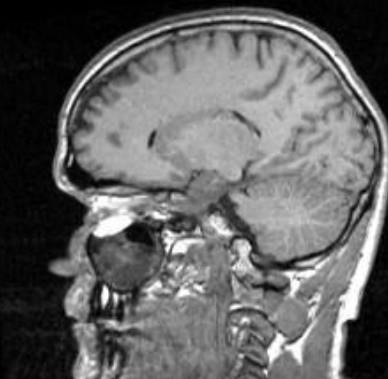
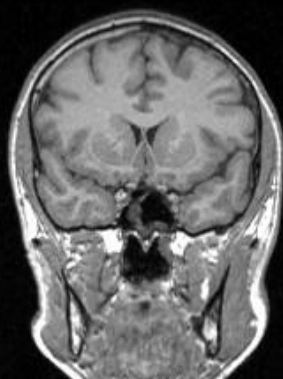
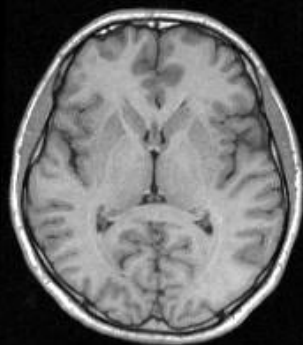


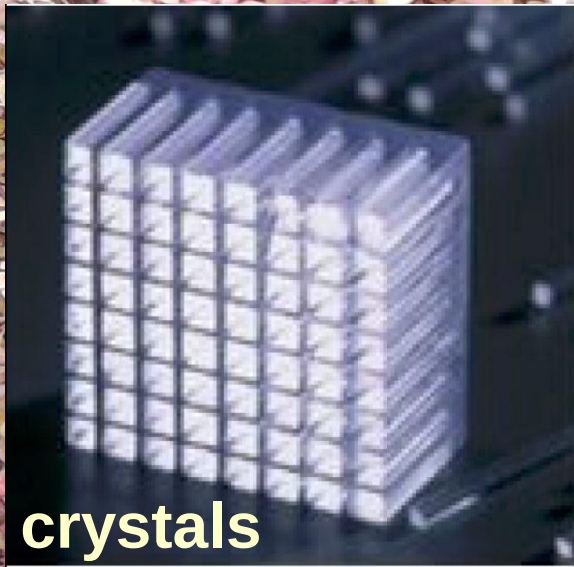
$$X = \frac{(B + C) - (A + D)}{A + B + C + D},$$



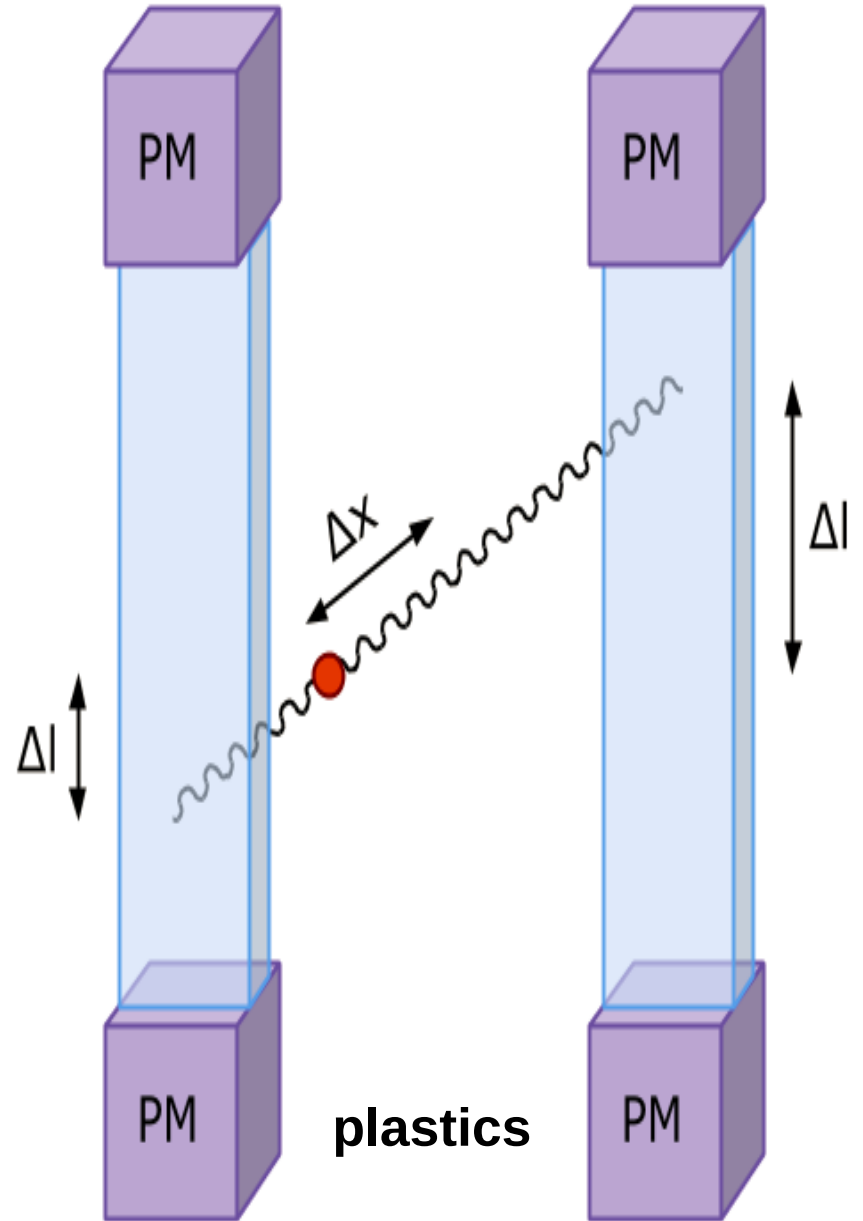




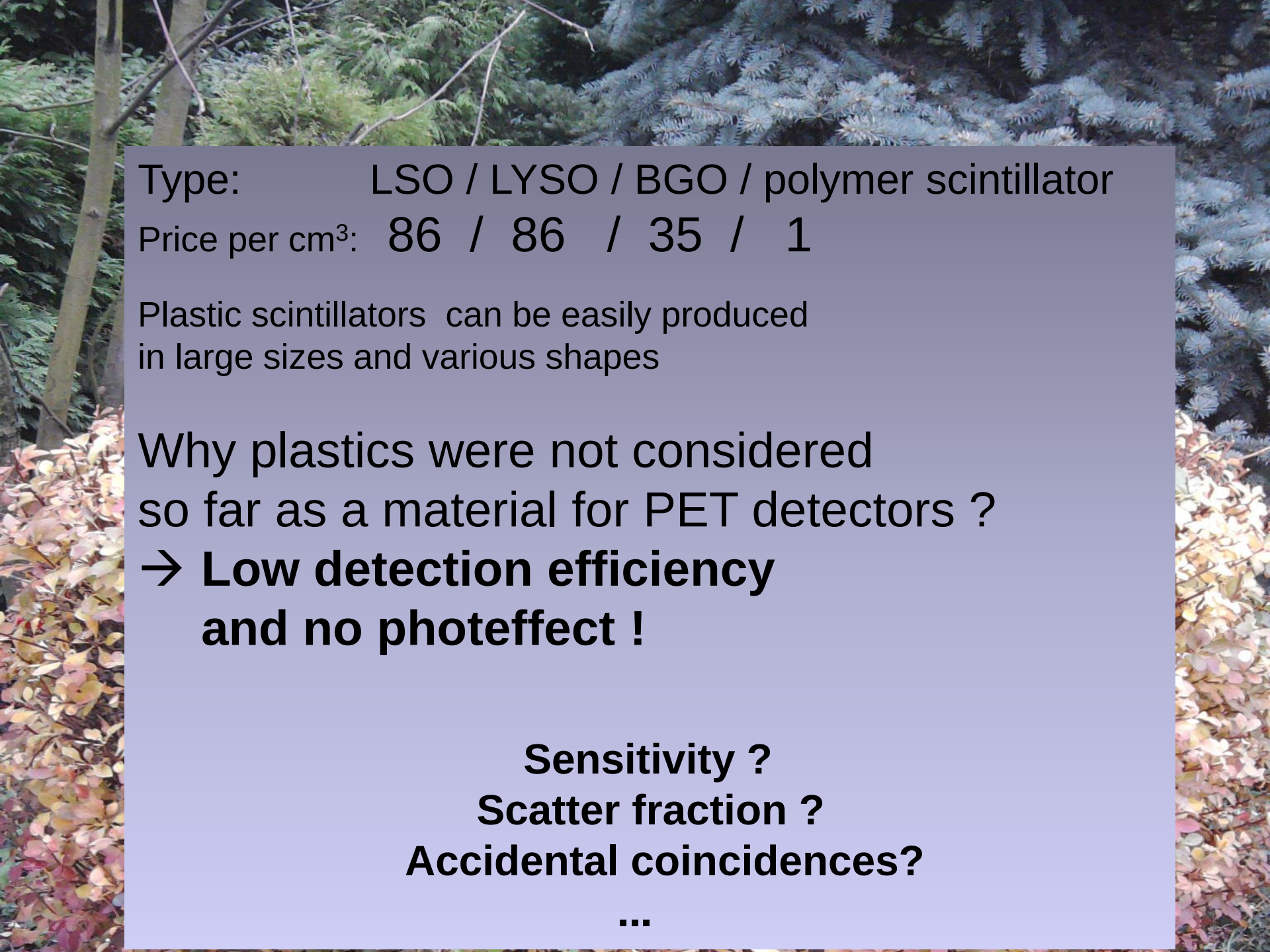




crystals



plastics



Type: LSO / LYSO / BGO / polymer scintillator

Price per cm³: 86 / 86 / 35 / 1

Plastic scintillators can be easily produced
in large sizes and various shapes

Why plastics were not considered
so far as a material for PET detectors ?

→ **Low detection efficiency
and no photeffect !**

Sensitivity ?

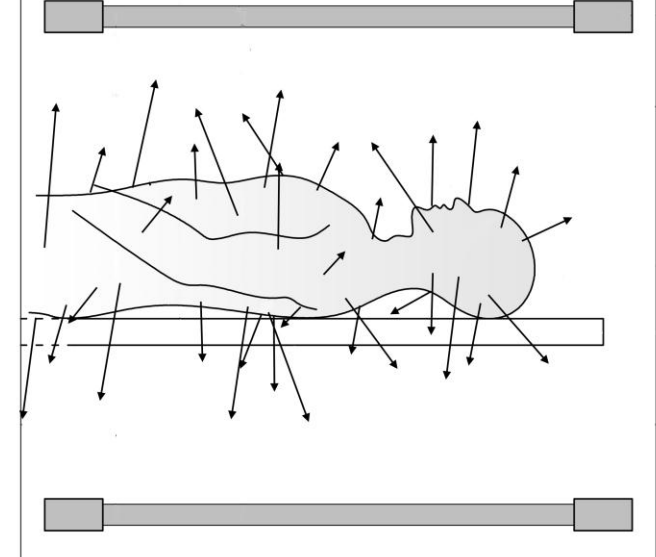
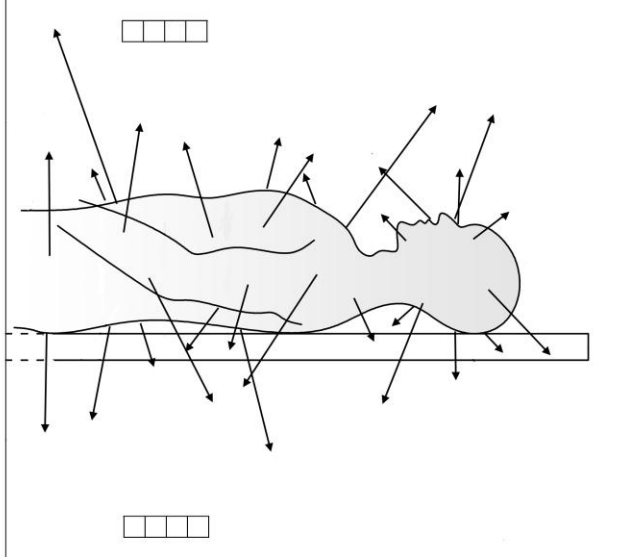
Scatter fraction ?

Accidental coincidences?

...

for the 2.5 cm layer the efficiency for the registration of events selected to reconstruct the image is for the plastic scintillator by
**a factor of about 20 smaller in relation to the BGO crystals
and about 40 times less compared to the LSO crystals**

name	type	density [g/cm³]	decay time [ns]	photons/ MeV	mean free path [cm]
BGO	crystal	7.13	300	6000	1.04
GSO	crystal	6.71	50	10000	1.49
LSO	crystal	7.40	40	29000	1.15
NE102A	polymer	1.032	2.4	10000	10.2
BC404	polymer	1.032	1.8	10000	10.2
RP422	polymer	1.032	1.6	10000	10.2



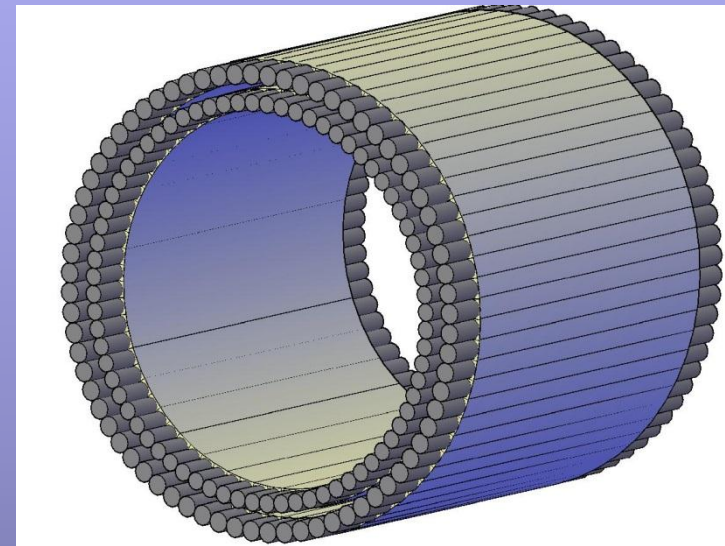
The cost of J-PET does not increase with the increase of the FOV

$\epsilon^2 = 20$ to 40 smaller efficiency

But

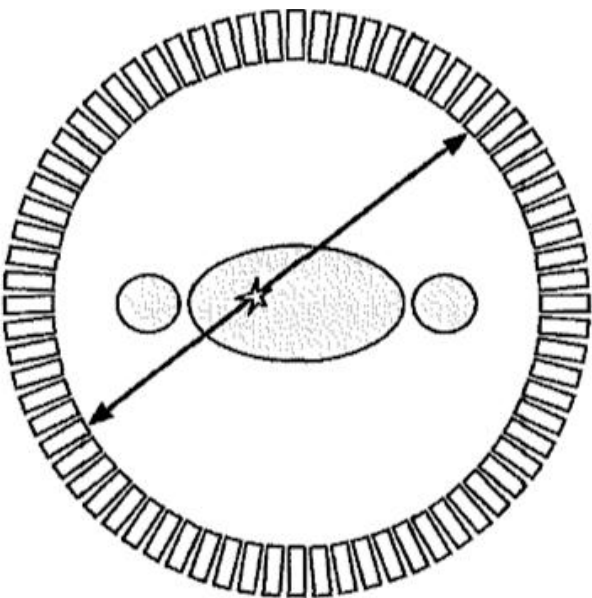
17cm $\rightarrow$ 100cm ----- $>$ factor of ~ 5
 600 ps $\rightarrow$ 200ps–300ps $\rightarrow$ factor of 3--2
 1m instead of ~ 17 cm ----- $>$ factor of 10
N layers in the strip-PET ---- $>$ factor **N^2**

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

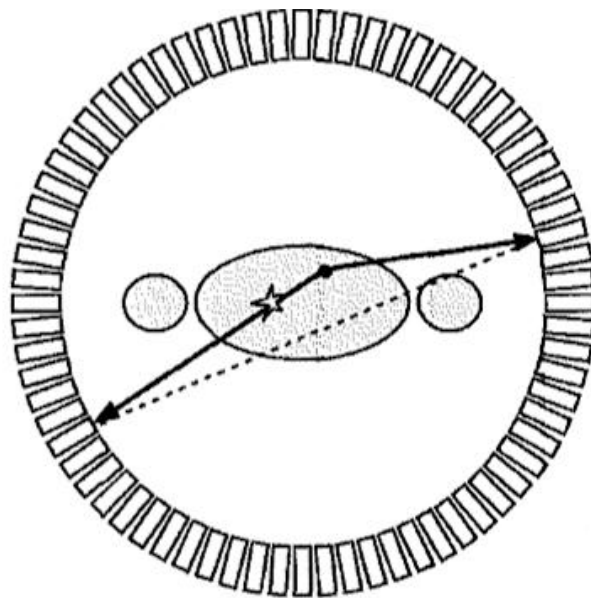


EVENTS

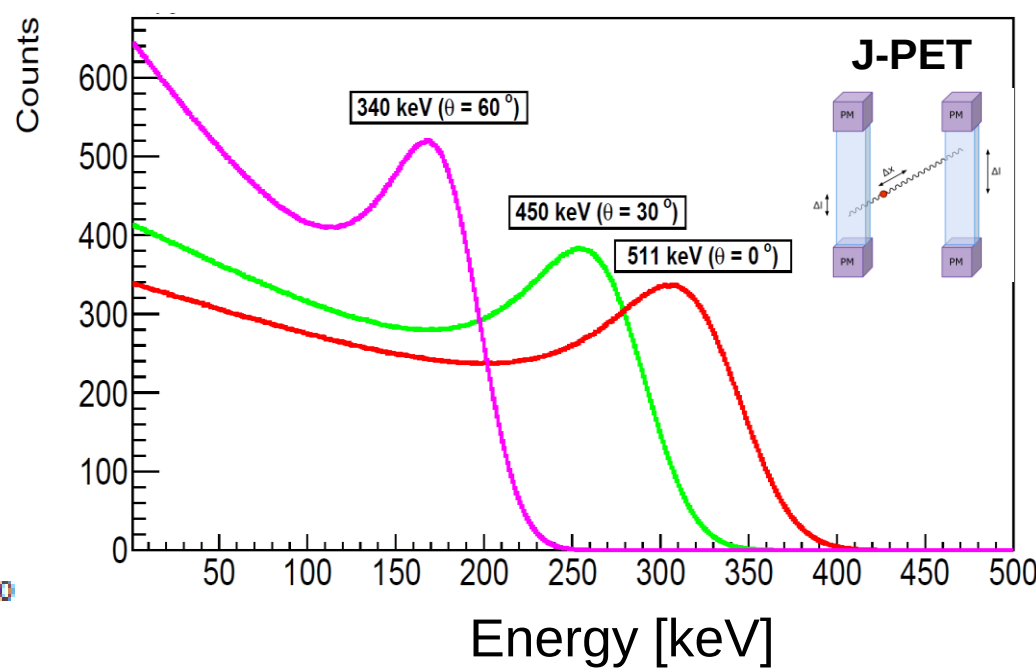
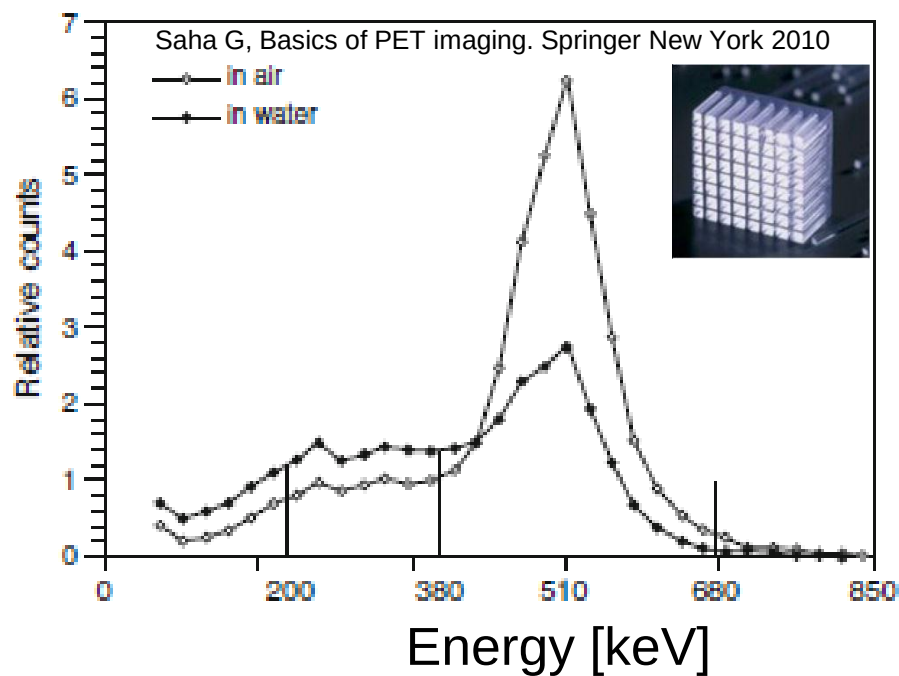
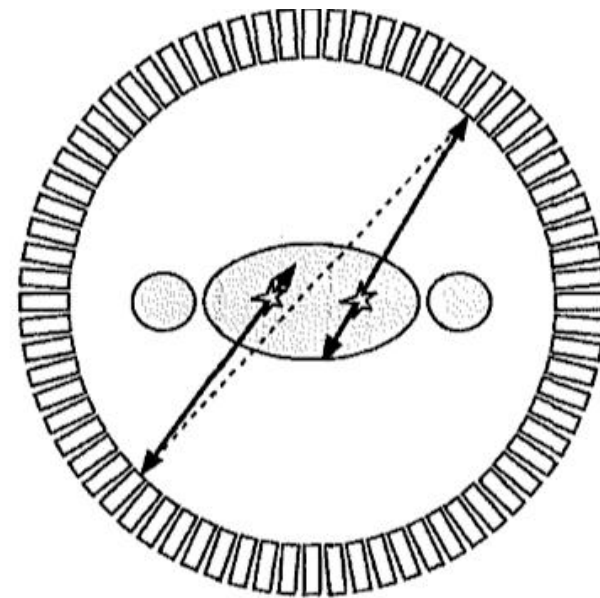
„true”



„scattered”



accidental



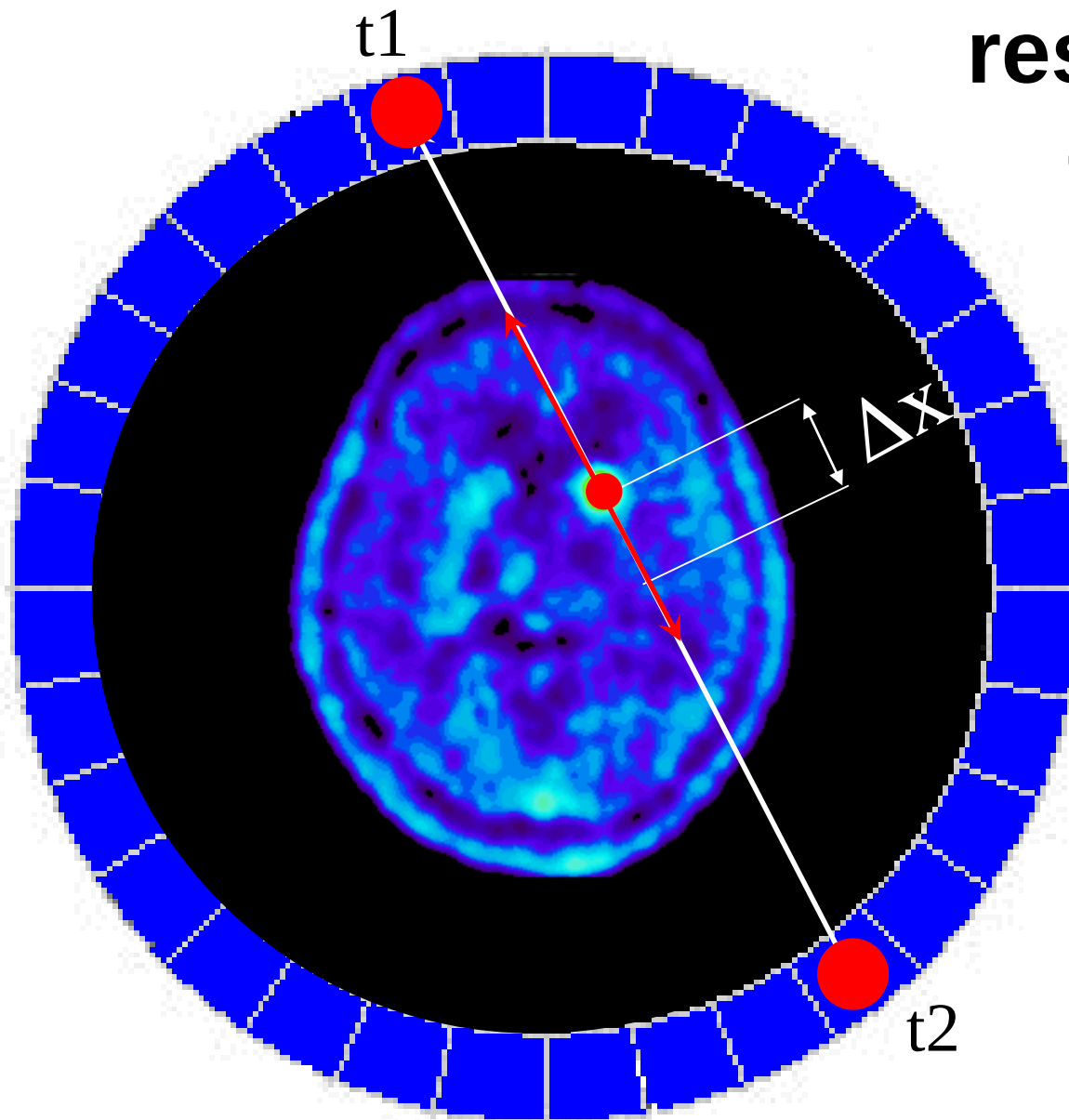
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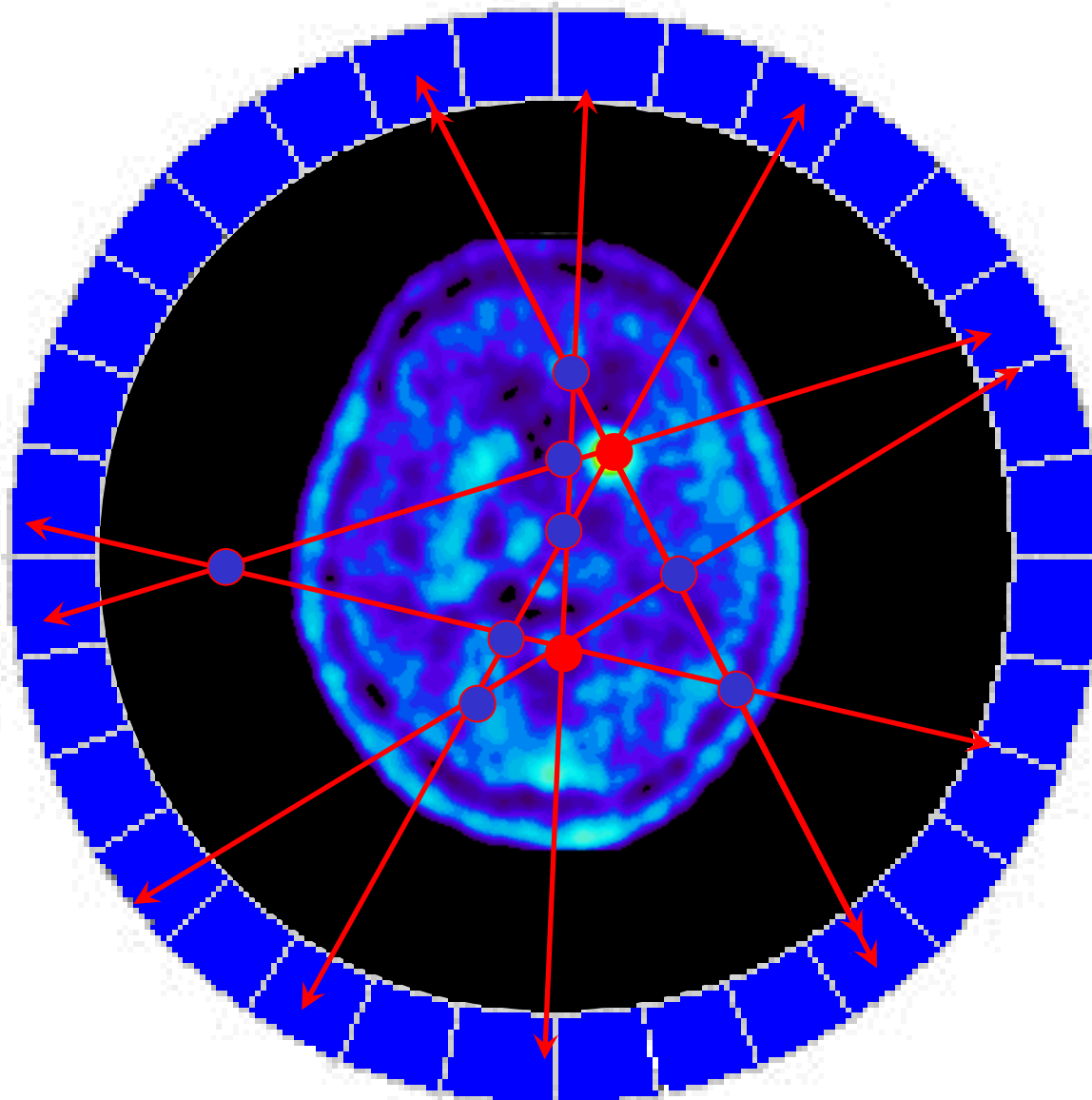
name	type	density [g/cm³]	decay time [ns]	photons/ MeV	mean free path [cm]
BGO	crystal	7.13	300	6000	1.04
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RP422	polymer	1.032	1.6	10000	10.2

PET-TOF

$$\Delta x = (t_2 - t_1) c / 2$$

**resolution
600ps**





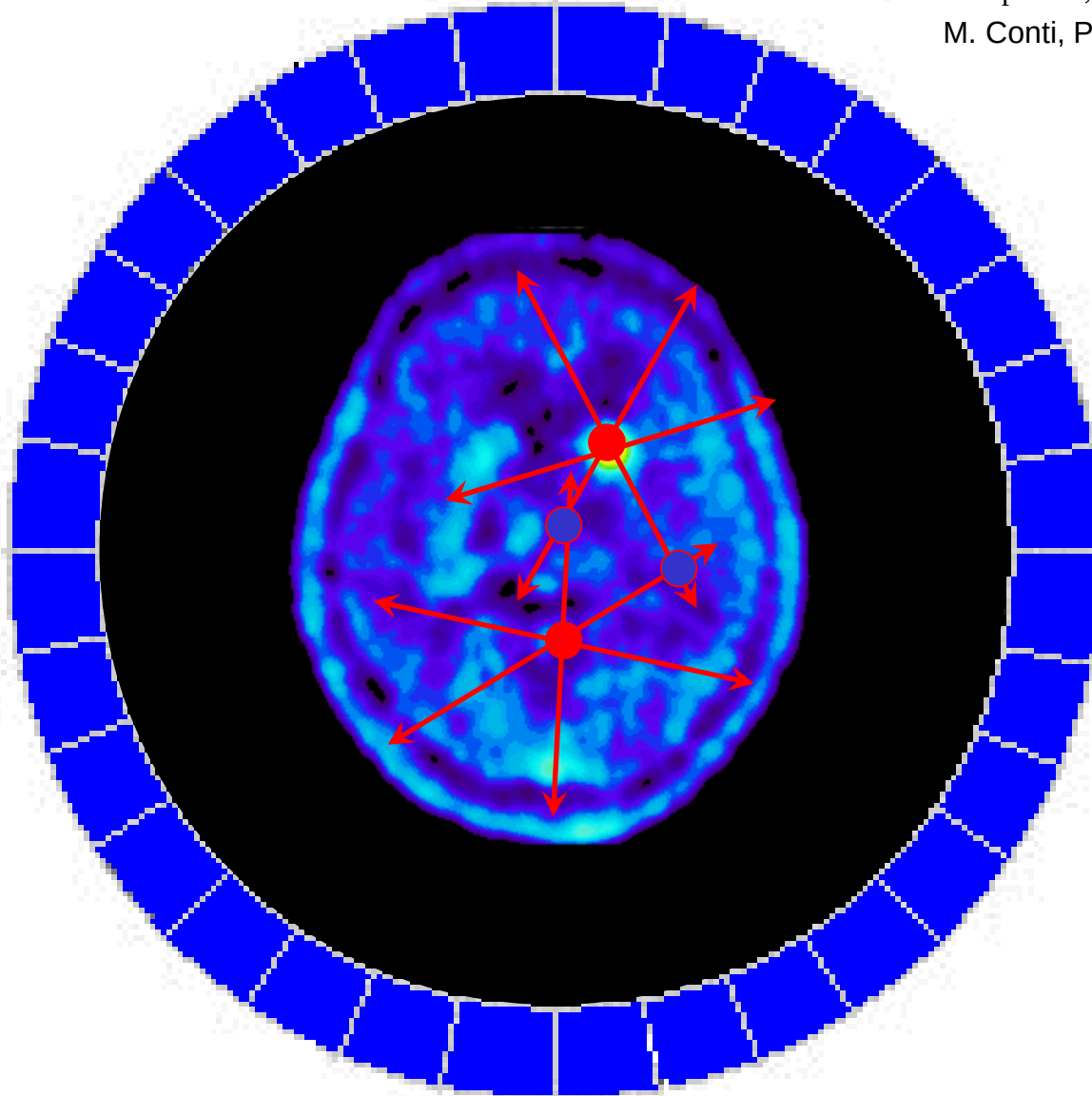
signal/background

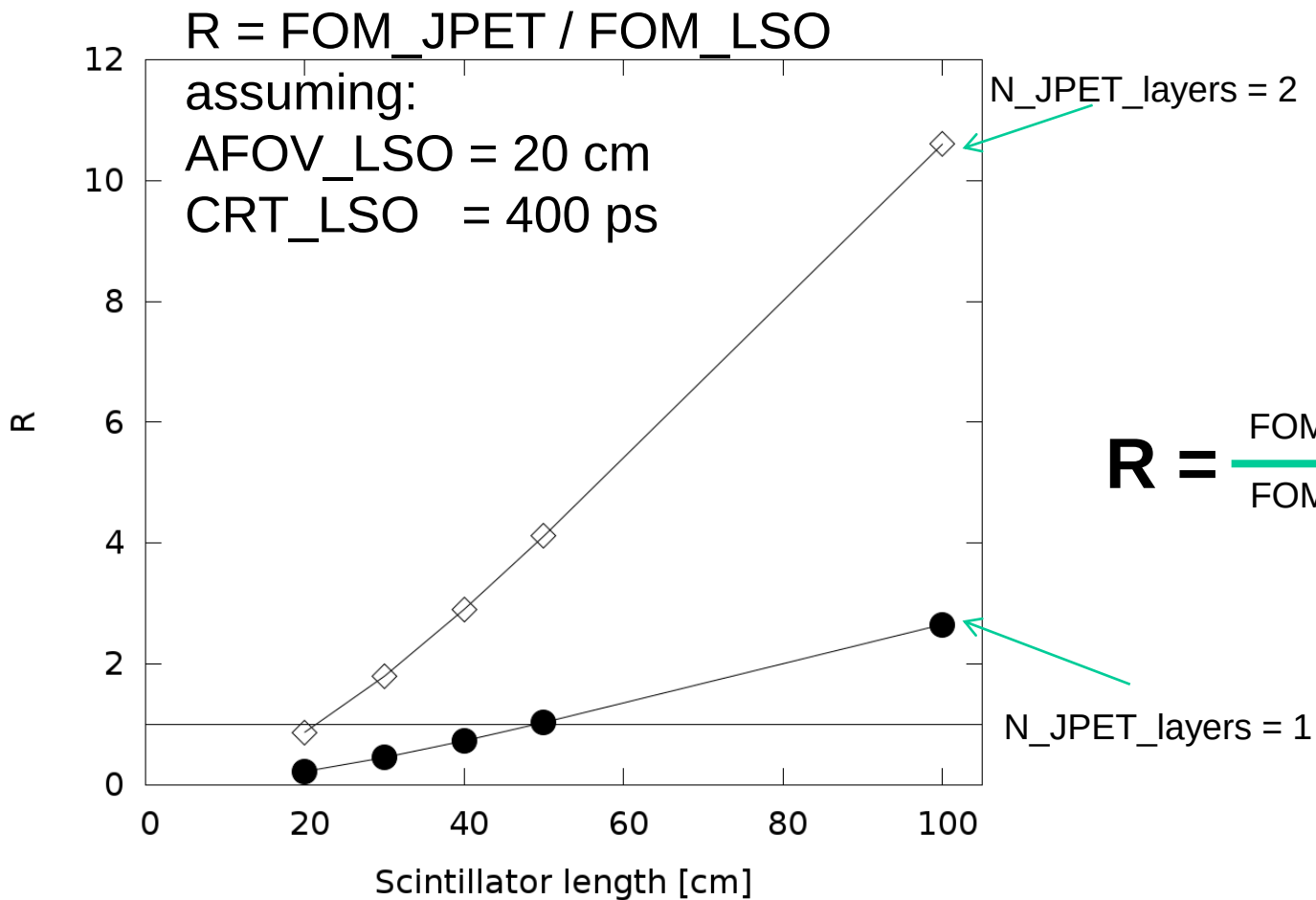
40cm/600ps improvement by factor of 4

$$\sim D / \Delta t$$

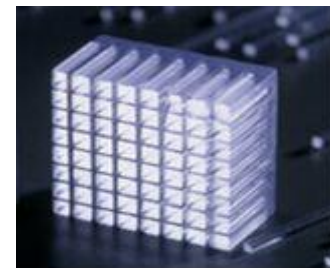
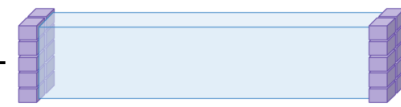
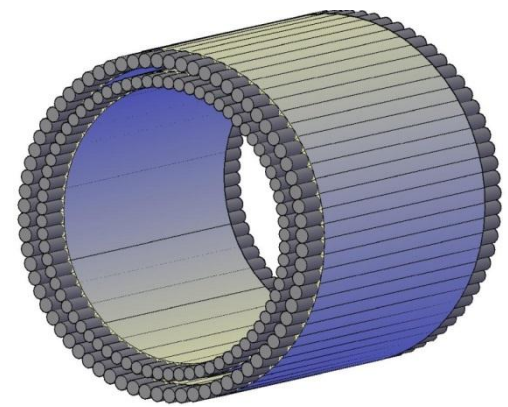
J. S. Karp et al., J Nucl Med 2008; 49: 462

M. Conti, Physica Medica 2009; 25: 1.





$$R = \frac{\text{FOM_JPET}}{\text{FOM_LSO}}$$



LSO

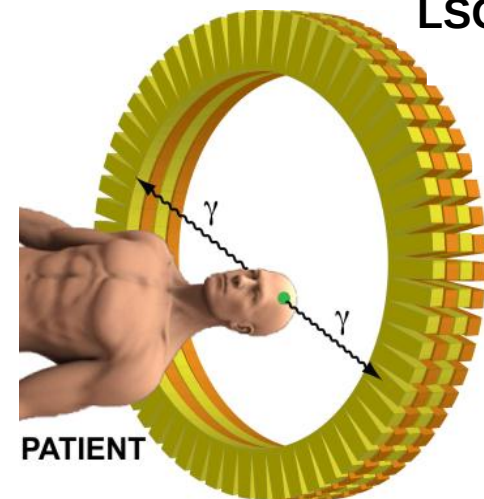


Figure of Merit for whole body imaging:

$$\text{FOM_whole_body} \sim \epsilon_{\text{detection}}^2 \cdot \epsilon_{\text{selection}}^2 \cdot \text{Acc} / (\text{CRT} \cdot \text{N_steps})$$

$$\text{FOM_whole_body} \sim \epsilon_{\text{detection}}^2 \cdot \epsilon_{\text{selection}}^2 \cdot \text{AFOV}^2 / \text{CRT}$$

P. M. et al., Phys. Med. Biol. 61 (2016) 2025

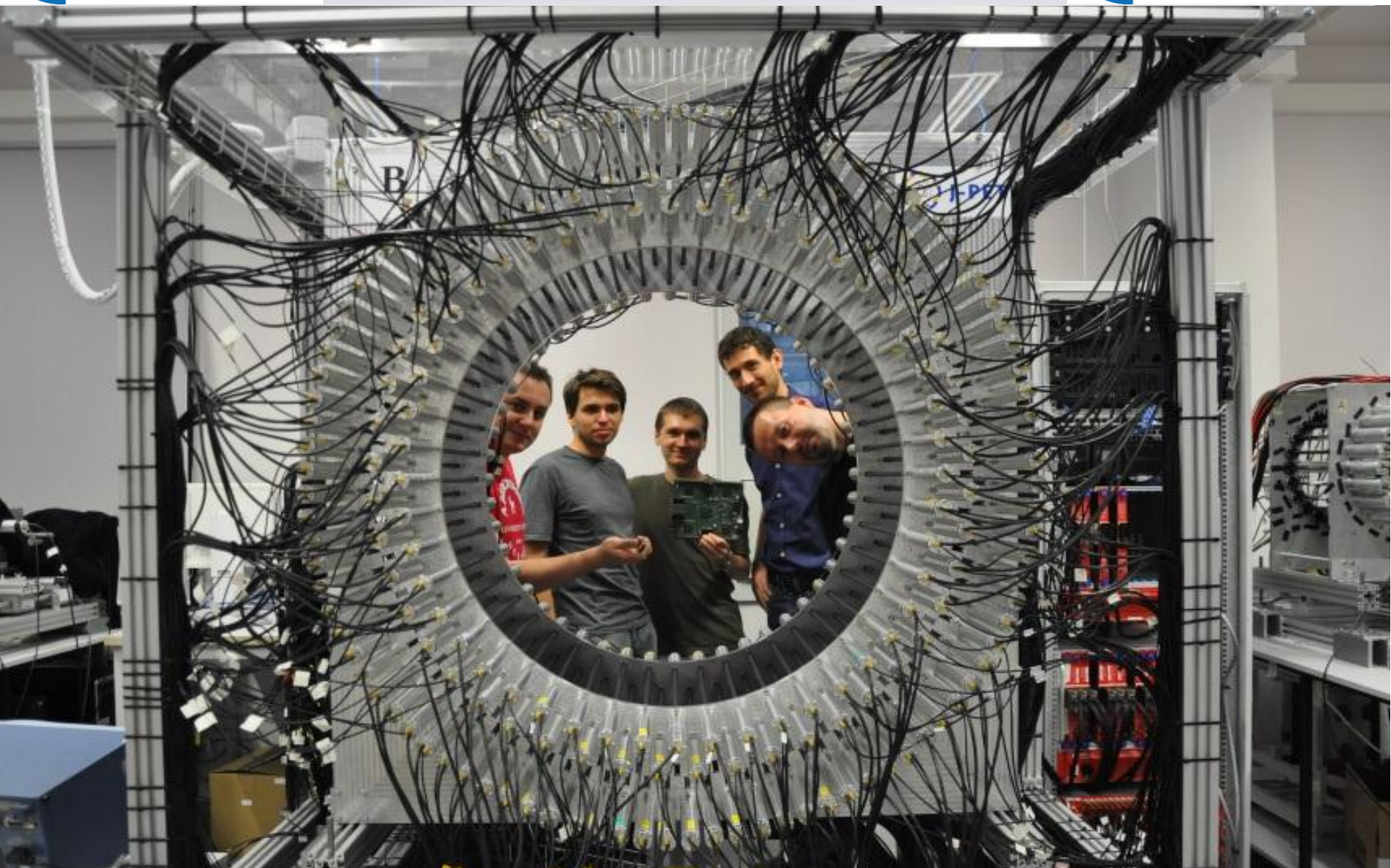


J-PET

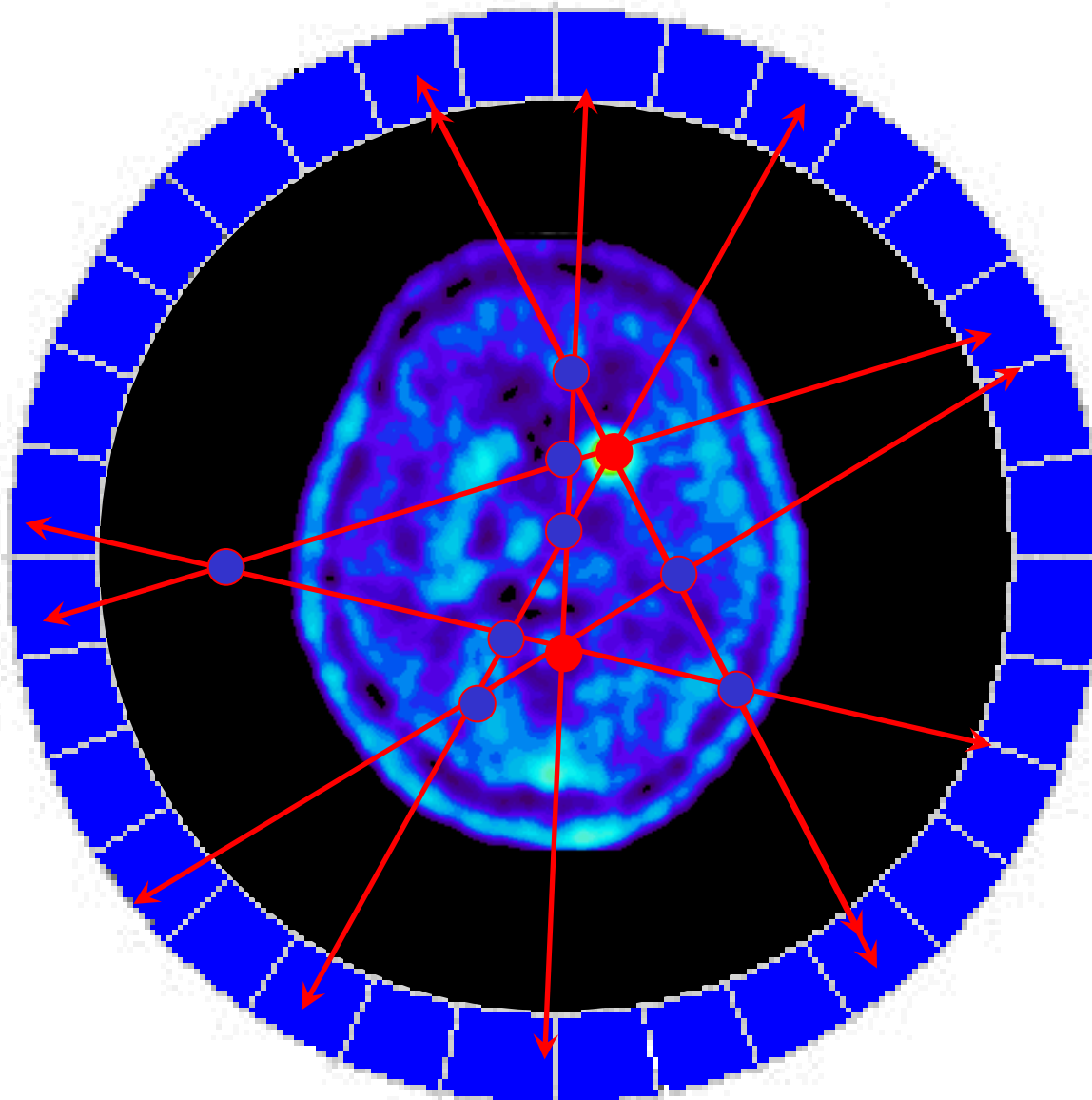
Jagiellonian PET



J-PET



AFOV: 17 cm $\rightarrow$ 50 cm ; TOF: 520 ps $\rightarrow$ 300 ps



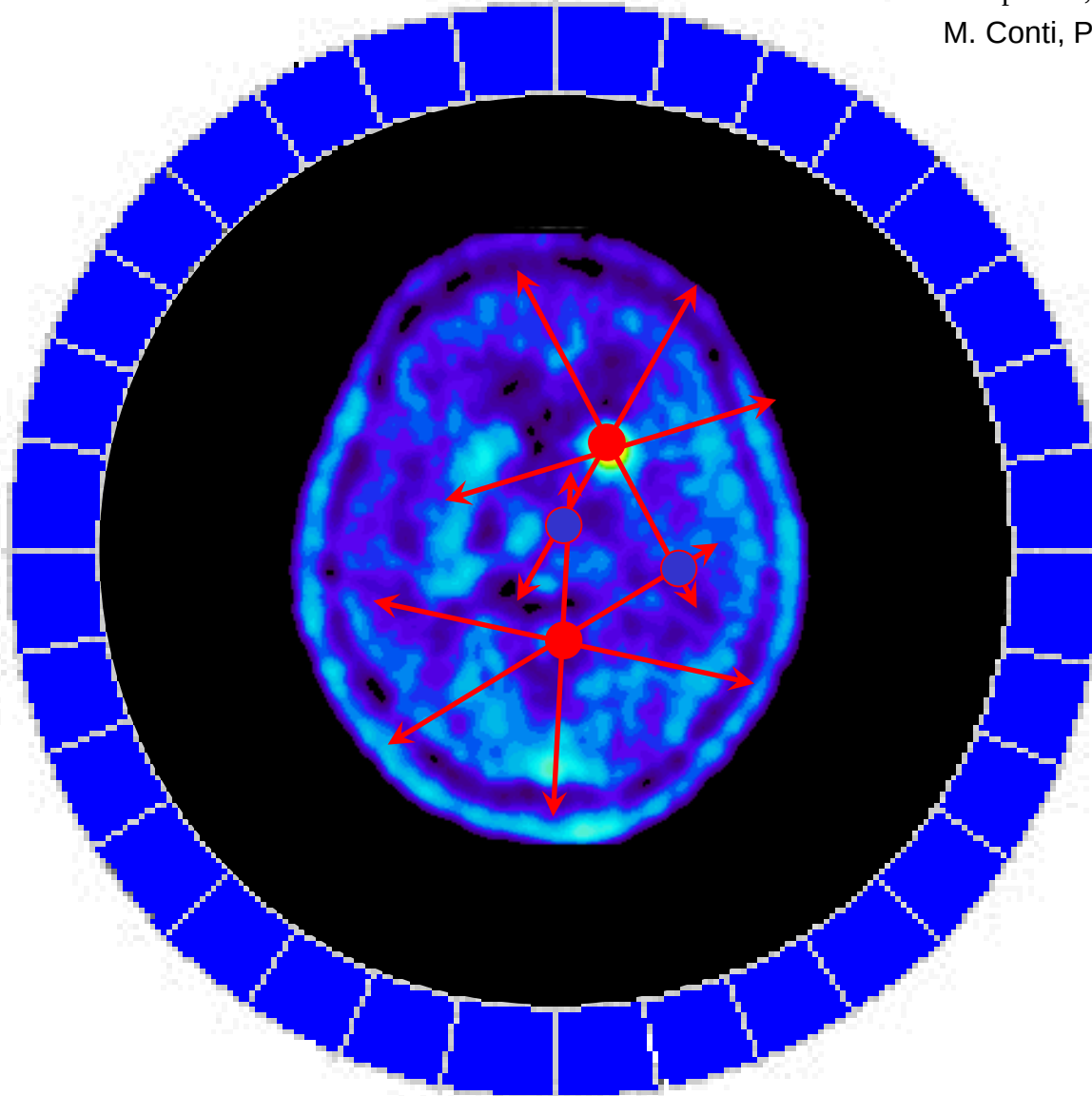
signal/background

40cm/600ps improvement by factor of 4

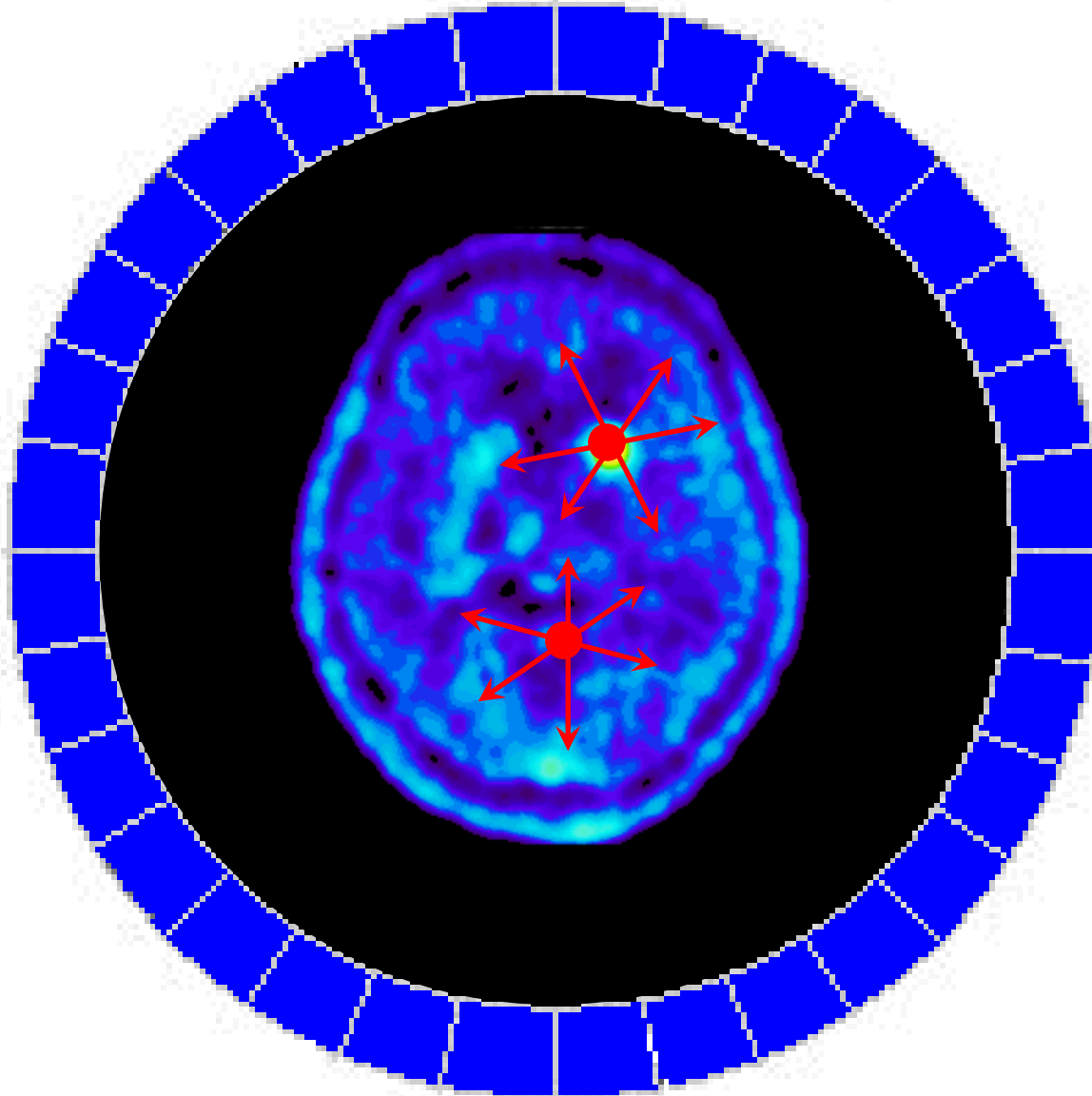
$$\sim D / \Delta t$$

J. S. Karp et al., J Nucl Med 2008; 49: 462

M. Conti, Physica Medica 2009; 25: 1.



signal/background 40cm/300ps improvement by factor of 8
 $\sim D / \Delta t$





- **Jagiellonian PET**

WHOLE BODY

LARGE ANIMAL

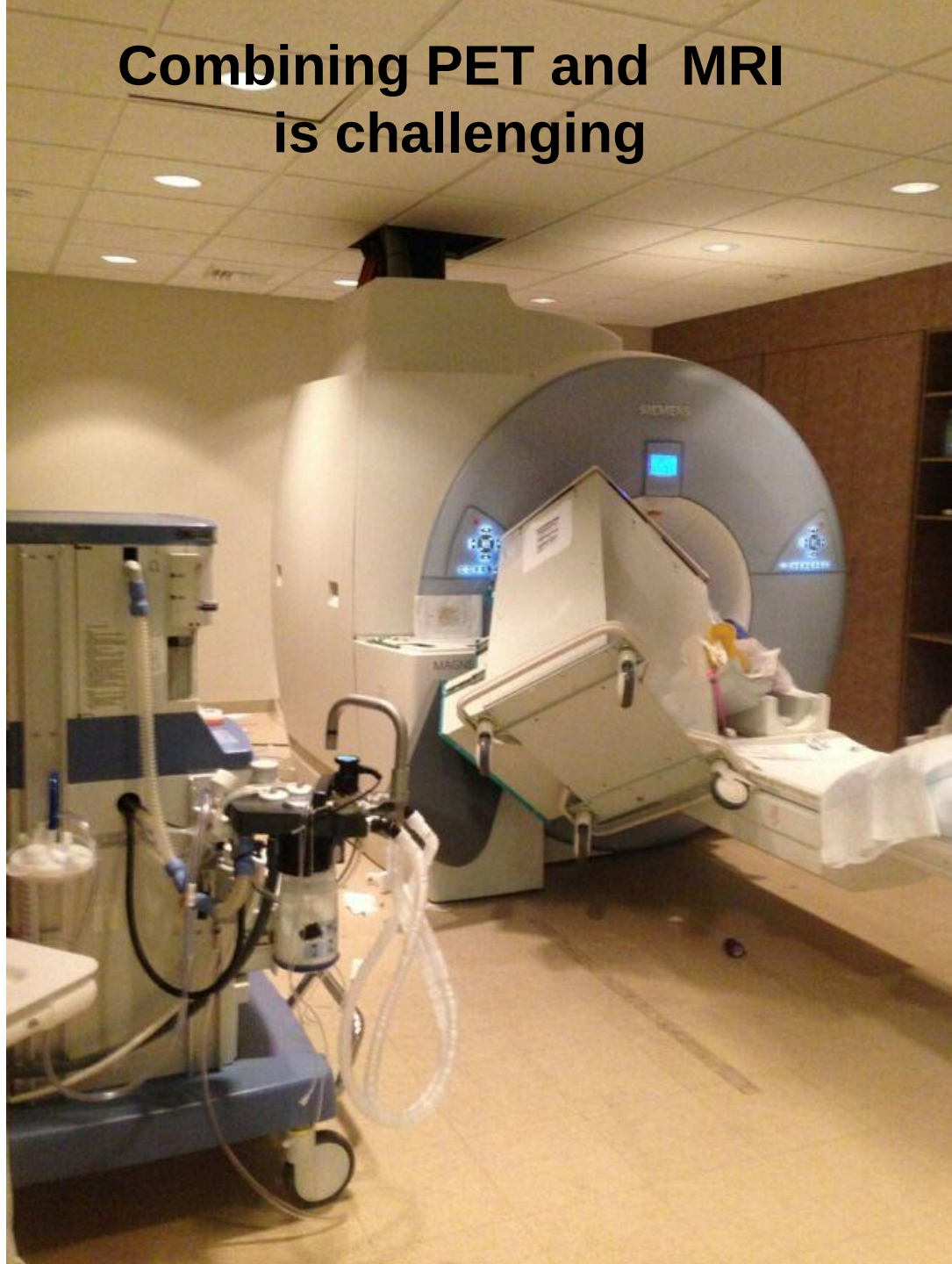
COST EFFECTIVE

CONFIGURABLE

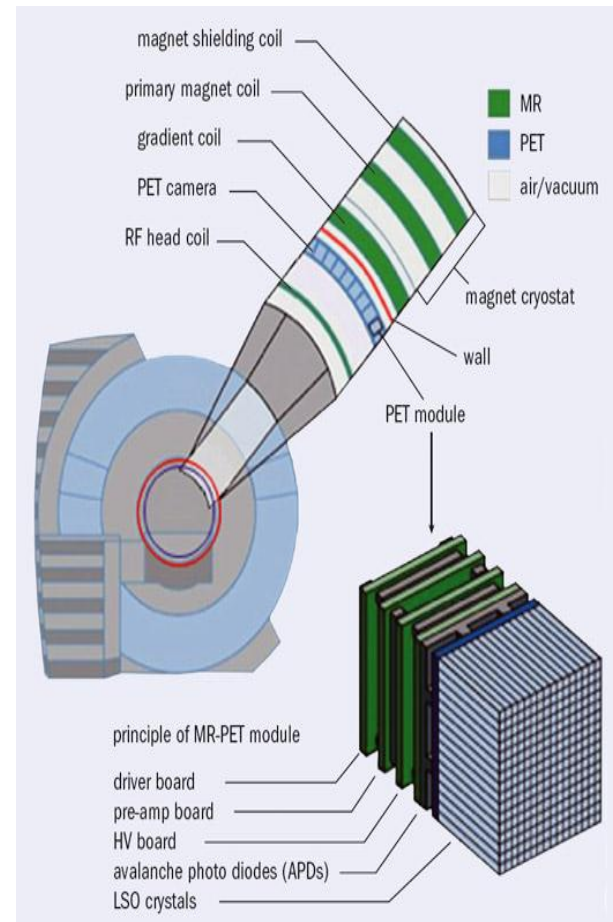
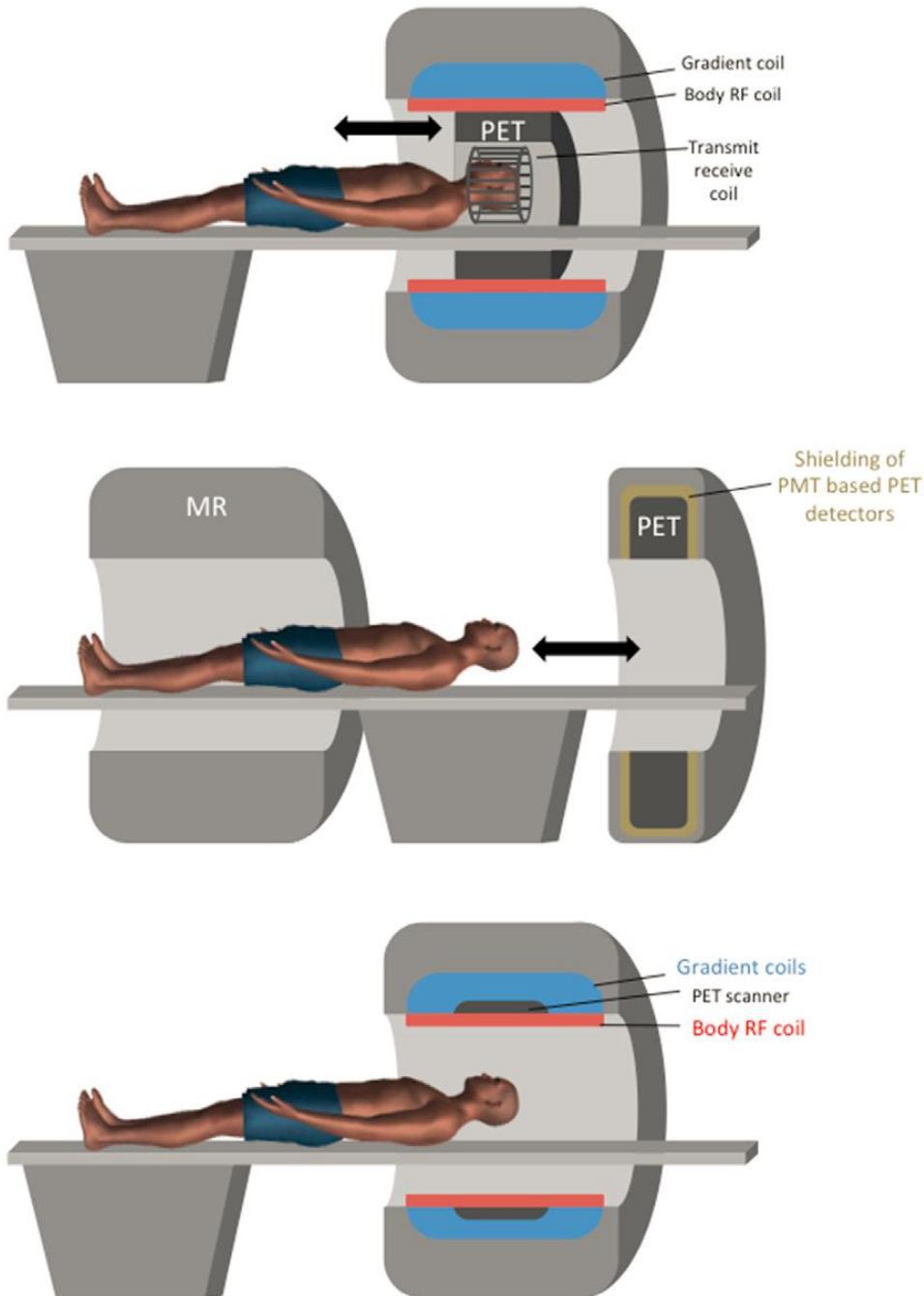
MRI COMPATIBLE

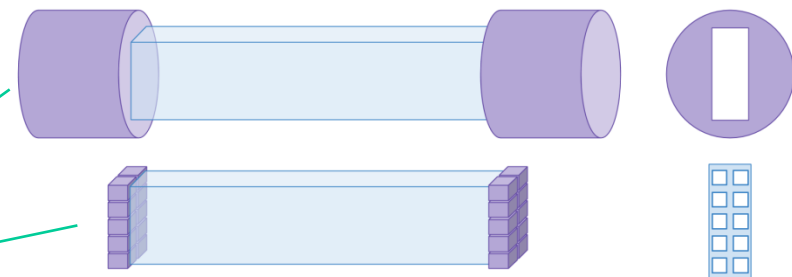
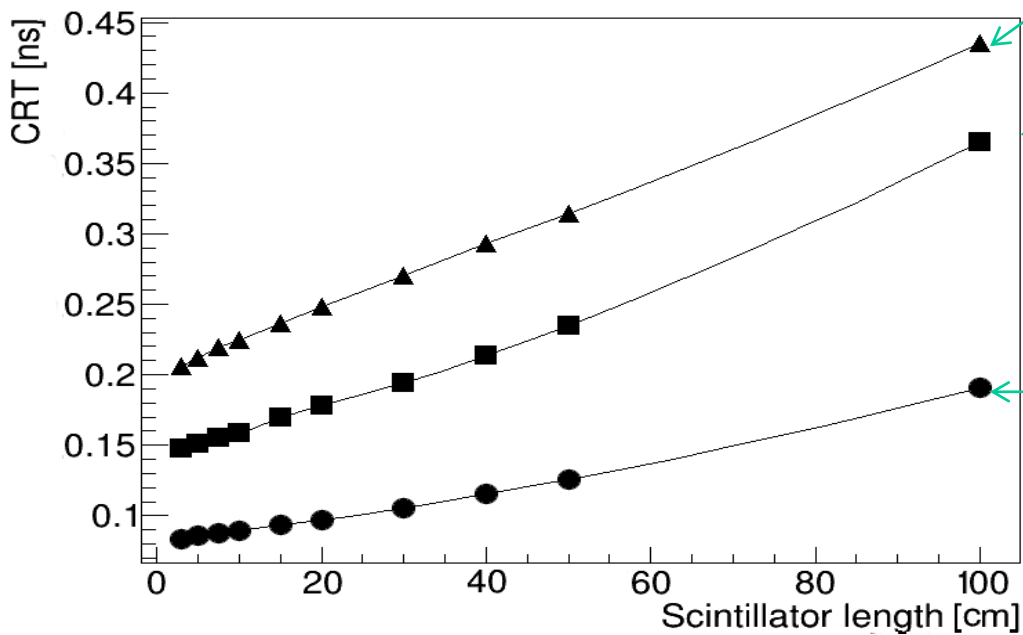
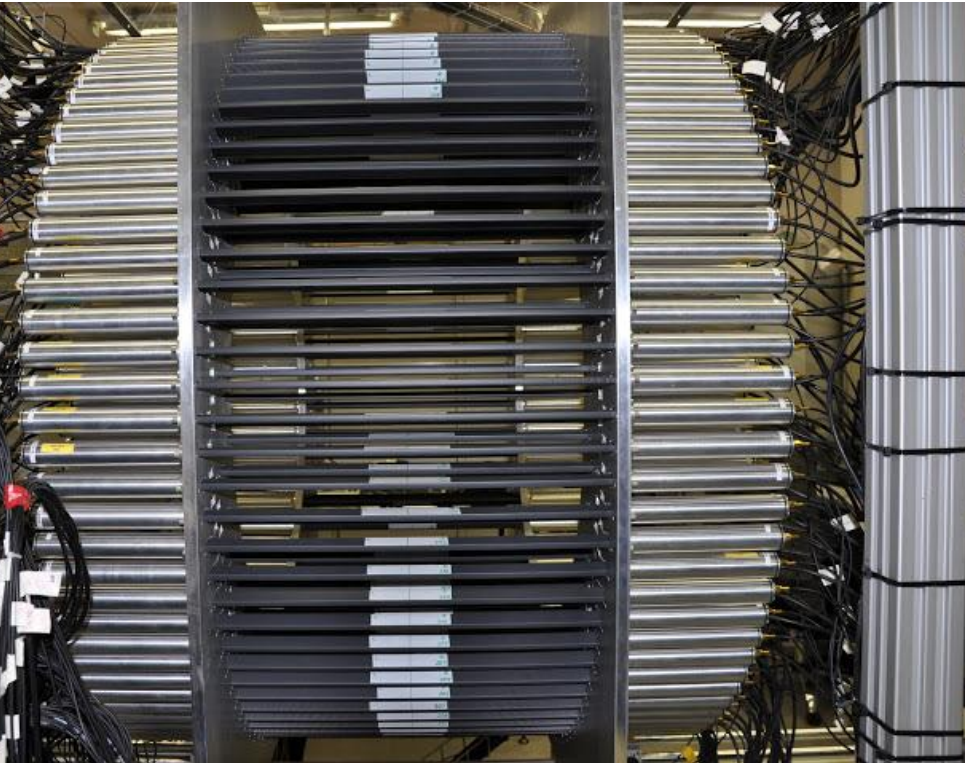
...

Combining PET and MRI is challenging



S. Vandenberghe, P. Marsden,
Phys. Med. Biol. 60 (2015) R115–R154

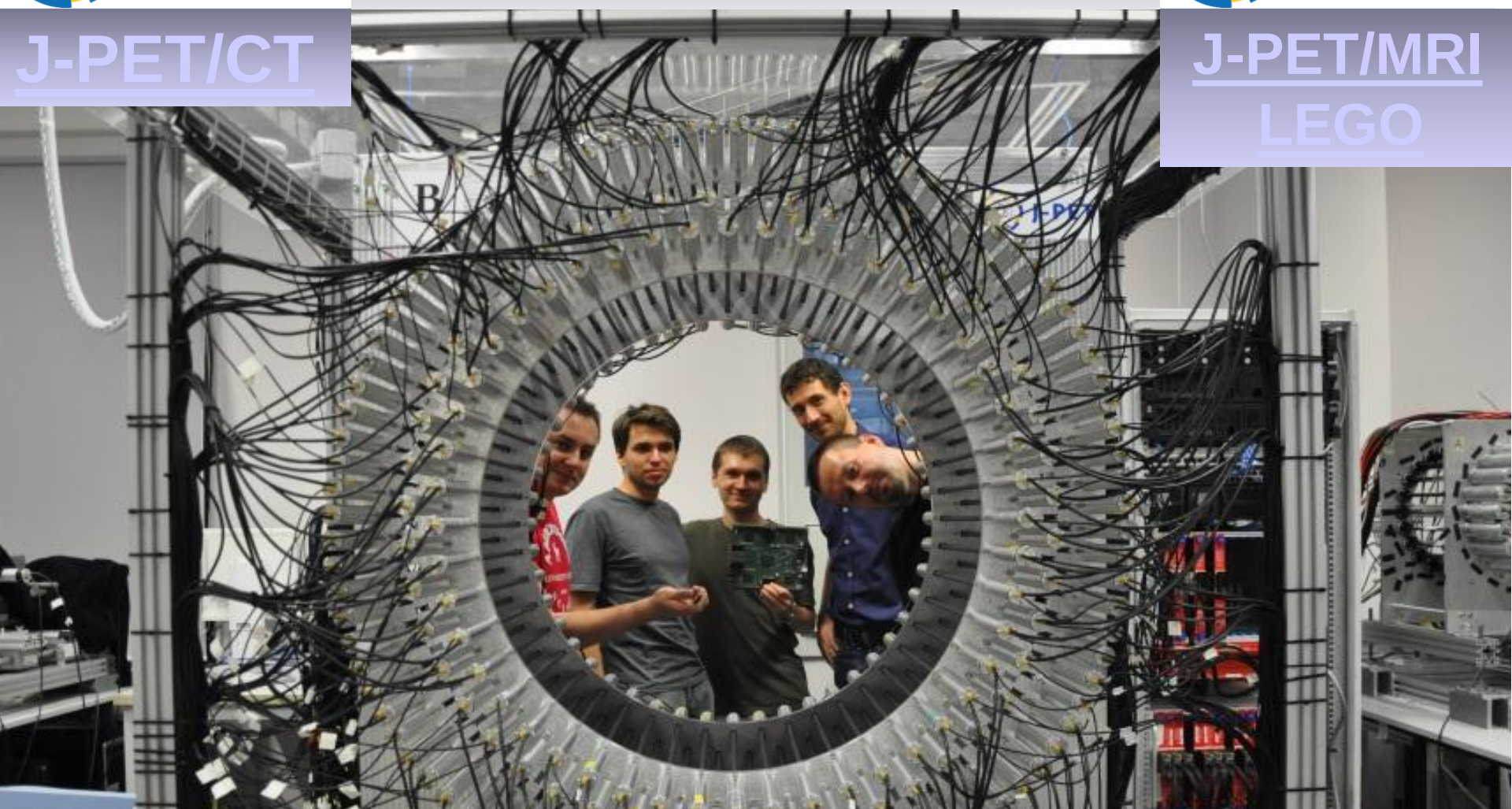




Limit of the J-PET

J-PET/CT

J-PET/MRI
LEGO

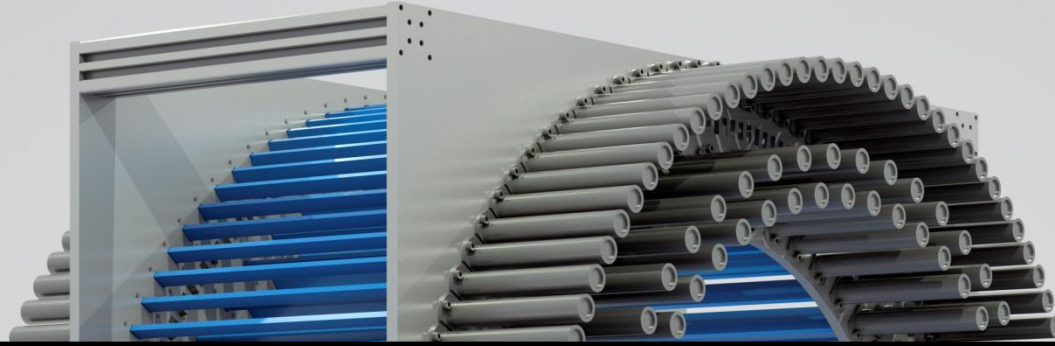


J-PET/CT: P. M., PCT/EP2014/068363 (2013)

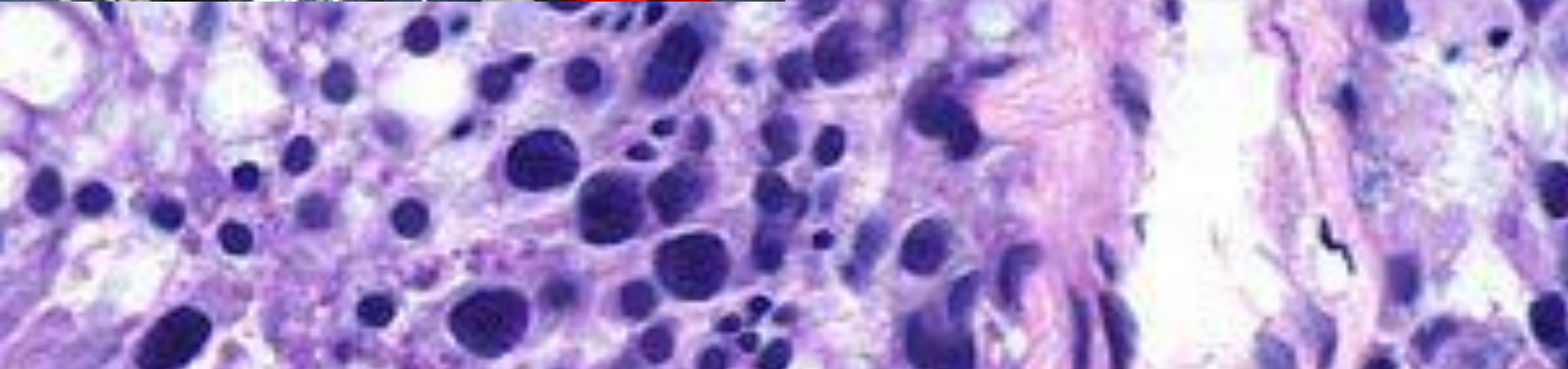
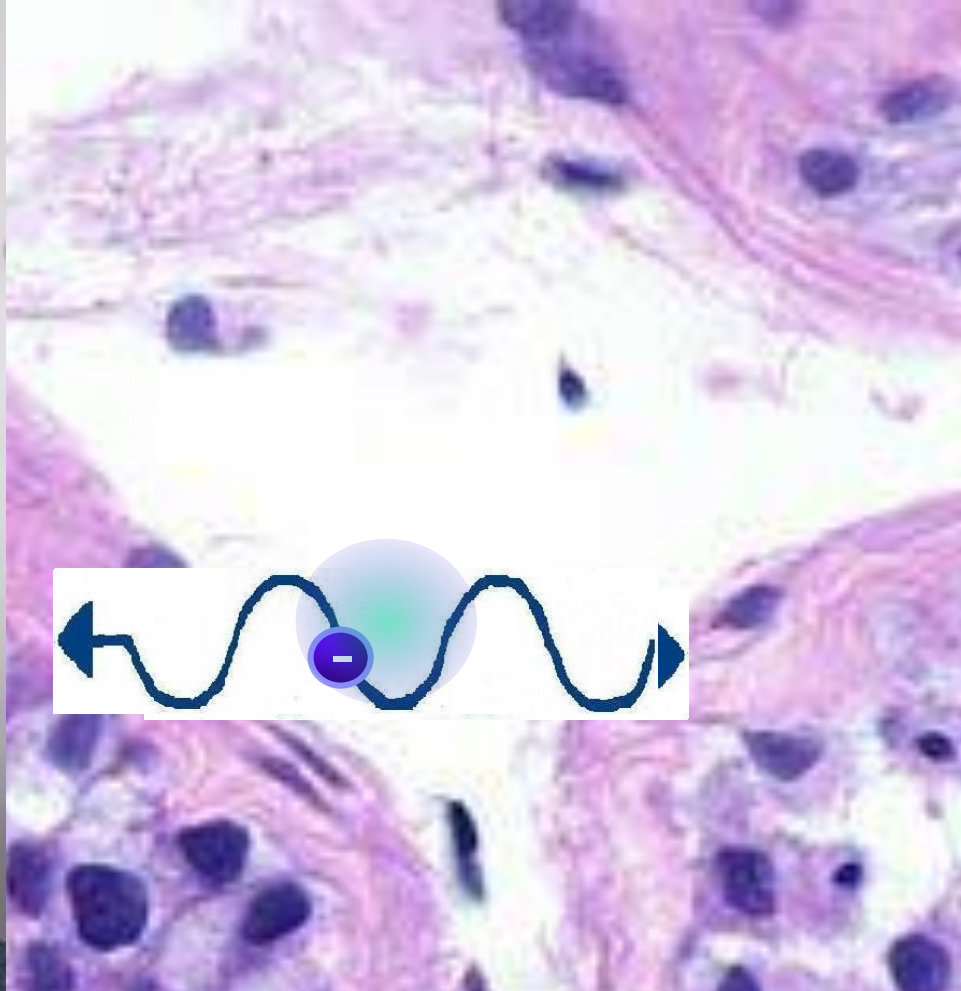
J-PET/MRI: P. M., PCT/EP2014/068373 (2013)

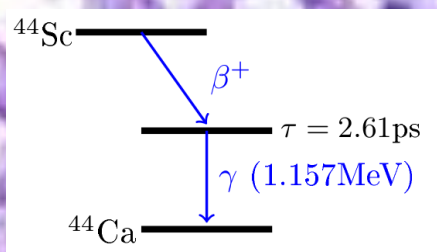
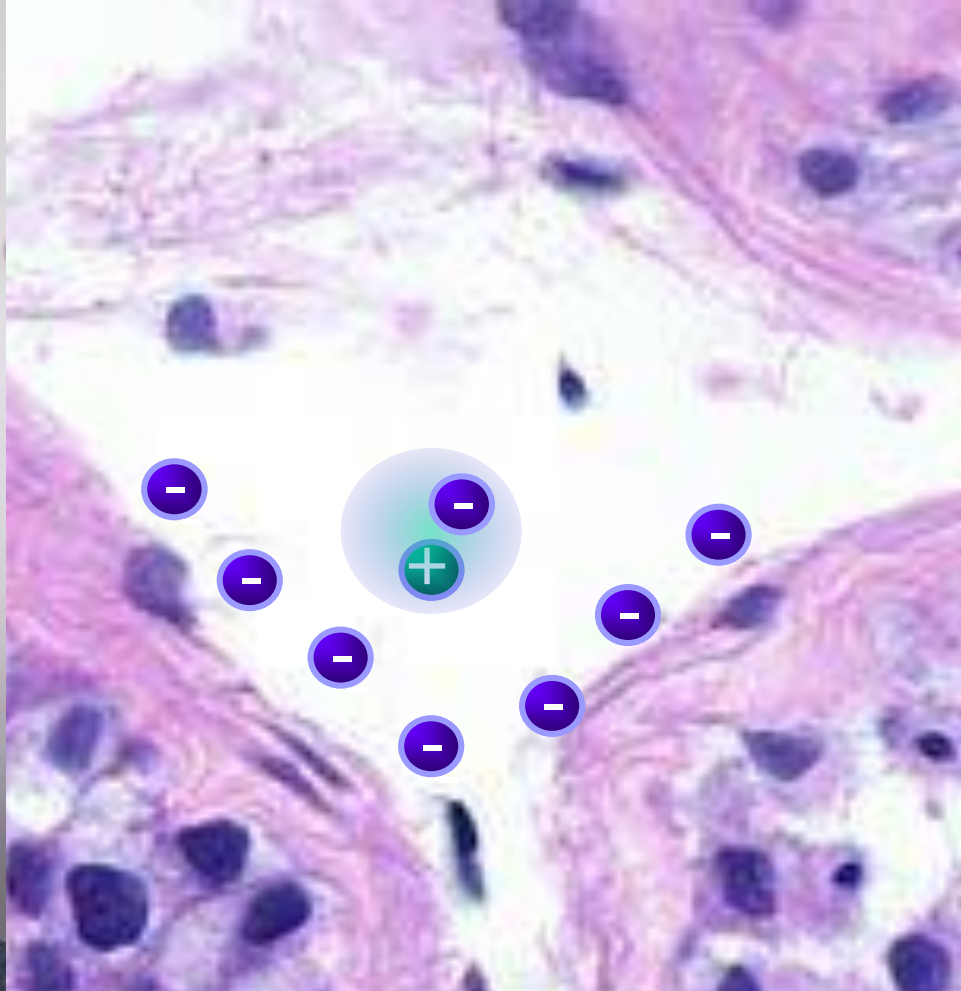
J-PET/MRI insert: B. Głowacz, P.M., M. Zieliński, P 413150 (2015)

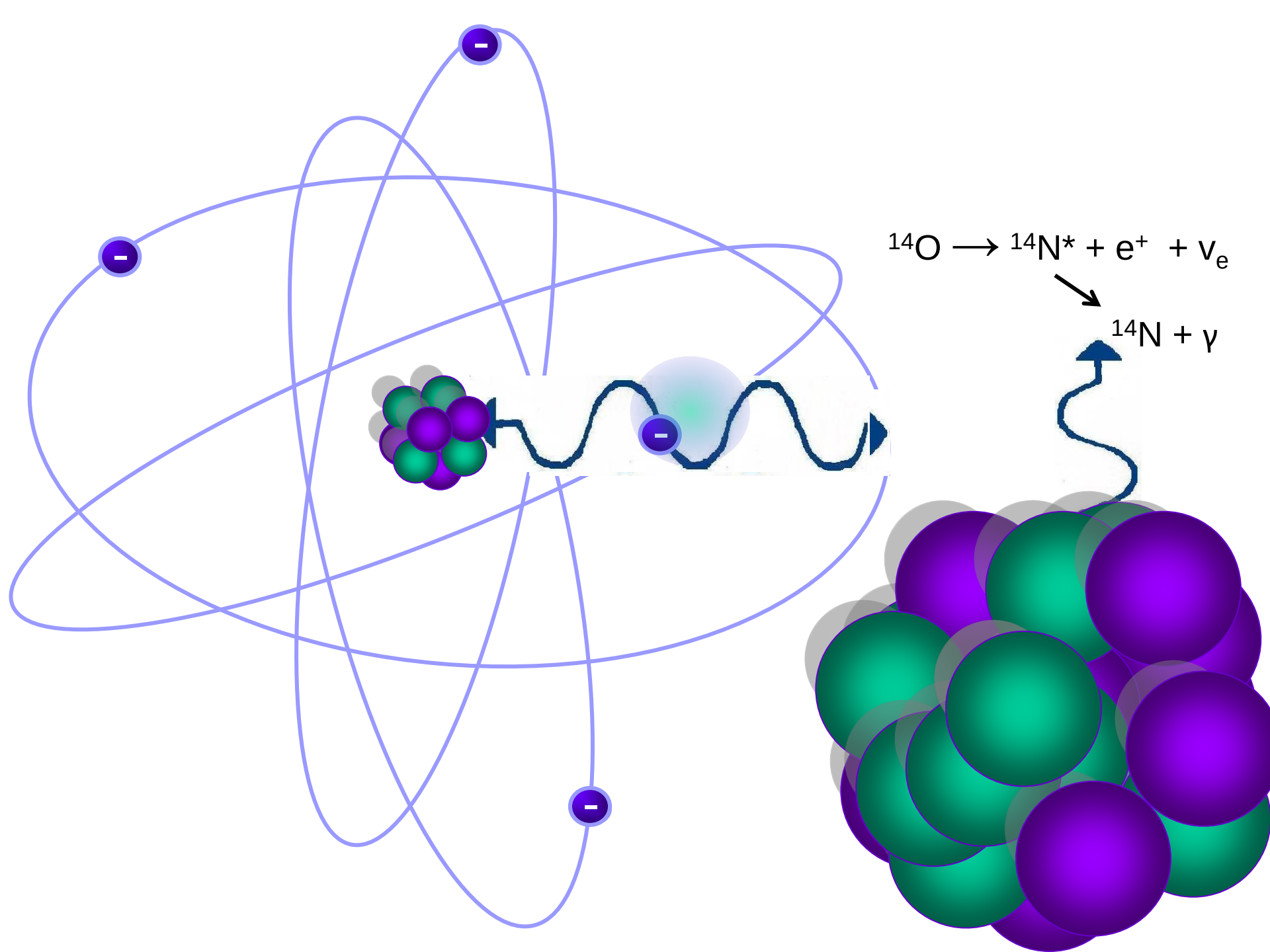
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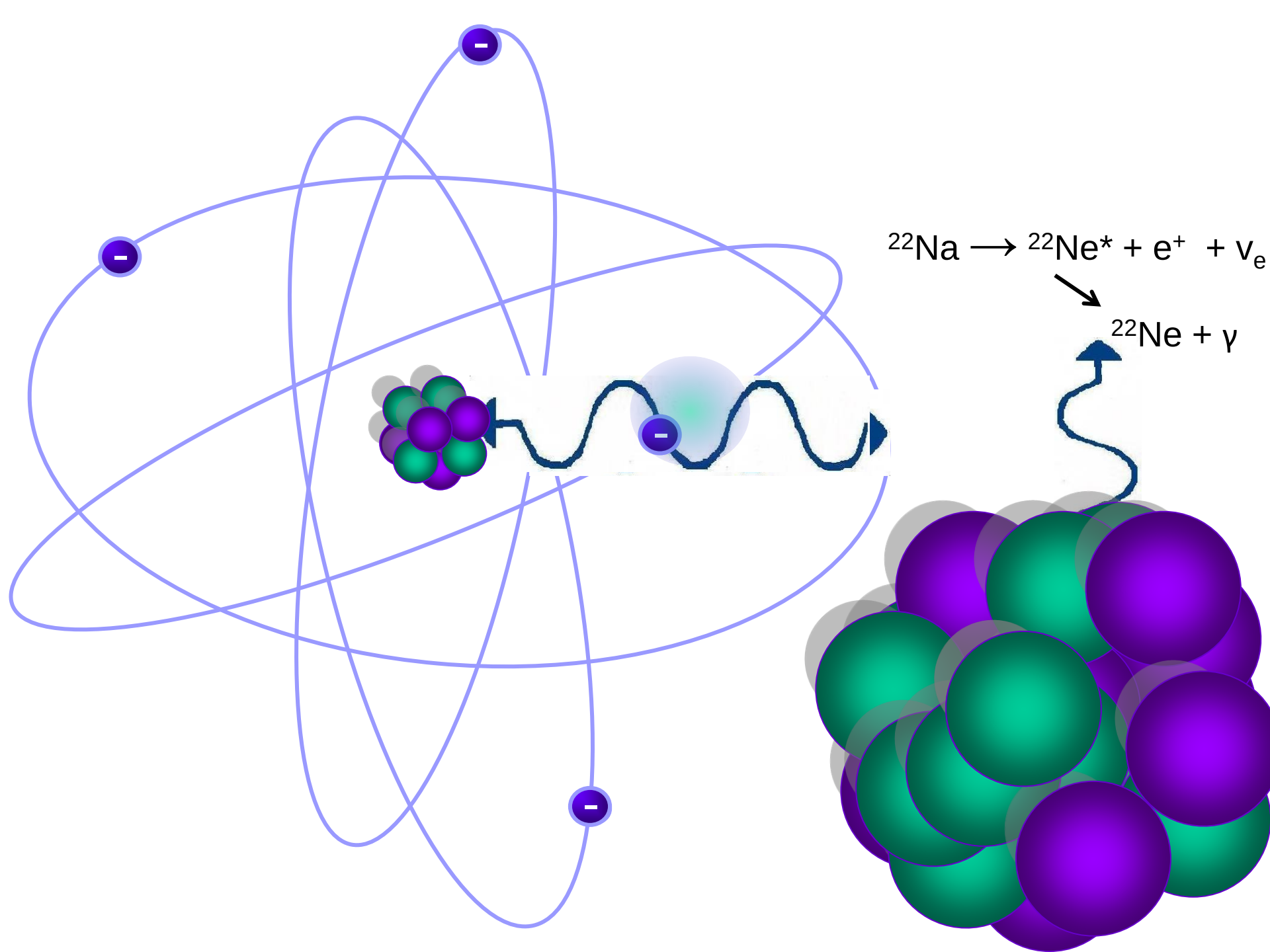


- **Jagiellonian PET**
- **Positronium**
- **Nanostructure of cells**
- **Discrete symmetries**
- **Quantum entanglement ...**

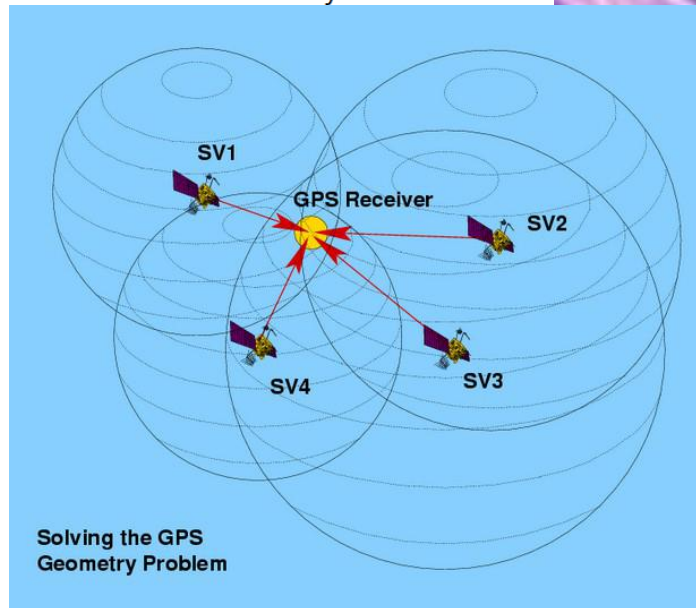
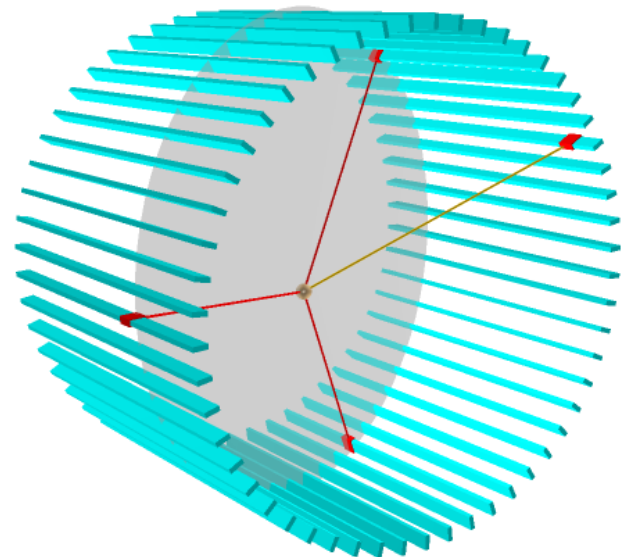
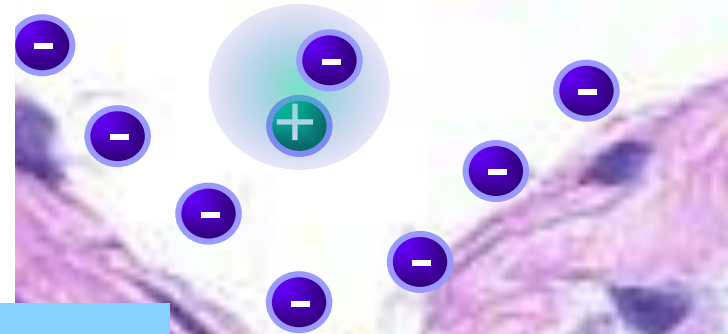
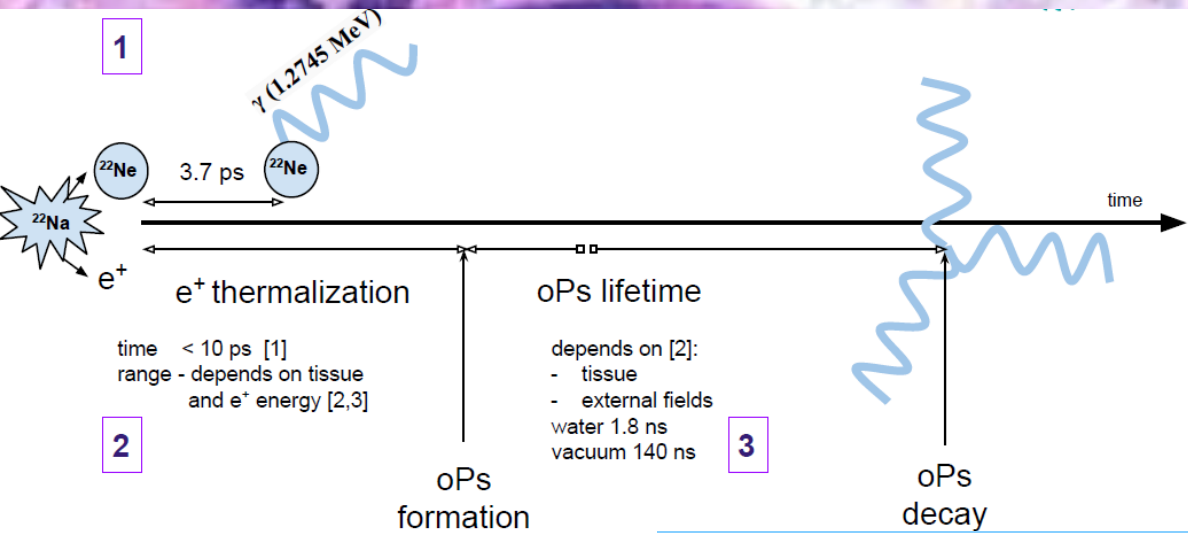


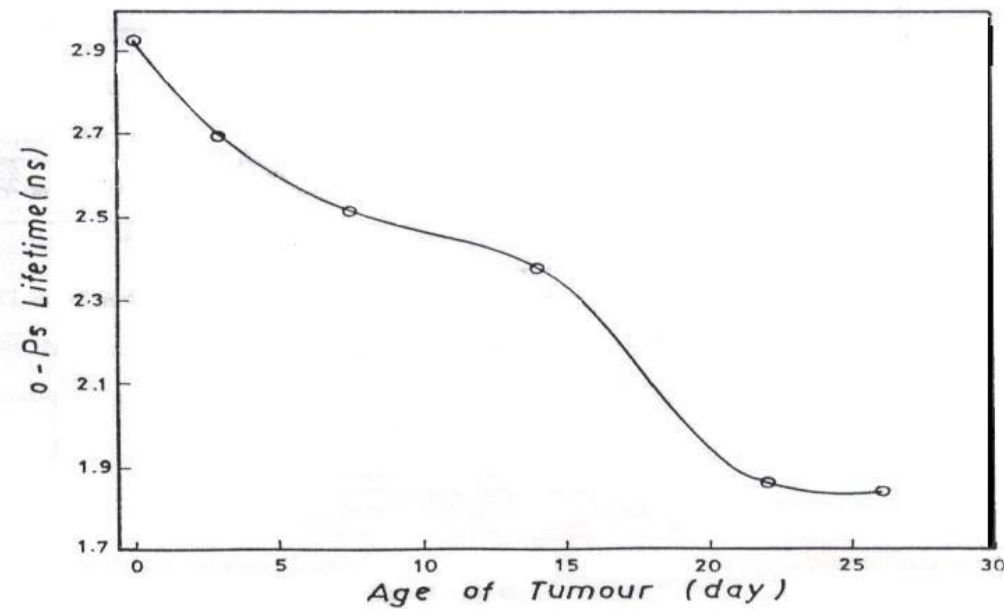




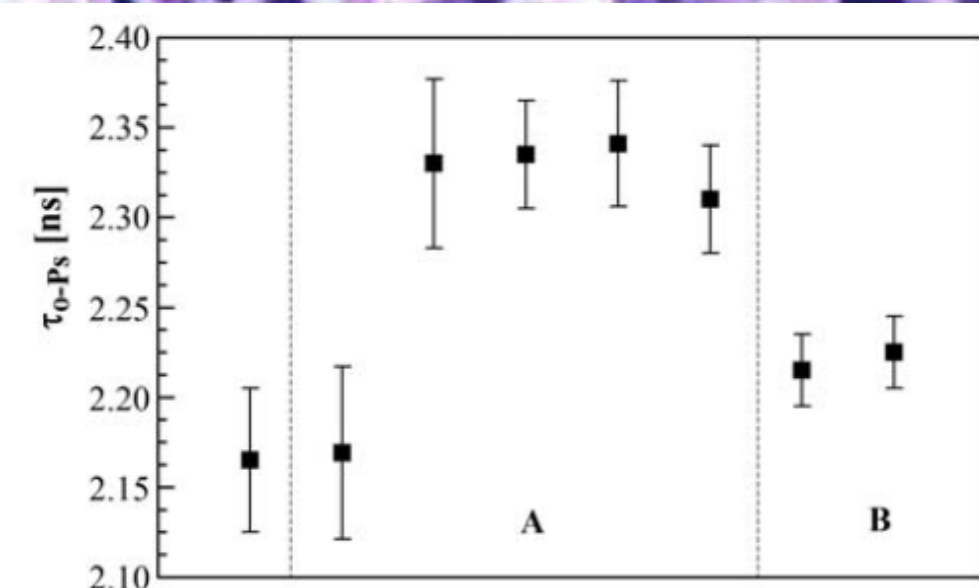
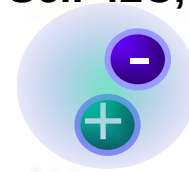


Ortho-positronium life-time tomography

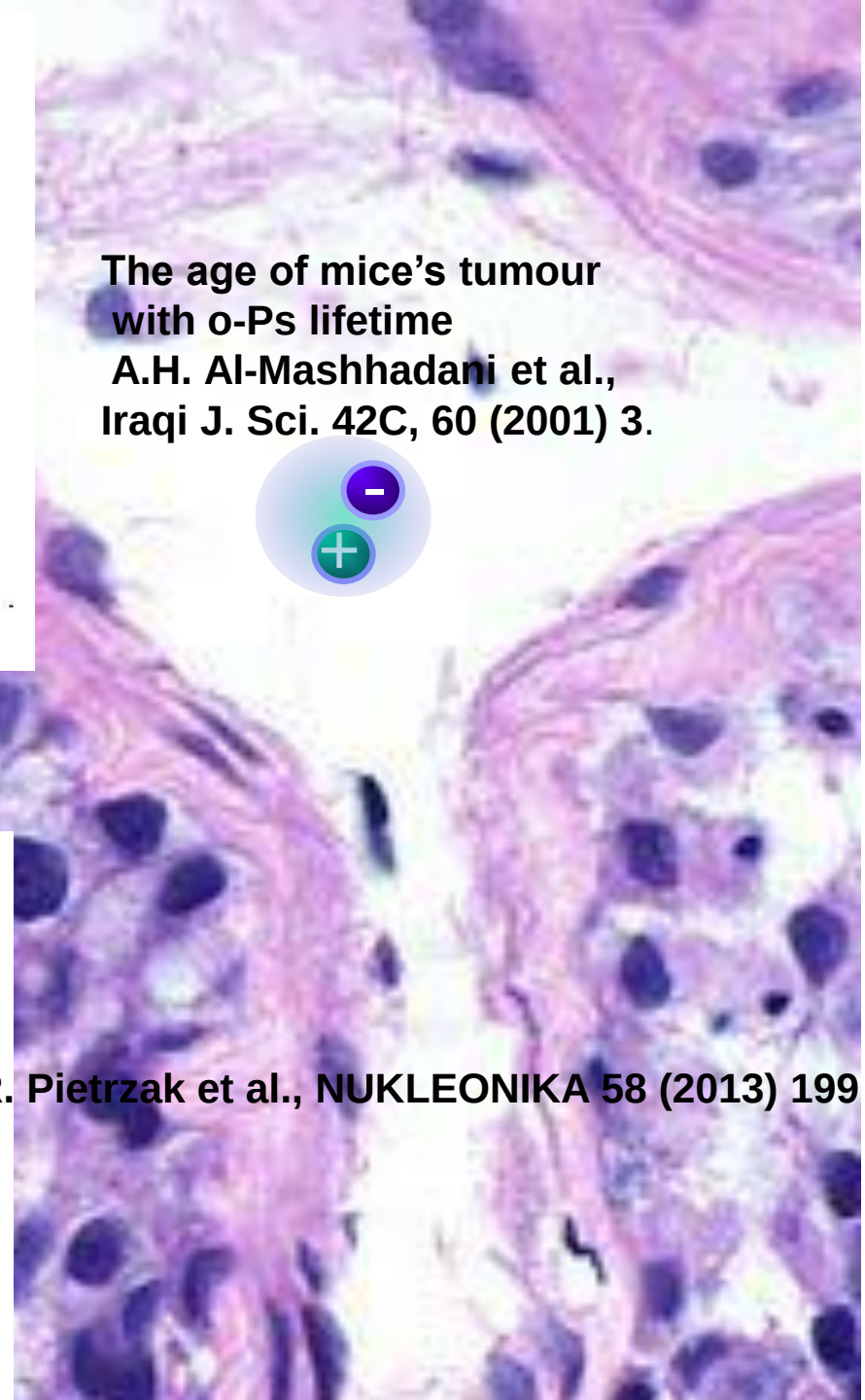


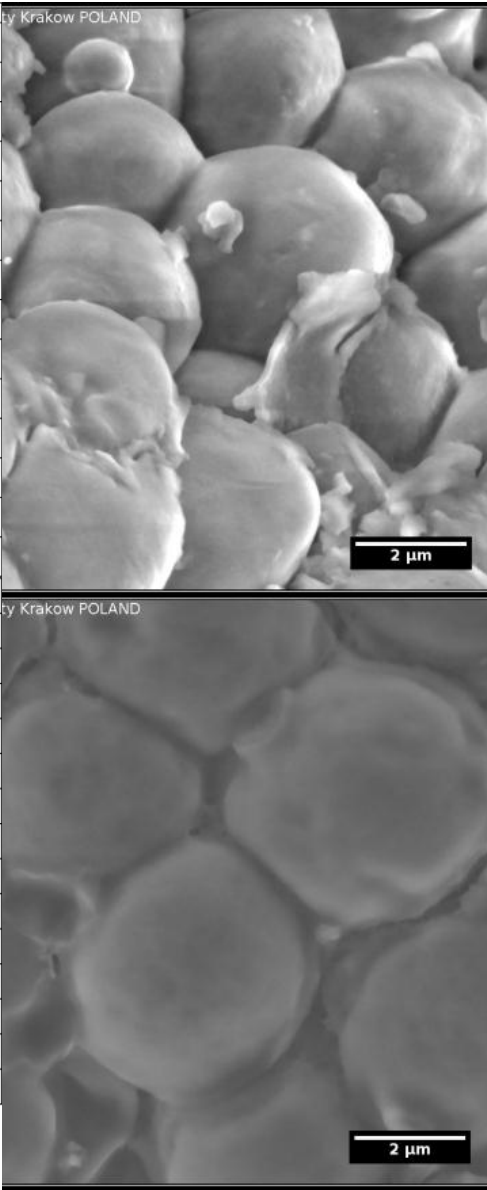
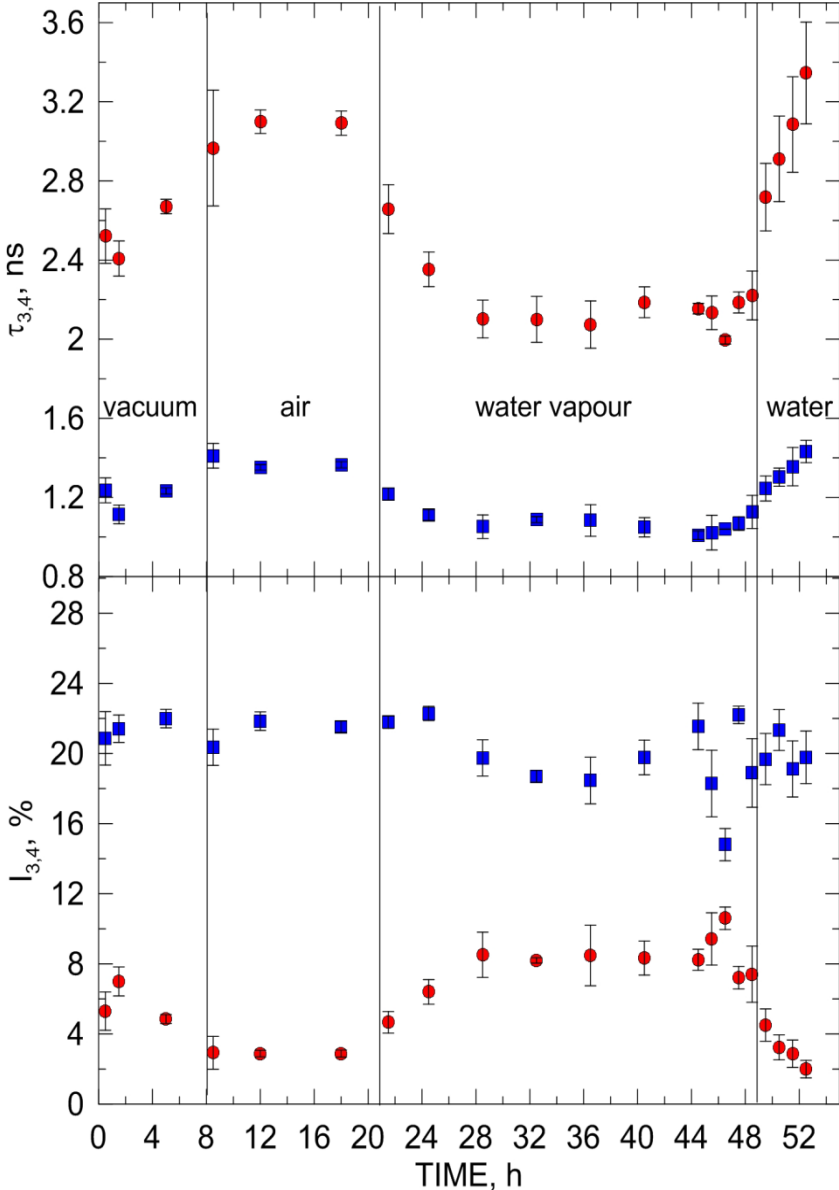


The age of mice's tumour
with o-Ps lifetime
A.H. Al-Mashhadani et al.,
Iraqi J. Sci. 42C, 60 (2001) 3.



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



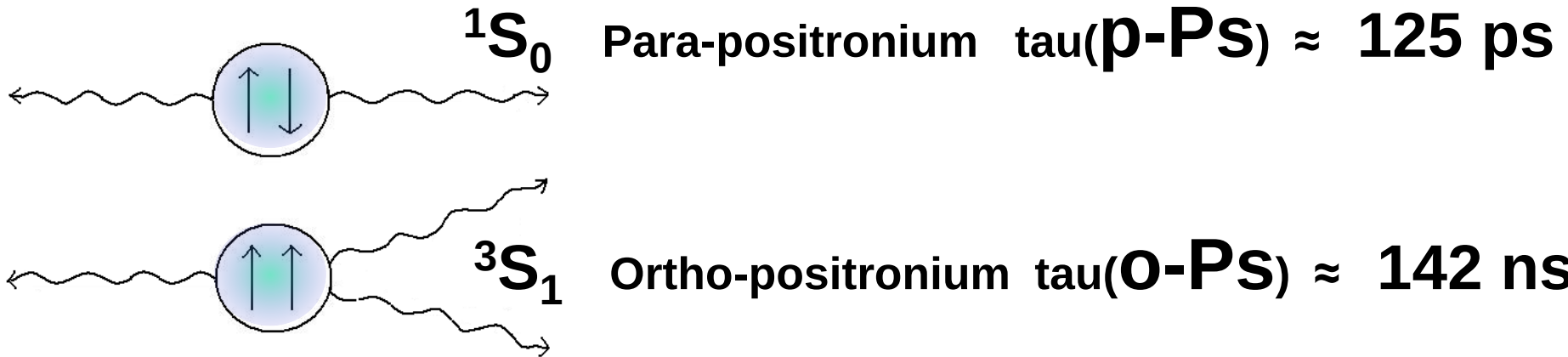


**J-PET: E. Kubicz, et al.,
Nukleonika 60 (2015) 749.**
Studies of unicellular
micro-organisms
Saccharomyces cerevisiae
by means of positron
annihilation lifetime
spectroscopy

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



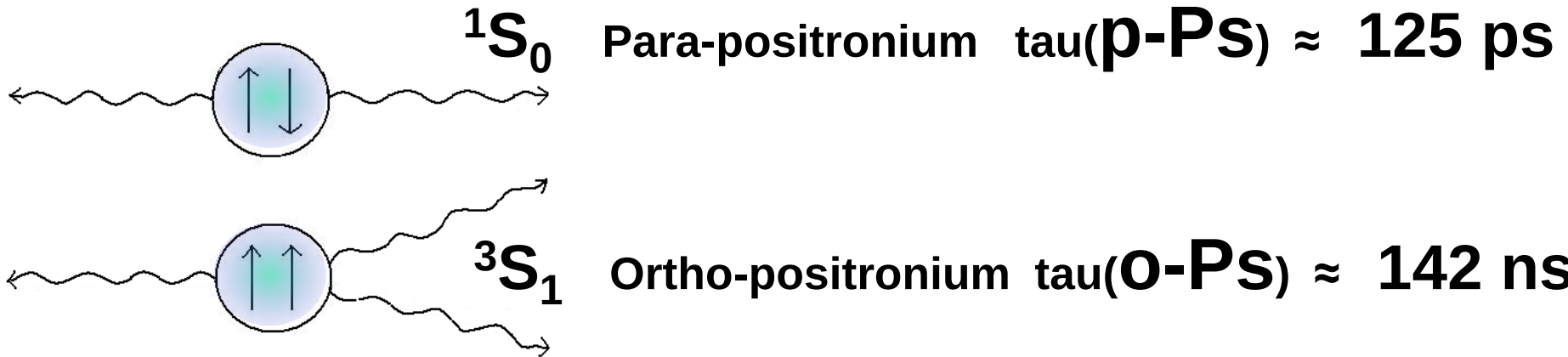
	$^1S_0$	$^3S_1$
L	0	0



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

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

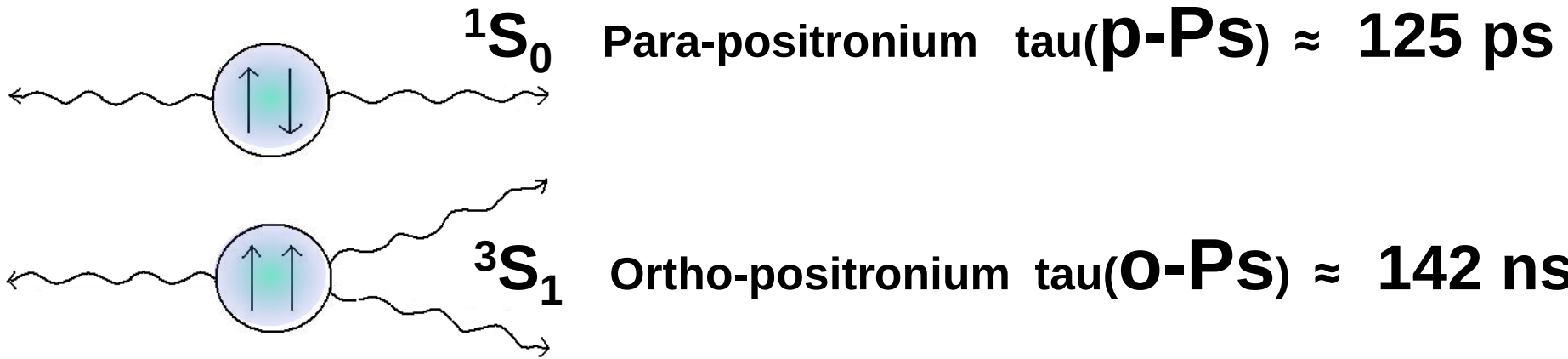
$$S = 1 \quad \uparrow\uparrow + \downarrow\downarrow$$



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

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

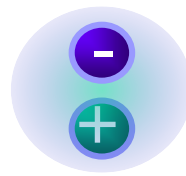
$$S = 1 \quad \uparrow\uparrow + \downarrow\downarrow$$



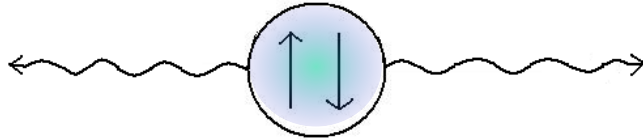
	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-
L=0 $\rightarrow$ P	-	-
CP	-	+

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

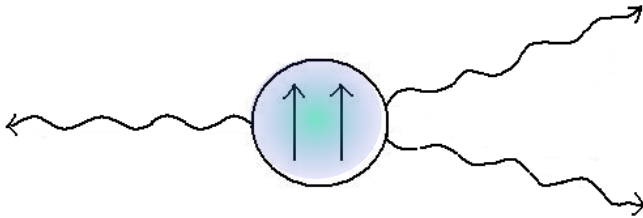
$$S = 1 \quad \uparrow\uparrow + \downarrow\downarrow$$



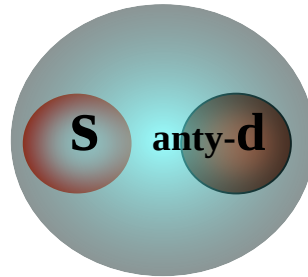
POSITRONIUM



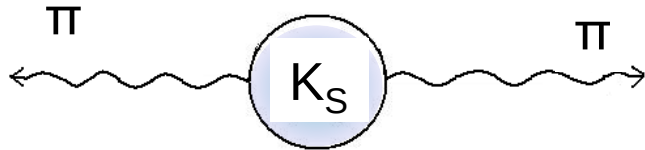
CP = + Para-positronium $\tau(p\text{-Ps}) \approx 125 \text{ ps}$



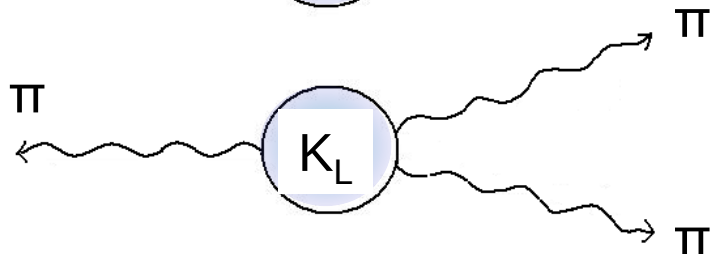
CP = - Ortho-positronium $\tau(o\text{-Ps}) \approx 142 \text{ ns}$



MESON K



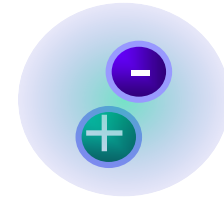
CP $\sim$ + $\tau(K_S) \approx 90 \text{ ps}$



CP $\sim$ - $\tau(K_L) \approx 52 \text{ ns}$

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 eigenstates.

**Electrons and positron are the lightest leptons so they can not decay
into lighter particles via weak interaction ...**

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).

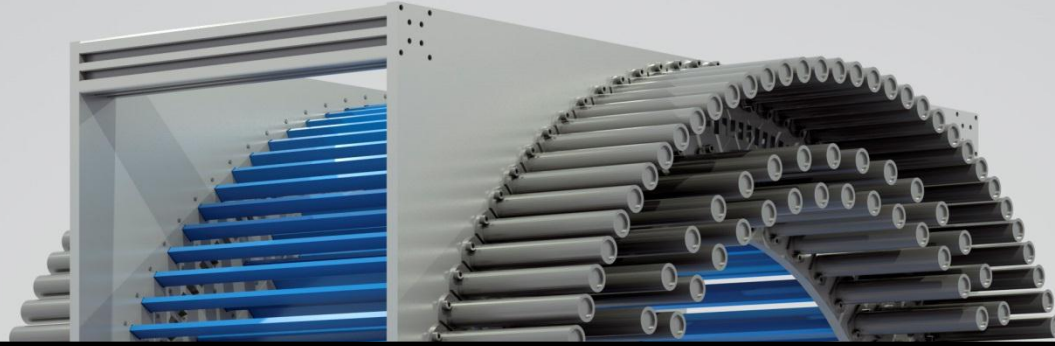
Purely Leptonic state !

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

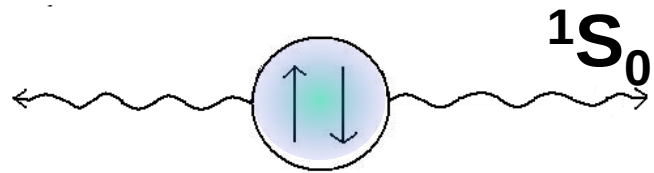
So far breaking of these symmetries was not observed for purely leptonic systems.

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

10^{-9} vs upper limits of $3 * 10^{-7}$ for C

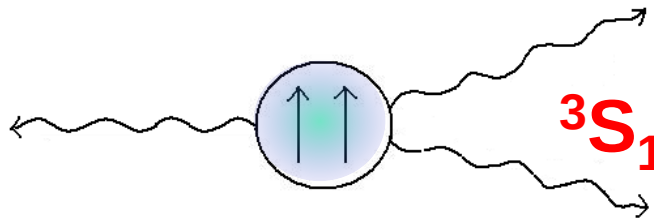


- **Jagiellonian PET**
- **Positronium**
- **Nanostructure of cells**
- **Discrete symmetries**
- **Quantum entanglement ...**



$1S_0$

Para-positronium $\tau(\text{p-Ps}) \approx 125 \text{ ps}$



$3S_1$

Ortho-positronium $\tau(\text{o-Ps}) \approx 142 \text{ ns}$

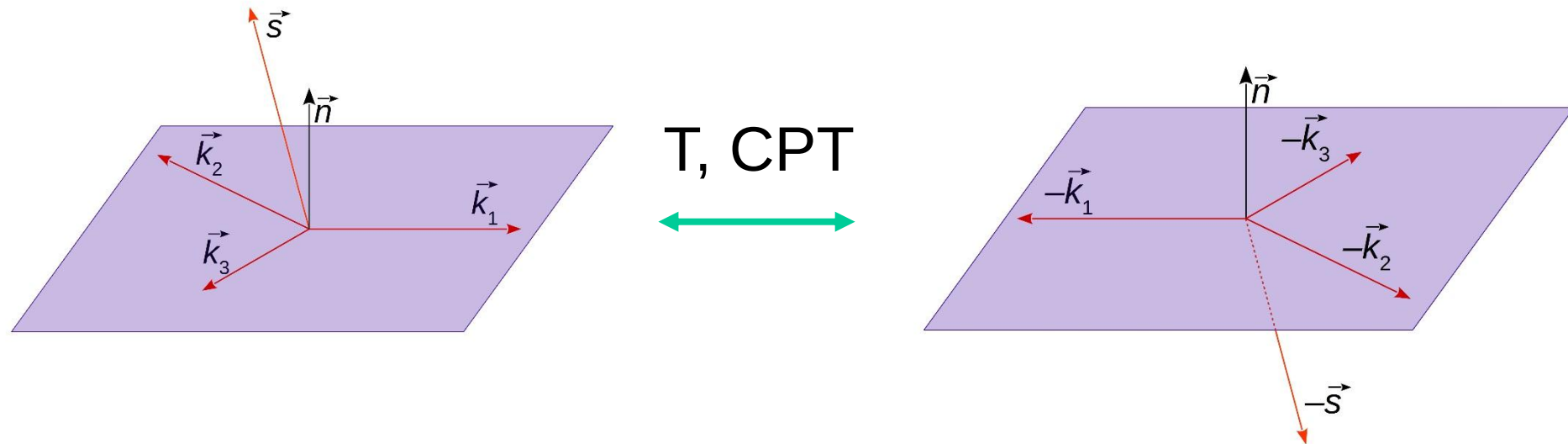
	$1S_0$	$3S_1$		2γ	3γ	4γ	5γ	...
C	+	-		+	-	+	-	

bound state mixing is not possible because there are no positronium states with opposite C-parity and the same J^P .

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 $o\text{-Ps} \rightarrow 3\gamma$ process, and their properties with respect to the C, P, T, CP and CPT symmetries.

$$|\mathbf{k}_1| > |\mathbf{k}_2| > |\mathbf{k}_3|$$

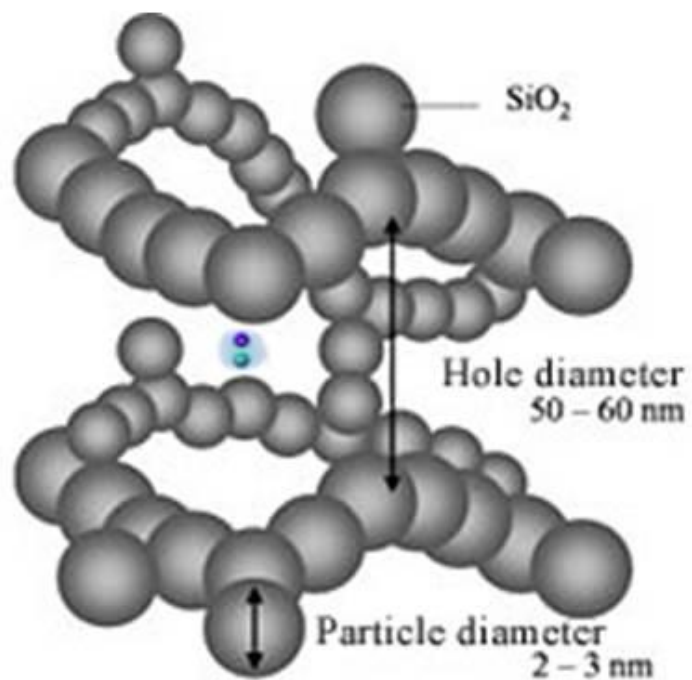
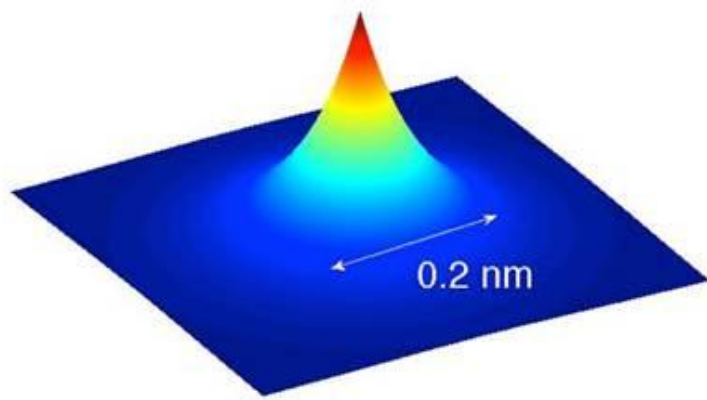


So far best accuracy for **CP and CPT violation** was reported by

-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).

positronium



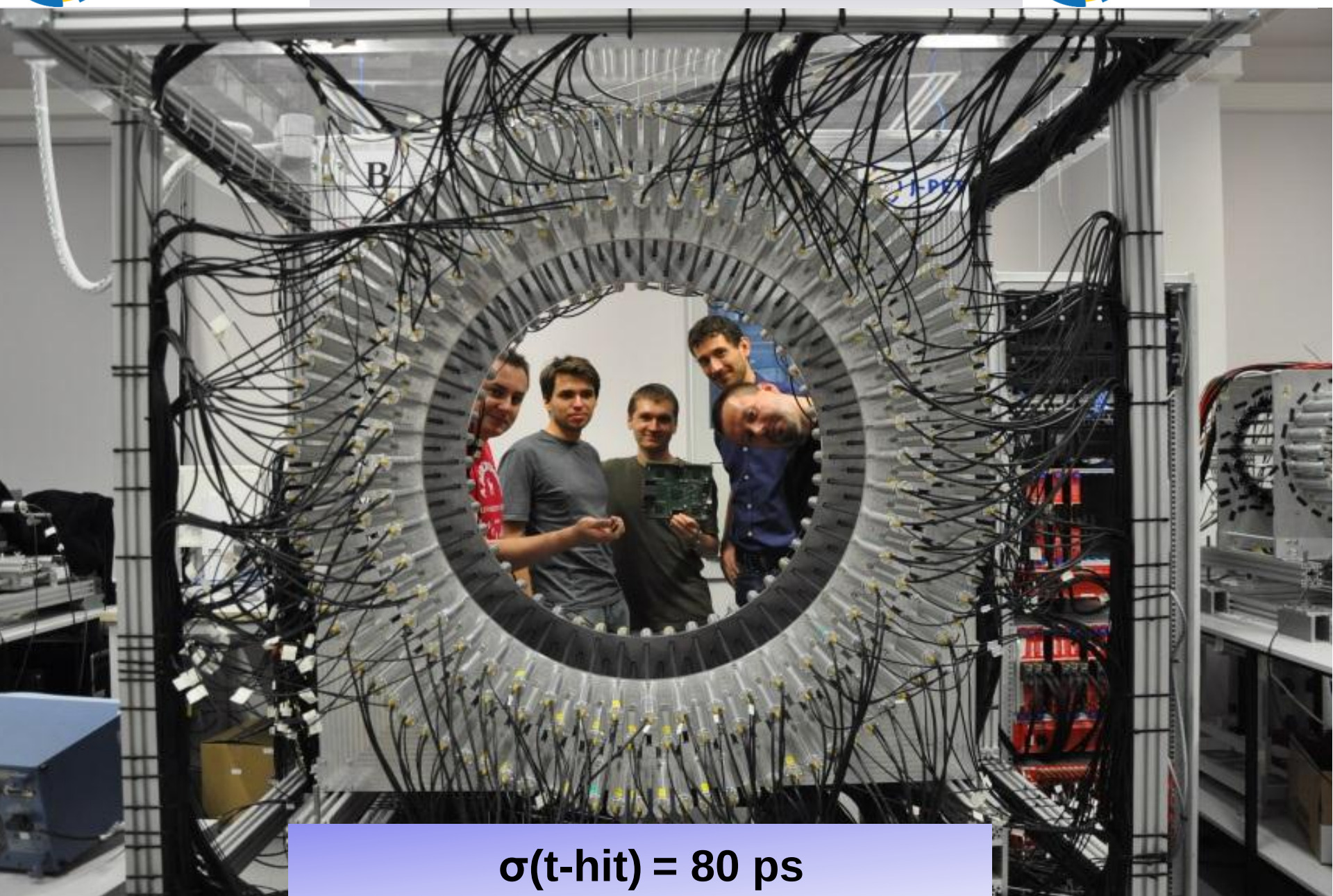


J-PET

Jagiellonian PET



J-PET



$$\sigma(t\text{-hit}) = 80 \text{ ps}$$

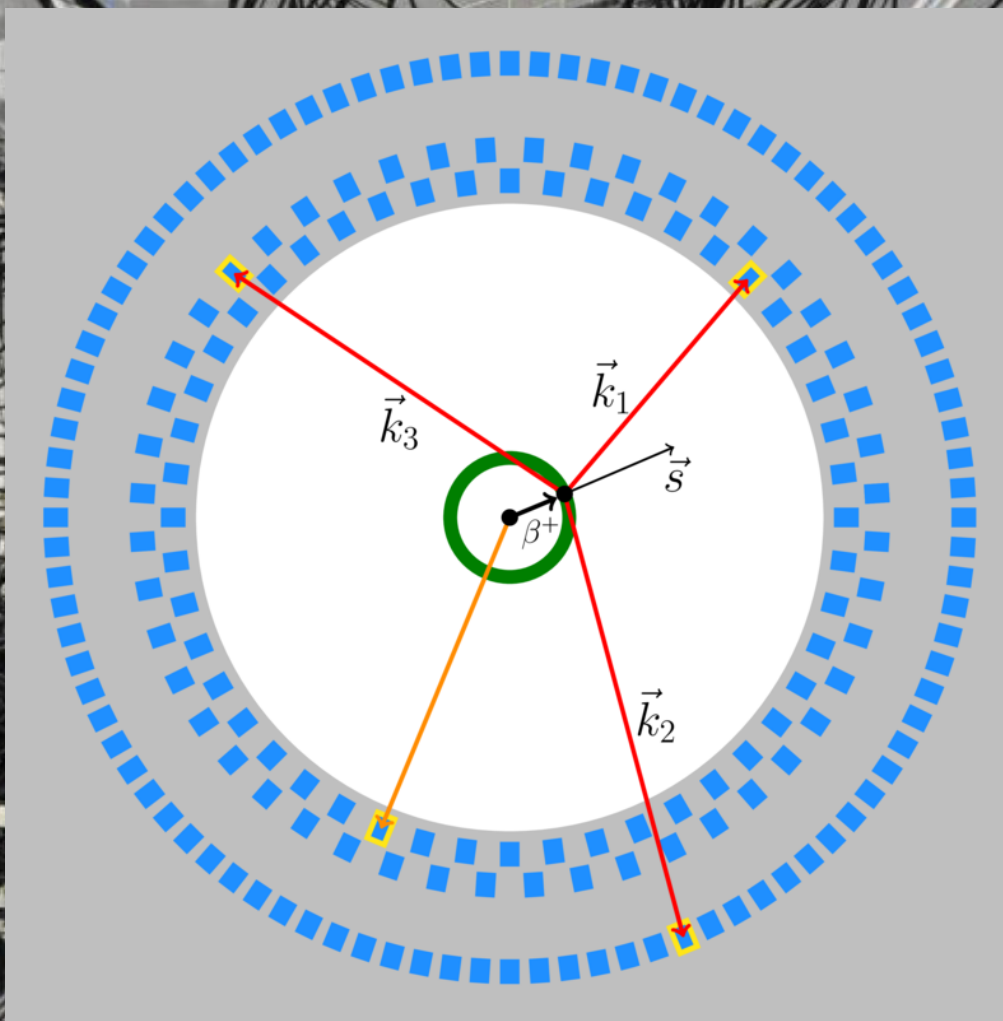


J-PET

Jagiellonian PET



J-PET



$$\sigma(t\text{-hit}) = 80 \text{ ps}$$

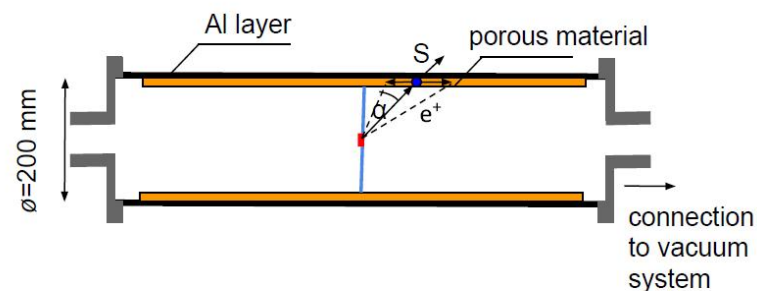
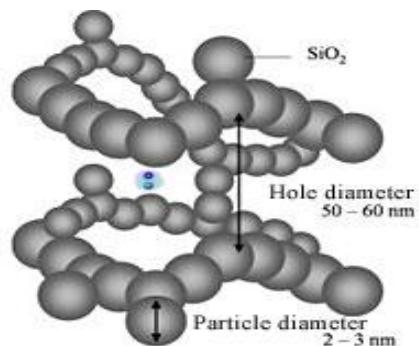


J-PET

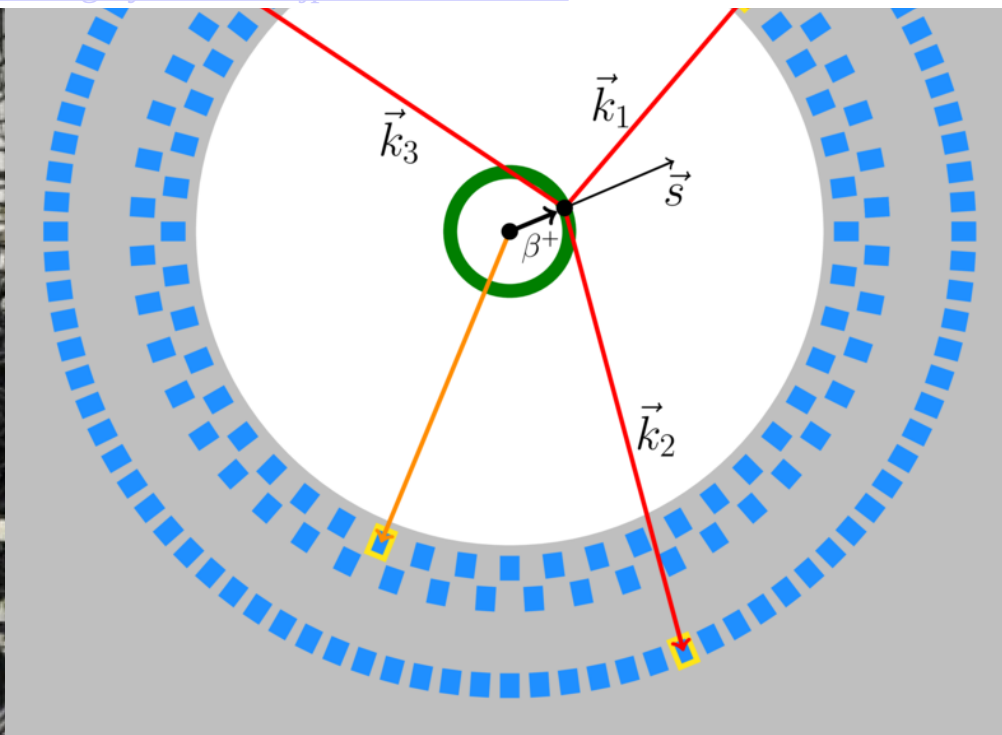
Jagiellonian PET



J-PET



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



$$\sigma(t\text{-hit}) = 80 \text{ ps}$$

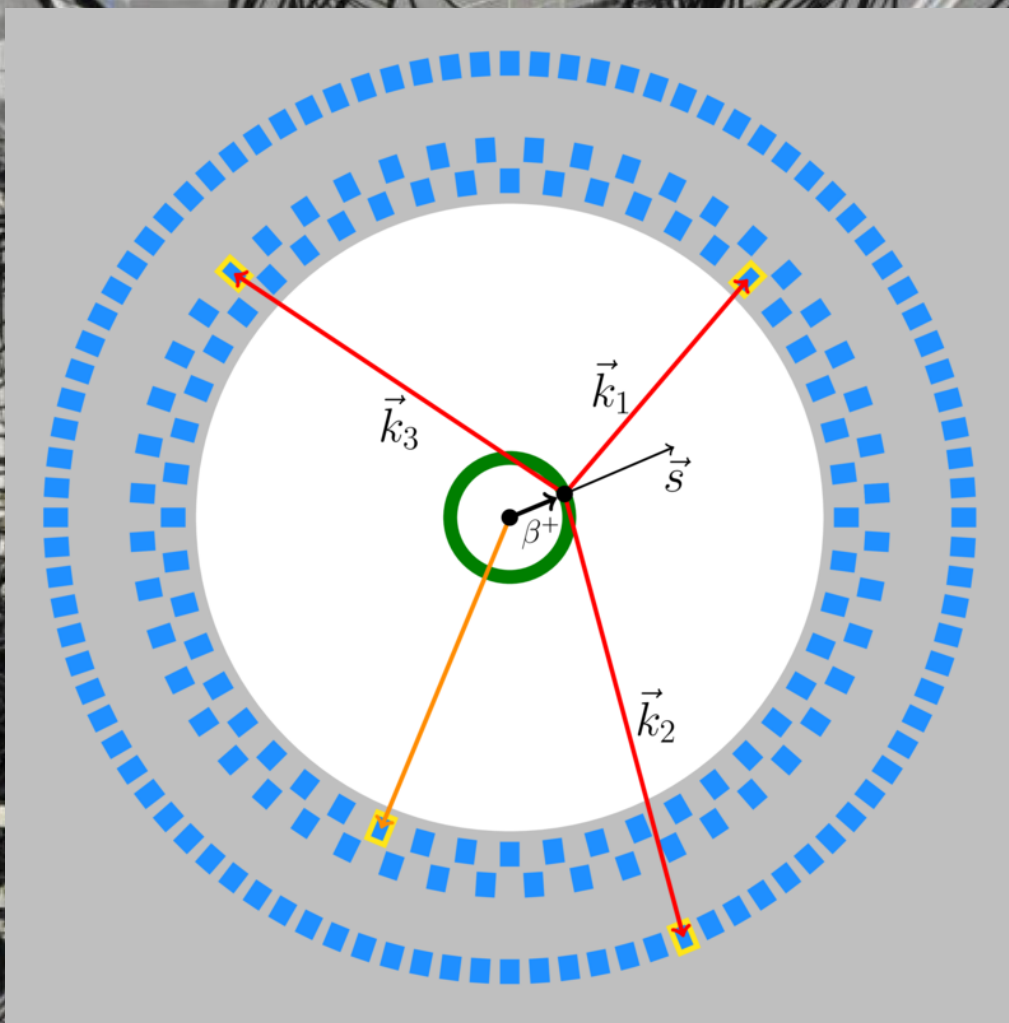


J-PET

Jagiellonian PET



J-PET



$$\sigma(t\text{-hit}) = 80 \text{ ps}$$

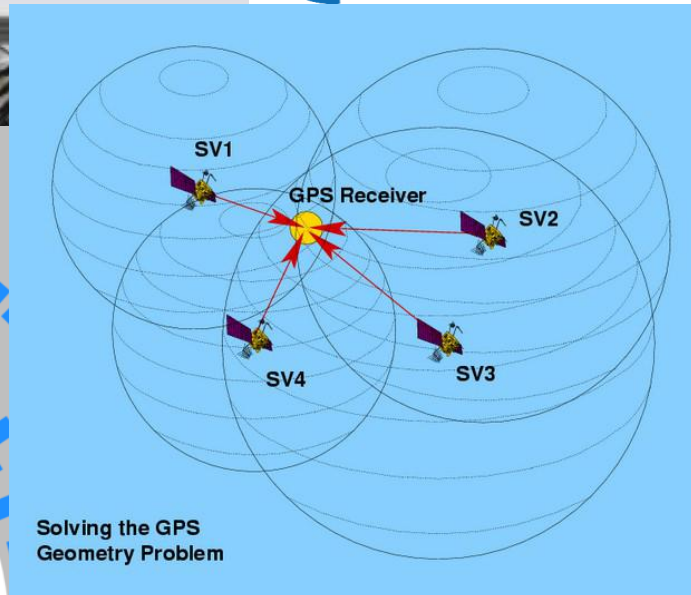
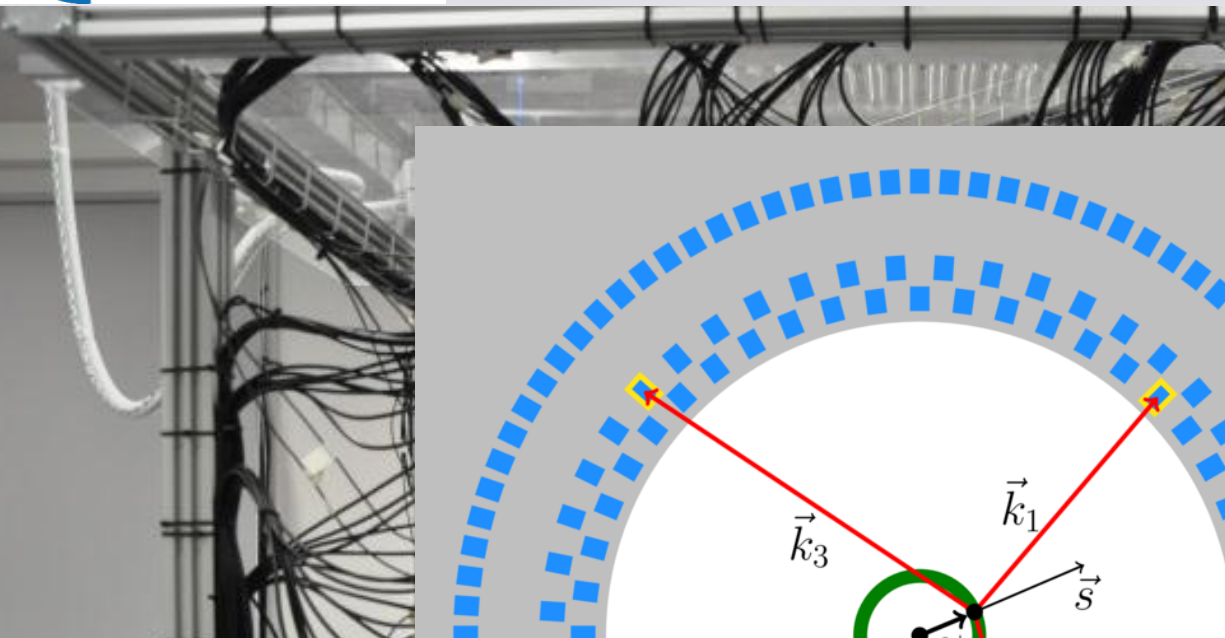


J-PET

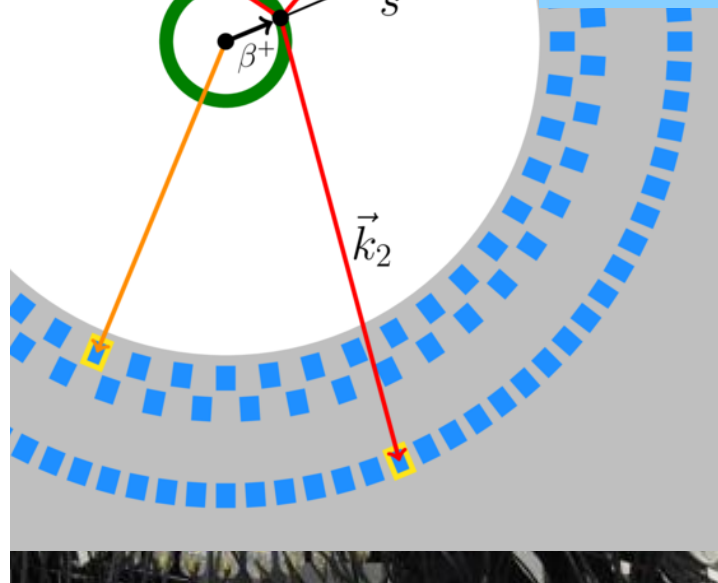
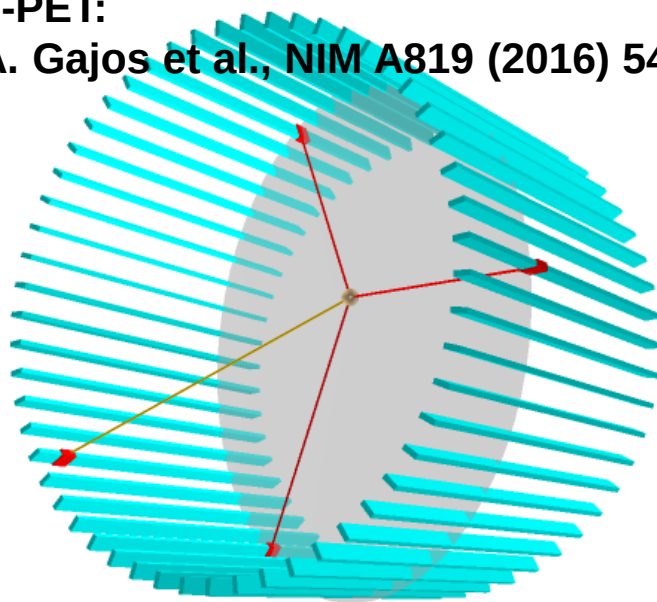
Jagiellonian PET



J-PET



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



$$\sigma(t\text{-hit}) = 80 \text{ ps}$$



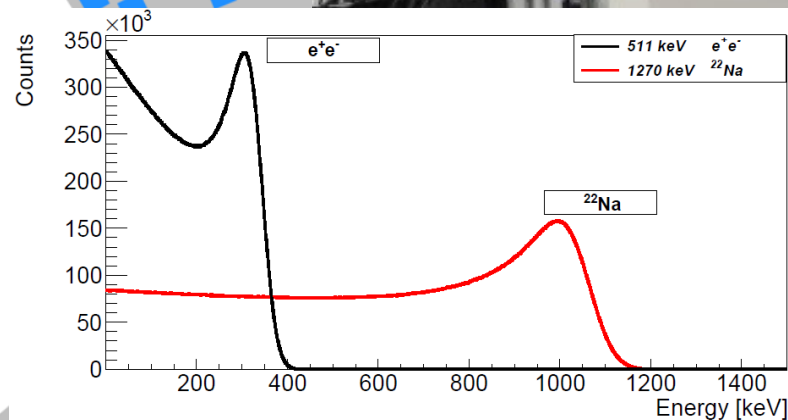
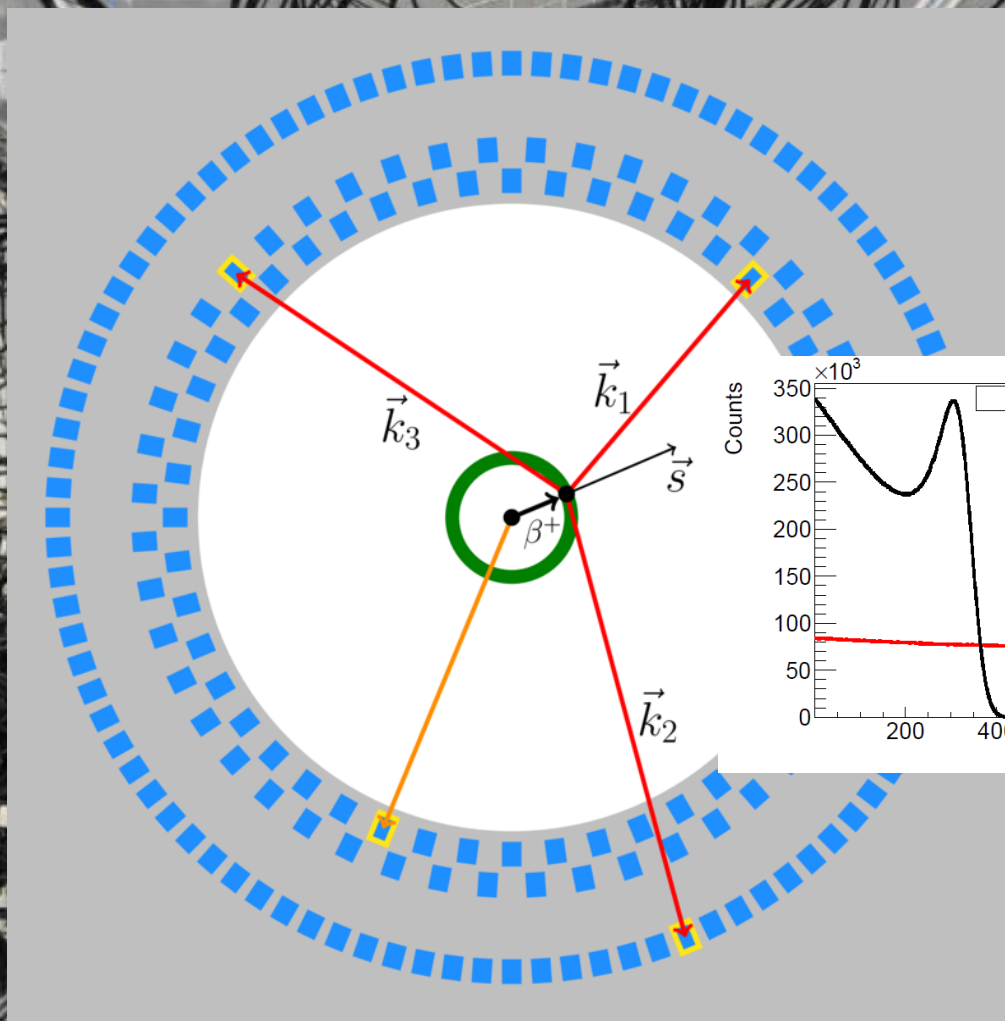


J-PET

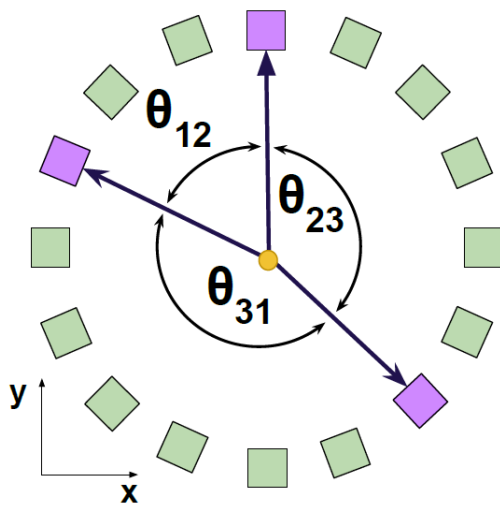
Jagiellonian PET



J-PET

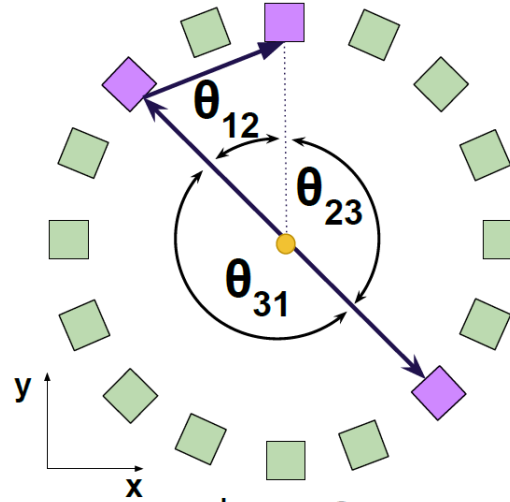


$$\sigma(\text{t-hit}) = 80 \text{ ps}$$



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

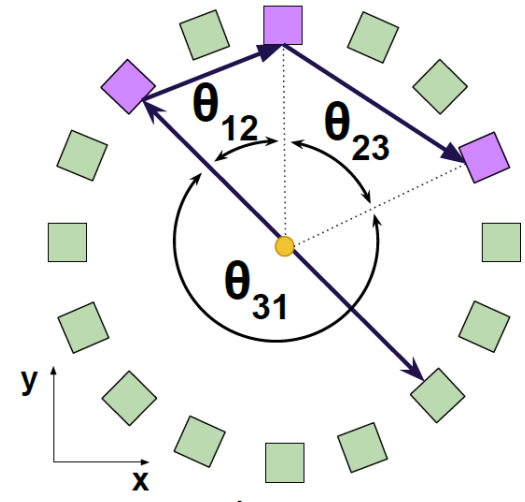
$$\theta_{23} > 180 - \theta_{12}$$



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

single scattered

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

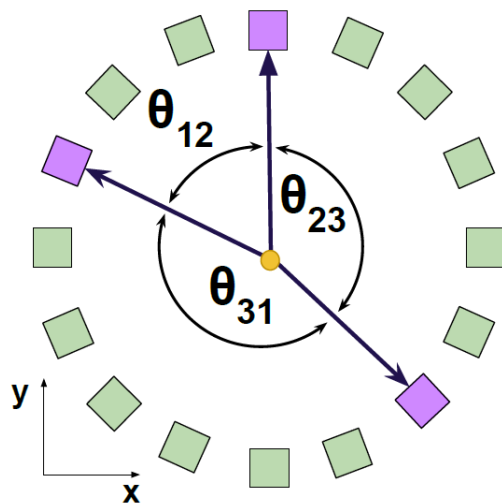


$e^+e^- \rightarrow 2\gamma$

double scattered

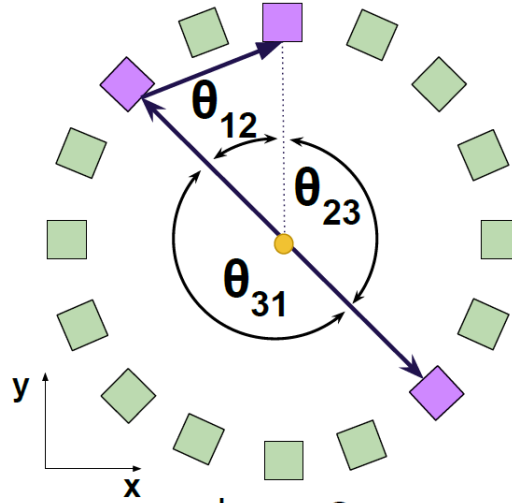
$$\theta_{23} < 180 - \theta_{12}$$

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



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

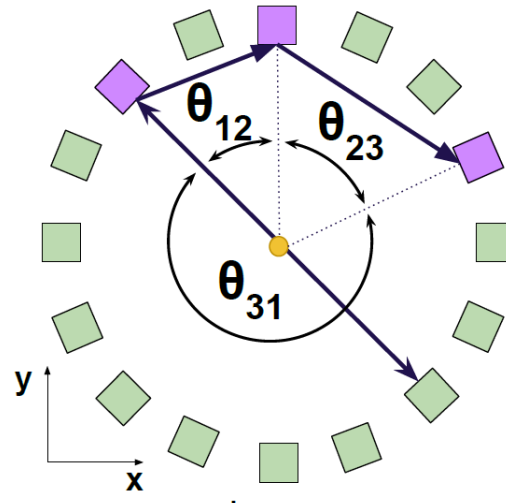
$$\theta_{23} < 180 - \theta_{12}$$



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

single scattered

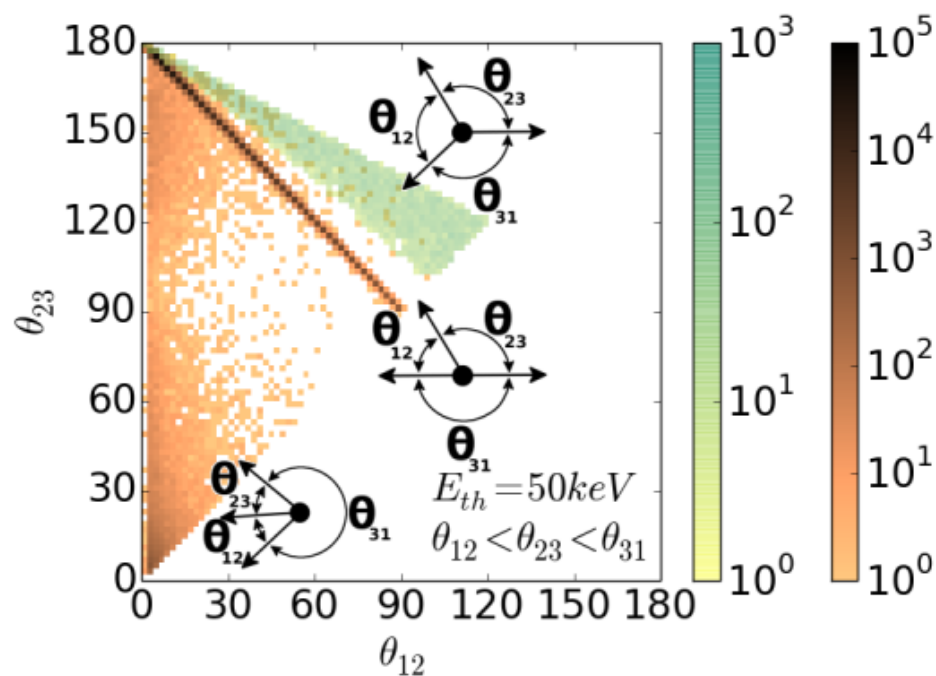
$$\theta_{23} = 180 - \theta_{12}$$

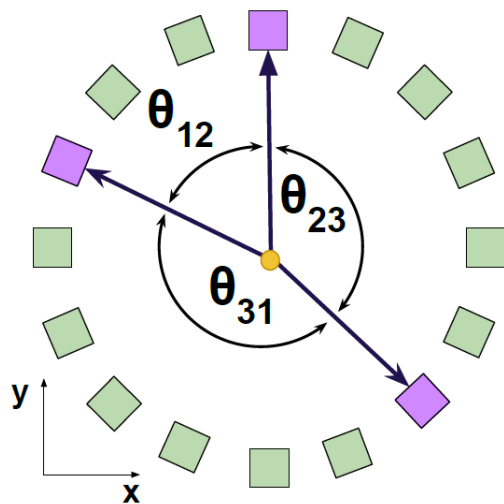


$e^+e^- \rightarrow 2\gamma$

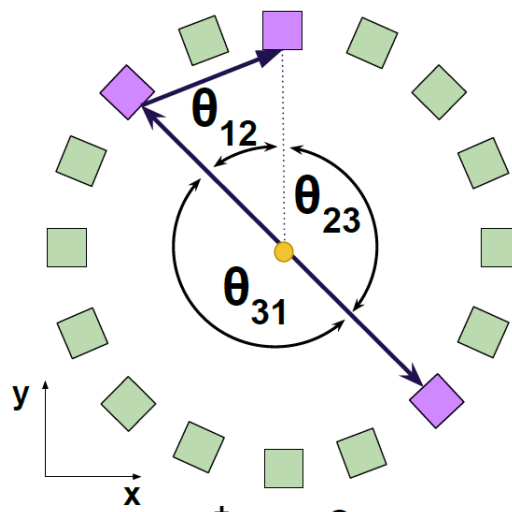
double scattered

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

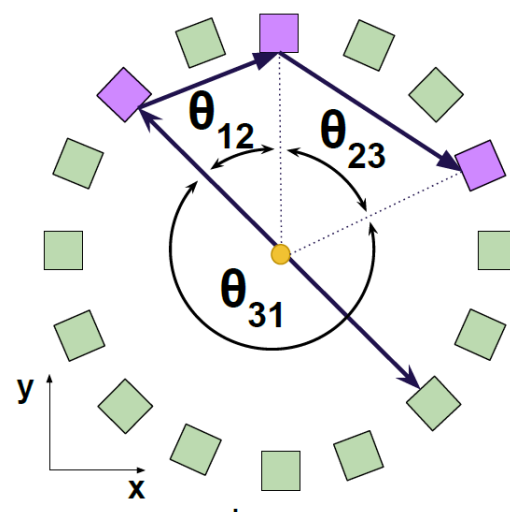




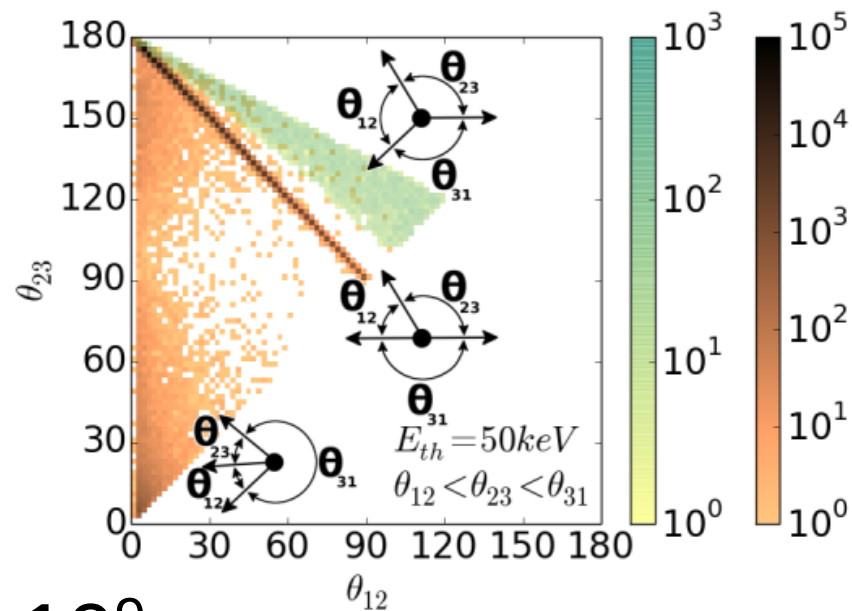
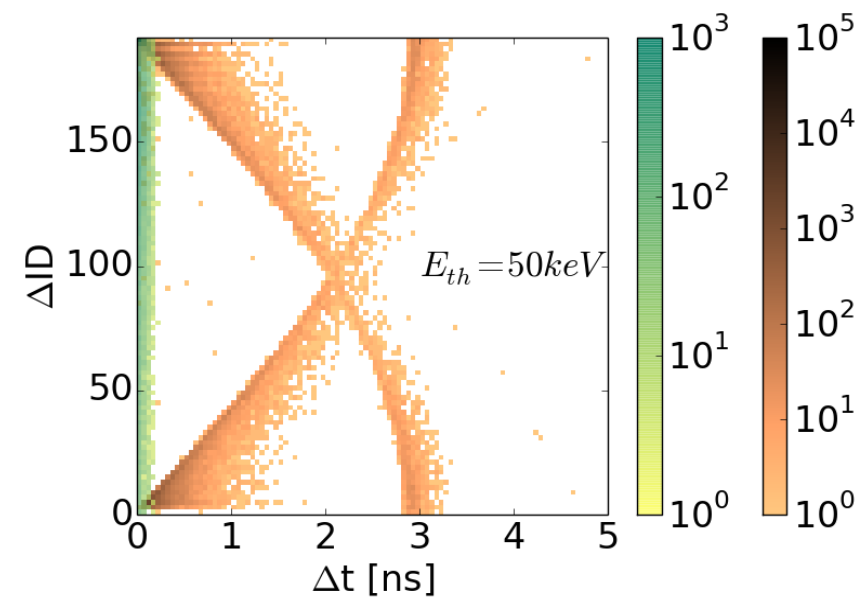
$o\text{-Ps} \rightarrow 3\gamma$



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



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



Reduction by factor 10^9

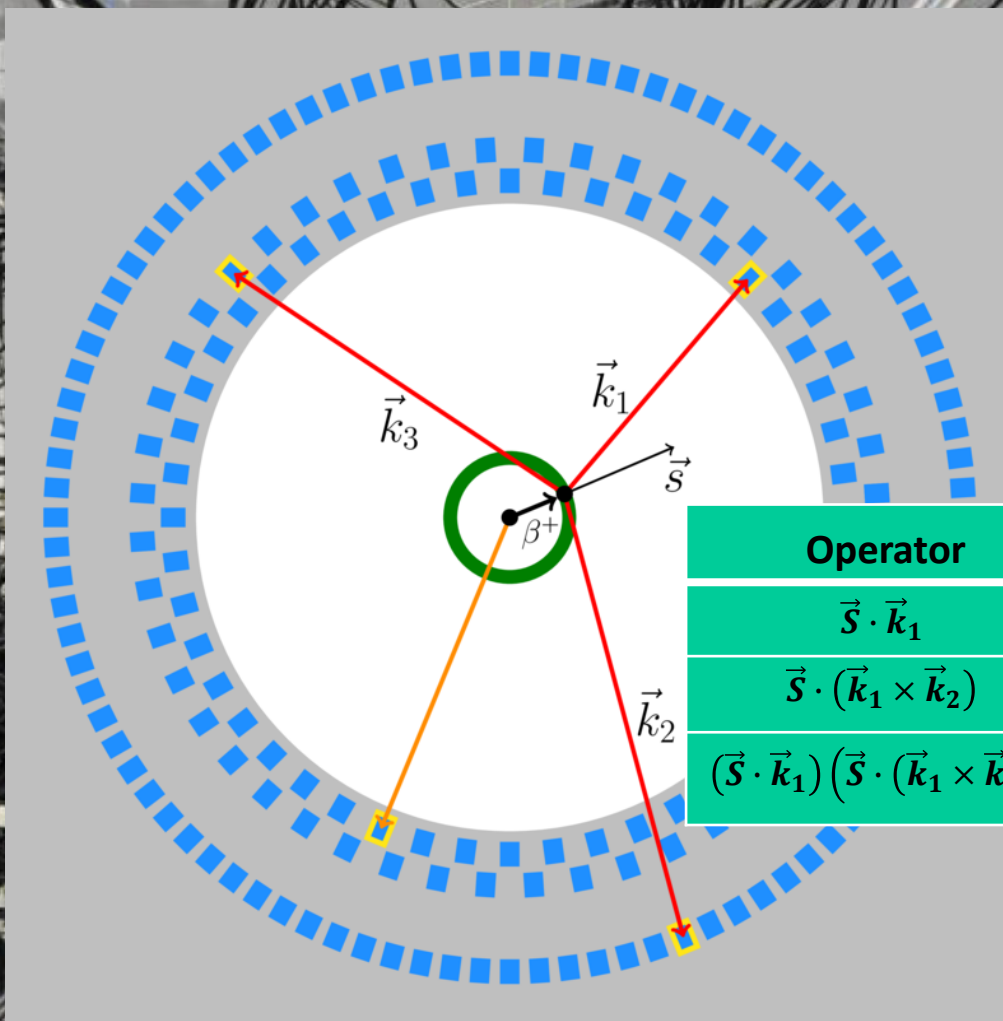


J-PET

Jagiellonian PET

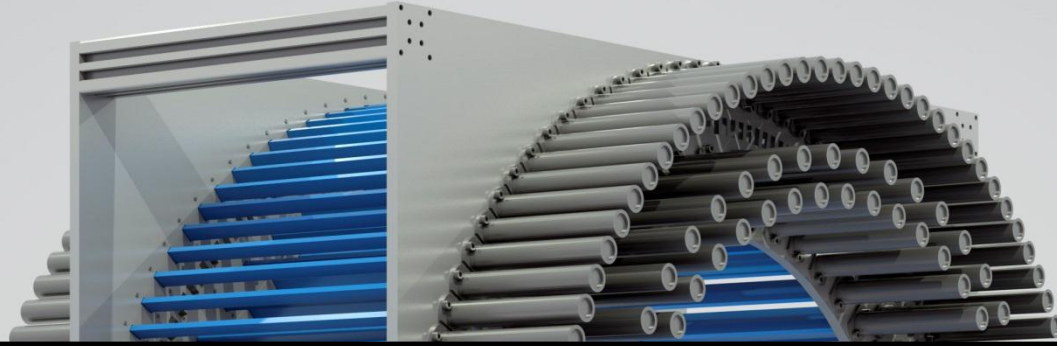


J-PET



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

$$\sigma(\text{t-hit}) = 80 \text{ ps}$$



- **Jagiellonian PET**
- **Positronium**
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- **Discrete symmetries**
- **Quantum entanglement ...**

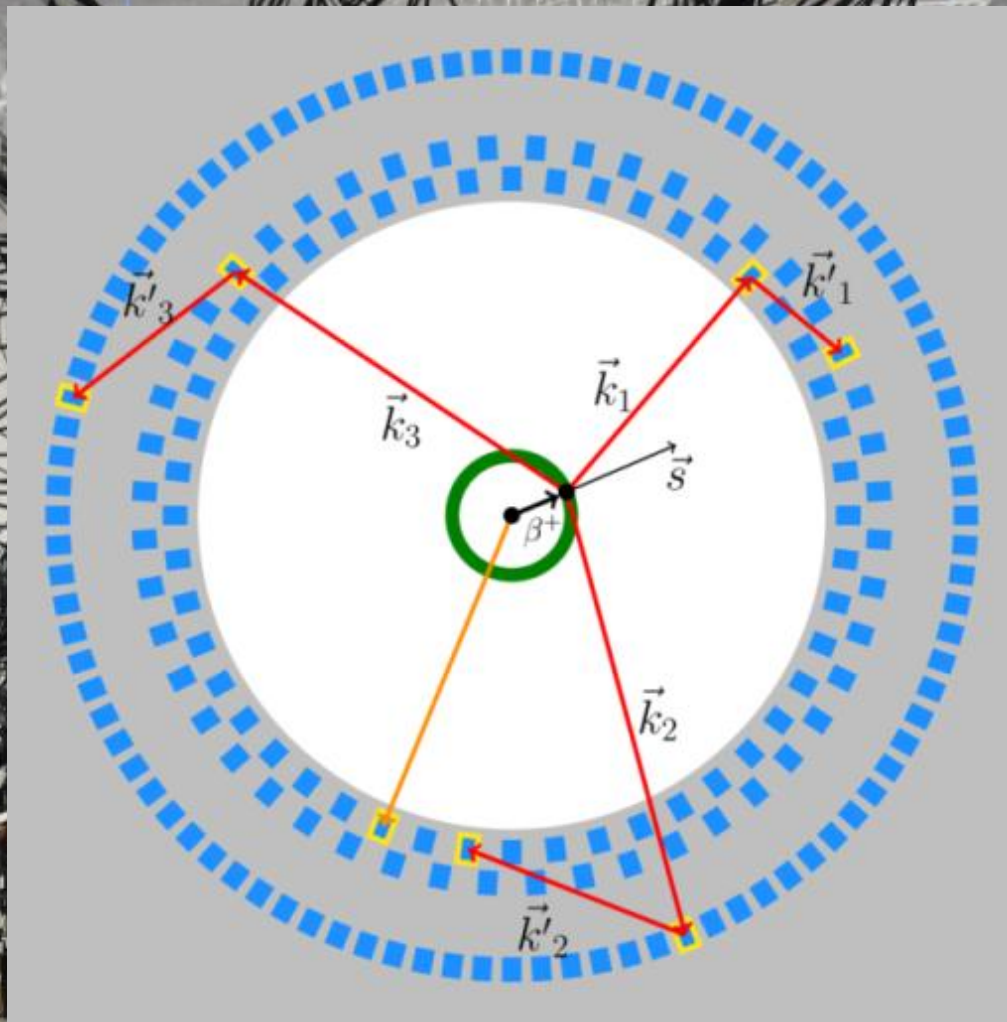


J-PET

Jagiellonian PET



J-PET



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

$$\sigma(\text{t-hit}) = 80 \text{ ps}$$

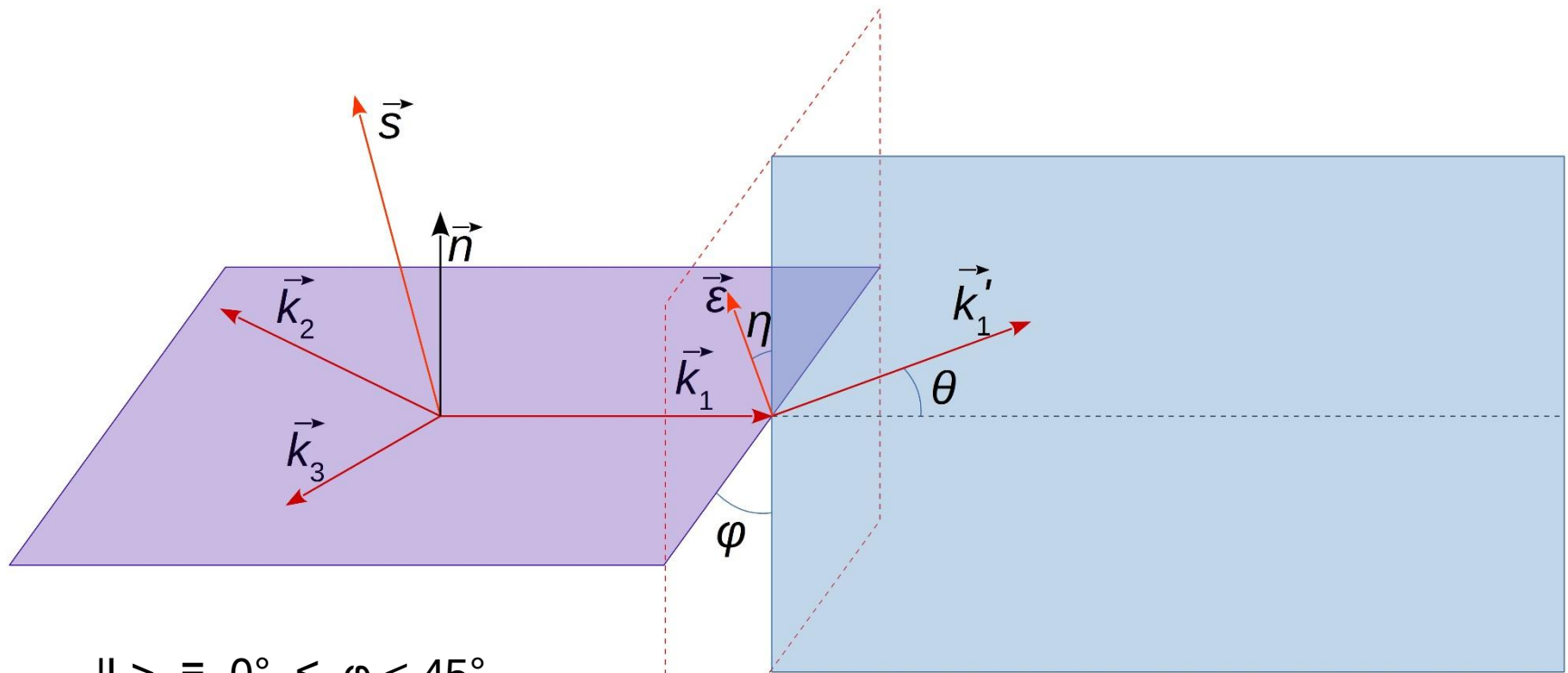


J-PET

Jagiellonian PET



J-PET



$$|L\rangle \equiv 0^\circ \leq \varphi < 45^\circ$$

$$|R\rangle \equiv 45^\circ < \varphi \leq 90^\circ$$

$$|\text{GHZ}\rangle = 1/\sqrt{2} (|RRR\rangle + |LLL\rangle)$$

$$|W\rangle = 1/\sqrt{3} (|RRL\rangle + |RLR\rangle + |LRR\rangle)$$





J-PET

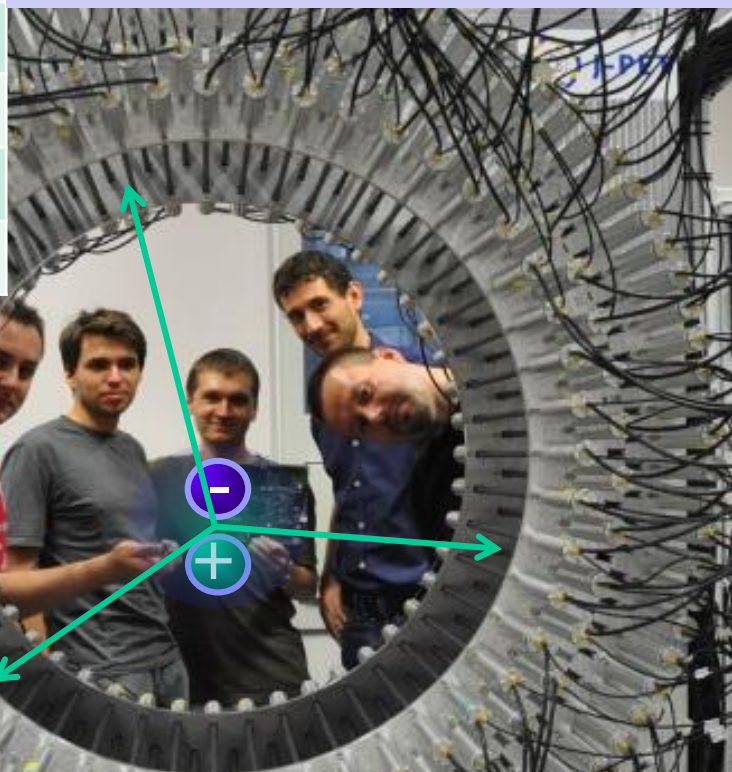
Jagiellonian PET



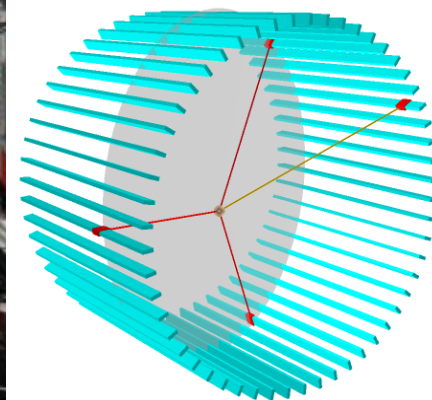
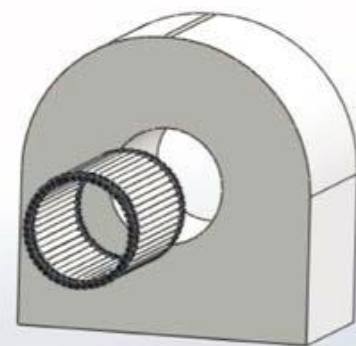
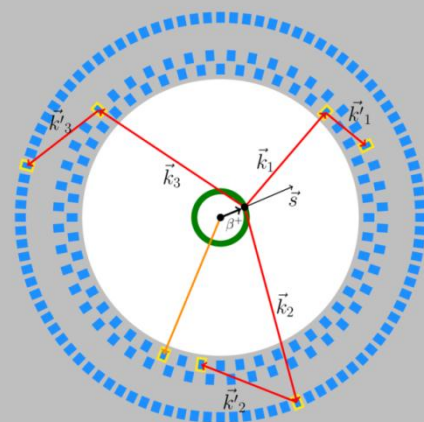
J-PET

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

KING SIZE PET FOR LARGE ANIMALS



crystals
→ plastics





J-PET

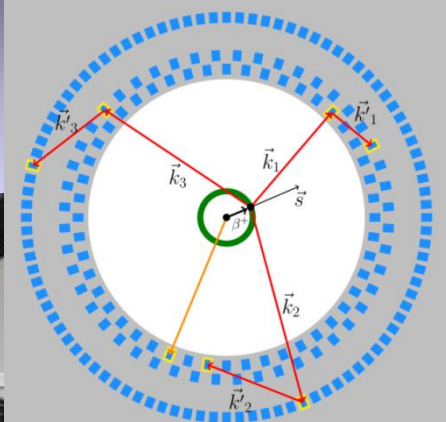
Jagiellonian PET



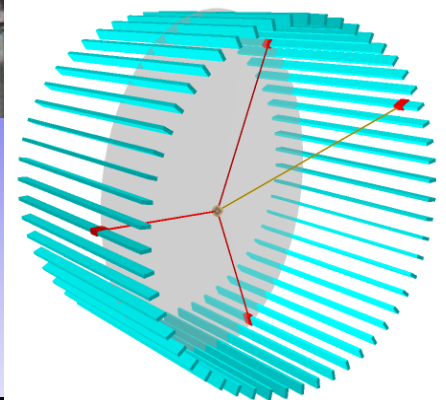
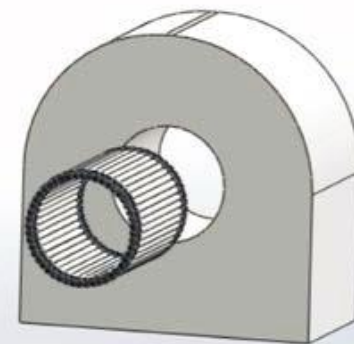
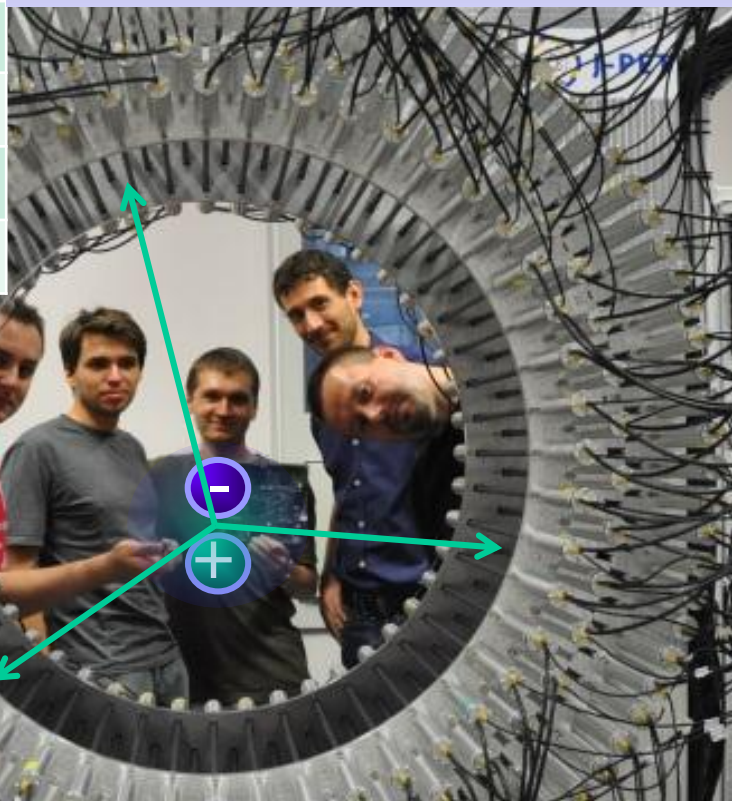
J-PET

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

KING SIZE PET FOR
LARGE ANIMALS



crystals
→ plastics



THANK YOU
FOR YOUR ATTENTION