

# Applications de la physique des particules au domaine de l'imagerie

Pr Christian MOREL  
Centre de Physique des Particules de Marseille



1895: **Rayons X** (W. Roentgen, Würzburg)  
Prix Nobel 1901



Wilhelm Roentgen (1845-1923)  
Prix Nobel de Physique (1901)



22 Dec 1895 – publiée dans le  
New York Times le 16 Jan 1896

# Développement de la radiologie (roentgenologie)

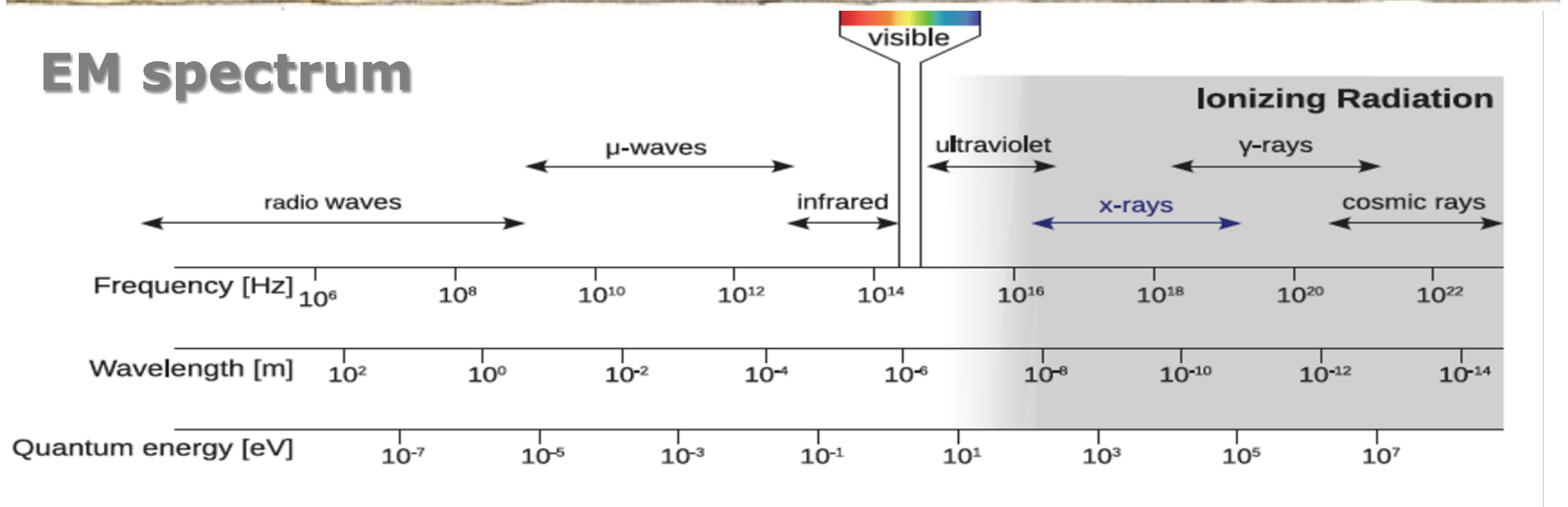
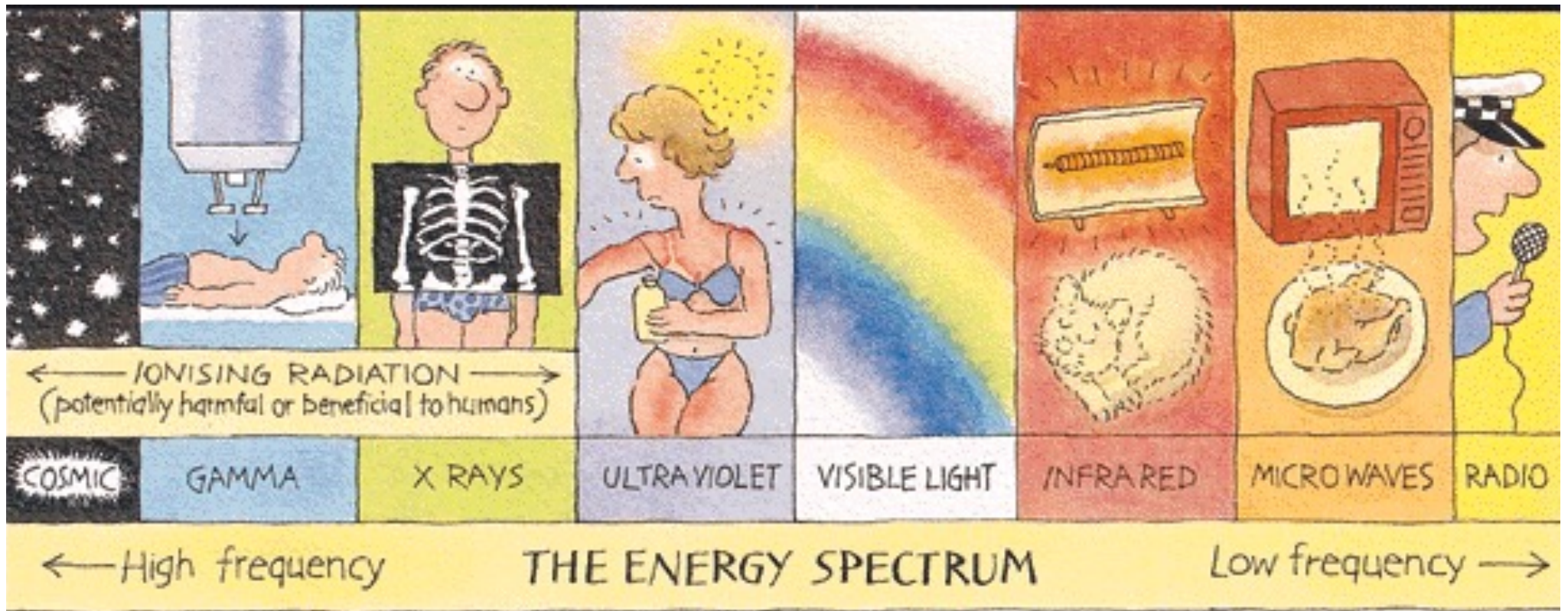


Hôpital Tenon (Paris, 1897)  
Antoine Béclère (1858–1939)

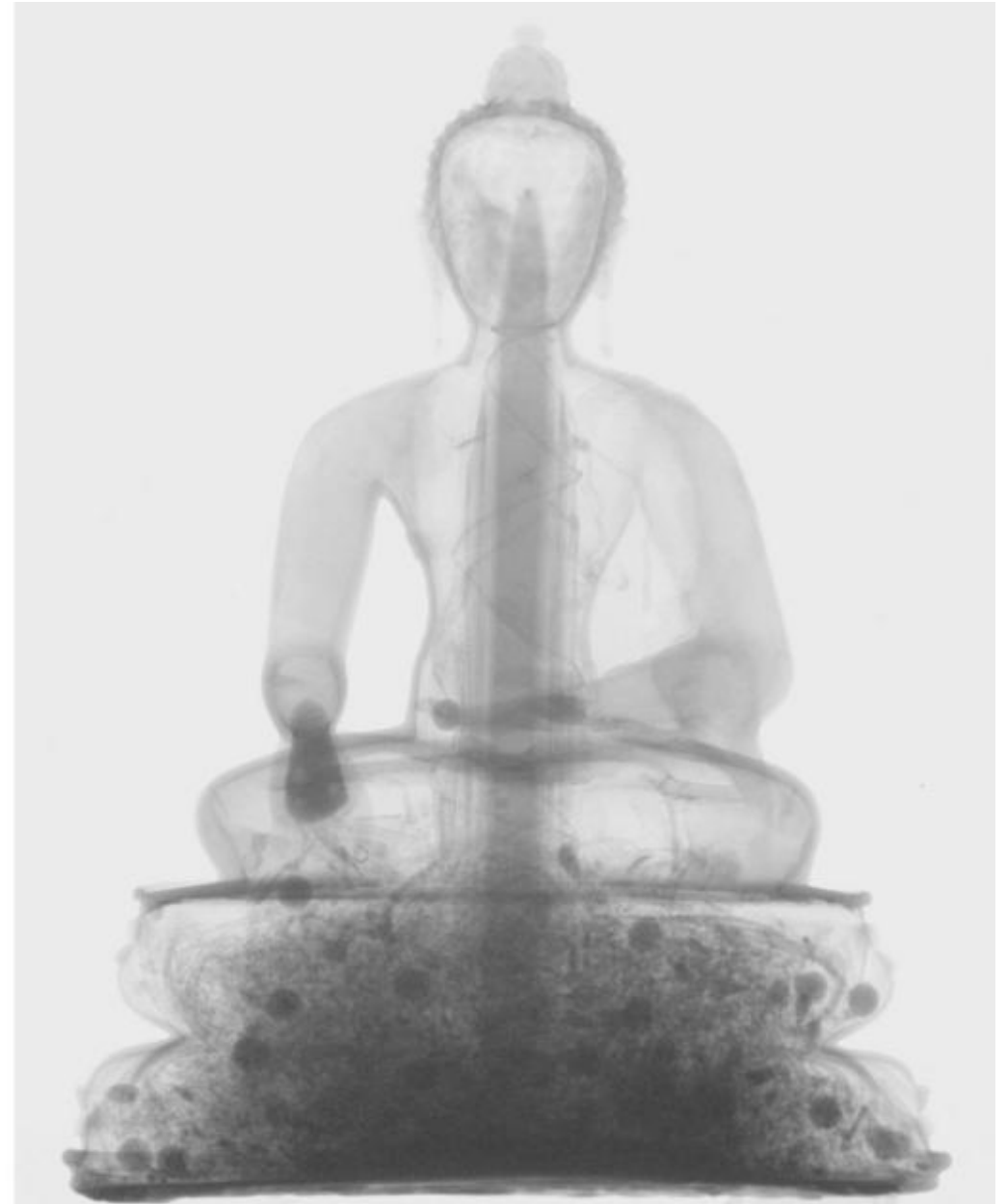


Radiological Renault «Petite Curie» (1916)  
Marie Curie (1867-1934)



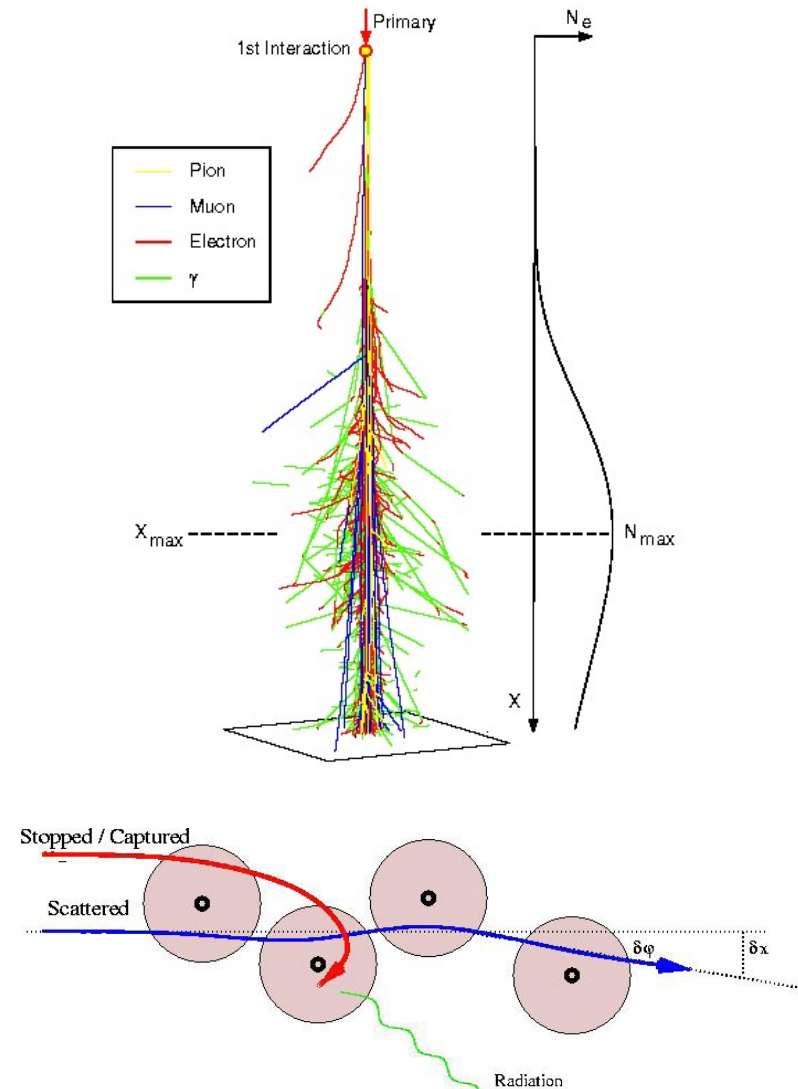
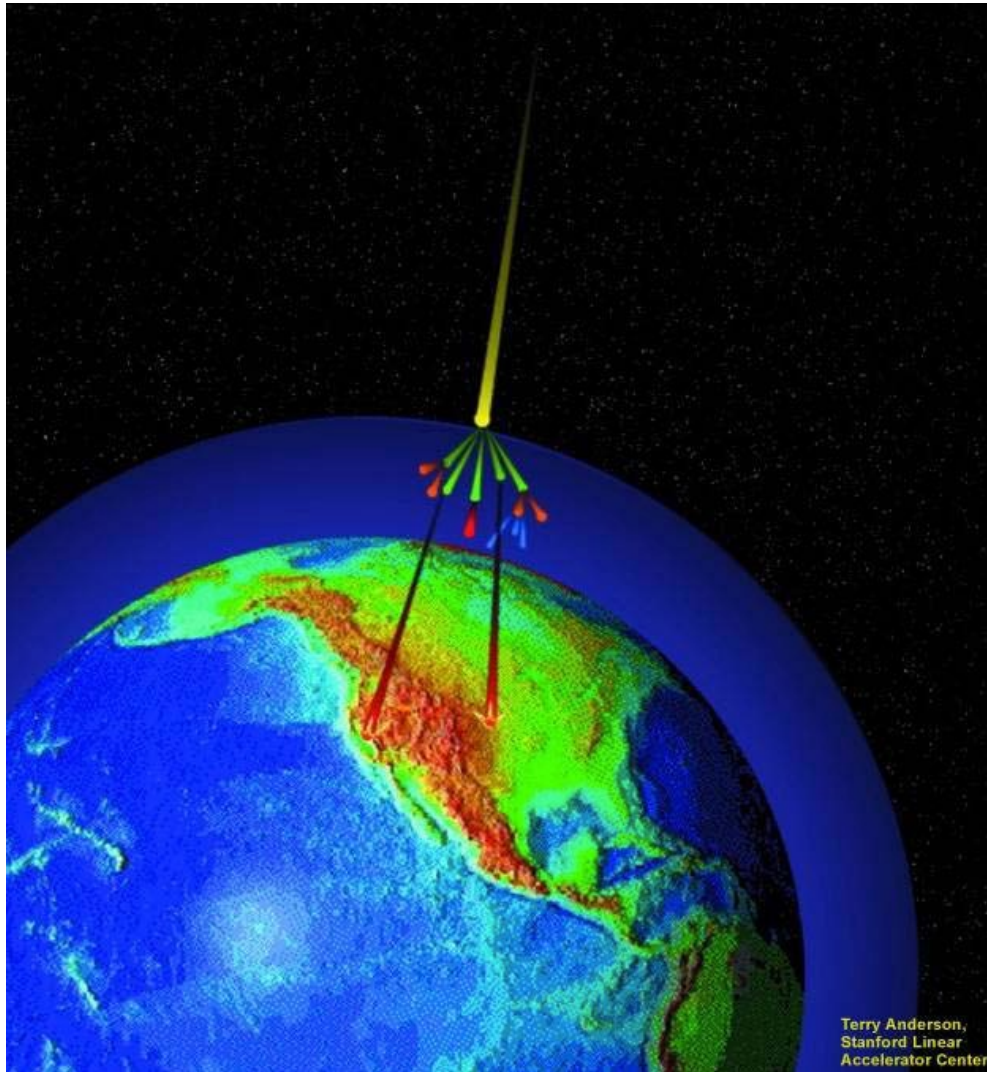


# Radiographie X et neutrons



Courtesy: Paul Scherre Institut (PSI)

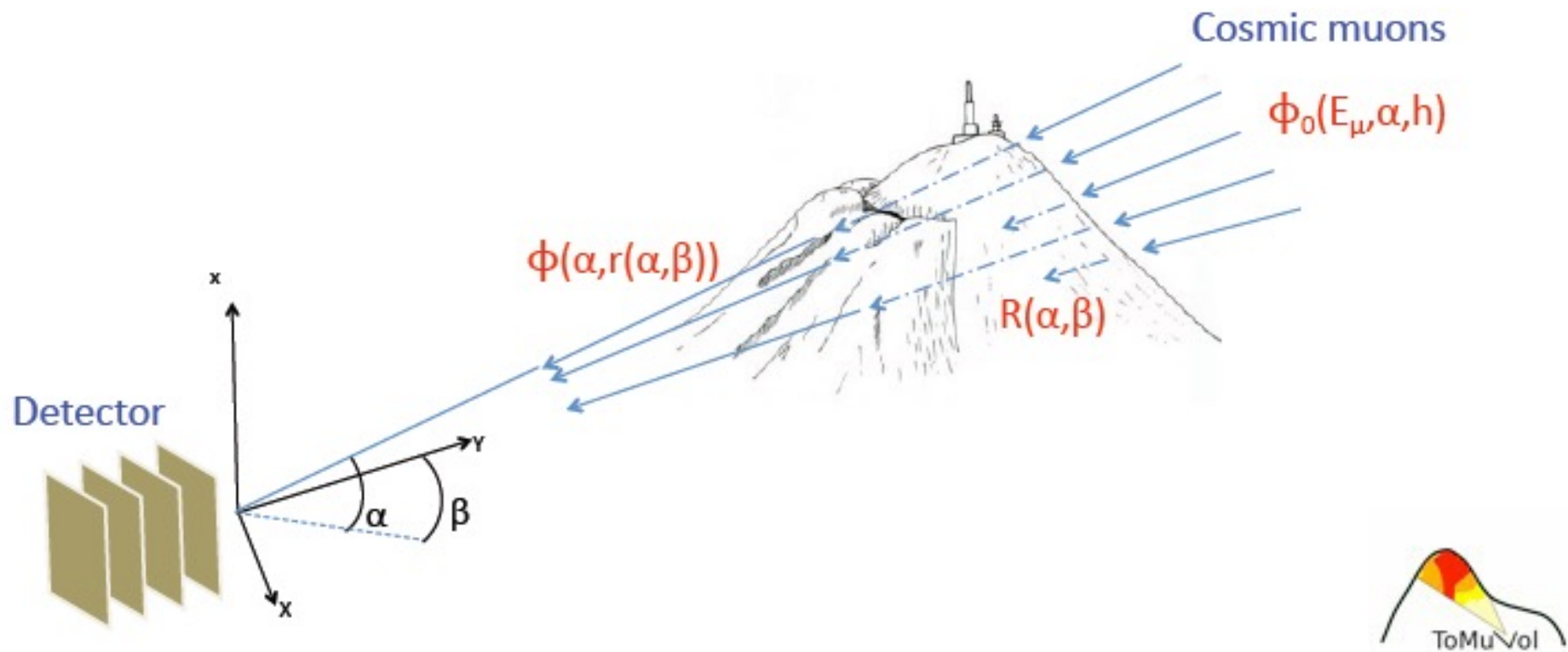
# Radiographie par transmission de muons cosmiques



- Au niveau de la mer, le taux de muons cosmiques est de 10,000 muons par mètre carré et par minute.
- Interaction des muons (positifs ou négatifs) dans la matière par capture ou par diffusion coulombienne.

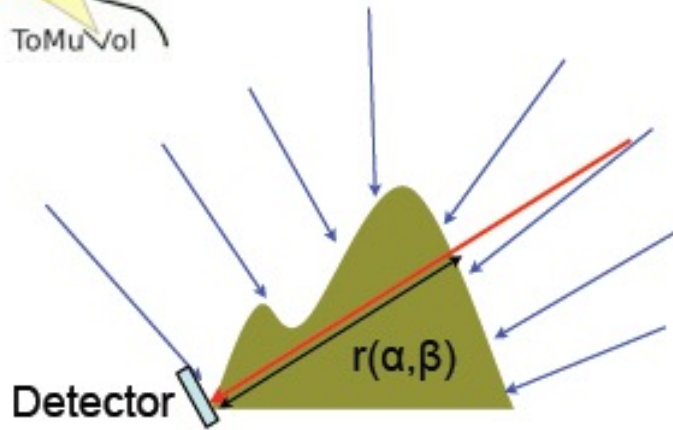
# Radiographie par transmission de muons cosmiques

La radiographie à muons permet d'imager de grands volumes ( $> 100 \text{ m}^3$ ) pour observer des structures de l'ordre de 1-10 m sans impératif de temps (scans pouvant durer plusieurs semaines à plusieurs mois). Elle permet d'étudier des structures aquifères, de déterminer la forme de cavités (p. ex. chambre magmatique ou cheminée de volcan) ou de surveiller des dispositifs de stockage souterrains de matières radioactives.



Courtesy: C. Cârloganu, LPC-Clermont

# Radiographie par transmission de muons cosmiques

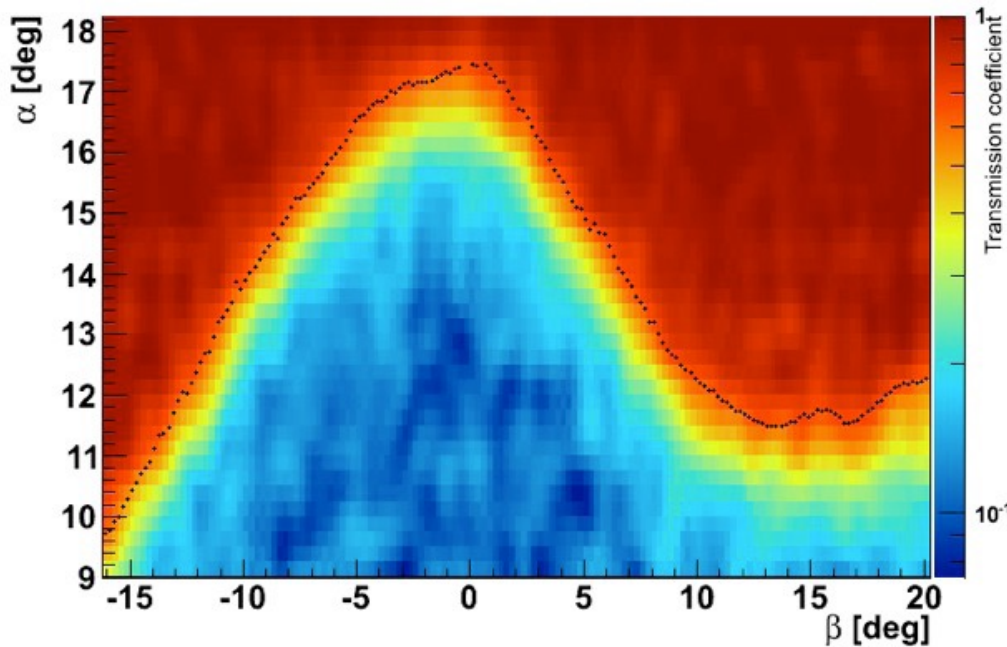


$$\mathcal{T}_\rho(\alpha, r(\alpha, \beta)) = \frac{\Phi(\alpha, r(\alpha, \beta))}{\Phi_0(\alpha)}$$

measured flux through volcano

open sky flux

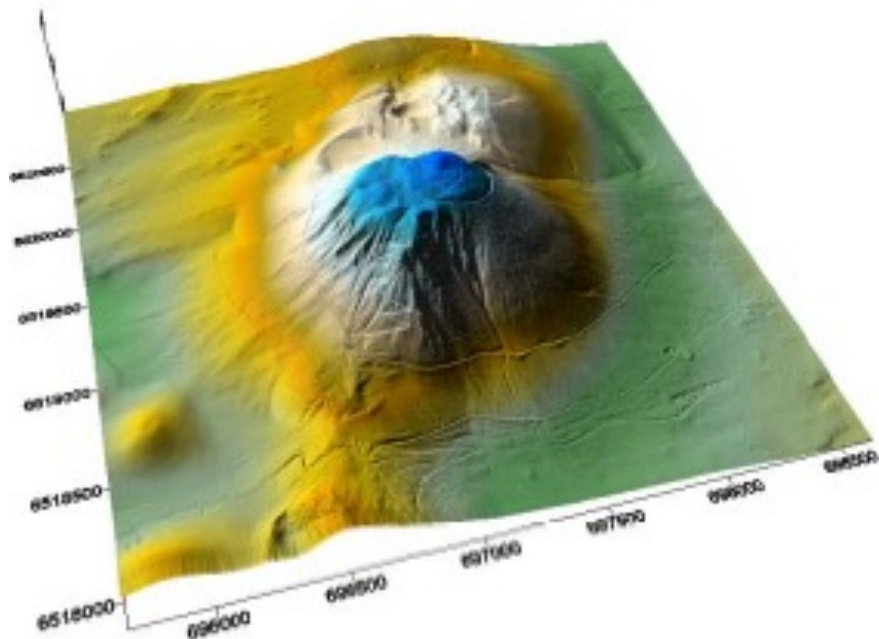
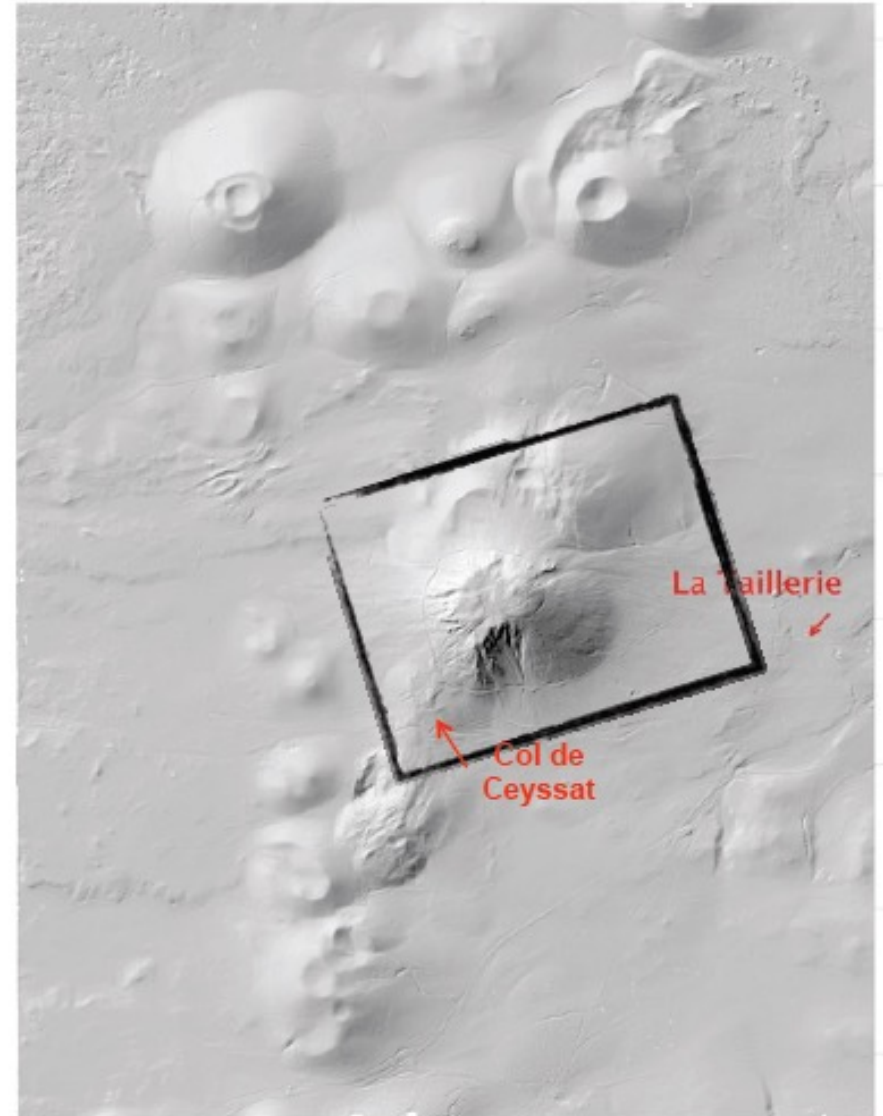
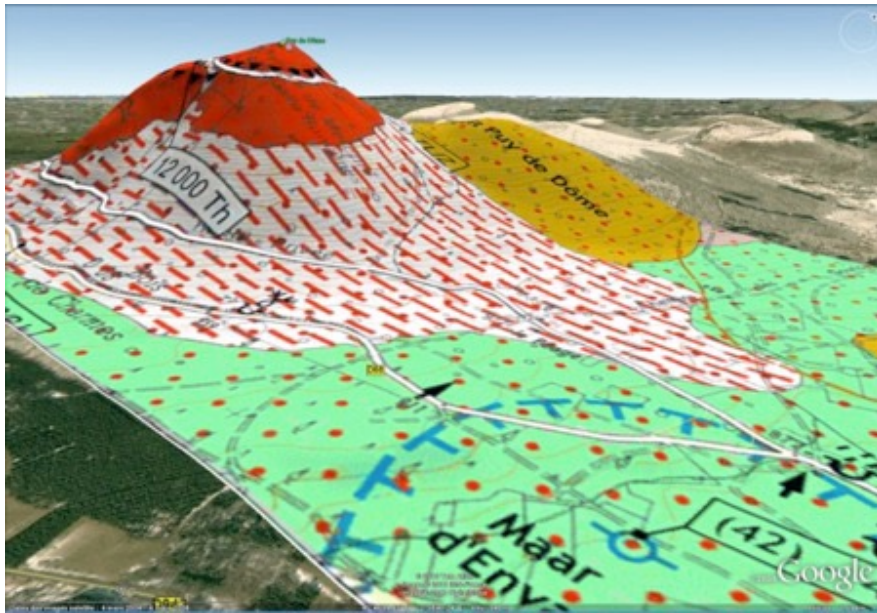
unknown density!



Courtesy: C. Cârloganu, LPC-Clermont



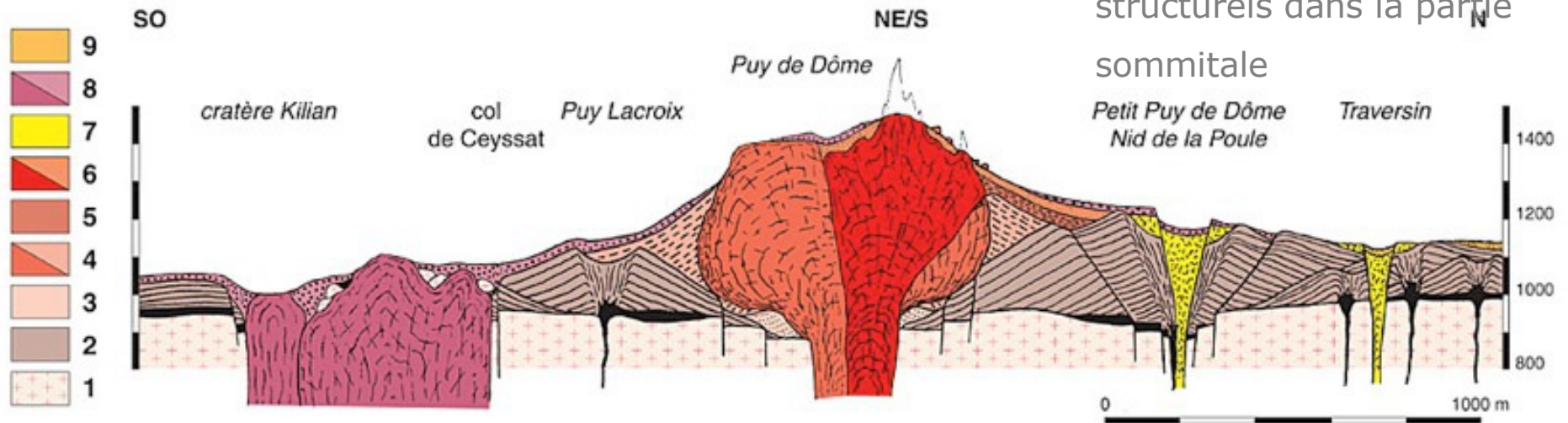
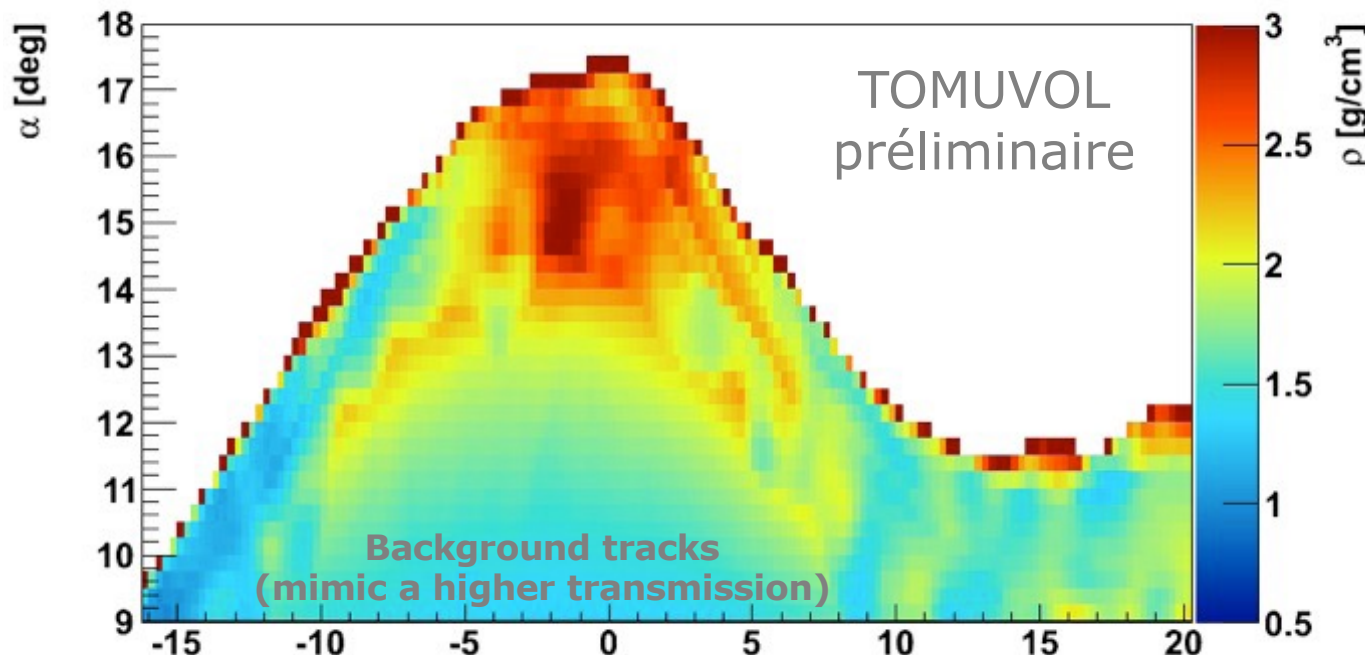
# Radiographie du Puy de Dôme par transmission muons cosmiques



Courtesy: C. Cârloganu, LPC-Clermont



# Radiographie par transmission de muons consiques



- Calcul du flux de muons transmis à travers le rocher normalisé par la mesure du flux à ciel ouvert
- Calcul du rapport du coefficient d'absorption mesuré divisé par l'épaisseur de rocher pour chaque ligne de visée donnée par la topographie (mesures au LIDAR)
- Evidance de contrastes structurels dans la partie sommitale

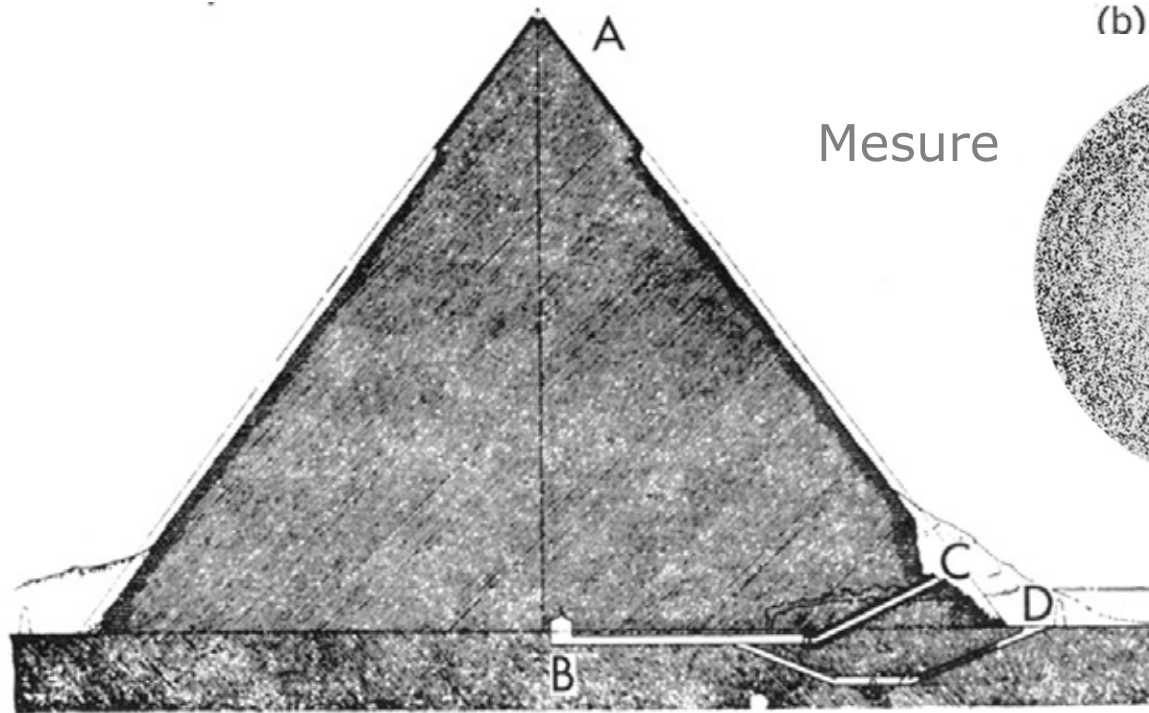
Courtesy: C. Cârloganu, LPC-Clermont

# Radiographie par transmission de muons cosmiques

Alvarez *et al.* Search for Hidden Chambers in the Pyramids. *Science* 167 (1970) 832



# Radiographie par transmission de muons cosmiques



Mesure

(b)



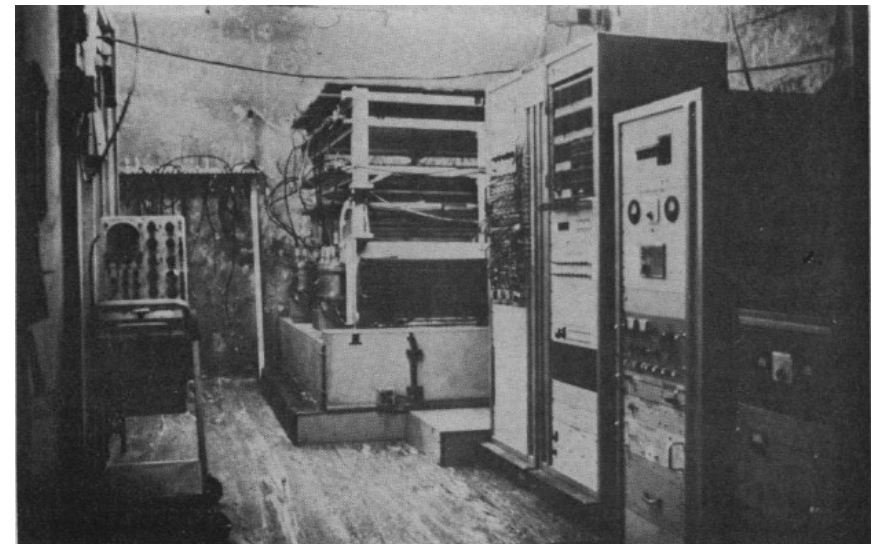
|  
S

Simulation



Effet résultant de la présence d'une chambre cachée 40 m au-dessus de la chambre de Belzoni.

Les chambres à étincelles sont placées dans la chambre de Belzoni (B) de la pyramide de Chephren.



# SCAN PYRAMIDS MISSION



HIP.INSTITUTE  
HERITAGE  
INNOVATION  
PRESERVATION



ARAB  
REPUBLIC  
OF EGYPT  
MINISTRY OF  
ANTIQUITIES

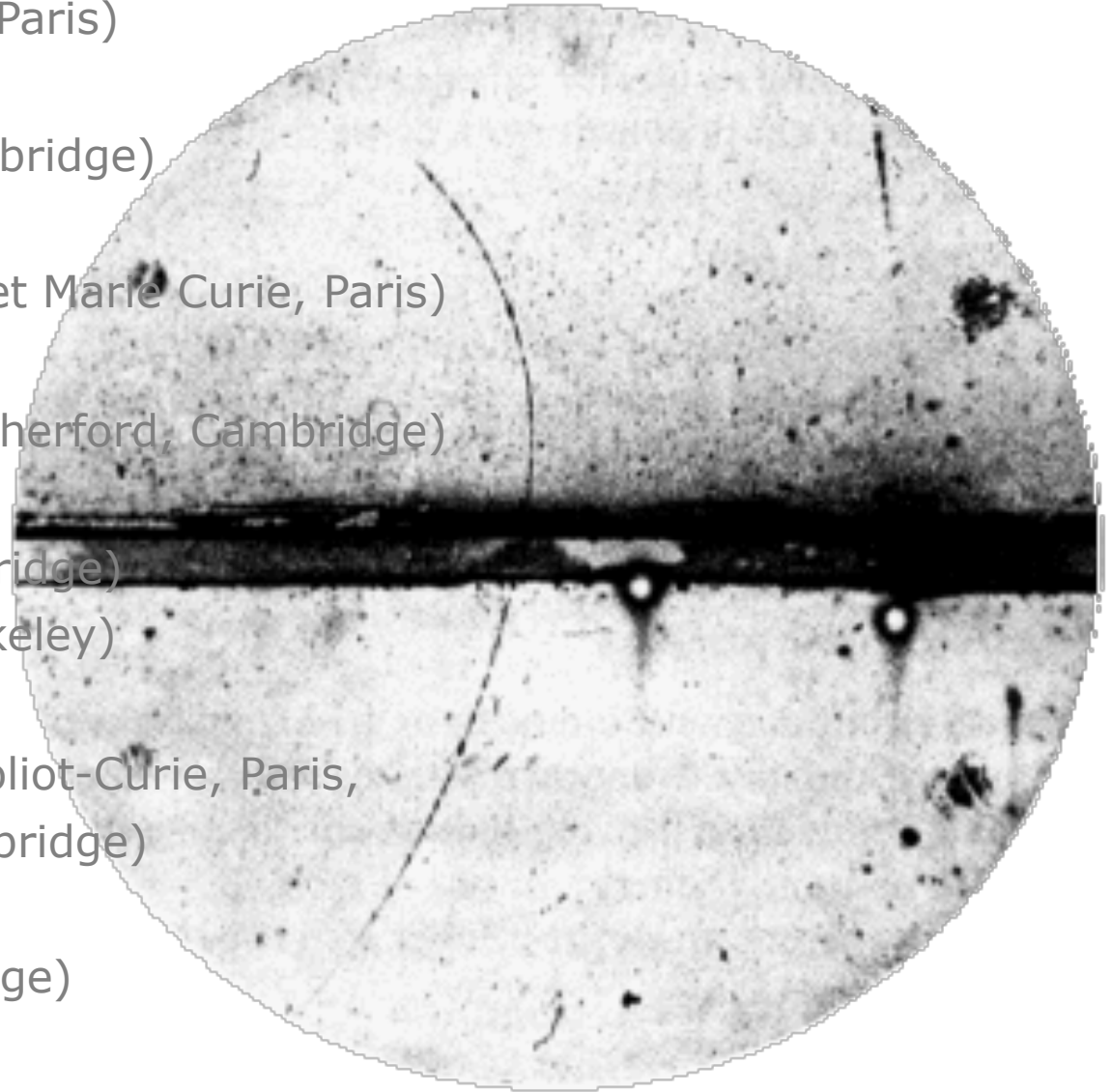


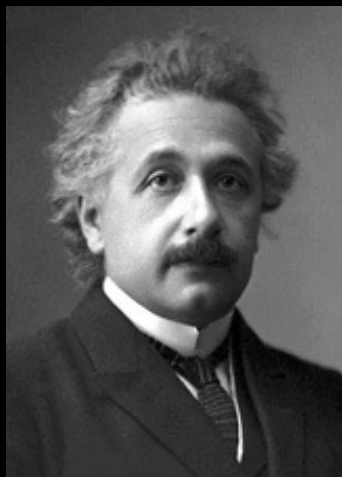
FACULTY OF  
ENGINEERING  
CAIRO  
UNIVERSITY



De la physique au détecteur – IN2P3 – Villa Clythia, Fréjus – 22-26 novembre 2021

- 1895: **Rayons X** (W. Roentgen, Wuerzburg)  
Prix Nobel 1901
- 1896: Radioactivité (H. Becquerel, Paris)  
Prix Nobel 1903
- 1897: **Electron** (J.J. Thomson, Cambridge)  
Prix Nobel 1906
- 1898: Radium et Polonium (Pierre et Marie Curie, Paris)  
Prix Nobel 1903, 1911
- 1899: Rayons alpha et bêta (E. Rutherford, Cambridge)  
Prix Nobel 1908
- 1911: Noyau (E. Rutherford, Cambridge)
- 1931: Cyclotron (E. Lawrence, Berkeley)  
Prix Nobel 1939
- 1932: Neutron (Frédéric et Irène Joliot-Curie, Paris,  
J. Chadwick, Cambridge)  
Prix Nobel 1935 (Chadwick)
- 1930: Trous (P.A.M. Dirac, Cambridge)  
Prix Nobel 1933
- 1932: **Positron** (C.D. Anderson, Berkeley)  
Prix Nobel 1936



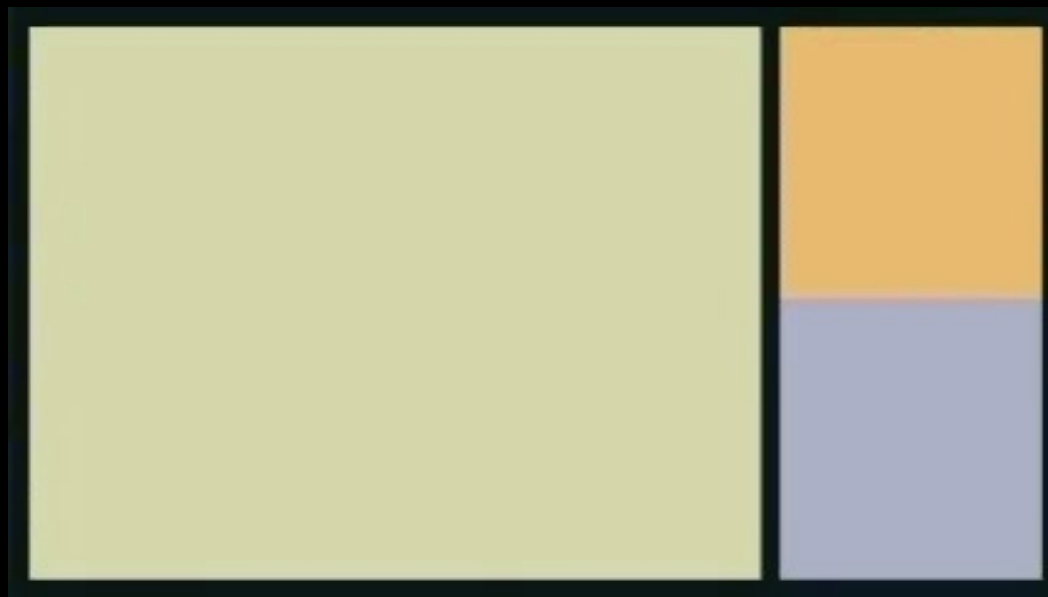


$$E=mc^2$$

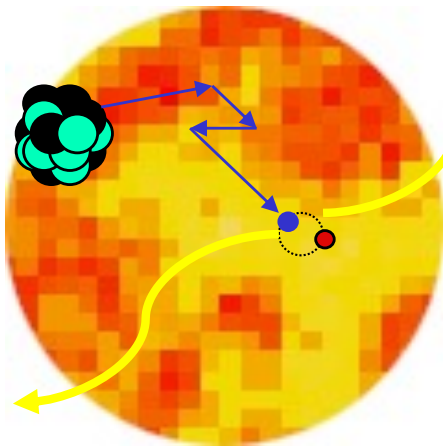
## Diffusion Compton

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

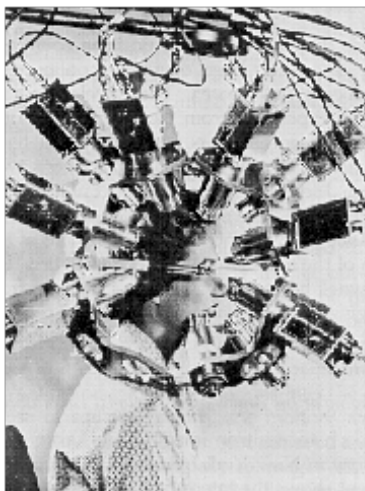
$$e^- + e^+ \rightarrow \gamma + \gamma$$



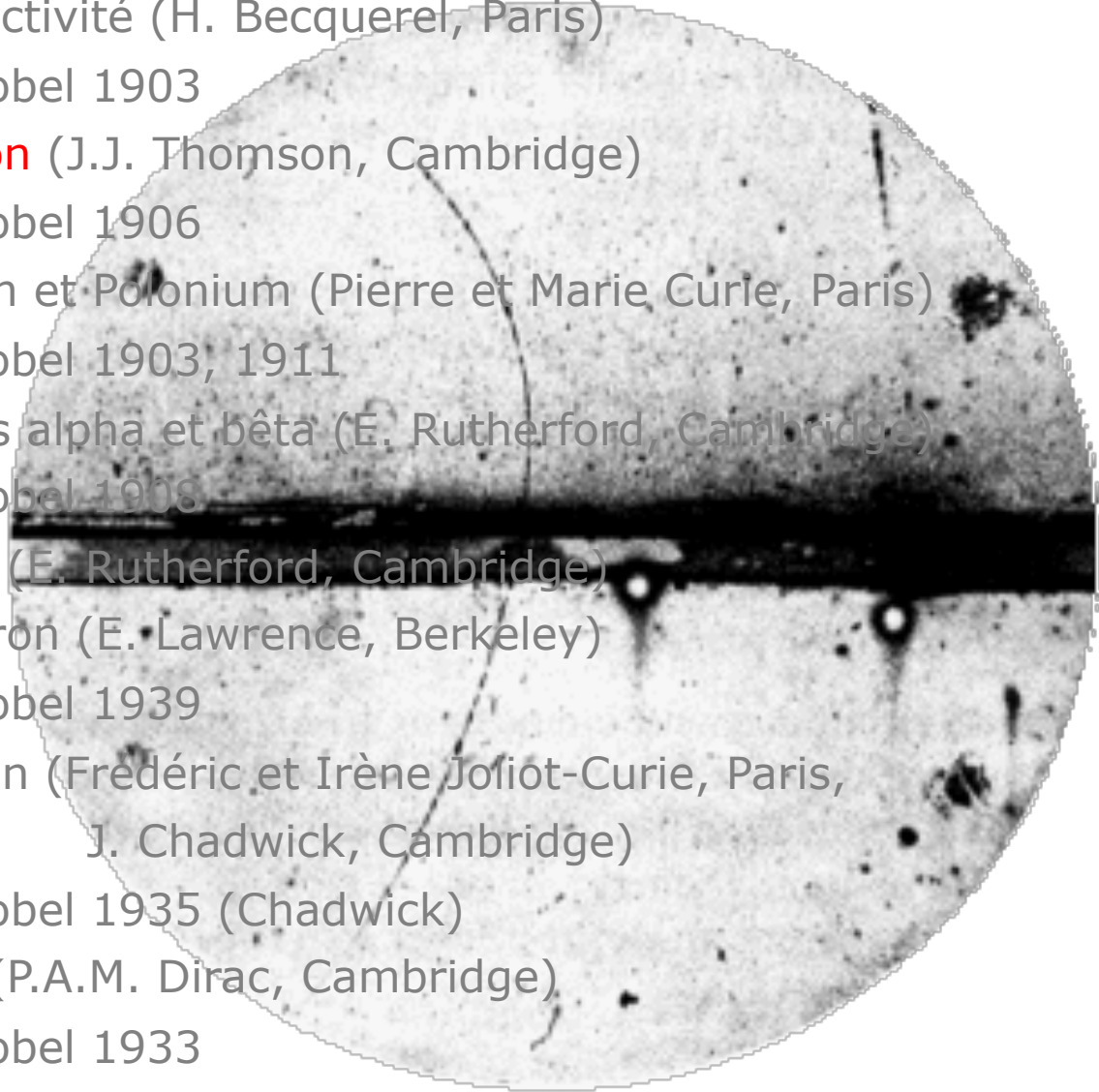
## Annihilation matière anti-matière



Wrenn *et al.* The use of positron emitting radioisotopes for the localization of brain tumours *Science* **113** (1951) 525



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- 1930: Trous (P.A.M. Dirac, Cambridge)  
Prix Nobel 1933
- 1932: **Positon** (C.D. Anderson, Berkeley)  
Prix Nobel 1936

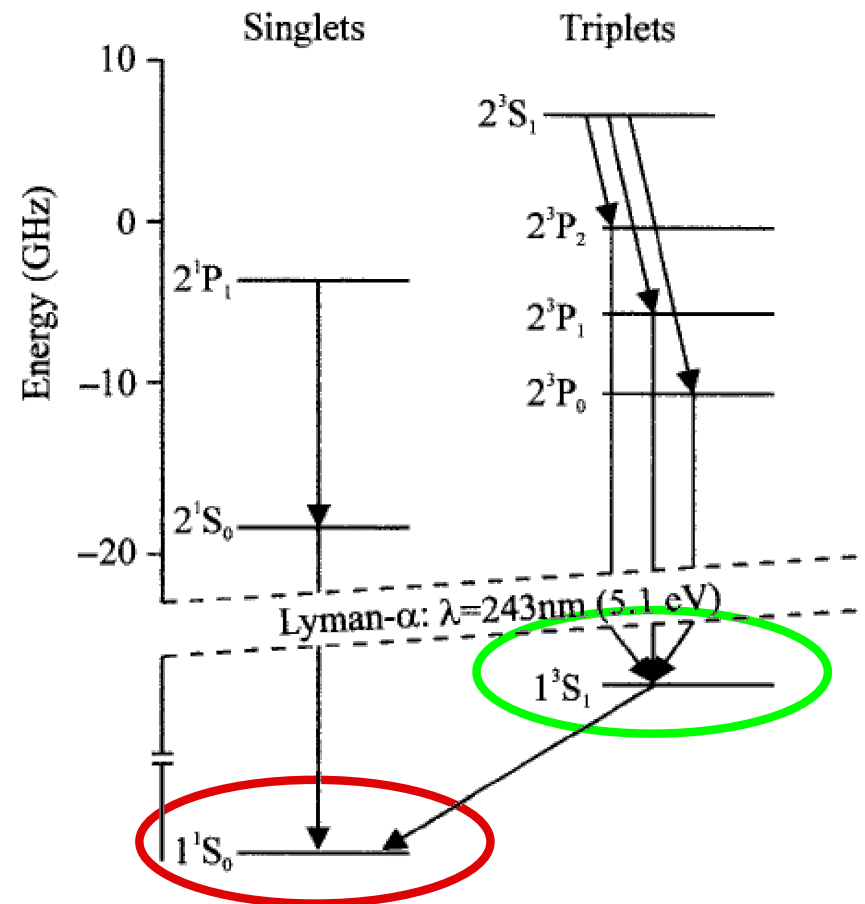




# The short, rich life of positronium (Ps)



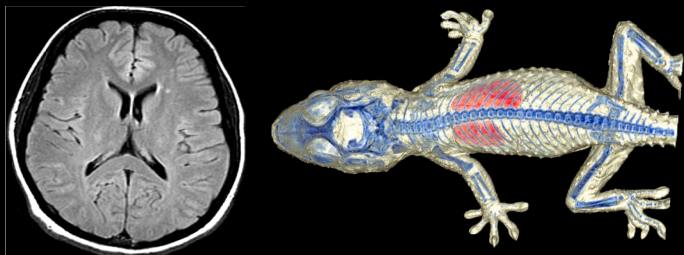
Une sculpture du professeur de physique Jens Zorn, U-Michigan, Ann Arbor



Parapositronium:  $\tau \sim 10^{-10}$  s  
État singulet  $\rightarrow$  désintégration en  
2 gammas

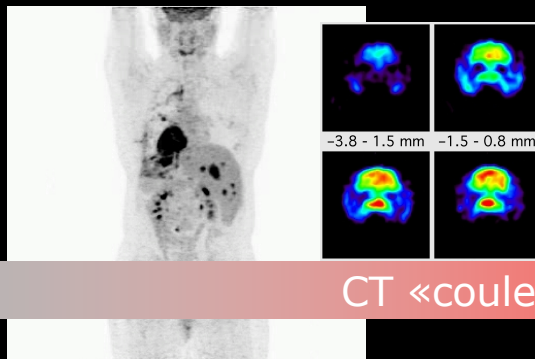
Orthopositronium:  $\tau \sim 10^{-7}$  s  
État triplet  $\rightarrow$  désintégration en  
3 gammas

# Imagerie anatomique



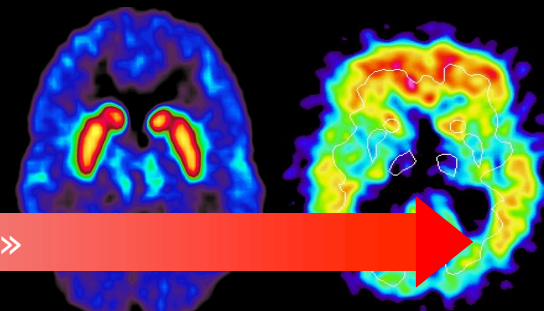
Imagerie par rayons X (CT, DXA)

# Imagerie fonctionnelle



CT «couleur»

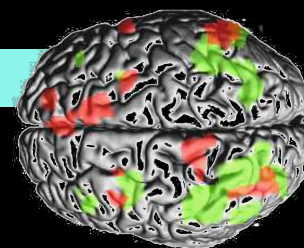
# Imagerie moléculaire



## Imagerie isotopique (TEP, TEMP)

mL, pMol

## IRM fonctionnelle

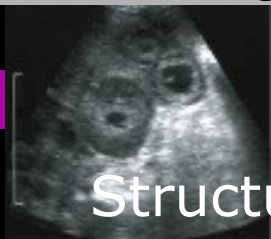


$\mu$ L, mMol- $\mu$ Mol

## Imagerie par résonance magnétique

## Spectroscopie par résonance magnétique

## Imagerie ultrasonore



Structure

Macroscopique

## Imagerie optique (FMT, FRT, bioluminescence, OCT, microscopie 2-photons)

Mécanisme

Cible

Microscopique

# Tomographie

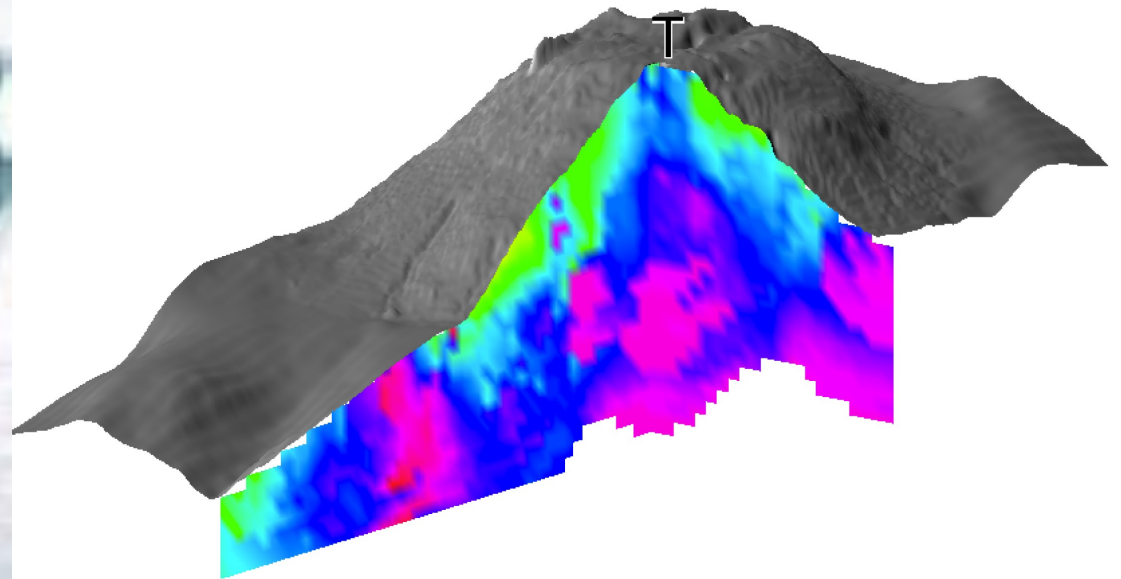
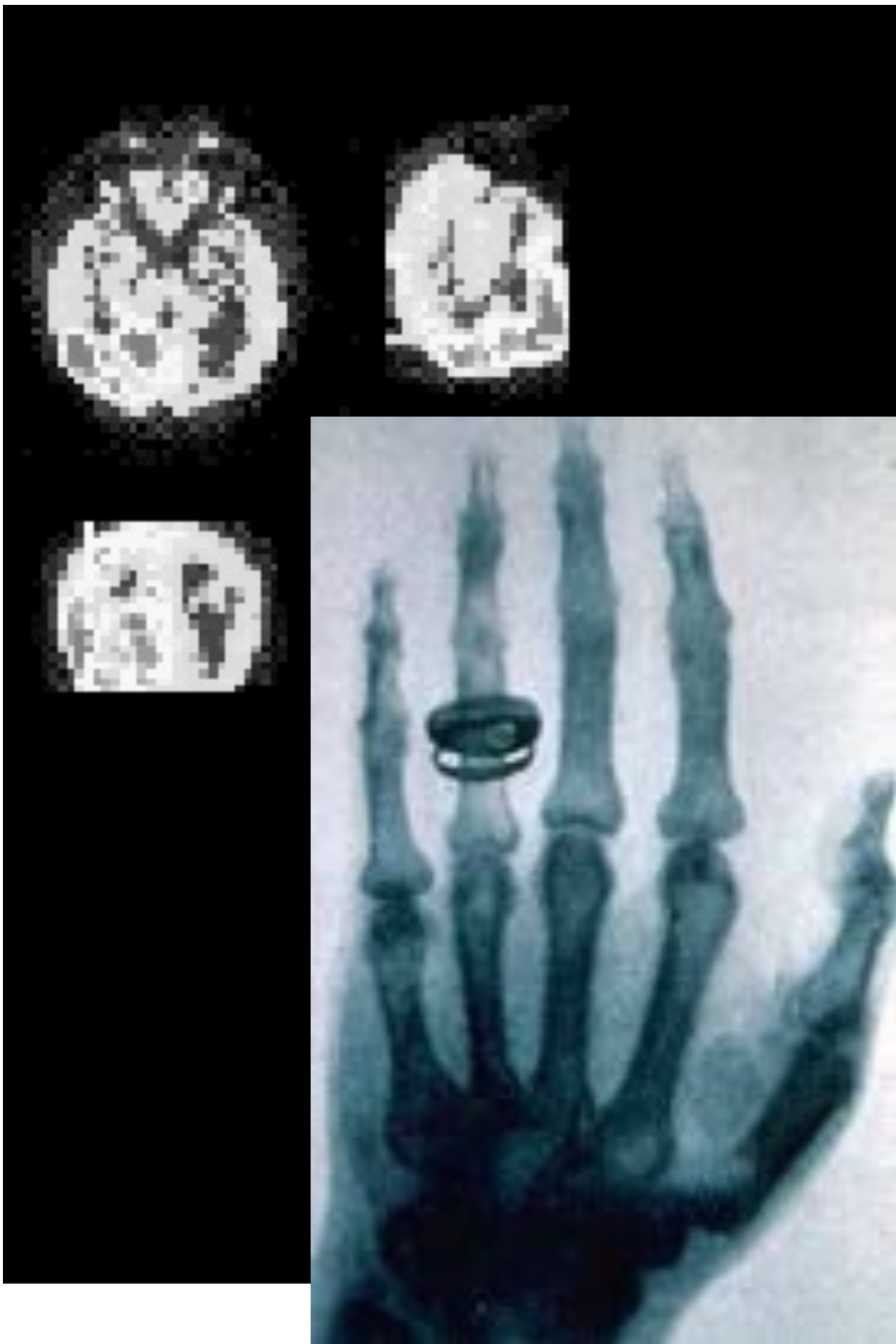
Du grec *tomos* (tranche)

+

*graphein* (écrire)

=

Représentation en coupes

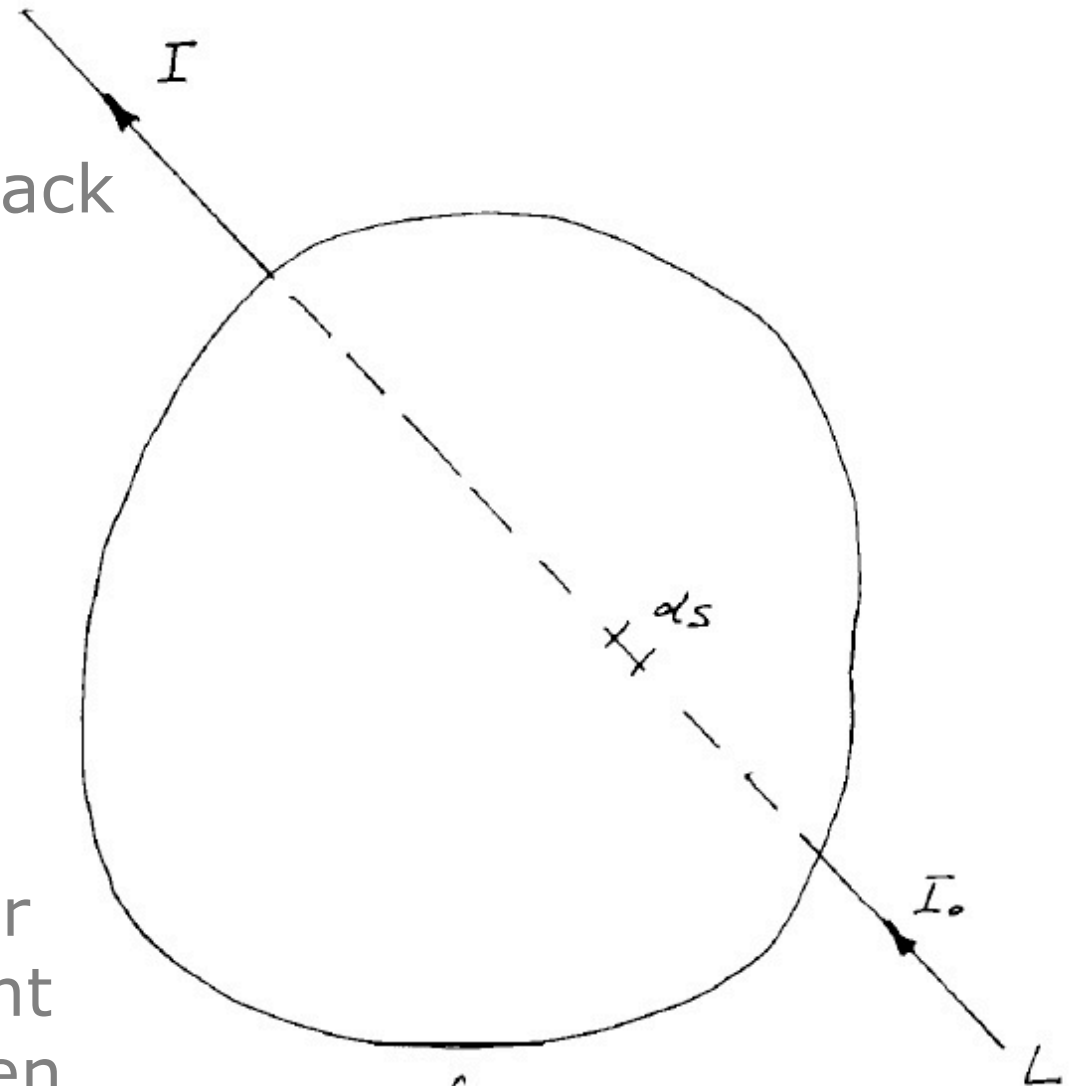


# Reconstruction tomographique en 2D

1963: Alan McLeod Cormack



Redécouvre une solution mathématique publiée par Radon en 1917 permettant de reconstruire un objet en 2D à partir de ses projections

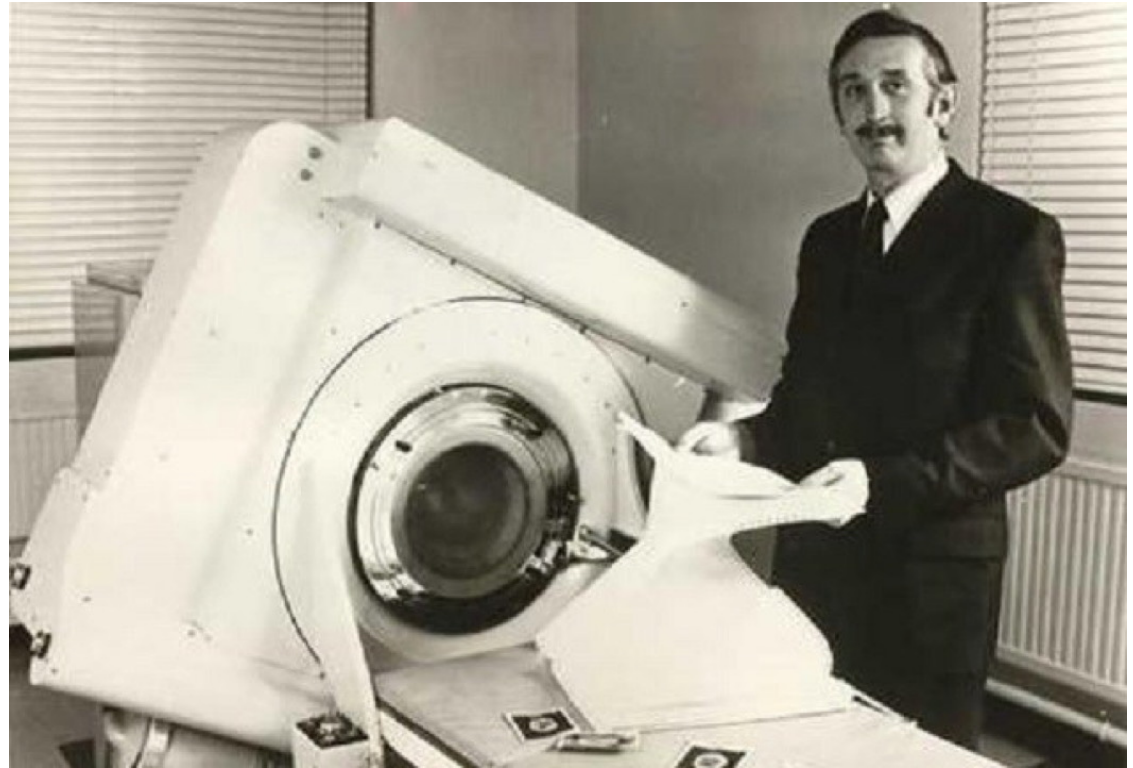
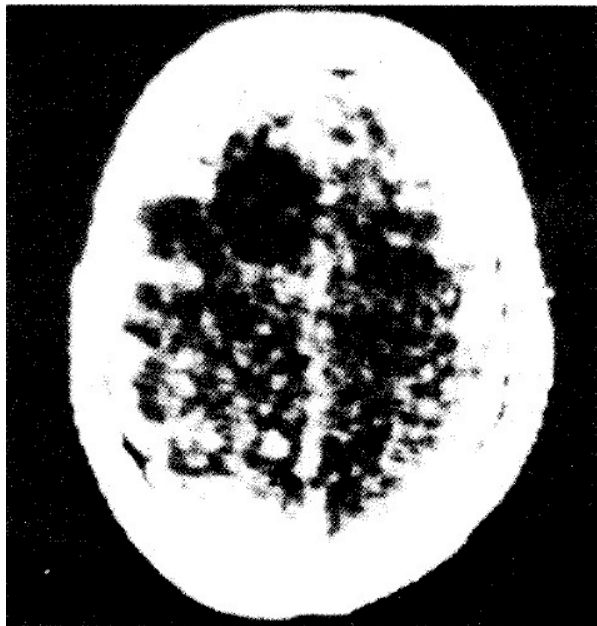


$$I = I_0 e^{-\int_L f ds}$$

# Computerized Tomography (CT)

Tomographie par rayons X (*vulgus scanner*)

Tomodensitométrie (TDM)



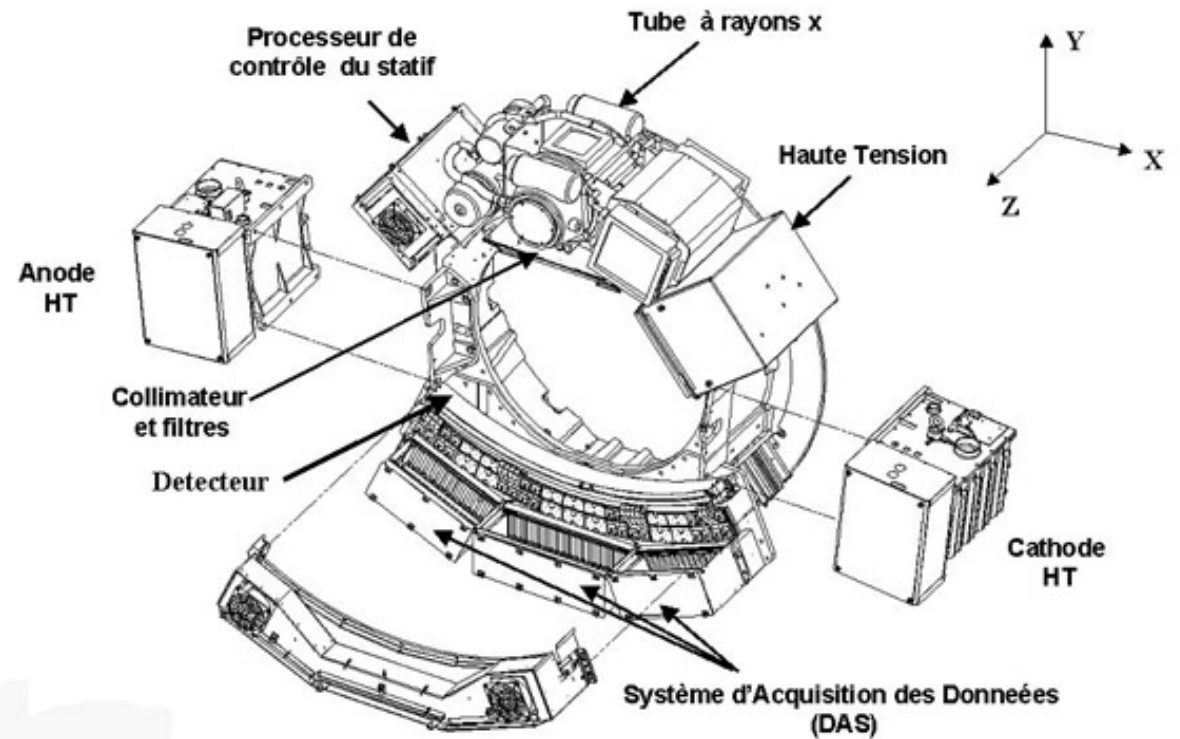
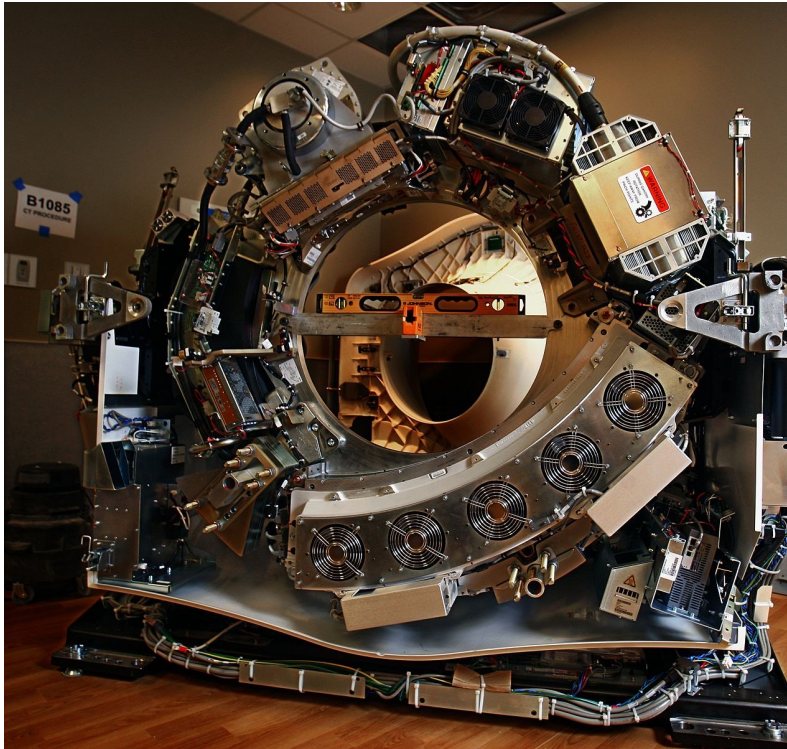
G. Hounsfield, J. Ambrose  
(Atkinson Morley Hospital, London, 1/10/1971)

# TDM, CT ou CAT (*Computed Assisted Tomography*) scan

1979: Hounsfield et Cormack reçoivent le prix Nobel de médecine pour le développement de la tomographie assistée par ordinateur



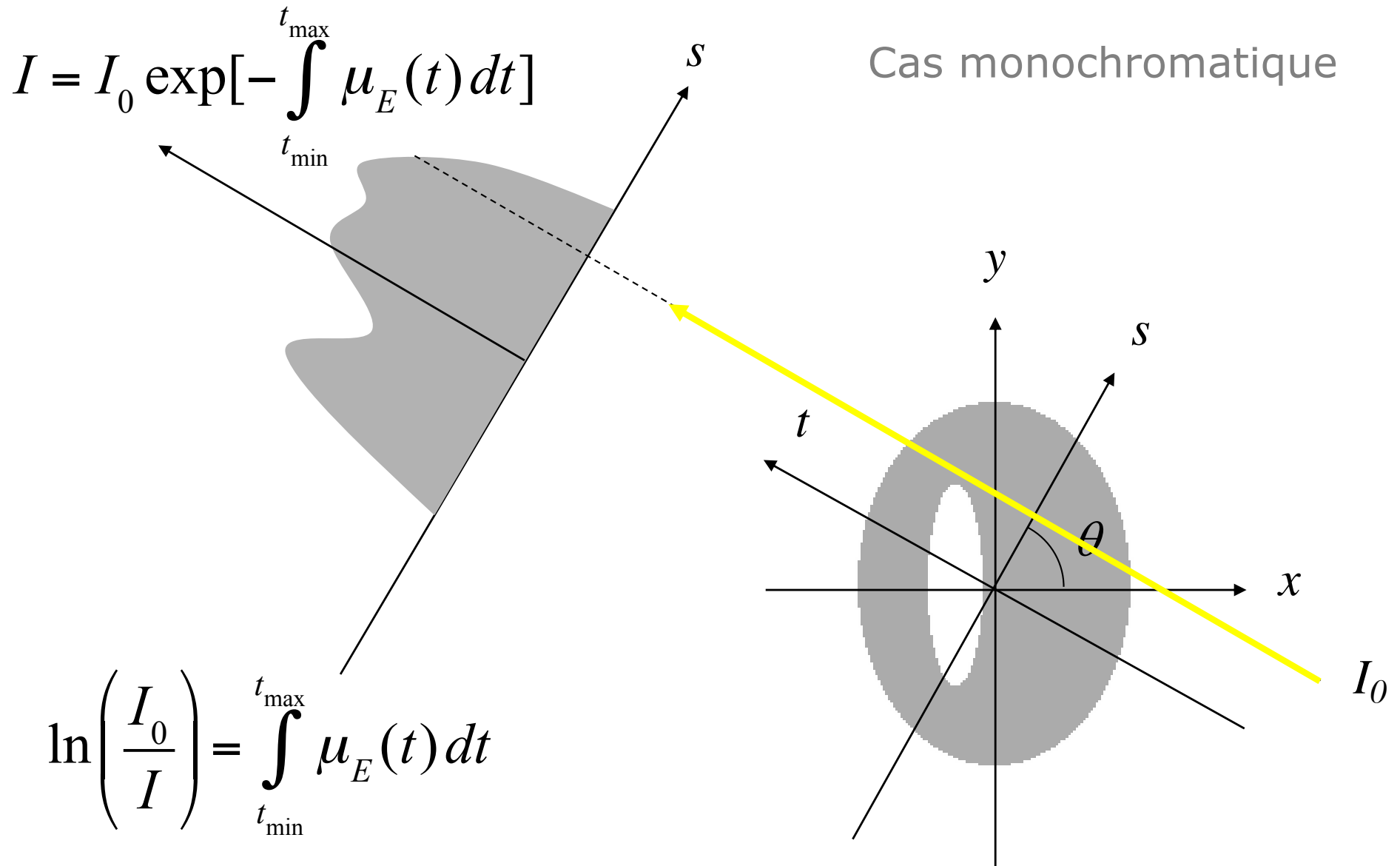
# X-ray CT scanner



<i>Diagnostic procedure</i>	<i>Typical effective dose (mSv)</i>	<i>Equiv. no. of CXR</i>	<i>Approx. equiv. period of background radiation</i>
CXR	0.02	1	3 days
CT head	2.0	100	10 months
CT chest	8	400	3.6 years
CT abdomen/pelvis	10	500	4.5 years

UK average background radiation = 2.2 mSv per year; regional averages range from 1.5 to 7.5 mSv per year.

# Tomographie par transmission de rayons X





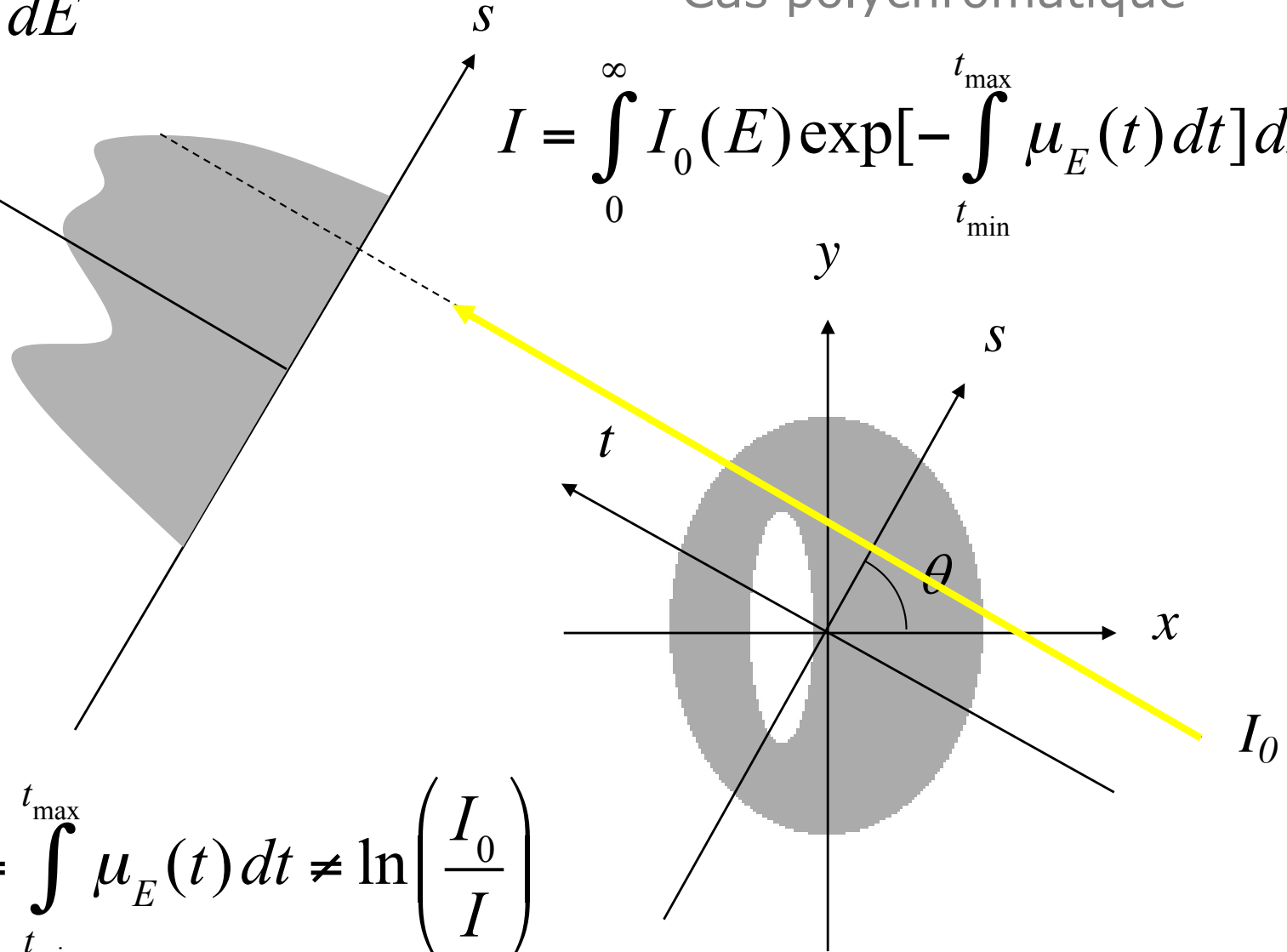
# Tomographie par transmission de rayons X

$$I_0 = \int_0^{\infty} I_0(E) dE$$

Cas polychromatique

$$I = \int_0^{\infty} I_0(E) \exp\left[-\int_{t_{\min}}^{t_{\max}} \mu_E(t) dt\right] dE$$

$$\ln\left(\frac{I_0(E)}{I(E)}\right) = \int_{t_{\min}}^{t_{\max}} \mu_E(t) dt \neq \ln\left(\frac{I_0}{I}\right)$$

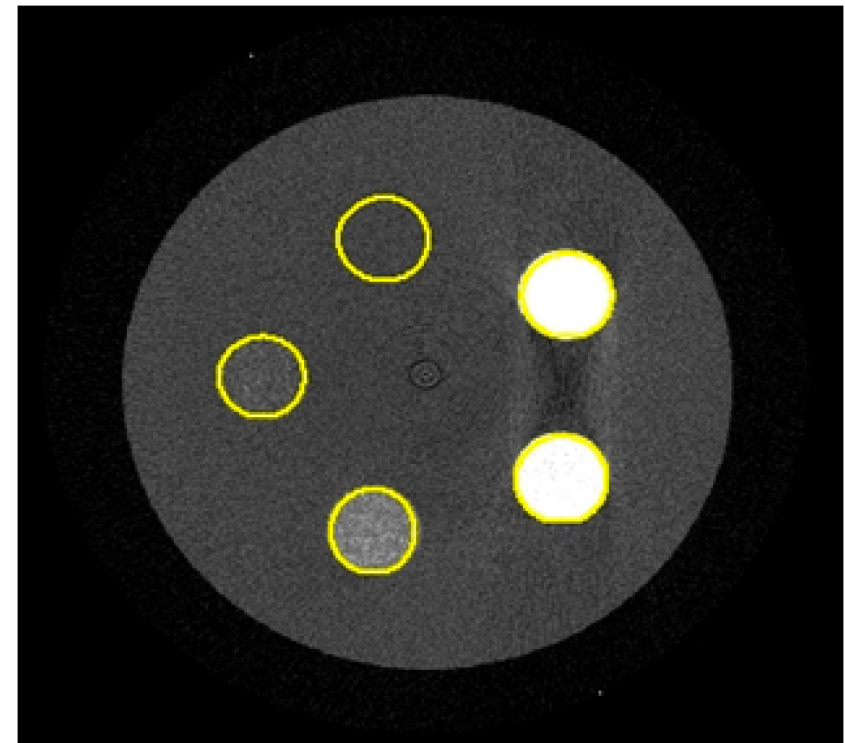
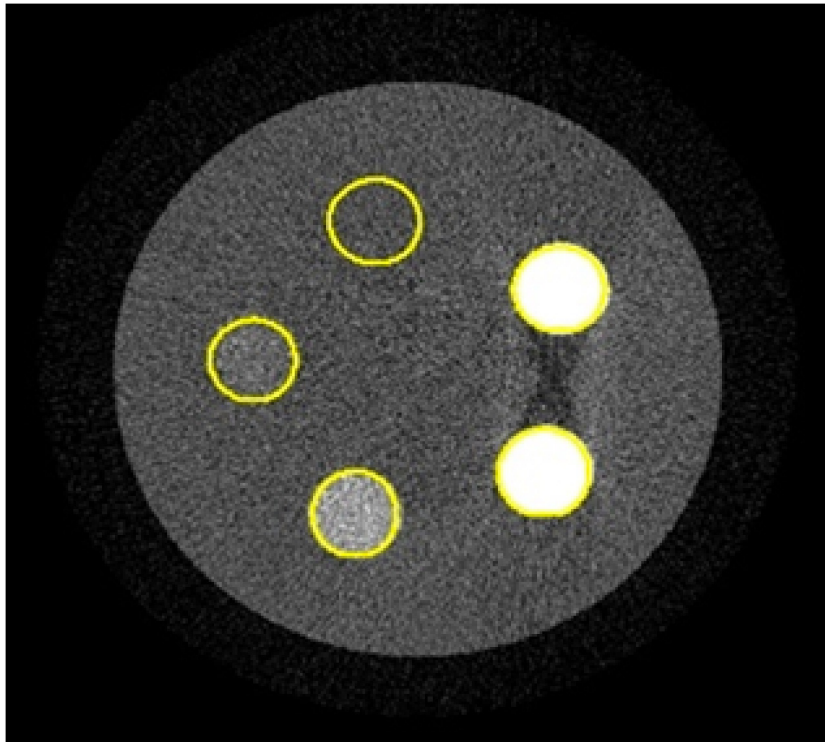


# Tomographie par transmission de rayons X

Cas polychromatique -> durcissement de faisceau

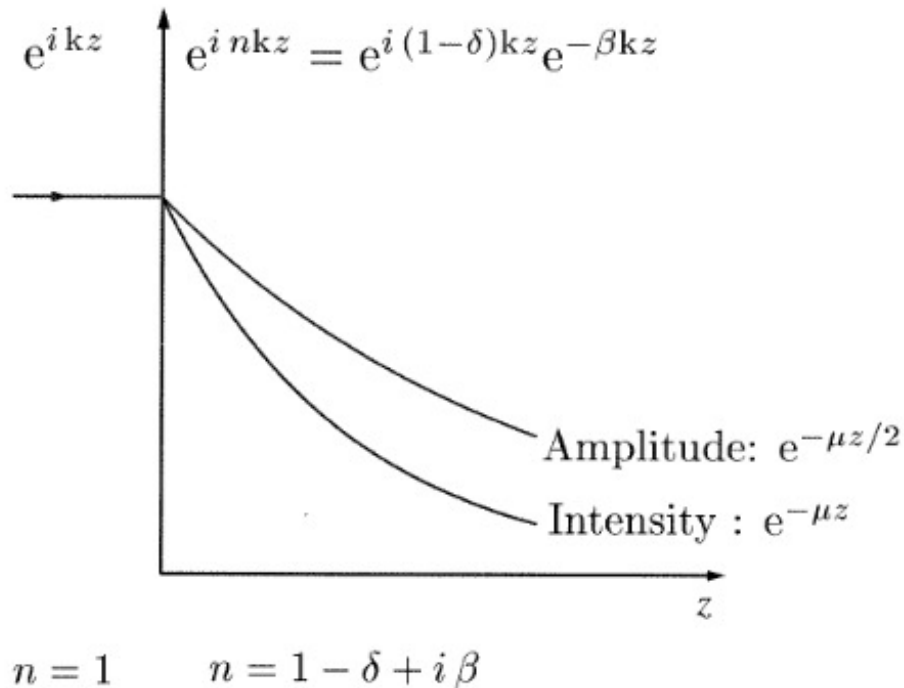
$$I_0 = \int_0^{\infty} I_0(E) dE$$

$$I = \int_0^{\infty} I_0(E) \exp\left[-\int_{t_{\min}}^{t_{\max}} \mu_E(t) dt\right] dE$$



$$\ln\left(\frac{I_0(E)}{I(E)}\right) = \int_{t_{\min}}^{t_{\max}} \mu_E(t) dt \neq \ln\left(\frac{I_0}{I}\right)$$

# Tomographie par contraste de phase



Partie réelle : déphasage  
 Partie imaginaire : absorption

$$\delta = \frac{\lambda^2 \rho r_0}{2\pi} \approx 10^{-6}$$

$\rho$  = densité électronique dans la matière  $\sim 1 \text{ e}/\text{\AA}^3$   
 $r_0$  = rayon classique de l'électron =  $2.82 \cdot 10^{-5} \text{ \AA}$   
 $\lambda$  = longueur d'onde des rayons X  $\sim \text{\AA}$

- Les rayons X sont des ondes électromagnétiques, qui ont une **amplitude** et une **phase**
- La phase est modifiée durant la propagation de l'onde en fonction de **l'indice de réfraction** des matériaux traversés
- La mesure du déphasage permet la **reconstruction tomographique de l'indice de réfraction** du milieu à la longueur d'onde des rayons X
- Des milieux d'atténuation similaires, mais d'indices de réfraction différents, peuvent alors être distingués

# Principe : mesure de l'angle de réfraction

L'objectif de l'imagerie par contraste de phase est de détecter le déphasage  $\varphi(x,y)$  du front d'onde, qui dépend directement de l'indice de réfraction.

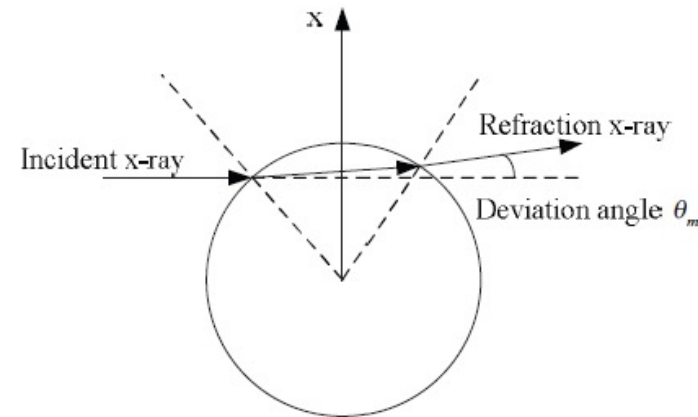
$$\varphi(x,y) = \frac{2\pi}{\lambda} \int \delta(x,y,z) dz \quad \rightarrow \quad \text{Transformée de Radon} \quad \rightarrow \quad \text{Tomographie de } \delta$$

En pratique, l'angle de réfraction  $\Delta\theta$  est mesuré et le déphasage  $\varphi(x,y)$  s'obtient par intégration.

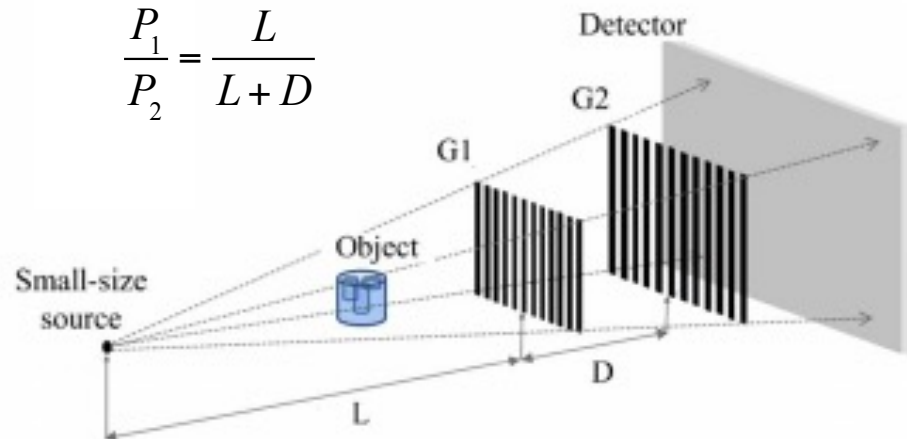
$$\Delta\theta(x,y) = \frac{\lambda}{2\pi} \frac{\partial \varphi(x,y)}{\partial x}$$

Pour  $\lambda < 0.1 \text{ nm}$ ,  $\Delta\theta \sim \mu\text{rad}$

Exploitation de l'effet Talbot consistant à utiliser 2 réseaux de diffraction G1 et G2 éclairés par un tube à rayons X. G1 est fixe et G2 est déplacé par pas d'une fraction de P2. L'intensité mesurée par le détecteur en fonction de la position de G2 varie comme un sinus dont la phase est reliée à l'angle de diffraction des rayons X par les réseaux.



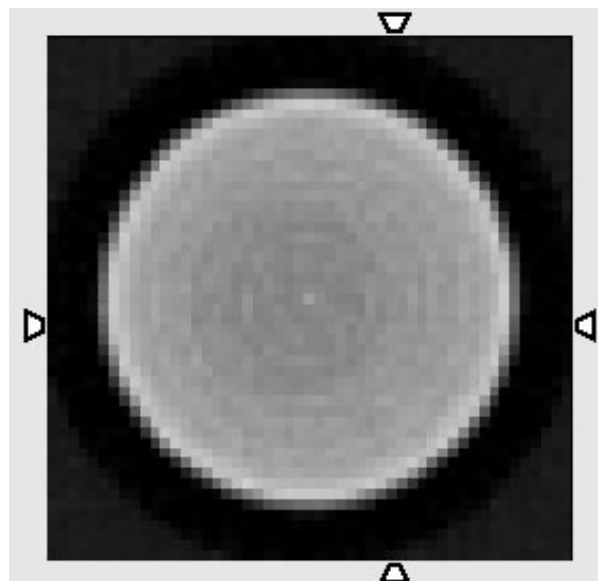
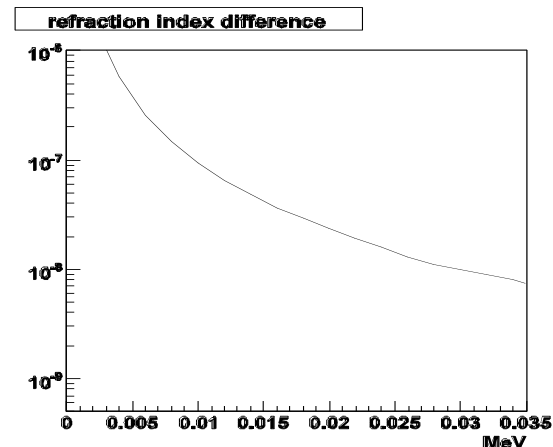
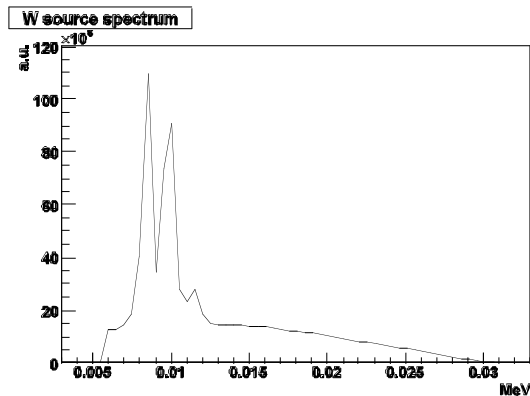
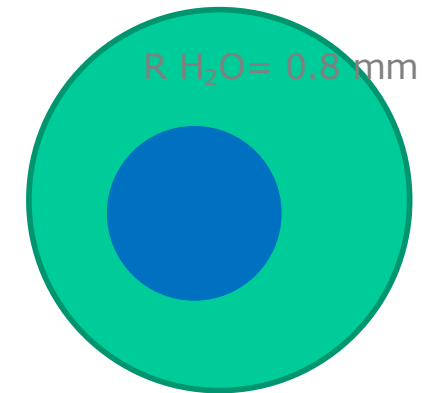
$$\frac{P_1}{P_2} = \frac{L}{L+D}$$



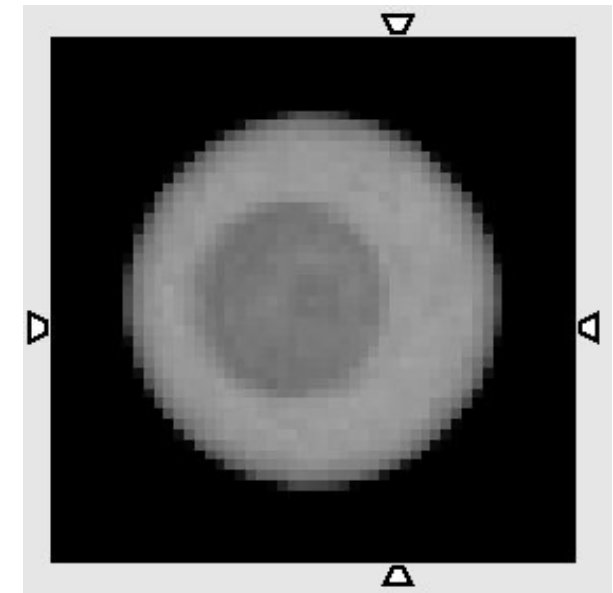
# Exemple simulé avec GATE

- PIXSCAN : 51 x 51 pixels, 130 x 130  $\mu\text{m}^2$
- Réseaux : P1=4  $\mu\text{m}$ , P2=4.4  $\mu\text{m}$ , L=140 cm, D=14 cm
- Pour chaque position angulaire de l'objet, G2 effectuée 11 pas de 0.4  $\mu\text{m}$
- Source : tube à anode de tungstène, taille du foyer: 10 x 10  $\mu\text{m}^2$
- Fantôme : 2 sphères de muscle et H<sub>2</sub>O décalées de 2 mm

R Muscle = 1.7 mm



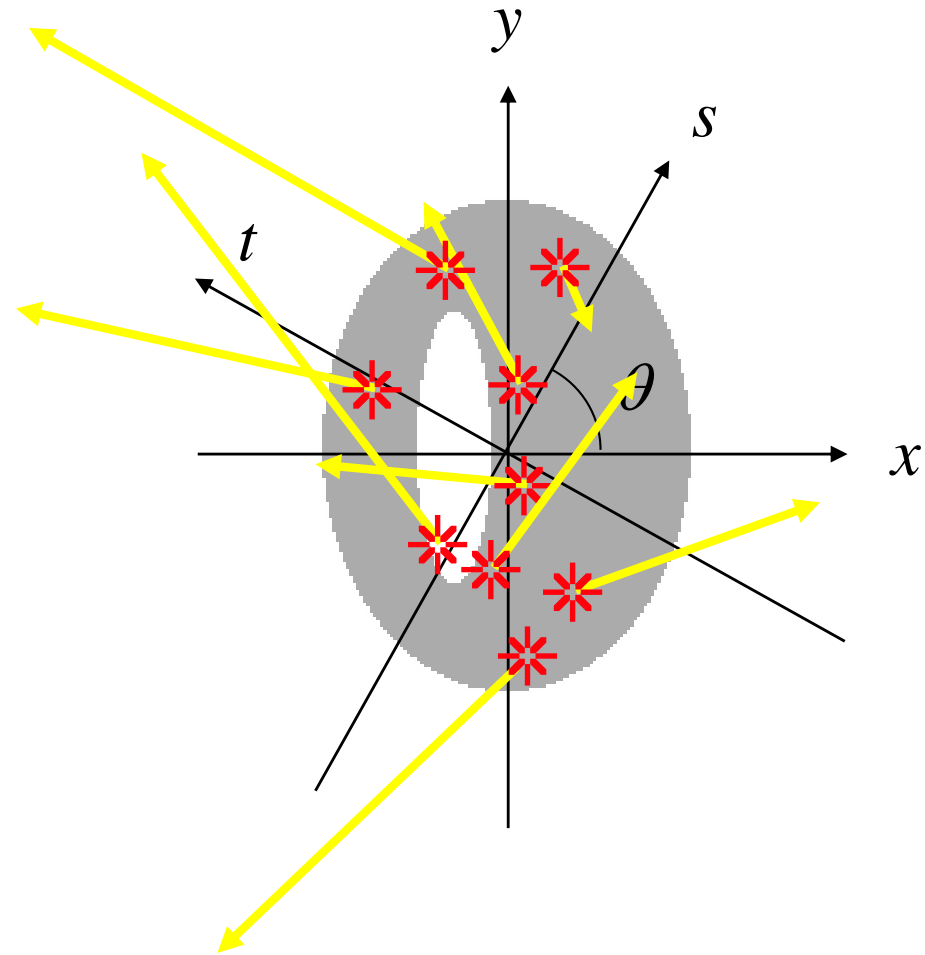
Reconstruction  
de l'amplitude



Reconstruction  
de la phase

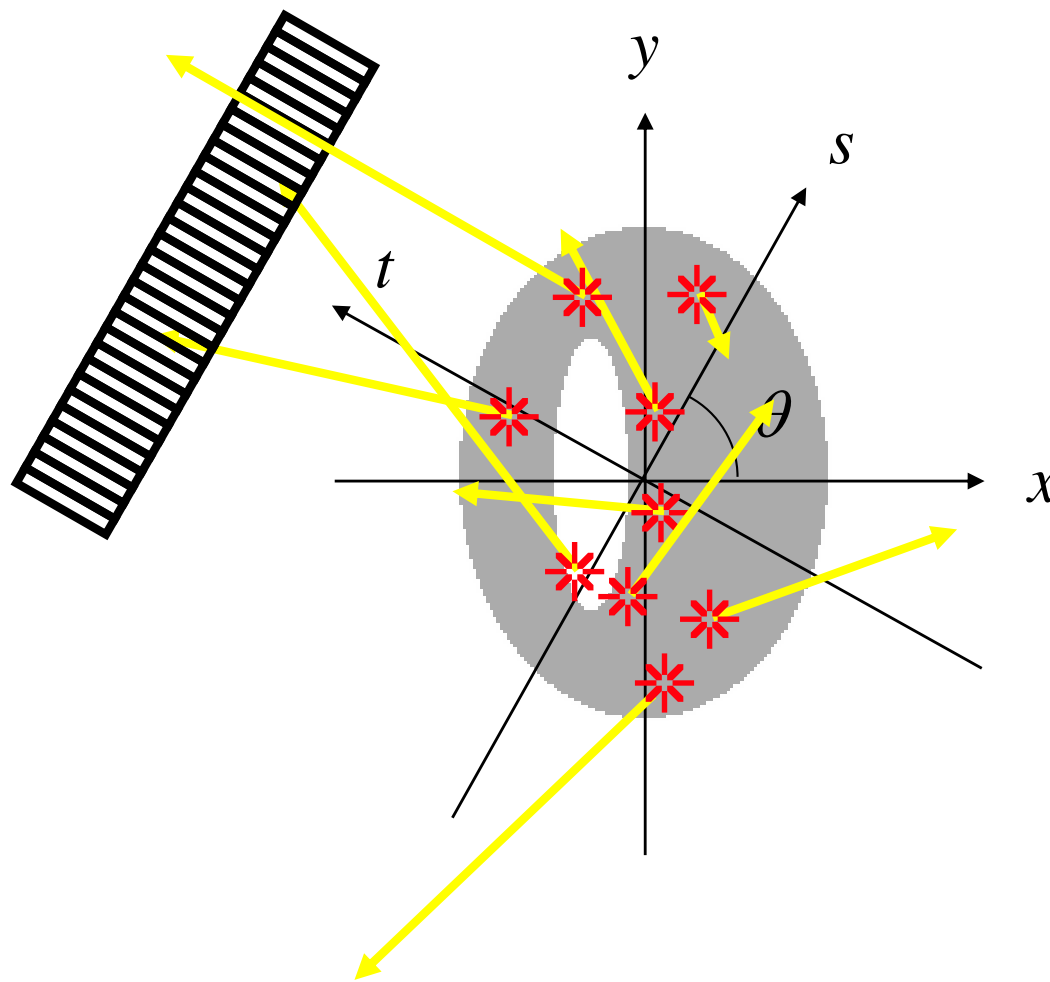
Courtesy: F. Cassol, CPPM

# Tomographie par émission de rayons gamma



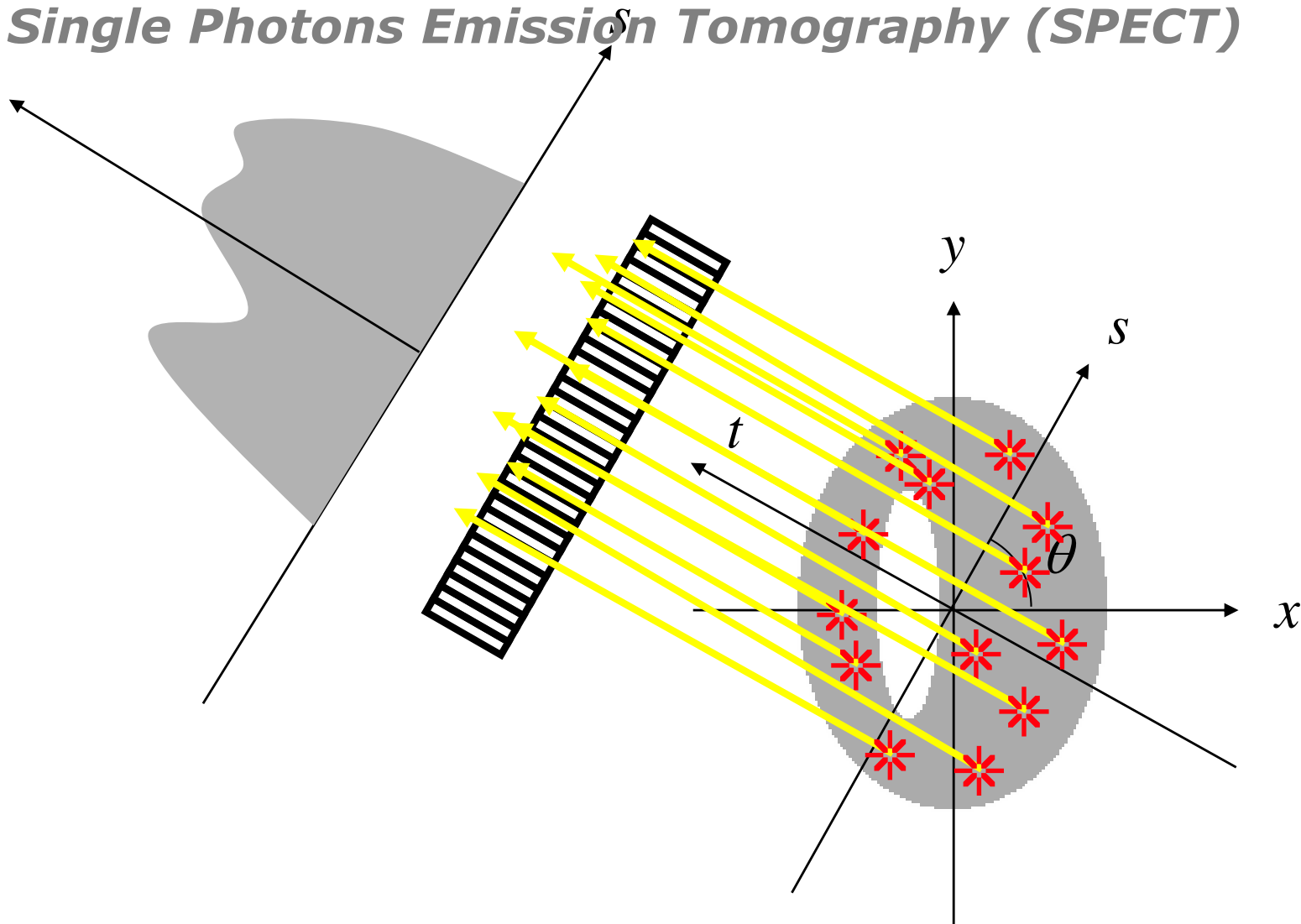
# Tomographie par émission mono-photonique (TEMP)

*Single Photons Emission Tomography (SPECT)*



# Tomographie par émission mono-photonique (TEMP)

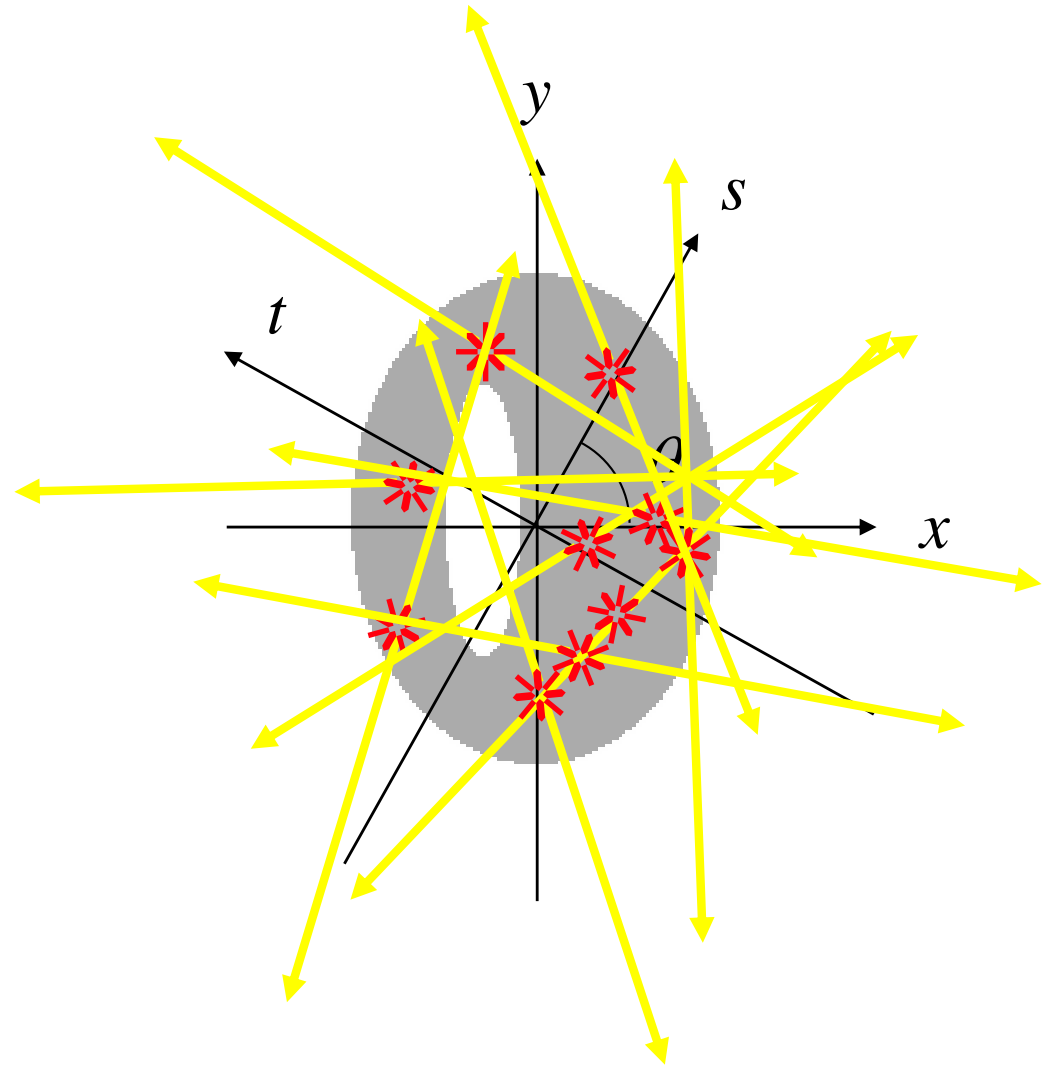
*Single Photons Emission Tomography (SPECT)*





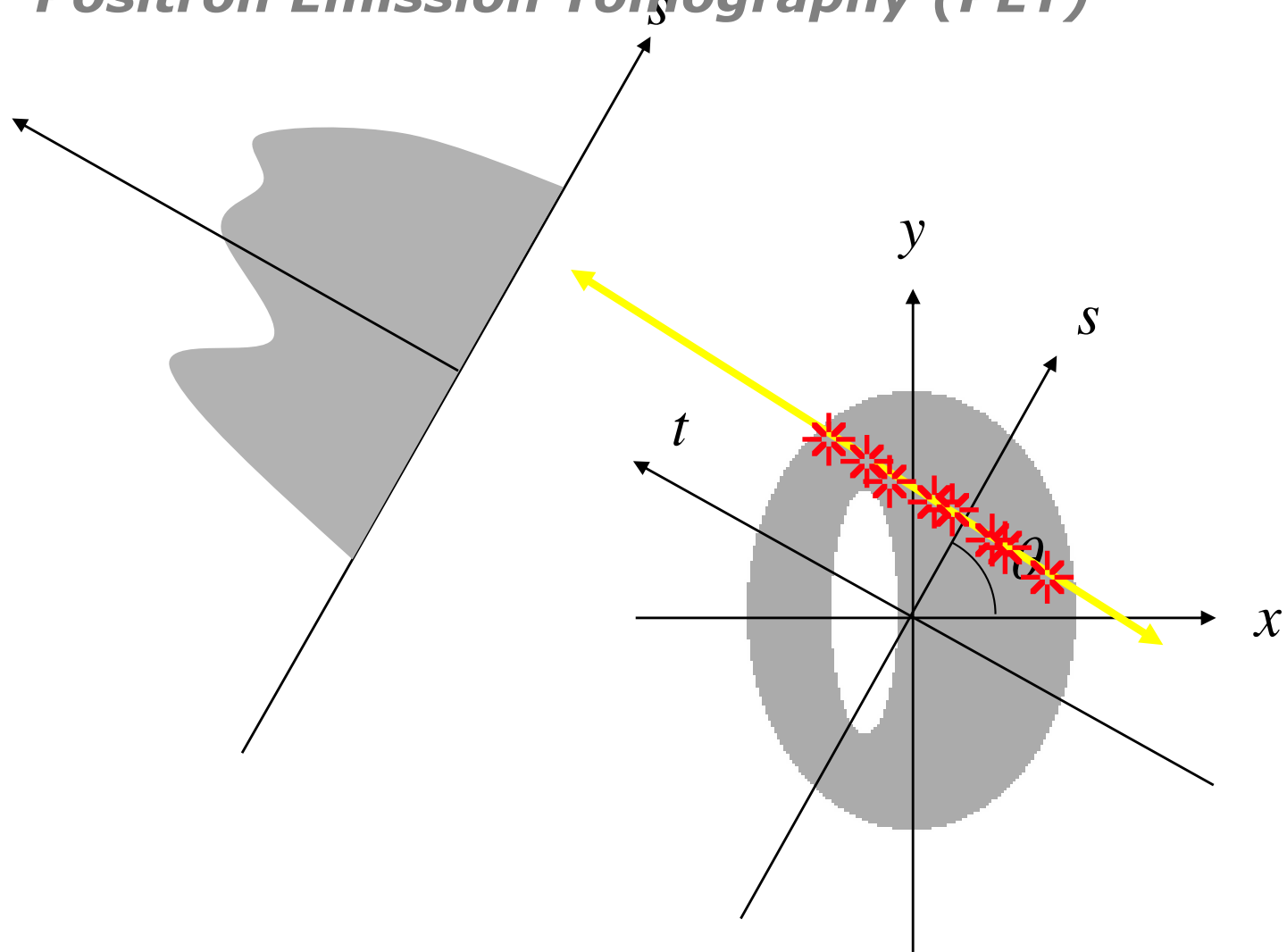
# Tomographie par émission de positons (TEP)

## *Positron Emission Tomography (PET)*

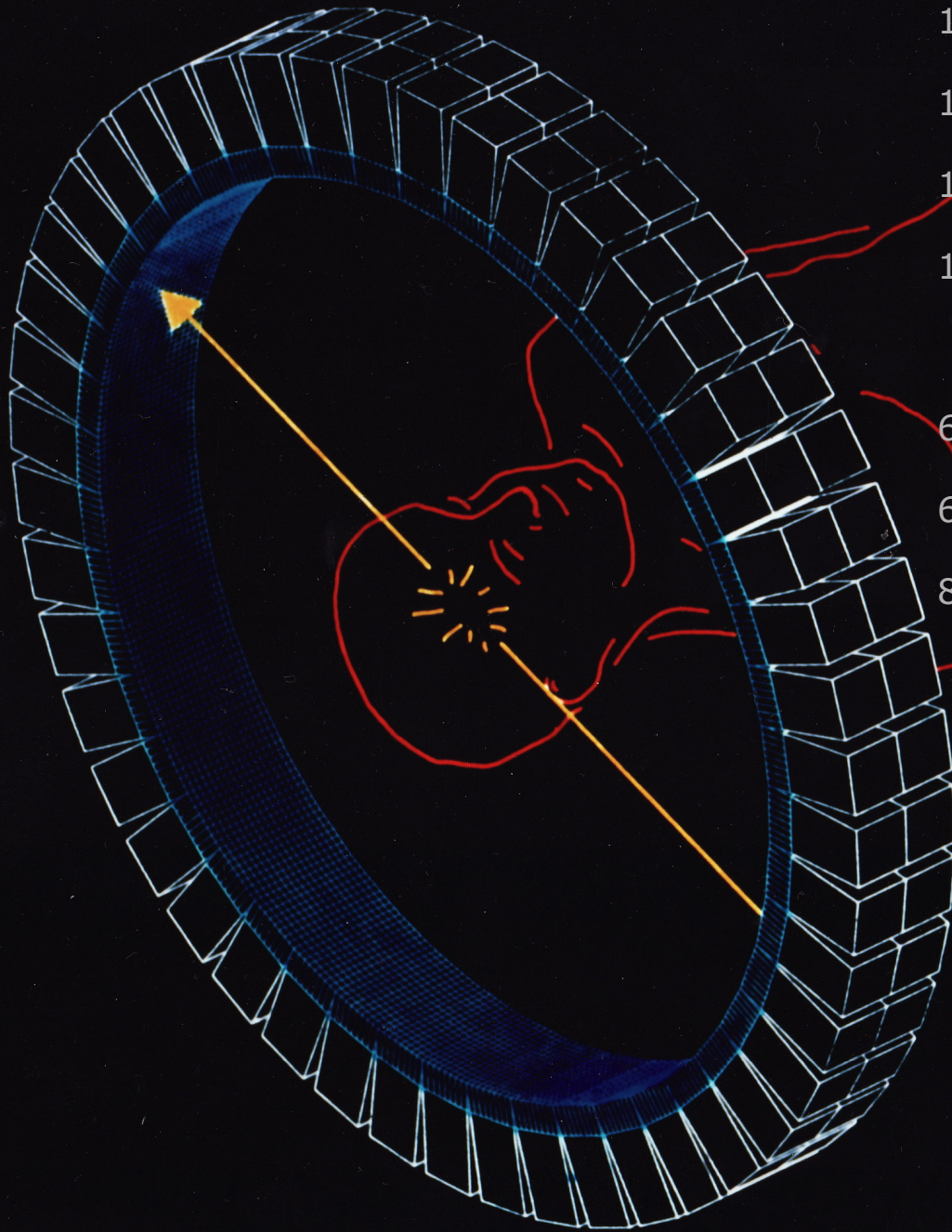


# Tomographie par émission de positons (TEP)

*Positron Emission Tomography (PET)*



# Tomographie par émission de positons (TEP)



$^{15}\text{O}$ (2 min)	511 keV
$^{13}\text{N}$ (10 min)	511 keV
$^{11}\text{C}$ (20 min)	511 keV
$^{18}\text{F}$ (110 min)	511 keV
$^{64}\text{Cu}$ (12,7 h)	511 keV
$^{68}\text{Ga}$ (68 min)	511 keV
$^{82}\text{Rb}$ (1,2 min)	511 keV

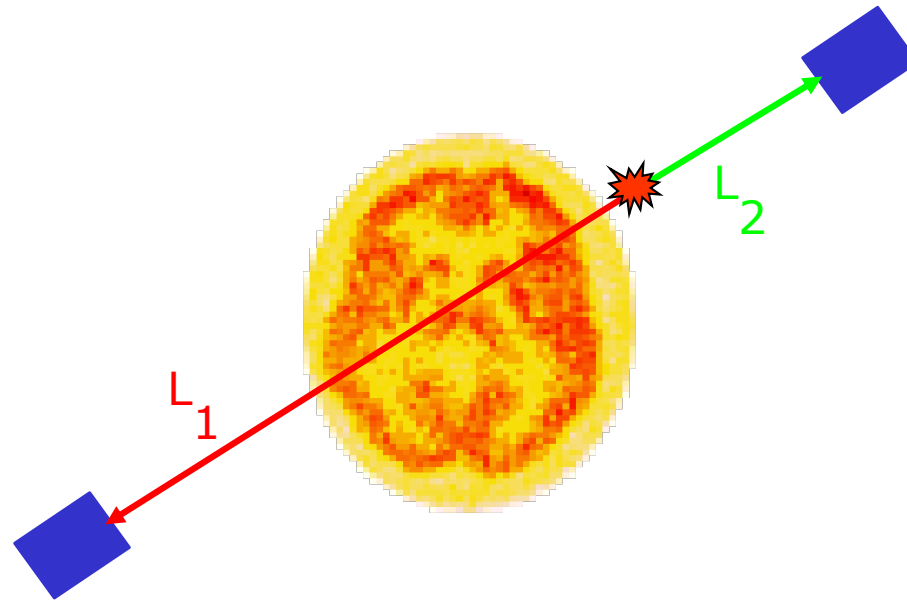
Sensibilité absolue  $\sim 10^{-2}$   
Résolution spatiale 3-5 mm  
Dose absorbée 5-10 mSv

M.R.C. Cyclotron Unit.  
Hammersmith Hospital.  
London.



$$P\{\gamma_1\} P\{\gamma_2\} = \varepsilon^2 e^{-\mu(L_1+L_2)}$$

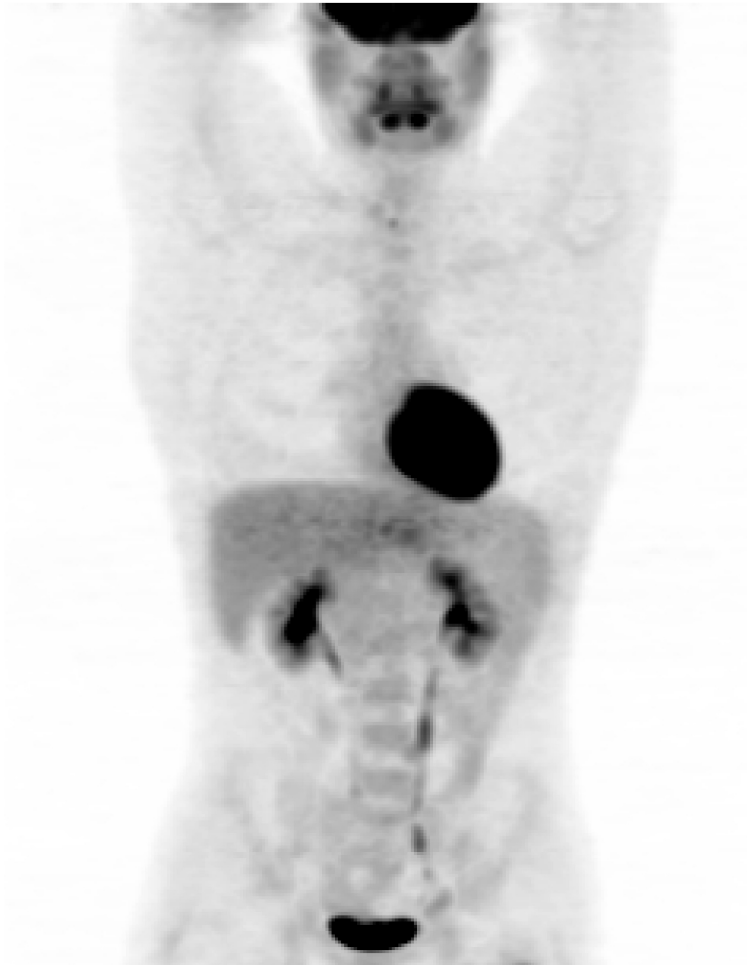
$$P\{\gamma_2\} = \varepsilon e^{-\mu L_2}$$



$$P\{\gamma_1\} = \varepsilon e^{-\mu L_1}$$

# Quantification

## Distribution normale de FDG



## Fixations physiologiques du FDG

Cerveau

Thymus (enfants)

Cœur

Élimination urinaire:

Reins

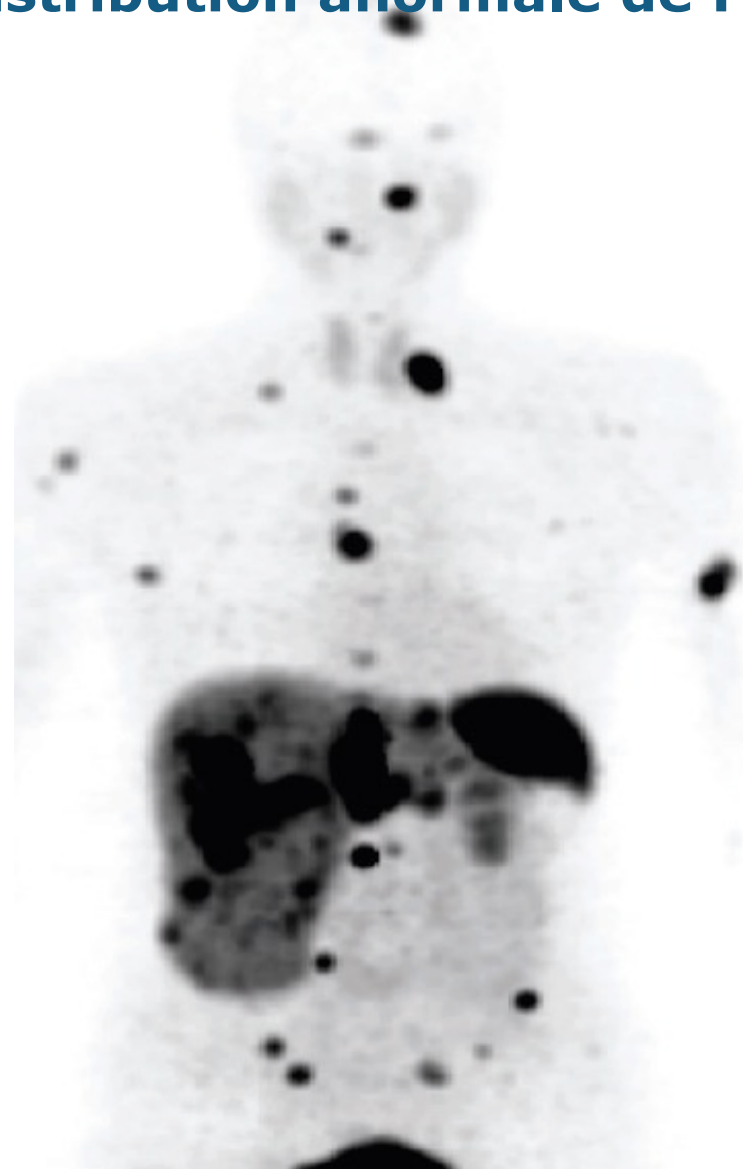
Uretères

Vessie

## Distribution normale de FDG



## Distribution anormale de FDG



# Clinique + Préclinique

microPET Focus 220



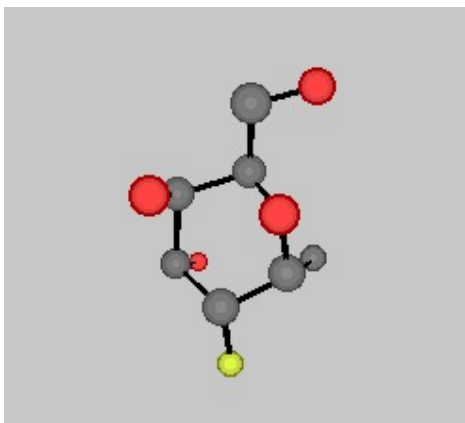
Souris  
6 MBq

ECAT EXACT HR+

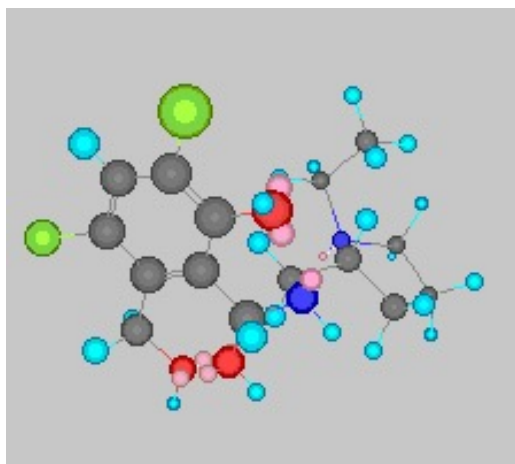


Humain  
390 MBq

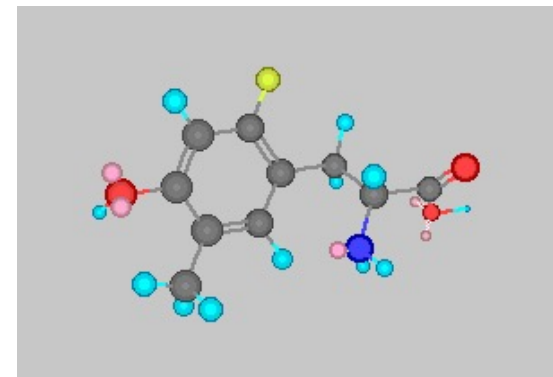
# Marquages radio-pharmaceutiques



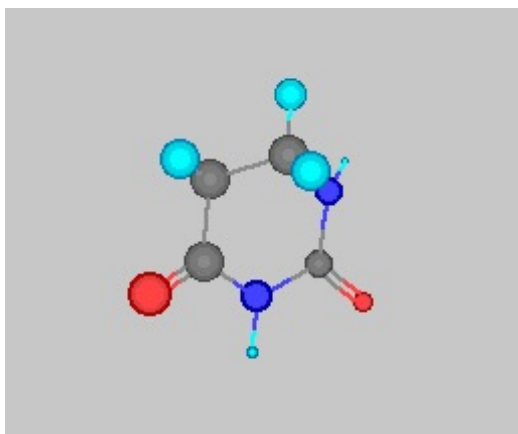
[<sup>18</sup>F]FDG



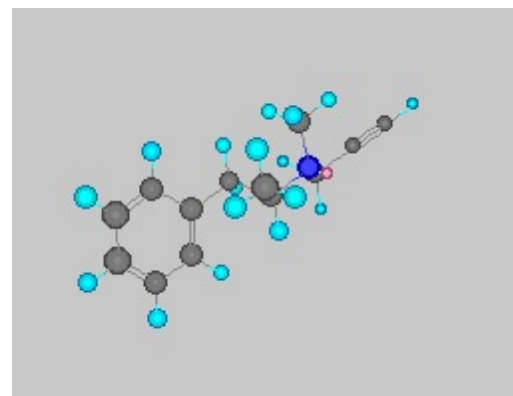
[<sup>11</sup>C]Raclopride



[<sup>18</sup>F]FluoroLDopa



[<sup>18</sup>F]Fluorouracil



[<sup>11</sup>C]L-deprenyl



$^{18}\text{F}$  (2 h)  $\text{H}_2^{18}\text{O}$  (p,n)  $^{18}\text{F}$

$^{20}\text{Ne}$  (d, $\alpha$ )  $^{18}\text{F}$

$^{11}\text{C}$  (20 min)  $^{14}\text{N}$  (p, $\alpha$ )  $^{11}\text{C}$

$^{13}\text{N}$  (10 min)  $^{12}\text{C}$  (d,n)  $^{13}\text{N}$

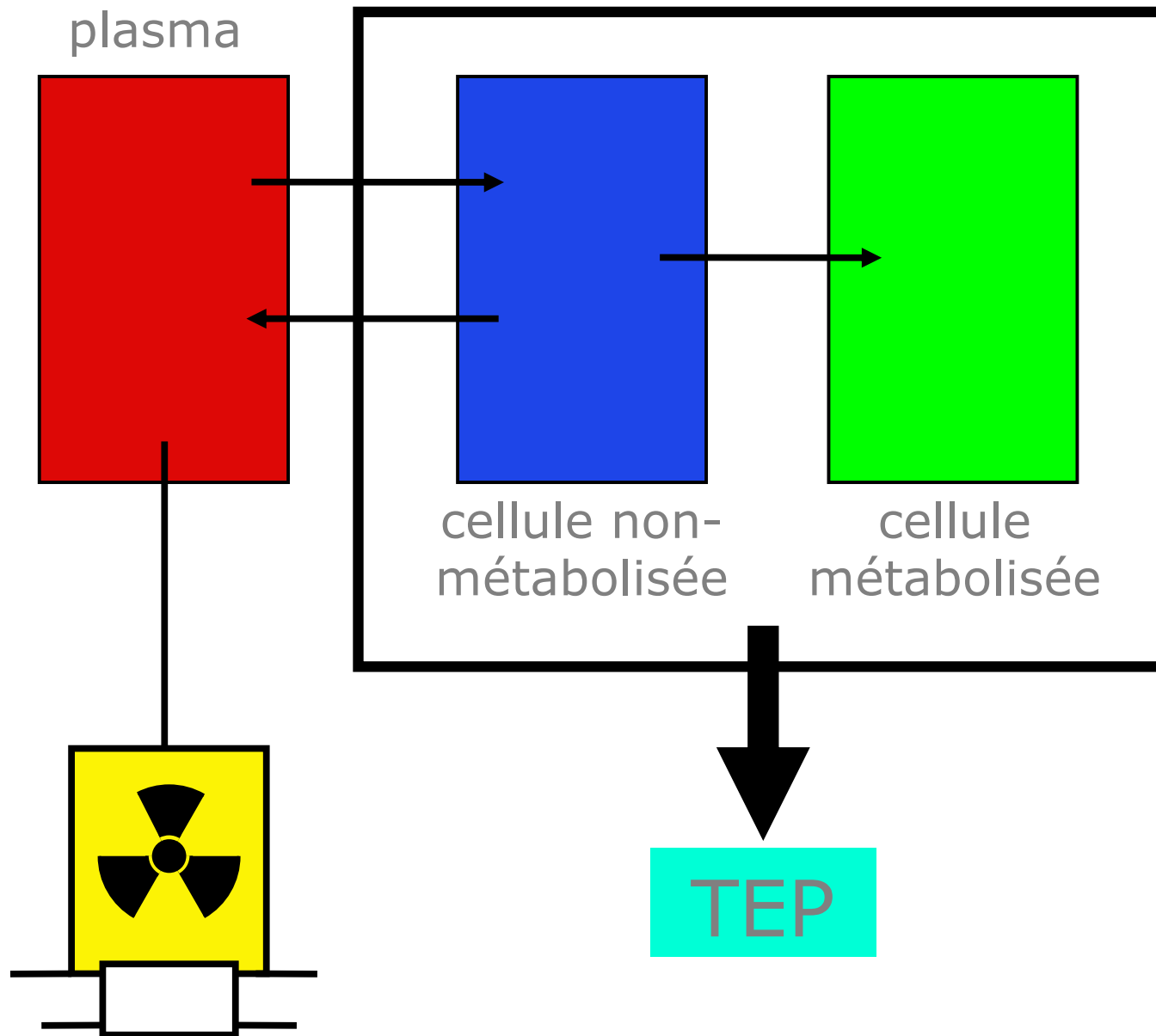
$^{13}\text{C}$  (p,n)  $^{13}\text{N}$

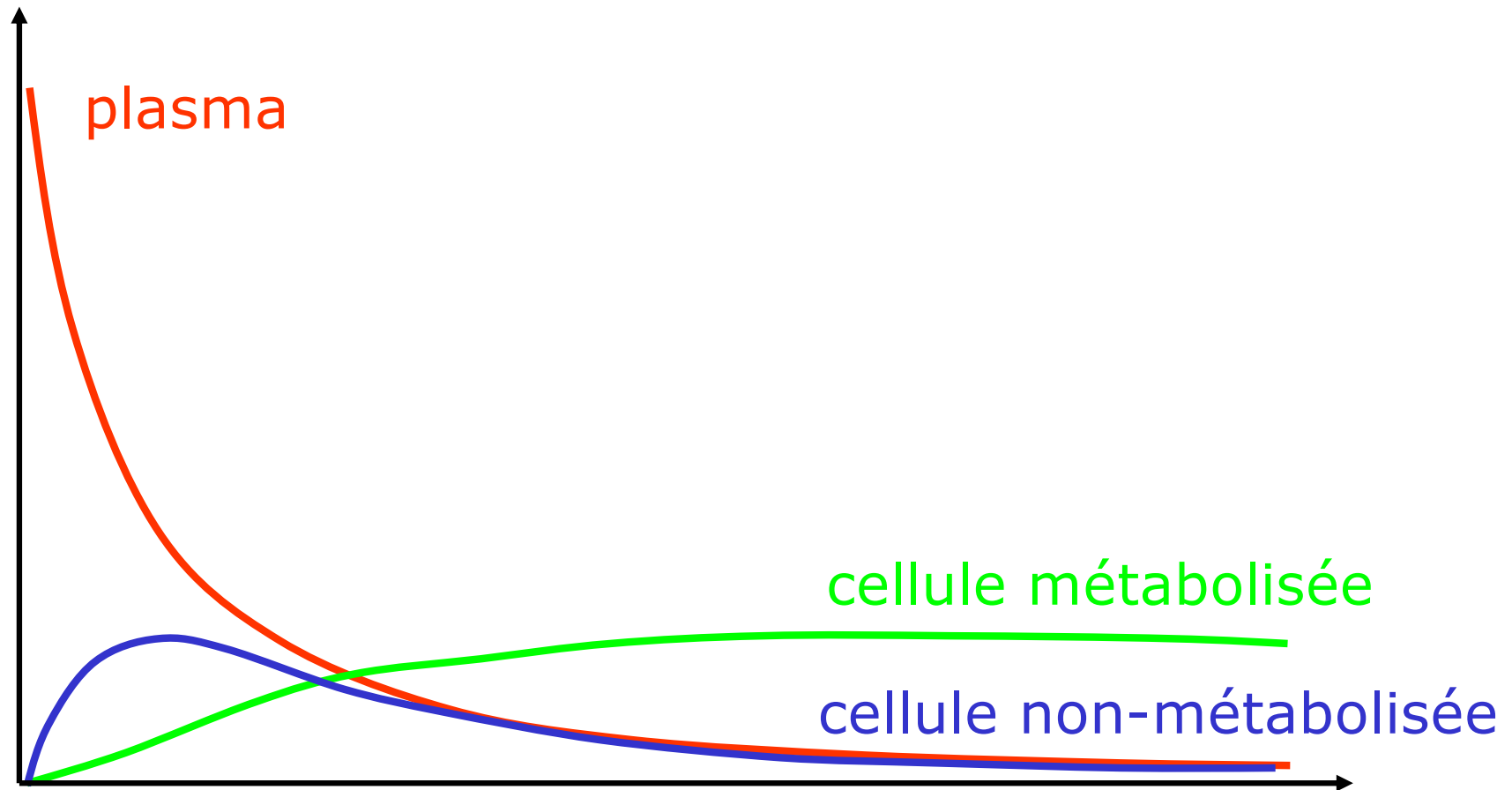
$\text{H}_2^{16}\text{O}$  (p, $\alpha$ )  $^{13}\text{N}$

$^{15}\text{O}$  (2 min)  $^{14}\text{N}$  (d,n)  $^{15}\text{O}$

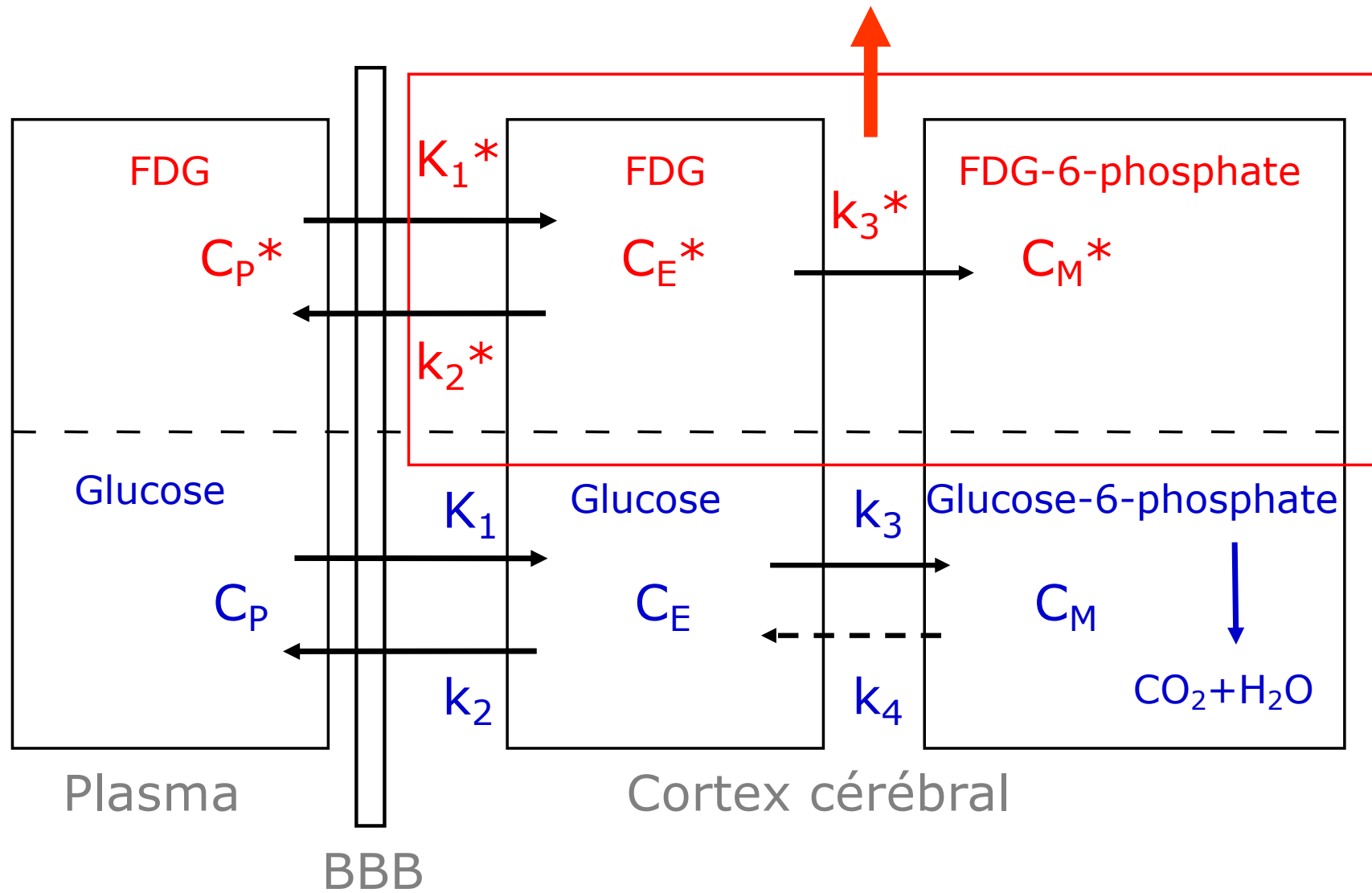
$^{15}\text{N}$  (p,n)  $^{15}\text{O}$







$$C_I^* = C_E^* + C_M^*$$



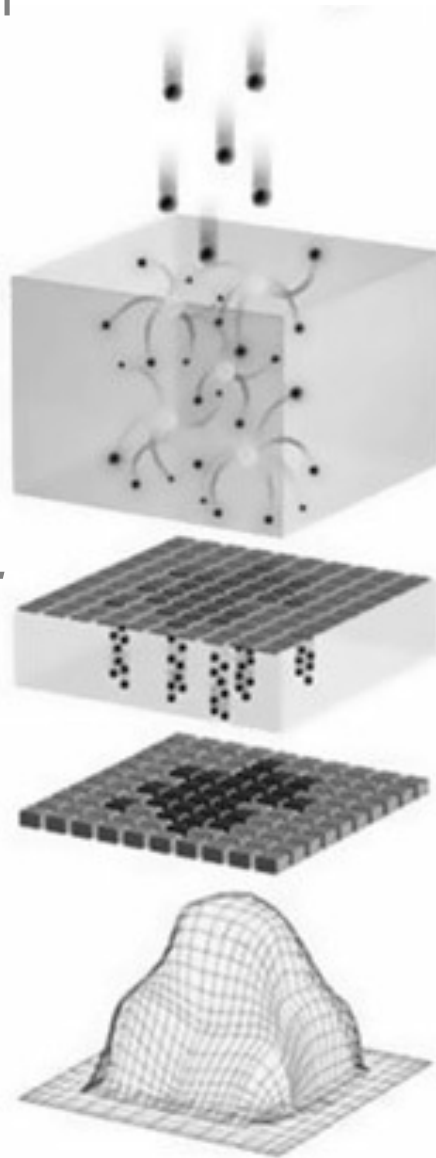
# X-ray detection paradigm

Indirect detection

Scintillator or phosphor screen  
*Radiation converted to light*

Photodetector (e.g. PMT, photodiode, CCD camera or CMOS pixel)  
*Light converted to electric signal*

Image



Direct detection

Gaz (e.g. Xe) or semiconductor (e.g. Si, CdTe, AsGa)  
*radiation converted to electric signal*  
Readout electronic circuit

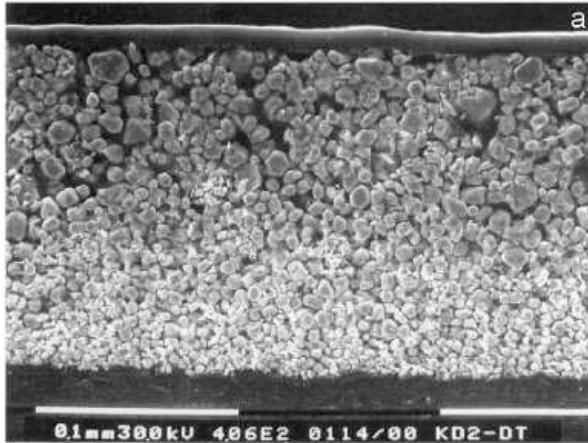
Image



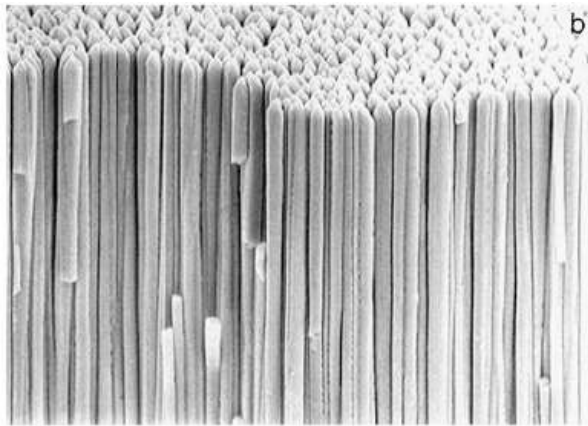
Courtesy: P. Russo and A. Del Guerra, INFN

# Energy integration detectors

## Converter



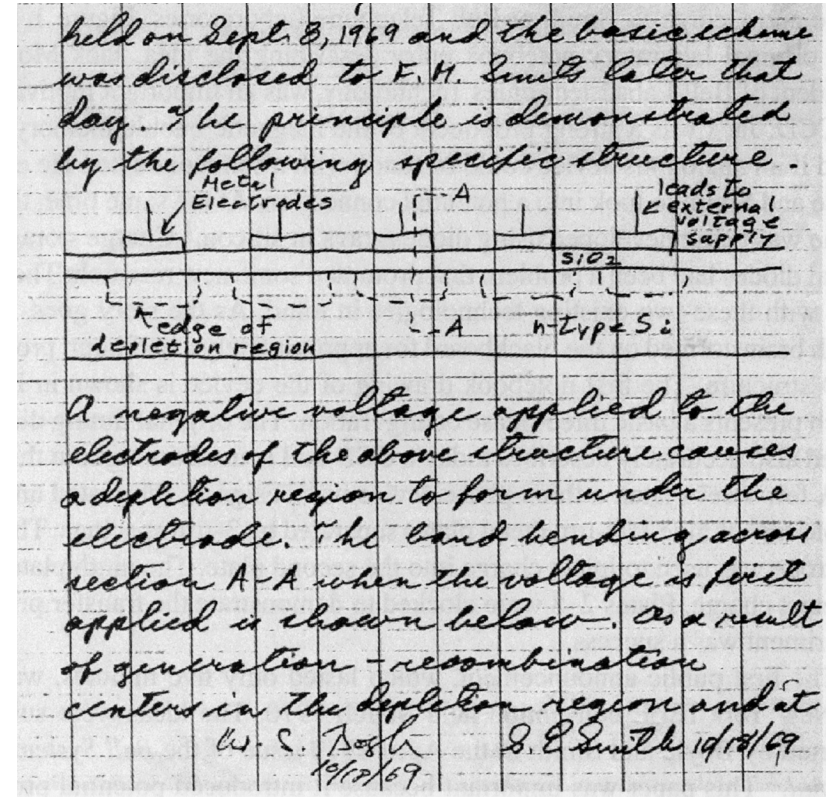
Gadolinium oxysulfide  
(GOS or Gadox,  $Gd_2O_2S$ )



Cesium iodide (CsI)

## Photodetector

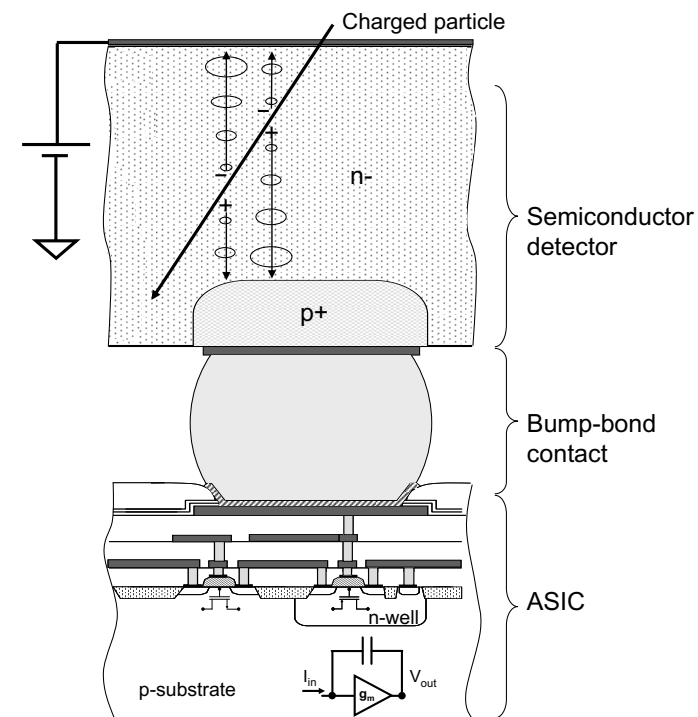
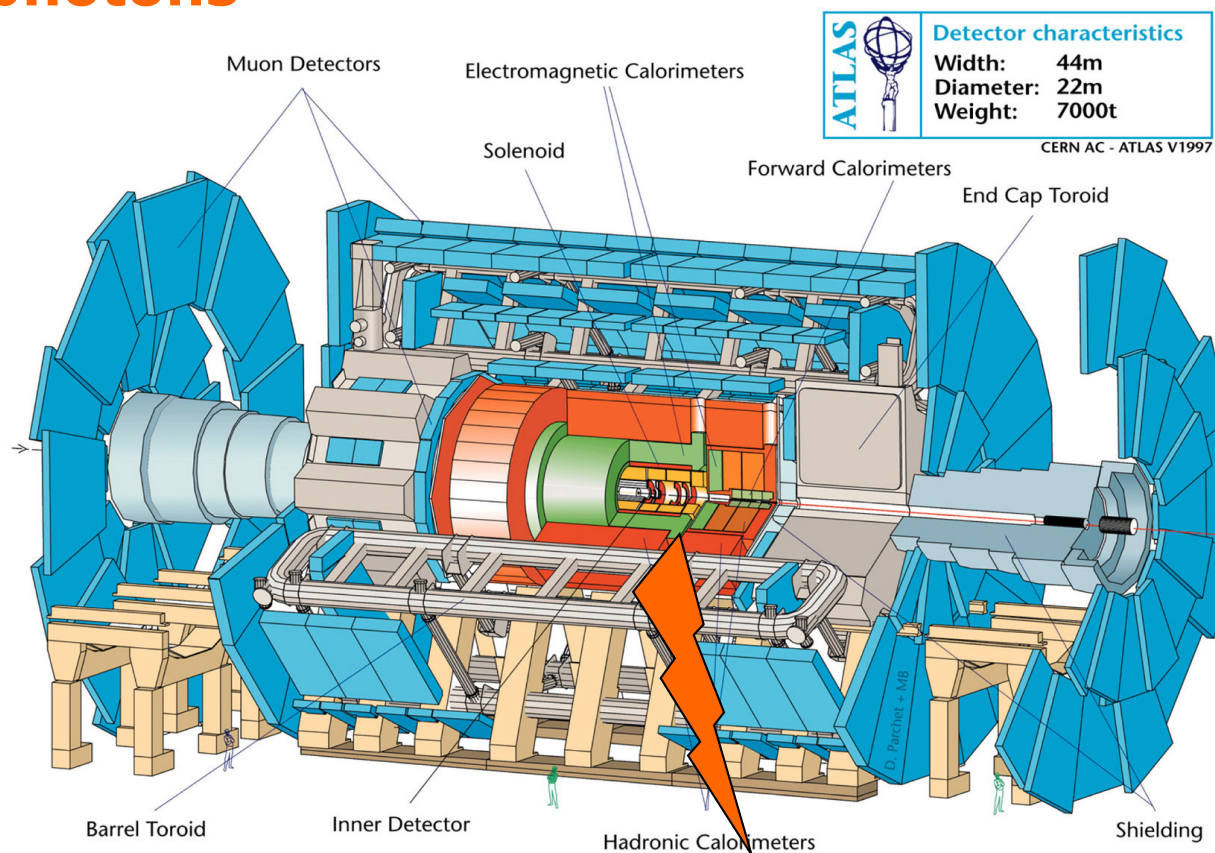
Charged Couple Device (CCD) camera



W.S. Boyle and G.E. Smith (Bell Labs, 1969)  
Nobel Prize in Physics (2009)

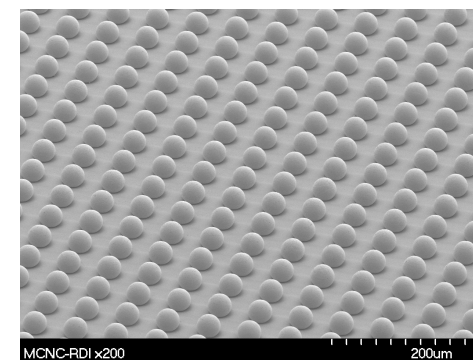
Complementary Metal-Oxide Semiconductor  
(CMOS) pixel

# Détecteurs à comptage de rayons X: une rupture technologique pour le développement du CT à comptage de photons

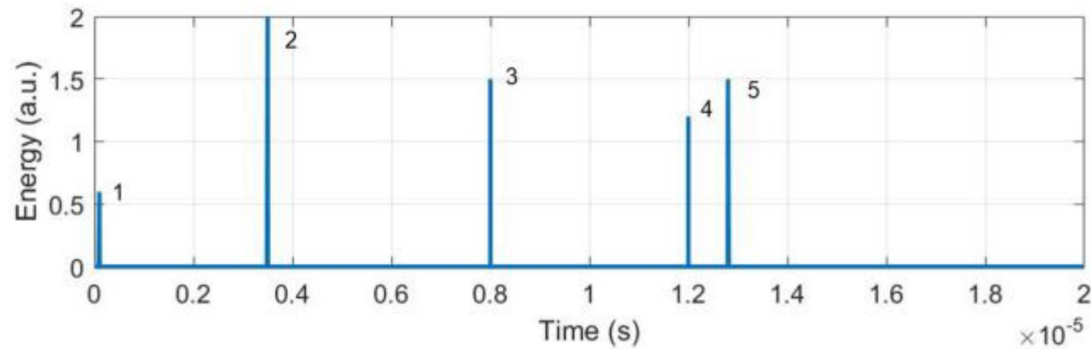


- Suppression du bruit
- Sélection de l'énergie
- Grande dynamique

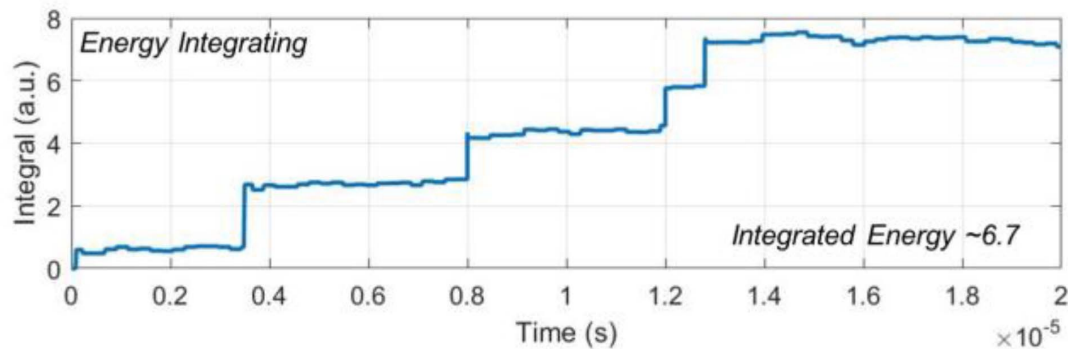
- ✓ Réduction de la dose
- ✓ Amélioration du contraste
- ✓ Développement du CT spectral



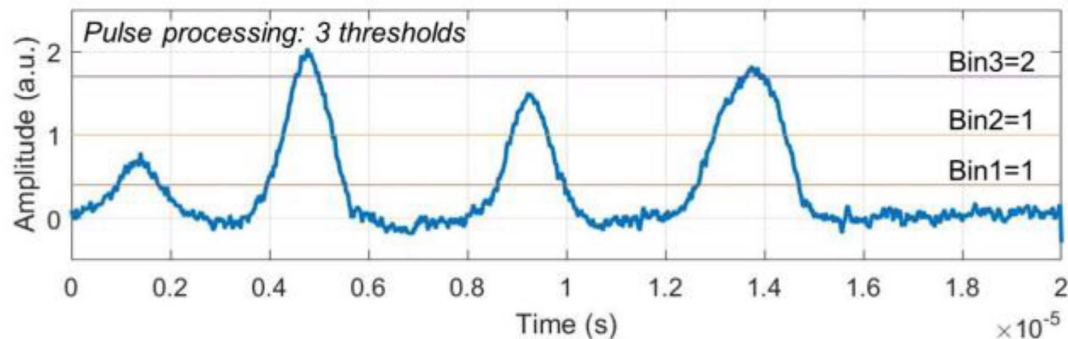
# Energy integrating versus photon counting detectors



Arrival times



Energy integrating detector (EID)

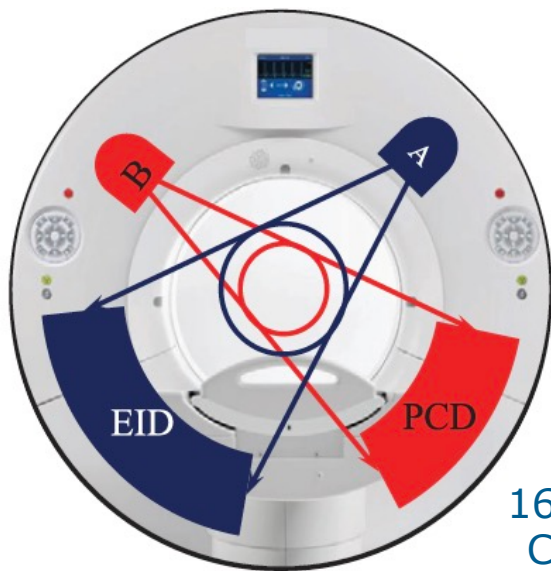


Photon counting detector (PCD)

Ballabriga *et al.*, IEEE TRPMS 5 (2021) 422



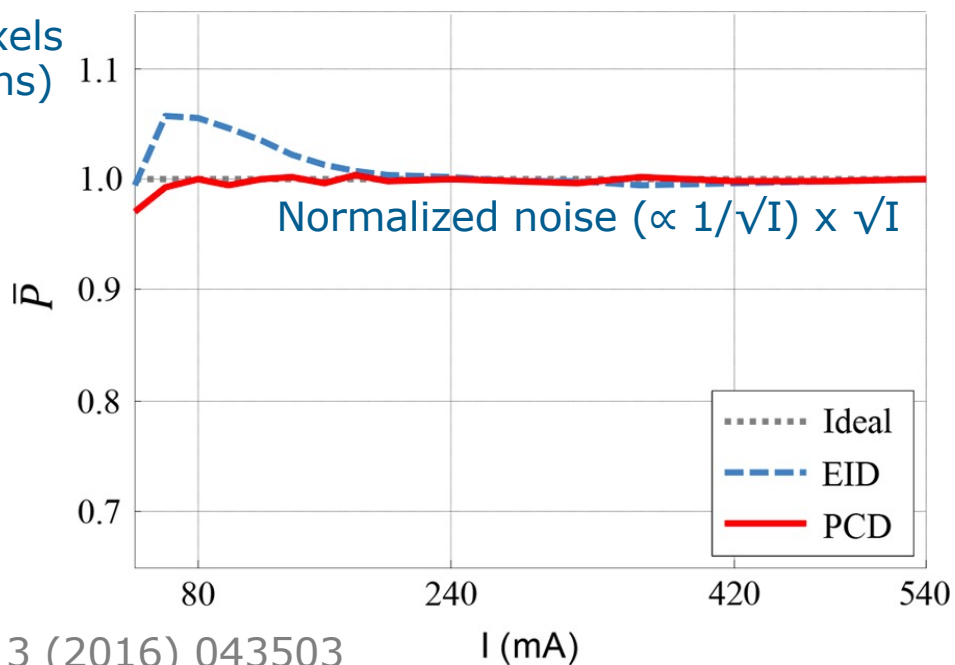
# Noise performance of low-dose-CT with EID and PCD



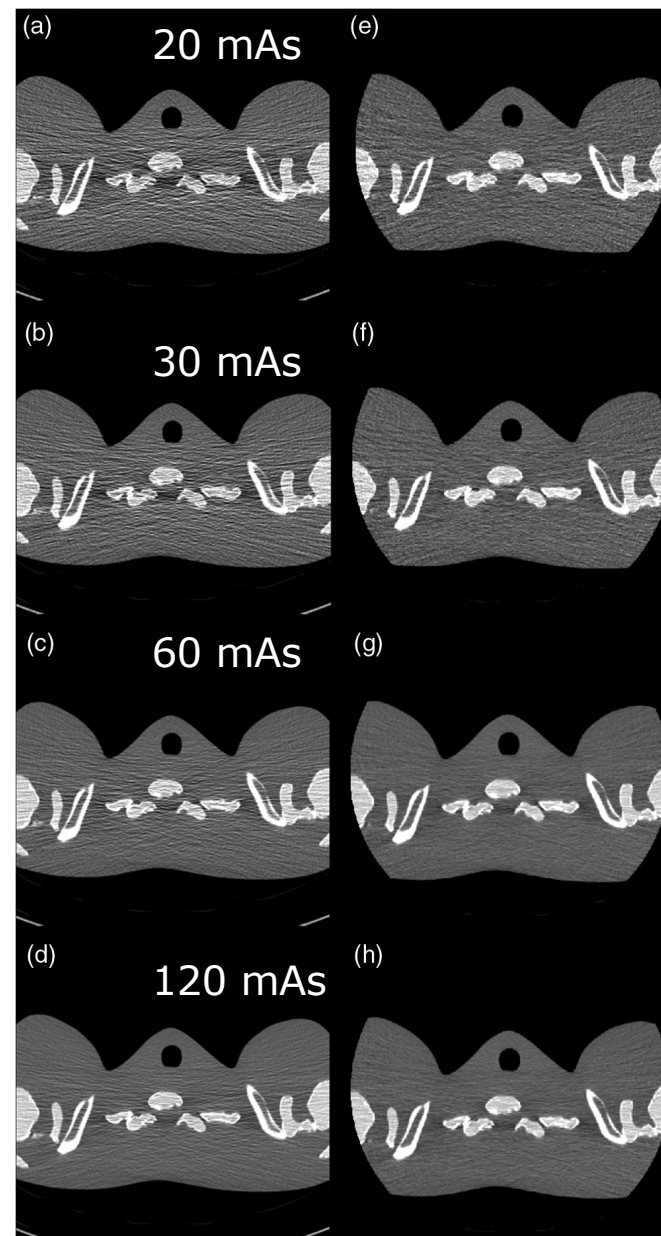
Mayo Clinic (Rochester)  
and Siemens Healthcare

16 mm thick  
CdTe pixels

Gadox/CMOS pixels  
(Stellar, Siemens)



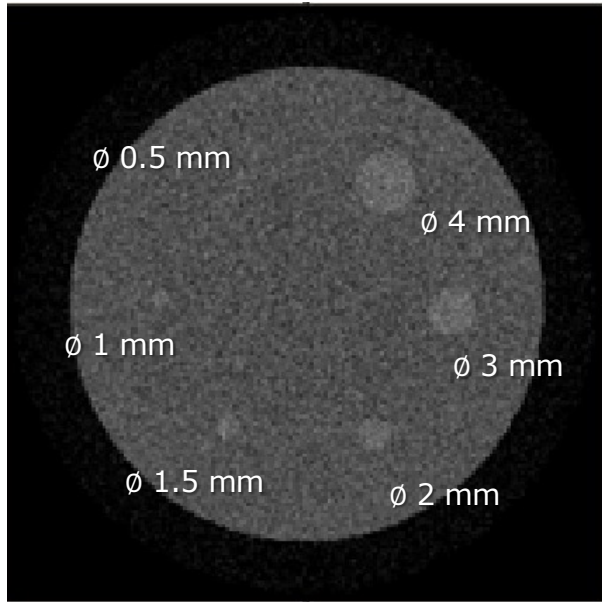
Yu *et al.*, JMI 3 (2016) 043503



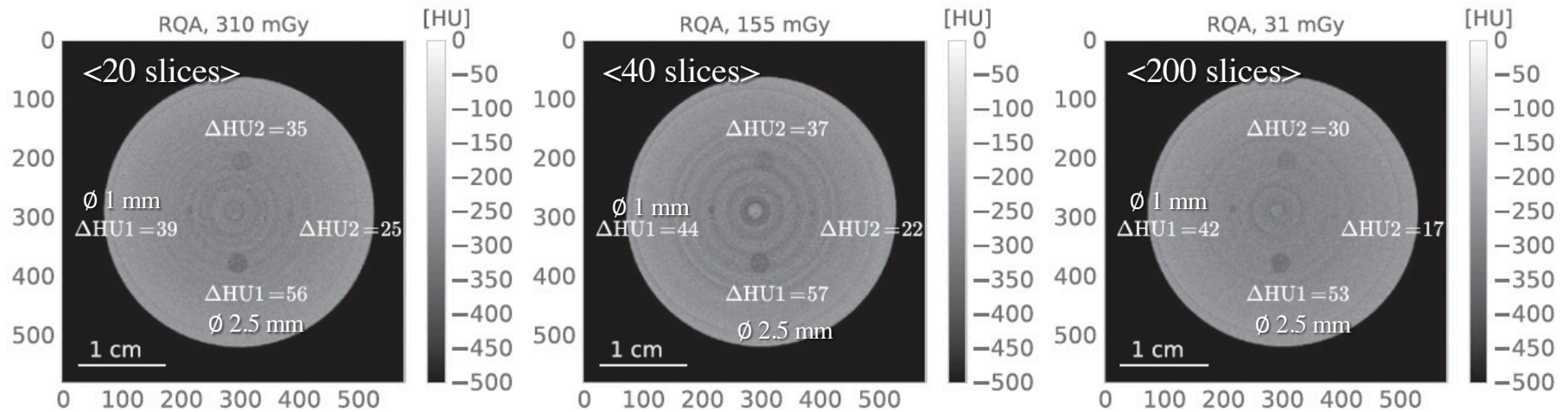
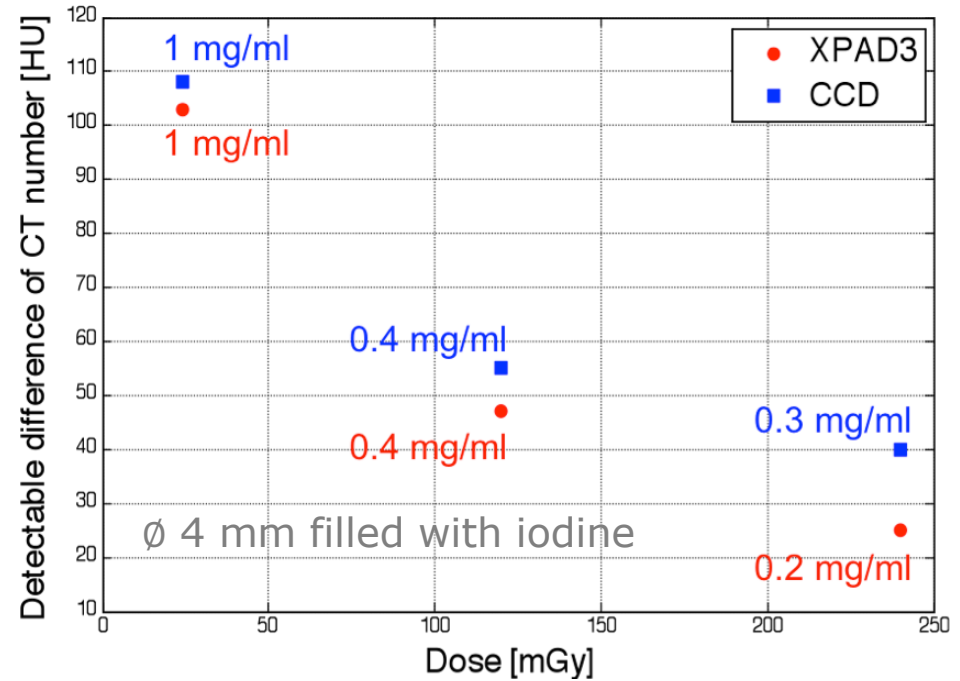
EID

PCD

# Comparison of contrast detectability with EID and PCD



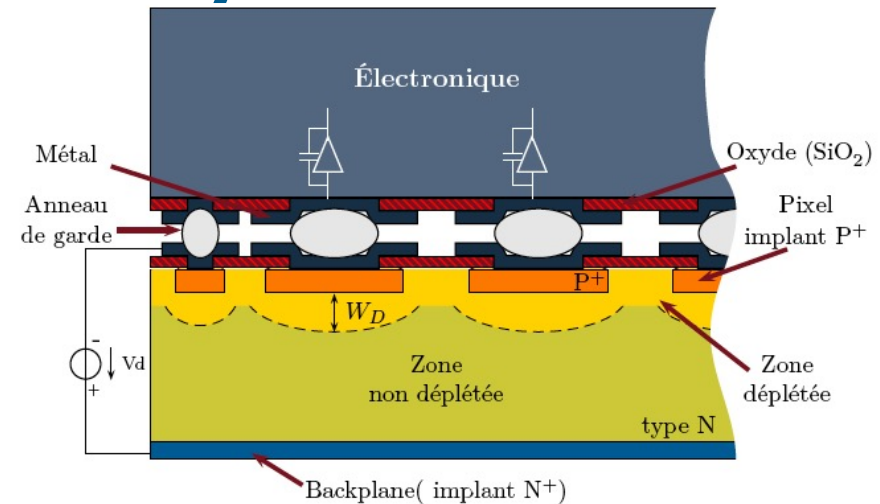
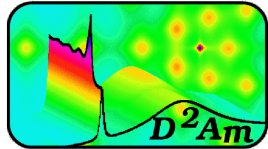
Ouamara *et al.*, IEEE NSS/MIC (2012)



QRM-microCT-LC phantom {  $\Delta HU_1 = 49$  HU  
 $\Delta HU_2 = 25$  HU

Cassol *et al.*, BPEX 2 (2016) 025003

# XPAD3: pixels hybrides de Si et CdTe pour la détection de rayons X



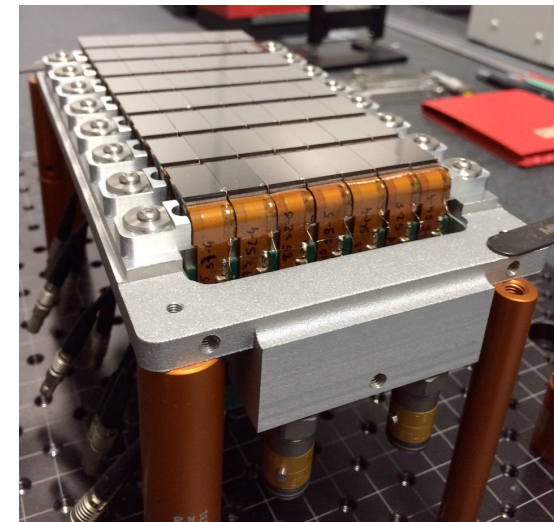
- **XPIX**: Développement des détecteurs à pixels hybrides XPAD.1 et XPAD3.2 avec des capteurs de Si et de CdTe

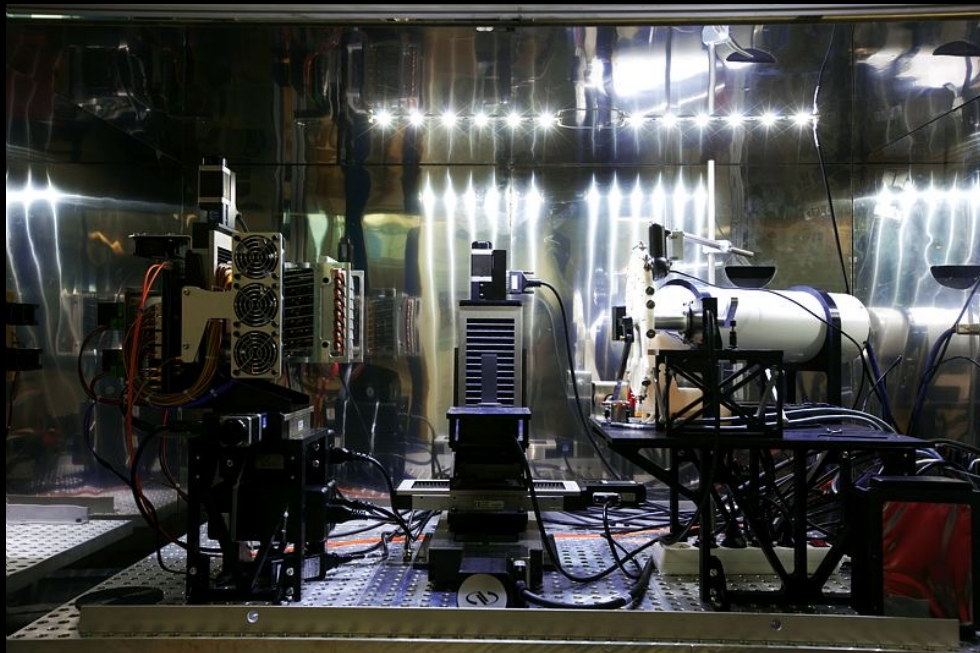
- > 0,5 Mpixels  $130 \times 130 \mu\text{m}^2$
- 240 images/s

- 2011 • 5-35 keV (XPAD3.1/Si: D1-3)
- 2013 • 5-60 keV (XPAD3.2/Si: D4-6)

**CHiPSpeCT** (PhysiCancer 12)

- 2015 • XPAD3.2/CdTe (D7)





Frame rate : 140 images/s

# Détecteur XPAD3: 500,000 pixels de 130 $\mu\text{m}$



## Angiographie de la souris

- Injection de 200  $\mu\text{L}$  d'ioméron 400
- Tube à anode de tungstène
- 90 kVp, 70 W
- Filtre 200  $\mu\text{m}$  Nb
- Temps d'exposition 10 ms/images
- Vitesse d'acquisition 69 images/s

## Prototype PC-CT PIXSCAN II

Real time



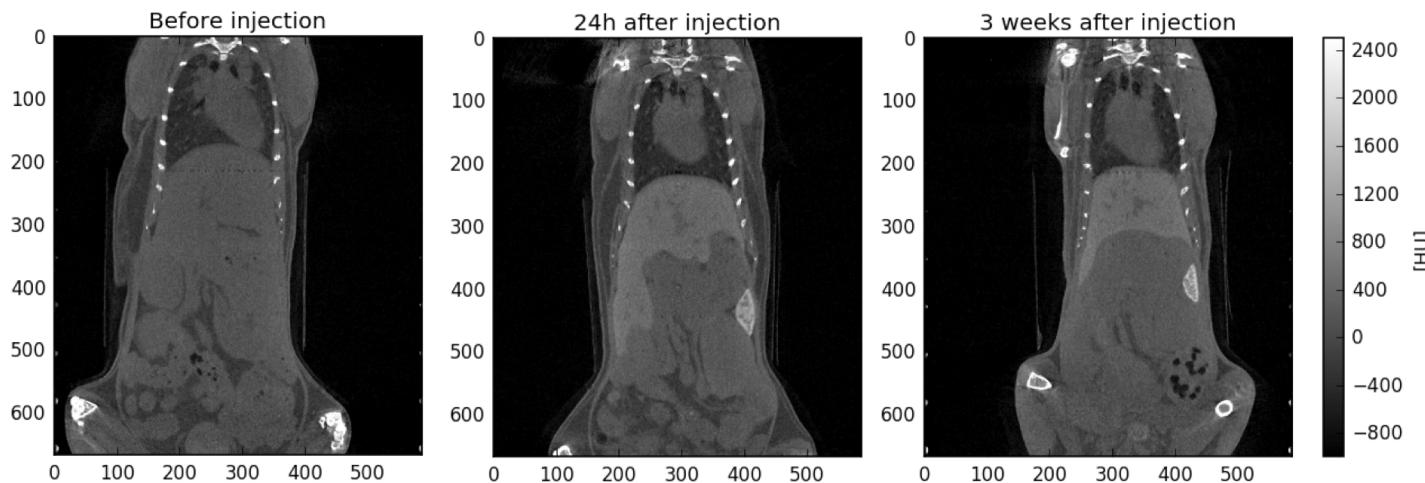
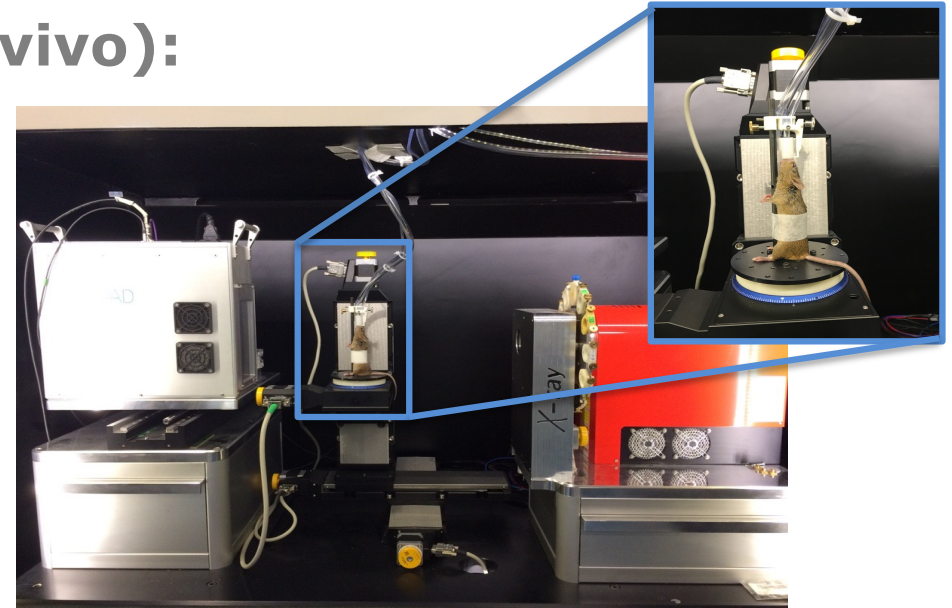
Replay x10



# Standard images with the prototype PIXSCAN-FLI/XPAD3

## Data acquisition protocole (in vivo):

- Standard absorption imaging
- Gaseous anaesthesia: 3 % Isoflurane
- Source: 50 kV/500  $\mu$ A/0.6 mm Al
- Data acquisition mode: continuous
- Pose duration: 575 ms + 50 ms DT
- Projections: 720 ( $0.5^\circ$ )
- Delivered dose: 177 mGy/acquisition



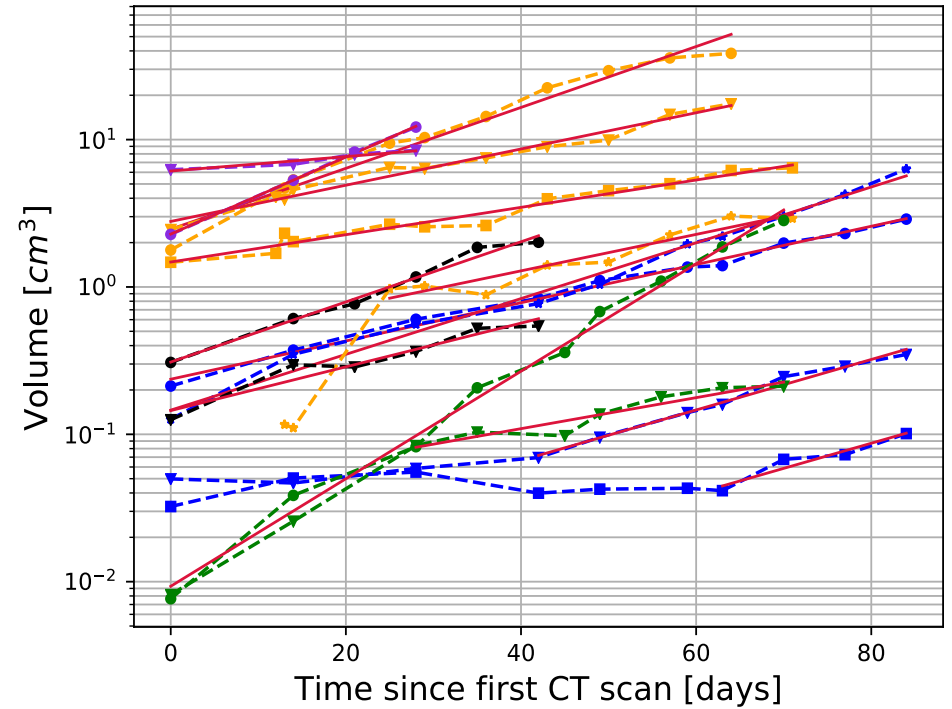
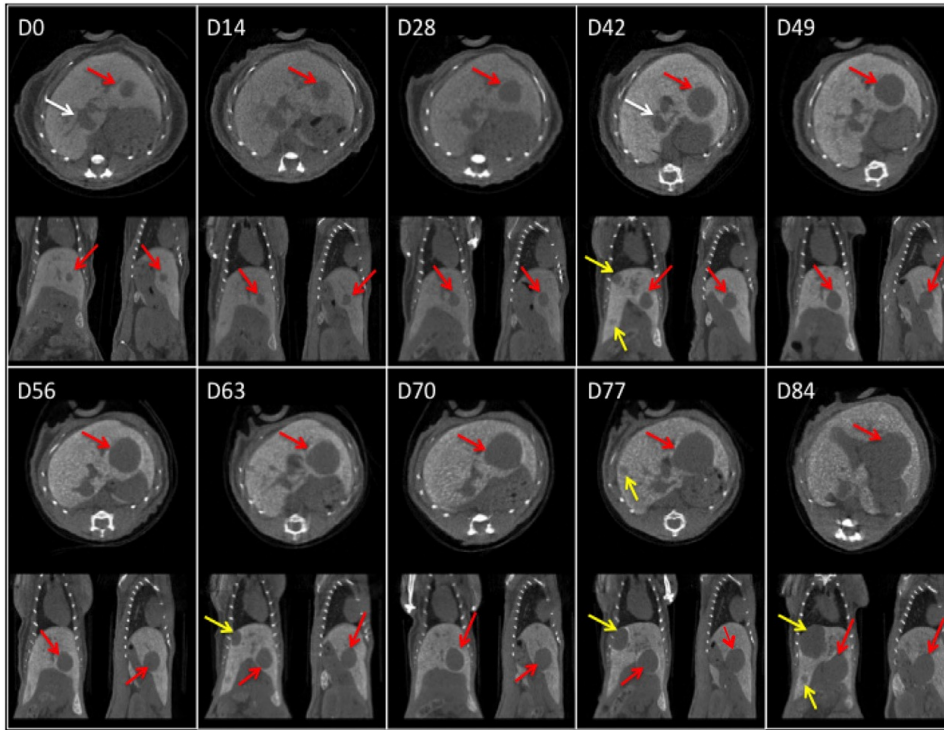
Choice of a hepato-specific contrast agent based on barium nanoparticles to enhance liver contrast over weeks by a factor 2 with regards to the other soft tissues  
→ **Ideal for longitudinal studies !**



– Coronal slices of a mouse imaged before, one day after and three weeks after injection of 100  $\mu$ L/30g of Exitron nano 12000

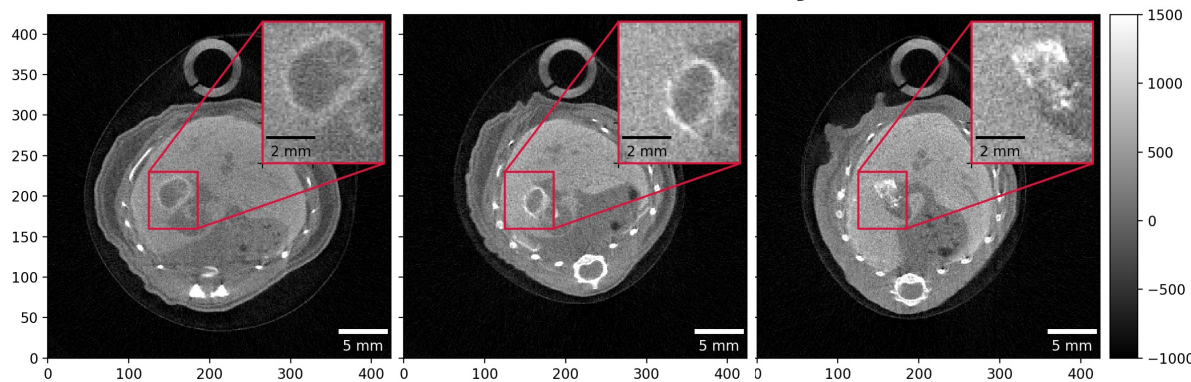
# First longitudinal study of liver tumour development in mice

F. Cassol et al., iScience 21 (2019) 68-83



Follow up of a mouse with an hepatocellular carcinoma for one month

**XPAD3/Si – 180 mGy**



Monitoring of the treatment response to an hepato-specific therapy (Mek + Bcl-XL inhibition\*) for 40 days

\*Y. Fan et al., Hepatology 66 (2017)



Name	Matrix	side ( $\mu\text{m}$ )	Energy thresholds	Peaking time (ns)	Maximum count rates (Mcps/pixel)	Maximum count rates (Mcps/ $\text{mm}^2$ )	Electronics Noise or energy resolution	Power per channel ( $\mu\text{W}$ )	CMOS node
Medipix3 (FPM-SPM) <sup>1</sup>	256x256	55	2	120	2.5	826.5	1.37keV FWHM @ 10keV	7.5	0.13 $\mu\text{m}$
Medipix3 (FPM-CSM) <sup>2</sup>	256x256	55	1+1	120	5.0E-01	163.5	2.03keV FWHM @10keV	9.3	0.13 $\mu\text{m}$
Timepix3 (CERN) <sup>3</sup>	256x256	55	10bits	30	1.6E-03	0.53	4.07keV FWHM at 59.5keV	15.2	0.13 $\mu\text{m}$
Pixirad Pixie II <sup>4</sup>	512x476	55.6	2	300	5.0E-01	161.5	1.45keV FWHM @ 20keV	12.5	0.18 $\mu\text{m}$
Samsung PC <sup>5</sup>	128x128	60	3	NS	NS	NS	68 e- r.m.s.	4.6	0.13 $\mu\text{m}$
Pixirad Pixie III <sup>6</sup>	512x402	62	2	125	1.0	260.1	6.6% FWHM @ 60keV	34	0.16 $\mu\text{m}$
Eiger <sup>7</sup>	256x256	75	1	30	4.2	711.1	121e- r.m.s. (low noise settings)	8.8	0.25 $\mu\text{m}$
PXD23K (AGH) <sup>8</sup>	128x184	75	2	48	8.5	1519.5	89e- r.m.s.	25	0.13 $\mu\text{m}$
X-Counter PC (PDT25-DE) <sup>9</sup>	256x256	100	2	NS	1.2	120	8.3keV FWHM @20keV 10keV FWHM @60keV	NS	NS
PXD18K (AGH) <sup>8</sup>	96x192	100	2	30	5.8	580	168e- r.m.s.	23	0.18 $\mu\text{m}$
FPDR90 (AGH) <sup>8</sup>	40x32	100	2	28	8.5	854.7	106e- r.m.s.	42	90nm
AGH_Fermilab <sup>10</sup>	18x24	100	2	48	NS	NS	84e- (Single pixel), 168e- (Charge summing)	34	40nm
Medipix3 (SM-SPM) <sup>11</sup>	128x128	110	8	120	4.5	375.7	1.43keV FWHM @ 10keV	30	0.13 $\mu\text{m}$
Medipix3 (SM-CSM) <sup>12</sup>	128x128	110	4+4	120	3.4E-01	28.1	2.2keV FWHM @10keV	37.2	0.13 $\mu\text{m}$
XPAD3 <sup>13</sup>	80x120	130	2	150	2.0	118.3	127e- r.m.s.	40	0.25 $\mu\text{m}$
Pilatus 2 <sup>14</sup>	60x97	172	1	110	6.0	202.8	1keV FWHM @ 8keV	20.2	0.25 $\mu\text{m}$
Pilatus 3 <sup>15</sup>	60x97	172	1	110	15.0	507.0	1keV FWHM @ 8keV	20.2	0.25 $\mu\text{m}$
Telesystems <sup>16</sup>	40x40	200	4	300-500	8.0E-01	20	5.36keV FWHM @ 122keV	94.4	0.25 $\mu\text{m}$
Dosepix (CERN) <sup>17</sup>	16x16	220	16	287	1.6	33.9	150 e- r.m.s.	14.6	0.13 $\mu\text{m}$
Siemens PC <sup>18</sup>	64x64	225	2	20	40.0	790.1	NS	NS	NS
Hexitec <sup>19</sup>	80x80	250	14bits	2000	1.0E-03	0.016	800eV FWHM @ 60keV, 1.1keV @ 141keV	220	0.35 $\mu\text{m}$
Philips Chromaix <sup>20</sup>	4x16	300	4	20	38.0	422.2	4.7keV @60keV (1 channel)	3000	0.18 $\mu\text{m}$
Ajat-0.35 (PC) <sup>21</sup>	32x64	350	1	1000	2.2	18.0	4keV FWHM @122keV	390.6	0.35 $\mu\text{m}$
Ajat-0.35 (ADC) <sup>22</sup>	32x64	350	64	1000	4.9E-05	4.0E-04	4keV FWHM @122keV	390.6	0.35 $\mu\text{m}$
CIX 0.2 (Bonn) <sup>23</sup>	8x8	353.6	1	NS	12.0	96	330e- r.m.s. (counting channel)	3200	0.35 $\mu\text{m}$
KTH_Lin_SPD <sup>24</sup>	160 ch.	447.2	8	10-20-40	272.0	1360	1.09keV @ 15keV (measured at 40kcps)	80000	0.18 $\mu\text{m}$
DxRay-Interon <sup>25</sup>	16x16	500	4	10	13.3	53	7keV FWHM @60keV, Min TH20keV	NS	NS
Ajat-0.5 <sup>26</sup>	44x22	500	2	1000-2000	NS	NS	4.7keV @122keV (1 channel)	413.2	0.35 $\mu\text{m}$
Hamamatsu <sup>27</sup>	64 ch.	632.5	5	NS	5.5	13.75	12keV FWHM @ 120keV	NS	NS
IDEAS <sup>28</sup>	64 ch.	894.4	6	50	4.0	5	7keV FWHM @60keV	4200	0.35 $\mu\text{m}$
GE-DxRay <sup>29</sup>	128 ch.	1000	2	30	11.6	11.6	4.75% at 122keV, CZT, 5pF Cin (1 Channel noise= 4.8keV FWHM)	2100	0.25 $\mu\text{m}$
BNL <sup>30</sup>	64 ch.	1241.0	5	40-80-160-320	4.0	5.5	5.5keV at 40ns peaking time/2.15keV at 320ns peaking time	4700	0.25 $\mu\text{m}$



# Hybrid pixels: many spin-offs

2003



[www.dxray.com](http://www.dxray.com)

2006

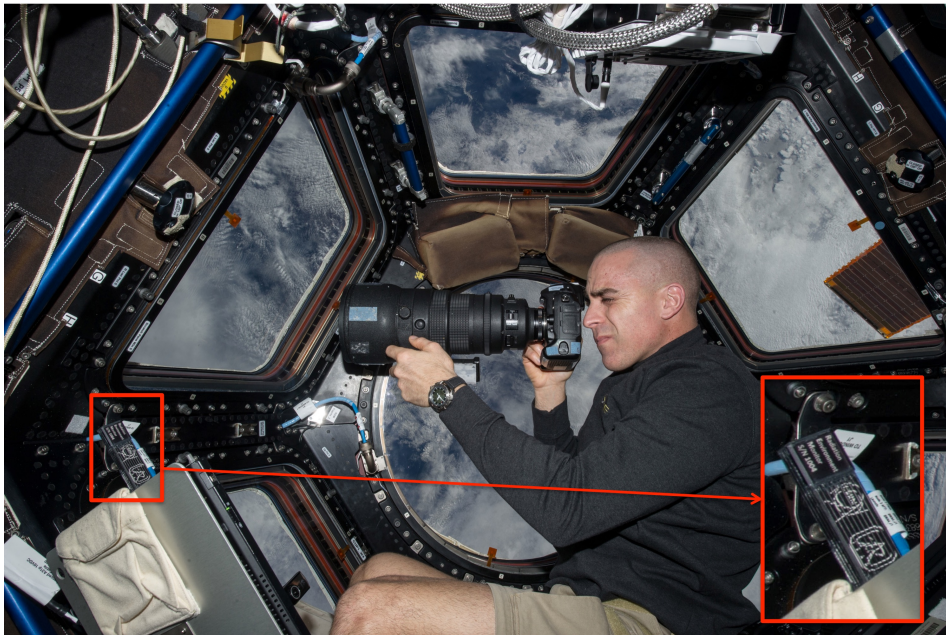


[www.dectris.com](http://www.dectris.com)


2010



[www.imxpad.com](http://www.imxpad.com)



2006



Pixelated X-Ray Detectors  
[www.xray-imatek.com](http://www.xray-imatek.com)

2011



Chromatic Photon Counting  
[pixirad.pi.infn.it](http://pixirad.pi.infn.it)

2011



AMSTERDAM SCIENTIFIC INSTRUMENTS  
[www.amscins.com](http://www.amscins.com)

2012



IMAGING THE UNSEEN  
[www.advacam.com](http://www.advacam.com)

2003



detect image identify  
[www.kromek.com](http://www.kromek.com)

2007



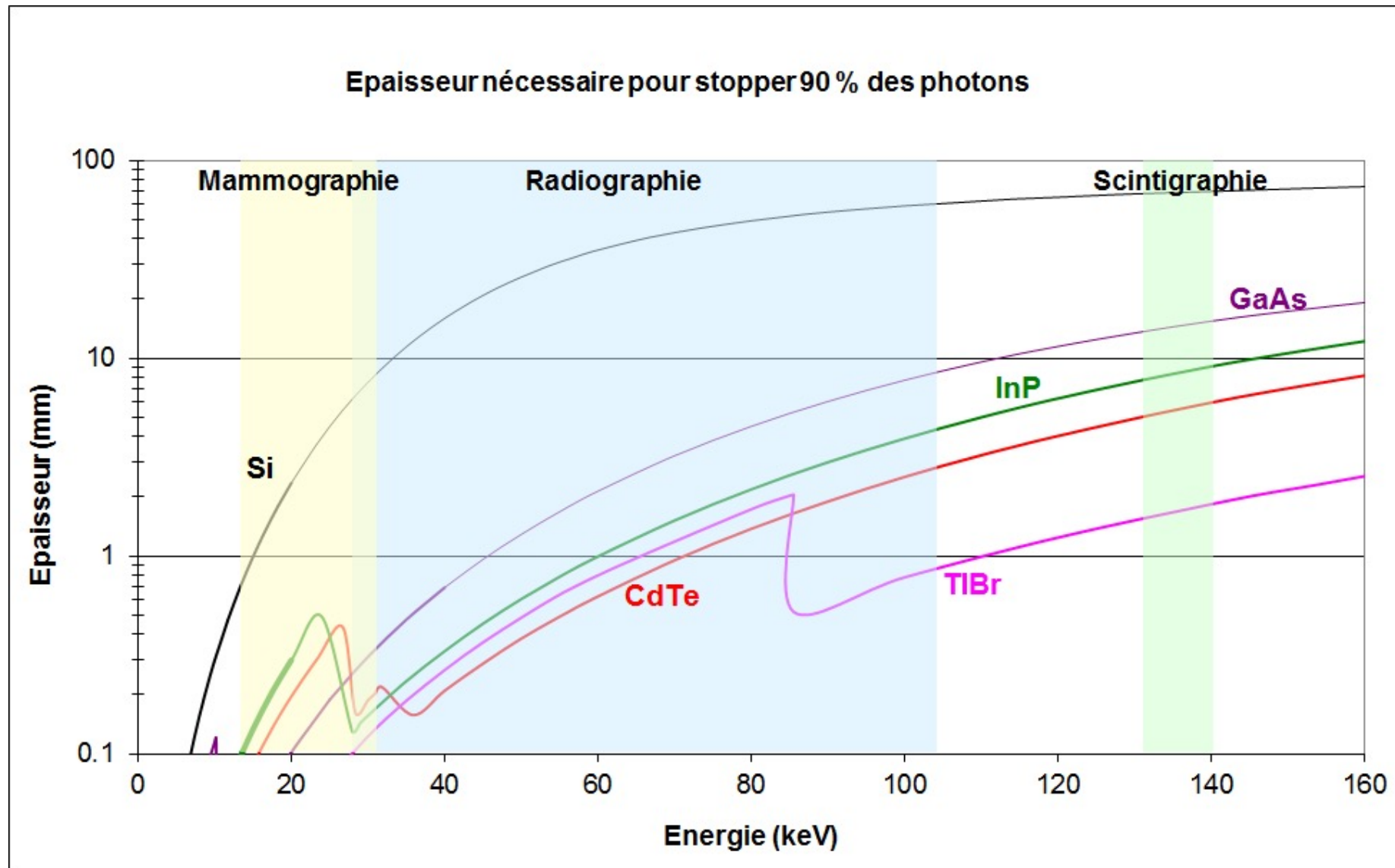
Medipix All Resolution System  
[www.marsbioimaging.com](http://www.marsbioimaging.com)

2011



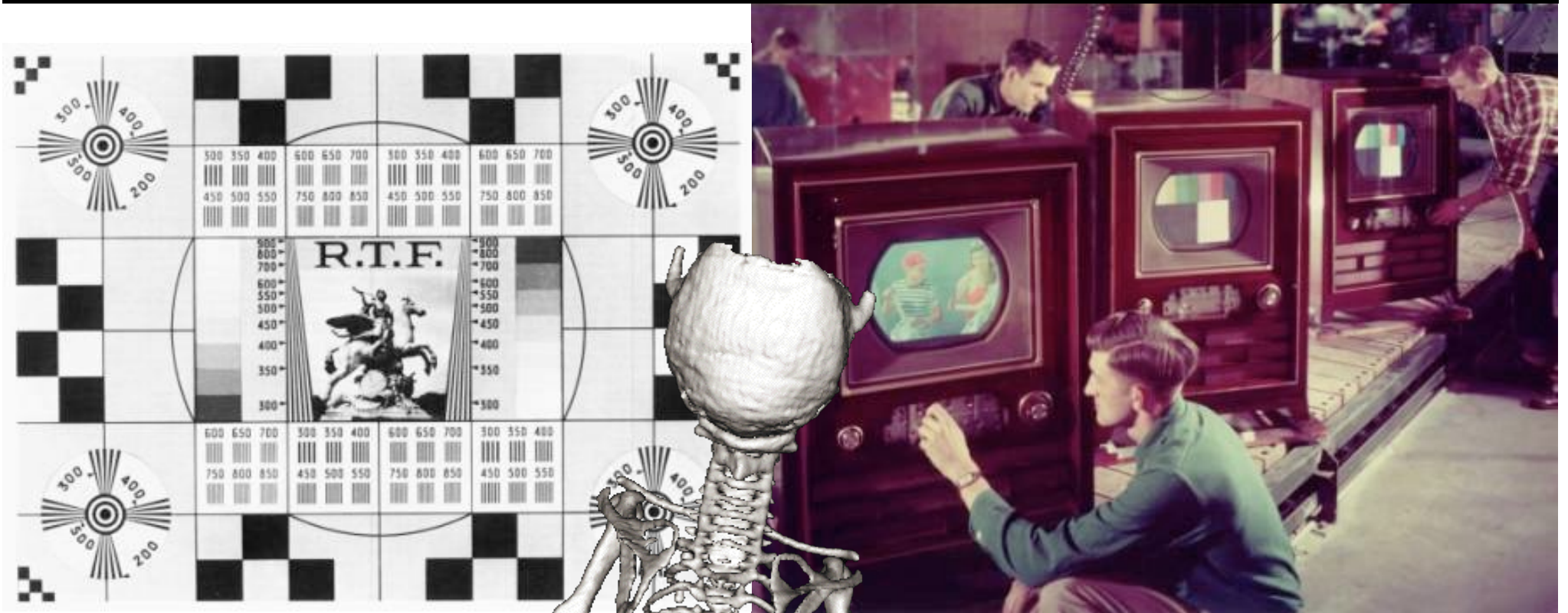
X-RAY IMAGING EUROPE  
[www.xi-europe.com](http://www.xi-europe.com)

# Capteurs pour la détection directe de rayons X

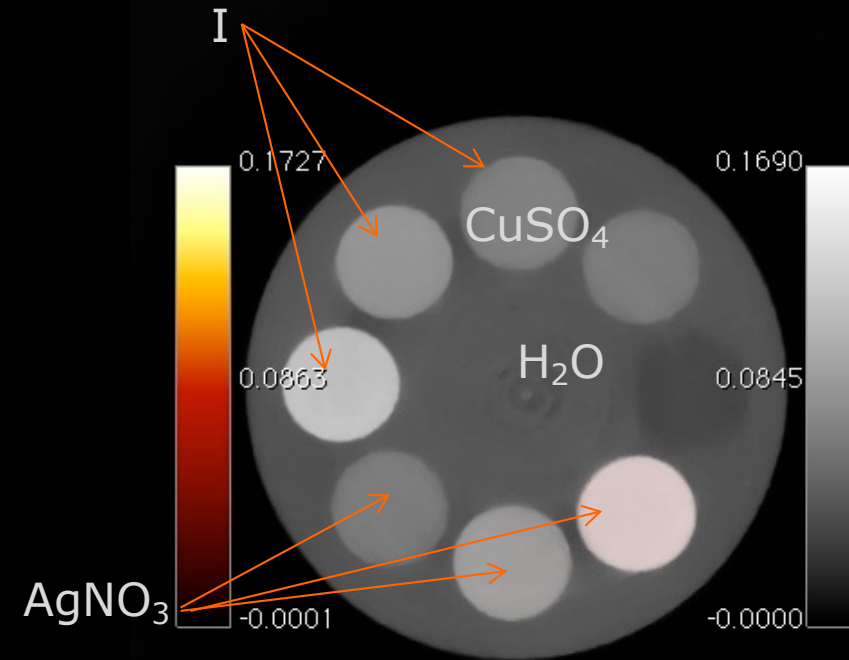
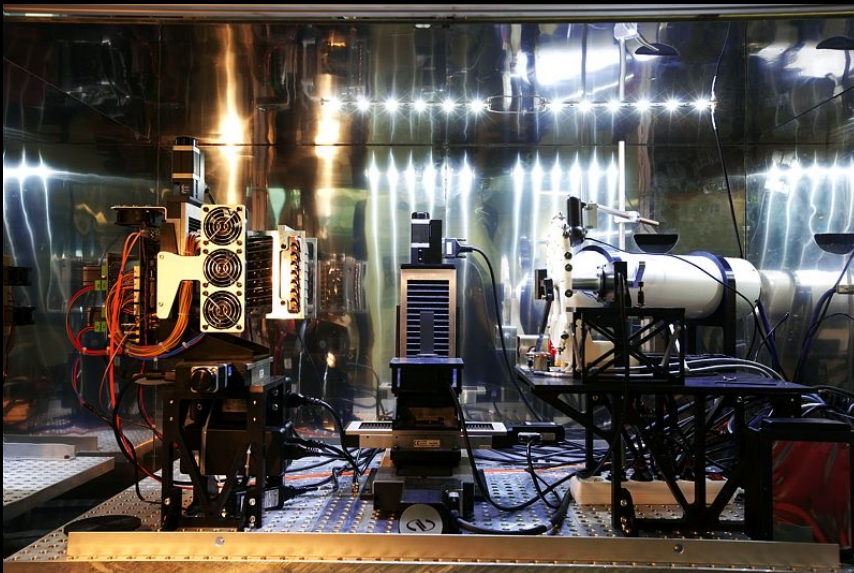
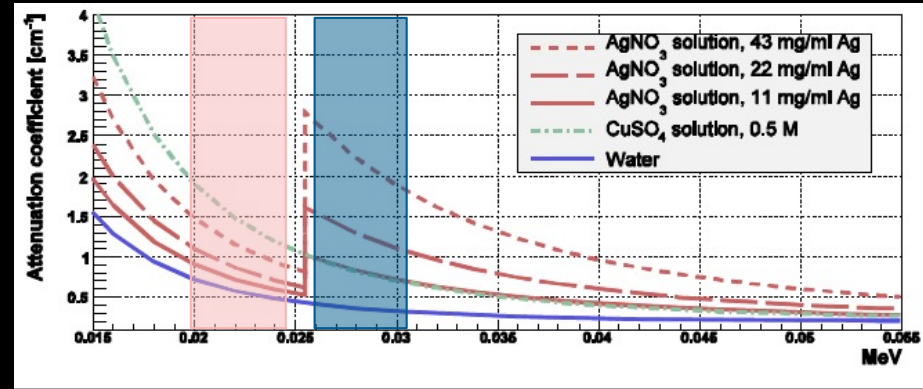


Courtesy: E. Gros d'Aillon, CEA-LETI

# CT spectral : du noir et blanc à la « couleur » grâce aux pixels hybrides

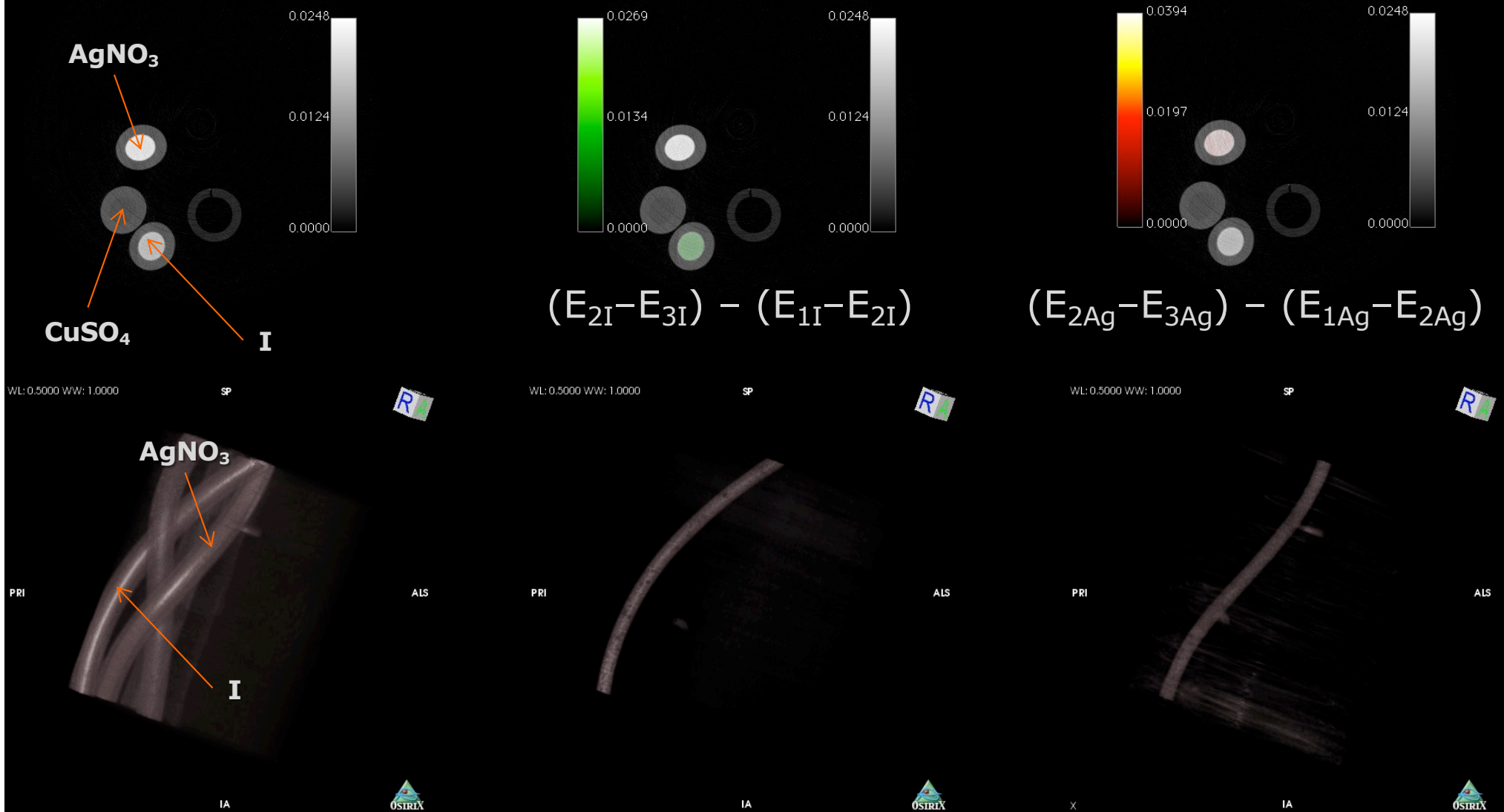


# CT spectral : du noir & blanc à la couleur



# CT spectral : du noir & blanc à la couleur

CT standard      Imagerie au K-edge de l'iode et de l'argent



Cassol *et al.*, IEEE Trans. Nucl. Sci. **60** (2013) 103

# CT spectral: une nouvelle modalité intrinsèquement anatomo-fonctionnelle

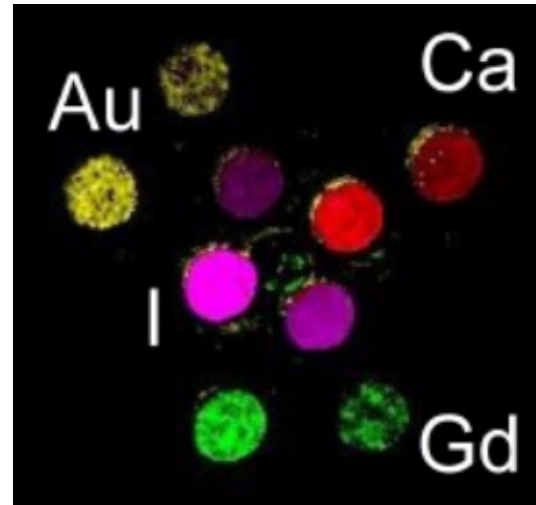
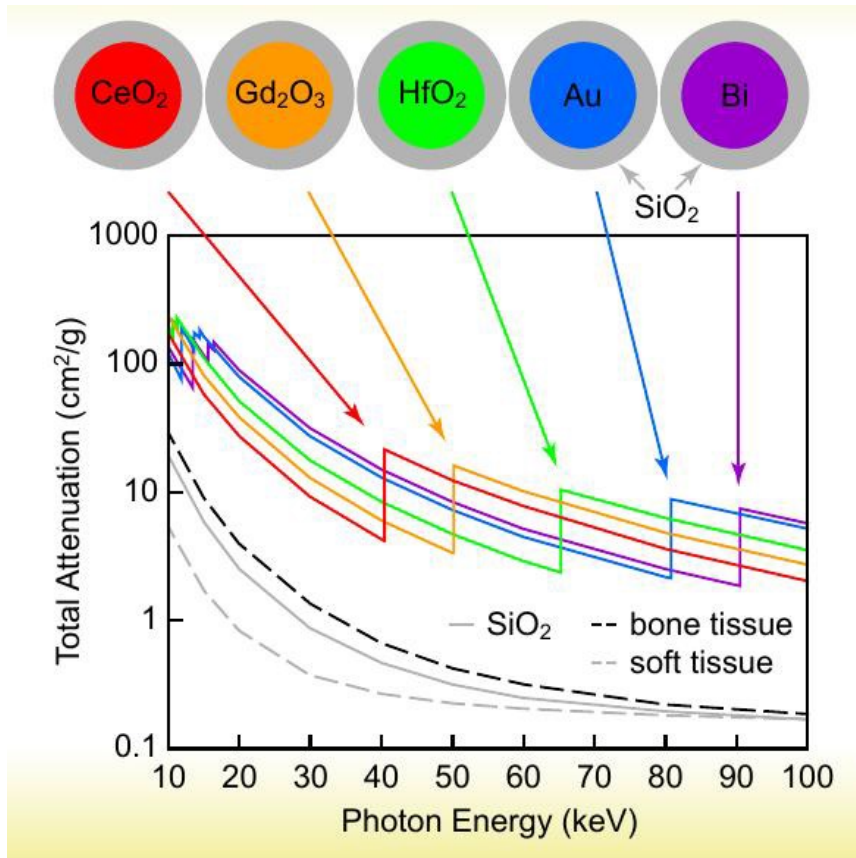


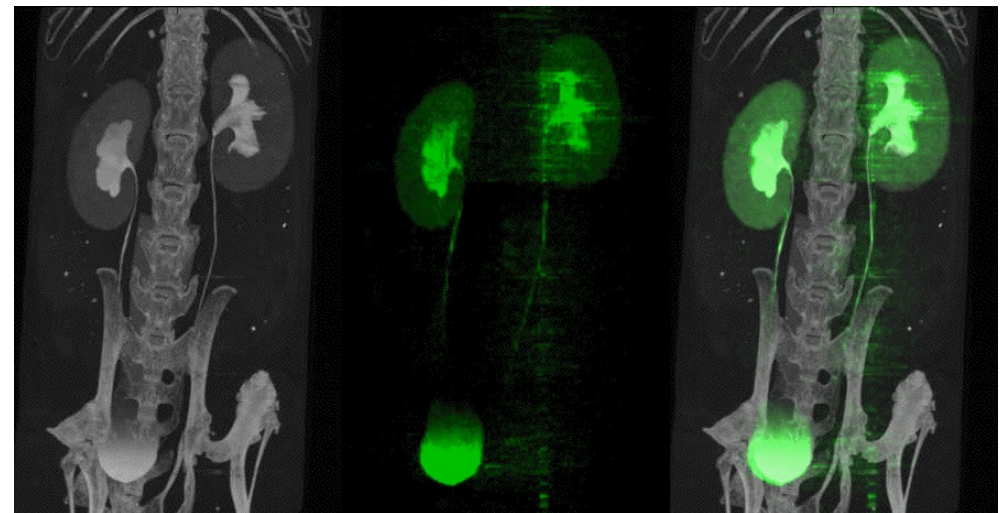
Image de MARS utilisant une gamme d'énergie clinique (CdTe-Medipix)

courtesy: A Buttler, Medipix Collaboration, Mars Bio-Imaging

LE Cole et al. *Nanomedicine* **10** (2015) 321

Imagerie au K-edge de l'iode utilisant des pixels composites avec le détecteur XPAD3

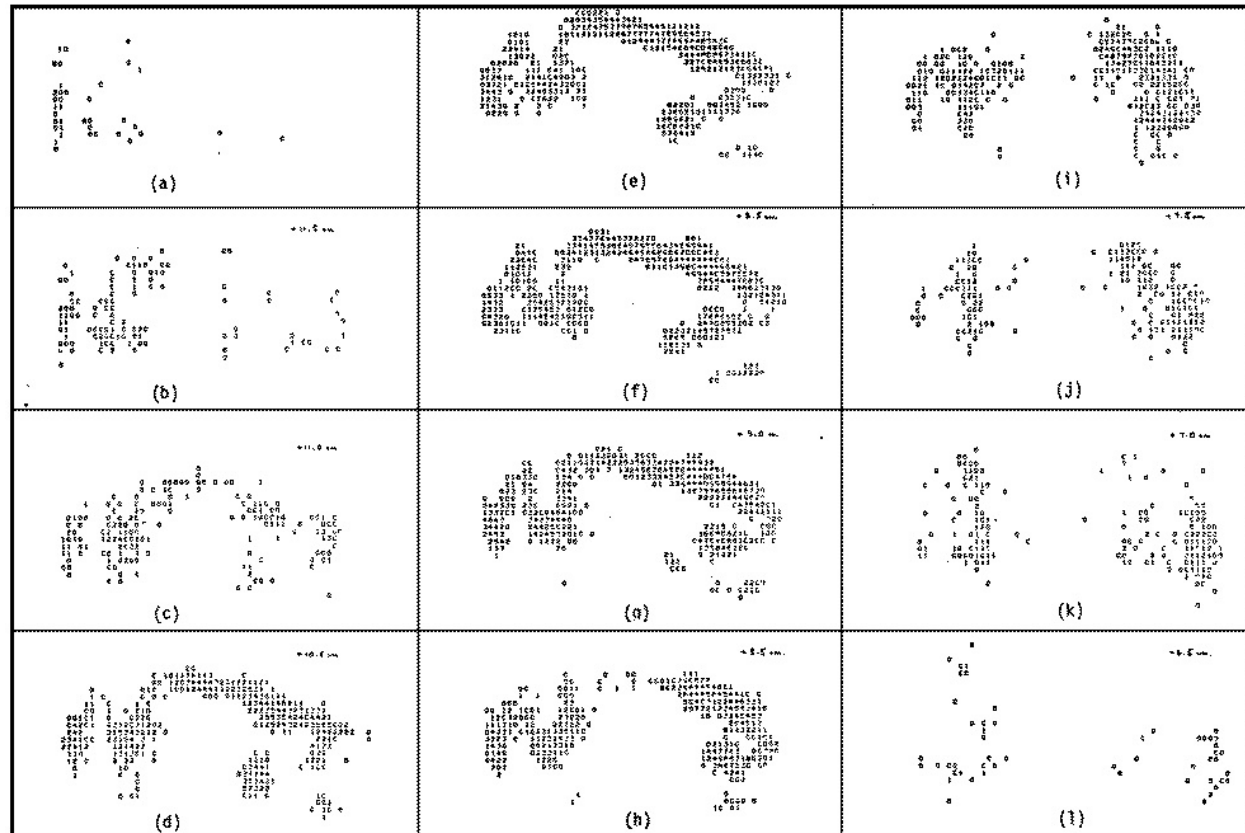
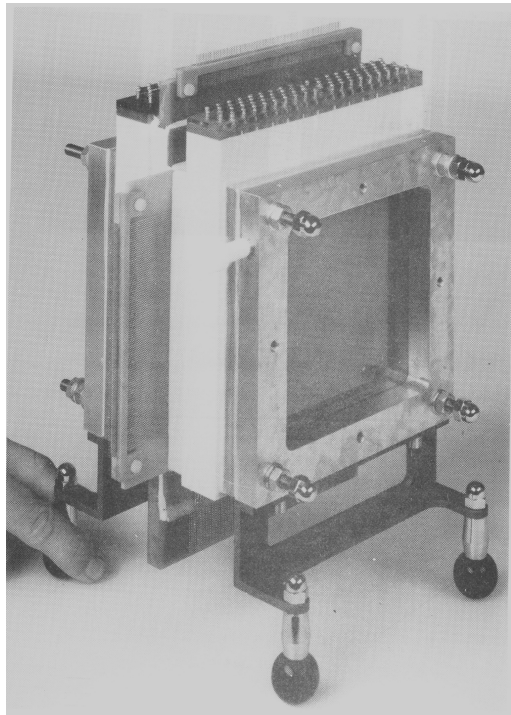
source: thèse Carine Kronland-Martinet



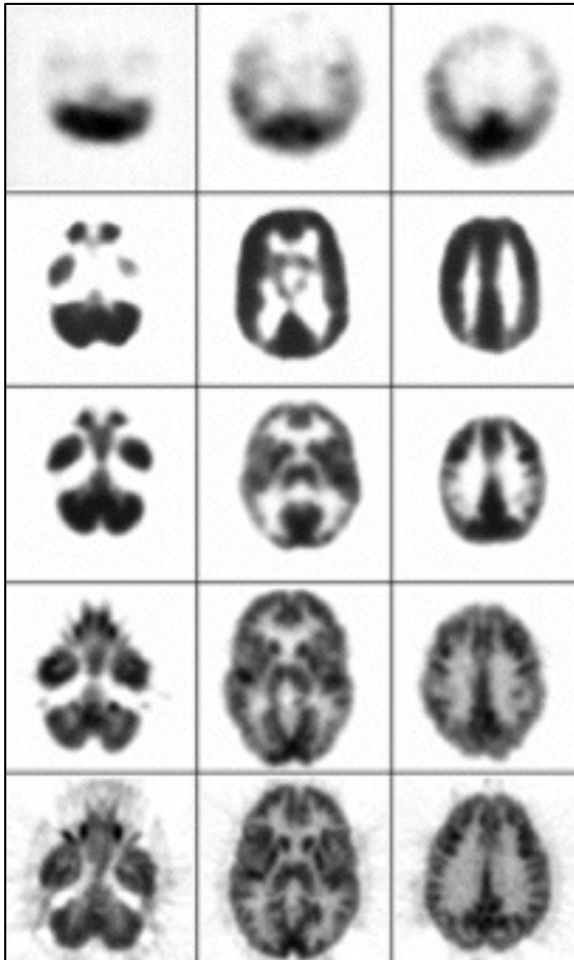
# Tomographie par émission de positons: premiers pas au CERN



1978: High Density Avalanche Chamber (HiDAC)  
(A Jeavons, DW Townsend)



# Progrès continu en instrumentation



PET III 1975

ECAT II 1977

NeuroECAT 1978

ECAT 931 1985

ECAT EXACT HR+ 1995



# Progrès techniques en TEP

	<b>BGO</b>	<b>LSO</b>	<b>GSO</b>
Densité [g/cm <sup>3</sup> ]	7.13	7.4	6.7
Z effectif	74	66	61
Decay [ns]	300	35-45	30-60
ph/MeV	8200	28000	10000
% NaI(Tl)	15	75	25



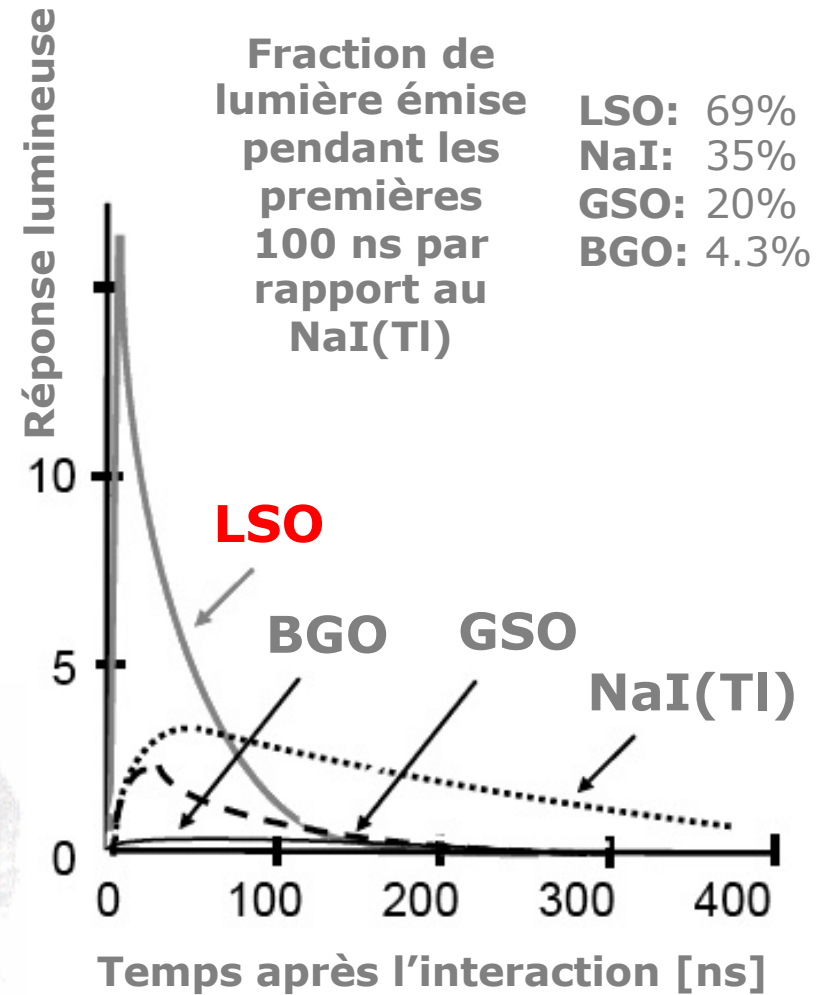
3DRP



FORE+OSEM



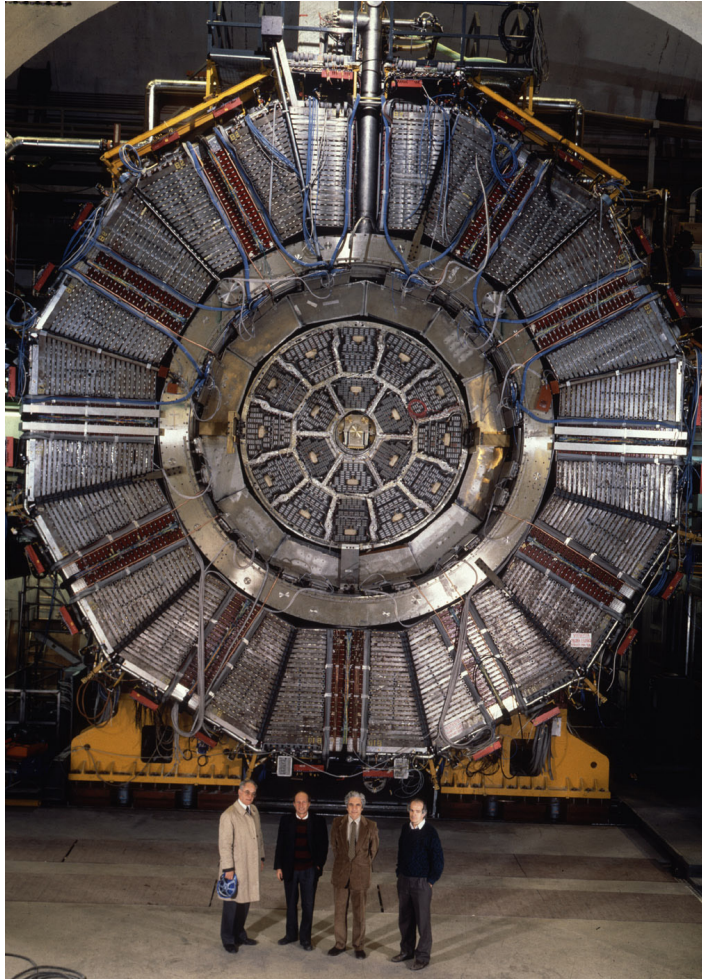
FORE+AWOSEM



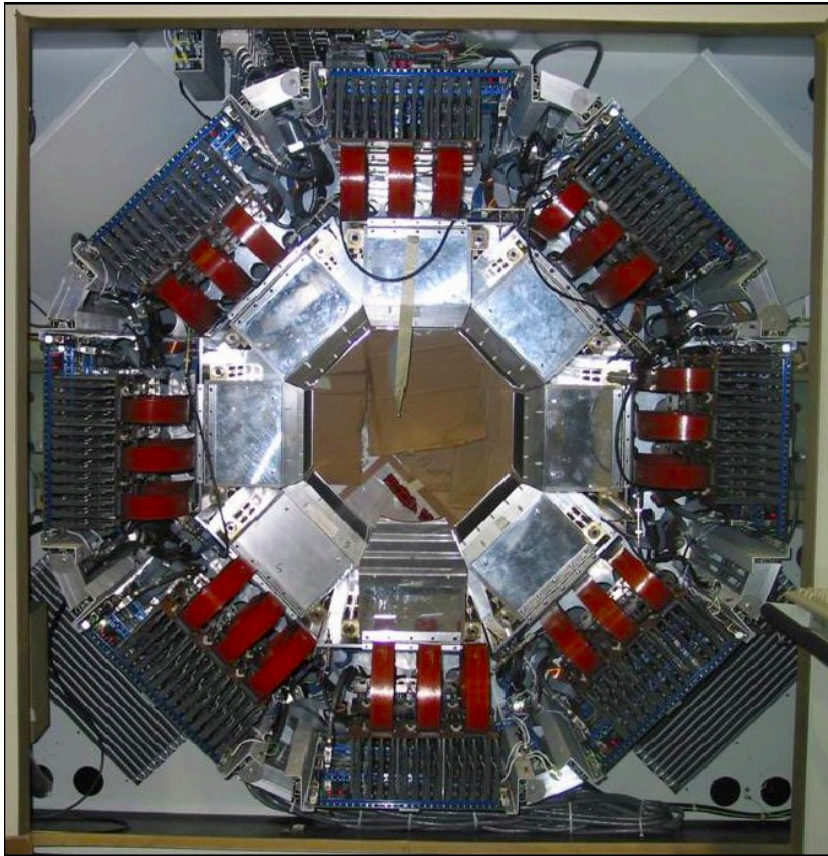
- ✓ Détecteurs
- ✓ Corrections de données
- ✓ Reconstruction d'images

Courtesy: DW Townsend, UPMC

# Application sociétale de la physique des particules

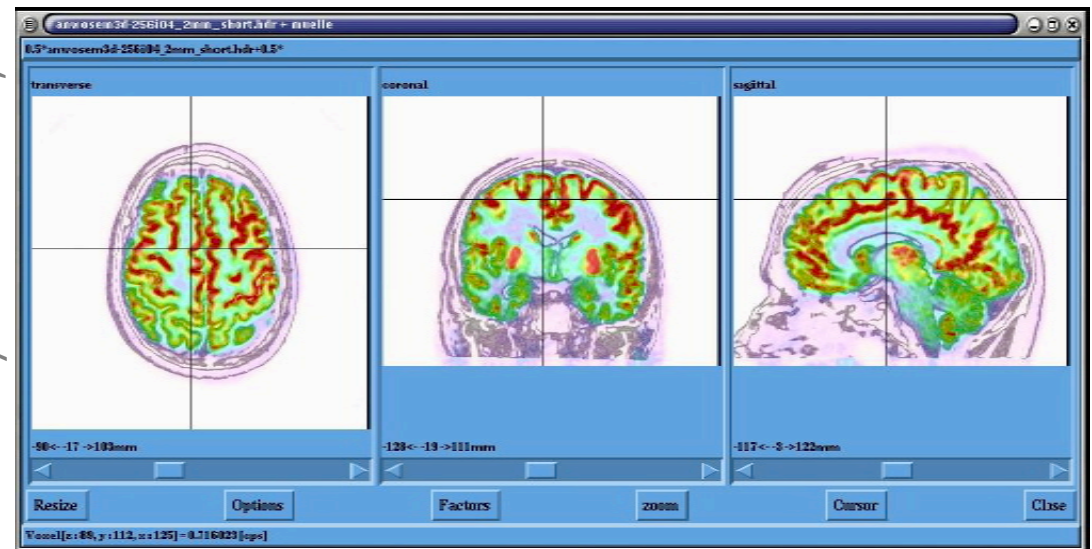
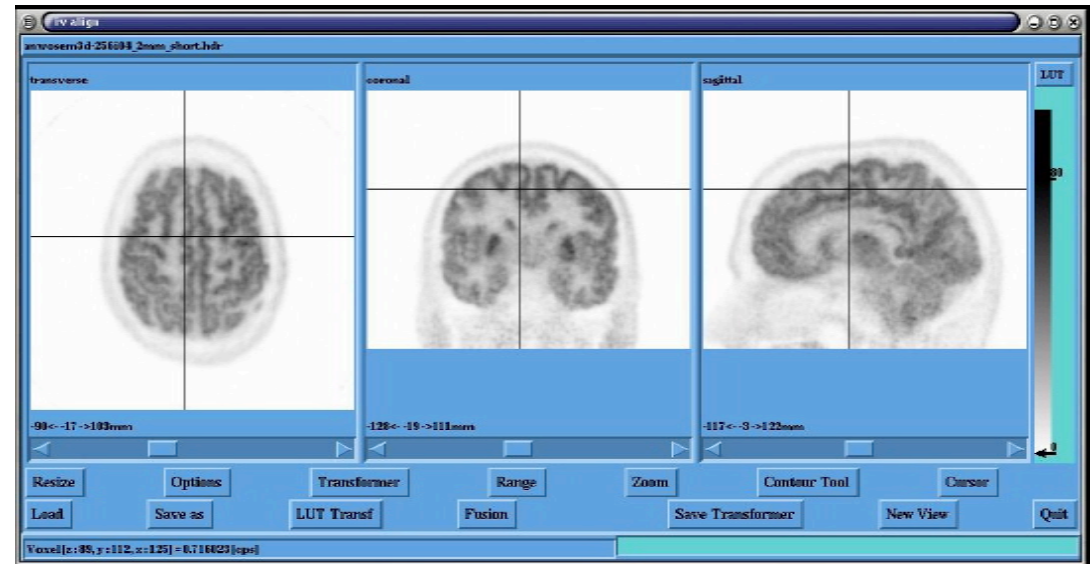


# High Resolution Research Tomograph (HRRT)



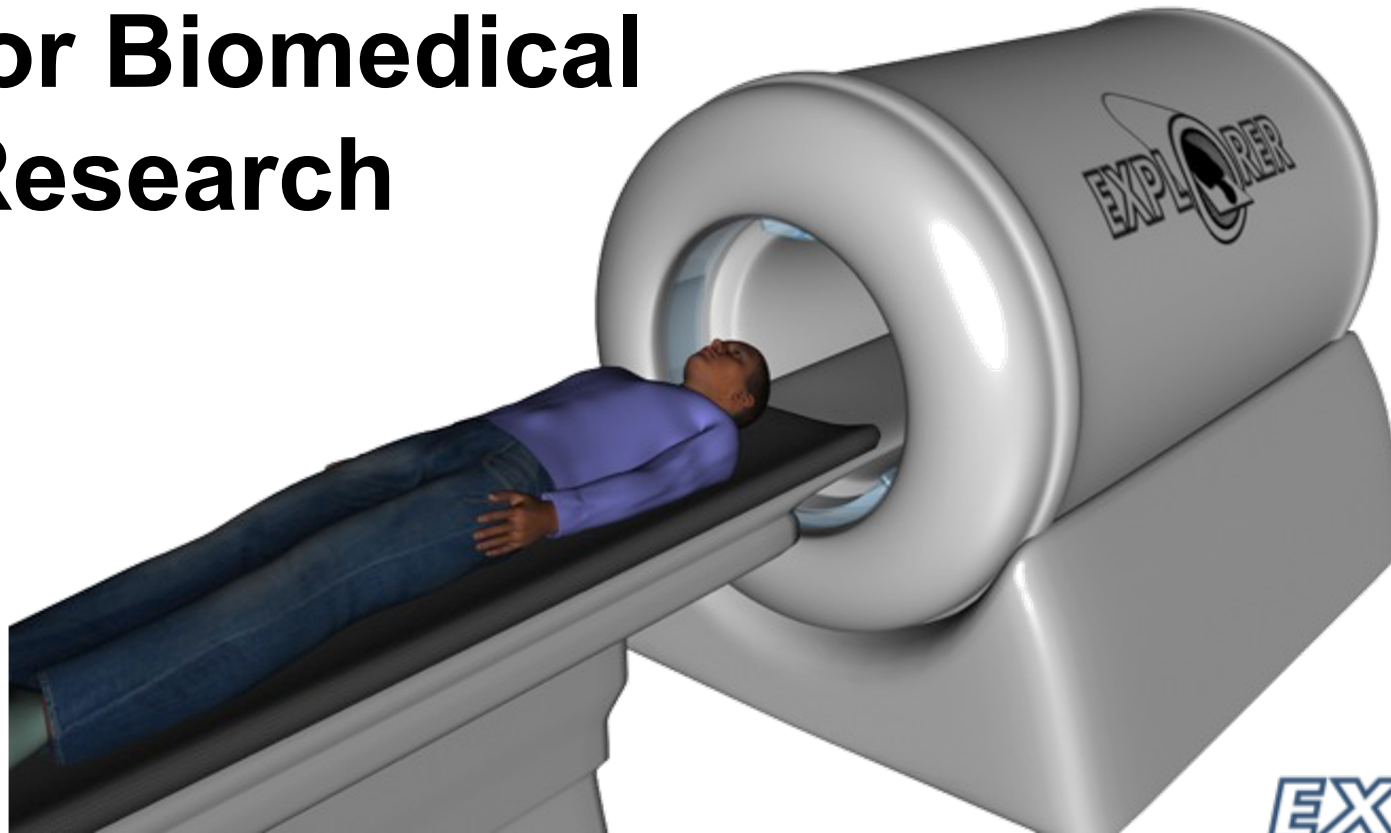
- LSO/GSO phoswich
- 153600 cristaux
- 1120 PMTs

Courtesy: K. Wienhard, Köln



40 min FDG fusionnée avec IRM-T1

# EXPLORER: A Total-Body PET Scanner for Biomedical Research



Sensitivity: x 40  
Low dose: ~ SFO-LHR transatlantic flight

[EXPLORER.ucdavis.edu](http://EXPLORER.ucdavis.edu)

# EXPLORER is Completed!

System:

Ring diameter: 78.6 cm  
Transaxial FOV: 68.6 cm  
Axial FOV: 194.8 cm



# of crystals: 564,480  
# crystal blocks: 13,440  
# of SiPMs: 53,760

# EXPLORER First Human Images

1 min scan, 81 min p.i.



20 min scan, 82 min p.i.

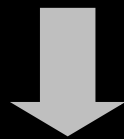


61-yo male, 65 kg; 164 cm; 7.8 mCi injected  
Credit: Zhongshan Hospital; Shanghai

# Anatomie + Fonction



TDM



Anatomie

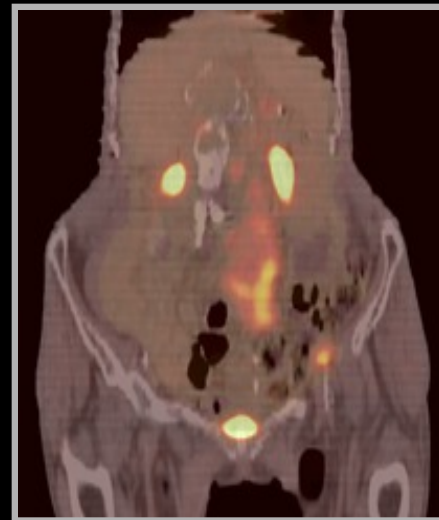
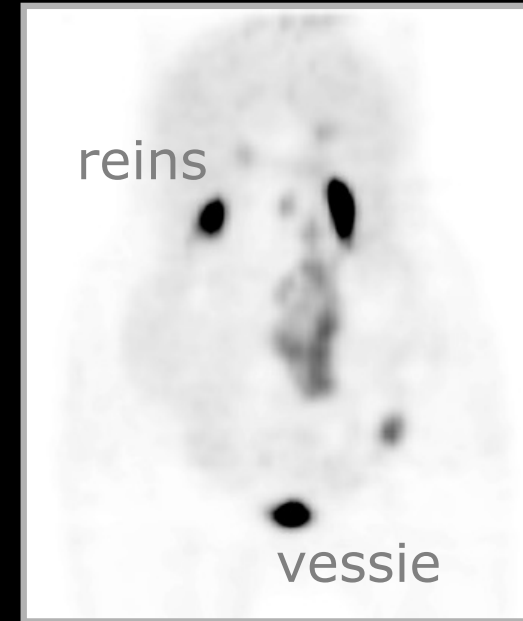
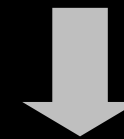


Image fusionnée



TEP

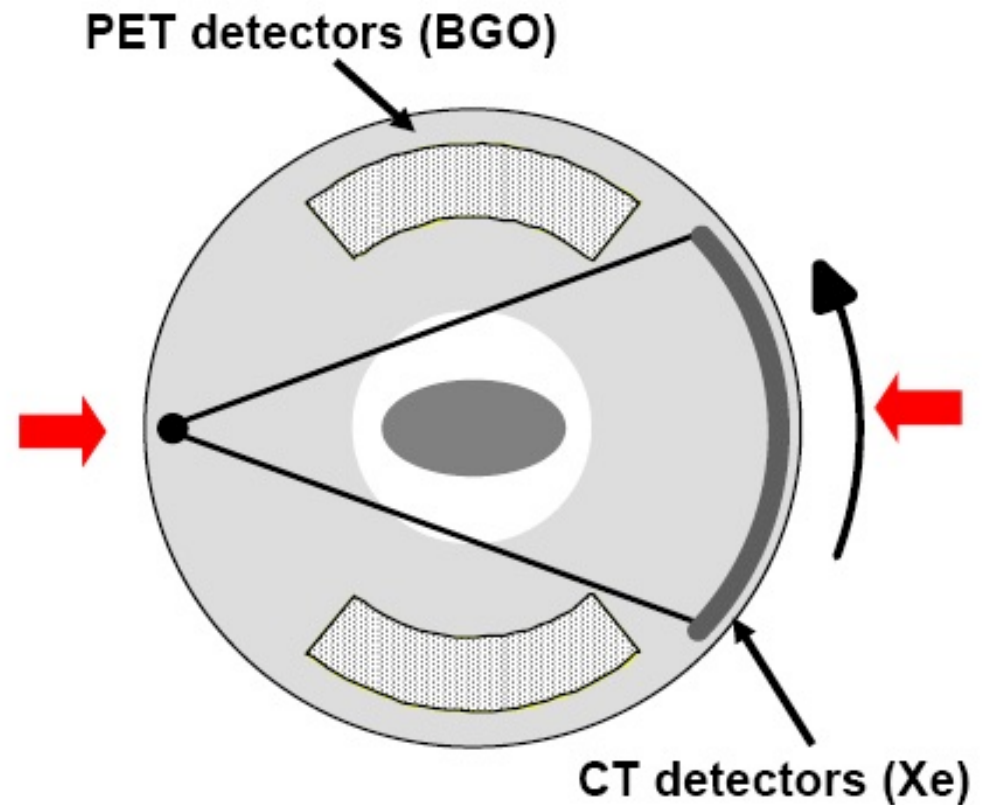
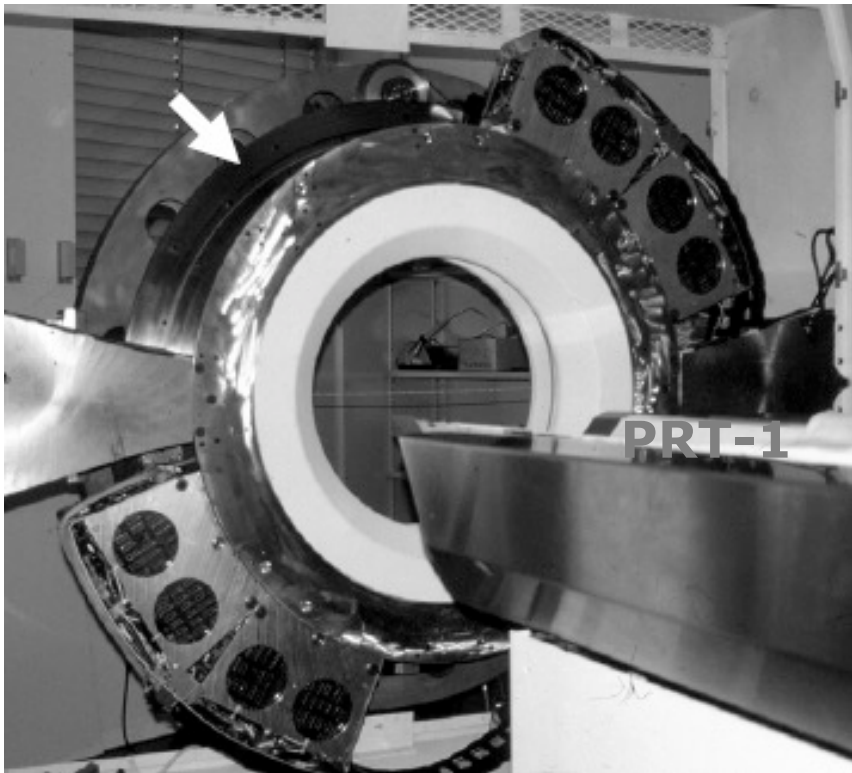


Fonction

Courtesy: DW Townsend, UPMC

# Invention du TEP/CT : une révolution médicale doublée d'une évolution technique

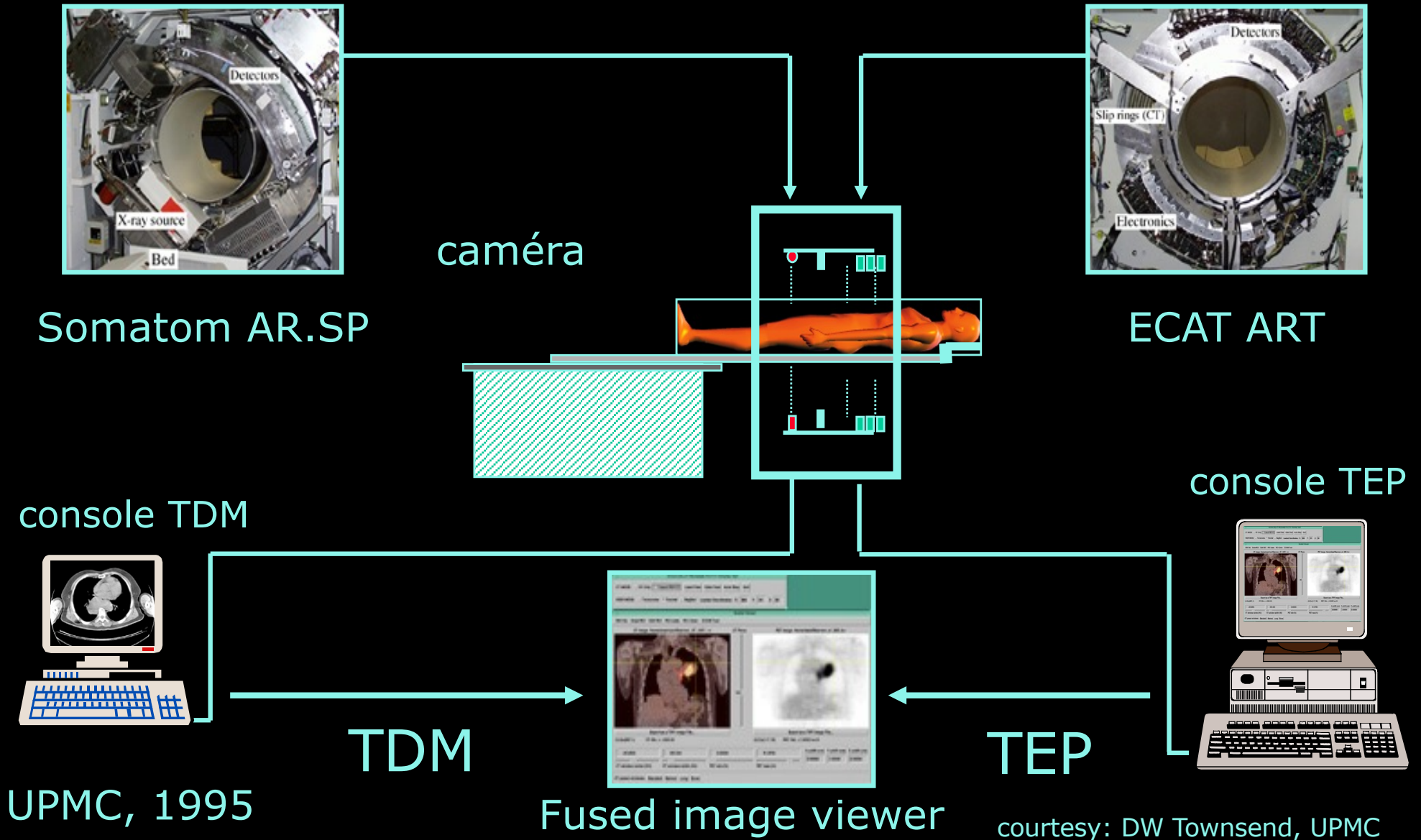
1991: Concept du TEP/CT, DW Townsend (HUG)



courtesy: DW Townsend, UPMC



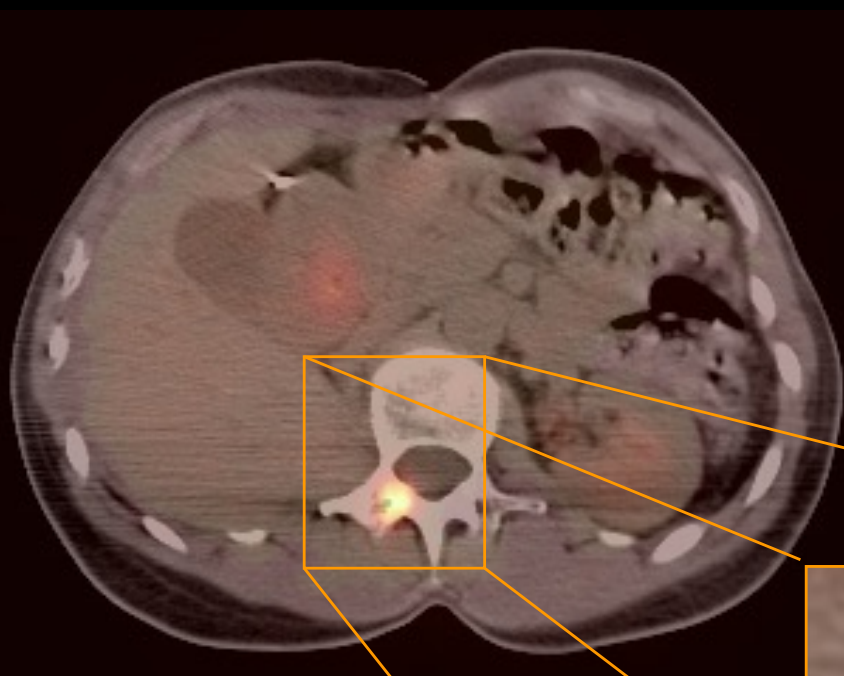
# TEP/TDM prototype design





CT: 160 mAs; 130 KV<sub>p</sub>; pitch 1.6; 5 mm slices

PET: 6.3 mCi FDG; 3 x 10 min; 3.4 mm slices



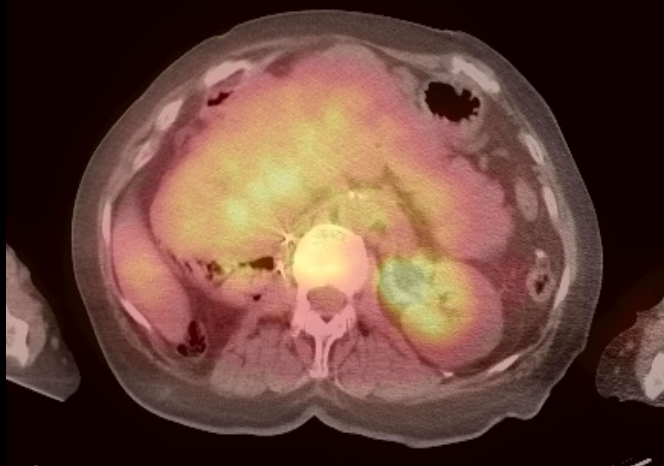
40 year-old woman with multiple endocrine syndrome (MEN-1) and history of malignant pheochromocytoma

MIBG scan one year ago showed right adrenal lesion; adrenal resected but no tumor found. PET suggested a lesion in the adrenal resection bed but PET/CT showed lesion located in spine.



UPMC, 1998

courtesy: DW Townsend, UPMC

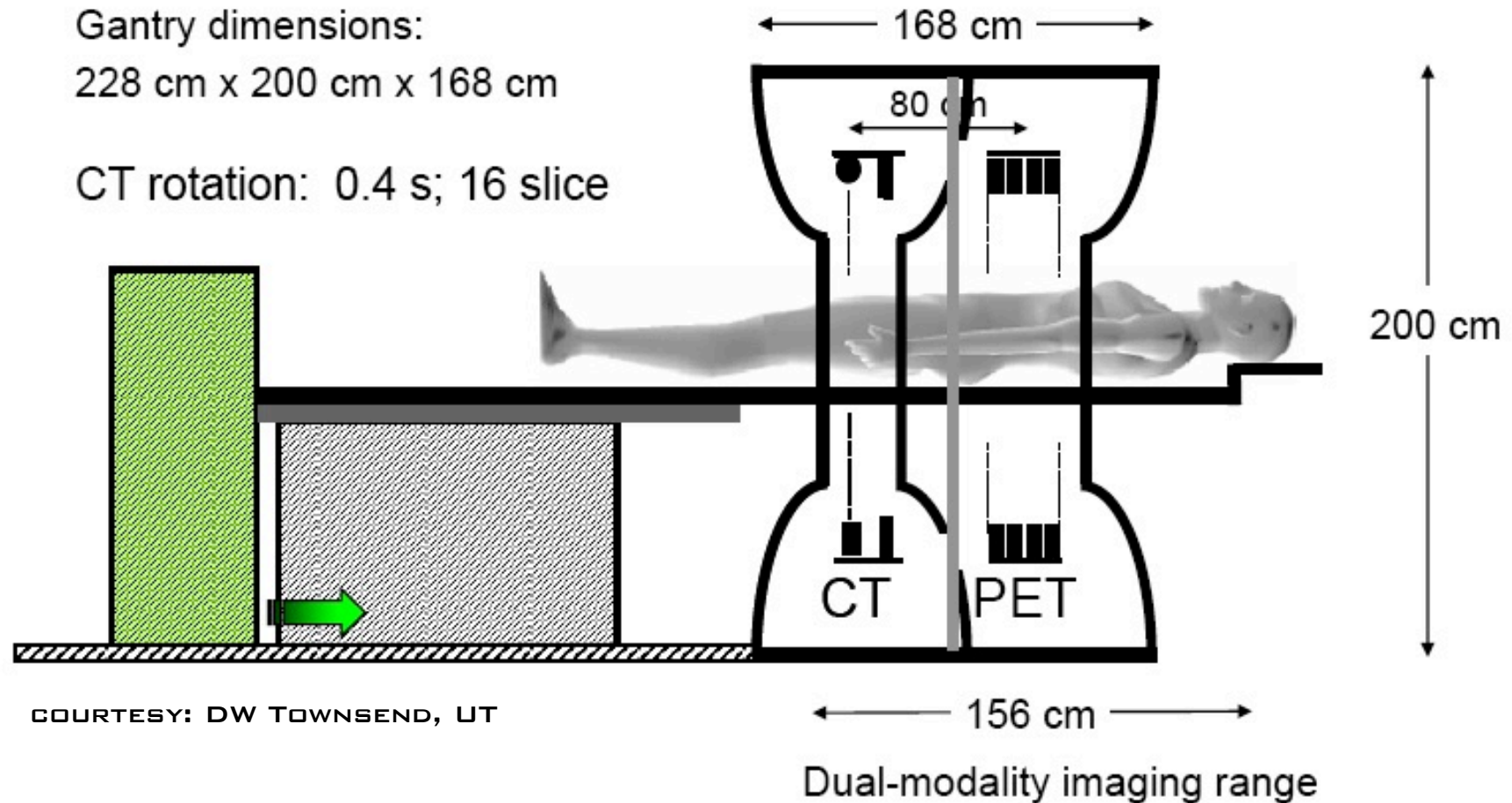


TIME MAGAZINE DEC  
2000



De la physique au détecteur – IN2P3 – Villa Clythia, Fréjus – 22-26 novembre 2021

# Design typique d'un scanner TEP/CT clinique



- 2001: premier scanner TEP/CT commercial installé à Zurich par GE
- 2005: plus de 650 scanners TEP/CT installés, 95% des ventes de scanners TEP

# Caméras hybrides TEP/CT



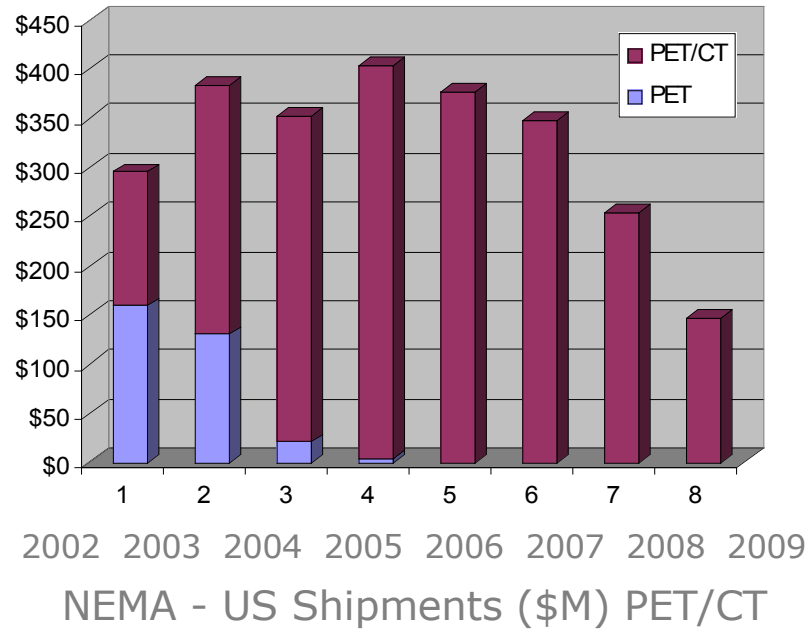
Discovery IQ, GE



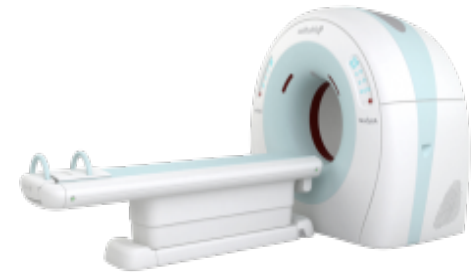
Gemini, Philips



Biograph, Siemens



uMI 510, United Imaging



AnyScan, Pozitron Teknik



Celesteion, Toshiba



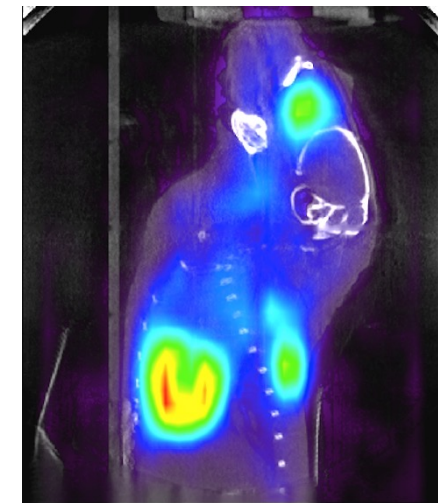
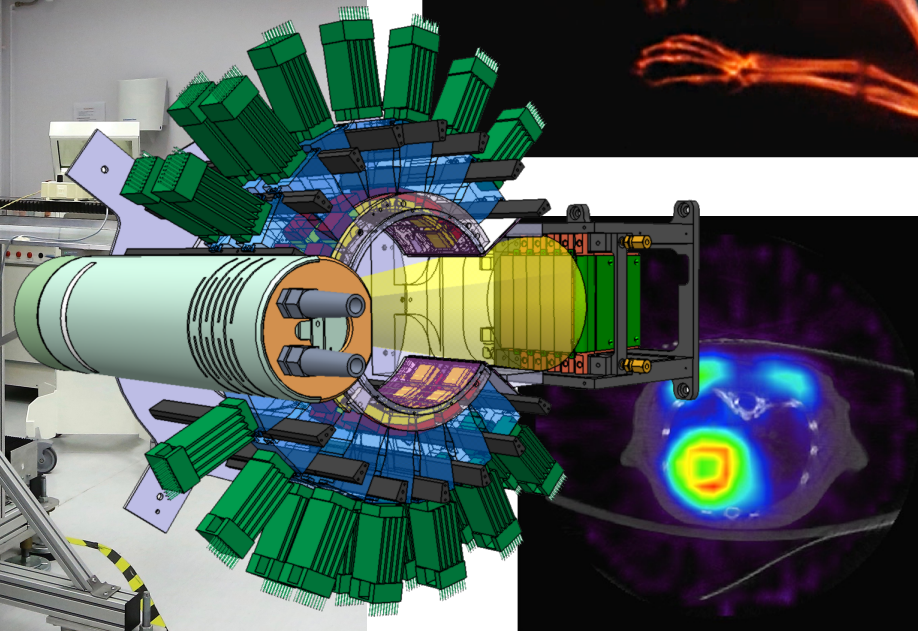
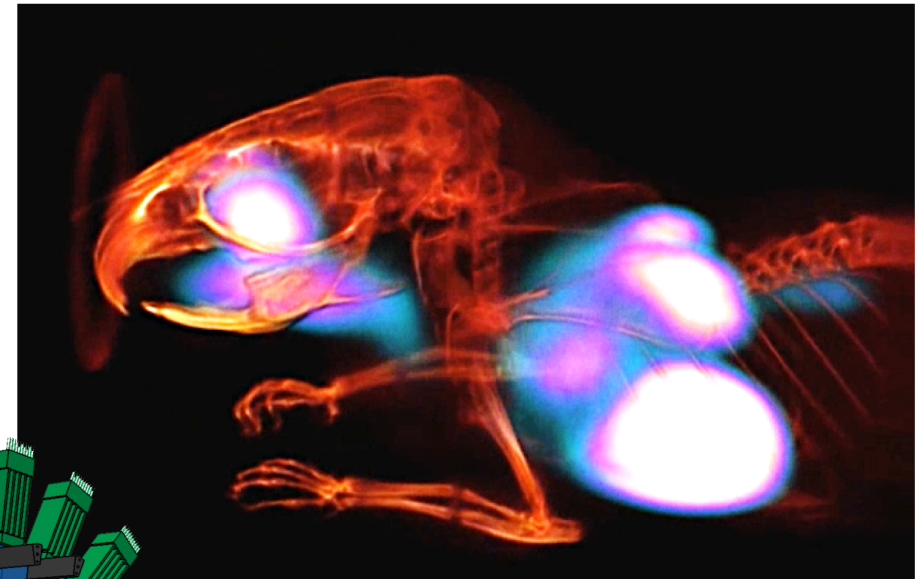
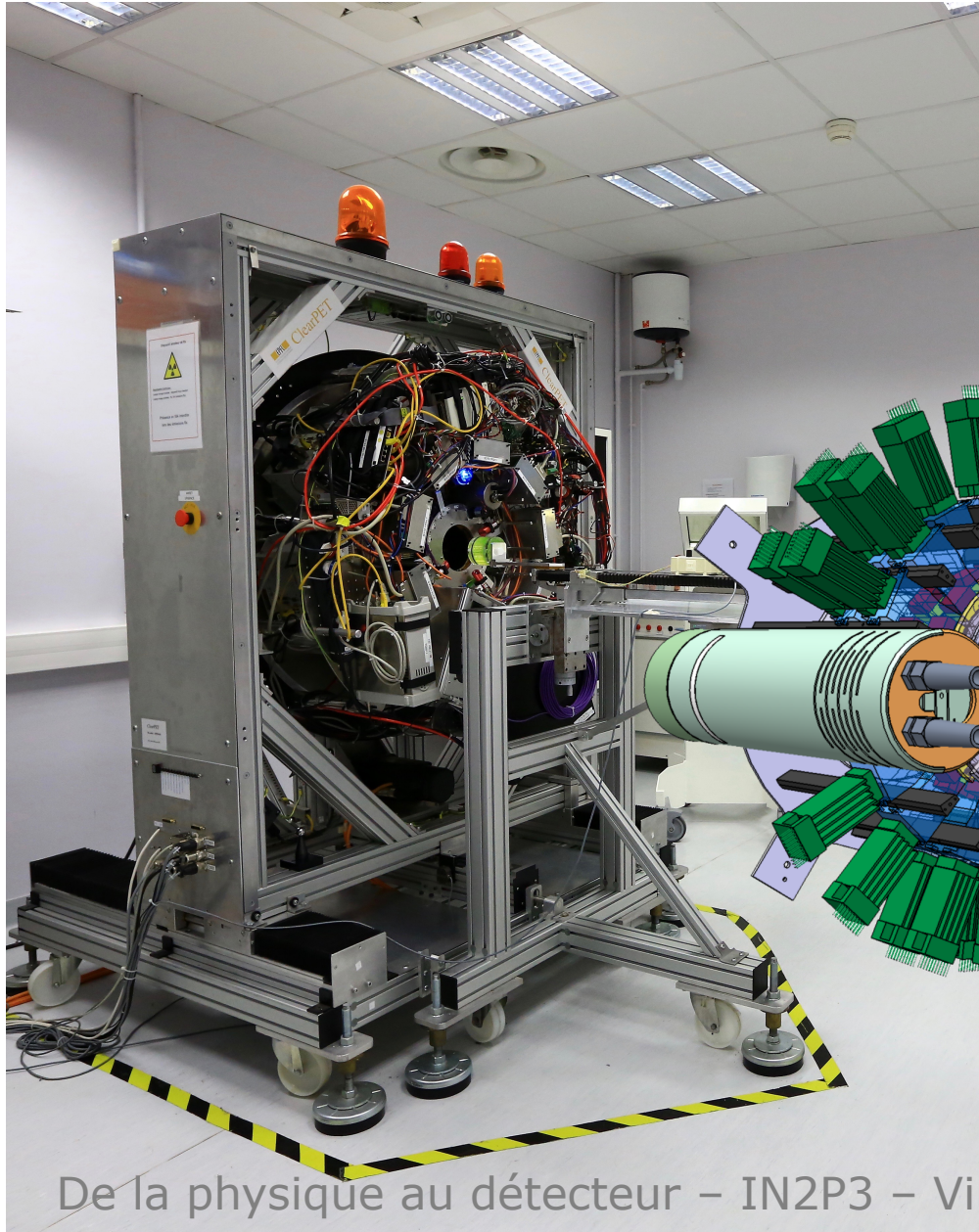
SceptreP3, Hitachi

courtesy: D.W. Townsend, UT

# TEP/CT simultané: preuve de concept avec le prototype ClearPET/XPAD

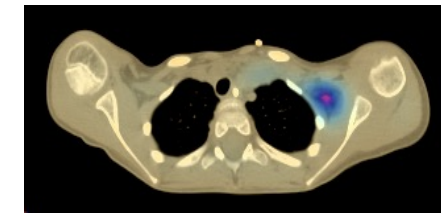
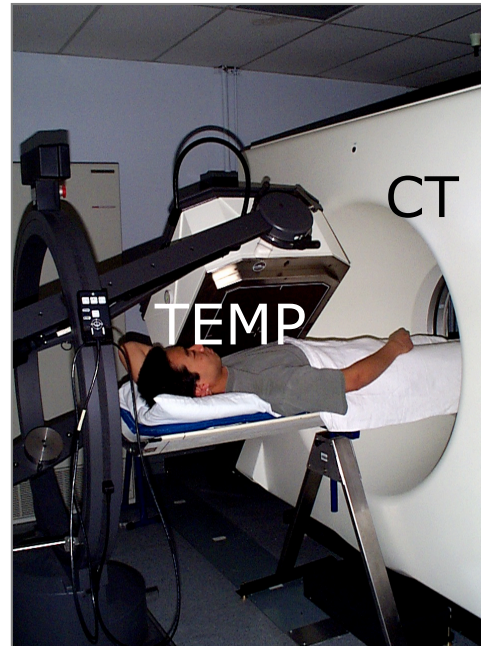
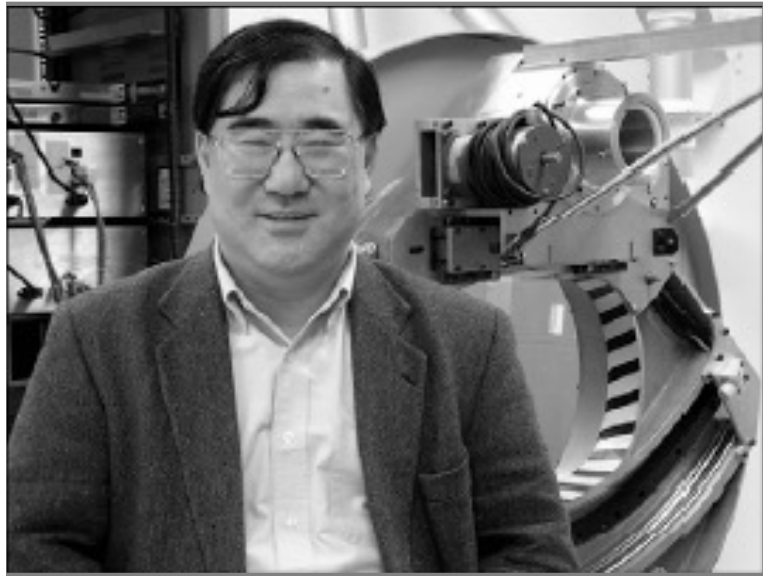


M Hamonet et al., Proc. IEEE NSS/MIC 2016



De la physique au détecteur – IN2P3 – Villa Clythia, Fréjus – 22-26 novembre 2021

# Caméra hybride TEMP/CT : Bruce H. Hasegawa



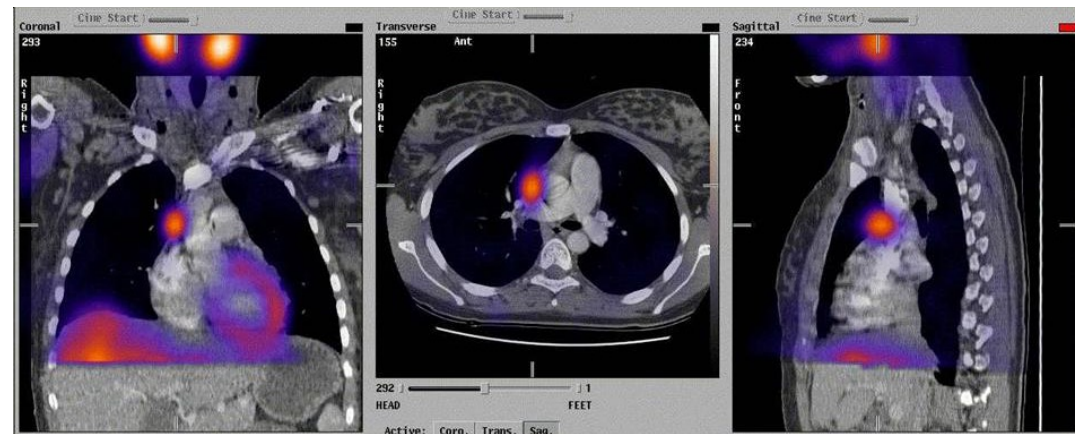
TEMP/CT

Courtesy: D.W. Townsend, UT

“CT is potentially more valuable for SPECT than for PET”

Dale L. Bailey. Is PET the Future of Nuclear Medicine ?  
Eur J Nuc Med & Mol Imag 30  
(2003) 1045-1046

$$1 + 1 = 4$$





# Caméras précliniques



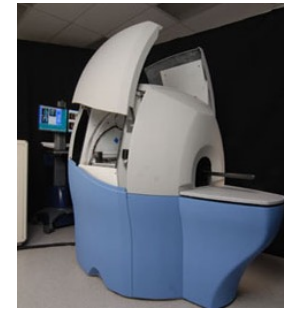
Module TEP



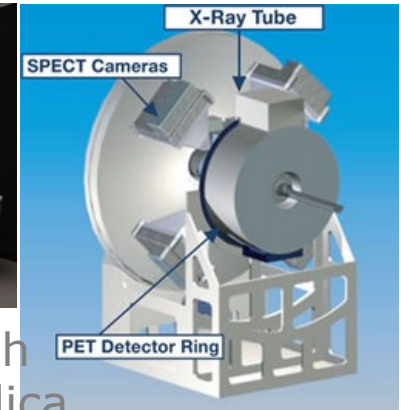
Module TEMP



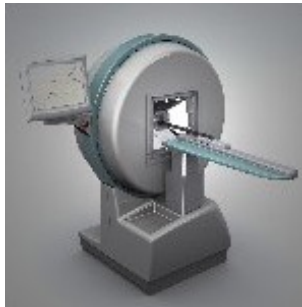
Module CT



FLEX Triumph  
Gamma Medica



TEP/TEMP/CT



NanoSPECT/CT  
Bioscan



CT



TEP/CT



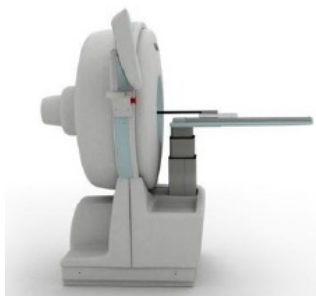
ClearPET  
raytest



TEP

Mosaic HP Philips

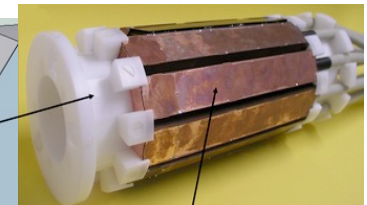
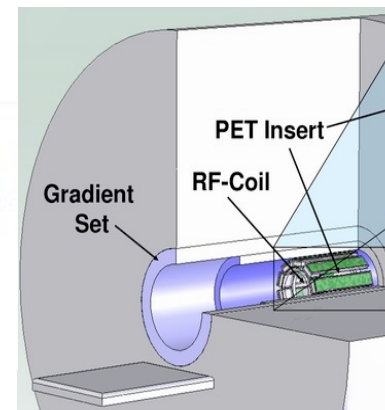
eXplore Vista, GE



NanoPET/CT



U-SPECT  
MILabs

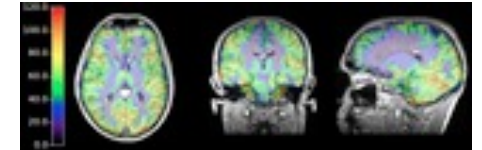


TEP/IRM

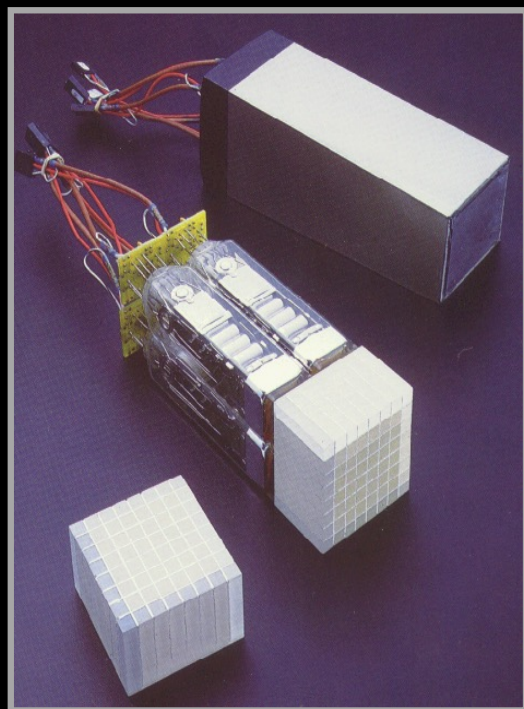
# 9.4 Tesla TEP/IRM hybride simultanée : une révolution technique doublée d'une évolution médicale ?



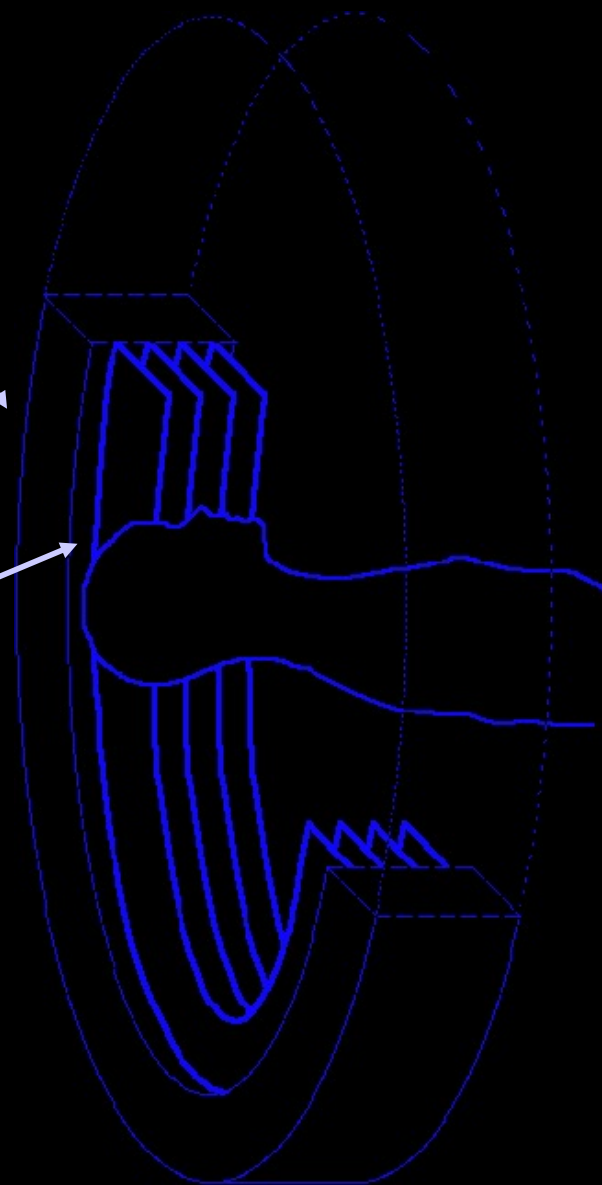
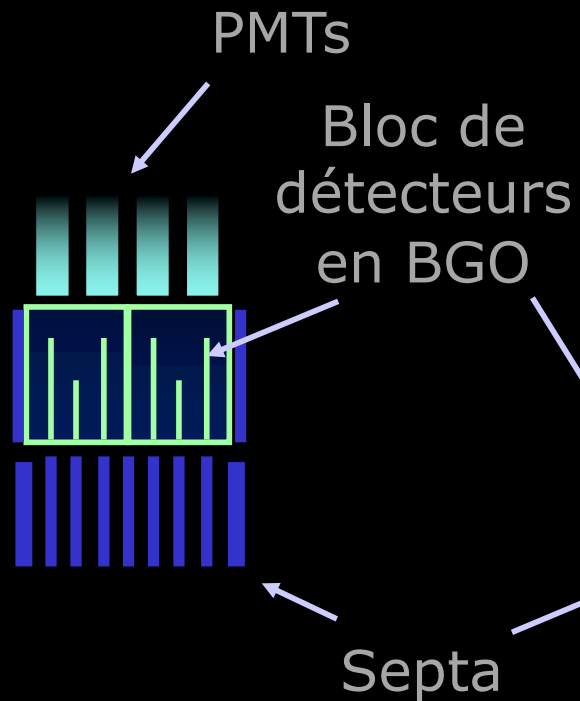
- Ouverture: 60 cm diamètre
- FOV axial: 50 cm
- Poids aimant: 57 tonnes
- 870 tonnes de fer doux
- Longueur: 3.70 m
- Energie stockée: 182.0 MJ
- Longueur du câble: 750 km



$$1 + 1 = ?$$



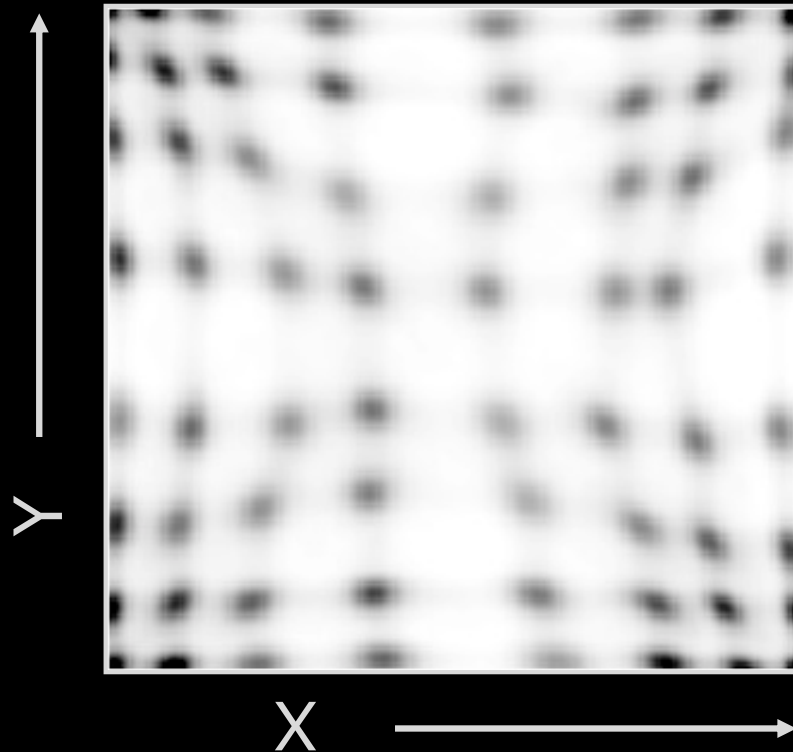
Bloc de détecteurs



## Caméra TEP avec septa

Courtesy: D. Townsend, UPMC

# Localisation spatiale dans un bloc de détecteurs



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

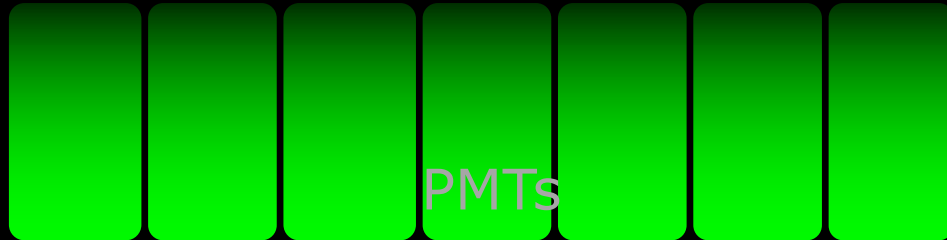
$$Y = \frac{(A + B) - (C + D)}{S}$$

$$S = A + B + C + D$$

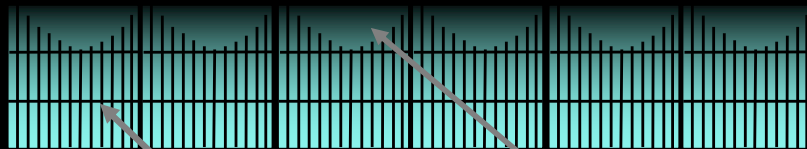
where  $LLD < S < ULD$

Courtesy: D. Townsend, UPMC

# Quadrant sharing panels

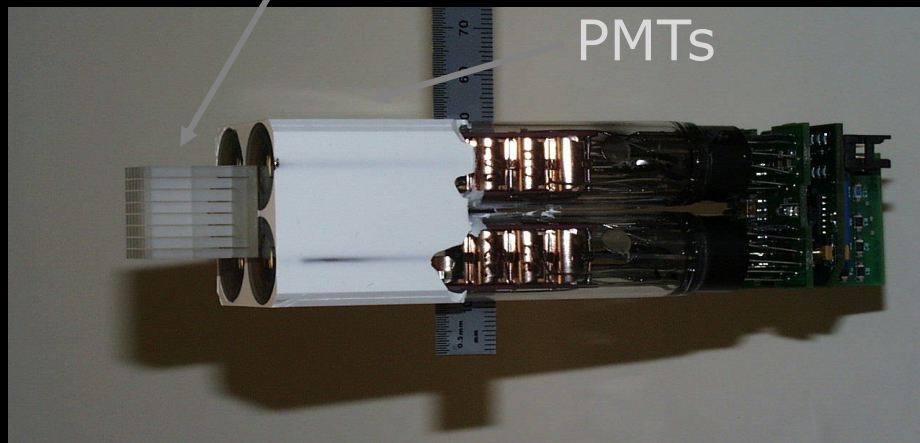
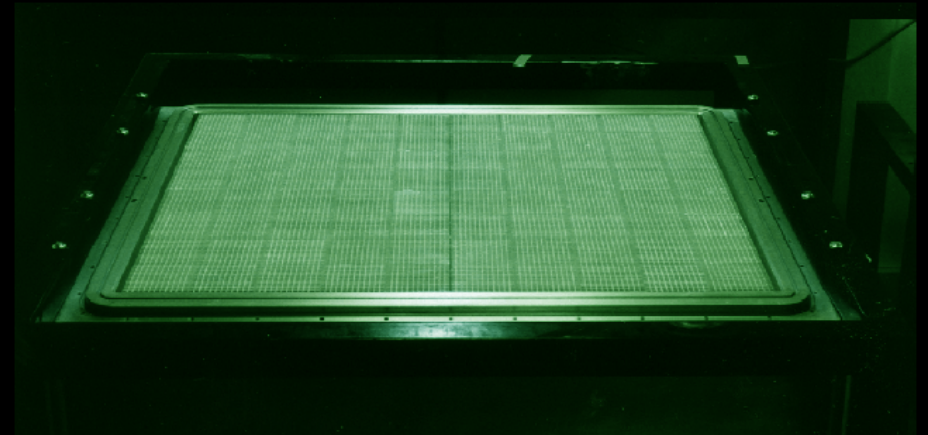


PMTs

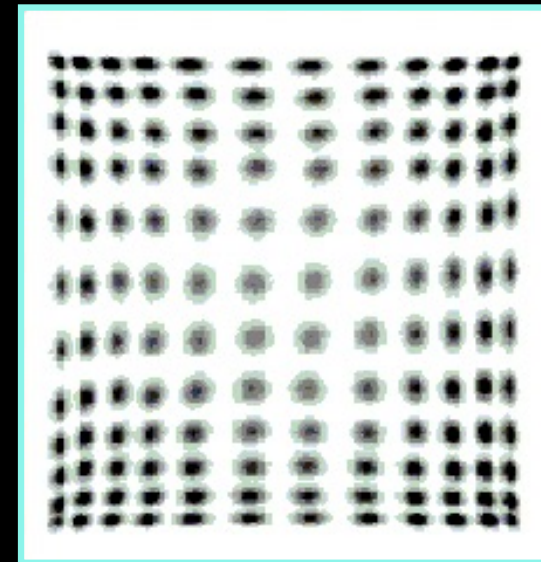


Scintillateur

Guide de lumière

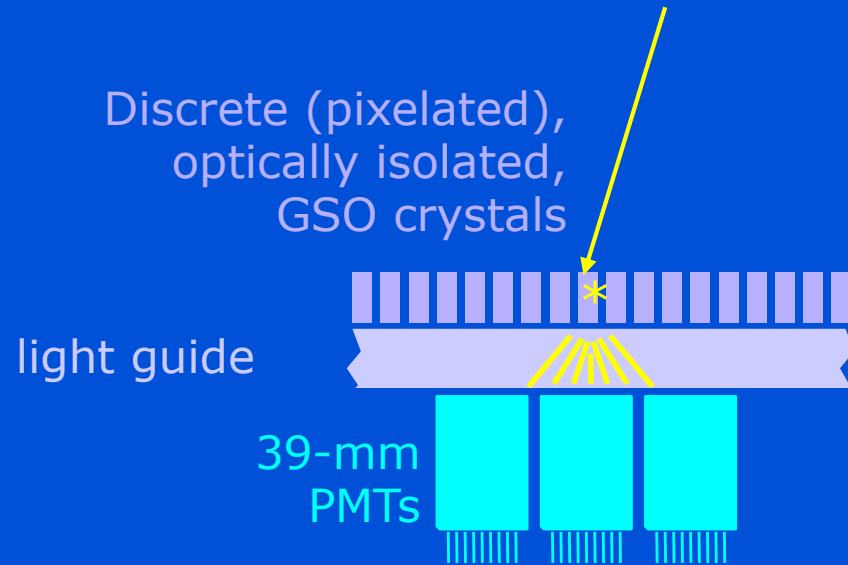


PMTs



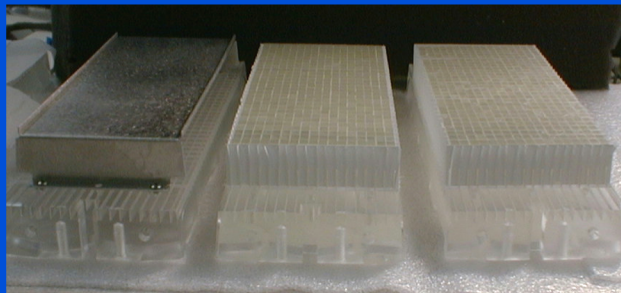
Courtesy: D. Townsend, UPMC

## Détecteurs pixelisés-continus



Ce design assure une  
réponse et une collection  
de lumière homogènes  
permettant de préserver  
au mieux la résolution en  
énergie

- individual scintillating crystals
- optically continuous lightguide
- closely packed PMTs

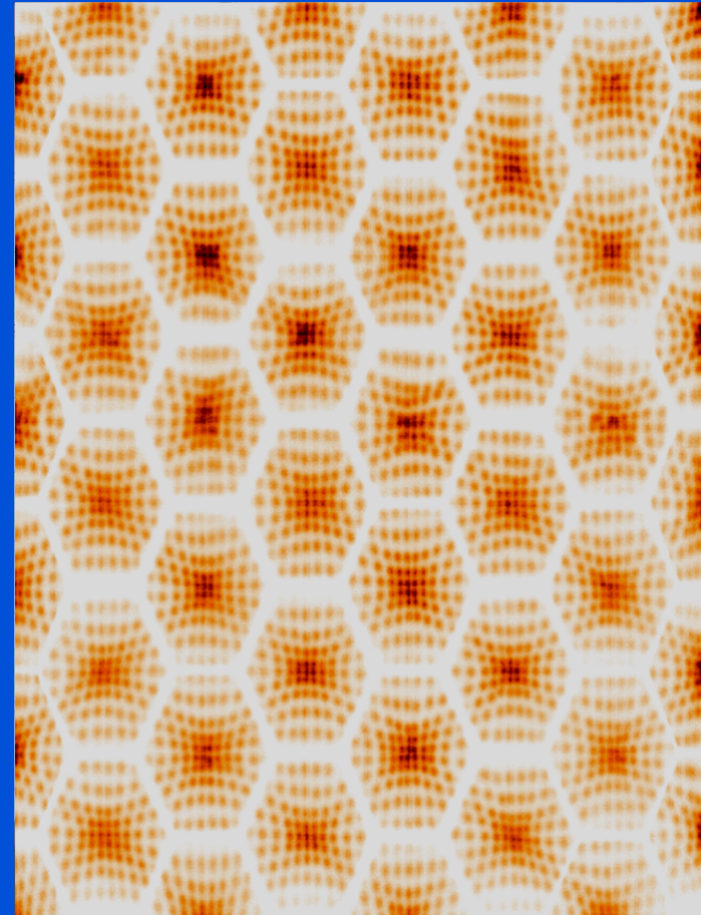


Courtesy: J. Karp, U Penn



**PHILIPS**

# Détecteurs pixelisés-continus

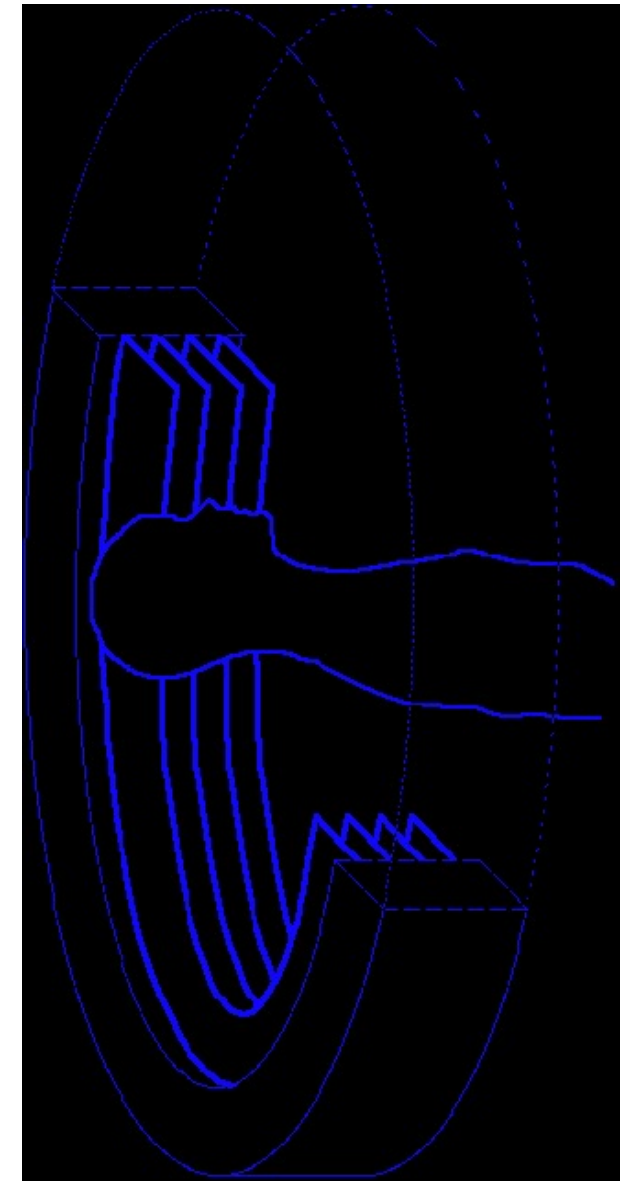
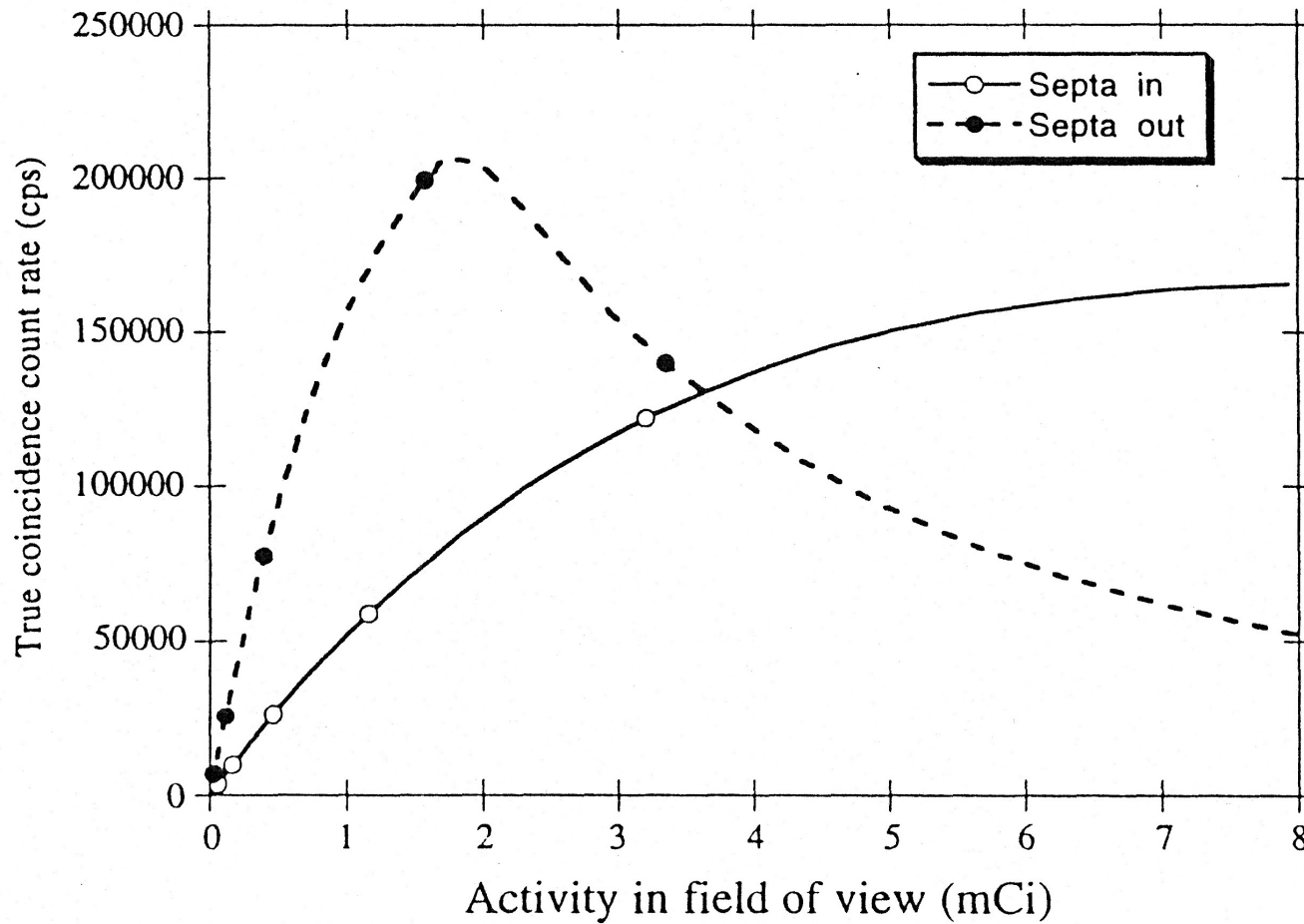


Courtesy: J. Karp, U Penn



**PHILIPS**

# Taux de comptage en TEP 2D et 3D

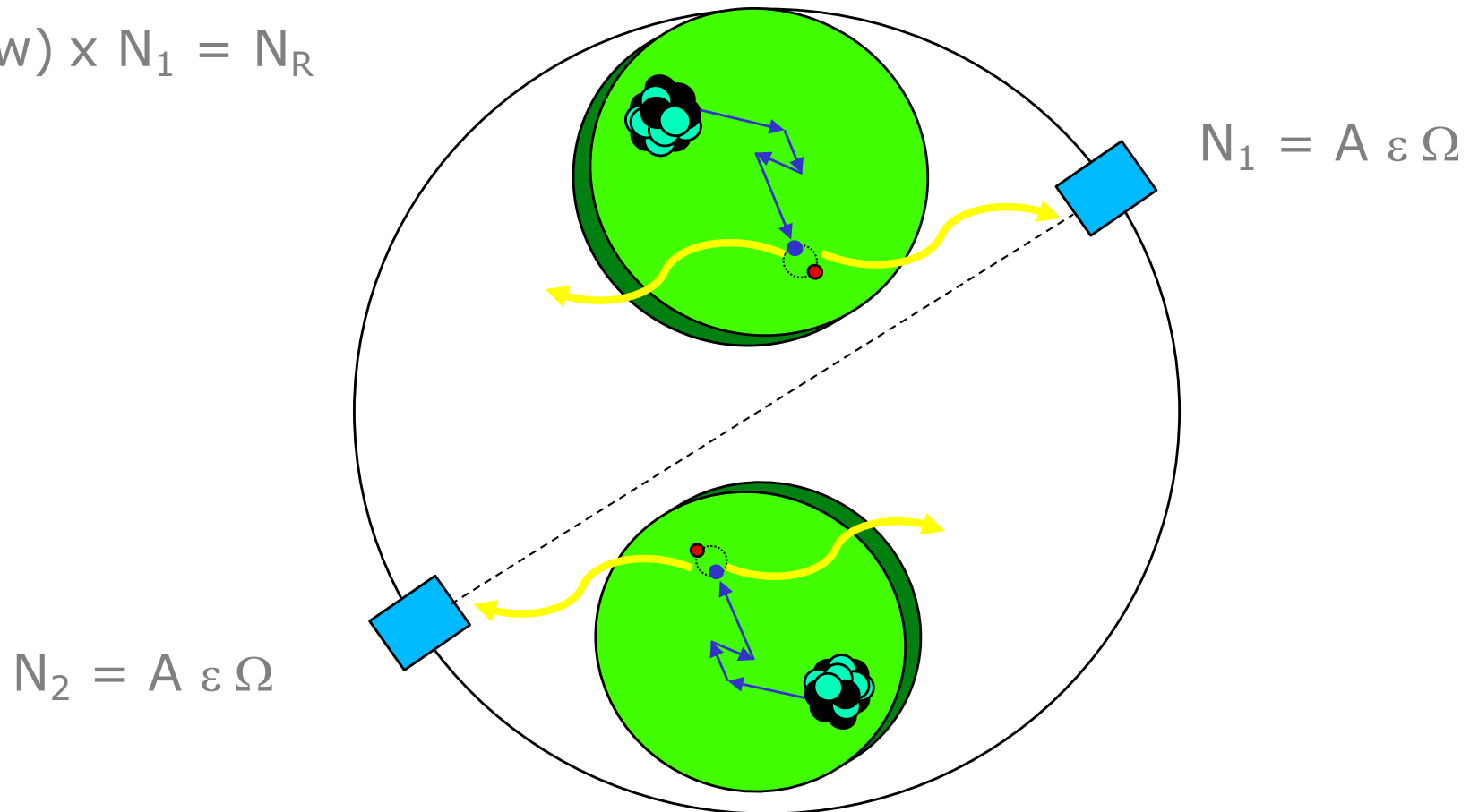




## Détection de coïncidences fortuites (*randoms*)

Lorsque  $N_1$  arrive avant  $N_2$

$$(N_2 w) \times N_1 = N_R$$



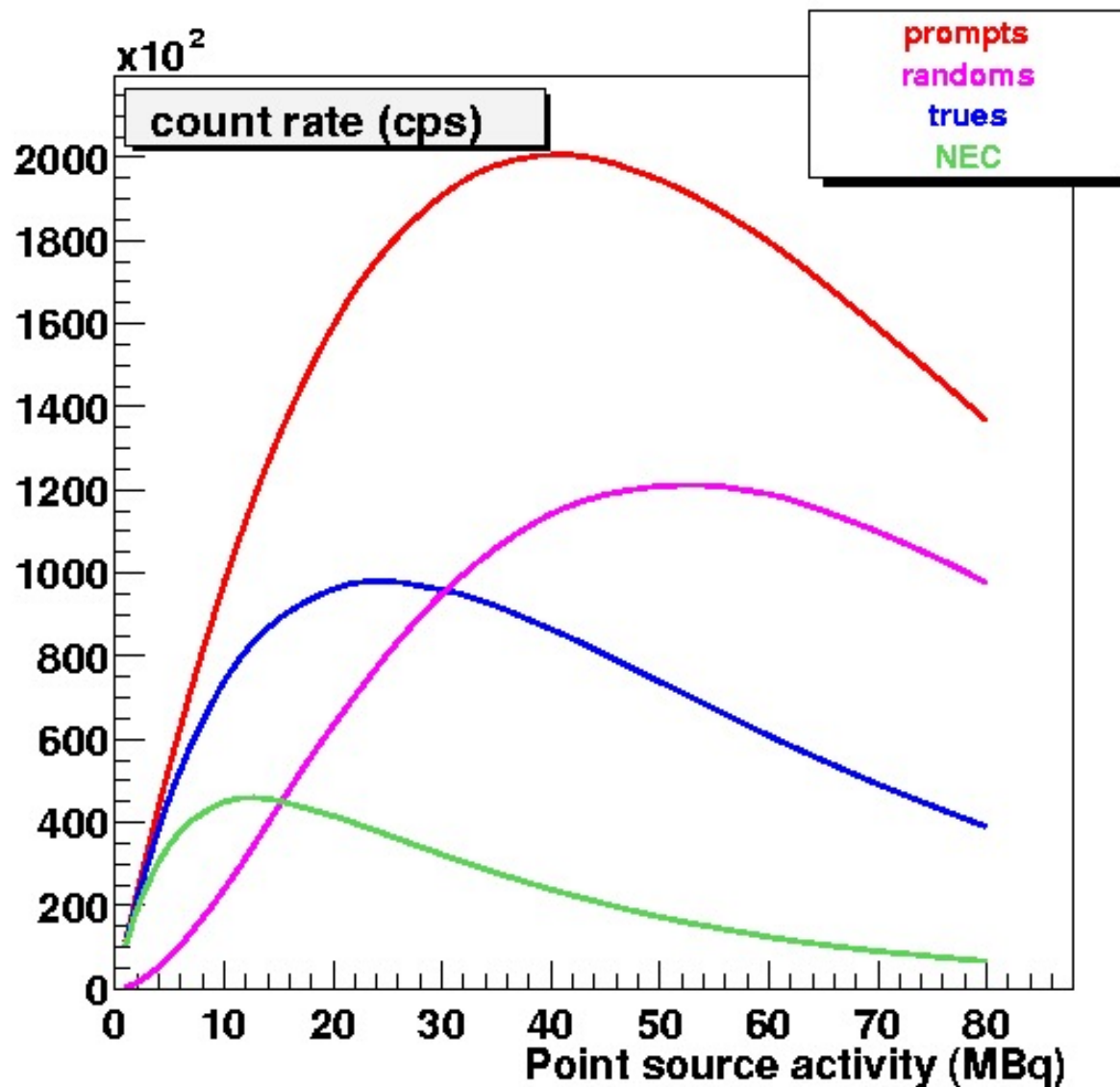
$$N_1 = A \varepsilon \Omega$$

$$N_2 = A \varepsilon \Omega$$

Lorsque  $N_2$  arrive avant  $N_1$

$$(N_1 w) \times N_2 = N_R$$

## Détection de coïncidences fortuites (*randoms*)



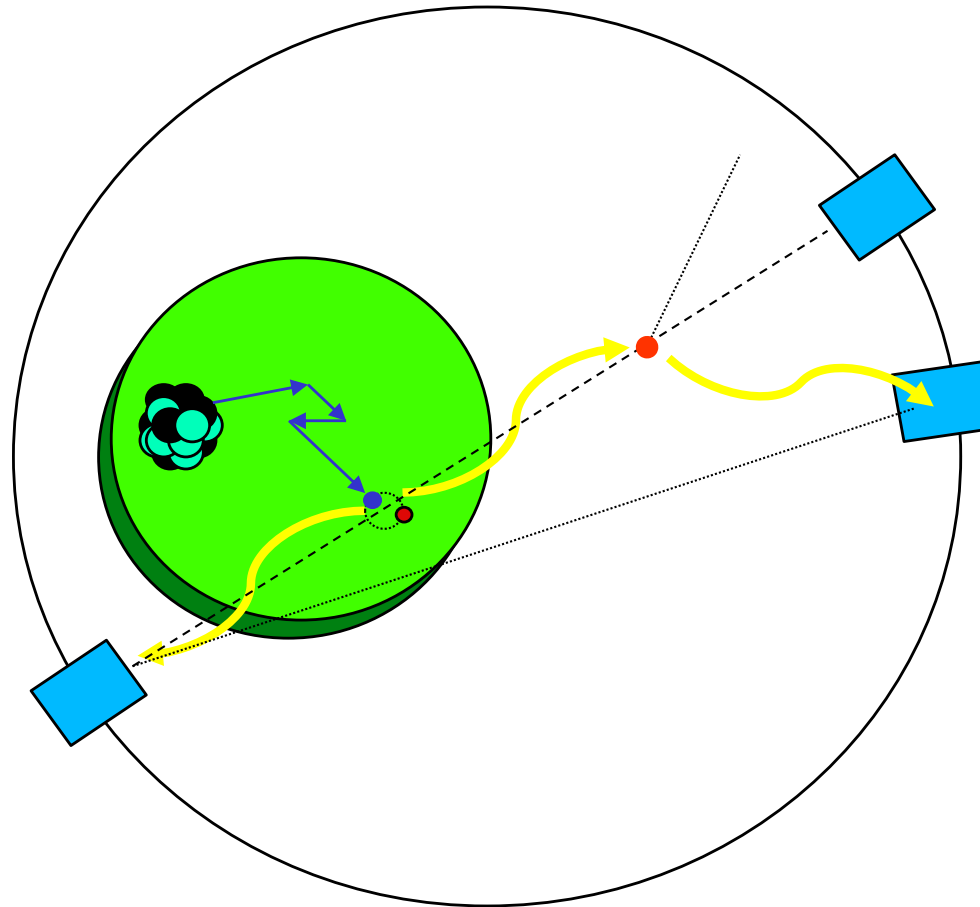
$$N_{\text{Prompts}} = N_{\text{Trues}} + N_{\text{R}}$$

$$N_{\text{R}} = (2 w) A^2 \varepsilon^2 \Omega^2$$

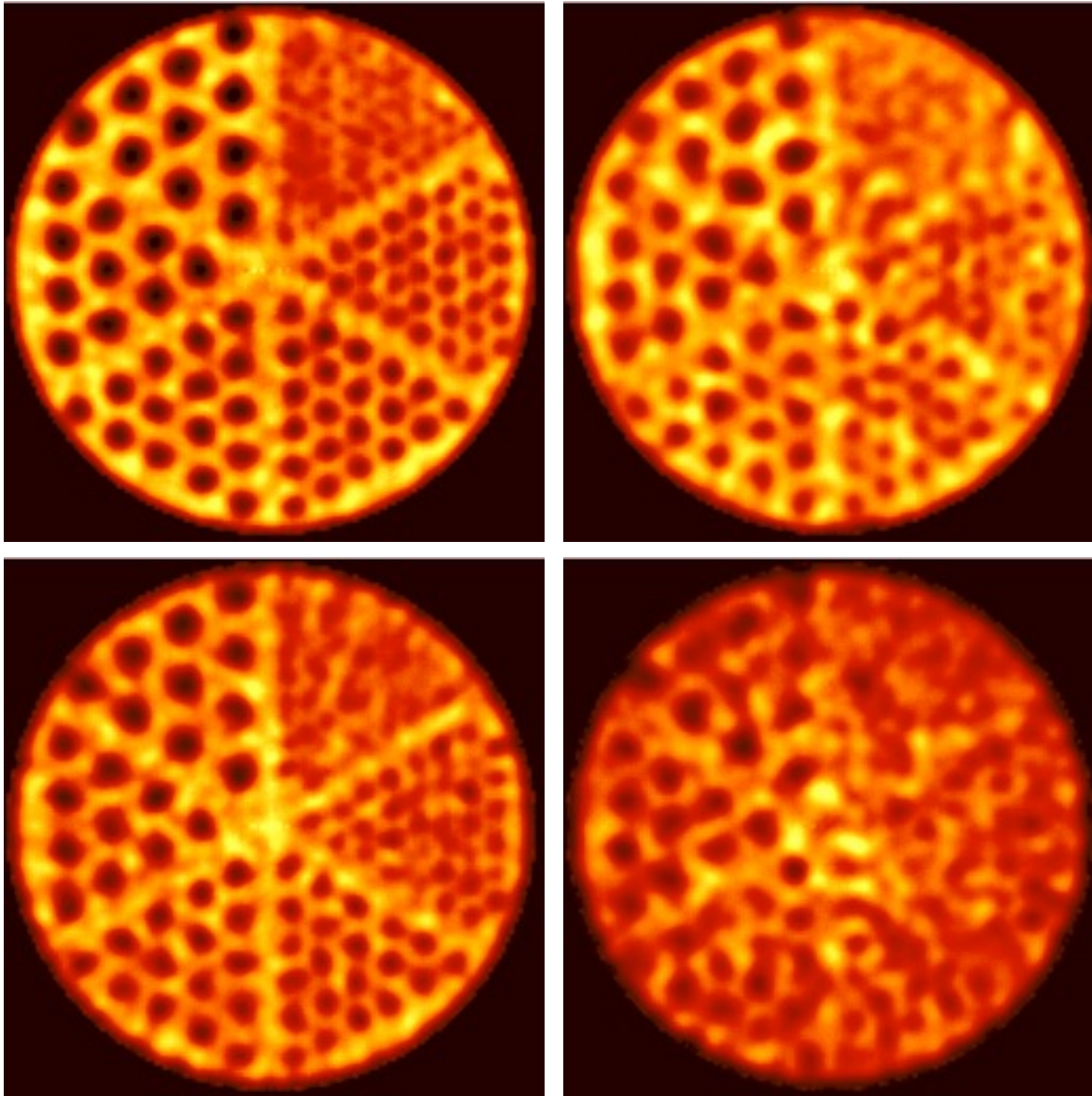
$$N_{\text{Trues}} = A \varepsilon^2 \Omega$$

$$\text{NEC} = N_{\text{Trues}}^2 / (N_{\text{trues}} + 2N_{\text{R}})$$

## Détection de coïncidences diffusées (*scatter*)



## Détection de coïncidences diffusées (*scatter*)

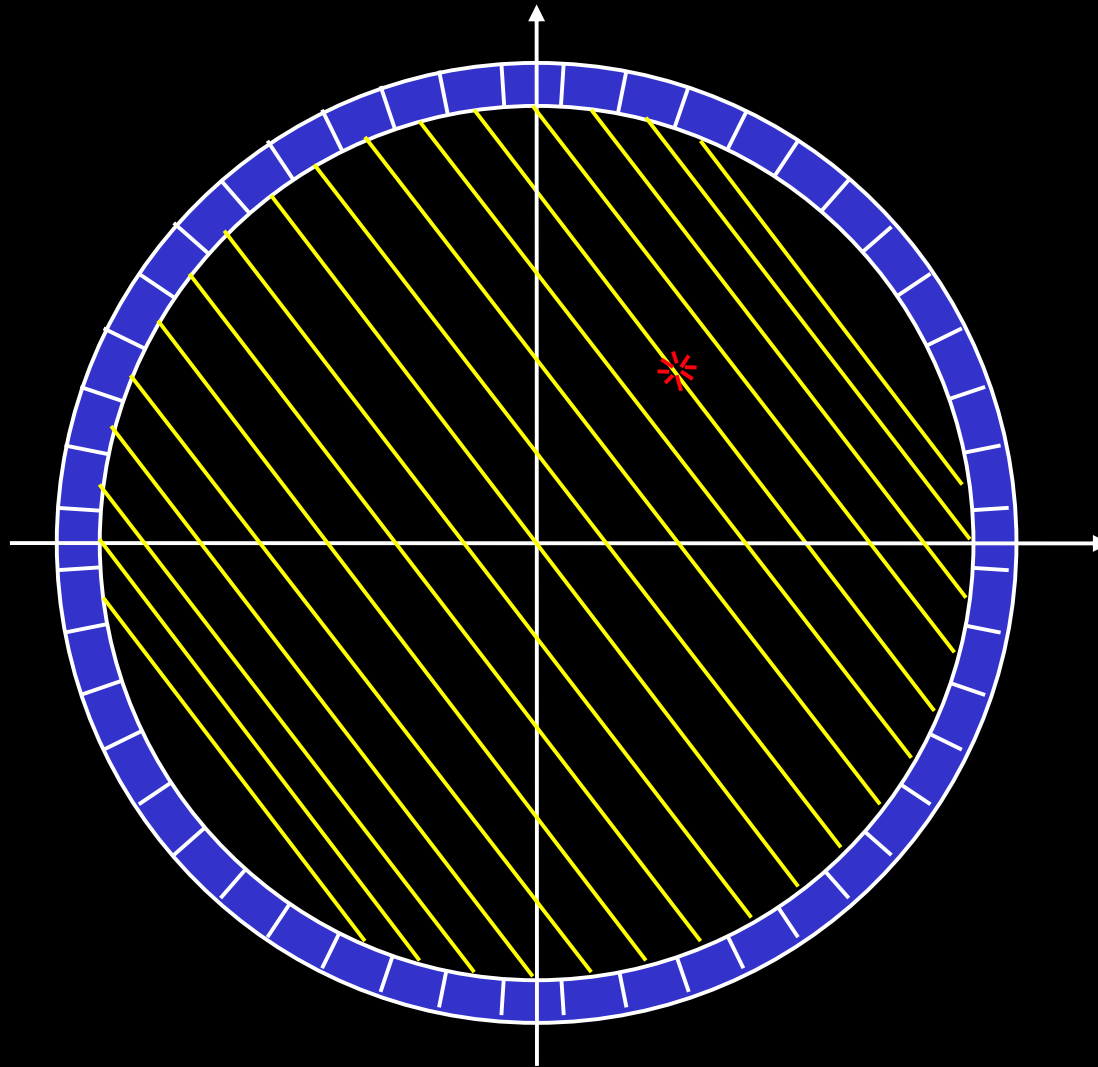


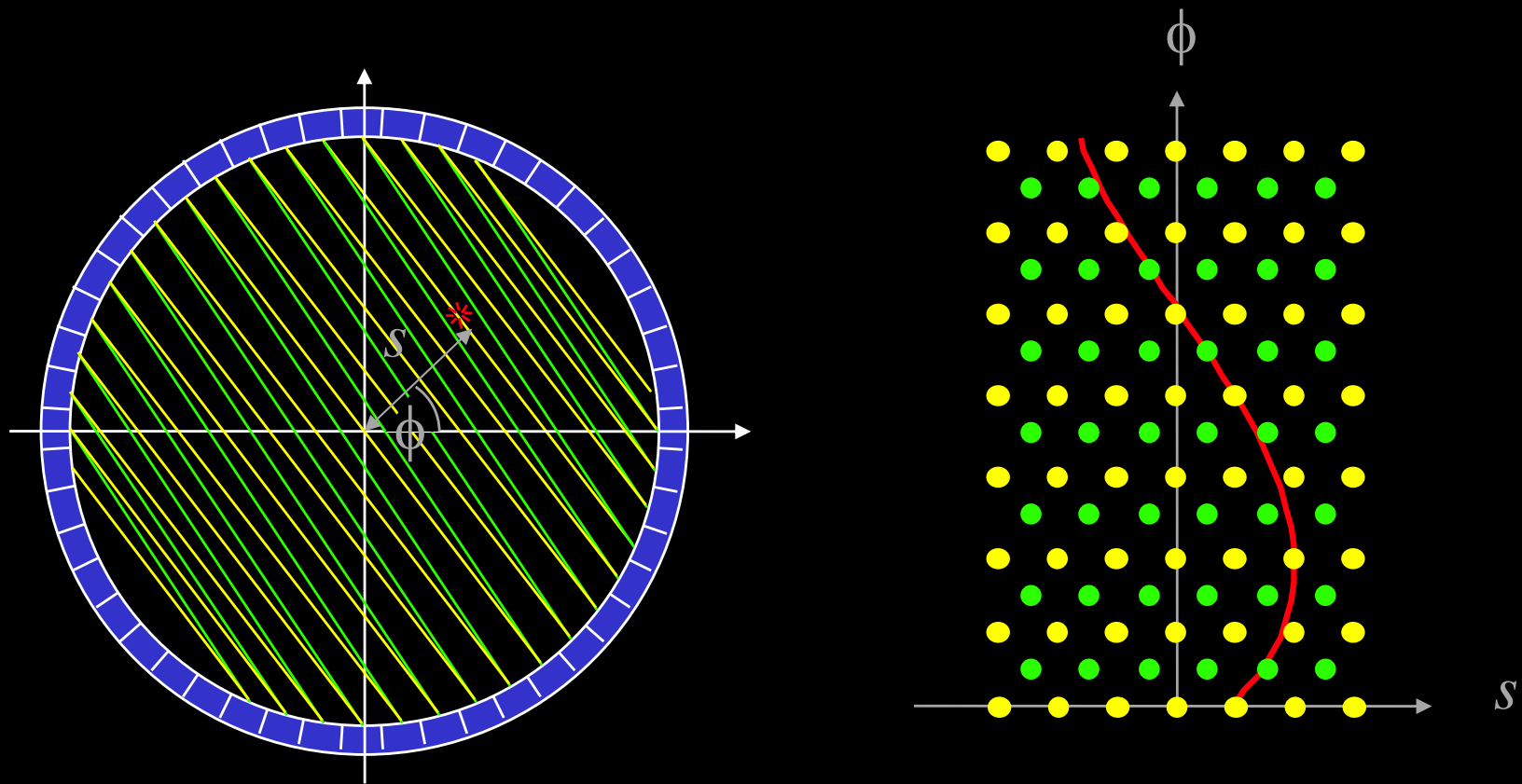
Simulation  
sans diffusion

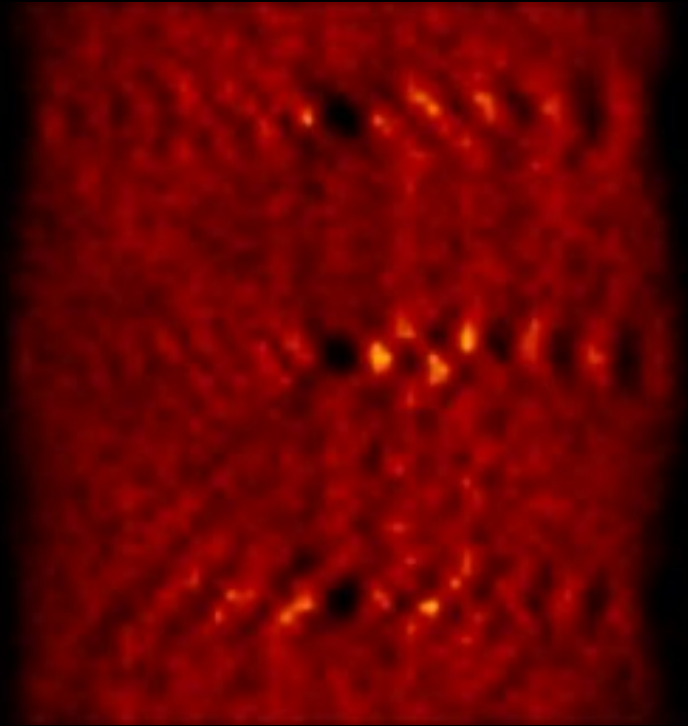
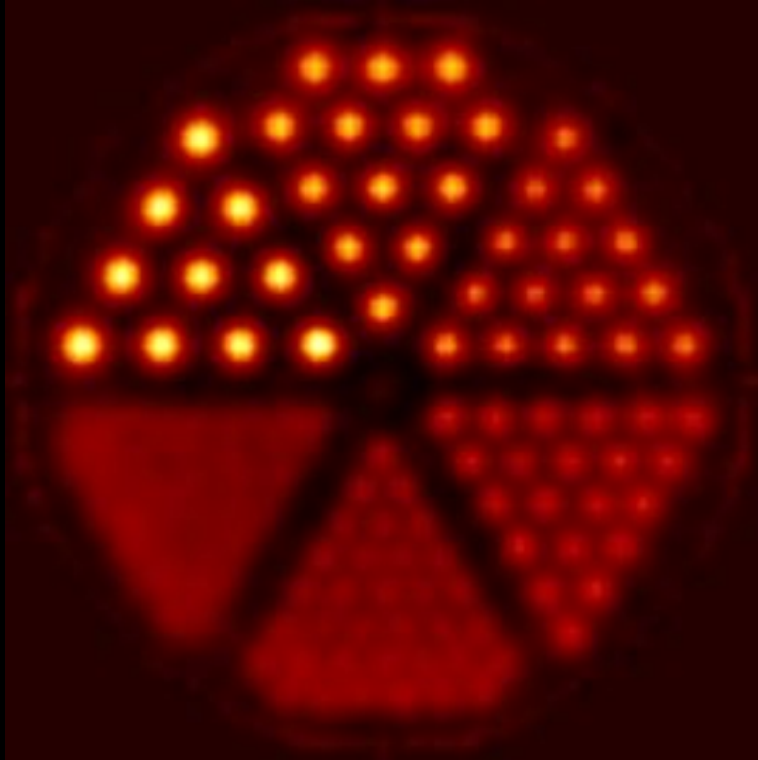
Simulation  
avec diffusions

# Scintillateurs inorganiques utilisés en TEP

	NaI	BGO	GSO	L(Y)SO	LuAP	LaBr <sub>3</sub>
Densité (g/cm <sup>3</sup> )	3.67	7.13	6.71	7.40	8.34	5.3
Numéro atomique effectif	51	75	59	66	65	52
Photo-fraction (%)	18	42	26	33	32	14
Temps de décroissance (ns)	230	300	30-60	35-45	17	25
Rendement (h <sub>v</sub> /MeV)	43000	8200	12500	27000	11400	60000
Maximum d'émission (nm)	415	480	430	420	365	370
Indice de réfraction	1.85	2.15	1.85	1.82	1.97	1.9

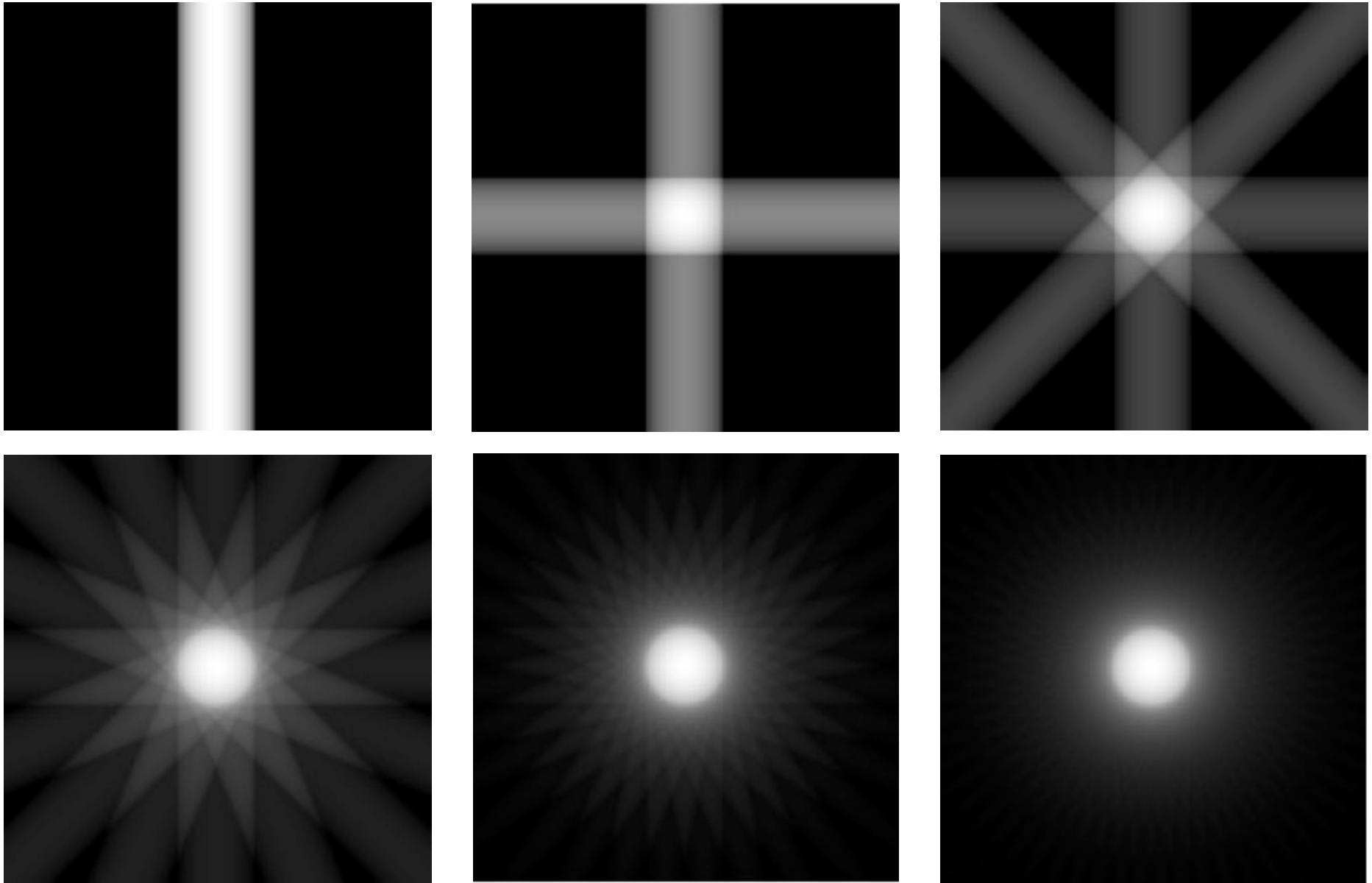








# Rétroprojection



Courtesy: S. Valton, Créatis, Lyon

# Reconstruction d'images tomographiques

Transformée de Radon  
Transformée  $X$

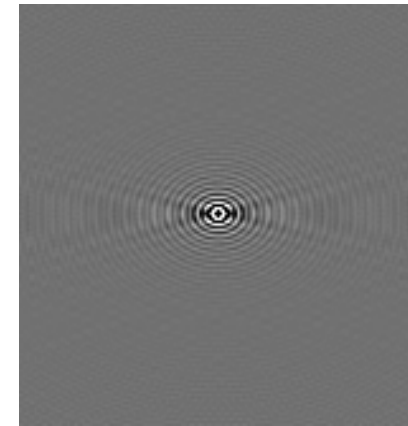


Espace direct

Transformée de Fourier



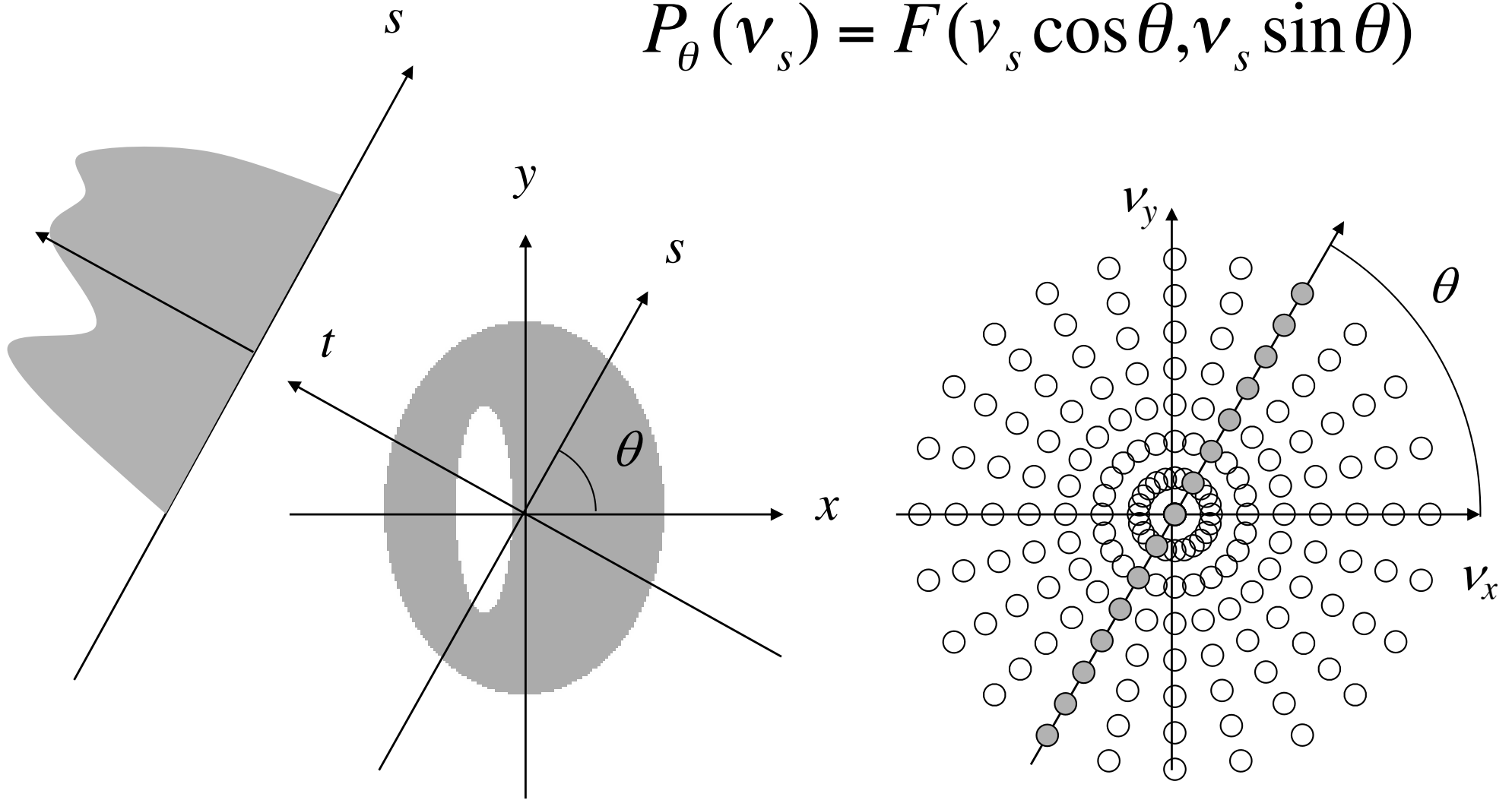
Espaces de projections



Espace des fréquences

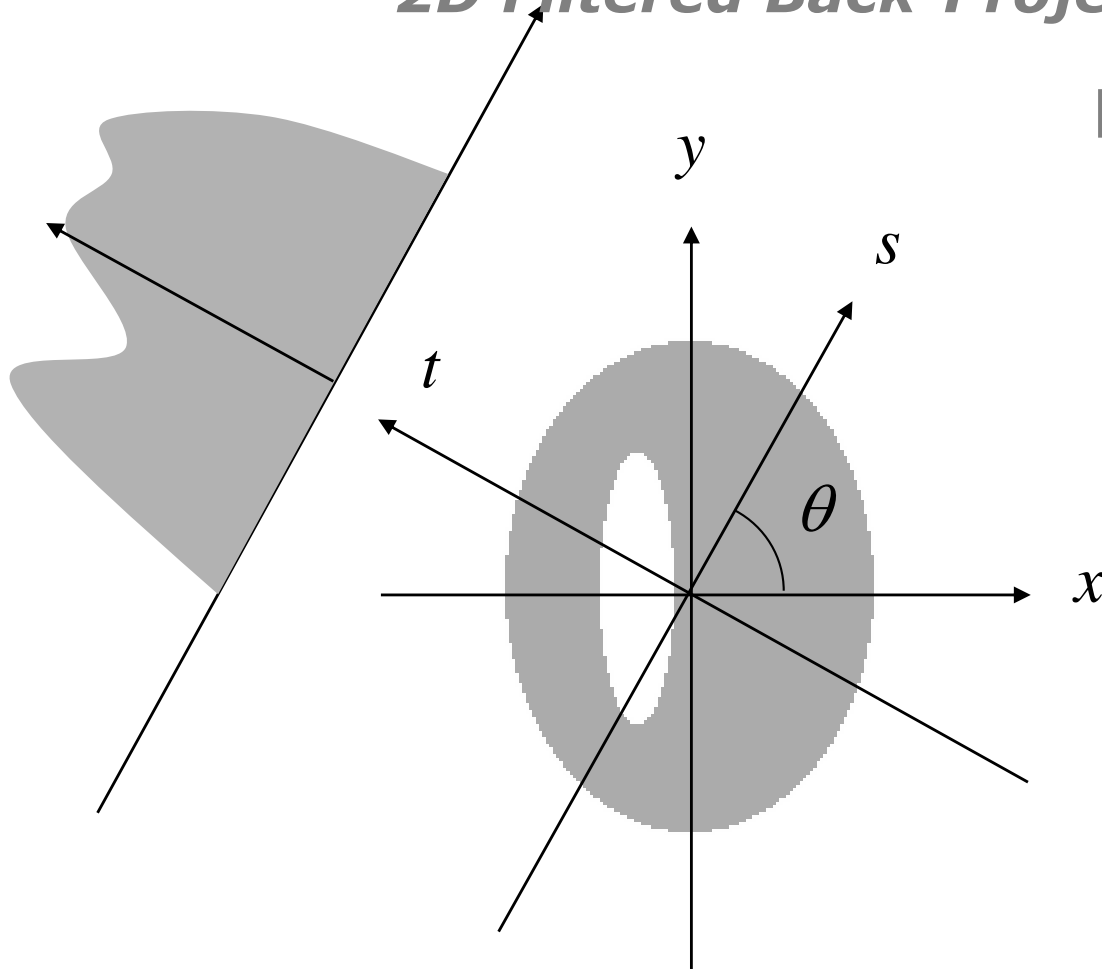
# Théorème de la coupe centrale

$$P_{\theta}(v_s) = F(v_s \cos \theta, v_s \sin \theta)$$



## Rétroprojection filtrée en 2 dimensions

### 2D Filtered Back-Projection (2D FBP)



Projection parallèle à  
1 dimension

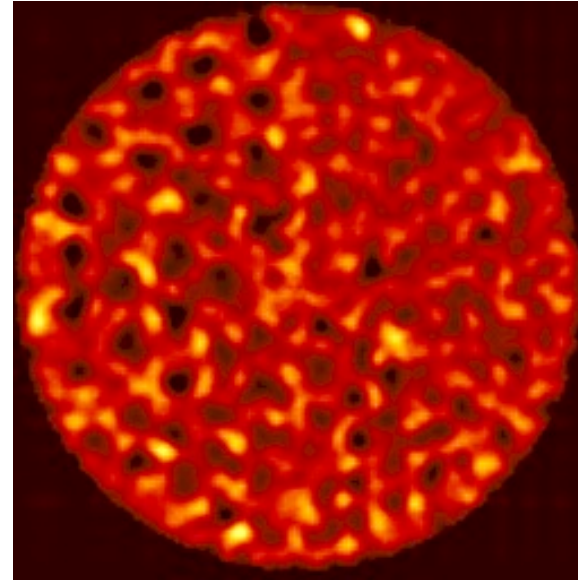
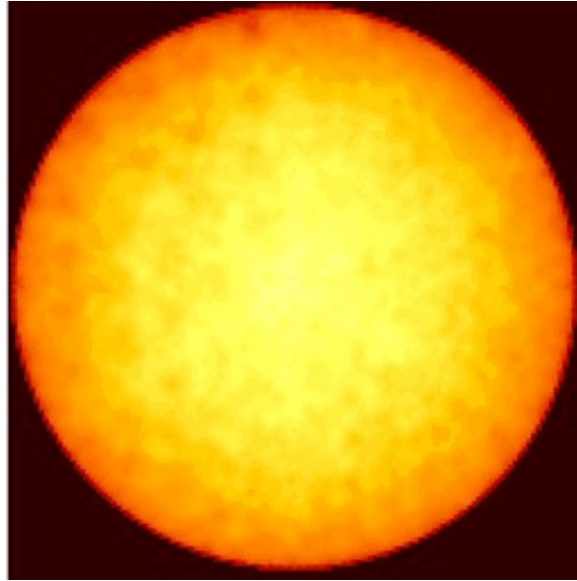
$$p_{\theta}(s) = \int_{-\infty}^{\infty} dt f(x, y)$$

Transformée de Fourier

$$P_{\theta}(v_s) = \int_{-\infty}^{\infty} ds p_{\theta}(s) e^{-i2\pi v_s s}$$

$$f(x, y) = \int_0^{\pi} d\theta \left[ \int_{-\infty}^{\infty} dv_s |v_s| P_{\theta}(v_s) e^{i2\pi v_s s} \right], \quad s = x \cos \theta + y \sin \theta$$

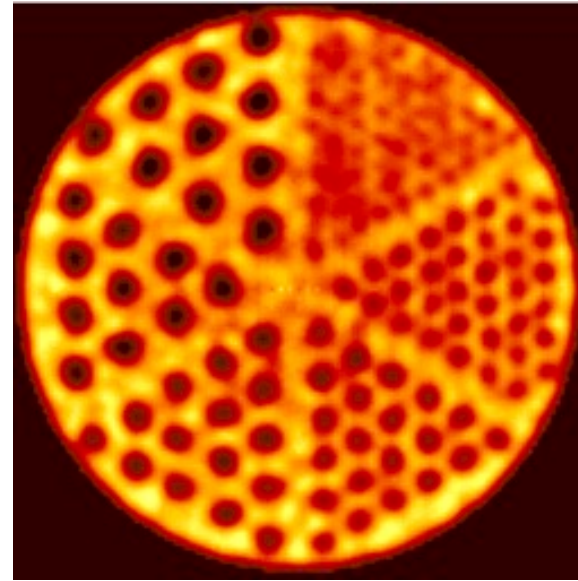
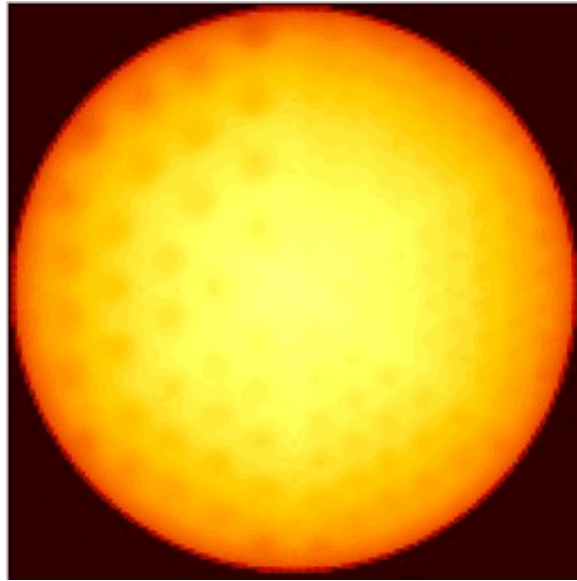
## Reconstruction 2D



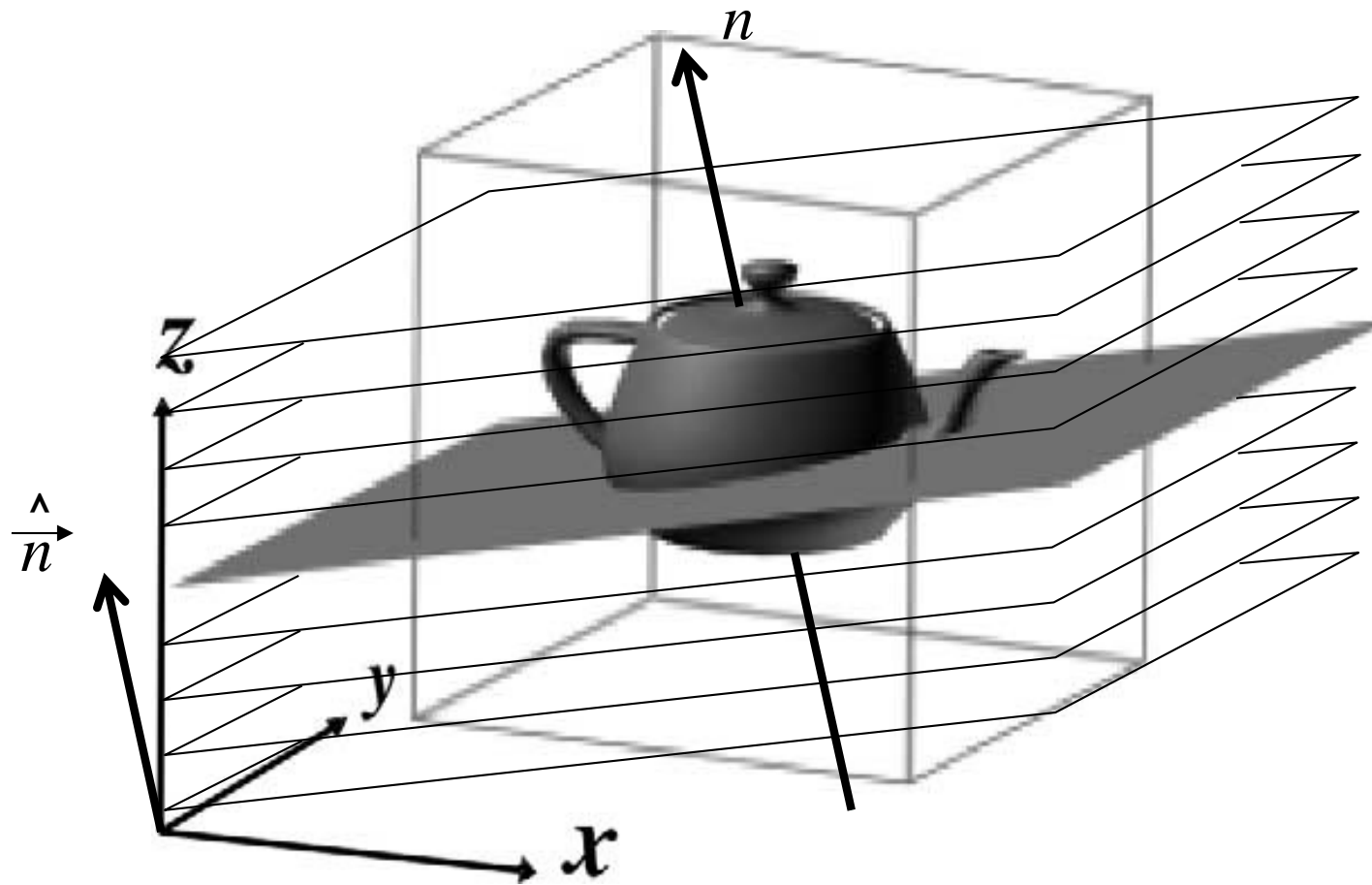
Rétroprojection non filtrée

Rétroprojection filtrée

## Reconstruction 3D

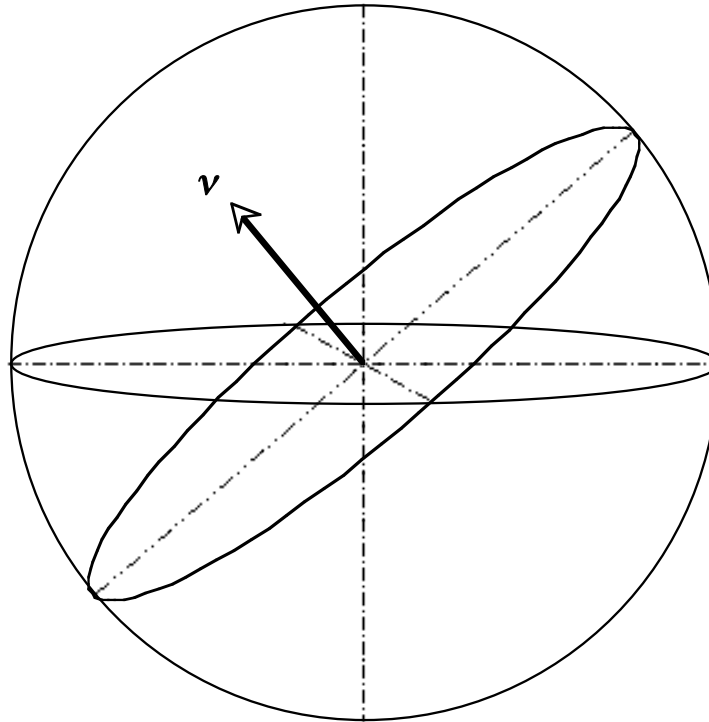


# Inversion de la Transformée de Radon en 3D



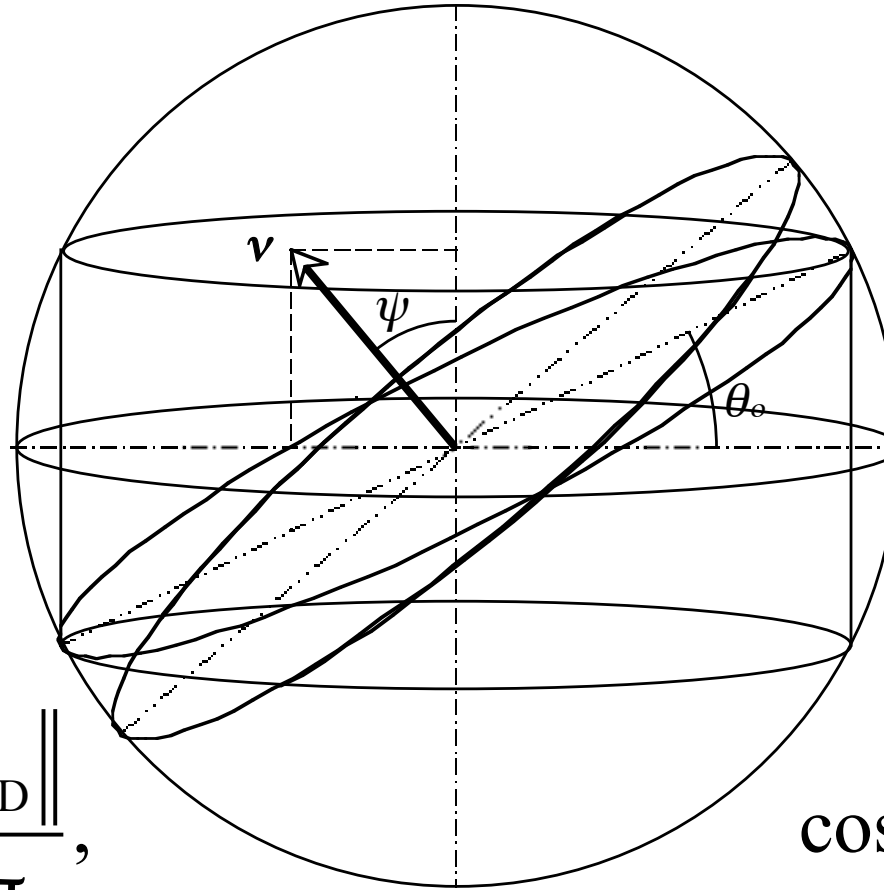
## Fonction de transfert de modulation du filtre en 2D

$$T(\vec{v}_{3D}) = \iint_{\Omega} d^2\hat{u} \delta(\hat{u} \cdot \vec{v}_{3D}) H(\hat{u}, \vec{v}_{3D}) = 1, \forall \vec{v}_{3D} \in \mathbb{R}^{3*}$$



$$T(\vec{v}_{3D}) = \iint_{4\pi} d^2\hat{u} \frac{1}{\|\vec{v}_{3D}\|} \delta(\hat{u} \cdot \frac{\vec{v}_{3D}}{\|\vec{v}_{3D}\|}) = \frac{2\pi}{\|\vec{v}_{3D}\|}$$

## Filtre de Colsher en 2D (1980)

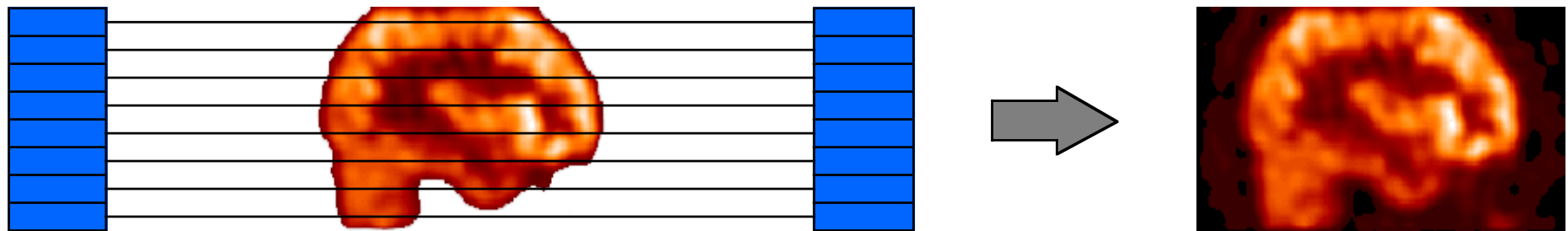


$$H_{Colsher}(\vec{v}_{3D}) = \begin{cases} \frac{\|\vec{v}_{3D}\|}{2\pi}, & \cos \psi \geq \cos \theta_0 \\ \frac{\|\vec{v}_{3D}\|}{4} \frac{1}{\arcsin(\sin \theta_0 / \sin \psi)}, & \cos \psi < \cos \theta_0 \end{cases}$$

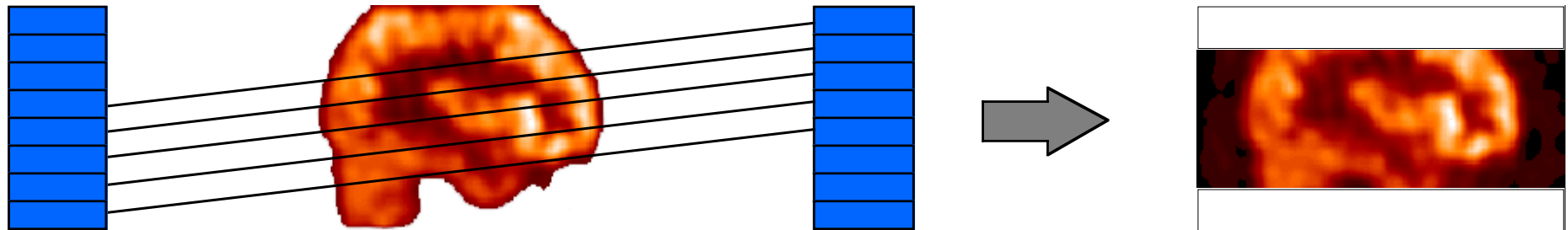


# Algorithme de re-projection 3D

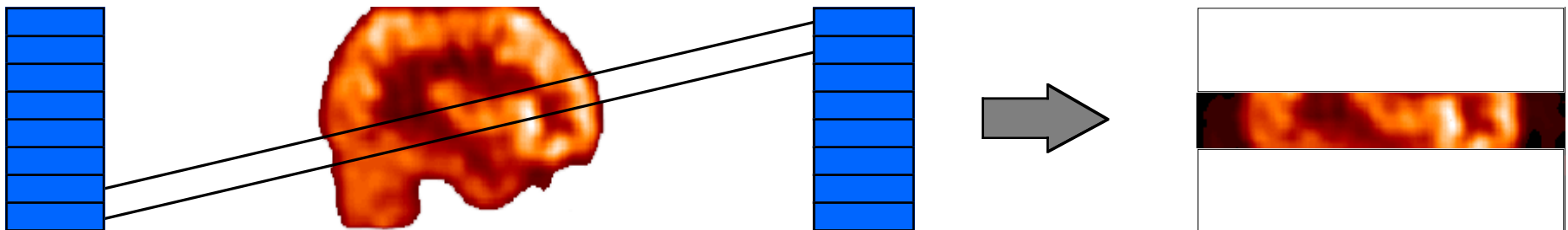
## 3D Re-Projection (3DRP)



$\delta = 0$ , projections directes



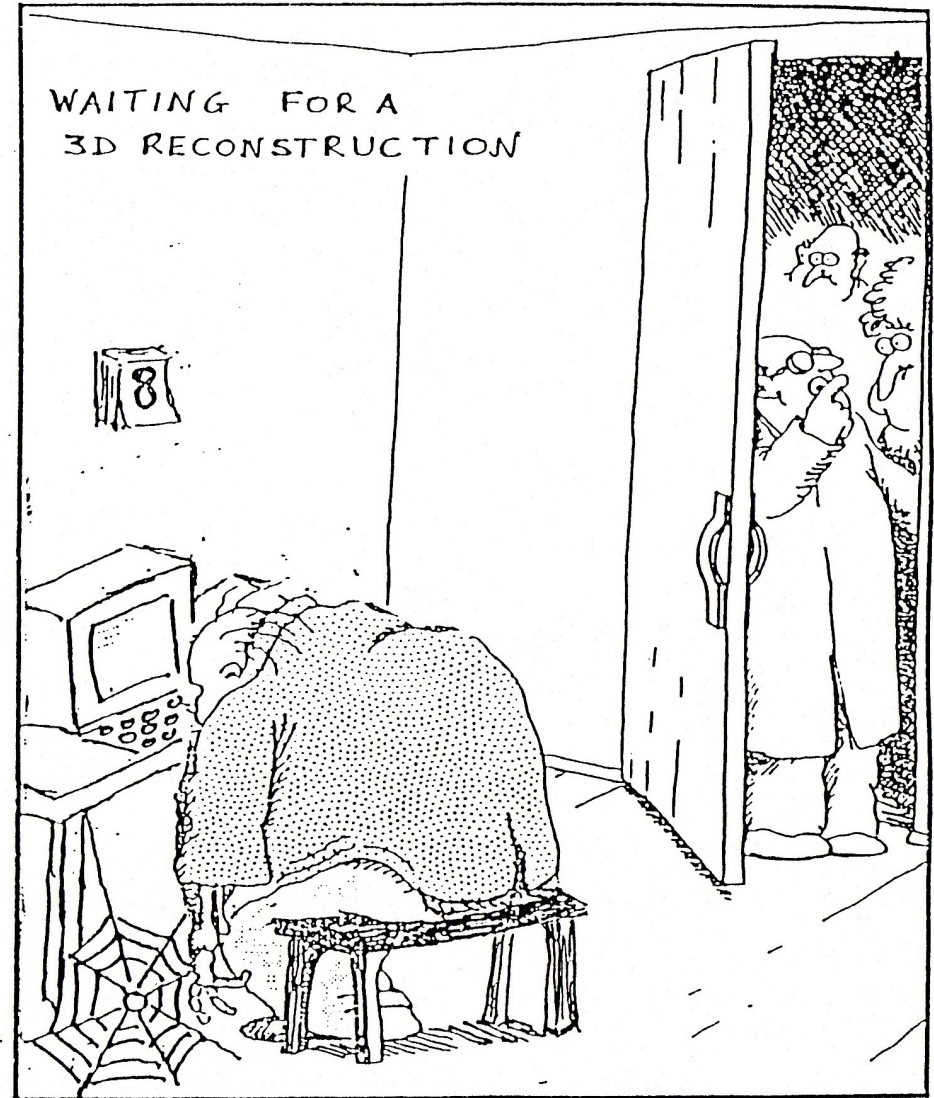
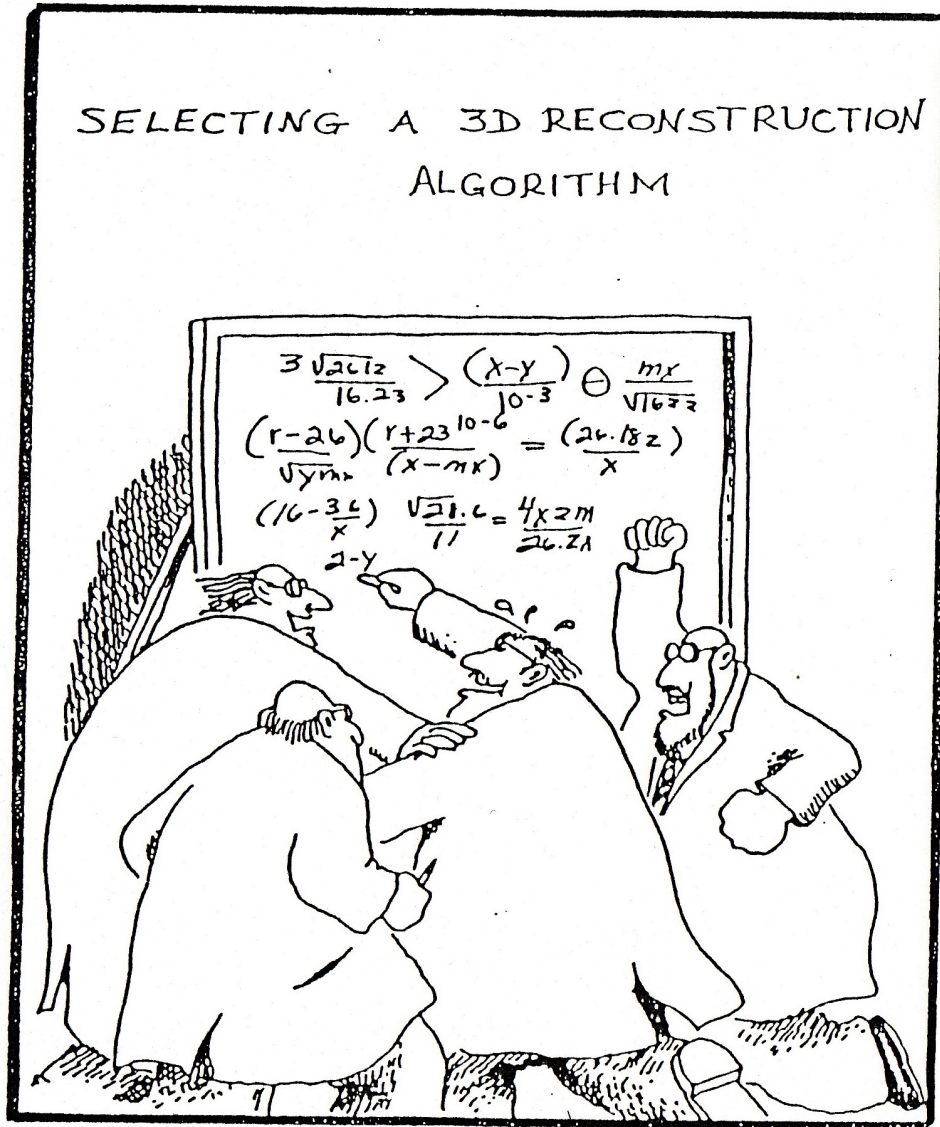
$\delta = 3$ , projections obliques



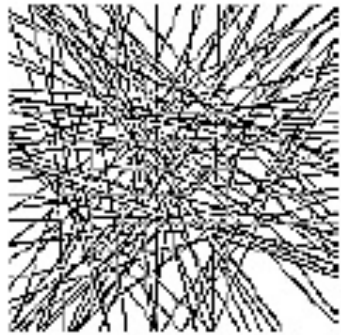
$\delta = 6$ , projections obliques

# Algorithme de re-projection 3D

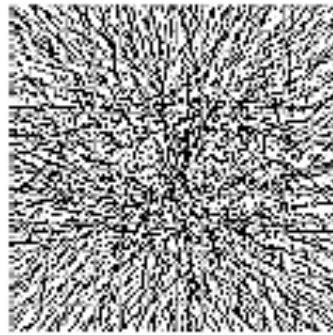
## 3D Re-Projection (3DRP)



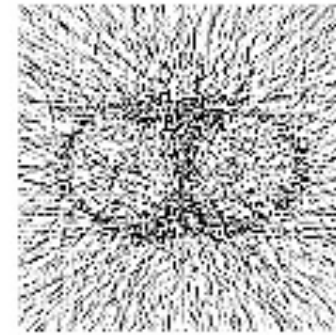
# Reconstruction d'images tomographiques et statistique de comptage



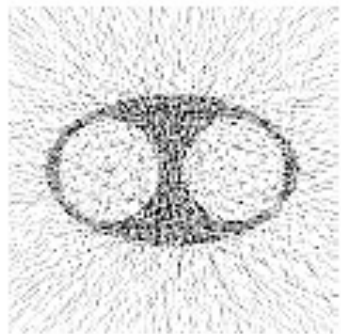
$10^2$



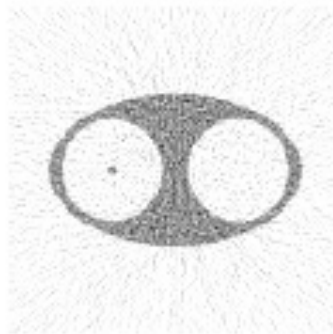
$10^3$



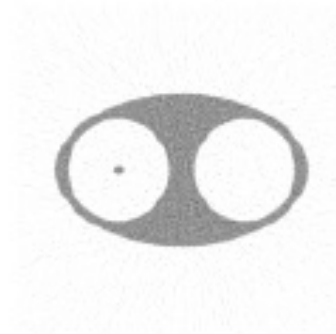
$10^4$



$10^5$



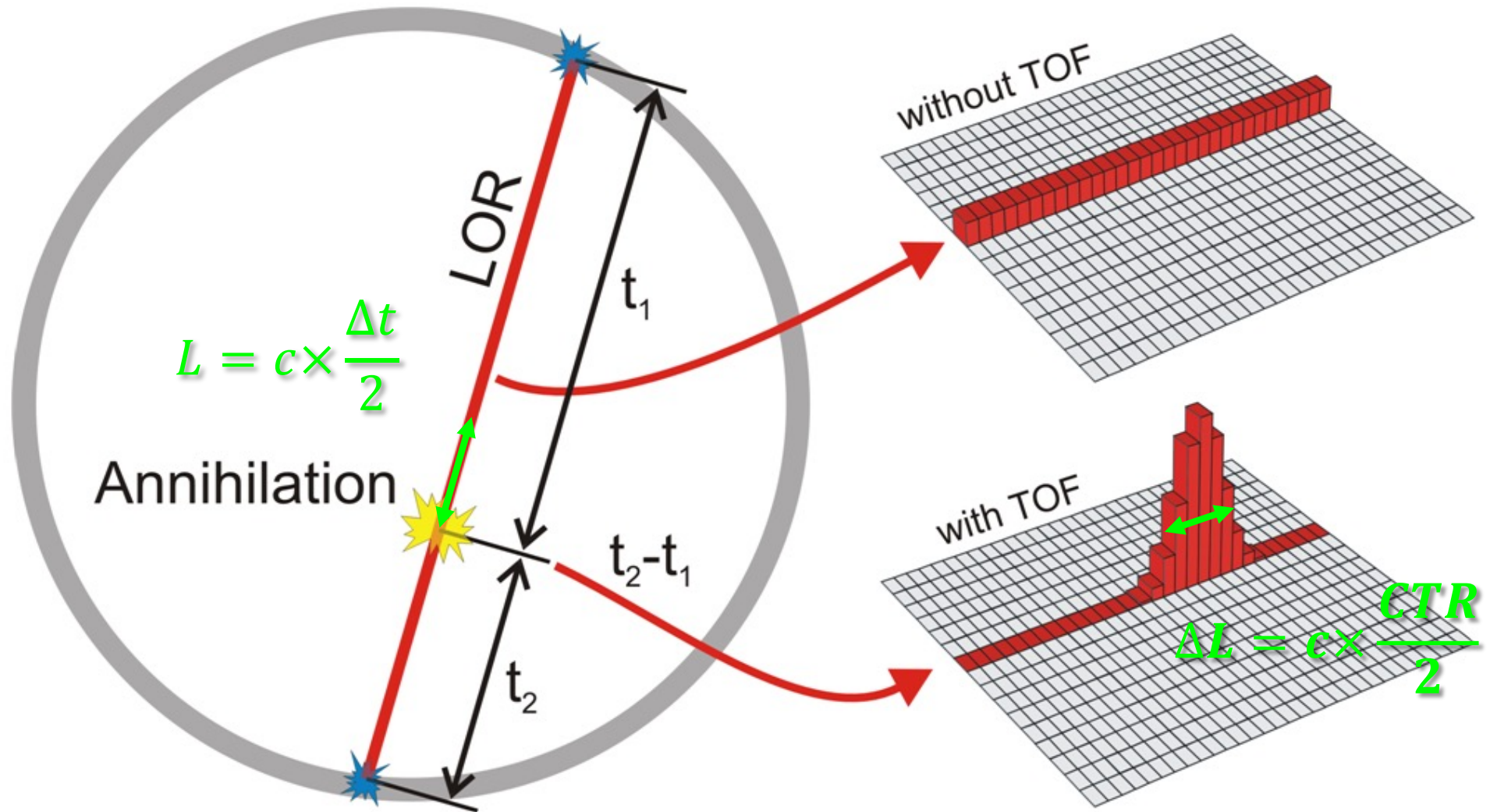
$10^6$



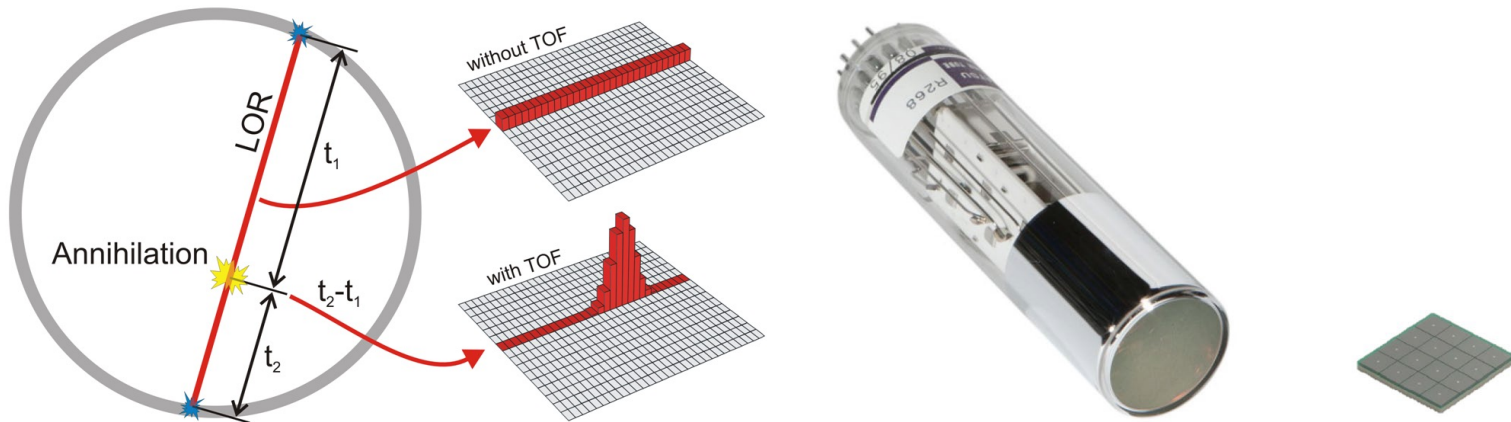
$10^7$

Courtesy: C. Comtat, CEA-SHFJ

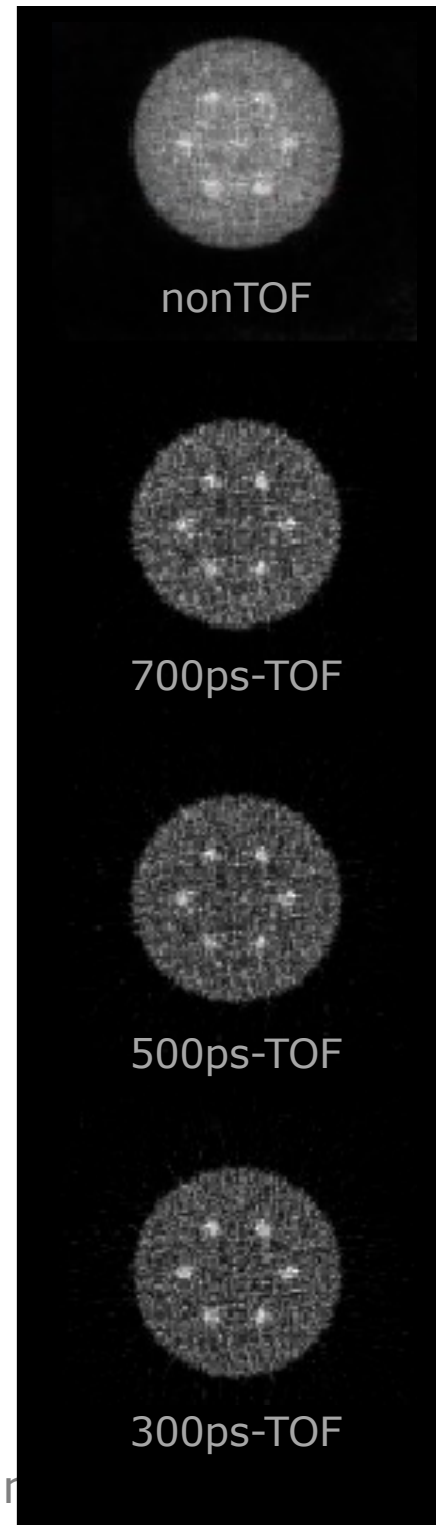
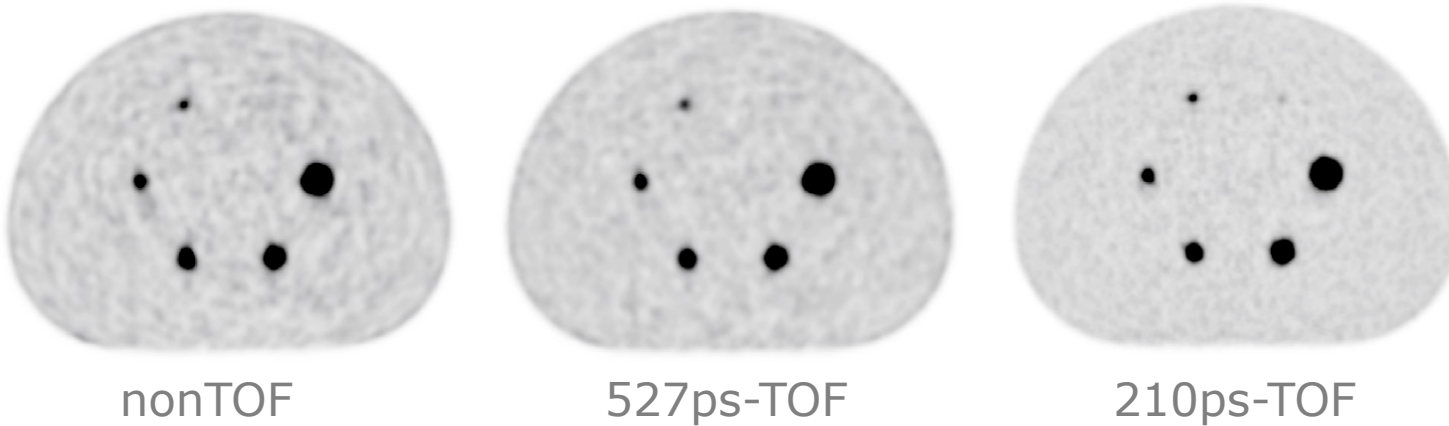
# TEP à temps-de-vol (TOF-PET)



# Time-Of-Flight (TOF)-PET

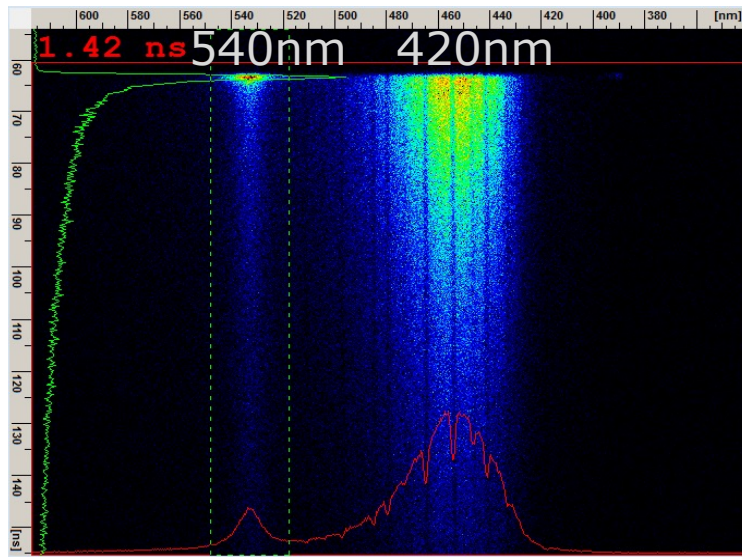
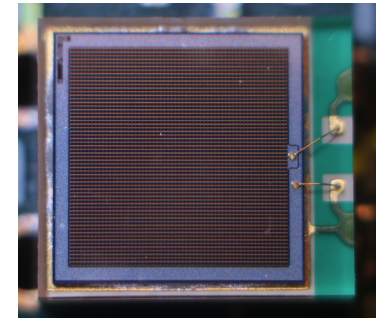
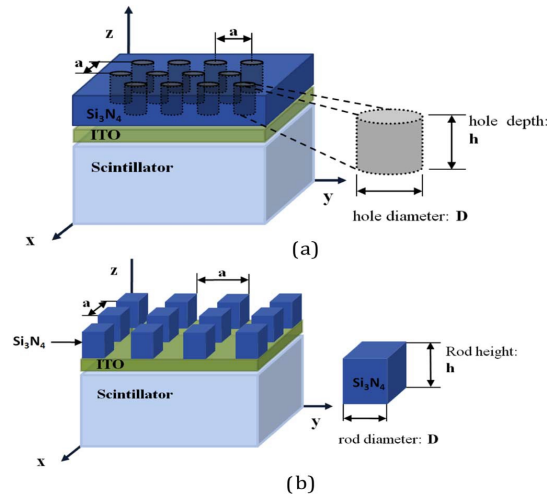
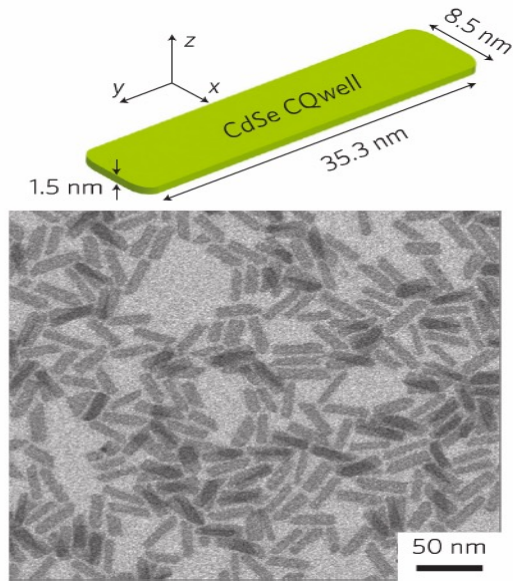


$$\left( \frac{SNR_{TOF}}{SNR_{nonTOF}} \right)^2 = \frac{2D}{c \times CTR}$$

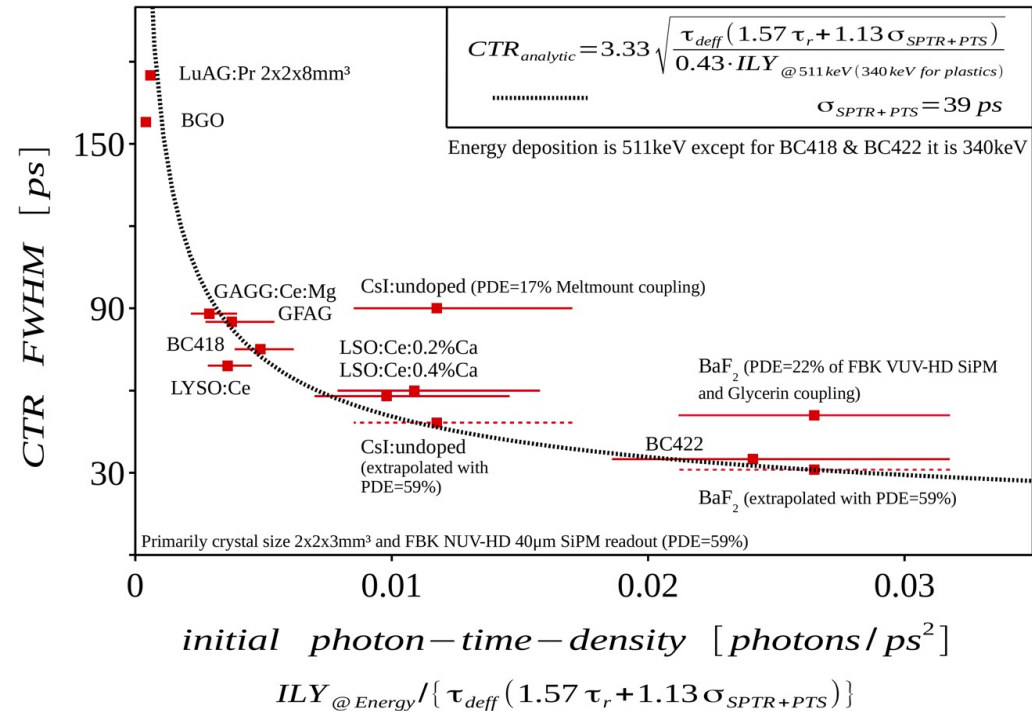


# Improving Coincidence Time Resolution (CTR)

P Lecoq et al. Nucl. Instrum. Meth. A 718 (2013) 569



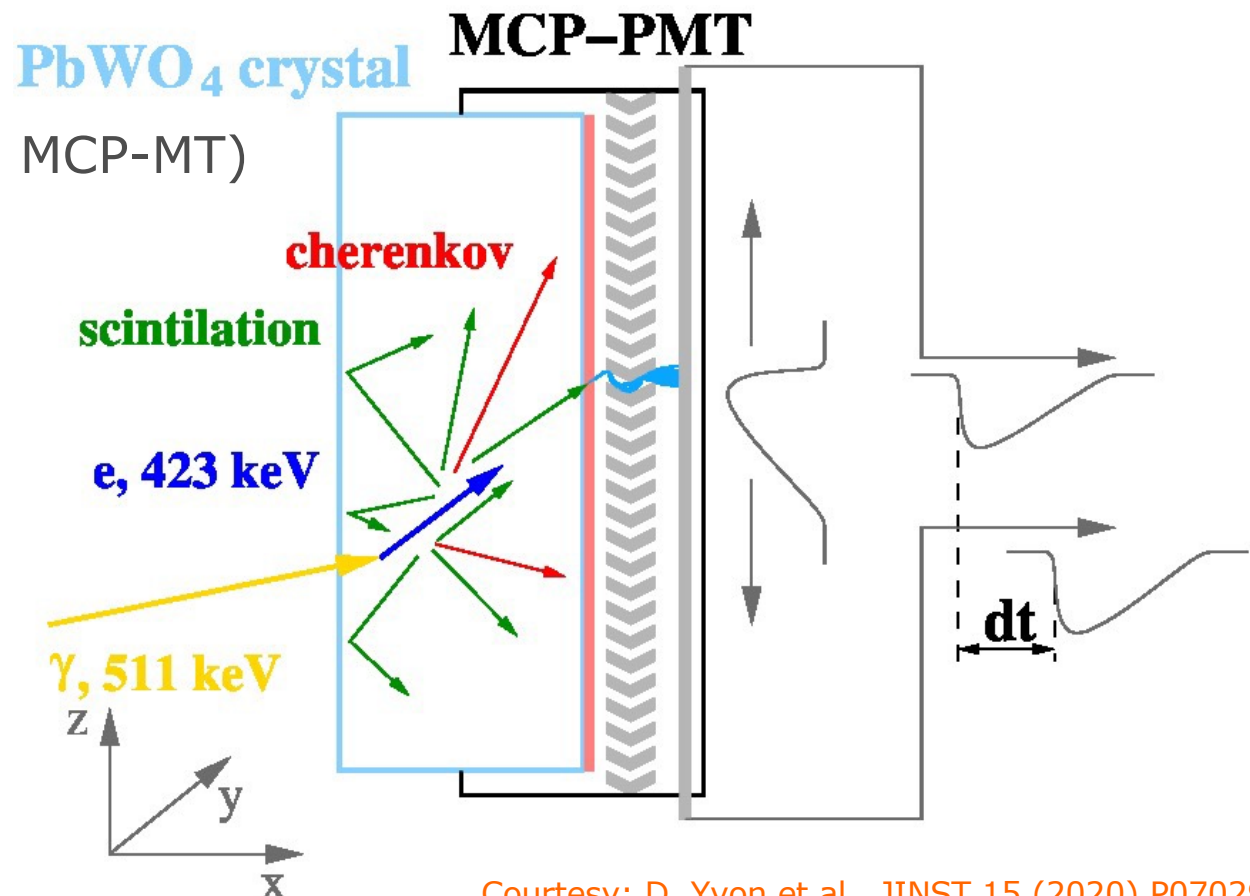
Courtesy: R. Martinez Turtos, CERN



S. Gundacker et al., Phys. Med. Biol. 65 (2020) 025001

- Détection des photons Cerenkov émis dans le  $\text{PbWO}_4:\text{Y}$
- Dépôt d'une photocathode ( $n \sim 2,7$ ) par évaporation directement sur la surface du cristal ( $n \sim 2,3$ )
- Encapsulation dans un tube multiplicateur à galette de micro-canaux (MCP-MT)

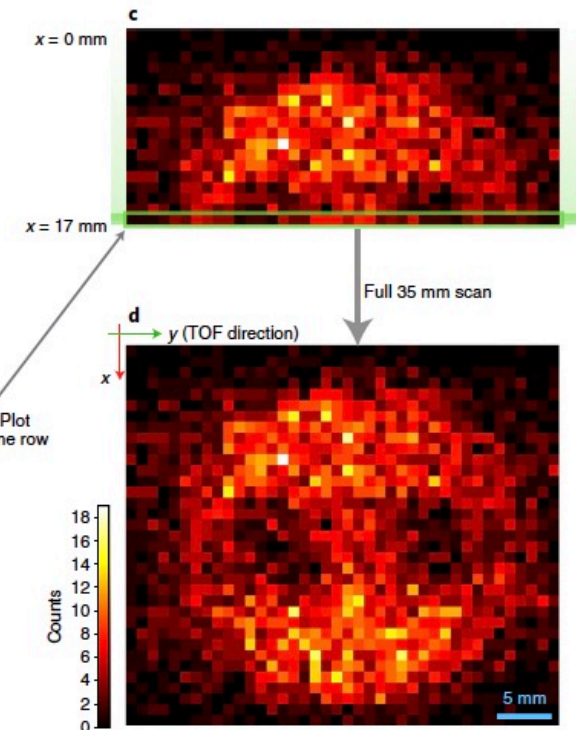
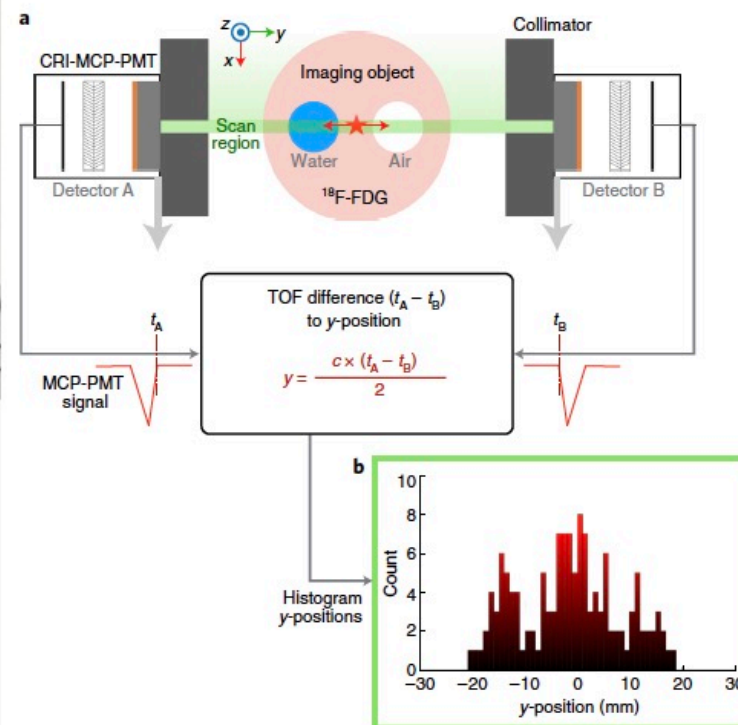
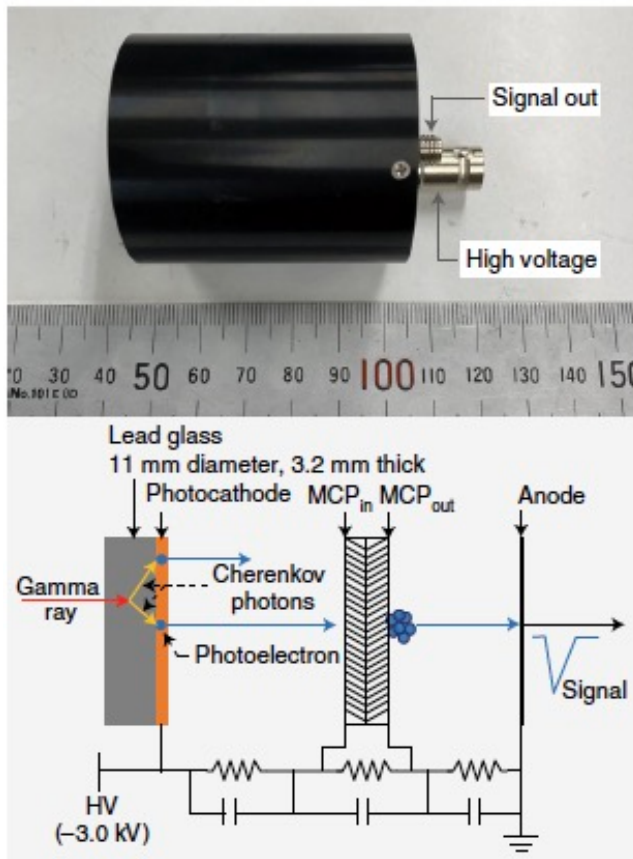
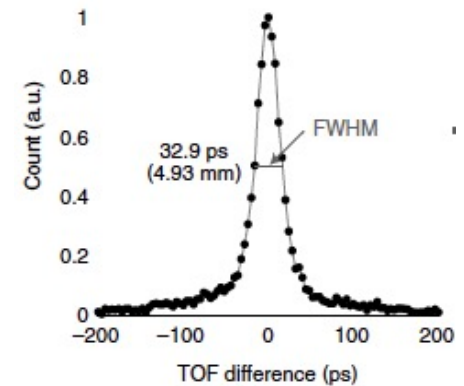
- CRT  $\sim 20$  ps FWHM (hors MCP-MT)



Courtesy: D. Yvon et al., JINST 15 (2020) P07029

# Reconstruction-free positron emission tomography

- Use of Cherenkov light for timing
- CTR 32.9 ps FWHM (4.93 mm)
- Direct positron emission imaging (dPEI)



Courtesy: S.I. Kwon et al., Nat. Photon. 2020



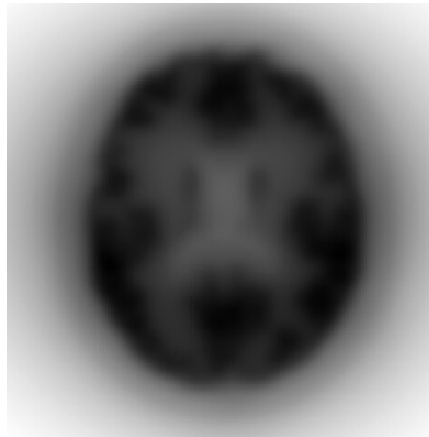
# Resolution in TOF-direction: $\sim 1.5$ mm

## Resolution in detector direction: 5 mm

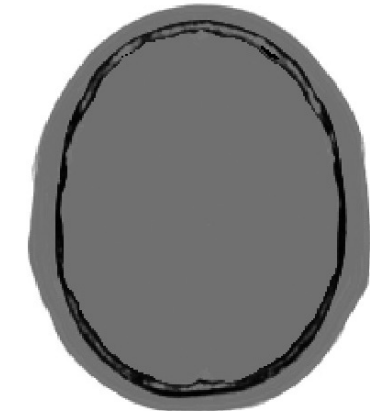
true activity



nonTOF backproj



TOF backproj



true attenuation



nonTOF OSEM



TOF OSEM

Courtesy: J. Nuyts, Univ Leuven

# The 10 ps challenge: a step toward reconstruction-less TOF-PET

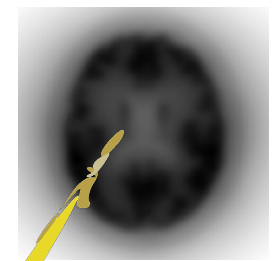
The 10 ps challenge:

- a spur on the development of fast timing
- an opportunity to get together
- an incentive to raise funding
- a way to shed light on nuclear instrumentation for medical imaging and beyond

One unique challenge launched for 5 to 10 years and operated by an international organisation with rules issued by the community based on the measurement of CTR combined to sensitivity

Several milestones and prizes:

- 3 years after the launch of the challenge: 1M€ expected for the **Flash Gordon Prizes** delivered to the 3 best certified achievements
- until the end of the challenge: 1M€ expected for the **Leonard McCoy Prize** for the first team meeting successfully the specifications of the challenge



Non-TOF  
backproj



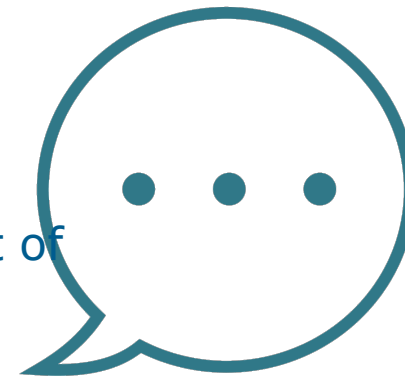
Non-TOF  
OSEM



10 ps TOF  
backproj



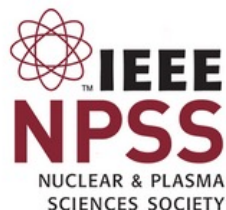
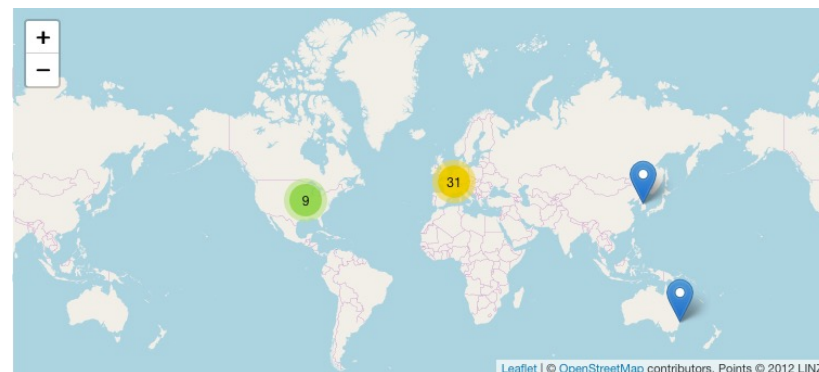
10 ps TOF  
OSEM



# The10ps-challenge.org



## Scientists



## Companies

IEEE NPSS NMISC





Association des anciens et  
amis du CNRS

<https://www.a3cnrs.org/>

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Rayons X : des premiers clichés radiographiques au scanner spectral / Christian Morel

Tomographie par émission de positons ( TEP ) / David W. Townsend

Simulation Monte Carlo en imagerie médicale / Sébastien Jan

Imagerie vibrationnelle des systèmes vivants / Hervé Rigneault

Multimodalité et imagerie médicale / Luc Bidaut

Systèmes hybrides TEP/IRM / Claude Comtat

Enjeux Européens de la R&D en imagerie médicale / Paul Lecoq

NeuroSpin, *voir le cerveau penser* / Fabrice Bonardi



N° 69- HIVER 2016/2017

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