

Imagerie biomédicale – physique

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

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De la physique au détecteur – IN2P3 – Villa Clythia, Fréjus – 24-29 novembre 2024

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)

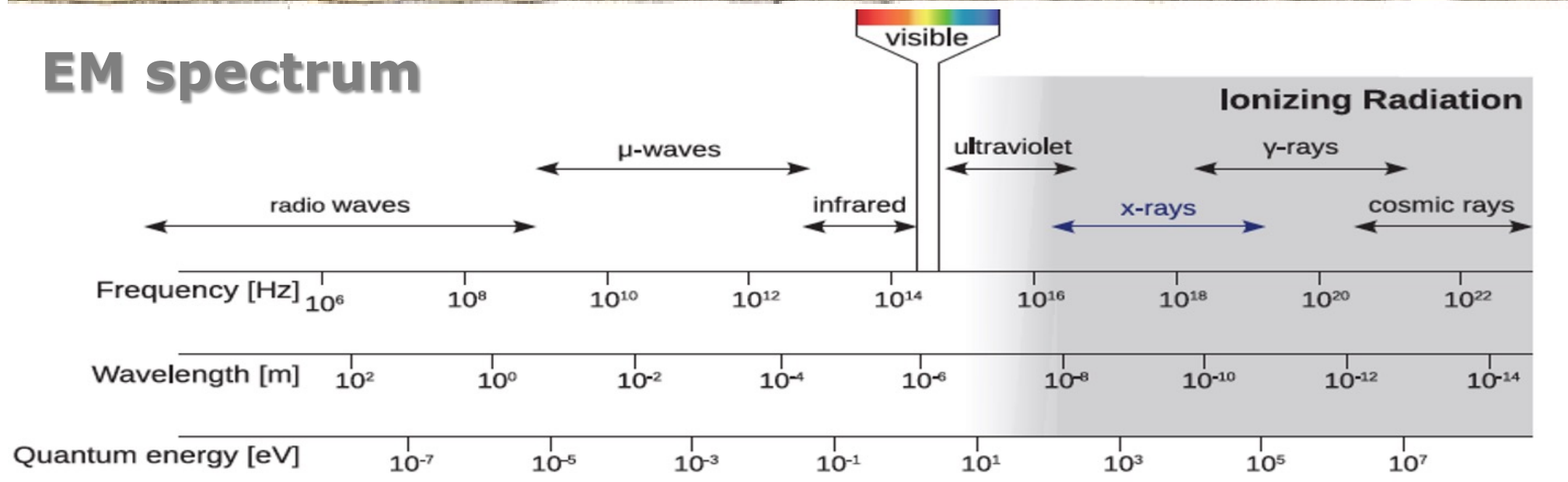
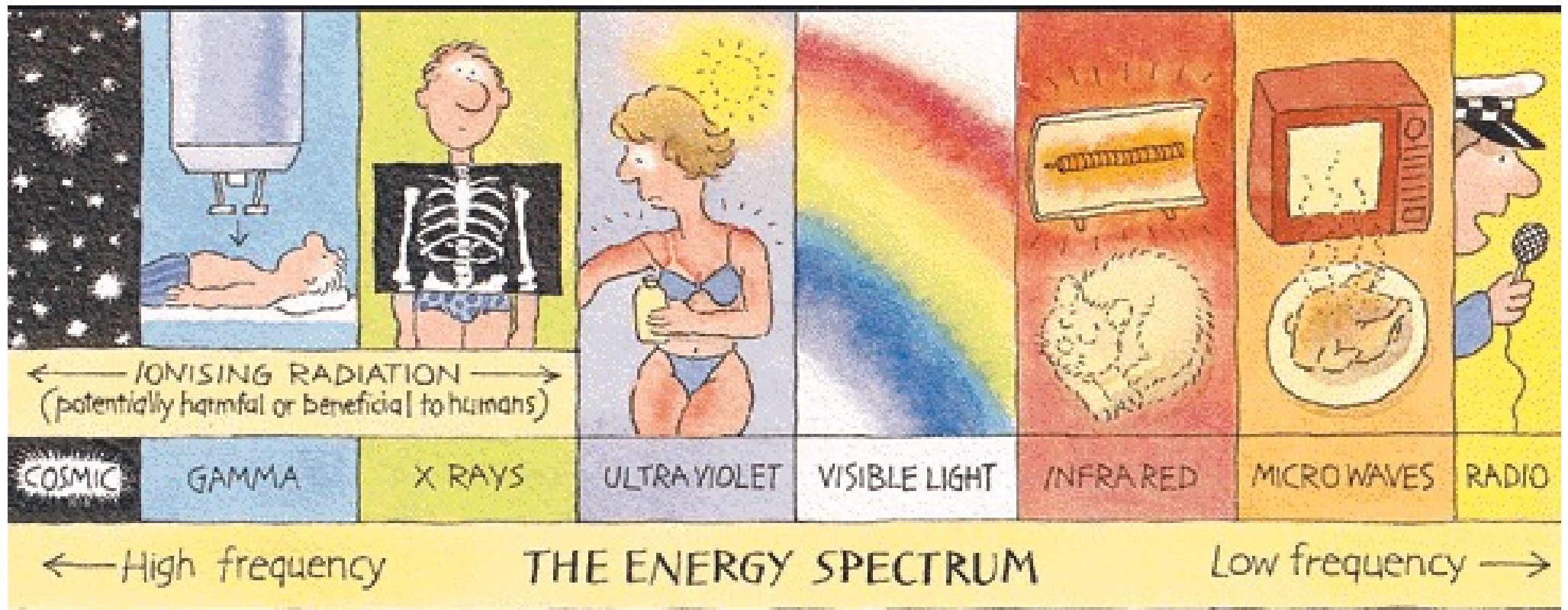


Hôpital Tenon (Paris, 1897)
Antoine Béclère (1858–1939)

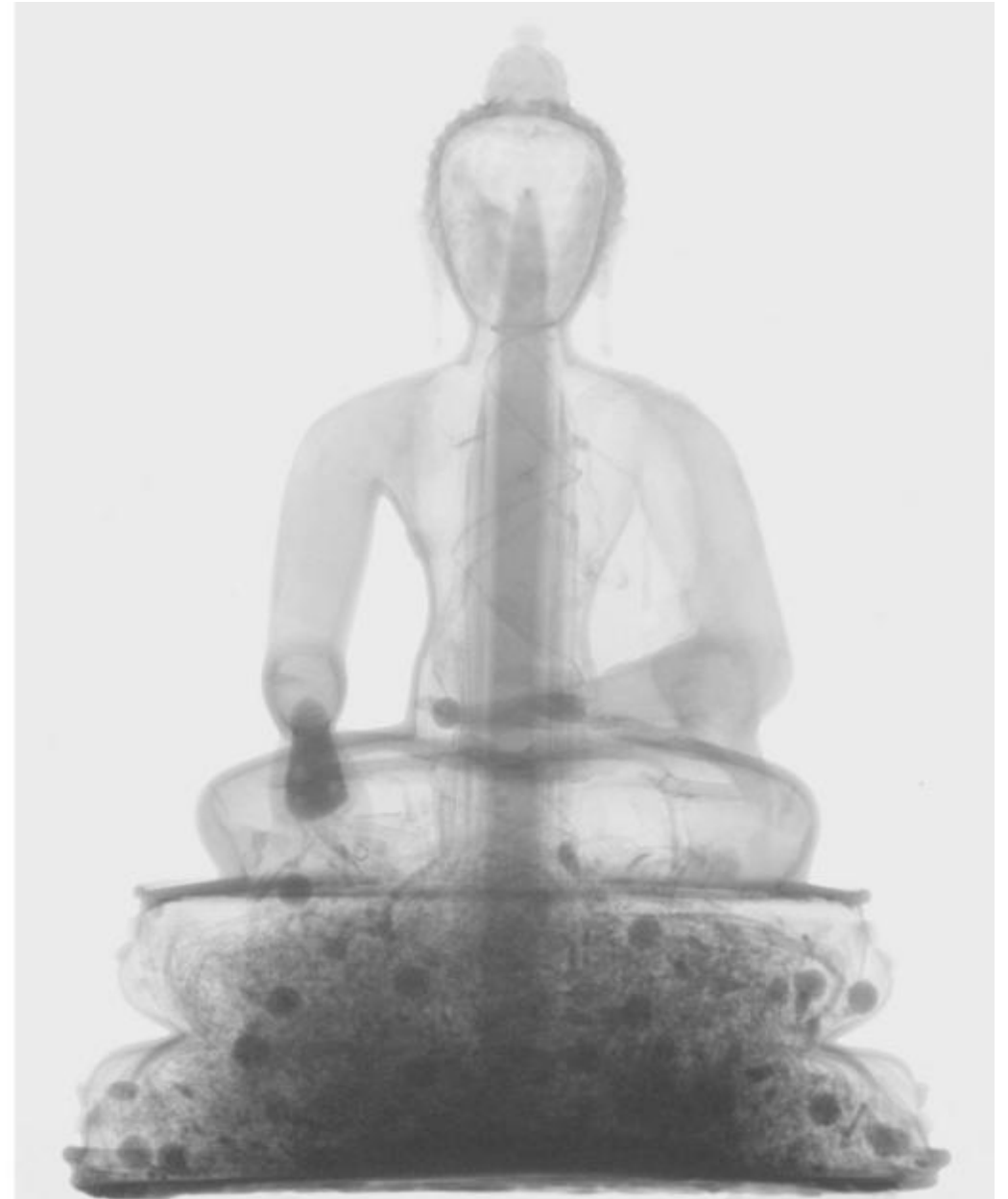


Radiological Renault «Petite Curie» (1916)
Marie Curie (1867-1934)



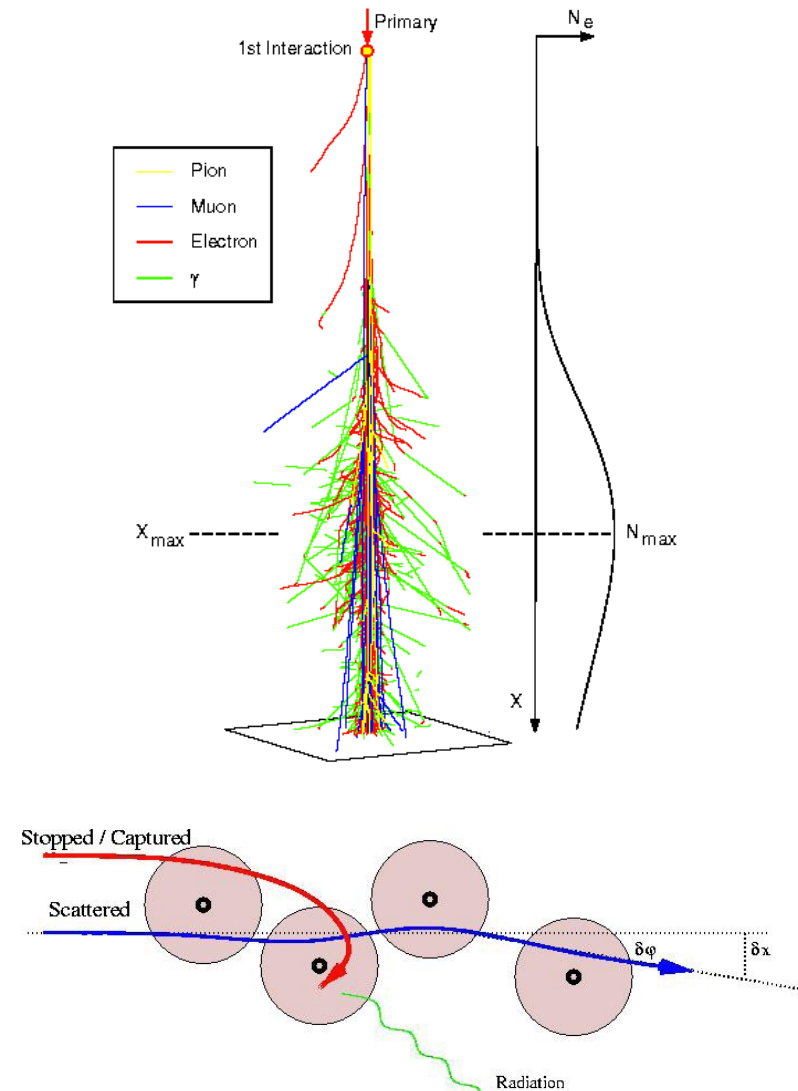
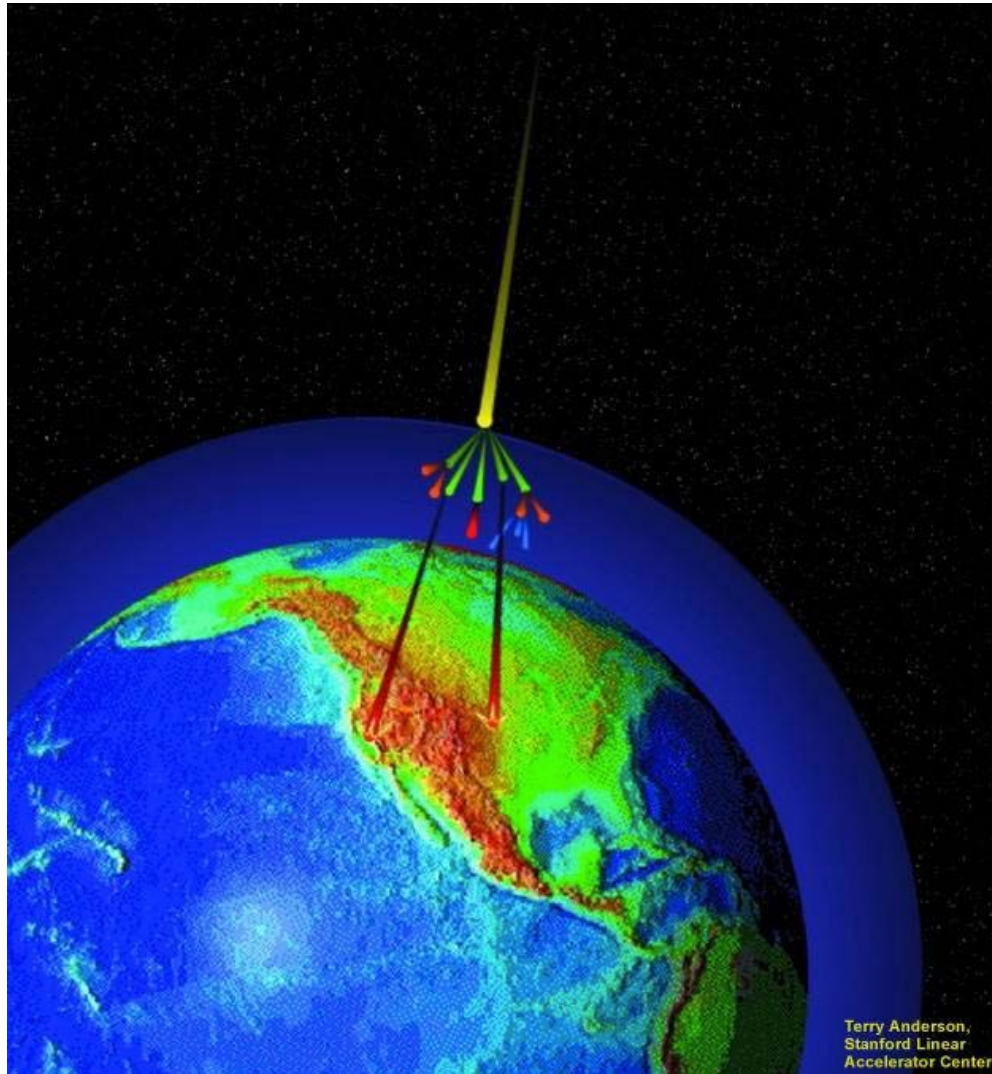


Radiographie X et neutrons



Courtesy: Paul Scherre Institut (PSI)

Radiographie par transmission de muons cosmiques



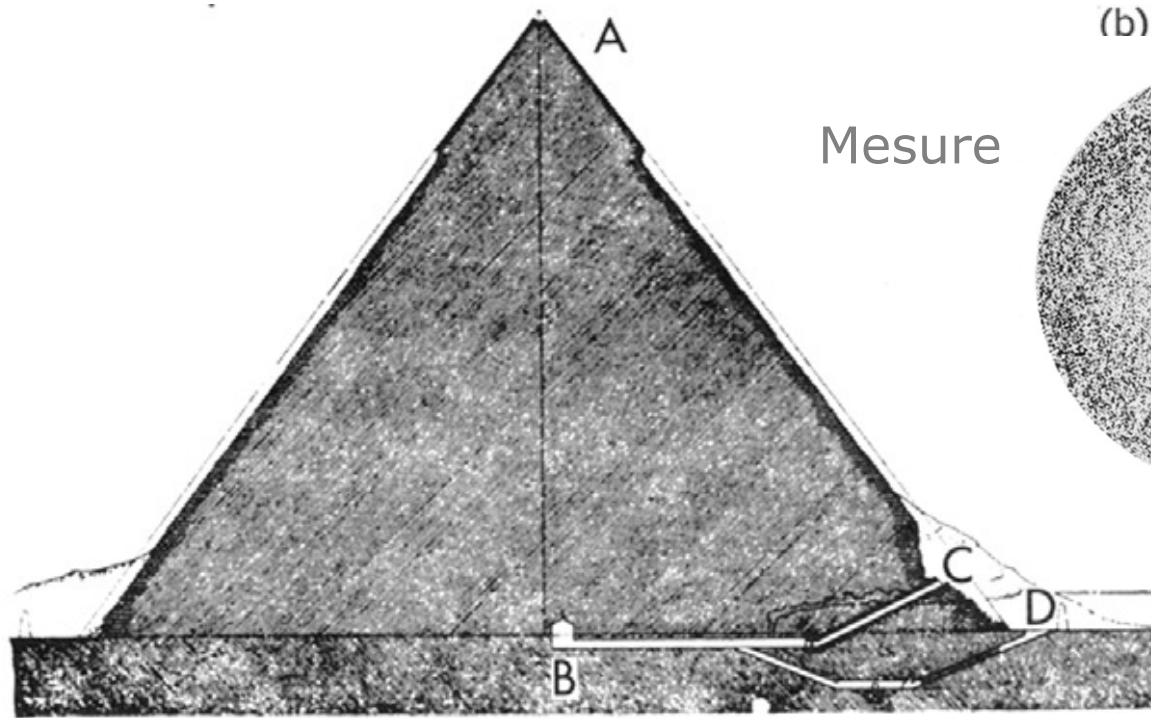
- Au niveau de la mer, le taux de muons cosmiques est de 10,000 muons par mètre carré et par minute.
- Interaction des muons (positifs ou négatifs) dans la matière par capture ou par diffusion coulombienne.

Radiographie par transmission de muons cosmiques

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

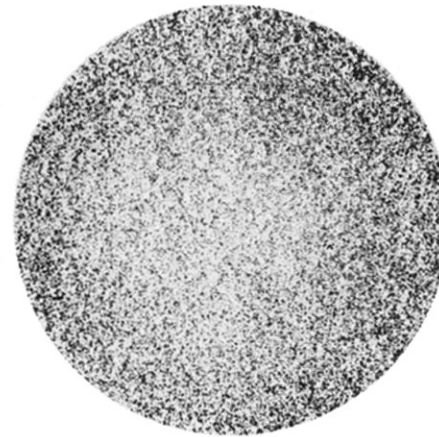


Radiographie par transmission de muons cosmiques



Mesure

(b)



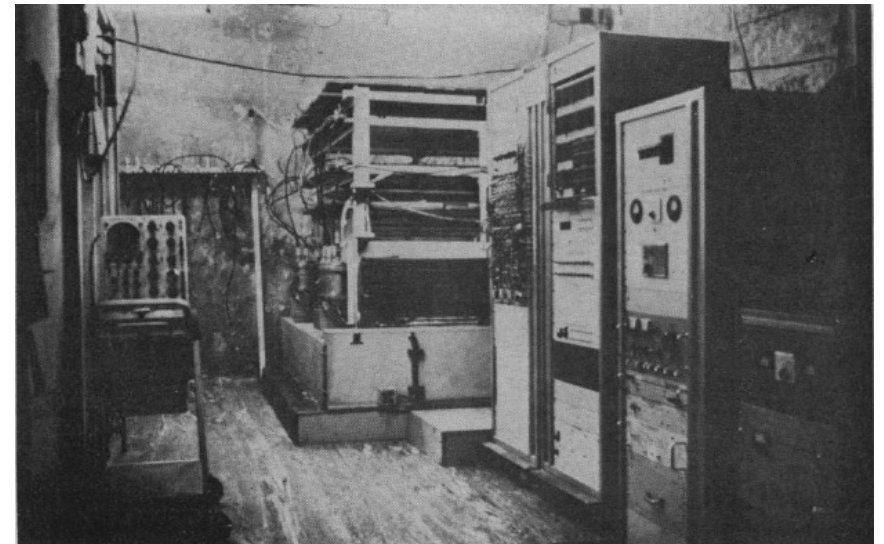
|
S

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 – 24-29 novembre 2024

Tomographie

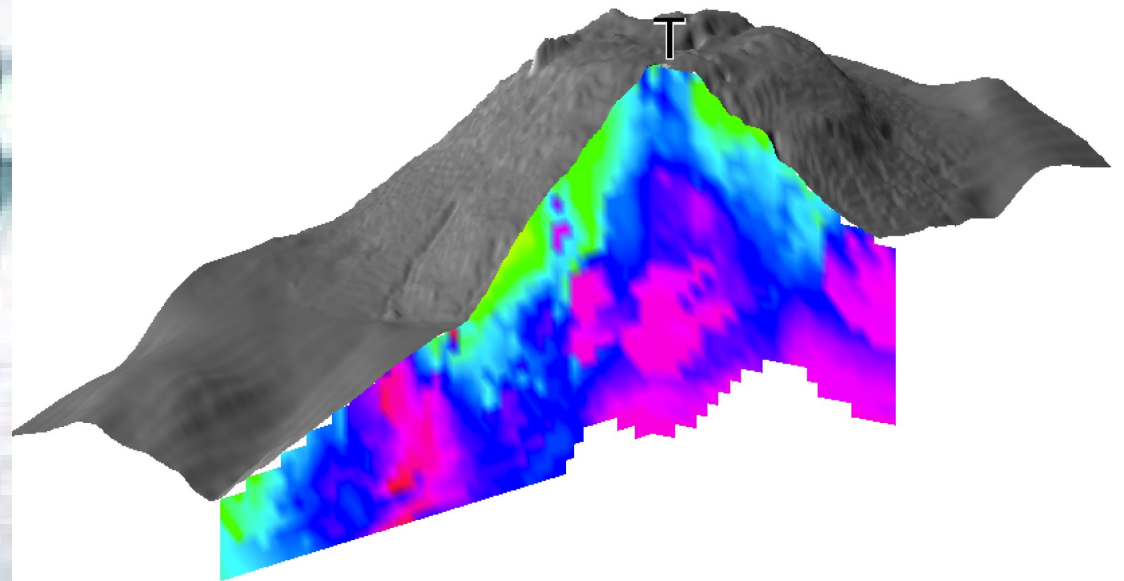
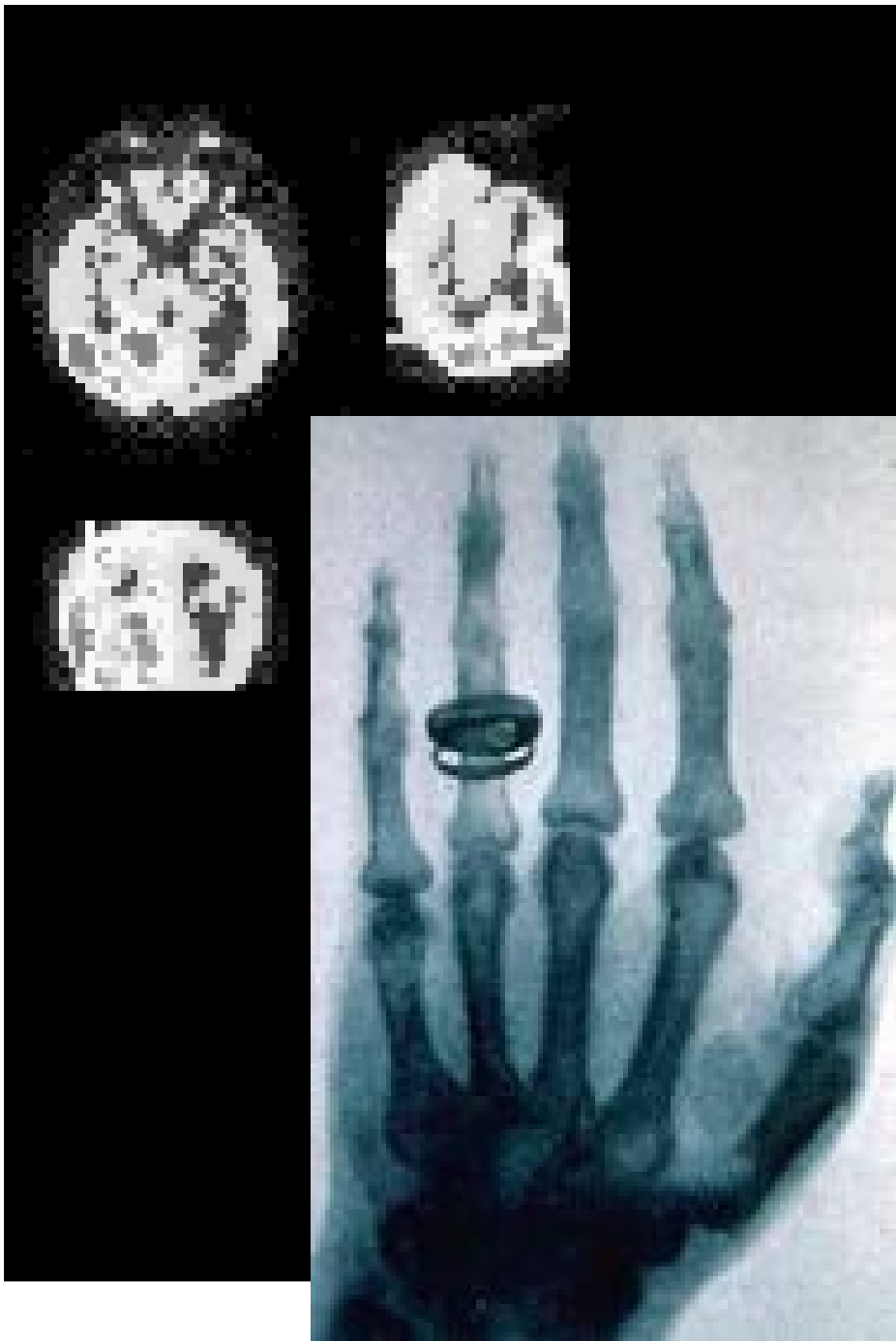
Du grec *tomos* (tranche)

+

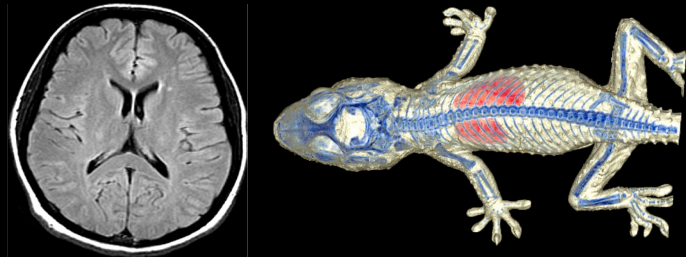
graphein (écrire)

=

Représentation en coupes

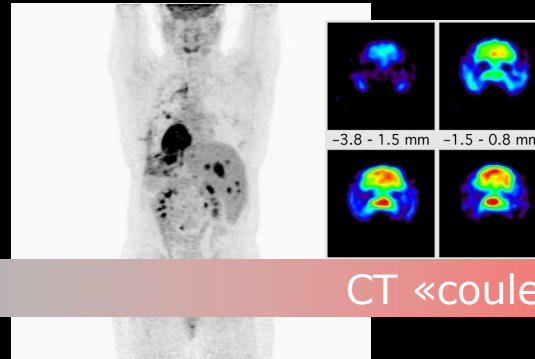


Imagerie anatomique



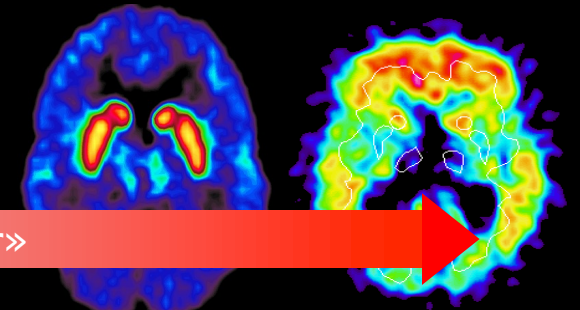
Imagerie par rayons X (CT, DXA)

Imagerie fonctionnelle



CT «couleur»

Imagerie moléculaire



Imagerie isotopique (TEP, TEMP)

mL, pMol

IRM fonctionnelle

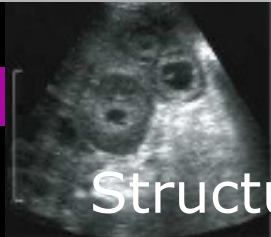


μL , mMol- μMol

Imagerie par résonance magnétique

Spectroscopie par résonance magnétique

Imagerie ultrasonore



Structure

Macroscopique

Mécanisme

Cible

Microscopique

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

Reconstruction d'images tomographiques

Transformée de Radon
Transformée X

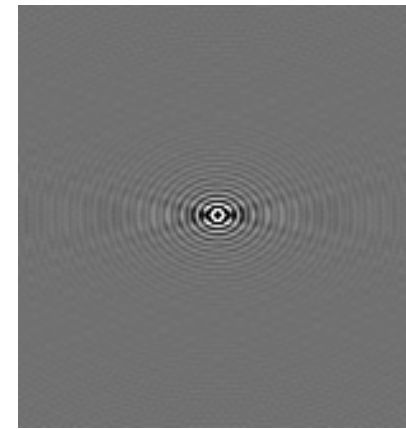


Espace direct

Transformée de Fourier

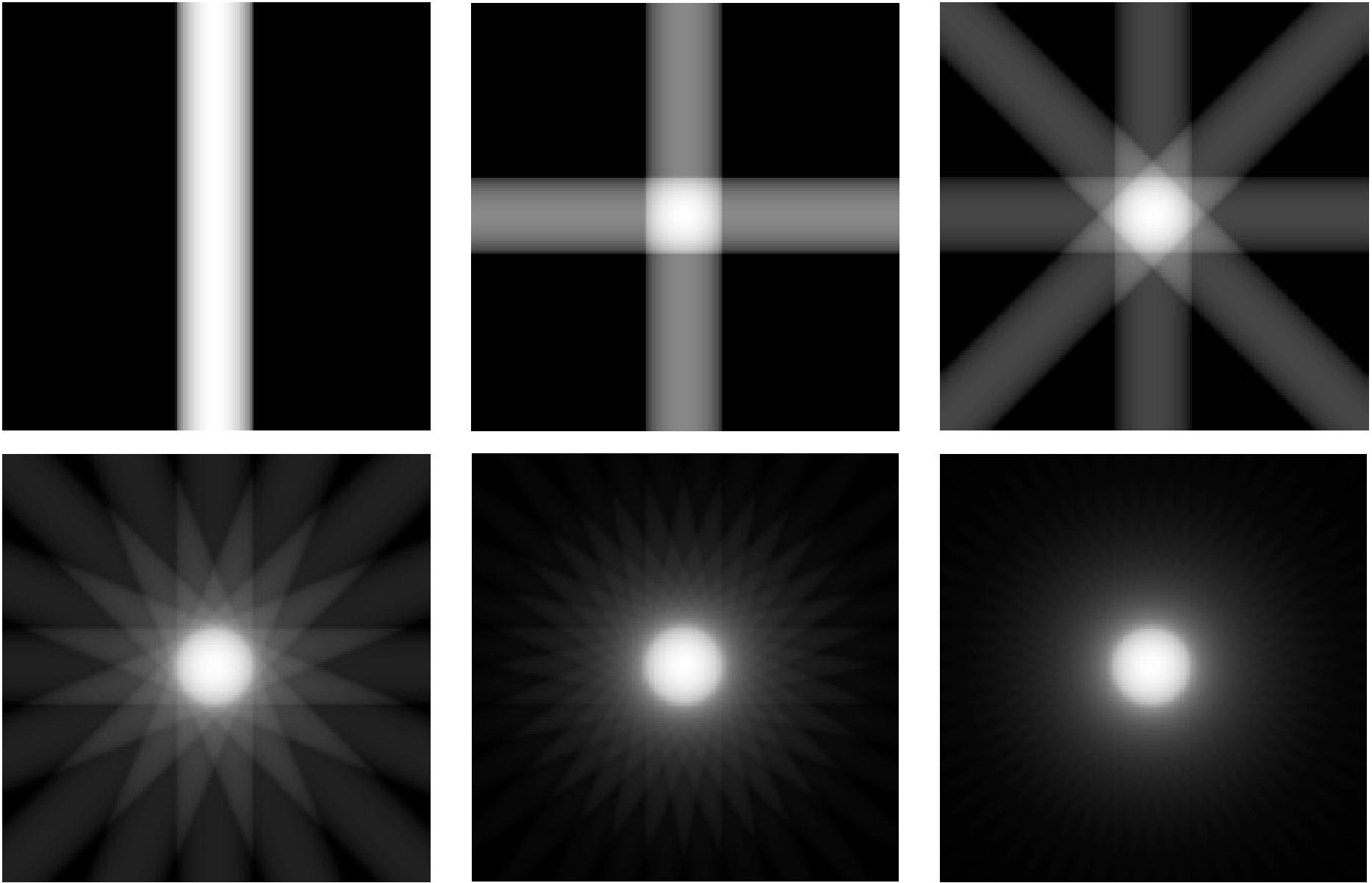


Espaces de projections



Espace des fréquences

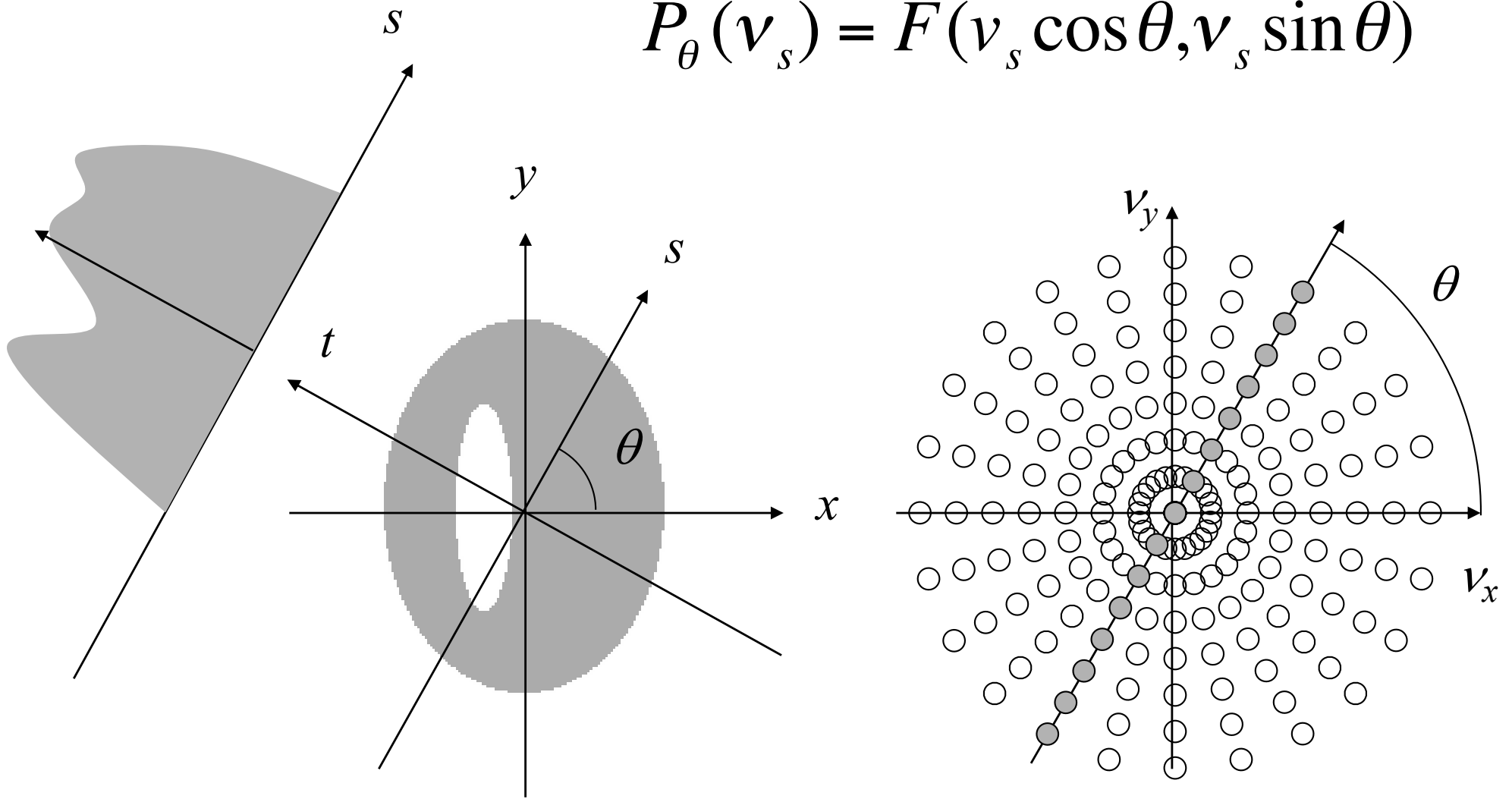
Rétroprojection



Courtesy: S. Valton, Créatis, Lyon

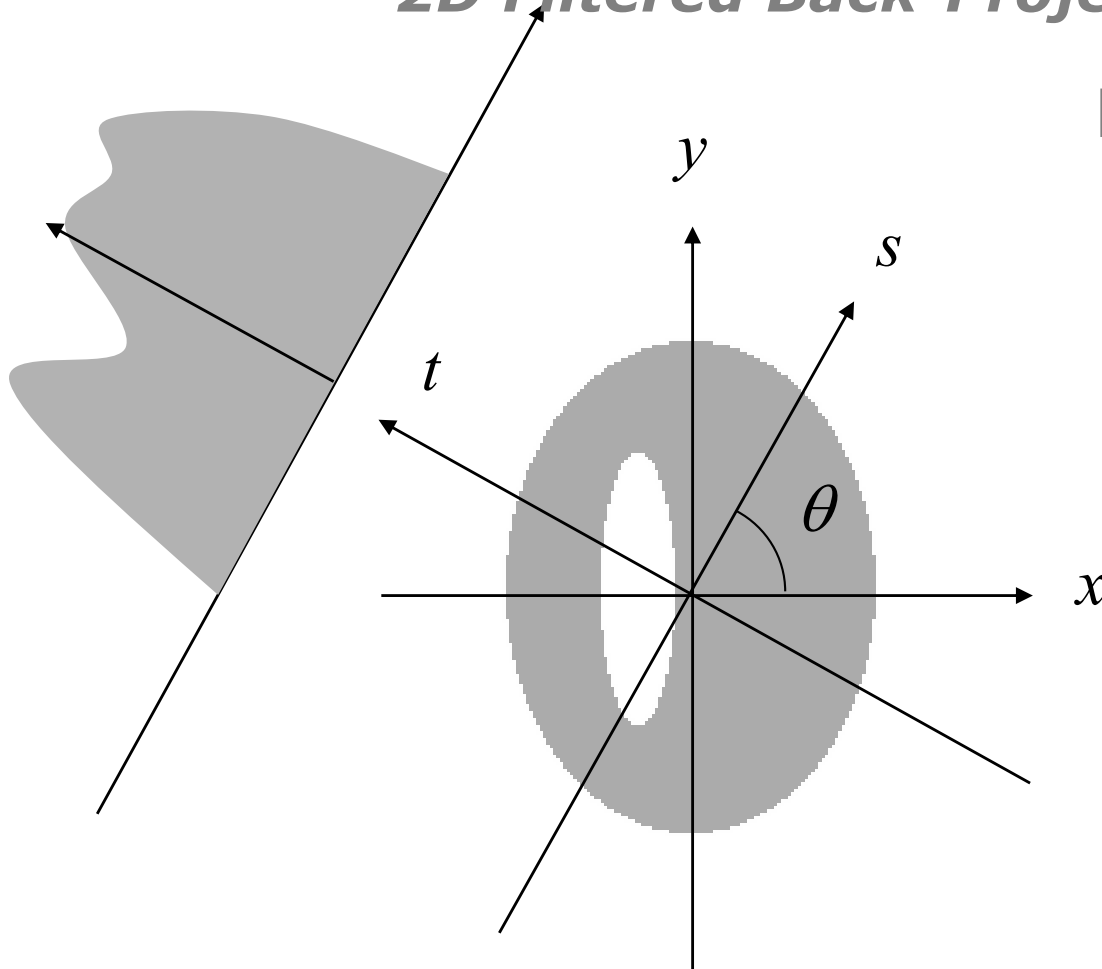
Théorème de la coupe centrale

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



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

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

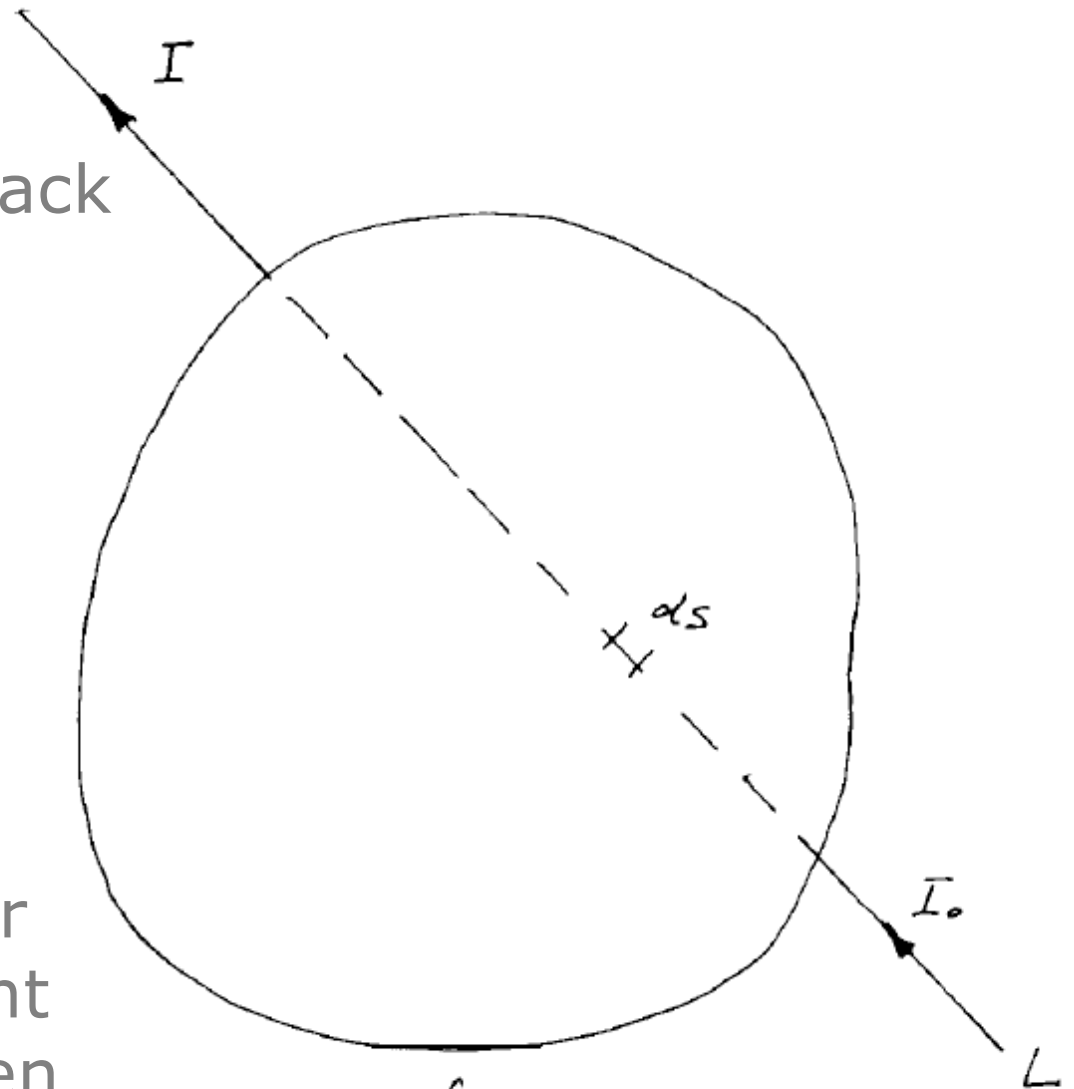
$$f(x, y) = \int_0^{\pi} d\theta \left[\int_{-\infty}^{\infty} dv_s |v_s| P_{\theta}(v_s) e^{i2\pi v_s s} \right], \quad s = x \cos \theta + y \sin \theta$$

Reconstruction 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

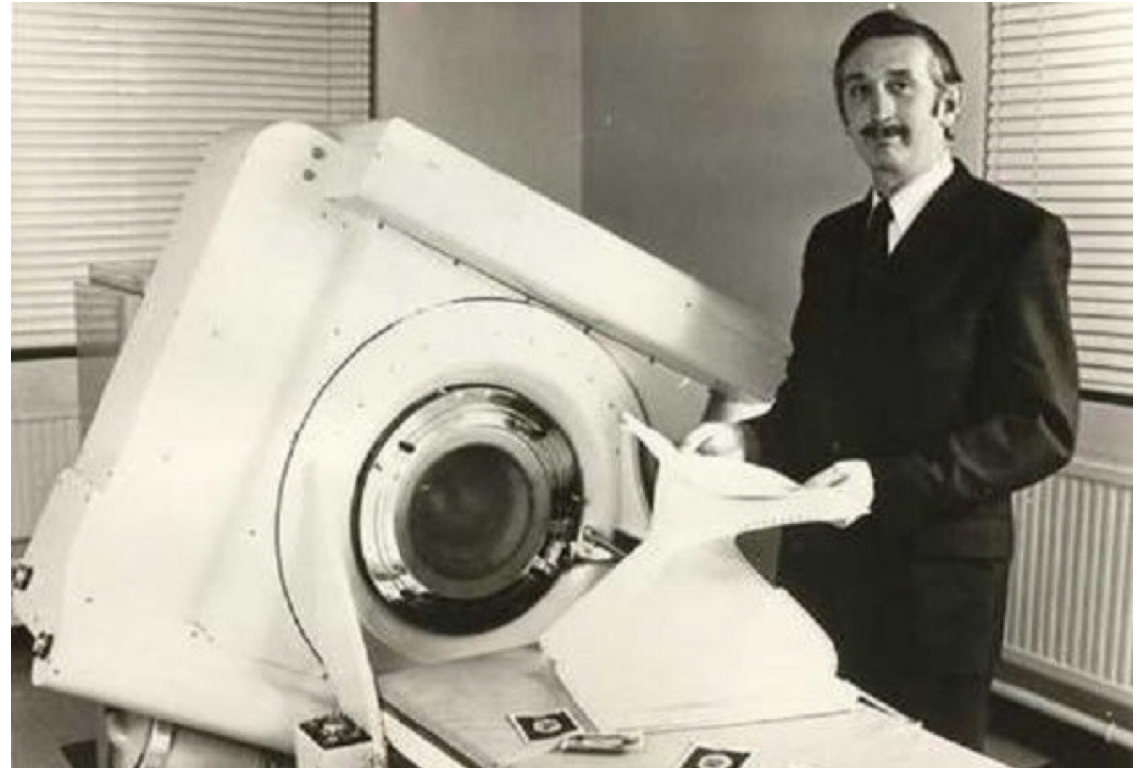


$$I = I_0 e^{-\int_L f ds}$$

Computerized Tomography (CT)

Tomographie par rayons X (*vulgus scanner*)

Tomodensitométrie (TDM)



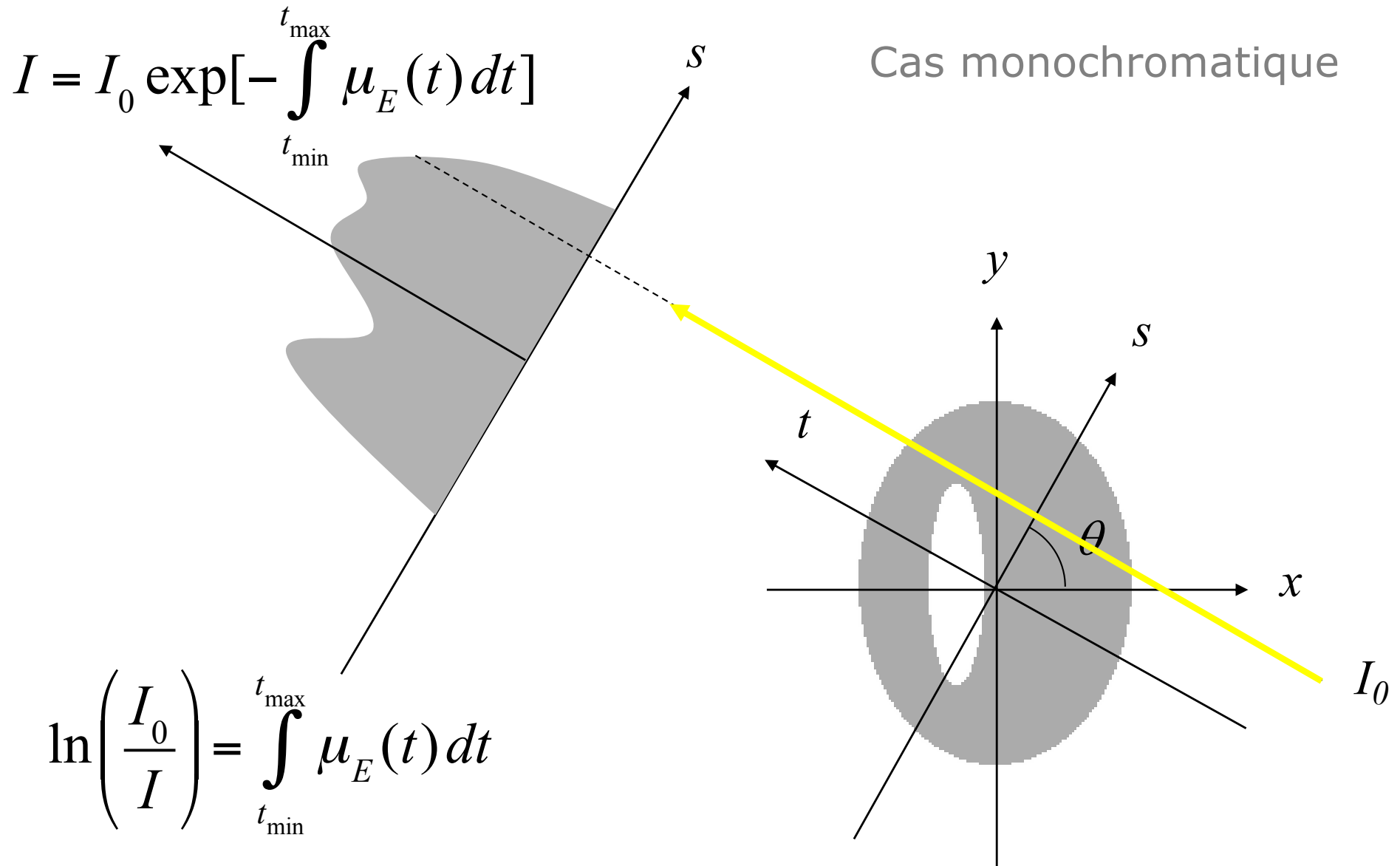
G. Hounsfield, J. Ambrose
(Atkinson Morley Hospital, London, 1/10/1971)

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

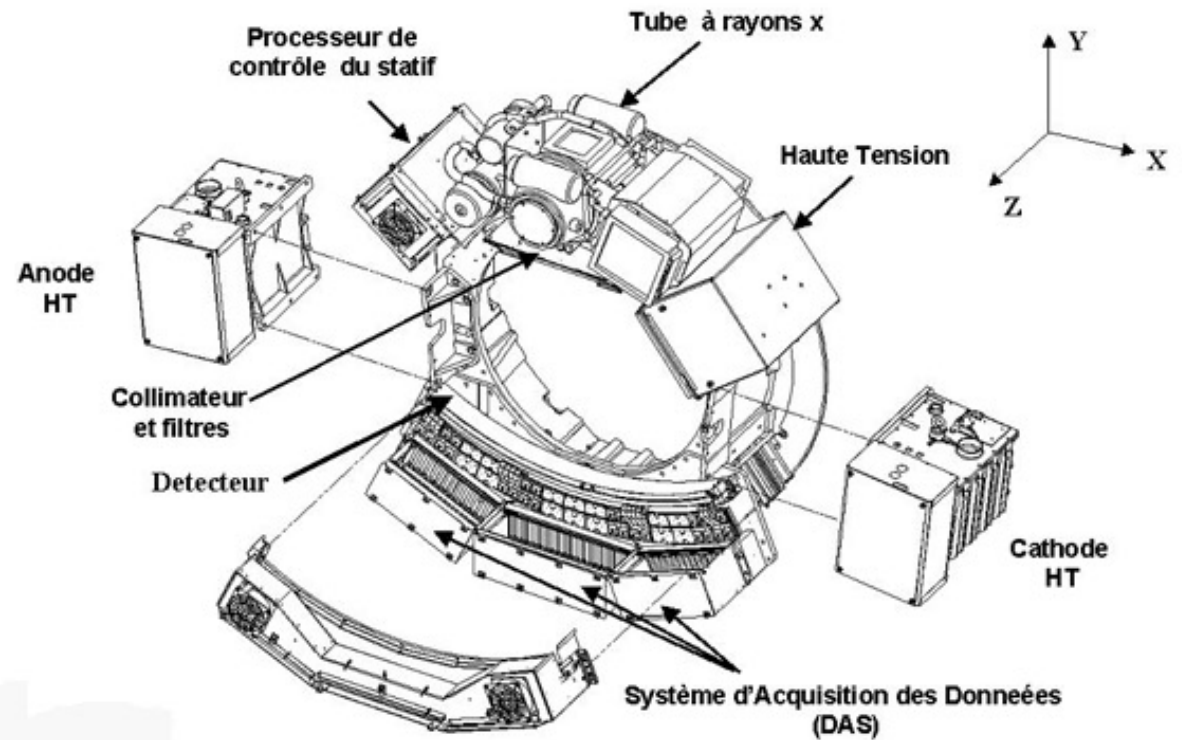
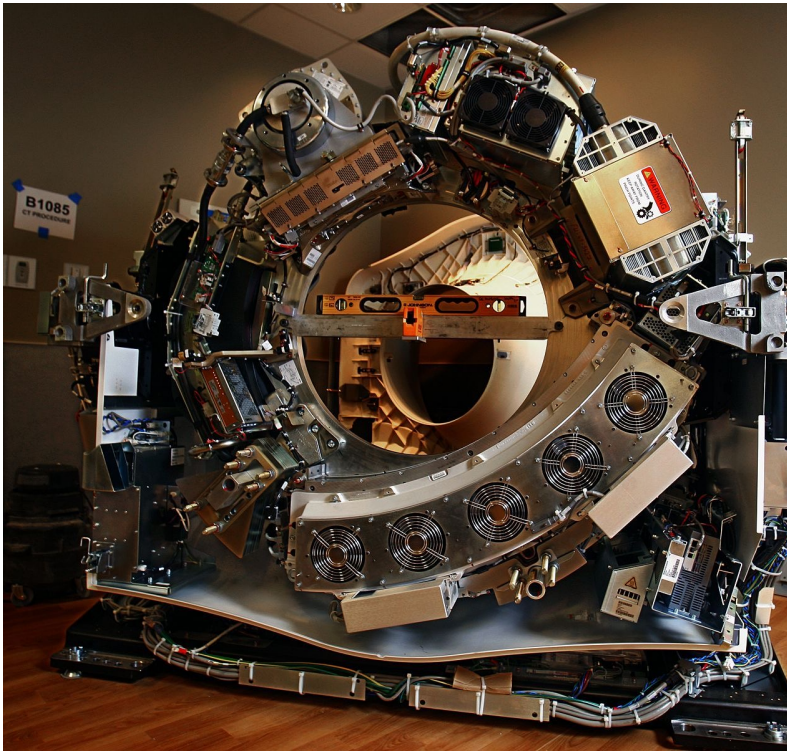
1979: Hounsfield et Cormack reçoivent le prix Nobel de médecine pour le développement de la tomographie assistée par ordinateur



Tomographie par transmission de rayons X



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.

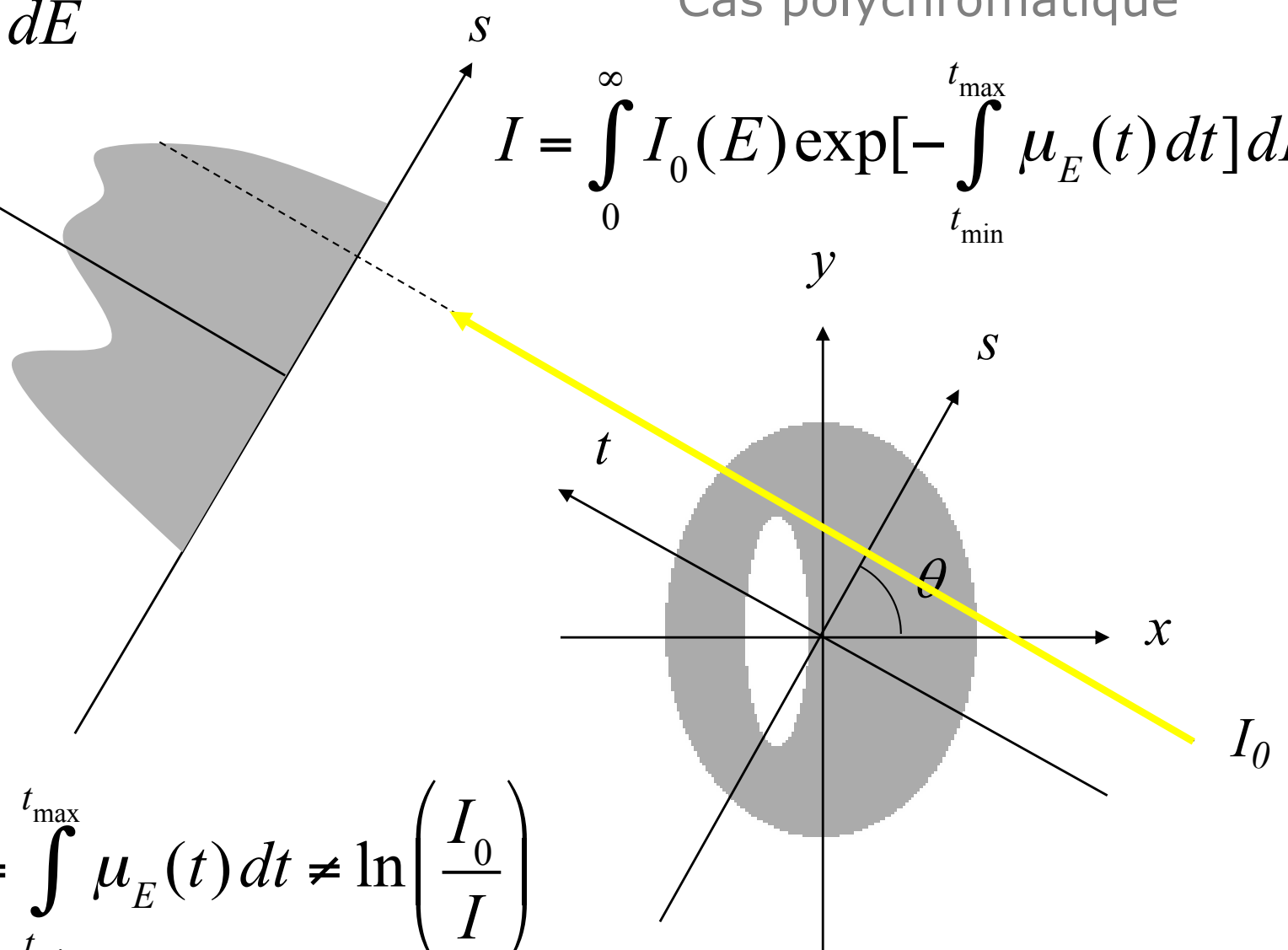
Tomographie par transmission de rayons X

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

Cas polychromatique

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

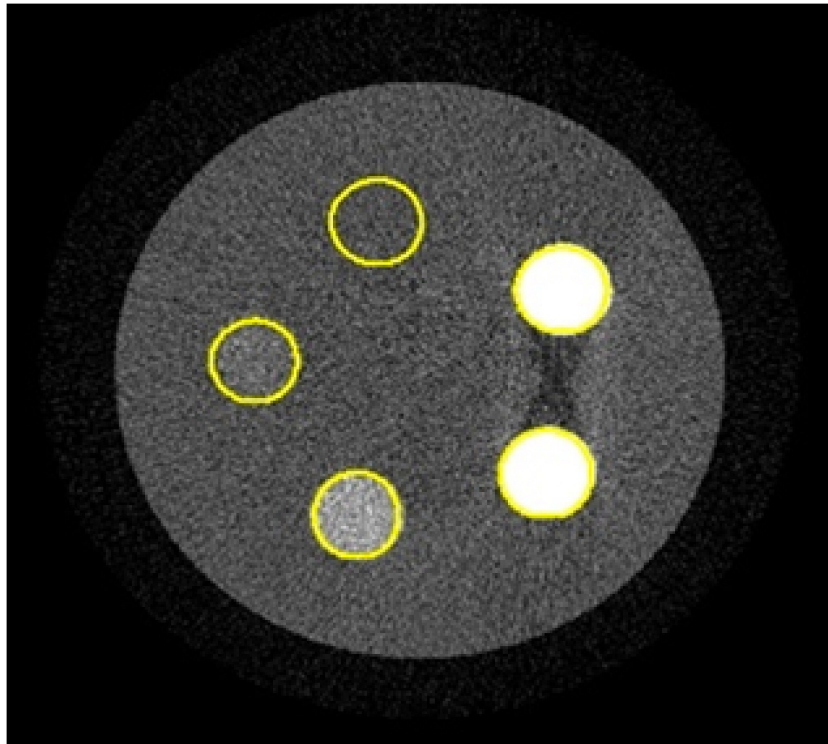
$$\ln\left(\frac{I_0(E)}{I(E)}\right) = \int_{t_{\min}}^{t_{\max}} \mu_E(t) dt \neq \ln\left(\frac{I_0}{I}\right)$$



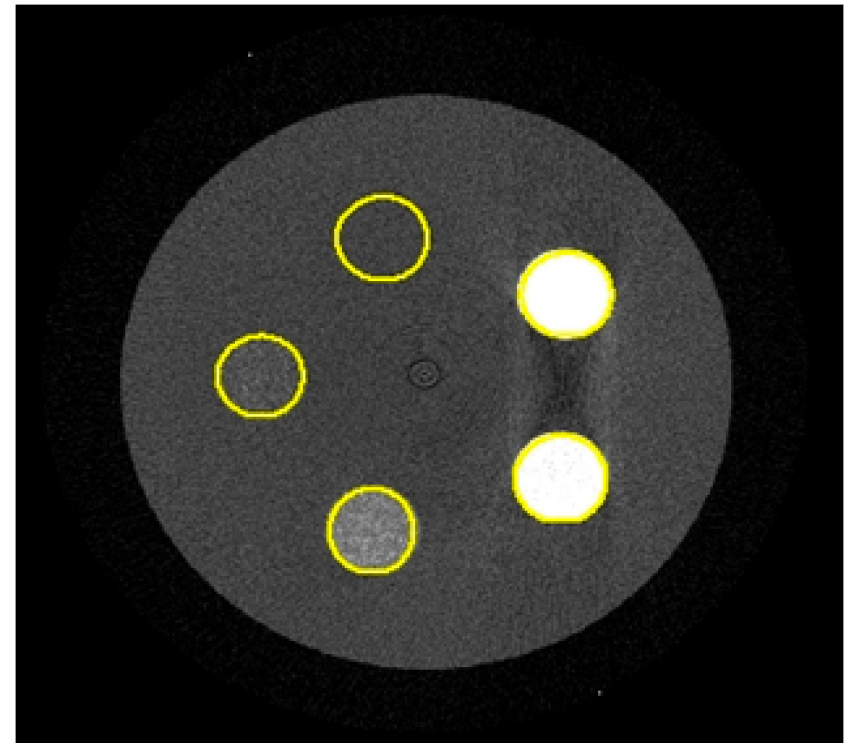
Tomographie par transmission de rayons X

Cas polychromatique -> durcissement de faisceau

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



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



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

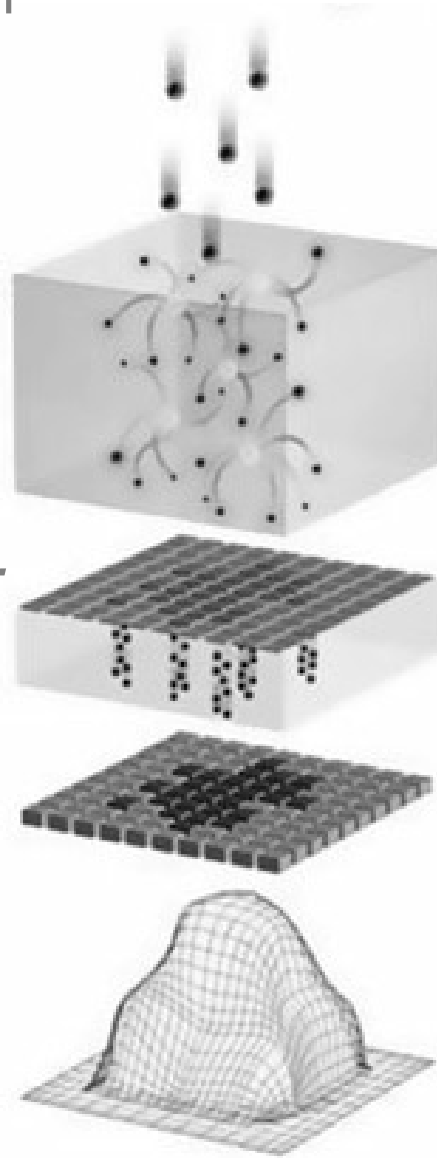
X-ray detection paradigm

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

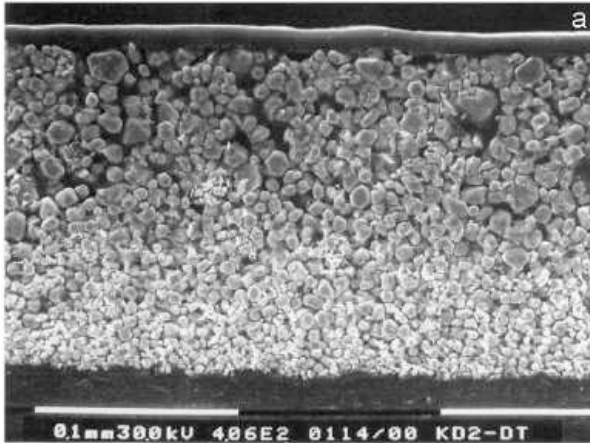
Image



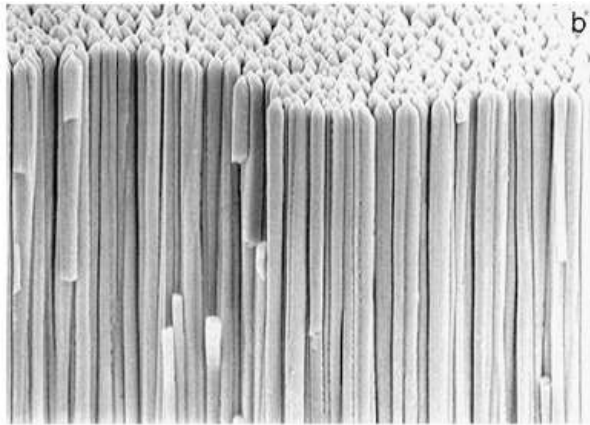
Courtesy: P. Russo and A. Del Guerra, INFN

Energy integration detectors

Converter



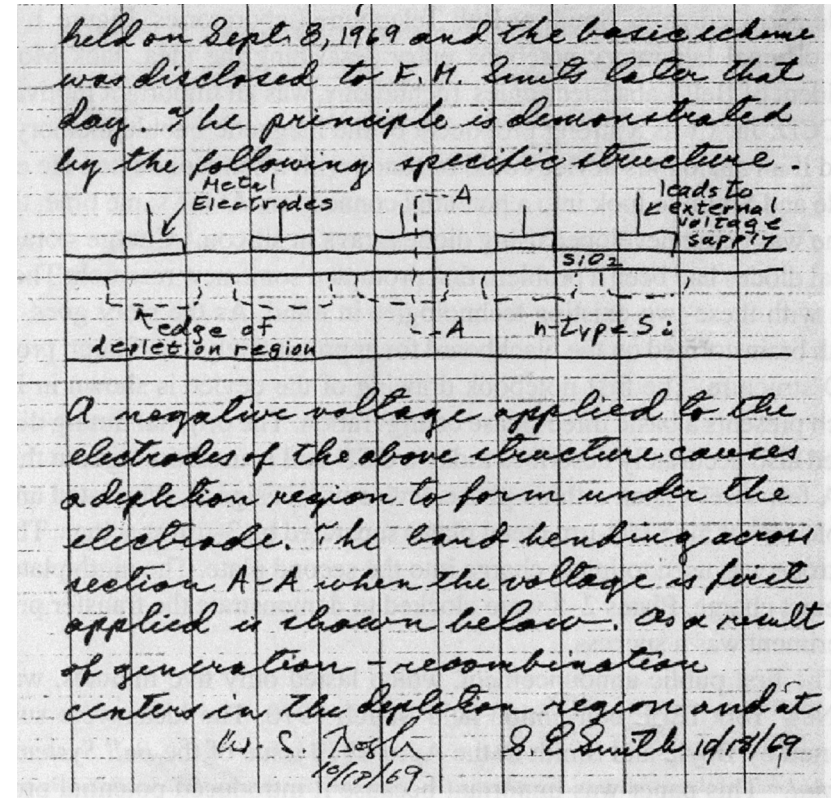
Gadolinium oxysulfide
(GOS or Gadox, Gd_2O_2S)



Cesium iodide (CsI)

Photodetector

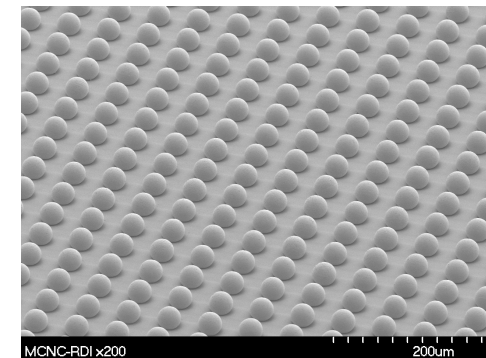
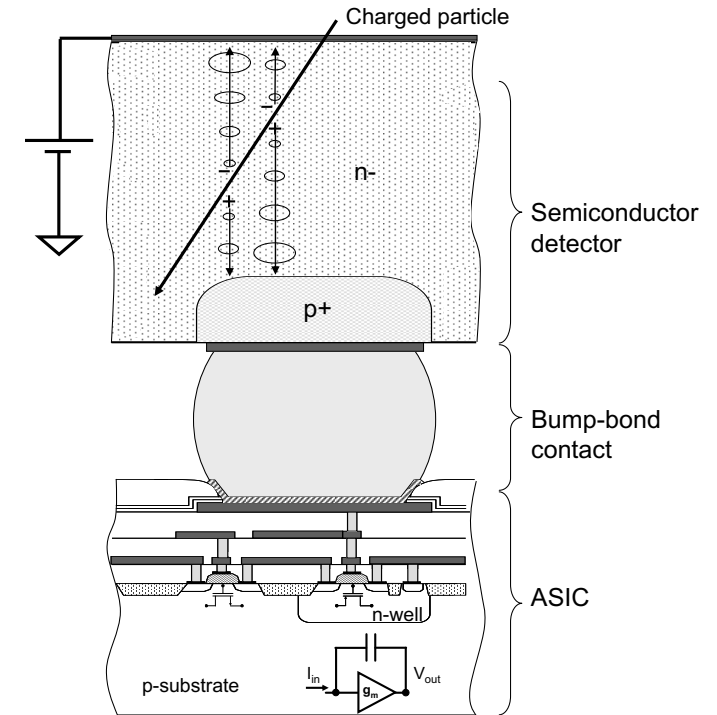
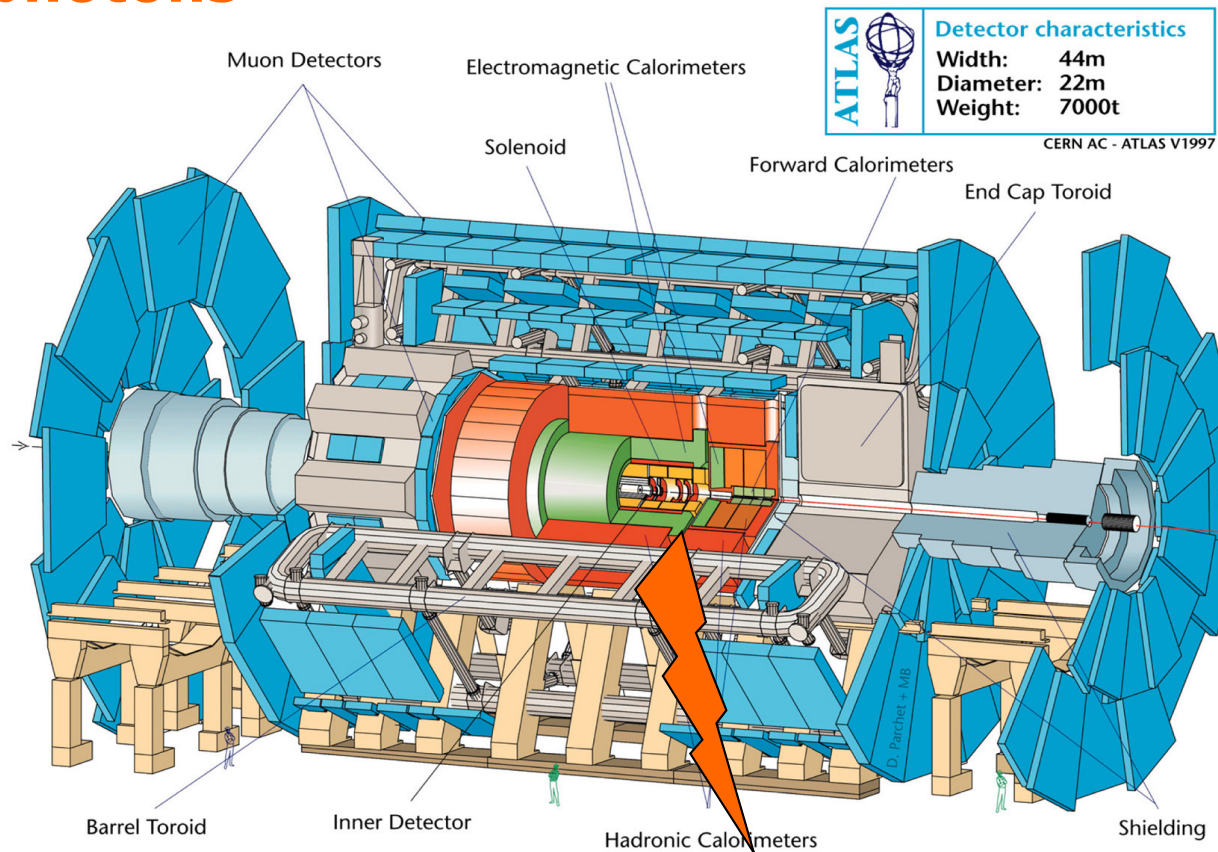
Charged Couple Device (CCD) camera



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

Complementary Metal-Oxide Semiconductor
(CMOS) pixel

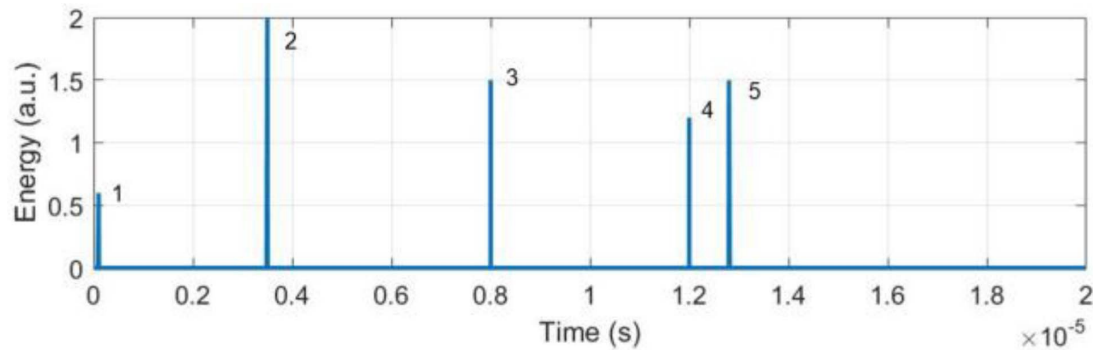
Détecteurs à comptage de rayons X: une rupture technologique pour le développement du CT à comptage de photons



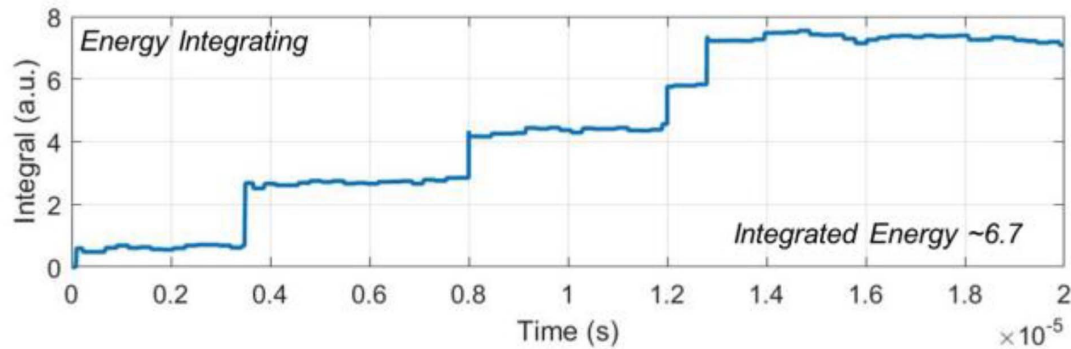
- Suppression du bruit
- Sélection de l'énergie
- Grande dynamique

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

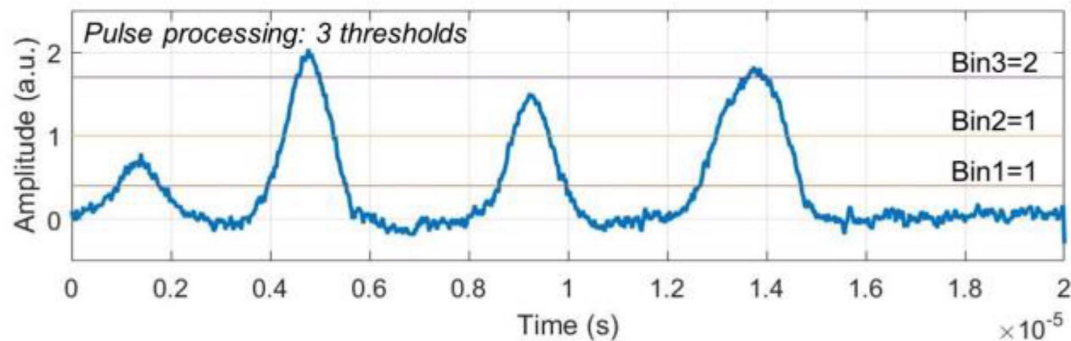
Energy integrating versus photon counting detectors



Arrival times



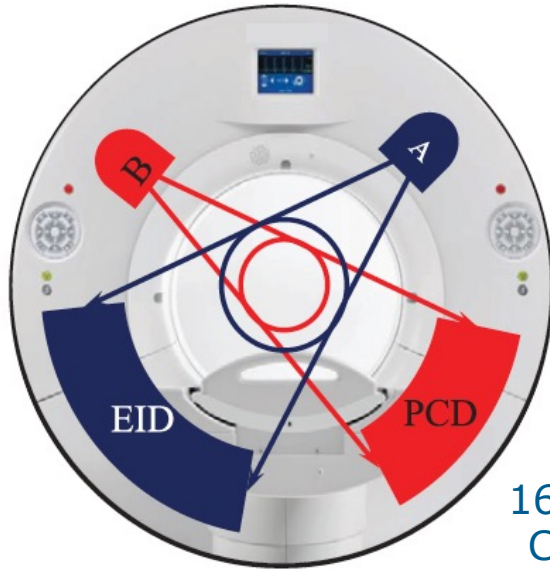
Energy integrating detector (EID)



Photon counting detector (PCD)

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

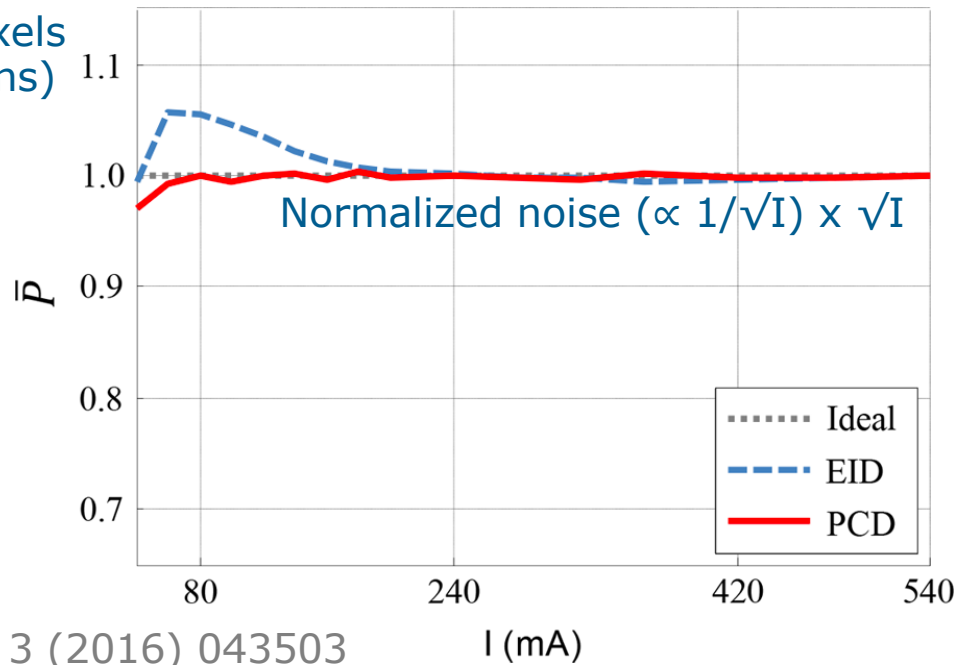
Noise performance of low-dose-CT with EID and PCD



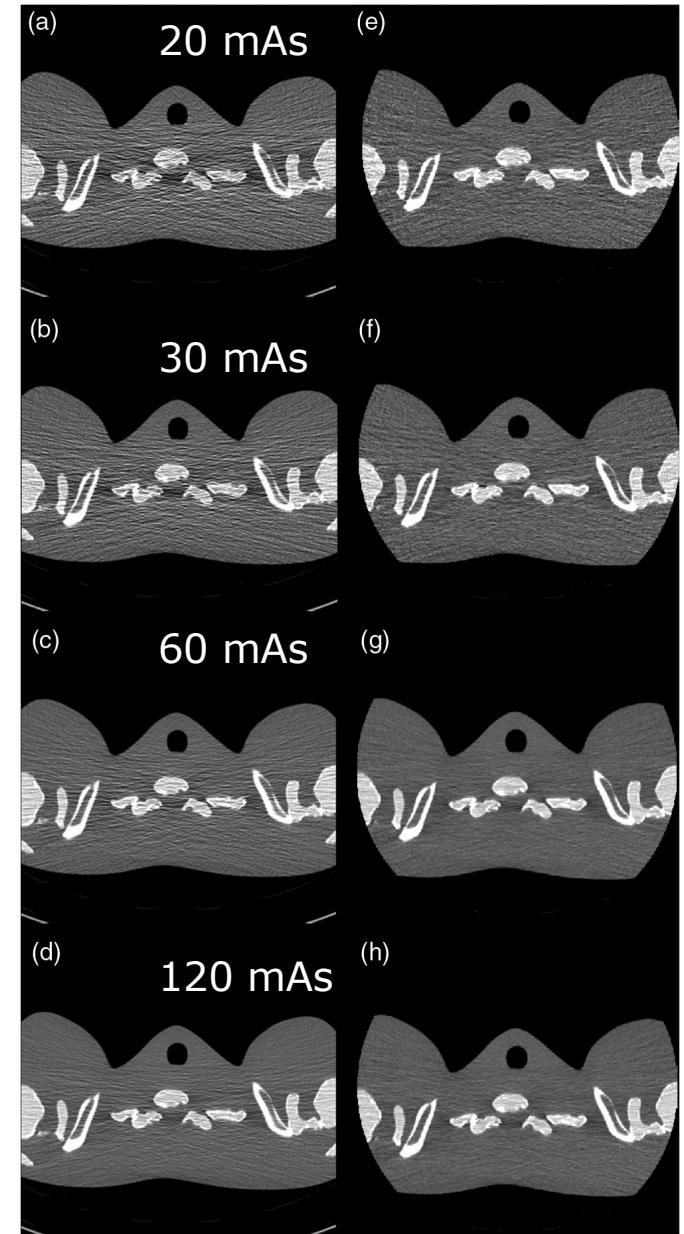
Mayo Clinic (Rochester)
and Siemens Healthcare

16 mm thick
CdTe pixels

Gadox/CMOS pixels
(Stellar, Siemens)



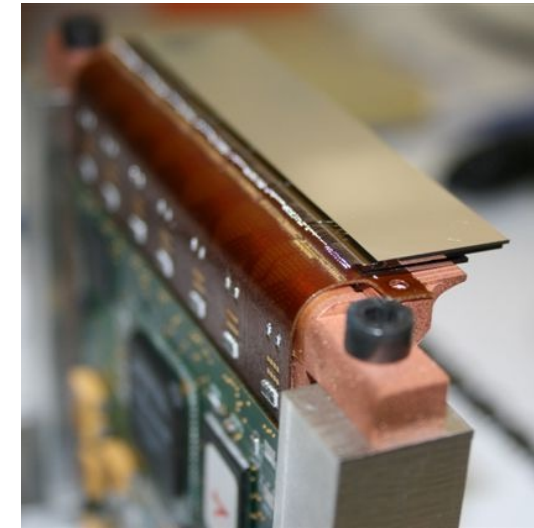
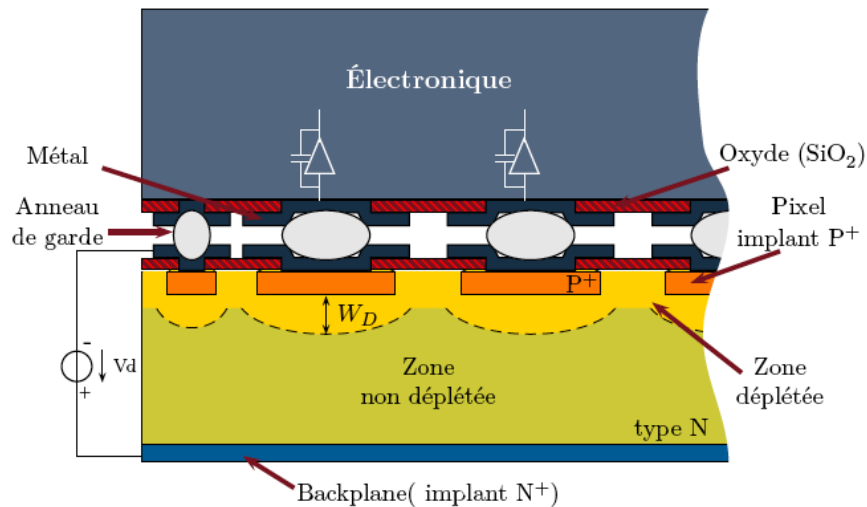
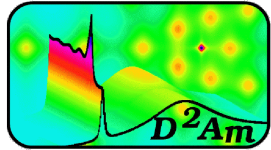
Yu *et al.*, JMI 3 (2016) 043503



EID

PCD

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



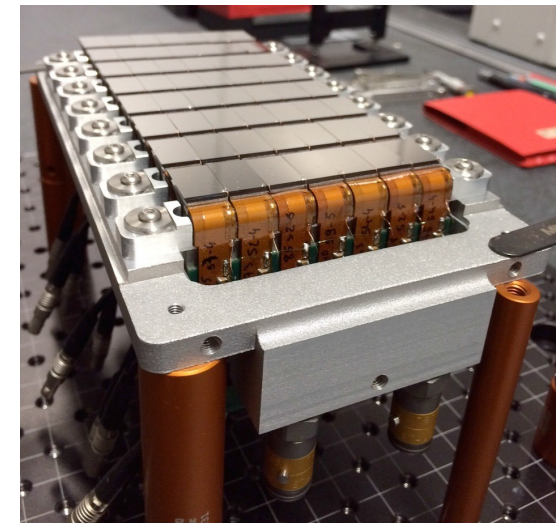
- **XPIX**: Développement des détecteurs à pixels hybrides XPAD.1 et XPAD3.2 avec des capteurs de Si et de CdTe

- > 0,5 Mpixels 130 x 130 μm^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)



Détecteur XPAD3: 500,000 pixels de 130 μm



Angiographie de la souris

- Injection de 200 μL d'ioméron 400
- Tube à anode de tungstène
- 90 kVp, 70 W
- Filtre 200 μm Nb
- Temps d'exposition 10 ms/images
- Vitesse d'acquisition 69 images/s

PC-CT avec le prototype PIXSCAN II

Temps réel



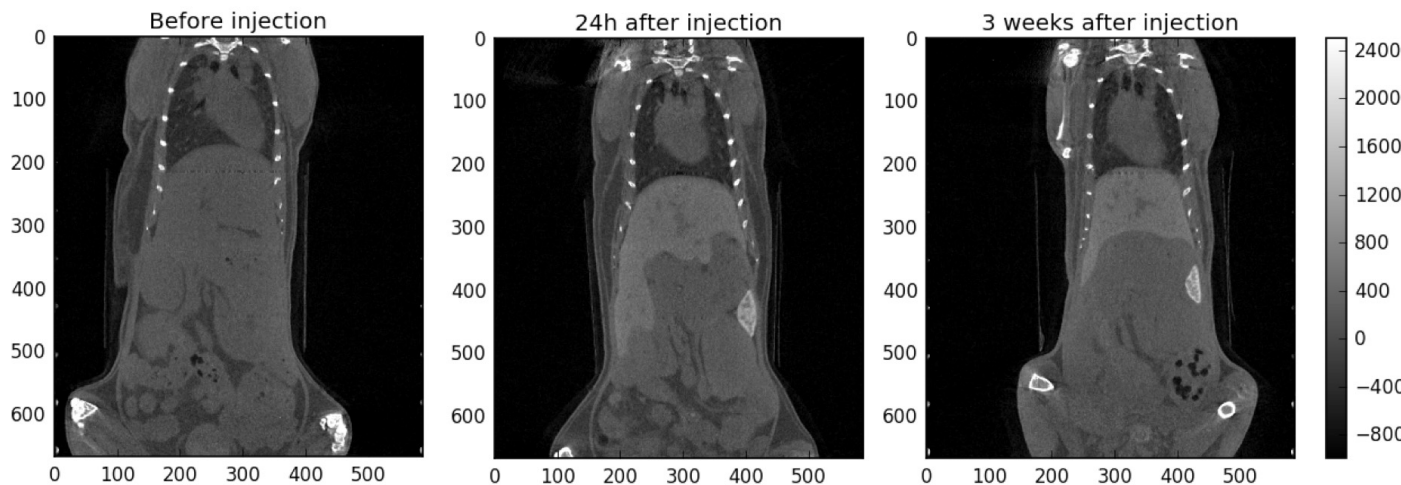
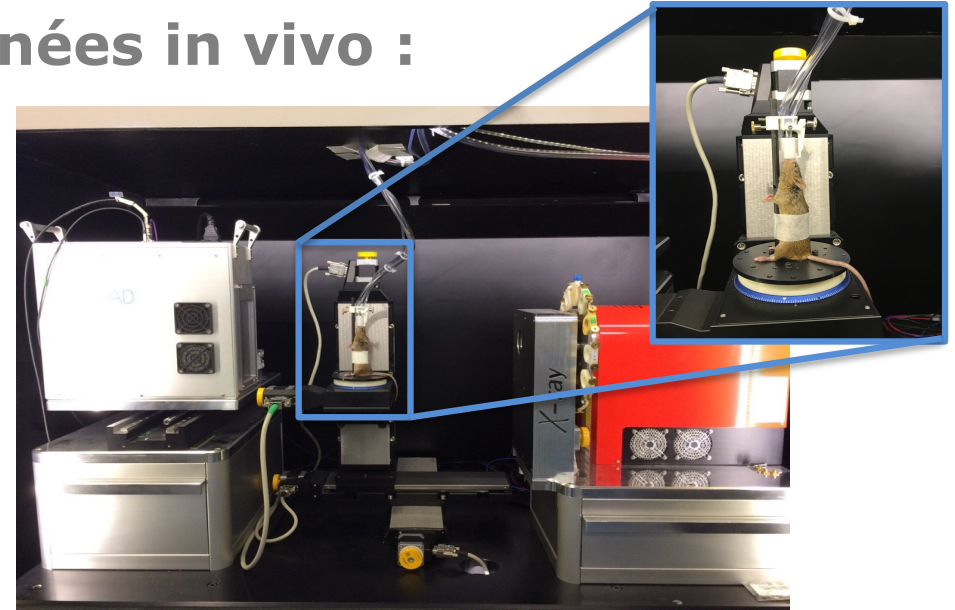
Replay x10



PC-CT avec le prototype PIXSCAN-FLI/XPAD3

Protocole d'acquisition de données in vivo :

- Imagerie d'absorption standard
- Anesthésie gazeuse : 3% d'isoflurane
- Source: 50 kV/500 μ A/0.6 mm Al
- Mode d'acquisition de données : continu
- Durée de pose : 575 ms + 50 ms DT
- Projections : 720 (pas de 0.5°)
- Dose délivrée : 177 mGy/acquisition



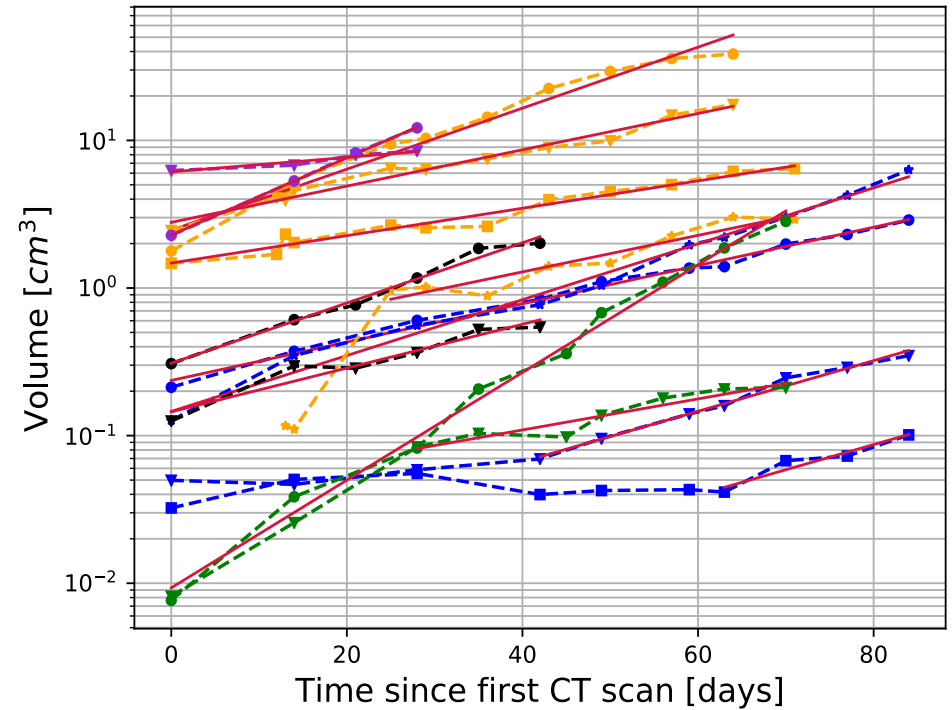
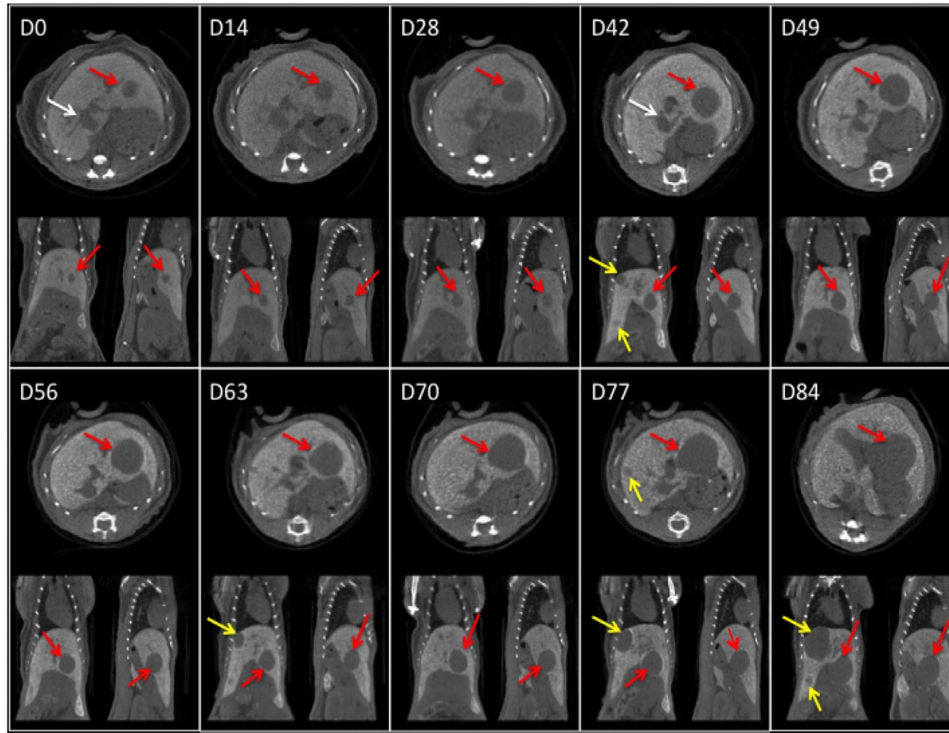
Choix d'un agent de contraste hépato spécifique à base de nanoparticules baryum pour rehausser x2 le contraste du foie par rapport aux tissus mous

→ Idéal pour des études longitudinales!

Coupes coronales d'une souris imagée avant, un jour après et trois semaines après l'injection de 100 μ L/30g d'Exitron nano 12000

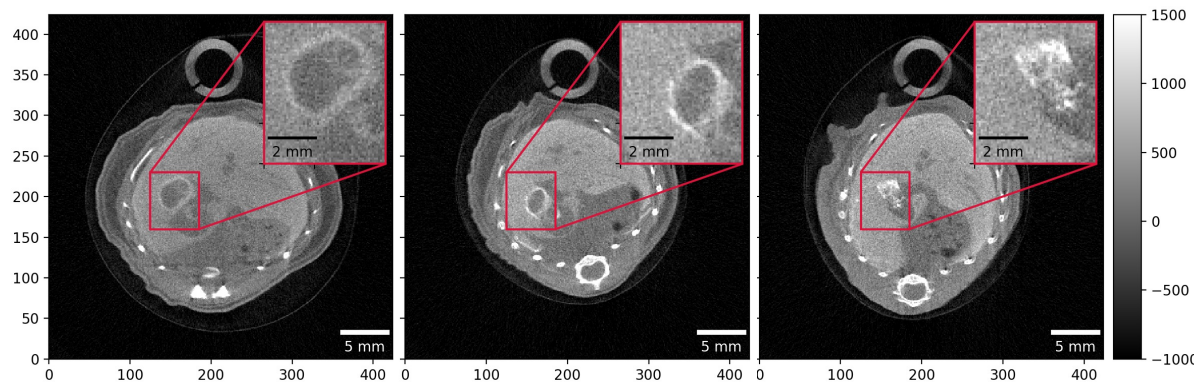
Premières études longitudinales de tumeurs du foie chez la souris

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



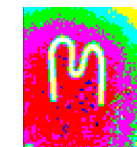
Suivi d'une souris avec un hépatocarcinome pendant trois mois

XPAD3/Si – 180 mGy



Suivi de la réponse au traitement par une thérapie hépato spécifique pendant 40 jours

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



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

Courtesy: R. Ballabriga, Medipix Collaboration, CERN

Pixels hybrides : de nombreuses spinoffs

2003



www.dxray.com

2006

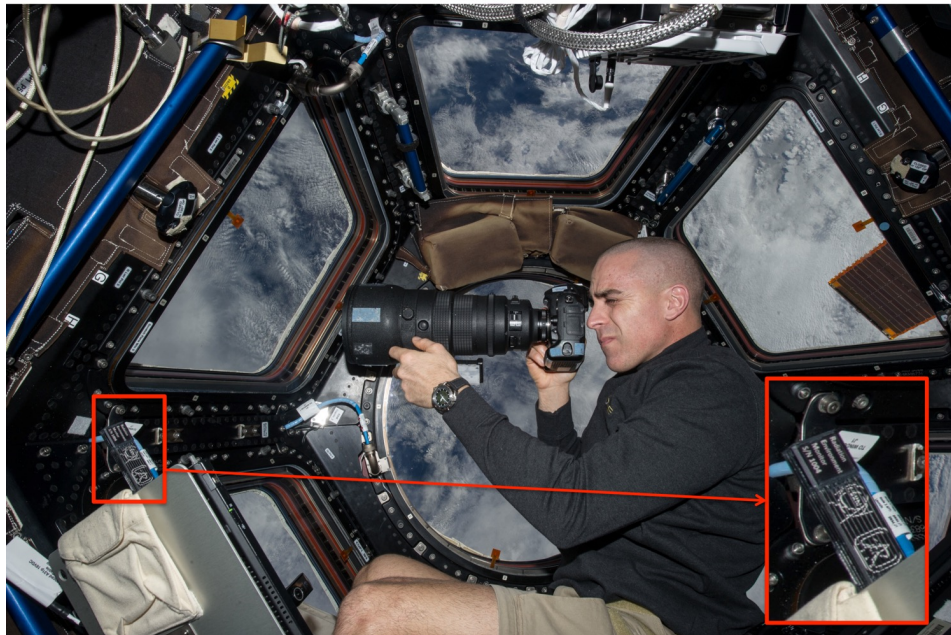


www.dectris.com


2010



www.imxpad.com



2006



Pixelated X-Ray Detectors
www.xray-imatek.com

2011



Chromatic Photon Counting
pixirad.pi.infn.it

Courtesy: NASA, photo ref. no. iss036e006175

2003




detect image identify
www.kromek.com

2007



www.marsbioimaging.com

2012



IMAGING THE UNSEEN
www.advacam.com

2011

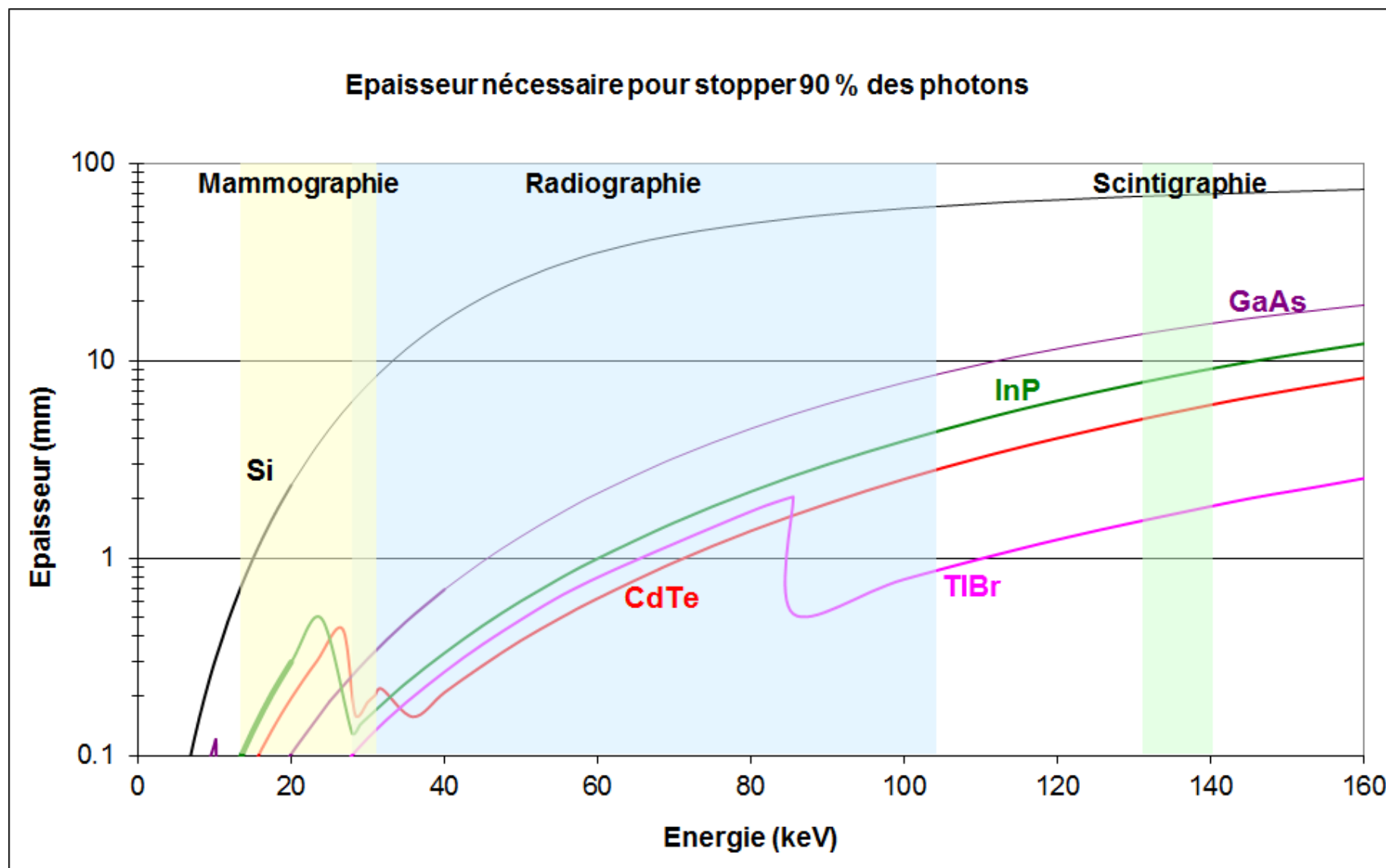


www.amscins.com



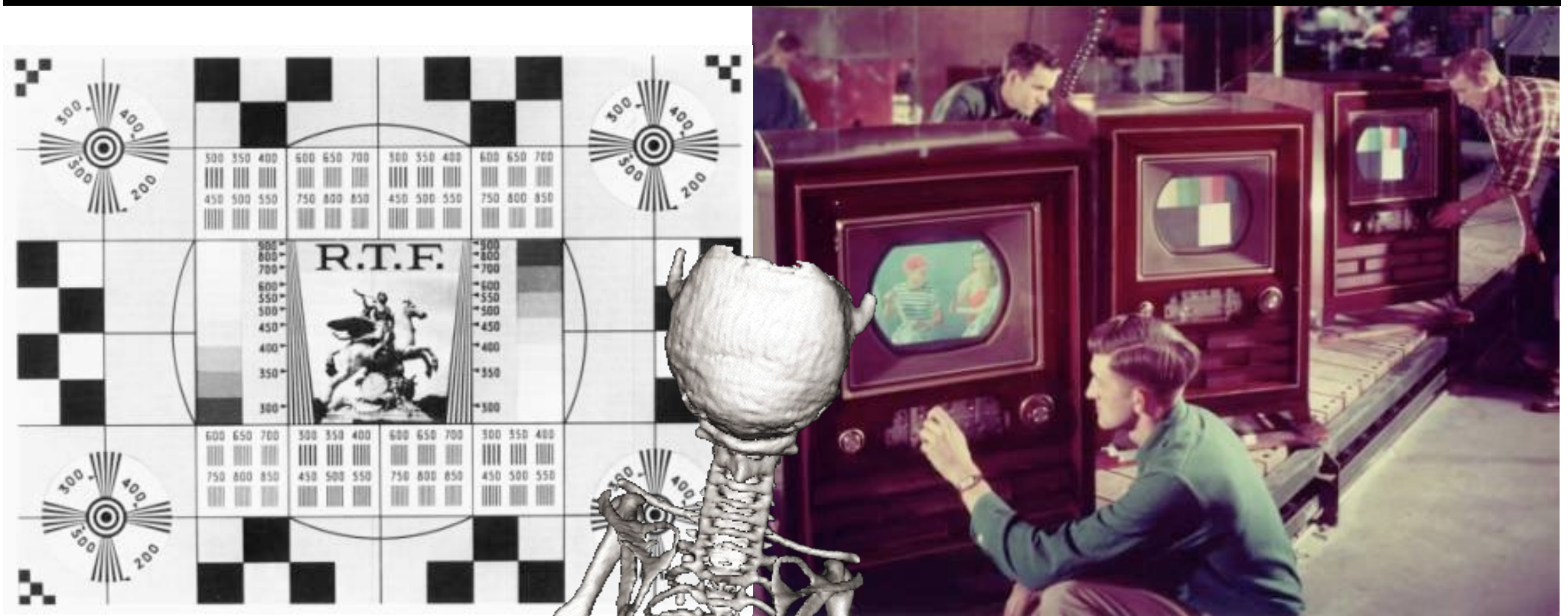
www.xi-europe.com

Capteurs pour la détection directe de rayons X

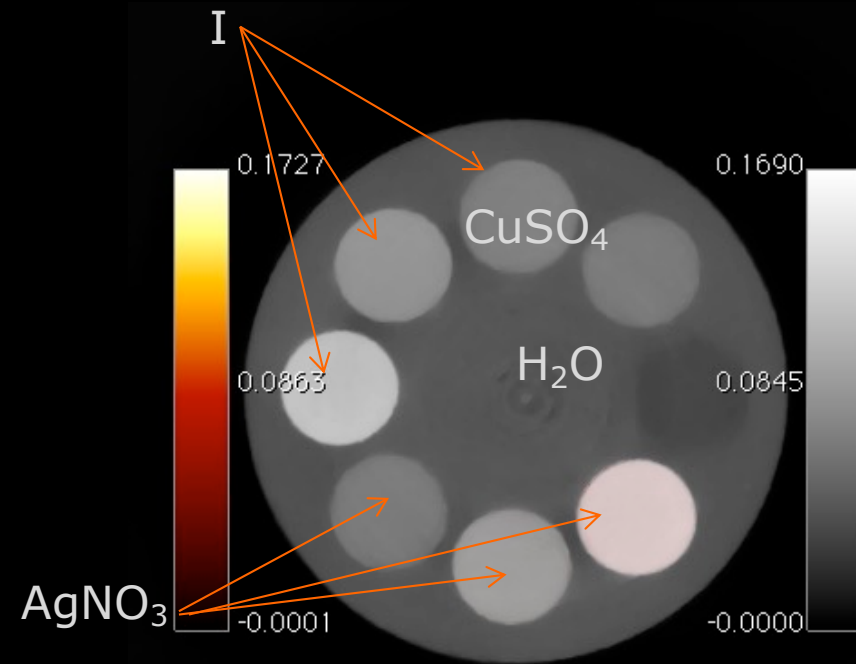
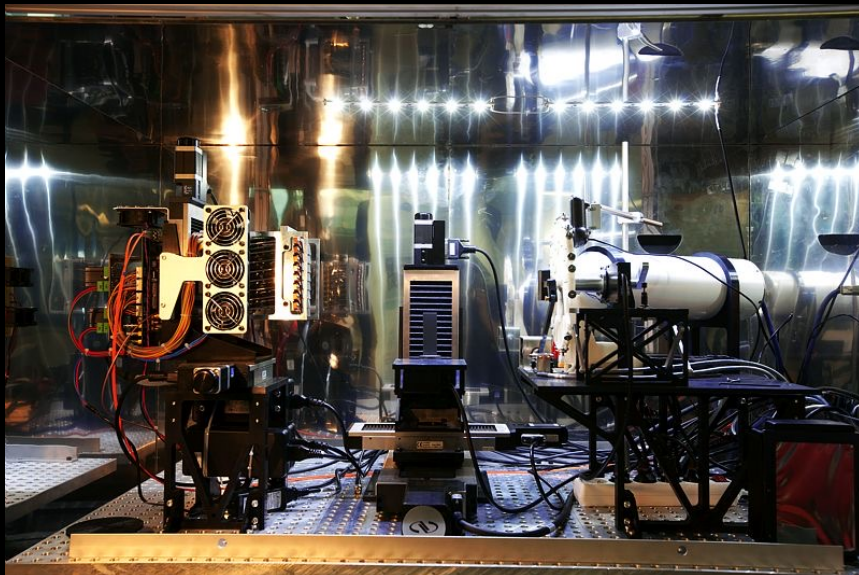
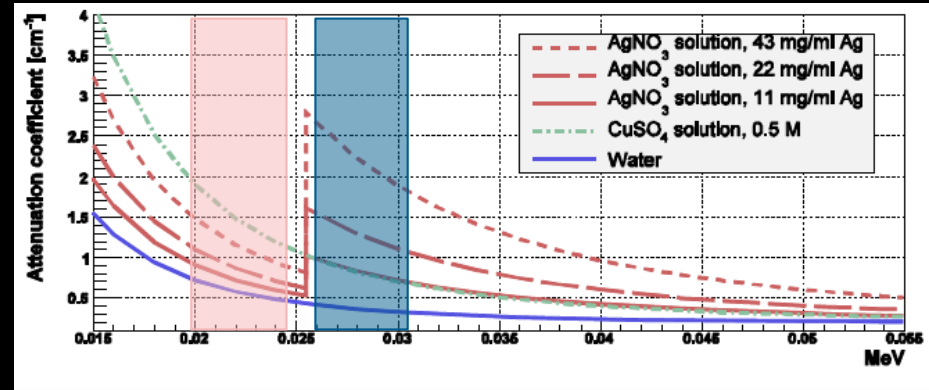


Courtesy: E. Gros d'Aillon, CEA-LETI

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

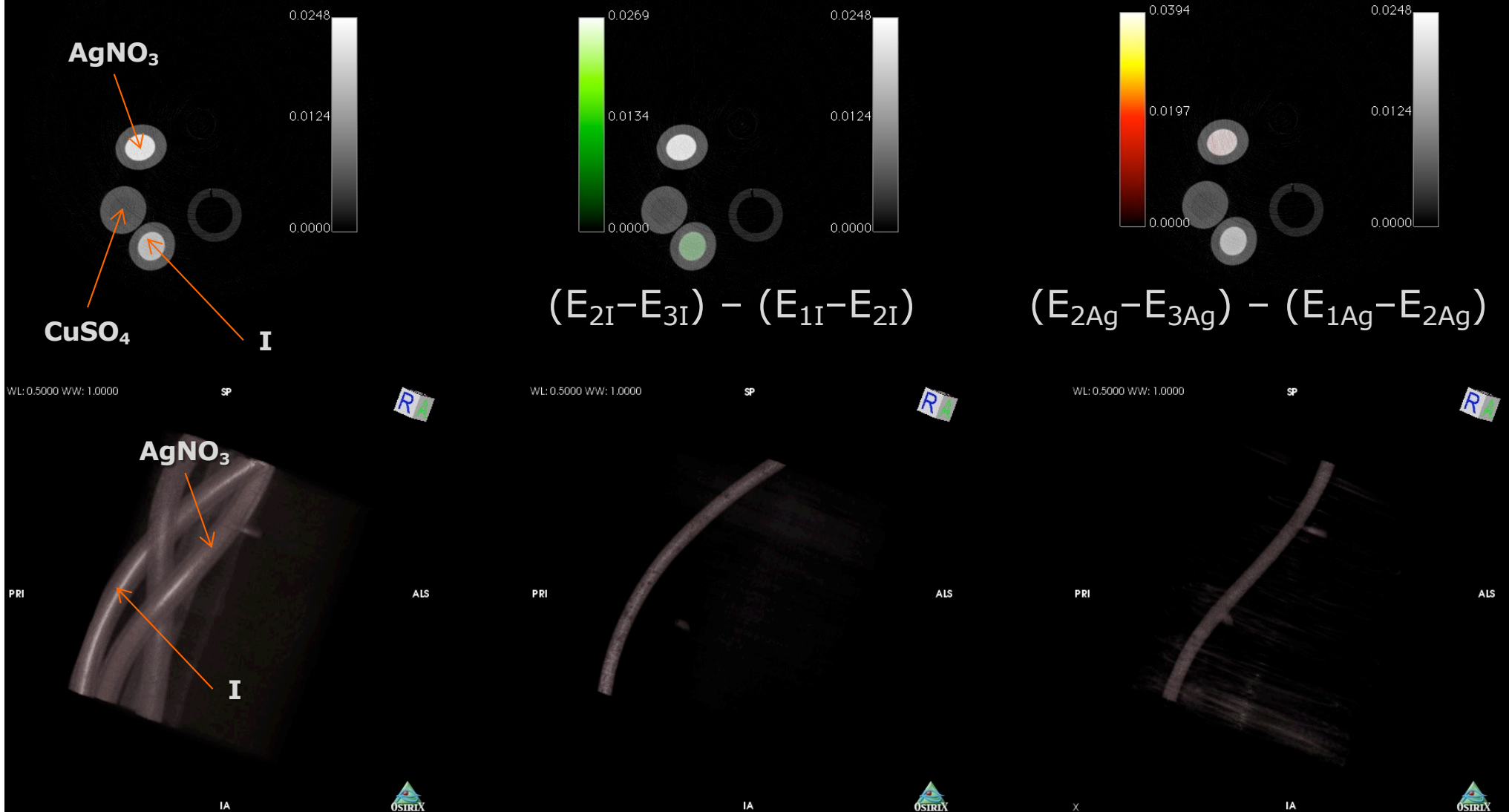


CT spectral : du noir & blanc à la couleur



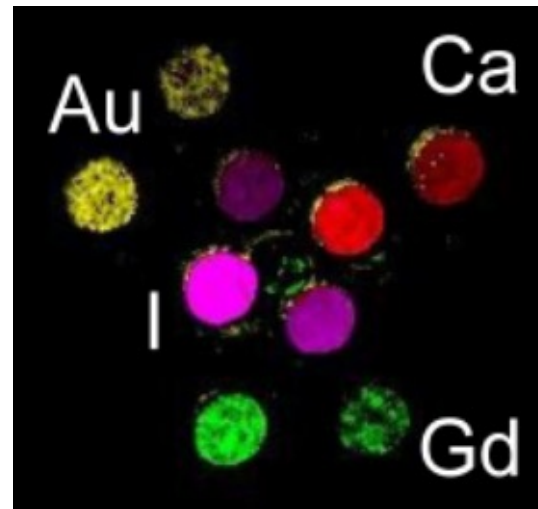
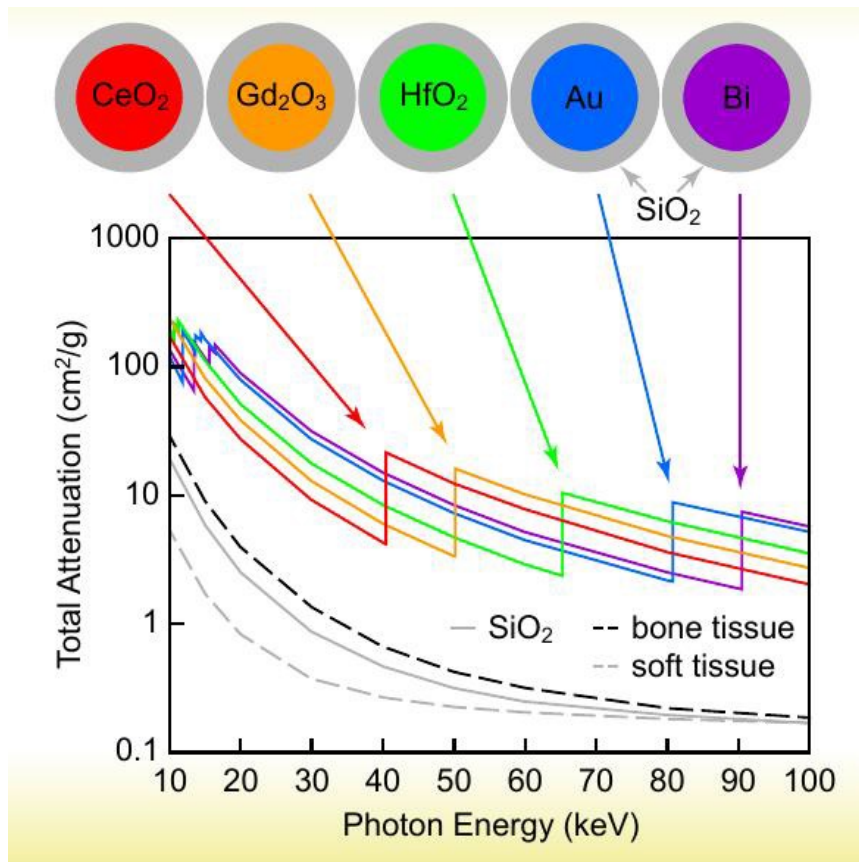
CT spectral : du noir & blanc à la couleur

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

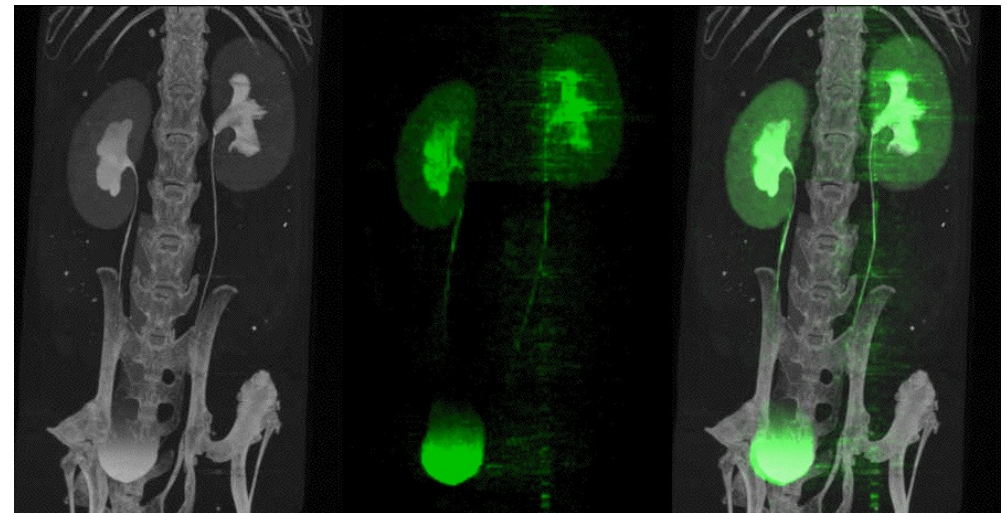


Courtesy: A Buttler, Medipix Collaboration, Mars Bio-Imaging

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

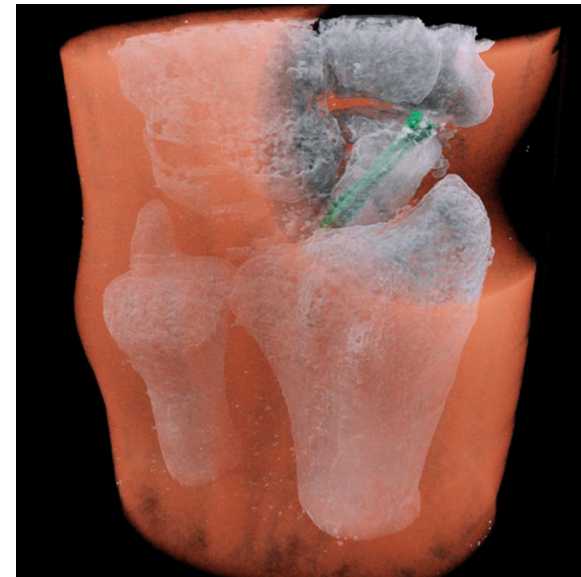


La PC-CT devient (pré-)clinique



Mars Bioimaging

- MARS Microlab 5X120 (pré-clinique)
- MARS Extremity 5X120 (recherche clinique seulement)
- CZT/Medipix3
- 110 μm pixel pitch
- 8 fenêtres d'énergie/pixel



La PC-CT devient clinique

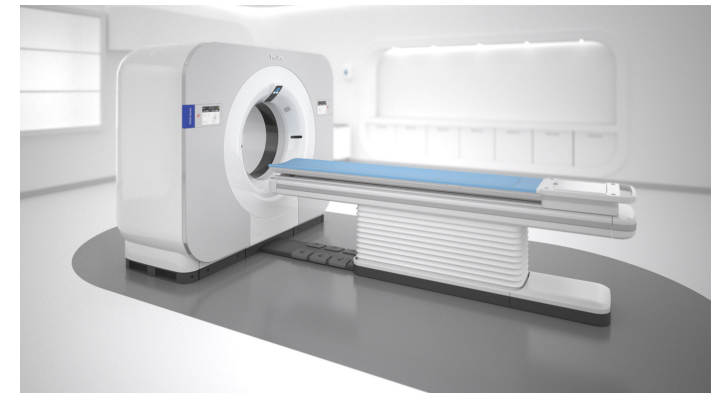
Siemens Healthineers

- NAEOTON Alpha
- CdTe
- FDA clearance 30/09/21



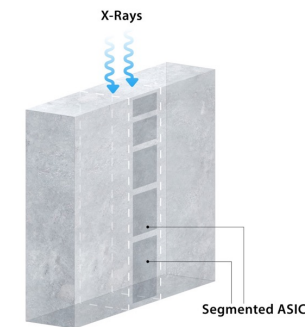
Philips Healthcare

- Spectral-CT 7500
- CZT
- SPCCT EU project



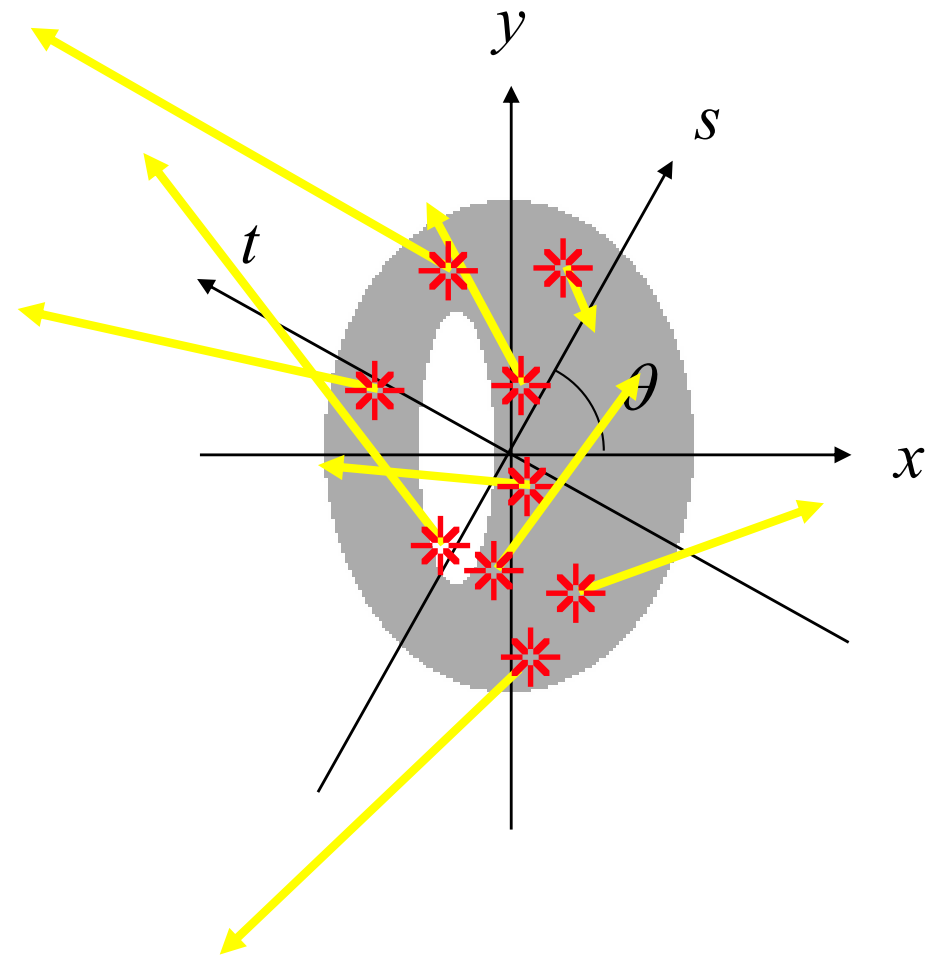
GE Healthcare

- Deep silicon detectors



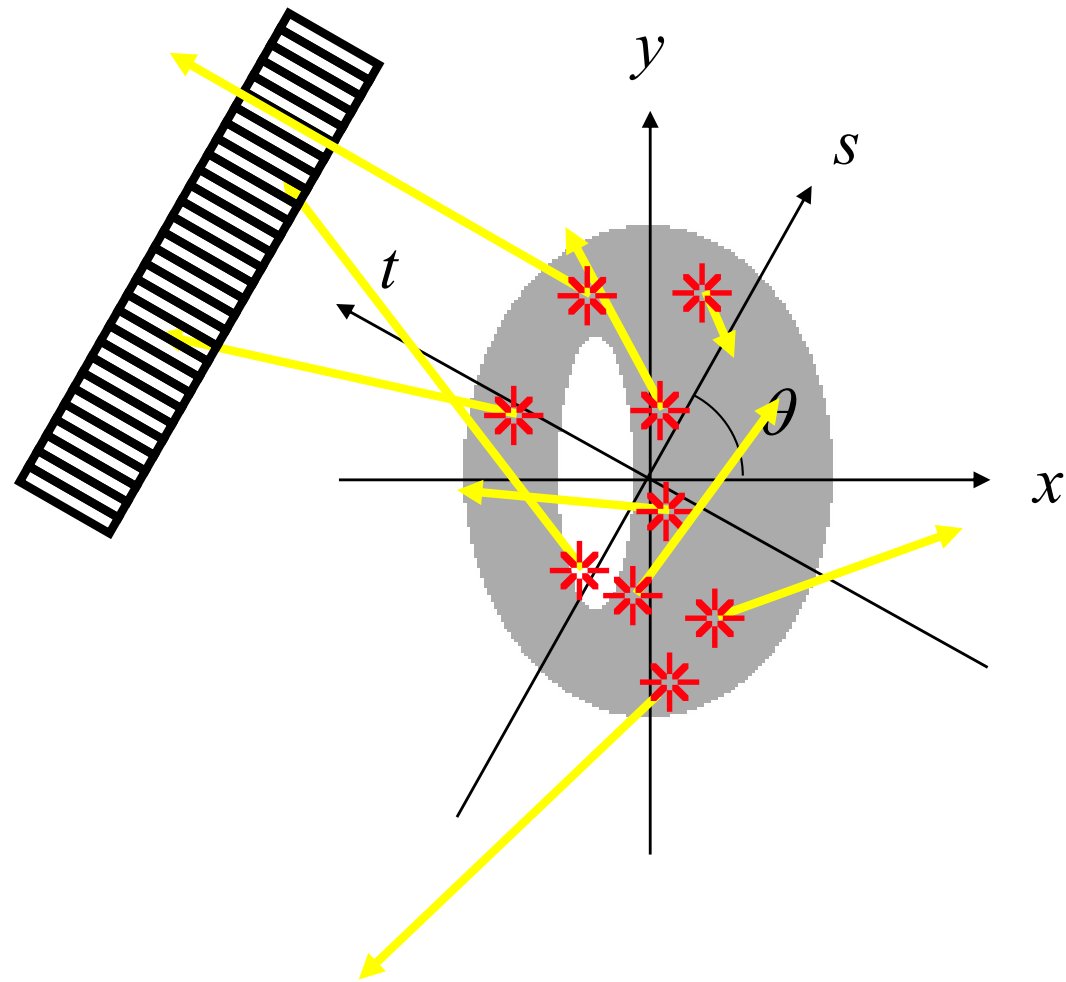
Edge on Geometry²

Tomographie par émission de rayons gamma



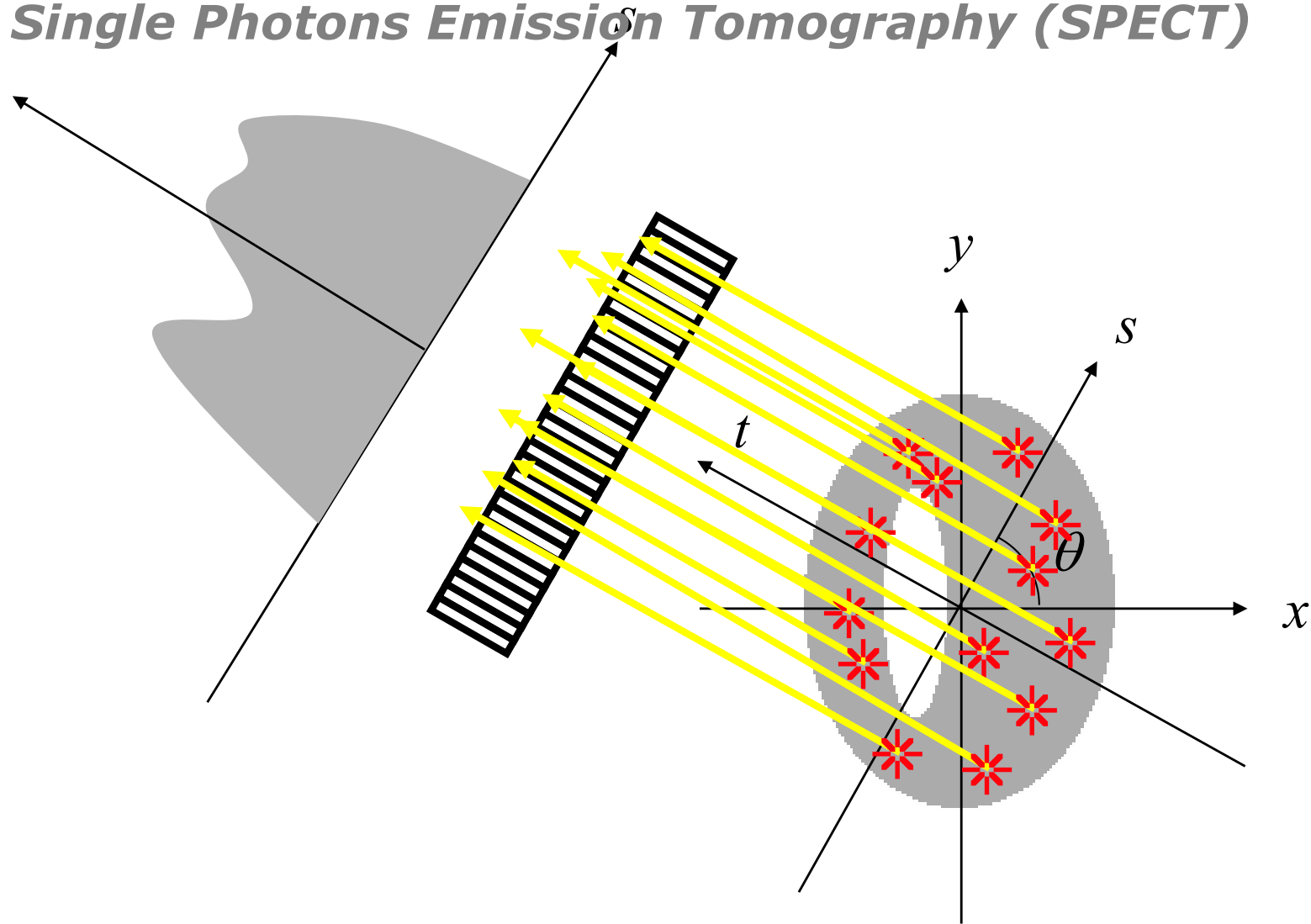
Tomographie par émission mono-photonique (TEMP)

Single Photons Emission Tomography (SPECT)

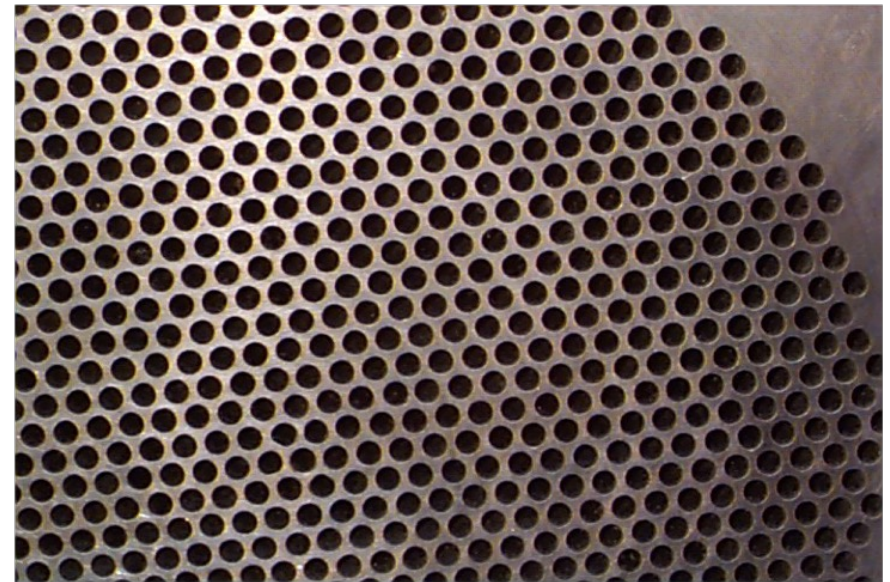
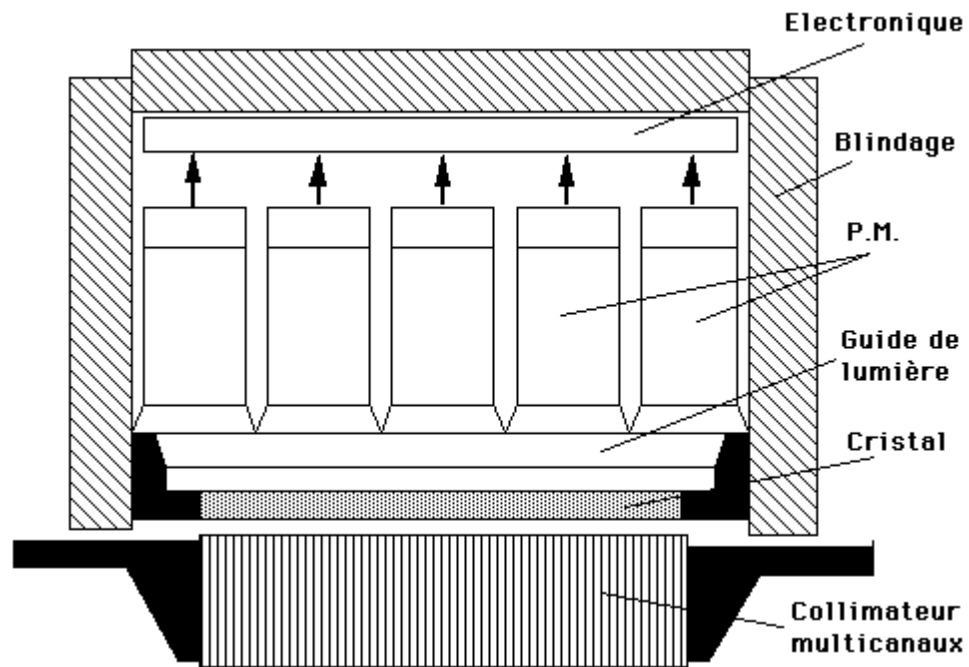


Tomographie par émission mono-photonique (TEMP)

Single Photons Emission Tomography (SPECT)



Caméra gamma (H. Anger, Berkeley, 1952)



H. Anger, *Scintillation camera with multichannel collimators.*
J Nucl Med 65 (1964) 515-531

Tomographie par émission monophotonique (TEMP)

Single Photon Emission Computered Tomography (SPECT)



^{99m}Tc (6 h) 140 keV

^{201}Tl (73 h) 70 keV

^{123}I (13 h) 159 keV

^{133}Xe (5 min) 81 keV



Sensibilité absolue

$\sim 10^{-4}$

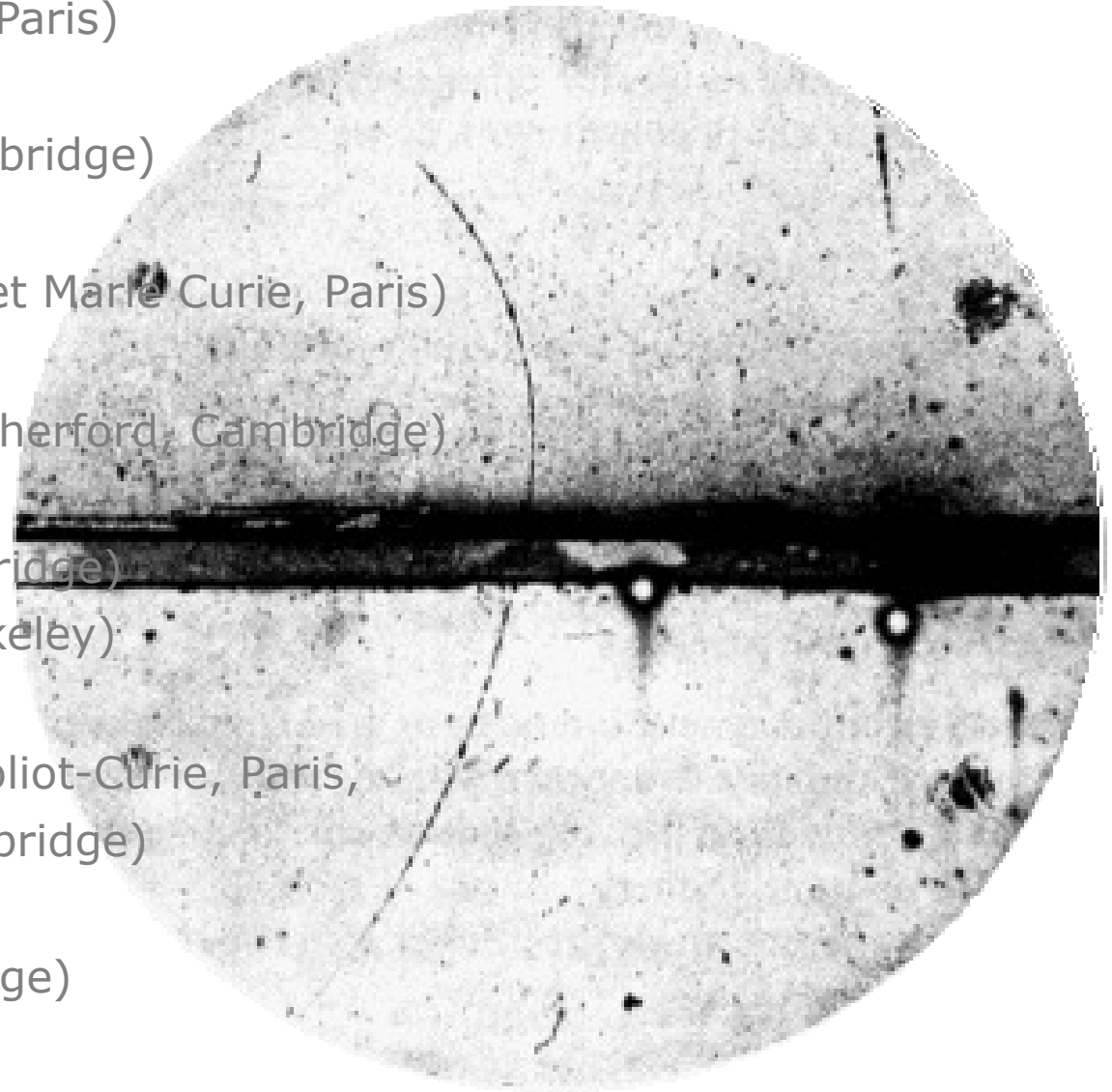
Résolution spatiale

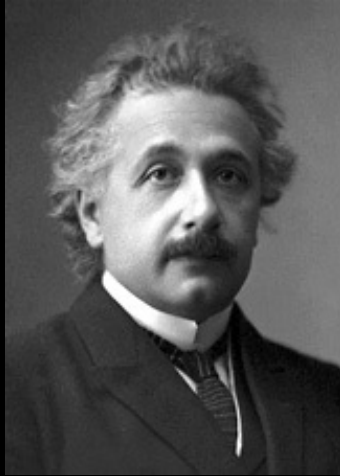
6-8 mm

Dose absorbée

5-30 mSv

- 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: **Positon** (C.D. Anderson, Berkeley)
Prix Nobel 1936





$$E=mc^2$$

Diffusion Compton

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

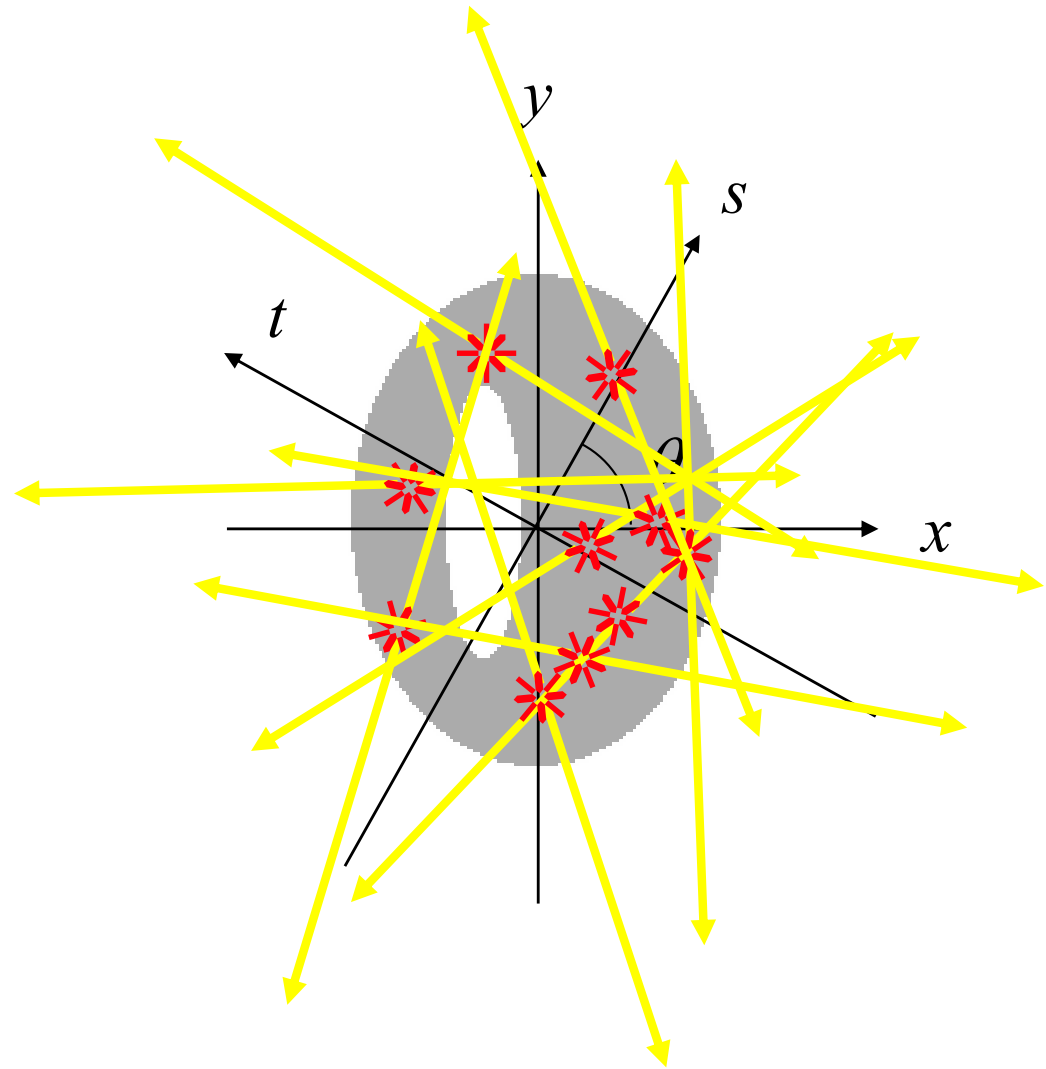
$$e^- + e^+ \rightarrow \gamma + \gamma$$



Annihilation matière anti-matière

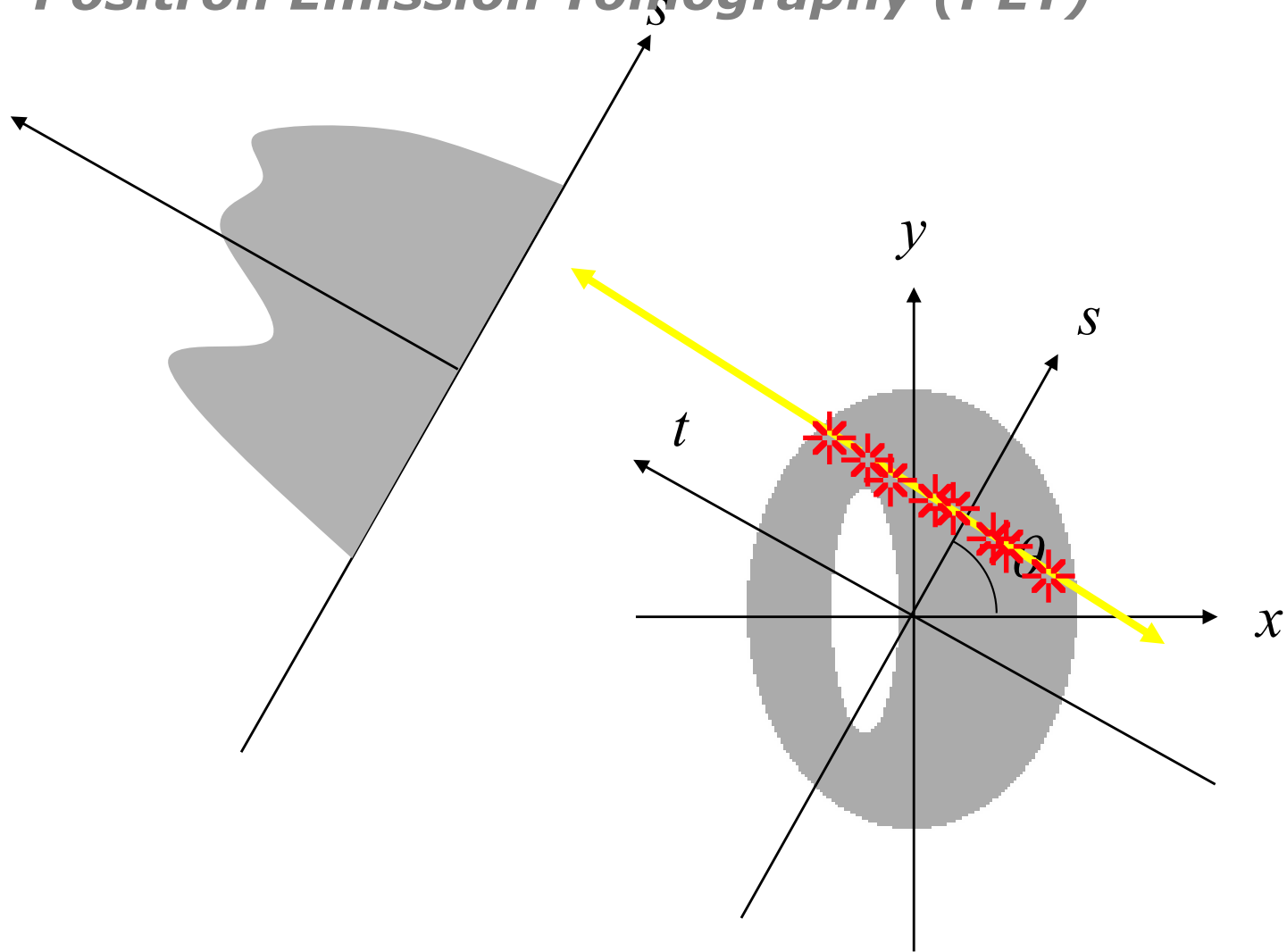
Tomographie par émission de positons (TEP)

Positron Emission Tomography (PET)

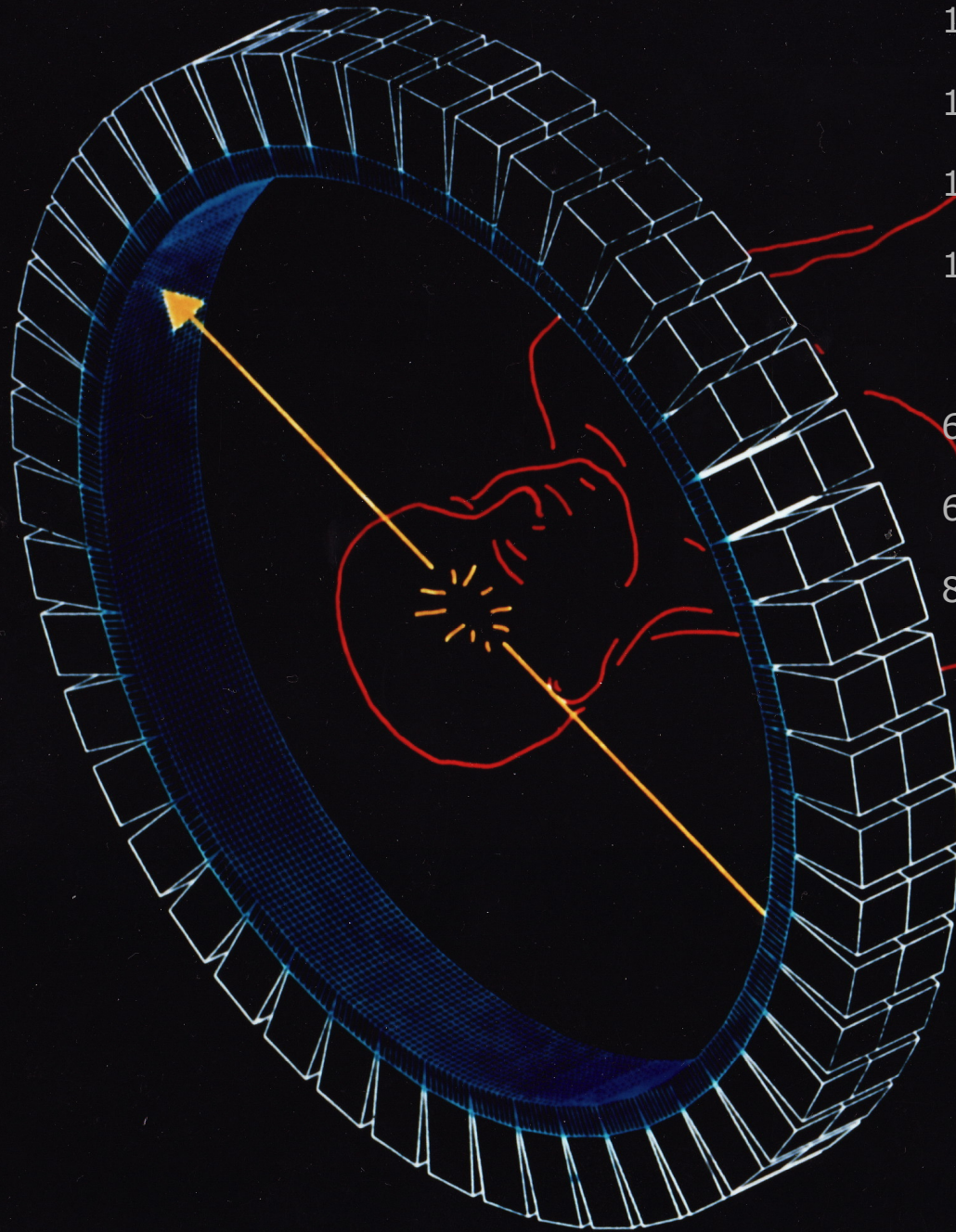


Tomographie par émission de positons (TEP)

Positron Emission Tomography (PET)



Tomographie par émission de positons (TEP)



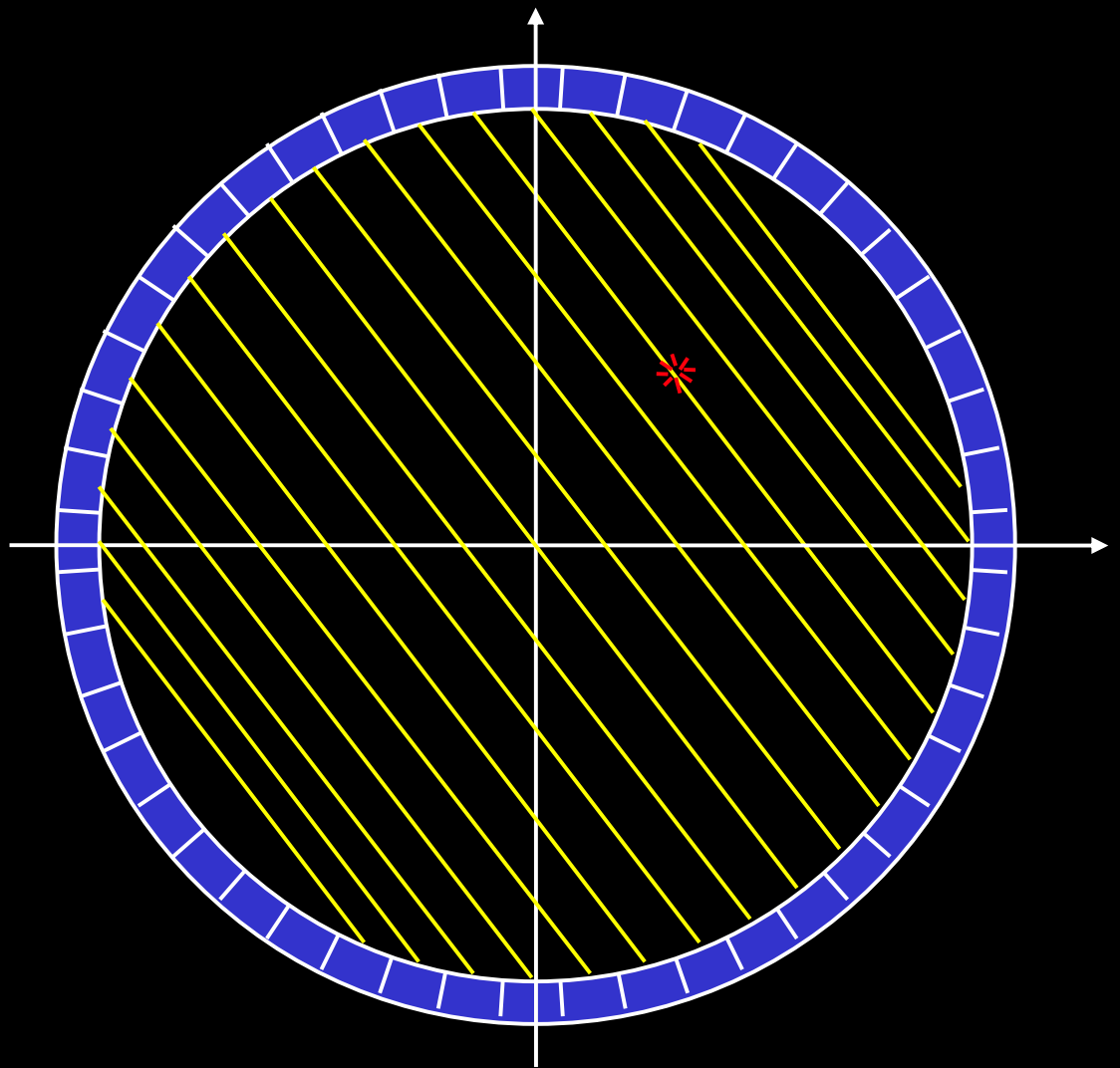
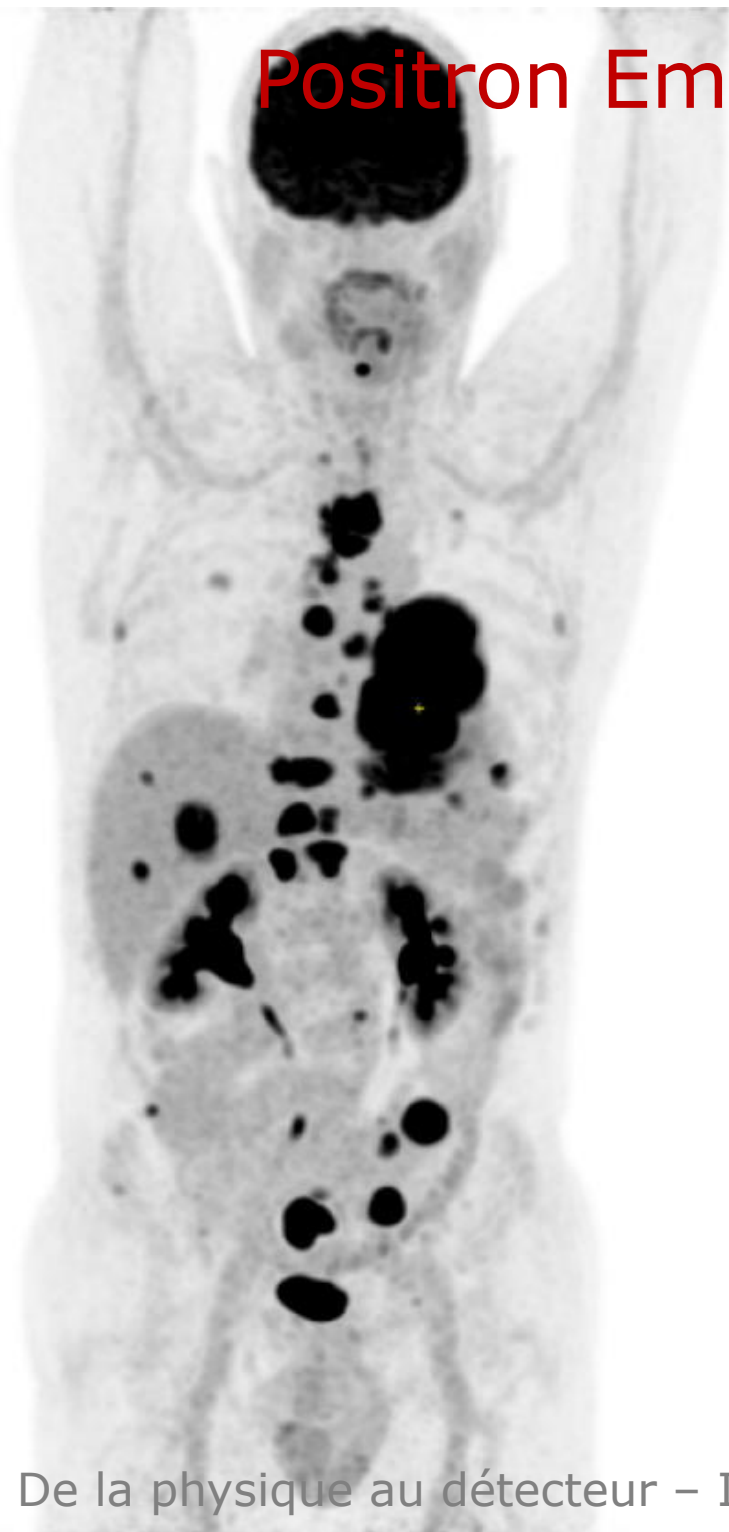
^{15}O (2 min)	511 keV
^{13}N (10 min)	511 keV
^{11}C (20 min)	511 keV
^{18}F (110 min)	511 keV
^{64}Cu (12,7 h)	511 keV
^{68}Ga (68 min)	511 keV
^{82}Rb (1,2 min)	511 keV

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

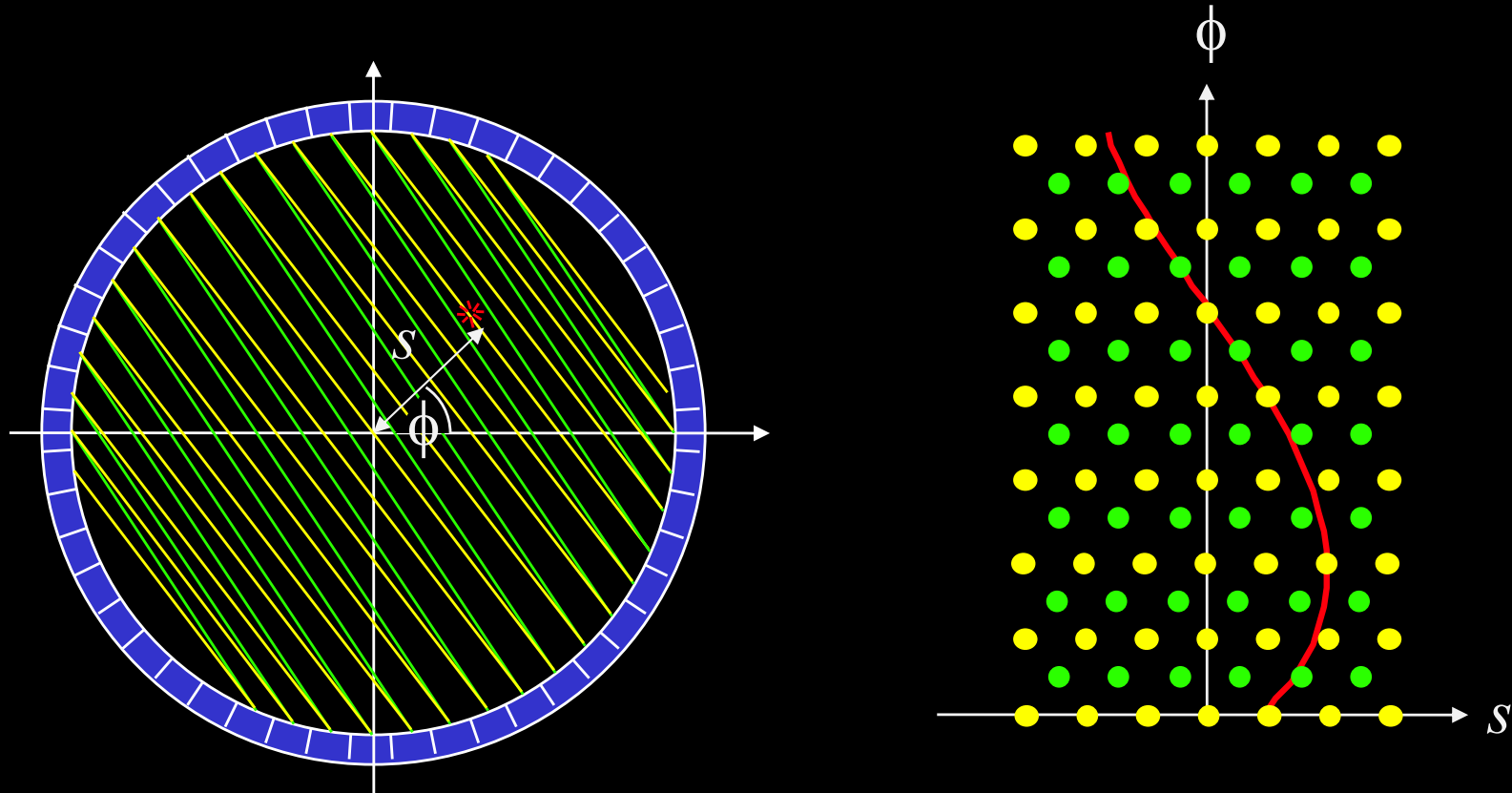
M.R.C. Cyclotron Unit.
Hammersmith Hospital.
London.



Positron Emission Tomography (PET)



Tomographie par émission de positons (TEP)



Sinogramme

Tomographie par émission de positons (TEP)

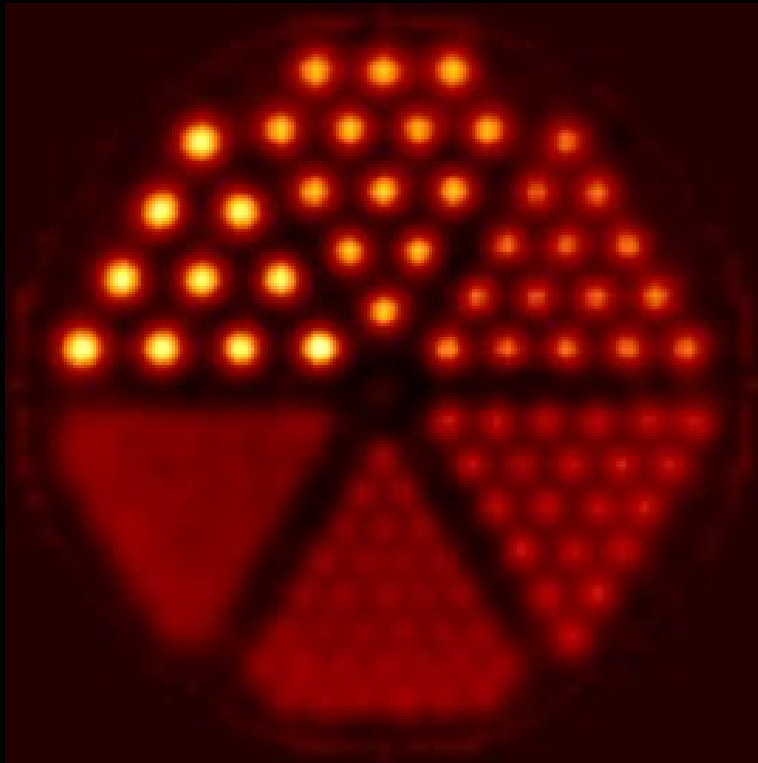
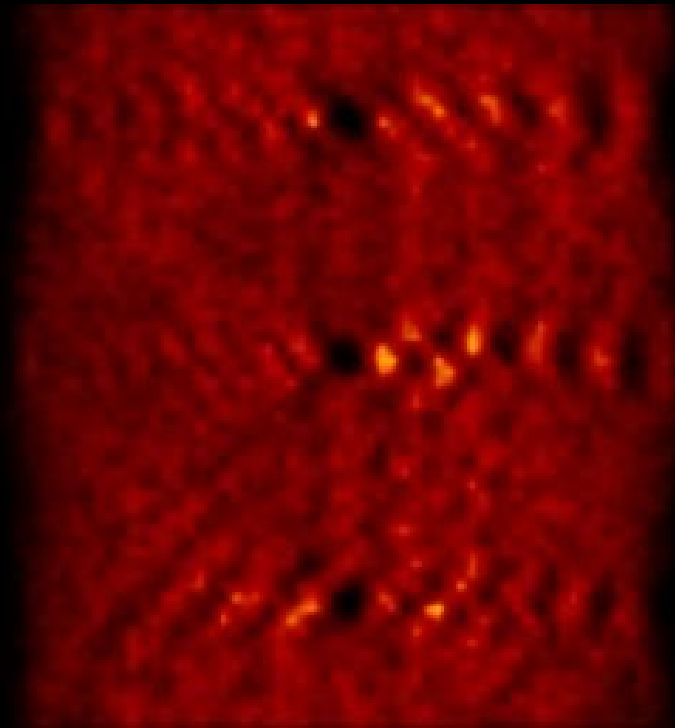


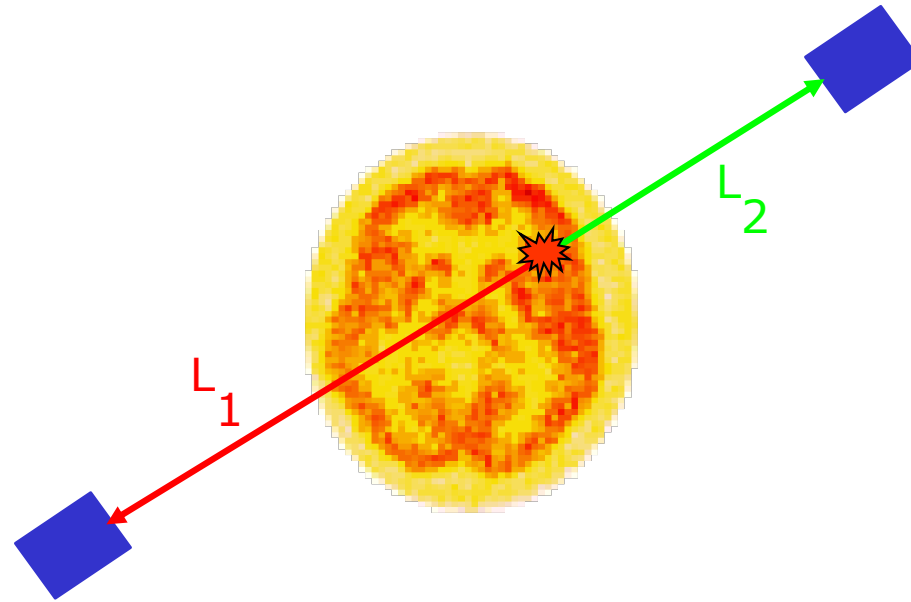
Image reconstruite



Sinogramme

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

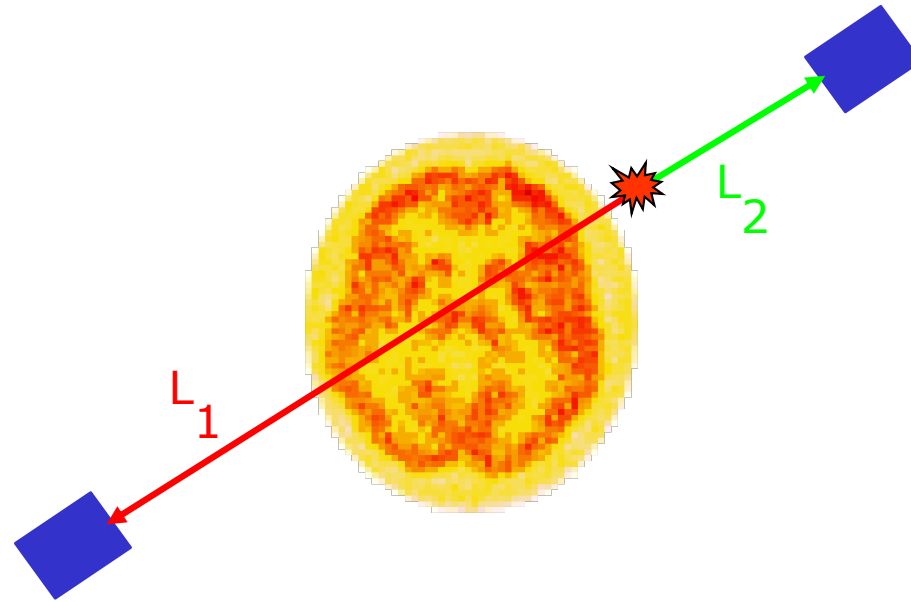
$$P\{\gamma_2\} = \varepsilon e^{-\mu L_2}$$



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

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

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

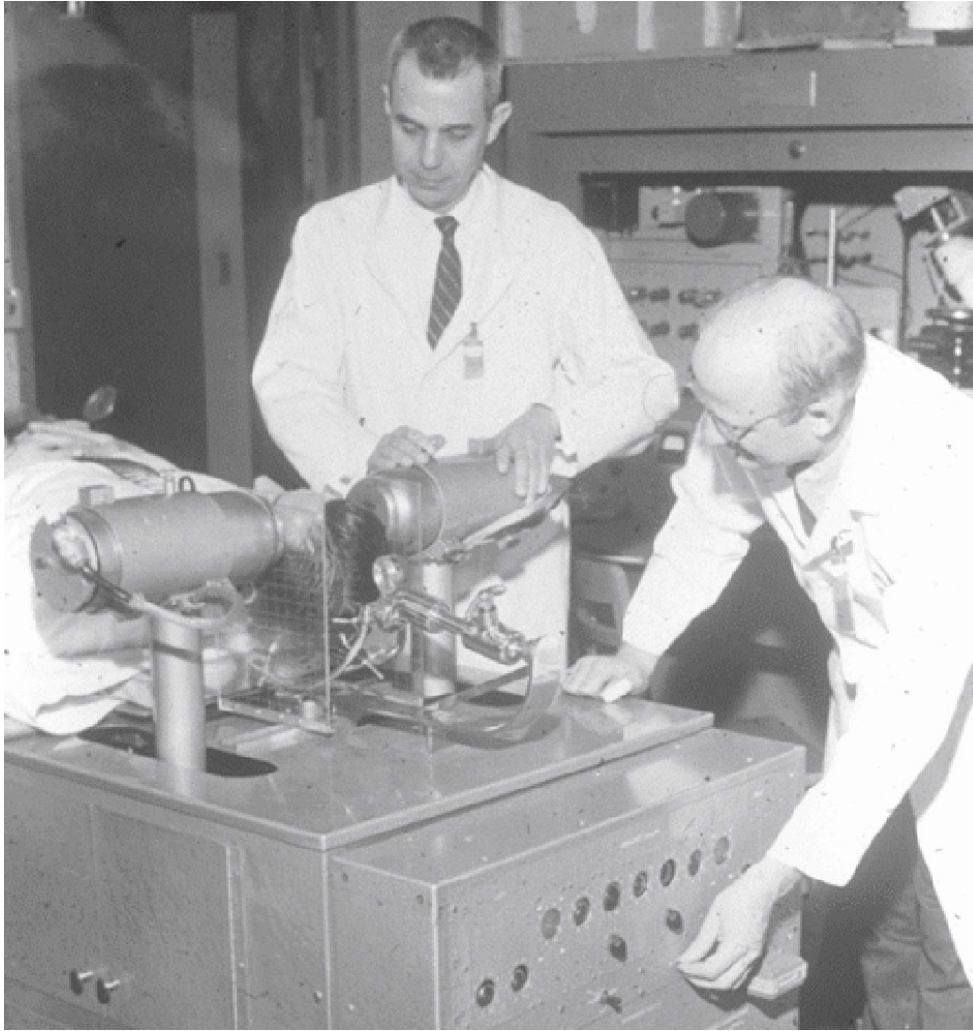


$$P\{\gamma_1\} = \varepsilon e^{-\mu L_1}$$

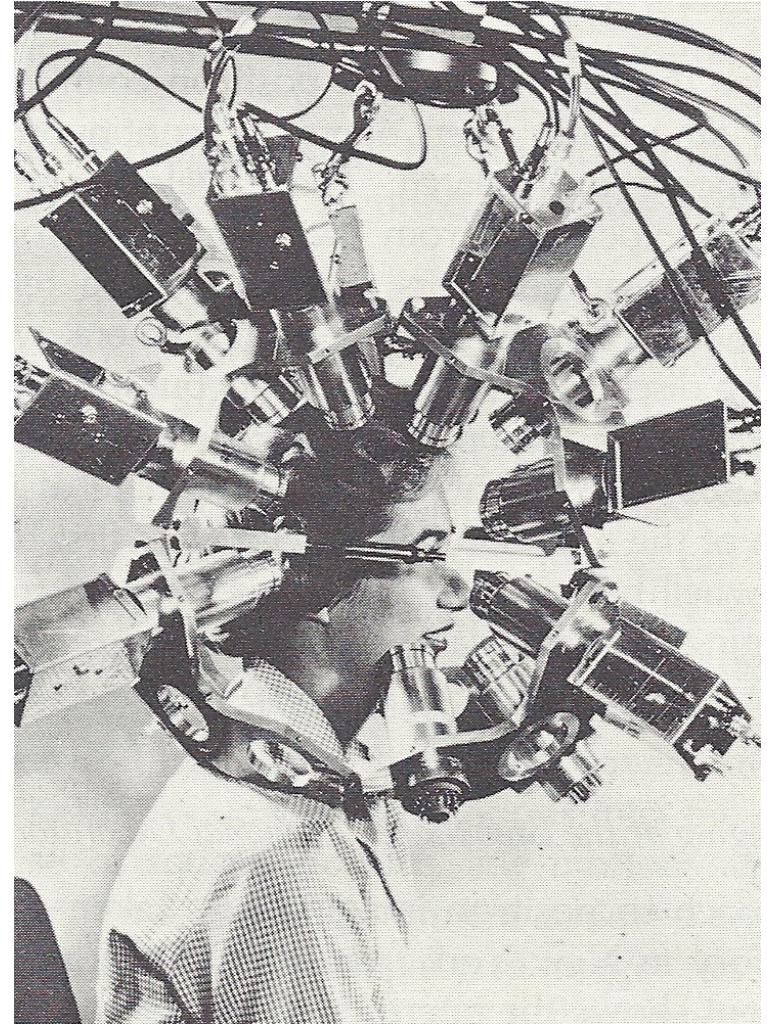
Quantification

Instrumentation TEP

G.L. Brownell, W.H. Sweet, Nucleonics 11, 40 (1953)

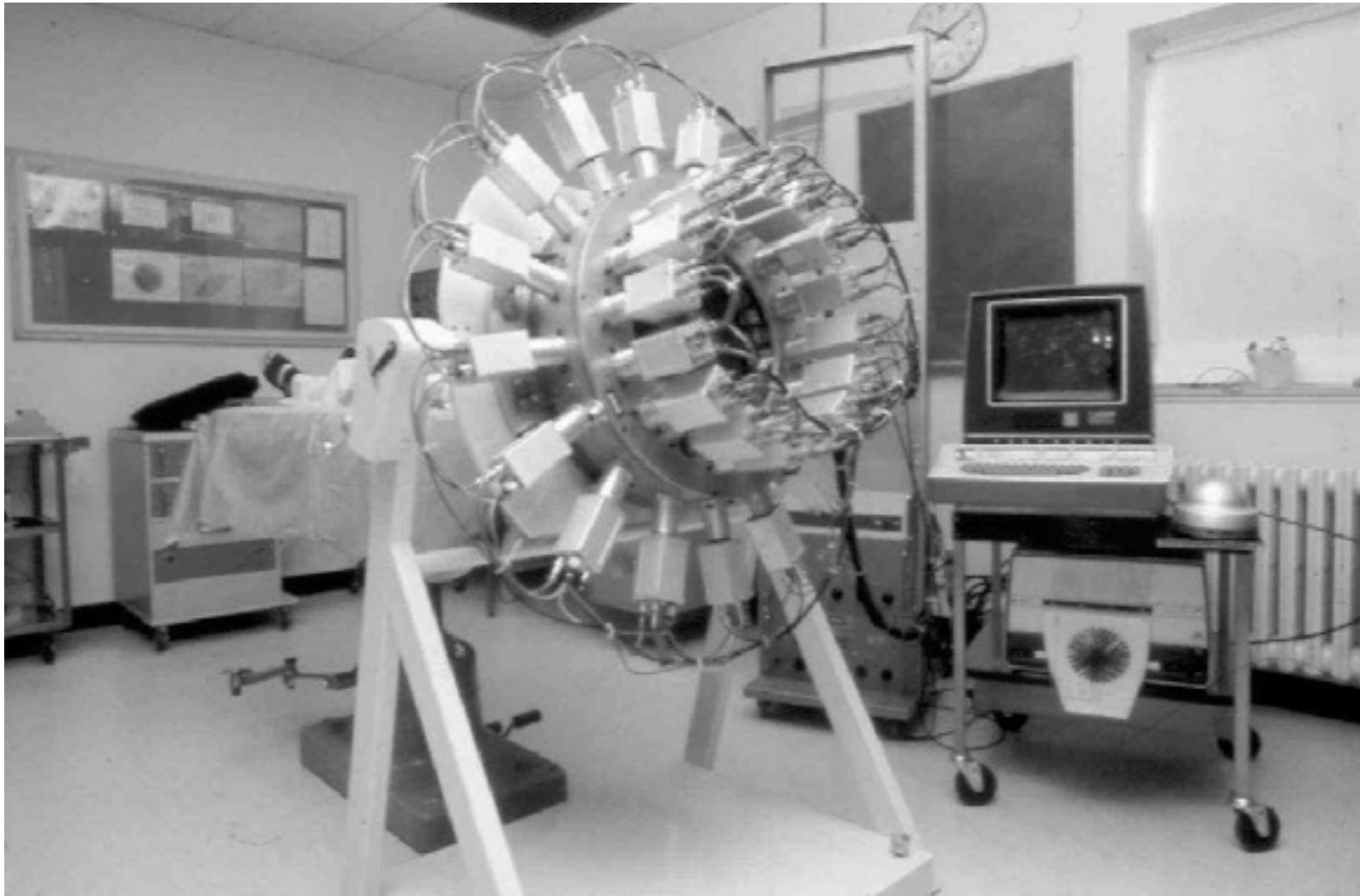


Aronov, Brownell, MGH, 1952



Robertson, BNL, 1960

Instrumentation TEP

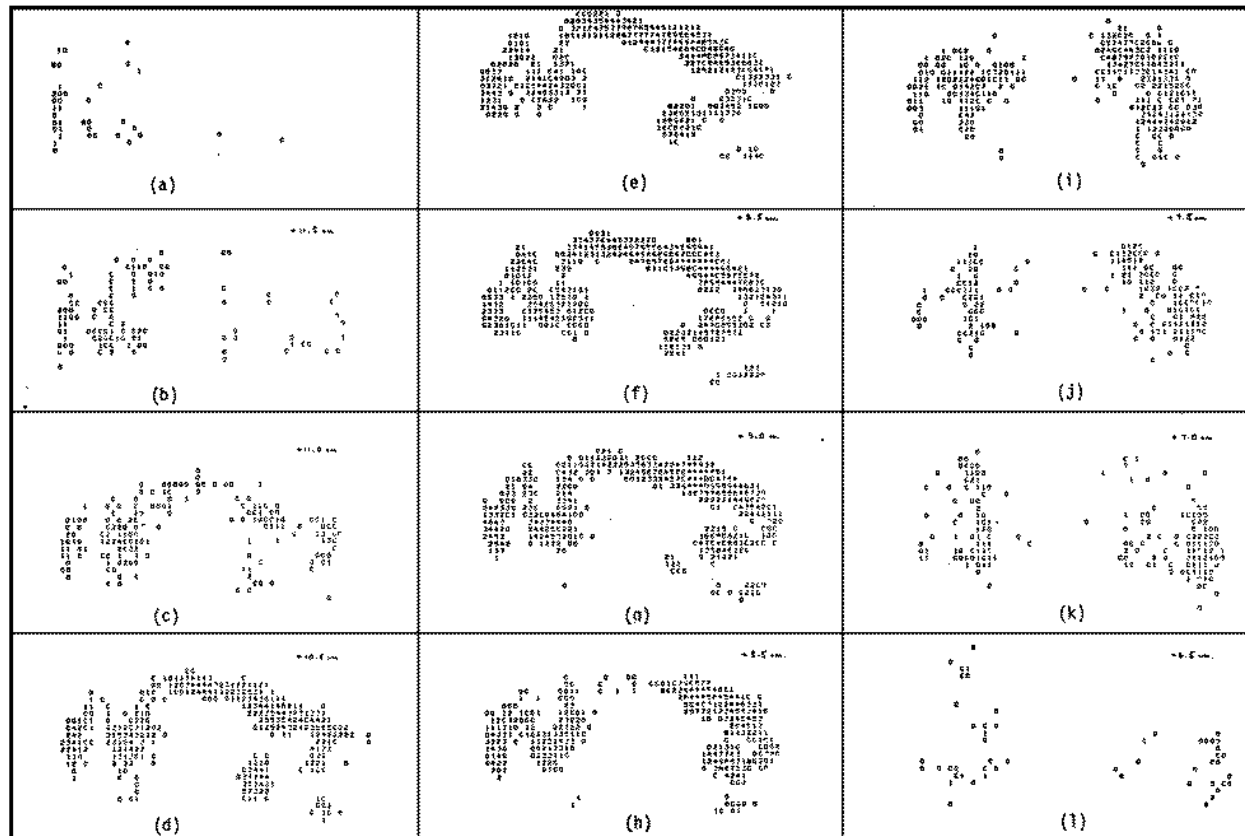
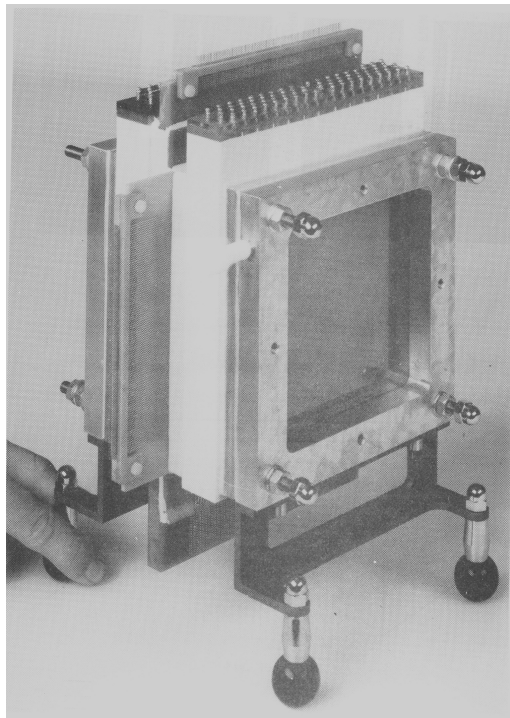


Head shrinker, BNL, 1961 -> Positome I, Yamamoto, McGill, 1975

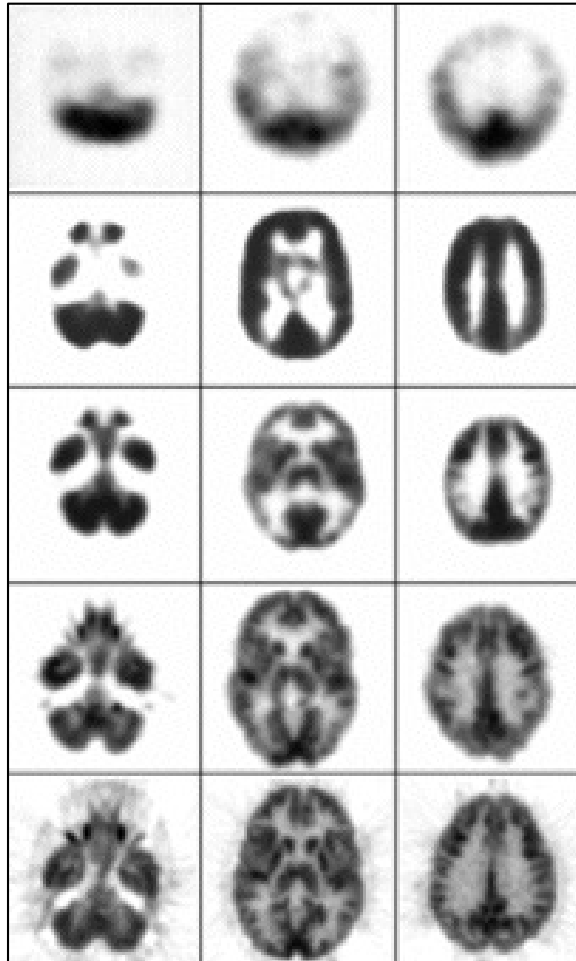
Tomographie par émission de positons: premiers pas au CERN



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



Progrès continu en instrumentation



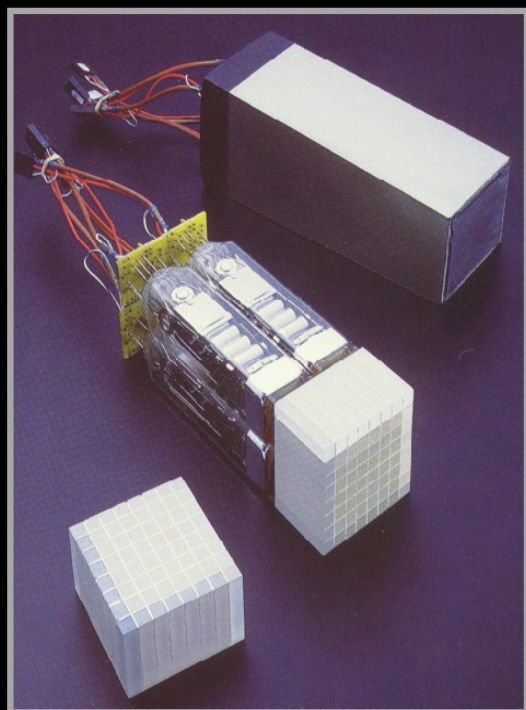
PET III 1975

ECAT II 1977

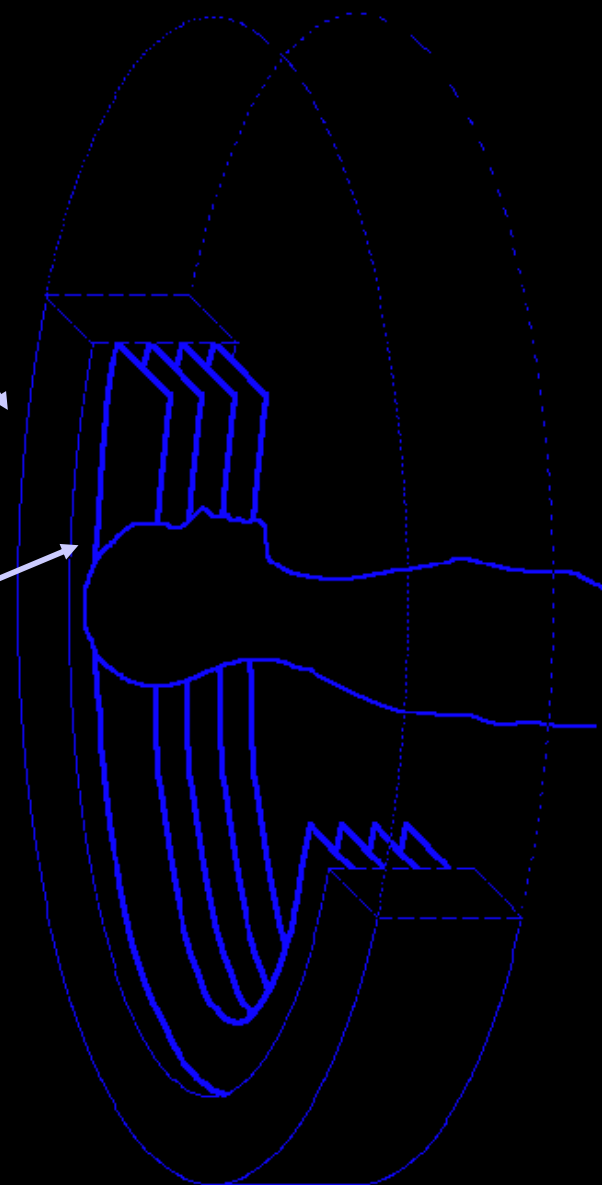
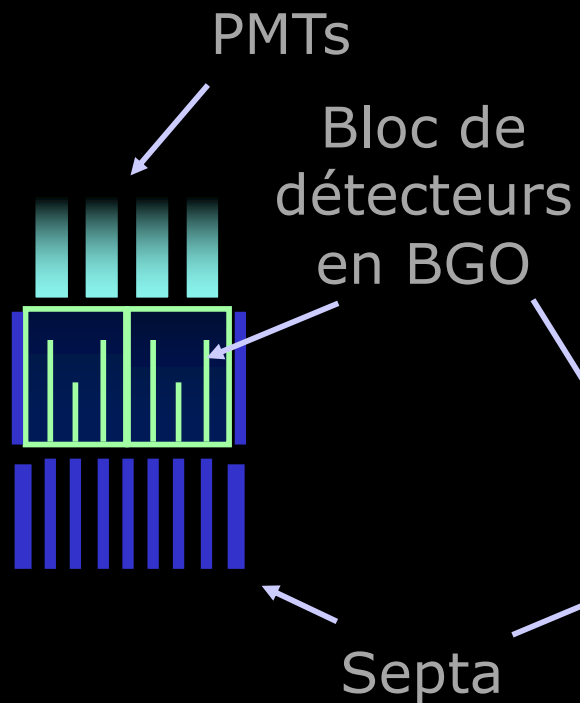
NeuroECAT 1978

ECAT 931 1985

ECAT EXACT HR+ 1995



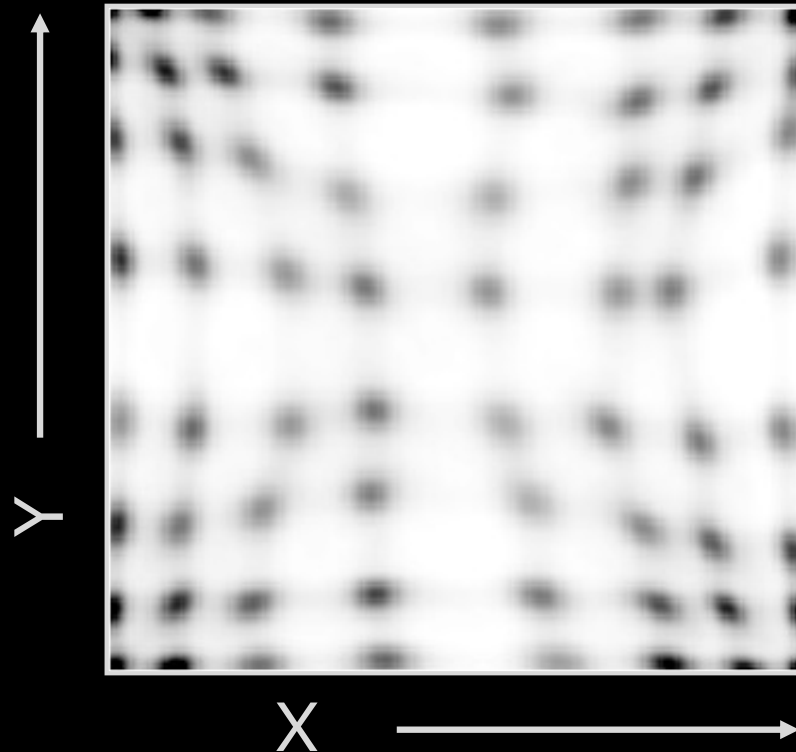
Bloc de détecteurs



Caméra TEP avec septa

Courtesy: D. Townsend, UPMC

Localisation spatiale dans un bloc de détecteurs



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

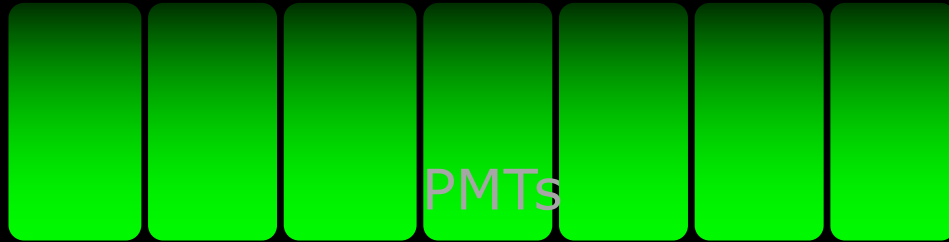
$$Y = \frac{(A + B) - (C + D)}{S}$$

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

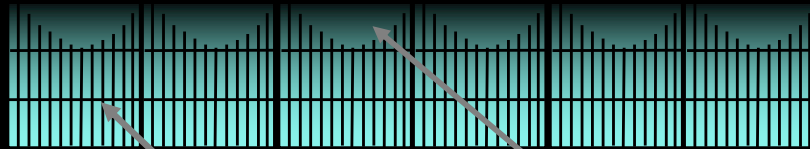
where $LLD < S < ULD$

Courtesy: D. Townsend, UPMC

Quadrant sharing panels

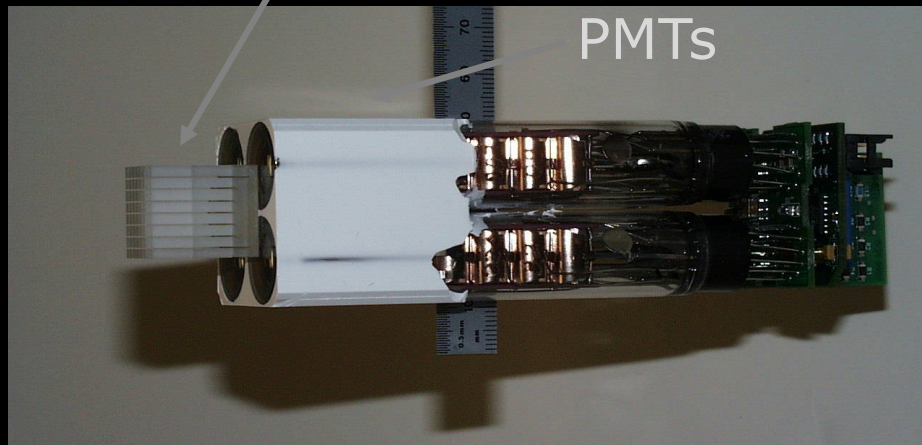
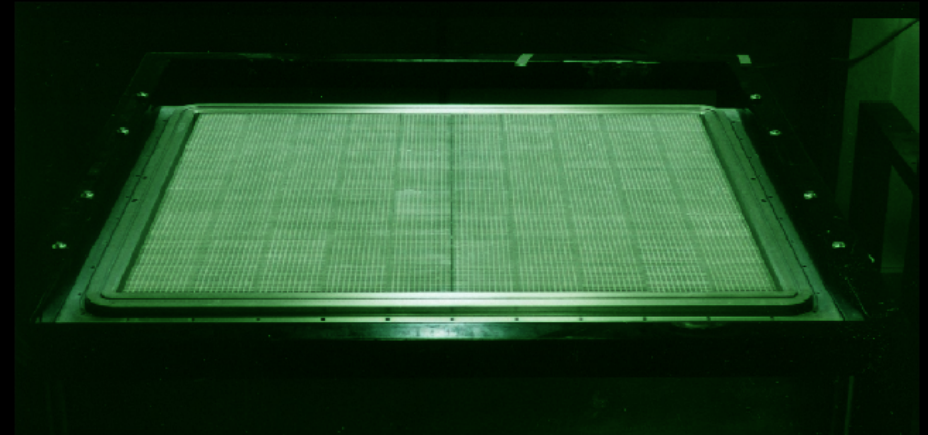


PMTs

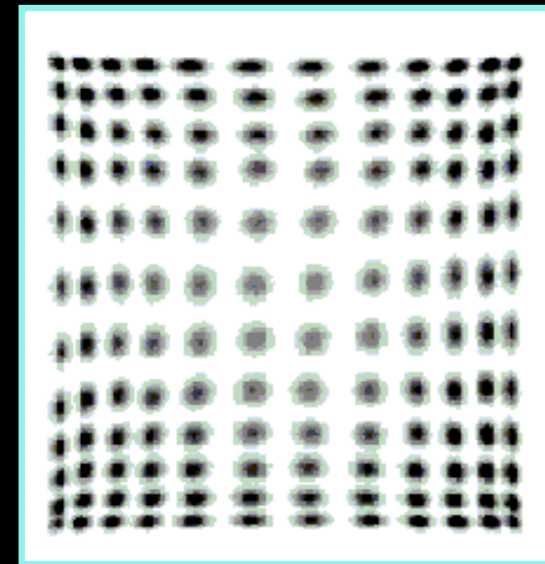


Scintillateur

Guide de lumière

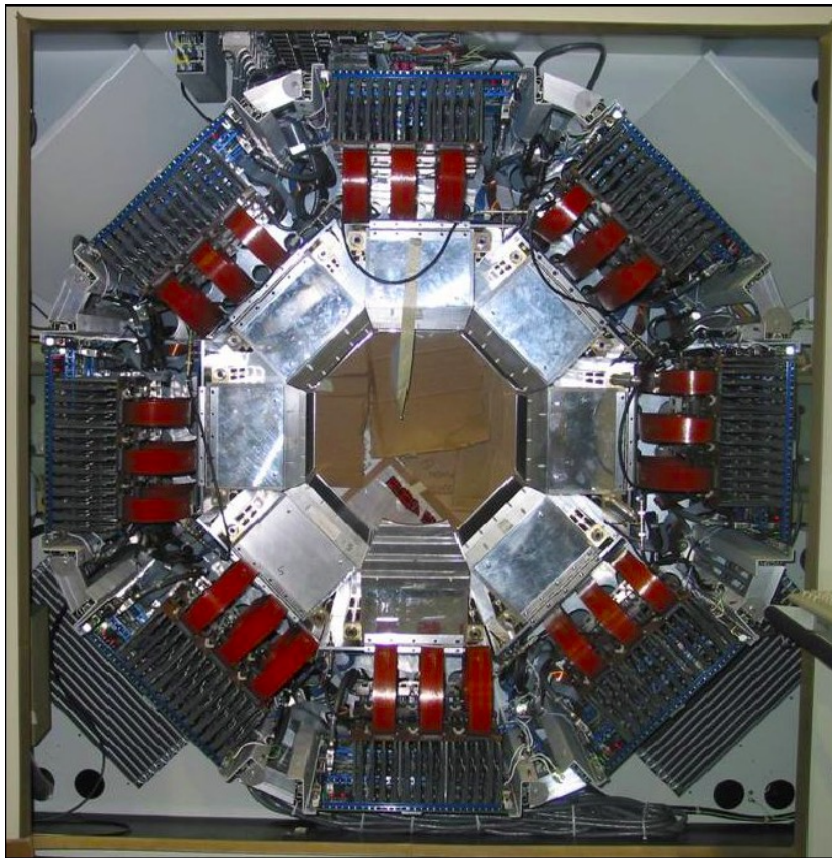


PMTs



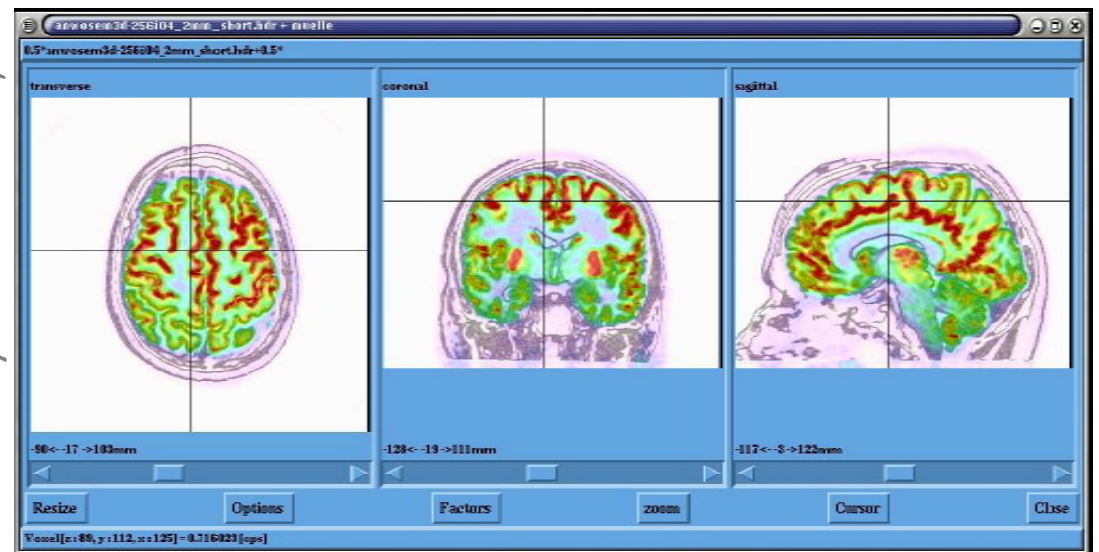
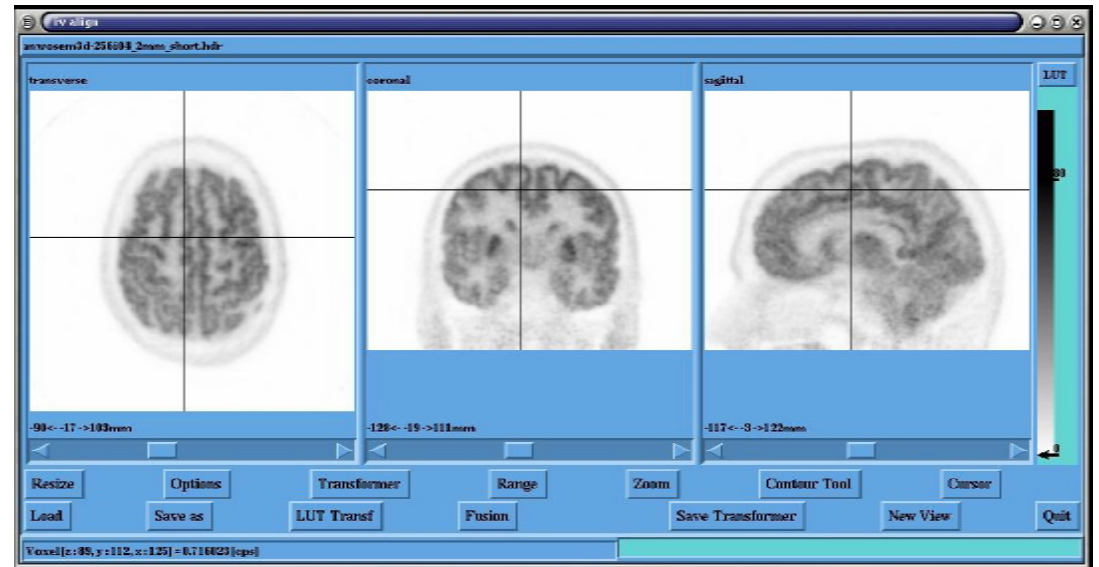
Courtesy: D. Townsend, UPMC

High Resolution Research Tomograph (HRRT)



- LSO/GSO phoswich
- 153600 cristaux
- 1120 PMTs

Courtesy: K. Wienhard, Köln



40 min FDG fusionnée avec IRM-T1

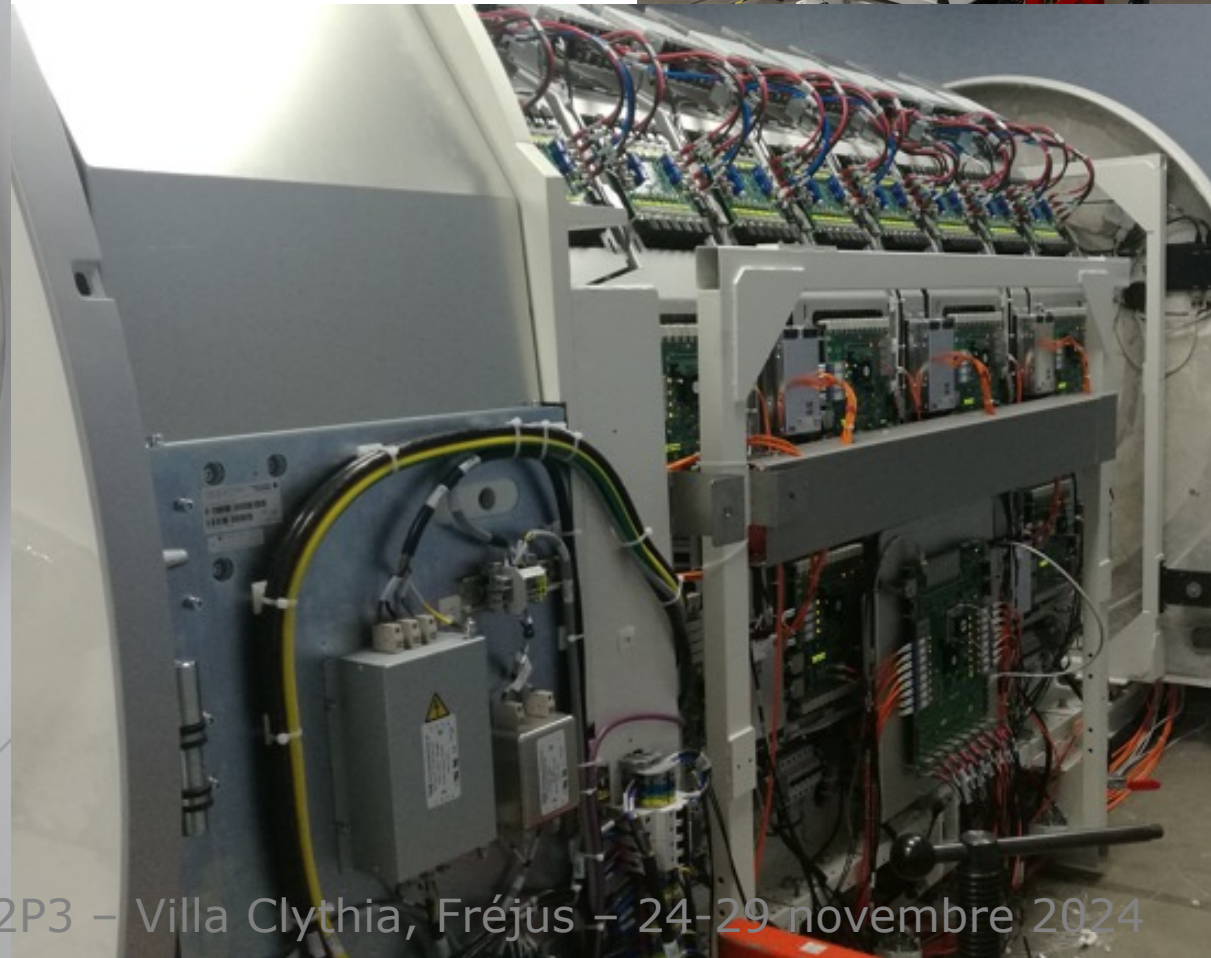
EXPLORER est construit !

Système :

Diamètre : 78.6 cm

FOV transverse : 68.6 cm

FOV axial : 194.8 cm

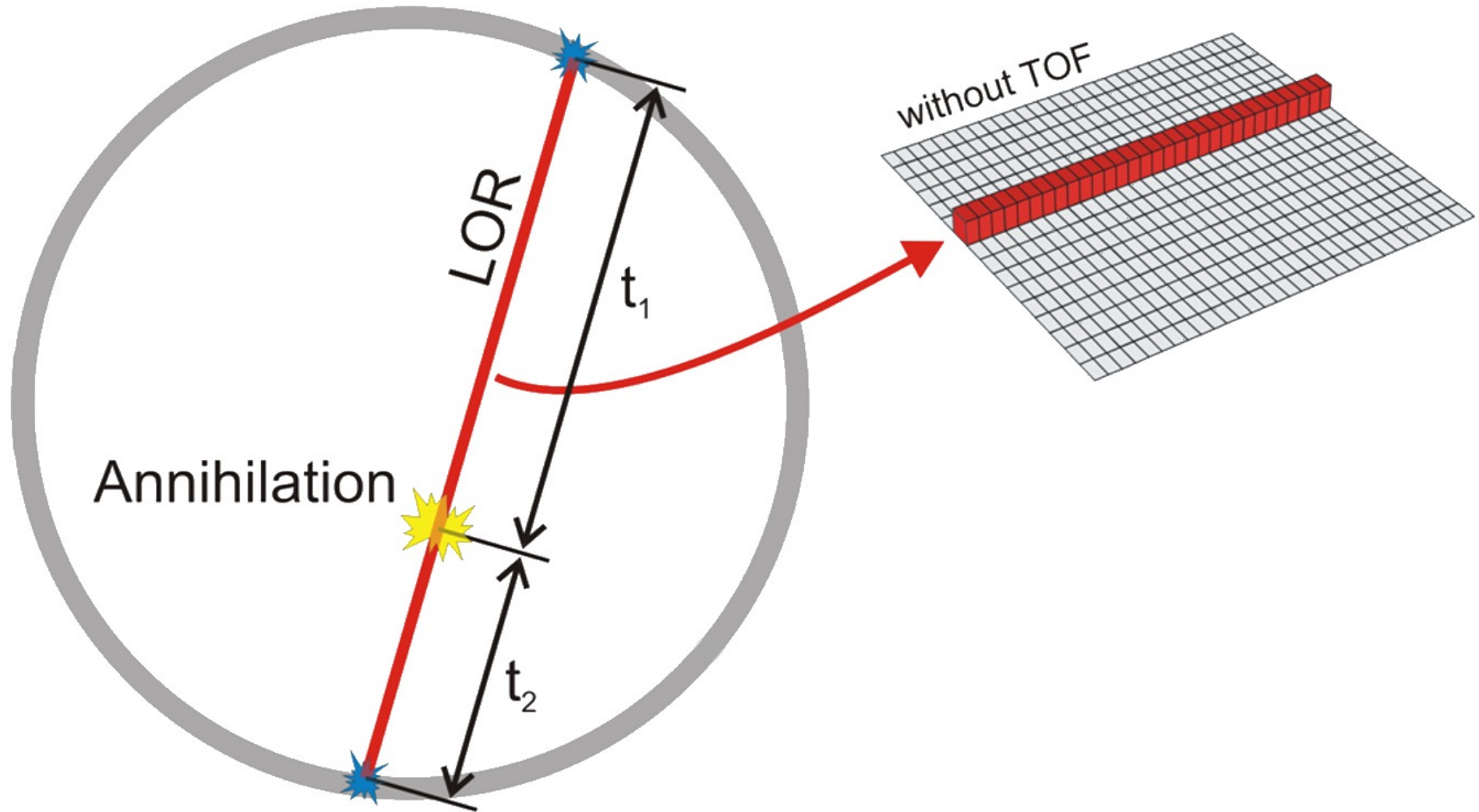


cristaux : 564,480

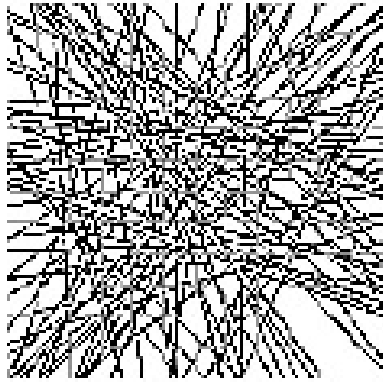
blocs de cristaux : 13,440

SiPMs : 53,760

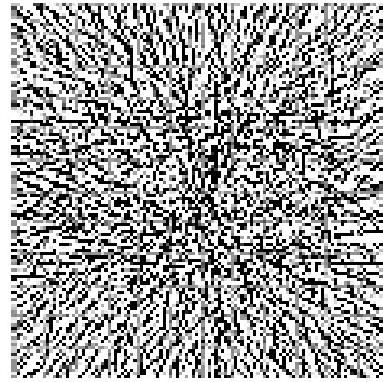
Rétroprojection



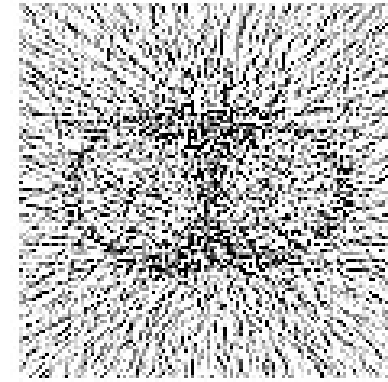
Tomographie et statistique de comptage



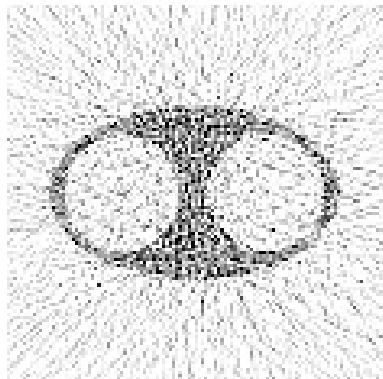
10^2



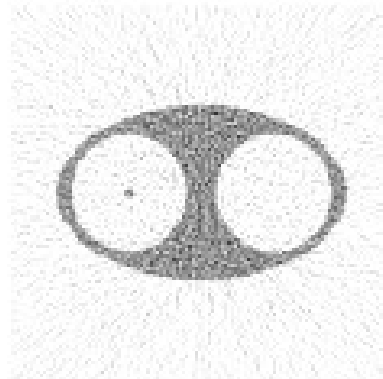
10^3



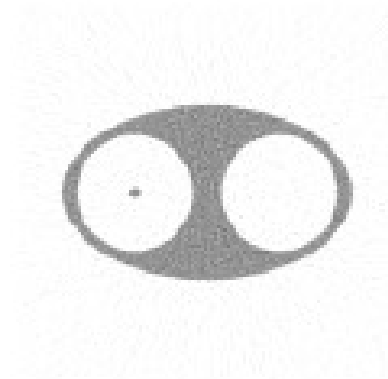
10^4



10^5



10^6



10^7

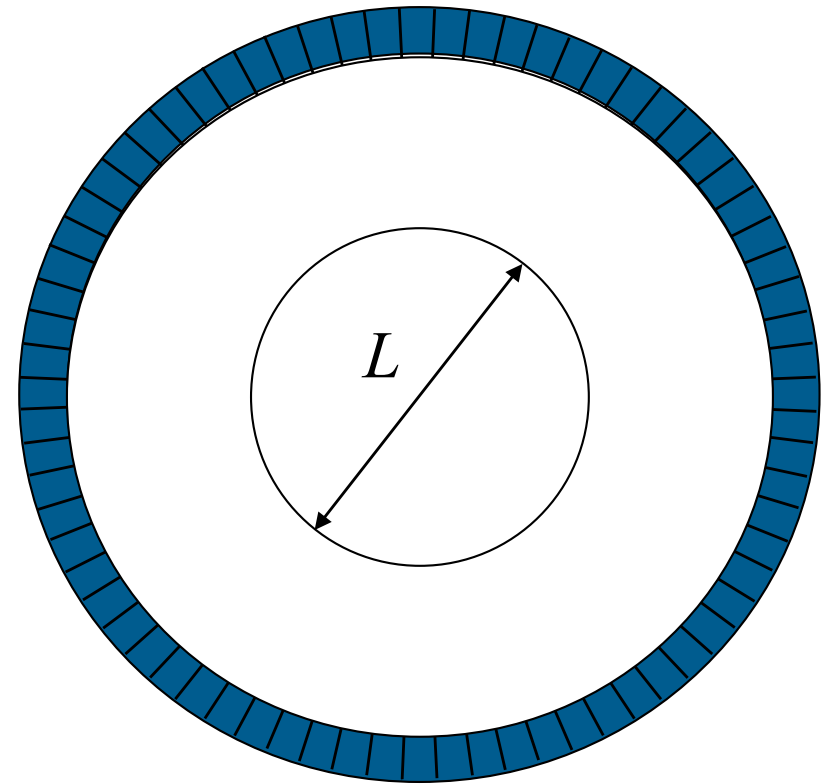
Courtesy: C. Comtat, CEA-SHFJ

SNR et statistique de comptage

$$\text{SNR} = \frac{A}{\Delta A} = \frac{N_{\beta^+}}{\sqrt{N_{\beta^+}}} = \sqrt{N_{\beta^+}}$$

$$\Rightarrow N_{\beta^+} = \text{SNR}^2$$

$$N_{\text{evt}} = \left(\frac{L}{d}\right)^3 \times \text{SNR}^2 \times \left(\frac{L}{d}\right)$$



Améliorer la résolution spatiale $\times 2 \Rightarrow$ Augmenter la statistique de comptage $\times 16$ pour obtenir le même SNR dans les voxels de l'image reconstruite

- ↗ Durée du scan
- ↗ Epaisseur du cristal (efficacité)
- ↗ Activité injectée
- ↗ Angle solide

Résolution radiale

$$R(s) = a \sqrt{\left(\frac{d}{2}\right)^2 + \frac{(w^2 - d^2)}{D^2} s^2 + b^2 + r^2 + (0.0022 D)^2}$$

d Taille du pixel

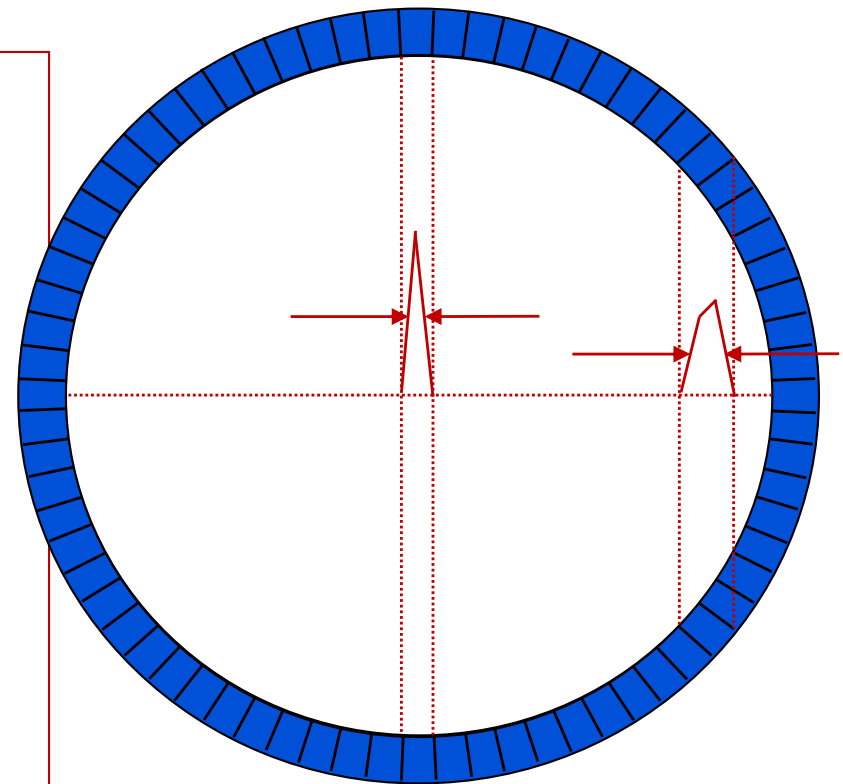
w Longueur du pixel

D Diamètre de l'anneau

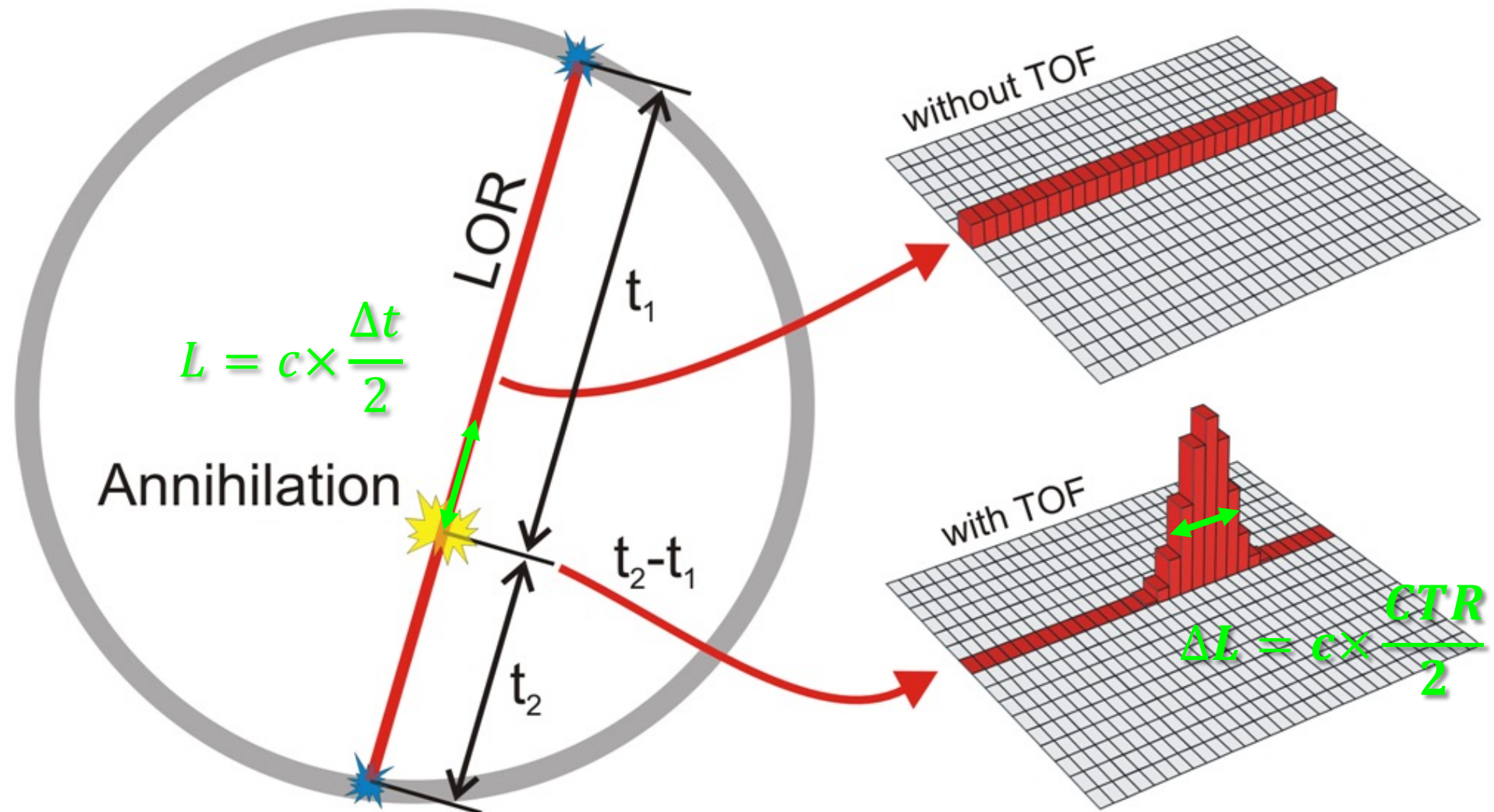
r Parcours du positon

b Diaphonie

a Algorithme de reconstruction d'image (1,1 - 1,3)



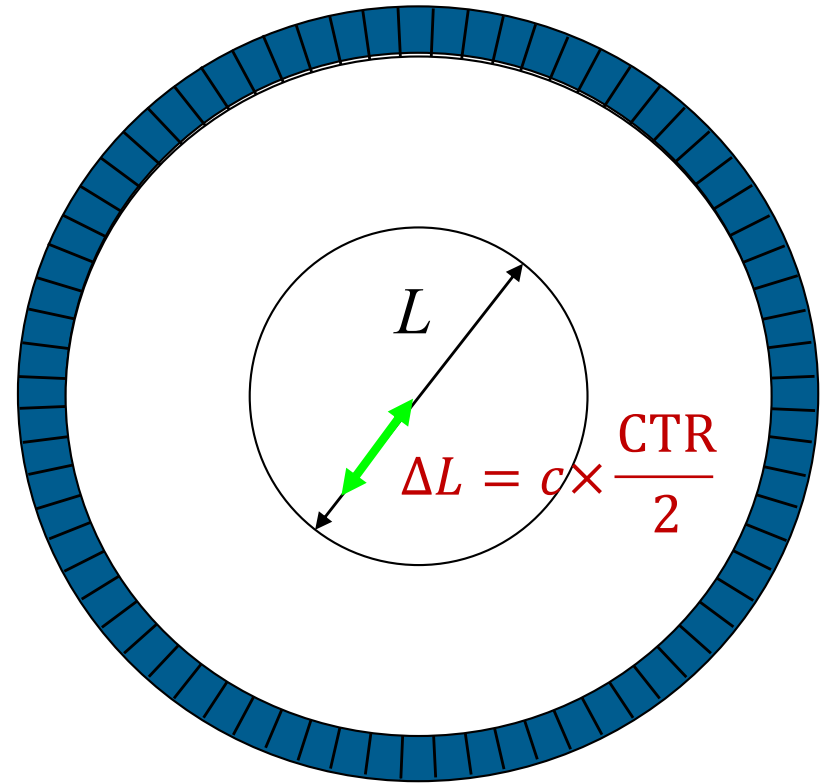
TEP à temps-de-vol (TOF-PET)



Impact de la TOF-TEP sur le SNR de l'image

$$N_{\text{evt}} = \left(\frac{L}{d}\right)^3 \times \text{SNR}^2 \times \left(\frac{L}{d}\right)$$

$$N_{\text{TOF}} = \left(\frac{L}{d}\right)^3 \times \text{SNR}^2 \times \left(\frac{\Delta L}{d}\right)$$

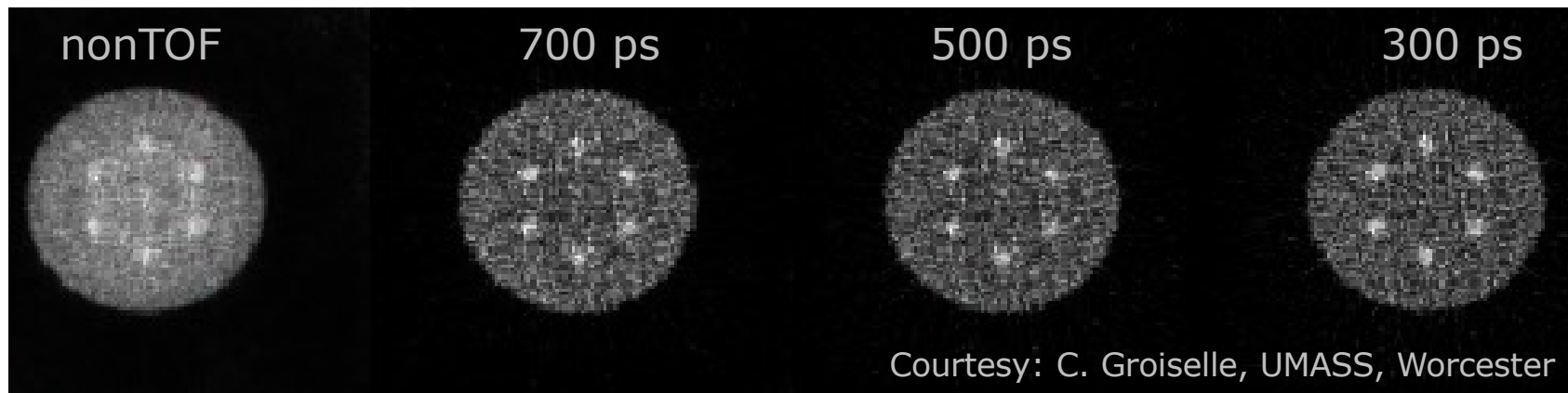
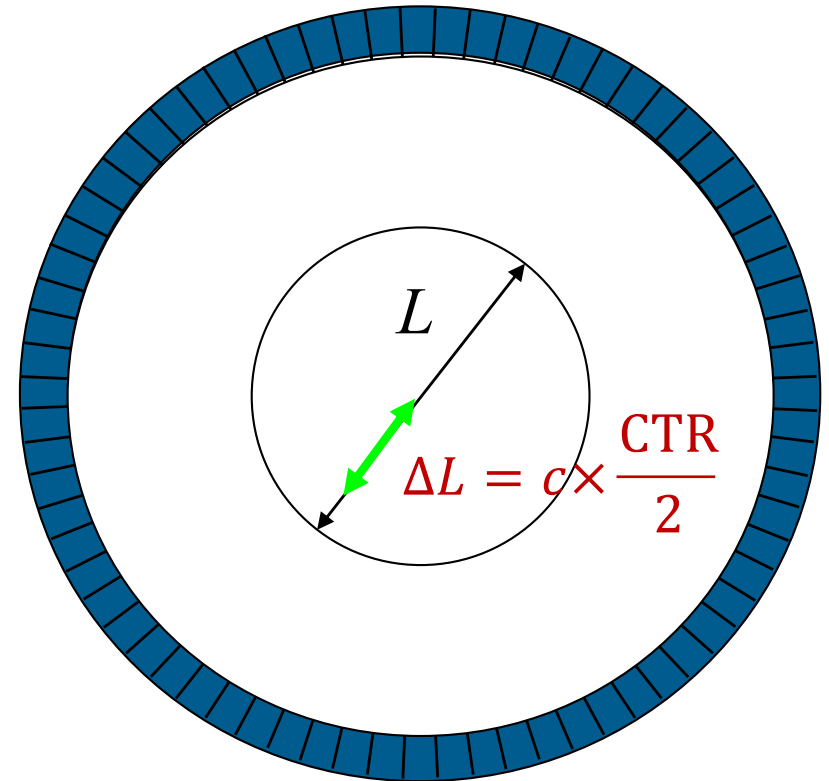


Impact de la TOF-TEP sur le SNR de l'image

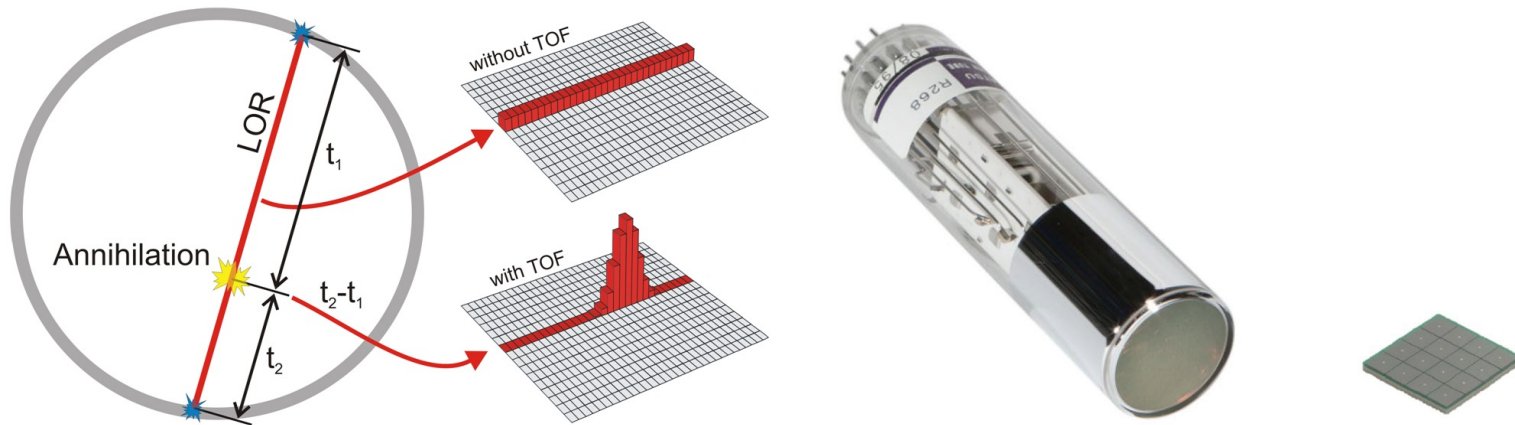
$$N_{\text{evt}} = \left(\frac{L}{d}\right)^3 \times \text{SNR}_{\text{nonTOF}}^2 \times \left(\frac{L}{d}\right)$$

$$N_{\text{evt}} = \left(\frac{L}{d}\right)^3 \times \text{SNR}_{\text{TOF}}^2 \times \left(\frac{\Delta L}{d}\right)$$

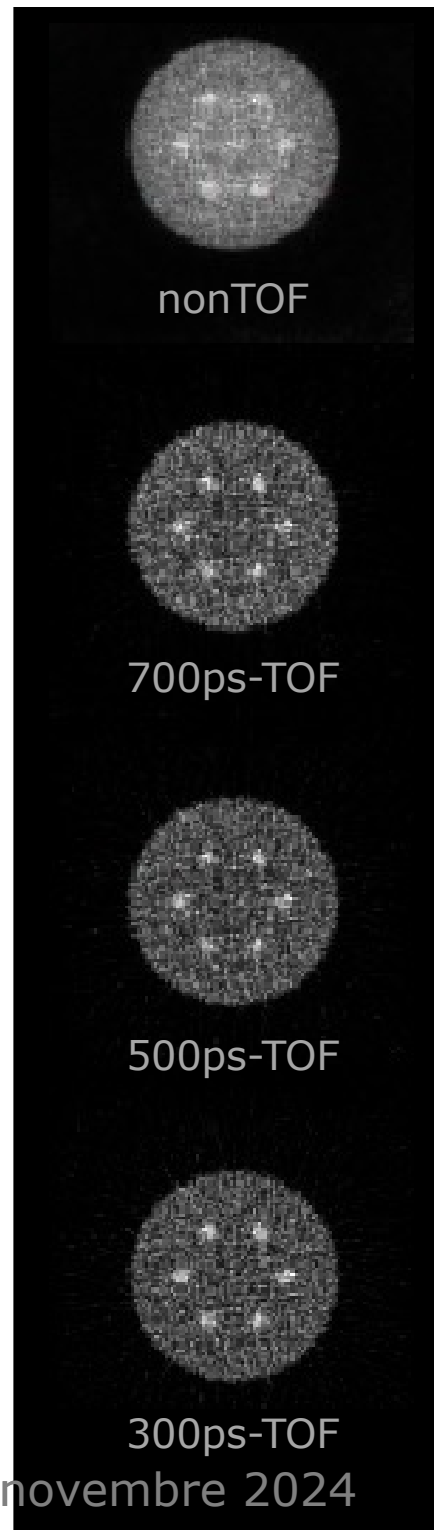
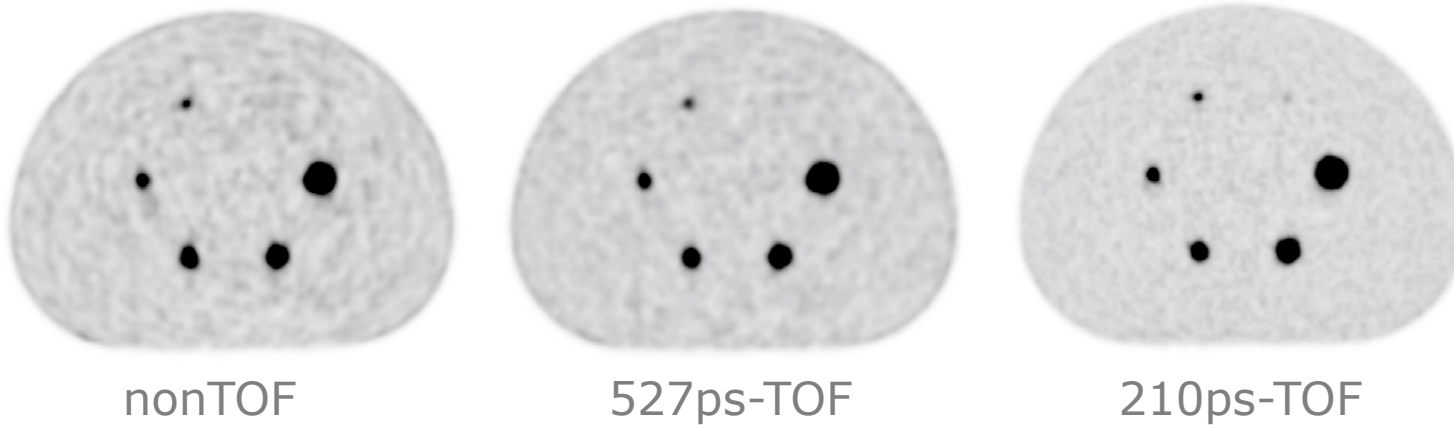
$$\left(\frac{\text{SNR}_{\text{TOF}}}{\text{SNR}_{\text{nonTOF}}}\right)^2 = \frac{2L}{c \times \text{CTR}}$$



Time-Of-Flight (TOF)-TEP



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



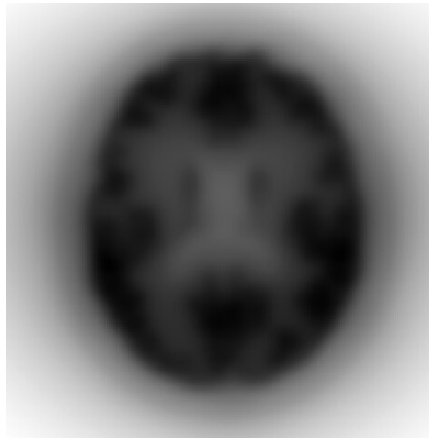
Resolution in TOF-direction: ~ 1.5 mm

Resolution in detector direction: 5 mm

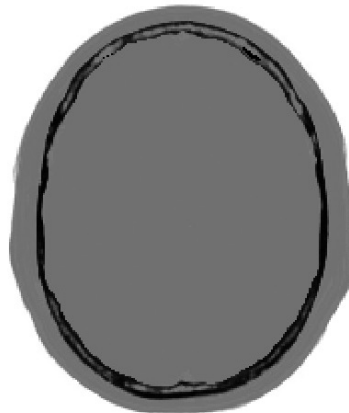
true activity



nonTOF backproj



TOF backproj



true attenuation



nonTOF OSEM

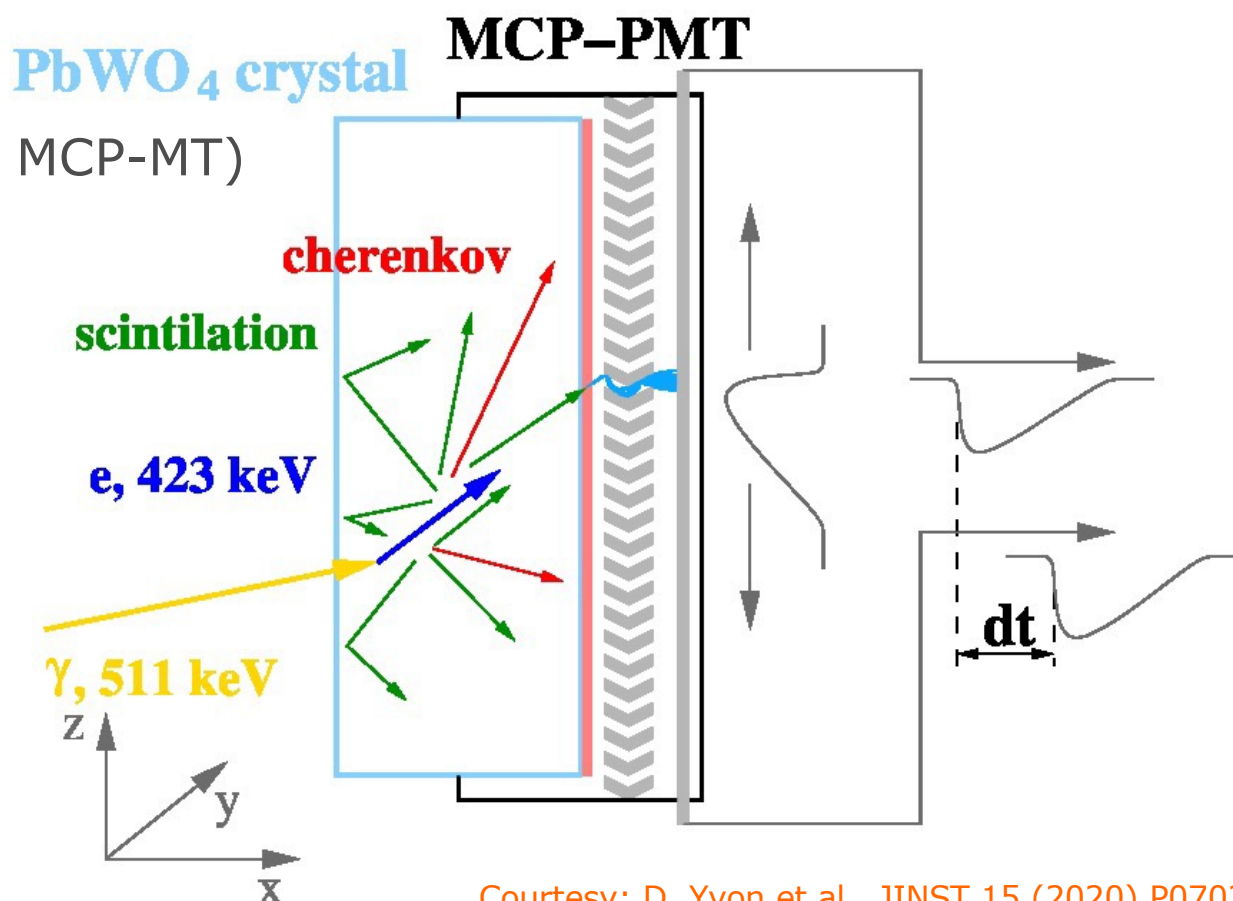


TOF OSEM

Courtesy: J. Nuyts, Univ Leuven

- 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)

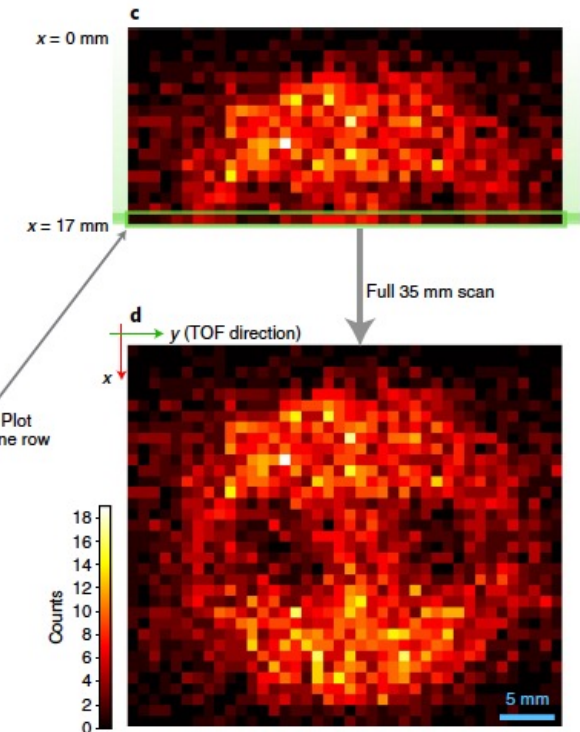
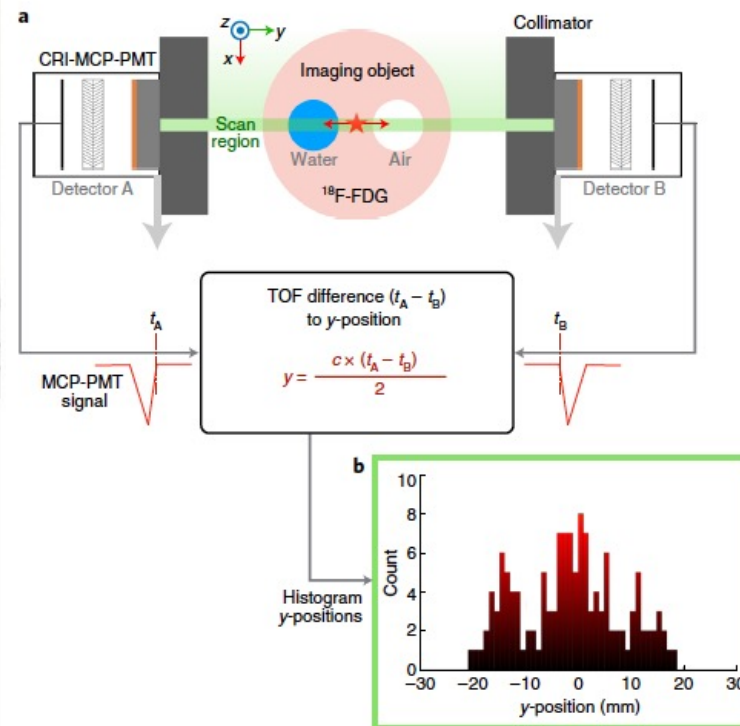
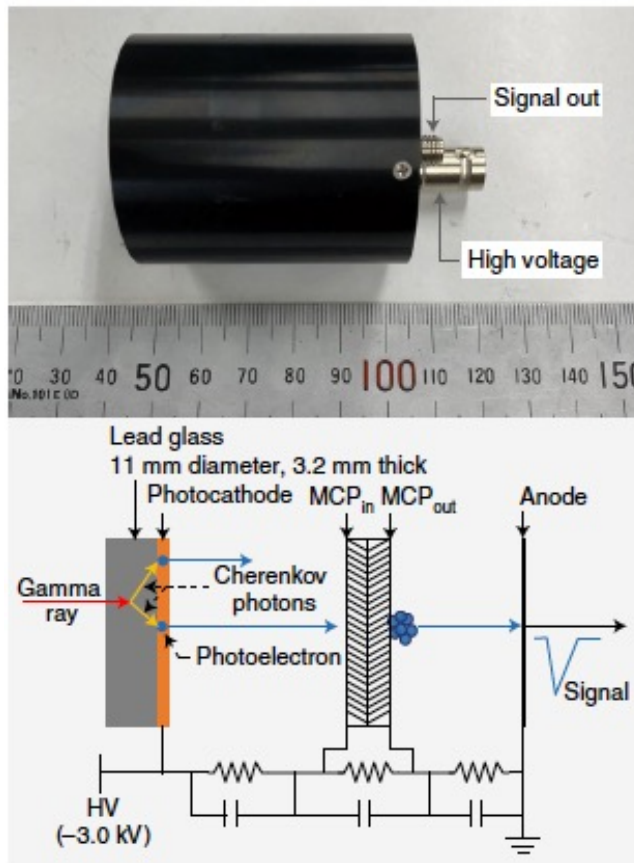
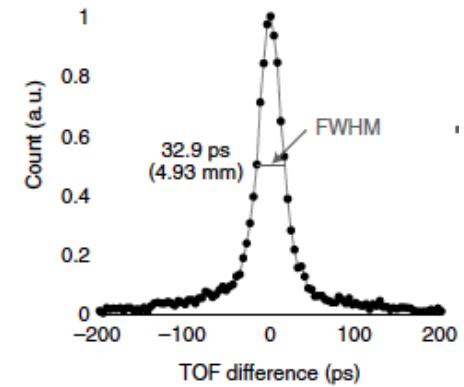
- CRT ~ 20 ps FWHM (hors MCP-MT)



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

Imagerie directe par émission de positons

- Utilisation de la lumière Tcherenkov pour l'étiquetage temporel
- CTR 32.9 ps FWHM (4.93 mm)
- Direct positron emission imaging (dPEI)

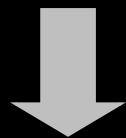


Courtesy: S.I. Kwon et al., Nat. Photon. 2020

Anatomie + Fonction



TDM



Anatomie



Logiciel
de fusion

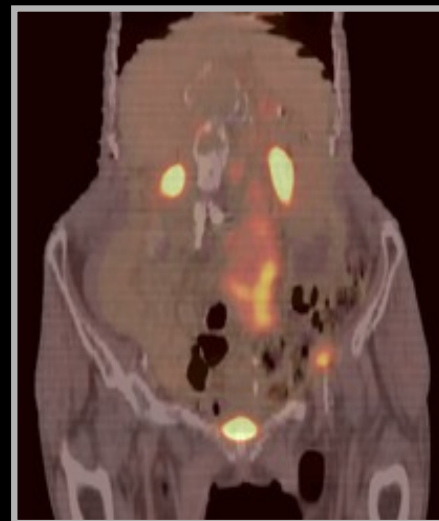
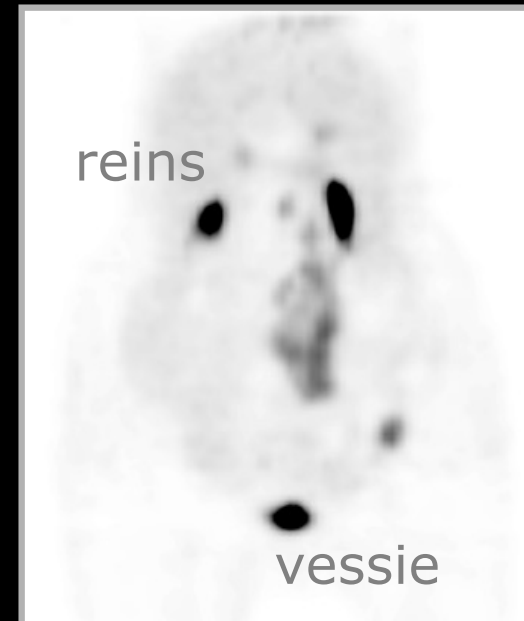


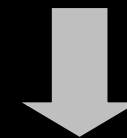
Image fusionnée



reins

vessie

TEP

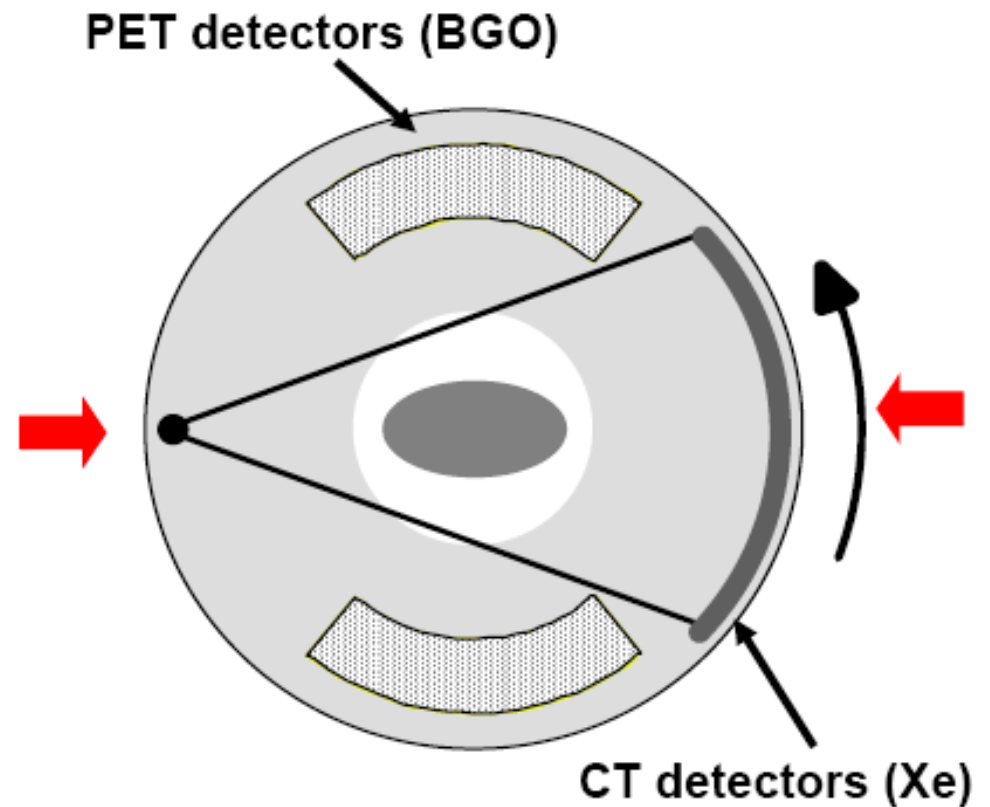
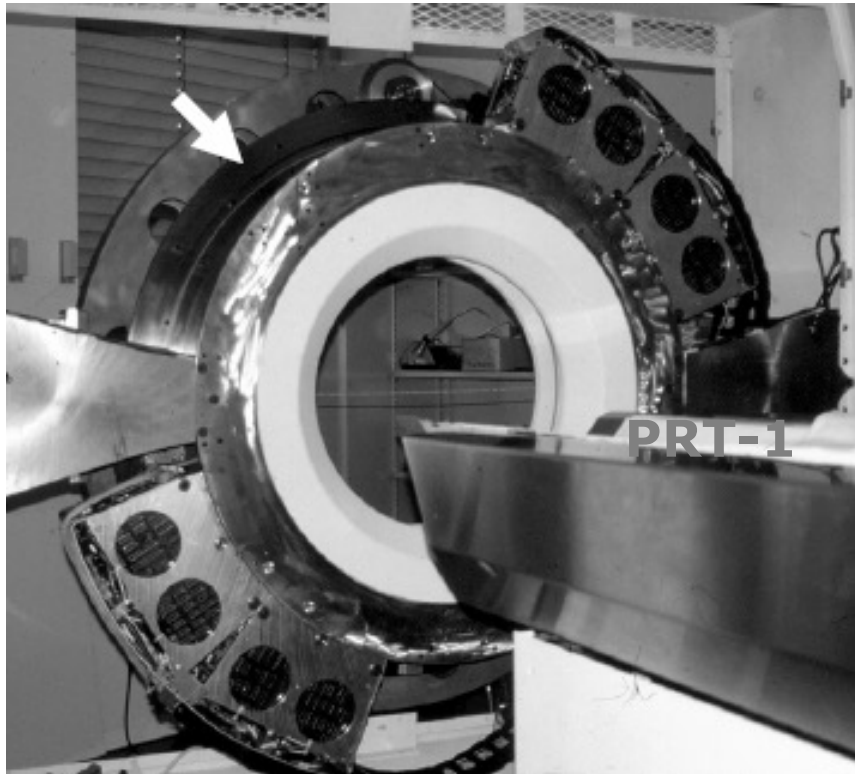


Fonction

Courtesy: DW Townsend, UPMC

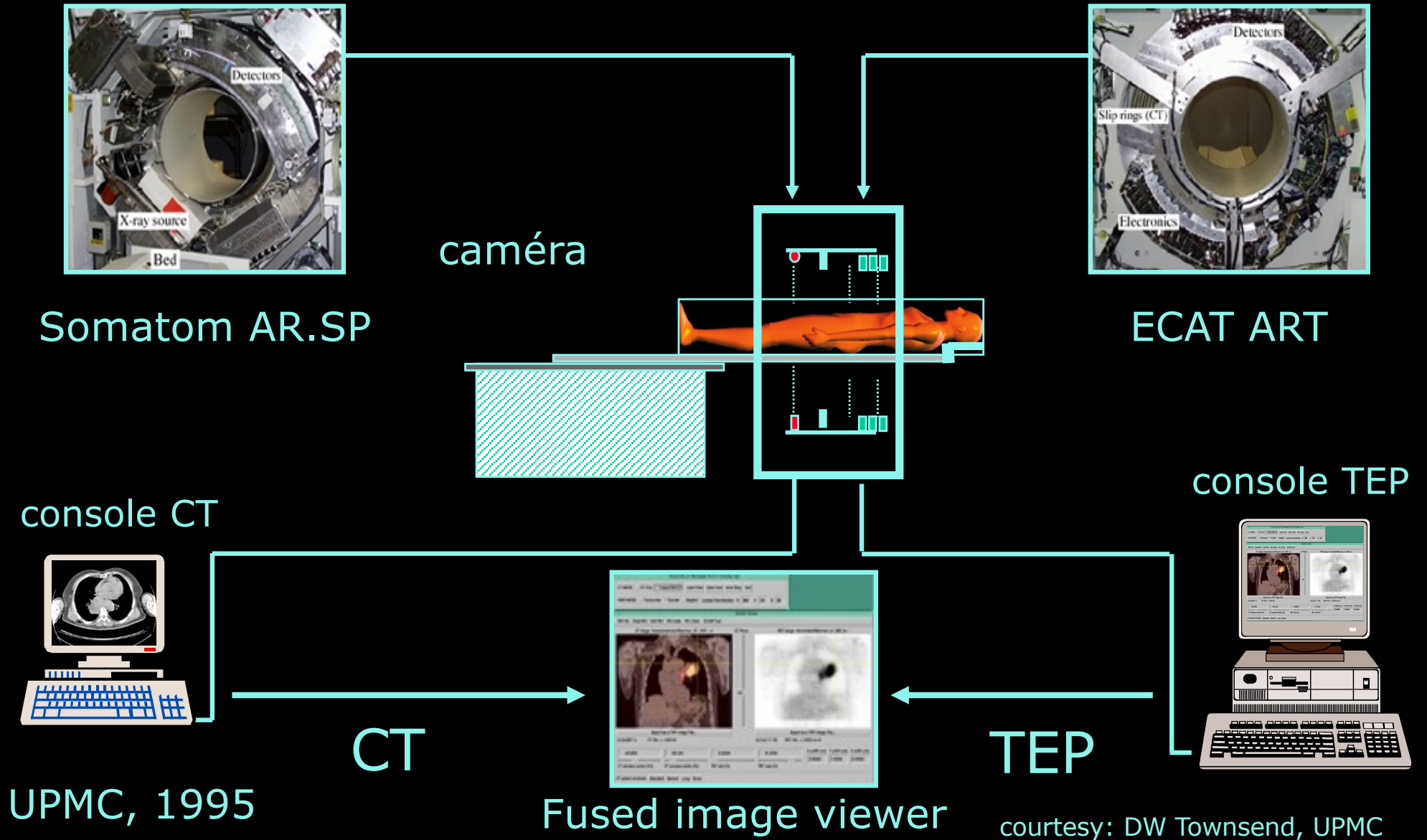
Invention du TEP/CT : une révolution médicale doublée d'une évolution technique

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



courtesy: DW Townsend, UPMC

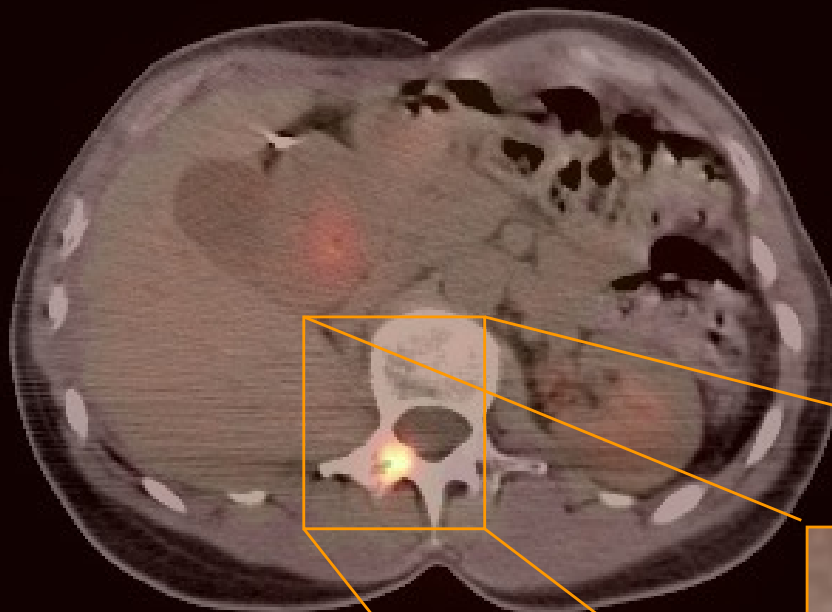
TEP/CT prototype design





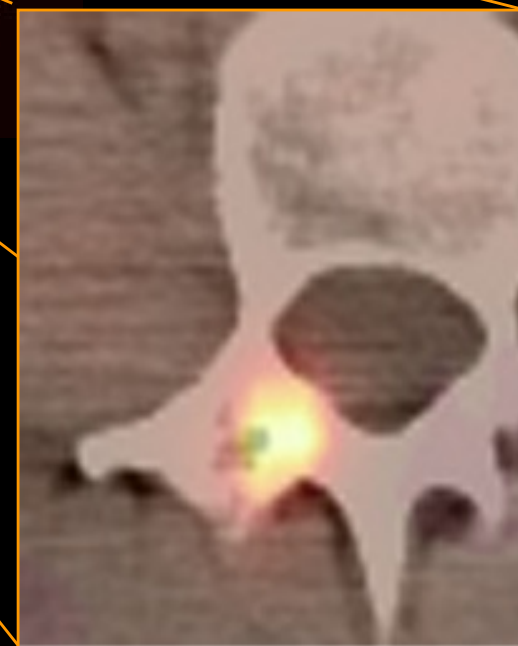
CT: 160 mAs; 130 KV_p; pitch 1.6; 5 mm slices

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



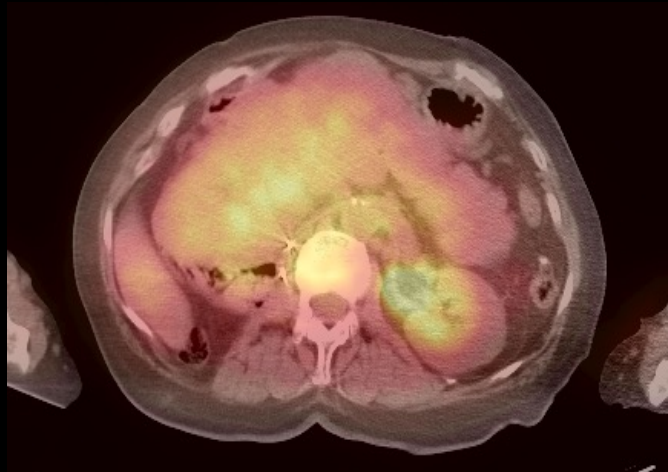
40 year-old woman with multiple endocrine syndrome (MEN-1) and history of malignant pheochromocytoma

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

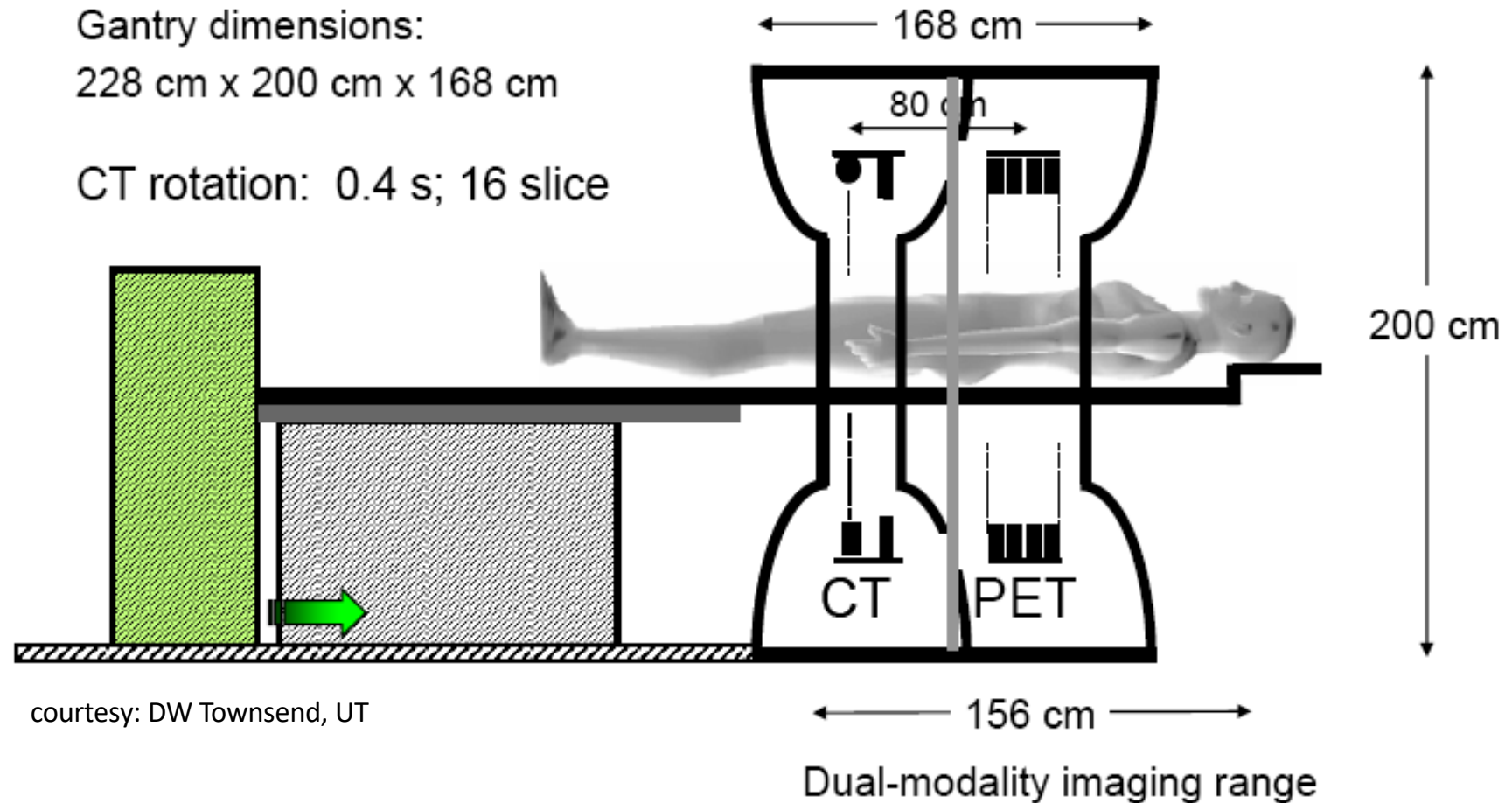


TIME magazine Dec 2000



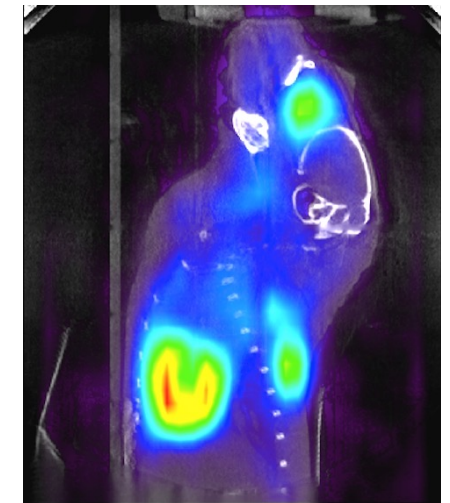
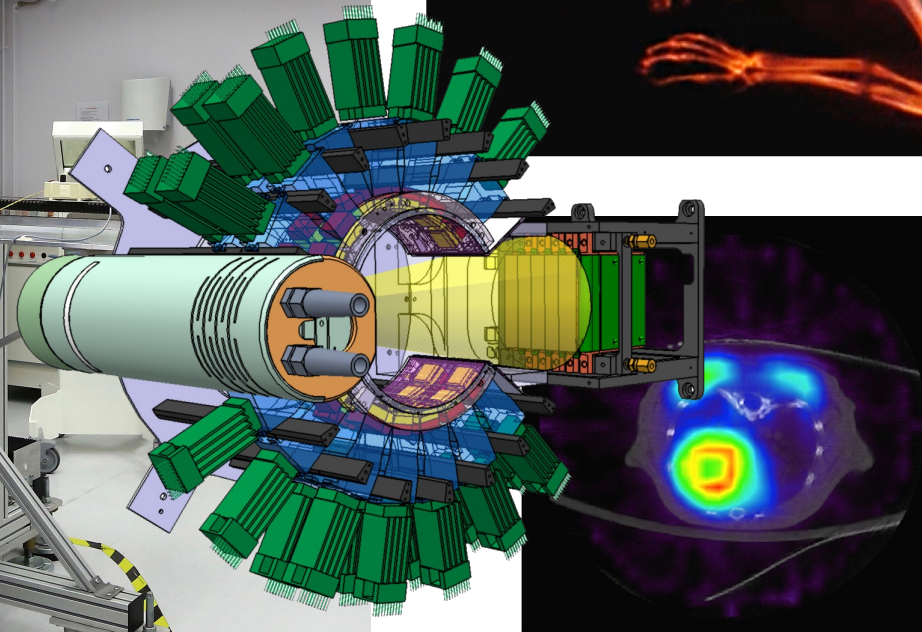
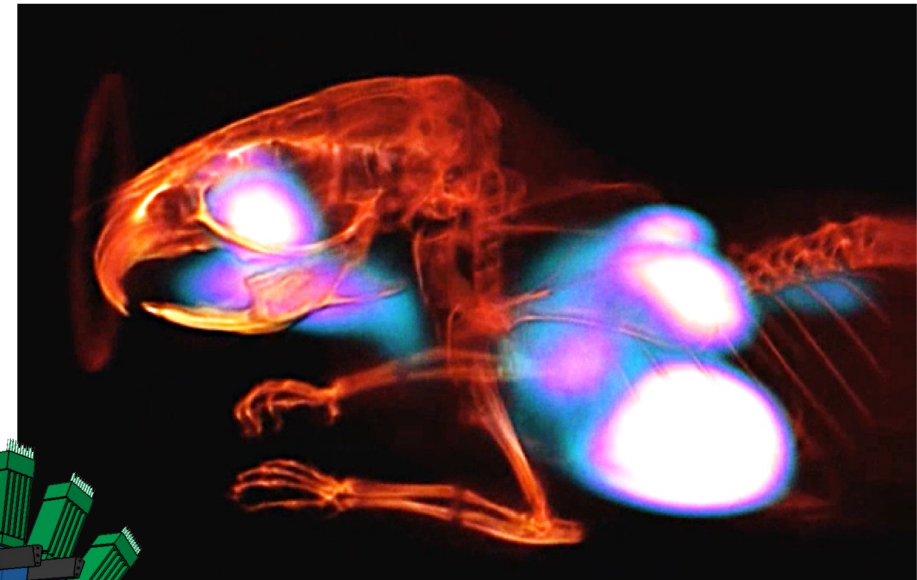
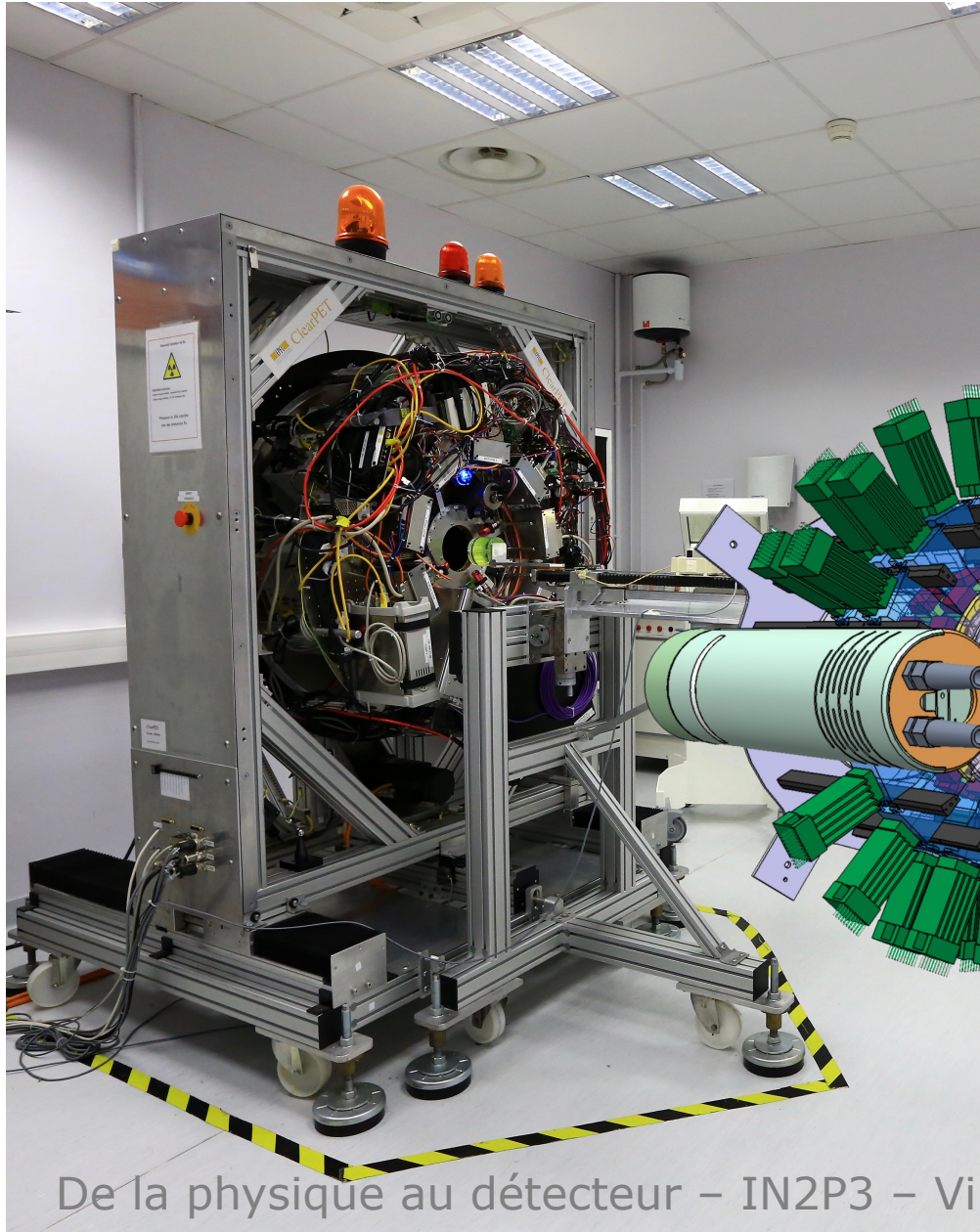
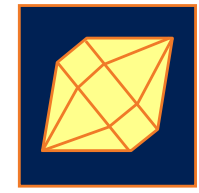
De la physique au détecteur – IN2P3 – Villa Clythia, Fréjus – 24-29 novembre 2024

Design typique d'un scanner TEP/CT clinique



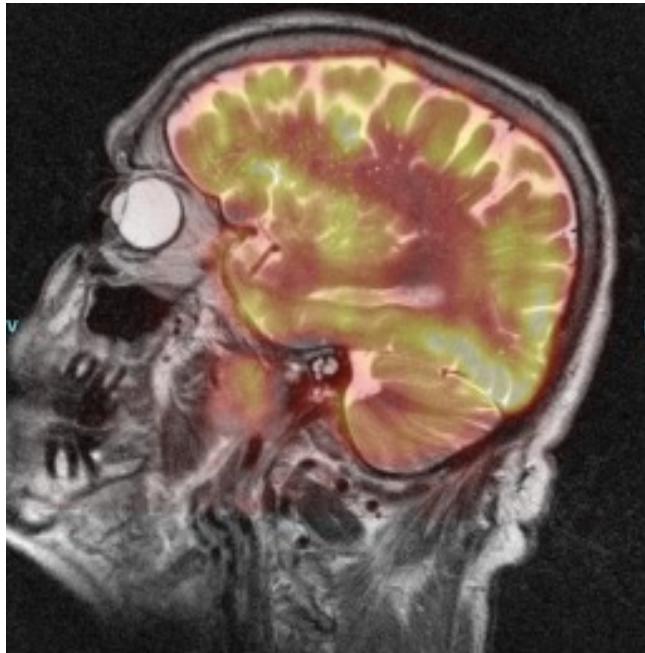
- 2001: premier scanner TEP/CT commercial installé à Zurich par GE
- 2005: plus de 650 scanners TEP/CT installés, 95% des ventes de scanners TEP

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



TEP/IRM

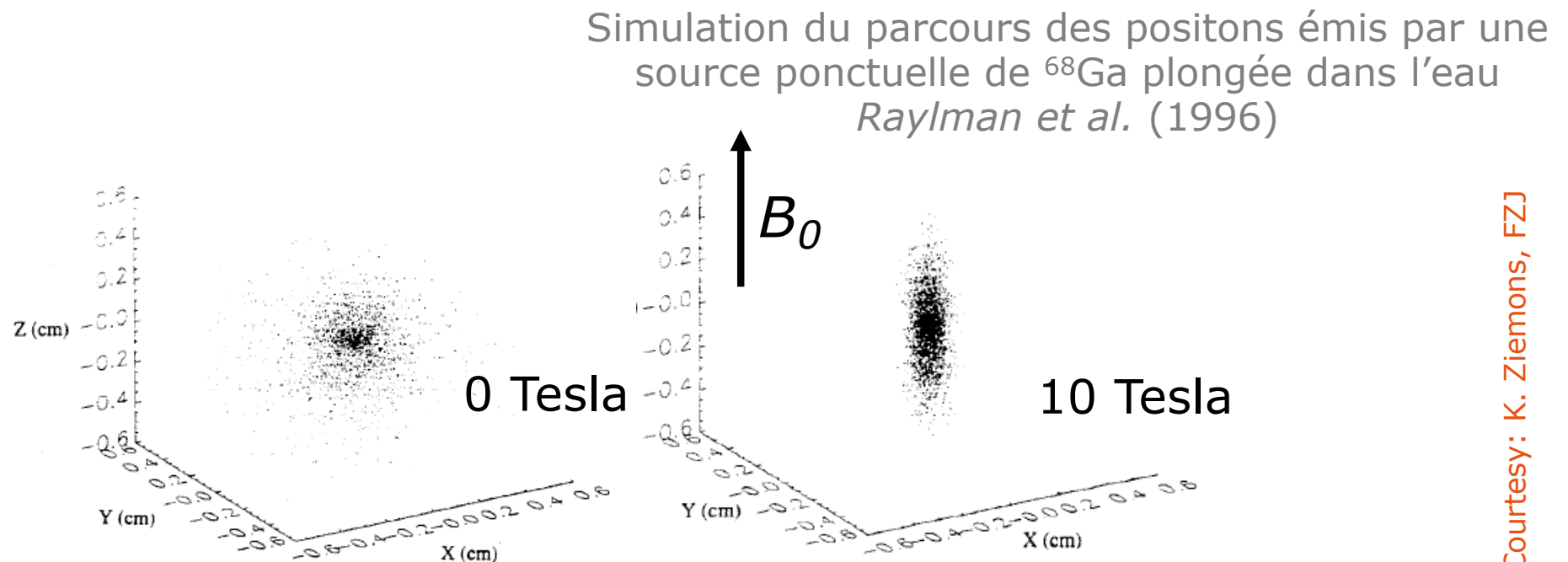
$$1 + 1 = ?$$



courtesy Pichler, Kolb, Schlemmer, UKT 2009

Imagerie hybride TEP/IRM: de quelques attentes non assouvies
L'amélioration de la résolution est négligeable pour la TEP !

- ⇒ Le parcours du positon limite la **résolution spatiale** de la TEP
- ⇒ **Réduction** du parcours du positon dans un champ magnétique élevé (*Iida et al. 1986*)
- ⇒ Cependant, la réduction est effective seulement dans le plan perpendiculaire au champ magnétique

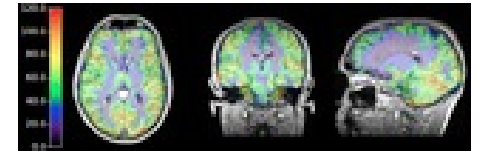
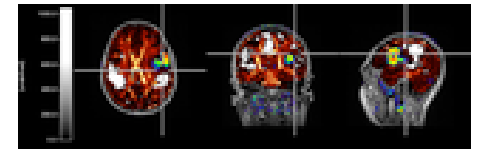
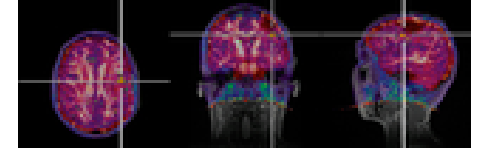


Courtesy: K. Ziemons, FZJ

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



$$1 + 1 = ?$$

En guise de conclusion...

TEP/CT a été une révolution médicale doublée d'une évolution technique

TEP/IRM semble être une révolution technique doublée d'une évolution médicale

NJ Shah, Forschungszentrum-Juelich

TEP/IRM/CT $1+1+1 = ?$

Still, the history [...] illustrates that predicting the effect of a hybrid system is difficult until it has been developed sufficiently to be applied to biomedical or clinical problems. When there is reasonable evidence of value to be gained, there is some truth to the saying "Build it and they will come." Therefore, it is important that research into the development and optimization of new hybrid imaging systems continue to be supported, as it offers one of the best opportunities for major technical innovation and impact in contemporary medical imaging science.

SR Cherry Semin. Nucl. Med. 39 (2009) 348



Association des anciens et
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<https://www.a3cnrs.org/>

Dossier : l'imagerie médicale

Imagerie moléculaire : *l'érosion des frontières* / David Brasse

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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Merci pour votre attention

Thank you for your attention

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