TOF&TB-PET

Focus sur l'imagerie TEP : défi 10 ps et corps-entier

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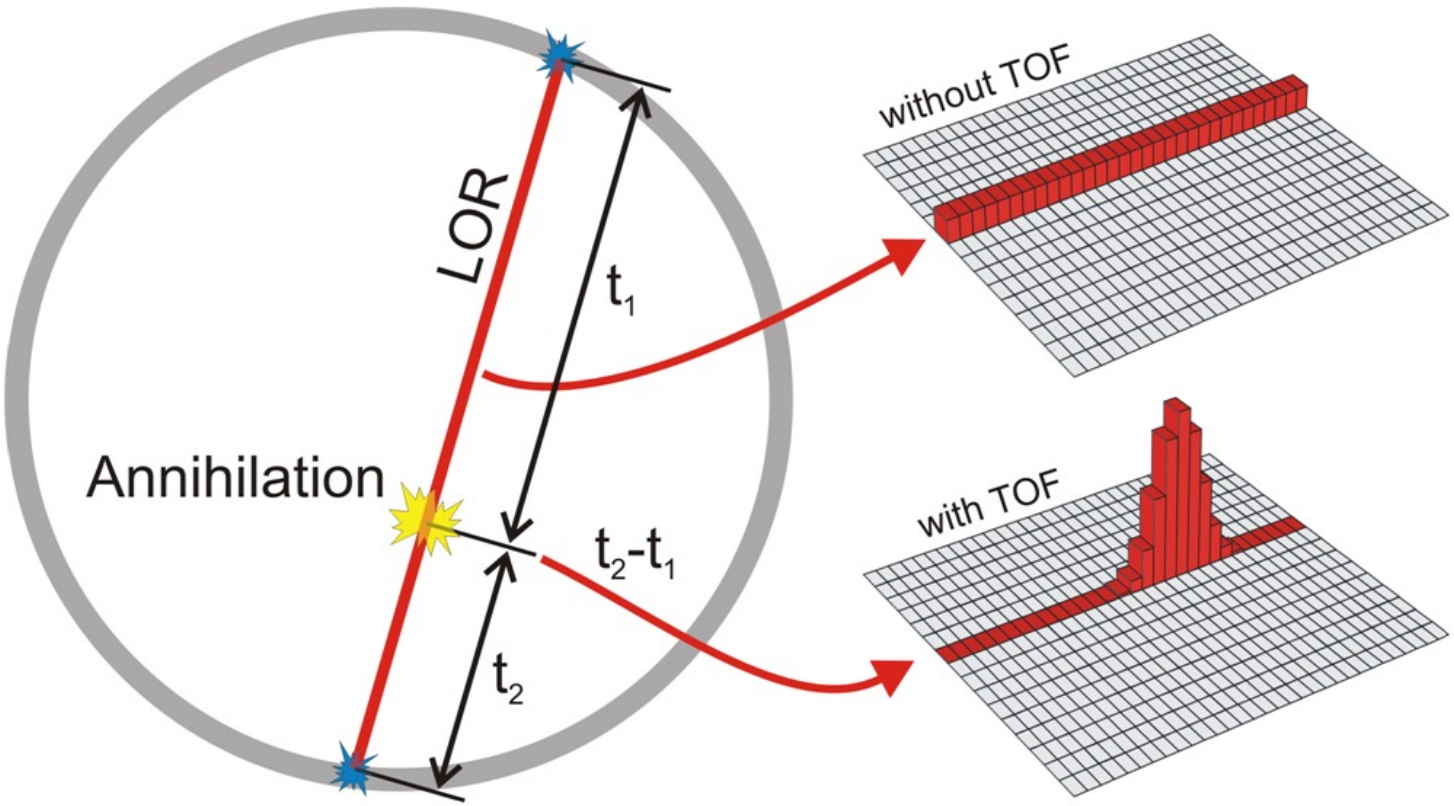
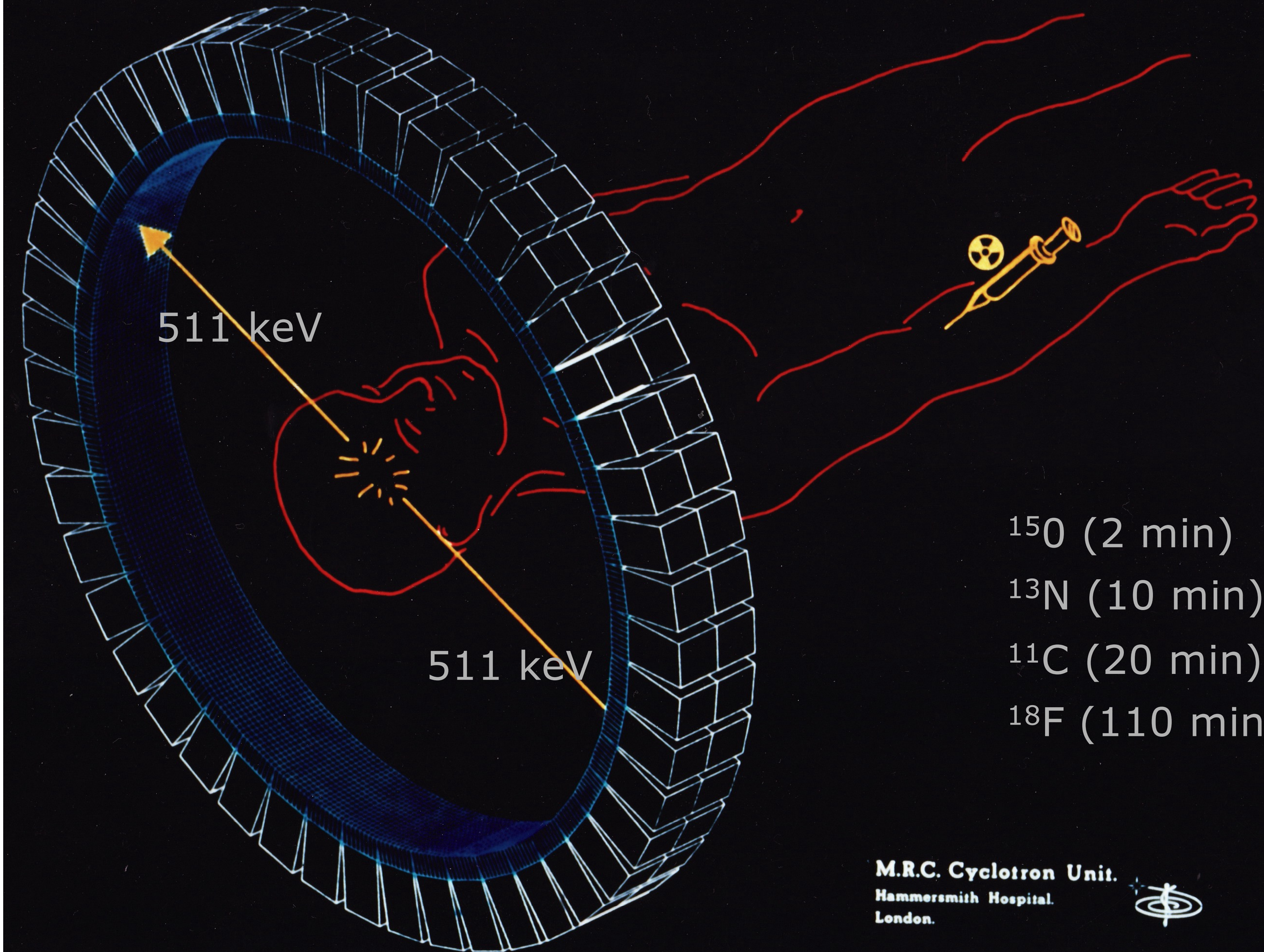


Positron Emission Tomography (PET)

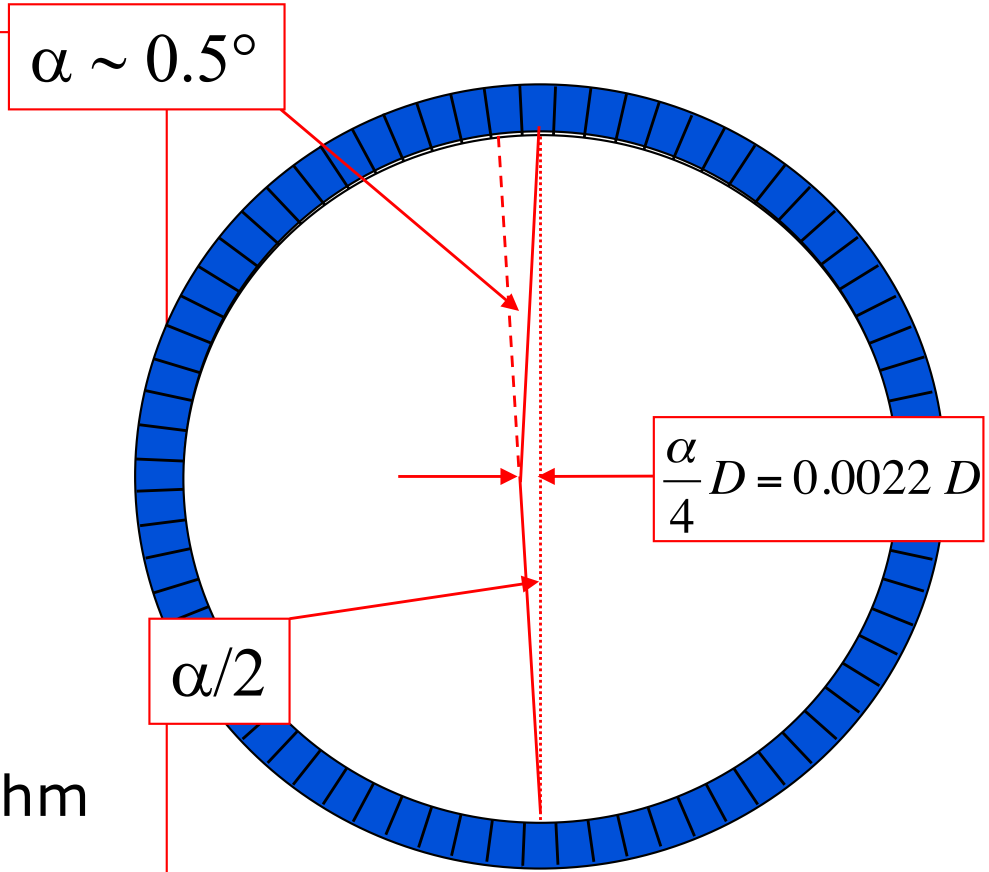


^{15}O (2 min)
^{13}N (10 min)
^{11}C (20 min)
^{18}F (110 min)

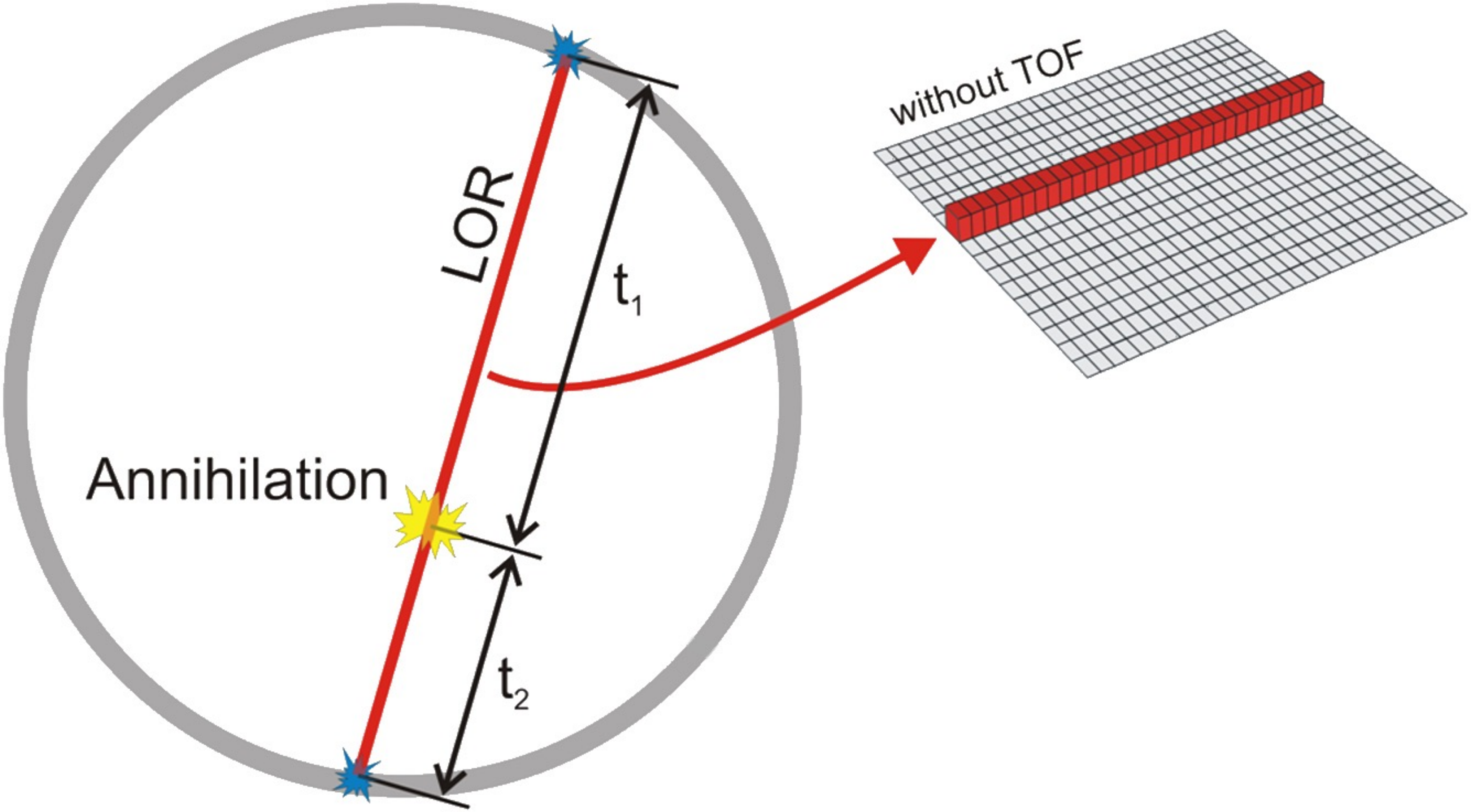
Spatial resolution

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

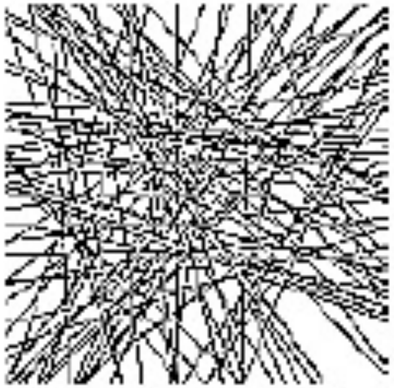
- d Pixel size
- w DOI resolution
- s Radial position
- D Ring diameter
- r Positron range
- b Detector crosstalk
- a Image reconstruction algorithm (1,1 - 1,3)



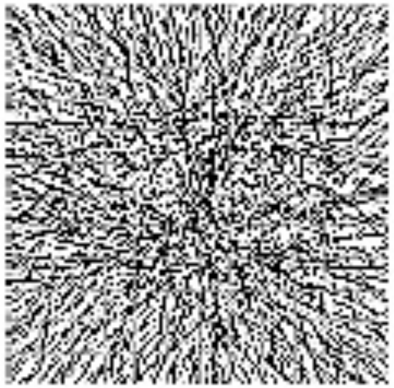
Backprojection



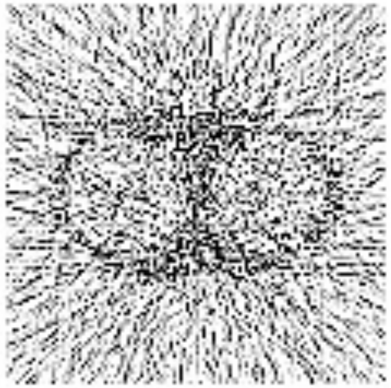
Tomography and counting statistics



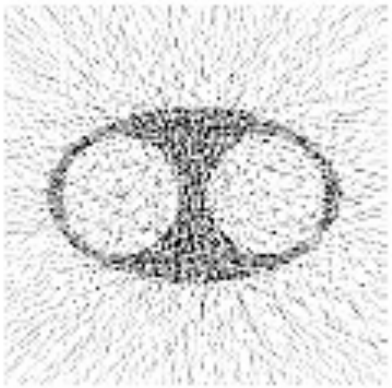
10^2



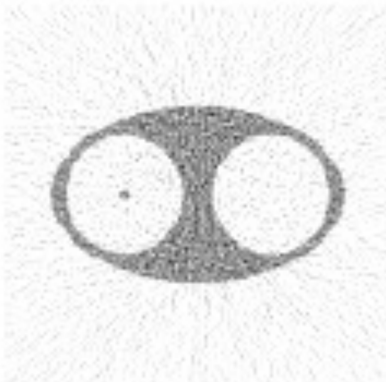
10^3



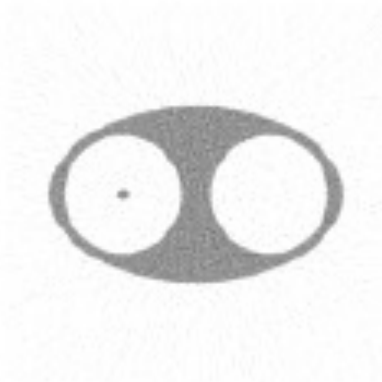
10^4



10^5



10^6



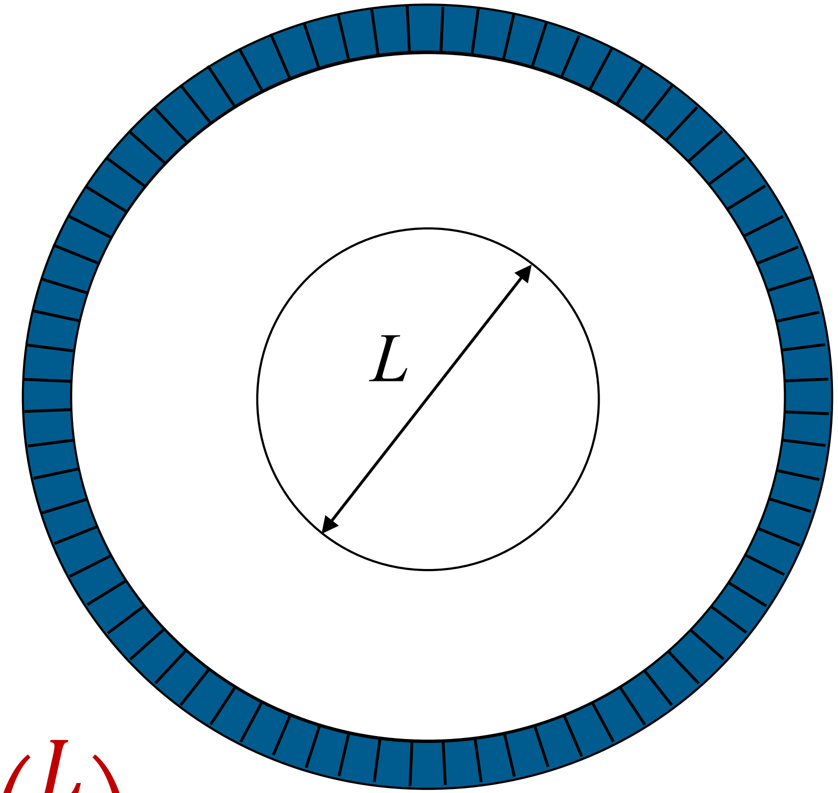
10^7

Courtesy: C. Comtat, CEA-Biomaps

SNR and counting statistics

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

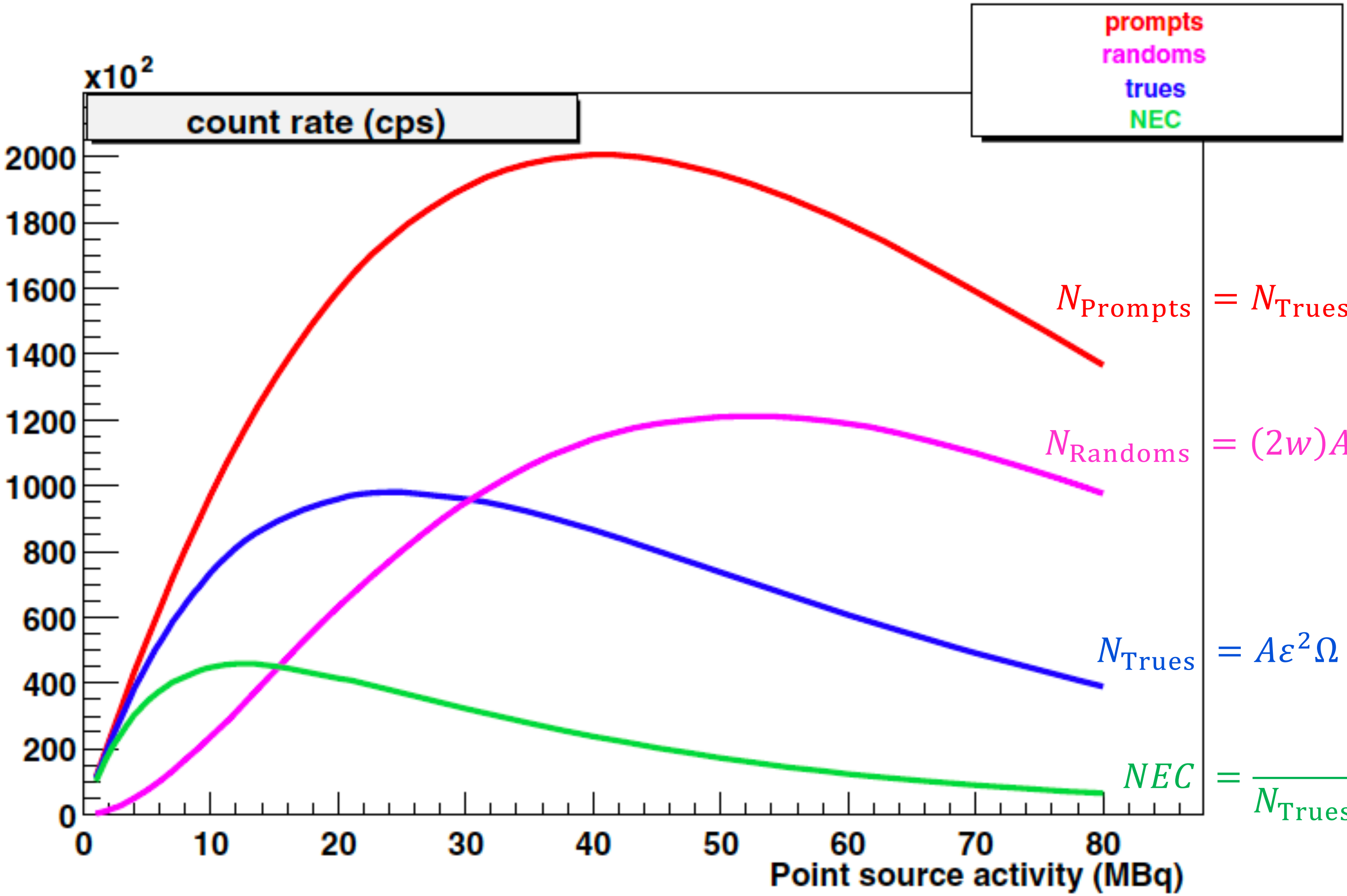
$$\Rightarrow N_{e^+e^-} = \text{SNR}^2$$



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

Improving spatial resolution x 2 ⟹ increasing counting statistics x 16 to get unchanged SNR in the reconstructed image voxels

Noise Equivalent Count Rate (NECR)



$$N_{\mathrm{Prompts}} = N_{\mathrm{Trues}} + N_{\mathrm{Randoms}}$$

$$N_{\mathrm{Randoms}} = (2w)A^2\varepsilon^2\Omega^2$$

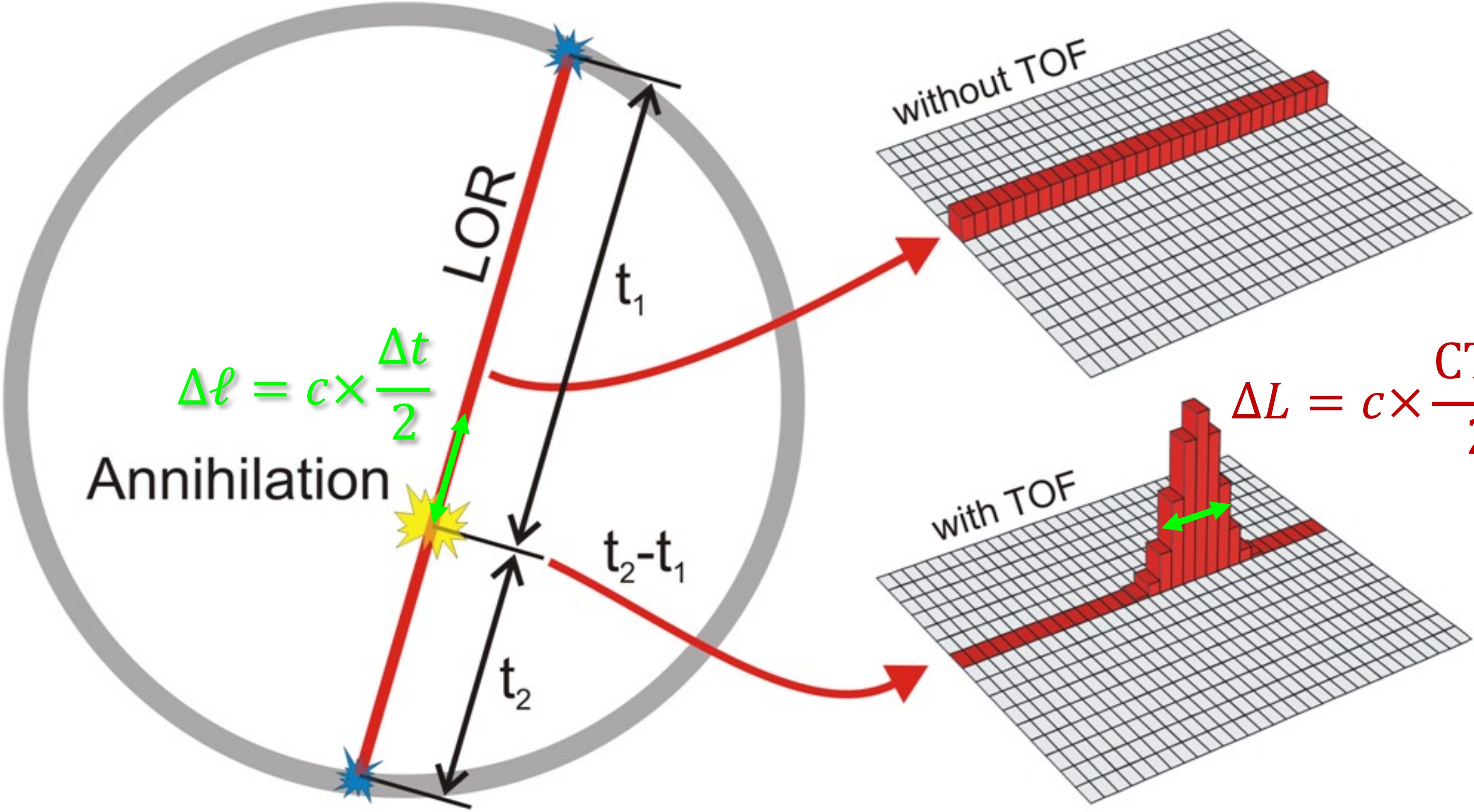
$$N_{\mathrm{Trues}} = A\varepsilon^2\Omega$$

$$NEC = \frac{N_{\mathrm{Trues}}}{N_{\mathrm{Trues}} + 2N_{\mathrm{Randoms}}}$$

Inorganic scintillators for PET

	NaI	BGO	BaF_2	L(Y)SO	LuAP	$LaBr_3$
Density (g/cm³)	3.67	7.13	4,88	7.10-7.40	8.34	5.29
Effective Z	51	74	53	65-66	65	52
Photofraction (%)	18	42	19	41	32	14
Decay time (ns)	230	300	0.6 620	35-45	17	15
Light yield (ph/MeV)	43000	8500	1430 9950	28-32000	11400	65000
Peak emission (nm)	415	480	220 310	420	365	300
Refraction index	1.85	2.15	1.47	1.82	1.97	1.9

Time-Of-Flight (TOF)-PET



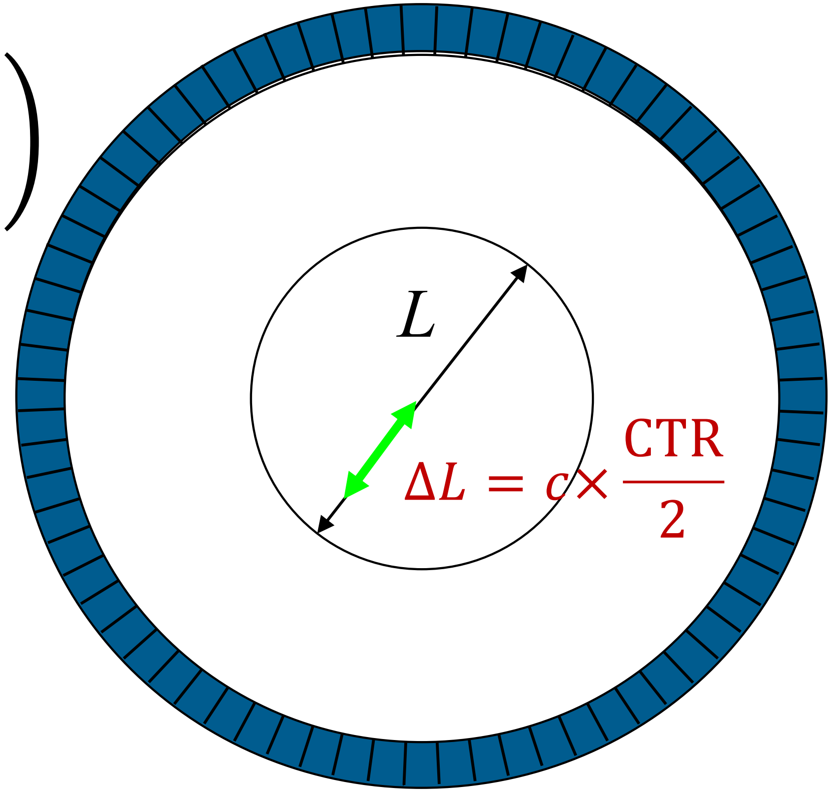
$$\Delta\ell = c \times \frac{\Delta t}{2}$$

$$\Delta L = c \times \frac{\text{CTR}}{2}$$

Impact of TOF-PET on image SNR

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

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

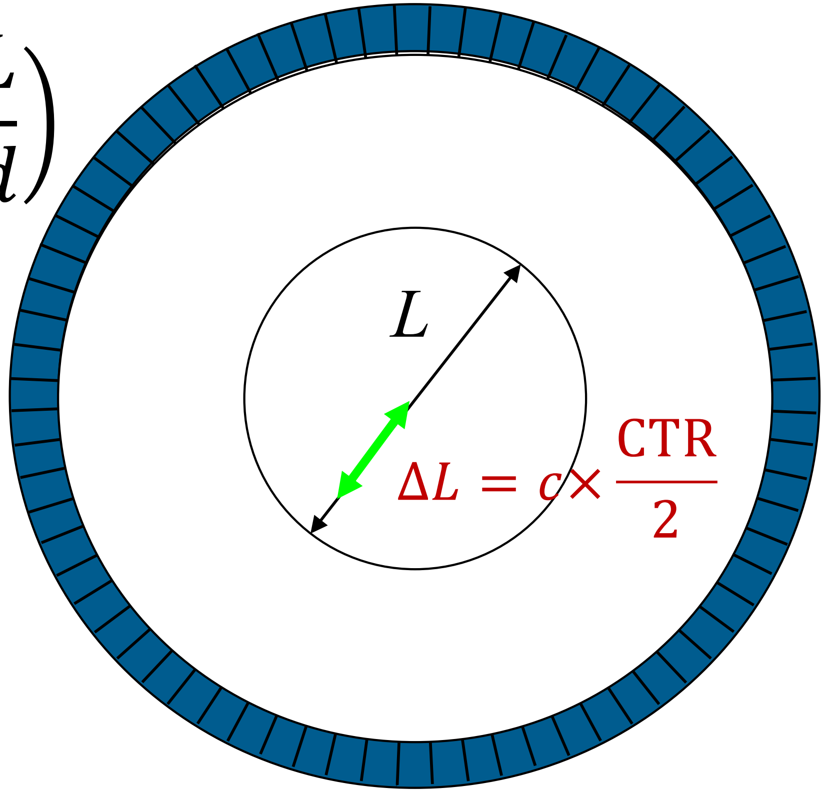


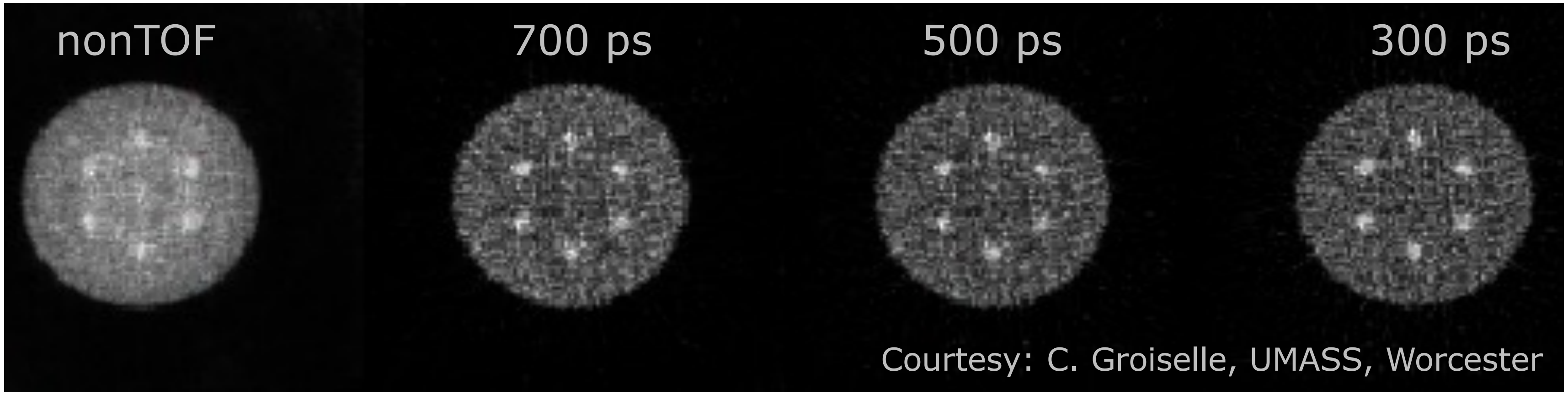
Impact of TOF-PET on image SNR

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

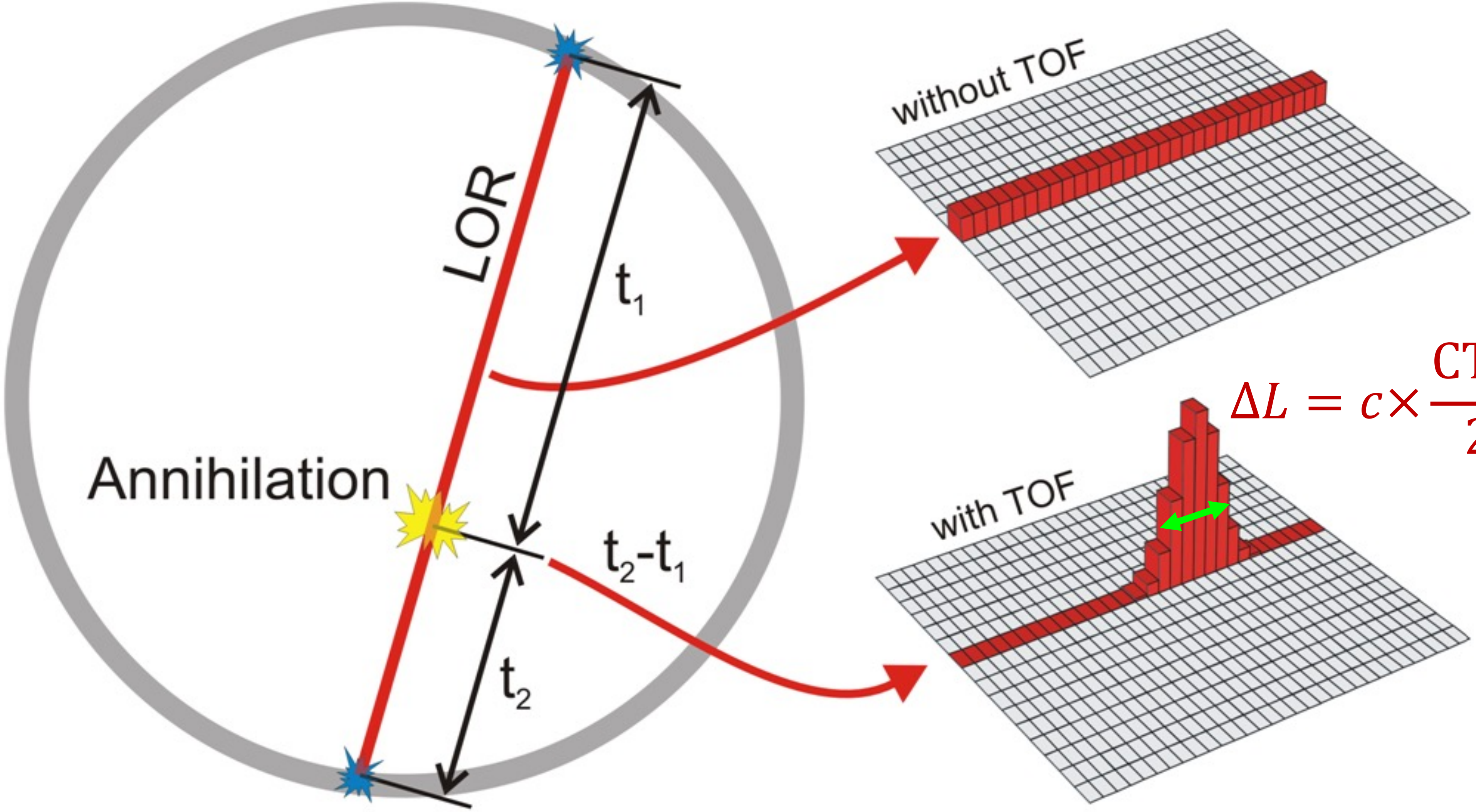
$$N_{\text{events}} = \left(\frac{L}{d}\right)^3 \times \text{SNR}^2_{\text{TOF}} \times \left(\frac{\Delta L}{d}\right)$$

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





Time-Of-Flight (TOF)-PET

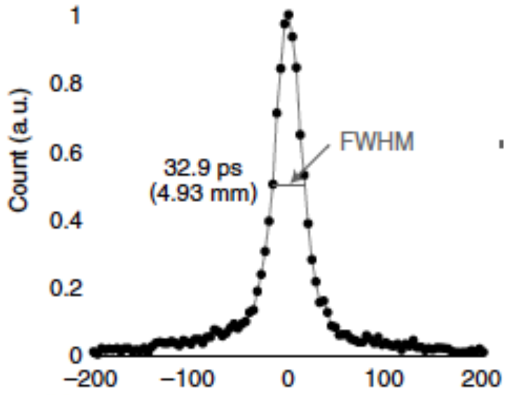


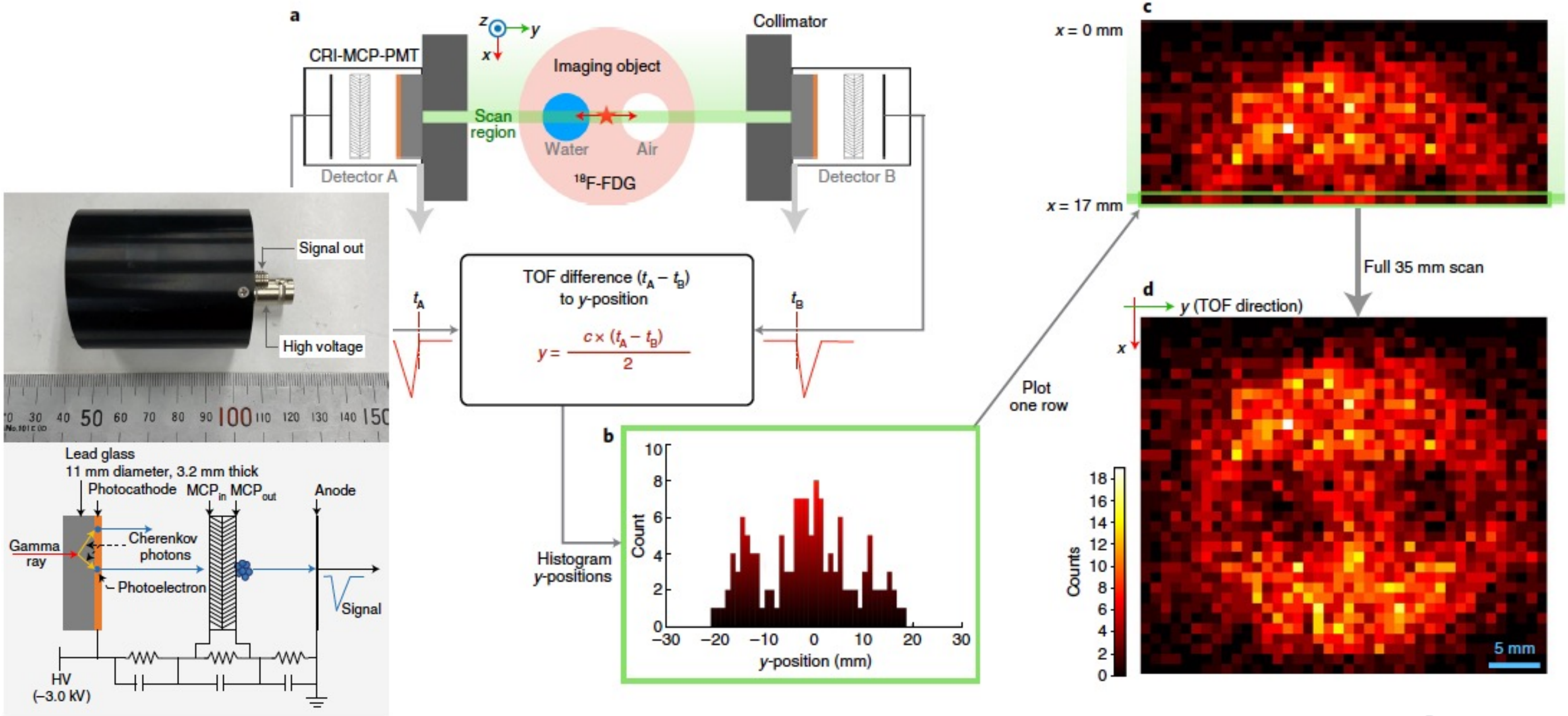
$$\Delta L = c \times \frac{\text{CTR}}{2}$$

$$30\ \text{cm/ns} \times \frac{10\ \text{ps}}{2} = 1.5\ \text{mm}$$

Reconstruction-free positron emission tomography

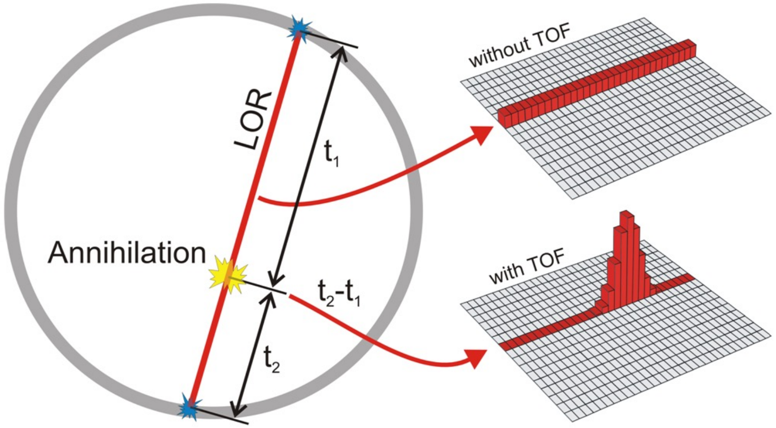
- Use of Cherenkov light for timing
- CTR 32.9 ps FWHM (4.93 mm)
- direct Positron Emission Imaging (dPEI)

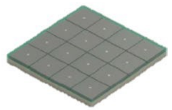




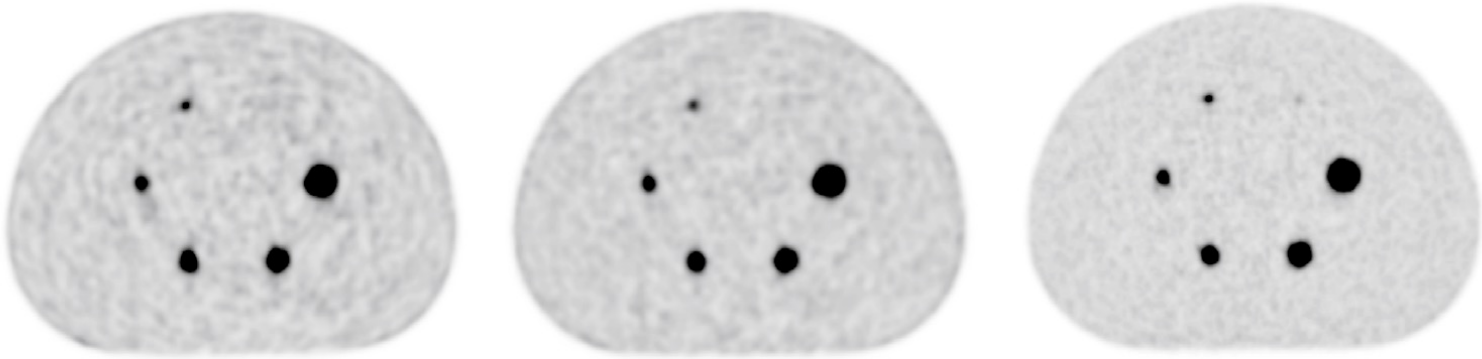
S.I. Kwon et al., Nat. Photon. 2020

State-of-the-art TOF-PET



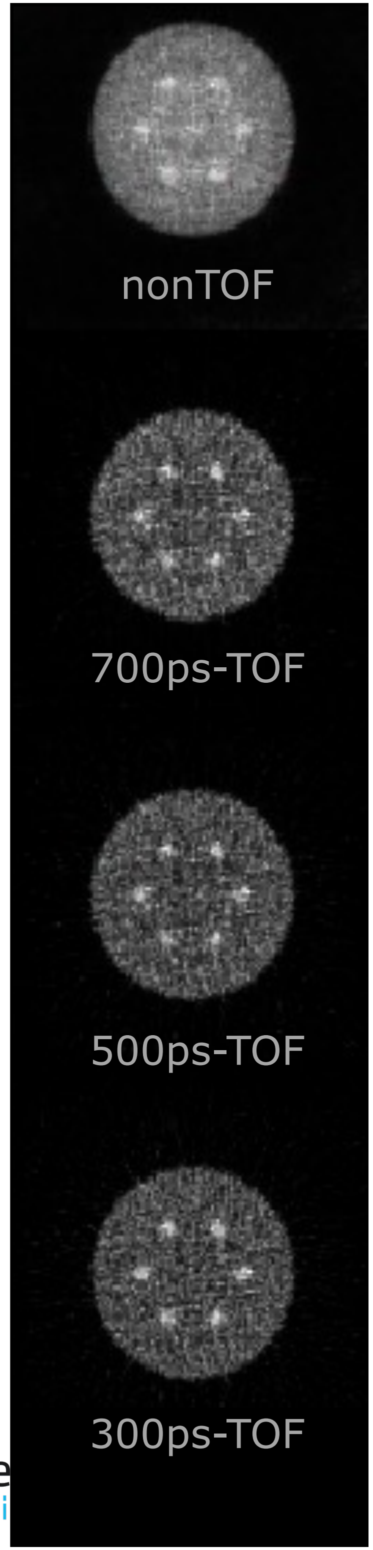


$$\left(\frac{SNR_{TOF}}{SNR_{nonTOF}}\right)^2 = \frac{2D}{c \times CTR}$$



nonTOF 527ps-TOF 210ps-TOF

M. Conti and B. Bendriem, Clin Transl Imaging 7 (2019) 139–147



Brief history of (TOF&TB-)PET scanners

60s: TOF-PET advocated by Anger (LBL), Brownell (MGH) and Budinger (LBL)

80s: First TOF-PET scanners for ^{15}O and ^{13}N imaging using CsF/PMT and BaF_2/PMT (PETT (St-Louis), TTV01-3 (Grenoble), TOFPET-I (Houston), SP3000/UW (Seattle))
CTR: 450-750 ps FWHM

90s: 3D-PET imaging with nonTOF-PET scanners using BGO/PMT

Mid-90s: nonTOF-PET/CT scanner using LSO/PMT
(4-6 ns coincidence time window)

Mid-00s: TOF-PET scanners using L(Y)SO/PMT or $LaBr_3$/PMT
CTR: 450-550 ps FWHM

Mid-10s: TOF-PET scanners using L(Y)SO/SiPM
CTR: 300-400 ps FWHM

End-10s: TOF-PET scanner using LSO/SiPM
Biograph Vision CTR: 210 ps FWHM

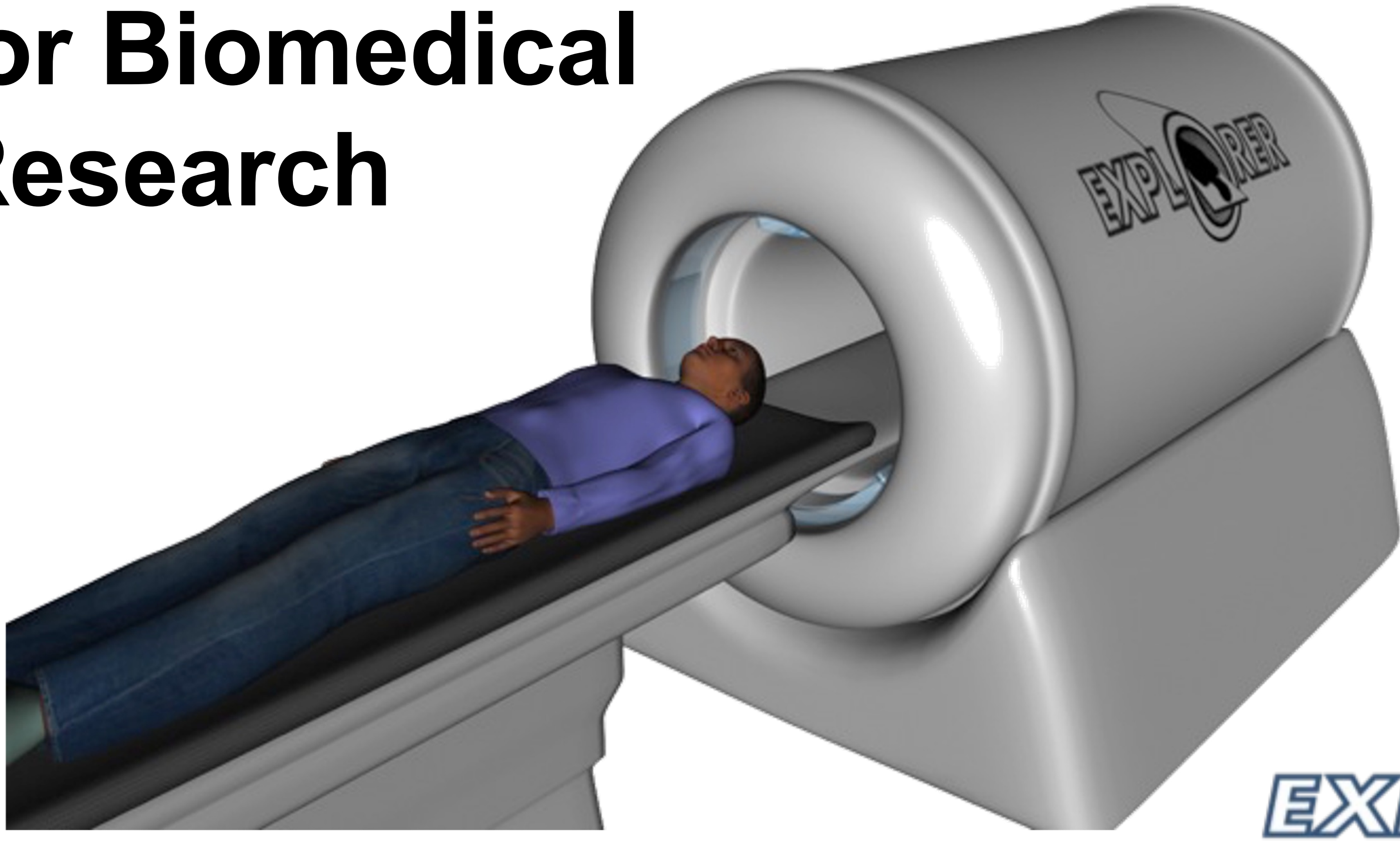
Total Body (TB)-PET using L(Y)SO/SiPM

EXPLORER: A Total-Body PET Scanner for Biomedical Research

UCDAVIS
UNIVERSITY OF CALIFORNIA

Penn

BERKELEY LAB



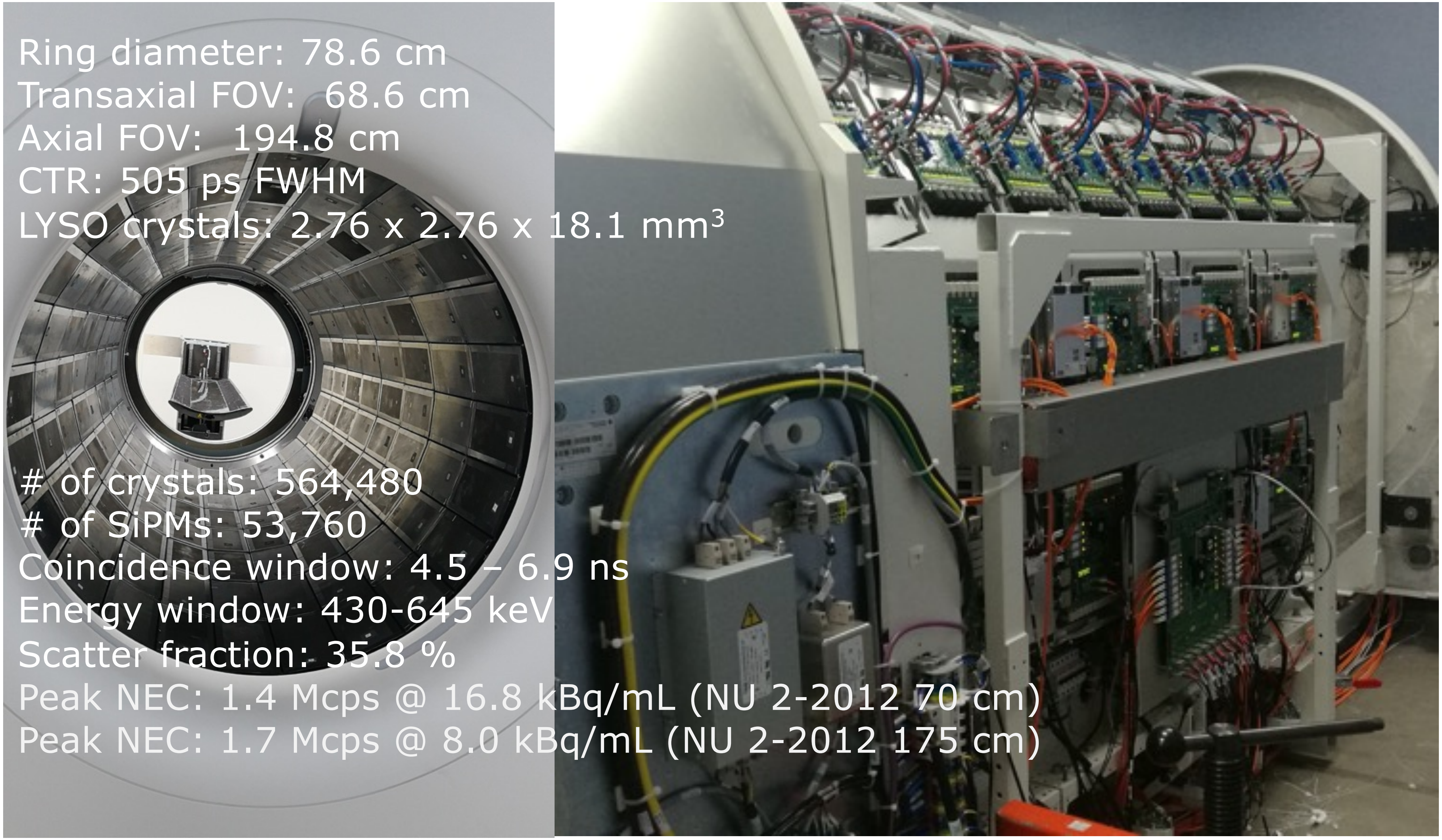
EXPLORER

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

EXPLORER.ucdavis.edu

Aix*Marseille université
cnrs IN2P3 Les deux infinis
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

Total Body-PET EXPLORER scanner



Ring diameter: 78.6 cm
Transaxial FOV: 68.6 cm
Axial FOV: 194.8 cm
CTR: 505 ps FWHM
LYSO crystals: 2.76 x 2.76 x 18.1 mm^3

\# of crystals: 564,480
\# of SiPMs: 53,760
Coincidence window: 4.5 – 6.9 ns
Energy window: 430-645 keV
Scatter fraction: 35.8 %
Peak NEC: 1.4 Mcps @ 16.8 kBq/mL (NU 2-2012 70 cm)
Peak NEC: 1.7 Mcps @ 8.0 kBq/mL (NU 2-2012 175 cm)

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CTR: 300-400 ps FWHM

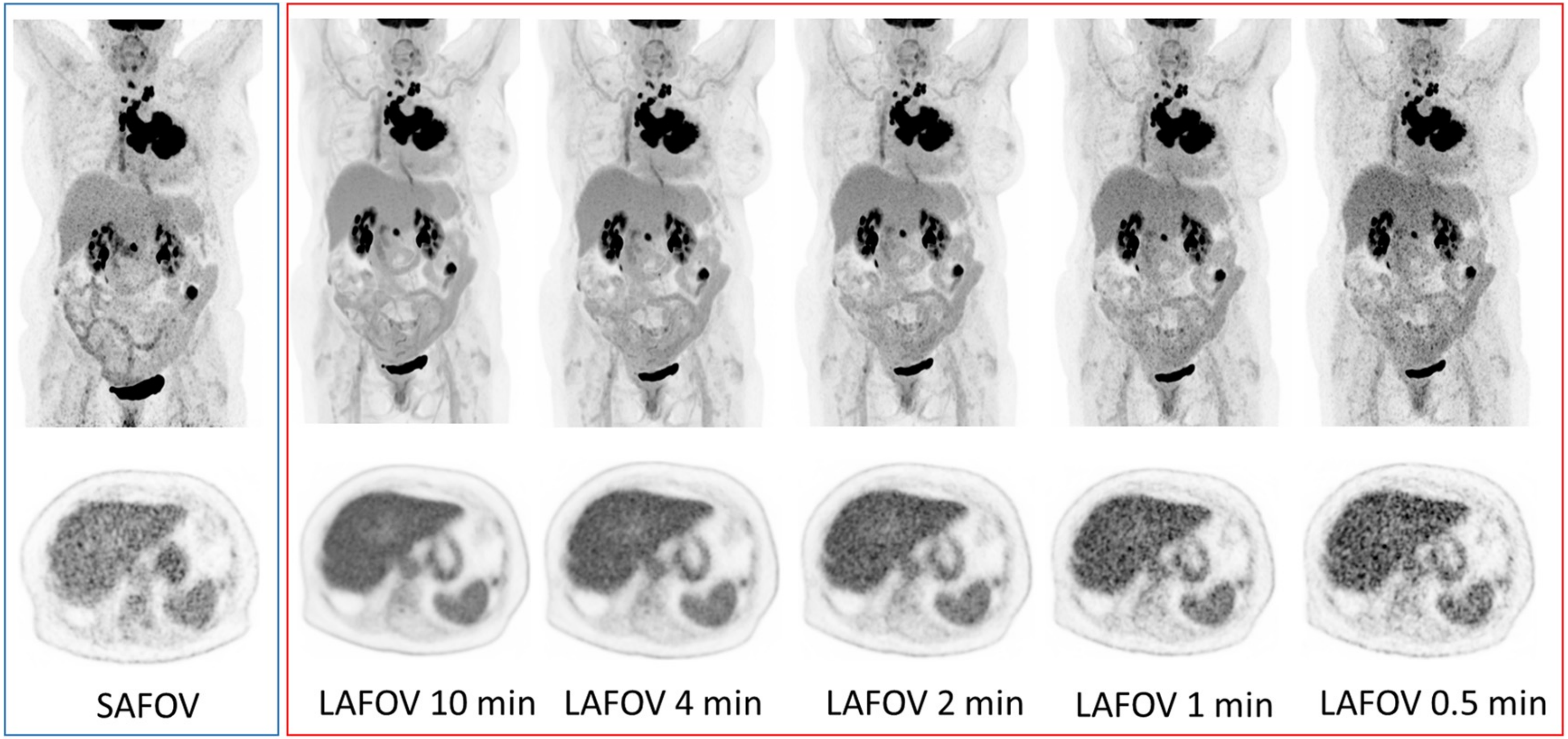
End-10s: TOF-PET scanner using LSO/SiPM
Biograph Vision CTR: 210 ps FWHM, AFOV: 26.3 cm

Total Body (TB)-PET using L(Y)SO/SiPM
uEXPLORER CTR: 505 ps FWHM, AFOV: 194.8 cm
PennPET EXPLORER CTR: 250 ps FWHM, AFOV: 140 cm
Biograph Vision Quadra CTR: 230 ps FWHM, AFOV: 106 cm

Total Body-PET scanner Biograph Vision Quadra

Ring diameter: 82 cm Transaxial FOV: 78 cm Axial FOV: 106 cm CTR: 230 ps FWHM LSO crystals: 3.2 x 3.2 x 20 mm^3	# of crystals: 243,200 # of SiPM arrays (16 x 16): 9,728 Coincidence window: 4.7 ns Energy window: 435-585 keV Scatter fraction: 37 % Peak NEC: 3.0 Mcps @ 27.5 kBq/mL (NU 2-2018)

G.A. Prenosil et al., JNM 2021

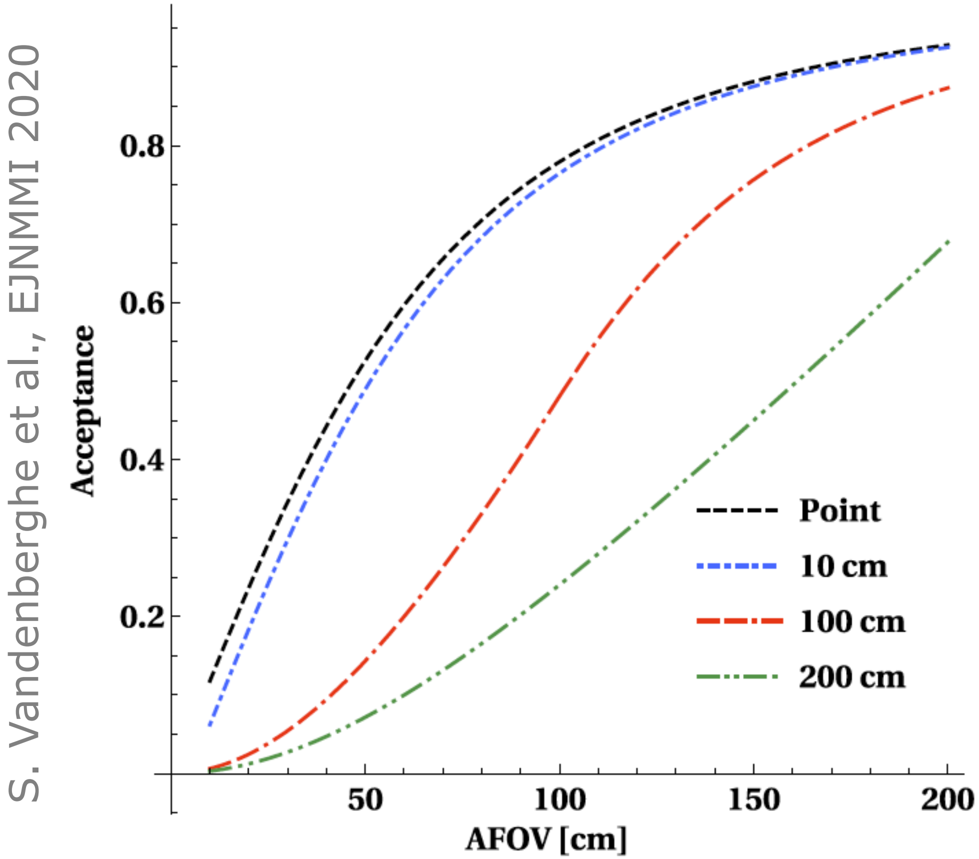


26.3 cm 16 min

106 cm

I. Alberts et al., EJNMMI 2021

Concluding remark: TB-PET ‖ TOF-PET ?



You'd rather have

200 ps TB-PET with 200 cm AFOV

or

20 ps TOF-PET with 20 cm AFOV

Time-of-flight PET data determine the attenuation sinogram up to a constant

(M. Defrise, A. Rezaei and J. Nuyts, PMB 2012)

TOF enables joint reconstruction of the activity and attenuation images with variances that both depend only on $\int k^2(x)dx$

(J. Nuyts, M. Defrise, C. Morel and P. Lecoq, subm. to PMB 2023)