10 ps: a Challenge for the Future of Positron Emission Tomography

Christian Morel
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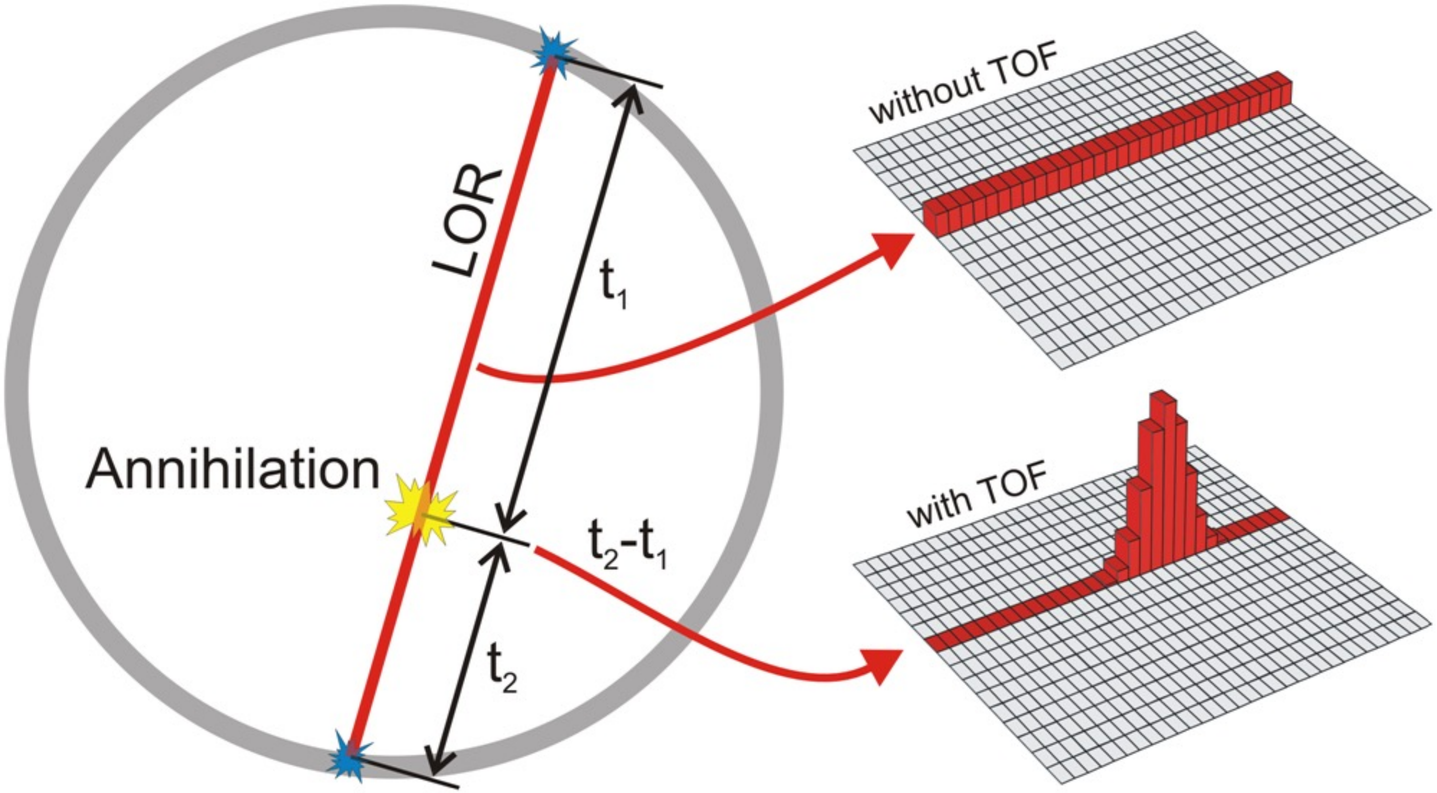
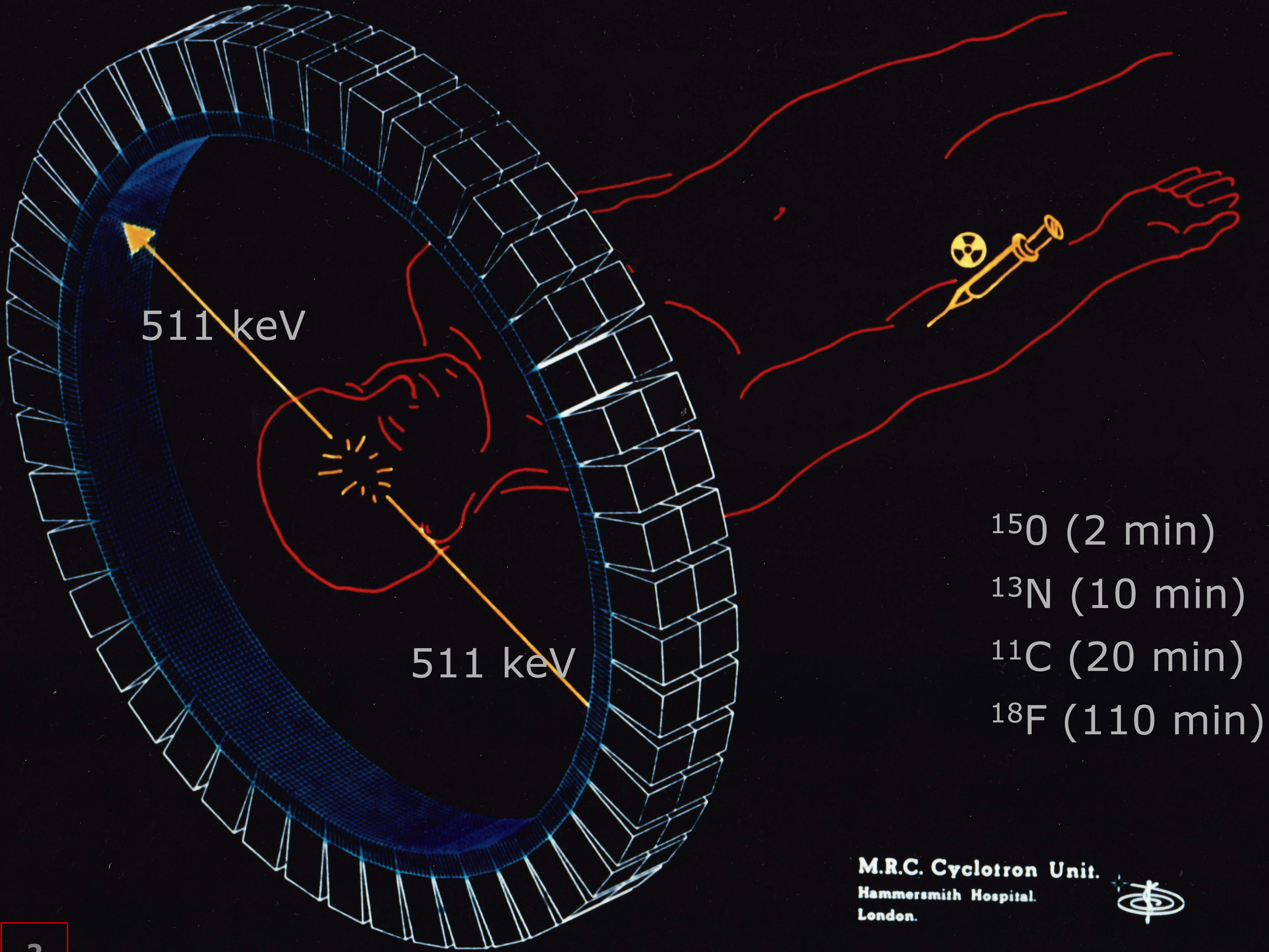


PHENIICS Fest — May, 16 2024 — Orsay

Positron Emission Tomography (PET)



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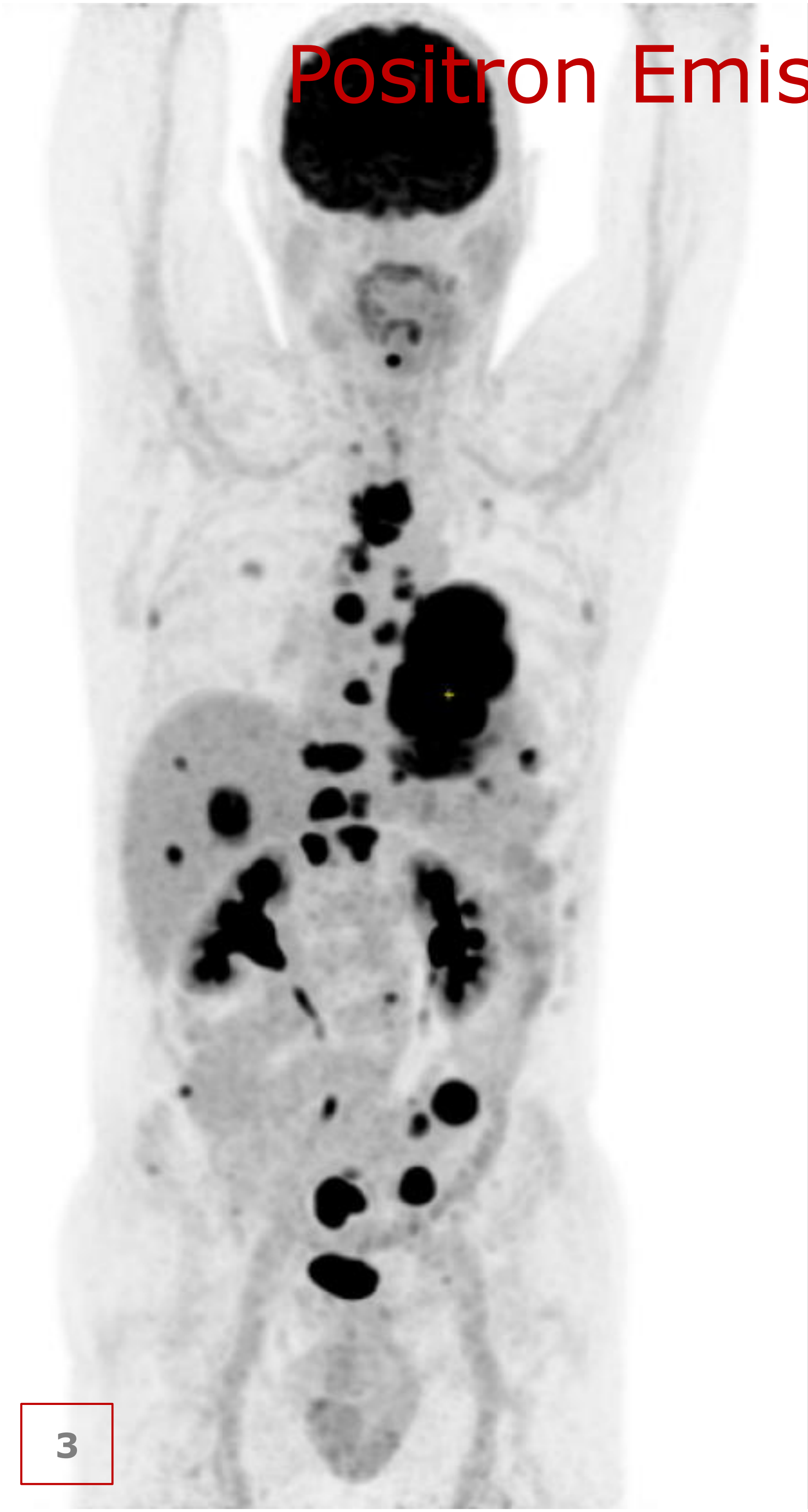
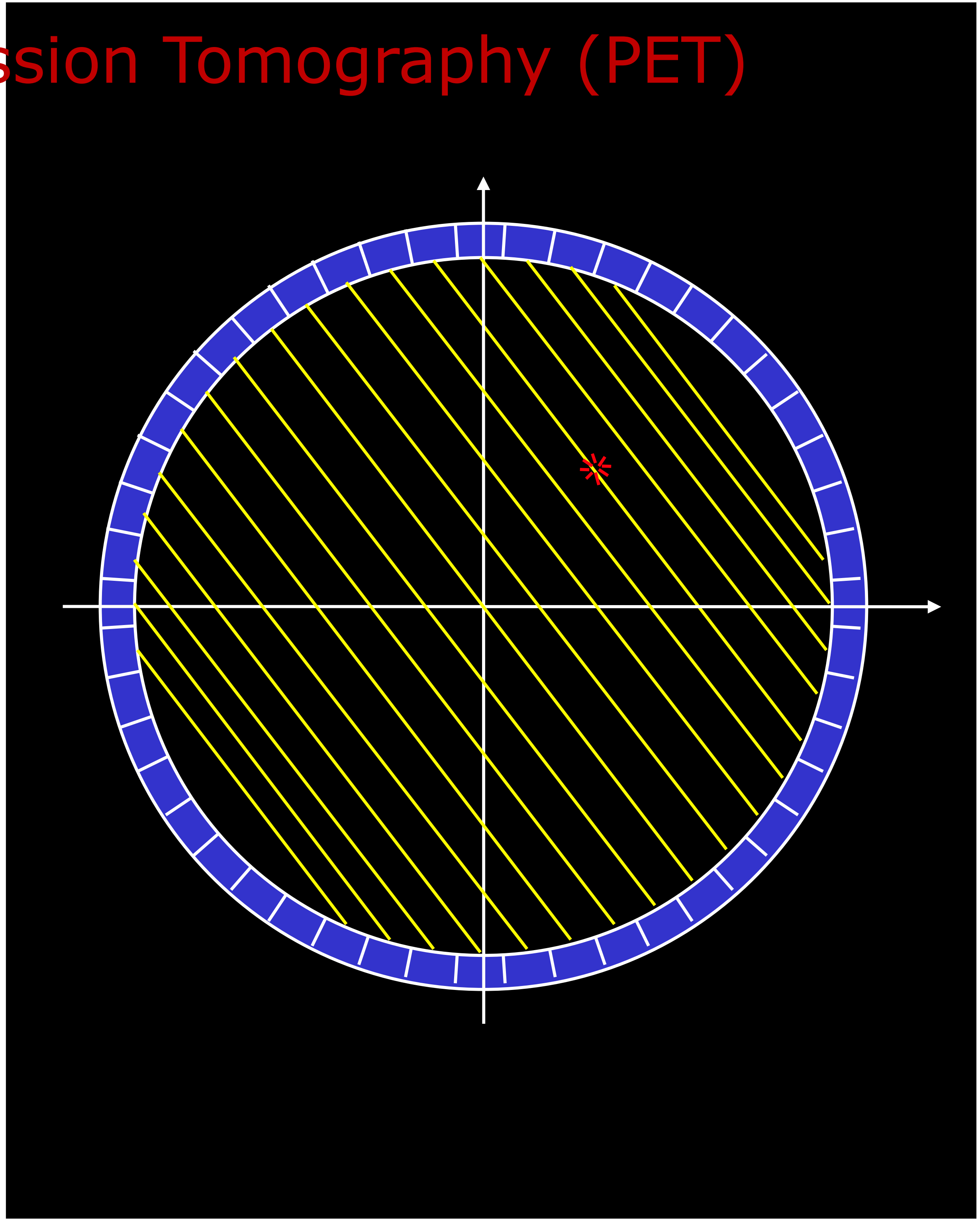
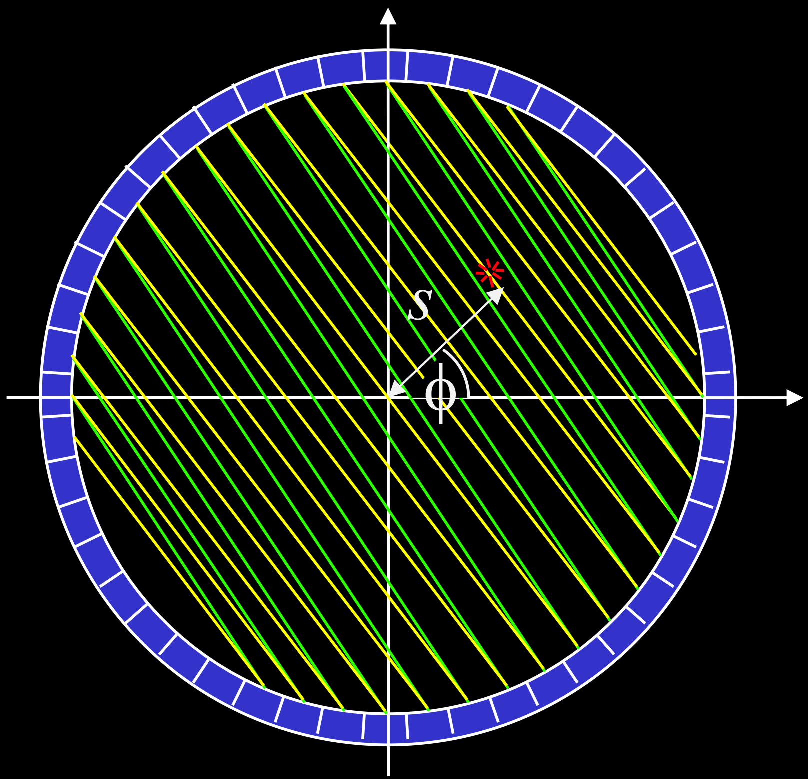
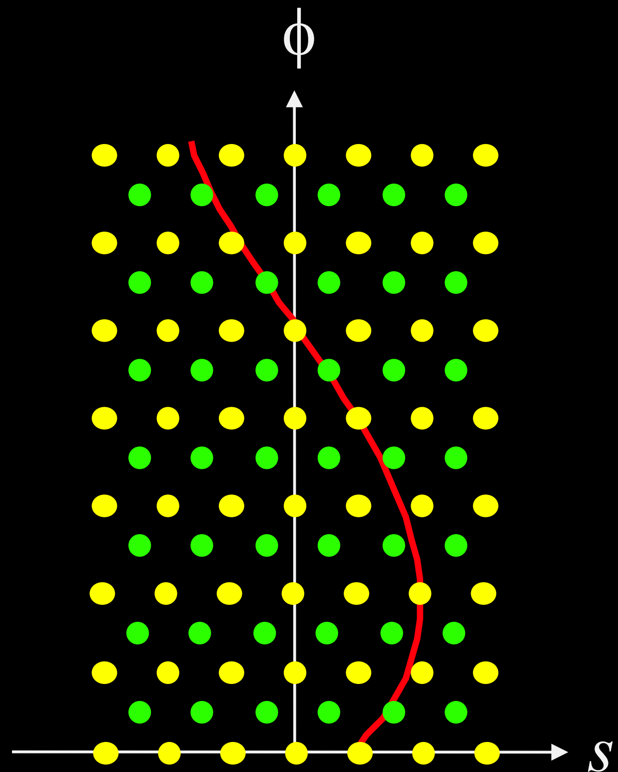




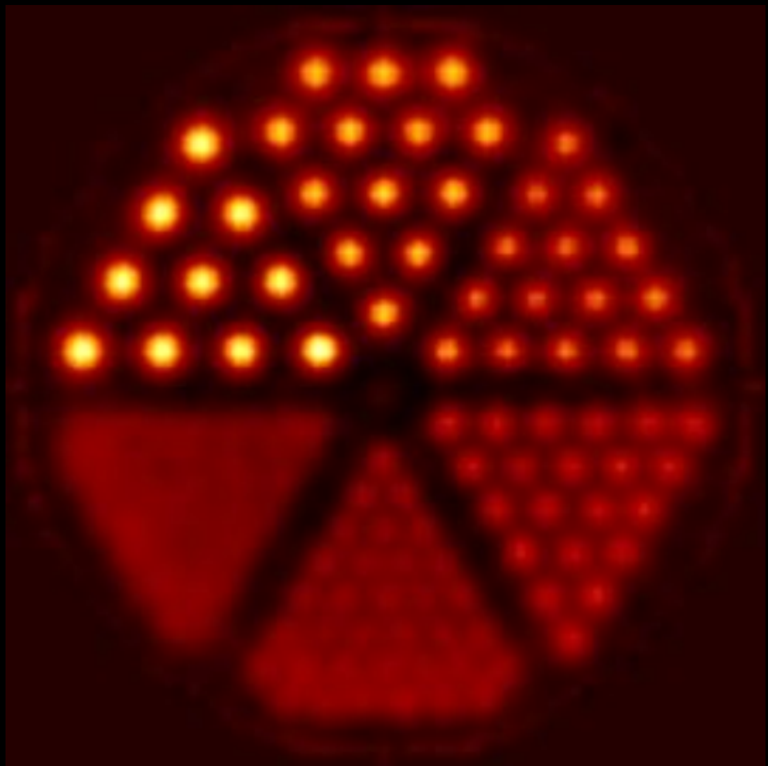
Positron Emission Tomography (PET)



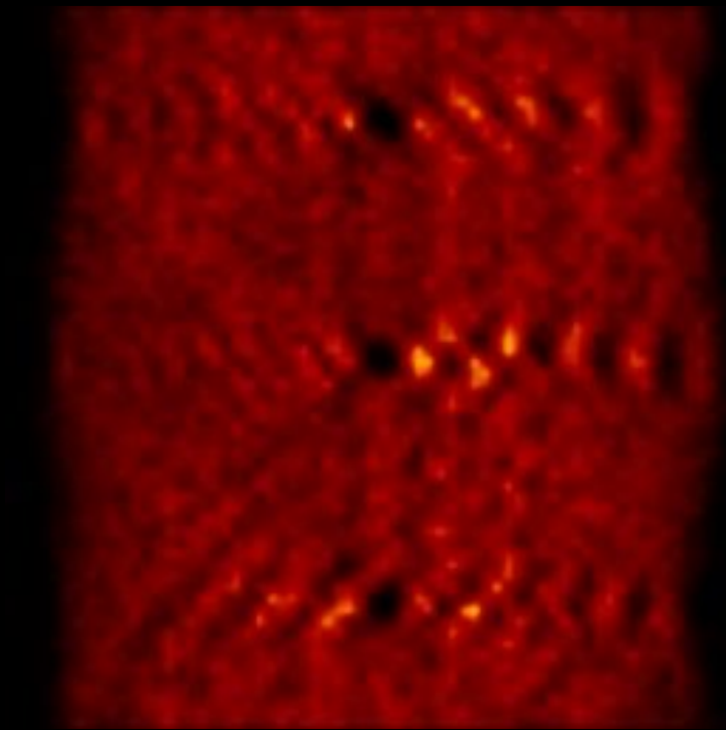


Sinogram

Positron Emission Tomography (PET)



Reconstructed image

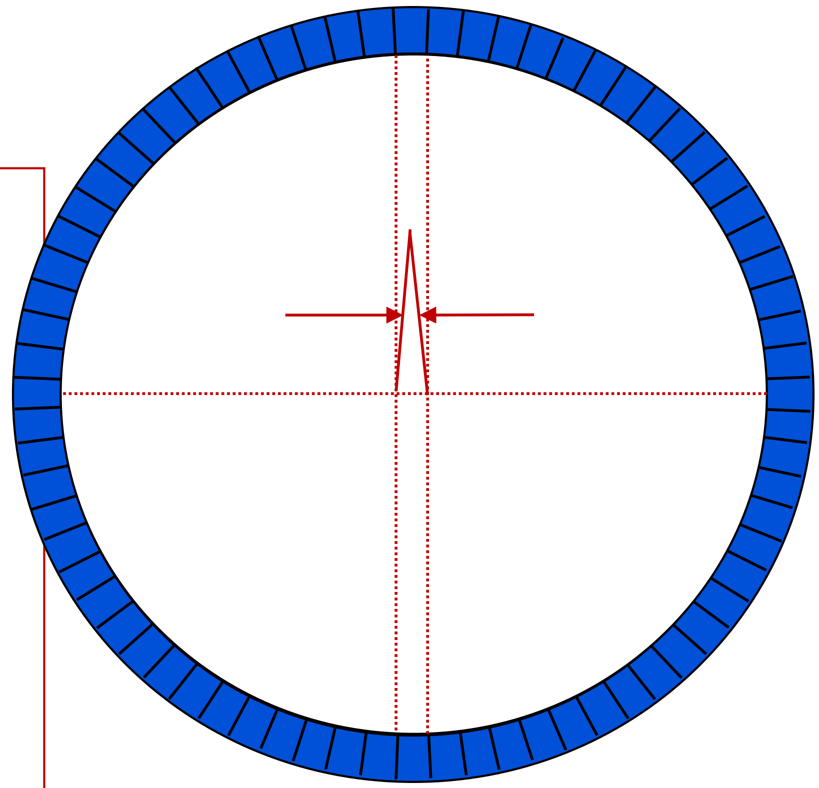


Sinogram

Radial spatial resolution

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

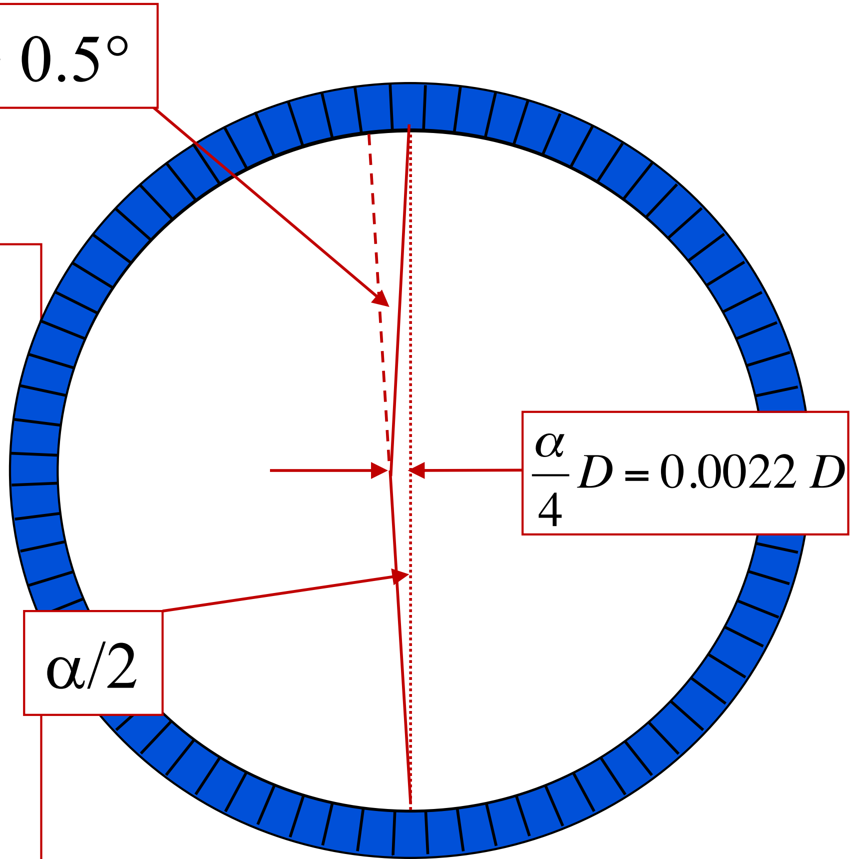
d	Pixel size
D	Ring diameter
r	Positron range
b	Detector crosstalk
a	Image reconstruction algorithm (1,1 - 1,3)



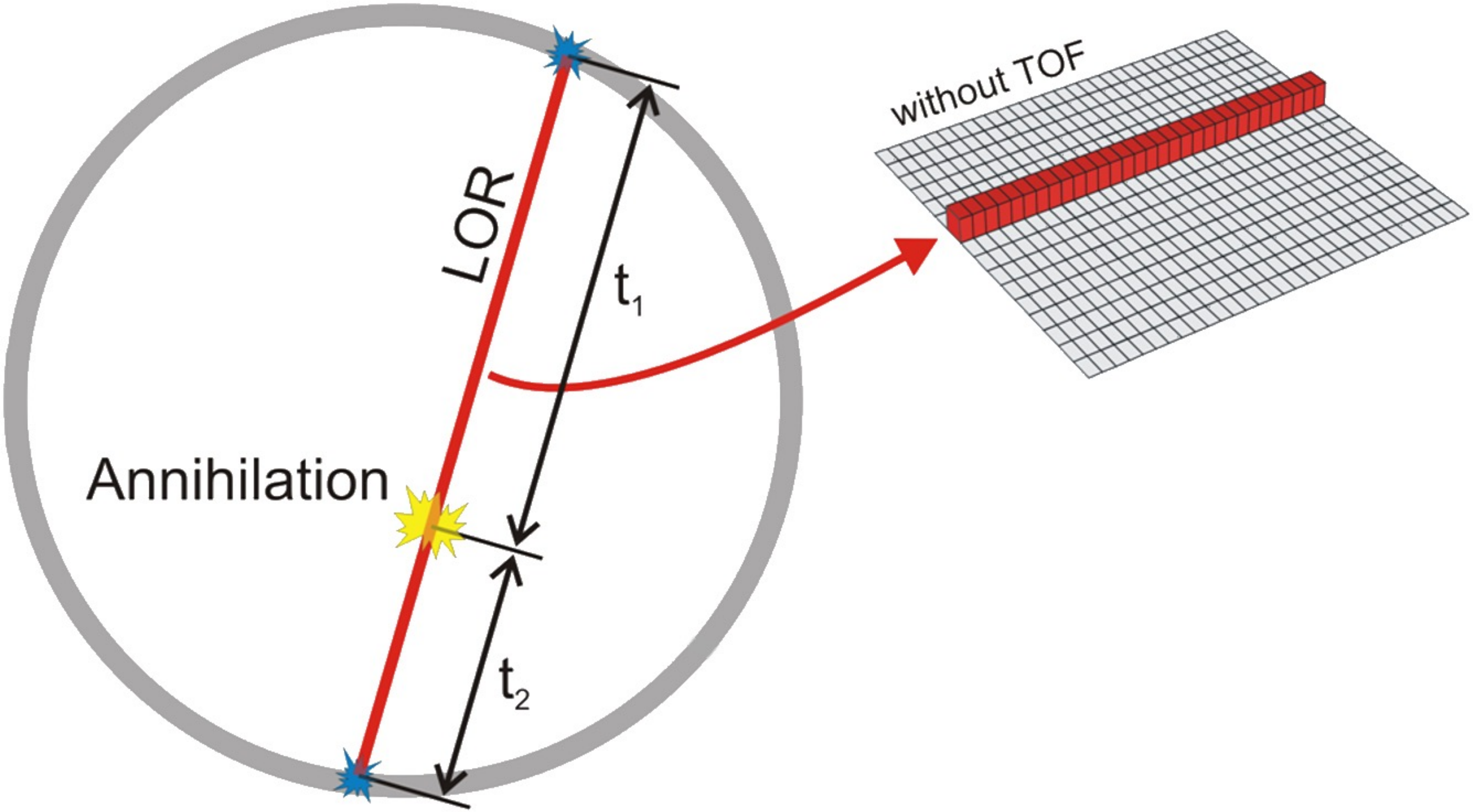
Spatial resolution at image centre

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

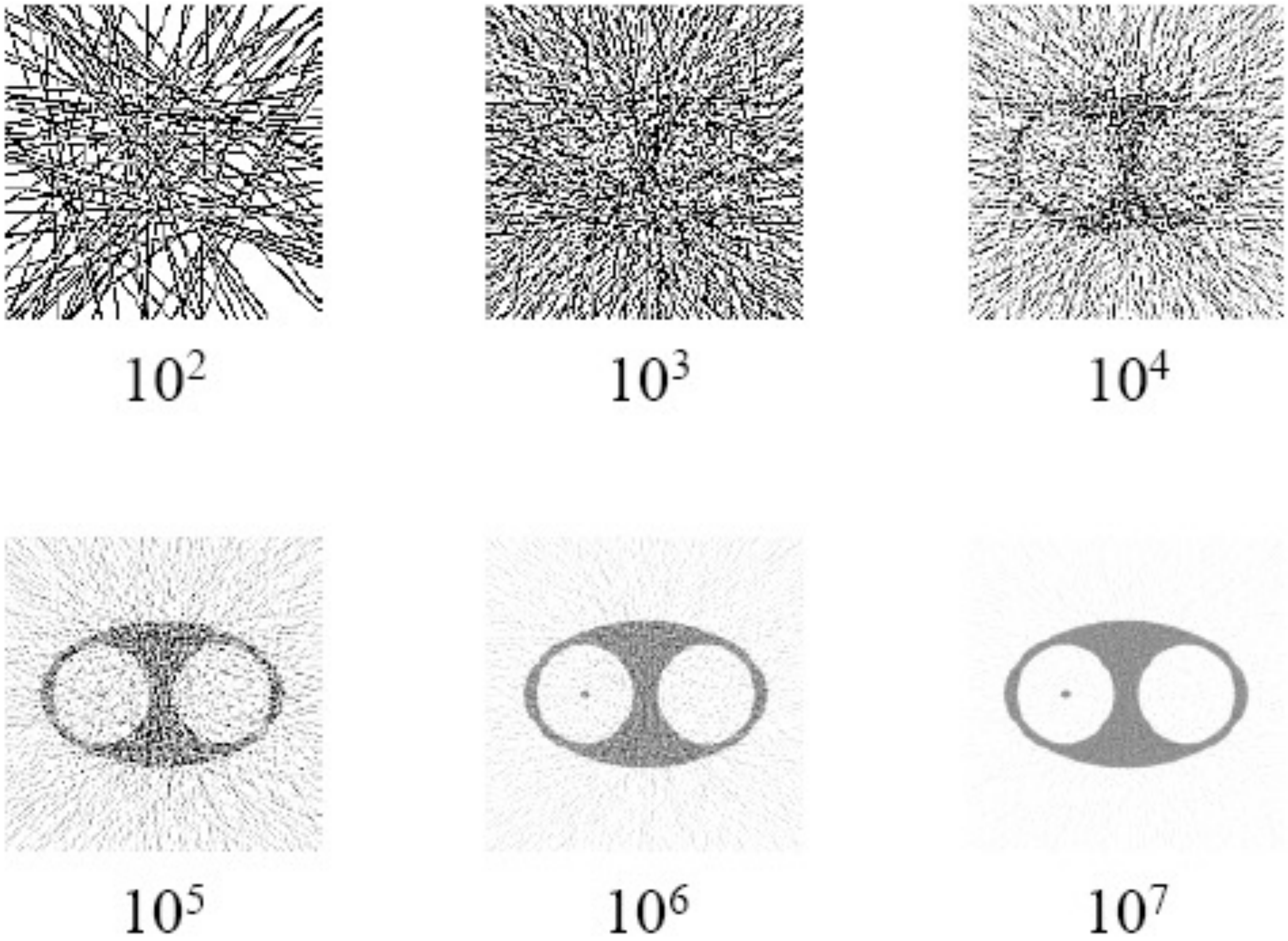
d	Pixel size
D	Ring diameter
r	Positron range
b	Detector crosstalk
a	Image reconstruction algorithm (1,1 - 1,3)



Backprojection



Tomography and counting statistics



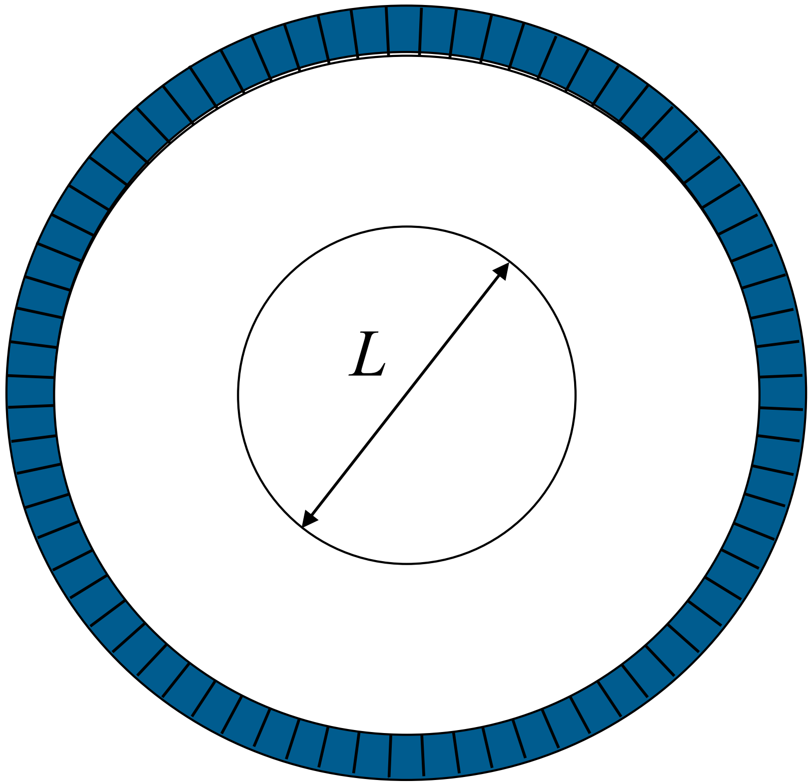
Courtesy: C. Comtat, CEA-SHFJ

SNR and counting statistics

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

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

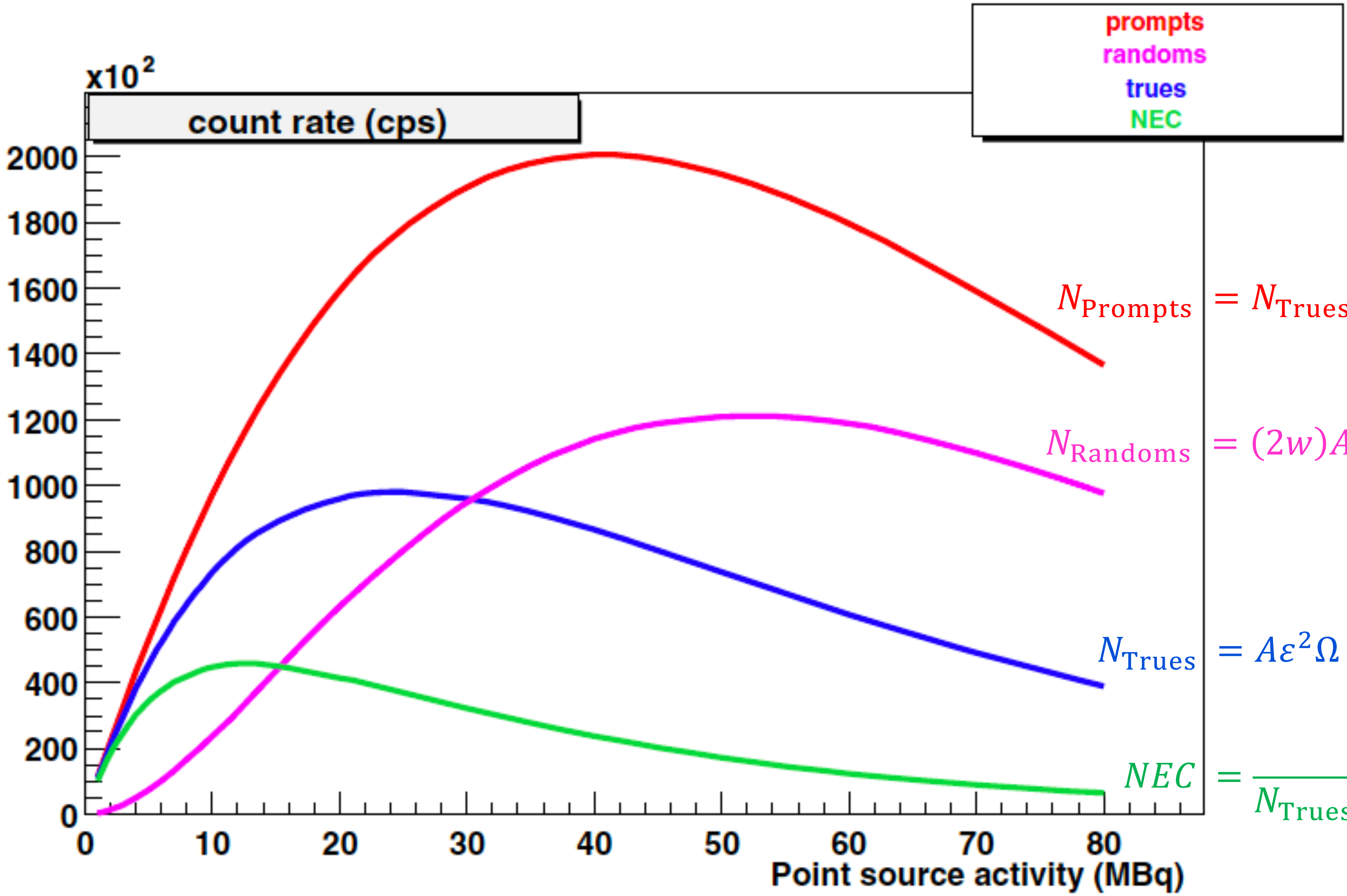
$$N_{\mathrm{evt}} = \left(\frac{L}{d}\right)^3 \times \mathrm{SNR}^2 \times \left(\frac{L}{d}\right)$$



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

- ↗ scan duration
- ↗ injected activity
- ↗ crystal thickness (crystal efficiency)
- ↗ solid angle

Noise Equivalent Count Rate (NECR)



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

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

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

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

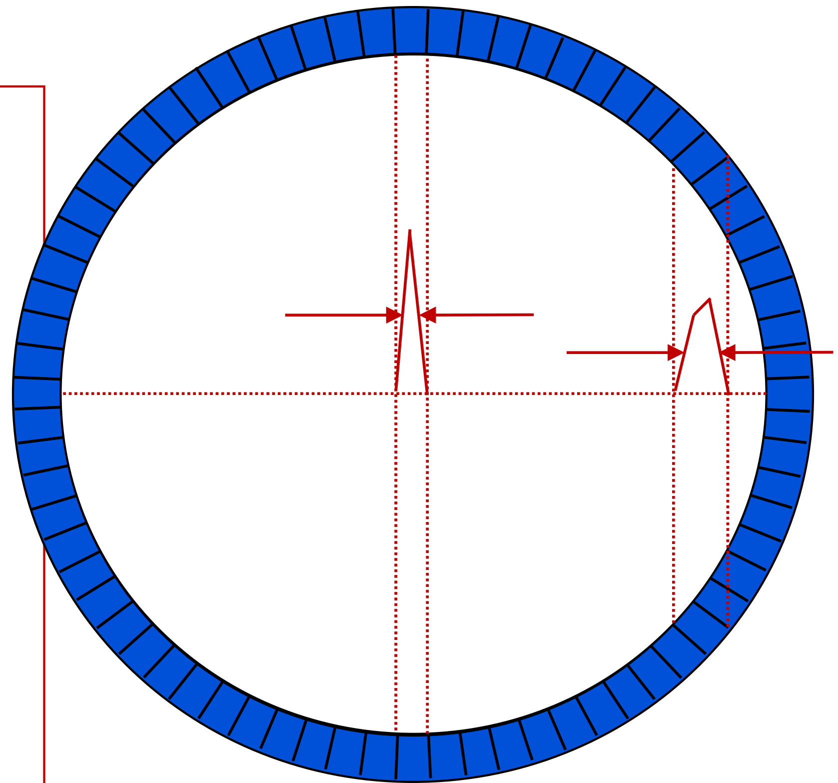
Inorganic scintillators for PET

	NaI	BGO	BaF_2	L(Y)SO	LuAP	$LaBr_3$
Density (g/cm^3)	3.67	7.13	4,88	7.40	8.34	5.3
Effective Z	51	74	53	66	65	52
Photofraction (%)	18	42	19	33	32	14
Decay time (ns)	230	300	0.6 620	35-45	17	16
Light yield (ph/MeV)	43000	8200	1430 9950	28000	11400	60000
Peak emission (nm)	415	480	220 310	420	365	300
Refraction index	1.85	2.15	1.47	1.82	1.97	1.9

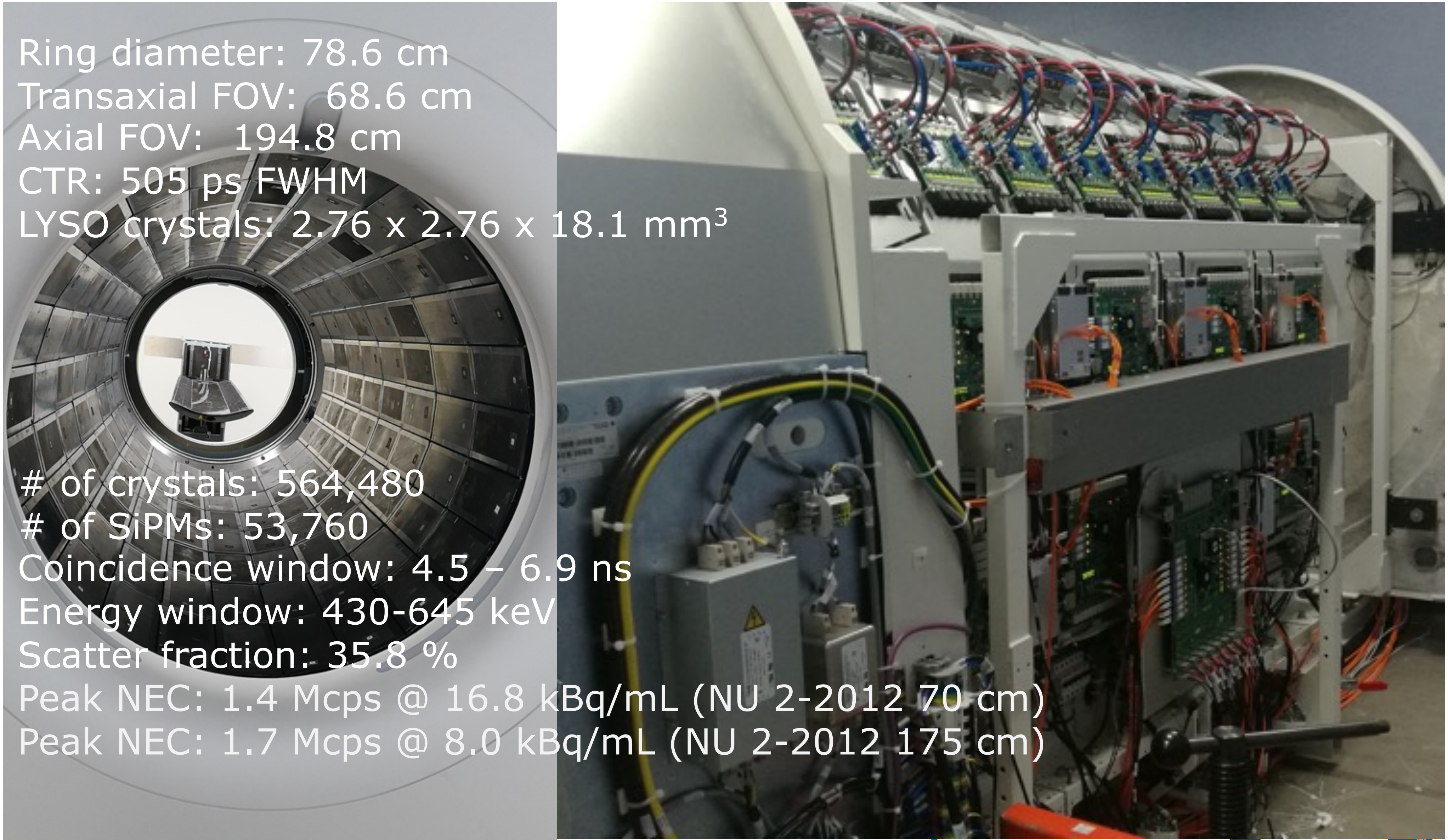
Radial spatial resolution

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

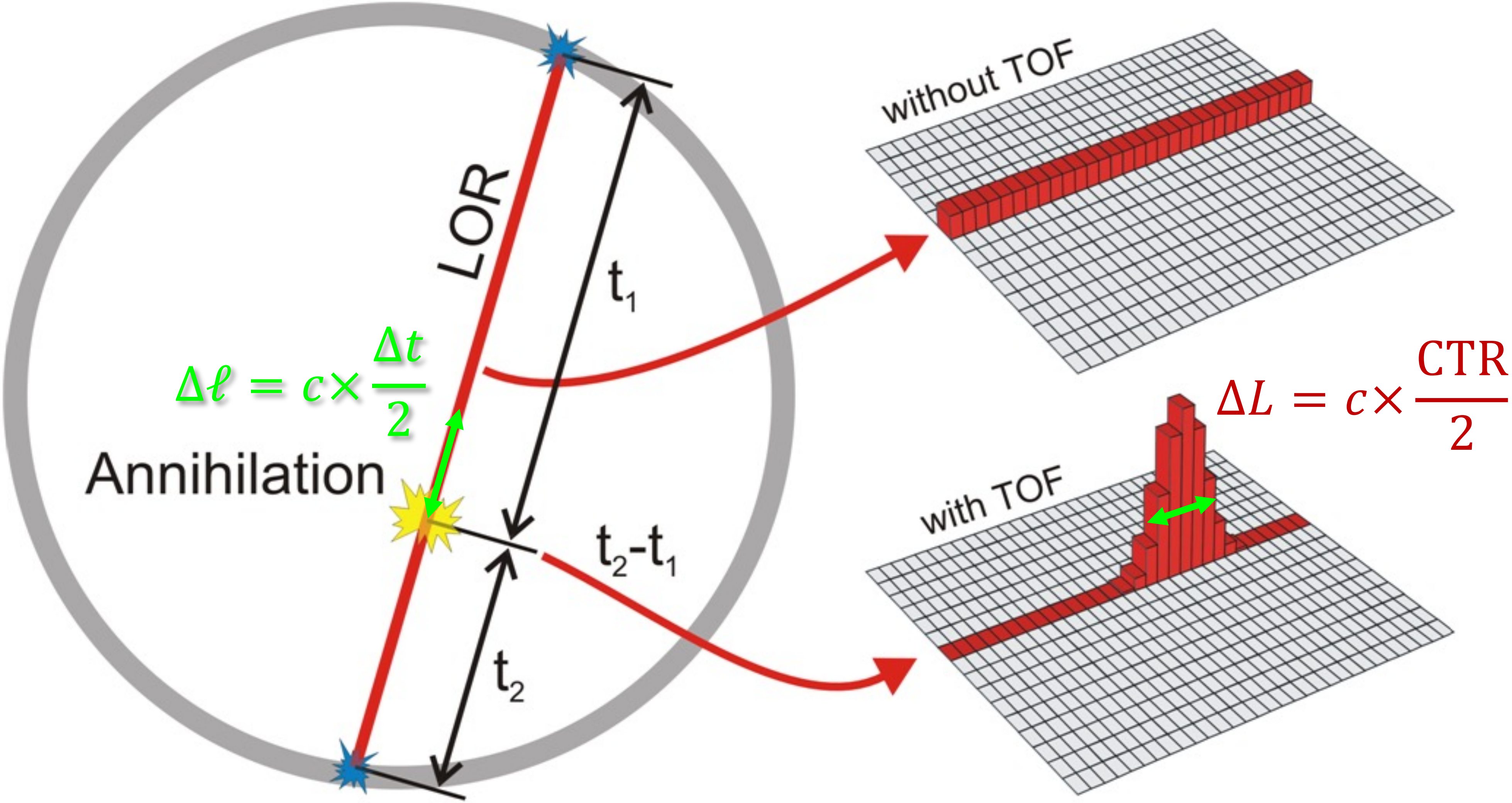
d	Pixel size
w	Pixels thickness
D	Ring diameter
r	Positron range
b	Detector crosstalk
a	Image reconstruction algorithm (1,1 - 1,3)



Total Body-PET EXPLORER scanner



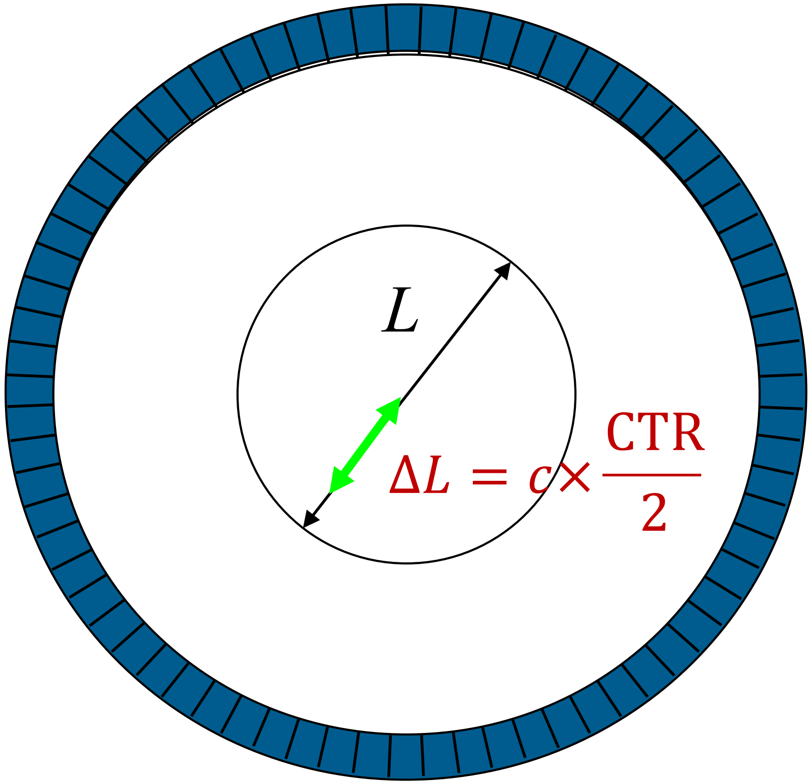
Time-Of-Flight (TOF)-PET



Impact of TOF-PET on image SNR

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

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

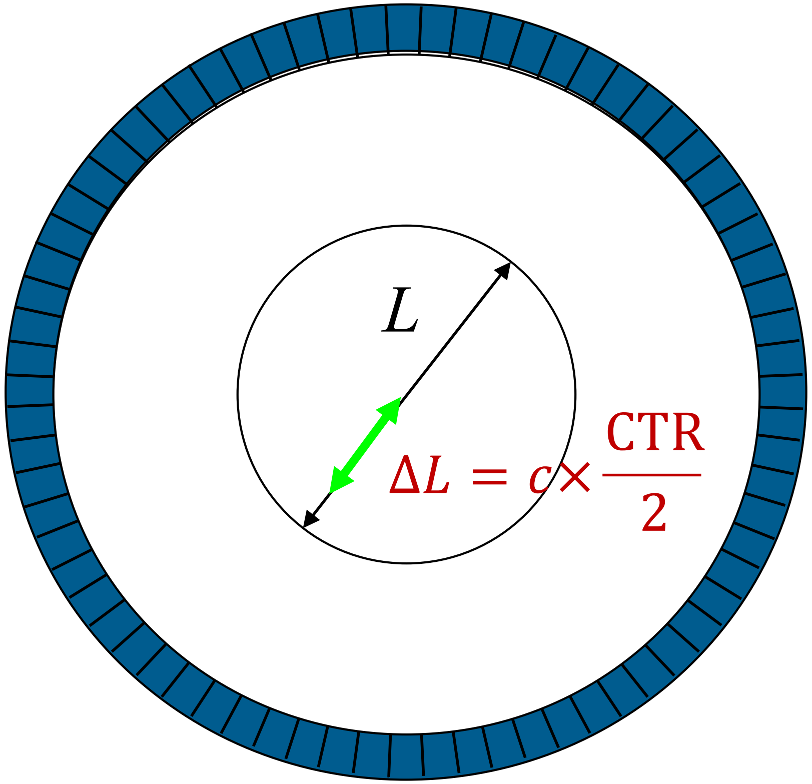


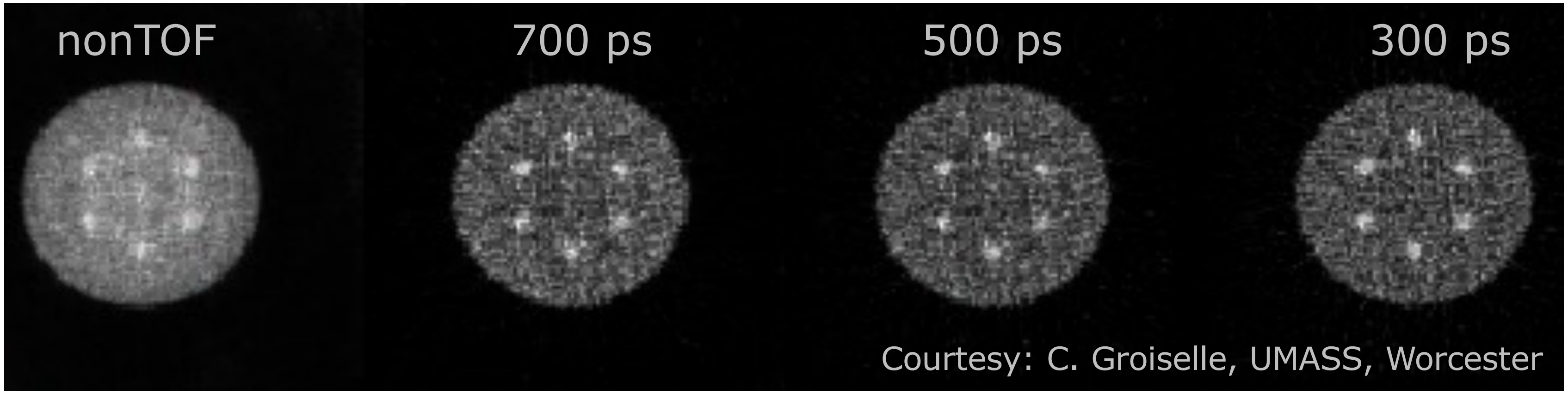
Impact of TOF-PET on image SNR

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

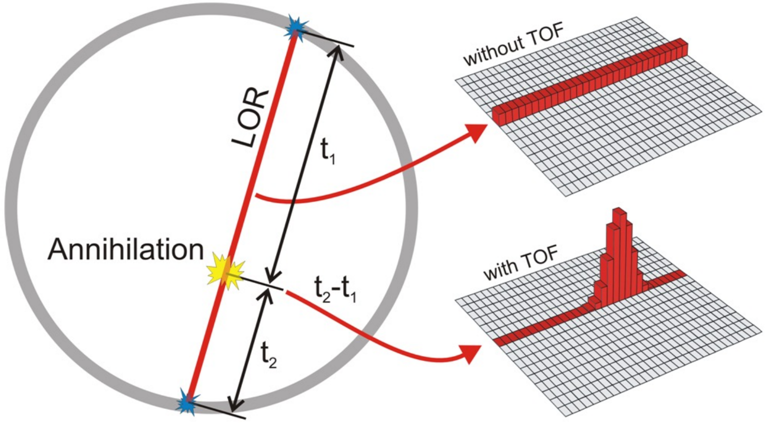
$$N_{\mathrm{evt}} = \left(\frac{L}{d}\right)^3 \times \mathrm{SNR}^2_{\mathrm{TOF}} \times \left(\frac{\Delta L}{d}\right)$$

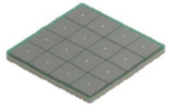
$$\left(\frac{\mathrm{SNR}_{\mathrm{TOF}}}{\mathrm{SNR}_{\mathrm{nonTOF}}}\right)^2 = \frac{2L}{c \times \mathrm{CTR}}$$



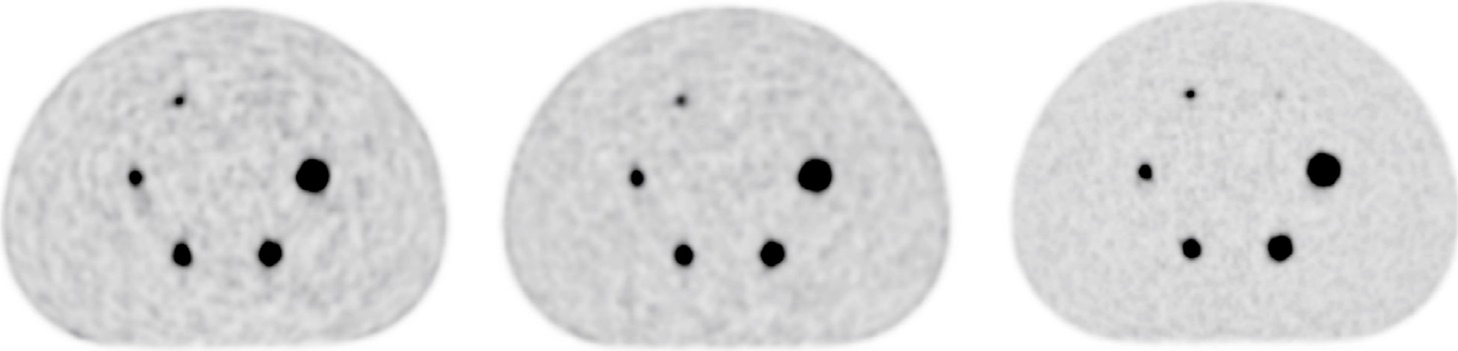


State-of-the-art TOF-PET

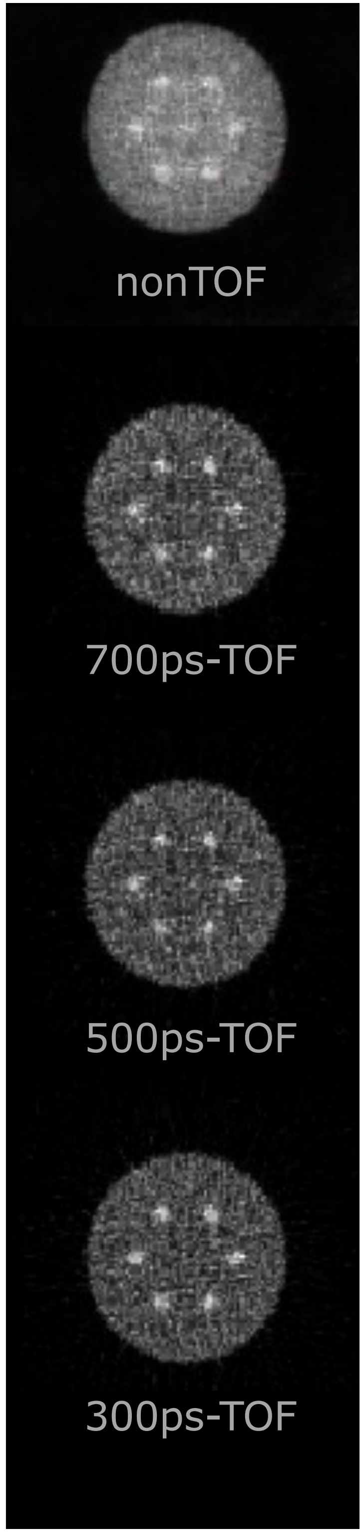




$$\left(\frac{SNR_{TOF}}{SNR_{nonTOF}}\right)^2 = \frac{2D}{c \times CTR}$$



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

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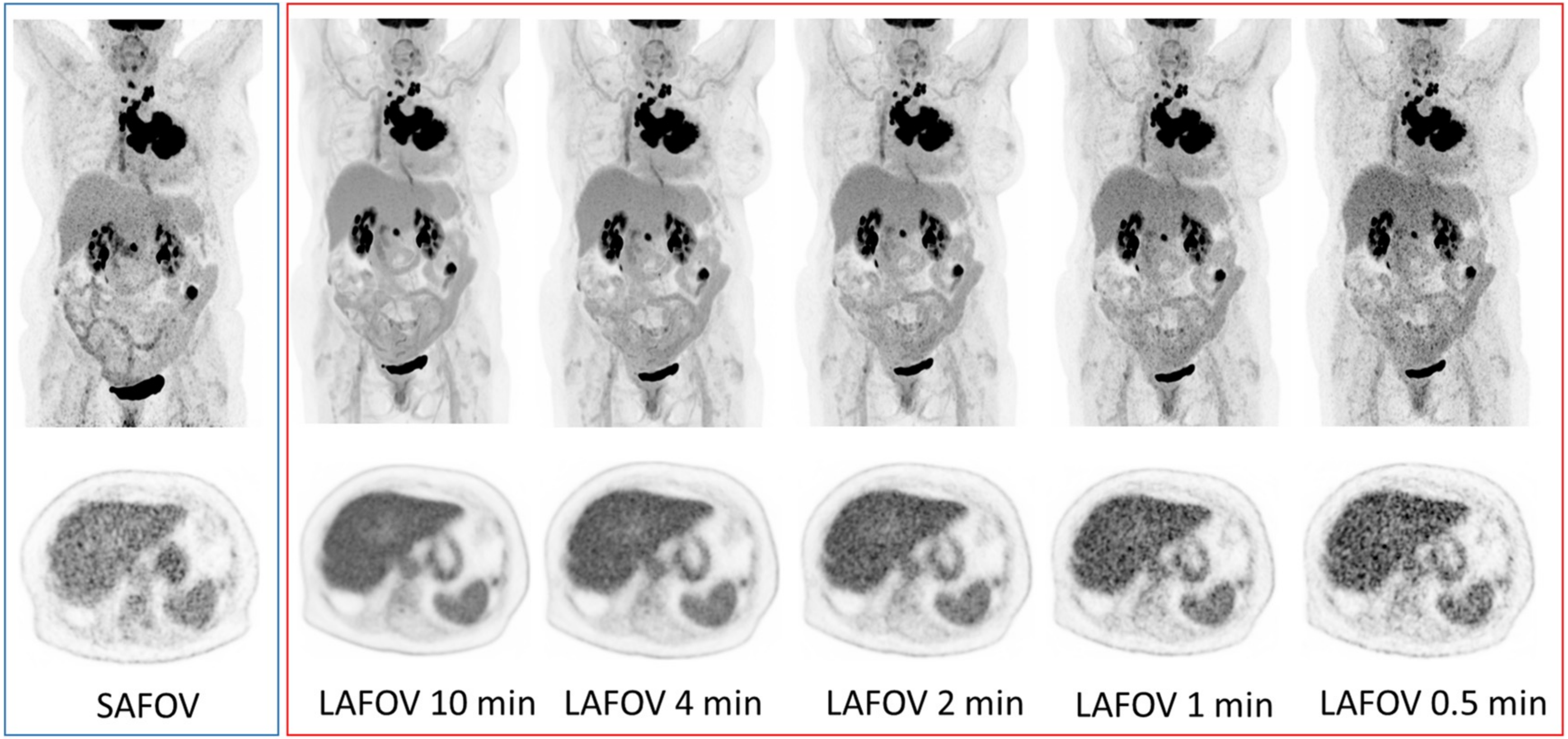
End-10s:	TOF-PET scanner using LSO/SiPM Biograph Vision CTR: 210 ps FWHM, AFOV: 26.3 cm Total Body (TB)-PET using L(Y)SO/SiPM uEXPLORER CTR: 505 ps FWHM, AFOV: 194.8 cm PennPET EXPLORER CTR: 250 ps FWHM, AFOV: 140 cm Biograph Vision Quadra CTR: 230 ps FWHM, AFOV: 106 cm

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

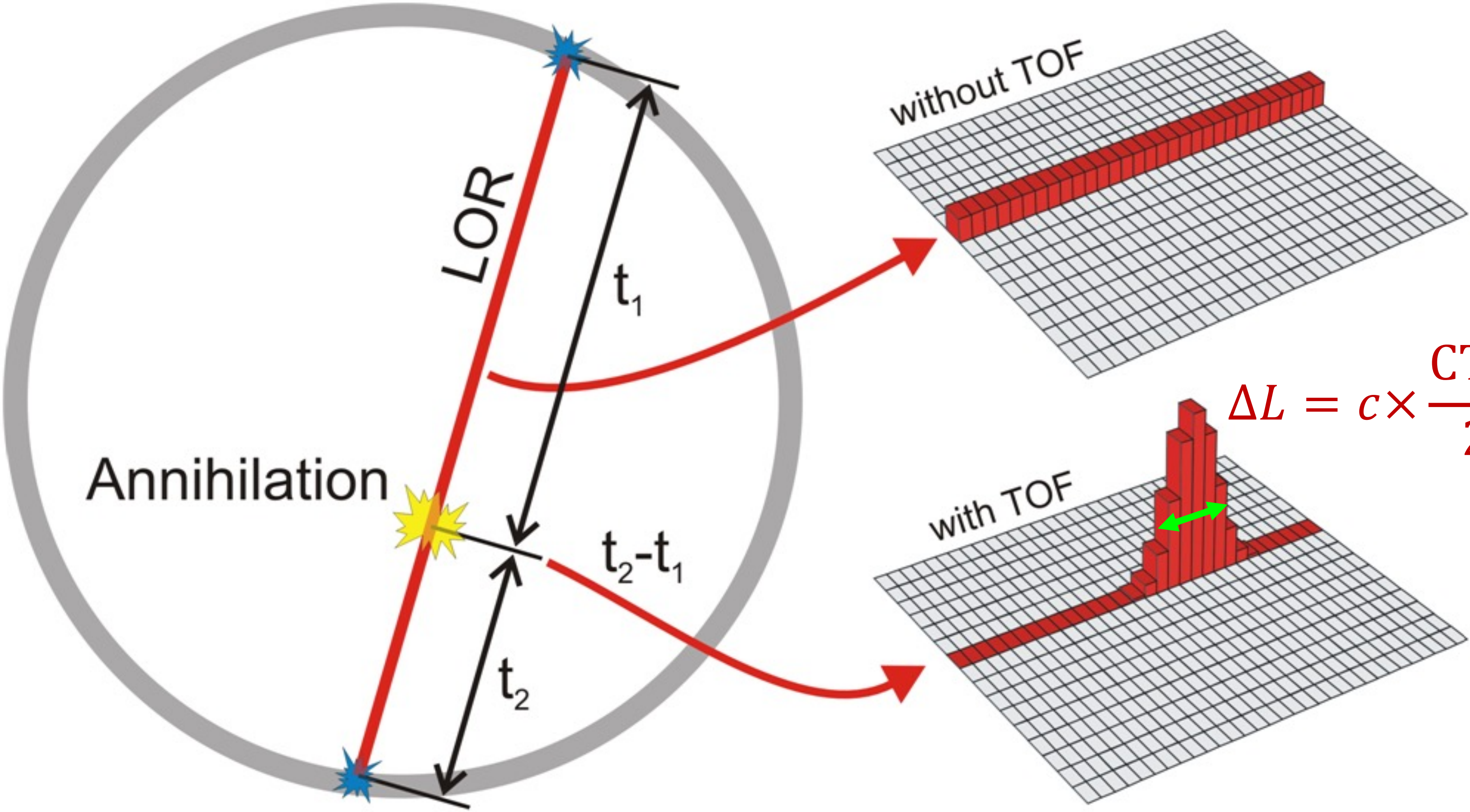


I. Alberts et al., EJNMMI 2021

26.3 cm 16 min

106 cm

Time-Of-Flight (TOF)-PET



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

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

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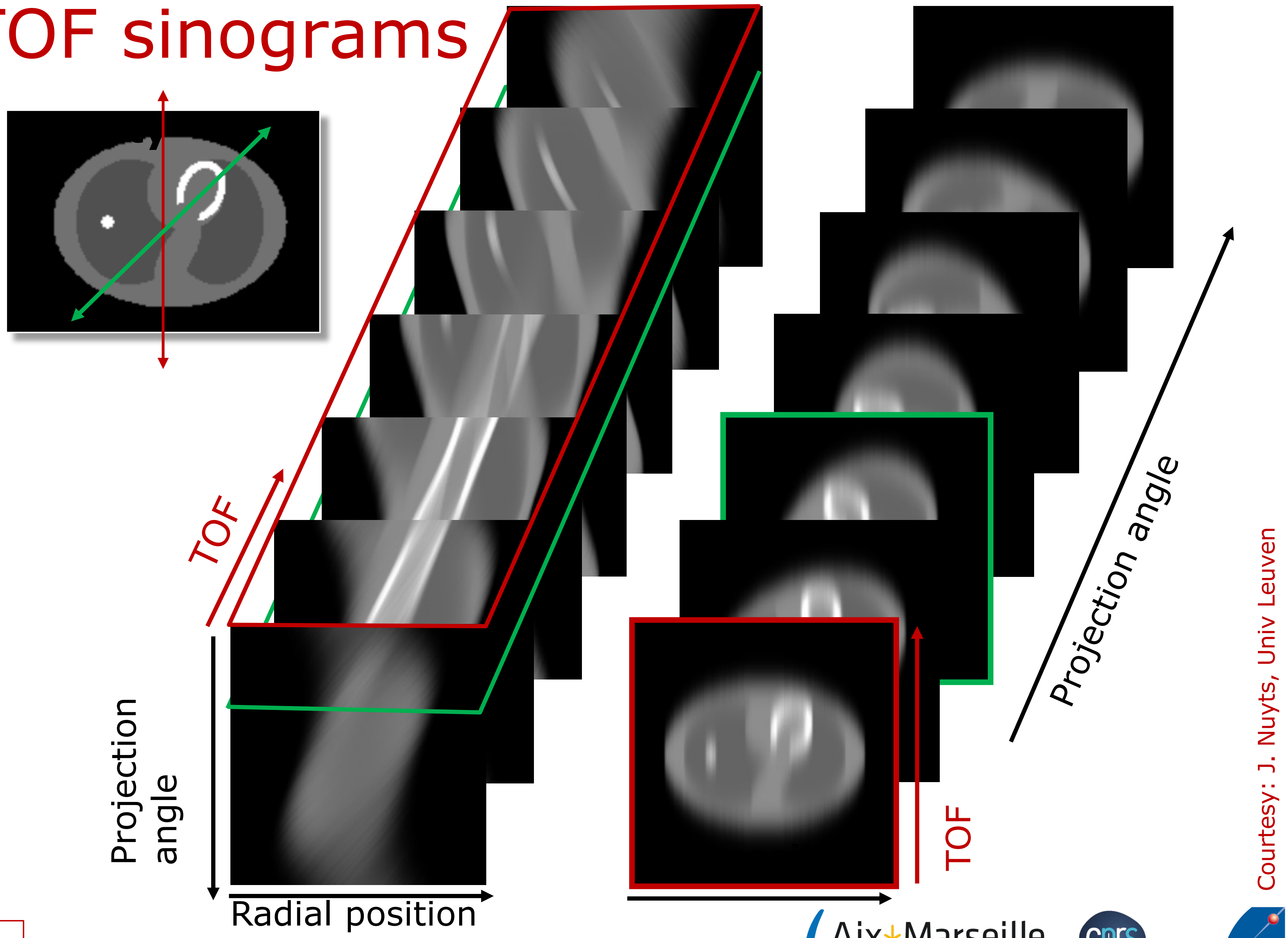
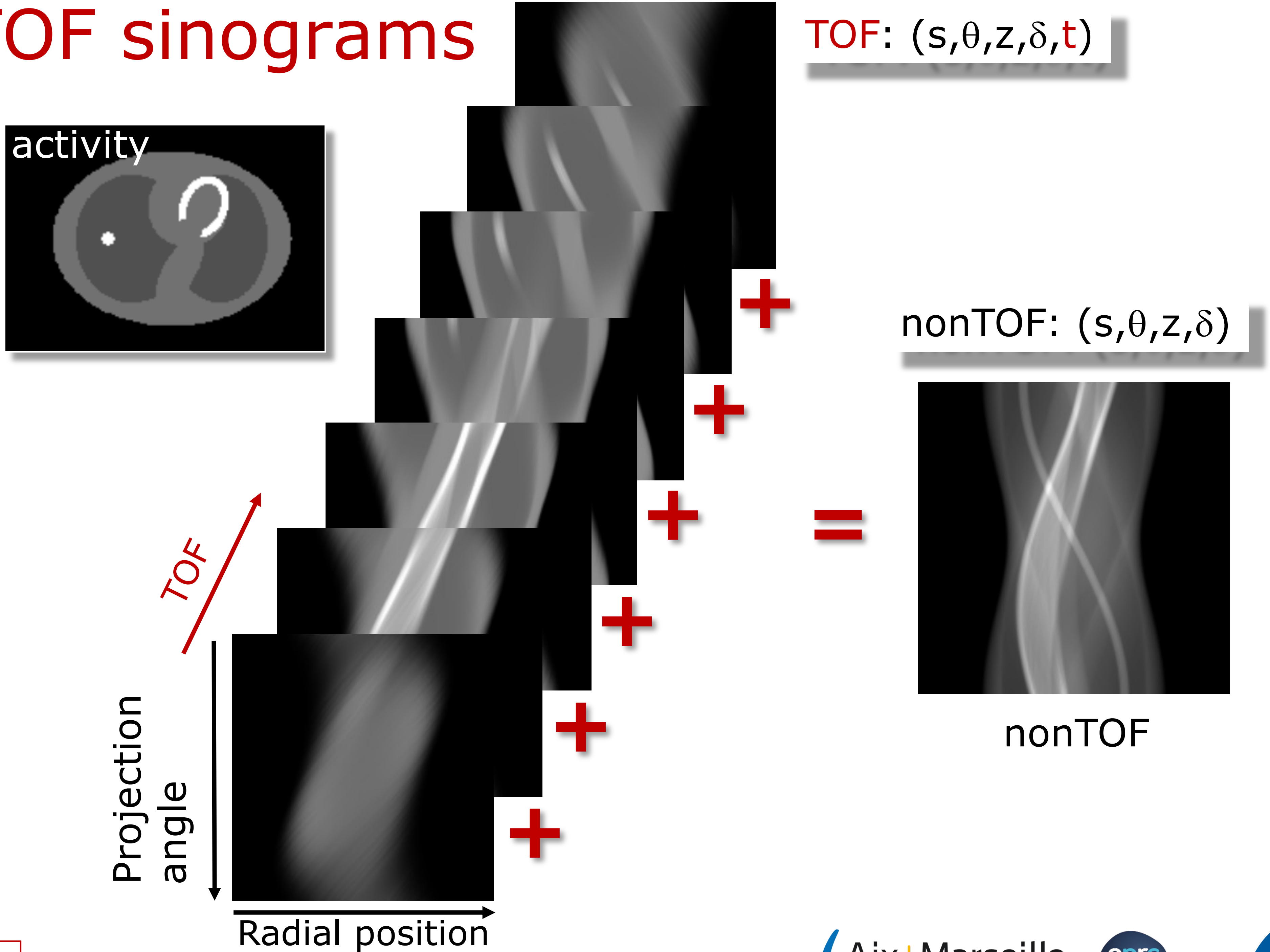
TOF sinograms



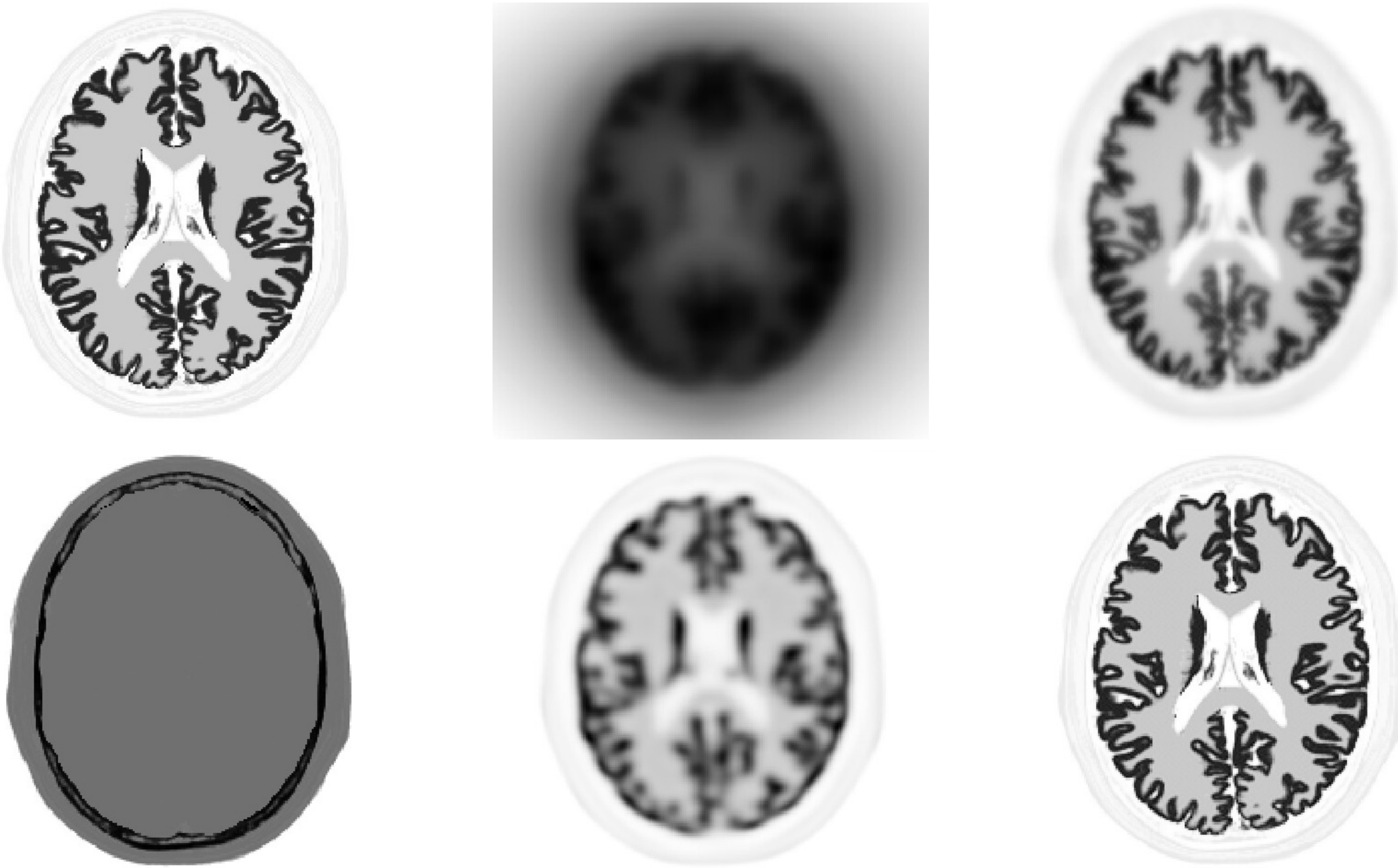
TOF sinograms



Courtesy: J. Nuyts, Univ Leuven

Resolution in TOF-direction ~1.5 mm
Resolution in detector direction 5 mm

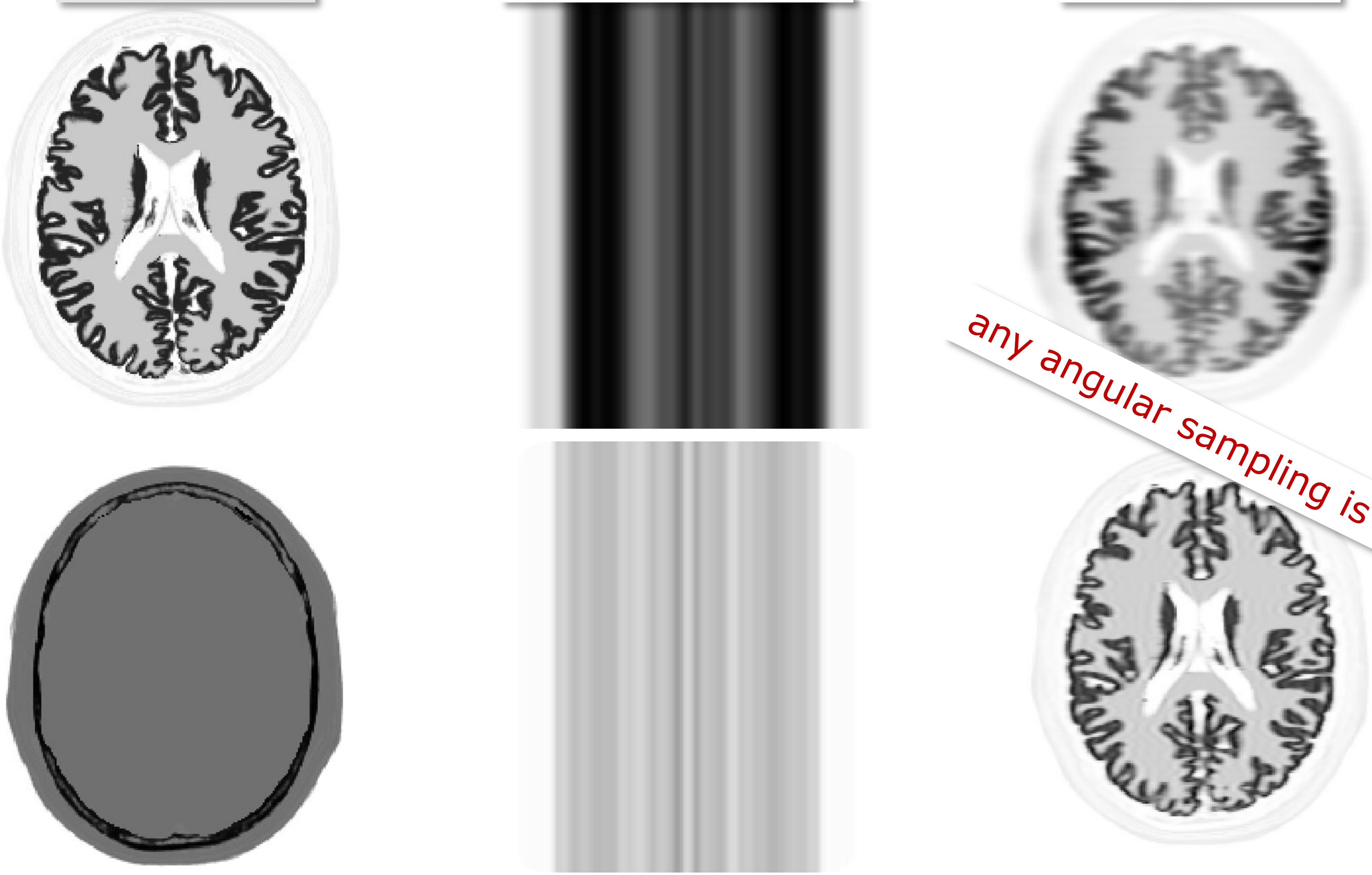
true activity | nonTOF backproj | TOF backproj



true attenuation | nonTOF OSEM | TOF OSEM

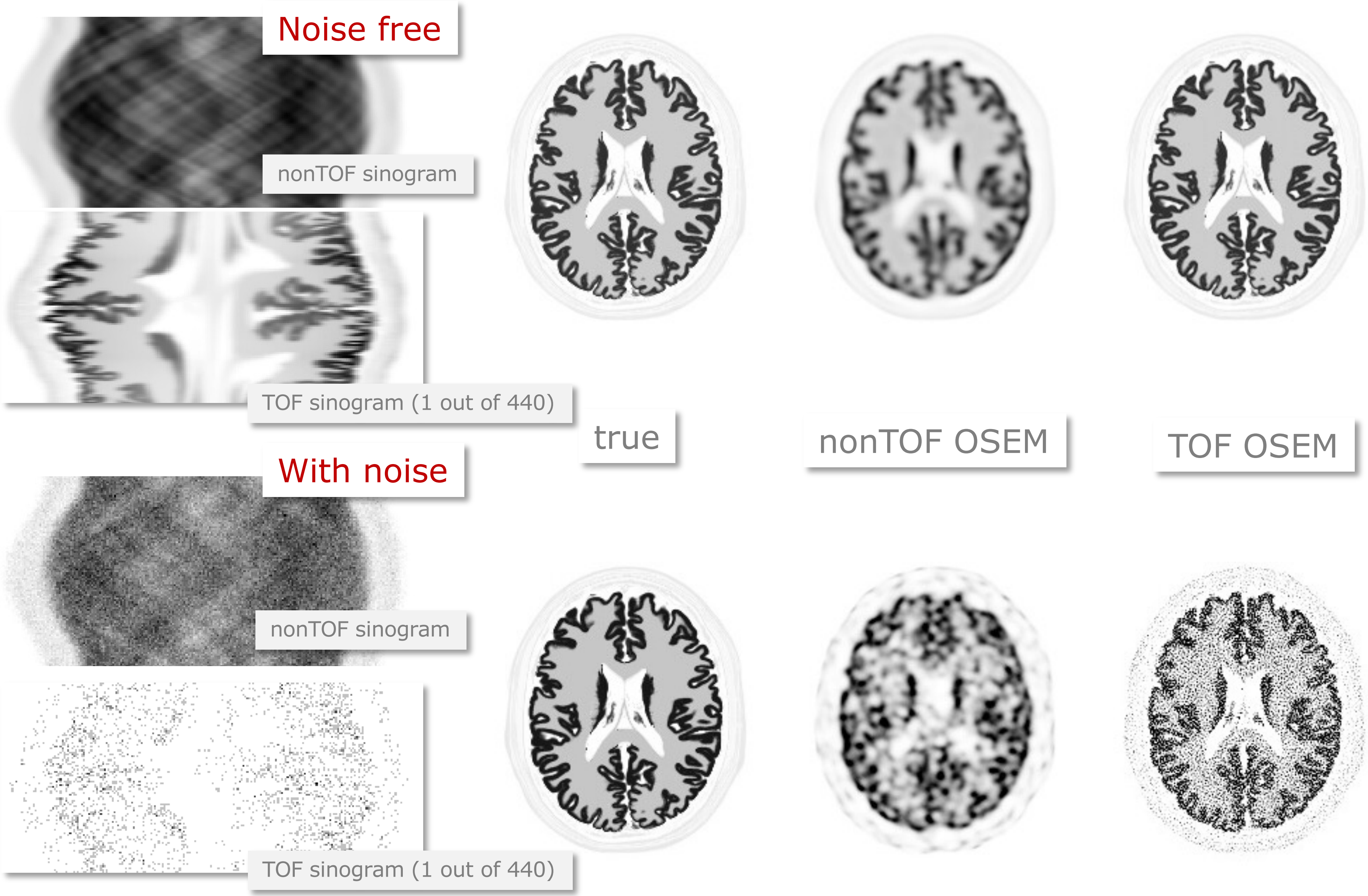
Courtesy: J. Nuyts, Univ Leuven

Using only the vertical projection angle

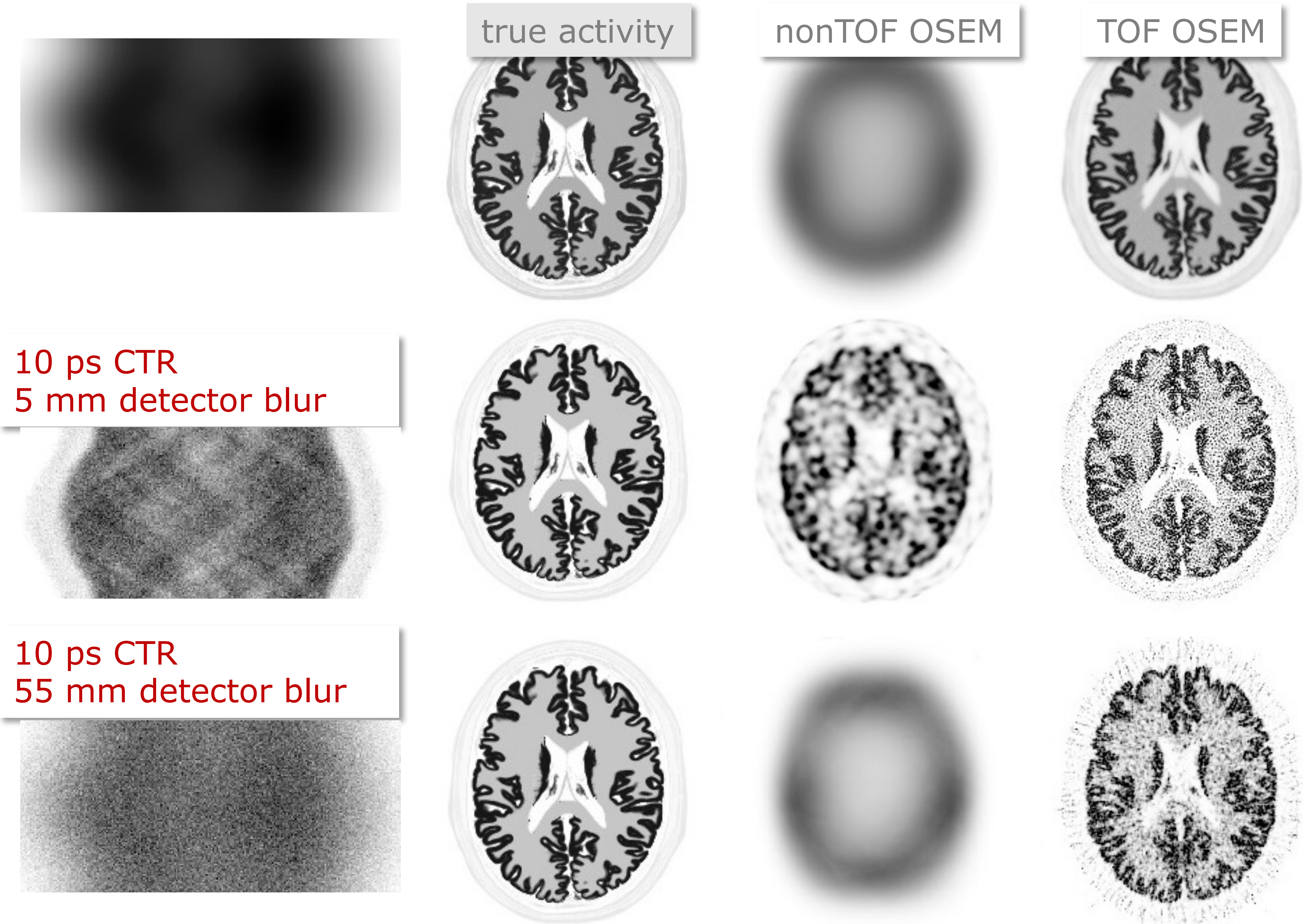


Courtesy: J. Nuyts, Univ Leuven

Signal to Noise Ratio (SNR)



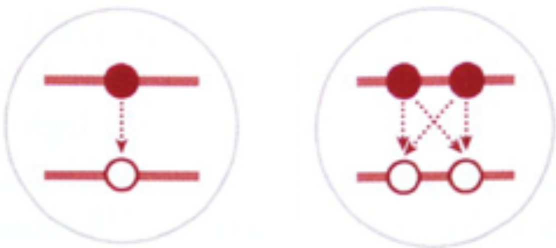
Courtesy: J. Nuyts, Univ Leuven



Courtesy: J. Nuyts, Univ Leuven

Sources possibles de photons prompts (< 1 ns)

Exciton/bi-exciton
stable at 300 K
(e.g. CdSe CQwells)



Activators Ce^{3+} : 5d-4f
Ca^{2+} & Mg^{2+} co-doping
$\tau_r \sim 20$ ps $\tau_d < 16$ ns

Hot intraband luminescence
0.1-10 ps
(e.g. $PbWO_4$, $CaWO_4$)

$$\frac{1}{\tau} = \frac{4e^2}{3\hbar c^3}\omega_{21}^3 \left|\vec{r}_{21}\right|^2$$

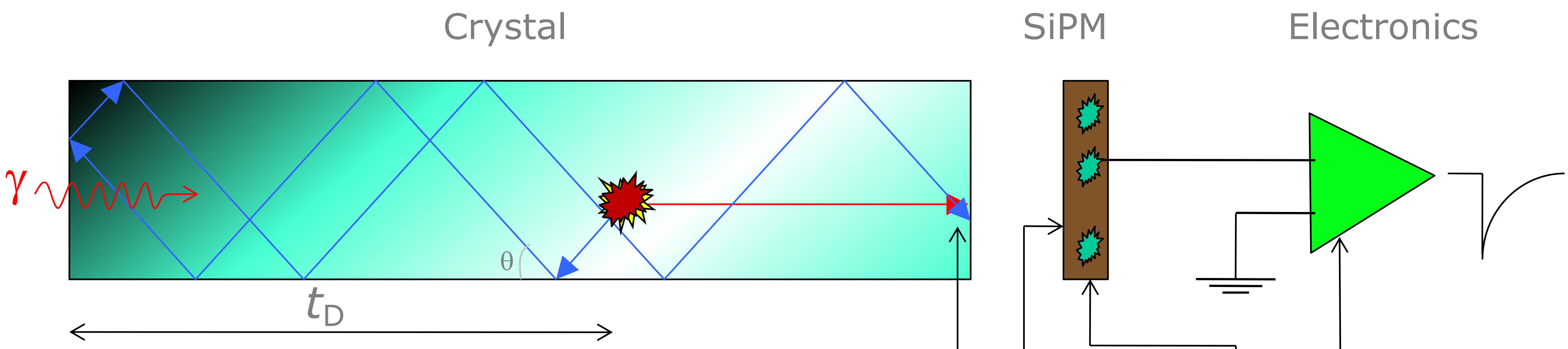
Cross luminescence
<1 ns (e.g. BaF_2)
< 300 nm
small light yields

High donor band semiconductors
< 1 ns (e.g. ZnO)
deactivated at room temperature

Cherenkov emission
$\tau \sim$ 5-10 ps

Courtesy: P. Lecoq, CERN

The detection chain



$t_{pe} = t_D + t_{ph} + t_{transit} + t_{SiPM} + t_{TDC}$

- t_D: Conversion depth
- t_{ph}: Scintillation process
- $t_{transit}$: Photon Transit Spread (PTS)
- t_{SiPM}: Single Photon Time Resolution (SPTR)
- t_{TDC}: TDC conversion time

$$p(t_{ph}) = h(t_{ph}) \frac{e^{-t_{ph}/\tau_d} - e^{-t_{ph}/\tau_r}}{\tau_d - \tau_r}$$

$$\text{CTR} \propto \sqrt{\frac{\tau_r \times \tau_d}{\text{LY}_{@energy}}}$$

Random deletion 1
Absorption, self-absorption affecting Light Transfer Efficiency (LTE)

Random deletion 2
SiPM Photon Detection Efficiency (PDE)

Unwanted pulses 1
Dark counts, Crosstalks
Afterpulses, Delayed-crosstalks

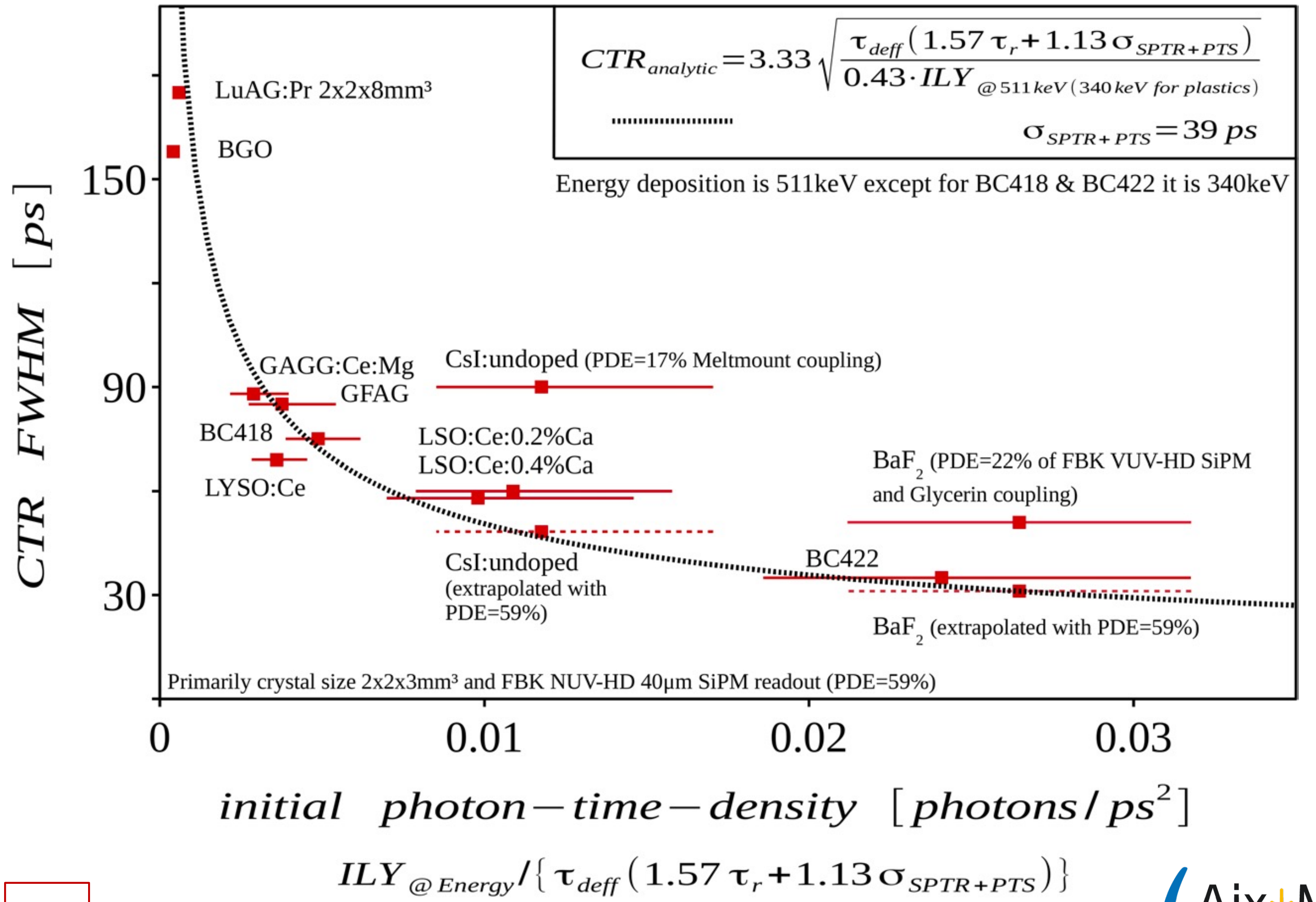
Unwanted pulses 2
Dark counts

Courtesy: P. Lecoq, CERN

State-of-the-art CTR measurements

$$\mathrm{CTR} = 2.35\sqrt{2}\Big/\sqrt{\underbrace{\mathrm{PDE}}_{\sim 59\%} \times \underbrace{\mathrm{LTE}}_{\sim 73\%} \times \underbrace{\mathrm{IPTD}}}$$

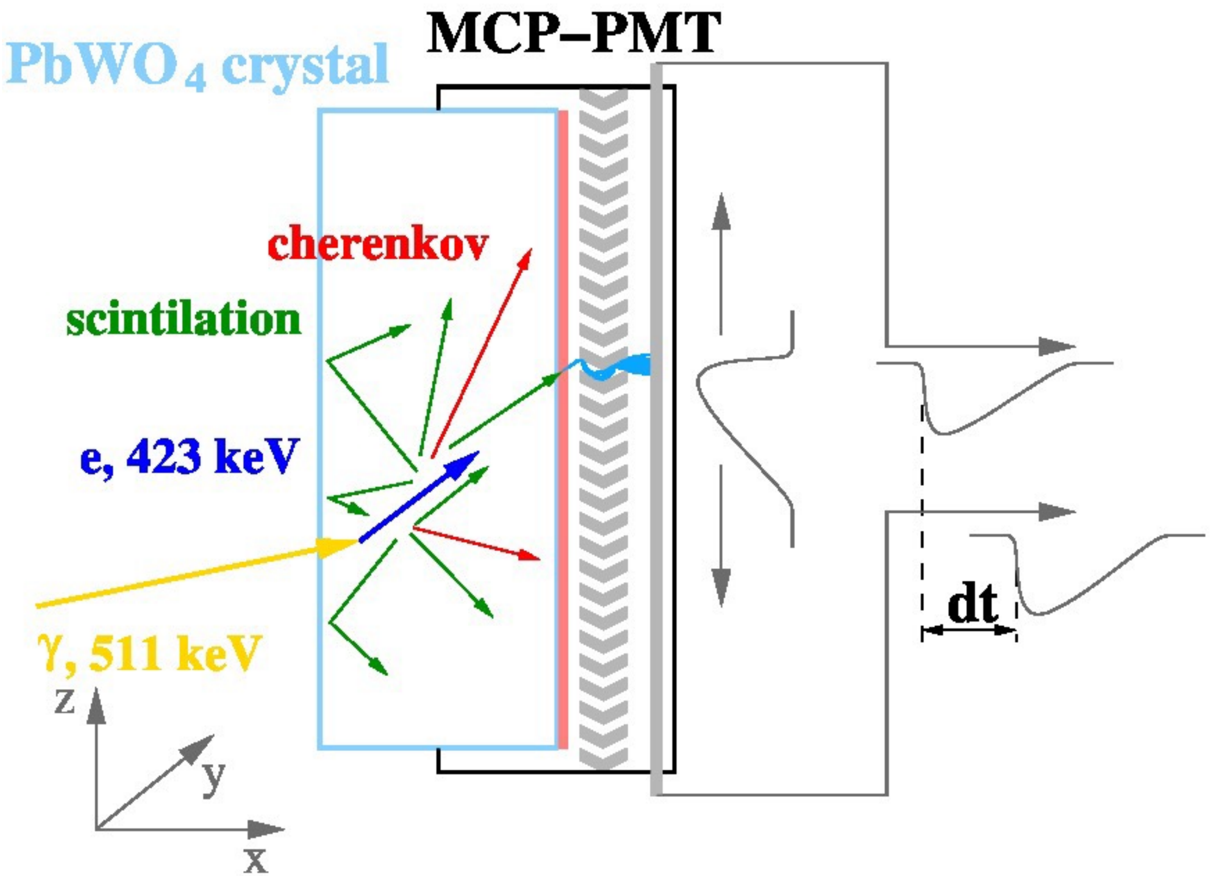
$$\mathrm{IPTD} = \frac{\mathrm{LY}_{@\mathrm{energy}}}{\tau_d\left(1.57\tau_r + 1.13\sigma_{\mathrm{SPTR+PTS}}\right)}$$



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

S. Vinogradov et al., Nucl. Inst. Meth. A 912 (2018) 149-153

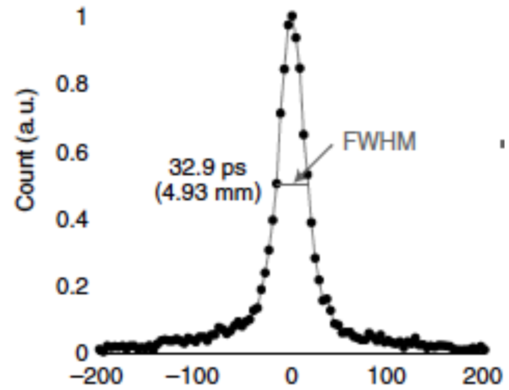
- Detection of scintillation and Cherenkov photons emitted in PWO
- Direct deposition of a photocathode (*n* ~2,7) on the crystal surface (*n* ~2,3)
- Encapsulation within a Micro-Channel Plate Multiplier Tube (MCP-MT)
- Coincidence Time resolution (CTR) ~20 ps FWHM (exluding MCP-MT)

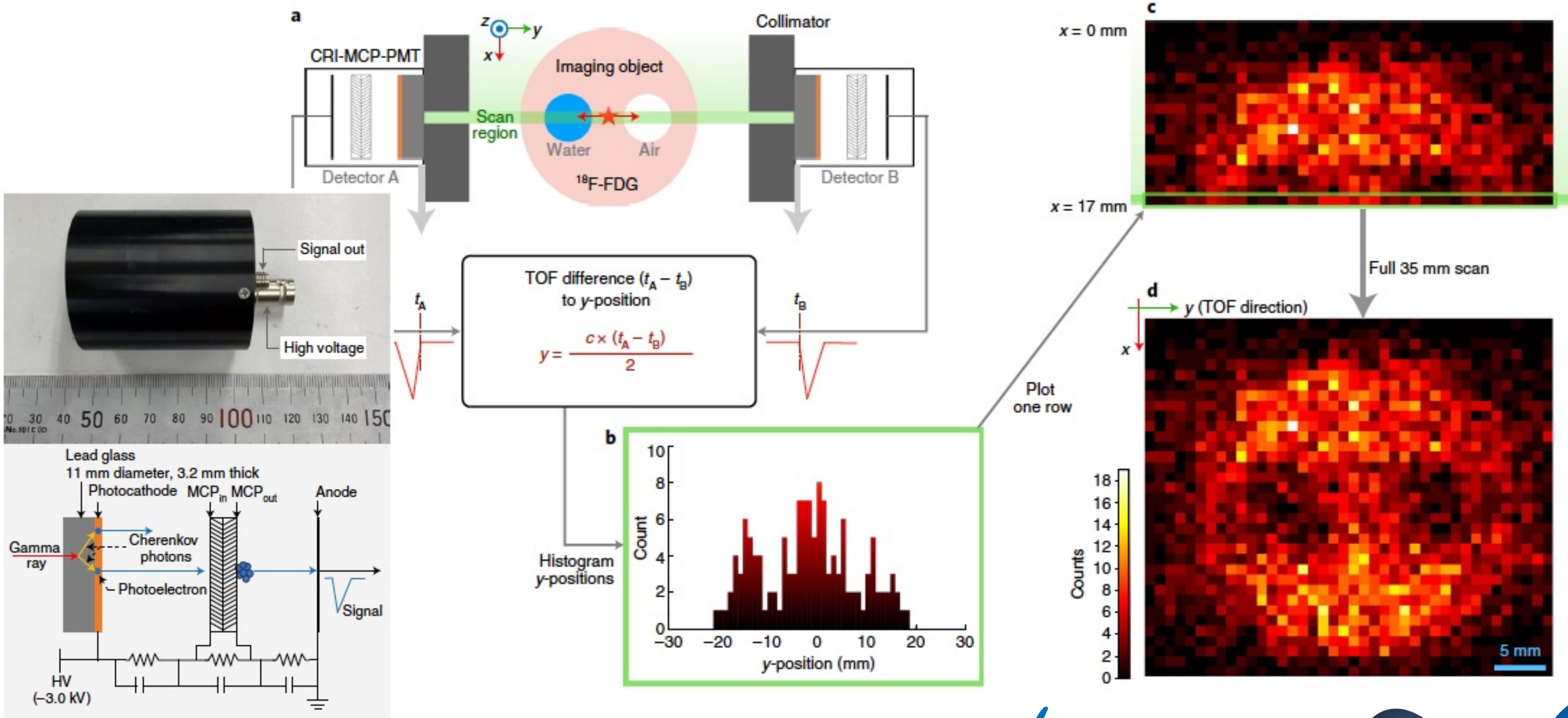


D. Yvon et al., JINST 15 (2020) P07029

Reconstruction-free positron emission tomography

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





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

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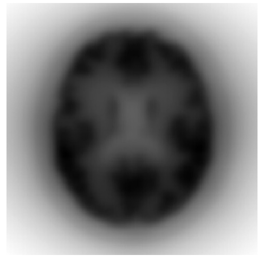
The 10 ps challenge: a step toward reconstruction-less TOF-PET

Thank you



nonTOF backproj

nonTOF OSEM

10ps TOF backproj

10ps TOF OSEM