

PET in the next decade instrumentation and image reconstruction

Johan Nuyts
KU Leuven



overview

- Effective sensitivity:
 - solid angle
 - TOF
 - spatial resolution
- TOF-PET
 - reconstruct attenuation from TOF-PET data
 - 30 ps TOF: no angular sampling needed
- Spatial resolution:
 - motion correction becomes essential!
- Deep learning
 - great tools
 - we must be critical!



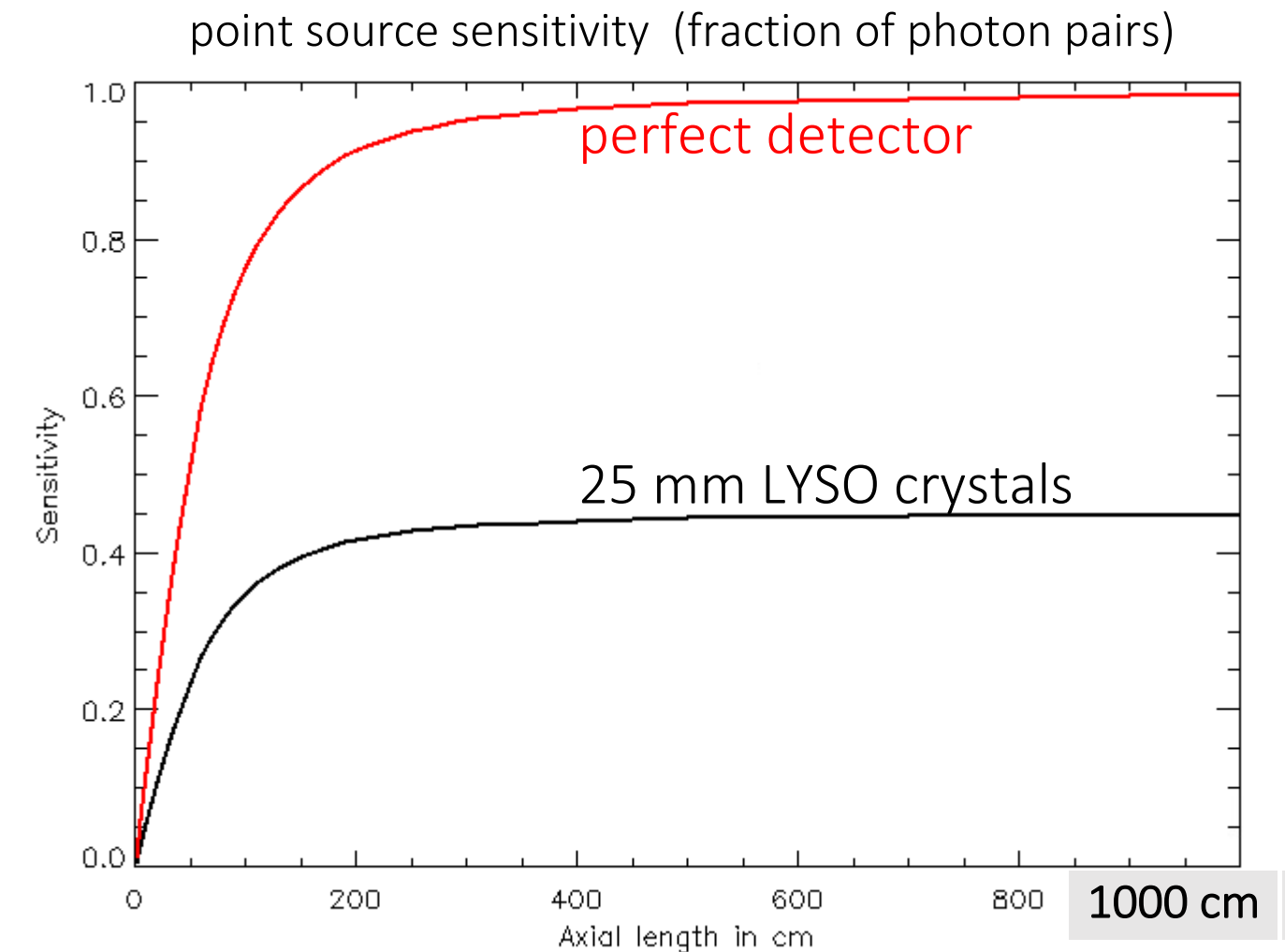
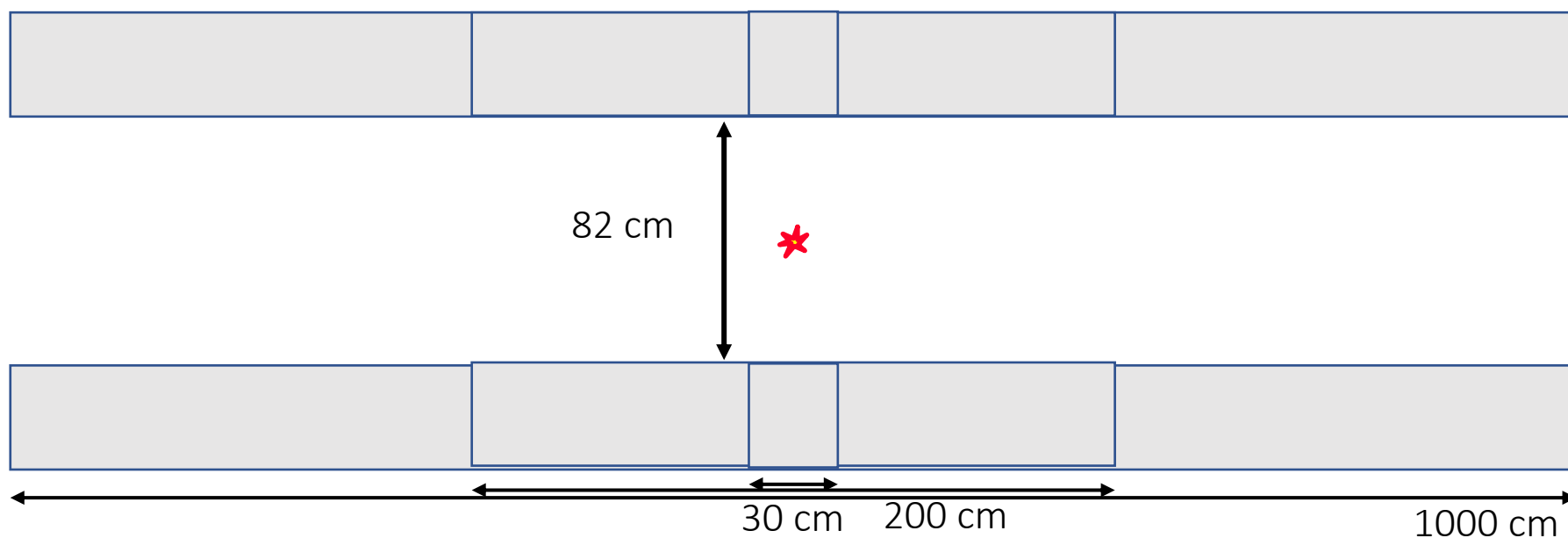
overview

- **Effective sensitivity:**
 - **solid angle**
 - **TOF**
 - **spatial resolution**
- TOF-PET
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Effective sensitivity: solid angle

point source sensitivity



$$\frac{\text{sensit @ 200 cm}}{\text{sensit @ 20 cm}} = 3.9$$

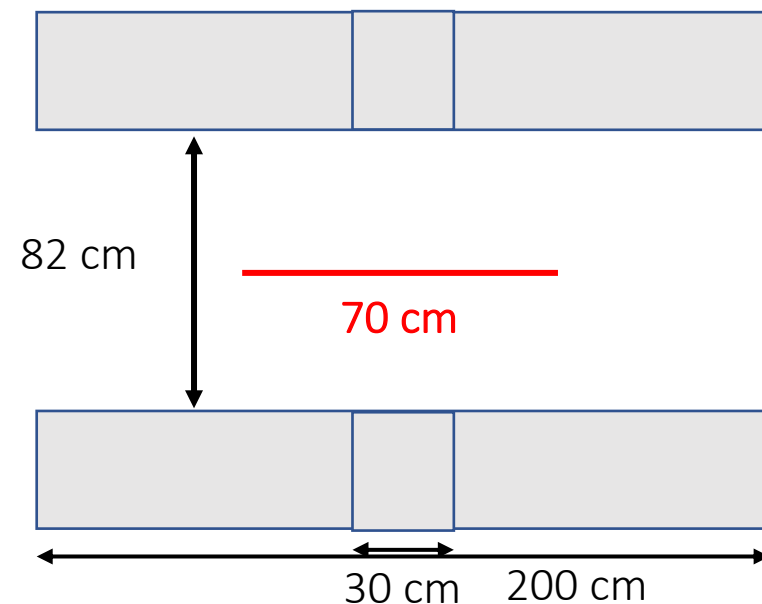
$$\frac{\text{sensit @ 200 cm}}{\text{sensit @ 30 cm}} = 2.7$$

$$\frac{\text{sensit @ 200 cm}}{\text{sensit @ 100 cm}} = 1.2$$

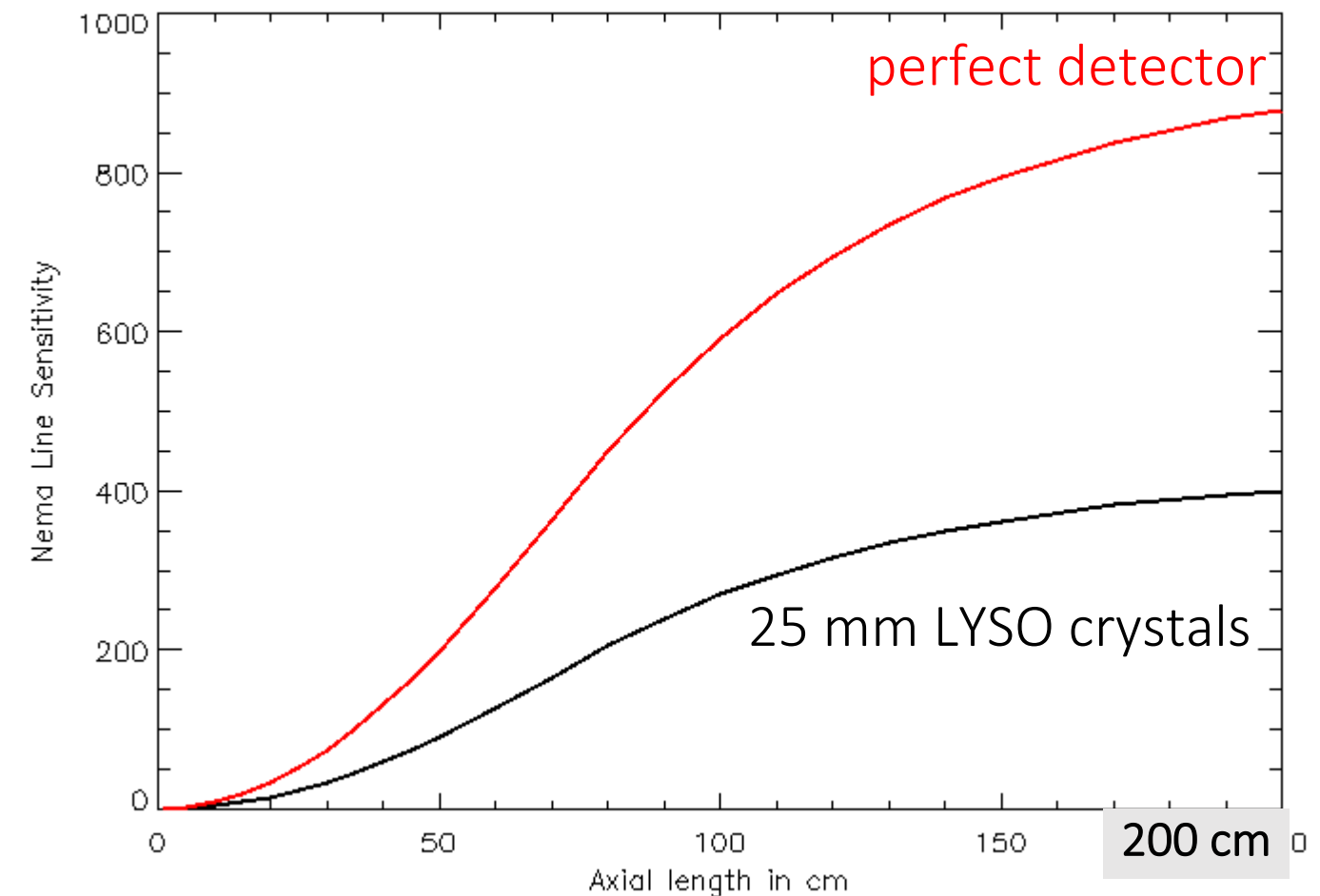


Effective sensitivity: solid angle

line source sensitivity



line source sensitivity (counts per s / kBq)



$$\frac{\text{line_sensit @ 200 cm}}{\text{line_sensit @ 20 cm}} = 26$$

$$\frac{\text{point_sensit @ 200 cm}}{\text{point_sensit @ 20 cm}} = 3.9$$

$$\frac{\text{line_sensit @ 200 cm}}{\text{line_sensit @ 30 cm}} = 12$$

$$\frac{\text{point_sensit @ 200 cm}}{\text{point_sensit @ 30 cm}} = 2.7$$

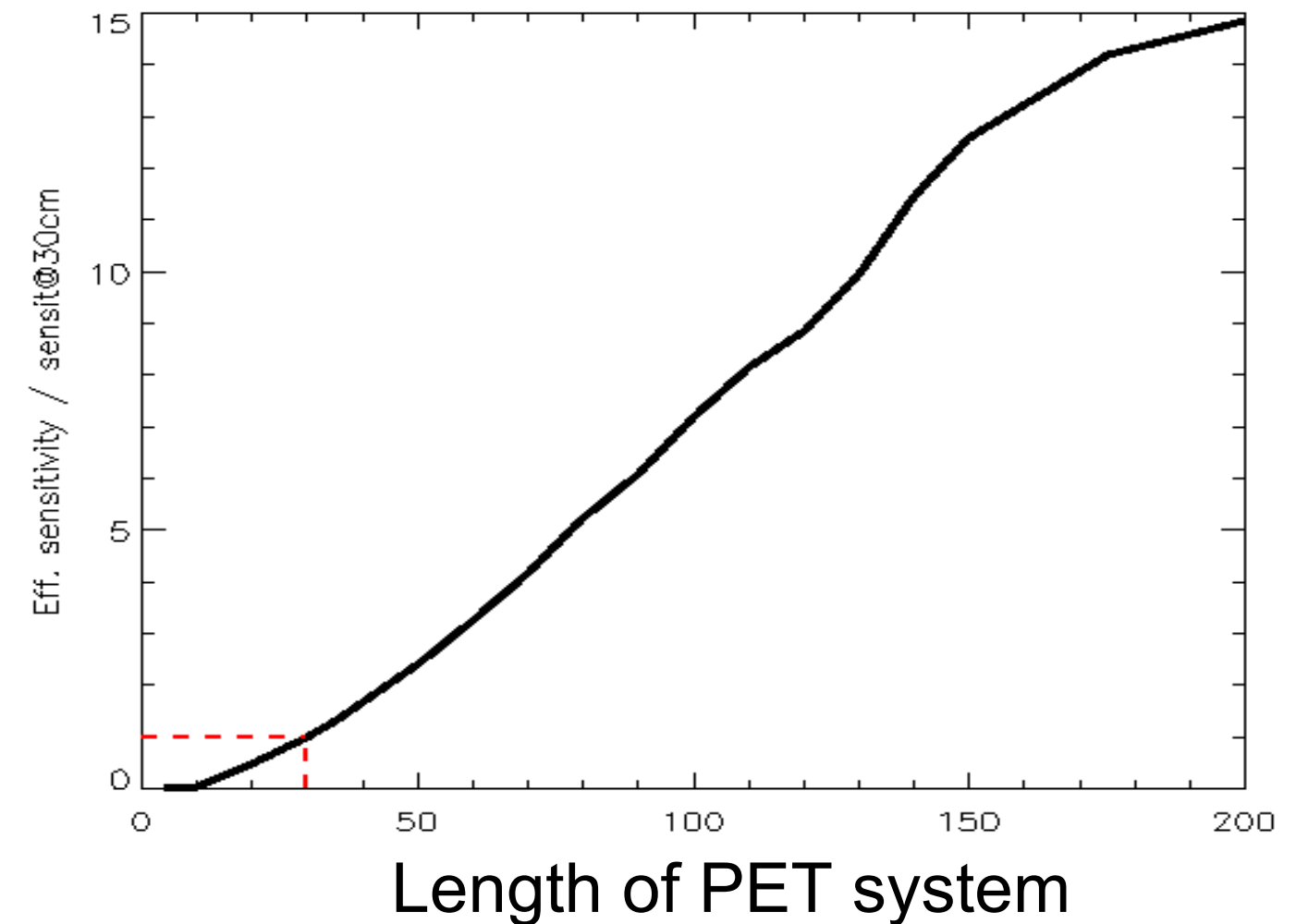
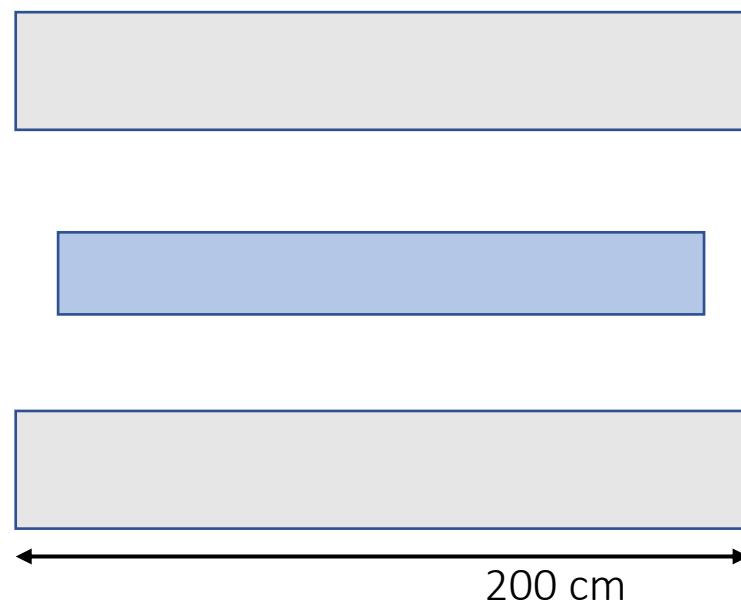
$$\frac{\text{line_sensit @ 200 cm}}{\text{line_sensit @ 100 cm}} = 1.5$$

$$\frac{\text{point_sensit @ 200 cm}}{\text{point_sensit @ 100 cm}} = 1.2$$



Effective sensitivity: solid angle

Minimum sensitivity achieved
with multi-bed WB scan



Cylinder

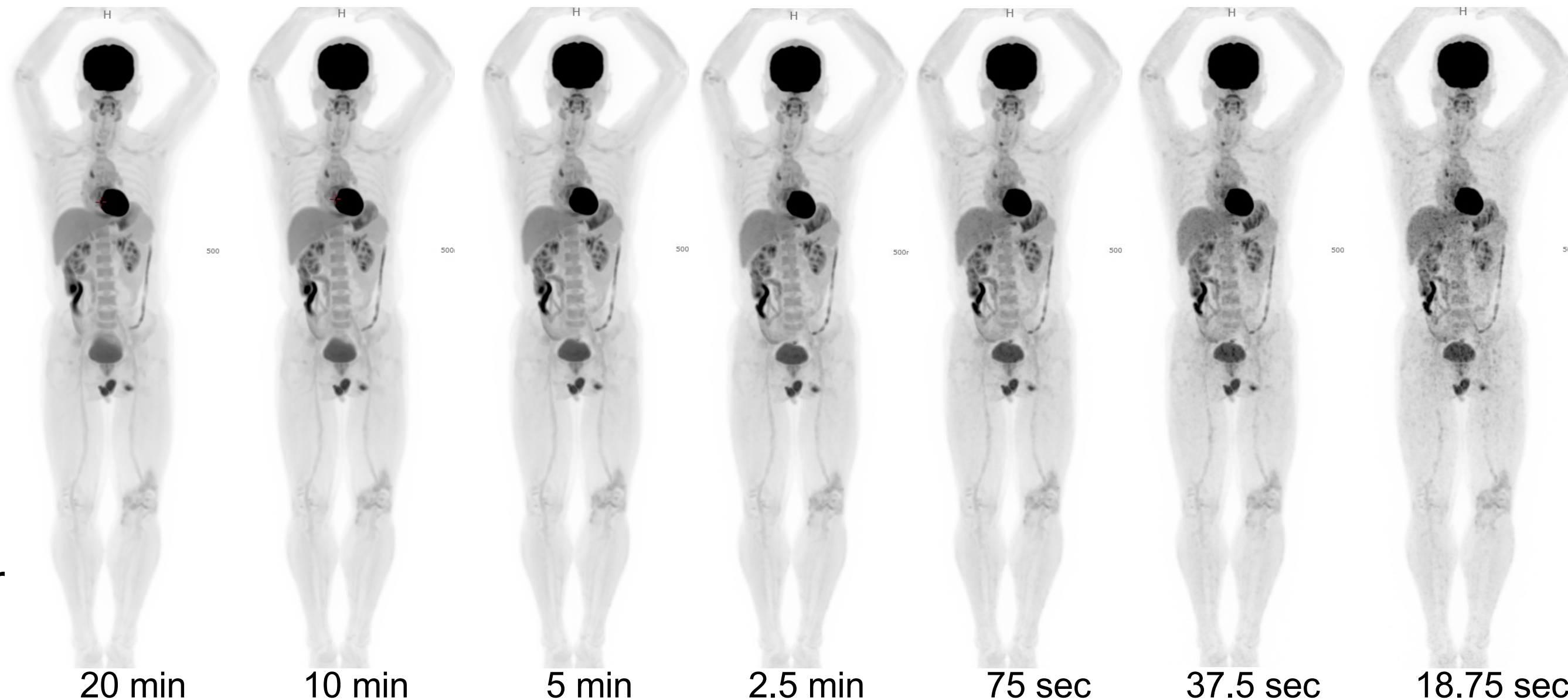
- 185 cm long
- 25 cm diameter
- attenuation 2/3 of water





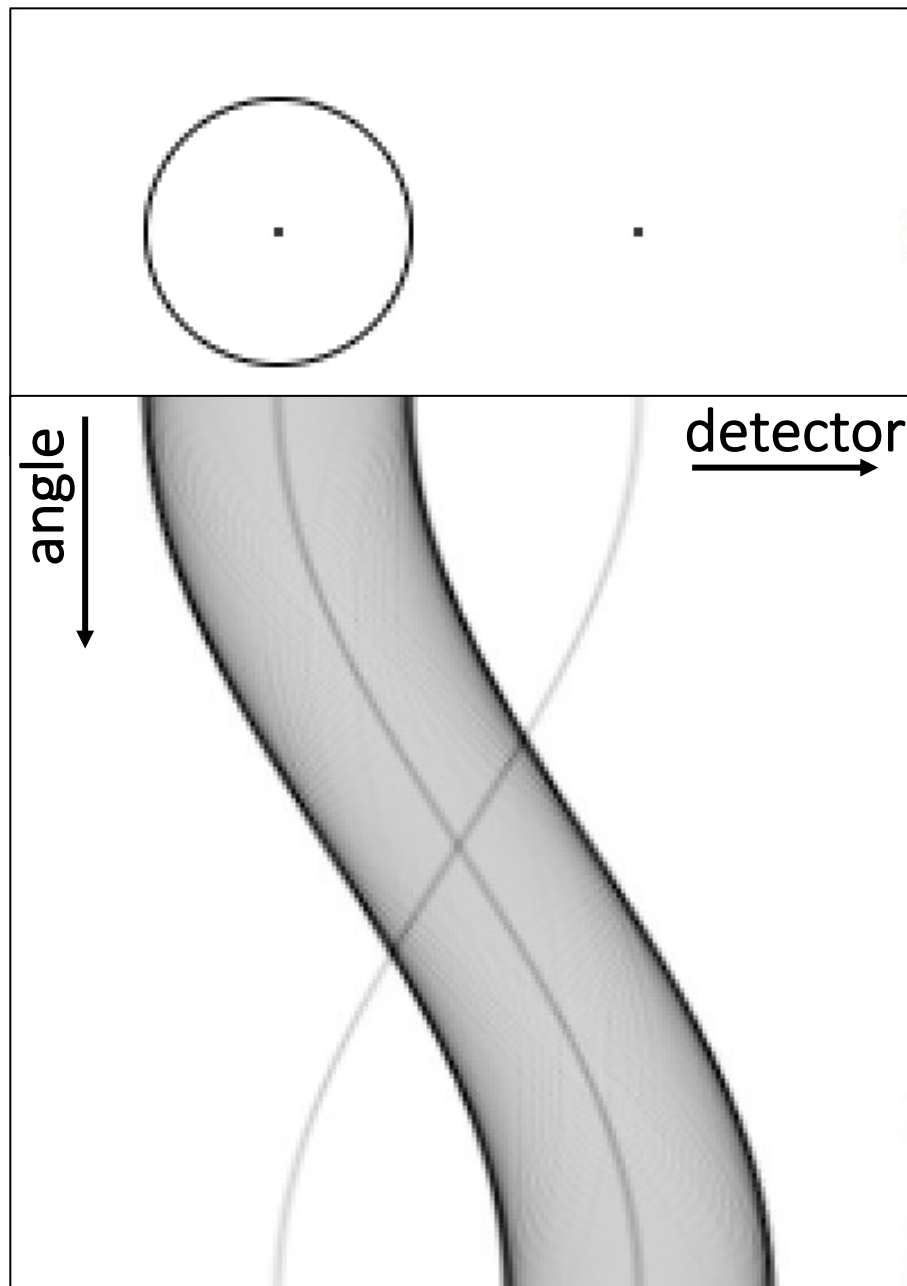
Age: 61
Gender: Male
Height: 164 cm
Weight: 65 kg

Tracer: FDG
Dose: 7.8 mCi
80 mins post injection

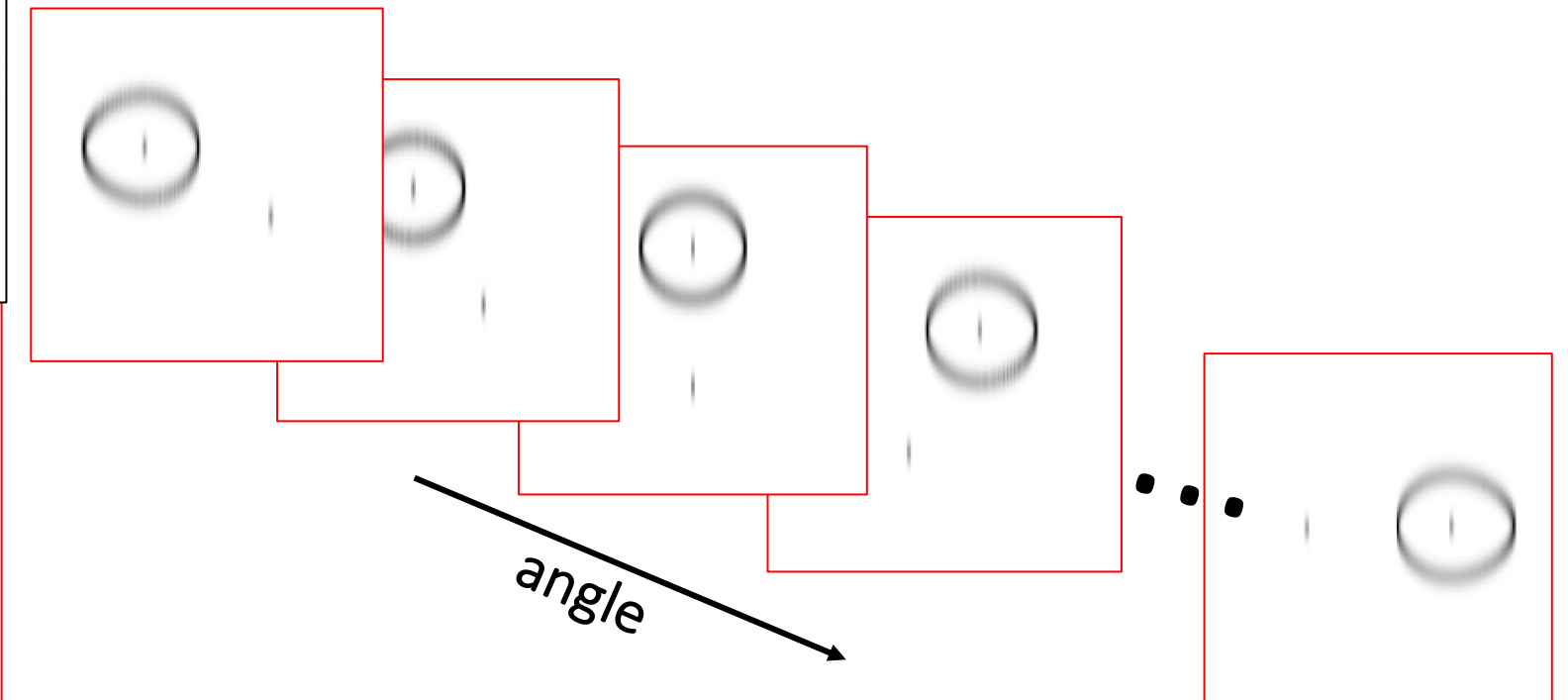
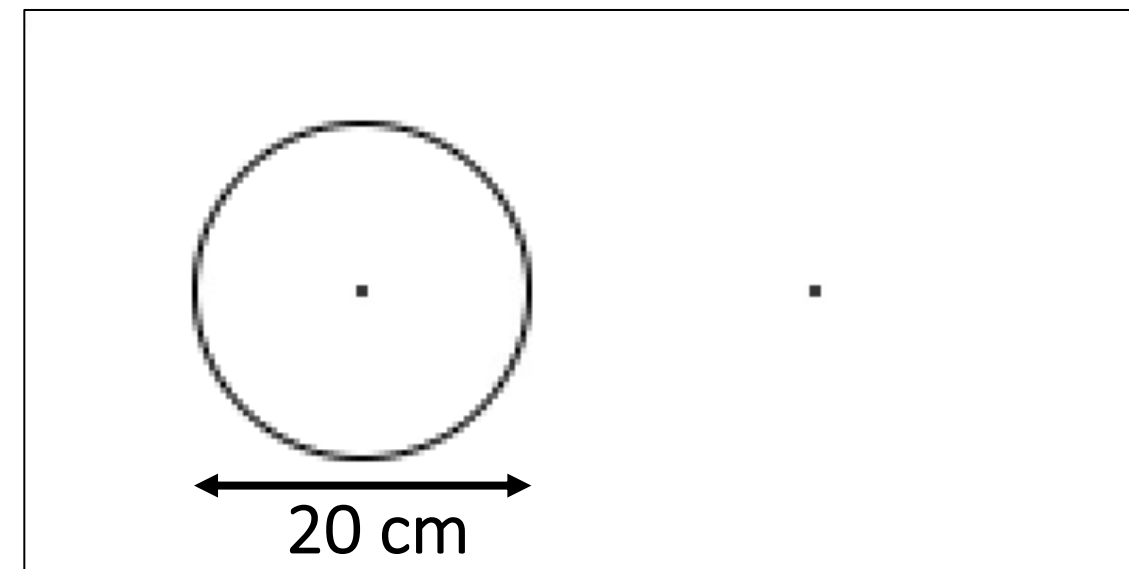
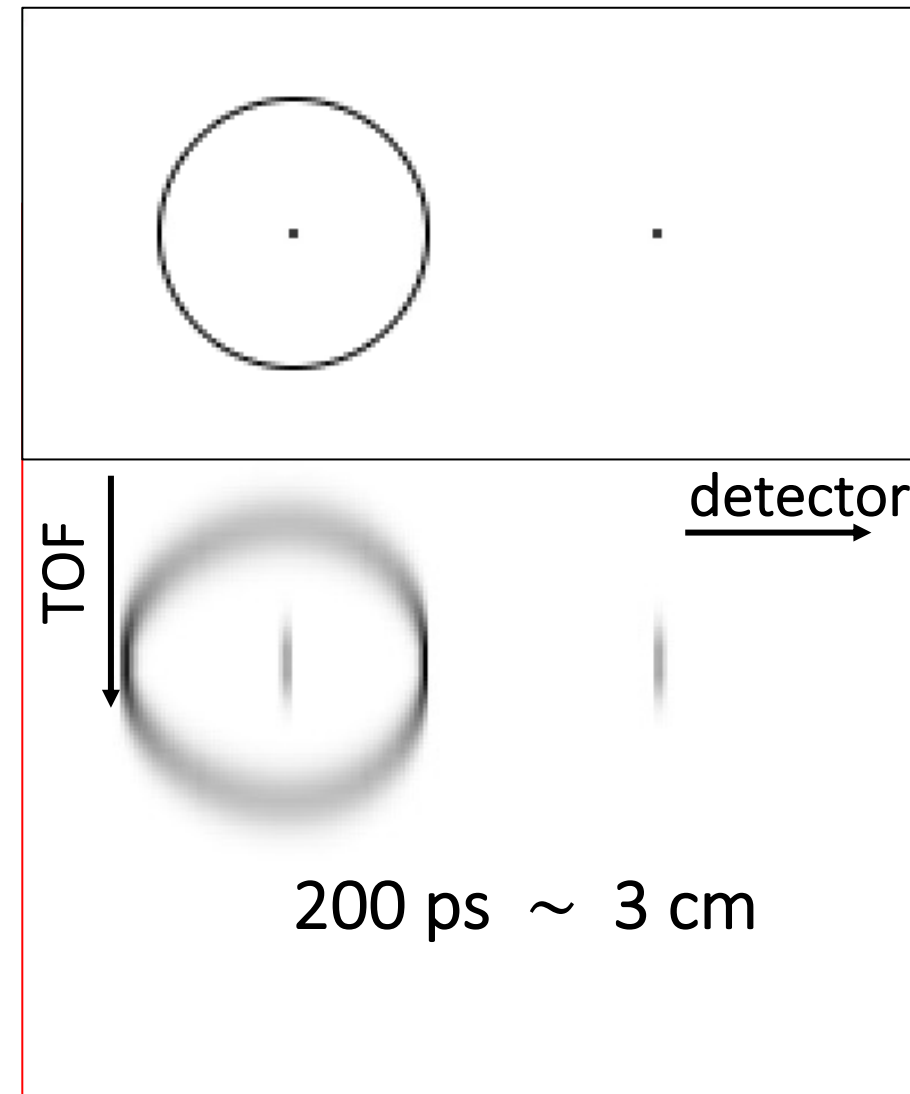


Effective sensitivity: TOF

non-TOF



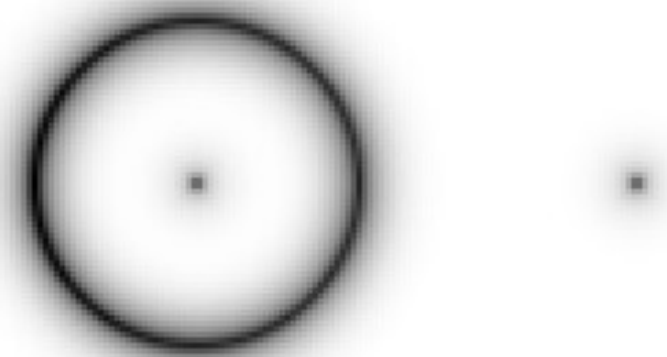
TOF 200 ps



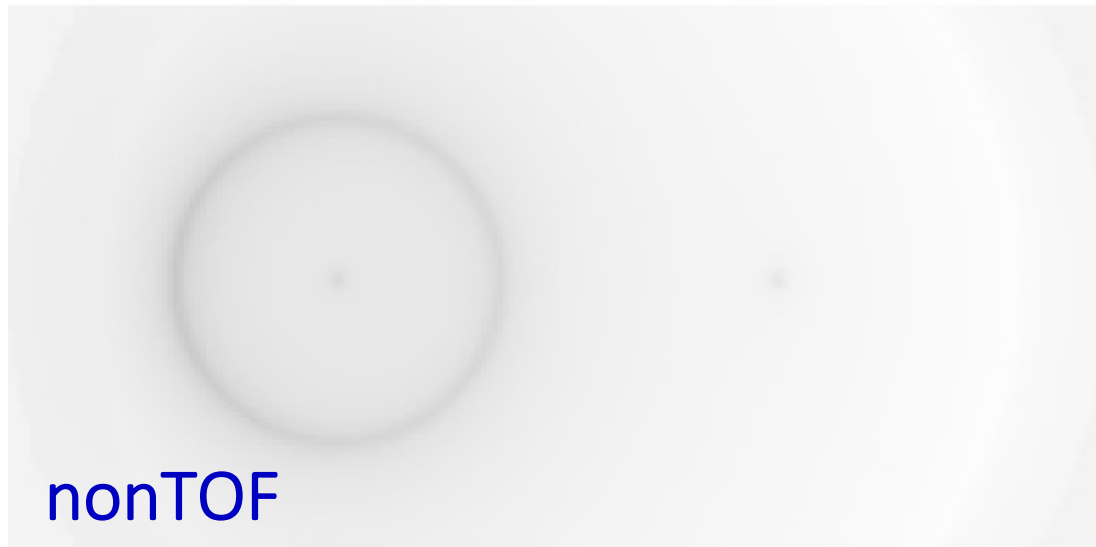
Effective sensitivity: TOF

MLEM reconstruction

TOF

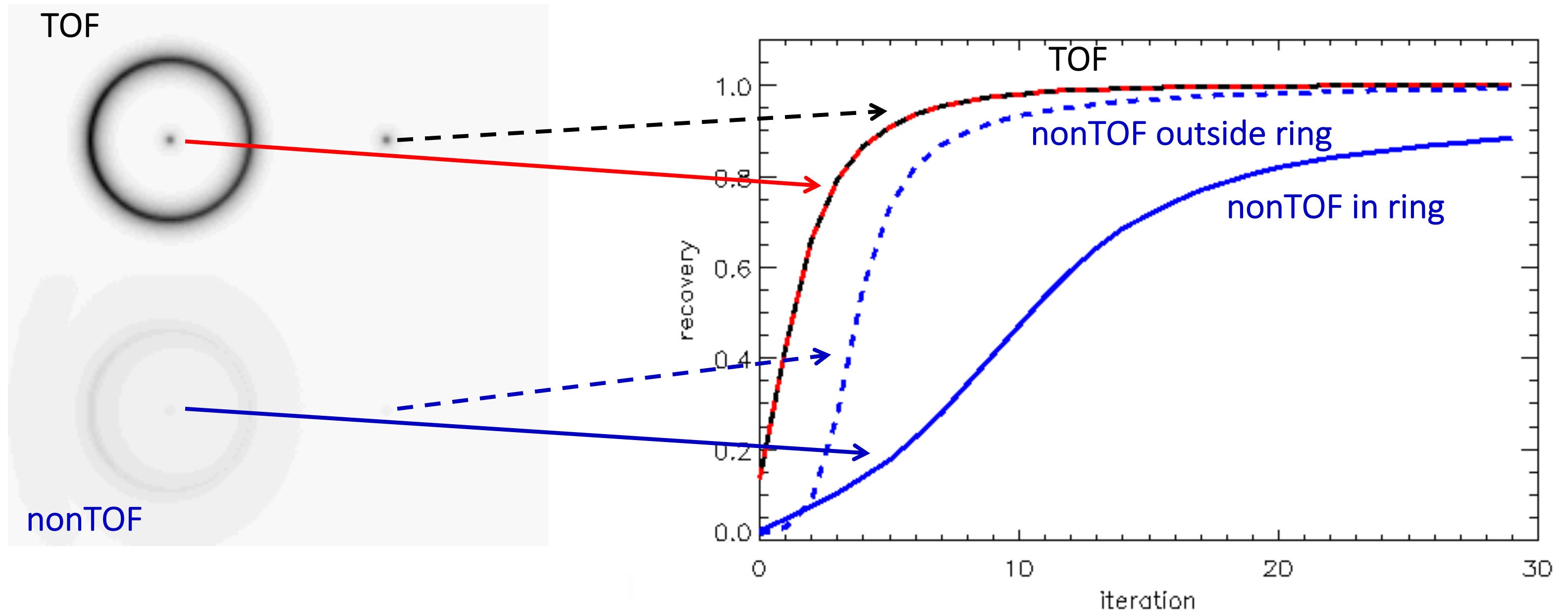


nonTOF



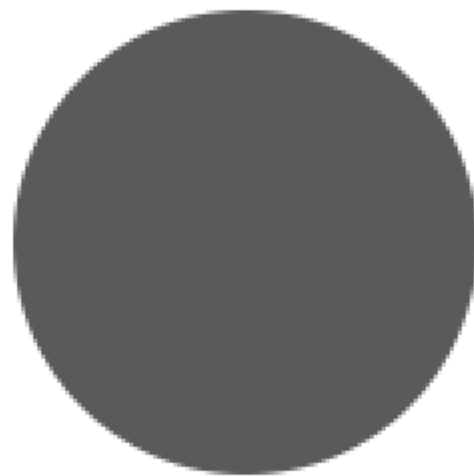
Effective sensitivity: TOF

MLEM reconstruction



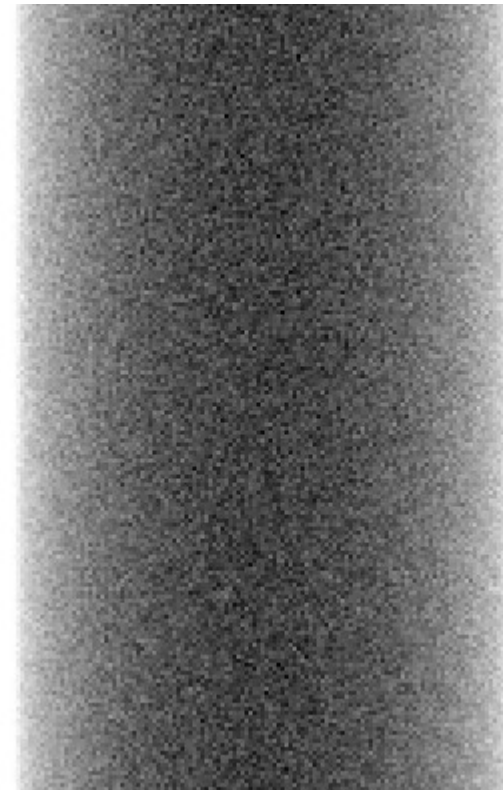
Effective sensitivity: TOF

true image



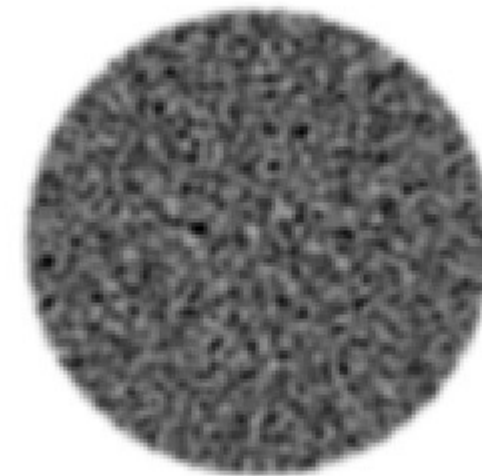
← 40 cm →

noisy TOF and
non-TOF
sinogram

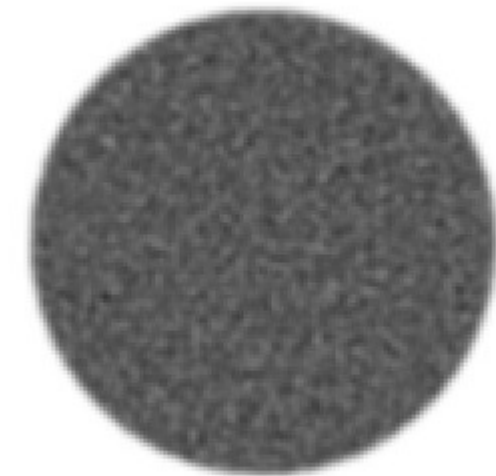


TOF: 200 *ps* ~ 3 *cm*

non-TOF MLEM



TOF MLEM



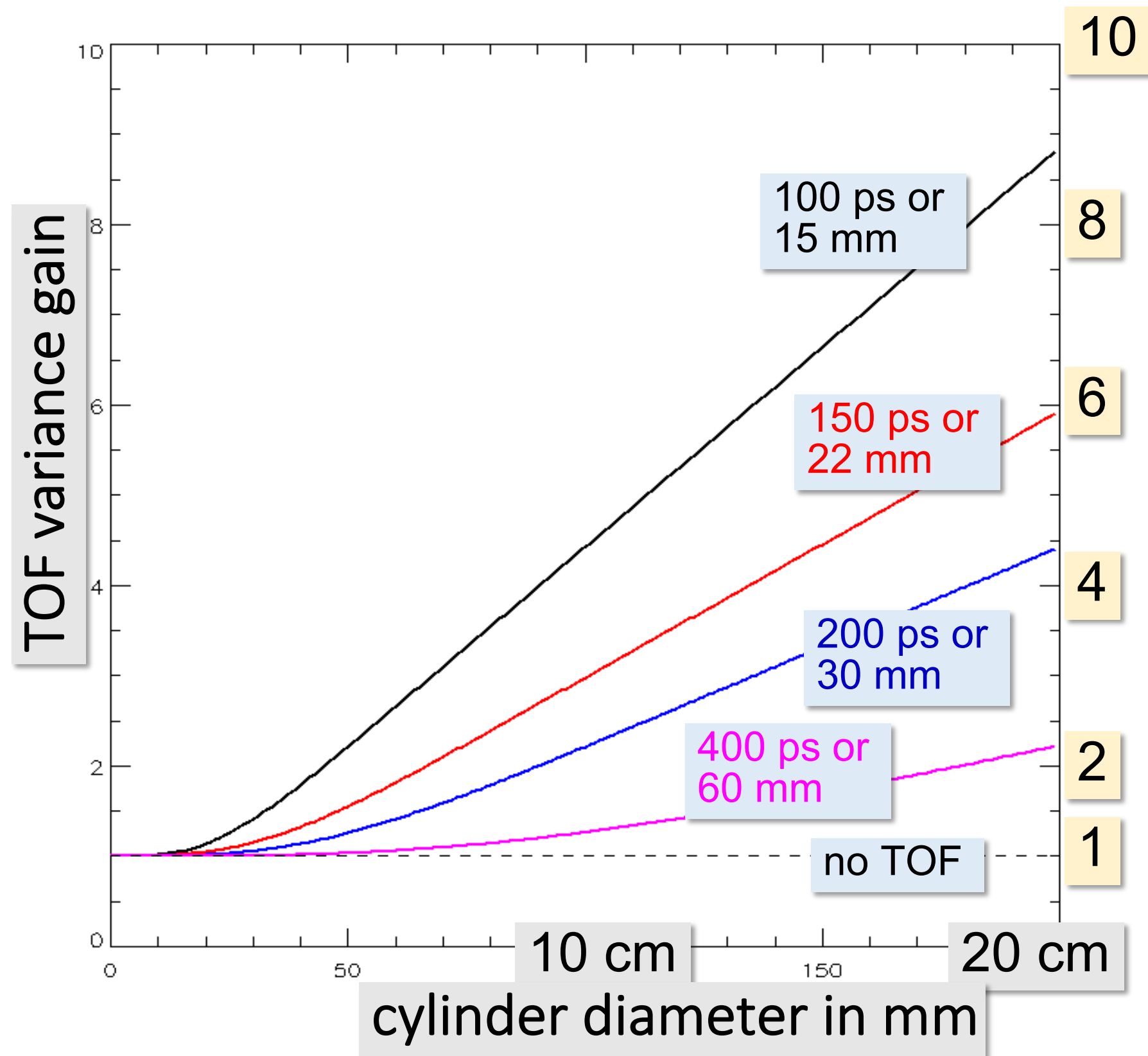
same resolution

TOF: 3 times less noise
or 9 times higher sensitivity

$$\frac{\text{var}_{\text{nonTOF}}}{\text{var}_{\text{TOF}}} = 0.664 \frac{40 \text{ cm}}{3 \text{ cm}}$$



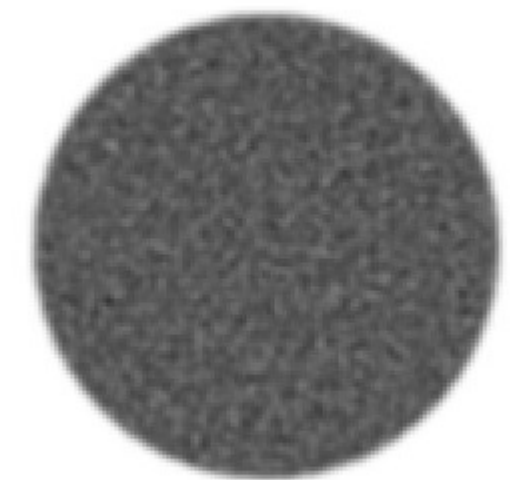
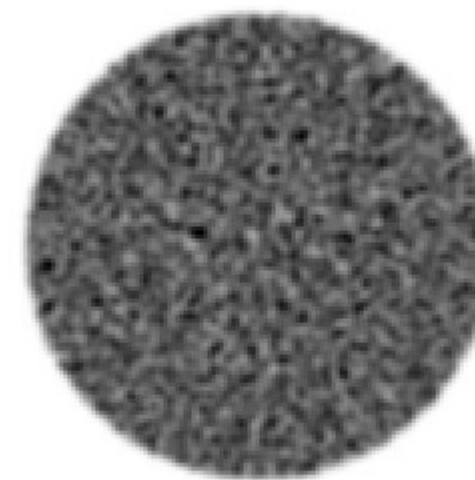
Effective sensitivity: TOF



non-TOF MLEM

TOF MLEM

same resolution



TOF: 3 times less noise
or 9 times higher sensitivity

$$\frac{\text{var}_{\text{nonTOF}}}{\text{var}_{\text{TOF}}} = 0.664 \frac{40 \text{ cm}}{3 \text{ cm}}$$



Effective sensitivity: spatial resolution

Effective sensitivity

desired spatial resolution

$$\frac{1}{\text{VAR}_{\text{PET}}} \sim \text{SNR}_{\text{PET}}^2 \sim (\text{SolidAngle})^P \times \frac{1}{\text{FWHM}_{\text{TOF}}} \times \frac{(\text{FWHM}_{\text{recon}}^2 - \text{FWHM}_{\text{system}}^2)^2}{(\text{FWHM}_{\text{postsmooth}})^4}$$

long scanner

- WB PET: $1 \leq P < 2$
- single organ: $P = 1$

small diameter: $P = 1$

system timing resolution

system spatial resolution

$$\text{SNR}_{\text{TOF}}^2 \sim \int_{-\infty}^{\infty} \text{TOFkernel}^2(x) dx$$



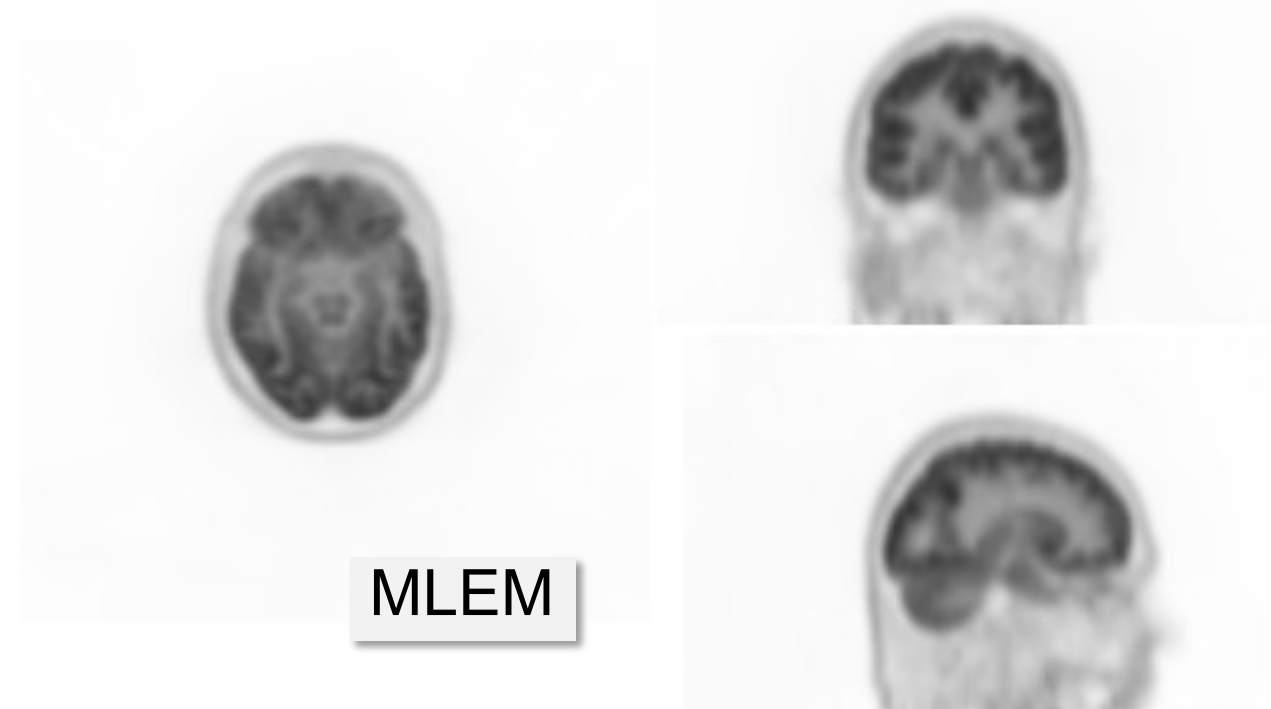
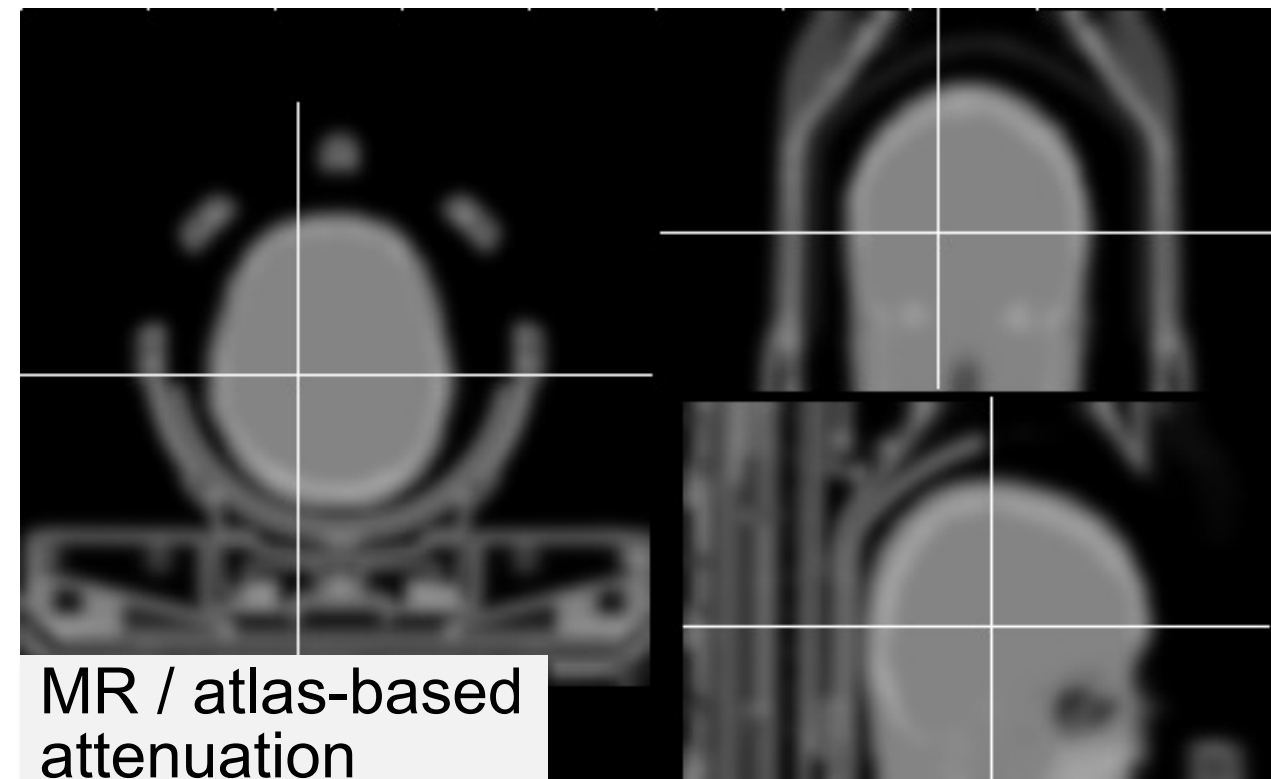
overview

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 - solid angle
 - TOF
 - spatial resolution
- **TOF-PET**
 - **reconstruct attenuation from TOF-PET data**
 - **30 ps TOF: no angular sampling needed**
- Resolution:
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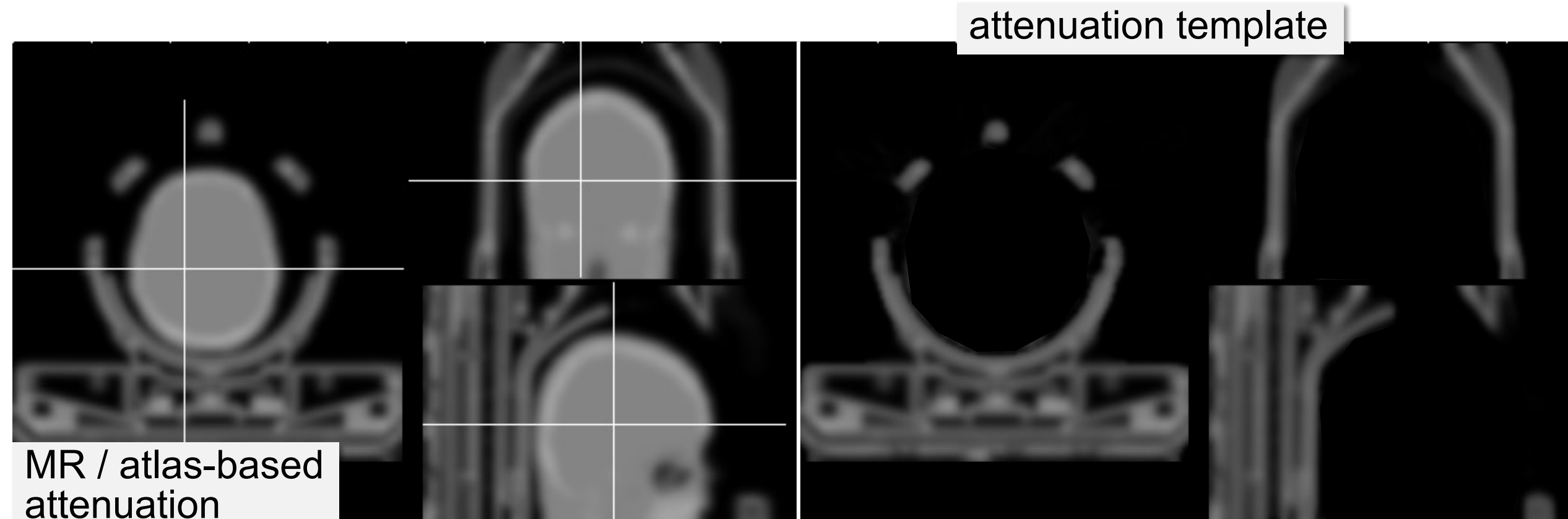


TOF: reconstruct activity and attenuation

GE Signa PET/MR
TOF: 380 ps



TOF: reconstruct activity and attenuation

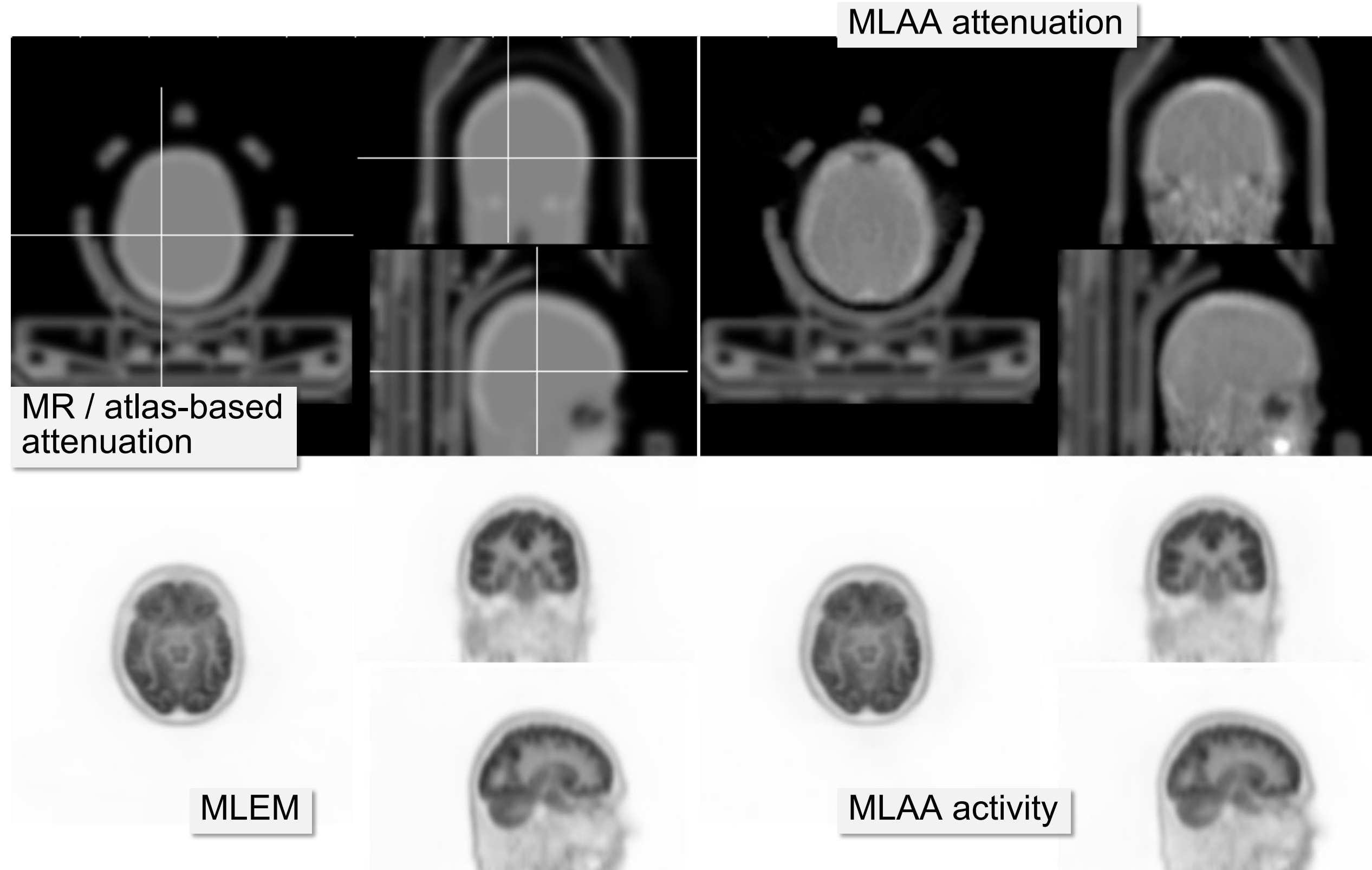


GE Signa PET/MR
TOF: 380 ps

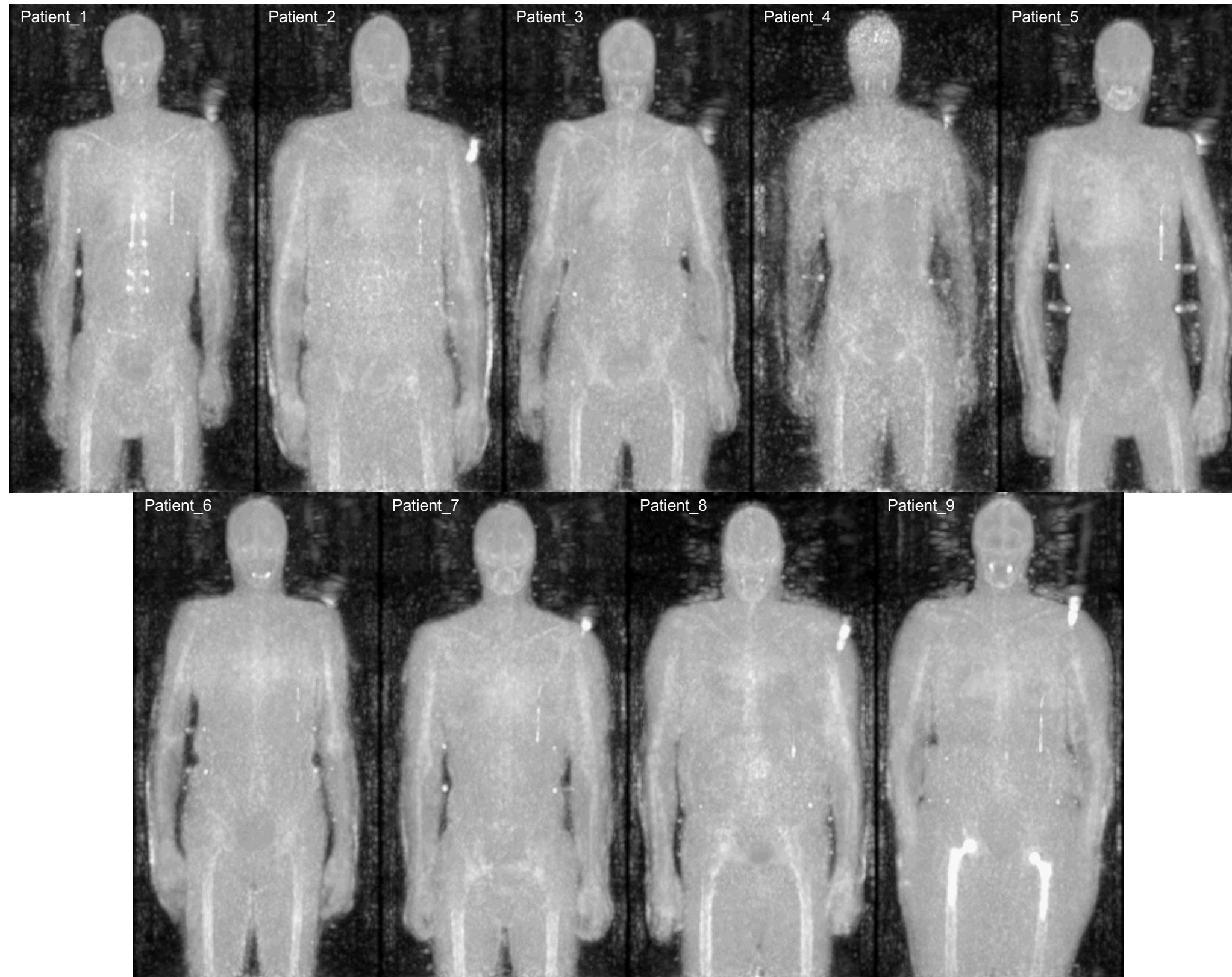


TOF: reconstruct activity and attenuation

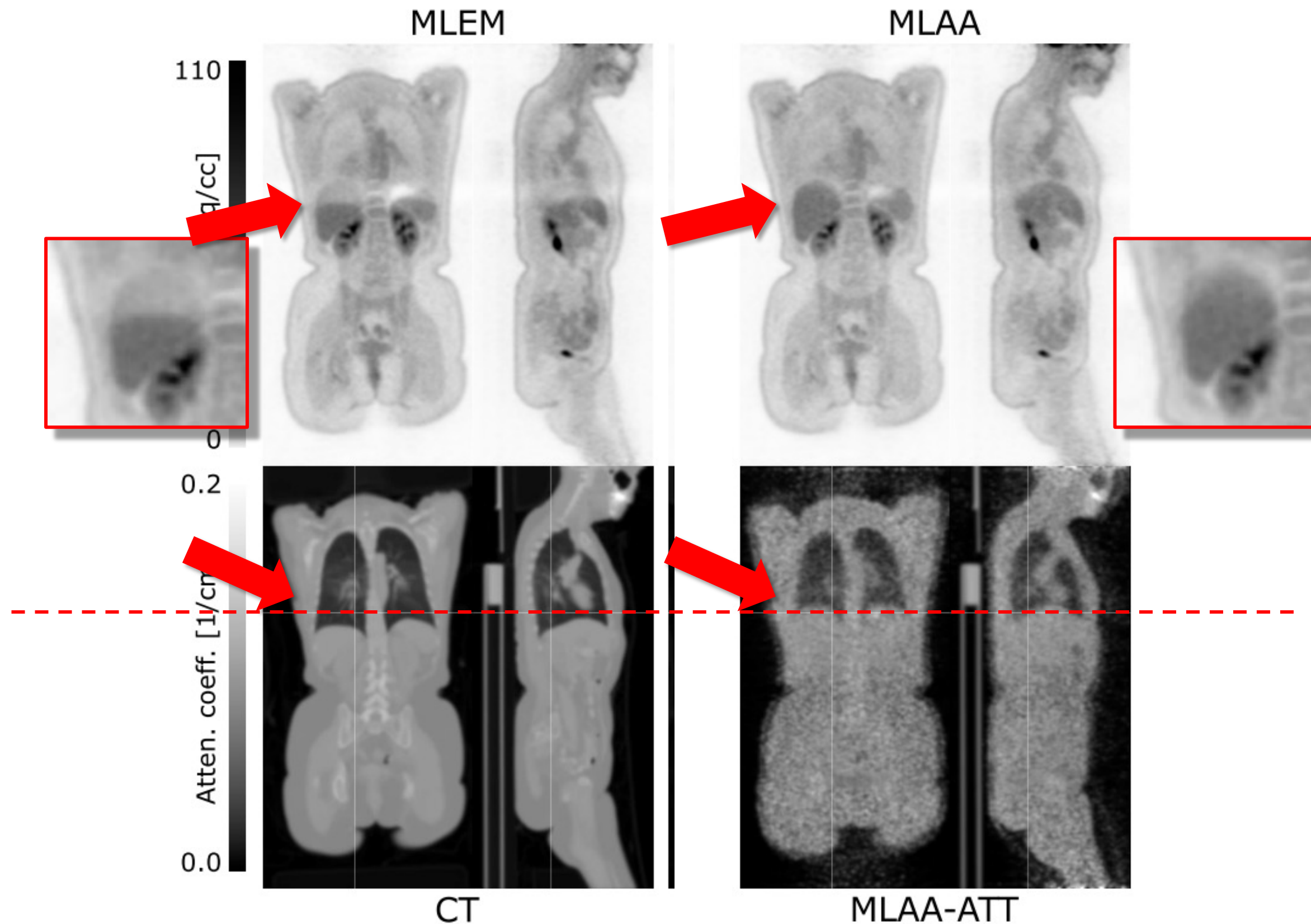
GE Signa PET/MR
TOF: 380 ps



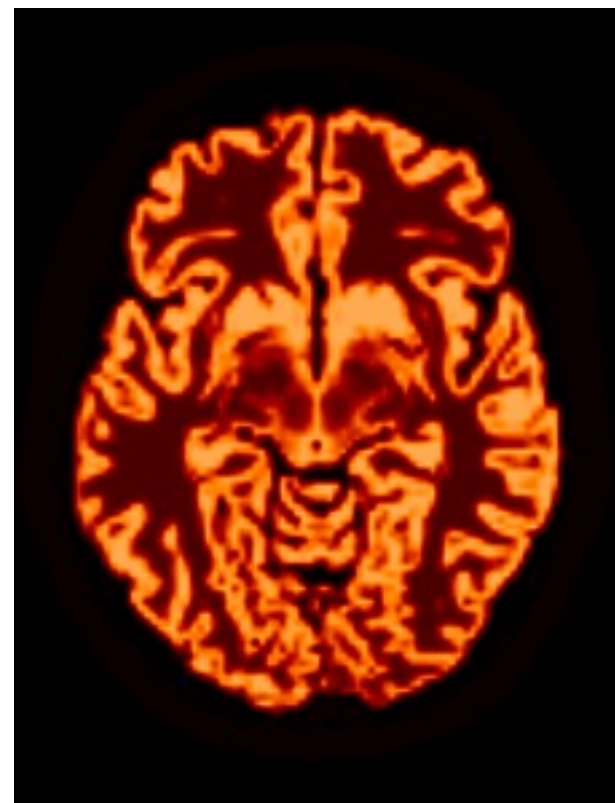
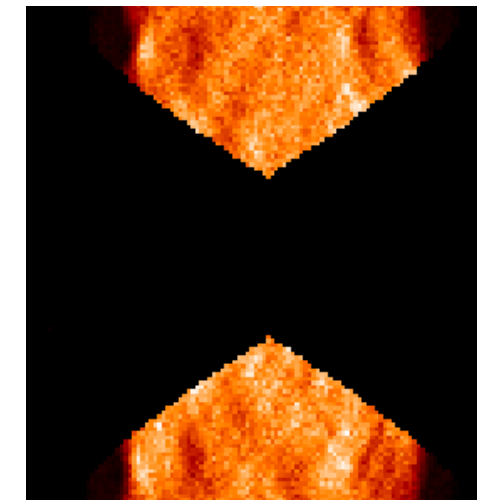
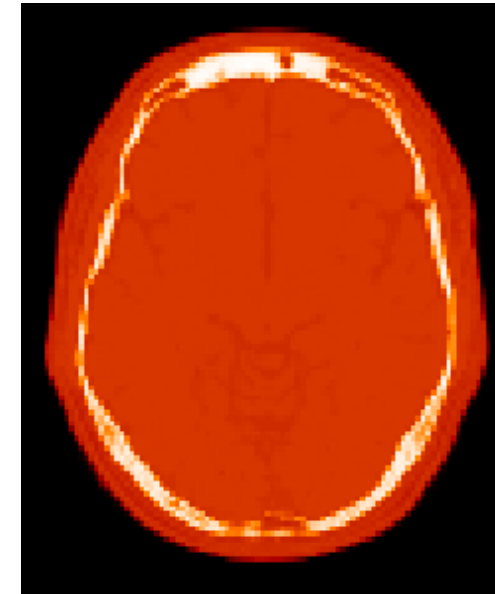
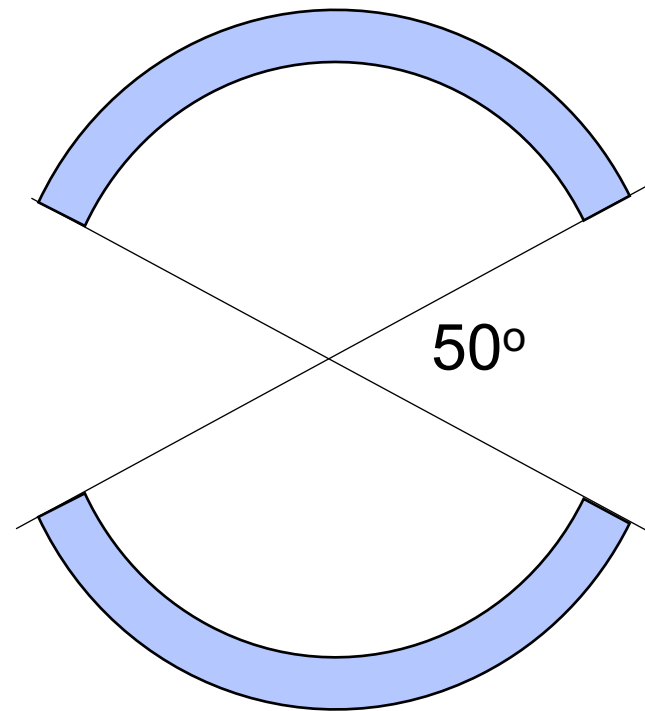
TOF: reconstruct activity and attenuation



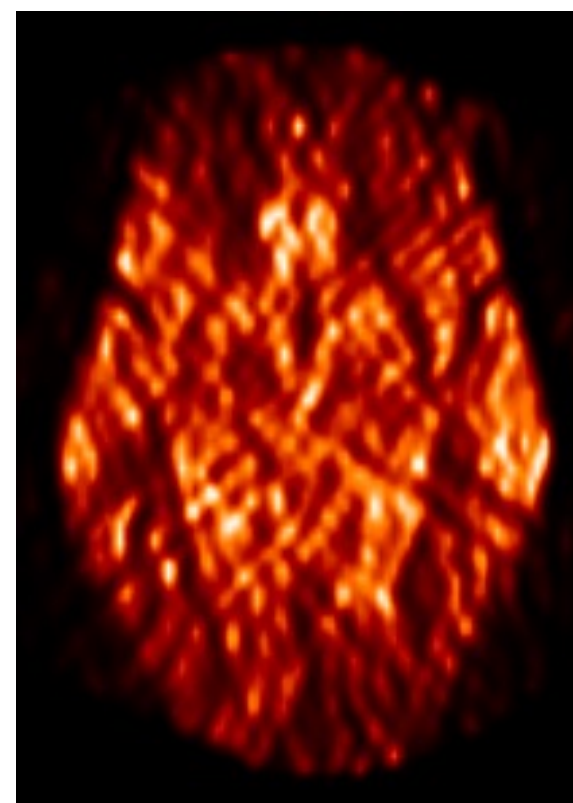
TOF: reconstruct activity and attenuation



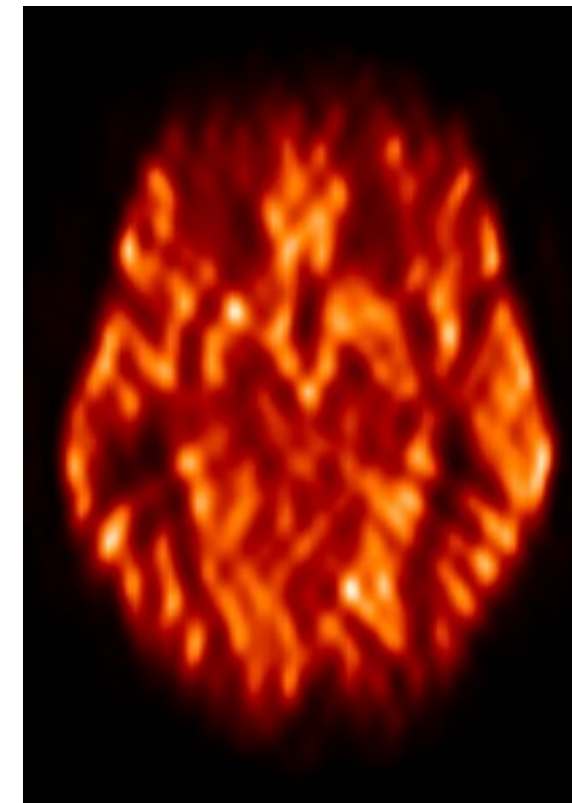
TOF: angular sampling



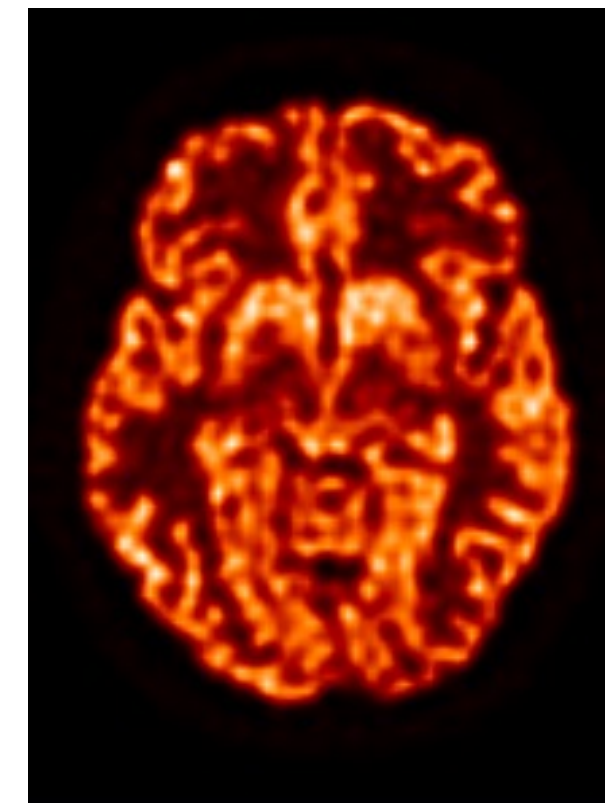
TRUE



non-TOF



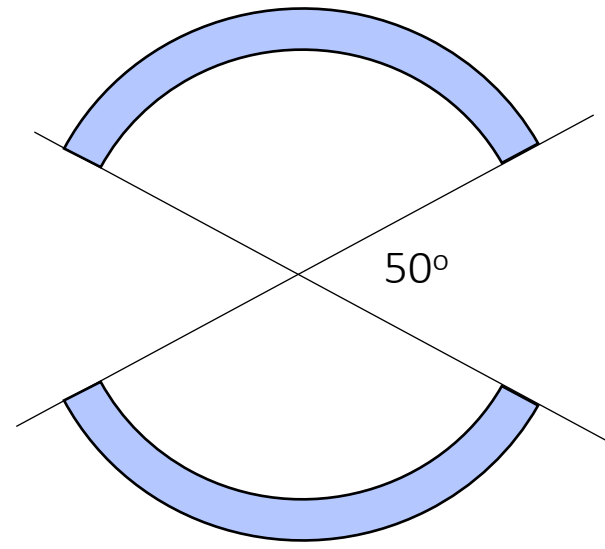
TOF 400 ps



TOF 30 ps

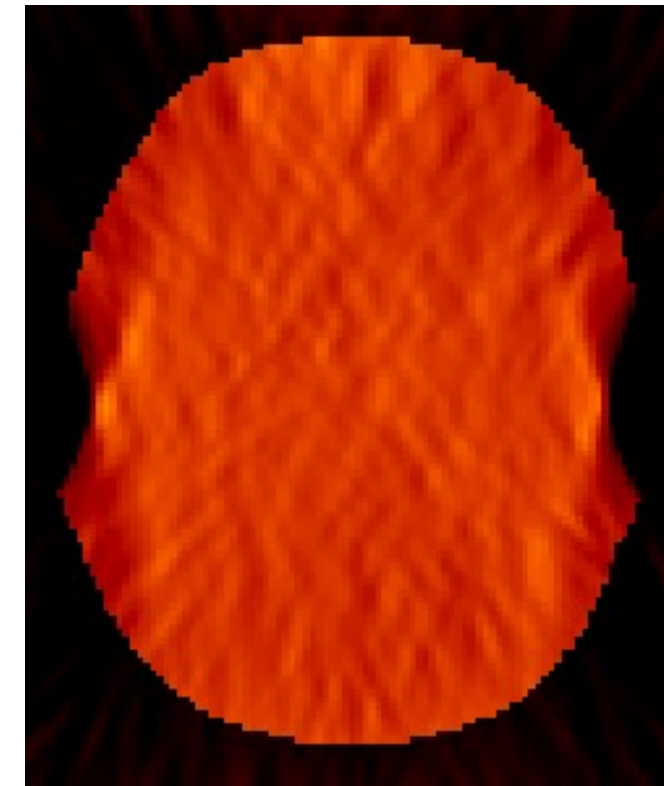
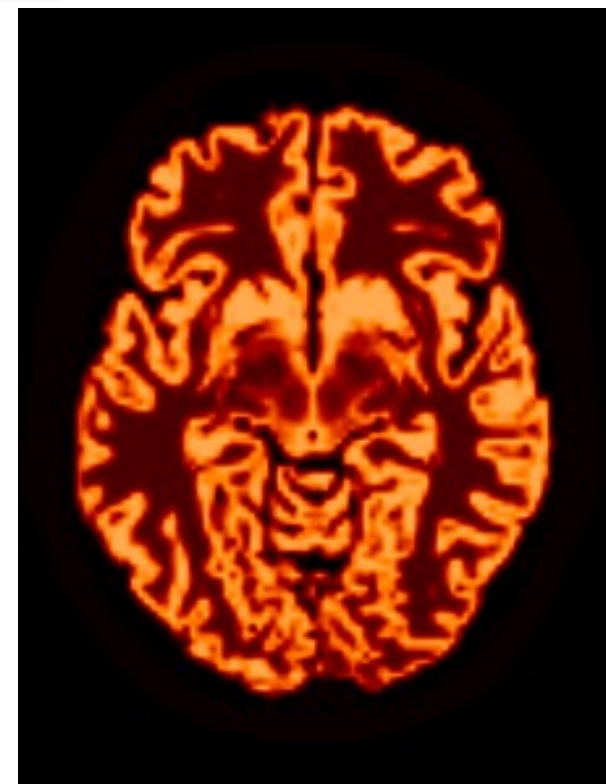
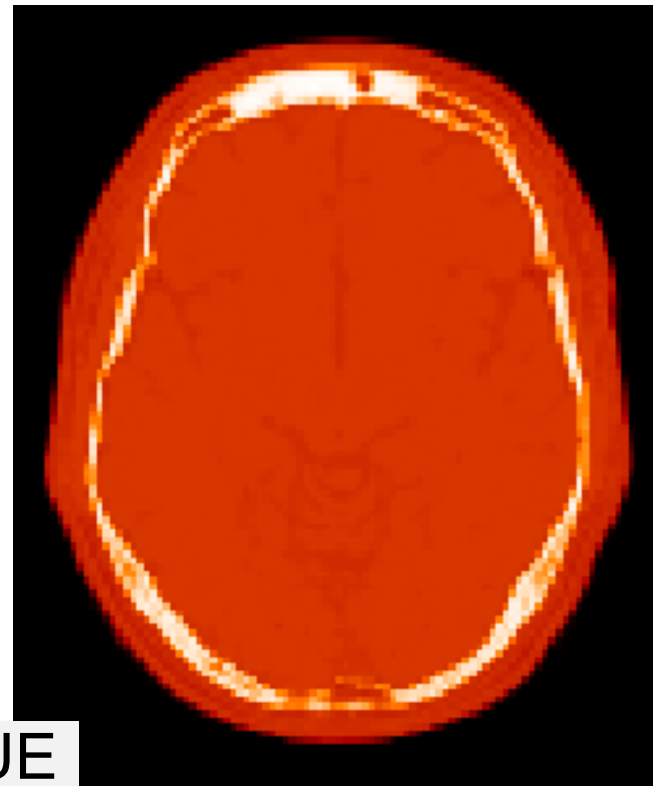


TOF: angular sampling

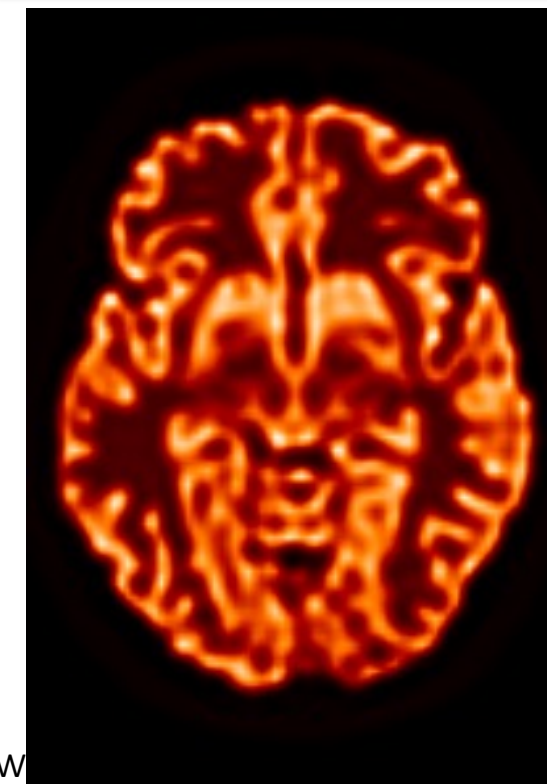


TOF 30 ps

TRUE



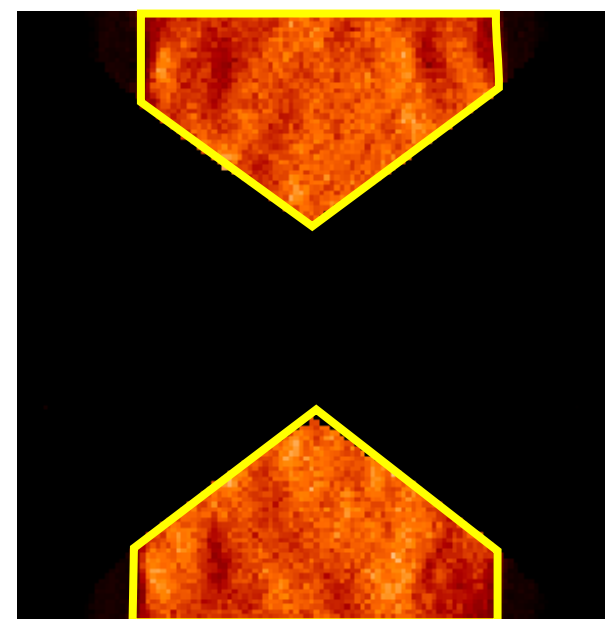
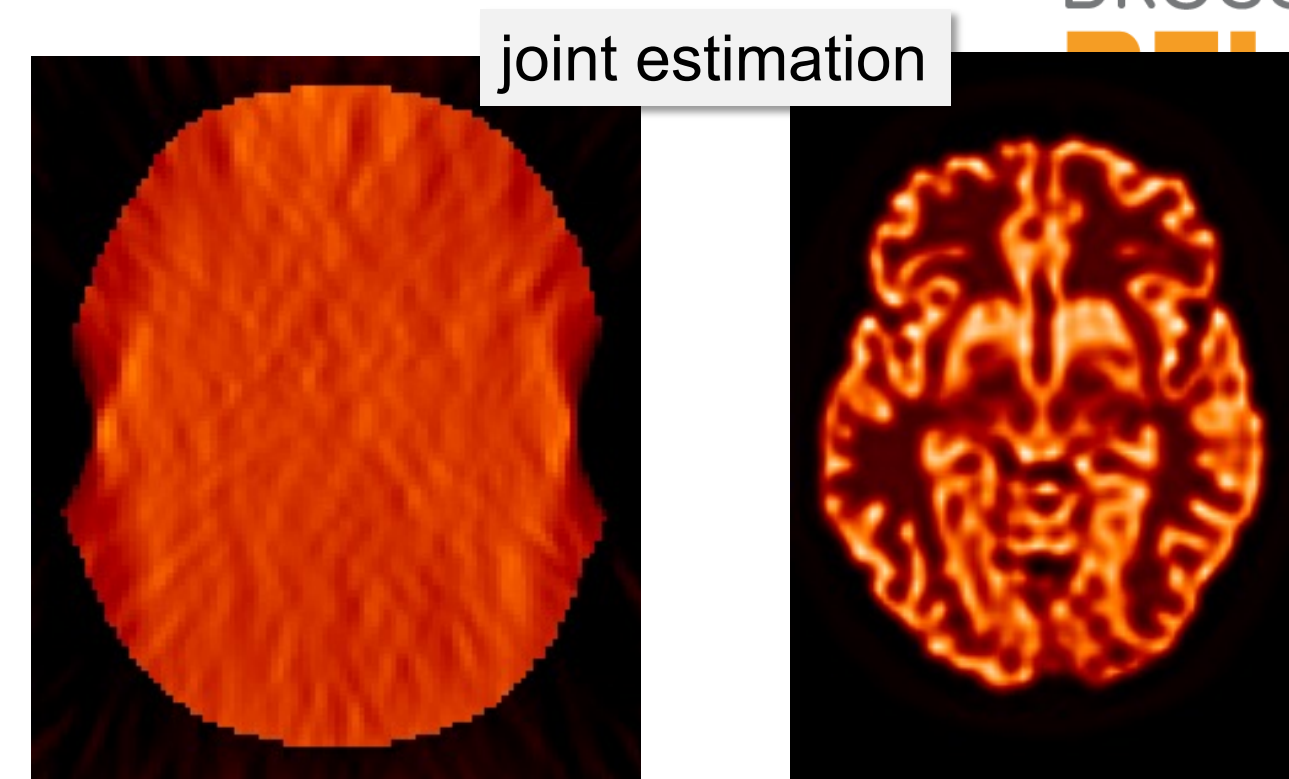
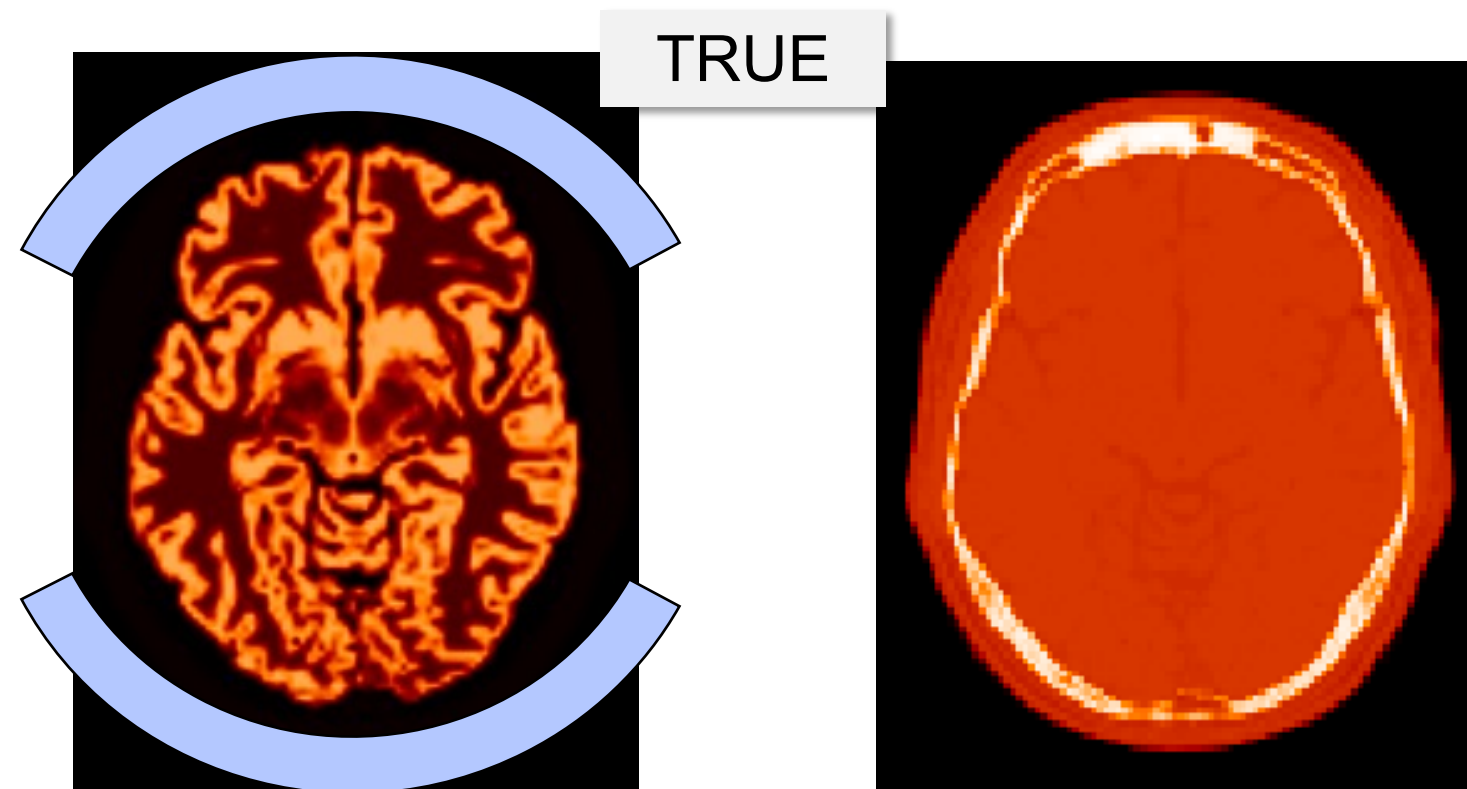
joint estimation
with MLAA



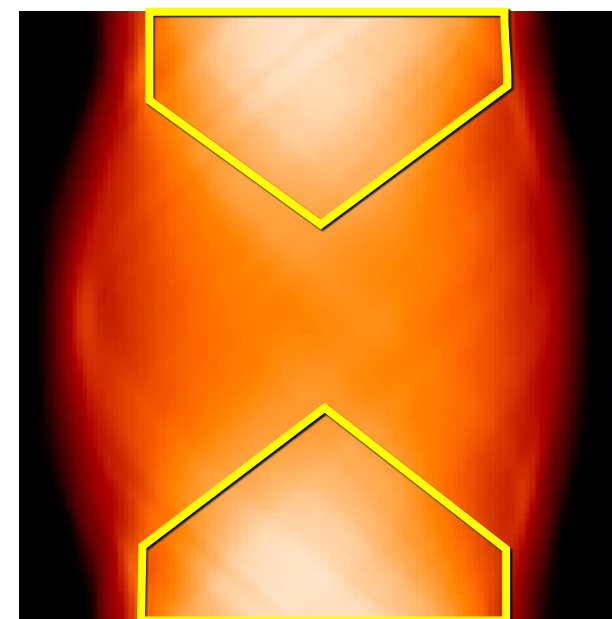
WWW



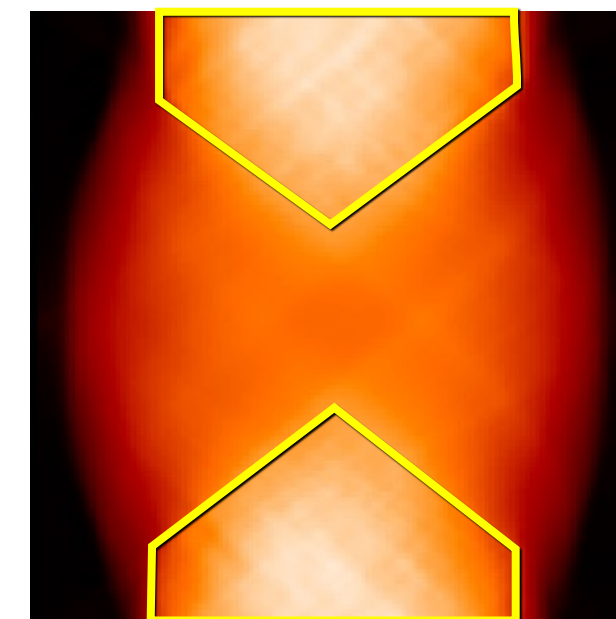
TOF: angular sampling



measured activity
sinogram

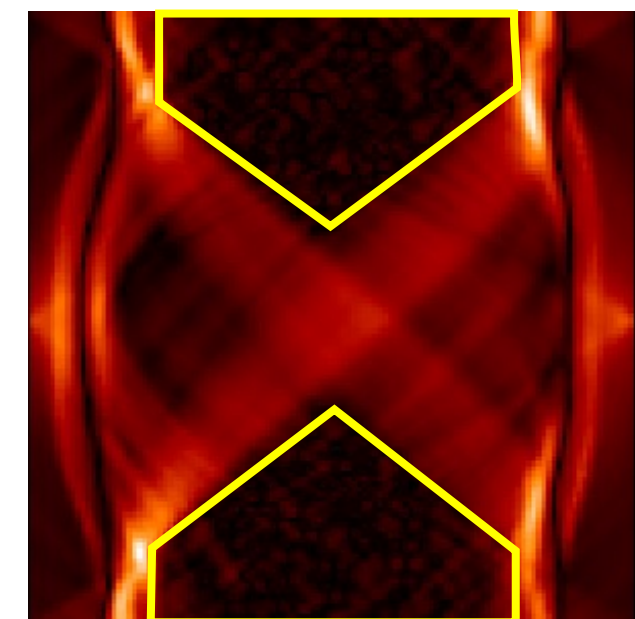


true attenuation



estimated
attenuation

www.belnuc.be



difference true
and estimated
attenuation



overview

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 - 30 ps TOF: no angular sampling needed
- **Resolution:**
 - **motion correction becomes essential!**
- Deep learning
 - great tools
 - we must be critical!



Spatial resolution: motion correction!

Richard Carson et al.,
Yale University

Data-Driven Motion Detection and Event-by-Event Correction for Brain PET: Comparison with Vicra
J Nucl Med 2020; 61:1397–1403

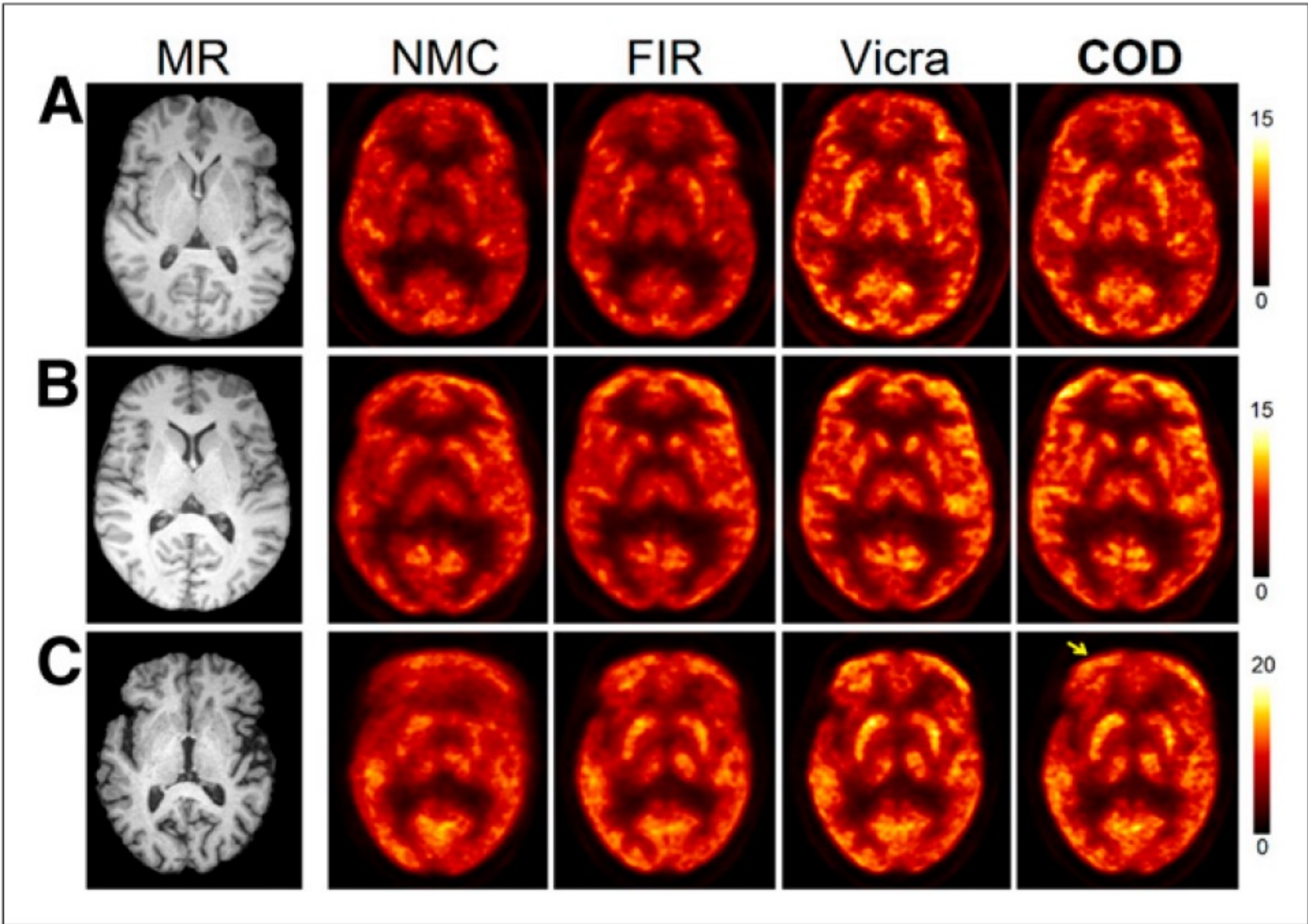
Yihuan Lu¹, Mika Naganawa¹, Takuya Toyonaga¹, Jean-Dominique Gallezot¹, Kathryn Fontaine¹, Silin Ren²,
Enette Mae Revilla¹, Tim Mulnix¹, and Richard E. Carson^{1,2}

¹Department of Radiology and Biomedical Imaging, Yale University, New Haven, Connecticut; and ²Department of Biomedical Engineering, Yale University, New Haven, Connecticut

Polaris Vicra



Passive Markers



Spatial resolution: motion correction!

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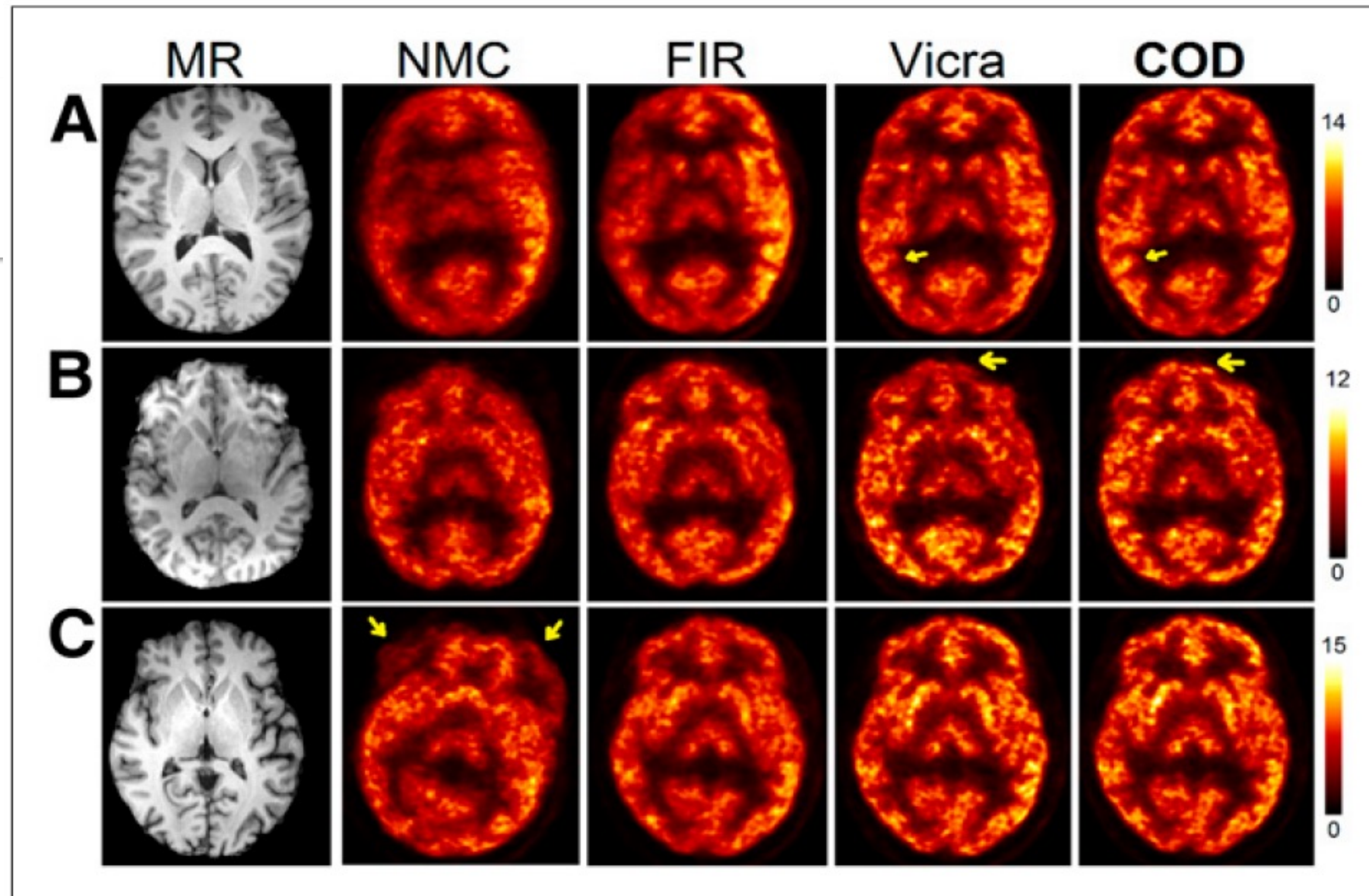
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Polaris Vicra



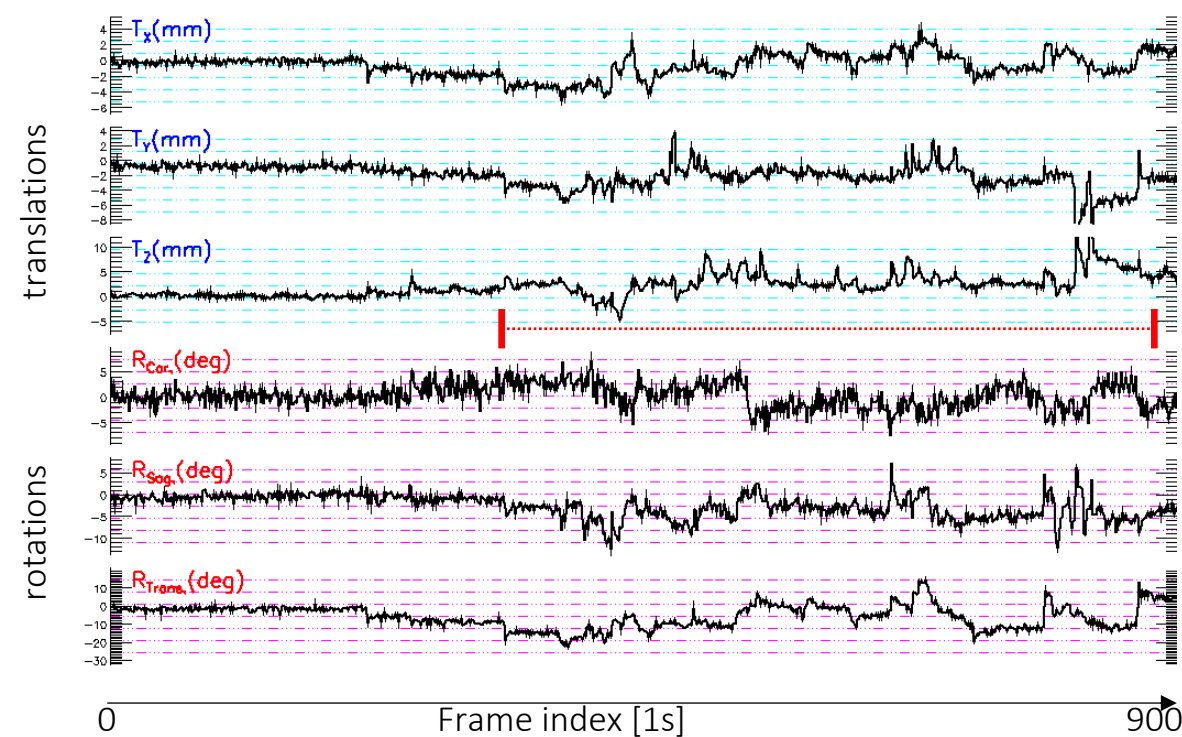
Passive Markers



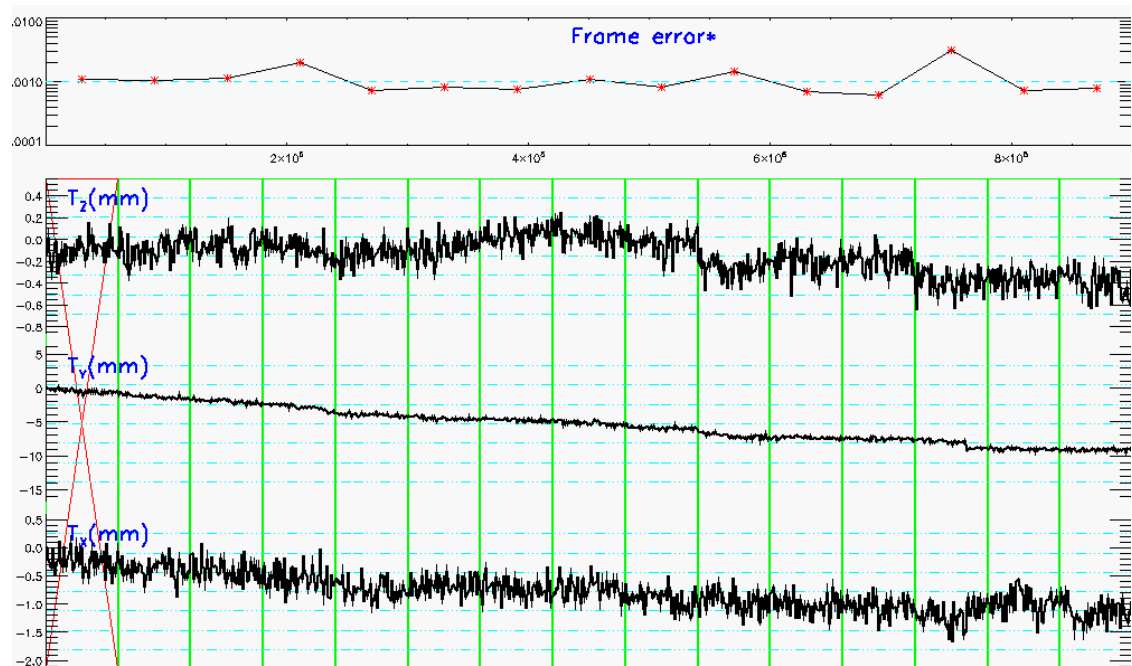
Spatial resolution: motion correction!

patient 1

Motion Estimates

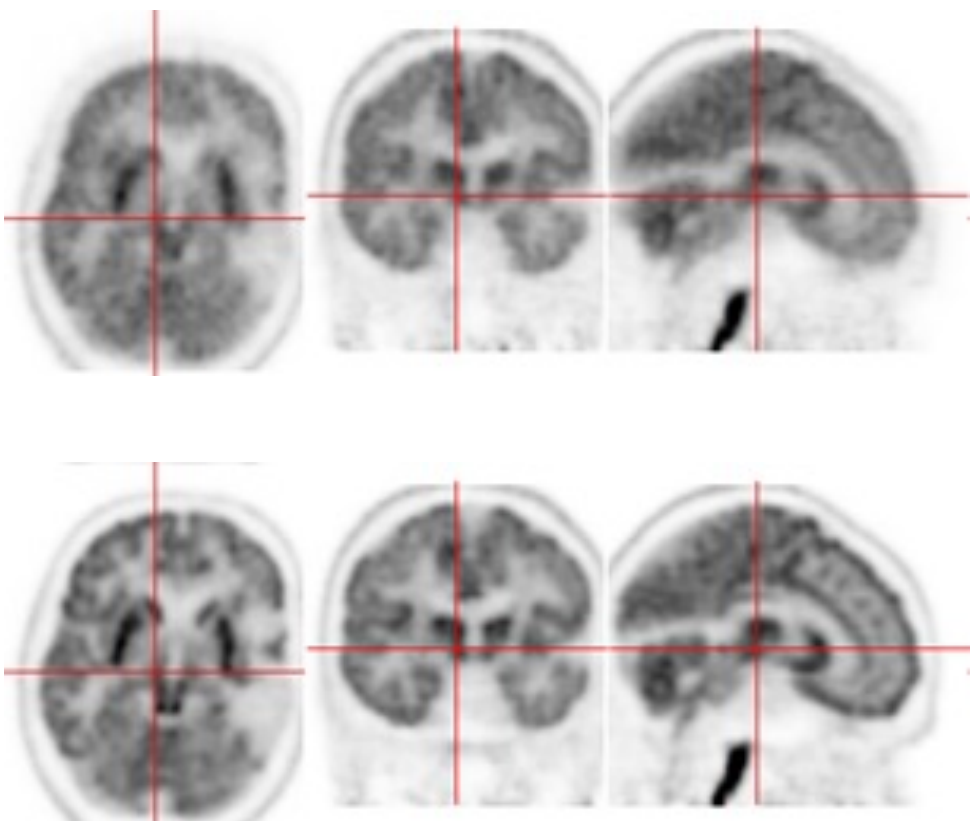


patient 5



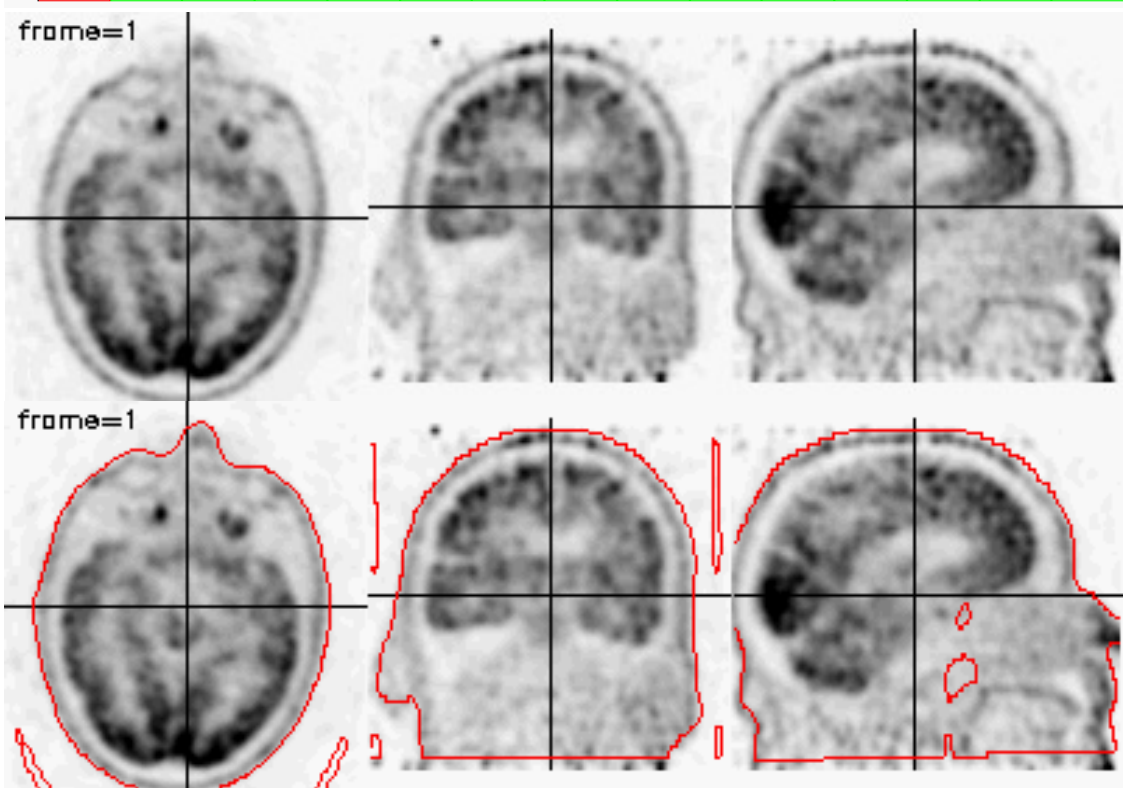
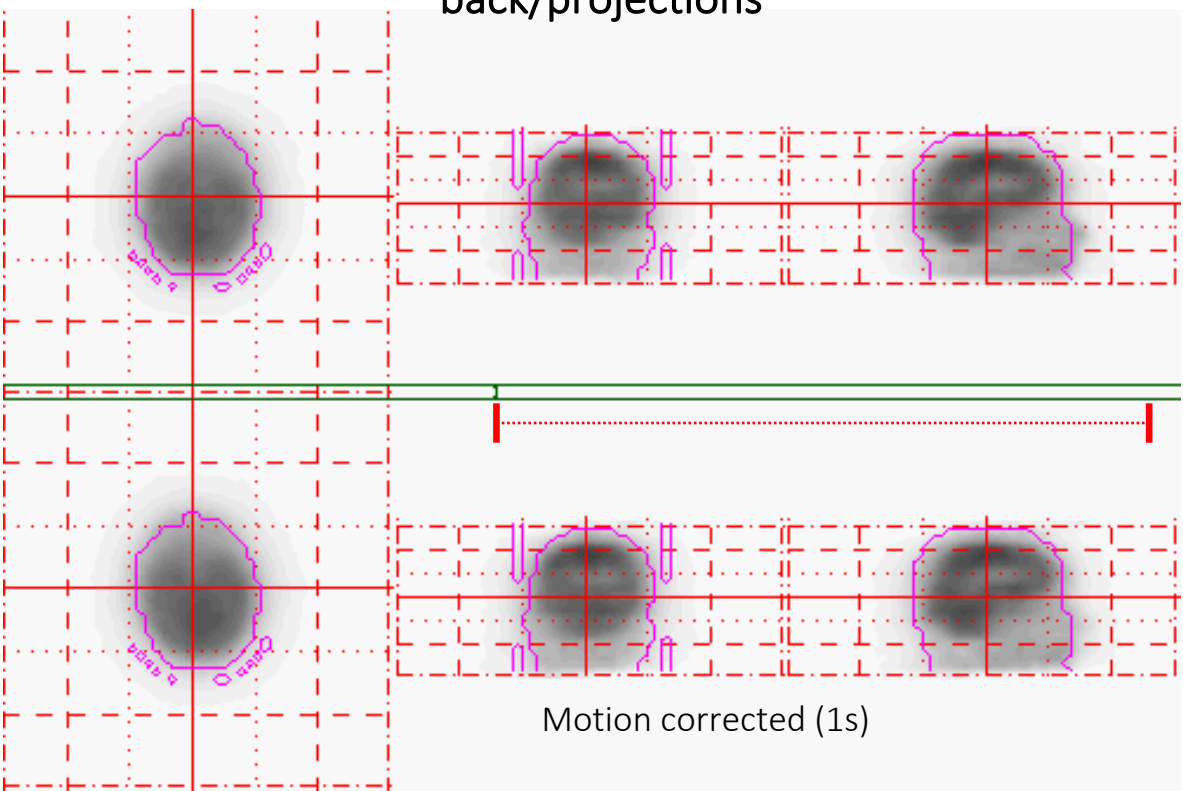
patient 3

No motion correction



Motion corrected

back/projections



Spatial resolution: motion correction!

Data-driven voluntary body motion detection and non-rigid event-by-event correction for static and dynamic PET

Yihuan Lu^{1,4}, Jean-Dominique Gallezot¹, Mika Naganawa¹, Silin Ren¹, Kathryn Fontaine¹, Jing Wu¹, John A Onofrey¹, Takuya Toyonaga¹, Nabil Boutagy², Tim Mulnix¹, Vladimir Y Panin³, Michael E Casey³, Richard E Carson¹ and Chi Liu¹
Phys. Med. Biol. 64 (2019) 065002 (13pp)

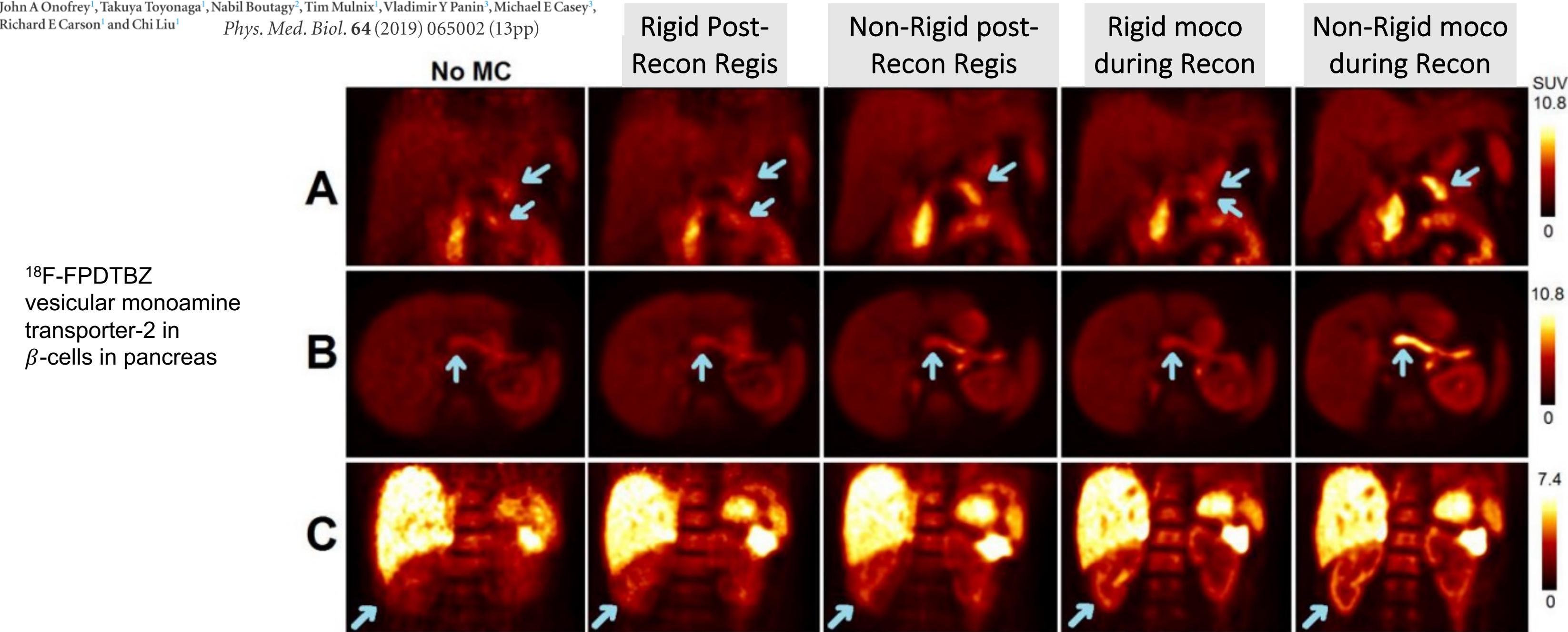


Figure 5. Reconstructions of sample $[^{18}\text{F}]$ FPDTBZ studies (0–120 min). (A) Coronal slices through the pancreas (arrows) of Study 1; (B) transverse slices through the pancreas (arrow) of Study 1; (C) coronal slices through the kidney (arrow) of Study 2.

overview

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Deep learning (just a short comment)

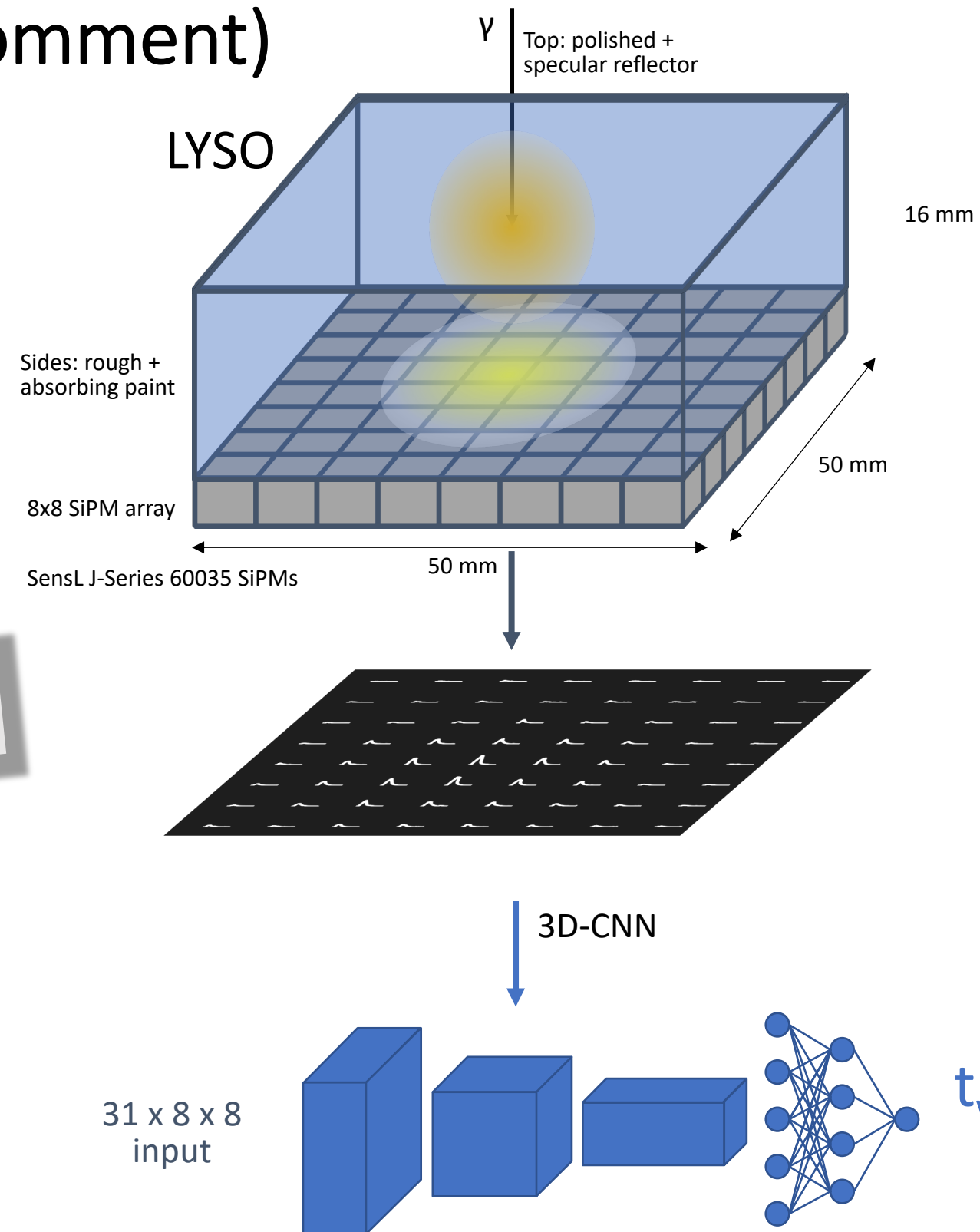
	σ	FWHM	FWTM
averaging	86 ps	177 ps	351 ps
2D-CNN	69 ps	151 ps	286 ps
3D-CNN	63 ps	141 ps	266 ps

Almost perfect training can be achieved,
no surprises during application!

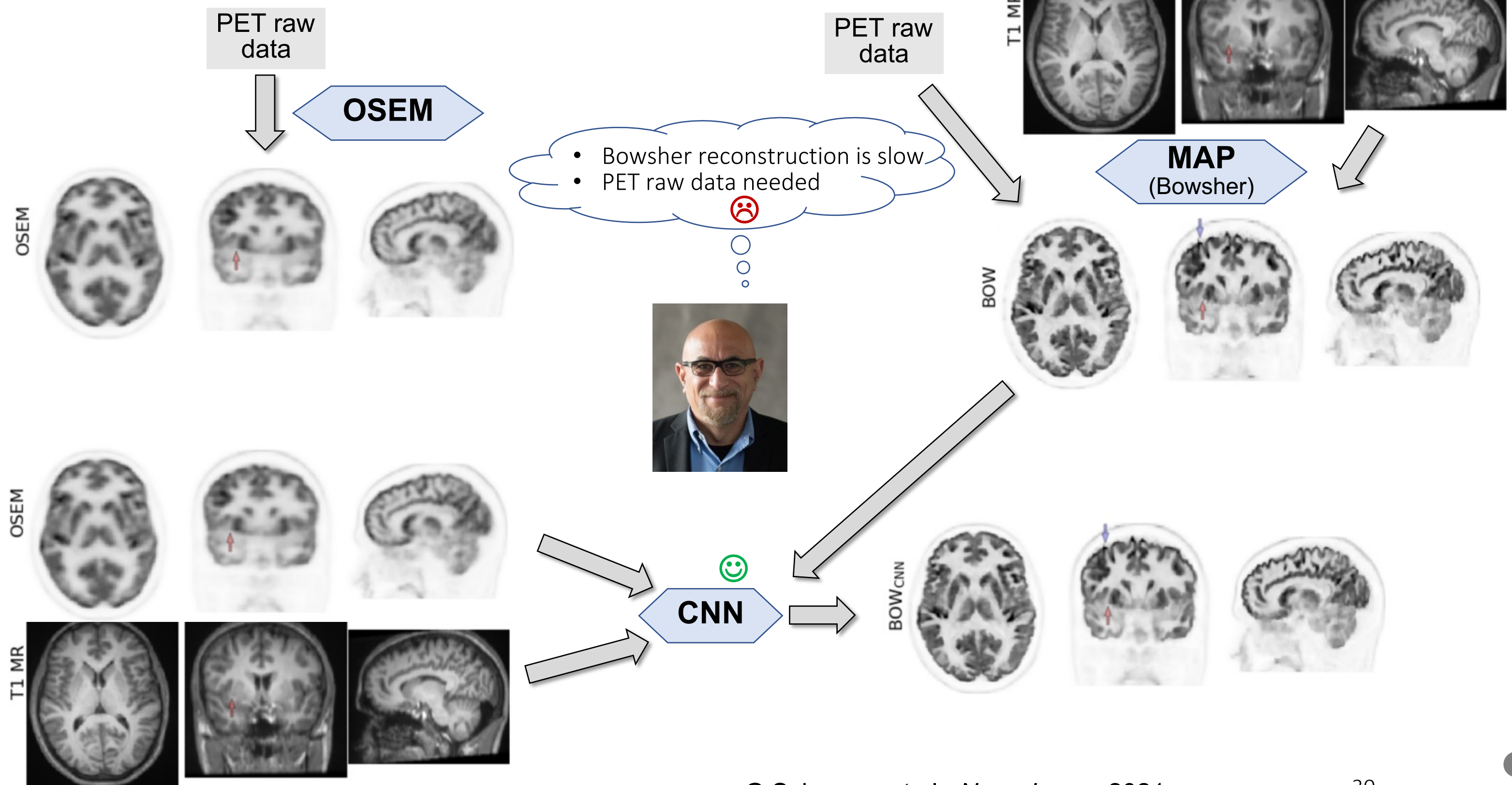
Mariele Stockhoff, Jens Maebe, Florence-Marie Muller, Maya Abi Akl,
Stefaan Vandenberghe, *Ugent*
J Maebe, S Vandenberghe, *Phys Med Biol* 2022

Nicola Belcari, *University of Pisa, Phys Med Biol* 2022

...



Deep learning (just a short comment)



Deep learning (just a short comment)

train CNN with

^{18}F -FDG NYU



good results, low bias, on
NYU ^{18}F -FDG images



bias on KULeuven ^{18}F -FDG
(different scan time after injection)

^{18}F -FDG NYU
+ KULeuven



no such bias on ^{18}F -FDG



still training data are not perfect
surprises during application possible

→ **validation**

^{18}F -FDG +
 ^{18}F -PE2I



no such bias on ^{18}F -PE2I



no such bias on ^{18}F - FET



Conclusion

- Effective sensitivity 

longer scanner (how long?), (much) better TOF, higher spatial resolution

- scan time shorter
- less activity
- less noise

- TOF-PET

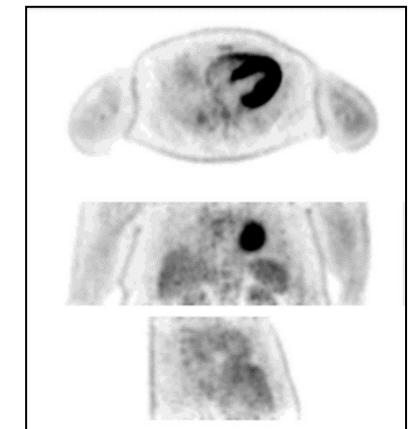
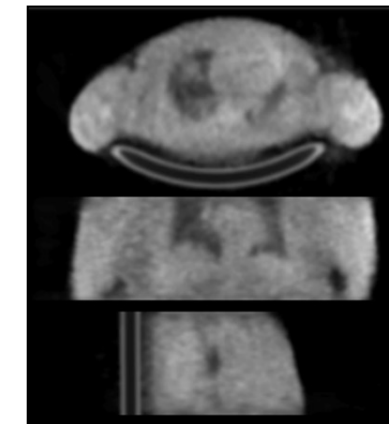
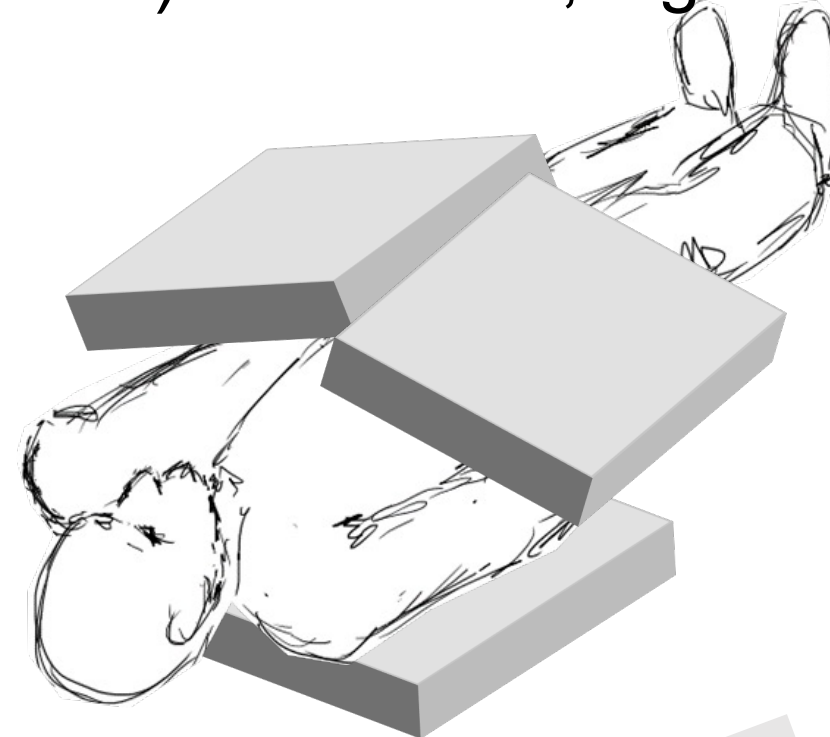
 ≤ 30 ps

- Spatial resolution

- improving continuously
- motion correction!

- Deep Learning 

- very powerful
- validation!

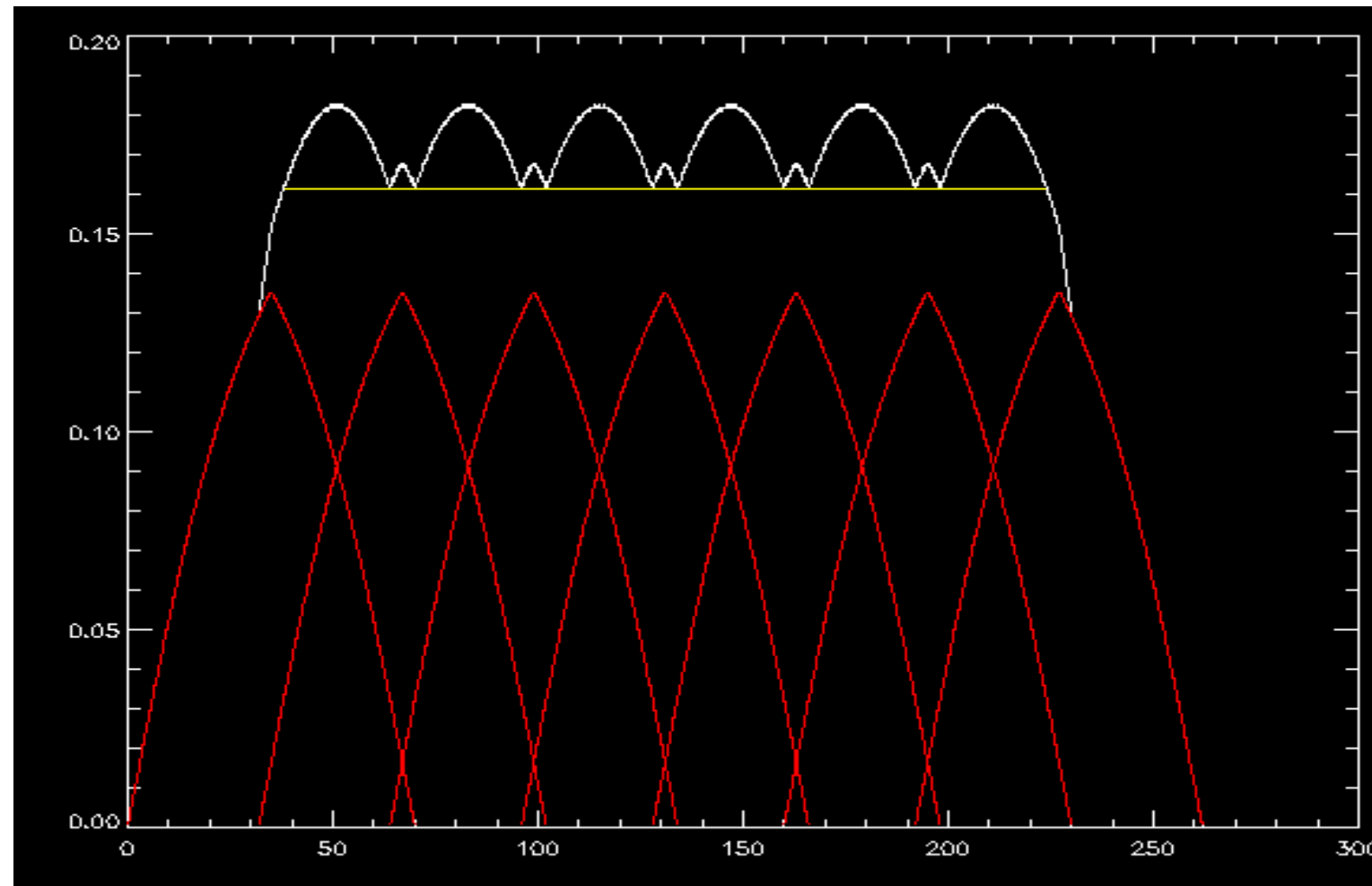
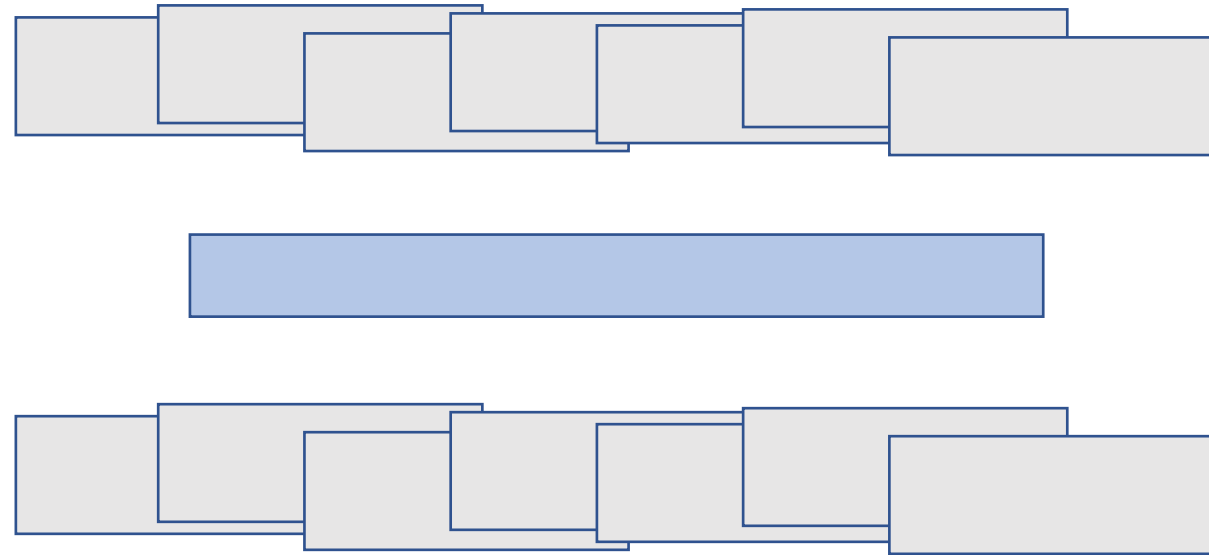


thanks

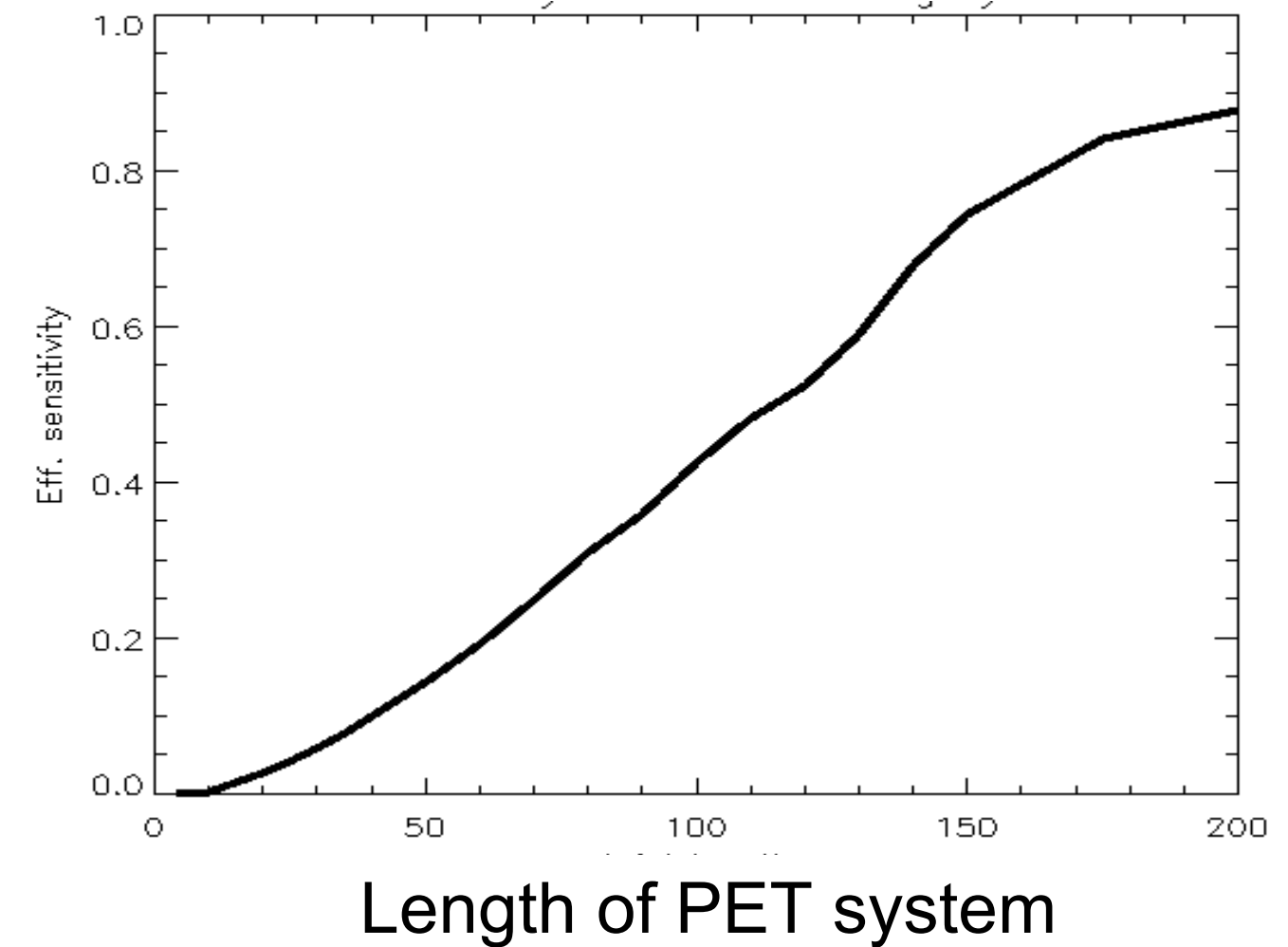




Effective sensitivity: solid angle



Minimum sensitivity achieved
with multi-bed WB scan



Cylinder

- 185 cm long
- 25 cm diameter
- attenuation 2/3 of water

