

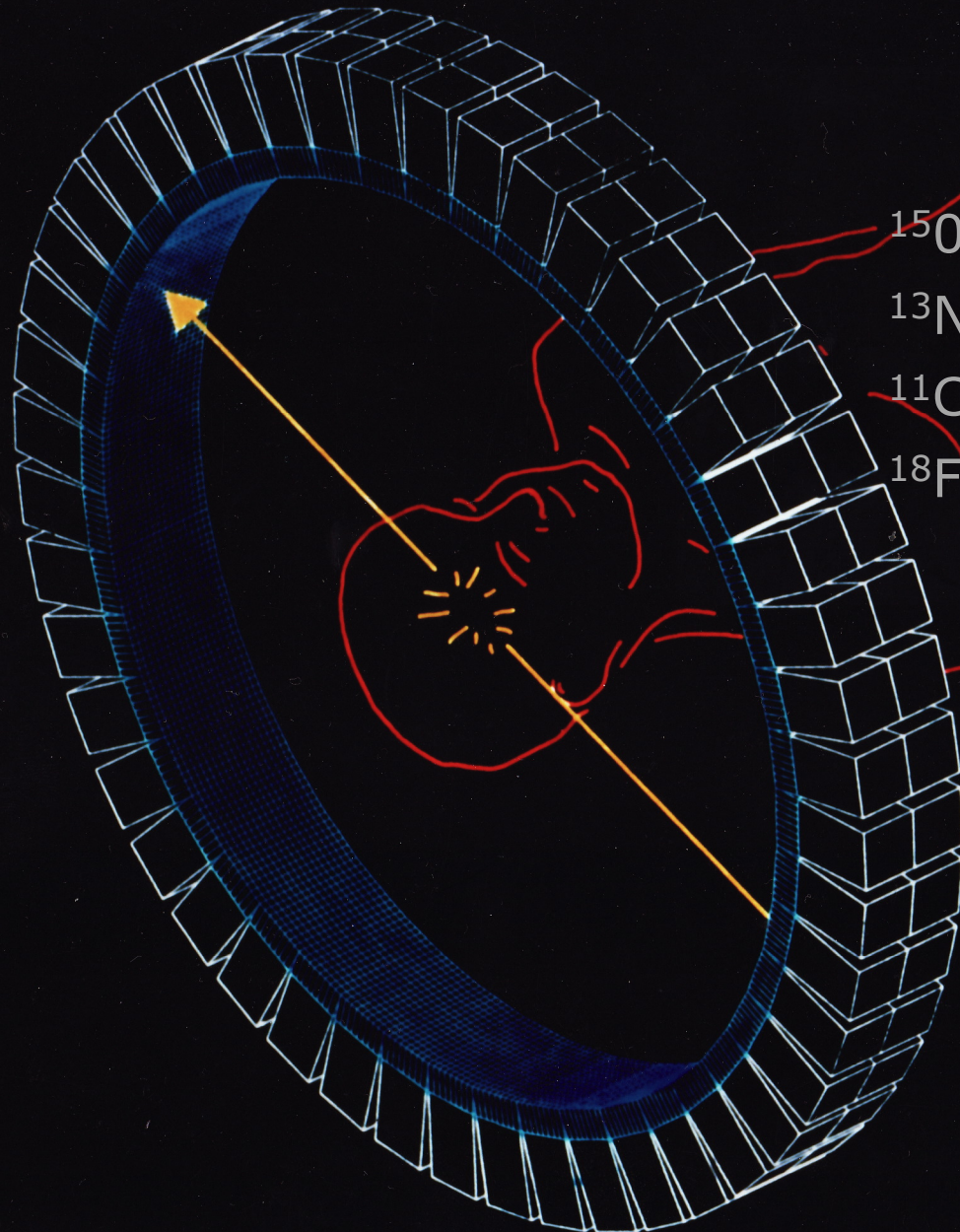
Journées Thématiques du Réseau Semi-conducteurs IN2P3-IRFU



Le défi 10 ps

Christian Morel



Tomographie par émission de positons (TEP)



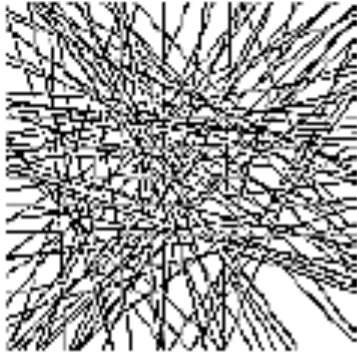
^{15}O (2 min)		511 keV
^{13}N (10 min)		511 keV
^{11}C (20 min)		511 keV
^{18}F (110 min)		511 keV

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

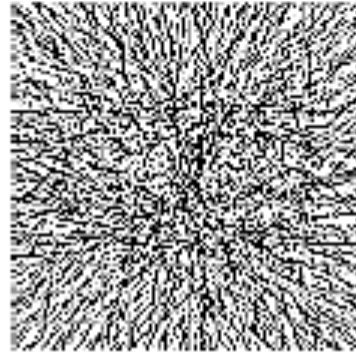
M.R.C. Cyclotron Unit.
Hammersmith Hospital.
London.



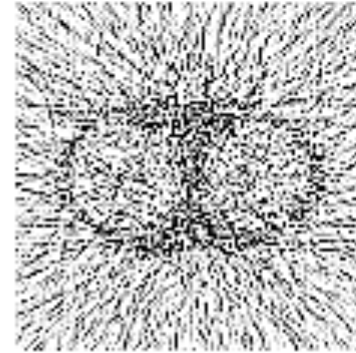
Reconstruction tomographique et statistique de comptage



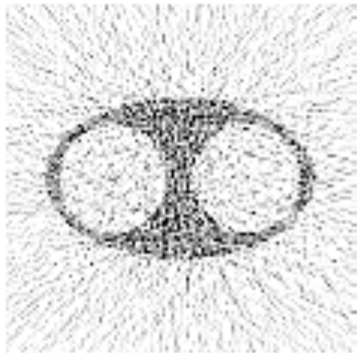
10^2



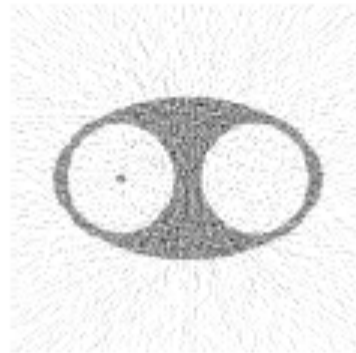
10^3



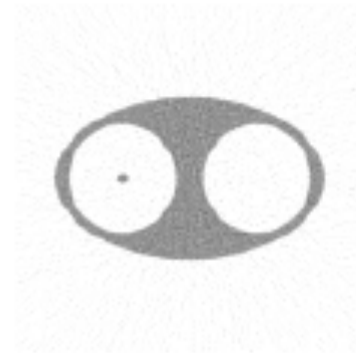
10^4



10^5



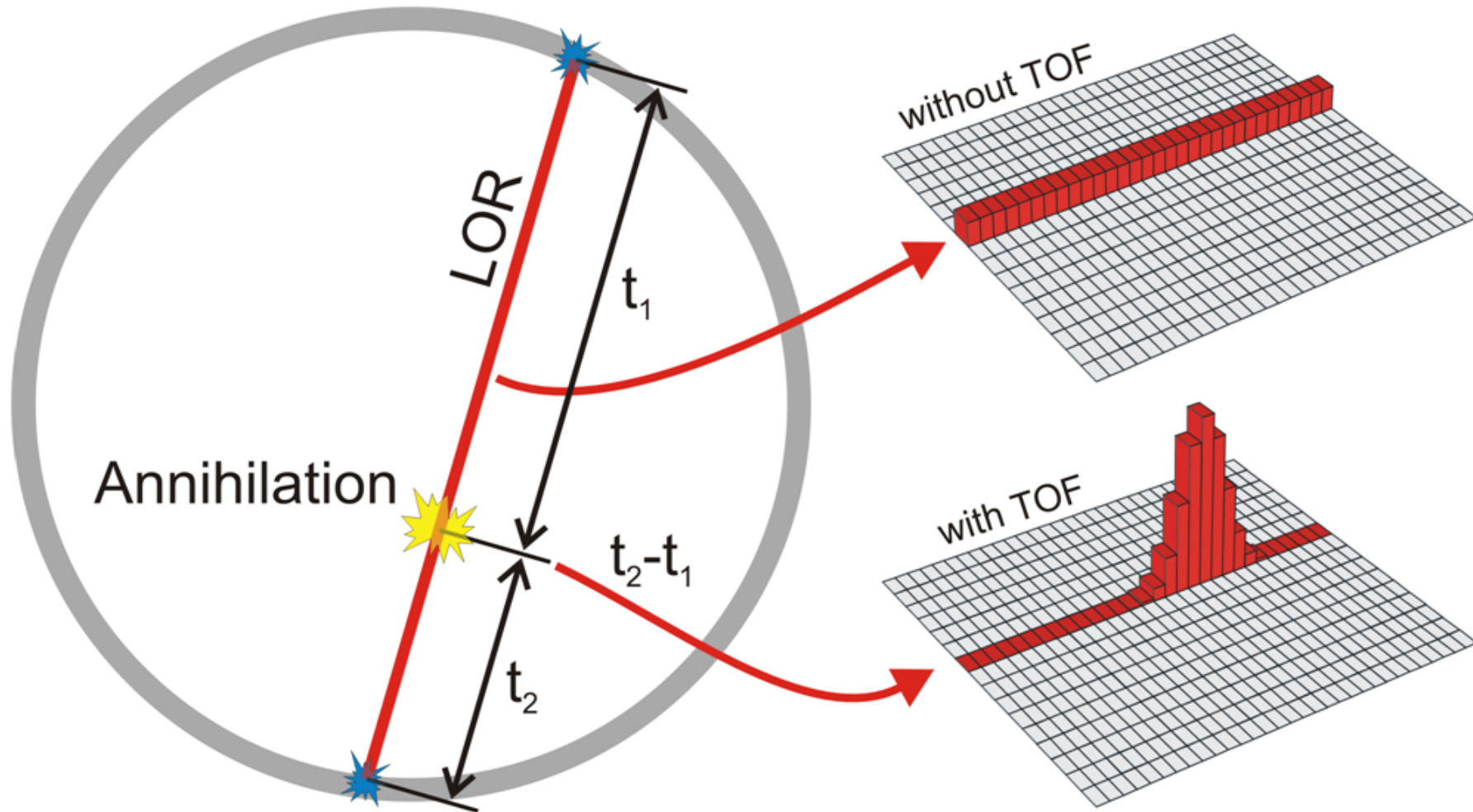
10^6



10^7

Courtesy: C. Comtat, CEA-SHFJ

Mesure du temps-de-vol (TOF) des photons d'annihilation



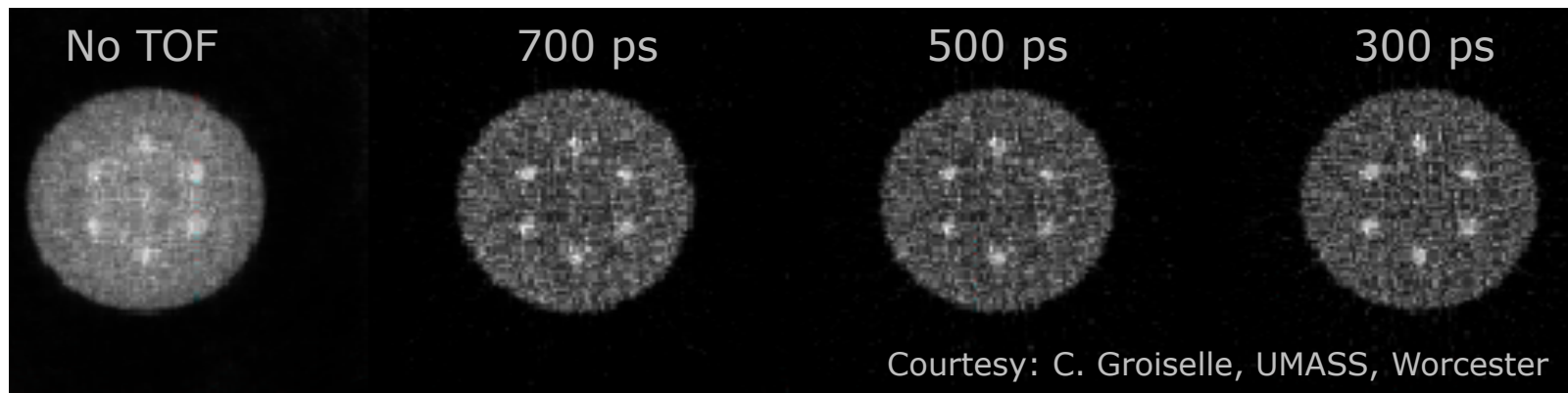
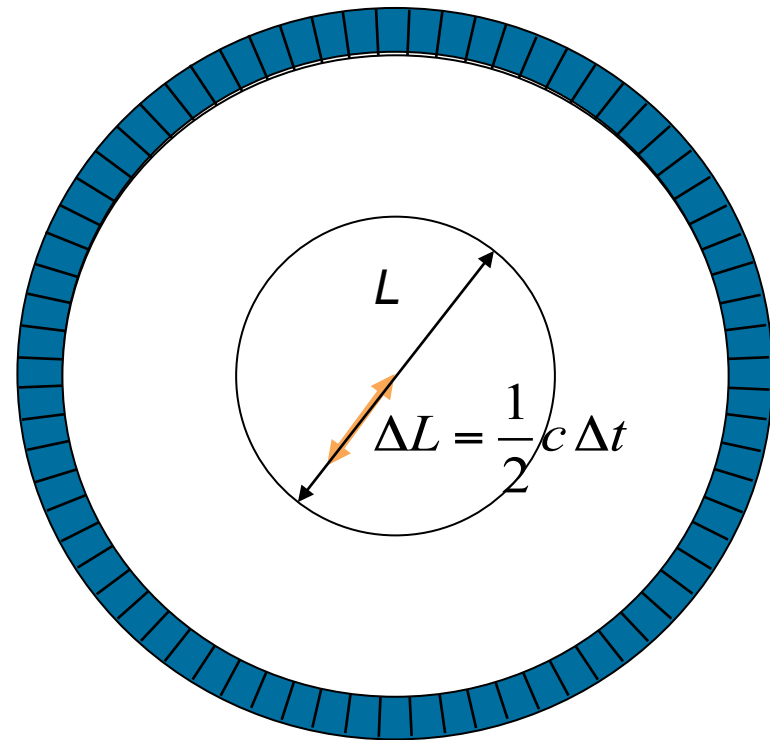
TOF-TEP et amélioration du rapport signal/bruit

$$N_{Tot} = \left(\frac{L}{d}\right)^3 \times \left(\frac{A}{\Delta A}\right)^2 \times \left(\frac{L}{d}\right)$$

$$N_{ToF} = \left(\frac{L}{d}\right)^3 \times \left(\frac{A}{\Delta A}\right)^2 \times \left(\frac{\Delta L}{d}\right)$$

Facteur de
réduction de
variance

$$f = \frac{L}{\Delta L} = \frac{2L}{c\Delta t}$$



Courtesy: C. Groiselle, UMASS, Worcester

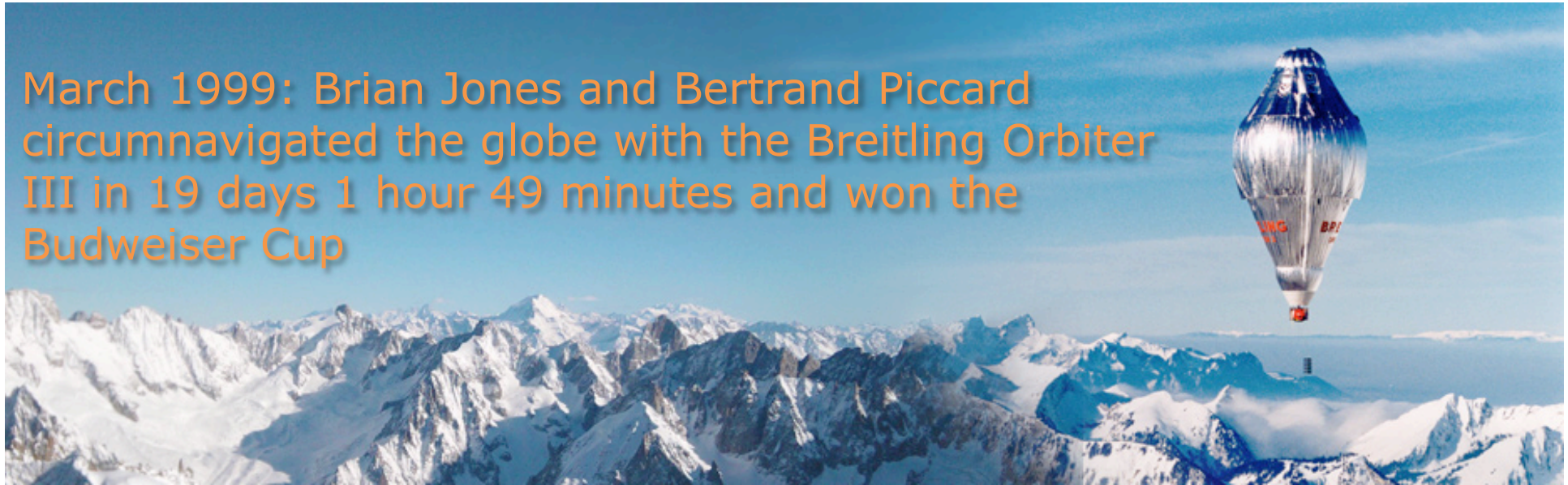
Why 10 ps TOF-PET?

- 14-fold improvement in SNR
- 20-fold dose reduction at equivalent SNR
 - ✧ Equivalent potential in dose reduction (0.5 mSv/scan)
 - ✧ Annual natural background: 2.4 mSv
 - ✧ Return flight Paris SFO: 0.11 mSv
 - Allows longer longitudinal studies
 - Reduces the cost of radiotracer production infrastructures
- Opens PET to new categories of patients (children, foetus)



1992: FAI raised a challenge for the first balloon circumnavigation of the globe

March 1999: Brian Jones and Bertrand Piccard circumnavigated the globe with the Breitling Orbiter III in 19 days 1 hour 49 minutes and won the Budweiser Cup



This was a clear-cut case to shed light on TOF-PET with $CTR < 10$ ps FWHM and raise a challenge on reconstruction-less positron tomography

Nuclear and CT imaging:
what drives it ?

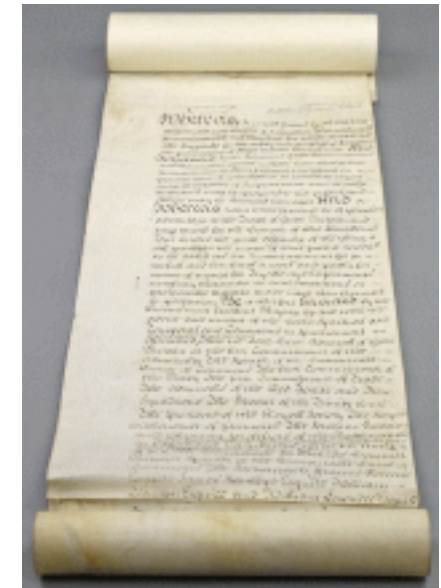


1714 : Longitude Act

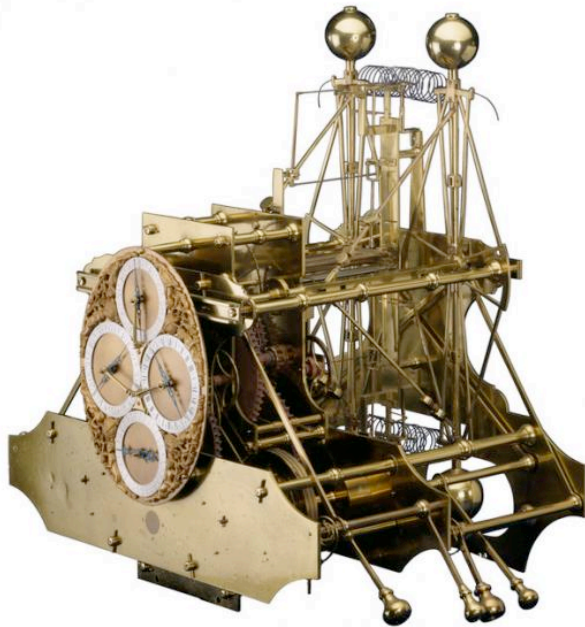
Le **Longitude Act** a été édicté par le parlement du Royaume Uni en juillet 1714 suite au naufrage du HMS Association, qui revenait du siège de Toulon, sur les récifs de Gilstone Ledges la nuit du 22 octobre 1707, causant la mort de mille quatre cents à plus de deux mille hommes.



Le Longitude Act fonde le **Bureau des longitudes** et offre un prix pour quiconque trouvera une méthode simple et pratique pour déterminer précisément la longitude d'un bateau.



John Harrison's H1 Marine Chronometer



Longitude rewards:

- ✓ £10,000 <math>< 1^\circ</math>
(= 110 km à l'équateur)
- ✓ £15,000 <math>< 40'</math>
- ✓ £20,000 <math>< 0,5^\circ</math>

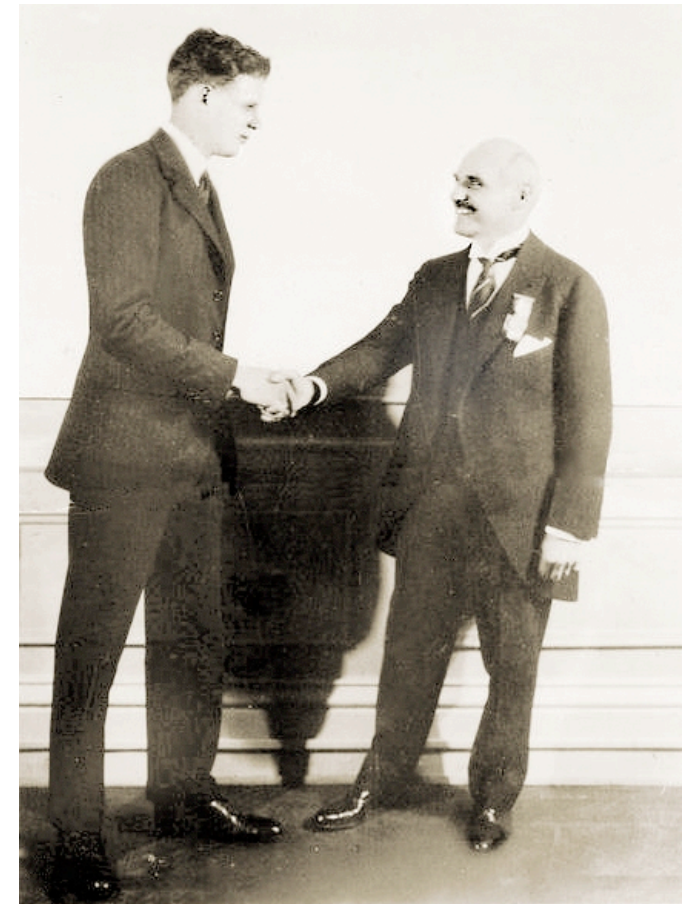
John Harrison a reçu £10,000 en 1765 (~1.33 million £ en 2016) pour le **développement du chronomètre de marine**

1919 : Raymond Orteig offrait un prix de 25,000 \$ au premier aviateur qui réaliserait un vol New York-Paris sans escale

L'offre du Prix Orteig était initialement valable pour une durée de 5 ans, puis fut renouvelée pour 5 ans supplémentaires en 1924



Mai 1927 : Charles Lindbergh effectuait le premier vol New York-Paris à bord du Spirit of Saint-Louis en 33 h et 30 minutes



XPRIZE is an innovation engine
 A facilitator of exponential change
 A catalyst for the benefit of humanity

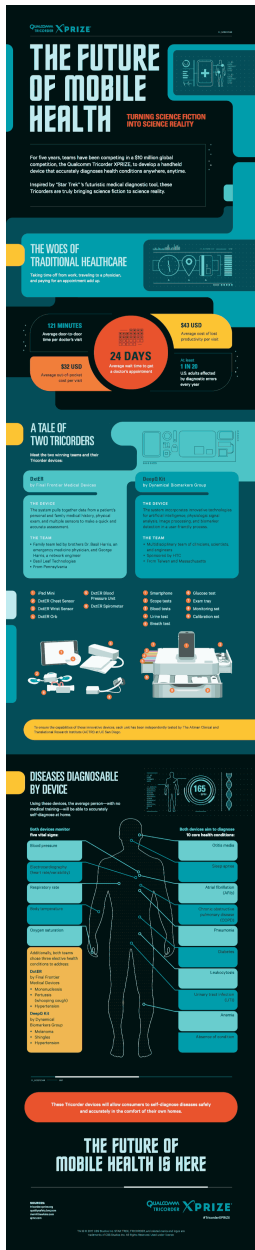


Fondation basée en Californie distribuant des prix de plusieurs millions de dollars pour des défis lancés dans les domaines de l'énergie & environnement, des sciences de la vie, de l'exploration et du développement

Son slogan est *rendre l'impossible possible*

Elon Musk, James Cameron, Larry Page, Arianna Huffington, Ratan Tata sont membres de son Conseil de d'administration

2012 : Qualcomm Tricorder XPrize 10 M\$



Horizon Prize



La Commission européenne a lancé une série de prix avec des récompenses entre 1 et 4 M€.

Ce sont des prix incitatifs qui offrent une récompense aux meilleures réponses à un défi défini, la solution proposée devant être novatrice, sécurisée et redimensionnable à l'échelle de l'Europe.

L'objectif est de stimuler l'innovation et de trouver des solutions aux problèmes qui importent aux citoyens européens.

Ces concours sont ouverts à toute sorte d'entité légale, y compris des personnes. Les propositions seront évaluées par des experts indépendants.

Two promotional banners for Horizon Prize challenges. The left banner is green and features a large green circle with the text "Horizon Prize" and "BIG DATA TECHNOLOGIES". Below the circle, it says "Crack the challenge and win", "€ 2 million", "Contest is open", "#horizonprize", and "ec.europa.eu/research/horizonprize/bigdata/". The right banner is dark blue and features a large purple circle with the text "Horizon Prize" and "BREAKING THE OPTICAL TRANSMISSION BARRIERS". Below the circle, it says "PHOTONMAP", "cracked the optical transmission challenge and won the prize", and "Team led by Technical University of Denmark". Both banners include the European Commission logo at the bottom right.

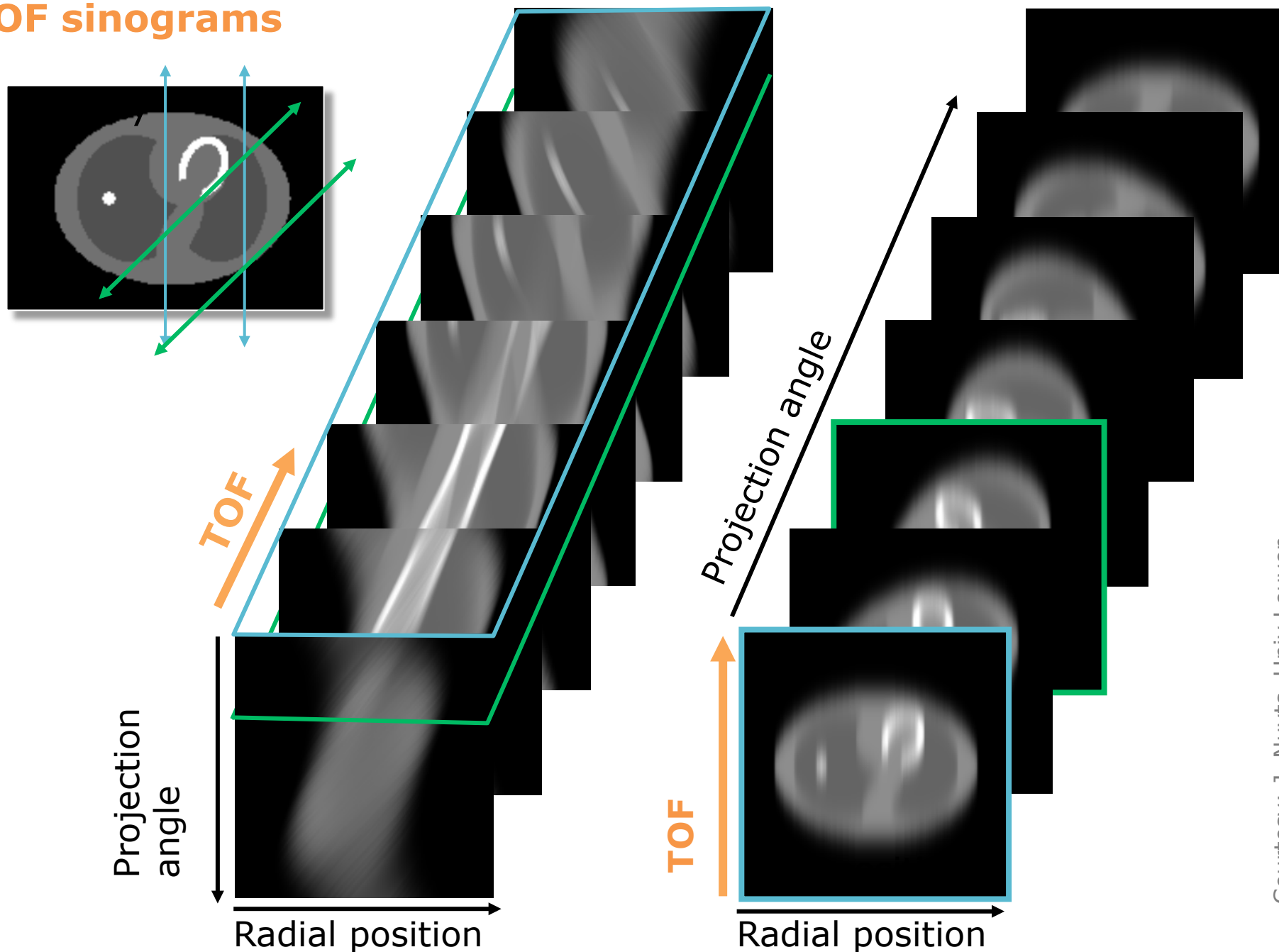
<http://ec.europa.eu/research/horizonprize>



11-12 Jun 2018: The French GDR MI2B organized a 10 ps challenge workshop in Paris

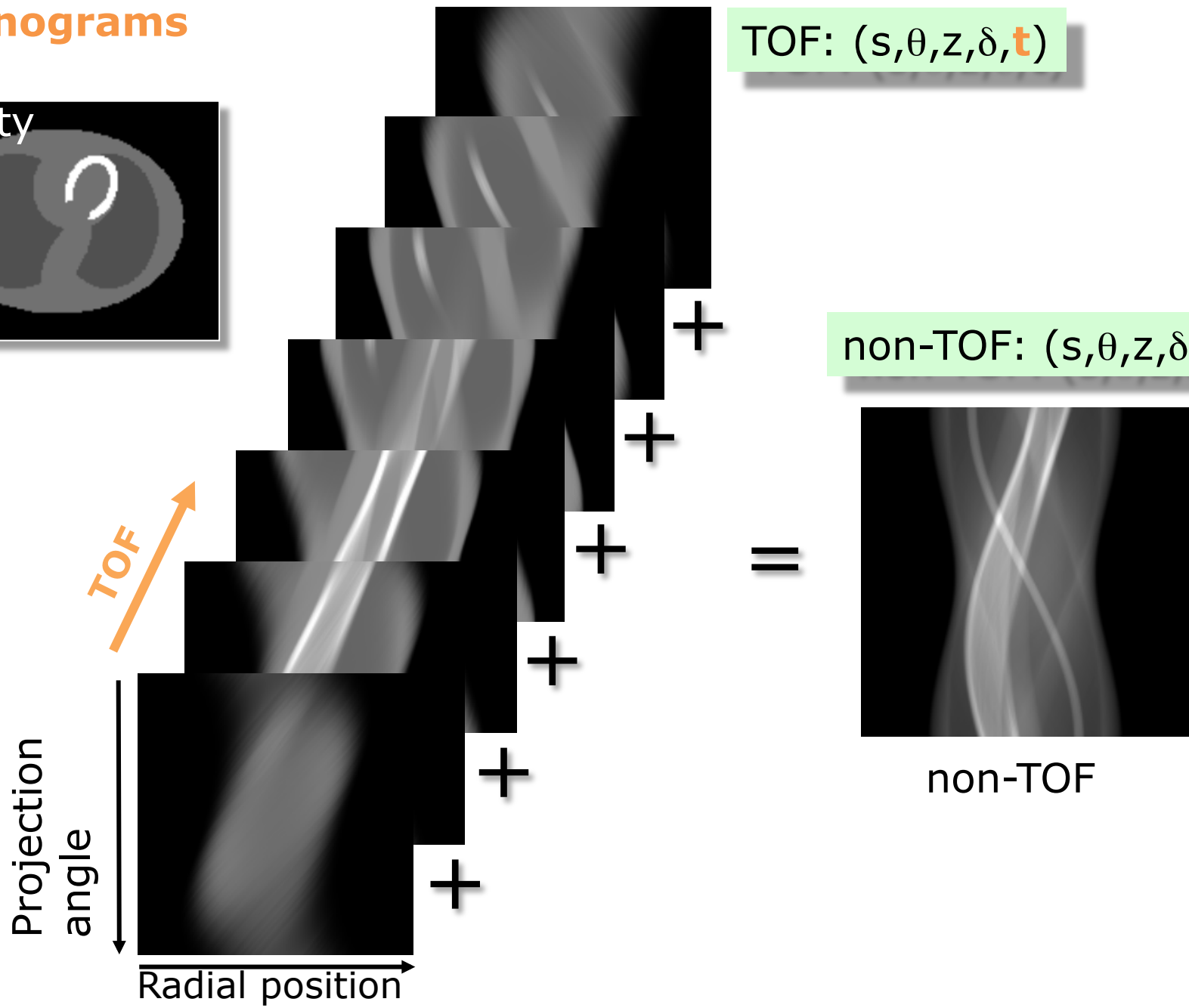
- **Contribute to the setting up of an international challenge:** thought-provoking on the 10 ps challenge motivations, expectations and implementation
 - for what purpose ?
 - for what goal(s) ?
 - with what organization ?
 - how to communicate ?
- **Motivations for the 10 ps challenge**
 - Promising technologies under development »»» P. Lecoq
 - Technical challenge with a strong clinical and societal impact »»» J. Nuyts

TOF sinograms



Courtesy: J. Nuyts, Univ Leuven

TOF sinograms



Courtesy: J. Nuyts, Univ Leuven

TOF-PET

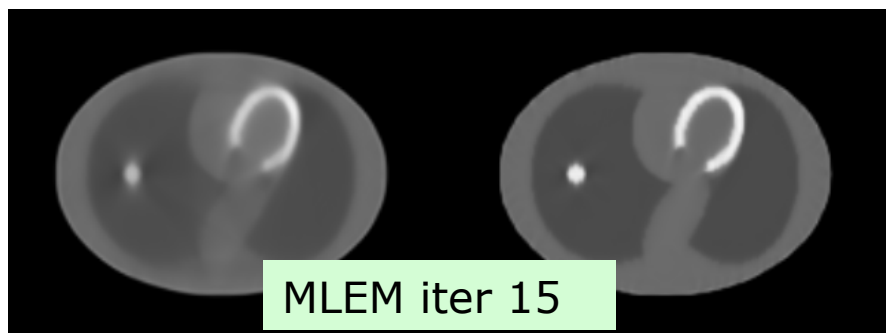


non-TOF backproj

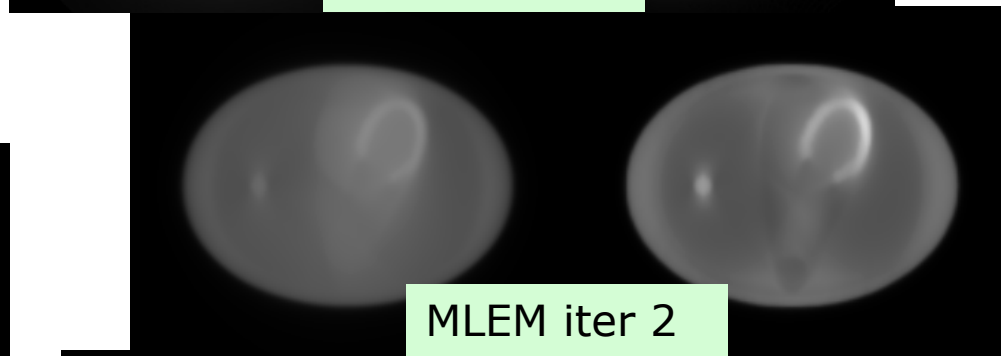
TOF **580 ps** backproj



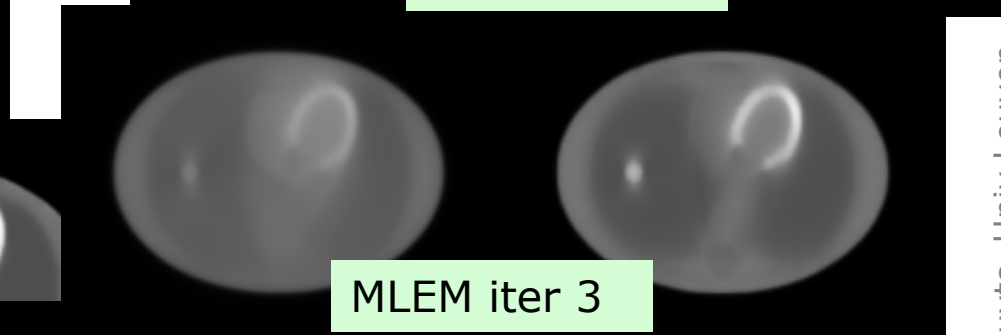
MLEM iter 1



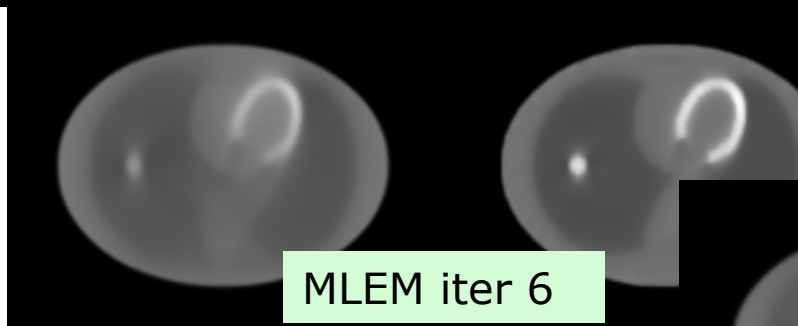
MLEM iter 15



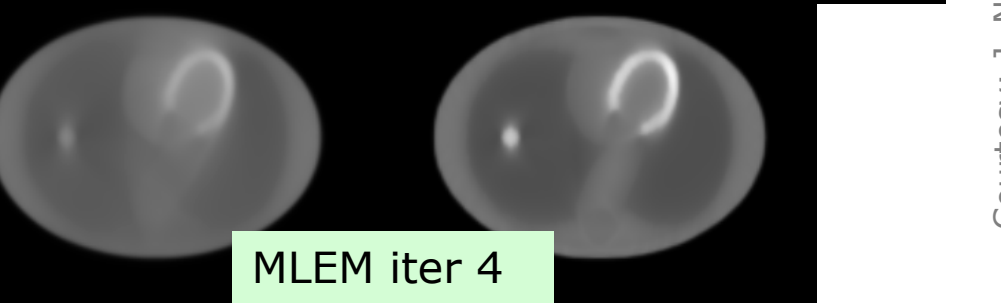
MLEM iter 2



MLEM iter 3



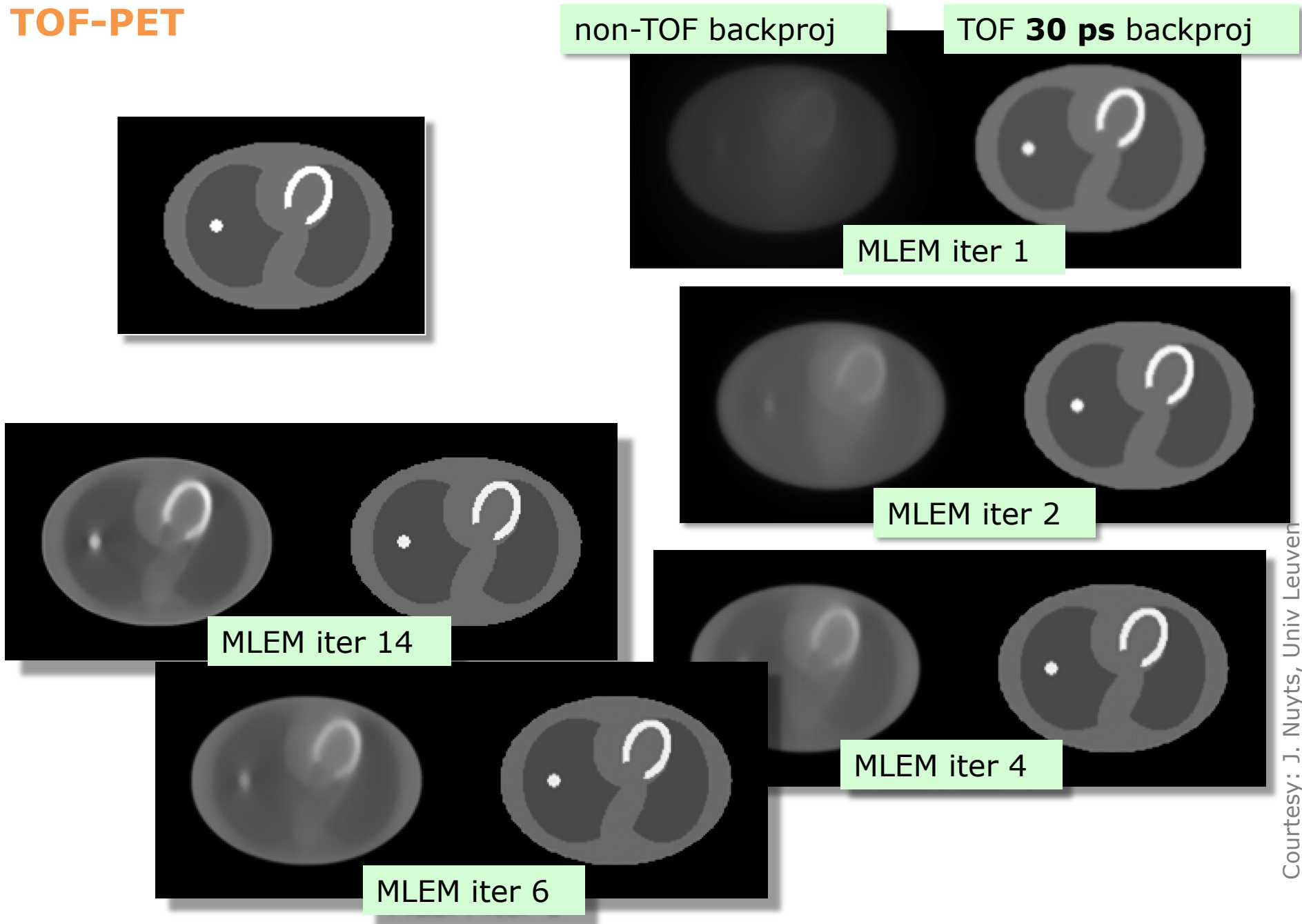
MLEM iter 6



MLEM iter 4

Courtesy: J. Nuyts, Univ Leuven

TOF-PET



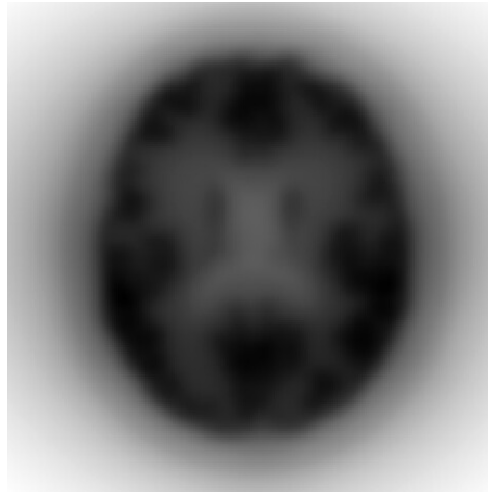
Courtesy: J. Nuyts, Univ Leuven

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

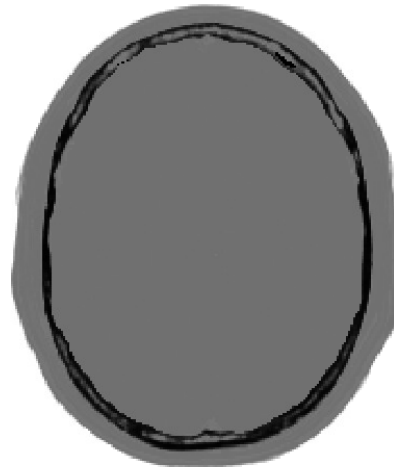
true activity



non-TOF backproj



TOF backproj



true attenuation



non-TOF OSEM



TOF OSEM

Courtesy: J. Nuyts, Univ Leuven

Same when only vertical parallel projection is used

true activity



non-TOF backproj

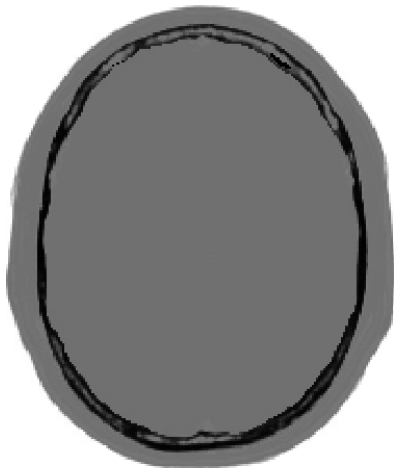


TOF backproj

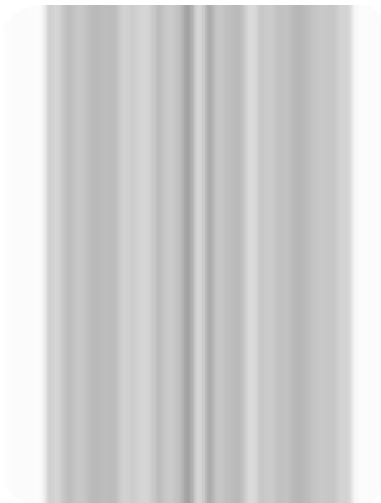


any angular sampling is fine

true attenuation



non-TOF OSEM

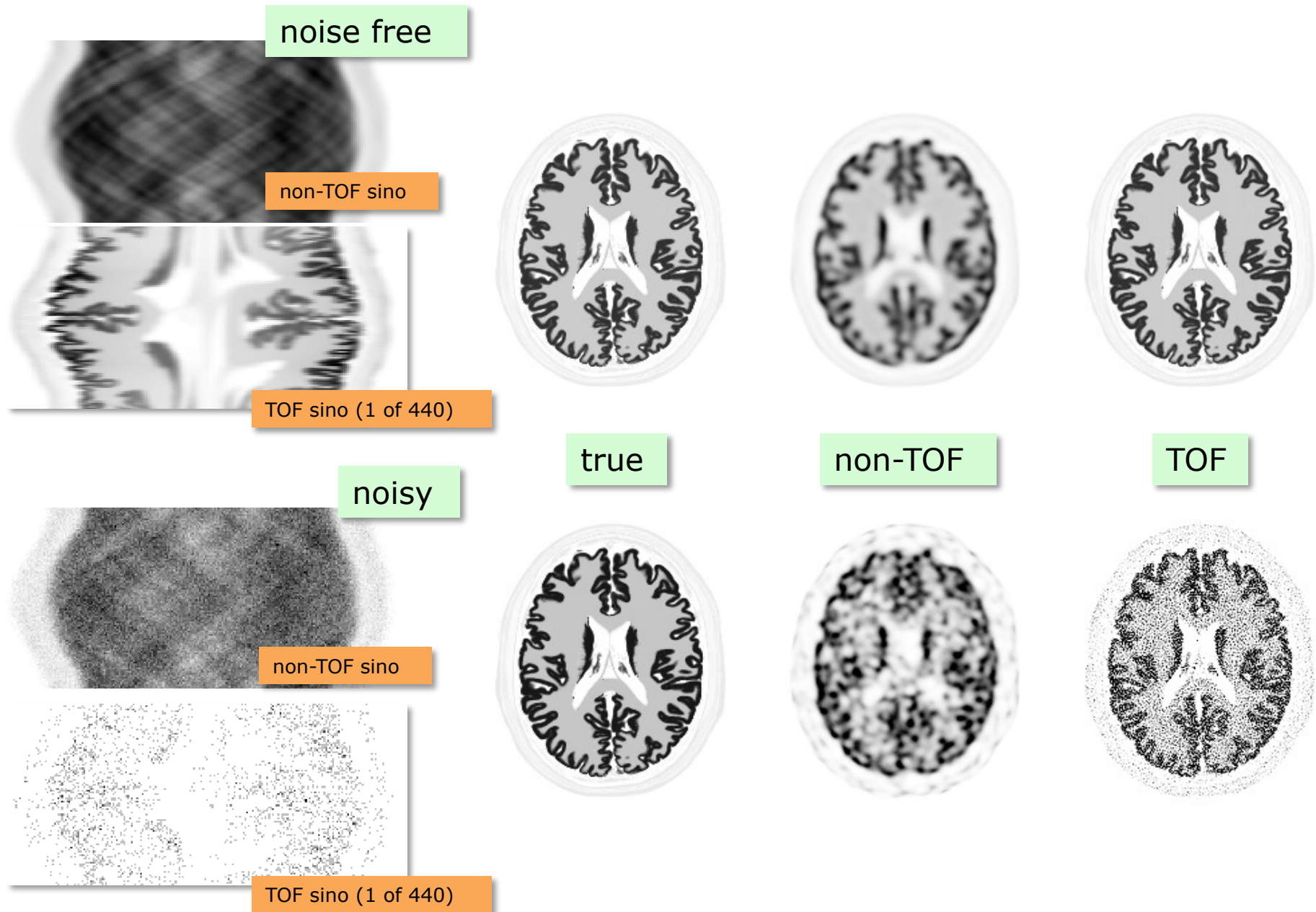


TOF OSEM



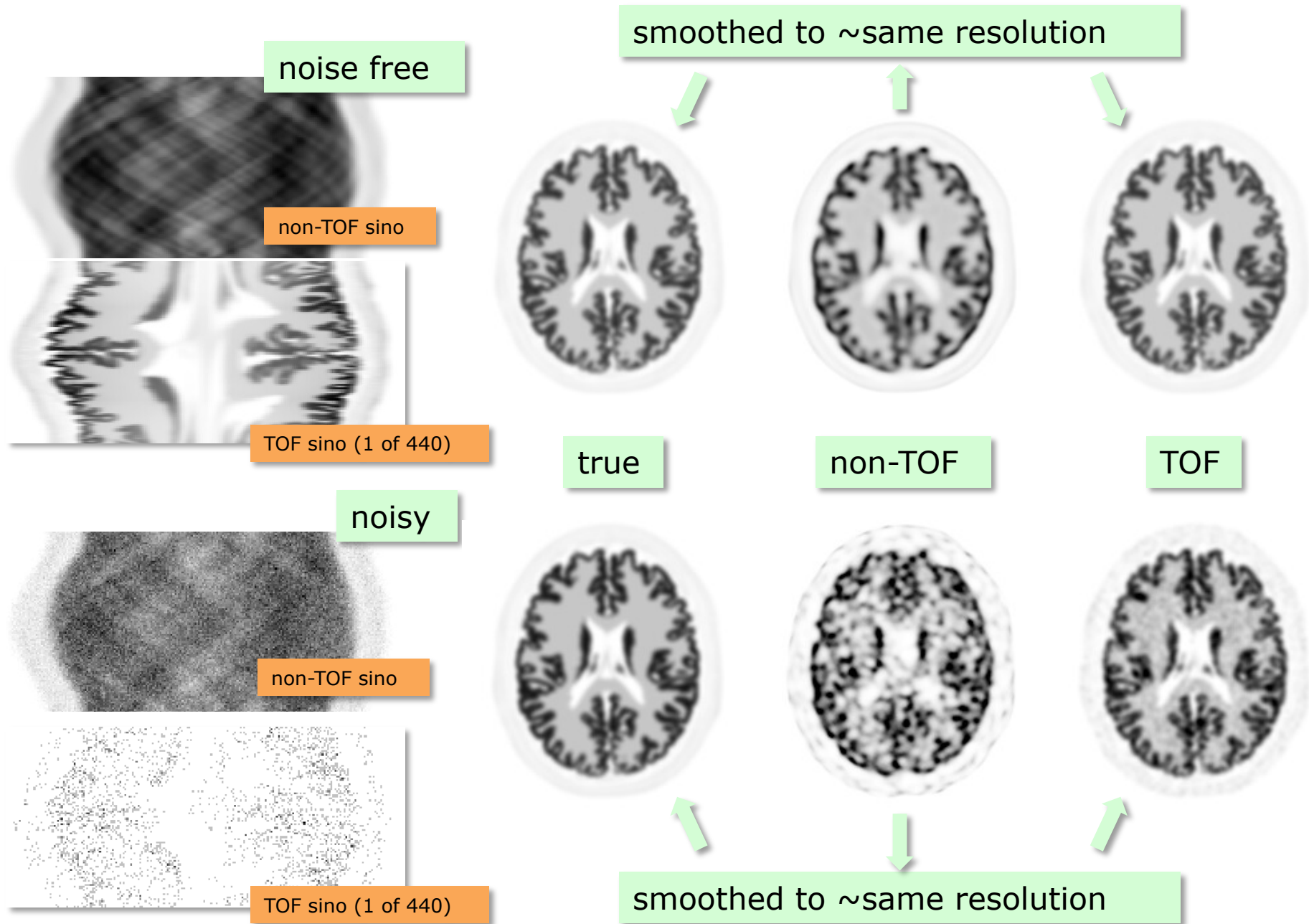
Courtesy: J. Nuyts, Univ Leuven

Signal to Noise Ratio (SNR)



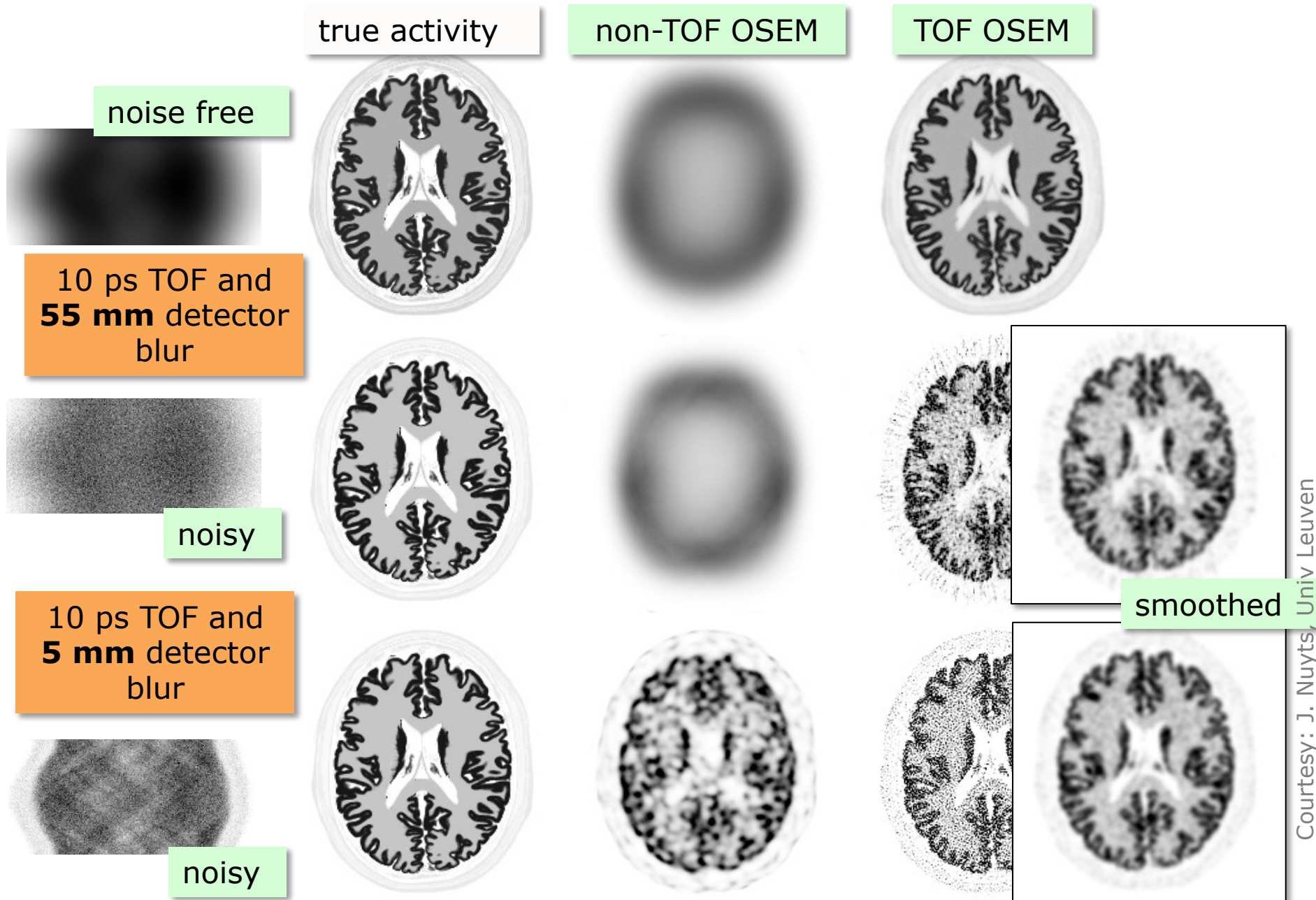
Courtesy: J. Nuyts, Univ Leuven

Signal to Noise Ratio (SNR)



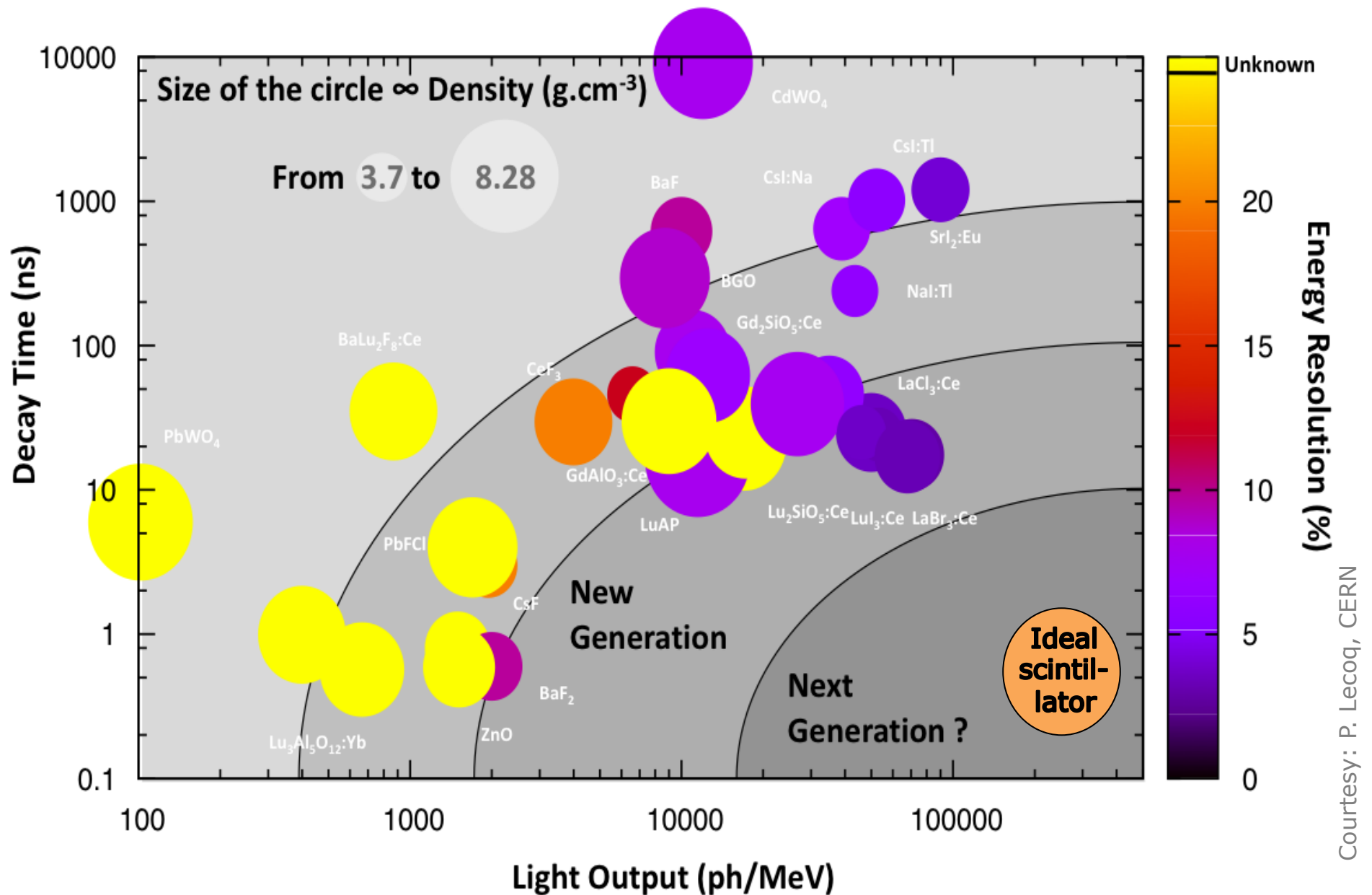
Courtesy: J. Nuyts, Univ Leuven

Signal to Noise Ratio (SNR)



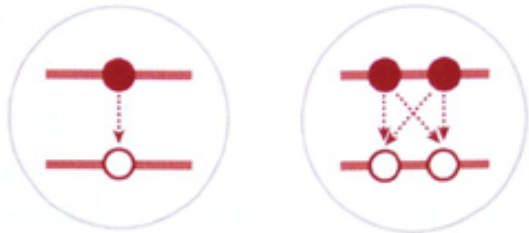
Courtesy: J. Nuyts, Univ Leuven

Classification des scintillateurs



Sources possibles de photons prompts (< 1 ns)

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



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

Hot intraband
luminescence
 $\sim 0.1 - 10 \text{ ps}$
(e.g. PbWO_4 ,
 CaWO_4)

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

Cross luminescence
 $< 1 \text{ ns}$ (e.g. BaF_2)
 $\lambda < 300 \text{ nm}$
faible rendement de
scintillation

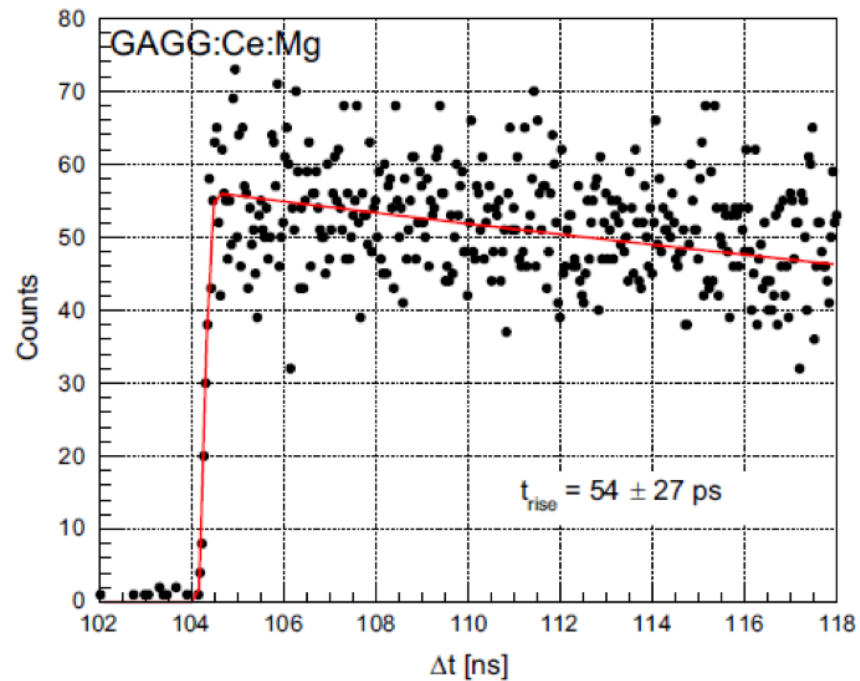
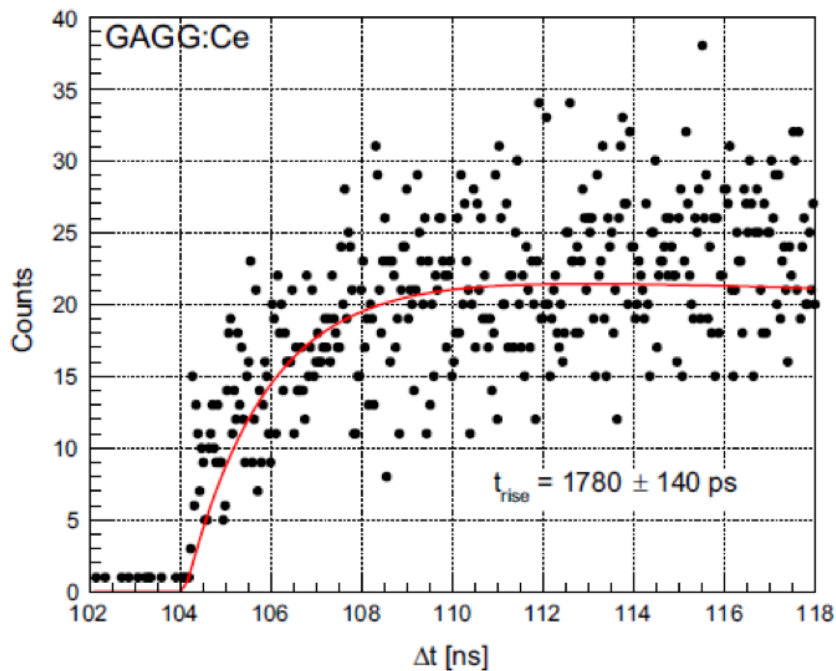
High donor band
semiconductors
 $< 1 \text{ ns}$ (e.g. ZnO)
désactivé à tempé-
rature ambiante

Emission Cerenkov
 $\sim 5-10 \text{ ps}$

Courtesy: P. Lecoq, CERN

Ingénierie de scintillateurs connus

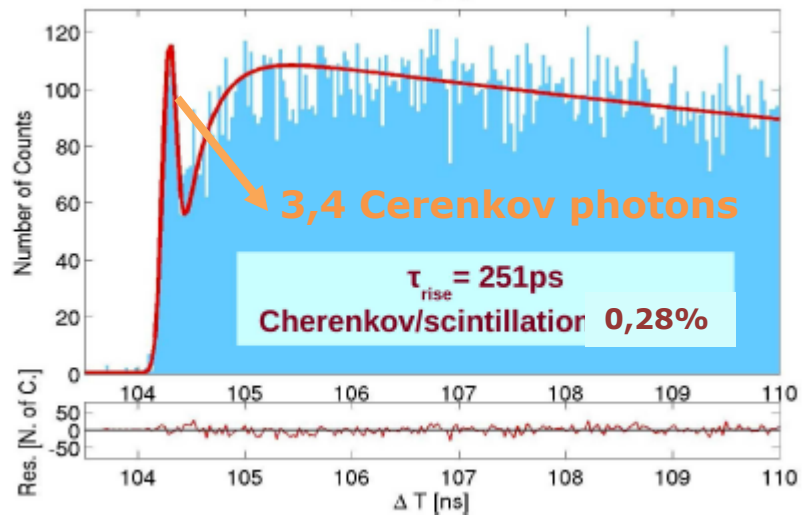
- Rendement de scintillation : $\leq 100'000$ ph/MeV
- Temps de déclin: $\tau_d \geq 10$ ns ~ 30 ph / 10 ps @ 511 keV
- Temps de montée :
 - Typiquement 100 ps (LYSO) jusqu'à plusieurs ns
 - Peut être réduit en co-dopage à ~ 20 ps (LYSO)



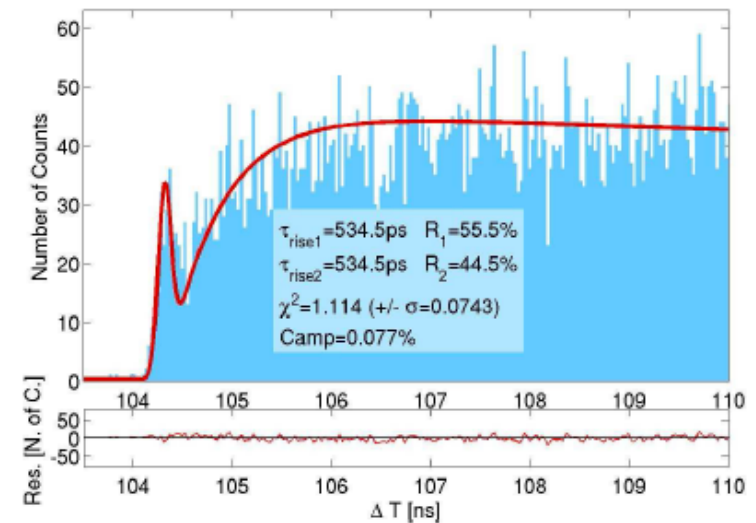
Courtesy: P. Lecoq, CERN

Cherenkov contribution

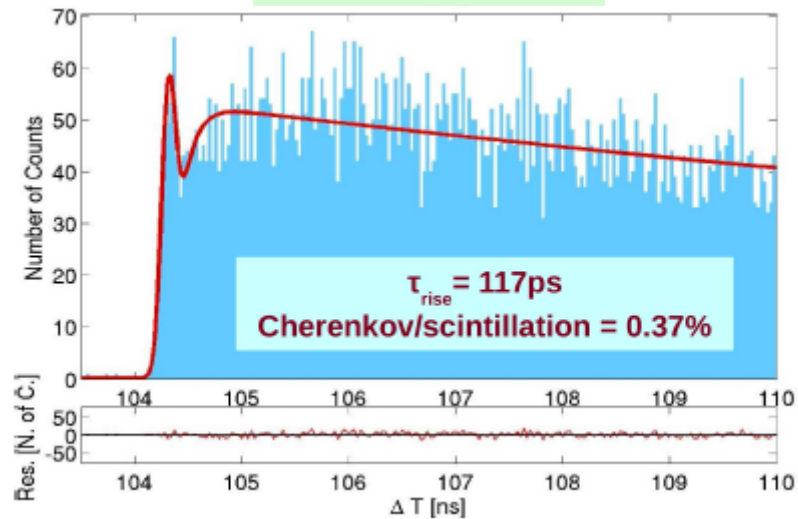
LuAG:Pr



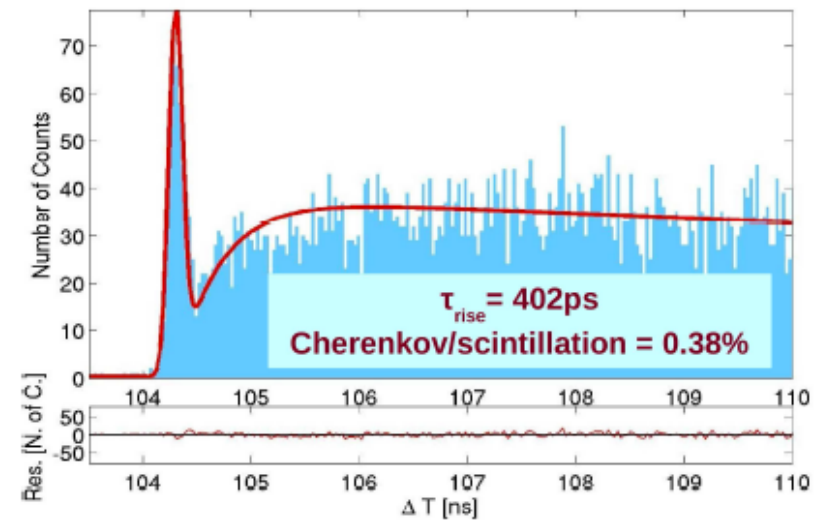
LuAG:Ce



LuAG:Pr,Ca



LuYAP:Ce

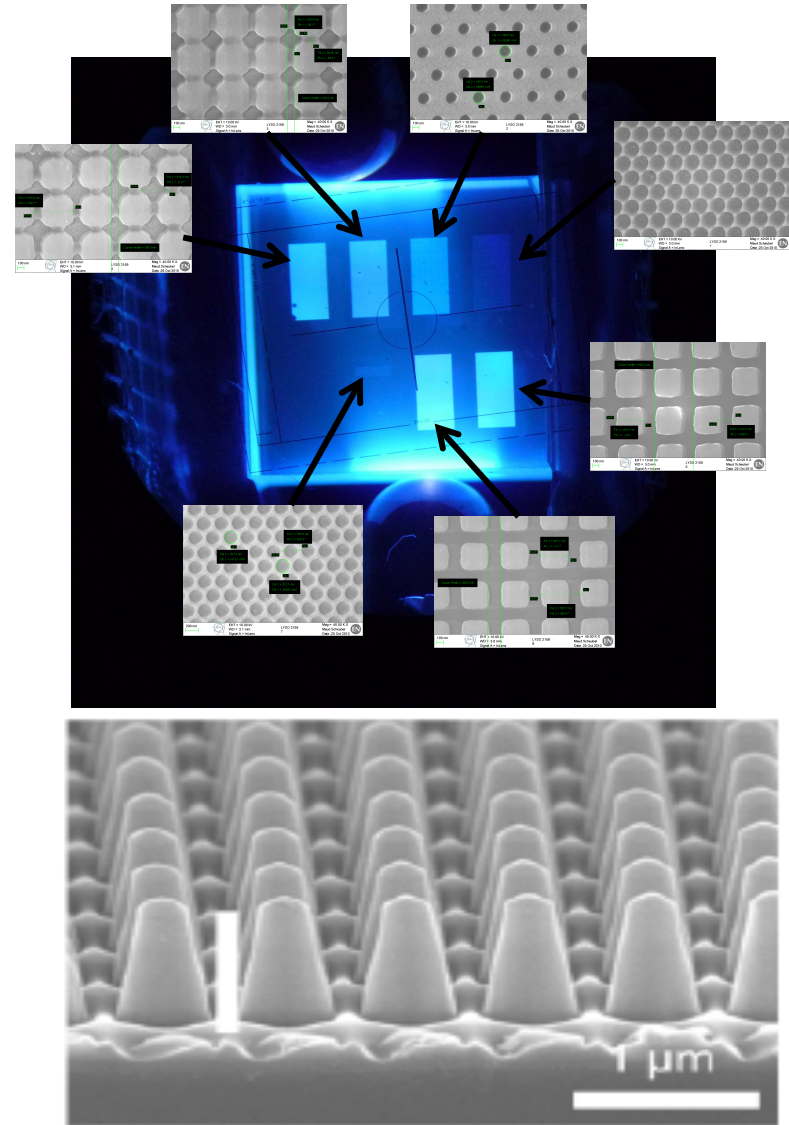


Courtesy: P. Lecoq, CERN

S. Gundacker *et al.*, Phys. Med. Biol. 61 (2016) 2802–2837

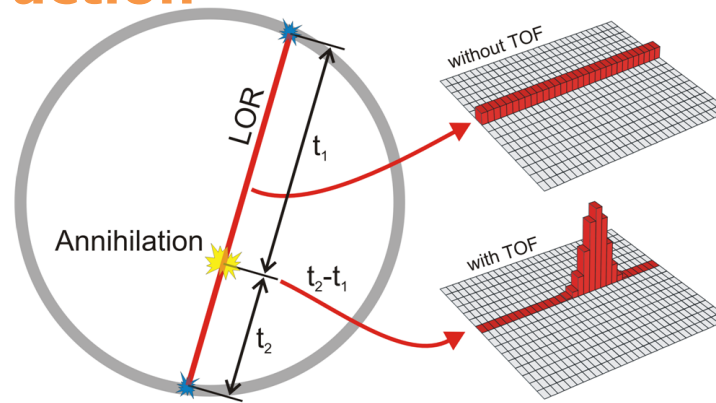
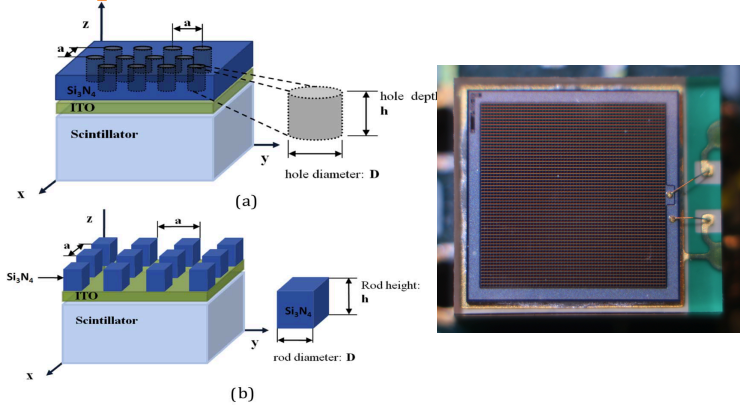
Utilisation de cristaux photoniques

- Amélioration de la résolution en énergie
 - par augmentation de la réponse lumineuse
 - par l'amélioration de l'efficacité de la collection de lumière grâce à l'utilisation de nano-implants
- Amélioration de la résolution en temps
 - par augmentation de la réponse lumineuse induisant la réduction de la gigue photo-statistique
 - Par redistribution de la lumière vers des modes de propagation les plus rapides dans le cristal

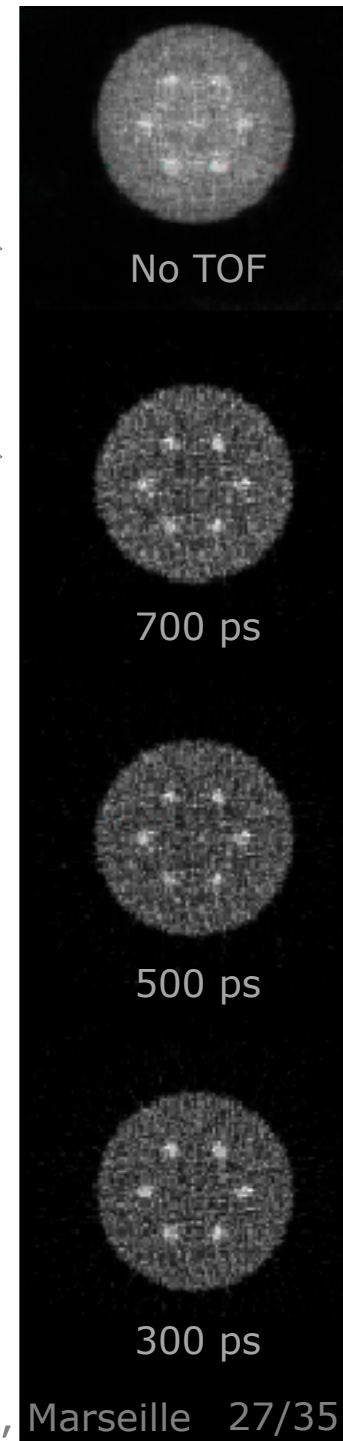
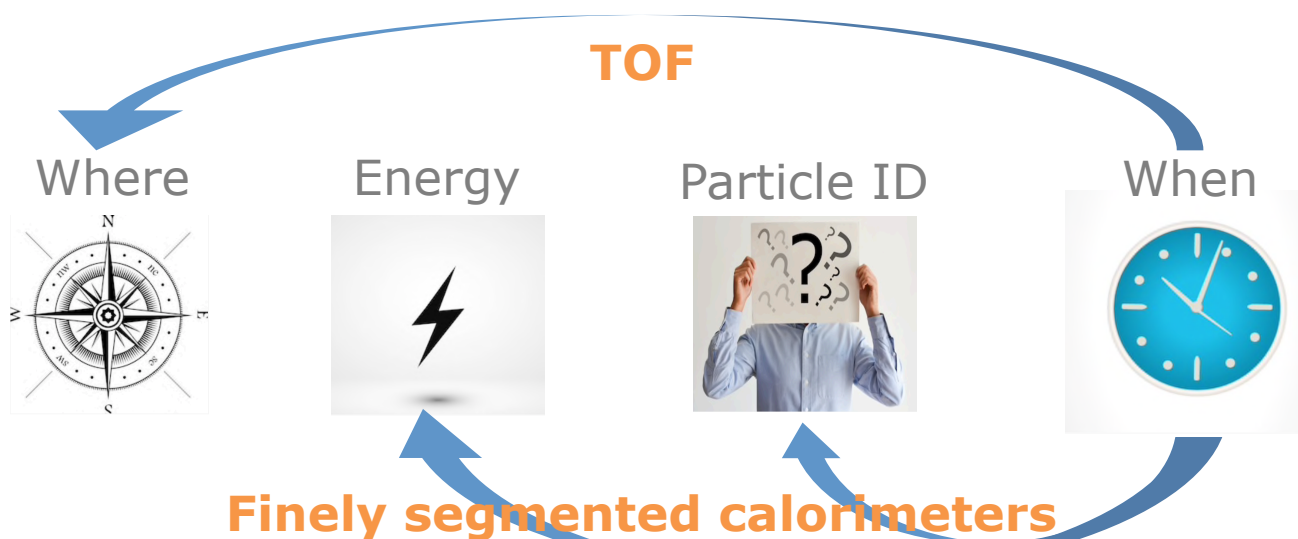


Courtesy: P. Lecoq, CERN

Timing rapide à scintillation : la route vers le TEP temps-de-vel sans reconstruction



FAST ADVANCED SCINTILLATION TIMING (2014-2018): <http://www.cern.ch/FAST-COST>



10 ps CRT fast timing

- Tomographie par émission de positons à temps-de-vol (TOF-PET)
- Réjection des diffusés en tomographie par rayons X
Best student oral presentation at IEEE NSS/MIC 2018, Sydney
- Calorimétrie, détecteurs à rayonnement de transition (TRD)
- Imagerie des gamma prompts en protonthérapie
- Positron annihilation lifetime spectroscopy (PALS) utilisée en science des matériaux
- Développement de LIDAR pour les véhicules autonomes (IR)
- Trajectographie 4D pour la physique des hautes énergies (particules chargées)

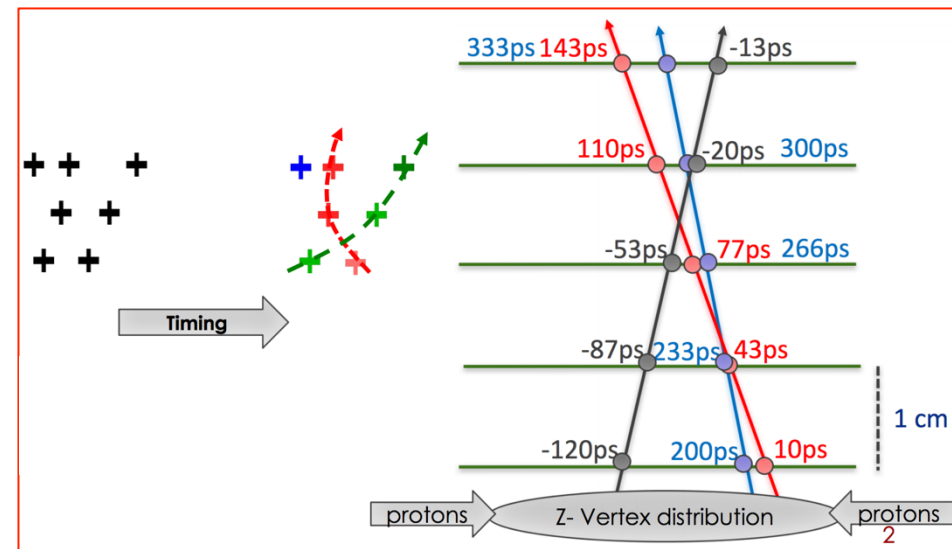
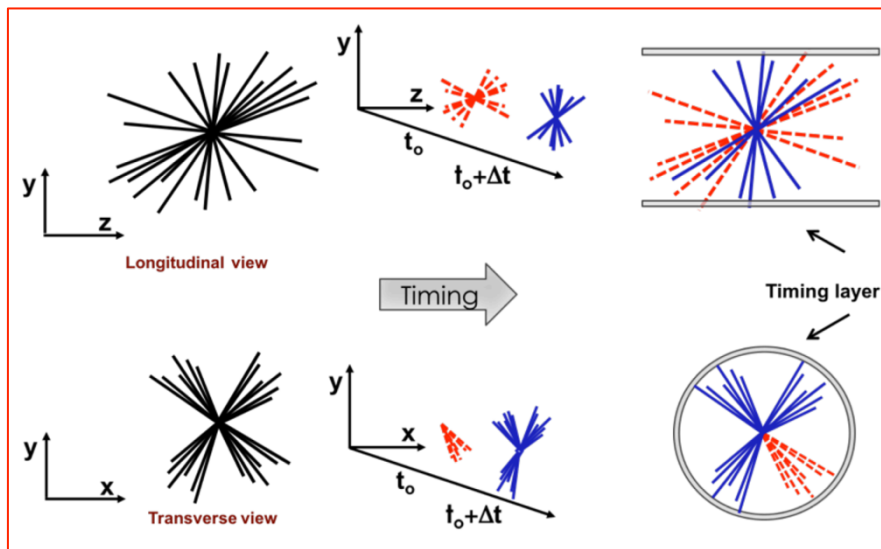


Le temps: « Tracking » en 4D

Need sub-nanosecond track time to suppress background in environments with large pile-up (HL-LHC, FCC) → **4D tracking**

Separate timing layers with coarser granularity
→ timing for reconstructed tracks
(e.g. HL-LHC upgrades **~30 ps**)

Timing within pixel layers
→ time info for pat rec
(e.g. **LHCb Upgrade II 20-200 ps**, depending on pixel size, radiation)

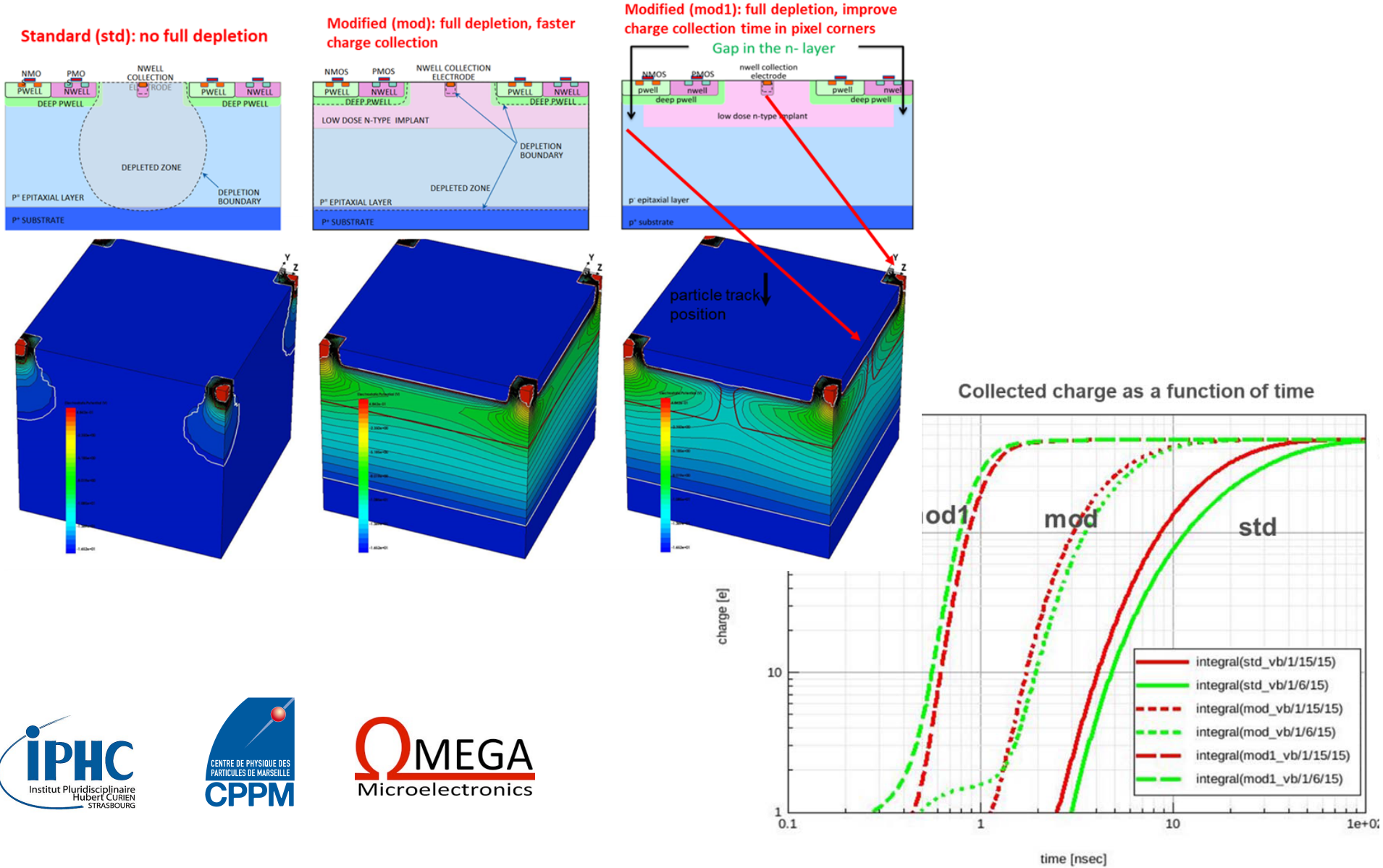


N. Cartiglia

- Trade-off between time resolution and pixel size / layer thickness
- FCChh needs track timing at **5 ps** up to **$6 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$** fluences



QUARTET, Quadruple measurements with Active pixel detectors for particle Tracking



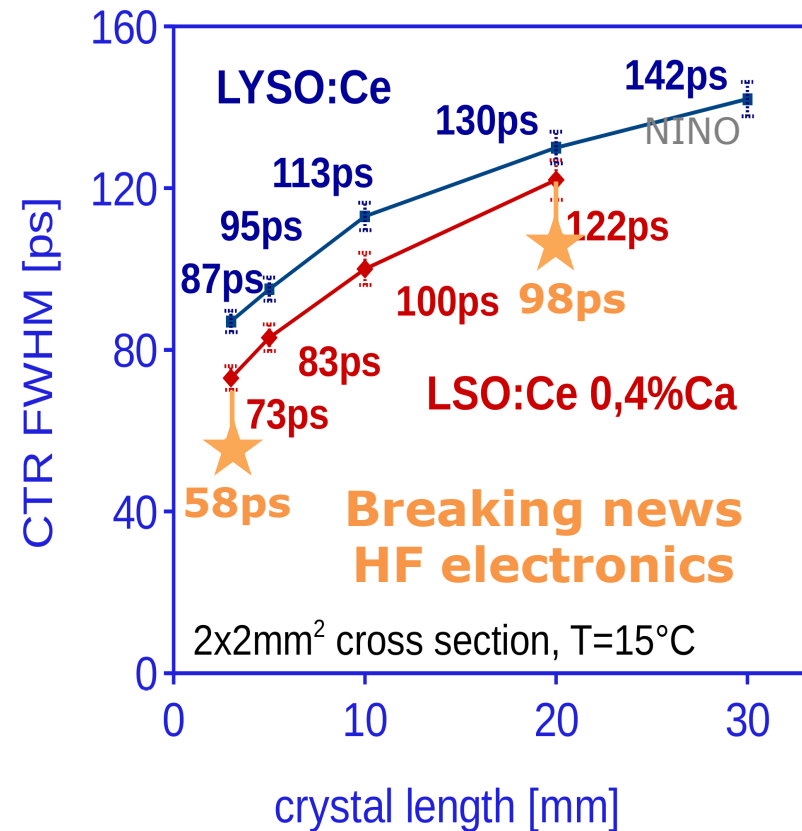
Etat-de-l'art (2019)



CTR: 214 ps FWHM

digital Biograph Vision PET/CT

Measured with FBK NUV-HD
(4 x 4 mm², 25 μm SPAD size)
2 x 2 mm² crystal cross
section, T=15° C



S. Gundacker *et al.*, 2016 JINST 11 P08008

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

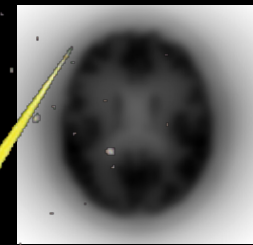
The 10 ps challenge:

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

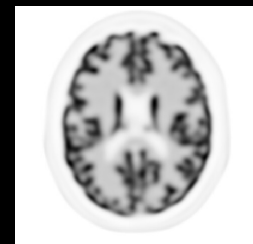
One unique challenge launched for 5 to 10 years and operated by an international organisation with rules issued by the community based on the measurement of CTR combined to sensitivity

Several milestones and prizes:

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



Non-TOF
backproj



Non-TOF
OSEM



10 ps TOF
backproj



10 ps TOF
OSEM

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

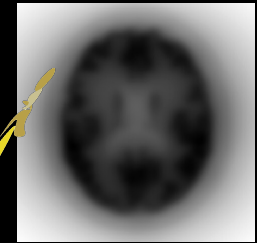
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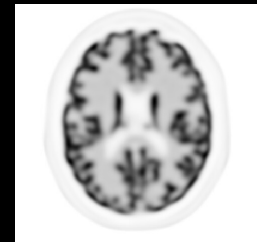
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Non-TOF
backproj



Non-TOF
OSEM



10 ps TOF
backproj



10 ps TOF
OSEM

The10ps-challenge.org



EUROPEAN INSTITUTE FOR BIOMEDICAL IMAGING RESEARCH

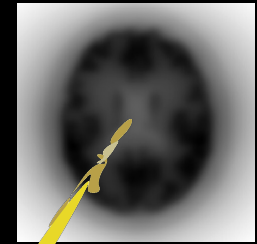


IEEE NPSS NMISC

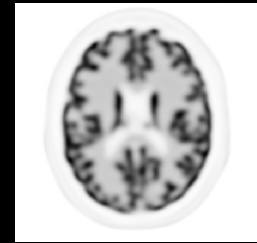


The 10 ps challenge: a step toward reconstruction-less TOF-PET

Thank you



Non-TOF
backproj



Non-TOF
OSEM



10 ps TOF
backproj



10 ps TOF
OSEM

