Association des physiciens et ingénieurs biomédicaux du Québec

Réduction de la dose en imagerie X 2D et 3D par la mesure de temps de vol de photons

R. Fontaine , ing. PhD

R. Espagnet, G. Bélanger, G. Lemaire, R. Rossignol, NEXT FRONTIER X Team

NEXT FRONTIER X project :

The Network Exploring X-ray Trade-offs - Future Research, Opportunities and Novel Technology Impact for Efficiency in Radiology and X-ray

3IT Institut interdisciplinaire d'innovation technologique UdS

Interdisciplinary Institute for technological Innovation (3IT), Université de Sherbrooke



$40M investment for the building

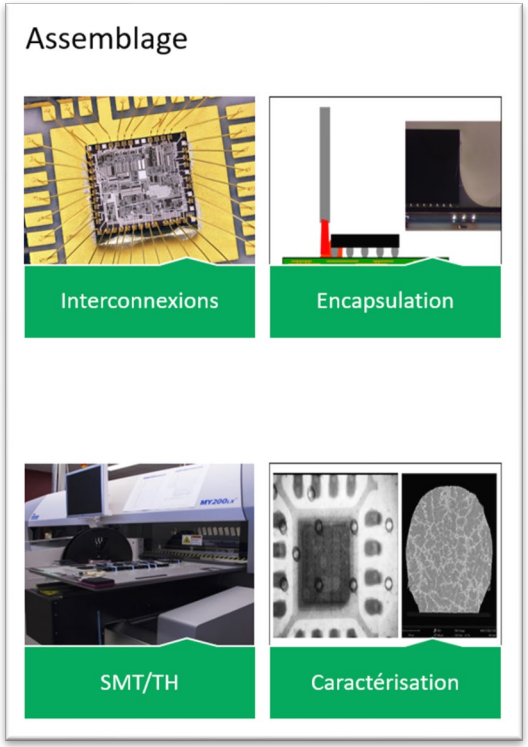
43 researchers from 6 faculties

48 research assistants and 31 technicians

137 master students, 139 Ph.D., 40 postdocs

We offer services in partnership with

- **Academia**
- **Industry**



5 platforms

3IT.Nano - (clean room 1600 m^2, Equipment >$25M)

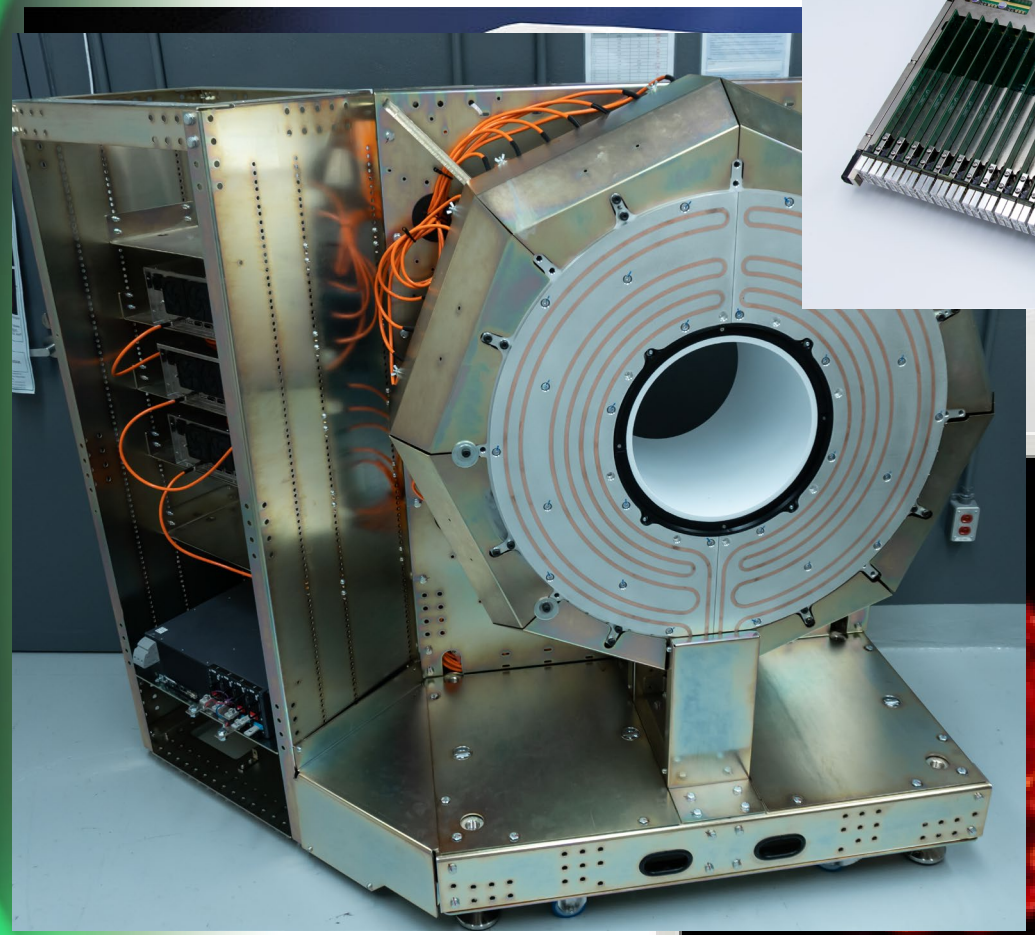
3IT.Micro - (design, packaging assembly, >800 m^2, $15M)

3IT.Studio - (experimental hall, 350 m^2, $0,25M)

3IT.Mécano - (Fablab, > 400 m^2, $7M)

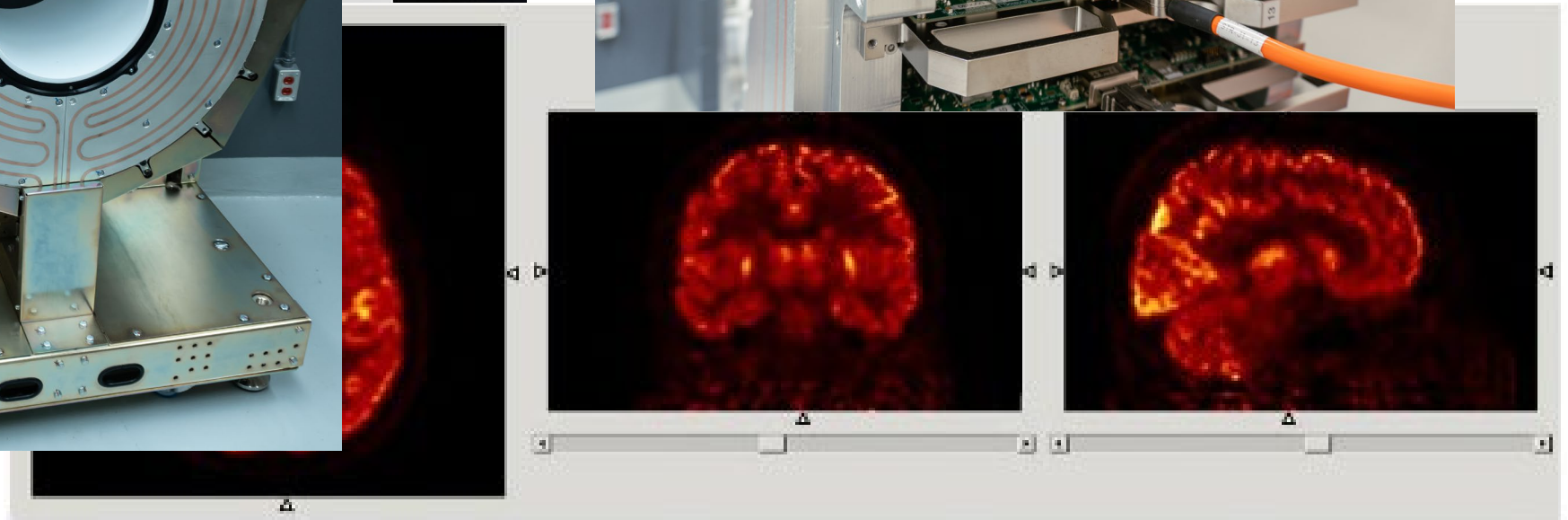
3IT.Hélios - (Solar Power plant 1 MW, > 400 m^2, $5M)

Example of a UHR Brain PET project (3IT-CIMS)

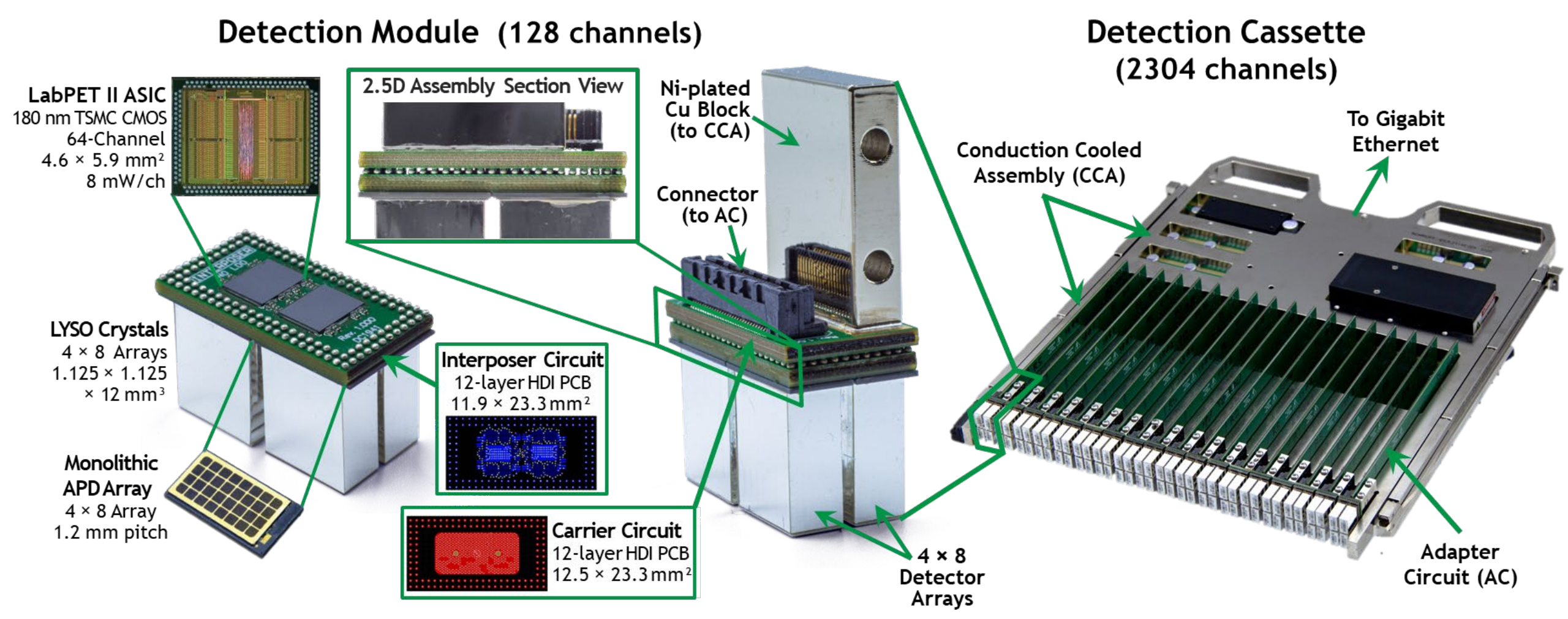








Example of a UHR Brain PET project (3IT-CIMS)



Plan de la présentation

- Qu’est-ce qu’un tomodensitomètre (CT)
- Comment réduire la dose
- Principe du temps de vol
- Initiative NEXT FRONTIER X

Dose : a scattering problem

Let’s start with:

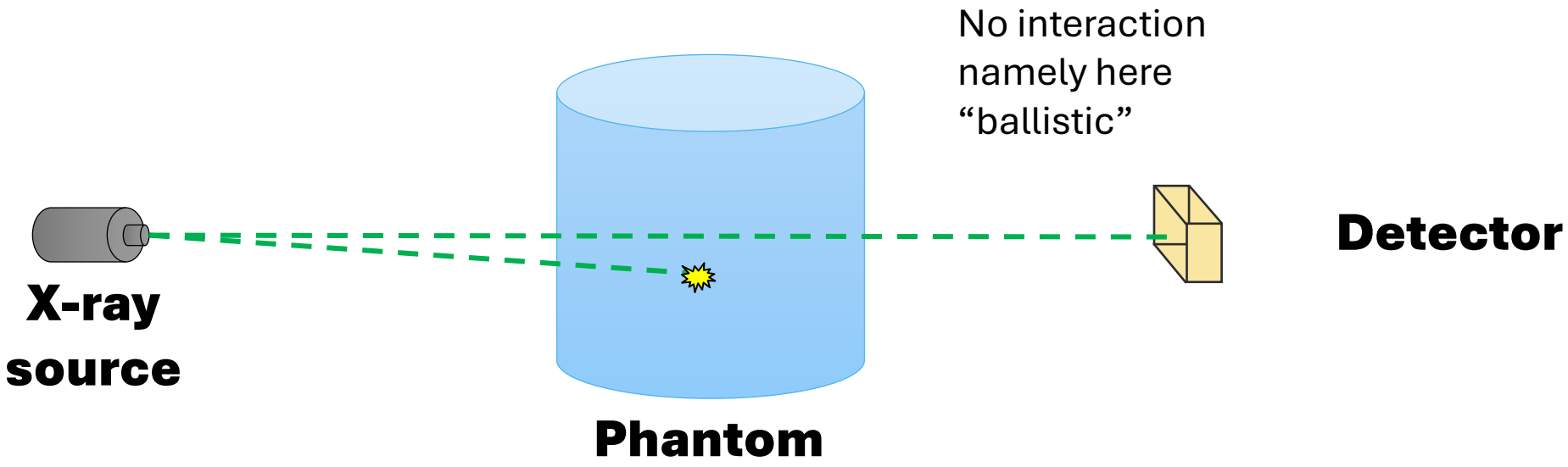
Physical interaction processes
&
Image quality requirements

(dose vs cost vs image quality



Physical interaction processes

A scatter problem

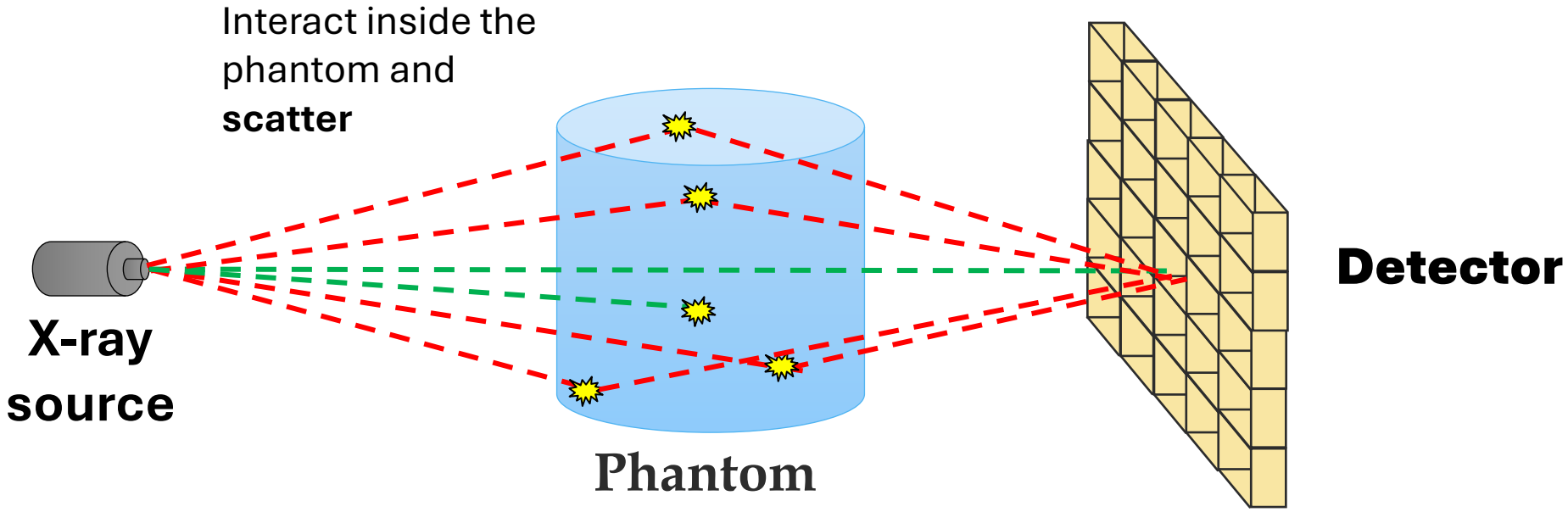


$$\mu = \mu_{pe} + \mu_{Com} + \mu_{Ray}$$

- The image is created by the contrast of the photons that are absorbed by photoelectric effect and the ballistics.
- We measure the total attenuation, which is the sum of the attenuation from the photoelectric effect, Compton and Rayleigh scattering.

Physical interaction processes

A scatter problem



$$\mu = \mu_{pe} + \mu_{Com} + \mu_{Ray} - f(\mu_{Com+Ray})$$

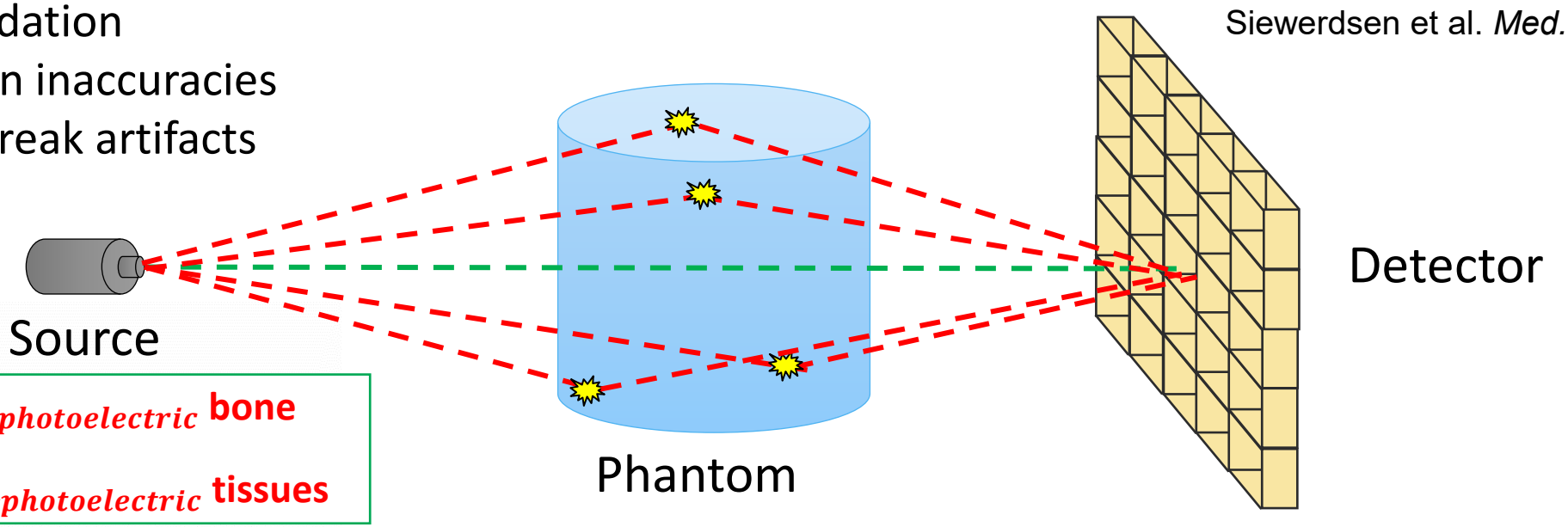
Need for diagnostic quality

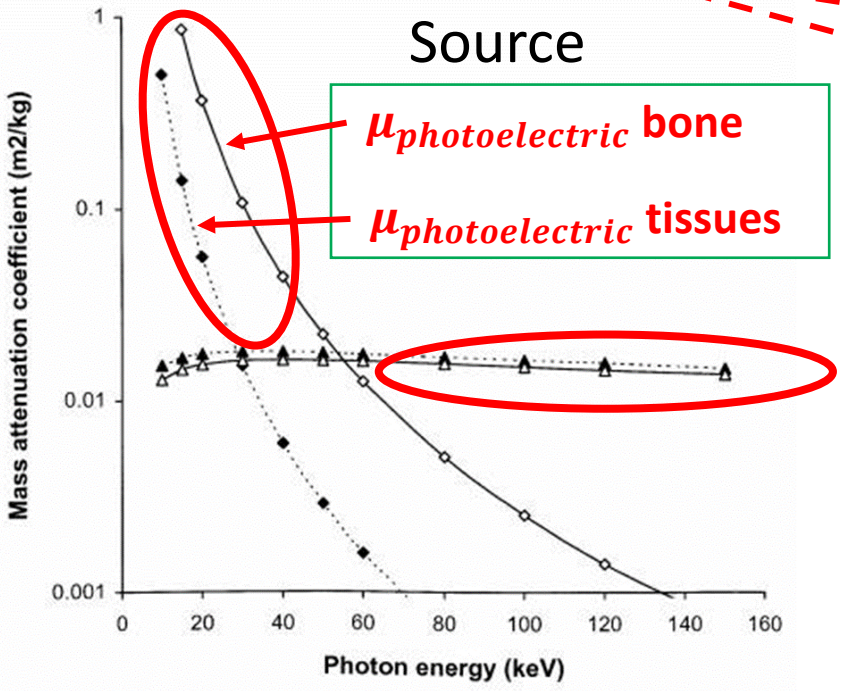
CNR high with low dose

Negative impacts from scatters:

- CNR degradation
- Attenuation inaccuracies
- Cup and streak artifacts

Siewerdsen et al. *Med. Phys.* (2001).





Energy above 70 keV carries more information because it passes more easily through the human body but..

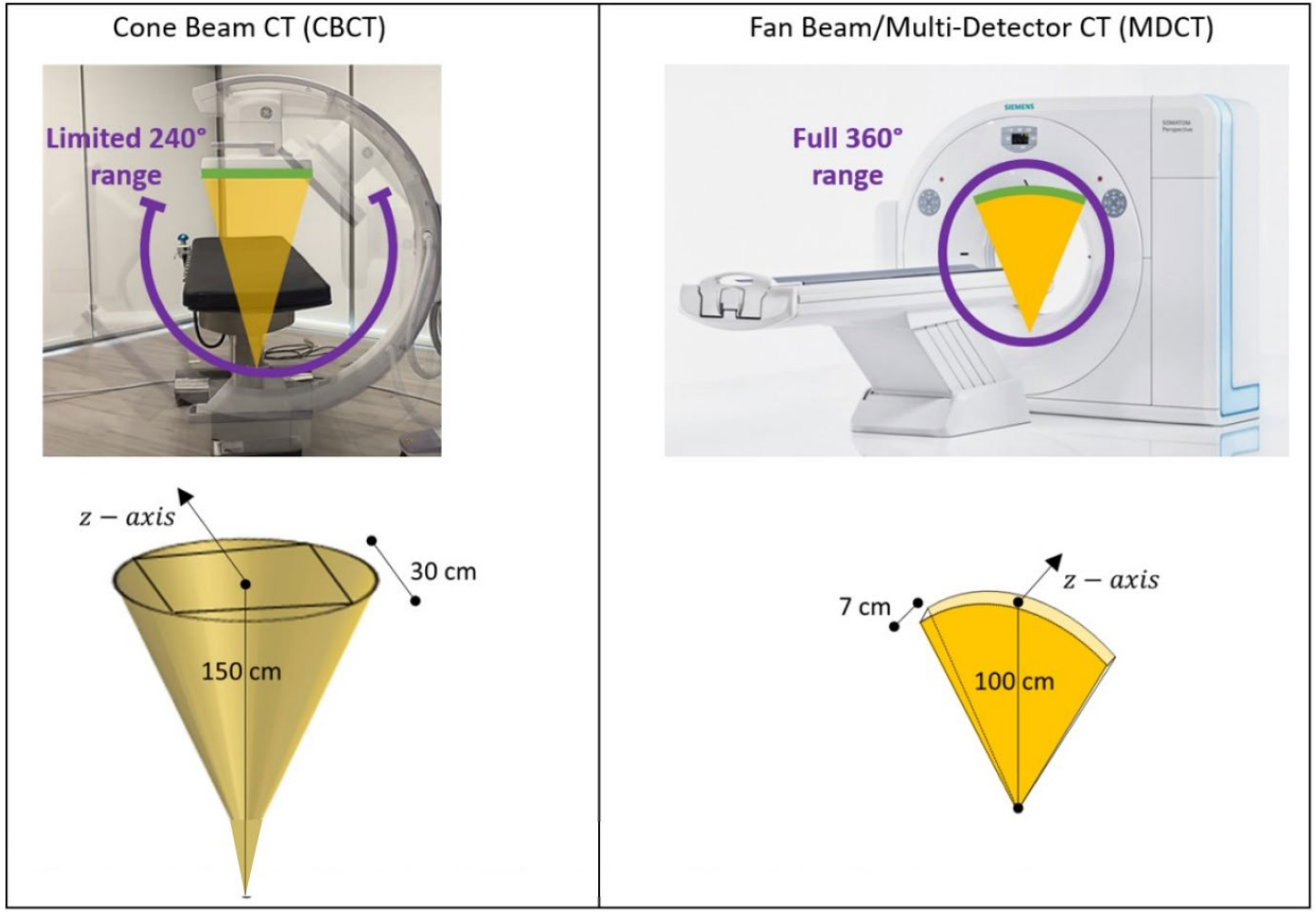
Scatters dominate for body imaging but do not generate contrast

$$\mu = \mu_{pe} + \mu_{Com} + \mu_{Ray} - f(\mu_{Com+Ray})$$

Physical interaction processes

Scatter rejection principle : Fan BEAM

Try to reduce scatters as much as possible a solution is to use fan-like X ray source + slice of detectors.

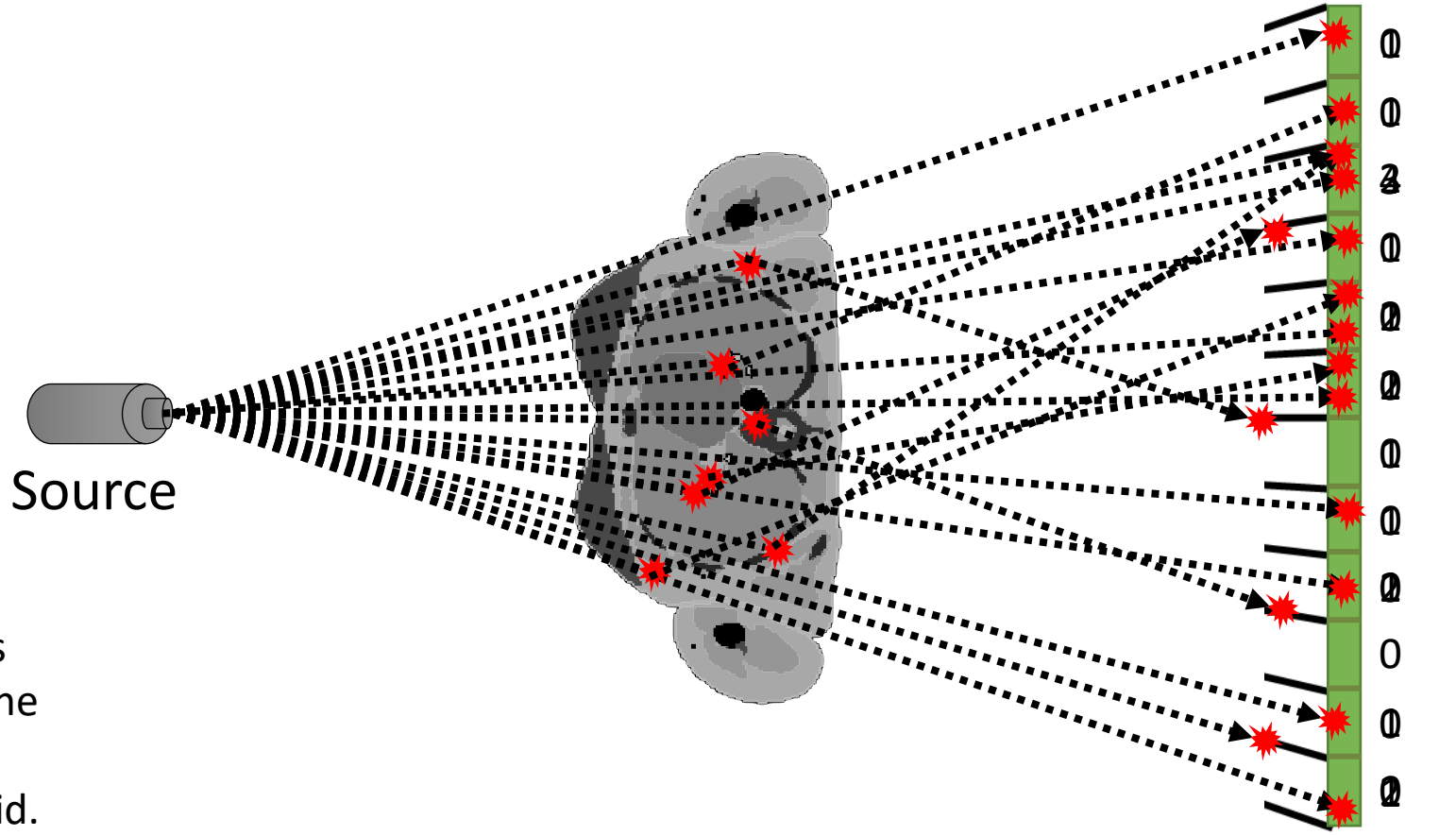


Source : Asto CT - Equine Standing CT - Learn More

Physical interaction processes

Scatter rejection principle : anti-scatter grid





Try to reduce scatters as much as possible, and the solution adopted is to install an anti-scatter grid.

Source : www.amazon.ca/-/fr/Moustiquaire-magnétique-pour-fenêtre-porte/dp/B0D7Q2HNYX

Scatter rejection principle

Current solution to the scatter problem: Anti-Scatter Grid

- Restores contrast (but not completely CNR!)
- Partial restoration of the attenuation coefficient
- Reduces scatter induced artefacts
- On the other hand:

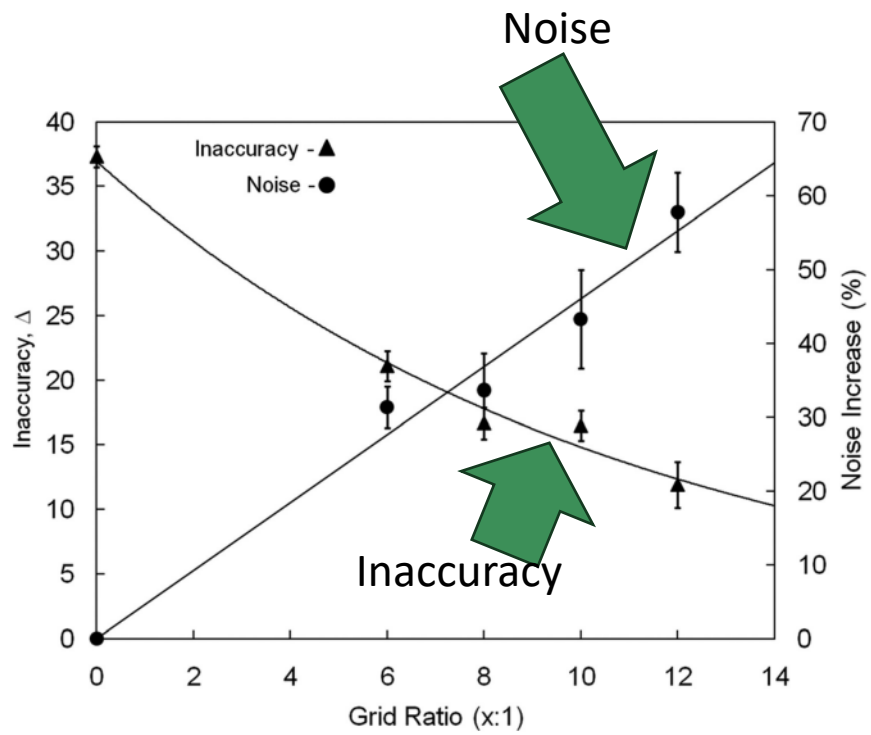
  Lowers the sensitivity by 15-50% [5]

To obtain a desired

CNR and sensitivity

=> Increase the dose !

Maybe another way is possible.. ToF..ToF..ToF

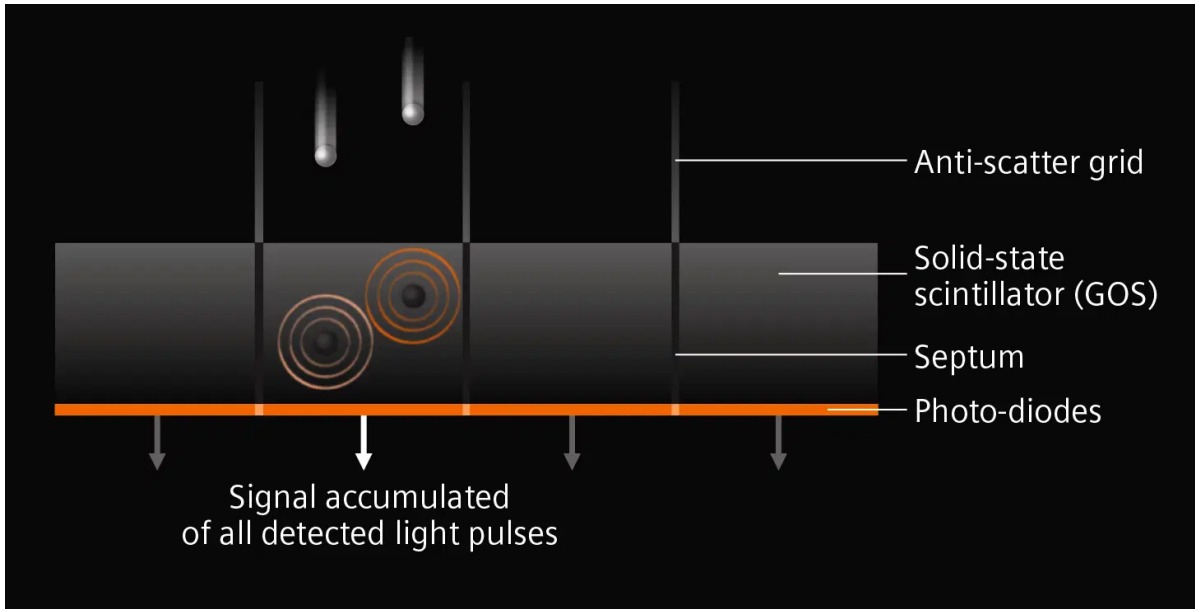


Effect of ASGs on the inaccuracy and noise in CBCT [6]

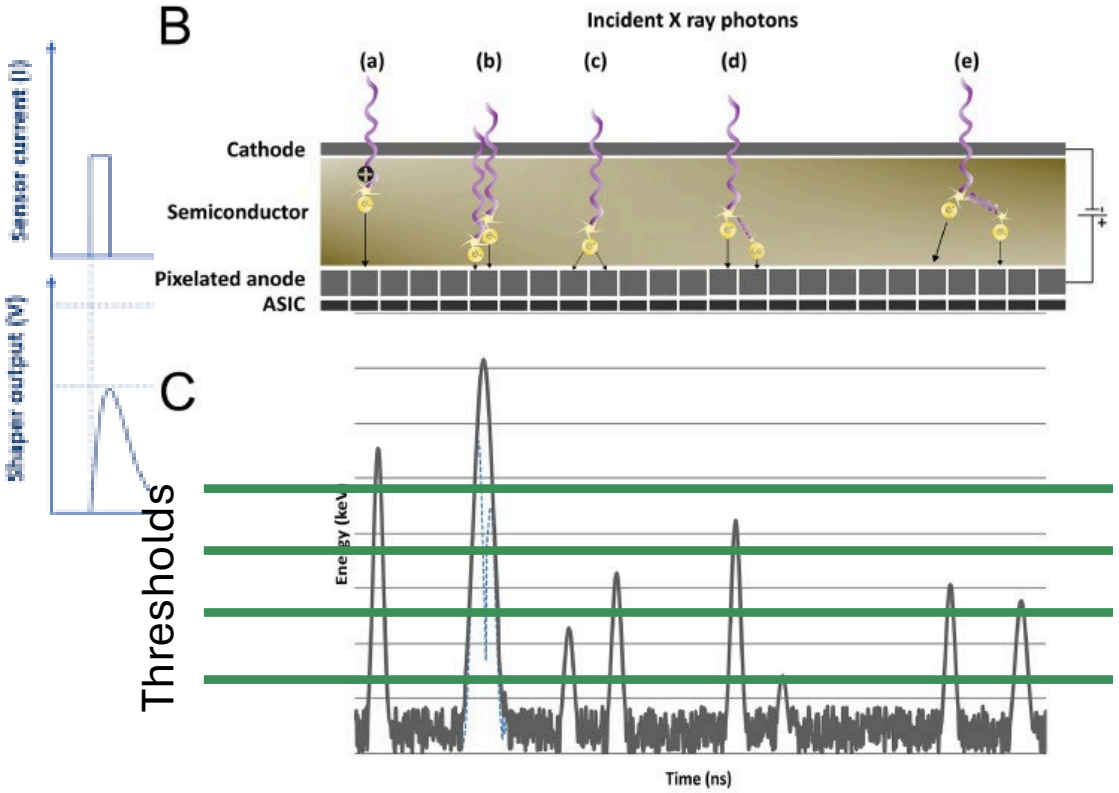
[5] M. Mizuta et al. (2012), Radiol Phys Technol, vol. 5, no. 1, pp. 46–52
[6] S. Schafer, J. W. Stayman, W. Zbijewski et al.,

How to reduce the dose?

The existing technologies



a) Current photon flux integration with ASG (Siemens)



b) Photon-counting technology

Source : https://www.siemens-healthineers.com/en-ca/computed-tomography/technologies-and-innovations/photon-counting-ct
Source : Greffier et al. Feb 2025
Source : ebrary.net/135305/engineering/pile_effects

How to reduce the dose?

A new path is proposed at U. Sherbrooke for dose reduction

X-ray without anti-scatter grid
&
Photon counting
with energy measurement

→ **Time of flight scatter rejection**

Can lead **to dose reduction factor of 2x** or **50% less dose**

ToF Scatter Rejection Principle

How do that?

To do this we need:

- Synchronized pulsed X-ray source
- Time-resolved detectors of very high precision (~10-200 ps FWHM)

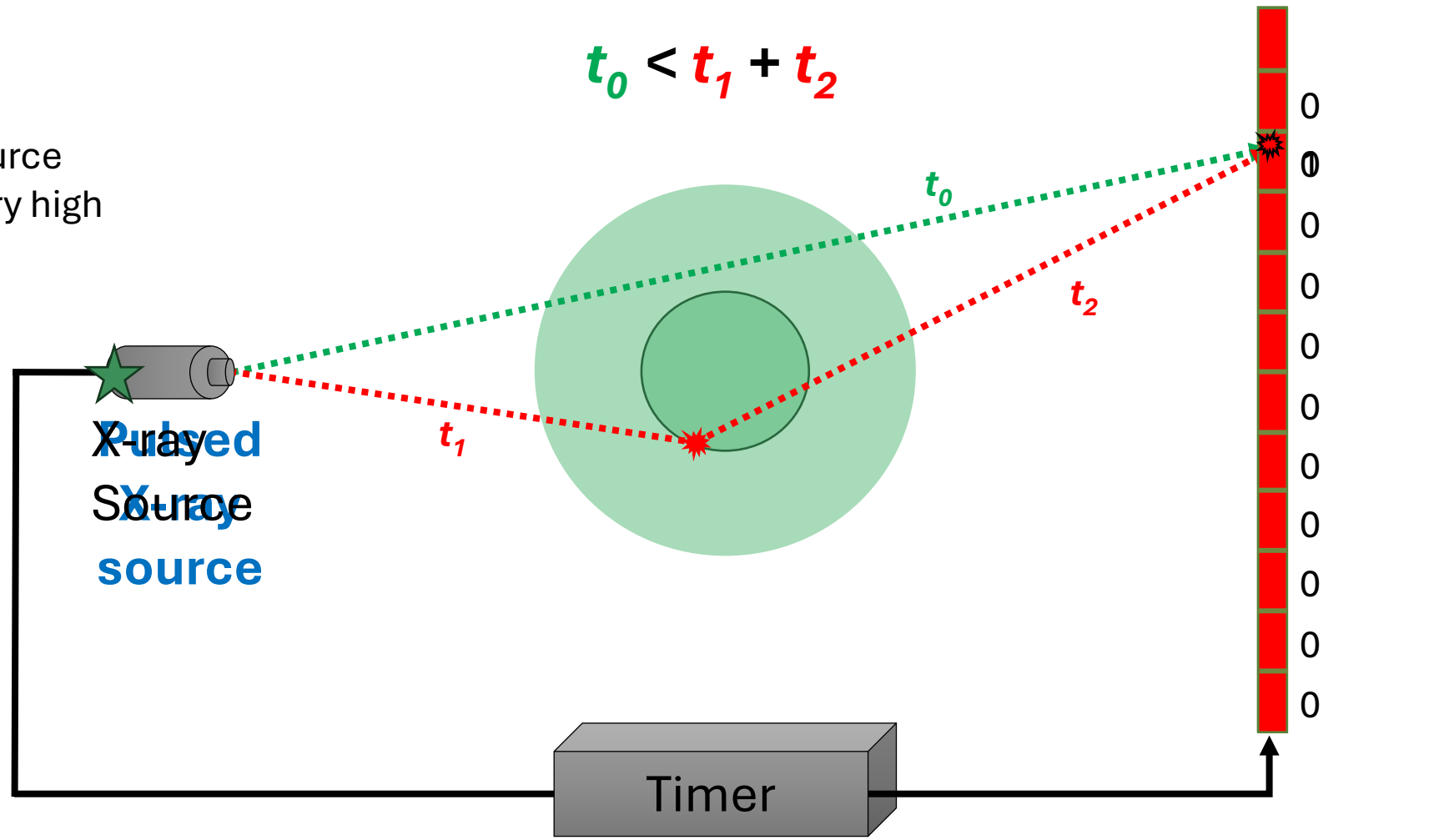
Threshold for rejection:

t_{th} ~10-500 ps FWHM

$$t_1 + t_2 > t_0 + t_{th}$$

Speed of light : 3 x 10^8 m/s

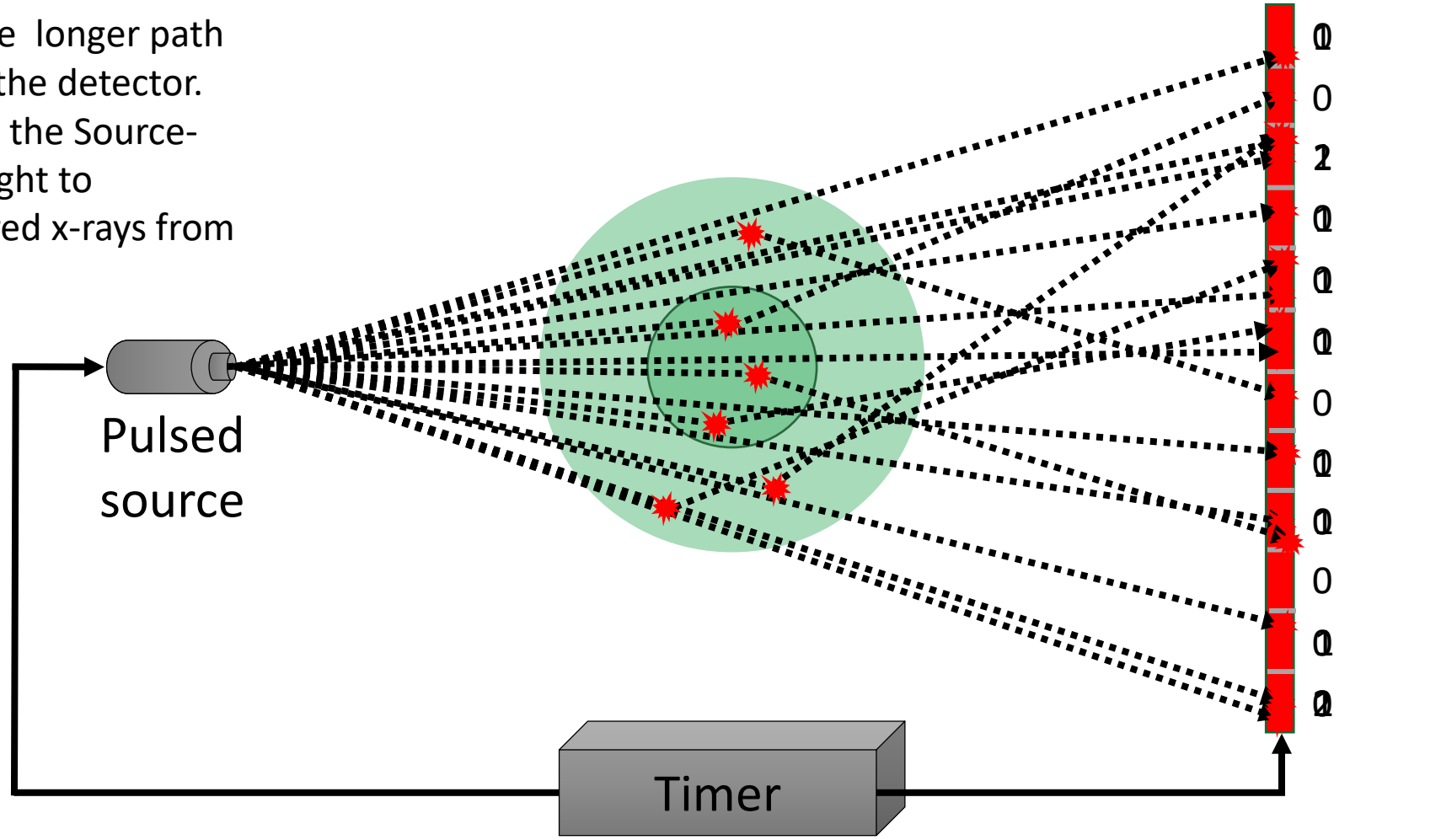
Light travels 3 mm in 10 ps



ToF Scatter Rejection Principle

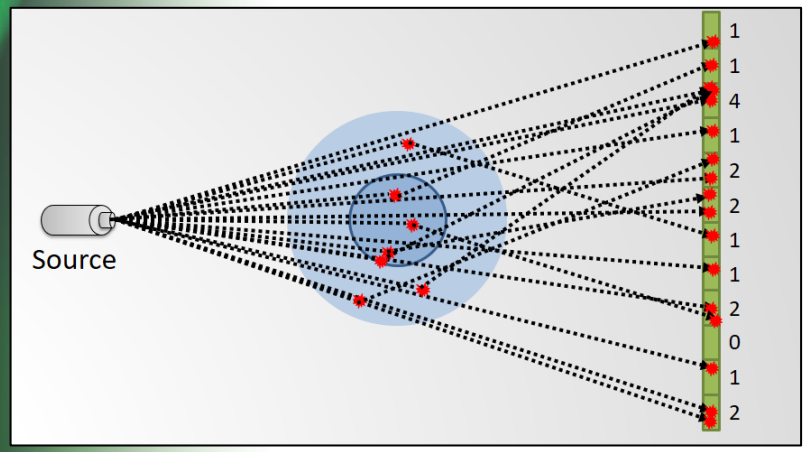
How do that?

Scattered x-rays take longer path from the source to the detector.
→ We can measure the Source-Detector time-of-flight to discriminate scattered x-rays from primary x-rays



ToF Scatter Rejection Principle

How do that?



$$+\mu_{Com}+\mu_{Ray}-f(\mu_{Com+Ray})$$

Time correlated detector array

Pulsed source

Timer

1
0
2
1
1
1
0
1
1
0
1
2

State of art in ToF X-ray technology

Simulation studies to this day

- Multiple simulation studies were done to assess the performance of the TOF method, and its requirements.

- All simulations were done using Geant4 and GATE, which uses well tested physics model to simulate the interactions of particles in matter.

GEANT4
A SIMULATION TOOLKIT

https://geant4.web.cern.ch/

GATE
opengatecollaboration.org

"Simulation done with small doses, so the images are not optimal because it takes a long time to simulate better."

Outline of the simulations

1 : Demonstrate the possibility to replace a ASG with ToF measurement
2 : Characterize the image performance related to ToF precision

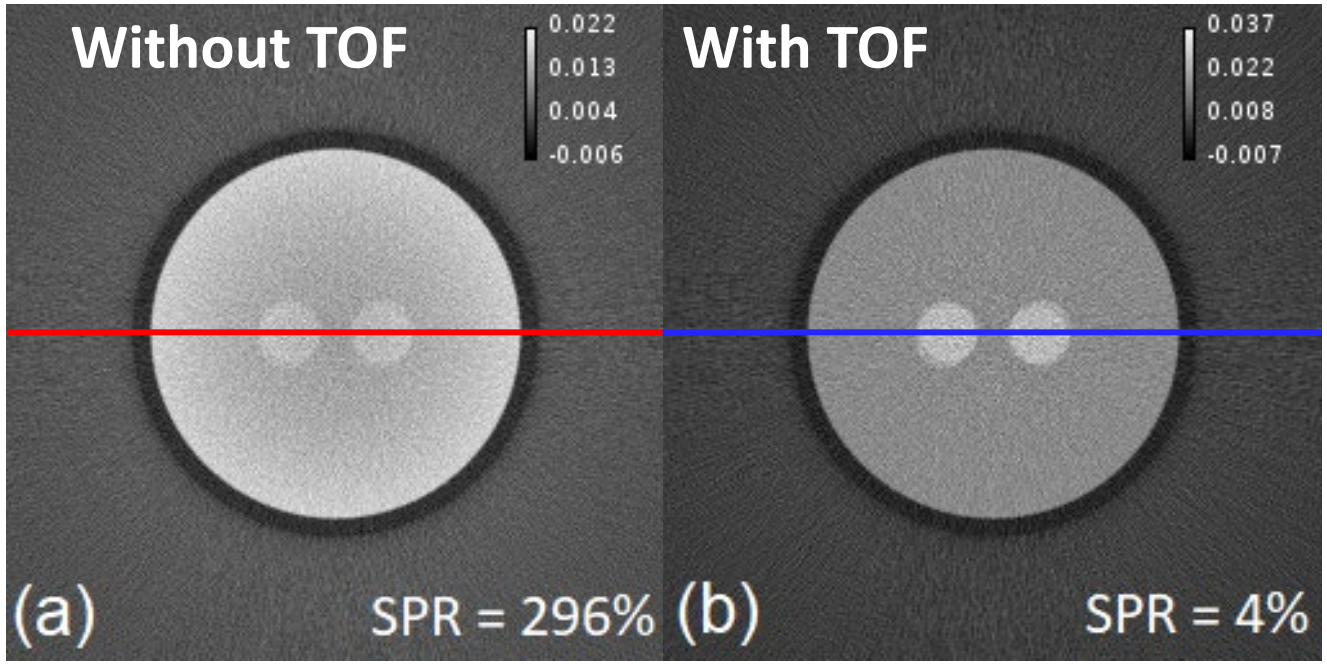
Metrics:

SPR & CNR & Dose

State of art in ToF X-ray technology

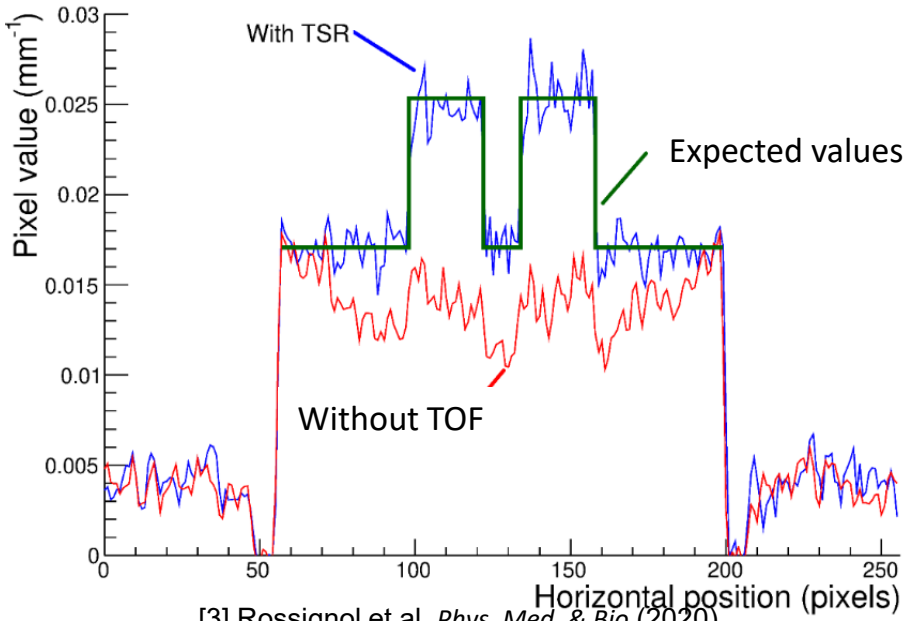
Scatter rejection by ToF

Two bones inserts in the water



a) CBCT simulated without ASG **b) With ToF scatter rejection**

SPR = Scattered counts / ballistic counts



[3] Rossignol et al. *Phys. Med. & Bio* (2020)

Line profile looks better: strong cup artefact reduction with a perfect ToF rejection

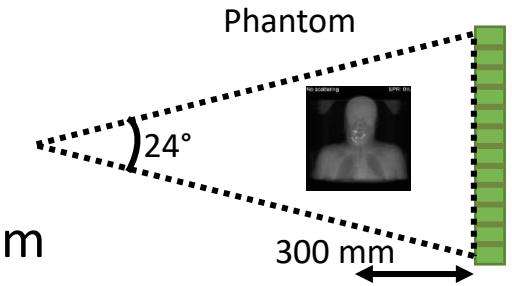
Slide from Julien Rossignol - Julien.Rossignol@usherbrooke.ca

State of art in ToF X-ray technology

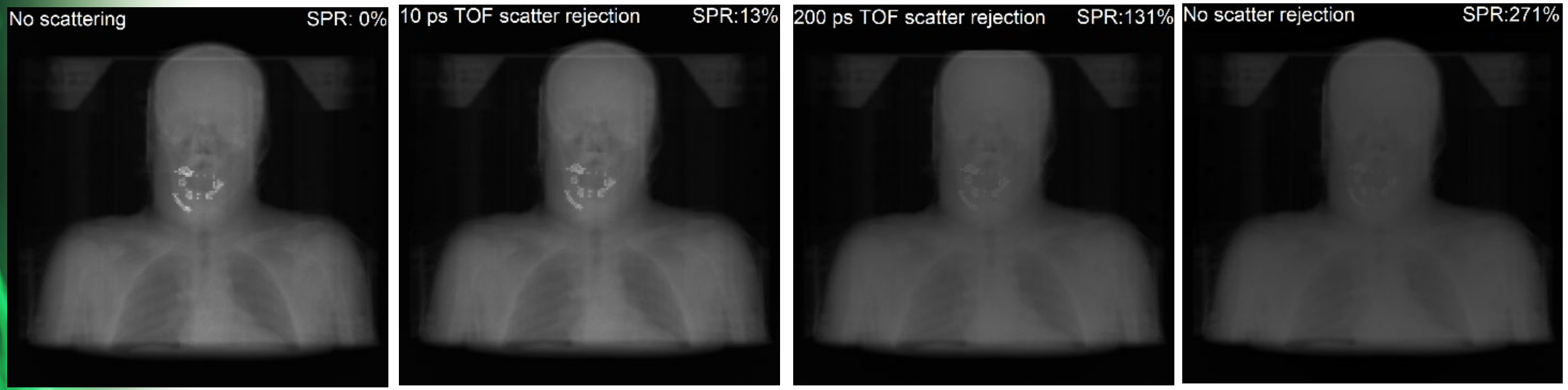
Scatter rejection by ToF windows in radiography

Simulation GATE :

- Without ASG
- Cone beam 80 keV
- Detectors : 640 x 640 x 2.5 mm^3 @ 300 mm behind phantom
- <20 keV are rejected



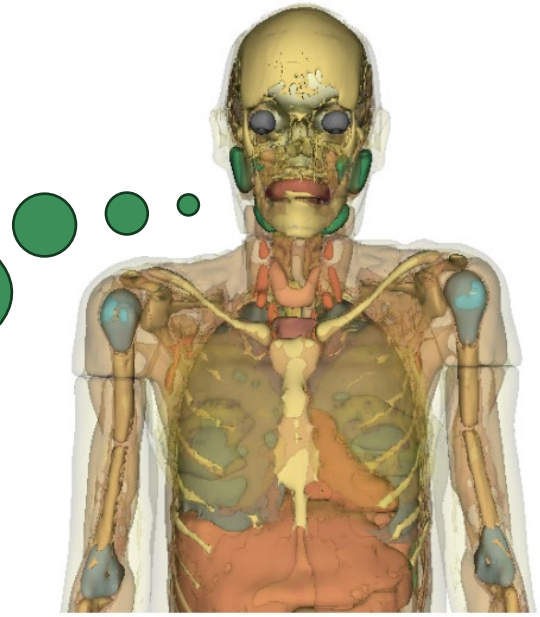
No scatter kept | **10 ps** | **200 ps** | **No scatter rejection**



Slide from: J. Rossignol et al. NSS-MIC 2021

Dose reduction at equivalent image quality CBCT vs ToF CBCT

A grid which reduces the sensitivity by 50% has a theoretical maximum dose reduction of 50%.



ICRP reference phantom used for the simulation [7] (visualizations by Julien Rossignol)

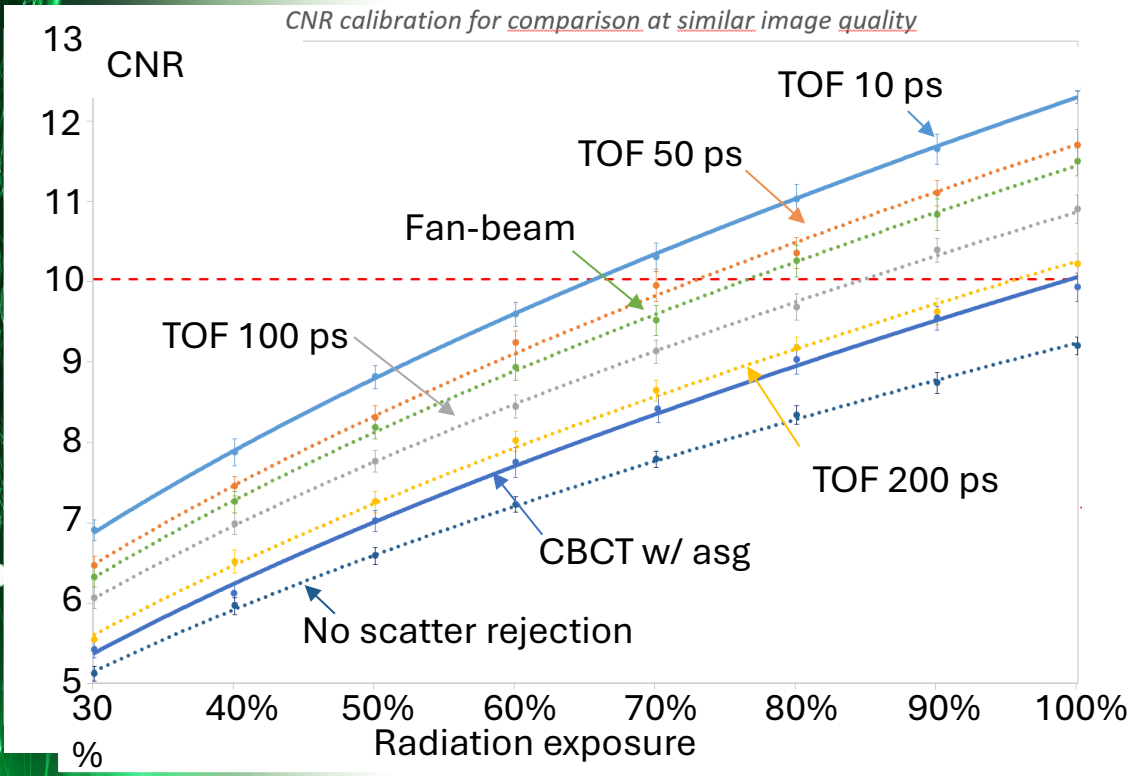
- Simulation study :
  CBCT with ASG Vs CBCT with TOF scatter rejection

- CNR is kept constant

[7] ICRP Publication 110 (2009), Annals of the ICRP, vol. 39, no. 2, pp. 1–44

Dose reduction at equivalent image quality CBCT vs ToF CBCT

- With a constant dose, CNR improve with TOF-CT threshold
- Dose reduction increase with TOF CT Threshold at



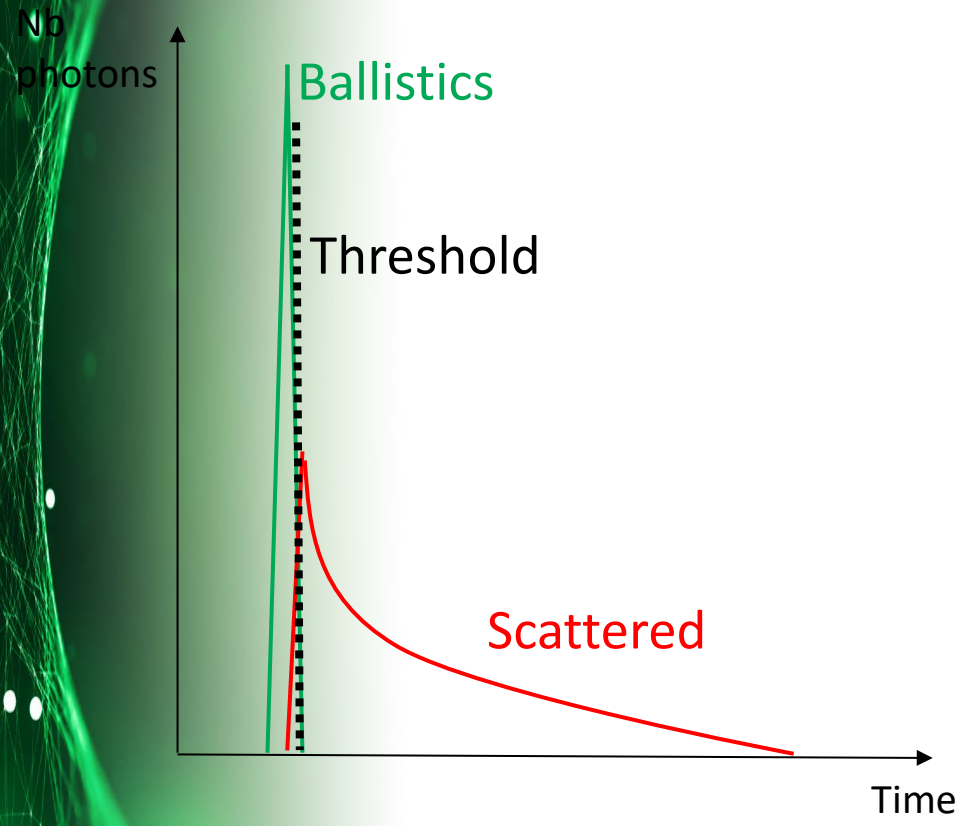
Simulation	CNR at 100% photon ($\alpha = 1$)	Dose reduction (at $\text{CNR}_\alpha = 9.9$)
CB TOF 10 ps	12.4	35%
CB TOF 50 ps	11.7	28%
CB TOF 100 ps	10.9	15%
CB TOF 200 ps	10.2	5%
Fan Beam	11.5	25%
CB with ASG	9.9	0%

- Dose reduction depend on the grid it is compared with

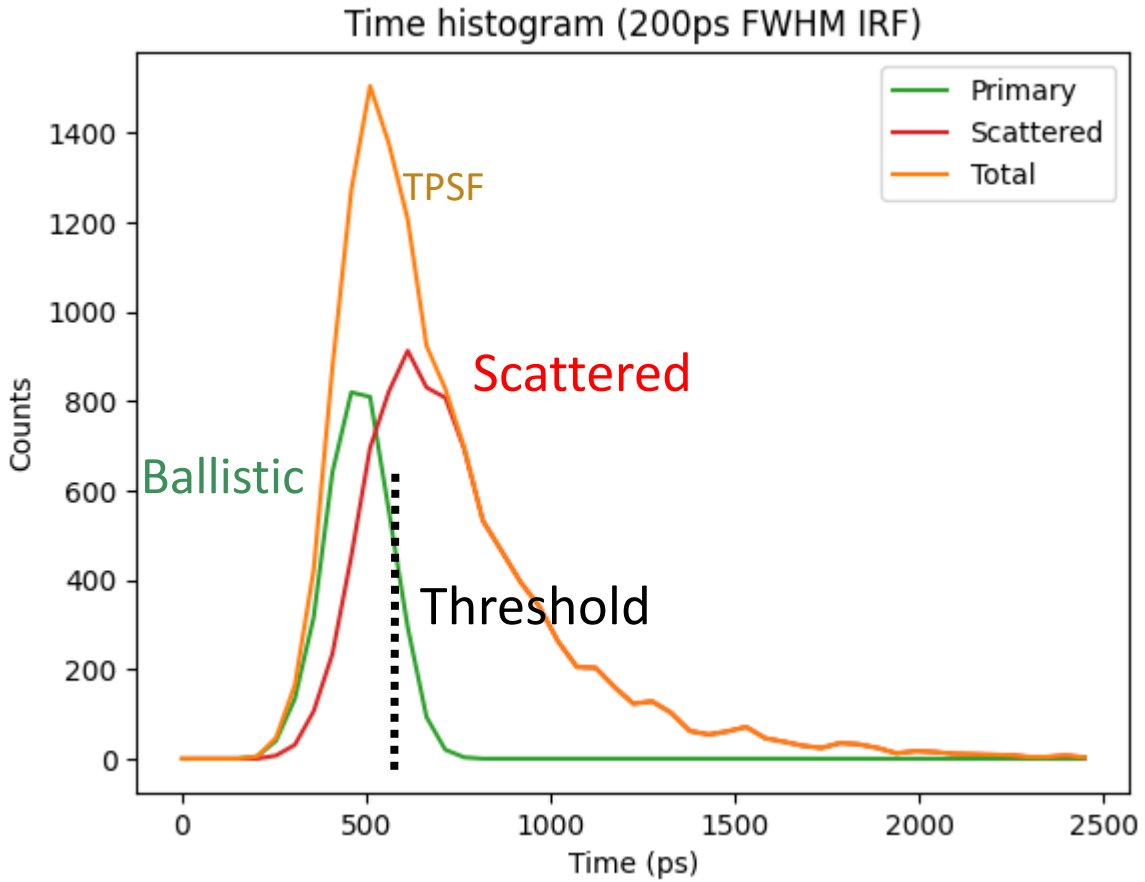
From G. Belanger, J.Rossignol, , Y. Berube-Lauziere, and R. Fontaine (2024), *Not submitted at this time*

Stat of art in ToF X-ray technology

Threshold a too simple way to scatter rejection?



Ideal TOF distribution



Measured TOF distribution

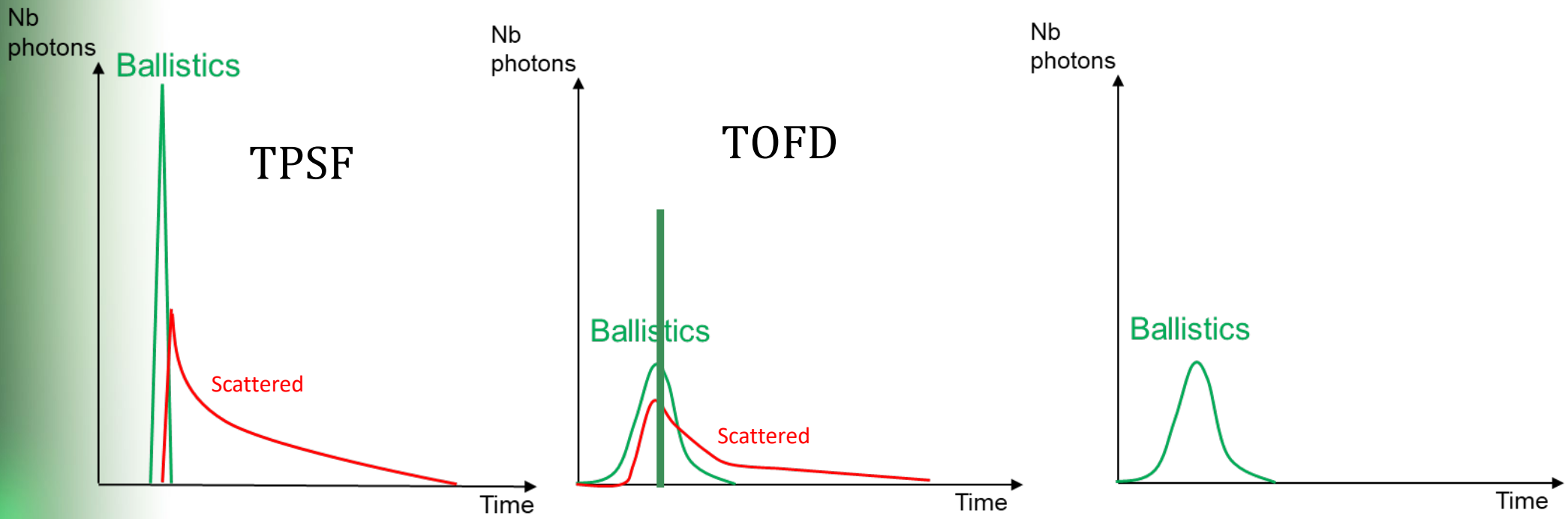
Stat of art in ToF X-ray technology

ToT scatter estimation for correction by deconvolution

Output of the detector: $\mathrm{TPSF}(\vec{r},t) = \mathrm{TOFD}(\vec{r},t) * S(t) * D(t)$

IRF

$S(t)$ is the X-ray pulse shape
$D(t)$ is the detector response function



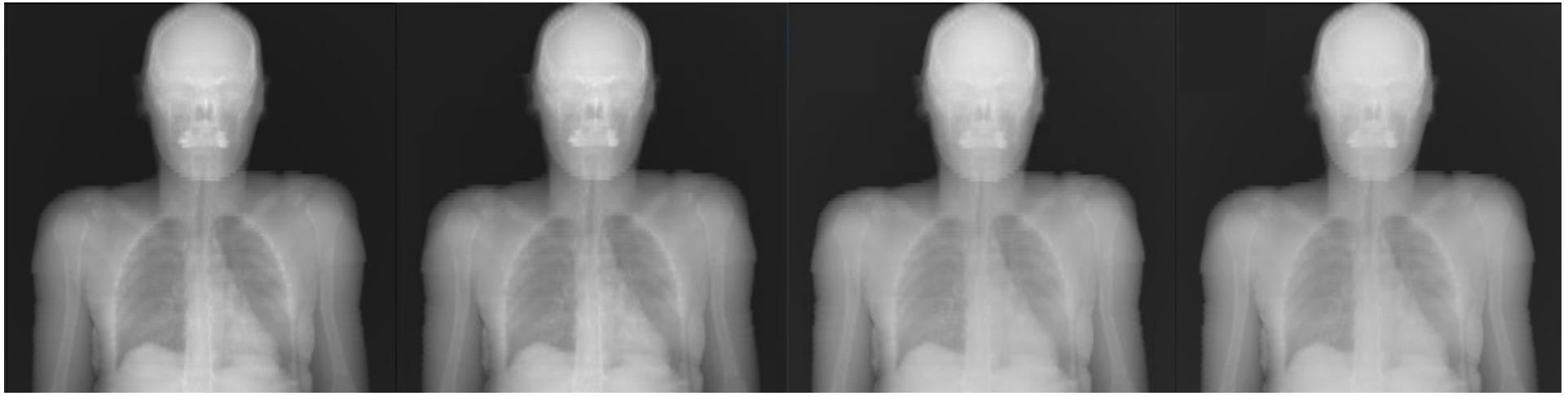
Rossignol et al. PMB 2024 Aug 29: 69(17)

Stat of art in ToF X-ray technology

Summary

300 ps FWHM Gaussian IRF

Perfect rejection	W/ deconvolution	Threshold only	No rejection



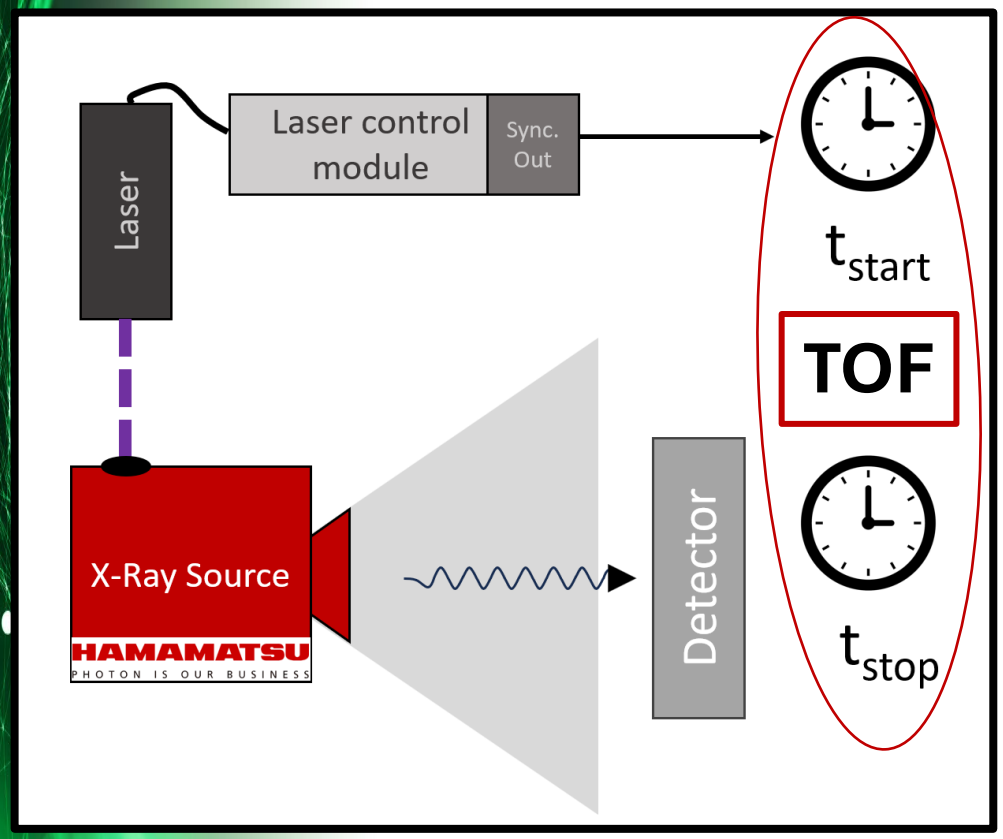
Normalised CNR	Normalised CNR	Normalised CNR	Normalised CNR
100 %	96.0 %	85.1 %	84.8 %
100 ps IRF :	98,9 %	85,4 %	*Patent submitted 2022

Is ToF-CT possible with current technology ?

Yes!

Meet the timing requirement between laboratory and simulation

SYSTEM OVERVIEW – X-ray source



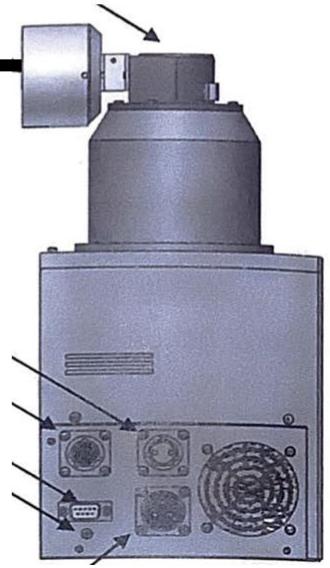
Laser control module



Laser head

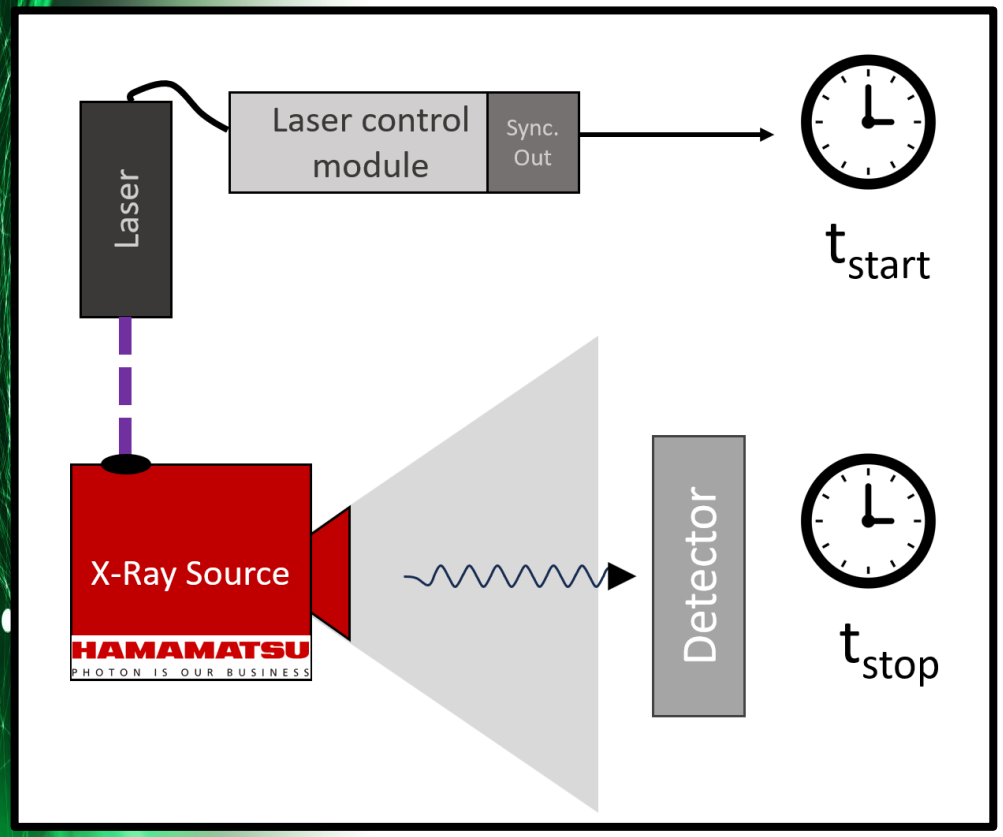


X-ray tube



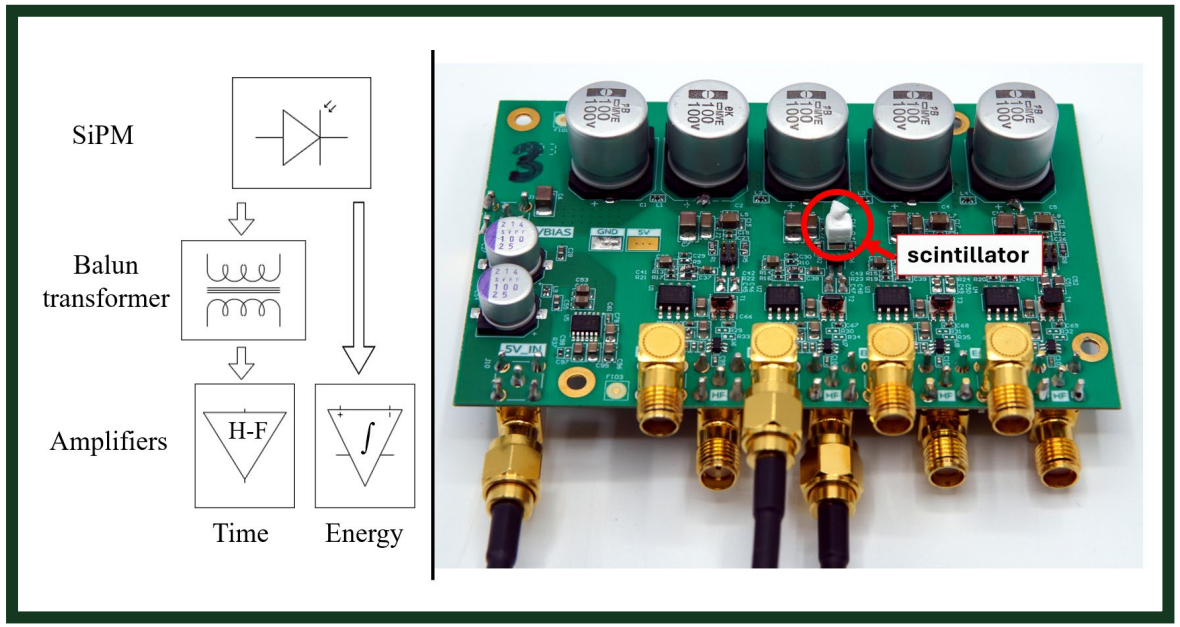
Photocathode	Conversion efficiency	45 mA/W (typ.)
X-ray source	Tube voltage	120 kVp (max.)
	Average tube current	10 µA (max.)
	Peak tube current	2 A (max.)
	Pulse width	< 100 ps (FWHM)
	Aperture	90°
Exposure rate @ 120 kVp - 1 MHz		1.88 R/min @ 30 cm
Dose rate @ 120 kVp - 1 MHz		1.285 Sv/hr @ 30 cm

SYSTEM OVERVIEW – Detectors



RF electronics

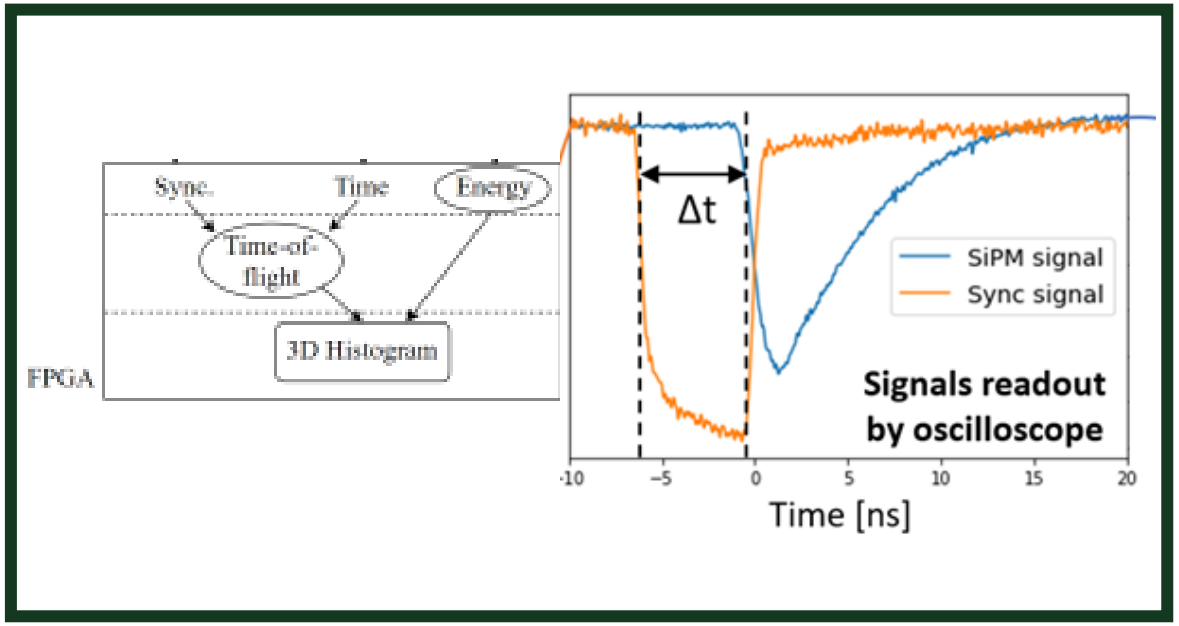
2: Prototype of 4-pixel detector module

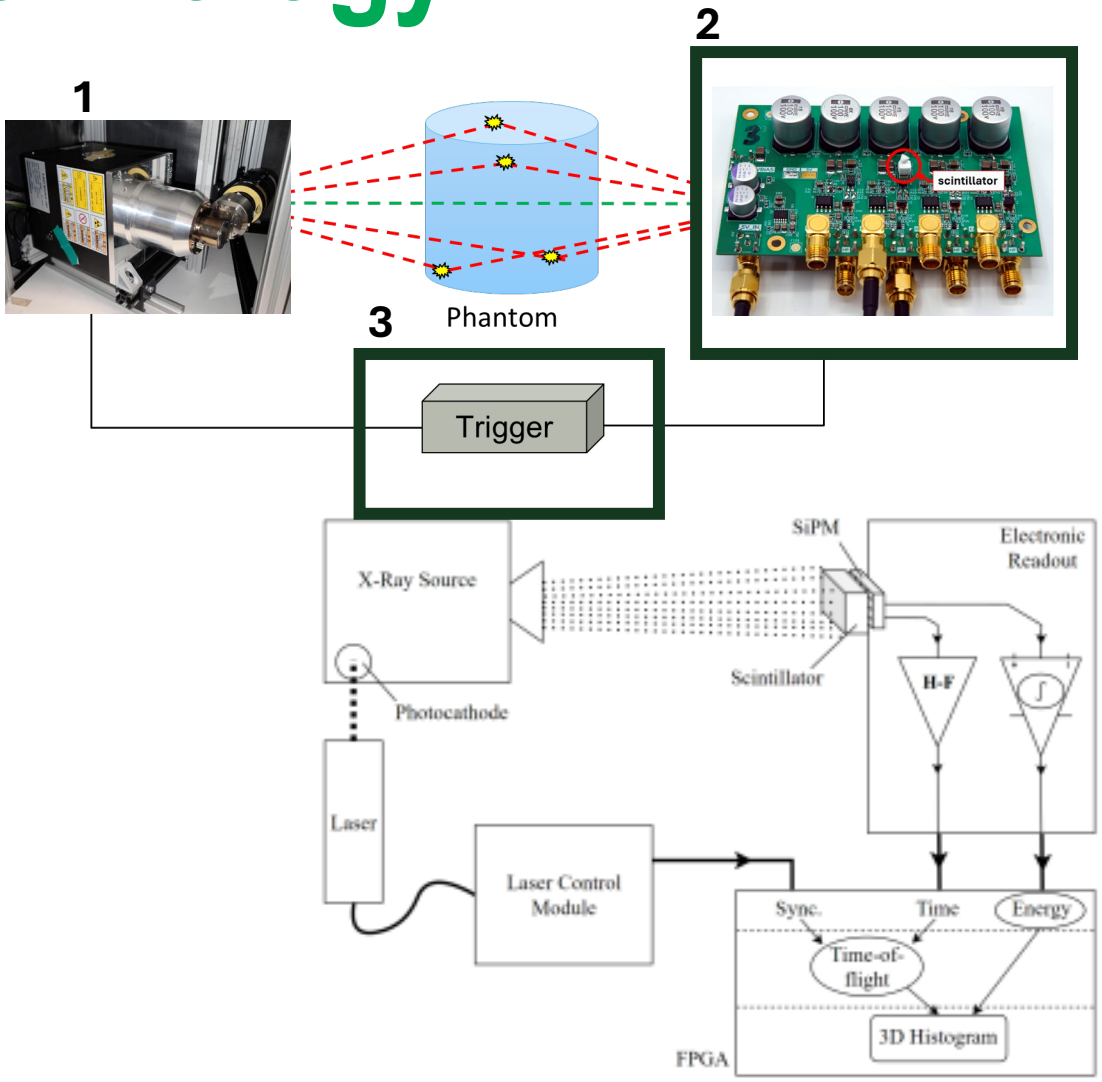


Stat of art in ToF X-ray technology

What we need? And have…

3: Synchronisation module (Time to digital converter)

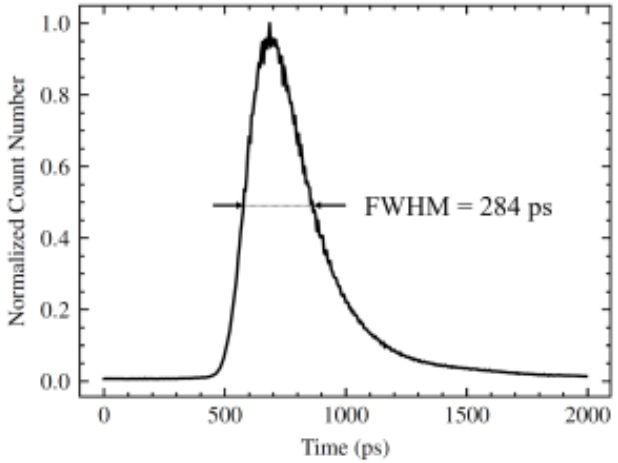




Stat of art in ToF X-ray technology

What we obtained ?

Without energy bin



With energy bin

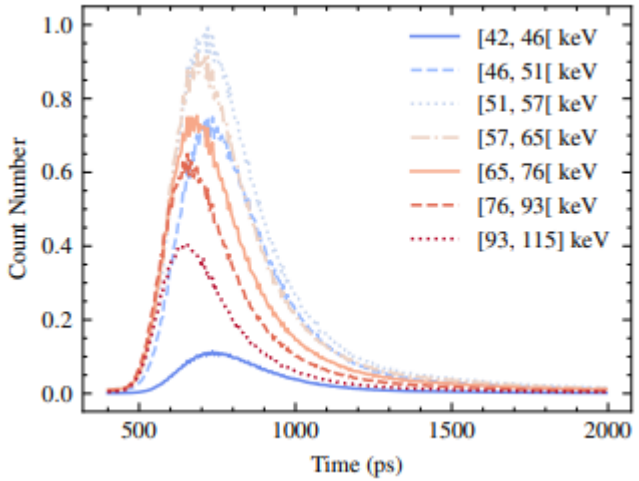
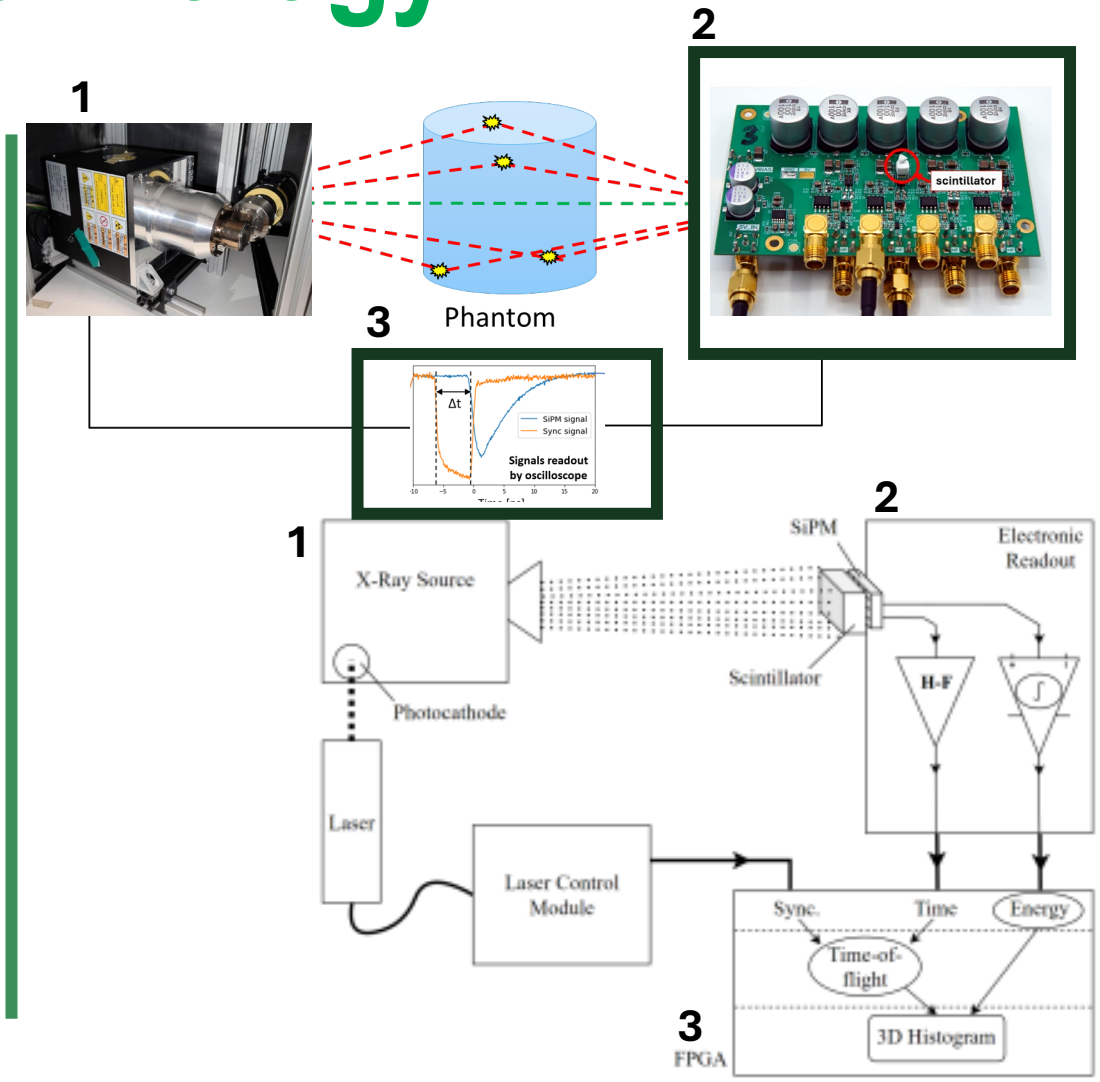
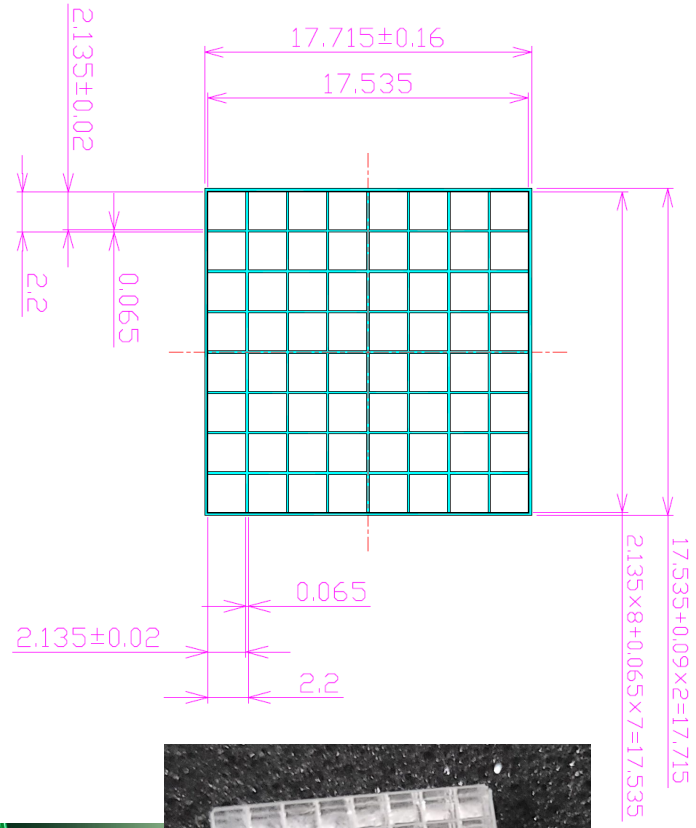


Fig. 14: Time response of the entire system, i.e. pulsed X-ray source detection by a scintillator-based photodetector, over the whole energy spectrum above 45 keV (V_{bias} = 39 V).



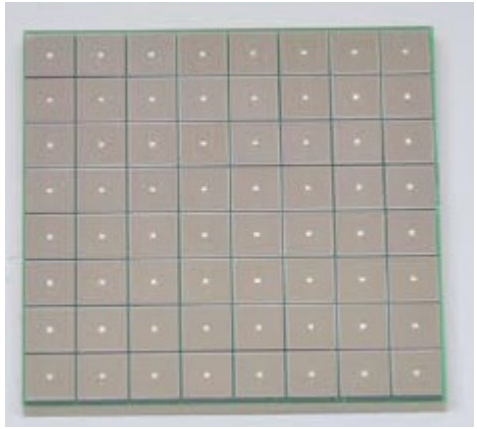
Multi pixel – set-up





Number of channels	-	64 (8 × 8)	-
Effective photosensitive area/channel	-	2 × 2	mm
Pixel pitch	-	50	μm
Number of pixels	-	1584	-
Fill factor	-	74	%

Parameter		Symbol	Value	Unit
Spectral response range		λ	320 to 900	nm
Peak sensitivity wavelength		λp	450	nm
Photon detection efficiency (λ=λp)*4		PDE	40	%
Dark count*5	Typ.	CD	300	kcps
	Max.		900	
Terminal capacitance		Ct	140	pF
Gain		M	1.7 × 10^6	-
Breakdown voltage		VBR	53 ± 5	V
Recommended operating voltage		Vop	VBR + 3	V
Vop variation between channels in one product	Typ.	-	0.1	V
	Max.		0.3	
Temperature coefficient of recommended operating voltage		ΔTVop	54	mV/°C

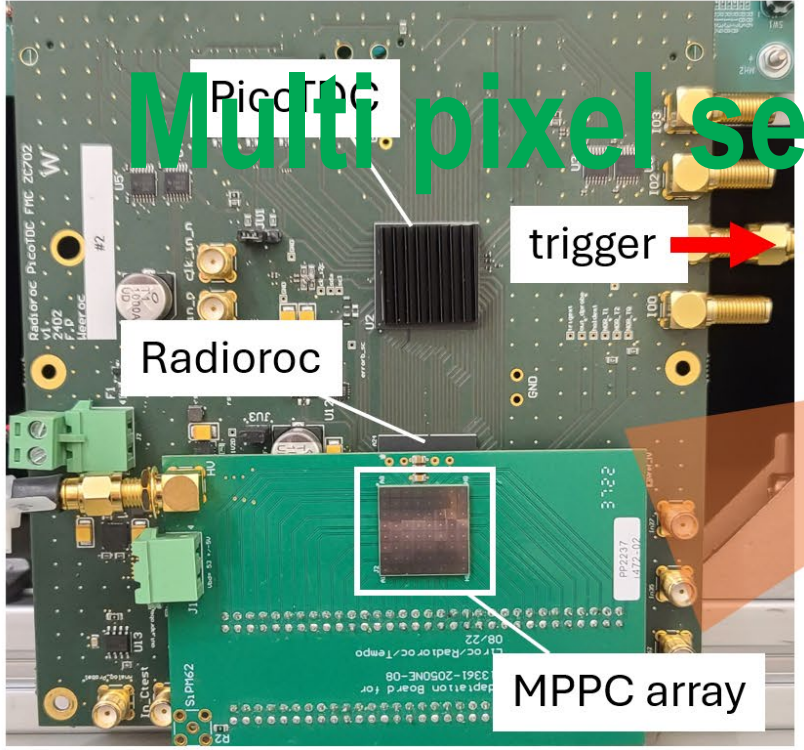


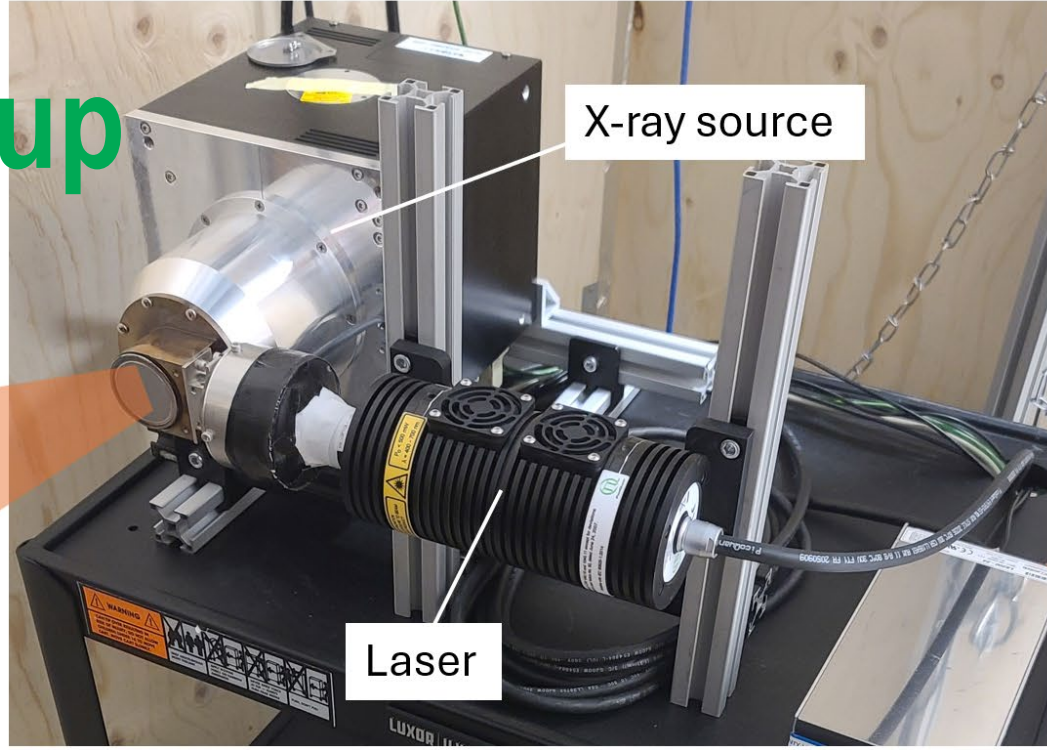
Fast-LGSO (Ce-doped$Lu_{2-x}Gd_xSiO_5$)

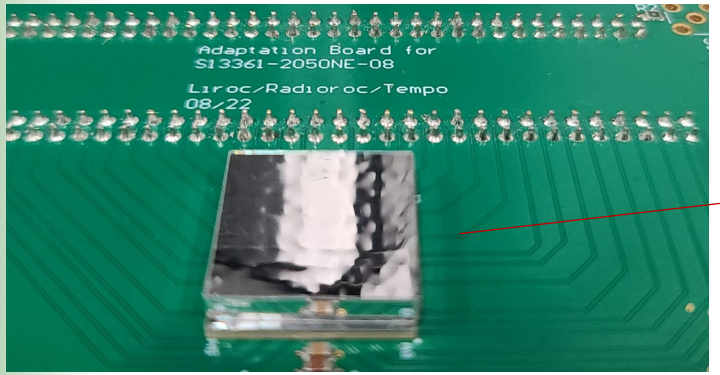
	Fast-LGSO
Light output (NaI=100)	~90
Decay time (ns)	30~36
Energy resolution (^{137}Cs, %)	8~10
Density (g/cm^3)	7.3~7.4
Hygroscopicity	No
Self-radiation	Yes

Lemaire et al, IEEE NSS/MIC 2025

Multi pixel set-up

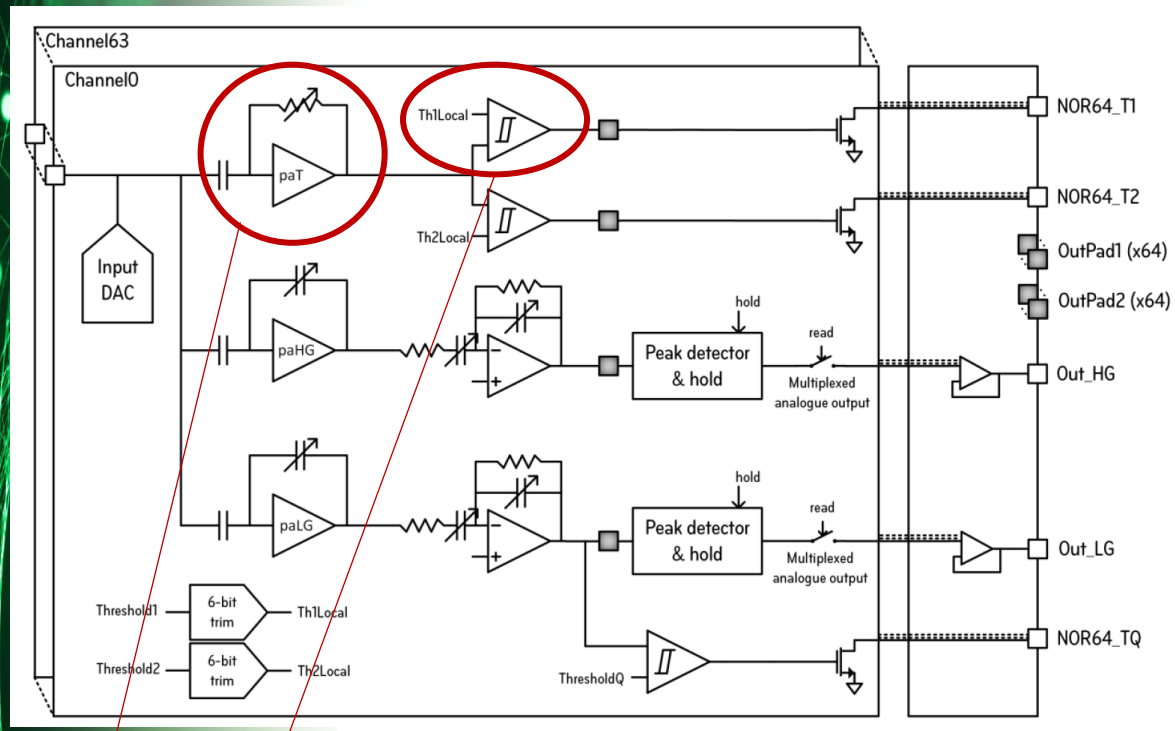






LGSO scintillator array

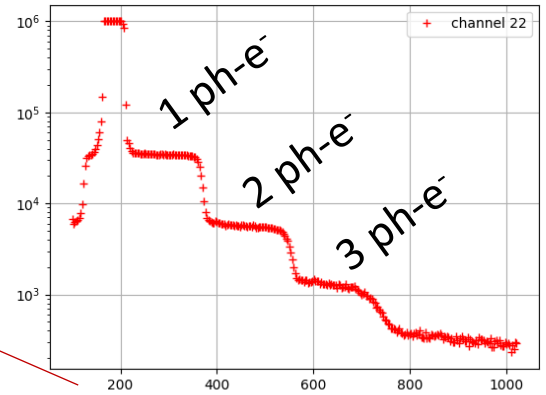
System Orerview – 64 channel Radioroc ASIC



Detector Read-Out	SiPM, SiPM array
Number of Channels	64
Signal Polarity	Positive
Sensitivity	Trigger on 1/3 of photo-electron
Timing Resolution	55 ps FWHM on single photo-electron @ 10^6 SIPM gain
Photocounting	200 MHz
Dynamic Range	Up to 2000 photo-electrons @ 10^6 SIPM gain
Packaging & Dimension	BGA 20x20 mm^2
Power Consumption	310mW – Supply voltage : 1.2 V
Inputs	64 analogue inputs with independent SiPM HV adjustments
Outputs	2 direct outputs per channel, selectable channel-per-channel, either : • 1 LVDS triggers • 2 TTL triggers • 1 TTL triggers and 1 analog outputs • 2 analog outputs 2 multiplexed analogue outputs 3 NOR64 trigger outputs
Internal Programmable Features (I2C)	64 HV adjustment for SiPM (64 x 8 bits), 3 trigger threshold tuning (10bits), channel-by-channel gain and shaping time adjustment (τ = 20 ns to 300 ns), individual trigger masking and cell powering.

gain

threshold



DCR : Dark Count Rate ≈ SiPM thermal noise

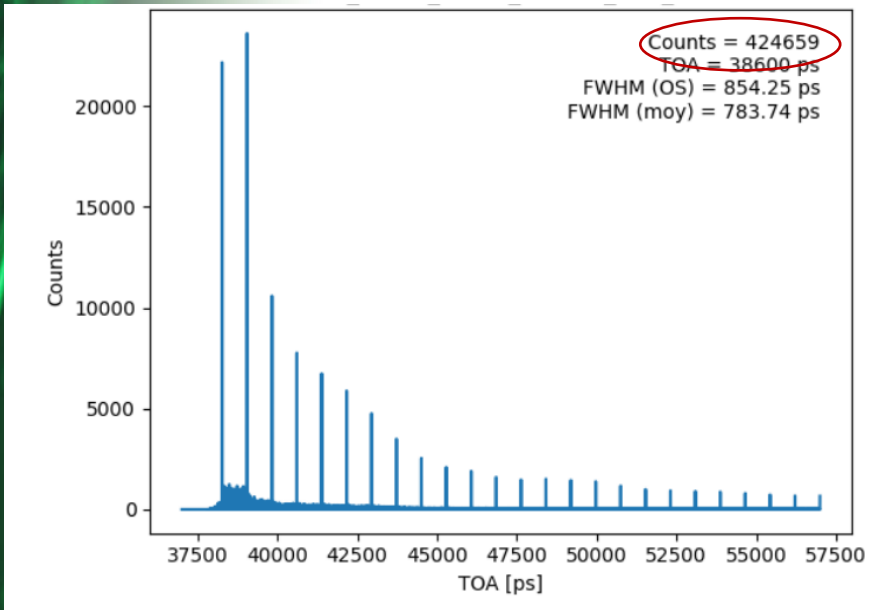
→ Dark count = 1,2,3,… SPADs (= photo-electron *ph-e⁻*)

→ n-SPADs events more probable than (n+1)-SPADs events

=> « Stairs » by sweeping detection thresholds and counting number of events

Lemaire et all, IEEE NSS/MIC 2025

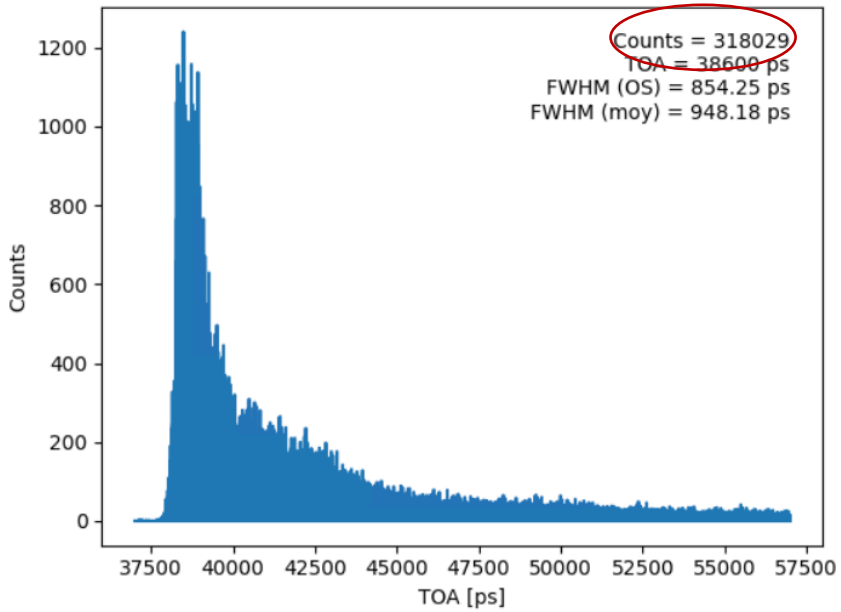
System overview - Preprocessing




```python
def shaver(hist, bins):
    offset = len(hist)//5

    p_ref = np.where(hist[offset:]==np.max(hist[offset:]))[0][0] + offset

    p_init = p_ref
    while p_init>=0:
        p_init -= 780.8/bins
    p_init += 780.8/bins

    p_list = np.arange(p_init, len(hist)-1, 780.8/bins, dtype=np.int32)

    for p in p_list:
        hist[p] = (hist[p-1]+hist[p+1])/2

    return hist
```

- ❑ Megabins period = 780.8 ps:
  - 3.05 ps bin → 256 bins
  - 6.1 ps bin → 128 bins
  - 12.2 ps bin → 64 bins
  - ...

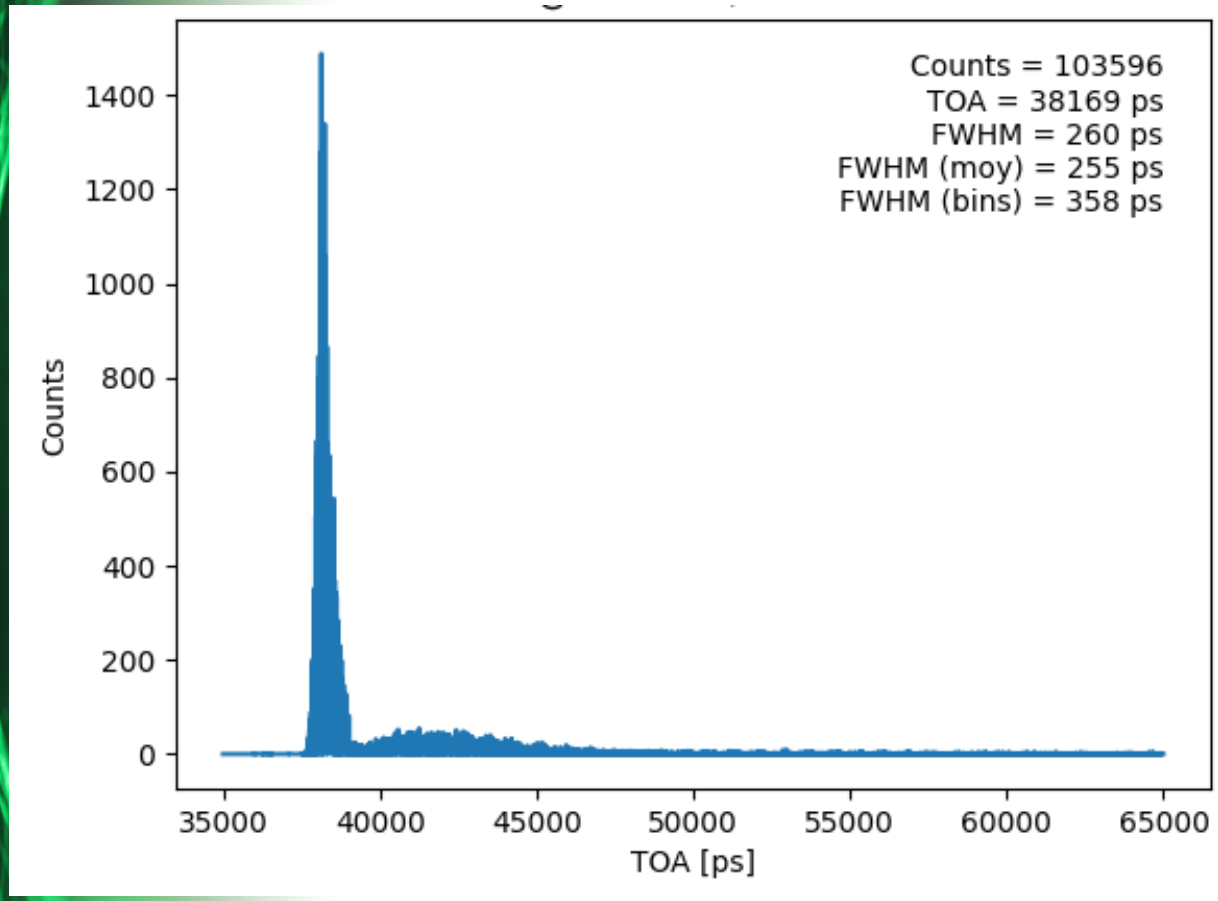
- ➢ Quick method : “shaving”
  = 25% data loss
- ➢ Best method : TDC calibration



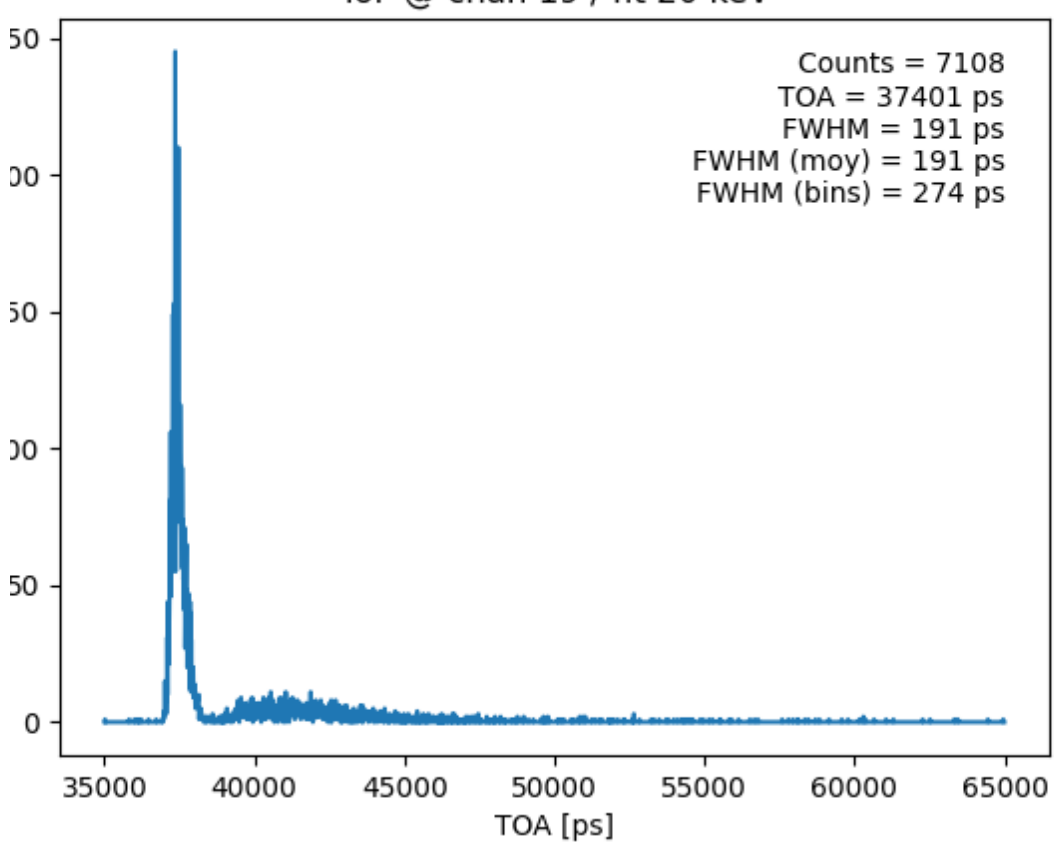
Lemaire et al, IEEE NSS/MIC 2025

Preliminary results

LGSO scintillator



New scintillator



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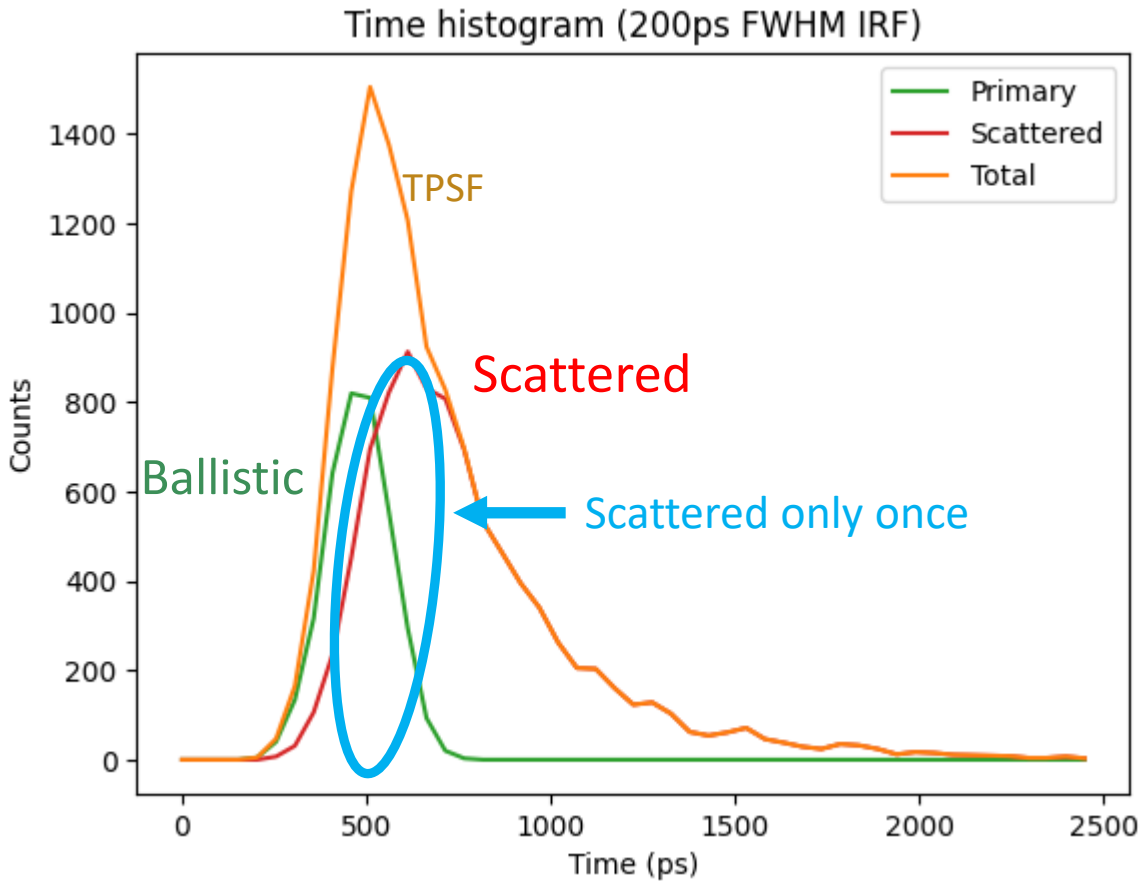
Potential for ToF X-ray technology

Scatter imaging

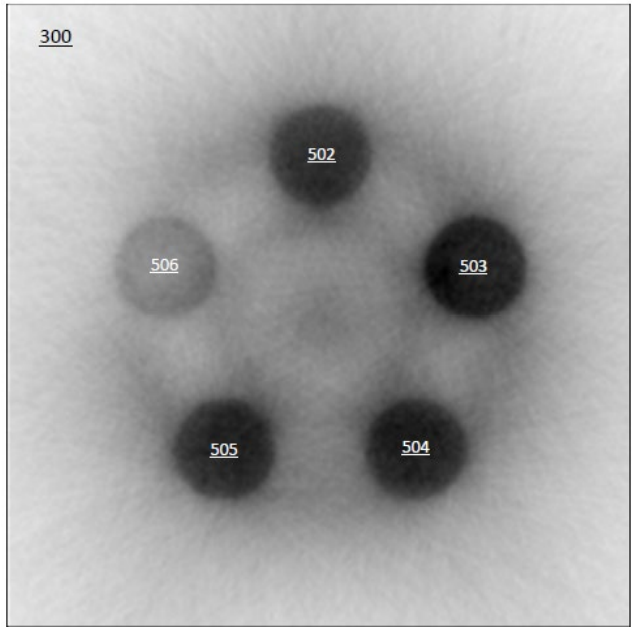


Measured TOF distribution

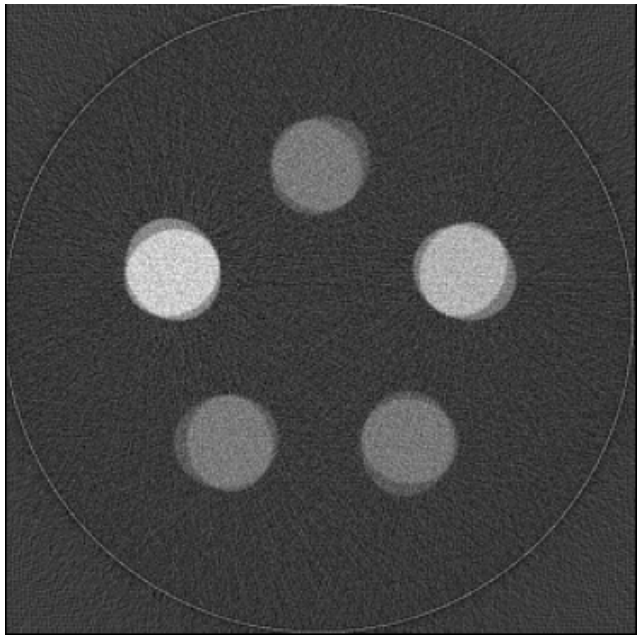
Potential for ToF X-ray technology

Scatter imaging

What if, rather than rejecting the scatters, they were used to create a new image and thus obtain more information?



Scattered photon image (diffusion coefficient)
(without attenuation correction)



Absorption image

Increase the efficiency of the imaging

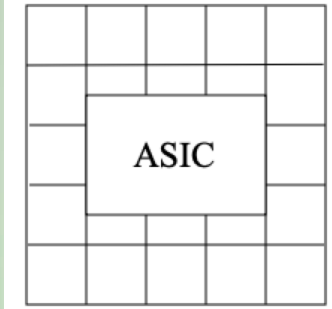
Patent submitted 2023

Short, mid- term expectations

Build scanner

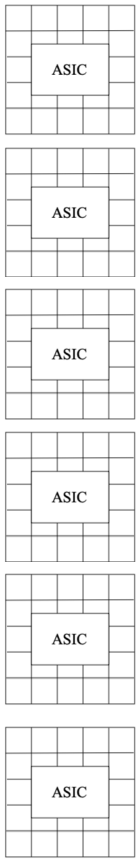
End 2025

A same detector module brick to build all the architectures



25 pixels with the electronics inside an ASIC

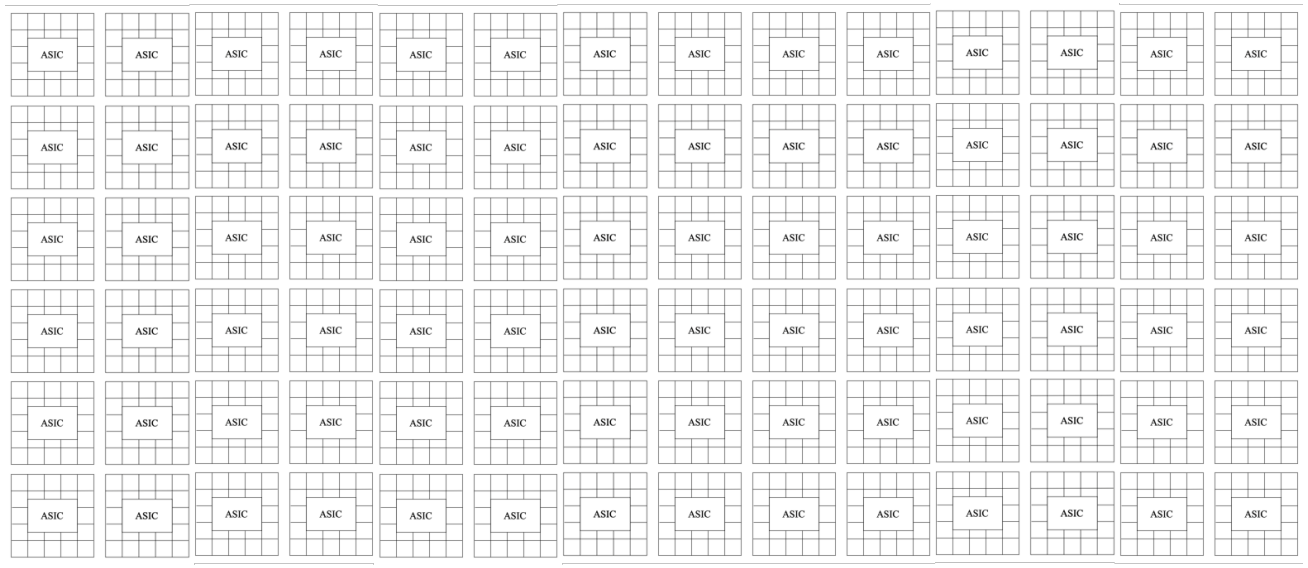
2027



Fan beam with 6x 25 pixels with 6 ASIC and embedded signal processing unit (ESPU)

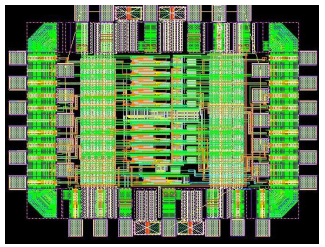


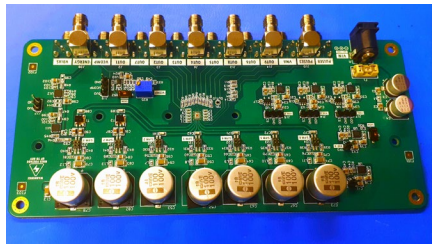
2028



Plaque with 14 x 6 x 25 pixels with 6 ASICs

An ASIC *(Application Specific Integrated Circuit)* for 8 channels is already in testing





Short, mid- term expectations

Timeline

FRQ-STRATEGIA Funded

Initiative TEMPSDEVOLX (1,1 M$)

⇩⇩

A ToF fan beam prototype for 2027 at Sherbrooke (Qc)

New Frontier in research Funds – Transformation ($24M)

2024 : Passed the LOI (25 out of 250 applications)

2025 : LOI Resubmitted 2025 (answer Oct 26th)

NEXT FRONTIER X project

⇩⇩

A) ToF radiography scanner (2028)
B) ToF Cone Beam CT (2030)

Implementation analysis + technology development in Pediatry in 3 Canadian provinces : Québec, Manitoba and Saskatchewan (2026-2031)

NEXT FRONTIER X in pediatry

- Better CNR
- Lower dose
- Conebeam CT
  - 12 cm at a time – NO sedation
  - Optimal axial uniformity

Short, mid- term expectations – NFRF-T

Study the transfer the technology to the healthcare systems

From the one-pixel laboratory measurement to clinical implementation

A HSS platform

I **Lacroix -**
Politic science
M-L **Arpin** -
Interdisciplinary management
A **Marchildon -**
Ethics
C-E **Daniel** -
Soft law regulatory

Support and guide the prototype development
Analysis and deployment of the technology in 3 Canadian province.

An engineer platform

R **Fontaine – Project leader**
Systems
M-A **Tétrault** -
Microelectronics
A **Corbeil Therrien** –
Data management
Y **Bérubé-Lauzière** –
Image reconstruction

Objectives

Develop the prototypes

Medicine platform

C **Viscogliosi** -
Technology implantation
D **Dufresne** –
Neuropaediatry
L **Beaulieu** –
Medicine physicist
E **Turcotte** –
Nucl med
B **Paquette** –
Physicists

Implementation
Clinical performance evaluation of dose and diagnostic efficiency

Collaborators and stakeholders

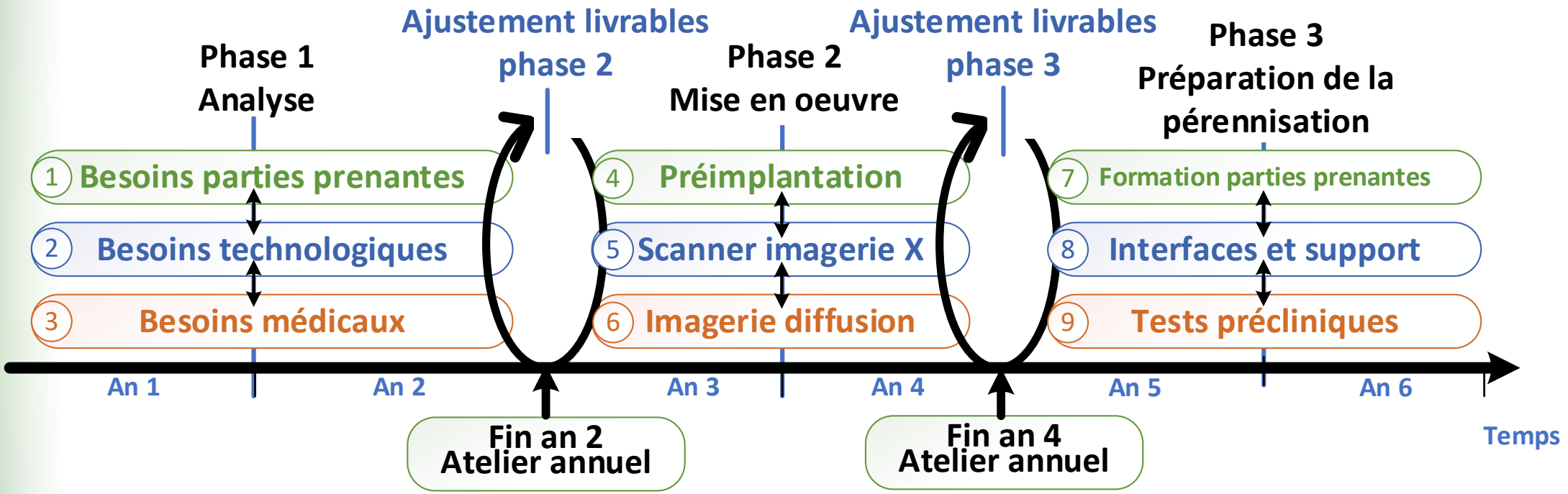
Health Canada, MSSS, CHUS, Ste-Justine, Ahuntsic, Manitoba care, SHA, CAR, COMP, SCP, OTIMROEPMQ

Hamamatsu, Siemens Healthineers Canada, Excelitas,

Triumph, CERN, RWTH

Support and guide the team

NEXT FRONTIER X in a figure



Interested in NEXT FRONTIER X ?

Email us:

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Romain.Espagnet@USherbrooke.ca



Conclusion

1. La TDM par temps de vol dépassera les performances du comptage de photons unique.
   - Meilleure qualité d'image
   - Réduction de dose
   - Capacité de scanner en conebeam
   - Ajout de l'imagerie par diffusion sans dose additionnelle

1. U. Sherbrooke conçoit cette première génération de scanner TDM-TdV
   - On RECRUTE des personnes étudiantes à la maîtrise et au PhD dans une équipe interdisciplinaire.

2. L'initiative NEXT FTRONTIER X vise le développement et l'étude d'une implantation et tente de créer un momentum Canadian pour changer l'imagerie X.

Thank you for your time

Rejean.Fontaine@USherbrooke.ca

