

Liquid xenon for nuclear medical imaging: outlooks on instrumentation

Marc-André Tétrault¹, for the LoLX collaboration

¹Université de Sherbrooke

Xesat, May 25th 2022

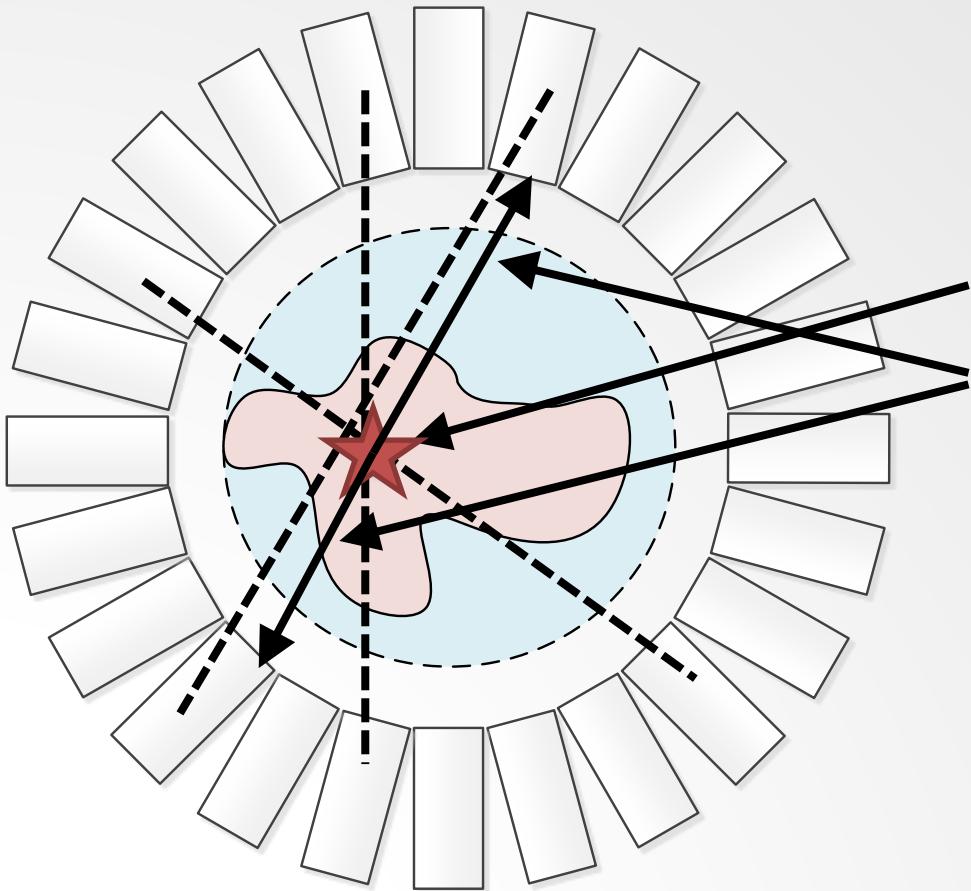


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Positron Emission Tomography

- Nuclear molecular imaging

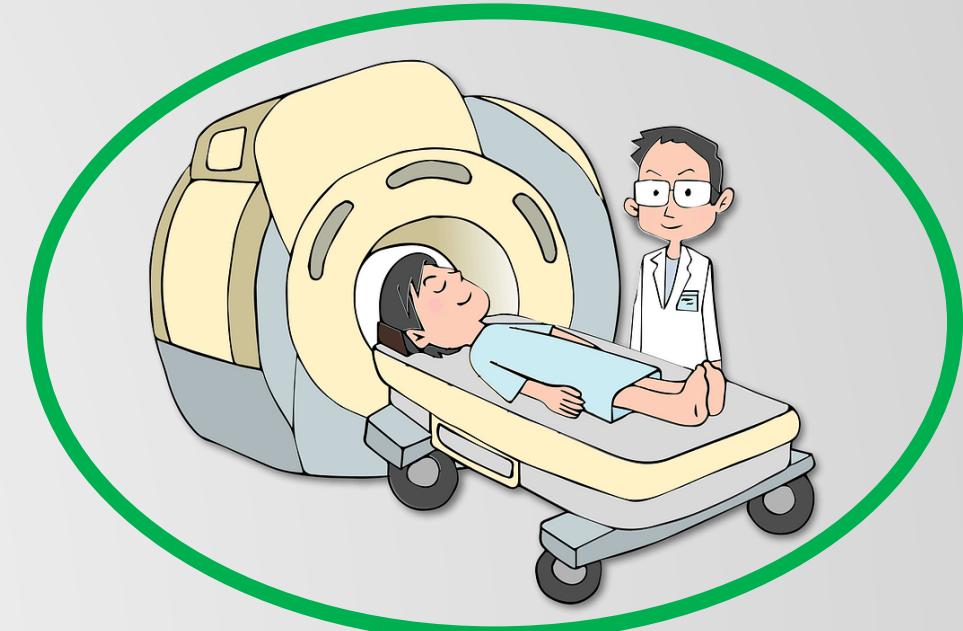
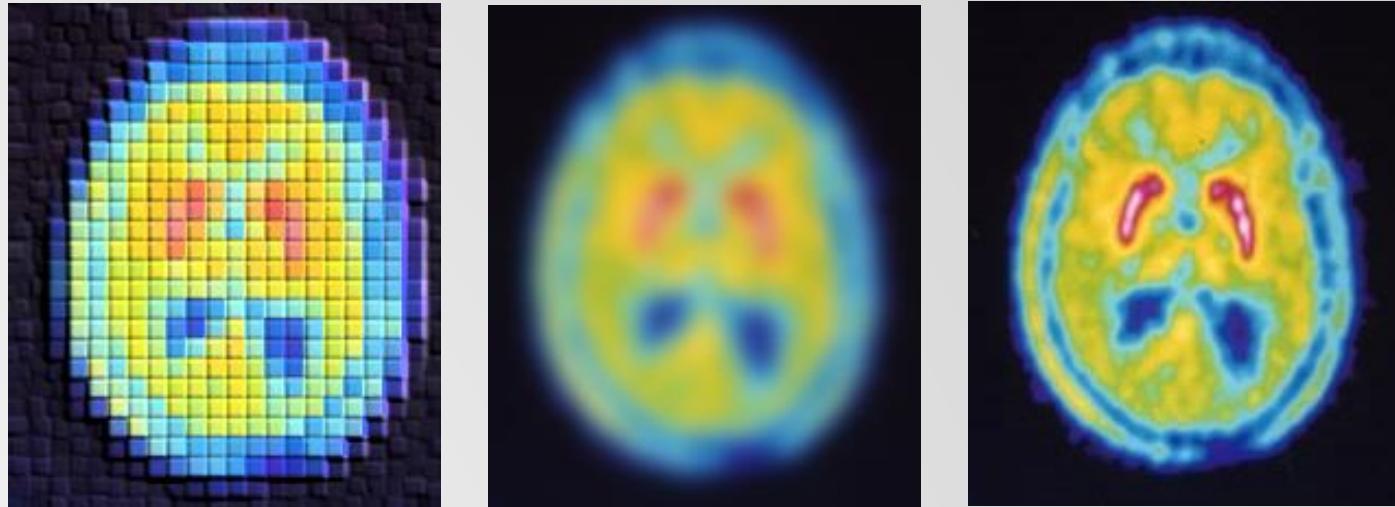


- Positron annihilation
- Collinear 511 keV particles
- Line of response



Goal of research in instrumentation for PET

- Image quality
 - Spatial resolution
 - Contrast to noise ratio
- Contrast = Sensitivity
 - Improve image or
 - Minimize dose to
 - Patient
 - Medical staff



Recent room temperature concepts

PET Explorer

- Full body PET
- High sensitivity
- 40x dose reduc.



<https://explorer.ucdavis.edu/news>

Badawi et al, JNM 2019

UHR/SAVANT

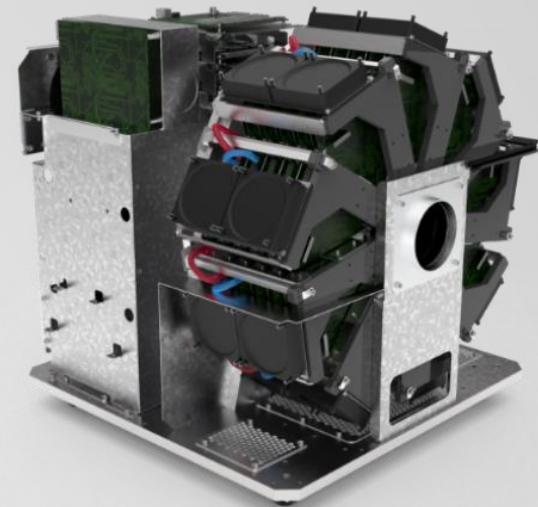
- 1:1 coupling
- no decoding
- Brain imaging



Lecomte et al, SNMMI 2022

Molecubes

- Monolithic slabs
- 64 SiPM/slab
- Preclinical

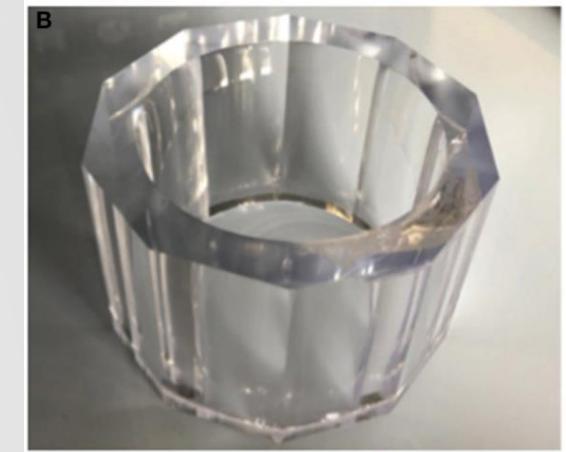


www.molecubes.com

Krishnamoorthy et al, PMB 2018

Full monolithic

- LYSO
- Sharing: TBD



Gonzalez et al, FM 2018

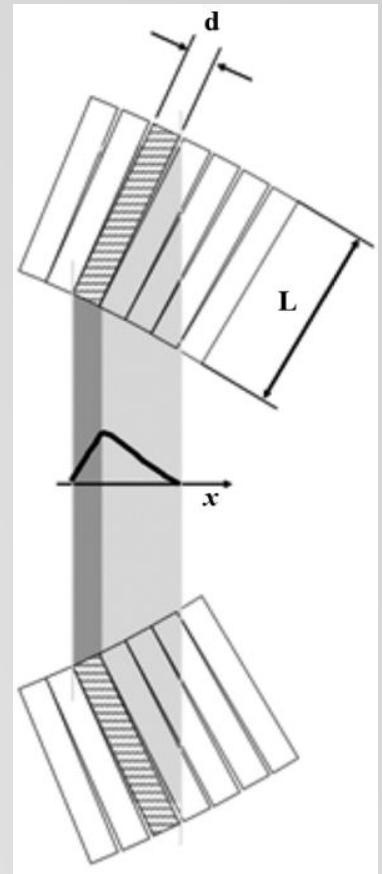
LXe for PET (and nuclear imaging)

- Masuda et al, NIM 1981
- Chepel et al, NIM 1997 (Coimbra University!)
 - Light + Charge
 - Multiwire chamber
- Doke et al, NIM 2006
 - Light only, PMT
- Miceli et al, JP 2011
- Gallin-Martel et al, NIM 2012
- Xemis-II (3-gamma), 2012-present
 - Previous talk
- PETALO, 2017-present
 - Next talk

All looking to improve detector

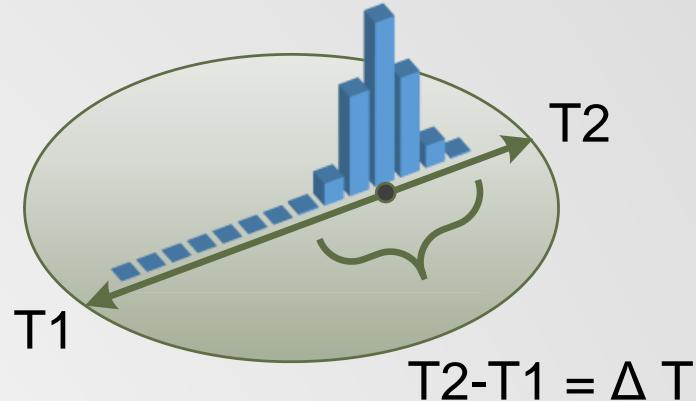
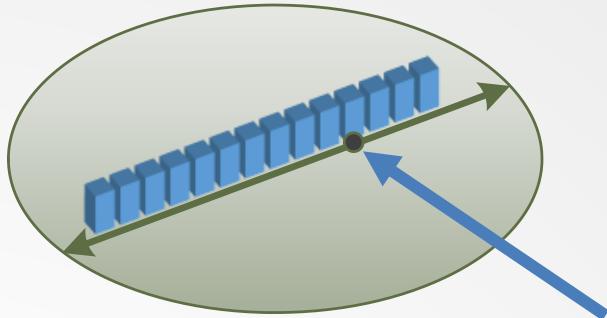
- Timing resolution
- Energy resolution
- Spatial resolution
- Parallax mitigation

Parallax error



Michaud et al, TNS 2010

Time of Flight to increase sensitivity

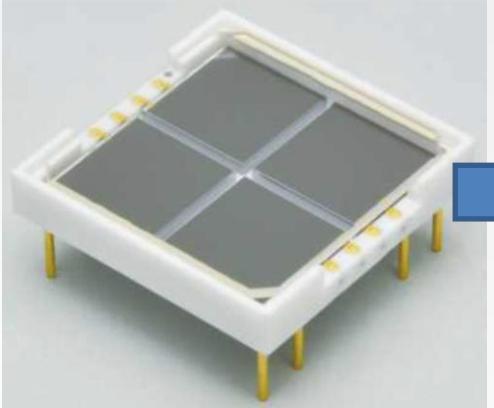


$$G_{sen} = \frac{2D}{c\Delta t}$$

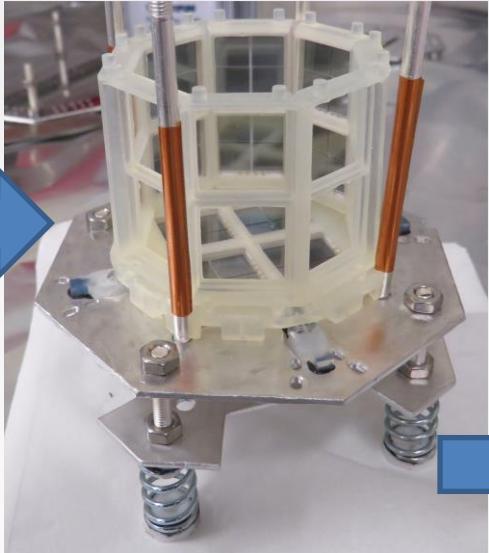
- Community goal of 10 picoseconds FWHM
 - <https://the10ps-challenge.org/>
 - Clinical systems @ 380 ps FWHM (LYSO crystals, Hsu et al, JNM 2017)
 - Lab setups @ 58.3 ps FWHM (LSO, Gundacker et al, PMB 2019)
- How close can we get with LXe?
 - Gomez-Cadenas et al, JI 2017: LXe + Cherenkov should reach 10 ps resolution (sensor-limited).
 - Need LXe cryostat and very fast photosensor to get experimental results

What is LoLX?

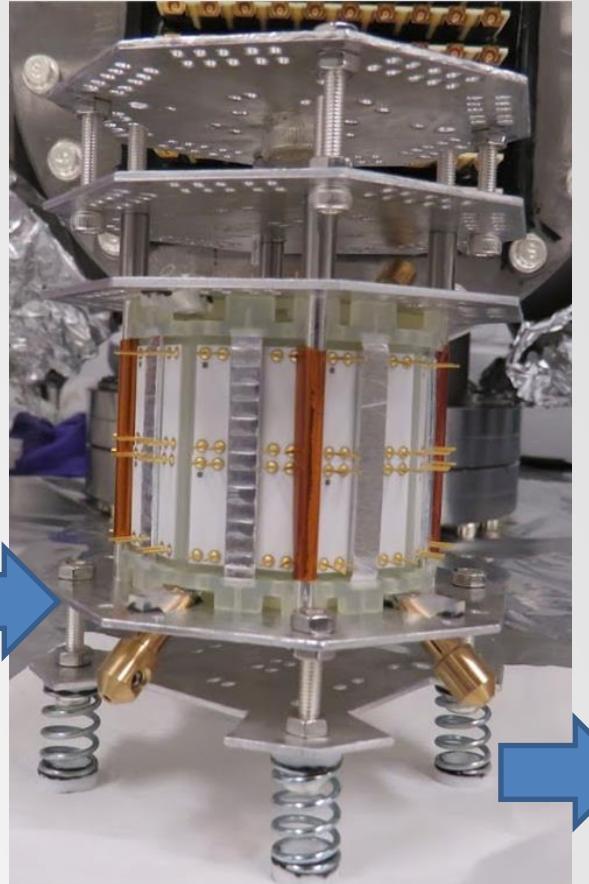
- Light only Liquid Xenon



1.5 cm x 1.5 cm VUV4 SiPM Quads
24 Hamamatsu modules



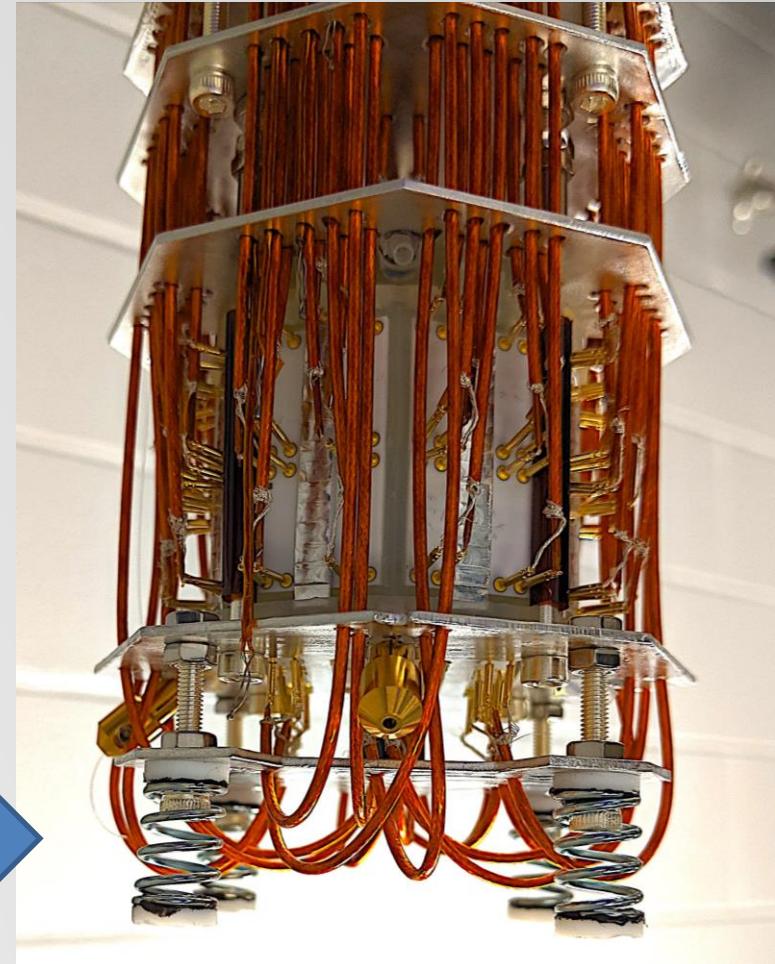
3D printed cage for SiPMs
during construction



Assembled LoLX Detector
(unwired)



WaveDAQ system (Meg-II)

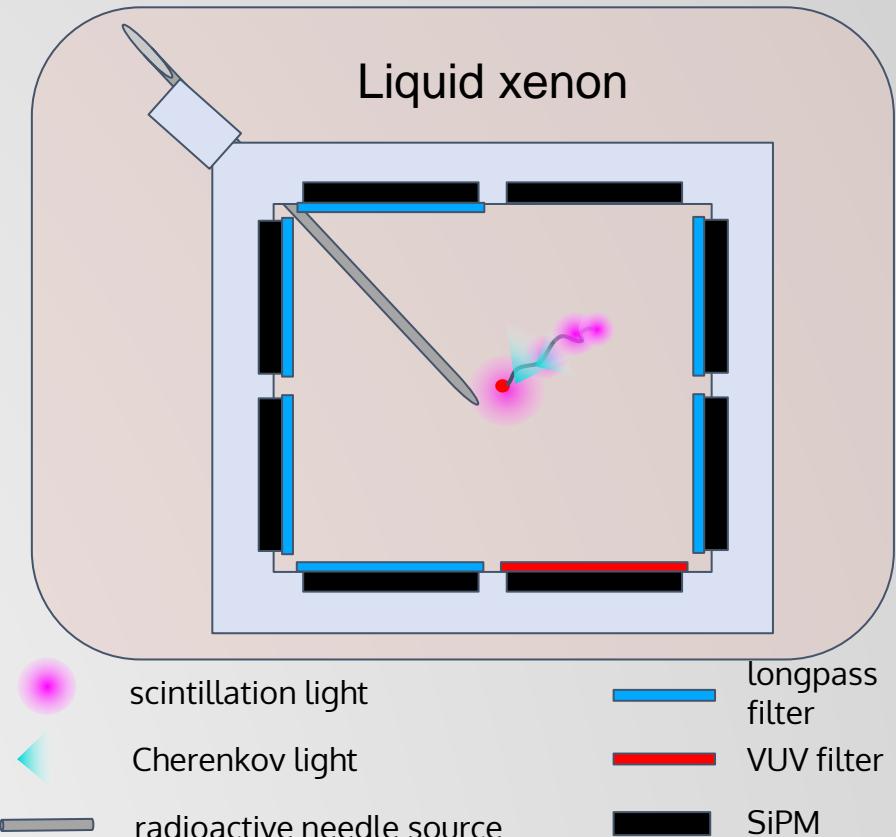


Assembled LoLX Detector
(wired)

Light only Liquid Xenon collaboration

- Physics goals (partial list)
 - Quantify Cherenkov using optics
 - Separate Cherenkov using timing
- Simulation goals
 - Validate photon transport in models
- Instrumentation goals
 - Quantify SiPM cross-talk
 - Ongoing analysis
 - Test emerging photosensors and concepts
 - Demonstrate 10-ps ToF-PET detector performance

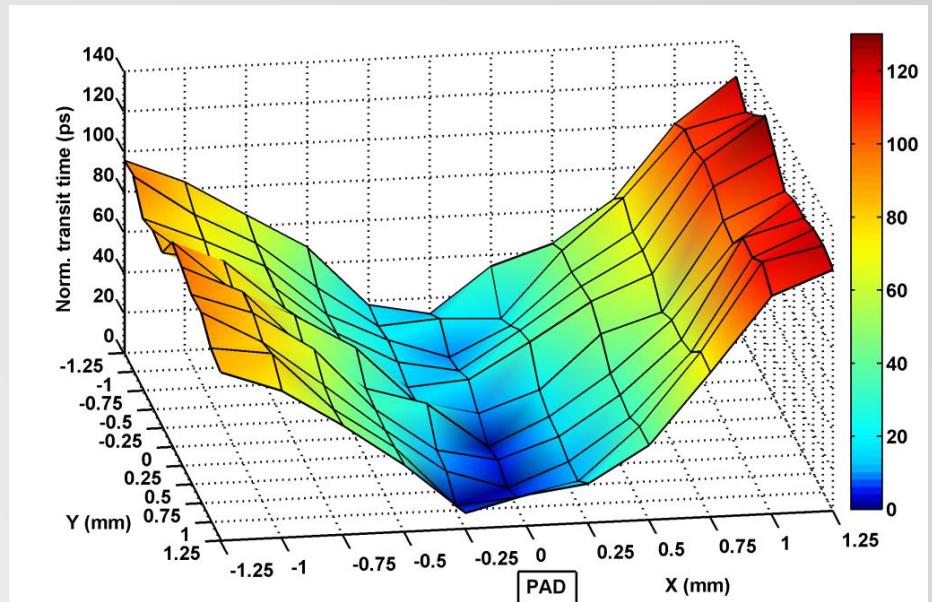
Source: Sr-90 beta (0.55 MeV) \rightarrow Y-90 beta (2.28 MeV)



(Figure by A. de St. Croix)

Barriers to 10 ps ToF-PET

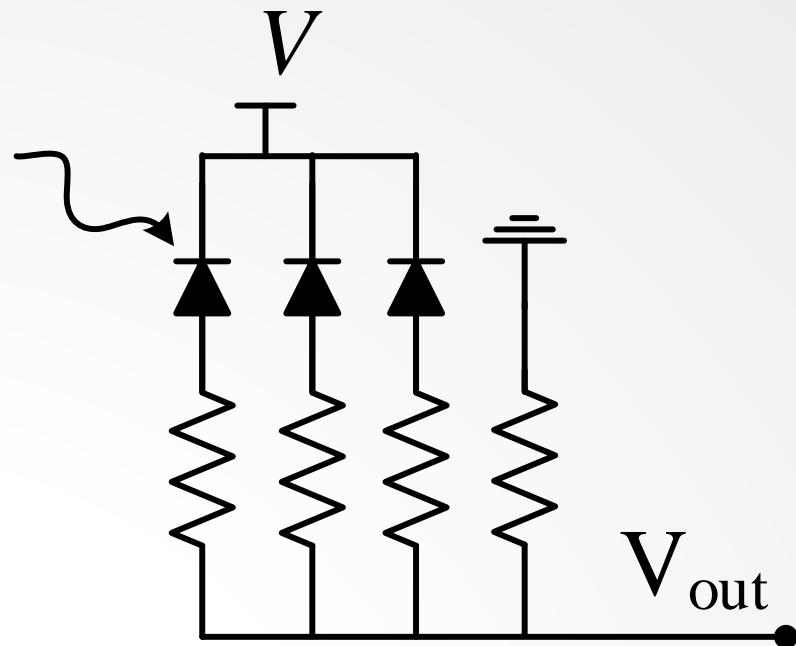
- In PET, photon statistics
 - For scintillation, $CTR \propto \sqrt{\frac{\tau_r \tau_d}{N_{pe}}}$
- Photosensor (SiPM)
 - Detection efficiency
 - Fill factor (or inversely, dead area)
 - Avalanche propagation
 - Readout electronics, parasitic cap.
 - Cell-to-cell skew ($\sim 35 \text{ ps/mm}$)
 - Nolet et al, IEEE TNS 2016



Acerbi et al, JI 2015; 3x3 mm² SiPM

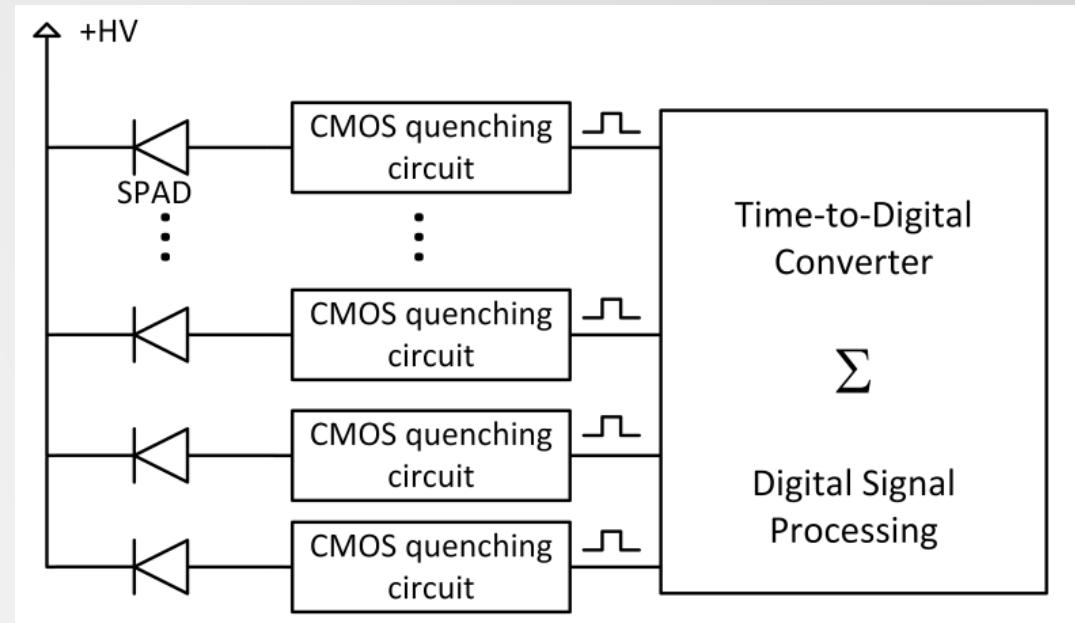
Types of SiPM

- Analog SiPM



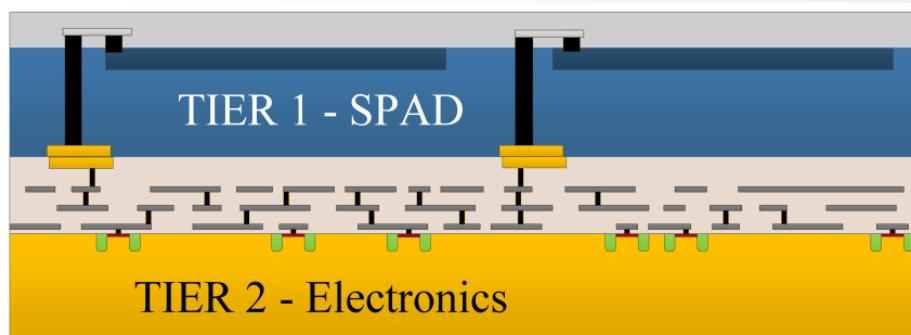
- Photon to digital converter

- a.k.a. digital SiPM
- Pratte et al, *Sensors* 2021

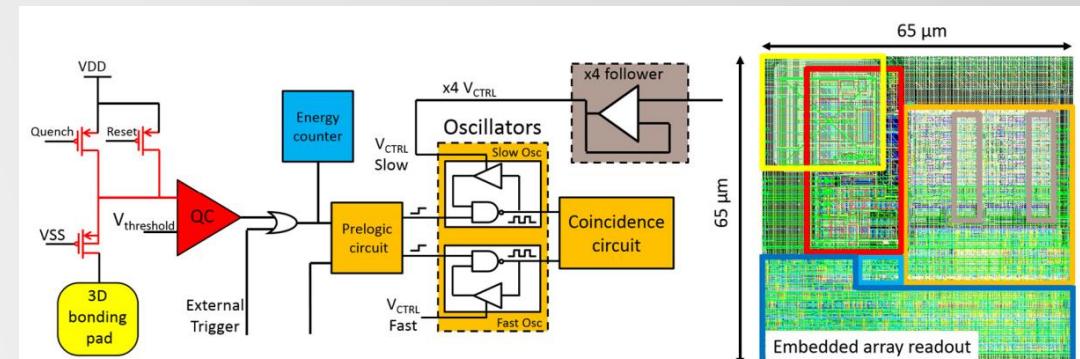


3D Integrated PDC R&D program

- J-F Pratte, UdeS
 - Combine good fill factor and smart electronics
 - Use optimal process for each layer
 - VUV photosensor layer in progress
 - Vachon, Master thesis 2021, UdeS
 - Commercial CMOS for timing and digital circuits



- « Some assembly required »
 - Photon counting in 180 nm
 - nEXO candidate photosensor
 - ps-range readout in 65 nm
 - 6.9 ps rms TDC @ 160 uW
 - Roy et al, IEEE TRPMS 2017
 - Array of 256 TDC cells
 - Nolet et al, NIM 2020



- LoLX Phase-3 roadmap sensor

Conclusion

- Improving sensitivity is a key path to better molecular imaging
- Large area SiPM and parasitics limit achievable LXe ToF-PET
- Instrumentation complexity is growing exponentially as timing is shrinking
 - 10 ps FWHM still seems possible!

LoLX collaboration



Fabrice Retière,
Austin de St. Croix,
Juliette Martin,
Liang Xie, Mayur Patel,
Peter Margetak

Simon Viel,
Bindiya Chana

Luca Galli,
Marco Francesconi



Thomas Brunner,
Soud Al Kharusi, Christopher
Chambers, Eamon Egan,
Bernadette Rebeiro,
Lisa Rudolph, David Gallacher

Pietro Giampa

Marc-André Tétrault,
El Mehdi Rtimi
Alaa Al Masri