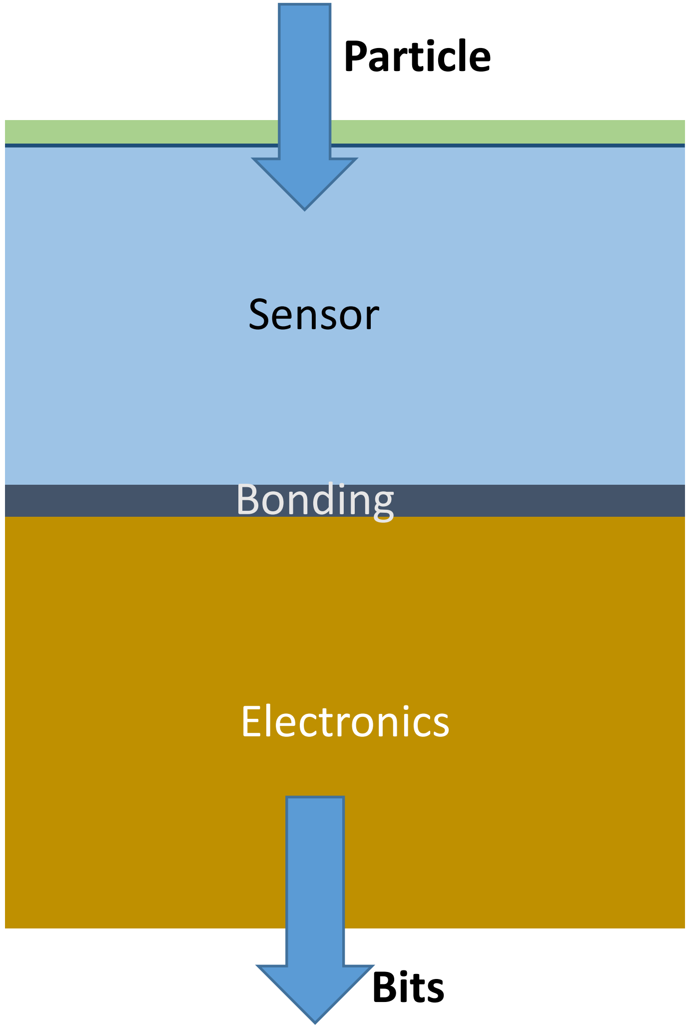
Photon/particle to Digital Converter

Fabrice Retière (TRIUMF)

For the PDC group

Discovery, accelerated

Concept. What is a PPDC?



- Particle = photon, Minimum ionizing particle, heavy ionizing particle,…
- Integrated system for sensing particle and generating digital data
- Two options
  - Monolithic, i.e. fully integrated
    - Thin, but forces drastic compromises
  - **Separate sensing and electronics features: this talk**

Outline

- Enable groundbreaking Discovery
- Physics meets technology
- Well connected and nibble
- Building a better world

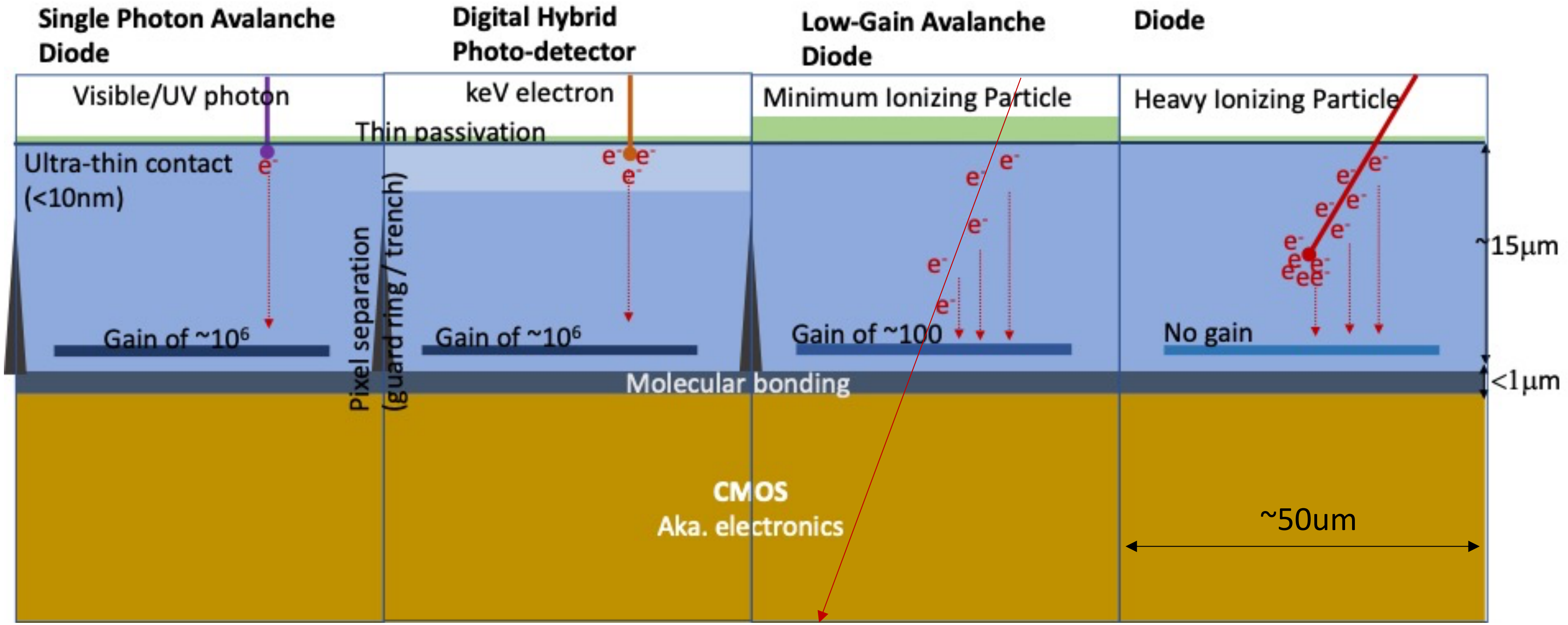
Enabling ground-breaking discovery

- Neutrinos
  - Hyper-Kamiokande - large area photon detection (350-500nm – room T)
  - DUNE - large area photon detection in Liquid Argon (128nm/420nm - 86K)
  - nEXO – large area photon detection in liquid Xenon (175nm – -100C)
  - P-ONE/IceCUBE
- Direct dark Matter detection
  - ARGO
  - DARWIN
- Colliders – Minimum ionizing particle
  - Tracking – radiation hard, low mass, high timing resolution
- Nuclear physics
  - Heavy ionizing particle detection
- μSR – the pico-second era

Performances – the picosecond era is here

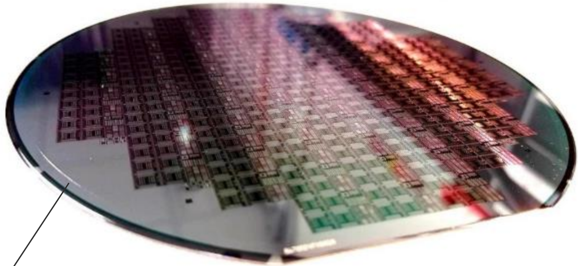
- Picosecond scale ~ mm scale
  - Digital integration enable managing jitters down to 10ps and probably 1ps
- Good for physics?
  - Identify each collision at the LHC – handle pile-up in high luminosity era
    - ~1 vertex/interaction per mm at high-luminosity LHC
  - uSR with plastic scintillator or ps-tracking detectors?
  - Gamma ray detection. Is there a fast-enough scintillator?
    - Pico-second scale is the holly grail for positron emission tomography
  - Cerenkov light – fast enough but not very bright
    - Compelling at GeV scale
  - Very fast excitation – de-excitation processes?
    - Femtosecond laser for measuring picosecond decay process?

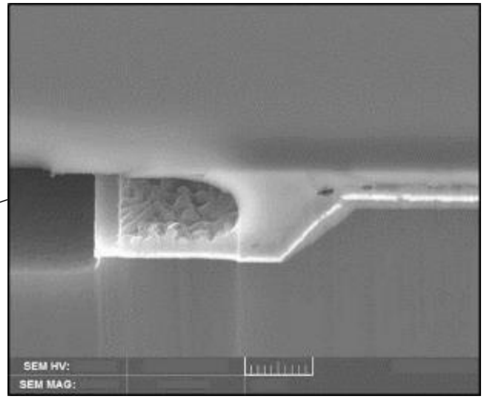
Technology scope



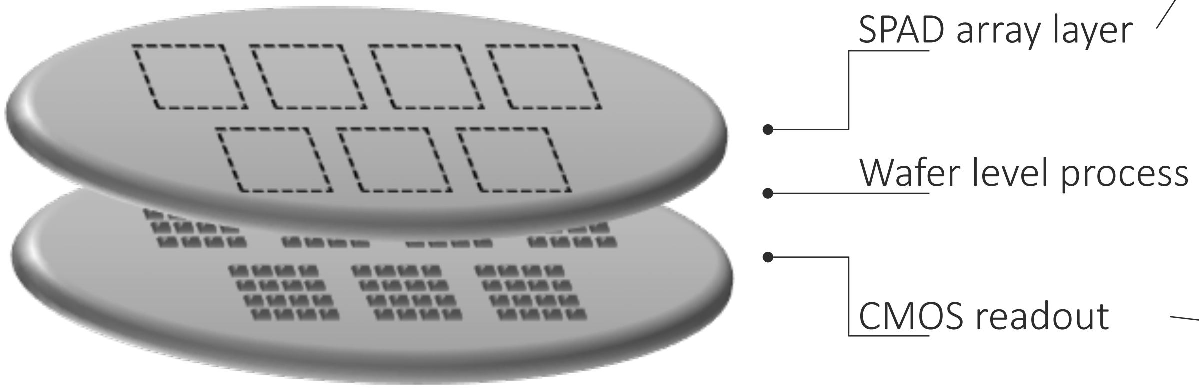
Building such an object – The Sherbrooke – DALSA partnership

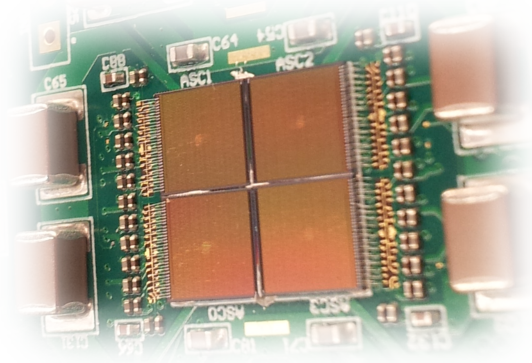
Partnership with Teledyne DALSA Semiconductor Inc.
(Bromont QC, Canada)


SPAD process

3D process


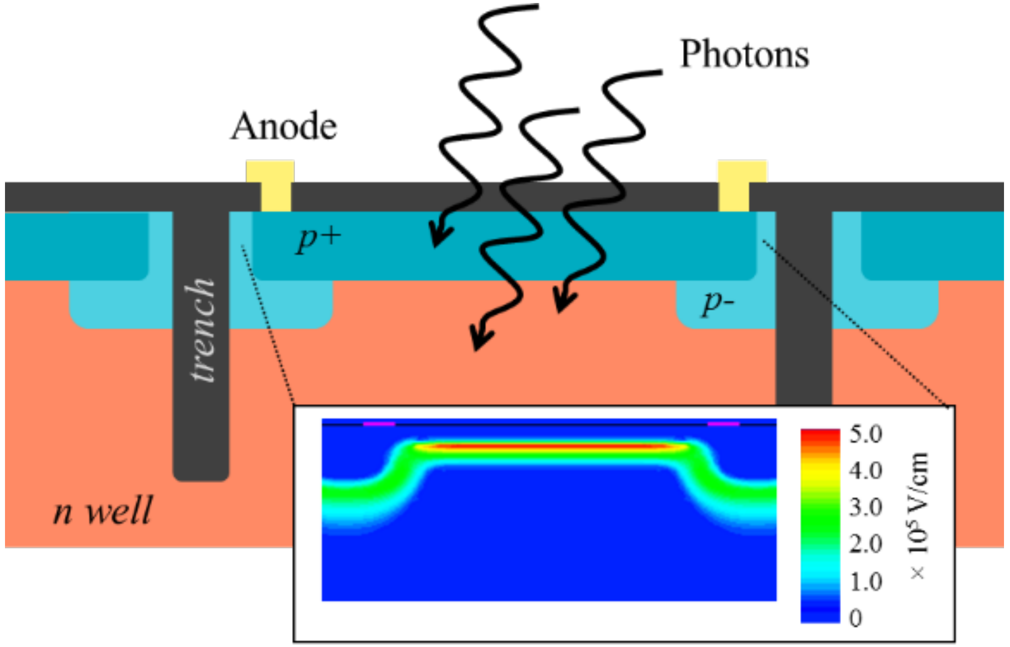
Wafer scale 3D digital SiPM technology




TSMC CMOS readout

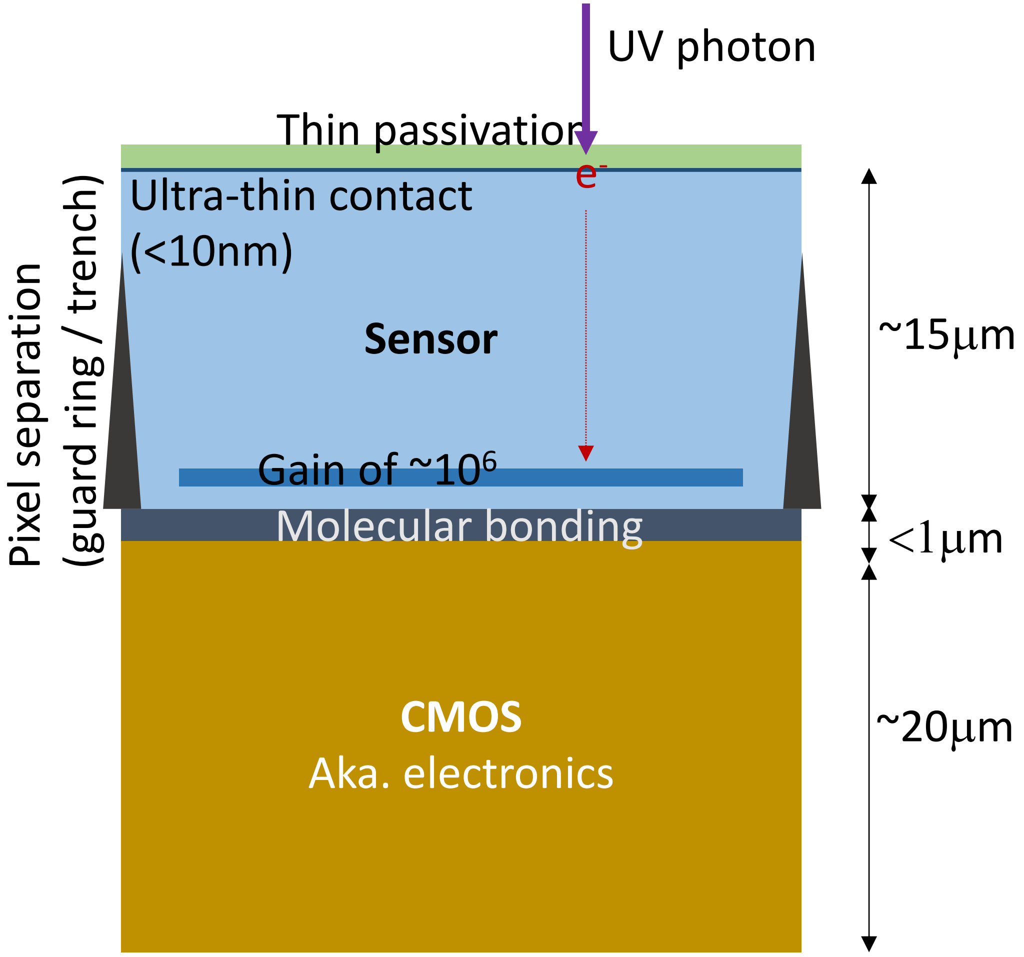
Sensor layer

- Current Single Photon Avalanche Diode (SPAD) concept
  - Front side illuminated photon sensor
  - UdeS design manufactured at TDSI
- Back-side illuminated concept
  - Efficiency >50% expected from 150nm to 700nm
    - Even pushing further in IR



- Beyond photon detection
  - Low gain avalanche diode
    - Very similar to SPADs
    - At LHC, radiation hardness is key
    - But what about μSR or nuclear physics usage (ISAC, EIC)?
  - Other materials such as GaN
    - Thomas Koffas's talk

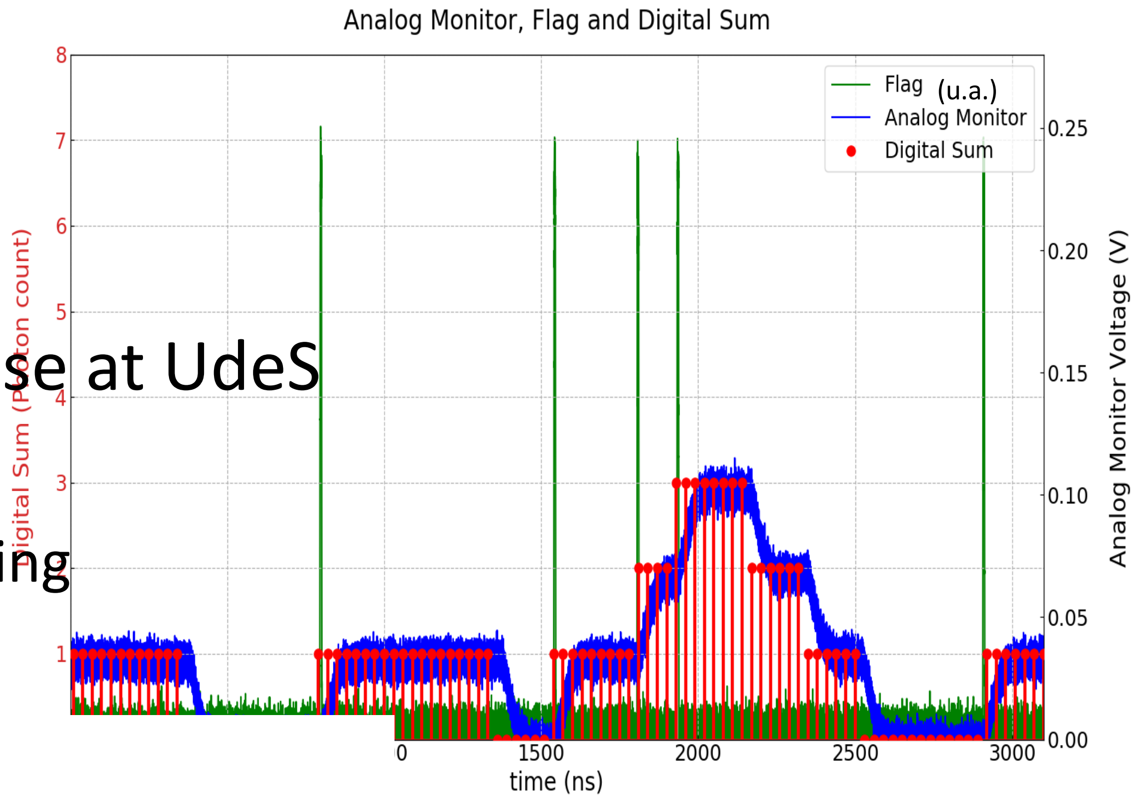
Back-side illuminated concept

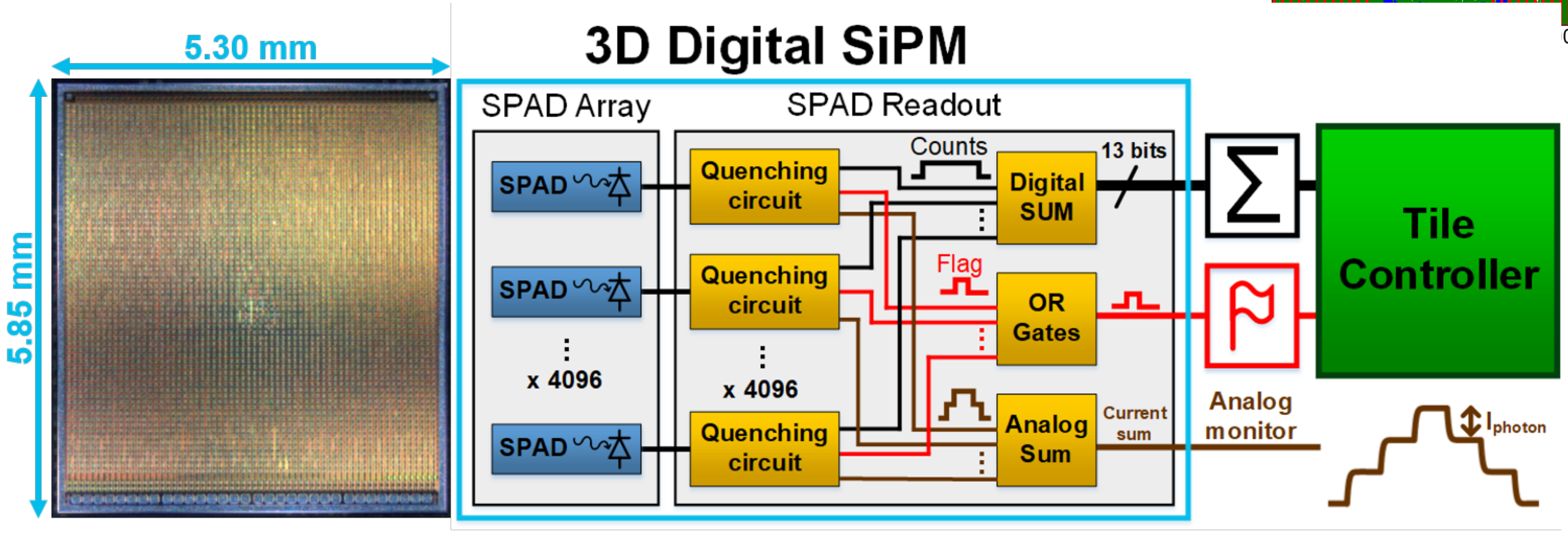


- TRIUMF's contributions
  - Design (Gallina - PhD)
  - Measurement and management of light emitted by SiPM (McLaughlin - PhD, Xie - *Msc*)
- Sensor manufacturing
  - DALSA line busy with front illuminated
    - Investigating other options
  - Require post bounding thinning
    - Investigating option of doing that at Teledyne-e2v (UK) – collaboration with J.Monroe at RHUL

Electronics layer

- Already very mature - outstanding expertise at UdeS
- Based on conventional CMOS technology
  - Essentially ASIC design with focus on fast timing





Discovery, accelerated

Bonding the two together

- Current technology: AlGe bonding, essentially bump bonding
- Next technology: molecular bonding
  - Pros: very strong bond enabling post bond thinning
  - Pros: scalable to 8-12” wafers
  - Cons: require extreme flatness of CMOS and sensor chips
  - Can be done at Teledyne-DALSA with some upgrade

Being nibble - 3DdSiPM → PDC → PPDC

- Technology pioneered by U.de Sherbrooke (UdeS) for photon detection
  - Original motivation was Positron Emission Tomography
  - Sensor and 3D assembly at Teledyne DALSA (TDSI, Bromont QC)
- TRIUMF involvement led to major investment by astro-particle physics community
  - CFI innovation fund 2017 led by M. Boulay (Carleton) with R. Kruecken (UBC lead)
  - NSERC SAP - nEXO project
  - McDonald Institute manpower support and venture funds
- Next step: a Canadian technology equipping major physics experiments
  - Major funding (10M$ scale) still required
  - Evolution beyond astro-particle physics and photon detection required

TRIUMF

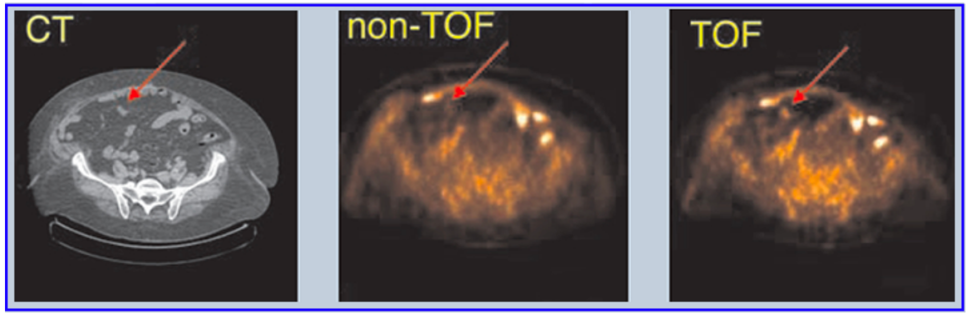
Being nibble – being connected

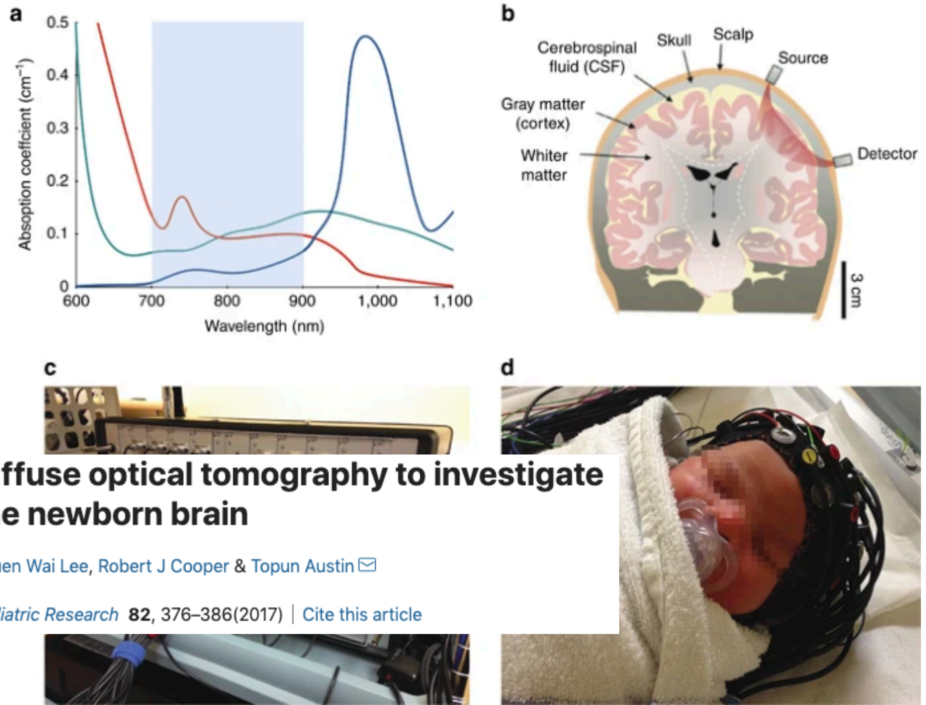
- High risk – high payoff projects that Canada is not used to pursuing
  - Require ~10M$ investment
- Funding from Canadian astro-particle physics likely to plateau at 5M$
  - Though we are investigating establishing a UK-Canada project
    - Injection of funding from UK + participation of Teledyne-DALSA
  - Though ARGO might get major funding…
- Broadening the project scope to the Canadian SAP community
  - LGADs in the context of HL-LHC
  - Many other applications are possible
- Broadening the project scope beyond SAP, CMMS,…
- But **we need engaged partners – PPDC collaboration**
  - And we are considering joining RD50

Building a better world – Medical imaging

- Time of Flight Positron Emission Tomography
  - 10ps coincidence timing resolution of 511keV gamma would drastically improve image quality
- Radiotherapy imaging
  - Next talk
- Diffuse optical tomography

- ***Medical doctor partners needed…***





Diffuse optical tomography to investigate the newborn brain

Chuen Wai Lee, Robert J Cooper & Topun Austin

Pediatric Research **82**, 376–386(2017) | Cite this article

Building a better world – Single Photon Air Analyzer

- Particulate (smoke) analysis in air using Mie scattering
  - And fluorescence
- Technology: VUV PDC & UV-C LED
  - Deep UV for probing sub-μm particulate → sensitivity & discrimination
  - Single photon enable lowest power dissipation → portable
  - → low cost?
- Arrays of connected sensors for rapid forest fire detection in populated area or worn by first responders

Vision for the next 20 years

- This is the coolest, most versatile technology I have ever worked on, but it is also the most expensive so can we pull it off?
- Yes, Yes, and YES,… However
  1. We need an attractive governance structure
     - Able to attract many in of you!
     - Enabling major contributions from many groups
  2. We need an efficient project management strategy
     - Must be risk mitigation oriented not schedule oriented due to R&D focus
  3. We need outstanding creativity in physics and engineering
  4. We need an efficient technology transfer strategy
- So Yes, we need TRIUMF to pull it off

If we succeed – a 4D world

- A Canadian technology having enabled discoveries
  - In astro-particle physics
  - At HL-LHC
  - In nuclear physics
  - In μSR
- And helping make tomorrow a better world
- And I guess, consumer market opportunities
- A venture well worth doing – And TRIUMF is the necessary glue to make it happen

TRIUMF

Current PI contributors

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Fabrice Retière and Reiner Kruecken (TRIUMF)

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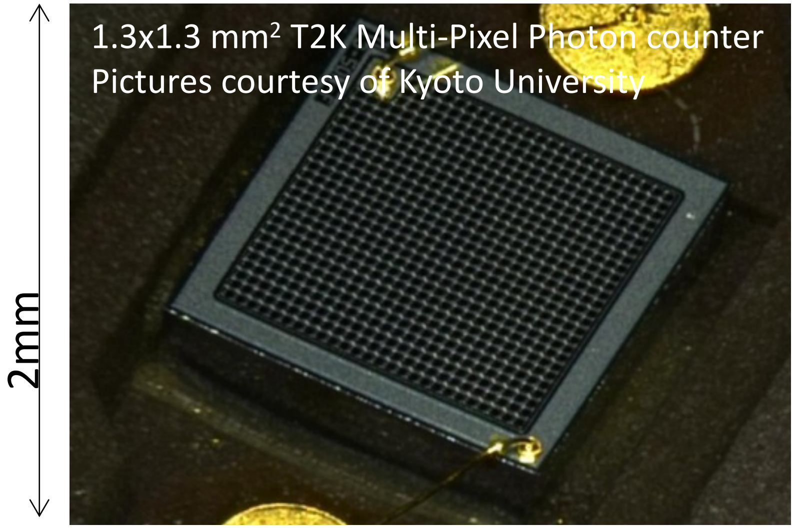
Jocelyn Monroe [ARGO] (RHUL, UK)

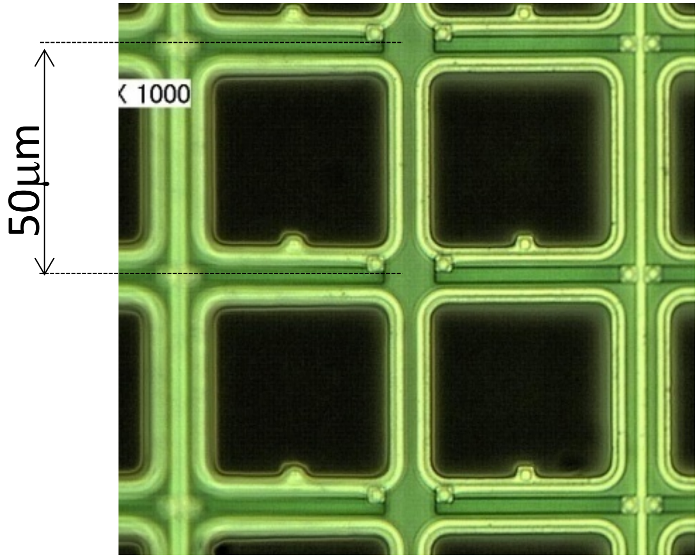
The end

Discovery, accelerated

Silicon photo-multipliers

- Single photon avalanche diode (SPAD) array
- Single photon detection capability
  - High gain
- Large manufacturing capabilities
- High efficiency
- Radiopurity
- “Low” dark noise if cold

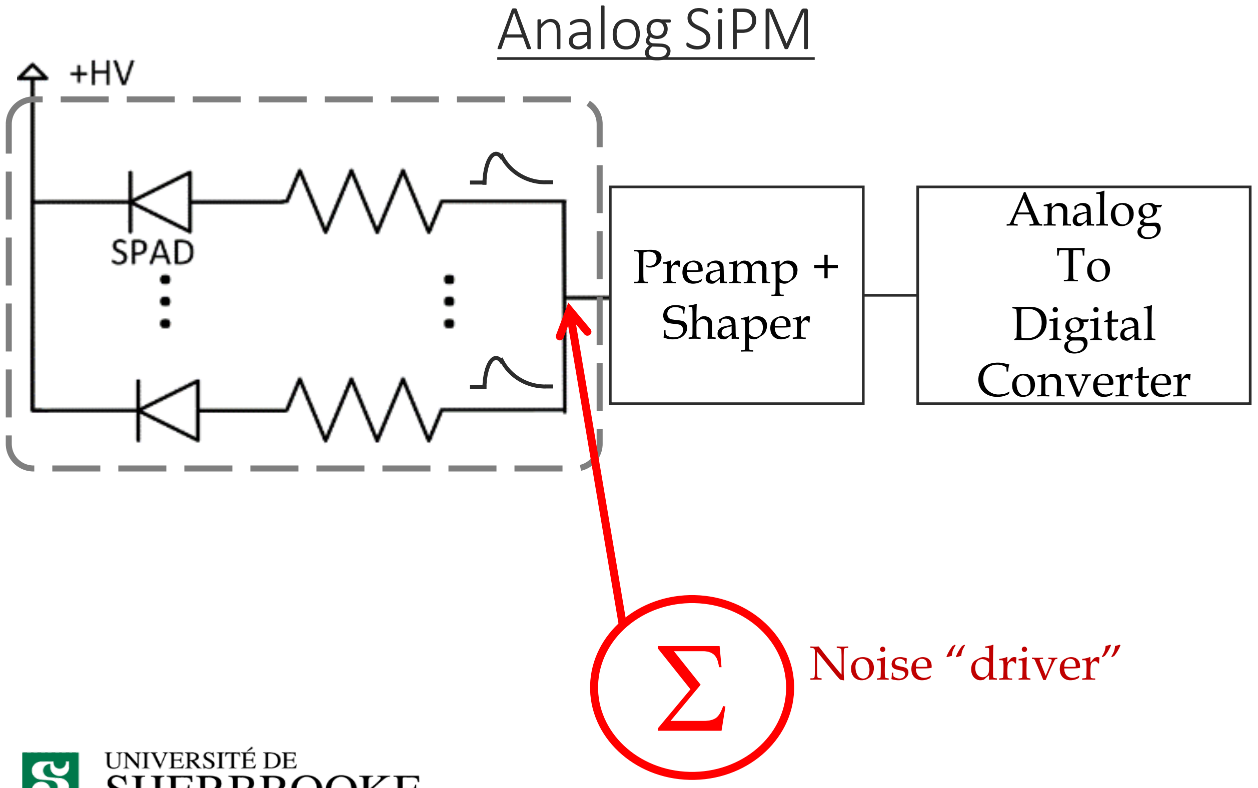


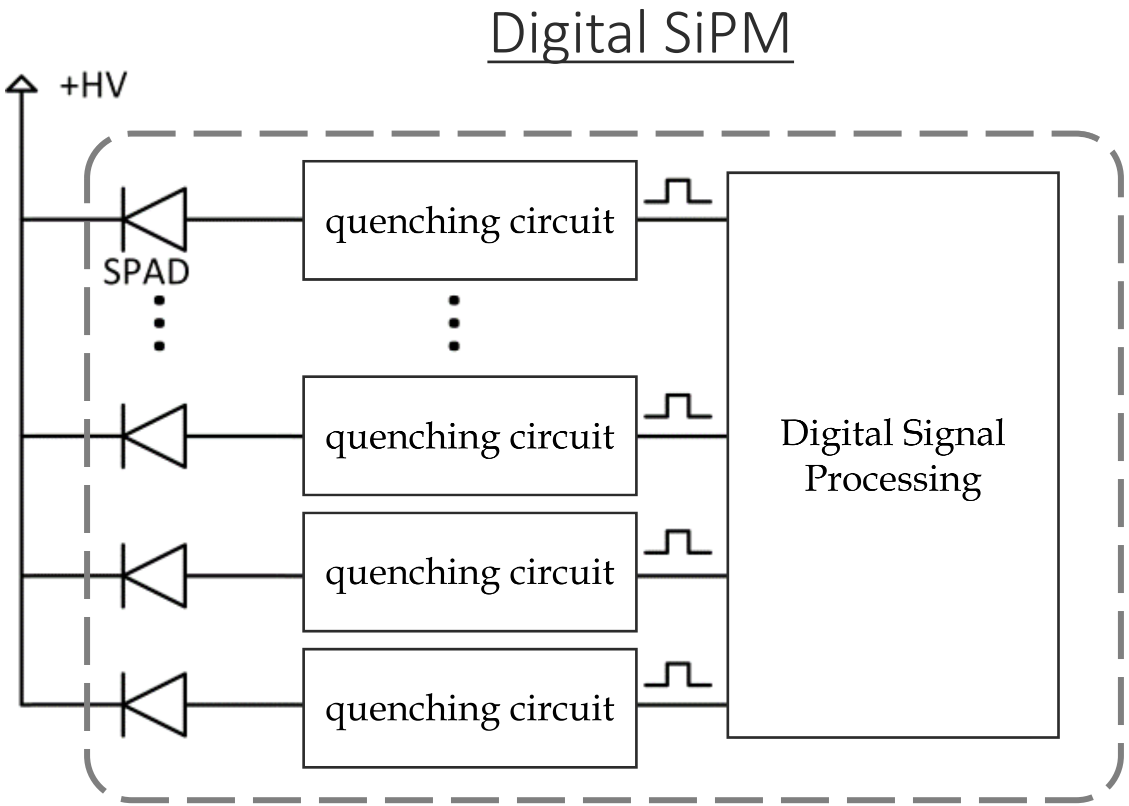


K. Yamamoto et al. PD07(04)

Going digital

Single photon avalanche diode (SPAD) is the basic unit cell of **analog and digital SiPM**





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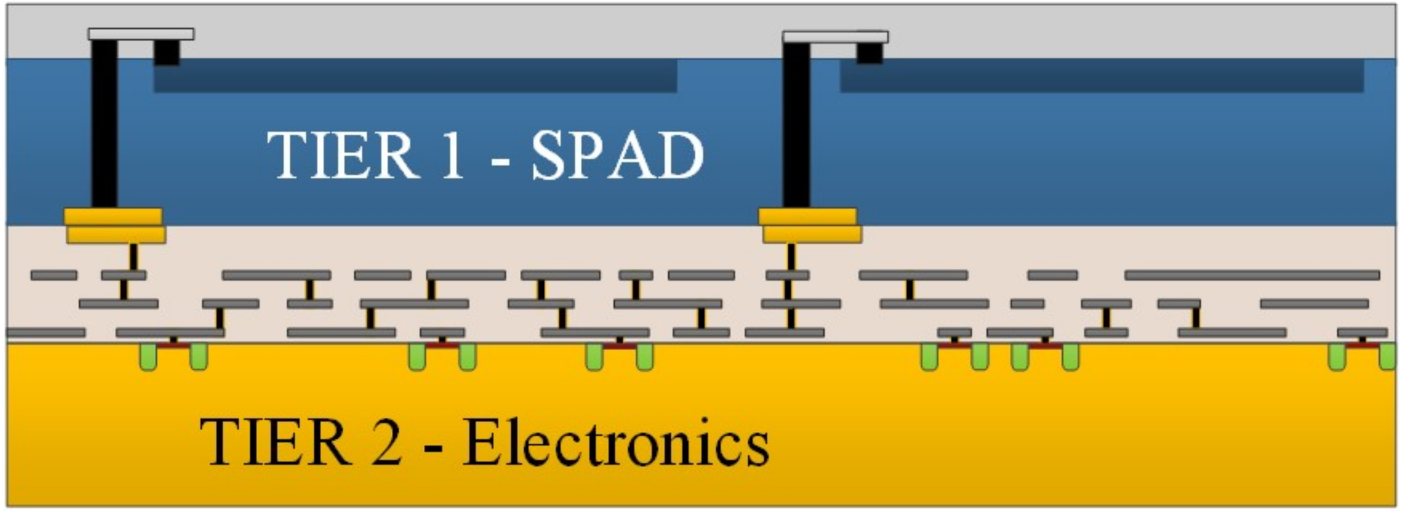
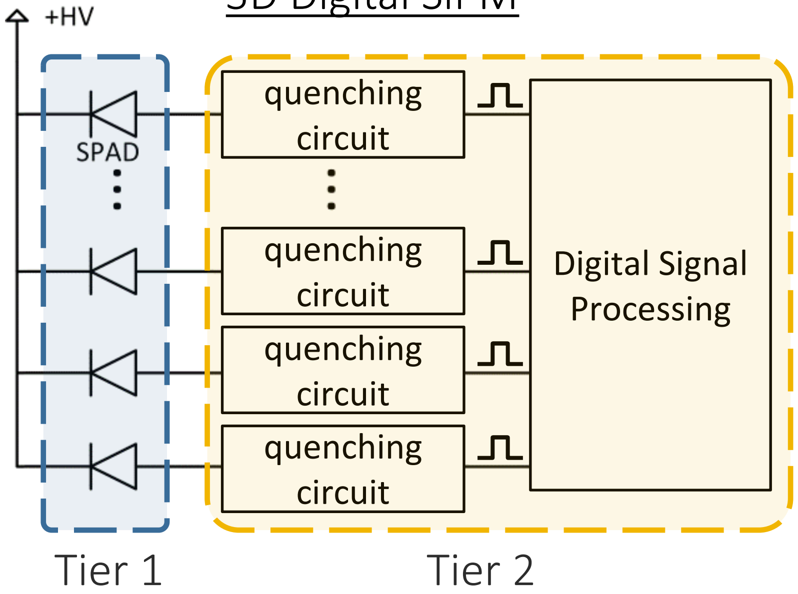
3D Digital SiPM / Photon-to-Digital Converter Concept

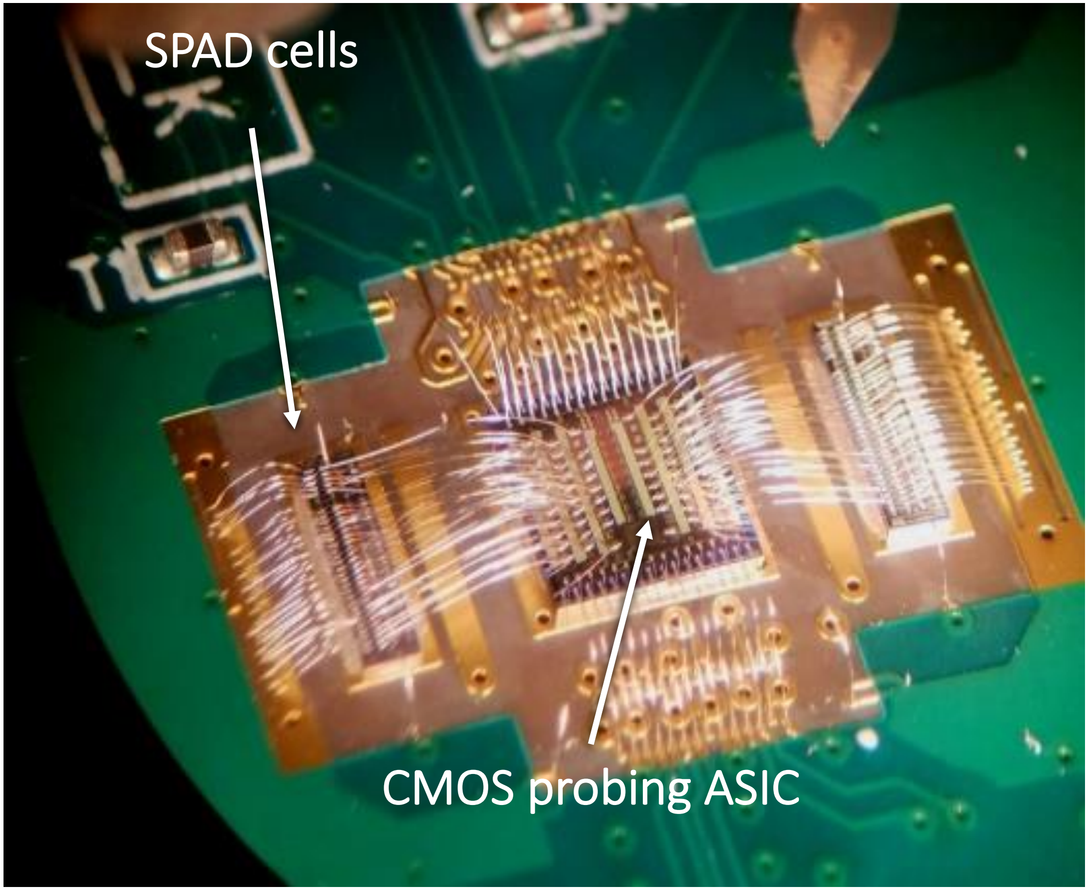


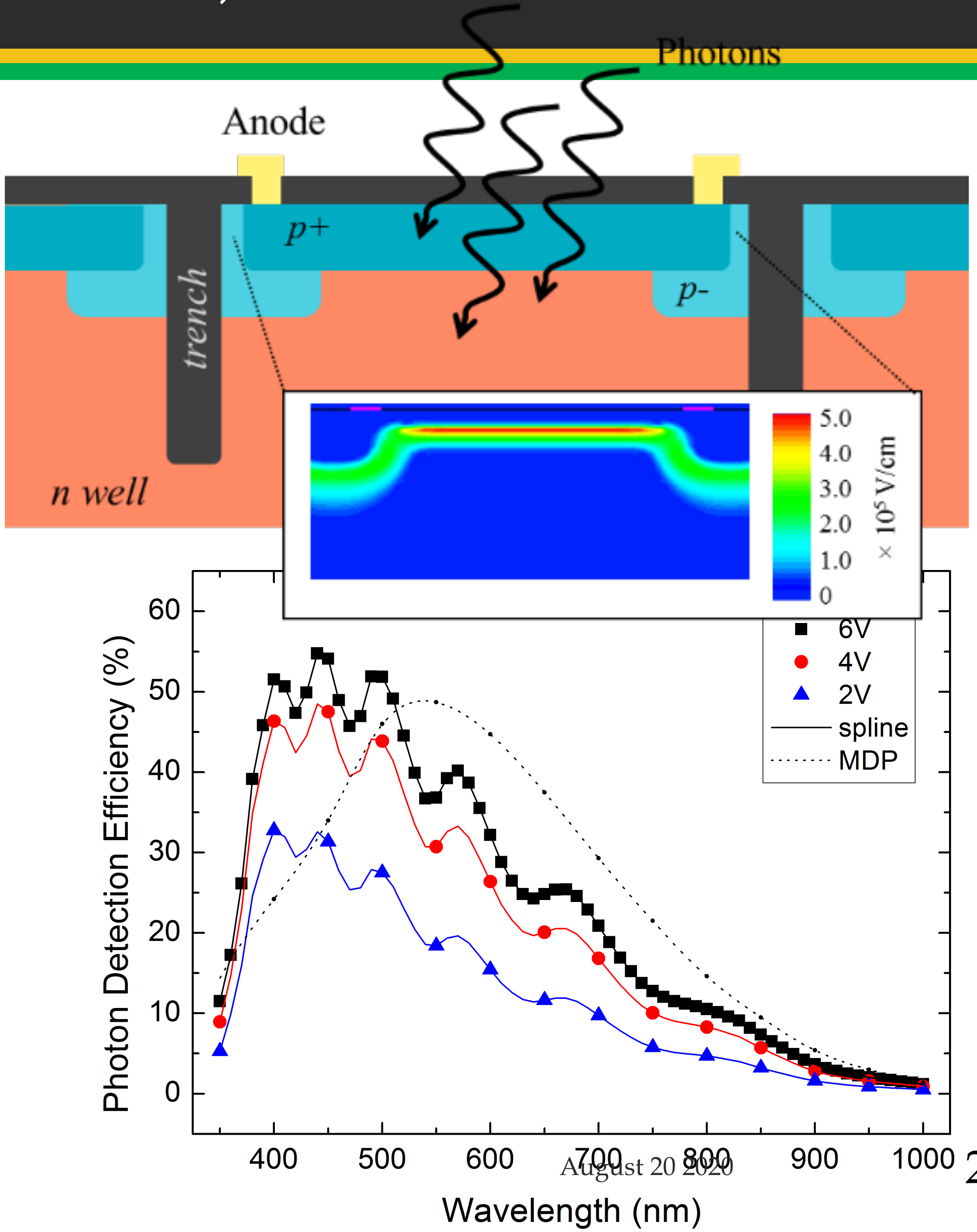
3D Digital SiPM



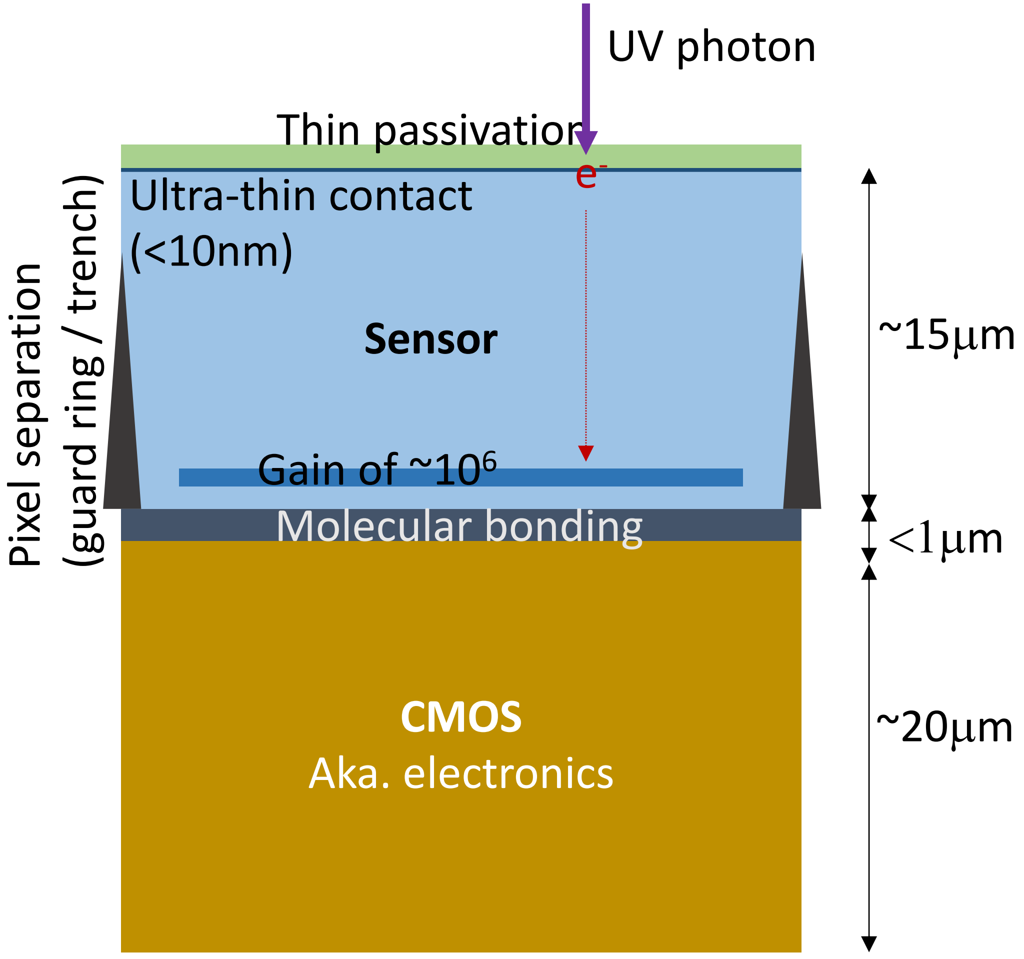
2D SPAD made-in Canada (Bromont, QC)

- 150 mm wafer (custom process using DALSA CCD production line)
- 1x1 to 5x5 mm^2 SPAD array

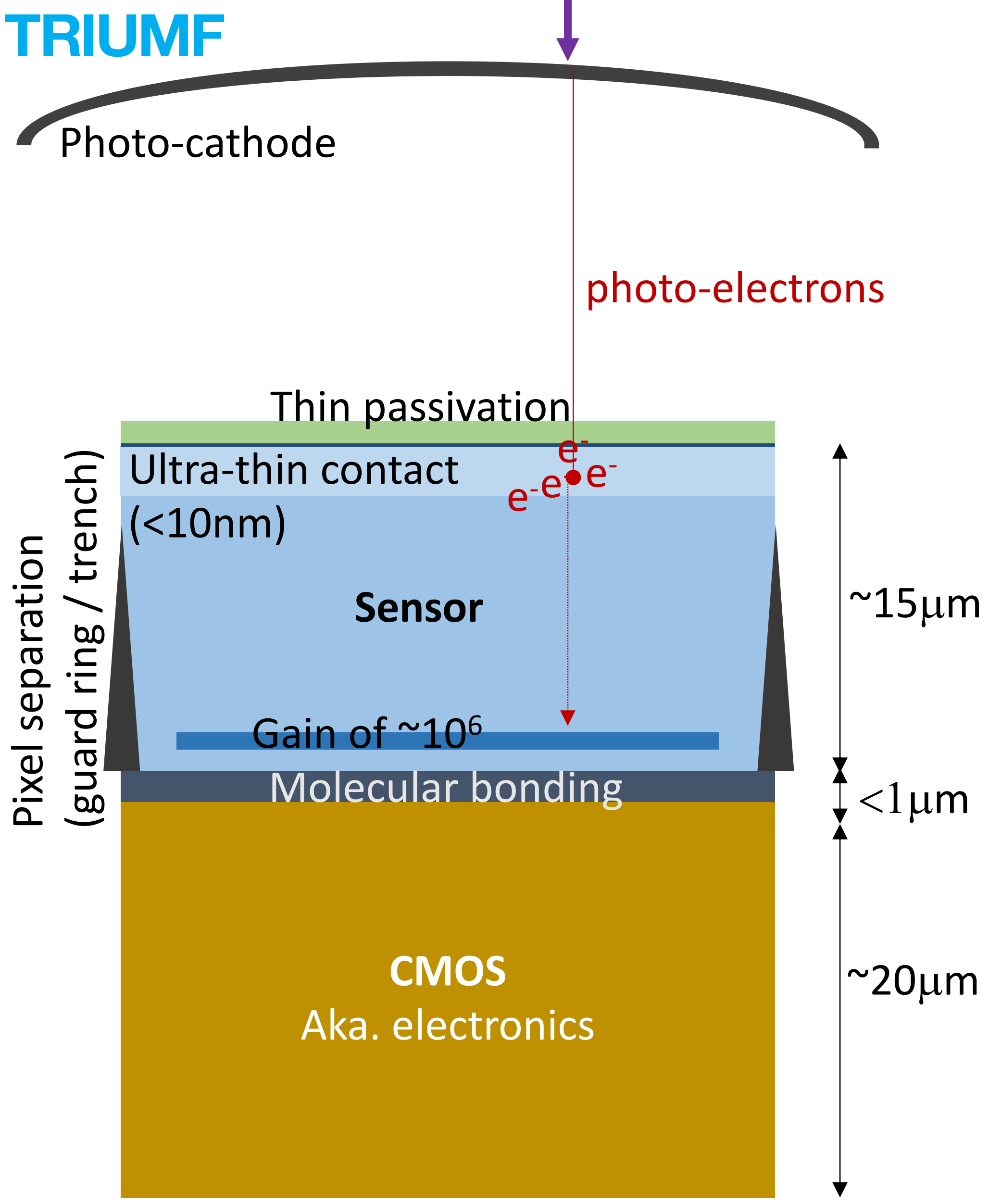




Hybrid solution for UV (120-400nm) photon



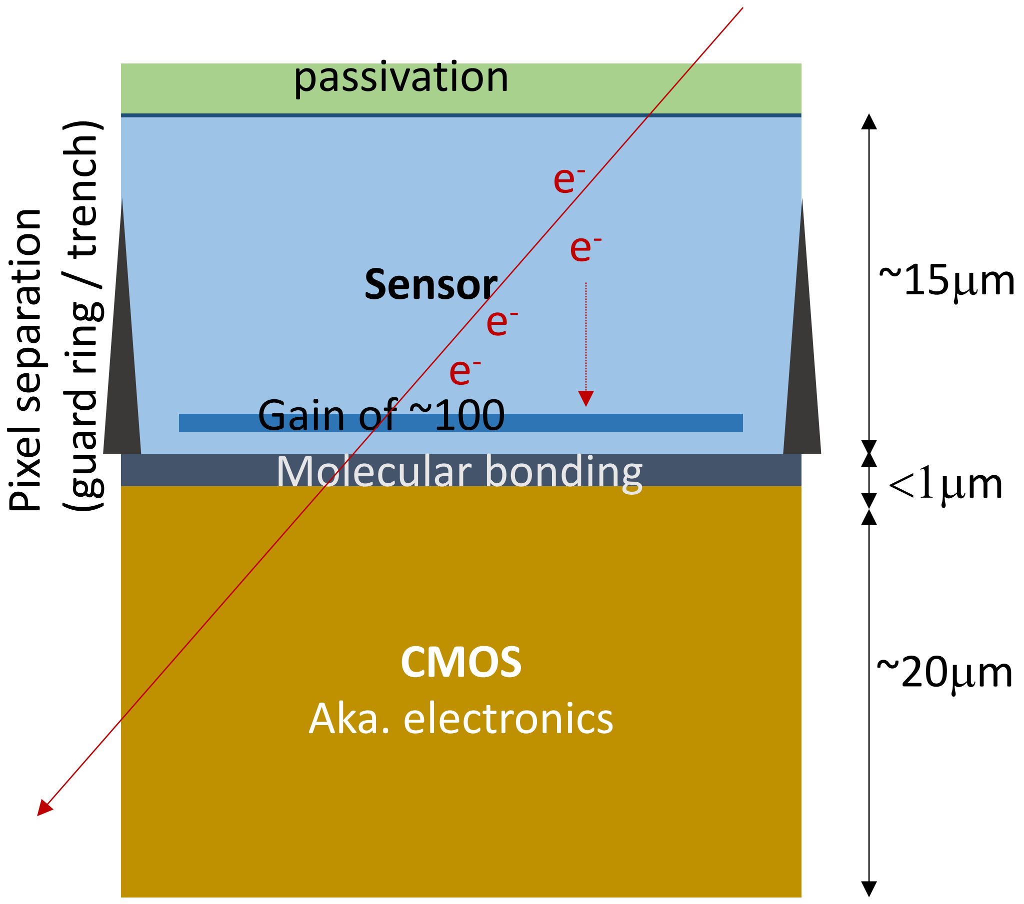
- Single photon avalanche diode
  - Gain > 10^5
- Advantages
  - Very high efficiency expected (>50%) in UV and visible
  - Single photon timing resolution <50ps
- Back-Side illuminated concept require significant R&D



Beating down dark noise

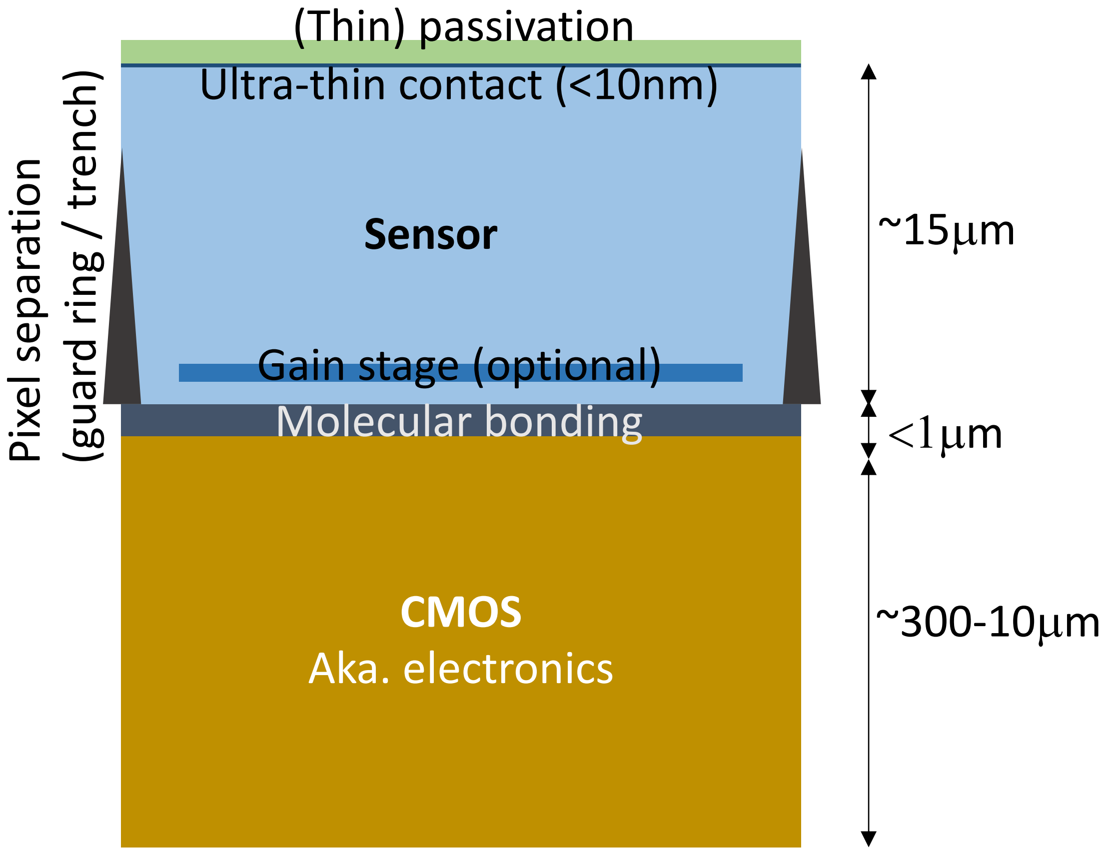
- Essentially identical constraints to VUV photon detections
  - Limit material in path of photo-electron
  - Charge collection very close to surface

Hybrid solution for tracking



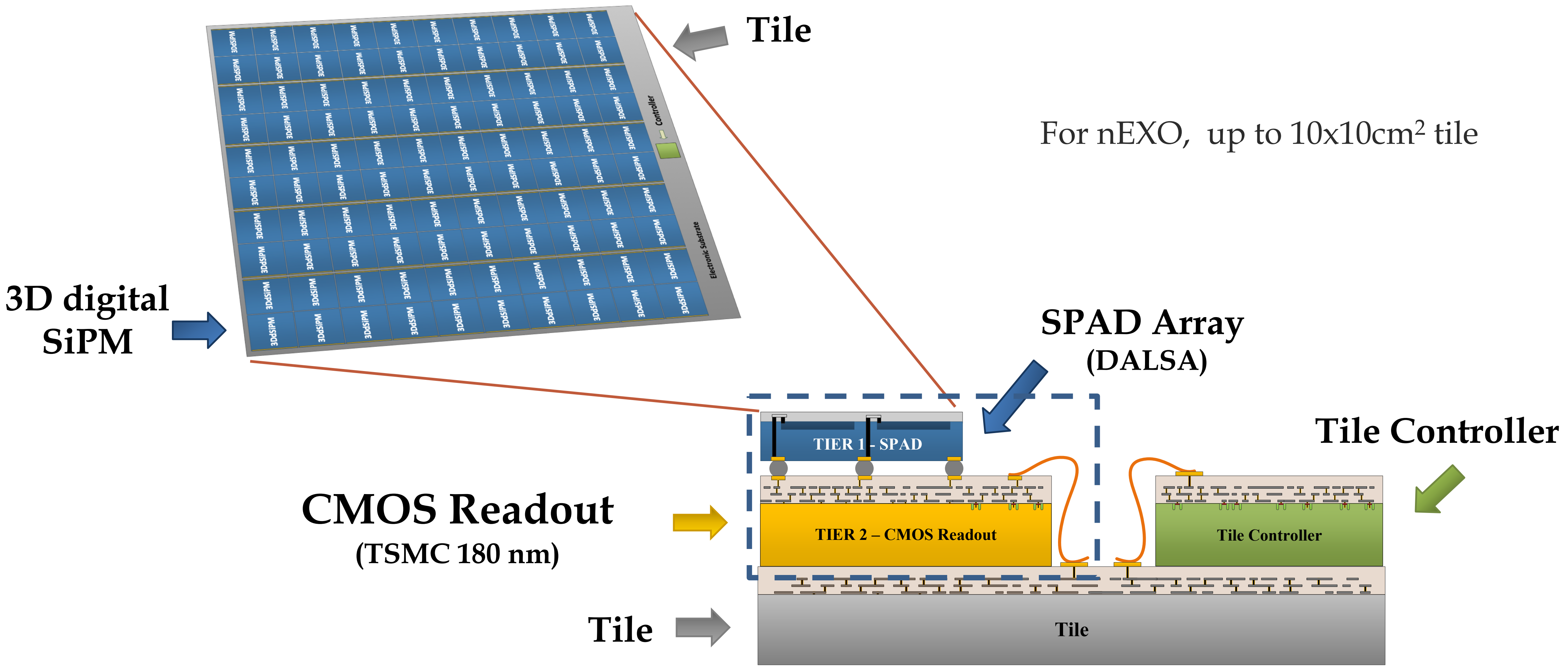
- Low Gain Avalanche diode for future colliders
  - Expected to be radiation hard
- Advantages for nuclear physics
  - Very thin
  - Timing resolution < 100ps

Back-side illuminated concept



- TRIUMF working on BSI design
  - Especially managing light emission during avalanche
- Manufacturing

From sensor to module



For nEXO, up to 10x10cm^2 tile