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The Array of Saturated Gain Avalanche Diode concept

Fabrice Retiere (TRIUMF)

Work done within the PHoton for Astro-particle and Applied Research (PHORWARD) group at TRIUMF

Special thanks for the development of this concept to Serge Charlebois (U. Sherbrooke), JF Pratte (U.Sherbrooke) and Juan Pablo Yanez (U.Alberta)

And simulation work but Tristan Sullivan and Sam de Jong (U. Victoria)

NSERC CRSNG

CANADA FIRST RESEARCH EXCELLENCE FUND | APOGÉE CANADA FONDS D'EXCELLENCE EN RECHERCHE

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

INNOVATION.CA CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

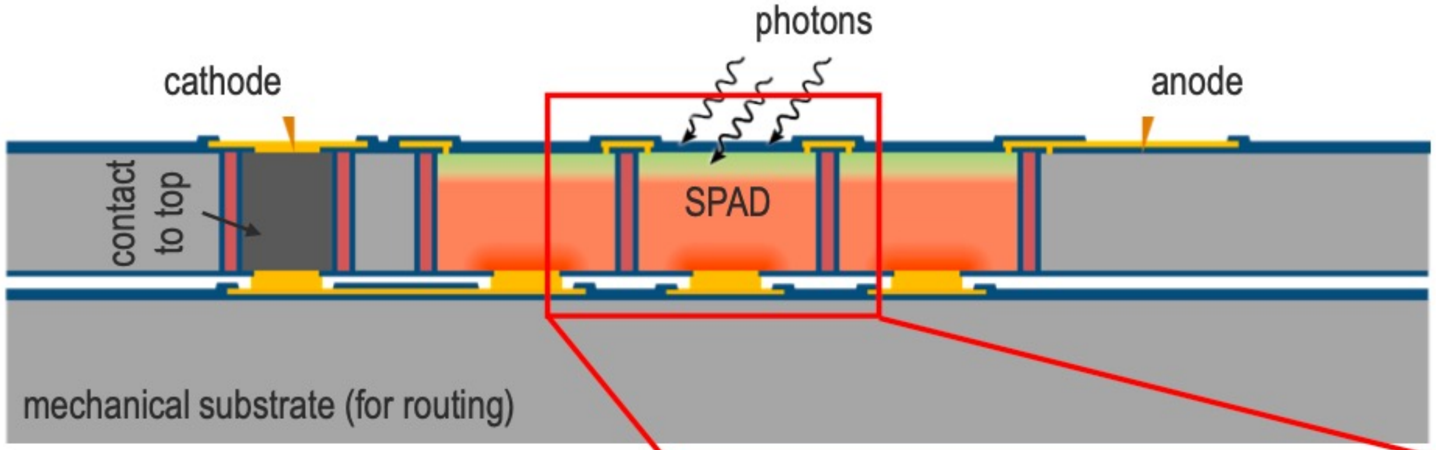
Discovery, accelerated

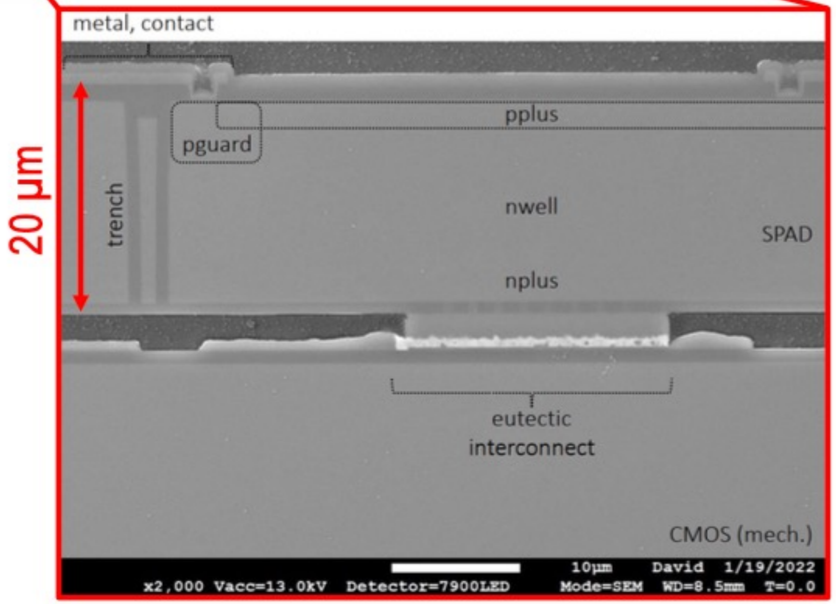
Motivation, 4-Dimensional detection

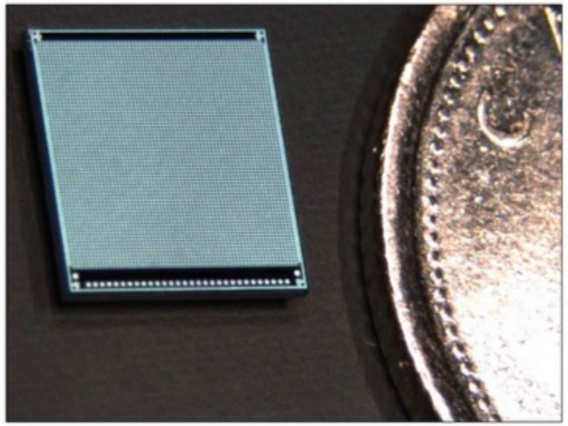
- Charged particle tracking with position resolution in the range of 0(50um) and timing resolution 0(20ps)
  - Position resolution has been available for a while with silicon pixel detectors
  - The game changing proposal is adding the timing resolution
- Enable identification of individual collision
- Enable tracking and particle identification by time of flight with the same detector

Building upon Photon to Digital Converter

- PDC developed for Astro-particle physics
- “Front-side” illuminated single photon detector
- Designed at U.Sherbrooke (QC, Canada)
- Built at Teledyne-DALSA (QC, Canada)





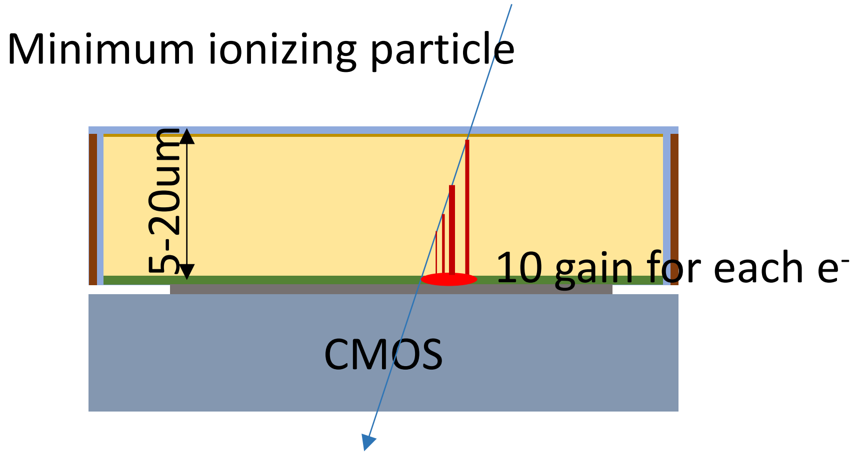


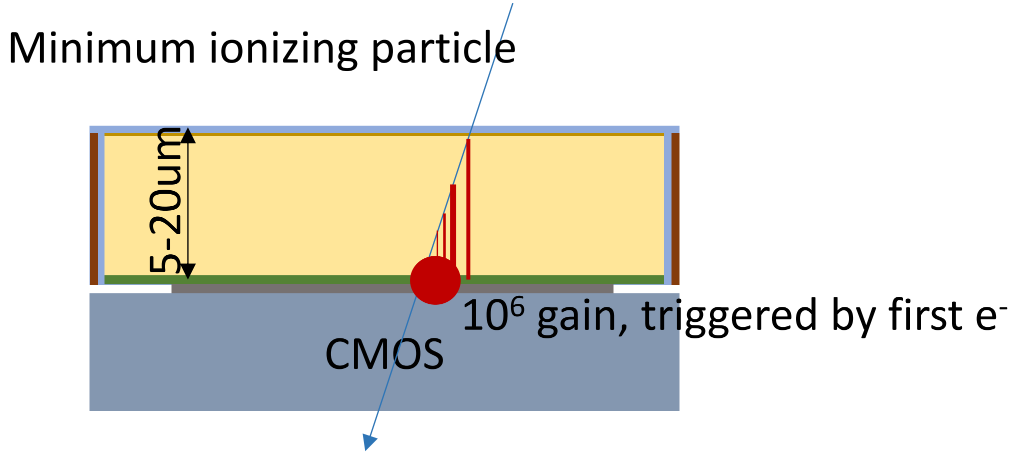
3D SPAD main die macro image (canadian 10¢ for reference)

Parent, Samuel, et al. "Single photon avalanche diodes and vertical integration process for a 3D digital SiPM using industrial semiconductor technologies." 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC). IEEE, 2018.

JF Pratte NSS 2022 plenary talk

Hybrid LGAD or hybrid SPAD





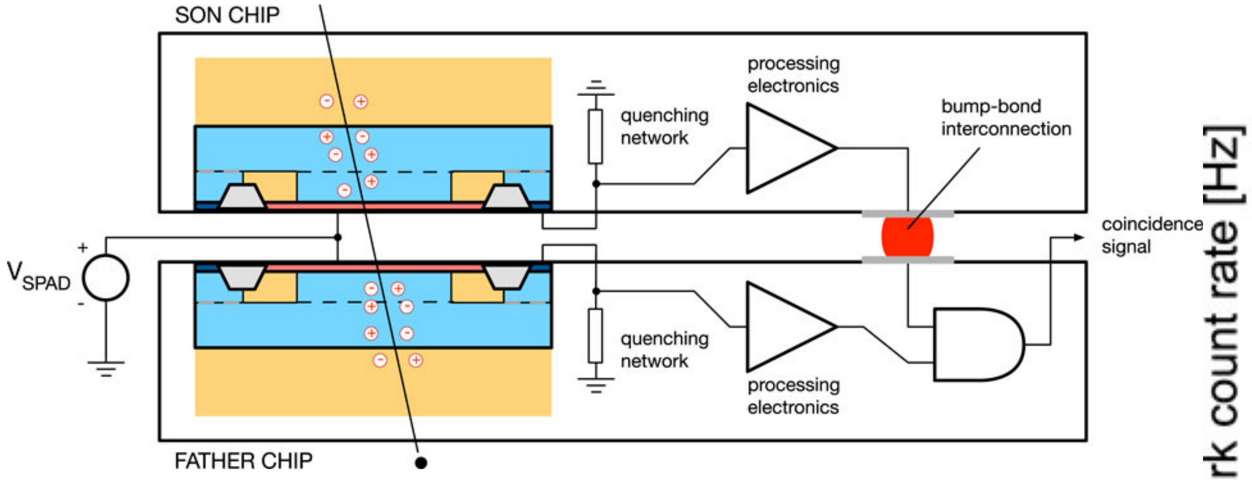
- Trench isolated hybrid LGAD
  - All ionization electrons contribute to signal formation
  - Signal on the order of 10^4 e-

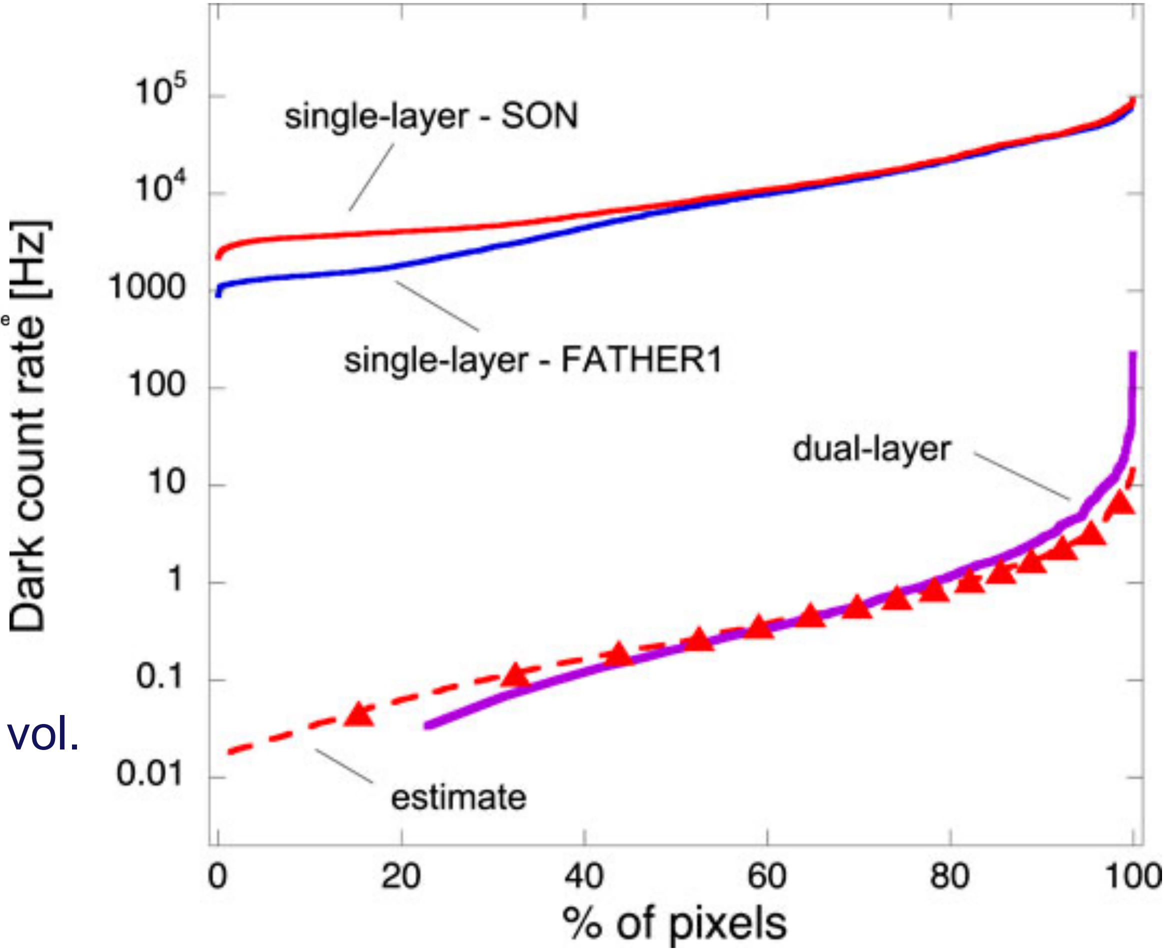
- Single Photon Avalanche Diode
  - Only first e- to reach the high field region does something
    - Low fluctuation
  - Signal on the order of 10^6

SPAD vs LGAD

- SPAD
  - Timing down to 10ps or better. Fire on single electron
    - No or very small contribution of the ionization fluctuation to timing resolution
    - High intrinsic gain 10^5 to 10^7, simplifying timing electronics
  - No energy deposition information
    - Same signal for 1 electrons or 20,000 electrons
  - Swamped by thermal noise ~50kHz/mm^2 at room temperature
    - Drops by roughly factor 10 every 20 degrees K/C.
- LGAD
  - Timing limited by energy loss fluctuations and electronics performance
    - Need low noise electronics
  - Can measure number of e- deposited albeit with some fluctuations
  - Not impacted by thermal noise

The complicated way around the dark noise issue





L. Ratti et al, “Layered CMOS SPADs for Low Noise Detection of Charged Particles”, *Frontiers in Physics*, vol. 8, 2021.

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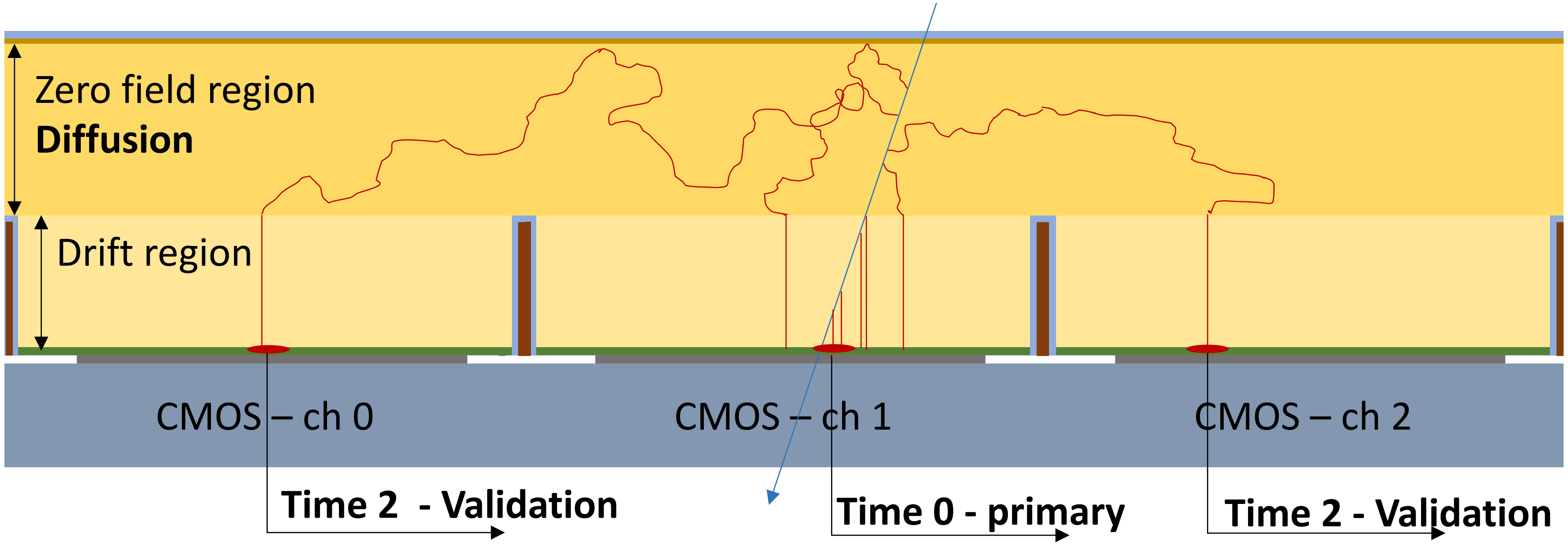
The ASGAD concept

- Geiger-mode avalanche diode region -> excellent timing
- Diffusion region for validating signal due to particle
  - ~300 e- per um produced by a MIP so need 0.1-1% diffusion probability to the neighbor for the validation signal to be always there

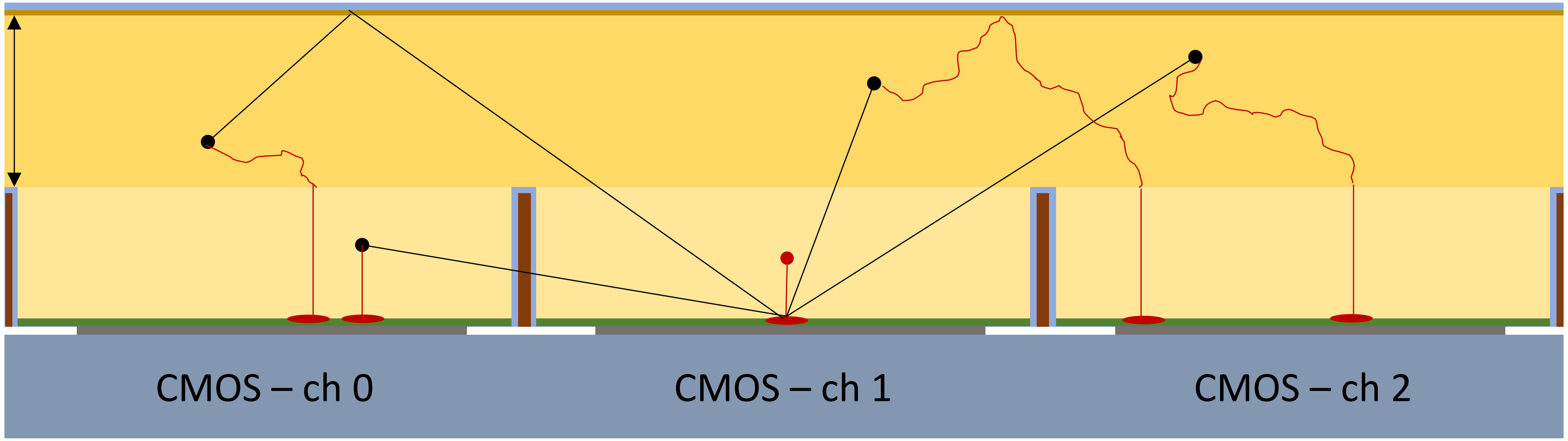


Particle tag = Primary * validation 1 * validation 2

Discovery, accelerated

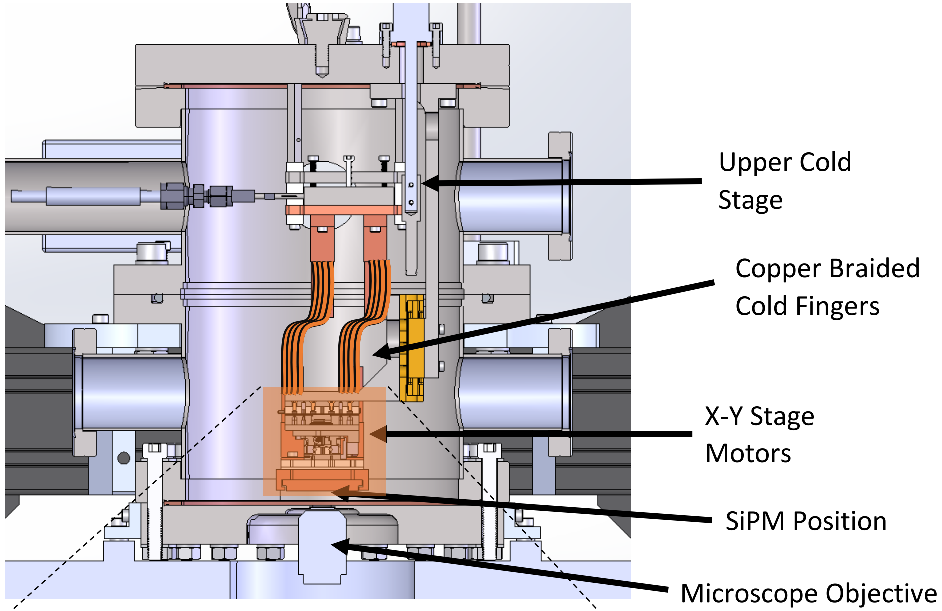
Easy? … Not so fast

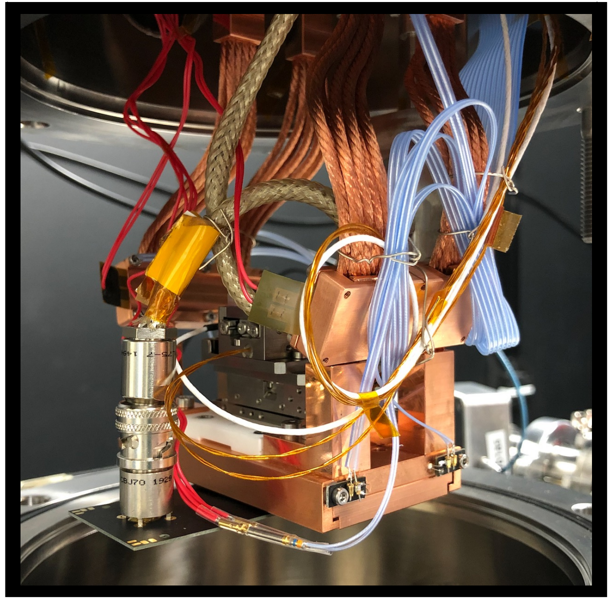
- Thermal background made worse by photon production in avalanches
  - Photons produced per avalanche 1-1,000
  - Electrons produced by photon absorption fire neighboring diodes



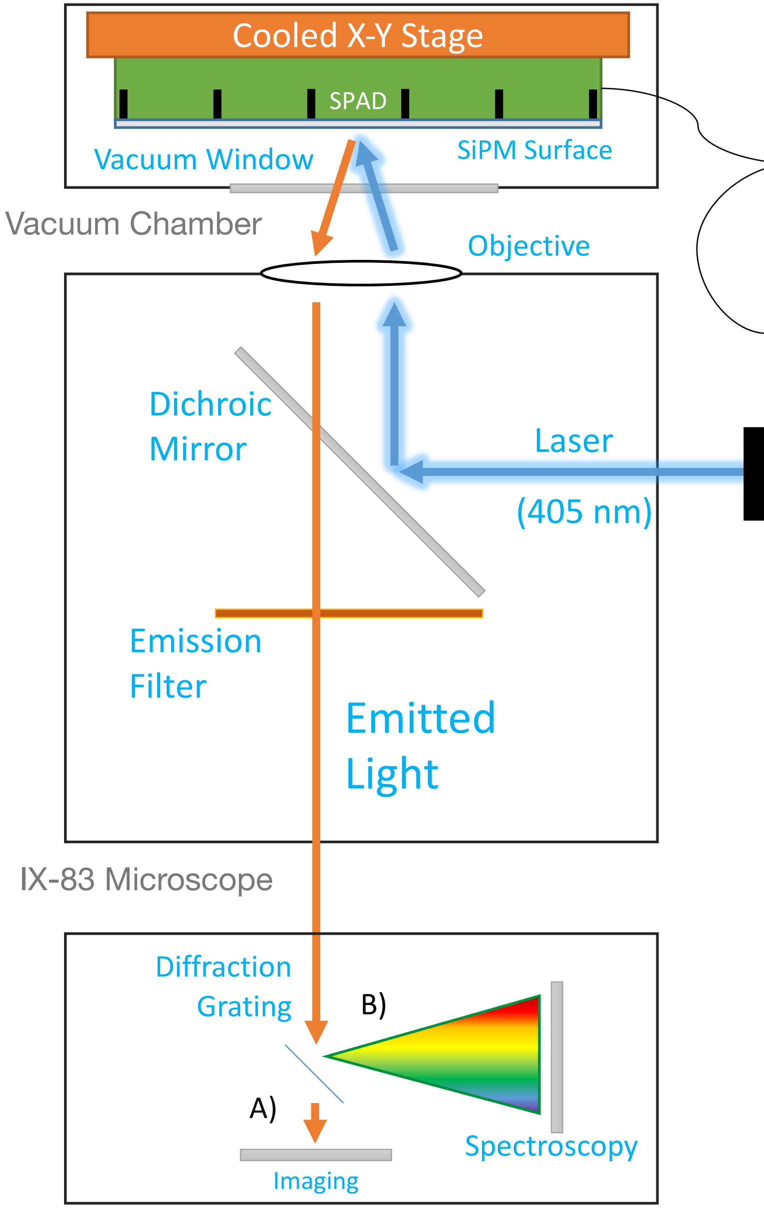
MIEL

Microscope for the Injection and Emission of Light

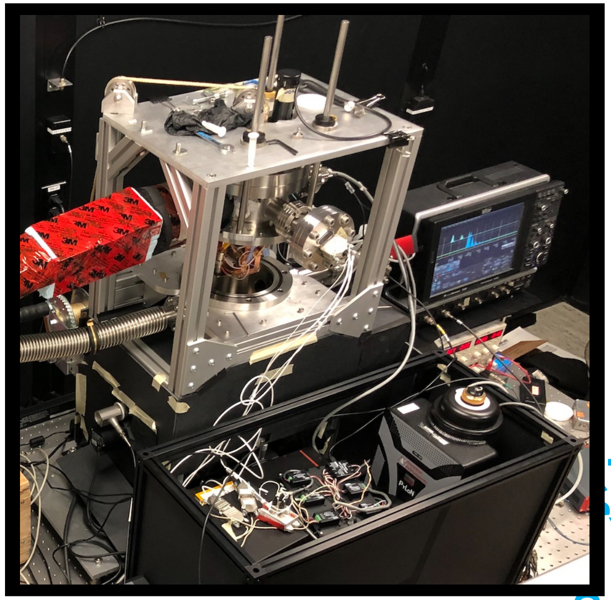




Cryogenically Cooled X-Y Stage with SiPM Mounted



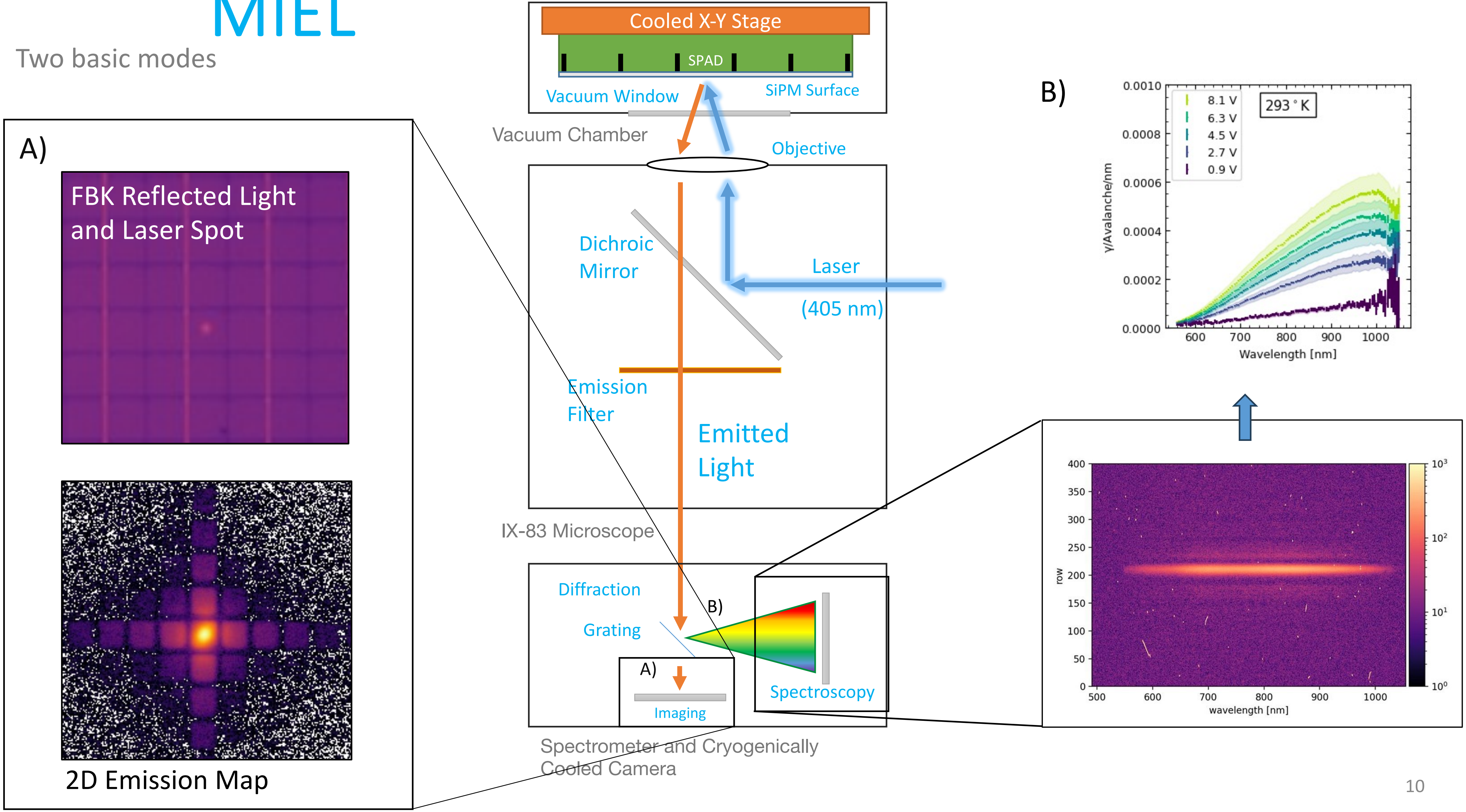
Spectrometer and Cryogenically Cooled Camera



The MIEL Experiment

MIEL

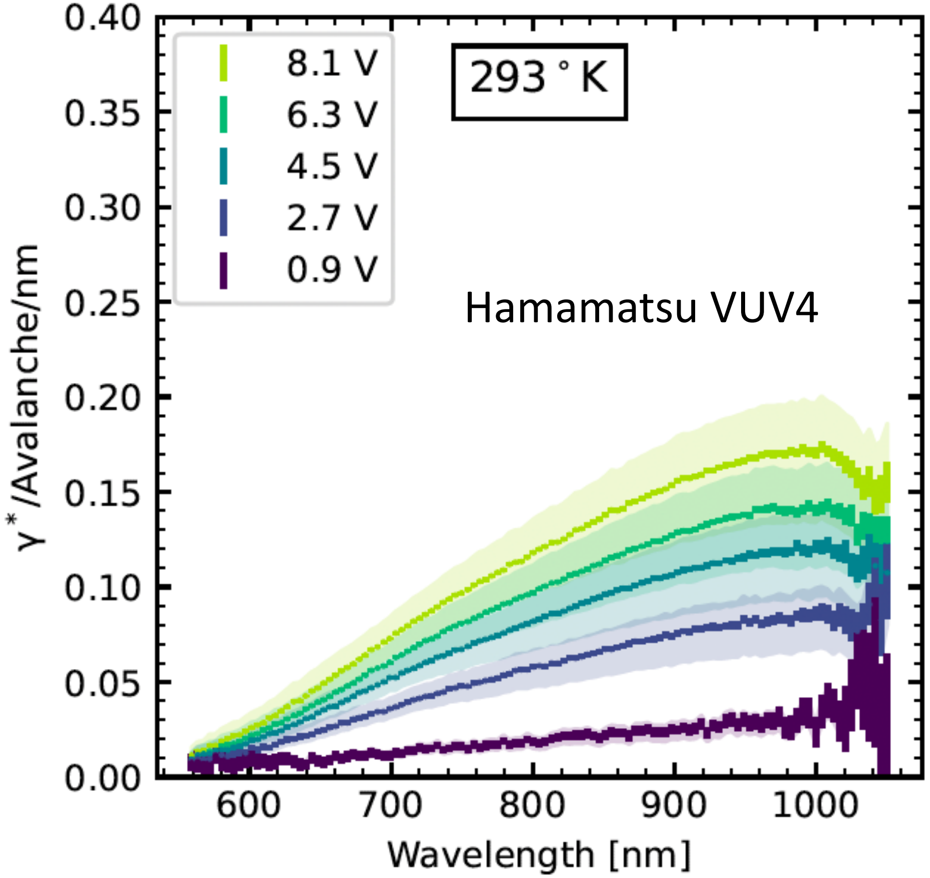
Two basic modes

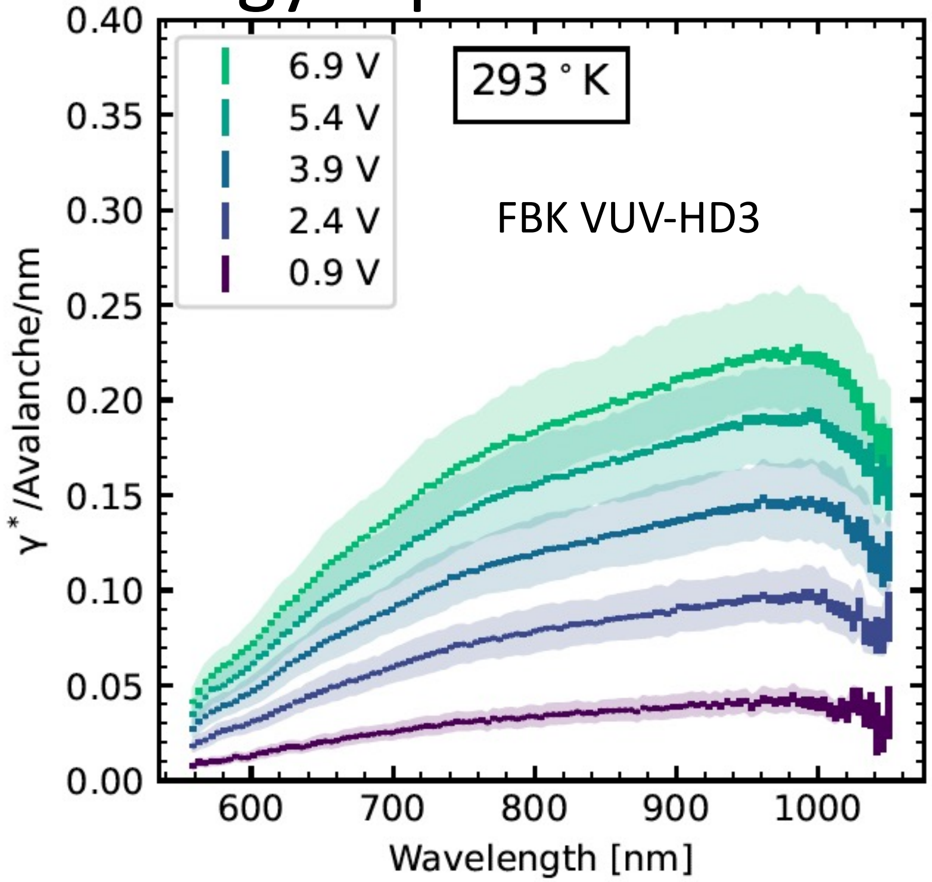


Photon production in avalanches and transport measured for VUV SiPMs

Key parameter is about 1 photon produced per 10^5 electrons

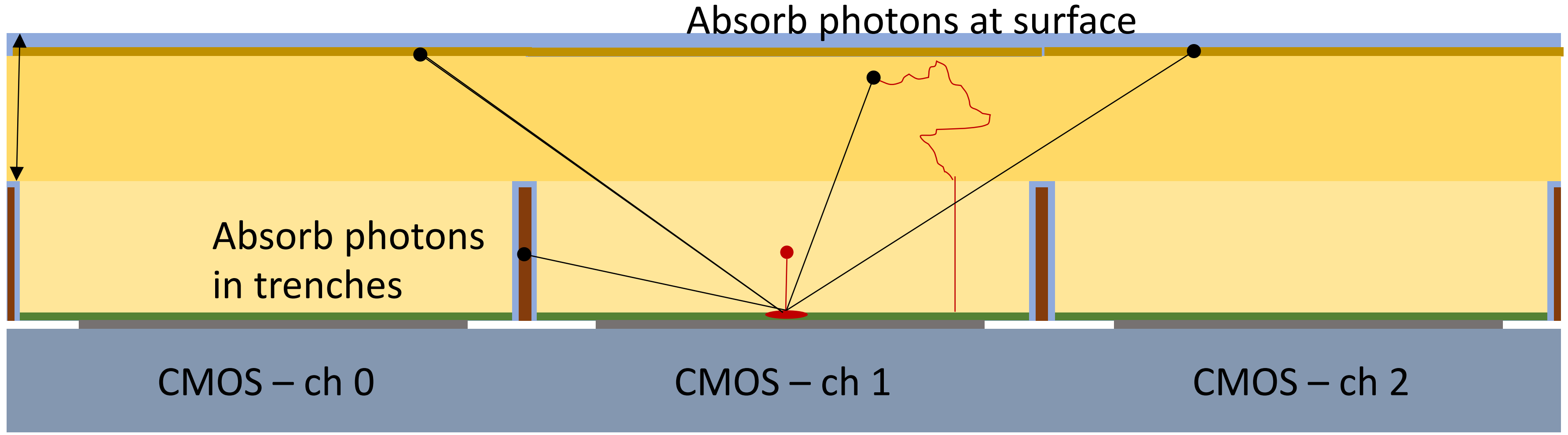
Typical gain is 10^6 to 10^7 but 10^5 technology is possible



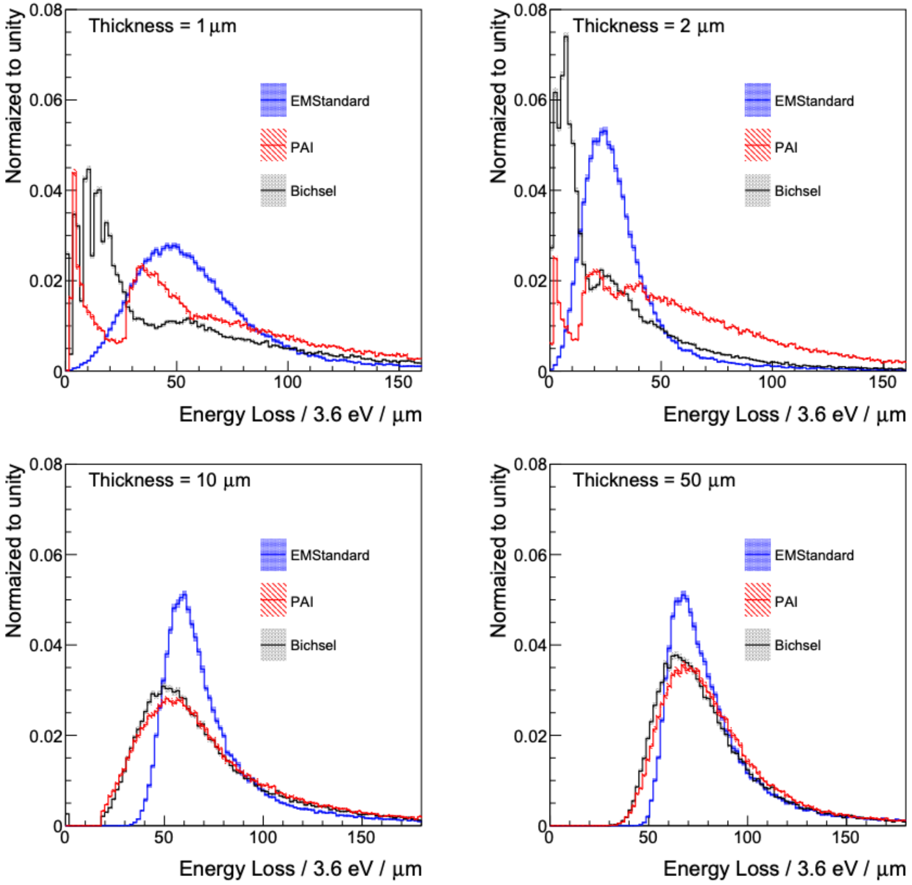


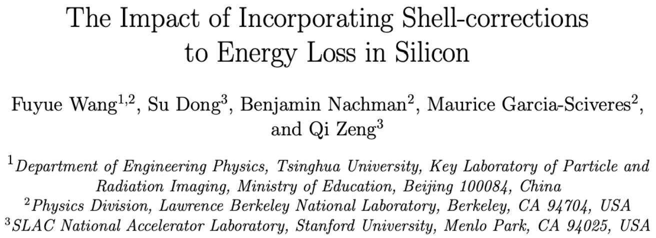
Mitigation strategies

- Minimize diffusion region thickness → limited by efficiency requirements
- Absorb photons at front and back surface
- Absorb photons in trenches
  - The smaller the pitch the better
- Minimize production by running at lowest possible gain
  - Gain scales by diode capacitance so the smaller the better



Optimization of performances




The Impact of Incorporating Shell-corrections
to Energy Loss in Silicon

Fuyue Wang[1,2], Su Dong[3], Benjamin Nachman[2], Maurice Garcia-Sciveres[2],
and Qi Zeng[3]

[1] *Department of Engineering Physics, Tsinghua University, Key Laboratory of Particle and Radiation Imaging, Ministry of Education, Beijing 100084, China*
[2] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94704, USA*
[3] *SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA*

- Diffusion region thickness 5-20 um
- Avalanche region thickness ~1um
  - Guarantee >1e- in high field region (mean free path 0.26um)
- Drift region thickness ~10um
  - Absorbs photons from avalanche
- Pitch for optimizing signal to noise
  - Though small pitch means $$ to achieve electronics performance with limited area
  - Though rectangular geometry possible

Quanta-Level Avalanche Diode Simulator (QLADS)

- Mixing charge carrier and photon transport – not currently available in TCAD programs
- Use Monte-Carlo techniques for all transport processes
- Aim is to make this package open source
- Development team
  - Concept: FR & Juan-Pablo Yanez (U. Alberta, AB, Canada)
  - Development: Sam De Jong and Tristan Sullivan (U. of Victoria, BC, Canada)

Quanta-Level Avalanche Diode Simulator (QLADS) for ASGAD

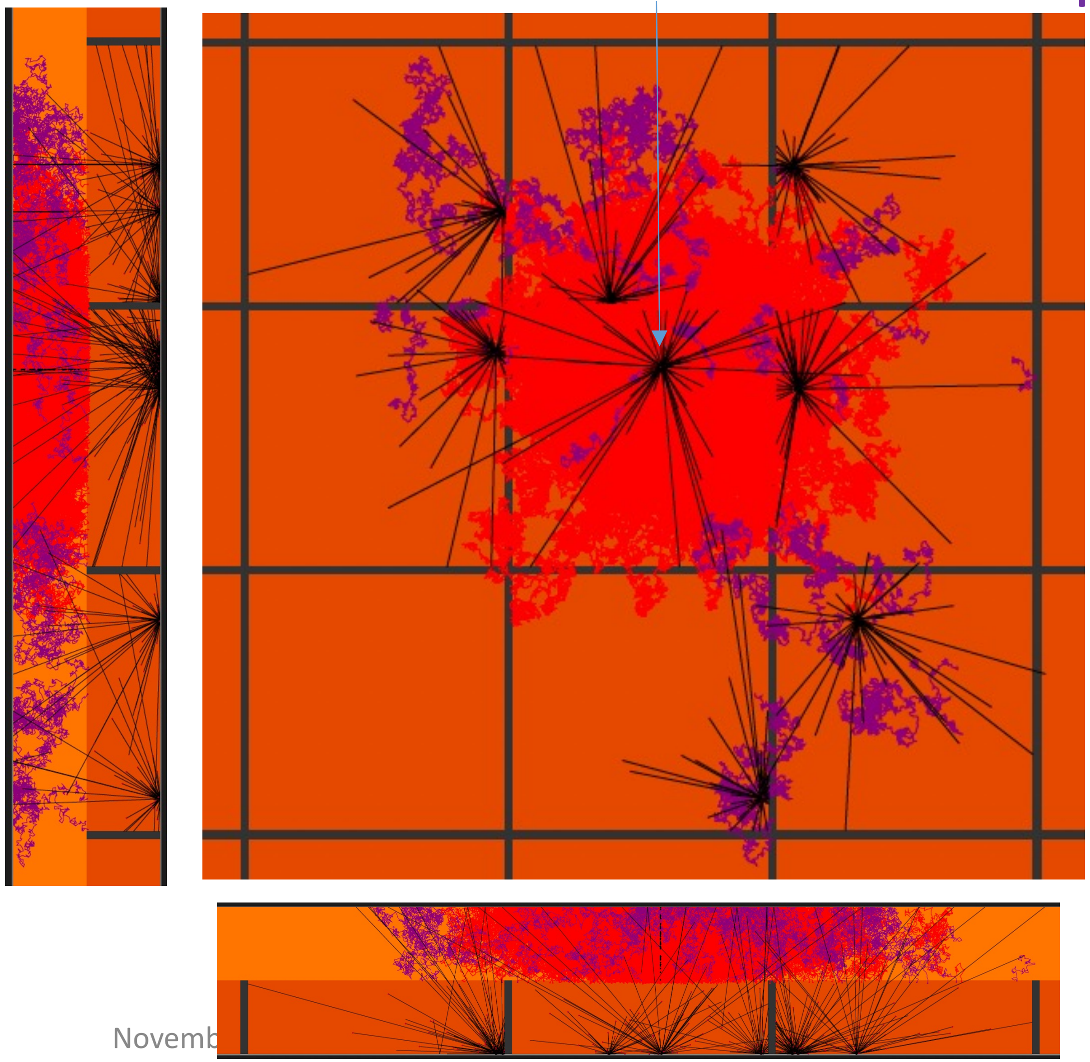
- Charge particle simulation
  - Use Bichsel cross-section for 45 GeV/c pions
  - Normal incidence randomly over all area
- Dark noise
  - Assess the probability distribution function for the number of avalanches produced by 1 seed avalanche
  - Use 50 Hz/mm^2 for scale

- Electron transport
  - Random walk
    - Diffusion constant = 3.9 um^2/ns
    - Electron life time = 100 ns
  - No explicit EField
- Photon from avalanches
  - Vary average number of photons per avalanche + Poisson statistics
  - Use measured spectrum
  - Track photons but absorb on all surfaces
    - Simplest but not most conservative

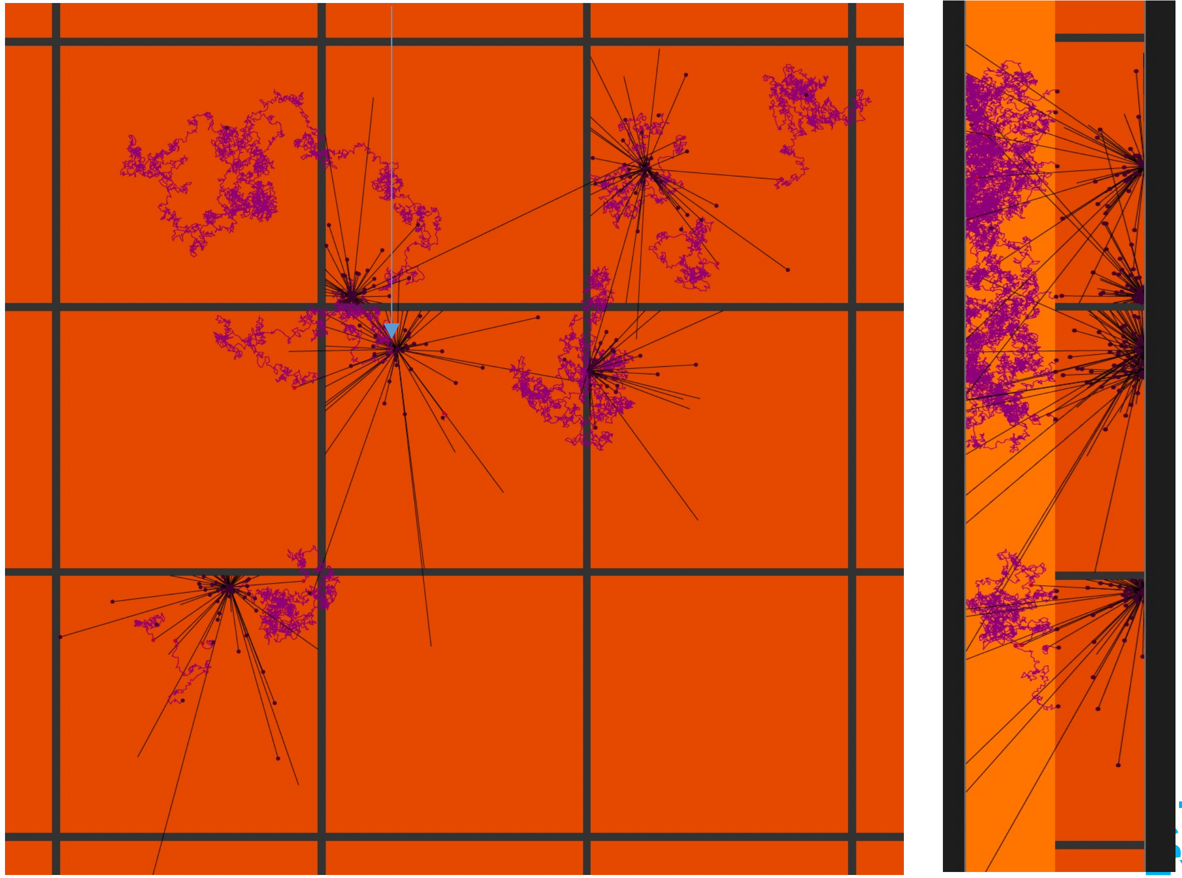
Event display

Primary e^- in red

e- from photons in purple



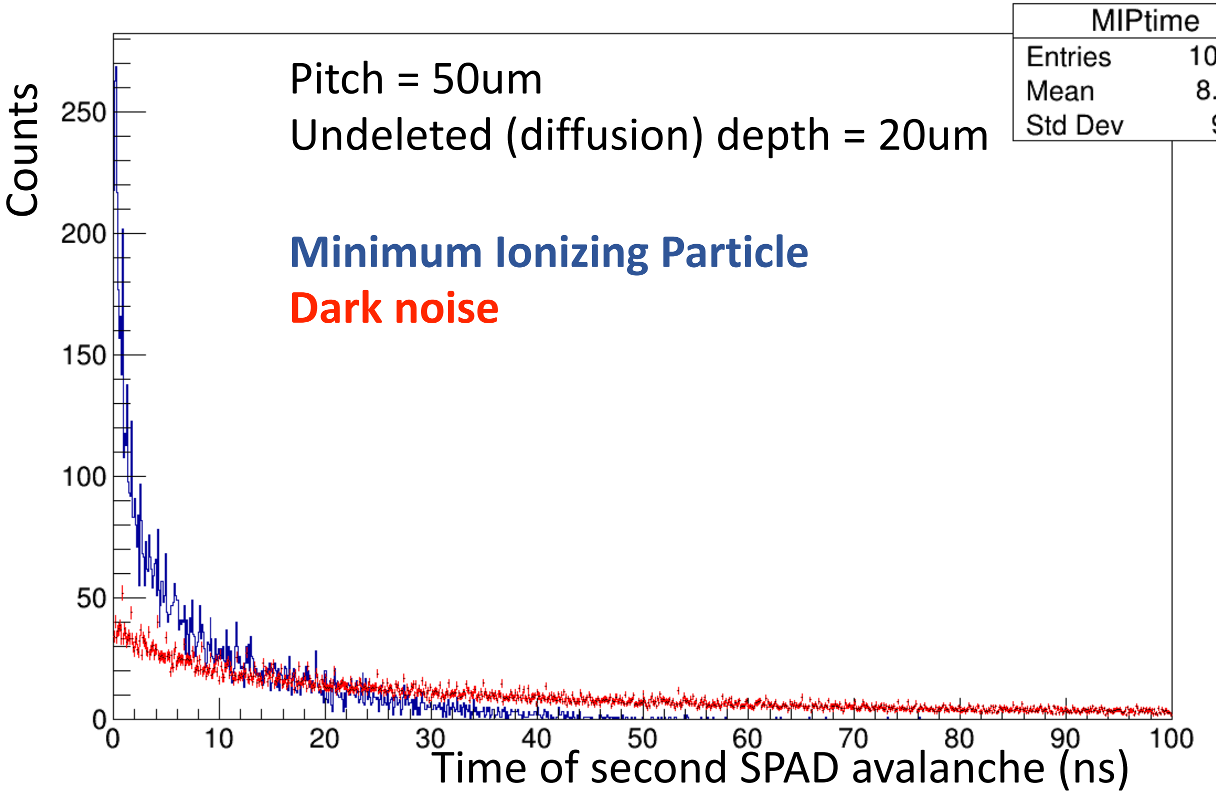
MIP



Single seed avalanche

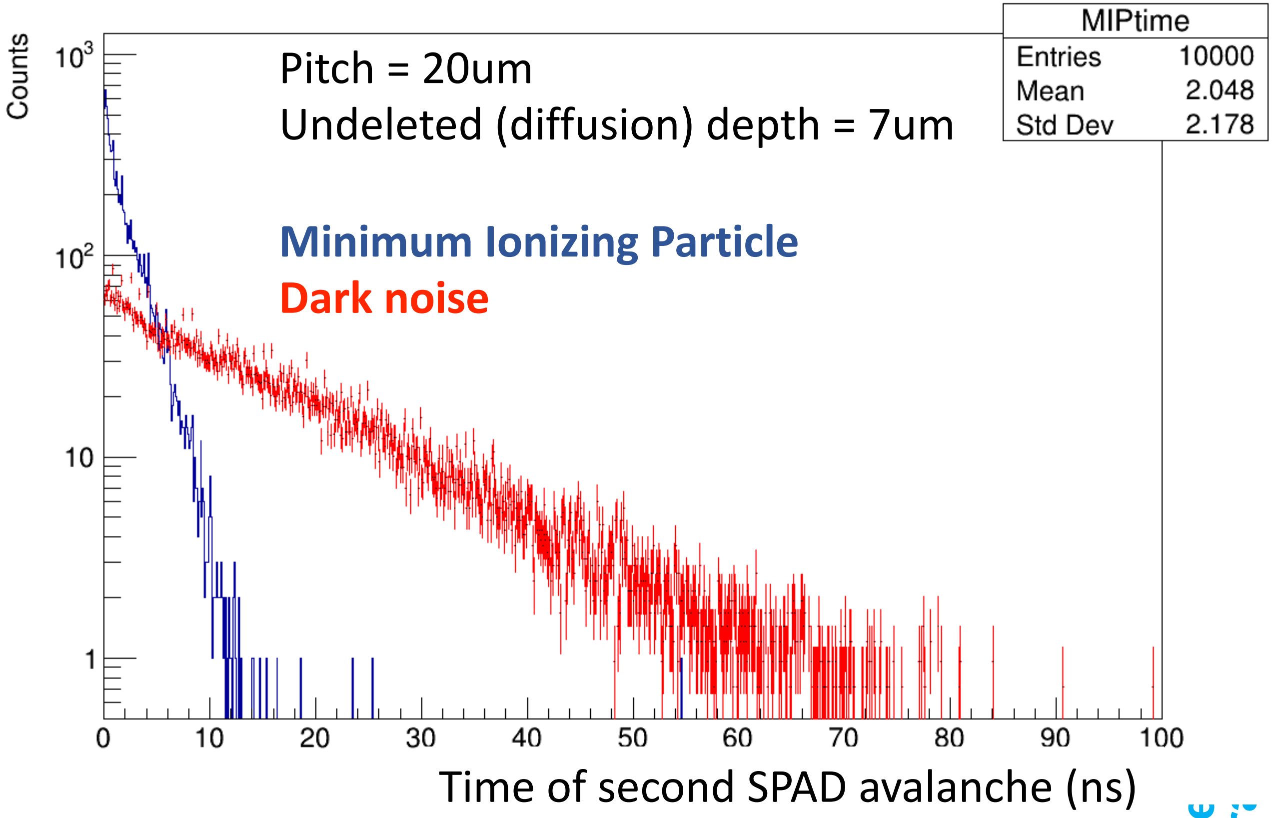
Diffusion time

Tristan Sulivan (Uvic)



Pitch = 50um
Undeleted (diffusion) depth = 20um

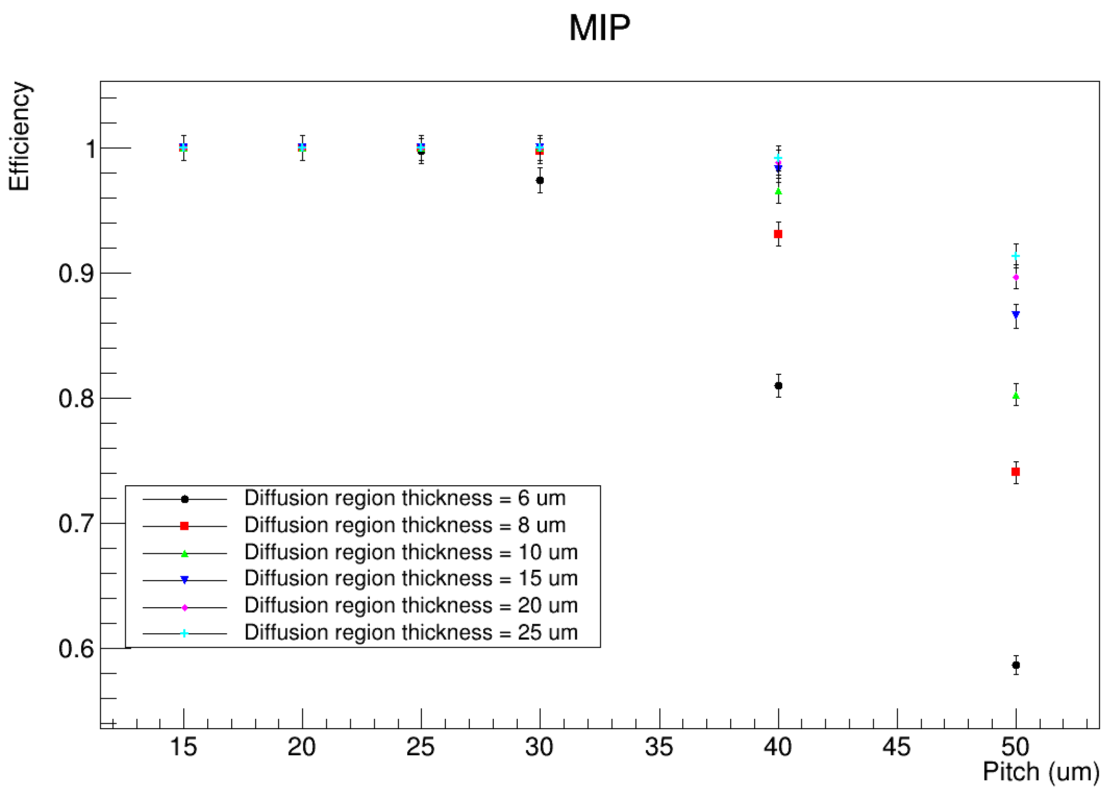
Minimum Ionizing Particle
Dark noise

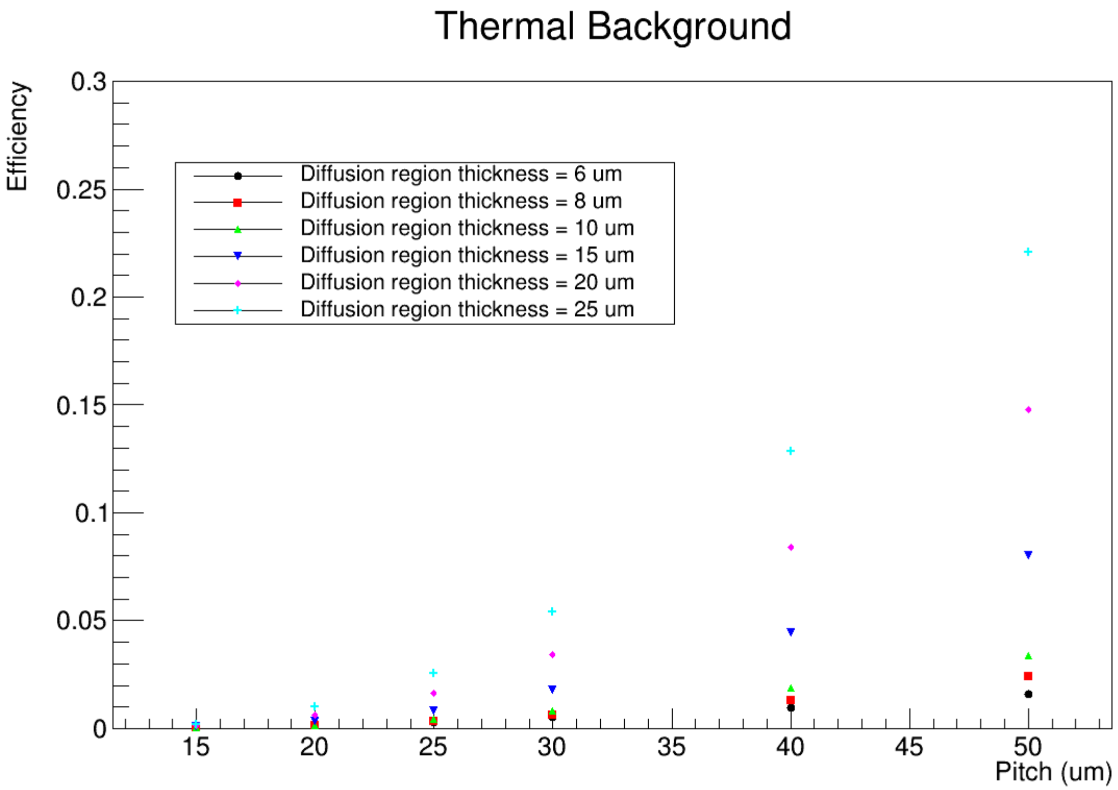


Pitch = 20um
Undeleted (diffusion) depth = 7um

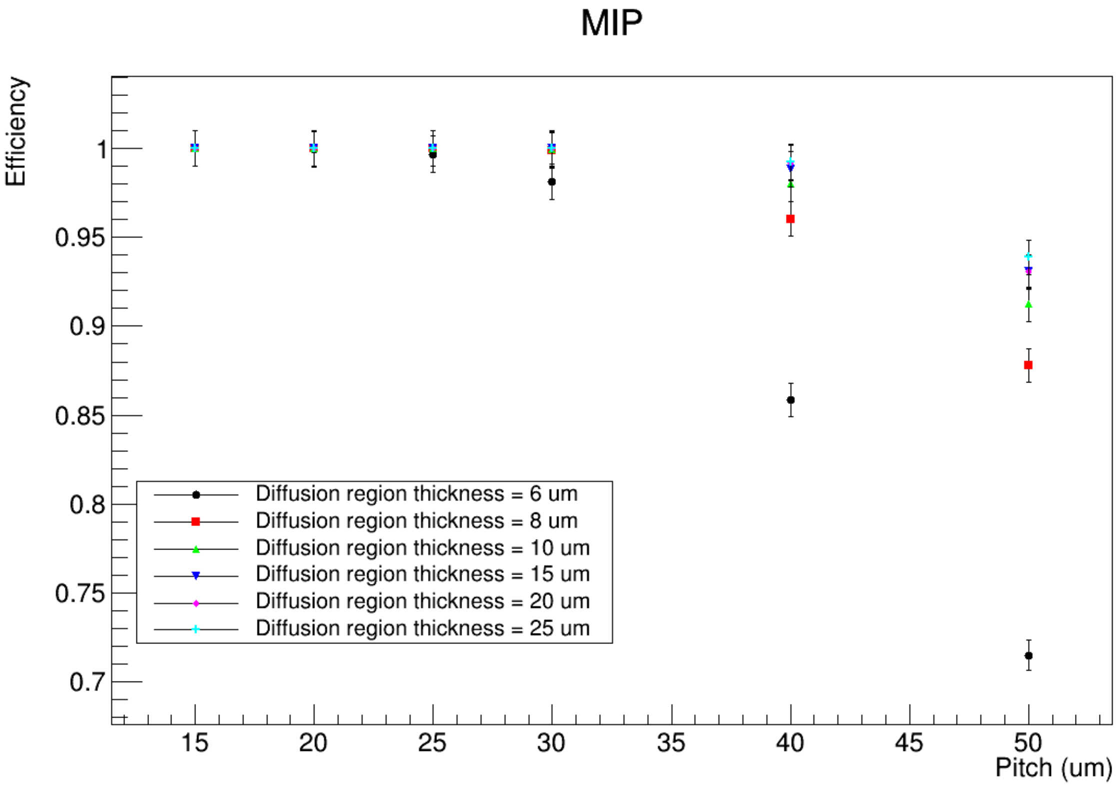
Minimum Ionizing Particle
Dark noise

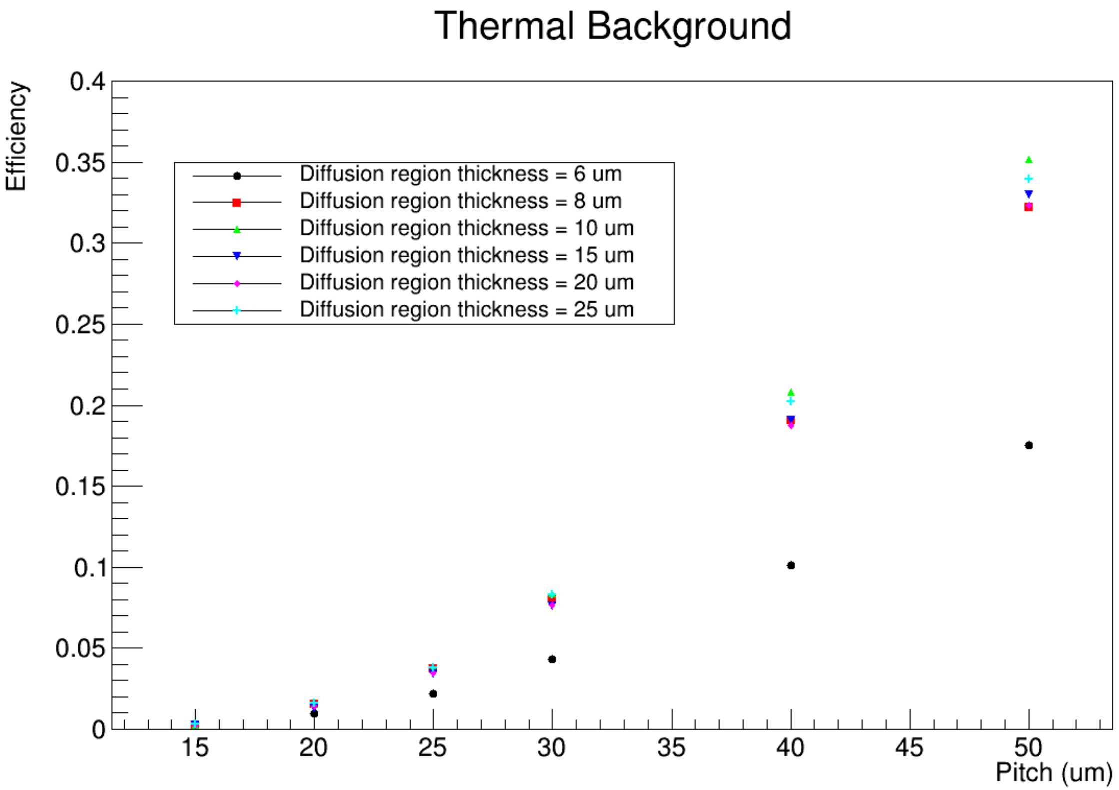
Full transparent/absorbing back surface





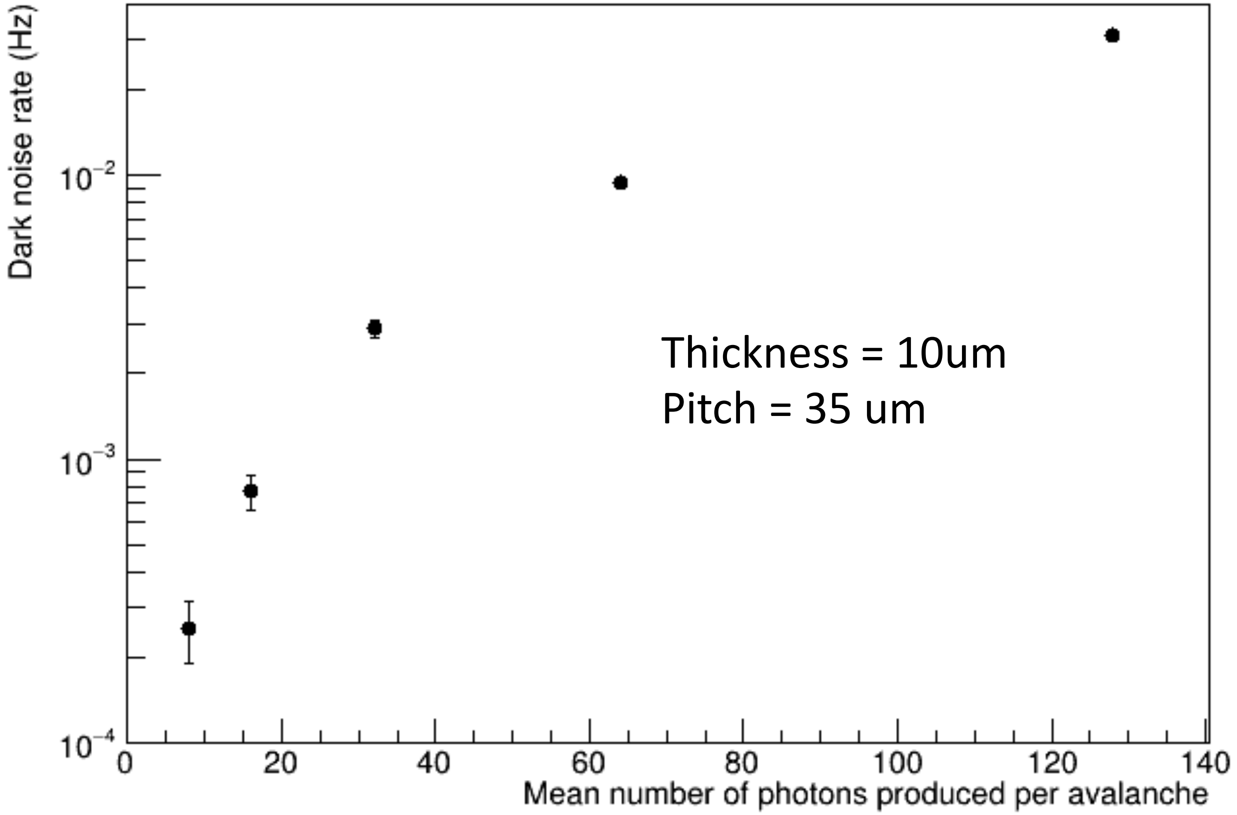
“Fresnel” reflection on back surface





Concerns

- Performances very sensitive to mean number of photons produced per avalanche
- Back surface must not reflect photons
- Timing
  - Diffusion is fairly slow
  - It takes up to 40ns to fire 2 Diodes
  - Time to trigger all the diodes can be 100ns
- Radiation damage
  - Similar to SiPMs so probably not so good



Thickness = 10um

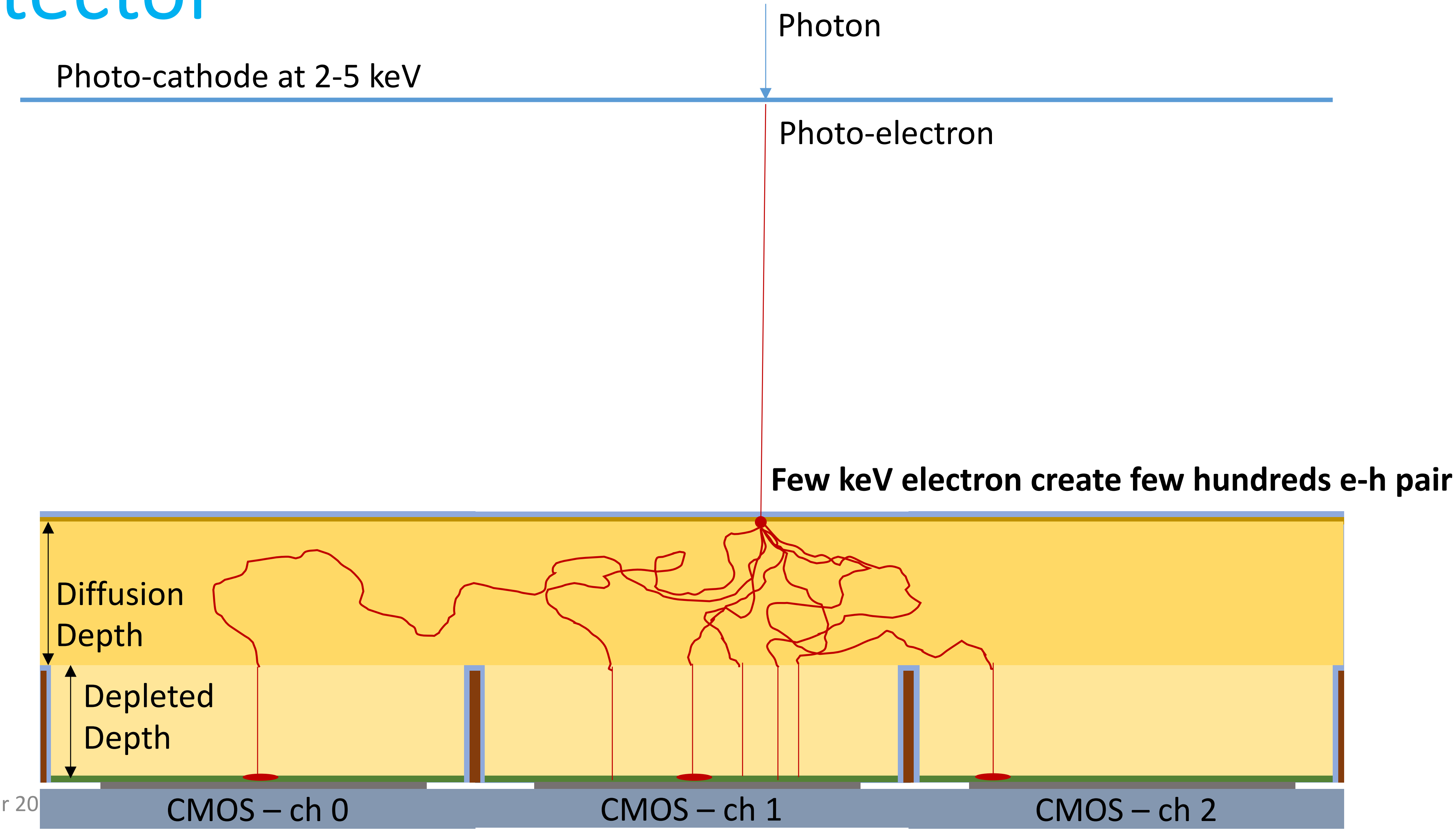
Pitch = 35 um

Summary and way forward

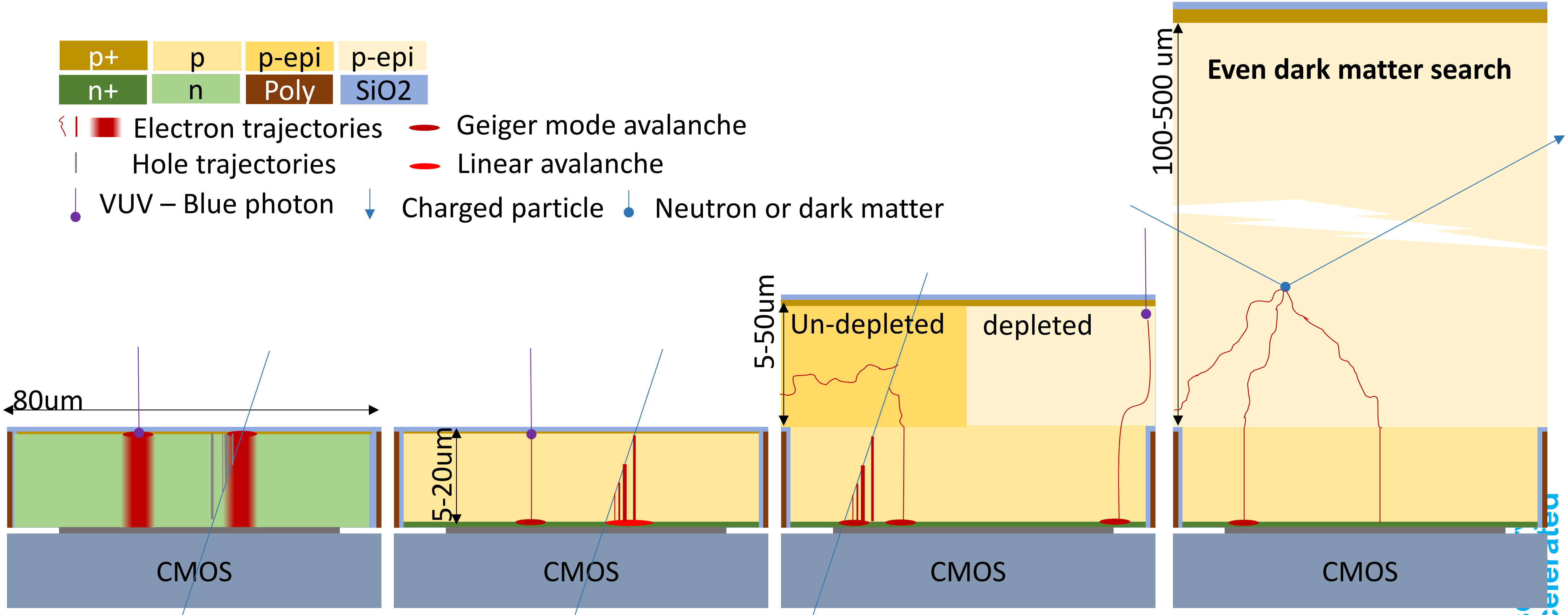
- Why ASGAD?
  - Timing, timing, timing. ASGAD only need to sweep one e- to high field region
  - 10 ps is the current frontier but more work on Efield engineering + CMOS can continue to bring this down
    - **Sub-1ps is on the horizon**
  - Thermal noise appears manageable

- Prototyping
  - Teledyne-DALSA as part of Back-side illuminated sensor development
    - Will happen but probably slowly due to resource competition with FSI SPAD
  - ... Interested partners?
    - **FBK**, We could start by making an analog prototype
    - Used old SiPMs? 10 years ago life time of carrier was long in bulk
      - Was changed to limit delayed cross-talk

Beyond ASGAD – Digital Hybrid Photo-detector



Beyond ASGAD – Back-side illuminated for everything



Front side avalanche diode

Back side avalanche diode

Extended

Ultra-thick

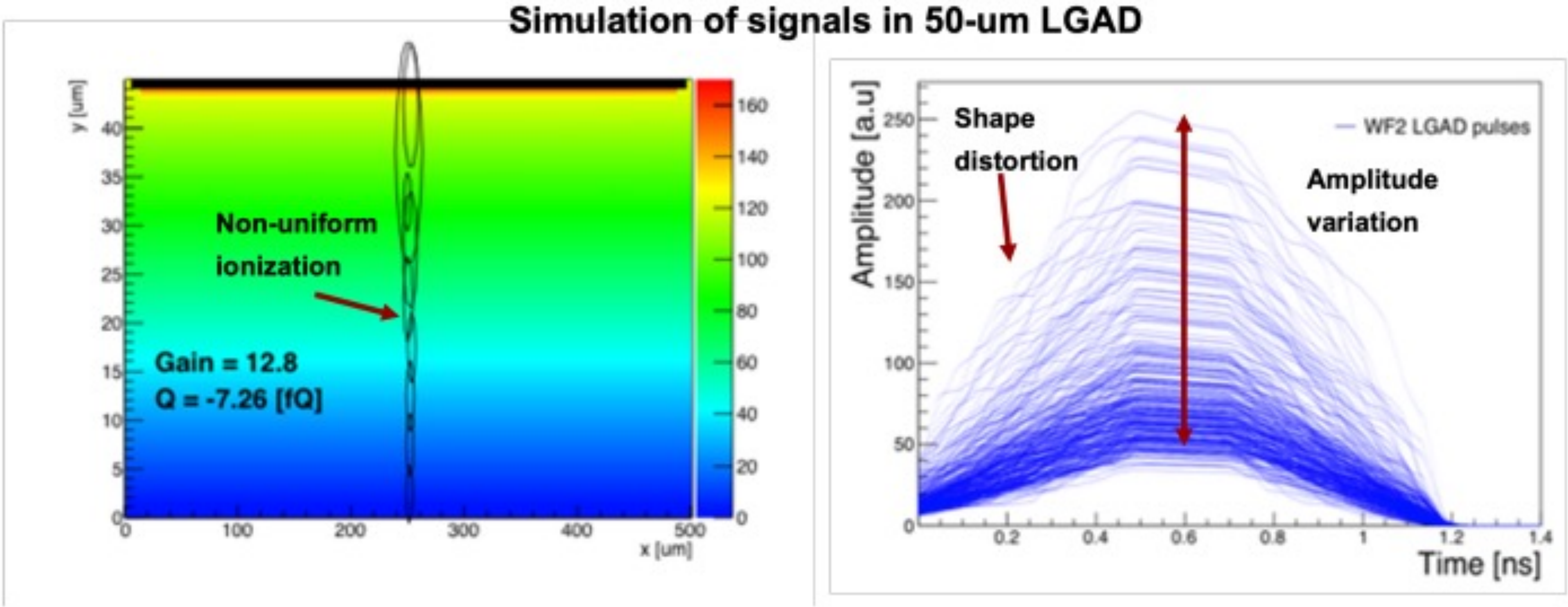
It does not always rain in Vancouver
Join our team!

4D Tracking: Present Status and Perspective

N. Cartiglia[a,*], R. Arcidiacono[a,b], M. Costa[a,c], M. Ferrero[a,b], G. Gioachin[c], M. Mandurrino[a], L. Menzio[a], F. Siviero[a], V. Sola[a,c], M. Tornago[a,c]

[a] INFN, Torino, Italy
[b] Università del Piemonte Orientale, Italy
[c] Università di Torino, Torino, Italy

LGAD, the 4D leading technology



$$\sigma_t^2 = \sigma_{Jitter}^2 + (\sigma_{Landau\ Noise} + \sigma_{Total\ ionization})^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

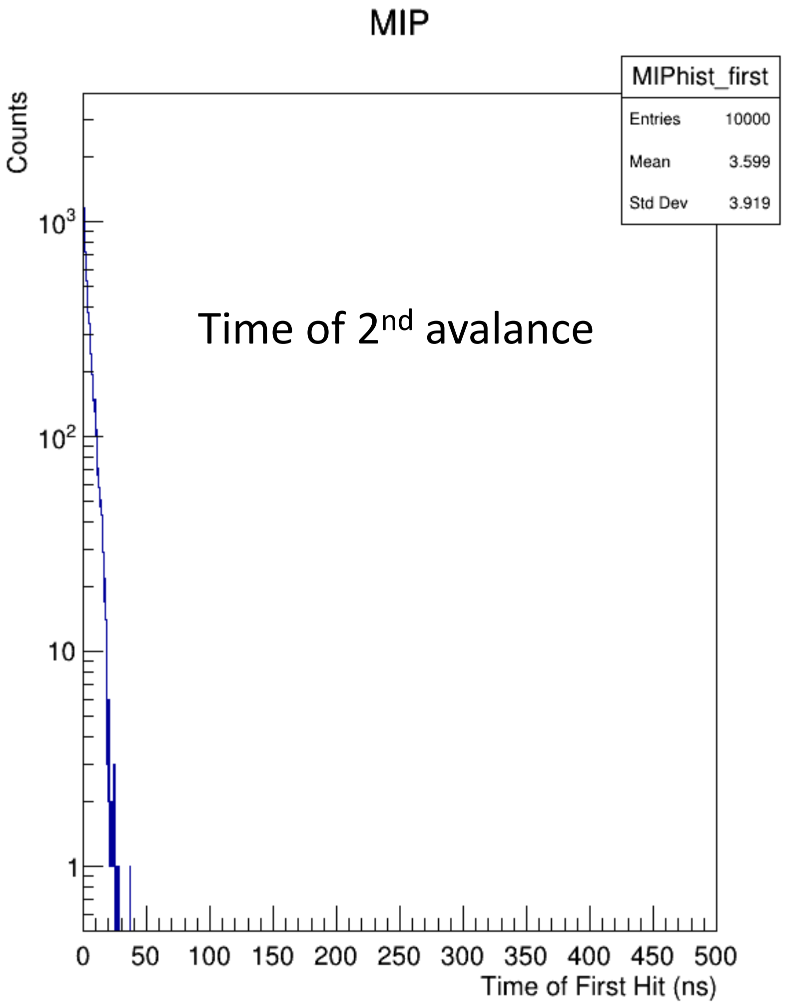
Digital electronics

Analog electronics

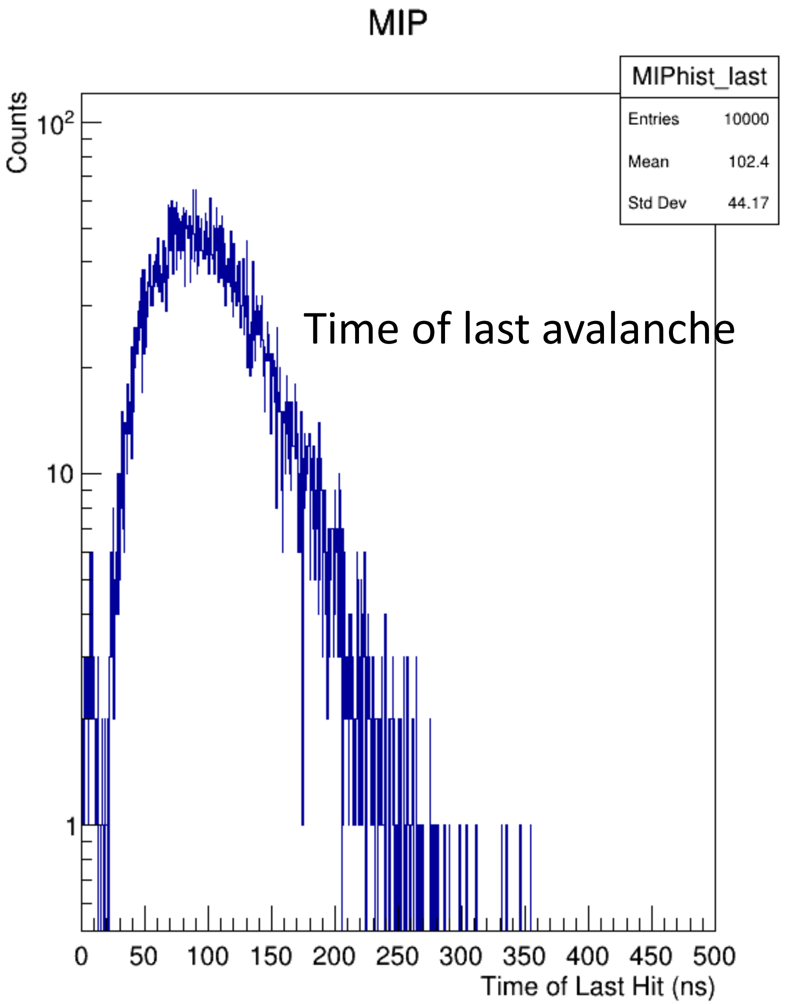
Ionization fluctuation

Efield uniformity

Timing delay

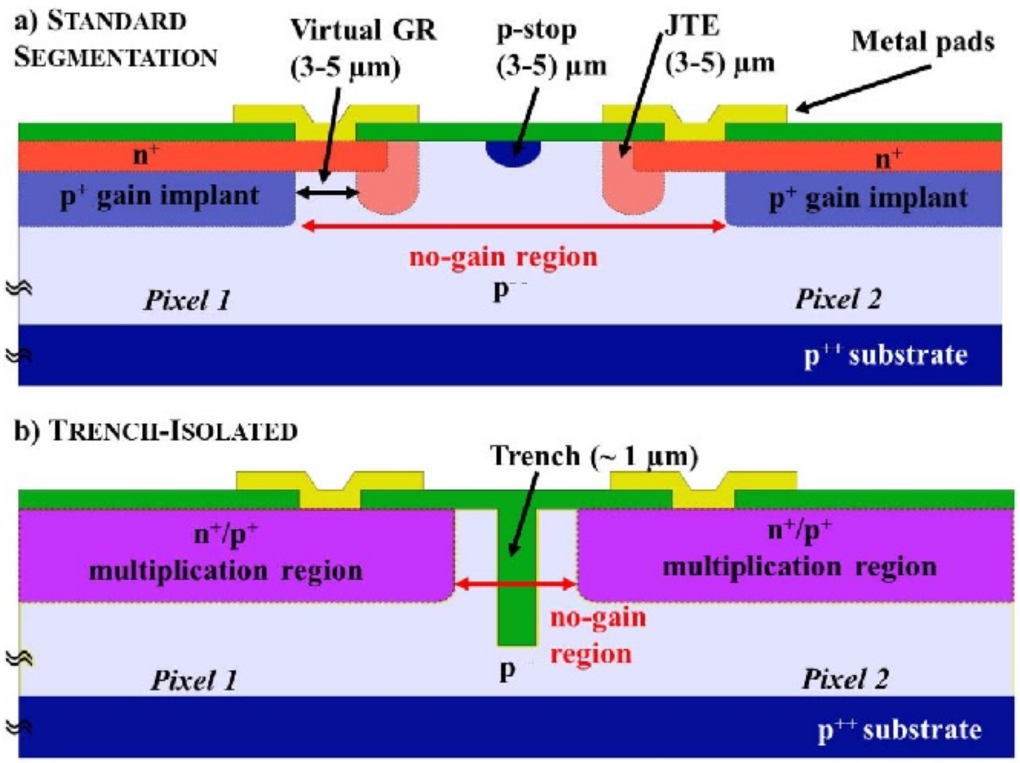


Time of 2nd avalance



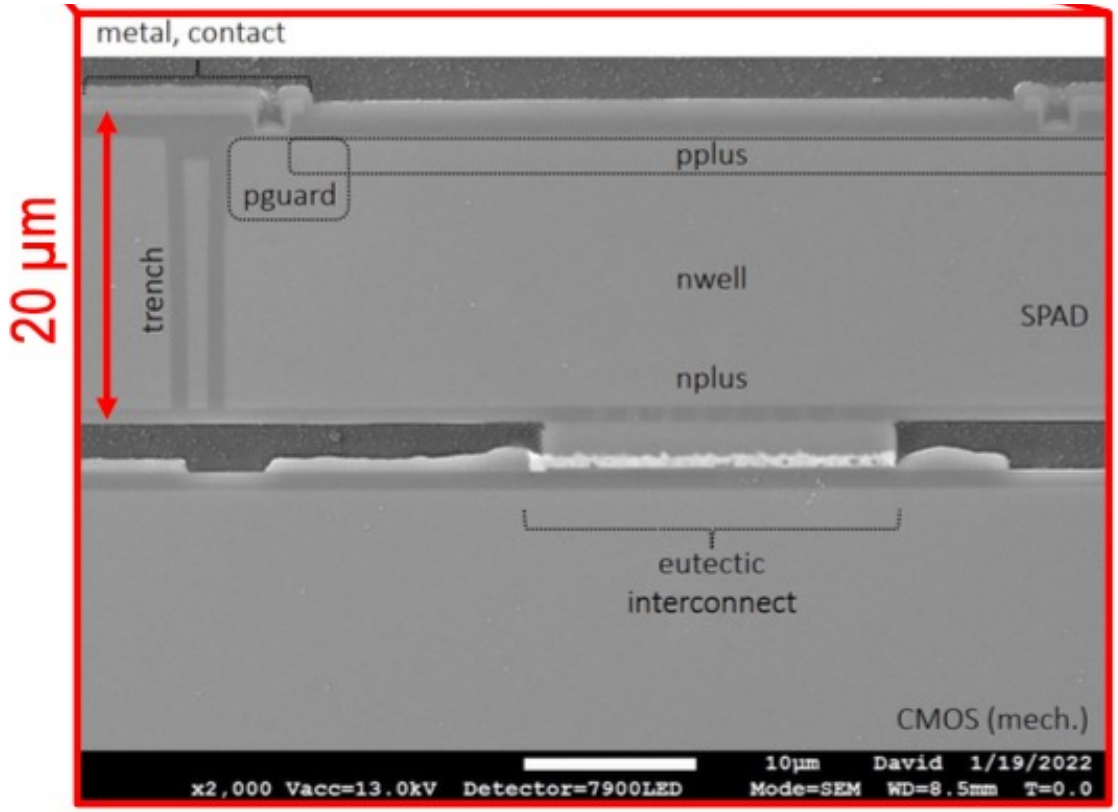
Time of last avalanche

From trench isolated LGAD to Single Photon Avalanche Diode

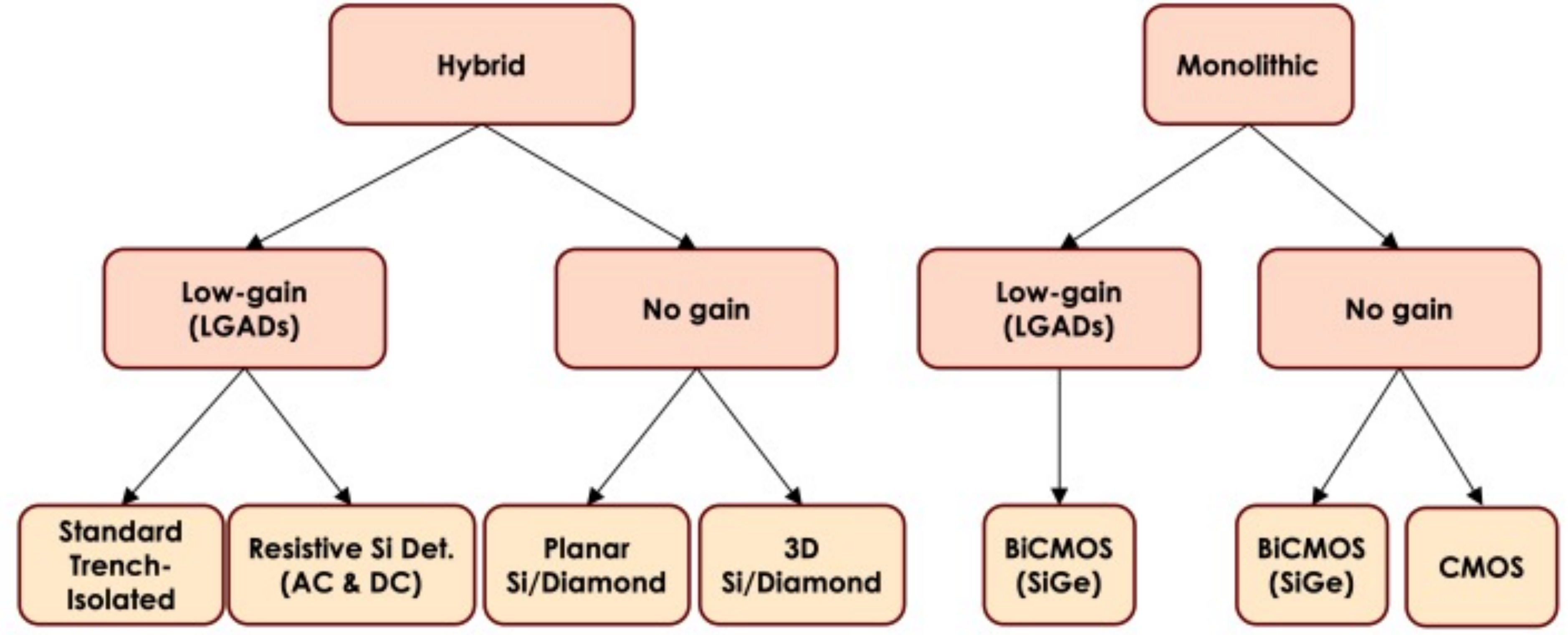


G. Paternoster et al. [10.1109/LED.2020.2991351](https://doi.org/10.1109/LED.2020.2991351)

Picture of a SPAD from the Photon to Digital Converter system



The technology landscape … so far



Hybrid

Low-gain (LGADs)

No gain

Standard Trench-Isolated

Resistive Si Det. (AC & DC)

Planar Si/Diamond

3D Si/Diamond

Monolithic

Low-gain (LGADs)

No gain

BiCMOS (SiGe)

BiCMOS (SiGe)

CMOS

4D Tracking: Present Status and Perspective

N. Cartiglia[a,*], R. Arcidiacono[a,b], M. Costa[a,c], M. Ferrero[a,b], G. Gioachin[c], M. Mandurrino[a], L. Menzio[a], F. Siviero[a], V. Sola[a,c], M. Tornago[a,c]

[a] *INFN, Torino, Italy*
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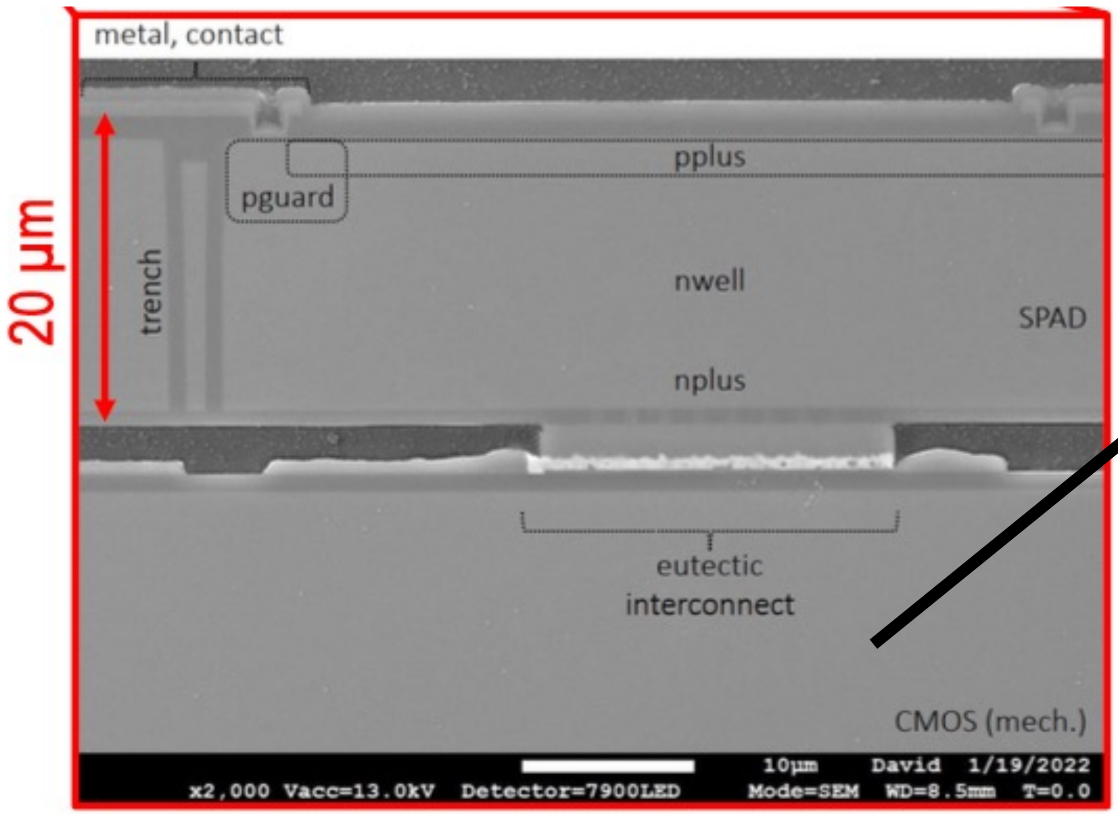
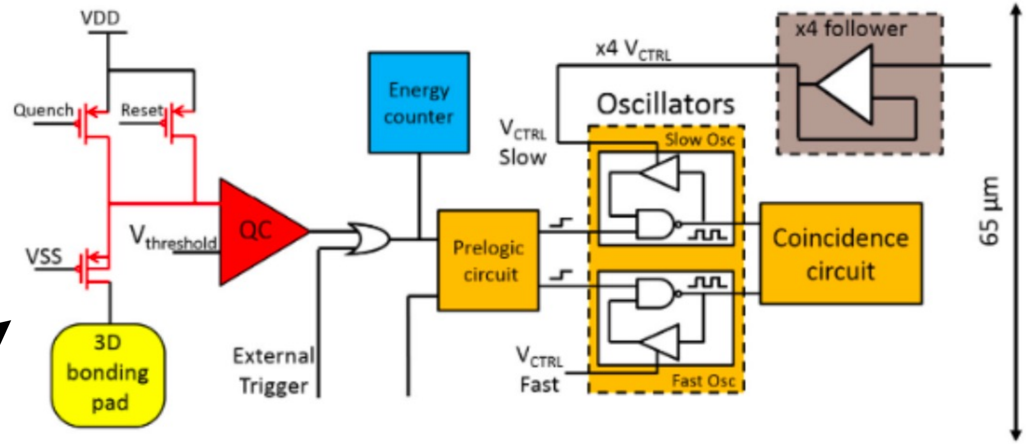
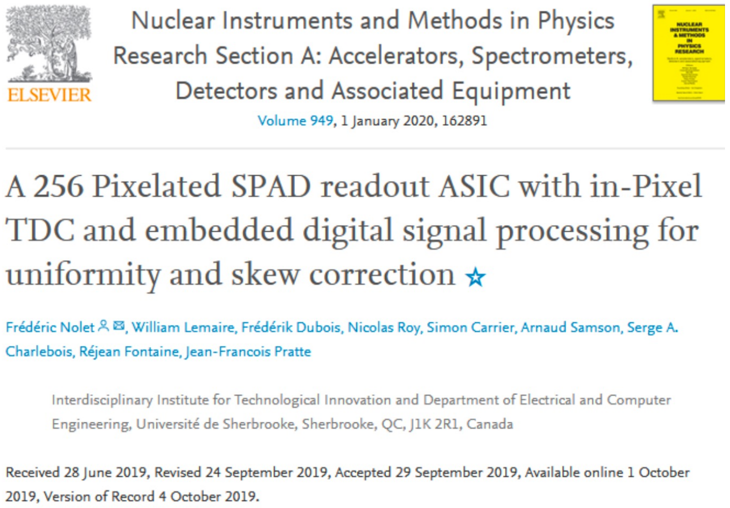
[c] *Università di Torino, Torino, Italy*

TDC integrated in each Single Photon Avalanche Diode (SPAD)







ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 949, 1 January 2020, 162891

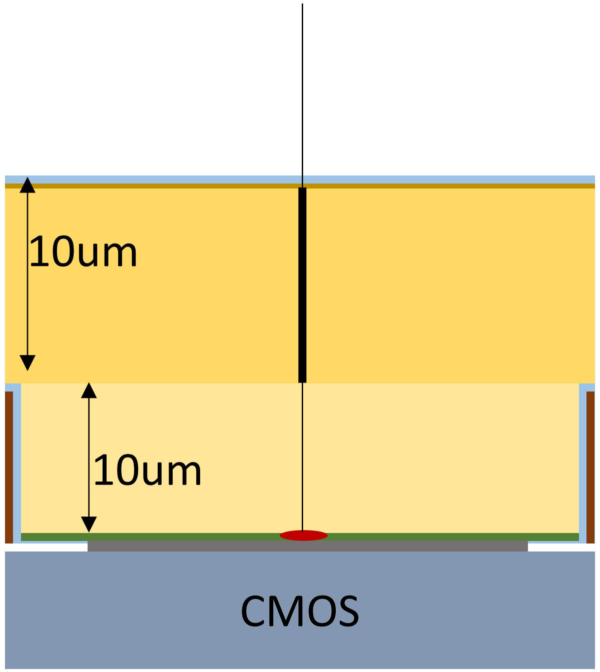
A 256 Pixelated SPAD readout ASIC with in-Pixel TDC and embedded digital signal processing for uniformity and skew correction ☆

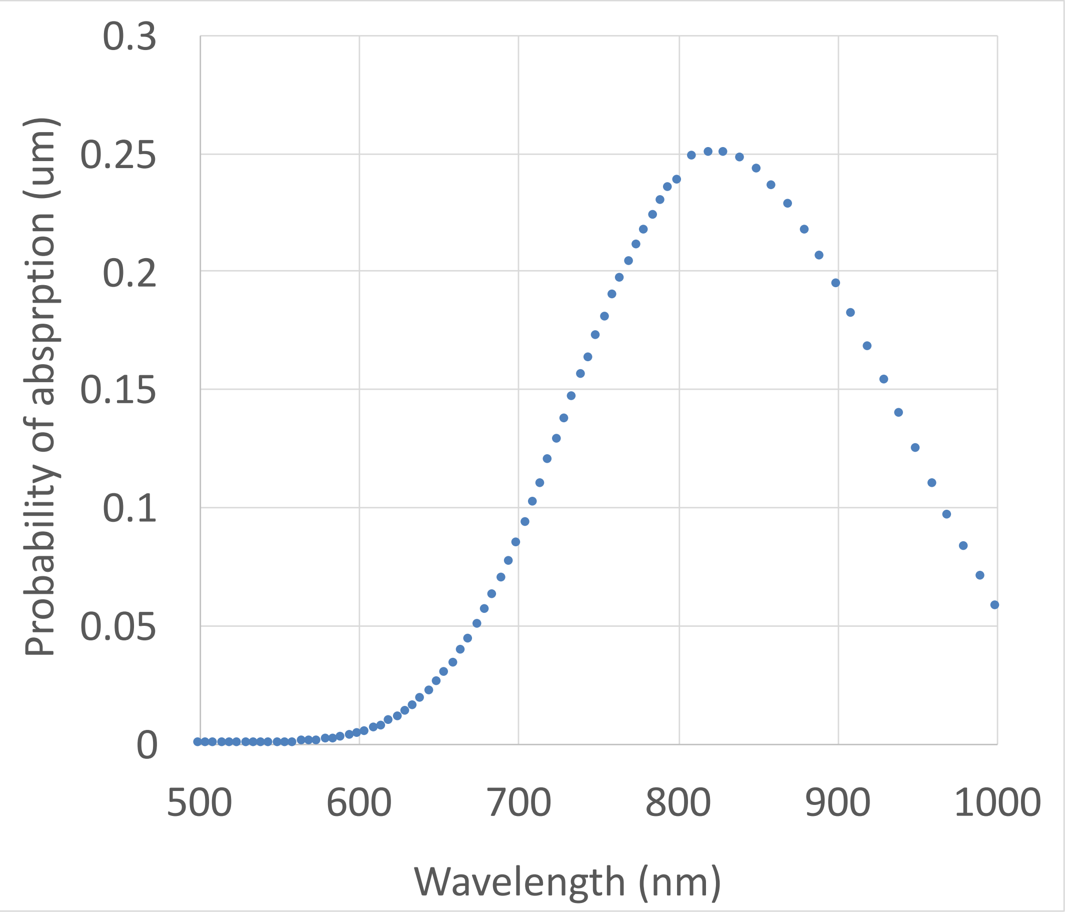
Frédéric Nolet, William Lemaire, Frédérik Dubois, Nicolas Roy, Simon Carrier, Arnaud Samson, Serge A. Charlebois, Réjean Fontaine, Jean-Francois Pratte

Interdisciplinary Institute for Technological Innovation and Department of Electrical and Computer Engineering, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1, Canada

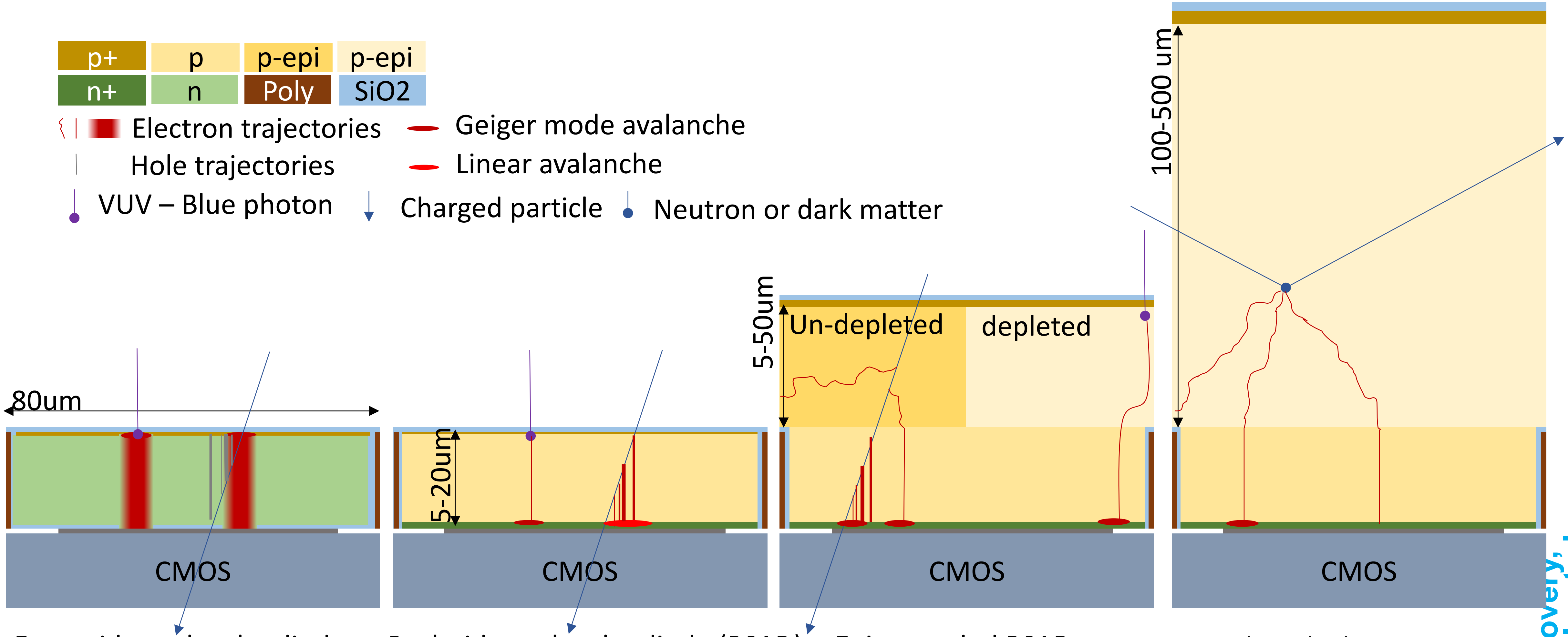
Received 28 June 2019, Revised 24 September 2019, Accepted 29 September 2019, Available online 1 October 2019, Version of Record 4 October 2019.

Wavelength that are problematic





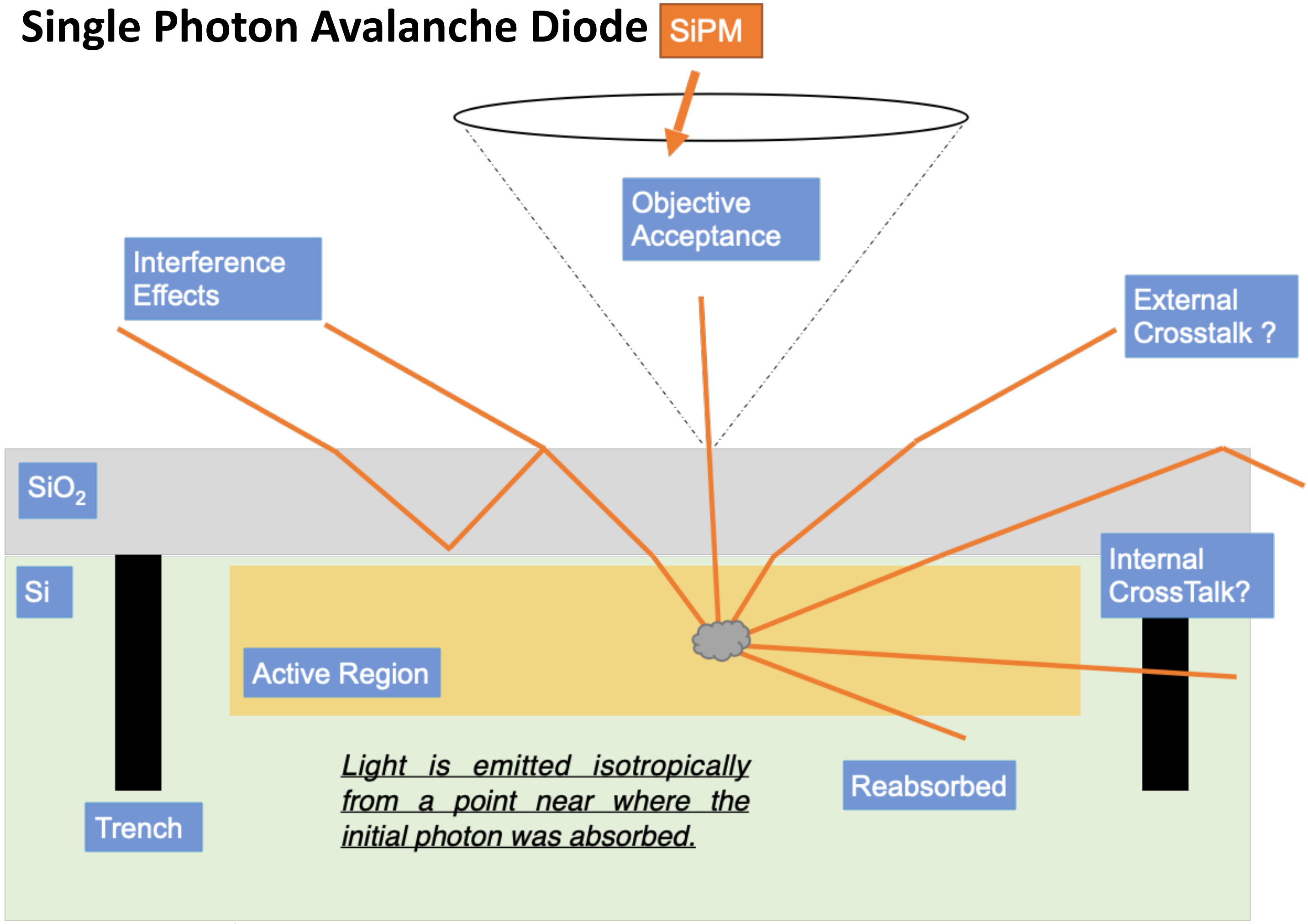
The 3D integrated master plan



Front side avalanche diode Back side avalanche diode (BSAD) Epi-extended BSAD Ultra-thick BSAD

Light emission to crosstalks

Single Photon Avalanche Diode



Light is emitted isotropically from a point near where the initial photon was absorbed.

- Light emission assumptions:
  - At p-n junction – maximum field
  - Isotropic
- External cross-talk
  - Photon escaping the SiPM surface
- Internal cross-talk
  - Photons being absorbed in a neibhoring SPAD
- We measure photons escaping with objective acceptance