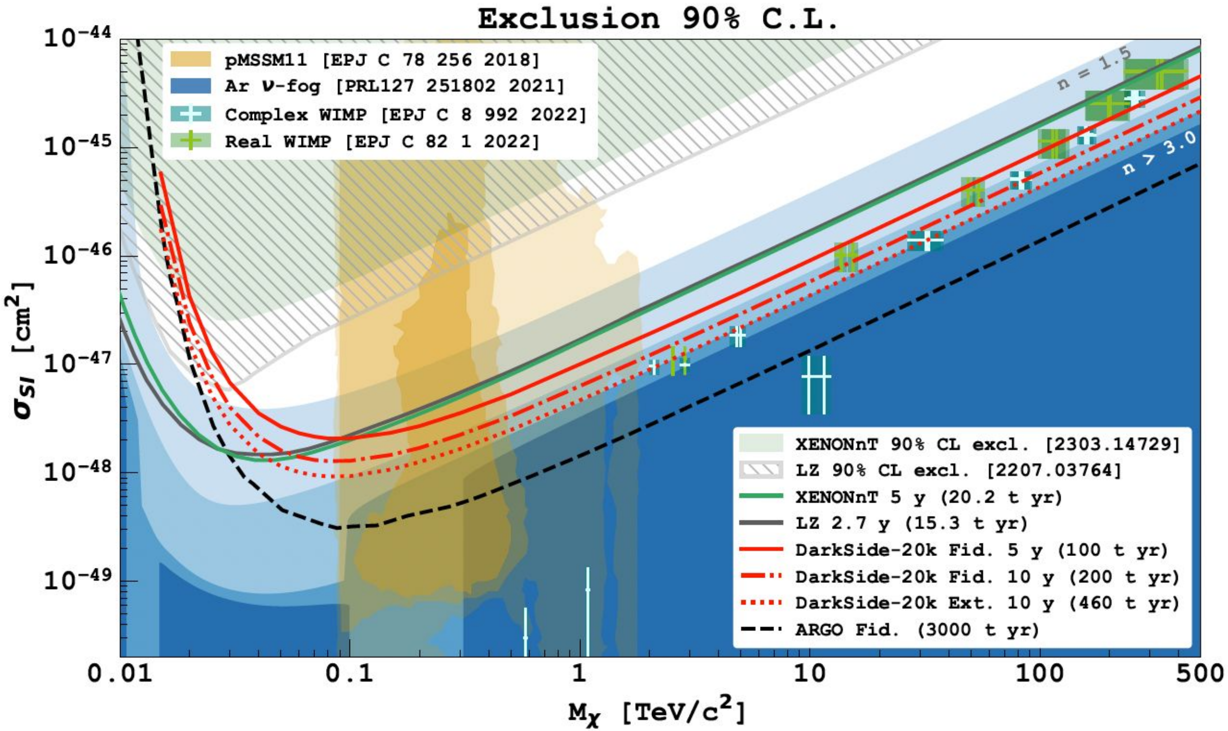
Silicon Photomuliplier (SiPM) Development for ARGO

Seraphim Koulosousas (On behalf of the Global Argon Dark Matter Collaboration)
Royal Holloway University of London
Lake Louise Winter Institute 2024

Science Motivation for SiPM Development

- One of the biggest drivers in Dark matter direct detection is reducing backgrounds whilst lowering energy threshold.
- To reach lower cross section sensitivity we need low energy threshold:
  - Every photon Counts!
- To reach lower cross section sensitivity we need to suppress backgrounds and increase exposure.
  - Every Bq Counts!

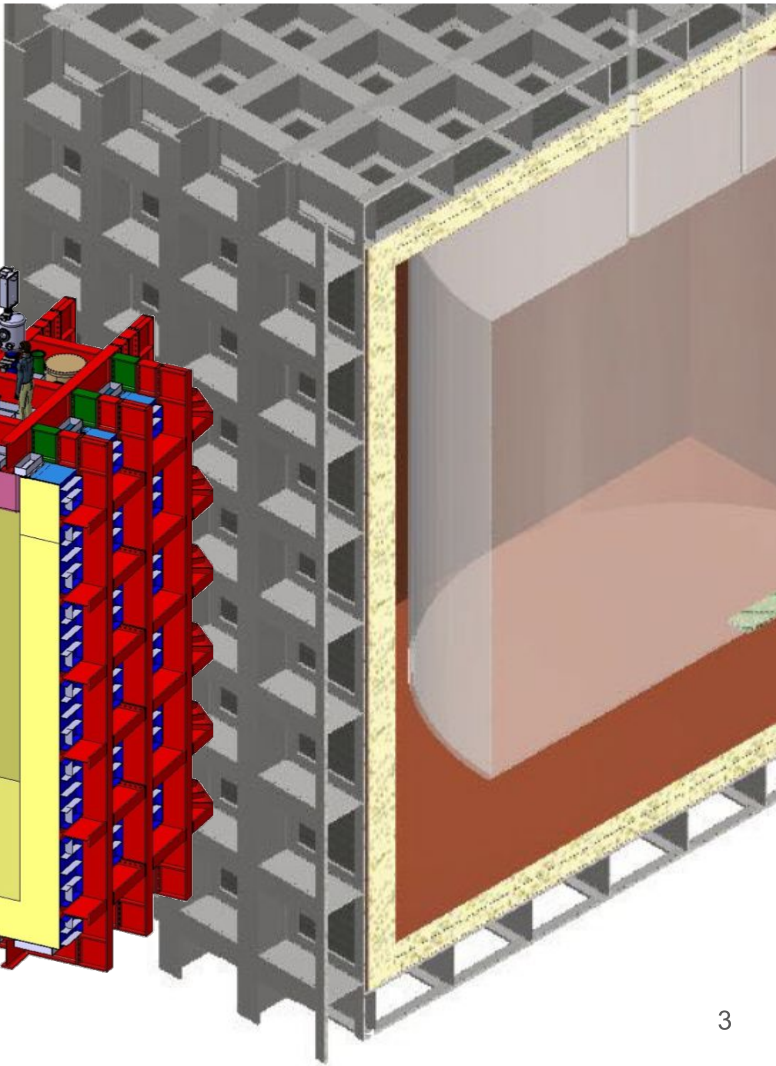


Detector Scaling

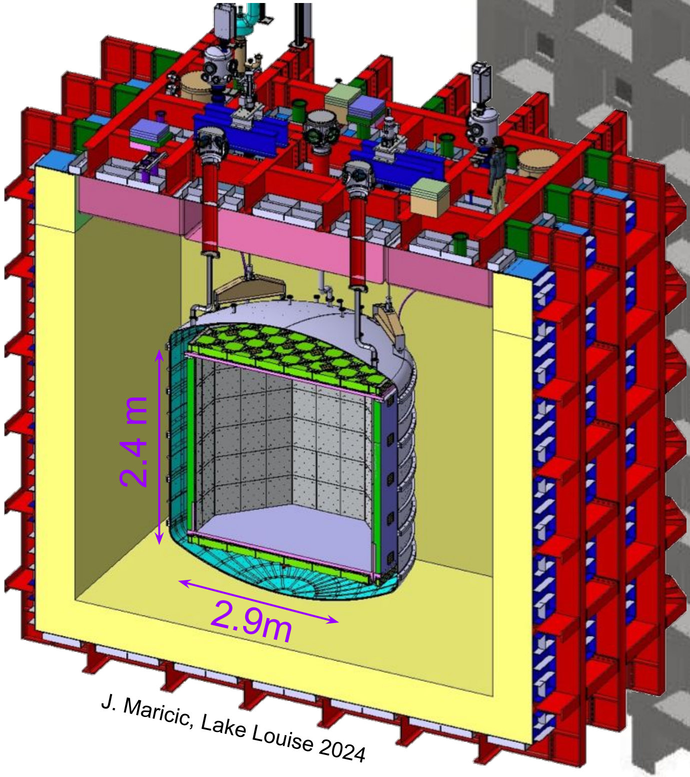
- Increasing Sensitivity means scaling your detector, In particular your readout surface area.

- How do we effectively scale the readout?
- How do we manage the data rate?
- How do we minimise the power consumption?
- Can we achieve the above in a cost effective manner.

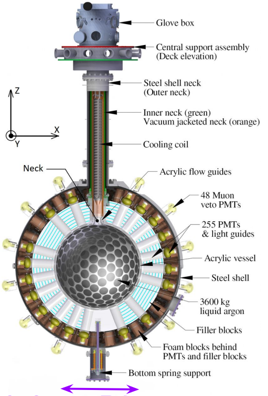
ARGO
Active Mass: ~400 tonne



Darkside-20k
Active Mass: 51 tonne

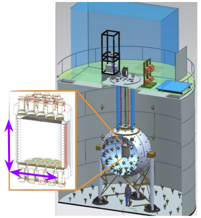


DEAP-3600
Active Mass: 3.2 tonne



0.85m Diameter

Darkside-50
Active Mass: 47kg

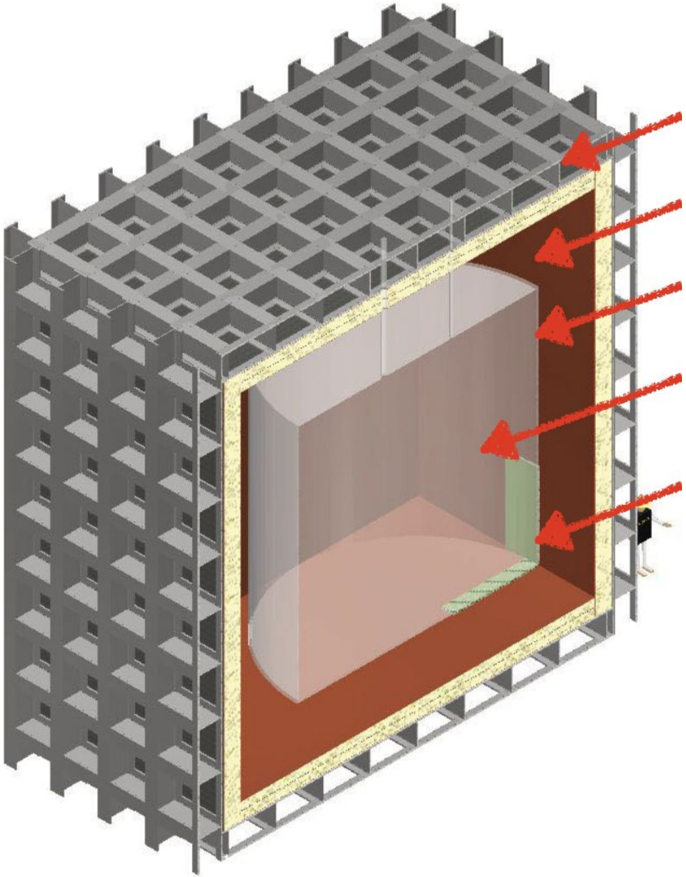


0.36m x 0.36m

ARGO Concept

<u>Requirements for readout system</u>

- Readout area 10x DarkSide-20k
- Require ultra-low background
- Single photon sensitivity
- Low noise
- Timing sufficient for pulse shape discrimination particle ID
- Manageable number of readout channels -> grouping
- Digital sensors, given
    - Operation 5k p.e/m^2s
    - Calibration 100k p.e./m^2s



Global Argon Dark Matter Collaboration (GADMC)

With many thanks for support to:

- CFI and NSERC (Canada)
- IN2P3 (France)
- INFN and MIUR (ITALY)
- STFC (UK)
- NSF and DOE (U.S.)
- Poland and Spain Ministries for science and education

UDS Université de Sherbrooke

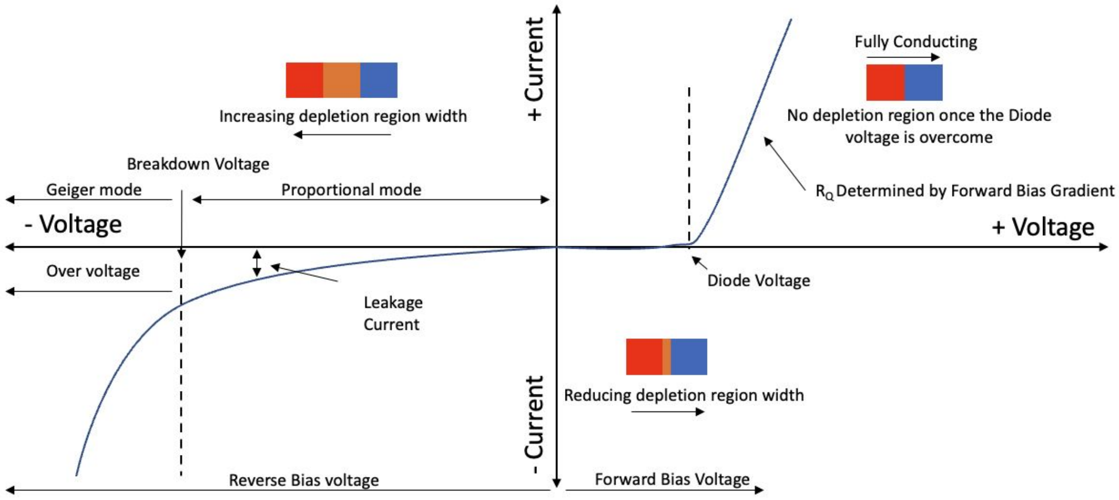
ASTROCENT NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

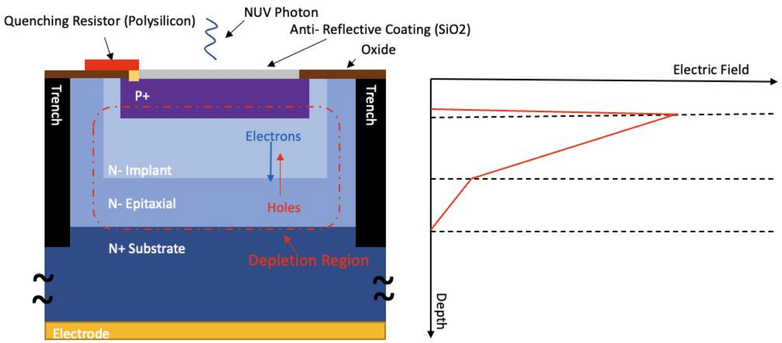
SiPMs 101

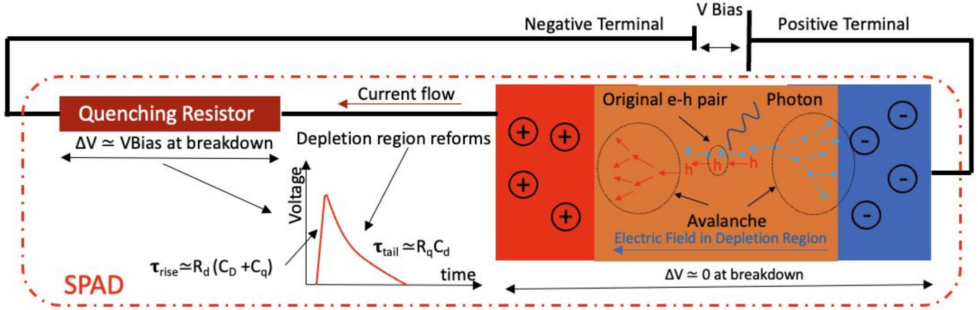
- SiPMs are large arrays of Single photon avalanche Diodes. (SPADs)
- SPADs are p-n junctions, engineered to operate above their breakdown voltage (geiger mode)
- Altering the doping profile allows for the electric field to be engineered, to optimize gain/noise characteristics.
- Signal created when photons absorbed in the active region liberate e-h pairs which create a avalanche.
- A resistor (polysilicon) in series passively quenches the avalanche producing the SiPM pulse response.

However! Noise sources from dark rate, cross talk, correlated delayed avalanches (CDA) such as after pulsing and delayed cross talk.

- Trenches to reduce optical cross-talk
- Doping optimisation to reduce CDA
- Electric field optimisation for Photon Detection Efficiency and DCR







Why SiPMs

Reaching ultra-low background:

- SiPMs are almost entirely silicon, which is low background!
- Future SiPMs look to incorporate processing on the same device. All silicon devices!

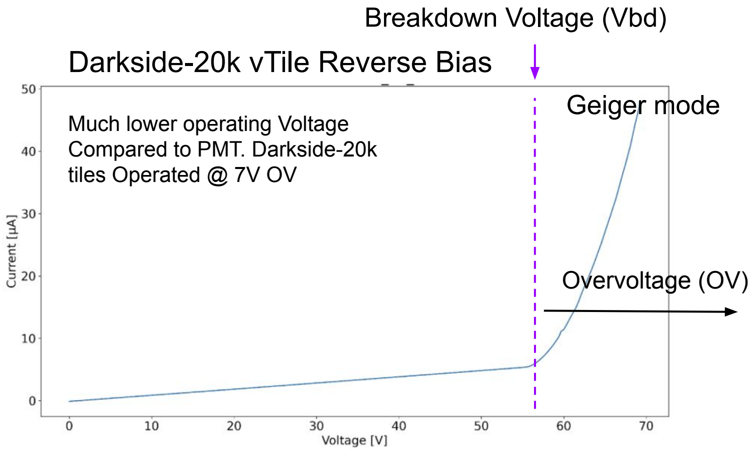
Reaching large area readouts:

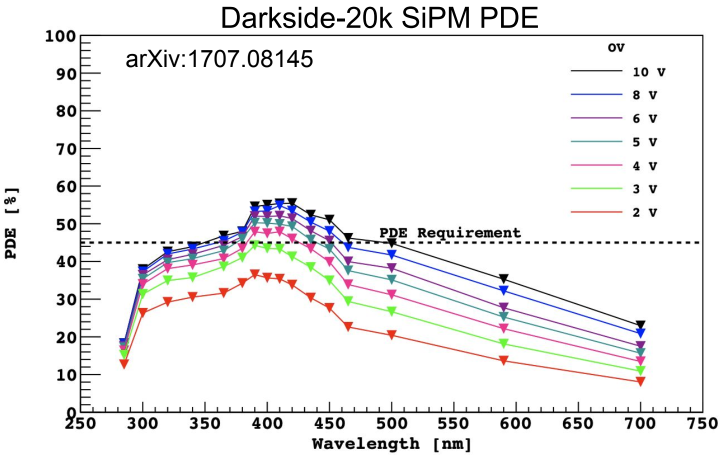
- SiPMs can be assembled into array detectors, requiring fewer readout channels (cables, connectors, etc.) per unit area
- SiPM production processes enable the industrial fabrication of readouts at relatively low cost per unit area

- SiPMs operate at lower voltage -> less complexity and lower energy usage

Maximizing light yield:

- SiPMs have lower dark noise (DCR) and higher photon detection efficiency (PDE) at cryogenic temperatures than PMT's.
- SiPMs can reach >95% fill factor -> better coverage of the detector volume.





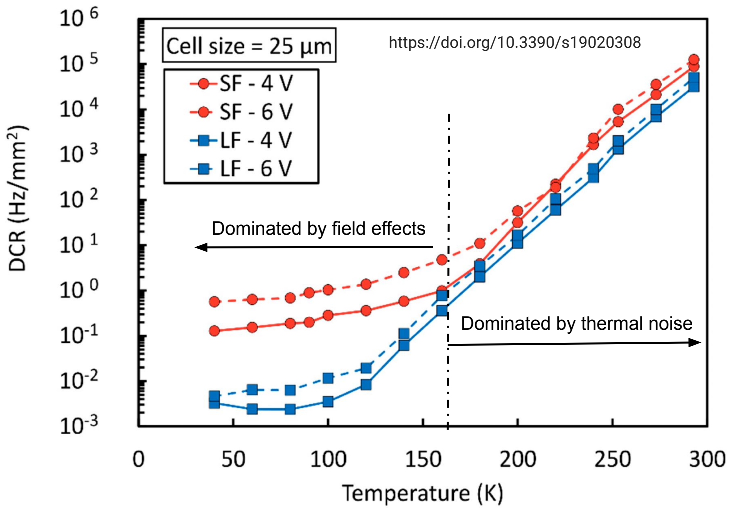
Noise Sources

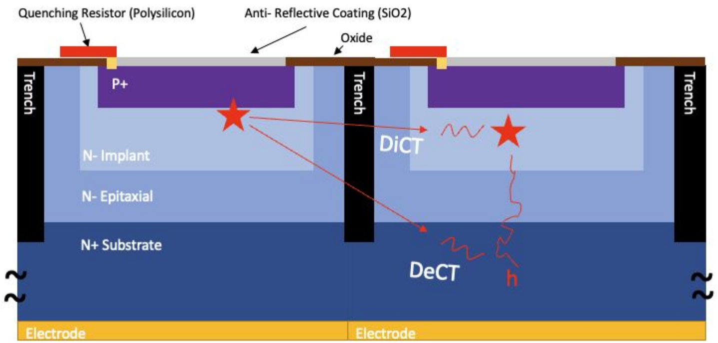
Uncorrelated:

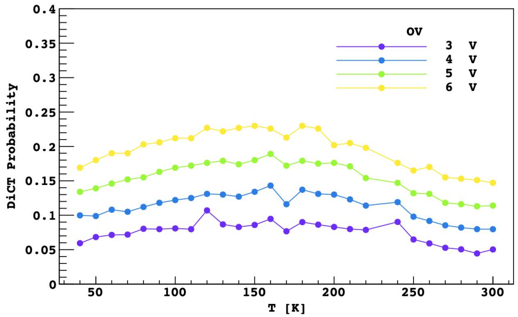
- Dark Count Rate (DCR)
  - Pulses triggered by thermal noise/ Field assisted tunneling.
    - < 150K DCR is dominated by field assisted tunneling.

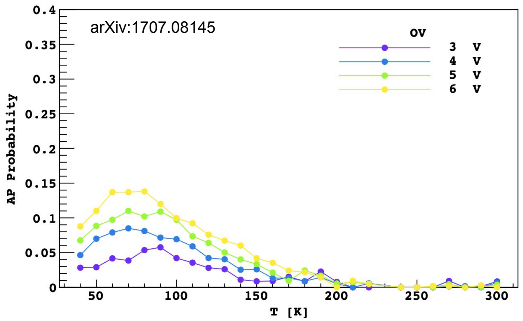
Correlated:

- AfterPulses (AP): Carriers become trapped during avalanche then get released after a period of time.
  - Mitigated by quenching resistance
- Optical Crosstalk: Photons generated in avalanche can propagate to neighbouring cells and trigger another avalanche.
  - Direct Cross Talk (DiCT) - Avalanche triggered in neighbouring SPAD by photon generated in initial avalanche.
  - Delayed Cross Talk (DeCT) - Charge carrier released in the silicon bulk
    - Both Mitigated by the insertion of trenches to optically isolate SPAD

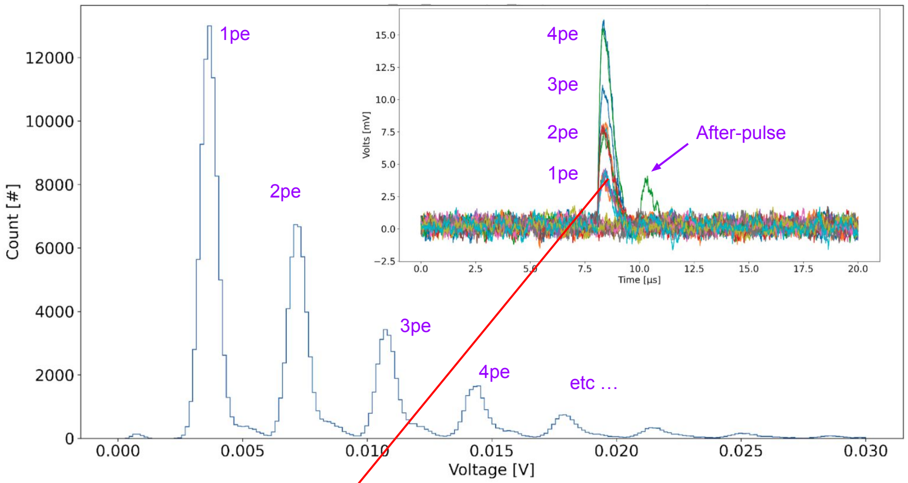








Why SiPM Arrays

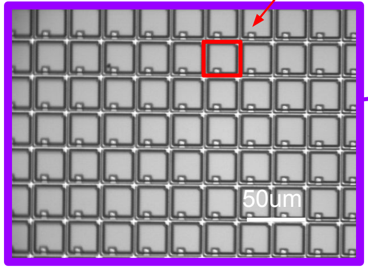


Reduces channel count in large-area readouts!

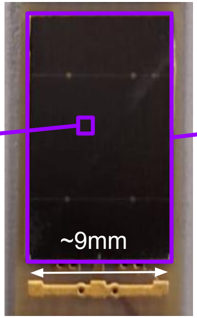
DarkSide-20k has shown:

- Can preserve single Photoelectron (pe) resolution
- SiPMs are a low noise, low form factor, high quantum efficiency
- Photon Detection Efficiency: > 40% at 77k
- Fast timing O(100ps)
- Dark count rate (DCR): ~0.01Hz/mm^2 at 77k
- SNR > 8 for 10x10 cm^2 TPC Photo Detection Unit (PDU)
- Readily mass produced. Utilise mature semiconductor manufacturing techniques.

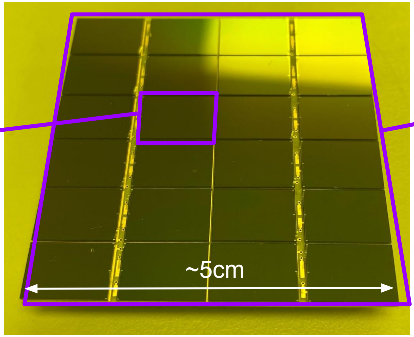
SPAD Array



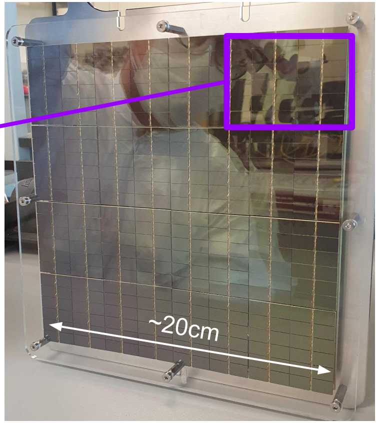
SiPM



Tile (24 SiPMs Grouped)

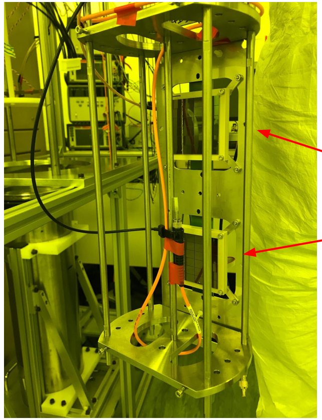


PDU (16 Tiles Grouped in 4s)



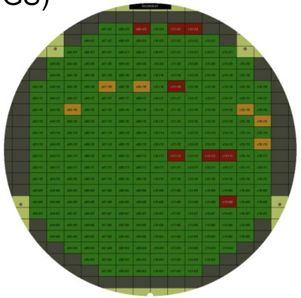
Performance of Darkside-20k SiPM Array Detectors

- Darkside UK collaborators has fully tested ~10% of the SiPM tiles that will instrument Darkside-20k inner veto.
  - ~120 tiles -> ~2800 SiPMs
  - Breakdown, SNR, DiCT, CDA measured for each tile
- Performance for each SiPM tracked from Wafer -> Tile -> PDU.
  - Performance measurements are stored on centralised database allowing for QA/QC analysis to be carried out from multiple sites.
- Pipeline is essential in the development of SiPM Devices
- See small variation in key performance metrics such as SNR, 1 p.e. Amplitude, etc…

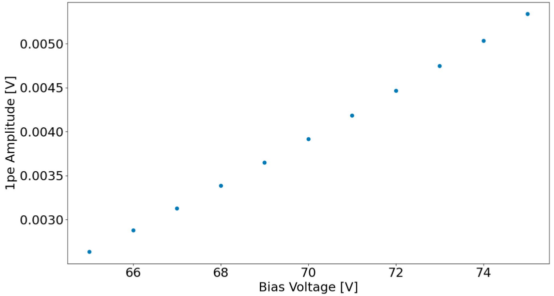


Two inner veto tiles in one of the UK test stands

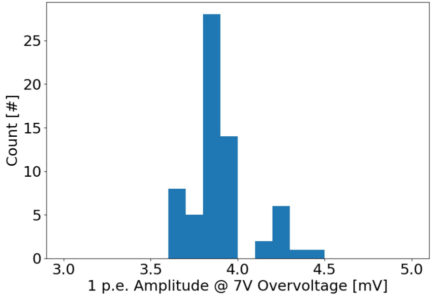
Each Wafer is cryogenically probed at Laboratori Nazionali del Gran Sasso (LNGS)



Each tile produced has key performance metrics such as 1p.e Amplitude/charge, SNR, AP, DiCT… etc measured



Tight grouping of metrics across multiple tiles a benefit of semiconductor fabrication techniques



Readout Electronics - Moving from Analog to Digital SiPMs

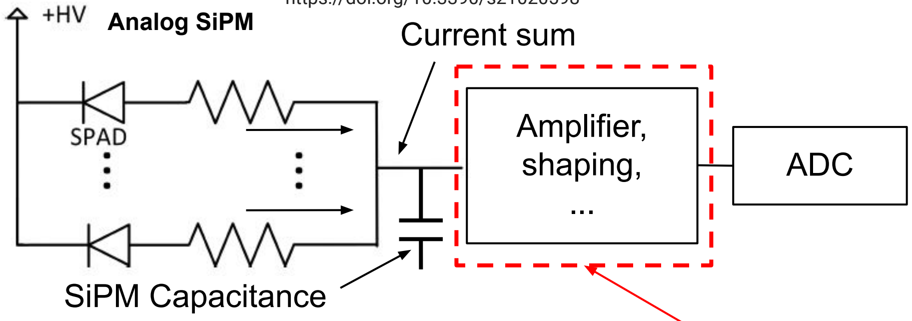
Analog SiPMs

- Requires discrete amplification components (i.e transImpedance amplifier)
- High output capacitance -> Electronic noise
- Large distance between SiPM and amplifier.

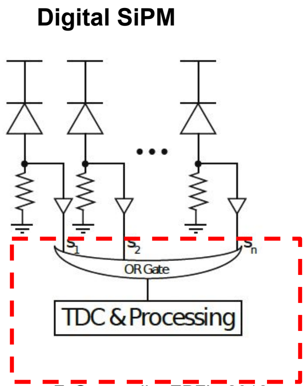
Digital SiPMs

- Each SPAD has its own pixel circuitry.
- Digital logic and electronics are fabricated on the same device
- Adds additional processing functionalities without the need of external components (e.g. Time-to-Digital Converter (TDC))

https://doi.org/10.3390/s21020598



Signal processing via discrete components

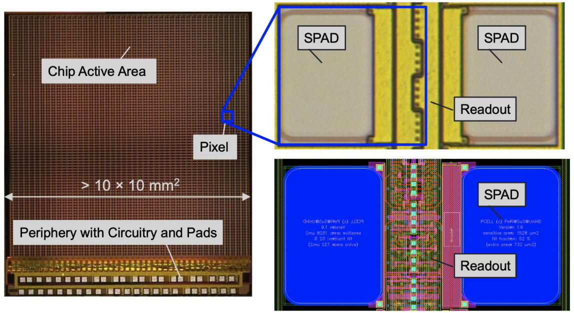


Signal processing fabricated on chip

F. Gramuglia, EPFL, 2018

Digital SiPM Architectures

2D Integration



In 2D integration the Read out Electronics are fabricated alongside the SPADs on the same side of the wafer.

Advantages

- Replace SiPM + Asic combination with a single device
- Same technology for sensor and logic
- Can turn off pixels with high DCR

Disadvantages

- Lower Fill Factor
- Limited Processing per pixel

P. Fischer et al, DRD2 2024

3D Integration

In 3D integration the readout electronics are fabricated on a separate wafer. The SiPM wafer and the electronics are then stacked (via hybrid bonding).

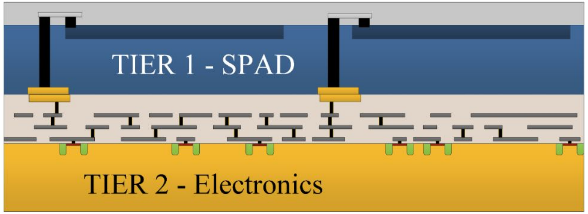
Advantages

- Direct connection between pixels and logic
- Increase Fill factor,
- Increase on chip processing capability
- Can turn off Pixels with High DCR

Disadvantages

- High Cost
- Requires multiple fabrication steps.
- Needs substantial R&D effort
- Limited access to fabs for R&D

F. Retiere, DRD2 2024



Pratte, J.-F. et al. *Sensors* **2021**, *21*, 598

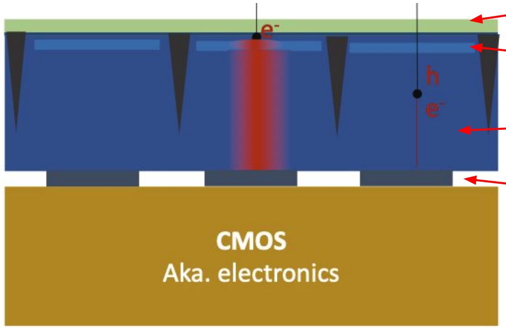
Active Canadian Development in 3D - Photon-to-Digital Converter (PDC)

UdS Université de Sherbrooke

TRIUMF

Digital SiPMs Optimised for Dark Matter Searches.

Front-side Illuminated



Thin Passivation ~100nm
Avalanche Region
Drift Field Region
Molecular Bonding

Front-side illuminated Design places the Avalanche region at the top of the SPAD

- Demonstrated NUV Sensitivity
- Sensor is on the surface so electronics can be placed on the underside of the same wafer.

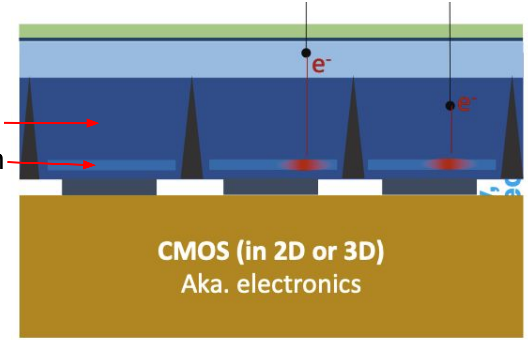
Université de Sherbrooke

Back-side Illuminated

Back-side illuminated Design places the Avalanche region at the bottom of the SPAD

- Visible to IR sensitivity can be achieved by controlling detector thickness
- VUV sensitivity can be achieved through surface processing.
    - Unconventional Anti-reflective coating
    - Graphene, 3D Structures
    - Would mitigate the reliance of wavelength shifting (Argon scintillation wavelength: 128nm)

Drift Field Region
Avalanche Region

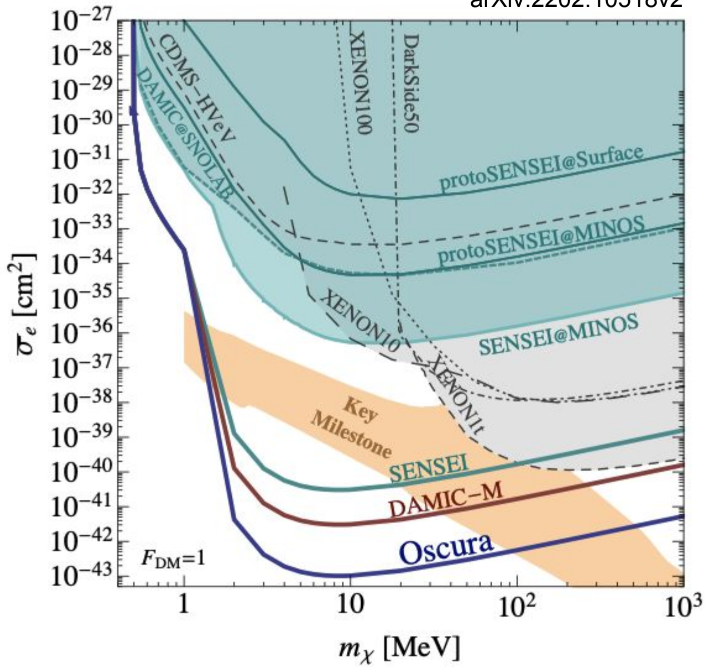


F. Retiere, DRD2 Meeting 2024

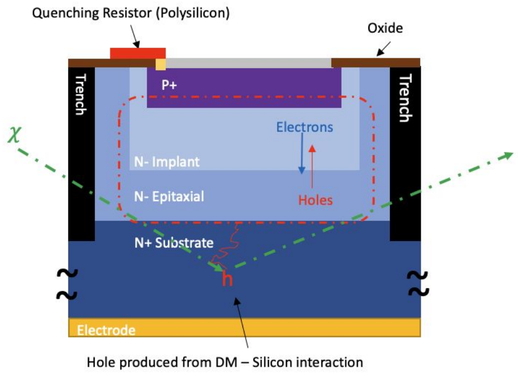
TRIUMF

SiPMs as Potential Low Mass Dark Matter Target

arXiv:2202.10518v2



- Current Noble liquid direct DM experiments are blind to low mass DM candidates as the recoil energy is below the detection threshold.
- SiPMs are excellent detectors for single photo-electrons.
- Low Silicon band gap energy ~eV could be leveraged to look for **electron recoils** in the SiPMs.
- ARGO will be instrumented with ~250m^2 of SiPMs -> ~300kg of Silicon.
- Looking for interactions in the silicon bulk via carrier diffusion could unlock a secondary target.



ARGO could use large silicon exposure to potentially look at ~MeV region of parameter space as well.

Summary and Outlook

SiPMs offer an attractive solution for large-area readouts, especially for low background experiments.

Future developments

- The large scaling required necessitates the move from Analog SiPMs -> Digital SiPMs
- Digital SiPM R&D is a very active area with multiple exciting avenues for development.
- Back-side illuminated SPAD could improve VUV sensitivity, remove the need to use wavelength shifter.
- Potential to use SiPMs as another avenue for Dark Matter Direct Detection.

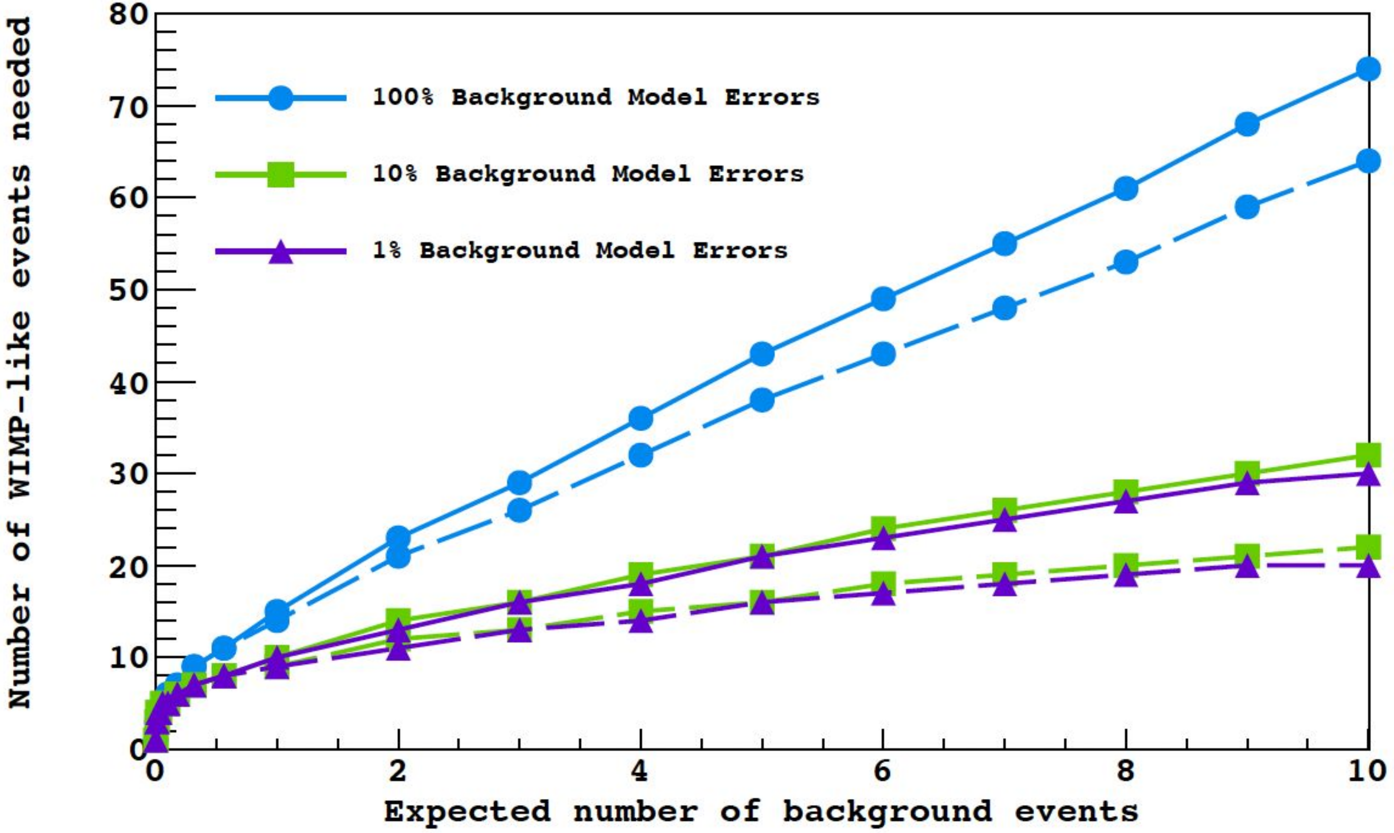
Thanks for Listening!

Université de Sherbrooke

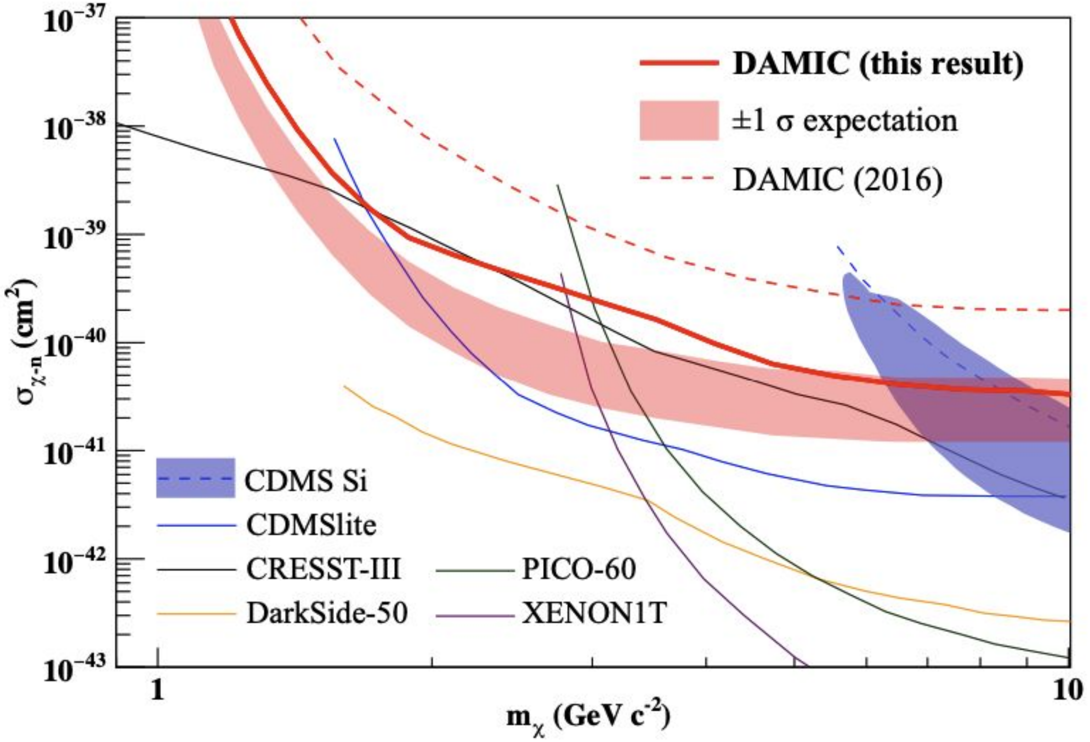
AstroCeNT
Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

Backup Slides

Darkside 20k Number of events for 5 sigma sensitivity

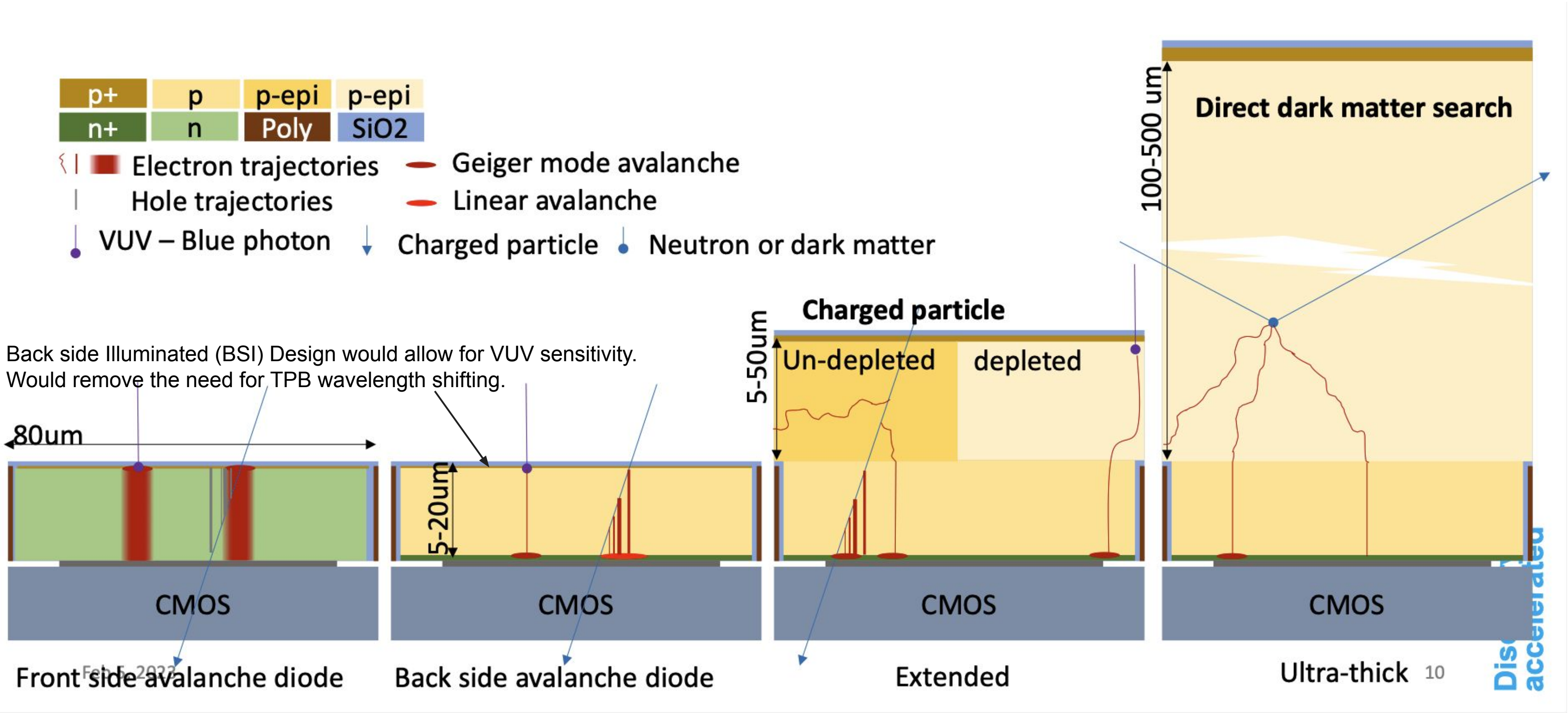


DAMIC 2020 Sensitivity (Nuclear Recoil)



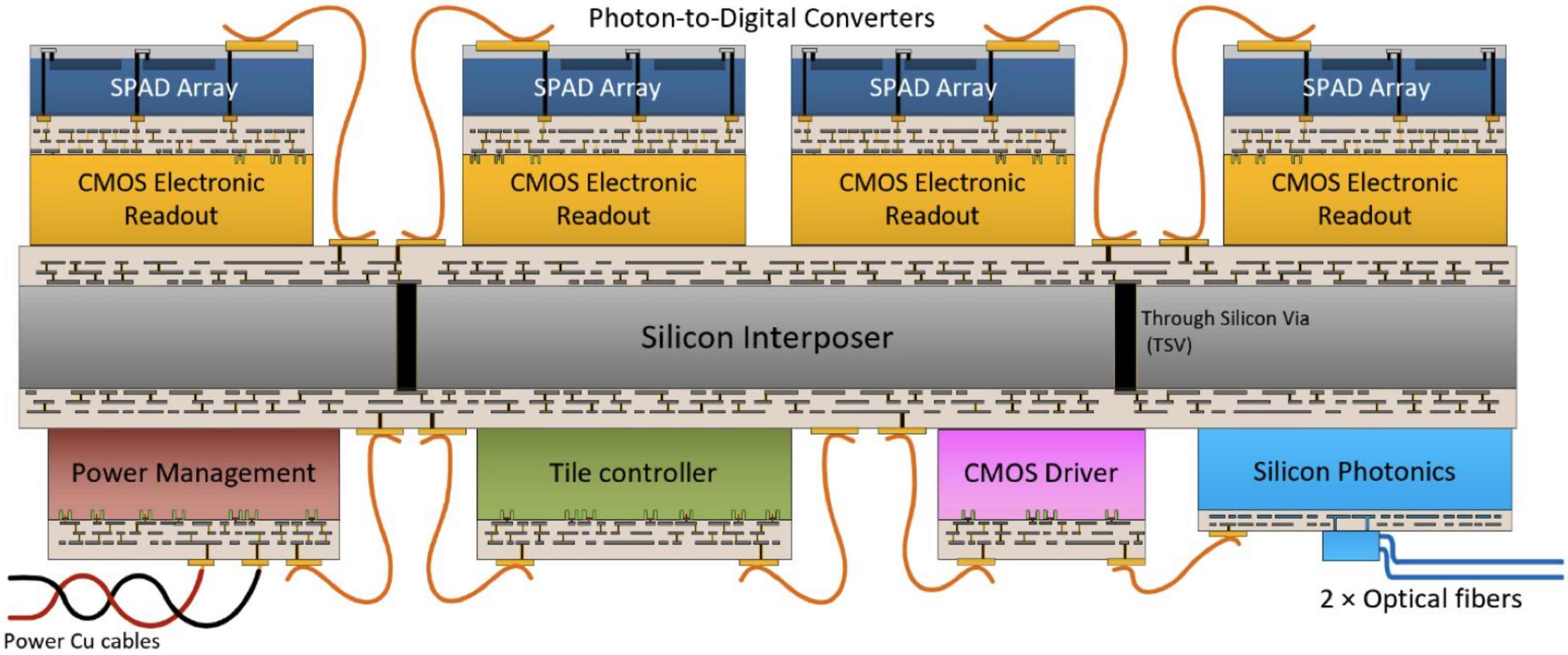
 arXiv:2007.15622

Digital SiPM Optimised for Dark Matter Searches



F. Retiere DRD2 Meeting 2024

PDC Complete Picture



F. Retiere DRD2 Meeting 2024