Searching for Low Mass Dark Matter in Silicon using Darkside-20k Silicon Photomulipliers (SiPMs)

Joint APP, HEPP and NP Conference 2024

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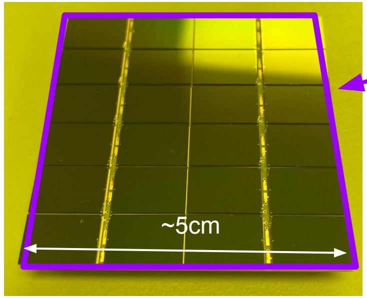
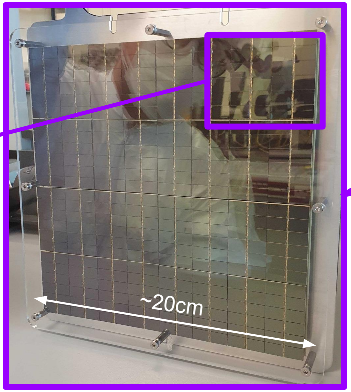
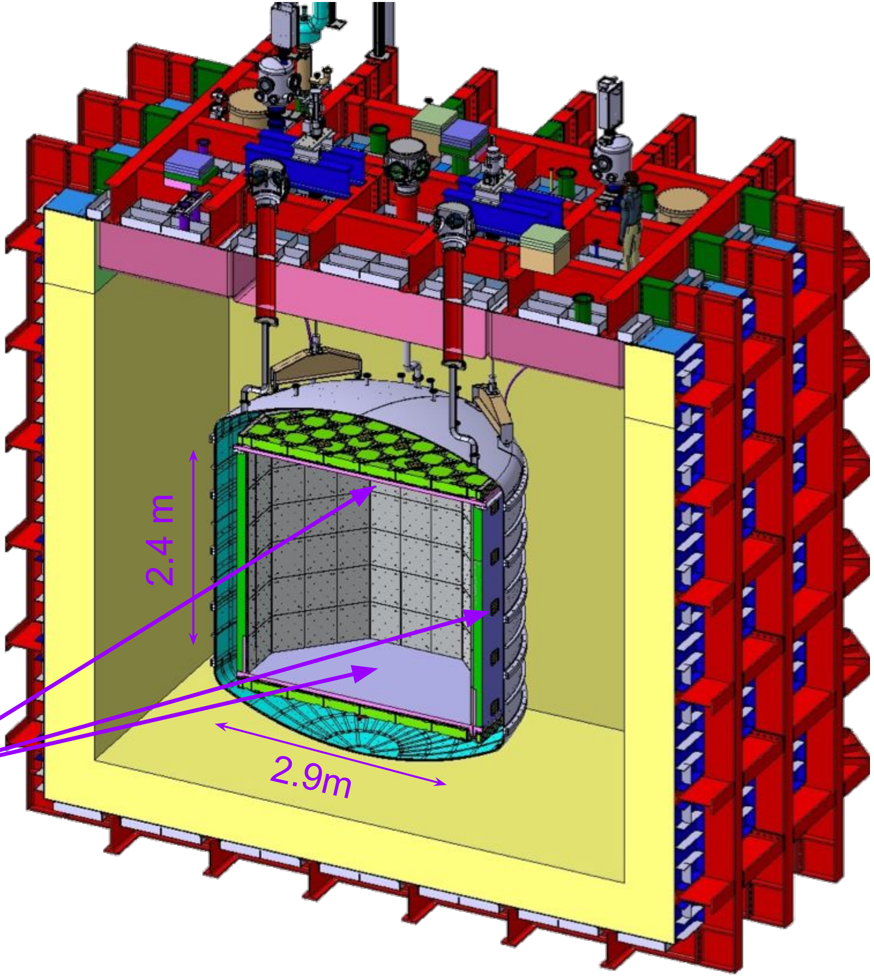
DarkSide-20k

- Dual Phase TPC
- 51 tonnes UAr active mass in TPC
- 200 Tonne-Year nominal exposure
- Instrumented with 30m^2 of SiPM Photodetectors (TPC, instrumented UAr inner and AAr outer veto)
  - First implementation of SiPM devices at scale in rare event search
- Under construction now at Gran Sasso Laboratory (INFN/LNGS), Ar fill planned in 2026

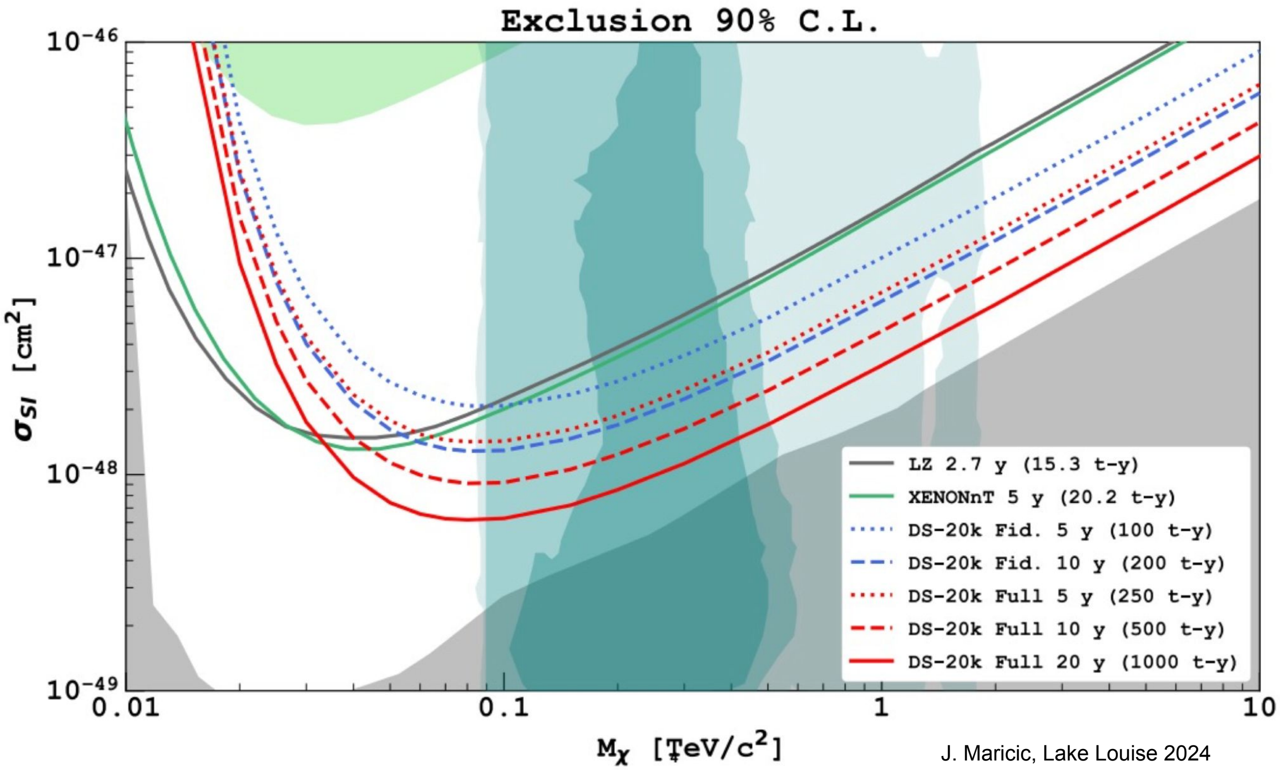






Darkside-20k Physics Reach

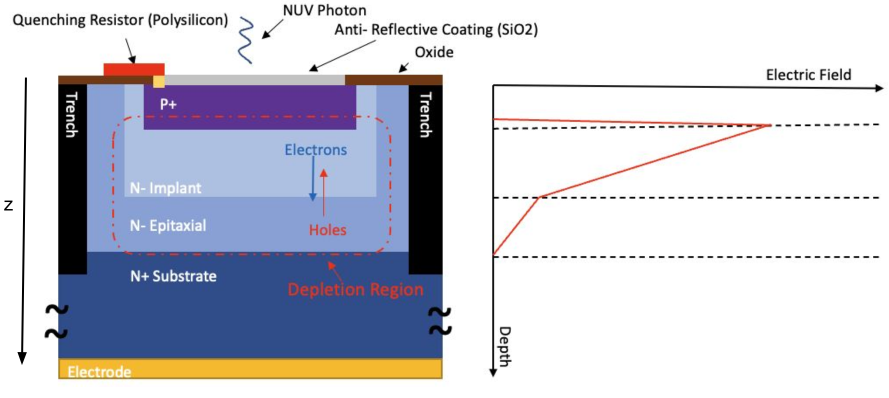
- Sensitive to Spin Independent interactions of dark matter with nuclei (NR signal) and electrons (ER signal)
- Sensitivity: 6.3 x 10^{-48}cm^2 for 1 TeV WIMP (90% C.L.) via NR
- 5σ Discovery: 2.1 x 10^{-47}cm^2 for a 1 TeV WIMP via NR
- Instrumental Background projection: <0.1 events in 200 t yr in NR ROI 30 ~ 200 KeVnr
- Neutrino Background projection: 3.2 events in 200 t yr in NR ROI 30 ~ 200 KeVnr

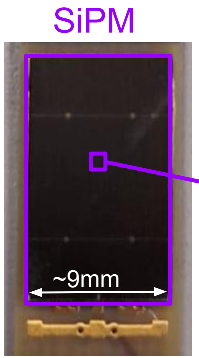


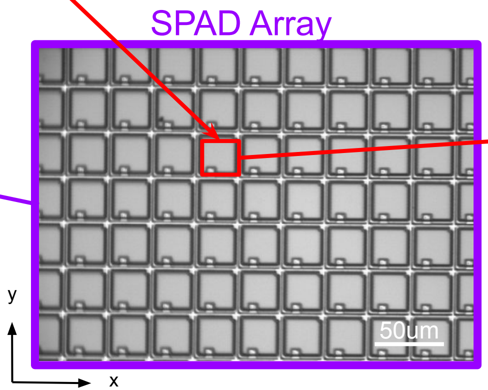
J. Maricic, Lake Louise 2024

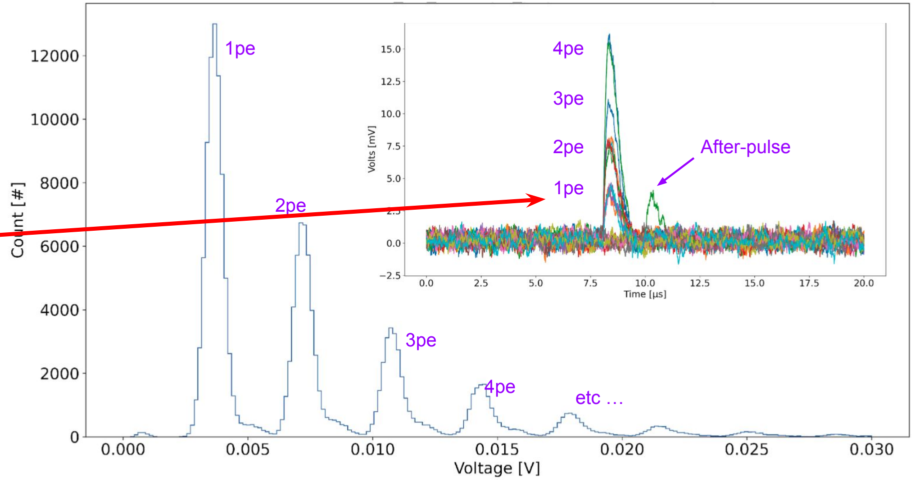
SiPMs 101

- SiPMs are large arrays of single photon avalanche Diodes. (SPADs)
- SPADs are p-n junctions, engineered to operate above their breakdown voltage (geiger mode)
- Single Photoelectron resolution
- Industrial driver: Fast Timing O(100ps), low cost
- DarkSide-20 driver: SiPMs have lower dark noise (DCR), higher photon detection efficiency (PDE) at cryogenic temperatures, and lower radioactivity than PMT's.





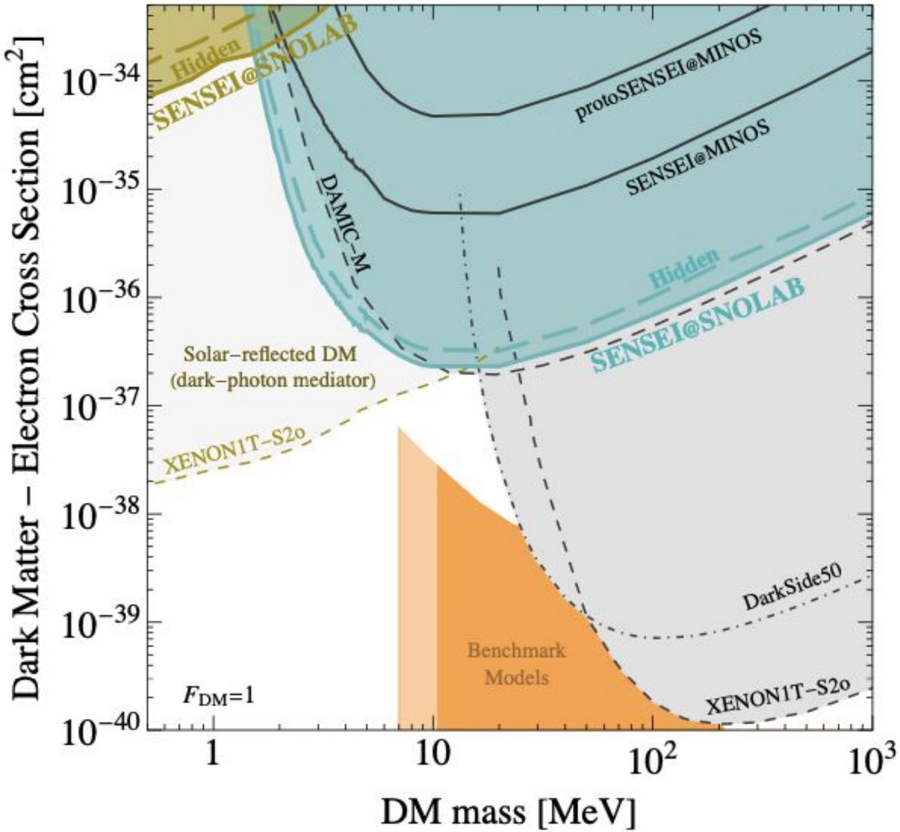




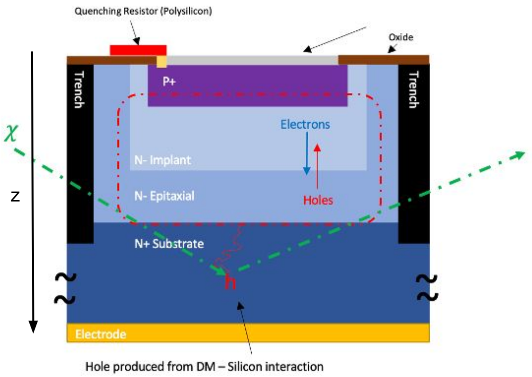
Light Dark Matter (LDM)

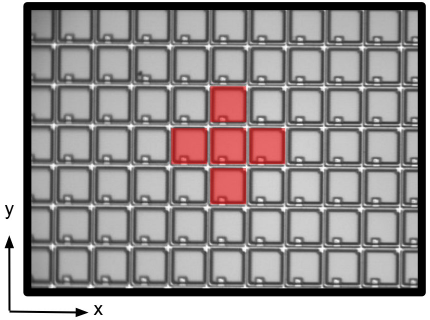
- LDM masses range in the MeV to GeV range
- Motivated by dark matter models beyond WIMPs, which require thermal history mechanisms beyond the standard freeze-out scenario.
  - sub-GeV mass scale arises naturally in range of models (i.e. asymmetric dark matter, hidden sector dark matter, …)
- Potentially Interacts with SM particles via exchange of vector (Dark photon), scalar (Higgs like), or pseudoscalar (axion like)
- The lower the energy required to liberate a charge carrier the better sensitivity you have to LDM.
- This is why Silicon has excellent sensitivity.

https://arxiv.org/pdf/2312.13342.pdf



Dark Matter Detection in Darkside-20k SiPMS





- DM-electron interactions in Silicon have interesting sensitivity to light dark matter (DM) due to Si low band gap energy ~1.12eV.
- Can carry out low energy searches down to the ~MeV mass scale with NRs, and ~sub-keV scale with ERs.

Observable:
- DM-electron scattering will produce electron/hole pairs in the substrate that can diffuse to the active region.
- Multi-pe hits from multi electron/hole pairs.

Challenges:
- Instrumental background from dark count rate (DCR)
- DM interaction backgrounds from bulk and surface radioactivity
- Carrier lifetime in the bulk limits charge collection
- Energy reconstruction in Geiger mode device

Background Sources

Uncorrelated:

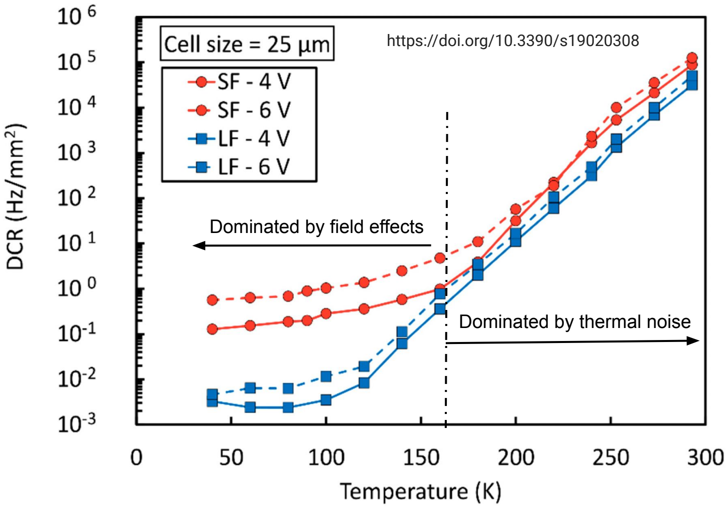
- Dark Count Rate (DCR)
  - At cryogenic temperature come from pulses triggered by thermal noise/ Field-assisted tunneling.
  - The largest noise contribution in this analysis

Correlated:

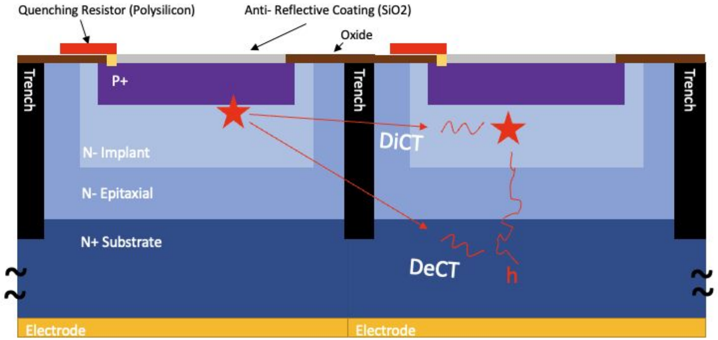
- Optical Crosstalk: Photons generated in avalanche can propagate to neighbouring cells and trigger another avalanche.
  - Direct Cross Talk (DiCT) - Avalanche triggered in neighbouring SPAD by photon generated in initial avalanche.
  - Delayed Cross Talk (DeCT) - Charge carrier released in the silicon bulk

Intrinsic Radioactivity Backgrounds:

- Silicon-32 (β-Decay): Is intrinsic to Silicon and represents the dominant radioactive background.
- Thorium-232 (α-Decay).
- Uranium-238 (α-Decay).
- Rates assumed in this analysis based on radioassay of DAMIC devices, though recently received DarkSide-20k assay.



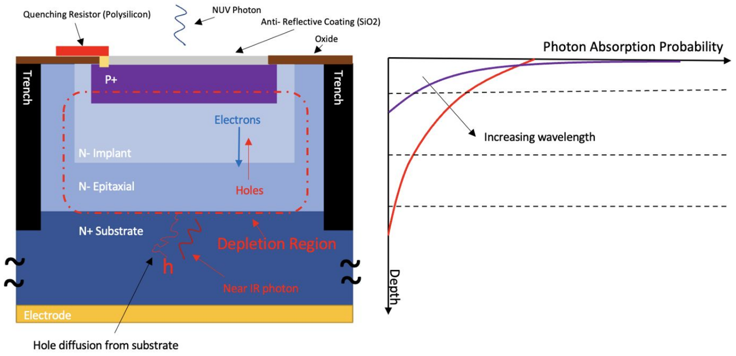
https://doi.org/10.3390/s19020308

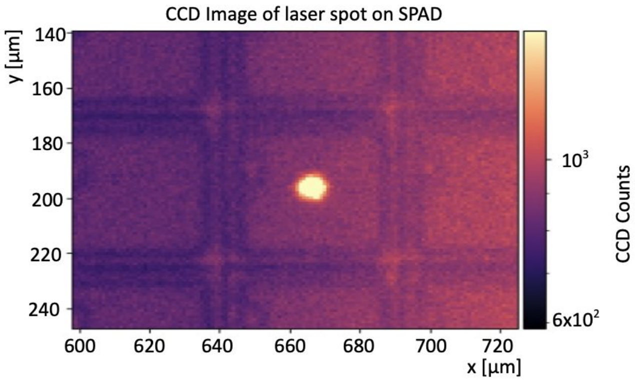


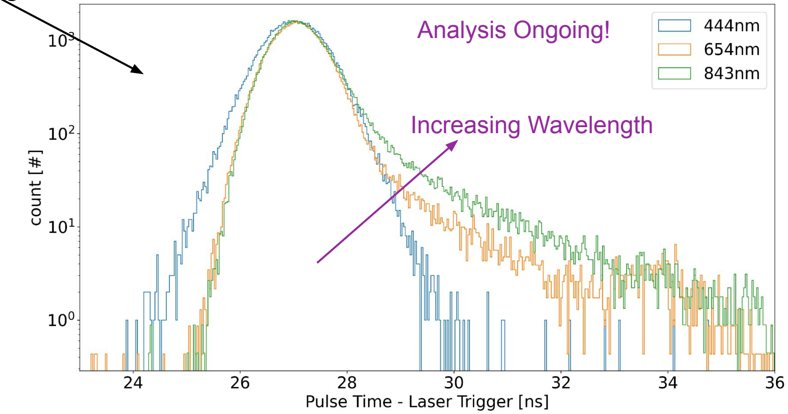
DarkSide-20k SiPM Charge Carrier Lifetime

https://arxiv.org/pdf/1703.04651.pdf

- The carrier (hole) recombination lifetime is assumed to follow an exponential distribution
- Stimulating an individual SPAD with infrared laser we can create charge deposited in the bulk, and measure time between creation and detection of carriers
- Time distribution of detected hits has contributions from laser time spread plus diffusion of charge carriers, which gives sensitivity to lifetime
- DarkSide-20k SiPMs charge carrier lifetime measured to be O(1ns)





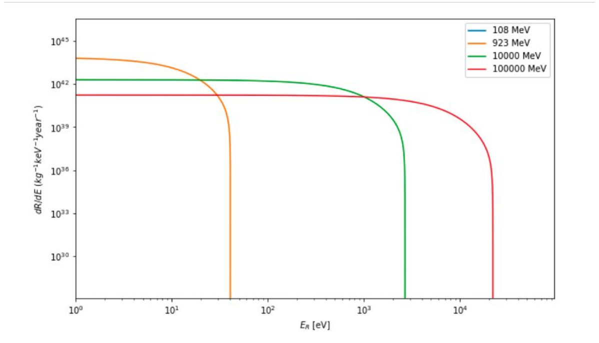


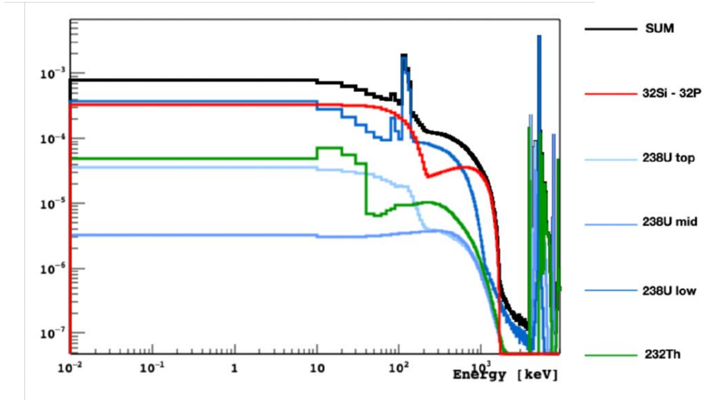
Analysis Ongoing!

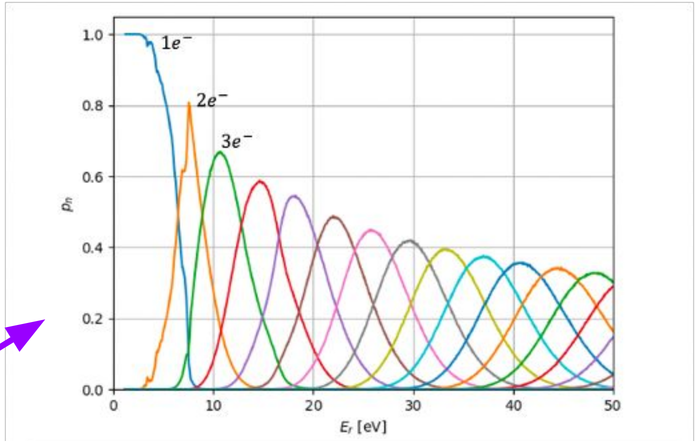
Increasing Wavelength

[1] https://arxiv.org/abs/1509.01598
[2] https://arxiv.org/abs/2004.10709

Simulation/Analysis Pipeline

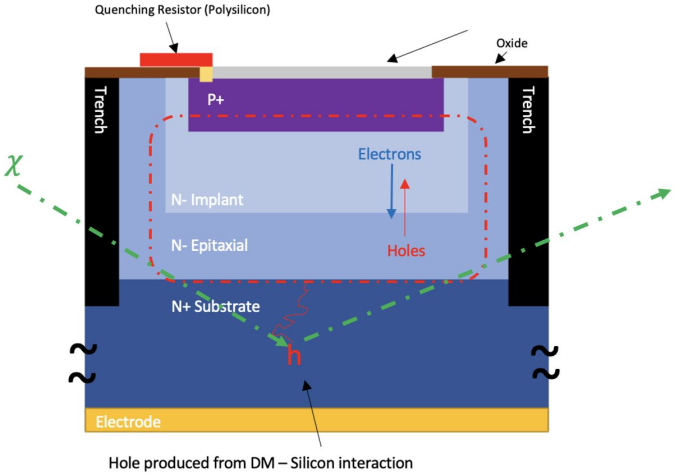


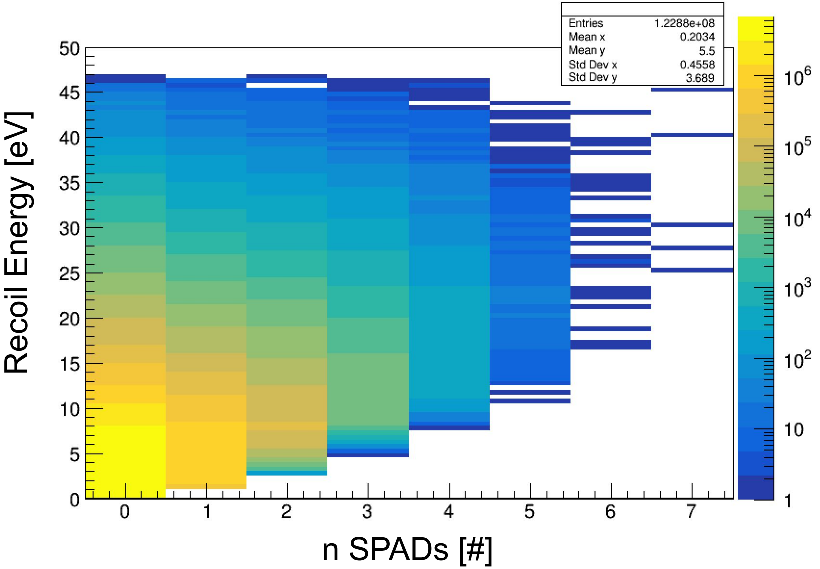




- Signal Spectra Generated using QEDark[1]
- Background Spectra generated by betashape and Geant4.
- Energy to # carrier conversion[2]

Simulation/Analysis Pipeline





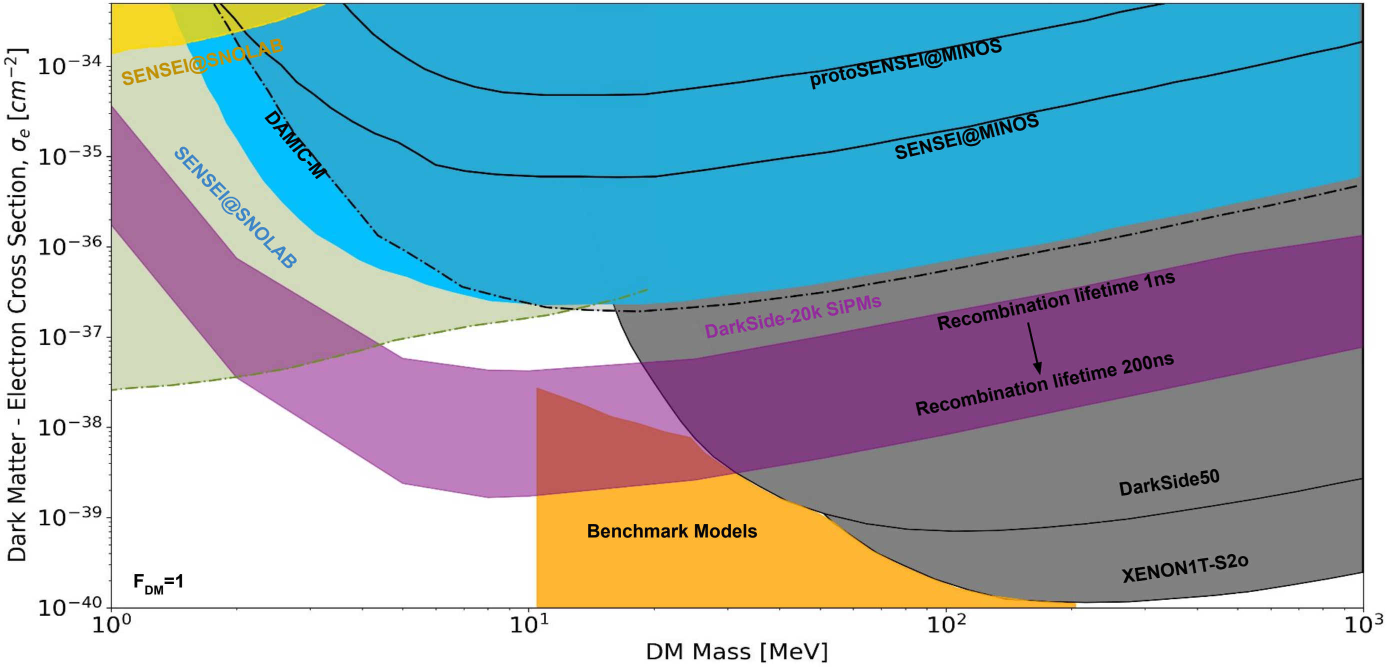
- Generated Carriers are randomly distributed in the bulk.
- Carriers are randomly walked and we count how many unique SPADs get triggered.

- Using the simulation we can generate a map from recoil Energy to nSPADs
- We use these maps in the PLR to determine projected sensitivity

Projected Sensitivity (Work Ongoing)

- 1 SPAD Threshold
- 5.8 kg-yr effective exposure. 27kg Si Array * 1 year * charge collection efficiency based on 1ns carrier lifetime.
- 100,000DCR events.
- Si32, Th232 and U238 rates taken from DAMIC Assay[1]
- DiCT values taken from darkside SiPM measurements
- Sensitivity increases as strong function of hole lifetime

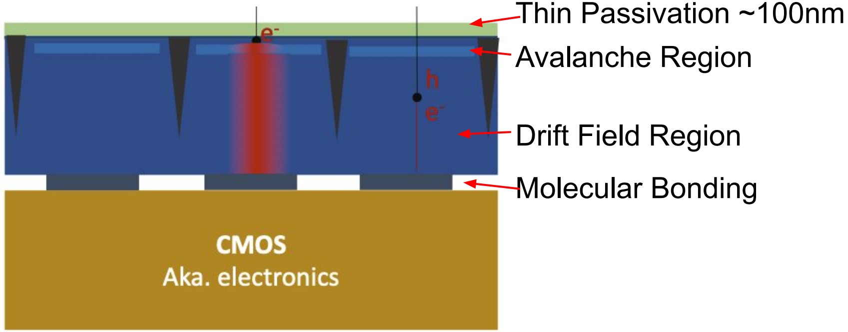
https://arxiv.org/pdf/2312.13342.pdf



[1] https://arxiv.org/abs/2011.12922

SiPMs Developments for Optimised Dark Matter Search

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

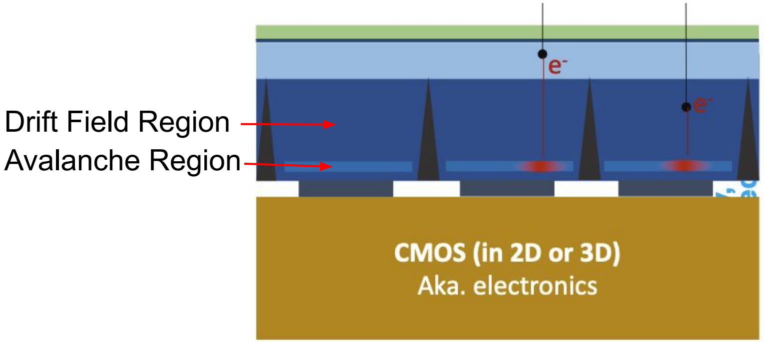
- Demonstrated NUV Sensitivity
- Sensor is on the surface so electronics can be placed on the underside of the same wafer.
- Digital 3D SiPMs can address each pixel, turning off noisy SPADs to lower DCR for dark matter search

Université de Sherbrooke

Back-side Illuminated

Back-side illuminated Design places the Avalanche region at the bottom of the SPAD, can also have digital readout as in FSI, plus…

- Full depletion possible for increased charge carrier lifetime
- Visible to IR sensitivity by controlling detector thickness
- VUV sensitivity can be achieved through surface processing.
  - Unconventional Anti-reflective coating R&D
  - 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

Conclusions

- DarkSide-20k aims to set leading exclusion limit in the WIMP parameter space.
- Will be first experiment to implement SiPM arrays at scale.
- SiPMs could offer an auxiliary target for low mass light dark matter searches.
- Huge potential for an optimised SiPM as a dedicated low mass dark matter detector.

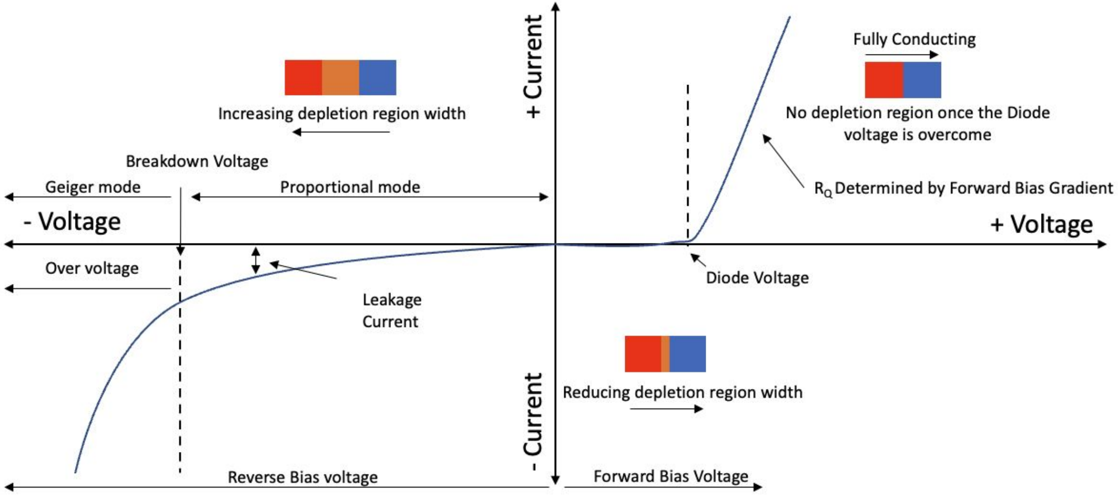
Backup

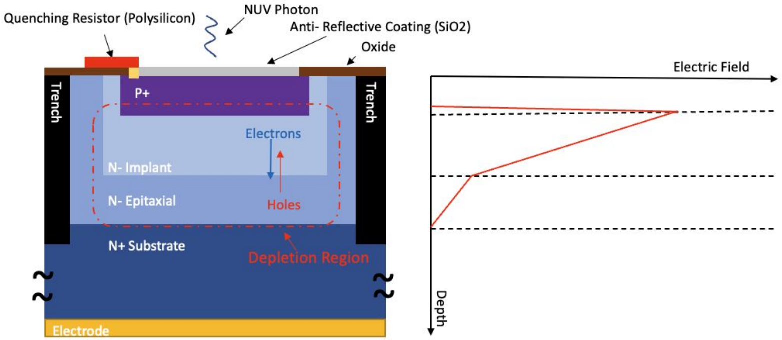
SiPMs 101 - Extended

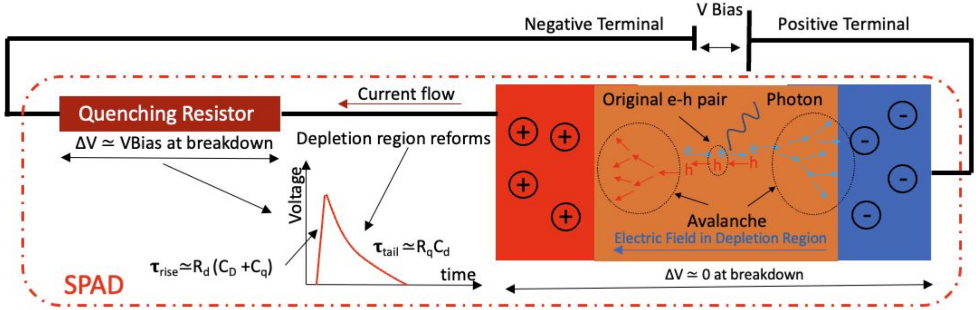
- SiPMs are large arrays of Single photon avalanche Diodes. (SPADs)
- SPADs are p-n junctions, engineered to operate above their breakdown voltage (geiger mode)
- Altering the doping profile allows for the electric field to be engineered, to optimize gain/noise characteristics.
- Signal created when 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.

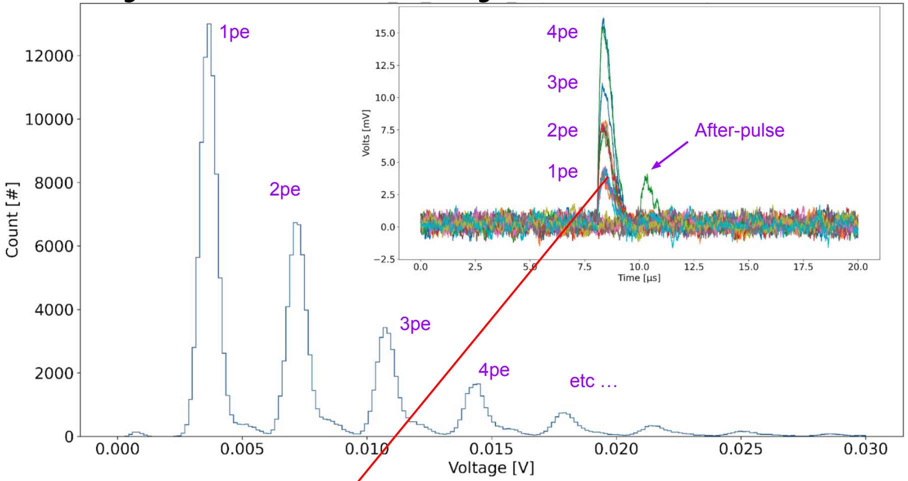
- Trenches to reduce optical cross-talk
- Doping optimisation to reduce CDA
- Electric field optimisation for Photon Detection Efficiency and DCR







Why SiPM Arrays



Reduces channel count in large-area readouts!

DarkSide-20k has shown:

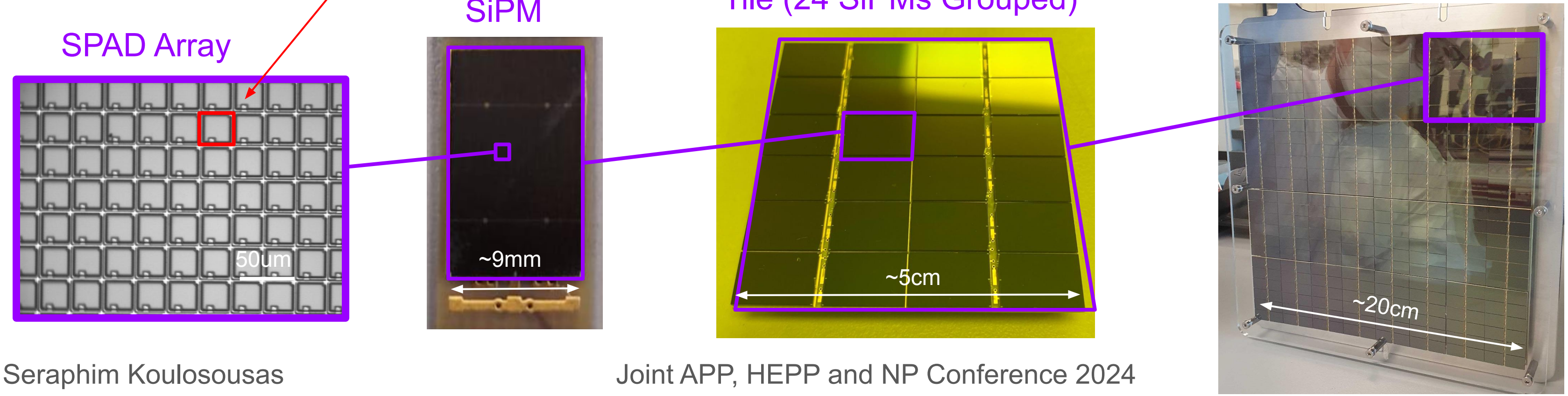
- Can preserve single Photoelectron (pe) resolution
- SiPMs are a low noise, low form factor, high quantum efficiency
- Photon Detection Efficiency: > 40% at 77k
- Fast timing O(100ps)
- Dark count rate (DCR): ~0.01Hz/mm^2 at 77k
- SNR > 8 for 10x10 cm^2 TPC Photo Detection Unit (PDU)
- Readily mass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

SPAD Array

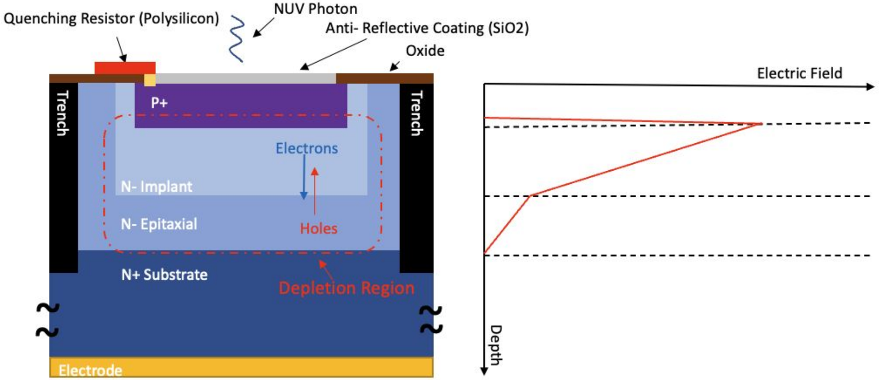
SiPM

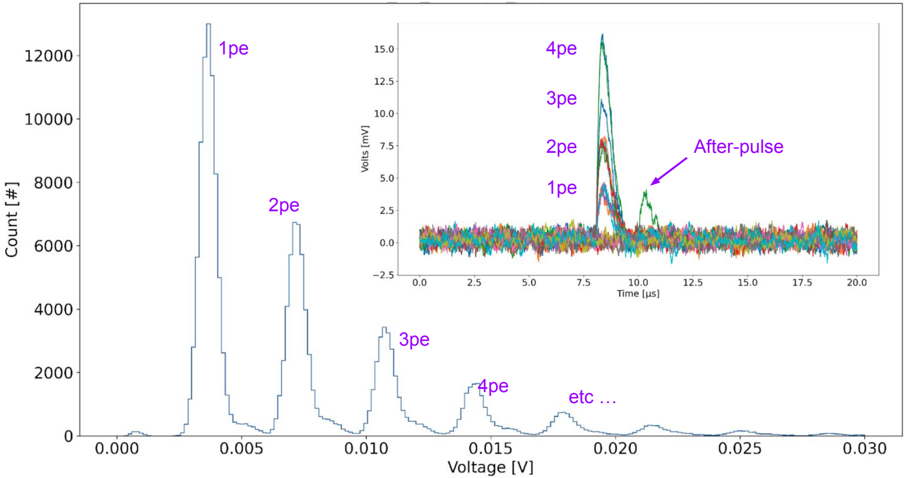
Tile (24 SiPMs Grouped)

PDU (16 Tiles Grouped in 4s)



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)
- 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.
- Experiments such as DAMIC, SENSEI and use Silicon as the target.
  - These Experiments mostly make use of CCDs which have slow readouts (multi-hr exposures) making background discrimination through timing unfeasible.

Dark Matter Detection in Darkside-20k SiPMS

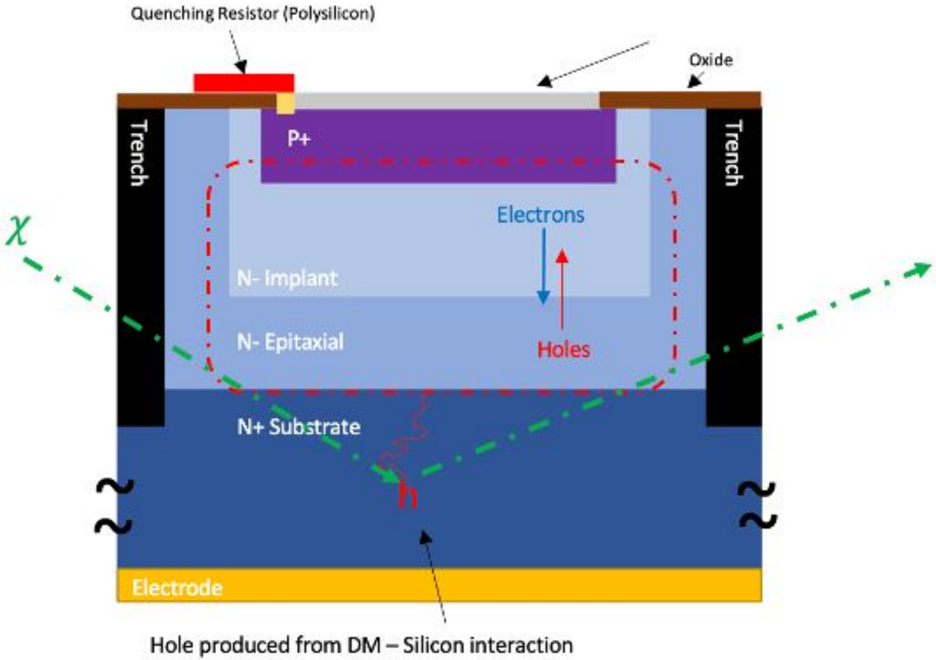
- DM-electron interactions in Silicon are interesting due to Si low band gap energy ~1.12eV.

- Silicon is an attractive target material for low energy searches down to the ~MeV Scale.

- Could potentially use DarkSide-20k Silicon Photomultipliers (SiPMs) as an auxiliary target.

- DarkSide-20k will be instrumented with 25m^2 of SiPMs -> 30 kg of silicon.
  - DAMIC-M recent results based of 85.23 g days integrated exposure[1]
  - SENSEI recent results based on 534.9g days[2]

- Detection would be via the diffusion of liberated charge carriers in the bulk of the SiPM to the avalanche region.



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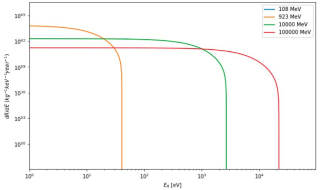
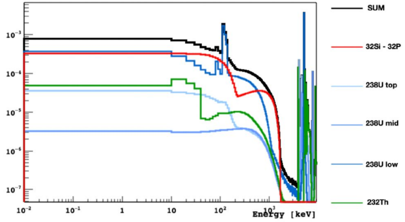
[1] https://arxiv.org/pdf/2302.02372.pdf
[2] https://arxiv.org/pdf/2312.13342.pdf

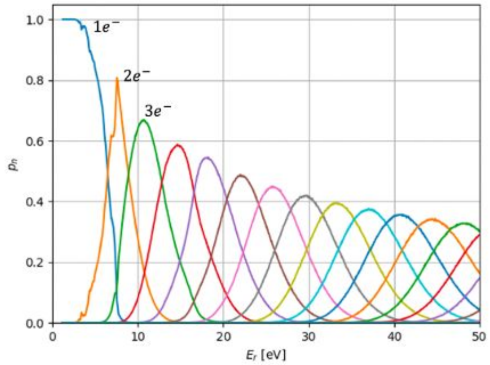
Simulation/Analysis Pipeline

Randomly Sample from Signal[2] and Background Spectra

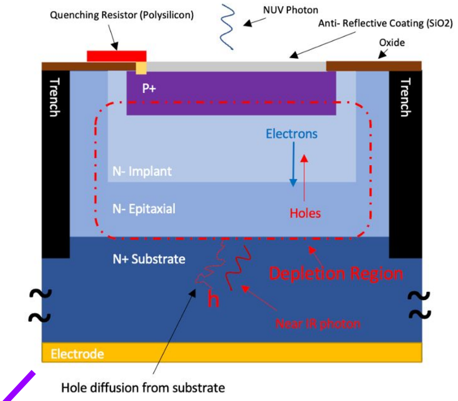




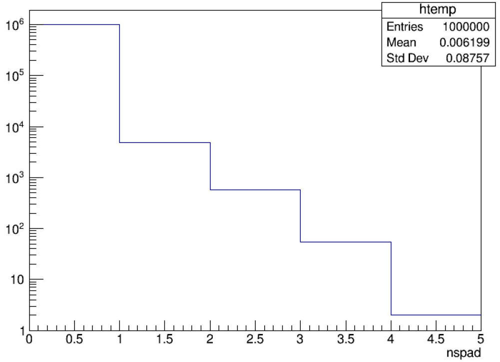
Convert Energy to e/h pairs[1]



Randomly walk e/h pairs in SiPM Simulation



Count # of unique SPADS triggered



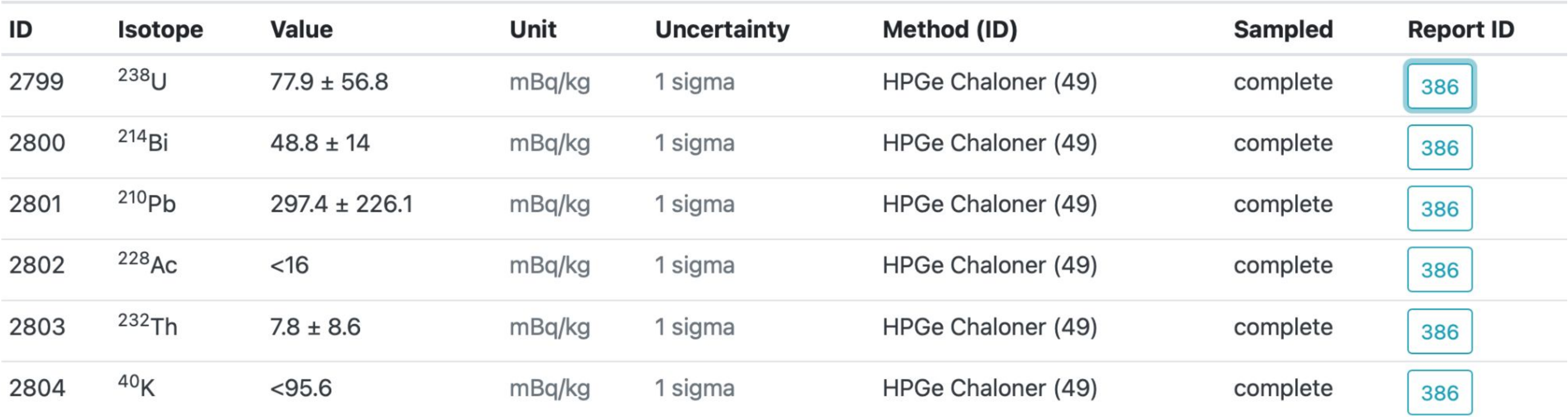
- Randomly walk e/h pairs from event and count nSPADs.
- Essentially, Convert the original energy spectra into a nSPAD spectra

PLR Analysis

- Use nSPAD spectra as pdfs for PLR Analysis.
- Include DCR
- Include DiCT

[1] https://arxiv.org/abs/2004.10709
[2] https://arxiv.org/abs/1509.01598

Boulby Assay



ID	Isotope	Value	Unit	Uncertainty	Method (ID)	Sampled	Report ID
2799	^{238}U	77.9 ± 56.8	mBq/kg	1 sigma	HPGe Chaloner (49)	complete	386
2800	^{214}Bi	48.8 ± 14	mBq/kg	1 sigma	HPGe Chaloner (49)	complete	386
2801	^{210}Pb	297.4 ± 226.1	mBq/kg	1 sigma	HPGe Chaloner (49)	complete	386
2802	^{228}Ac	<16	mBq/kg	1 sigma	HPGe Chaloner (49)	complete	386
2803	^{232}Th	7.8 ± 8.6	mBq/kg	1 sigma	HPGe Chaloner (49)	complete	386
2804	^{40}K	<95.6	mBq/kg	1 sigma	HPGe Chaloner (49)	complete	386