Physics Division Early Career Research Proposals

Jeff Holmes (Physical Sciences Directorate, Program Manager for Office of Science Proposals)

Wolfgang Schreyer (Physics Division, Neutron Symmetries Group)

Oskar Hartbrich (Physics Division, Relativistic Nuclear Physics Group)

Stefano Castro Tognini (Computational Sciences and Engineering Division, Scalable Engineering Applications Group)

OAK RIDGE National Laboratory

08/06/2026

Neuromorphic AI Edge Processing on Large-Area Single-Photon Sensors

Oskar Hartbrich

Oak Ridge National Lab

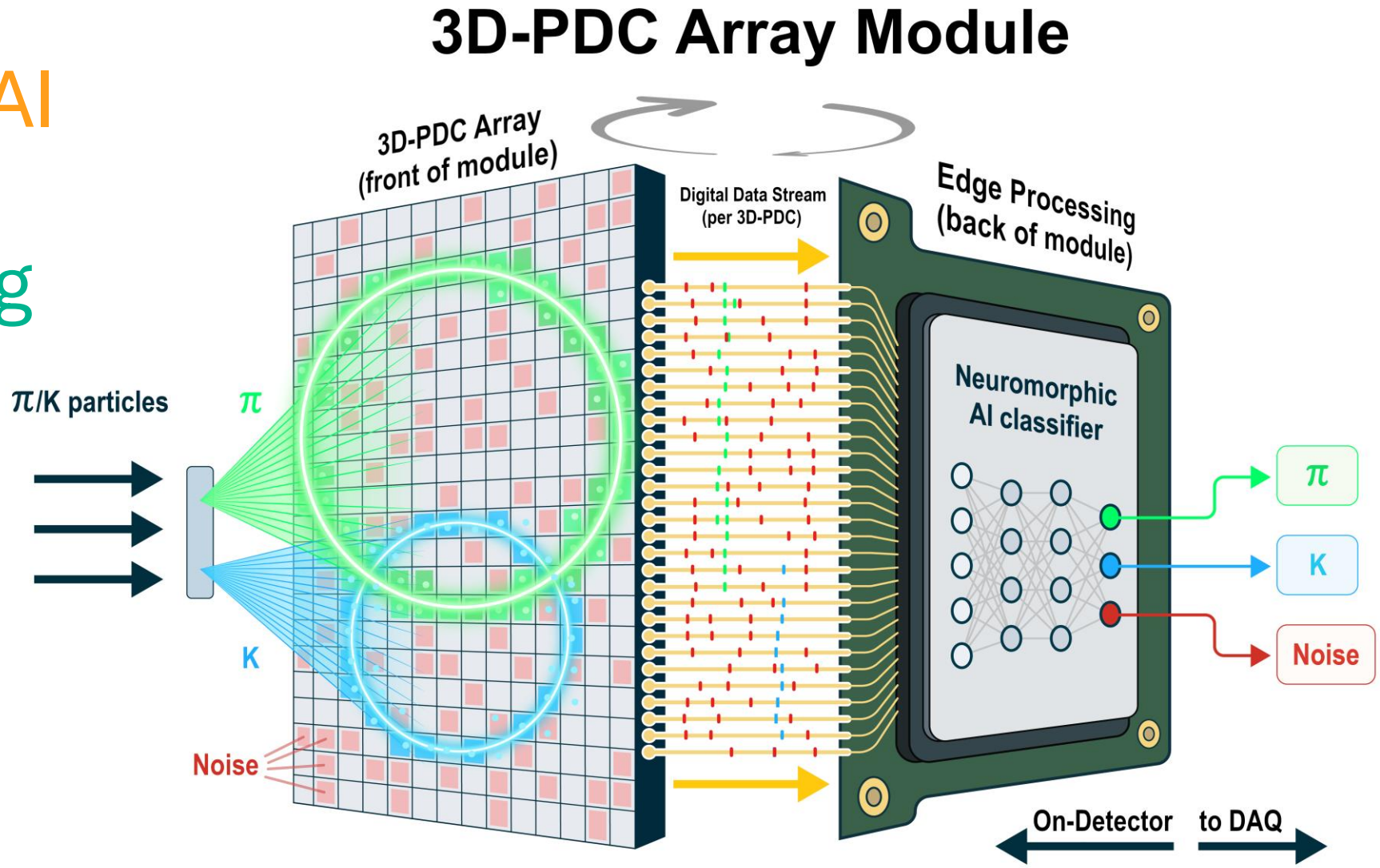
U.S. DEPARTMENT of ENERGY

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

Neuromorphic AI

Edge Processing

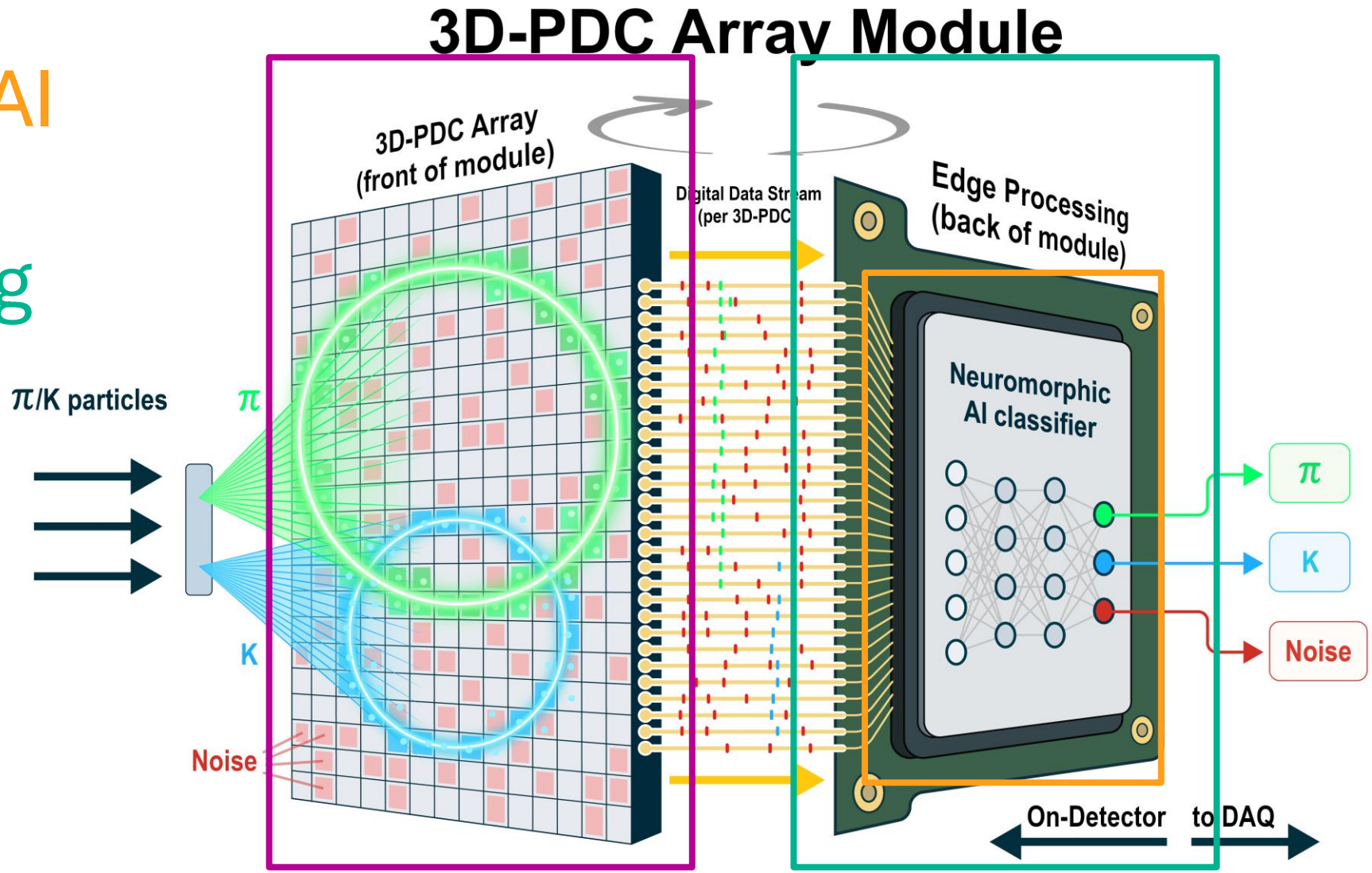
on Large-Area Single-Photon Sensors



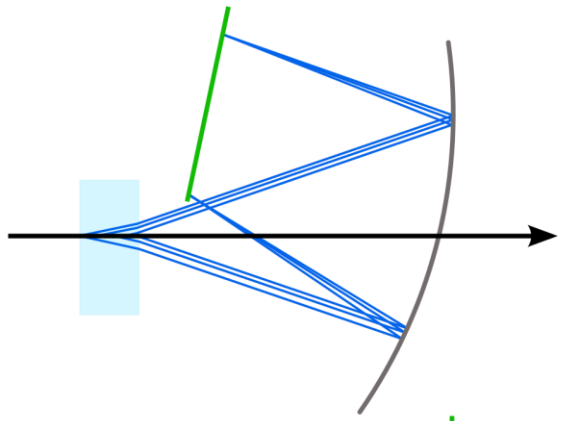
Neuromorphic AI

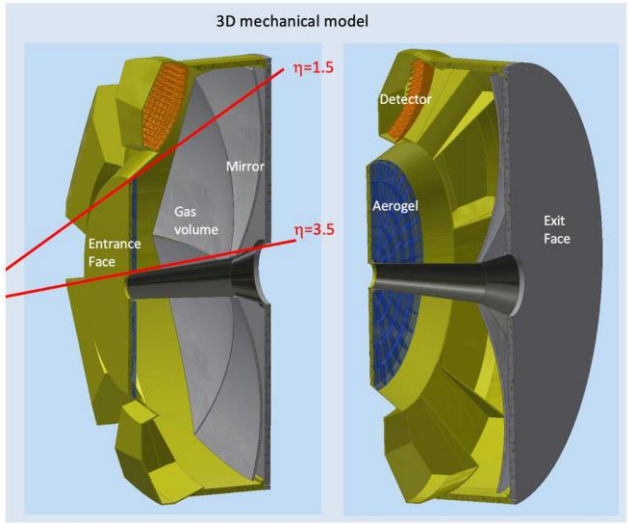
Edge Processing

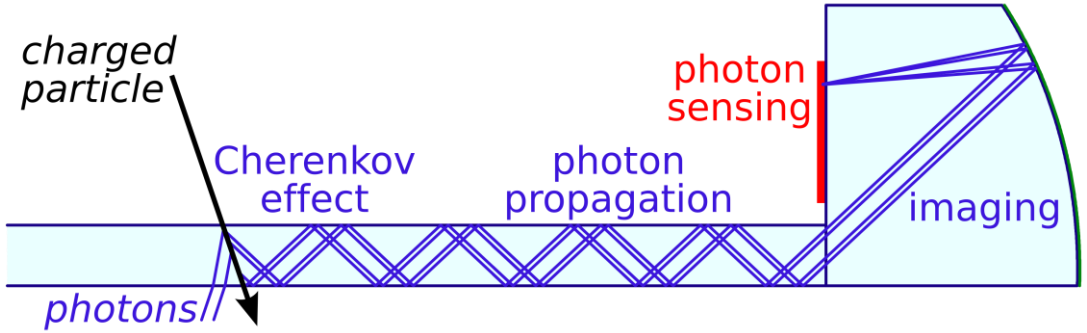
on Large-Area Single-Photon Sensors

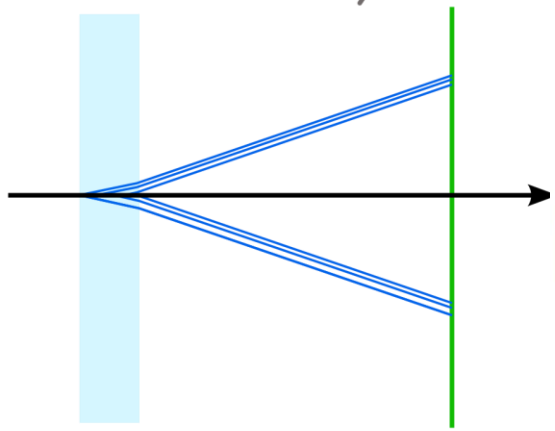


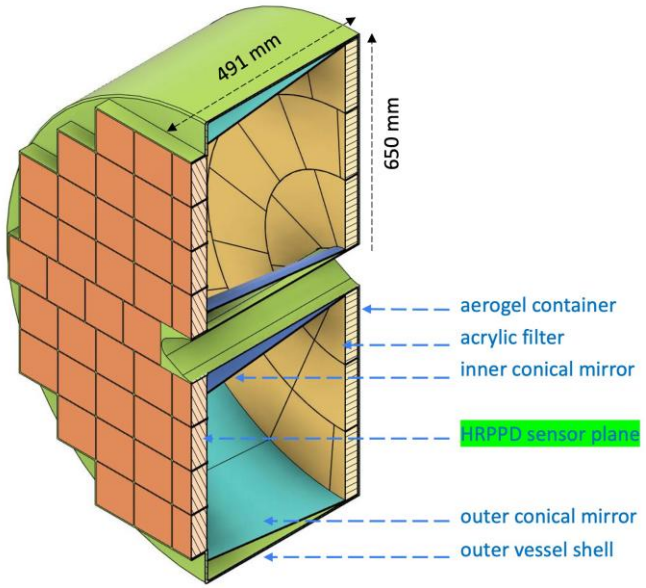
Cherenkov Particle Identification Detectors require Large-Area Single-Photons Sensors

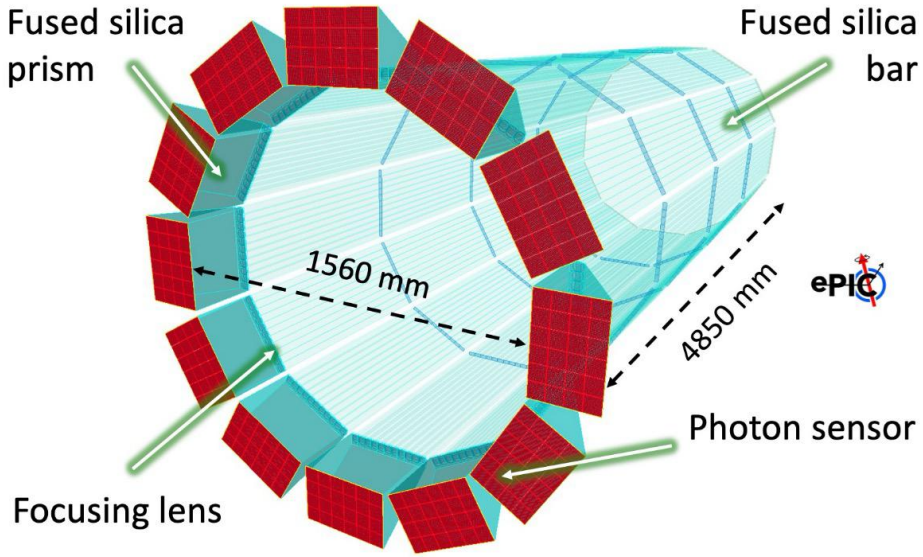






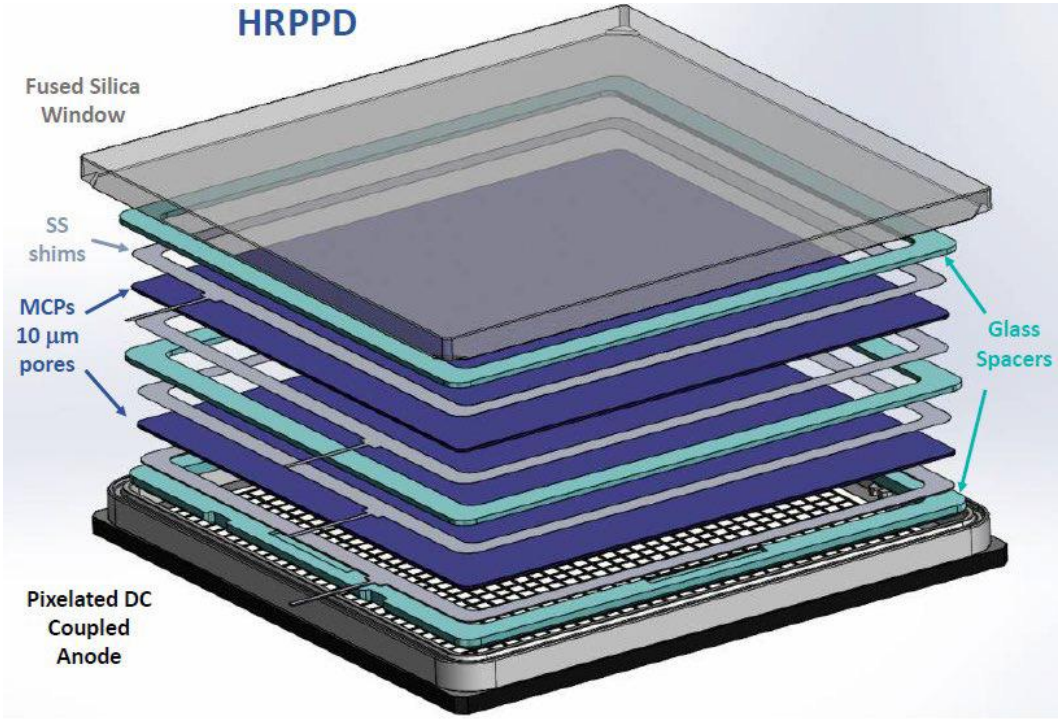






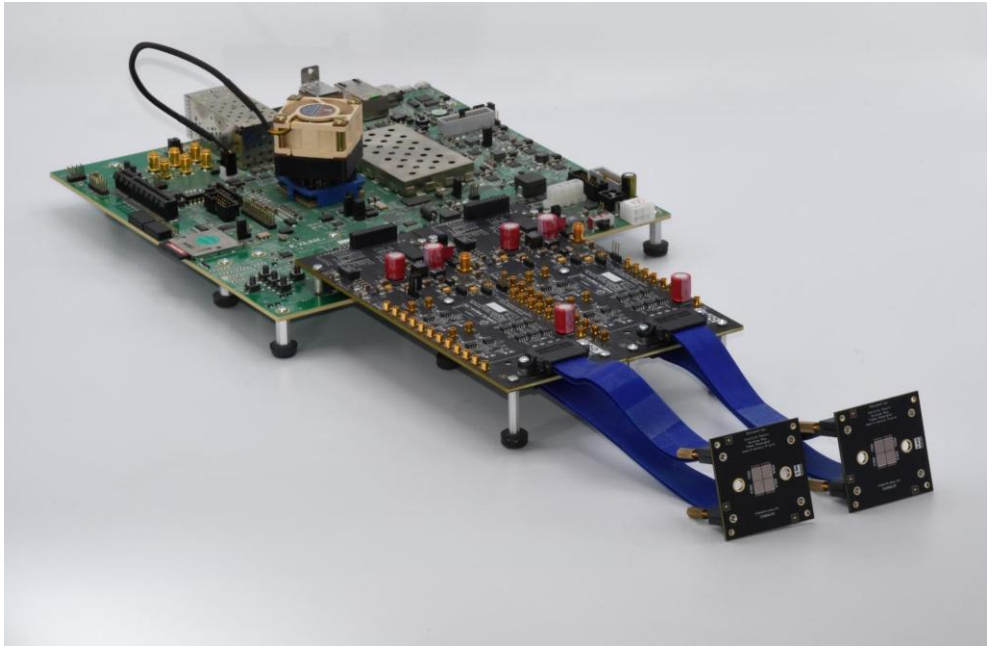
Technologies for
Large-Area Single-Photons Sensors

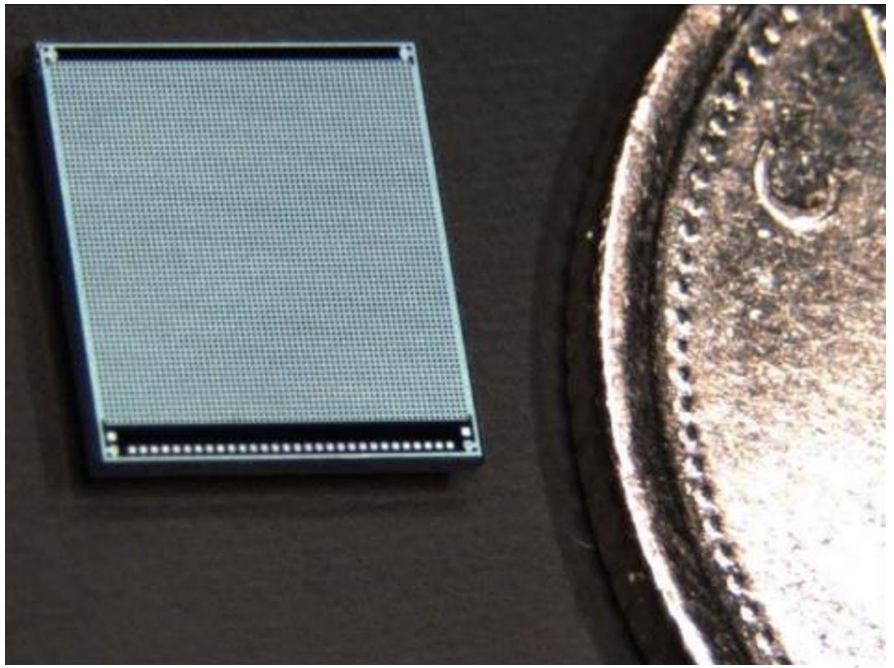
- Arrays of SiPMs:
    - Require complicated mixed-signal electronics for digitization
    - Very high dark noise rate, increasing with irradiation
- MCP-PMTs/HRPPDs:
    - Nobody really builds MCP-PMTs anymore
- Incom “HRPPD”:
    - Prototype stage
    - Reliability? Affordability?
    - Only remaining viable option



ORNL/UdeS 3D-PDCs as Large-Area Single-Photons Sensors

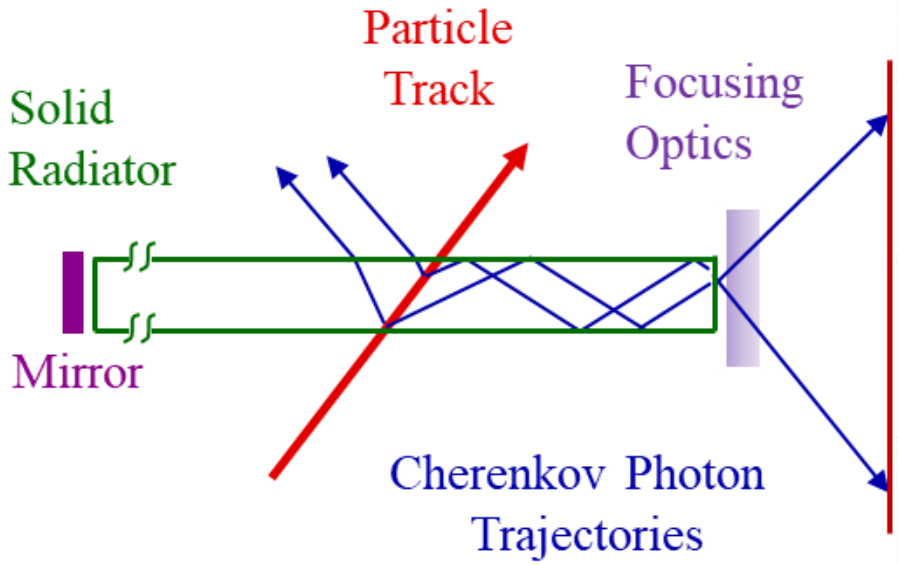
- 3D-PDCs: “Digital SiPMs” developed by ORNL/U de Sherbrooke
    - Vertical integration of two dies per sensor
        - SPAD layer for photon sensing
        - CMOS layer for readout
- Prototypes exist and work~5x5mm^2 size
- Straight-to-digital approach advantages over analog SiPMs:
    - Can disable noisy pixels (mitigates radiation damage)
    - No analog processing (simplifies everything)
    - Digital data stream (great for immediate processing)
- Nobody has built large arrays yet.

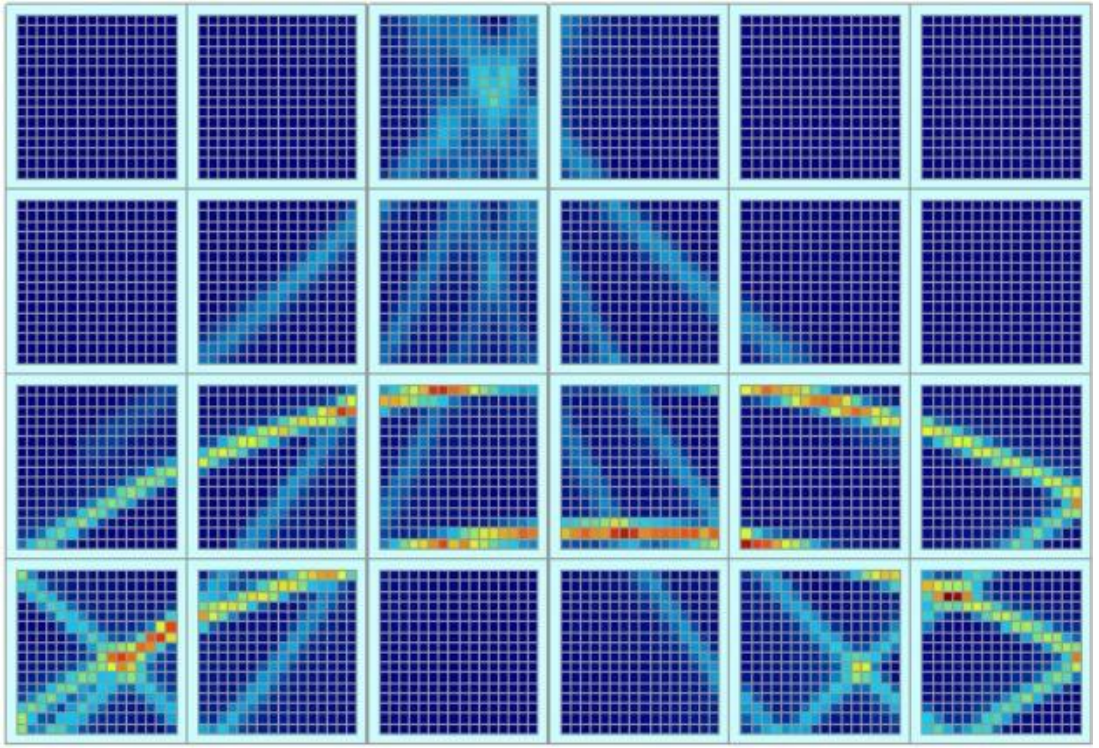




Edge Processing
for Signal Detection and Noise Rejection

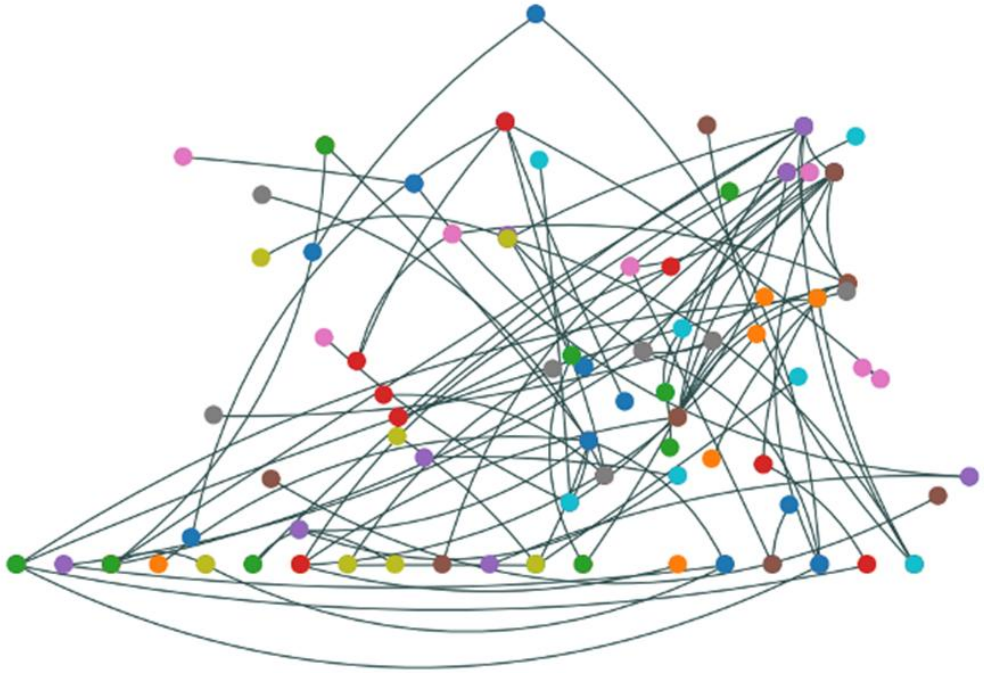
- Dark noise rate of large 3D-PDC arrays will still be high
    - Can we reject noise signals before they leave the sensor?
- Cherenkov signals are rich in spatial and temporal features
    - Hard to fully grasp analytically, but ML…





Spiking Neural Networks: Neuromorphic AI to classify photon patterns in realtime

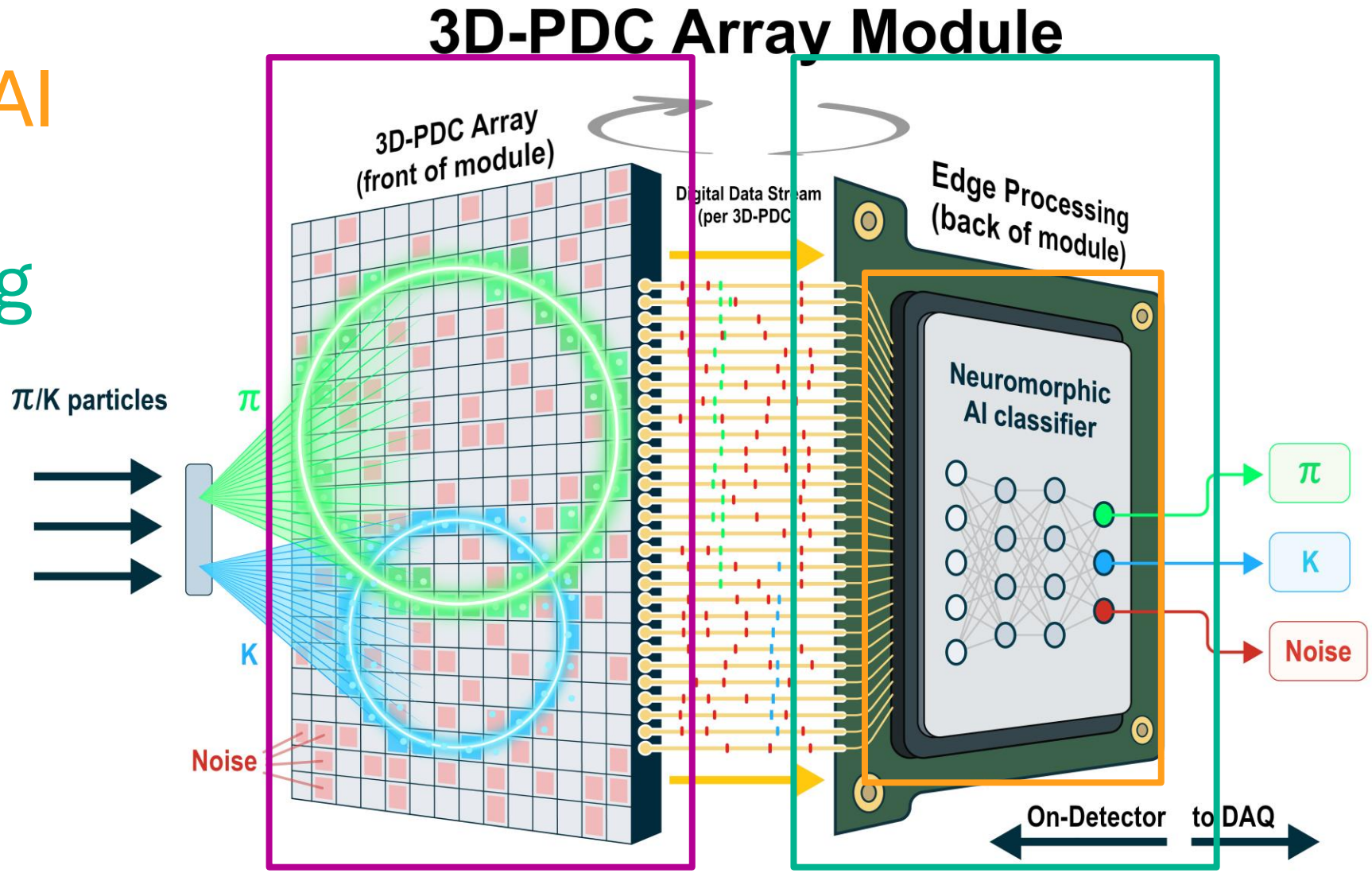
- SNNs encode input data as time-ordered “spike trains”
    - Spikes activate neurons based on arrival timing and propagation delay between neurons
- Extremely resource and power efficient in FPGA implementations
    - Hard to train, need data encoded in pulse train format
- ORNL and UTK have tremendous expertise in SNNs
    - UTK TennLab
    - Many ORNL projects in NNSA space, also HEP (NeuroPIX)
- 3D-PDCs natively provide “textbook” pulse train data



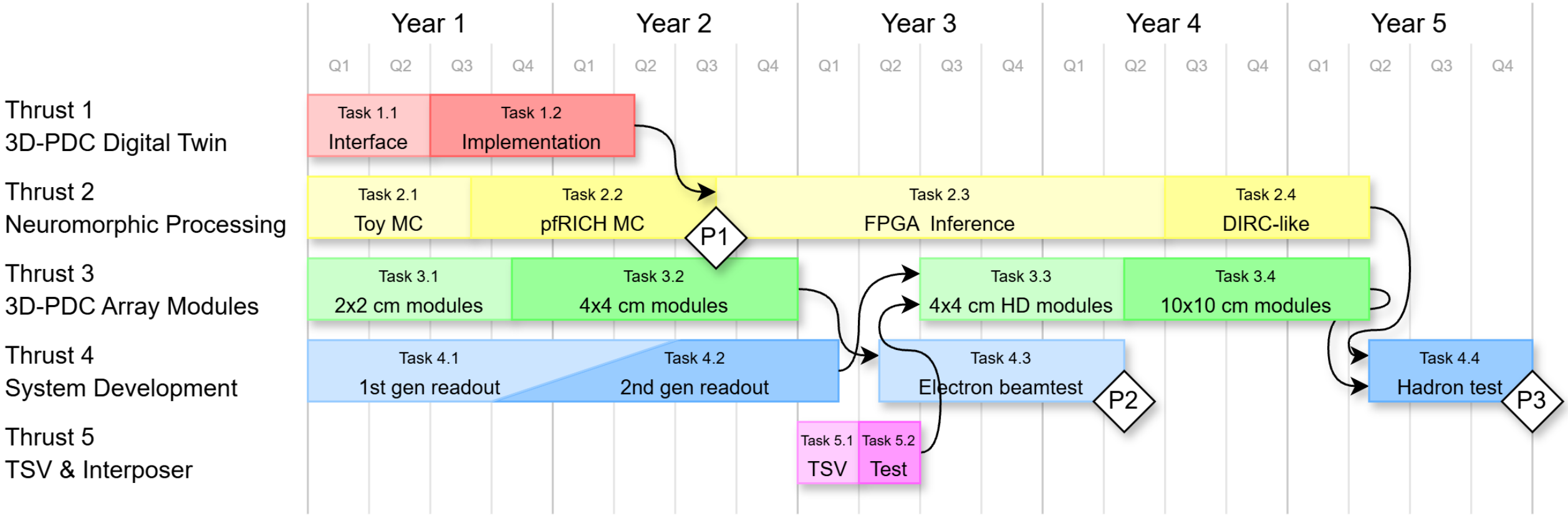
Neuromorphic AI

Edge Processing

on Large-Area Single-Photon Sensors



Spiking Neural Networks: Neuromorphic AI can classify photon patterns in realtime



Summary & Lessons Learned

- I propose to build large arrays of 3D-PDCs to fill a need for large-area single photon sensor technologies in HEP/NP
- Combine these arrays with on-sensor SNN processing to reject noise at the source
- The proposed program combines **simulation** based software tasks with **electronics** R&D and firmware development, including several **prototype device** milestones

- Talk to your ORNL program manager
    - (I planned to submit to High Energy Physics, ended up submitting to Nuclear Physics. This topic would have been dead in the water in HEP)
- PSD support was invaluable in preparation
    - Register for the ECRP cohort, even if you don't think you will submit a proposal that year
    - Jeff, Erica, Adam, Andrea all were **incredibly** helpful
    - (not only for this proposal, but other proposals as well)