FERMILAB-SLIDES-21-113-QIS

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A multi-channel cryogenic low-noise skipper-CCD readout ASIC

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Troy England[1], Fabricio Alcalde Bessia[2,3], Hongzhi Sun[1], Leandro Stefanazzi[1], Davide Braga[1], Miguel Sofo Haro[2,4], Shaorui Li[1], Juan Estrada[1], Farah Fahim[1]

[1]Fermi National Accelerator Laboratory, Batavia, Illinois, USA

[2]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

[3]Instituto Balseiro, San Carlos de Bariloche, Argentina

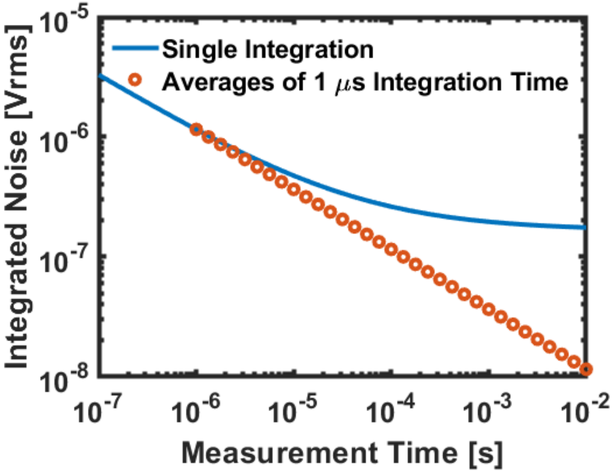
[4]Centro Atómico Bariloche, Instituto Balseiro, Comisión Nacional de Energía Atómica (CNEA), Argentina

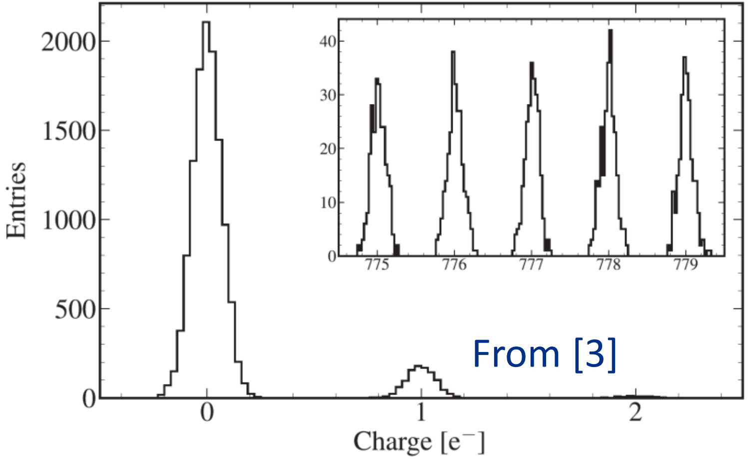
Talk Abstract

- Skipper CCDs provide exceptionally low noise useful for dark matter detection
- MIDNA ASIC enables scaled cryogenic Skipper CCD readout
- Noise performance proven to specification at room temperature with CCD
- Liquid nitrogen measurements show functionality with more to come
- Future development will integrate more sensitive signals and averaging capability

Skipper CCDs for Exceptionally Low Noise

- Skipper CCDs and similar technologies enable the non-destructive readout of the same pixel many times [1-4]
  - The noise can be lowered by averaging many shorter reads rather than one long read
  - It continues the decreasing noise trend with longer measurement times otherwise limited by 1/f noise
- There are still limits to this approach
  - Leakage in the charge transport in the CCD (low)
  - Speed of the various readout stages and clocking
- A skipper CCD has demonstrated the lowest ever, 0.068 e^{-}_{rms}, noise floor in CCDs [3]



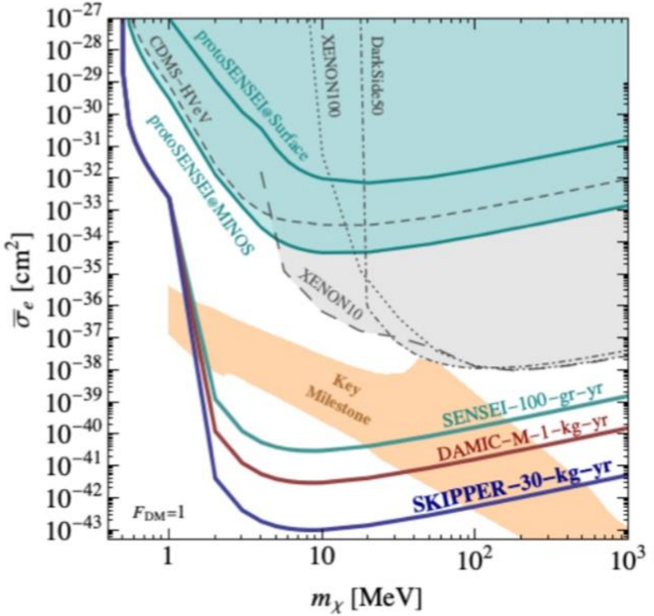


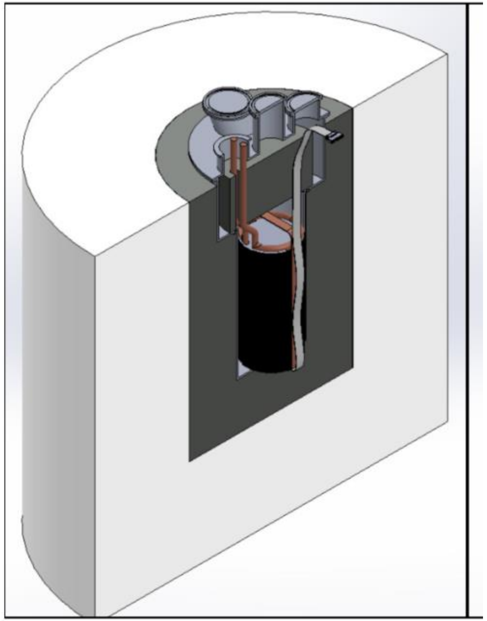
[1] White et al., "Characterization of Surface Channel CCD Image Arrays at Low Light Levels."
[2] Janesick, J.R., et al. "New advancements in charge-coupled device technology: sub-electron noise and 4096×4096 pixel CCDs."
[3] Tiffenberg, Javier, et al. "Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD."
[4] Fernández Moroni et al., "Sub-Electron Readout Noise in a Skipper CCD Fabricated on High Resistivity Silicon."

OSCURA 4 year Research and Development Effort

"DOE Dark matter New Initiatives" FNAL, LBNL, PNNL, U. Chicago, U. Washington, Stony Brook University.

Fermilab is leading the effort to develop a skipper-CCD dark matter detector with active mass of 10 kg of Silicon.





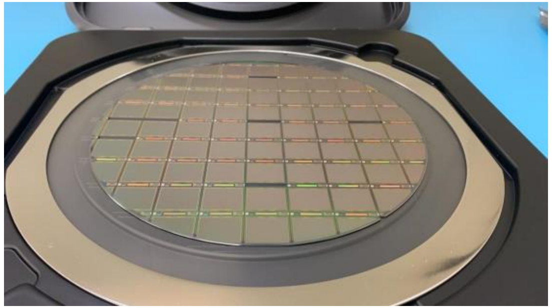
24 Gigapixel digital camera for dark matter!

Cooling, readout, packaging and testing of the required **4000 skipper-CCD sensors require engineering solutions that are not available yet for scientific CCDs.**

Sensors designed by Steve Holland at LBNL.

Radiation background required is ≈10x lower than state of the art experiments.

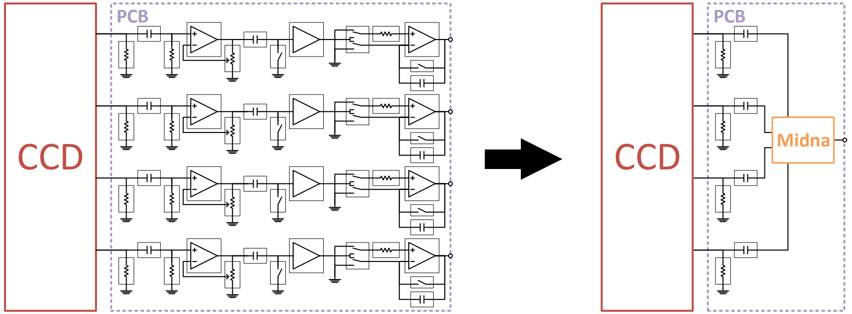
Fabrication of **skipper-CCDs is being adapted to the changes in the semiconductor industry. We have new CCDs from Microchip** and are testing the fabrication results.



Taking the skipper-CCDs to their full potential as dark matter detectors.

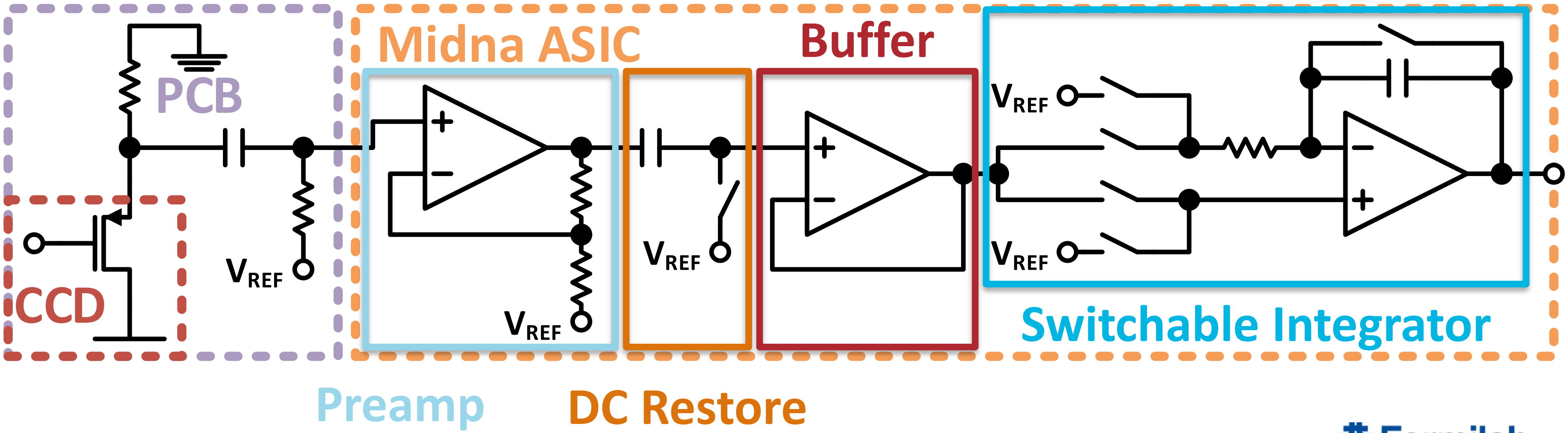
An ASIC to Support Scaling to 28 Gigapixels, MIDNA

- MIDNA is a prototype cryogenic low-noise skipper-CCD readout ASIC
- It is an enabling technology for the OSCURA dark matter detection project
- Integrates multiple readout channels onto a single chip, replacing numerous costly PCB components and saving valuable physical space
  - 4 channels on prototype chip
- Uses 2.5 V transistors for voltage room in 65 nm CMOS process
- Operates at 120 Kelvin for optimum CCD performance
  - COTS devices not guaranteed to specification
- *The ASIC input referred noise must be less than one third of the CCD output noise*
  - Most difficult and constraining requirement



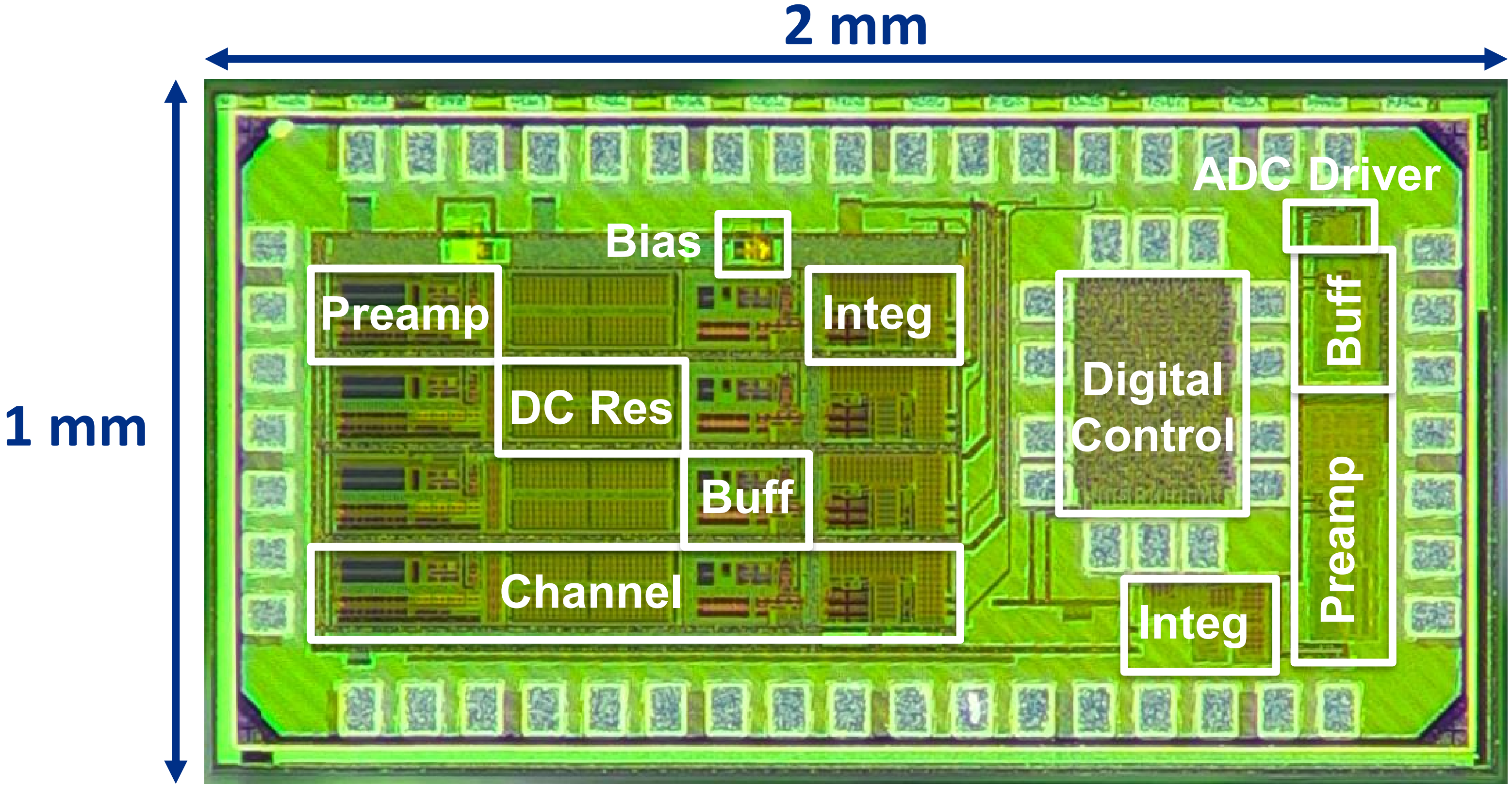
MIDNA Signal Chain

- Preamplifier largely responsible for noise performance drives power consumption
- DC Restore prevents the saturation of the integrator sticking baseline to V_{REF}
- Buffer to provide the current necessary for the Integrator
- Switchable Integrator to implement CDS on chip with efficient bandwidth



Chip Image and Tape Out Structures

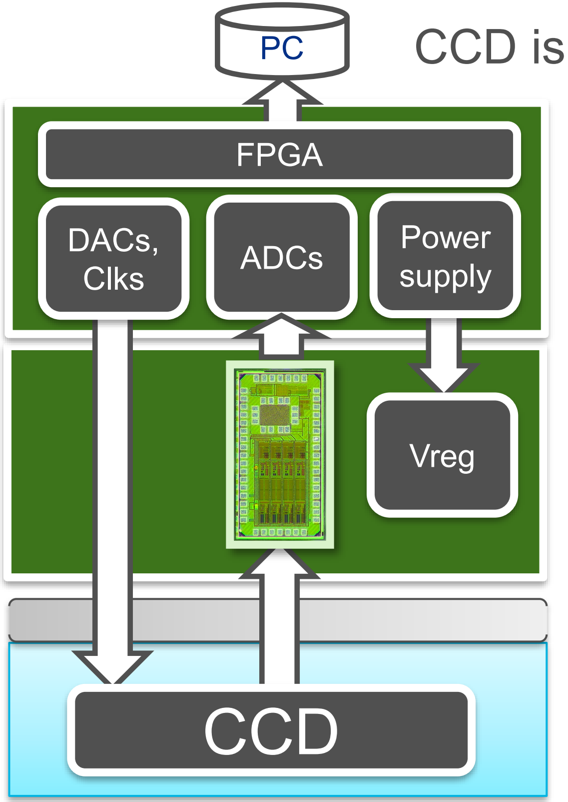
- Each channel is about 150 µm x 1 mm; Chip is 2 mm x 1 mm



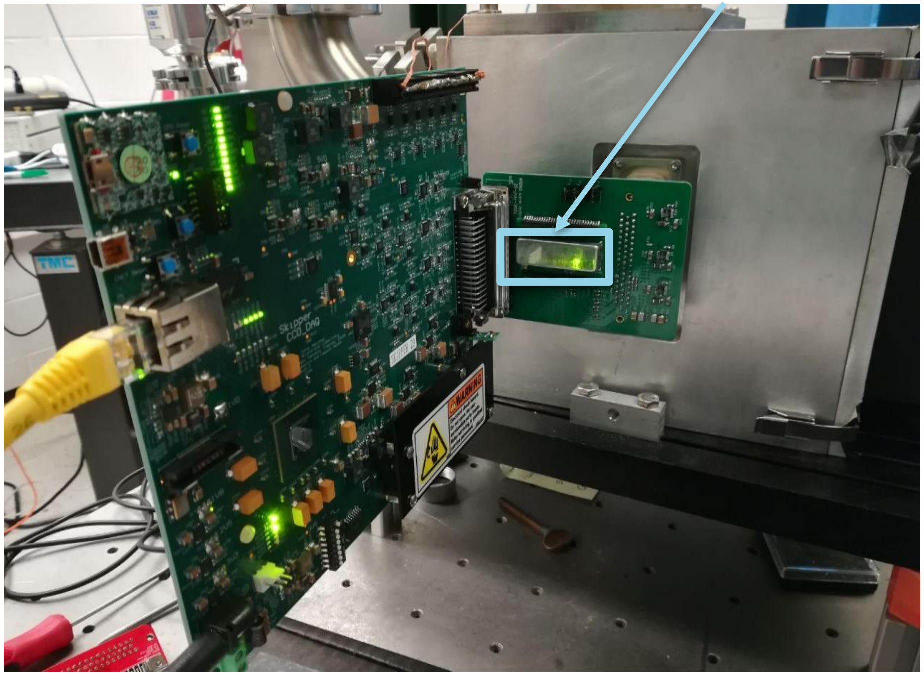
Room Temperature MIDNA with Cooled CCD Testing Setup

DAQ board and MIDNA at room temperature

CCD is in cold chamber at ≈ 120 Kelvin

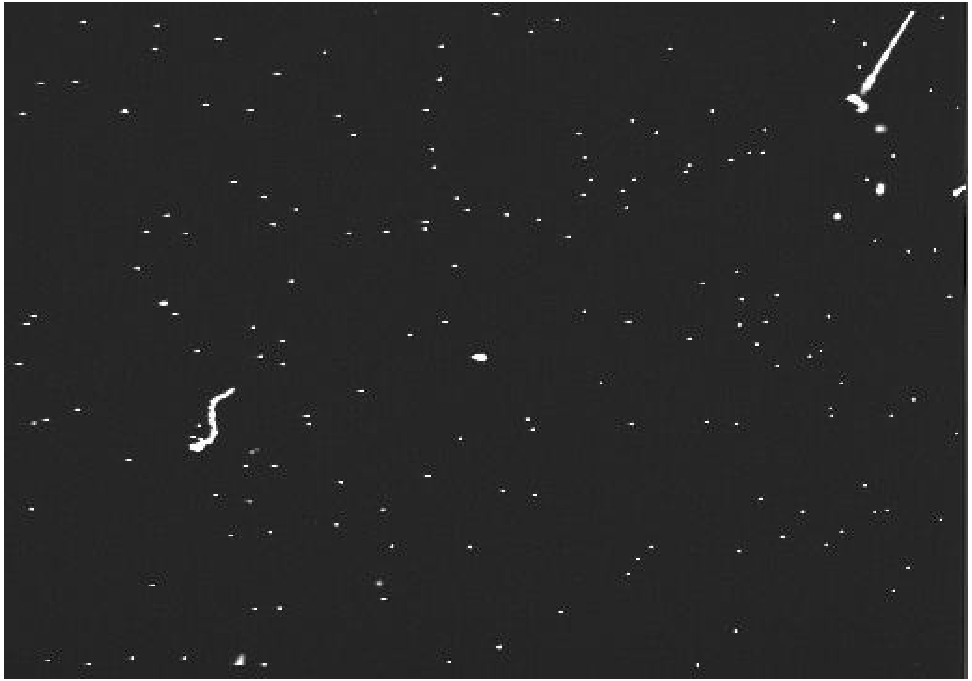


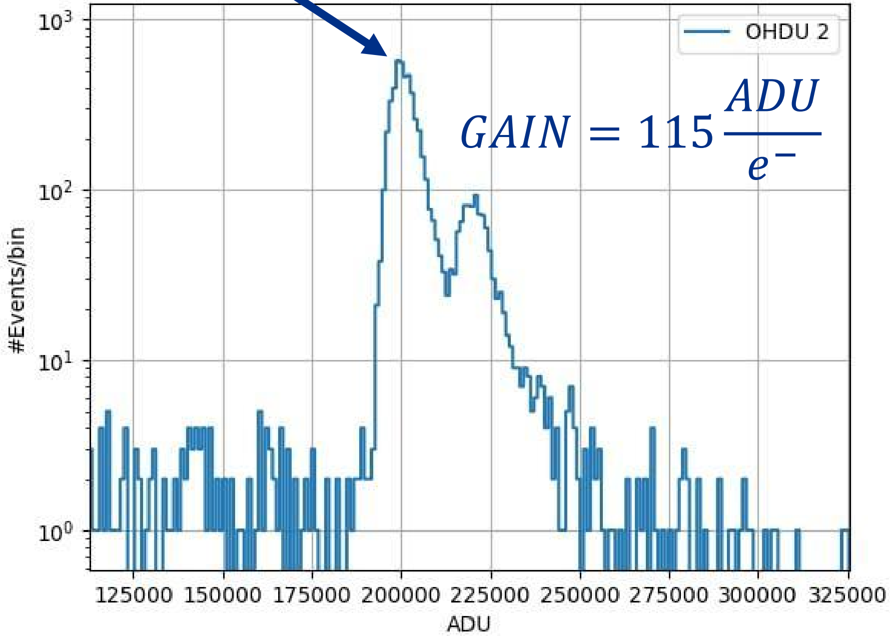
MIDNA (shielded)



Room Temp. MIDNA and Cooled CCD Gain Measurements

- Fe-55 X-ray source ➔ 5.9 keV photons ➔ 1639 e- on average
- Histogram of single photon hits

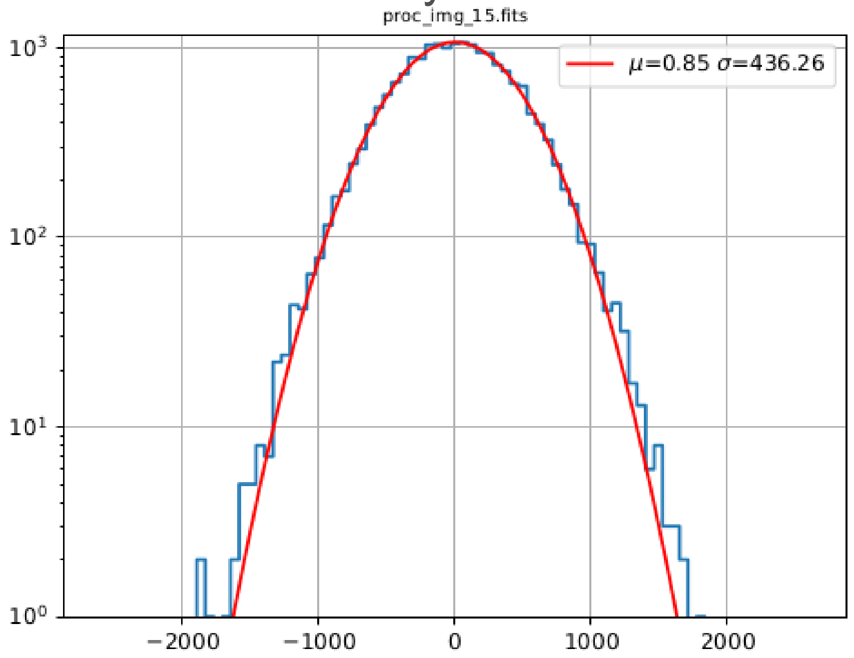




$$GAIN = 115\,\frac{ADU}{e^-}$$

Room Temp. MIDNA and Cooled CCD Noise Measurements

- Measured as the standard deviation on the overscan pixels, region of no charge
- 10 μs integration time in each direction
- Noise dominated by CCD



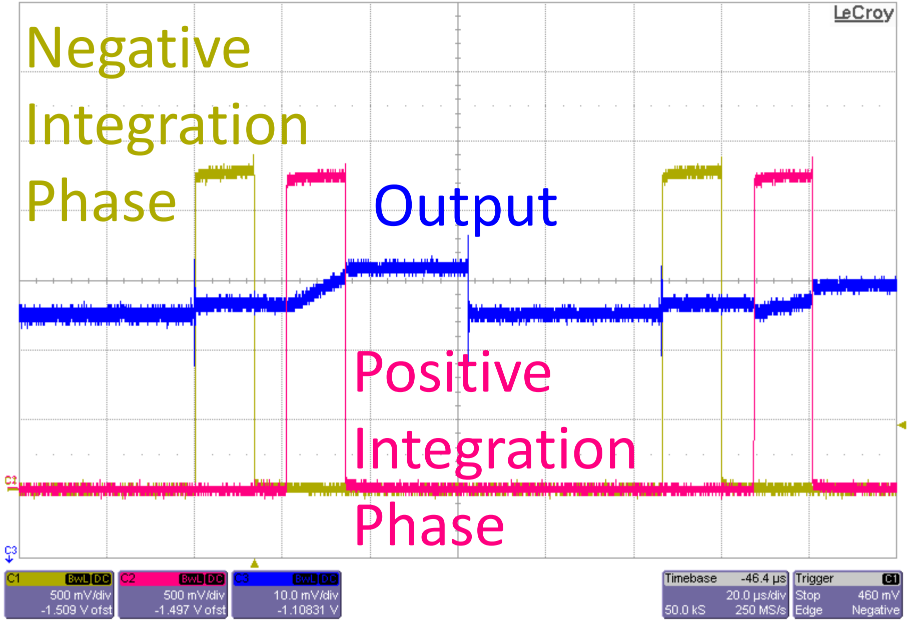
$$NOISE = \frac{STD}{GAIN} = \frac{[ADU]}{\left[\frac{ADU}{e^-}\right]}$$

	Noise
Simulated	3.10 e^-_{rms}
Measured	3.79 e^-_{rms}

Matches performance of discrete solution with smaller footprint and at one tenth of the power!

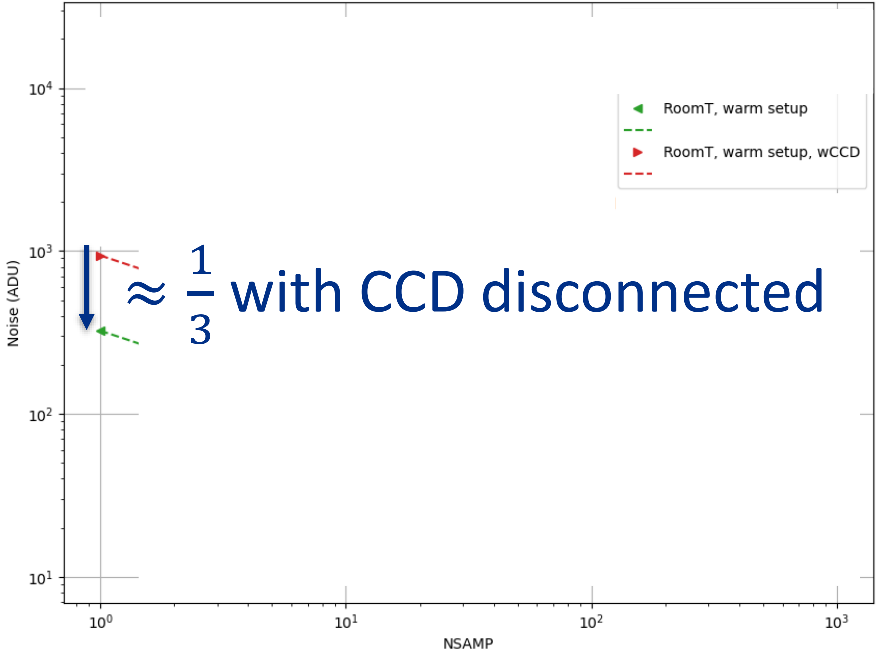
Cooled MIDNA Functionality

- Functionality proven in liquid nitrogen!
- Measurements inside of temperature controlled dewar are still in progress



Noise Measurements at Room Temperature and Liquid Nitrogen

- At room temperature, single integration noise with MIDNA alone is successfully 1/3 of noise with CCD included!



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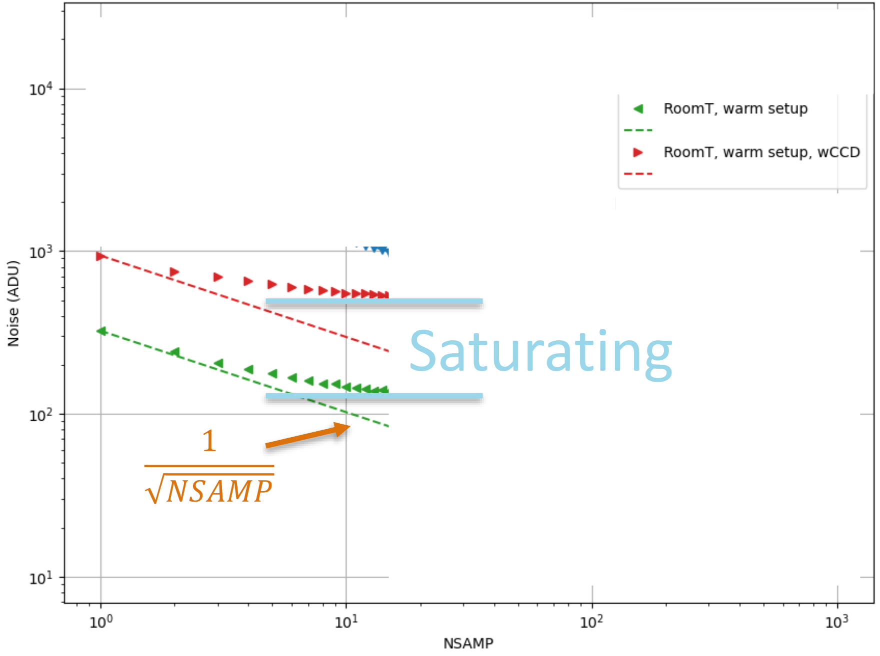
- Mitigations are being investigated



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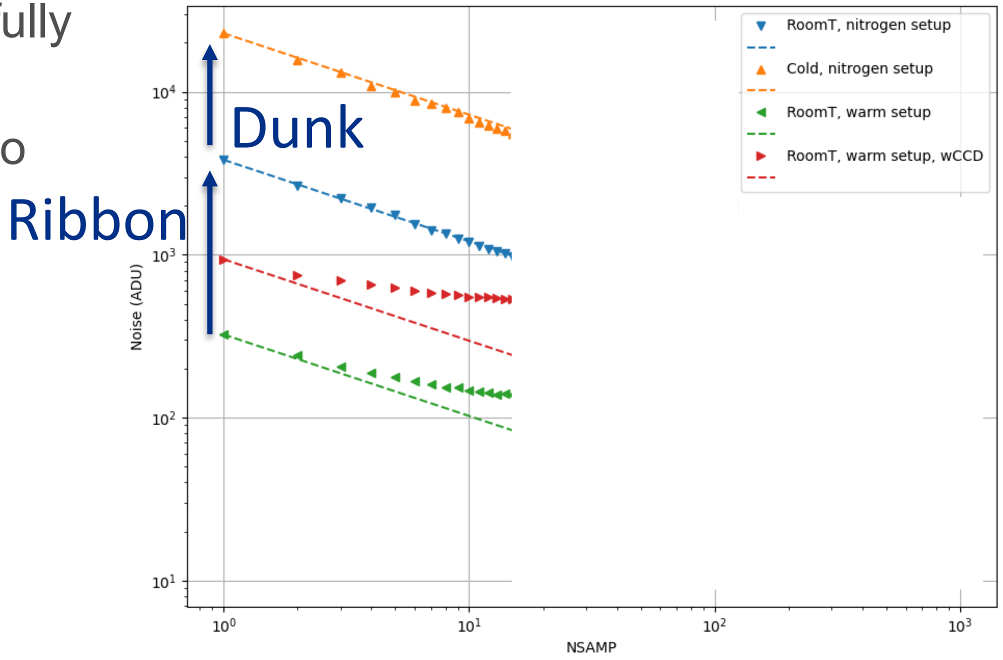
- Dunking continues to make it worse



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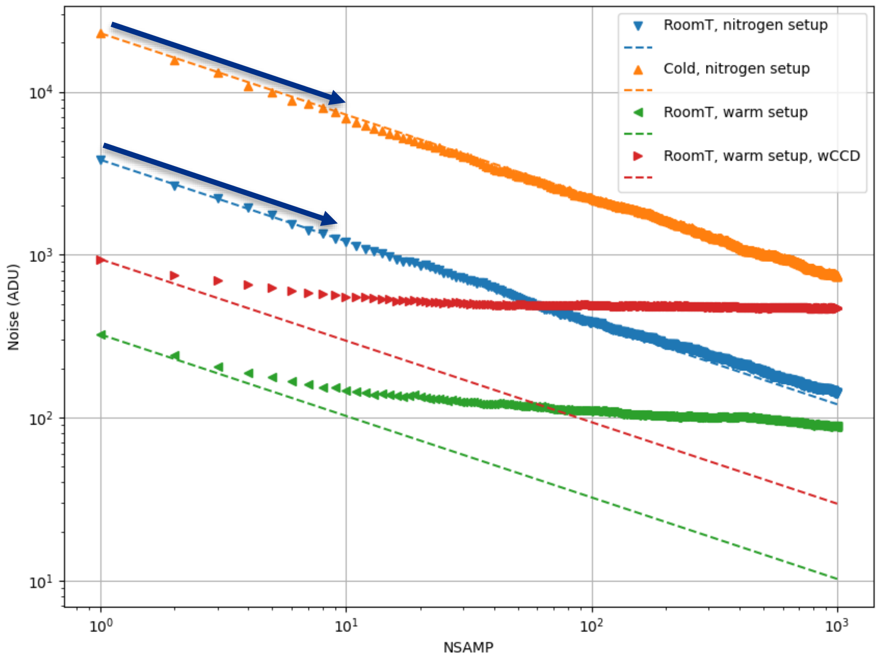
- Mitigations are being investigated
- Liquid nitrogen setup requires long ribbon cabling that is coupling in noise even without dunking
- Dunking continues to make it worse
- Follows $\frac{1}{\sqrt{NSAMP}}$ much better while starting much higher
- More work to come



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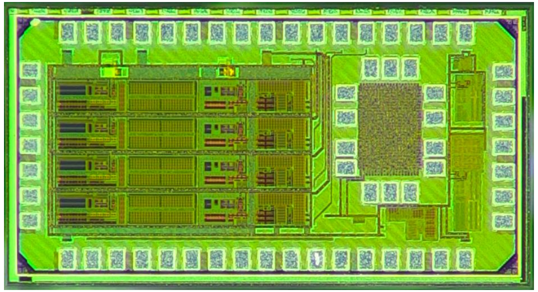
Results and Future Work for MIDNA

- Successfully less than 1/3 of CCD noise even at room temperature!
- Cryogenic functionality down at 77 Kelvin!
- Controlled temperature testing with CCD in progress

- Starting design work for next version of chip
- Grow to many more channels to follow the CCD, up to 64
  - Project scaling is currently limited by cost of readout
- Integrate reference generator and analog-to-digital converter
  - Greatly reduce the sensitive analog signals going off chip
- Enable digital processing of data on chip
  - The ADC combined with on-chip memory enables many averaged reads internally
  - Improves noise, power, and complexity compared to analog solutions, especially off chip

MIDNA Chip Image



Thanks!