A Cryogenic Readout IC with 100 KSPS in-Pixel ADC for Skipper CCD-in-CMOS Sensors

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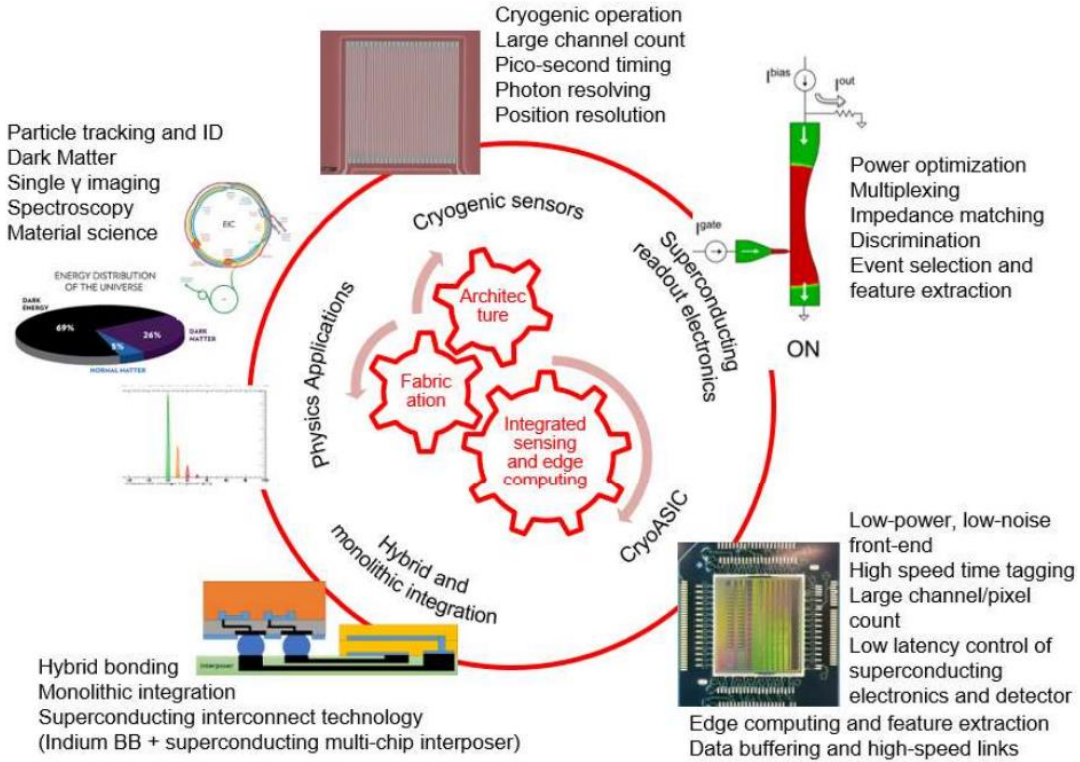
Developing the Hybrid Cryogenic Detectors of the Future

- Advances in HEP, DM detection, quantum imaging demand better detectors:
  - → Extreme **spatial/temporal resolution**
  - → Extreme **environments** (cryo, rad-hard)
  - → Extremely **low noise** (< 1 e-)
- Multi-year DOE collaboration to co-design:
  - → New **sensors**
  - → New **readout electronics**
  - → New **packaging/integration**



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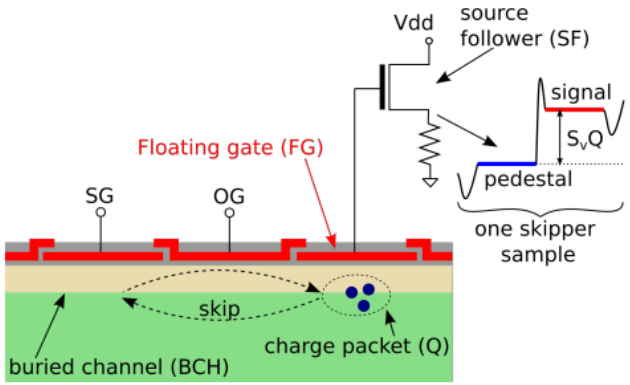
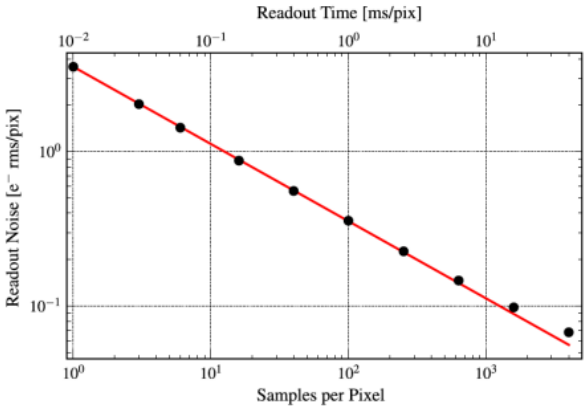
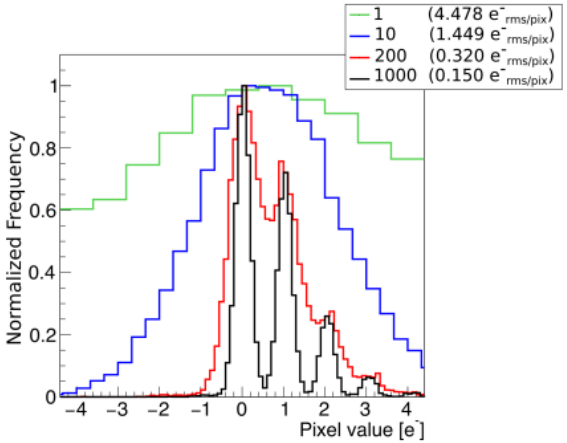
Skipper CCD-in-CMOS

- Incident particles create e-h pairs in the CCD substrate.
- Charge packets create a small voltage that can be sensed by a CMOS amplifier.
- Noise can be dramatically reduced by **“skipping”** charge packet back and forth and sampling it many times.







10.1103/PhysRevLett.119.131802 [1]

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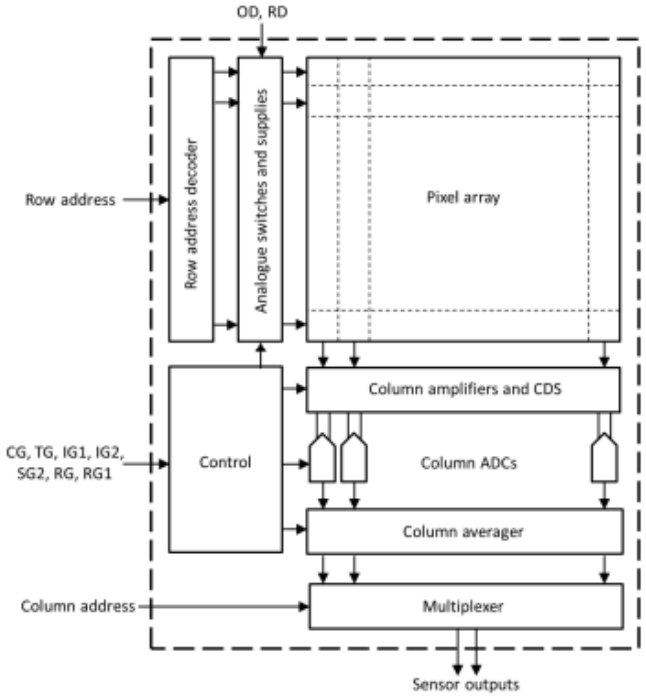
Reading Out a CCD Image Sensor

Monolithic, Column-Parallel



Stefanov, et al. [2]

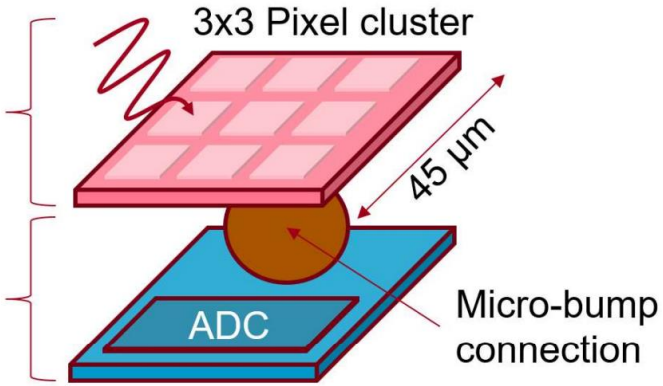
Hybrid, Per-Pixel

Skipper ASIC:

- Pixel matrix with skipper functionality

Readout ASIC:

- ADCs
- Real-time data processing
- Fast I/Os



Per-Pixel readout offers $\approx O(n)$ speedup, but at a cost:

Severely constrained power and layout area for the front-end and ADC circuits.

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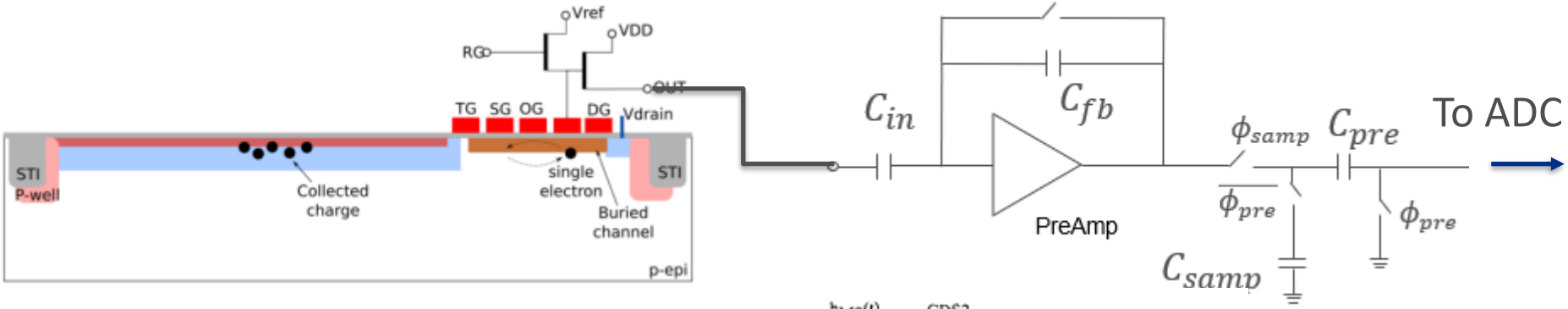
How to Detect a Single Electron

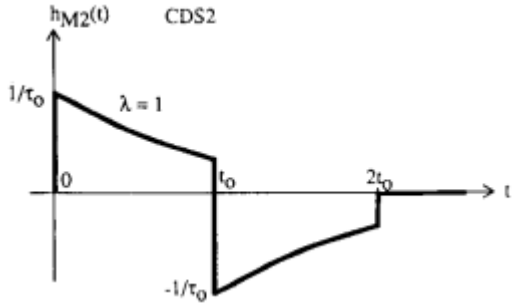


1 electron…

→ Source Follower output: 115 uV

→ Pre-Amp output: 1.15 mV

Equivalent output noise: 550 uV, or 0.48 e-



Impulse response of a CDS circuit.
H.M. Wey and W. Guggenbuhl [3]

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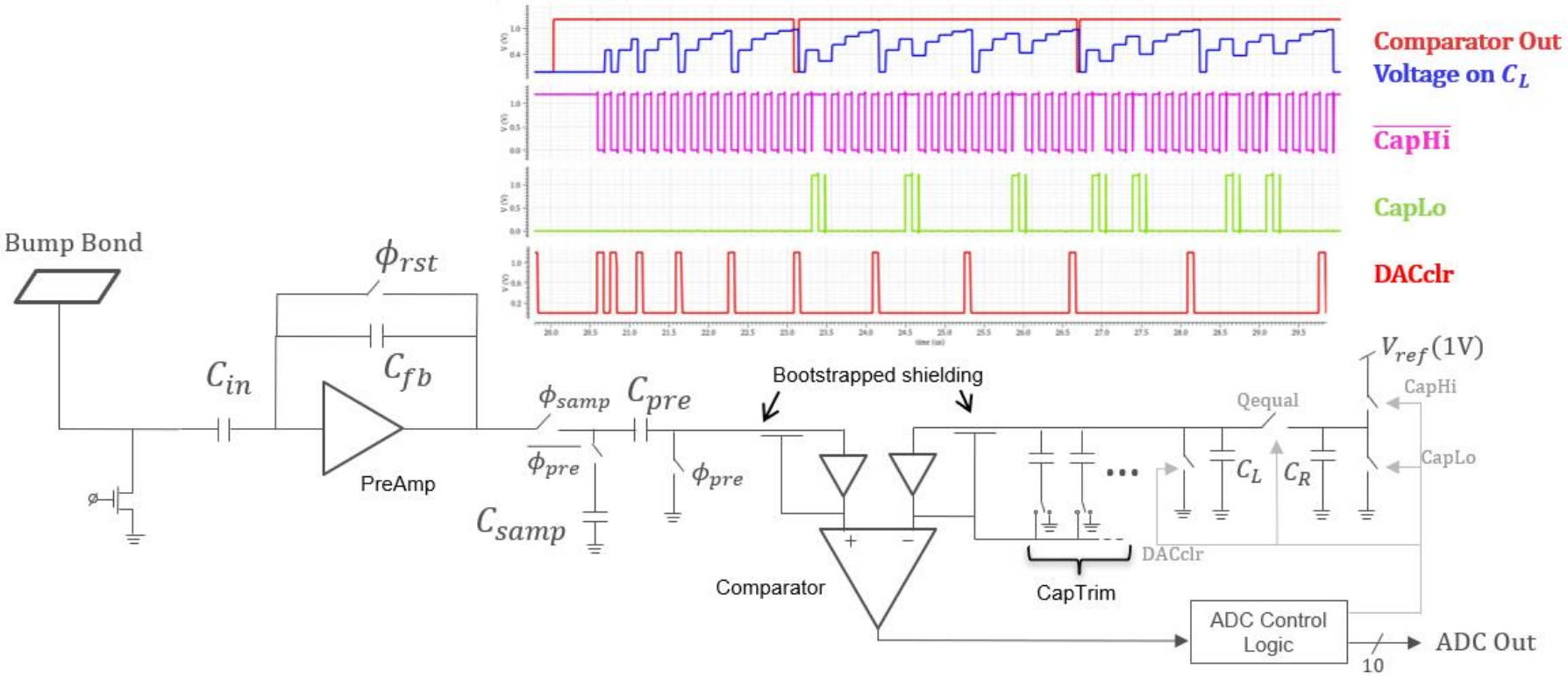
How to Detect a Single Electron (and Digitize it)



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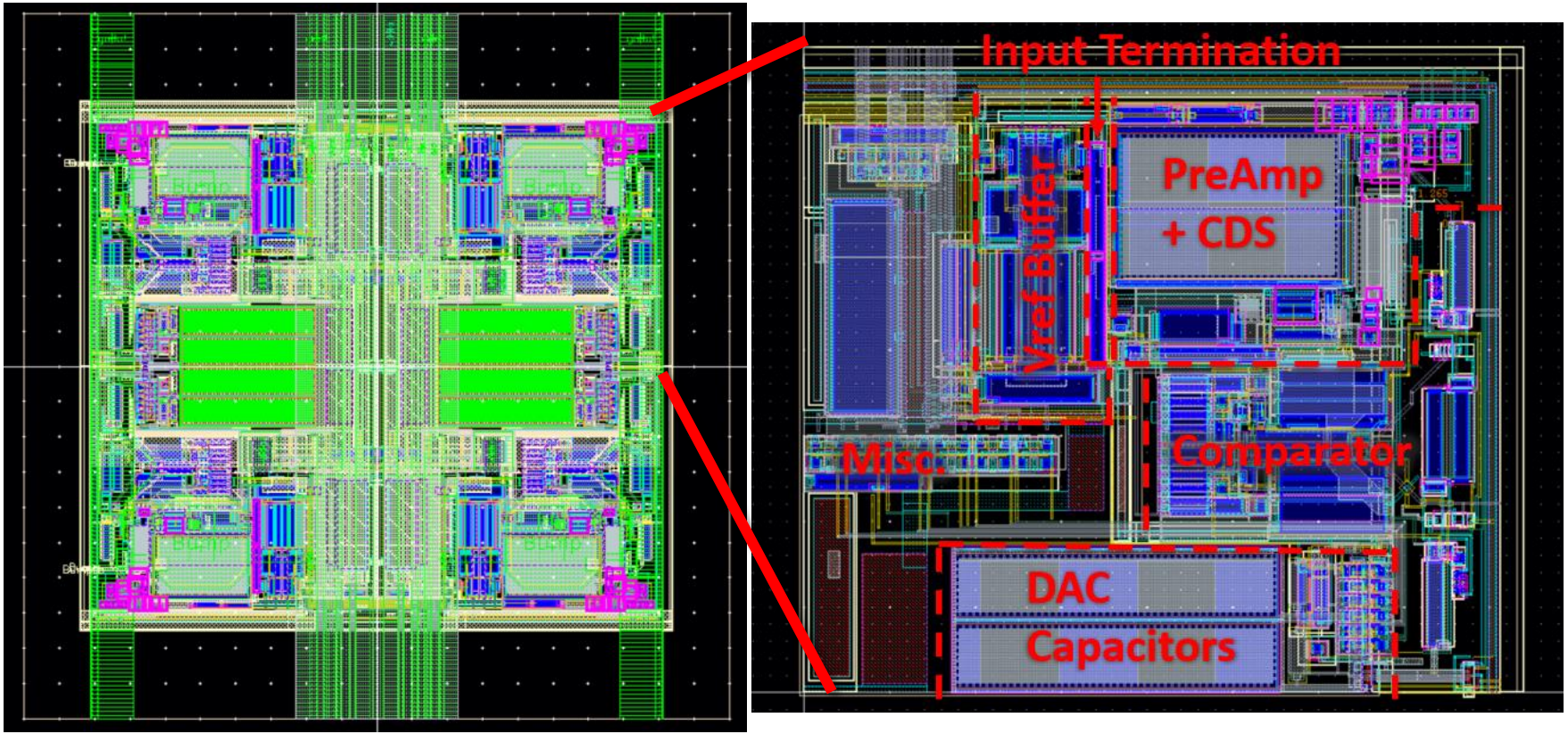
In Silicon…



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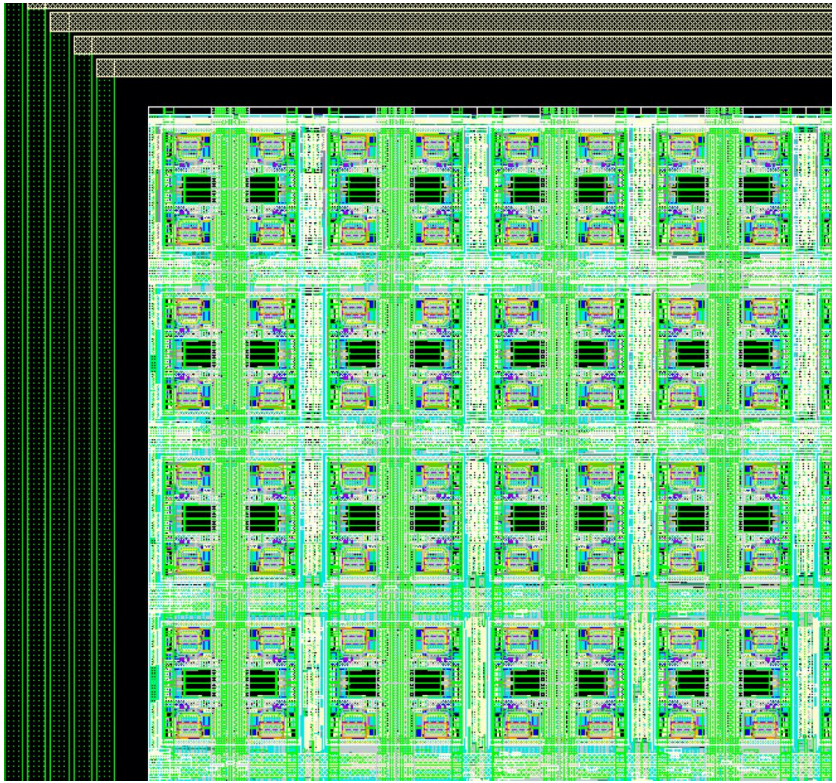
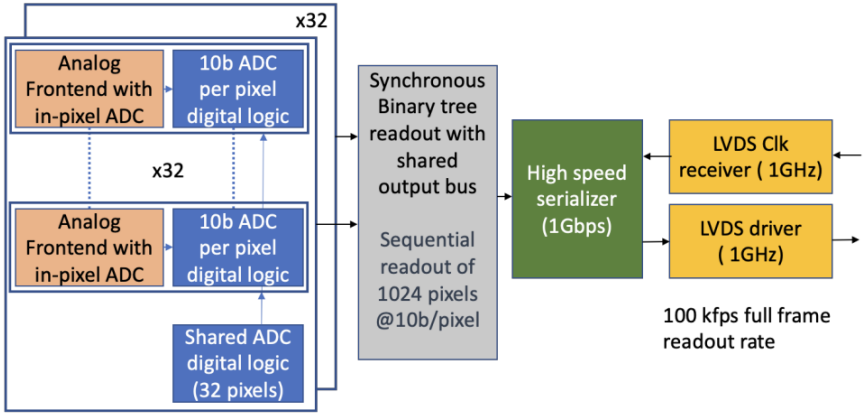
How to Detect a Single Electron (and Read it Out)





10b * 100 kHz * 1 MPix = 1 Tbps!

Data compression is important:

- Zero-suppression
- PCA
- ML-based Autoencoder

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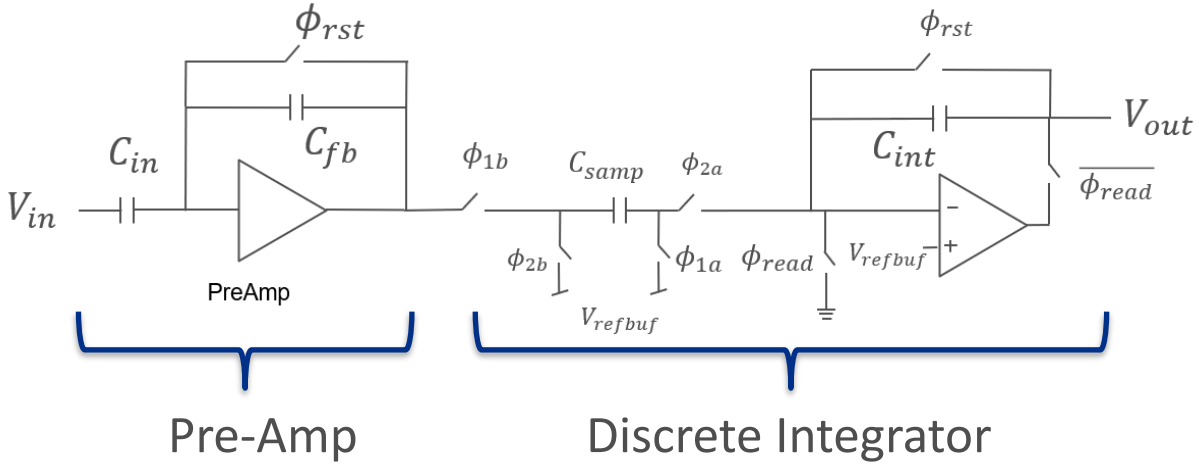
What's Next?

- **Test Chip in June 2022**
- **In-Pixel Sample Pileup**

  10x sample pileup: ENC 0.48 e- → 0.15 e-



- **Full-reticle tapeout early 2023**

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Thanks to Contributors

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SLAC:

L. Rota, M. Sharma

References

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[2] Stefanov KD, Prest MJ, Downing M, George E, Bezawada N, Holland AD. Simulations and Design of a Single-Photon CMOS Imaging Pixel Using Multiple Non-Destructive Signal Sampling. *Sensors*. 2020; 20(7):2031. https://doi.org/10.3390/s20072031

[3] H. M. Wey and W. Guggenbuhl, "An improved correlated double sampling circuit for low noise charge coupled devices," in IEEE Transactions on Circuits and Systems, vol. 37, no. 12, pp. 1559-1565, Dec. 1990, doi: 10.1109/31.101279.

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[6] T. Zimmerman, G. Deptuch, and F. Fahim, “Compact, low power, high resolution adc per pixel for large area pixel detectors.” U.S. Patent 11,108,981, issued August 31, 2021