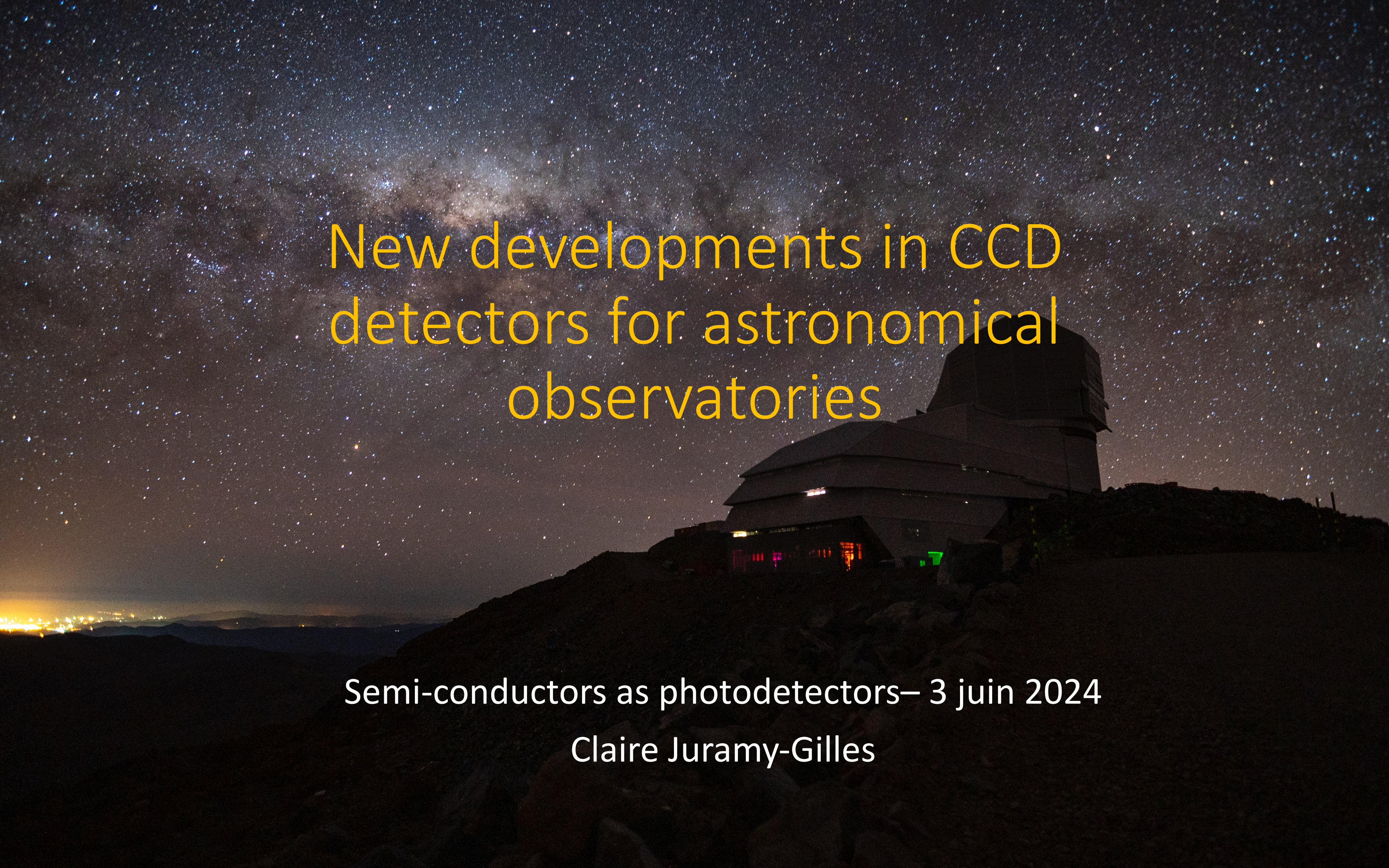


New developments in CCD detectors for astronomical observatories

Semi-conductors as photodetectors– 3 juin 2024

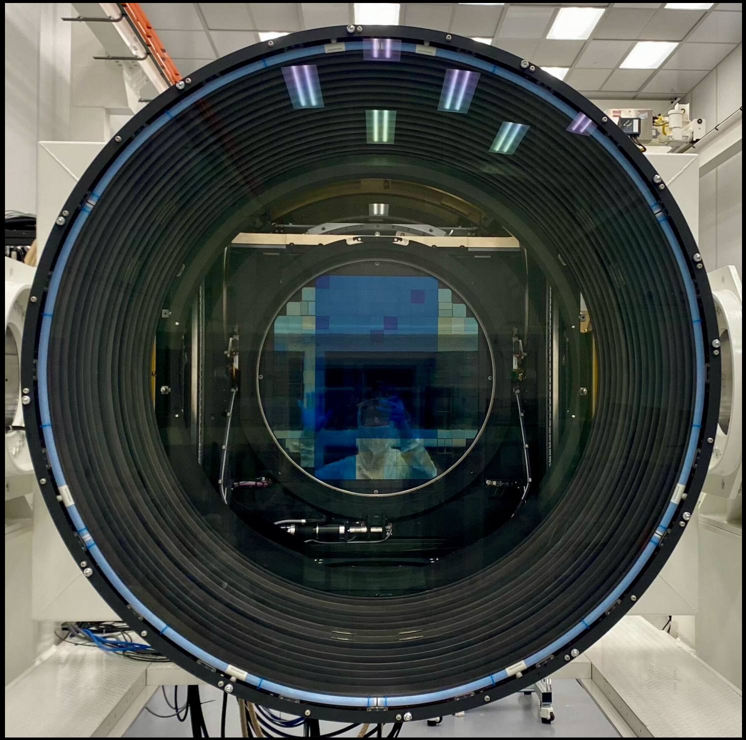
Claire Juramy-Gilles

A CCD for every occasion?

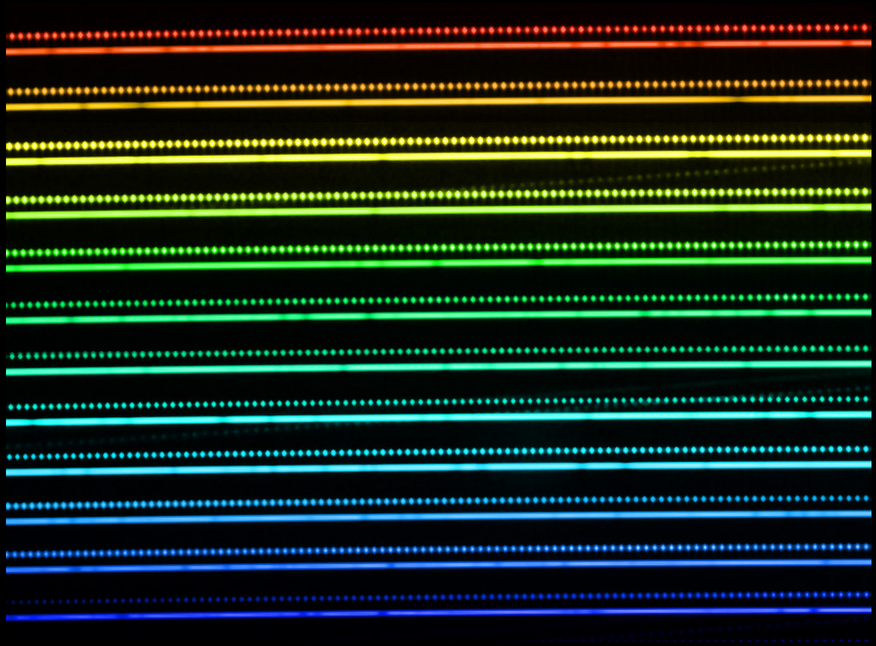
- Traditional CCDs
- CCDs vs CMOS
- Photon counting: EMCCDs
- Skipper CCDs
- Multi-Amplifier Sensing CCDs
- SiSeRO design for readout
- … and more innovations coming up

Traditional CCDs

- Multiple applications in astronomy and astrophysics: UVOIR, X-rays
- Varied requirements: low/high signals, background, radiation hardness



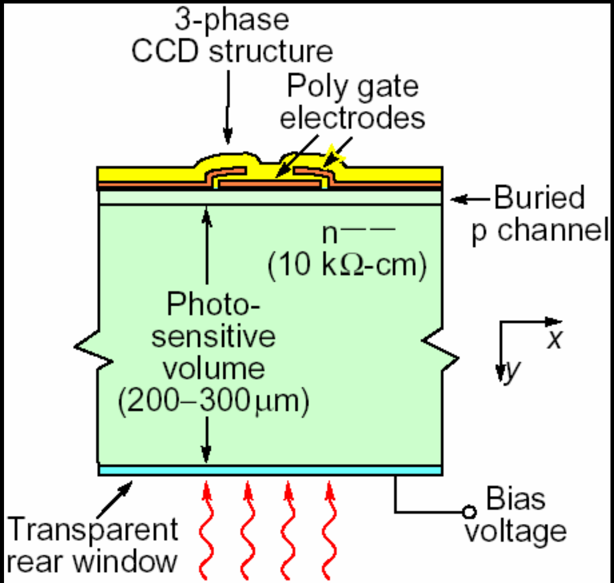
LSST



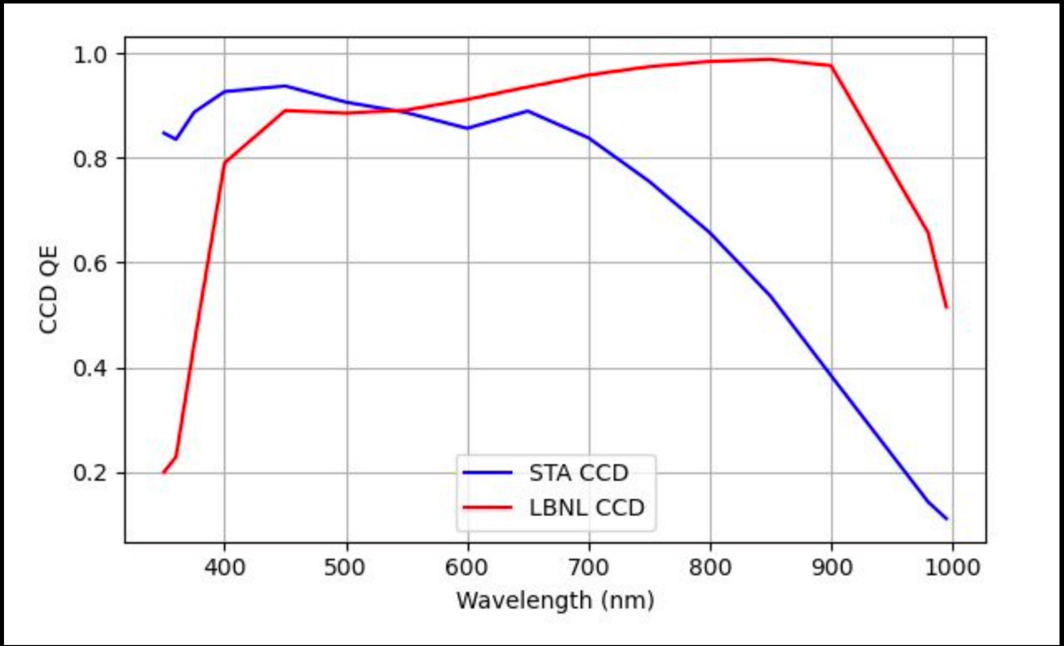
ESO, MPQ: frequency comb

CCD performances and processes

- Quantum efficiency in NIR: thickness
- n-channel (Teledyne-e2v, Semiconductor Technologies Associates Inc) and p-channel (LBNL, FermiLab, Hamamatsu)
- Radiation hardness



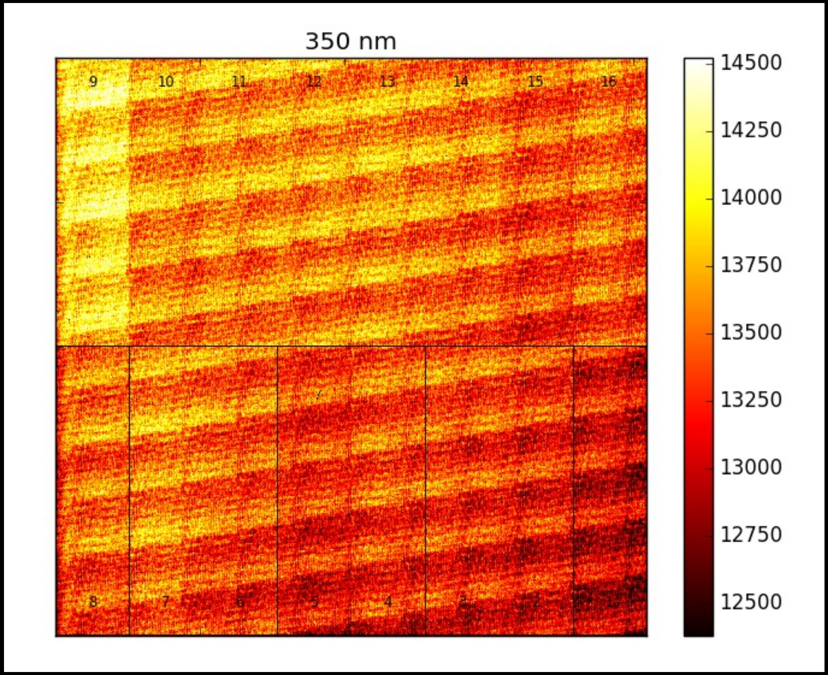
S. Holland: LBNL CCDs



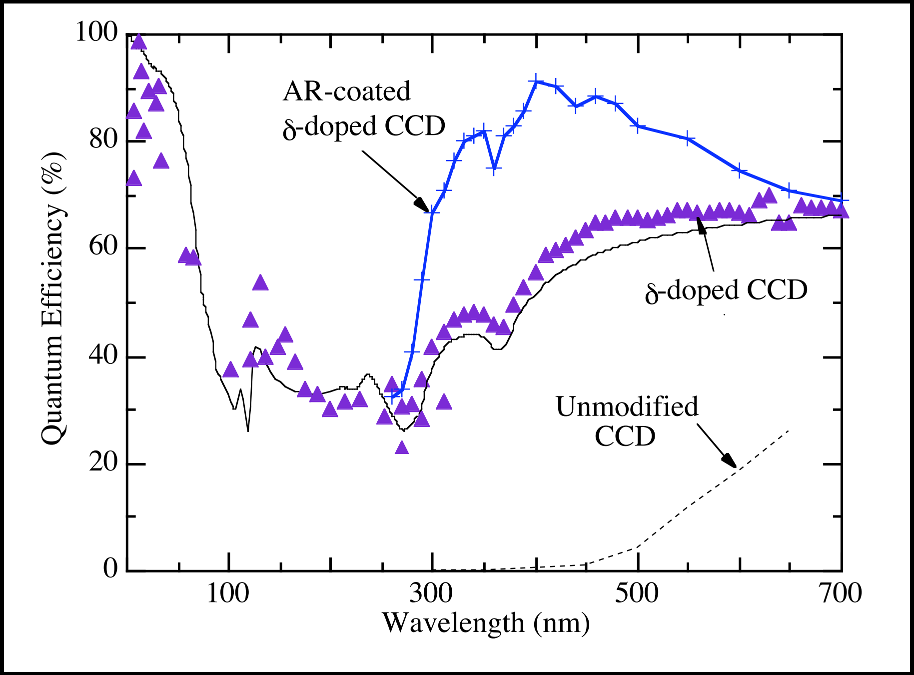
J. Guy: DESI CCDs

CCD performances and processes

- Back-illuminated, thinned
- Quantum Efficiency in UV and blue: coating
- Development of 2D delta-doped CCDs with Molecular Beam Epitaxy

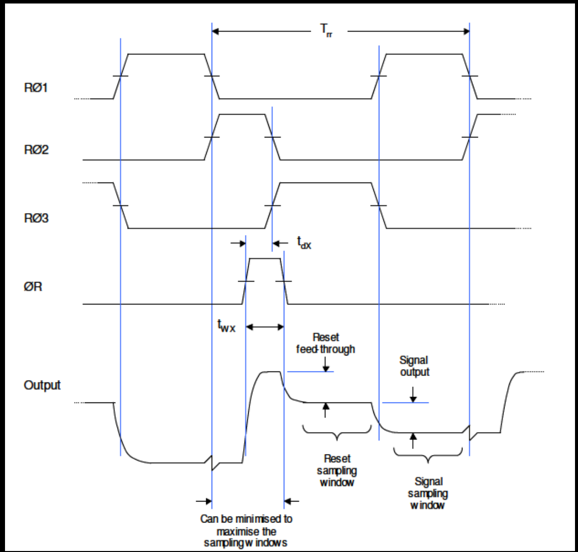


T-e2v CCD250, LSST

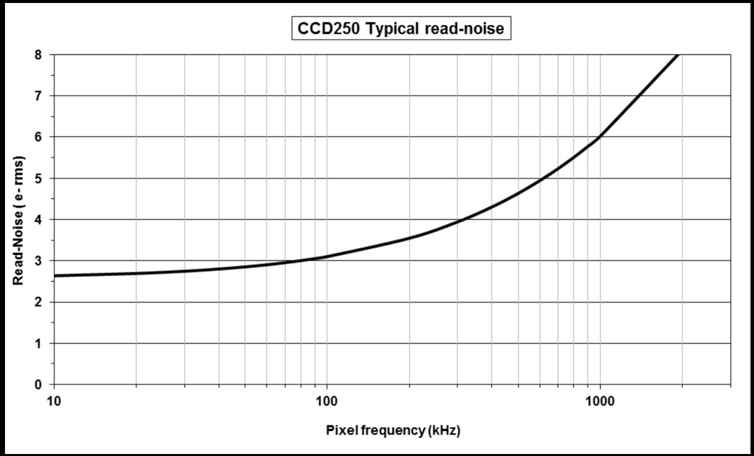


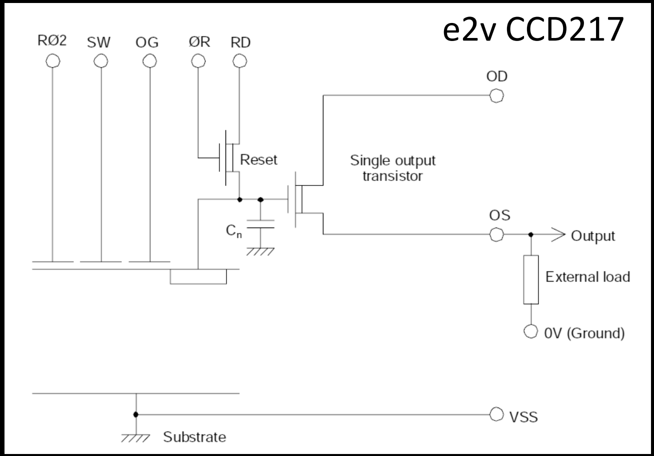
JPL, Caltech

Pros and cons of traditional CCDs



- ⊕ Linearity, full well ~100s ke (depending on pixel size)
- ⊕ Low dark current: ~e/pix/hour (depending on temperature)
- ⊖ Serialized readout: efficienty of the charge transfer (CTE), readout time
- ⊖ Noise corner of the MOSFET output transistor
- ⊖ Pixel reset: kTC noise subtraction

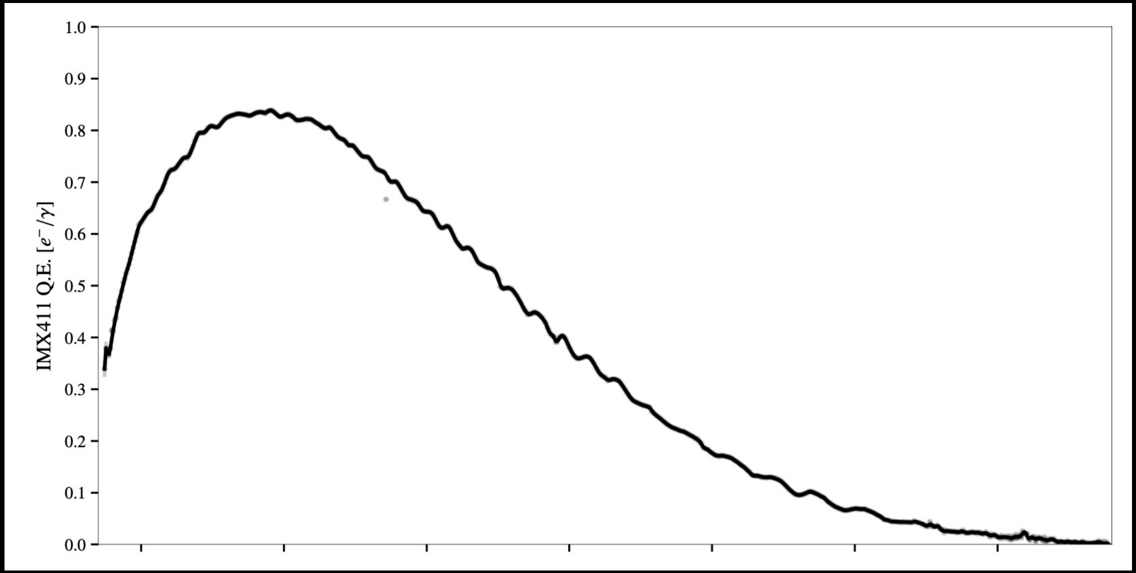




The competition from CMOS sensors

… for astronomy/astrophysics UVOIR imaging

- “CMOS sensors” = 1 amplifier/pixel, multiplexed readout
- Pixel size, Quantum Efficiency: development of dedicated back-illuminated, high-resistivity CMOS sensors

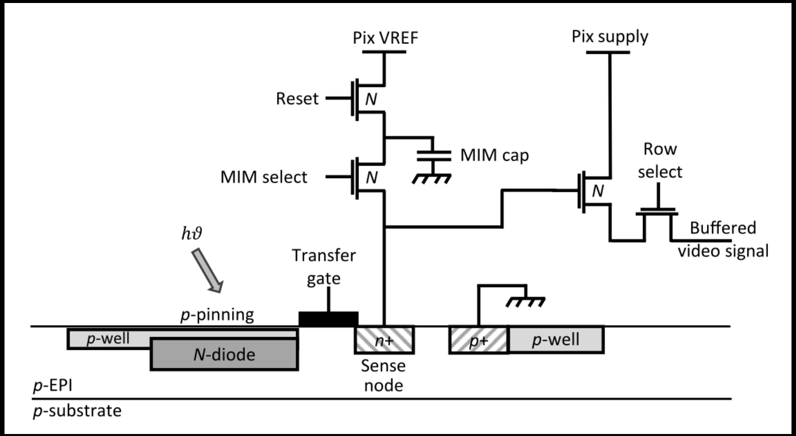


M. Betoule, Sony IMX411ALR in QHY411M (151 Mpix)

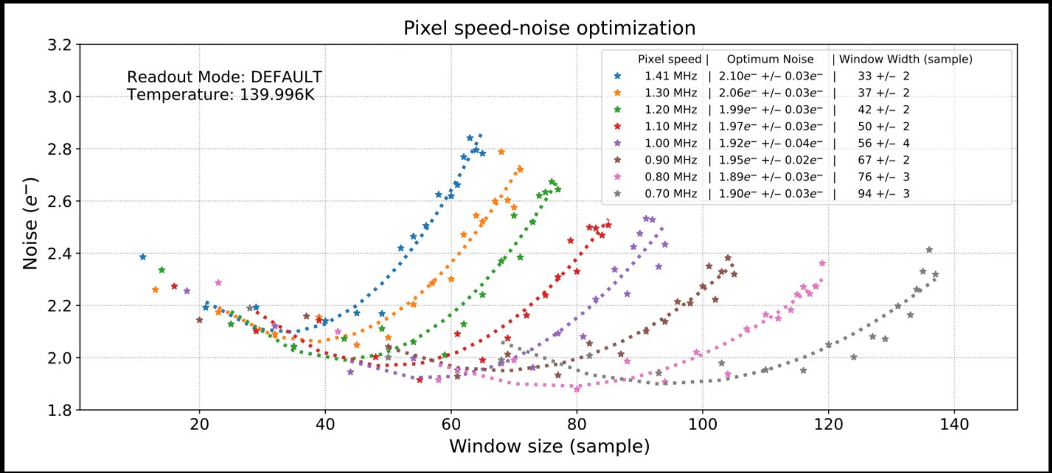
T-e2v COSMOS-66 (64Mpix)

The competition from CMOS sensors

- Complexities (and opportunities) in the readout :
  - Electronic shutter (rolling/global)
  - High Dynamic Range (readout with high/low gain)
- Energy consumption, self-heating, dark current, inter-pixel capacitance



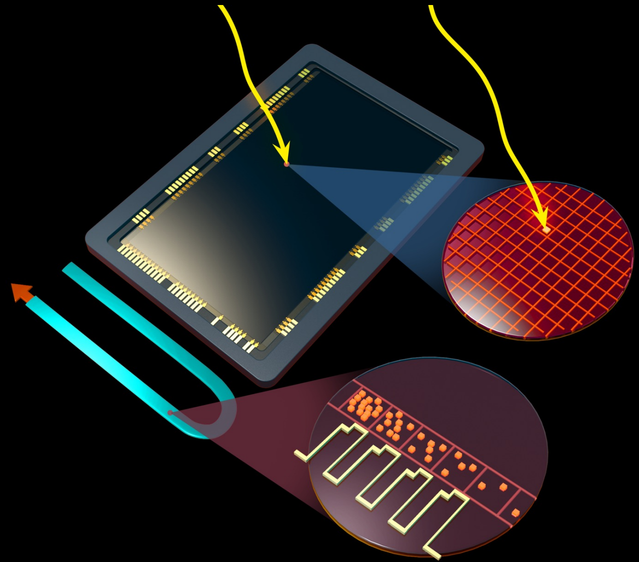
J. Janesick, 5T pixel with pinned photodiode

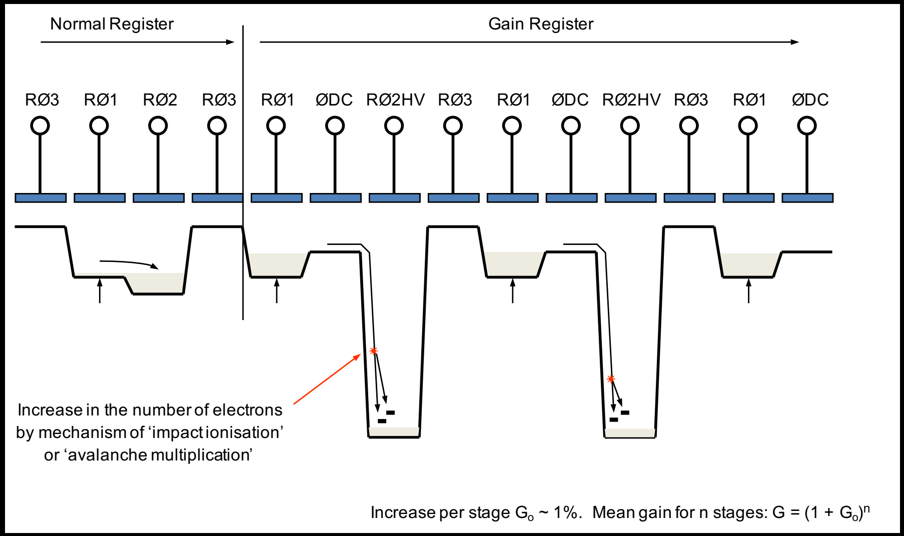


T. Greffe, SRI International 4kx2k prototype for UVEX, 2D delta-doped, Archon + FPGA 100 MS/s readout

Photon counting: Electron-Multiplying CCDs

- Also in use: Silicon APDs (avalanche photodiodes) arrays
- EMCCD: suppress read noise, also amplify dark current and clock-induced charges, additional noise from stochastic process
- T-e2v CCD311: reduce cosmic rays overspill through use of dump gate to remove high signals

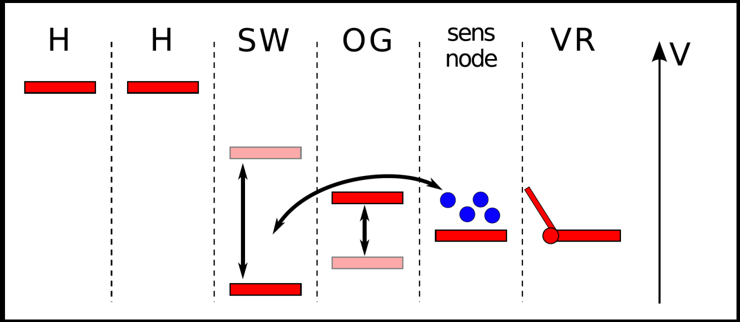




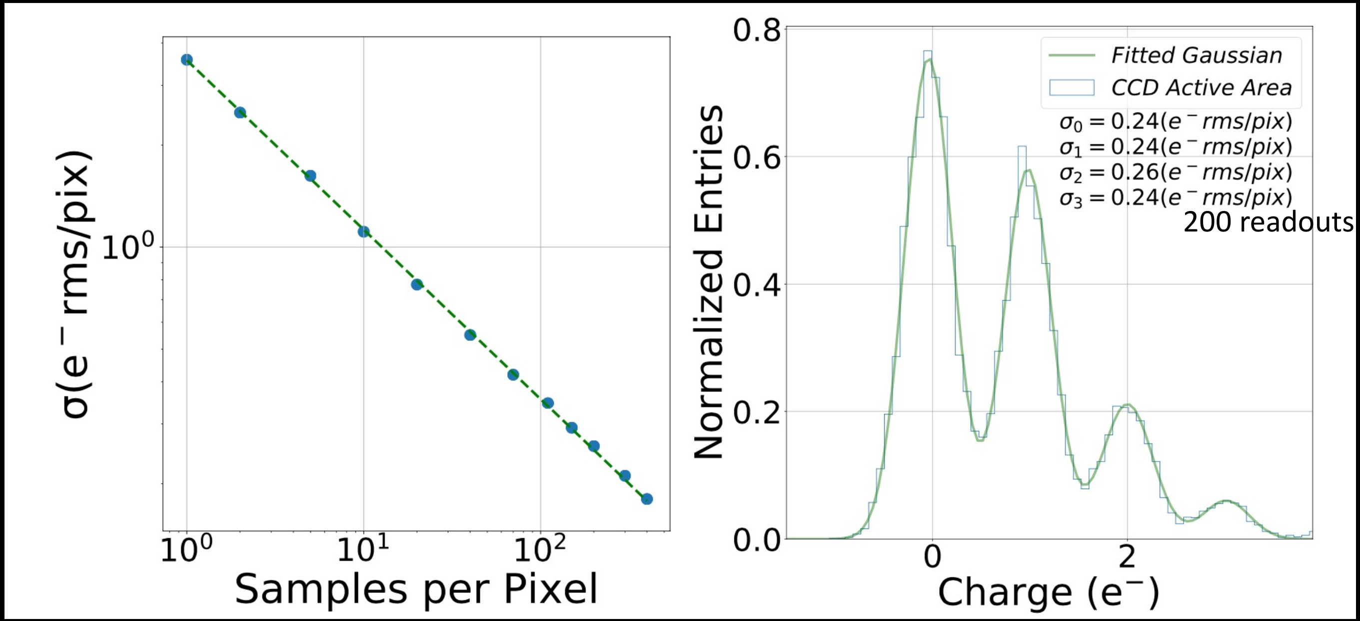
T-e2v

Below 1 electron noise : skipper CCDs

- 'Skipper': pixel charge moved back and forth to readout node
- N readouts of the same charge: statistic reduction of noise in √N
- Bonus: gain measurement



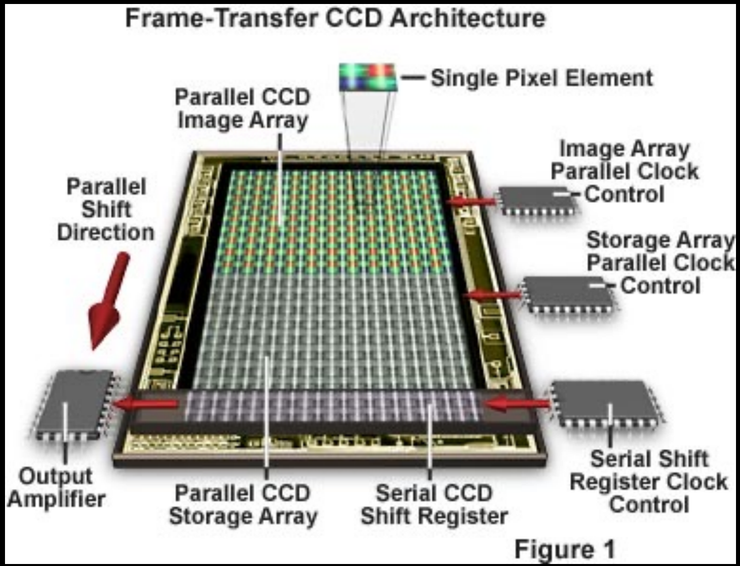
J. Tiffenberg 2017



A. Drlica-Wagner, SPIE2020

Below 1 electron noise : skipper CCDs

- Readout time
- Frame-transfer: readout during exposure
- Use of skipper readout only in regions of interest

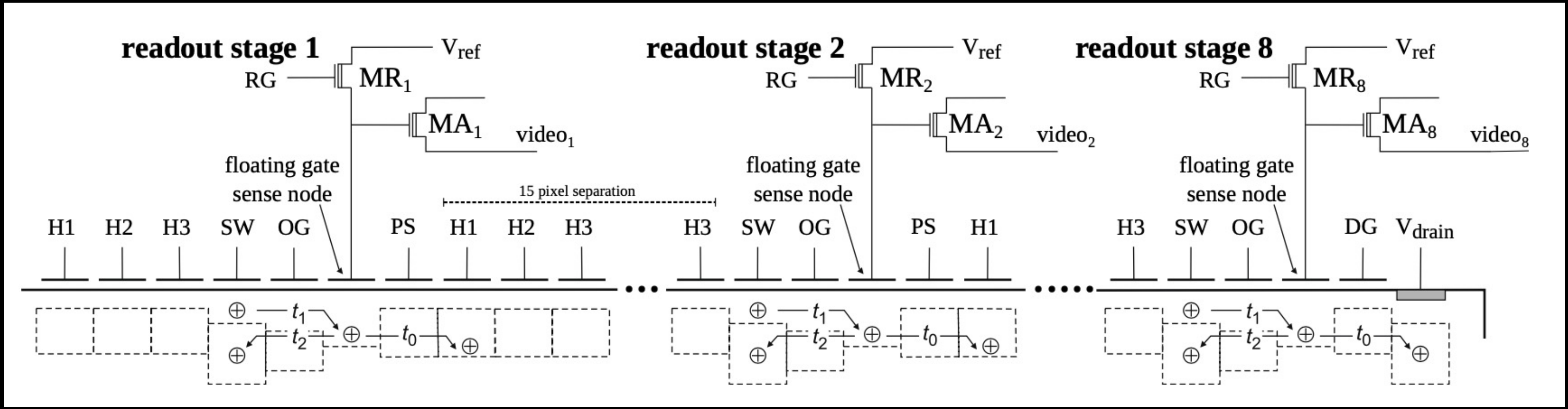


Hamamatsu

STA, Inc skipper prototype

Multi-Amplifier Sensing (MAS) CCDs

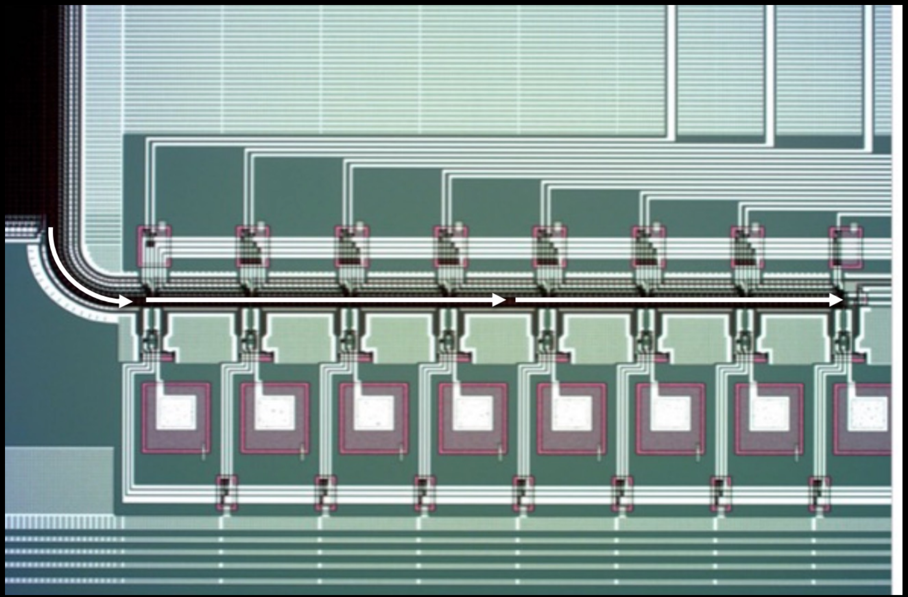
- Repeated readout of the same charge… in sequential amplifiers
- Average (or weighted average) on 8, 16, 32 channels
- Readout system
- Correlated noise suppression: read the same value at different times

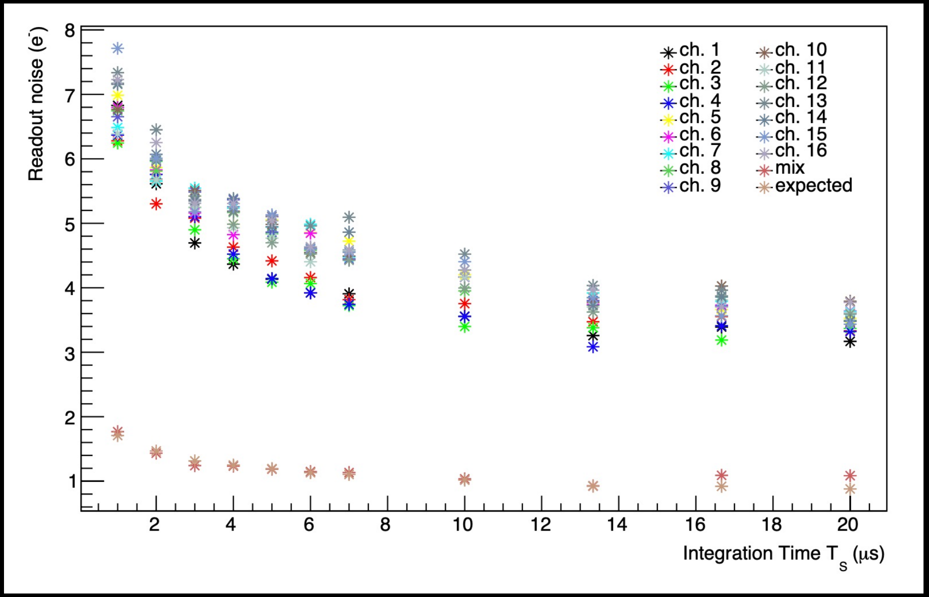


G. Fernandez Moroni,
FermiLab

MAS CCDs Implementations

- FermiLab / Lawrence Berkeley National Laboratory
- Skipper CCDs for dark matter, tests for astronomy, MAS prototypes



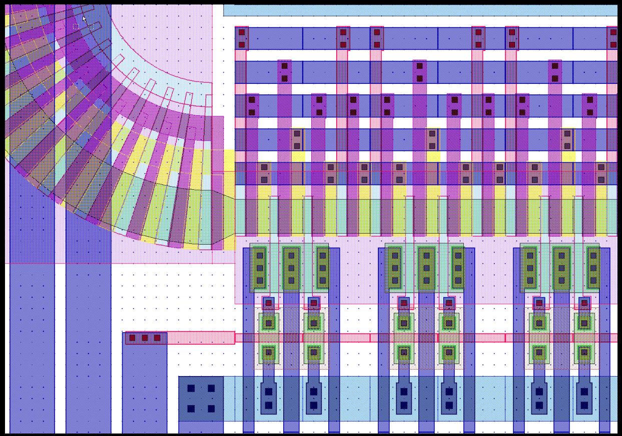


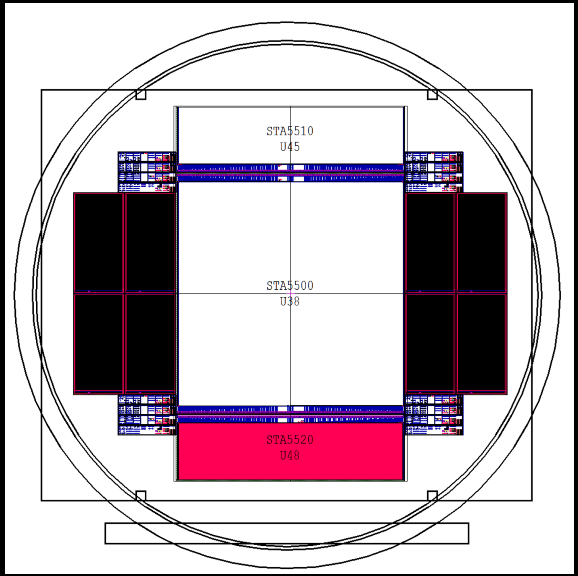
G. Fernandez Moroni

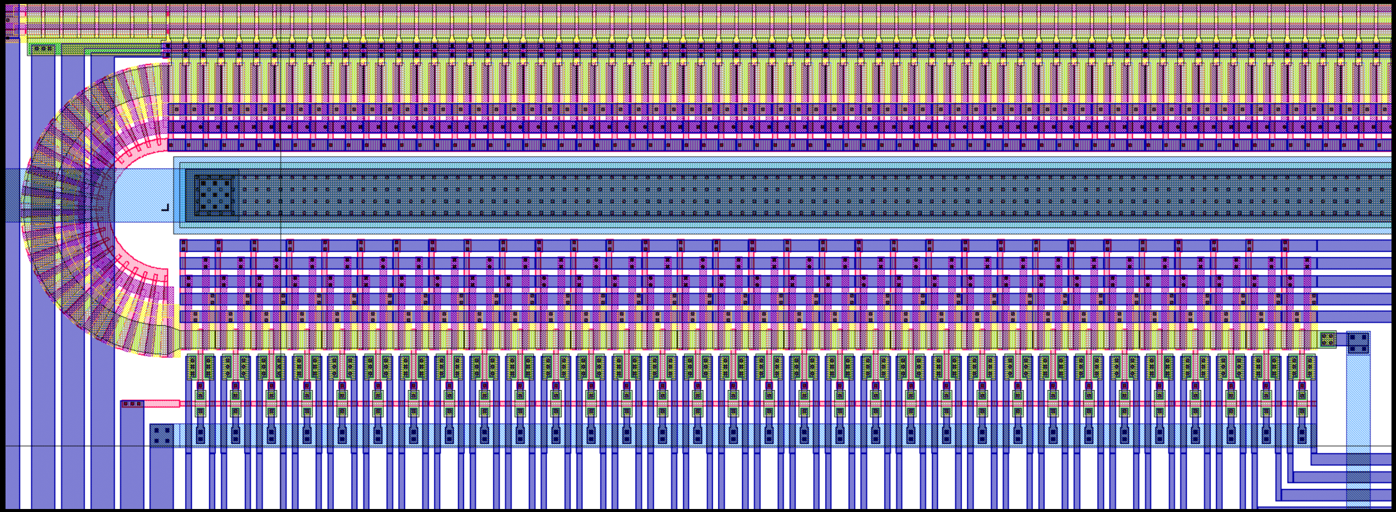
K.Lin

MAS CCDs Implementations

- STA5500
- Differential outputs
- Turn-around

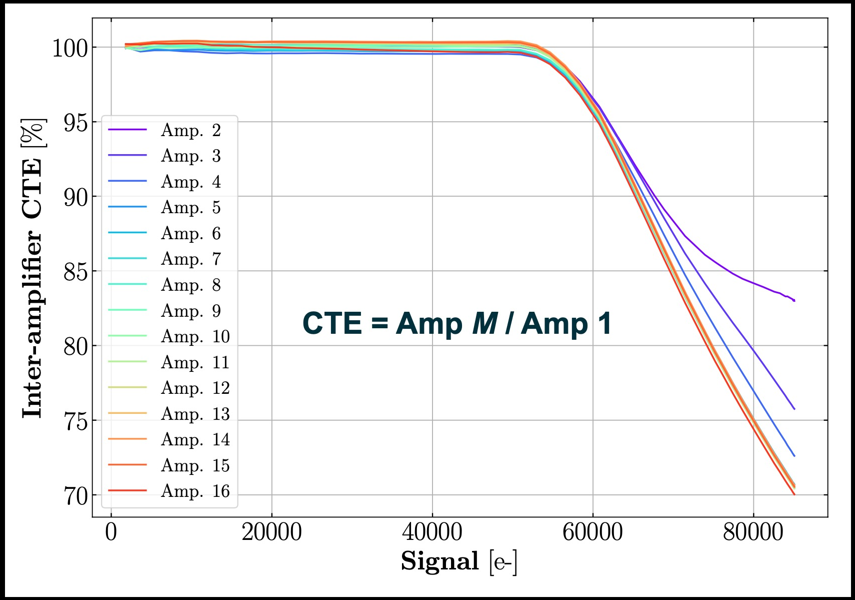




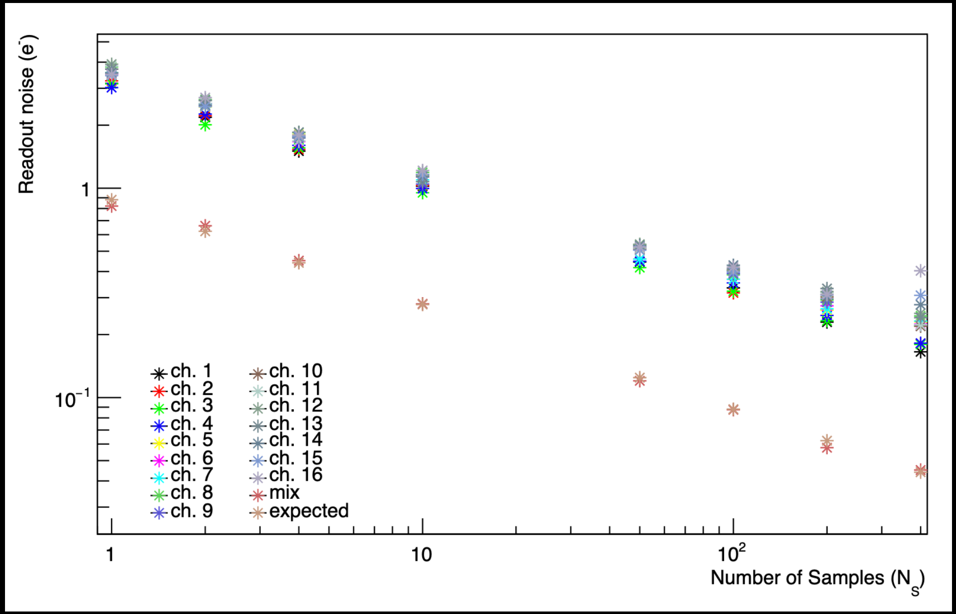


Multi-Amplifier Sensing (MAS) CCDs

- Challenges: clock-induced charges, transfer efficiency at high flux
- Optimization of clock voltages: noise vs full well
- Can be combined with skipper mode



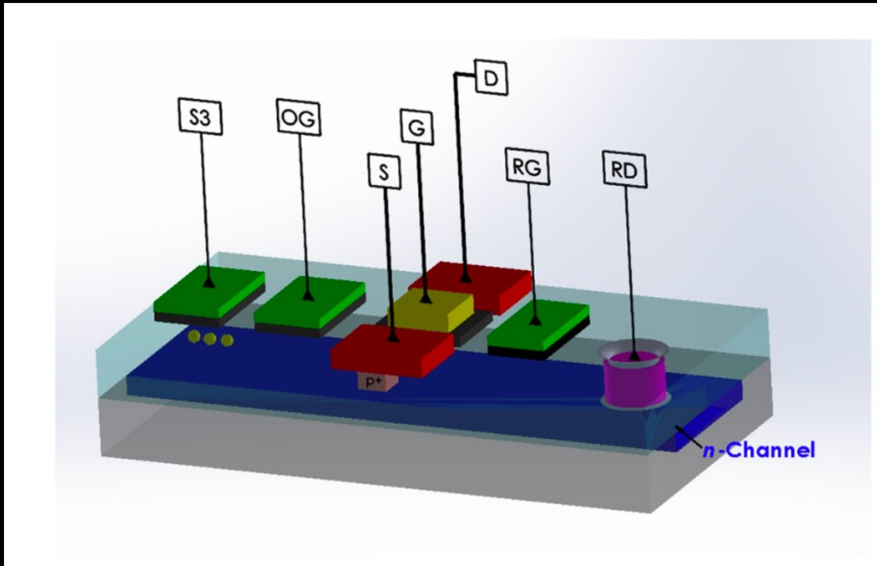
K.Lin

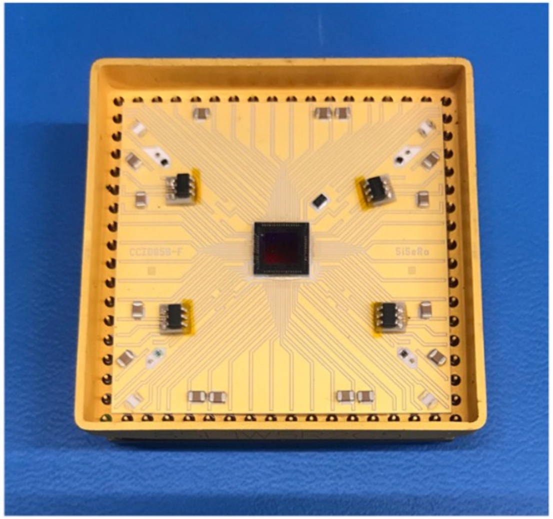


G. Fernandez Moroni

SiSeRO CCDs

- = Single electron Sensitive ReadOut
- Pixel charge modulates current in readout transistor
- Faster readout (X-ray), high conversion gain, no kTC, compact
- Expect 1e noise at 1 MHz for 1500 pA/e

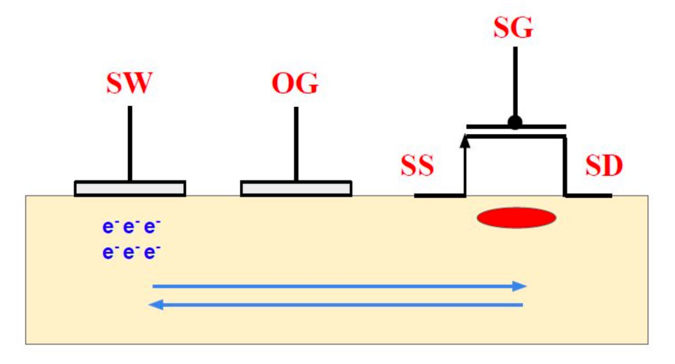




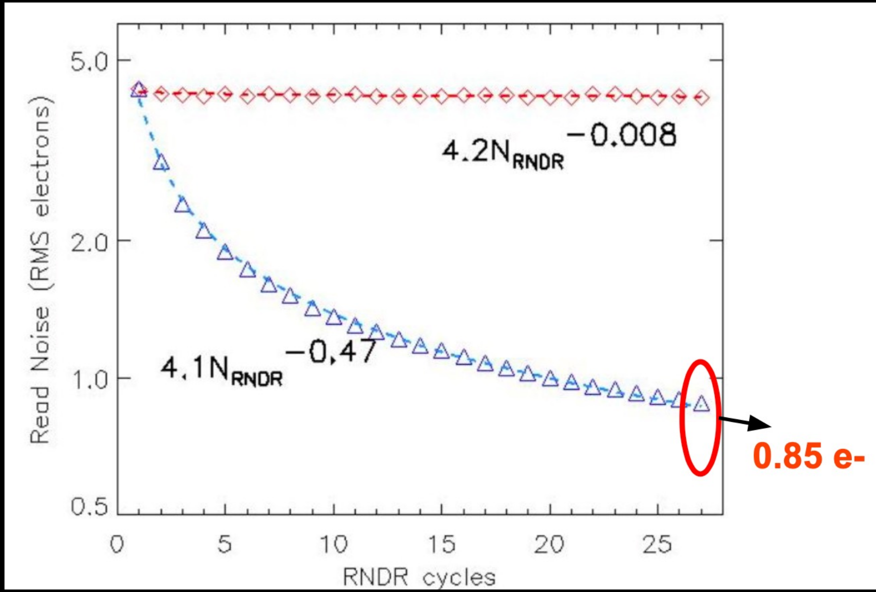
MIT Lincoln Lab CCID85F prototype

SiSeRO CCD Implementations

- Prototyping: moved to buried channel SiSeRO, 1/f noise filtering
- Tested Repetitive Non-Destructive Readout (RNDR)
- Also demonstrated by FNAL/LBL with NMOS FET on p-CCD
- Combined with multi-amplifier architecture



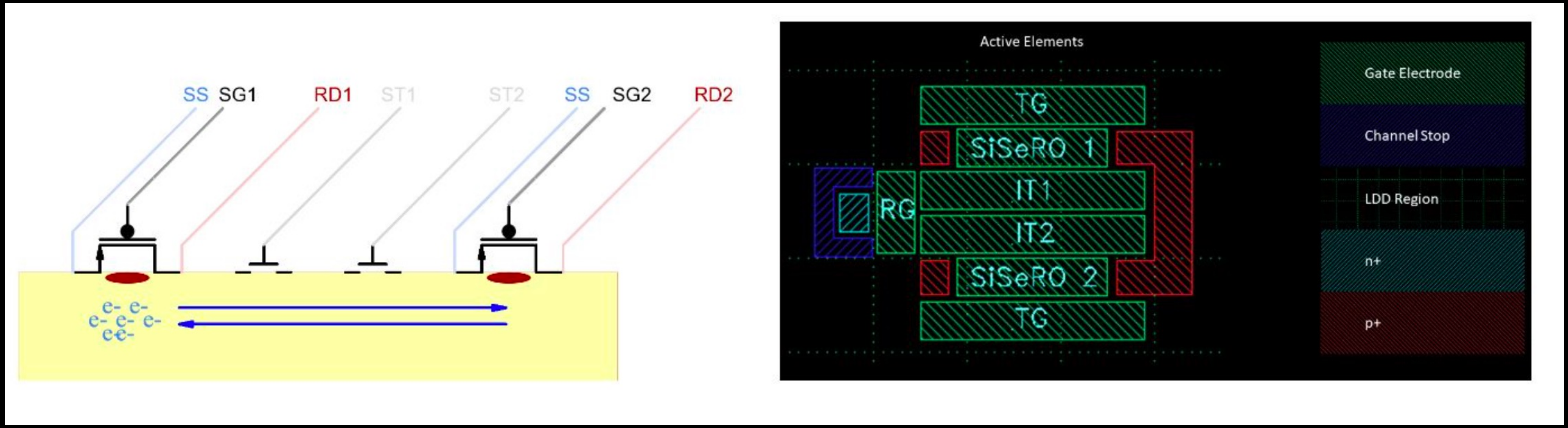
T. Chattopadhyay



More innovations on the way

Other sensors benefitting from CCD R&D:

- Skipper CMOS
- Active Pixel Sensor with two SiSeROs per pixel, with alternating measurements of baseline and pixel values on two channels on the same output



T. Chattopadhyay

Some takeaways

- Innovations on all fronts for CCDs: sub-e noise, readout speed, output amplifier
- Convergent evolution of CCDs and CMOS sensors: outputs, noise reduction strategies
- Dedicated sensors for astronomical observations: back-illuminated, high-resistivity, pixel size, new designs
- Development costs