Pixel sensors for ground and space astronomical observatories

Pixel2024 – 18 November 2024

Claire Juramy-Gilles

LPNHE PARIS

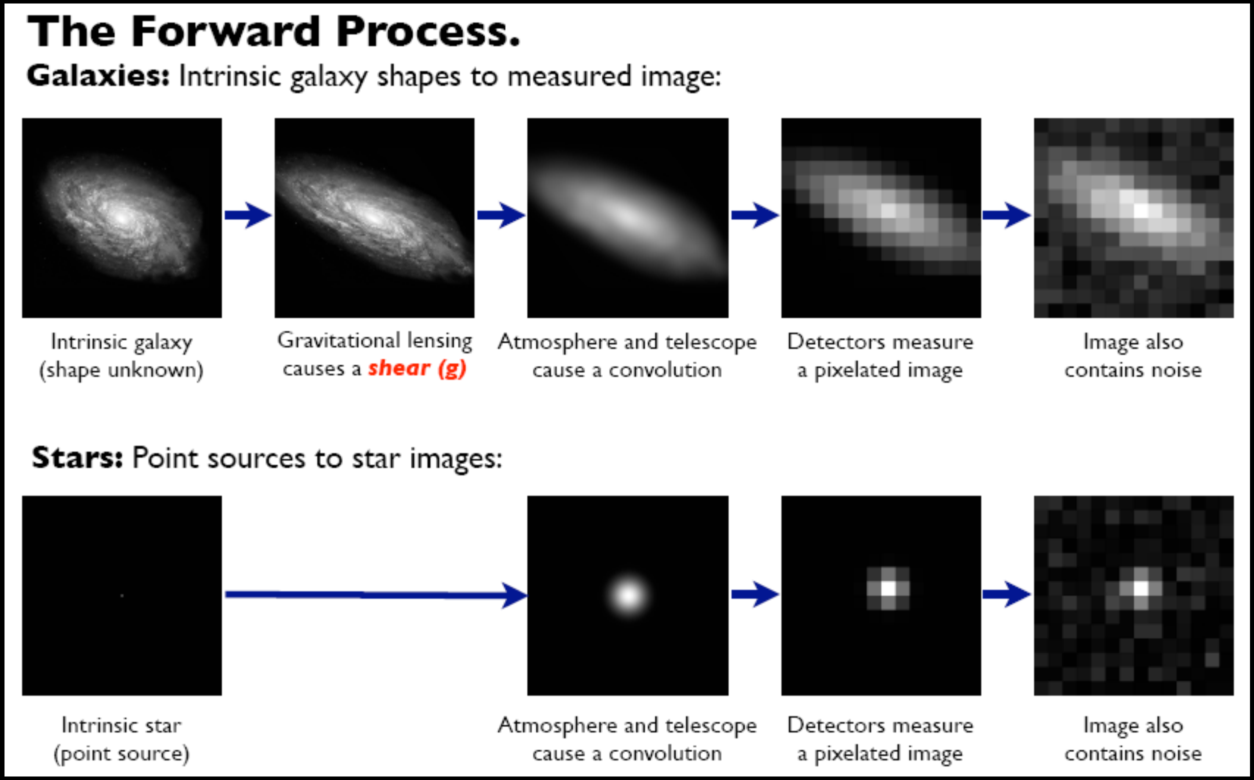
VERA C. RUBIN OBSERVATORY

The precision frontiers

- Focusing on a few highlights of semi-conductor pixel sensors for the UV/Vis/NIR, among many current and future projects
- Challenges for astrophysics, cosmology, exoplanets: stretching the limits of instrumental precision
  - Photometric accuracy
  - Astrometric precision
  - Shape measurement systematics
  - Spectral fidelity
  - “Photon-starved” observations
  - High-contrast observations
  - Photon-counting
- Precision requirements drive both sensor design and characterization (“we’ll fix it in the software”)

Shape measurement for cosmology

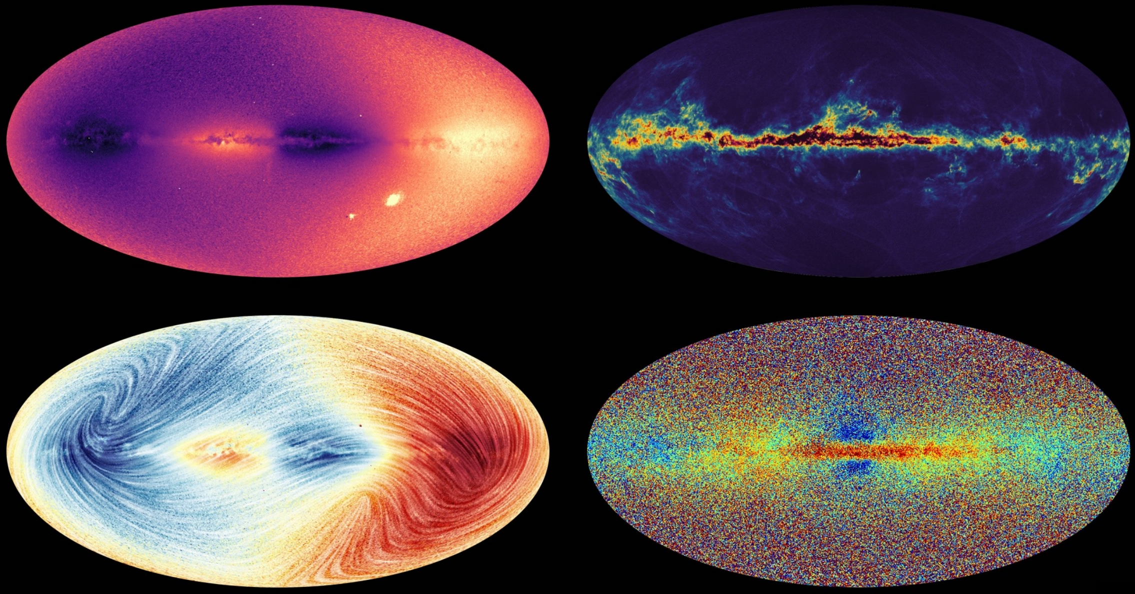
- Weak Lensing: gravitational shear on background galaxies
- Requirements to control contributions to shear systematics (Euclid, LSST)



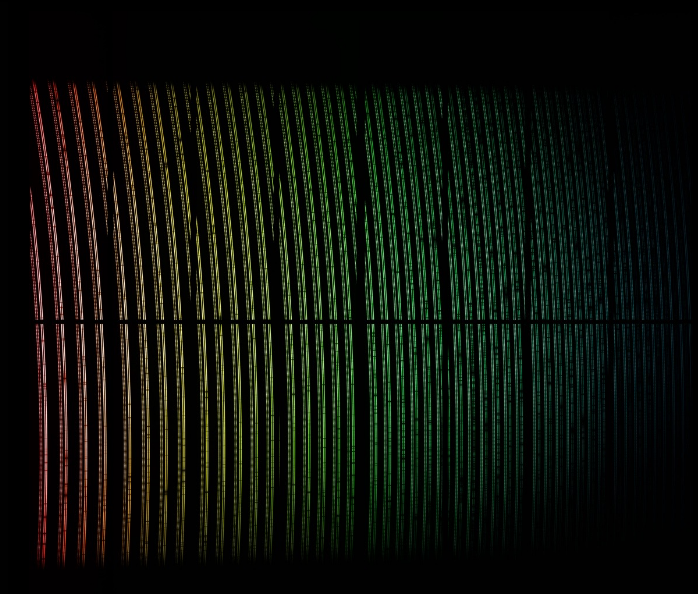
T. Tyson, ISPA 2024

Sub-pixel information extraction

- Astrometric precision (Gaia: star centroids ~ 10^{-3} pixel, MICADO@ELT)
- Velocity measurements in spectra (ESPRESSO@VLT: target 0.1m/s, or 2 nm over 10 µm pixels)



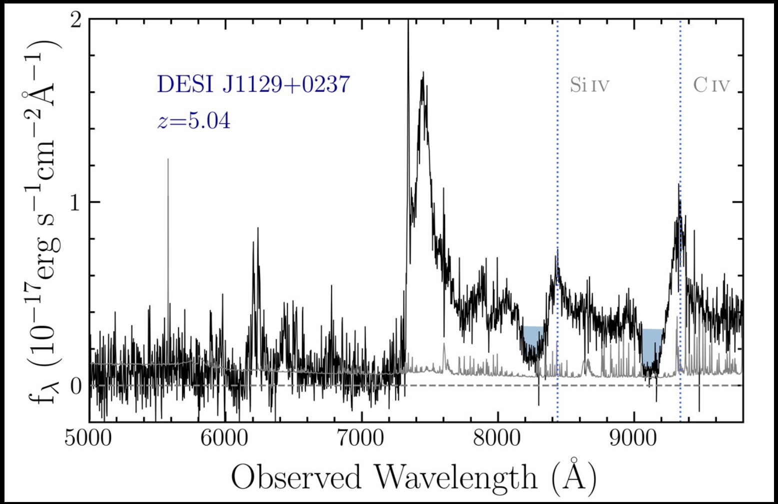
ESA/GAIA/DPAC: The multi-dimensional Milky Way



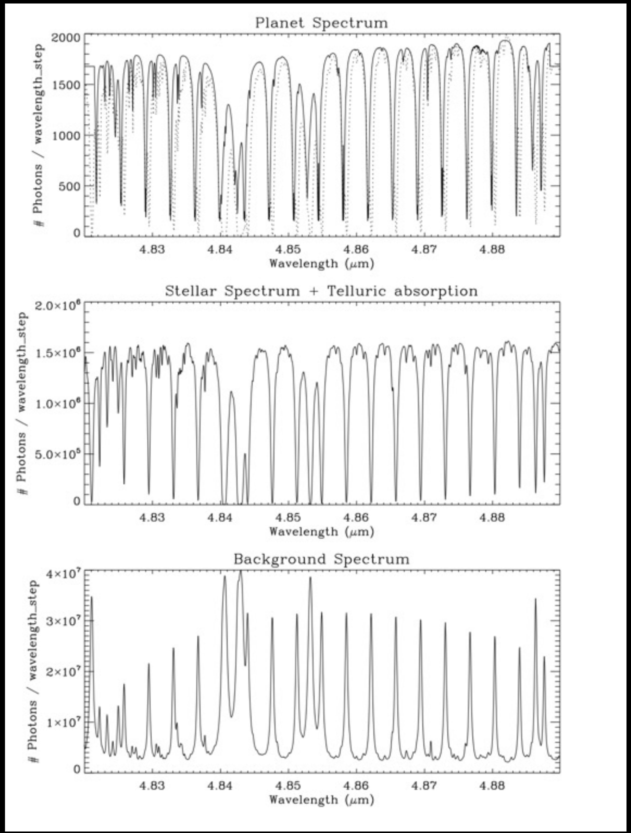
ESO/ESPRESSO Team

Single photon detection, sub-electron noise

- Habitable world searches and characterization: photon-starved or high-contrast
- Line-of-sight spectra from quasars, massive multi-object cosmological surveys (DESI)
- UV astronomy, redshifted inter-galactic emission (FIREBall-2)



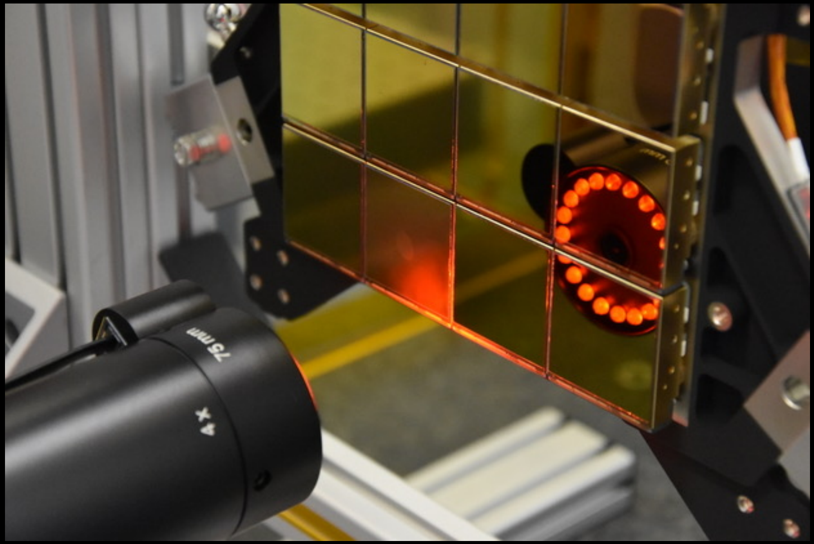
J. Yang (DESI)



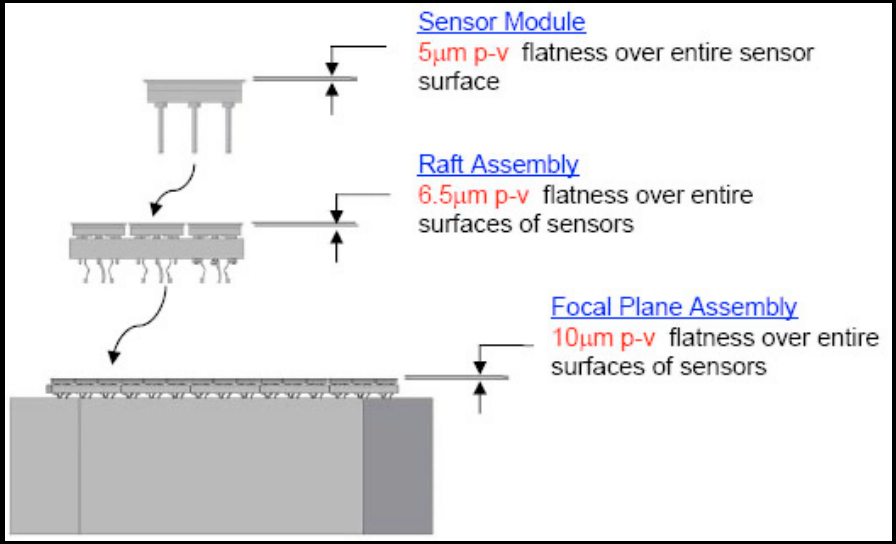
METIS simulated spectrum (Snellen et al. 2015)

A required preliminary: sensor mechanical design

- Optical quality across large focal plane arrays: strong requirements on flatness and positioning of sensors
- Sensor packaging, behavior after cooling
- Curved sensors: shape requirements, stress on photosensitive bulk



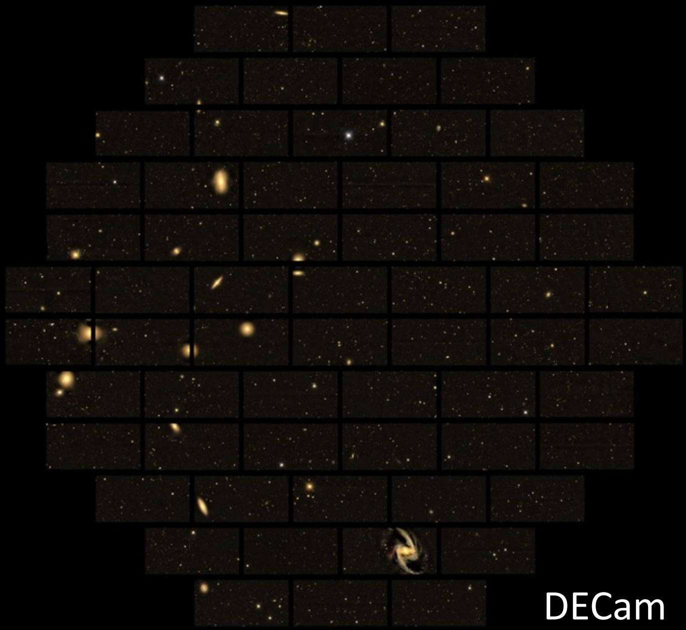
Euclid NISP (CPPM/LAM)



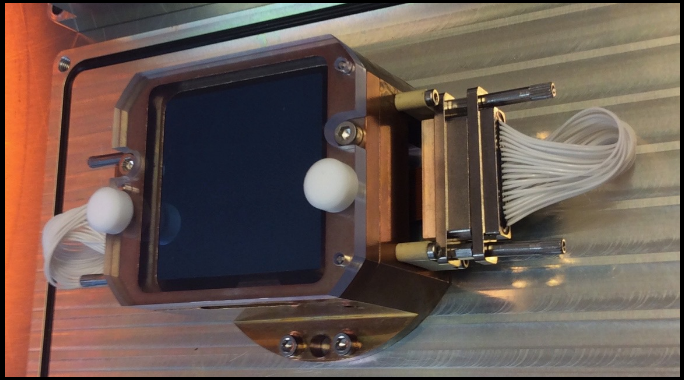
LSST

CCDs for astronomy

- Mature technology, availability of manufacturing facilities, scalable
- n-channel (Teledyne-e2v, Semiconductor Technologies Associates Inc) and p-channel (LBNL, FermiLab, Hamamatsu)
- Uniformity, inter and intra-pixel
- Linearity, up to full well ~100s ke- (depending on pixel size)
- Low dark current: ~e/pix/hour (depending on temperature)
- Radiation hardness (displacement damage from protons)



DECam

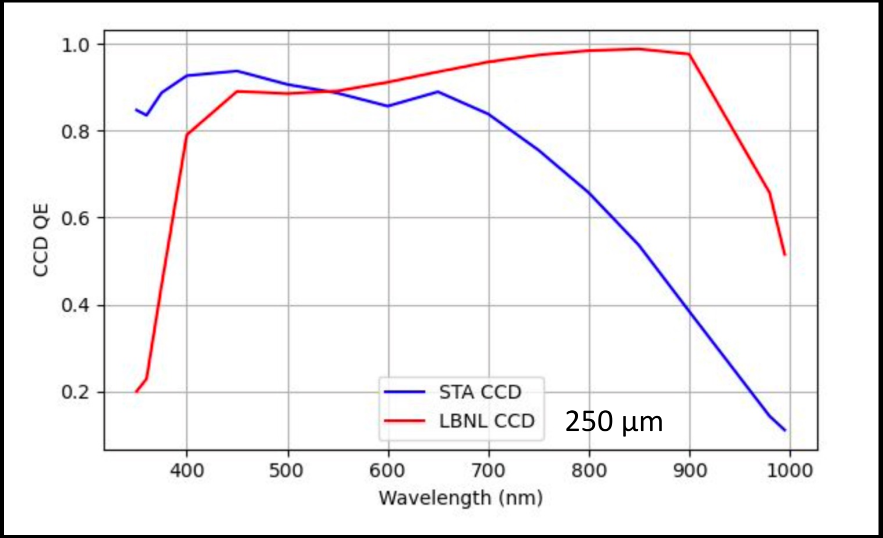


C. Juramy: T-e2v CCD250

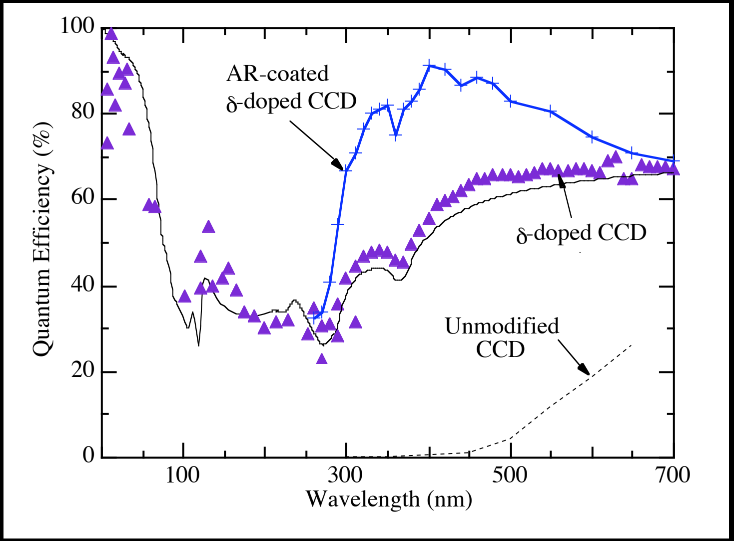
Quantum Efficiency

- Near Infra-Red: high-resistivity, thick, fully-depleted substrate
- Blue and UV: back-illumination, Anti-Reflective coating
- Improvement for UV sensors: development of 2D delta-dopped surface with Molecular Beam Epitaxy (JPL)

➢ Not exclusive to CCDs, but require dedicated design and process



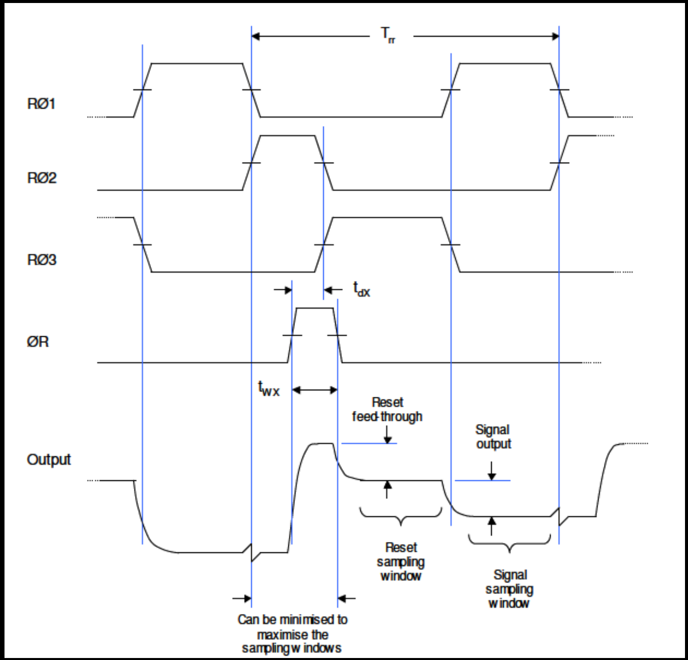
J. Guy: DESI CCDs

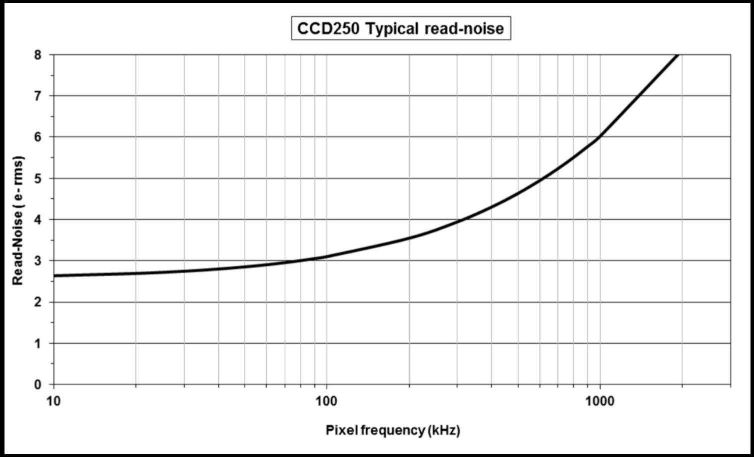


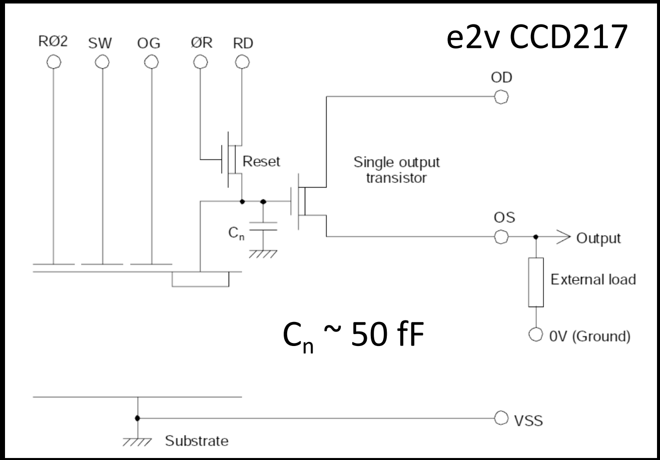
JPL, Caltech

Limitations of traditional CCDs

- Serialized readout: efficiency of the charge transfer (CTE), readout time
- Pixel reset: requires Correlated Double Sampling for kTC noise subtraction
- Noise corner of the MOSFET output transistor

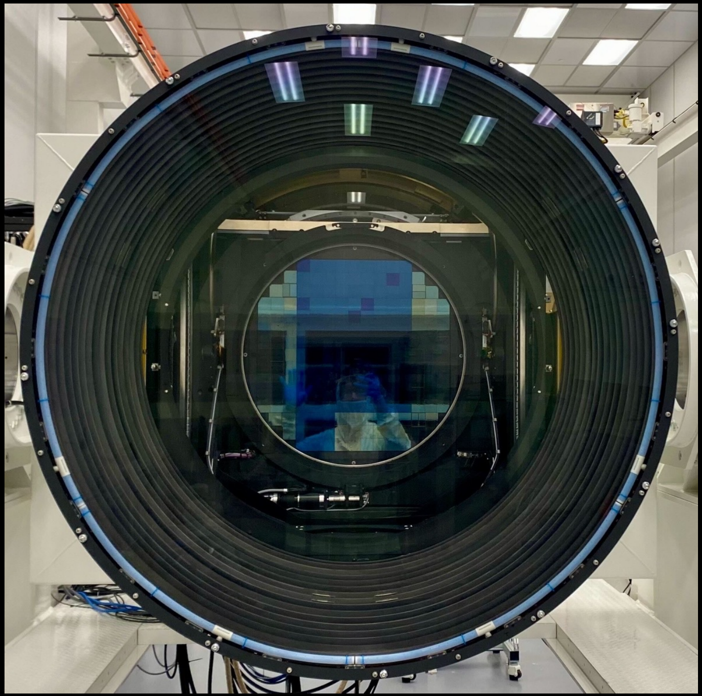


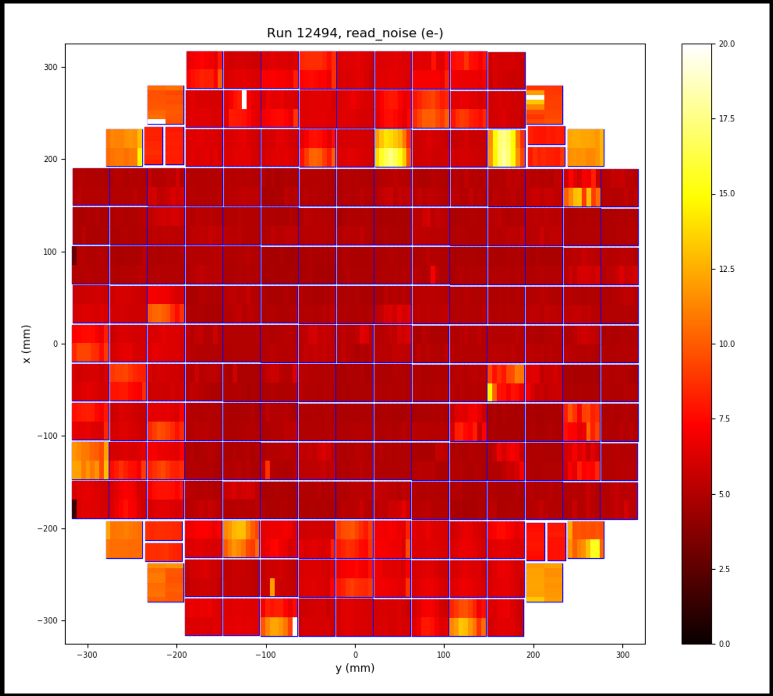




CCD focal plane: LSSTCam

- 189 science CCDs, 4k x 4k, 16 output channels
- Characterization: full suite of ‘electro-optical’ tests
- Optimization of operating parameters and readout sequence (2 s goal)

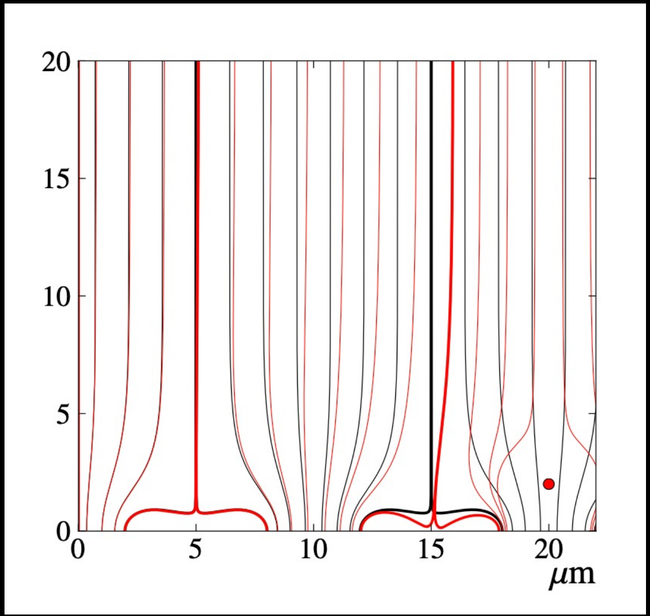




LSST

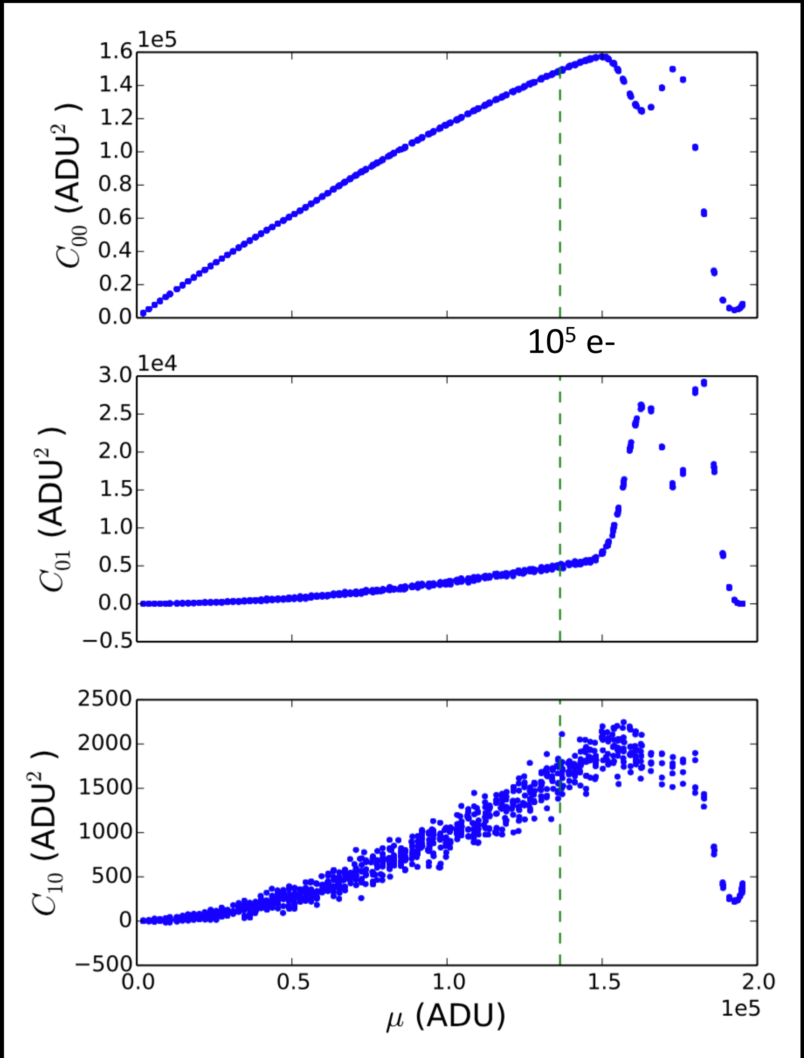
The “Brighter-Fatter” effect

- Any sensor type
- Photon Transfer Curve (variance vs flux)
- Multi-usage diagnostic tool: linearity, BF parameters, charge transfer efficiencies



A. Guyonnet

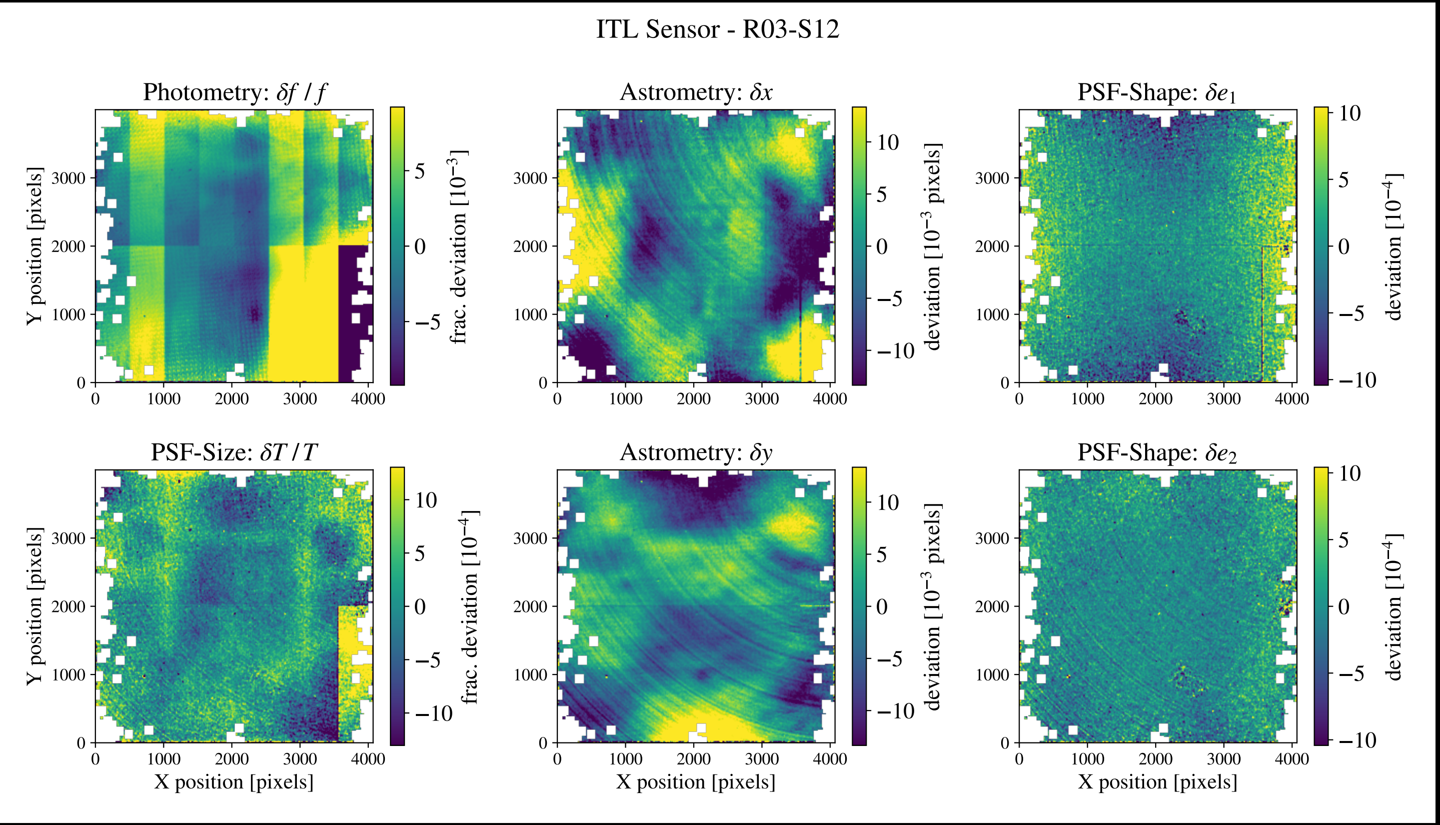
P. Doherty



P. Astier

More shape distortion sources

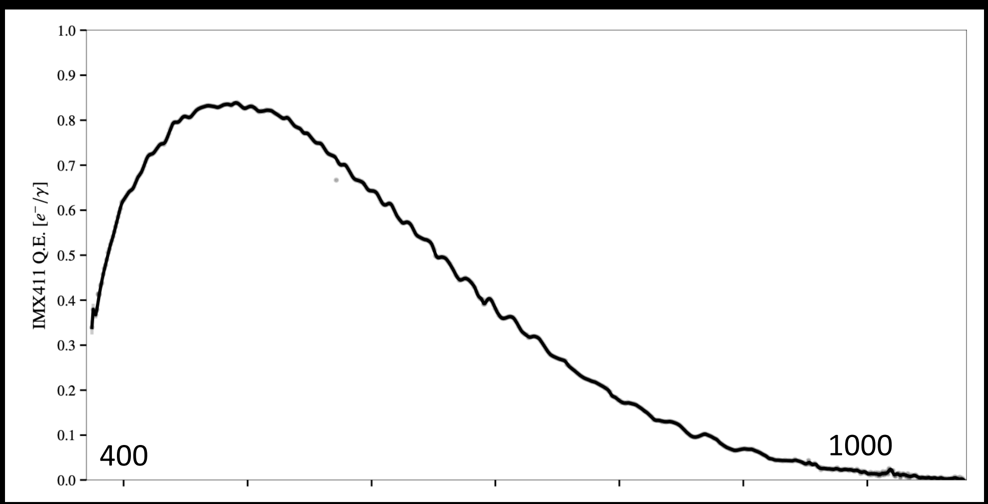
- Scanning with ‘artificial stars’
- ‘Tree rings’, segment boundaries, support structure



J. Esteves

CMOS sensors in astronomy

- "CMOS sensors" = 1 amplifier/pixel, multiplexed readout
- Use of commercial designs: readout speeds, pixel size
- Development of back-illuminated, sub-e noise (Hamamatsu ORCA-Quest), high-resistivity CMOS sensors with 10-µm pixels (Teledyne-e2v COSMOS)

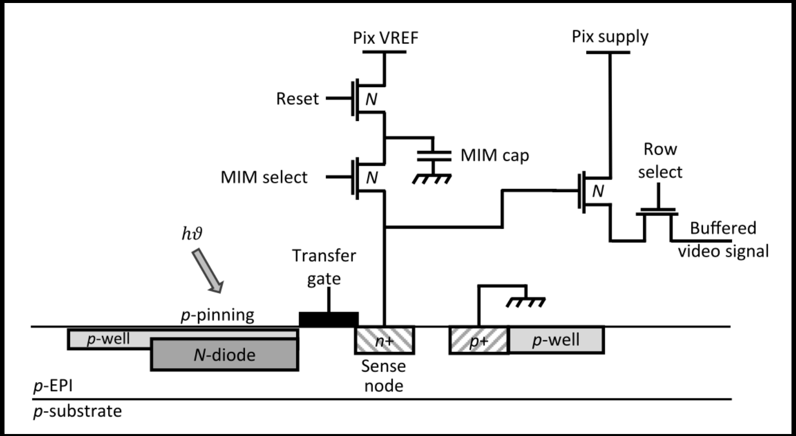


M. Betoule, Sony IMX411ALR in QHY411M (151 Mpix)

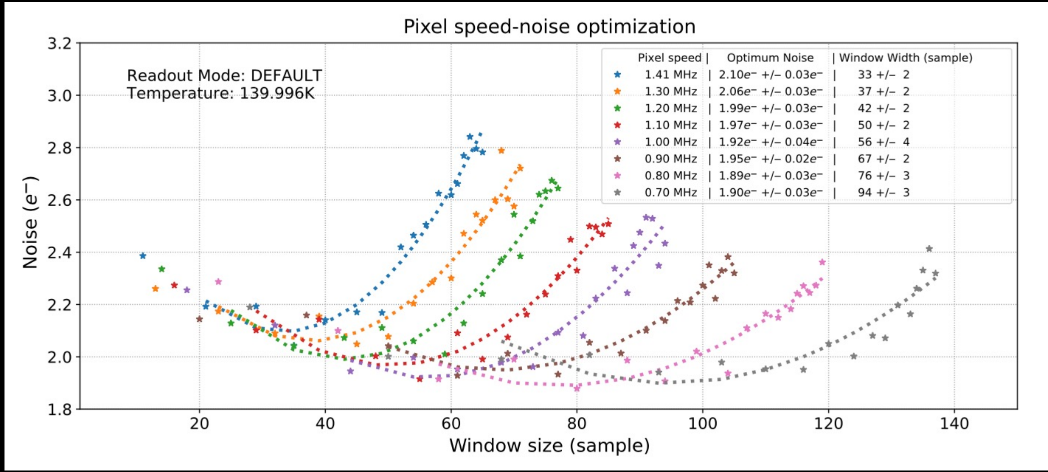
T-e2v COSMOS-66 (64Mpix)

Dedicated CMOS sensor designs

- 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



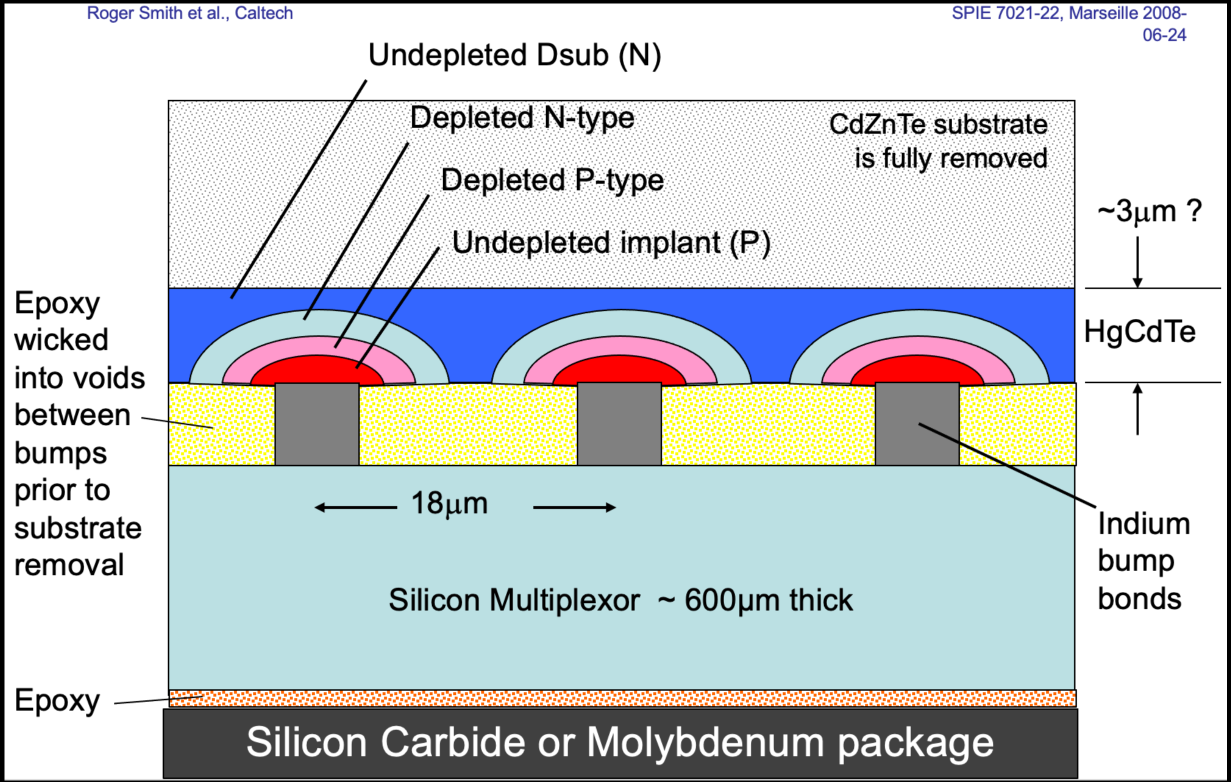
J. Janesick, 5T pixel with pinned photodiode



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

Near-Infrared Hybrid Imaging Sensors

- $Hg_{1-x}Cd_xTe$ for tunable cutoff, ~ 1.7 to 5.3 µm (Teledyne H2RG, H4RG-15, H4RG-10)
- Bump-bonded to CMOS-style readout: up-the-ramp sampling
- Process costs, yield
- InGaAs
- Germanium CCD



R. Smith

The persistent persistence

- Reported decay times up to 14h (Euclid, ESO, SPHEREx)
- Trapped charges (with varying time constants) + reduced depleted region
- History-dependent (resets): characterization, data reduction

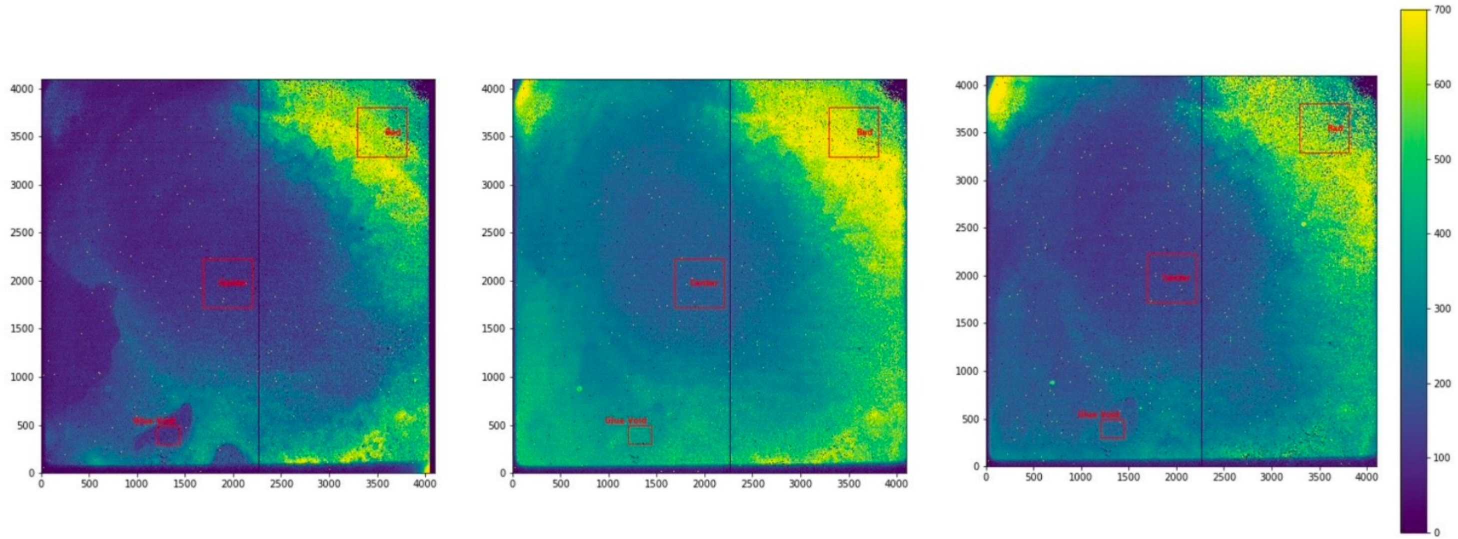


Figure 9, persistence maps (ADU) for the same detector after 830s of de-trapping for 40K (left), 65K (middle) and 80K (right).

A wider array of issues

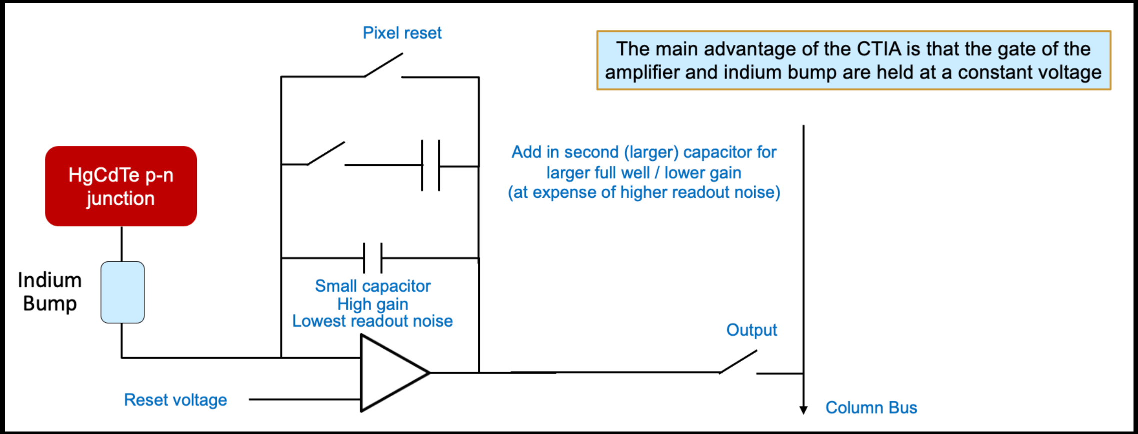
E. George, ESO

- Cosmetics, epoxy voids
- Charge diffusion
- Inter-pixel capacitance, along with brighter-fatter
- Crosshatch pattern: intra-pixel QE variation caused by stress in HgCdTe, diffraction
- Non-linearity of the source follower amplifier
- Download limitation: 1 slope/pixel, plus some references (Euclid)

➢ Already improved

More promising developments

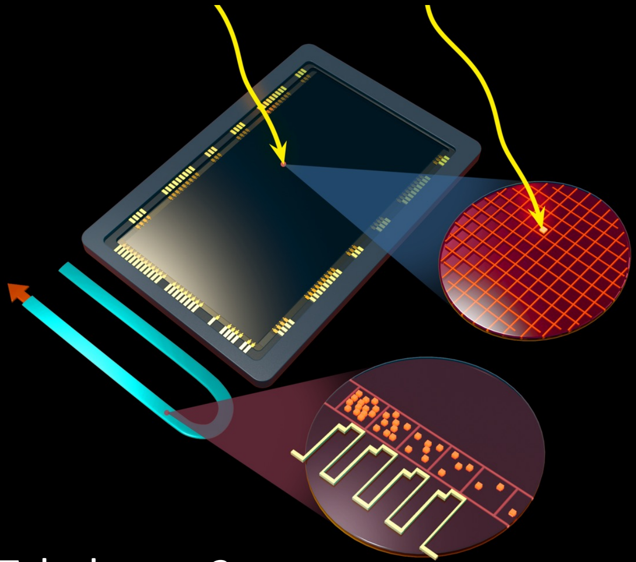
- Persistence: improved passivation process, but lower yield (Roman Space Telescope)
- In-pixel amplifiers: Capacitive Trans-Impedance Amplifiers
  - Teledyne: GeoSnap-18 for METIS@ELT
  - Fix for persistence, inter-pixel capacitance, brighter-fatter, operation in fully-depleted mode
  - Challenges from higher power (glow), readout noise



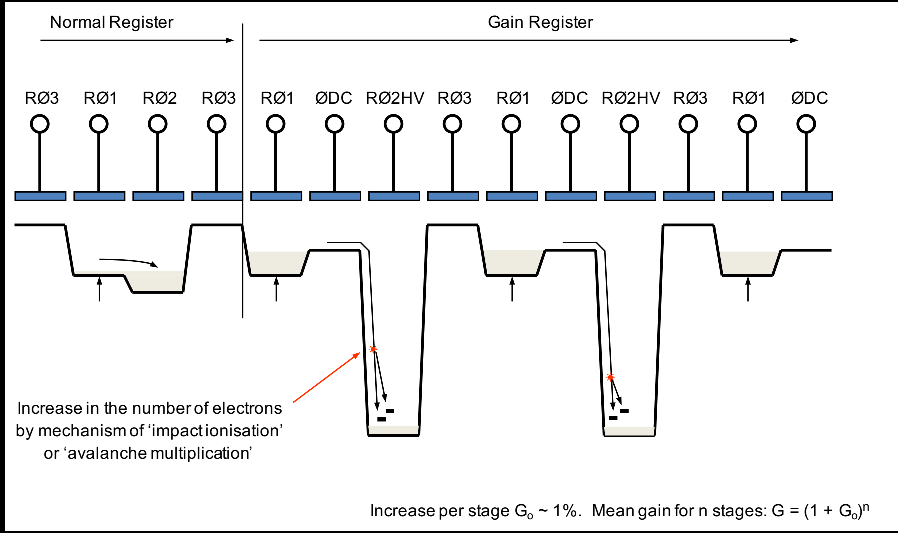
J. Beletic, Teledyne

Photon counting: Electron-Multiplying CCDs

- EMCCD: suppress read noise, also amplify dark current and clock-induced charges
- T-e2v CCD311: reduce cosmic rays overspill through use of dump gate to remove high signals, selected for Roman Coronagraph Instrument
- Also in development: avalanche photodiode arrays (Si or HgCdTe)

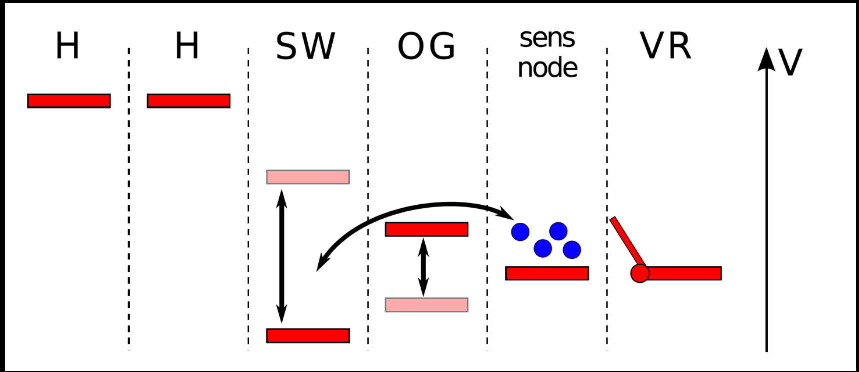


Teledyne-e2v

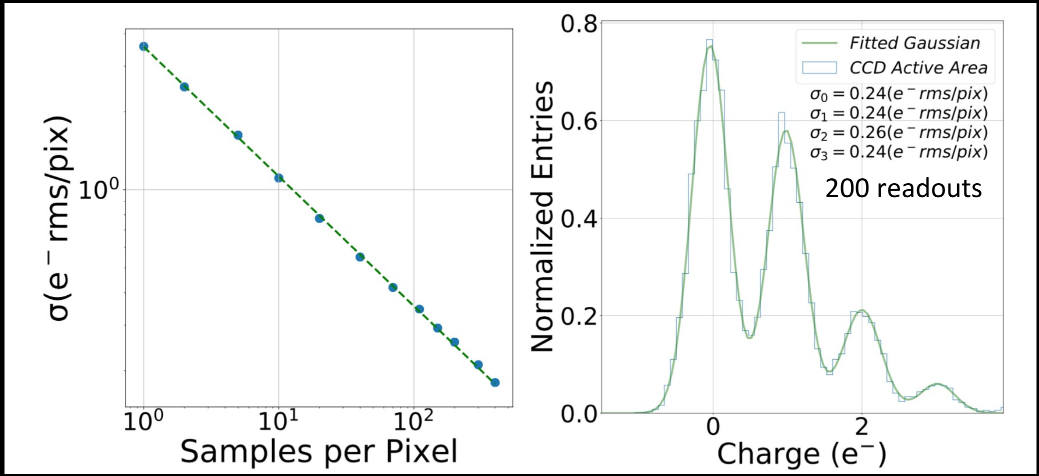


Below 1 electron noise : skipper CCDs

- 'Skipper': pixel charge moved back and forth to readout node (floating gate output stage)
- N readouts of the same charge: statistic reduction of noise in √N
- Bonus: gain measurement
- Dark Matter experiments, first test on sky
- Readout time:
  - Frame-transfer: readout during exposure
  - Use of skipper readout only in regions of interest



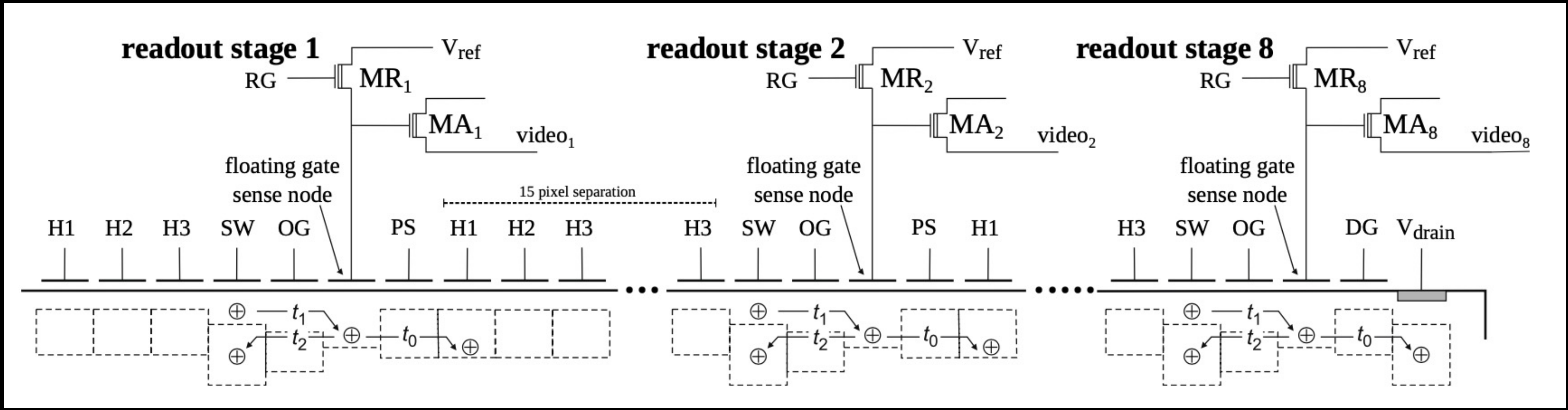
J. Tiffenberg (2017)



A. Drlica-Wagner (2020)

Multi-Amplifier Sensing (MAS) CCDs

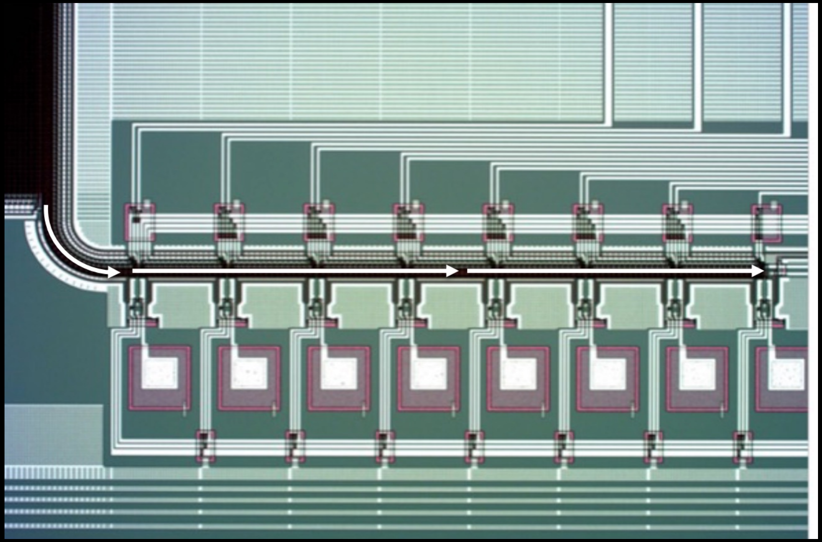
- Repeated readout of the same charge in sequential amplifiers
- Average (or weighted average) on 8 /16 / 32 channels
- Correlated noise suppression: read the same value at different times
- Can be combined with skipper mode
- Readout system



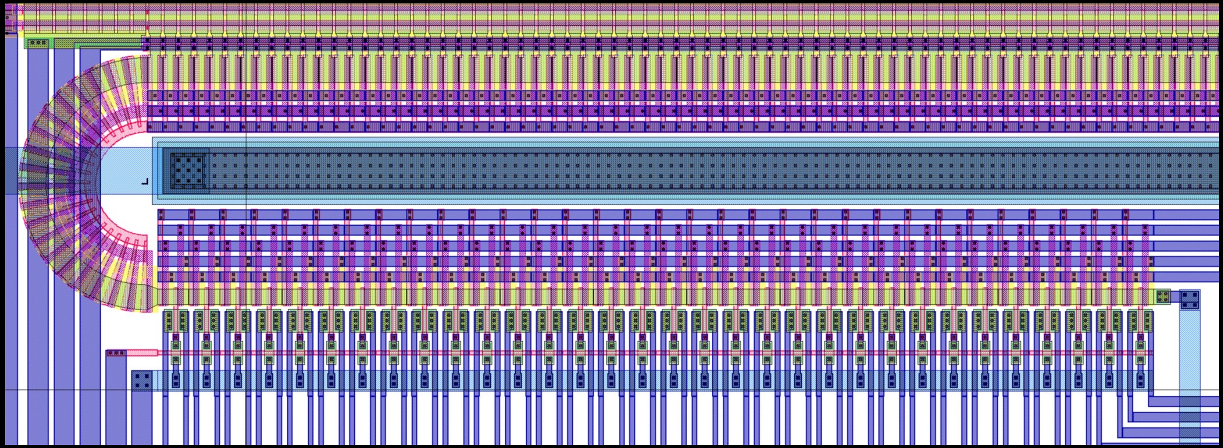
G. Fernandez Moroni, FermiLab

MAS CCDs prototype implementations

- FermiLab / Lawrence Berkeley National Laboratory prototypes
- STA5500 from STA, Inc:
  - 180˚ turn-around
  - 4x32 differential outputs



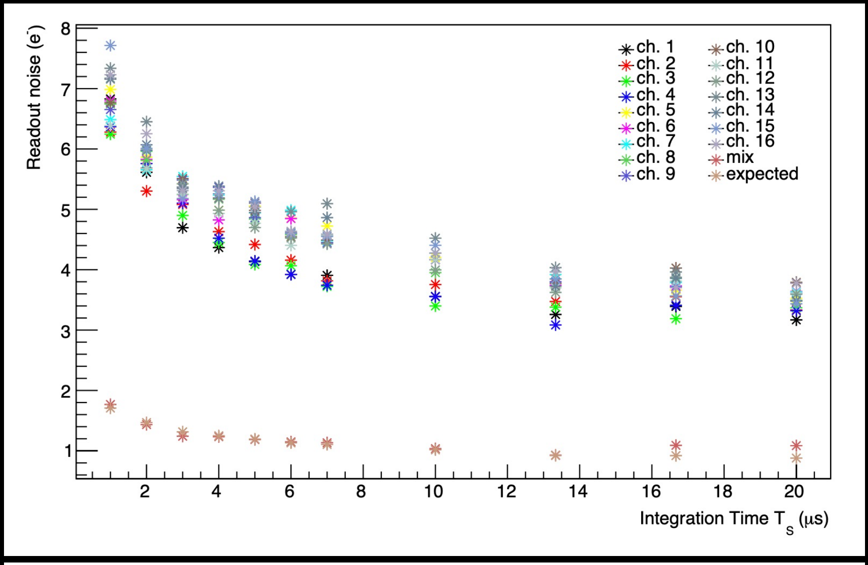
FermiLab

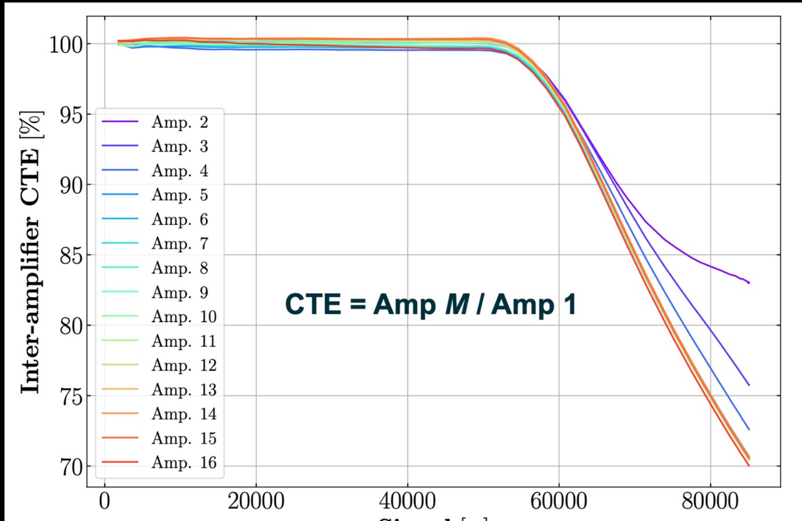


STA5500

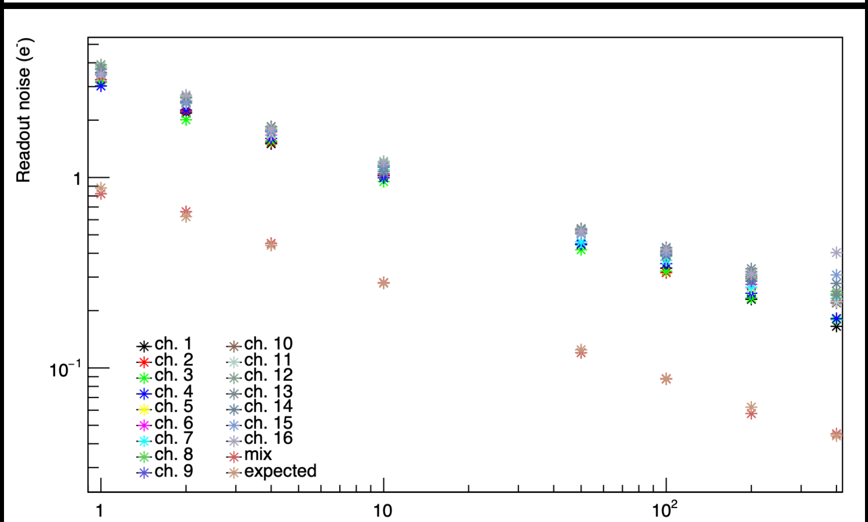
MAS CCD performances

- Demonstrated noise reduction
- Clock-induced charges, transfer efficiency at high flux
- Clock voltages: trade-off between noise and full well





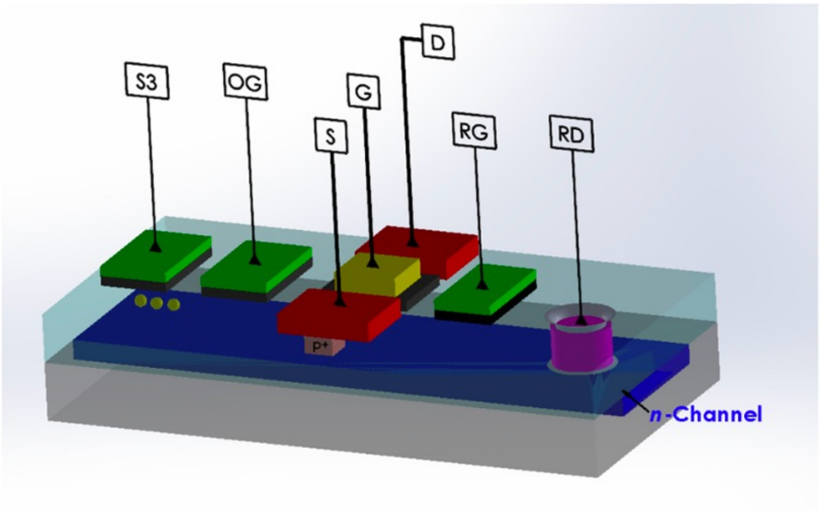
K.Lin

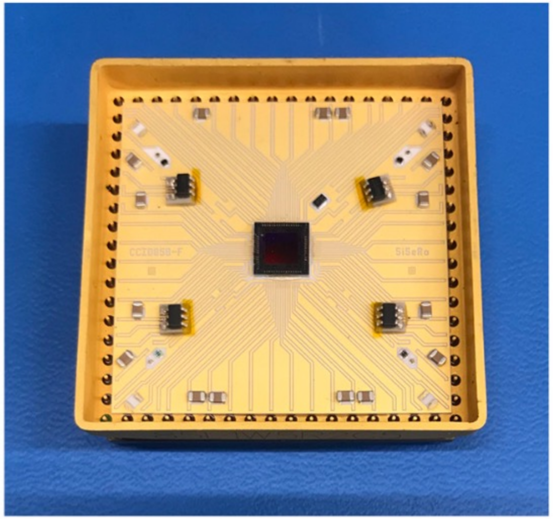


G. Fernandez Moroni

SiSeRO CCDs

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

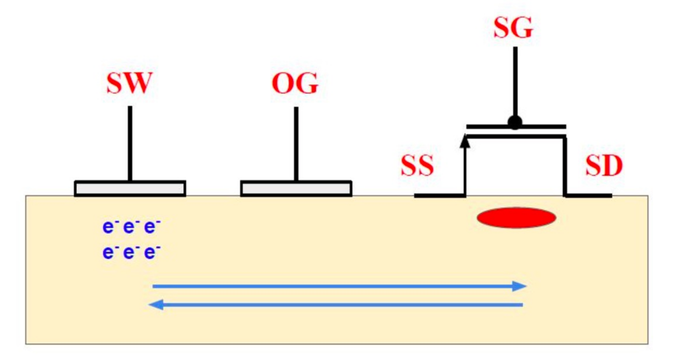


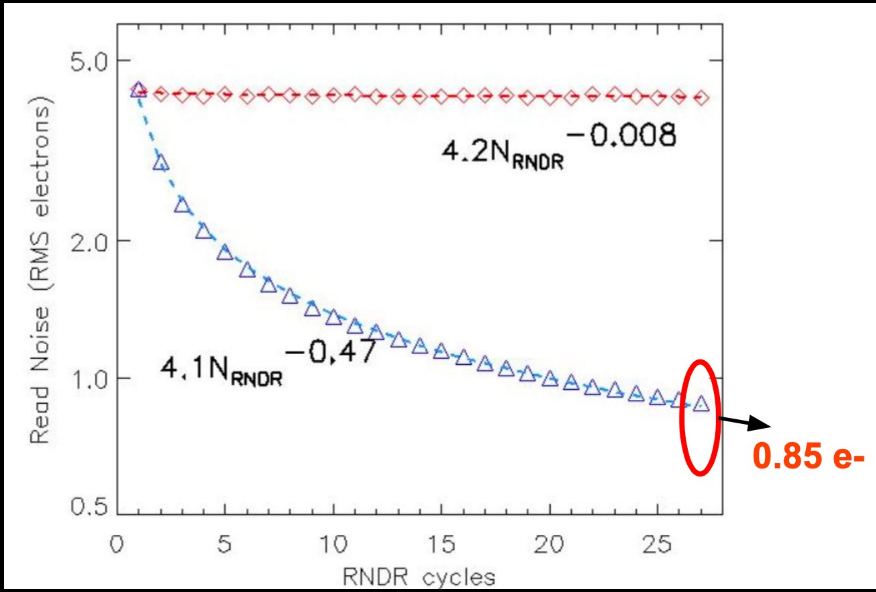


MIT Lincoln Lab CCID85F prototype

SiSeRO CCD Implementations

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



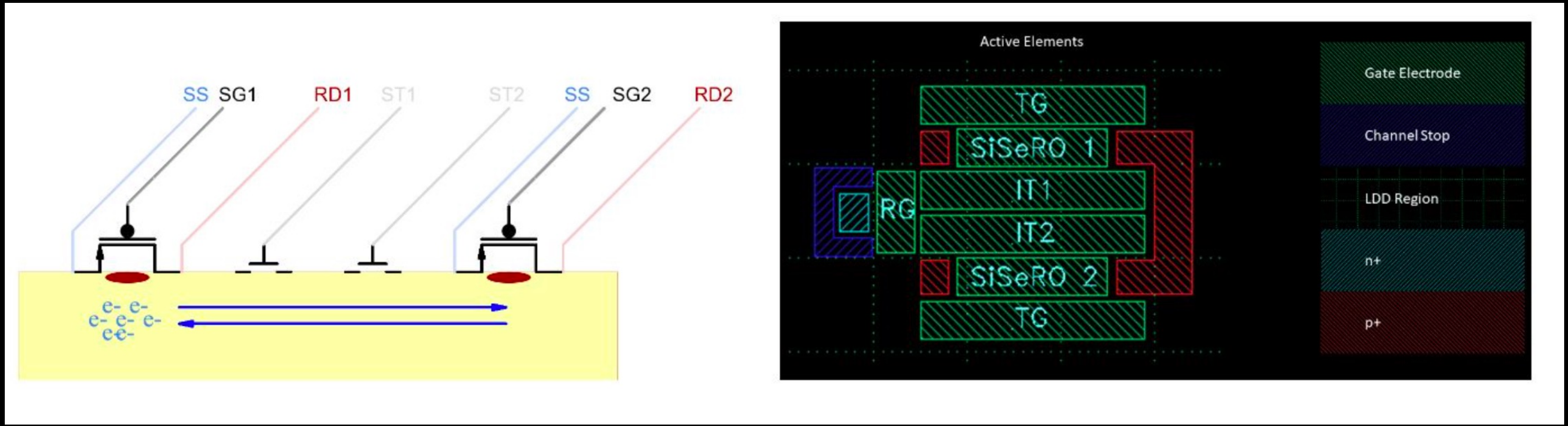


T. Chattopadhyay

More innovations on the way

Other sensors benefitting from CCD R&D:

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

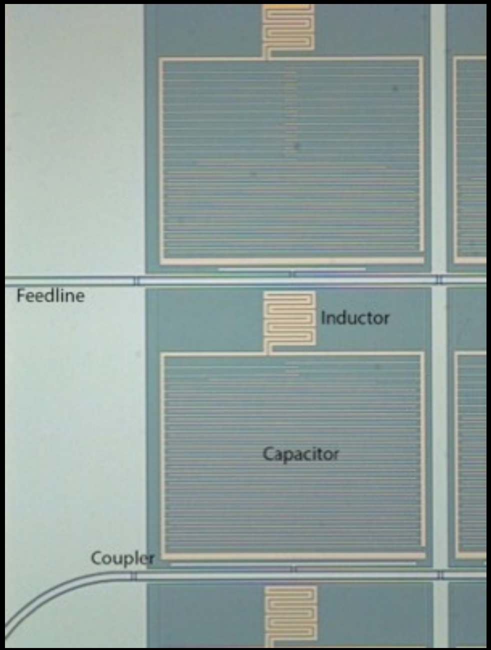


T. Chattopadhyay

But that's not all…

Other technologies are climbing up the technological readiness levels:

- Micro-Channel Plates
- Silicon-On-Insulator
- Transition Edge Sensors
- Microwave Kinetic Inductance Detector
- Superconductive Nanowire Single Photon Detector
- Quanta Image Sensor



B. Mazin: MKID pixel

Some takeaways

- Achieving the goals of UVOIR current and future projects requires detailed characterization and understanding of sensors
- Innovations on all fronts for CCDs: sub-e noise, readout speed, output amplifier
- CMOS sensors: use of commercial designs vs. optimization for astronomical requirements
- Convergent evolution of CCDs and CMOS sensors
- Non-Si sensors still present extra challenges (and costs)