Imaging sensors for space applications

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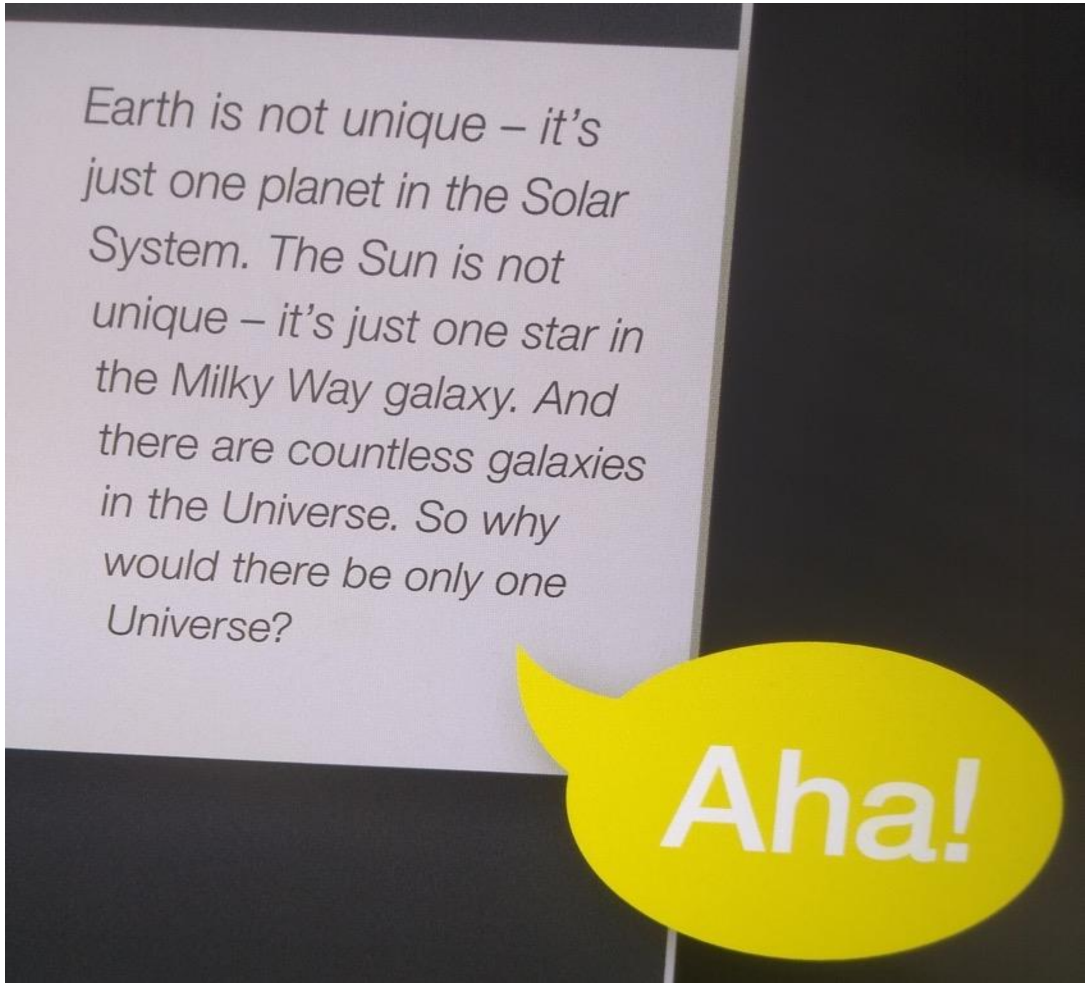
The multiverse of detectors



Outline

Covered topics:

- Basic concepts behind the operation of (imaging) sensors
- Detector technologies
- *Characterising and simulating detectors*

Not covered (in details):

- *Solid-state/semiconductor physics*
- *Basic principle of a photo-diode/p-n junction*
- *Dark current mechanisms and mitigations*
- *Sense node circuits*
- *(non-destructive) readout modes*
- *Detector specifications*
- *Detector technology for particle physics*
- *Detector manufacturing*
- *Detector packaging*
- *Detector readout electronics*
- *Radiation effects on detectors*
- *SNR computation*
- *….*

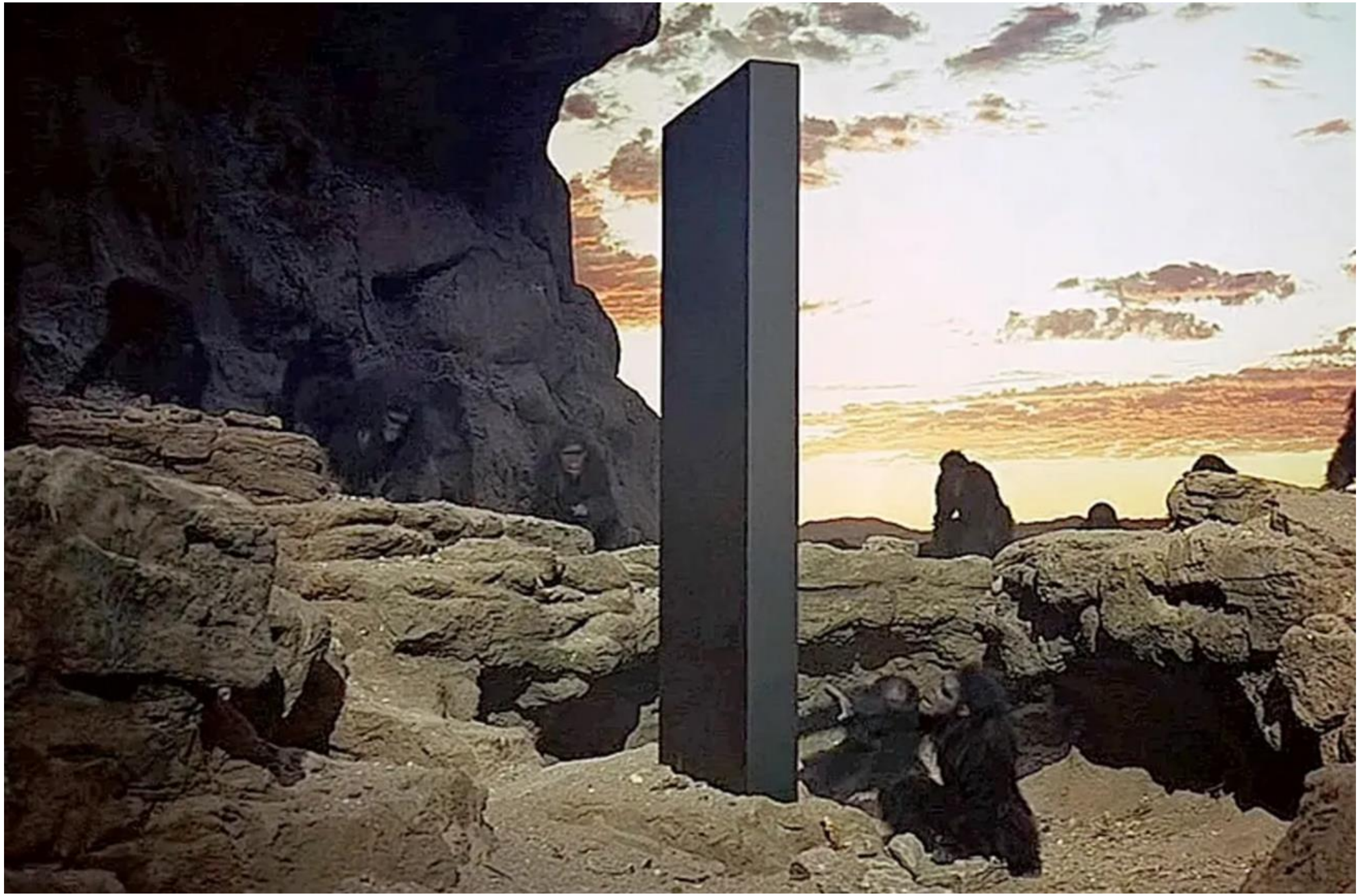
What is a detector?

detector = sensor

Oxford English dictionary "**3.** An instrument or device for detecting the presence of anything liable to escape observation, for indicating any deviation from normal conditions, or the like." "**g.** Any of various devices or circuits designed to carry out detection"

My own def.: "Opto-electronics component or device which convert light or charged particle signal into an electric and/or digital signal."

How does a detector/sensor look like?

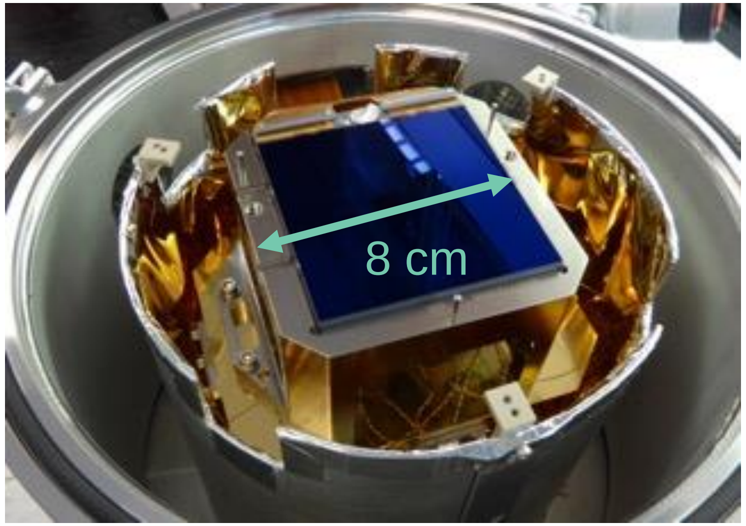


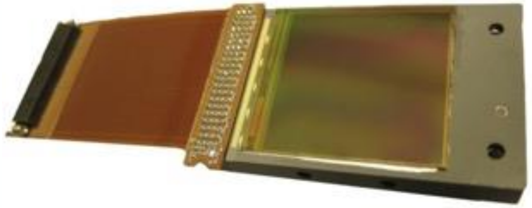
How does a detector/sensor look like?

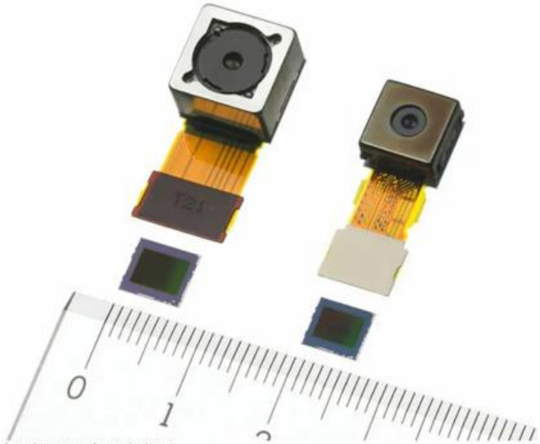
A2.1. Functional and Performance Requirements

	Parameter	Value	Units	Comments	Verification
Dimensions					
REQ-1	Number of pixels	≥ 2k x 2k	pixels	Larger arrays can be proposed.	Design
REQ-1a	Number of pixels	≥ 256 x 256		For visible wavelength demonstrator only.	Design
REQ-2	Pixel size	10 ≤ x ≤ 20	µm	Square pixel	Design
REQ-3	Fill-factor	>90	%	Active collection area	Design
REQ-4	No. outputs	16		Readout through 1, 4, 8 or 16 outputs shall be possible.	Design/test
Operation					
REQ-5	Read-out mode	Global Shutter			Design/test
REQ-6	Frame rate	≥ 1	Hz	Minimum frame rate for full frame readout through 16 outputs.	Design/test
REQ-7	Integration time	Min: 10 Max: no limit	µs s	Tint should be externally controlled.	Design/test
REQ-8	Windowing	Required		Multiple window readout – selectable window sizes – minimum is one window 1k x 1k.	Design/test
REQ-9	APD gain	1 – 1000		Gain stability vs bias voltage and operating temperature shall be characterised.	Design/Test
Electro-optical Performance					
REQ-10	Cut-on wavelength	≤ 0.8 ≤ 0.4	µm µm	With visible demo. Without visible demo. At 50% QE max.	Test
REQ-11	Cut-off wavelength	≥ 2.5	µm	For absorber region, at 50% QE max.	Test
REQ-12	QE x Fill Factor	> 70	%	With appropriate AR coating, between 0.85 and 2.45 um.	Test
REQ-13	Cross-talk	<4	%	Summed total from all neighbouring pixels, at	Test

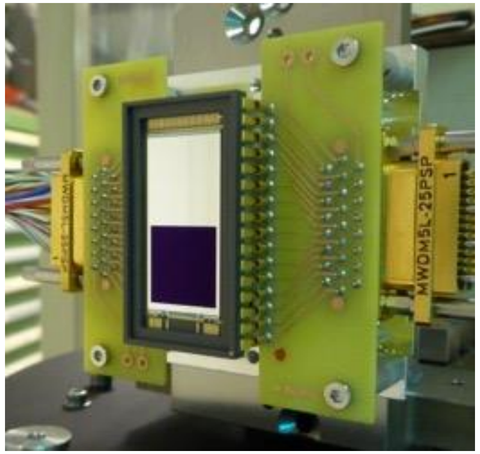
How does a detector/sensor look like?

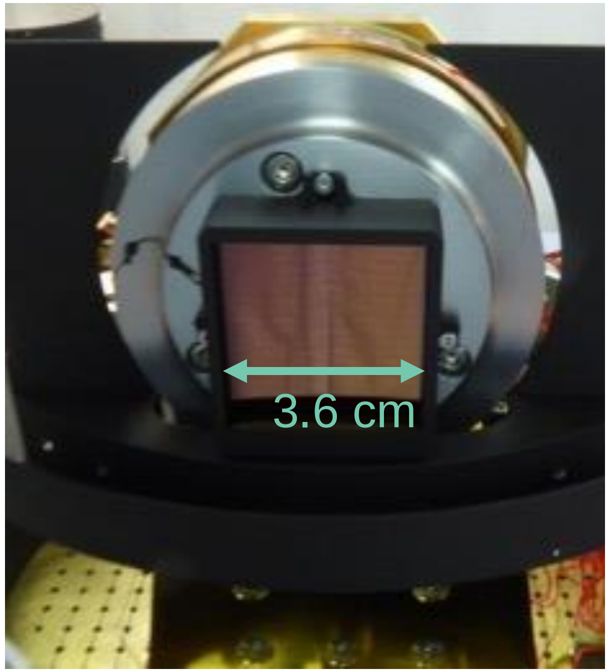




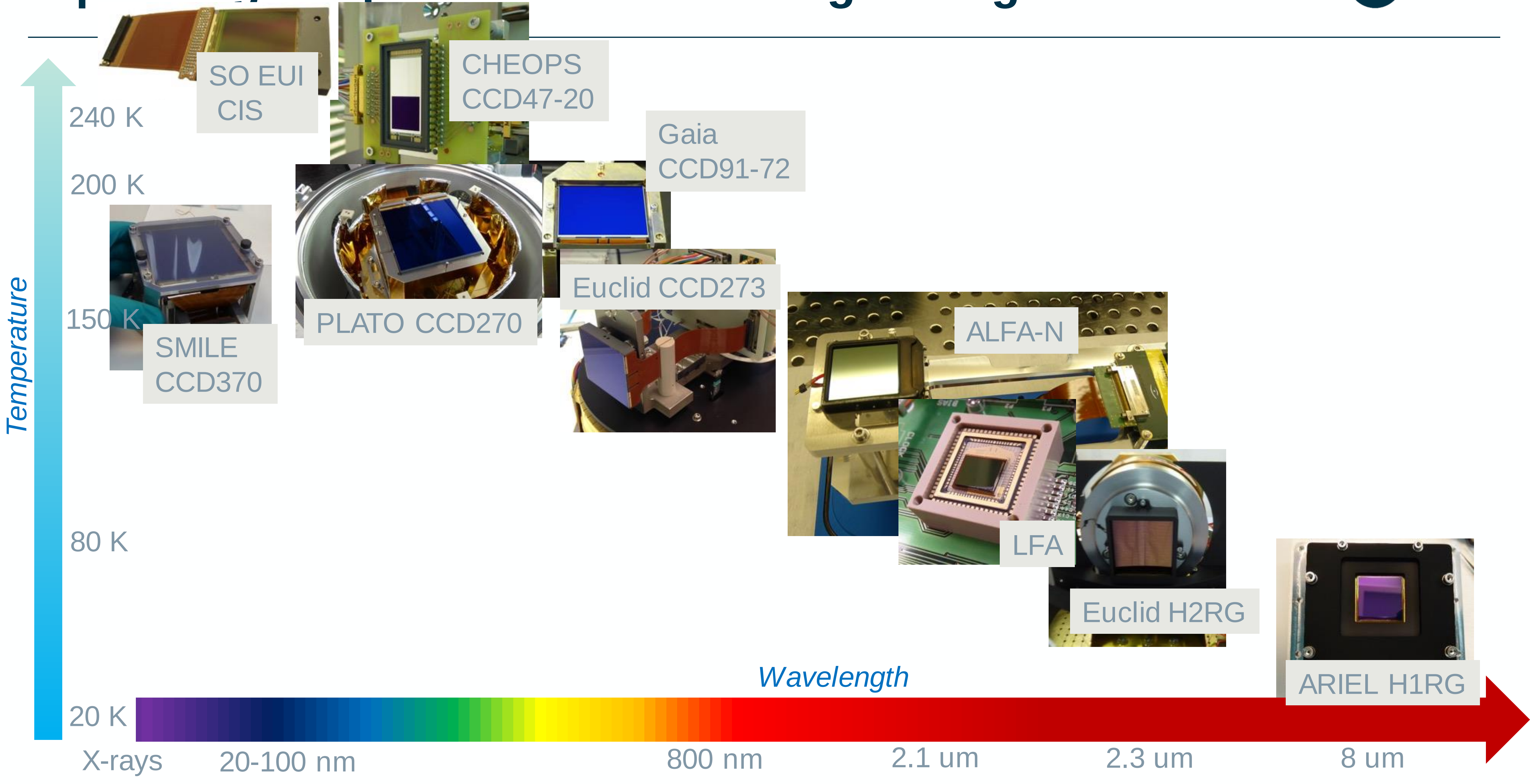


Smartphone sensors. Source: gigazine.net

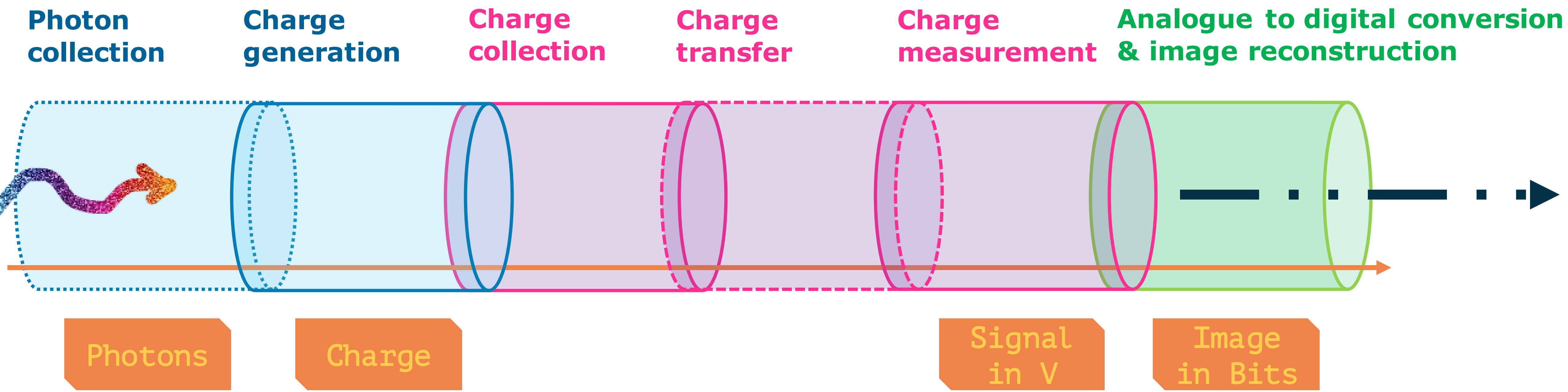




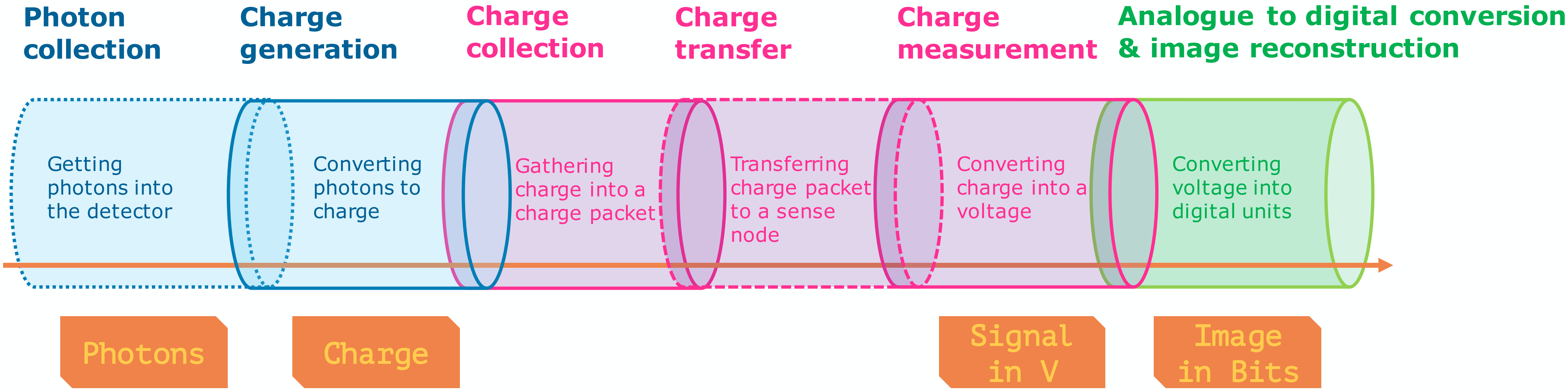
Operating temperature vs. wavelength range



5+ basic functions of a detector

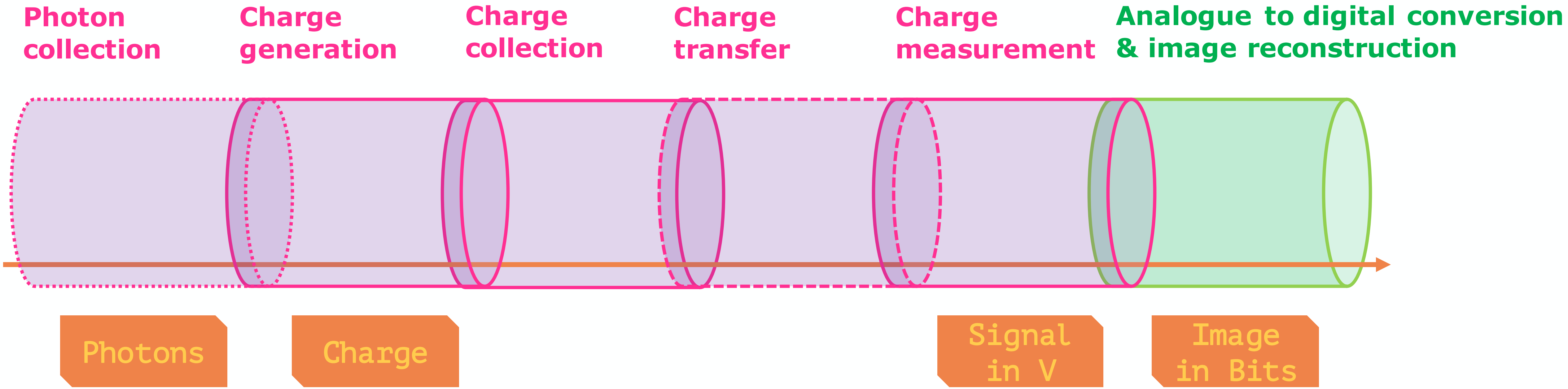


5+ basic functions of a detector



Detector technologies: monolithic sensors

- *All functions are performed in a single layer/block/component:*



\- Almost limited to Si (also Ge is possible)
\+ Easier to manufacture, well suited for visible wavelength range/UV/X-ray
Examples: APS (Active Pixel Sensor)/CMOS image sensors, and CCDs (Charge-Coupled Device)

CCD vs CMOS general operation

Image Sensor Architectures for Digital Cinematography

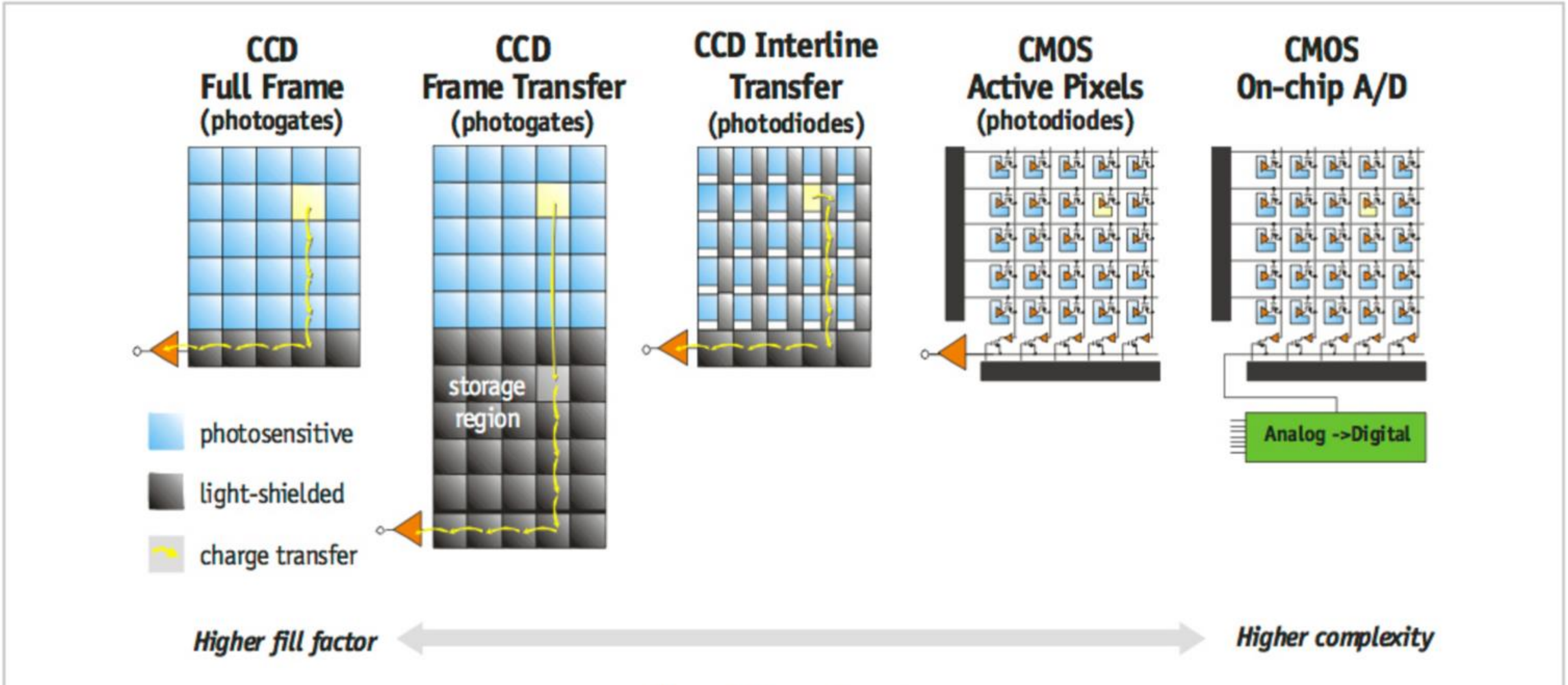
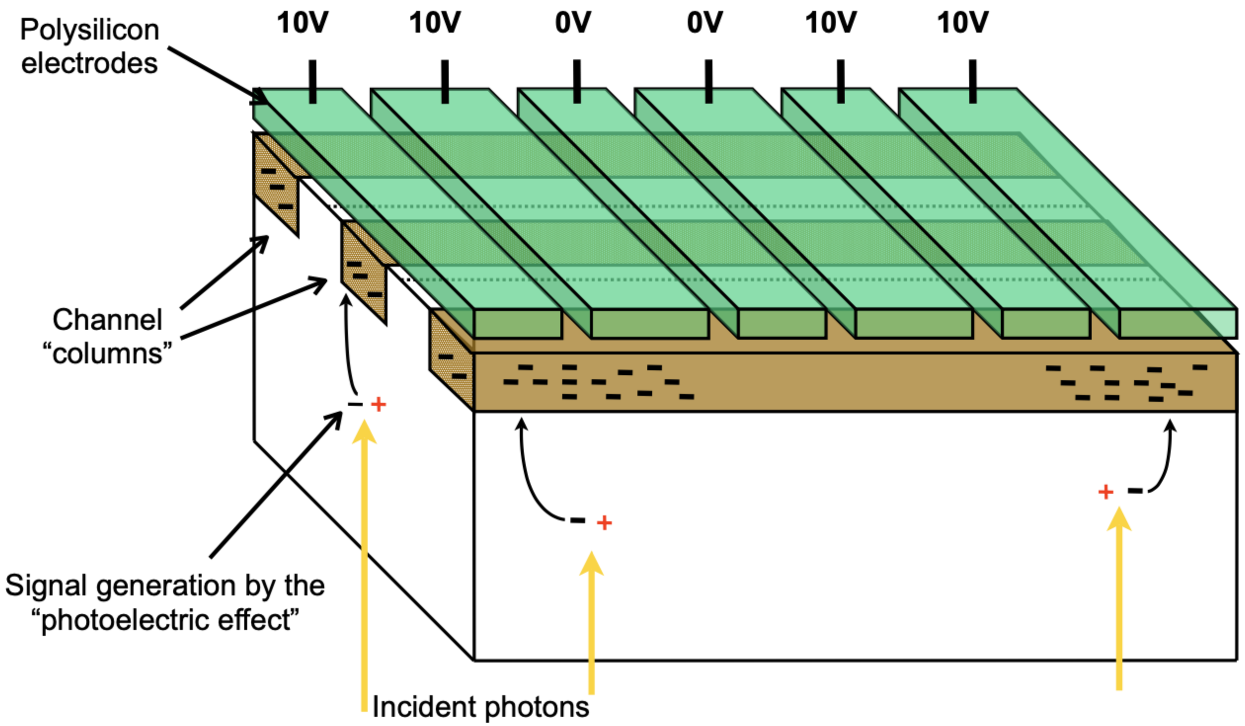
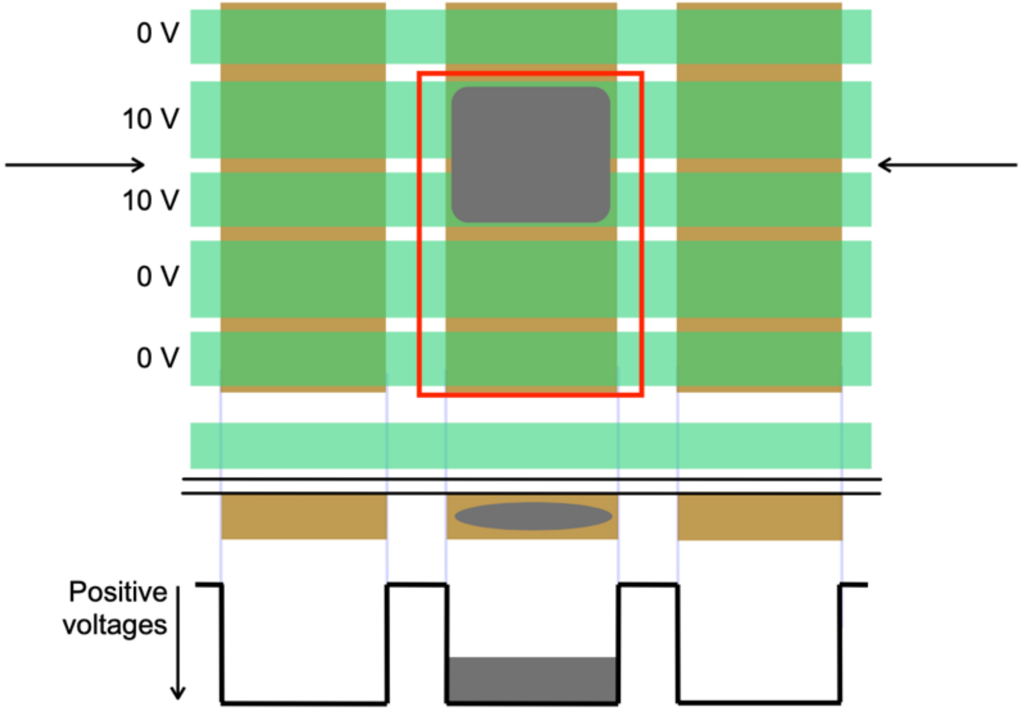


Figure 5. Imager Layouts

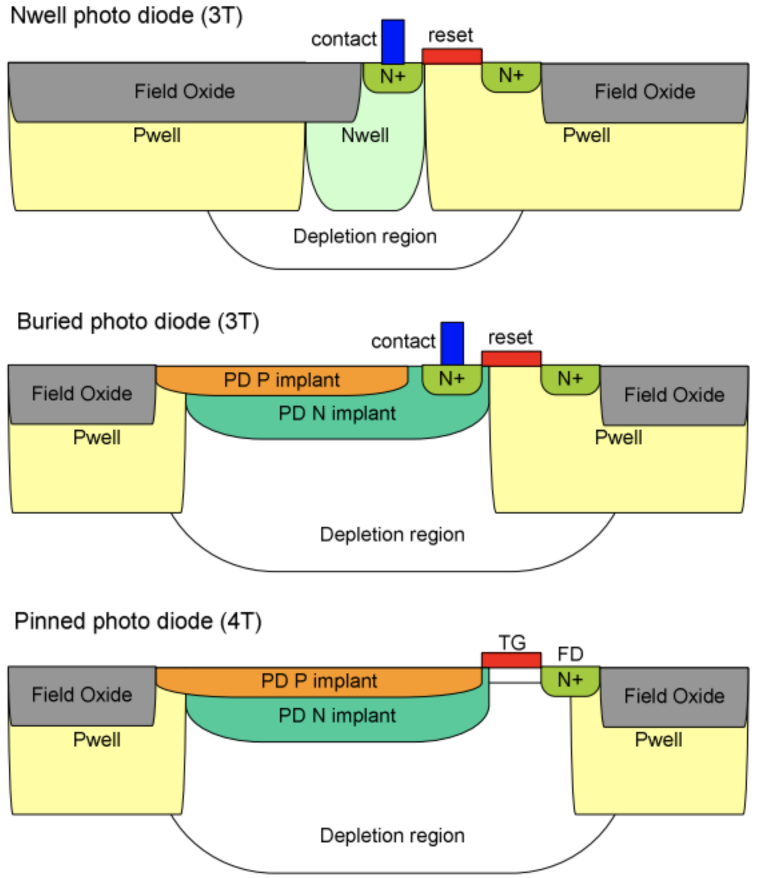
Image courtesy of: https://johnbrawley.wordpress.com/2012/09/17/aaton-delta-penelope/fill-factor/

In CCDs pixel do not (really) exist!

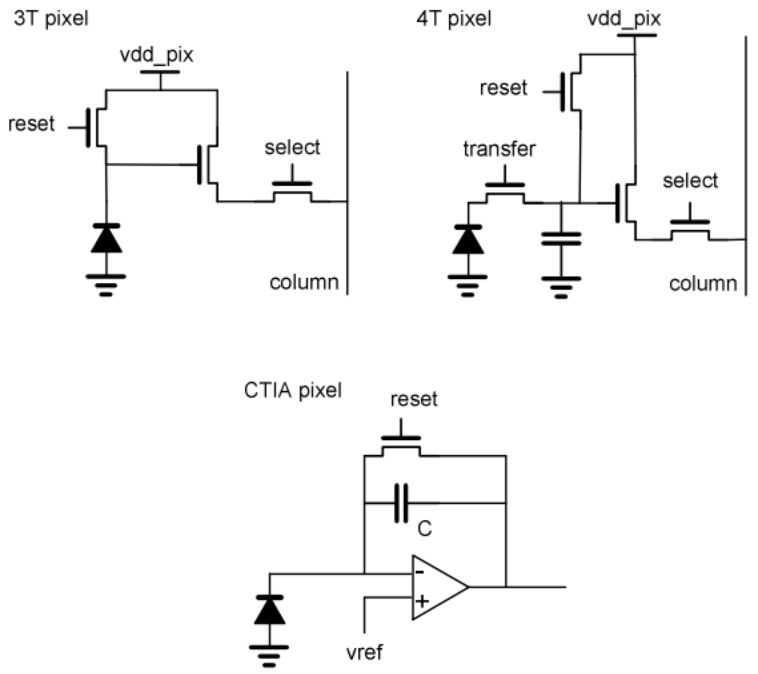




Example of CMOS pixel architecture



Source follower



Different pixel circuits have different CHC, noise, linearity etc.

CCDs vs. CMOS image sensors: pros & cons

CCD pros:

- Simpler pixel architecture, single sense node per channel => higher EO performance in general: (e.g., QE, read noise, FWC => dynamic range etc.)
- Unique Charge-Domain Time-delayed integration capability

CCD cons:

- More sensitive to radiation (CTI)
- More power hungry
- Obsolescence (old technology)
- Very few manufacturers
- Few applications outside space/science

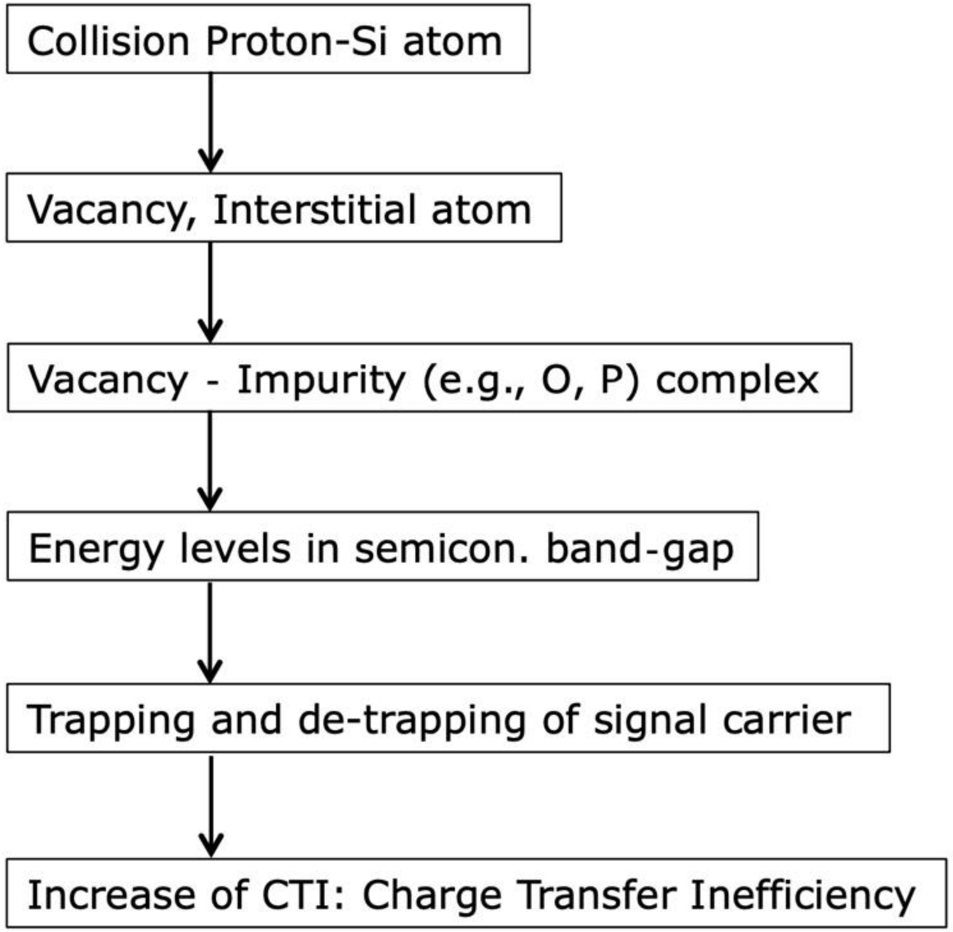
CMOS pros:

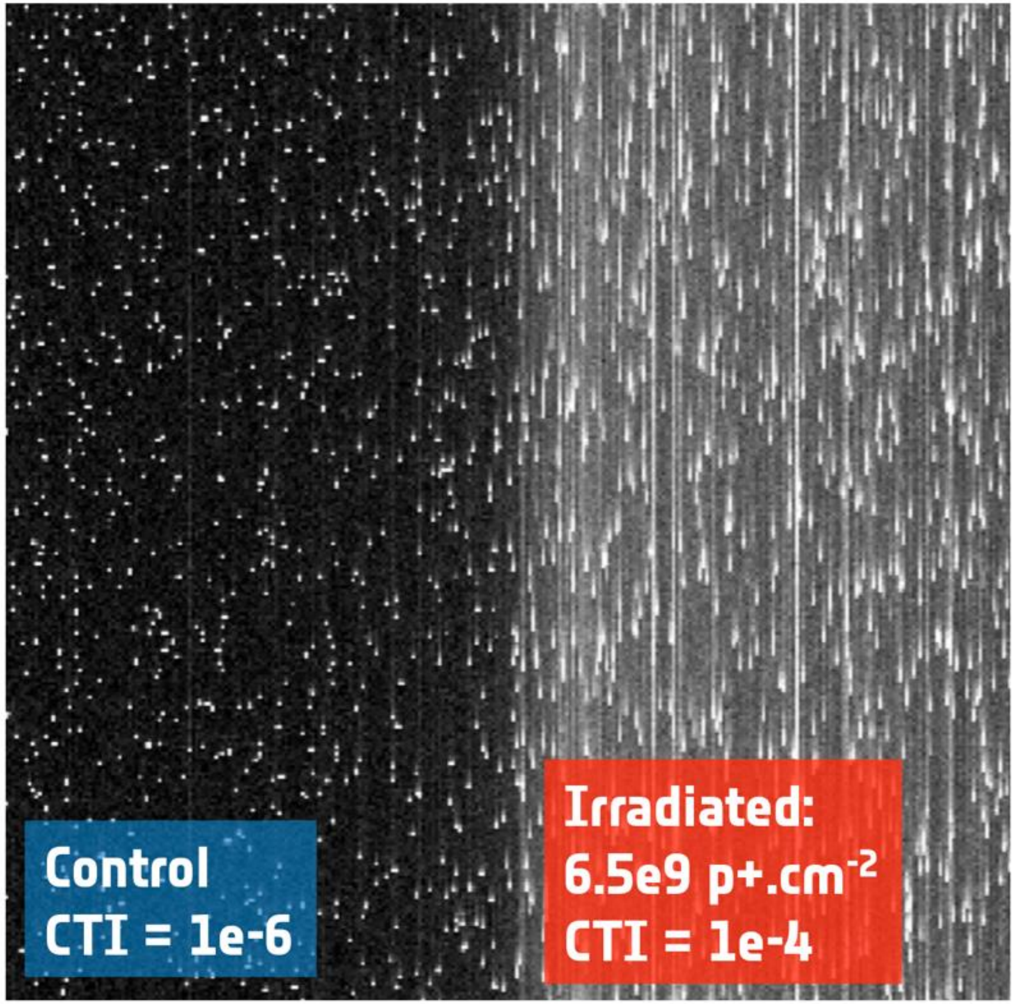
- Lower power dissipation
- Faster readout speeds (higher temperature of operation)
- Programmable readout => more flexible
- Less sensitive to radiation
- Lower cost (not entirely true for space applications)
- Big market

CMOS cons:

- Pixel circuitry more complex => more noise sources
- Poorer EO performance than CCDs in general

Radiation-induced CTI

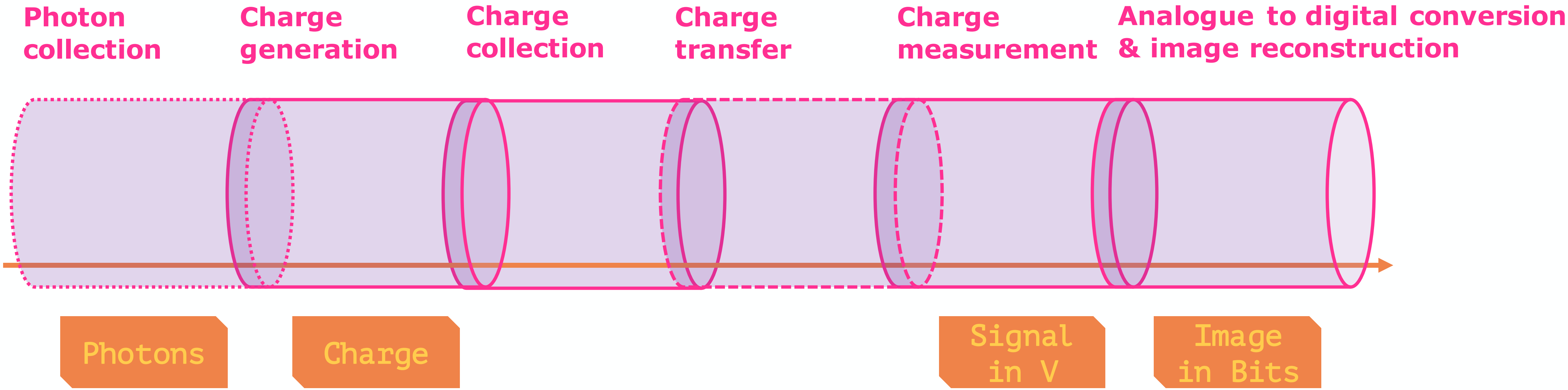




PLATO e2v CCD270 :
image acquired while illuminated by Fe55 X-ray source

Detector technologies: monolithic sensors digital on-chip

- *All functions are performed in a single layer/block/component including A2D conversion*



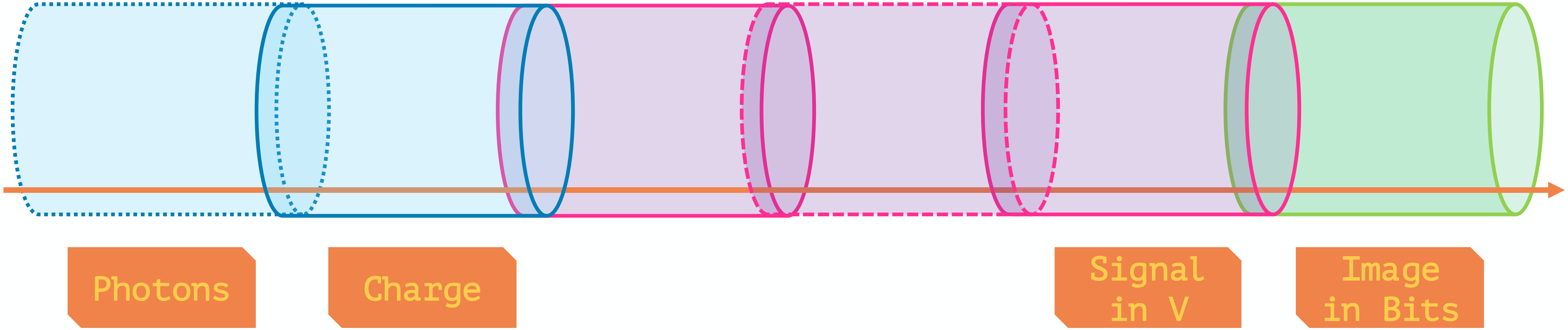
May also include on-chip generation of bias and clocks
Exclusively CMOS image sensors
Note: New ROIC generation can have digital functions

Detector technologies: hybrid sensors (for Vis-IR λ)

2 different "layers":

- *Photosensitive layer takes care of photon collection and conversion to charge*
- *Readout integrated circuit (ROIC) takes care of the following steps*

Photon collection | **Charge generation** | **Charge collection** | **Charge transfer** | **Charge measurement** | **Analogue to digital conversion & image reconstruction**



- More complex to manufacture (e.g. hybridization step)
+ Photosensitive layer can be optimized to wavelength range of interest by choice of material: MCT (HgCdTe), InGaAs, InSb, Si, superlattice arrangements etc.
Well suited for NIR to long-wave infrared sensors but also hard X-ray to Gamma-ray

Detector technologies: hybrid sensors

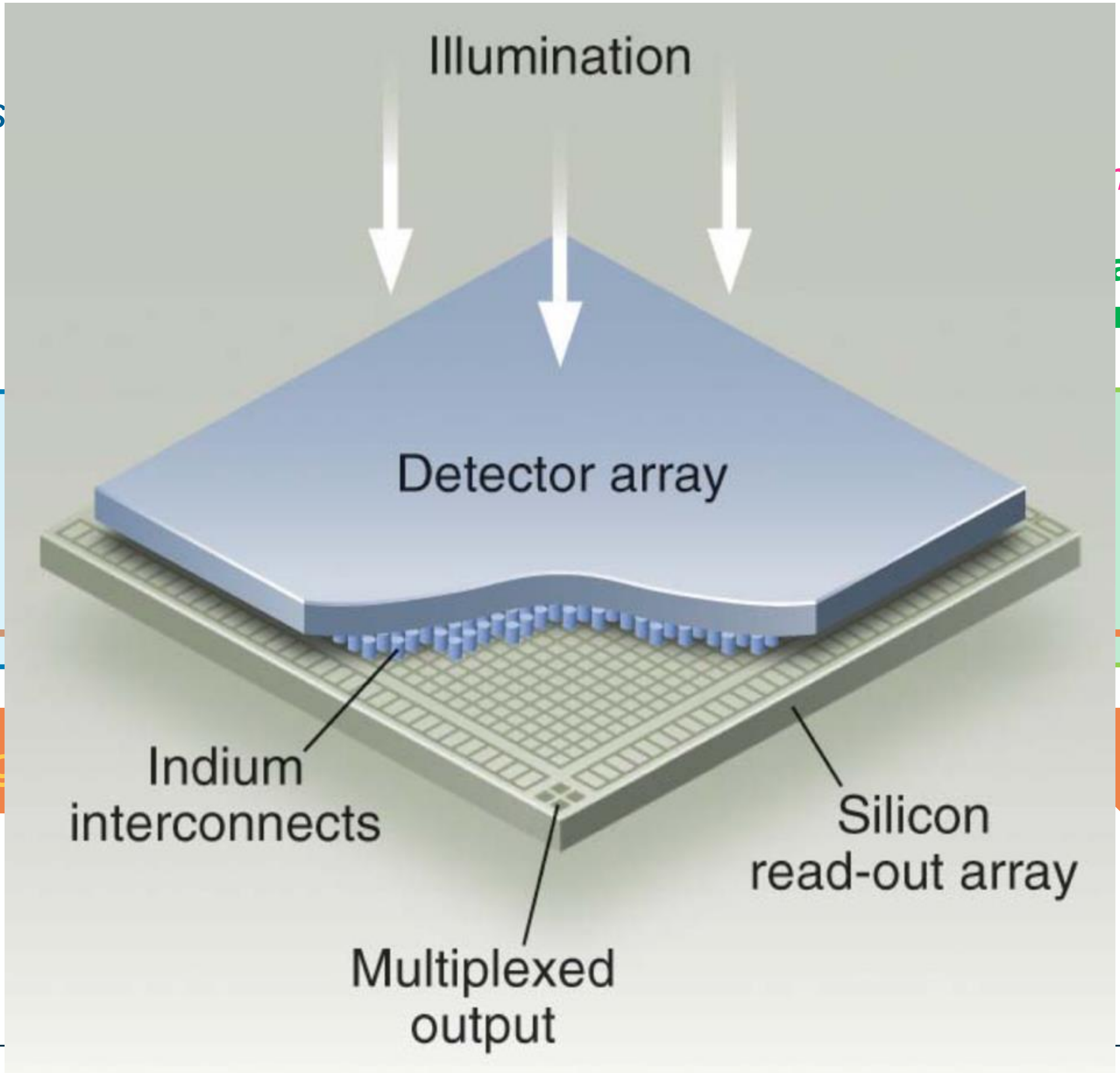
2 different “layers”:

- *Photosensitive layer takes*

he following steps

Photon collection | **Charge generation** | **alogue to digital conversion mage reconstruction**

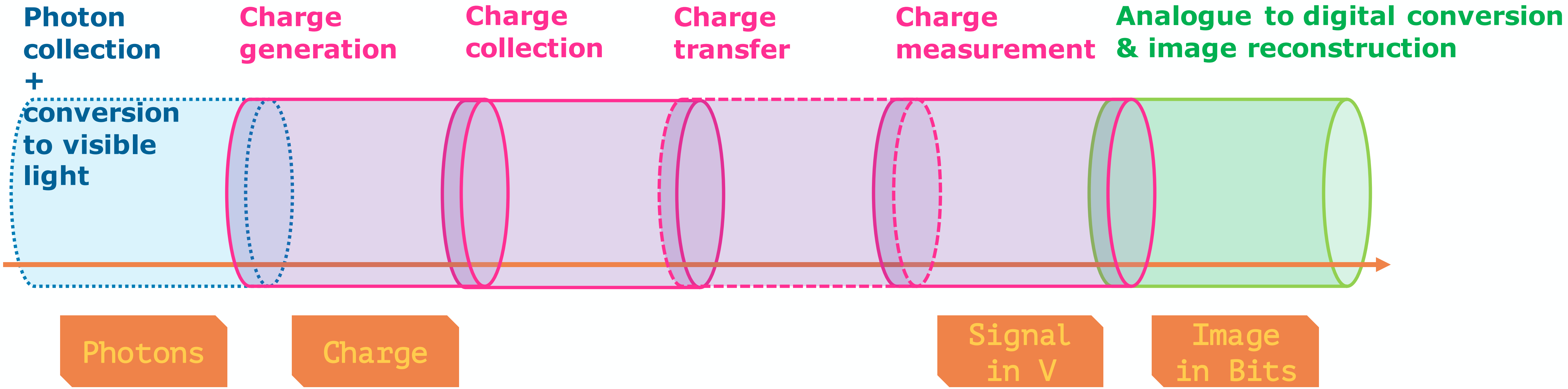
Photons | Charg | Image in Bits



Detector technologies: hybrid sensors (for X and γ λ)

2 different "layers":

- *Photosensitive layer takes care of photon collection and conversion to visible light*
  - *Silicon drift detectors takes care of the following steps*



For hard X-ray to Gamma-ray detection
Photo-collection performed by scintillating crystal e.g. CsI(Tl) Cesium Iodide doped with Thallium

Detec

2 different '
- Photose

Photon collection + conversio to visible light

conversion ion

Photo

For hard X
Photo-coll

lium

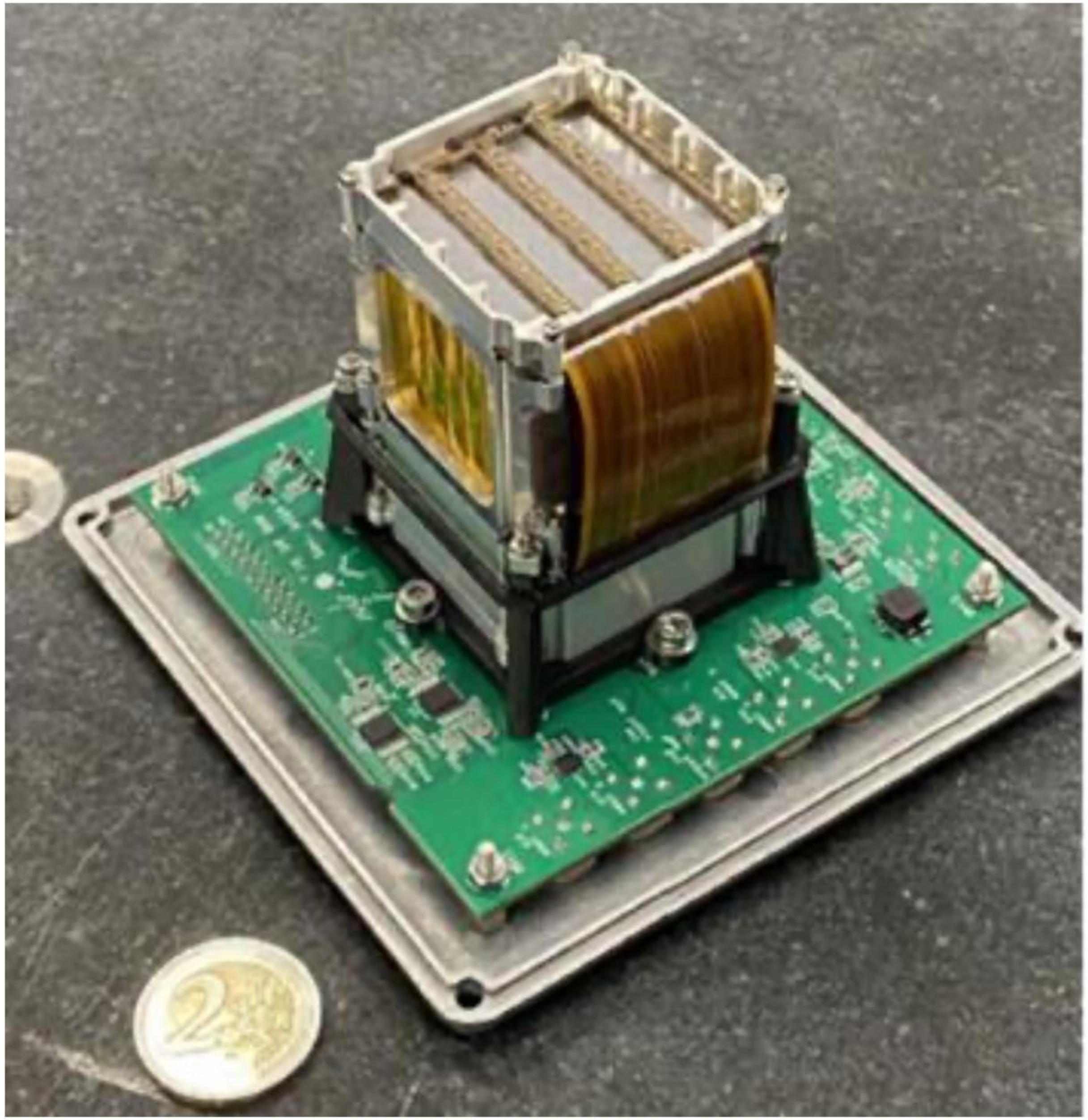
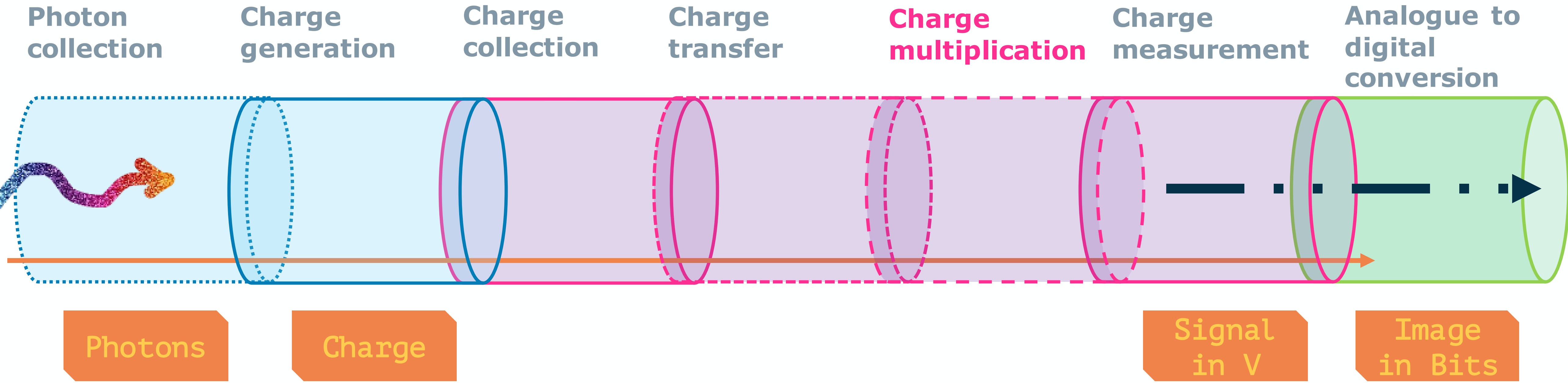


Figure 4-1 XGIS DM ready for tests mounted on the TE board.

One extra function: multiplying charge

- *Charge multiplication can occur in the "photo-sensitive layer" (APDs = Avalanche photo-diodes)*
- *Or right before charge measurement (e.g. EMCCDs)*



+ To boost SNR!
- At the expense of dynamic range
- Complexity of manufacture

The detector zoo!

Well-known manufacturers and detectors for space application

Monolithic sensors

- **Monolithic CMOS imaging sensor (CIS):** Te2v (UK) *CIS115, CIS120*, Caeleste (Be) *ELFIS*, Imasenic (Sp), AMS (Be, former CMOSIS) etc.
- **Charge-Coupled Devices CCDs:** Te2v (former e2v), Teledyne Dalsa (Ca), MIT Lincoln Labs (US), STA (US)

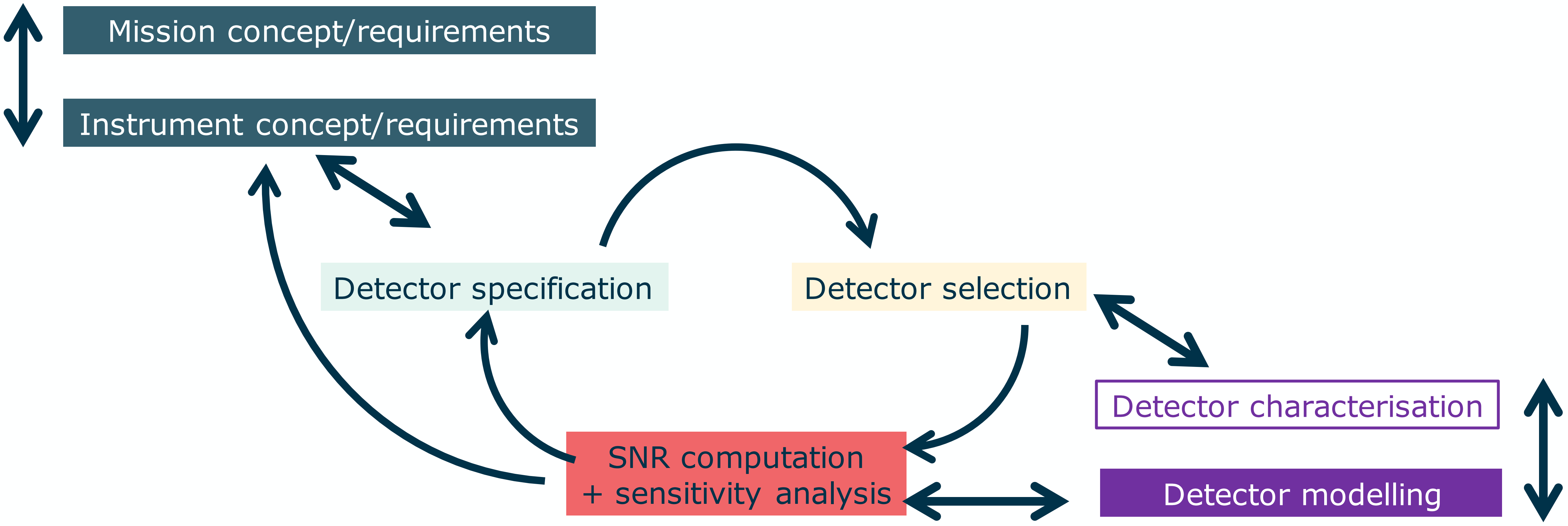
Hybrid sensors

- **MCT/HgCdTe/MerCadTel hybridised arrays**: Teledyne (US) *HxRGs, CHROMA,* Lynred (Fr, former Sofardir) *ALFA, NGP, Cobra* AIM (Ge) etc.
- **Avalanche photo-diode arrays (APDs)**: Leonardo (UK) *Saphira*
- **Superlatice T2SL:** Irnova (Sweden)

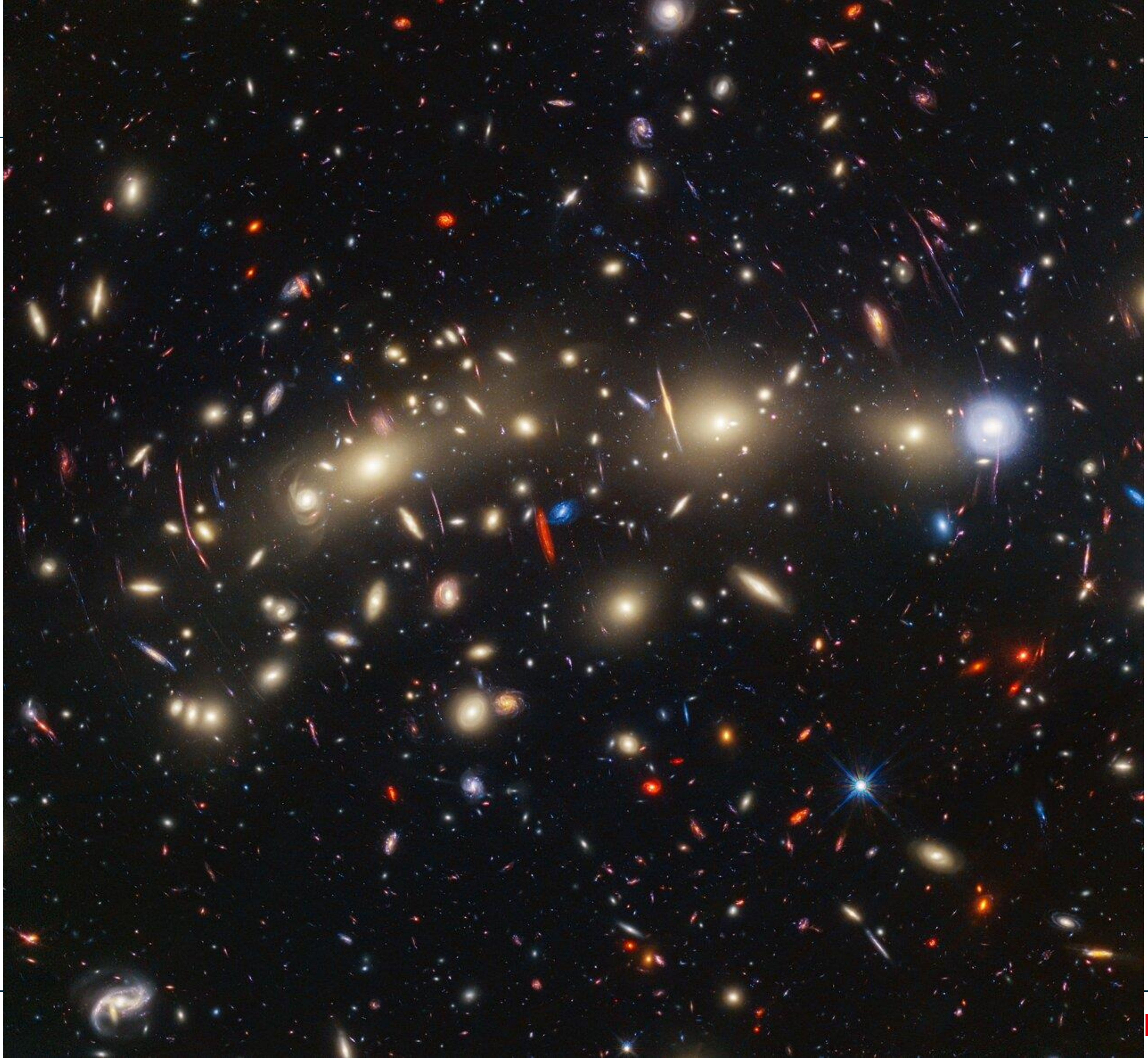
And we did not speak of..

- TES (Transition Edge Sensor), Superconducting Tunnel Junction (STJ), KID (Kinetic Inductance Detector) which rely on superconducting material (operating at <1 K) and can measure also the energy of the incoming photon
- Microbolometers: measure change in resistance/temperature due to incoming photons
- Flavours of CCDs: full frame, frame transfer, EM (electron-multiplying), TDI (Time-delayed integration), IMO (Inverted Mode Operation), Hi-Rho back-biased etc.
- Flavours of CMOS devices: Linear arrays, TDI CMOS etc.
- And probably much more!

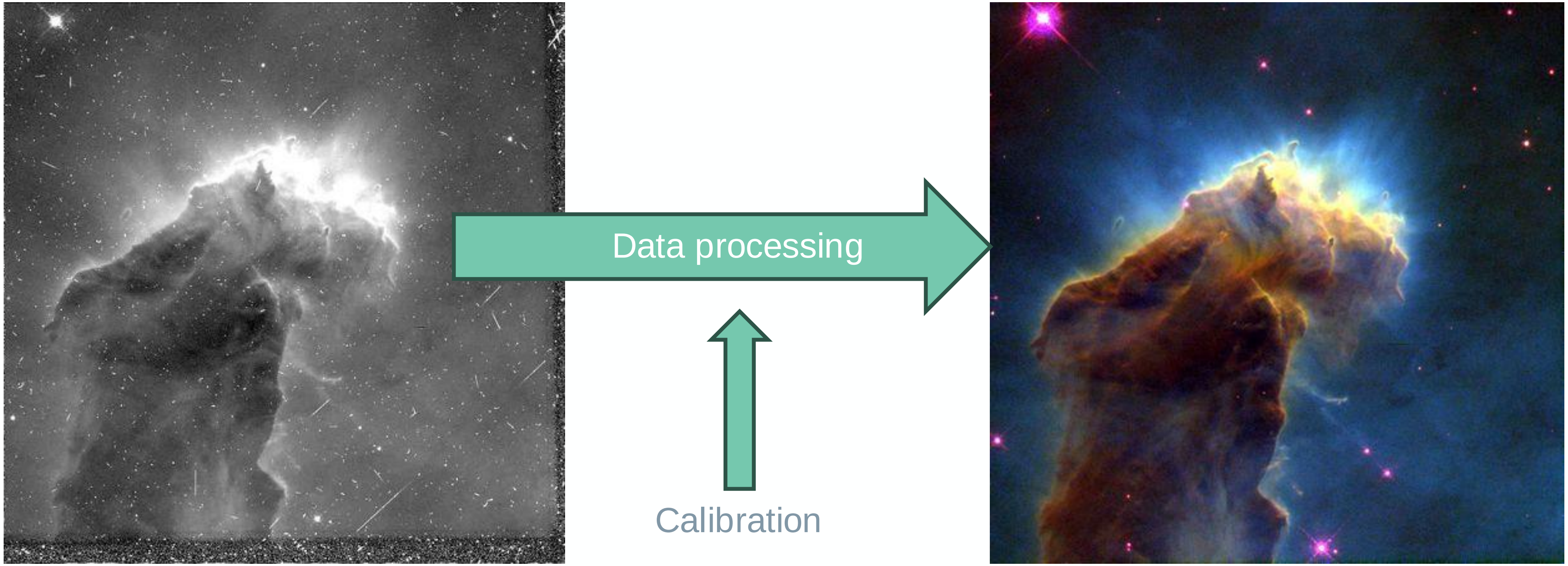
How to choose from so many sensors/technologies?



Check the bonus slides to go in more details

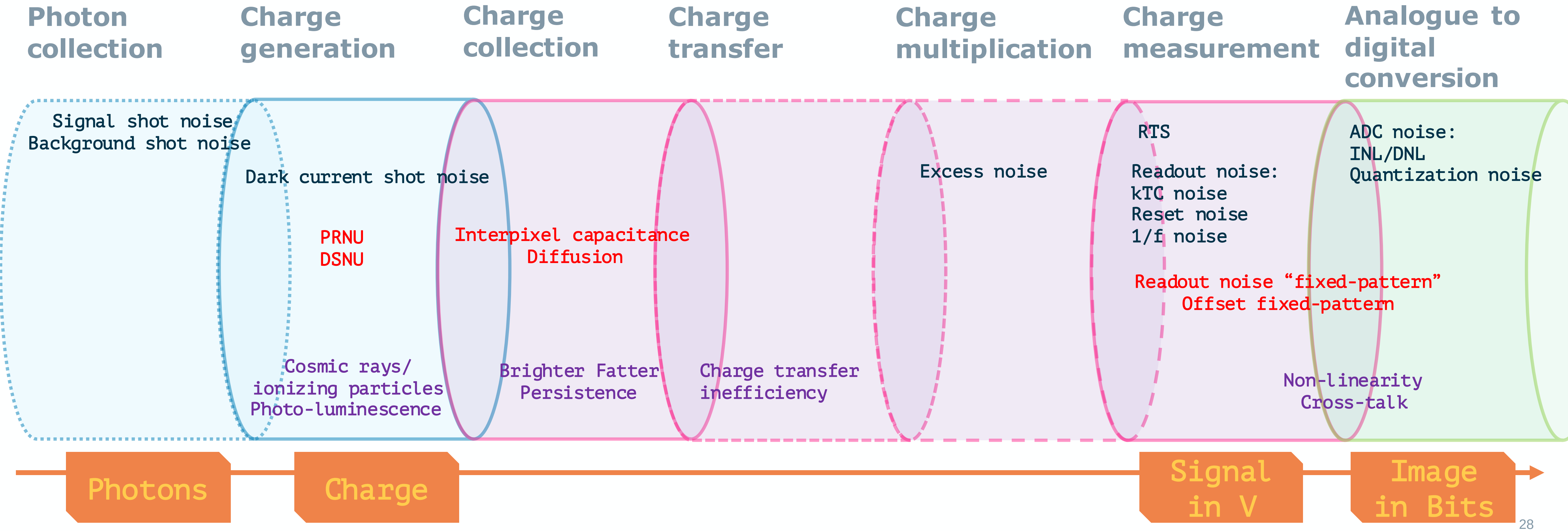


From raw images to final data product



Noise sources

Temporal effect only
Spatial effect only (fixed-pattern)
Signal dependent effect or/and mixed (i.e. spatiotemporal)



Radiation effects: a non-exhaustive list

Non-ionizing (displacement damage)

- Increase of Charge Transfer Inefficiency (for CCDs)

  ⇒ *decrease in SNR, signal distortion*

  ⇒ *measurement error/bias*

- Increase of dark current

  ⇒ *decrease in SNR*

- Increase of detector defects

  ⇒ *decrease of operability*

- Change of persistency properties (for IR MCT-type devices)

  ⇒ *decrease of operability*

Ionizing

- Cosmic rays (imaging of ionizing tracks)

  ⇒ *pollution of data stream*

- Charging of oxides

  ⇒ *flat-band voltage shift*

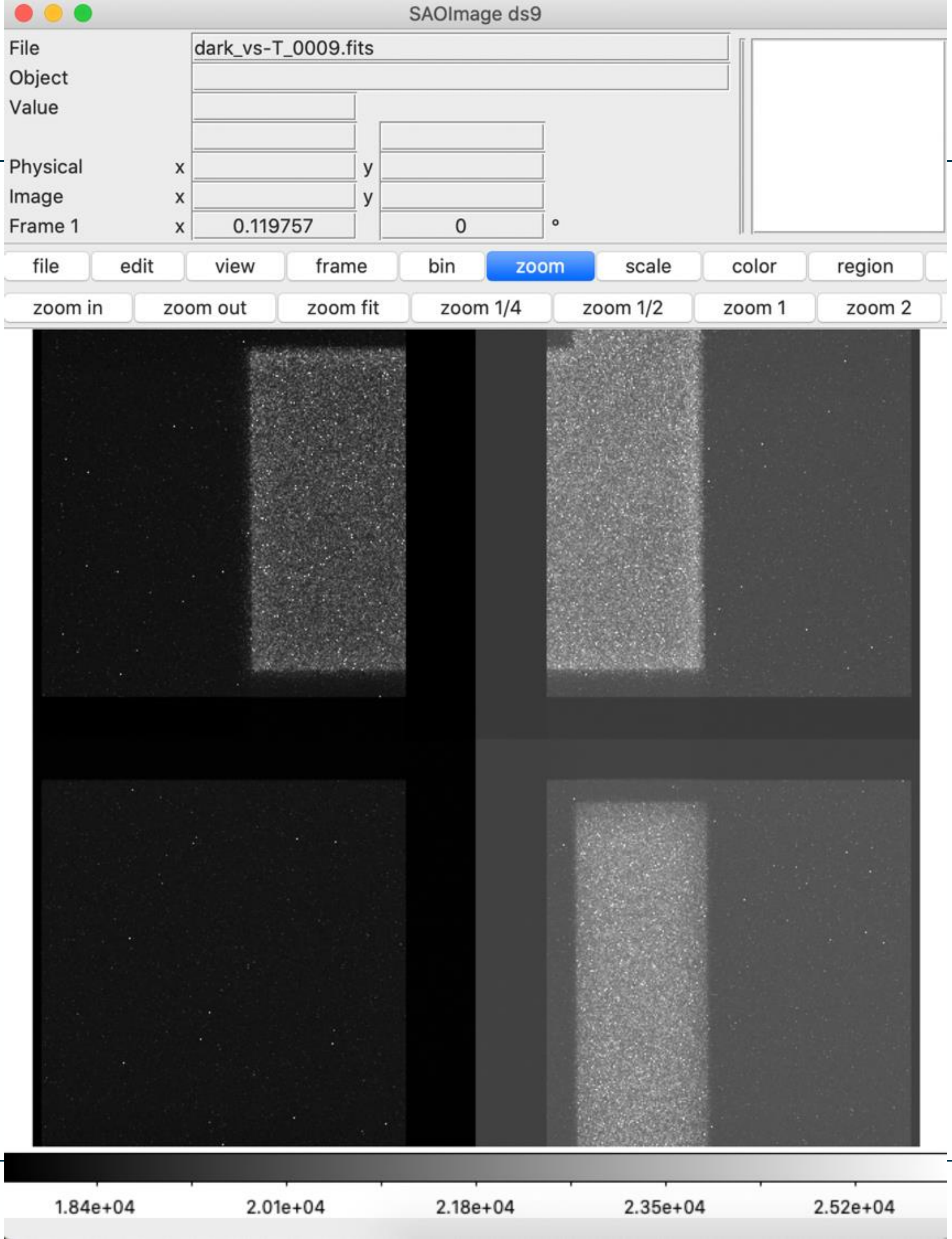
  ⇒ *shift of operation point*

Single Event Effects

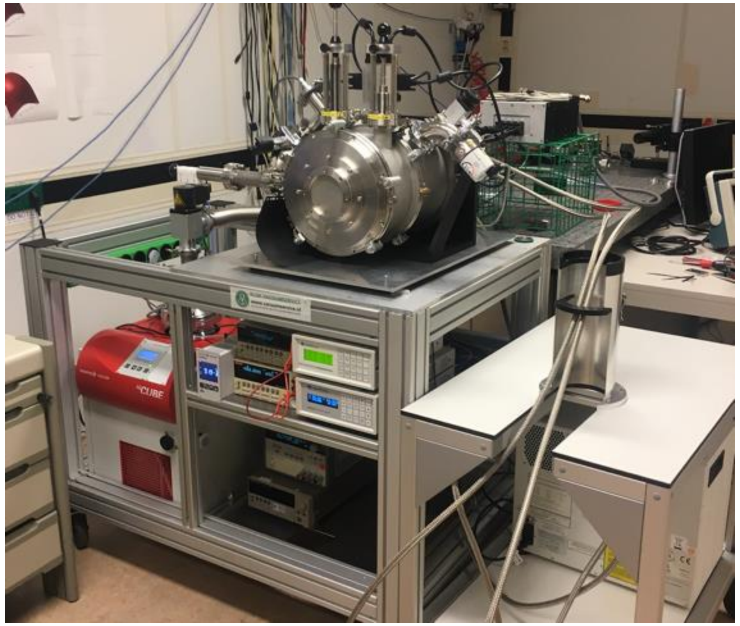
⇒ *logic upset*

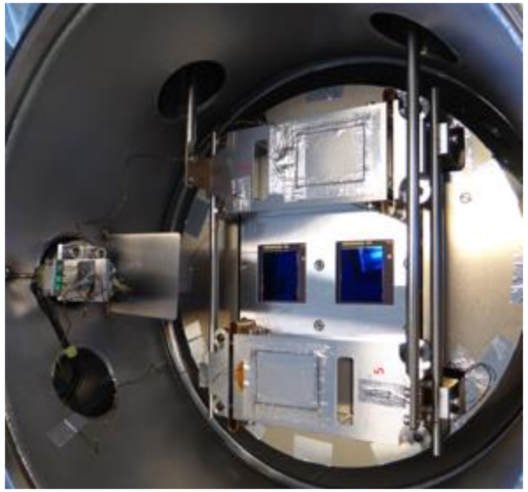
⇒ *component failure/misbehave*

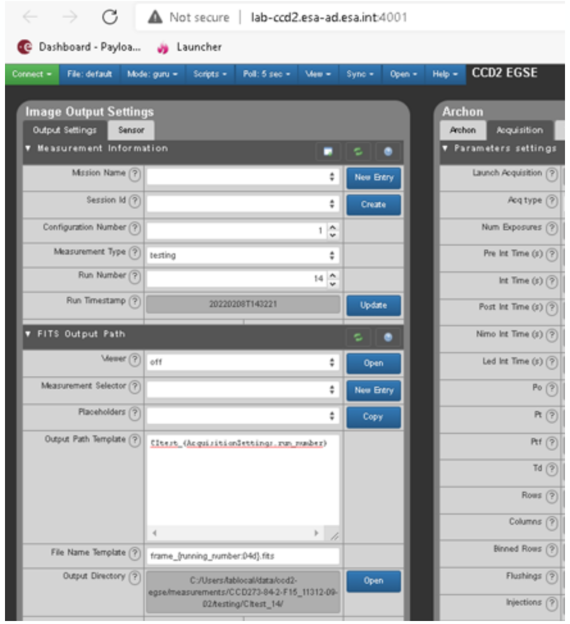
Characterising detectors

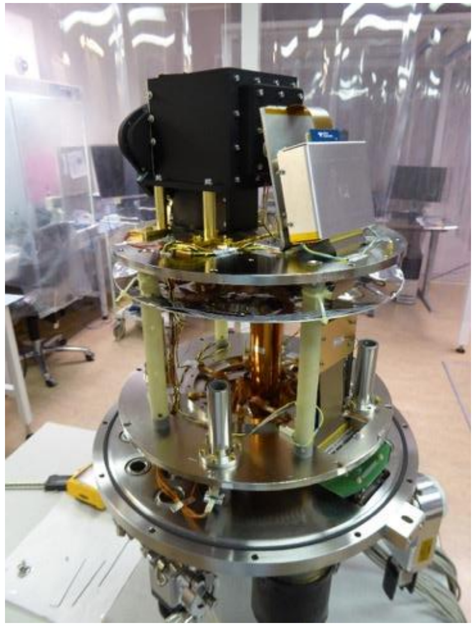


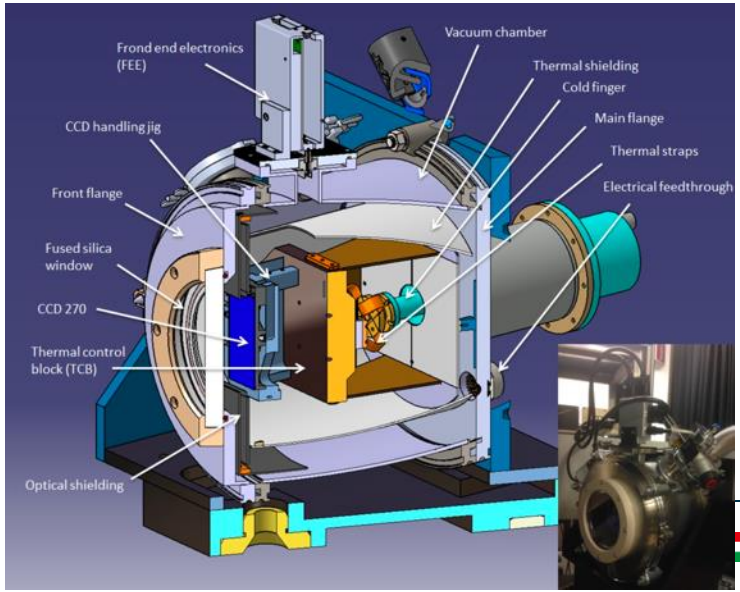
SCI lab: overview of test benches

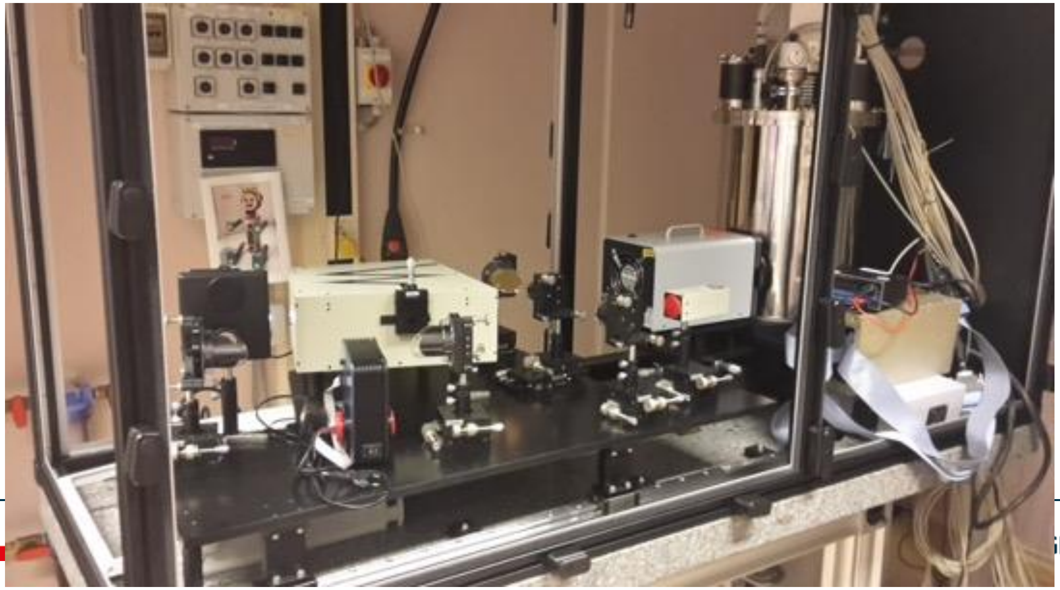












Mission-specific experiments

- **Cold irradiations:** CHEOPS CCD47-20*, ARIEL H1RG**, PLATO CCD270***

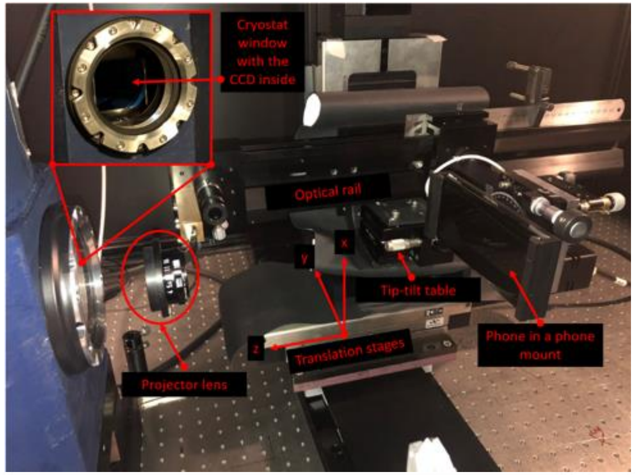
**P. Verhoeve et al, SPIE Proc. 2022?*

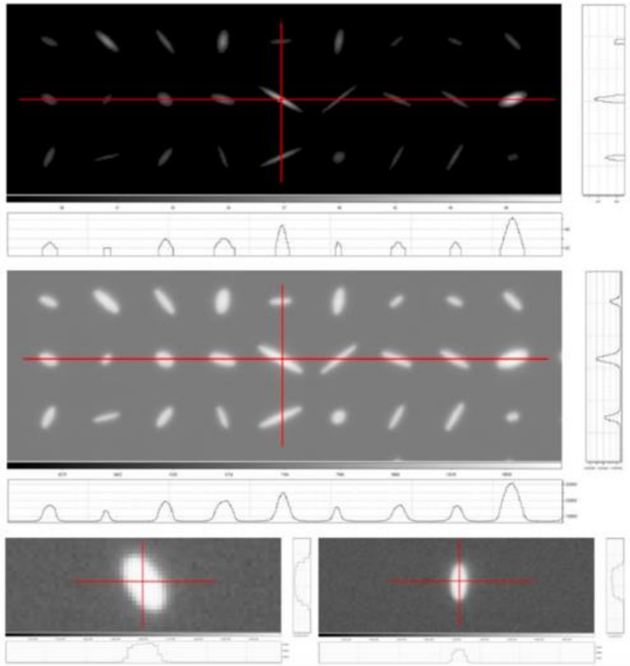
***Impact of proton radiation on the Ariel AIRS CH1 HAWAII-1RG MWIR detector, P.-E. Crouzet et al, SPIE Proc. 2020*

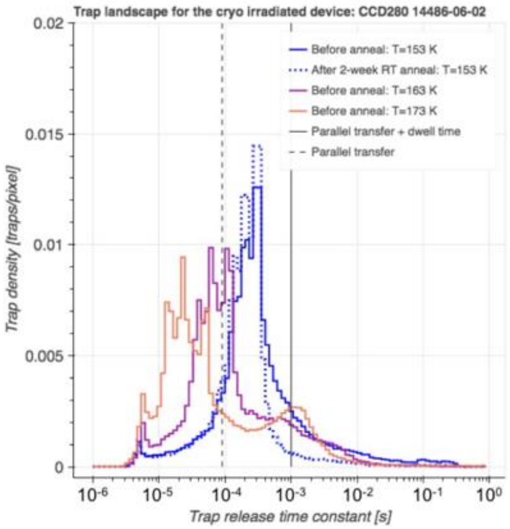
****Comparative Study of Cryogenic Versus Room-Temperature Proton Irradiation of N-Channel CCDs and Subsequent Annealing, T. Prod'homme et al. IEEE Nucl., Trans. 2019*

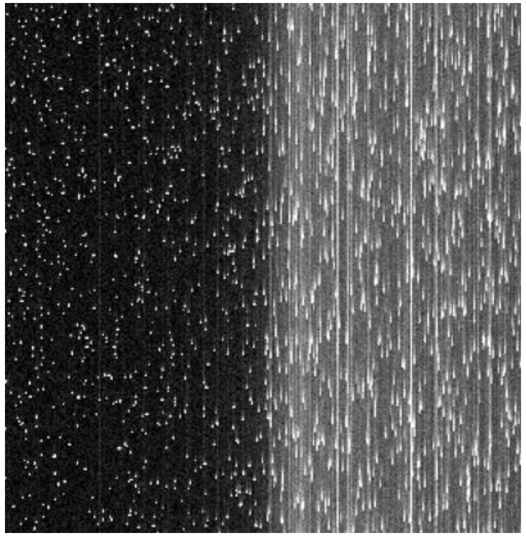
- Representative scene projections on irradiated Euclid CCD273

A smartphone-based arbitrary scene projector for detector testing and instrument performance evaluation, T. Prod'homme et al. SPIE proc. 2020









Other

- Intrapixel response measurement (subpixel spot projector)

Optical and dark characterization of the PLATO CCD at ESA, P. Verhoeve et al. SPIE proc. 2016

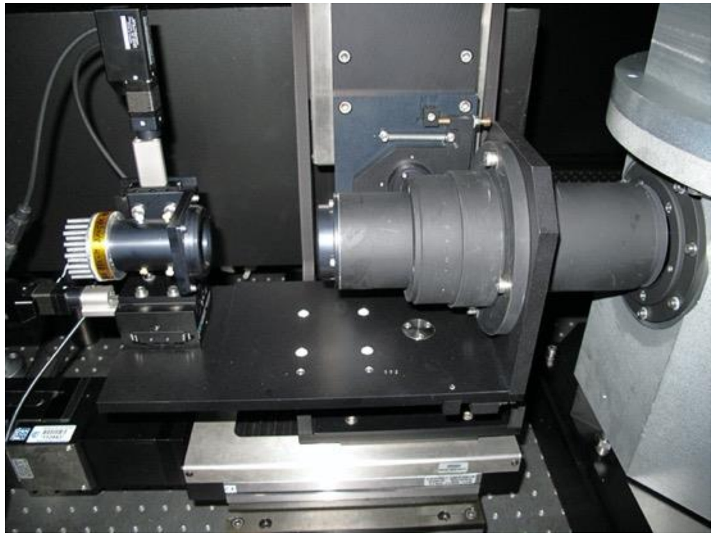
- QE validation and comparison: e.g. NIR-LFA vs. HxRG

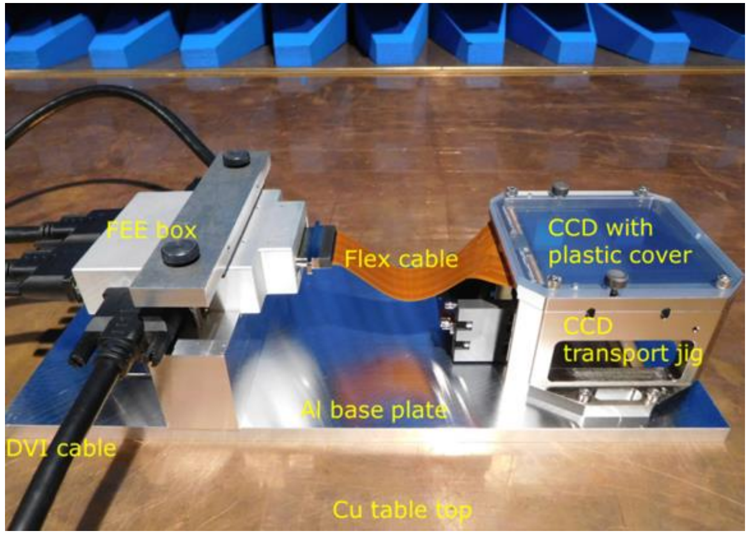
Quantum efficiency performances of the NIR European Large Format Array detectors tested at ESTEC, P.-E. Crouzet et al, SPIE Proc. 2015

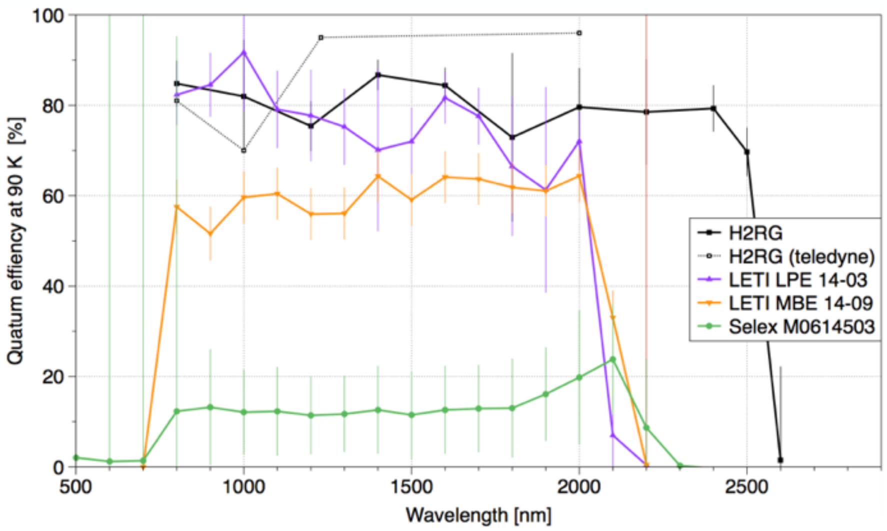
- Persistence measurements: e.g. Euclid H2RG

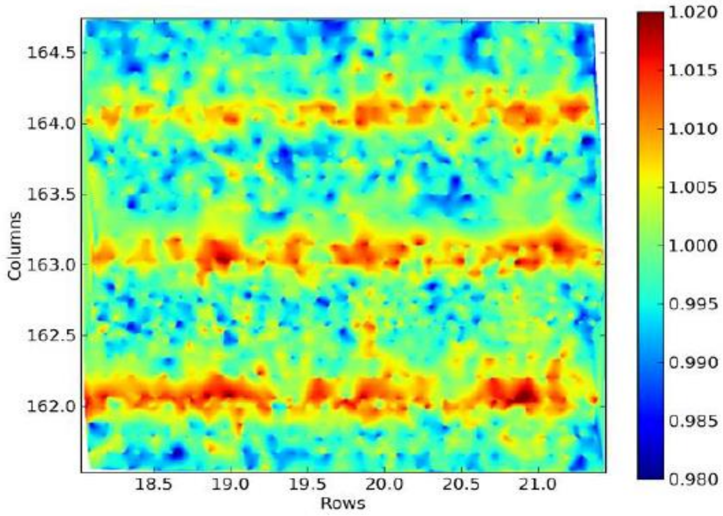
Comparison of persistence in spot versus flat field illumination and single pixel response on a Euclid HAWAII-2RG at ESTEC, P.-E. Crouzet et al, SPIE Proc. 2016

- And more: EMC testing, cross-hatch investigation etc.









Why simulating detection chains?

Instrument and detector simulations are needed each stage of a project

Technology and concept trade-off	Definition
Performance estimate	Design
Instrument parameter optimization	Design Consolidation
Performance verification	Manufacture & Testing
Data processing pipeline validation	Launch/First light
Instrument optimization and calibration	Commissioning
Performance verification	First science data
Calibrating out instrumental effect	Operation
Supporting data analysis	Scientific exploitation

https://esa.gitlab.io/pyxel/

Some references to go deeper

- CCD: “Scientific Charge-Coupled Devices” book by Janesick
- Monolithic CMOS: “General introduction to CMOS image sensors” paper/tutorial by Innocent
- MCT hybridised arrays: “Imaging Sensor Technologies for Astronomy, Planetary Exploration & Earth Observation” 2019 by Beletic
- “High-level numerical simulations of noise in CCD and CMOS photosensors: review and tutorial“ 2014 paper by Konnik and Welsh

Bonus slides

Detector specifications: the questions to ask?

- What is my desired wavelength range?
- **What is my scene**? Field of view? Size of focal plane? Operation concept?
- What is the size of the optical PSF?
- What type of measurements your instrument will perform? Spectroscopy => SNR and Dynamic Range are important, Photometry , Astrometry => SNR + pixel resolution, Morhpology => any contribution to the instrument PSF, pixel resolution, noise contributions?
- What is the temperature operating range?
- What are driving my requirements? Dynamic range? Frame rate? Readout noise?
- What is my radiation environment?

Detector specifications: the basics

Dimensions

Format

Pixel size

Fill-factor

Substrate Epitaxial thickness

No. of outputs

Operation

Read-out mode

Frame rate

Integration time

Windowing

Voltages and power supplies

Power dissipation

Operating temperature

Electro-optical Performance

QE (quantum efficiency)

Cross-talk

MTF (modular transfer function)

Defects

Dark current

DSNU (Dark signal non-uniformity)

Read noise

Charge Handling Capacity/Full Well Capacity

Non-linearity

PRNU (Pixel Response Non-Uniformity)

RTS (Random Telegraph Signal)

Image lag

Environment

TID (Co60)

TNID (Proton testing)

SEE threshold (Heavy ion testing)

Detector specifications: the basics

Dimensions

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Frame rate

Integration time

Windowing

Voltages and power su[illegible]

Power dissipati[illegible]

Operating te[illegible]perature

Electro-optical Performance

QE (quantum efficiency)

Cross-talk

MTF (modular transfer function)

Defects

Dark current

DSNU (Dark signal n[illegible]

Read noise

Charge [illegible]ty/Full Well Capacity

N[illegible]

PR[illegible] Response Non-Uniformity)

[illegible] (Random Telegraph Signal)

Image lag

Environment

TID (Co60)

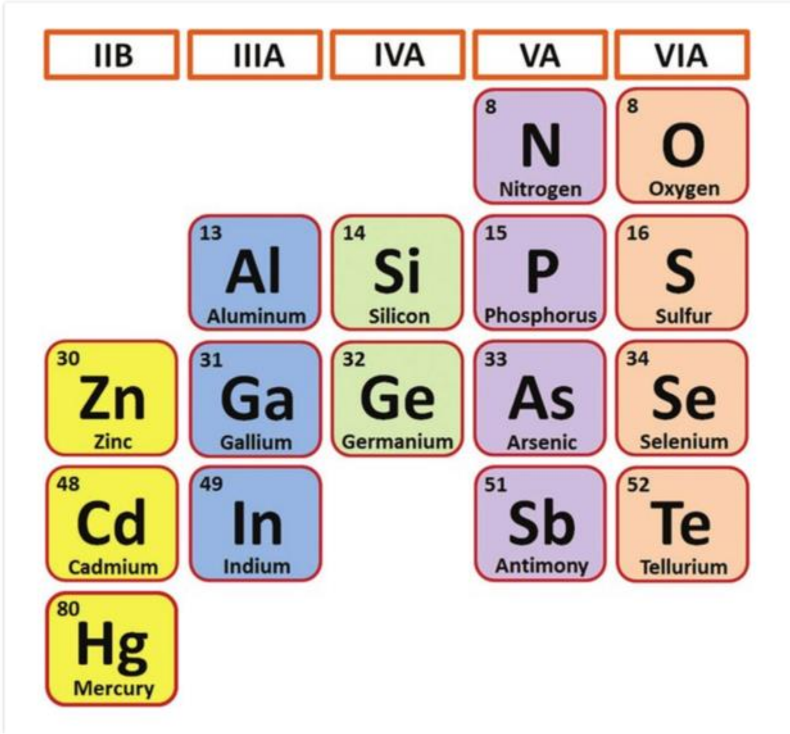
TNID (Pr[illegible]ting)

SE[illegible]shold (Heavy ion testing)

For an existing detector, the detector specs can be found in the manufacturer datasheet

Which detector for which wavelength?

- To generate an electron-hole pair the photon energy has to be greater than semiconductor bandgap
- Semiconductor bandgap = minimum energy Eg for an e- to go from valence to conduction band
- Planck-Einstein relation: $E\ (J) = h*\nu = h*c\ /\ \lambda$ with Planck constant: h = 6.63*10-34 J.s, c (speed of light) = 300000 km/s
- Energy of a photon depends uniquely on its wavelength: $\mathbf{E(eV)=1.2398/\ \lambda\ (\mu m)}$



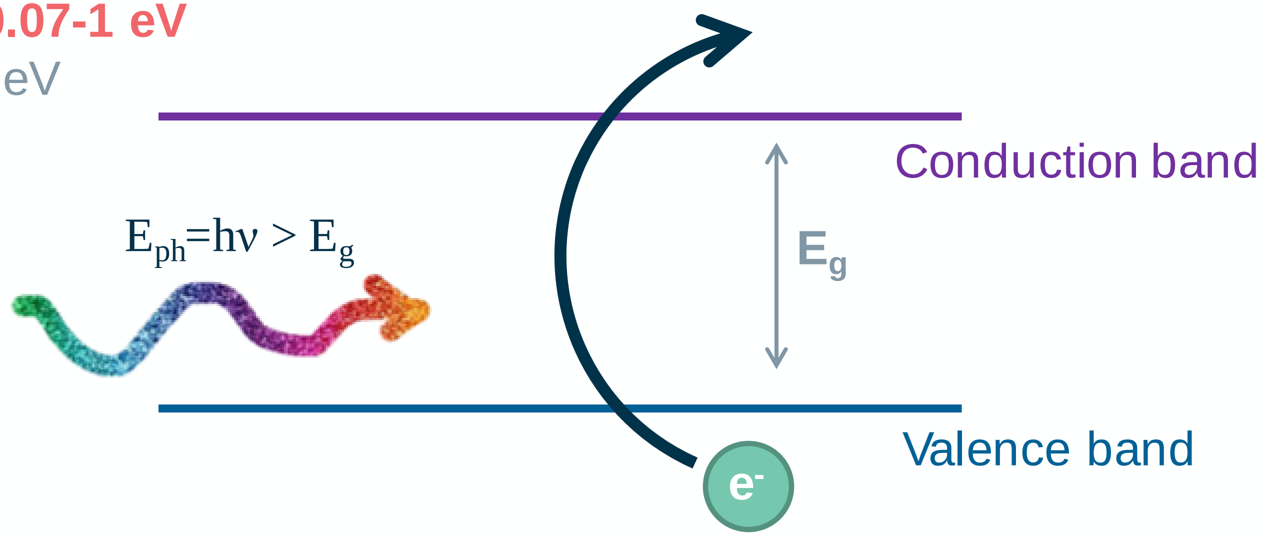
E_g(Si) = 1.12 eV

E_g(Ge) = 0.67 eV

E_g(InGaAs) = 0.5-0.7 eV

E_g(HgCdTe) = 0.07-1 eV

E_g(InSb) = 0.23 eV



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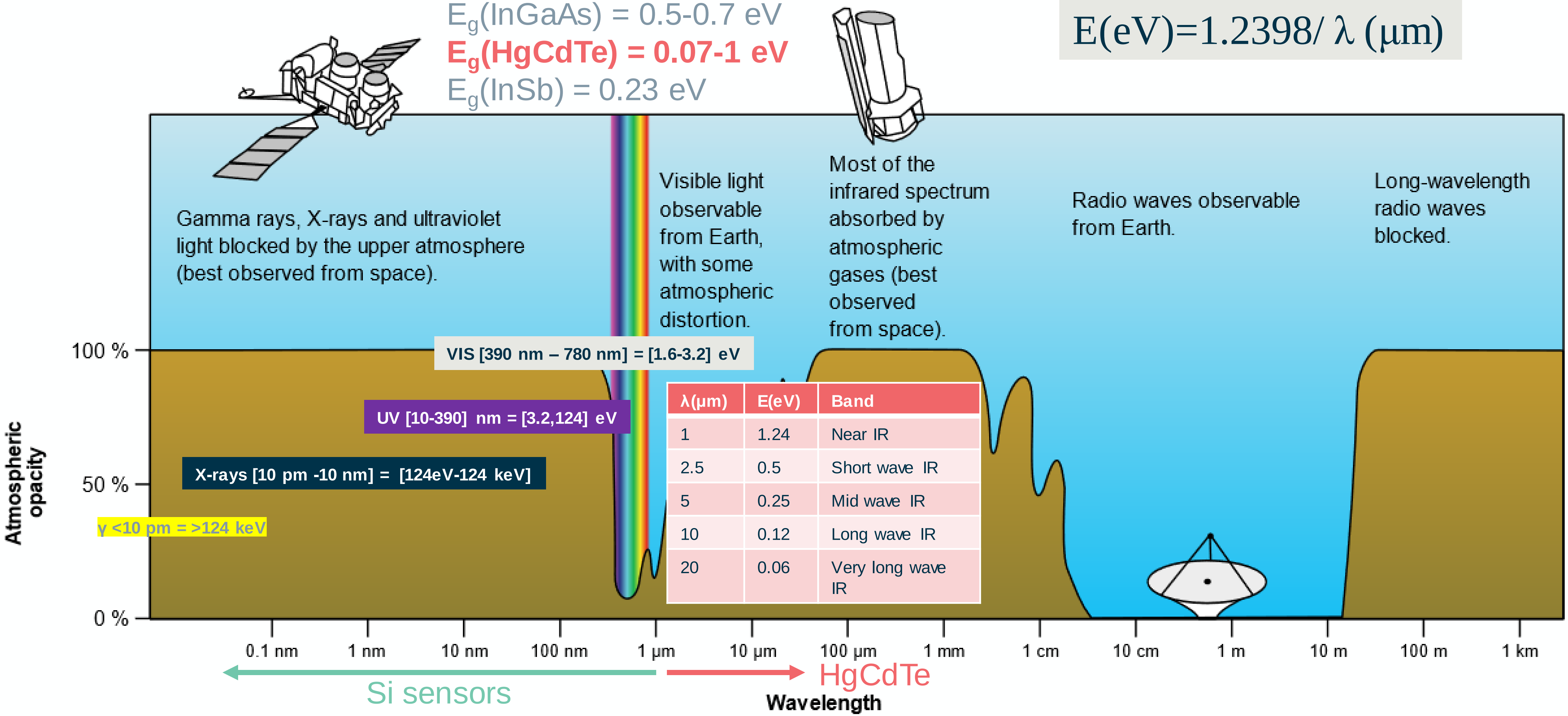

λ(µm)	E(eV)	Band
1	1.24	Near IR
2.5	0.5	Short wave IR
5	0.25	Mid wave IR
10	0.12	Long wave IR
20	0.06	Very long wave IR