caeleste

There is only one way to be perfect for an image sensor

There are uncountable ways for an image sensor to be imperfect

the Anna Karenina principle

Imperfections of high-performance image sensors

Lorentz Workshop, 9-13 Feb 2015, Leiden

Bart Dierickx, Caeleste

abstract

The Silicon image sensor or ROIC translates the opto-electric signal in electronic information.

This process is not perfect.

We will discuss the major sources of error, noise and non-uniformity and possible countermeasures.

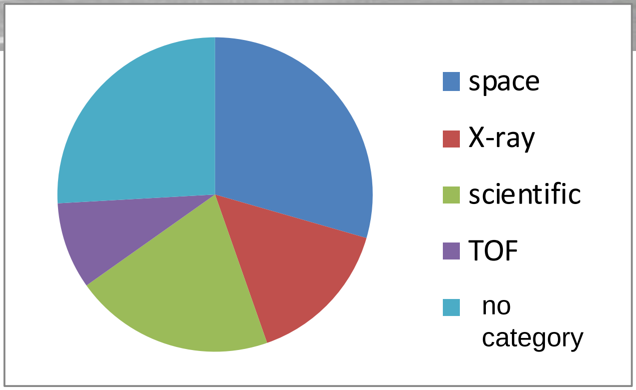
About Caeleste

caeleste

Founded 2006
Mechelen, Belgium
20 MS/PhD

Mission
and business model

supplier of
custom designed
beyond “State of the Art”
image sensors



Caeleste heritage

caeleste

- ⇒ Pioneering contributions to radhard and cryogenic operation
- ⇒ Large number of historical imager/ROIC designs for particle physics, X-ray integrating and photon counting, electron integrating and counting imagers
- ⇒ Cover full track from concept, design to series production
- ⇒ IP-portfolio
- ⇒ Close relationships with foundry technologists
- ⇒ Expertise in circuit & device physics & technology
- ⇒ Routine radhard design (TID, TnID, SE, SEL)
- ⇒ Proton & SE hard pixels

Disclaimer

- This paper focuses on imager sensor imperfection, while understanding the root causes
- This is not a course on image sensor concepts nor on their use
- Technology countermeasures and calibration of many types of imperfections are just superficially treated
- No guarantee on effectiveness of techniques. It is known that specifically here the talent and commitment of the IC or system designer is key.

abbreviations

Pixel	from picture element
Imager	from image sensor
T(I)D	total (ionizing) dose
SE, SEU	single event, single event upset
ROIC	readout IC. in this case the imager sensing the light from the scintillator or the current from the direct detector
SNR, S/N	Signal to Noise ratio
S	Signal: the result of a measurement, typically [V]
N	Noise: the error on a measurement, typically [V_{RMS}]
PSN	Photon shot noise
XPSN	X-ray photon shot noise
NL	Non-linearity
FPN,PRNU, DSNU	Fixed pattern noise, photo-response non-uniformity, dark signal non-uniformity
IS	Image Sensor, imager
(orange)	Imperfection source
(red)	Generates temporal noise
(blue)	Generates spatial noise, variability, non-uniformity
(green)	Gradual performance degradation
(purple)	Yield issues, defects and in-the-field failure

Outline

caeleste

Imperfections
Imperfect performance
Variability
Radiation damage
Calibration
Take home message

Imperfections: their origins

Imperfect performance

- Quantum Efficiency
- Noise
- Dark current

Variability, defects, yield

- FPN, PNRU, DSNU
- Yield

Radiation damage

- Total Dose, Single Events
- Radhard design

Calibration

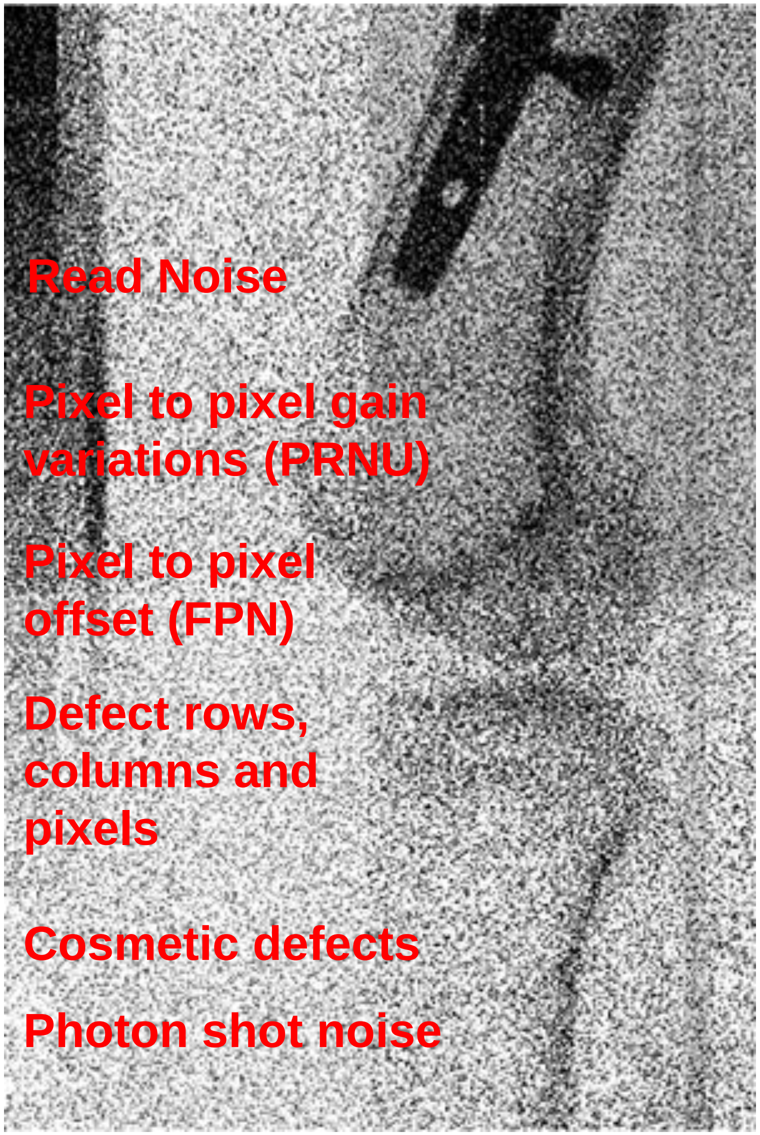
- What can be completely/partially/not calibrated
- Calibration in the presence of non-linearity

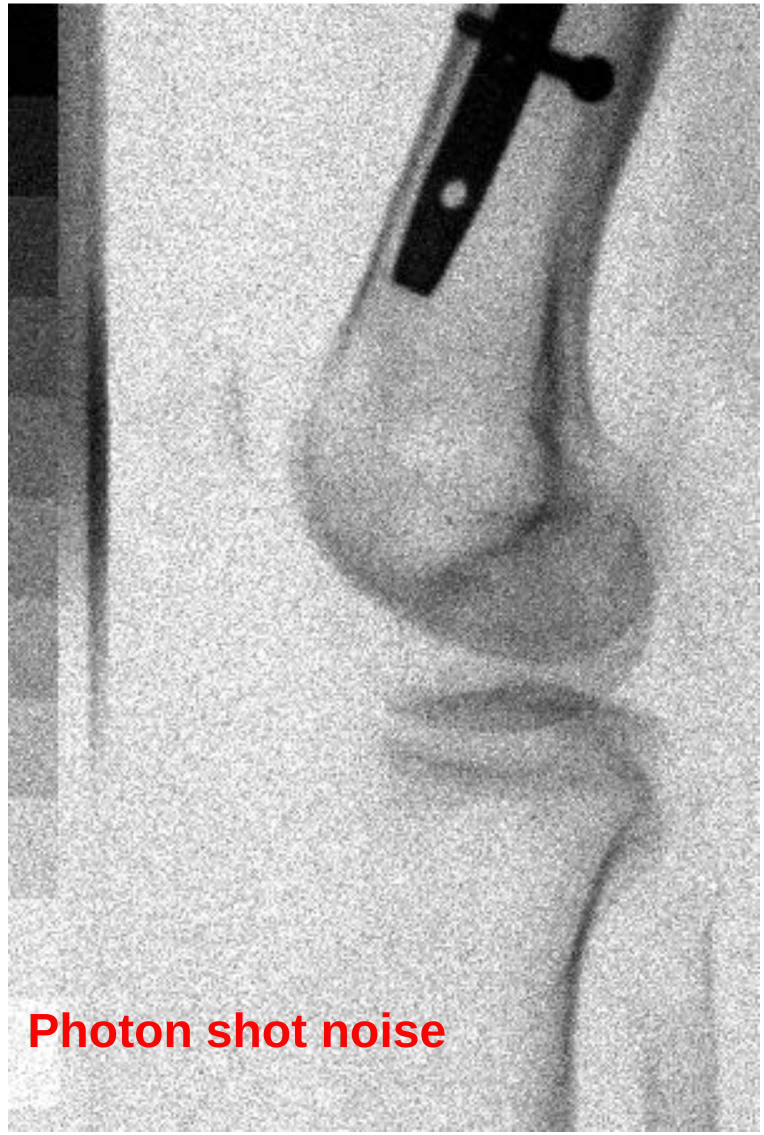
Take home message

Imperfections

Their origins

Imperfections





caeleste

Imperfections per origin

Nature

Randomness

- Molecular variability
- Device noise
- (X-) Photon shot noise

Damage

- Radiation damage
- Other degradation mechanisms

Technology

- Non-linearity
- QE * FF
- Process variability
- Cosmetic defects
- Yield

Users

- Expectations
- Imperfect calibration

Imperfections per phenomenon

Offset variability

- Molecular and process variability
- Device noise

Non-reproducibility

- Crosstalk
- Hysteresis, memory effects
- Technology drift, radiation damage
- °T drift
- Yield

Non-linearity

- Circuit non-linearity
- Saturation
- Image lag
- Dark current and photo current have different equilibrium points

Gain variability

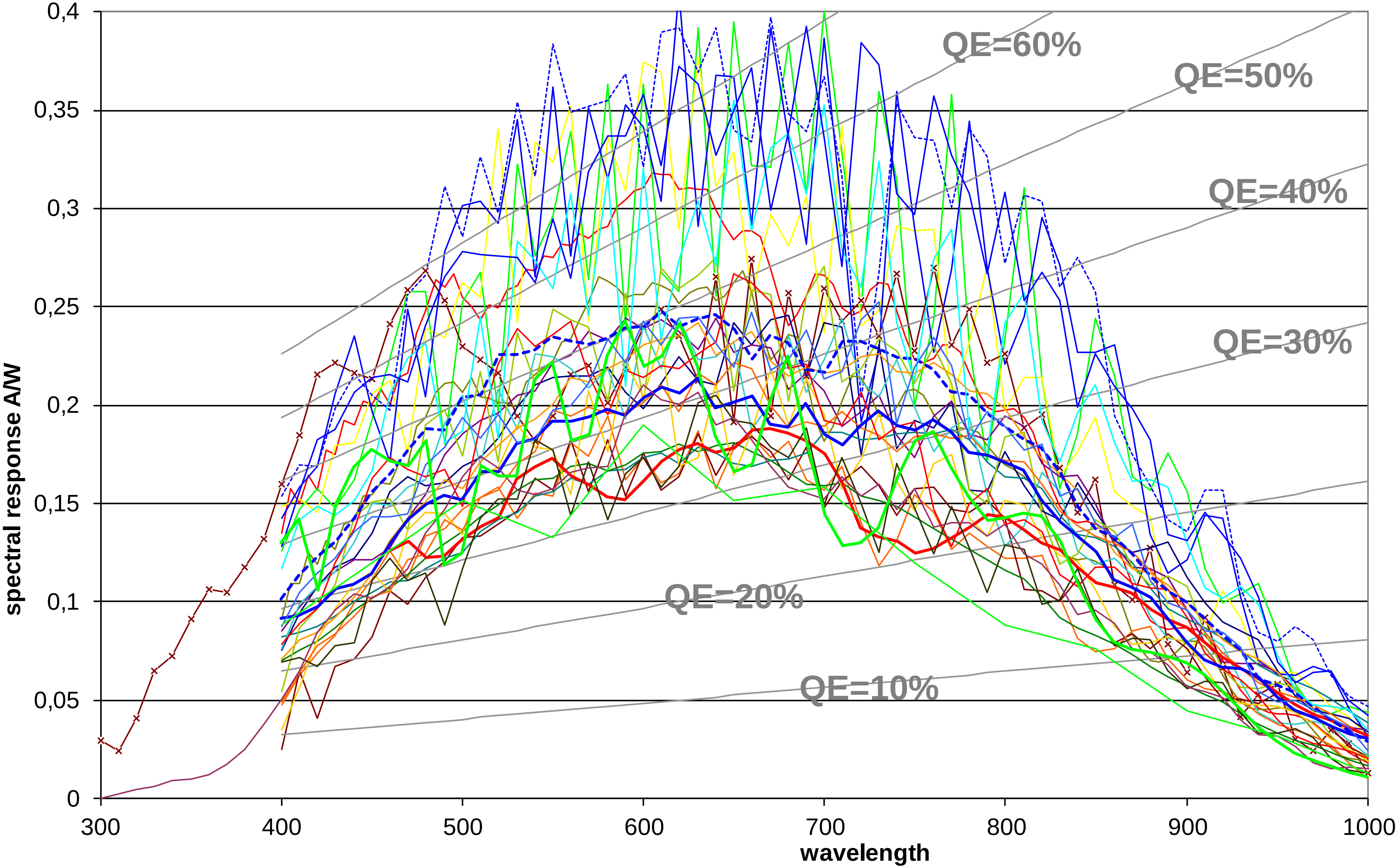
- (X-) Photon shot noise
- PRNU
- Cosmetic defects

Imperfect performance

QE, Noise, Dark current

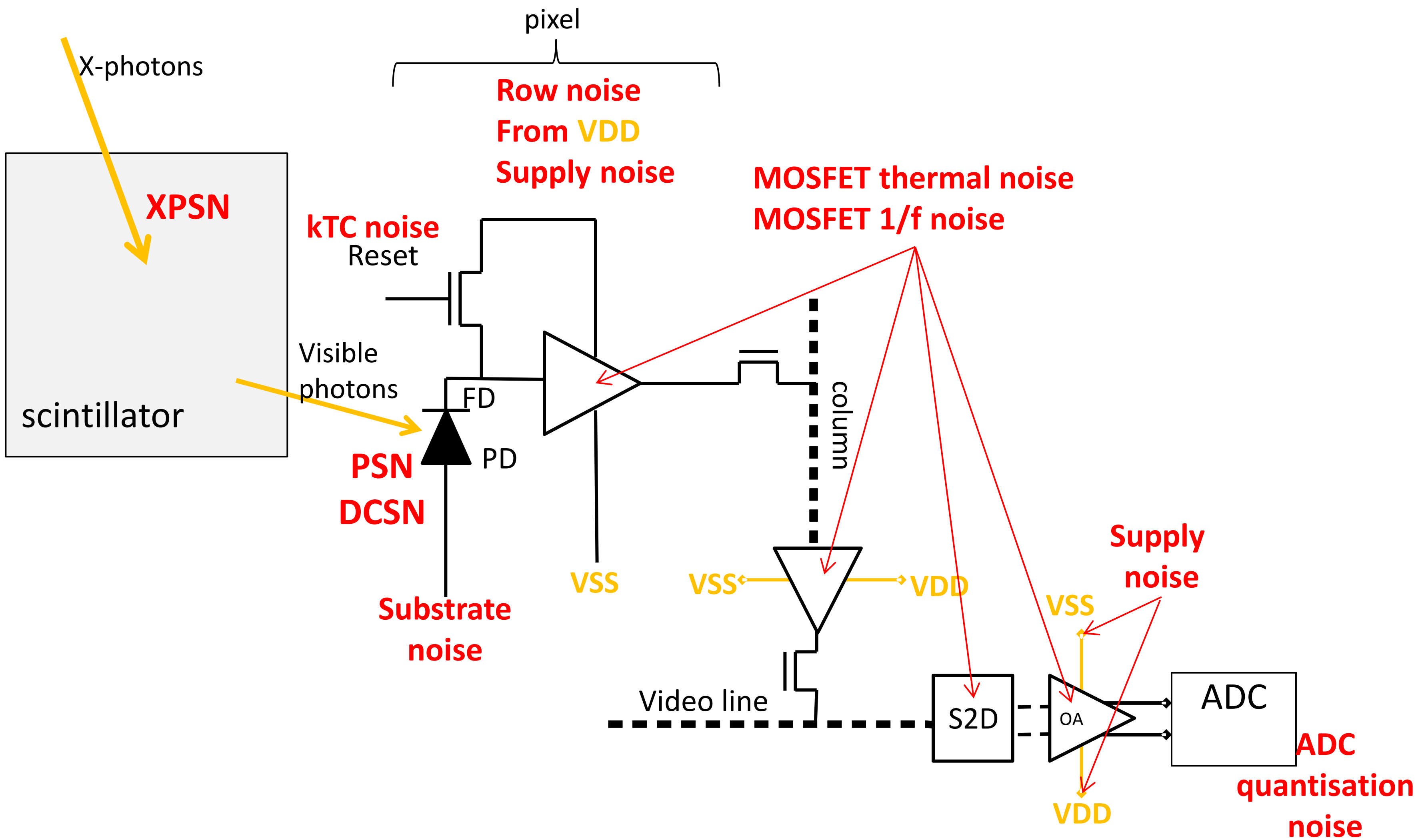
Quantum Efficiency CMOS, FSI

caeleste



Temporal Noise

caeleste



Swank noise

A charge-integrating X-ray imager

⇒ SNR ideally limited by X-photon shot noise (XPSN)

⇒ Scintillator or direct detector limitation: Not every X-photon generates the same amount of secondary electrons/photons

⇒ XPSN increases with a “factor”

Does photon counting solve this?

⇒ *Yes:* each photon has exactly the same weight

⇒ *No:* missed photons or false hits, sometimes due to... Swank noise

Dark current

caeleste

Diode “leakage” current in the absence of light

⇒ Noise on the photo-Signal: DSNU, DCSN

Physical root cause:

⇒ “generation centers”

⇒ Thermally activated e-h+ creation

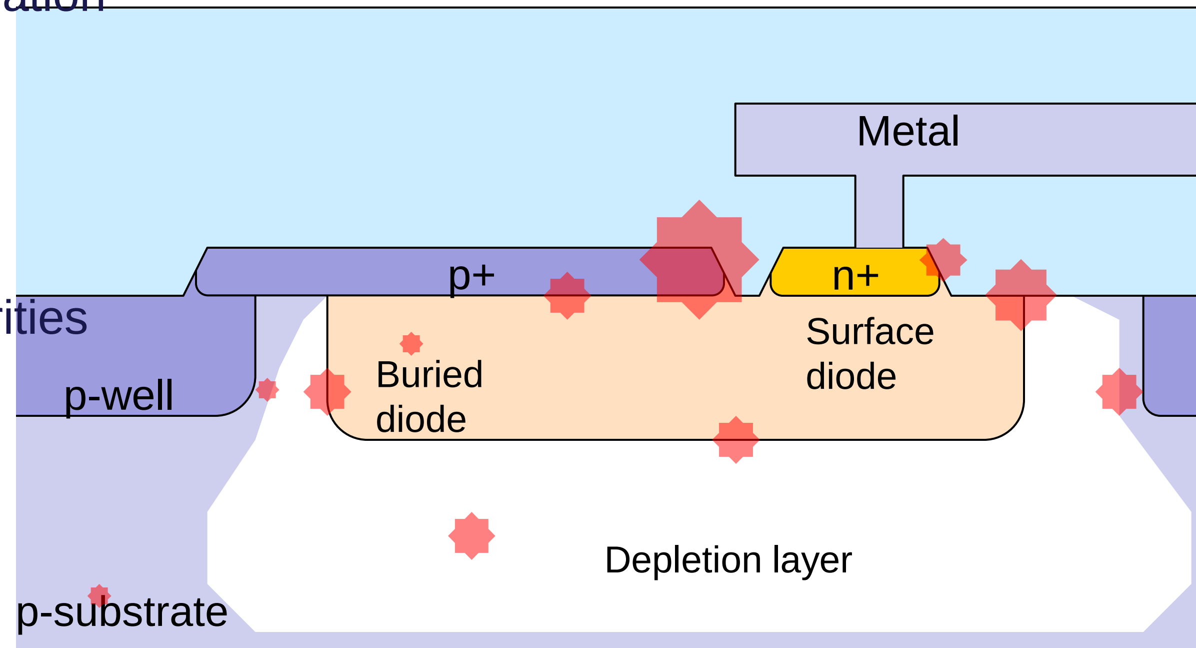
Generation centers

⇒ at mechanical stress

⇒ crystal defects, cluster impurities

⇒ unsaturated dangling bonds

⇒ enhanced in electric field



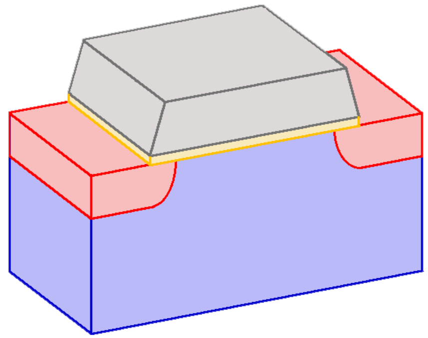
caeleste

Variability

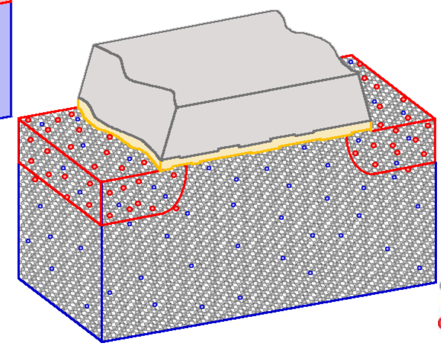
Non-uniformity, defects & yield

Atomic and molecular scale randomness

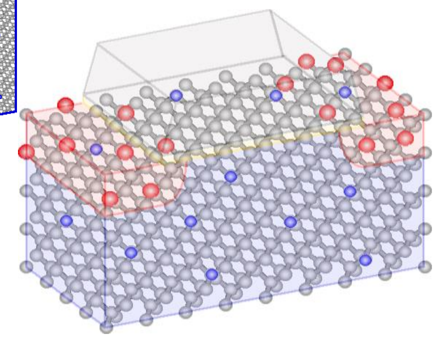
caeleste



The transistor model - yesterday



A 25nm MOSFET in production today



A 4.2nm MOSFET in production in 2023

Intrinsic Process Fluctuations:

- ⇒ Random discrete dopant atoms
- ⇒ Line edge roughness from photon statistics litho
- ⇒ Line edge roughness from molecular nature photo resist
- ⇒ Interface roughness by random (poly-) crystalline or amorphous matching
- ⇒ Layer thickness variation from random deposition from solution or plasma
- ⇒ Layer thickness variation from randomly reacting molecules
- ⇒ ….

Extrinsic

Techology related randomness

→ Equipment contamination and drift
→ spatial and temporal variations of temperature
→ Chemical composition variations
→ Position of circuit versus local neighborhood (µm scale)
→ Position of circuit on wafer
→ Position of wafer in equipment

Effect:

→ Intra-chip random variability (mismatch)
→ Intra-chip systematic variability
→ Inter-chip, inter-wafer, batch-to-batch variability

Most of it results in
→ Random offset (FPN)
→ Reproducible offset

Yield

caeleste

Large arrays

⇒One defect kills full device?

⇒Design is such that defect does not proliferate

- Short/open in pixel kills the pixel, not the row/column and certainly not the array
- Keep pixels simple

Off-chip countermeasures:

⇒Redundancy is not possible (absent pixel cannot? be interpolated)

⇒Algorithms anticipate missing pixels

is Photon counting the solution against randomness?

The worse thing you can do - for yield

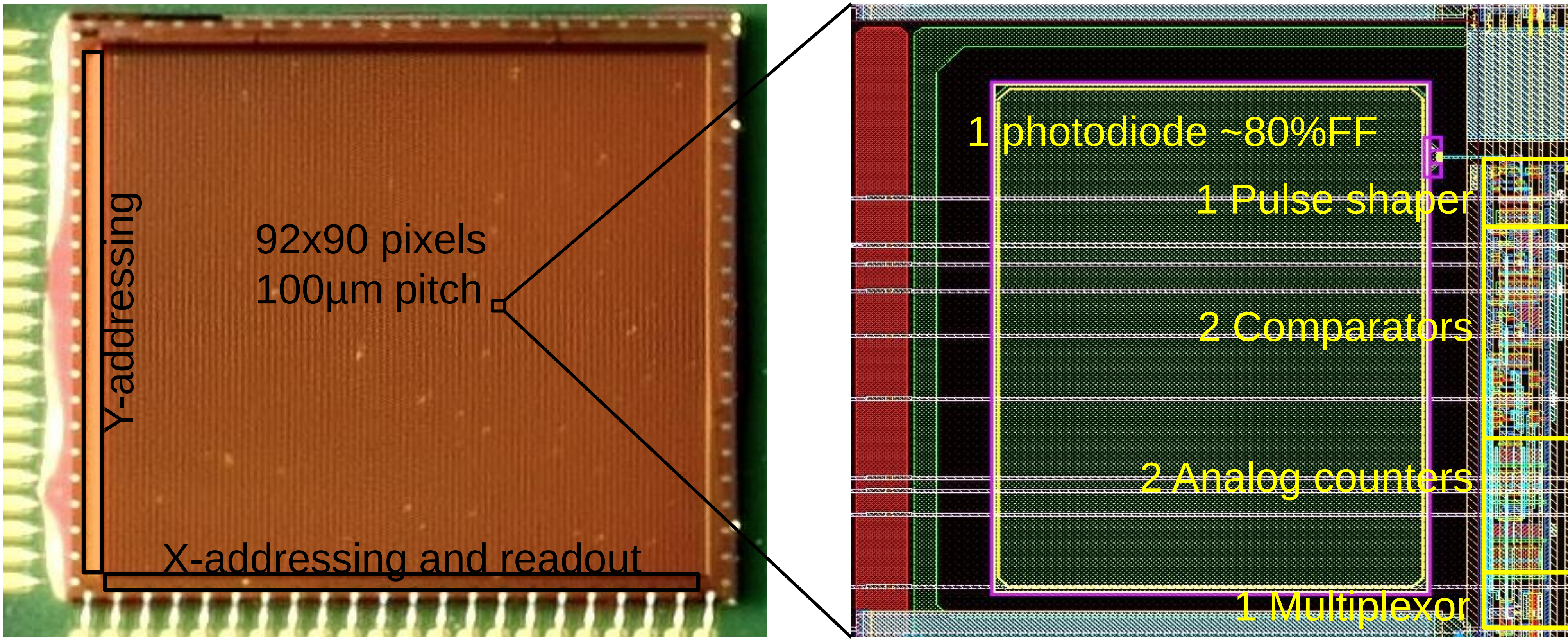
Yet, photon counting can offer superior detectivity

⇒"classic pixel": 3 transistors or 4 transistors / pixel

⇒"brute force photon counter": 500...1000 transistors/pixel

⇒Caeleste approach: analog domain photon counting, ~30 T/pixel

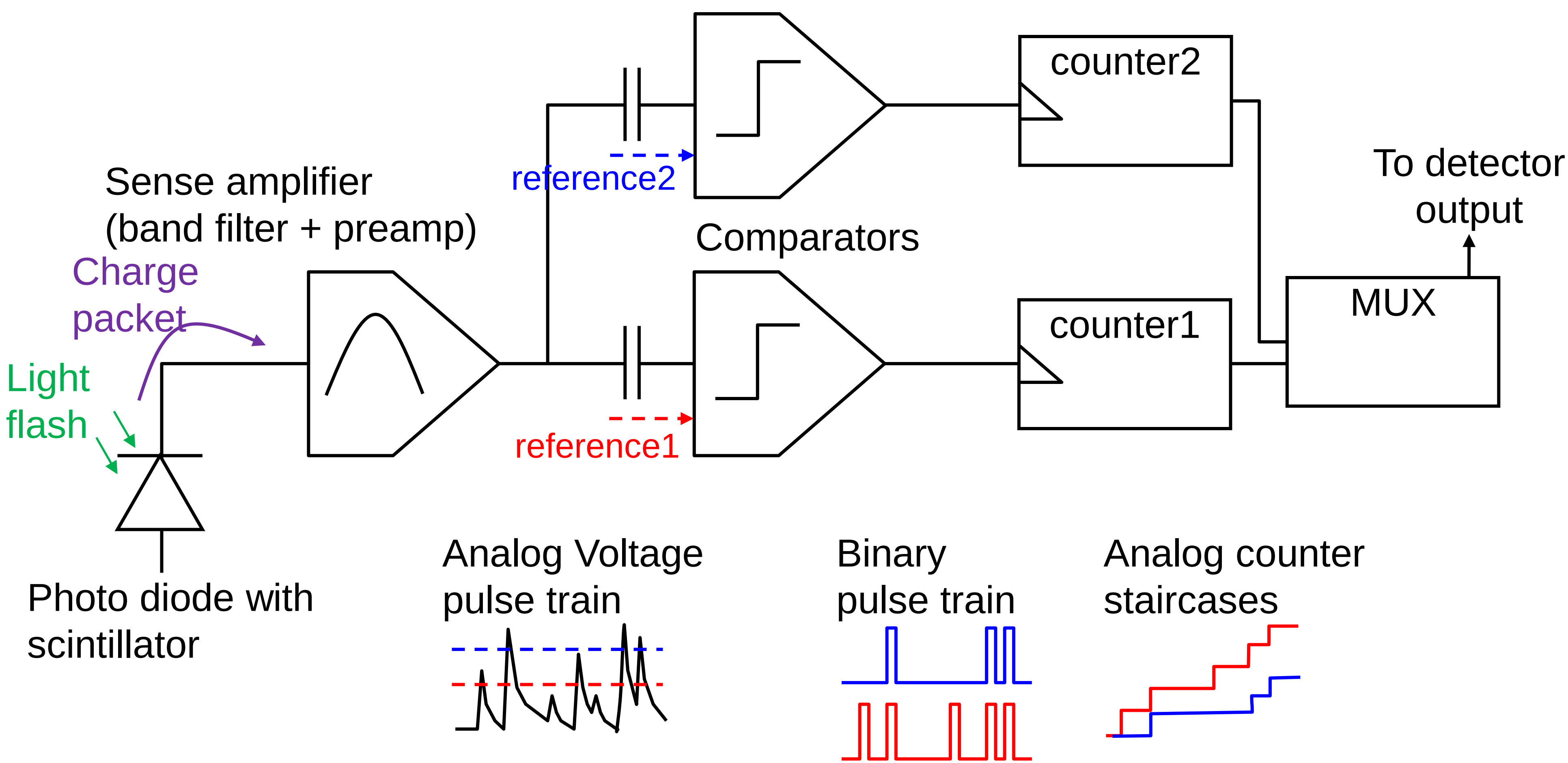
QX2010 device
2-energy photon counting with 45 T/pixel



B.Dierickx, S.Vandewiele, B.Dupont, A.Defernez, N.Witvrouwen, D.Uwaerts, “Two-color indirect X-ray photon counting image sensor”, IISW 2013

QX2010 pixel topology: a two energy channel counter

caeleste



Radiation damage

Total Dose & Single Events

TID total ionizing dose

Radiation:

⇒Primarily X, γ, but essentially all particles

Degradation mechanism:

⇒Creation of positive space charge in the SiO2 (SiN) dielectric layers. MOSFET failure after ~100kRad

⇒Creation of interface states at Si-SiO2 interface

⇒Gradual increase of dark current

⇒*Particles:* displacement damage creating “hot” and “RTS” (blinking) pixels

TID total ionizing dose

Effect on CMOS circuits:

⇒ Moderate shift of Vth & μ degradation and 1/f noise increase

⇒ Parasitic S-D leakage via STI/field in nMOSFETs resulting in large dissipation and malfunction

Effect on CMOS pixels:

⇒ Moderate offset shift and 1/f noise increase

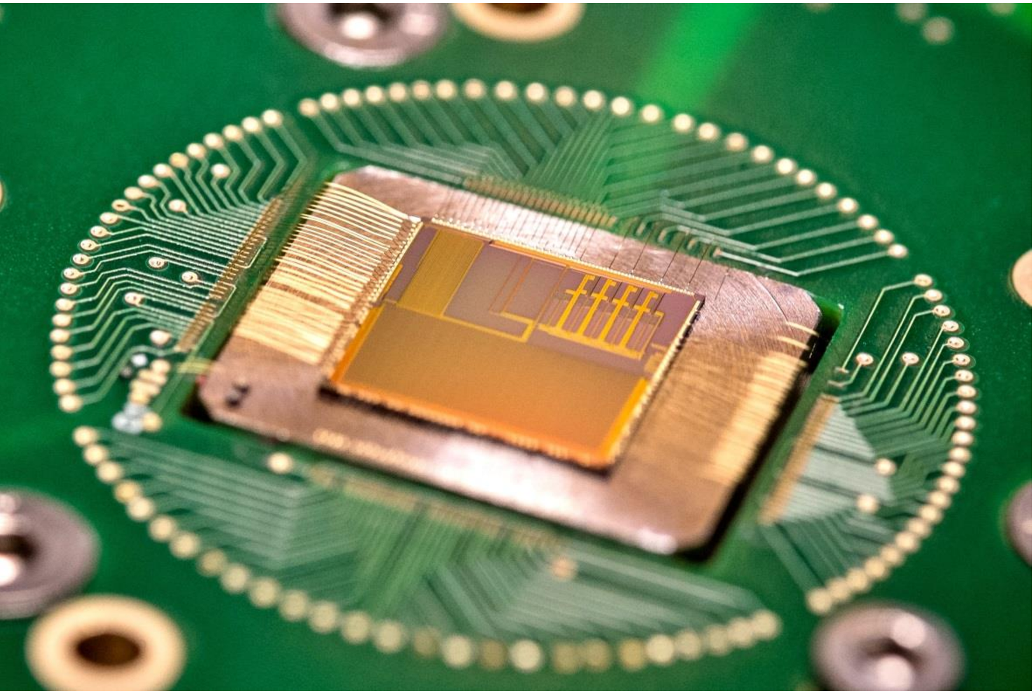
⇒ Lateral shunting between pixels

⇒ Lower gain and increased PRNU

⇒ Increased average Dark Current , DNSU and DCSN

caeleste

The “CES” IR ROIC



Fully radhard & $cryo_{77K}$

UMC018

Digital: DARE library

Analog: CaelesteRH

>>1MRad

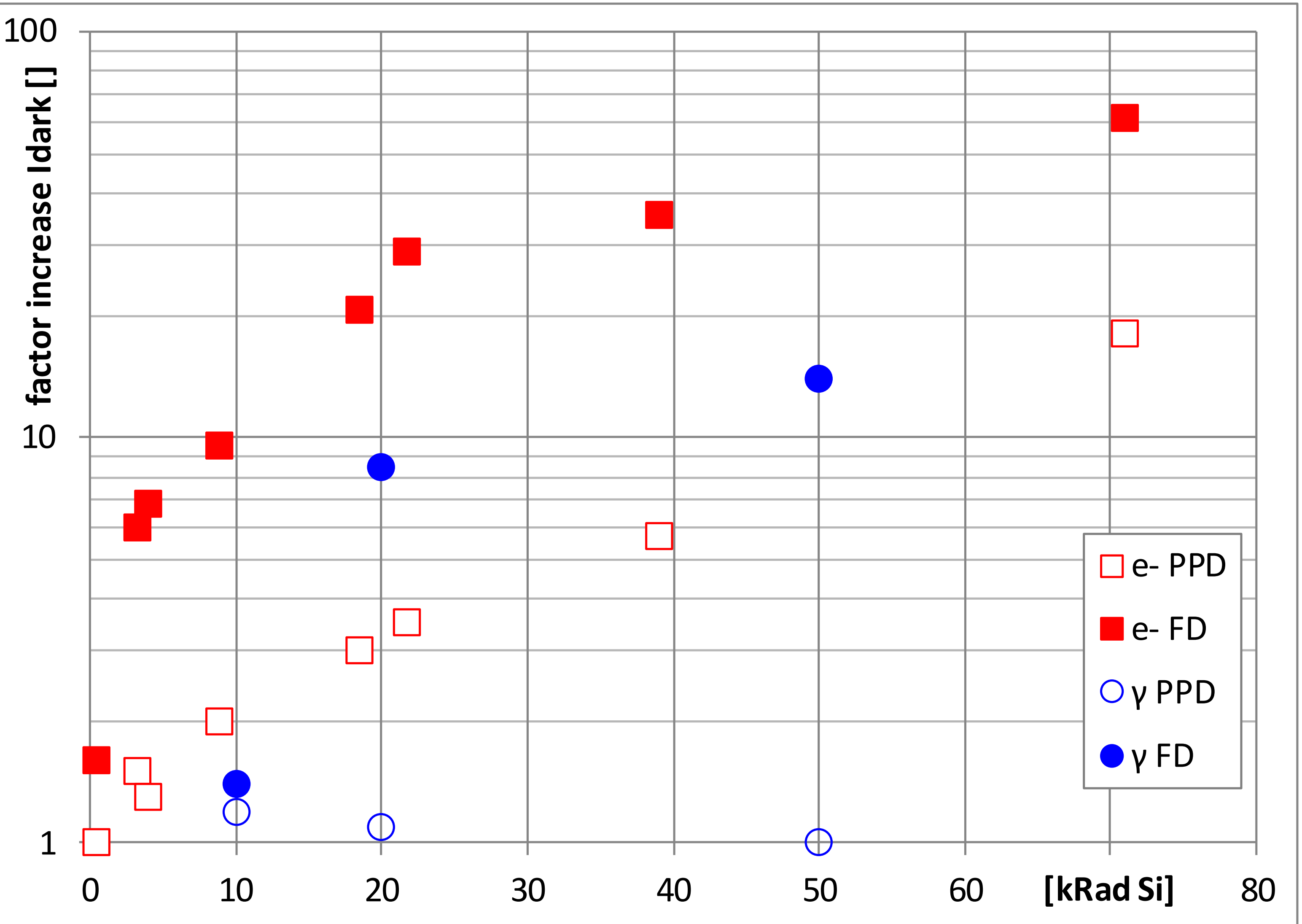
ESA consortium

Caeleste+Easics+Selex

2014

TID Gamma ≠ Electrons

caeleste



TID of

- 300keV electrons
- 1.2/1.3 MeV gamma ^{60}Co

LAP2010 device

Tower TSL018

10 devices; many pixels per device

I_{dark} Effect on

- Buried PPD
- Surface FD

SE[U]

single event [upset]

Also SEE, SEFI, SET, SEGR, SEB, SEL ...

SEU

Radiation

⇒X, γ, e-, and heavier particles

Dominant effect :

⇒Creation of instantanous + or – charge packet

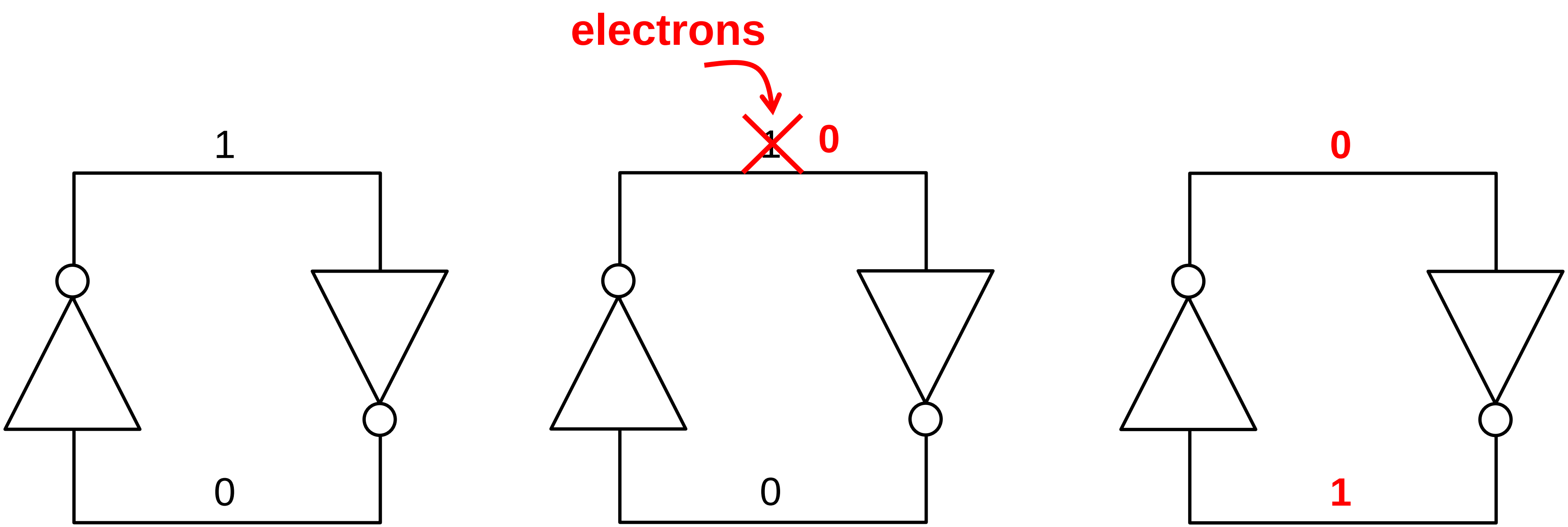
Effect on CMOS and CMOS pixels:

⇒ register or memory losing information

⇒ flash seen by the photodiode

SEU

⇒The loss of bits in SRAM cells or Flip-flops



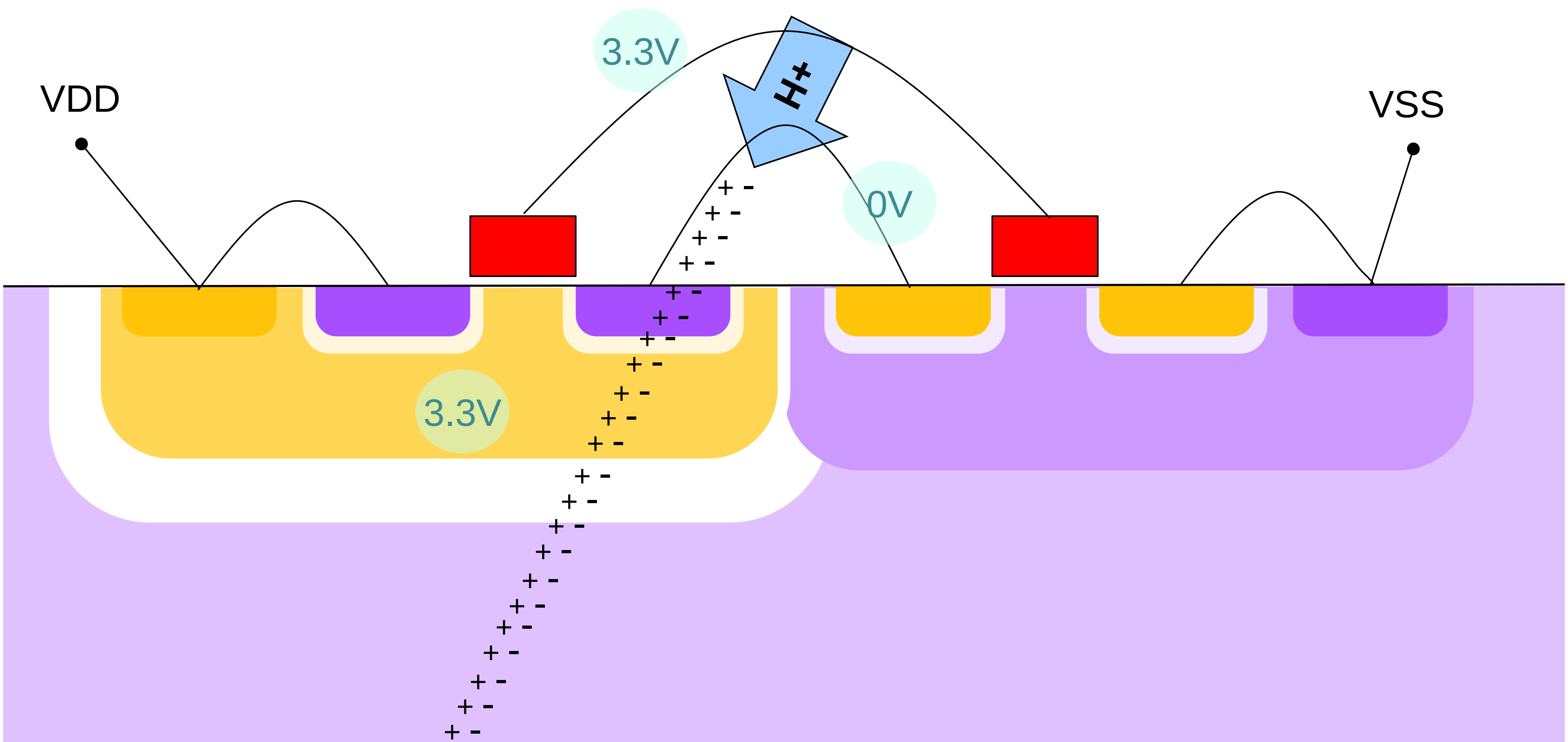
SEU

Mechanism

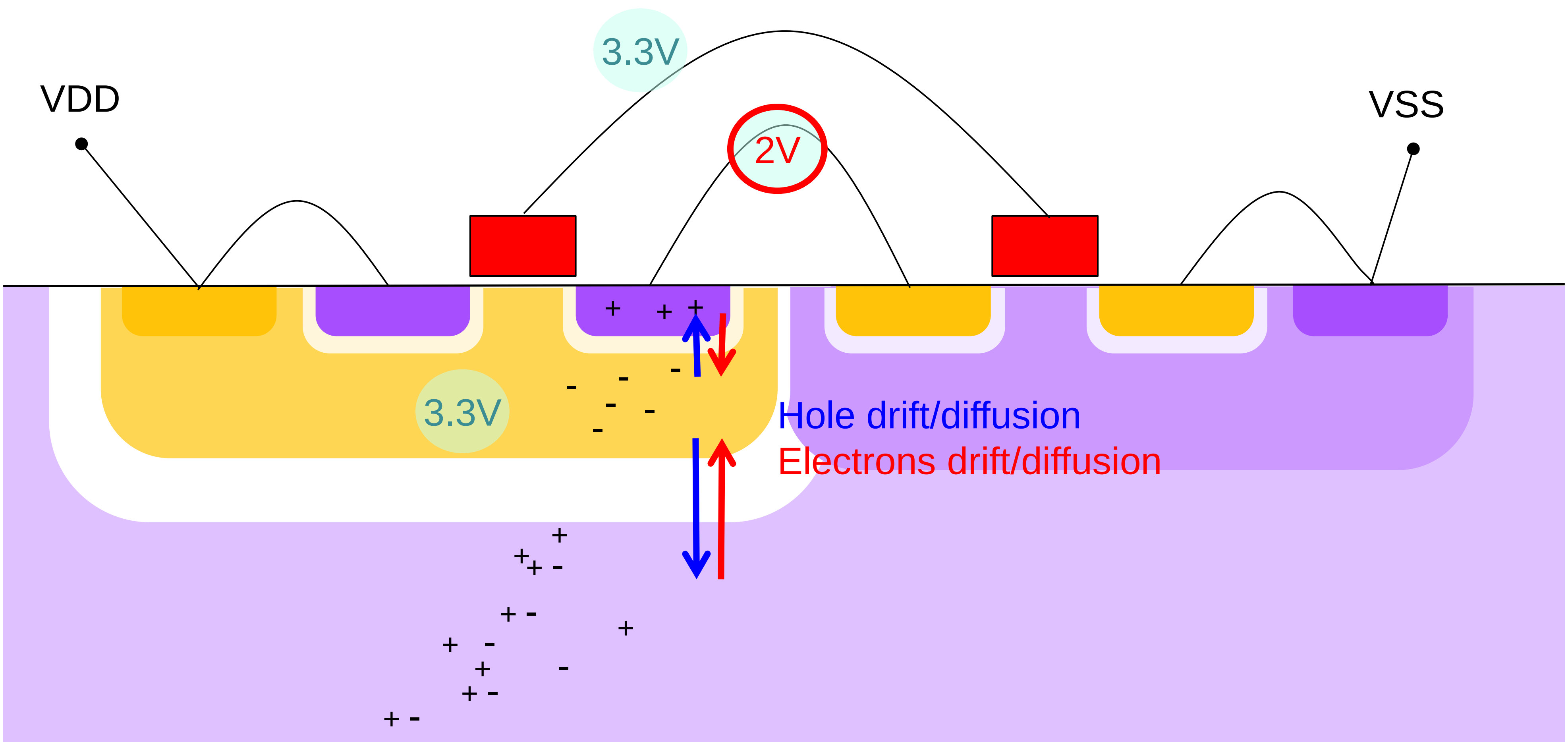
- Particle deposited charge packet charges one node of a latch to the opposite logic value

caeleste

Flipping the invertor @t_0

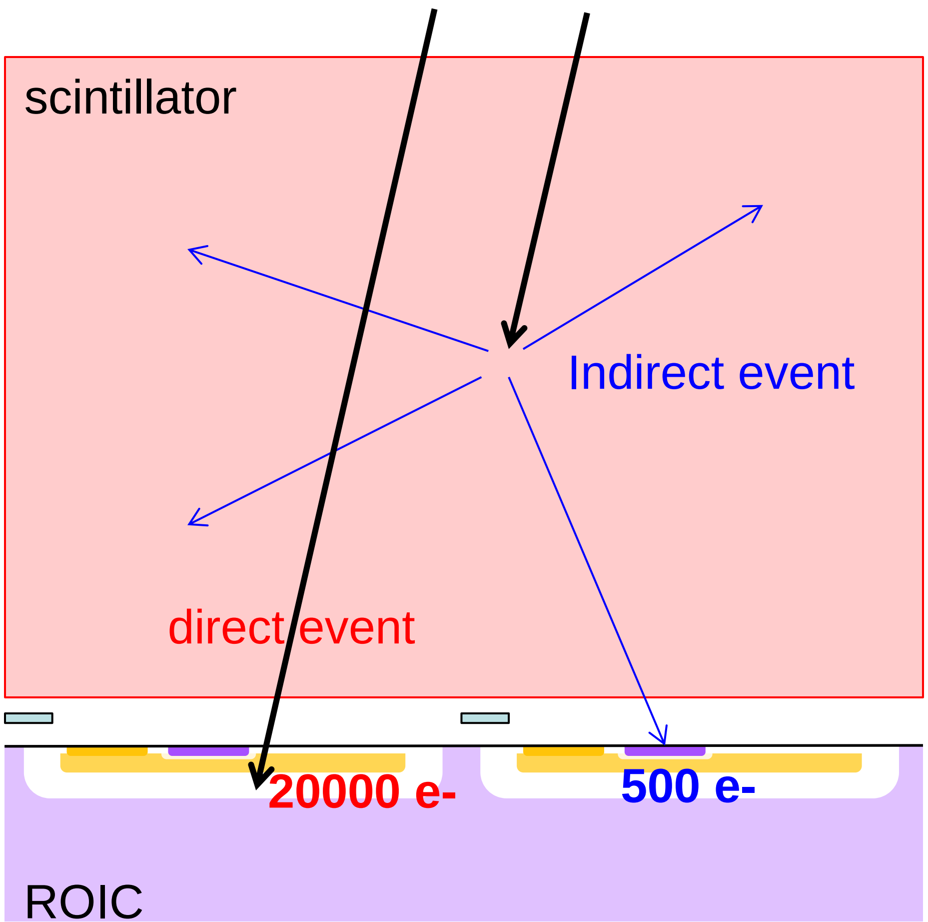


Flipping the invertor @t_0+0.5ns



A direct detection in an indirect detector is a kind of SEU

caeleste



ROIC:

- Shallow optical volume
- Low capture cross section
- Direct event **~20000 e-**

Scintillator

- Near complete absorption
- Indirect event **~500 e-**

“salt & pepper noise”

Calibration

The limits of calibration

What is calibration?

caeleste

real/raw pixel Signal = *ideal* pixel Signal + Noise

“Noise” = error on the measurement

Calibration =

Retrieving the ideal pixel signal, off-chip, after the measurements

Using calibration information

⇒Environmental (°T)

⇒Calibration frames

Why calibration

caeleste

Noise has many contributors

⇒Contributors can be split in temporal and spatial

⇒Contributors can be purely stochastic, or, correlated to a parameter that can be measured outside the pixel in time or space

Hypothesis, claim:

⇒Any such correlated contributor can be calibrated

caeleste

What can be calibrated

Anything that is stable or reproducible over time can be calibrated using a pre- or post-recorded measurement(s)

⇒FPN, PRNU, DSNU and other static “spatial” noises

⇒Column-wise and row-wise FPN, many other cosmetic flaws

⇒Non-linearity.

Anything correlated to an unambiguously known parameter can be calibrated using that parameter

⇒ Temperature drift, using the temperature, and calibration points at an arbitrary number of temperatures

- Thus not: drift due to radiation damage as this damage is not known per-pixel

⇒ Row- or column- correlated pixel noise, versus the reference signal measured on [dark] pixels on those rows/columns

What can not be calibrated

Those contributors that are truely stochastic

⇒ Fundamental read noise — *Yet: photon counting*

⇒ PSN photon shot noise, X-PSN

⇒ DCSN shot noise due to dark current — *Yet: cooling, better materials*

⇒ Swank noise, Fano-noise — *Yet: material choice and geometry*

Those contributors whose underlying mechanism cannot be /are not determined at measurement time

⇒ Radiation damage effect on FPN, PRNU, DCNU, drift

Defects

⇒ Defect pixels or groups of pixels — *Yet: spatial interpolation, algorithmic adaptations*

What is imperfectly calibrated

Where the calibration operation itself induces S/N loss

⇒ Numerical operations and finite accuracy (ADC ENOB)

⇒ subtraction of large numbers: offset correction of pixels with large dark current: reduces range

⇒ correlated double sampling

Where we optimize one parameter sacrificing another

⇒ MTF ("sharpness") deconvolutions increase noise

⇒ Numerical linearization affecting $\partial S/\partial power$ or $\partial N/\partial power$ hence $\partial S/\partial N$

Where the calibration data drifts too fast or is too complex to be tracked

⇒ 1/f noise (flicker noise) in MOSFETs

⇒ Power-on transients

⇒ Electronic crosstalk, EMI, supply&ground noise

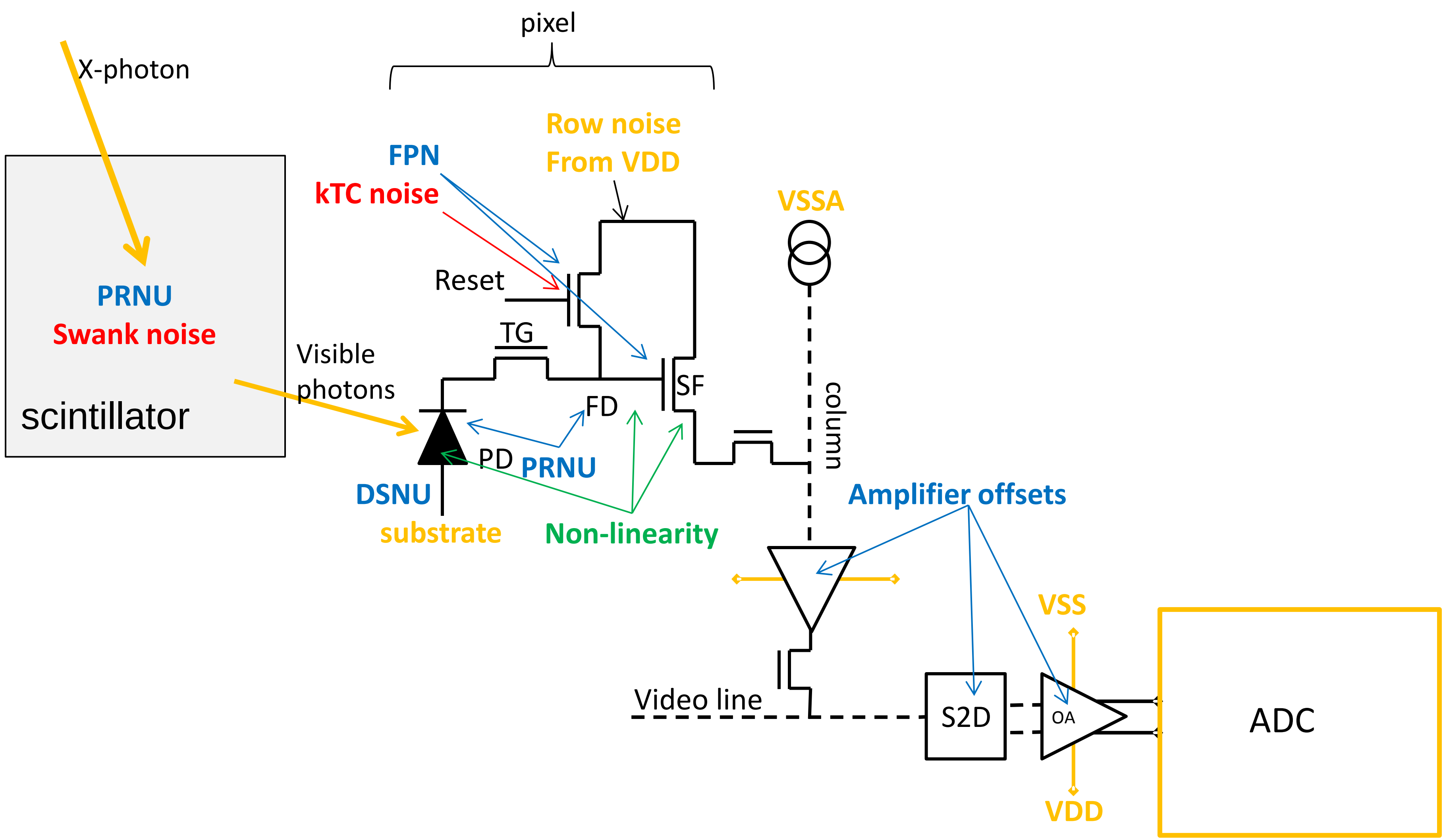
How should you calibrate?

General rule

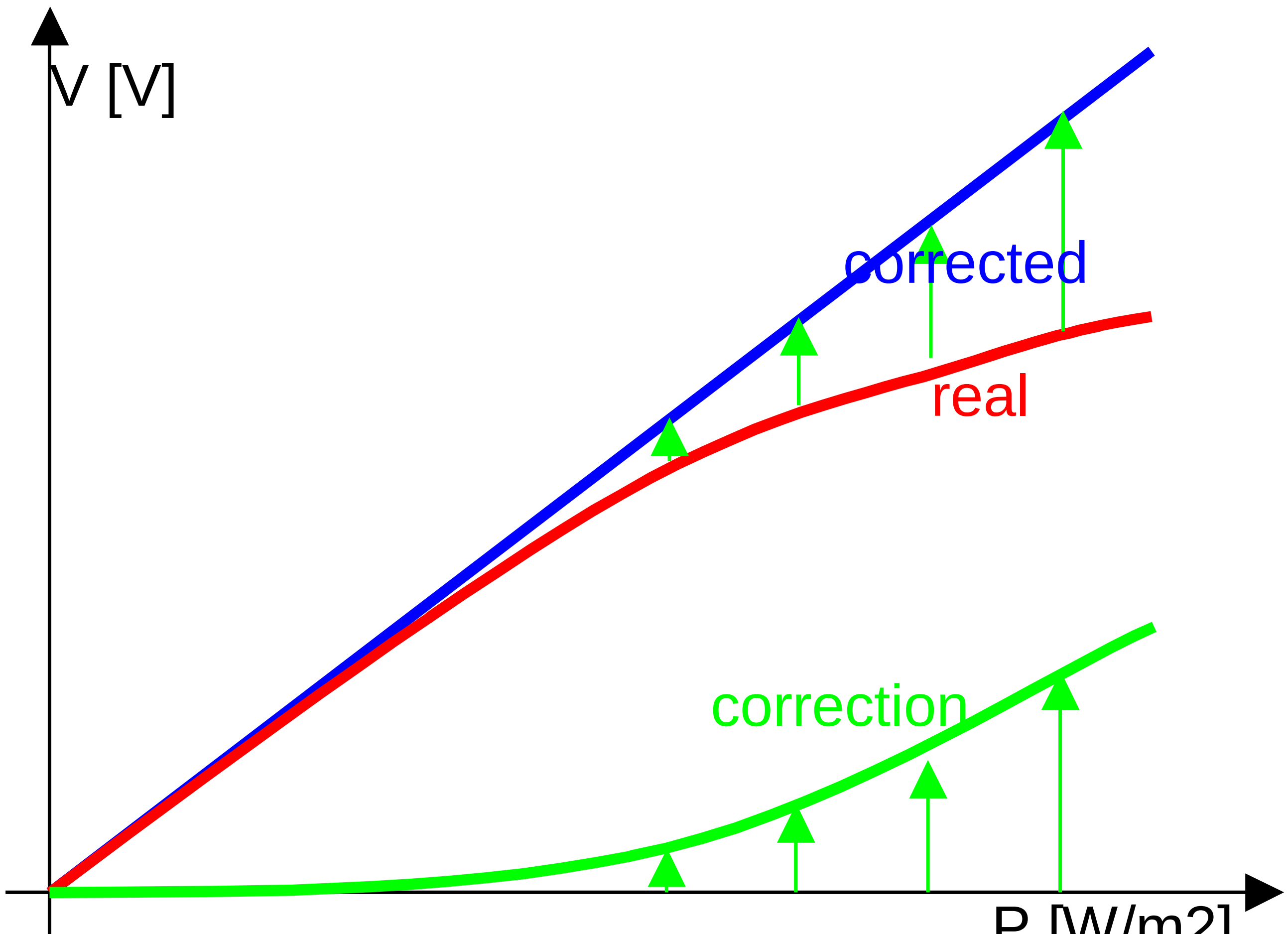
⇒Calibration happens in the reverse order of the occurrence of the contributors

Signal path

caeleste



Non-linearity



Non-linearity makes calibration hard

Example for static noises, scintillator based detection, pixel only

As entering the signal

*PRNU due to scintillator
*PRNU due to photodiode
+DSNU of photodiode
+FPN due to RESET transistor
~Non-linearity of FD
*PRNU due to FD
*DSNU of FD
+°T drift of SF
+FPN due to SF
~Non-linearity of SF

Calibration sequence

inverse~ SF non-linearity
-FPN due to SF
-°T effect of SF
-DSNU of FD
/PRNU due to FD
inverse~ FD non-linearity
-FPN of RESET transistor
-DSNU of photodiode
/PRNU due to photodiode
/PRNU due to scintillator

Non-linearity makes calibration hard

Example for static noises, scintillator based detection, pixel only

As entering the signal

*PRNU due to scintillator
*PRNU due to photodiode
+DSNU of photodiode
+FPN due to RESET transistor
~Non-linearity of FD
*PRNU due to FD
*DSNU of FD
+°T drift of SF
+FPN due to SF
~Non-linearity of SF

Cannot be measured separately!

Not easy to measure separately
And if so, comes with noise penalty

Calibration sequence

inverse~ SF non-linearity
-FPN due to SF
-°T effect of SF
-DSNU of FD
/PRNU due to FD
inverse~ FD non-linearity
-FPN of RESET transistor
-DSNU of photodiode
/PRNU due to photodiode
/PRNU due to scintillator

Dual approach to calibrate including non-linearity

caeleste

A.

The linearity(ies) is small

⇒System can still be considered sufficiently linear

⇒All non-linearities combined in one, per pixel, OFFSET+GAIN+NL correction

⇒Often sufficient to approximate NL with a 2nd order term. The error created thus is a GAIN error, =1st order term, calibrated as such.

⇒NL can be identical for all pixels, or have a per-pixel coefficient

$$V_{ideal}(x,y) \approx V_{calibrated}(x,y)$$

$$= a(x,y)) + b(x,y).V_{raw}(x,y) + c(x,y)V_{raw}(x,y)^2 + \ldots$$

Offset FPN,DSNU — Gain PRNU — NL

Dual approach to calibrate including non-linearity

caeleste

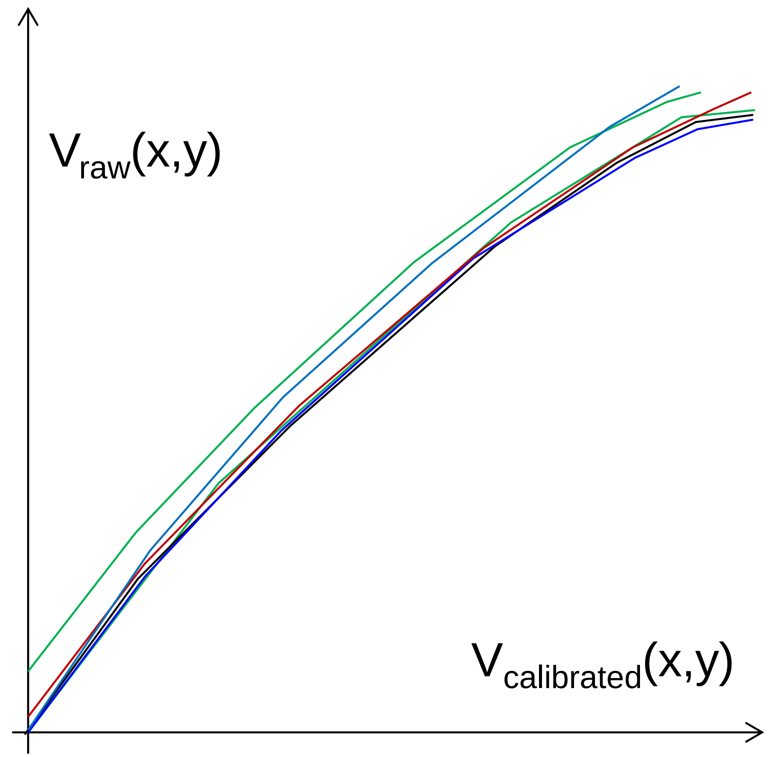
B.

The linearity is large and occurs at multiple places in signal path

→ Per pixel combining all calibrations in 1 polynomial OFFSET+GAIN+NL correction is not possible (not good enough)

→ Brute force
  - → calibrate a per-pixel look-up table, piece-wise linear or interpolatable
  - → do this for every operation condition °T, t_{int}, kVP, settings...

→ Reduce #data by common sense



Take home message

conclusions

Take home

caeleste

Imagers / ROICs are imperfect

⇒ We can blame nature and technology

In theory everything is calibratable, except

⇒ X-photon shot noise (fundamental)

⇒ Swank + PSN (should not be fundamental)

⇒ Read noise, but still made as low as possible

⇒ DCSN, but still made as low as possible

⇒ Hysterisis and other forms of non-reproducibility

Calibration is hard due to non-linearities

Thank you