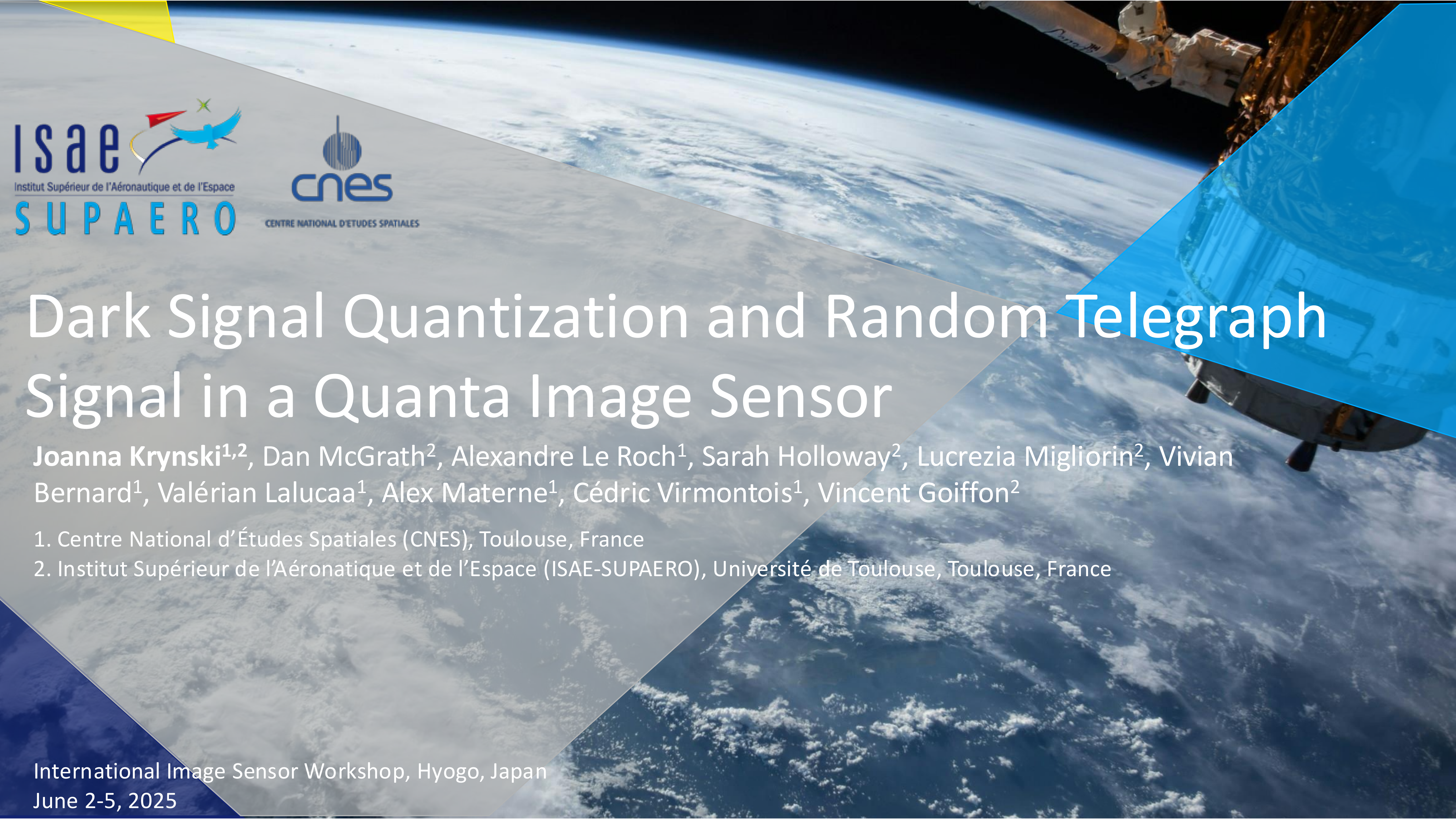


Dark Signal Quantization and Random Telegraph Signal in a Quanta Image Sensor

Joanna Krynski[1,2], Dan McGrath[2], Alexandre Le Roch[1], Sarah Holloway[2], Lucrezia Migliorin[2], Vivian Bernard[1], Valérian Lalucaa[1], Alex Materne[1], Cédric Virmontois[1], Vincent Goiffon[2]

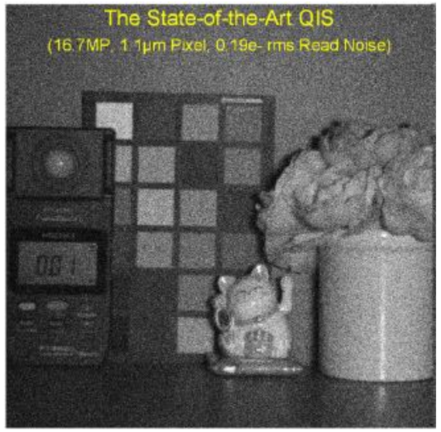
1. Centre National d’Études Spatiales (CNES), Toulouse, France
2. Institut Supérieur de l’Aéronatique et de l’Espace (ISAE-SUPAERO), Université de Toulouse, Toulouse, France

International Image Sensor Workshop, Hyogo, Japan
June 2-5, 2025

Context of study

- Recent advances in CMOS image sensors enables counting of photoelectrons
  - Ultra-low dark current
  - Deep sub-electron read noise

Gigajot Technology Inc., 2021.



Ma, Chan and Fossum, 2022. IEEE Trans. Electron Devices. 69(6).

- Technology-under-test: Gigajot QIS16
  - 1.1 µm pixel pitch, 4096x4096, room temperature operation

- Observation of output signal in absence of light – dark signal – can reveal characteristics of parasitic electron generation

QIS is an electron-counting camera

Technological overview

4-transistor CMOS image sensor pixel layout with high conversion gain (CG) and low noise

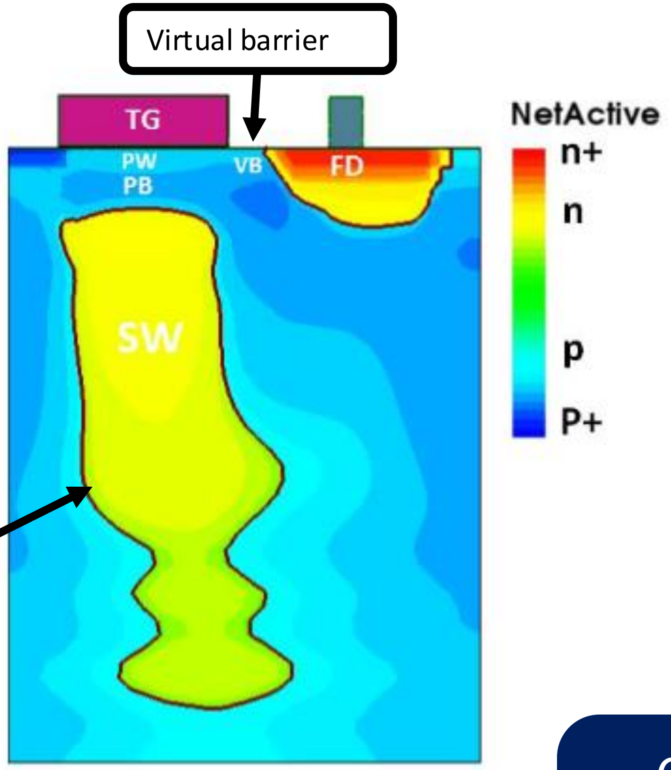
Pump-gate pixel

$$\uparrow \mathrm{CG} = \frac{q}{C_{FD}} \downarrow$$

- ✓ Reduce physical overlap between PD and gates
- ✓ Custom doping profile to isolate FD

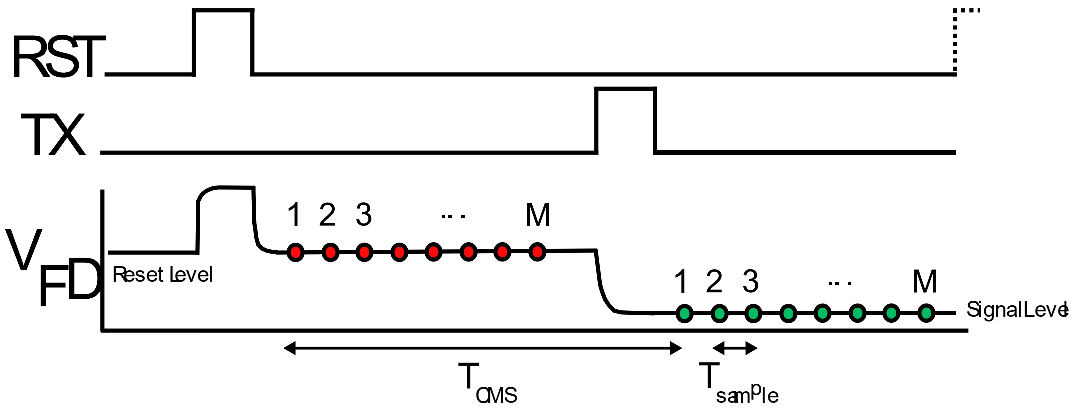
CG = 340 µV/e^-

Ma et al., 2021. IEEE Trans. Electron Device Lett. 42(6).



Ma and Fossum, 2015. IEEE Trans. Electron Device Lett. 36(9).

Correlated Multiple Sampling

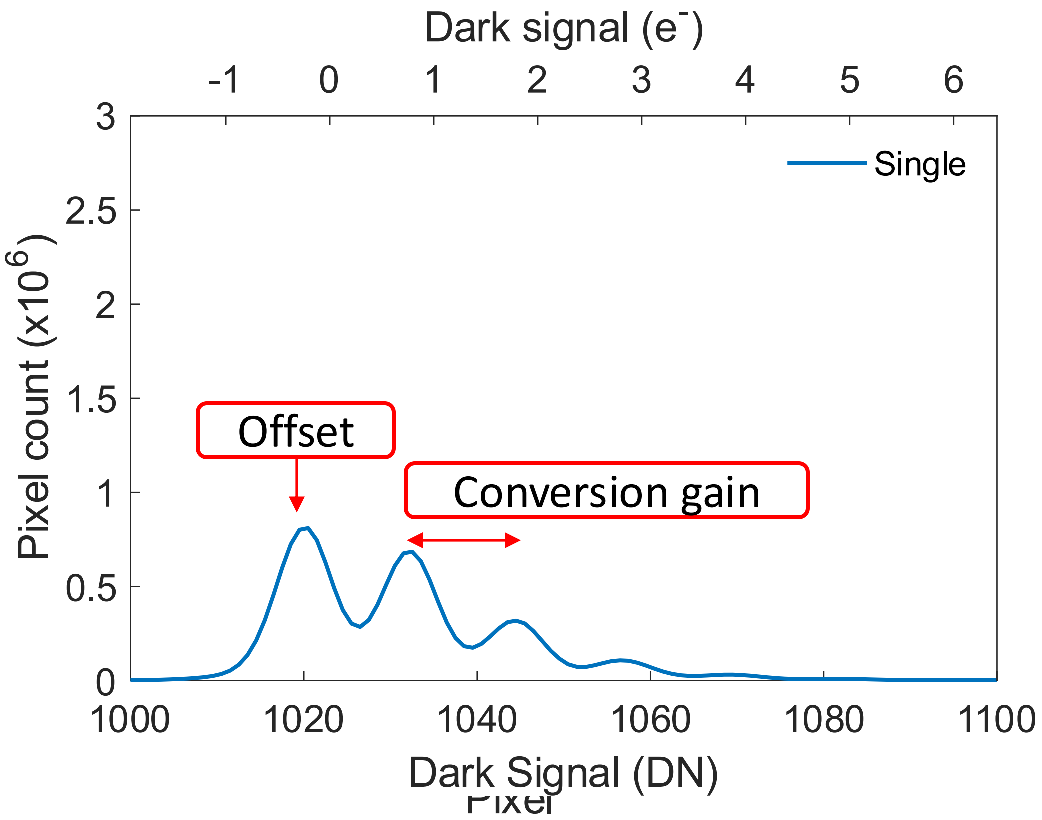


- ✓ Averaging of Reference and Signal levels over M samples reduces correlated noise

Combination of reduced dark current and low noise enables counting of single electrons

Spatial quantization of dark signal

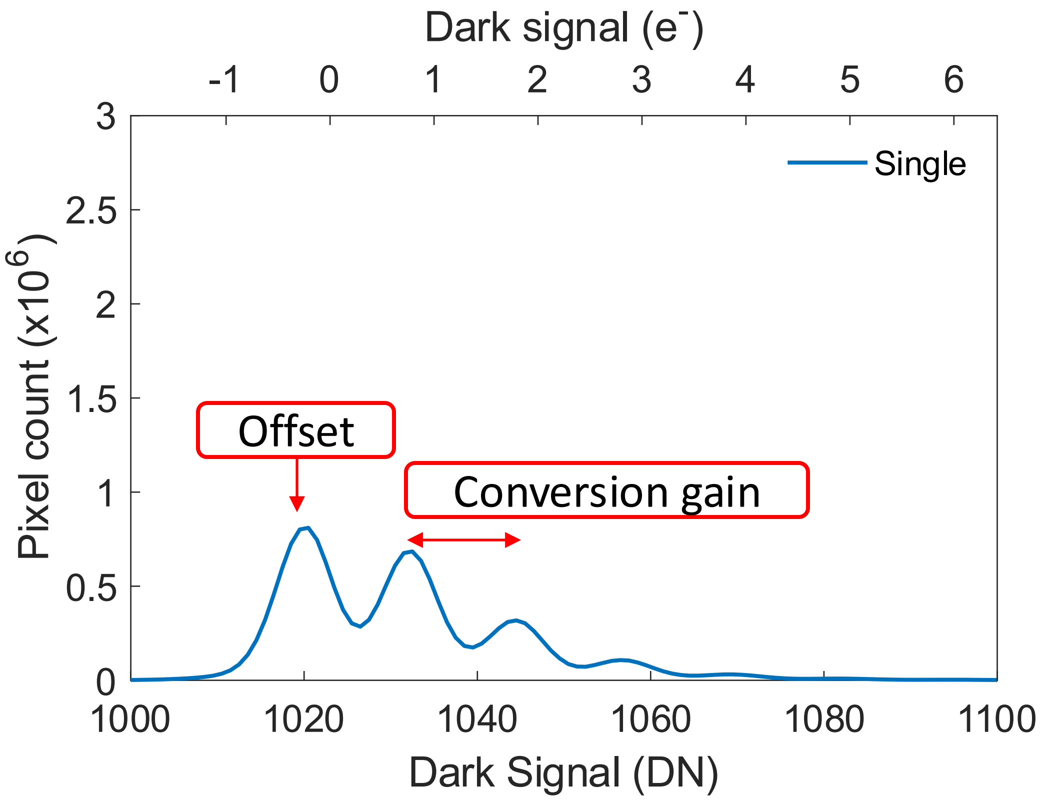
T_{int} = 8 s, T_{sensor} = 40 °C

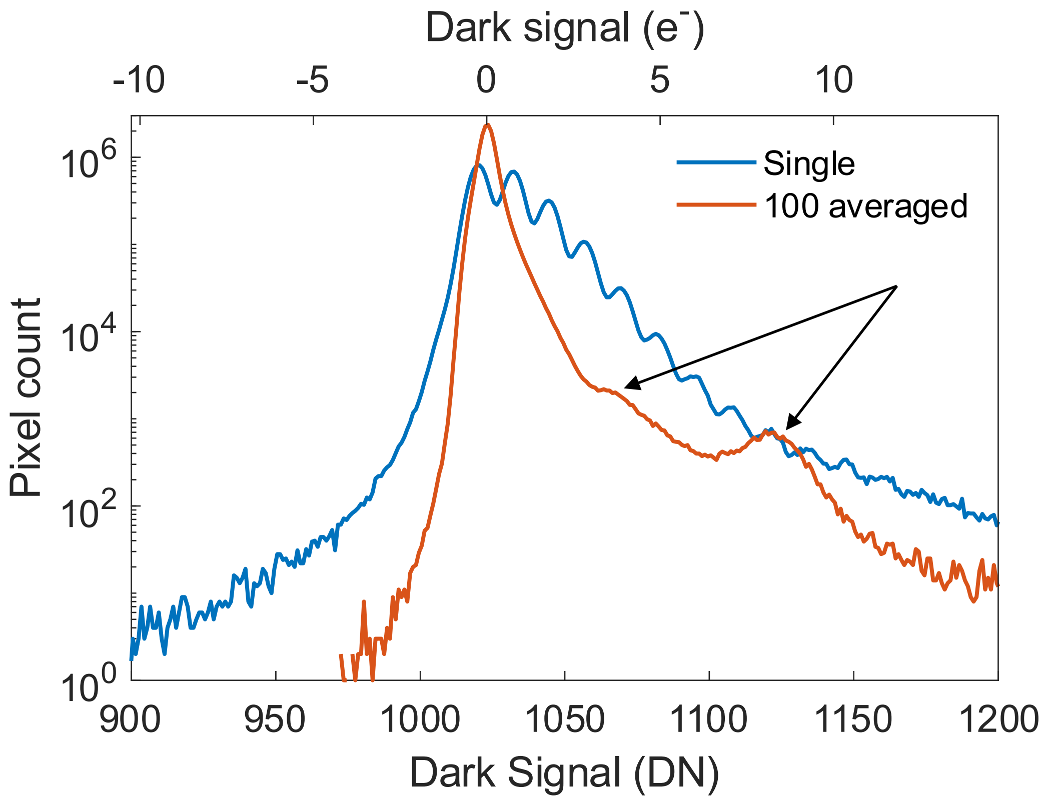


Histogram from single dark frame shows quantization of dark electrons: *Dark carrier Counting Histogram* (DCH)

Spatial quantization of dark signal

T_{int} = 8 s, T_{sensor} = 40 °C



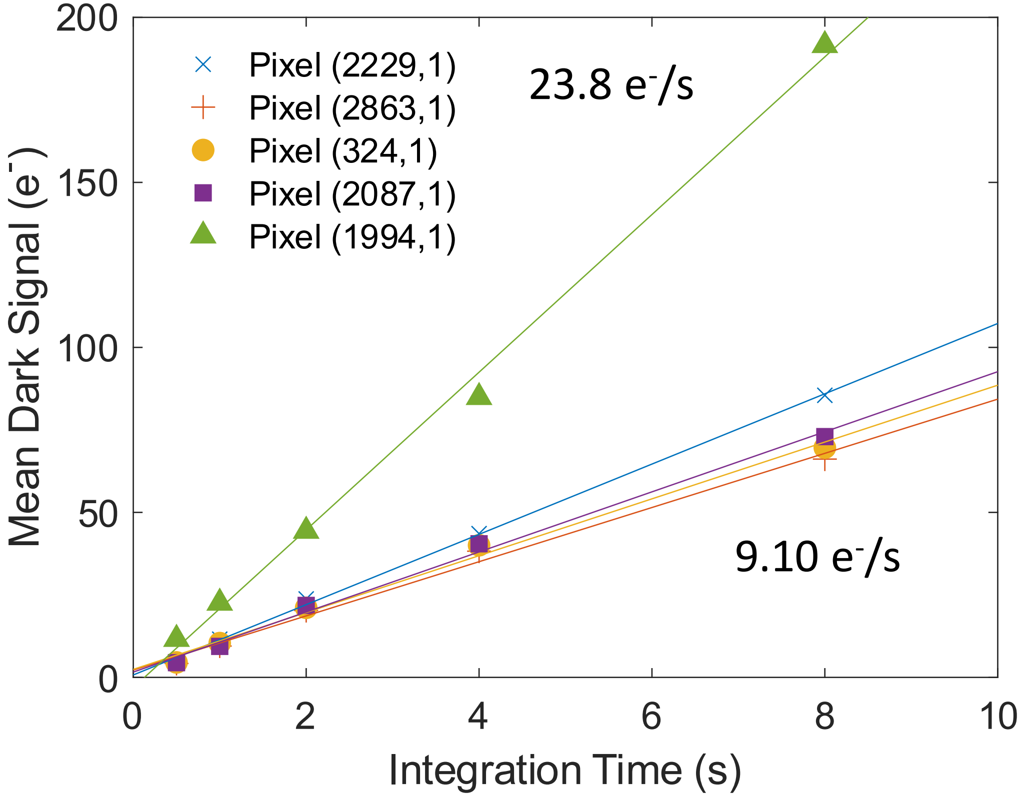


Histogram from single dark frame shows quantization of dark electrons: *Dark carrier Counting Histogram* (DCH)

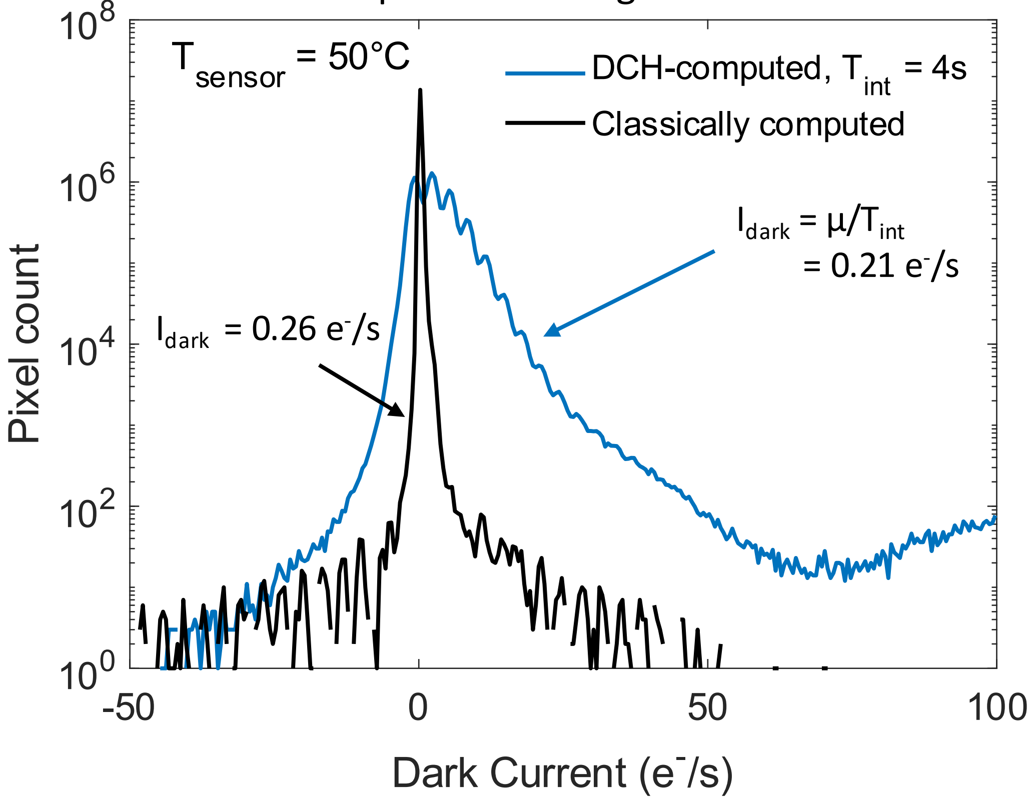
Averaging blurs electron peaks but reveals characteristics related to defects

DCH versus dark current histogram

"Classical" extraction of dark current

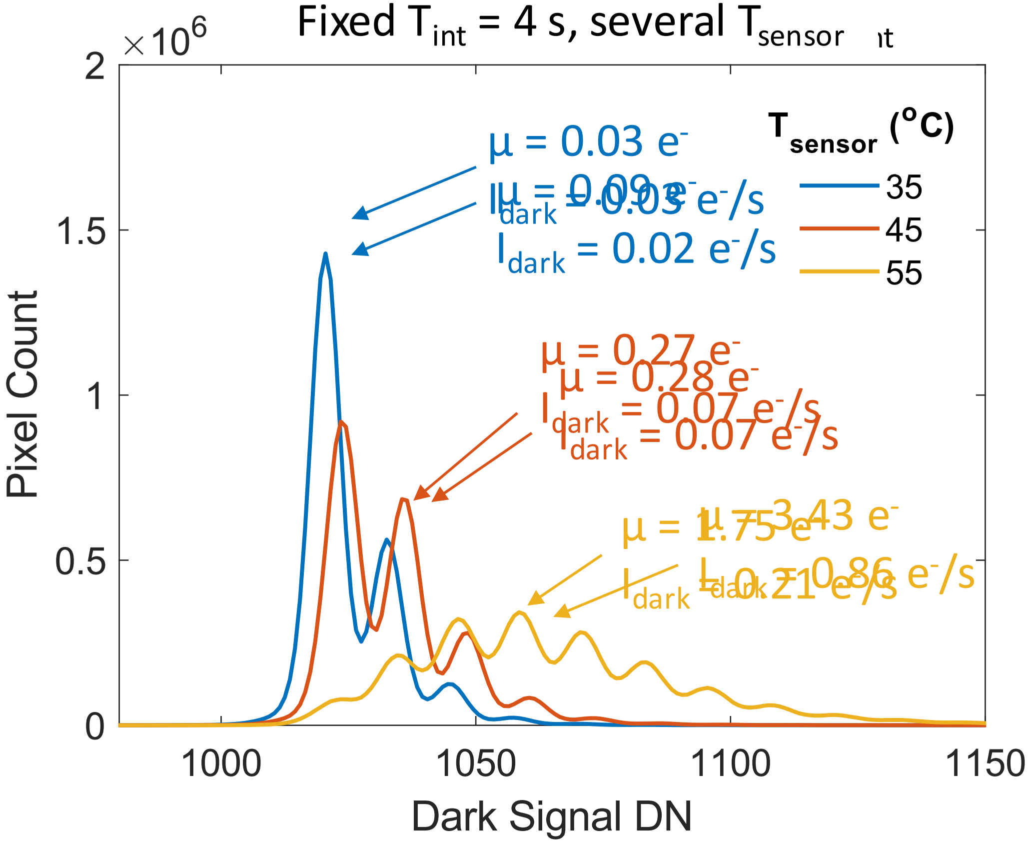


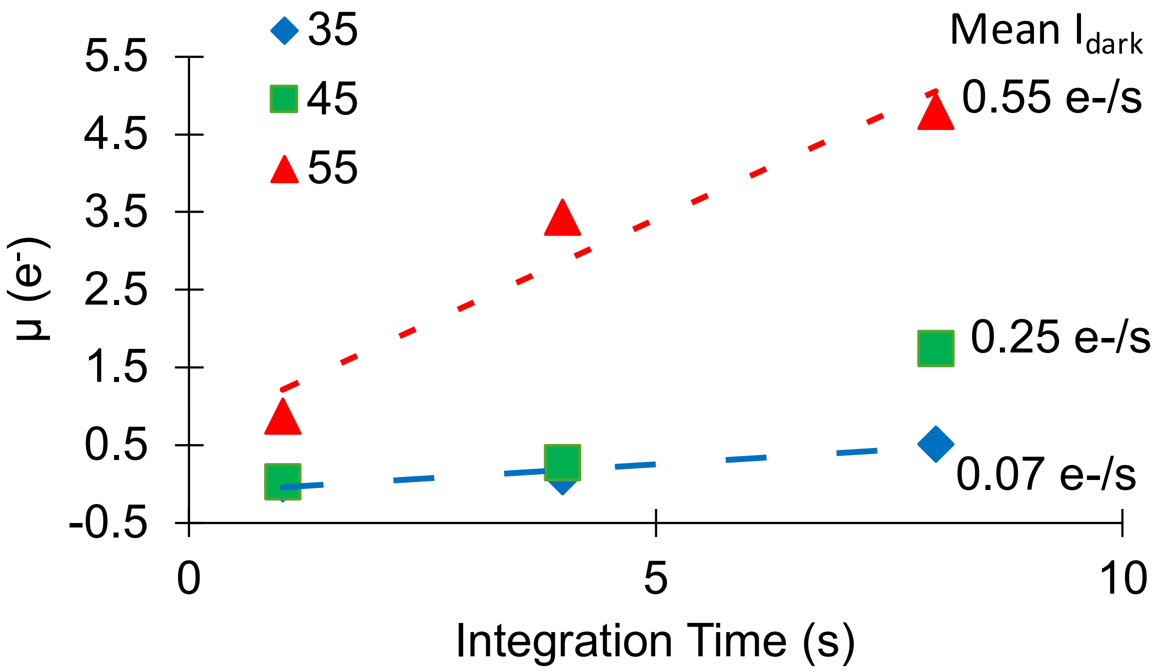
1. Take dark frames for several integration times
2. Average mean signal per pixel, plot against time
3. Extract slope in linear regression



Averaging dark frames to calculate dark current reinforces mean value of distribution

Dark signal evolution with T_{int} and Temperature

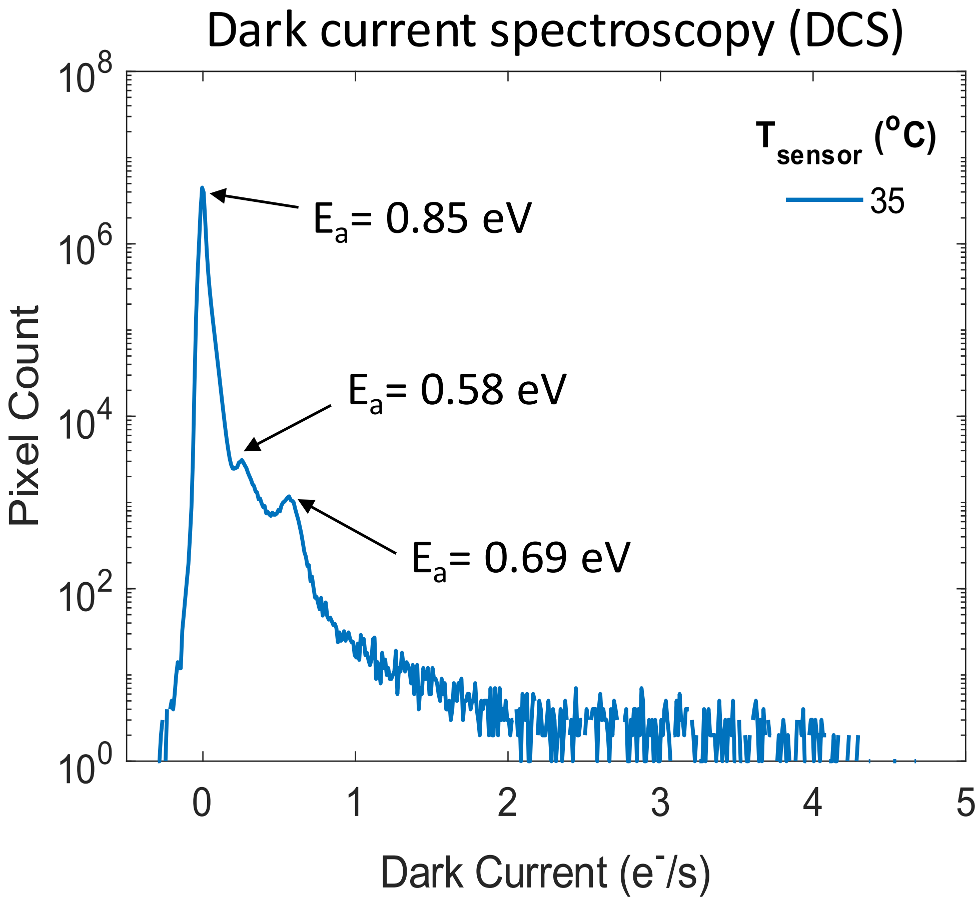


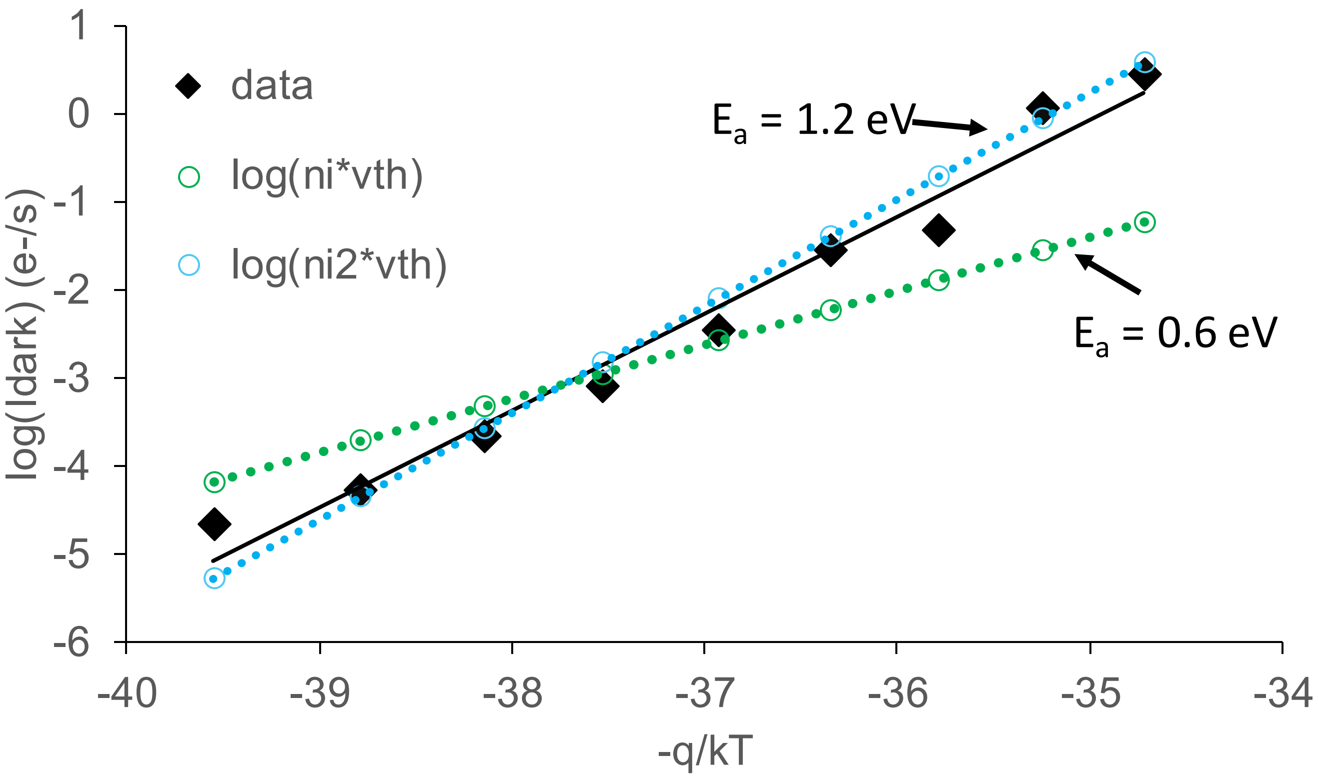


Number of peaks and mean of distribution augment with T_{int} and Temperature

Dark current can be calculated using a single dark frame or with several dark frames

Dark current evolution with temperature

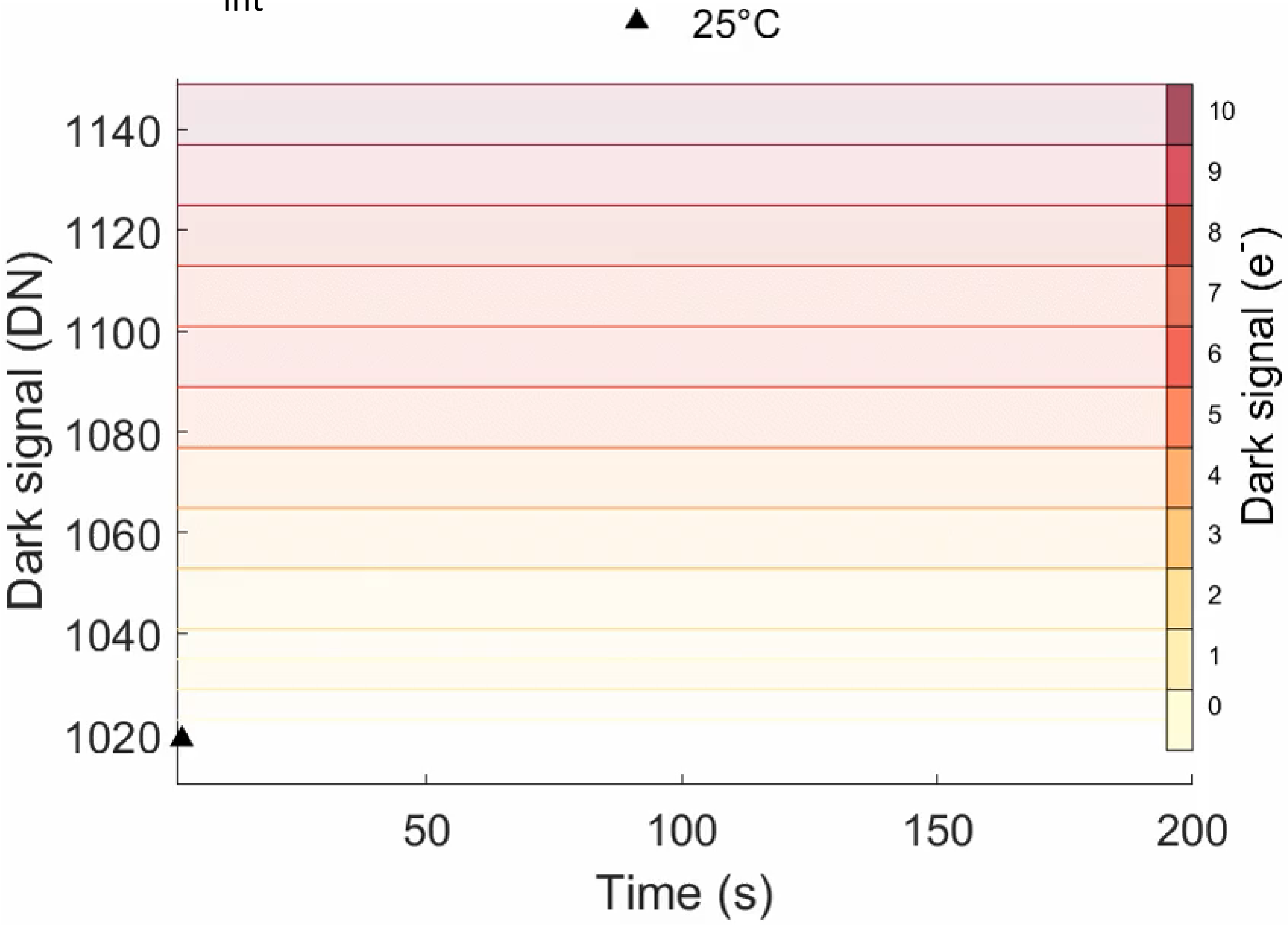




Further study of peaks will enable identification of remaining active defects in ultra-low dark current CIS

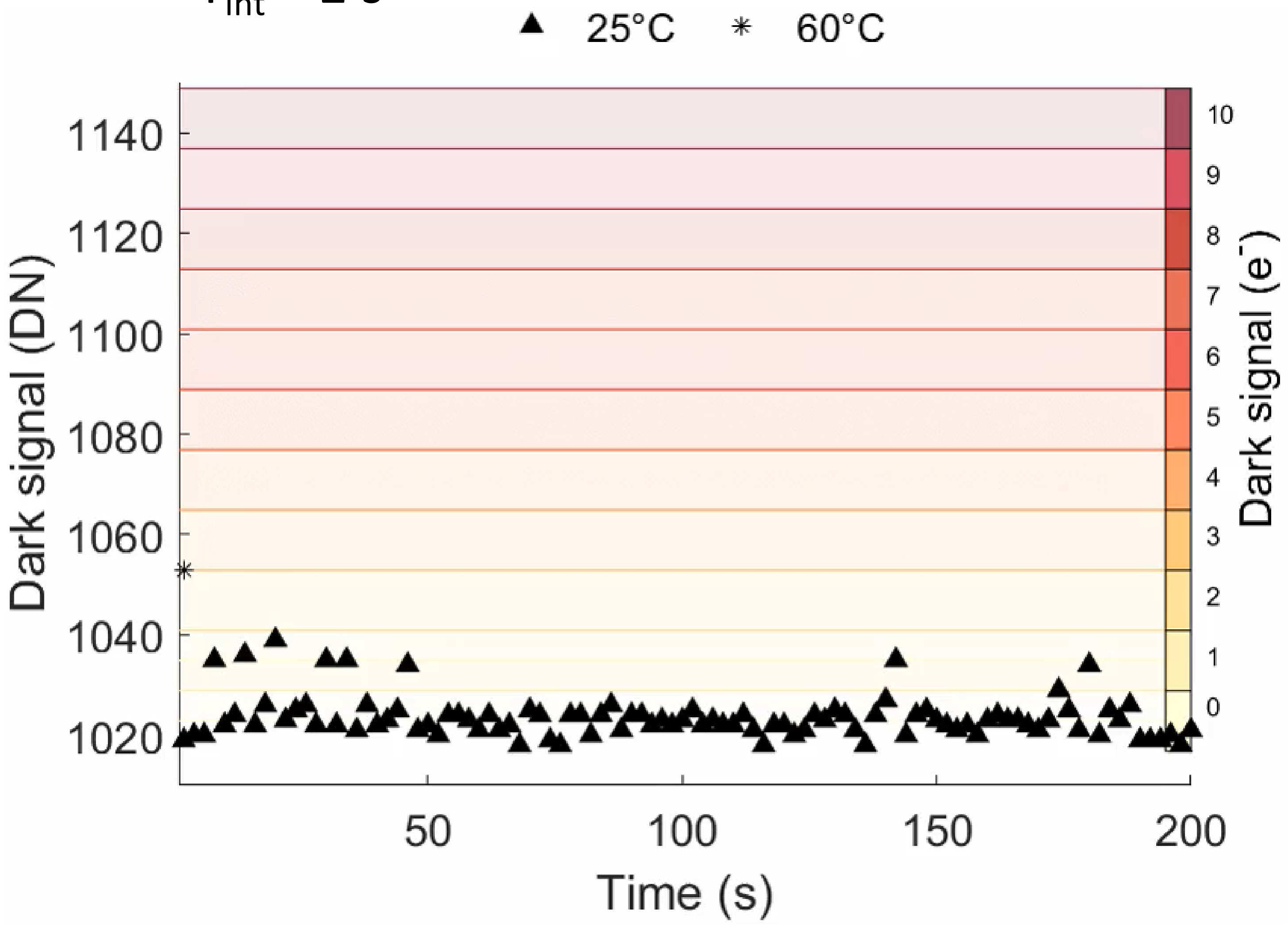
Observing single electron generation

$T_{int} = 2$ s

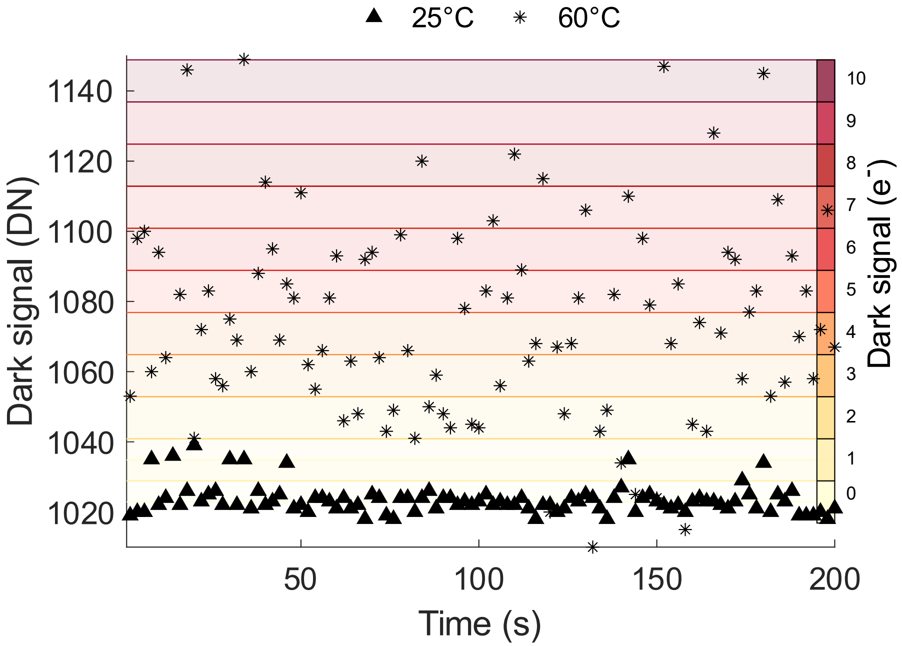


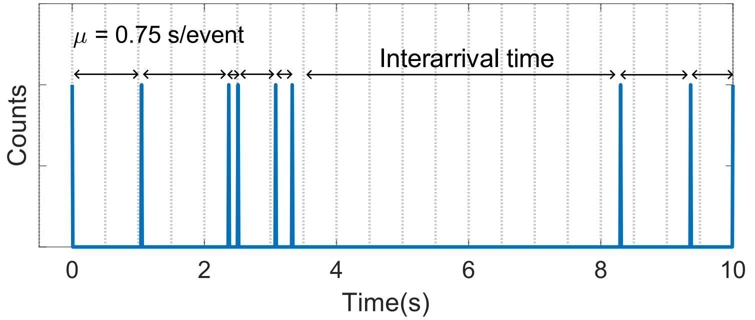
Observing single electron generation

$T_{int} = 2$ s

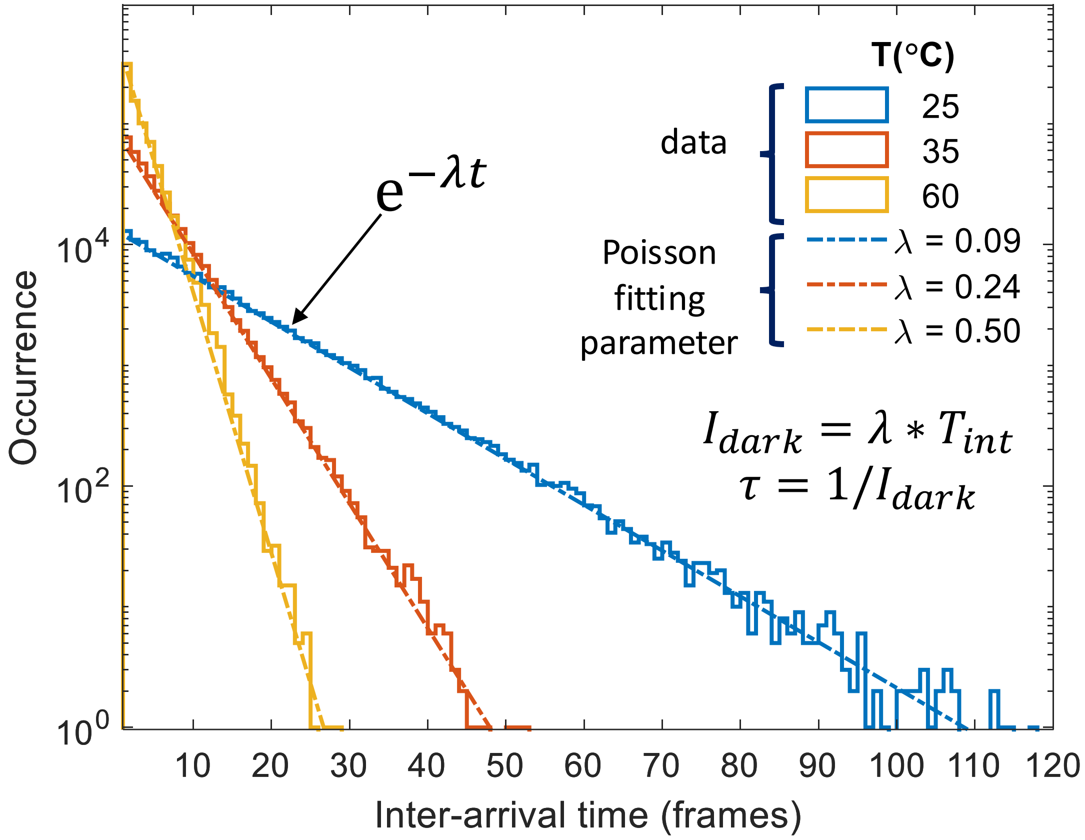


Observing single electron generation



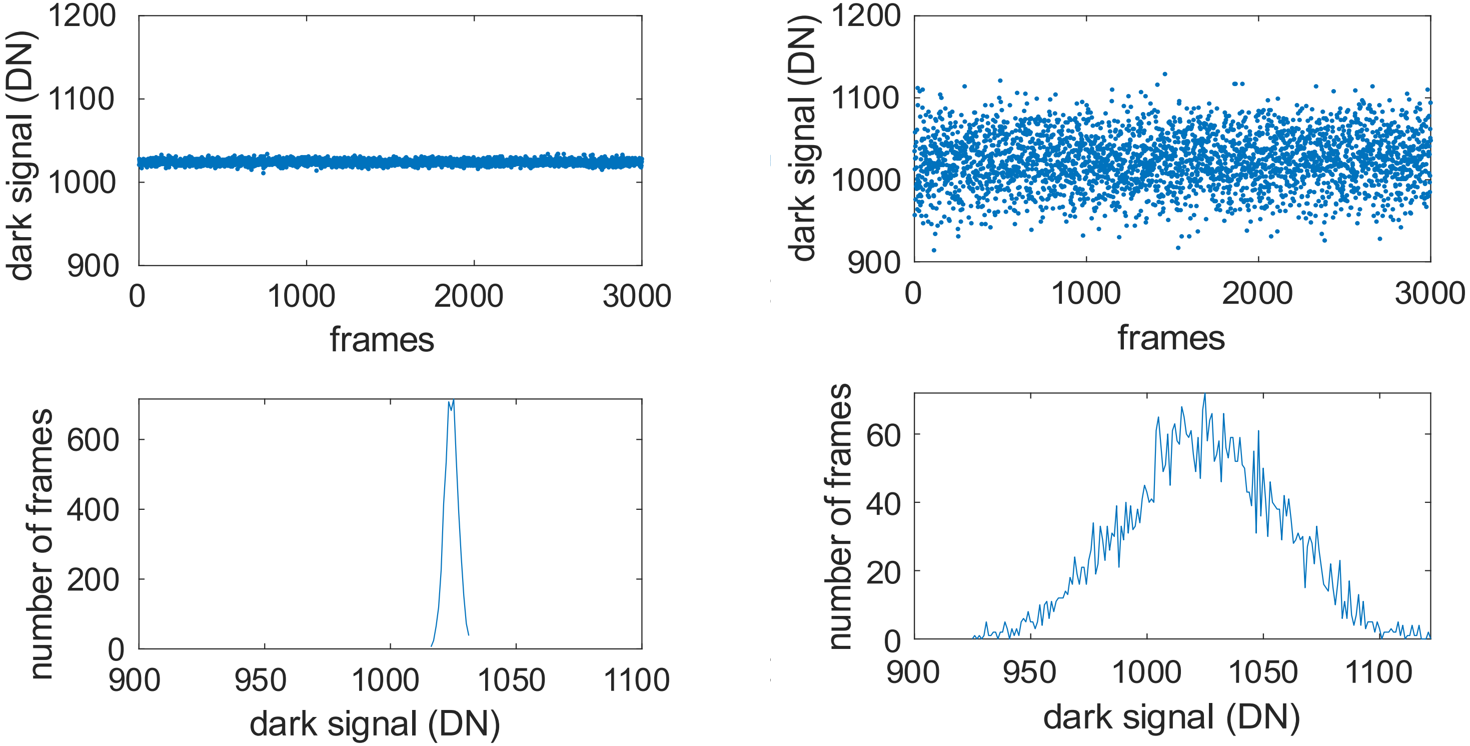


T_{int} = 2 s, 16 000 frames, T_{sensor} = 25 – 60°C



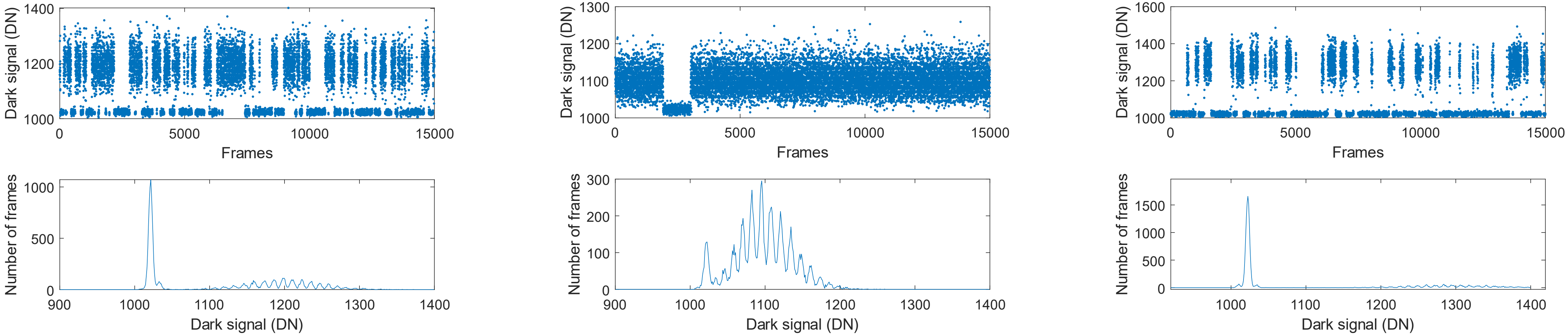
Poisson distribution of electron generation is well observed
Single mean parameter λ describes pixel dark current and carrier lifetime

Dark signal phenomena



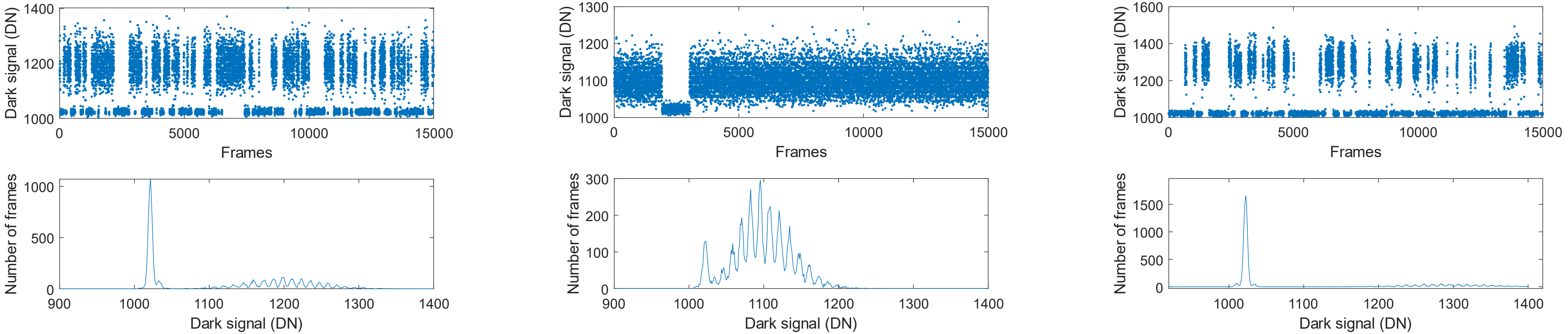
Vast majority of pixels exhibit small mean dark signal and low temporal noise

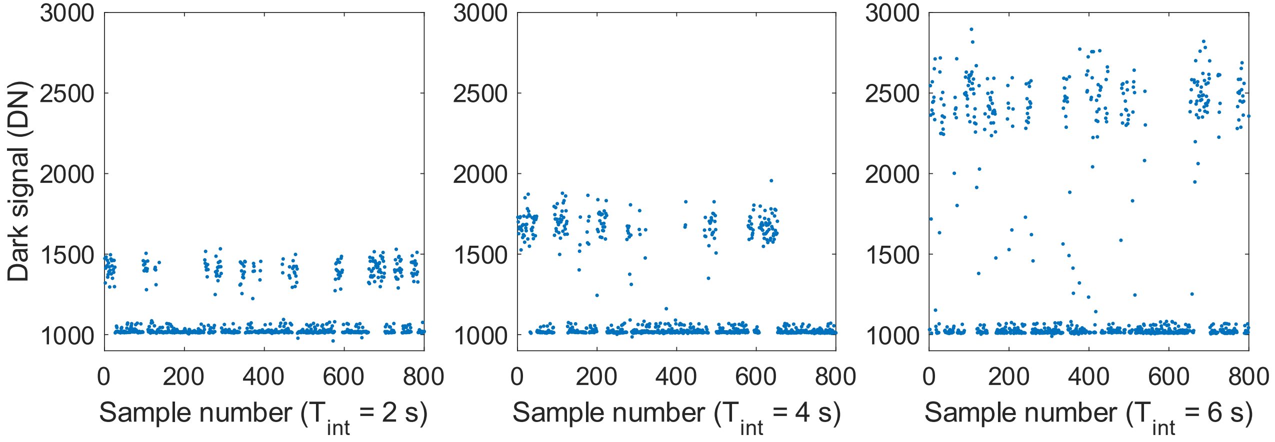
Dark signal phenomena



Few pixels (<<1%) exhibit bi-level dark signal and two histogram populations

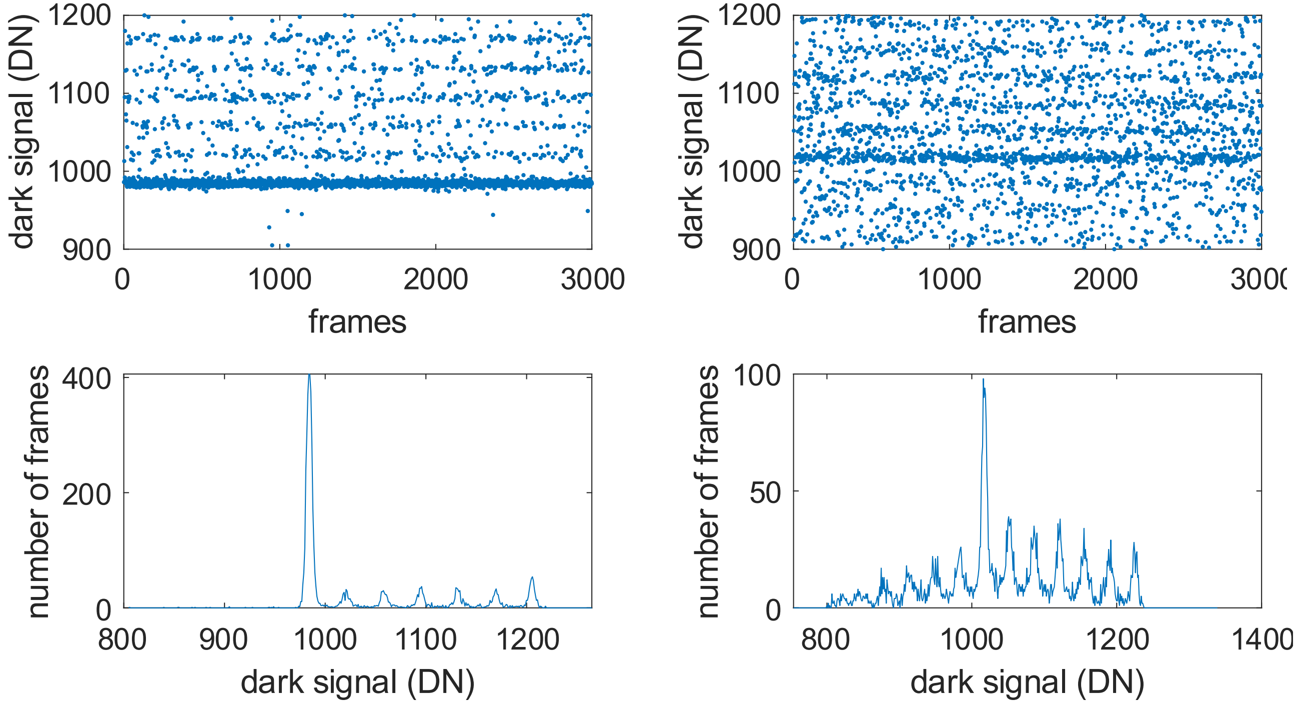
Dark signal phenomena





Dark Current RTS: Discrete dark signal fluctuations + dependence on T_{int}

Dark signal phenomena

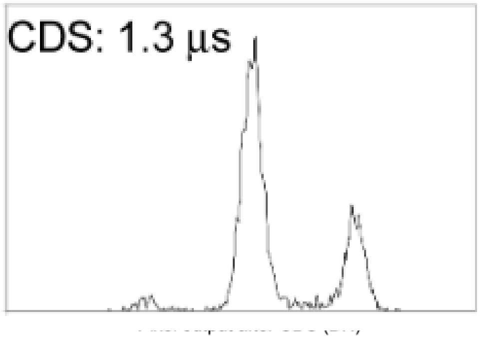


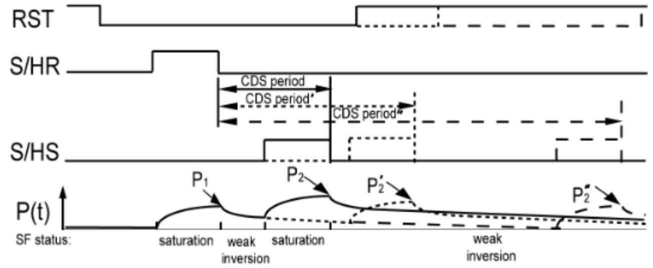
Pixels with highest noise exhibit discrete bands in temporal trace and evenly space peaks in histogram

Multiple traps + CDS?

Single trap + CMS?

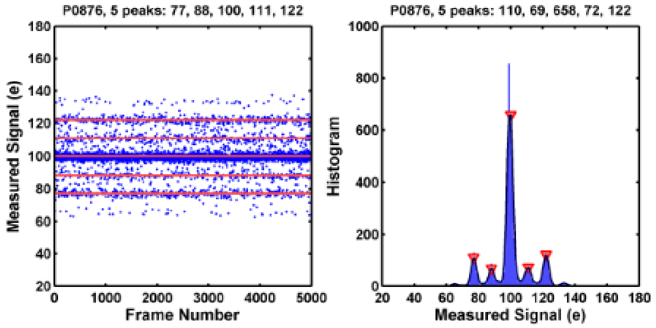
What is known about SF-RTS?





Three peak histogram due to **CDS**. Asymmetry due to **SF inversion status**

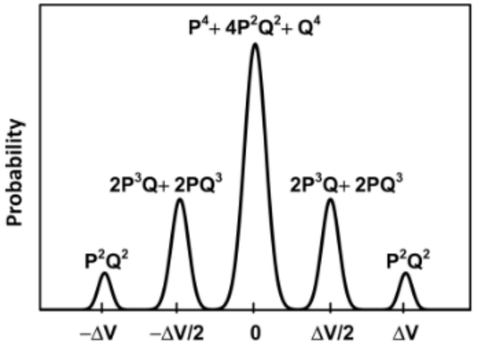
Wang et al., IEDM 2006.



Observation of multiple peaks, attributed to **multiple defects**.

Chao et al. 2017. IEEE JEDS. 5(1).

Chao et al., 2017. MDPI Sensors. 17(12)

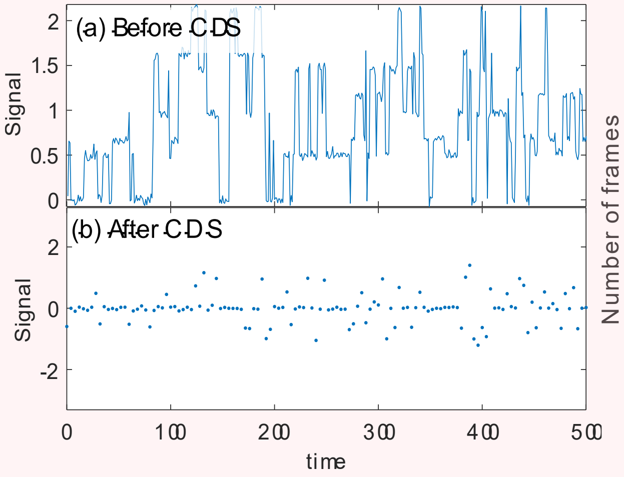


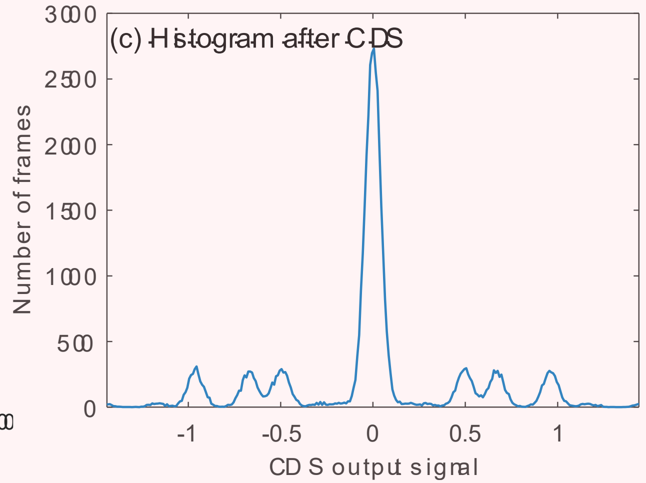
Proposed multiple peaks from CMS, but **no strong experimental confirmation**

Chao et al., 2019. MDPI Sensors. 19(24)

Simulation of RTS

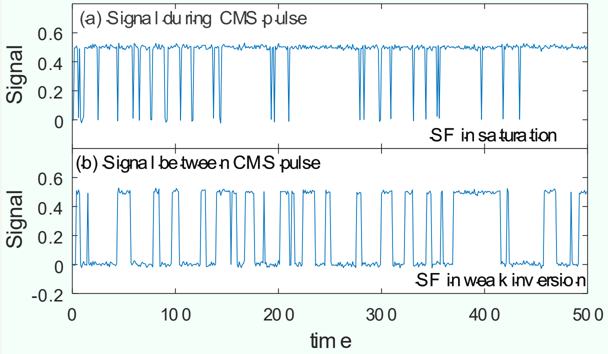
1. Multiple defects and correlated double sampling

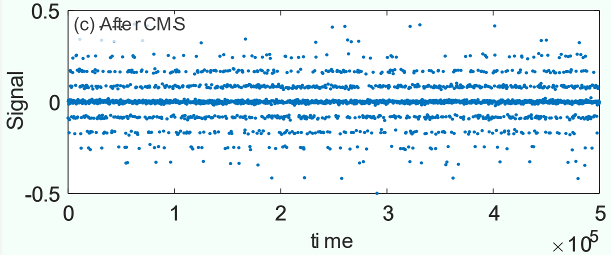


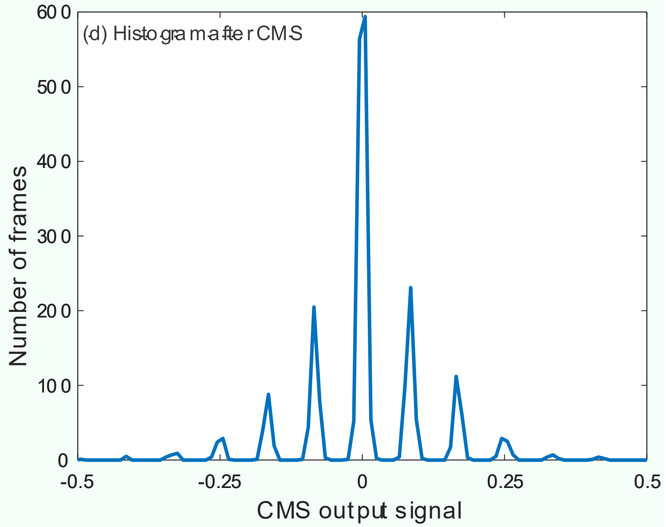


- × More than three defects required to see correct number peaks
- × Uneven peak spacing

2. Single defect and correlated multiple sampling





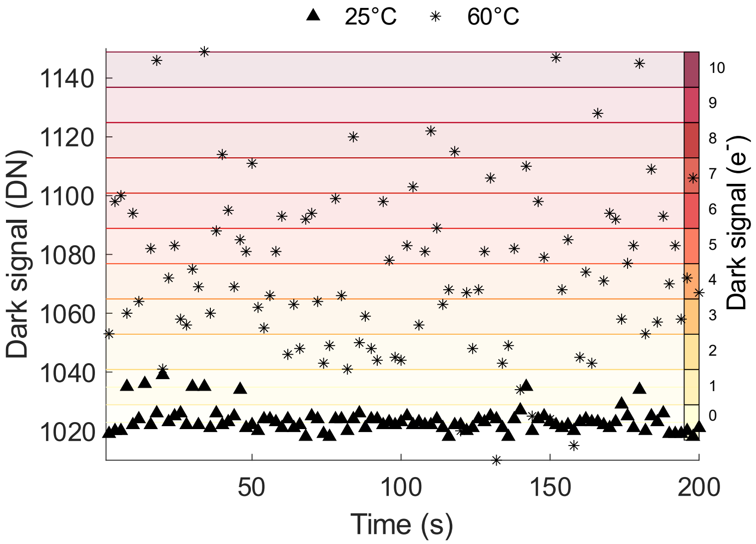


- ✓ Even spacing
- ✓ Correct number of peaks

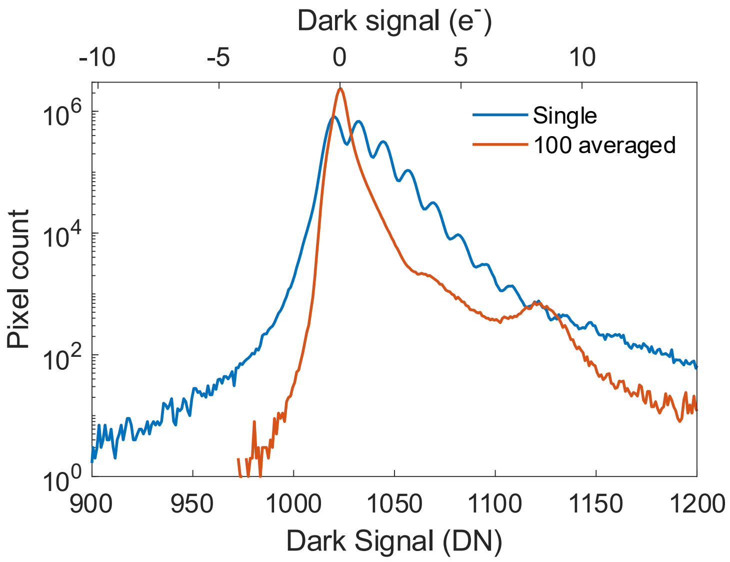
⚠ Asymmetry still to be investigated

CMS is more likely source of discrete peaks in output dark signal histogram

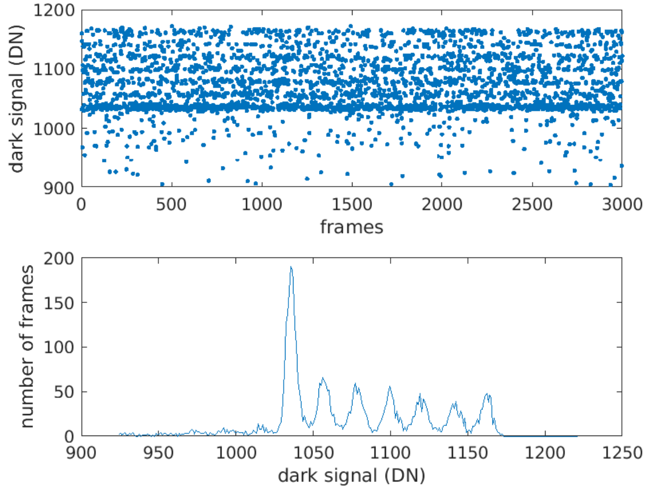
Conclusion and perspectives



QIS deep-sub electron read noise enables single-electron counting



Dark current measurements reveal defect characteristics



Dominant noise is SF with CMS playing role in observed dark signal quantization

Fine identification of dark current limiting defects and their intimate properties in state-of-the-art CMOS sensors

Further simulation of SF status during CMS is needed

isae
Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

cnes
CENTRE NATIONAL D'ETUDES SPATIALES

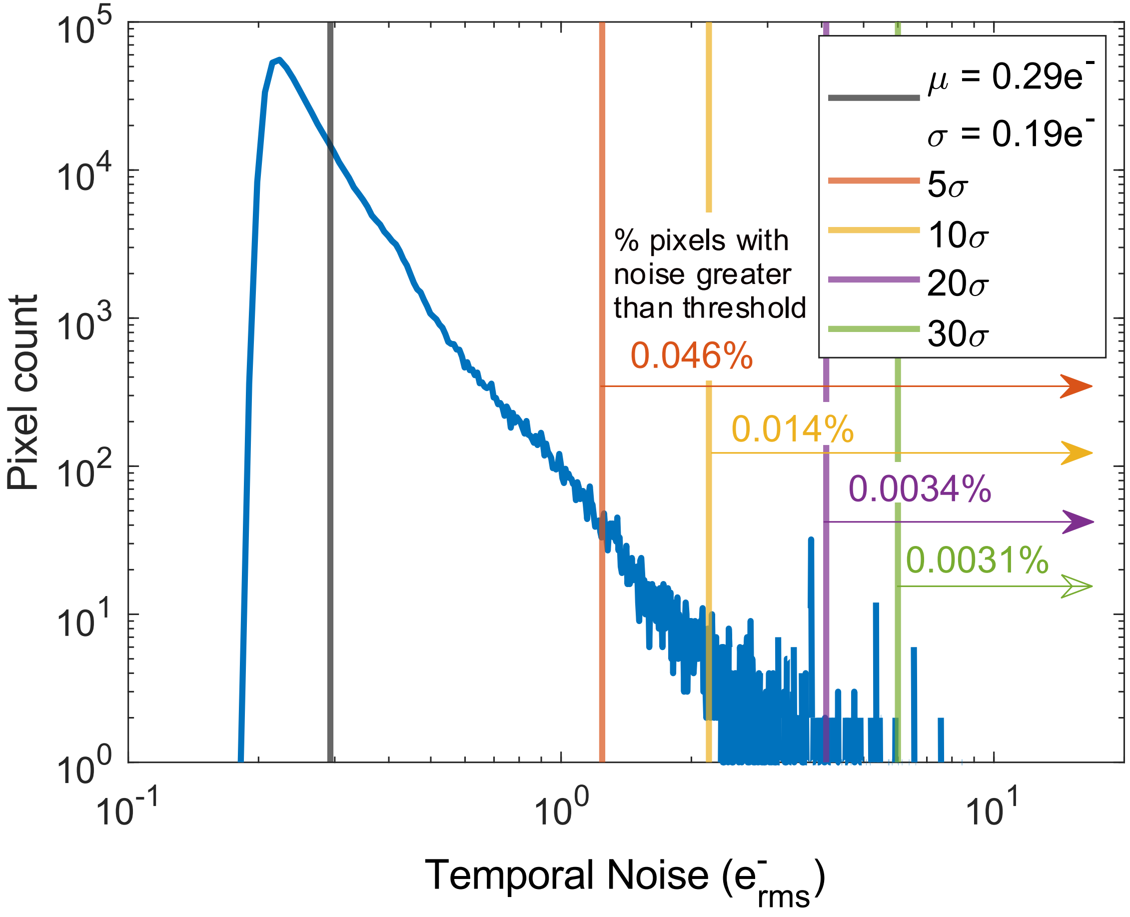
Thank you for your attention!

Temporal noise in state-of-the-art CIS

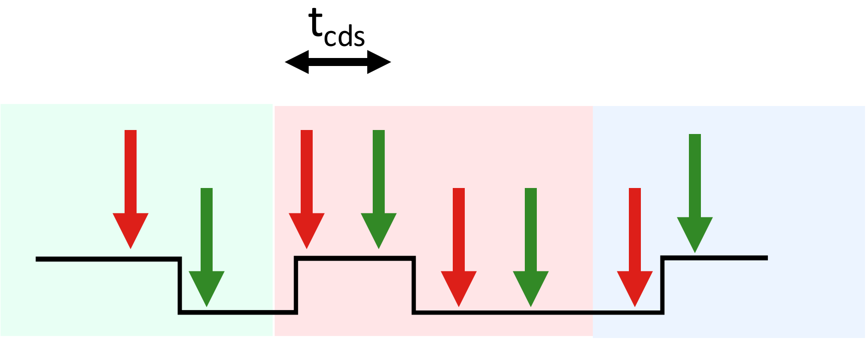
- kTC (reset) noise
  C = 0.15 fF
  T = 300 K
  $q = \sqrt{k_b T C} \approx 5\, e^-$
- Photodiode dark current
  $\sqrt{D} \sim \sqrt{0.05} = 0.22\, e^-$

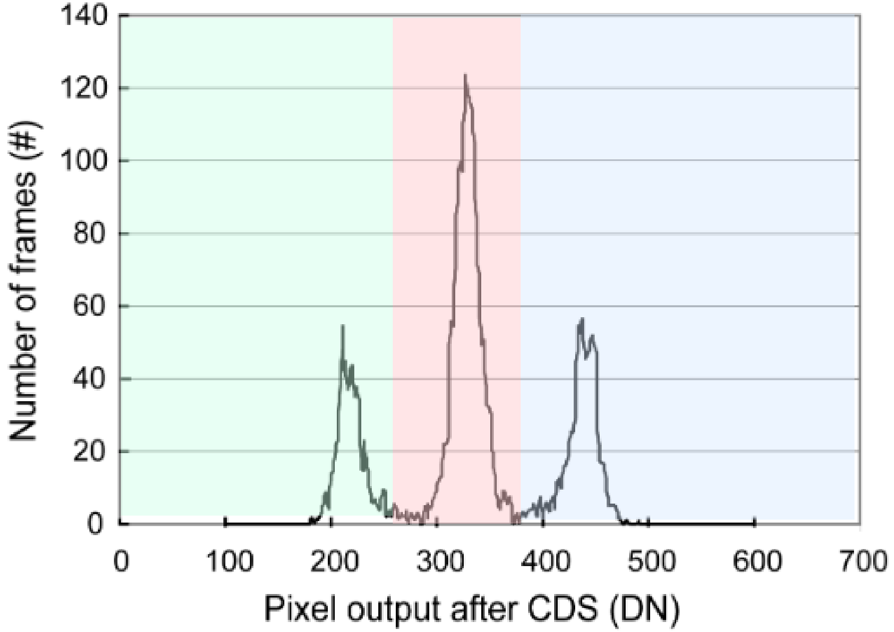
- 1/f and random telegraph signal

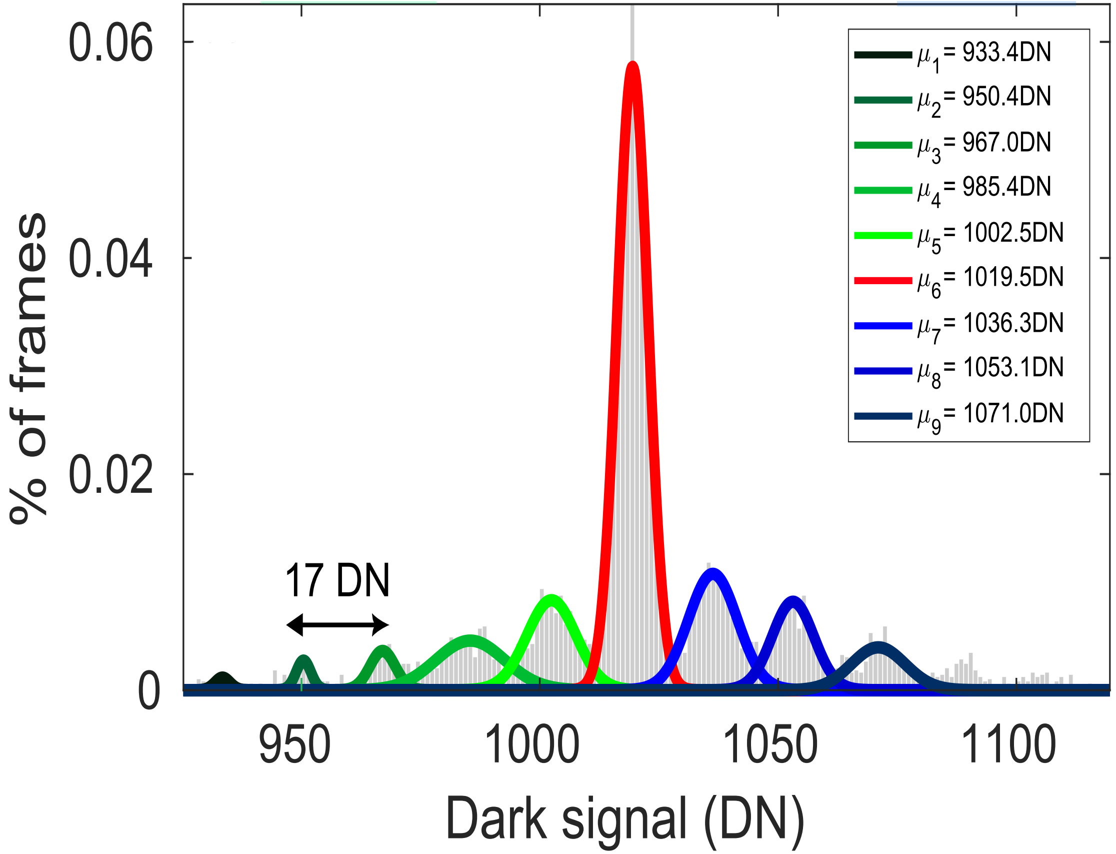
Improvements in CIS process shift dominant noise source from photodiode to source follower



Source Follower RTS in a QIS

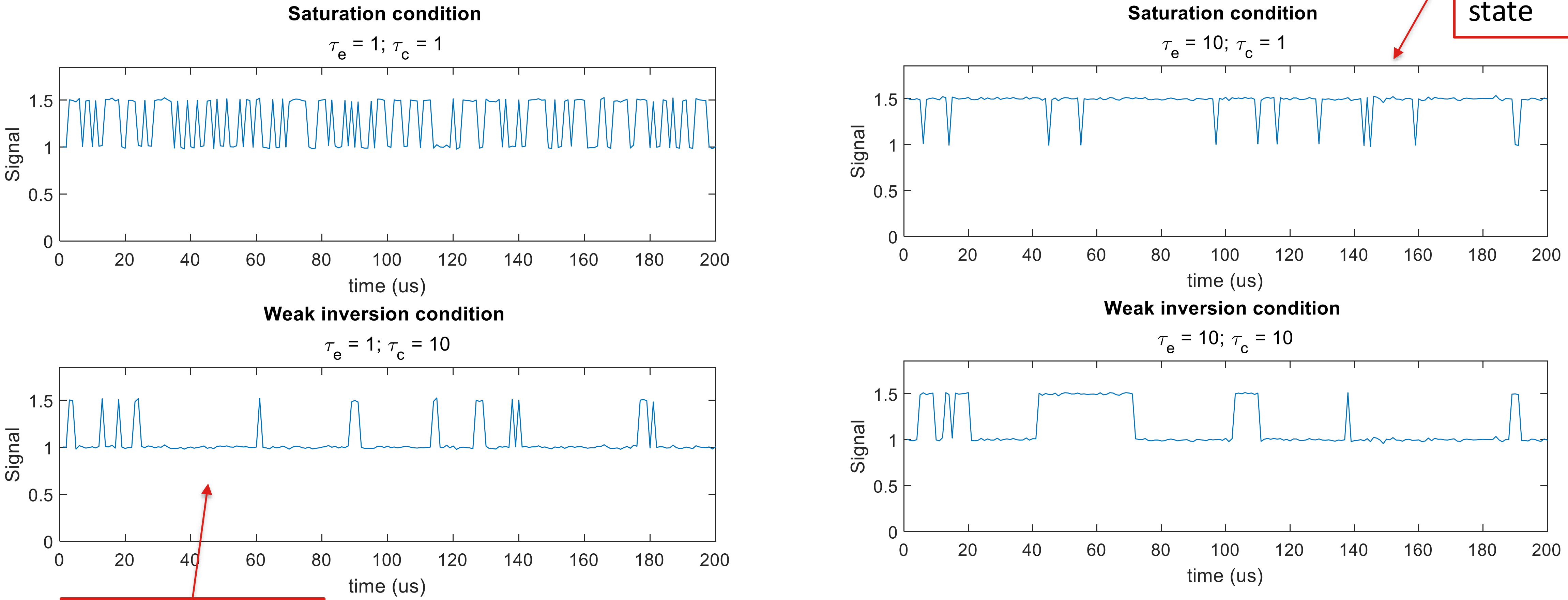



Wang, IEDM 2006


CDS is CMS with M = 1

M samples should produce M peaks on each side of central peak

Influence of τ_e and τ_c

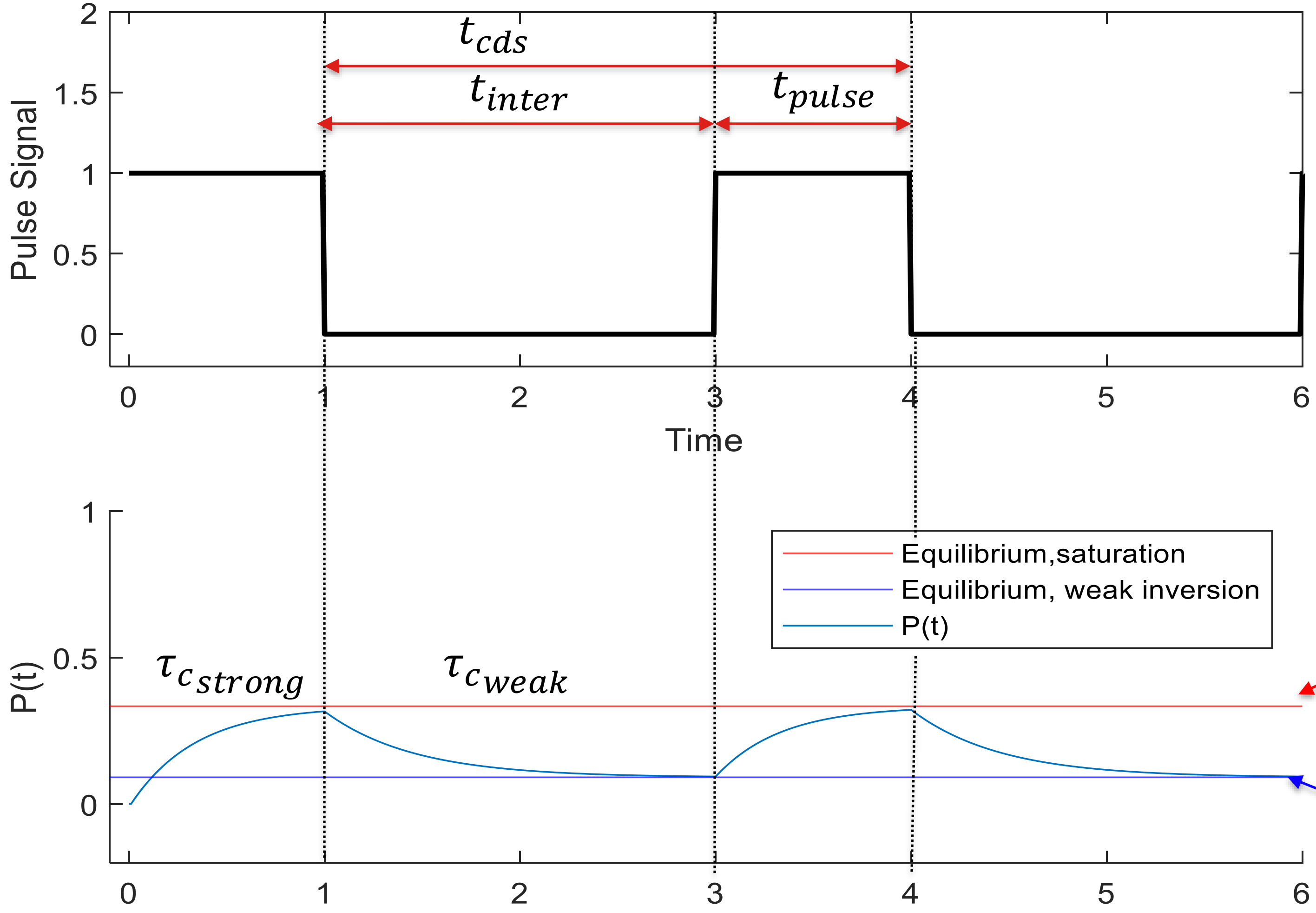


$\tau_e > \tau_c$: more time spent in high (empty) state

$\tau_c > \tau_e$: more time spent in low (occupied) state

- Capture time constant τ_c changes with SF bias condition
- SF in saturation during CDS sample pulse, weak inversion in inter-sample period

Simulation of SF inversion status



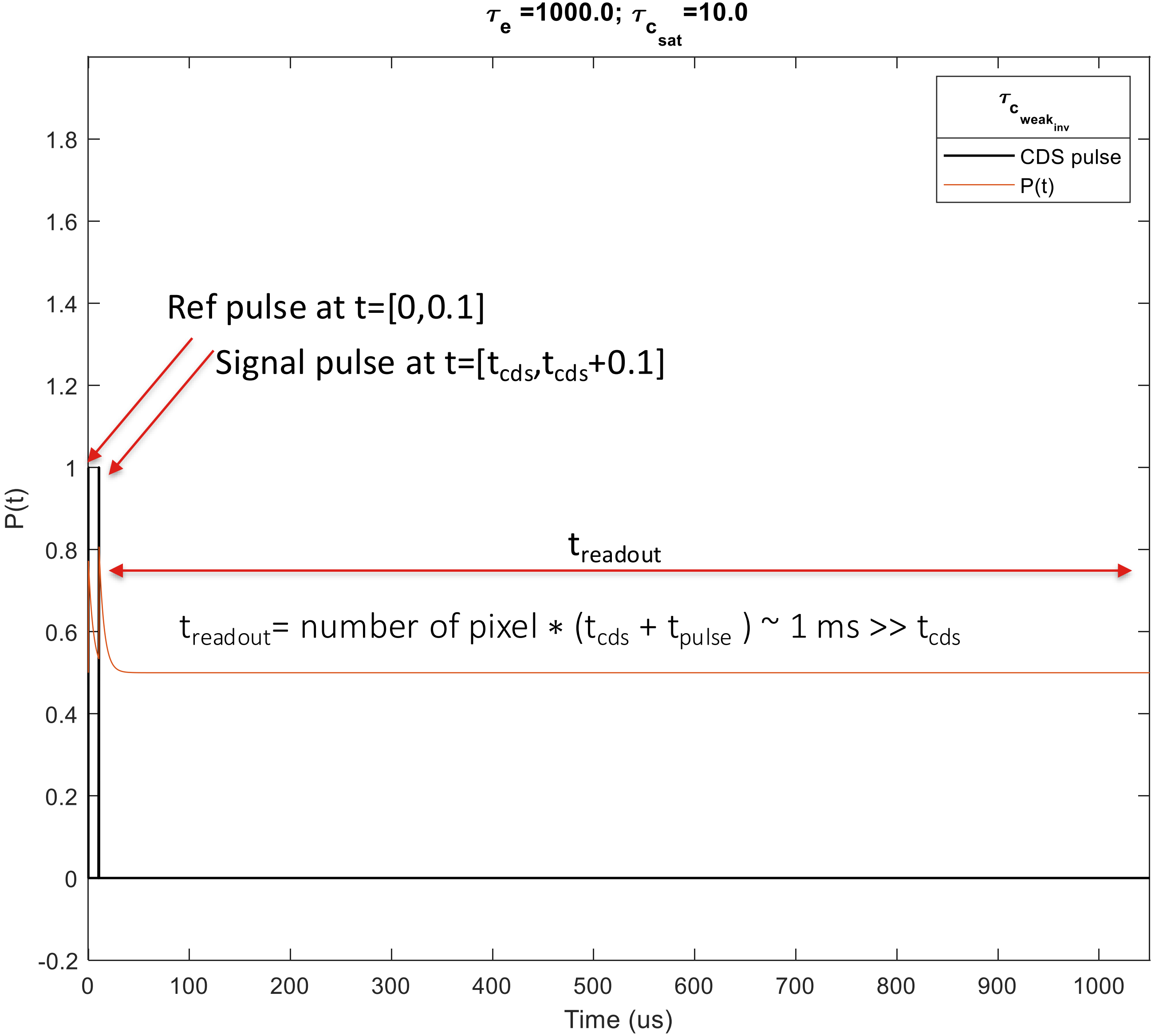
$$P_{eq} = \frac{\tau_e}{(\tau_e + \tau_{c_{sat}})}$$

$$P_{eq} = \frac{\tau_e}{(\tau_e + \tau_{c_{weak}})}$$

Implementing a readout period

Parameter	Value (us)
t_{pulse}	0.1
t_{cds}	10.5
τ_e	1000**
$\tau_{c_{weak}}$	varies
$\tau_{c_{sat}}$	10

- Pixel SF remains in weak inversion while other pixels are read out. For simplicity taken to be 100 times the CDS period (to speed up calculation).
- RTS signal is only generated up to one time step greater than t_{cds}
- Loop over 10 000 times and build CDS output statistics



Ref pulse at t=[0,0.1]

Signal pulse at t=[t_{cds},t_{cds}+0.1]

$t_{readout}$

$t_{readout}$= number of pixel ∗ (t_{cds} + t_{pulse}) ~ 1 ms >> t_{cds}