Modeling the e-APD SAPHIRA/C-RED ONE camera at a low flux level

Detector Modelling Workshop 2021

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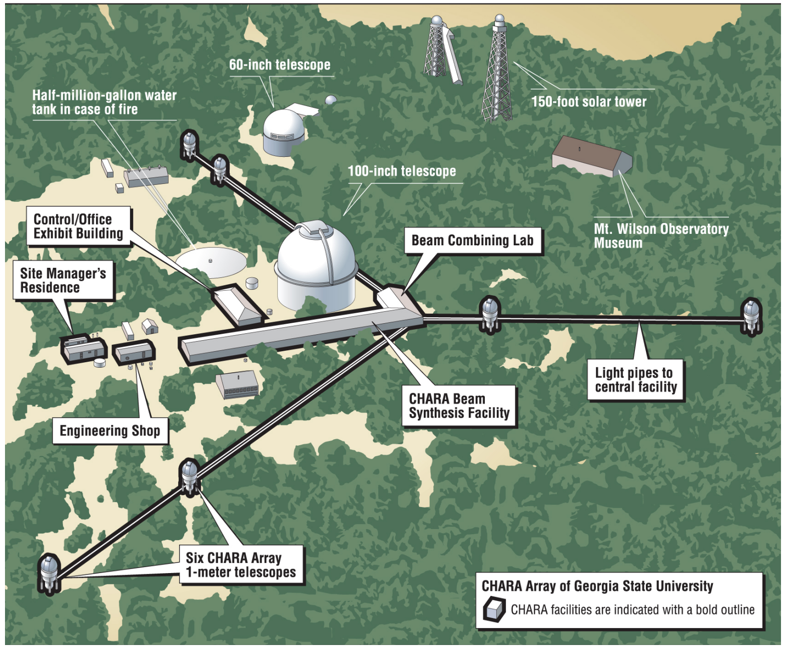
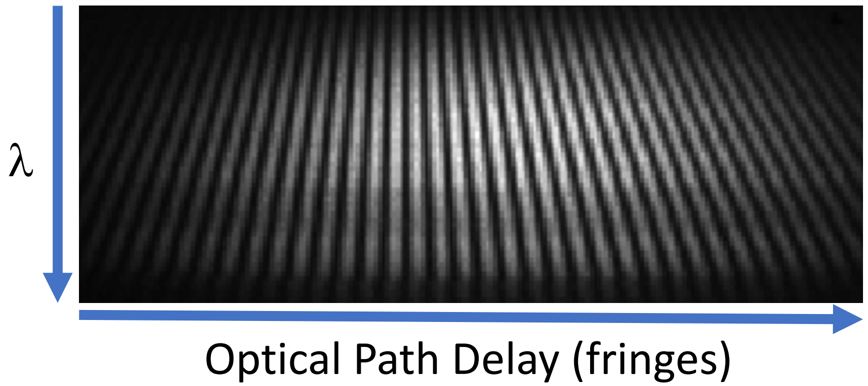
Application: NIR interferometry

- Better angular resolution than direct imaging but sensitivity limitations
- Atmospheric seeing
  => Time scale = 10 ms (H- and K-band)
- Needs:
  - fast (> 200 Hz)
  - sensitive (QE > 50 %)
  - low readout noise (< 1 e^-/frame/pixel)
  - large format (> 200 x 200 pixel)

=> e-APD is a breakthrough



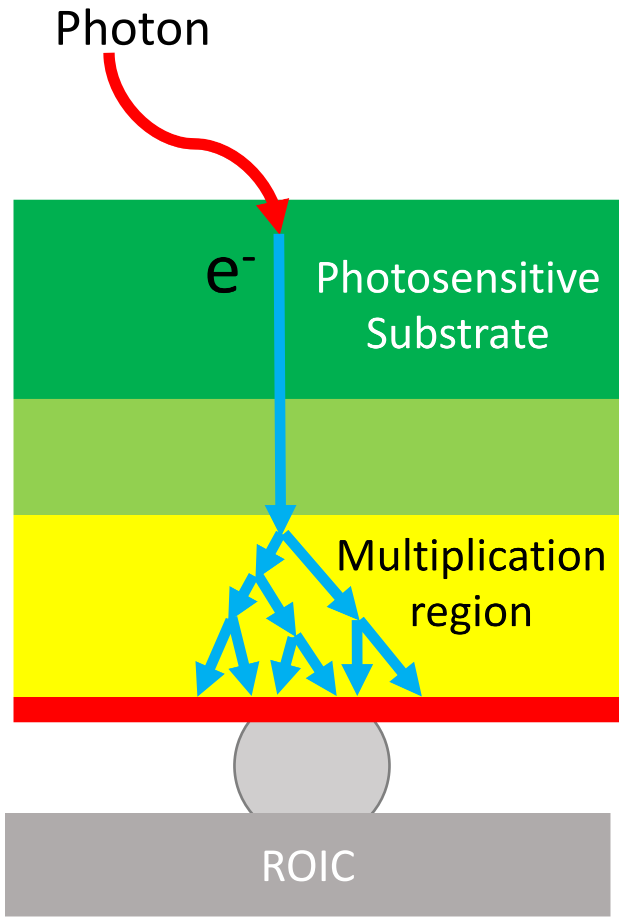


Electron Avalanche PhotoDiode (e-APD)

Bias voltage in the multiplication region accelerate the electron
⇒ Collision ionization
⇒ Avalanche effect

Characterized by :

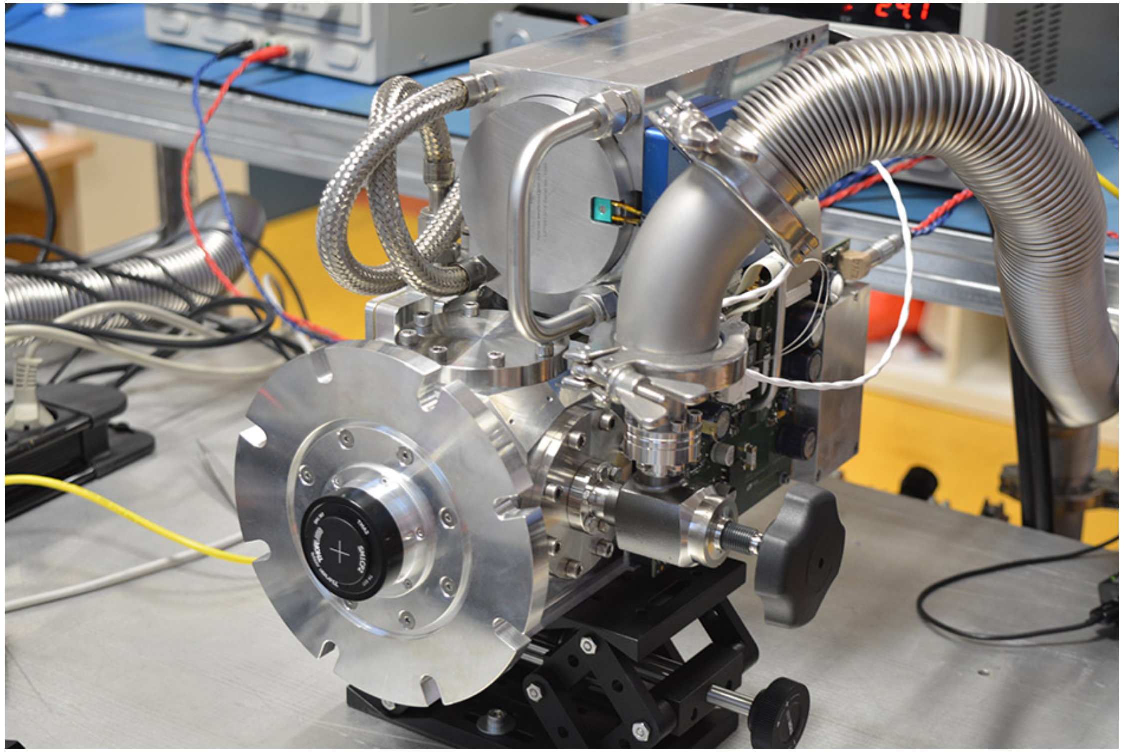
- Mean avalanche Gain
- Excess Noise Factor (ENF)



1 photon → M electrons

C-RED ONE camera

- Use a Mark13 SAPHIRA e-APD from Leonardo
- Developed by First Light Imaging (FLI)
- Installed in the MIRC-X instrument (1.1 to 1.9 μm)

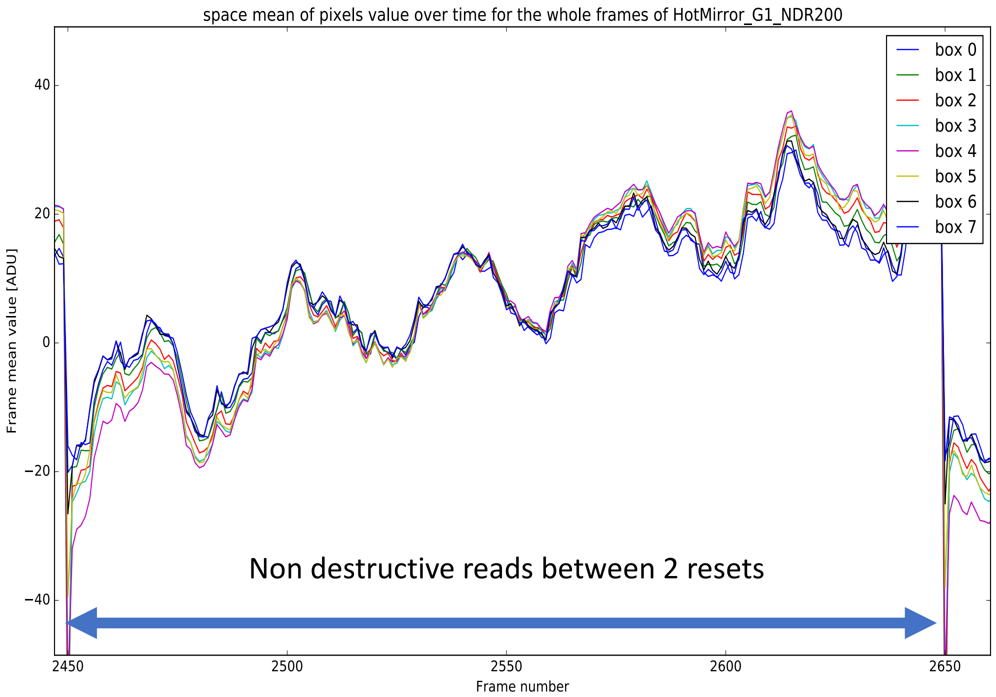


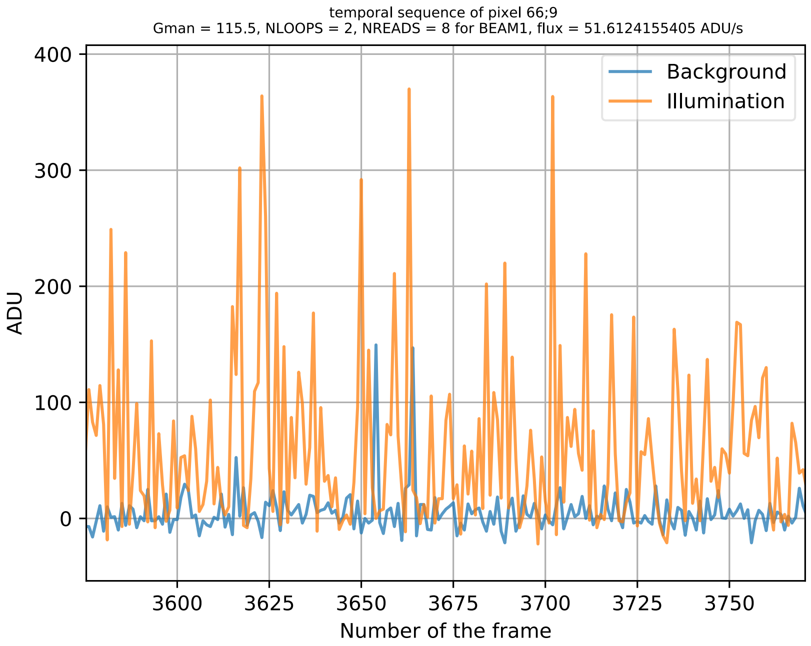
Manufacturer characteristics :

- 320 x 256 pixels
- Avalanche gain up to 300
- System Gain : 0.77 ADU/e^-
- **ENF = 1.25**
- FPS max of 3.5 kHz
- **Dark current < 200 e^-/pixel/s**
- **Read out noise < 1 e^-/pixel/read**

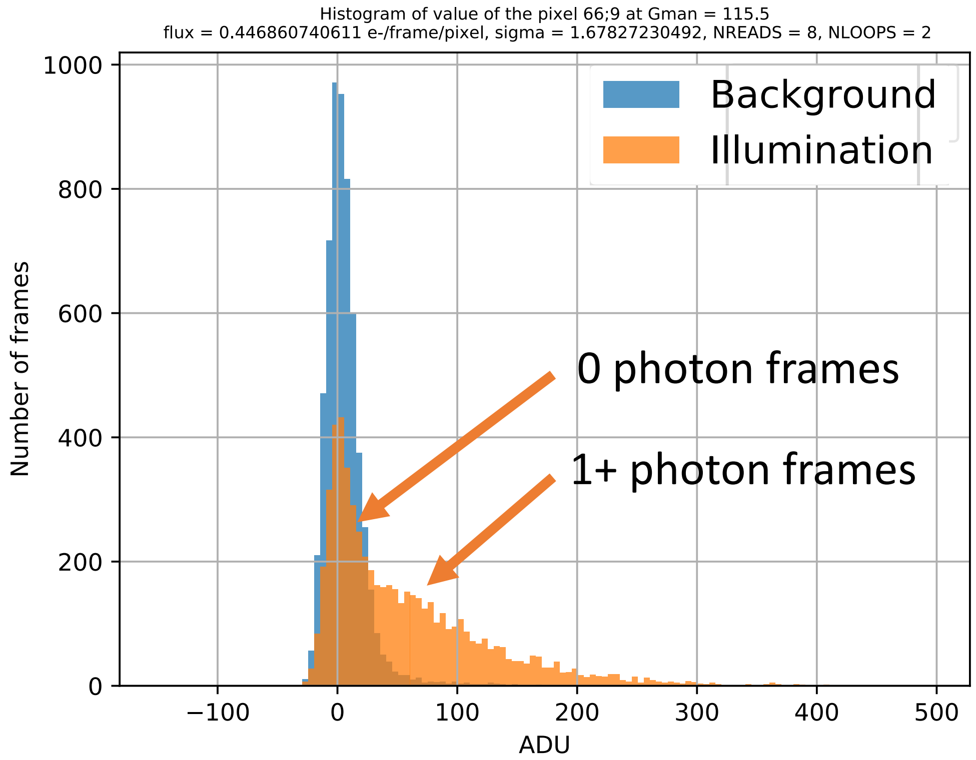
Extracting temporal sequence

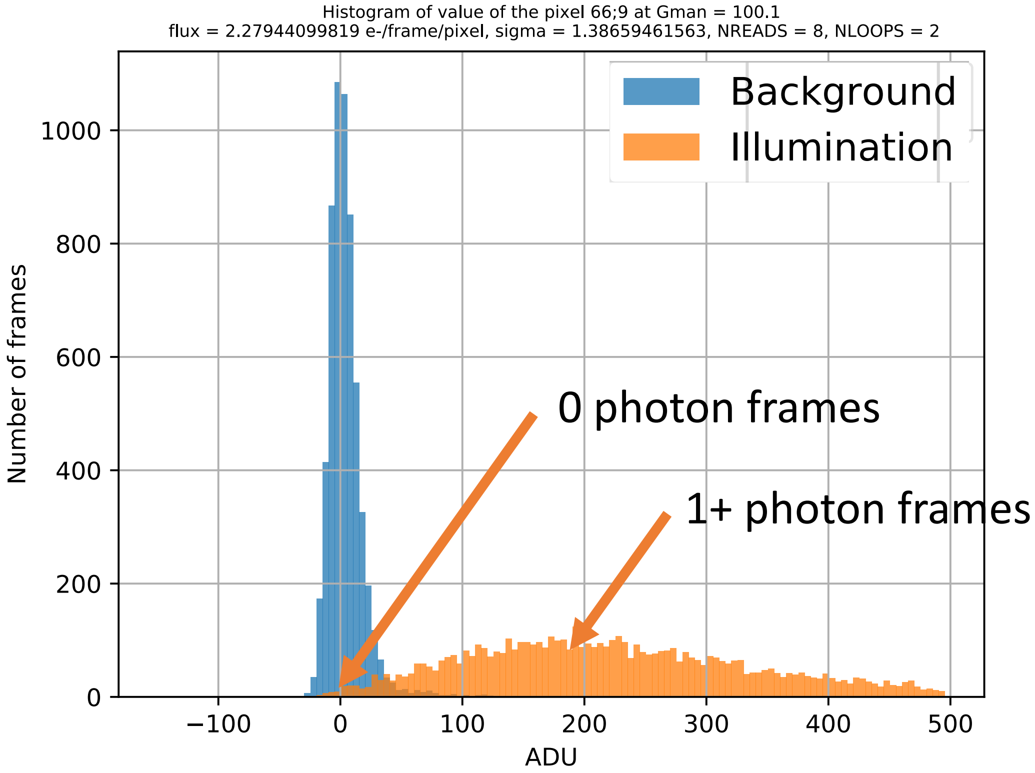
- Sub-window of 320 x 20 pixels, 16 reads per frame
  - ⇒ Frame rate = 1900 Hz
- Extract temporal sequence of one illuminated pixel
- Subtract median value of several not illuminated pixels of the same line
  - ⇒ Take off the sinusoidal parasitic signal





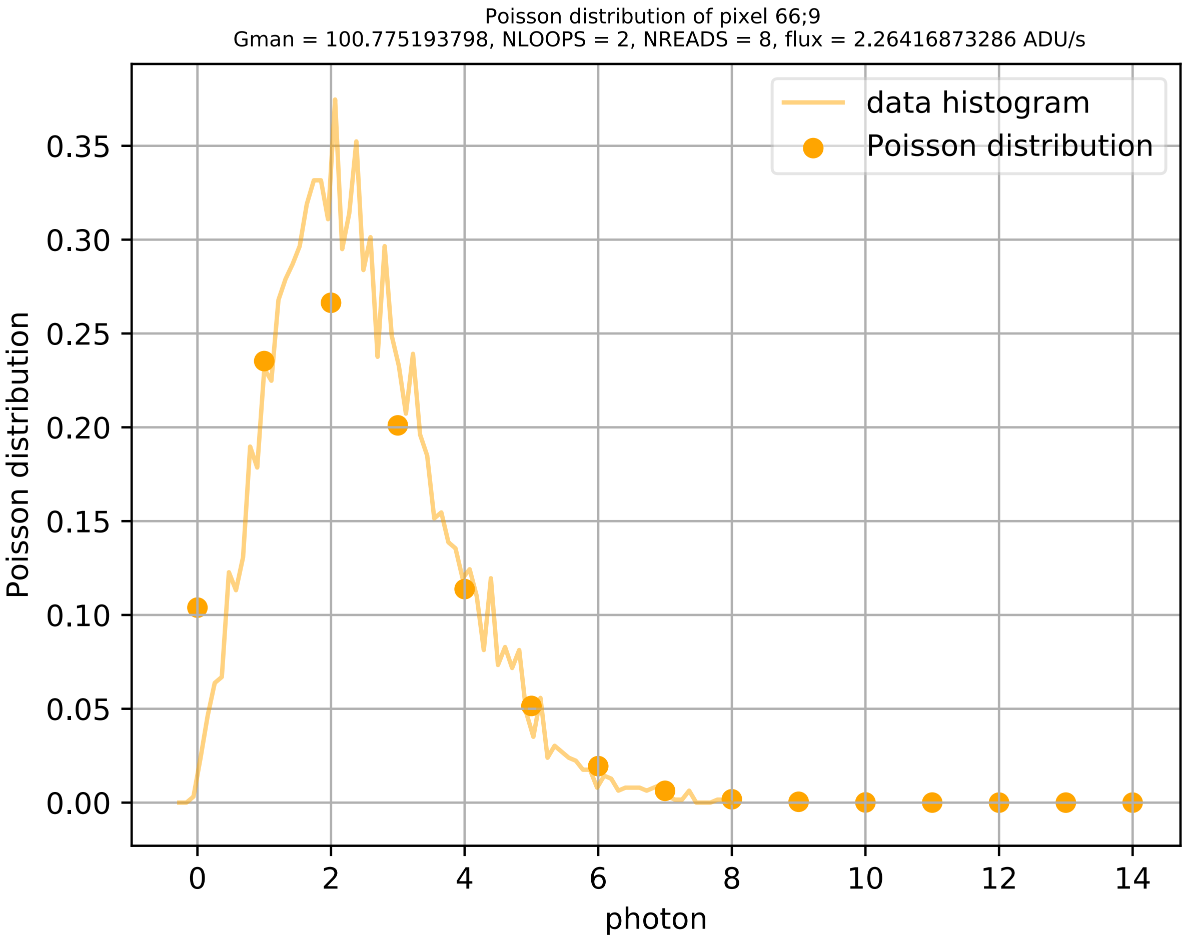
Histograms of count





- No clearly separated peaks => no photon counting ?
- A break between 0 photon events and the others at low flux

Comparison with Poisson distribution



$F (e^-) = \langle ADU \rangle / G_{man}$

Poisson distribution for F not consistent with histogram :

Fraction of 0-photon :

- Poisson = 10%
- Data ≈ 2.5%

⇒Total gain is false

Modeling the count distribution

$$Histo(G, F, ENF, adu) =$$

$$\overbrace{\sum_p}^{(3)} \left[\overbrace{Poisson(p, F)}^{(2)} \cdot \overbrace{M(ENF, adu/G) * M(ENF, adu/G) * ...}^{(1) \quad p-1 \text{ convolutions}} \right] * \overbrace{BKG(adu)}^{(4)}$$

1) Distribution of p-photons events:

   0 photon => Dirac in 0

   1 photon => M

   2 photons => M convolved by itself

   …

2) Weighting with the corresponding rate of the Poisson distribution, for a given F

3) Addition of the different p-photons distributions

4) Convolution of the result by the Background histogram

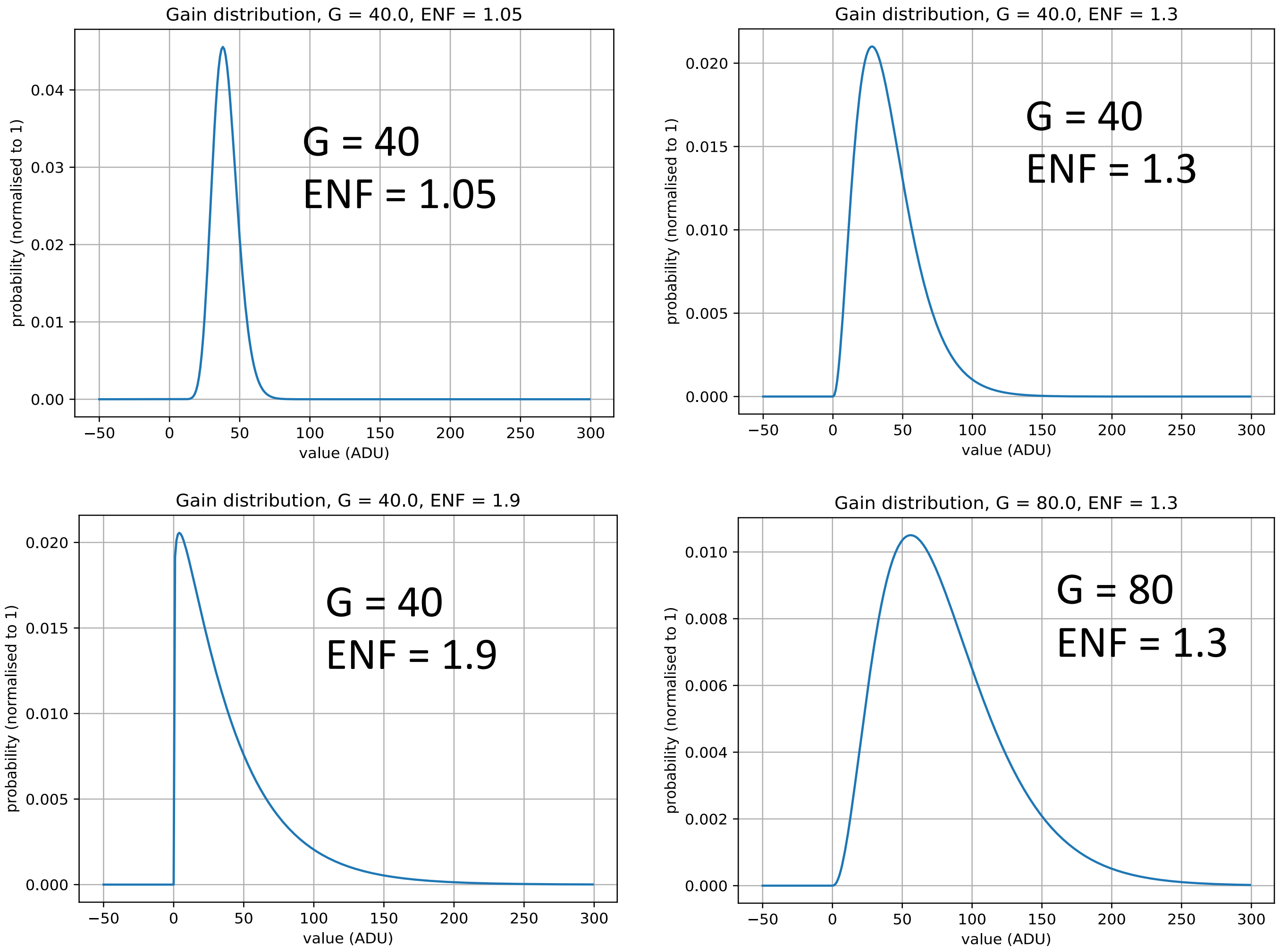
Model of gain distribution M

Gain distribution (M) : Defines mean gain (G) and ENF

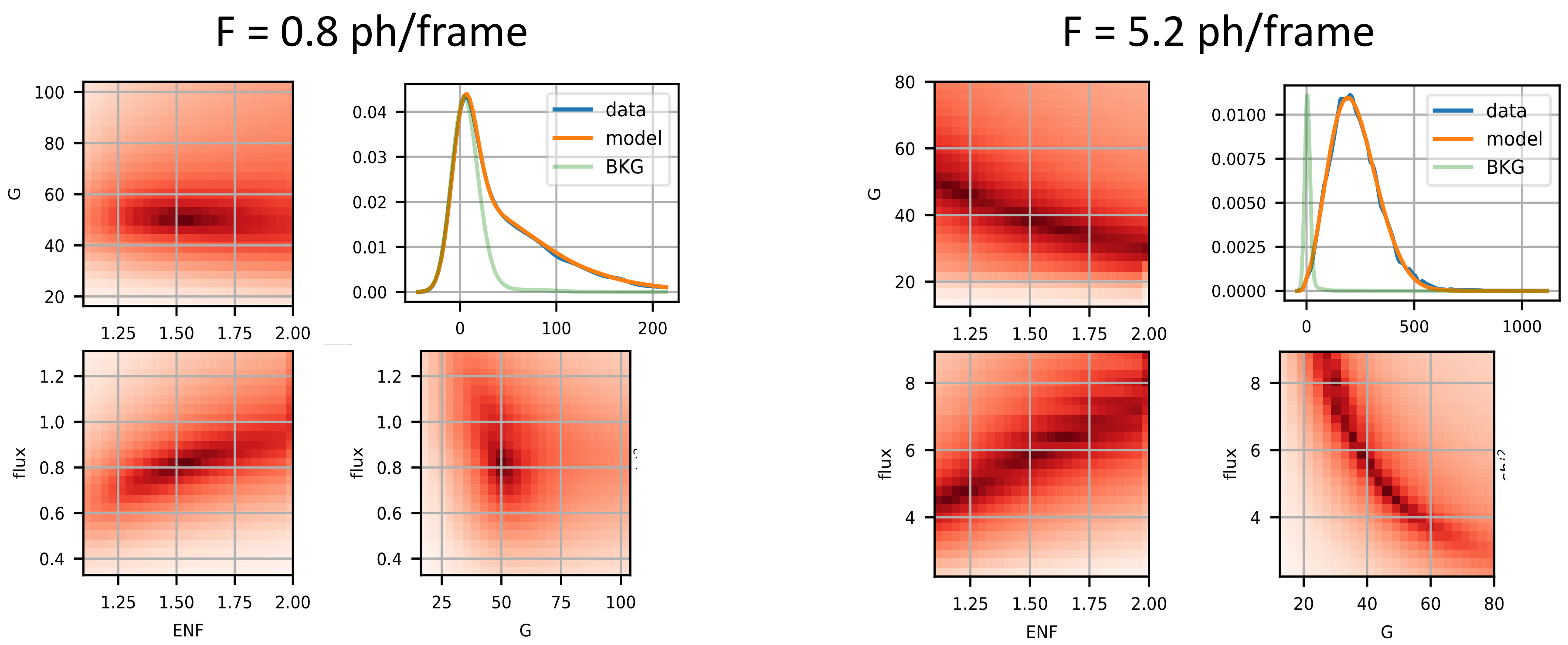
G = $\langle M \rangle$

ENF = $\frac{\langle M^2 \rangle}{\langle M \rangle^2}$

Gamma distribution

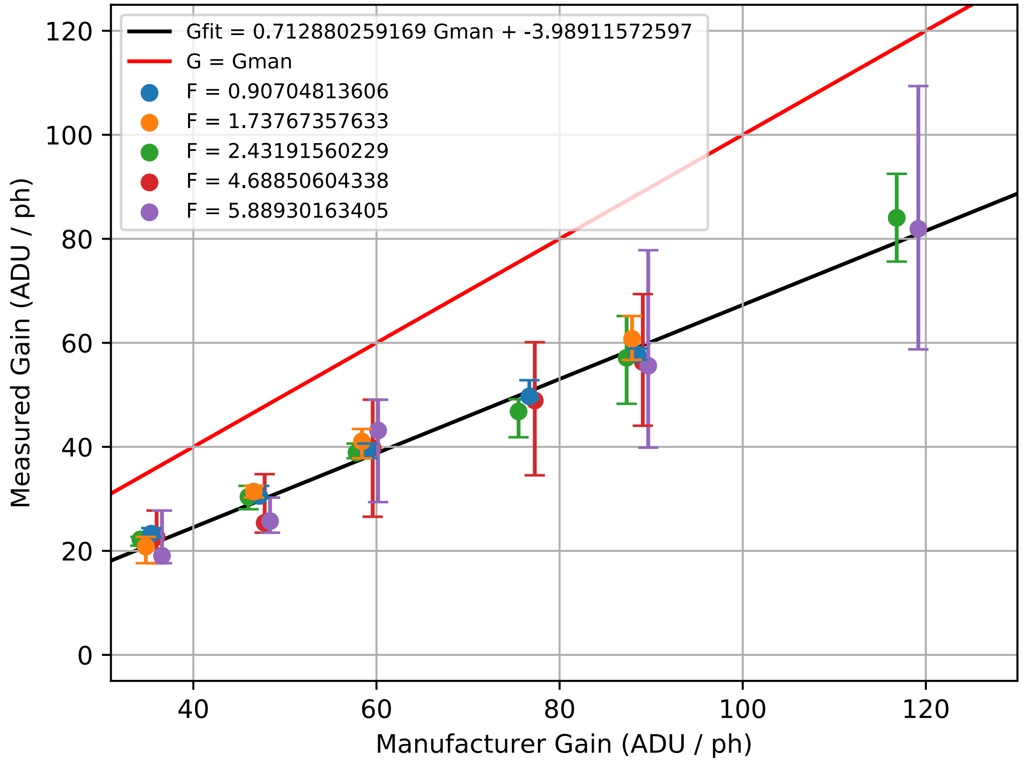


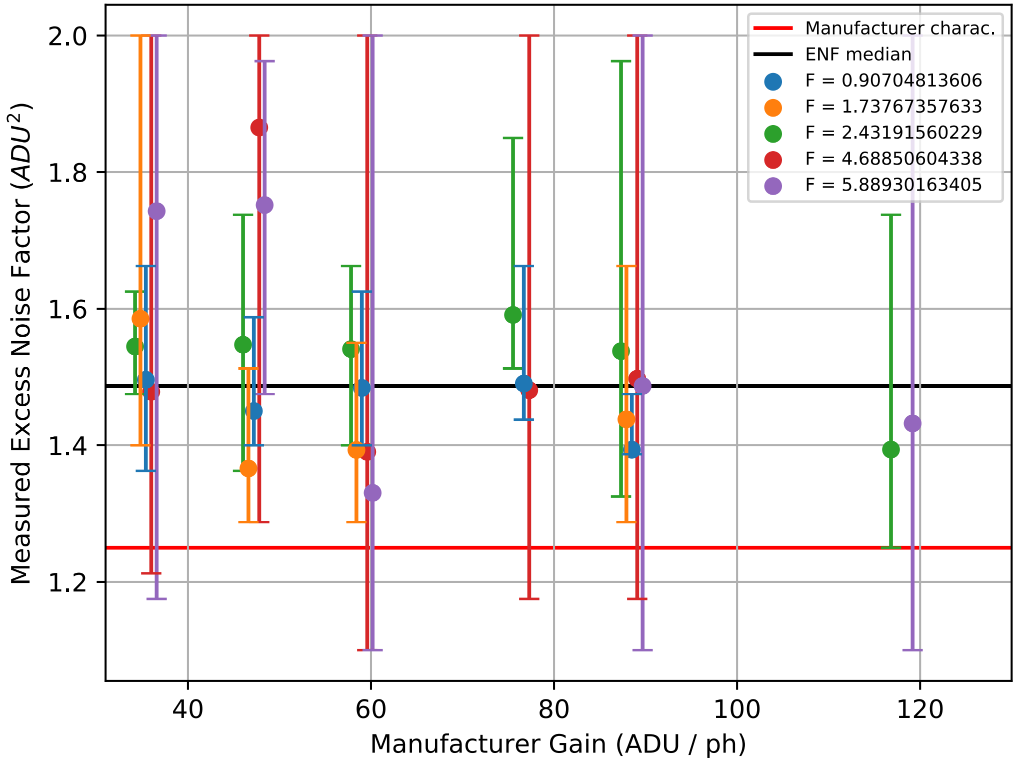
Fitting method



- Exploration of the parameter space to perform χ^2 maps
- Best-fit model convincingly reproduces data histogram at all fluxes and gains
- A single solution found in the parameter space at low flux
- Degeneracy of solution at high flux (F > 3 e^-/frame/pixel)

Results

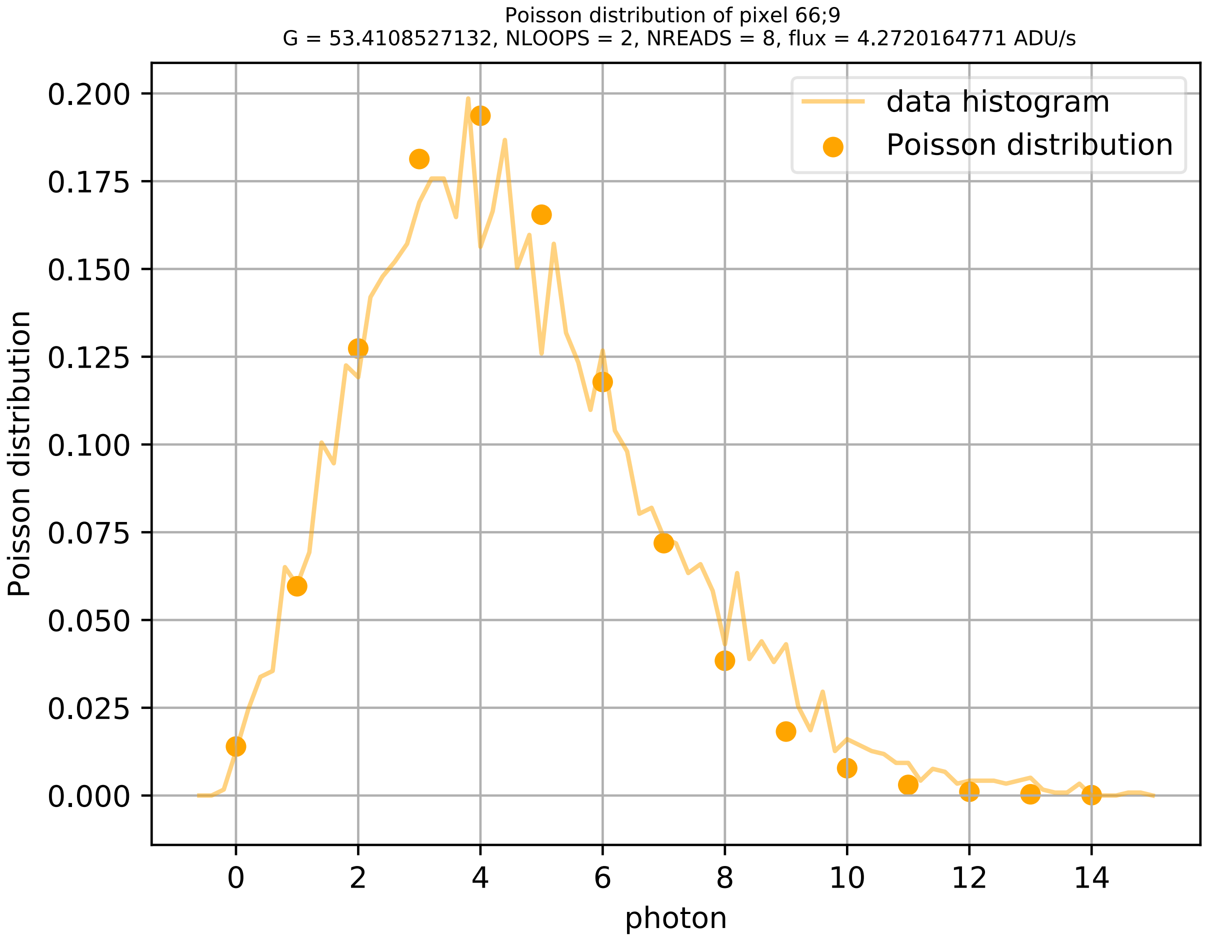




Lanthermann et al. 2019

- Results consistent for the same requested gain at different flux
- Some outliers for ENF, but from unconstrained high flux
- G_{mes} / G_{man} = 0.70 $\pm$ 0.04
- ENF = 1.47 $\pm$ 0.03

Comparison with Poisson distribution

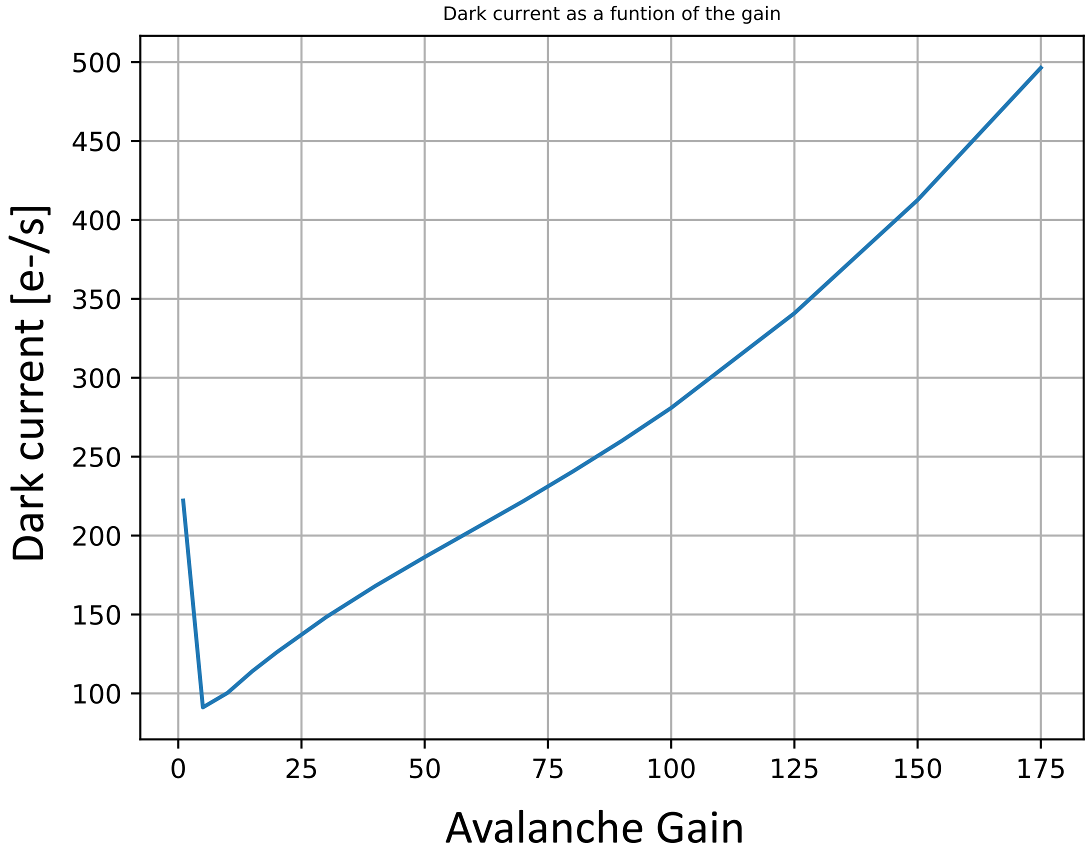


New gain
→ New flux
→ New Poisson distribution

Poisson distribution consistent with histogram

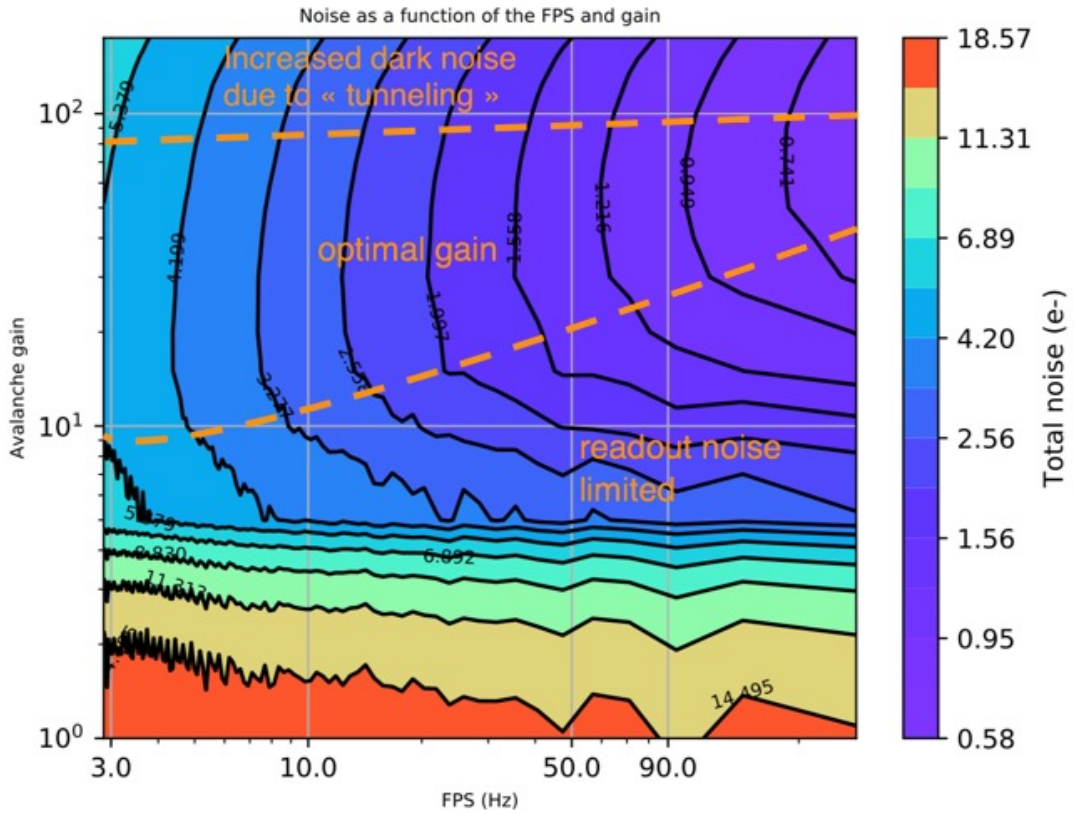
C-RED ONE optimization
Dark current

- Minimum dark current = 90 e^-/s compatible with expected H-band background
- Tunnel effect increasing dark current in e^-/s with gain



Lanthermann et al. 2018

Noise vs. Frame rate and gain

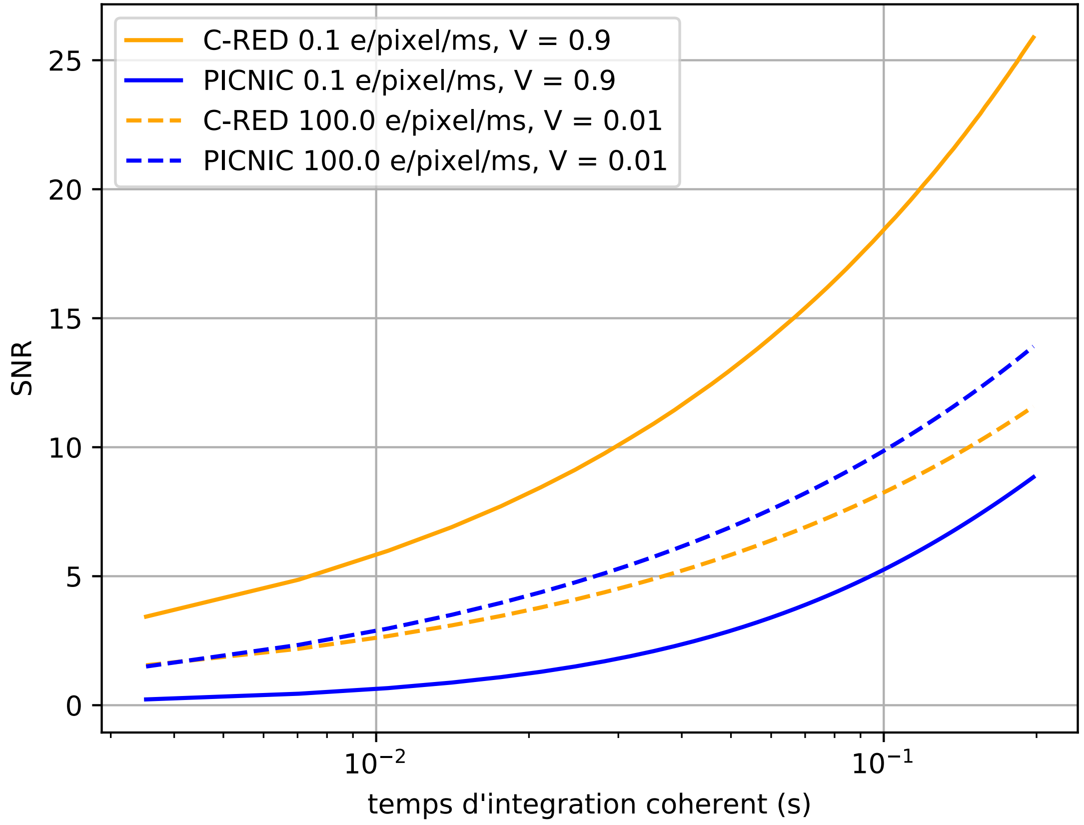


Lanthermann et al. 2018

- Noise < 1 e⁻/frame/pixel at high frame rate and for avalanche gain between 20 and 175
- Wide range of gains and frame rates limited by background

=> Recommended avalanche gain = 60

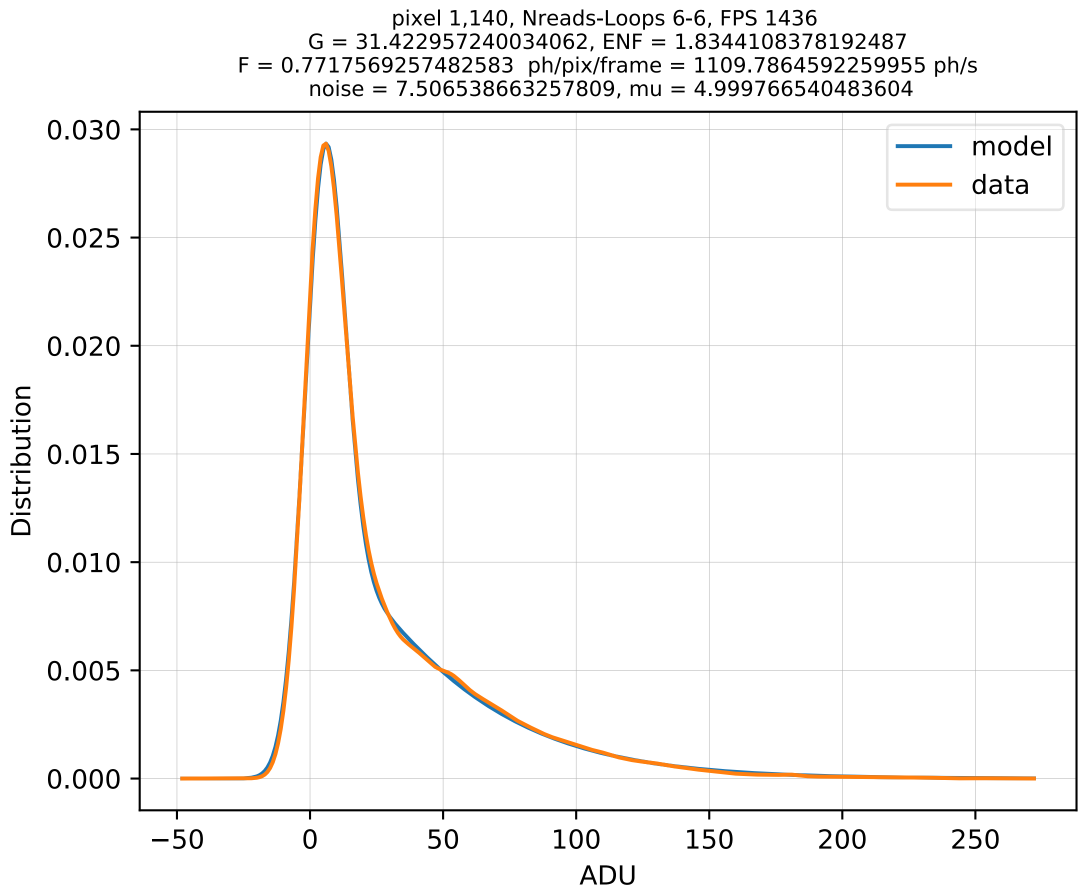
Comparison between MIRC and MIRC-X



Lanthermann et al. 2019

- Bright targets (stellar surfaces imagery): similar performance with MIRC
- Faint targets (YSOs, Massive stars): 10x less flux required than MIRC

Adapting the Model to K-band: MYSTIC



Background flux is high enough already:

- Replaced the background histogram by a gaussian
  - 2 new parameters :
    - sigma: readout noise
    - mu: position of the maximum

⇒ Data well reproduced by the model
⇒ Results consistent throughout different camera's configurations
⇒ Higher ENF value, need to be investigate further

Conclusions

- Proposed model works : total gain and ENF constrained,
  - Advantages : no need of preexisting calibration, typical operational flux
- Spotted a mistake in the manufacturer calibration of the gain
- ENF of 1.47 ± 0.03 compared to the expected 1.25
- Good cosmetic and overall behavior:
  - Reset anomaly
  - 90 Hz parasitic signal
- Real improvement of MIRC-X performances compared to MIRC:
  - Background limited
- K-band model needs further investigation