FIREBall-2 EMCCD for photon-starved UV astronomy: modelling, tradeoffs and future upgrades

1. Introduction (context, principles, specs)
2. EMCCD modelling
3. Performance & tradeoffs
4. Challenges & potential mitigation strategies

Vincent Picouet, PostDoc
California Institute of Technology

+ B. Milliard, G. Kyne, D. Schiminovich,
E. Hamden, A. Khan… & the whole FIREBall team

Credits: W. Mouser

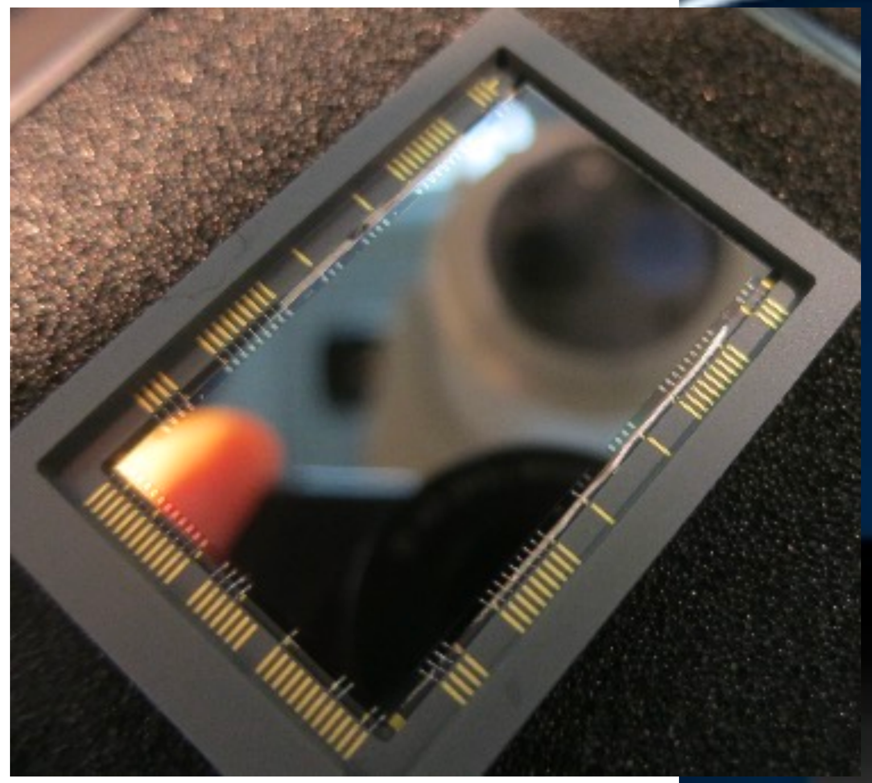
Introduction: Photon starved astronomy with FIREBall-2

FIREBall-2: a balloon-borne UV multi-slit spectrograph coupled to a 1m telescope to observe the CGM emission at z~0.7

- Goal
  - Science path finder: Map the faint gas around galaxies/quasars
  - **Test bench: Advance readiness level of technologies**

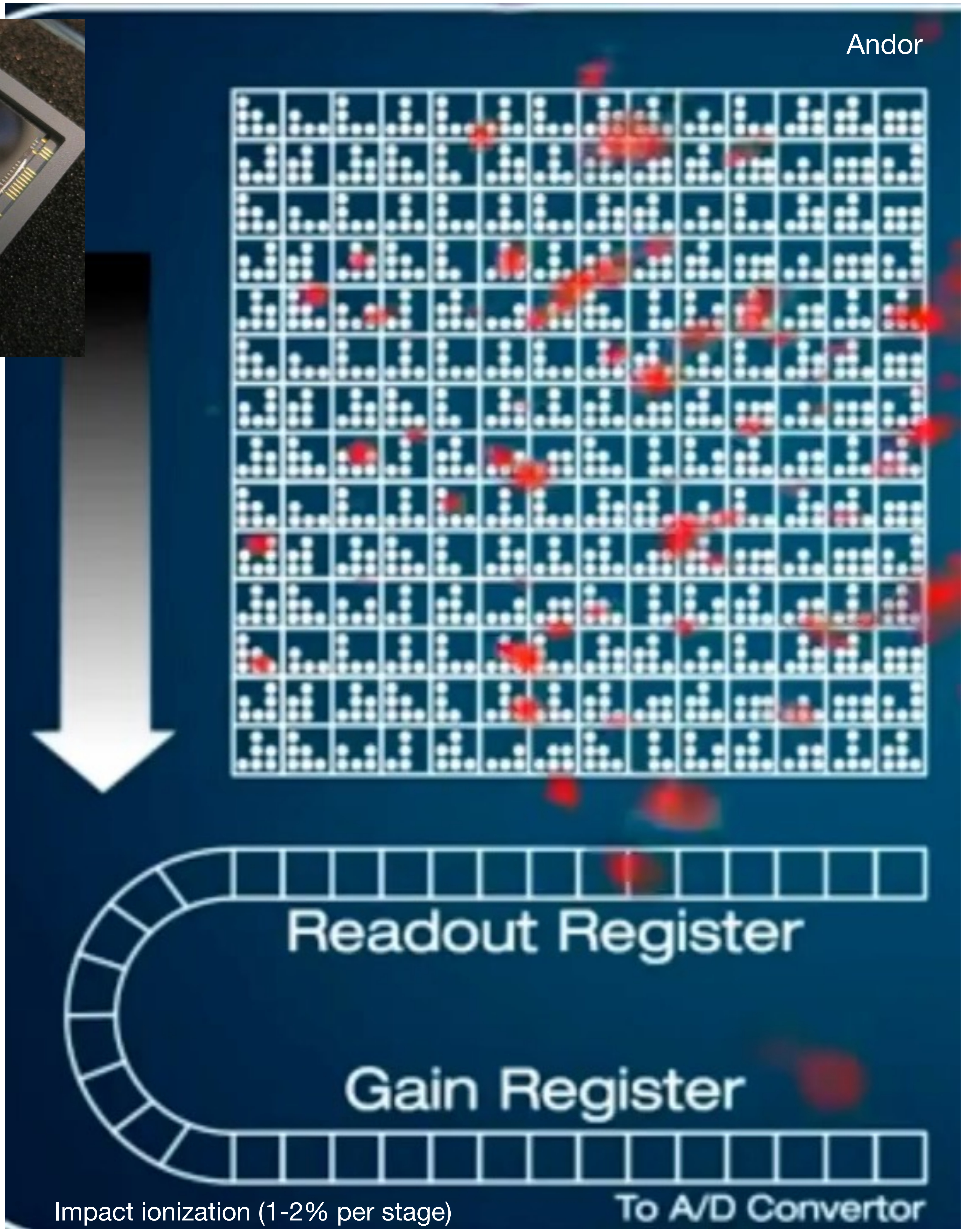
- Cutting edge technology to observe this faint/diffuse emission:
  - Aspheric high efficiency grating (LAM)
  - Sub-arcsecond pointing system (CNES)
  - **High QE e2v EMCCD + NüVü controller (JPL/Caltech)**
    - Flew successfully in 2018 (Picouet 2020, Kyne 2019)

Introduction: EMCCD principles

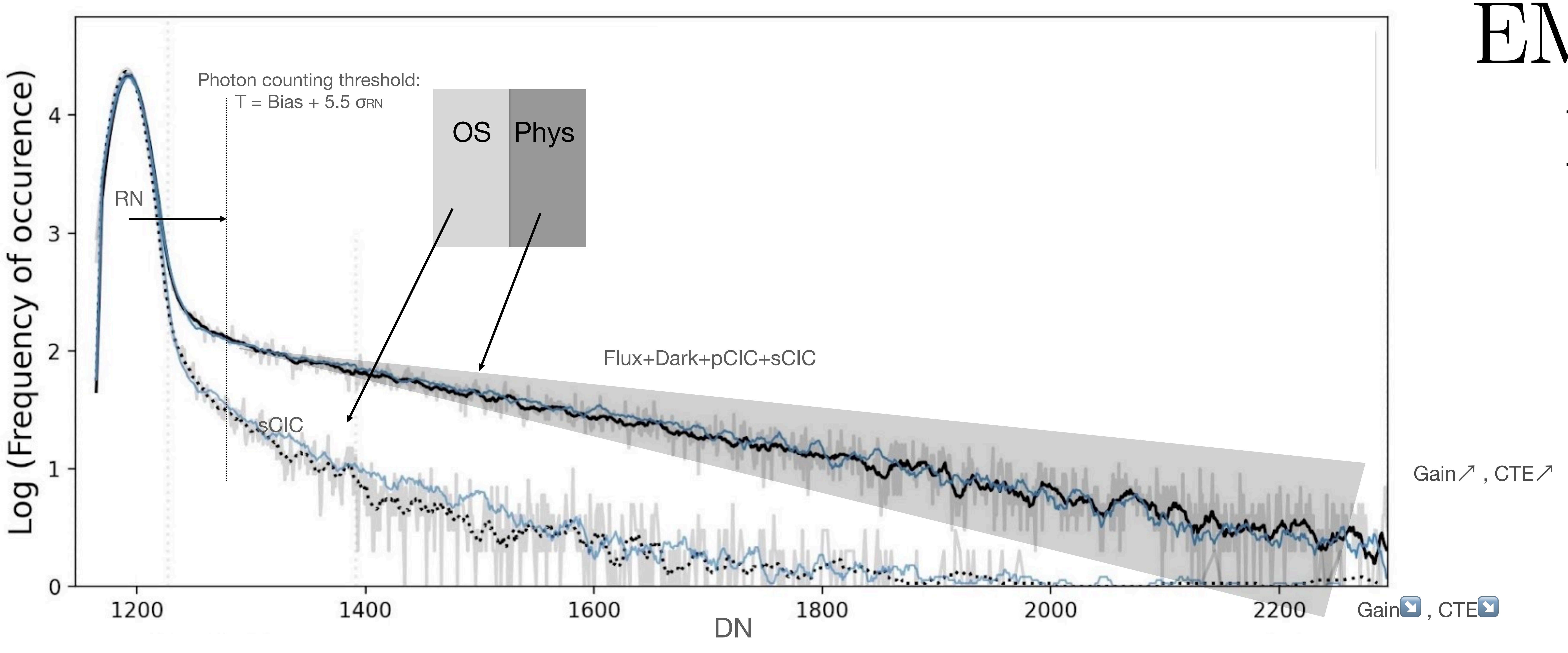


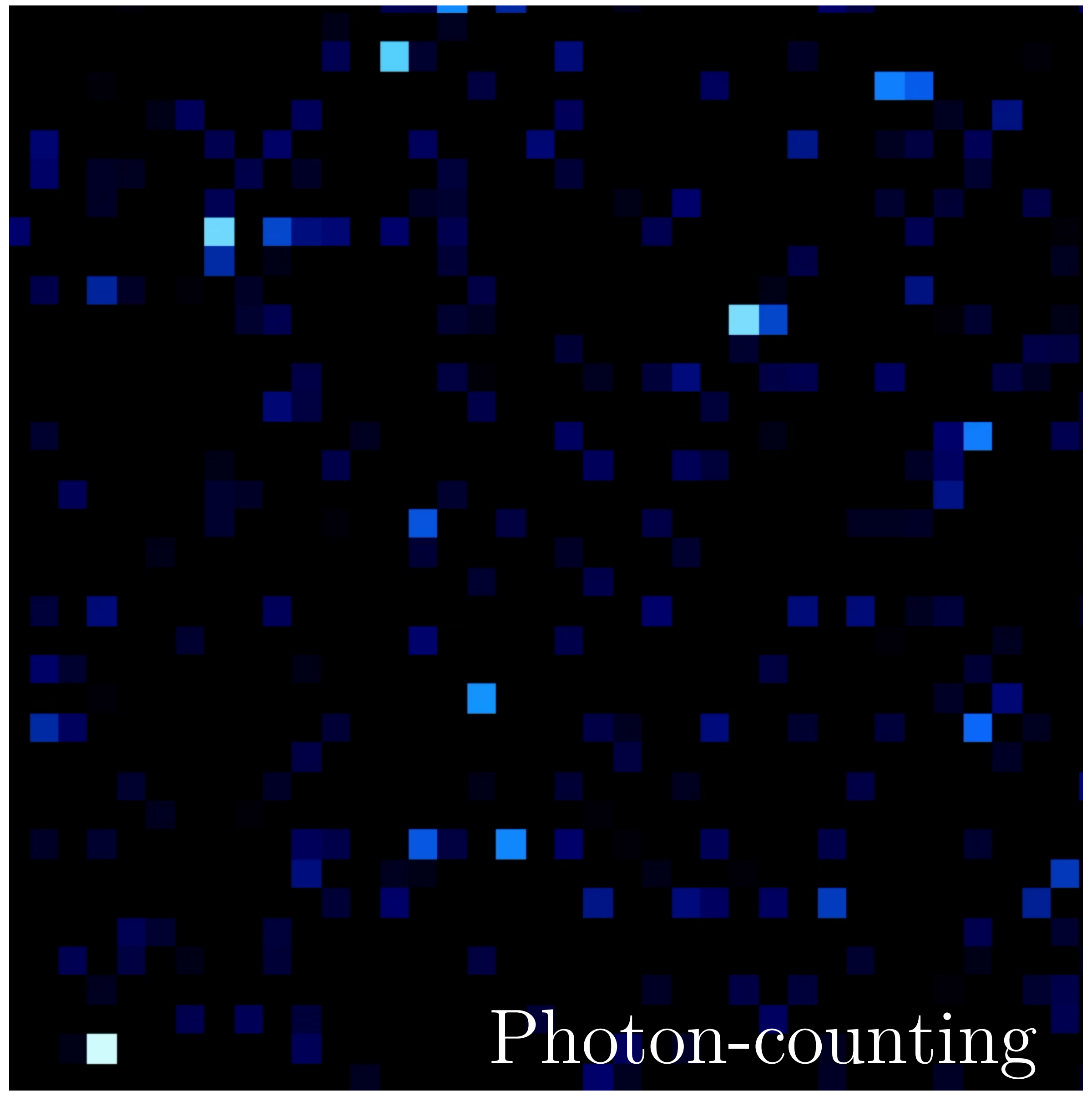
- FIREBall-2 CCD 201
    - High QE$_{UV}$ (~60%) due to p-type delta doping, enhanced by depositing 3 layers antireflection (AR) coatings (Nikzad 2012)
    - Can achieve low dark at low temperature (<<1e-/pix/h).
    - Photon starved astronomy is limited by read noise level
      ➛ EMCCD interest

- EMCCDs amplify electrons
    - To suppress the read noise
    - Clock induced charges & dark are also amplified !
    - Stochasticity generates an excess noise factor (ENF) of $\sqrt{2}$



EMCCD baseline performance

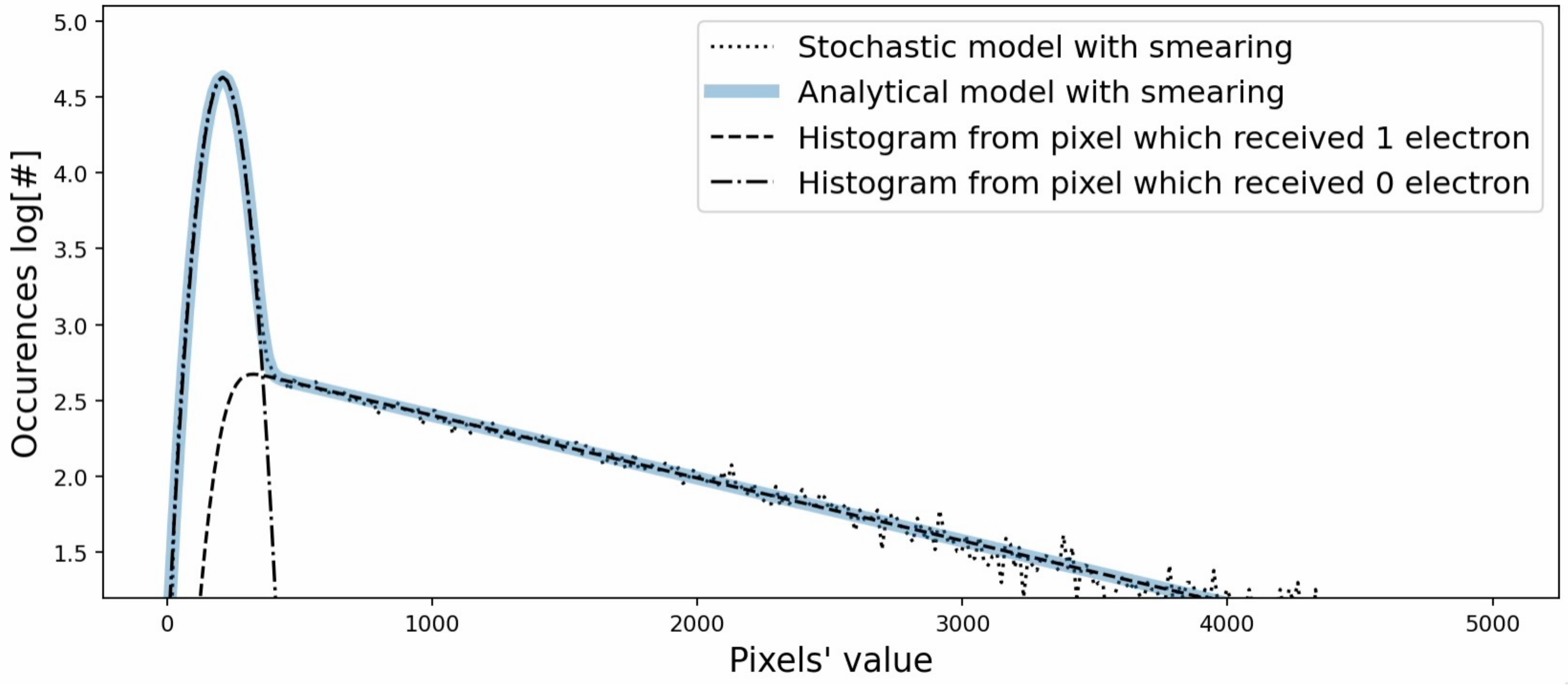




Noise performance		Other performance	
Read noise (e^-)	• ~20e^- ➝ 0e^- with amplification	**Amplification gain**	• ~2000 e^-/e^- on FIREBall • Linear fit working inly if CTE=1, CIC<<Flux<<1,
Dark current noise	• Facing a plateau around 0.5e^-/pix/hour below -110°C (amplified)	**Excess noise factor**	• $\sqrt{2}$ factor: Suppressed by thresholding under strict conditions (CTE~1, F<<1e^-/pix/frame, G/RN>>10)
Clock induced charges	• ~0.01e^-/pix/frame (amplified)	**Charge transfer efficiency**	• Appears at T<-80°C, in the amplification register • Similar to exponential decay independent from pixel intensity

Goal: design a model that would unbiased estimation of all parameters (RN, Dark, CIC, Gain, smearing)

EMCCD modelling



- **Interest**
  - Assessing unbiased **detector parameters** (from Flux/CTE)
  - Performing bayesian **photon counting** & assess photon counting efficiency
  - Analyzing and **optimizing detector performance** in different scenario

$$p(n_{ic};\Theta) = ((G(g) \circ P(\lambda)) * N(RN, b))(n_{ic})$$

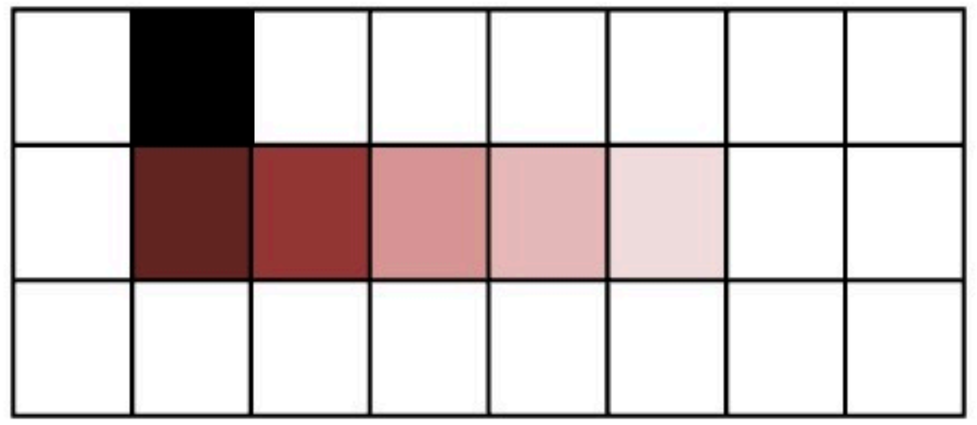
- Easy to do a stochastic model: draw pixels value by combining Gamma(poisson)+Normal
- Also several analytical/parametric models (Hirsch 2013, Harpsoe 2012) ➛ automatic fitting

$$= \frac{\lambda e^{-\lambda}}{\mathbf{g}} \exp\left(-\frac{n_{oe}}{\mathbf{g}}\right) {}_0\tilde{F}_1\left(;2;\frac{n_{oe}\lambda}{\mathbf{g}}\right)$$

- **Allow to access all the parameters**
  - Amplification gain: ± 50 ADU/e-
  - Amplified electrons (Flux+dark+CIC): ± 0.02 e-
  - Readout noise: ± 0.1 ADU
  - Semi amplified CIC, and parallel CIC (0sec exposure): ± 0.005 e-
  - Bias: ± 0.1 ADU

$$= \begin{cases} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\lambda - \frac{(\mathbf{f}n_{ic})^2}{2\sigma^2}\right) + \frac{2}{\mathbf{g}} F_\chi(2\lambda; 4, 2\mathbf{f}n_{ic}/\mathbf{g}) & n_{ic} > 0 \\ \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\lambda - \frac{(\mathbf{f}n_{ic})^2}{2\sigma^2}\right) & n_{ic} \leq 0 \end{cases}$$

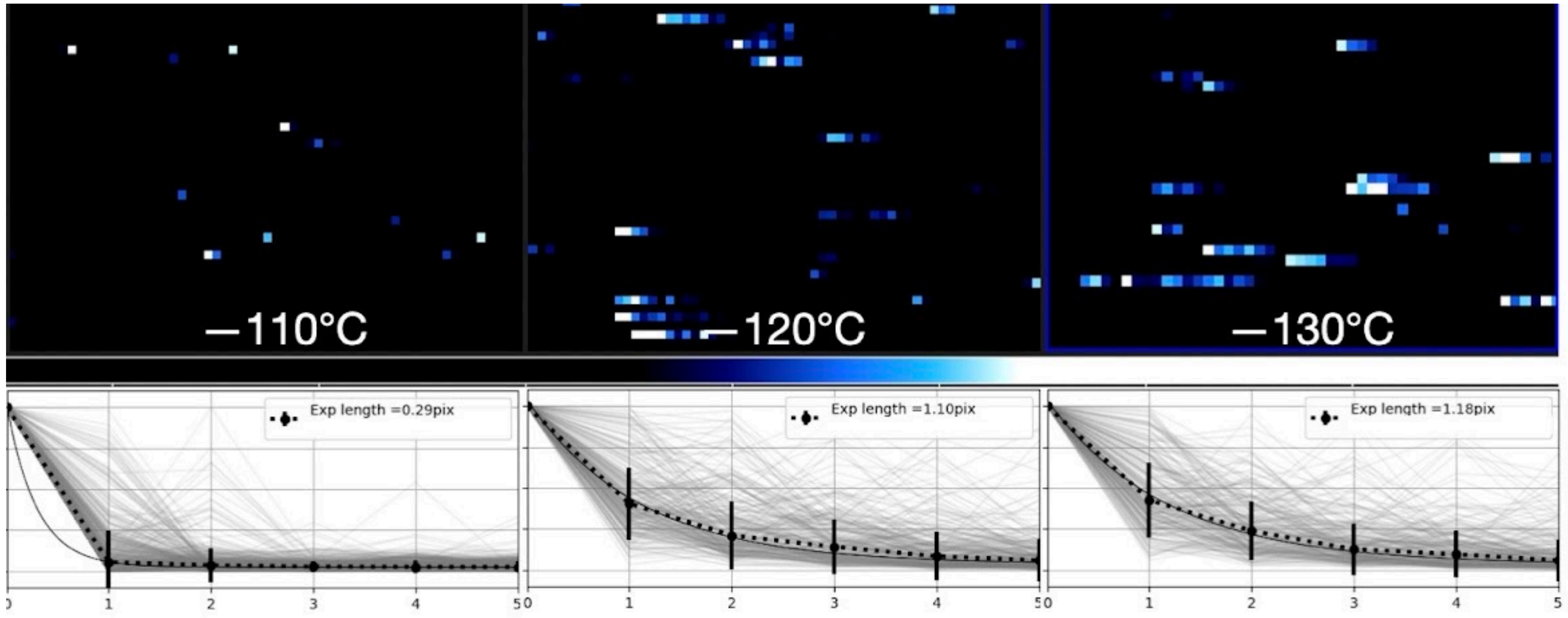
EMCCD modelling: The issue of smearing

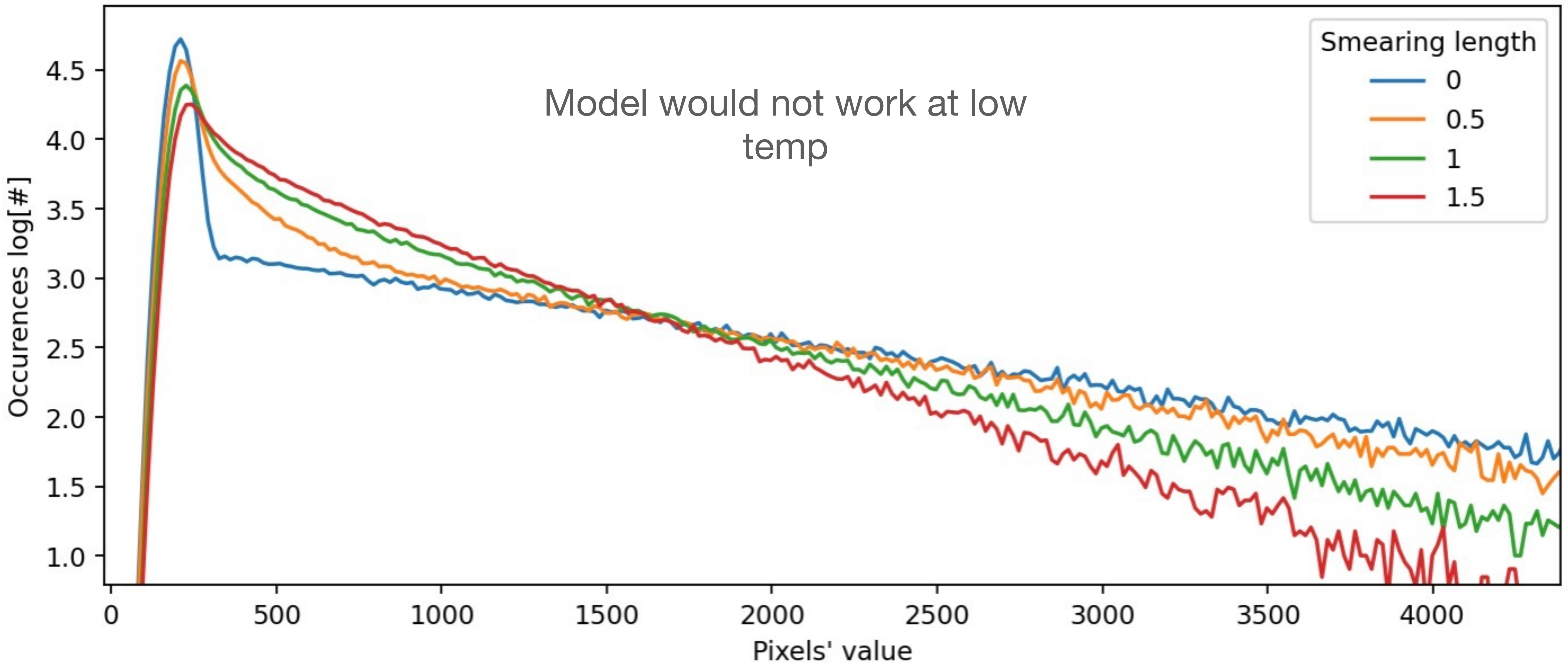


- Charge transfer inefficiency:
  - Smears the pixels values on following pixels
  - Appears below <-80°C
  - Has an **enormous** impact on the histogram
    - Can reduce the effective gain by factor >3
  - Can lower photon counting efficiency

- Fits really well an exponential profile
  - Independent of first pixel intensity
  - BUT hot pixels, CR & OS can give ≠ results

- So added it easily to the stochastic model
  - $\mathrm{Gamma}(\mathrm{Poisson}(F),G)*\exp^{-1/\mathrm{smearing}}+N(\mathrm{Bias},\sigma_{\mathrm{RN}})$
  - Fits everything (with low high flux, smearing, etc)
- & combined a smearing toy model to Harpsoe 2012
  - Works in nominal low flux conditions
  - Allows automatic fitting

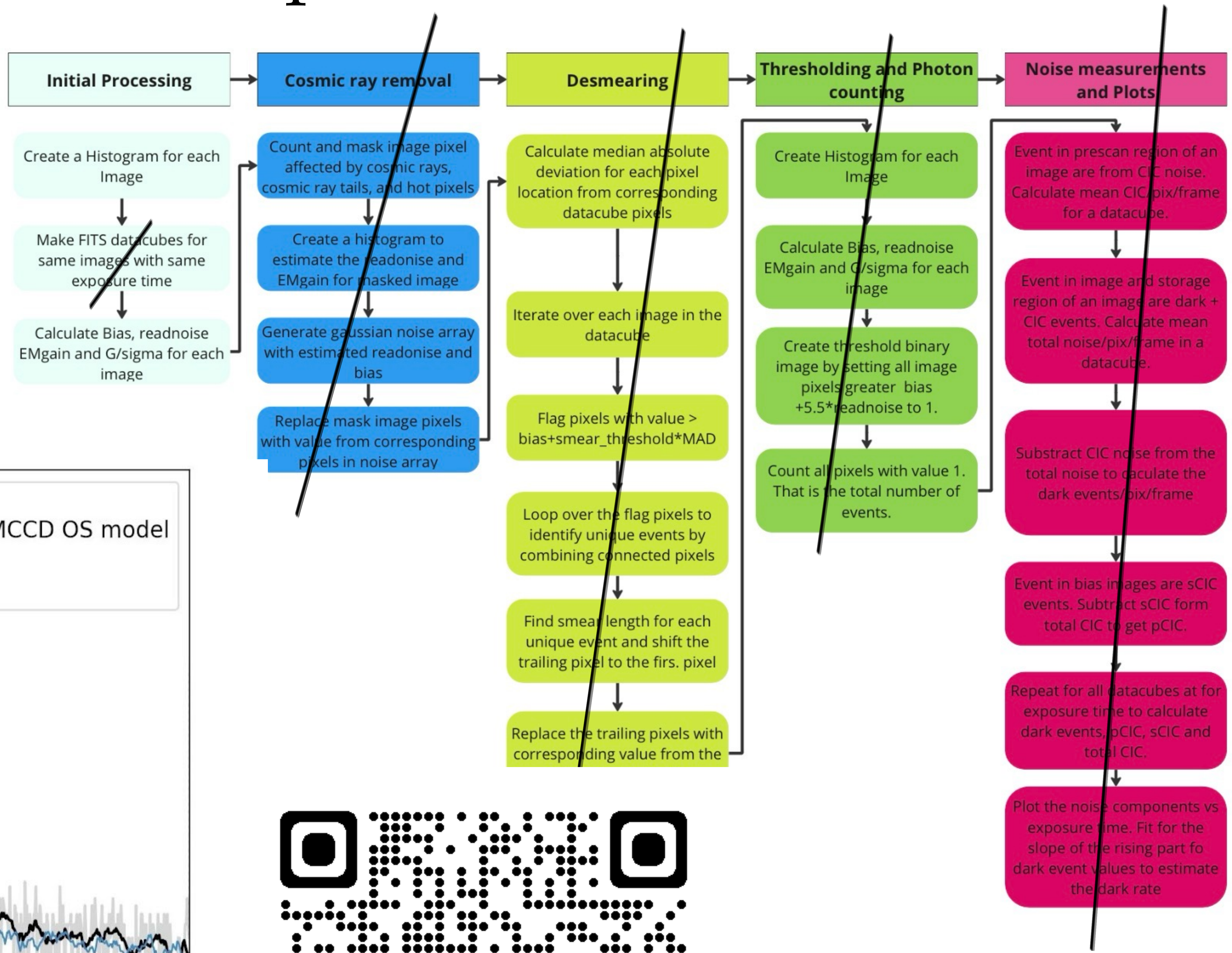


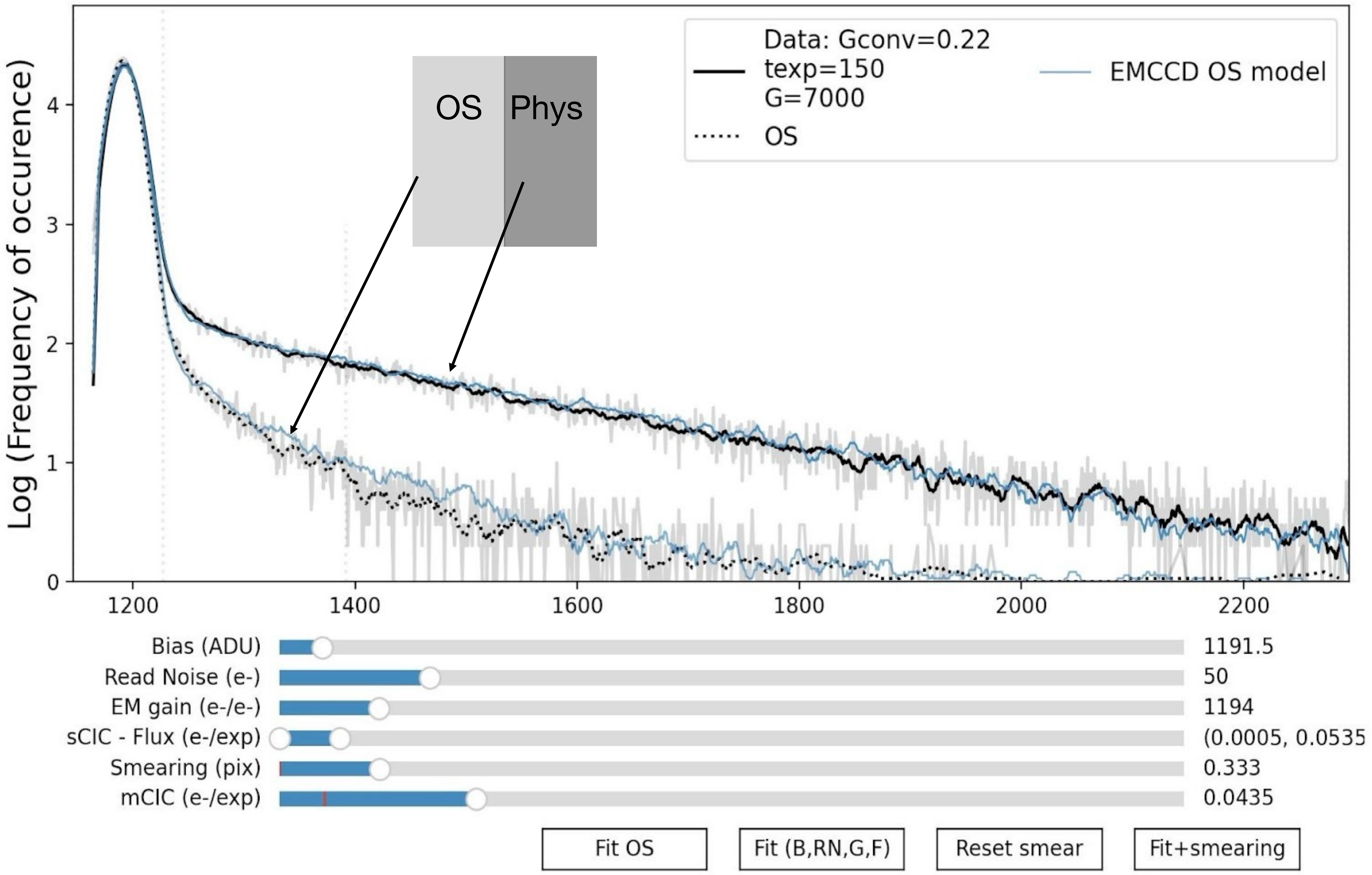


Retrieving all the parameters

Fitting method:

- Estimate smearing on the image and fix it
- Fit **Bias** and **readout noise** on OS region
- Fit **Gain,Flux & Smearing** (on physical region):
  - ➢ **pCIC** for 0 second exposure
  - ➢ **dark current** for long dark exposure
- Fit **sCIC** on OS region





https://github.com/vpicouet/pyds9plugin

EMCCD performance

Noise performance		Other performance	
Read noise (e^-)	• ~20e⁻ ➛ 0e⁻ with amplification • ↗ with readout (RO) frequency	**Quantum efficiency**	• >60% on instrument range (λ ∊ [190-220] nm) • Similar QE in the optical (λ ∊ [300-900] nm), that is going to suppressed with multilayer di-electric coating
Dark current noise	• Facing a plateau around 0.1e⁻/pix/hour below -110°C (amplified!)	**Amplification gain**	• ~2000 e⁻/e⁻ on FIREBall • Linear fit working inly if CTE=1, CIC<<Flux<<1,
Clock induced charges	• ~0.01e⁻/pix/frame (amplified!) • ↘ with RO frequency, ↗ with gain	**Charge transfer efficiency**	• Appears at T<-80°C, in the amplification register • Similar to exponential decay independent from pixel intensity
Excess noise factor	• $\sqrt{2}$ factor that can be suppressed by thresholding under strict conditions (CTE~1, F<<1e⁻/pix/frame, G/RN>>10)	**Cosmic ray impact**	• Tail of about 5x100 pixels • High cosmic-ray rate in stratosphere (>2 p/cm^2/sec)

And induced trade offs and challenges...

Exposure time calculator and image simulator

ETC:
- Examine the instrument efficiency
- Explore the SNR evolution under different scenarios
- Run different trade studies

Image simulator:
- Analyse and get used to simulated image
- Improve reduction pipeline
- Adapt detection strategy

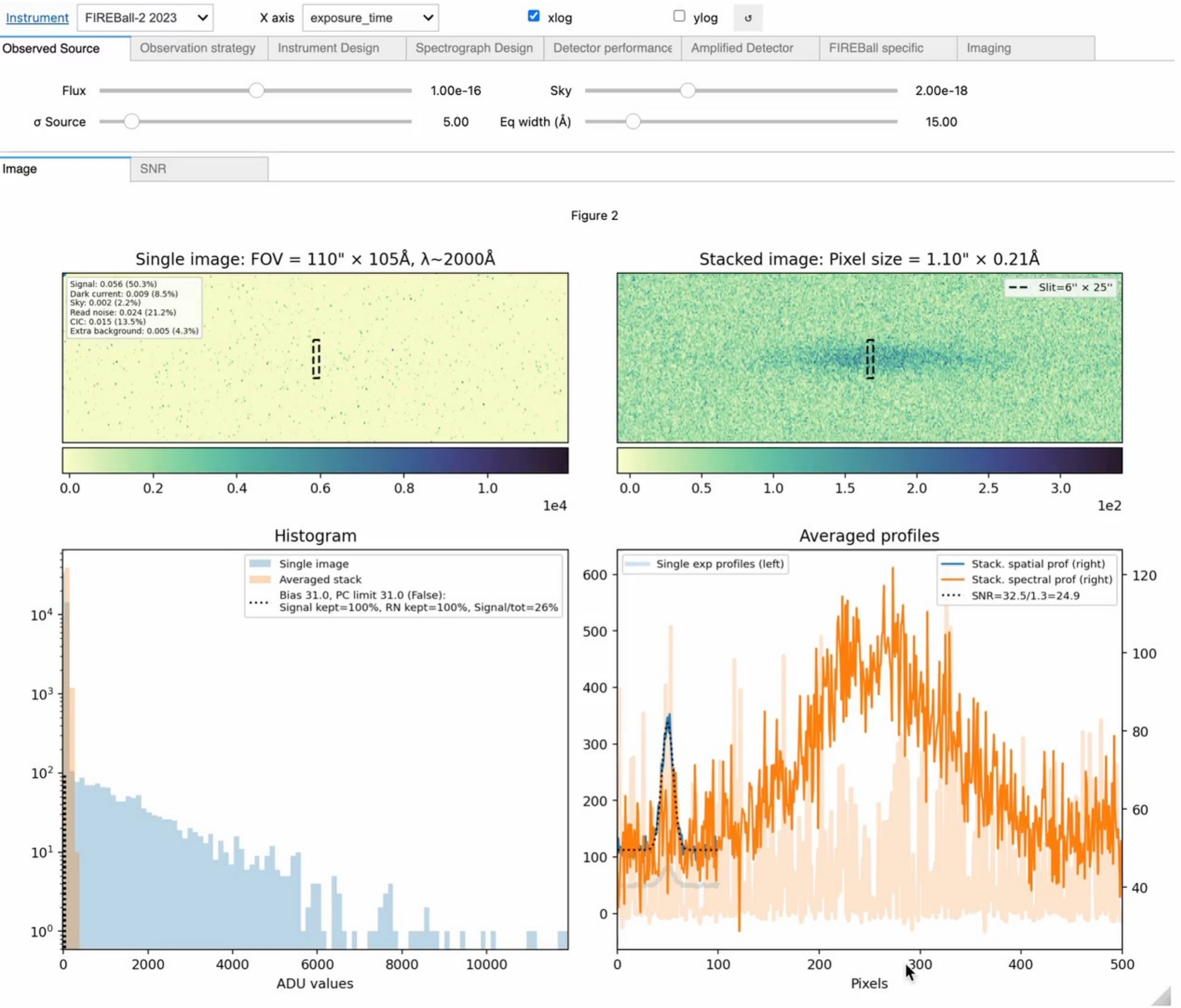
Source	Observing strategy	Instrument design	Spectrograph design

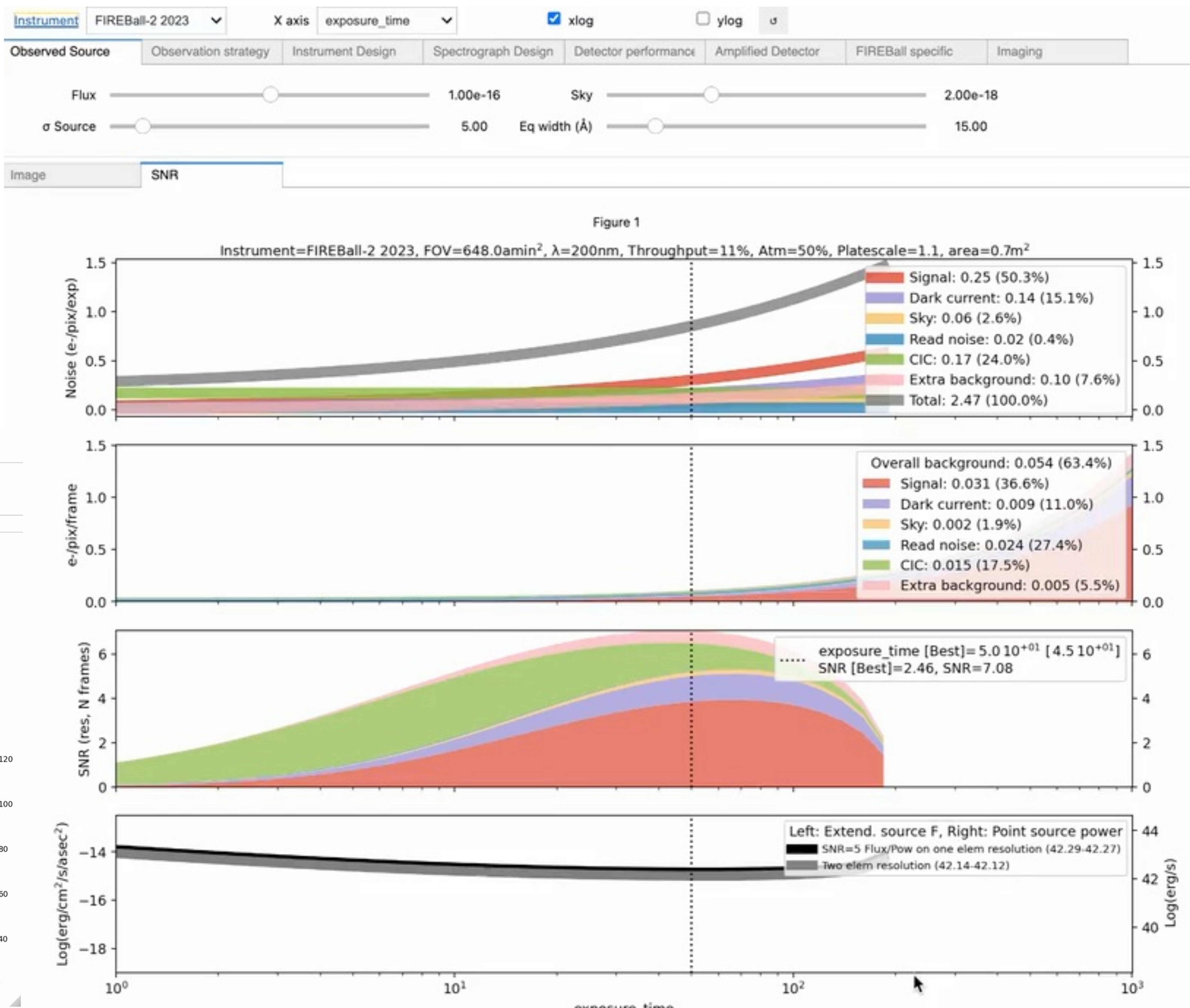
• Flux
• Sky
• Source extension
• Source's line width
	• Exposure time
	• Total acquisition time
	• Atmospheric transmission
	• Observed wavelength
	• Distance to source/line center
		• Collecting area
		• Plate scale
		• Instrument throughput
		• Spatial resolution
		  ◦ at detector
		  ◦ [at mask]
			• Spectral resolution
			• Slit width
			• Dispersion

Detector parameters	**EMCCD**	**FIREBall specifics**	**Imaging**

• Quantum efficiency
• Dark current, read noise
• Readout time
• Pixel size
• Image loss due to cosmic ray
	• EM gain
	• CIC thresholding
	• Smearing exponential length
		• Fixed detector parameters:
		  ◦ Dark(T)
		  ◦ Smearing(T)
		  ◦ CIC(EmGain)
		• Temperature
		• Thresholding photon counting
		• Threshold
			• Full well of the detector
			• Conversion gain
			• Throughput(λ) FWHM to add the λ dependency.

Exposure time calculator and image simulator





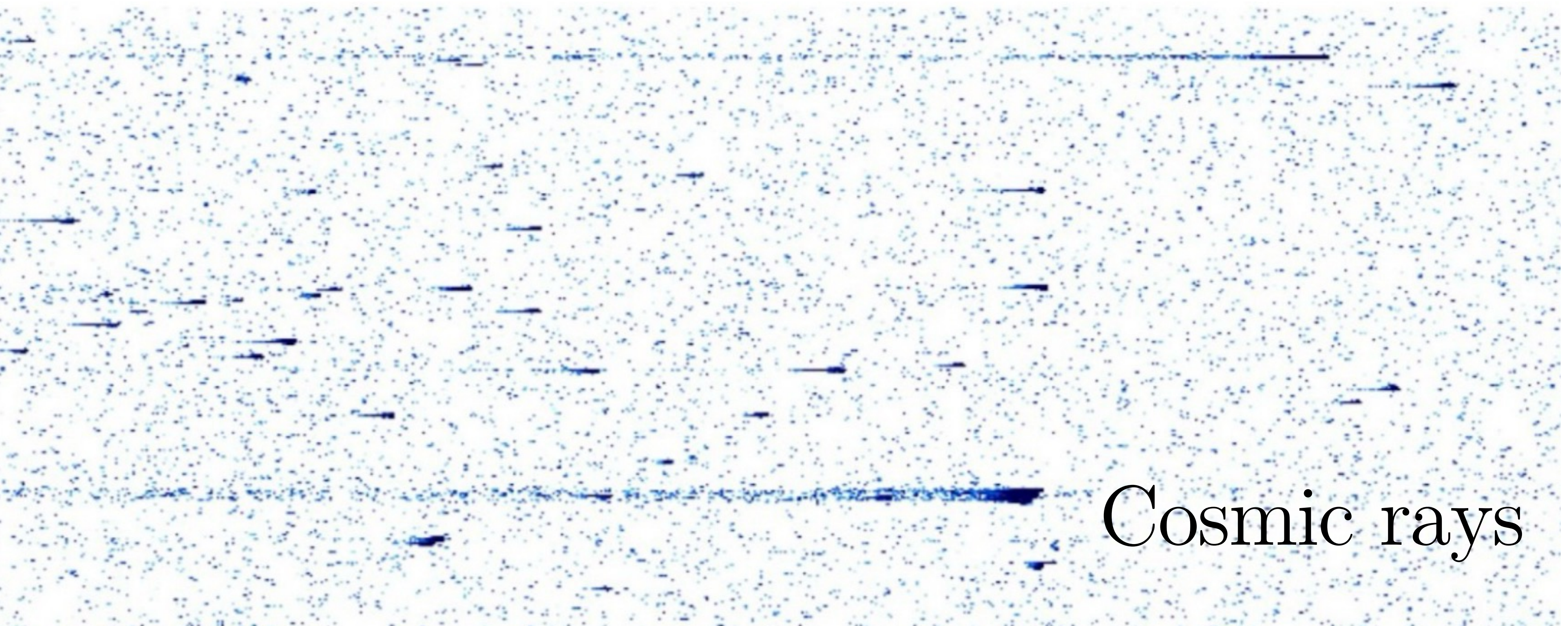
Exposure time calculator and image simulator **for spectro-imagers**

https://github.com/vpicouet/spectro-imager-etc

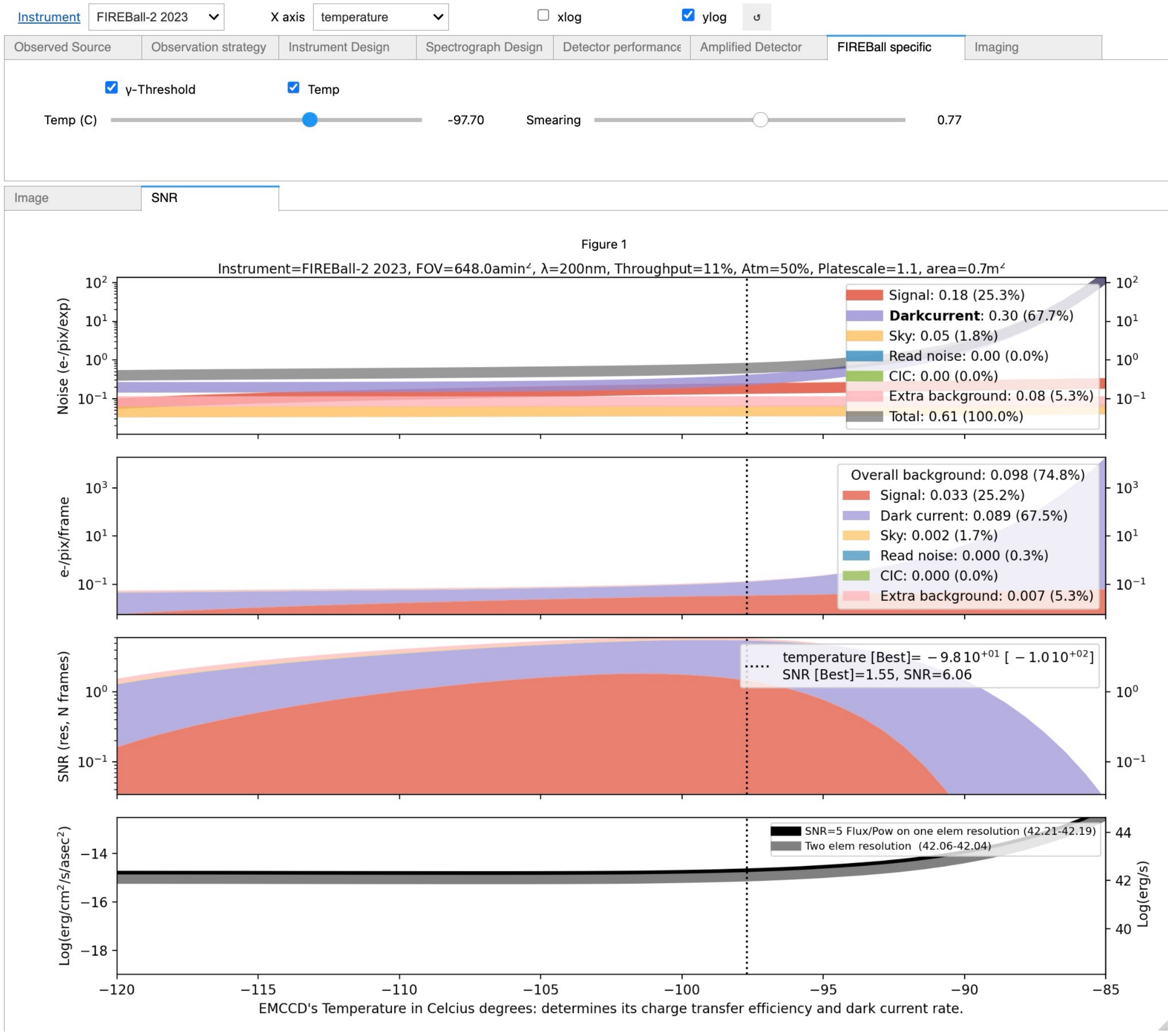
.	Charact.	Unit	FIREBall-2 2018	FIREBall-2 2023	MOSAIC	GALEX FUV	GALEX NUV	UVEX NUV	CASTOR DMD	KCWI red	KCWI blue	MUSE wide	MUSE narrow	SHERE IRDIS	NIRSPEC	LUMOS	NISP	SUMIRE PFS Blue	ELT Harmony	SPHEREx	JUNO-UVS	CETUS	Blue MUSE	CHaS
Instrum. design	wavelength	nm	200	200	600	152.8	227	200	2000	700	450	700	700	1000	600	150	1000	500	600	1000	150	250	450	500
	Spectro description	.	Multi slit	Multi slit	Fibers	Slitless	Slitless	Long slit	DMD MOS	Slicer	Slicer	Slicer	Slicer	Long slit	Multi-Object	MOS	Slit less	Fiber	Slicer	Lin. var filters	Slit	MSA MOS	Slicer	Lenslet
	FOV_size	amin2	648.00	648.00	40.00	4608.00	4464.00	441000.00	6.73	0.19	0.19	1.00	0.02	0.03	**9.60**	4.80	1983.19	6084.00	0.02	284760.00	3600.00	289.00	2.00	100.00
	Bandpass	nm	197-213	197-213	450-700	135-175	175-280	115-265	150-300	560-1080	350-560	465-930	465-930	950-1650	600-28500	100-200	900-1192	380-650	800-1350	750-2420	68-210	180-350	350-580	400-900
	pixel_scale	"/pix	1.100	1.100	0.250	1.500	1.500	1.030	0.100	0.147	0.147	0.200	0.025	0.012	0.100	0.330	0.300	0.939	0.040	6.200	148.000	0.400	**0.200**	0.430
Spectro design	Bandwidth	Å	160	160	2500	400	1050	1500	1500	5200	2100	4650	4650	7000	279000	1000	2920	2700	5500	16700	1420	1700	2300	5000
	Spectral_resolution	λ/dλ	1300	1300	4000	200	90	1500	1500	1300	1300	3000	3000	350	1000	8000	380	2300	3300	41	75	1000	4000	10000
	Slitwidth	"	6	6	**3**	3600	3600	16	0.2	0.35	0.35	0.200	0.025	0.1	1.6	**0.10**	42	1.1	0.040	12600	90.00	2.00	**0.200**	2
	Slitlength	"	25	25	**3**	3600	3600	3600	**20**	1.35	0.35	0.200	0.025	11	3.0	**3.00**	NA	1.1	0.06	NA	432.00	360.00	**0.200**	2
	dispersion	Å/pix	0.21	0.21	**0.63**	2.50	6.06	0.04	1.40	0.30	0.20	0.40	0.40	11.00	14.29	**0.04**	**13.00**	**0.70**	**0.69**	**4.18**	1.00	0.42	**0.40**	0.37
Telescope	Name	.	FB	FB	ELT	GALEX	GALEX	UVEX	CASTOR	Keck	Keck	VLT	VLT	VLT	JWST	LUVOIR	EUCLID	Subaru	ELT	SPHEREx	JUNO	CETUS	VLT	MDM
	Altitude	km	35	35	3	1000	1000	1000	1000	4	4	3	3	3	1000	1000	1000	4	3	1000	1000	1000	**3**	2
	Collecting_area	m2	0.785	0.707	1195	0.196	0.196	0.442	0.780	78.500	78.500	52.810	52.810	52.81	34.21	176.000	1.13	52.810	1195	0.031	0.00001	1.77	**52.810**	3.791
	Atmosphere	%/100	0.50	0.50	0.92	1.00	1.00	1.00	1.00	0.90	0.90	0.90	0.90	0.92	1.00	1.00	1.00	0.90	0.92	1.00	1.00	1.00	**0.90**	0.60
	Sky	erg/cm2/s/"2/Å	4.60E-16	2.00E-18	5.00E-18	2.00E-18	2.00E-18	2.00E-17	1.00E-18	1.13E-17	1.76E-17	1.13E-17	1.13E-17	1.50E-17	3.00E-17	2.00E-17	1.00E-18	1.70E-17	5.00E-18	**1.00E-18**	1.00E-18	1.00E-18	**1.13E-17**	1.59E-17
Obs. Startegy	Signal	erg/cm2/s/"2/Å	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16	1.00E-16
	PSF_source	" (σ)	5	5	5	5	5	5	16	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	Line_width	Å	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15						
	acquisition_time	hour	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2						
	exposure_time	sec	50	50	900	1000	1000	300	600	1600	1600	500	500	20	1000	1000	565	60						
	lambda_stack	Å	0.21	0.21	**0.63**	2.50	6.06	0.04	1.40	0.30	0.20	0.40	0.40	**11.00**	14.29	**0.02**	**13.00**	**0.7**						
	Δx	"	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0						
	Δλ	Å	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0						
Instr perf	PSF_RMS_mask	" σ	2.50	2.50	0.10	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.0						
	PSF_RMS_det	" (σ)	3.00	3.00	0.10	1.83	2.26	0.85	0.30	0.59	0.59	0.02	0.02	0.30	0.10	0.02	**0.23**	1.6						
	Throughput	%/100	0.11	0.11	0.17	0.16	0.16	0.20	0.70	0.30	0.30	0.25	0.20	0.25	**0.20**	0.80	0.50	0.5						
Detector	Detector_type	.	emCCD	emCCD	urv CCD 16	MCP	MCP	CMOS	CMOS	emCCD	emCCD	CCD	CCD	H2RG 2 2x1k	CCD	emCCD	HgCdTe	CCD 2						
	pixel_size	µm	13	13	**6.5**	**37.00**	**37.00**	10	10	15	15	15	15	18	18.00	6.5	16	15						
	readout_time	sec	0.5	5.0	100.0	0.0	0.0	3.0	**3.0**	16.0	16.0	95.0	95.0	0.8	10.0	0.0	10.0	106						
	RN	e-/pix	107	**40**	2.3	0	0	2	**2**	3	3	2.6	2.6	4	16	3	28	2.						
	Dard_current	e-/pix/hour	1	1	18	0.049	0.049	3.6	**3.6**	3	1	3	3	210	7	18	14	1.						
	QE	%/100	0.50	**0.40**	0.8	0.12	0.08	**0.9**	**0.9**	0.85	0.85	0.70	0.70	0.95	0.70	0.13	0.75	0.						
	cosmic_ray_loss_per_sec	./sec	0.0050	0.0050	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.00						
FB specific	smearing	pix	1.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.						
	CIC_charge	e-/exp	0.015	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0						
	EM_gain	e-/e-	1400	1700	1	1	1	1	1	1	1	1	1	1	1	1	1	1						
	extra_background	e-/pix/hour	3	0.5	0.10	0.10	0.10	0.10	0.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.1						
Imag.	Full_well	kADU	56	52	60	60	60	60	60.00	60	60	60	60	60	60	60	60	60						
	conversion_gain	ADU/e-	0.5	1	1	1	1	1	1.00	1	1	1	1	1	1	1	1	1						
	Throughput_FWHM	Å	300	400	2500	400	1050	1500	1500	5200	2100	4650	4650	7000	279000	1000	2920	270						

EMCCD Tradeoffs

- **Exposure time (t_{exp})**
  - CIC & RO time lower SNR at low t_{exp}
  - Cosmic ray masks an image fraction $\propto t_{exp}$
- **Temperature**
  - Dark current ↗ with T°
  - Smearing appears at T<-80°C & increases
    ➛ preventing efficient photon counting
  - Charact the T° dependancy gives $T_{opt}°$
- Photon counting threshold
- *Controller frequency*
- *Charge clearing*
- *Gain vs CIC*



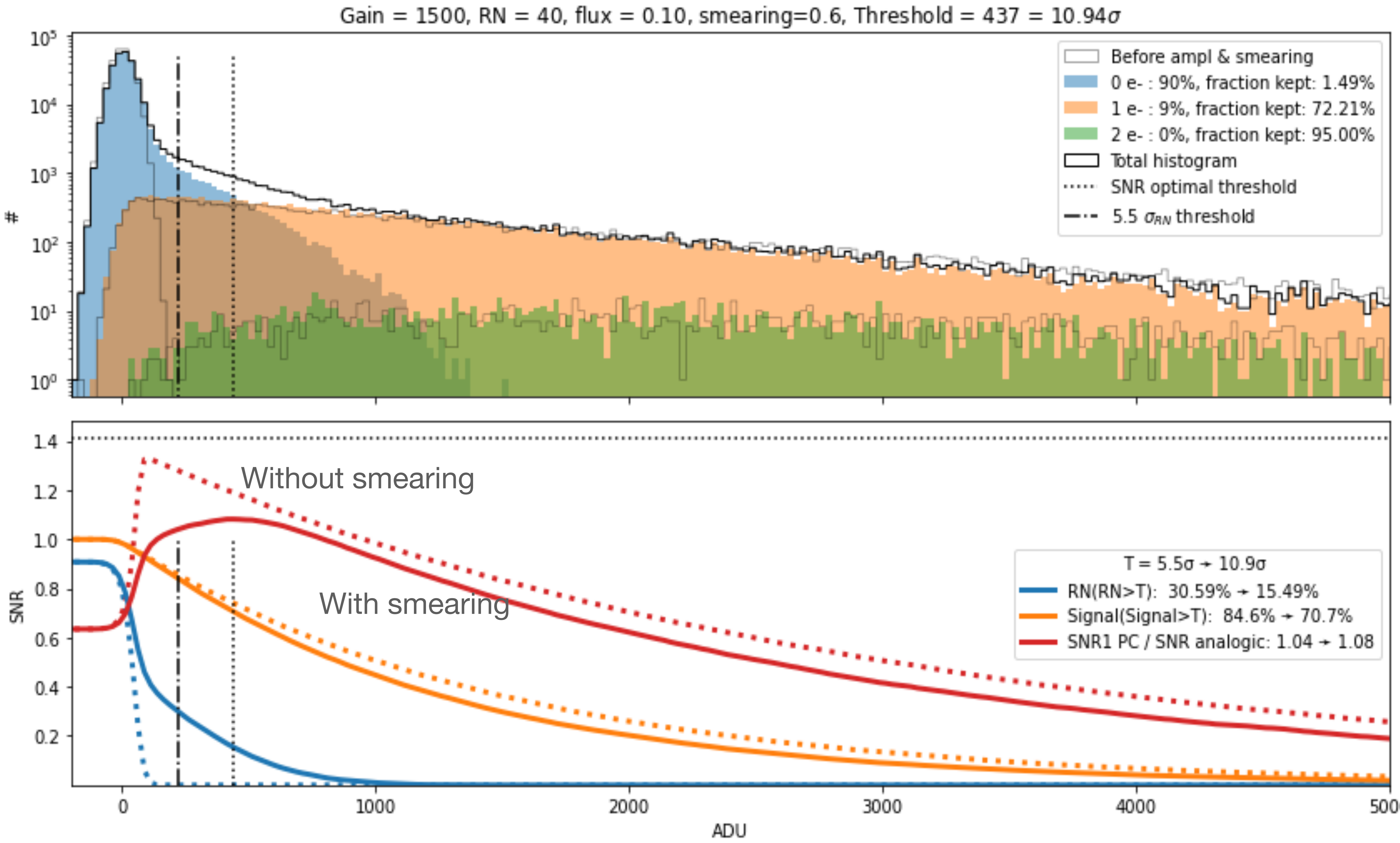
Cosmic rays



Photon counting threshold

$$SNR(T) = \frac{S \times \frac{N_{e^- > 0, ADU > T}}{N_{e^- > 0}}}{\sqrt{\frac{N_{e^- > 0, ADU > T}}{N_{e^- > 0}} \times (S + \sigma^2_{CIC} + \sigma^2_{DC} + \sigma^2_{SKY}) + \frac{N_{e^- = 0, ADU > T}}{N_{e^- > 0, ADU > T}}}}$$

- ENF = √2
- SNR gain (SNRthreshold/SNRanalogic) ∈ [0,√2]
- ➛ √2 when CTE~1, F<<1e/pix/frame, G/RN>>10
- ➛ 0 when CTE<<1, G➛RN, F>>1
- 5.5σ limit ~optimal only when no smearing
- In presence of smearing
  - Requires correction/inversion
  - Or higher thresholding limit



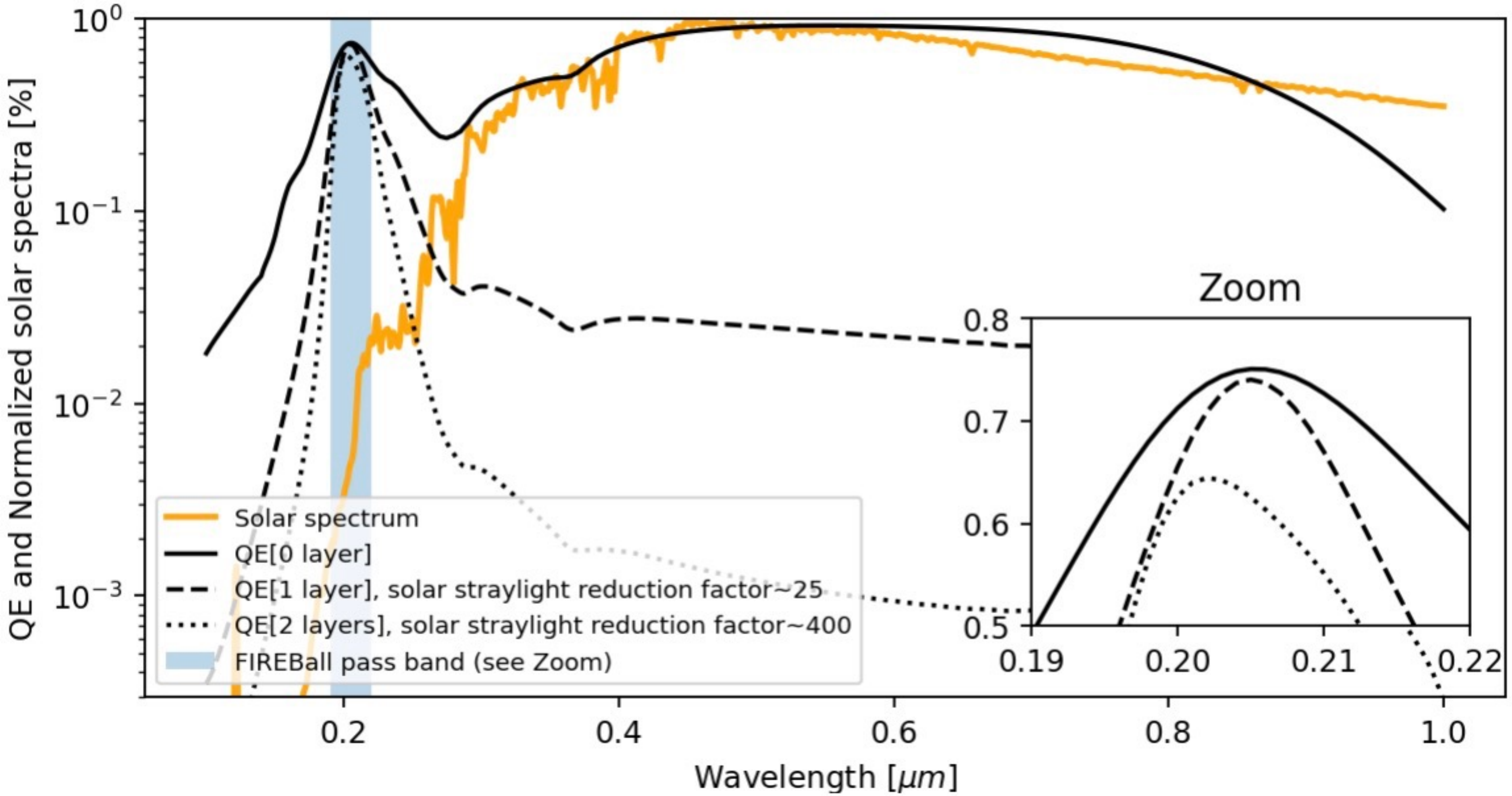
Challenges and adaptation

1. Sky background & Straylight
   - ➢ EMCCD red blocking filter
2. Dark plateau at low T°
   - ➢ cooling, EMCCD filter?
3. Cosmic ray impact
   - ➢ Overspill register addition

Challenges and adaptation: EMCCD red blocking filter

Current EMCCD:
- Delta doping for UV optimization (QE_{int}=100%)
- 3 layers antireflection coatings to boost QE_{tot}
- QE is also high in visible! ➛ Red leak issue!

Adaptation:
- Addition of 1-2 layer metal-dielectric filter to suppress the out-of-band light
- 15% reduction of QE_{UV} per layer
- Factor ~20 reduction of QE in visible



Challenges and adaptation: Dark plateau at low temperature

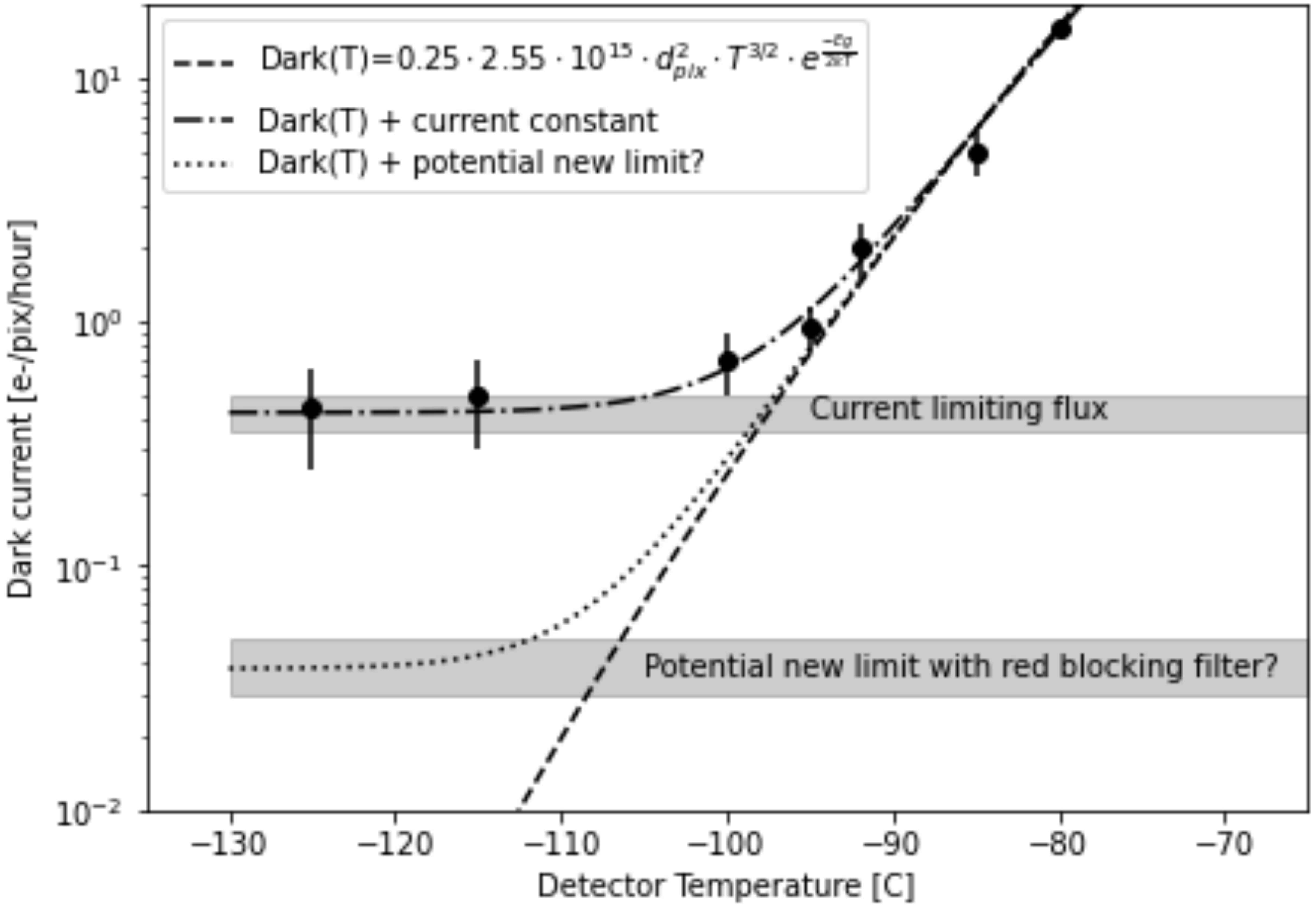
- Dark values plateauing at low temperature (<-100°C)
  - non-temperature dependent component…
  - Low-level light leaks?
  - Photons from the tail of thermal black-body emission?
  - Smearing biased estimation?

- Ongoing experiment at UoA shows the plateau value reduces when detector surrounding is cooled (A. Khan in prep)
- This could be consistent with NIR black body emission
- EMCCD QE is not constrained above 1 µm

- Number of Black Body photon reaching the detector:

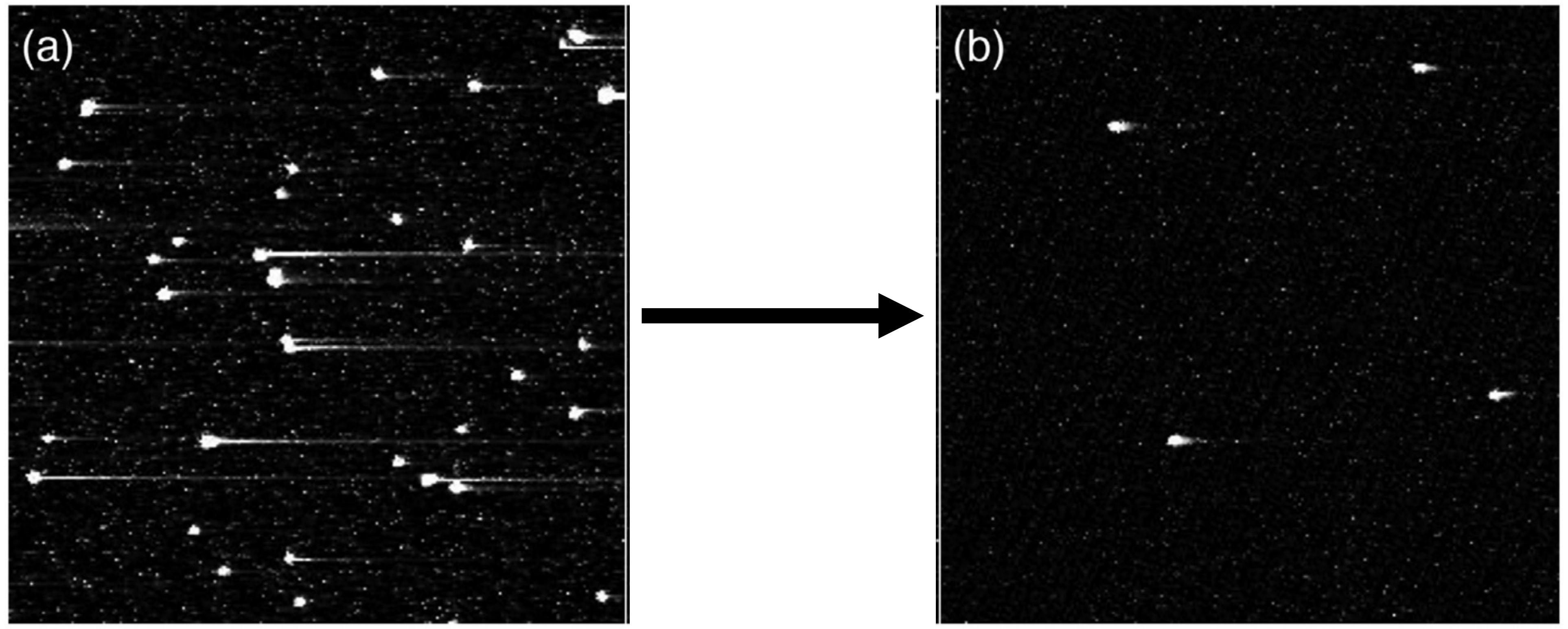
$$N = A \times \Omega \times t \times \int_{\lambda_{\text{start}}}^{\lambda_{\text{end}}} \frac{2c}{\lambda^4} \left(\frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1} \right) \times \mathbf{QE}(\lambda), d\lambda$$

- Possibilities:
  - Reduce instrument T° seen by EMCCD
  - **Reduce QE in the NIR/visible**

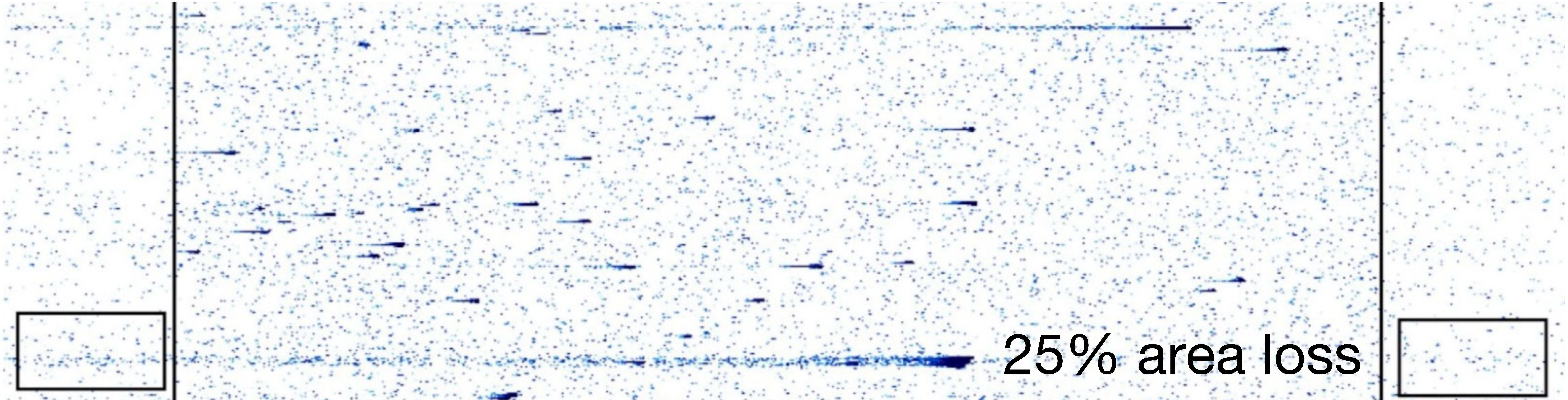


Challenges and adaptation: Cosmic ray impact

- Rate >2 particles/cm2/sec (500 times higher than on ground)
- At optimal exposure time, 25% of the image is masked
- Overspill register reduces CR tail by ≥3
- High exposure time without cosmic rays and should increase the possible SNR by >15%
- Should be able to implement this change late 2025



P. Morrissey 2023: Effect of the Overspill Drain on an energetic cosmic ray at an EM gain of 1000



Conclusion

- EMCCDs boast impressive potential but can be intricate
- They require precise optimization to unlock their full capabilities
- Ongoing significant technological progress
    - Red blocking filter
    - Cosmic ray impact mitigation [Morissey 2023]
- Still a lot to learn and optimize
- Important *current* limiters for FIREBall science
    - *Red leak ➛ mitigation in progress*
    - *Cosmic ray impact ➛ mitigation in 2025?*
    - Charge transfer inefficiency (smearing) at low temperature
        - ➛ Correction? Inversion
- EMCCD remain competitive for FIREBall science
- Efficiency for low surface brightness detection is slightly higher than what is achievable with MCPs

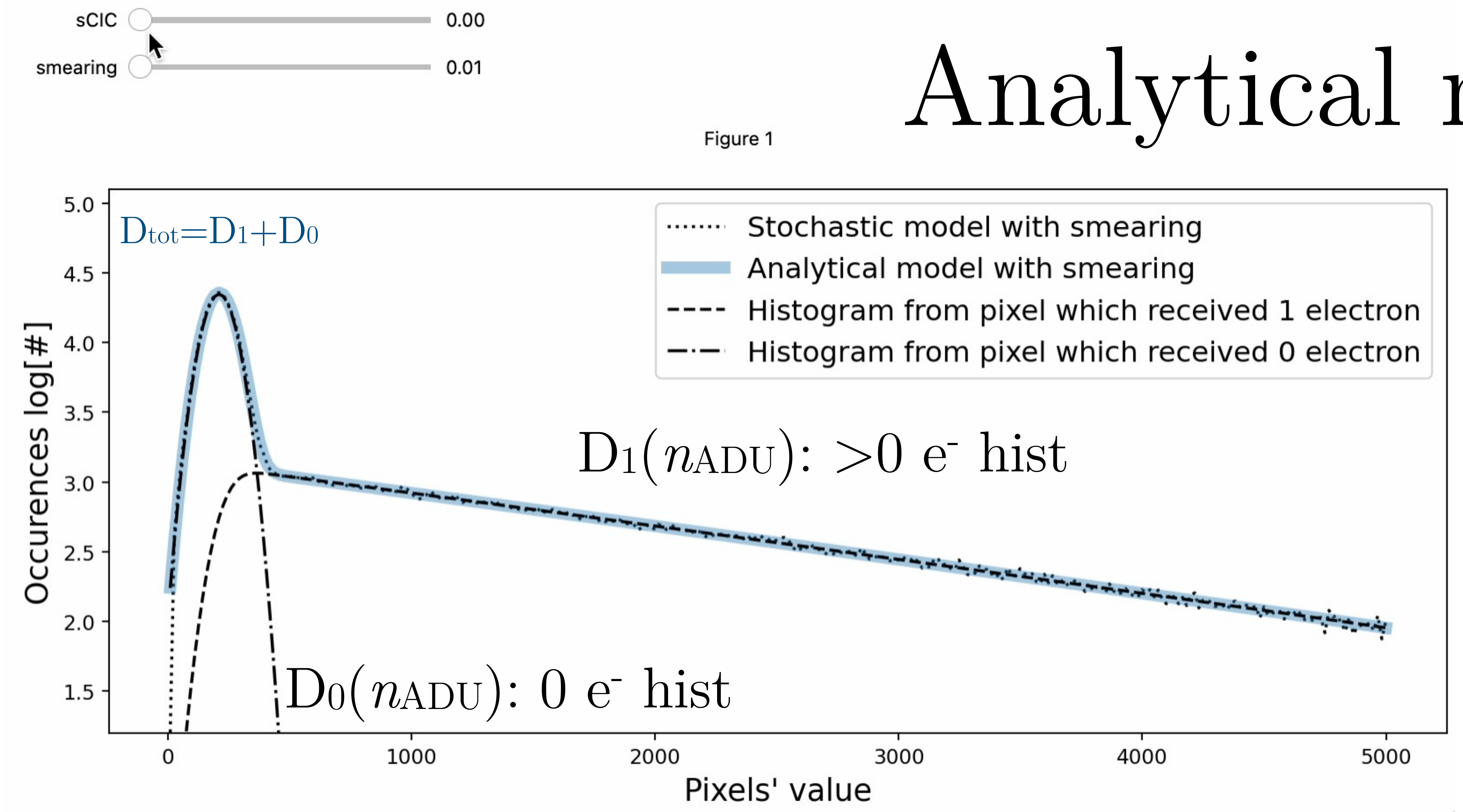
Credits: P. Balard

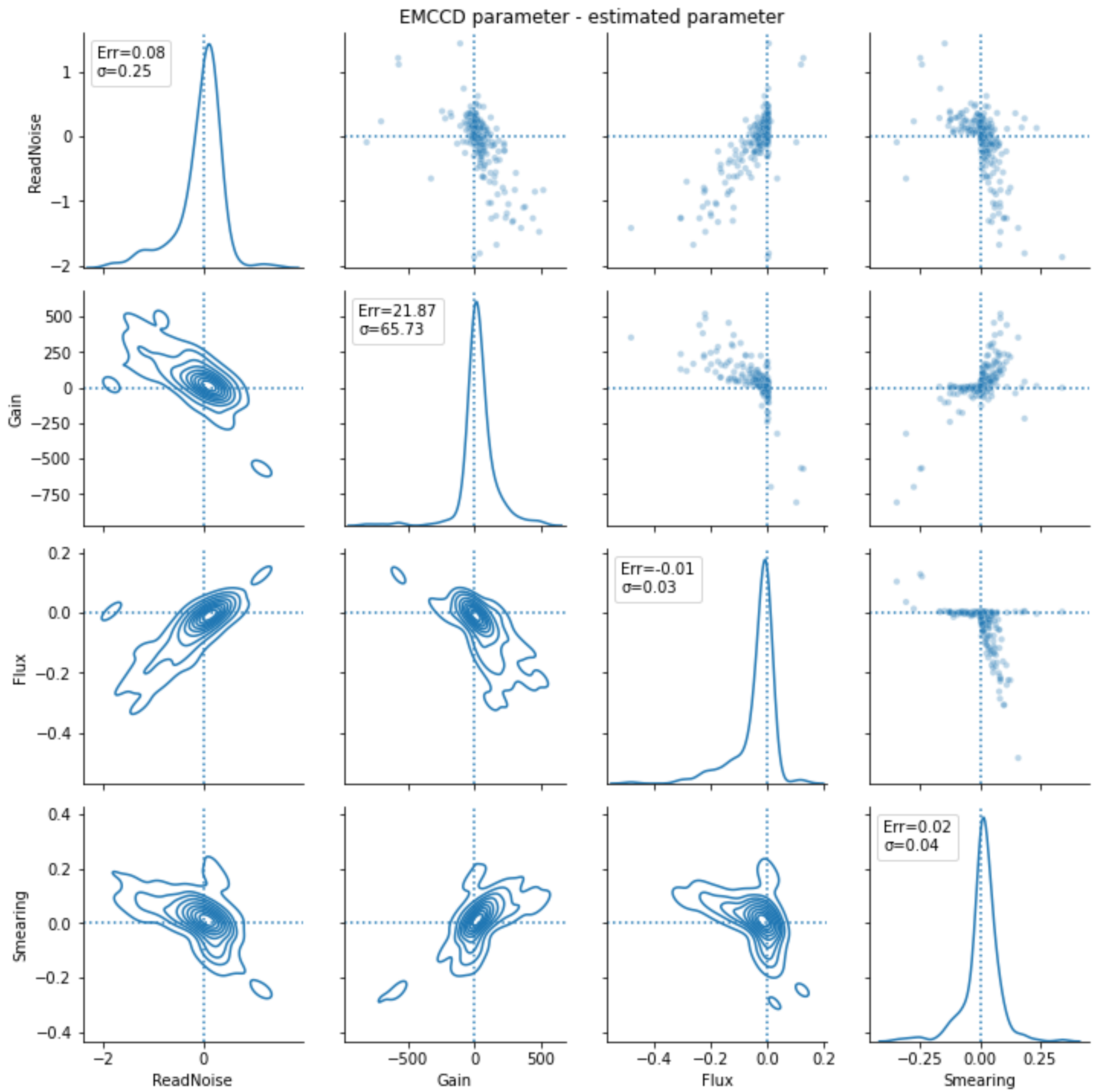
Thanks for your attention

Questions?

Vincent Picouet
vpicouet@caltech.edu

Analytical model and automatic fitting





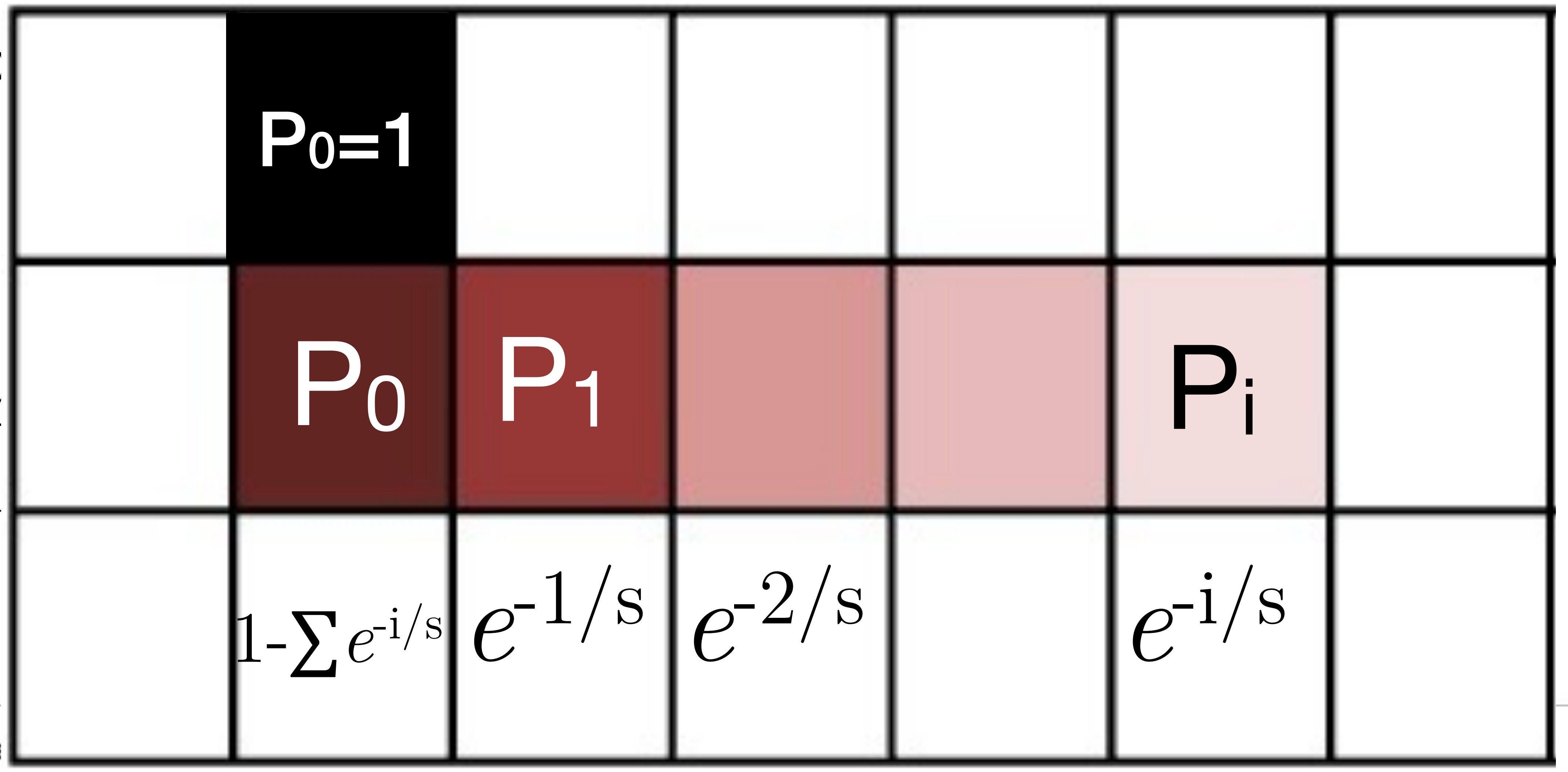
- Analytical toy model description of smearing (hypothesis: low flux)
    - Reduce $D_1(n_{ADU})$ by $D_1(n_{ADU} \sum e^{-i/smearing})$
    - Transfer this energy to the adjacent pixel

  = replacing D_0 by $D_{Tot}(n_{ADU} \times e^{-1/smearing})$
    - Iterate on following 3-4 pixels for low CTE
- Allows automatic fitting (even smearing)
- Work still in progress, some degeneracy

Challenges and adaptation: EMCCD processing codes

Smearing correction/inversion

- Calculate median absolute deviation for each pixel locatic
  pixels
- Iterate over each image in the datacube
- Flag pixels with value > bias+smear_threshold*MAD
- Loop over the flag pixels to identify unique events by con
- Find smear length for each unique event and shift the tra
- Replace the trailing pixels with corresponding value from



Challenges and adaptation: EMCCD processing codes

Bayesian photon counting

- Assess the detector parameters: bias, readnoise, gain, CIC, Dark, smearing.
- Prior assessment:
  - If this is a flat image, the average flux could be assessed using histogram fitting from step 1.
  - It is also possible to derive a prior for any given pixel. Either by dividing the image (potentially smoothed) by the gain or if the astronomical source in known by using a simulation or the exposure time calculator.
- Use these parameters to model an similar histogram or a sequence of histogram for different fluxes, distinguish the different population of pixels based on the number of photon electrons they received
- For each flux/histogram:
  - For each number of photon electrons (n), find the value of ADUs at which the distribution in ADU (P(n)) crosses the distribution of P(n-1) and P(n+1). Use these values to assign to each pixel the number of photo electrons they most likely received.

Overspill register

Morissey 2023: Flight photon counting electron multiplying charge coupled device development for the Roman Space Telescope coronagraph instrument

- Overspill register parallel to the gain register to mitigate the effects of cosmic rays.
- Early results indicate the gain register overspill is very effective at eliminating tails from cosmic rays

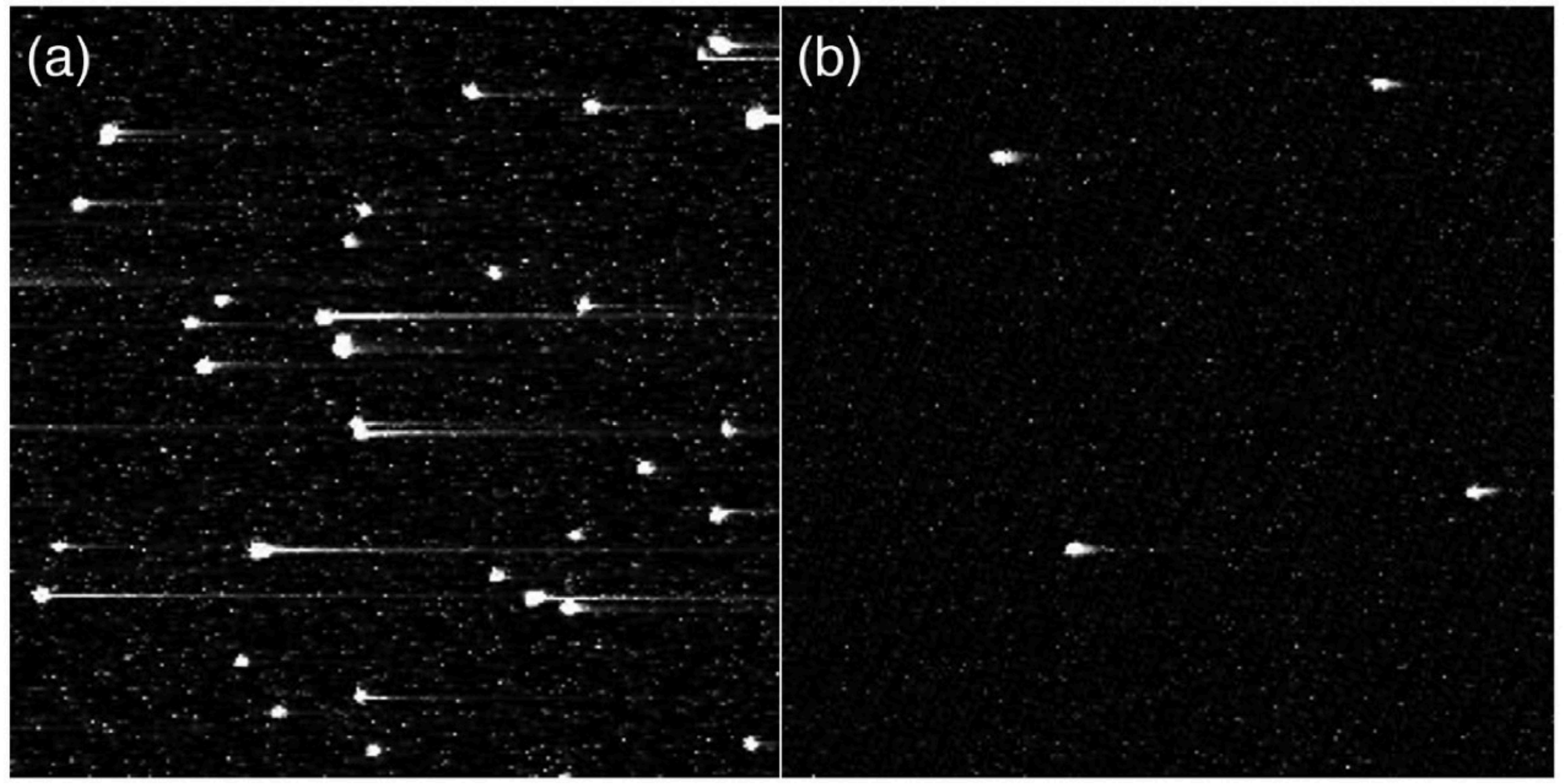
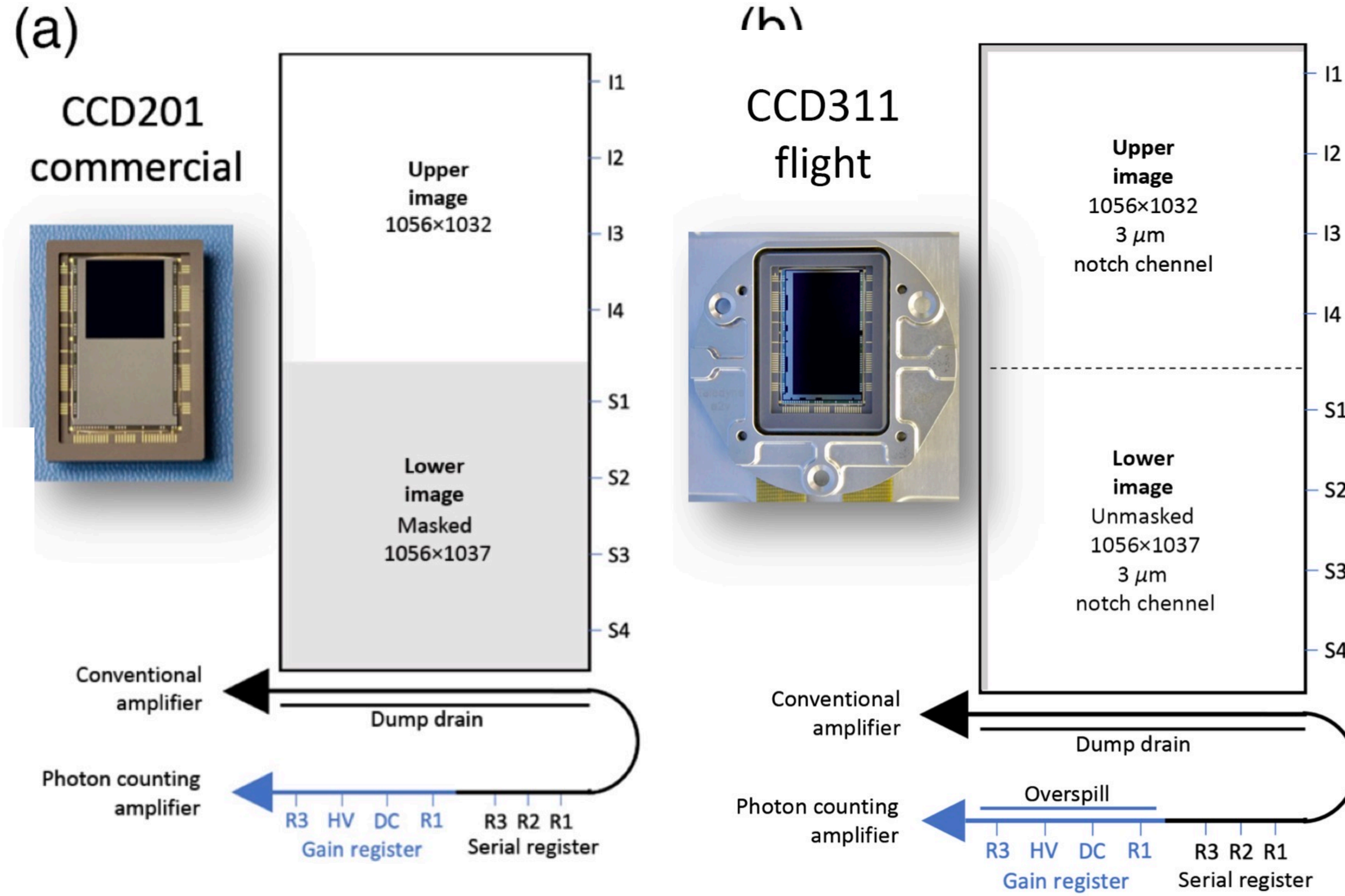


Fig. 21 A comparison of cosmic ray tails observed in the lab with the camera operating at high gain (>1000×). (a) A 256 × 256 image section from the CCD201 and (b) the CCD311 under similar conditions. The operating temperature was −105°C. The improvement is quite significant with tails in the commercial sensor example of over 100 pixels and only 40 pixels in the flight design as a result of the overspill.



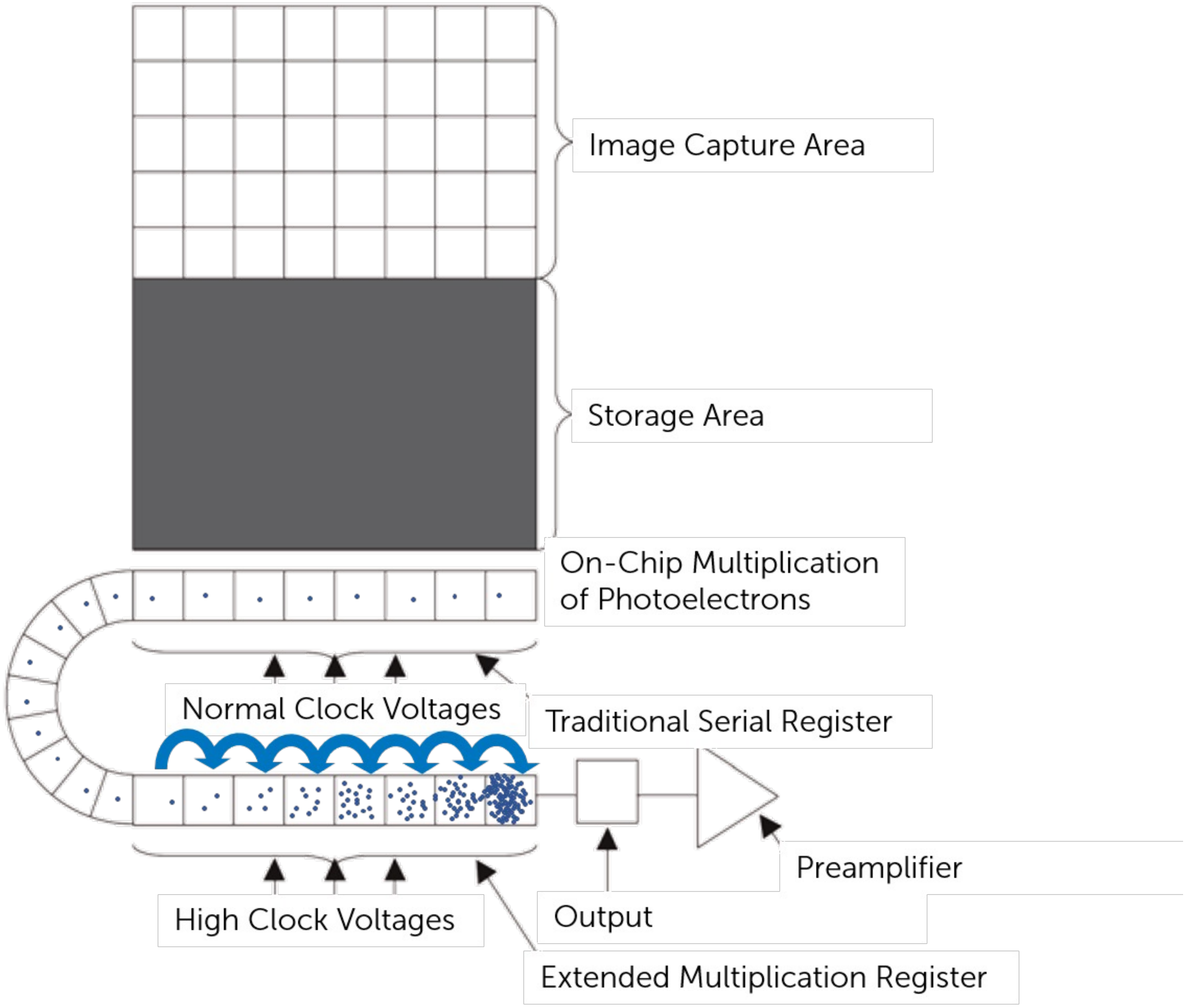


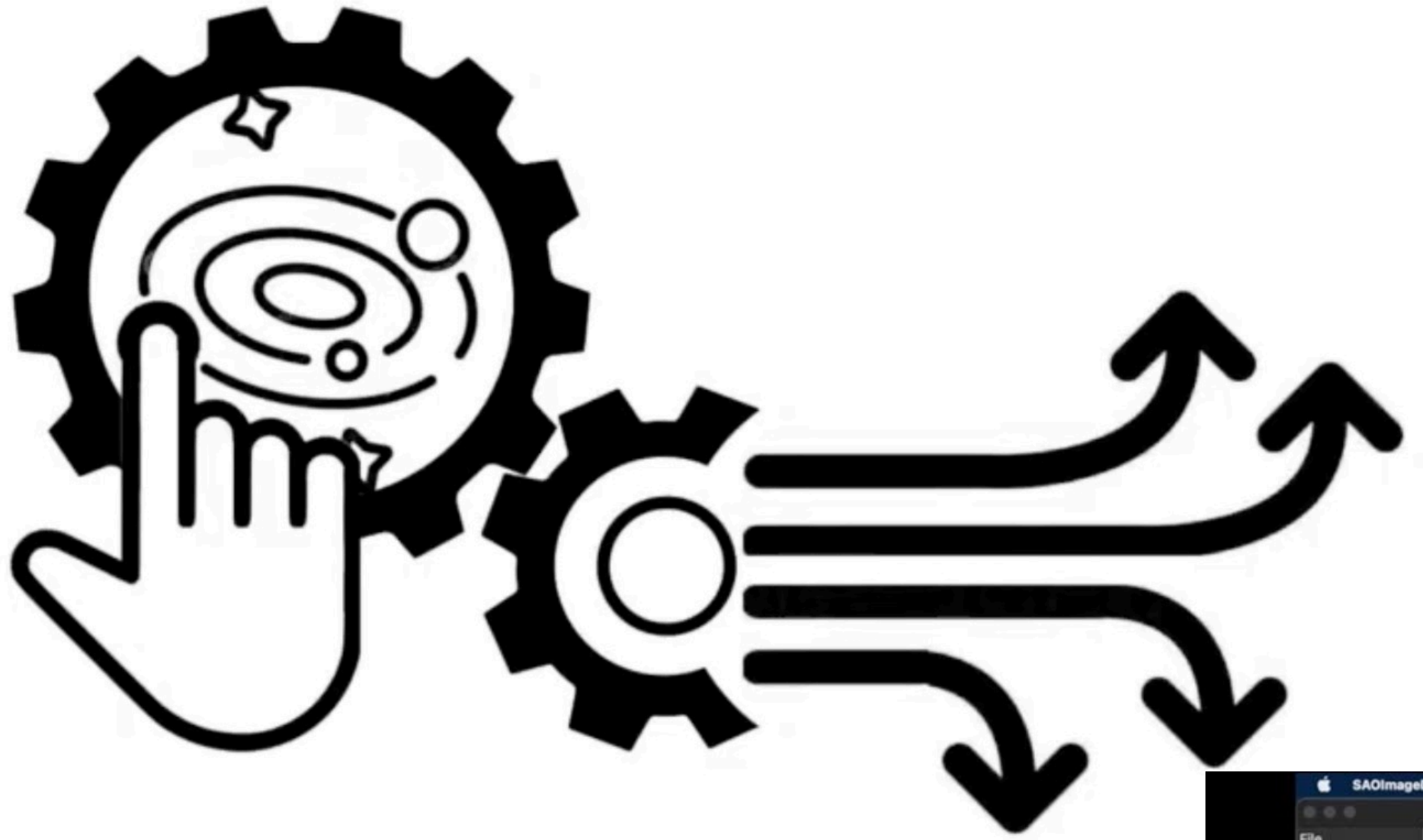
Image Capture Area
Storage Area
On-Chip Multiplication of Photoelectrons
Normal Clock Voltages
Traditional Serial Register
Preamplifier
Output
High Clock Voltages
Extended Multiplication Register

Interactive image processing scalable into a multi-processing pipeline with

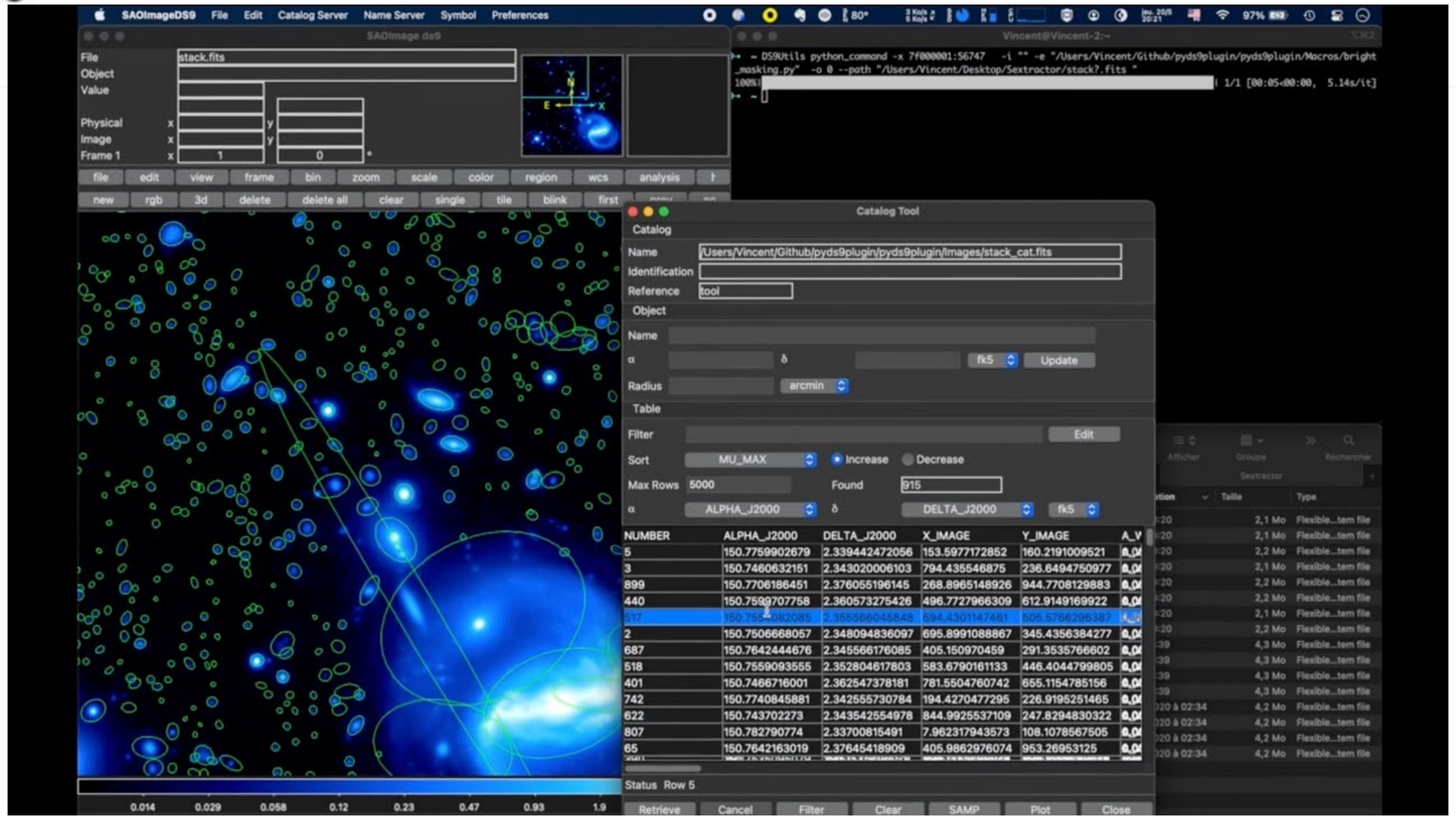
DS9 quick look plug-in

https://github.com/vpicouet/pyds9plugin

Picouet 2021: Tackling the issue of image processing via plugins: the example of pyds9plugin



- **Instrumentation:** Centering, trough-focus...
- **Observations' reduction:** Stacking, background removal...
- **Performance verification:** Radial profile, 2D/3D fitting...
- **Research-grade analysis:** Source/artefact extraction...
- Or simply turn your Python codes into DS9 Macros



Summary

- The need for image processing applications
- Challenges for image processing tools
- The interest of fits-viewers plugins
- Introducing pyds9plugin
- Conclusion

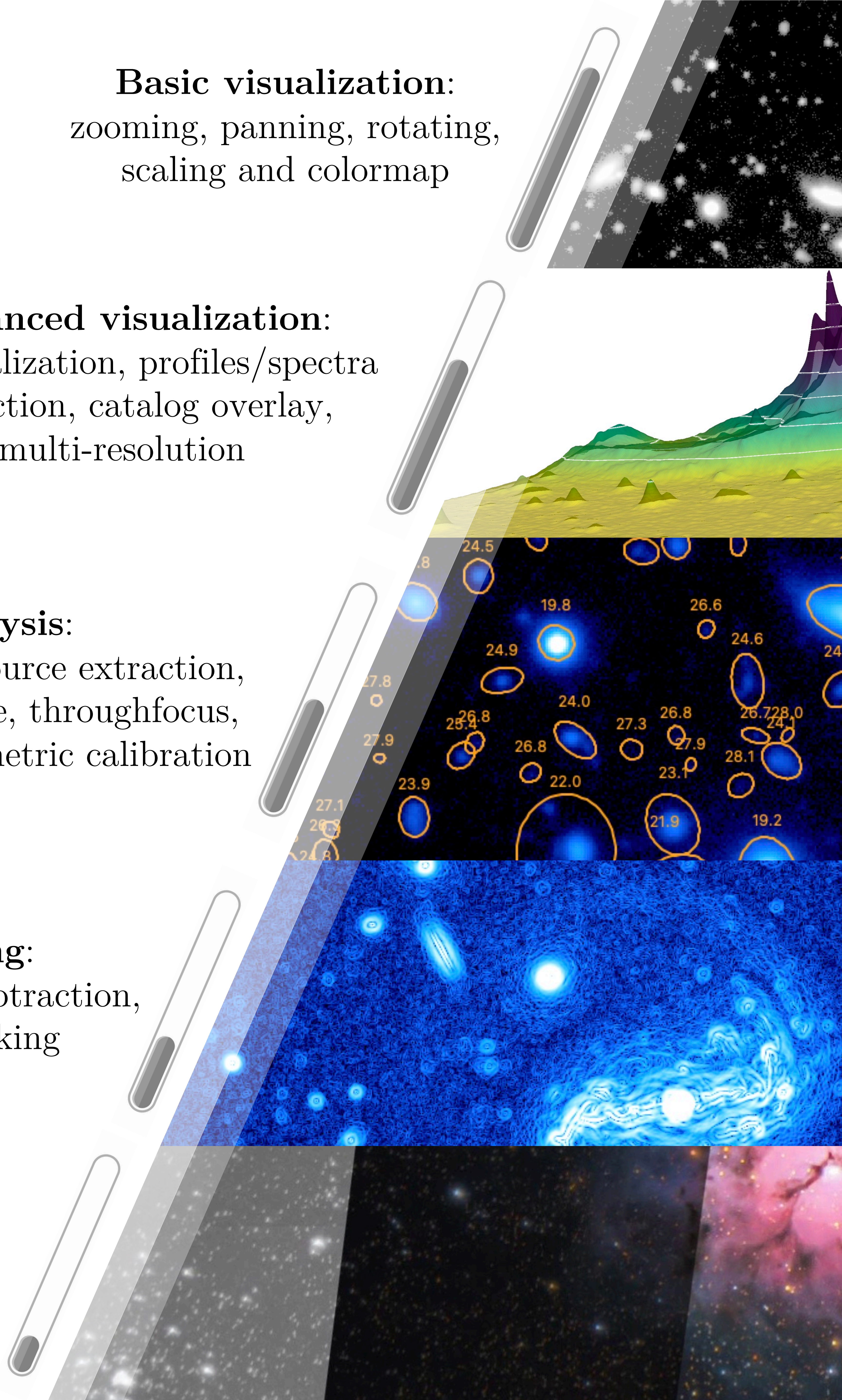
Basic visualization: zooming, panning, rotating, scaling and colormap

Enhanced visualization: 3D visualization, profiles/spectra extraction, catalog overlay, multi-resolution

Image analysis: radial profile, fitting, source extraction, photometry, light-curve, throughfocus, noise estimation, astrometric calibration

Image processing: stacking, background subtraction, deconvolution, masking

Research-grade pipeline: All the above on a set of images with multi-processing



The different functions