Electron Multiplication CCDs

Applications in astronomy

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Contents :-

- What is an Electron Multiplication CCD (EMCCD)
- Astronomical uses for EMCCD technology
- A specific example - ULTRASPEC
- EMCCD Issues
- Astronomical results and future work

Conventional CCD

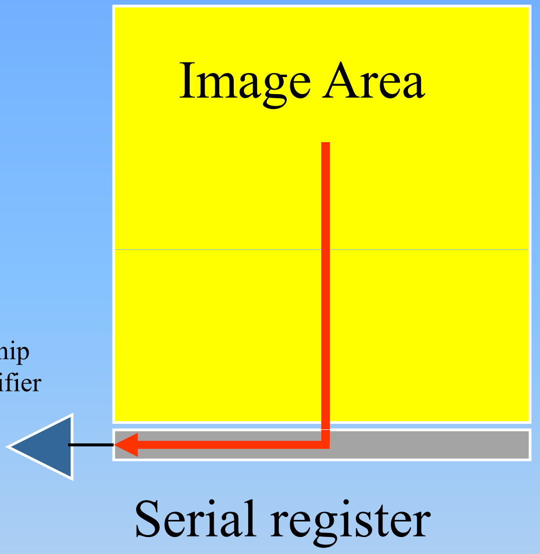


Image Area

On-Chip Amplifier

Serial register

EMCCD

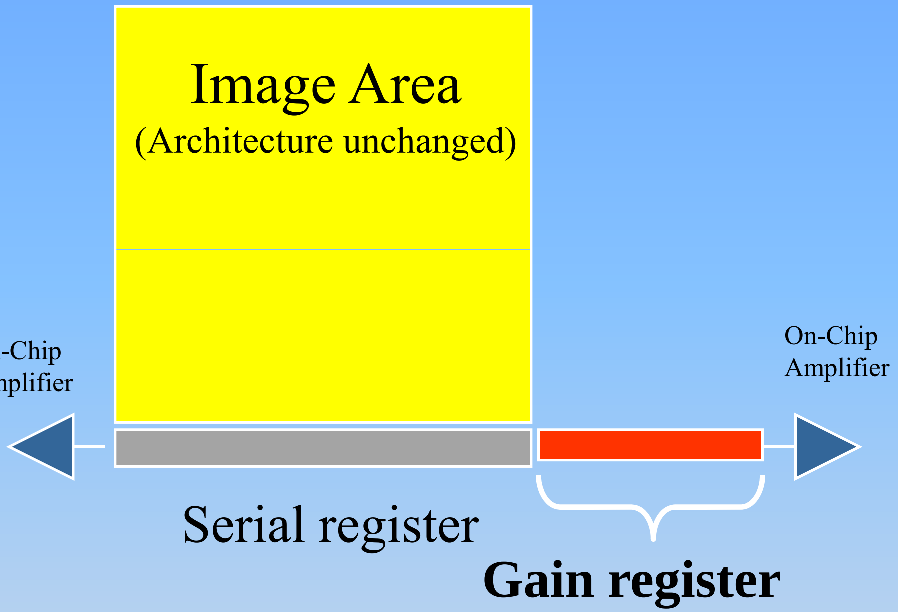


Image Area

(Architecture unchanged)

On-Chip Amplifier

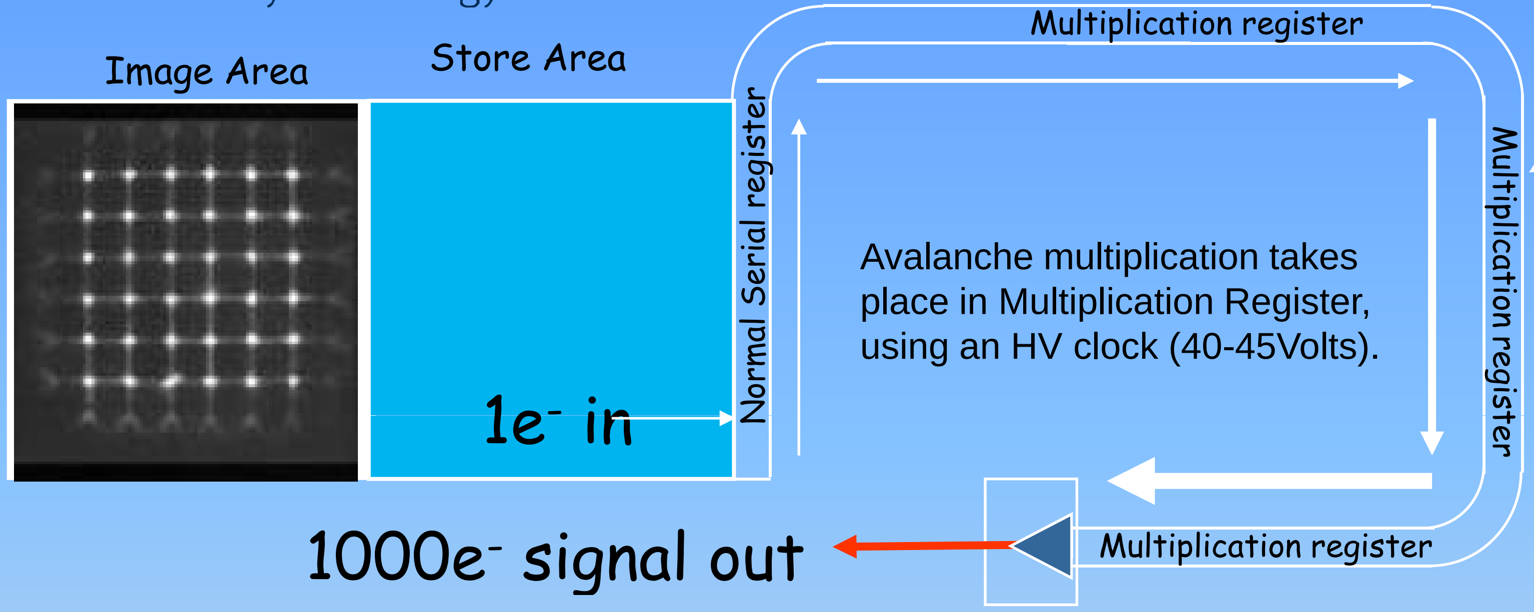
On-Chip Amplifier

Serial register

Gain register

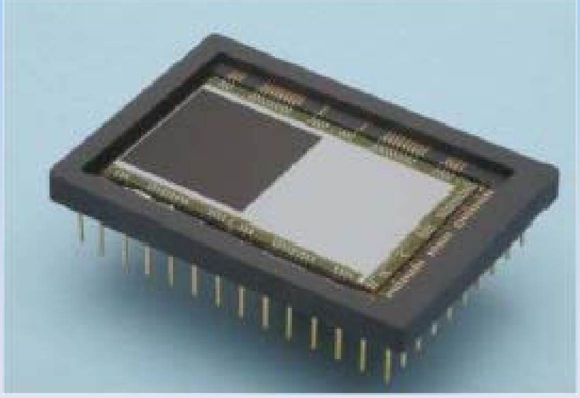
- Extended serial register = Gain register
- Use electron multiplication to boost signal
- Requires high voltage clock to cause multiplication
- Small probability per stage but use lots of stages

Multiplication

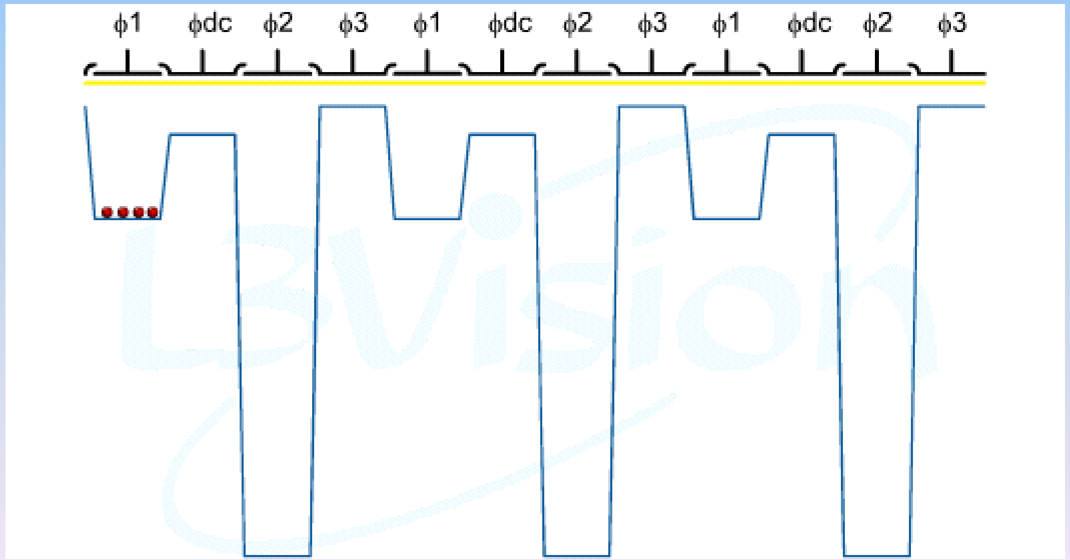


Avalanche multiplication takes place in Multiplication Register, using an HV clock (40-45Volts).

>600 stages

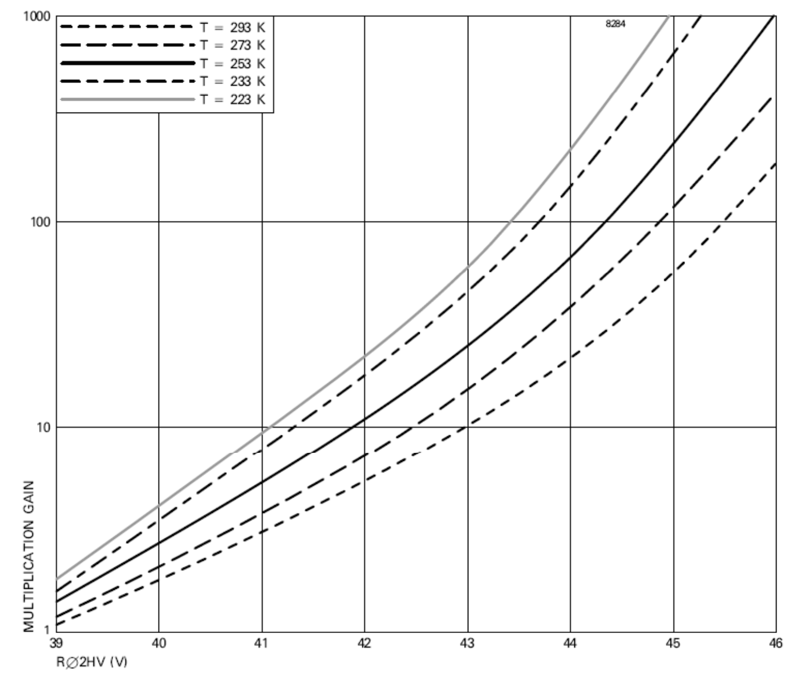


CCD201



e2v demonstration

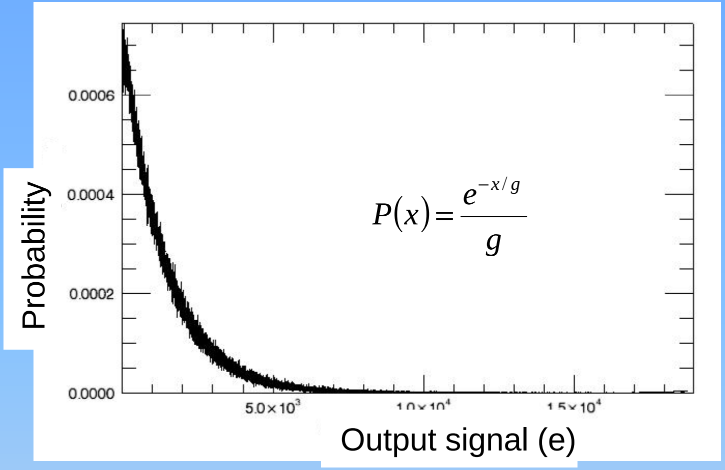
TYPICAL VARIATION OF MULTIPLICATION GAIN WITH LEVEL AT DIFFERENT TEMPERATURES



Probability of electron generation~1%-2%
but gain = $(1+p)^n$ for n=600 then g=7600

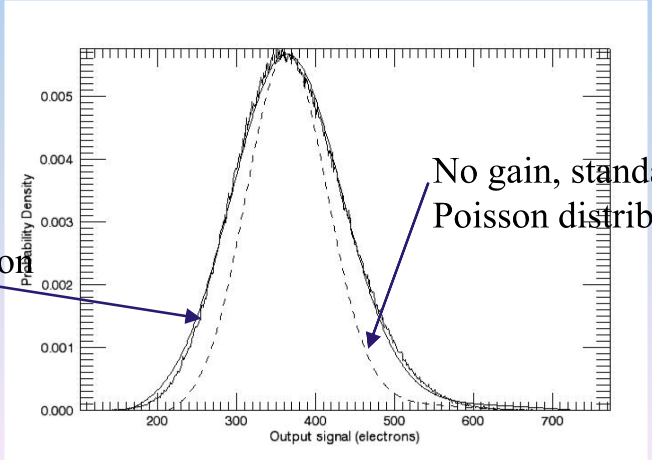
$$S/N = \frac{S}{\sqrt{2S + \left(R/g\right)^2}}$$

Monte Carlo analysis of electron multiplication process



$$P(x) = \frac{e^{-x/g}}{g}$$

1 input electron, g=1000



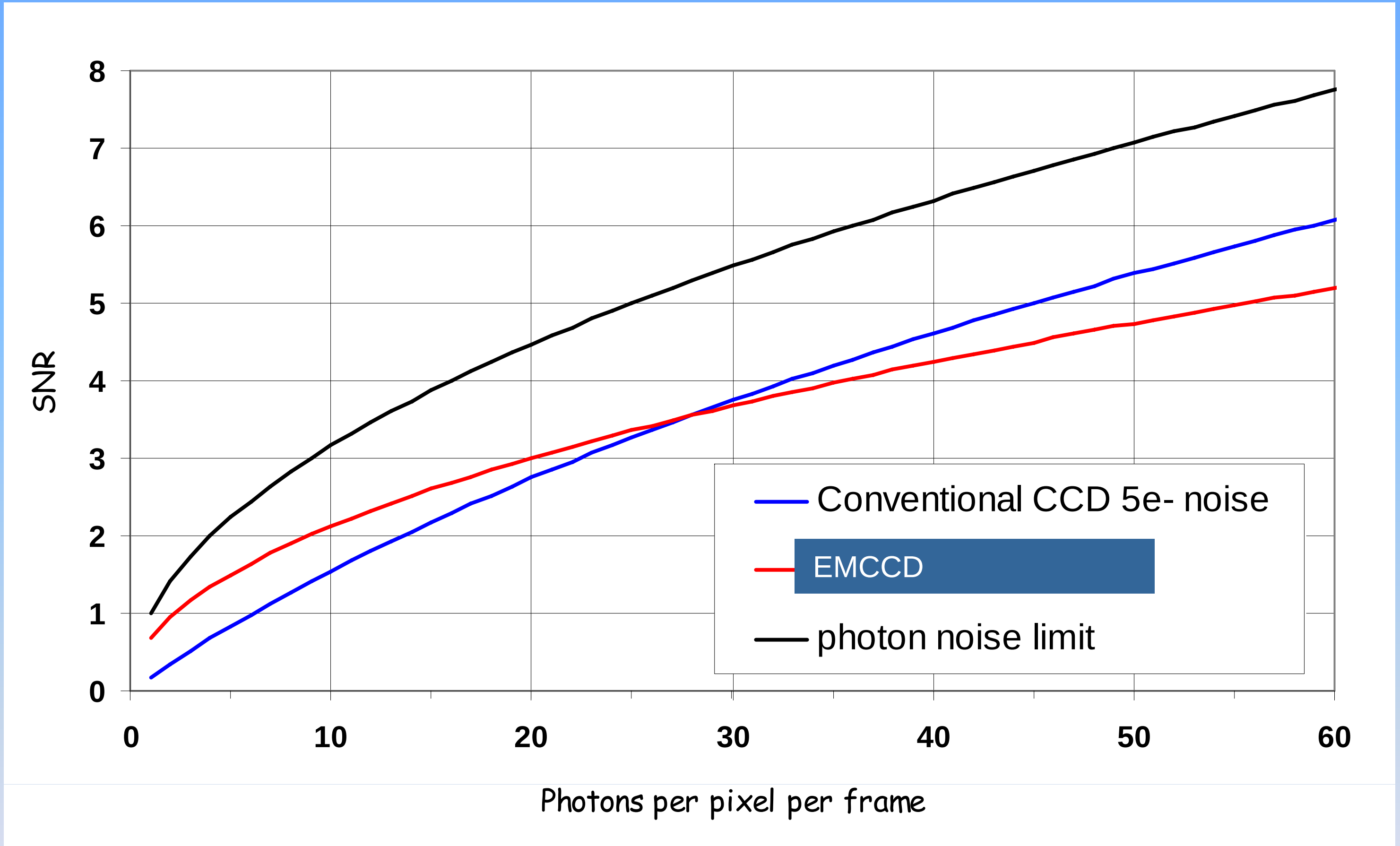
With gain, √2 wider distribution

No gain, standard Poisson distribution

350 e = 50 input electrons, g=7

EMCCD range of operation

So at higher exposure levels the EMCCD actually performs worse than a normal CCD



EMCCD wins due to zero read noise

EMCCD loses due to multiplication noise

EMCCD Applications

Ground based telescopes – resolution is limited by changing atmosphere (timescales ~ 10ms)

Application areas :-

- Lucky Imaging
- Adaptive Optics (wave front sensing)

High frame rate => photon starved => need very low read noise

characteristics required :-

good QE (> 90%)
>1 kHz frame rates
Large area >200 x 200 pixels
< 1 e- rms read noise

Lucky Imaging

- Freeze atmospheric effects by taking snapshot pictures very fast

- Combine the best of these snapshots (when atmosphere has least effect) to improve resolution

- Need large size of detector to be efficient and match available telescopes (> 512 x 512 pixels)

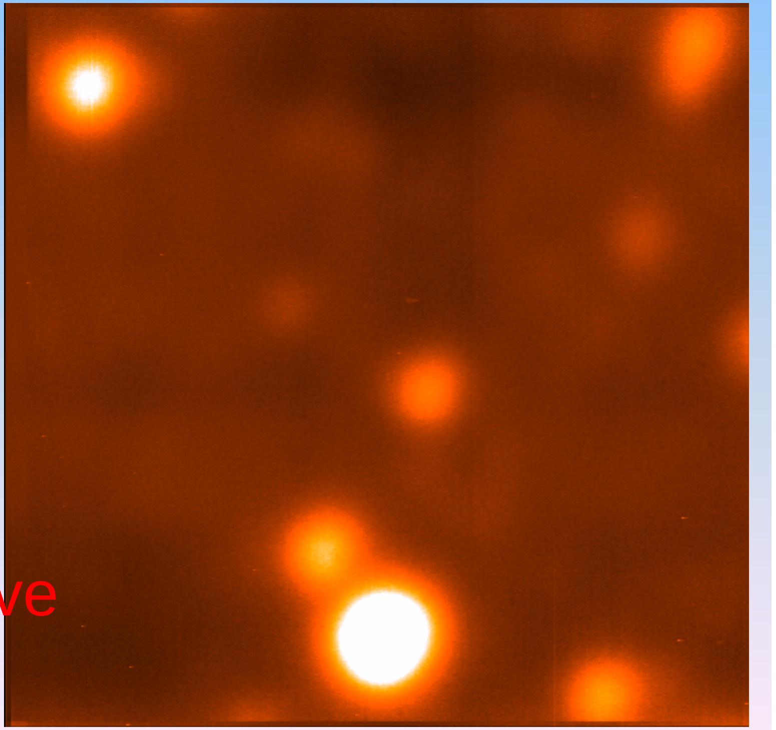
- Need fast frame rate (for CCDs, high frame rate => high pixel rate => high read out noise)

- Need zero noise since combining images means noise increases as √(Number of frames)

LuckyCam – IoA, University of Cambridge (Craig Mackay)

- E2v Technologies CCD97 – 512 x 512 EMCCD, thinned and back illuminated
- 10 MHz pixel rate (> 100 e- rms noise before gain)
- x 2000 multiplication gain to give < 1e- rms read noise

The Globular cluster M13 as imaged conventionally by the Palomar 200 inch telescope, followed by M13 as imaged with the Lucky Camera on same telescope.



Commercial uses in ground based surveillance – EPSRC funding under “Crime detection and Prevention” initiative

Wave Front Sensing for Adaptive Optics

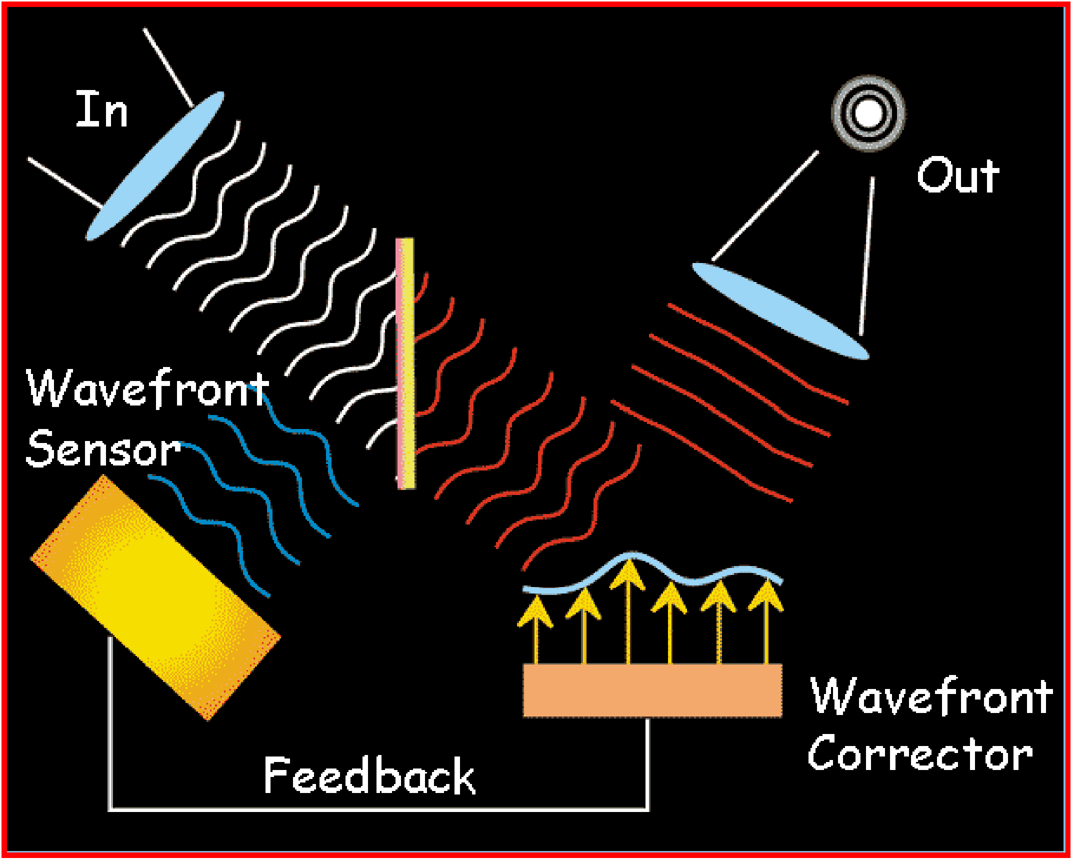
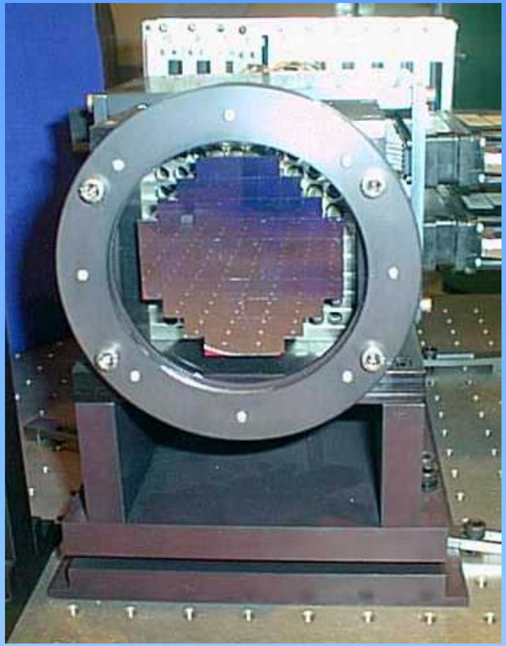


Image from Gordon Love, Durham



NAOMI deformable mirror

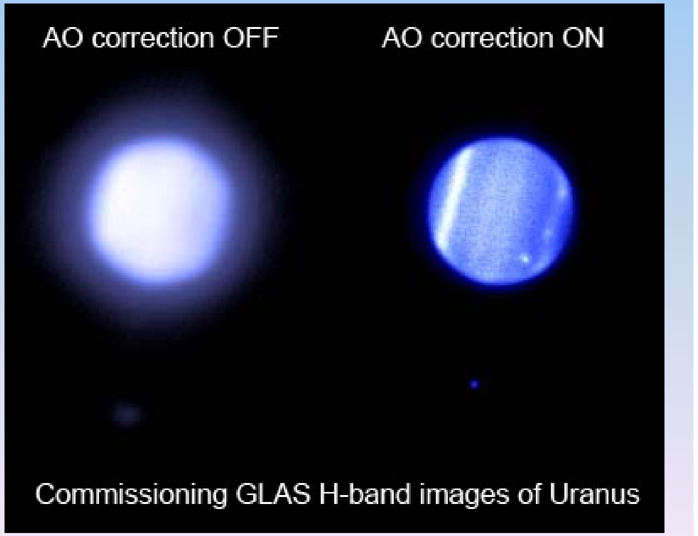


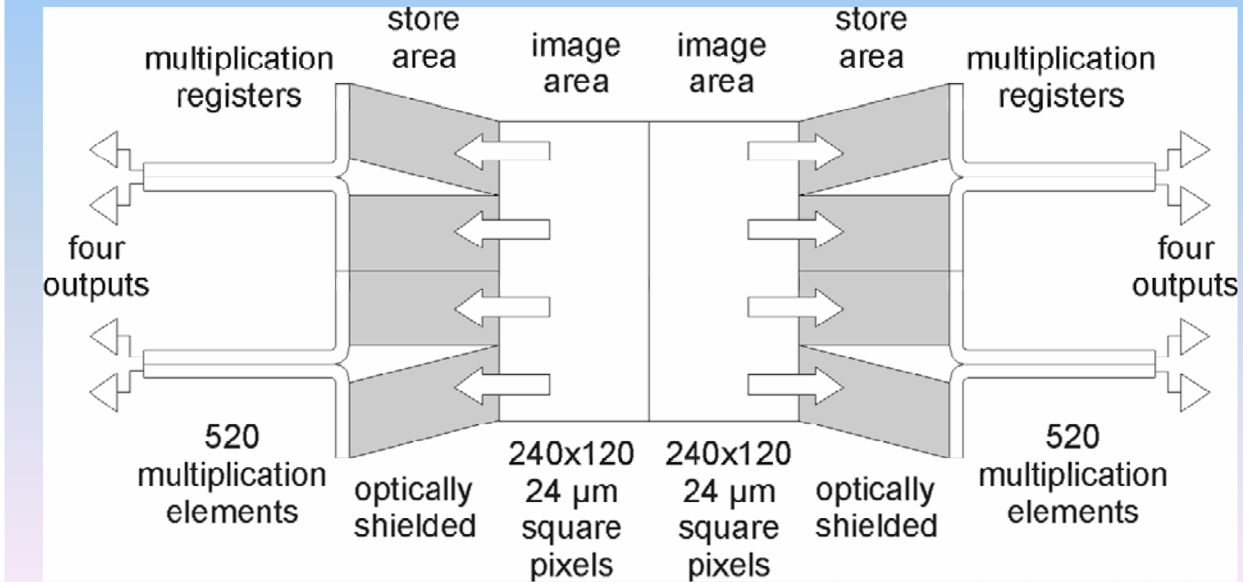
Image from ING GLAS

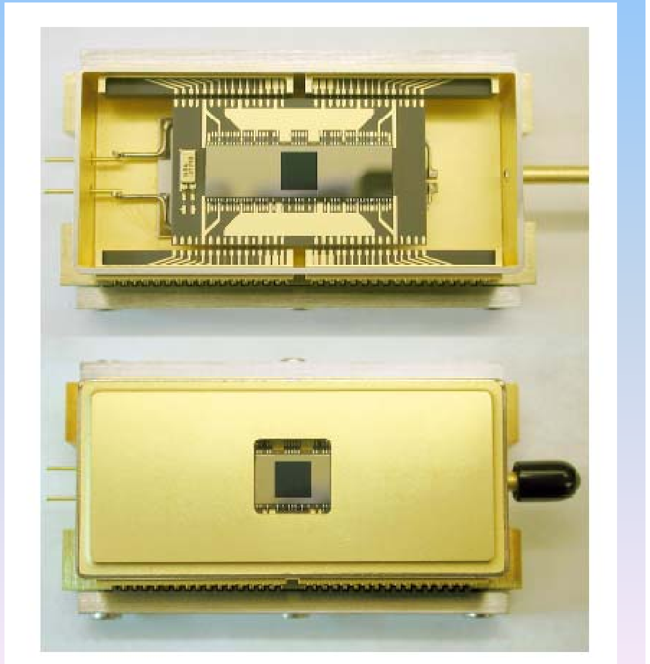
WFS – detector requirements

ESO/OPTICON sponsored detector development at e2v Technologies

- 240x240 (24 um) pixels
- >1500 Hz frame rate
- Peltier cooled to -50C
- 8 outputs each with EM gain stage, > x 500 gain
- Brand new high speed controller development - OCAM (Marseilles)

– 220 Mbytes/s, 15 Mpixels/s



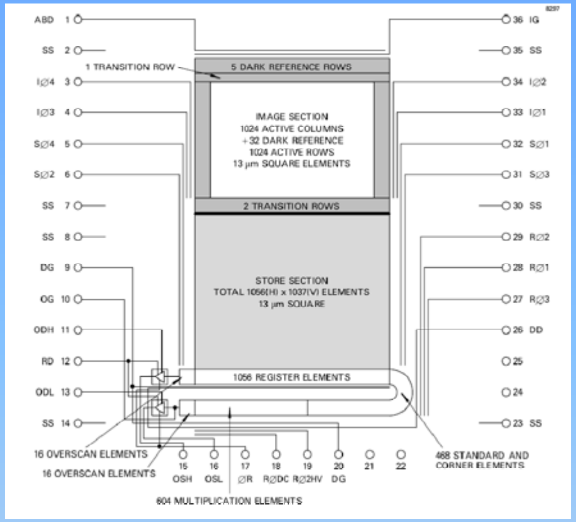


e2v – CCD220

ULTRASPEC

- OPTICON - EEC - with matching UK funding.
- “Cheap and Cheerful” technology demonstrator – to prove the performance of EMCCDs in a real astronomical context
- A high-speed, spectroscopic camera.
- Used with mature spectrograph on large telescope.
- Based on existing ULTRACAM system.

EMCCD - E2V CCD201



ULTRASPEC

EFOSC2 - Low resolution optica imager/spectrometer

- Avalanche gain (10 levels, from 1-2000)
- Normal or avalanche output
- Binning/Windowing in both dimensions (by 1,2,4,8) – note software binning now possible !!!

Performance of ULTRASPEC

Output	**Pixel Time (µs)**	**Frame rate (s)**	**Read noise (e- rms)**	**Window Rate (Hz) (1000 x 100 pixels)**
Normal	11.5	13.1	2.3	
	3.4	3.9	4.1	
Avalanche (no gain)	12.7	14.63	5.3	
	< 2	2.5	22.3	11
Avalanche (with x 1000 gain)	<2	2.5	0.02	10

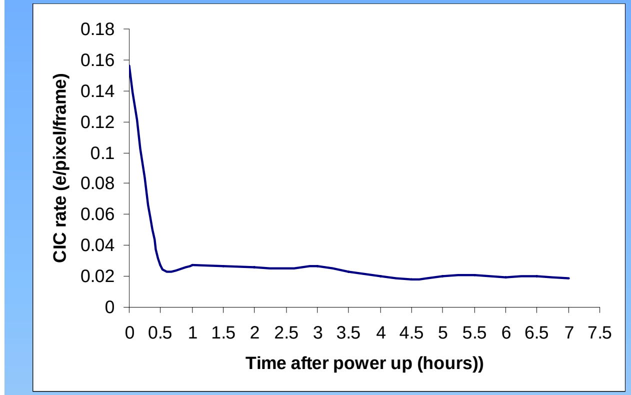
- Dark Current < 4 e$^-$/pixel/hour, @160K
- Standard astronomical CCD in all other respects, such as QE, linearity etc.

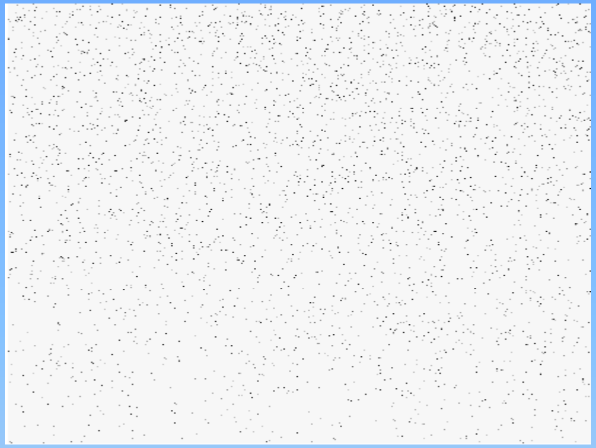
ISSUE - Clock Induced Charge (CIC)

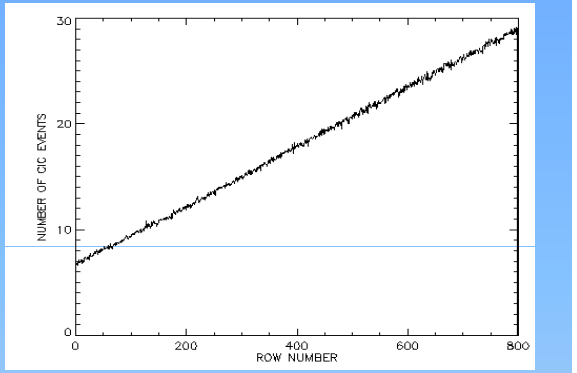
Clock-induced charge (CIC) is spurious signal generated by the operation of transferring signal through the device.

- Not seen in “normal” CCD because dominated by read out noise
- Seen in EM CCDs because of gain
- Trapped electrons can be liberated and captured within a pixel
- Occurs on clock edges when changing electric field occurs
- Occur on both Vertical and Serial clocks

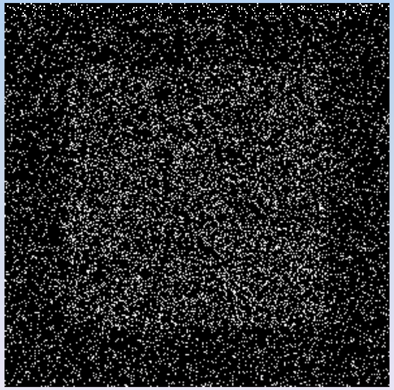
MOVIE of CIC events in CCD



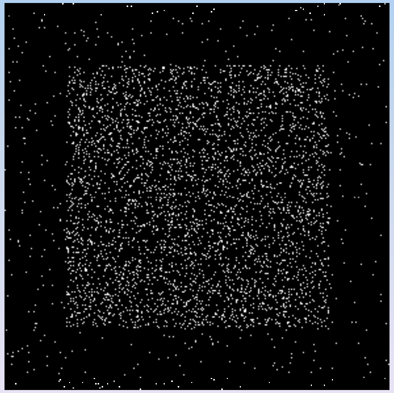




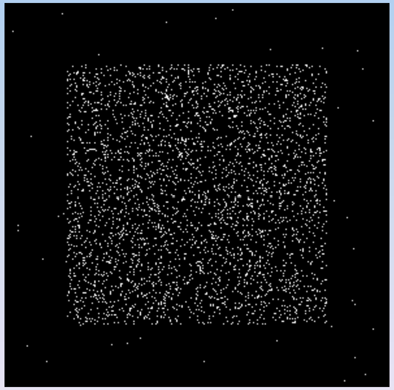
Modelled effects of different levels of CIC for a mean signal of 0.1 e per pixel per frame.



CIC=0.1 e/p/f



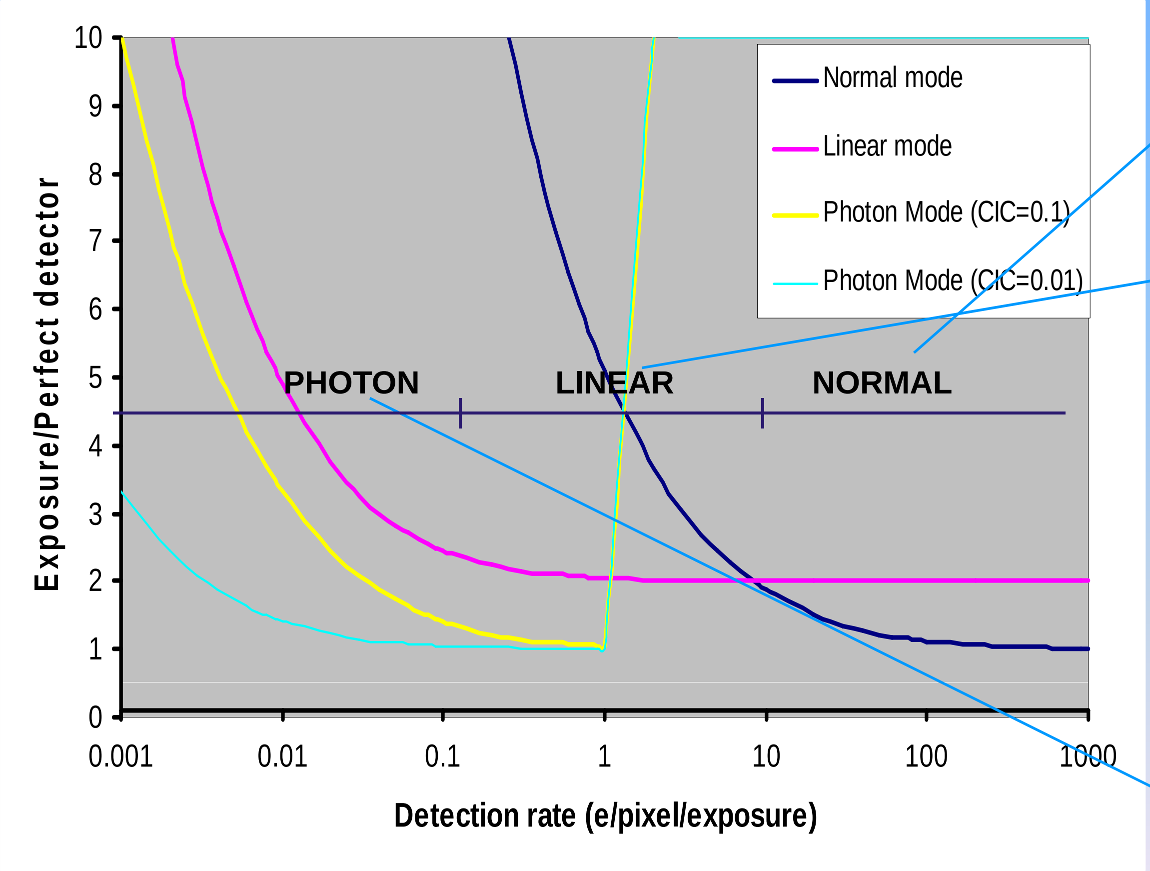
CIC=0.01 e/p/f



CIC=0.001 e/p/f

SNR = signal-to-noise ratio
N = no. of photo-e$^-$/pixel
σ = readout noise in e$^-$/pix
CIC = no. of clock induced charges in e$^-$/pixel/frame

Exposure time to reach a given SNR compared to a "perfect" detector of identical QE.



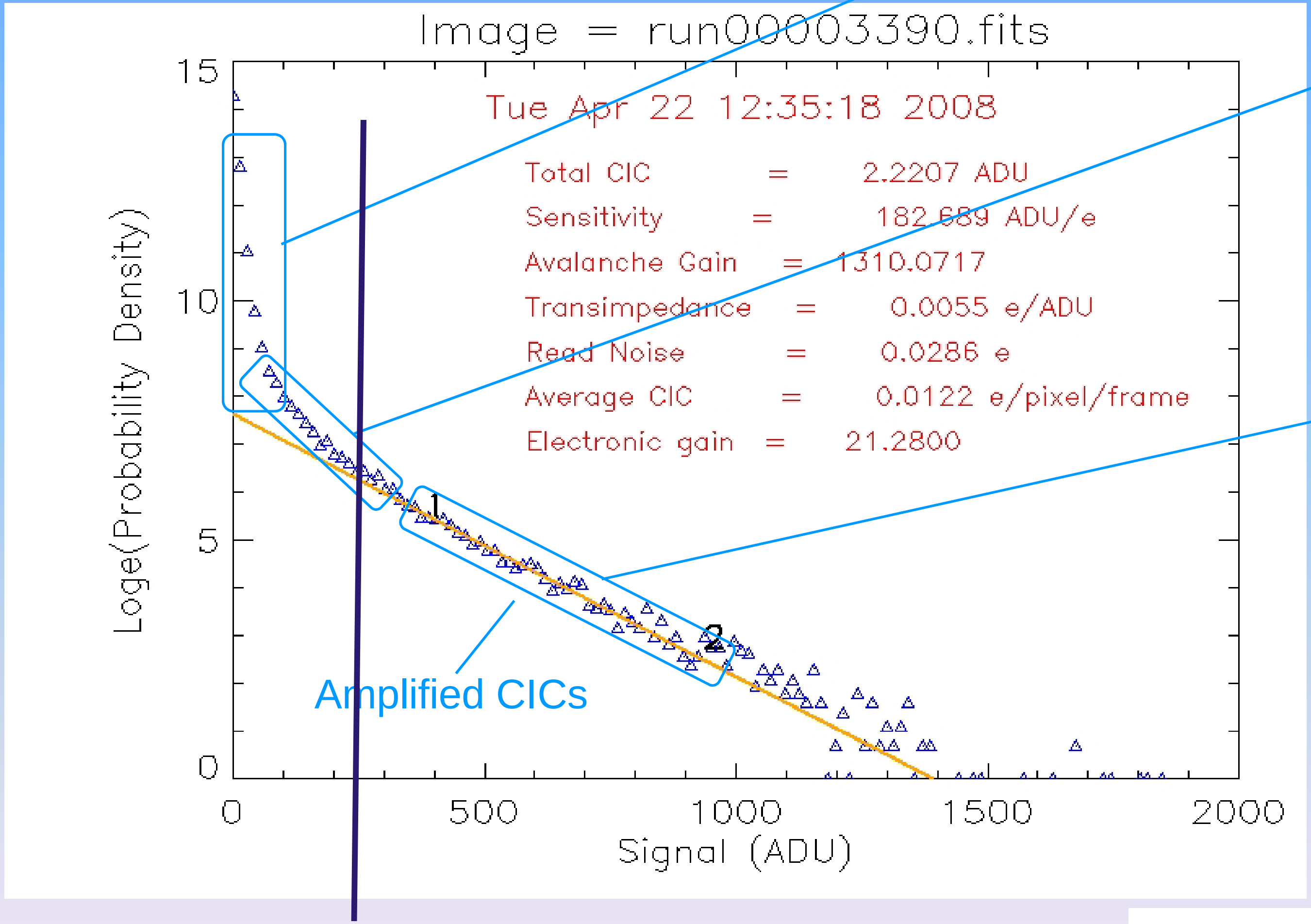
$$SNR_{CCD} = \frac{N}{\sqrt{N+\sigma^2}}$$

$$SNR_{LINEAR} = \frac{N}{\sqrt{2N+CIC}}$$

$$SNR_{PC} = \frac{N}{\sqrt{N+CIC}}$$

Performance Issues

Histogram of counts in a bias frame with avalanche gain



Total CIC = 2.2207 ADU
Sensitivity = 182.689 ADU/e
Avalanche Gain = 1310.0717
Transimpedance = 0.0055 e/ADU
Read Noise = 0.0286 e
Average CIC = 0.0122 e/pixel/frame
Electronic gain = 21.2800

Peak due to bias level.
Spread due to readout noise

Serial CICs or
charge transfer issues

Slope gives the gain

$$p_1(x) = \frac{1}{g} e^{-x/g}$$

$p_1(x)$ = probability of an output x for a single electron input, with mean gain g

Amplified CICs

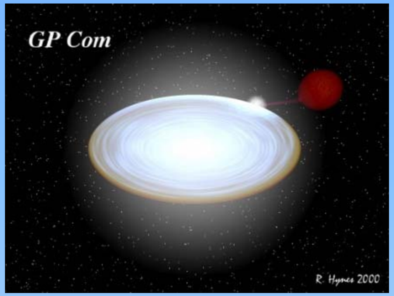
Optimum PC Threshold at ~5σ → See Daigle paper in SPIE. →

$$QE_{new} = QE_{old} e^{-T/g}$$

T = threshold

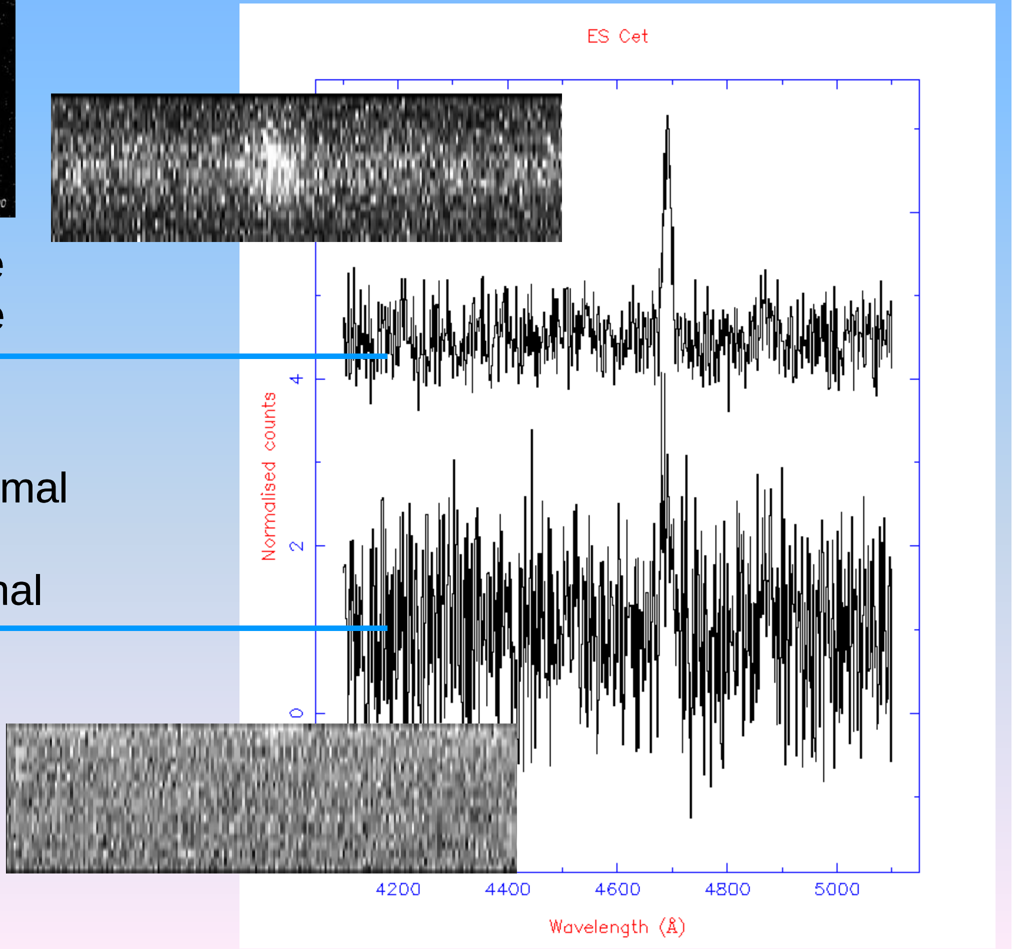
Astronomical performance

ES Cet



10-second spectrum of ES Cet using the avalanche output of ULTRASPEC on the ESO 3.6m Telescope.

10-second spectrum taken using the normal output of ULTRASPEC. Improvement in SNR~3, equivalent to using a conventional CCD on a 6.3m telescope.



EMCCDs are likely to revolutionize astronomical spectroscopy. Every observatory should have one !

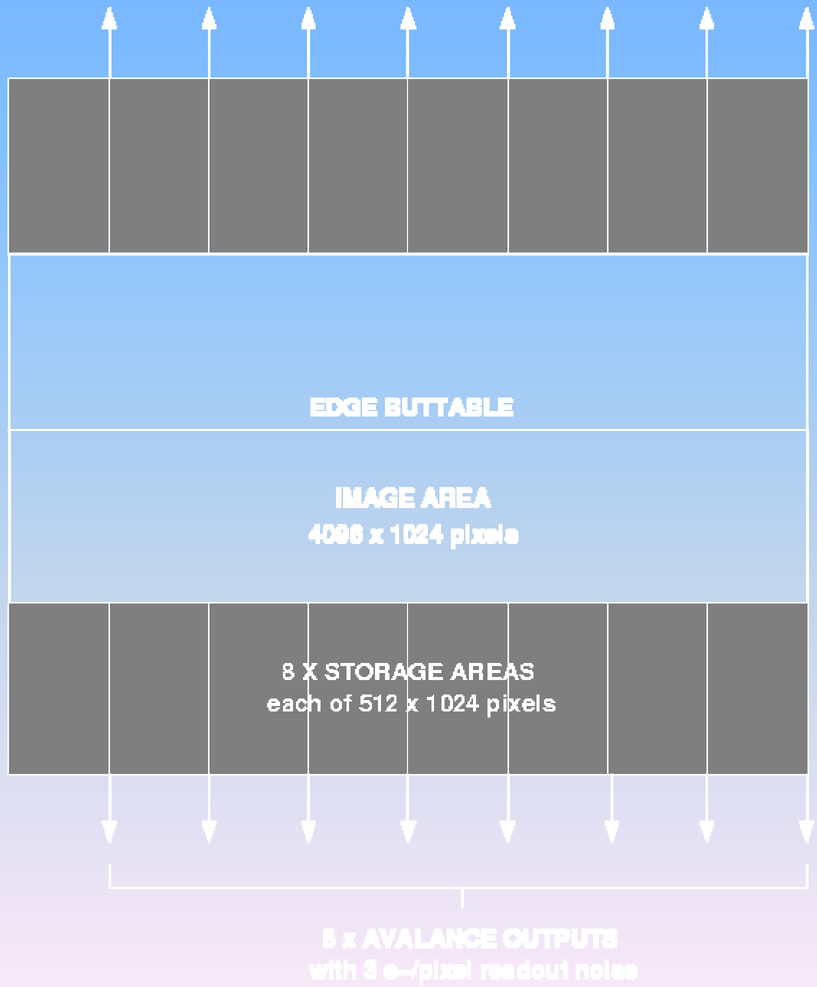
The future - ULTRASPEC2 ?

Problems:

- CCD size
- Controller design

Solutions:

- Procure a new large-format, multi-output chip – 4k x 2k as shown or even 4k x 4k
- New controller development – NGC, IoA and Marseille



Conclusions :-

- EMCCDs prove themselves – x3 SNR improvem

- CIC issues – more work required

- New large EMCCD format – funding required