Low Light Level CCD
Performance and Issues

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Overview of the Talk

Introduction to L3CCD (EM CCD)

ULTRASPEC

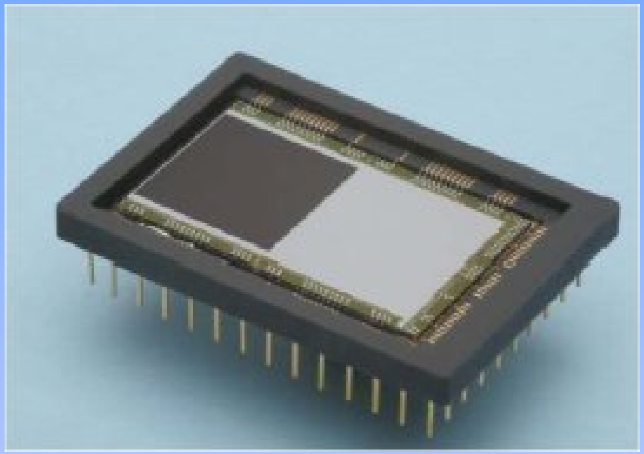
Performance and Issues

New L3 CCD Proposal

Introduction to L3CCD

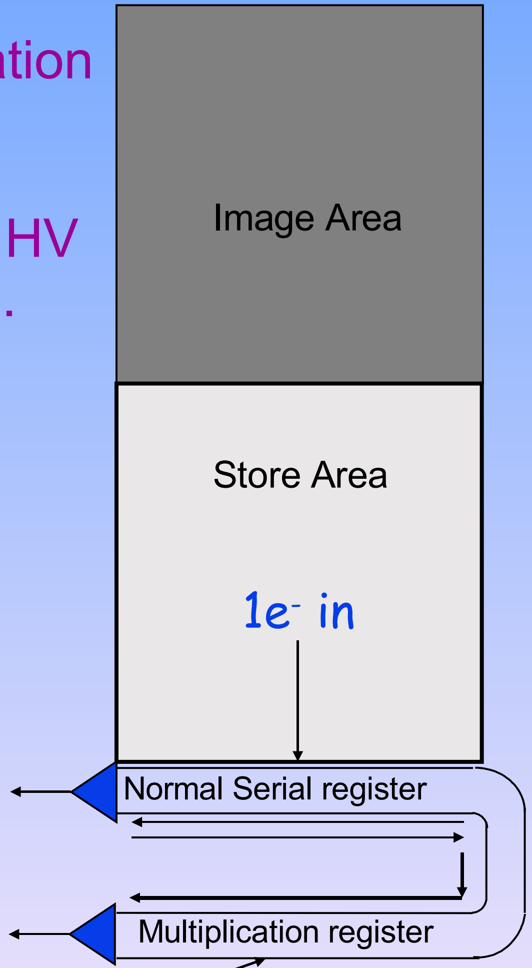
- **Conventional CCD**
  - Close to ideal performance
  - Read noise ~3e^- (low readout rates)
  - Long time to readout
  - Noise increases with pixel rate
  - Readout noise dominates in low light level applications
- **Increase S/N**
  - Reduce read noise
  - Boost the input signal
    - Integrate longer
    - Photo-multiply before readout

Low Light Level CCD



CCD201 1024x1024

Electron multiplication takes place in avalanche gain Register using an HV clock (38-43Volts).



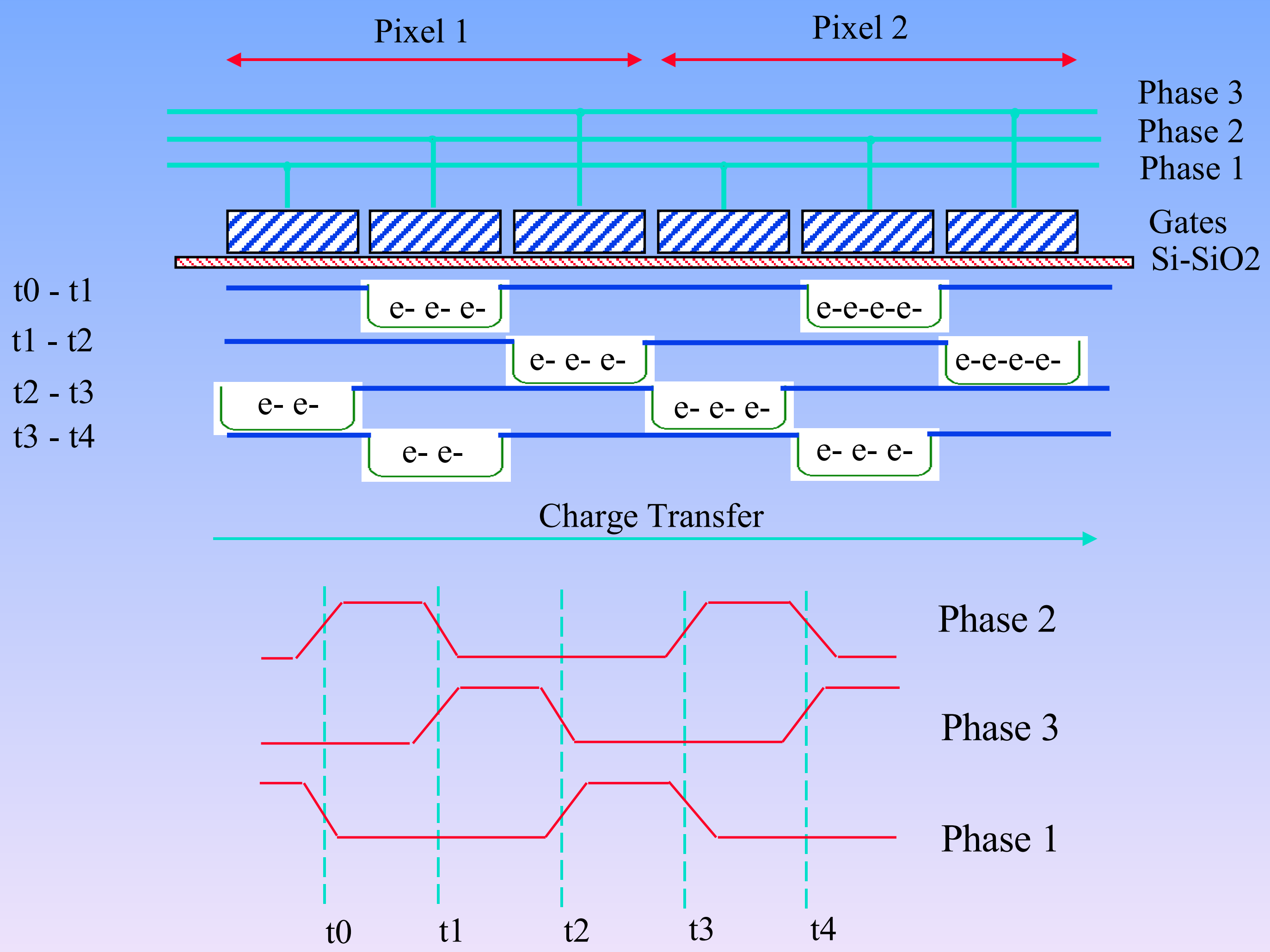
$$S/N = \frac{S}{\sqrt{S+R^2}}$$ → Standard output

$$S/N = \frac{S}{\sqrt{S+\left(R/g\right)^2}}$$ → 1000e⁻ signal out

Gain term

High voltage clock

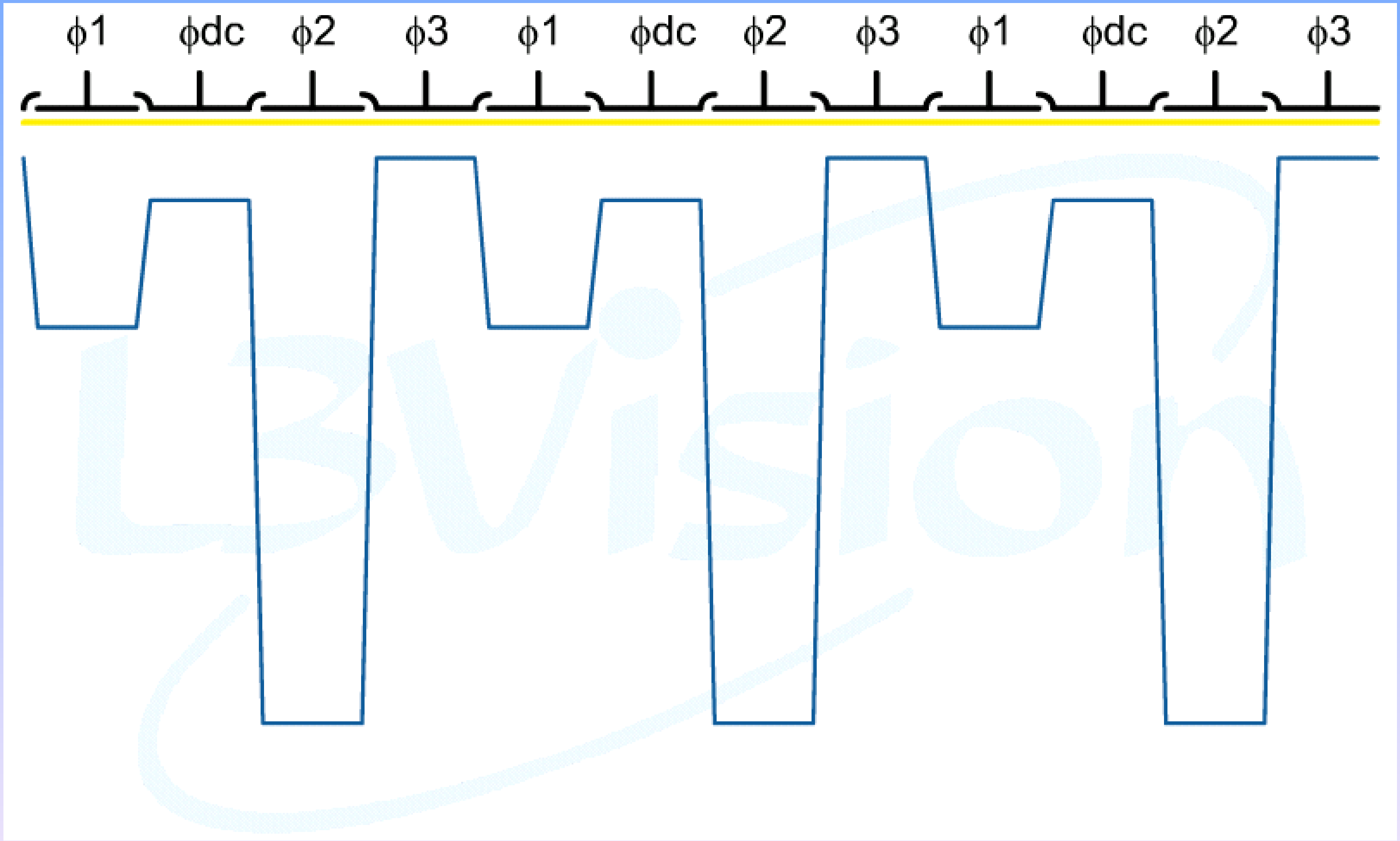
Charge Coupling Mechanism



Avalanche Gain Mechanism

- **Impact Ionisation**
  - High electric field set by HV clock ~100kV/cm
    - Two electrodes – one at fixed DC, other clocked HV
  - Transferring electrons collide with crystal lattice and liberate new electrons
  - These liberate further new electrons
  - Probability is 1 - 2% per stage
- **Gain = $(1+P)^N$**
  - Depends on number of gain stages
  - Applied electric field
  - Operating temperature
- **A 600 stage gain register with 0.015 probability can give ~7500 signal gain**

Electron Multiplication



Avalanche Gain Process

Statistical Process

Mean gain

Variance in the gain

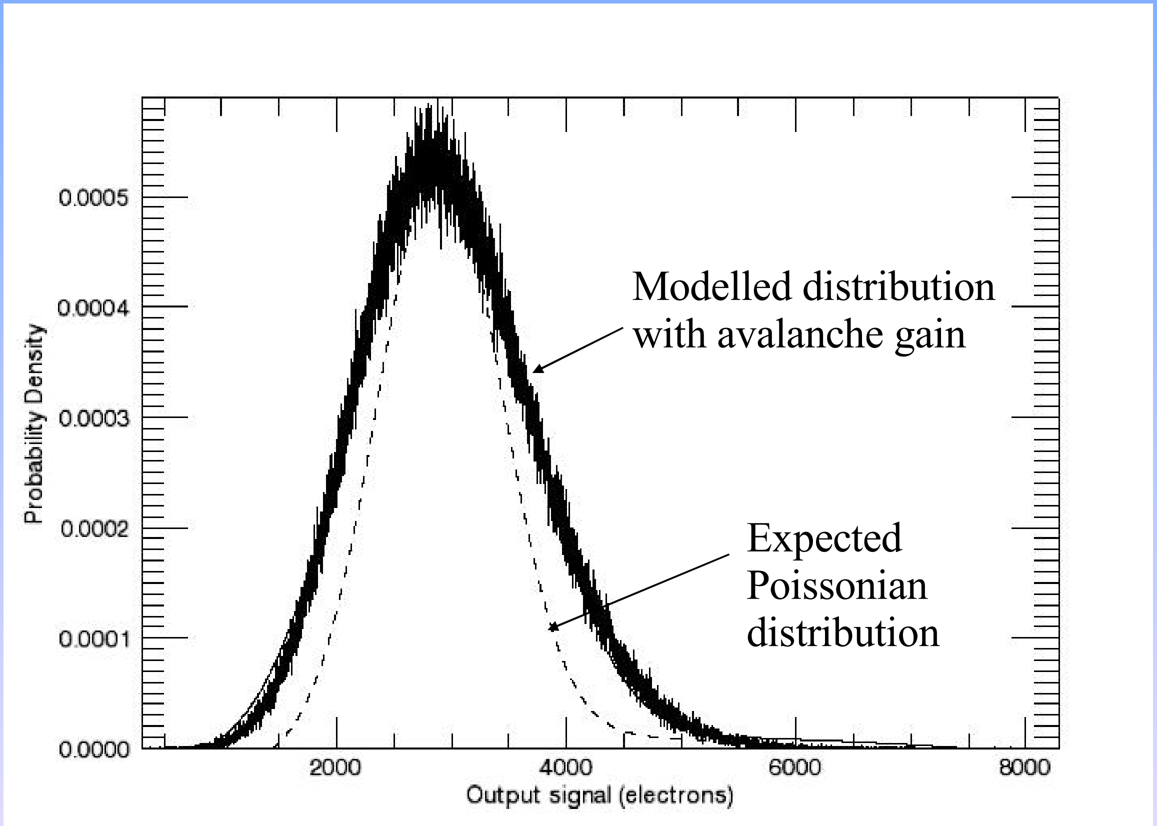
Increases the variance in the output signal by 2

Effective QE reduces by factor of 2

Monte-Carlo Analysis of the Gain process

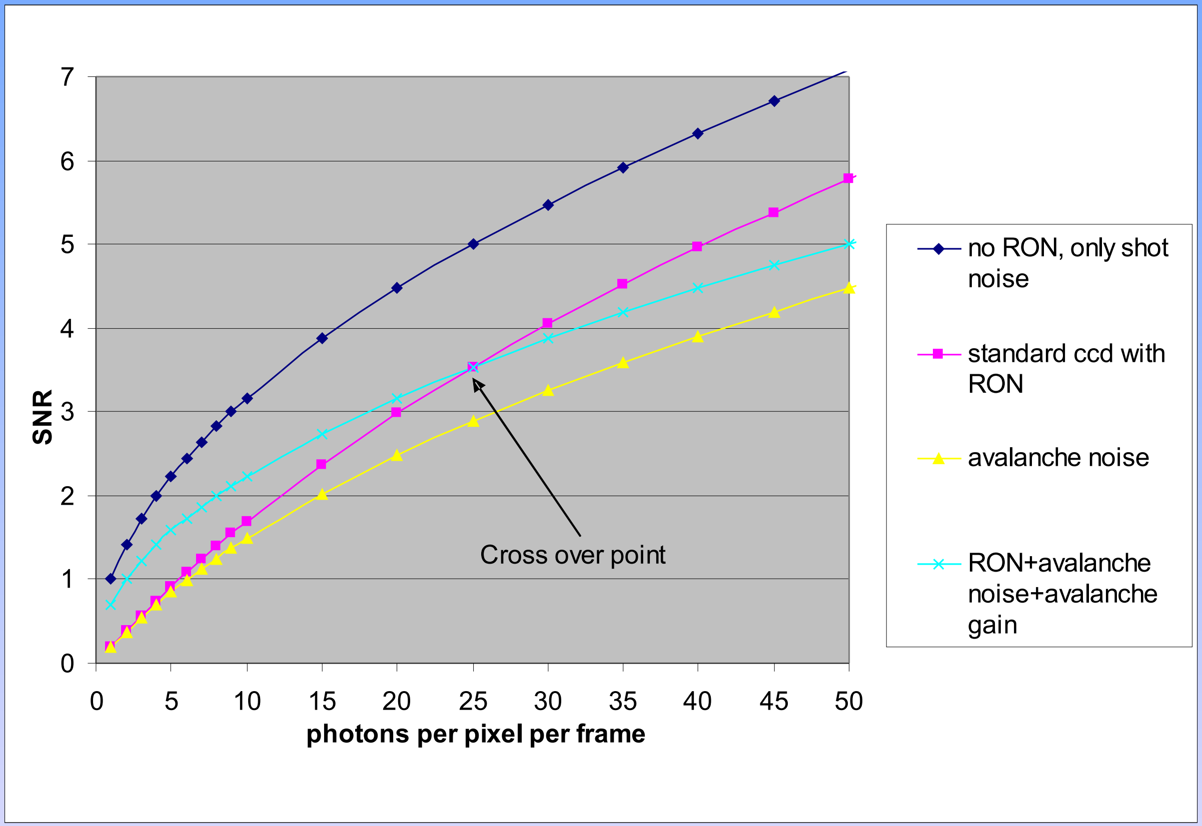
The sigma of the distribution is √2 times higher than the Poissonian distribution

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



Input = 30e$^-$, Avalanche gain = 100

L3 CCD Wins in Low Light Regime



High time resolution imaging, spectroscopy

Adaptive optics

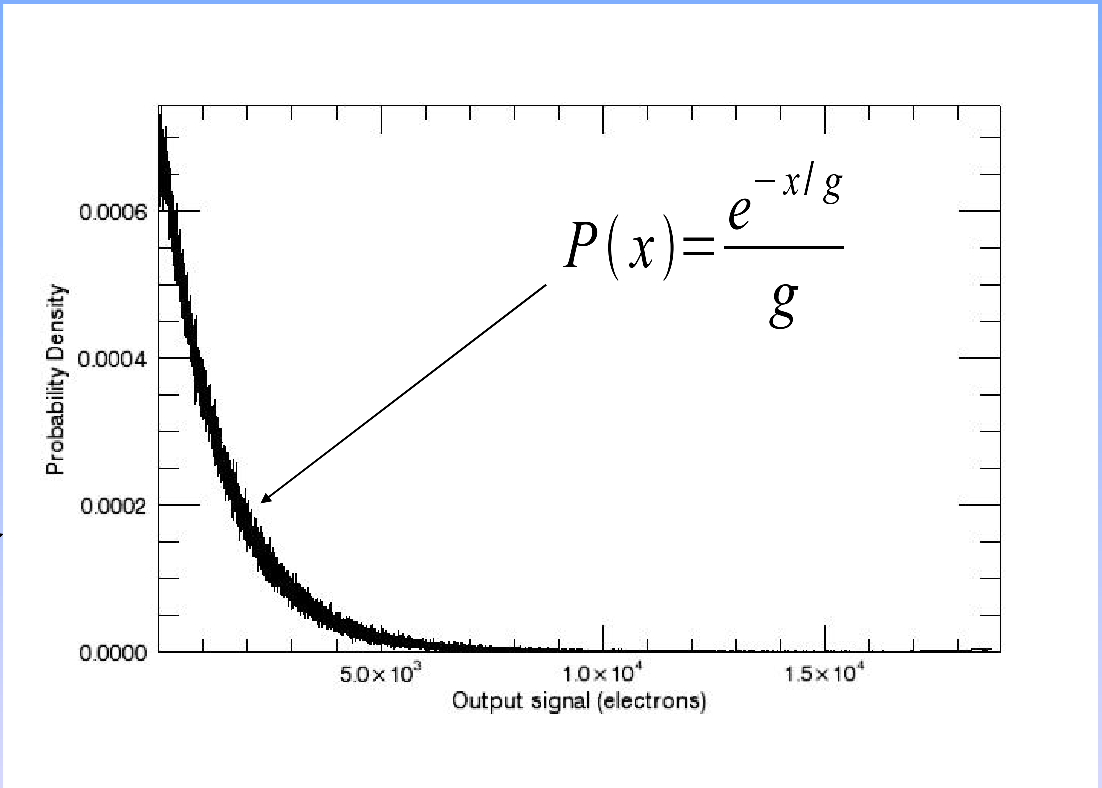
Photon counting

Lucky Astronomy

Even with the gain variance, the L3CCD wins over the standard CCD for low light level applications

Gain of the Multiplication Register

Statistics of the multiplication process give range of output values for 1e input events



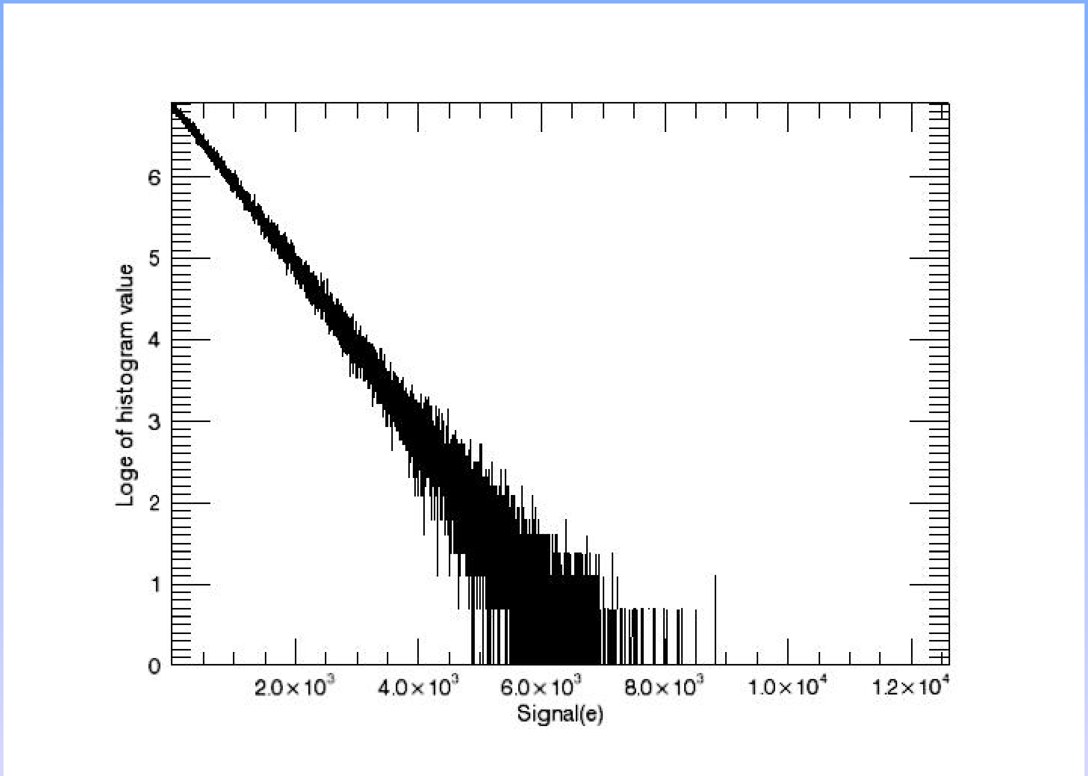
$$P(x) = \frac{e^{-x/g}}{g}$$

Monte-Carlo simulation using IDL for 1e input events

Input = 1e$^-$, Avalanche gain = 1000

Gain of the Multiplication Register

- Plot Log e of the histogram
- The inverse slope gives the gain of the avalanche register
- Gain calculated this way agrees very well when compared with standard output



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Talk Overview

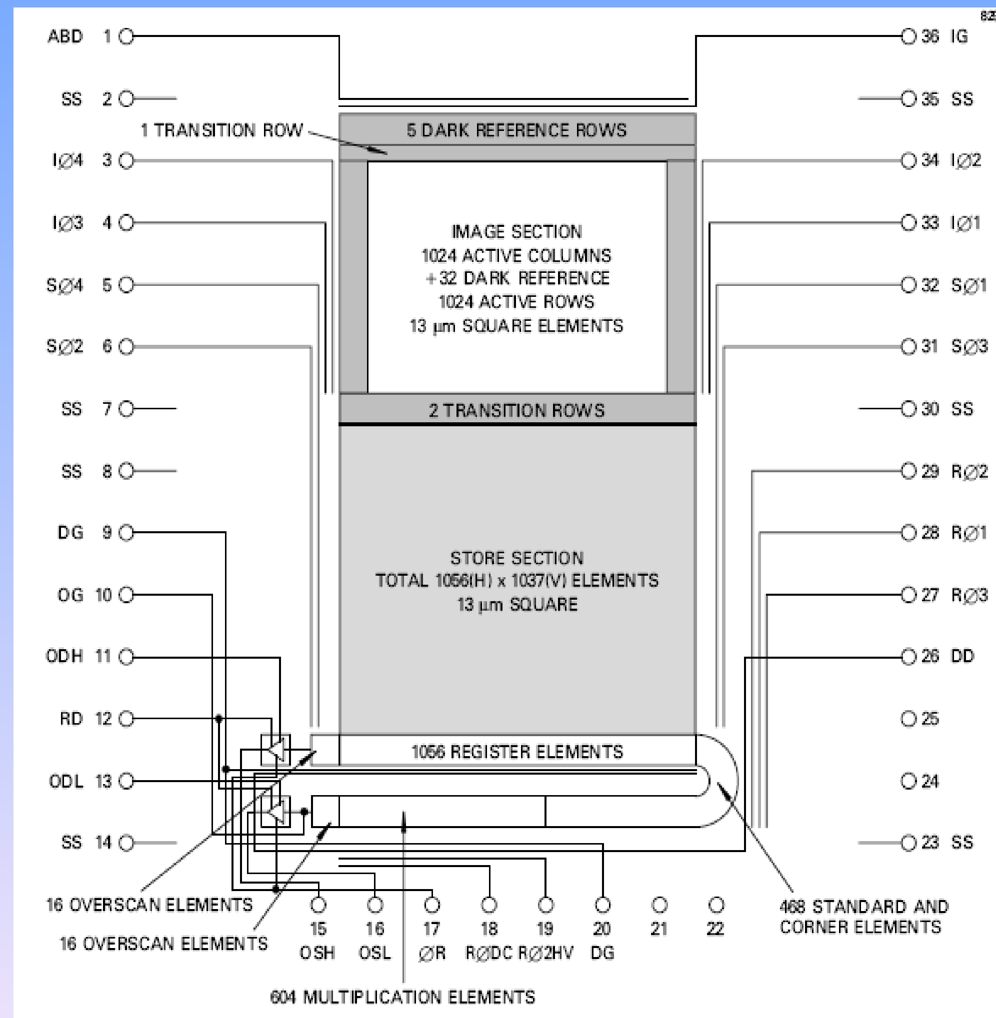
- Introduction to L3CCD (EM CCD)
- ULTRASPEC
- Performance and Issues
- New L3 CCD Proposal

ULTRASPEC

- ULTRASPEC – high speed spectro-photometer camera commissioned on ESO La Silla 3.6 m telescope on EFOSC instrument
- Based on new Electron Multiplication CCD technology – OPTICON funded project to show benefits of this technology
- Frame transfer architecture also given read out efficiency improvements
- New high voltage clock board developed for SDSU-III controller

E2V CCD201

- **1K Frame Transfer CCD**
- **2-Phase Image / storage registers**
- **Two Outputs**
  - Conventional output
  - Avalanche output
- **604 Multiplication elements**



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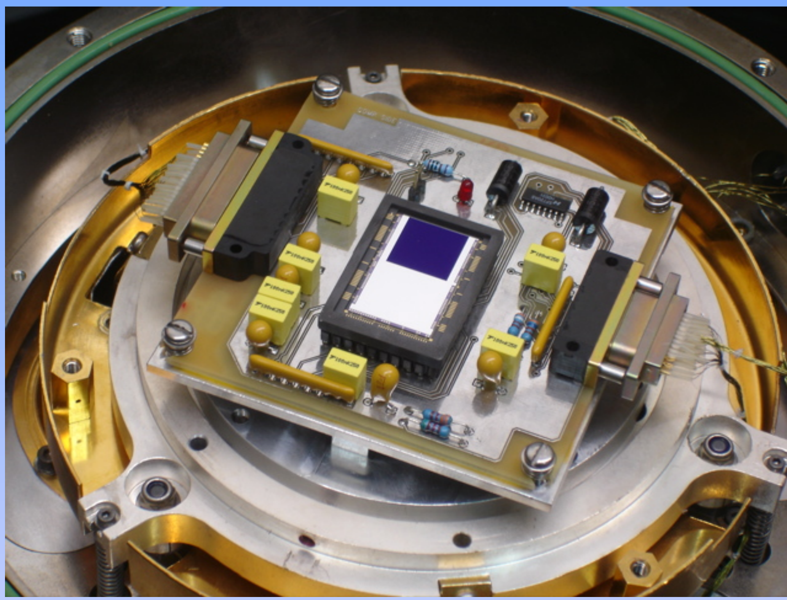
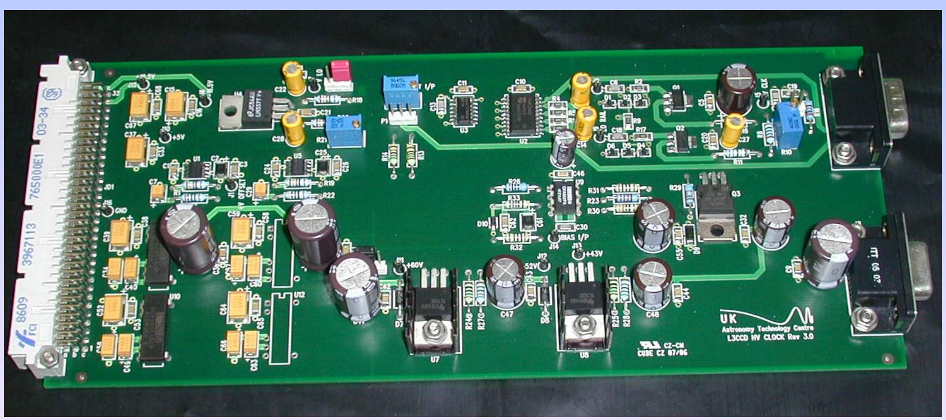
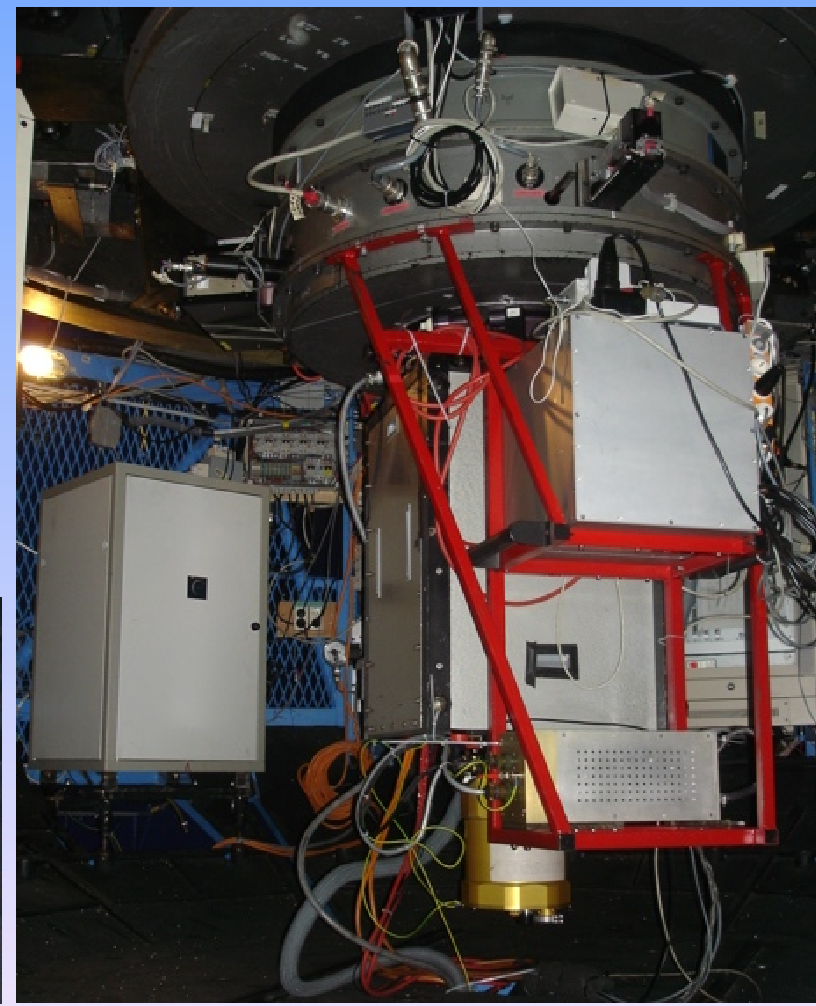
ULTRASPEC – High-speed Spectroscopy with zero read noise







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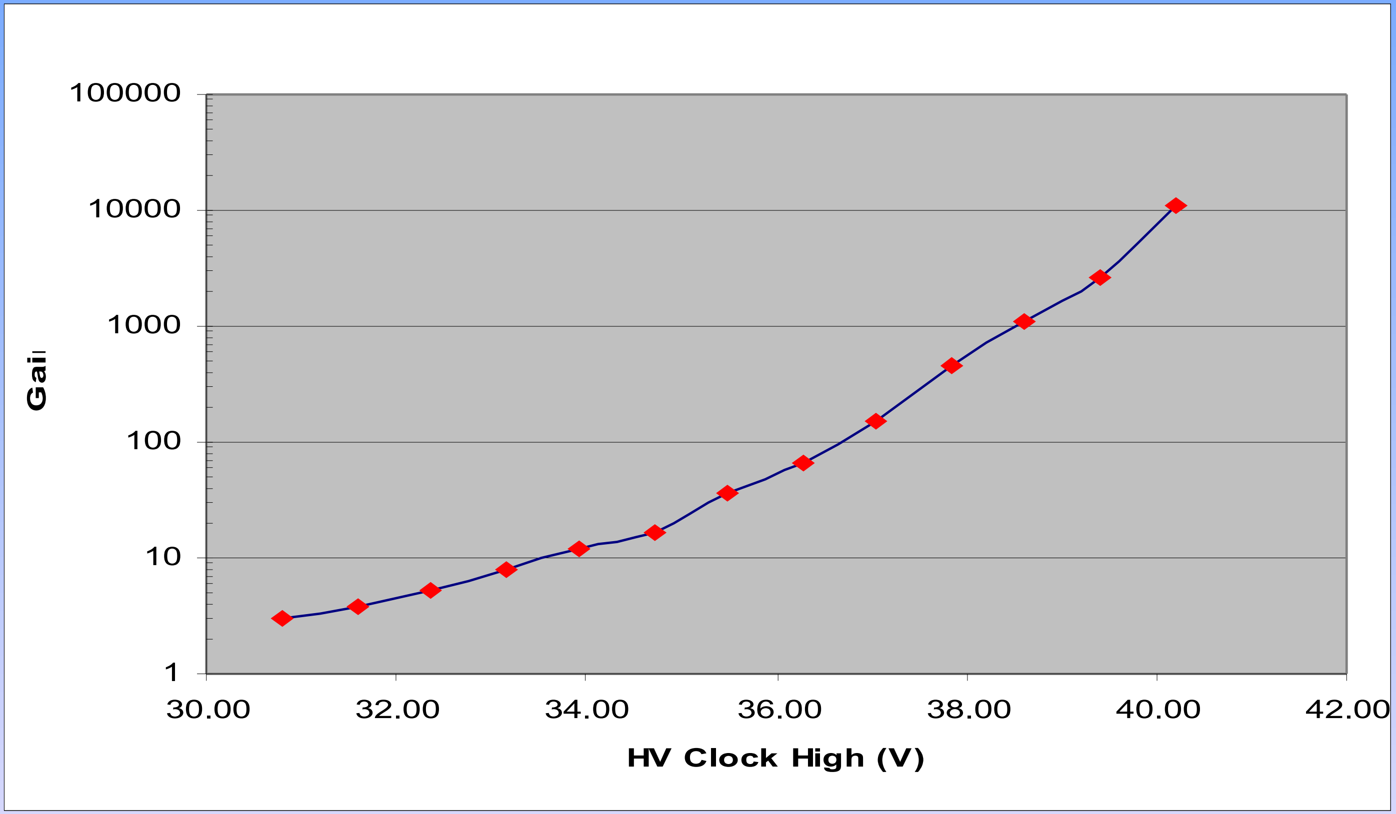
Performance – Read Noise

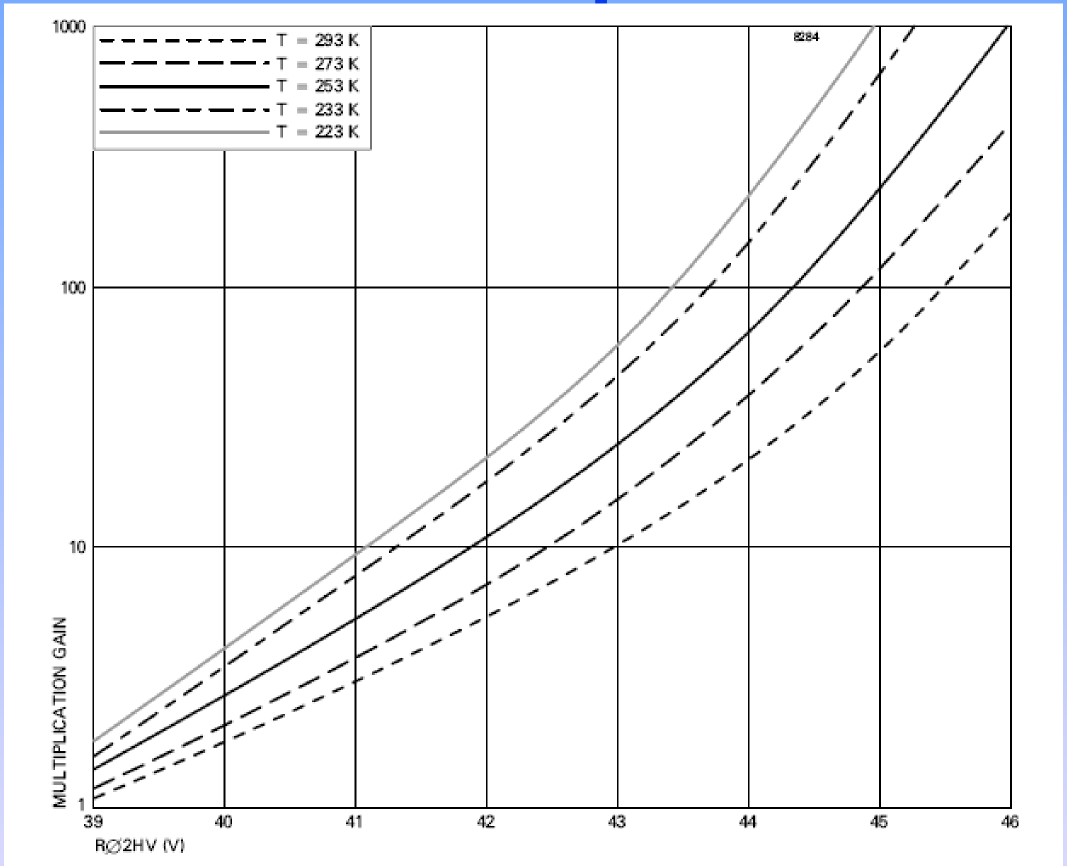
Parameter	Normal Output		Avalanche Output (Avalanche Gain = 1)	
	Slow Speed	Fast Speed	Slow Speed	Fast Speed
Gain (e/DN)	0.8	3.1	4.1	15.5
Read Noise	4.0e	10.2e	10.6e	24.7e
Frame time	4.8s	1.7s	9.7s	3.4s
Window (Y=100)	0.24s	0.09s	0.46s	0.17s

Gain Controlled by HV Clock



Under software control
Possible to have different gain for different parts of the CCD
Gain can also be switched off – no gain noise

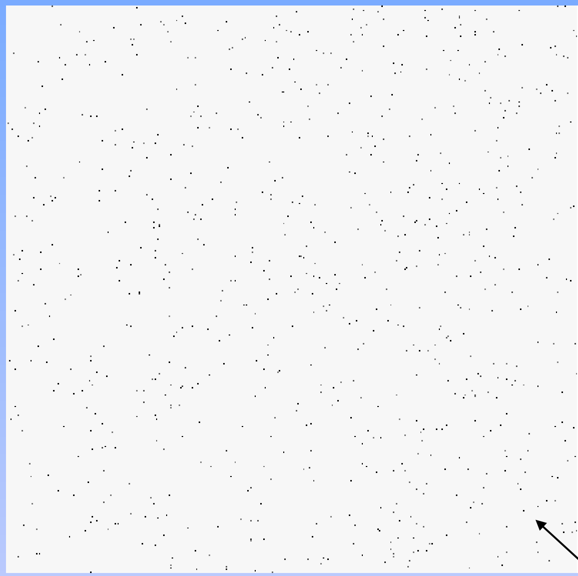
Gain Varies with Temperature

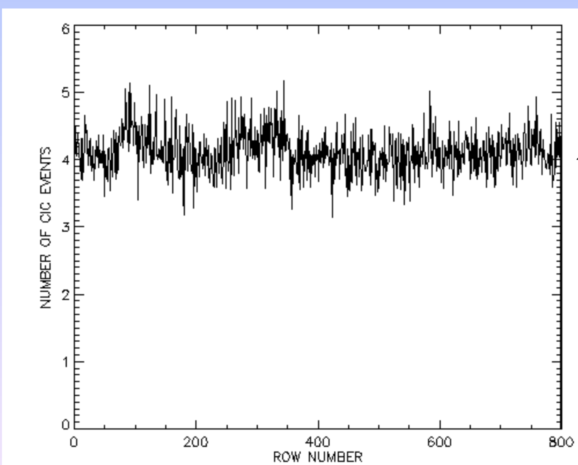


Gain increases at lower temperature due to increased probability of the impact ionisation

Lattice vibrations are less at lower temperatures

Clock Induced Charge



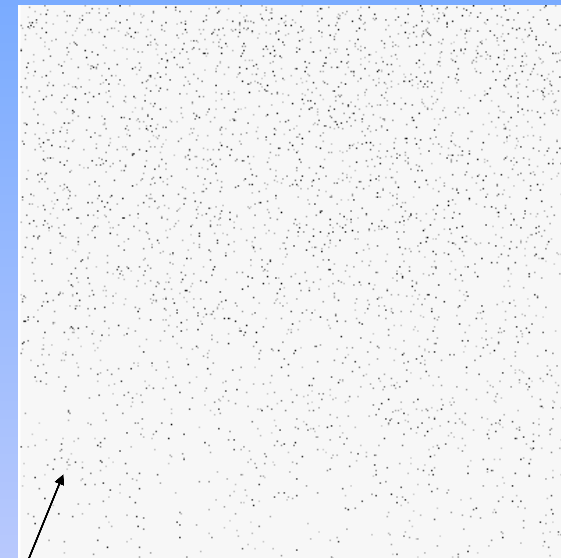


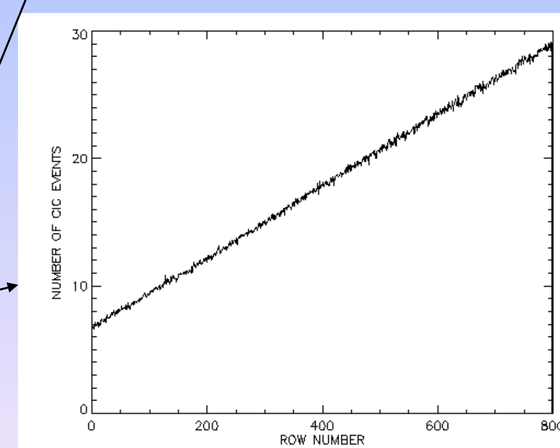
- Clock induced charge occurs in every CCD
- Dominated by readout noise in standard CCD

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

Serial register only

Serial and prallel





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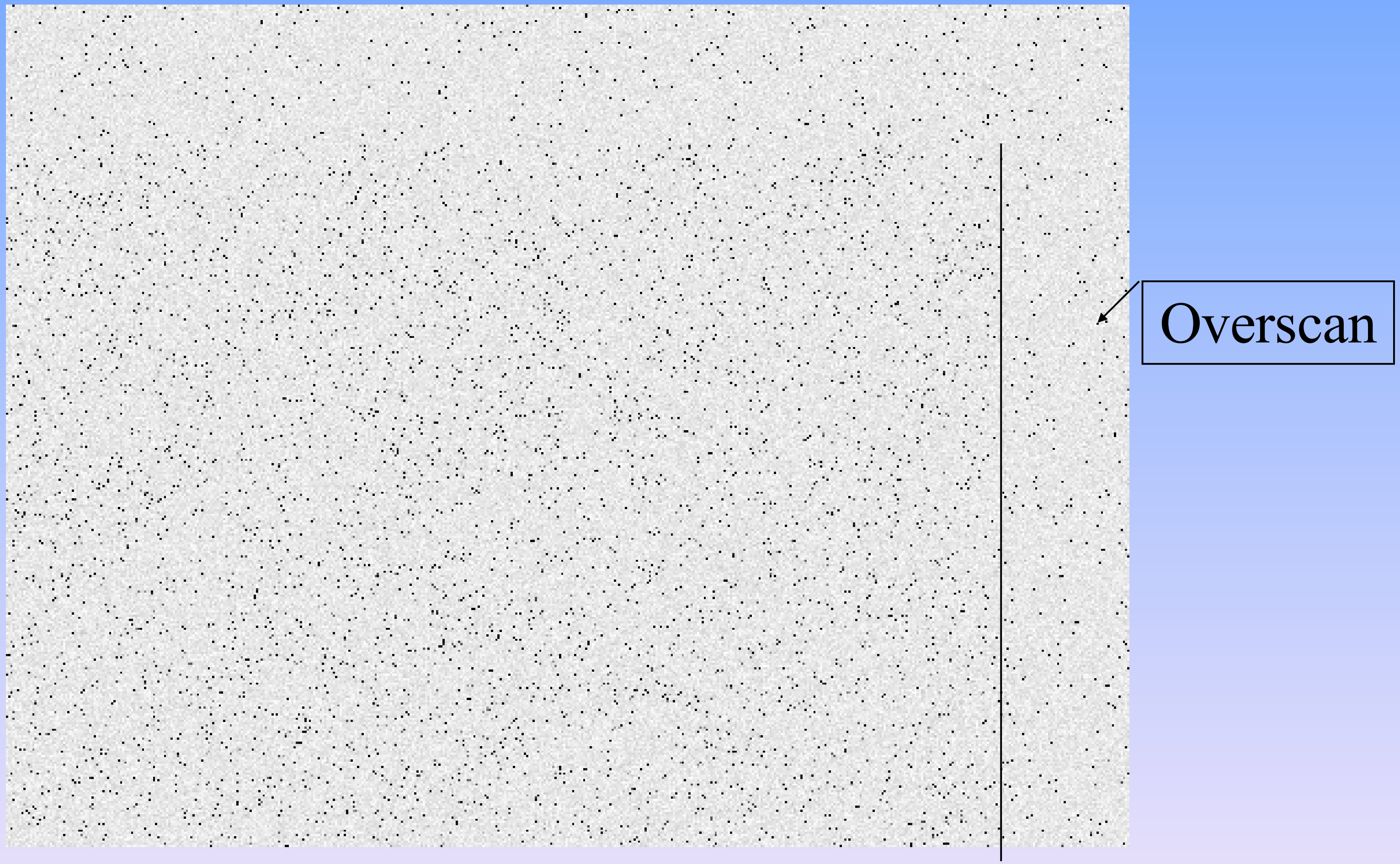
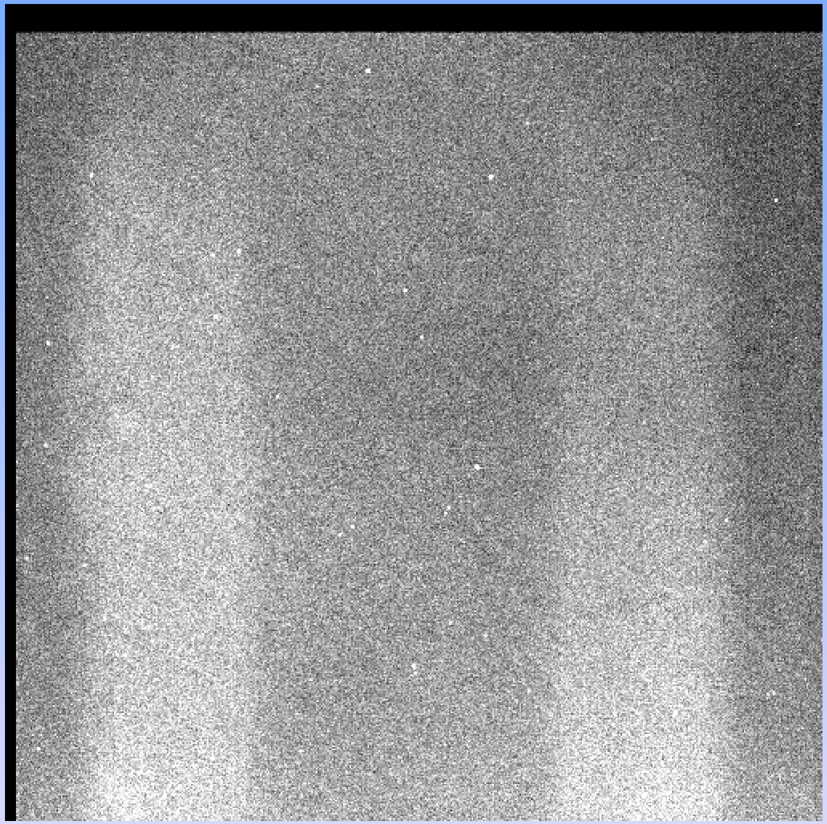
Performance - CIC

Average CIC in a frame	=	10.23 ADU
System Sensitivity	=	221.29 ADU/e
Avalanche Gain	=	1055.29
Transimpedance	=	0.0045 e/ADU
Read Noise	=	0.013 e = 2.94 ADU
Average CIC in a frame	=	0.046 e/pixel/frame

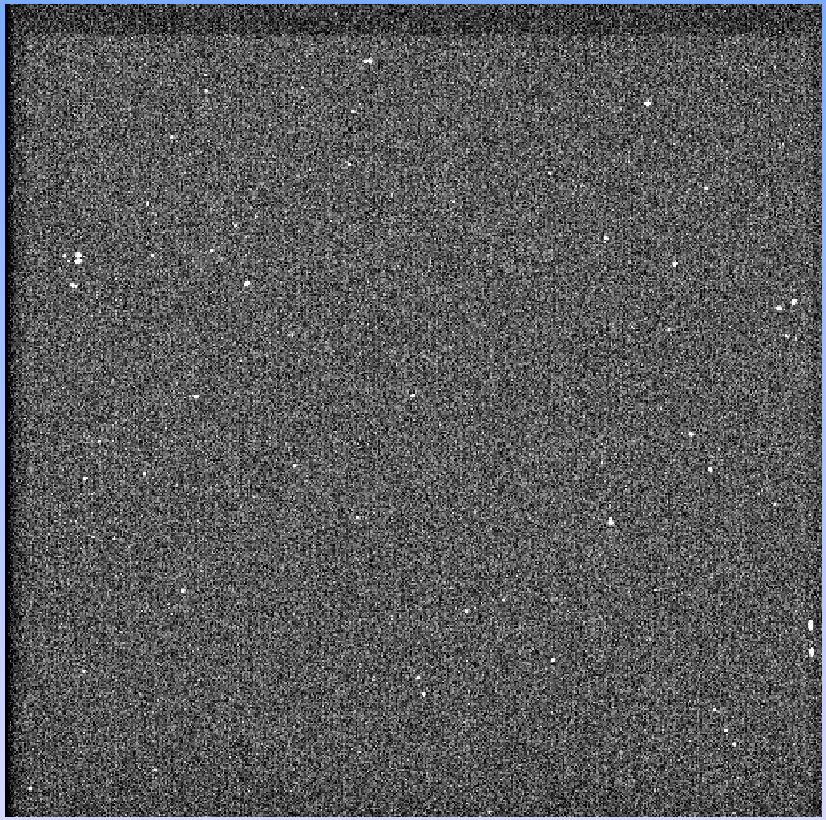
CIC Simulated



L3 Performance – Dark



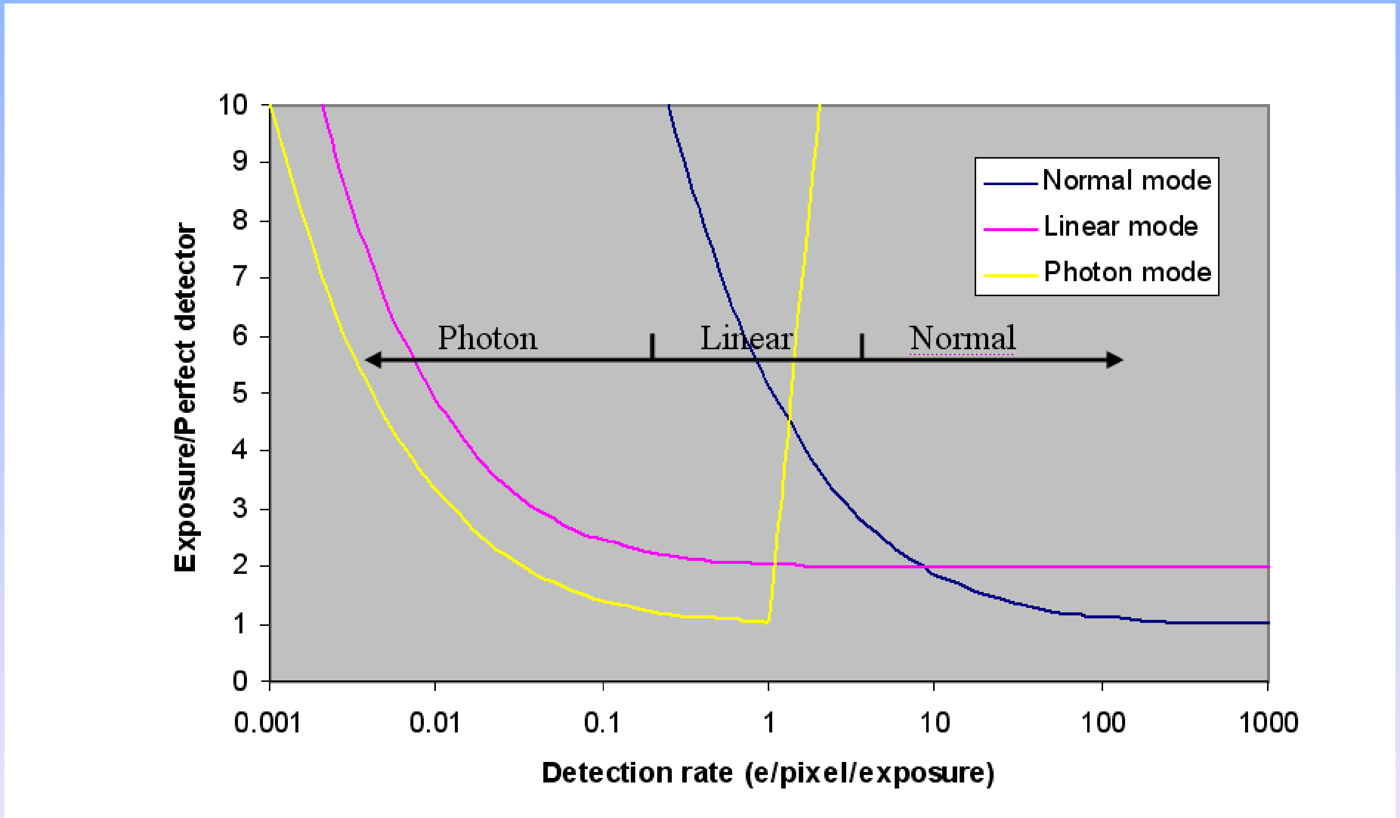
Non-inverted operation



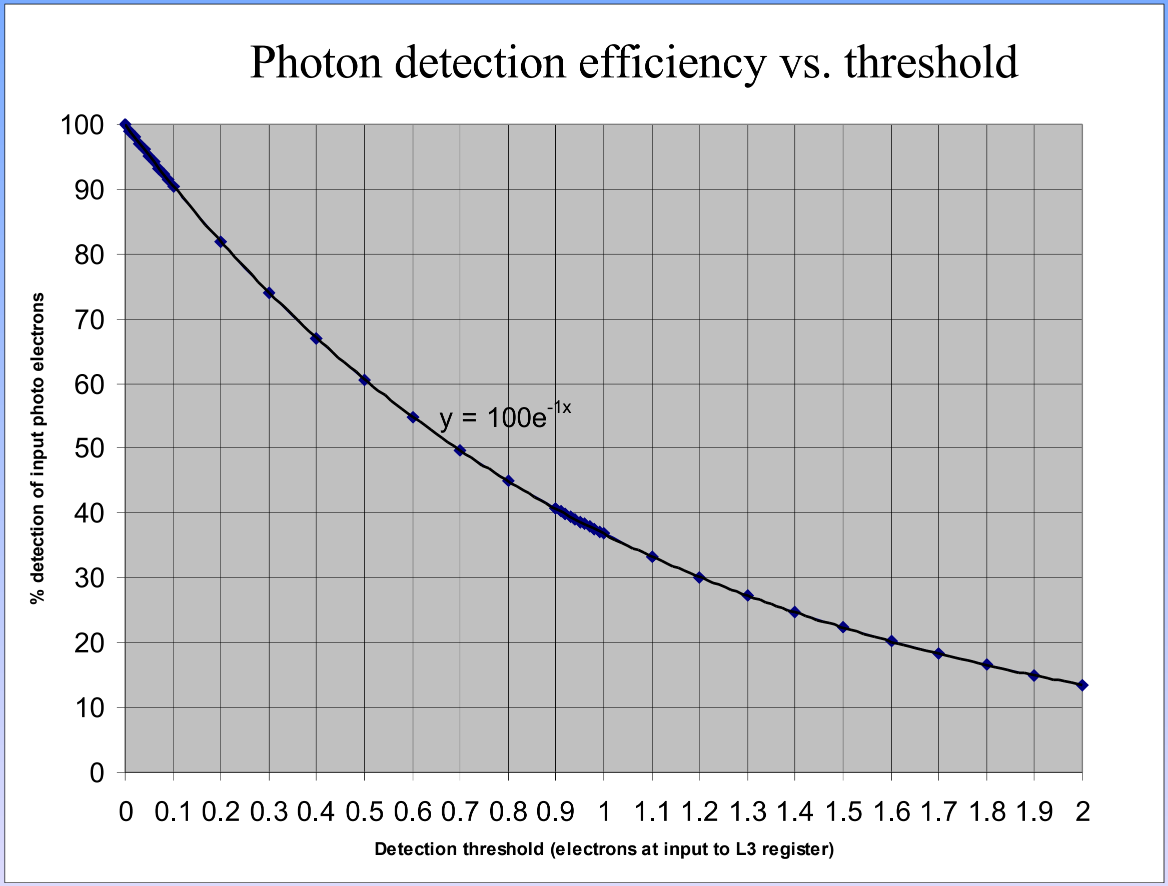
Inverted operation

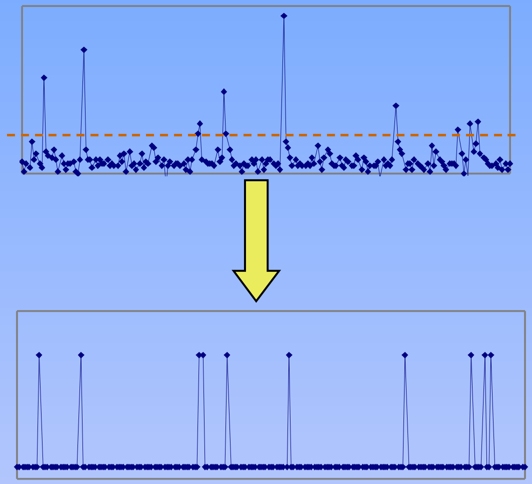
Operating Regimes

The three operating modes of an EMCCD, shown in terms of the exposure time required to reach a given signal to noise ratio compared to a perfect shot noise limited detector, all else being equal.



Photon Counting





- No loss in S/N
- Ideal performance
- Low CIC
- Critical threshold

Threshold is normally set at 5σ

Avalanche gain is set at 10 times of the threshold

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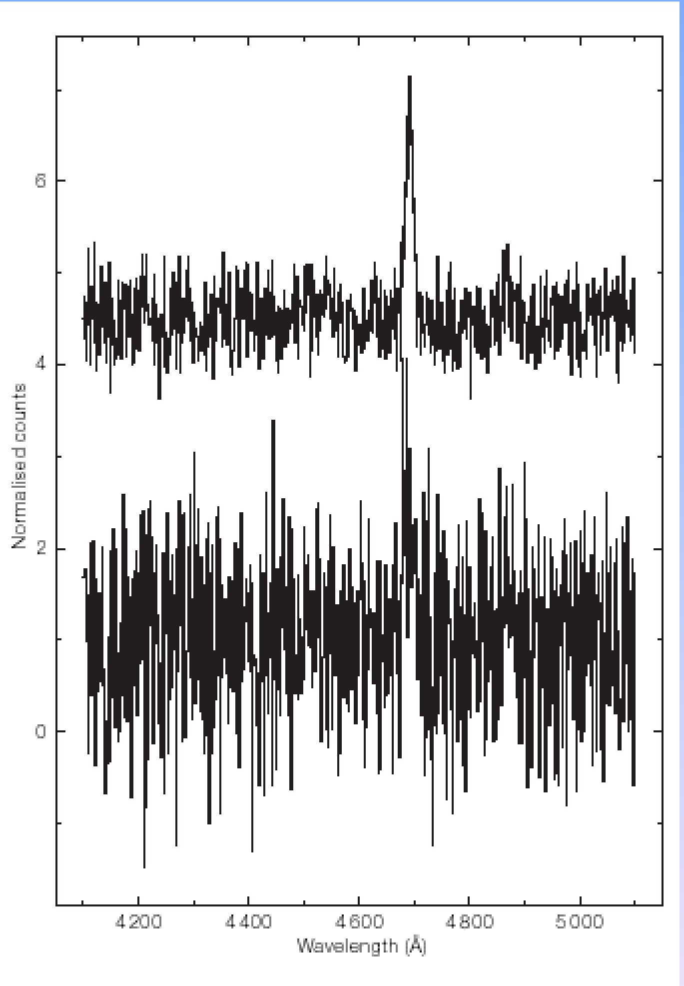
Normal vs. Avalanche Outputs

- L3 Camera commissioned with EFOSC2 at ESO's 3.6m Telescope in La Silla (Dec. 06)
- Top: 10s Spectrum using avalanche output of the UltraSpec
- Bottom: 10s of Spectrum using normal output (conventional CCDs)
- S/N Gain: Factor of three
- 3.6m Telescope with L3 CCD is equivalent to 6.4m telescope with conventional CCD
- Dead time negligible with EM CCDs compared to the conventional CCDs



ESO Messenger, March 07

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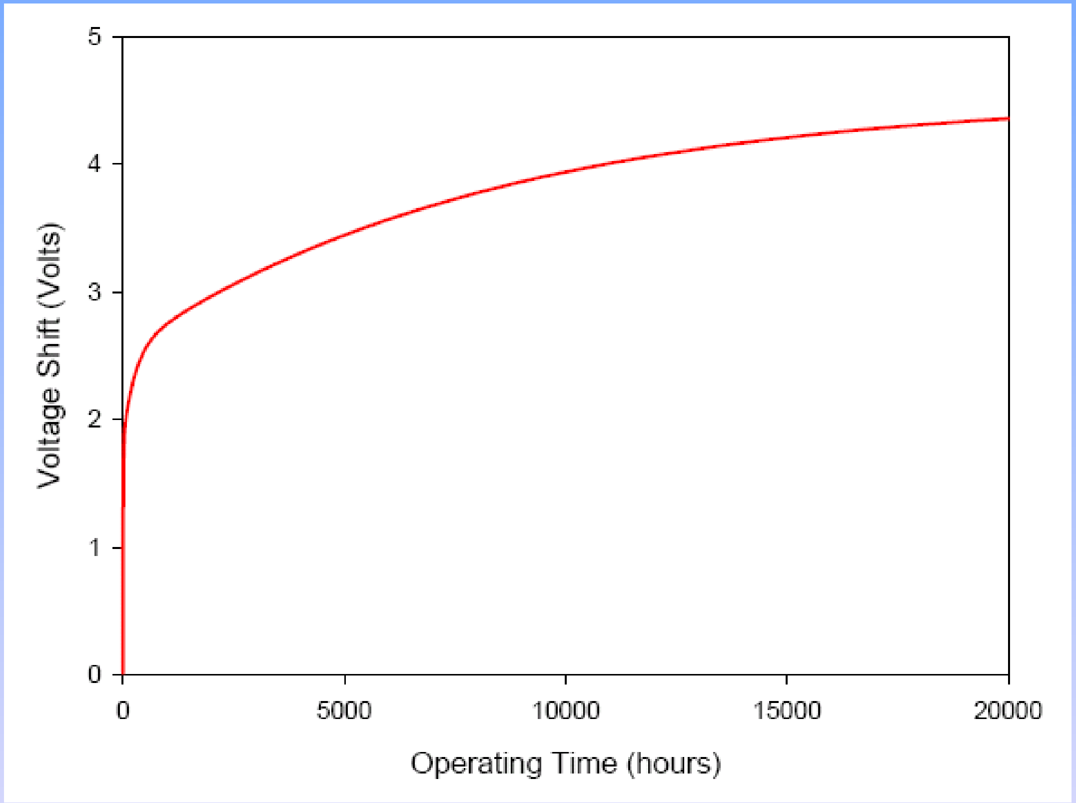
Ageing Effect

- **Drop in multiplication gain over time**
  - Shift in the high voltage clock amplitude
- **Ageing time constants**
  - Short term
  - Long term
- **Depends on signal size**
- **Function of gain**



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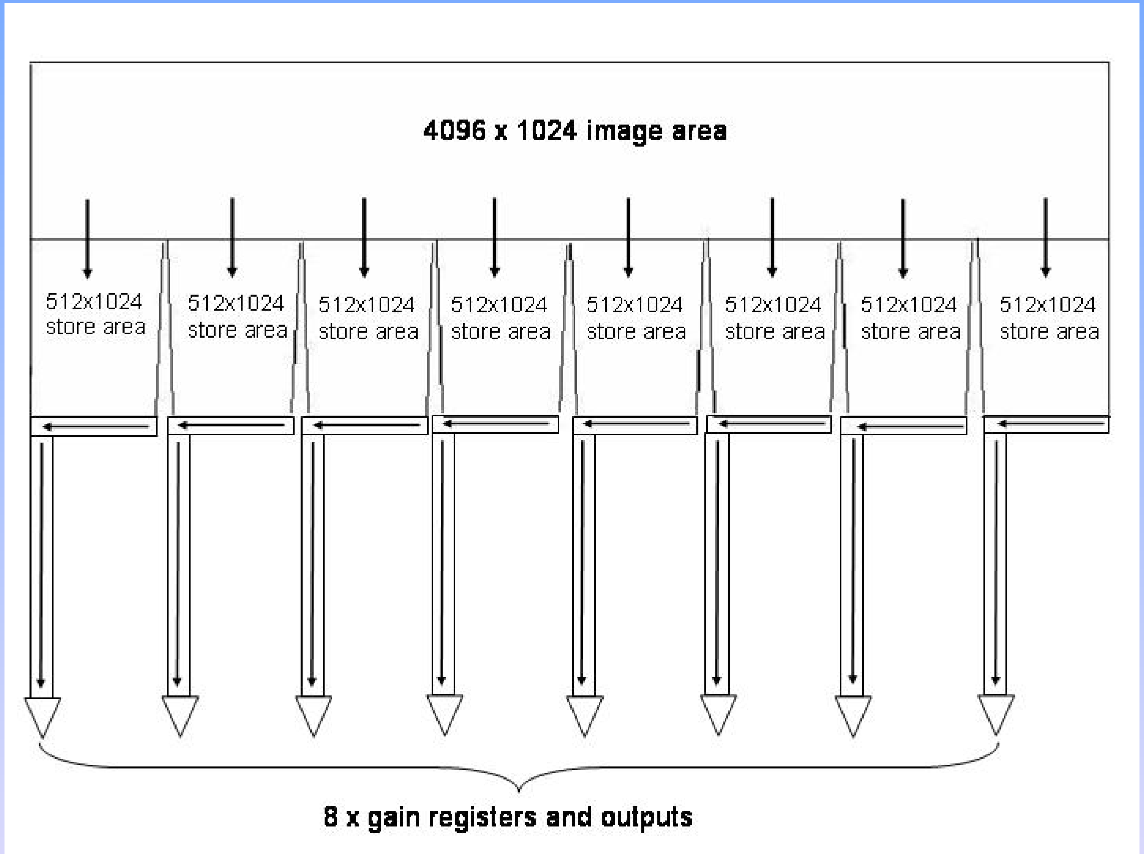
New L3 CCD Proposal



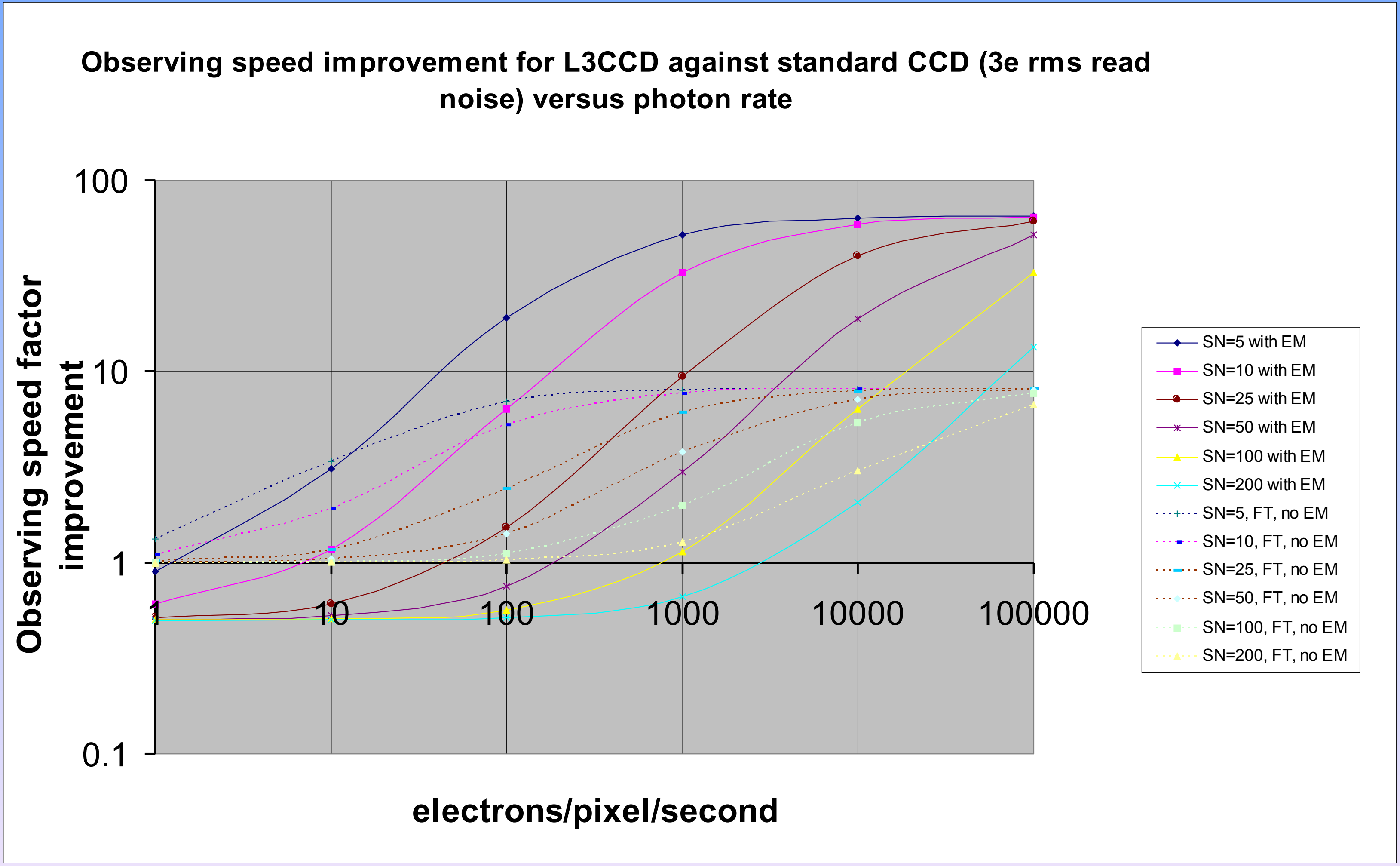
Looking for £1M funding for new EM CCD to cover spatial/spectral range and increased read speeds because of FT architecture

ESO agreed to lend the NGC

Details of Specifications

4096 x 1024 pixels for imaging and likewise for storage
2µm-15µm square pixels, with 100% pixel fill factor.
8 outputs, 3 e rms at 100 kHz pixel but can operate at 7.5 MHz.
10 Hz full frame rate.
Thinned and back illuminated.
E2V Technologies "Astro" broadband AR coating.
2 phase vertical clocking.
A minimum of Grade 1 cosmetic quality.
Flatness better than 15 µm peak to valley across full length of detector.
Reference/dark rows, columns and blank elements to be supplied on the CCD.
Each of output to have separate Output Drain (OD) and Reset Drain (RD) pins.

Efficiency of the New Design



Thank You