Large Area Near Infra Red Detectors for Astronomy

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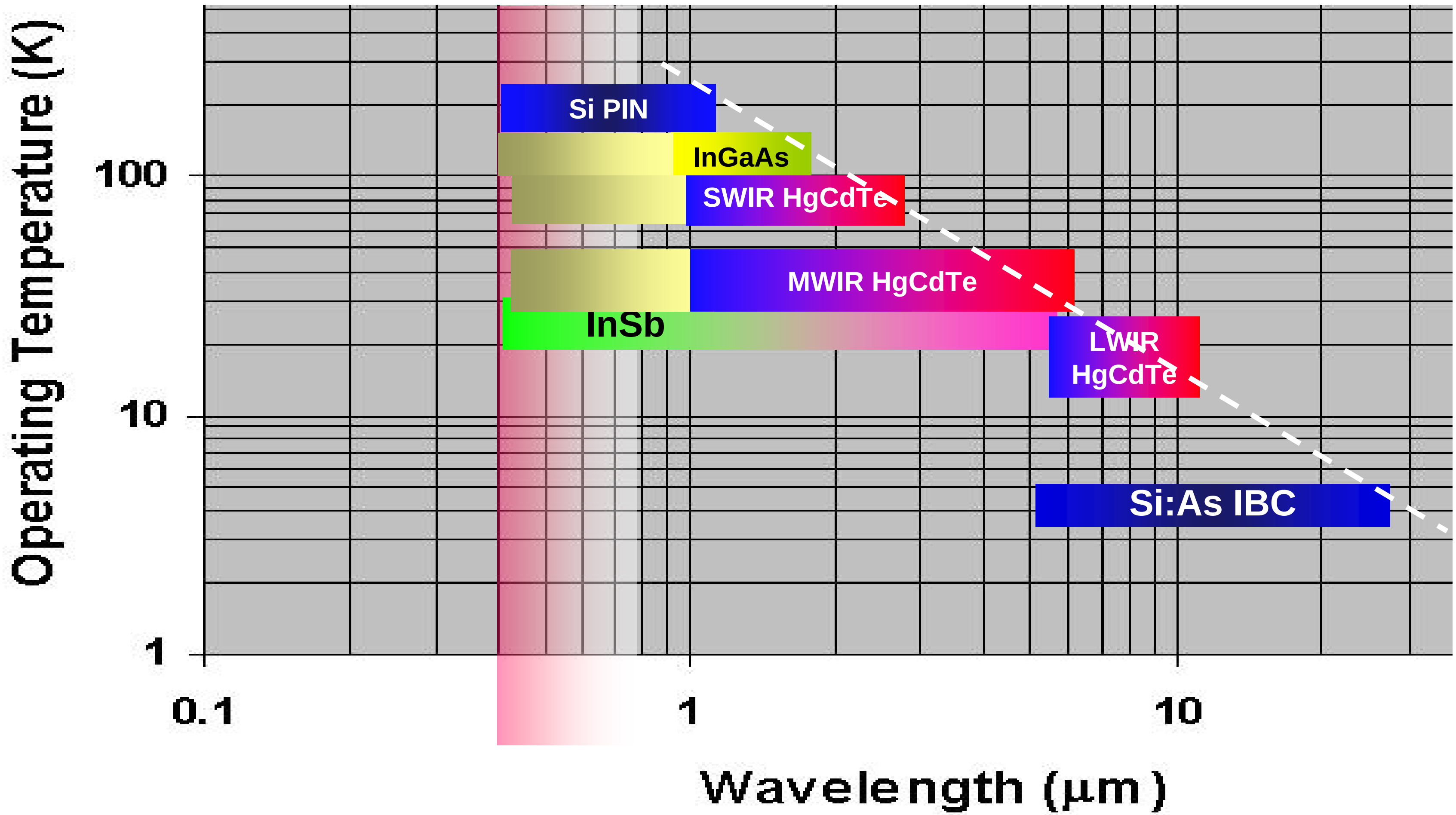
Presentation overview :-

•Description of IR FPA technology
•Characteristics and measured performance of latest NIR detectors
•Problems and issues with present detectors
•Look ahead, future technology drivers

Temperature and wavelengths of high performance detector materials.



Approximate detector temperatures for dark currents << 1 e-/sec

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IRFPA Manufacturing Process

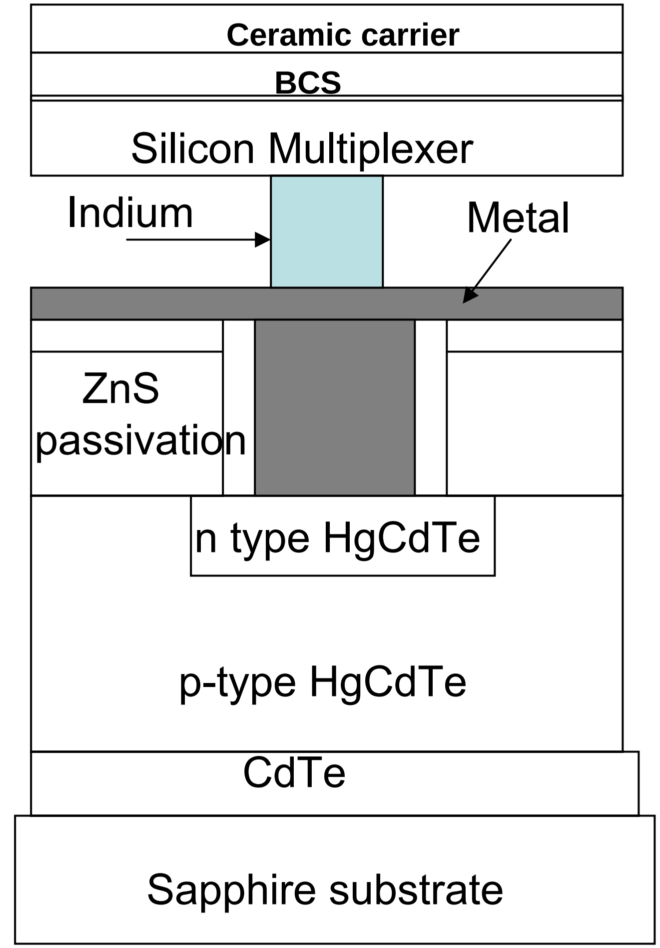
• The HgCdTe wafers are prepared by first growing a thin buffer layer of CdTe on the sapphire substrate by metal organic chemical vapor deposition (MOCVD). The photosensitive HgCdTe is then grown via liquid phase epitaxy (LPE) from a Te—rich melt on to the buffered sapphire substrates to produce 2" or 3" HgCdTe wafers.

• The photovoltaic detectors are formed by boron ion implantation at room temperature followed by annealing. The detector architecture here is n-on-p.

• The junctions are passivated by ZnS or CdTe.

• Metal pad deposition for contact to the junction and ground.

• Indium columns are evaporated to provide interconnects for subsequent hybrid mating.



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Liquid Phase Epitaxy (LPE)

The salient features of a conventional LPE system are :-

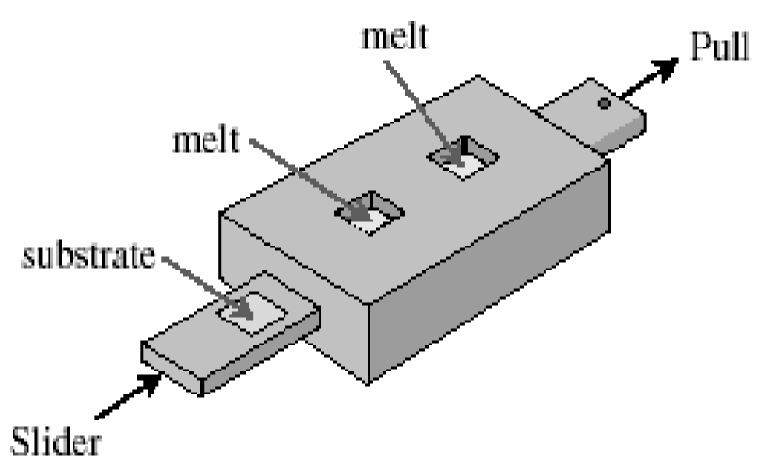
.A substrate is brought into contact with a saturated solution of the film material at an appropriate temperature. The substrate is then cooled at a suitable rate to lead to film growth.

• a boat to contain the melts and to separate them both from each other and the substrate until the start of the growth process

• a reducing atmosphere to prevent the formation of oxides during growth

• the ability to control the temperature of the furnace and hence that of the melts and substrate

• a means of both bringing the melt solution and the substrate into contact at the start of the growth process and of separating the two at its conclusion



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Liquid Phase Epitaxy

Advantages :-

- Simple technique in use for many decades
- Inexpensive equipment, low cost, low risk
- Higher deposition rates wrt other processes such as MBE
- Low defect concentration
- Excellent control of chemical reactions (stoichiometry)

Disadvantages :-

- Difficult to control ultra thin layer
- Poor surface uniformity/quality
- Poor surface morphology (crystal orientation)
    - High dark current
    - Low QE, vary with temperature (especially low temperature)
    - Persistence problems

However used successfully in Rockwell HAWAII detectors and Raytheon VIRGO detectors.

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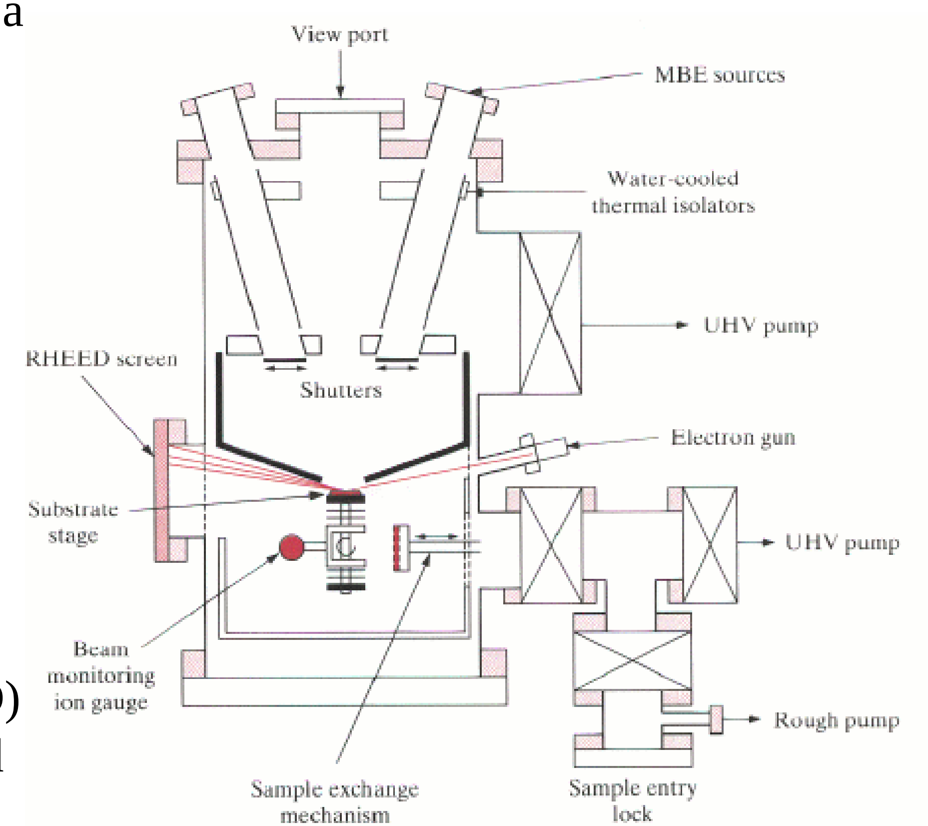
Molecular Beam Epitaxy (MBE)

Molecular beam epitaxy - is simply a refined form of vacuum evaporation. Heat a material in a cell in a vacuum until a vapour is formed which then effuses as a stream of individual molecules onto our sample.



Salient features :-

•Ultra High Vacuum chamber

•Mechanical cooled shutter for stopping

•Heating the substrate controls the growth, rotation controls uniformity

•Reflection High Energy Electron Diffraction (RHEED) – used for feedback on process (imaging of a diffracted electron beam) => this insitu diagnostic allows the growth process to be controlled to a degree not possible in other methods

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Molecular Phase Epitaxy

Advantages :-

• Band gap engineering – using RHEED etc. can control epi thickness to atomic level – so called Monolayer growth (rate ~ 1 atomic layer/second)

•Excellent control of doping profiles and compositional structure etc. – single atomic layers possible because of very low deposition rates possible, also low temperatures required

•Low level of defects and dislocations especially when lattice matched to CdZnTe substrates => lower dark current, higher uniform QE (CdZnTe substrate has better refractive index match)

Disadvantages :-

•Very High vacuum requirements

•Complex and very costly equipment

•Longer processing times compared to LPE (typically 1 um/hour)

•CdZnTe only available in small, low yield and expensive wafers

Example is Rockwell HAWAII-2RG detectors for JWST

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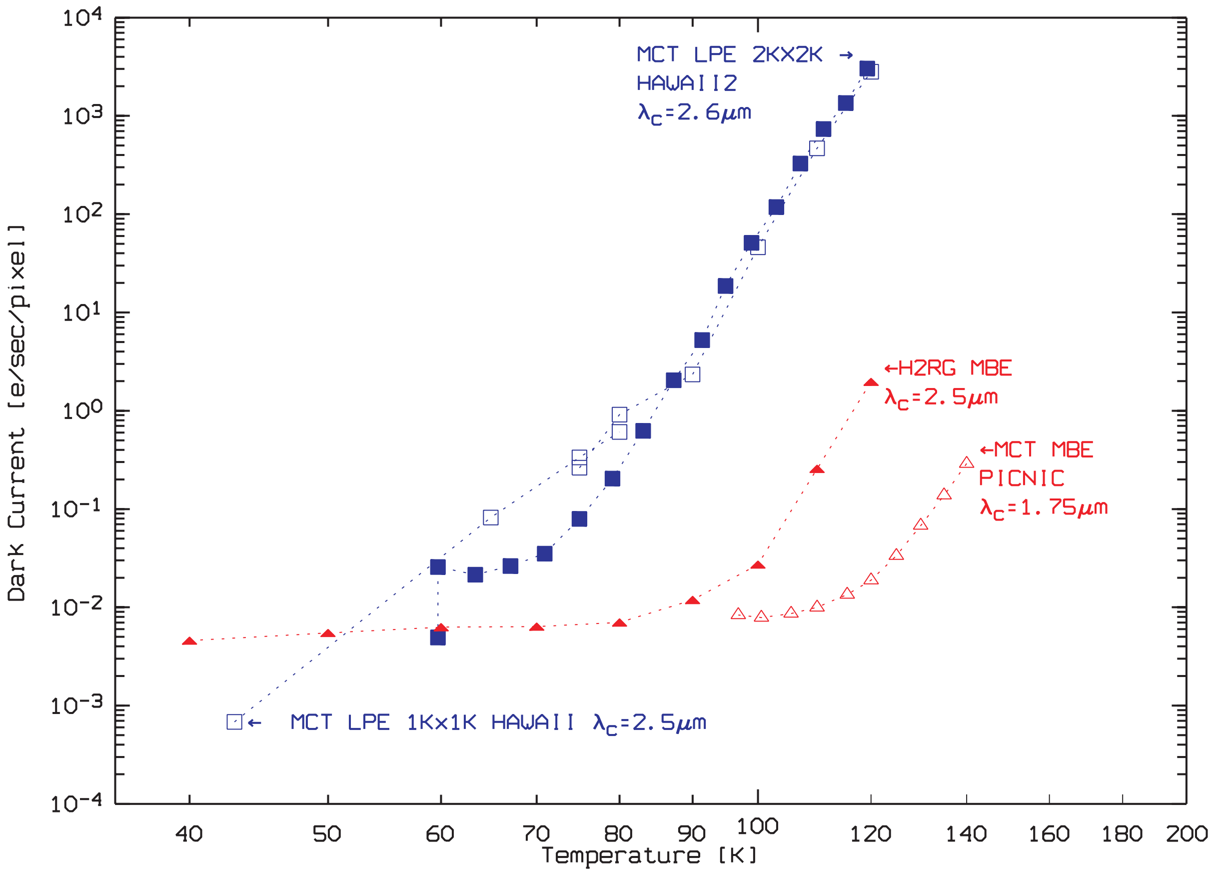
Dark current versus temperature HgCdTe LPE / MBE



- LPE λ_c=2.5μm

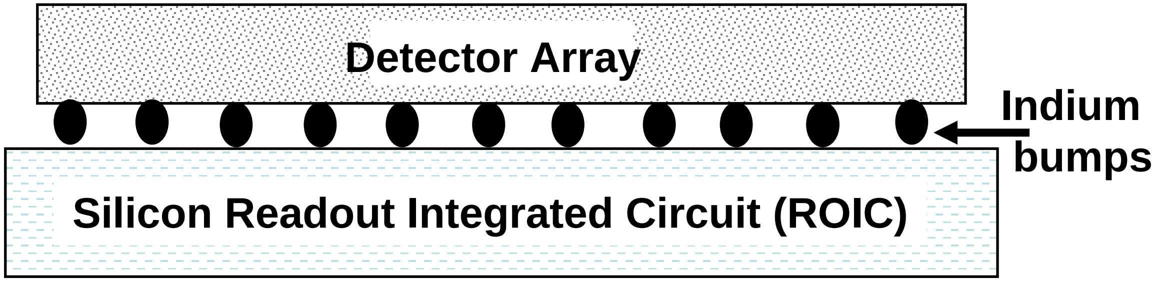
  ■ Hawaii2 2Kx2K
  □ Hawaii1 1Kx1K

- MBE λ_c=2.5 / 1.7 μm

  ▲ Hawaii-2RG 2Kx2K λ_c=2.5μm
  △ PICNIC 256x256 λ_c=1.7μm

- MBE at T<80K I_{dark} < 0.01 e/s/pixel
- at T=100K $I_{MBE}=I_{LPE}$ /1660
- Good λ_c=2.5μm MBE material can be used in liquid bath cryostats

IR detector hybridised to Silicon Multiplexer Circuit



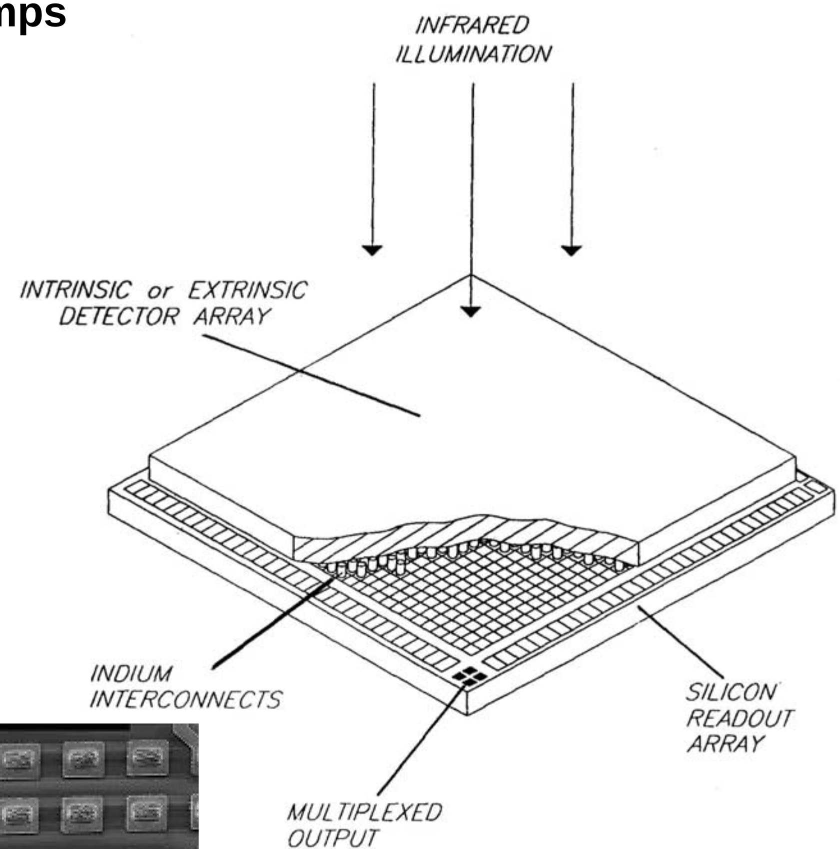
Over 4,000,000 indium bumps per detector !

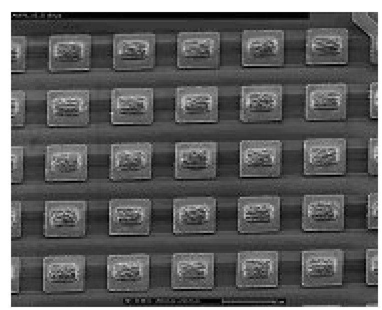
Flip Chip Bonding :-

- Standard Industrial process

- Indium used because of excellent low temperature thermal and electrical properties

- Large forces required - > 100kgm, for cold welding





SEM image

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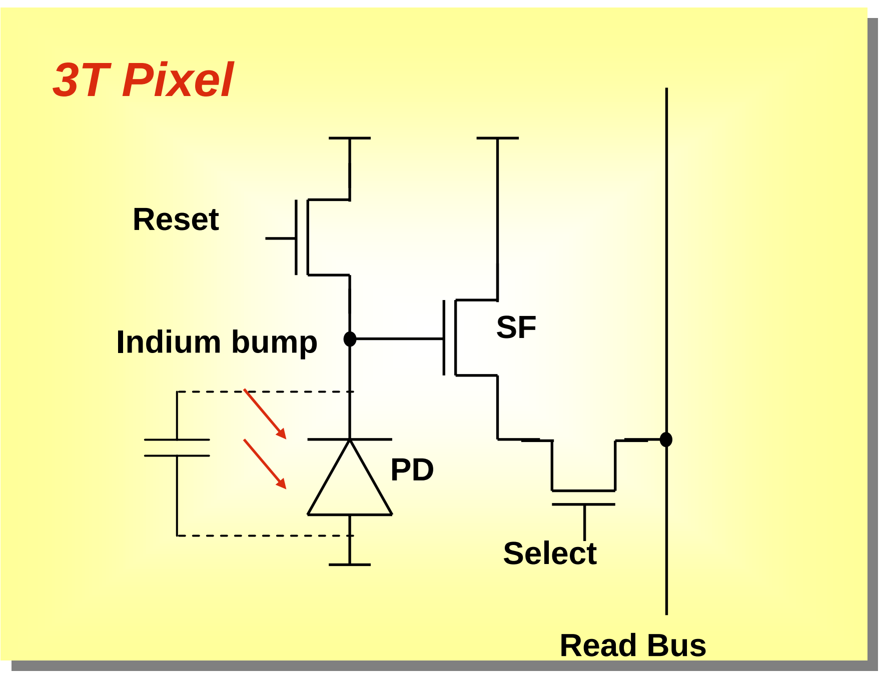
IRFPA Pixel Circuitry

•Photocurrent is stored directly on the detector capacitance as shown in the figure, requiring the detector to be reverse-biased to maximize dynamic range.

•The detector voltage modulates the gate of a source follower whose drive FET is in the cell and whose current source is common to all the detectors in a column. The limited size of the cell transistor constrains its drive capability and thus the electrical bandwidth of the readout.

•SFD works very well at low backgrounds, long frame times and applications where MOSFET glow must be negligible compared to the detector dark current. (Others such as DI and CTIA used for high background etc)



- *Source Follower per Detector*
- *3 transistors per unit cell*
  - *Source Follower Driver FET*
  - *RESET FET*
  - *Row Enable FET*

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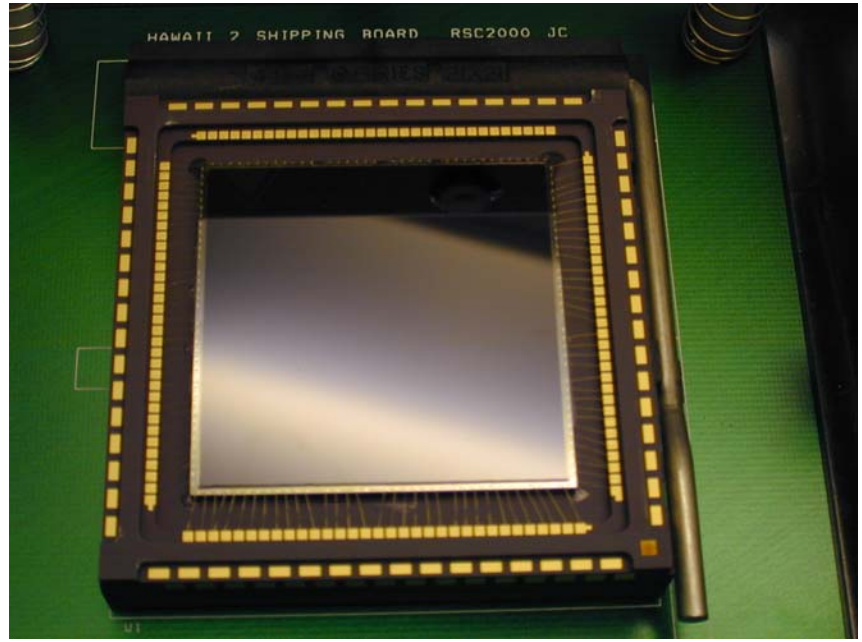
Example NIR Detector Types

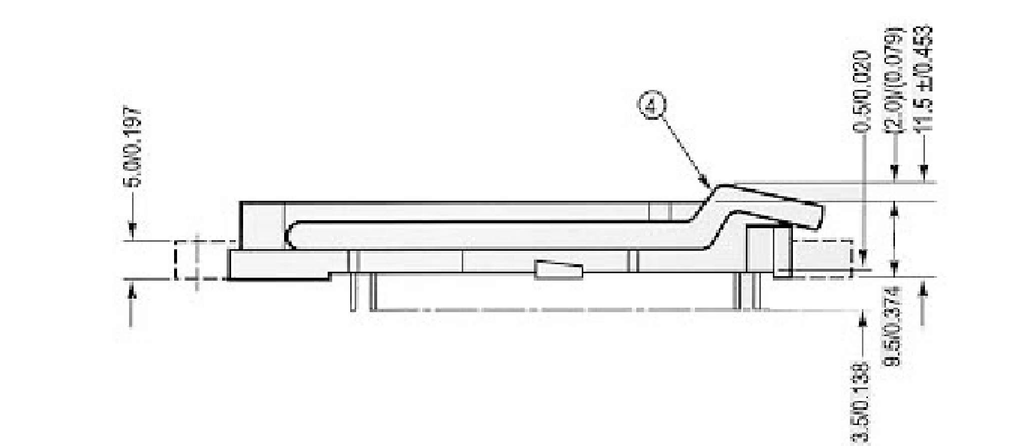
Characteristics and measured performance

1. Rockwell HAWAII-2 for WFCAM
2. Raytheon VIRGO for VISTA
3. Rockwell HAWAII-2RG for JWST and future projects ?

HAWAII-2 – WFCAM detectors

- 2k x 2k format, 18µm square, HgCdTe on Sapphire substrate (LPE) - N on P diodes
- 4 quadrants of 1k x 1k
- 32 channels
- 12 clocks, and 6 bias supplies
- Non buttable
- Electrical/thermal interface through 400 pin PGA





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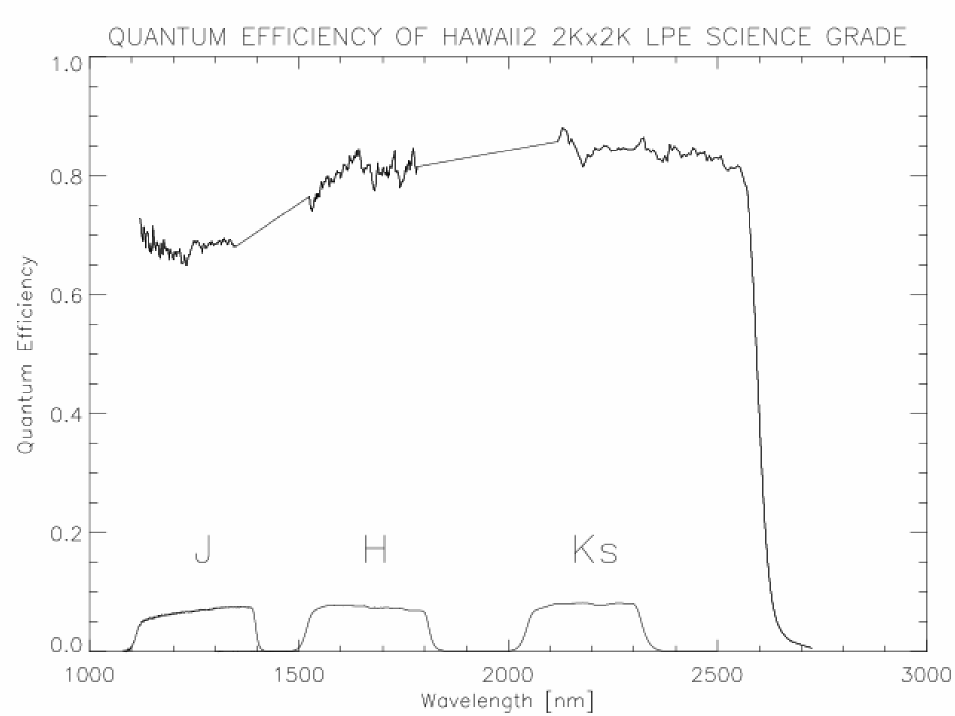
Performance of Hawaii-2 LPE in WFCAM

• Operating temperature	-75 K
• Pixel rate	- 180 kHz
• Frame readout time	- 0.73 s
• Dark current	- <1 e/pixel/s
• Transimpedance	- 3.6 μV/e*
• Gain change v. Signal	- ~2%(10-90% full well)
• Read noise (pixel-to-pixel)	-15 e^- (rms)
• Full well	-180 ke^-
• Non linearity	-~2%(10-90% full well)

*determined using signal/shot noise method



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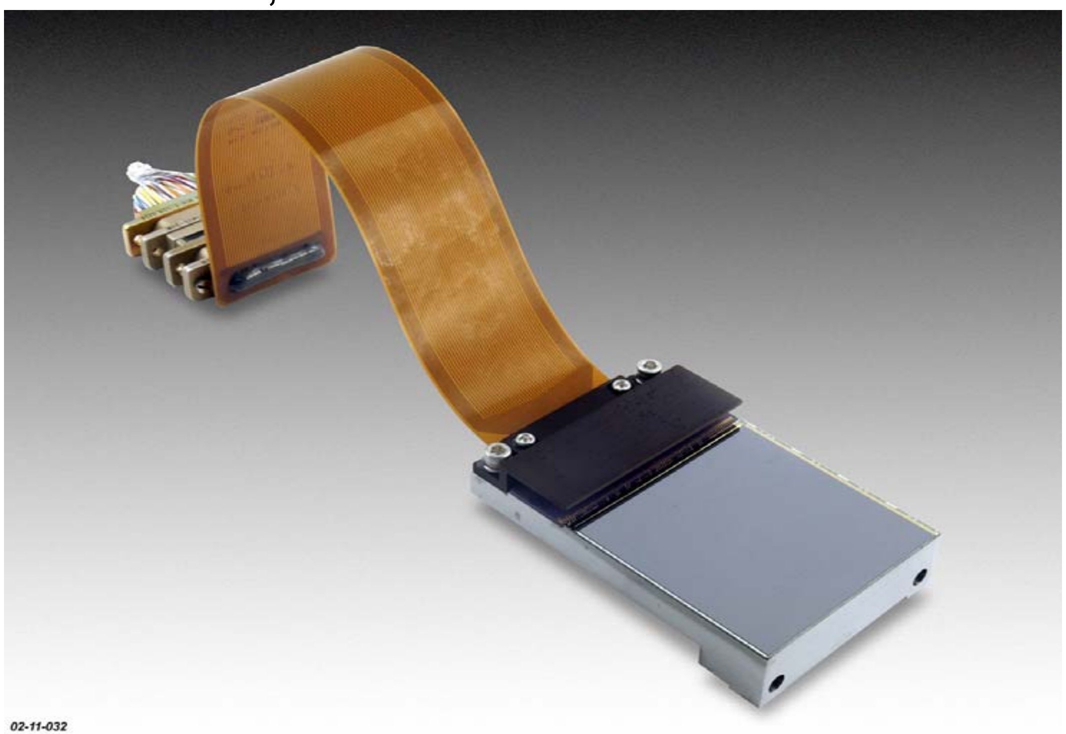
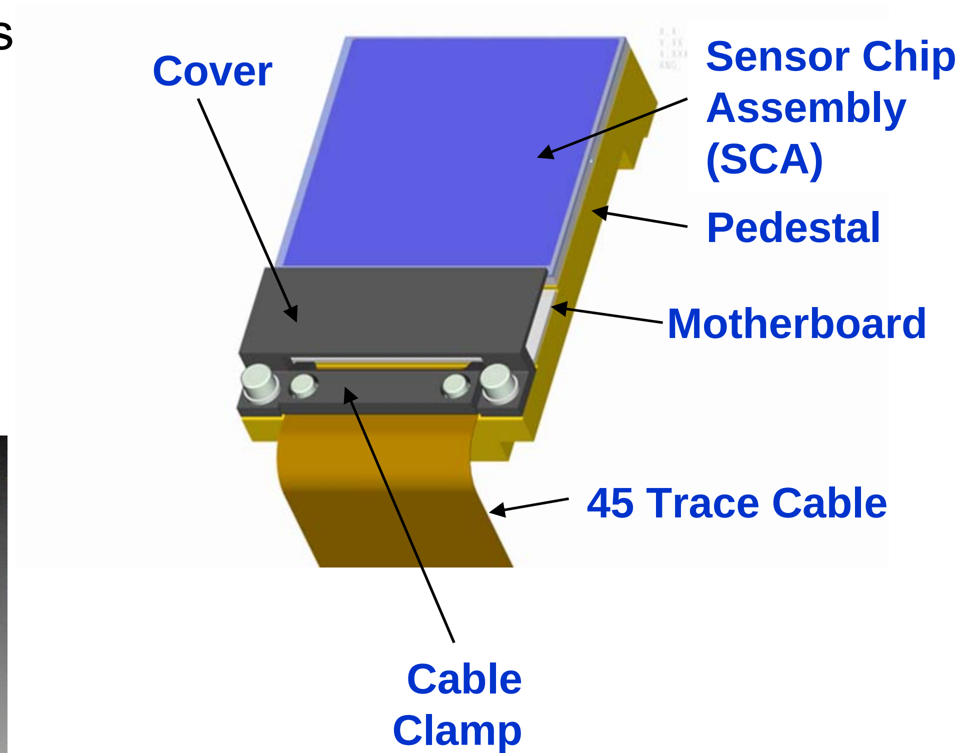
Raytheon VIRGO – VISTA detector

- 2048 x 2048, 20 um square pixels
- HgCdTe (LPE) on CdZnTe – P on N diodes
- 3-side buttable
- 45-trace cable
- 51-pin micro-D MDM connector
- 16 outputs
- 5 clocks, 13 biases





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Performance of VIRGO SCA-45 detector for VISTA

Parameter	VISTA Requirements	Science detector VM301-SCA-45 (72K)
Quantum efficiency	> 38% (J) > 47% (H) > 47% (Ks)	92% (J) 100% (H) 95% (Ks)
Well depth	>100ke$^-$	140ke$^-$ (0.7V bias)
Dark generation	<8 e$^-$/pix/sec	0.63e$^-$/pix/sec
Read noise	<32 e$^-$ (rms)	15 e$^-$ (rms)
No. of outputs	< 1sec frame rate	16 outputs (1.001s)
Non-linearity	<3%	3.3% (100ke$^-$ FW)
Pixel defects	<4%	<1%
Flatness	< 25μm (for FPA)	~6μm (p-v)

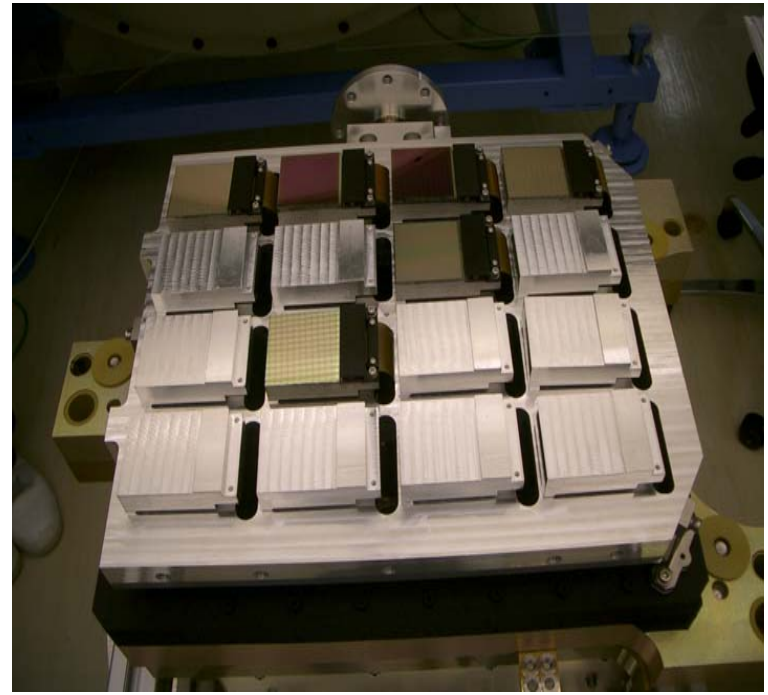

Figure 1 VISTA mosaic of 16 2Kx2K arrays populated with 4 bare Si multiplexers having no IR active layers and two hybridized engineering grade 2Kx2K HgCdTe VIRGO arrays.

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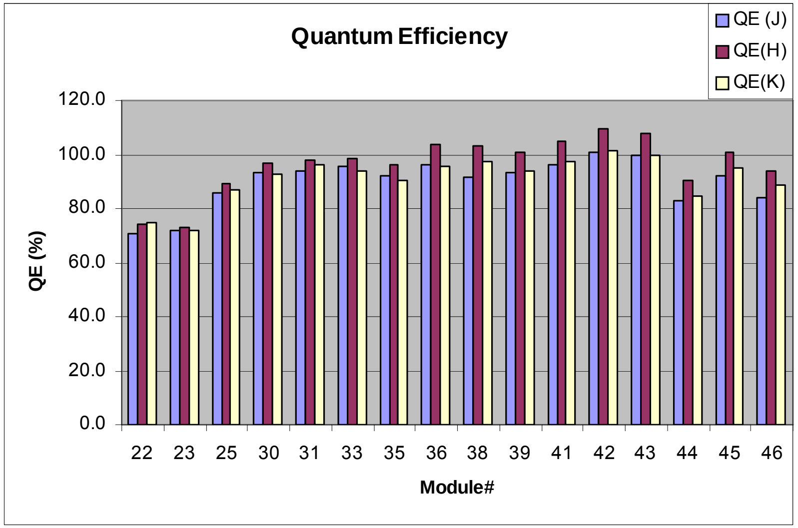
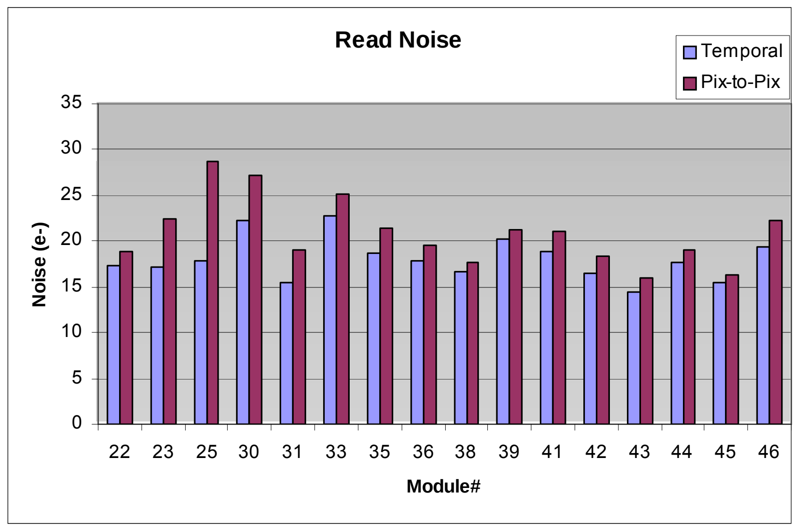
VIRGO detector homogeneity



- QE peaks in H band
- AR coating optimised for H band
- Couple of earlier detectors ~ 70%
- Radiometry uncertainty ~ 12%

- Close agreement between temporal and pixel-to-pixel read noise
- The detector that showed large difference has dark pattern at 0.5V bias
- The dark for those detectors is higher at 0.5V than at 0.7V bias



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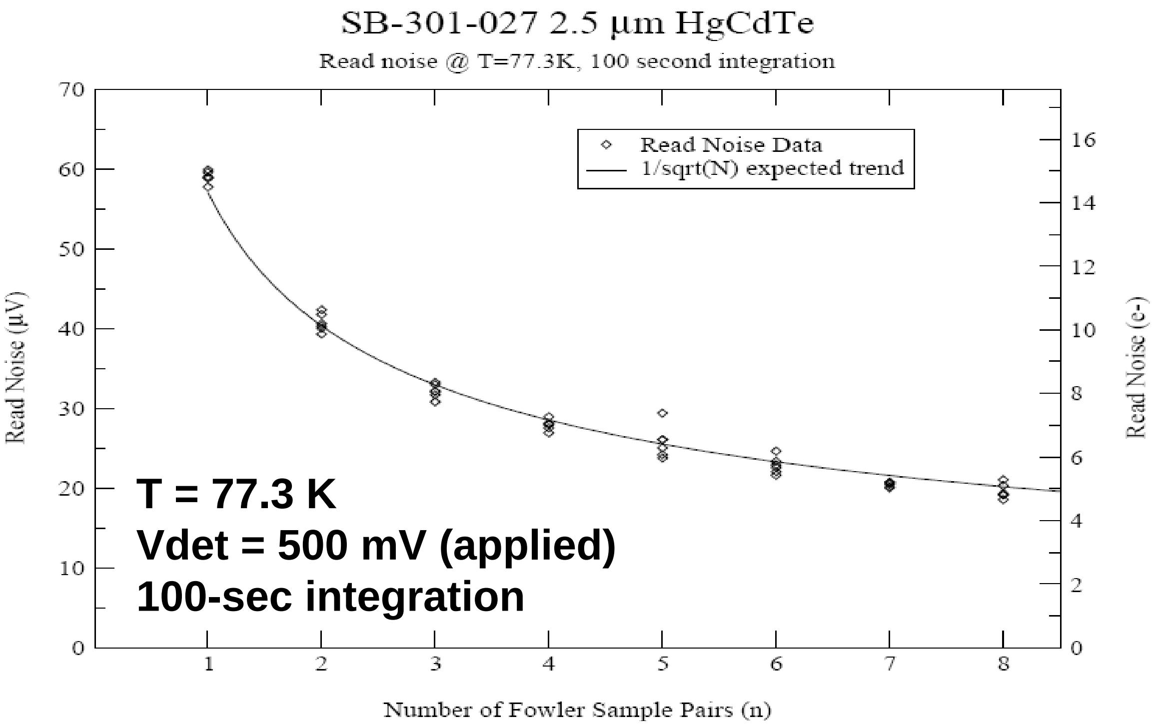
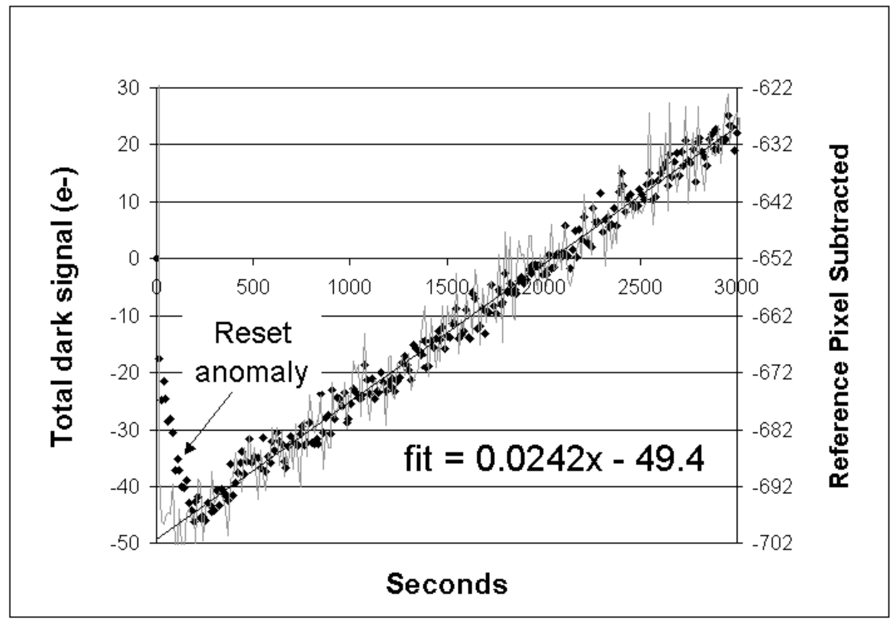
Other performance parameters for NIR detectors



Read Noise on SCA 27, U. of Rochester: ~15 e- rms with CDS, ~5 e- rms with Fowler-8

Caltech Measurements
Dark current is 0.025 e-/sec at 79 K after suitable settling (RVS measured 0.92 e-/sec)
Complete settling takes ~10 hours!
Measured mux glow = 0.04 e-/read



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Comparison between VIRGO and HAWAII-2

Parameter	VIRGO	HAWAII-2	Comments
Format	2048 x 2048	2048 x 2048	Complexity similar, one has more outputs, other has more biases etc.
Pixel size	20μm	18μm	
Quantum efficiency	**> 85 % (JHK)**	**~ 60 % (JHK)**	Inter-pixel capacitance taken into account
Well depth	>150ke$^-$ (0.7V vbias)	180ke$^-$ (1.0V bias)	
Dark generation	<1 e$^-$/pix/sec	<1e$^-$/pix/sec	
Read noise	<16 e$^-$ (rms)	<15 e$^-$ (rms)	
Frame rate **Reset time** **CDS time (5s integr.)**	**1 Hz (16 outputs)** **1 s** **6 s**	**1.4 Hz (32 outputs)** **10 ms** **5.7 s**	VIRGO requires 1 s reset time
Non-linearity	<3.3%	<2.0%	
Gain versus Signal	~ 10%	~ 2%	
Flatness	6μm (p-v)	< 10μm (p-v)	
Efficiency (5s integr.) **(5*QE/CDS time)**	**0.60**	**0.50**	
Cost	$300k	$350k	

HAWAII-2 to be replaced by HAWAII-2RG

HAWAII-2RG Detectors

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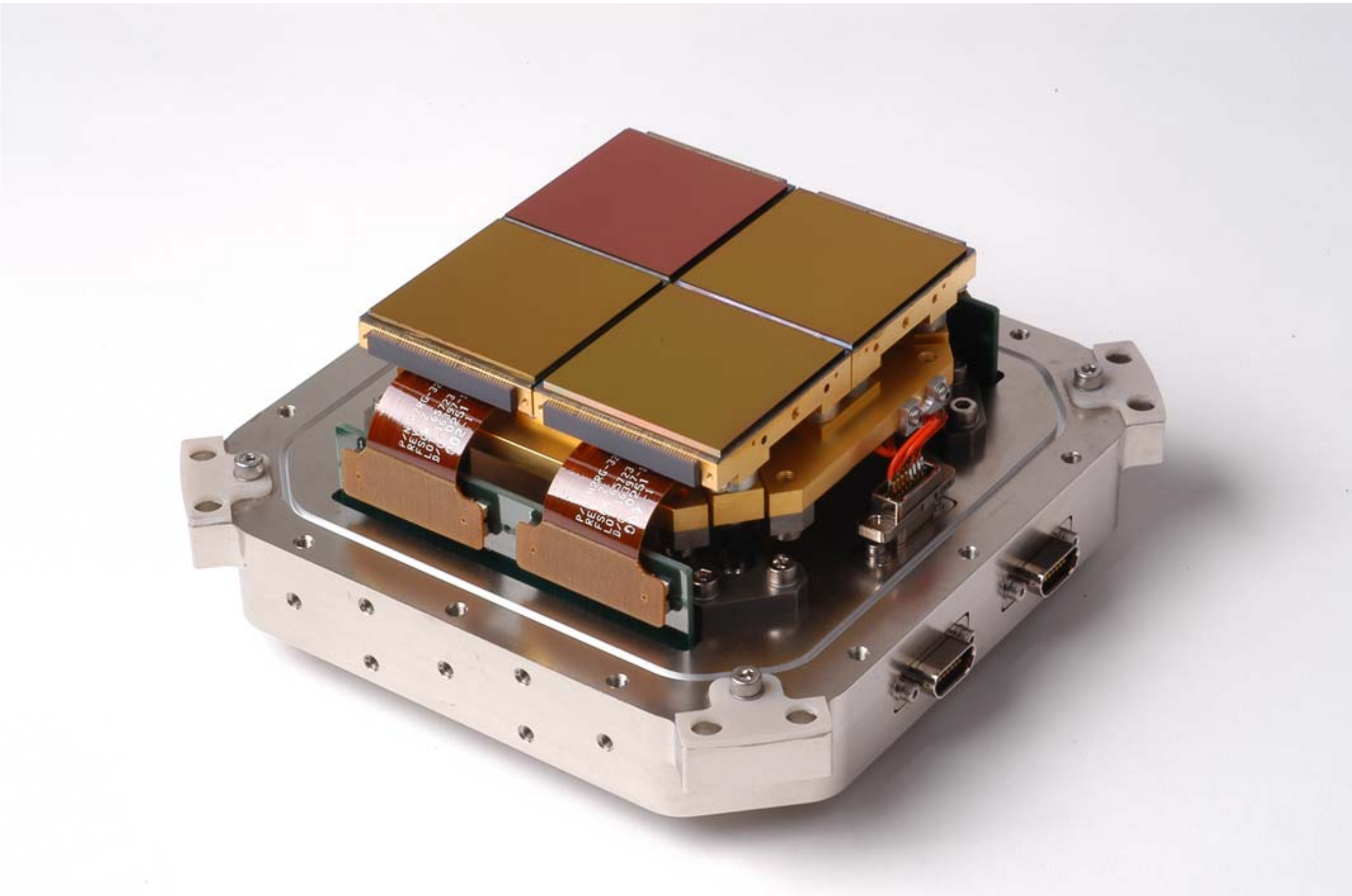

HAWAII-2
13M FETs, 0.8 um CMOS
LPE on sapphire

HAWAII-2RG
25M FETs, 0.25 um CMOS
MBE on CdZnTe

What do all the extra transistors do ?

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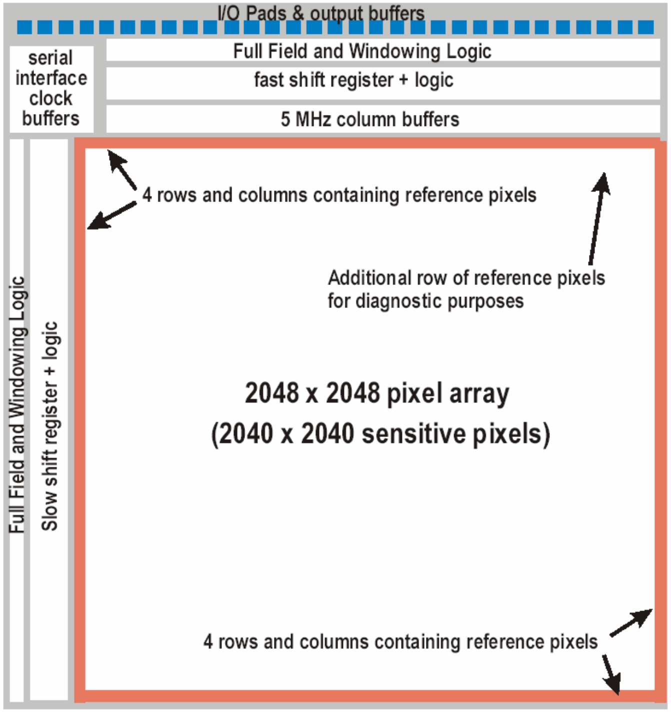
HAWAII-2RG

Number of outputs	Frame time in astronomy (slow) mode (100 kHz)	Frame time in imaging (fast) mode (5MHz)
1	42 s	840 ms
4	NGST: 10.5 s	210 ms
32	1.3 s	26 ms (320 Mbytes/s)

- Easy interface to new SideCar ASIC – no controller required !!!
- Internal gain selection from 1 to 16, step size of x 1
- Forward and reverse scan directions to allow corner to centre scanning
- Pixel by pixel, line by line and global reset options
- Very low power
- On chip temperature sensors

HAWAII-2RG characteristics

R is for Reference pixels



Two types of reference pixels:-

– Separate reference output for permanent tracking of signal drift and system noise.

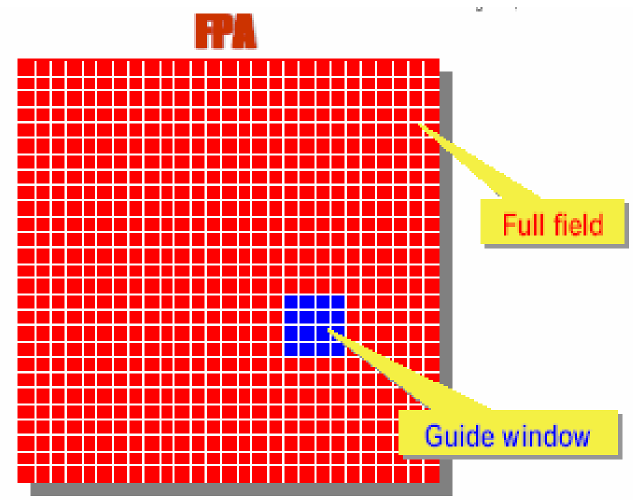
– Four rows/columns of reference pixels on each side of the array

G for Guide mode

•Random Access to any windowed region on chip (programmable)

•Separate guide output or interleaved with other 32 outputs

•Single pixel or window reset possible



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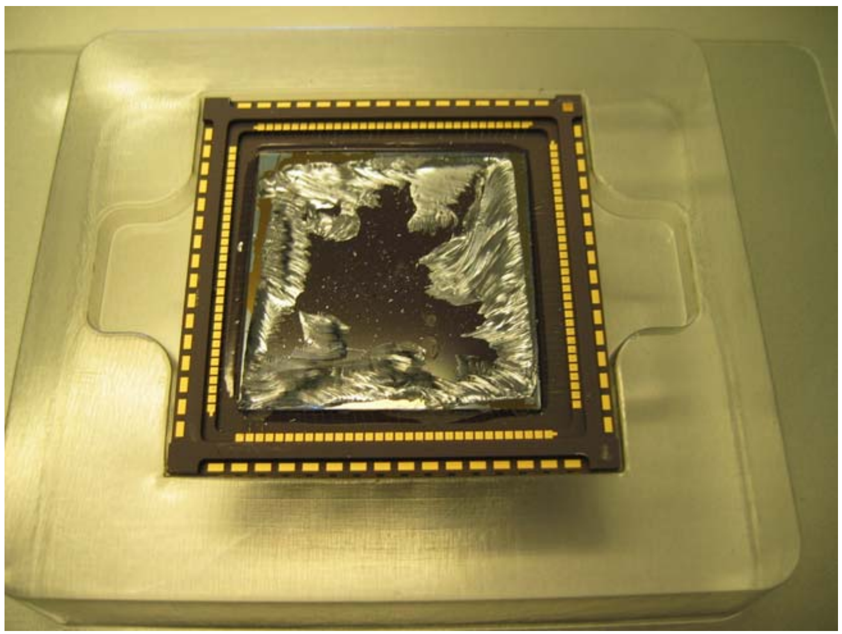
Problems and Issues with present detector technology

Hybridised Materials causes problems :-

Thermal mismatch between materials can cause catastrophic failure !!!

•Use Balanced Complex Structure to bend one material to another
•Use Silicon instead of CdZnTe but high number of dislocations
•Slow cooling rates (< 1K/s)
•Multiple thermal cycling before delivery (>10 cycles)



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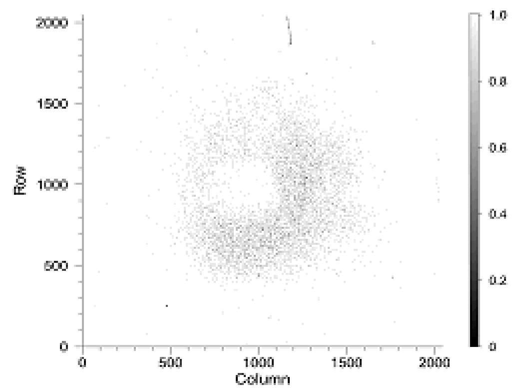
However VIRGO detectors seem very robust :-

Cooling rate ~ 5k/minute

Pass/Fail Information	Baseline 5 TCs		Post 15 TCs		Post 55 TCs		Post 105 TCs		Change from Previous Results
Spec Lo	0.20		0.20		0.20		0.2		
Spec Hi	1.50		1.50		1.50		1.5		
#Pixels Passing	4143759	98.79%	4148240	98.90%	4148029	98.90%	4147727	98.89%	-302
#Pixels Lo	50071	1.19%	45336	1.08%	45112	1.08%	45524	1.09%	412
#Pixels Hi	474	0.01%	728	0.02%	1163	0.03%	1053	0.03%	-110
#Pixels Masked	0	0.00%	0	0.00%	0	0.00%	0	0.00%	
#Pixels Total	4194304	100.00%	4194304	100.00%	4194304	100.00%	4194304	100.00%	

Opens in center preexisted (Undersqueezed Hybrid).
Module 28 very stable during Thermal Cycle.
Changes are statisically insignicant.
No corner outages.

Pass/Fail Information	After vacuum leak of chamber. Post 115 TCs		Post 205 TCs		Back to normal Post 305 TCs	
Spec Lo	0.20		0.20		0.20	
Spec Hi	1.50		1.50		1.50	
#Pixels Passing	4144484	98.81%	4189543	99.89%	4146261	98.85%
#Pixels Lo	49173	1.17%	4586	0.11%	47317	1.13%
#Pixels Hi	647	0.02%	175	0.00%	726	0.02%
#Pixels Masked	0	0.00%	0	0.00%	0	0.00%
#Pixels Total	4194304	100.00%	4194304	100.00%	4194304	100.00%



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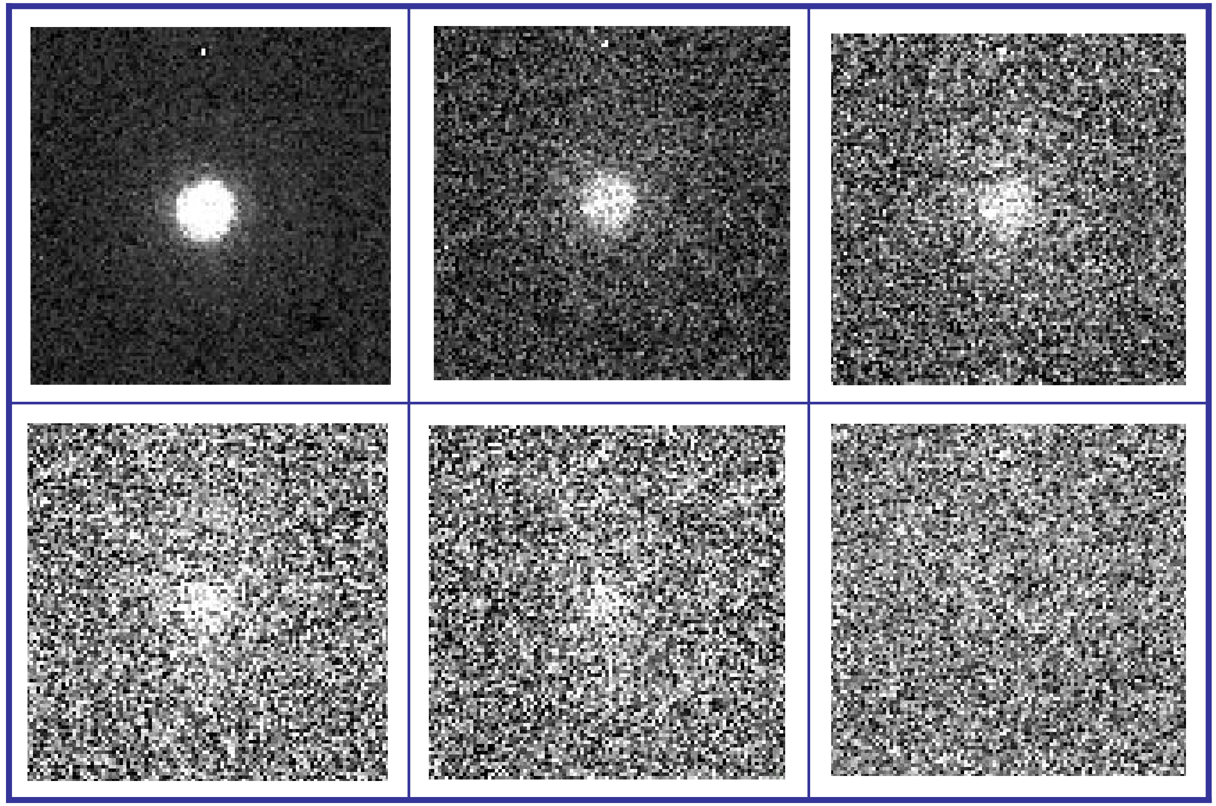
Persistence problems – Long time constants ?

Test :

- 200ke fluence
  - 10sec exposure
- Cold blank
- 10s dark integrations

- For fluence levels below the saturation, persistence is negligible. As soon as the fluence exceeds the saturation level, persistence can be observed.
- This threshold effect may indicate that traps in the surface passivation layer are filled when the p-n junction moves from reverse bias toward forward bias.

Persistence testing in VIRGO detectors



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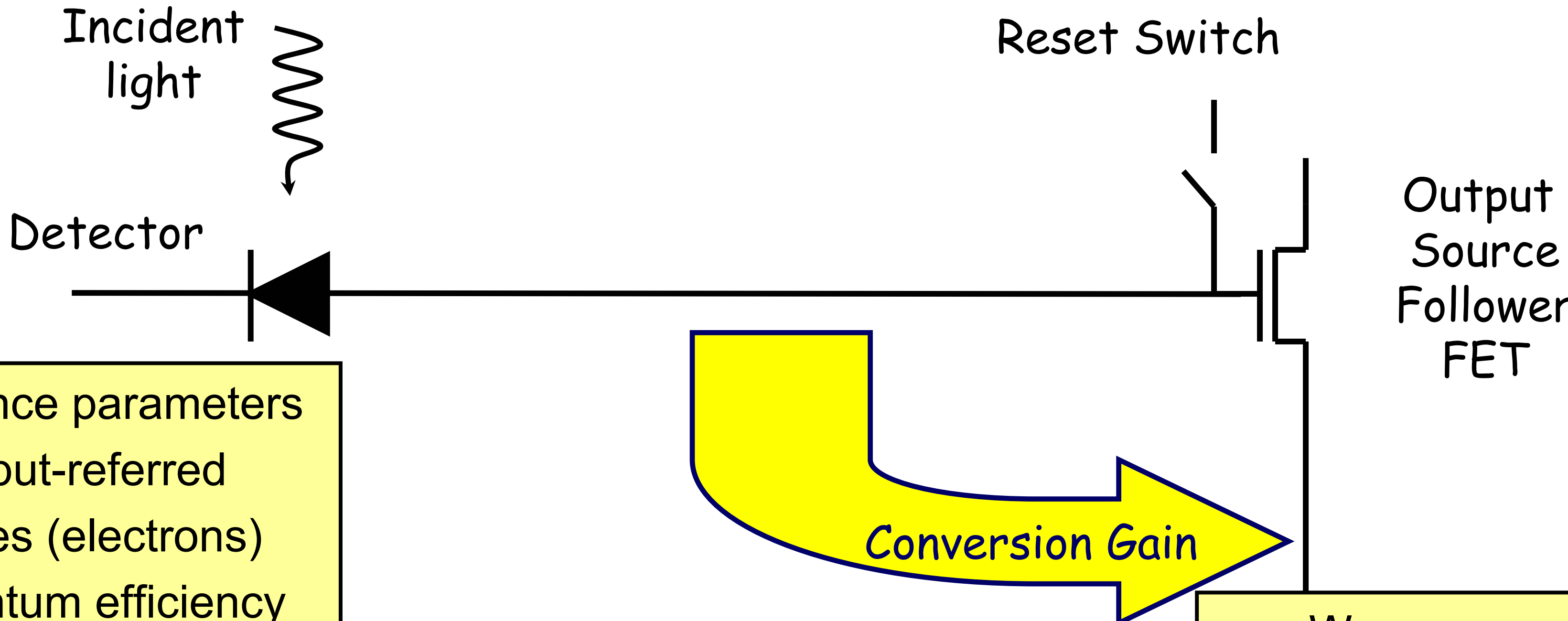
Conversion Gain Measurements (e/ADU) – are they correct ?



Performance parameters are input-referred quantities (electrons)

- Quantum efficiency
- Dark current (e- / s)
- Noise (e- rms)

We measure output-referred quantity (volts)

Conversion gain
= electron charge / capacitance, **V = Q / C**
expressed as microvolts per electron

Include with controller and ADC transfer function to give e/ADU

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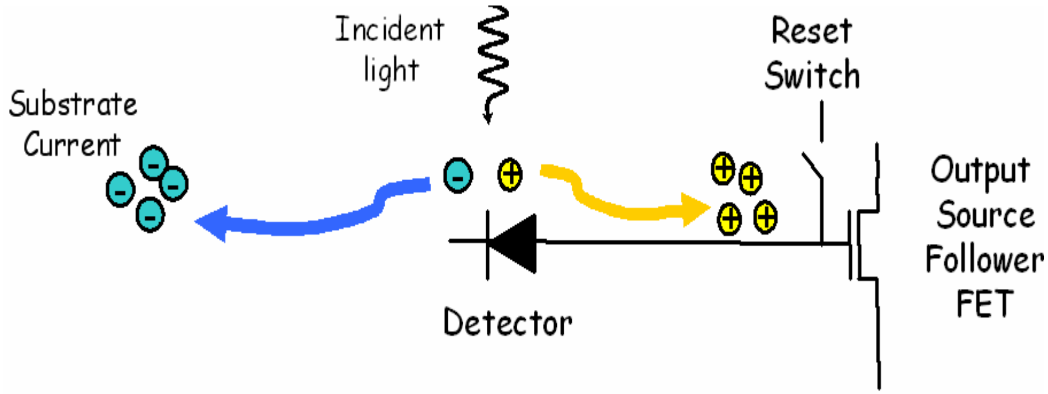
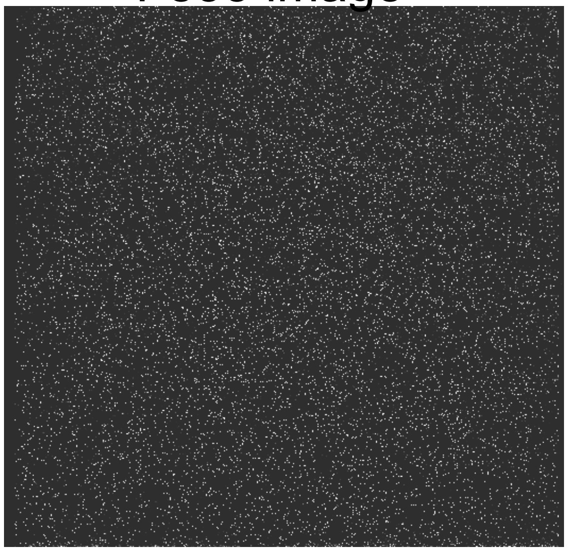
Three ways to measure conversion gain



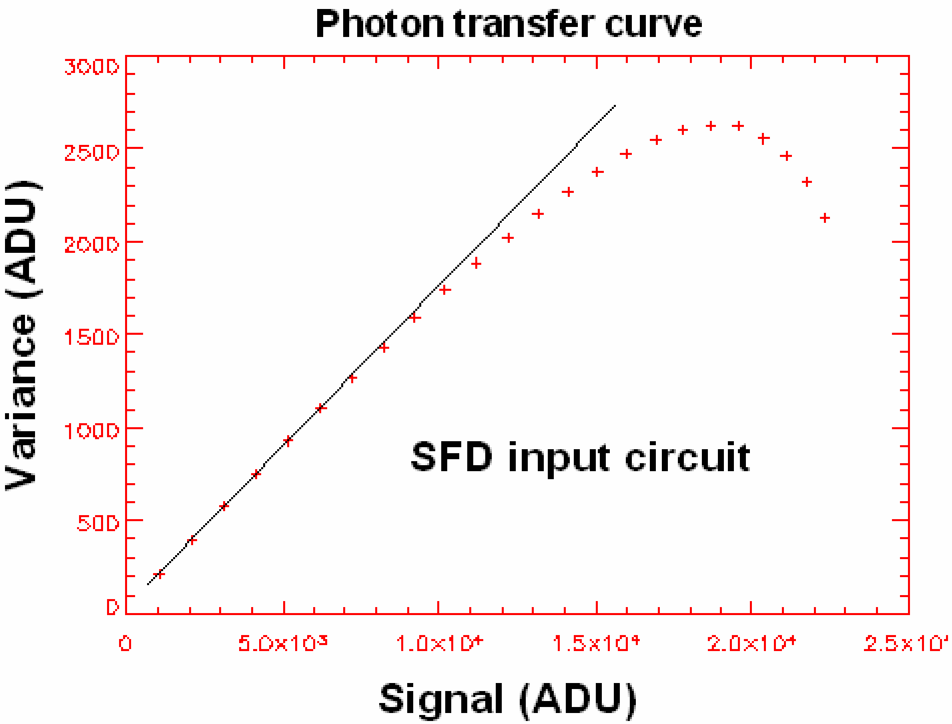
Can measure substrate or reset current to know how many electrons on gate.
Divide by voltage change at FET output to get electrons per millivolt.

Fe55 image



1620 e produced to give a direct measure of e/ADU

Vary light level over portion of dynamic range
Plot signal variance vs. signal mean
Slope of variance vs. mean gives the conversion gain



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Inter-pixel Capacitance Issues

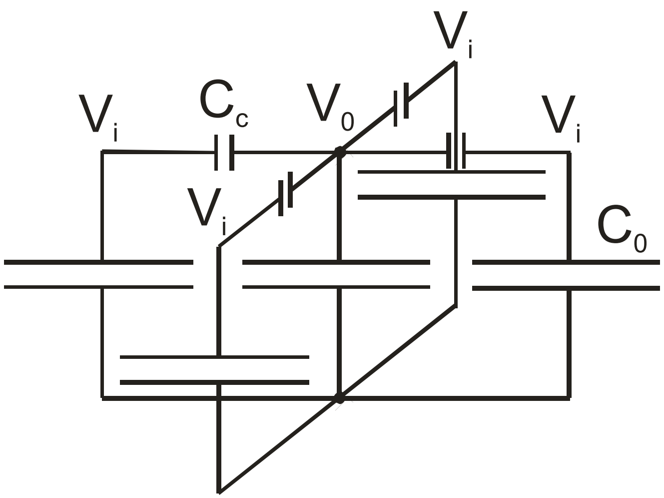
Signs of problems:

> 100% quantum efficiency

Cosmic ray crosstalk in 18-20 µm pixels

Fe55/Direct current and Signal/Noise conversion gain measurement differ

V = Q / C



C_0=pixel capacitance
C_c=coupling capacitance
$x=C_c/C_0$

then, the apparent capacitance C_A is given by :- $C_A=C_0(5x+1)/(x+1)$

Implications :-

•Dampens photon shot noise, =>Gain measured as Signal/Noise needs correction (5x+1)/(x+1) (thus QE, Noise, dark current rate)

•Reduced image contrast

•Degraded detector MTF

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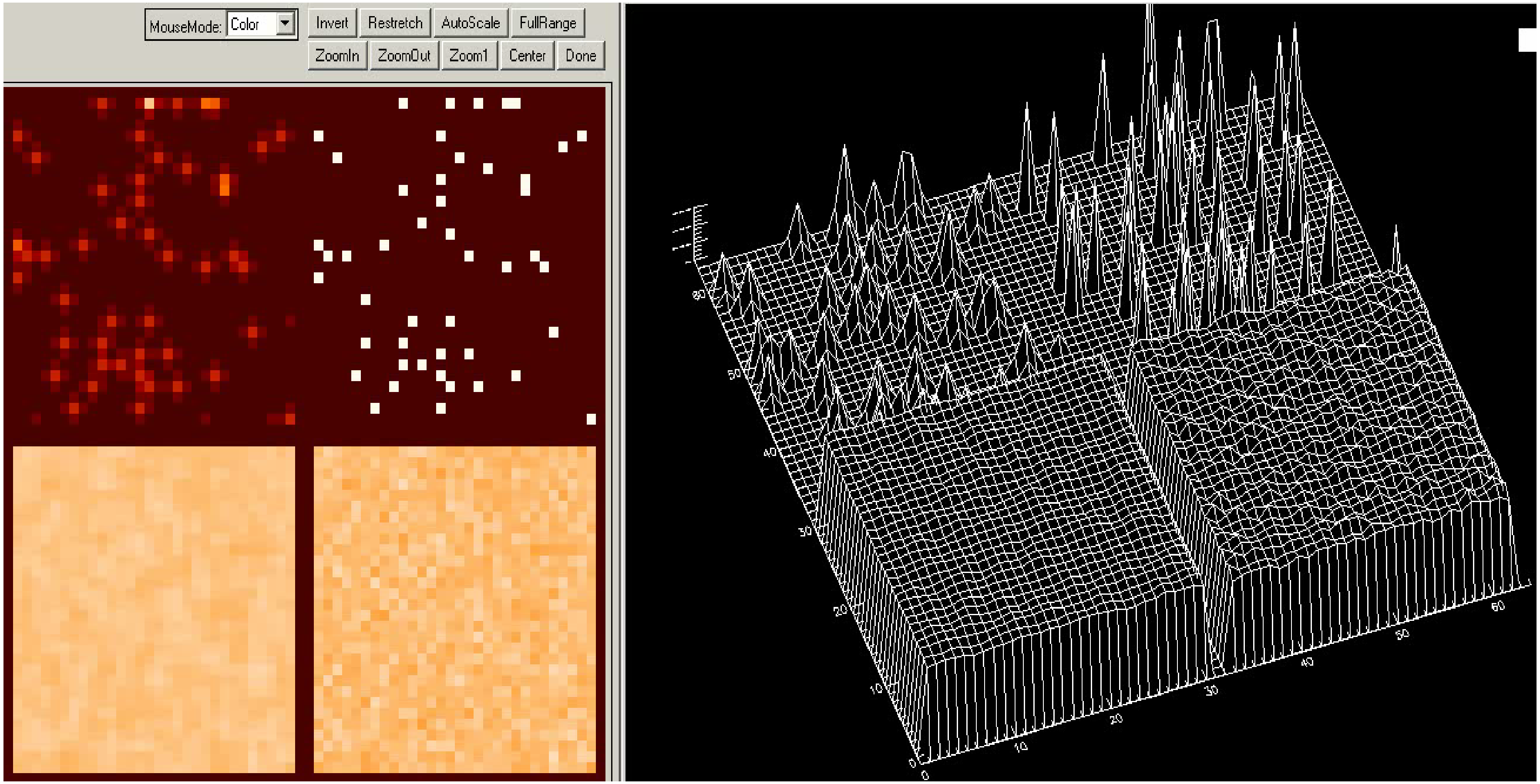
Interpixel capacitive coupling – IDL simulation

snapshot:
single
photons

integrated
Image:



coupling no coupling

Low noise Higher Noise

(IDL code supplied by G. Finger, ESO)

Same signal level

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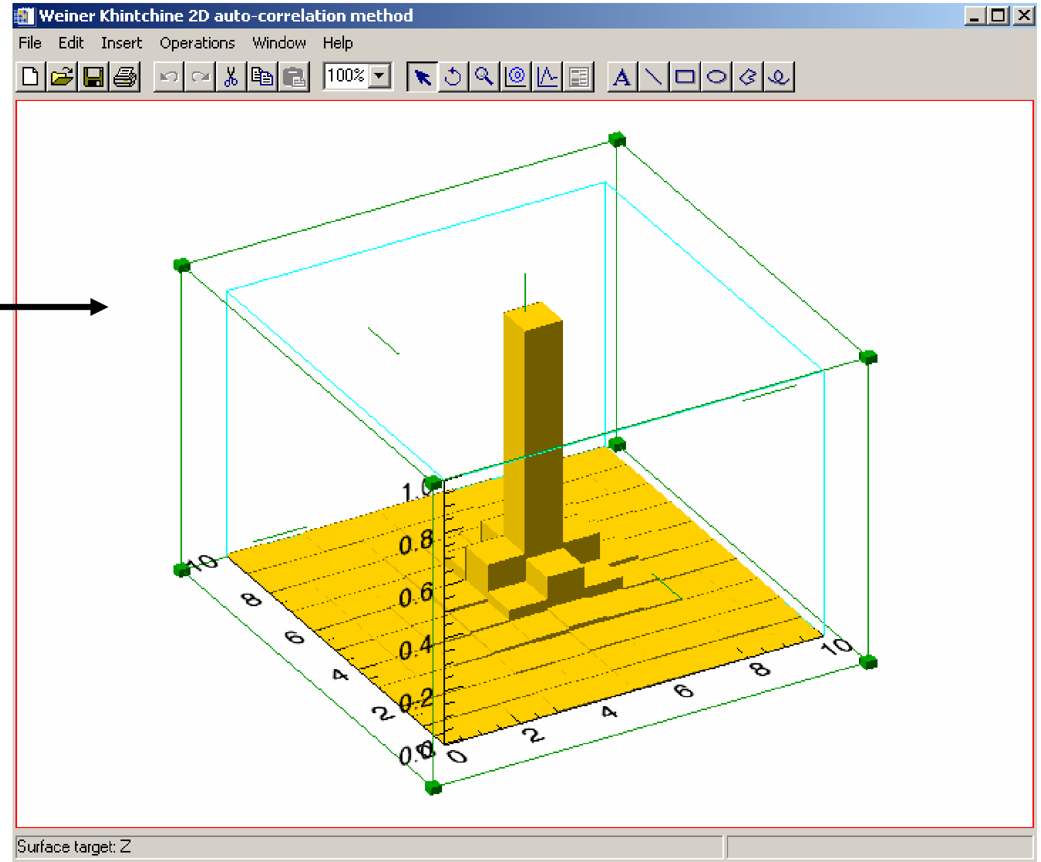
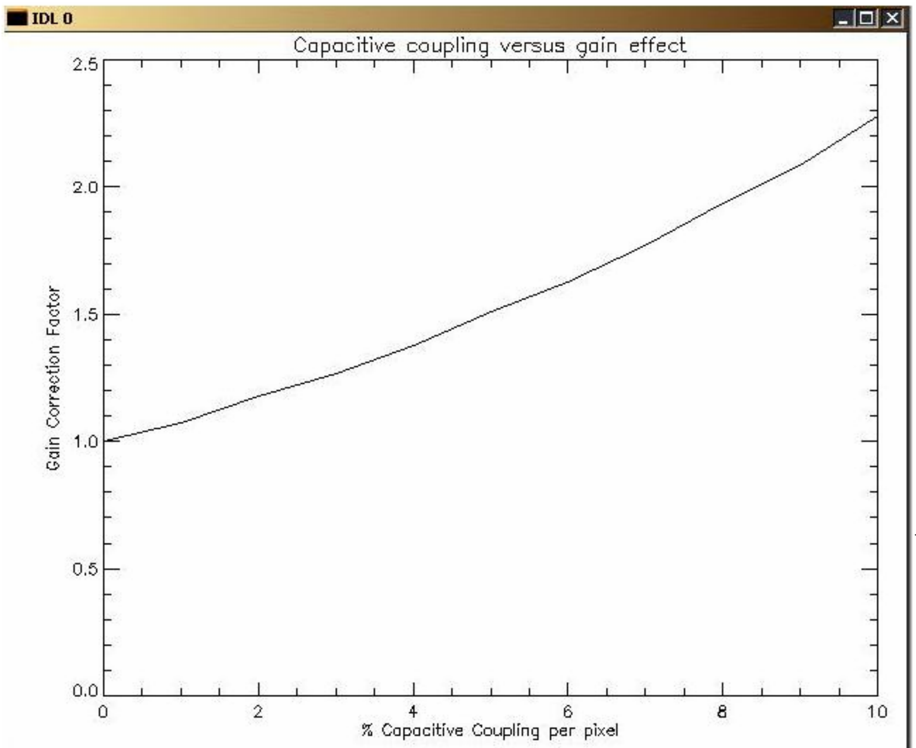
Modelled effect of inter pixel capacitive coupling on calculated transimpedance

Stochastic method based on 2D autocorrelation

– results given for HyViSi detector
14% for nearest pixels
5% for corner pixels
1% for 2 pixels away !





Capacitive coupling versus Noise

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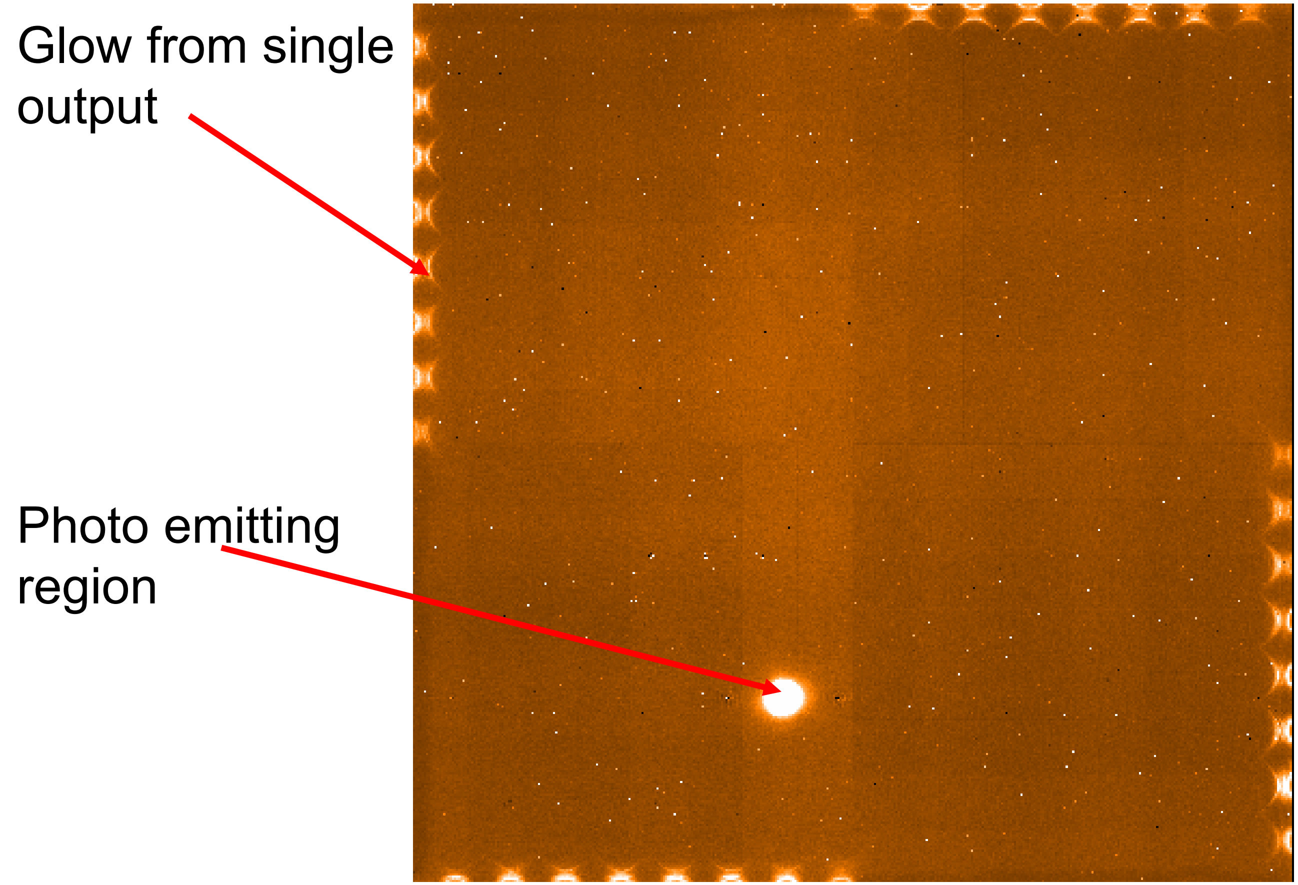
Inter-pixel Capacitance – what is the impact ?

Capacitive crosstalk of 1% to each neighbouring pixel will attenuate noise amplitude by 4% and result in an 8% error in the measurement of noise power (variance) and thus in noise-squared versus signal resulting in at least 8% more observing time to achieve the expected signal to noise ratio.

Device	Type	Correction Factor
Rockwell HyViSi	2kx2k, 18 um hybridised Si PIN diodes to HAWAII-2 MUX	2.1 => 50% QE drop from advertised values
Rockwell HAWAII-2 and HAWAII-2RG	2kx2k, 18 um hybridised MCT diodes to HAWAII-2 MUX	1.2=>measured QE of 80% drops to 67%
RVS VIRGO	2kx2k,20um hybridised MCT diodes	1.04
RVS ALADDIN III	1kx1k, 27 um hybridised InSb diodes	1.20

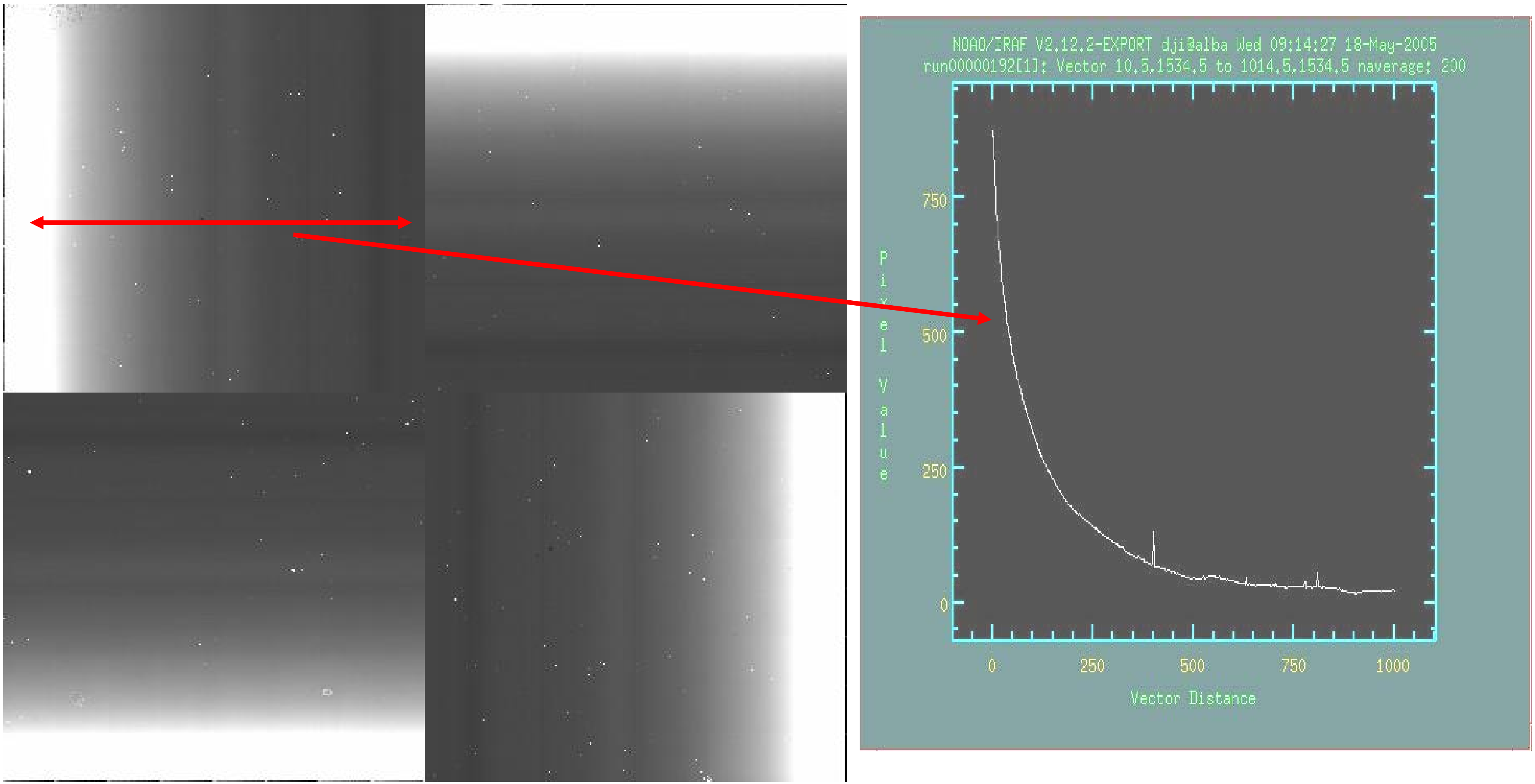
Electro-luminescence of HAWAII-2 with 32 channel output modes



Multiple sampling reduces readout noise until limit reached by shot noise from Electro-luminescence.

Newer detectors such as the HAWAII-2RG has shielding implemented on chip to eliminate glow.

CDS Bias Frame – Reset Anomaly Issues in HAWAII-2 detectors



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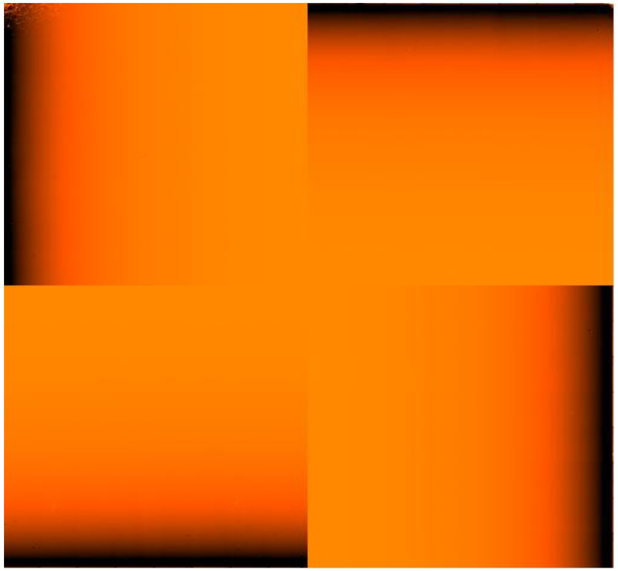
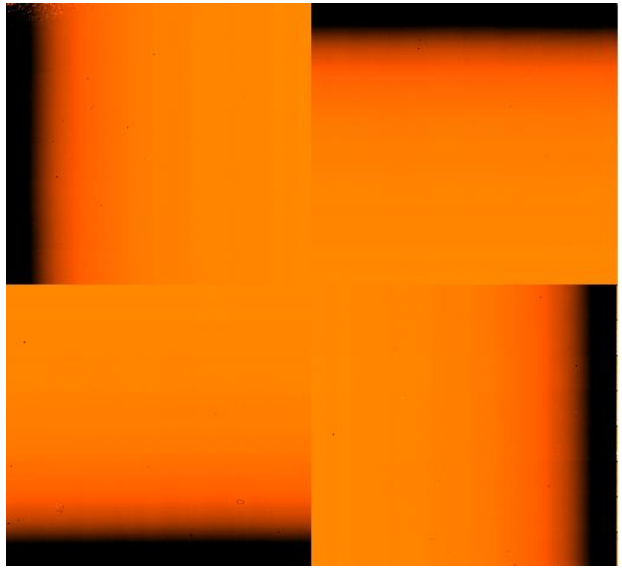
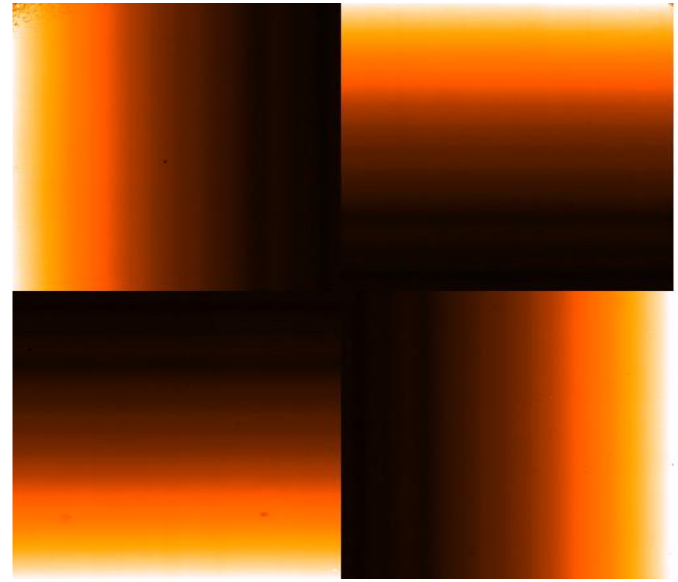
More Importantly – Stability Issues for Flat Fielding



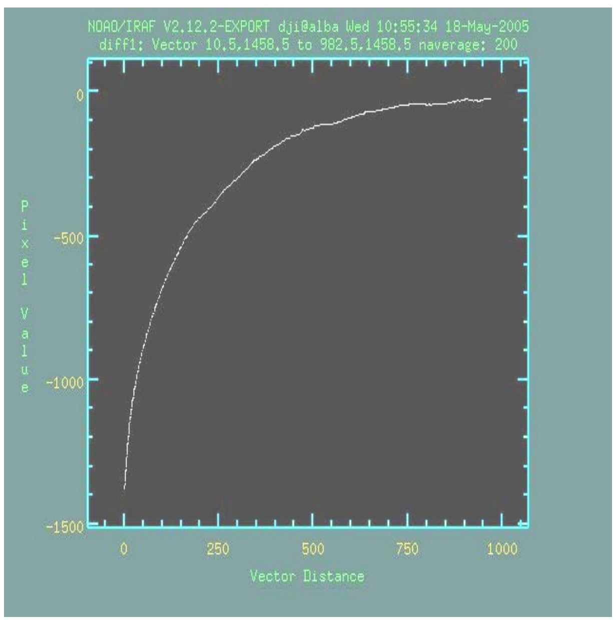
CDS2 – CDS1

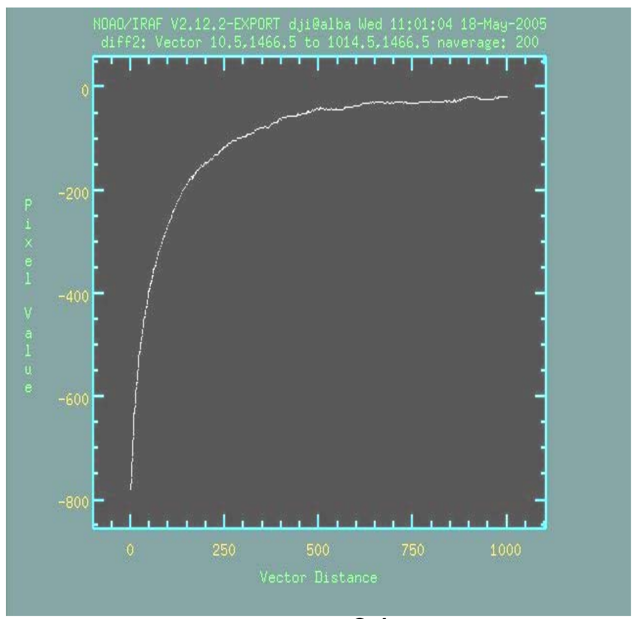


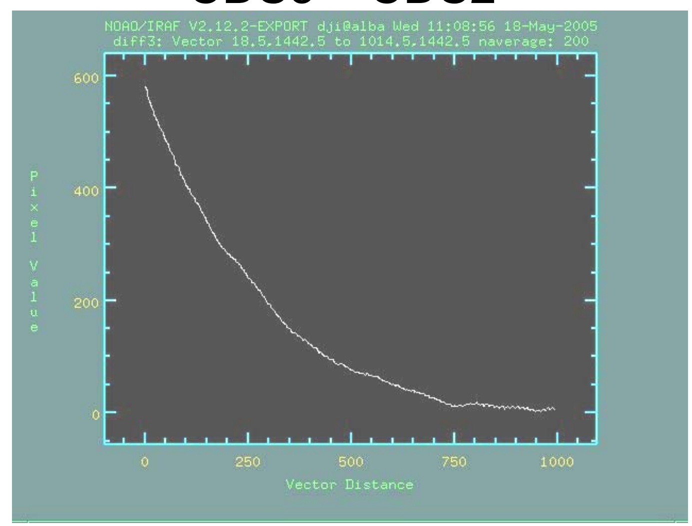
CDS3 – CDS1



CDS3 – CDS2







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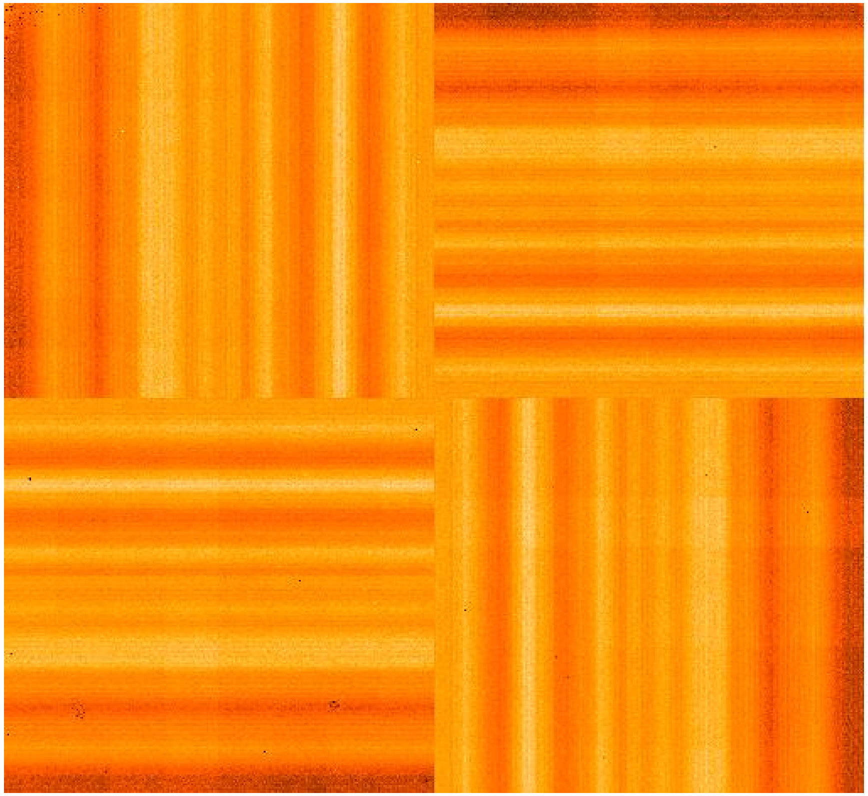
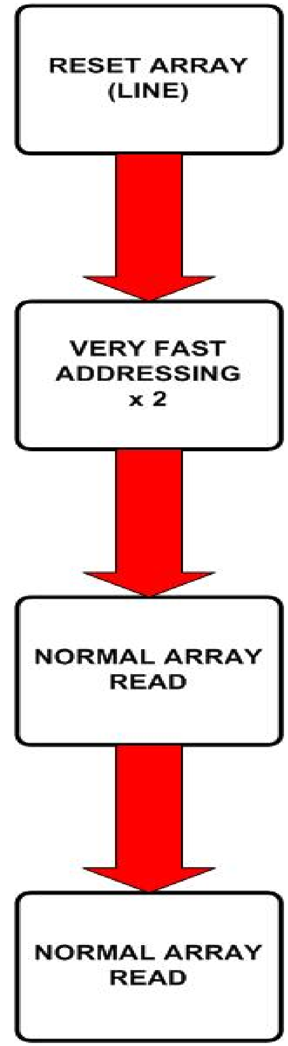
More Importantly – Flat Field Stability



CDS2 – CDS1 = CDS3 - CDS2 etc.

- Now Stable Flat Fielding
- Low Frequency Banding now seen
- Solution – fast “throw away” reads after reset

Reset Stabilisation Algorithm



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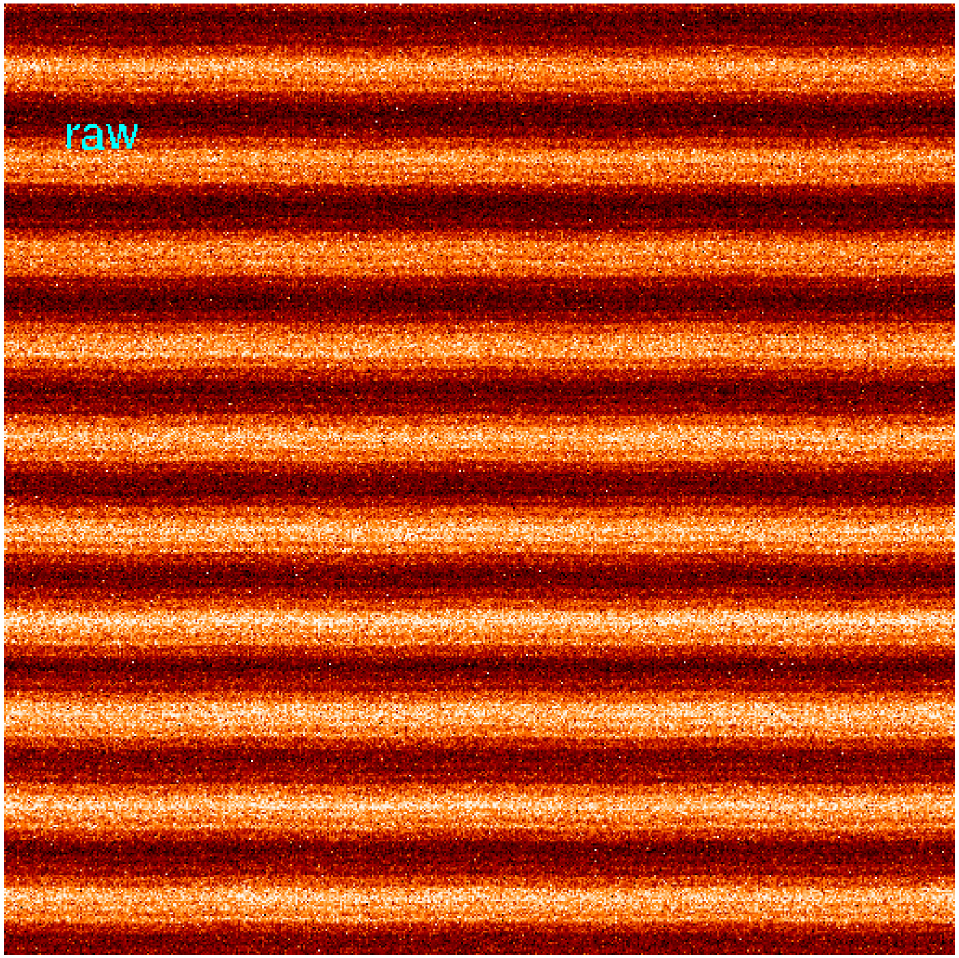
low frequency noise suppression with embedded reference pixels

-better solution are real reference
Rows and columns as per HAWAII-2RG



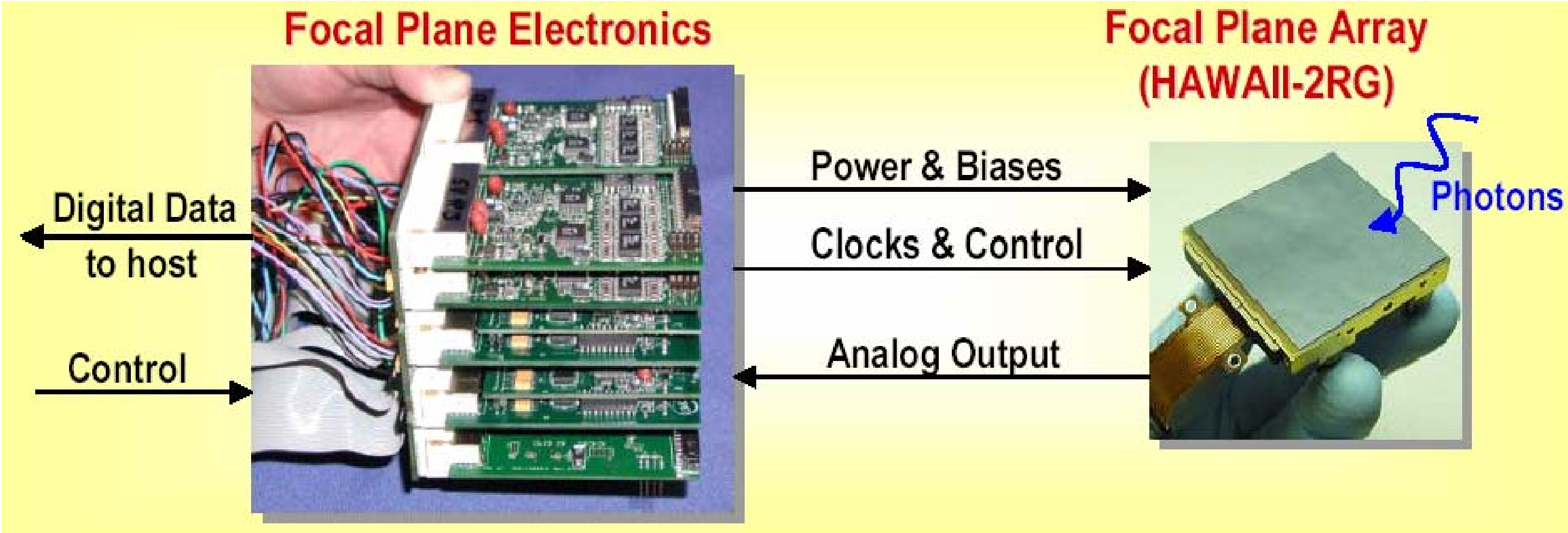
- Integration time 1.01 s
- high frequency stripes in direction of fast shift register are 50 Hz pickup, low frequency are 10 Hz
- Noise 45 erms
- For each row subtract average of 8 embedded reference pixels on right and left edge of the array
- With 32 channels reference pixels are read twice every 420 μs
- Noise 24 erms
- Linear interpolation of reference for each pixel using reference pixels of row and reference of subsequent row

- (data from G. Finger, ESO)

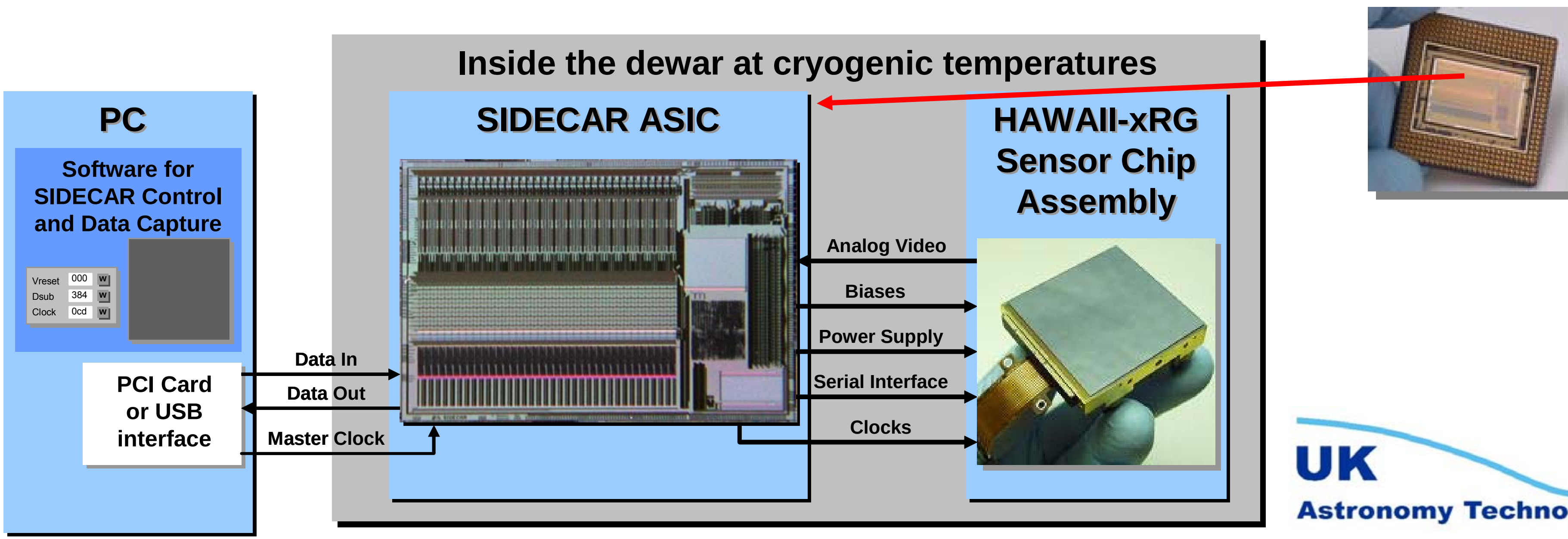
And the future ?

- IR Camera systems on a chip
- Size/Cost Considerations
- New technology

Replace all the camera controller electronics with….



Single chip ASIC solution



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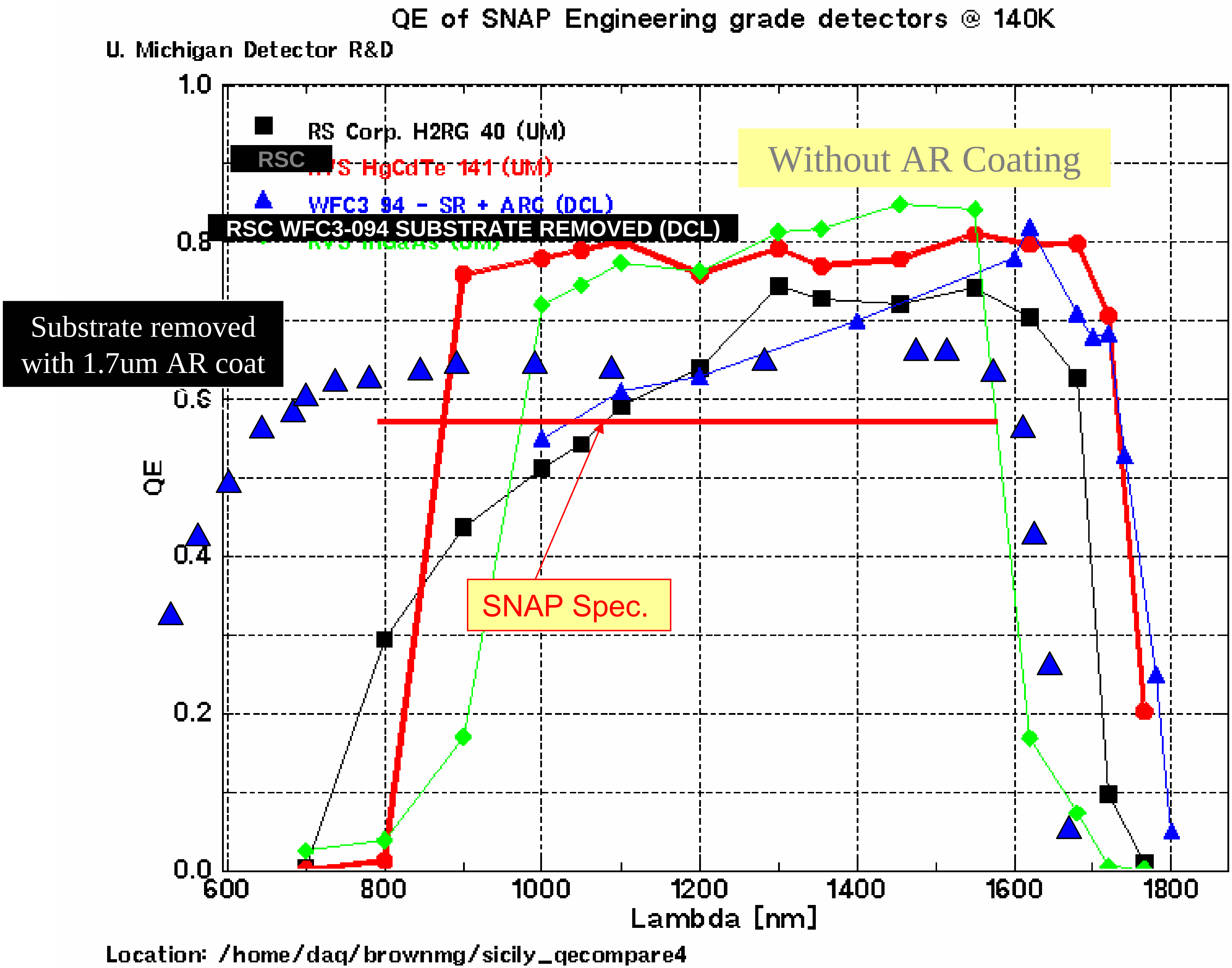
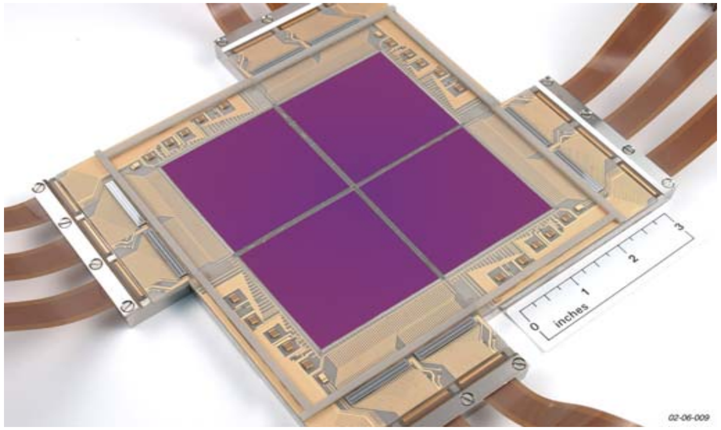
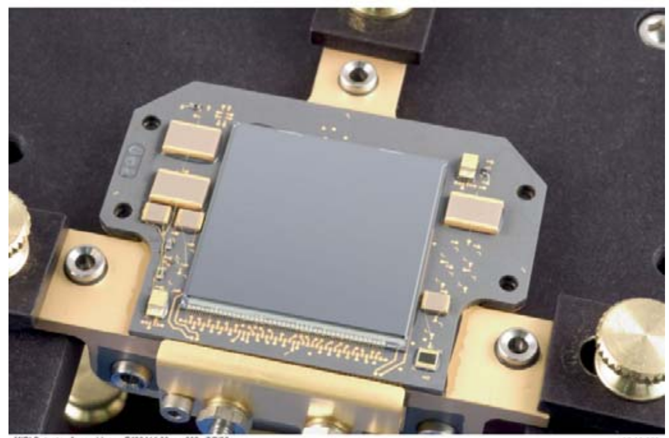

QE of SNAP Engineering grade detectors @ 140K
U. Michigan Detector R&D
RS Corp. H2RG 40 (UM)
RSC
HgCdTe 141 (UM)
WFC3 94 - SR + ARC (DCL)
RSC WFC3-094 SUBSTRATE REMOVED (DCL)
Without AR Coating
Substrate removed
with 1.7um AR coat
SNAP Spec.
QE
1.0
0.8
0.6
0.4
0.2
0.0
600
800
1000
1200
1400
1600
1800
Lambda [nm]
Location: /home/daq/brownmg/sicily_qecompare4

Other detector types available



1. Raytheon ORION
2. 2048 x 2048 25 um pixels
3. 0.6 – 5 um InSb device
4. 10 frames/s
5. 2 edge Buttable
6. < 25 e noise
7. 30K operation

1. Raytheon SB305
2. 1k x 1k, 25 um pixels
3. 3 um – 28 um Si:As device
4. Low background/1 Hz
5. 3 edge Buttable
6. Low noise
7. 7K operation



MIRI Detector Assembly, pn E423414.00, sn 002 - 7/7/05 05-06-252

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Size and Cost Considerations in the ELT Era

•Detector/Camera system on a chip is a necessity

•***CCD pixel ~ $0.01***

=> Need to bring cost down significantly

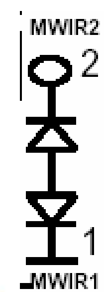
•***IR FPA pixel ~ $0.12***

(100s of detectors required per ELT instrument to match pixel scale/FOV)

•Reliance on USA manufacturers, no European company making such large arrays

•Smaller pixels but larger number e.g. 4k x 4k, 9um HAWAII-2RG device

Silicon Substrates (rather than CdZnTe) – reduced manufacturing costs and thermal issues - leading to direct growth of HgCdTe on Si via buffer layer (ELT ?)



•For differential Imaging/Exoplanet searches - in 2 wavebands, rather than 2 optical trains

•IR+CCD avalanche gain structures for <1e noise

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Acknowledgements :-

- Rockwell Scientific, Thousand Oaks, California
- Raytheon Vision Systems, Santa Barbara, California
- ESO, Garching
- Scientific Detectors Workshop, Taormina, Sicily, 2005