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# Milestone-7: EMCCD Status

## WFIRST Coronagraph Stanford Meeting n. 9

**2016–08-09**

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# EK-7 Detector Milestone

## 2.3.7 Key Milestone 7

**Spectrograph detector and read-out electronics is demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.**

**Significance**: A spectrograph sensor with sufficiently low read noise and dark current has been identified as one of the technology gaps for the coronagraph instrument. Passing Milestone 7 will demonstrate that [illegible] and both sensor and read-out electronics that posse[illegible] onagraph science requirements have been identified a[illegible]

**Detector milestone was based on EMCCD performance**

**Verification Method:** Samples of the sensor selected for the IFS are operated using flight-like electronics and tested under dark and imaging conditions. The dark tests provide all the sensor-specific noise levels. If the sensor is an EMCCD (currently considered the likely choice) the test will include read noise, dark current, and clock induced charge. Charge transfer efficiency will be measured using spot images at various locations on the sensor. The tests will be done before and after irradiation with the appropriate fluence of protons to mimic the on-orbit conditions.

**Testing Completed late 2015**

Excerpted from *WFIRST-AFTA CGI Technology Development Plan*

JPL Doc D-81964, 17 March 2014

# IFS Detector Status Summary

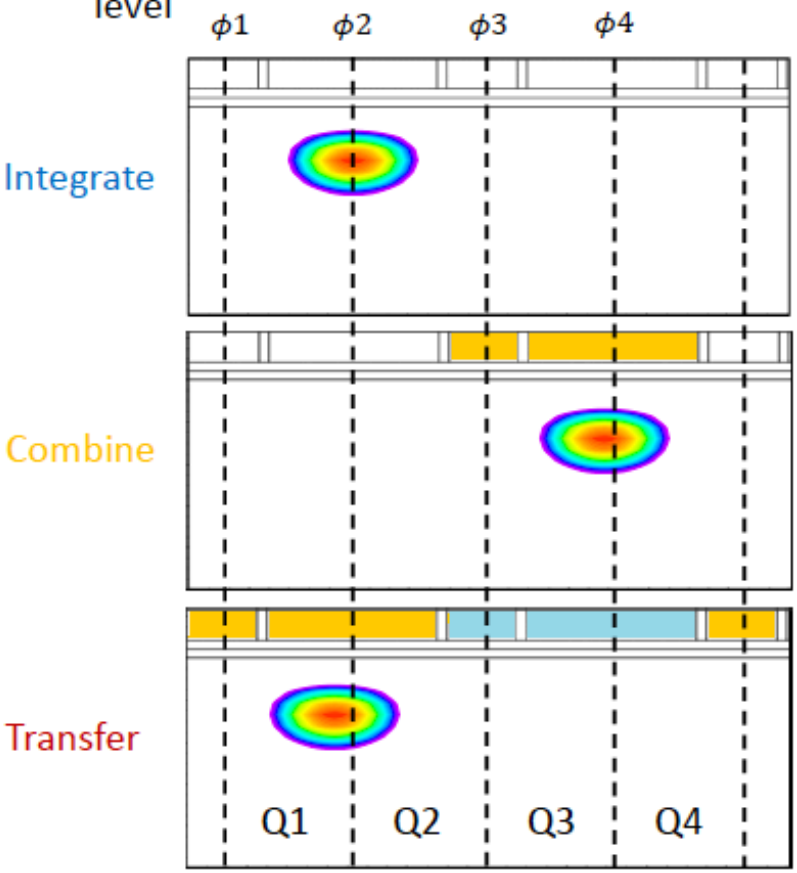
- **Low flux PSF measurements have demonstrated detection as low as 0.05 e-/sec/PSF**
  - Where PSF core size is 2×2 pixels
  - Reasonable simulation of flight EMCCD frame
    - Neglect exo-zodi
    - Brightest RV planet (HD62509, V = 1.15 mag)
    - Perfect speckle subtraction
    - No read noise, i.e. photon counting
    - Dark current = $5\times10^{-4}$ e-/pix/sec
    - CIC = $5\times10^{-3}$ e/pix/frame

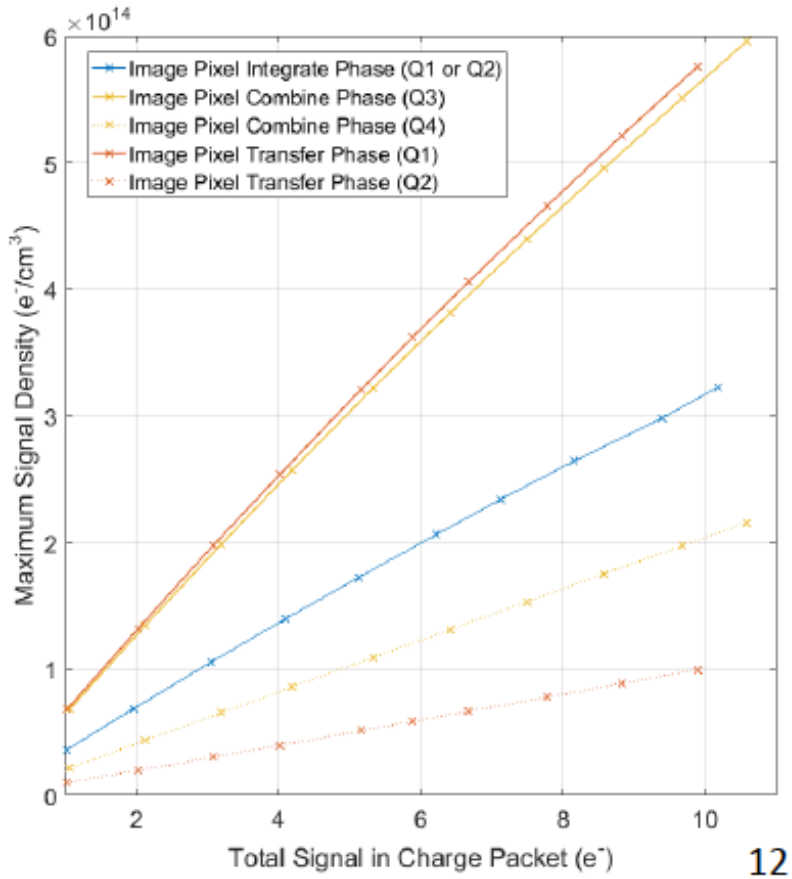
- **Trap-defect model of image IFS image degradation in same regime as measurement**
  - TCAD produced 3D charge packet density profiles for each charge transfer step in both image pixels and serial register pixels
  - Incorporation of final inputs from the Silvaco TCAD model are in progress

# Charge densities from TCAD

## Image Pixel Results

- Peak densities in each quadrant behave as expected as a function of the total signal level

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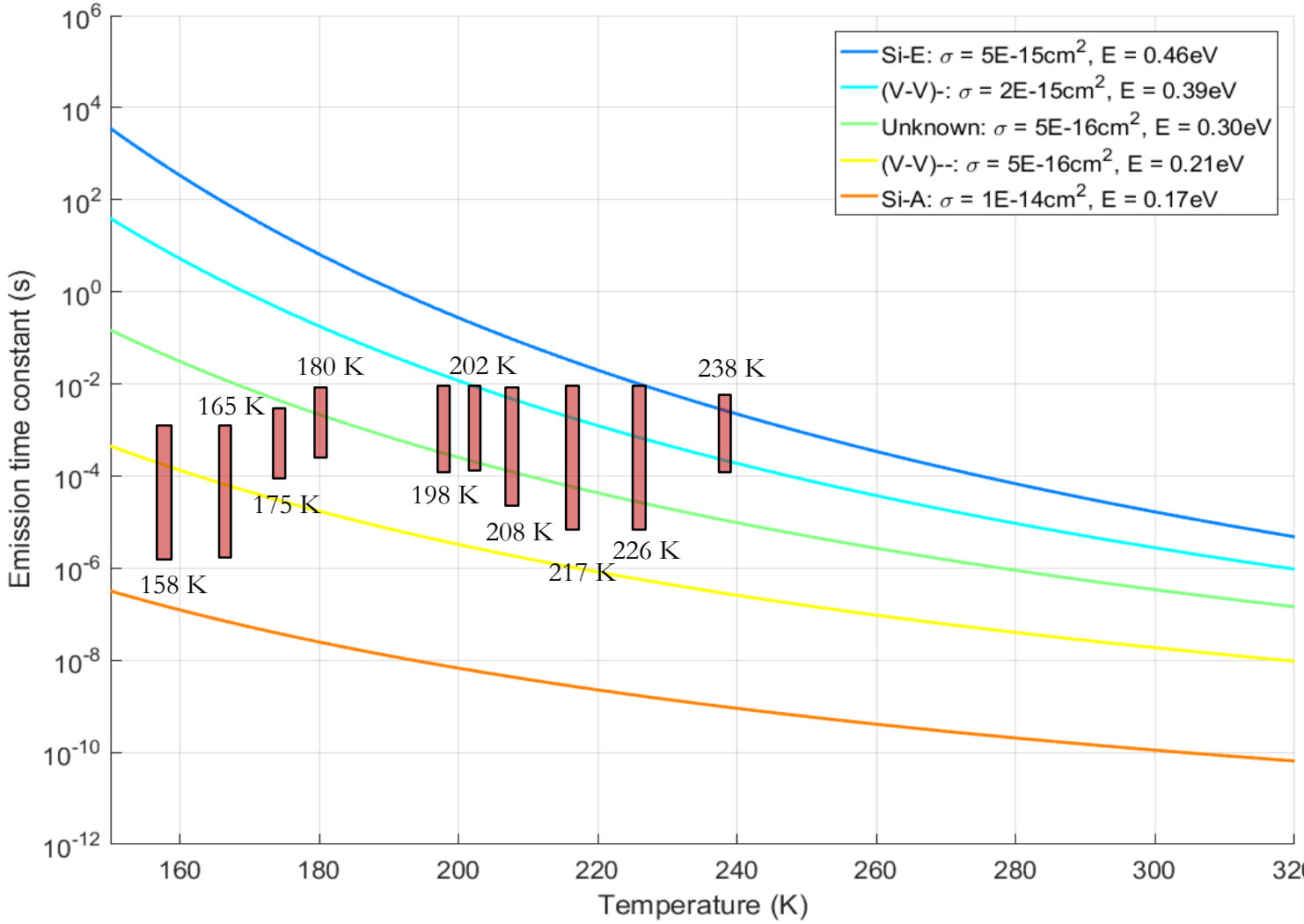
# Trap parameter space measured

Plot shows parameter space probed overlaid on diagram of trap emission time constants as a function of temperature (literature values)



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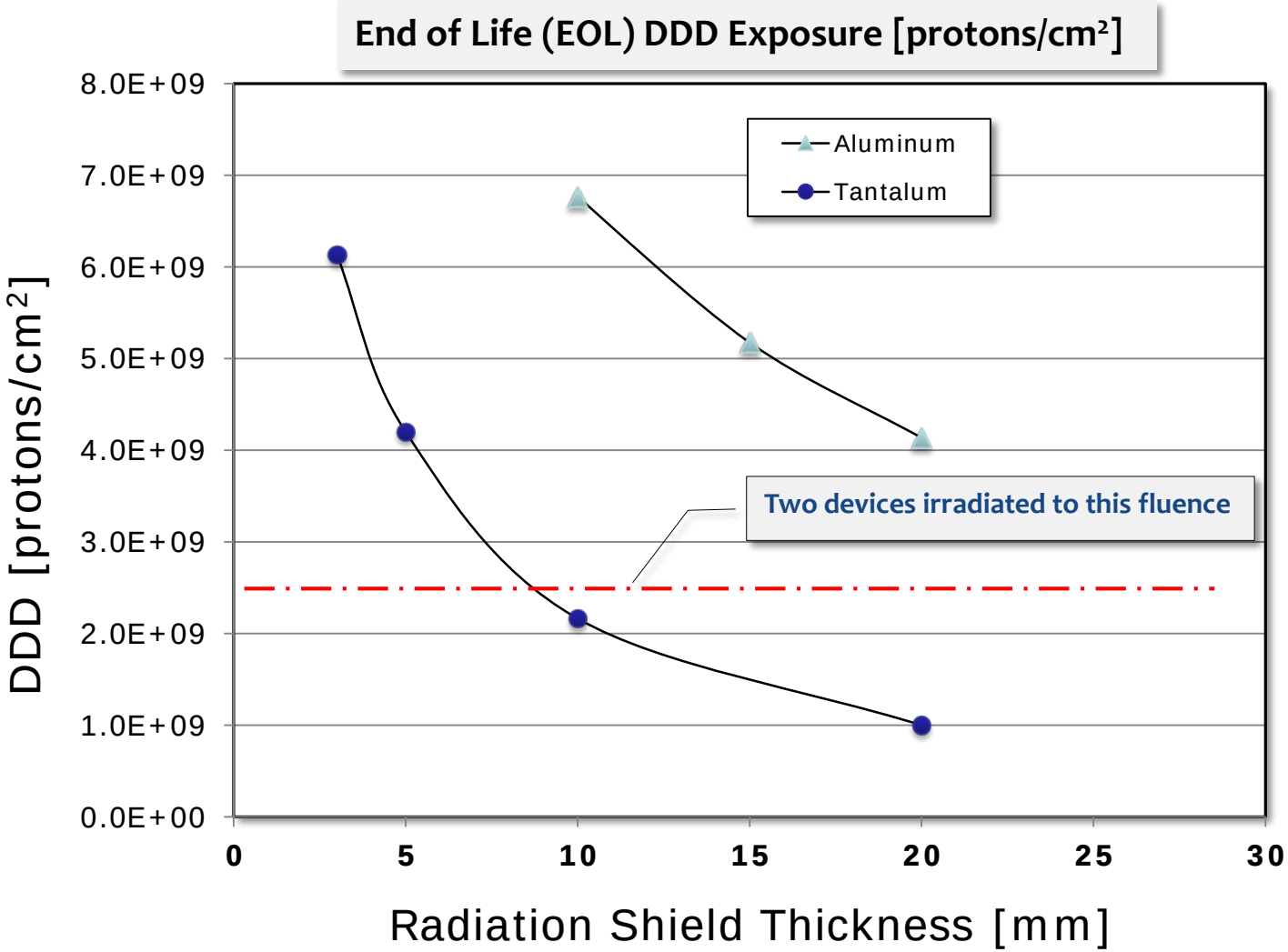
# Limits of shielding




Data from analysis by Michael Cherng

*JPL Internal Memo 5132-15-015*, 18 March 2015

# Pre-Phase A IFS Detector Requirements

## How the current set of detector requirements were developed

- Pre-Phase A detector L4 requirements are based on a combination of technology capability and CGI/IFS requirements from the Science Definition Team (SDT).
- A CGI/detector science yield model was used to validate detector capability-driven requirements
  - Science yield model is a full end-to-end model of the coronagraph instrument with CGI/adaptive optics front end and IFS + detector backend (assumed IFS requirements)
  - Ran model to compare the planet characterization yield of several detector technologies – EMCCD yield exceeded all others
  - This model was used to predict science yield using best known EMCCD performance
- All pre-Phase A work was focused on the EMCCD
  - Capability driven requirements:
    - Dark current
    - Clock Induced Charge
    - (effective) Read Noise
    - Quantum Efficiency
    - pixel pitch, array format
  - Capability (except QE) has been verified in a commercial camera – NüVü EMN-2 Camera
- The test-bed IFS (PISCES) design assumed the e2V EMCCD

# Key & Driving Requirements

- Phase A Level 2b IFS requirements may have impact on our August EK-7 milestone
- Desirable to relax requirement on lenslet sampling of PSF core

**Key Requirements Impacting detector**

- SNR – assumed 5 but >10 may be needed for IFS?
  - Example: SNR = 5, each 18% band requires ~ observation time
- Spectral resolution – currently 70
  - Can R and SNR be traded?
- Spectral bands – currently three bands centered at 660, 770, 890nm
- Spectral band width – currently 18%

# Low Flux Detection

Leon Harding

Jet Propulsion Laboratory
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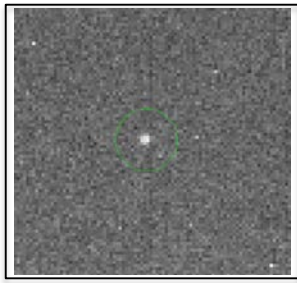
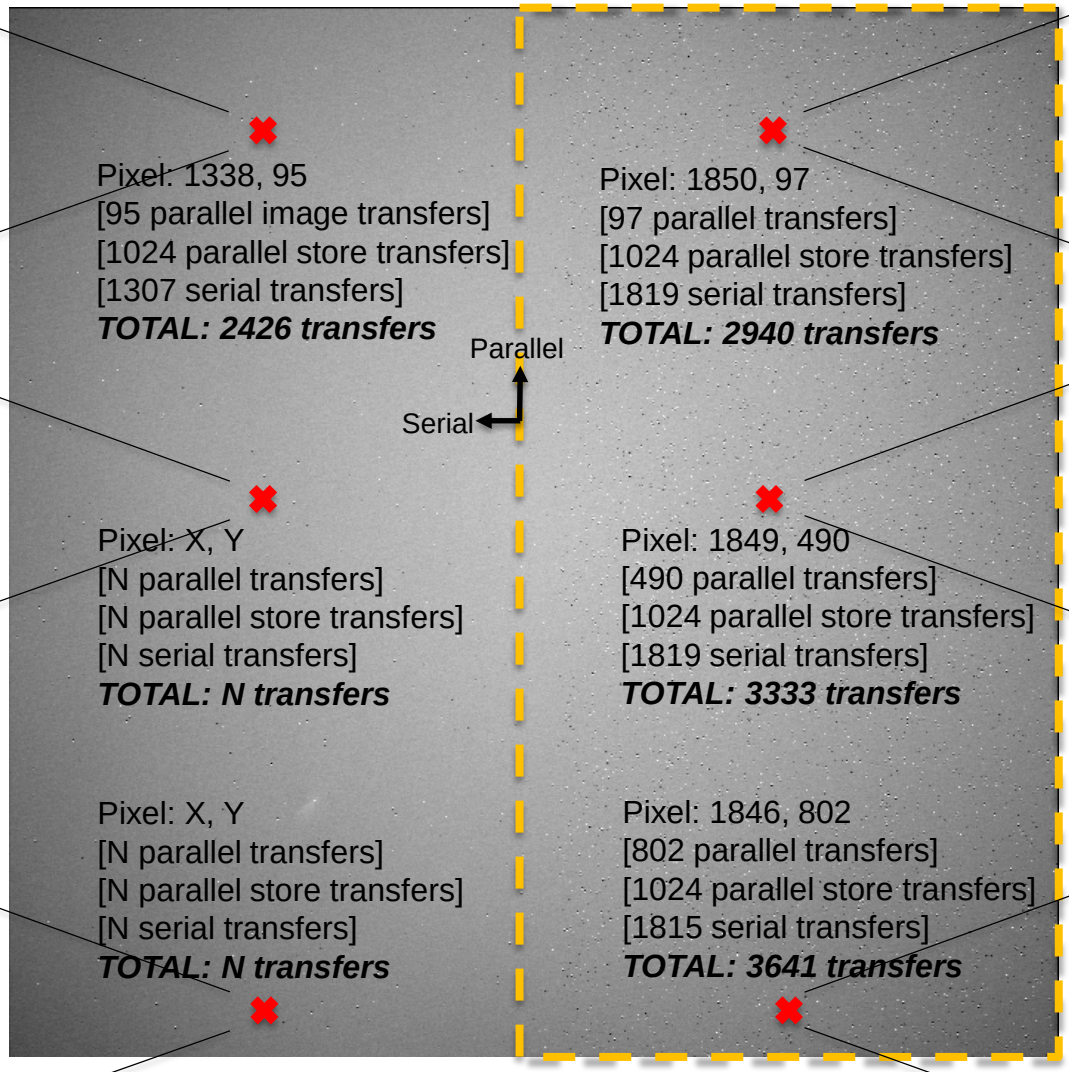
# 1 e- in 3x3 pixel core (Photon Counting Mode)

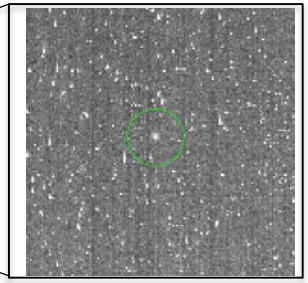
**FWHM = 3 pixels; 7200 - 10800 x 1 sec thresholded (PC) frames; ~0.1 e-/pix**

✖ = PSF pixel position

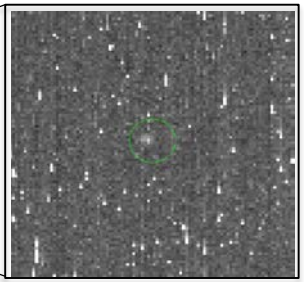
FWHM = 3 x 3 pixels



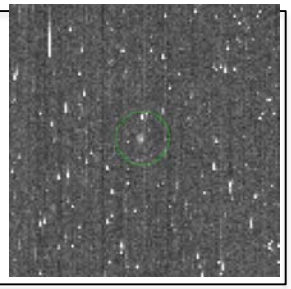


*Ongoing*

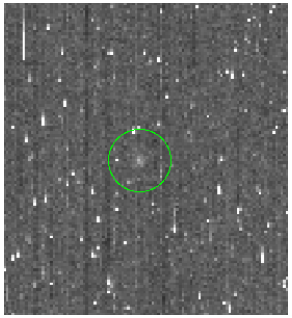
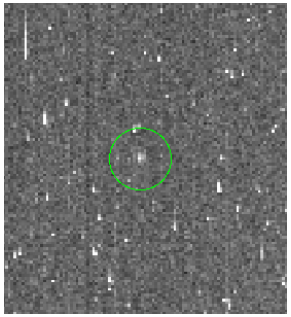
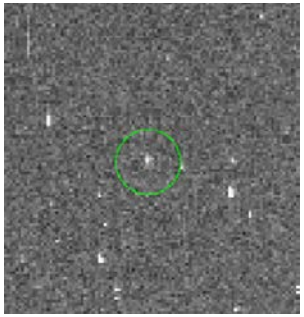
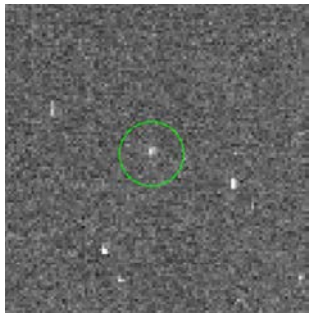
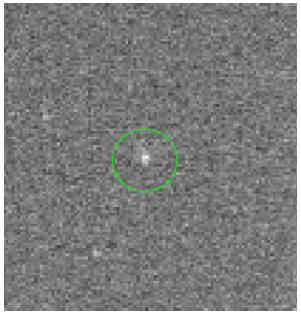
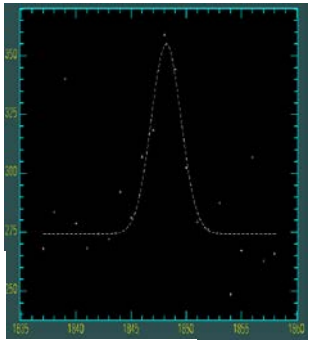
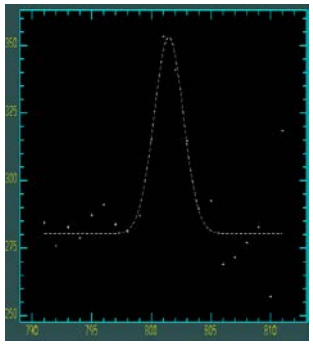
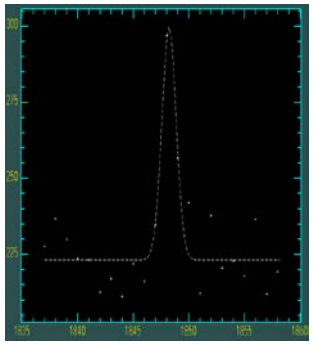
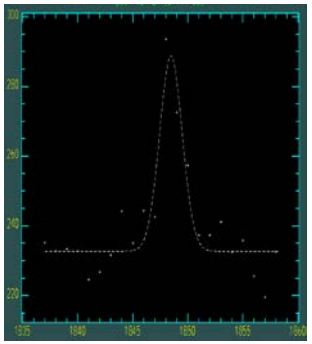
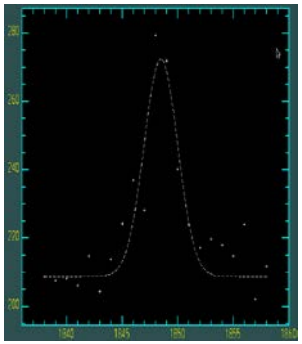


*Ongoing*



# Technology -- Low Noise Detector

- **Modeling**
  - CEI delivered more analysis products to be used in the detector trap model
- **Image Measurements**
  - Data post processing continued on measurements of low flux point spread function on a radiation-damaged EMCCD.
  - Photometry calculations were at the center of this processing activity.
  - PSF and dark current were measured at various temperatures
  - PSF and Clock induced charge (CIC) were measured for various $R\phi$1,2,3 voltages

| $CCD_{temp}$ = -85 C | -90 C | -95 C | -100 C | -105 C |
|---|---|---|---|---|
|  |  |  |  |  |
| *Dark current = 0.091 e-/px/s* | *Dark current = 0.0048 e-/px/s* | *Dark current = 0.0021 e-/px/s* | *Dark current = 0.0016 e-/px/s* | *Dark current = 0.0013 e-/px/s* |
|  |  |  |  |  |
| *Peak = 72 e-* | *68 e-* | *75 e-* | *55 e-* | *70 e-* |

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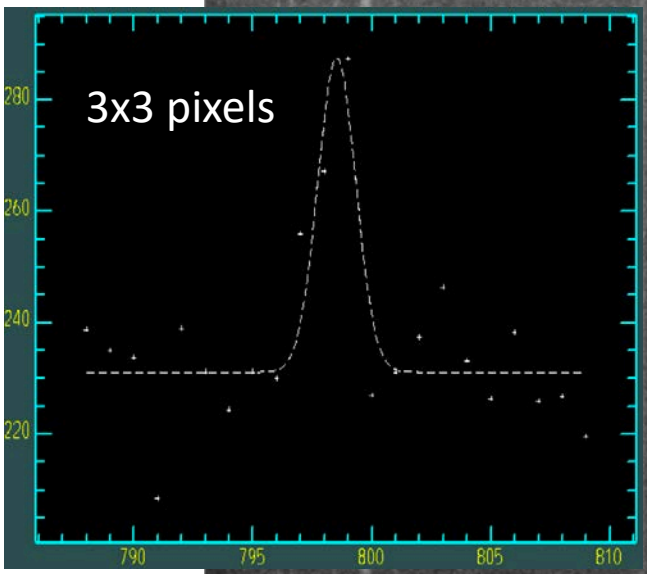
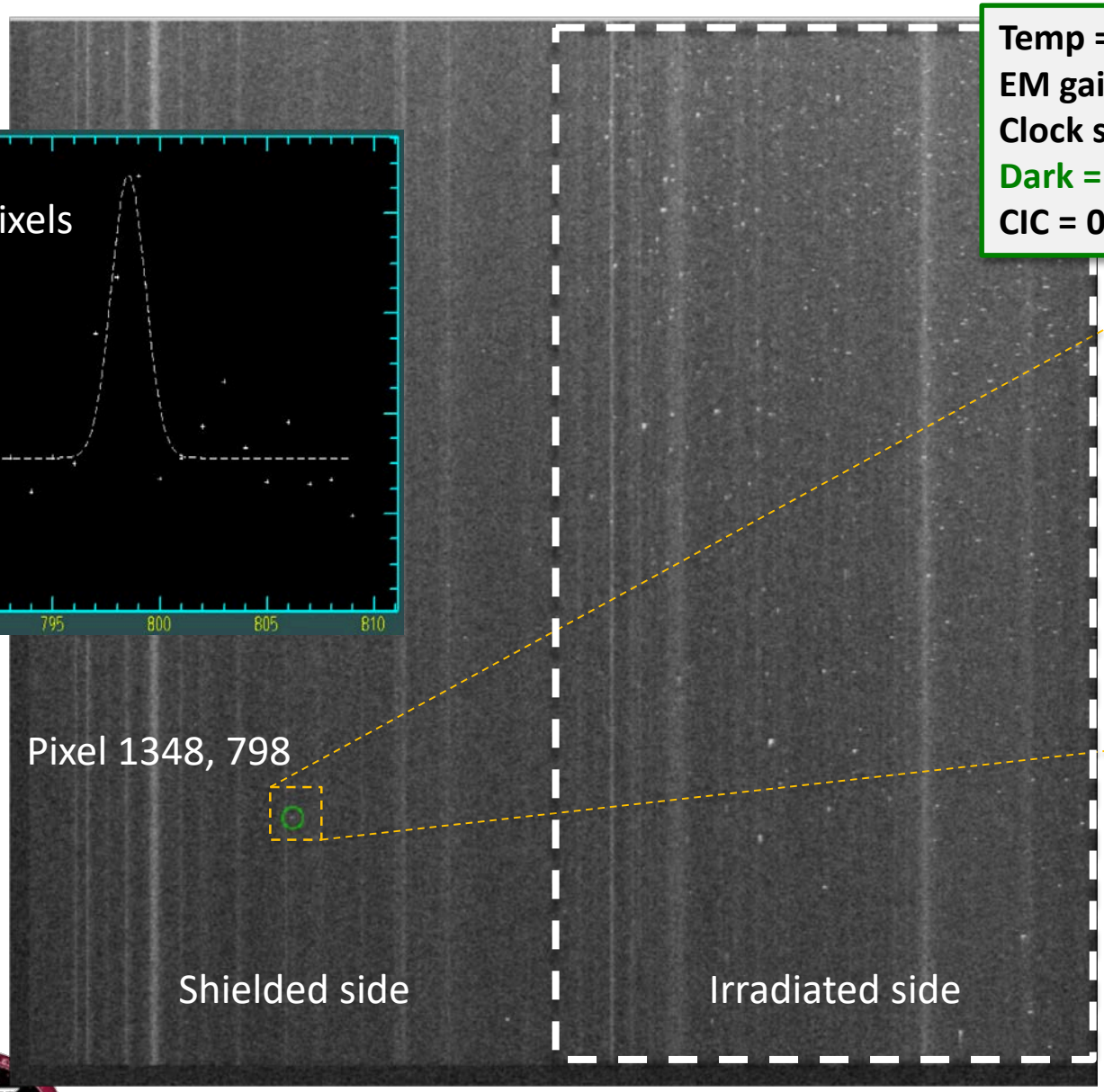
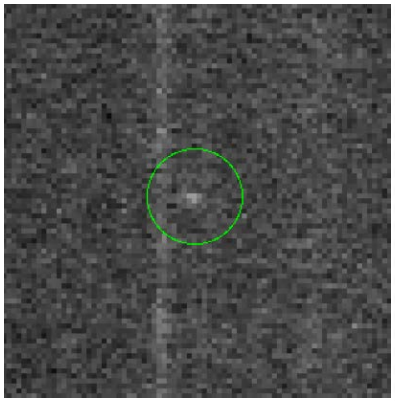
# PSF Measurement – BOL (JPL)

Temp = -105 C (168 K)
EM gain = 1100
Clock swing (serial = +10 V)
Dark = 0.0004 e-/px/sec
CIC = 0.002 e-/px/fr



PSF = 0.05 e-/fr/PSF
PSF = 3×3 pixels

Serial
Parallel

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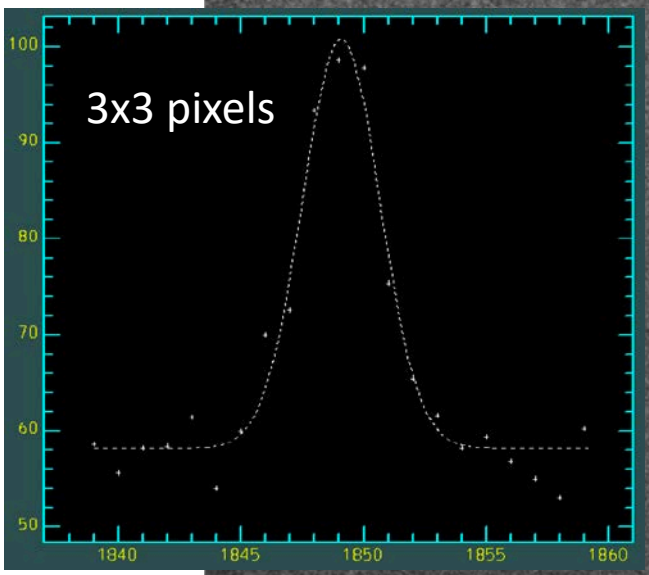
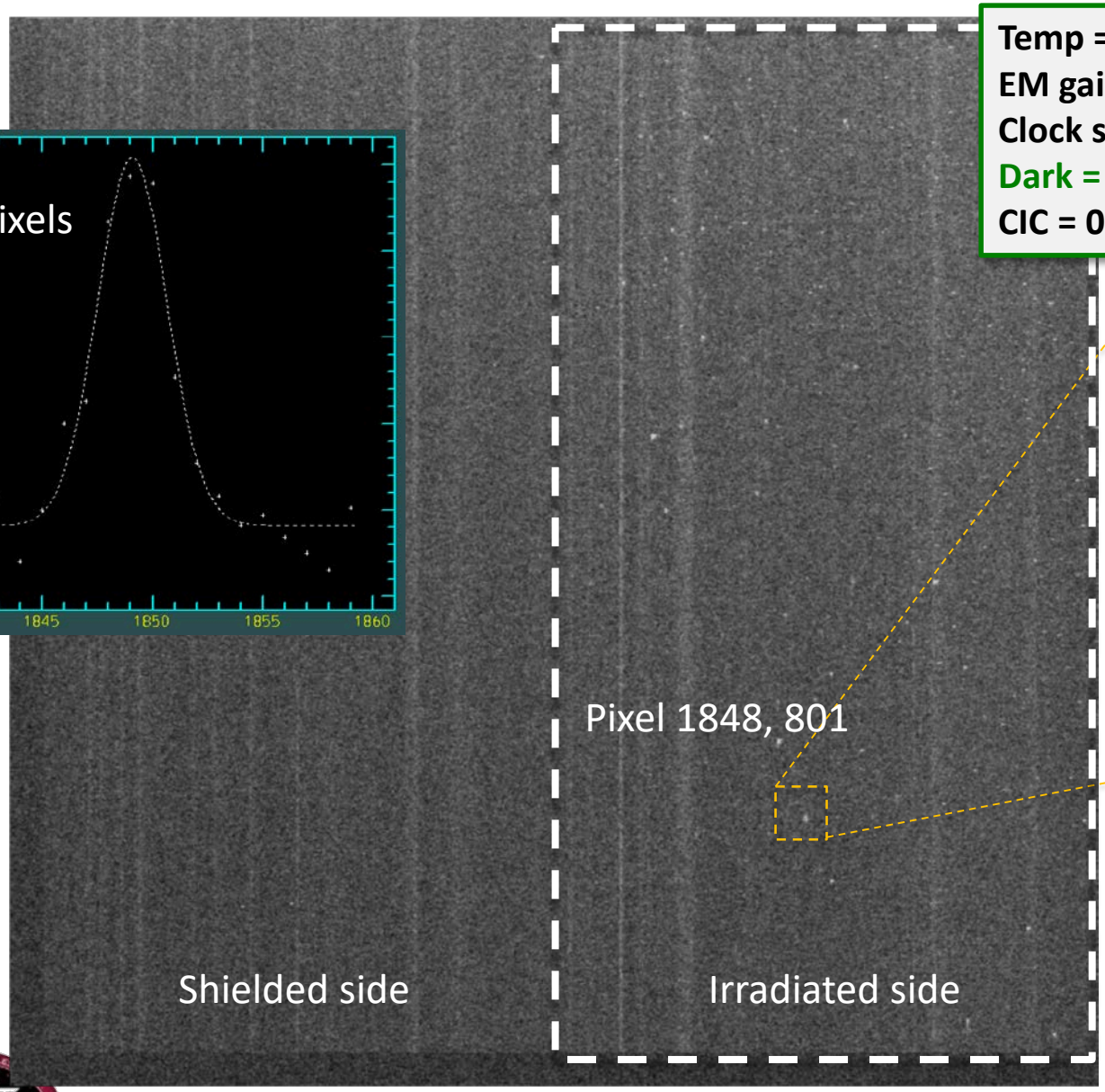
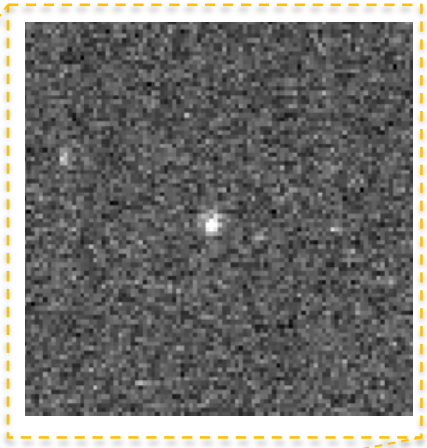
# PSF Measurement – EOL (JPL)

Temp = -105 C (168 K)
EM gain = 1100
Clock swing (serial = +10 V)
Dark = 0.0007 e-/px/sec
CIC = 0.002 e-/px/fr



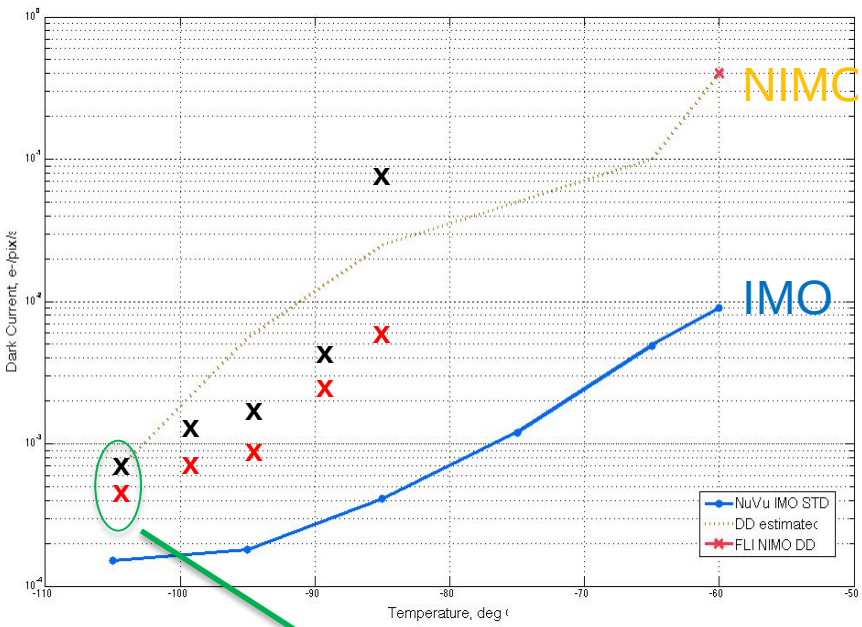
PSF = 0.15 e-/fr/PSF
PSF = 3×3 pixels

Serial

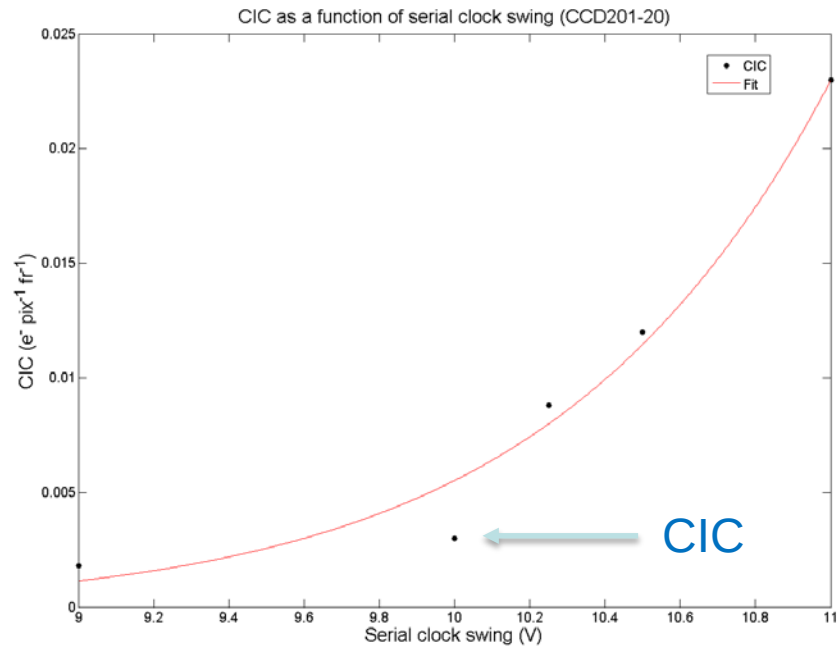
Parallel

# DC and CIC

## DARK CURRENT




## Clock induced charge




***RESULTS:***

DC (shielded): 0.00048 e-/pix/sec
DC (damaged): 0.00075 e-/pix/sec
CIC: 0.0026 e-/pix/fr

# IFS Flux Simulation

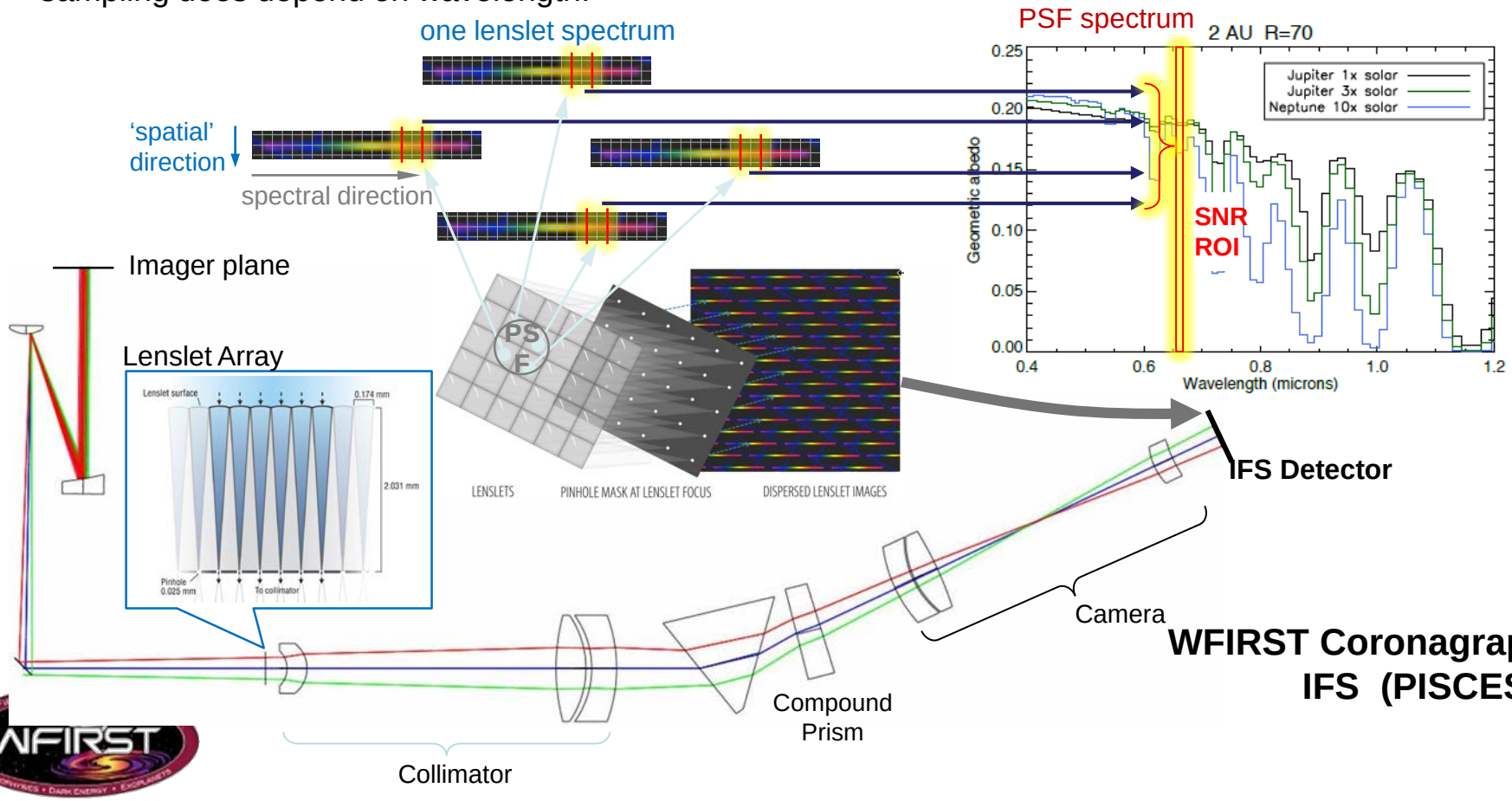
Bijan Nemati, Bobby Effinger, Don Pontrelli

# Detector Pixels in the IFS Configuration

For the IFS, the SNR region of interest (ROI) comprises the collection of pixels that altogether are involved in the photometry of a *single spectral element*

The system is constant-dispersion, therefore the sampling in the spectral dimension is set, and not wavelength dependent. However, the spatial sampling does depend on wavelength.

$$m_{pix} = \left(N_{lens}\frac{\lambda_i}{\lambda_{min}}\right)^2 \cdot 2_{spec} \cdot N_{spat}\left(\frac{\lambda_i}{\lambda_{min}}\right)$$




**WFIRST Coronagraph IFS (PISCES)**

# Milestone 7 Demonstration Frame

- Question being answered:

  *Can we read out a frame with flight-like signal and background levels?*

- Why is this question interesting:
  - The IFS flux is ultra low. Frame rates have to be high. The combination means most frames have no signal. Under these conditions, charge transfer inefficiency (CTI) and charge deferment from radiation induced traps, can be a serious concern.
- Signal and Background Desired for the Demonstration
  - **Signal:** We want to know how low we can go in terms of signal per frame and still be able to see the signal.
  - **Background:** We want it close to flight levels. If the background is **lower** than flight, *from trap-defect point of view*, it is a more stringent test.

- This is the most urgent question, but not the only one!
  - For the milestone time frame this was considered the most important additional question we wanted to address.

# Milestone 7 Settings and Assumptions

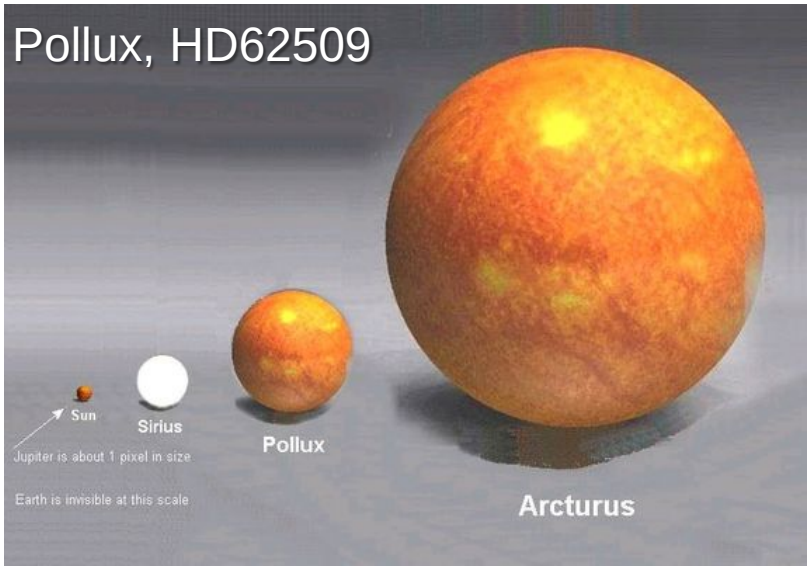
- IFS1 channel (660 nm, 18%BW, R=70)
- 2 lenslets across PSF
  - 4 lenslet spectra per psf core
  - 2x2 pixels SNR region per lenslet spectrum
- Post processing is perfectly effective ()
  - Decouple photometry and sensing from speckle stability issues
- Detector
  - Read noise = 0
    - photon counting
  - Dark current = 5e-4 e/pix/s
  - CIC = 5e-3 e/pix/frame
  - No excess noise factor

| Detector and IFS Design Settings | | | |
|---|---|---|---|
| **Detector Architecture** | | | |
| **Item** | **Value** | ***Units*** | ***Comments*** |
| Dark current | **5E-04** | *e/pix/s* | *best we can expect in ~IMO* |
| Clock Ind. Charge | **5E-03** | *e/pix/fr* | *achievable from lab* |
| Read noise | 0 | *e* | *eff. Read noise below* |
| EM gain | 1000 | *X* | *0* |
| Quantum Eff. | 72% | *QE* | *Includes Ph. Ctg. Eff. Loss* |
| Pixel Size | 13 | *μm* | |
| f_SR | 0.079 | | *frac. Of core light in SNR ROI* |
| Desired mpix | 16.0 | | *pixels in SNR ROI* |
| Excess Noise Fac. | 1.00 | *ENF* | *Robbins 2003, w/ N=200* |
| Frame Rate | 0.1000 | *Hz* | *Wes used 300s* |
| **Focal Plane Architecture** | | | |
| Imager Critical λ | **450** | *nm* | *Nyquist sampled* |
| Imager Sampling | 0.34 | *(λ/D) / pix* | |
| IFS Critical λ | **660** | *nm* | *Nyquist sampled* |
| IFS Lensl per PSF | **2** | *lenslets* | *across PSF core* |
| IFS Spatial Samp | **2** | *rows* | *pixels in spatial dir.* |
| IFS Spectral Samp | **2** | *cols* | *pixels / spect. Elem.* |
| IFS sampling on sky | 0.028 | *arcsec* | */ lenslet @ crit. λ* |

These are doable specifications for the case of doing **photon counting**.

# Nominal Target System for Milestone 7

- **Pollux (HD62509, RV planet host)**
  - Would be the first system we would try to characterize
  - V = 1.15 mag
  - Mass = 2.9×Jupiter
  - Radius = 13×Earth
- Assume
  - SNR = 5 requires
  - 86 frames @ 10s/frame




**SNR**

Time to SNR

| Item | Value | Units | Comments |
|---|---|---|---|
| Required Time to reach SNR | 8.62E+02 | s | |
| | 0.24 | hr | |
| | 0.01 | days | |

Final SNR

| Item | Value | Units | Comments |
|---|---|---|---|
| SNR Check | 5.00 | SNR | |
| Signal | 48.2 | e | Total Signal |
| Noise | 9.6 | e | Total Noise |
| Frames Needed | 86.2 | frames | for SNR target |

Final Noise Contributions

| Item | Value | Units | Comments |
|---|---|---|---|
| Shot | 6.944 | e | signal shot noise |
| Speckle | 5.525 | e | <sp> shot noise |
| Zodi | 0.687 | e | zodi shot |
| Dark Current | 2.626 | e | |
| CIC | 2.626 | e | |
| Read | 0.000 | e | |
| Speckle Structure | 0.000 | e | residual Speckle |

In One Frame

| Item | Value | Units | Comments |
|---|---|---|---|
| SNR for 1 Frame | 0.5385 | SNR | |
| Signal | 0.559 | e | |
| Noise | 1.04 | e | |
| Shot | 0.75 | e | |
| Speckle | 0.60 | e | 5.120085757 |
| Zodi | 0.07 | e | |
| Dark Current | 0.28 | e | |
| CIC | 0.28 | e | |
| Read | 0.00 | e | |
| Speckle Struc. | 0.00 | e | |

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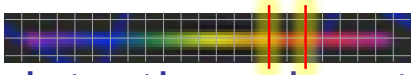
# Test Scene Specifications

Based on a single lenslet spectrum

one lenslet spectrum



Desire a detection when the signal and the background are below these levels:

- Signal:
  - < 0.035 e-/pix/frame
- Background (noise variance)
  - < 0.068 e-/pix/frame
- Or, Detector noise rates:
  - Dark < 5e-4 e-/pix/sec
  - CIC < 5e-3 e-/pix/frame

| Item | Value | Units | Comments |
|---|---|---|---|
| **In 1 Spectrum: what we replicate in lab experiments** | | | |
| Signal in 1 spectrum | **0.14** | *e-* | *in 1 spectral element from 1 lenslet* |
| Noise in 1 spectrum | **0.52** | *e-* | *RSS of all noise sources* |
| Pixels in 1 spectrum | **4.0** | *pix* | *in 1 spectral element from 1 lenslet* |
| Total Noise Variance | 0.27 | *e-* | *sum of squares of noise contributions* |
| Shot | 0.37 | *e-* | *in 1 spectral element from 1 lenslet* |
| Speckle | 0.30 | *e-* | *in 1 spectral element from 1 lenslet* |
| Zodi | 0.04 | *e-* | *in 1 spectral element from 1 lenslet* |
| Dark Current | 0.14 | *e-* | *in 1 spectral element from 1 lenslet* |
| CIC | 0.14 | *e-* | *in 1 spectral element from 1 lenslet* |
| Read | 0.00 | *e-* | *in 1 spectral element from 1 lenslet* |
| SNR in 1 specrtum | 0.269 | *SNR* | *in 1 spectral element from 1 lenslet* |
| SNR in 1 frame full SNR ROI | 0.539 | *SNR* | *from all spectral elements/lenslets* |
| No. of frames | 86.2 | *fr* | |
| SNR after all frames | 5.0 | | *assuming SNR goes as sqrt(Nfr)* |
| | | | |
| Fraction of light in SNR ROI | 0.079 | *f_SR* | 12.6 |
| No. of spectra per PSF core | 4 | *spectra* | |
| Total pixels involved | 16.0 | *pix* | *in SNR region* |
| | | | |
| **Settings used for official evaluation** | | | |
| Observation Mode | IFS 1 | | |
| SNR Target | 5 | | |
| Detector Type | PC EMCCD | | |
| Coronagraph Type | SPC | | |
| RV System | 24 | *HD62509* | |
| Frame Time | 10 | *s* | |
| Post-proc Factor | 0% | f_pp | |
| exo+local factor | 1 | zodi | |
| Imager Critical λ | 450 | nm | |
| IFS Critical λ | 660 | nm | *For the milestone make it 660* |
| IFS Lensl per PSF | 2 | lenslets | |
| IFS Spatial Samp | 2 | rows | |
| IFS Spectral Samp | 2 | cols | |

**We want these conditions satisfied at the beginning of mission.**

**Would also want to assess at end of mission.**

# Backup charts

# Photon counting at 0.1 e- PSF

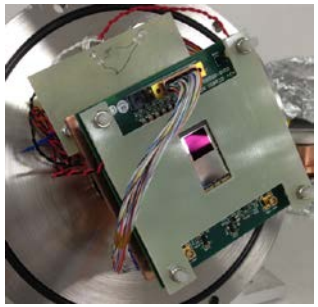
- *Detector parameters*:
  - Substrate voltage, Vss = 0 V (NIMO)
  - φDC = +3.66 V
  - Serial clock high level = +10 V
  - Serial clock low level = 0 V (Swing = 10 V)
  - Parallel clock high level = +5 V
  - Parallel clock low level = -5 V
  - Rφ2HV = 42.20 V (EM gain = 1100)
  - Sensor temperature = -105 C (168 K)
  - T_int = 1 sec
  - Parallel frequency = 1 MHz
  - Serial frequency = 10 MHz
  - *Filter combination: ND1xND3xND1 = 0.0027% transmission*

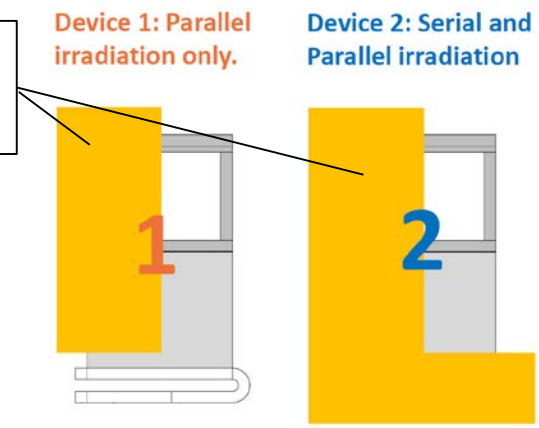
# Radiation Testing

## Displacement Damage Dose (DDD)

### Single exposure of Displacement Damage Dose (DDD) at room temperature

- **Survivability test of detector for 2.5 x $10^9$ protons $cm^{-2}$ dose [10 MeV equivalent]**
  ~Corresponds to 3 years at L2 orbit with Ta shielding
- Paul Scherrer Institute Beamline, Switzerland in April 2015
- Assessed degradation of:
  - Read Noise, EM gain, Clock Induced Charge, Dark current, Charge Transfer Efficiency
- T = 293 K during irradiation;
- 165 ±2 K during post exposure measurement
- Unbiased during exposure






### Four separate exposures of Displacement Damage Dose (DDD) at cryo-temp

- **Characterize the performance degradation at intermediate points in 6 year life cycle**
- Performance fully characterized before campaign and after each of four doses
- Facility: Helios 3 Beamline, Harwell, UK
- T = 165 ±2 K for irradiation; (±5 K during measurements)
- Biased during exposure to monitor flatband voltage shift
- DUT Science-grade EMCCD m/n 201-20
- Four cumulative doses summing to 7.5 x $10^9$ pr/$cm^2$ [10 MeV equivalent]

| Exposure Dose [$10^9$ protons/$cm^{-2}$] | Cumulative Dose [$10^9$ protons/$cm^{-2}$] |
|---|---|
| 0 | 0 |
| 1 | 1 |
| 1.5 | 2.5 |
| 2.5 | 5 |
| 2.5 | 7.5 |

# Image Degradation

- Radiation campaign revealed significant increase in silicon lattice defects in the regime of DDD ~$10^9$ protons/cm$^2$
- Defects are manifested as charge traps that reduce CTE
- CTE was characterized before and after irradiations
- It was not known how to specify required CTE value nor trap density requirement for very low flux IFS images
- Original planet yield model did not include CTE
  - Assumed charge transfer efficiency = 100%
- A model of image degradation became necessary

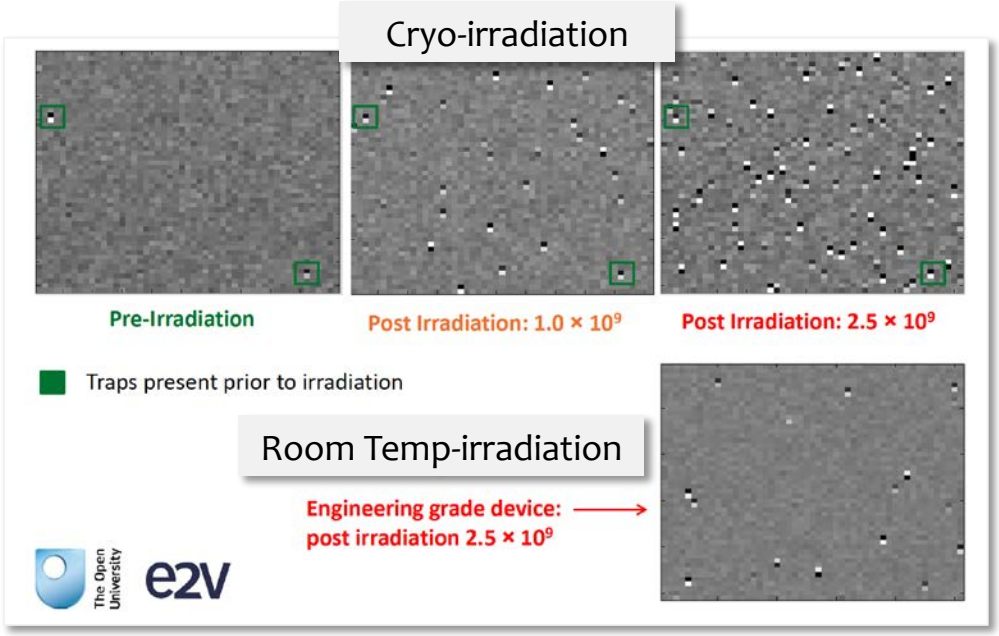
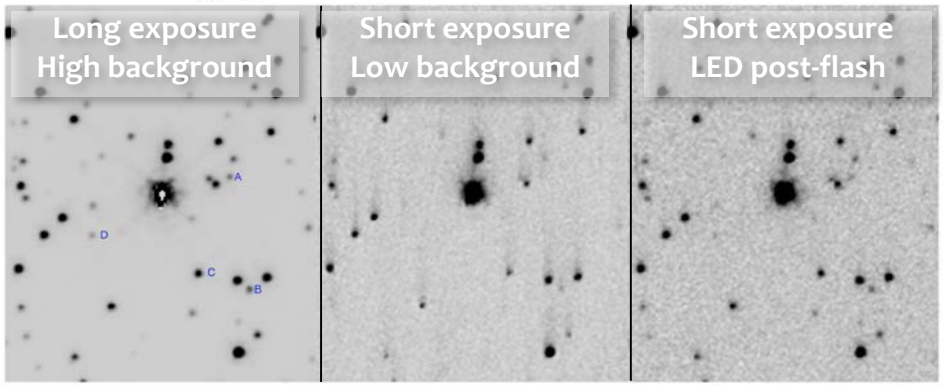



Figure 6.16: Mitigation of CTE Losses Using a Modest Increase in Image Background




WFC3

A portion of the Omega Cen central field far from the readout amplifier. The left panel shows the result of a stack of eight 700s images, with minimal CTE losses. The middle panel shows a stack of nine 10s exposures with only ~2e⁻ natural background each; note the charge trails due to CTE loss extending upwards from each source in the field. The right panel is a stack of nine 10s exposures with ~16e⁻ background total (sky + post-flash) in each image.