Jet Propulsion Laboratory
California Institute of Technology

GaAs(P)-based Detector Alternatives for the WFIRST Coronagraph

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Flight Instrument Detectors and Camera Systems
Section 389N

31 January 2017

Outline

- Detector Requirements
- Contextual summary of L3CCD design and measurements, and HST experience
- A primer on risk and detector lifetime with respect to radiation and radiation shielding
- Alternate competitive detector concepts
  - MCP designs
  - Electron-bombarded CCD/CMOS
- Discussion of design maturity and TRL
- Pros and Cons
- Recommendations

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Requirements and Motivation

- The WFIRST coronagraph will directly image a planet in the vicinity of a nearby star. The predicted signal is exceedingly faint, and beyond the reach of typical detectors.
- Requirements for this technology demonstration are in development with the science team, with a goal of setting threshold requirements that are capability-based.

Lifetime:	6 years
Band of interest:	450-950nm
Detection to S/N=5 (Nemati):	
IFS1:	4.0e-4 $e\text{-}px^{-1}\text{-}s^{-1}$ (4 days)
Imaging2:	4.6e-3 $e\text{-}px^{-1}\text{-}s^{-1}$ (1 day)

Compare these to typical dark currents of 1-2 $e\text{-}px^{-1}\text{-}hr^{-1}$

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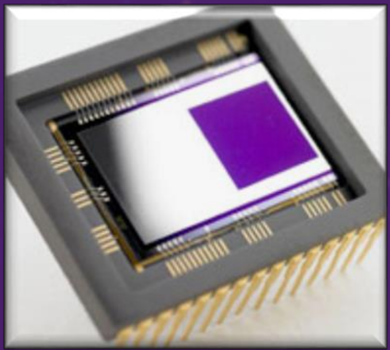
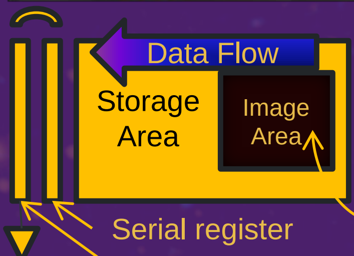
L3CCD Concept

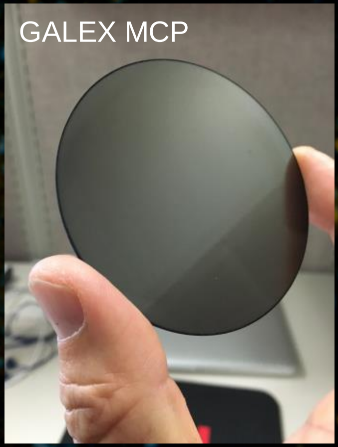
e2v L3 Technology

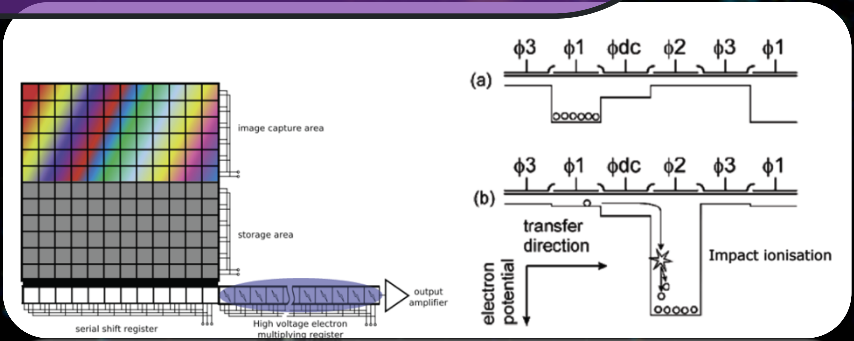


- New technology from e2v enables high QE CCD imaging and **zero read noise** photon counting.
- A **Low Light Level (L3) extended serial register** operating at elevated voltage (~50V) amplifies signals well above the level of the read noise.



L3 functional diagram

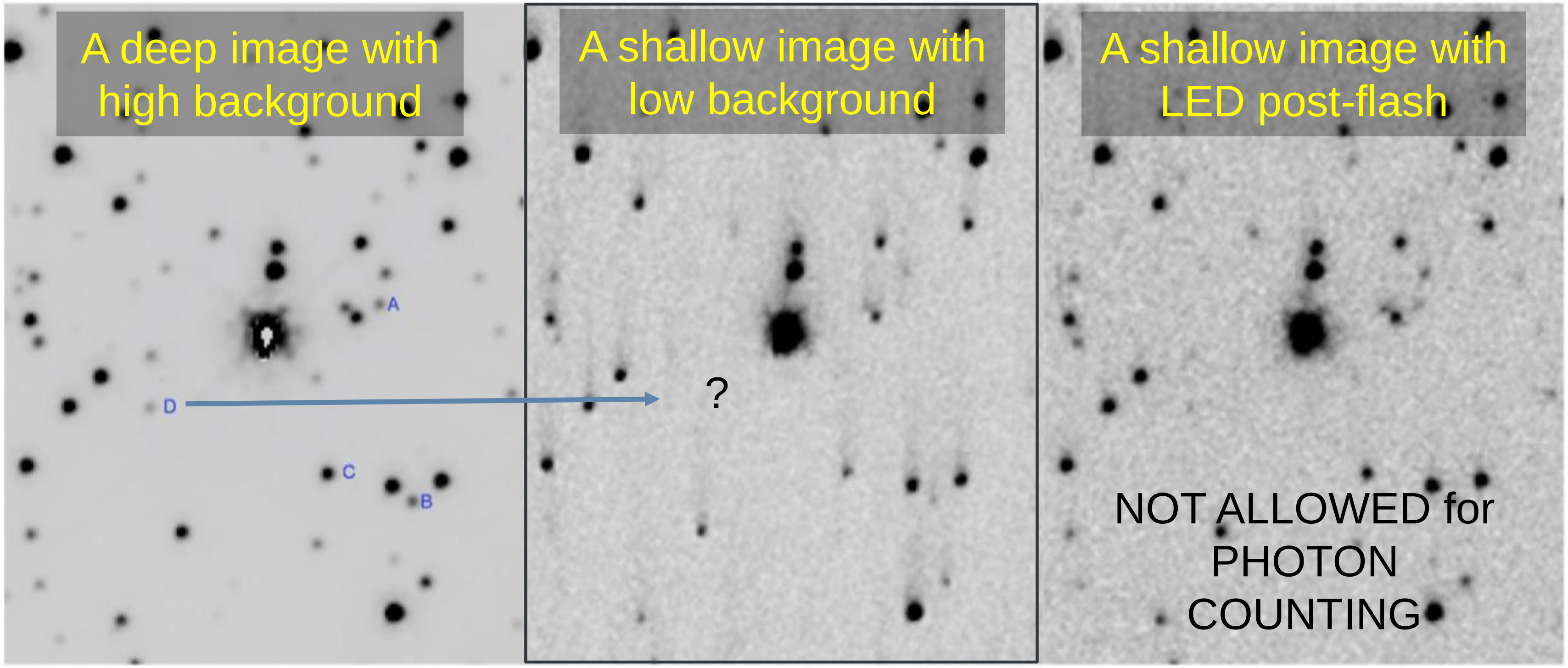




L3CCD provides
- ✓ **High QE**
- ✓ **Low dark current**

…without HV!

HST WFC3 Experience: Charge Transfer Efficiency Degrades with Radiation

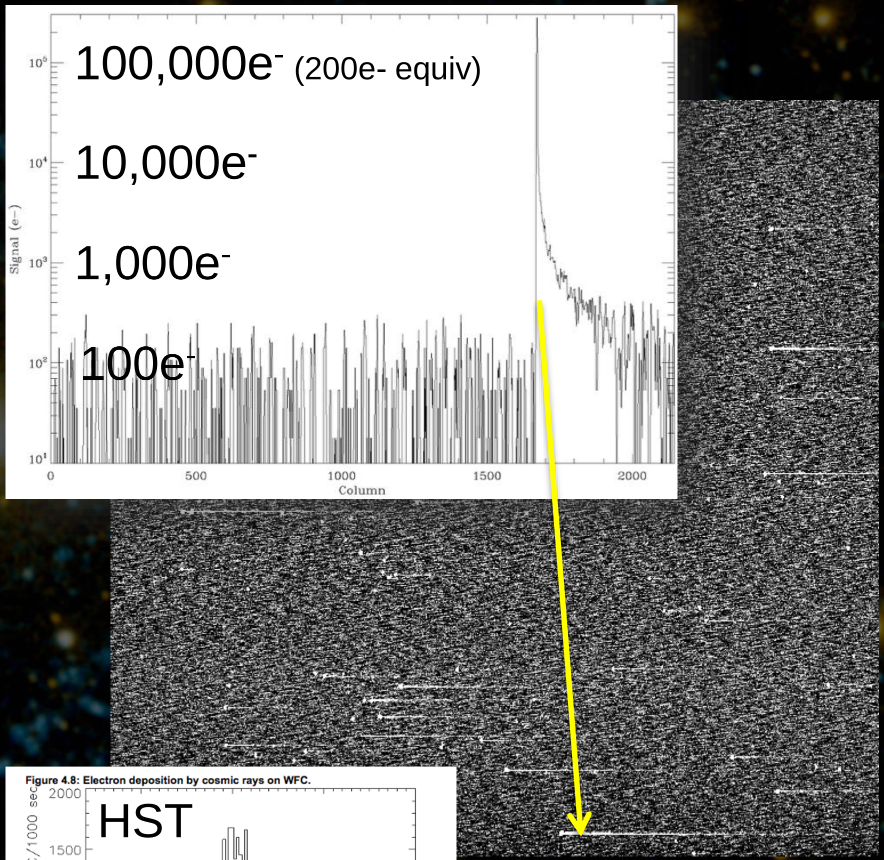


A portion of the Omega Cen central field far from the readout amplifier. The left panel shows the result of a stack of eight 700s images, with minimal CTE losses. The middle panel shows a stack of nine 10s exposures with only ~2e⁻ natural background each; note the charge trails due to CTE loss extending 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.

WFC3 Instrument Handbook

Cosmic Ray Tails

- Full frame science-grade CCD201 image.
  - Temp = -85 °C (188 K)
  - Gain = 500
  - Exposure = 500s
  - Read Noise = 90e$^-$
- Cosmic ray tails and the requirements of photon counting (<0.1 photons-s^{-1}-pixel^{-1}) push the L3CCD to short frame times, while radiation damage pushes the L3CCD to long frame times.



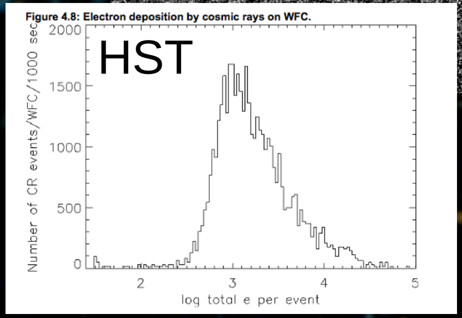
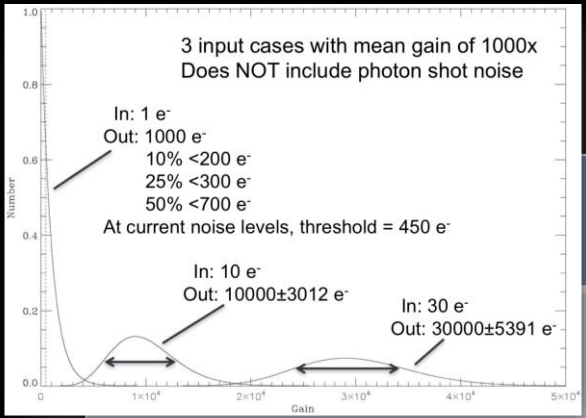


Image courtesy L. Harding

Cosmic Rays Tails Are Mitigated by Photon Counting at the Expense of Increased CIC

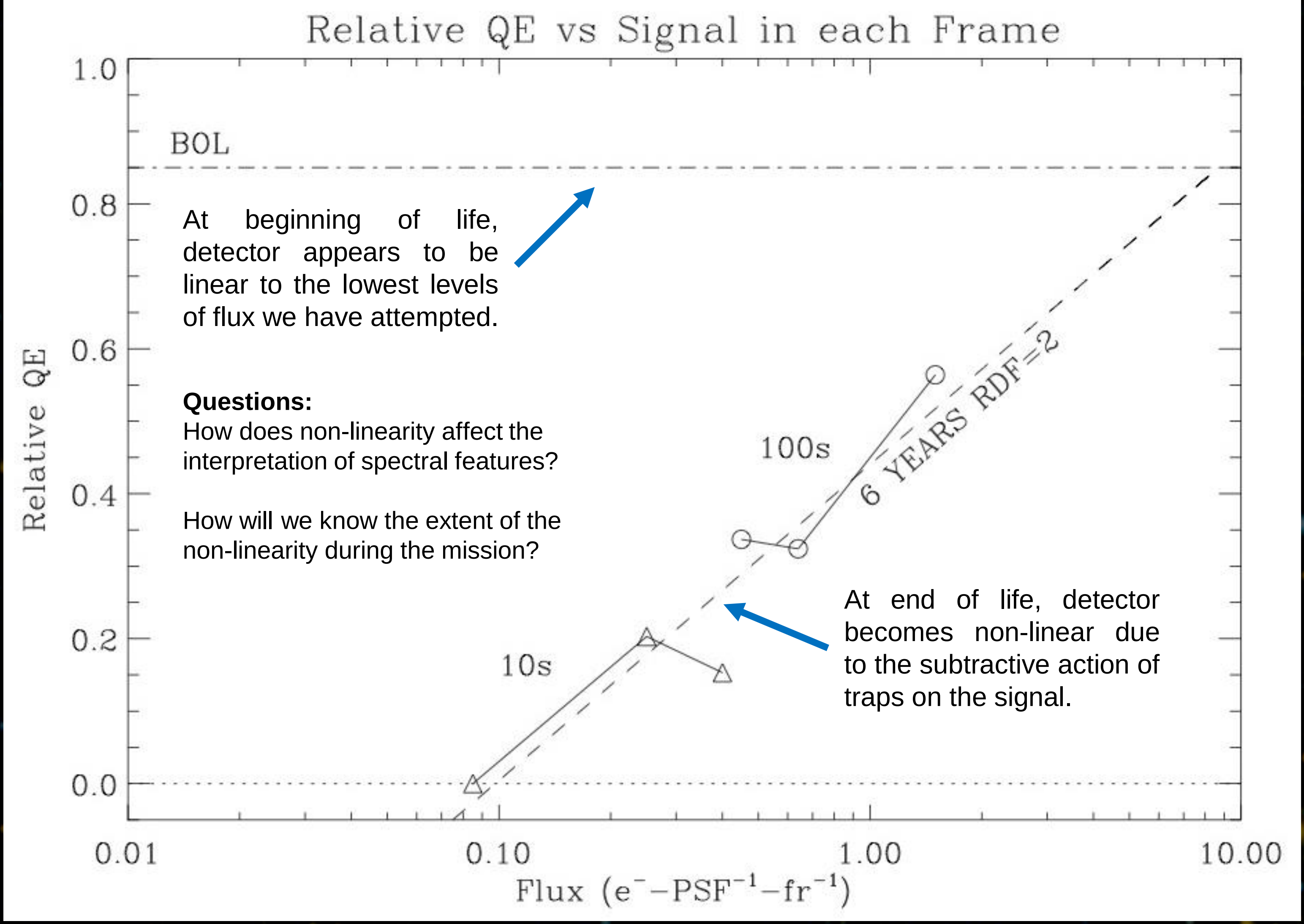


*CIC effectively sets a dark current floor of 0.14 e$^-$-px^{-1}-hr^{-1}

Limiting noise is shown in RED.

	Long Frames	Short Frames	
Mode	EM Analog	EM Analog	Photon Counting
Effective QE	0.45	0.45	0.75
Total Exposure	100000 s		
Frame Time	2000 s	20 s	20 s
Frames	50	5000	5000
Read Noise (90e-)	±1.3 e$^-$	±13 e$^-$	0 e$^-$
*CIC (3e-3 e$^-$-px^{-1}-fr^{-1})	0.15 e$^-$	15 3.9 e$^-$	15 3.9 e$^-$
Dark Current (2 e$^-$-px^{-1}-hr^{-1})	55 7.4 e$^-$	55 7.4 e$^-$	55 7.4 e$^-$
Gain	500	1000	1000
Detection Limit (5)	CR-limited	77 e$^-$	42 e$^-$

L3CCD Relative QE vs Flux



At beginning of life, detector appears to be linear to the lowest levels of flux we have attempted.

Questions:
How does non-linearity affect the interpretation of spectral features?

How will we know the extent of the non-linearity during the mission?

At end of life, detector becomes non-linear due to the subtractive action of traps on the signal.

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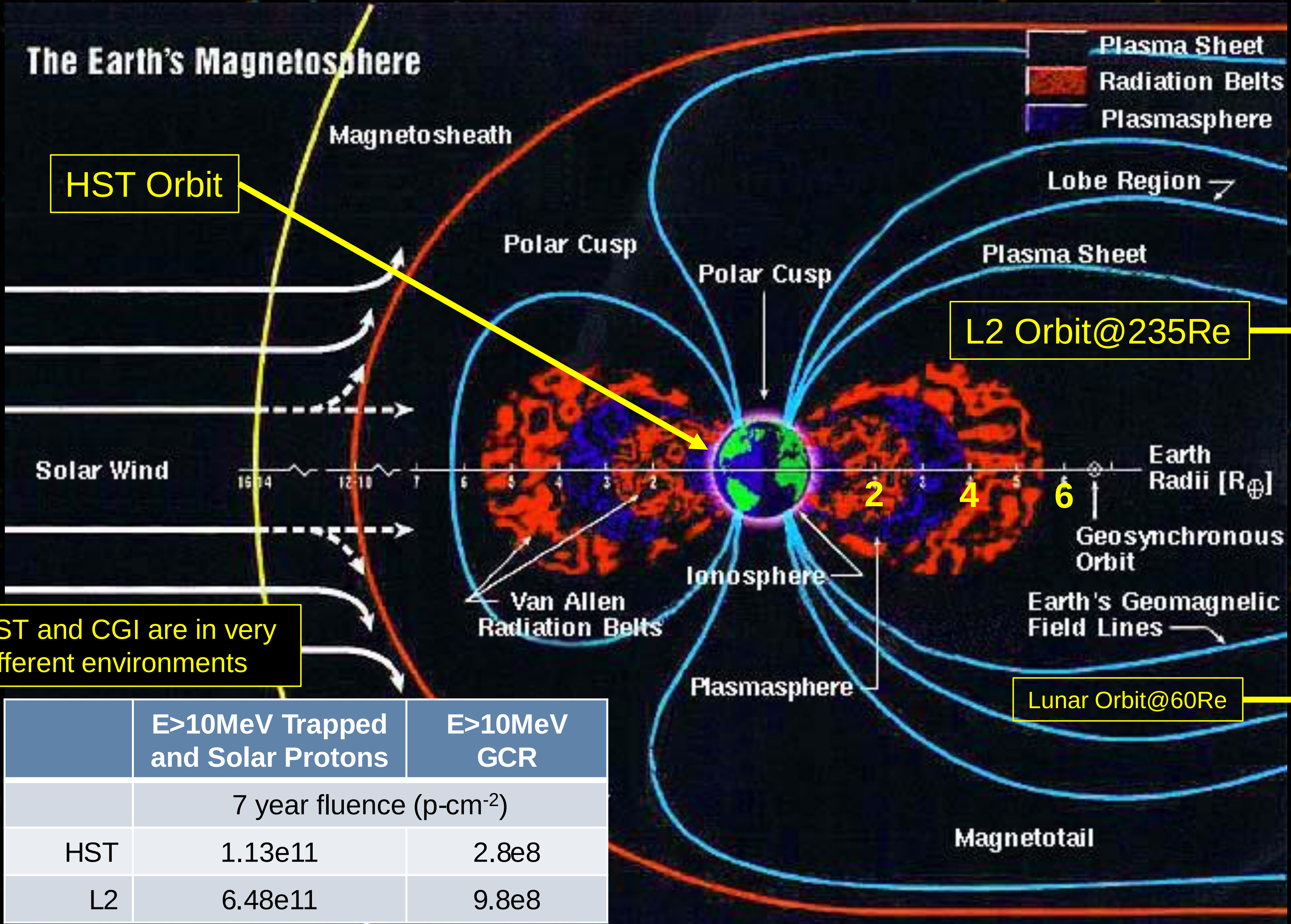
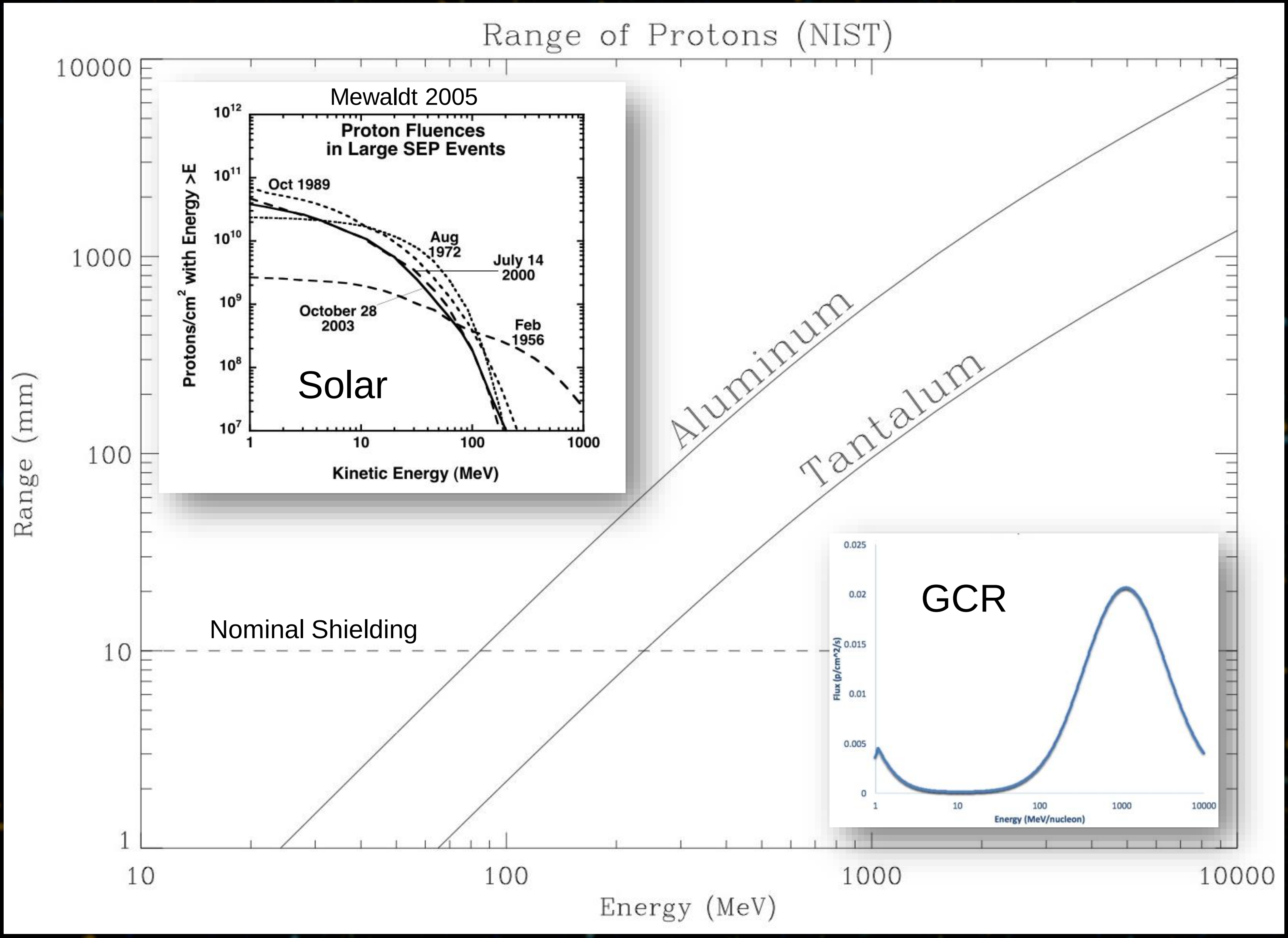
LEO vs L2



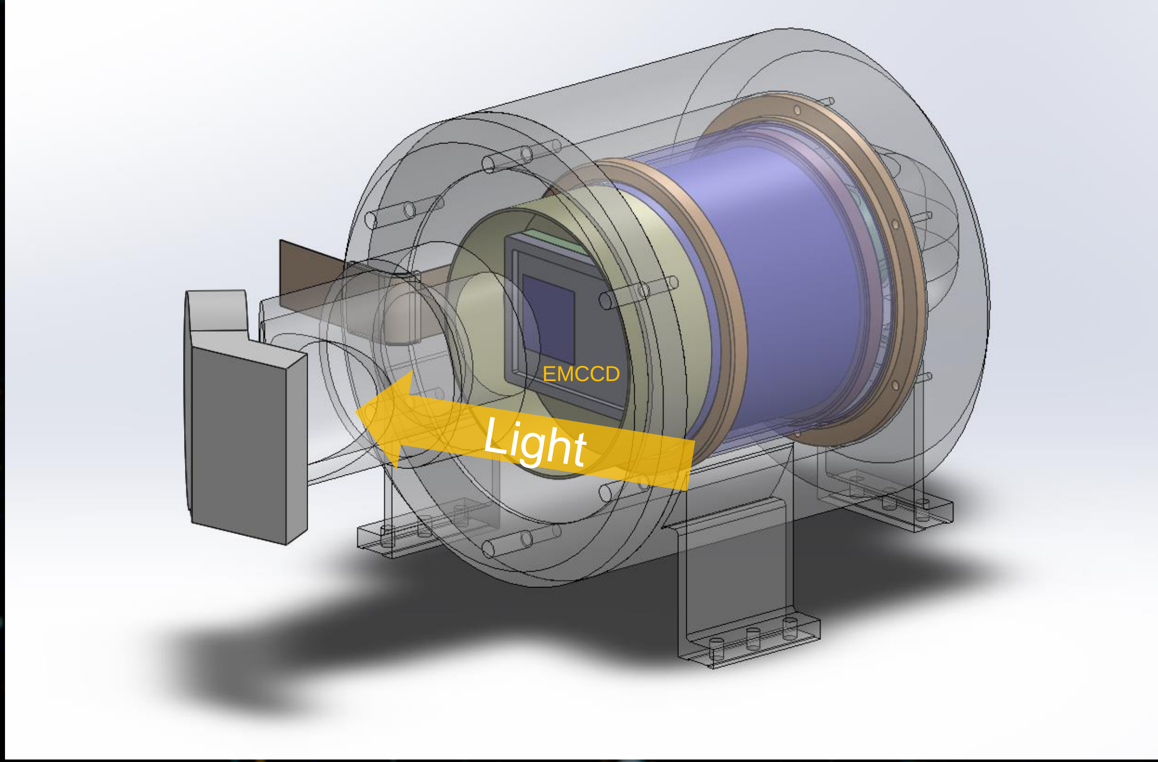
	E>10MeV Trapped and Solar Protons	E>10MeV GCR
	7 year fluence (p-cm^{-2})	
HST	1.13e11	2.8e8
L2	6.48e11	9.8e8

Range of Protons in Matter

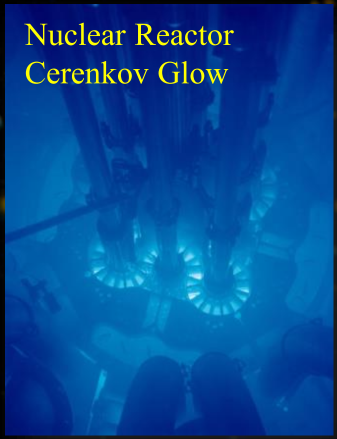


WFIRST CGI Radiation Shield Concept

Completely enclosed, 1cm Ta Shield Concept



- Light enters, but energetic particles do not have a direct path to CCD
- Scattered electrons appear to require a window somewhere
- Secondary production is currently under investigation (Bremsstrahlung, Cerenkov, etc)
- We are attempting to optimize the shield thickness against the production of secondary particles.



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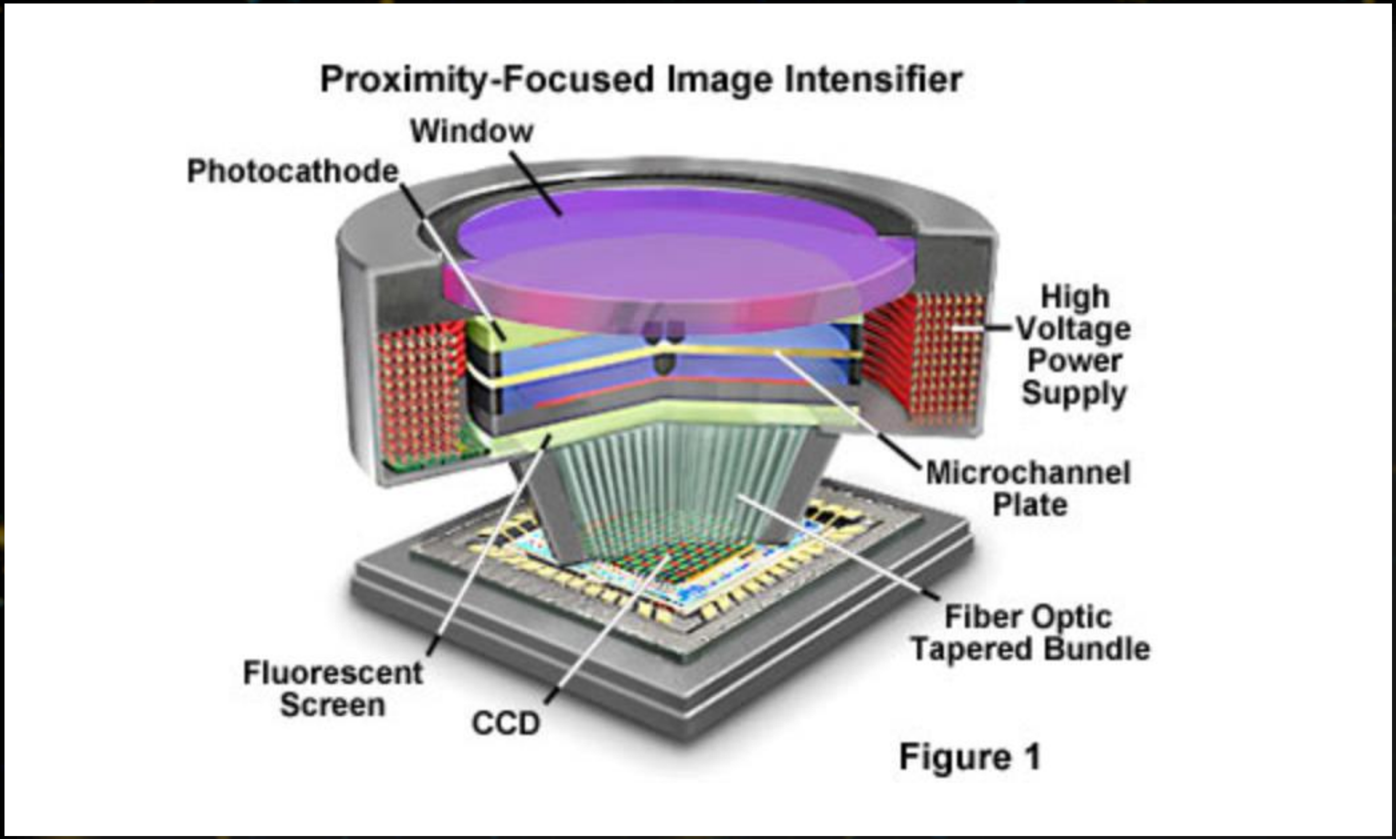
An MCP Intensified Alternative

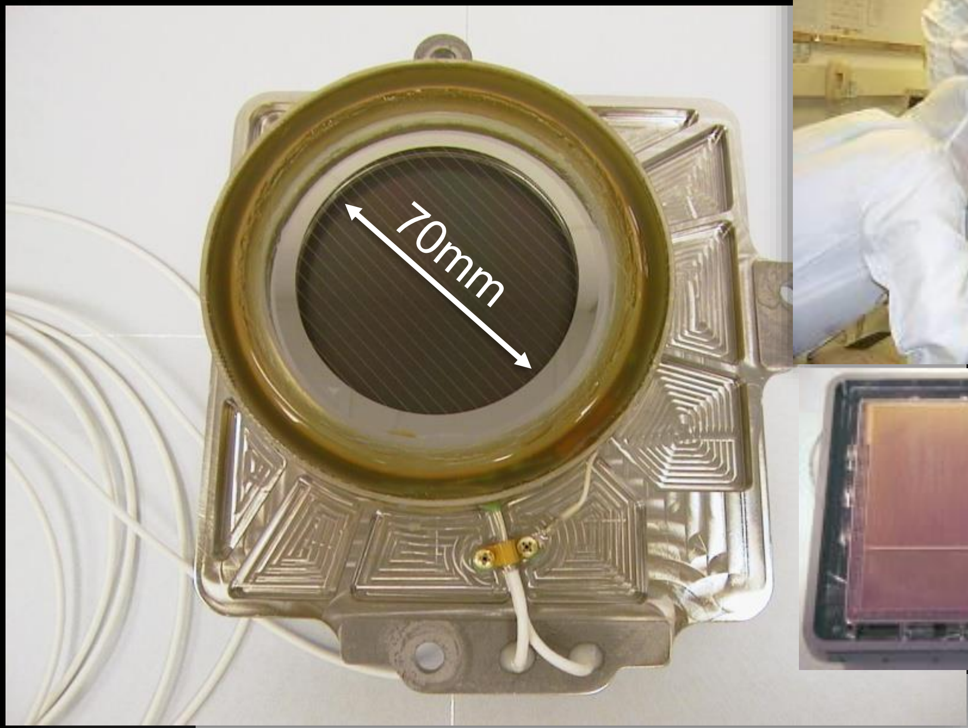


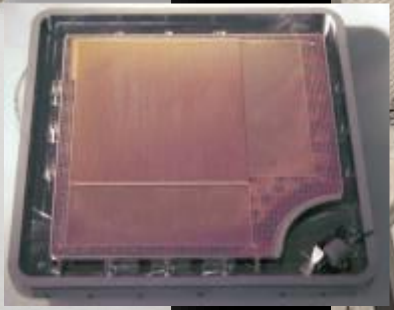
PRO
- Flight heritage
- Rad hard
- Low noise

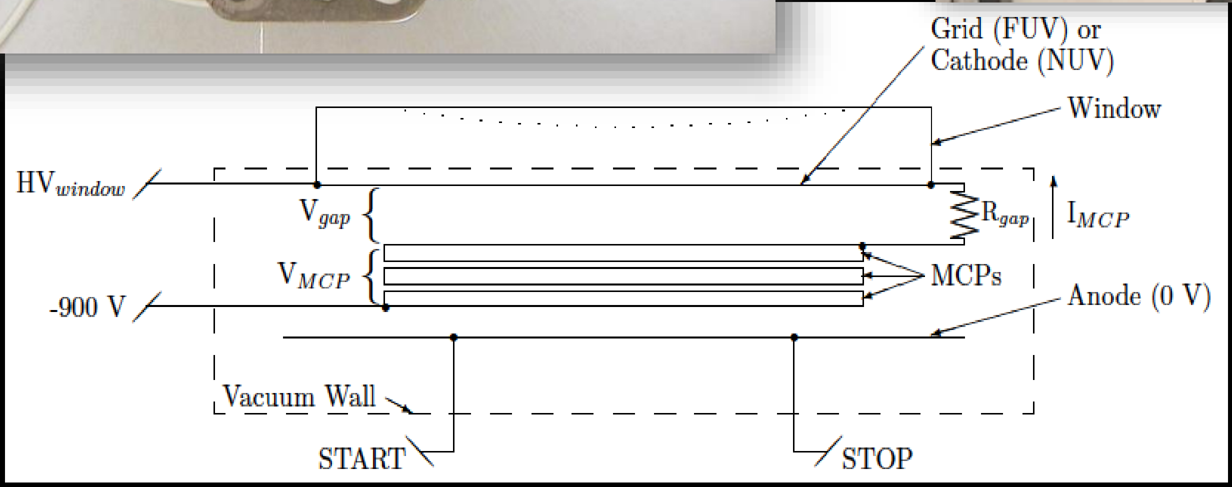
CON
- Modest QE
- High voltage
- Three parts

Laboratory performance of this rugged, flight-proven design will be representative of flight performance at T+6 years in the absence of any catastrophic failure.

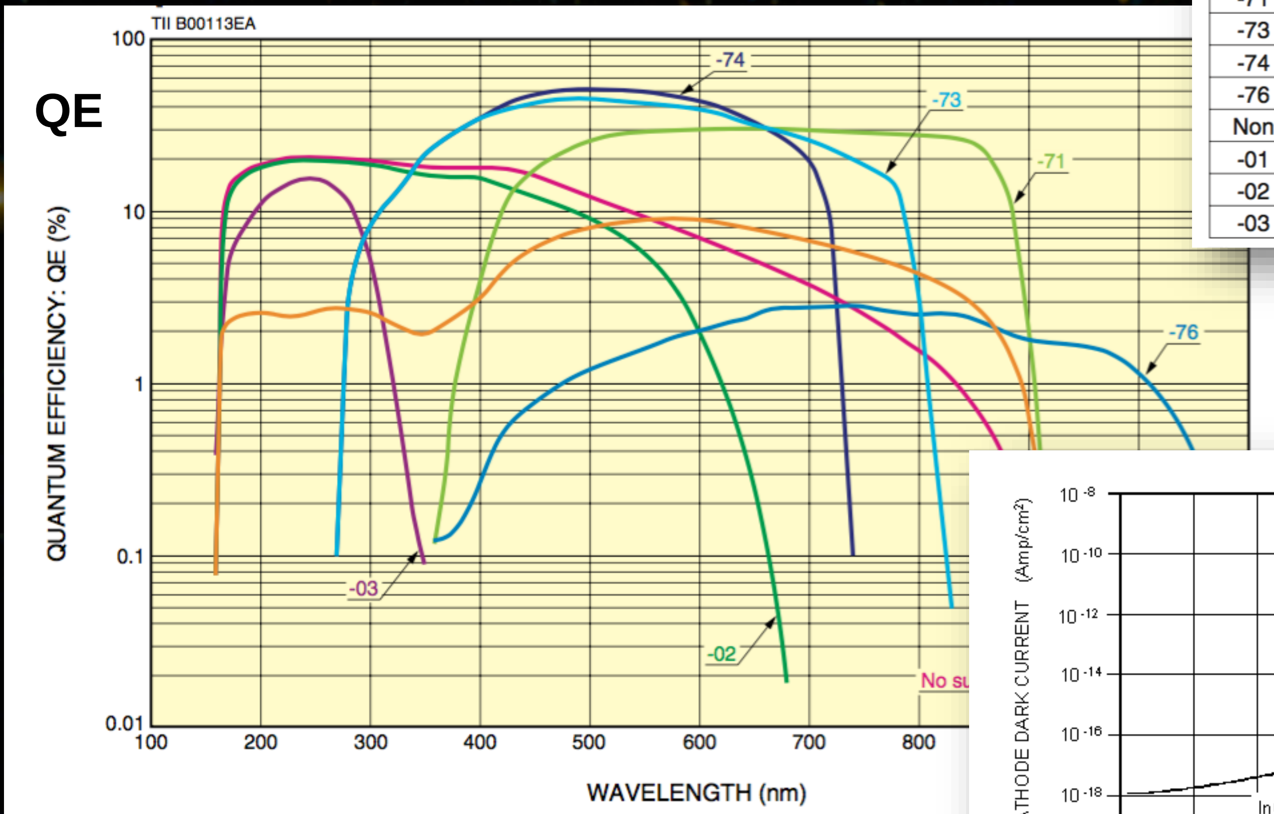
GALEX MCP Detector



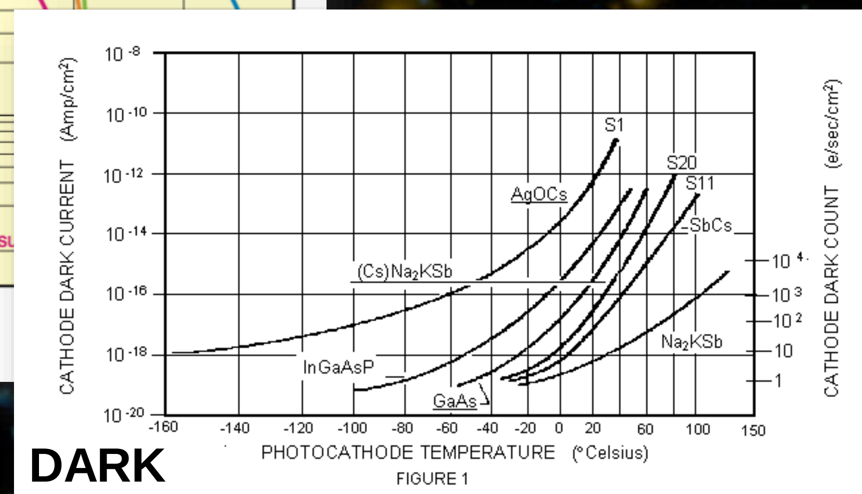




MCP Intensifier Performance



Suffix	Photo Cathode	Input Window
-71	GaAs	Borosilicate Glass
-73	Enhanced Red GaAsP	Borosilicate Glass
-74	GaAsP	Borosilicate Glass
-76	InGaAs	Borosilicate Glass
Non	Multialkali	Synthetic Silica
-01	Enhanced Red Multialkali	Synthetic Silica
-02	Bialkali	Synthetic Silica
-03	Cs-Te	Synthetic Silica



A GaAsP (-74) Intensifier operating at -20 °C will have a visible band QE (cathode) of up to 50% and a dark current of 30 c-s^{-1}-cm^{-2}, which scales to an equivalent CCD dark of 0.18 c-px^{-1}-hr^{-1}.

Detector Noise vs Quantum Efficiency

(it all depends on what dark the EMCCD can achieve)

Consider the S/N of a moderate QE MCP detector vs a high QE EMCCD:

$$SN_{mcp} = QE_{mcp} * I / [QE_{mcp} * I + \cancelto{0}{RN^2_{mcp}} + D_{mcp}]^{0.5}$$

$$SN_{ccd} = QE_{ccd} * I / [QE_{ccd} * I + \cancelto{0}{RN^2_{ccd}} + CIC_{ccd} + D_{ccd}]^{0.5}$$

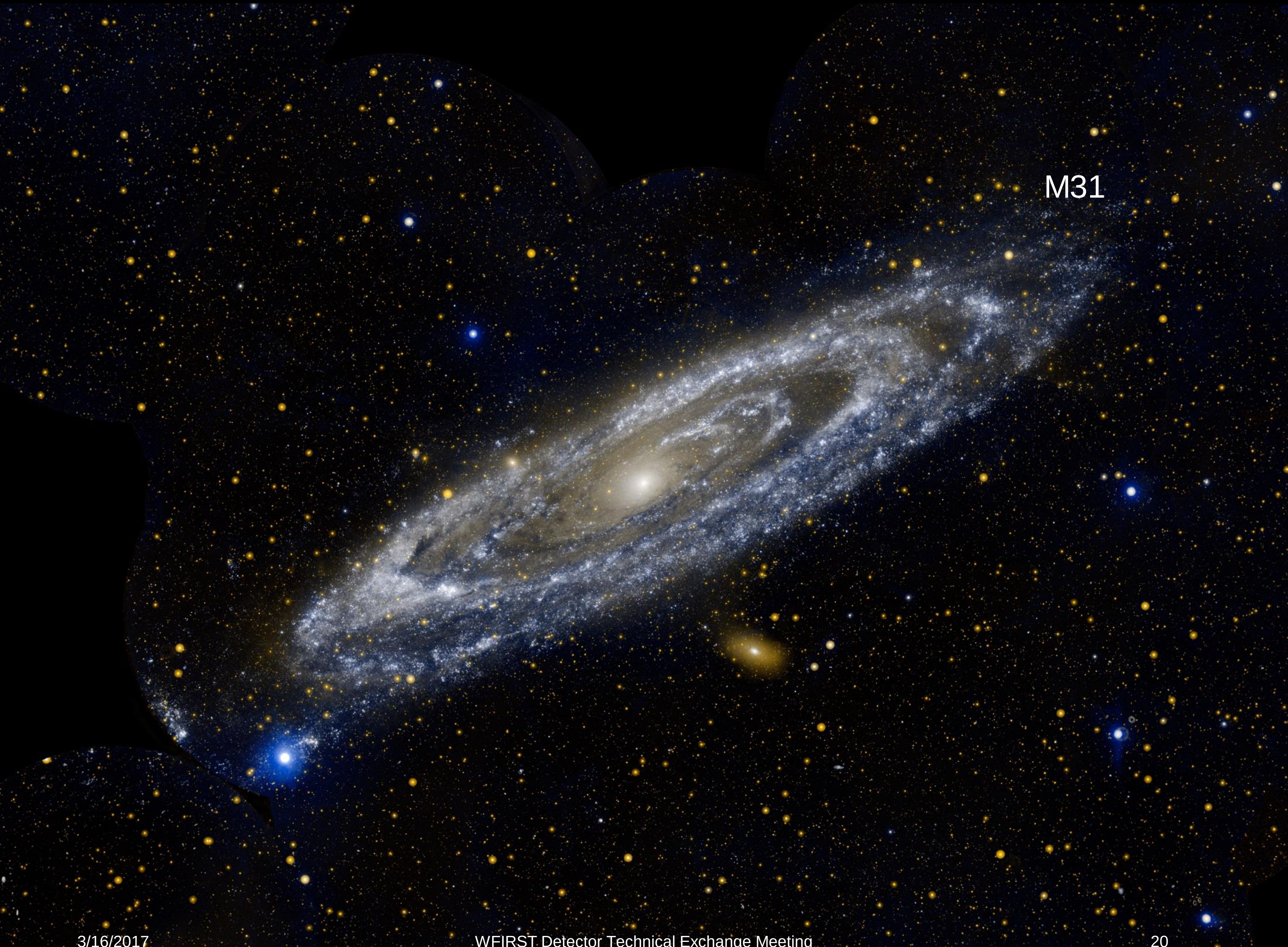
Low signal limit:

$$\longrightarrow SN_{mcp}/SN_{ccd} = QE_{mcp}/QE_{ccd} * [CIC_{ccd} + D_{ccd}]^{0.5} / D_{mcp}^{0.5}$$

and if CIC can be neglected as well,

What is D_{ccd}?

$$SN_{mcp}/SN_{ccd} = QE_{mcp}/QE_{ccd} * [D_{ccd}/D_{mcp}]^{0.5} = 0.3*3 = 1$$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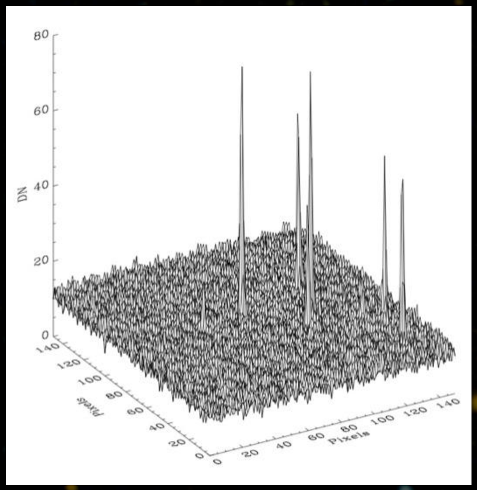
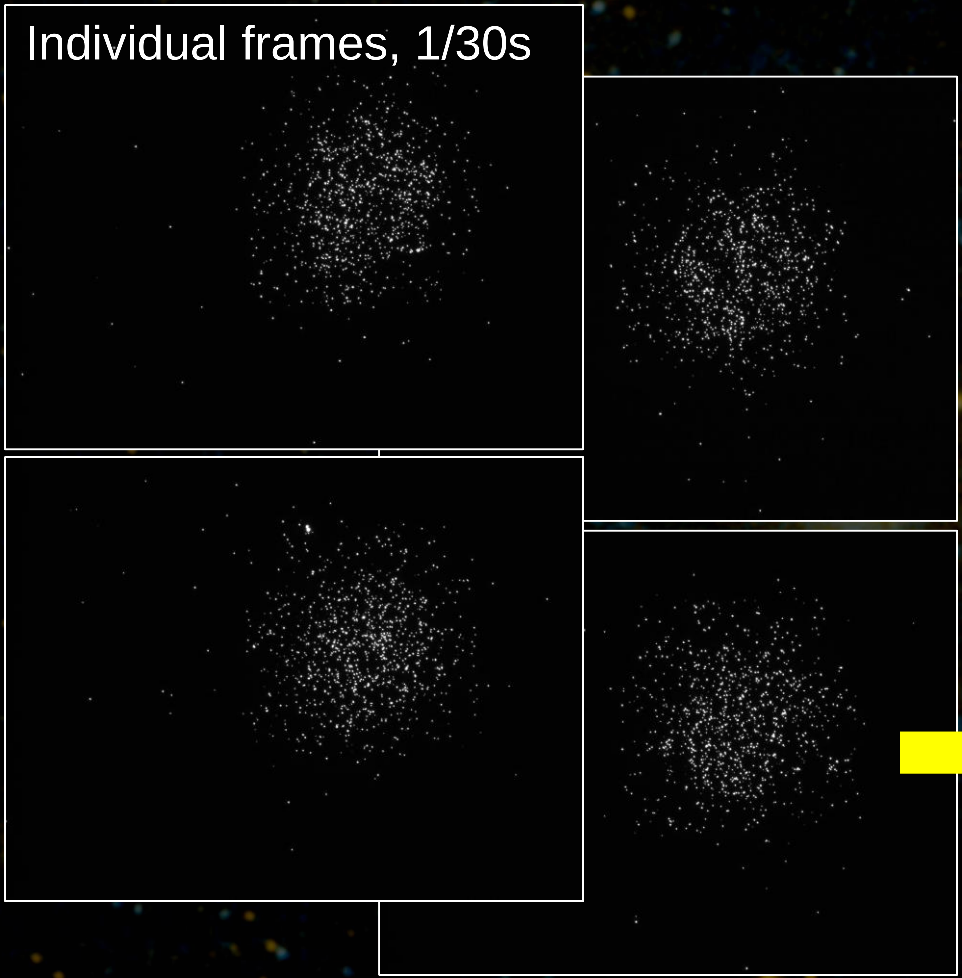
iCCD Laboratory Evaluation 1

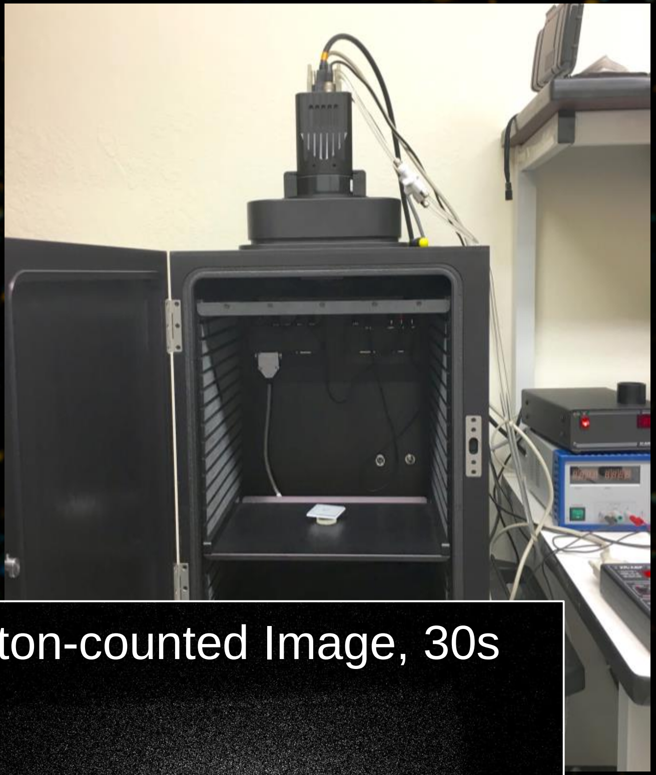
- We have identified a commercial iCCD camera with a GaAsP (optical) cathode that runs at -20 C and 120 fps (640x480). The active area of the detector is 12.8x9.6mm, comparable to the e2v CCD201.
- Other cathodes are available and could be special ordered.
- Dark frame test data confirms a rate of 29.5 $c/s/cm^2$, which scales to 0.18 $c\text{-}px^{-1}\text{-}hr^{-1}$ (very low!) in a 13 μm square pixel. This is at least as good as the beginning-of-life dark current of the CCD. **Unlike the CCD, MCP dark will not degrade during the mission lifetime.**

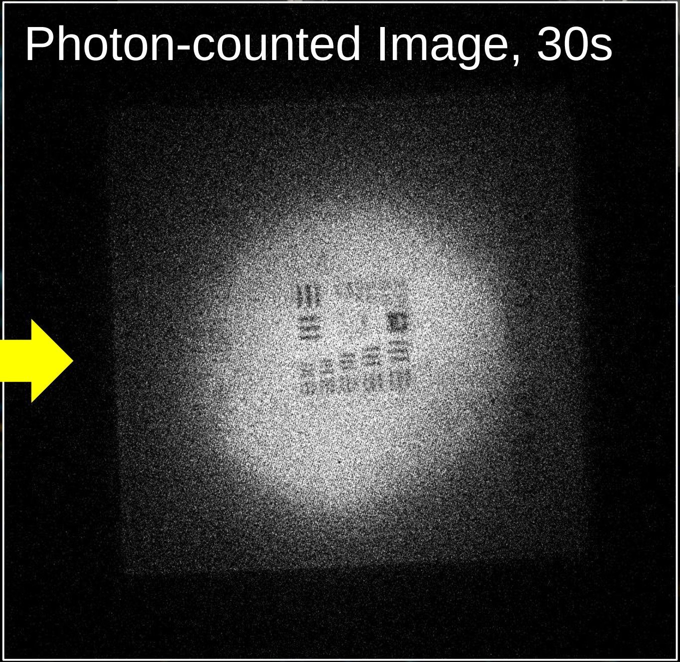


iCCD Laboratory Evaluation 2



Individual frames, 1/30s

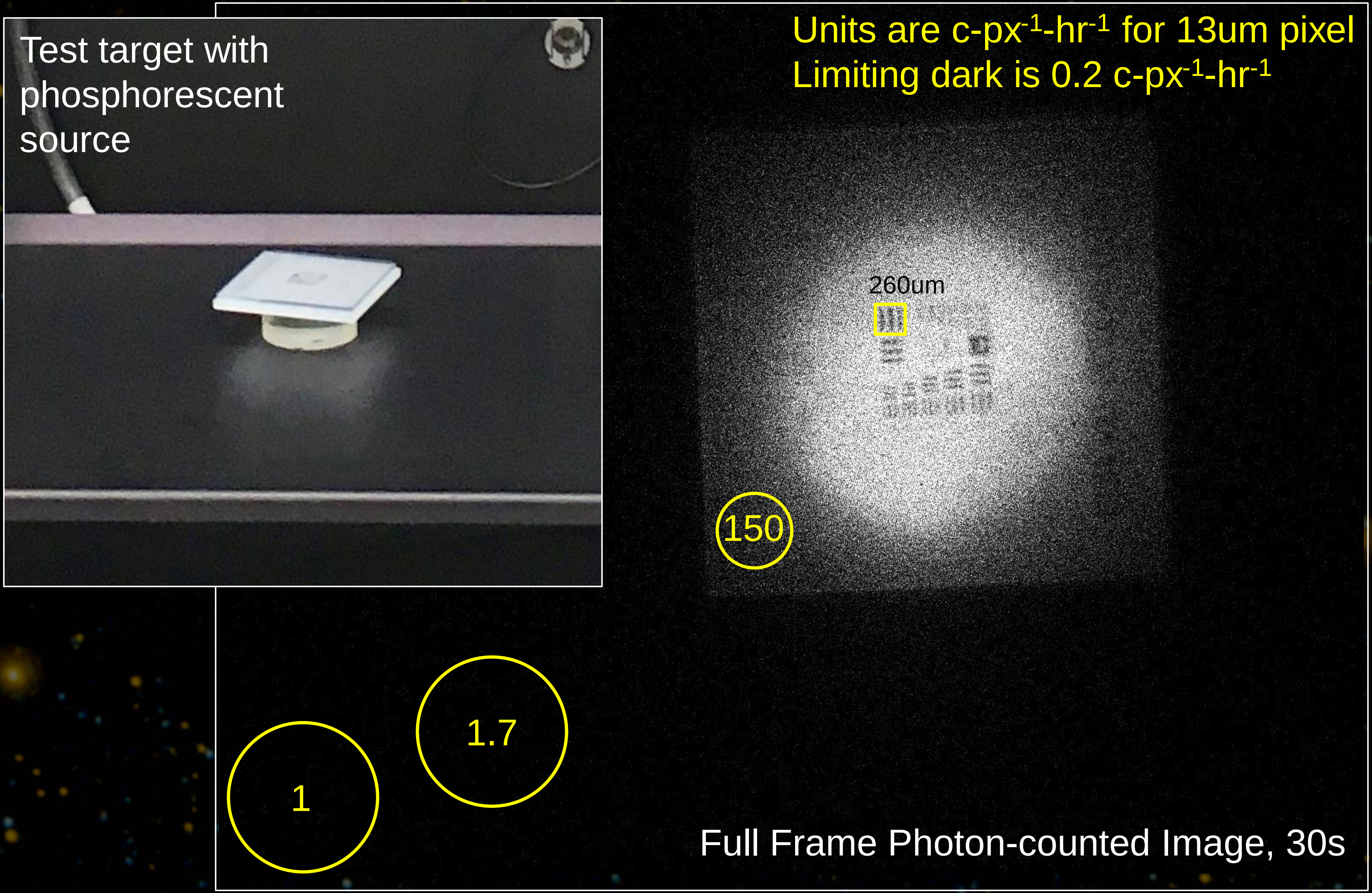




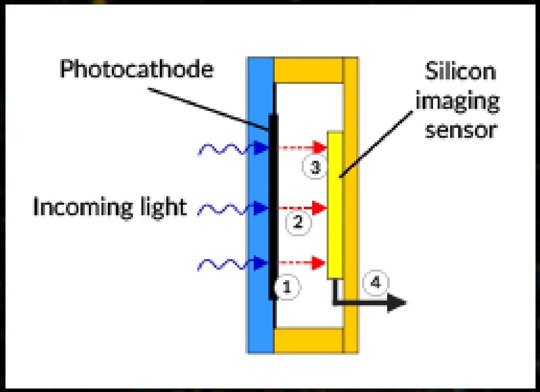
Photon-counted Image, 30s

We don’t have much data on this presently-unfunded concept, but the resolution looks in line with expectations.

iCCD Laboratory Evaluation 3



EBAPS Concept



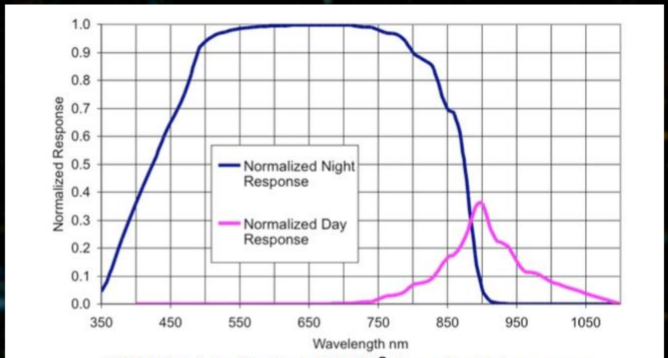


FIGURE 4.1 GaAs EBAPS® Spectral Response

TABLE 3.1 NightVista, ISIE6, and ISIE10 key specifications

	NightVista	ISIE6	ISIE10
Format	VGA 640 x 480	SXGA 1280 x 1024	SXGA 1280 x 1024
Pixel Size	12.0µm x 12.0µm	6.7µm x 6.7µm	10.8µm x 10.8µm
Optical Format	1/2" (9.8mm diagonal)	2/3" (11mm diagonal)	1" (17.7mm diagonal)
Frame Rate	30 frames per second	27.5 frames per second	Up to 37 frames per second
Video Output	RS-170 or interlaced digital video	10 bit Digital Output, progressive scan	10 bit Digital Output, progressive scan

TABLE 3.2 Common EBAPS Sensor Characteristics

	Photocathode	GaAs (500nm – 900nm Band)
	High Voltage Power Supply	Gated for Dynamic Range Control
*	**24 Hour Capability**	Daytime imaging with High Voltage off

Similar GaAs cathode to iCCD but no MCP:
- Compact design
- Potentially higher QE, better linearity, lower HV

L3CCD BOL/EOL vs GaAs and GaAs(P)

	PC L3CCD		Cathode Designs		
	BOL	**EOL**	GaAs(P) I	GaAs(P) II	GaAs
Band (QE>20%)	350-950nm	350-950nm	350-700nm	350-750nm	450-850nm
Peak QE	93%	93%	50%	50%	30%
Charge detection factor	0.85	0.85	0.6	0.6	0.6
Non-linearity factor	1	.4	1	1	1
Cosmic ray factor	.992	.916	1	1	1
dQE	78%	29%	30%	30%	18%
CIC ($e\text{-}px^{-1}\text{-}fr^{-1}$)	0.003	0.003	0	0	0
Dark ($e\text{-}px^{-1}\text{-}hr^{-1}$)	0.1	2	0.2	0.4?	0.6?
Cerenkov/Flr ($e\text{-}px^{-1}\text{-}hr^{-1}$)	2?	2?	0?	0?	0?
Read (e^-)	0	0	0	0	0
Frame (s)	10	100	<0.1	<0.1	<0.1
Noise (e^-: 100 hrs, 16px)	44-71	58-81	17.9	25.3	31
dQE/Noise	**1.1-1.8**	**0.36-0.5**	**1.7**	**1.2**	**0.6**

MCP Test Program Path Forward

- Resolution
  - Needs to be quantitatively evaluated
- High count rate operability
  - Can the cathode be successfully gated to demonstrate flight-like target acquisition of bright stars (including with planned ND)?
  - Are bright features/stability of the dark hole problematic?
- Dark rate
  - What is the actual dark rate for the three variants of the GaAs(P) cathode?
  - Can the dark rate be further improved with a reduction in temperature below -20 °C?
  - Can Cerenkov/fluorescence/cosmic rays be removed effectively with no impact on the detector dark current?
- Lifetime
  - What is the lifetime expectation for the GaAs(P) cathode under realistic illumination conditions, including target acquisition?
  - Can realistic fault protection protect the cathode against pointing errors?

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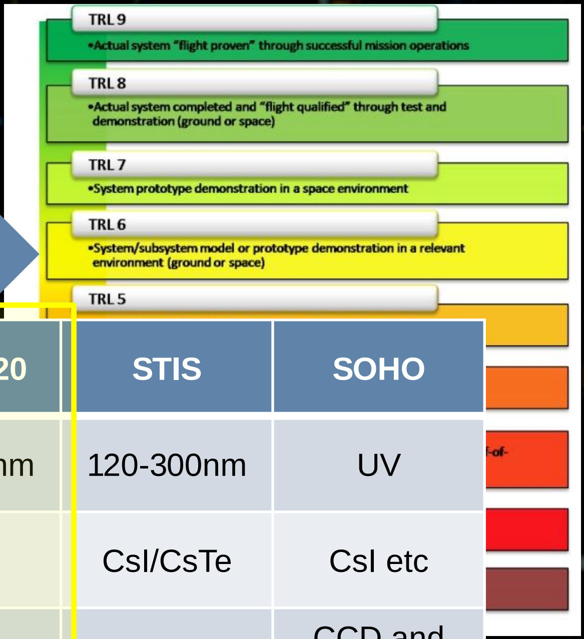
TRL Estimation



iCCD~6 based on SWIFT/MARS2020

	EBAPS	iCCD/CMOS	SWIFT/XMM UVOT	GALEX	Mars2020	STIS	SOHO
Band	400-850nm	400-850nm	170-650nm	120-300nm	400-850nm	120-300nm	UV
Cathode	GaAs	GaAs(P)	S20	CsI/CsTe	GaAs	CsI/CsTe	CsI etc
Readout	CMOS	CCD/CMOS	CCD	Anode	CCD	Anode	CCD and anode
Sealed Tube	✓	✓	✓	✓	✓	✓	✓
HV	2kV	5kV	5kV	5kV	5kV	3kV	1-5 kV
Operating Temp	-20° C	-20° C	+20° C	+20° C	0° C	+20° C	+20° C
Launch date	N/A	N/A	2004	2003	2020	1997	1995
Mission?	N/A	N/A	Operating	10 years	N/A	Operating	Operating

EBAPS TRL~4?

The closest proxies to the proposed iCCD/CMOS backup are the successful NASA SWIFT and ESA XMM Newton. Both are photon counting iCCD detectors identical in concept but with UV-optical S20 cathodes instead of the optical-NIR GaAs(P) cathode. The forthcoming Mars2020 SuperCam uses a sealed MCP intensifier with a GaAs cathode.

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iCCD/CMOS PROS and CONS

- PROs
  - The iCCD/CMOS design is likely to behave in flight the same as measured on the ground, and to not change significantly over time. It is rad-hard.
  - The iCCD/CMOS will exhibit the same linear response at beginning and end of mission (within the flux range of interest)
  - Designs that are nearly identical have flown (and are currently operating), providing an excellent baseline to establish performance expectations.
  - The iCCD/CMOS design can be framed rapidly, allowing Cerenkov and fluorescence light (but not phosphorescence) to be filtered.
  - The GaAs(P) cathodes exhibit very low dark current
  - Cooling is only required to -20 to -30 °C (vs -100 °C L3CCD).
  - Long lifetime may enable a starshade application at T+6-9 years
- CONs
  - The iCCD/CMOS can't match the BOL L3CCD performance, particularly in the RED.
  - The iCCD has lower QE than the L3CCD across the spectrum.
  - High Voltage is required
  - **Careful planning** for acquisition, operations, and fault protection is required.

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Recommendations

- The L3CCD is a novel new photon counting detector with high QE that is baselined for the WFIRST coronagraph. The detector has demonstrated a significant degradation in performance due to radiation damage at the JPL-recommended test level (2x 95% confidence level). The log-normal nature of the solar radiation dose means the *most likely* fluence is substantially lower.
  - R1: The science team should carefully evaluate the implications of the measured L3CCD performance and provide feedback on the requirements for a successful mission.
  - R2: The instrument team should further invest in the L3CCD technology to improve its performance in a radiation environment over the expected mission life.
  - R3: The instrument team should invest in reduced-level L3CCD radiation testing in order to better understand the performance risks at more likely exposure levels.
- The MCP detector has been around for decades and has a well-established heritage of successful space flight applications. Even though it has lower QE, its performance is competitive with the L3CCD for wavelengths <750nm because of its low background, which is not expected to change over the mission.
  - R4: The Project should consider investment in a commercial iCCD system that can be evaluated prior to PDR as a risk-reducing backup to the L3CCD.
- The EBAPS detector is a recent development with similar performance expectations to the MCP (perhaps with improved dQE, linearity and contrast), while providing operation at ~1/3 the voltage of the MCP in a compact, single-piece package.
  - R5: The EBAPS detector is a promising technology that could be evaluated by JPL as part of a general enhancement of photon counting detector expertise, but likely is too immature at this time to provide a compelling alternative to the iCCD/iCMOS design.

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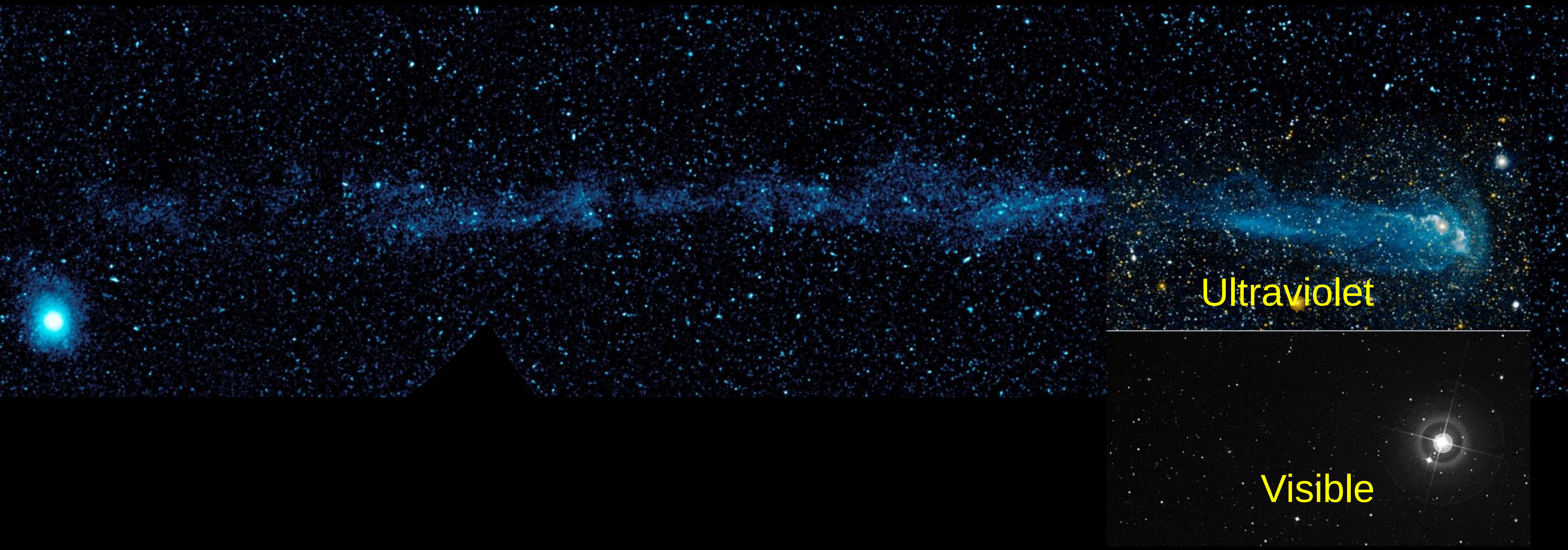
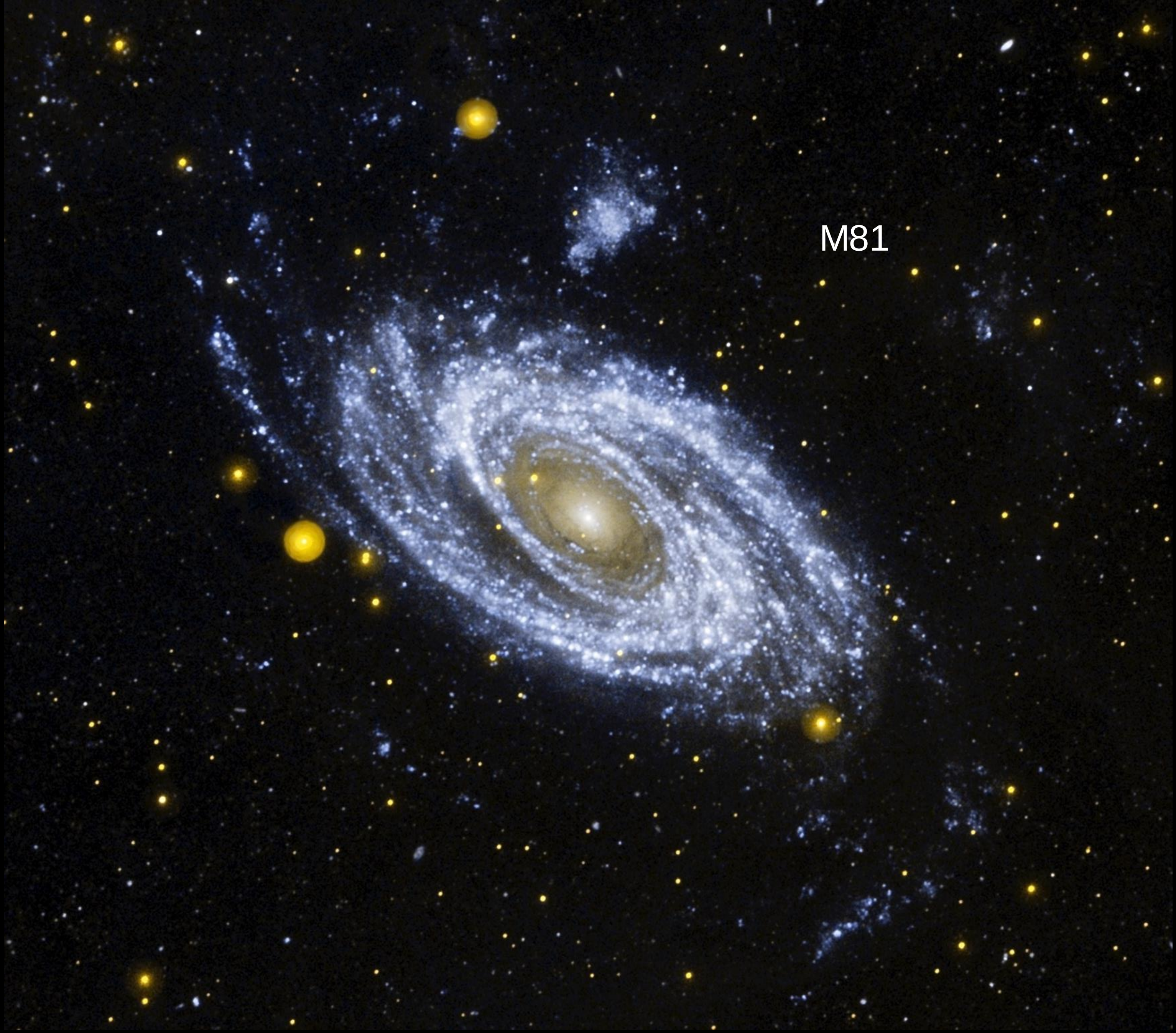
Mira




Stephan's Quintet


NGC6744


M81

Backup

Some Alternate Detectors

	CMOS	EMCCD	MCP-Intensified CMOS/CCD	MCP-Anode Readout
Format	1kx1k, 2kx2k	1kx1k, 2kx2k	18, 40mm standard	GALEX 70 mm
Resolution*	~12μ m	~25μ m	~25μ m	40μ m
Read noise	~1-5e^-	0	0	0
Dark current	Si	Si	Cathode	Cathode
Rad-hard	Yes	No	Yes	Yes
Cryogenic	Yes	Yes	No	No
High Voltage	No	No	Yes	Yes
Flight heritage	✗**	✗	✓	✓

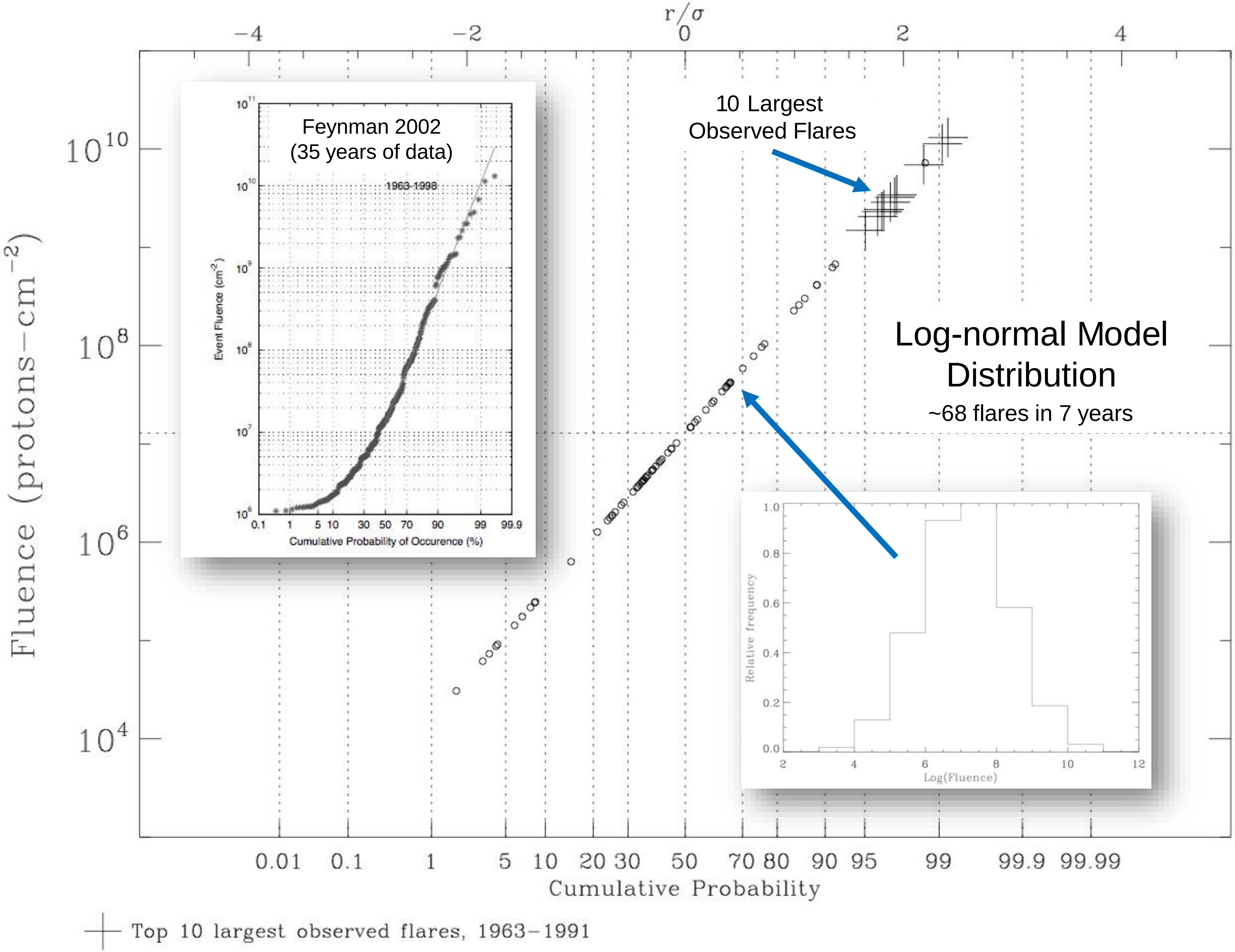
*Resolution is FWHM or 2 pixels
**There is currently no flight experience with CMOS requiring 1e- measurements

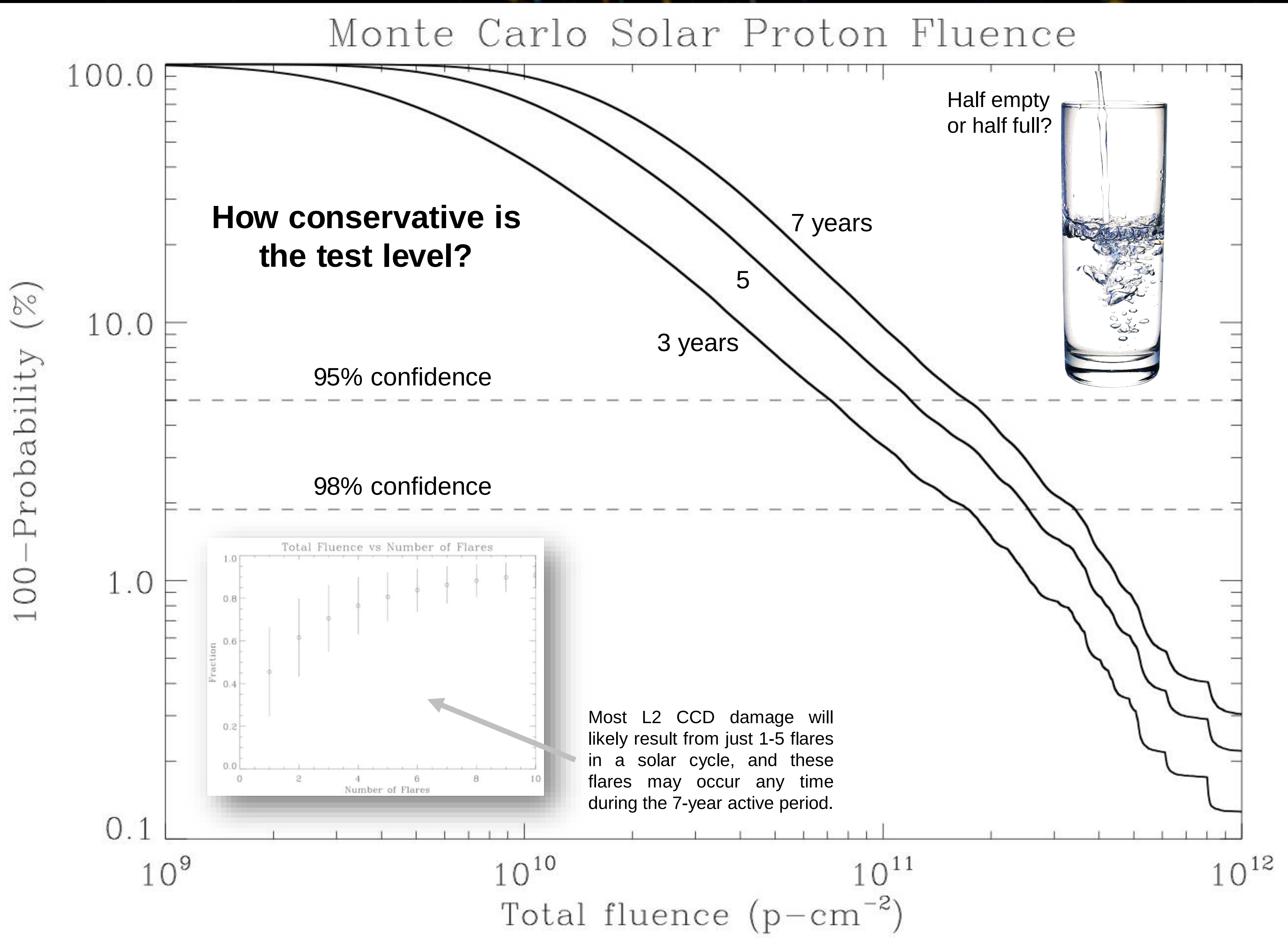
Highest QE
Good Resolution

Lowest Noise
Most Rugged

Also EBAPS

E>10MeV Event Fluence Distribution

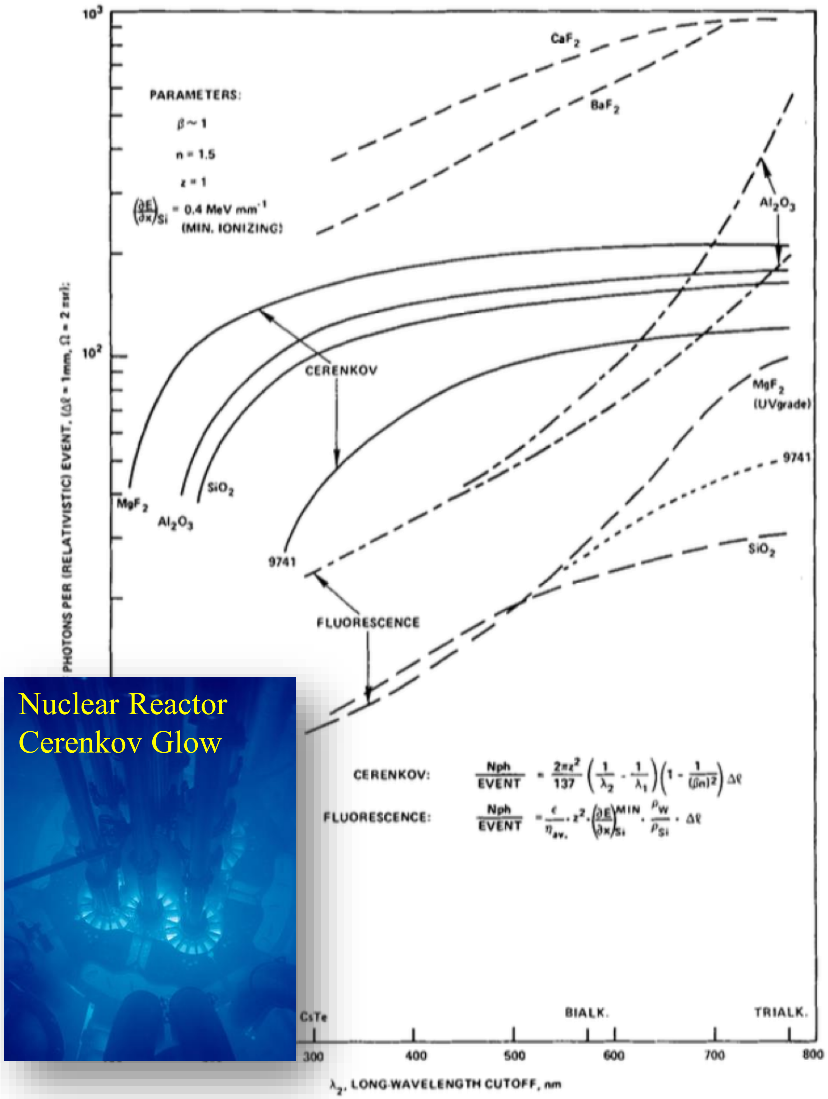



Monte Carlo Solar Proton Fluence
100.0
10.0
1.0
0.1
100−Probability (%)
10^9
10^{10}
10^{11}
10^{12}
Total fluence (p−cm^{-2})
How conservative is the test level?
7 years
5
3 years
95% confidence
98% confidence
Half empty or half full?
Total Fluence vs Number of Flares
Fraction
Number of Flares
Most L2 CCD damage will likely result from just 1-5 flares in a solar cycle, and these flares may occur any time during the 7-year active period.

Cerenkov Radiation and Phosphorescence

High energy particles (cosmic rays) travelling through matter radiate with a blue glow from the **Cerenkov effect**. In space, this can produce an undesirable background in an integrating detector such as the EMCCD.

- The direct imaging channel currently has a protective fused silica window in front of it that will produce Cerenkov light.
- The IFS has a thick CaF_2 lens close to the CCD that will also produce Cerenkov light.
  - CaF_2 is also known to be a potential source of **phosphorescence**
- **Preliminary estimates are that Cerenkov light in the DI window will enhance the EMCCD detector dark current, and may dominate the background in the IFS**.
- A readout faster than the cosmic ray rate can successfully mitigate Cerenkov (>>10fps).



Shielding Experiments

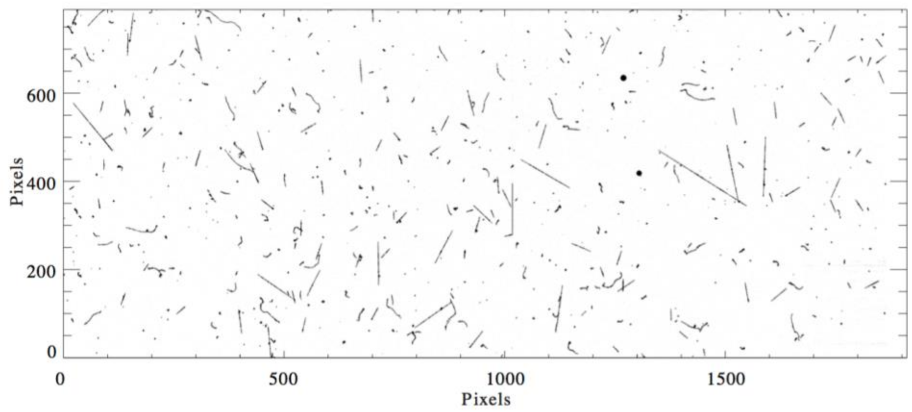
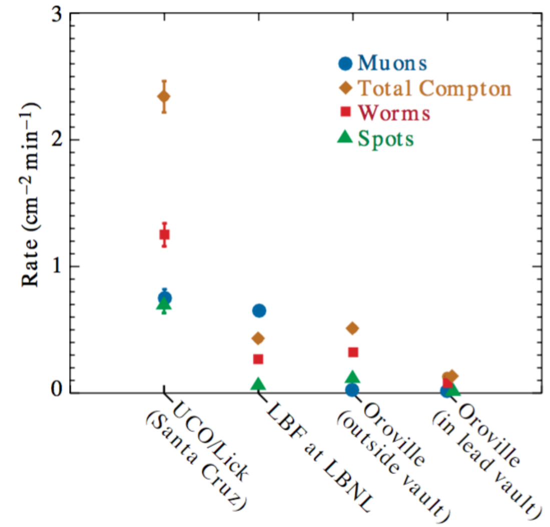


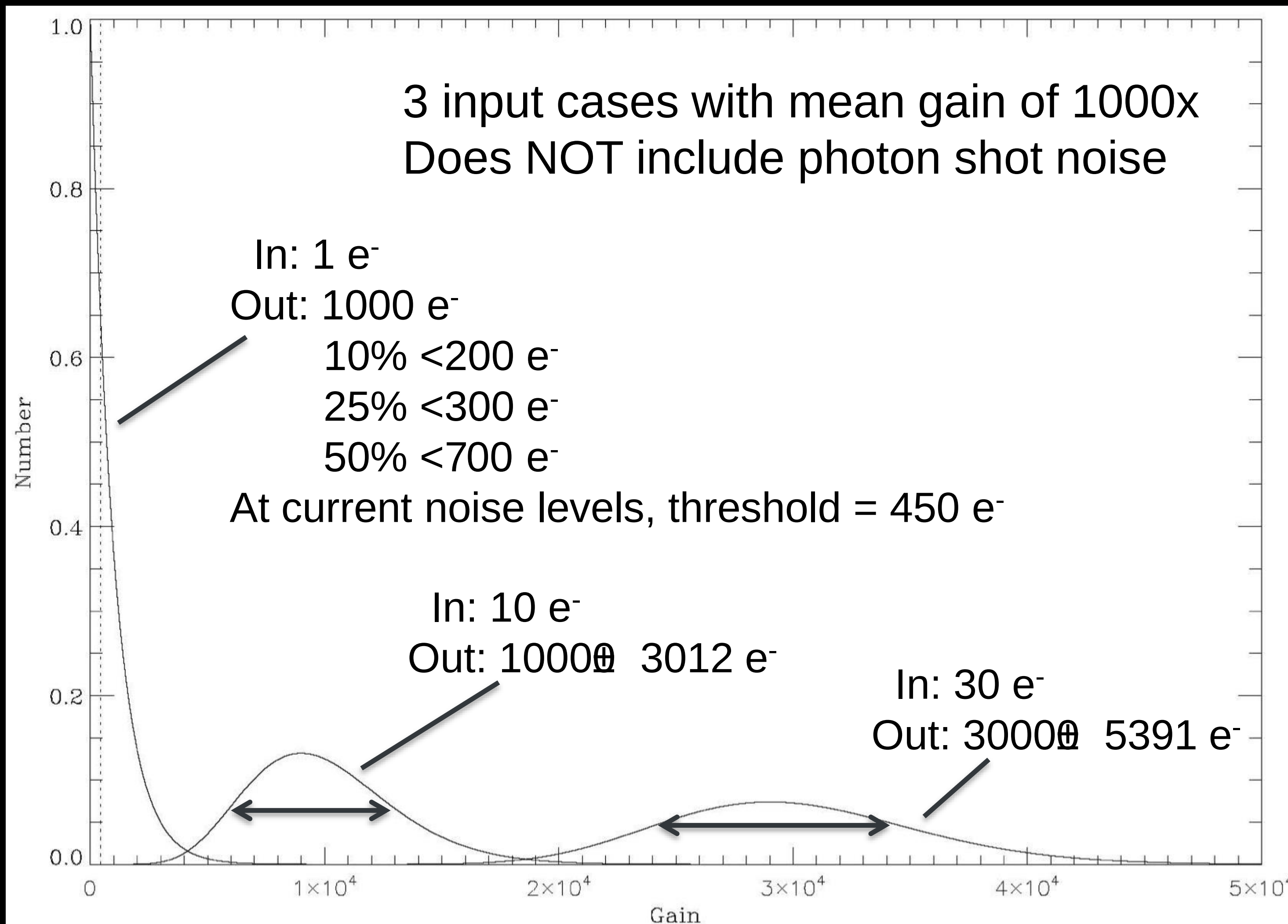
Figure 1. A 1980 pixel × 800 pixel subfield of a 3600 s dark exposure (totally depleted 270-μm thick LBNL CCD, NOAO CCD laboratory in Tucson), showing cosmic-ray muons (straight tracks), worms (low-energy electrons),and spots. While the spots look insignificant, they are about as abundant as the worms and can indicate considerable deposited energy.



Smith et al SPIE 2002:

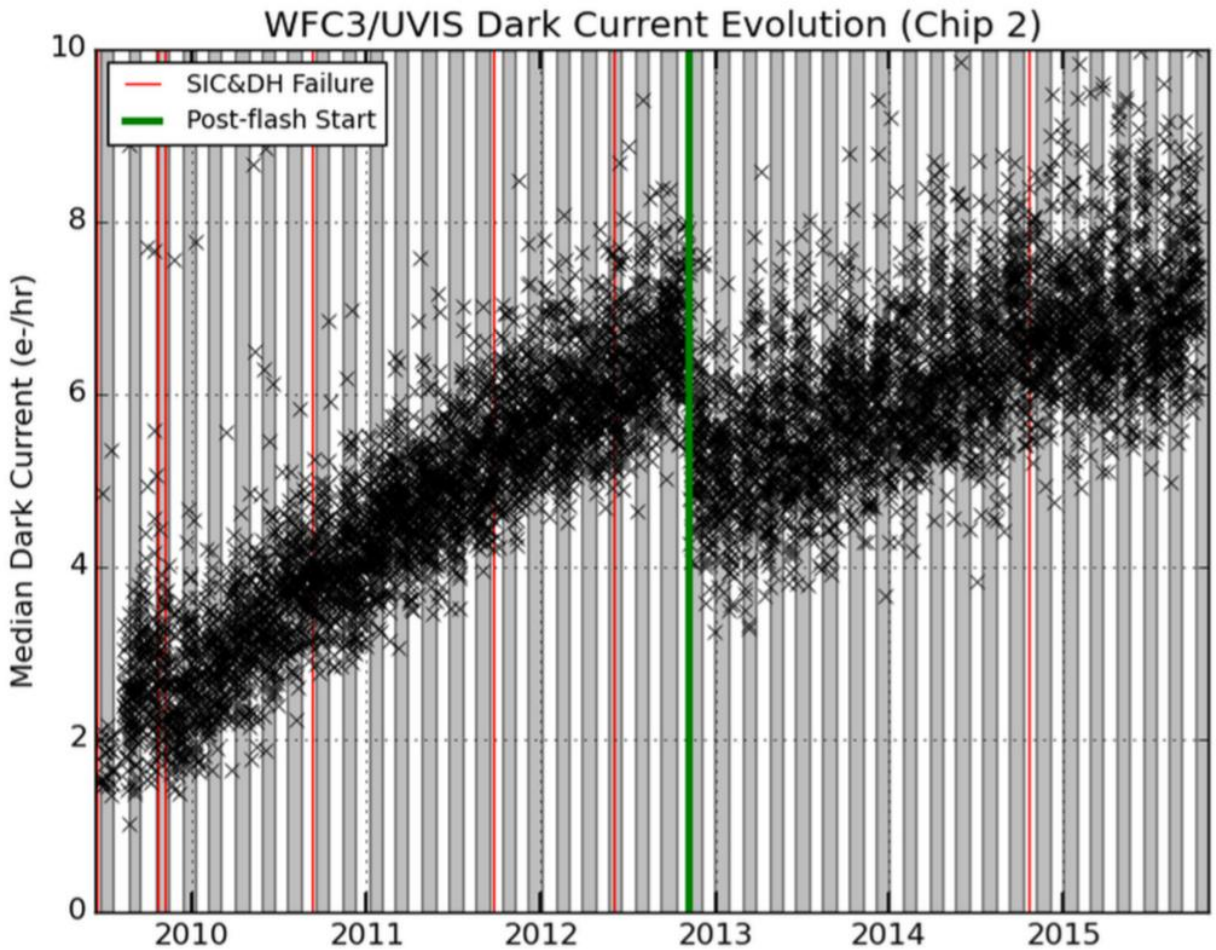
- Particle track shapes in a thick CCD can distinguish radioactive decays from muons.
- Muon energies are of order GeV, while radioactive decay gammas are of order MeV.
- The muon rate was unaffected by 1.5m of low background cement shielding
- The muon rate was affected by 480 meters (!) of water

Theoretical Considerations



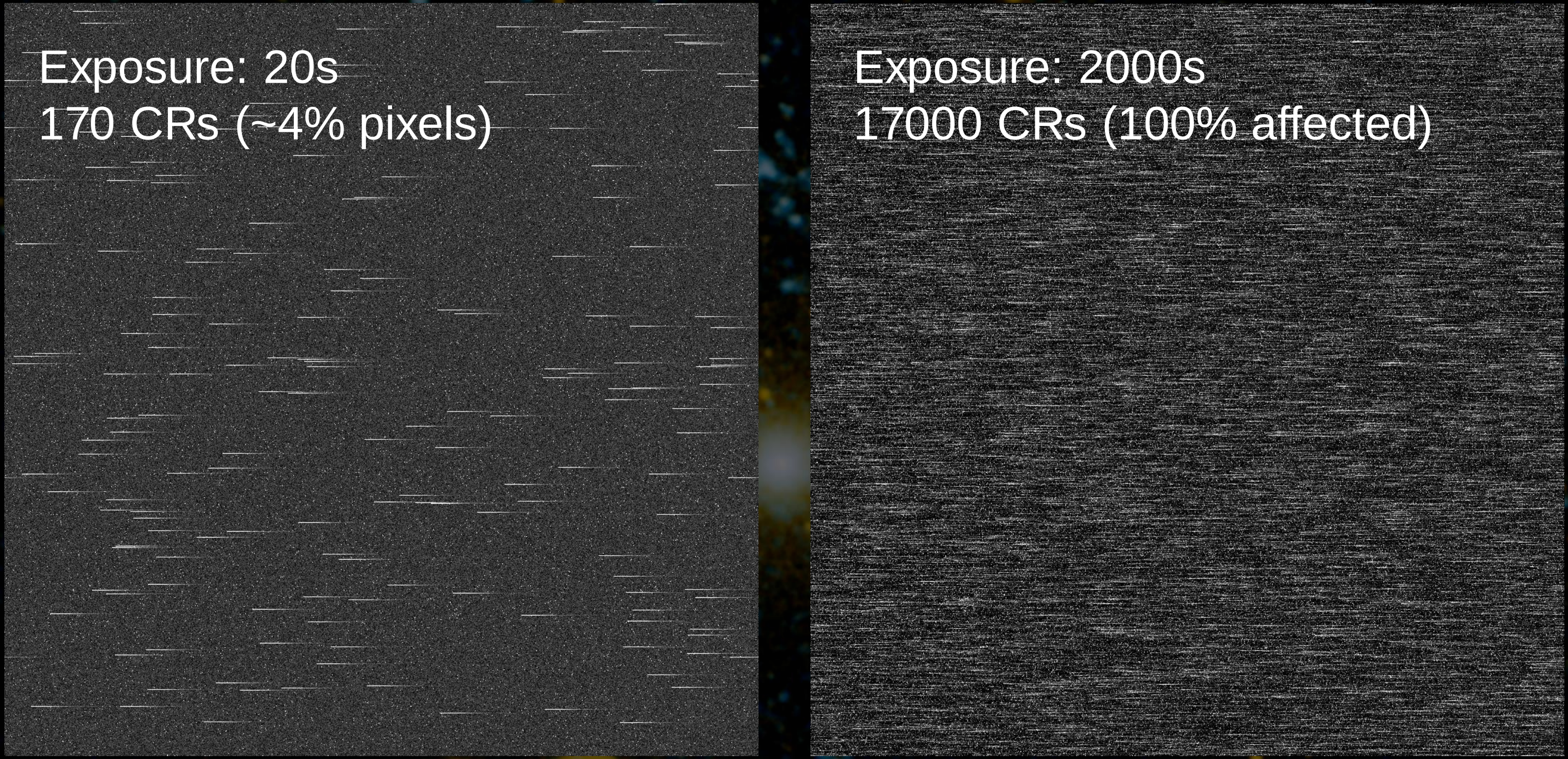
HST WFC3 Experience: Dark Current

Figure 5.7: Median dark current of the WFC3/UVIS detector measured on orbit from June 2009 to Oct 2015. The use of post-flash accounts for the discontinuity in Nov 2012.



WFC3 Instrument Handbook

Cosmic Ray Consequences



The expected L2 CR flux of 5 cm^{-2}-s^{-1} combined with >100 pixels of EM register smear has very important consequences for the EMCCD:

1. Frame times must be short (<100s)
2. Read noise and CIC become relatively more important
3. Photon counting is required to overcome these noise sources.
4. Low level CTE becomes a critical performance parameter

EMCCD Radiation Damage

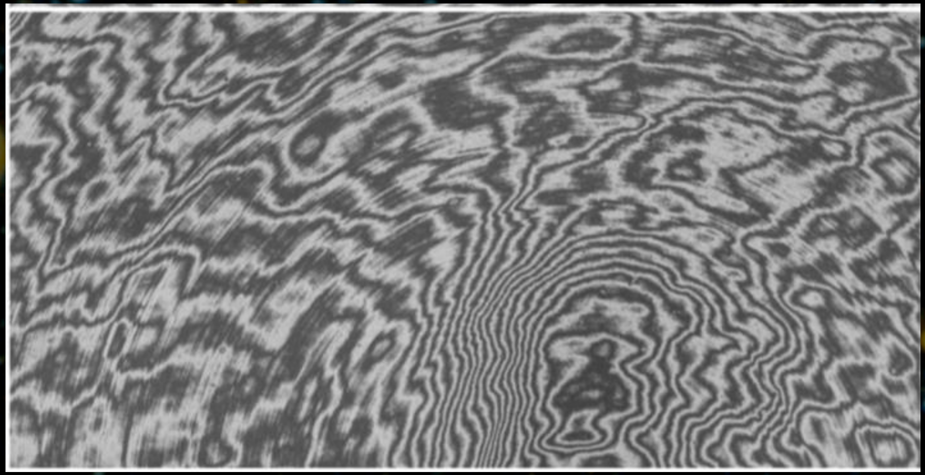
- Radiation damage is a major focus of the JPL program to qualify EMCCDs for flight. Testing is underway, but the likely outcome is that a careful effort will be required to shield the EMCCDs during the 6 year WFIRST mission.
  - Shielding yields diminishing returns beyond a certain point.
- Considerable experience from HST is available on the consequences of radiation damage in thin silicon CCDs much like the CCD201.
  - Experience from the HST WFC3 shows that faint object detections are vulnerable to traps created in the silicon by energetic particles.
  - Traps capture the charge they need to be satisfied (additive), allowing a large fraction of high signal events to proceed.
  - Traps capture the **entire signal** from an EMCCD detection (never more than 1 e^-). This trapped signal will be released at a later time, displacing the detection and lowering the signal-to-noise ratio in the process.

EMCCD Dark Current

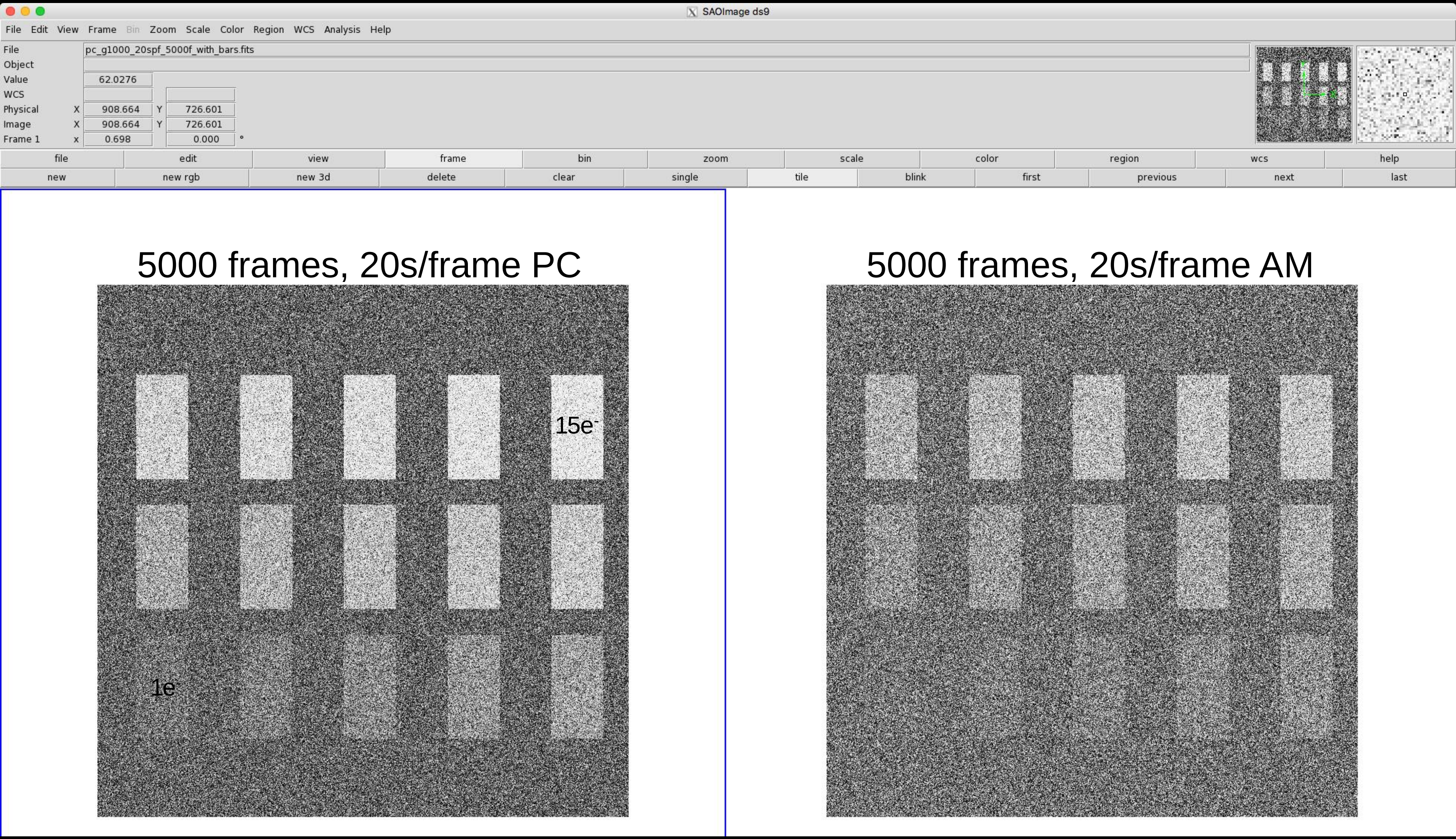
- The EMCCD can in principle achieve very low dark current, and this is required to make detections at the low levels we anticipate. At -85 °C, dark current (~2 e^{-}-pixel^{-1}-hr^{-1}) is the limiting source of noise in the photon counting EMCCD.
  - Efforts to drive the dark current to extraordinarily low levels have been thwarted by degraded CTE, which smears images as the detectors are cooled below about -110 °C.
  - Dark variability has been observed with a power cycle or bright illumination that exposes surface traps. This enhanced dark (~10x) may take hours to decay.
  - The high frame rate constraint imposed by cosmic rays places a CIC noise floor of about 0.14 e^{-}-pixel^{-1}-hr^{-1} regardless of the dark current that may be achieved.
- HST experience shows that the dark current can be expected to rise steadily in flight as the device is exposed to radiation.
  - Dark current and hot pixel enhancement in flight is typically mitigated by monthly “anneal” cycles during which the detector is warmed to 20 °C. This anneal cycle is likely to be required by the WFIRST EMCCD and may be a ~10% burden on operational efficiency.

EMCCD Red Fringing

- The EMCCD is fundamentally a thin silicon CCD like any other. Silicon becomes transparent at long wavelengths (>700nm), which is why red sensitive CCDs use much thicker substrates (~10X) than the CCD201, at the expense of higher noise and lower resolution.
  - Red light “etalons” inside the 10 μm silicon CCD epitaxial layer, causing interference fringes that are a function of the incident light bandwidth, position and focal ratio.
  - The effect of fringes may have a significant impact on the interpretation of integral field spectra, which will be distributed all across the detector.
- The HST WFC3 employs a thin e2v CCD that is in many respects similar to the CCD201. The WFC3 instrument handbook reports ~30% fringing at the longest red wavelengths.


HST WFC3 977 nm

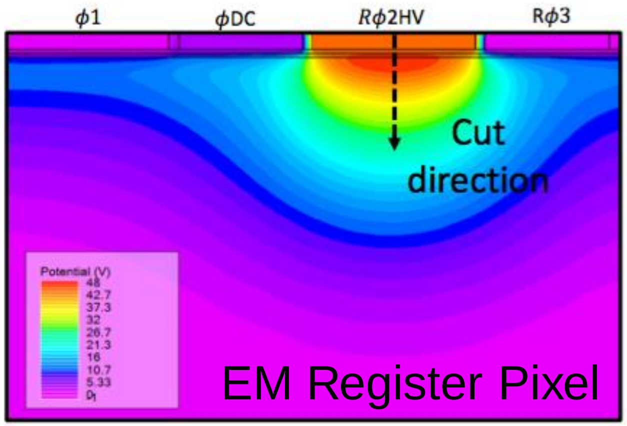
Results: PC vs Analog Mode

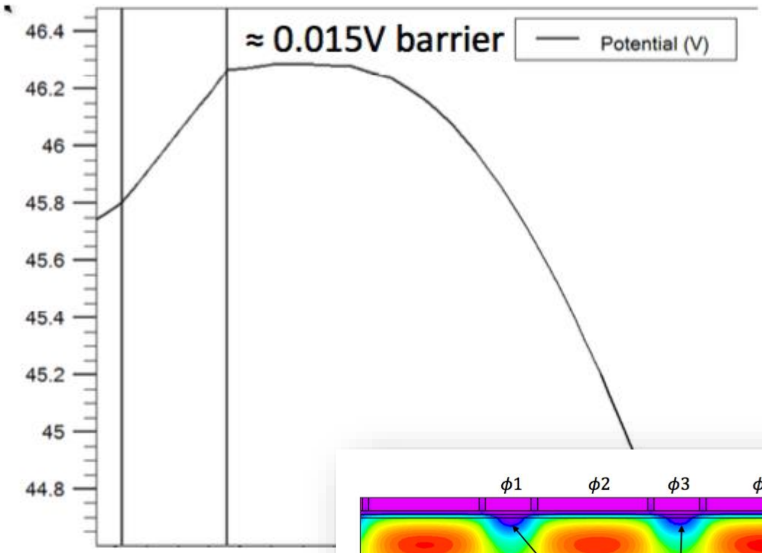


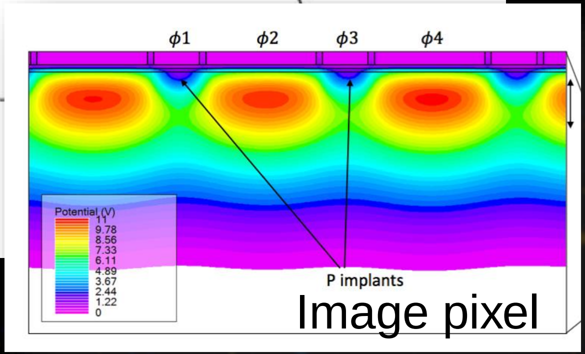
Surface Charge Trapping in an EM Register

- For larger signals, the peak charge storage density starts to become comparable to the dopant density. The potential well starts to be deformed due to the storage of signal and so the potential barrier with respect to the surface is reduced. Signal starts to interact with interface traps.

Signal in well ≈ 6000e⁻







The Open University e2V

Courtesy N. Bush, CEI

Jet Propulsion Laboratory
California Institute of Technology