ULTRAVIOLET DETECTORS FOR LOW SURFACE BRIGHTNESS ASTRONOMY

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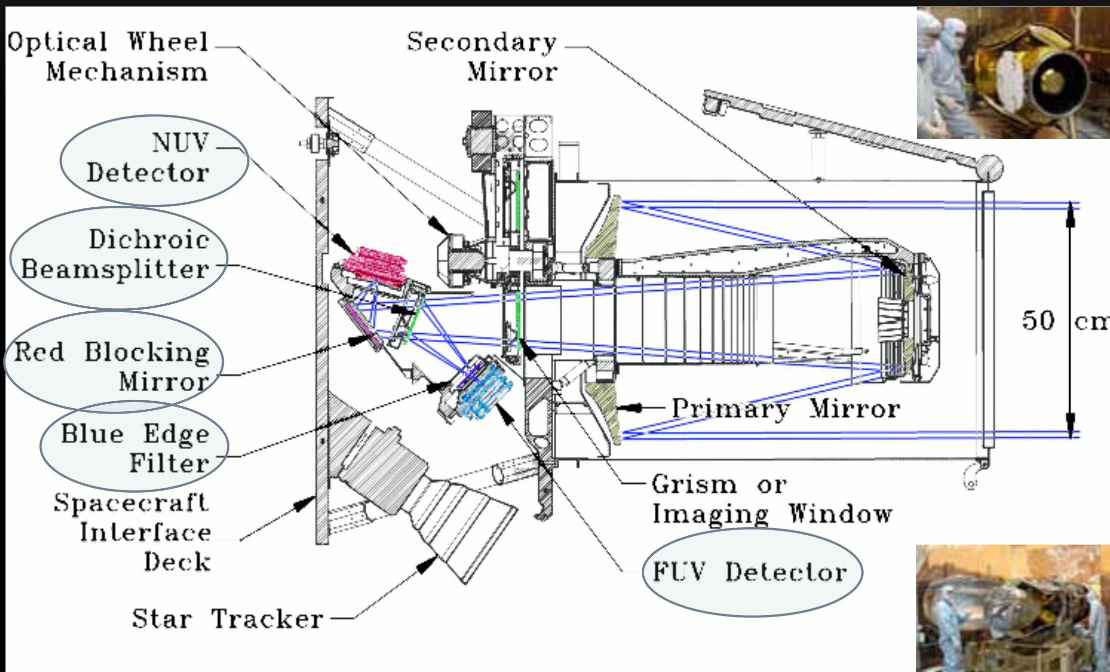
OVERVIEW



Our group is operating the NASA Small Explorer GALEX, a UV all-sky survey mission now completing its eight year mission.

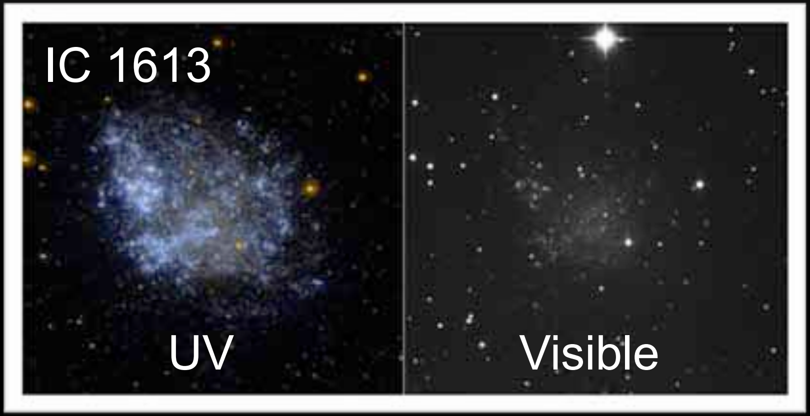
- **Why the UV, why photon counting?**
- **Technologies for what's next.**
- **Results**

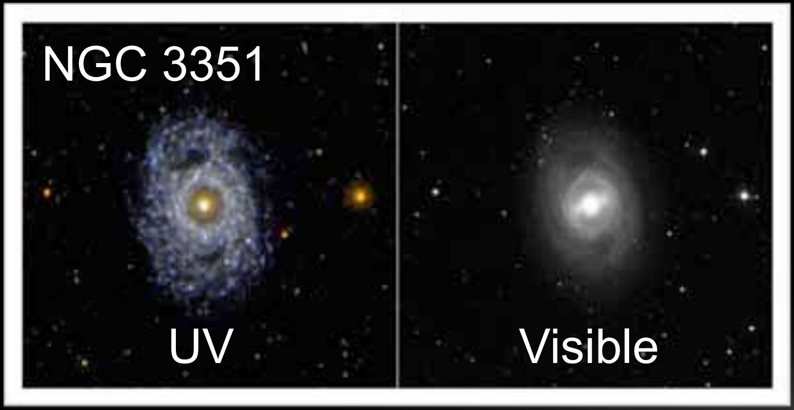
WHY PHOTON COUNTING?

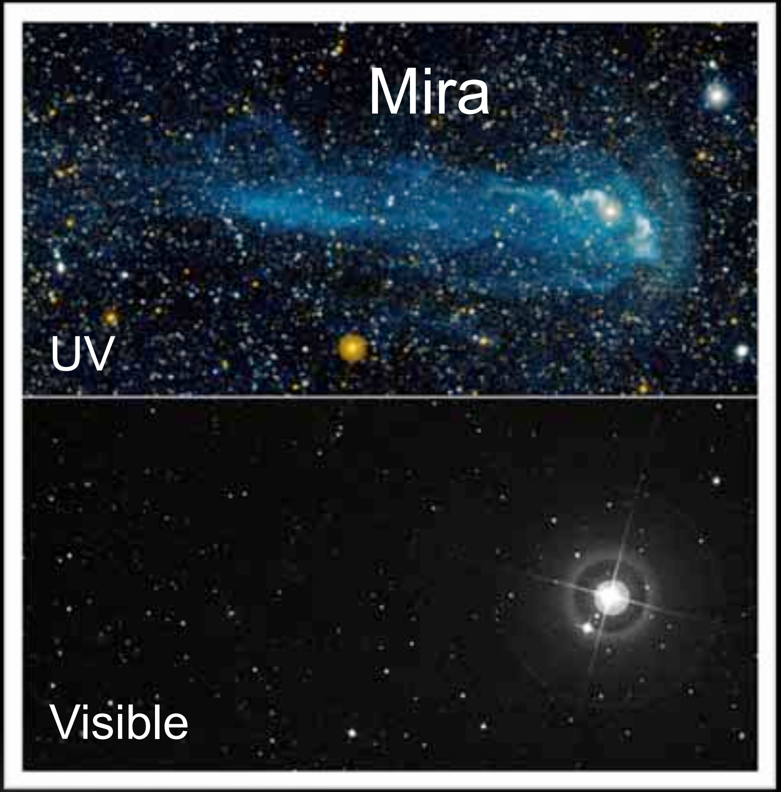
GALEX FUV ~ 2000 cps (1.25 deg FOV)

- About ½ is "background"
- 500 photons-s^{-1}-cm^{-2}-sr^{-1}-$Å^{-1}$
- In a pixel (~1"), this translates to only
-         ~1e-8 photons-s^{-1}-cm^{-2}-$Å^{-1}$
- Even broad band, that's ~10^{-4} c-s^{-1}-$pixel^{-1}$
- **Reasonable exposures are completely dominated by conventional CCD read noise at the 1 e^- level!**

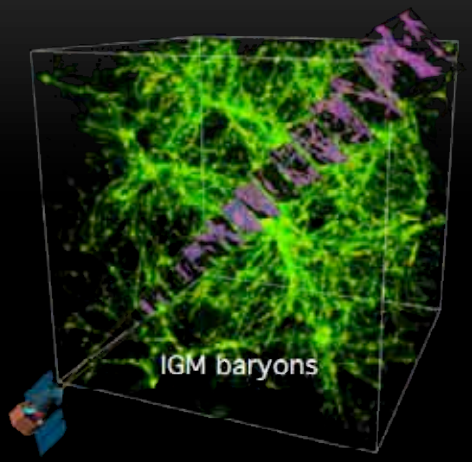
DARK UV SKY ENABLES FAINT DETECTIONS







FOLLOW-ON MISSION GOALS



A small and affordable instrument size and weight with demonstrated and large sensitivity gain will improve selection odds.

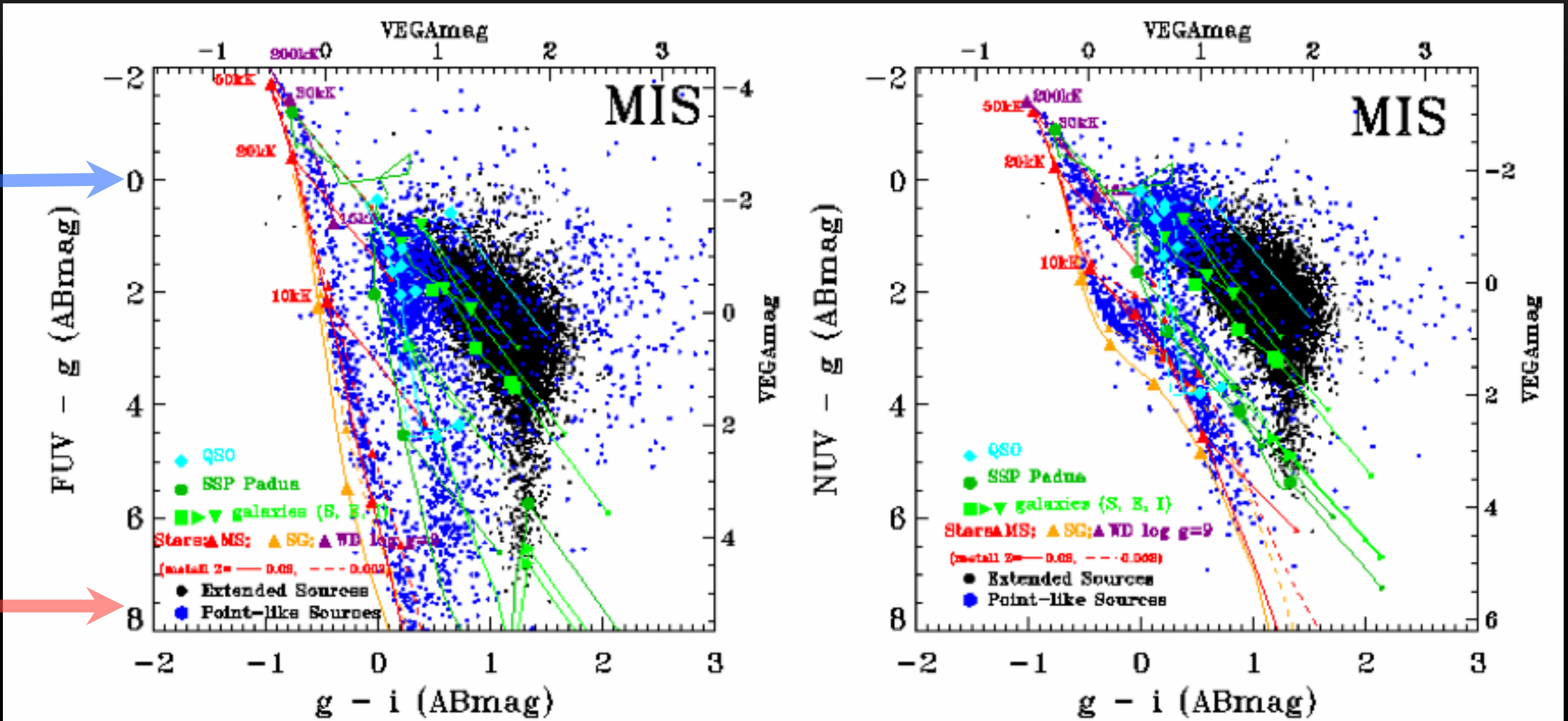
- High QE requires AR-coated, δ-doped silicon
- Low noise requires L3 technology
- Red leak requirements are manageable
- Decreased sky background is desirable

  - ➢ Spectroscopy
    - ✓ IGM
    - ✓ All the things GALEX looks at, but in narrow bands for improved S/N

"Red Leak" Requirements

F(FUV)/F(opt) = 1

F(FUV)/F(opt) = 1/1000



GALEX Medium-deep survey data, Bianchi et al (2007)

Nearly **all** objects that GALEX detects have 0.001<F(FUV)/F(opt)<1

The long wavelength filtering (red blocking) requirement for GALEX detected objects is <u>much less stringent</u> than generally quoted.

DELTA DOPING

1992
Applied
Physics
Letters

Growth of a delta-doped silicon layer by molecular beam epitaxy on a charge-coupled device for reflection-limited ultraviolet quantum efficiency

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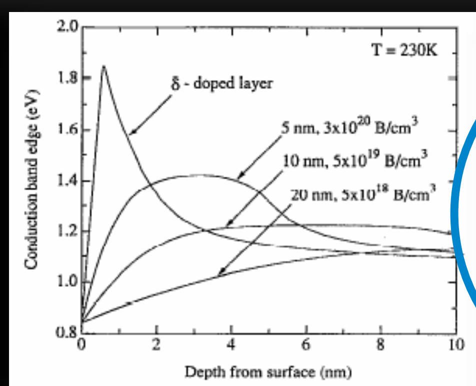
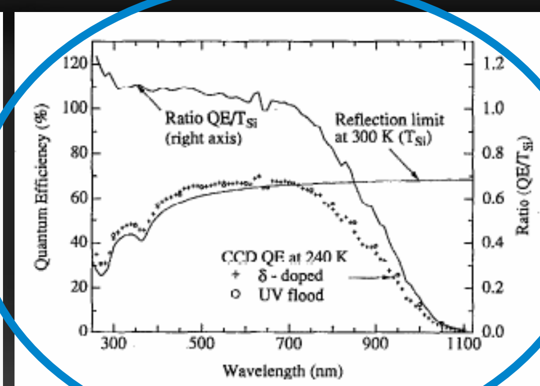
(Received 28 April 1992; accepted for publication 30 June 1992)

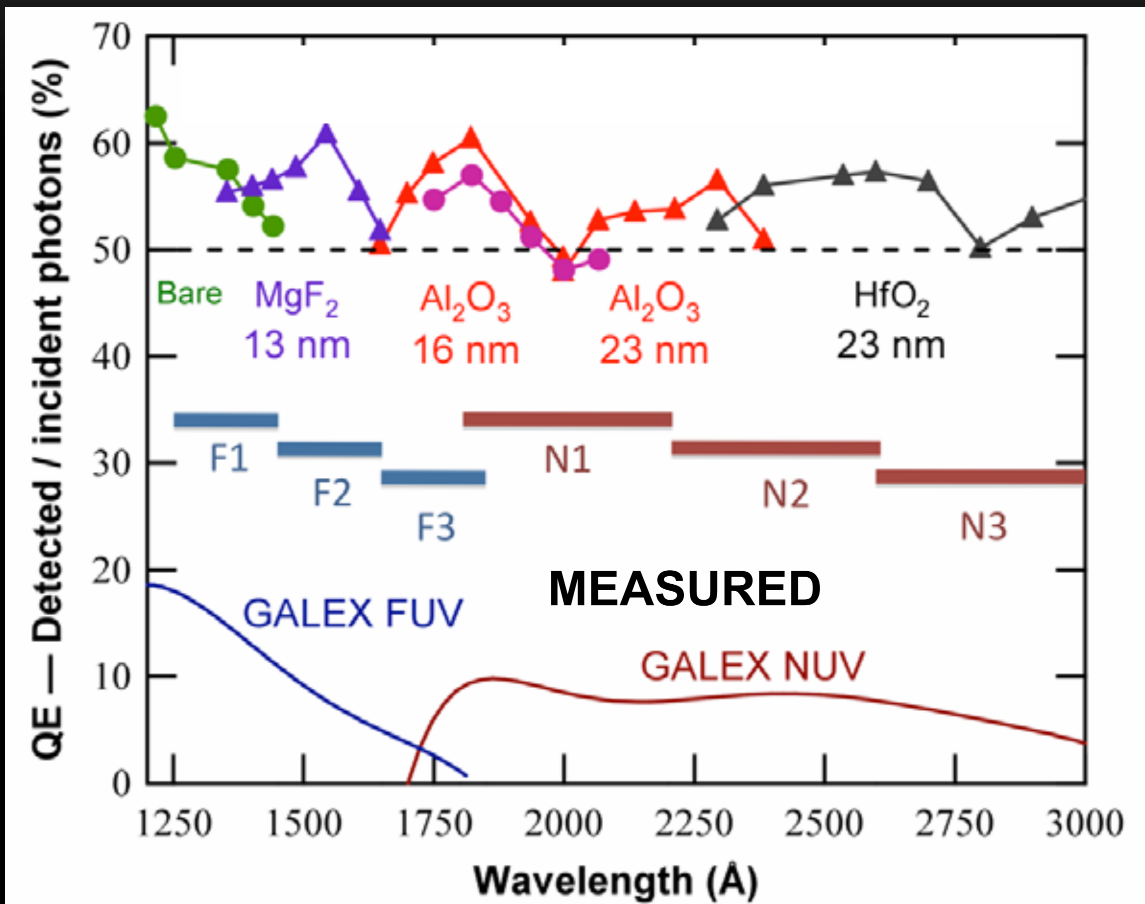
We have used low-temperature silicon molecular beam epitaxy to grow a δ-doped silicon layer on a fully processed charge-coupled device (CCD). The measured quantum efficiency of the δ-doped backside-thinned EG&G Reticon CCD is in agreement with the reflection limit for light incident on the back surface in the spectral range of 260–600 nm. The 2.5 nm silicon layer, grown at 450 °C, contained a boron δ-layer with surface density $\sim 2\times10^{14}$ cm^{-2}. Passivation of the surface was done by steam oxidation of a nominally undoped 1.5 nm Si cap layer. The UV quantum efficiency was found to be uniform and stable with respect to thermal cycling and illumination conditions.

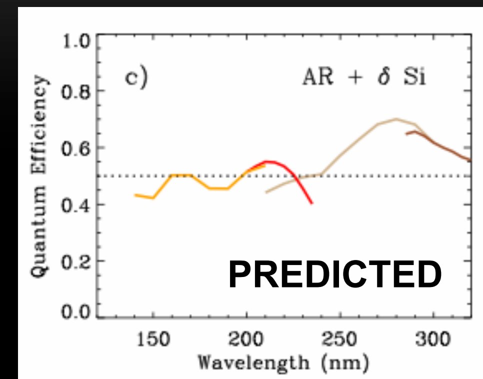


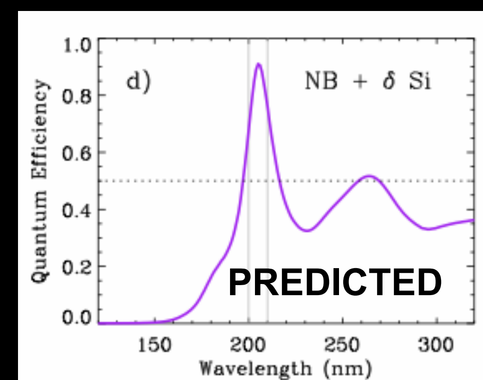


!

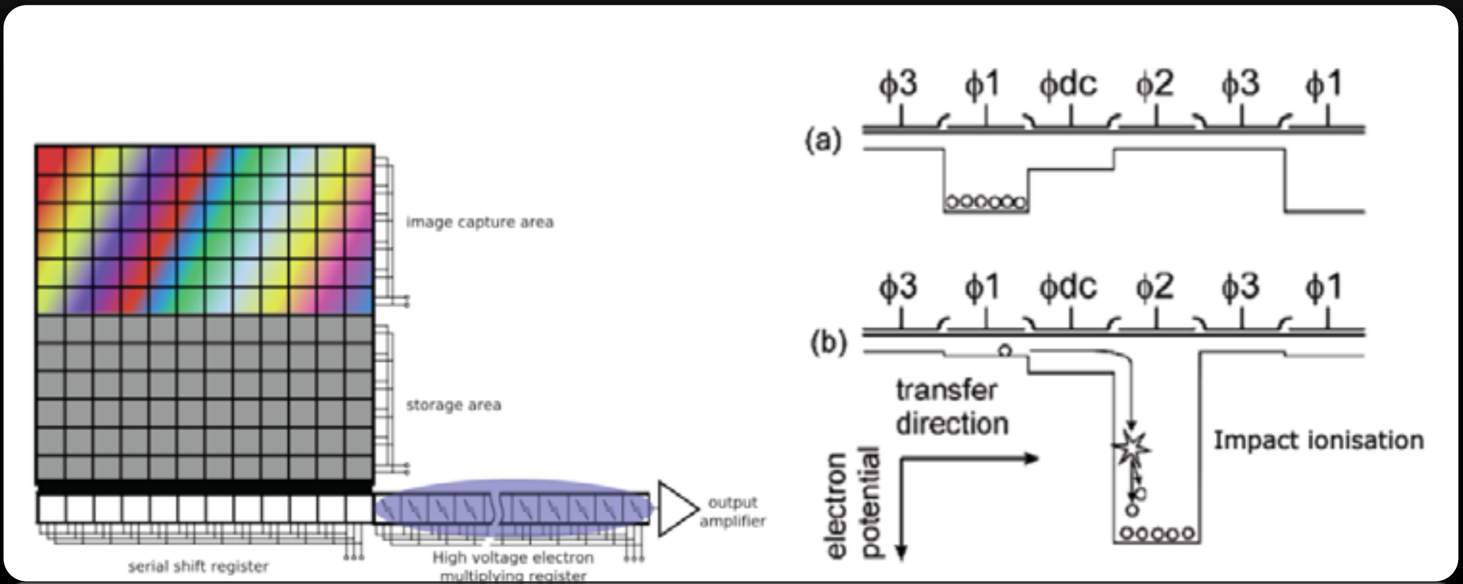
δ DOPING ACHIEVES EXCELLENT QE

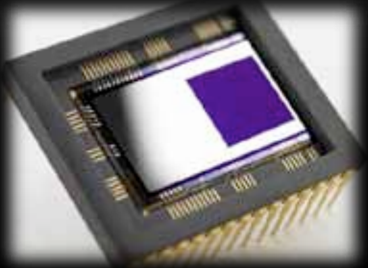




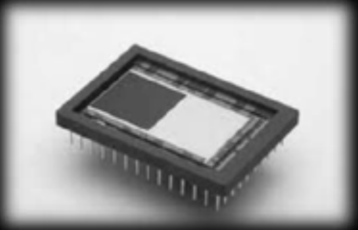


e2v L3 TECHNOLOGY ENABLES PHOTON COUNTING





CCD97: 0.5k x 1k format
8.2 x 16.4 mm



CCD201: 1k x 2k format
13.3x26.6 mm

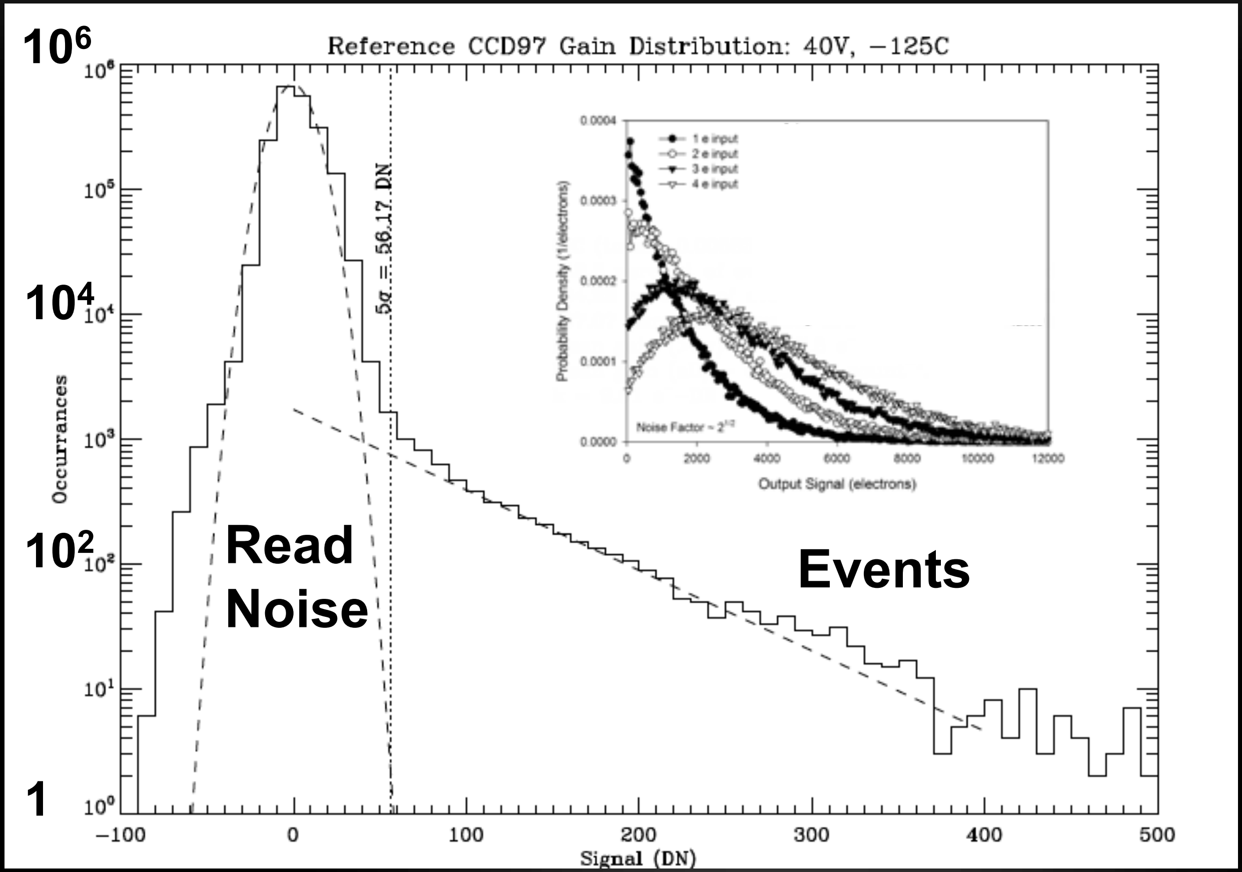
In principle this technology is scalable to any CCD format!

CONFIGURABLE L3 GAIN REGISTER PROVIDES WIDE DYNAMIC RANGE

There are 3 primary, configurable modes of operation:

1. Conventional Mode
   - Gain stage deactivated
   - Normal, direct-imaging CCD characteristics dominated by read noise
2. Analog mode with electron multiplication
   - Gain stage is active 30-50V (G~10-100)
   - Read noise is reduced dramatically, even with high frame rates
   - Data is otherwise read out conventionally
   - Uncertainty between the gain and number of input counts leads to √2 reduction in signal-to-noise ratio
3. **Photon counting mode**
   - **Gain stage fully active 40-50V (G~1000)**
   - **Data is read through a discriminator typically set at 5σ read noise**
   - **Because all events are assumed to be the result of a single electron detection, √2 noise is completely eliminated!**

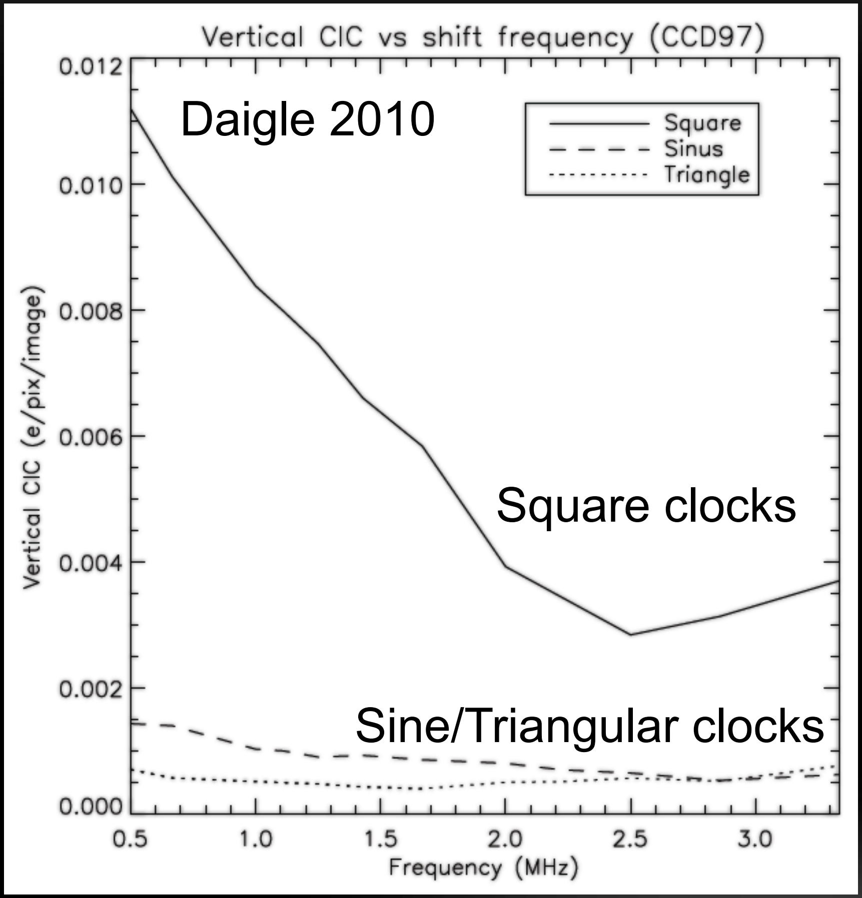
L3 TECHNOLOGY REBALANCES CONVENTIONAL CCD NOISE SOURCES



Sources:

- Read Noise
- CIC
- Dark Current

CLOCK SHAPING REDUCES CIC



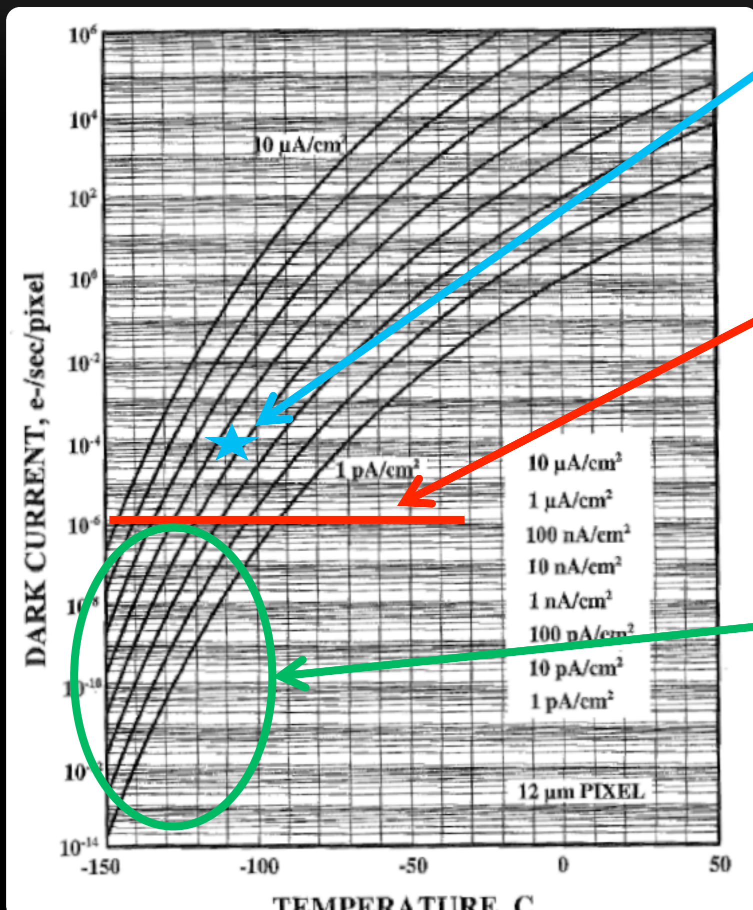
- Clock Induced Charge (CIC) is the "new" dark current.
- CIC is produced ONLY during readout.
- CIC exists in conventional CCD cameras, but is negligible compared to read noise.
- Longer frame times reduce this contribution
- Commercial controllers (e.g. NuVu) are ALREADY available with refined clock shaping engineered to minimize this noise source.

DARK CURRENT

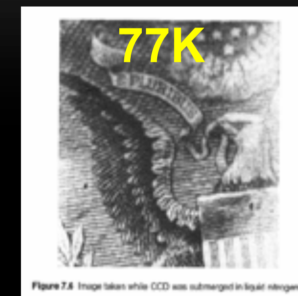
e^{-}-pixel^{-1}-hr^{-1}

1

3×10^{-3}



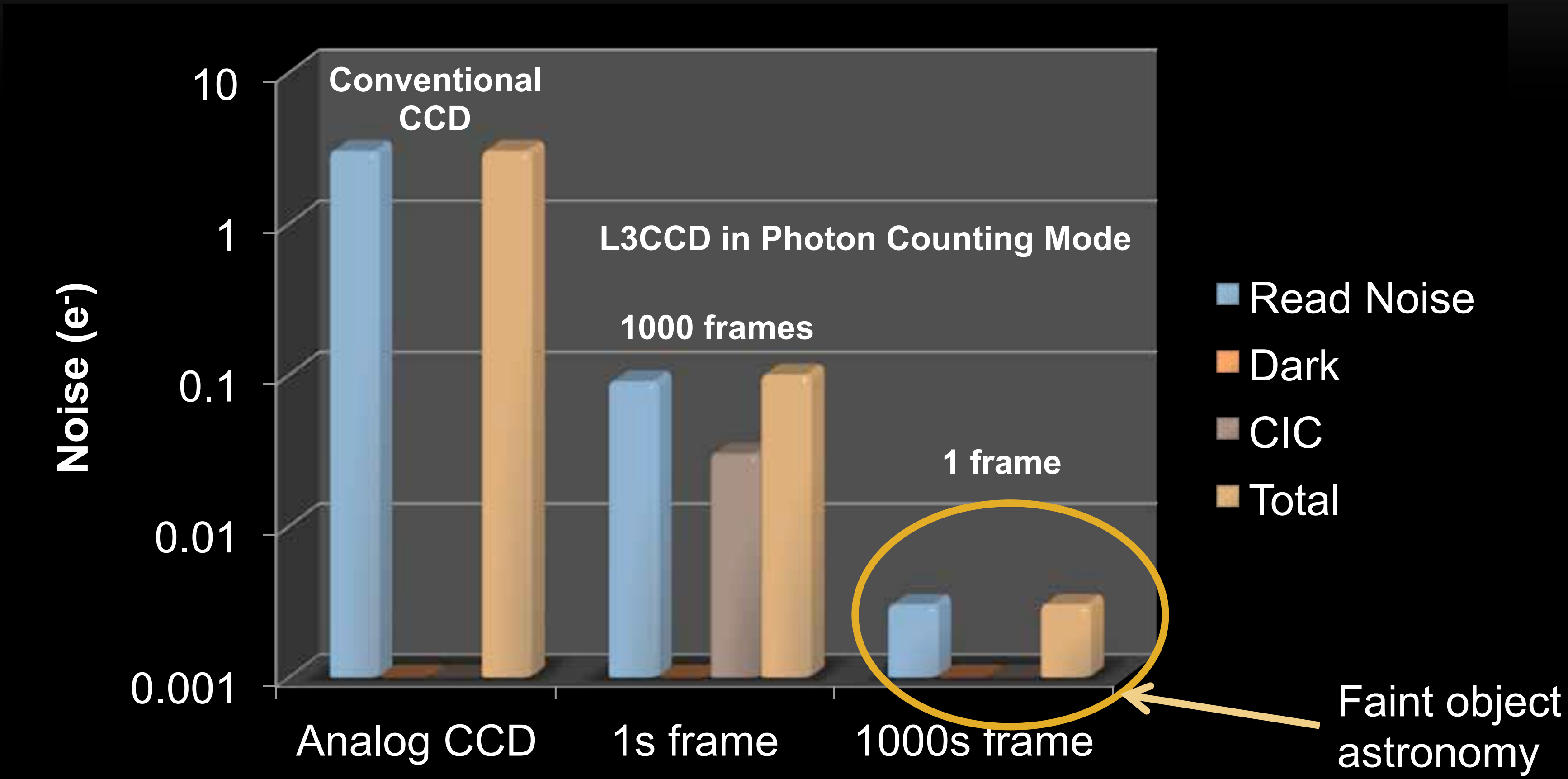
e2v **non-inverted**, back-illuminated CCD (measured)



GALEX FUV
~0.7 c-s^{-1}-cm^{-2}

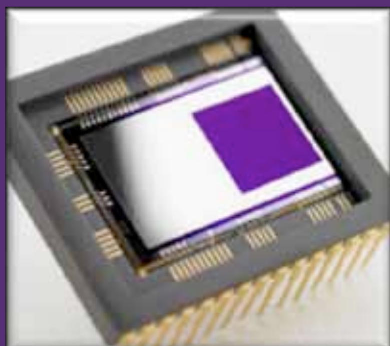
There is plenty of parameter space available to drive the silicon dark below typical photocathode values. This parameter space can also be used to maintain the low dark rate as the device ages.

OPTIMIZING FOR PHOTON COUNTING PERFORMANCE

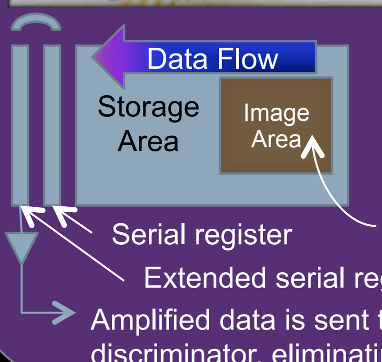


DELTA-DOPED L3 DETECTORS CAN IMPROVE UV PERFORMANCE BY AN ORDER OF MAGNITUDE

e2v L3 Technology

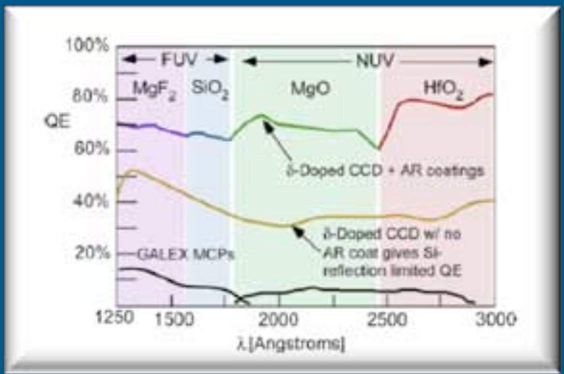


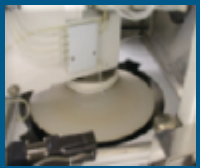
- New technology from e2v enables high QE CCD imaging and **zero read noise** photon counting.
- A **Low Light Level (L3) extended serial register** operating at elevated voltage (~50V) amplifies signals well above the level of the read noise.



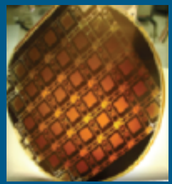
L3 functional diagram

JPL Delta Doping





Wafer Polish



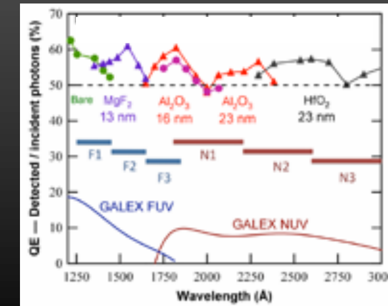
Wafer Thinning

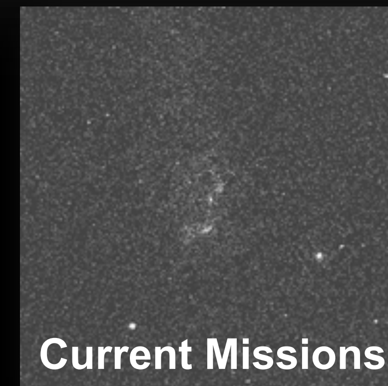
MBE/Delta Doping

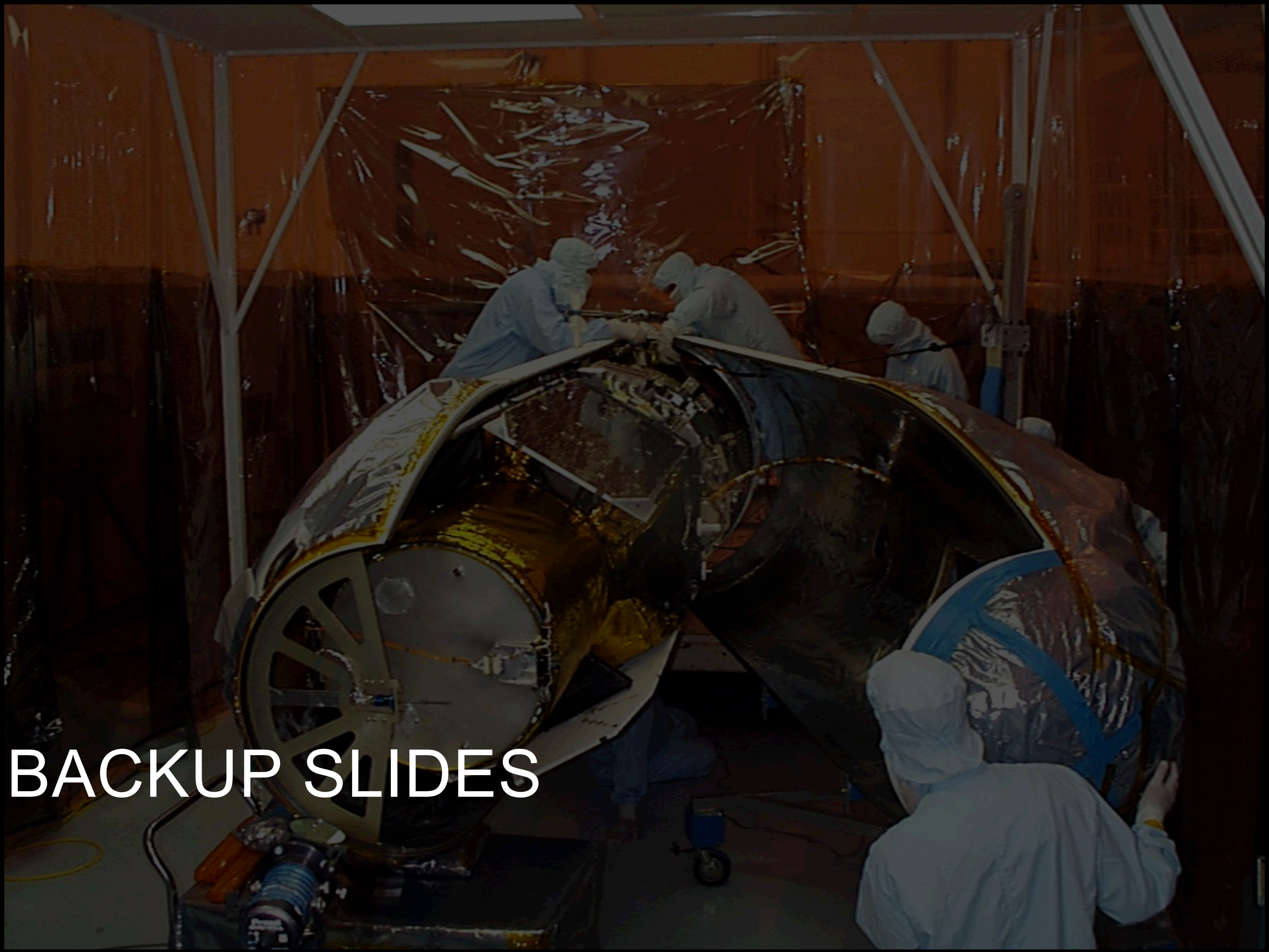
- JPL **Delta Doping** technology sensitizes L3 CCDs to the ultraviolet.
- A **10X** improvement in performance is possible over existing MCP detectors.

UV L3 CCD Summary

			Now	2020
Performance	Format		0.5k x 1k	4k x 4k
	Photon Counting		✓	✓
	QE	1216 Å	60%	>80%
		2000 Å	50%	
		3000 Å	55%	
		6000 Å	80%	
	CIC		0.001 e^--px^{-1}-fr^{-1}	<0.001 e^--px^{-1}-fr^{-1}
	Dark		<1 e^--px^{-1}-hr^{-1}	<0.001 e^--px^{-1}-hr^{-1}
	Dynamic Range		Configurable by frame rate, up to 0.1 e^--px^{-1}-fr^{-1}	
	Energy Resolution		✗	✗
	Curvature		Possible	✓
	High Voltage		50 V	50 V
	TRL		4	>6 ($2M, 2 years)
Risk	Cooling		150 K	
	Contamination		Materials Selection, Monthly Thermal Cycle	
	Radiation		SAA-avoiding, Low Earth Orbit, Frame Stacking	
	Red Leak		Spectroscopy/Coatings	
	Cost		Industry Leverage	

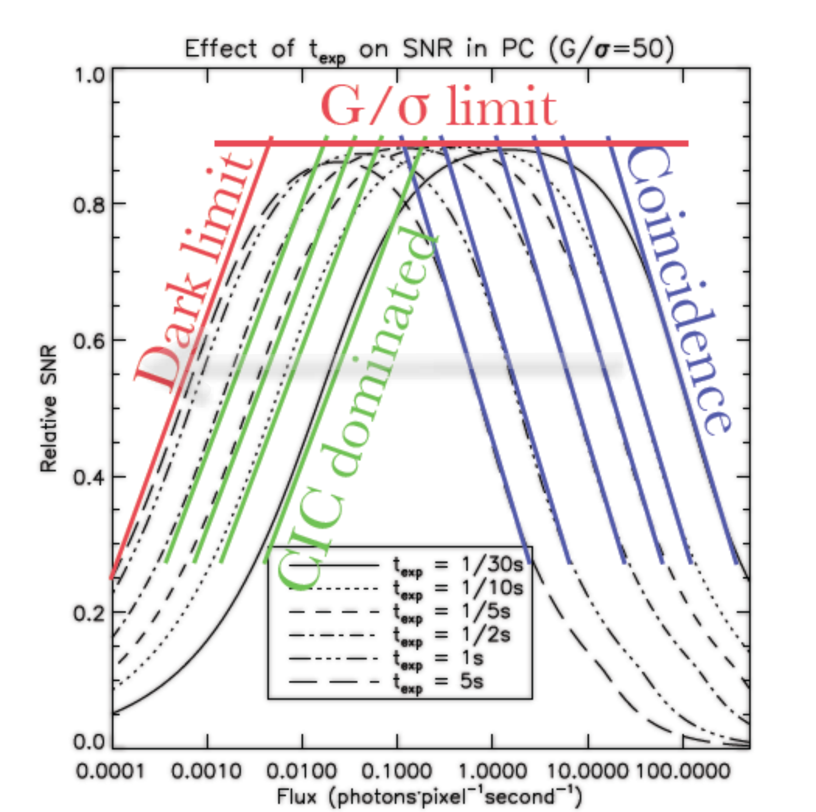






BACKUP SLIDES

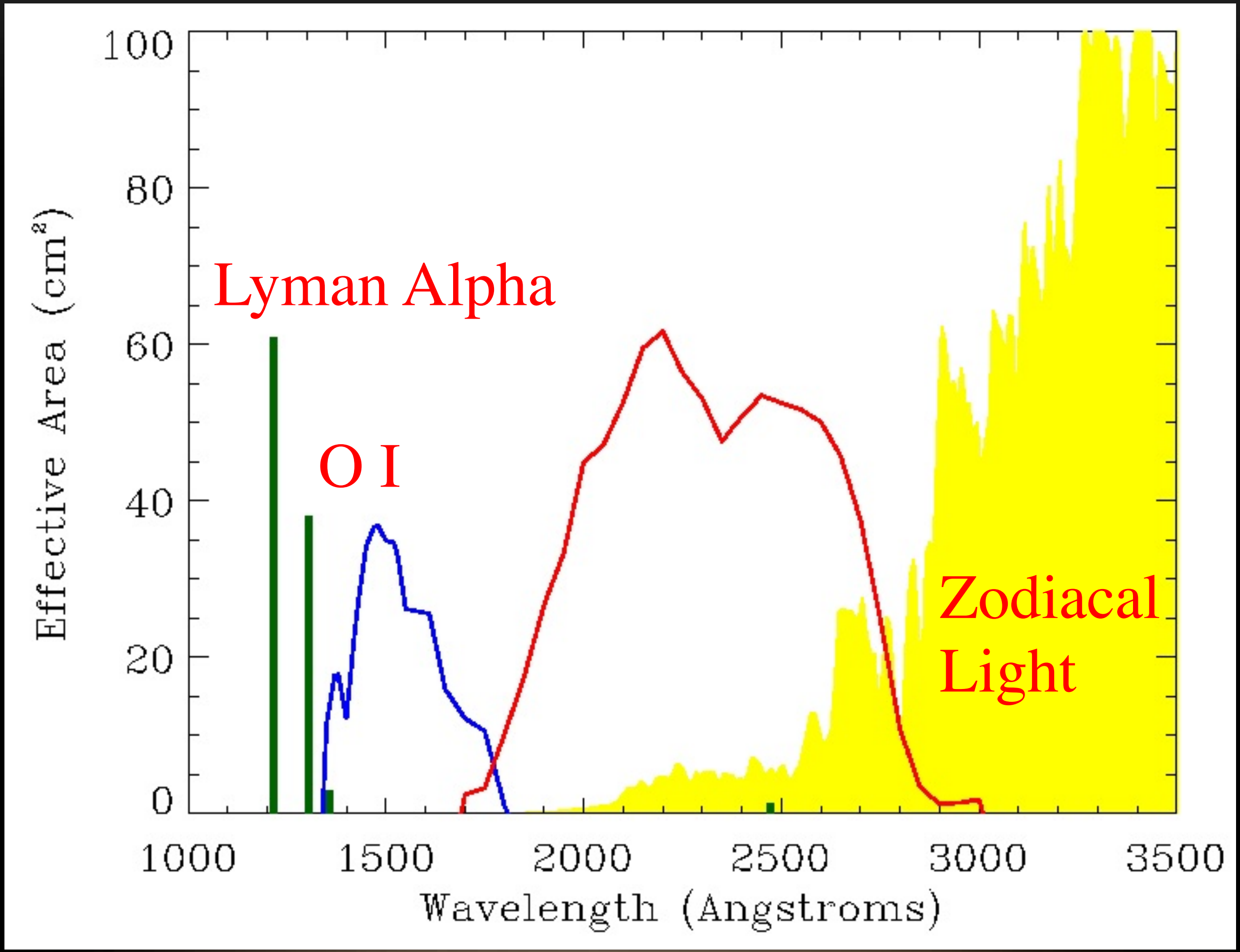
L3 CCD NOISE LIMITS



Daigle 2010

- Fundamental noise sources at the faint end and saturation at the bright end limit all photon counting detectors.
- Parameters can be optimized for the flux regime of interest.
- Cold operation allows extremely low flux detection.
- Long integrations have an equivalent effect.

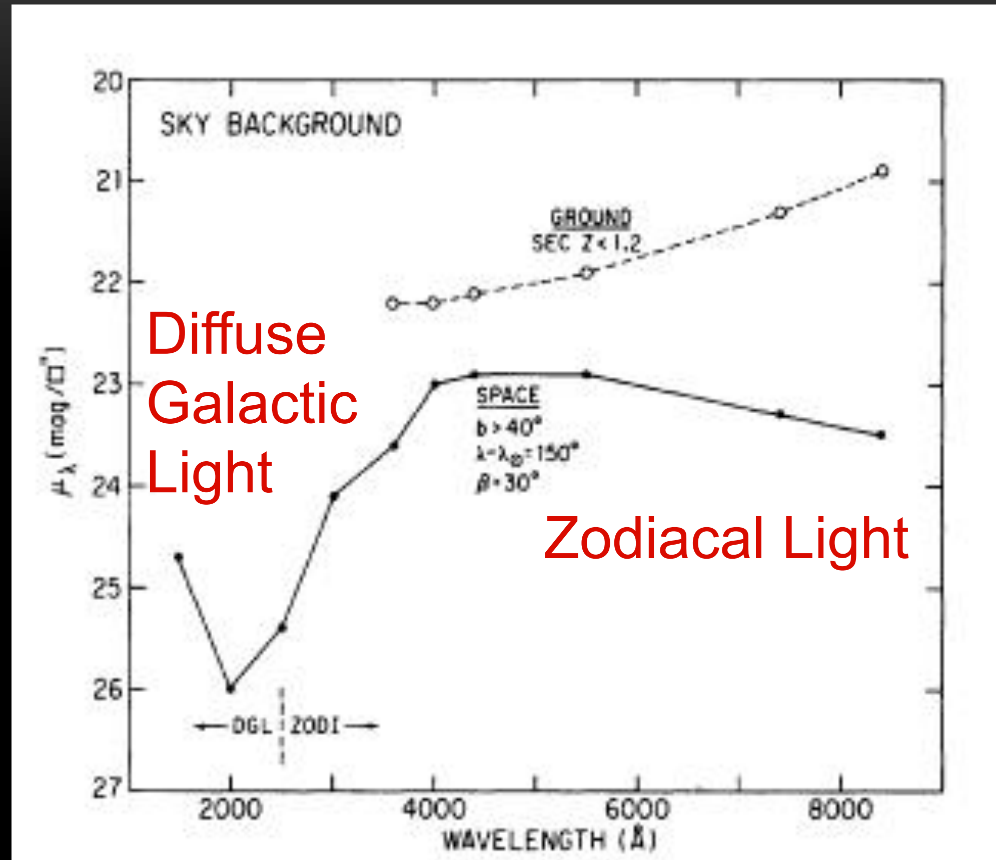
GALEX UV COATINGS



For sky background-limited observations...

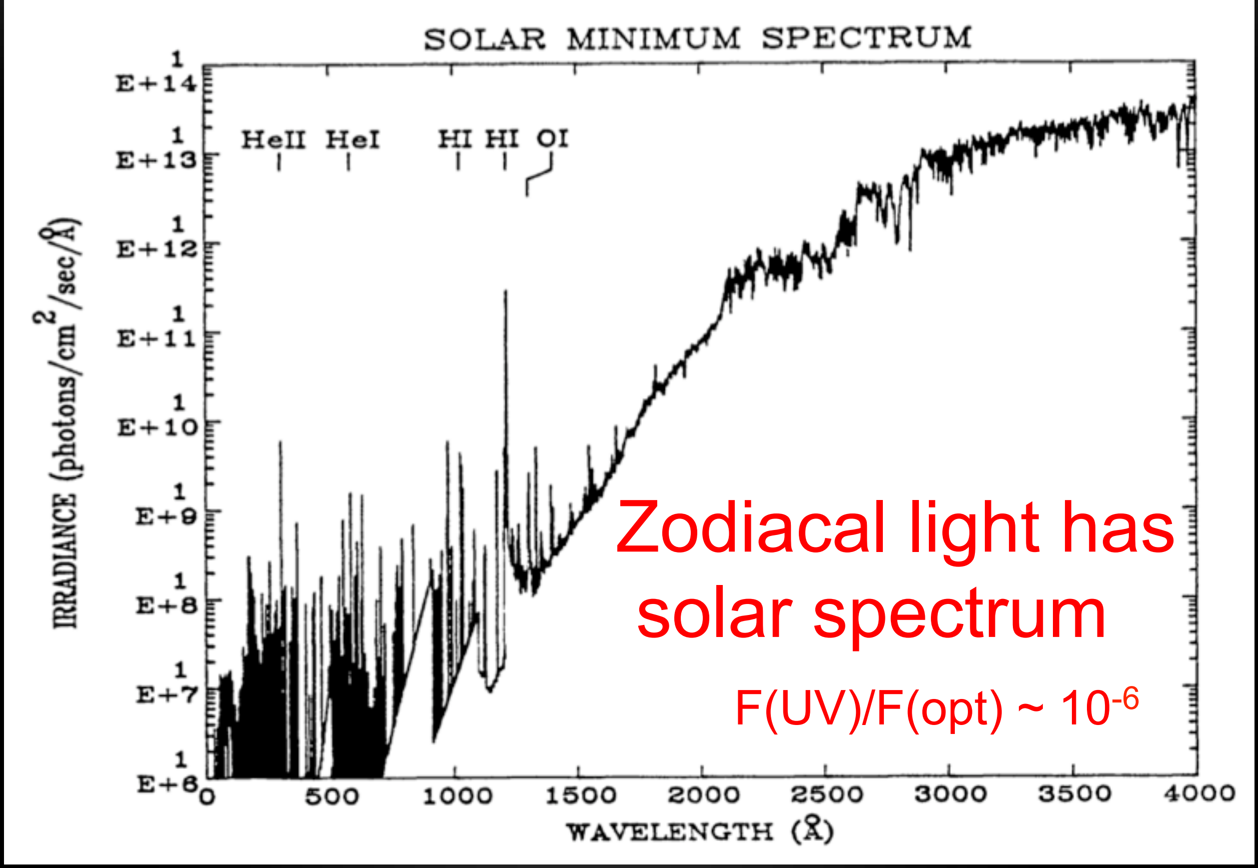
F(UV)/F(opt)~0.01

Background in the FUV is not dominated by zodiacal light



O’Connell (1996)

For sky background-limited observations...



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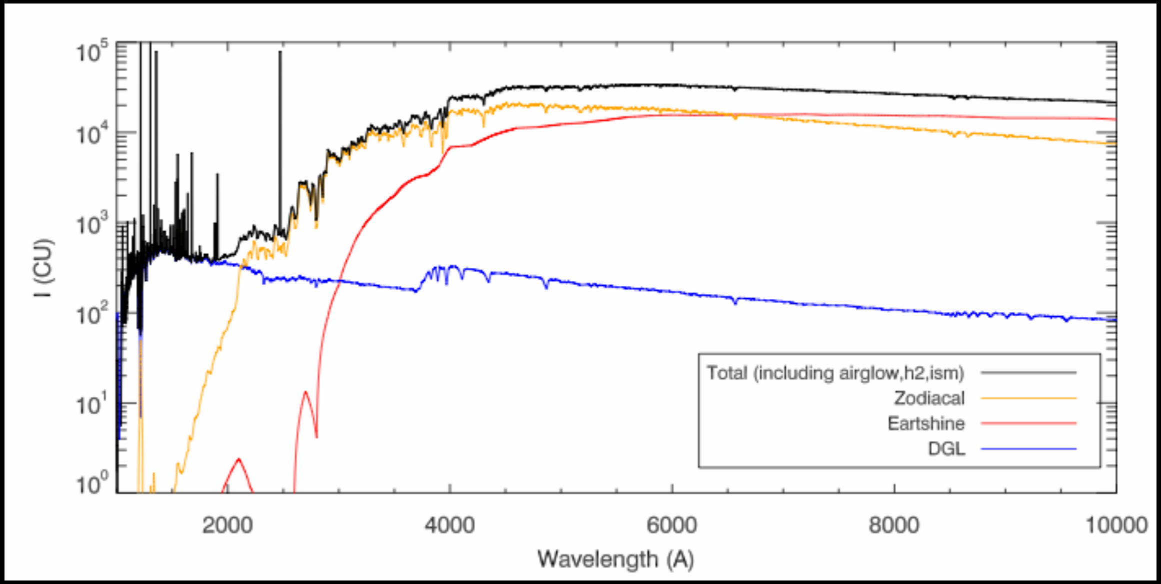

For sky background-limited spectroscopy...

...a single grating is sufficient

Realistic simulation of diffuse backgrounds for UV integral field spectrograph (with sensitivities sufficient to detect IGM emission).

Background is dominated by astrophysical backgrounds (not instrumental e.g., scattering, red leak, etc.)