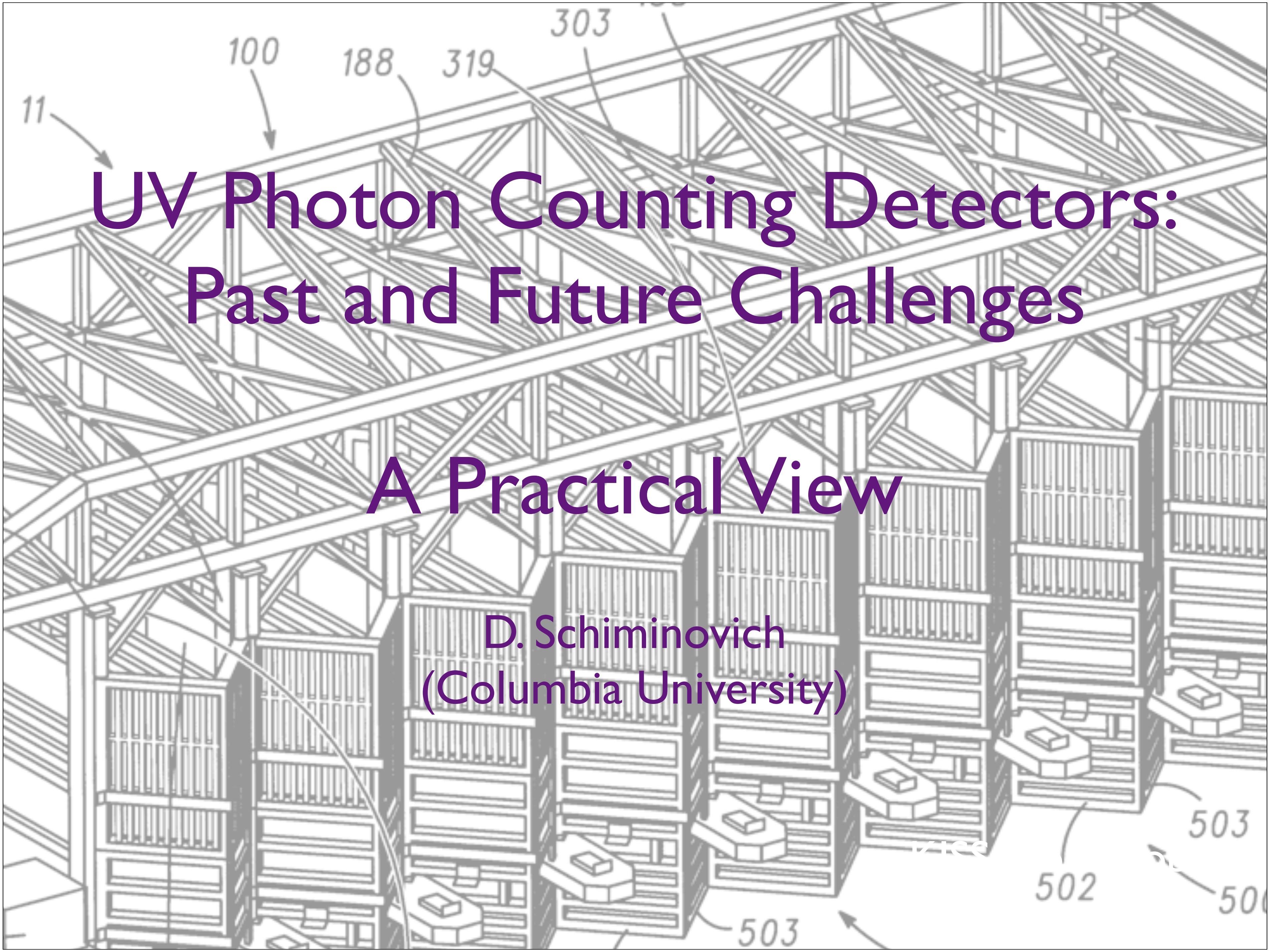
UV Photon Counting Detectors: Past and Future Challenges

A Practical View

D. Schiminovich
(Columbia University)

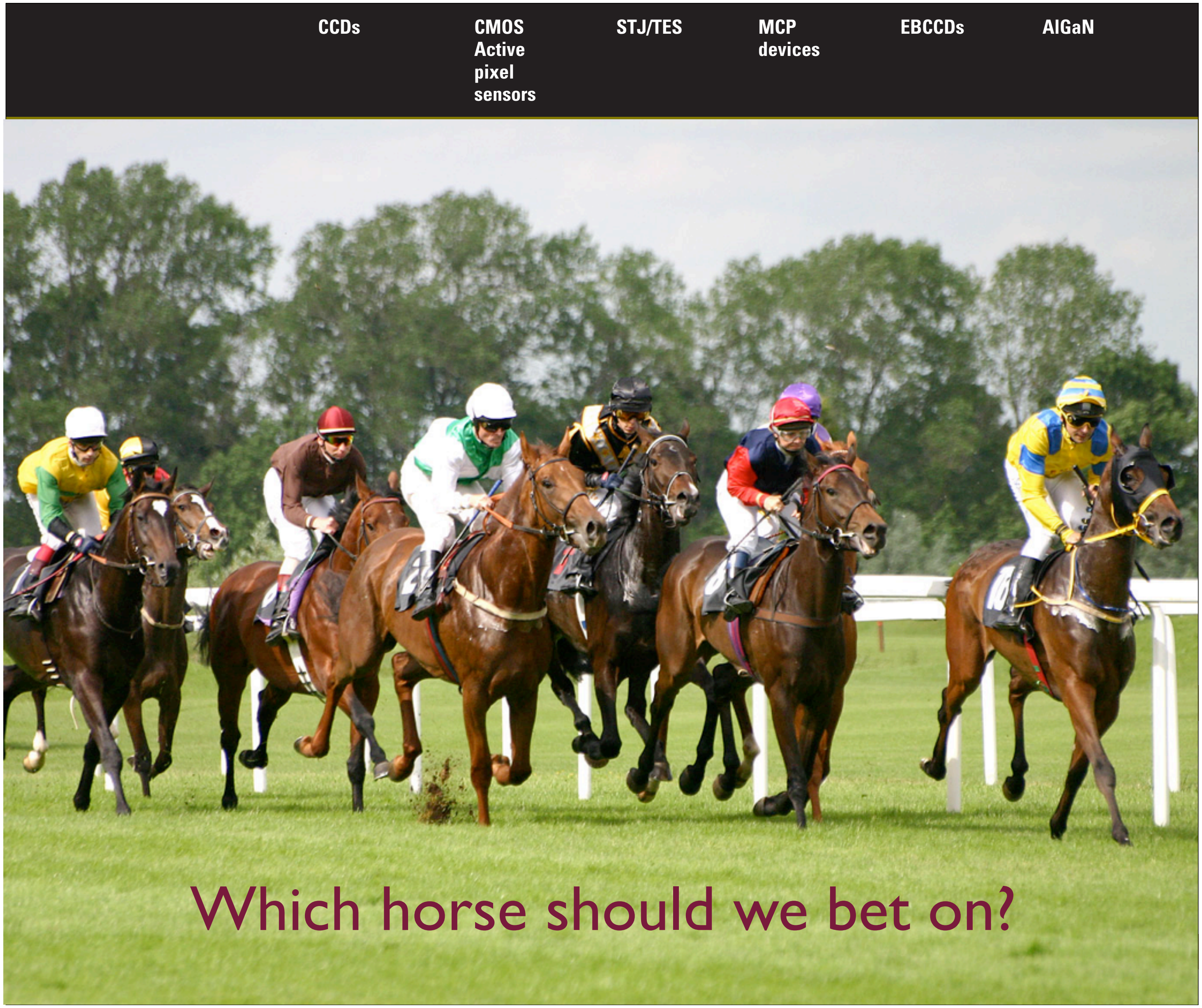


	CCDs	CMOS Active pixel sensors	STJ/TES	MCP devices	EBCCDs	AlGaN
Performance						
Wavelength range	visible-uv	visible	visible-uv	solar-blind uv	solar-blind uv	solar-blind uv
DQE (%)						
FUV (130nm)	45 JPL			33	*50 CsI*	*60*
NUV (250mm)	58 WFC3			10 STIS	*30 CsTe*	*80*
Vis (600mm)	80	50	50	$< 10^{-6}$	$< 10^{-6}$	$< 10^{-6}$
Format (pixels)	4k x 2k: 2 butted	1k x 1k	2 x 2 TES 6 x 6 STJ	16k x 1k: 2 butted	320 x 256	256 x 256
Pixel size (μm)	15 x 15	7.5 – 15 sq	20 – 25 sq	6 x 30	30 x 30	25 x 25
Read-noise (e^- rms)	5	20 - 30	none†	none	5*	unavailable
Dark noise (cnts/sec/res el)	6.7×10^{-3}	high	0	$< 2 \times 10^{-5}$	$\sim 4 \times 10^{-6}$	$\sim 8 \times 10^{4}$
Global Dyn Rng (cnts/sec)			400k	21k	123k	
Local Dyn Rng (Cnts/sec/pix)			20k	8	45	
Full well	75k	300k				
Energy Resolution (at 400nm) (E/ΔE)	none	none	5 STJ 20 TES	none	none	none
Environment						
Radiation Hard	no	yes (1Mr)	yes	yes	yes	yes
Lifetime (cnts/mm^2)	radiation	radiation	coolant	10^{11}	10^{12}	radiation
High voltage	no	no	no	yes	yes	no
CTE	0.999995	n/a	n/a	n/a	n/a	n/a
Op temperature (°C)	-85	-85	0.1 - 0.3K	25	25	25
Power (w)	50††	0.01		40	20	
Readiness						
TRL	8	3	2	8	8	2

"Ultraviolet and Visible Detectors for Future Space Astrophysics Missions"

Blades Report/ Roadmap ~(2000)

<u>Not included</u>
APD array,
EMCCD/L3CCD
MKID
Nanowire
others...



"Ultraviolet and Visible Detectors for Future Space Astrophysics Missions"

Blades Report/ Roadmap ~(2000)

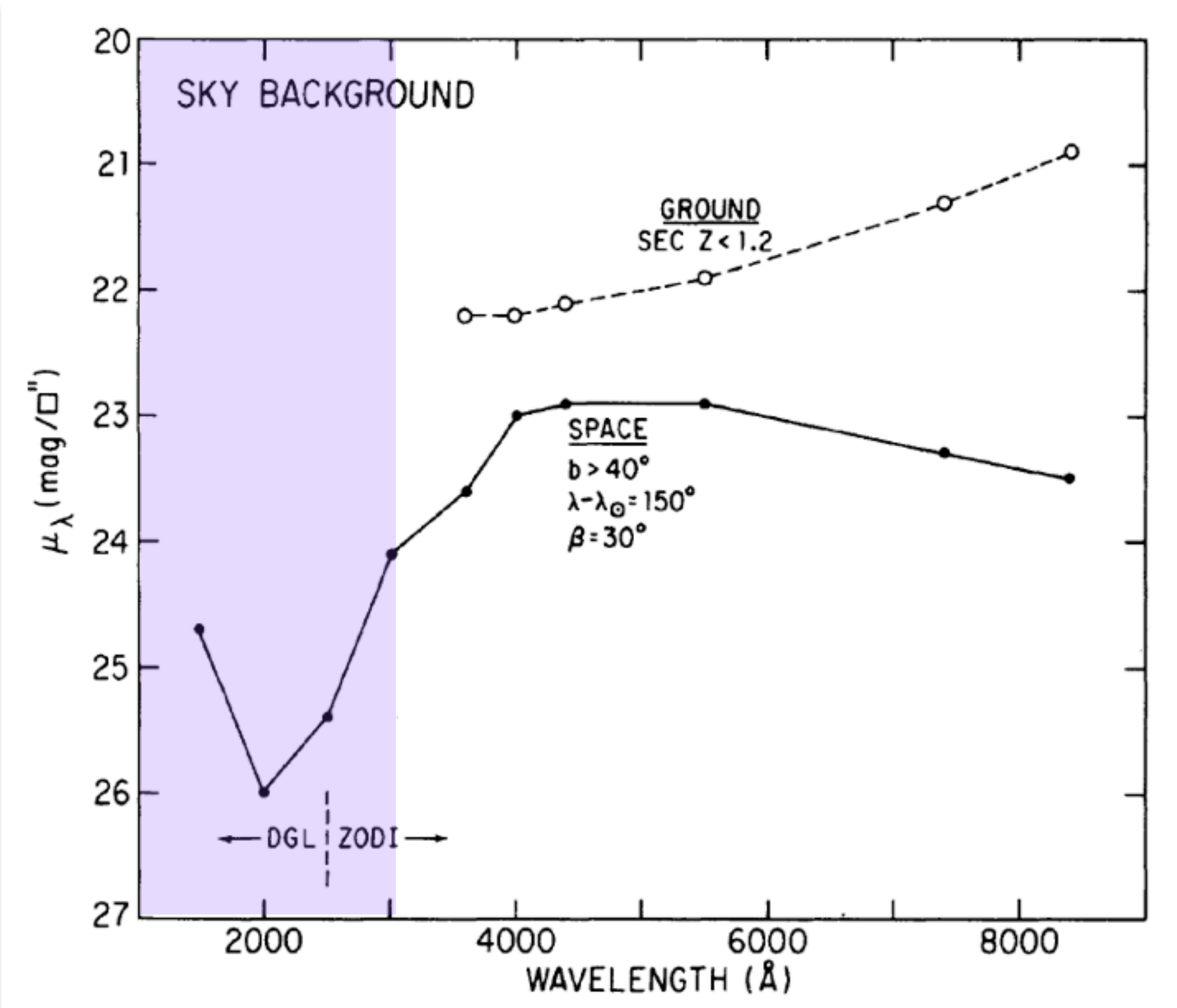
Not included
APD array,
EMCCD/L3CCD
MKID
Nanowire
others...

What detector to choose?

Which horse should we bet on?

- Blades Report concluded appropriately:
  - "No single current or emerging detector technology covers, in any optimal way, the UV-Vis spectral region. A multifaceted approach is required...."
- What are the drivers pushing technology?
  - *astronomical* applications
  - *other scientific and engineering* applications
  - *commercial* applications
- What detectors are available now, or in next 2-4 years?
  - This is what we'll be testing/launching in next 10-15 years

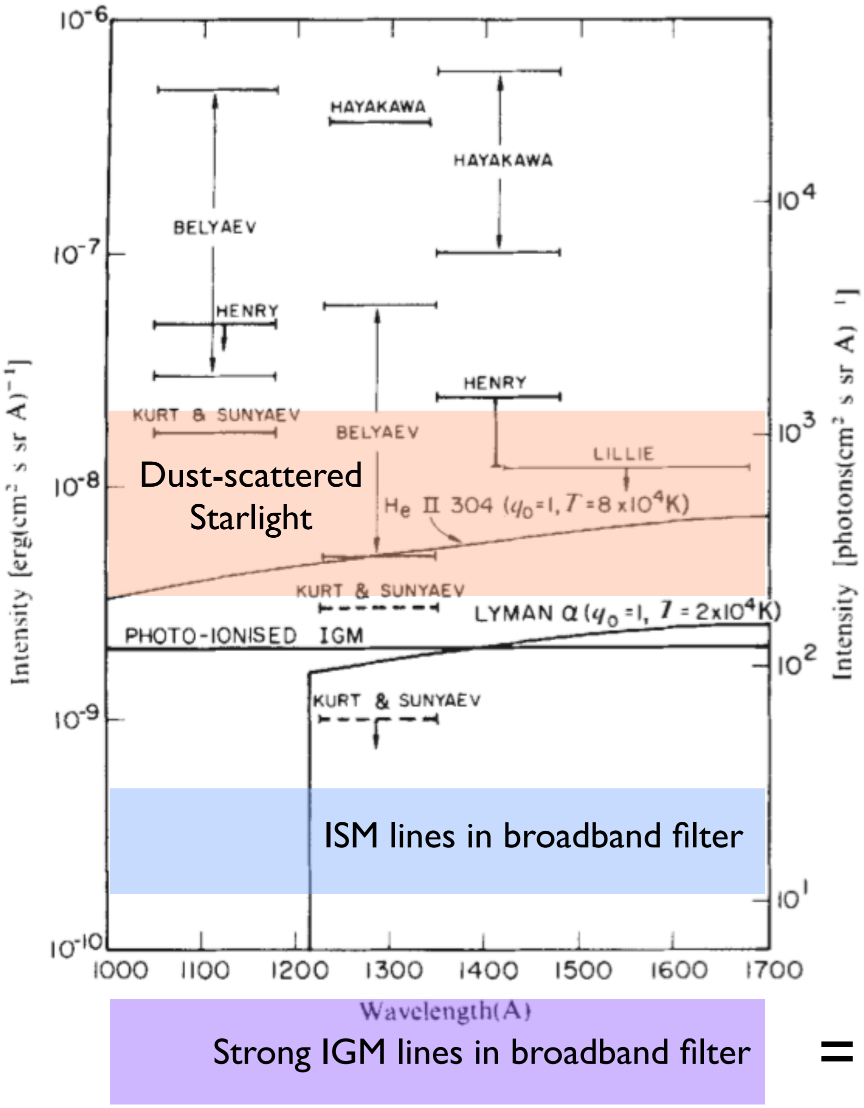
UV Applications: The Dark UV Sky



Low sky background drives detector noise/background requirement

O'Connell (1987)

UV Applications: IGM
Cosmic Far Ultraviolet Background ~ 40 years ago



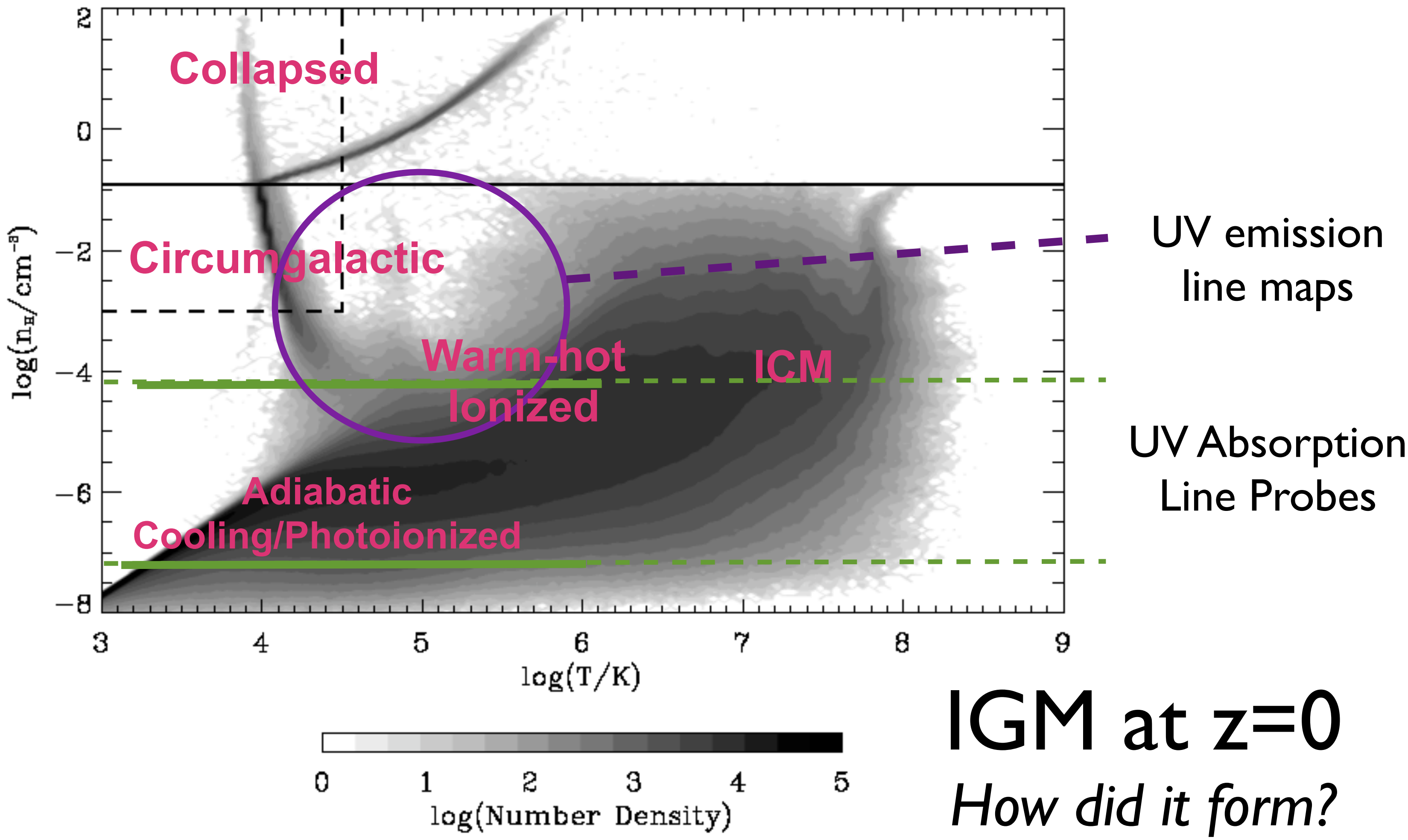
= 100 LU

Local and Galactic components of diffuse light are probably weak enough at high latitude to allow detection of a cosmic flux of approx 10^{-9} erg (cm^2 s sr Å)$^{-1}$. A sensitivity at this level can be achieved with current instrumentation.

Models assume uniform critical density component

Davidsen, Bowyer & Lampton, Nature (1974)

UV Applications: IGM
Emission and Absorption Line Spectroscopy



IGM at z=0

How did it form?

Furlanetto et al (2004)

UV Applications: IGM (+ISM)
Emission and Absorption Line Spectroscopy

$$I_{background,UV} \sim 500 \frac{\text{ph}}{\text{cm}^2 \ \text{sr} \ \text{Å} \ \text{s}} = 500\,\text{CU} \sim 28.5 \text{ mag arcsec}^{-2}$$

Emission Line Mapping

R~5000-10000
(~50 km/s)

Photon-limited to

$$\sim 100 \frac{\text{ph}}{\text{cm}^2 \ \text{sr} \ \text{s}} = 100\,\text{LU}$$

Explorer class mission
(c.f. Martin talk)

Absorption Line Tomography

e.g. galaxy as background source
moderate-high resolution,
low-moderate S/N

e.g. if aperture ~1” (HST/COS)

photon-limited to ~28.5 mag

Any mission within next
30 years and beyond

Photon counting detectors critical for these applications

Other UV Science Applications for Photon-Counting Detectors (incomplete list)

Transient/Timing Phenomena
(SN, GRB, novae, CVs, flares, pulsars,....)

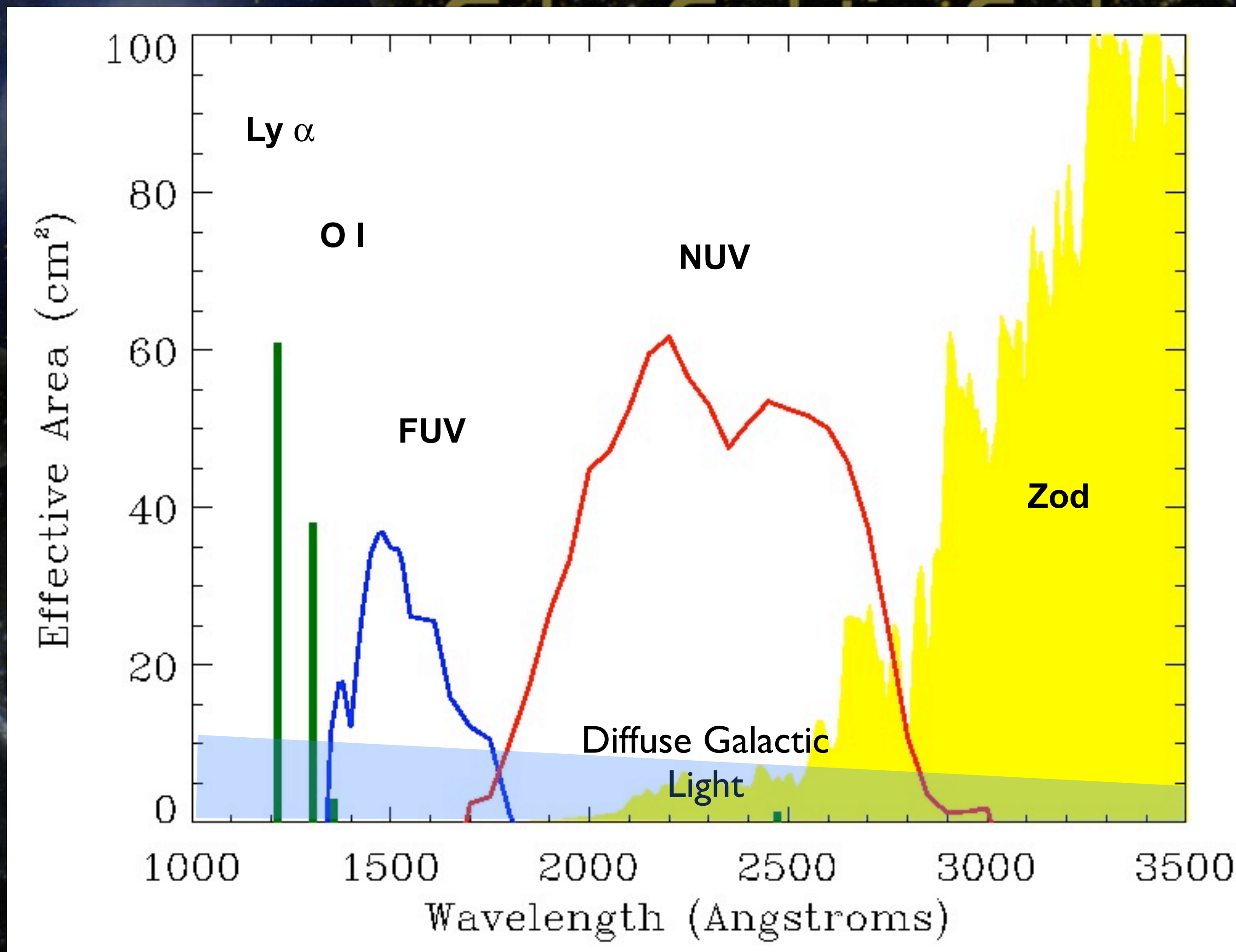
Faint stellar population studies in local universe:
detailed star formation and galaxy assembly history

Time-resolved exoplanet follow-up
(incl. atmospheres, aurora, biosignatures)

....

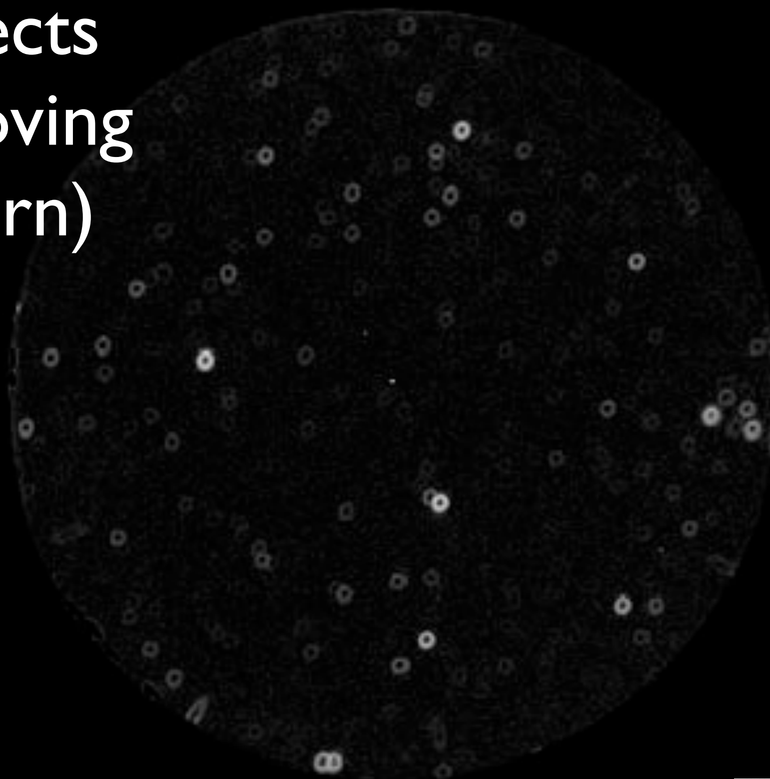
Photon counting detectors also provide
operational/calibration benefits

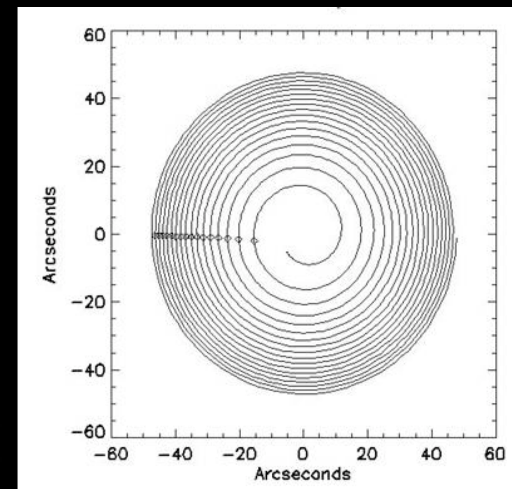
GALEX



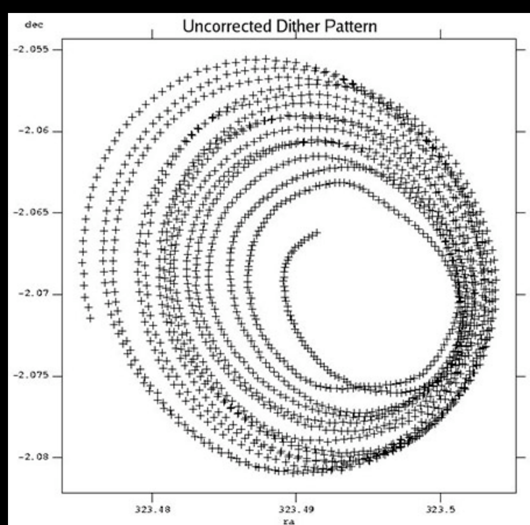
More than a trillion photons have been collected over 6 years

GALEX collects data while moving (dither pattern)

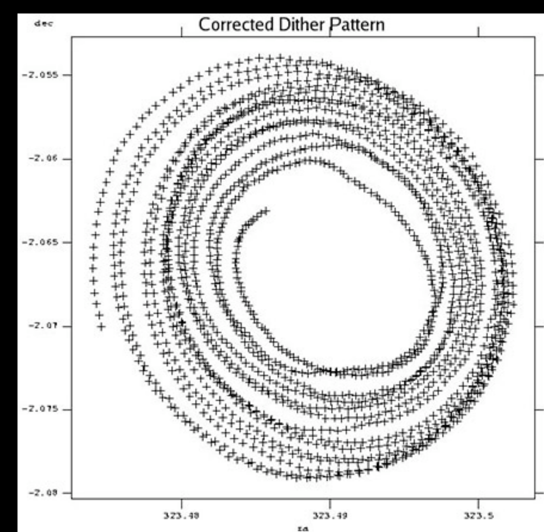




Ideal



Uncorrected



Corrected

GALEX Photon Counting

GALEX Time-tagged photon data

- Time-tagged photon data can be collected while moving (relax attitude control requirements)
- Many aspects of calibration including aspect solution can be refined ex post facto. (Optimal aspect reconstruction)

$$\bar{J}_{\mathrm{ML}} = \arg\max_{\bar{J}} \left\{ \sum_{p} \sum_{i} s_p(i + j_p) \ln[r_{\mathrm{ML}}(i, \bar{J})] - r_{\mathrm{ML}}(i, \bar{J}) - \ln[s_p(i + j_p)!] \right\}.$$

Aspect solution
Photon list
ML image

- Provides excellent compression for sparse images
- Allows time-series analysis on millisecond-second timescales (for astronomical sources and other transient/artifacts)

Transformations can be determined ex post facto

Aspect Solution

Distortion/Offset/"Walk"

$$p_i(\alpha, \delta, t) = A(\alpha, \delta | x_{FP}, y_{FP}, t) \times T(x_{FP}, y_{FP} | x_{Det}, y_{Det}, q, xa, t) \times$$

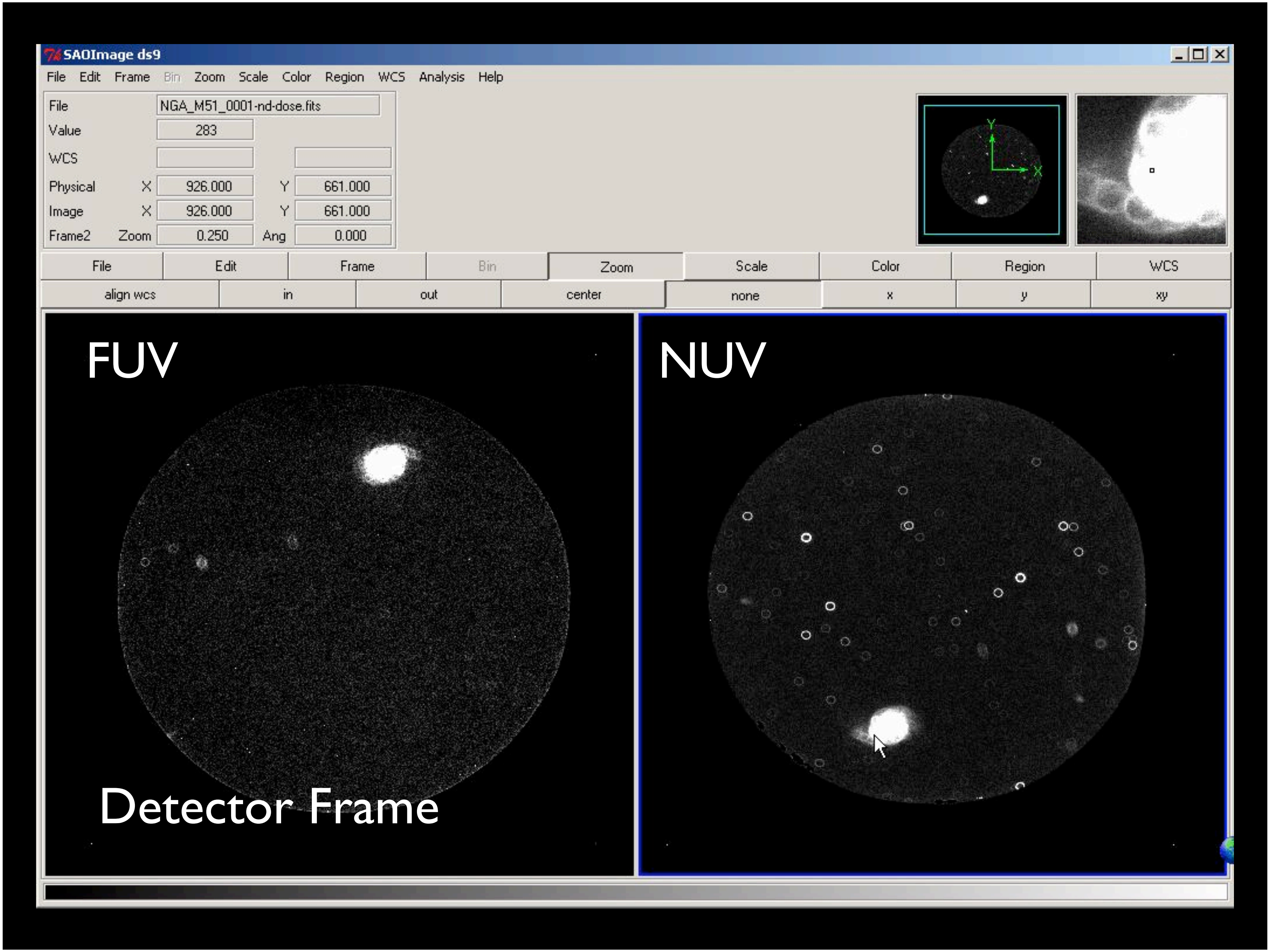
$$\times R(x_{Det}, y_{Det}, q, xa, t | \text{photon word}_i)$$

Detector Position Encoding

$$phot_i(\alpha, \delta, t) = A\ T\ R\ (\text{photon word}_i)$$

Photon sky position

Digitized photon word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File NGA_M51_0001-nd-dose.fits
Value 283
WCS
Physical X 926.000 Y 661.000
Image X 926.000 Y 661.000
Frame2 Zoom 0.250 Ang 0.000
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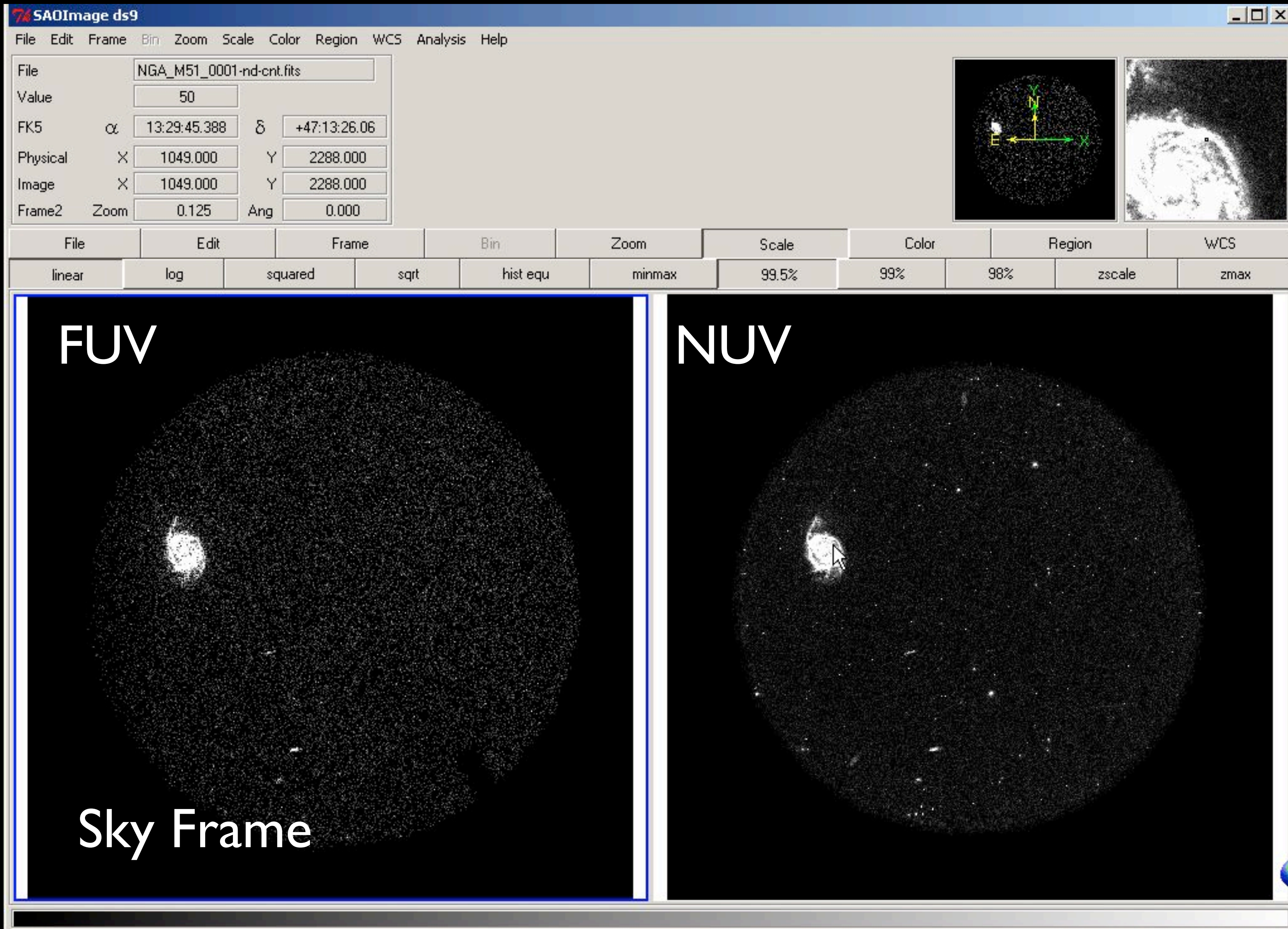
align wcs in out center none x y xy
FUV
NUV
Detector Frame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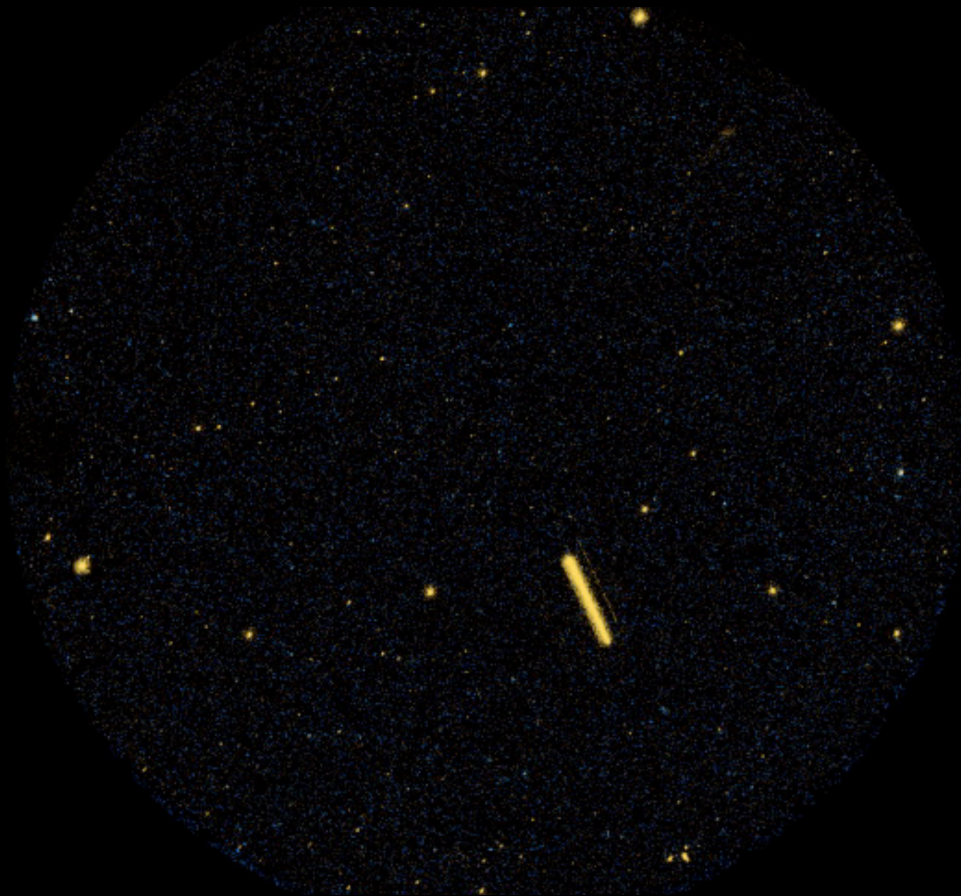
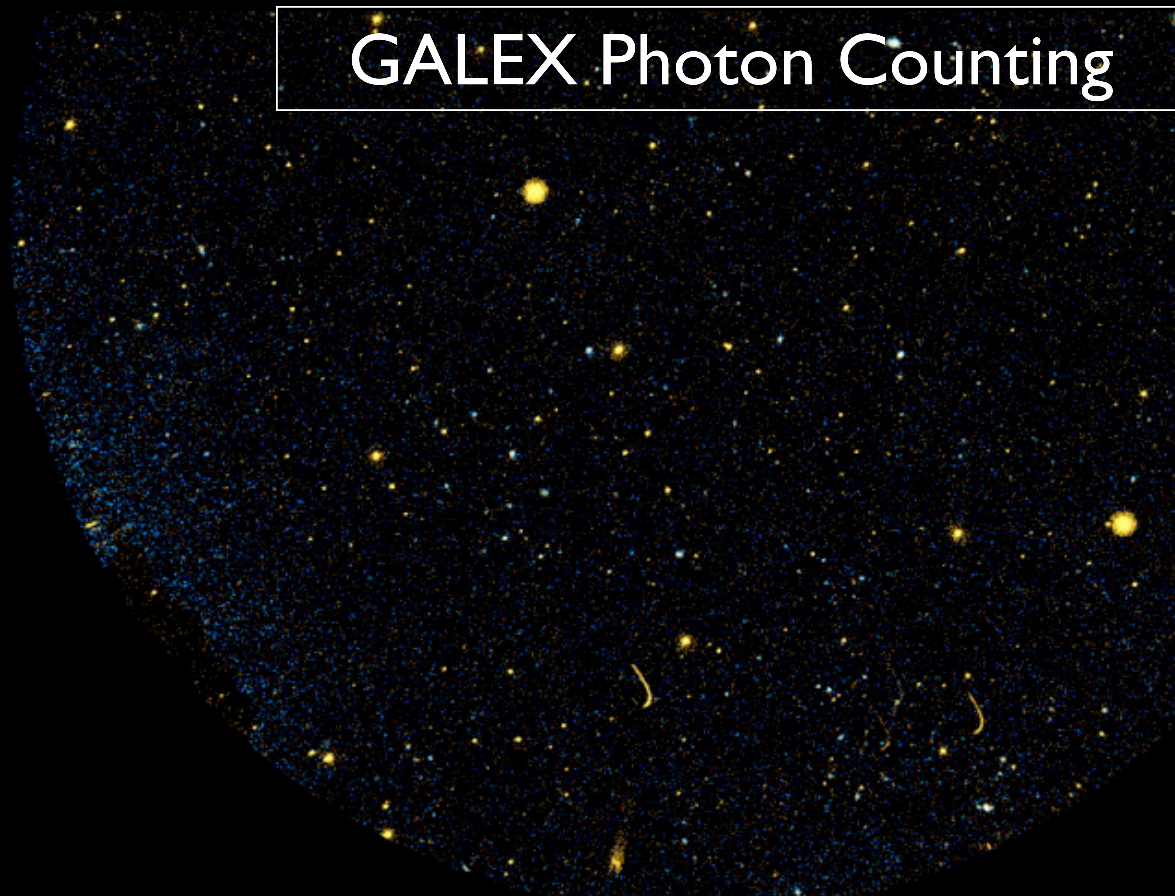
Physical X 1049.000 Y 2288.000
Image X 1049.000 Y 2288.000
Frame2 Zoom 0.125 Ang 0.000
File Edit Frame Bin Zoom Scale Color Region WCS
linear log squared sqrt hist equ minmax 99.5% 99% 98% zscale zmax
FUV
NUV
Sky Frame

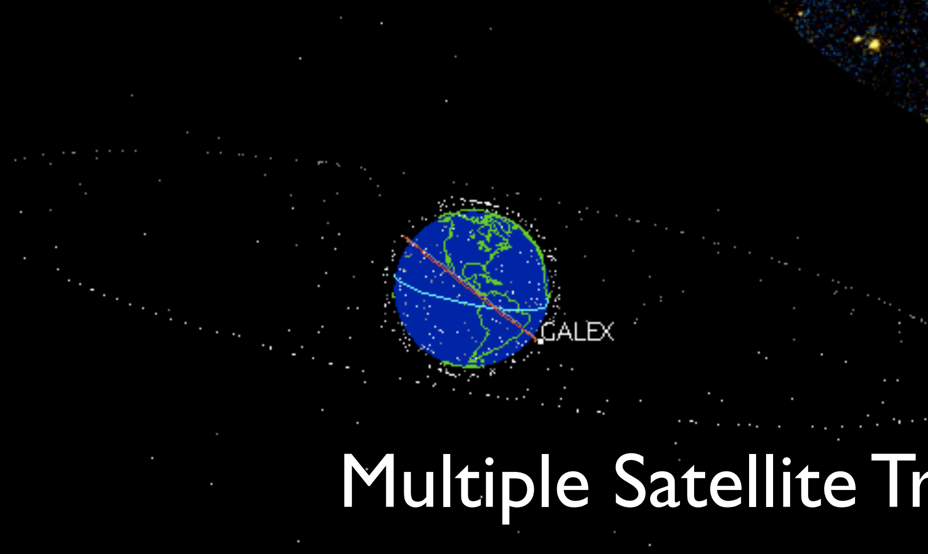
GALEX Photon Counting



Satellite Transit ~ 10 min

GALEX Photon Counting





Multiple Satellite Transit ~ 10 min

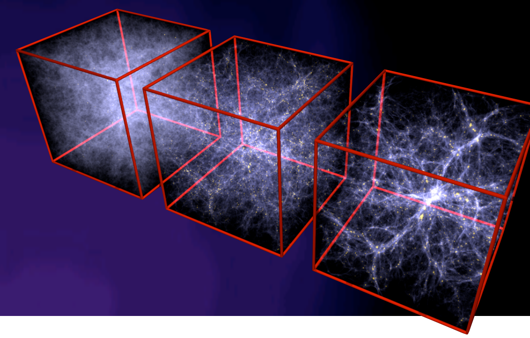
GALEX Photon Counting

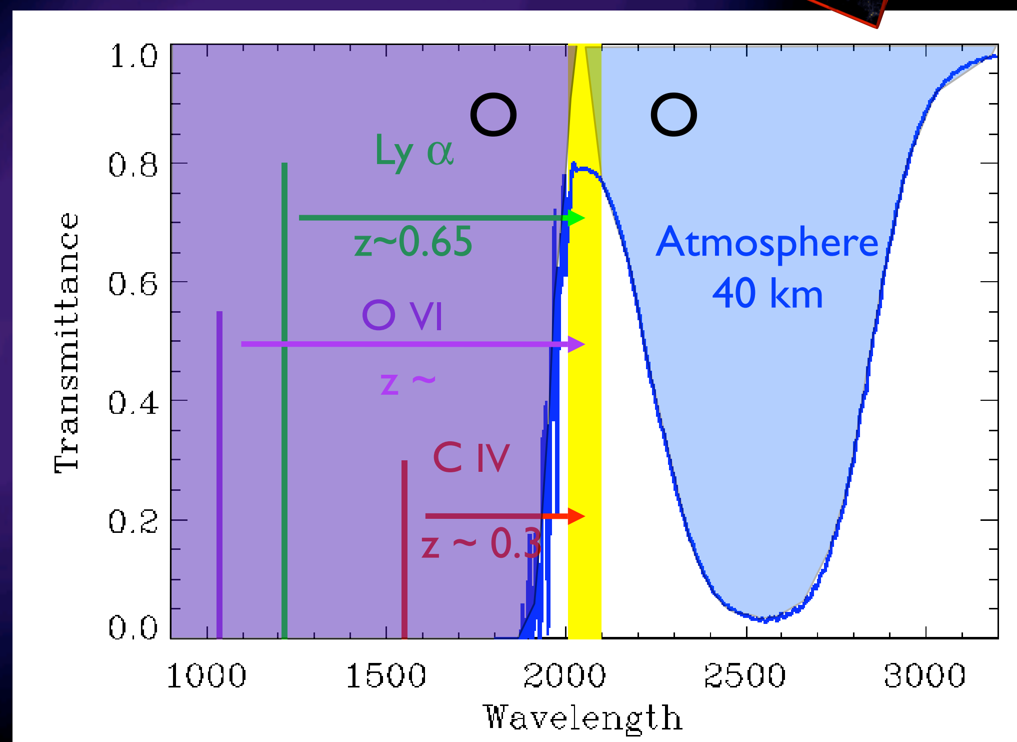
M-Dwarf Flare Star ~ 20 min (Welsh et al 2005)

FIREBall Photon Counting

Mapping the IGM from a Balloon

The FIREBall Experiment (cf Martin talk yesterday)

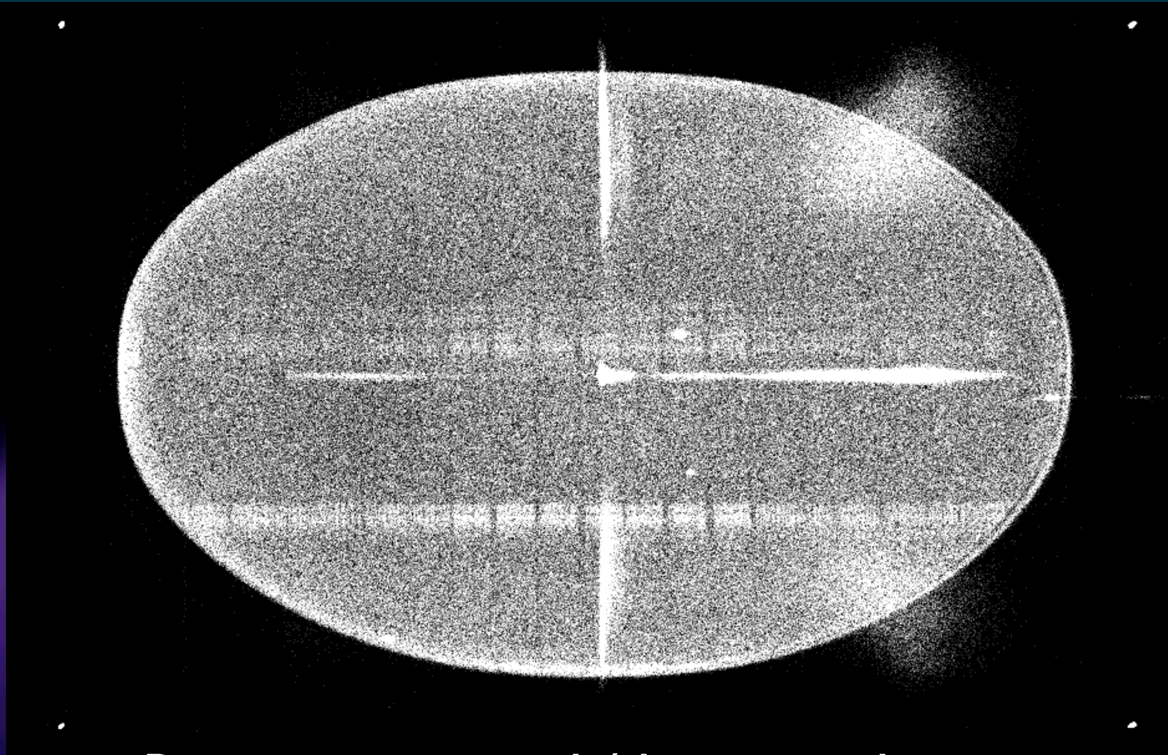




FIREBall Photon Counting

Mapping the IGM from a Balloon

First aspect-reconstructed photon counting data from an integral field unit (& first IFU in the UV)

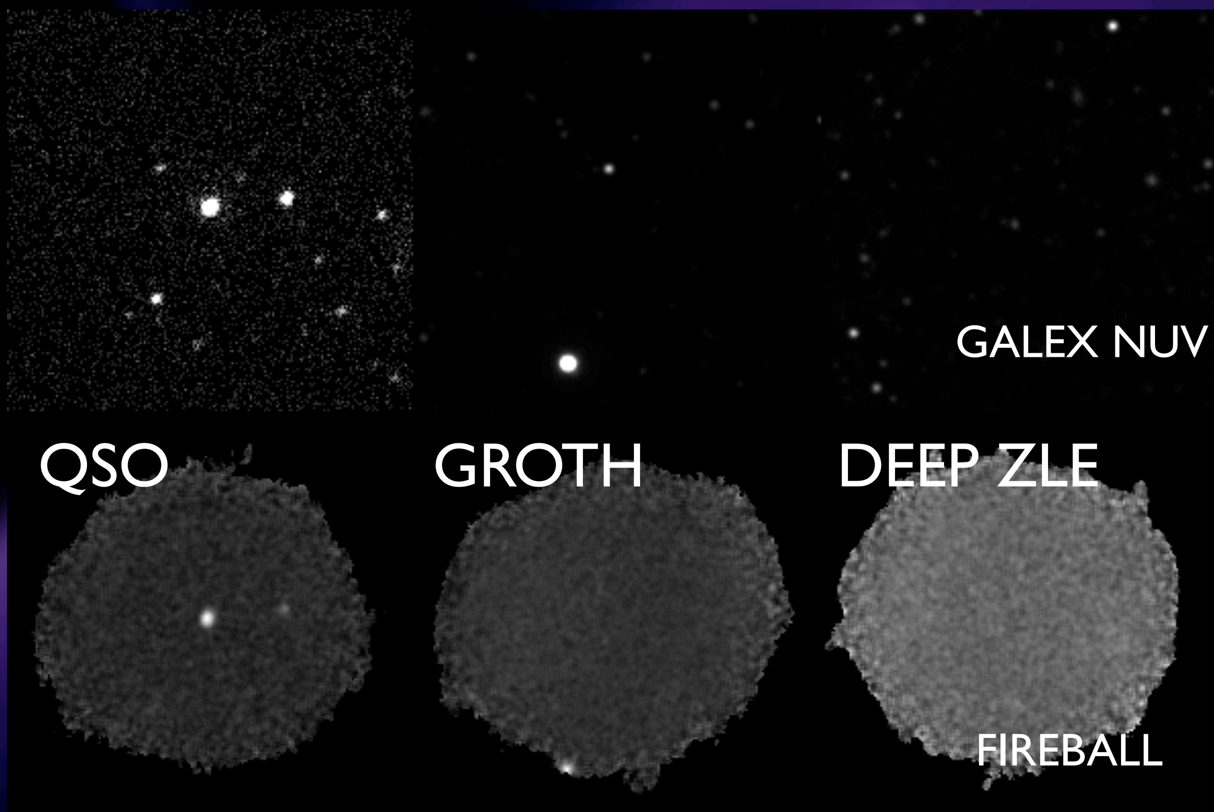


Raw spectrograph/detector data
from 3 deep observations (5 hours)

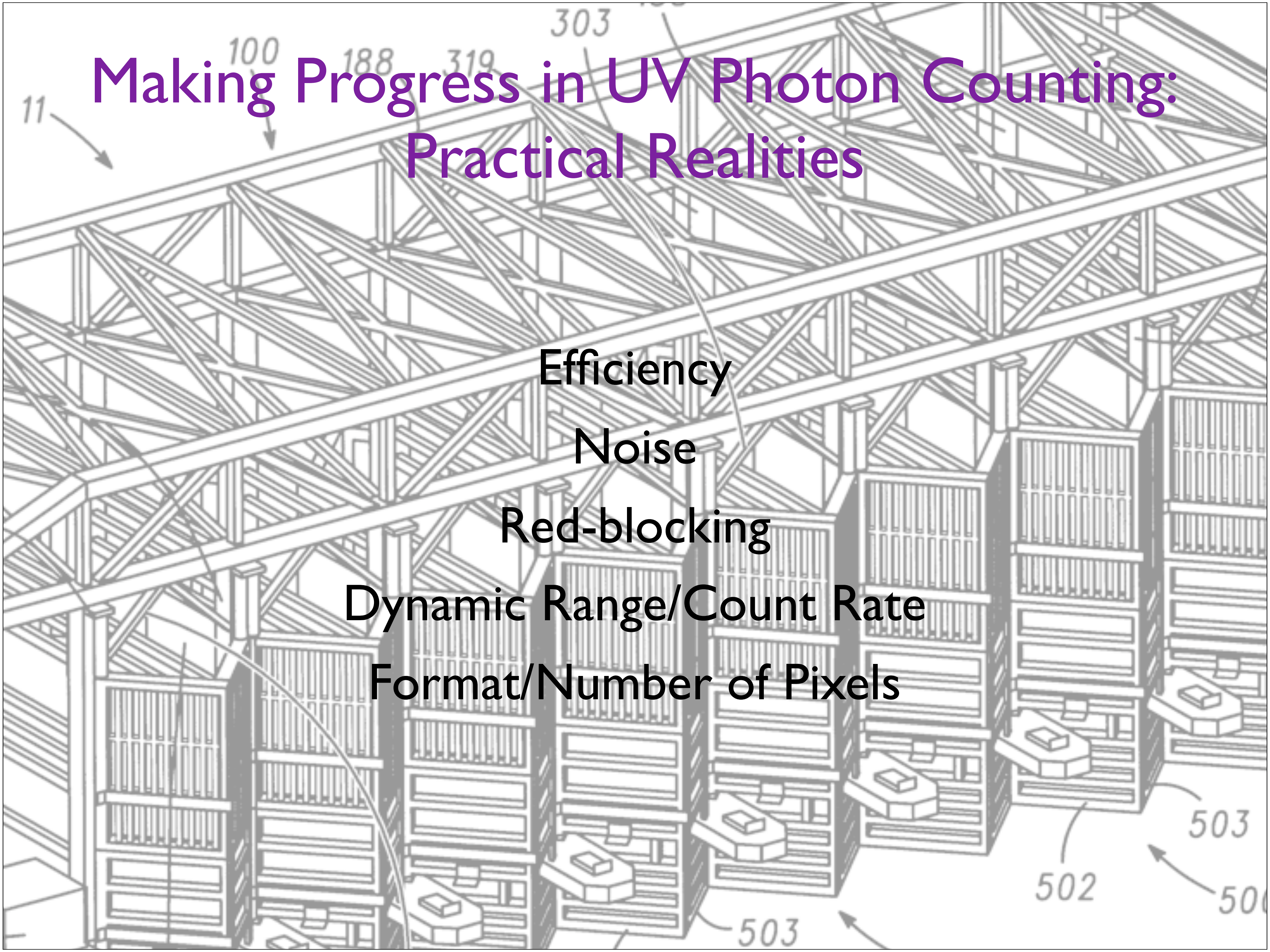
FIREBall Photon Counting

Mapping the IGM from a Balloon

First aspect-reconstructed photon counting data from an integral field unit (& first IFU in the UV)



Making Progress in UV Photon Counting: Practical Realities



Efficiency

Noise

Red-blocking

Dynamic Range/Count Rate

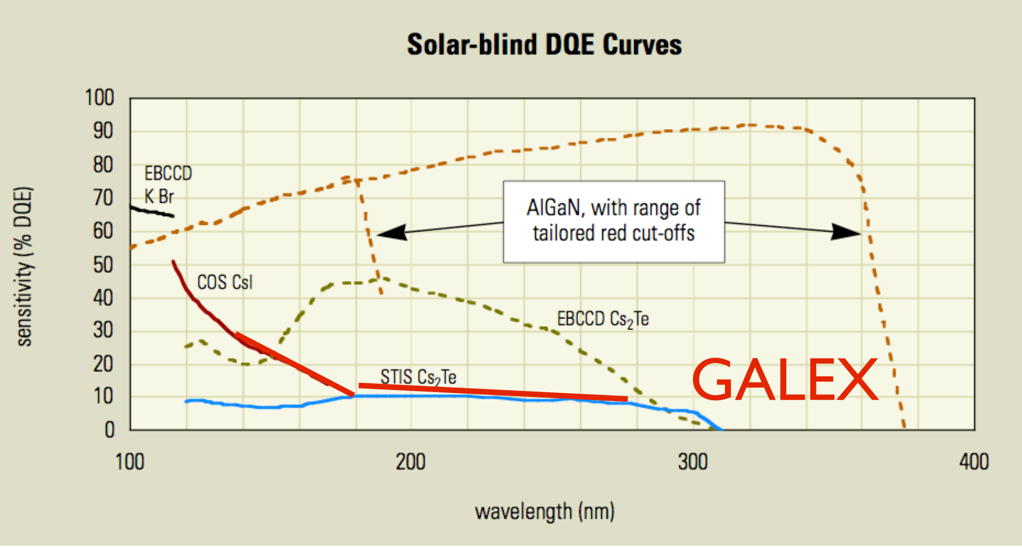
Format/Number of Pixels

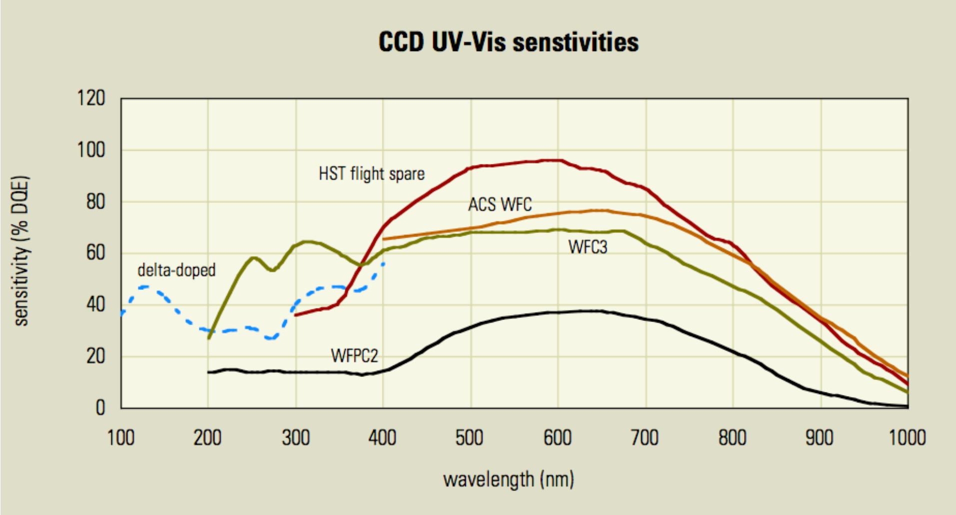
Efficiency

GALEX MCP detectors have 10-30% QE FUV 10-15% QE NUV

Significant potential for improvement by factors of ~2-5...

...but QE gains have been slow to materialize in new flight-ready units





UV-visible detectors (2000)

Noise: HST/WFC3 UVIS

UVIS/F625W

Description

Sloan Digital Sky Survey r′ filter.

Figure A.79: Integrated system throughput for F625W.

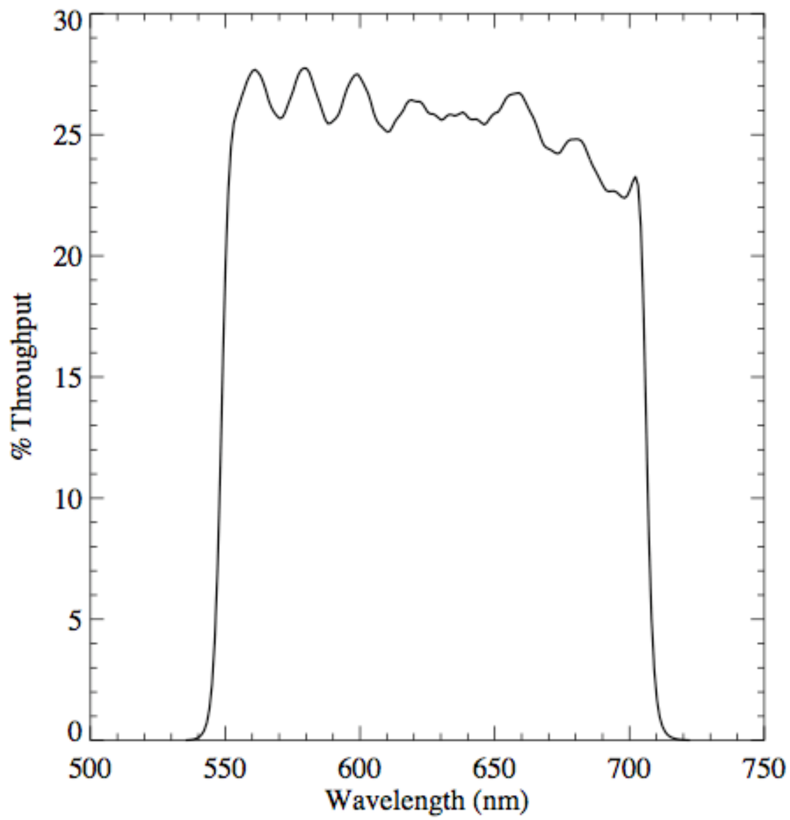


Figure A.80: Point source S/N vs. V+ABv for the F625W filter, assuming high sky backgrounds and a 5×5 pixel aperture.

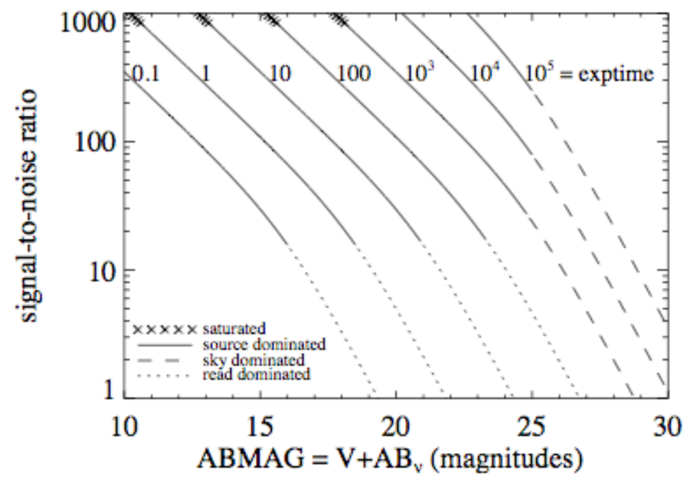
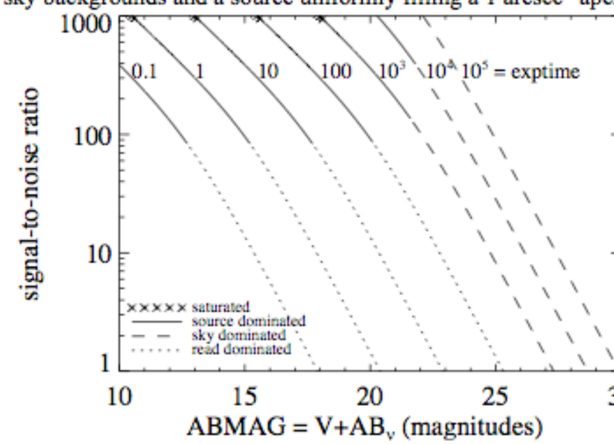


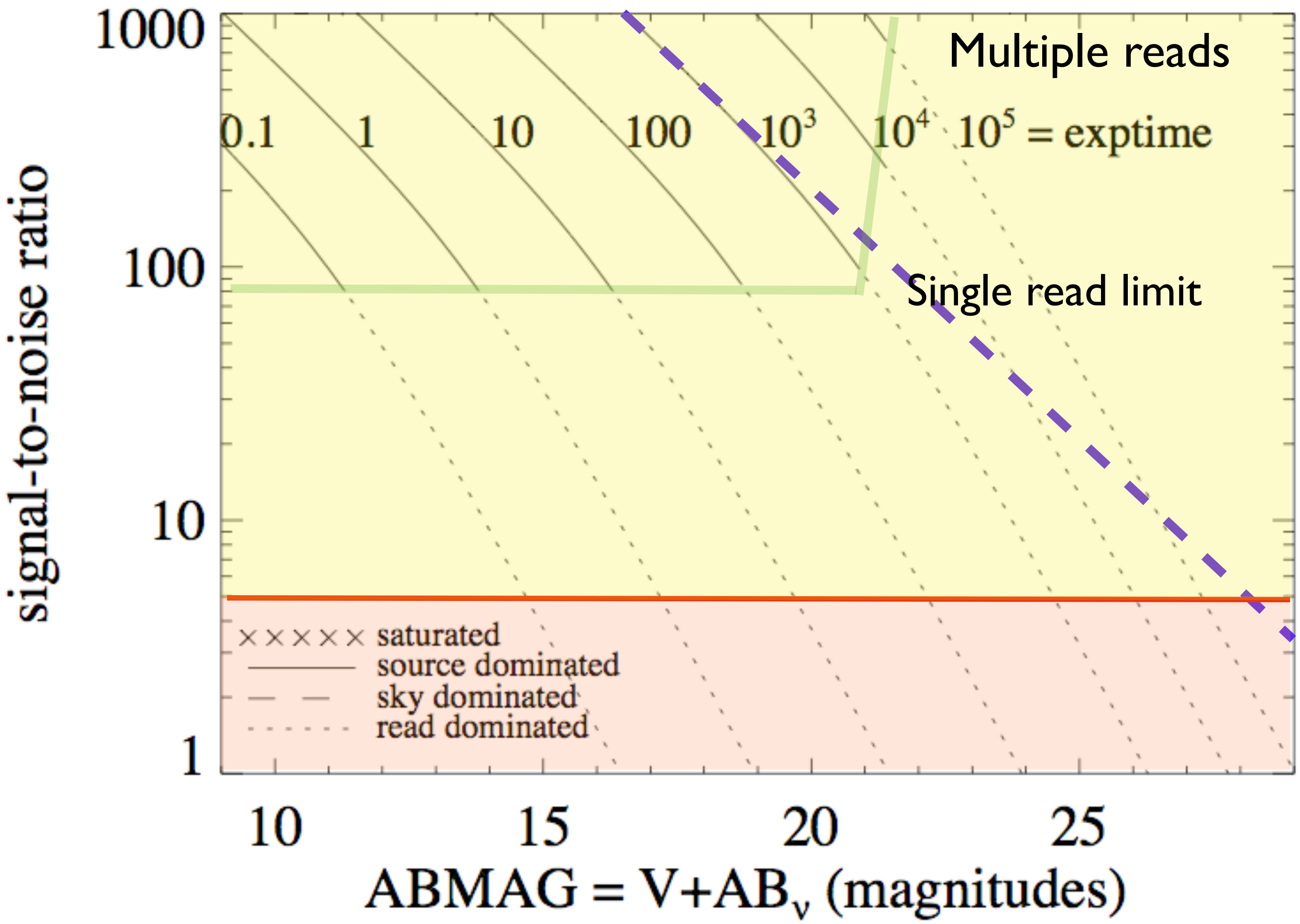
Figure A.81: Extended source S/N vs. V+ABv for the F625W filter, assuming high sky backgrounds and a source uniformly filling a 1 arcsec^2 aperture.

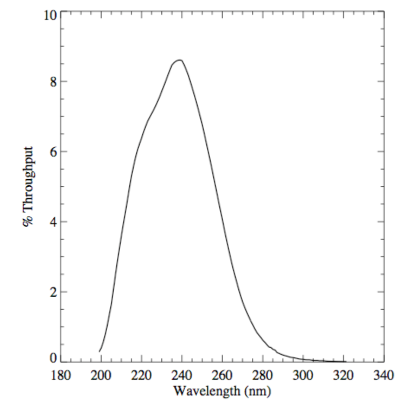


Typical ~1 hour exp, SDSS r-band, sky-dominated at faint limit

Noise: HST/WFC3 UVIS F225W (1")

Challenge for high resolution imagers





Photon counting detector yields x30 increase in depth

$$\frac{S}{N} = \frac{I_\lambda \Omega A_{eff} \Delta\lambda t}{\sqrt{I_\lambda \Omega A_{eff} \Delta\lambda t + I_{sky,\lambda} \Omega A_{eff} \Delta\lambda t + N_{pix}}}$$

$$\log\frac{S}{N} = -0.2 m_v + k$$ Photon limited

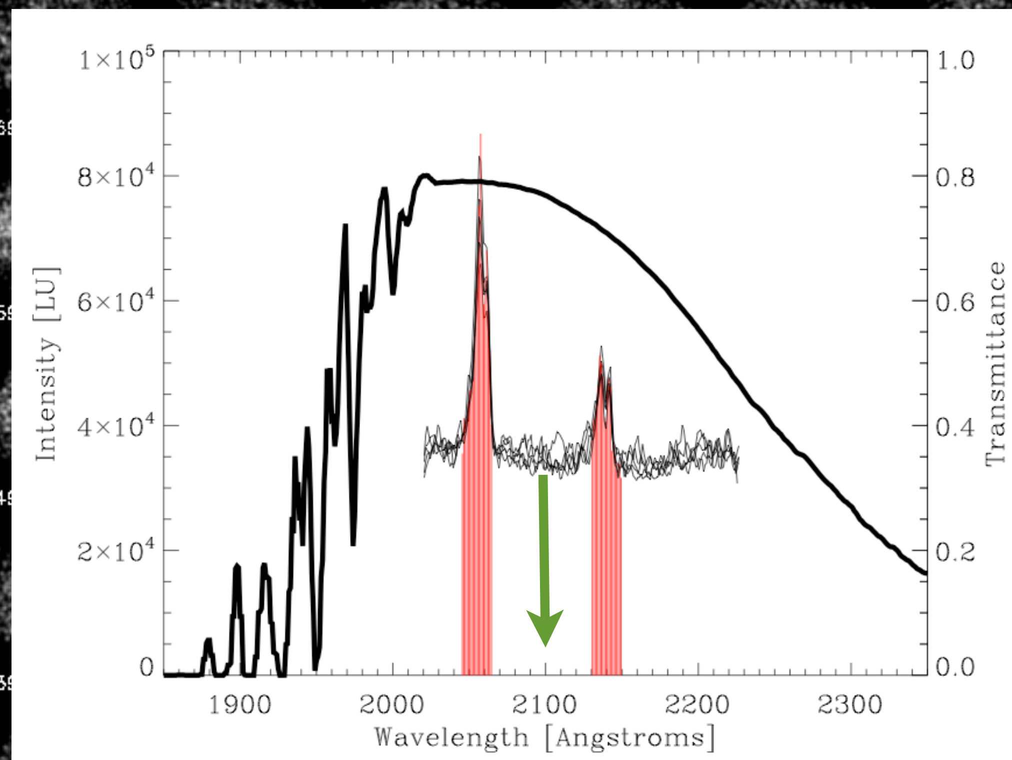
$$\log\frac{S}{N} = -0.4 m_v + k$$ Read limited

Noise: MCP FIREBall Experiment

First generation FIREBall experiment still limited by dark count rate from GALEX spare NUV detector

Aside for energy resolving detectors:

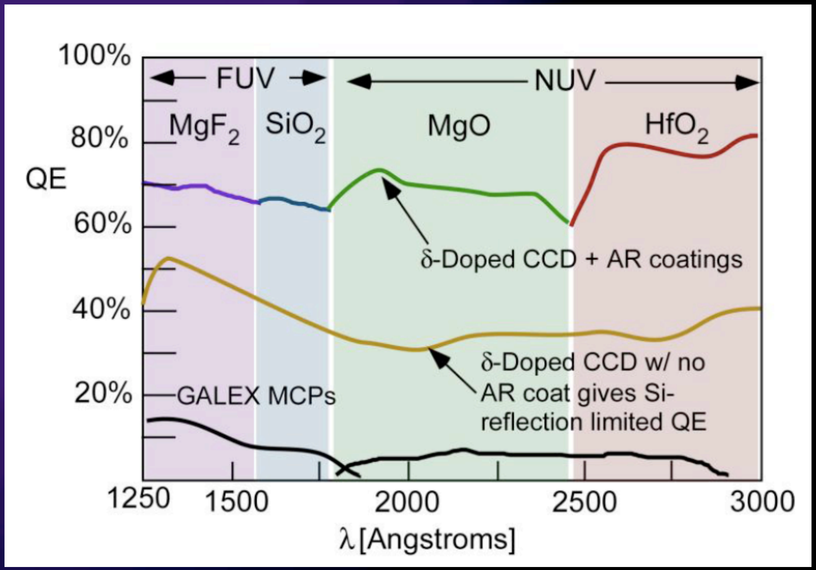
From balloon altitudes NO nightglow bands w/ ~6-8 nm separation require resolving power R> 50 at 200 nm to avoid



Noise: MCP FIREBall Experiment

First generation FIREBall experiment still limited by dark count rate from GALEX spare NUV detector

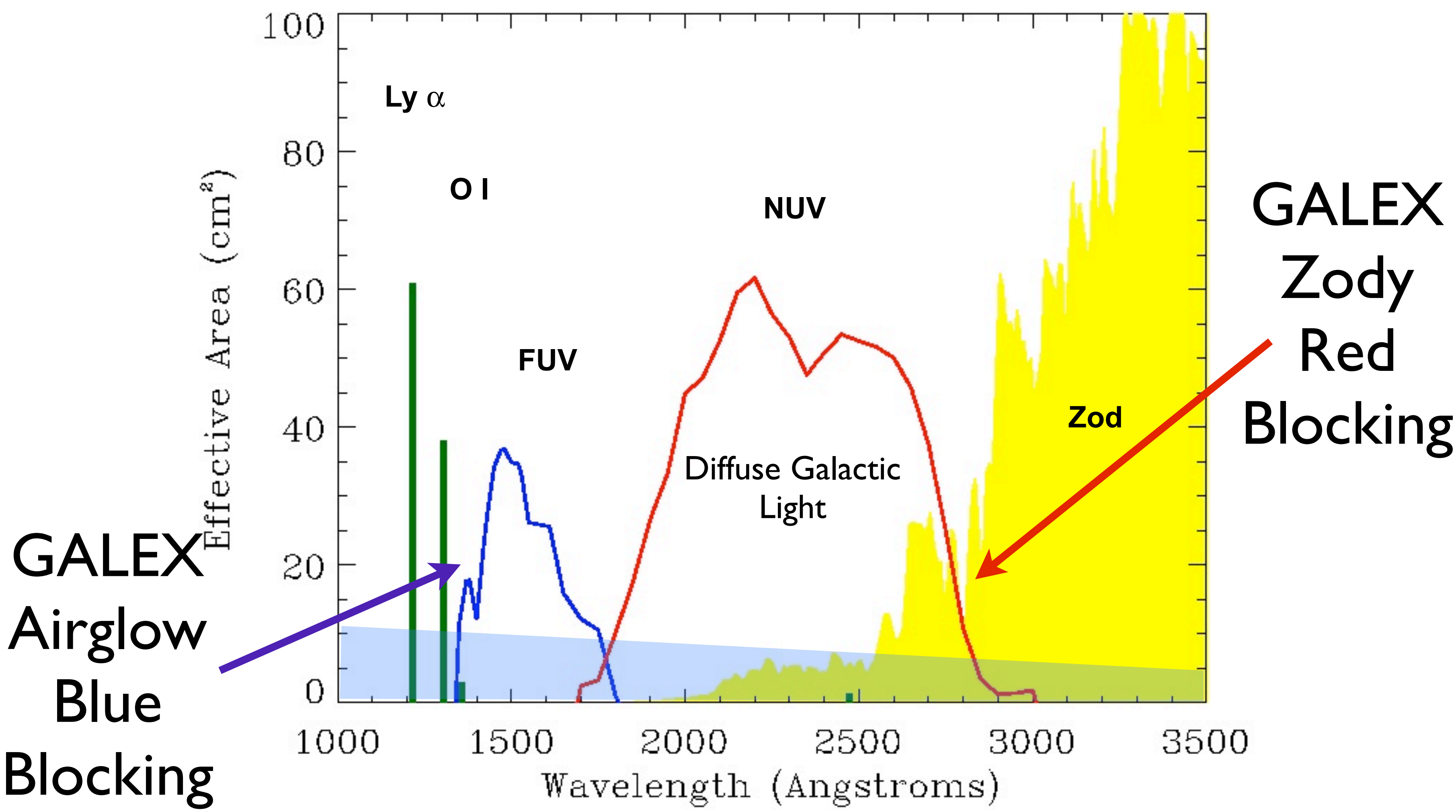
- Efficiency/throughput gains provide a tremendous boost, but only feasible with non-MCP, Si detectors
- Next generation instrument combines efficiency gains on Si in UV (AR+delta-doping) with low noise CCD (L3CCD)



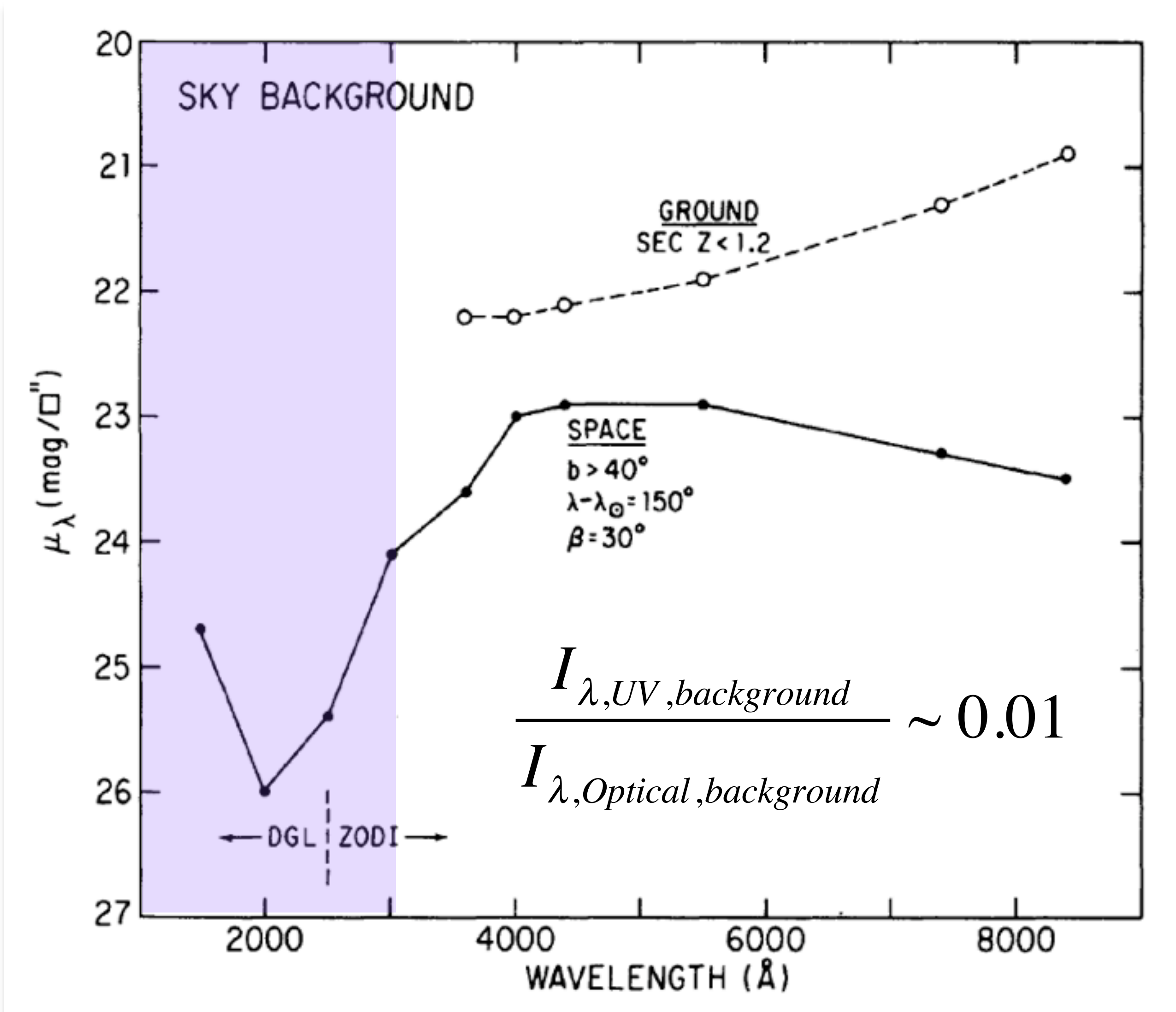
e.g. P. Morrissey next talk

Nikzad, Hamden

Red leak: Solar-blind does not necessarily mean that no red-blocking is needed



Red leak: At the same time, red blocking/solar blind requirement need not be 'draconian'

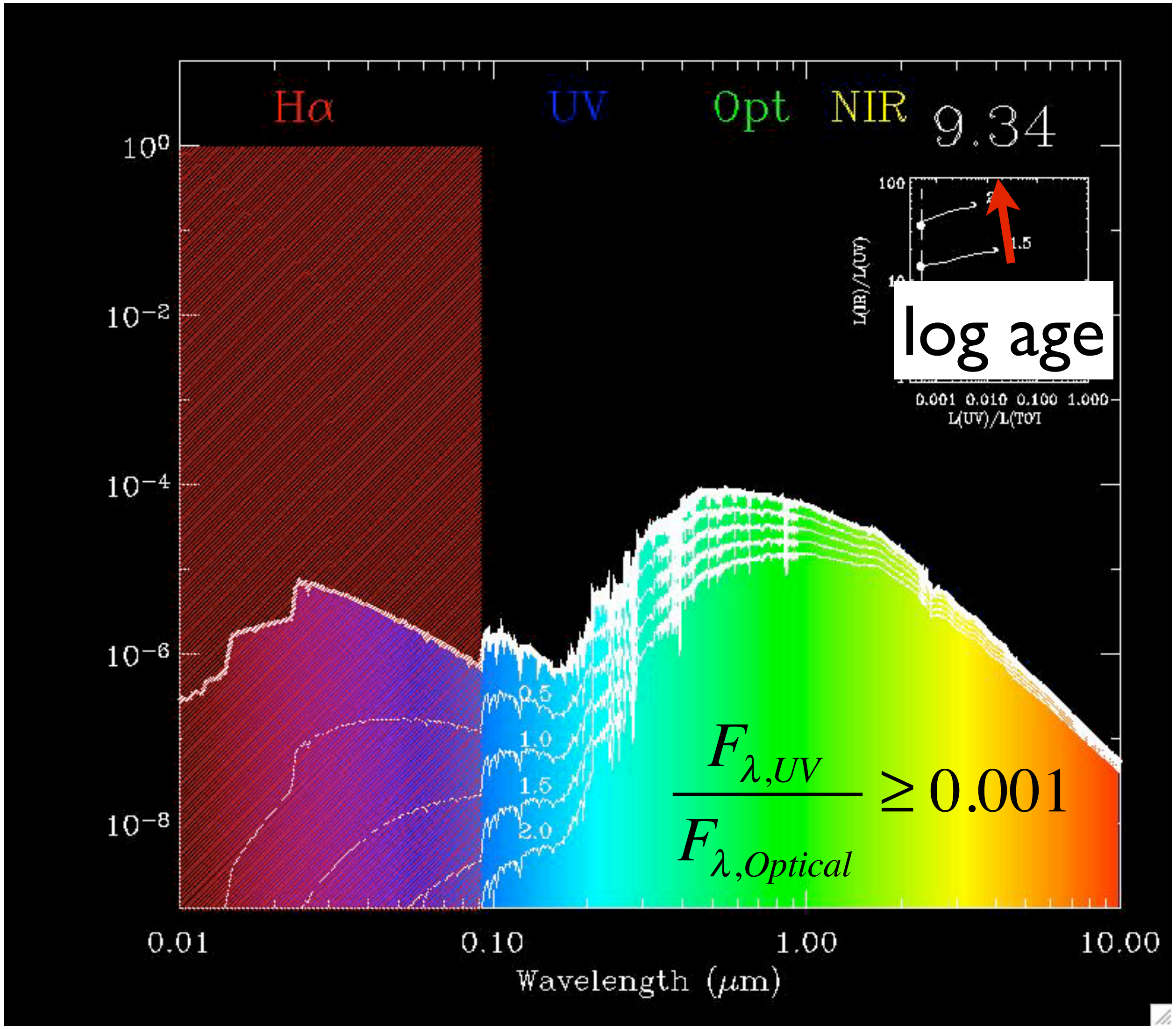


$$\frac{I_{\lambda,UV,background}}{I_{\lambda,Optical,background}} \sim 0.01$$

Out-of-band rejection requirement $\sim 10^{-3} - 10^{-4}$

Manageable in spectrograph and/or with high efficiency multilayer filters

Red leak: At the same time, red blocking/solar blind requirement need not be ‘draconian’



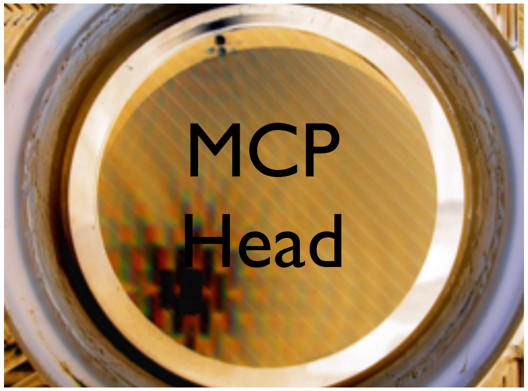
e.g. stellar populations in galaxies are not extremely “red”

Rejection $\sim 10^{-3}$ - 10^{-4}

Some rare objects, & cool stars

Dynamic Range/Count Rate

GALEX detectors



MCP Anode
Fast-timing
(~ADC)
Electronics

Digital photon
word processor

~100 kHz
(MCP operational
considerations,
burn-in, safety)
100 Hz local

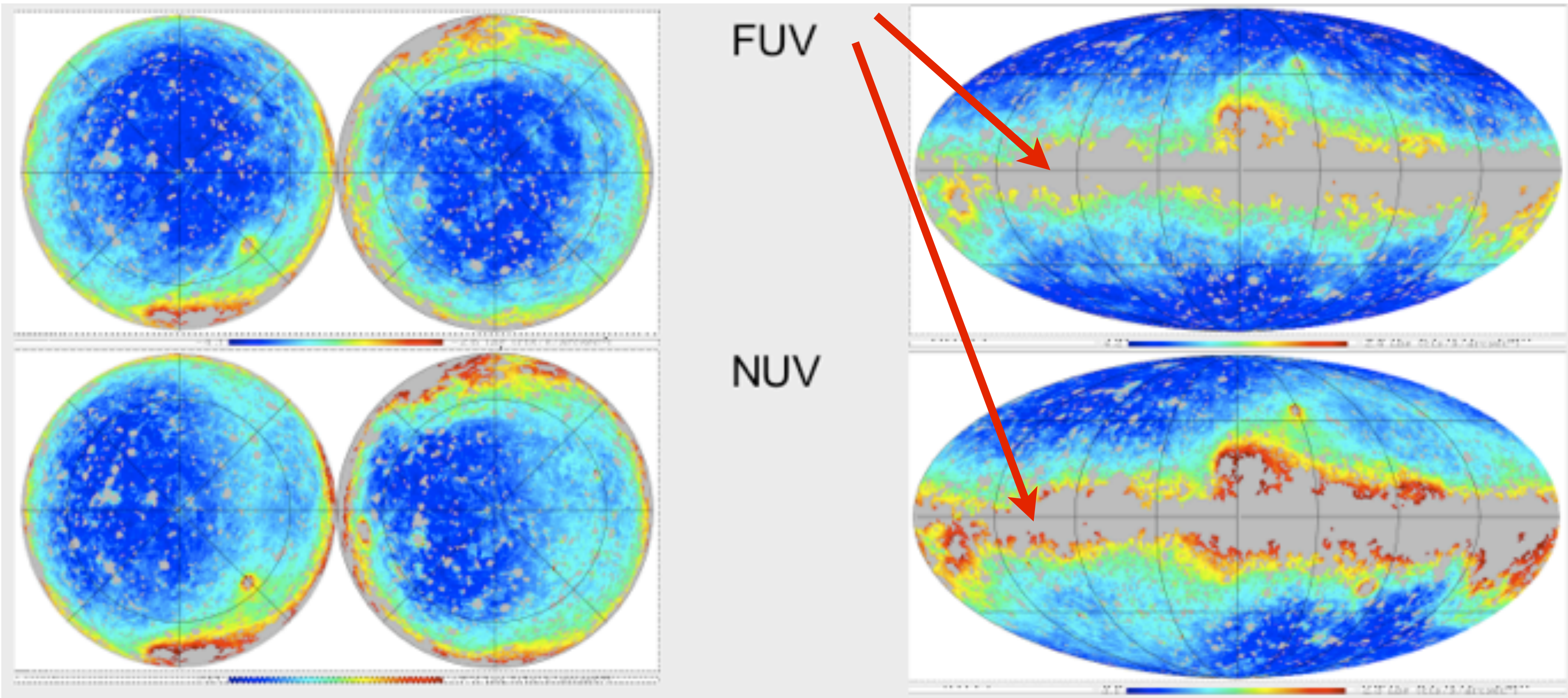
>1 MHz

200 kHz
(Delays, bit
transfer rate)

On GALEX operational and downstream limits are the bottleneck

Dynamic Range/Count Rate

Often extremely important for *wide-field* experiments



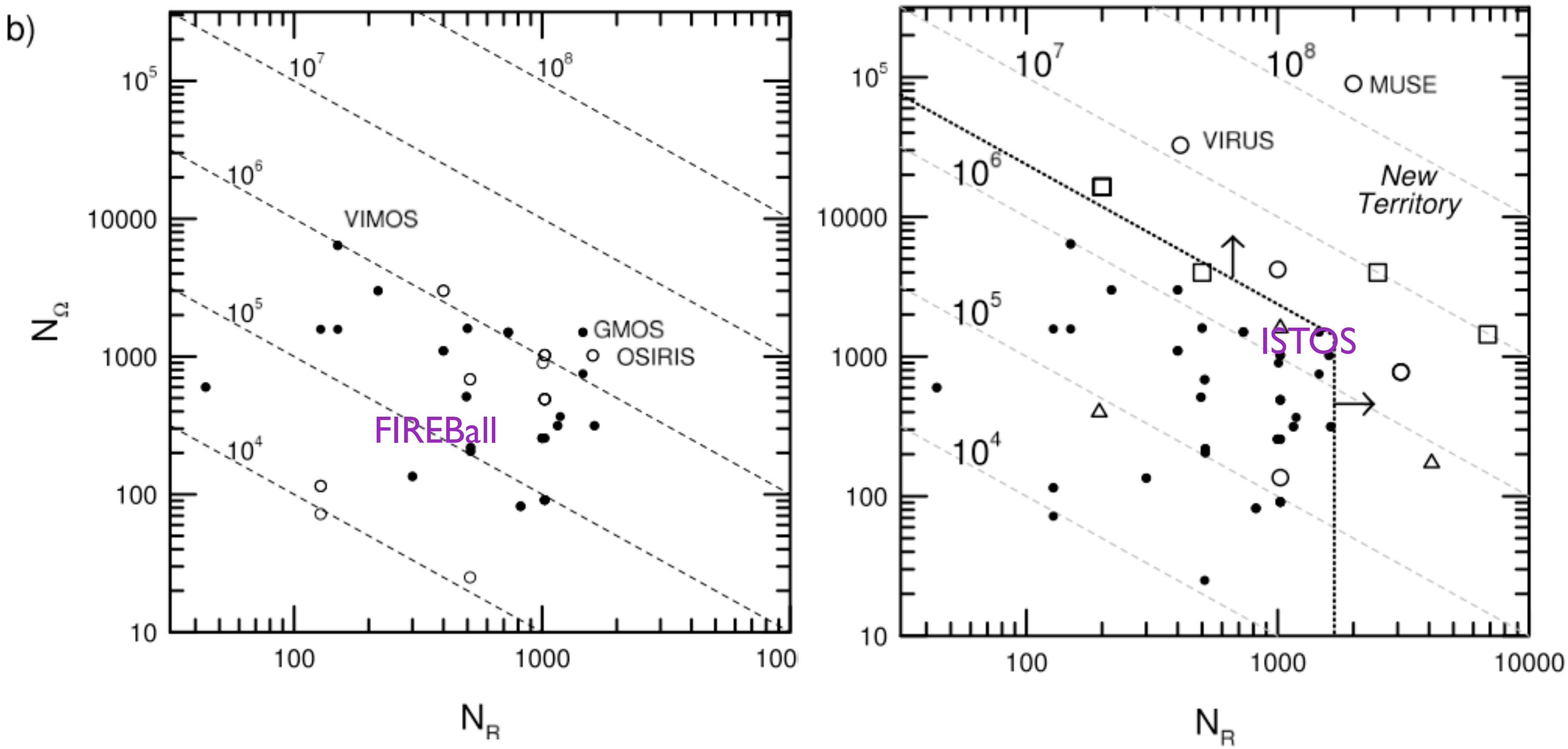
GALEX All-sky Imaging Survey

Total Duration = 5,000,000 seconds = 0.2 Trillion Photons

Format/Pixels

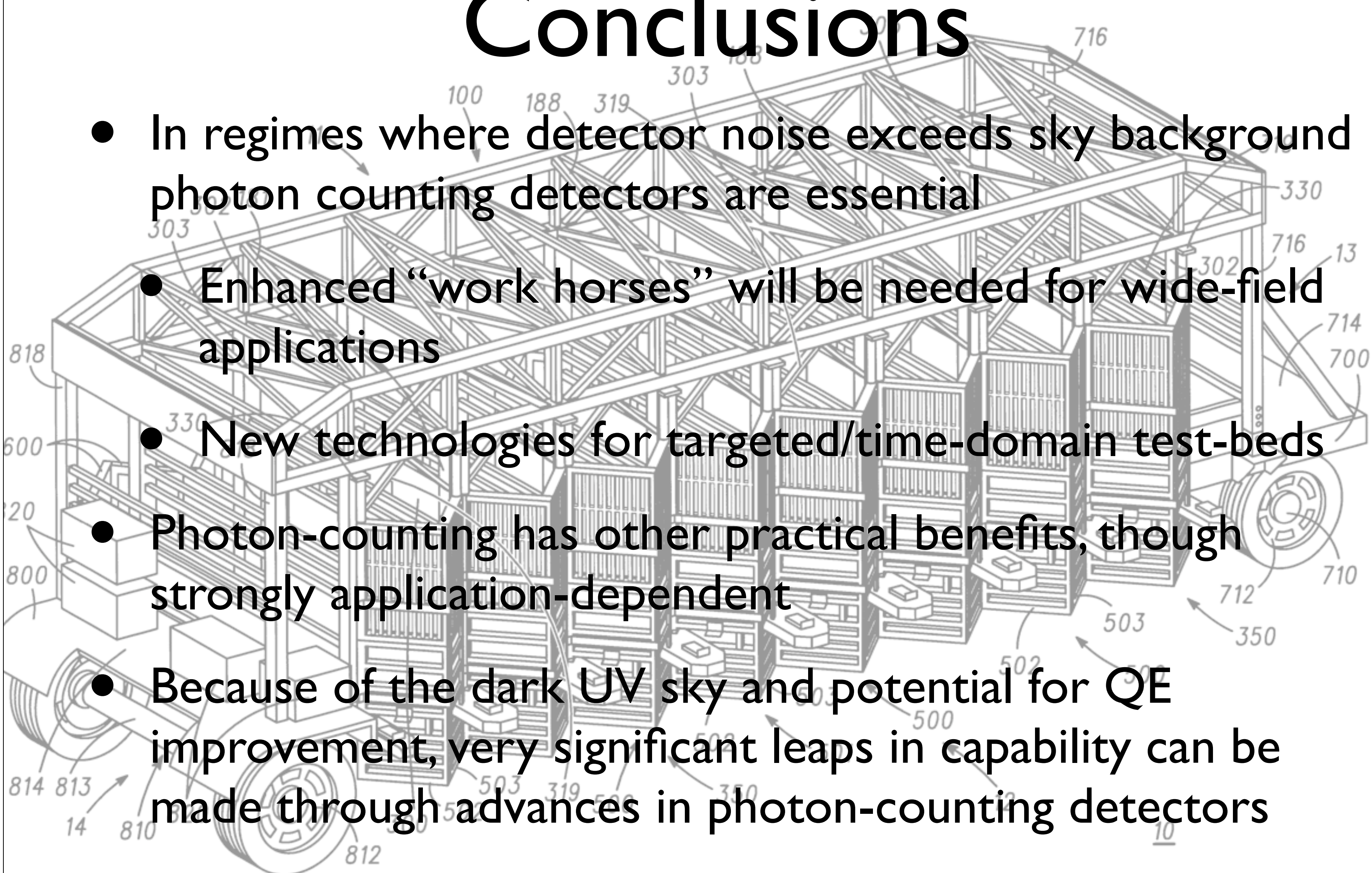
- “Workhorse Technologies”
  - Kepler focal plane CCDs (vis): 42 Mpix
  - GALEX MCP detectors: ~2 Mpix
- These are hard to beat and mitigate gains from much smaller “3-d” detectors
  - At 200x200x50 may start to become competitive, but still some years off

Number of resolution elements of present/future optical IFU/spectrographs



Bershady (2010)

Conclusions



- In regimes where detector noise exceeds sky background photon counting detectors are essential
  - Enhanced "work horses" will be needed for wide-field applications
  - New technologies for targeted/time-domain test-beds
- Photon-counting has other practical benefits, though strongly application-dependent
- Because of the dark UV sky and potential for QE improvement, very significant leaps in capability can be made through advances in photon-counting detectors