Detector Possibilities for HabEx

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HabEx STDT meeting

August 3, 2016

CL#16-3782

HabEx Assumed Parameters

HabEx Primary Requirements (*Notional*)

- Mission Parameters (taken from PAG reports and whitepapers):
  - Aperture likely <~ 8m
  - Monolithic or segmented primary
  - 10^{-10} contrast in the HZ of nearby stars, with R>70 spectro-imaging
  - *Optimized for exoplanet direct imaging* in optical and NIR
  - Orbit: likely L2 or Earth-trailing
  - *Secondary payload TBD*

After
post processing?

The WFIRST Experience (So Far)

WFIRST Choices for Sensors

- **Conventional CCD**
  - \+ well known, high TRL
  - – read noise > ~3e- → most likely too high for our purposes
- **EMCCD (electron multiplication)**
  - \+ very low (<0.01 e-) read noise, photon counting possible, TRL reasonably high
  - – excess noise factor, charge induced current
- **Scientific CMOS (sCMOS)**
  - \+ high frame rate, read noise down to 1 e-
  - – lower QE (~60%), limited FOV in some cases

Journal of Astronomical Telescopes, Instruments, and Systems 2(1), 011007 (Jan–Mar 2016)

Technology advancement of the CCD201-20 EMCCD for the WFIRST coronagraph instrument: sensor characterization and radiation damage

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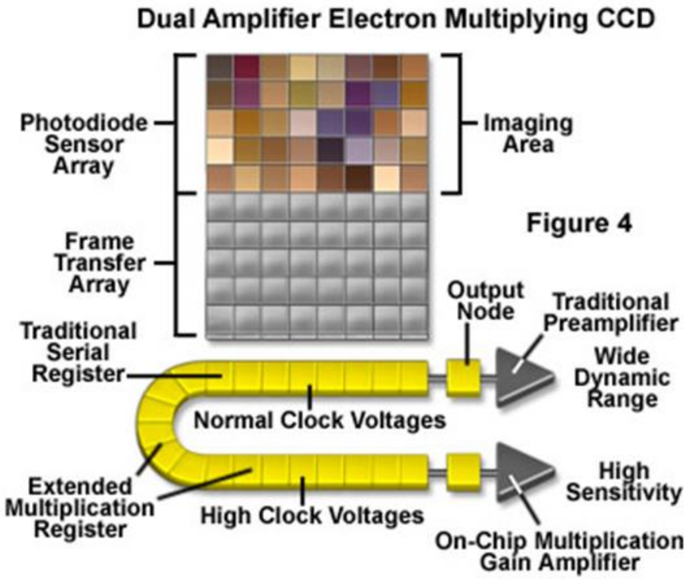
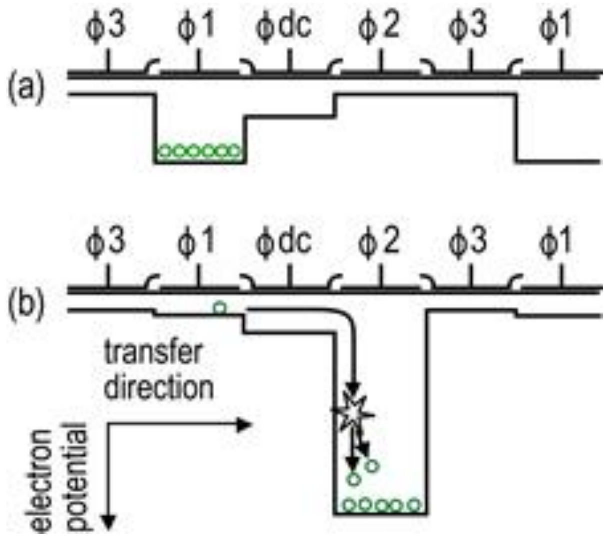
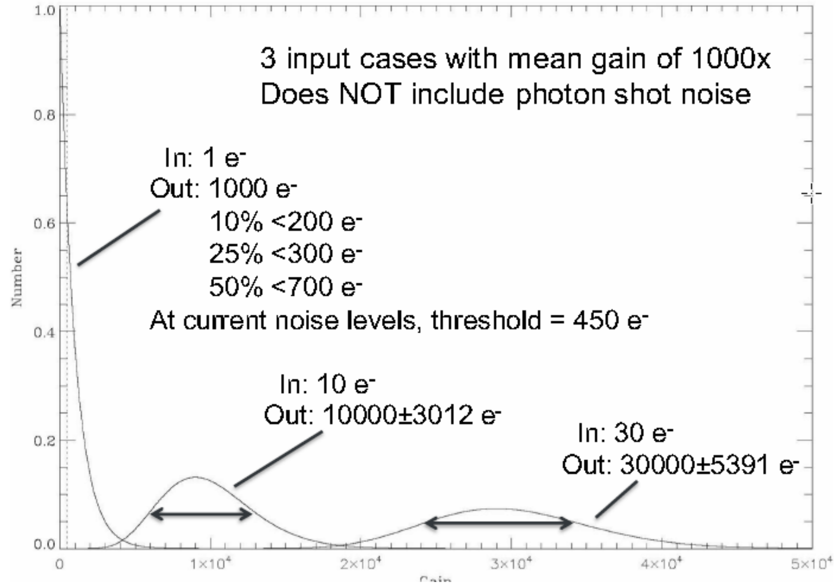
Electron Multiplication (EM) CCD’s

- In traditional CCD’s the pixels are clocked out in parallel into a serial register where they are then read out.
- In an EMCCD they are routed instead to an extended multiplication register with a high-voltage phase (10’s of V) where they undergo multiplication.
- At each gain stage there is a small (typically < 2%) chance of getting an extra electron
- Since there are hundreds of multiplication elements there can be a large gain:

$$G_{EM} = (1+p)^N \quad \text{e.g.} \quad (1+1.5\%)^{600} \sim 7500$$



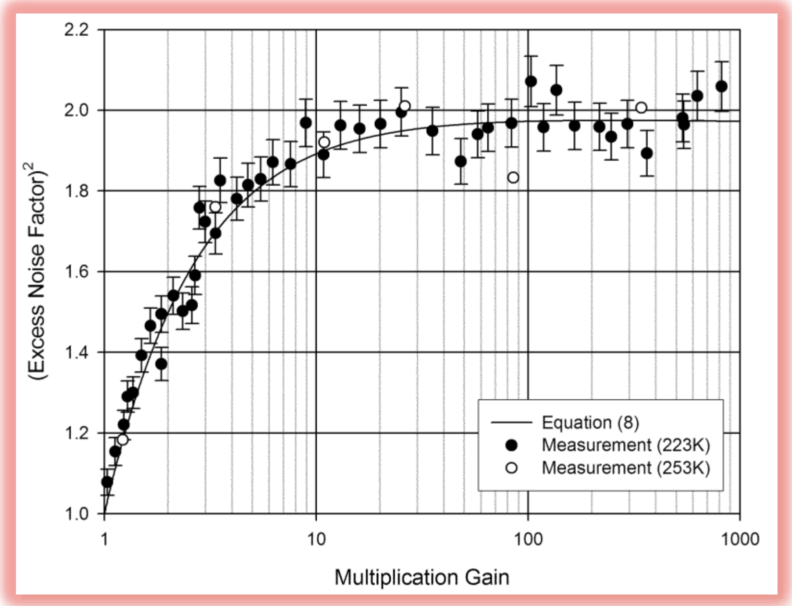




Consequences of Electron Multiplication

- The main benefit of electron multiplication is a boost to the signal while the read noise is still the same as for ordinary CCD
    - This effectively translates to a lower effective read noise

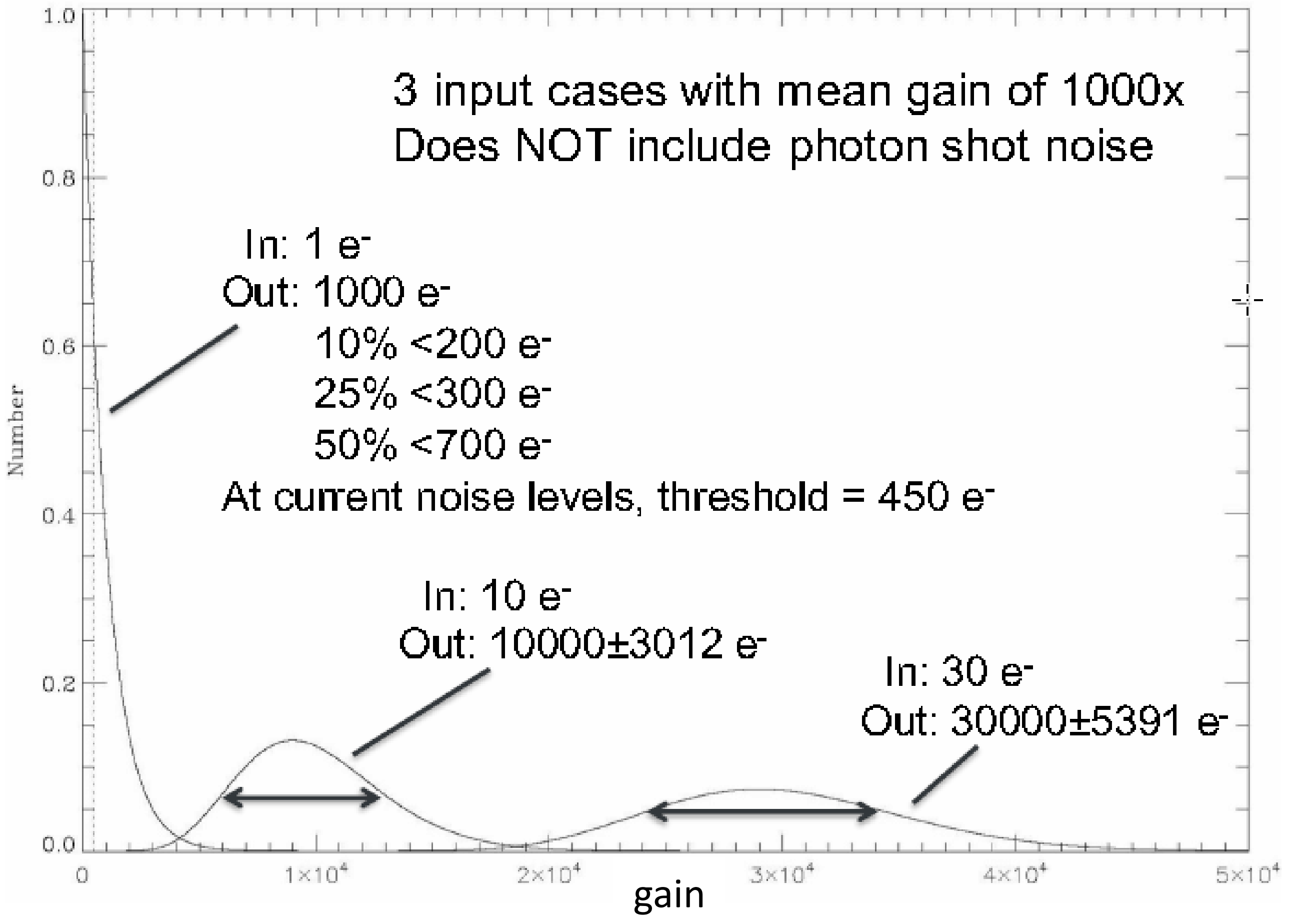
- The price we pay for this benefit:
    1. The electron multiplication is a stochastic process, so that the gain is not the same every time. This introduces an 'excess noise factor' (ENF) $\sim \sqrt{\mathbf{2}}$
    2. The high voltages and high frequencies create clock-induced charge (CIC) $\sim 10^{-3}$ e-/pix/frame.
    3. The full-well (hence dynamic range) is proportionately reduced.



Getting The Full Value: Photon Counting

- With high enough frame rates, it is possible to get into a regime where the number of expected photons per pixel per frame is low
- If there are almost never > 1 photons likely to hit a pixel in one frame time, can go into photon counting mode
- Here we set a threshold high enough to avoid false positives but low enough not to lose efficiency
- The advantage of photon counting is that the Excess noise factor is gone.

Patrick Morrissey

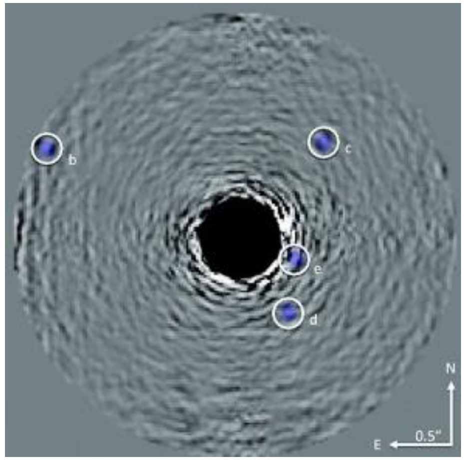


Coronagraph SNR

- For the coronagraph the SNR is given by

$$SNR = \frac{S}{N} \qquad \text{where:} \quad S = r_{pl}\, t \qquad r_{pl} = \Phi A \tau \eta$$

$$\begin{cases} \Phi & : \text{photon flux} \\ A & : \text{collector area} \\ \tau & : \text{transmission} \\ \eta & : \text{QE} \end{cases}$$

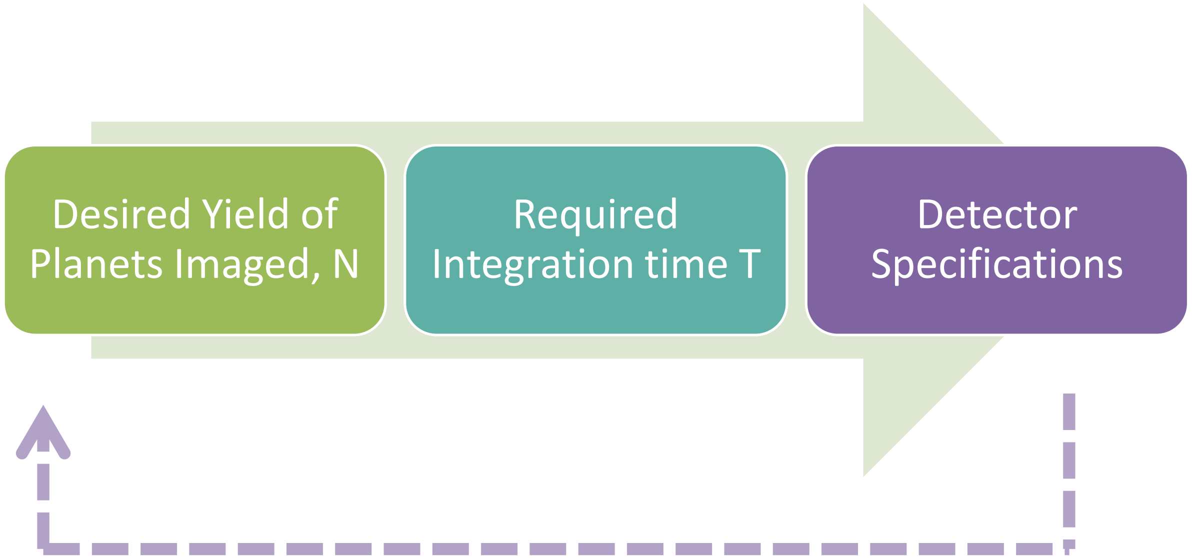


$$N = \sqrt{\sigma^2_{shot} + \sigma^2_{zodi} + \sigma^2_{spec} + \sigma^2_{spstr} + \sigma^2_{\det}}$$

- σ^2_{shot}: shot noise of planet light
- σ^2_{zodi}: shot noise from zodiacal dust (local + exo)
- σ^2_{spec}: shot noise of mean speckle
- σ^2_{spstr}: residual speckle structure (after post-processing)
- $\sigma^2_{\det}$: detector noise

Detector parameters of most importance:

1. QE
2. Read Noise
3. Dark current
4. Frame Rate
5. Clock-induced Charge (CIC)



Important metric: Requisite time to reach SNR

- Analytical expression for SNR:

$$SNR_p = \frac{S}{N_p} \quad \text{where} \quad \begin{cases} S = r_{pl}\, t \\ N_p = \sqrt{r_n^p\, t + \sigma_{sp}^2} \end{cases} \qquad r_{pl} = f_{SR}\, \Phi_*\, C_{pl}\, A_{PM}\, \tau_{pl}\, \eta$$

$$r_n^p = \underbrace{f_{SR}\, F^2 \left[\Phi_*\, C_{pl}\, \tau_{pl} + \Phi_* C_{CG} I_{pk} m_{pix} \tau_{sp} + \left(\frac{d\Phi_Z}{d\Omega}\, \Delta\Omega_{PSF} \right) \tau_Z \right]}_{\text{photonic}} A_{PM}\, \eta + \underbrace{F^2 \left[i_d m_{pix} + q_{CIC} \frac{m_{pix}}{t_{fr}} \right] + \frac{m_{pix}}{t_{fr}} \left(\frac{\sigma_r}{G_{EM}} \right)^2}_{\text{electronic}}$$

$$\sigma_{sp}^2 = n_{sp} t^2 \quad \text{where} \quad n_{sp} = \left(f_{pp} \cdot f_{SR} \cdot \Phi_* C_{CG} I_{pk} m_{pix} \tau_{sp}\, A_{PM}\, \eta \right)^2$$

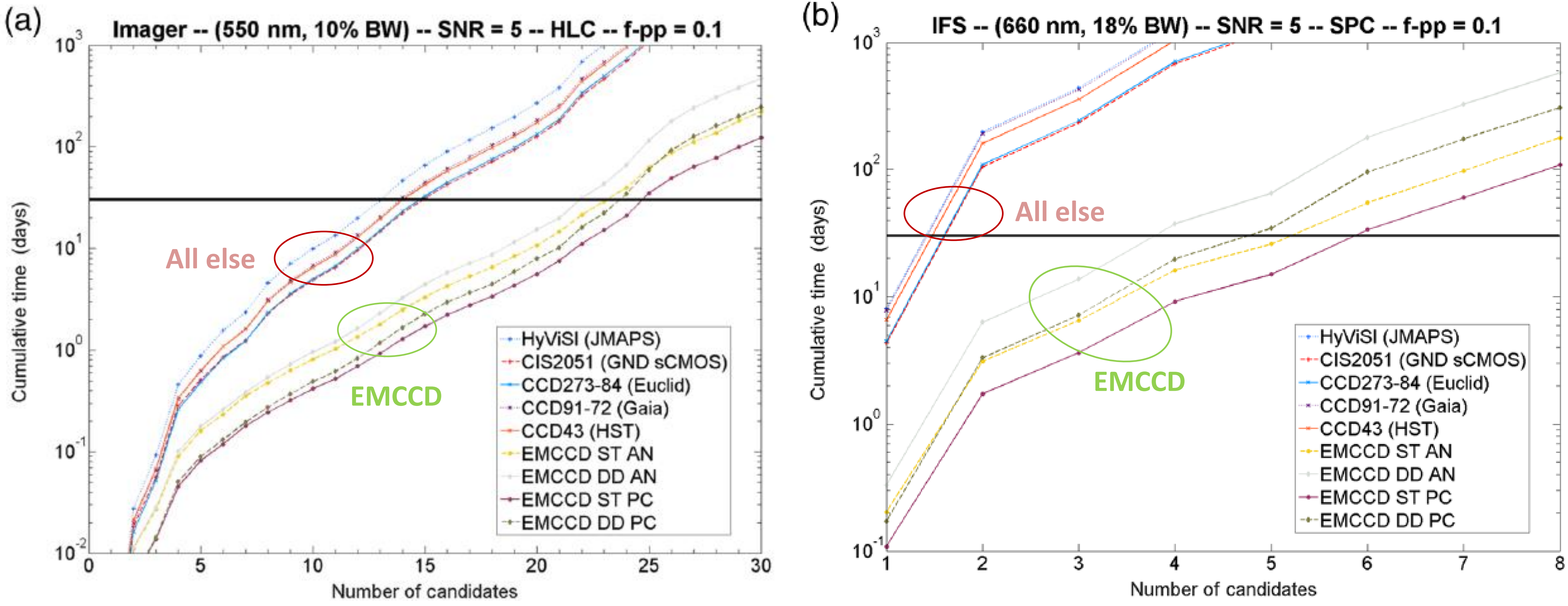
Can invert the equation to get the requisite time to get to a desired SNR:

$$\rightarrow t = \frac{SNR^2\, r_n}{r_{pl}^2 - SNR^2\, n_{sp}}$$

Note that there could be <u>no solution</u> to *t* for sufficiently poor contrast!

How much of a difference do EMCCD's make?

WFIRST Examples



Expected Rates with HabEx

Typical Scene Photometry:

10 milli-photons/sec into planet core

- Core ≡ area under the PSF within the FWHM contour ($\sim\lambda/D$ wide)

Typical Imaging Mode Rates

Assume solar system at 12 pc, imaging Earth

0.007 phot/sec into the planet PSF core

0.067 phot/sec from Zodi (2 Zodi assumption)

0.006 phot/sec from Speckle

Adapting WFIRST Photometry to HabEx (Rough)

HABEX OBSERVING SCENARIO INPUT PARAMETERS

Collector Diameter	6	m	Diameter of PM
Sec. Obsc. frac	30%	of diam	
Scenario	IFS 1		
SNR Target	5		
Detector Type	PC EMCCD		
Coronagraph Type	HLC		
Star Brightness	5.00	mag	
Star Distance	12.00	pc	
Planet Radius	1	Re	
Planet SMA	1	AU	
Frame Time	100	s	Specify a time
Post-proc Factor	10%	f_pp	resid. speckle str.
Zodi (Exo+local)	2	zodi	(loc+exo) / loc
Contrast Improvement	2	X	over WFIRST HLC
Coron. Raw Contrast	7.8E-10	before post processing	
Planet Contrast	2.3E-10		
Science Instrument	IFS		
Center lambda	6.60E-07	m	V-band ctr.
Bandwidth	18%	--	V-band is 16.18%
Spec Resolution	70	R	

Scene Signal and Background (per Frame)

Core (photons)

Item	Value	Units	Comments
Planet Phot	0.099	phot	PSF core (photon)
Speckle Phot	0.133	phot	PSF core
Zodi Phot	1.383	phot	PSF core

Core (phot/s)

Item	Value	Units	Comments
Planet Phot Rate	9.9E-04	phot/s	PSF core (photon)
Speckle Phot Rate	1.3E-03	phot/s	PSF core
Zodi Phot Rate	1.4E-02	phot/s	PSF core

Per Pixel (photons)

Planet Phot	0.005	phot	per pixel (in core)
Speckle Phot	0.01	phot	per pixel
Zodi Phot	0.1	phot	per pixel

Per Pixel (elec/s)

Planet Elec Rate	3.7E-05	e/s	per pixel (in core)
Speckle Elec Rate	5.0E-05	e/s	per pixel
Zodi Elec Rate	1.0E-02	e/s	per pixel

SNR

Time to SNR

Item	Value	Units	Comments
Required Time to reach SNR	2.0E+06	s	
	564.78	hr	
	23.53	days	

Final SNR

Item	Value	Units	Comments
SNR Check	5.00	SNR	
Signal	1443.4	e	Total Signal
Noise	288.7	e	Total Noise
Frames Needed	20332.1	frames	for SNR target

Final Noise Contributions

Item	Value	Units	Comments
Shot	37.993	e	signal shot noise
Speckle	44.168	e	<sp> shot noise
Zodi	142.268	e	zodi shot
Dark Current	140.291	e	
CIC	44.364	e	
Read	0.000	e	
Speckle Structure	195.083	e	residual Speckle

SNR By Frame

Item	Value	Units	Comments
SNR 1 Frame	0.0476	SNR	
Signal	0.07	e	
Noise	1.49	e	
Shot	0.27	e	
Speckle	0.31	e	
Zodi	1.00	e	
Dark Current	0.98	e	
CIC	0.31	e	
Read	0.00	e	
Speckle Struc.	0.01	e	

Nominal HabEx Target and Scaling from Habex to WFIRST Tables

distance	10.0	pc	
SMA min	0.60	AU	
HABEX diam	6.00	m	
Nom Wavelength	550	nm	
DiffLimitHabex	0.019	arcsec	
Planet Angle min	0.060	arcsec	
WAmin	3.17	lam/D	
WFIRST WA min	3.00	lam/D	
scale factor	0.95	Apply to HX WA to look up in WF table	
Planet albedo	0.4	a	
Working Angle	3.67	λ/D	
Lookup WA	3.47	λ/D	scale factor applied

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	19.4		pixels in SNR ROI
Excess Noise Fac.	1.00	ENF	Robbins 2003, w/ N=200
Frame Rate	0.0100	Hz	Wes used 300s

Focal Plane Architecture

Imager Critical λ	450	nm	Nyquist sampled
Imager Sampling	0.34	(λ/D) / pix	
IFS Critical λ	600	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	0.010	arcsec	/ lenslet @ crit. λ

Rates of signal and background into the SNR region of interest

Stellar Flux

Item	Value	Units	Comments
Photon Flux	1.5E+08	ph/(s*m2)	
Gen. Phot Flux	1.1E+08	ph/(s*m2)	From GSPEC (RV list)
Planet Contrast	2.3E-10		Planet Contrast
Planet Elec Rate	7.1E-04	e/s	PSF core (electron)
Speckle elec rate	9.59E-04	e/s	PSF core (electron)
Local Zodi	22	mag/as^2	brightness density
Flux per solid ang.	1.7E+12	ph/s/m2/rad2	inc. exo zodi
Zodi elec rate	1.0E-02	e/s	per pixel
Noise Rate Total	0.022	e/s	all but Speckle struc.

Throughput

Item	Value	Units	Comments
τ_{obs}	0.84	--	obscuration fraction
τ_{pup}	1	--	pupil mask obscuration(HLC)
τ_{occ}	0.39	--	occulter transmission
HabEx Improvement	3	X	better throughput
τ_{core}	0.093	--	frac of pl light in PSF core
τ_{ref}	0.53	--	transmissions and reflections
τ_{fil}	0.90	--	transmissin of BW filter
τ_{pol}	0.48	--	polarizer
τ_{pl}	1.8%	--	planet throughput
$\tau_{speckle}$	19.0%	--	polarizer
τ_{zodi}	7.5%	--	planet throughput

Scenario

Scenario	BW	Center λ	R	Focal Plane Type
Custom	5%	6.00E-07	0	Imaging
Imaging 1	10%	4.50E-07	0	Imaging
Imaging 2	10%	5.50E-07	0	Imaging
IFS 1	18%	6.60E-07	70	IFS
IFS 2	18%	7.70E-07	70	IFS
IFS 3	18%	8.90E-07	70	IFS

Telescope

Telescope Parameters

Item	Value	Units	Comments
Diffraction Limit	1.10E-07	rad	FWHM on sky (λ/D)
	0.02268913		
Col. Area	28.274	m^2	Area of PM
Nspec	13	spectral elements	

Detector Configurations

Imaging Detector Options

Option	CCD	EMCCD	PC EMCCD	Comments
Read Noise (e-)	3	75	0	
EM Gain	1	1000	1000	
ENF	1	1.41	1	
Pixel Size	13	13	13	
Ph. Counting eff.	1	1	0.8	Fraction above Phot. Ctg Discr. Threshold

Focal Plane Attributes

Item	IFS	Imaging	Units	Comments
Shape	streak	circle	--	
f_SR	0.079	1.0	--	
mpix	19.36	6.76	--	

Coronagraph

Coronagraph Specs

Item	HLC	SPC	Units	Comments
Radius	1.58E-01	2.37E-01	arcsec	
Intensity	6.62E-12	5.06E-12	--	Speckle intensity at r (normalized to flux)
Contrast	7.79E-10	3.33E-09	--	Intensity/PSF_Peak
Core Throughput	3.09E-02	2.91E-02	--	Frac light incident on primary in FWHM of P
PSF Peak	4.25E-03	1.52E-03	--	Frac light in peak pixel of PSF centered at r &
Area	2.01E-03	4.98E-03	arcsec^2	Area of FWHM of PSF centered at r
Occular Transmission	3.94E-01	2.06E-01	--	Occulter*lyot stop transmission at r
Min Working Angle	2.10	2.40	λ/D	Throughputs
Max Working Angle	10.50	9.20	λ/D	Throughputs
τ_{ref}	0.53	0.49	--	Throughputs
CG intrinsic sampling	0.30	0.20	λ/D / pix	sampling used by John Krist in generating C
CG intrinsic mpix	8.73	19.63	λ/D / pix	pixels within PSF core assuming instrinsic sa

HabEx Comparison: CCD vs. Photon Counting EMCCD

CCD

HABEX OBSERVING SCENARIO INPUT PARAMETERS

Collector Diameter	6	*m*	*Diameter of PM*
Sec. Obsc. frac.	30%	*of diam*	
Scenario	IFS 1		
SNR Target	5		
Detector Type	CCD		
Coronagraph Type	HLC		
Star Brightness	5.00	mag	
Star Distance	12.00	pc	
Planet Radius	1	Re	
Planet SMA	1	AU	
Frame Time	2000	s	*Specify a time*
Post-proc Factor	5%	f_pp	*resid. speckle str.*
Zodi (Exo+local)	2	zodi	*(loc+exo) / loc*
Contrast Improvement	2	X	*over WFIRST HLC*
Coron. Raw Contrast	7.8E-10	before post processing	
Planet Contrast	2.3E-10		
Science Instrument	IFS		
Center lambda	6.60E-07	m	*V-band ctr.*
Bandwidth	18%	--	*V-band is 16.18%*
Spec Resolution	70	R	

Scene Signal and Background (per Frame)

Core (photons)

Item	Value	Units	Comments
Planet Phot	1.972	phot	PSF core (photon)
Speckle Phot	2.665	phot	PSF core
Zodi Phot	27.652	phot	PSF core

Core (phot/s)

Item	Value	Units	Comments
Planet Phot Rate	9.9E-04	phot/s	PSF core (photon)
Speckle Phot Rate	1.3E-03	phot/s	PSF core
Zodi Phot Rate	1.4E-02	phot/s	PSF core

Per Pixel (photons)

Planet Phot	0.102	phot	per pixel (in core)
Speckle Phot	0.14	phot	per pixel
Zodi Phot	1.4	phot	per pixel

Per Pixel (elec/s)

Planet Elec Rate	4.6E-05	e/s	per pixel (in core)
Speckle Elec Rate	6.2E-05	e/s	per pixel
Zodi Elec Rate	1.2E-02	e/s	per pixel

SNR

Time to SNR

Item	Value	Units	Comments
Required Time to reach SNR	4.0E+06	s	
	1108.73	hr	
	46.20	days	

Final SNR

Item	Value	Units	Comments
SNR Check	5.00	SNR	
Signal	3542.1	e	Total Signal
Noise	708.4	e	Total Noise
Frames Needed	1995.7	frames	for SNR target

Final Noise Contributions

Item	Value	Units	Comments
Shot	59.5	e	signal shot noise
Speckle	69.2	e	<sp> shot noise
Zodi	222.9	e	zodi shot
Dark Current	196.6	e	
CIC	13.9	e	
Read	589.7	e	
Speckle Structure	239.4	e	residual Speckle

SNR By Frame

Item	Value	Units	Comments
SNR 1 Frame	0.1189	SNR	
Signal	1.77	e	
Noise	14.93	e	
Shot	1.33	e	
Speckle	1.55	e	
Zodi	4.99	e	
Dark Current	4.40	e	
CIC	0.31	e	
Read	13.20	e	
Speckle Struc.	0.12	e	

Nominal HabEx Target and Scaling from Habex to WFIRST Tables

distance	10.0	pc	
SMA min	0.60	AU	
HABEX diam	6.00	m	
Nom Wavelength	550	nm	
DiffLimitHabex	0.019	arcsec	
Planet Angle min	0.060	arcsec	
WAmin	3.17	lam/D	
WFIRST WA min	3.00	lam/D	
scale factor	0.95	Apply to HX WA to look up in WF	
Planet albedo	0.4	a	
Working Angle	3.67	λ/D	
Lookup WA	3.47	λ/D	scale factor applied

PC EMCCD

HABEX OBSERVING SCENARIO INPUT PARAMETERS

Collector Diameter	6	*m*	*Diameter of PM*
Sec. Obsc. frac.	30%	*of diam*	
Scenario	IFS 1		
SNR Target	5		
Detector Type	PC EMCCD		
Coronagraph Type	HLC		
Star Brightness	5.00	mag	
Star Distance	12.00	pc	
Planet Radius	1	Re	
Planet SMA	1	AU	
Frame Time	100	s	*Specify a time*
Post-proc Factor	5%	f_pp	*resid. speckle str.*
Zodi (Exo+local)	2	zodi	*(loc+exo) / loc*
Contrast Improvement	2	X	*over WFIRST HLC*
Coron. Raw Contrast	7.8E-10	before post processing	
Planet Contrast	2.3E-10		
Science Instrument	IFS		
Center lambda	6.60E-07	m	*V-band ctr.*
Bandwidth	18%	--	*V-band is 16.18%*
Spec Resolution	70	R	

Scene Signal and Background (per Frame)

Core (photons)

Item	Value	Units	Comments
Planet Phot	0.099	phot	PSF core (photon)
Speckle Phot	0.133	phot	PSF core
Zodi Phot	1.383	phot	PSF core

Core (phot/s)

Item	Value	Units	Comments
Planet Phot Rate	9.9E-04	phot/s	PSF core (photon)
Speckle Phot Rate	1.3E-03	phot/s	PSF core
Zodi Phot Rate	1.4E-02	phot/s	PSF core

Per Pixel (photons)

Planet Phot	0.005	phot	per pixel (in core)
Speckle Phot	0.01	phot	per pixel
Zodi Phot	0.1	phot	per pixel

Per Pixel (elec/s)

Planet Elec Rate	3.7E-05	e/s	per pixel (in core)
Speckle Elec Rate	5.0E-05	e/s	per pixel
Zodi Elec Rate	1.0E-02	e/s	per pixel

SNR

Time to SNR

Item	Value	Units	Comments
Required Time to reach SNR	1.2E+06	s	
	346.43	hr	
	14.43	days	

Final SNR

Item	Value	Units	Comments
SNR Check	5.00	SNR	
Signal	885.4	e	Total Signal
Noise	177.1	e	Total Noise
Frames Needed	12471.3	frames	for SNR target

Final Noise Contributions

Item	Value	Units	Comments
Shot	29.8	e	signal shot noise
Speckle	34.6	e	<sp> shot noise
Zodi	111.4	e	zodi shot
Dark Current	109.9	e	
CIC	34.7	e	
Read	0.0	e	
Speckle Structure	59.8	e	residual Speckle

SNR By Frame

Item	Value	Units	Comments
SNR 1 Frame	0.0476	SNR	
Signal	0.07	e	
Noise	1.49	e	
Shot	0.27	e	
Speckle	0.31	e	
Zodi	1.00	e	
Dark Current	0.98	e	
CIC	0.31	e	
Read	0.00	e	
Speckle Struc.	0.00	e	

Nominal HabEx Target and Scaling from Habex to WFIRST Tables

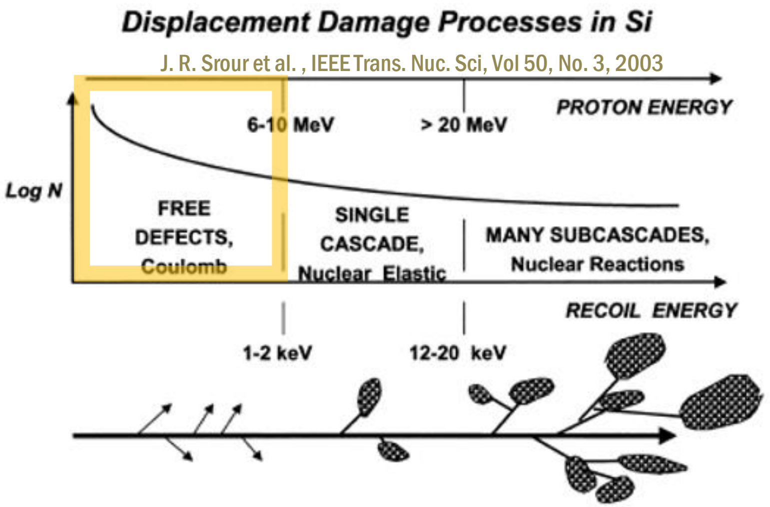
distance	10.0	pc	
SMA min	0.60	AU	
HABEX diam	6.00	m	
Nom Wavelength	550	nm	
DiffLimitHabex	0.019	arcsec	
Planet Angle min	0.060	arcsec	
WAmin	3.17	lam/D	
WFIRST WA min	3.00	lam/D	
scale factor	0.95	Apply to HX WA to look up in WF	
Planet albedo	0.4	a	
Working Angle	3.67	λ/D	
Lookup WA	3.47	λ/D	scale factor applied

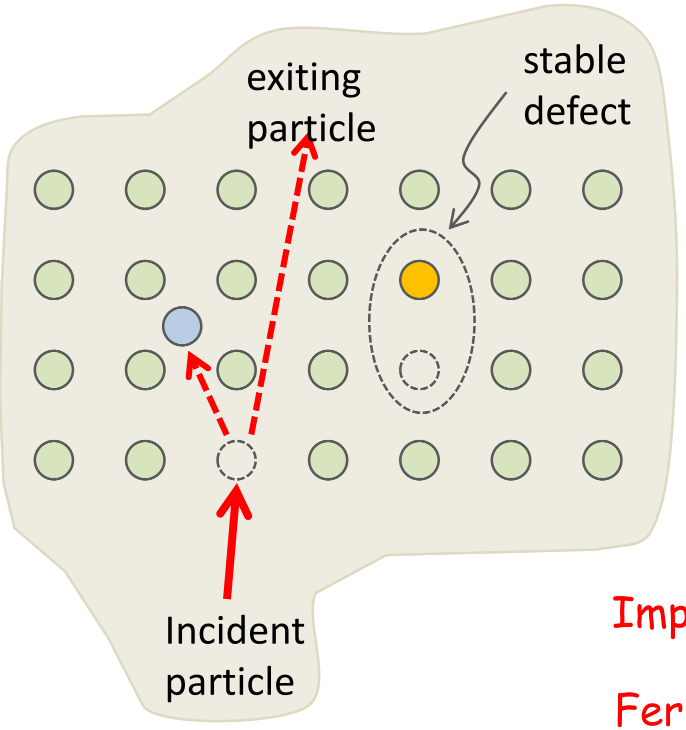
Is the search over? Not Quite!

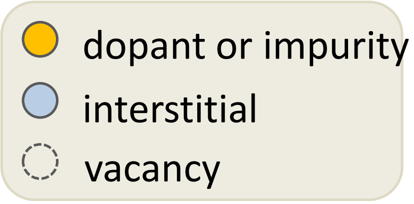
- One other important factor especially for any CCD type device is **charge transfer efficiency** (CTE)
- There are two main sources of inefficiency
  1. Interactions of charge packets with the clocking potentials
  2. **Traps** from radiation damage

Lattice ions impacted by incoming particles leave behind vacancies or ions in interstitial positions (Frenkel pairs).

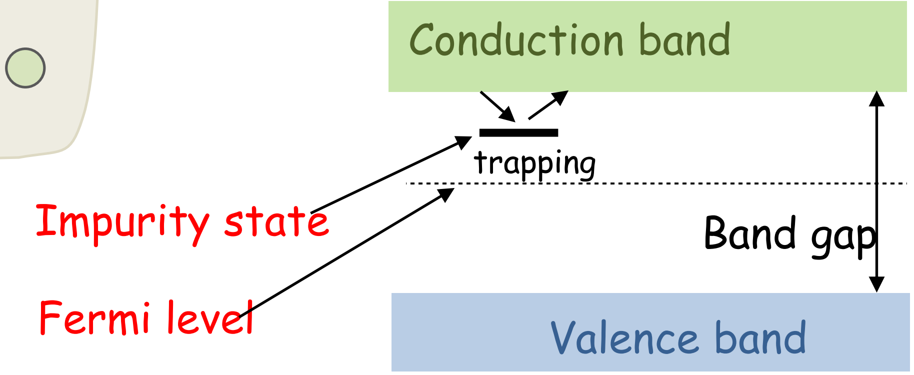
- Low energy particles → point defects
- High energy particles → cluster defects







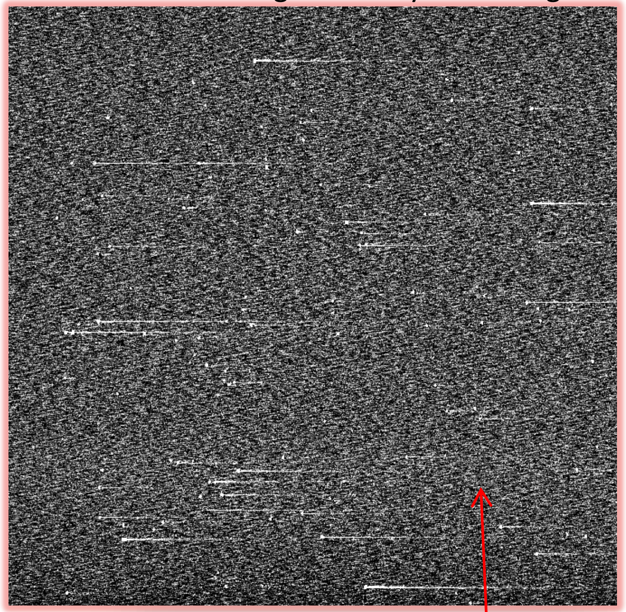
Terminology:
PKA: primary knock-on atom
Frenkel pair: interstitial + vacancy

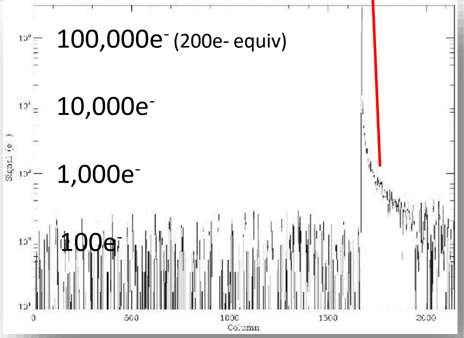


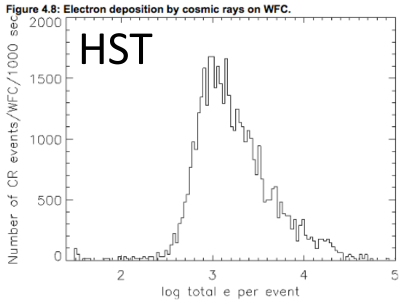
Cosmic Rays Limit Frame Exposure Times

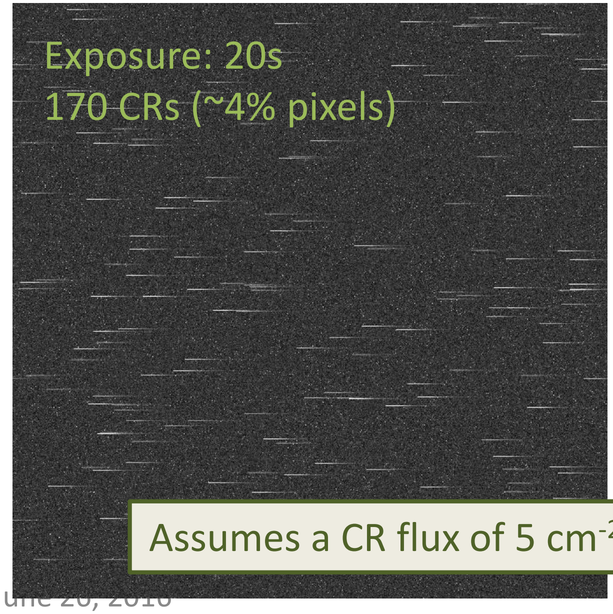
- Full frame science-grade CCD201 image.
  - Temp = -85 °C (188 K)
  - Gain = 500
  - Exposure = 500s
  - Read Noise = 90e$^-$
- Observed tails extend hundreds of pixels, disappearing into the large read noise
  - Tails will be worse at 165K
  - Tails will be worse at higher gain
  - Tails will consume multiple rows
  - There will be many more in space

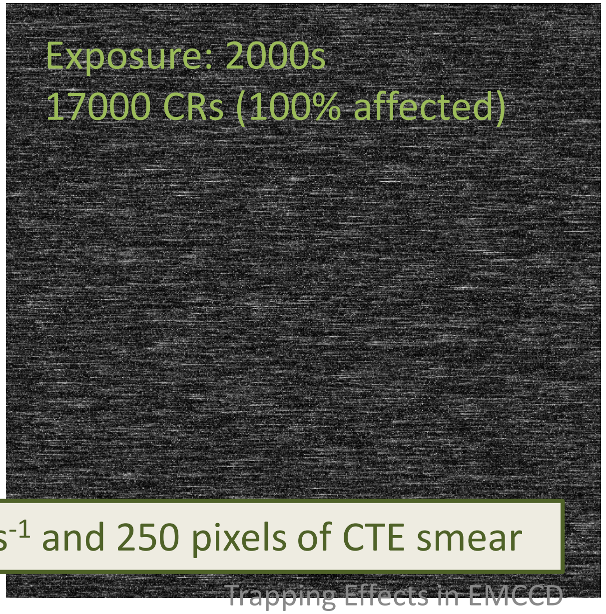
Image courtesy L. Harding









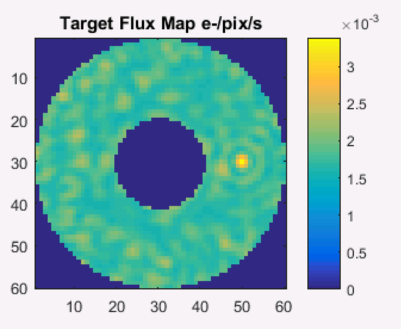


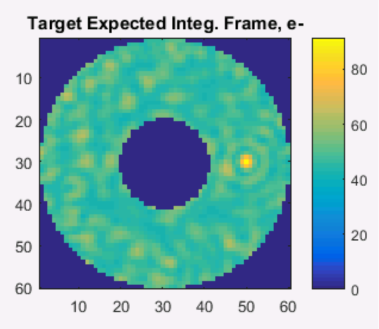
Assumes a CR flux of 5 cm^{-2}-s^{-1} and 250 pixels of CTE smear

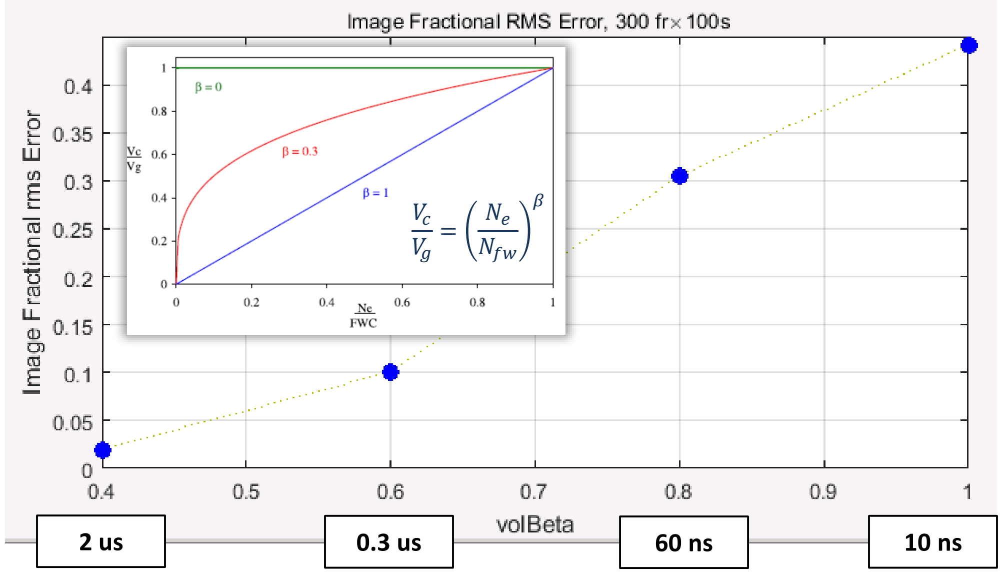
Fractional RMS Error vs. Trap Capture Time

- Fast trap capture times cause the most image degradation

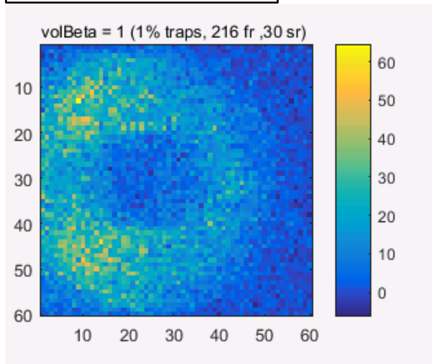
(with 1% Frame and Serial Traps)



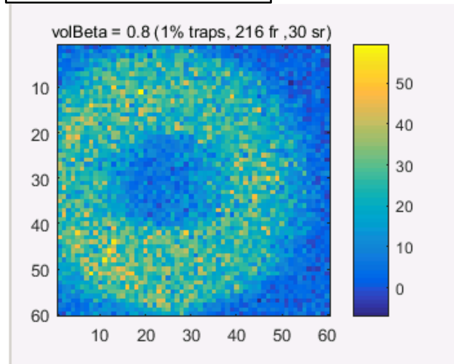




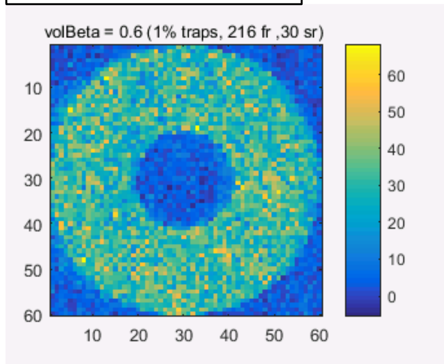
Tau_capture = 10 ns



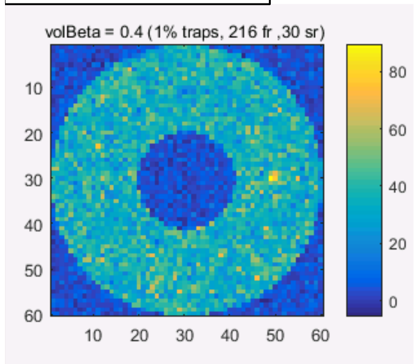
Tau_capture = 60 ns



Tau_capture = 0.3 us



Tau_capture = 2 us



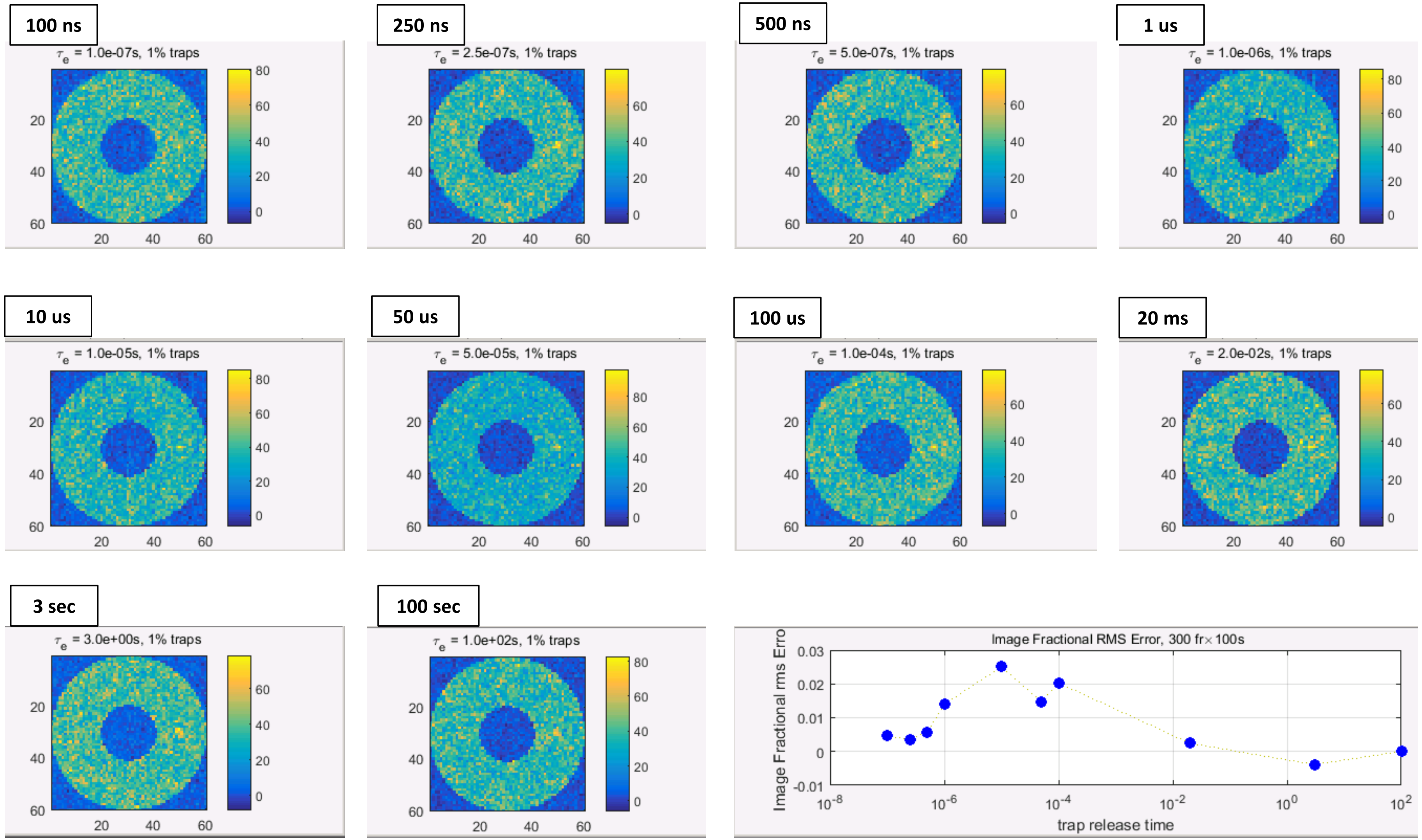
Analysis by Bobby Effinger

Fractional Error vs. Trap Release Time

(with 1% Frame and Serial Traps)

$\boldsymbol{\beta = 0.5}$:

Expected and realistic case



What aspects do we look for in a detector?

- For a coronagraph, ideally photon counting
- Low Noise
  - Read Noise < 1 e- / pix / frame
  - Dark Current < 1e-3 e- / pix / sec
  - Clock Induced Charge < 1e-2 e- /pix/ frame
- Enough Pixels
- High Quantum Efficiency
- Graceful response to cosmic rays
  - Displacement damage → traps
  - Ionizing Dose → image degradation
- High Charge Transfer Efficiency (in CCD type architectures)

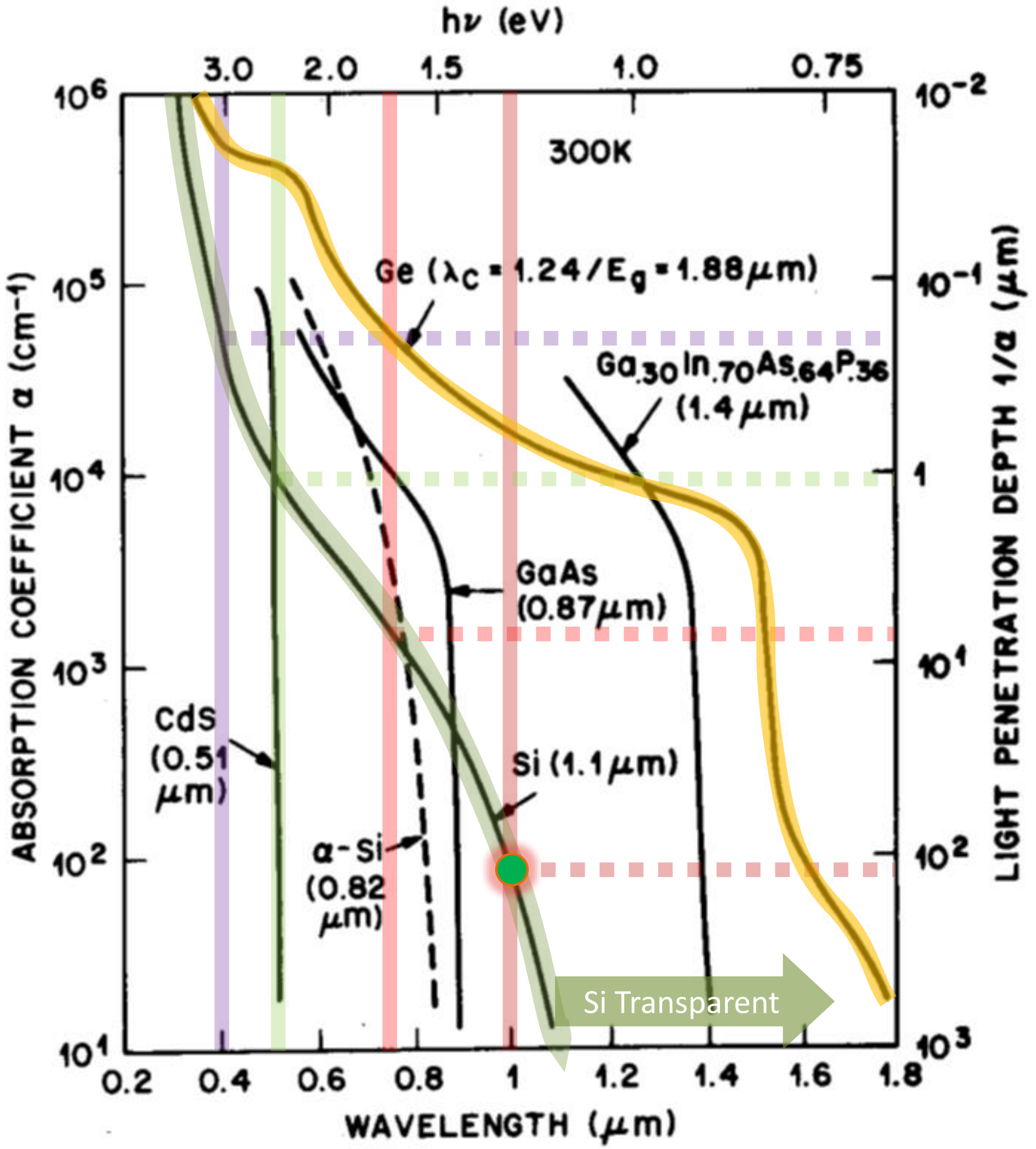
What can be done for the 900nm-1000nm region?

- Light entering sensor is absorbed according to:

$$I = I_0 \, e^{-\alpha z}$$

  - α (cm^{-1}) is the absorption coefficient
  - Penetration depth is $1/\alpha$

- At penetration depth, only 1/e (37%) of the incident photons are left. The absorbed photons ($1 - 1/e = 63\%$) participate in signal creation:
  - This becomes the upper bound for QE
- Important example:
  - Silicon with ~100 um thickness has a QE upper bound of 63% at a wavelength of 1 μm (see figure)
  - This thickness is achieved by 'deep depletion' (DD) and has the additional advantage of less fringing in narrow band light at the red end
  - But care needed to avoid greater surface dark current



Source for graph:
Spectral Response of Silicon Image Sensors, Arnaud Darmont, Aphesa (www.aphesa.com), White paper, April 2009

Possible Sensors to Explore Further for HabEx

Detector Type	CCD/ CMOS	Format	Pixel Size (microns)	Read Noise (e-)	Dark Current (e-/pixel/s)	QE 400nm 650nm 1000nm	Issues
CCD201 (e2v)	EMCCD	1k x 1k (or 1 x 2)	13	6e-3 /pixel/frame	1e-4 at 160K	52%, 90% 11%	Electron Multiplying CCD in single photon (high gain) mode, If used in lower-gain mode, shot noise is multiplied by sqrt(2). Performance may degrade with radiation due to electron traps in imaging area.
Electron Bombarded CMOS	CMOS (with gain)	1920 x 1200 (M611)		Low			Very new, but worth pursuing for a 2030 mission. Made by Intevac.
Micro Channel Plate	Micro Channel	~ 1k x 1k		Very Low	~ 3e-5 (very low)		Efficiency loss due to micro channel fill factor. But significant flight heritage. Traps not an issue. Best for 600 nm and bluer.
Geiger-Mode Avalanche Photodiode	CMOS	256 x 256	25	0 theoretical			Large arrays are low TRL. Have not demonstrated theoretical performance. Pixels smaller than 20 microns would be difficult.
Skipper CCD	Front-Illuminated CCD	1k x 1k	15	As low as 0.2 e			Lab only? Output stage allows non-destructive reads, so multiple reads reduce noise.
BAE/Fairchild sCMOS	Front-illuminated CMOS	2560 X 2160	6.5	1-2	Extrapolated to 0.001 at 150 K	36%,54% 4%	Cannot read out in a way that reduces noise further for long integration time (cannot do non-destructive reads - per Boyd Fowler at BAE/Fairchild)
MKIDs	Super Conducting						Must cool to milli-K range. Resolving power of 70 not demonstrated.

Credit: parts of this data from Marc Foote, JPL Div. 38