CCD and CMOS Imaging Devices for Large (Ground Based) Telescopes

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BNL

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"Large Telescopes"

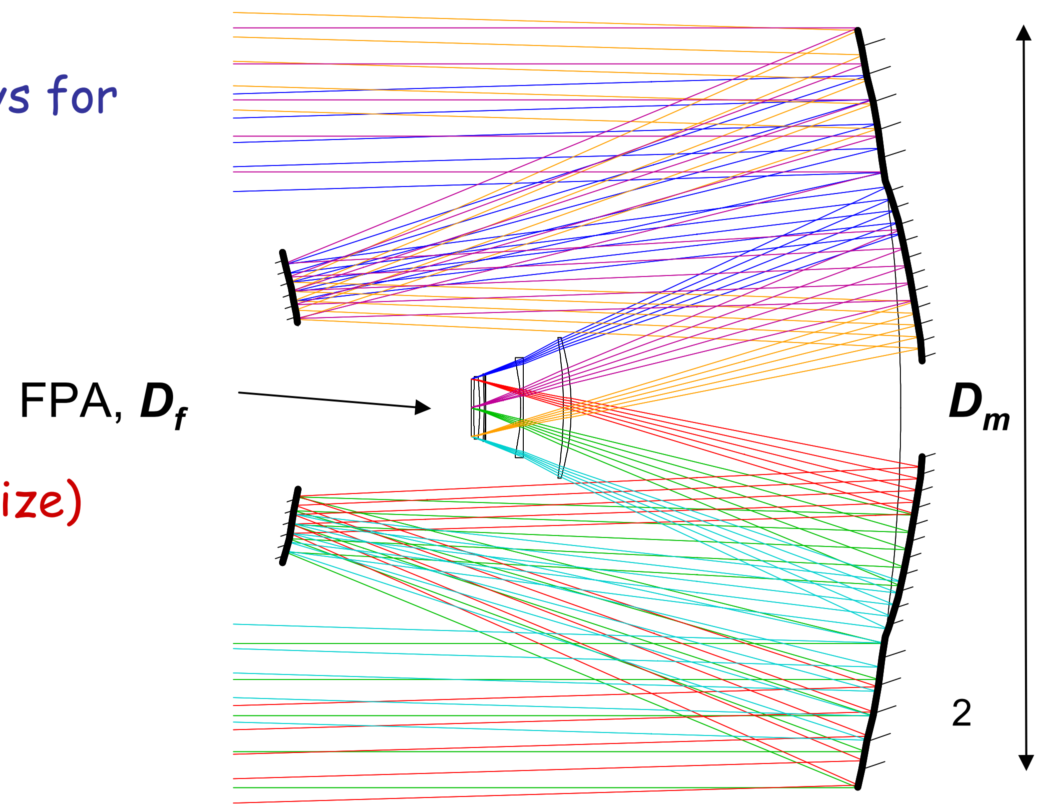
		Survey telescope	Deep probe
Primary Mirror	*dia.*= D_m, *Area*= ***A***	***Large (~8m)***	***Very large (~30m)***
f-number	***f /#***	***~ 1/1.2***	***~ 1/30-40***
Focal Plane Array *dia.*= D_f		***Large (~60cm)***	***Medium (~20cm)***
Field of View	$\Omega \; \alpha \; D_f / D_m$	***~3-4 degrees***	***~20 arc min***
Etendue	$A\Omega$	***~330m²deg²***	
Plate Scale	arcsec/μm	***0.2***	

<u>Science Drivers:</u> Wide area surveys for dark energy studies

<u>FPA Requirements:</u>

- Increase Area
- Increase QE in near IR
- Reduce PSF (diffusion and pixel size)
- Increase readout speed

e.g., Pan STARRS, LSST



Growth of mosaics

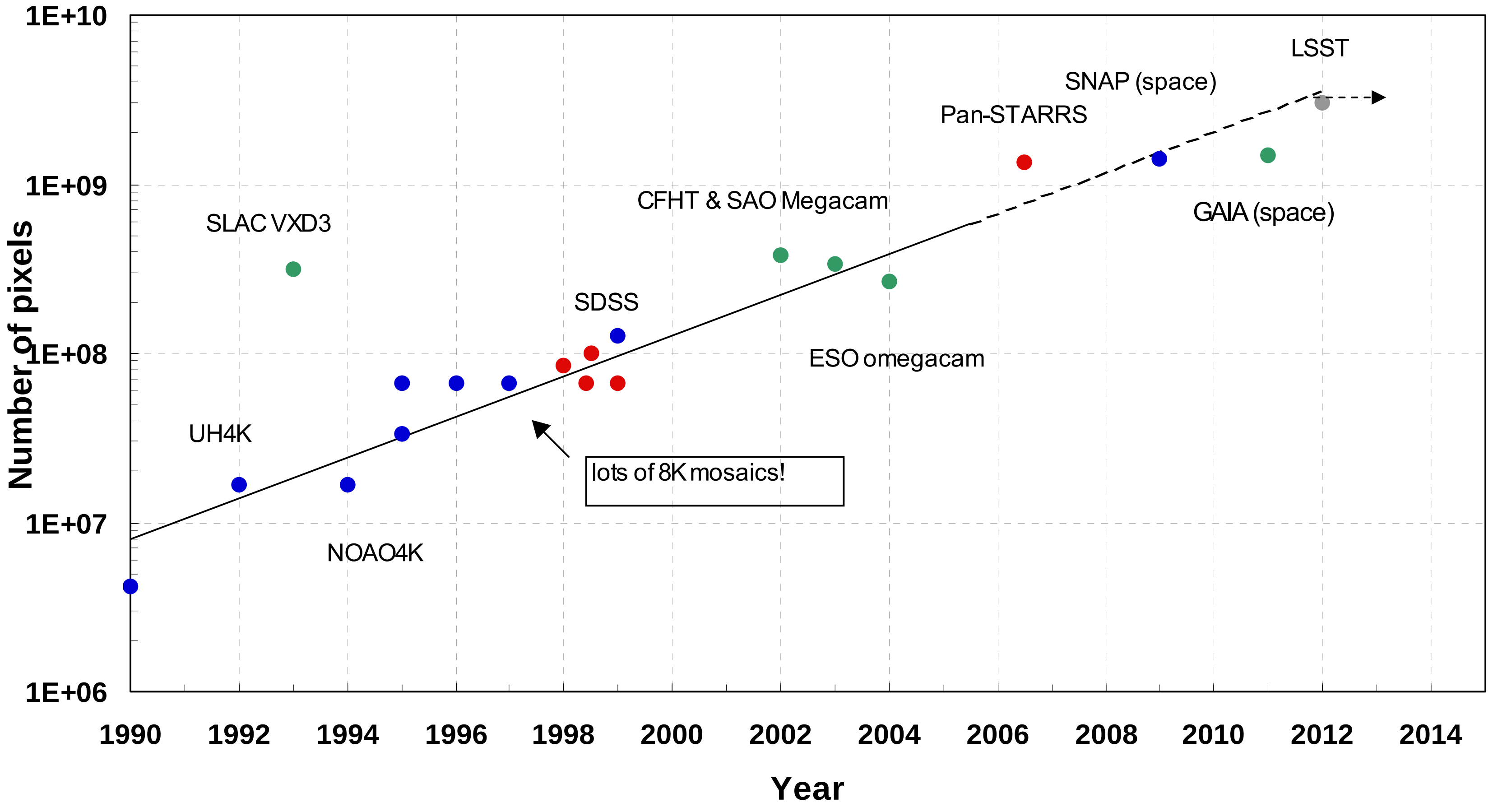
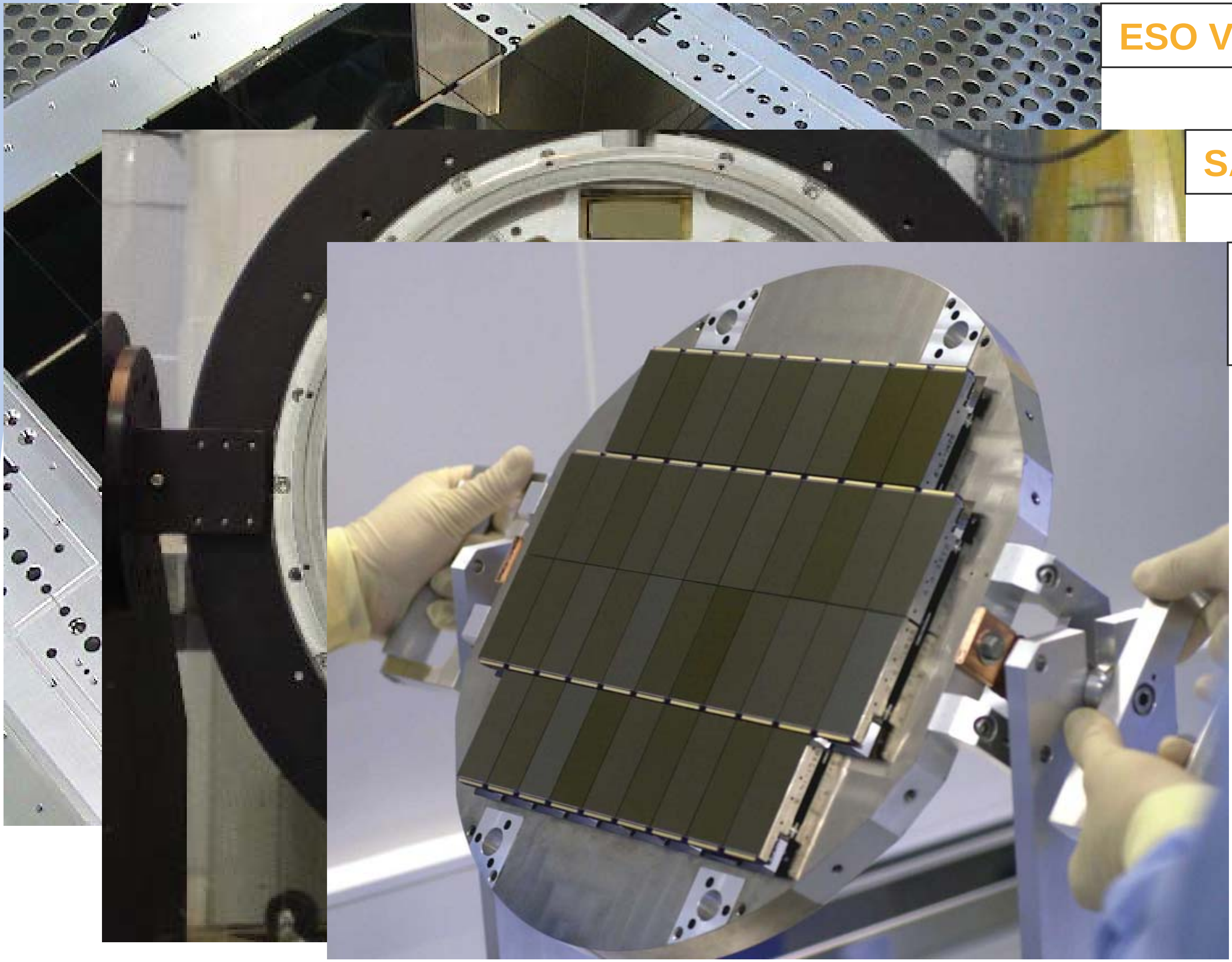


Illustration of focal plane sizes, from Luppino/Burke 'Moores' law

Focal plane size doubles every 2.5 years

From: Burke, Jorden, Vu, SDW Taormina 2005

Ground-based mosaics-3



ESO VST Omegacam

SAO MMT Megacam

CFHT Megacam

Operational- April 2003

SAO MMT Megacam

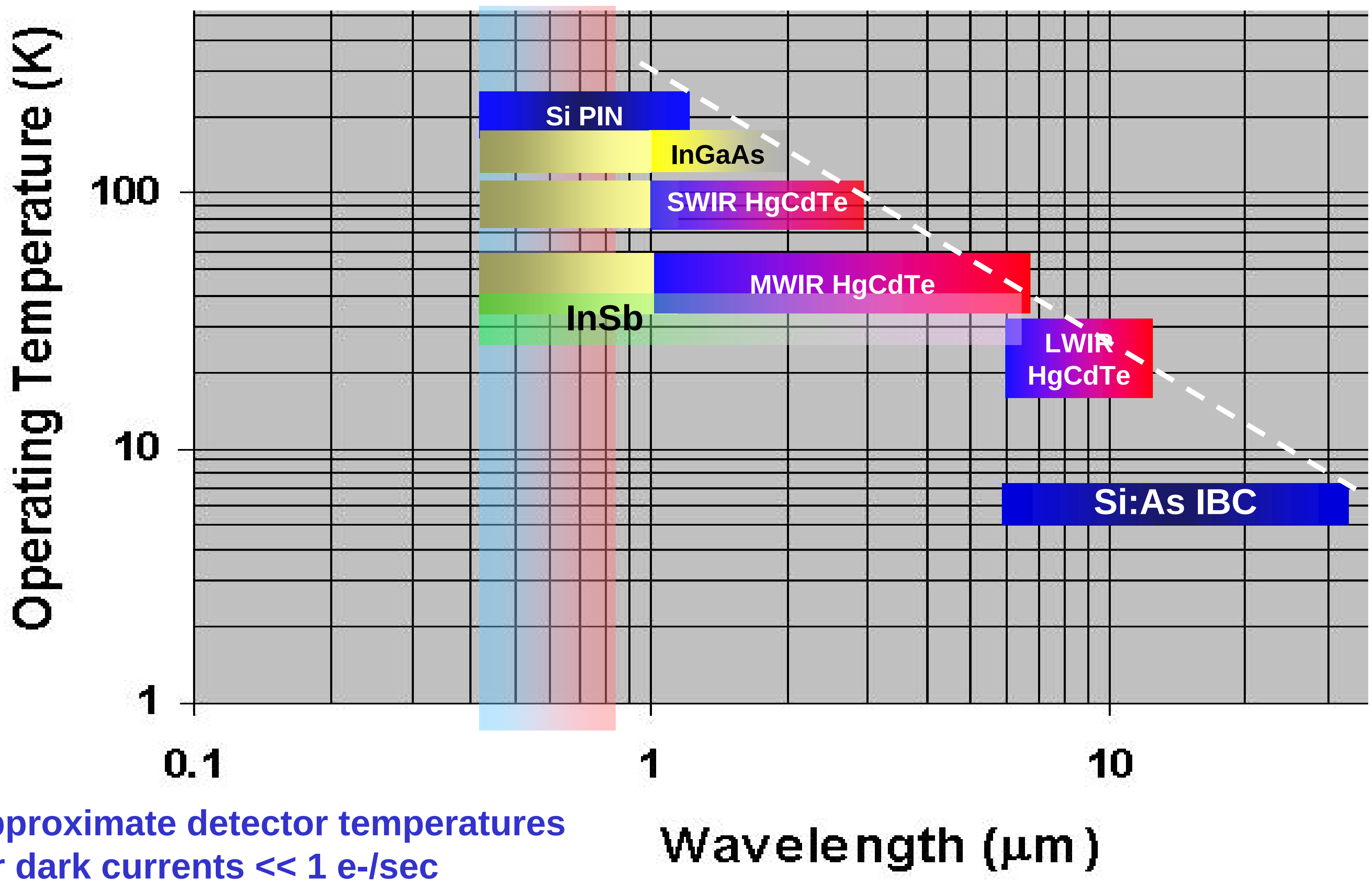
4x9

E2v CCD42-90

2048x4608 13.5 micron pixels

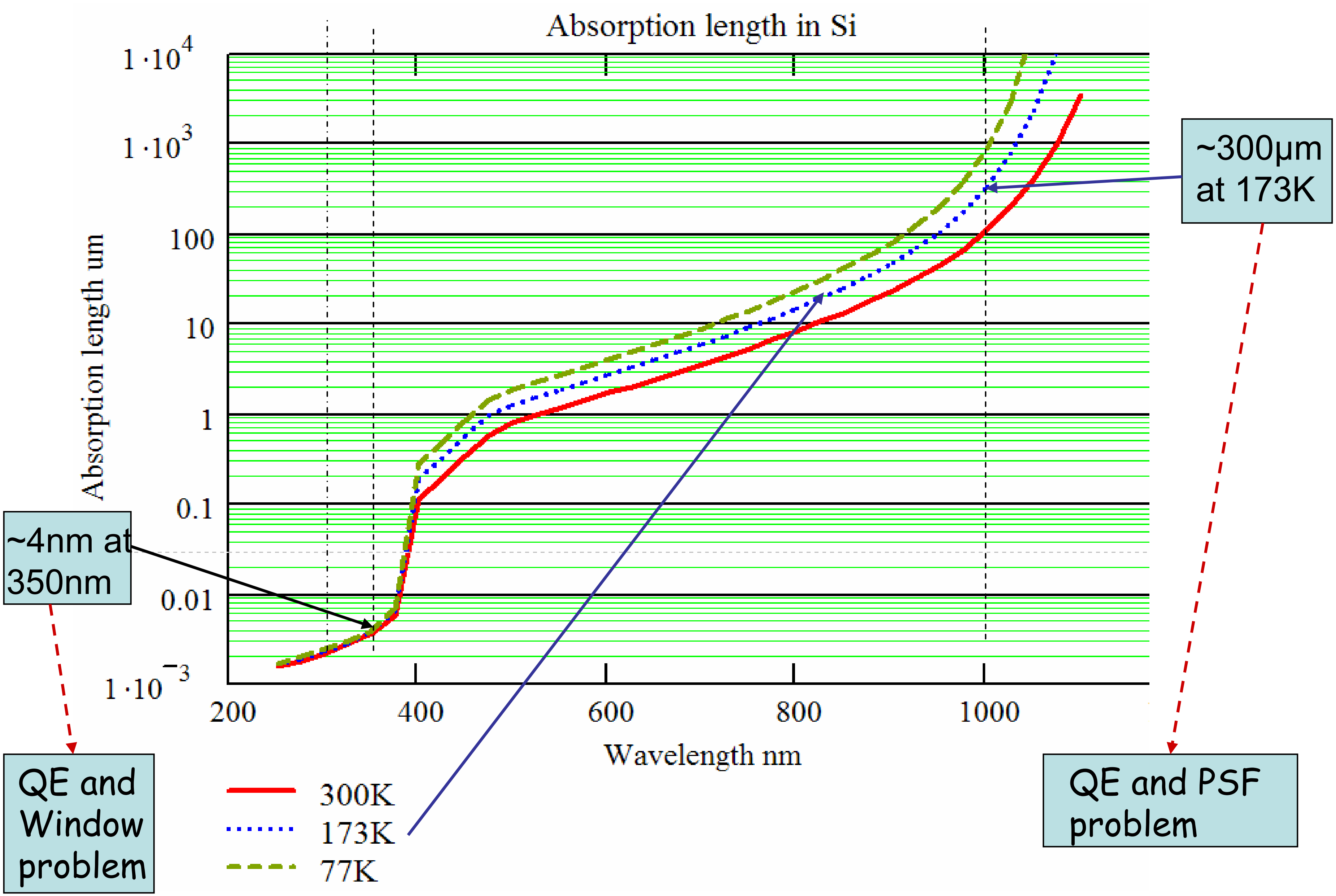
200kHz

Temperature and Wavelengths of High Performance Detector Materials



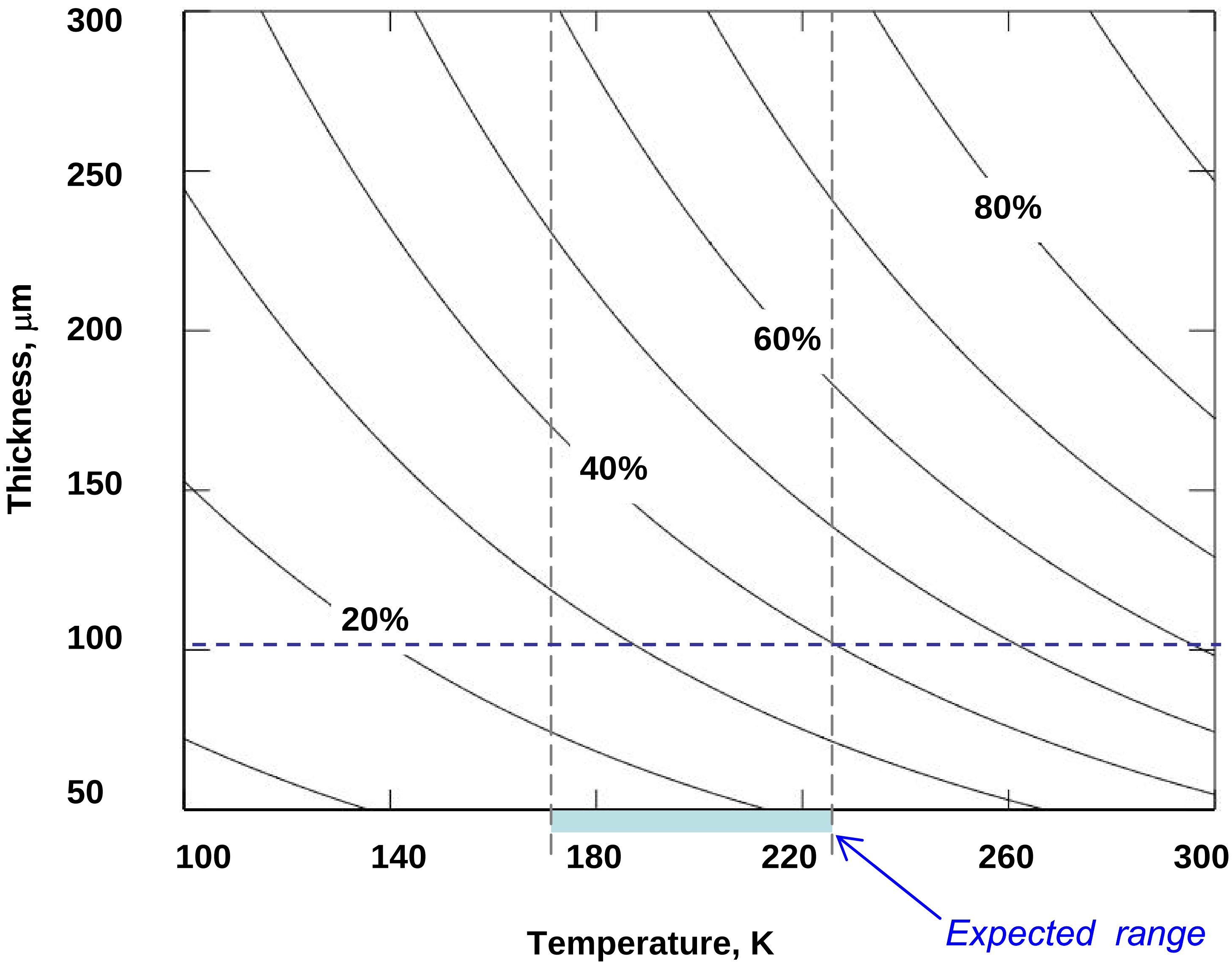
Approximate detector temperatures for dark currents << 1 e-/sec

From: Loose, Hoffman, Suntharalingam, SDW, Taormina 2005

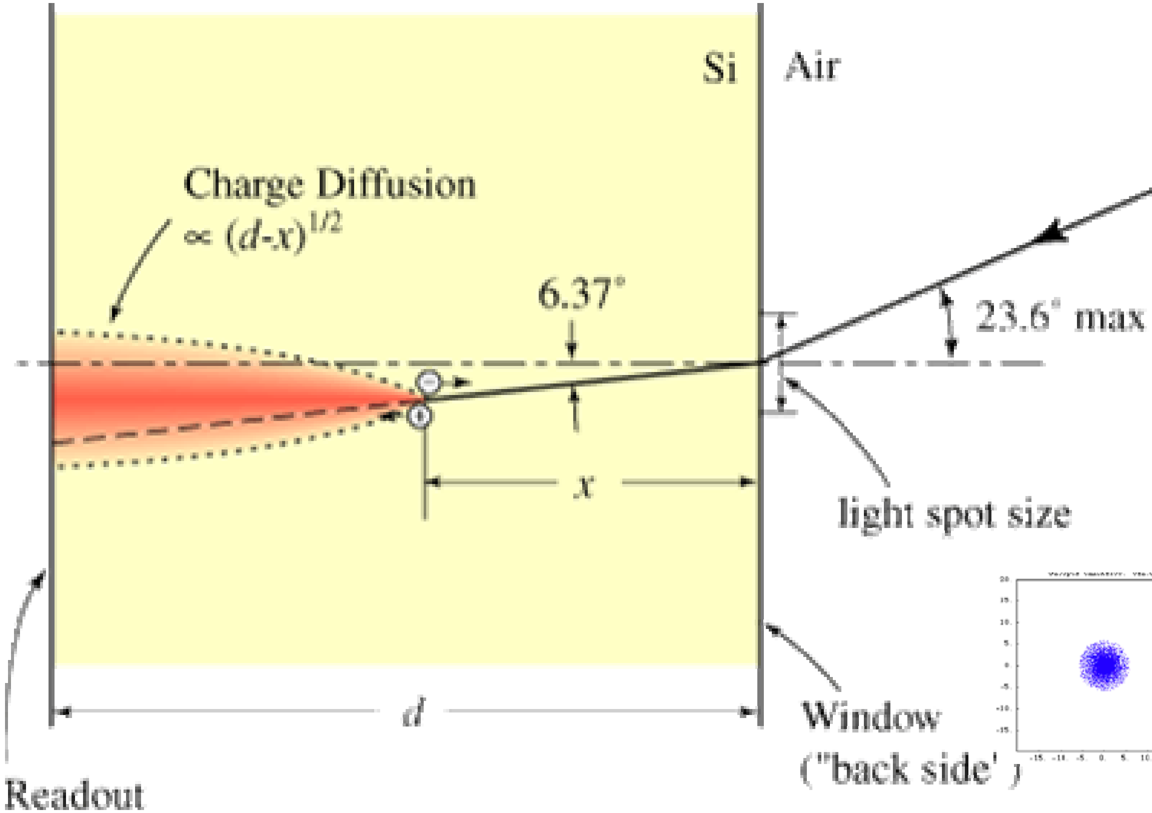


Absorption length in Si
Absorption length um
$1 \cdot 10^4$
$1 \cdot 10^3$
100
10
1
0.1
0.01
$1 \cdot 10^{-3}$
200
400
600
800
1000
Wavelength nm
300K
173K
77K
~300µm at 173K
~4nm at 350nm
QE and Window problem
QE and PSF problem

Internal QE vs temperature and silicon thickness, for ***1000nm*** wavelength.

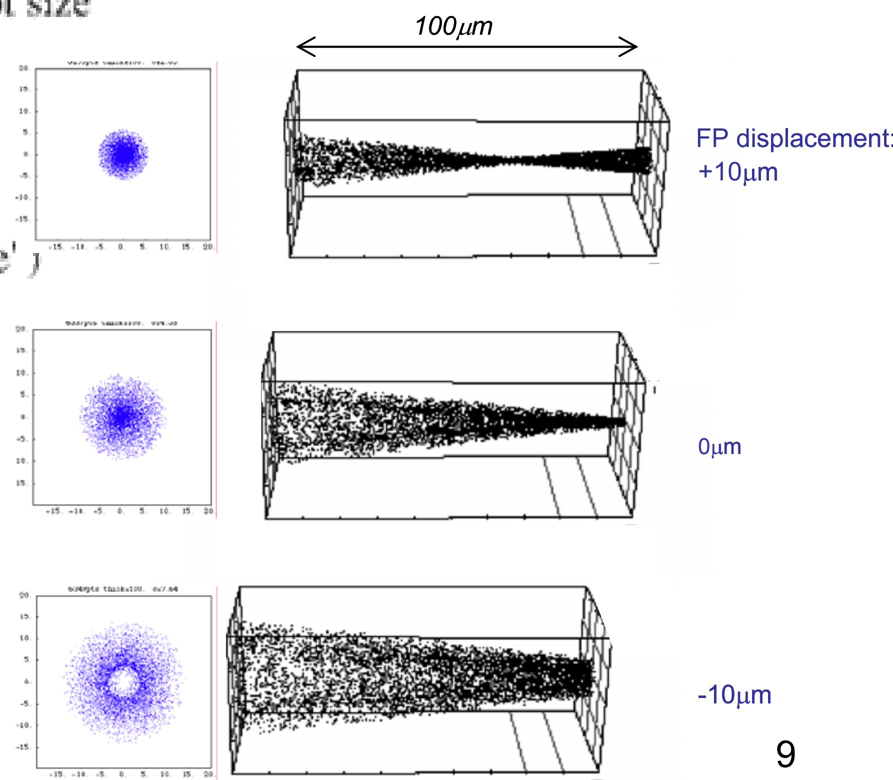


Point Spread Function (PSF) in Si



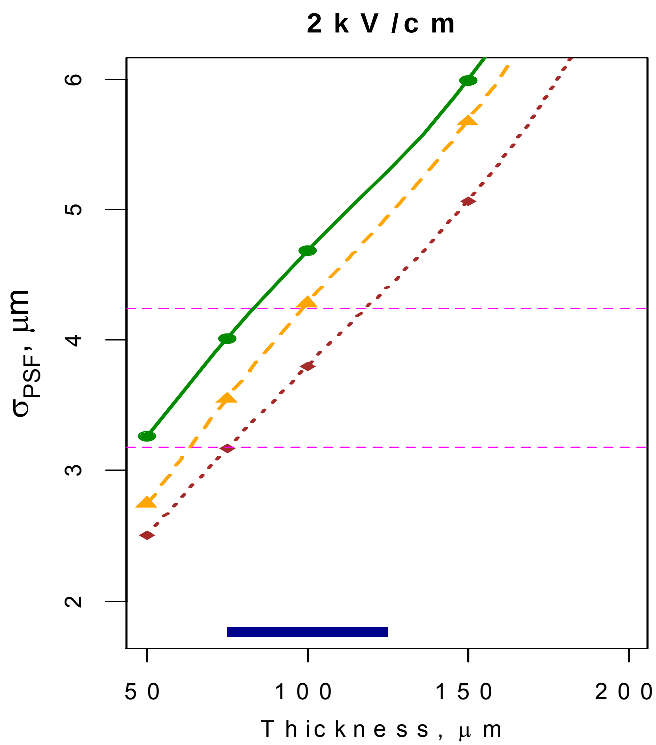
LSST (f~1.2!)

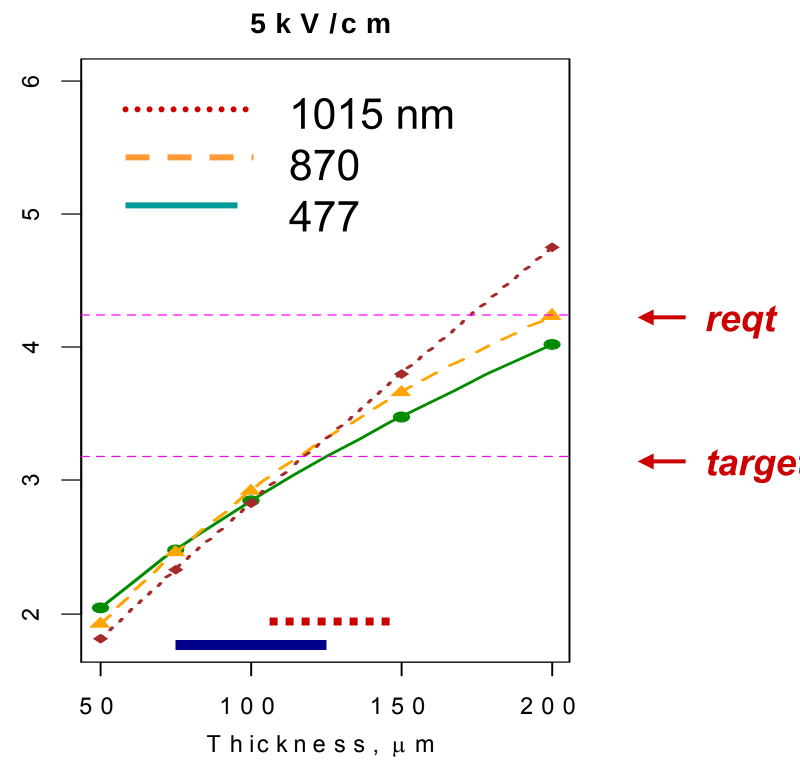
Simulation by P. Takacs, BNL:



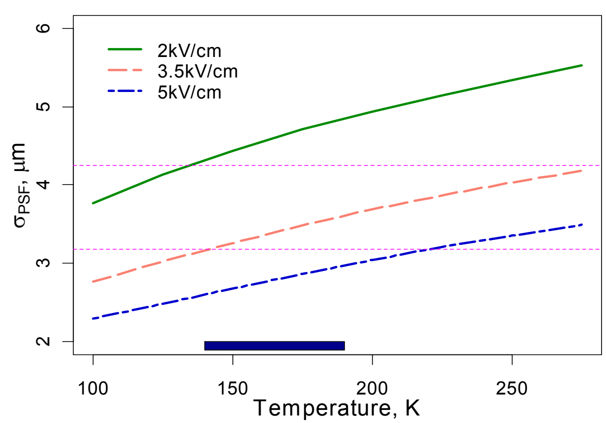
Light spot, cone, absorption→ionization, charge diffusion → PSF

Monochromatic PSF *rms* vs. thickness and electric field





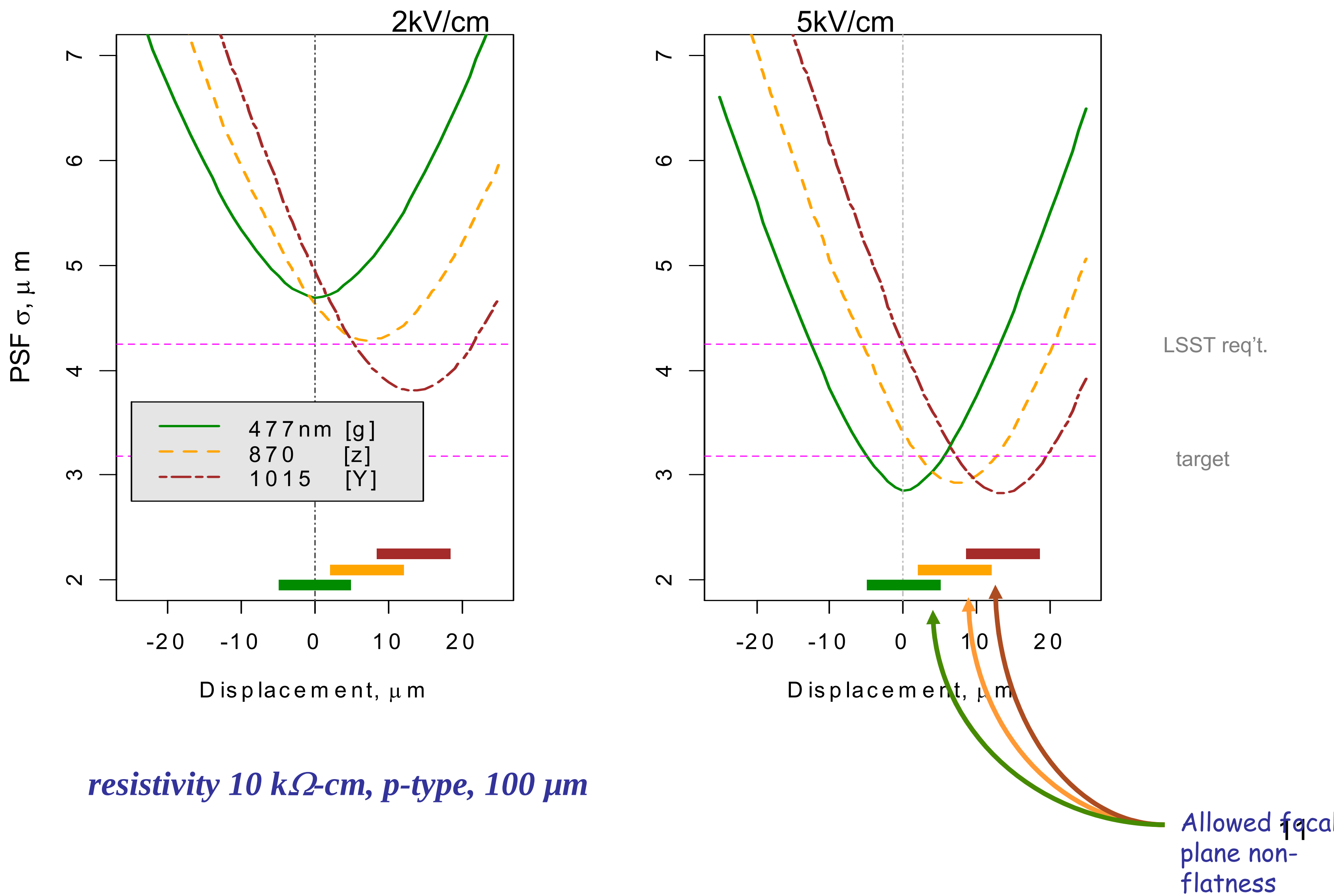
PSF vs T and E for electrons



- *Includes effects of diffusion and divergence.*
- *Velocity saturation effects included*
- *Focal plane position adjusted at each thickness and wavelength for minimum overall PSF.*

resistivity 10 kΩ-cm, p-type, overdepleted

Optimal focal plane position varies with wavelength due to divergence of f/1.2 beam



resistivity 10 kΩ-cm, p-type, 100 μm

Partial vs Full Depletion

- **Conventional CCDs 15-20 μm thick on 20-100 ohmcm silicon cannot be fully depleted with 15-20 volts.**

  ***PSF (rms)* ~ *<u>thickness of undepleted region</u>* (≥~6-7 μm)**

- **Full depletion essential for minimal charge spreading,**

  PSF (rms) < ~ 4 μm

- **Methods to ensure full depletion:**

  - ***High-resistivity substrate* >5 kohm cm**

  - ***Bias on p+ (n+) back-surface* (30-50 volts on 100 μm)**

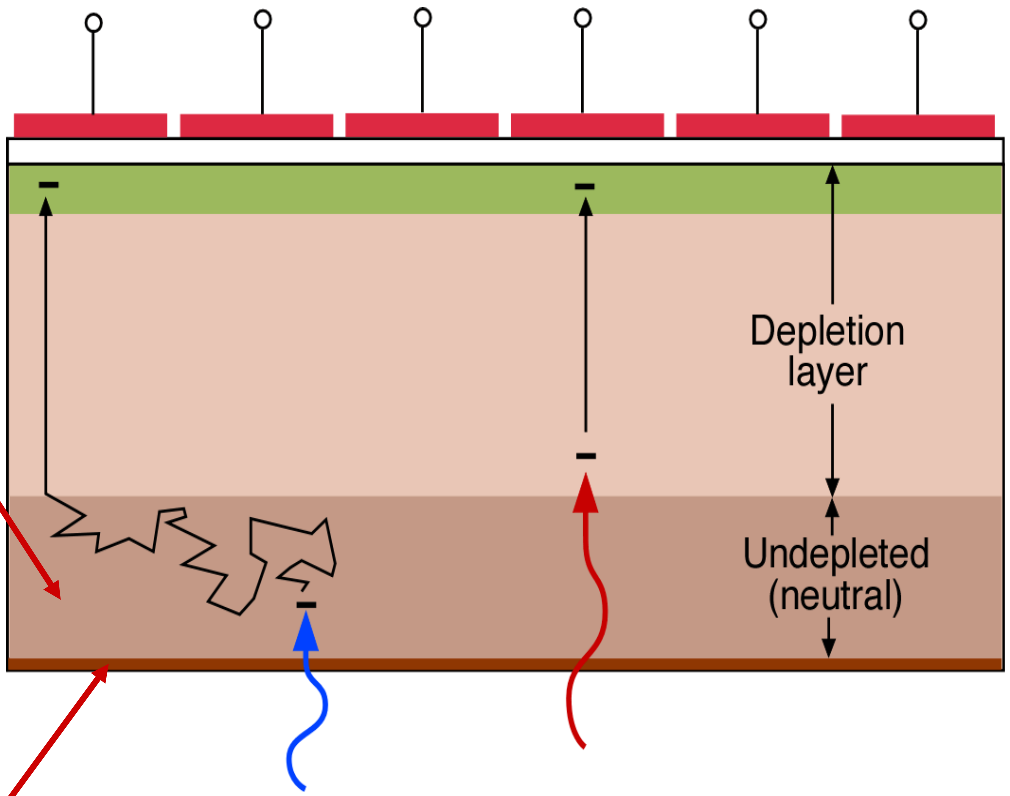
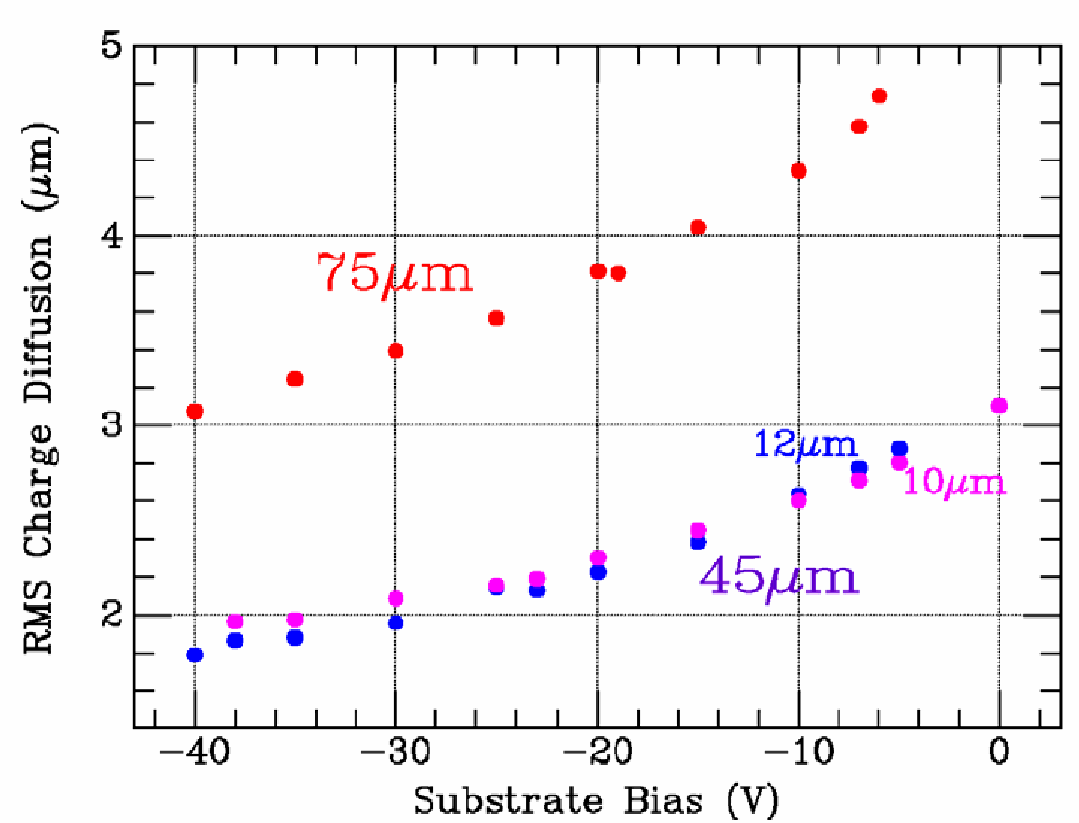


Illustration from:
Barry Burke

Can the predicted small diffusion be achieved?

CCDs developed at LL for PanSTARRS.
B. Burke, J. Tonry, et al. results:



Calculation incl.velocity saturation effects predicts ~2.5 μ m rms at 40 volts for electrons (p-substrate).

For LBNL/SNAP CCD results see S.Holland, this conference

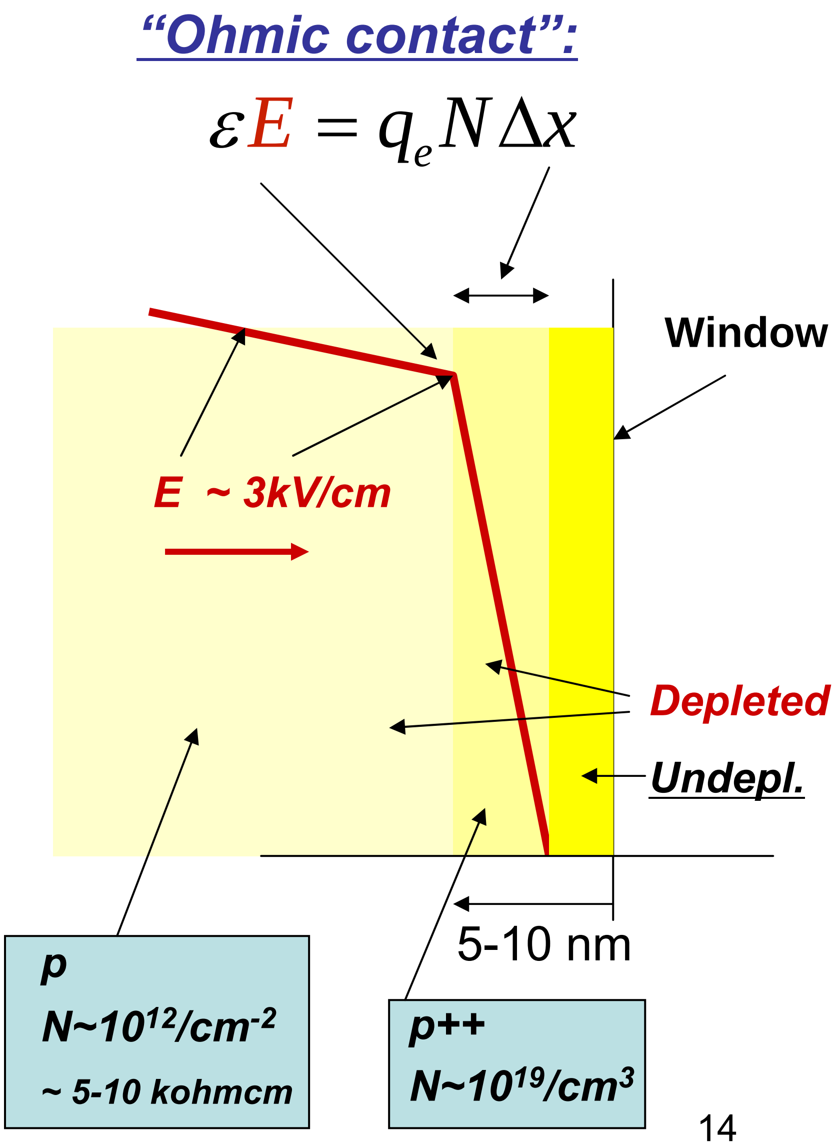
Window Technology

A highly doped layer at the window required to terminate the field and leave a thin conductive layer at the surface.

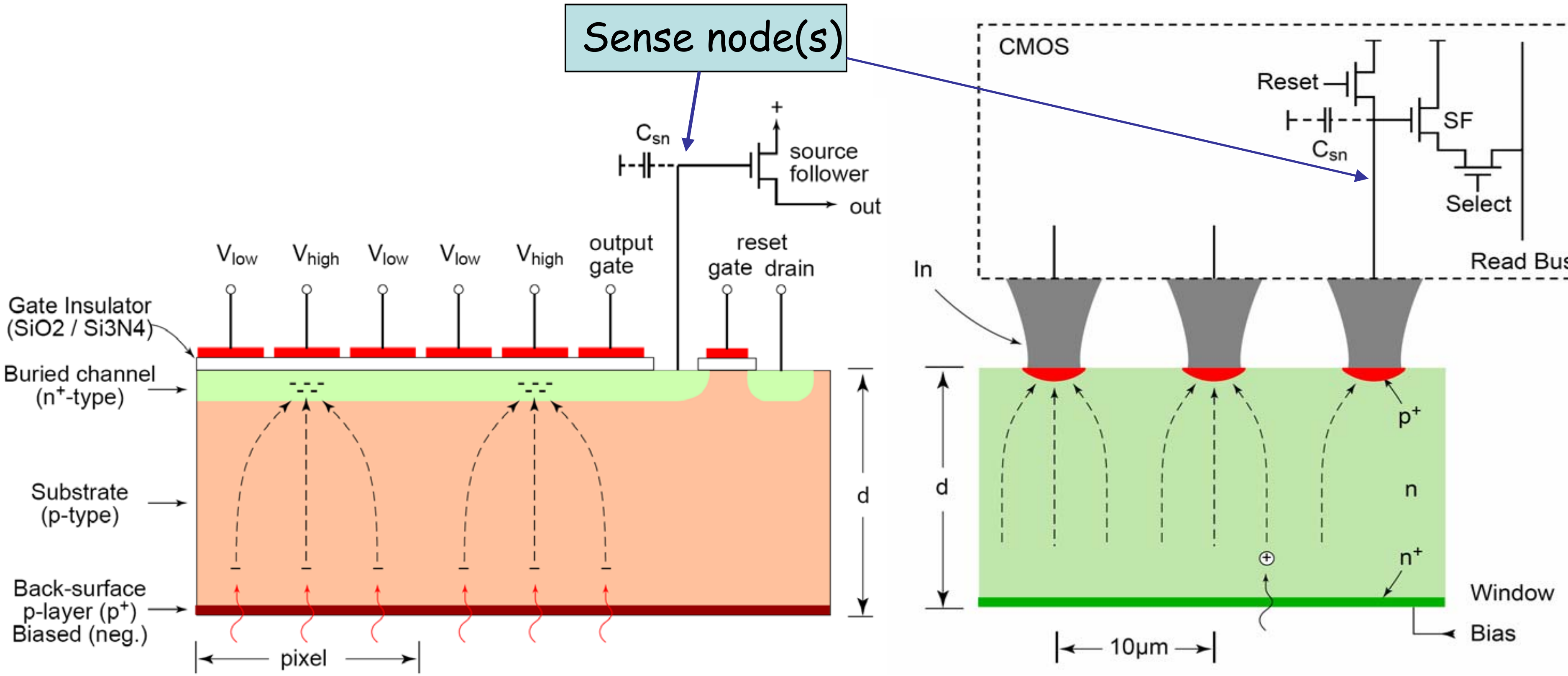
Highly doped layer thickness <~10 nm to allow uv light into the sensitive (depleted) region.

Technologies under development (must be compatible with antireflective coating):

- *Ion implantation followed by laser annealing - low T process (LL)*
- *Doped polysilicon deposition – high T process (LBNL), presentation by S. Holland*
- *Chemisorption charging – very good for uv response, but no conductive layer (ITL)*



CCD   Hybrid PIN-CMOS



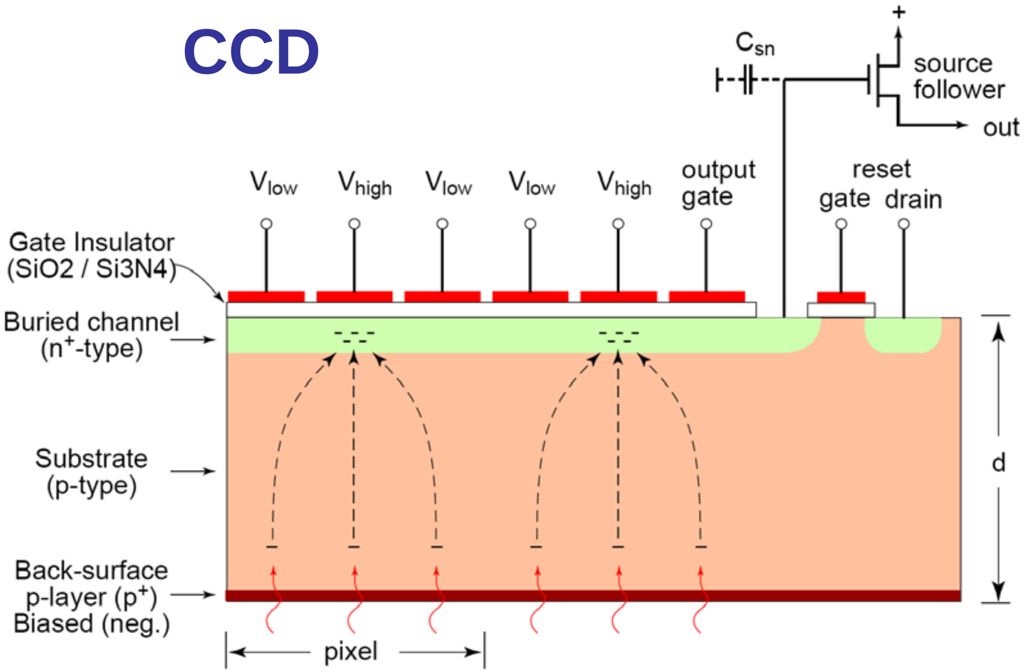
•In a CCD, the signal charge is transferred ***serially*** by a noiseless process (very high CTE) to ***a single sense node,*** where it is converted to a signal voltage.

•Pixels are read out ***after*** the integration is completed.

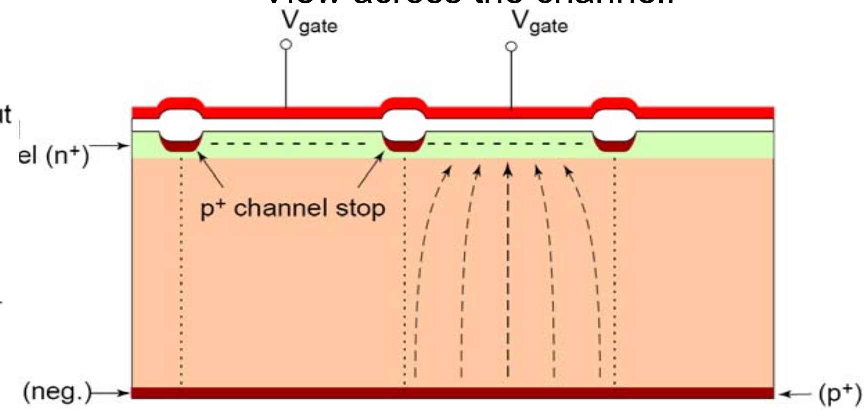
•In a PIN CMOS sensor, the charge to voltage conversion takes place ***in parallel at the sense node of each pixel***.

•The signal voltage can be read out “up the ramp” ***during*** integration.

CCD

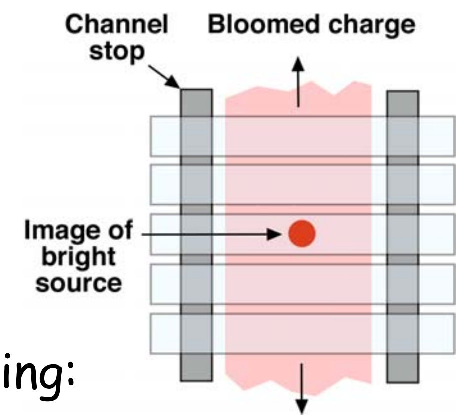


View across the channel:



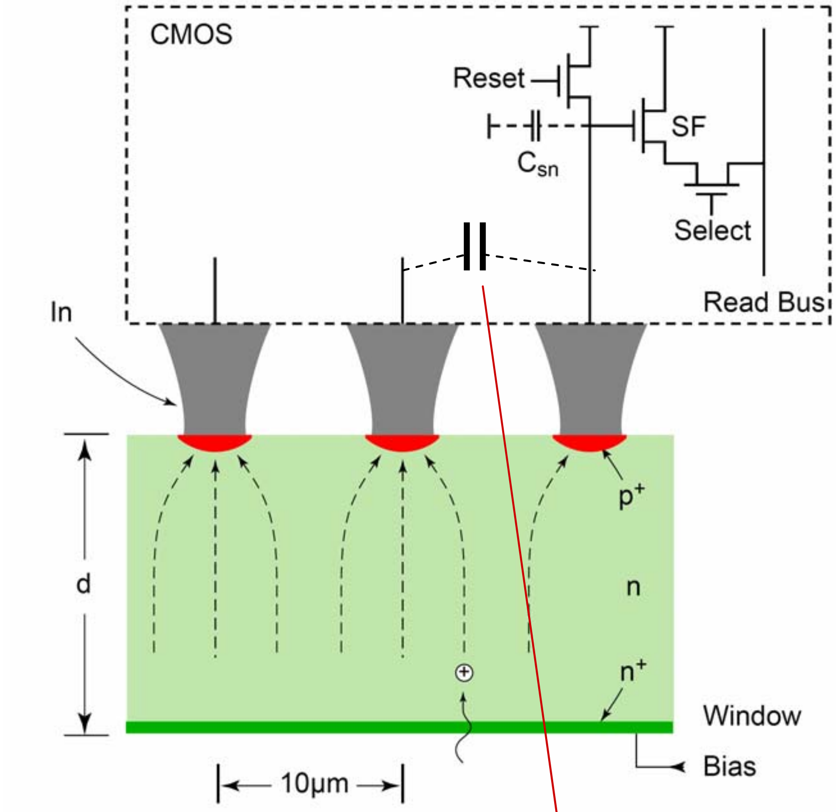
- Photoresponse non-uniformity <1%
- Dark current in inversion mode ~0.001 e/pixel sec
- Correlated double sampling each clock cycle
- More complex clock amplitude and phasing requirements
- High power dissipation with segmented readout
- Independent window biasing→design constraints

- Blooming:

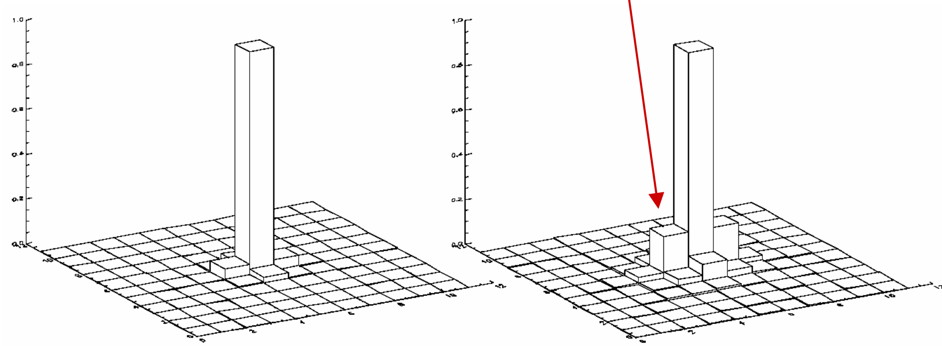


PIN-CMOS

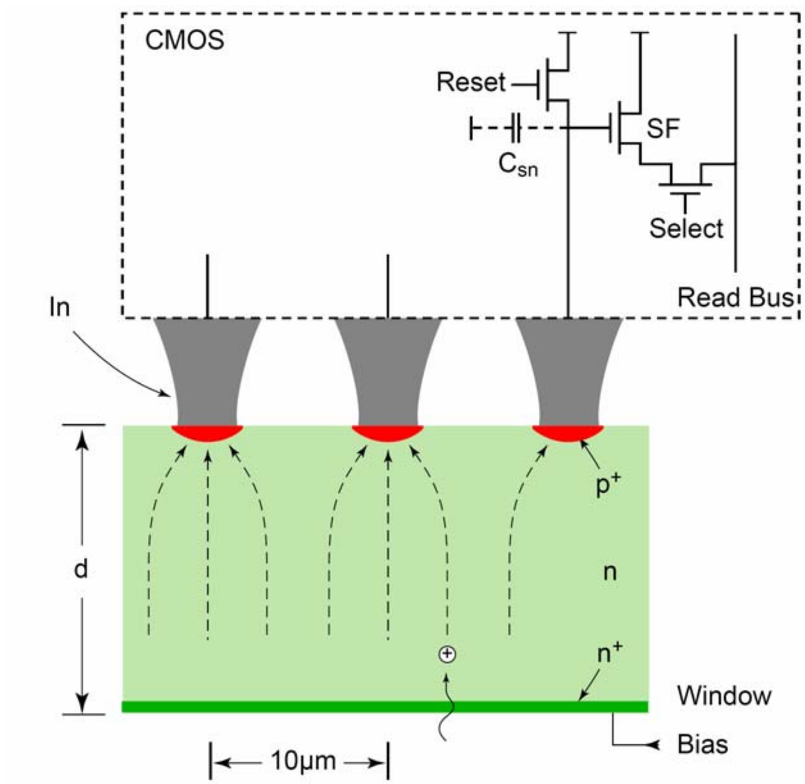
- Independent optimization of the PIN and CMOS design and processing
- Electronic shutter by reset transistors
- Blooming control
- Large dynamic range by readout "up the ramp"; addressable guider readout
- Lower power dissipation, low voltage for CMOS
- Fixed pattern noise
- pixel-to-pixel (stable) gain differences due to amplifier per pixel
- capacitive (deterministic) crosstalk to adjacent pixels
- CDS over longer time intervals

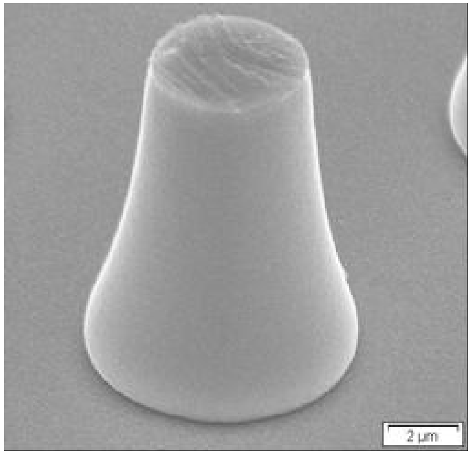


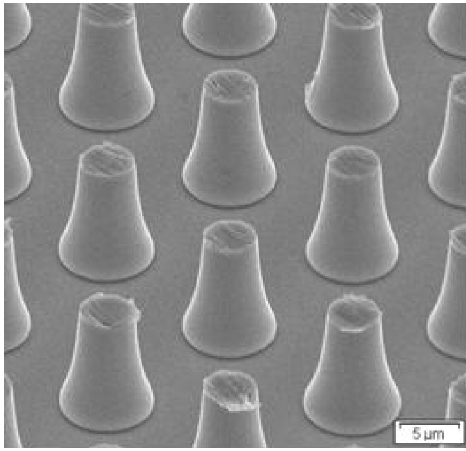
J. Beletic. Et al.:



Indium Bump Bonding

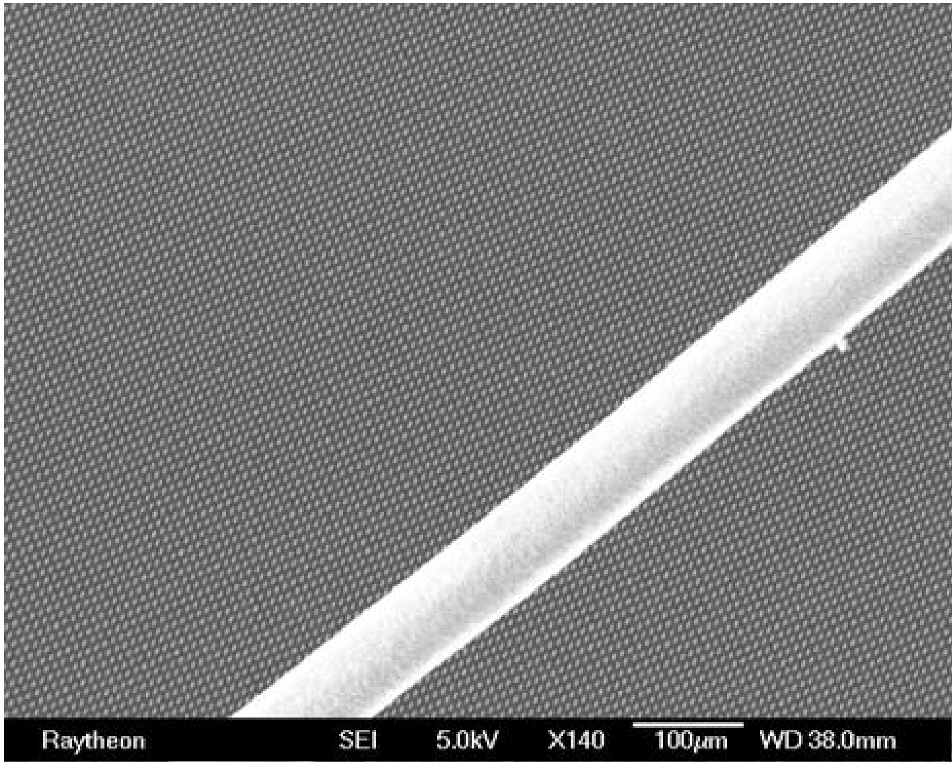






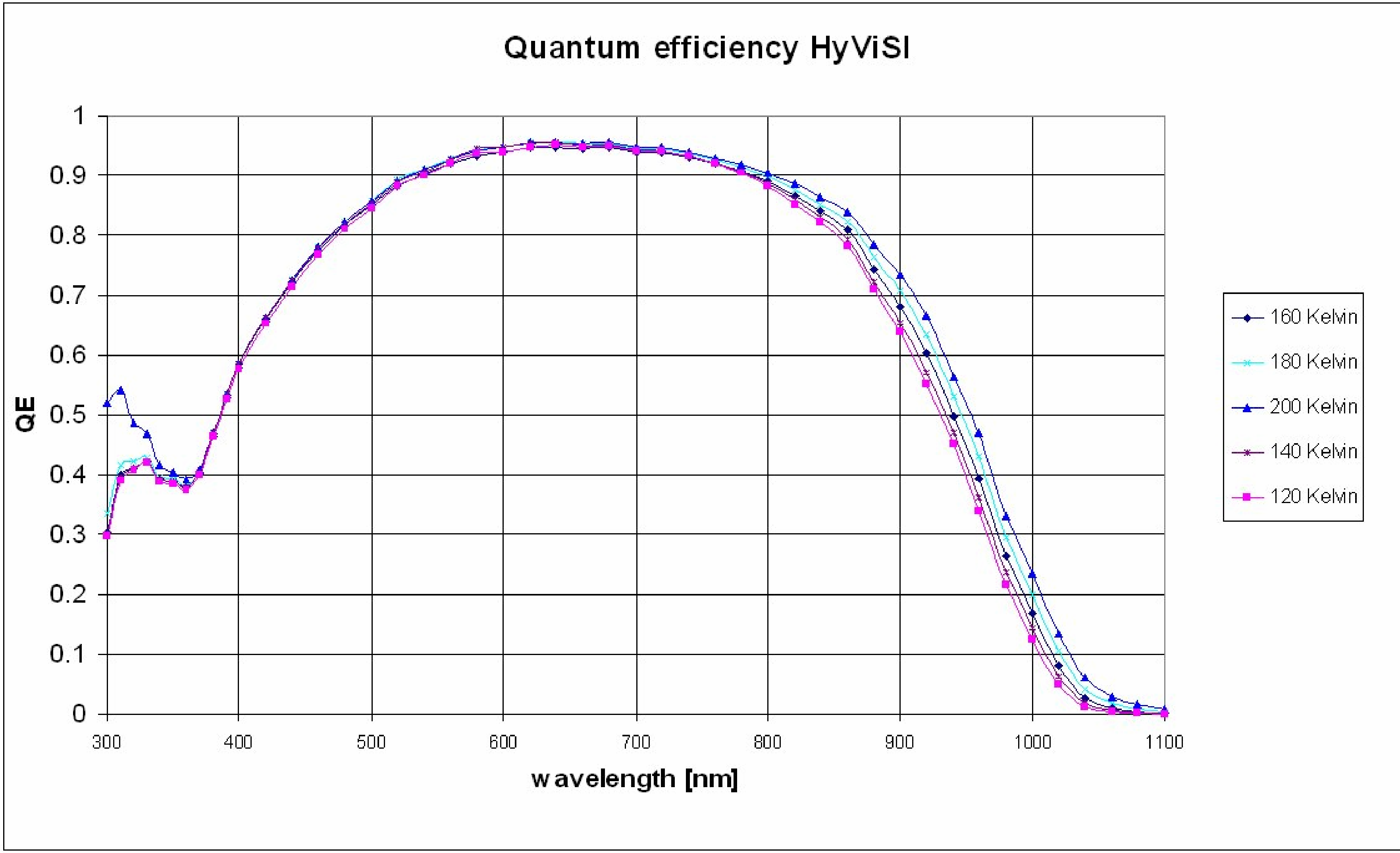
Bond yield by RVS and RSC >0.999

Indium interconnect array on 8 um centers compared to a human hair.



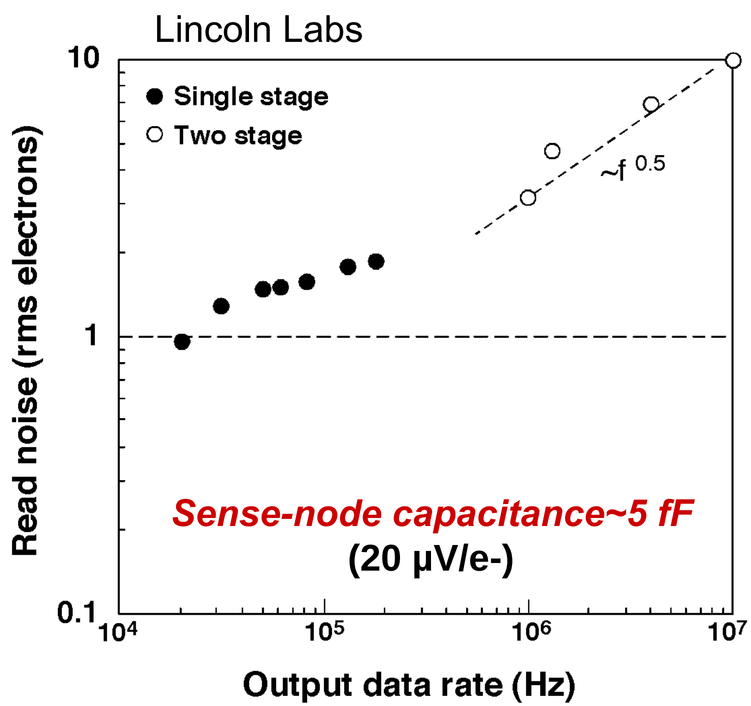
From: K.T. Veeder et al., "Enabling Technologies for Large Hybrid Focal Plane Arrays with Small Pixels", Raytheon Vision Systems

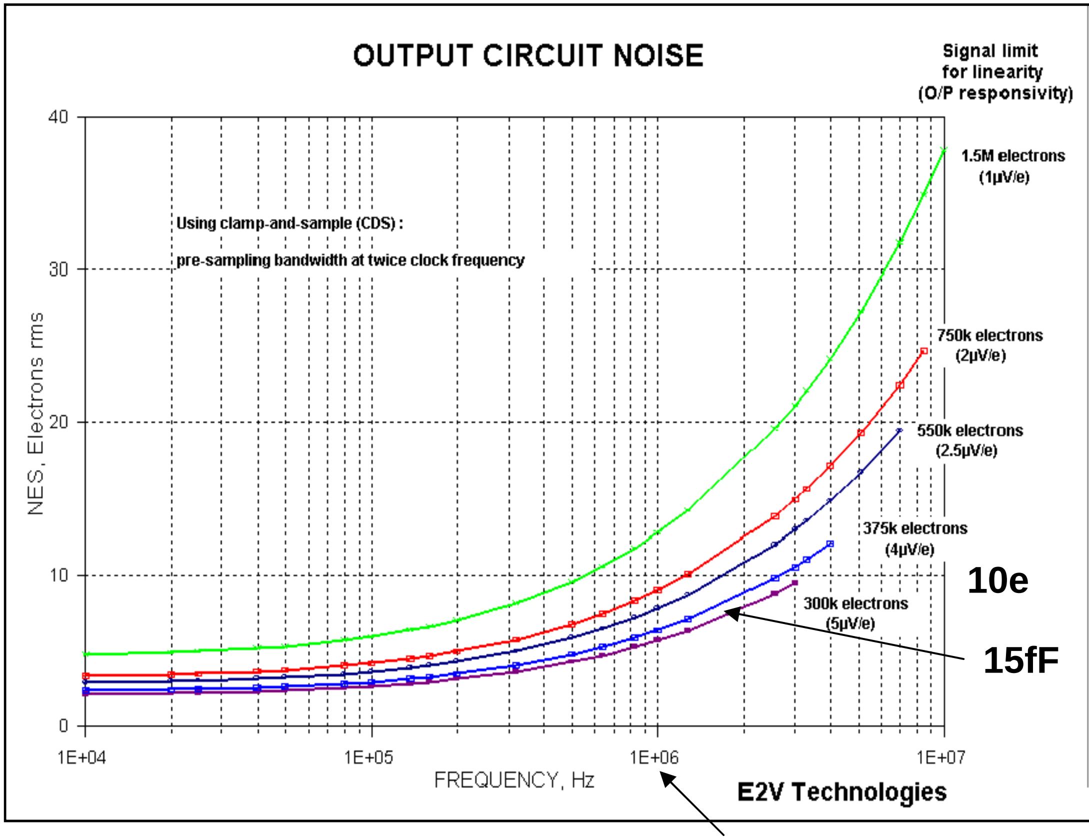
RSC - H2RG (2Kx2K, 18 μm pixel) HyViSI *Measured quantum efficiency (courtesy Reinhold Dorn, ESO).*



This HyViSI array has a detector layer that is 75 microns thick and a single layer anti-reflection coating of SiO_2 that is 1200Å thick.

Readout Noise in CCDs



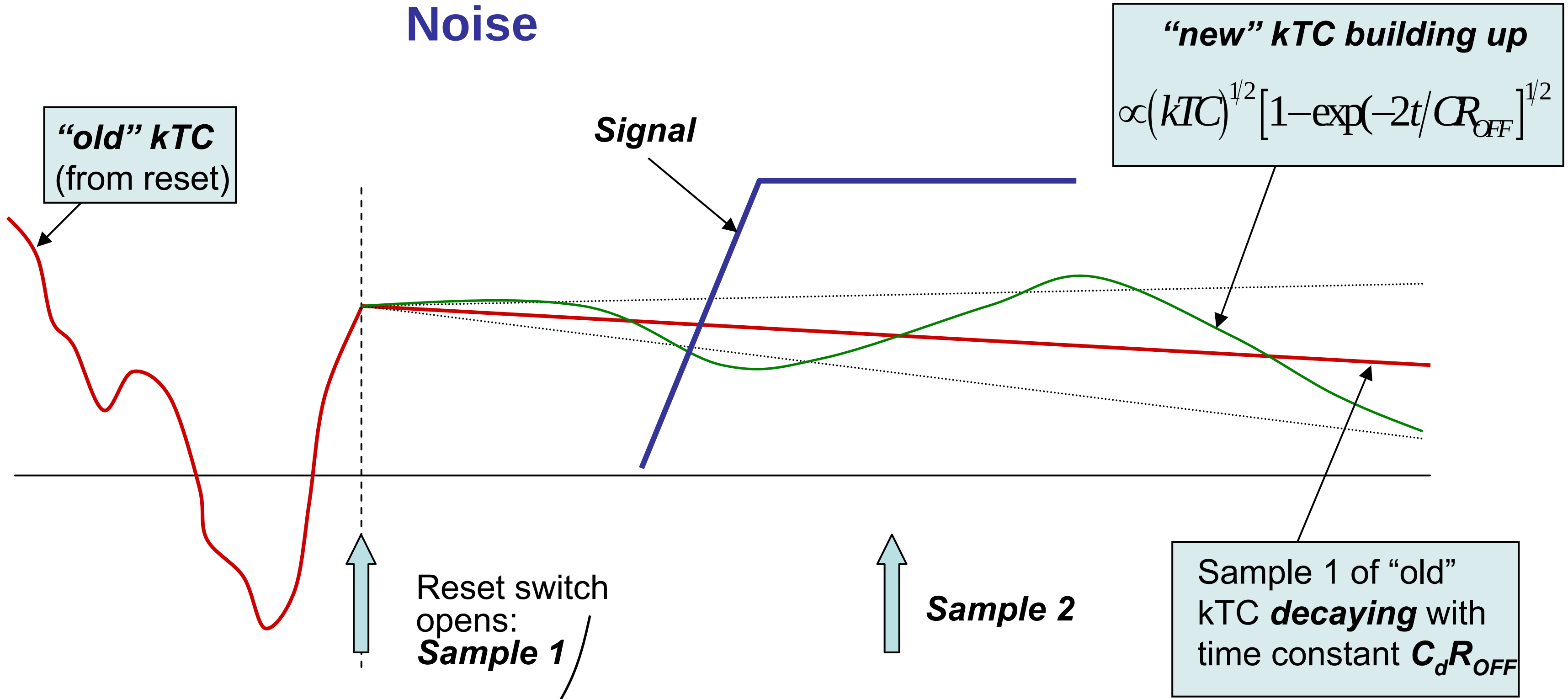


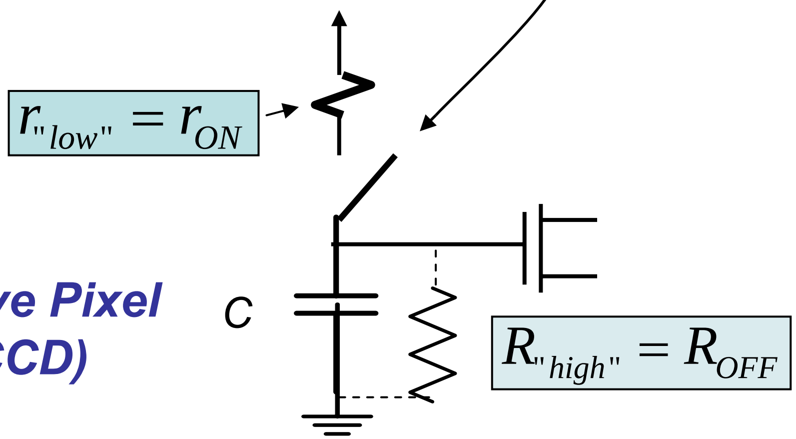
<u>Source Follower transistor:</u>	<u>By CCD process:</u>	<u>MOS(P):</u>
Channel length L:	~4-6 µm	~0.4-0.5 µm
Channel width W:	~45 µm	~10 µm
Power:	***5-10 mW***	***<100 µW***

For equal noise!

Results From: Burke, Jorden, Vu, SDW Taormina 2005

Correlated Double Sampling (CDS) and *kTC* Noise





Active Pixel (or CCD)

$$R_{OFF} / r_{ON} \sim 10^6 - 10^{11}$$

Example:

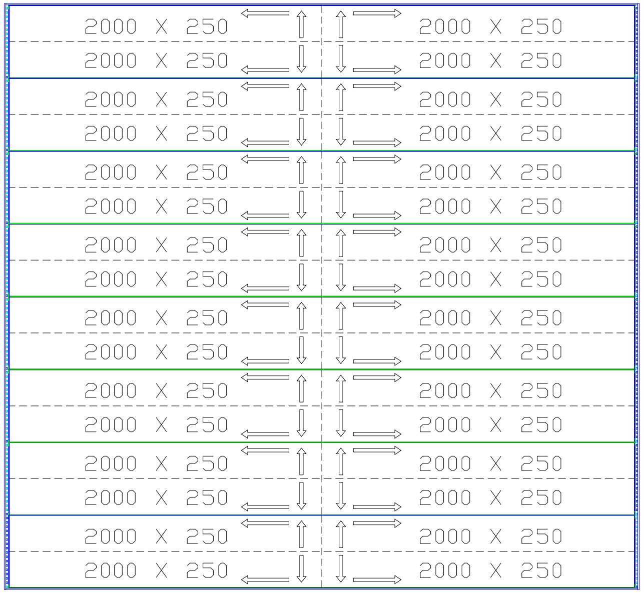
C ~ 20 fF → *kTC~40 e rms!*

r_{ON}~ 10^3 ohms $r_{ON}C$ ~ 20 ps

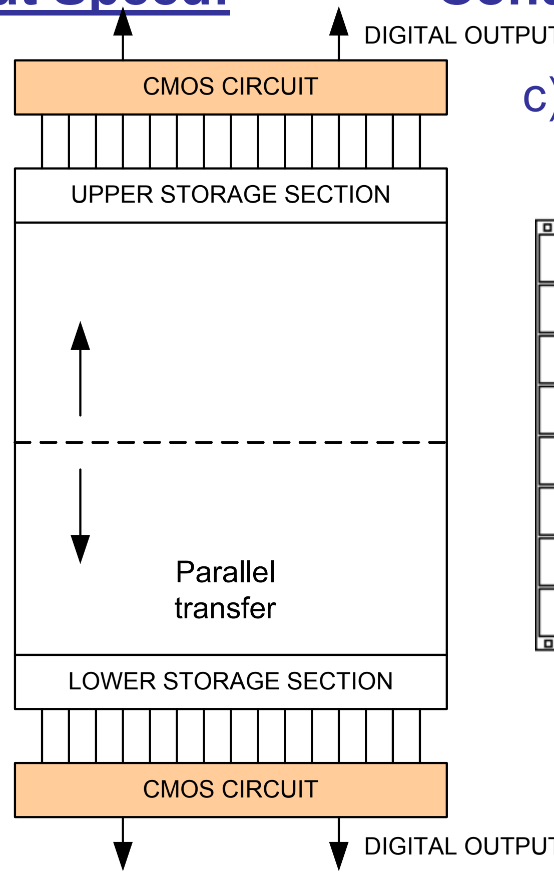
R_{OFF}~ 10^{13} ohms $R_{OFF}C$ = 0.2 s

Segmenting CCDs for Readout Speed: Condition: < 5 e rms

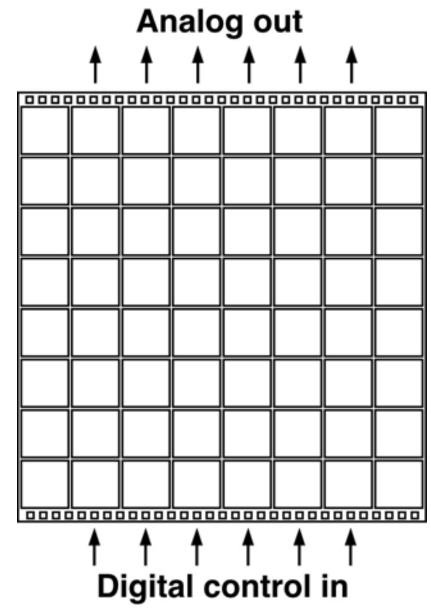
a)



b)



c)



All arrays 4kx4k=16 Mpixels

	a)	b)	c)
Segments:	Up to 32	Up to 2x4k!	64 (or more)
Advantages:	Short columns – -*blooming localized*	High frame rate	Combination of a) and b) if not an OTA
Disadvantages:	*Non-contiguous imaging* due to serial registers	Long columns (*blooming*)	Density of outputs too low for direct bump bonding to CMOS readout
Application:	LSST-like telescopes	X-ray detectors	
Source followers:	*on* CCD	*On* or *off* CCD	On CCD (Pan STARRS), or off

Trends:

- CCDs ~75-200 μm thick for astronomy (more for x-rays) – -being developed by several manufacturers.
- Conventional CCD readout will be limited to a small number of segments (power dissipation, number of connections).
- Silicon PIN CMOS remain to be proven and accepted in astronomy. If so, will prevail for short readout times. CCDs will still be best for long integration times.
- Pixel size will bottom out (full well charge, readout time, …).
- CCD-CMOS hybrids need to be explored for high performance imaging in astronomy (they are being actively developed for other fields).