Lecture 13

Going even fainter

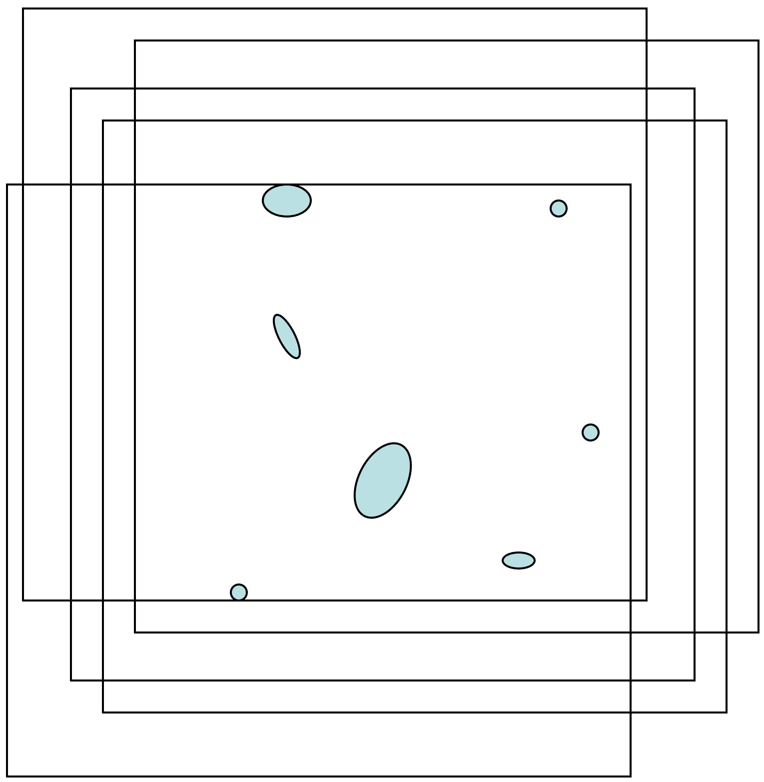
Super-flats

Shift-and-stare imaging

Fringing removal

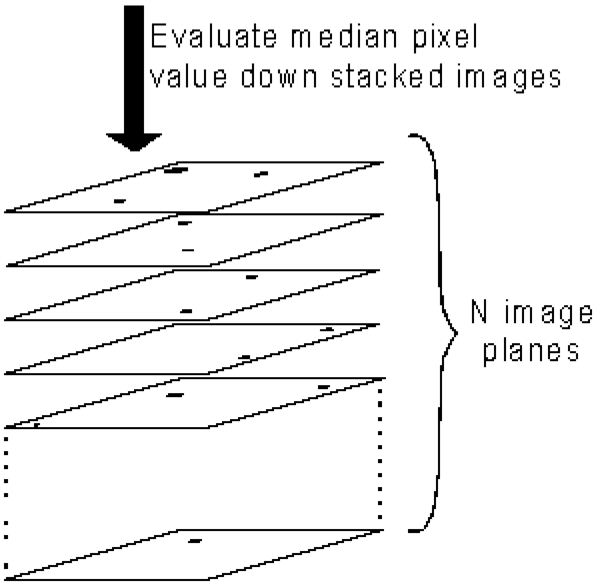
Wide-field cameras

Shift-and-stare imaging



Stars and galaxies are dis-registered between exposures. However, systematic errors in the CCD are registered in each frame.

Shift-and-stare supersky



All features on the CCD (systematic errors) remain fixed on the CCD and thus are at shifted positions relative to the stars and galaxies in the shift-and-stare image stack. Next: debias each image.

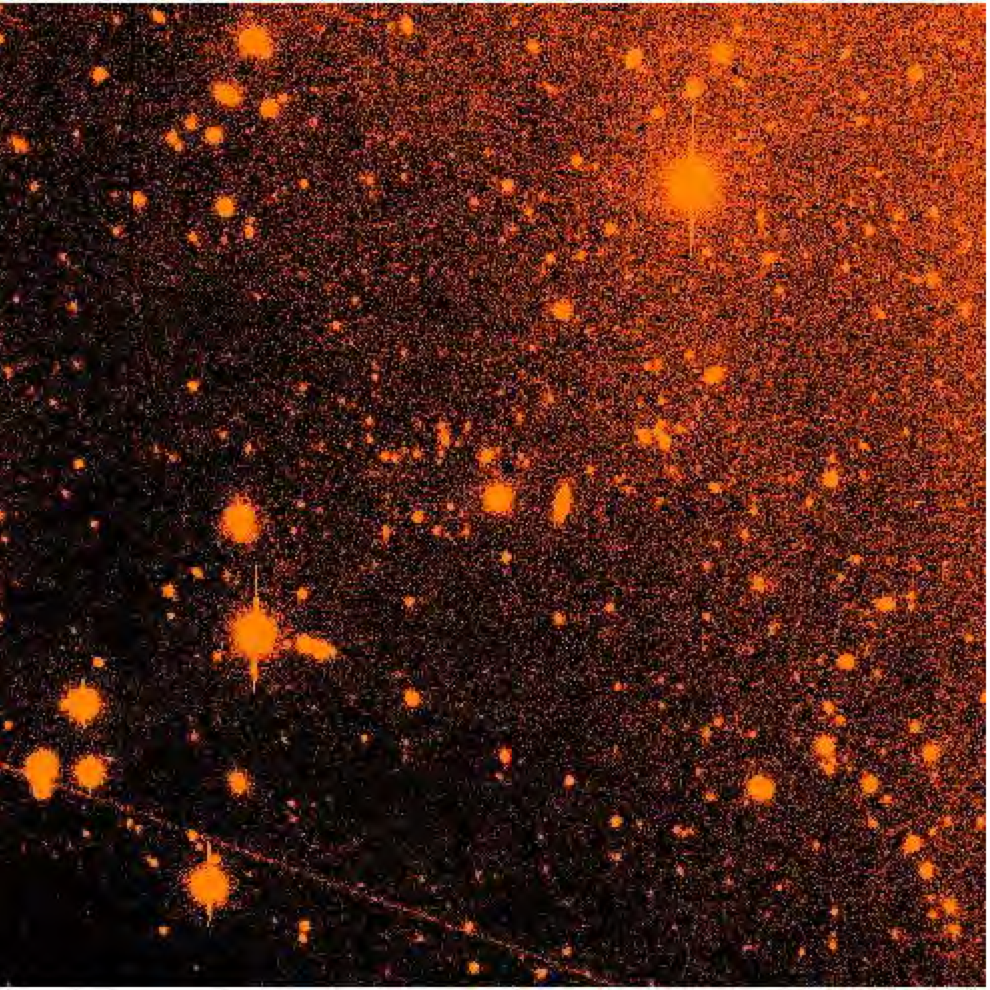
For each pixel in this stack take the median average over the stack. The most probable value for that median average pixel will be unbiased by the objects and will have a scatter given by the random sky shot noise divided by root number of images. This is the raw supersky flat.

This image has one last systematic: additive fringing due to interference of coherent light from emission lines in the night sky.

To get the supersky flat, we need to construct a "fringe frame" and subtract.

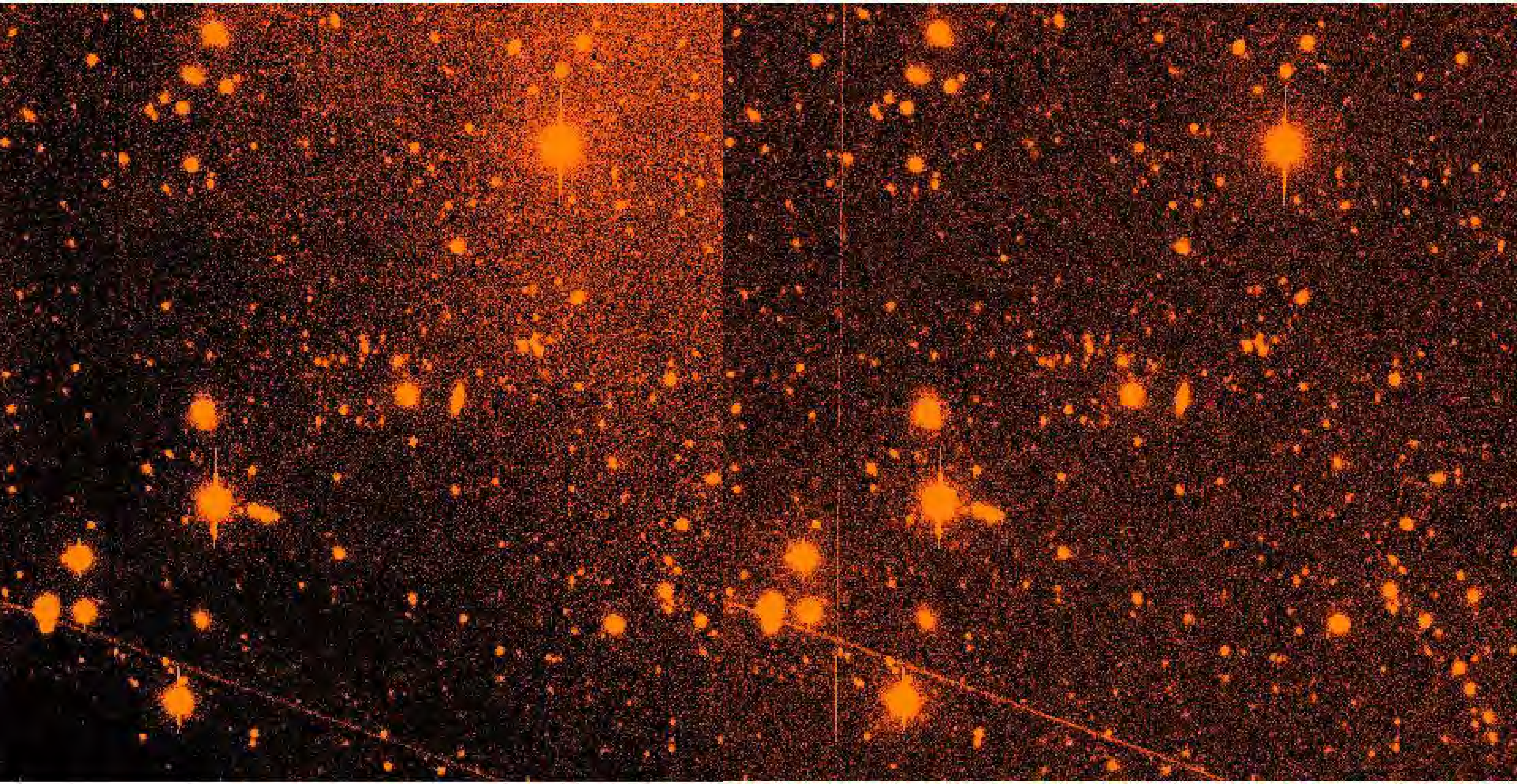
superflats

Before flat fielding



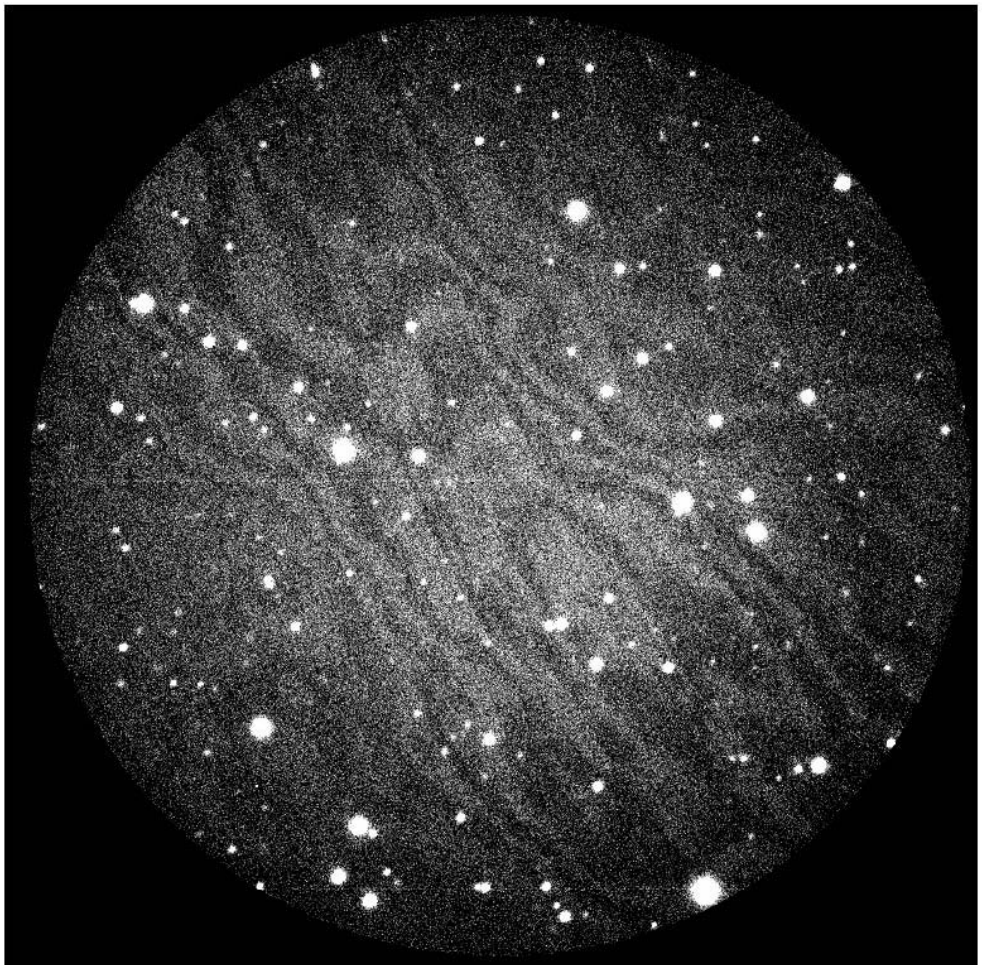
superflats

After flat fielding



Fringing

Output = [OBJ + SKY(1+fringe)] QE + BIAS + NOISE



This is true if fringing is due to photons from a narrow line interfering, and if the rest of the photons in the broad bandpass are incoherent.

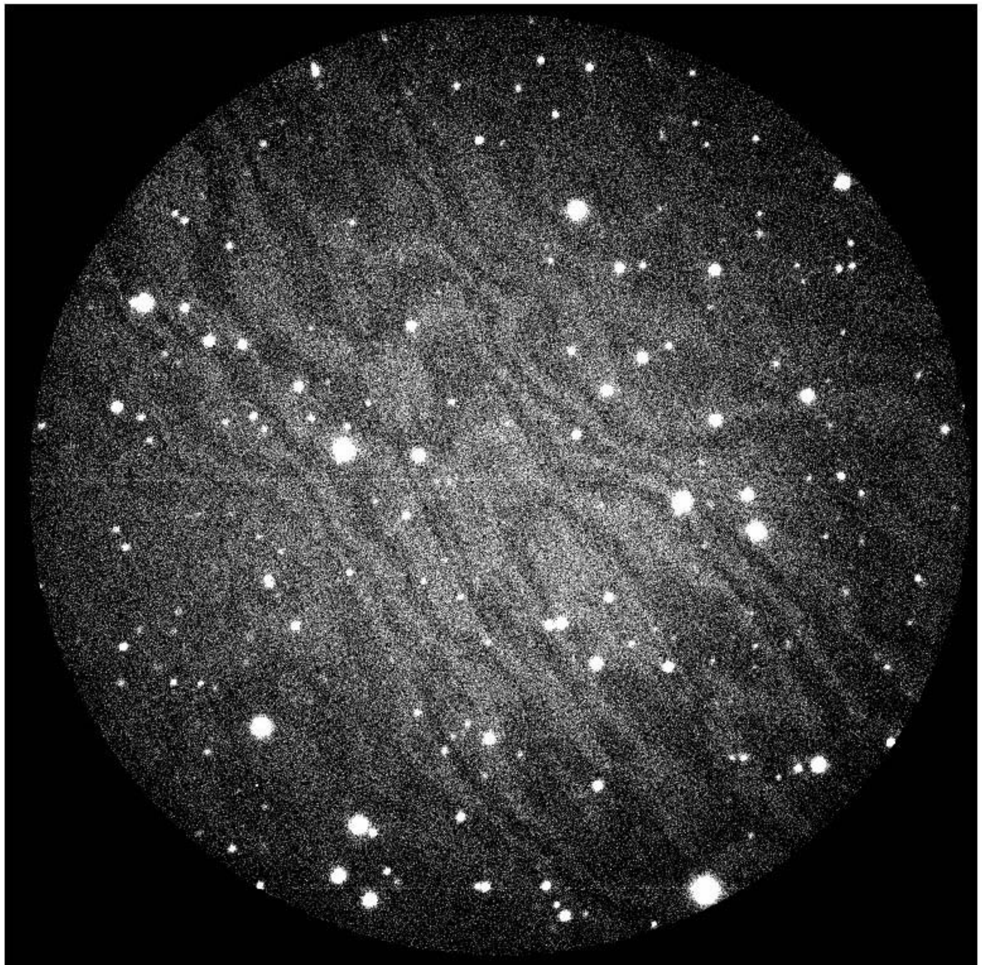
Suppose however we go to a very narrow bandpass filter. Then all photons from that filter are nearly coherent and interfere. Moreover there is no additional "sky":

Output = [OBJ + SKY*fringe] QE + BIAS + NOISE

This fringe modulation is degenerate with a QE variation. This is what happens in a spectrograph.

De-fringing

Output = [OBJ + SKY(1+fringe)] QE + BIAS + NOISE



Consider a median of a stack of shift-stare exposures:

Output – BIAS = [SKY(1+fringe)] QE

Objects gone. Now make a median of a stack of dome exposures, debias, scale and subtract:

Output-B – α(DOME-B) = fringe * QE

Normalize this by DOME-B ~ QE, and you have a fringe pattern frame. Finally smooth this fringe pattern frame on scales small compared with the fringe wavelength.

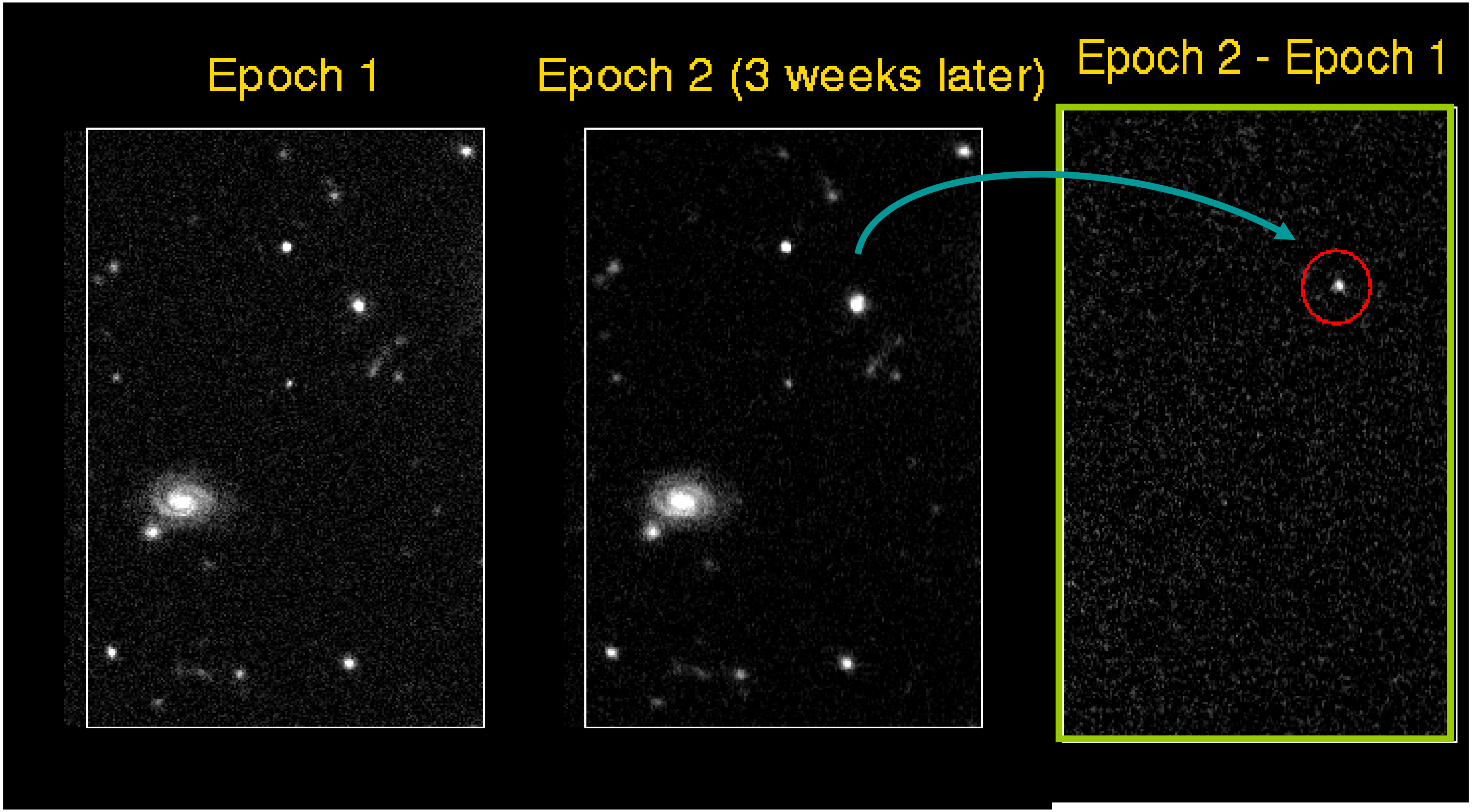
Scale and subtract this from science exposures, individually.

Not quite the last systematic !

KPNO
CCD
mosaic

Scattered light in the camera and telescope optics must be minimized.
This is an example of a pre-filter which reduces systematics.

Frame Subtraction

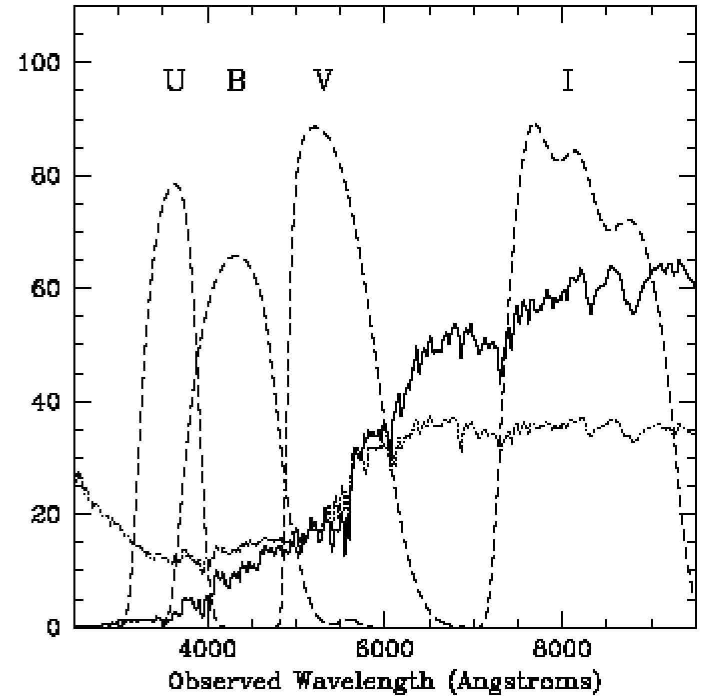


In clean parts of image, residual systematic errors are at 0.0002 sky

Effective wavelength

λ_{eff} is mean λ of detected photons:

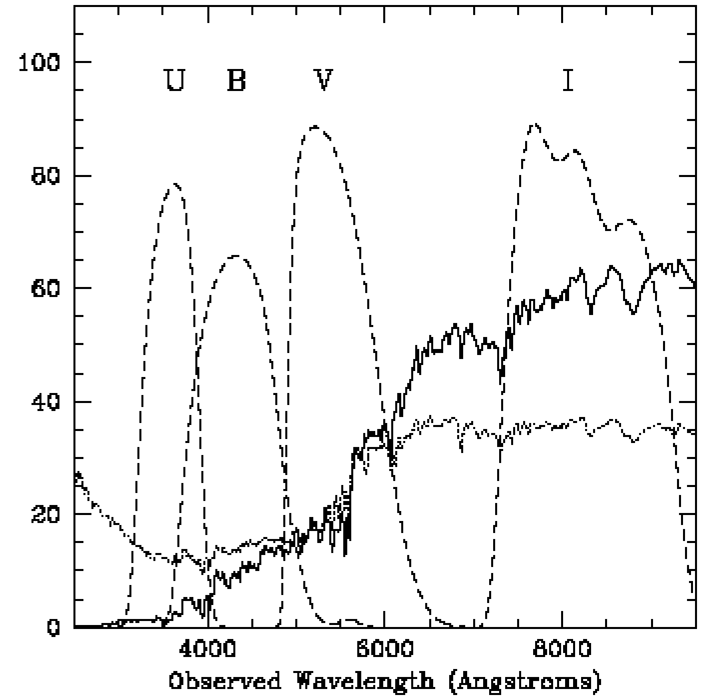
$$\lambda_{eff} = \frac{\int P(\lambda) F(\lambda) \lambda d\lambda}{\int P(\lambda) F(\lambda) d\lambda}$$



- **λ_{eff} depends on both:**
  - **Passband $P(\lambda)$**
  - **Spectrum shape $F(\lambda)$.**
- **What if $F(\lambda)$ is unknown? Then λ_{eff} is unknown too.**
- **Systematic: sky spectrum (used for flat-fielding) is different than object spectrum. Error proportional to passband width.**

Resulting systematic photometry error

Dividing by the supersky flat produces an image which appears "superflat." But we have made a systematic error in the QE calibration for an object with a different spectrum from sky background. Sky spectrum varies across the filter passband differently than the object spectrum.

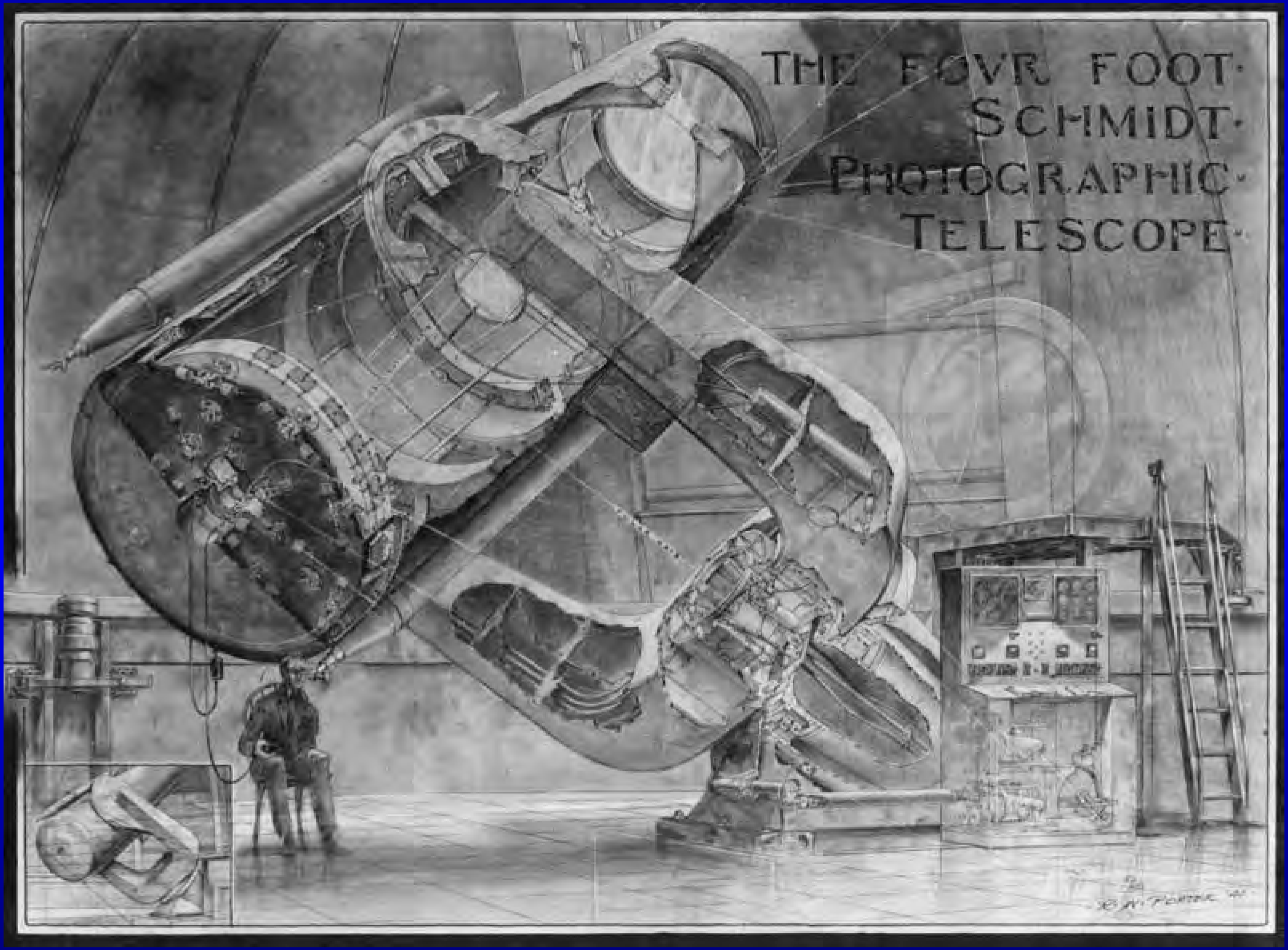


$$= \frac{\int P(\lambda)F(\lambda)\lambda d\lambda}{\int P(\lambda)F(\lambda)d\lambda}$$

where:

- Filter passband $P(\lambda)$
- Sky flux spectrum $Fsky(\lambda)$
- Object flux spectrum $Fobj(\lambda)$

Long history of discovery via sky surveys



Exploration

- Wavelength
- Angular resolution
- Area surveyed
- Depth
- Time resolution

deep wide fast

Figure of Merit

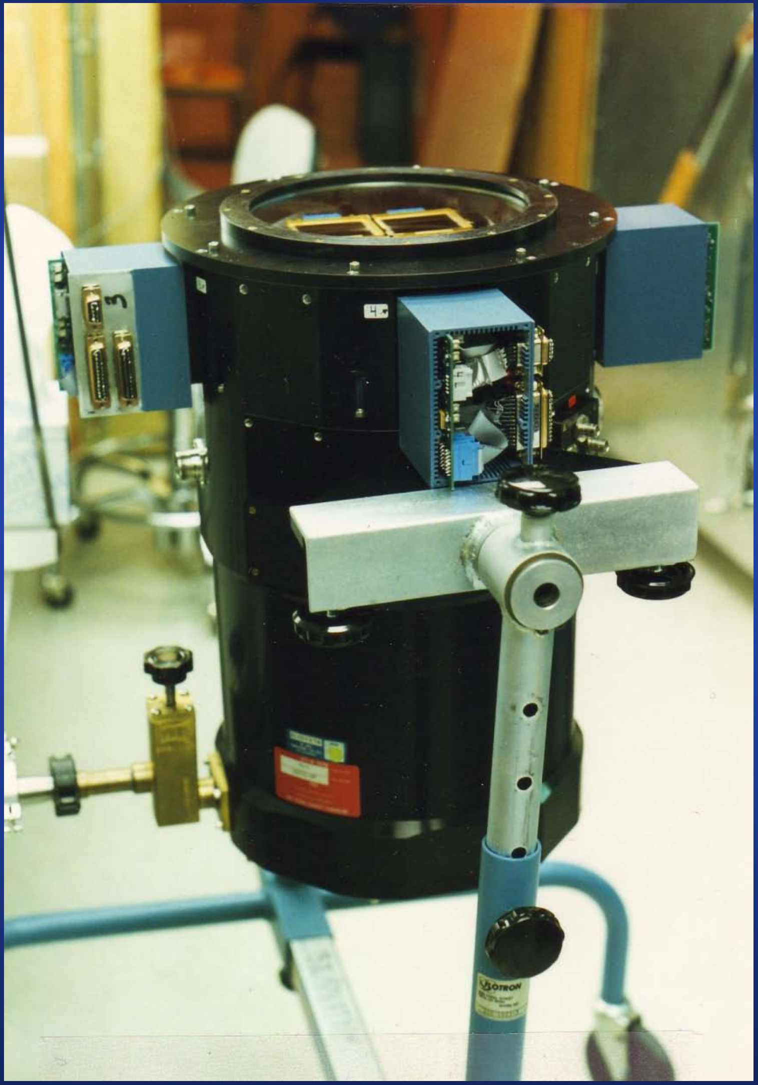
Area surveyed (number of objects found) to some SNR at some magnitude limit, per unit time:

$$\frac{N}{t} = \frac{\overbrace{\varphi^{2}_{obj}}^{\text{Science goals}}\ \overbrace{A\,\Omega\,QE\,\varepsilon}^{\text{Apparatus \& Eff.}}}{\underbrace{(SNR)^{2}}_{\text{Science goals}}\ \underbrace{\varphi_{sky}\,(\delta\Omega)}_{\text{site \& optics}}}$$

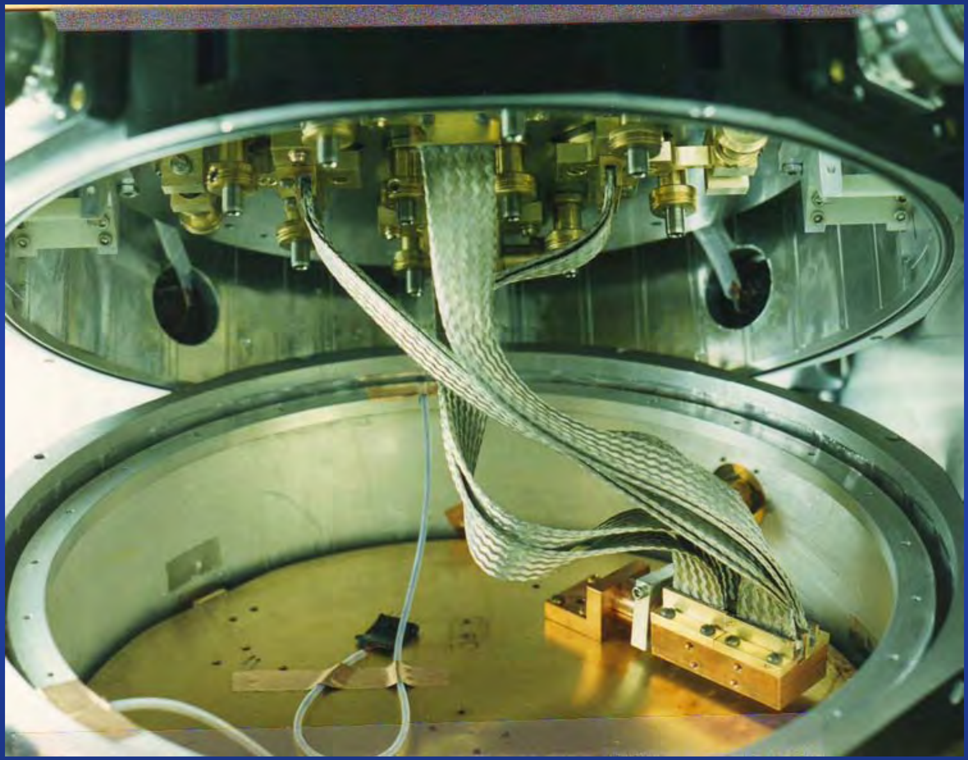
A – aperture **Ω – camera FOV** **QE – det. Eff.**

ε – observing eff. **Φsky – sky flux** **δΩ – seeing footprint**

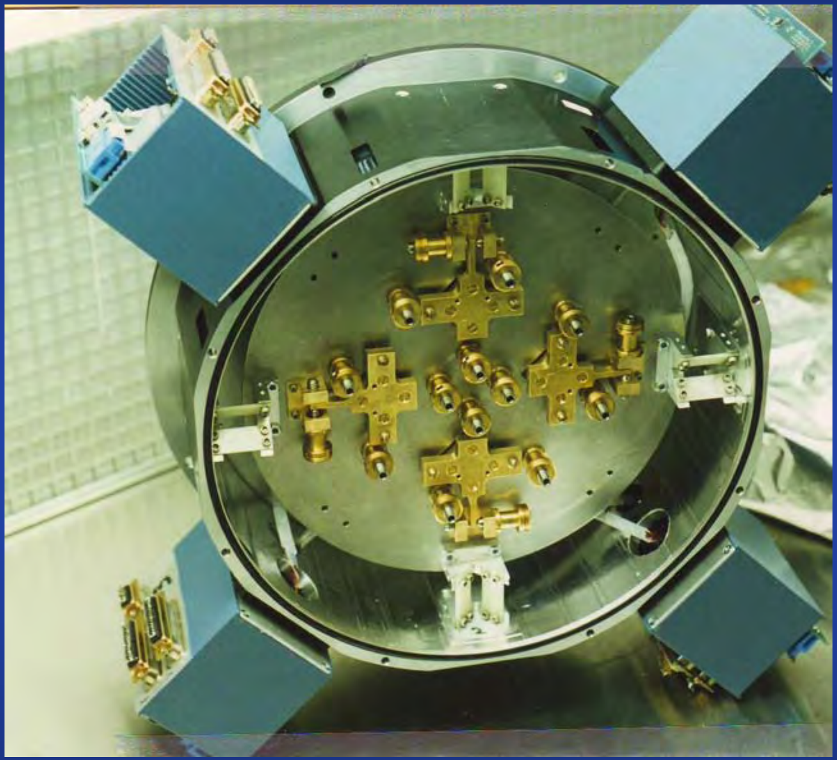
Big Throughput Camera 1986-96



Inside the BTC

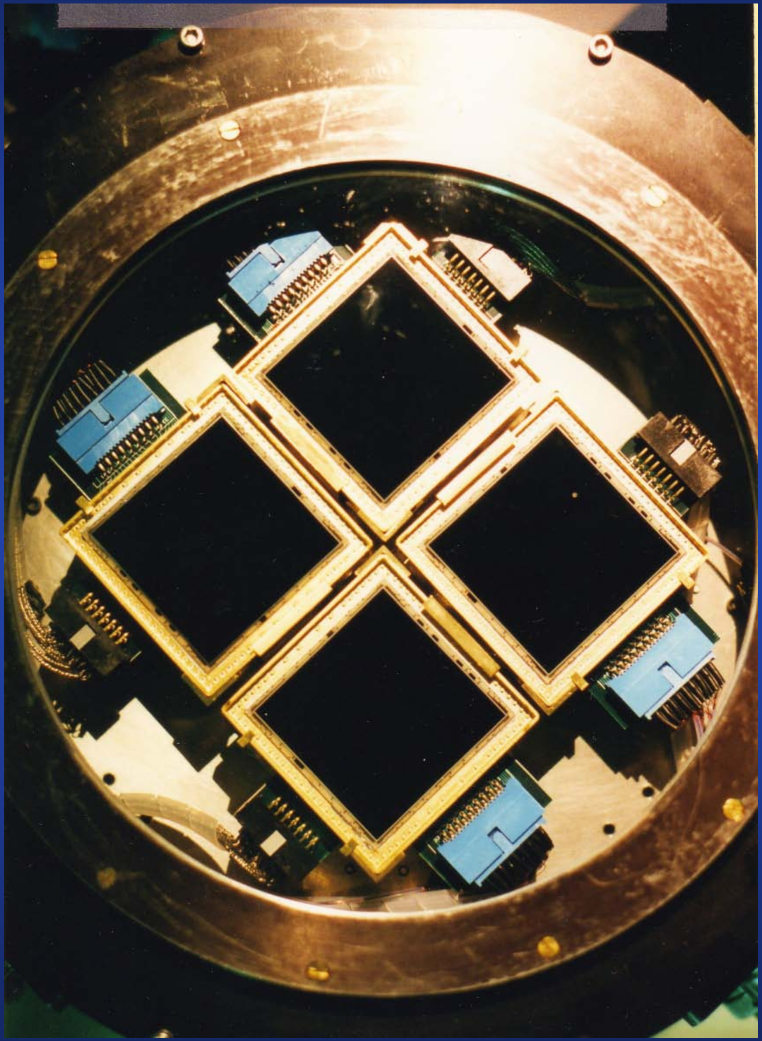


LN2 cold plate with straps to CCDs

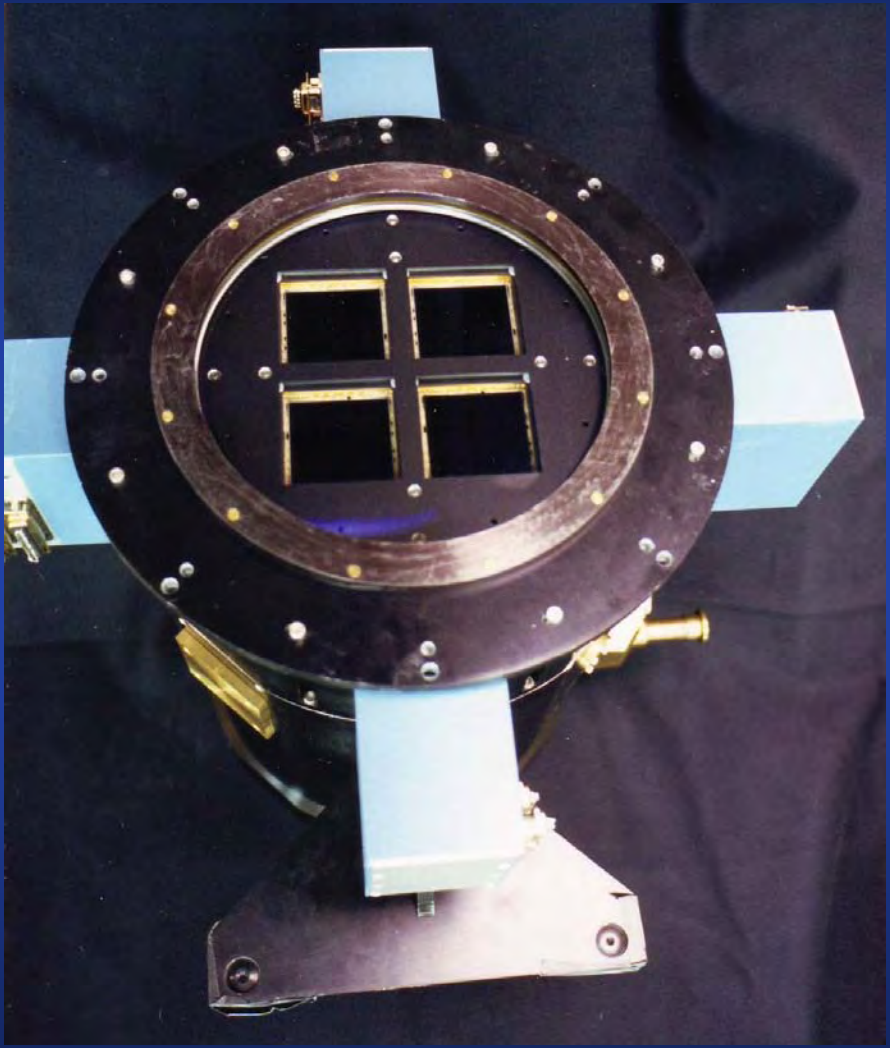


CCDs are individually adjusted z, tilt

Inside the BTC

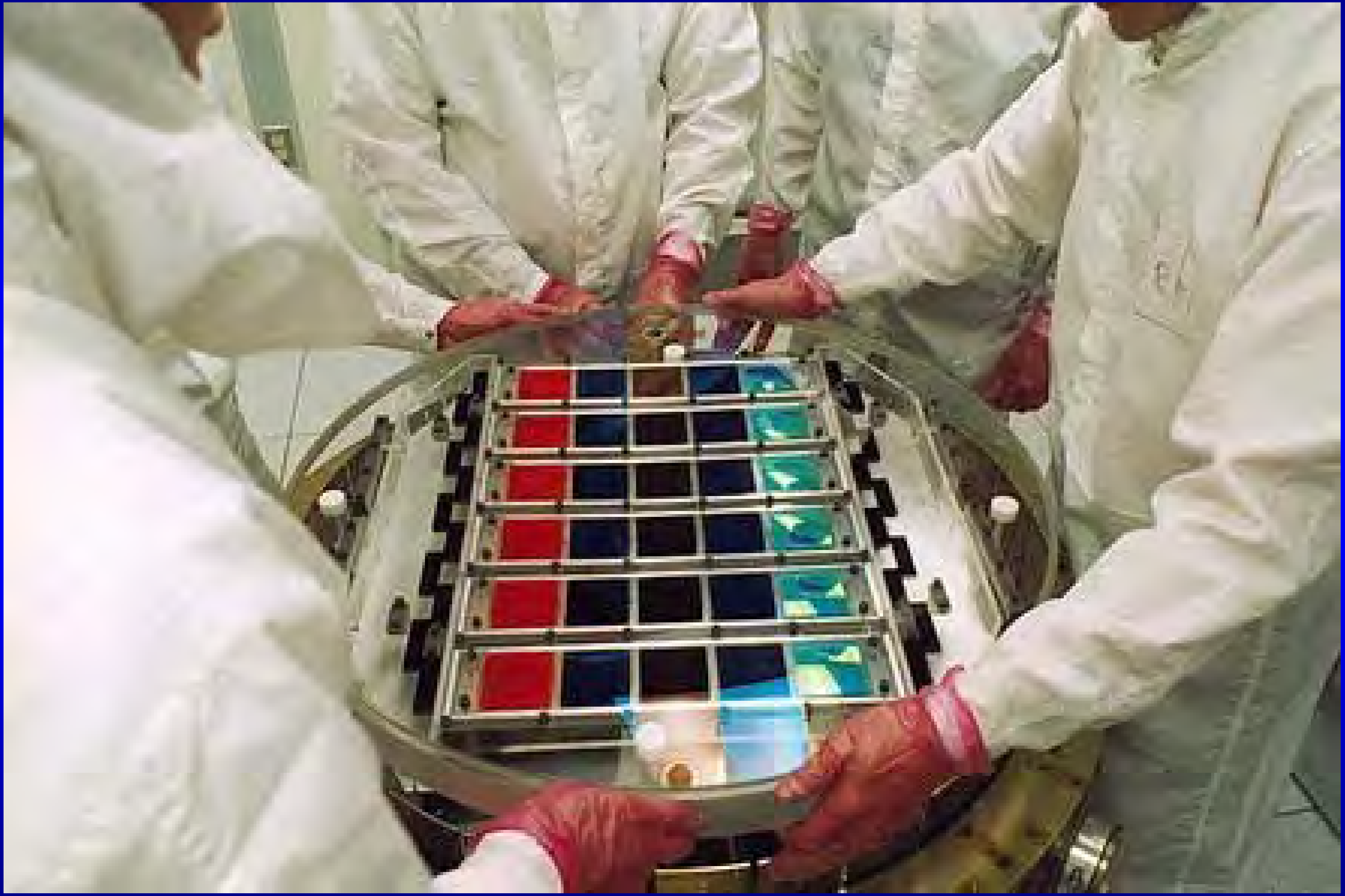


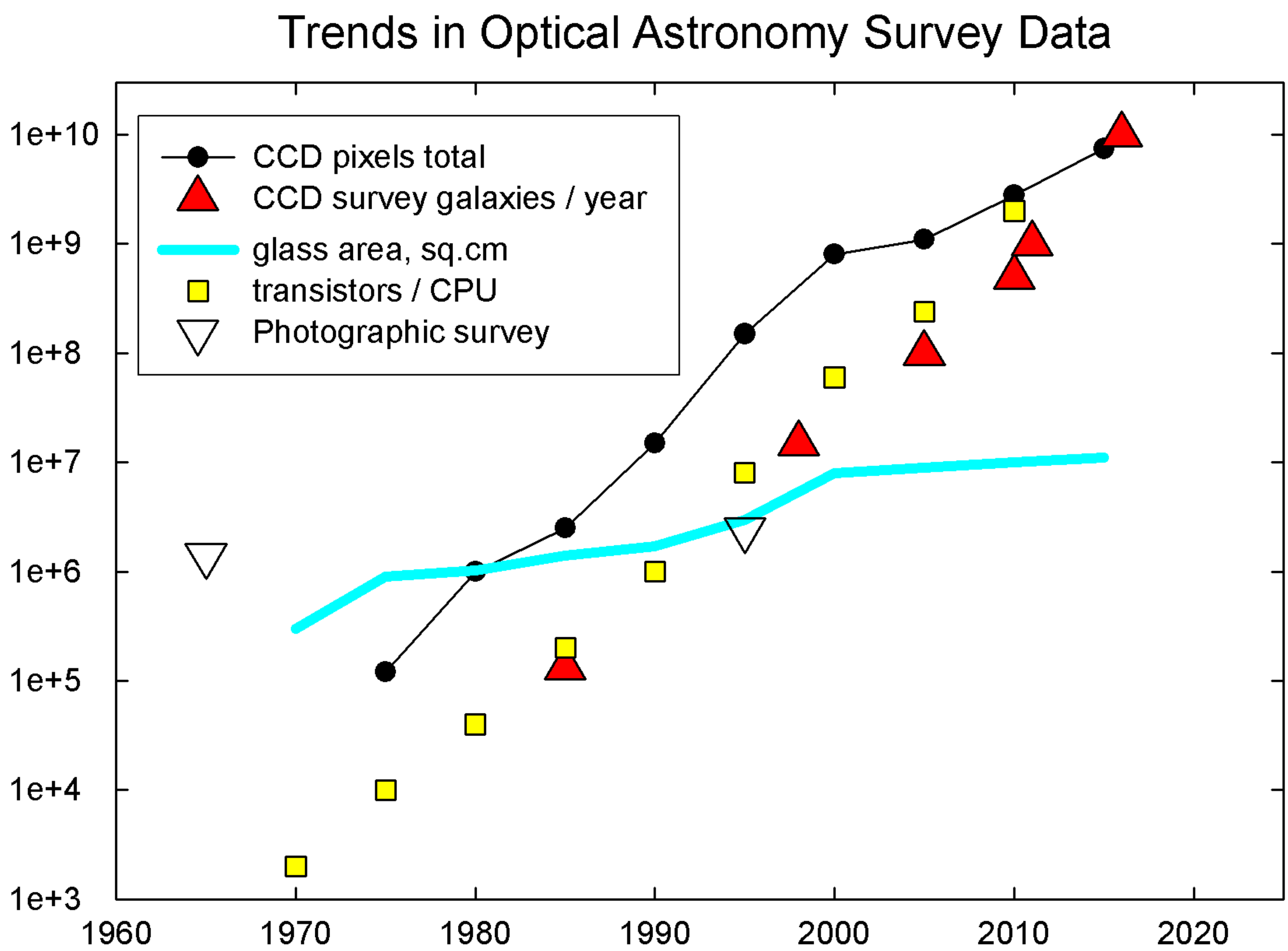
Without baffling



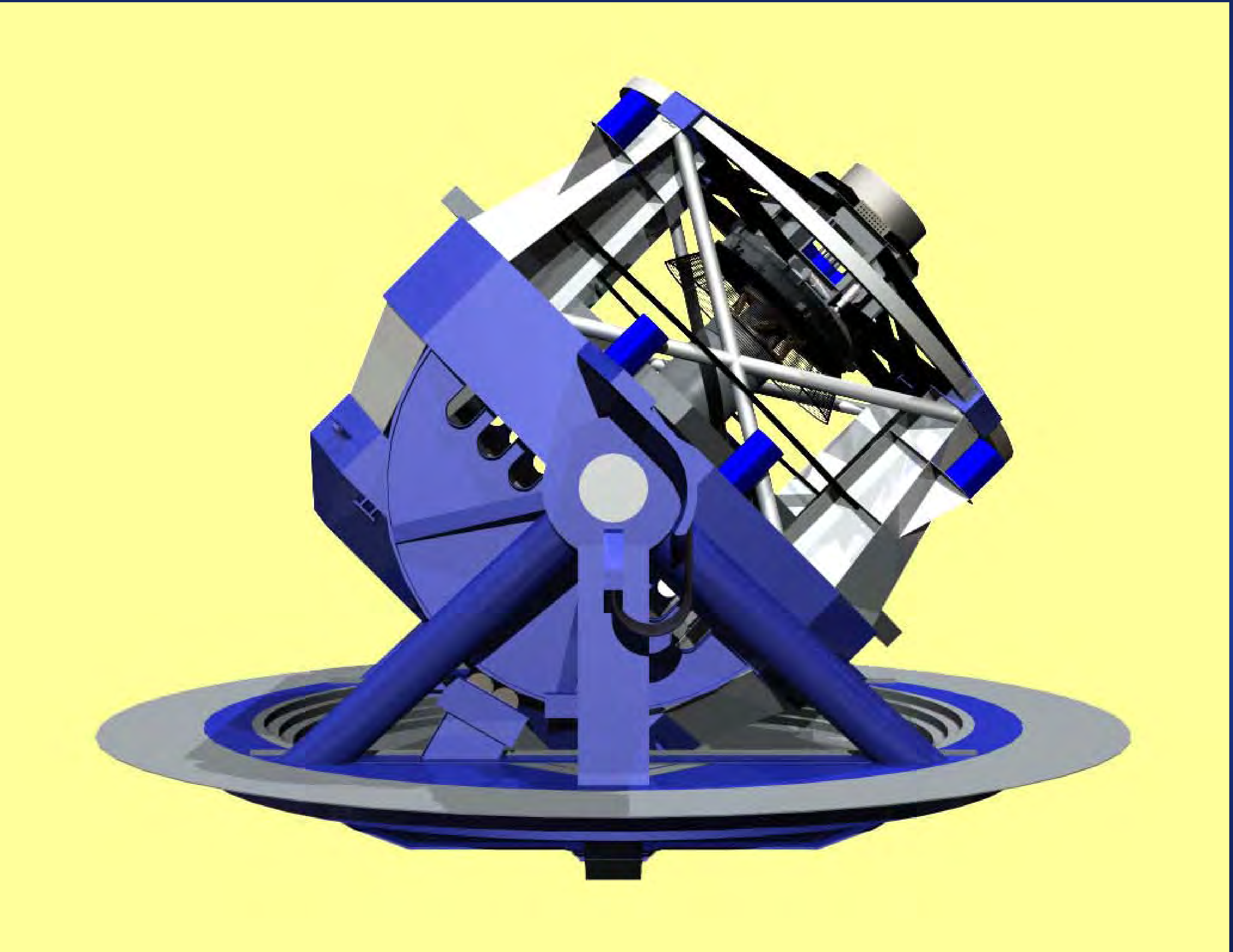
With baffling

Sloan Digital Sky Survey CCD mosaic

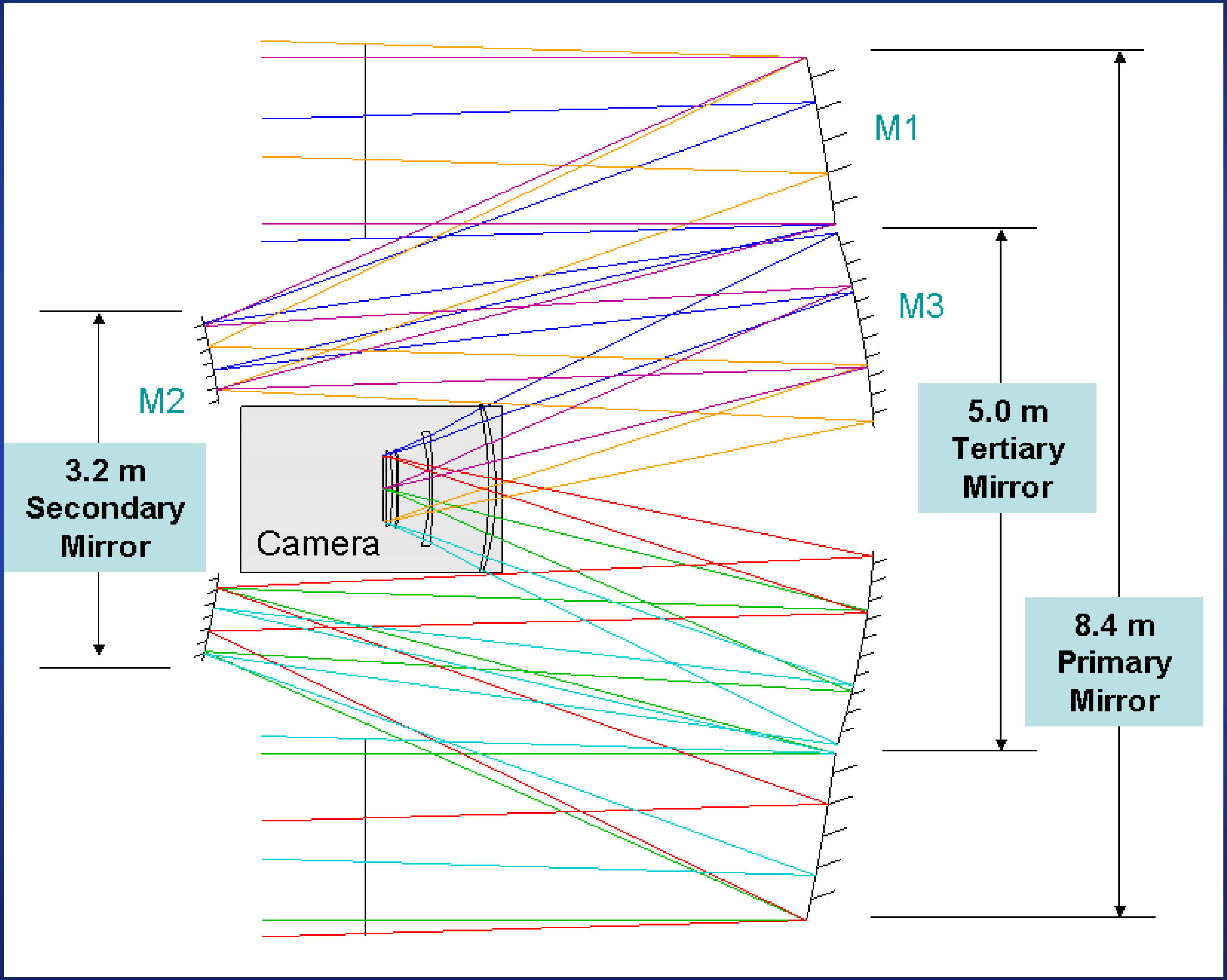



Trends in Optical Astronomy Survey Data
CCD pixels total
CCD survey galaxies / year
glass area, sq.cm
transistors / CPU
Photographic survey
1e+10
1e+9
1e+8
1e+7
1e+6
1e+5
1e+4
1e+3
1960
1970
1980
1990
2000
2010
2020

Large Synoptic Survey Telescope



LSST optical design



Must survey unprecedented volume: deep + wide + fast

- number of objects surveyed at a given surface brightness is proportional to the optical etendue

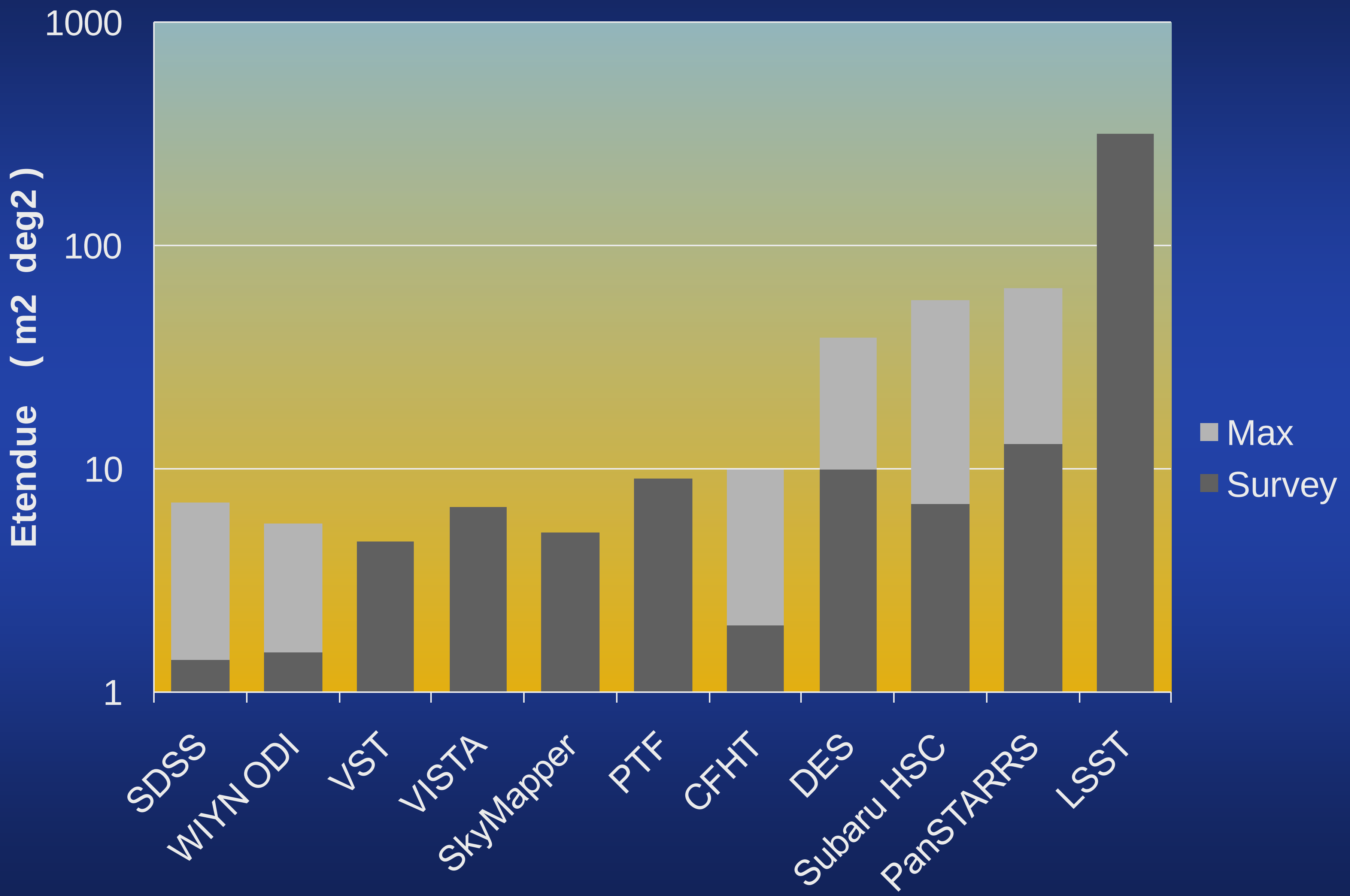
- etendue = aperture x field of view
  m^2 deg^2

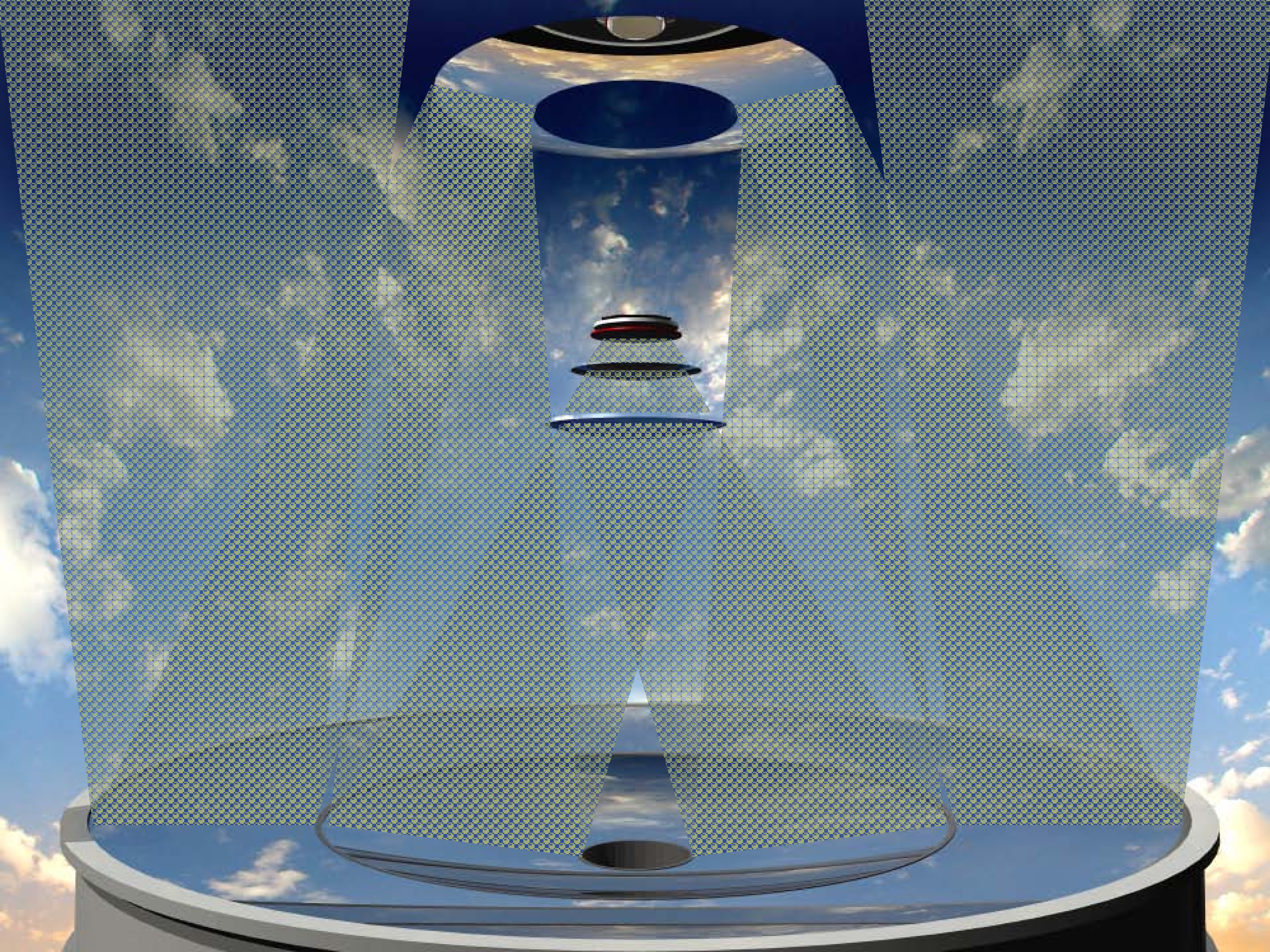
LSST: 318 m^2 deg^2

Including obscuration + vignetting

(4-meter NOAO telescopes: 4 m^2 deg^2)

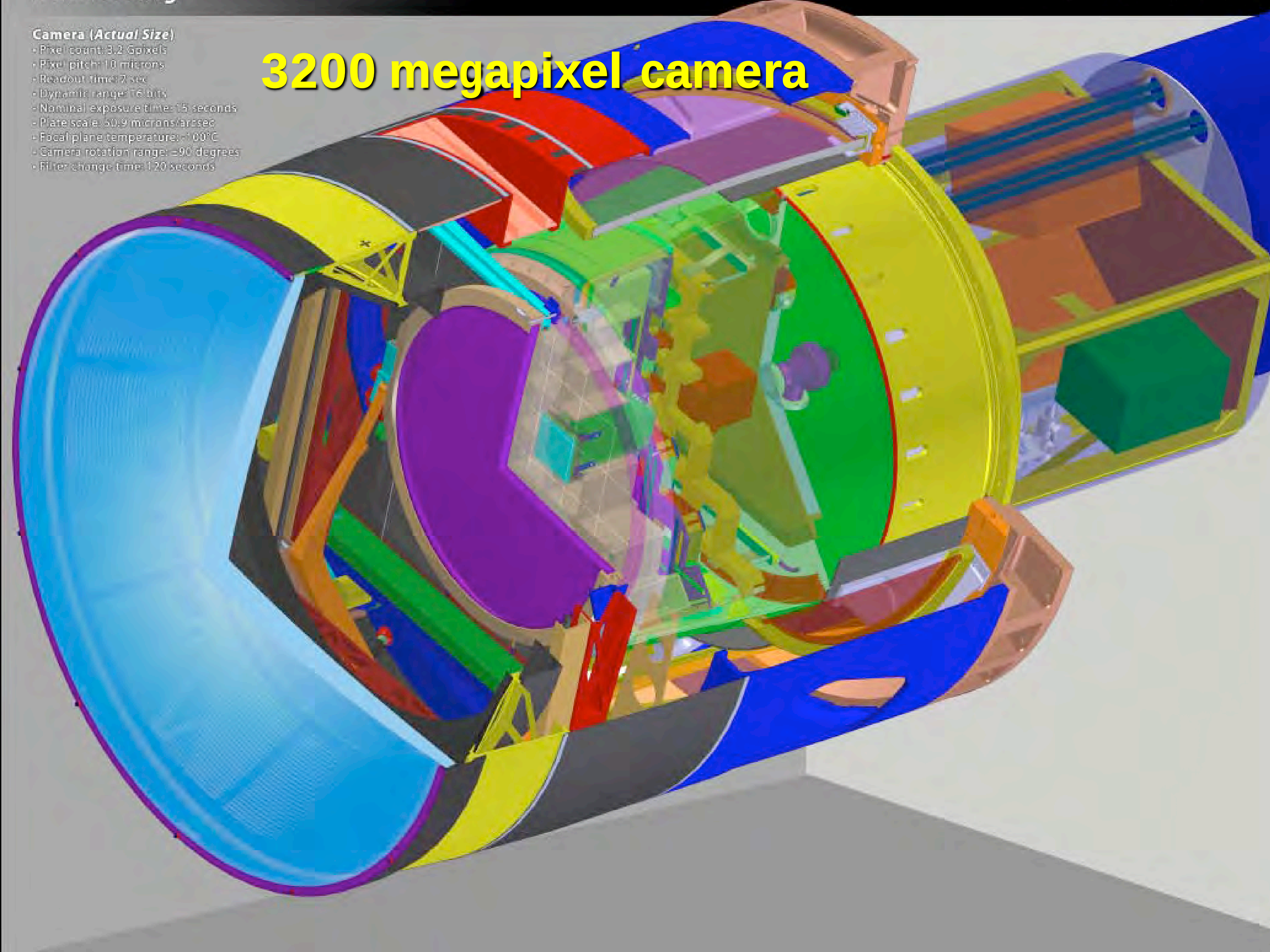
Étendue of current and planned survey telescopes & cameras





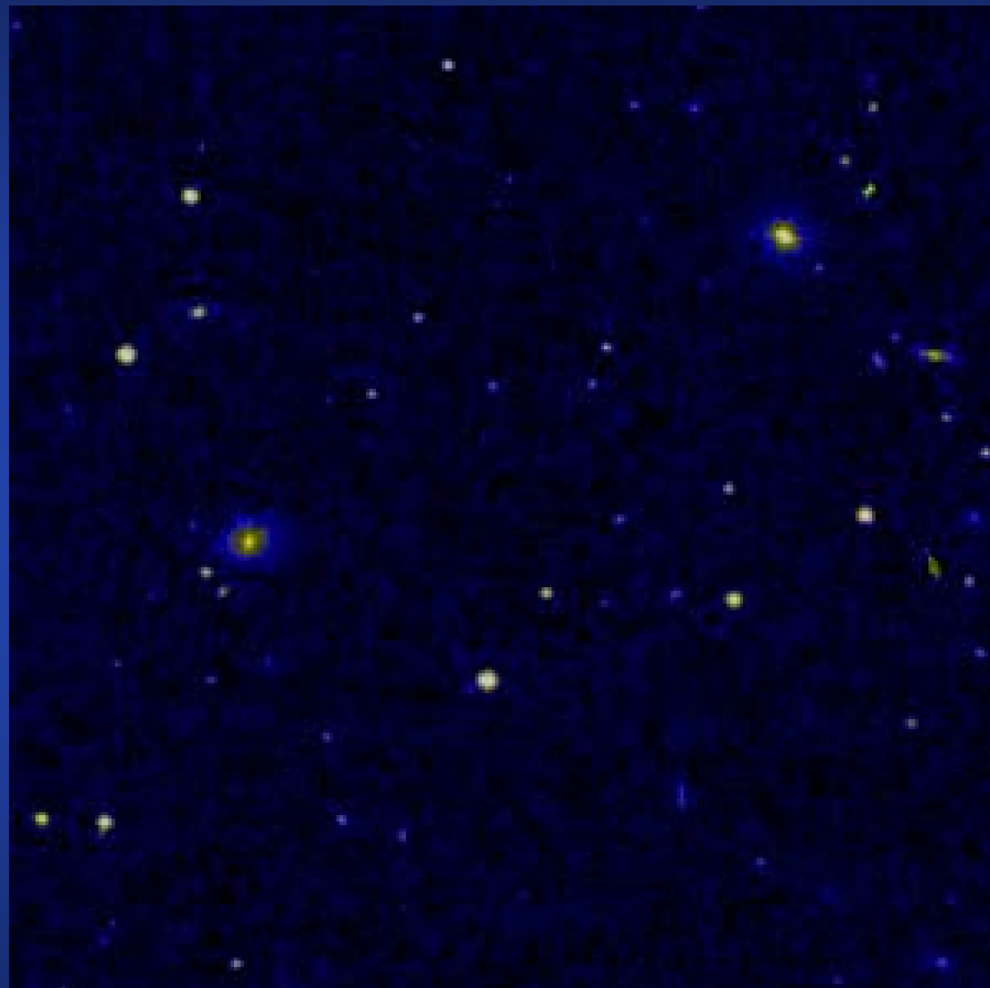
Fabrication of LSST mirrors

3200 megapixel camera

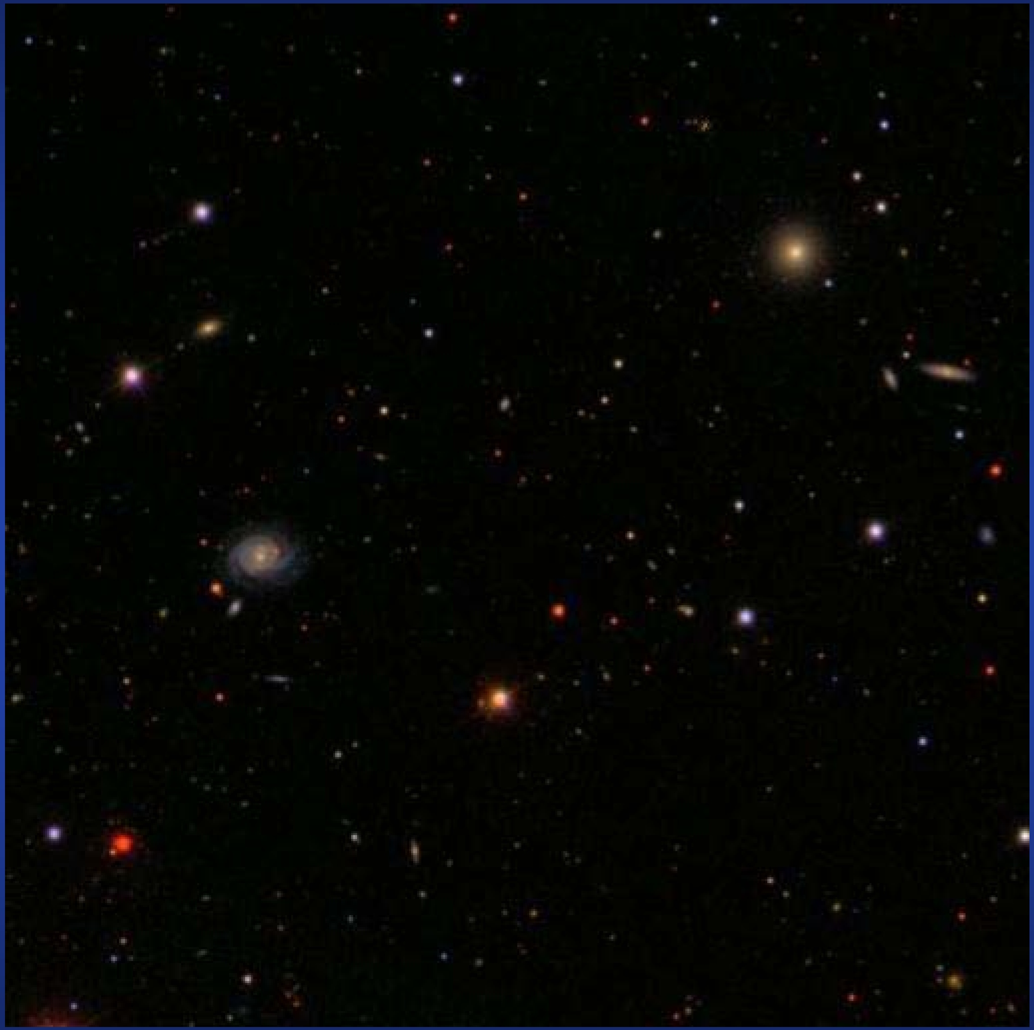


DSS: digitized photographic plates

7.5 arcminutes



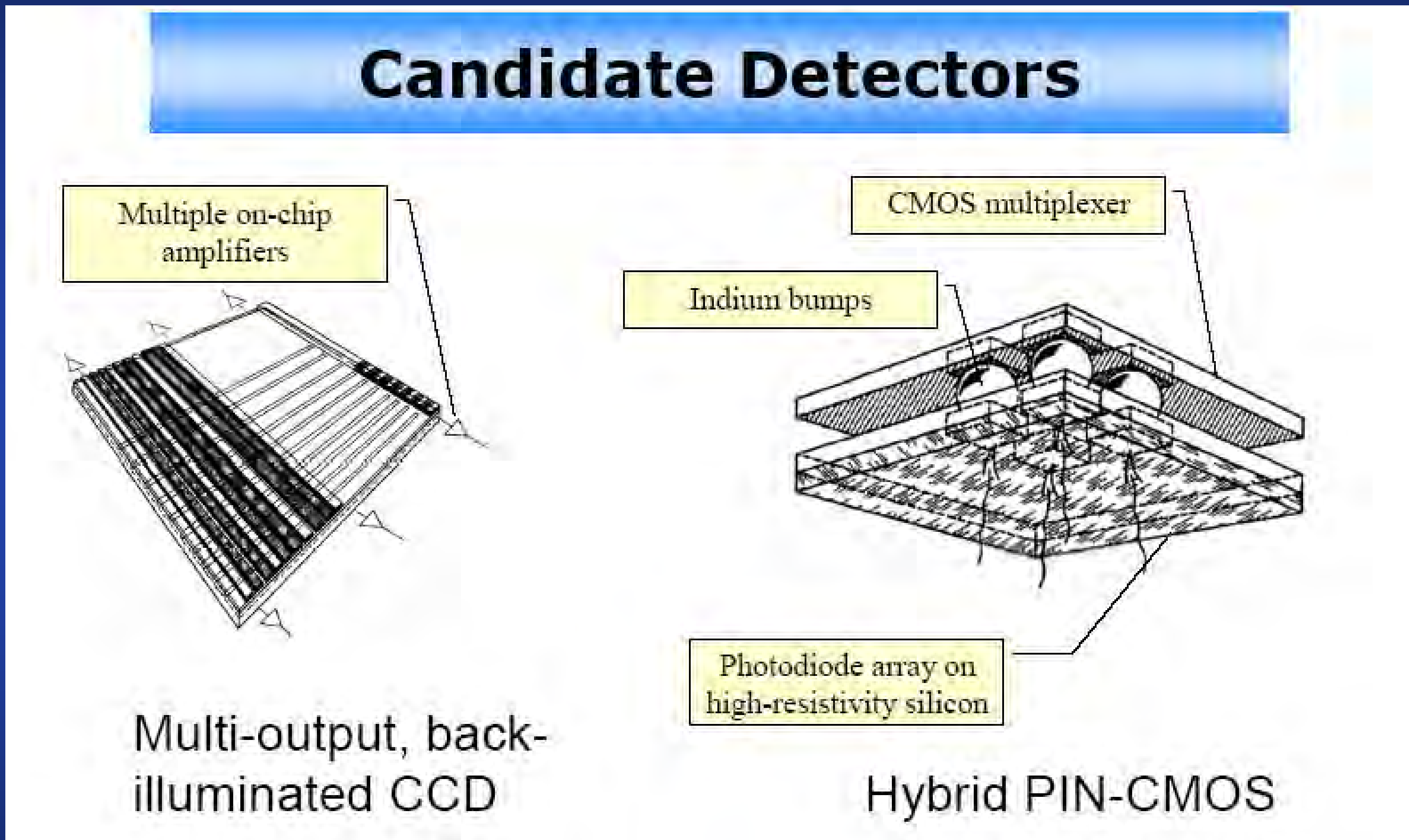
Sloan Digital Sky Survey



LSST -- almost

2800 galaxies
i<25 mag

Next Generation Imager



Advances in State-of-the-Art needed for LSST Detector

- The focal plane array will have about an order of magnitude larger number of pixels ***(~3 gigapixels)*** than the largest arrays realized so far.

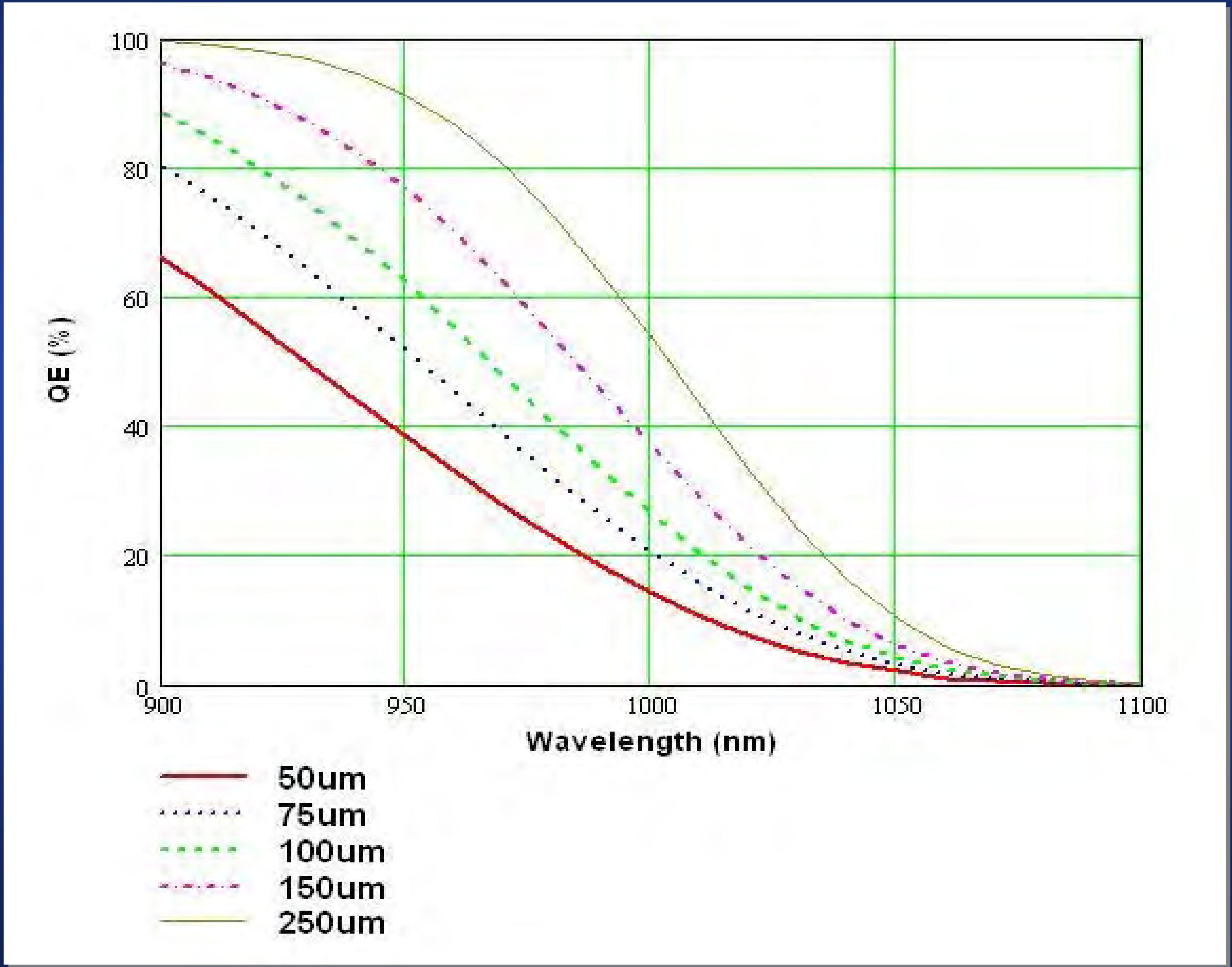
- The effective pixel readout speed will have to be about two orders of magnitude higher than in previous telescopes in order to achieve a readout time for the telescope of ~***1 - 2 seconds .***

- The CCDs will have to have an active region ***~100 µm thick*** to provide sufficiently high quantum efficiency at ~1000 nm, and they will have to be (over)depleted so that the signal charge is collected with minimum diffusion as needed to achieve a narrow point spread function.

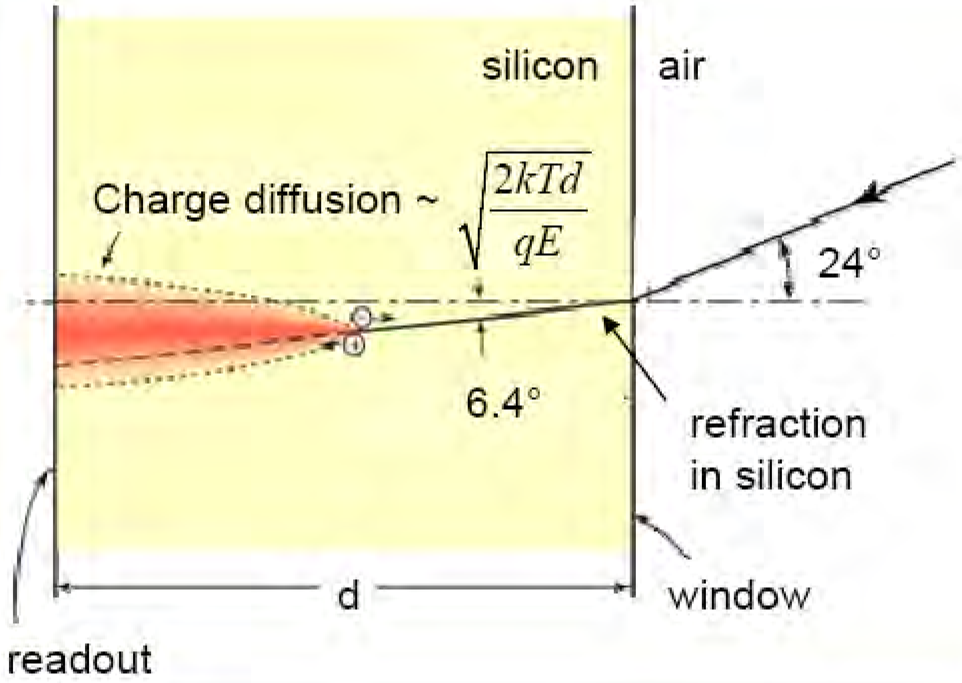
- Packaging ensuring sensor flatness and alignment in focal plane to ***<5µm*** (not routinely achieved with presently delivered devices by industry).

- ***Extensive use of Application Specific Integrated Circuits*** to make the readout of a large number of output ports practical, and to reduce the number of output links and penetrations of the dewar.

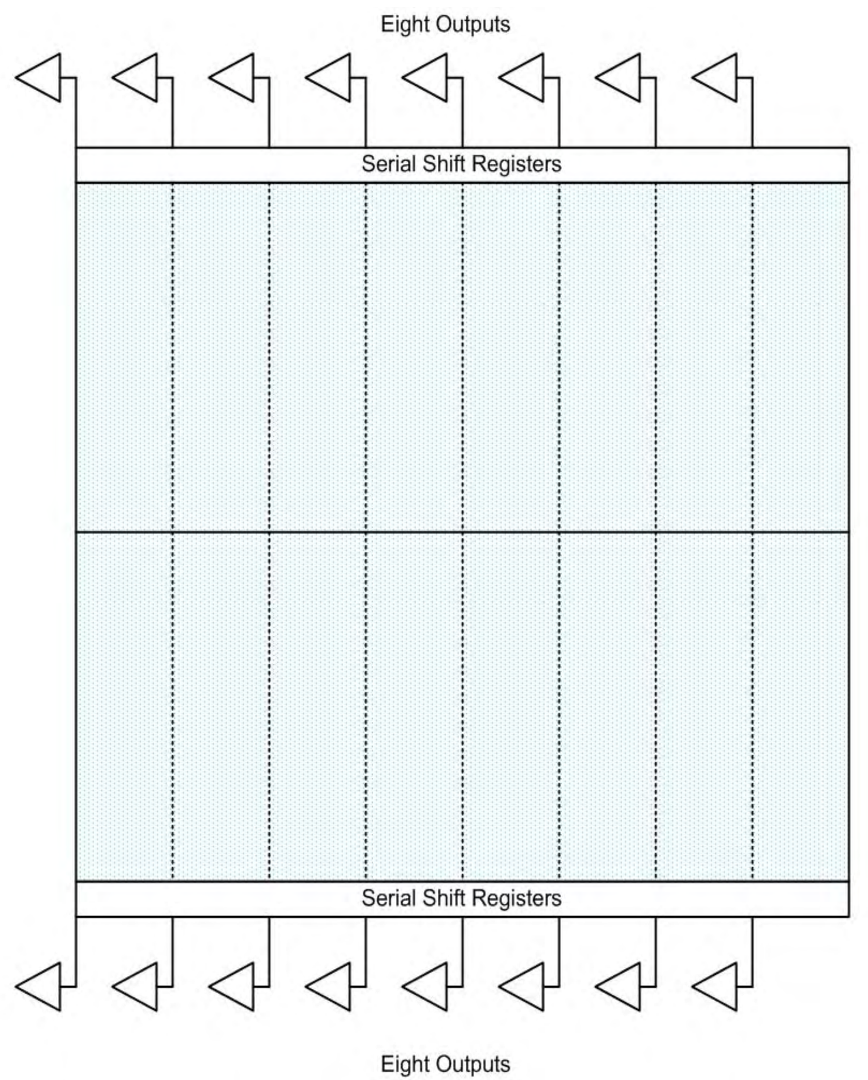
Internal quantum efficiency of silicon as a function of wavelength, for thickness of 50, 75, 100, 150, and 250 μm.



Point Spread Function



Outline of the 16 megapixel – 32 port CCD, showing the partitioning and charge movement for the hardwired split parallel and serial registers. All pinout for the device is along the left and right edges. The fill factor in this design is 96.5%.



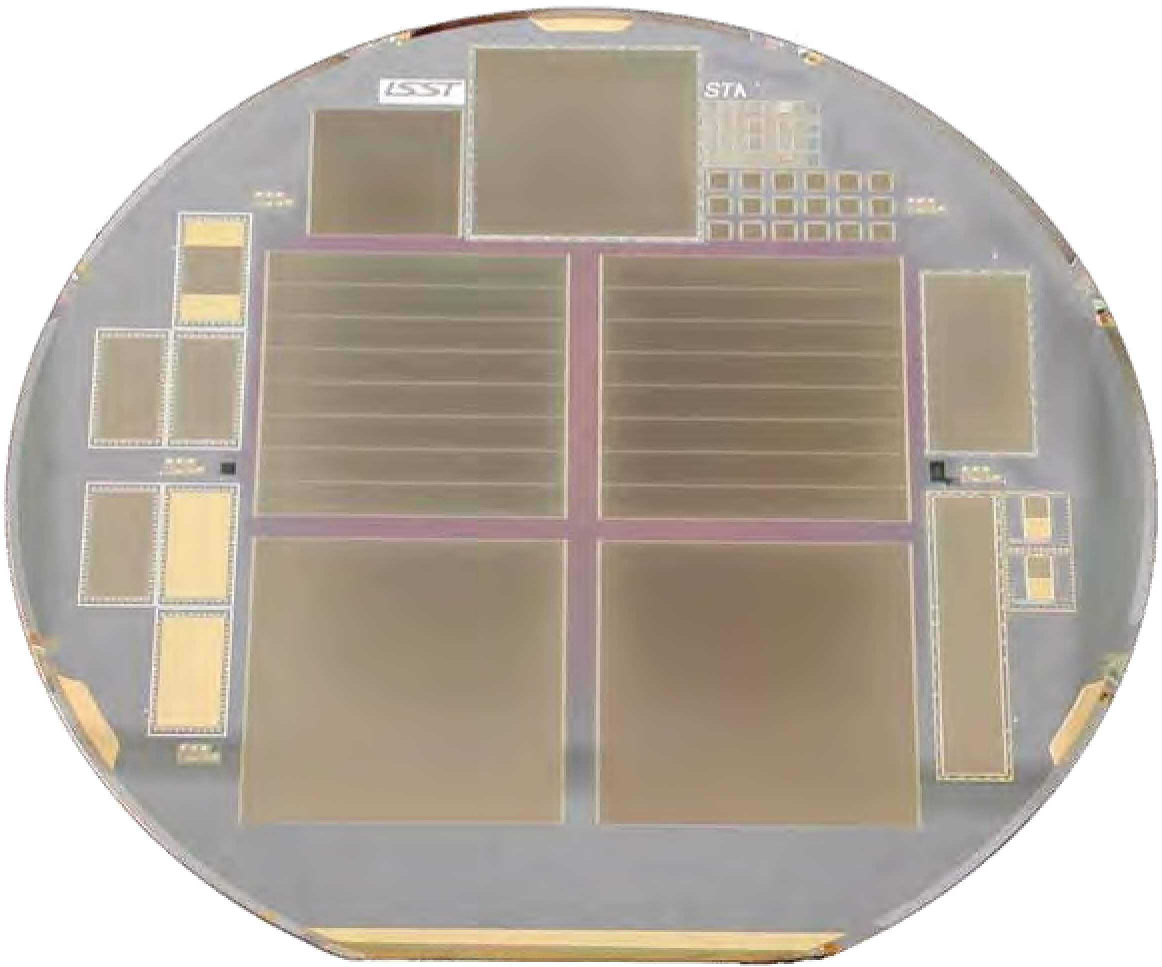
Segmented readout to achieve the required readout time (1 second target) with moderate clock frequency (to minimize read noise and crosstalk), (e.g., 0.5 Mpixels/output readout at 250-500kHz).

10 µm pixels

Full well > 90,000 e

Sensor thickness : 100 µm

Outline of the 16 megapixel – 32 port CCD, showing the partitioning and charge movement for the hardwired split parallel and serial registers. All pinout for the device is along the left and right edges. The fill factor in this design is 96.5%.



Segmented readout to achieve the required readout time (1 second target) with moderate clock frequency (to minimize read noise and crosstalk), (e.g., 0.5 Mpixels/output readout at 250-500kHz).

10 µm pixels

Full well > 90,000 e

Sensor thickness : 100 µm


LSST
Large Synoptic Survey Telescope
CONSTRUCTION OF THE
SYNOPTIC SURVEY TELESCOPE
submitted to the National Science Foundation
February 2007
Paul O'Connor
BNL

An alternative to the CCD array

- An array of photodiodes, each with its own sense node and transistor amplifiers

  Advantages: massive parallel readout, no blooming

  Disadvantage: each pixel has its own non-linearity

- A multiplexer which addresses every pixel

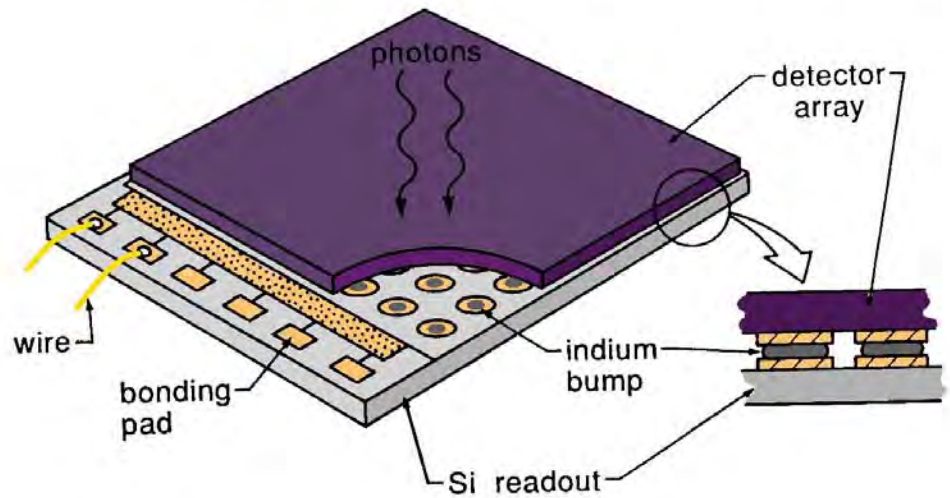
  Advantage: instant reset or multiple non-distructive reads.

  i.e. no shutter required!

  Disadvantage: correlated double sampling cannot be done on each pixel locally

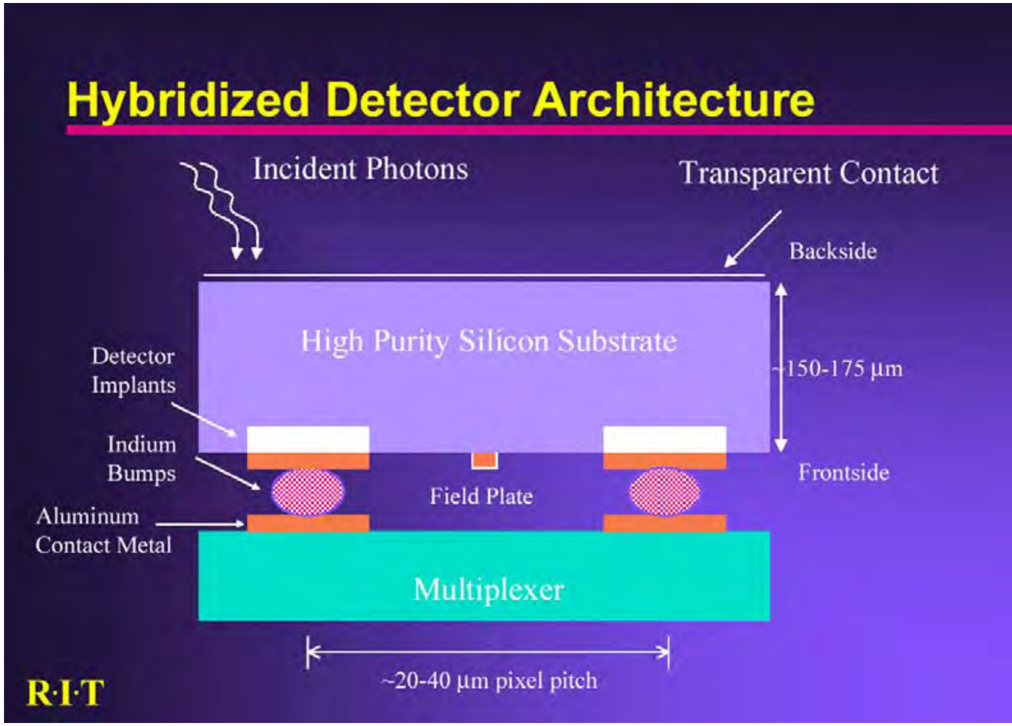
Hybrid CMOS Sensor Architecture

- Detector array is bonded to silicon MUX using indium bumps
- Pixels are defined by implants
- Under pressure, indium deforms and surface oxidation cracks allowing indium to cold-weld
- Epoxy is wicked into the space between indium bumps to increase mechanical strength



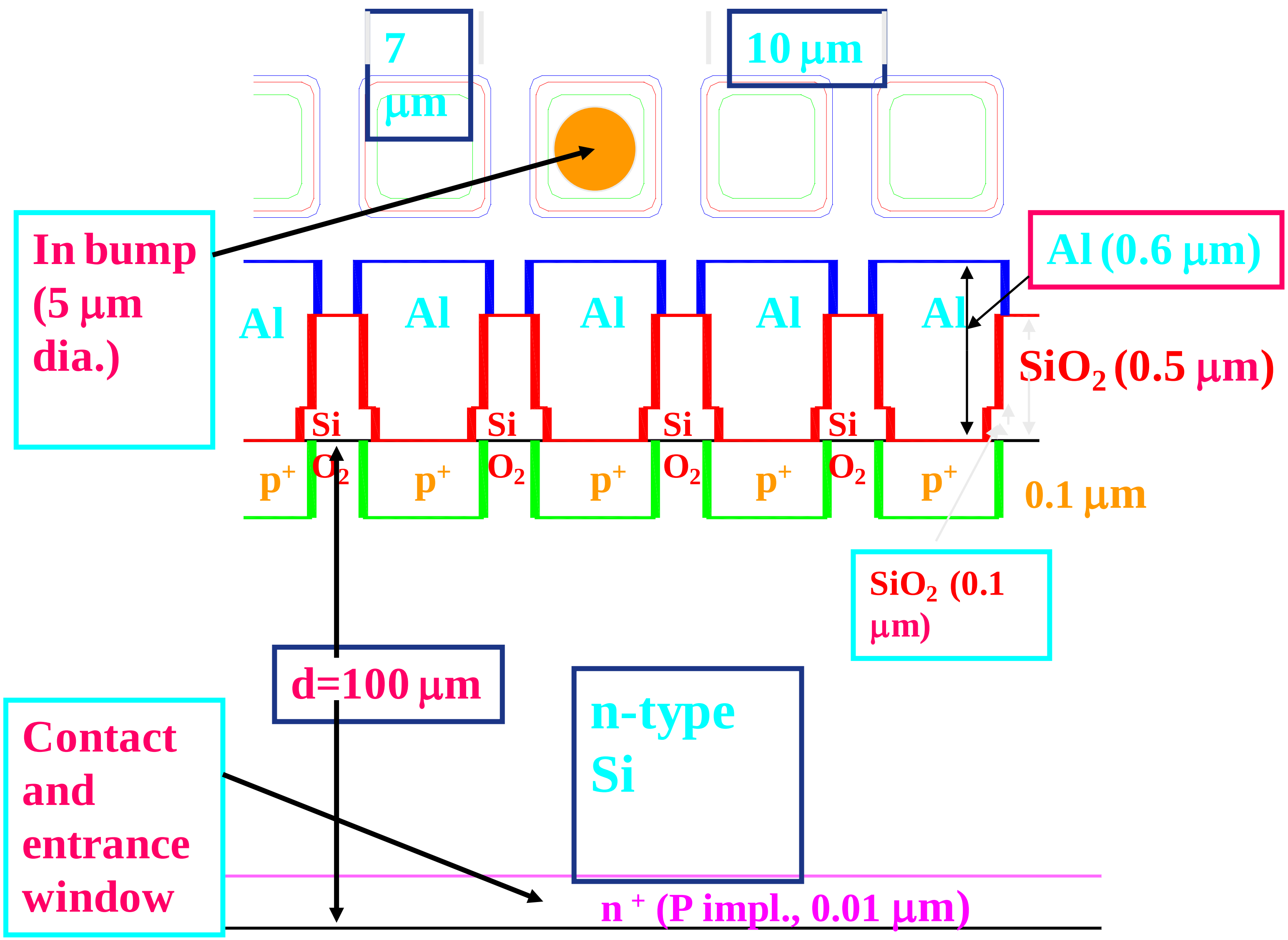
Si PIN array bump-bonded to CMOS readout

- **A hybrid Si-PIN-CMOS detector, analogous to near-infrared (NIR) array detectors.**
- **3-D separation of photon detection from readout facilitates separate optimization of**
  - **CMOS readout electronics (multiplexer)**
  - **Si PIN detector array**
- **Thickness, QE, PSF, operating voltage considerations are the same as for CCDs.**
- **Bump bonding technology on 10 μ scale required.**

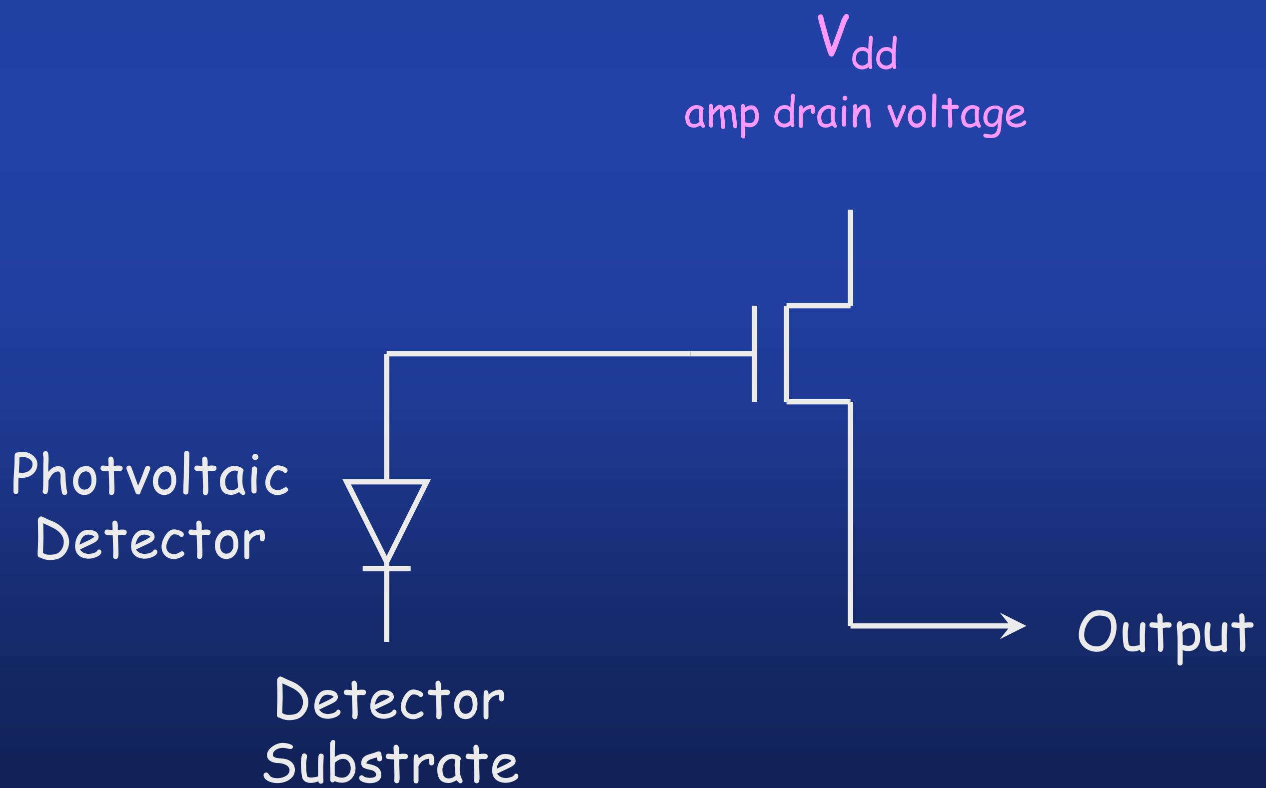


This technology has potential in the longer term for better performance in some respects (lower blooming effects, electronic shutter) than CCDs

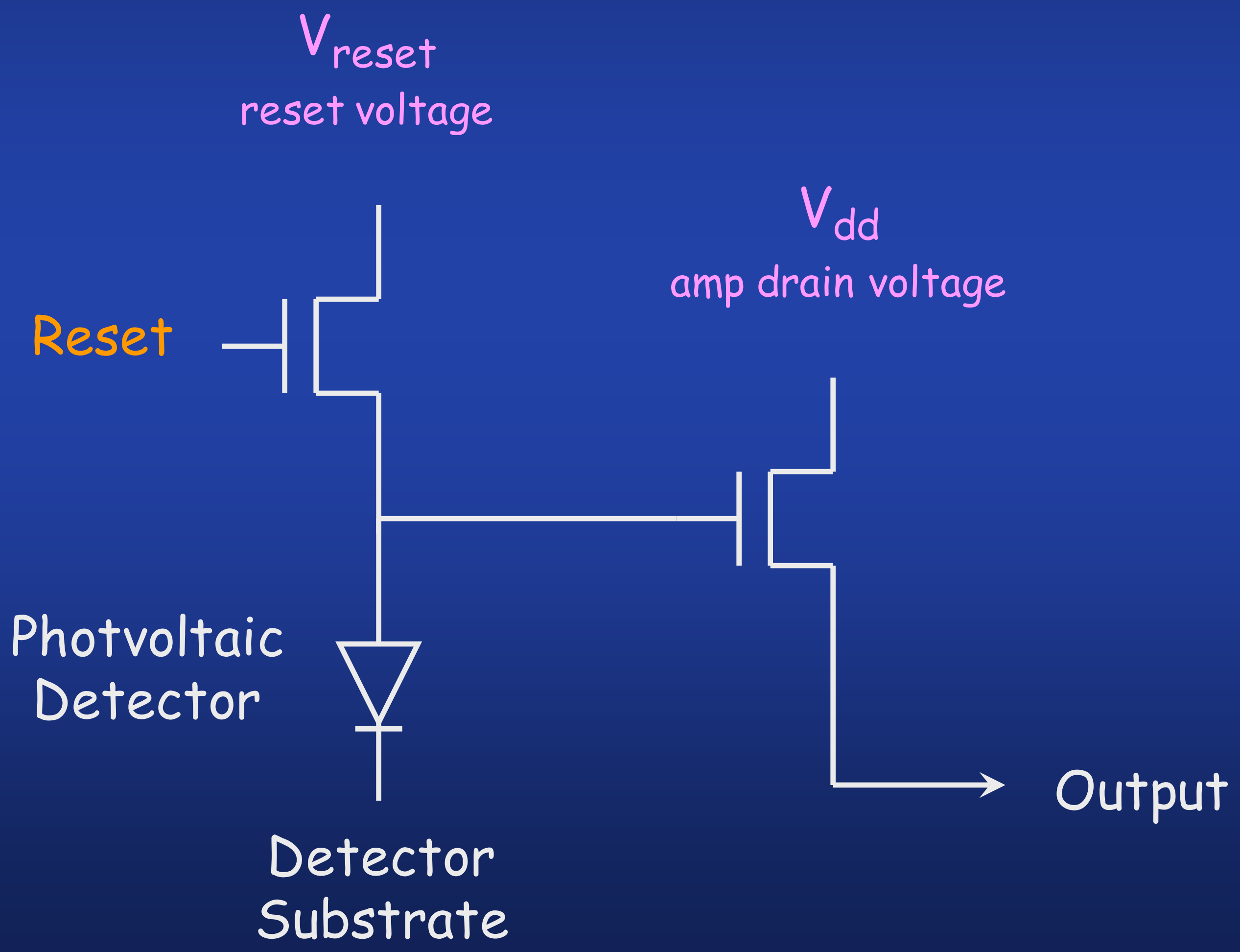
High resistivity (5 kΩcm) PIN detector array, fully depleted (V_{depl}~7 V), to be bonded to CMOS readout:



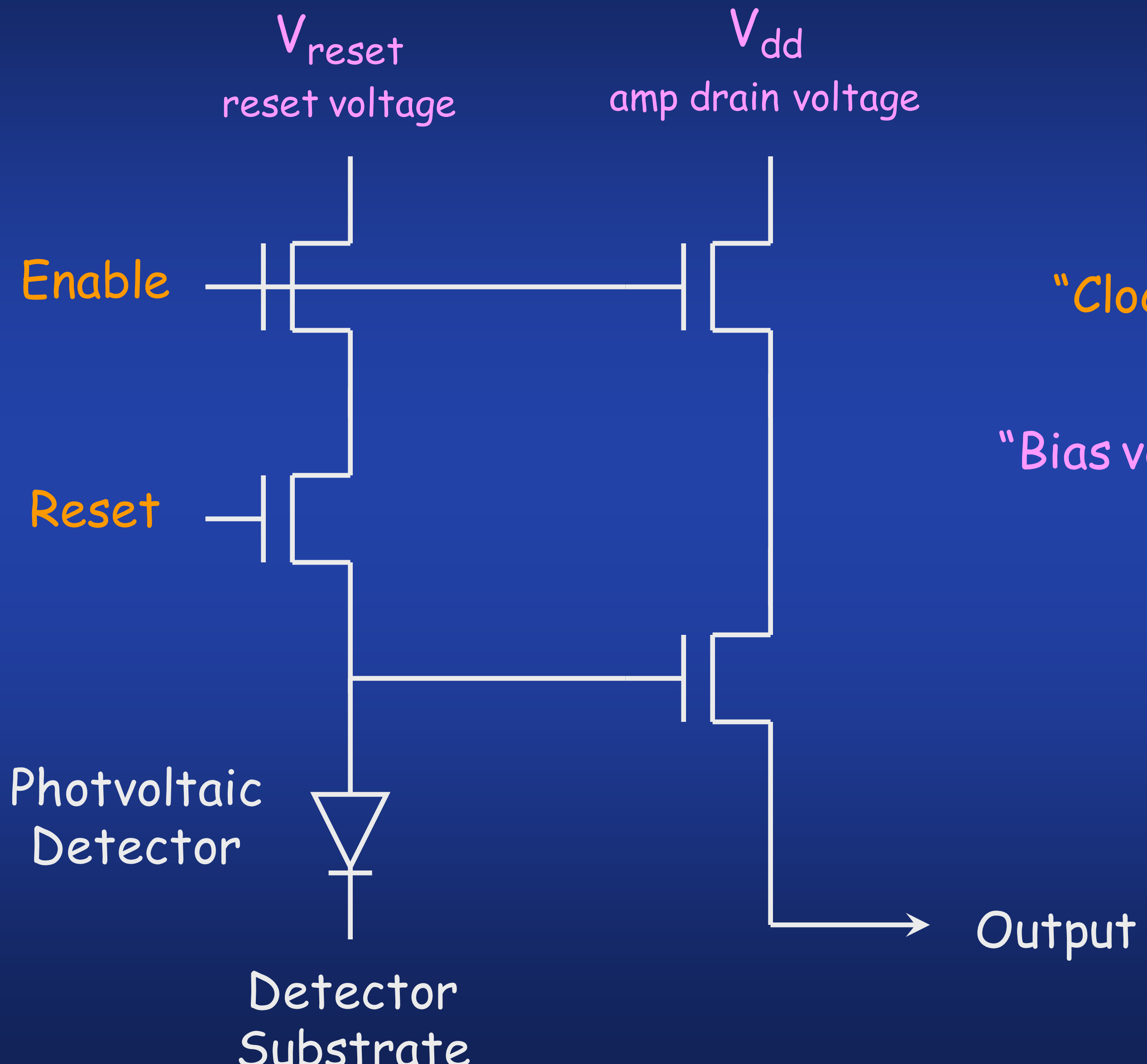
multiplexer pixel architecture



multiplexer pixel architecture



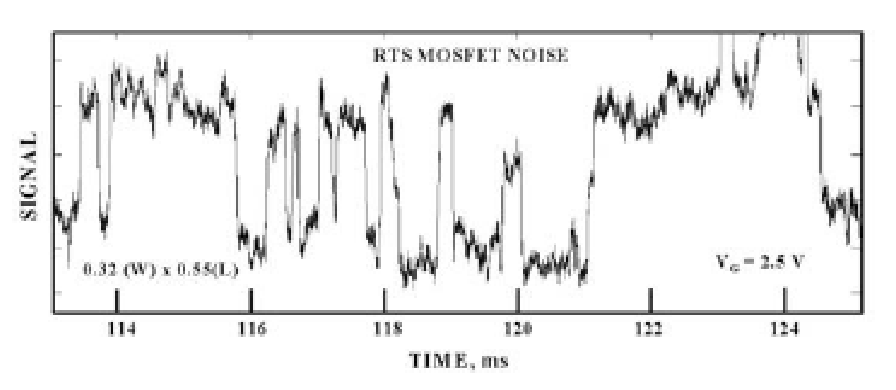
multiplexer pixel architecture

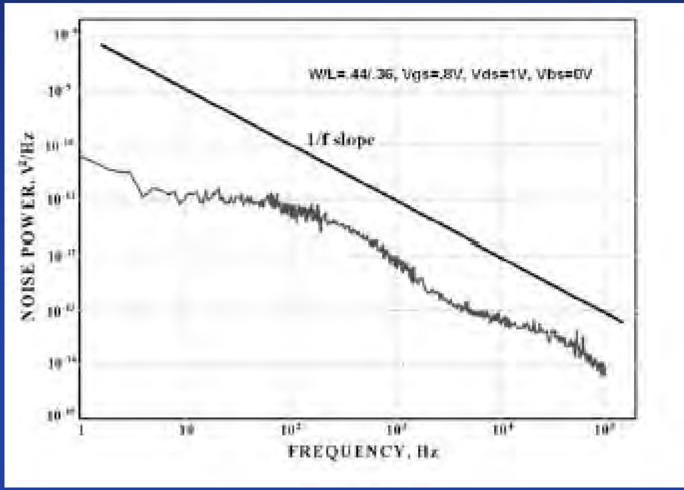


"Clock" (orange)

"Bias voltage" (purple)

Hybrid CMOS MOSFET noise

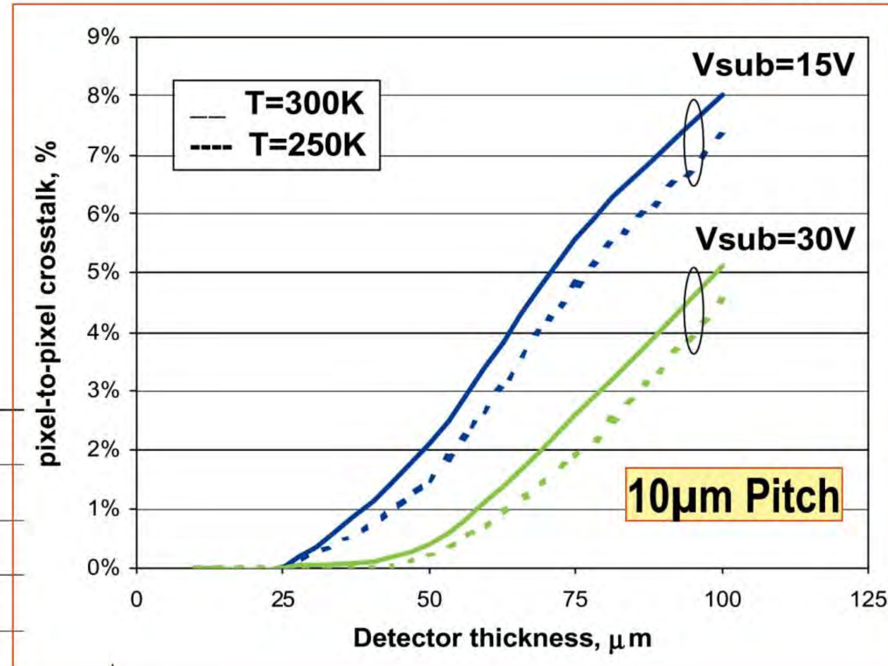


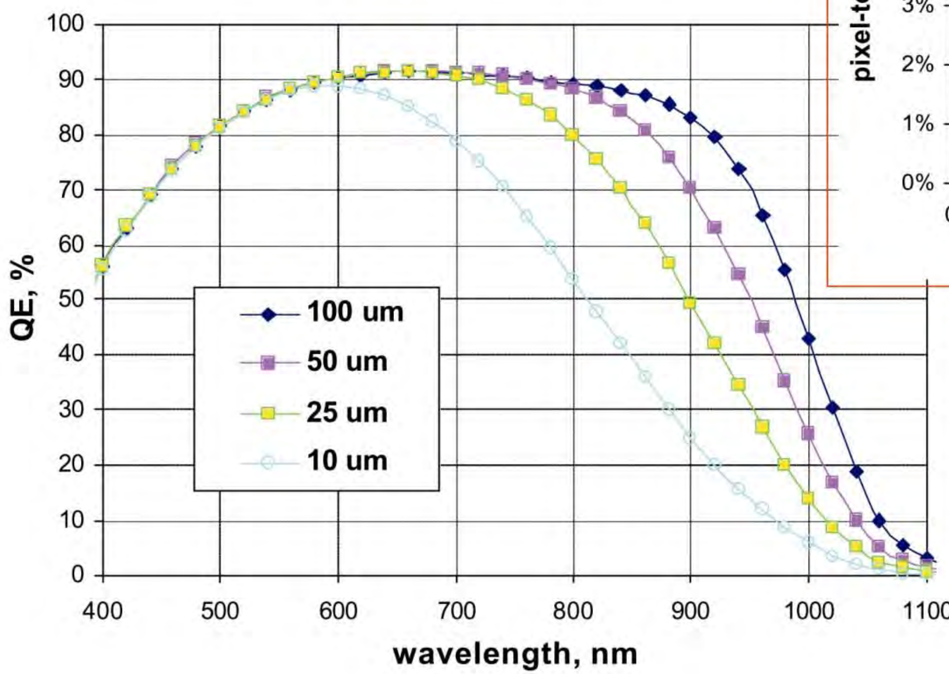


Several transistors under each 10 micron pixel: FET gate area is very small, leading to RTS noise. Hybrid CMOS arrays are thus inherently more noisy than CCD arrays.

Trade NIR QE vs. Crosstalk

- e.g., Targeting 70% QE at 900 nm vs. <2% Crosstalk for "~10µm Pitch"





Next time: Automated photometry

- Search each line in an image for pixels above some threshold.
  Bayesian prior: convolve with PSF or expected object kernel

- Use a moving average updated sky as threshold
- Define objects as connected above-threshold convolved pixels in x,y
- Deblend overlapping objects
- For each resulting object, measure the integrated flux with a kernel, and measure various intensity moments
- Generate a list (catalog) of detected objects, and their photometry

Example software: FOCAS, Sextractor, DoPhot