Gemini 8m, Chile
Large Magellanic Cloud
SITe 1Kx1K CCD,
24um pixels,
Backside illuminated.\
Illuminated only by starlight.

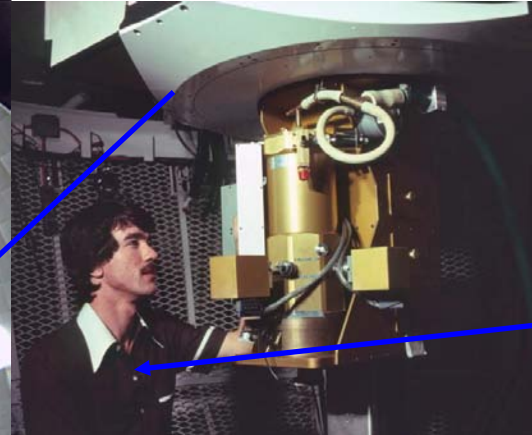
Astronomical Demands on CMOS Imaging Sensors

Roger Smith

Caltech

2011-01-05

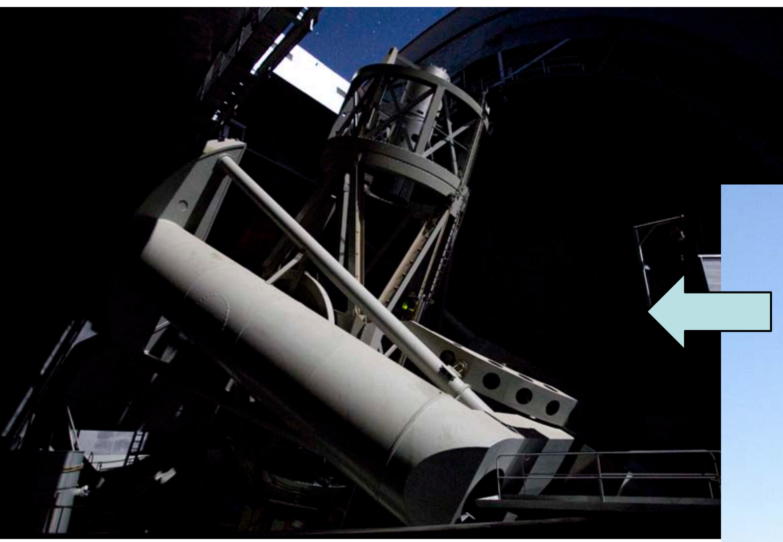
Single pixel 1-5µm photometer



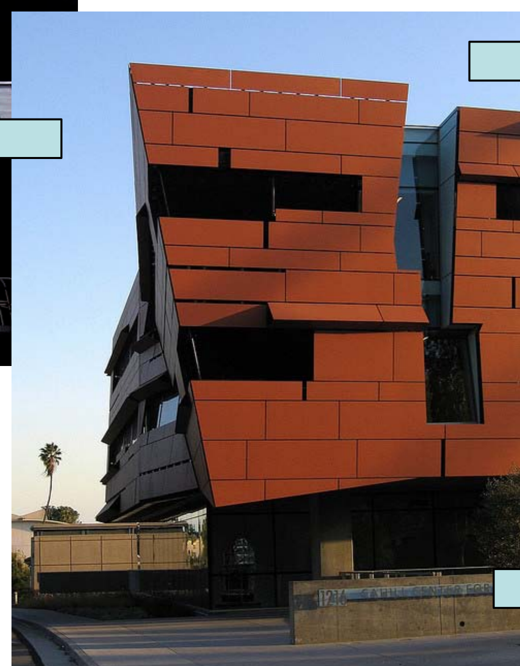
Yes, this is me in 1979

Anglo-Australian 3.9m Telescope

Thirty Meter Telecope



Palomar 5m Telescope



Astronomy Department @ Caltech

Two Keck 10m Telescopes

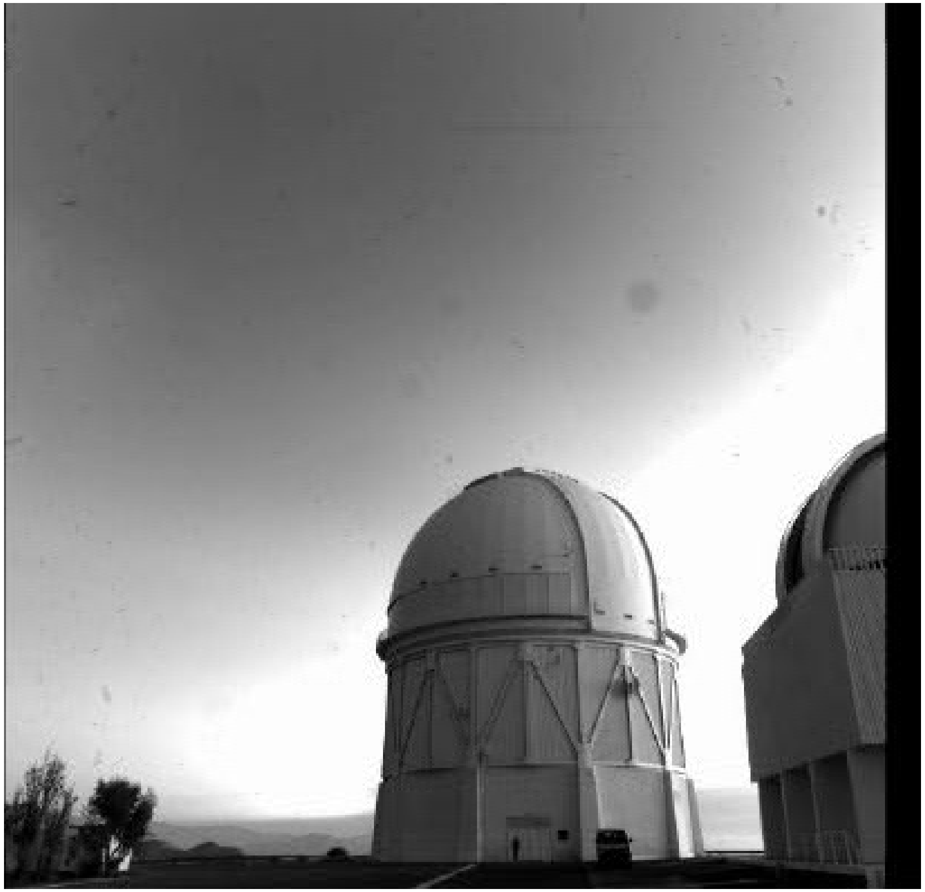
Cerro Tololo

National
Optical
Astronomy
Observatories

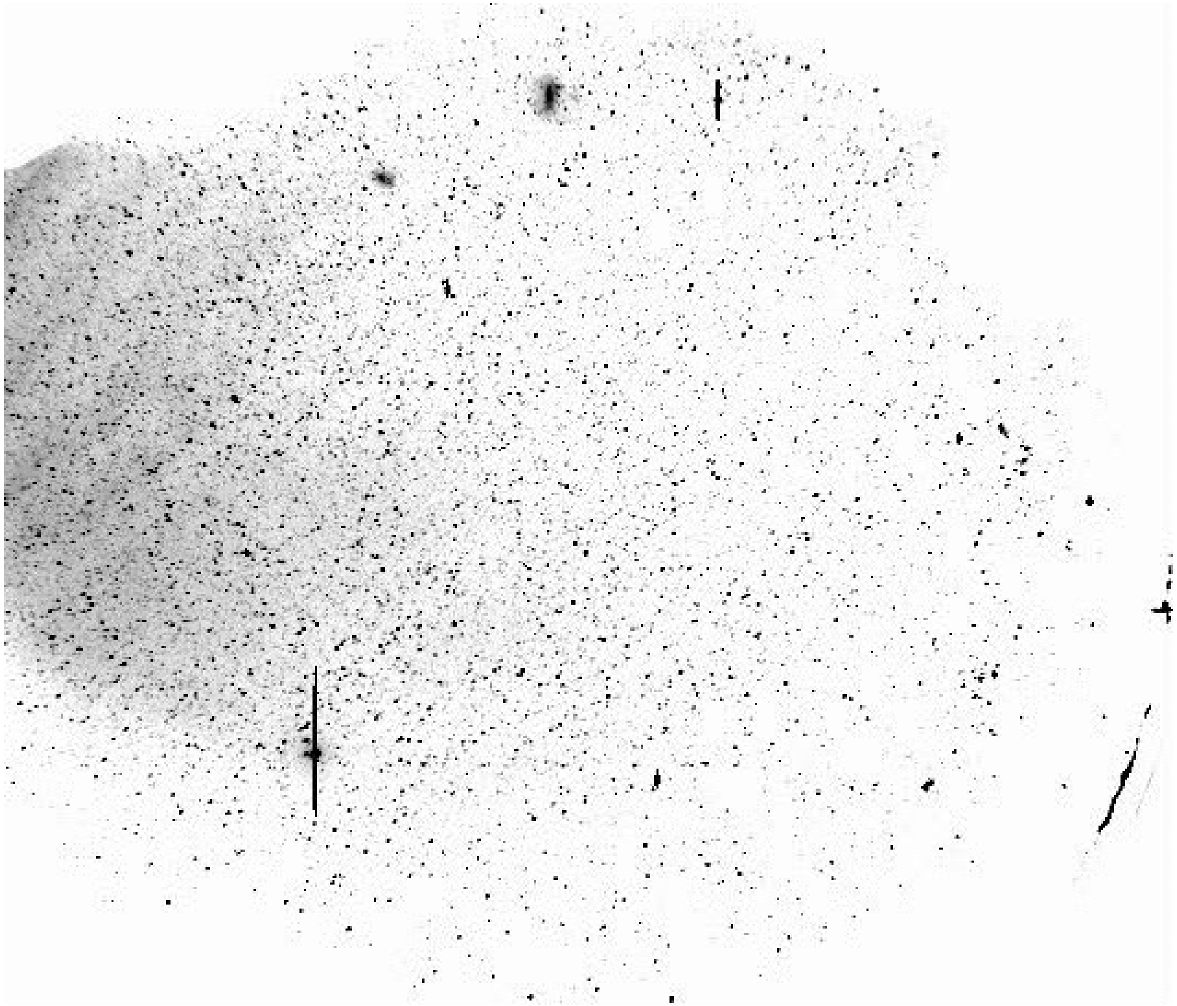
Chile

20s exp, f/8
2Kx2K CCD
24µm/pixel
Backside
illuminated

Movies under starlight alone



Waves of Airglow revealed at >700nm



Fish eye lens looking at southern sky on cloudless night.

Black=bright

00:30 – 03:30 am

Not how airglow intensifies as earth turns into the solar wind

Related scientific imaging markets

- Astronomy, professional and amatuer
- Chemistry
- Medical imaging and microbiology
- Xray spectroscopy and imaging
- Surveillance

The scientific Imaging Market is much smaller than consumer and military markets, but unit prices are much much higher.

They tend to promote technical innovation and enlist academia in understanding device physics so with benefits the big markets.

Not bad for public relations either.

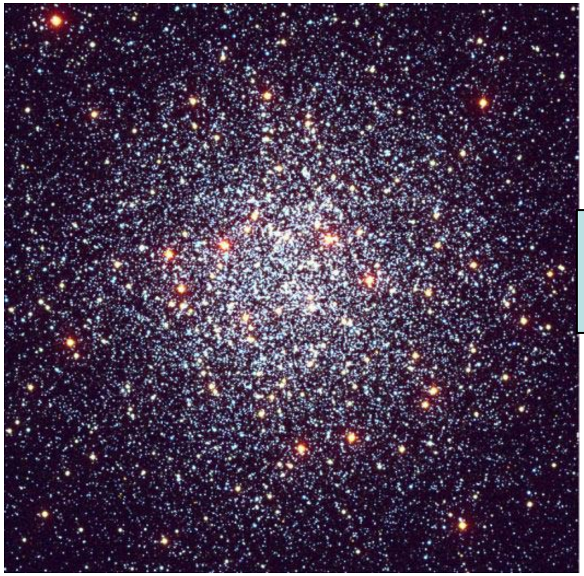
Introduction

Astronomical insights come from statistical trends in very large data sets,

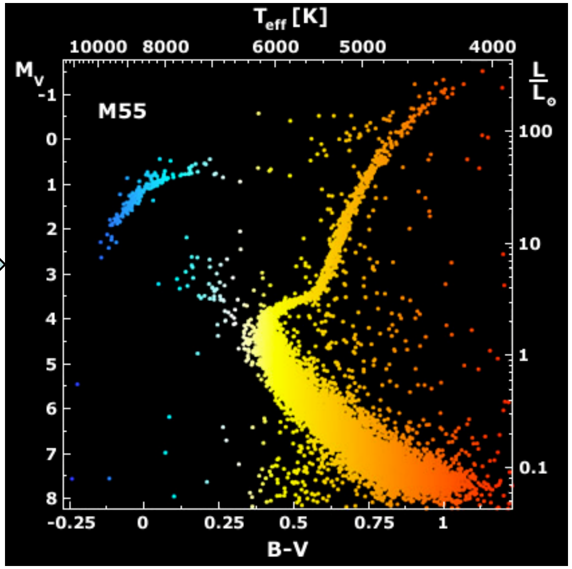
or from objects which are very rare (eg. supernovae), and thus can only be discovered in very large data sets.

Example of statistical trend

Age dating globular cluster: stars formed from common primordial material.



Broadband photometry



Stable performance to allow calibration,
100% fill factor; low intrapixel response variation;
Prefer square pixels and uniform pixel area.
High dynamic range, linearity,
Moderately low noise and low stable dark current.
High QE over broad wavelength range.

Sensor requirements are challenging

- Sensor area (cost)
- Low light … QE, fill factor, read noise and dark current.
- Photometric accuracy, linearity, crosstalk, charge loss/deferral, image persistence, QE hysteresis, spectral response flatness and fringing.
- Spectral resolution and wavelength range.
- Large signal intensity range
- Geometric accuracy; PSF shape, pixel size uniformity
- Frame rate and/or duty cycle in some applications

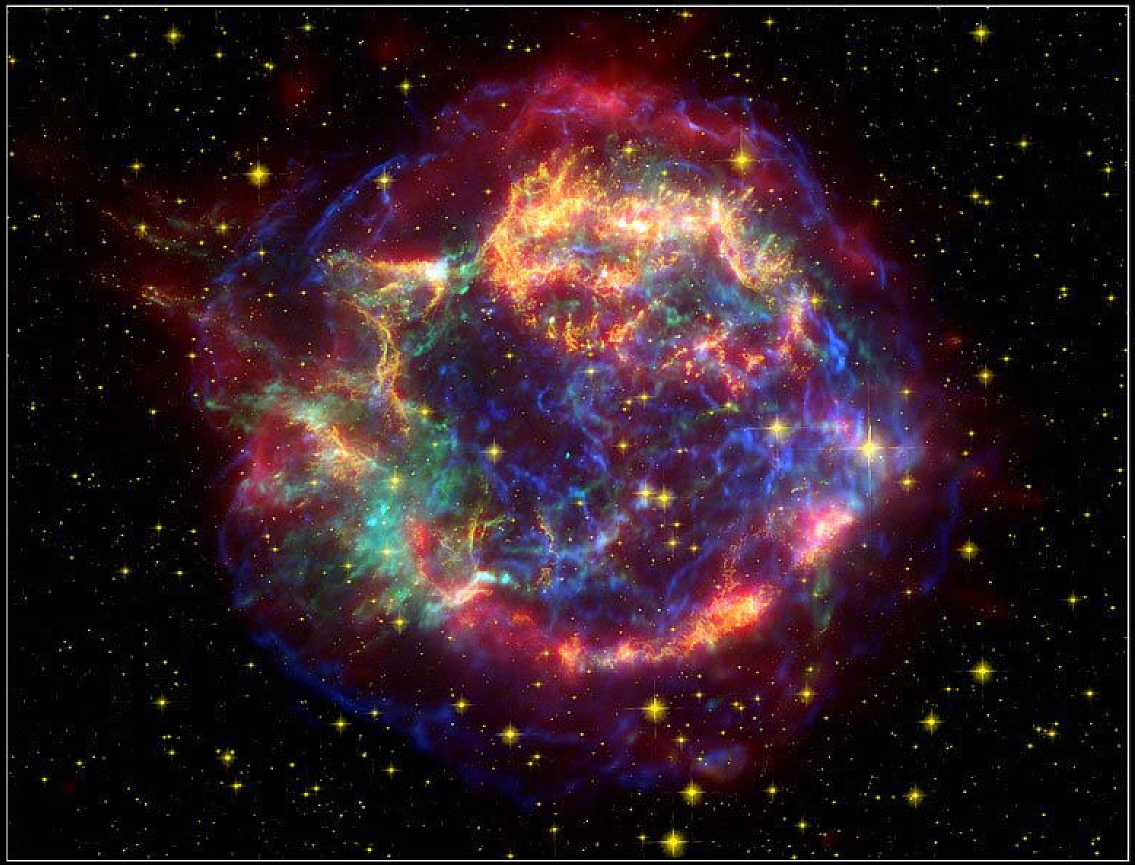
Some Astronomical Applications

Let's looks at how some of these examples drive sensor requirements….

- Widefield imaging surveys:
  - Broad-band photometry: eg. Galaxy distances by Photo-Z, age of clobular clusters derived from stellar color-magnitude diagram.
  - Narrow band imaging:, emission nebulae, supernova remnants, spectroscopic survey BAO
  - Transients > 1 day: Supernova, GammaRay Bursters, eclipsing and/or accreting binaries, etc
  - Very high S/N on bright stars: planet search via transits.
  - Galaxy shapes: mapping dark matter/energy using weak gravittaional lensing.
  - High speed transients: lensing by Kuiper Belt Objects, and TBD !
- Spectroscopy, point source and integral field, and surveys
  - Very high spectral resolution for tracing galactic assembly through chemical abundances
  - Radial velocity for galaxy kinematics, or planetary studies.
  - Large surveys of galaxy spectra at medium resolution to map clumping of matter in the cosmos (Baryonic Acoustic Oscillations)
- High Spatial Resolution Imaging: increased senistivity, or crowded fields.
- Astrometry: millipixel centroid precision; accurate pixel grid.
  - Investigate black hole at galactic center by tracing the proper motion of stars.
- Polarization, especially at high frame rate for solar astronomy.

Single object example:
Narrow band imaging of supernova remnant

This is a combination of optical data with Xray and Infrared.



Cassiopia A Supernova Remnant
NASA / JPL-Caltech / O. Krause (Steward Observatory)
ssc2005-14c

Spitzer Space Telescope • MIPS
Hubble Space Telescope • ACS
Chandra X-Ray Observatory

Interference fringes caused by internal reflections between front and back surface of detector become a serious problem for extended sources like this.

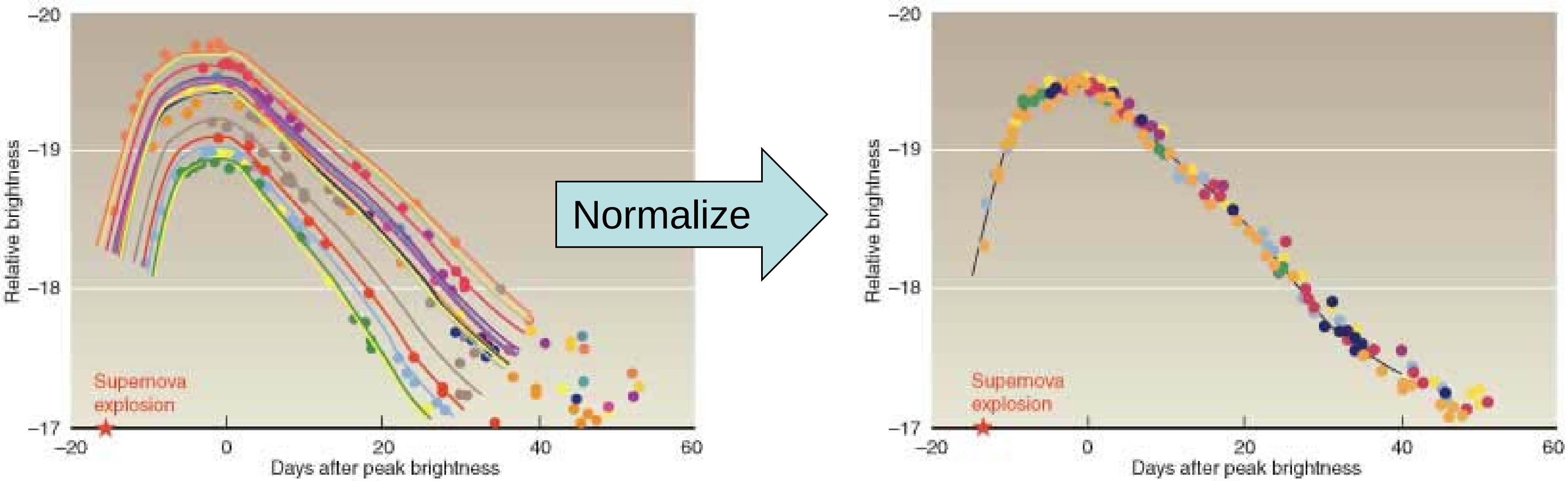
Such effects occur at the red wavelength cutoff where absoption length approaches thickness.

Making the device thicker helps fringes wash out in a converging beam. Good AR coating performance near cutoff decreases modulation depth.

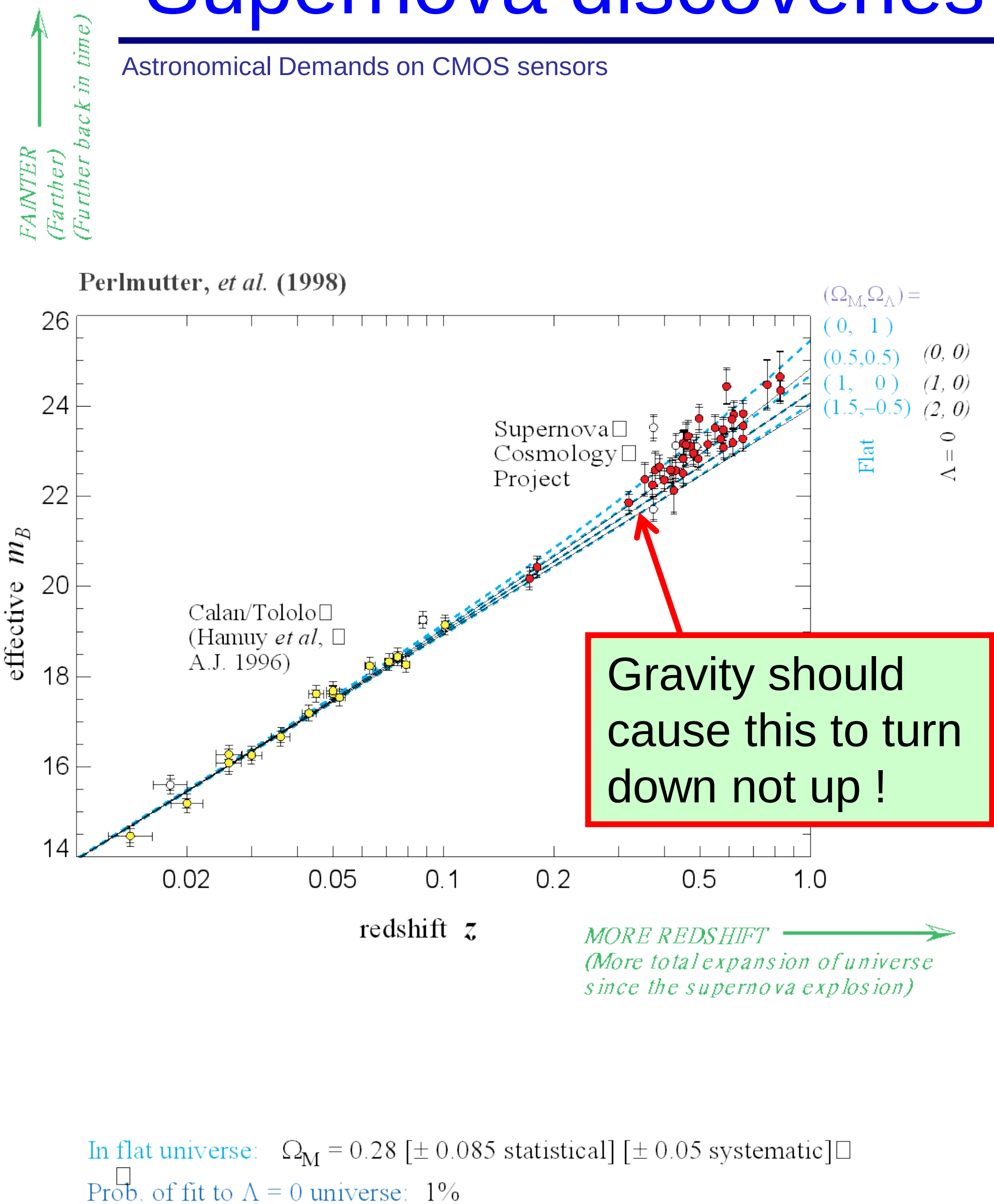
Surveys for rare objects:

Supernovae in distant (faint) galaxies

- Type Ia supernovae allow us to measure cosmological distances with high accuracy since their true brightness is highly predictable since the initial condition is known:
  - They occur when large stars in a binary system accrete material from a neighbor, and eventually acquire enough mass to enter graviational collapse.
- The peak intensity can be predicted after fitting to a template for the light curve (intensity vs. time), …eg. to correct for time dilation due to their recession velocity.



Wide field instruments made rare Supernova discoveries possible



- In 1990s the advent of large format CCDs with high sensitivity and stable response made it possible to measure the brightness of millions of galaxies every ~5 days, and to automatically compare brightness to search for supernovae whose brightness becomes significant compared to the entire galaxy.
- Using the ratio of apparent to true brightness astronomers sought to measure how fast gravity was slowing down the expansion of the universe after the big bang, but the discovered **NEW PHYSICS**. The universe was found to be accelerating, under the influence of some unknown energy source, dubbed “dark” energy because we don’t know what it is.

Sensor requirements

For fast survey rate:

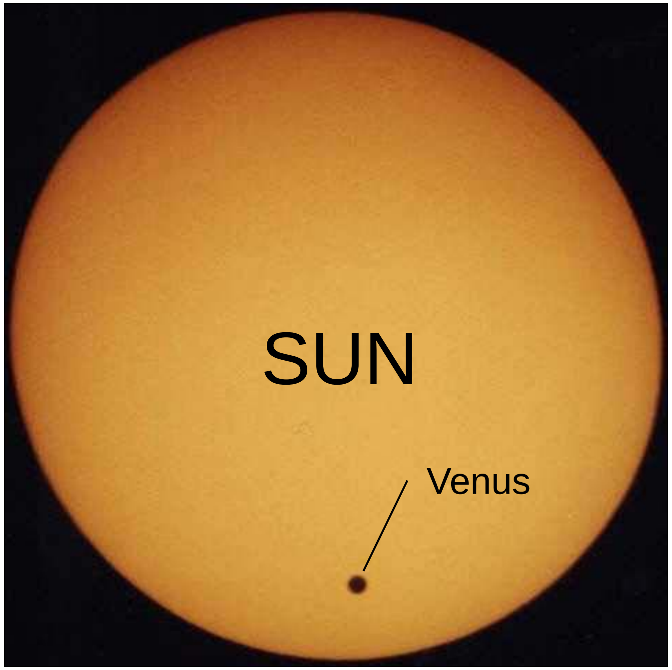
- Low cost per unit area. 100-2000 cm^2, 15µm/pixel
- High sensitivity over broad spectral range.
- Red response since distant objects are moving rapidly away form us so that the spectrum is doppler shifted to the red.
- Low dead time (for readout) between exposures.

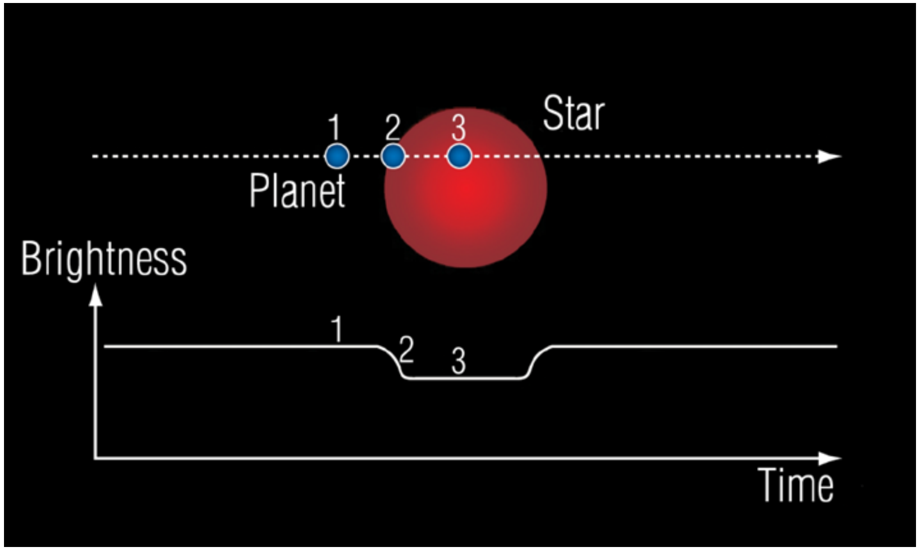
Data quality:

- Stable photometry, good long term calibration: 100% fill factor, low intrapixel response variation.
- Moderately low read noise (6e-) and dark current. (0.03 e-/s)
- Low charge diffusion and crosstalk between pixels.
- Low/correctable interchannel crosstalk channels,

Surveys for rare objects:
Planets passing front of bright stars

- To understand planet and solar system formation and the prevalence of planets that could support life we first need a census of planet properties (size, density, temperature). Planets are too small to be resolved so…
- Look for dimming of star as planets pass in front. Habitable rocky planets are very small compared to the star and can't be too close (hot), so we need stable photometry to detect 100 ppm dip over long periods (days)





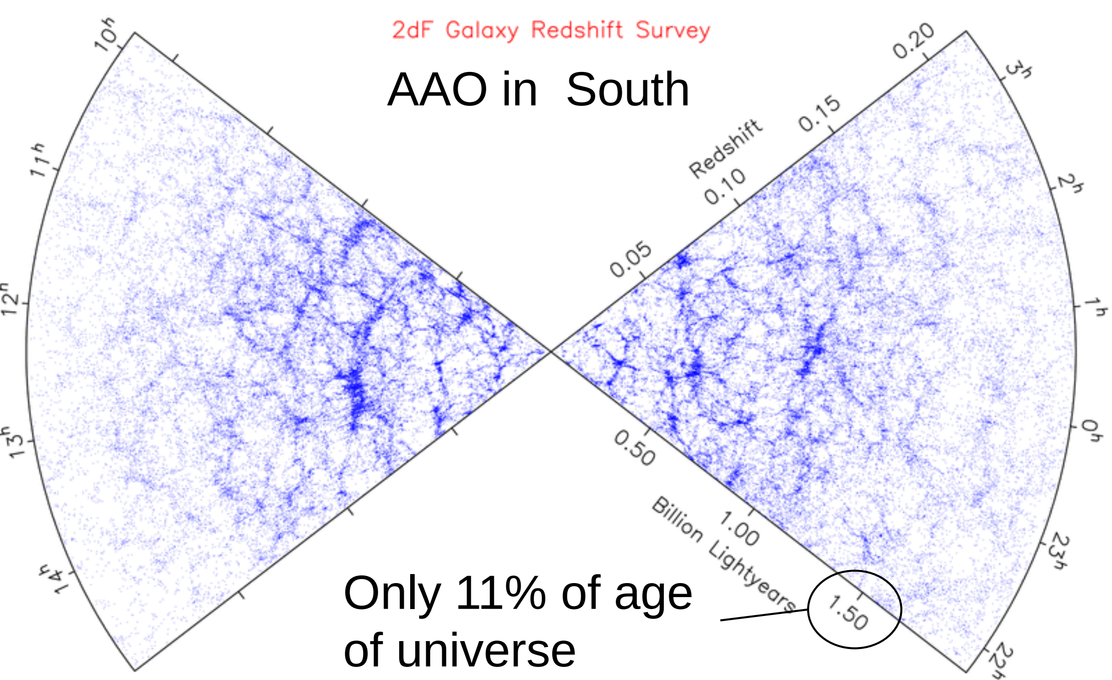
Requirements for Transits

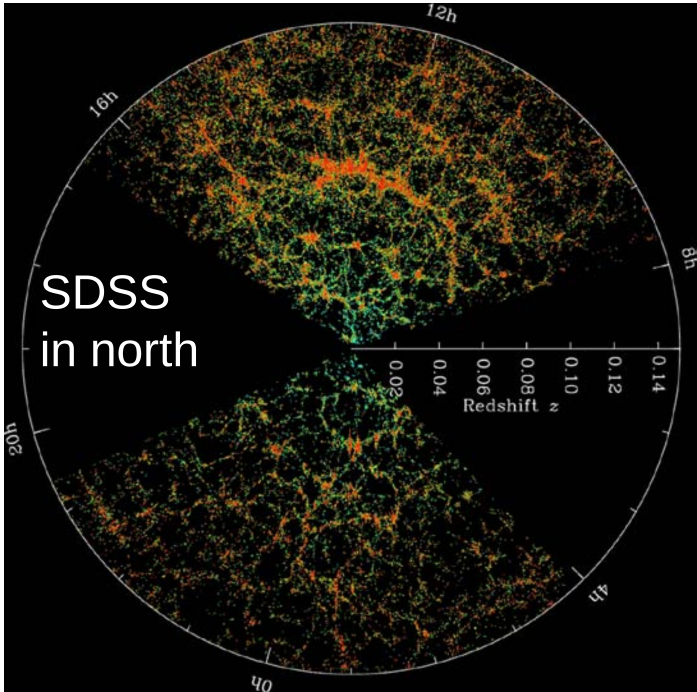
- Lots of pixels since stars must be monitored for period longer then orbit (years!).
- For shot noise to be <100ppm need >10^8 photons so stars are bright.
  - large pixel capacity
  - high observing efficiency for short exposures (buffering in pixel, fast readout during next exposure.
  - this points to charge-transfer pixels rather than integrating signal on photodiode's junction capacitance.
  - longer exposures reduce data rate requirements: switching in additional sense node capacitance as saturation approaches would extend dynamic range without loss of noise performance on faint pixels
- Photometry must not change as pointing or PSF width change.
  - Low intrapixel response variation (100% fill, backside illuminated)
  - Good pixel size uniformity.
  - Good linearity
  - Spreading light over more pixels help with photometric precision but increases source confusion.
  - Gain and sensitivity must be stable over long times (temperature, bias voltage, prior illumination).
  - Electronic offsets must be stable (with bias voltage and temperature); dark current must be stable inless negligible … easy with adequate cooling.

Baryonic Acoustic Oscillations

Spectroscopic surveys for cosmology

- The evolution of the “clumping” of matter as a function of time since the big bang can be compared with theoretical models to see which model comes closest to describing why the expansion of the universe is accelerating.
- Medium resolution spectra on millions of distant (faint)galaxies place tell us their velocity, then the Hubble curve to translates this to a distance and thus age (due to the speed of light delay).
- Fourier analysis tells us the dominant frequencies (seen at their earliest in the Cosmic Microwave Background), and how this has evolved since the big bang.





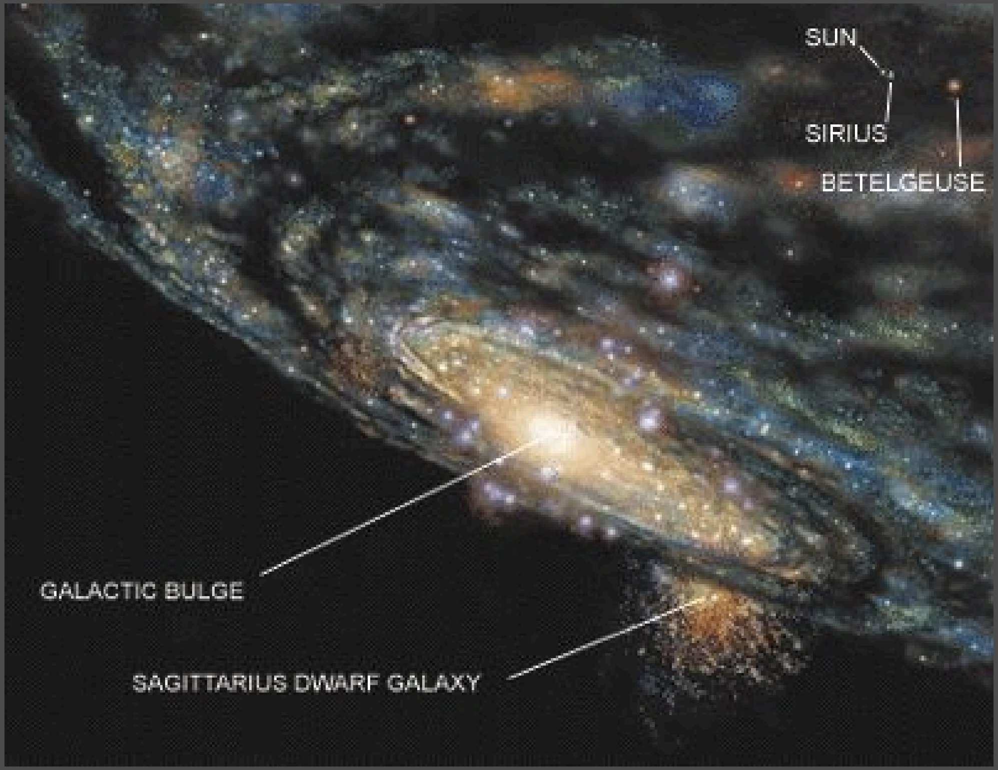
Sensor requirements for BAO

- Need millions of medium resolution spectra (R>3500 to get between atmospheric emission lines at λ>700nm);
- Eg: WFMOS = 2400 fibers select objects, ~12*5200 pixels per fiber so 150 Mpix, 12µm/pixel.
- Distant galaxies are red-shifted so need to extend QE as far to the red as possible (to λ>950nm)
- Distant Galaxies are faint and signal per pixel is very low after dispersion by spectrograph, so high QE low read noise (<2e-) and low dark current (<0.001 e-/s) are highly desirable.
- Best sensitivity comes when light is concentrated in few pixels so need 100%, fill factor, low intrapixel response variation, and low charge diffusion between pixels and correctable crosstalk.
- There must be no signal loss mechanisms at low light levels.
- Readout time < 20s

Sag DEG

Sagittarius Dwarf Elliptical Galaxy (SagDEG, Sag dSph)

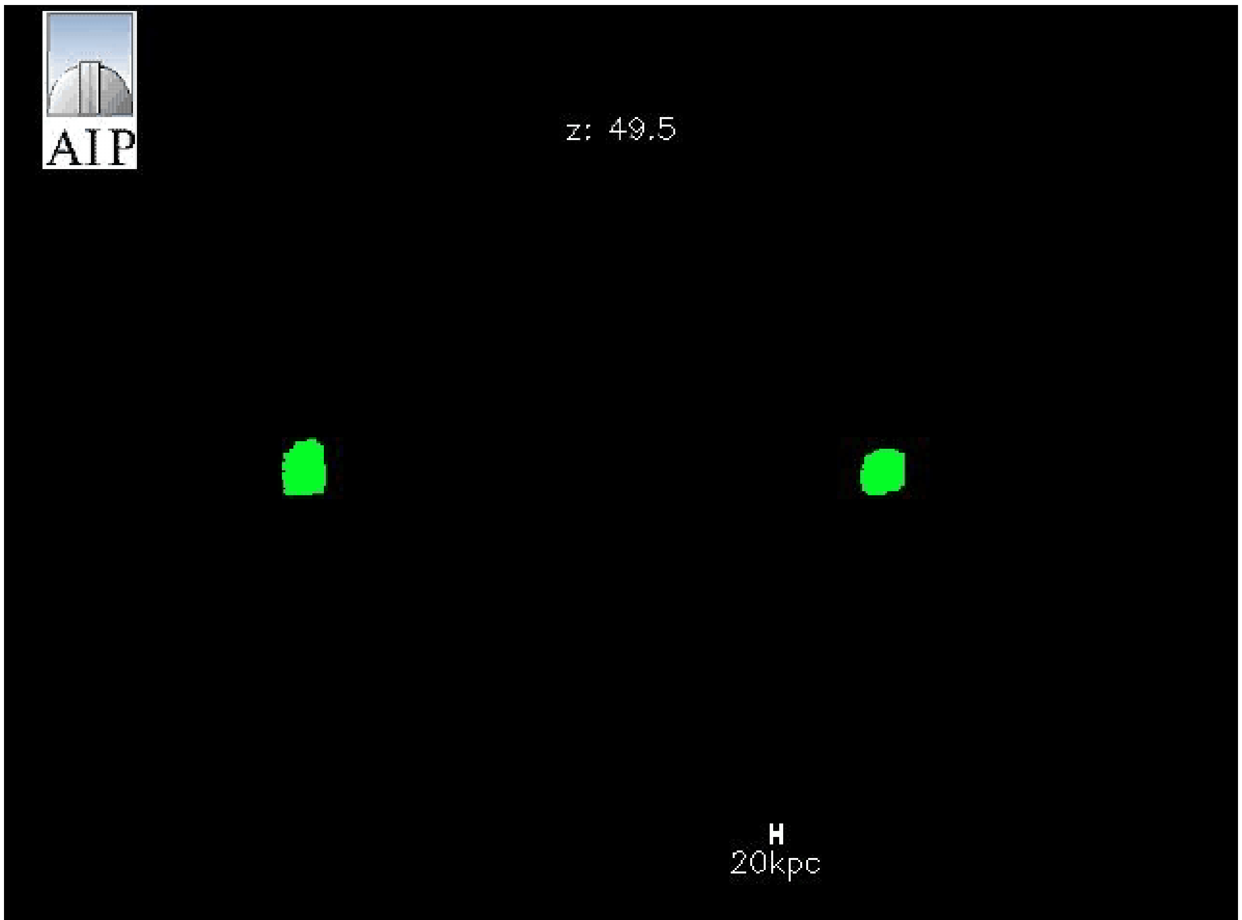
A satellite galaxy of the Milky Way and the second closest external galaxy after the Canis Major Dwarf. It is populated, as is usual for a dwarf elliptical galaxy, by old yellowish stars. Obscured by large amounts of dust in the galactic plane, SagDEG was discovered as recently as 1994. It has four known globular clusters – M54, Arp 2, Terzan 7, and Terzan 8 – of which M54 is easily the brightest and was the first extragalactic globular cluster ever found, by Charles Messier in 1778.



SagDEG orbits our galaxy in less than one billion years and must therefore have passed through the dense central region of the Milky Way at least 10 times during our galaxy's lifetime. The fact that it has remained intact suggests that SagDEG may contain a significant amount of dark matter that helps to bind it together. It is, however, apparently now in the process of being disrupted by tidal forces of its massive neighbor. This may lead to its globular clusters and many of its other stars finding a new home in the Milky Way's halo, while its remaining stars escape to become solitary intergalactic travelers.

High resolution spectroscopy for Galactic Archeology

High resolution spectroscopy (λ/Δλ > 20,000) allows relative abundance of elements in stars to be used to identify stars of similar origin to find sub-populations belonging to other galaxies absorbed into our own: the Saggitarius Dwarf was discovered this way.



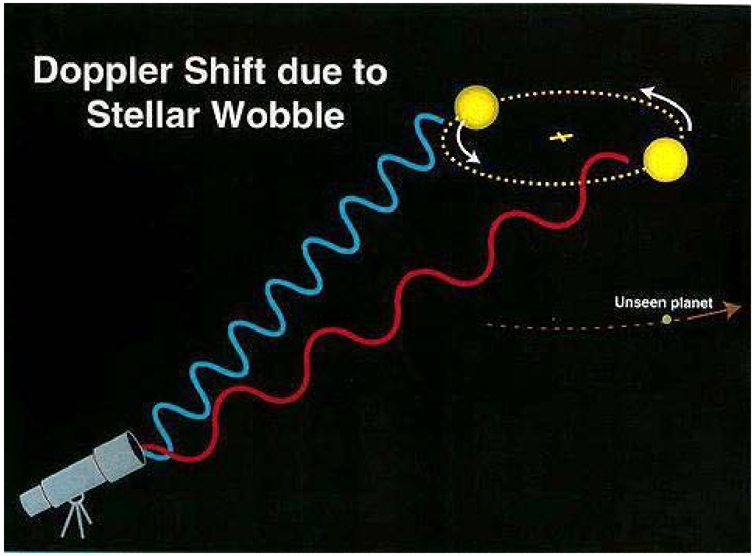
Top view

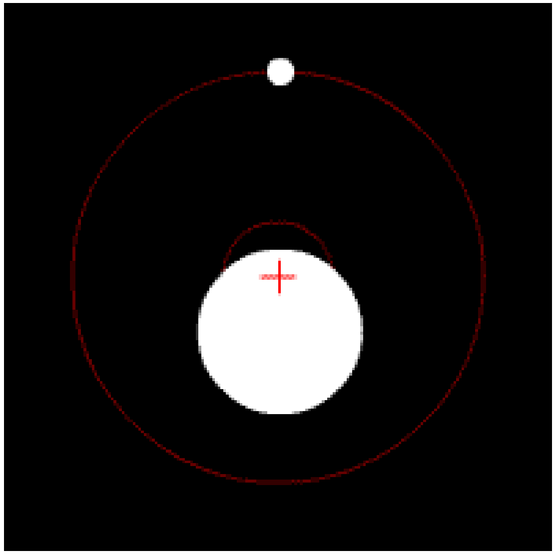
Side view

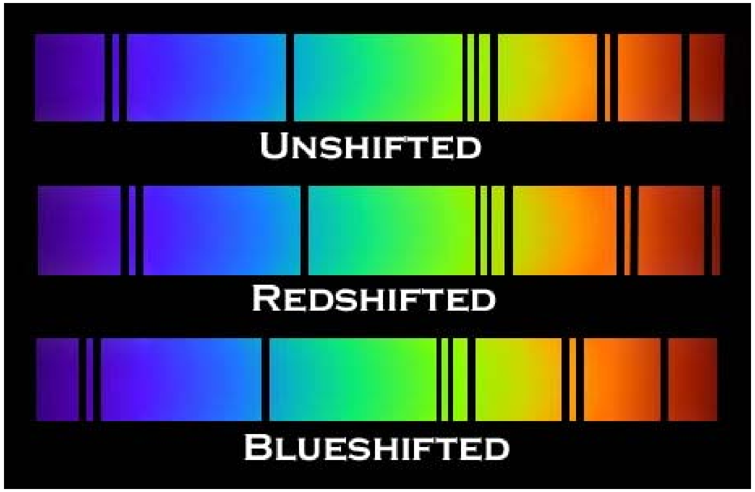
Simulation of gravity at work from big bang to formation of spiral galaxy

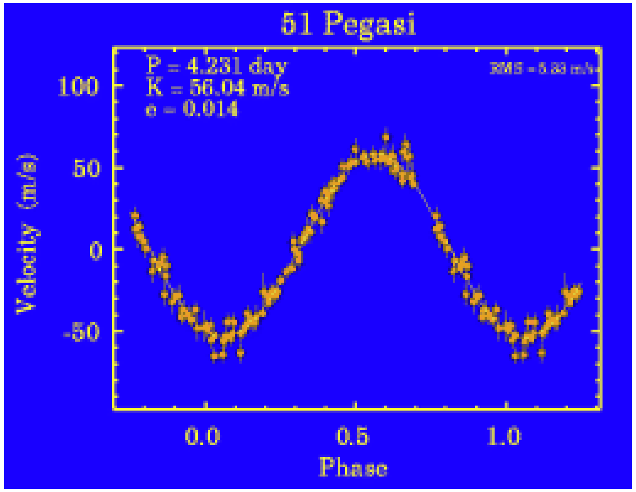
illustrating galactic mergers

High resolution spectroscopy:
planet detection by radial velocity









CMOS for high resolution spectroscopy

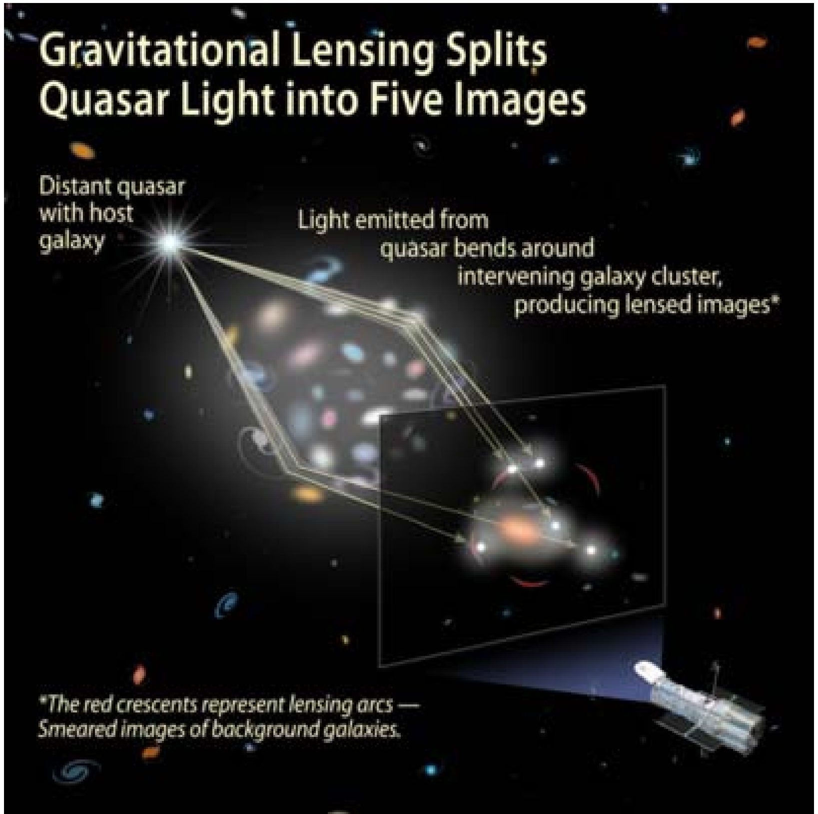
To get down to 1m/s doppler shift need very high dispersion (and a very stable spectrograph etc).

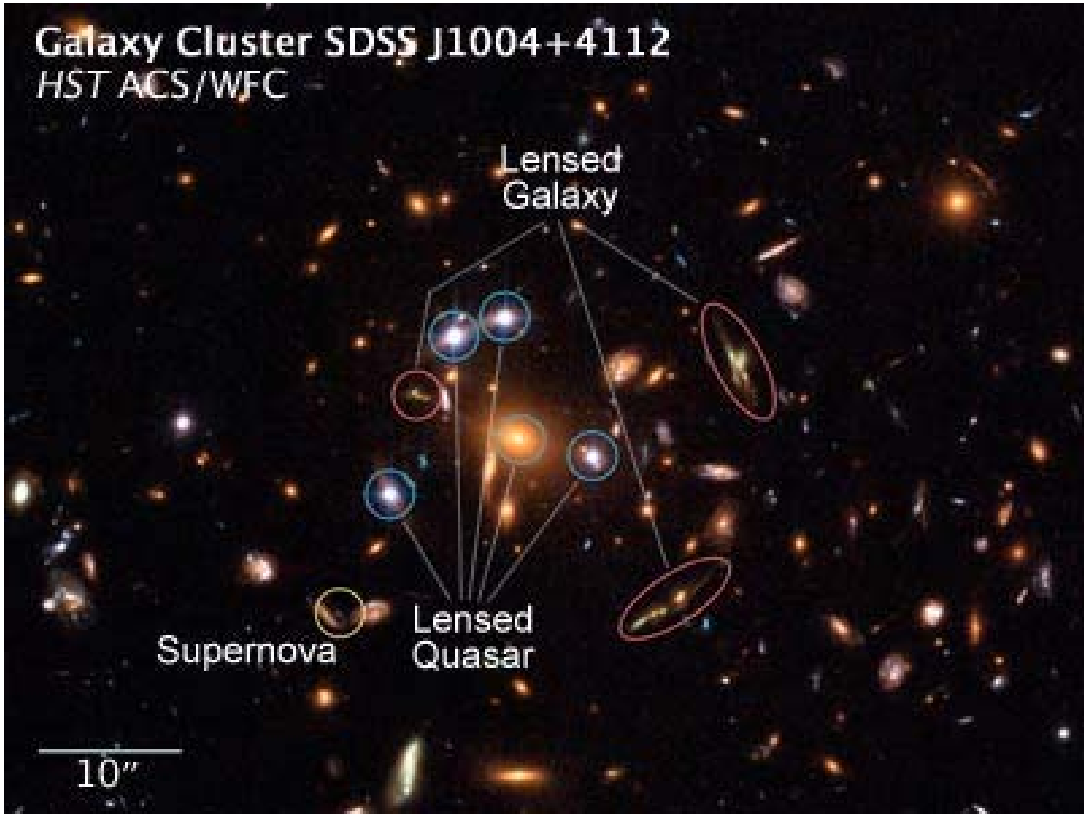
Signal per pixel is thus low. To get spectra for more stars than just the very brightest stars, we need:

- Very low noise and dark current.
- Decent QE, for 400nm < λ < 800nm (redder would be good to support proposed transit searches around cooler stars.)
- To minimize errors in line position, uniform response throughout pixel and uniform pixel size.

Gravitional lensing

- We can detect mass even if it omits no light….
- The distortion of space time by gravity, predicted by Einstein was first verified by Eddington by measuring how the relative position of stars changed when the light passed close to the sun (during a total lunar eclipse in ~1918)



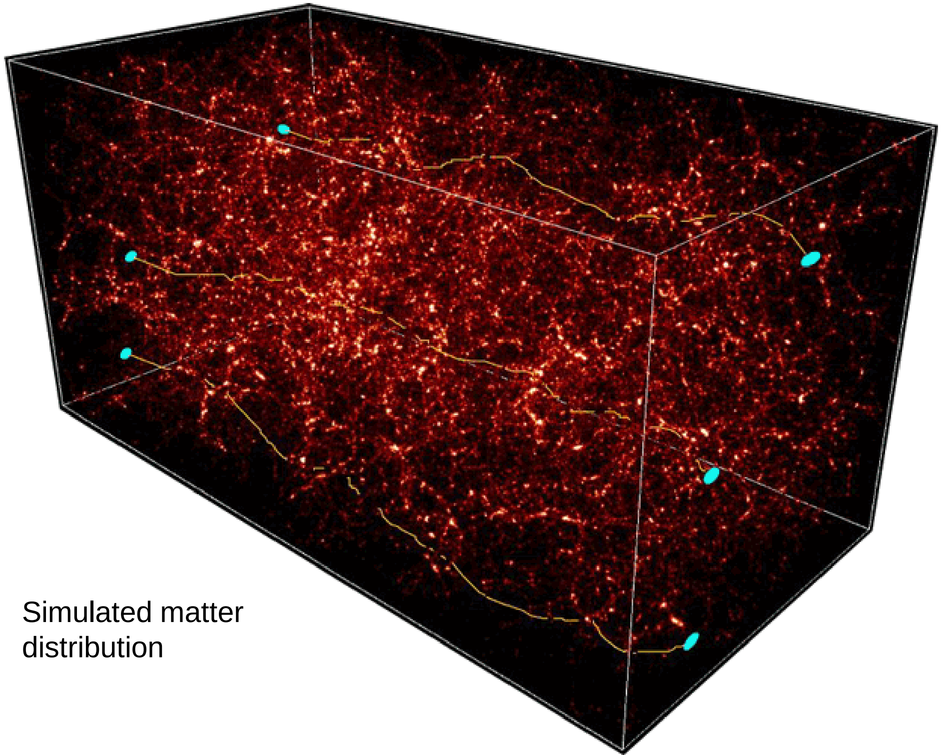


Weak Gravitational Lensing Survey

to map dark matter distribution

Looking between and beyond the stars of our galaxy, we see galaxies everywhere. If space time was not curved by gravity then the ellipticity vectors of these randomly oriented and irregularly shaped galaxies which carpet the sky would average to zero, but they do not !

By selecting galaxies by distance (obtained from photometric redshift) then averaging spatially, with some tricky math the distribution of matter along the line of sight can be inferred. This map includes dark matter which dominates luminous (baryonic) matter.



Simulated matter distribution

This requires a very wide and deep survey with sufficient resolution to measure barely resolved galaxies with detector induced ellipticity <0.1%

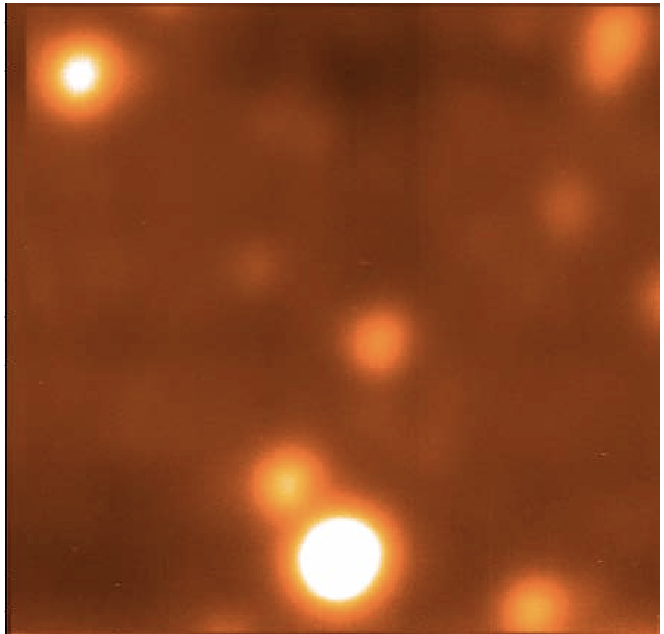
Sensor properties for WL survey

- Lots of high quality pixels at low cost …again; All of the features noted except high dynamic range.
- Need to push sensitivity to longer wavelengths to get red-shift from photometry in multiple bands
- The most distant galaxies are the most numerous (scales by volume), but these are the faintest so sensitivity is crucial.
- Most of the WL signal comes from galaxies which are barely resolved and we we need to reduce uncorrectable ellipticity errors to 0.1% so we need to minimize any pixel shape, diffusion or electrical coupling variation which depends on direction.
- PSF shape (optics, atmosphere, telecope pointing) dominates the shape signal and has to be measured using bright foregorund stars and then deconvolved from galaxy images, so uncorrectable non-linearity would be a problem.

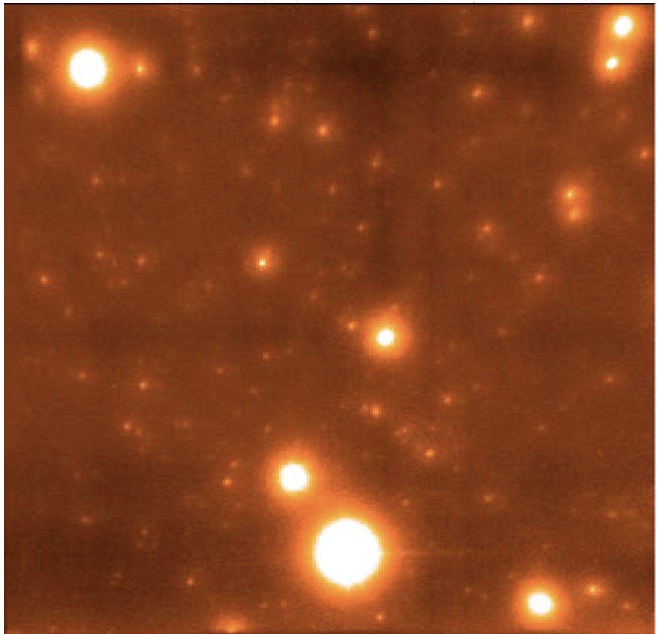
Time resolved: Lucky Imaging

- Lucky Imaging takes advantage of the fact that for on telescopes with aperture less than 2m (or larger telescopes with low order adaptive optics) the atmosphere delivers a flat (but tilted) wavefront by chance abut 10% of the time.
- By collecting images at about 100Hz, post processing can to select only the best images, then shift and combine them to achieve very high spatial resolution over the full isoplanatic patch. Due to its larger aperture the Palomar 5m has achieved higher resolution than Hubble at 800nm.

Seeing limited on P200



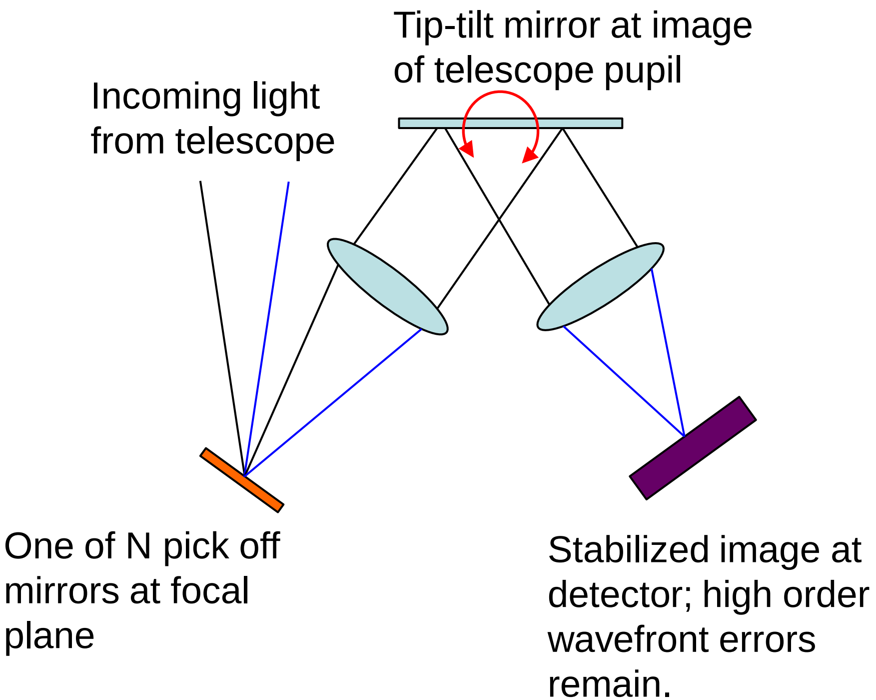
Lucky imaging behin AO system on P200



CMOS advantages for lucky imaging

- Normally Electron Multiplication CCDs (e2v L3CCD) are used due to severe requirement for low noise at at high frame rate. This limits dynamic range if photon counting or causes a 50% S/N hit if integrating the intensified signal due to gain noise.
- CMOS has been capable of sub electron noise if:
  - Charge transfer pixel
  - Small transistors for low sense node capacitance
  - Buried channel to suppress RTS or 1/f noise.
- To achieve this at high frame rate (avoiding the speed noise trade)
  - In pixel bandwidth limiting to filter buffer noise (and maybe some gain in pixel too)
  - Fast multiplexing with multiple channels

An even better Lucky Imager



- Major reduction in data rate and noise requirements if image shift is done optically.
- Then simply discard images in real time using second transfer gate.
- Move only charge that is not discarded to sense node
- Read region of interest around brightest star in field
  - derive tip-tilt input signal
  - Determine whether to discard image.

This made possible by fast region of interest readout interleaved with science acquisition and fast transfer of charge from

Acquisition and guide cameras

- Large area for acquisition and guide star selection; the area is drive by the probability of finding a sufficiently bright guide star. (We wood prefer to avoid using a pick off mechanism.)
- 10-100Hz readout of (multiple) guide star(s) is easily achieved if the region location can be written as an XY address rather than as a series of clock pulses to a serial register carrying row and column select bit.
- A CMOS imager requires no separate guide camera if the guide stars can be selected from anywhere within the science field and read out while the science image is in progress.
  - By choosing stars on opposite sides of the focal plane, rotation information is also obtained.
  - Having a large area available for guide star selection also allows more than one guide star to be used. This can not only improve S/N but reduces calibration induced errors and the centroiding effects of quantizing into pixels.

Need ROI readout at randomly addressable locations concurrent with science exposure
(and possibly interleaved with full frame readout (eg one after each full line).

Adaptive Optics

Shack-Hartman Wavefront Sensors:

A lenslet array subdivides the pupil and forms a rectilinear grid of spots each of whose motion reflects the local wavefront tilt across the section of the pupil sampled.

A higher order wavefront sensor for a large telescope requires 256x256 to 1Kx1K pixels, with very low noise (<2e-) at up to 1000Hz frame rate, and QE optimized for one of the following depending on the AO system:

- UV; microsecond resolution range gating for raleigh beacon:
- 589nm only for sodium beacon
- As red as silicon can go for natural guide stars.

Curvature Wavefront Sensors

This kind of WFS is less common perhaps in part due to senor limitations. CMOS could change that.

Accumulate two signals from either side of focus alternately.

If we have two sense nodes with separate transfer gates for each pixel, then multiple focus cycles can be accumulated per read to avoid the read noise limit. Low noise readout is still highly desireable.

This two-output-per-pixel-architecture could be used for the lucky imaging camera with one node simply providing the charge discard function.

It could also find use for polarimetry or any other fields where synchronous demodulation is needed.

Sensor Improvements

First lets summarize strengths,

and weaknesses

CMOS strengths for ground based

- Lower cost per unit area ? (due to wafer size and yield)
- 100% observing duty cycle. Sense nodes act as frame store; no image area is lost.
- Lower noise (Sarnoff/Janesick have published sub electron noise for buried channel)
- Better speed-noise trade. Limit noise bandwidth in pixel then multiplex.
- Efficient fast Regions of Interest. Store start address on board.
- No charge blooming along columns (though some CCDs have anti-blooming structures too).
- Non-destructive readout possible.
- Dynamic range:
  - Electronic shuttering by charge transfer can support very short exposures.
  - For long enough exposures, can use random addressing to vary exposure time by pixel.
  - In thoery extra sense node capacitance could be switched in as needed.

Additional CMOS strengths for space

- More radiation tolerant; traps only affect one pixel.
  - For CCDs charge transfer efficiency degrades as traps are created, though ten times more slowly for p-channel which collect holes than n-channel which collect electrons.
- Smaller pixels possible: may have an advantage for diffraction limited imaging.
- Lower/fewer voltages
  - Easier to control with ASICs
  - Clocking and readout electronics can be integrated into sensor but this may not be cost effective and carries a fill factor penalty for large focal planes.
- Lower power at higher frame rates
  - Relevant for earth observing.

Other parameters to get right

- Read noise < 2e- (6e- for imaging); buried channel for low 1/f or RTS
- Pixel size = 10-15µm
- Pixel capacity > 100,000 e-/pix
- Dark current < 0.001 e- / s
- Linearity at high signal levels… ok, if can be calibrated
- Linearity at very low signal levels …no charge loss effects.
- Inter-channel crosstalk < 10^{-4}.
  - Must be able to digitize a saturated signal so that its crosstalk can be calibrated out.
- Intrapixel sensitivity uniformity (backside illuminated and thick so front surface not seen)
- Minimize interference fringes in the red: thicker better; use multilayer AR coating to put one peak at fringing wavelength to minimize internal reflection from back-surface.
- Uniformity of pixel area for flat field calibration accuracy. Tricky to keep field lines perpendicular to surface when thickness > ~pixel width.

How does CMOS lag CCD ?

- Typical noise is too high but here we can beat the CCD.
- Pixel size needs to be bigger (10µm-15µm)
  - not a fundamental problem?
- Scaling to large formats.
  - Reticle stitching ? … may not be necessary (discuss later)
  - Packaging for close butting on mosaics. Goal >90% fill factor.
  - I/O for backside with high fill factor.
  - Flatness, after thinning and mounting.
- Need backside illumination for 100% fill factor and uniform pixel response; no lenslets please.

How does CMOS lag CCD, continued

- QE and fill factor
  - Backside illumination is new for CMOS; thinning, packaging and back surface treatment will drive up costs.
  - For blue, need to adopt same back surface treatments as for CCDs. Order of preference: delta doping (MBE), chemisorption (Mike Lesser), or Boron implant with laser anneal (used by e2v, MITLL)
  - For red response need thicker (higher resistivity silicon). Do we need a two layer approach: high resistivity detector layer, low resistivity readout. Silicon-On-Insulator technology may make this practical.
  - Apply backside bias to control lateral charge diffusion; essential for thickest devices

Pixel Architecture

Where to sense the charge?

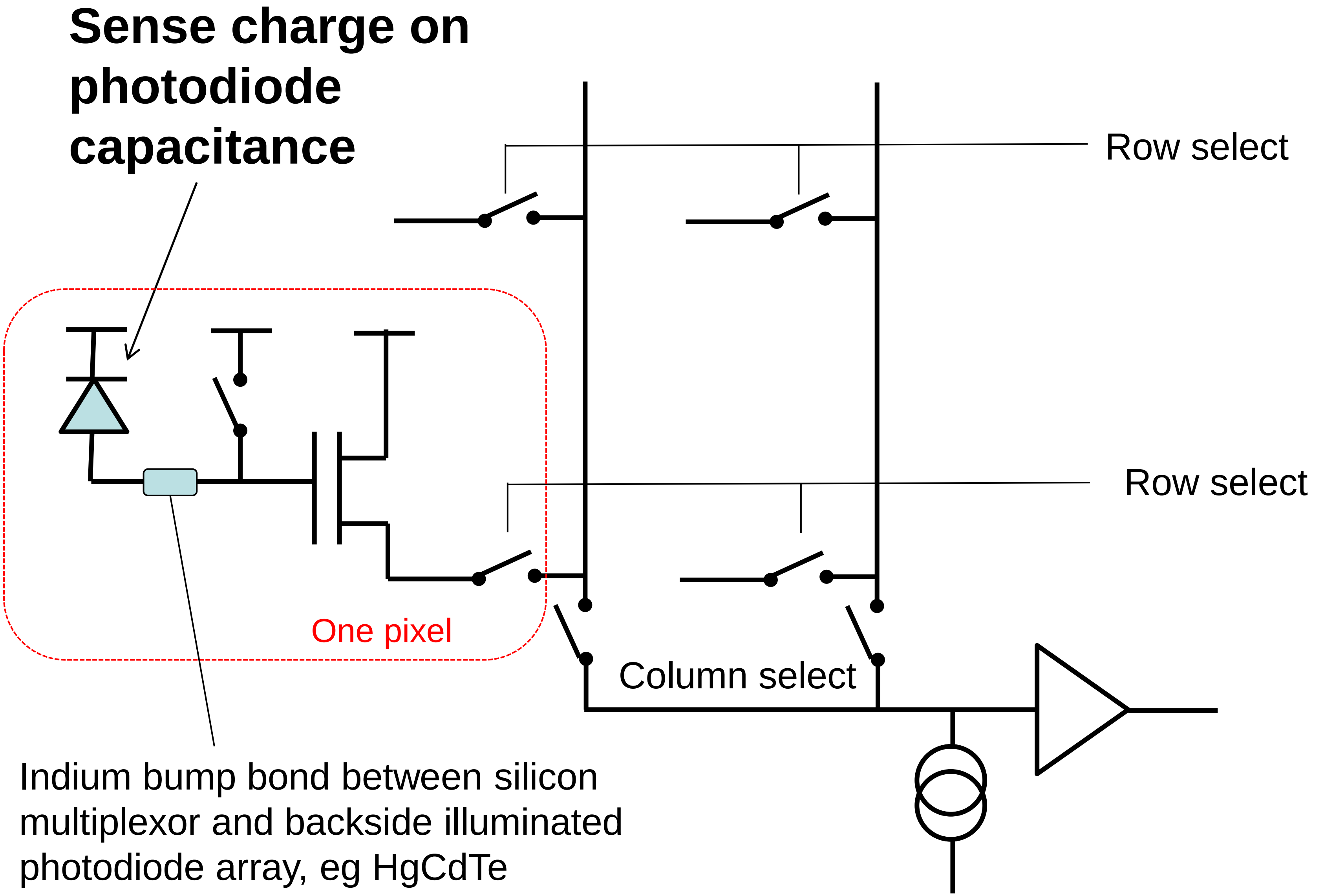
Sense charge on photdiode

- Charge accumulated and measured on PN junction capacitance of photodiode.
- Photocurrrent reduces reverse bias. Saturation when depletion region collapses.
- Only option when photodiode is on a separate layer (such as HgCdTe or InSb for $\lambda > 1\mu m$)

Charge Transfered to adjacent sense node

- Each pixel works like the last pixel in a CCD serial register.
- Charge is transferred to smaller sense node capacitance
- For an all silicon design this is the only option we should consider since it has many advantages.

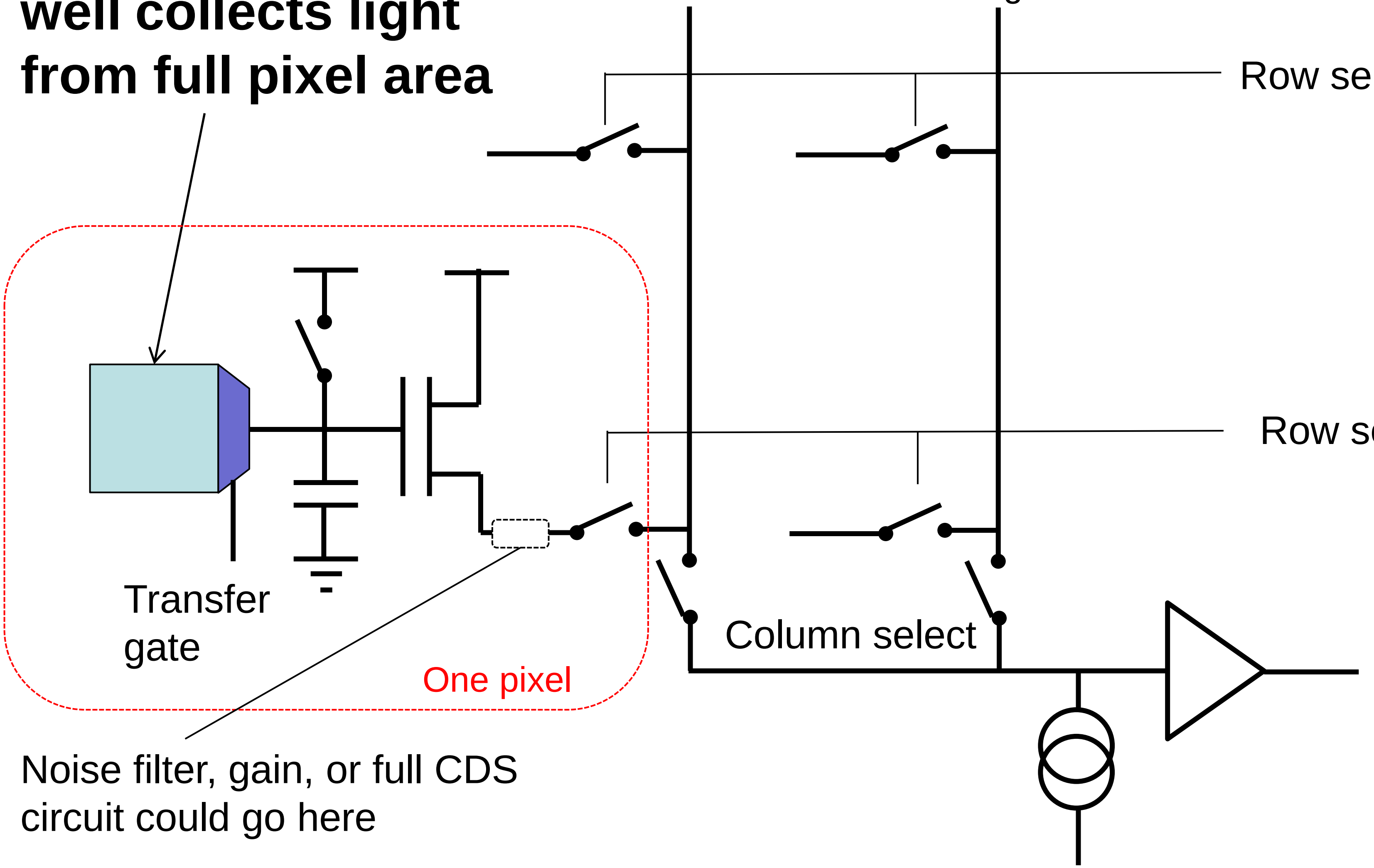
Pixel layouts: 3T pixel



Pixel layouts: charge transfer pixel

CCD like potential well collects light from full pixel area

Backside illuminated: E field lines collect light from behind transistors on front surface to give 100% fill factor



Noise filter, gain, or full CDS circuit could go here

Feature comparison

On diode

- Smaller pixel needed to increase µV/e-, but smaller pixel collects less light and increases required pixel rate.
- CDS performed over full exposure time so noise BW includes lots of low frequency power.
- Highly susceptible to ambient temperature and bias voltage changes during exposure time.
- Very sensitive to self heating induced by clocking pattern.
- Image persistence as depletion edge moves across traps.
- Non linear due to change in junction capacitance.

Charge Transfer

- Lower noise: Signal voltage boosted by low sense node capacitance; not tied to pixel size.
- Lower noise: CDS performed on shorter time scale that can be independently optimized (matched to 1/f corner frequency).
- Short CDS time scale provides immunity to bias voltages, ambeint temperature and self heating.
- Can be linear in theory.
- Image persistence can be eliminated.
- Signal is buffered in sense node so 100% duty cycle is possible. Read time Is not critical to observing efficiency. Very short exposures without rolling shutter.
- Can have more than one output port per pixel.

Detector Architecture

Thoughts about how to build large focal planes cost effectively.

Large CCD focal planes: the competition

Typically 4 side buttable CCDs, 2Kx2K, 15µm pixels.

NOAO Mosaic, PTF, CFHT Megacam, MMT Megacam,
SuprimeCam, HyperSuprimeCam

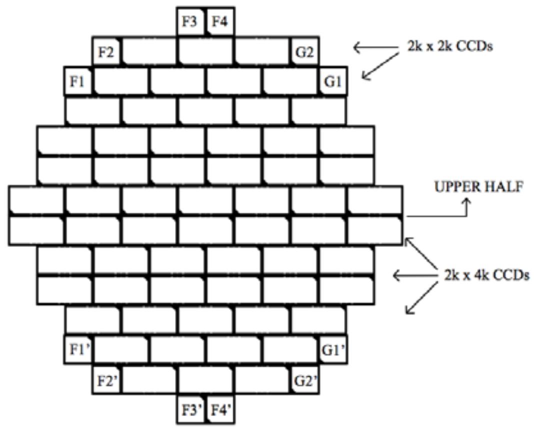
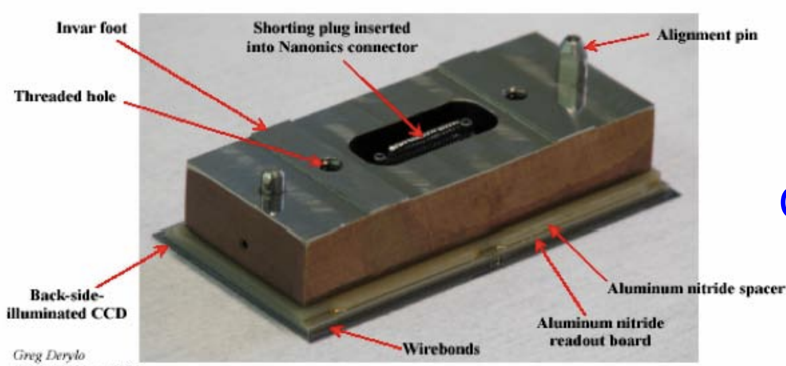
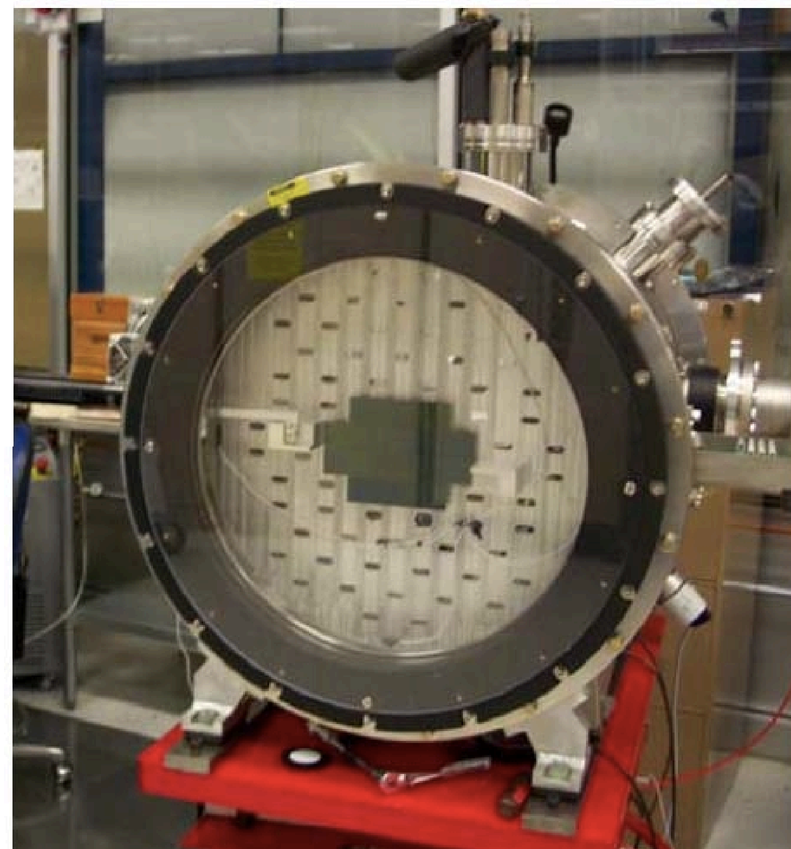


Figure 2-1 The DECam Focal plane is shown above. There are 62 2k x 4k CCDs. In the focal plane diagram, G labels the guide CCDs, and F labels the focus/alignment CCDs.



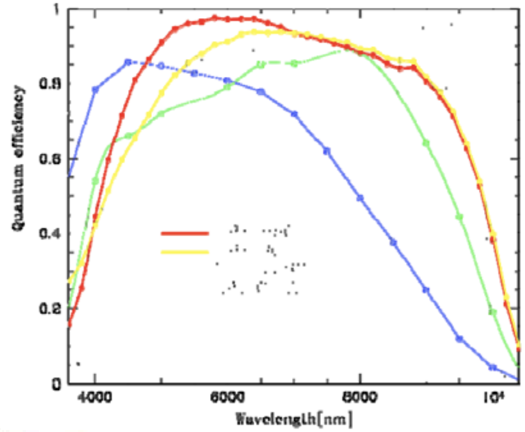
Fermi Lab's Dark Energy Survey Camera, under construction

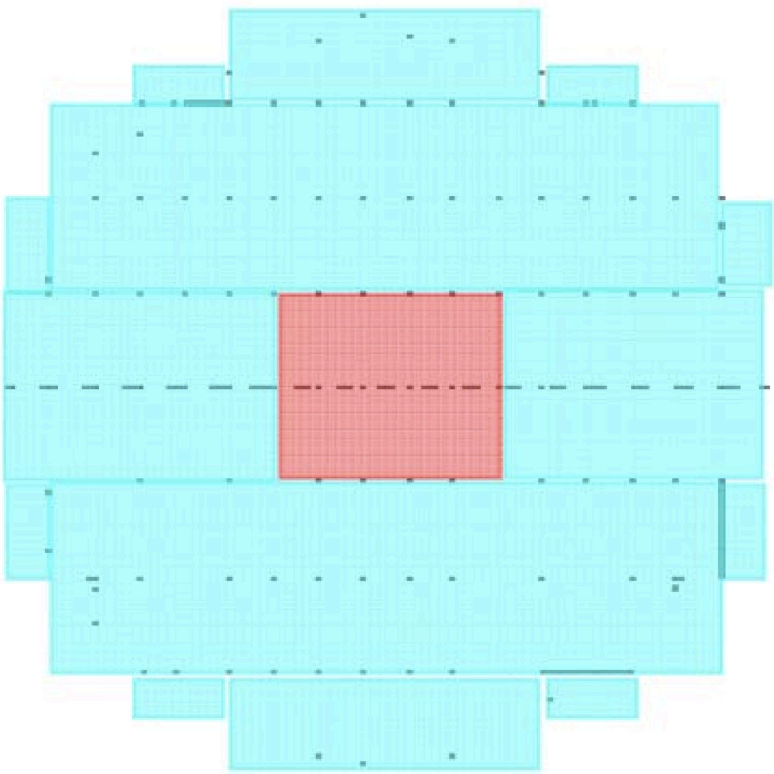


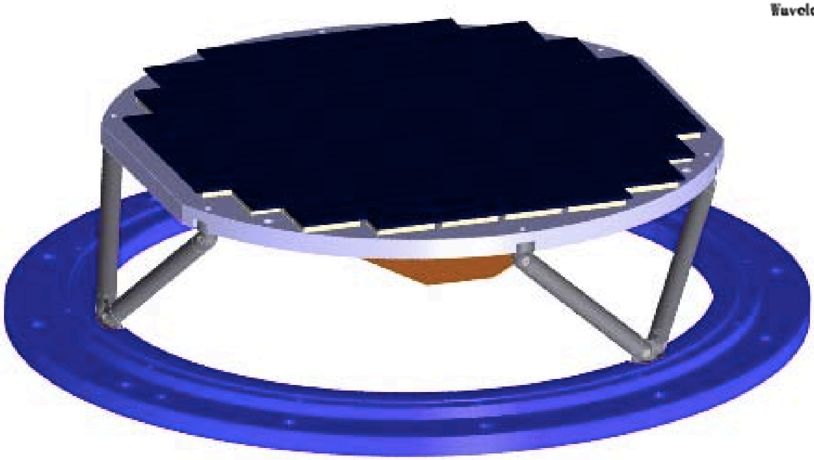
Large CCD focal planes: the competition

HyperSuprimeCam for Subaru:

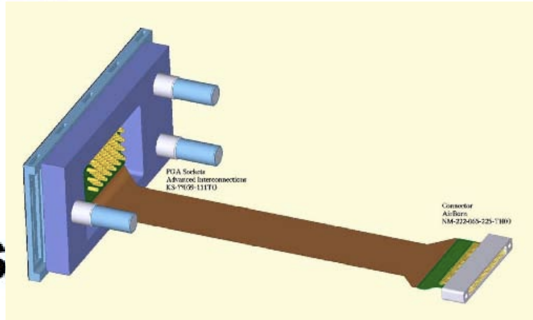
imaging area = 2190 cm^2





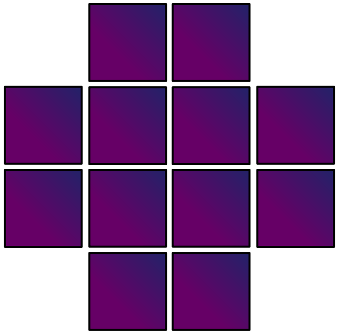


112 + 4 Guides



$$/area is dropping for CCDs

- Several instruments plan to use wafer scale CCDs 92mm x 92mm which provide better fill factor for same gaps and cost only $\$1200/\mathrm{cm}^2$
  - E2V 9Kx9K @ 10um/pixel, 16 outputs
  - STA 10Kx10K @ 9um/pixel, 16 outputs
- eg. Next Generation “Palomar Transient Factory”



← 376mm →

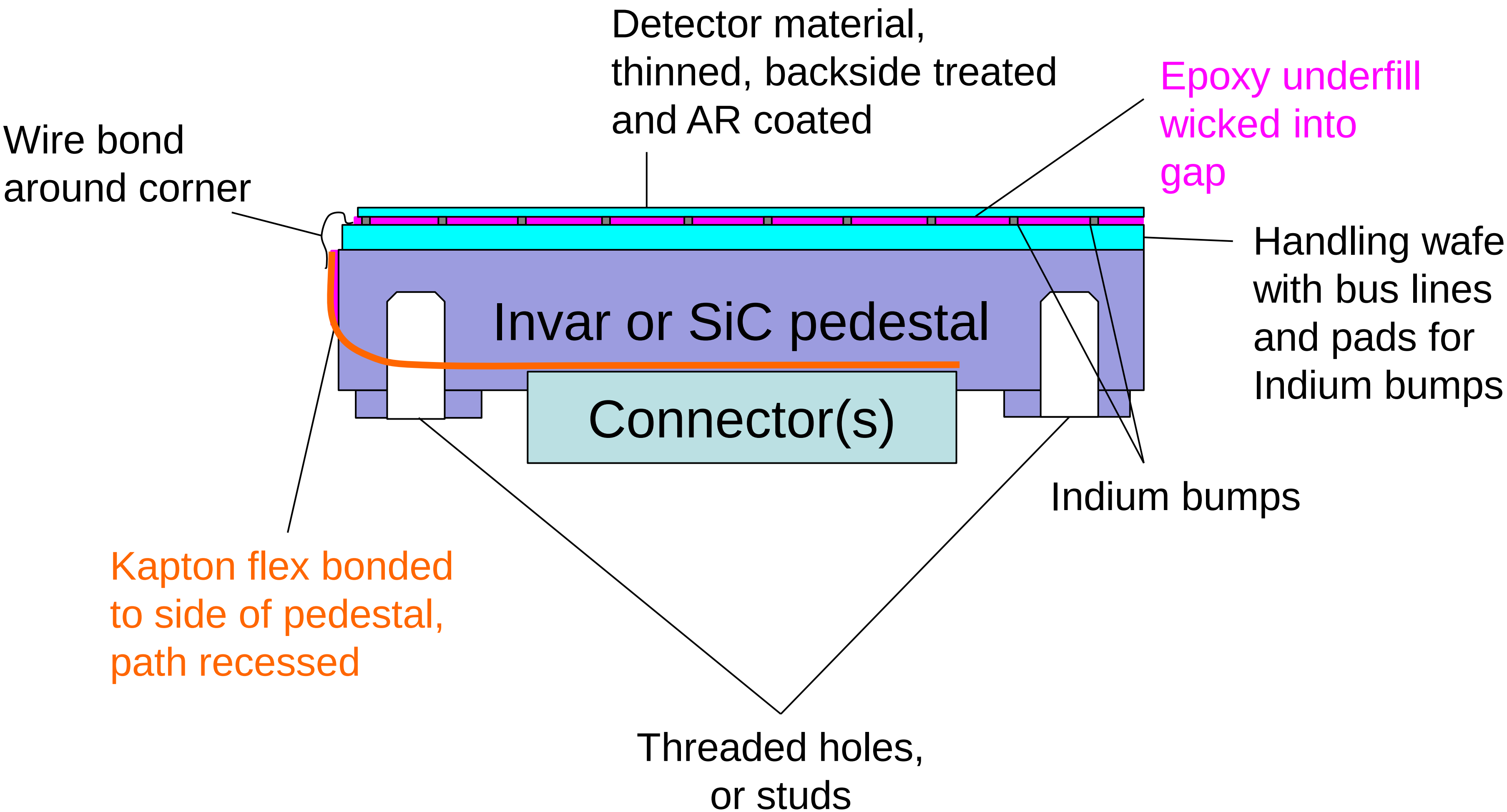
96% fill factor is very good.

Active area = 35 sq.deg on sky

Suggestion for high yield on large CMOS

- Most surveys can tolerate gaps provided that fill factor is high.
- Wafer scale imager will minimize number of devices and reduce area lost in gaps between tiles.
- Design to minimize propagation of failure so we can use almost every wafer.
- Make sensors the size of full reticle, but don't use stitching.
- Indium bump bond to bus lines on supporting wafer, which is required for thinned device anyway. There could be additional circuitry on this layer.
- If pads for Indium bumps are 100µm then inactive fraction for 15mm detector (say) is 1.3%
- If device is shorting a power bus then don't connect it.
- Most other failures will only affect a single row, column or pixel.

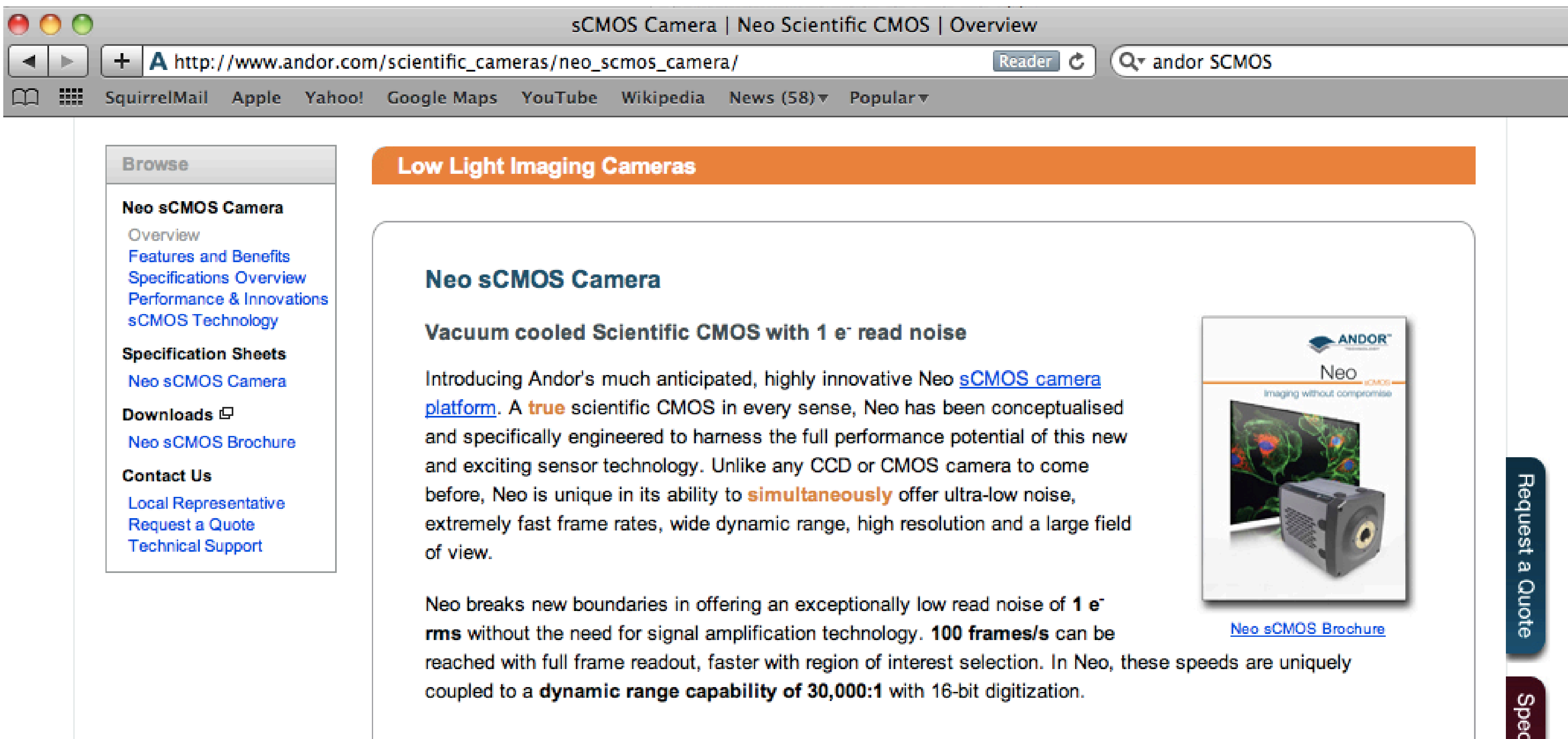
Packaging concept



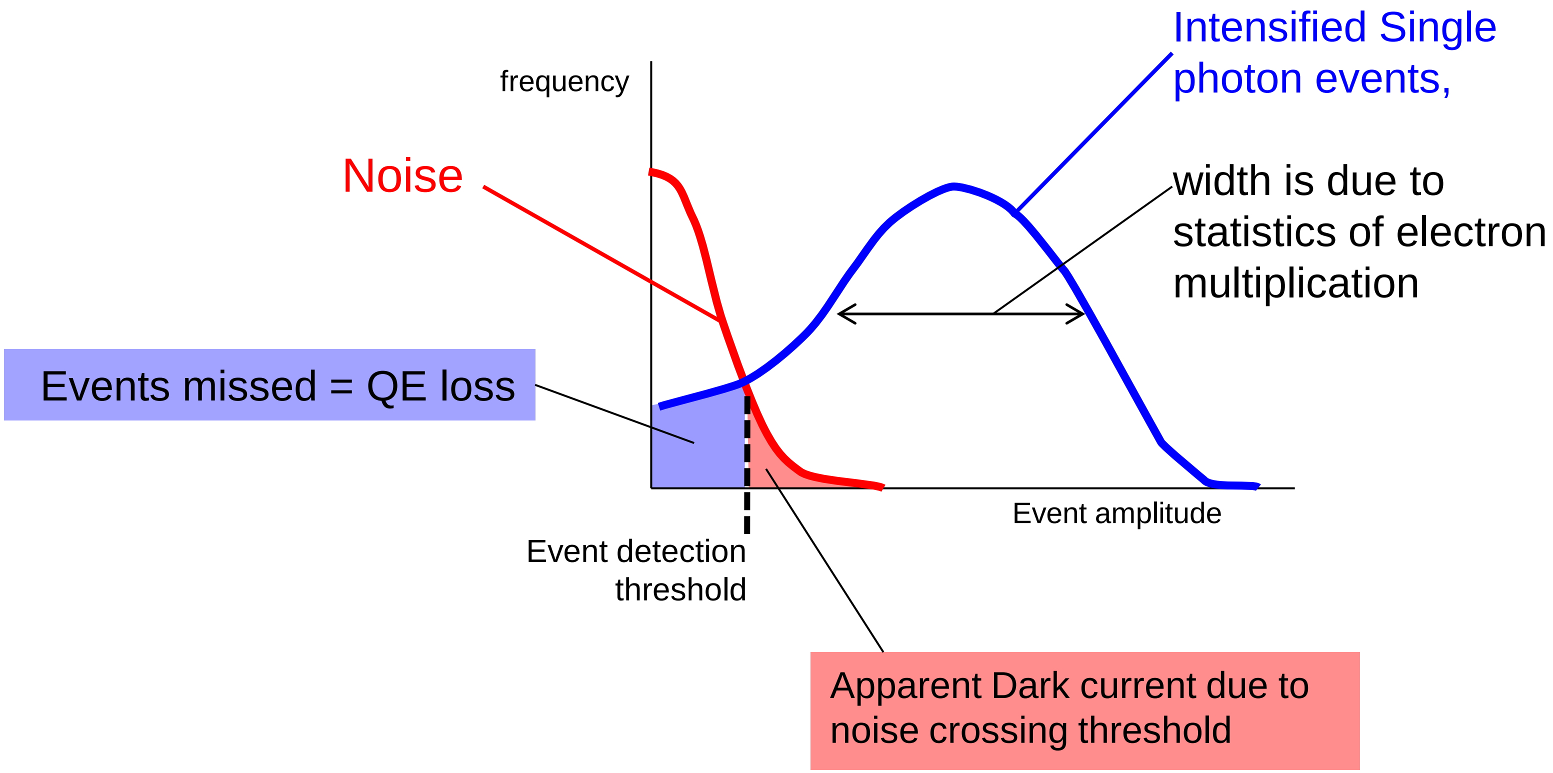
Very low noise without slow readout !

VERY EXCITING: can get near-photon-counting in integrating sensor:

- Andor Neo: 1e- noise on 5.5Mpix at 40Hz; 1.4e- at 100Hz.
- Sarnoff have demonstrated sub-electron noise.



Photon Counter Optimization problem

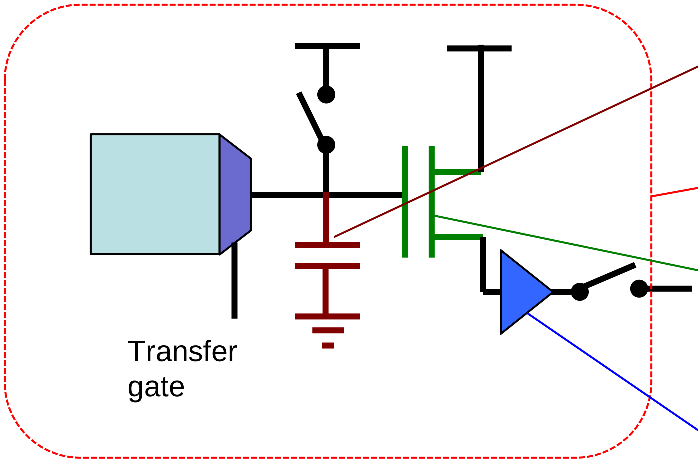


Low Noise CMOS versus Electron Multiplication CCD

- Integrating sensor has much larger dynamic range: no event coincidence losses.
- Don't need high frame rate to avoid coincidence, sensor size is not limited by I/O bandwidth.
- No sub-threshold or spurious events (see previous slide)
- Electron Multiplication CCDs can be operated in integrating mode without counting individual photons but they then from excess noise due to gain variation among events. This "excess noise" relative to shot noise is equivalent to a loss of QE.

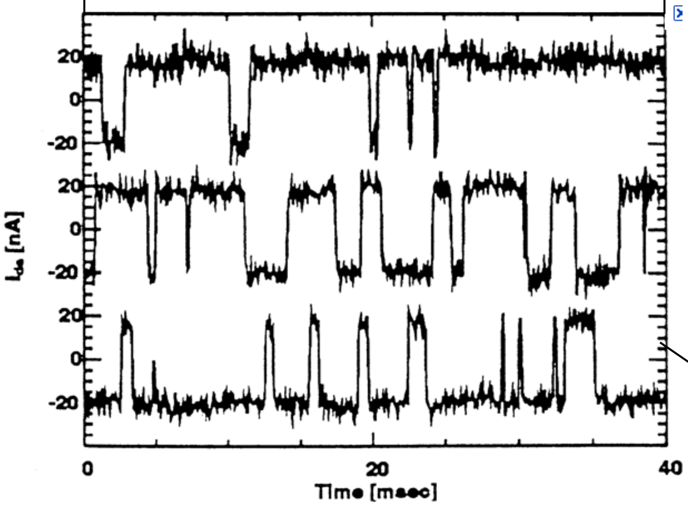
This will be a big advantage for high resolution or UV spectroscopy where signals are very weak,
or for guiding, adaptive optics and Lucky Imaging where short exposures are required.

How to get low noise:



- Small sense node capacitance to boost signal above buffer FET's voltage noise.
- Charge transfer pixel with CDS on time scale of 10µs to 100µs, (not the full exposure time like 3T pixel)
- Need buried channel FET to avoid Random Telegraph Signal or 1/f noise due to traps near FET channel.
- In-pixel band limiting (noise filtering) breaks the trade between readout (multiplexing) speed and noise BW. Can AD convert twice per pixel and subtract digitally to assure good CMRR, or use clamp-sample circuit to do analog subtraction. Need to be clever to save power.

RTS noise in small transistors



RTS noise is bistable FET gain due to single electron trap near channel. Multiple uch traps cause 1/f noise, but as transistors get very small they are likely to contain only one trap. They occur on wide range of timescales.

Surface versus buried channel

Figure 4.2: Energy band structure for a surface-channel CCD. A potential well forms at the semiconductor-oxide interface.

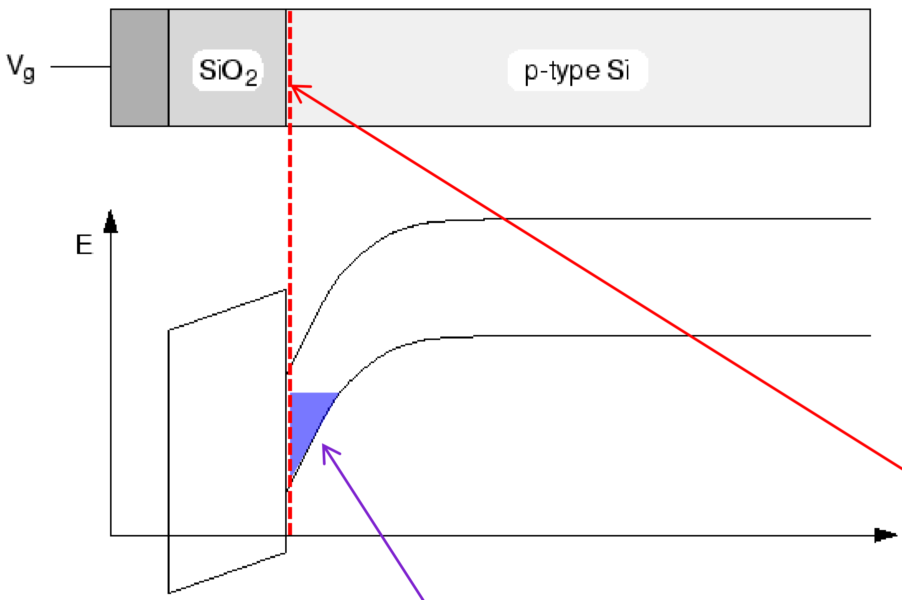
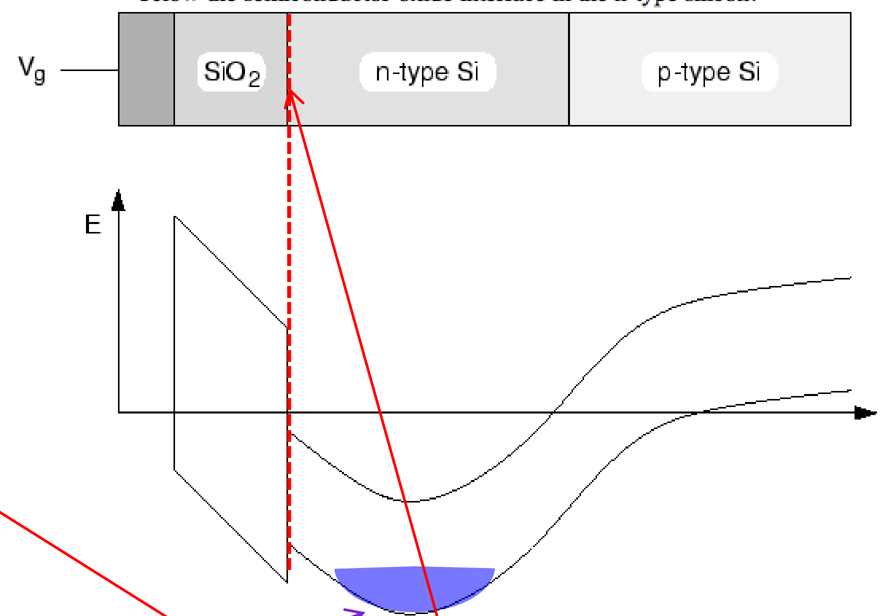


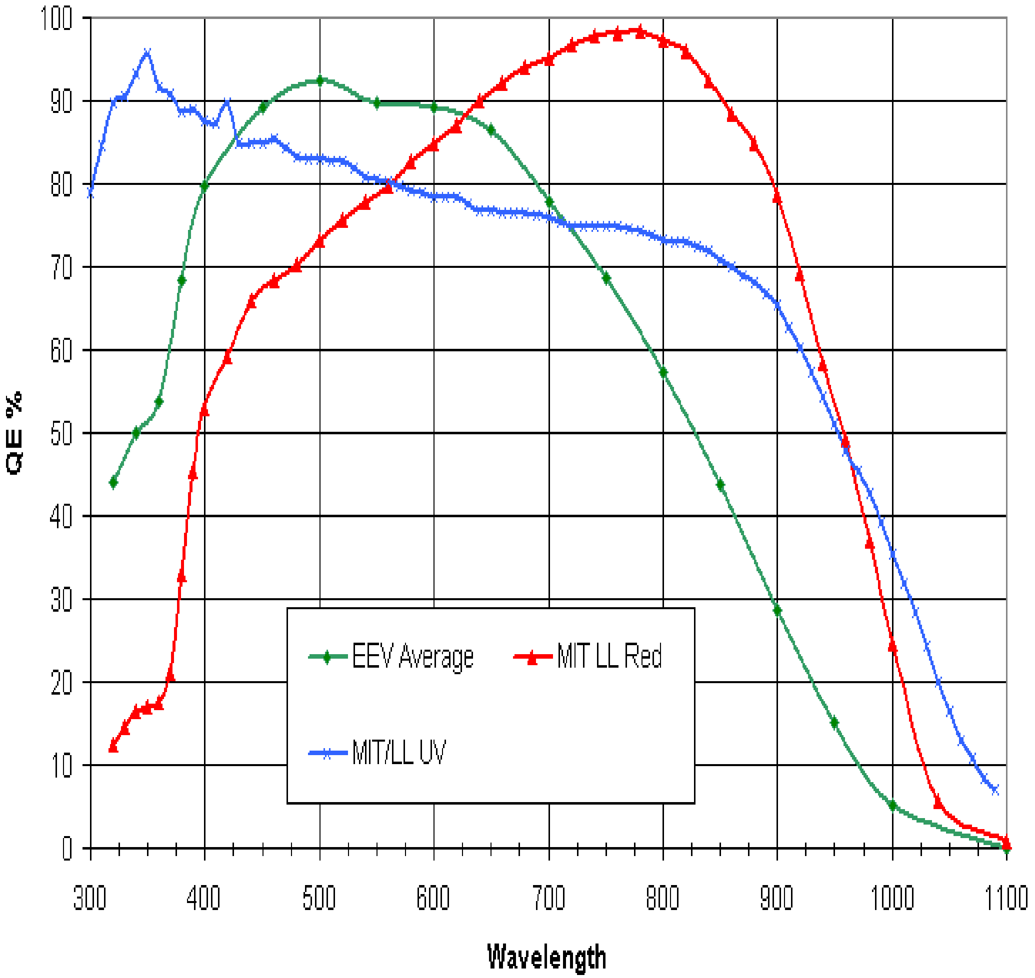
Figure 4.3: Energy band structure for a buried-channel CCD. A potential well forms below the semiconductor-oxide interface in the n-type silicon.



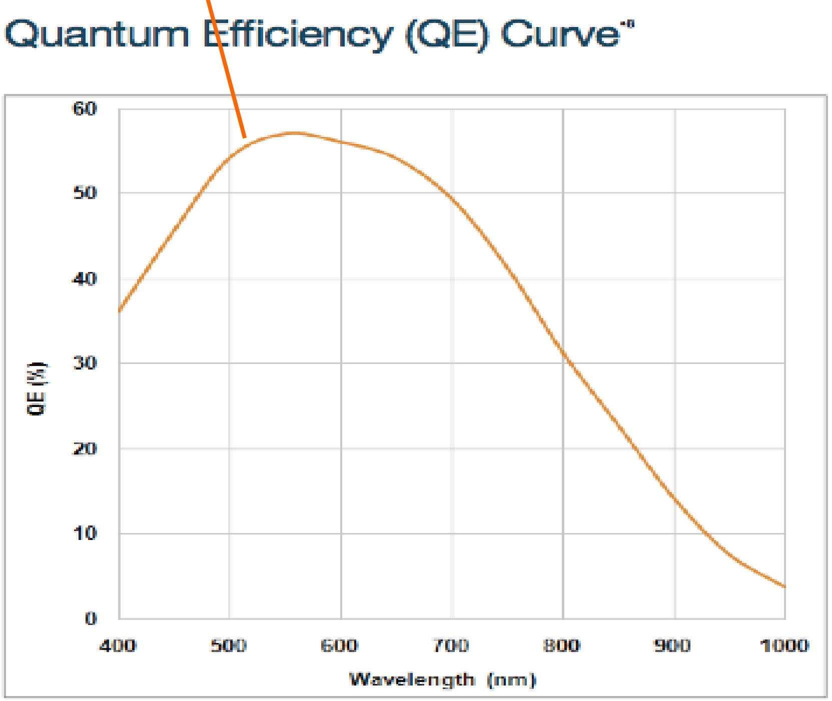
- Doping to create PN junction, moves potential minimum and thus stored charge and away from the traps at the SiO_2 interface.

Can QE be improved?

Various CCDs

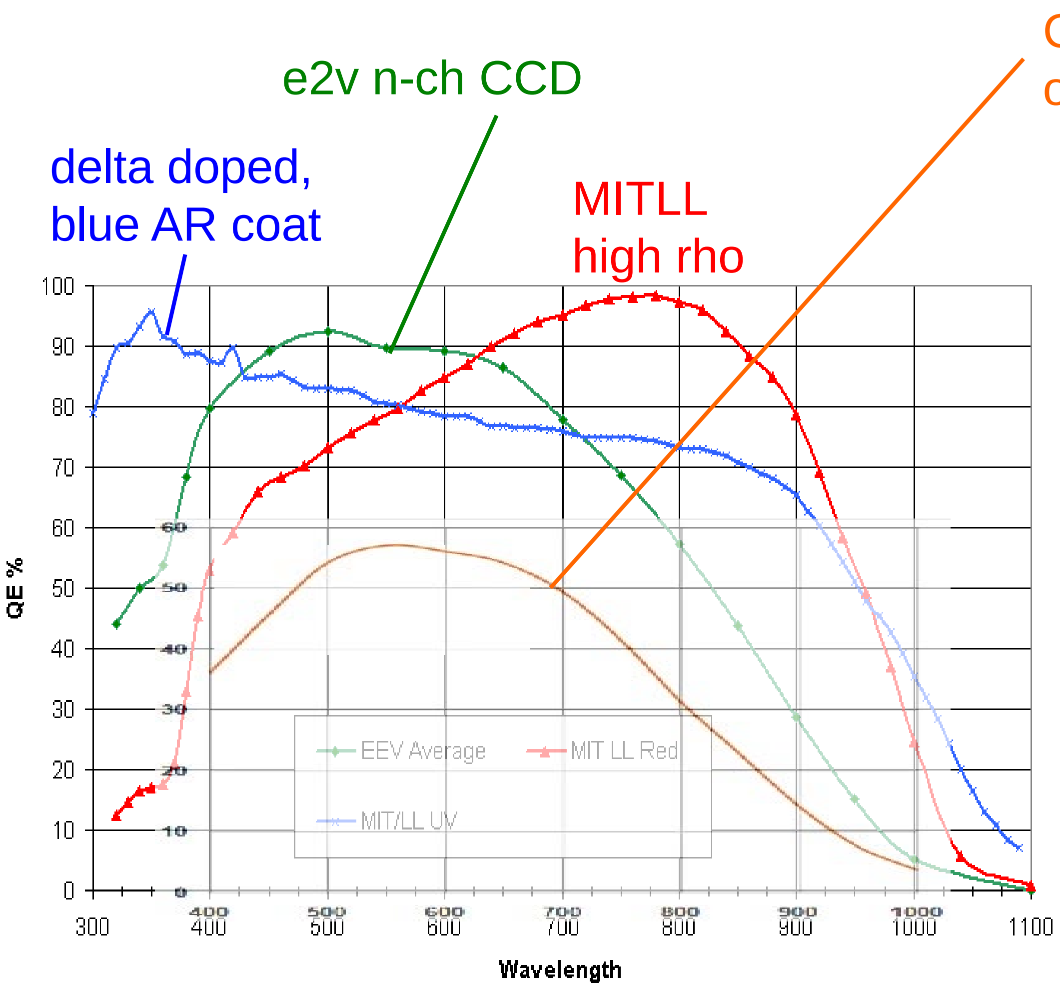


Recently released CMOS: Andor Neo



CMOS QE displayed on same scale

Newer CCDs are starting to be made with multilayer coatings giving >90% over most of their range making the performance differential even greater than shown here.



For high QE, need:

- Backside illumination
- AR coating (preferably > 1 layer)
- Thick (low resistivity silicon)
- If thickness > pixel size, need backside bias to deplete through full thickness.

Currently more common for CMOS:

- Frontside with lenslets
- Thin, low resistivity

Front side vs backside illumination

Conventional front-illuminated CCD:

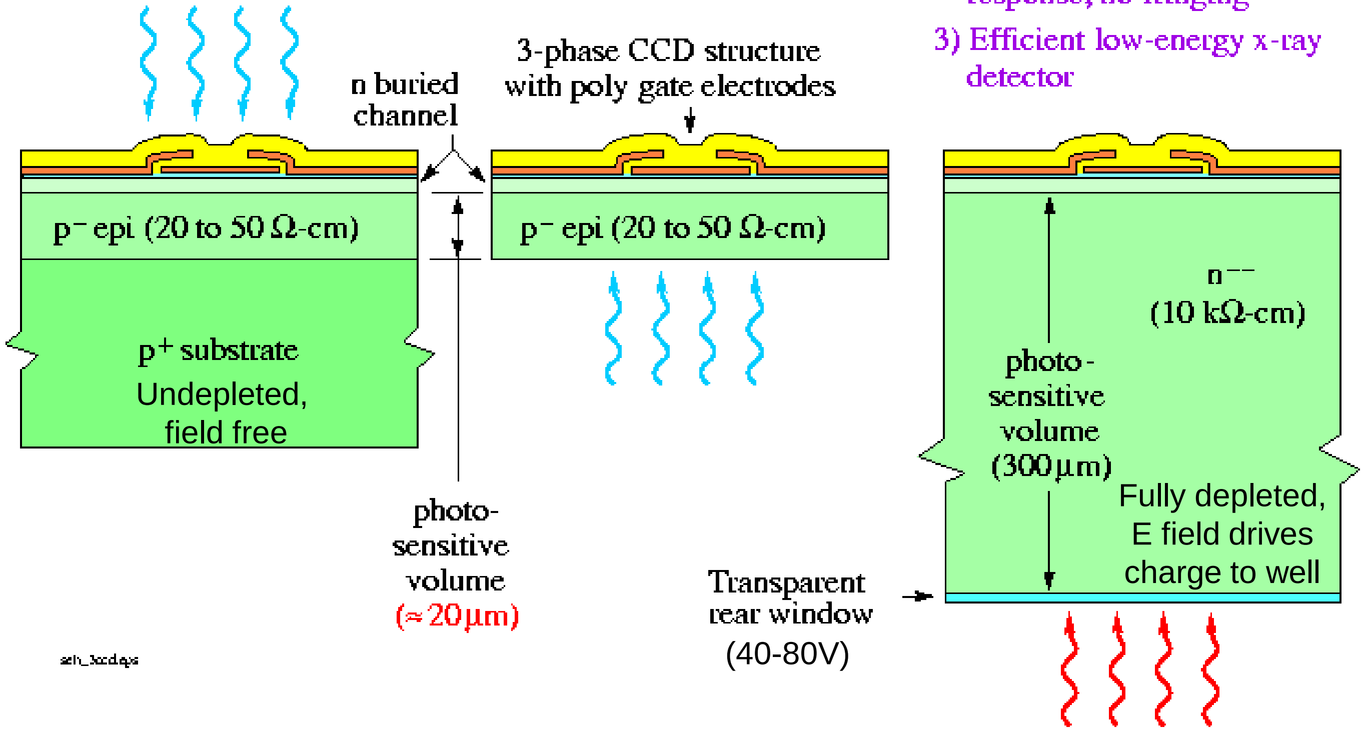
1) Poor blue response due to absorption in polysilicon gate electrodes
2) Interference patterns

Thinned CCD with back illumination:

1) Thinning is difficult and expensive
2) Poor near-IR response
3) Fringing

LBNL thick CCD with back illumination:

1) Conventional MOS process with no thinning => "inexpensive"
2) Good blue to near IR response; no fringing
3) Efficient low-energy x-ray detector



Thinning

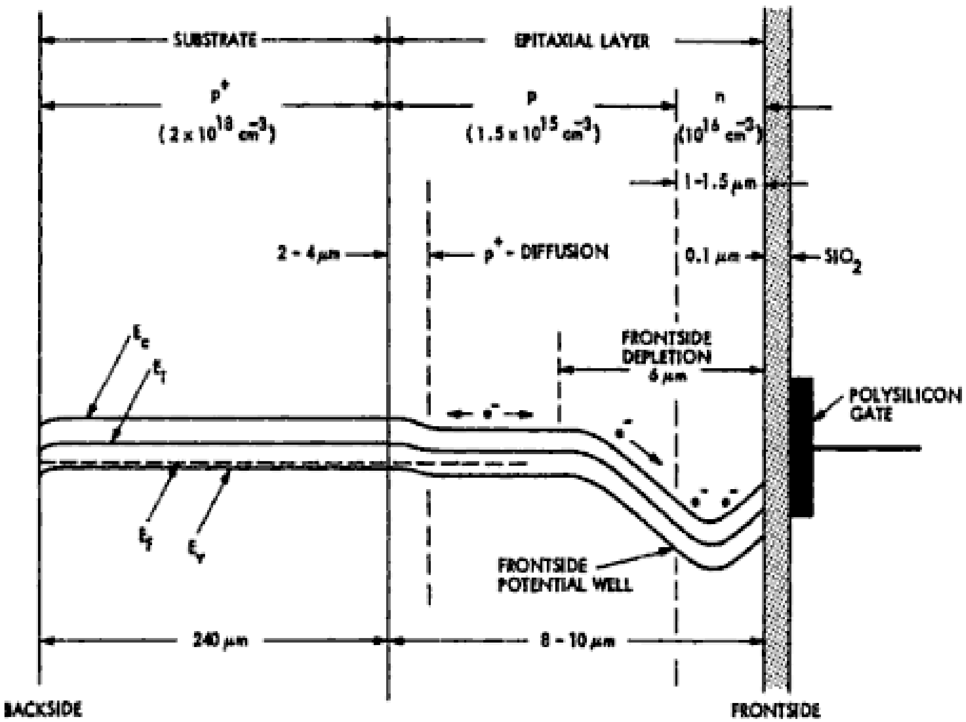


Figure 3.30(a) Cross-section of substrate and epitaxial layers before thinning is performed.

- E-field only extends a short distance into silicon.
- Charge entering from back is absorbed within 10µm or so (except for longest wavelengths)
- This charge will diffuse laterally if CCD thickness > pixel size unless there is a an E-field created by a transparent backside electrode.
- Generally the devices are lapped then etched to reduce thickness so that lateral diffusion is minimized.

Backside potential well

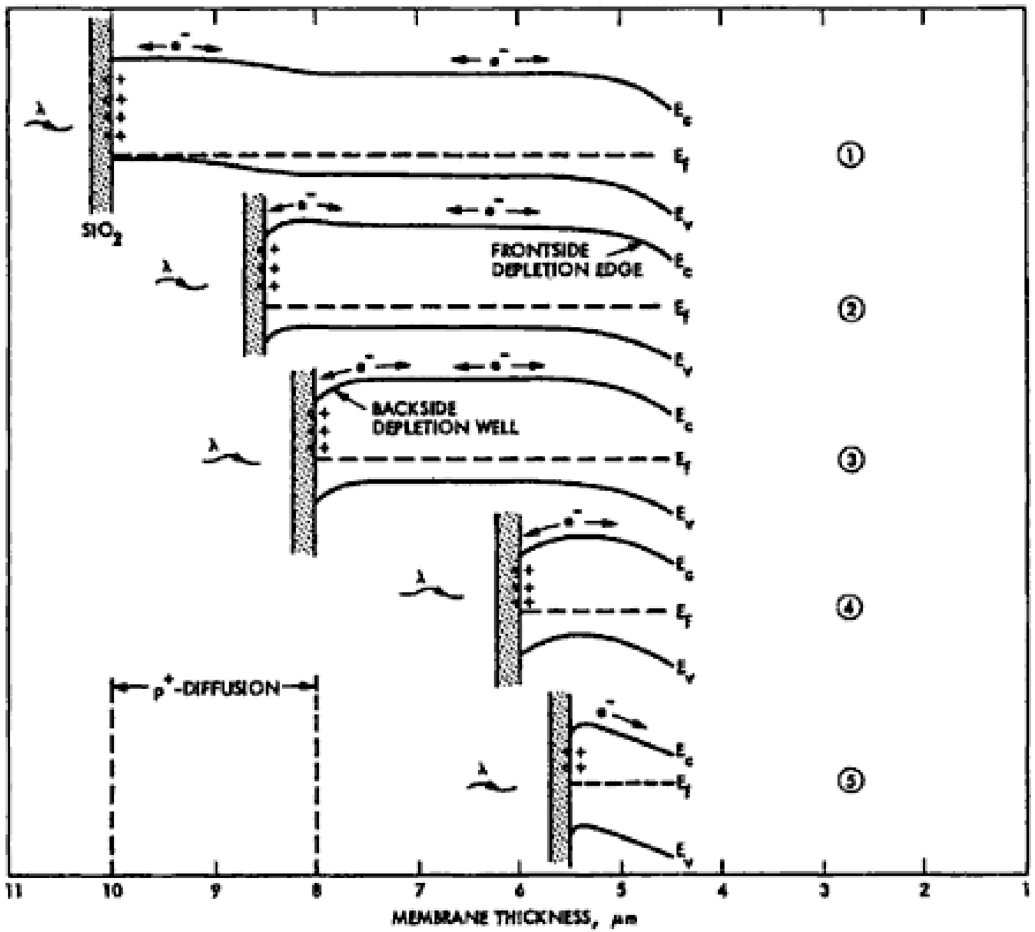
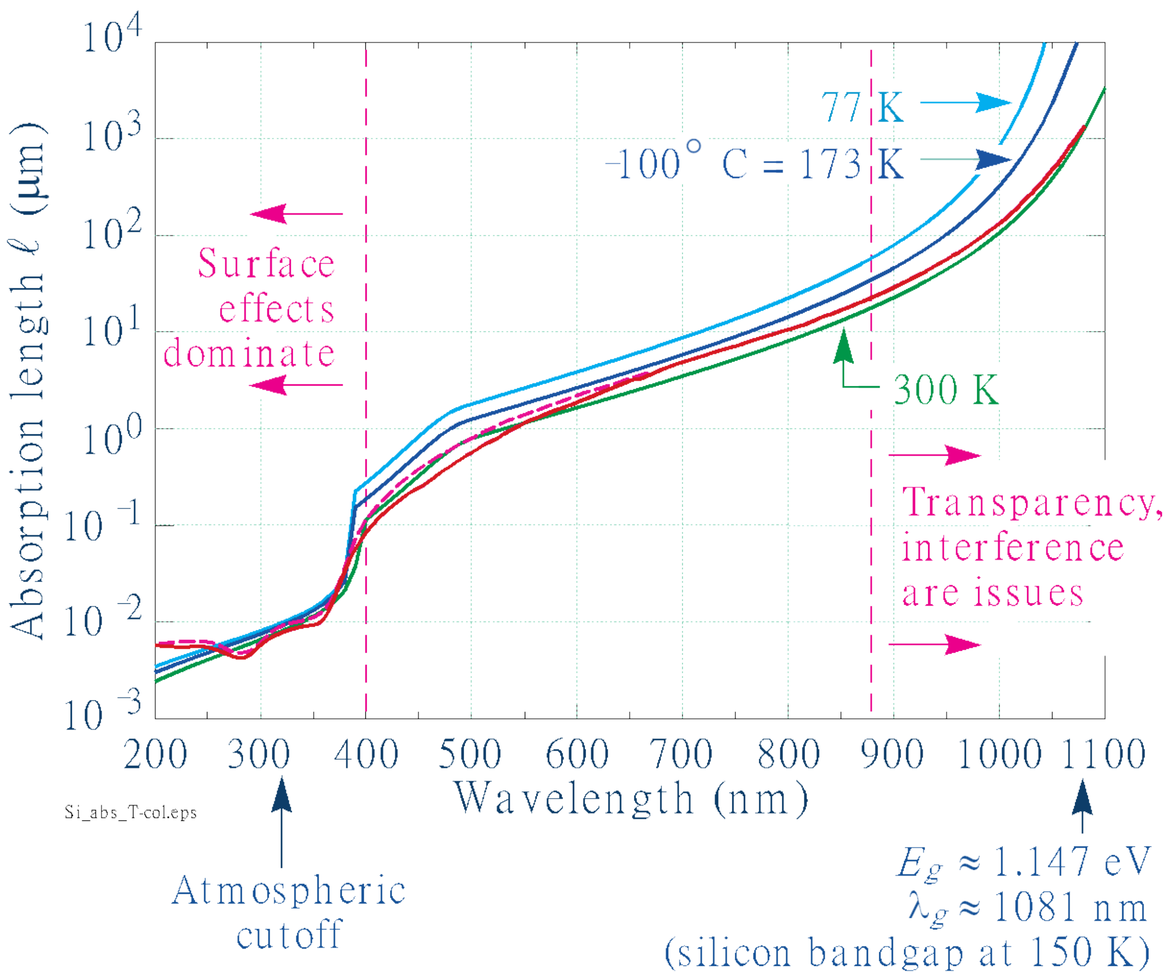


Figure 3.33(c) Energy band diagrams for the five regions labeled in Fig. 3.33(b).

As fresh oxide grows after thinning a fixed positive charge develops in traps at the surface. Photo-electrons produced there by blue light gets trapped and not collected.

To counteract this a high concentration dopant monolayer can be deposited by MBE, or (less effectively) a Boron implant with laser anneal, or a thin metal catalyst layer can be deposited. See “Scientific CCDs” by Jim Janesick.

How thick ?

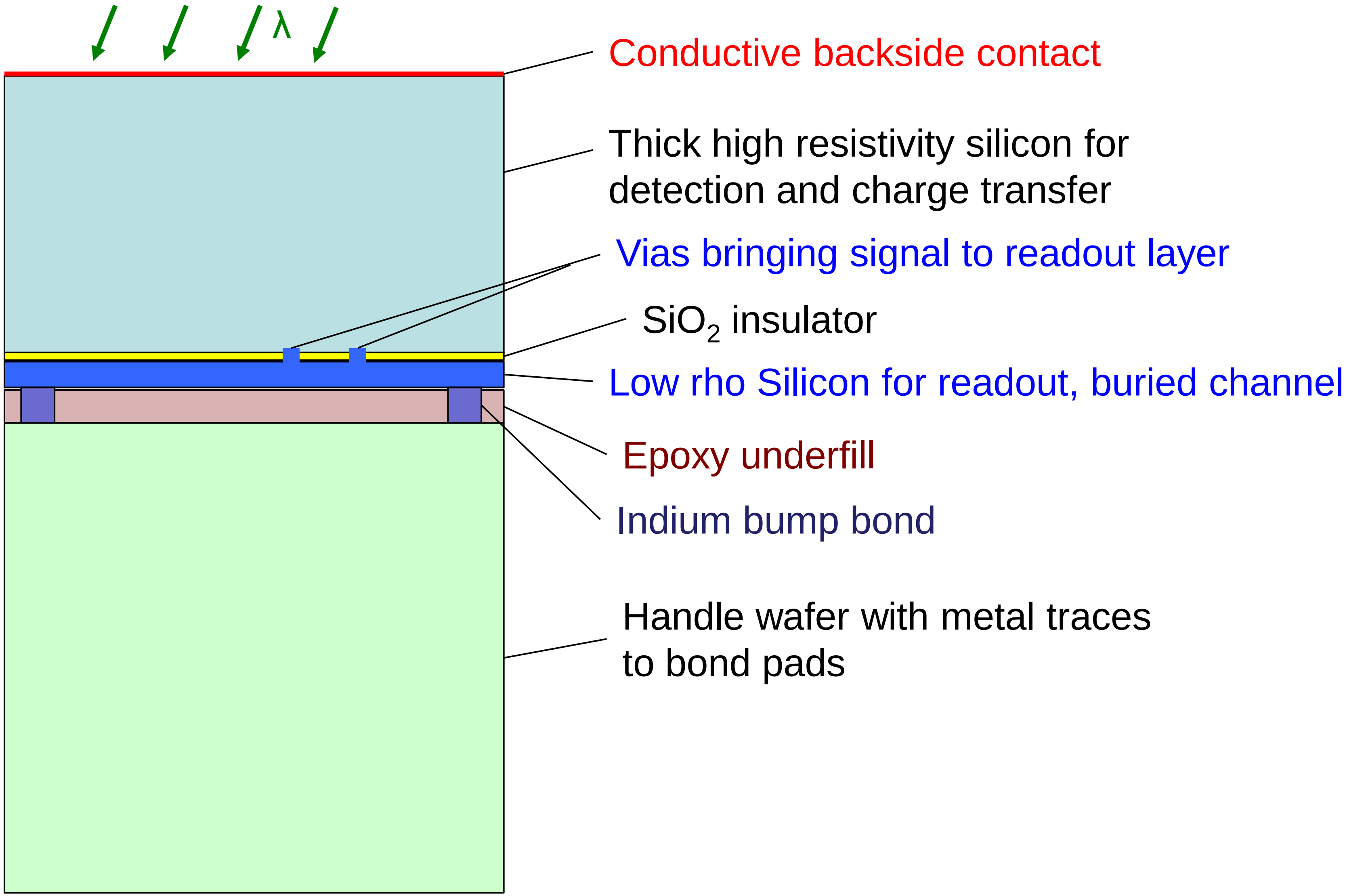


Need to increase thickness get enhanced red response.

Need back side to be a conductive electrode with moderately high voltage applied to push charge towards front surface before it diffuses laterally

Need higher resistivity so fields propagate deeper and to reduce required backside voltage to reasonable levels. Is this incompatible with CMOS?

Silicon On Insulator for thick devices?



Development Tasks

- Increase pixel size
- Support efficient region of interest readout
- Make in very large formats; first, test approach at smaller scale.
- Reduce noise.
- Back side illumination:
  - Packaging for flatness and close four side butting.
  - Thinning (how much depends on resistivity)
  - Back surface charging
  - (2 layer) AR coating
- Increase thickness for better red response
  - Higher resistivity
  - Backside electrode (ITO or delta doping)