Development of Back-Illuminated, Fully-Depleted CCD Image Sensors for use in Optical and near-IR Astronomy

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working with

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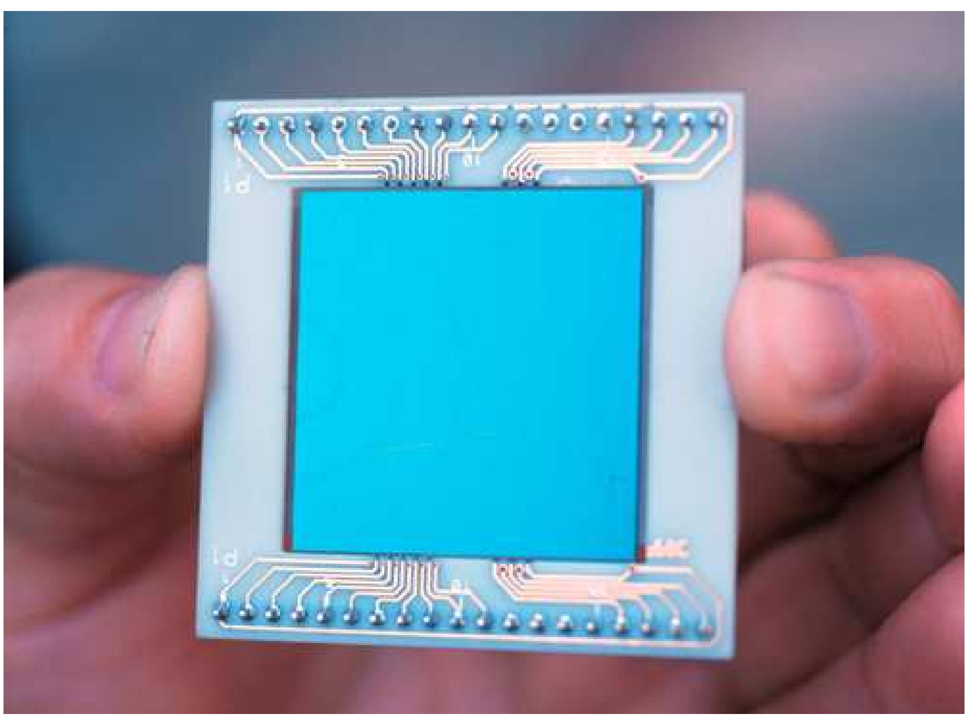
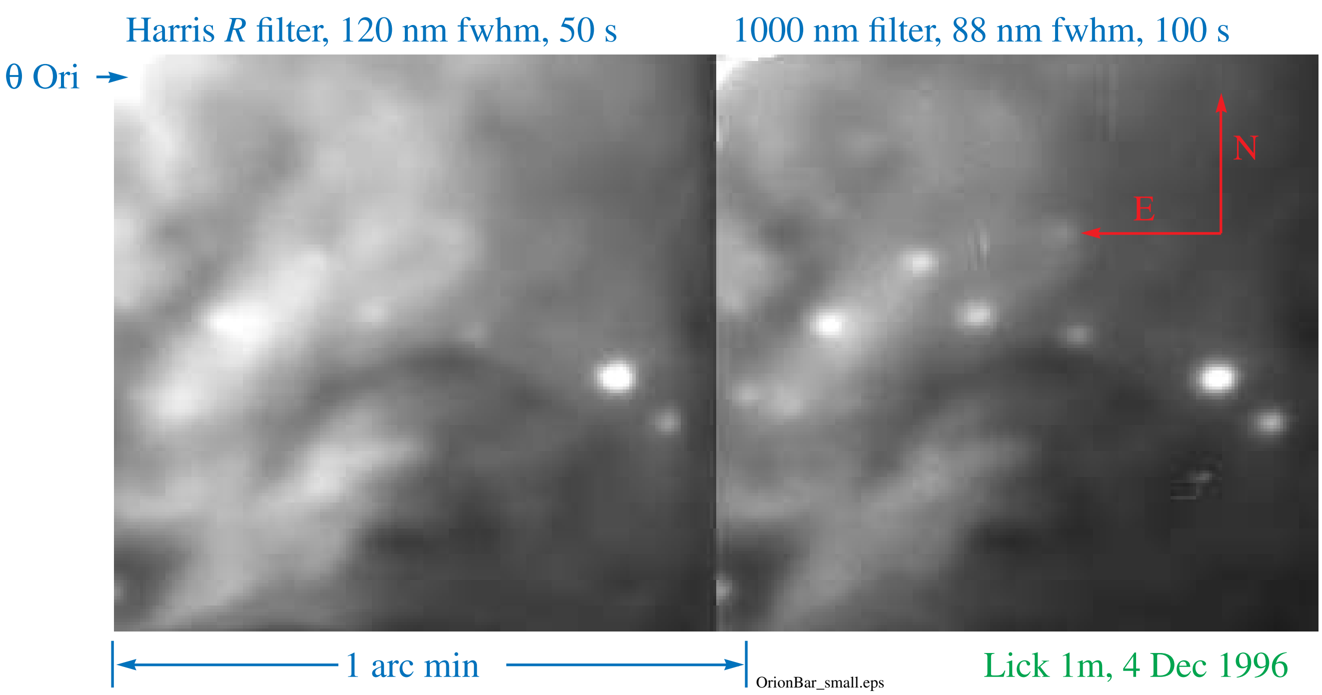


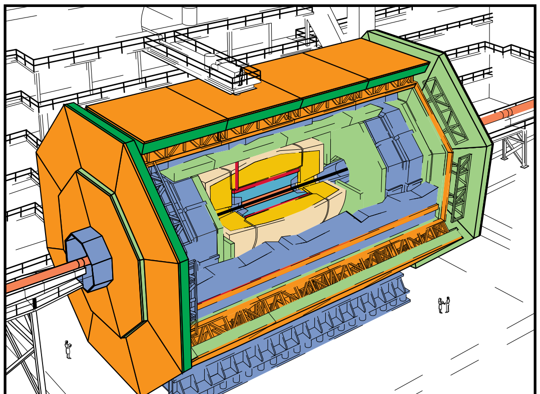
What should I talk about in 20 minutes?

We've done a lot of things, but for a short talk I will discuss the following:

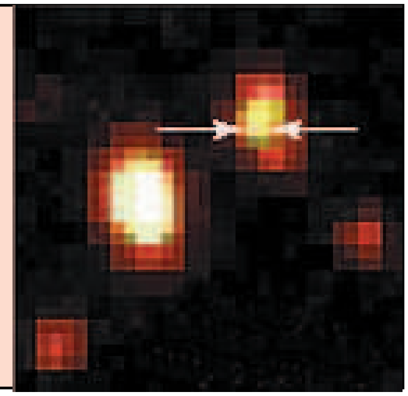
- Background and motivation:
  The LBNL bright idea
- Prototype run
  (200 × 200 CCD's, plus test structures, 1996-97)
- Large-format fabrication run
  (characterization in progress)
- Conclusions and the future



Background and motivation:

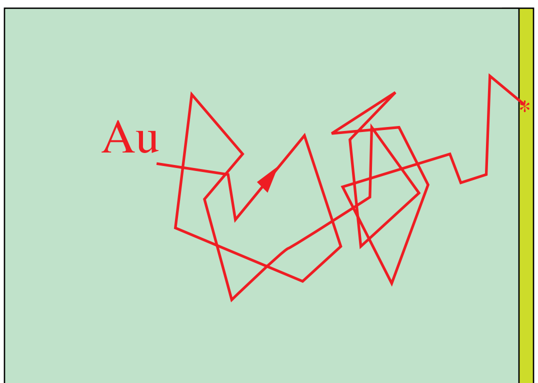


Strip detectors for SDC

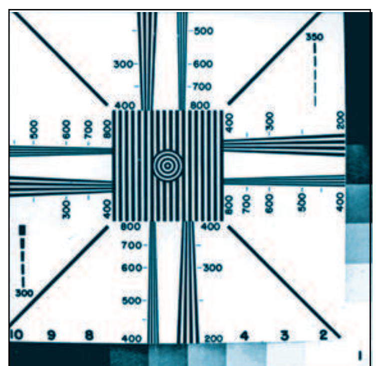


High-redshift supernova search

Need for improved CCD's (near-IR sensitive, inexpensive)

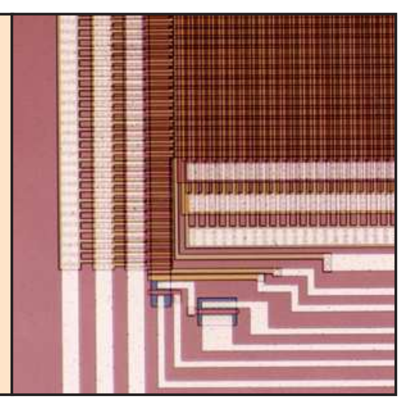


High-ρ, depleted *n*-type silicon, processed with active gettering



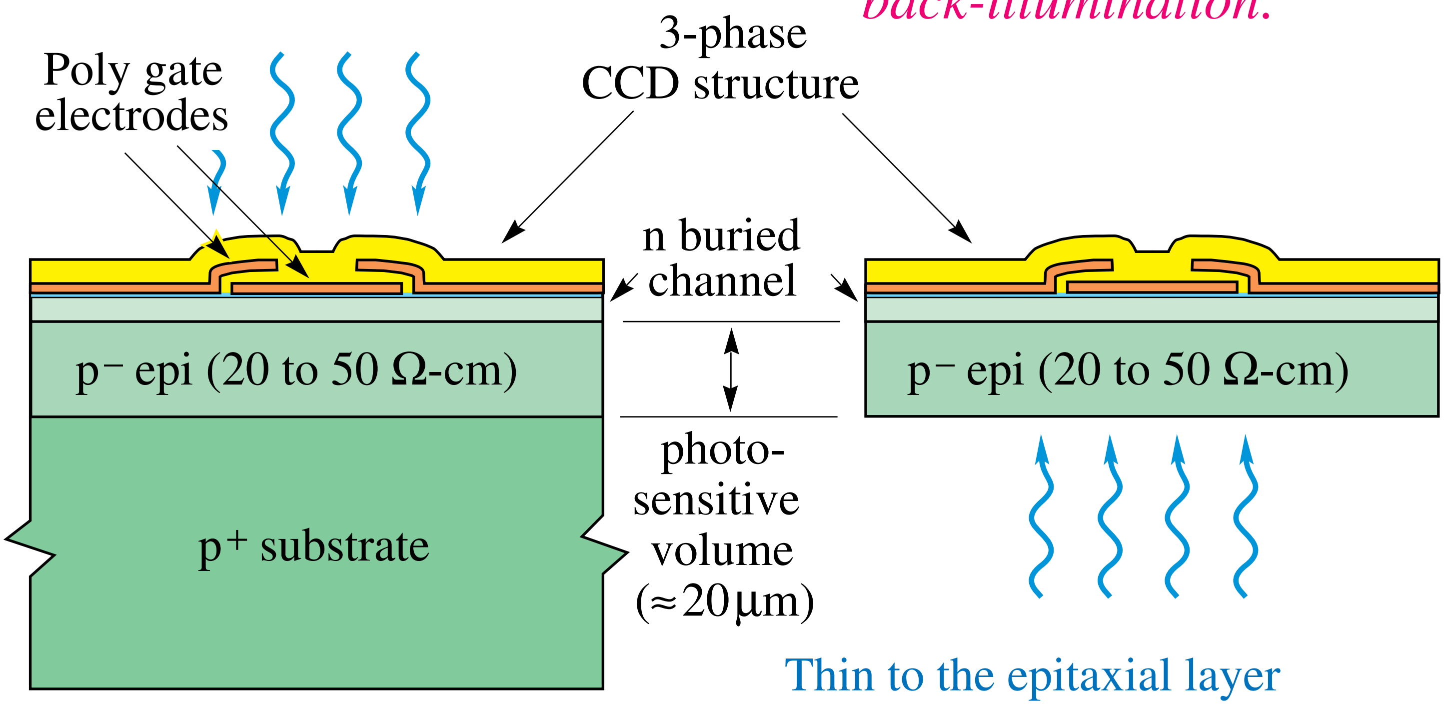
Testing at UCO/Lick

LBNL CCD's: high-ρ, depleted *n*-type silicon, not thinned



Front-illuminated CCD:

Thinned CCD with back-illumination:



Thin to the epitaxial layer thickness (≈20µm)

Drawbacks:

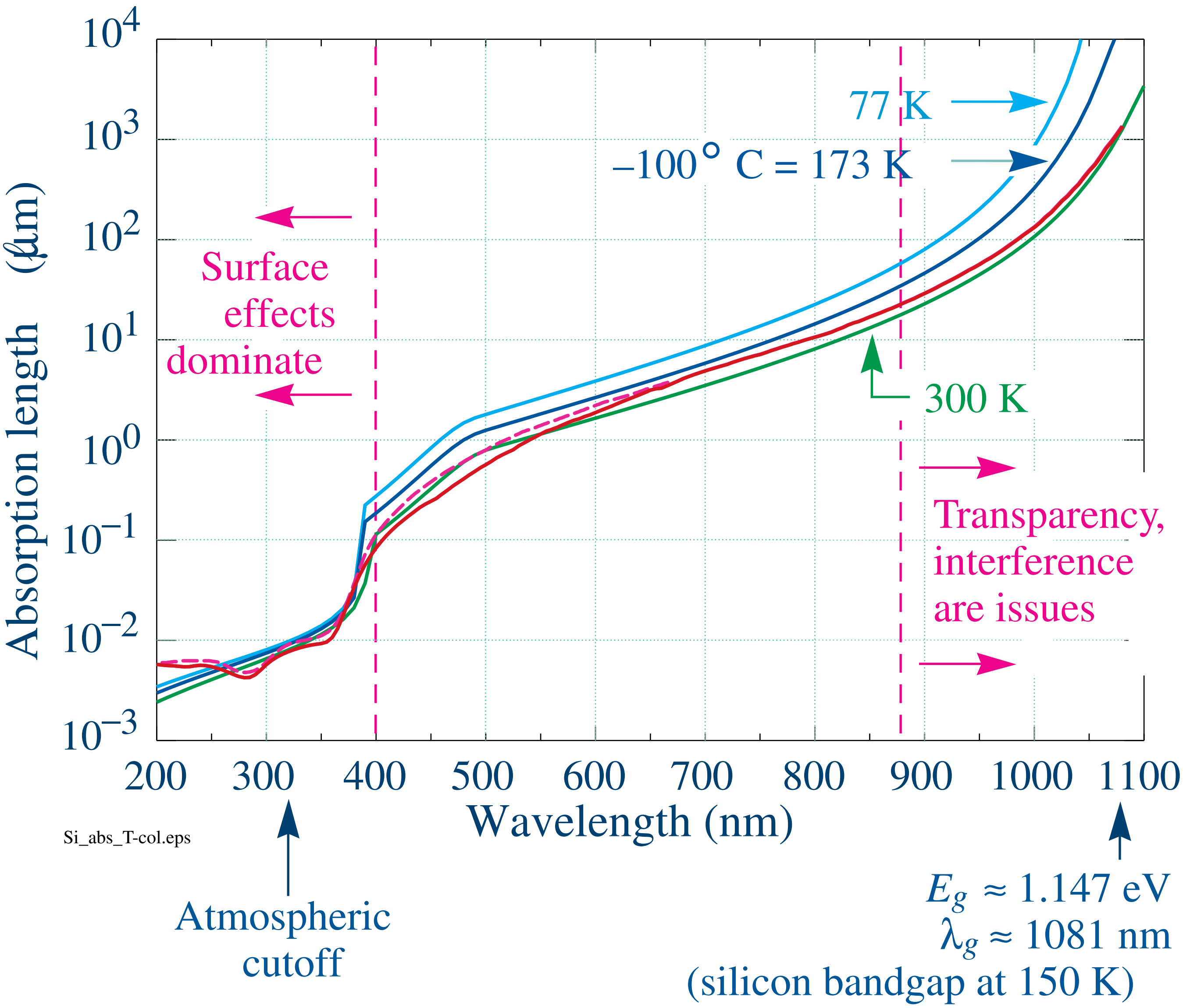
1) Poor blue response due to absorption in polysilicon gate electrodes
2) Poor near-IR response due to thinness of the epitaxial layer
3) Interference patterns due to gate structure

Drawbacks:

1) Thinning is difficult and expensive
2) Associated flatness problems
3) Requires back-side charging
4) Poor near-IR response
5) Interference (fringing)
6) Lateral diffusion in field-free region (degraded PSF)
7) *e* buildup at rear surface locally inverts field

seh_ccd.eps

This is the most important transparency I will show!

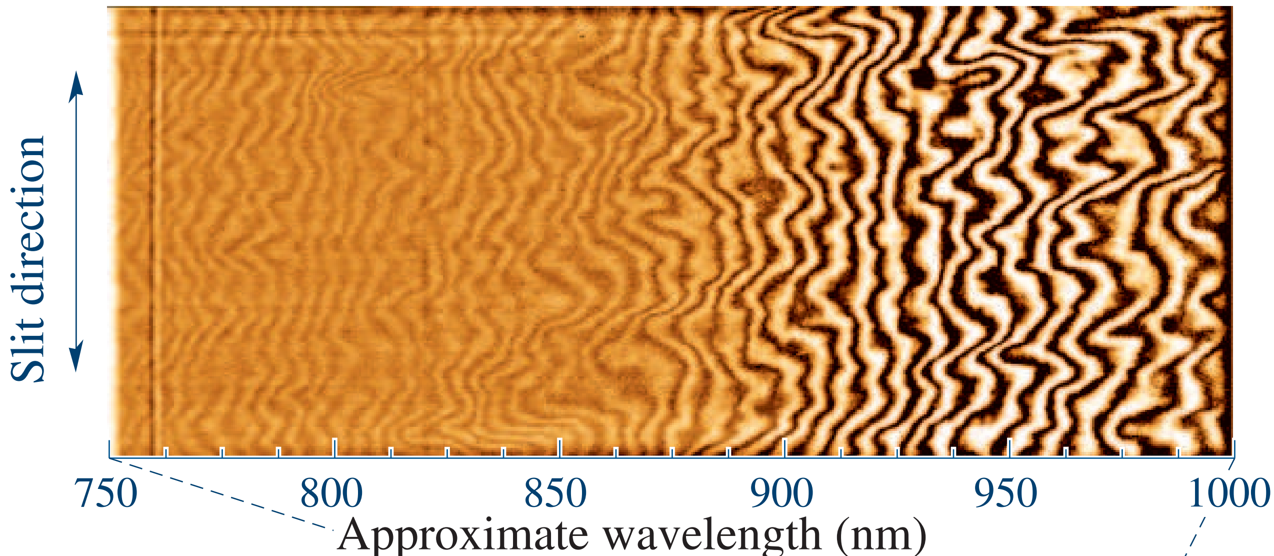


For the long wavelength end, temperature is important

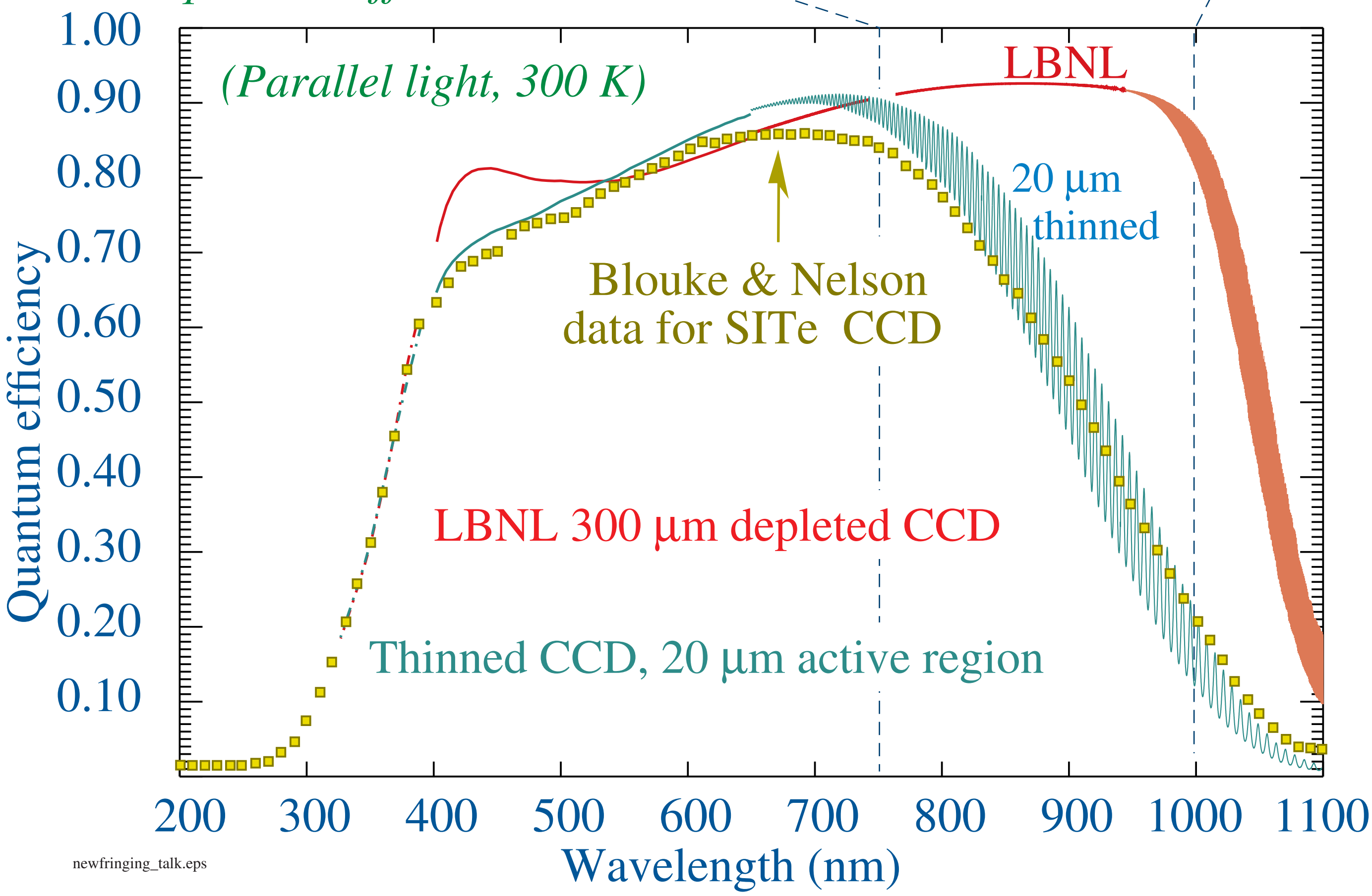
Astronomical CCD's operate near −100° C to achieve noise-limited performance

Red curve is empirical; other curves are calculated from phenomenological fits by Rajkanan *et al.*

Locally smoothed white-field spectrum with the Keck low-resolution spectrograph (< 1996 CCD):

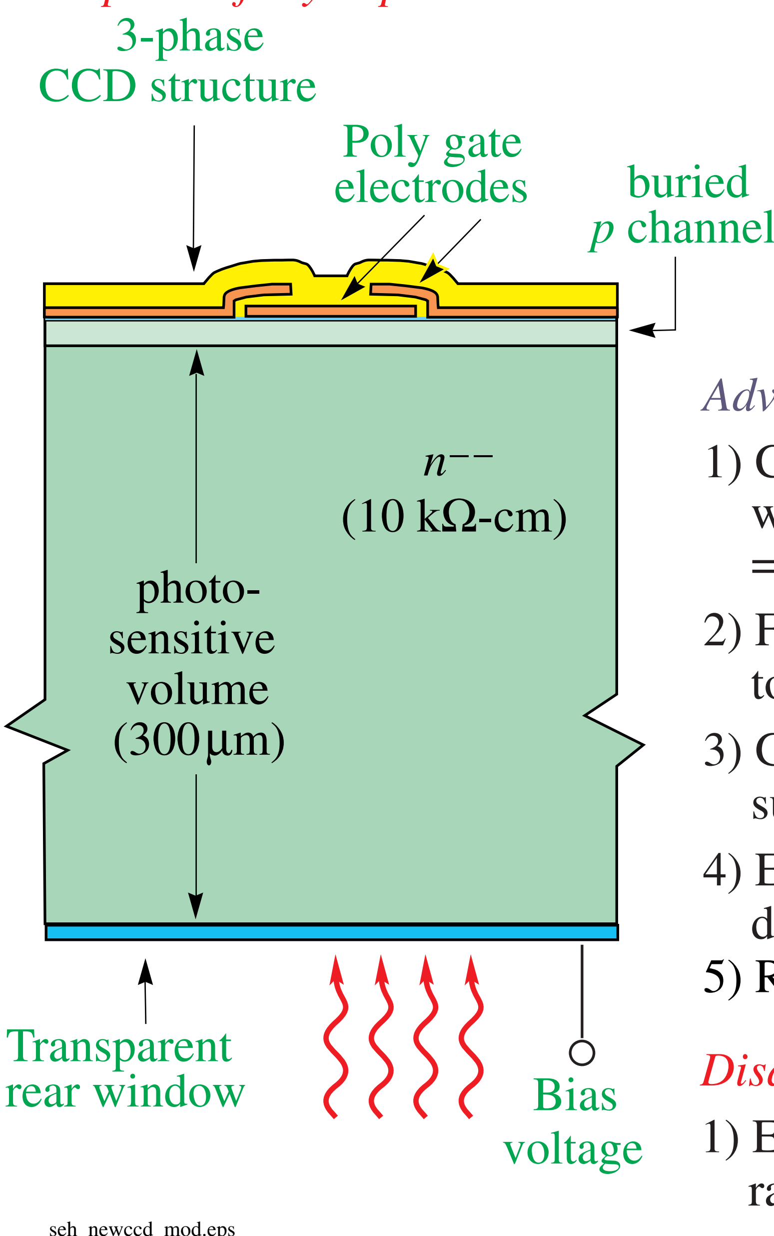


Calculated quantum efficiencies:



newfringing_talk.eps

The LBNL approach:
Make a thick CCD on a high-resistivity n-type substrate, to operate fully depleted with rear illumination.



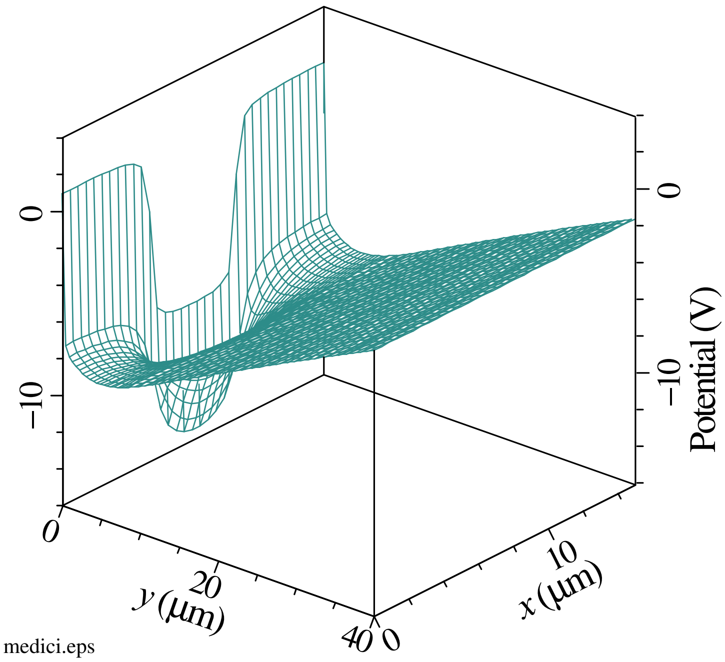
Advantages:

1) Conventional MOS processes with no thinning => "inexpensive"
2) Full quantum efficiency to > 1 µm => no fringing
3) Good blue response with suitably designed rear contact
4) Efficient low-energy x-ray detector
5) Radiation hard?

Disadvantages:

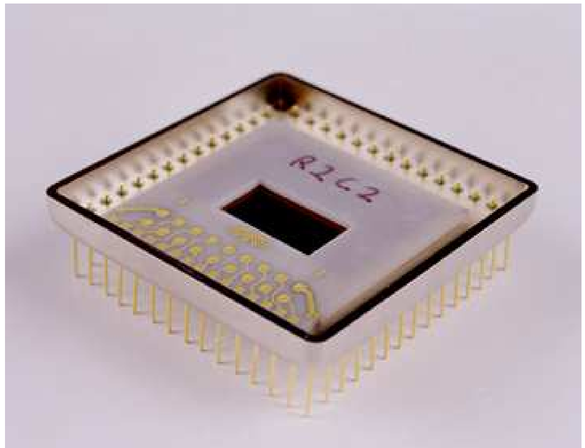
1) Enhanced sensitivity to radiation (x-rays, cosmic rays, radioactive decay)

Simulation results via MEDICI:



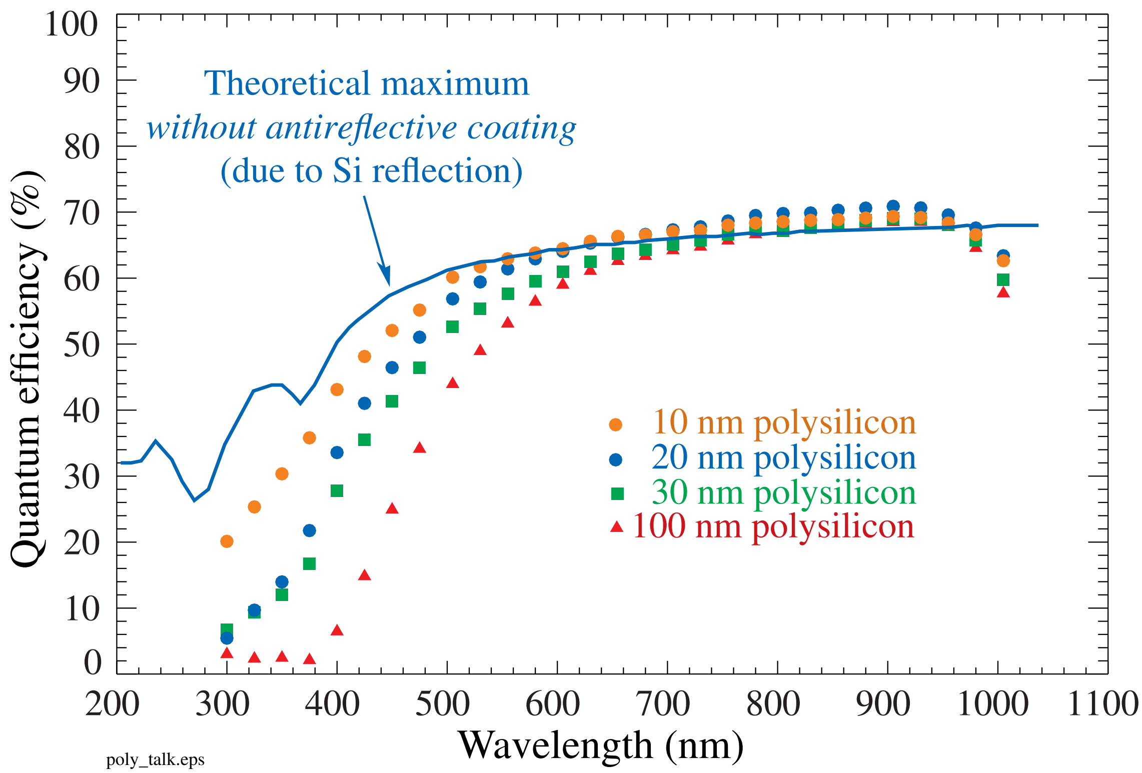
medici.eps

Prototype run (1996-97) 200 × 200 15-μm pixel CCD's plus hundred of test structures

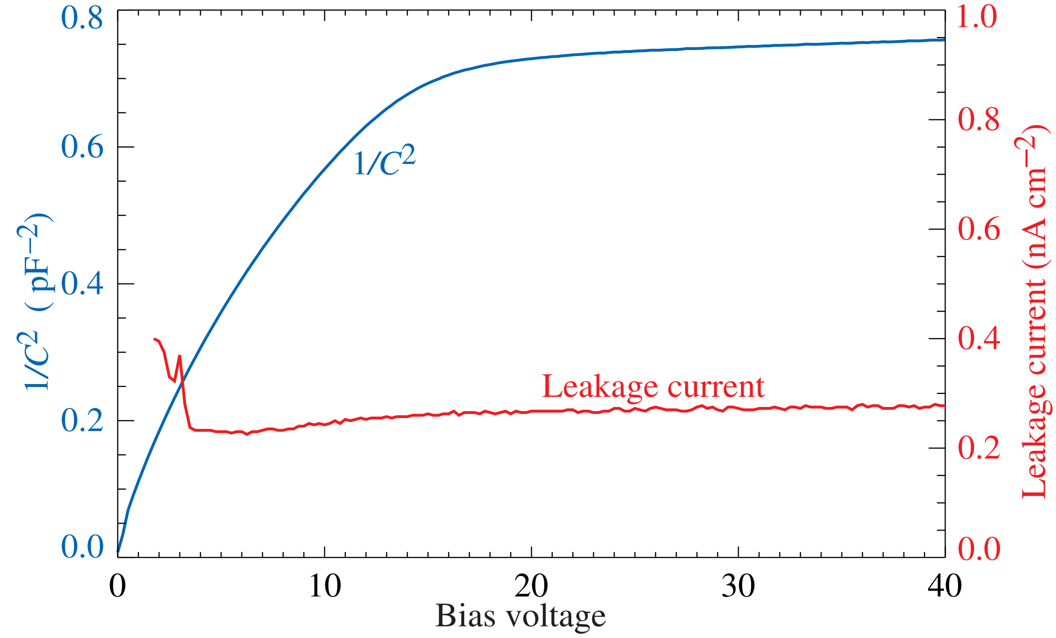


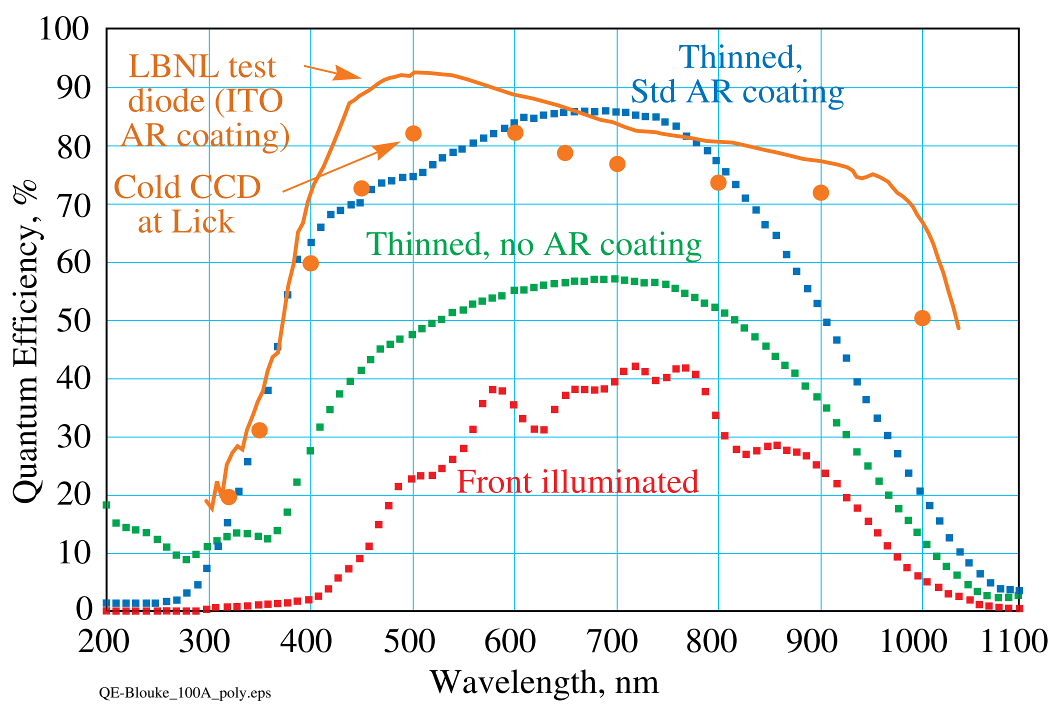
Issue 1: Rear window design

Maintaining minimal gettering:



Indium-tin oxide transparent electrode, for back-surface contact *and* antireflection coating

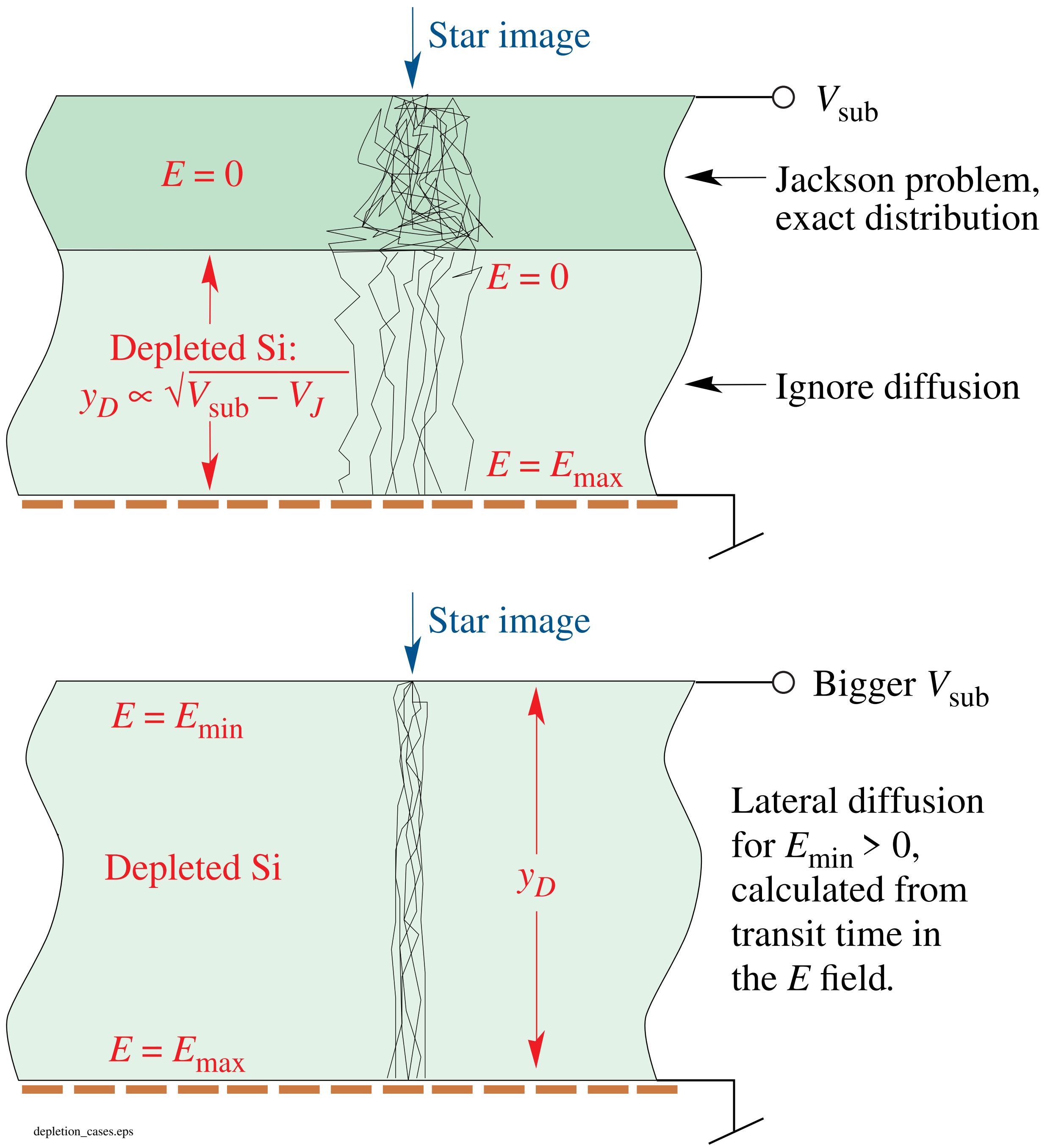




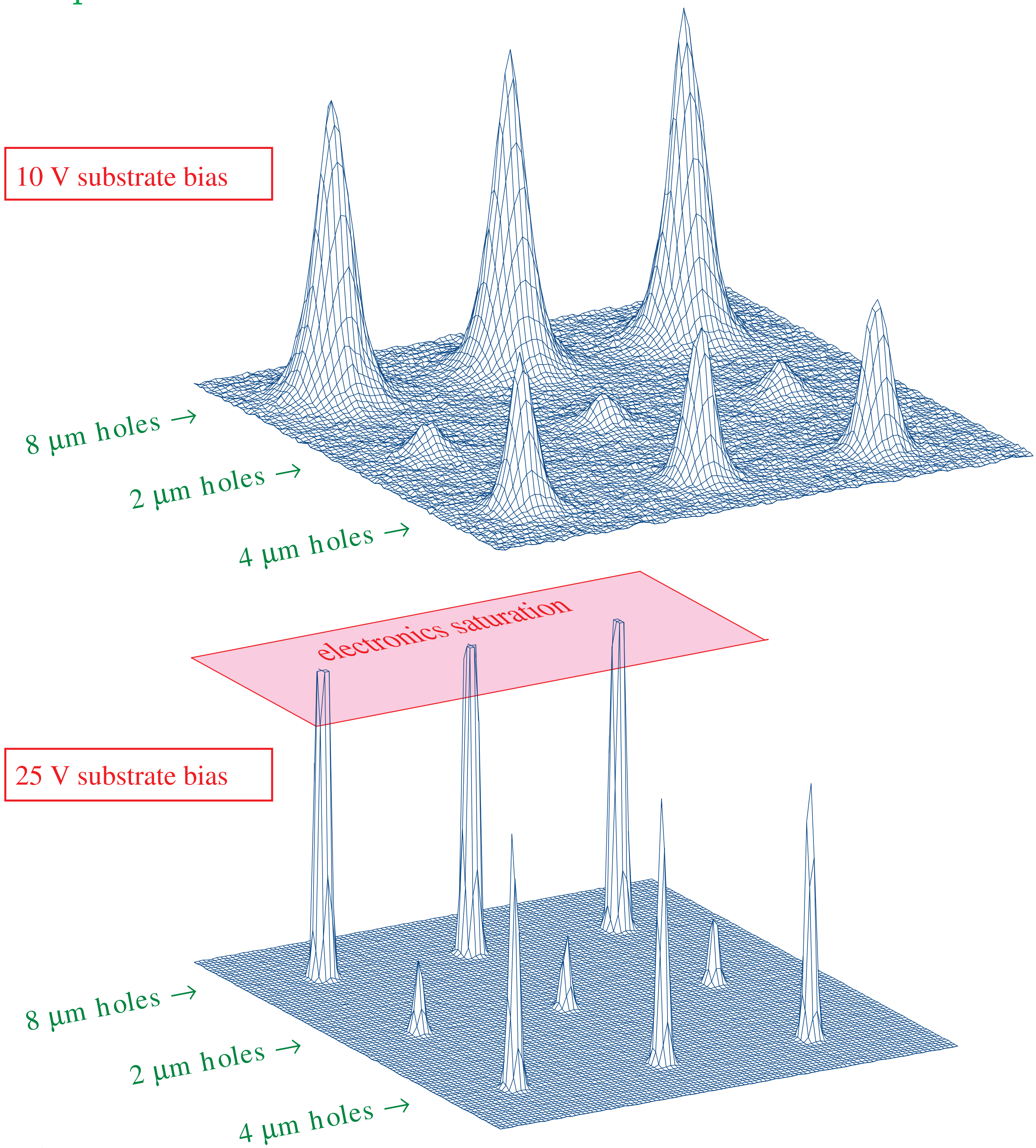
$\Longrightarrow$ Later, add SiO_2 to AR coating, to flatten QE and increase red and near-IR response

Issue 2: Spatial resolution

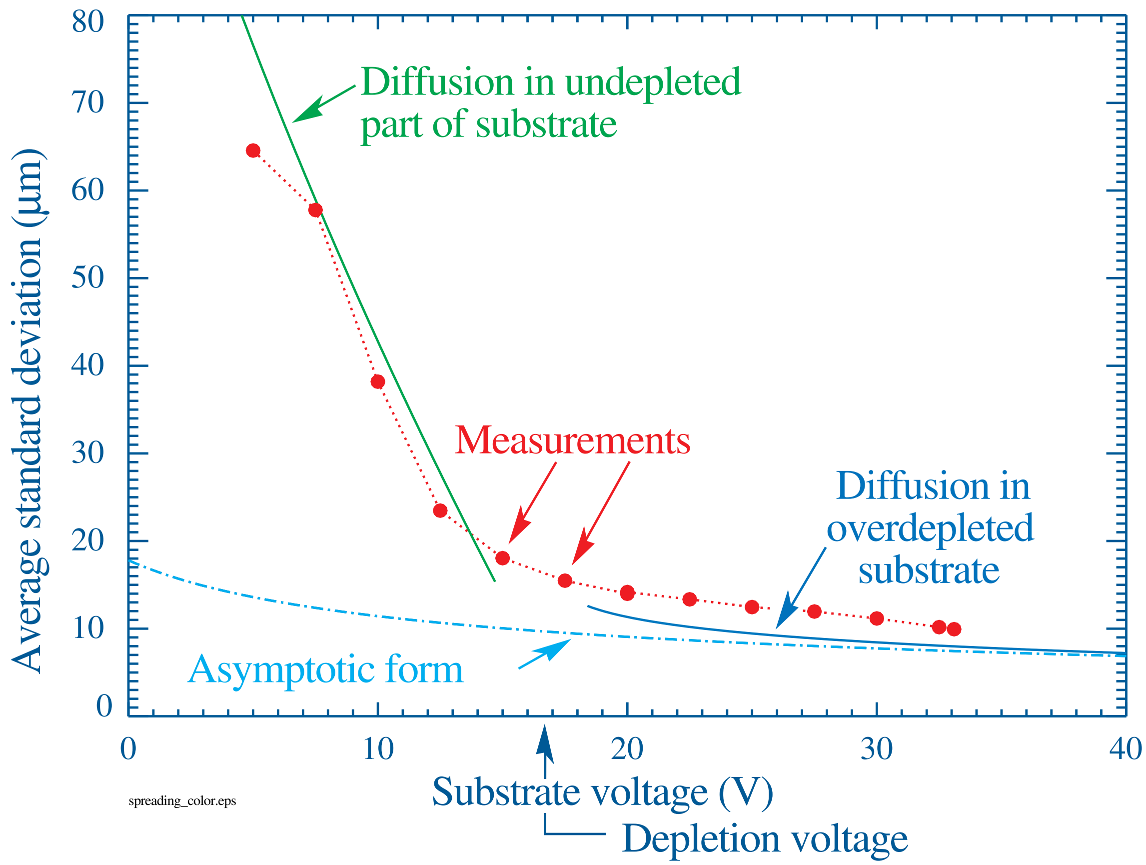
(diffusion of photo-generated holes during drift from back to potential wells)



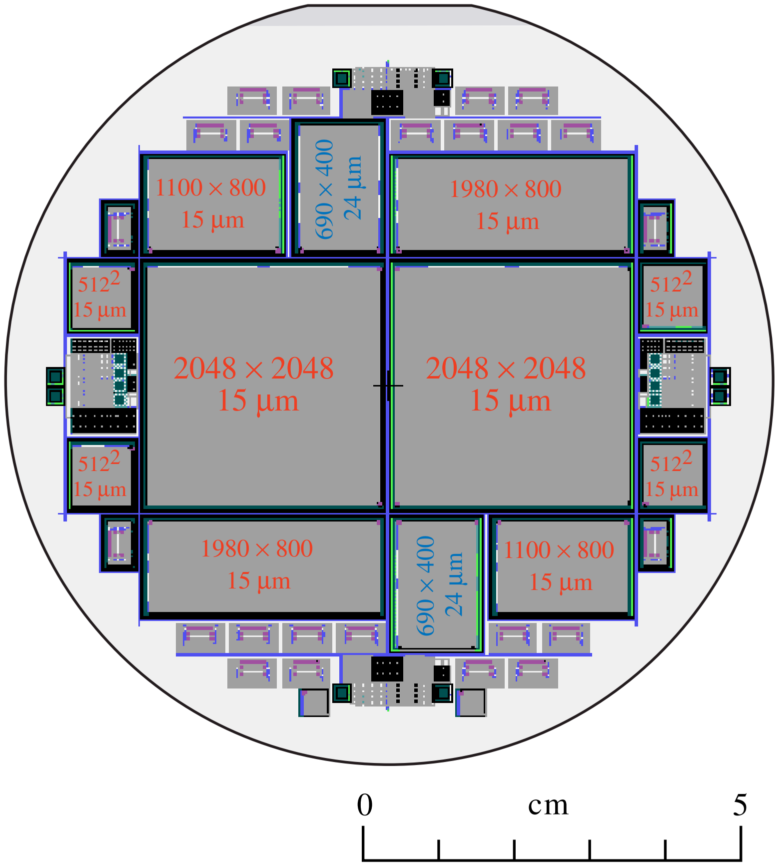
— Measured by exposing CCD to blue light through a pinhole mask



surface.eps


Diffusion in undepleted
part of substrate
Measurements
Diffusion in
overdepleted
substrate
Asymptotic form
Average standard deviation (μm)
Substrate voltage (V)
Depletion voltage
spreading_color.eps
0
10
20
30
40
50
60
70
80

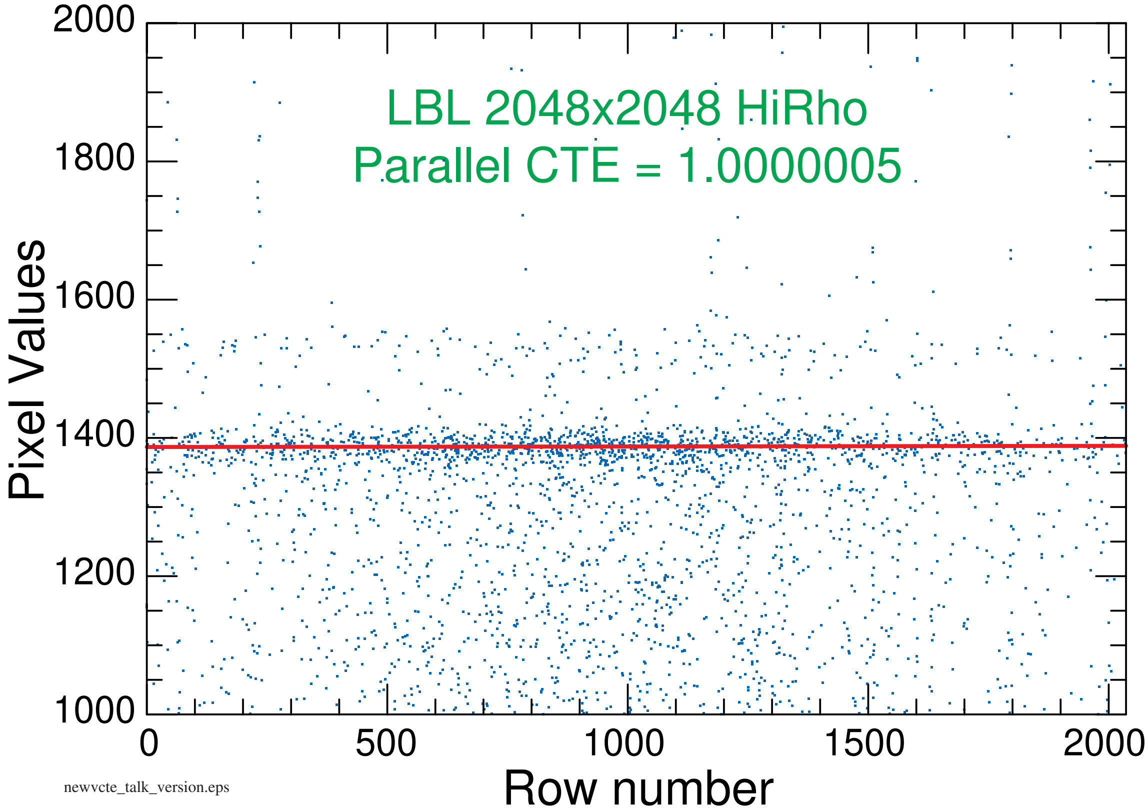
Large-format LBNL fabrication run (testing in progress)



- Variety of large-format CCD's, ranging up to 2048×2048 15-μm pixel chips
- Two amplifiers/CCD
- Frame store or frame transfer
- Serial notch implant for low-level CTE
- Two-layer (ITO + SiO_2) antireflective coating
- Output source follower variations for noise studies

Characterization at Lick/UCO

e.g. ^{55}Fe (K capture) $\rightarrow$ ^{55}Mn+ 5.90 keV (88%) or 6.49 keV (12%) x-rays:

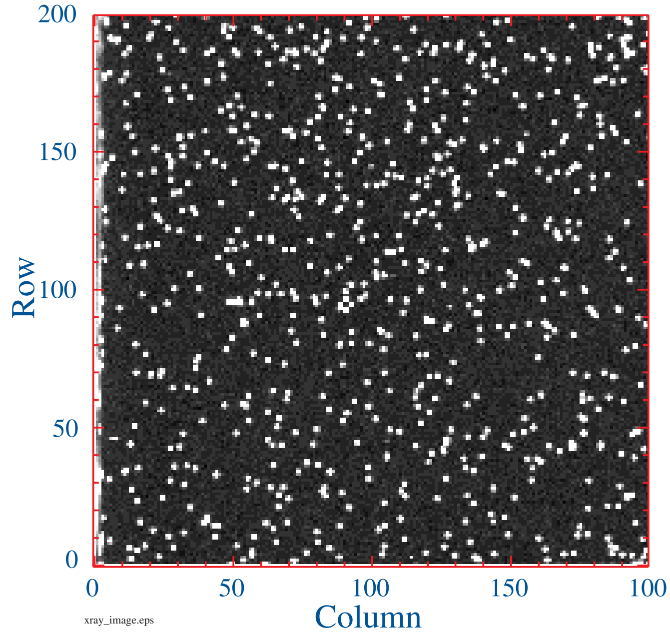


Typical test results at -125° C (?)

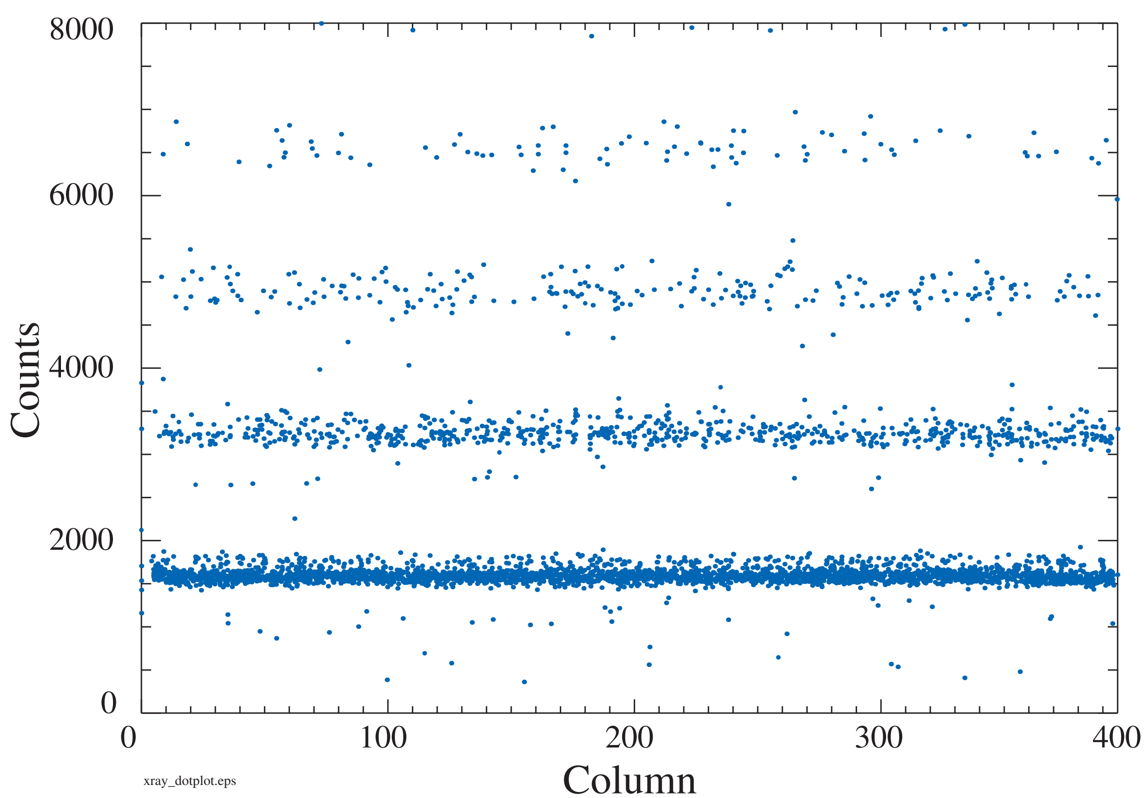
- Charge transfer efficiency $\gtrsim 0.999995$
- Read noise 4.0 e^- at 20 kpixels/s
- Dark current 0.003 e^-/pixel/s
- Full well > 300 ke^-

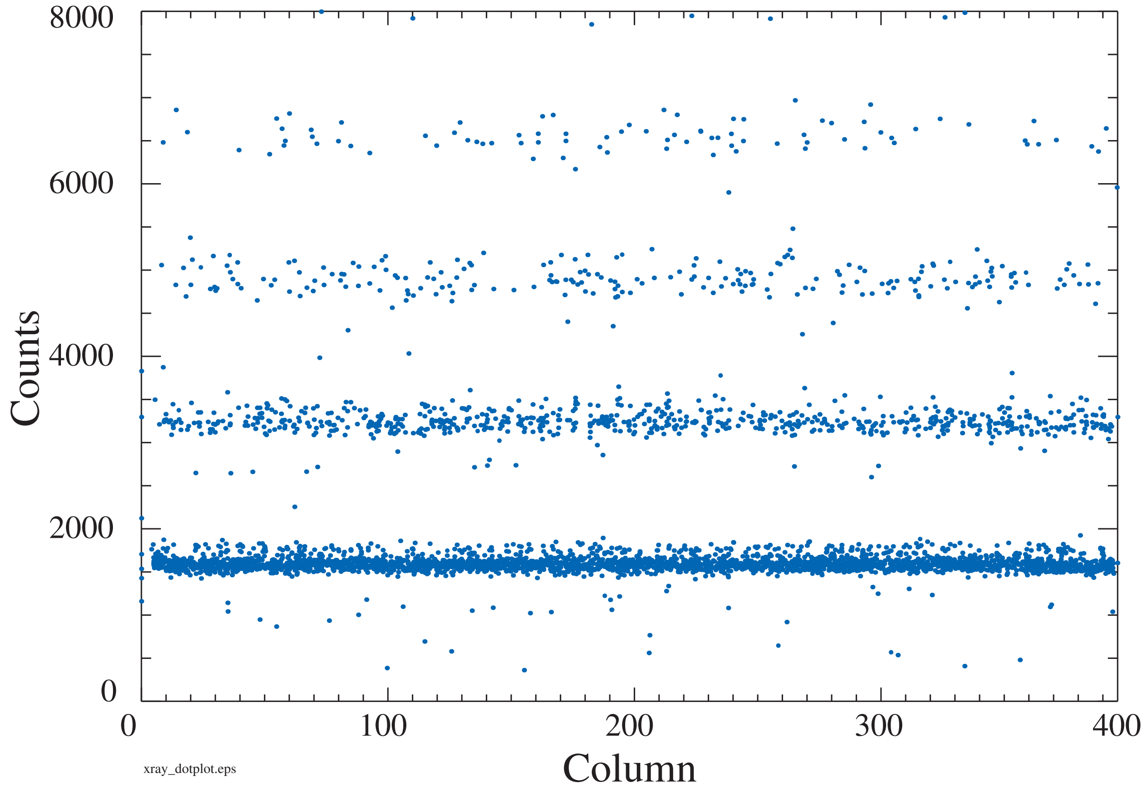
—— Measurements by Richard Stover and Mingzhi Wei at UCO/Lick Observatory

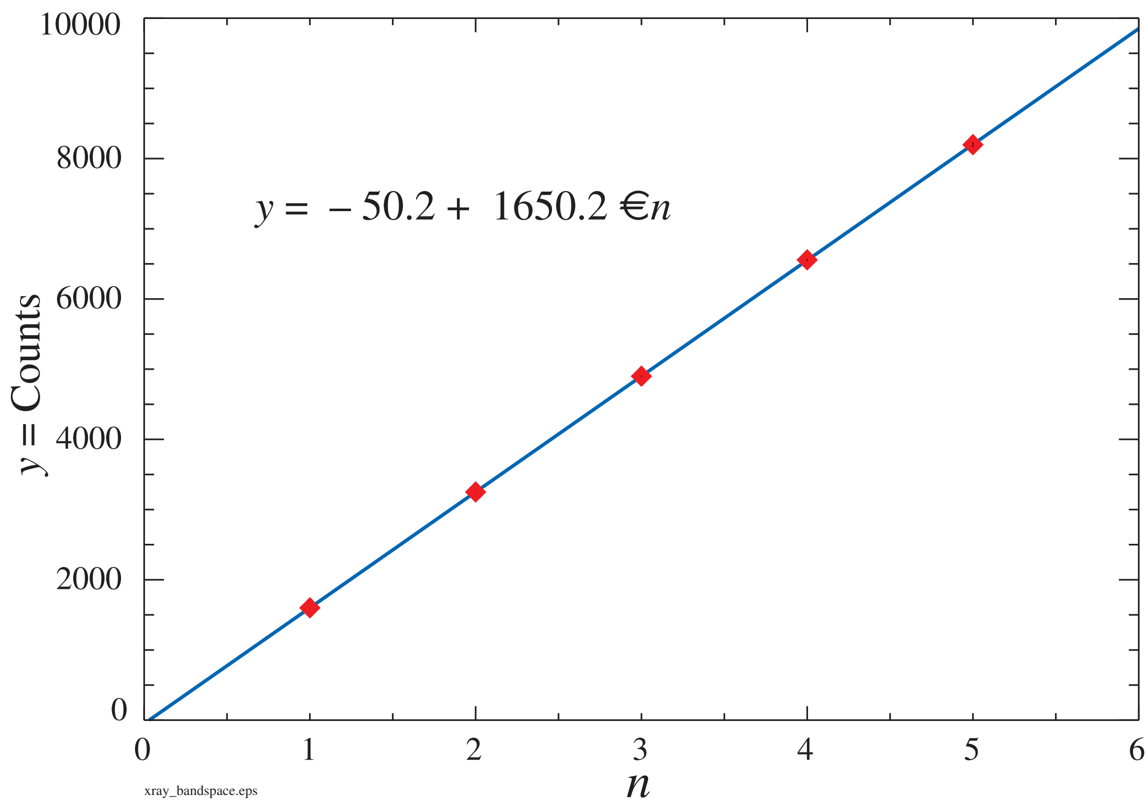
High-energy physicists might prefer to see the x-ray analysis done a different way. Because of pileup, each cluster can be 1, 2, 3, ...x-ray energy deposits:



(only corner of image is shown)

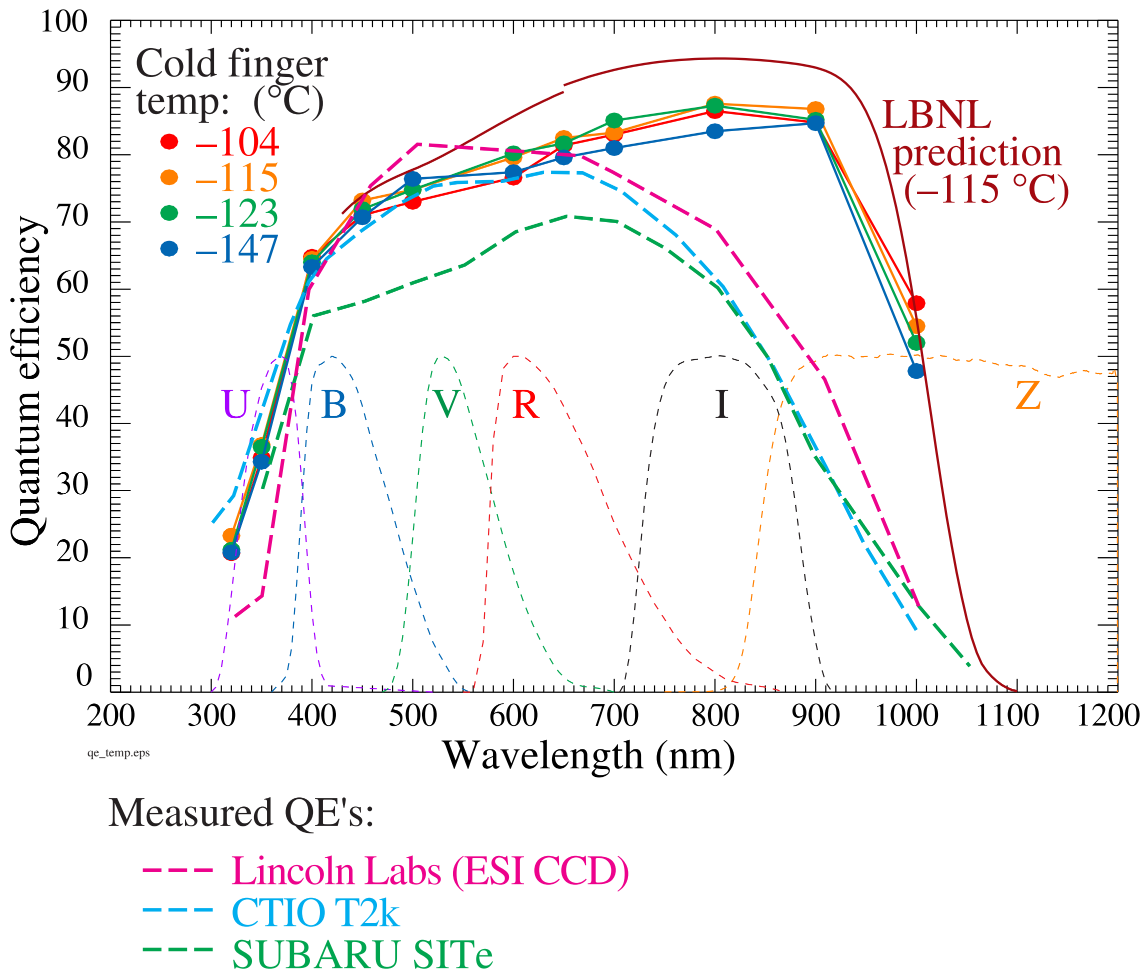



8000
6000
4000
2000
0
Counts
0
100
200
300
400
Column
xray_dotplot.eps


10000
8000
6000
4000
2000
0
y = Counts
y = − 50.2 + 1650.2 €n
0
1
2
3
4
5
6
n
xray_bandspace.eps

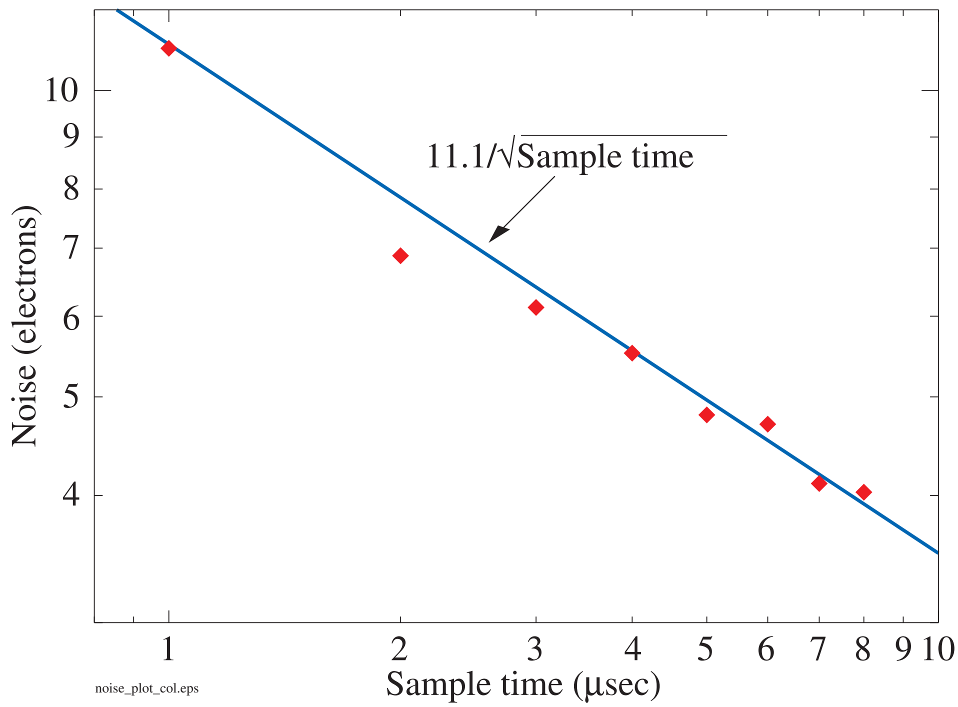
QE measurements are preliminary!

- Some of us believe the Lick measurements could be as much as 10% low
- The back window on this first back-illuminated large-format CCD was imperfect
- A 950 nm narrow-band filter was not available

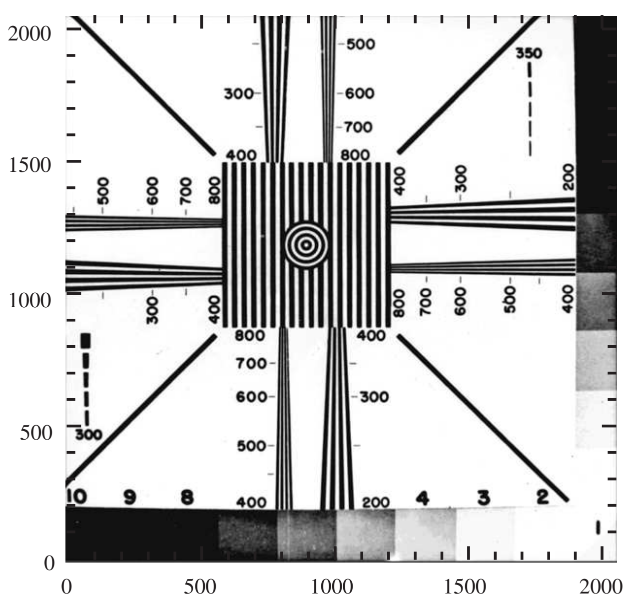


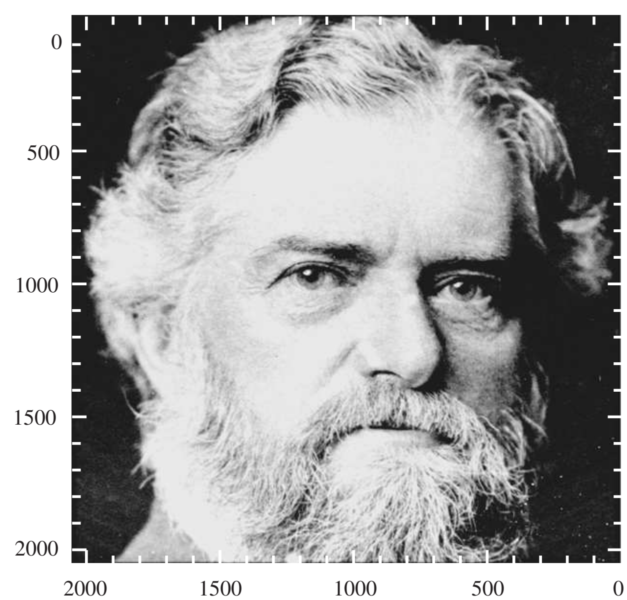
⟹ But blue response is at least as good as for other back-illuminated CCD's, and red response is far superior

Dependence of noise on readout speed:



And, finally, a test pattern and image of Simon Newcomb on the first back-illuminated 2048 $\times$ 2048 15 μm pixel LBNL CCD:

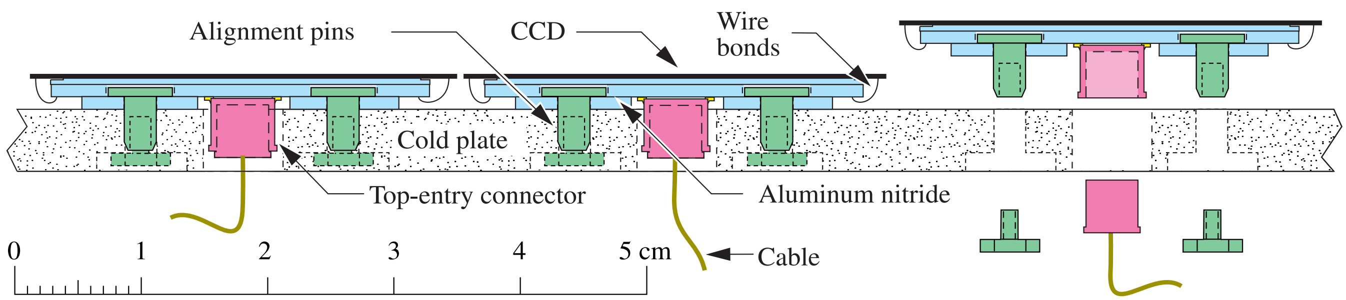




Packaging: default 4-side abutment

Unlike thinned CCD's, ours provide no back-side access to the connection pads!

Easiest approach seems to be to wirebond *inward*, to a circuit board epoxied to the "front" of the CCD



These connections could then be brought out the back, through a slit in the cold plate, via a subminature connector attached to the aluminum-nitride circuit card. Indexing/mounting pins are included in the package. Screw-in extenders facilitate installation and handling

Wirebonding to the cantilevered Si chip has already been demonstrated

The down side is that we need several wafer thicknesses between the pixels and the saw cut, or ~ 1 mm, to bring the fields down to zero

THE FUTURE

$\Longrightarrow$ Using present 2048×2048 15 μm pixel devices,

- make direct comparison to thinned CCD's in a Lick Observatory spectrometer
- develop mosaic imaging camera utilizing 4-side abutability

$\Longrightarrow$ 2048×4096 development for the ESI (Echellette Spectrograph & Imager) at the Keck Telescope

Further data and list of papers can be found at
`http://pdg.lbl.gov/~deg/ccd.html`

THE CONCLUSION IS EASILY STATED:

We believe that totally depleted CCD's of the kind described here will soon replace all others for astronomical applications

NGC 7662, Lick 1m with the 200×200 prototype LBNL CCD, 1996 Jul 30